

NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ
FACULTY OF PHYSICS, ASTRONOMY AND INFORMATICS
INSTITUTE OF ASTRONOMY



The Assembly of Star-Forming Galaxies: Evolution of the Main Sequence and Dust Obscuration out to $z \sim 6$

Jude Vijayanga Wijesekera

Dissertation submitted in partial fulfillment
of the requirements for the degree of
DOCTOR OF PHILOSOPHY IN ASTRONOMY

Doctoral thesis written under the supervision of:

dr hab. Maciej Koprowski, prof. UMK

&

auxiliary supervisor: dr hab. Magdalena Kunert-Bajraszewska, prof. UMK

Toruń, 2026

Abstract

One of the key challenges in observational astronomy is to understand the complete picture of star formation rate density (SFRD) across cosmic time. In this thesis, we aim to build on our previous knowledge by analysing two fields, COSMOS and UDS, and combining them with far-infrared maps from the *Herschel* Space Observatory and James Clerk Maxwell Telescope (JCMT) to analyse, through stacking, approximately 100,000 *K*-band-selected galaxies.

Throughout this thesis, I analyse three key areas: presenting a new determination of the star-forming main sequence (MS); presenting a new determination of the evolving far-infrared (FIR) galaxy luminosity function (LF) and the resulting inferred evolution of dust-obscured star-formation rate density (ρ_{SFR}) out to redshift $z \sim 6$; and presenting an evolution of dust attenuation in star-forming galaxies with UV slope, stellar mass, and redshift out to $z \sim 5$.

In the first part of the research, we apply the dust emission curve to the stacked FIR photometry to derive IR luminosities and their associated star formation rates (SFRs). We find that the function form of the MS is linear with the $\text{SFR}-M_{\star}$ relationship that flattens at high stellar mass and that normalization increases exponentially with redshift. We also show that the peak dust temperature increases steadily from 20 K at $z = 0.5$ to about 50 K at $z = 5$. Variability in the shapes of the MS is most likely related to the different dust temperatures assumed when deriving SFRs in the absence of FIR data.

In the second part, we estimate the contribution of faint and low-mass sources to the LF. By adding high-resolution ALMA follow-up study of the JCMT SCUBA-2 S2CLS submillimeter imaging, we estimate the contribution of bright and high-

mass sources to the bright end of the LF. Our results find that the evolution of the characteristic luminosity (L_*) increases monotonically with redshift, evolving as $L_* \propto z^{1.38 \pm 0.07}$, while the typical number density (Φ_*) stays the same up to $z \simeq 2.24$ and then declines as $z^{-4.95 \pm 0.73}$ at higher redshift. By summing this evolving LF, we can directly measure the cosmic dust-obscured star-formation rate density up to $z \sim 6$.

The final part of this research is a calibration of the so-called infrared excess ($IRX \equiv L_{IR}/L_{UV}$) with its dependence on the physical properties of galaxies. We find that the IRX – β relationship matches a standard Calzetti-like curve for redder galaxies ($\beta \geq -1$), but the slope of this curve becomes less steep as stellar mass increases. We develop a mass-dependent $IRX - \beta$ calibration where the reddening law slope follows a tight quadratic function on stellar mass, $\mathcal{M} = \log(M_*/M_\odot)$. We further identify a tight $IRX - M_*$ correlation that increases monotonically but exhibits a significant turnover at the highest masses for $z \leq 2 - 3$, consistent with the suppression of gas accretion and dust growth in the most massive systems.

Streszczenie

Jednym z kluczowych wyzwań astronomii obserwacyjnej jest zrozumienie pełnego obrazu gęstości tempa formowania się gwiazd (SFRD) w czasie kosmicznym. W niniejszej pracy zamierzamy wykorzystać naszą dotychczasową wiedzę, analizując dwa pola, COSMOS i UDS, i łącząc je z mapami dalekiej podczerwieni z Obserwatorium Kosmicznego Herschela i Teleskopu Jamesa Clerka Maxwella (JCMT), aby przeanalizować, poprzez nałożenie, około 100 000 galaktyk wybranych w paśmie K.

W niniejszej pracy analizuję trzy kluczowe obszary: przedstawiam nowe określenie głównego ciągu formowania się gwiazd (MS); przedstawiam nowe określenie funkcji jasności ewoluującej galaktyki (LF) w dalekiej podczerwieni (FIR) i wynikającą z tego wnioskowaną ewolucję gęstości tempa formowania się gwiazd (SFR) w przesłoniętym pyłem obszarze do przesunięcia ku czerwieni z 6; i przedstawia ewolucję tłumienia pyłu w galaktykach gwiazdotwórczych z nachyleniem UV, masą gwiazdową i przesunięciem ku czerwieni do $z \sim 5$.

W pierwszej części badań stosujemy krzywą emisji pyłu do fotometrii w podczerwieni (FIR), aby wyznaczyć jasności w podczerwieni i związane z nimi wskaźniki formowania się gwiazd (SFR). Stwierdzamy, że postać funkcyjna MS jest liniowa z zależnością $SFR-M_*$, która spłaszcza się przy wysokiej masie gwiazdowej, a normalizacja rośnie wykładniczo wraz z przesunięciem ku czerwieni. Wykazujemy również, że szczytowa temperatura pyłu stale rośnie od 20 K przy $z = 0,5$ do około 50 K przy $z = 5$. Zmienność kształtu MS jest najprawdopodobniej związana z różnymi temperaturami pyłu przyjmowanymi podczas wyznaczania wskaźników formowania się gwiazd przy braku danych FIR.

W drugiej części szacujemy wkład słabych i małowasywnych źródeł do LF.

Dodając wysokorozdzielcze badanie ALMA obrazowania submilimetrowego JCMT SCUBA-2 S2CLS, szacujemy udział jasnych i wysokomasywnych źródeł w jasnym końcu pasma niskich częstotliwości. Nasze wyniki wskazują, że ewolucja charakterystycznej jasności (L_*) rośnie monotonicznie wraz z przesunięciem ku czerwieni, ewoluując wraz z $L_* \propto z^{1,38 \pm 0,07}$, podczas gdy typowa gęstość liczbowa (Φ_*) pozostaje taka sama do $z \simeq 2,24$, a następnie spada wraz z $z^{-4,95 \pm 0,73}$ przy wyższych przesunięciach ku czerwieni. Sumując te ewoluujące pasma niskich częstotliwości, możemy bezpośrednio zmierzyć gęstość tempa formowania się gwiazd przesłoniętego pyłem kosmicznym do $z \sim 6$.

Ostatnim etapem tych badań jest kalibracja tzw. nadmiaru promieniowania podczerwonego ($\text{IRX} \equiv L_{\text{IR}}/L_{\text{UV}}$) wraz z jego zależnością od właściwości fizycznych galaktyk. Stwierdzamy, że zależność $\text{IRX}-\beta$ odpowiada standardowej krzywej podobnej do krzywej Calzettiego dla bardziej czerwonych galaktyk ($\beta \geq -1$), ale nachylenie tej krzywej staje się mniej strome wraz ze wzrostem masy gwiazdowej. Podsumowując, wprowadzamy nową metodę opartą na masie, aby dokładniej korygować próbki galaktyk w zakresie promieniowania ultrafioletowego/optycznego pod kątem absorpcji pyłu.

Acknowledgements

First and foremost, I wish to express my heartfelt gratitude to my supervisors, Dr. hab. Maciej Koprowski, Prof. UMK, and Dr. hab. Magdalena Kunert-Bajraszewska, Prof. UMK, for selecting me and believing in me throughout my PhD journey. I am sincerely grateful for their guidance, patience, and support during my most challenging times. I would especially like to thank my primary supervisor, Dr. hab. Maciej Koprowski; you have shown me what it means to be a top-notch yet humble researcher and have provided the best example of academic excellence and professionalism. Under his mentorship, I gained invaluable lessons in critical thinking and problem-solving. I will deeply miss our engaging conversations about astronomy and nature.

My sincere gratitude to our PhD director, Prof. Dr. hab. Wiesław Nowak; without his guidance, I would not have been able to continue my career. Also, my gratitude goes to our AST secretary, Agnieszka Górską-Pukownik, for her support. Special thanks to our director of the Institute of Astronomy, Dr Hab. Krzysztof Katarzyński, for understanding my situation during my accident.

My heartfelt gratitude to my dear, beautiful wife, Meriesha, for her understanding, patience, support, and care throughout my PhD. I also want to thank my lovely daughter, Joanna, for her bright smile and the joy she brought, which made even the toughest days so much brighter. I'm truly blessed to have both of you in my life. A very special thanks to my entire family, Nimali; my father, Wolvin; and my wife's entire family: her mother, Creeta; her father, Clement; and her grandpa.

I would also like to express my gratitude to the National Science Centre, Poland (SONATA 16 grant 2020/39/D/ST9/03078). Finally, I want to express my deep

gratitude to God Almighty, Father of Jesus Christ, for the opportunity to study His beautiful Universe, for giving me a second chance to return to live with my family, and for all the grace He has shown me.

Declaration

Except where otherwise stated, the research undertaken in this thesis was the unaided work of the author. Where the work was done in collaboration with others, a significant contribution was made by the author. Also, this work has not been submitted for any other degree or professional qualification except as specified.

J. V. Wijesekera

27th April 2026

Contents

Abstract	ii
Streszczenie	iv
Contents	ix
List of Abbreviations	xii
List of Figures	xiv
List of Tables	xvii
1 Introduction	1
1.1 Selection of high-redshift star-forming galaxies	1
1.1.1 What are star-forming galaxies?	2
1.1.2 Local infrared-luminous galaxies	2
1.1.3 Negative K-correction	3
1.1.4 Instruments and Most Important Surveys	5
1.1.5 Variations in Spectral Energy Distributions	9
1.1.6 Identification of Multi-wavelength counterparts	10
1.2 Far-Infrared and sub-millimetre maps	14
1.2.1 <i>Herschel</i> maps	14
1.2.2 sub-millimetre maps	14
1.2.3 Monte Carlo Simulations	15
1.2.4 Estimation of Observational Parameters	16
1.2.5 Number Counts	17

1.3	Redshifts & Spectral Energy Distribution fitting.	18
1.3.1	SED fitting techniques	18
1.3.2	Extracting physical properties of galaxies from SED	19
1.3.3	Acquiring redshifts	21
1.3.4	Redshifts distribution	21
1.4	Stacking method	23
1.4.1	Basic definition	23
1.4.2	Confusion Noise	23
1.5	Molecular gas and Star formation	24
1.5.1	Detection of Molecular gas	24
1.5.2	Deriving conversion factor of CO-to-H ₂	24
1.5.3	CO-Excitation ladder	25
1.5.4	Molecular gas mass & CO line Luminosity	26
1.5.5	Molecular gas fraction and gas consumption	28
1.6	Physical properties & Galaxy Evolution	29
1.6.1	Stellar masses	29
1.6.2	Star formation rates	31
1.6.3	Cosmic Infrared Background	34
1.6.4	Specific Star formation rates and the main sequence	34
1.6.5	Calibration of IRX- β and IRX- $M_{\star}$	35
1.6.6	Luminosity function	37
1.6.7	Star formation rate density	39
	References	43
	Publications constituting the dissertation	57
	Author Contribution statement	60
	The tasks of the PhD project	63
	Papers	64
1.7	Article A	64

1.8 Article B	77
1.9 Article C	92
Co-author contribution statements	106
1.10 Article A	106
1.11 Article B	112
1.12 Article C	118
Summary and future projects	124
1.13 Summary	124
1.13.1 Summary	124
1.13.2 Future work	127

List of Abbreviations

AGN Active Galactic Nucleus. 9, 19, 26, 31, 33, 37

ALMA Atacama Large Millimetre/submillimeter Array. 6

CIB Cosmic Infrared Background. 34

DSFGs Dusty Star-Forming Galaxies. 1, 9–11, 14, 15, 19, 20, 23, 29, 34

FIR Far-Infrared. 1, 6, 10, 14, 19, 32, 36

HR Hertzsprung–Russell. 30

IMF Initial Mass Function. 19, 20, 29–31, 33

IRAS Infrared Astronomical Satellite. xiv, 3, 34

LF Luminosity Function. 37–39

LIRGs Luminous Infrared Galaxies. xvi, 39, 41

MIR Mid-Infrared. 1, 10

NIR Near-Infrared. 1, 6, 12

SED Spectral Energy Distribution. xv, 9, 10, 15, 18–21, 29

SFGs Star-Forming Galaxies. xvi, 1, 2, 5, 18, 36

SFH Star Formation History. 19, 20, 29, 30

SFR Star Formation Rate. xvi, 2, 19, 23, 29, 31–36, 38, 40, 41

SFRD Star Formation Rate Density. 38–42

SMG Sub-Millimeter Galaxy. xv, 6, 12, 13, 22, 26, 29

SPS Stellar Population Synthesis. 30

sSFR Specific Star Formation Rate. 34, 35

SSP Simple Stellar Population. 29

ULIRGs Ultra-Luminous Infrared Galaxies. xiv, xvi, 5, 39, 41

UV Ultraviolet. xiv, 1–3, 20, 30–33, 35–37, 40–42

List of Figures

1.1	IRAS 08572+3915 is observed across a variety of wavelengths. The color composite in the center represents wavelengths from far-UV to near-infrared, using a blue-to-red color scheme, and highlights the intricate composite characteristics of ULIRG systems. Lonsdale et al. (2006).	3
1.2	The figure illustrates the observed fluxes of a typical ULIRGs across a wide range of redshifts ($1 \leq z \leq 10$). The main key feature is that the flux densities remain constant within the ~ 1 mm band up to $z \sim 10$. Two data models are used to simulate how the observed flux varies with the redshifts. One dataset uses a composite spectrum from typical submillimeter galaxies (mid-infrared to radio wavelengths), and the other uses a scaled spectrum based on the galaxy Arp 220 (optical and near-infrared wavelengths). The solid grey band marks the redshift range ($0.5 \leq z \leq 3.0$) where such galaxies have been most easily detected and studied, and also those selected at $850 \mu m$ (Cowie et al., 1996). The grey shaded areas represent redshifts where these extremely luminous objects are considered rare: in the left area at low redshift ($z \leq 0.5$) because there are not many of them, and in the right area at high redshift ($3.5 \leq z \leq 6.3$) because they are challenging to confirm spectroscopically. So far, no purely star-forming galaxy of this kind has been found beyond $z \approx 6.4$. Figure adopted from Casey et al. (2014).	5

- 1.3 Variation in DSFG spectral energy distributions (SEDs) with dust temperature. Colder dust shifts the peak toward longer wavelengths, whereas warmer dust shifts it toward shorter wavelengths. Vertical dashed lines indicate common survey bands at $250\,\mu\text{m}$ and $850\,\mu\text{m}$ 10
- 1.4 This figure illustrates the submillimeter galaxy SXDF 850.6 at different wavelengths. From left to right, it displays optical and near-infrared images (using filters from u to K bands), **Spitzer** IRAC mid-infrared channels (3.6 , 4.5 , 5.8 , and $8.0\,\mu\text{m}$), MIPS $24\,\mu\text{m}$, and VLA $21\,\text{cm}$ radio data. The SMA $880\,\mu\text{m}$ contours range from 2σ to 5σ . The source is not detected in optical or near-infrared images, but it becomes clearer at longer wavelengths, exhibiting a distinct radio counterpart. This pattern highlights the importance of multi-wavelength observations for finding dusty, high-redshift galaxies. Figure adapted from Hatsukade et al. (2010). 11
- 1.5 Example of various beam sizes across different maps with wavelengths ranging from $3.6\,\mu\text{m}$ to $500\,\mu\text{m}$. The top three beam sizes exhibit lower confusion levels and higher resolution compared to the bottom three. In contrast, the larger beam sizes in the lower section result in the total flux being a mix of multiple sources. The image was created using Gemini A.I. 16
- 1.6 A combined continuum-subtracted spectrum in the rest-frame range of $0.4 - 1.2\,\text{mm}$ high-redshift submillimeter galaxies has been created from 22 SPT SMGs, displayed at a resolution of $500\,\text{km s}^{-1}$. Notable CO and CI lines, among others, are distinctly observable. The middle panel illustrates the signal-to-noise ratio (SNR) corresponding to the top panel. This figure is taken from Spilker et al. (2014). 22
- 1.7 CO excitation ladder, i.e. the CO line flux $S_{J-(J-1)}$ as a function of J and normalized to $S_{1\rightarrow 0}$, are colored for different source types and connected for individual objects. The dashed gray line shows constant brightness temperature on the R-J scale, i.e. $S \propto \nu^2$. Image extracted from the Carilli and Walter (2013). 27

1.8	The plot represents the SFR- $M_{\odot}$ relation for SFGs ($1.5 < z < 2.5$) observed in PACS/ <i>Herschel</i> from COSMOS and GOODS fields. The solid black line shows the main sequence (MS) of these galaxies at a mean redshifts $z \sim 2$, according to Daddi et al. (2007). Above this line we have the starburst region, as shown by the dashed and dotted lines. The image is drawn from (Rodighiero et al. (2011)).	36
1.9	The evolution of the integrated infrared (8–1000 μm) luminosity function across redshift, showing a strong increase in the characteristic luminosity $L_{\star}$ with lookback time. Adapted from Casey et al. (2014).	40
1.10	The contribution of infrared luminosity-binned (sub-LIRGs, LIRGs, & ULIRGs) galaxies to the total cosmic SFR density, showing the preeminent role of LIRGs at $z \sim 1$ and ULIRGS at $z \gtrsim 1.5$. Adapted from Casey et al. (2014).	41
1.11	The cosmic star formation history	42

List of Tables

1.1	Single-dish facilities used for DSFG discovery.	7
1.2	Single-dish submm surveys.	9

Introduction

Over the three years of the PhD programme, I have studied and analysed in depth the history of star formation, extending to epochs when the Universe was only 1% of its current age. This introduction provides the background in observational astronomy that we used in our thesis.

1.1 Selection of high-redshift star-forming galaxies

One of the main challenges in observational astronomy is understanding the physical properties of star-forming galaxies across cosmic history. From the previous studies have confirmed that ultraviolet (UV) and optical radiation from massive young stars is absorbed by dust and re-emitted at far-infrared (FIR) and submillimeter wavelengths, which together account for a significant fraction of star-forming activity in the Universe. Galaxies that are star-forming (SFGs) and dusty star-forming (DSFGs) at high redshift have been crucial for reconstructing the cosmic history of star formation. Deep-field surveys, including optical, near-infrared (NIR), mid-infrared (MIR), and submillimeter observations, are combined to show that DSFGs contribute significantly to the cosmic infrared background. This background has an energy density equal to that of all the radiation observed at UV optical wavelengths.

1.1.1 What are star-forming galaxies?

The most common galaxy type in the Universe is the star-forming galaxies (SFGs), which converts its gas into stars. This star-formation activity dominates the key features of photometric and spectroscopic appearance. In addition, the most identifiable characteristic of SFGs is the presence of a population of massive, young stars that emit ultraviolet (UV) radiation. However, UV radiation is absorbed or scattered by interstellar dust particles and re-emitted as infrared (IR) radiation. Therefore, measuring star formation in very dusty regions is best done with infrared observations (Kennicutt Jr, 1998). Previous studies have confirmed that a tight relation between stellar mass (M_*) and star formation rate SFR characterizes the majority of star-forming galaxies. This relationship is referred to as the "main sequence of galaxies" (Brinchmann et al., 2004; Elbaz et al., 2007; Noeske et al., 2007; Kennicutt Jr and Evans, 2012). SFGs with very high SFRs strongly deviate above the MS plane and are known as starbursts, while quiescent/passive galaxies lie below it (see Figure 1.8). According to the above-described framework, we can classify galaxies by their SFR, which is central to our understanding of high-redshift galaxy observations.

1.1.2 Local infrared-luminous galaxies

Galaxies in the nearby Universe are particularly bright in the far-infrared and are known as local Infrared luminous galaxies. At the beginning of the 1980s, the Infrared Astronomical Satellite (IRAS) found groups of Luminous Infrared Galaxies (LIRGs; $L_{\text{IR}} > 10^{11} L_{\odot}$) and even brighter Ultra-Luminous Infrared Galaxies (ULIRGs; $L_{\text{IR}} > 10^{12} L_{\odot}$) (Sanders and Mirabel, 1996).

Most local ULIRGs are gas-rich spiral galaxies going through major mergers. These dramatic events drive large amounts of gas into the center of the galaxies, leading to strong bursts of star formation and increased AGN activity. While these events are uncommon in the nearby Universe today, they are important physical examples for understanding high-redshift DSFGs, which were common during the peak of cosmic star formation. However, these galaxies are useful as models, but impor-

tant questions remain. Research is still ongoing on whether these local starbursts truly reflect populations from high redshift or represent a different mode of star formation. We need to determine whether local ULIRGs are essentially larger versions of their merger progenitors, or whether the unique conditions in high-redshift environments alter the interactions among gas, dust, and stars.

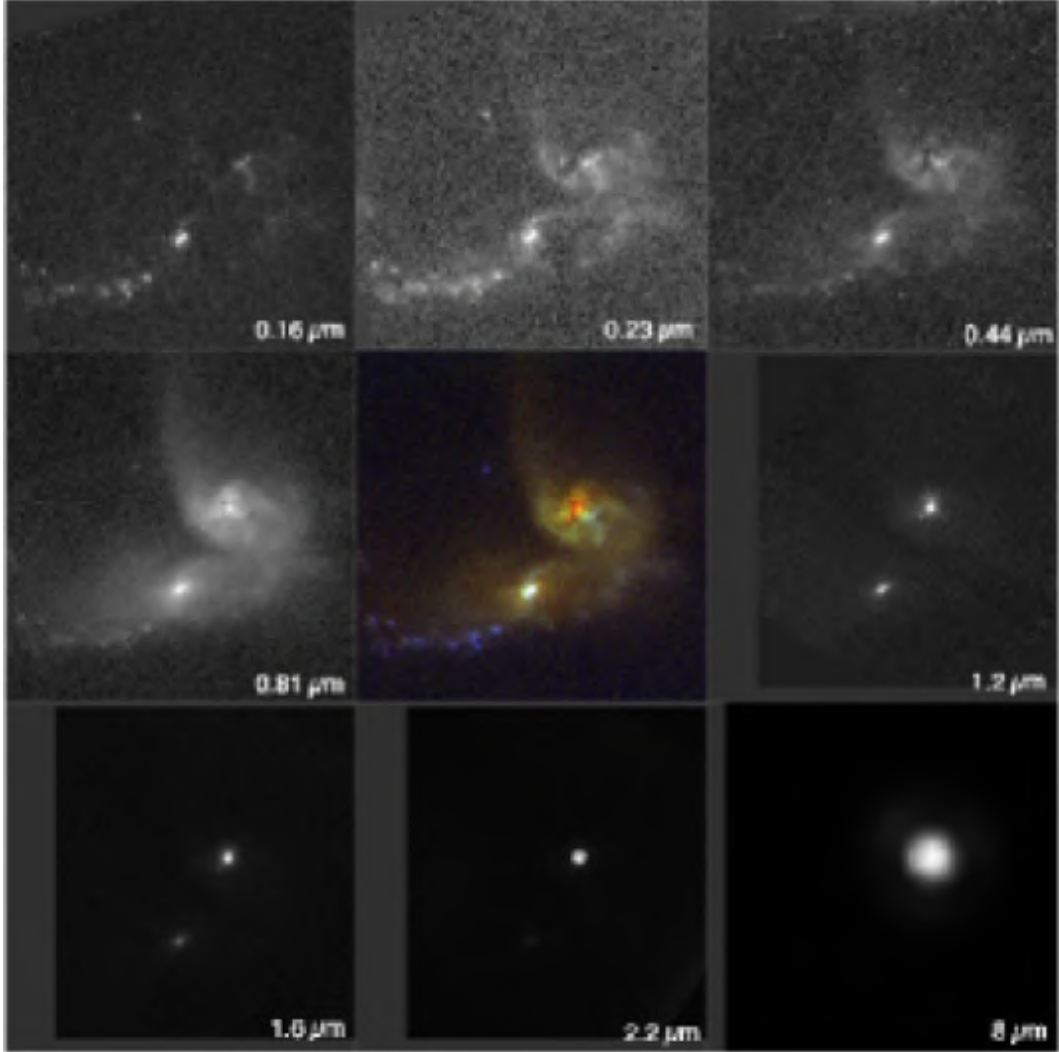


Figure 1.1: IRAS 08572+3915 is observed across a variety of wavelengths. The color composite in the center represents wavelengths from far-UV to near-infrared, using a blue-to-red color scheme, and highlights the intricate composite characteristics of ULIRG systems. Lonsdale et al. (2006).

1.1.3 Negative K-correction

In submillimeter astronomy, we consider the negative k-correction to be one of the most distinctive features, and this effect directly relates to the physics of dust emis-

sion in star-forming galaxies. The FIR emission from dust is well described by the modified blackbody curve, which is usually peaked around $\sim 100\,\mu\text{m}$ in the rest frame. Due to the cosmological expansion, rest-frame spectra of galaxies at high redshifts (z) are shifted to longer observed wavelengths. The crucial point is that the Rayleigh-Jeans part of this spectrum, in which dust emission rises steeply (as observed brightness rises with frequency $S_u \propto u^{2+\beta}$), gets redshifted into submillimeter bands. This interplay between the sharp increase of the rest-frame emission and cosmological dimming leads to a nearly constant observed flux over an extensive range in redshift ($1 \lesssim z \lesssim 8$). This effect indicates that deep surveys at $850\,\mu\text{m}$ or $1\,\text{mm}$ are almost equally effective in probing galaxies at moderate to very high redshifts (see Fig. 1.2). According to Fig. 1.2, observed flux densities of the optical and NIR decrease with increasing redshift; on the other hand, flux densities of submillimeter and mm bands show a steady flux-redshift relation. The reason for this constant flux is the negative K-correction, where the redshifted peak of the dust SED compensates for cosmological dimming, and it makes high-redshift star-forming galaxies nearly as easy to detect as those at lower redshifts in these specific bands. In the late 1990s, the initial SCUBA surveys exploited a negative K-correction, enabling the discovery of a hidden population of bright, dust-obscured galaxies that had gone unnoticed in earlier optical surveys.

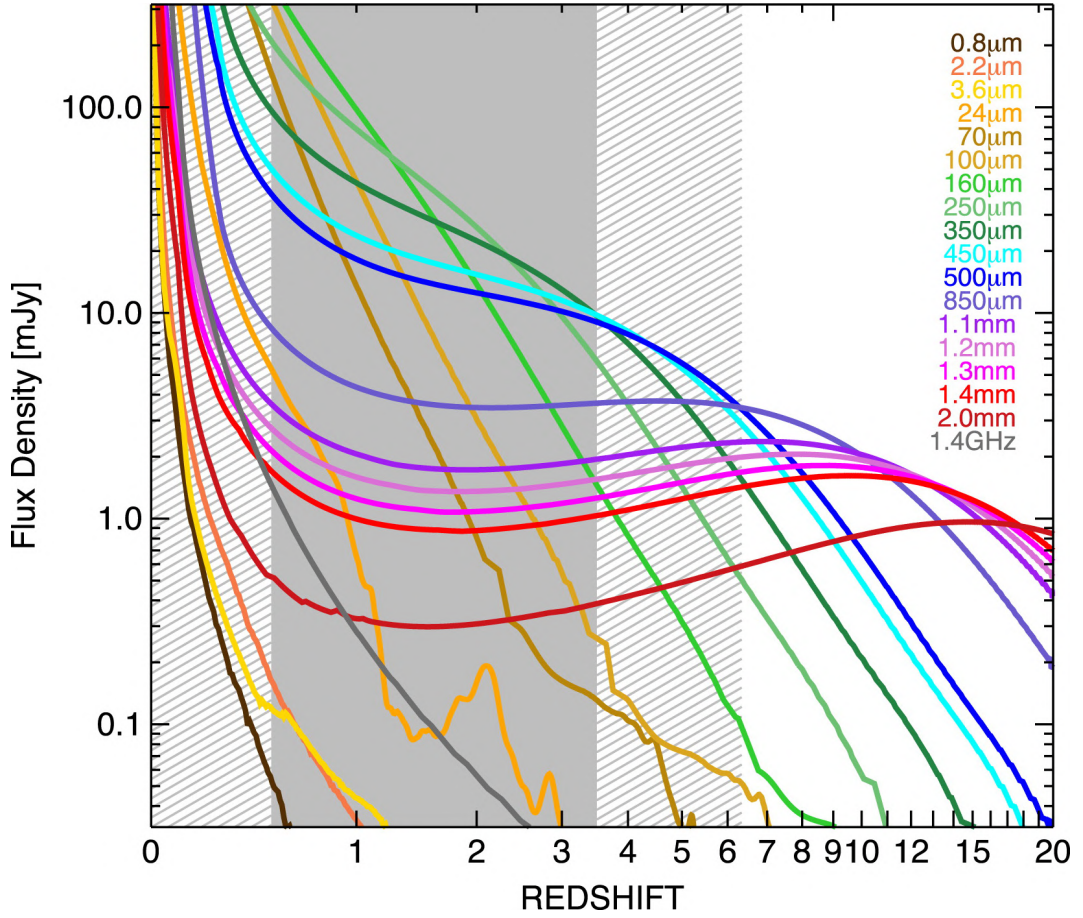


Figure 1.2: The figure illustrates the observed fluxes of a typical ULIRGs across a wide range of redshifts ($1 \leq z \leq 10$). The main key feature is that the flux densities remain constant within the ~ 1 mm band up to $z \sim 10$. Two data models are used to simulate how the observed flux varies with the redshifts. One dataset uses a composite spectrum from typical submillimeter galaxies (mid-infrared to radio wavelengths), and the other uses a scaled spectrum based on the galaxy Arp 220 (optical and near-infrared wavelengths). The solid grey band marks the redshift range ($0.5 \leq z \leq 3.0$) where such galaxies have been most easily detected and studied, and also those selected at $850 \mu\text{m}$ (Cowie et al., 1996). The grey shaded areas represent redshifts where these extremely luminous objects are considered rare: in the left area at low redshift ($z \leq 0.5$) because there are not many of them, and in the right area at high redshift ($3.5 \leq z \leq 6.3$) because they are challenging to confirm spectroscopically. So far, no purely star-forming galaxy of this kind has been found beyond $z \approx 6.4$. Figure adopted from Casey et al. (2014).

1.1.4 Instruments and Most Important Surveys

Before the advent of the common-user bolometer array (SCUBA) on the *James Clerk Maxwell Telescope*, IRAS and COBE had discovered SFGs, which revealed that these galaxies emit almost all their energy in the infrared due to dust obscura-

tion. Despite IRAS showing that dust-obscured starbursts exist and COBE showing 50% of all starlight was hidden by dust, SCUBA’s point-source sensitivity (the first deep blank field maps at $850\ \mu m$ (Smail et al., 1997)) was able to finally localise this missing energy by identifying individual, high-redshift sources known as submillimeter galaxies (SMGs). Following the observations from SCUBA, using *Spitzer*, *Herschel*, and balloon-borne missions were carried out to identify more dusty galaxies, covering a large area of the sky and discovering hundreds of thousands of sources (Barger et al., 1998; Gruppioni et al., 2013; Daddi et al., 2005). Table 1.1 represents the single-dish instruments that were used for the discovery of SMGs at wavelengths longward and include $250\ \mu m$.

Extensive surveys using deep optical and NIR data, including GOODS, COSMOS, and CANDELS, have mapped the total mass in galaxies throughout the history of the Universe. The Atacama Large Millimetre/submillimeter Array (ALMA) also contributes by providing high-resolution images and accurate redshift measurements, which have helped resolve long-standing uncertainties in the identification of DSFGs. Together, these surveys give us the data we need to understand how stars have formed in the Universe over time.

Furthermore, the most important submillimeter surveys are presented in Table 1.2 using Table 1.1. Combining both tables 1.1 and 1.2 clarifies the field area and depth. Even though we have FIR/(sub)mm wavebands, we still require multi-wavelength detections to estimate physical parameters of galaxies because the flux of a galaxy at a given wavelength depends on its intrinsic luminosity, redshift, and dust temperature as well (i.e. characteristic of spectral energy distribution).

Table 1.1: Single-dish facilities used for DSFG discovery.

Instrument	Telescope	Years	Beam	Wave-band	Sensitivity	Reference
IRAS	IRAS	1983	0.5' ^a	12 μm	0.4 Jy	Neugebauer et al. (1984)
			0.5' ^a	25 μm	0.5 Jy	
			1.0' ^a	60 μm	0.6 Jy	
			2.0' ^a	100 μm	1.0 Jy	
ISOPHOT	ISO	1995–1998	7''	15 μm	14 mJy	Lemke et al. (1996)
			11''	25 μm	90 mJy	
			44''	100 μm	250 mJy	
			79''	180 μm	800 mJy	
SCUBA	JCMT	1997–2005	15''	850 μm	1 mJy	Holland et al. (1999)
			7''	450 μm	30 mJy	
MAMBO-1	IRAM 30 m	1998–2002	11''	1.2 mm	0.8 mJy	Kreysa et al. (1999)
MAMBO-2	IRAM 30 m	2002–2011	11''	1.2 mm	0.8 mJy	
SHARC-II	CSO	2002–2013	9''	350 μm	5 mJy	Dowell et al. (2003)
BOLOCAM	CSO	2002–2013	30''	1.1 mm	1.9 mJy	Laurent et al. (2005)
MIPS	<i>Spitzer</i>	2003–2009	6''	24 μm	7 μJy	Rieke et al. (2004)
			17''	70 μm	0.8 mJy	
			38''	160 μm	9.4 mJy	
FIS	<i>AKARI</i>	2006–2011	26''	65 μm	9.2 mJy	Murakami et al. (2007)
			36''	90 μm	3 mJy	
			56''	140 μm	36 mJy	
			64''	160 μm	120 mJy	
BLAST	BLAST	2008	33''	250 μm	18 mJy	Devlin et al. (2009)
			46''	350 μm	13 mJy	
			66''	500 μm	12 mJy	
SPIRE	<i>Herschel</i>	2009–2013	18''	250 μm	5.8 mJy	Griffin et al. (2010)
			26''	350 μm	6.3 mJy	
			36''	500 μm	6.8 mJy	
PACS	<i>Herschel</i>	2009–2013	12''	160 μm	0.9 mJy	Poglitsch et al. (2010)
			7''	100 μm	0.4 mJy	
			5''	70 μm	0.4 mJy	
WISE	WISE	2009–2011	7''	12 μm	0.2 mJy	Wright et al. (2010)

Instrument	Telescope	Years	Beam	Wave-band	Sensitivity	Reference
			12''	22 μm	1.2 mJy	
AzTEC	JCMT	2005–2006	19''	1.1 mm	1.5 mJy	Wilson et al. (2008)
	ASTE	2007–2008	29''	1.1 mm	1.2 mJy	
	LMT (32 m)	2011–2015	9''	1.1 mm	–	
	LMT (50 m)	2015–	6''	1.1 mm	–	
LABOCA	APEX	2006–	19''	870 μm	1.2 mJy	Siringo et al. (2009)
ACT	ACT	2007–	54''	1.1 mm	6.0 mJy	Swetz et al. (2011)
			69''	1.4 mm	3.7 mJy	
			98''	2.0 mm	2.3 mJy	
SPT	SPT	2008–	69''	2.0 mm	1.3 mJy	Mocanu et al. (2013)
			63''	1.4 mm	3.4 mJy	Vieira et al. (2010)
SABOCA	APEX	2009–	8''	350 μm	30 mJy	Siringo et al. (2010)
GISMO	IRAM 30 m	2011–	24''	2.0 mm	0.1 mJy	Staguhn et al. (2012)
SCUBA-2	JCMT	2011–	15''	850 μm	0.7 mJy	Holland et al. (2013)
			7''	450 μm	1.7 mJy	

Note. ^a The IRAS detector’s pixels were much larger than the beamsize.

Table 1.2: Single-dish submm surveys.

Instrument	Wavebands	Fields	Area	Reference
SCUBA	450, 850 μm	A370 & Cl2244-02	$\sim 10 \text{ arcmin}^2$	Smail et al. (1997)
SCUBA	850 μm	Lockman Hole, SSA13	$\sim 6 \text{ arcmin}^2$	Barger et al. (1998)
SCUBA	850 μm	HDF	$\sim 9 \text{ arcmin}^2$	Hughes et al. (1998)
SCUBA	850 μm	7 cluster fields	45 arcmin^2	Smail et al. (1998)
SCUBA	850 μm	ELAIS N2 & Lockman Hole East	260 arcmin^2	Scott et al. (2002)
SCUBA	850 μm	HDF-N	165 arcmin^2	Borys et al. (2003)
SCUBA	850 μm	CUDSS	60 arcmin^2	Webb et al. (2003)
MAMBO	1.2 mm	ELAIS N2 & Lockman Hole	160 arcmin^2	Greve et al. (2004)
MAMBO	1.2 mm	COSMOS	400 arcmin^2	Bertoldi et al. (2007)
MAMBO	1.2 mm	GOODS-N	287 arcmin^2	Greve et al. (2008)
AzTEC	1.1 mm	COSMOS	0.15 deg^2	Scott et al. (2008)
LABOCA	870 μm	CDFS	0.25 deg^2	Weiß et al. (2009b)
BLAST	250–500 μm	ECDFS	10 deg^2	Devlin et al. (2009)
SPT	1.4 mm	...	87 deg^2	Vieira et al. (2010)
SCUBA	850 μm	Lockman Hole East, SXDF	0.2 deg^2	Coppin et al. (2006)
AzTEC	1.1 mm	Lockman Hole East, SXDF	1.47 deg^2	Austermann et al. (2010)
SPIRE	250–500 μm	H-ATLAS	$\sim 570 \text{ deg}^2$	Eales et al. (2010)
MAMBO	1.2 mm	Lockman Hole North	566 arcmin^2	Lindner et al. (2011)
AzTEC	1.1 mm	COSMOS	0.72 deg^2	Arexaga et al. (2011)
SPIRE	250–500 μm	HerMES	$\sim 380 \text{ deg}^2$	Oliver et al. (2012)
SCUBA-2	450 μm	UDS & COSMOS	210 arcmin^2	Roseboom et al. (2013); Geach et al. (2013)

1.1.5 Variations in Spectral Energy Distributions

Recent studies have shown that DSFGs share common properties, such as IR luminosity, but their spectral energy distributions (SED) have shown significant differences. Furthermore, variations, such as dust temperature (T_{dust}), emissivity index (β), and the presence of AGNs can shift the peak of FIR emission and the slope of

the submillimeter spectrum.

Warmer dust produces more luminous emission that is easier to detect in the MIR, and on the other hand, colder dust appears more often in submillimeter counts. These natural SED differences make it difficult to interpret survey data and can introduce selection bias. Considering these reasons, estimating physical parameters from the SED, it is important to choose radiative transfer models or empirical templates carefully to get accurate values for infrared luminosity, dust mass, and star formation rate. Figure 1.3 illustrates the impact of dust temperature on the FIR SED of DSFGs.

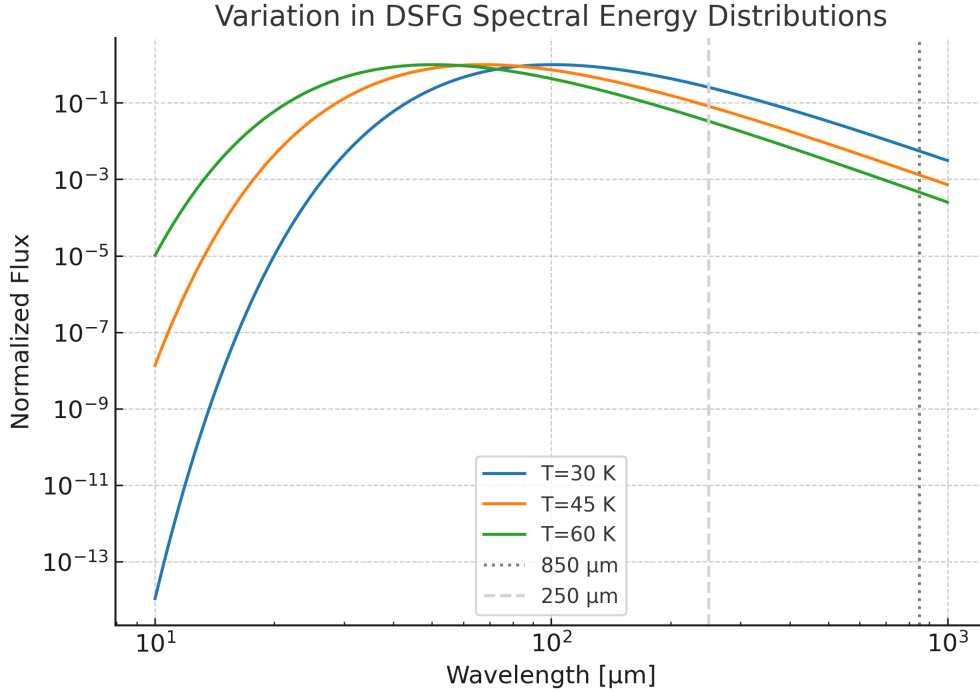


Figure 1.3: Variation in DSFG spectral energy distributions (SEDs) with dust temperature. Colder dust shifts the peak toward longer wavelengths, whereas warmer dust shifts it toward shorter wavelengths. Vertical dashed lines indicate common survey bands at $250\text{ }\mu\text{m}$ and $850\text{ }\mu\text{m}$.

1.1.6 Identification of Multi-wavelength counterparts

Still, in modern astrophysics, we have a substantial challenge to link submillimeter observations to the corresponding objects identified at optical, near-infrared, or radio wavelengths for dusty star-forming galaxies. Because the early submillimeter

instruments had large beam sizes of $\sim 15''$, corresponding to ~ 120 kpc at $z \sim 2$. As a result, there may be multiple possible matches within a single beam. Early surveys with deep optical imaging often yielded ambiguous results (Smail et al., 1997). A notable discovery was the deep radio observations at 1.4 GHz, due in part to the known far-infrared/radio relationship followed by nearby starbursting regions studied by Helou et al. (1985) and Ivison et al. (1998) (i.e. Figure 1.4).

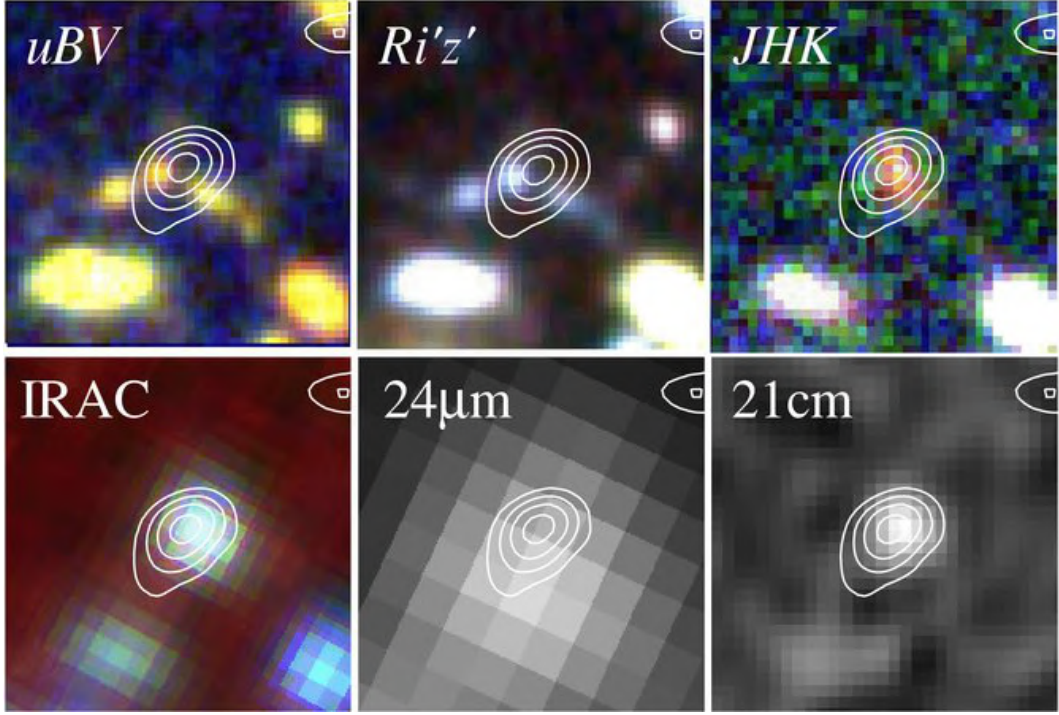


Figure 1.4: This figure illustrates the submillimeter galaxy SXDF 850.6 at different wavelengths. From left to right, it displays optical and near-infrared images (using filters from u to K bands), *Spitzer* IRAC mid-infrared channels (3.6 , 4.5 , 5.8 , and $8.0 \mu\text{m}$), MIPS $24 \mu\text{m}$, and VLA 21 cm radio data. The SMA $880 \mu\text{m}$ contours range from 2σ to 5σ . The source is not detected in optical or near-infrared images, but it becomes clearer at longer wavelengths, exhibiting a distinct radio counterpart. This pattern highlights the importance of multi-wavelength observations for finding dusty, high-redshift galaxies. Figure adapted from Hatsukade et al. (2010).

Radio counterparts:

For DSFGs, one of the earliest and most robust methods of obtaining accurate positions has been deep 1.4 GHz radio observations. The correlation between far-infrared radiation and the amount of radio emission suggests that, even in this case, the radio emission traces the location of star formation. Radio interferometry

can produce images with very compact beams, with precision to fractions of an arcsecond. This makes it easier to pinpoint optical or NIR counterparts to SMGs that typically have positional uncertainties of $\sim 10\text{--}15''$ (Ivison et al., 2011; Smail et al., 1997). In practice, about 60 % of bright SMGs can be matched to radio counterparts, and among those, most have detectable optical/NIR emission.

24 μm Counterparts:

The *Spitzer*/MIPS 24 μm band is susceptible to warm dust emission, and this has been used for the identification of the submillimeter counterparts. Therefore, SMGs are expected to be bright at these wavelengths, as SMGs are typically massive, dust-rich systems (Ivison et al., 2011). Even though there is a strong relation between the mid-infrared and far-infrared, a few problems can be seen: when $z < 4$, there is a special feature that can be observed in the warm dust continuum of galaxies, which is affected by polycyclic aromatic hydrocarbon (PAH) emissions and silicate absorption, and could bias the global spectrum. Such a distortion of the continuum then translates into a modification of the depth at which surveys probe galaxies at different redshifts. Another issue is the high surface density of 24 μm sources: although this crowding is not as extreme as in optical surveys, it is substantially higher than in the radio, increasing the chance of false associations. However, because 24 μm data are widely available and relatively deep, this band has become the natural secondary option, after radio imaging, for identifying counterparts to submillimeter sources.

8 μm Counterparts (IRAC):

The *Spitzer*/IRAC 8 μm band is widely used to maximise identification rates. Additionally, this band probes the rest-frame near-infrared emission, which is dominated by light from older stellar populations in submillimeter galaxies (SMGs). Given that SMGs are generally massive systems with evidence of evolved stars, it is natural to expect them to be relatively luminous at these wavelengths (Dye et al., 2008; Michałowski et al., 2010; Wardlow et al., 2011). In practice, the 8 μm data can be beneficial when neither radio nor 24 μm detections are available. Several

studies have demonstrated that IRAC imaging can detect likely IR counterparts of SMGs that were previously undetected (e.g., Ashby et al. (2006)). However, a severe limitation is posed by the extremely high density of IRAC sources in deep extragalactic fields. The large number of detections increases the likelihood of chance associations, so statistical methods such as likelihood-ratio analysis are necessary to identify physically meaningful associations. These observations are challenging to obtain; however, $8\ \mu\text{m}$ imaging remains a viable alternative (but see additional constraints on SED fitting).

Multiplicity:

The multiplicity is the primary reason for bias in inferences from submillimeter observations, because the flux of faint sources is such that more than one galaxy can lie within the same beam at single-dish resolution. In most cases, detected fluxes from SMGs are ultra-luminous but contaminated by multiple sources because of the increased beam size. This contamination effectively increases the measured flux density and hinders the association of physical properties with individual galaxies. Studies by Wang et al. (2011) have found that considerable fractions of SMGs are in fact multiple through Submillimetre Array (SMA) interferometric observations.

The advent of ALMA has revolutionised this area, with ALMA Cycle 0 observations of 122 LABOCA-selected $870\ \mu\text{m}$ sources from the Extended Chandra Deep Field South (ECDFS) survey (Weiß et al., 2009). These high-resolution maps showed that 30–50% of the single-dish detections resolved into multiple components (see Hodge et al. 2013; 2013). These results initially suggested that multiplicity effects may be an important factor, casting doubt on the interpretation of number counts and luminosity functions derived from single-dish surveys. However, more detailed studies have found that the actual impact of multiplicity is mild. As outlined in Koprowski et al. (2014), it was shown that among the brightest LABOCA sources, only about 10% exhibit a noticeable contribution from a secondary companion, with this contribution accounting for more than roughly 20% of the total flux—similarly to other independent studies like Hezaveh et al. (2013); Chen et al. (2012), it was found that only about 10% of SMGs that are brighter than 10 mJy

are actually composed of multiple galaxies. Most of them are mainly dominated by a single galaxy. These results show that although multiple sources are important, especially the brightest ones, it does not mean that most of the submillimeter population comes from them.

1.2 Far-Infrared and sub-millimetre maps

One of the most effective ways to analyse dusty star-forming galaxies (DSFGs) is to create maps at FIR and submillimeter wavelengths. These maps, combined from thousands of individual detector readings, reveal the sky as it glows from the thermal emission of dust. Unlike optical images, which show areas illuminated by stars, these long-wavelength maps reveal hidden areas where the strongest star formation typically occurs.

1.2.1 *Herschel* maps

The advent of the *Herschel* Space Observatory has remarkably improved our ability to see the dusty Universe. The *Herschel*'s Spectral and Photometric Imaging Receiver (SPIRE) surveyed large areas of the sky using the wavelengths at 250, 350, and 500 μm from 2009 to 2013. Major projects, such as the *Herschel* Multi-tiered Extragalactic Survey (HerMES) (Oliver et al., 2012) and the *Herschel*-ATLAS Survey, (Eales et al., 2010) have identified more than a million galaxies, providing researchers with robust data to study the DSFG population. These surveys demonstrated high effectiveness in detecting galaxies at low to intermediate redshifts ($z < 2$), due to the alignment of dust emission peaks with the SPIRE bands. The broad coverage achieved by *Herschel* further enabled the identification of rare, extremely luminous objects. Many of these turned out to be gravitationally lensed galaxies in the distant Universe, giving us a closer look at early star formation.

1.2.2 sub-millimetre maps

Even though the *Herschel* observations are effective for low and intermediate redshifts, ground-based telescopes that operate at wavelengths longer than *Herschel*'s,

such as $850\ \mu\text{m}$, $1.1\ \text{mm}$, and $2.0\ \text{mm}$, are essential for studying the most distant DSFGs. These maps trace the thermal continuum emission from cold dust within galaxies because they probe the Rayleigh-Jean tail of the dust emission spectrum. One important benefit of observing at submillimeter wavelengths is the negative K-correction. When a dusty galaxy is at a higher redshift, its SED shifts to longer wavelengths. At submillimeter wavelengths, this means that the bright dust emission peak shifts into the observed band, helping to offset the dimming due to distance. Because of this, a galaxy with the same luminosity looks about as bright from $z = 1$ up to $z = 8$ or even farther. This method makes submillimeter surveys more effective at finding the most distant and active star-forming galaxies in the Universe. Instruments such as SCUBA-2 on the JCMT, LABOCA on APEX, and AzTEC on the LMT have conducted deep surveys of small areas, enabling astronomers to detect fainter and possibly more distant galaxies than *Herschel* could. In particular, those maps from single-dish telescopes are subject to significant instrument noise, atmospheric variations, and, especially, a large beam size. Extracting data from those maps requires a strong statistical characterisation.

1.2.3 Monte Carlo Simulations

Confusion noise presents significant challenges for the analysis of submillimeter maps obtained from single-dish telescopes. The large beam sizes, typically $15\text{--}30\ \text{arcsec}$, often cause multiple faint sources to blend into a single, brighter source. This blending creates a fundamental limit on detecting faint sources, as the sky becomes increasingly crowded with overlapping galaxies (see Figure 1.5). To address this issue, advanced Monte Carlo simulations are used to generate artificial maps by adding random sources with known brightness and positions to noise maps derived from actual observations. Conducting thousands of these simulations enables the investigation of the statistical properties of the observed maps. This methodology facilitates the measurement of key observational parameters, the assessment of catalog completeness, and the estimation of the false detection rate.

Beam Size and Source Confusion Across the Infrared Spectrum (Real Data)

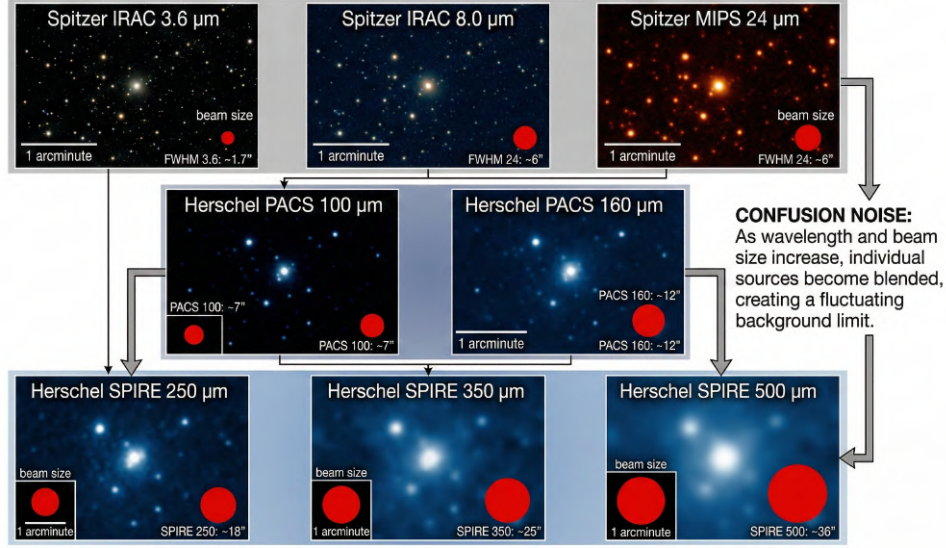


Figure 1.5: Example of various beam sizes across different maps with wavelengths ranging from $3.6 \mu\text{m}$ to $500 \mu\text{m}$. The top three beam sizes exhibit lower confusion levels and higher resolution compared to the bottom three. In contrast, the larger beam sizes in the lower section result in the total flux being a mix of multiple sources. The image was created using Gemini A.I.

1.2.4 Estimation of Observational Parameters

Before extracting sources from raw maps, the baseline properties of the maps must be defined. The two most important parameters are the beam size (Point Spread Function, or PSF) and the noise. Parameters, including source flux and positional data, derived from these maps often exhibit biases that must be corrected before physical interpretation. Monte Carlo simulations serve as the principal method for quantifying these effects.

Deboosted Flux Densities: The flux we measure for a source is not always its actual intrinsic flux. This is due to two “flux boosting” effects. The first is a statistical phenomenon known as *Eddington bias*. Because the number of faint galaxies is vastly greater than the number of bright ones, any given peak of emission is statistically more likely to be an ordinary faint galaxy scattered up by positive noise than a rare, intrinsically bright galaxy scattered down.

The second effect is *confusion boosting*, in which the light increases the measured flux of a source by combining with light from other faint, unresolved galaxies that

happen to fall within the same telescope beam. Simulations allow us to quantify the average magnitude of this boosting as a function of signal-to-noise ratio (S/N), enabling us to calculate a more accurate “deboosted” flux for each source.

Positional Accuracy: The larger beam of a single-dish telescope makes it difficult to pinpoint the exact position of a source; instrumental noise and confusion from the surroundings can cause the apparent emission peak to be off-centre. This positional uncertainty can be quantified by comparing known input positions of fake sources with their measured output positions in simulations. Thus, we can define a statistically stable matching radius, r_s , to search for the corresponding source in the improved-resolution data (e.g., optical or radio). This radius is typically expressed in terms of the S/N by:

$$\Delta\theta \approx \frac{\text{FWHM}}{2 \times (\text{S/N})} \quad (1.1)$$

Completeness and Contamination: Simulations enable us to quantify the fraction of real sources at a given flux density that are successfully detected (completeness) and the fraction of detected sources that are actually spurious noise peaks (contamination). This is crucial for determining the optimal S/N threshold for source detection and for correcting statistical measurements, such as number counts.

1.2.5 Number Counts

A key basic output of a survey of galaxies observed with submillimeter aperture photometry is the galaxy "number counts" – a cosmic census revealing the number of sources are detected per unit area in the sky of galaxies brighter than a given flux density, S . This statistic, which can be presented as differential counts dN/dS (number per flux interval), constitutes an essential and direct test of models of galaxy formation and evolution. A theoretical model that fails to represent the observed number counts accurately suggests a significant flaw in its understanding of how dusty galaxies form and evolve. Analytic functions typically fit the measured number counts to give their shape. Popularly used parameterizations are the double power-law or, more physically motivated, a Schechter function (Schechter, 1976),

given by:

$$\frac{dN}{dS} = \frac{N_0}{S_0} \left(\frac{S}{S_0} \right)^{-\alpha} e^{-S/S_0}, \quad (1.2)$$

where α describes the steep power-law slope at the faint end, reflecting the rapidly growing population of less luminous galaxies. At the same time, the exponential term creates a cut-off at the bright end ($S > S_0$), corresponding to the rarity of extremely luminous sources. S_0 is the characteristic flux density at the "knee" of the function, and N_0 is a normalisation constant.

However, in practice, the functional form of number counts is a two-dimensional projection of a more complex three-dimensional reality. They are the integral of the actual galaxy luminosity function over all redshifts, modulated by the distance and the K-correction. The transition from the luminosity function to observationally motivated number counts (where the learned quantity is flux density) is not straightforward. If the luminosity function is of Schechter form (at a given redshift), then the resulting number counts will not be Schechter as well. This is because at the high flux density end, the number counts are dominated by low-redshift galaxies plus lensed sources, and their signal can be subtracted photometrically from that in maps; and at the faint end, the source number counts are made up mostly of moderate- to high-redshift objects.

1.3 Redshifts & Spectral Energy Distribution fitting.

1.3.1 SED fitting techniques

Extracting the physical properties of SFGs from multiwavelength photometry is intrinsically model-dependent. In general, we use three well-known methods, such as: (i) empirical or semi-empirical template fitting; (ii) parametric greybody (modified blackbody) plus mid-IR power-law forms; and (iii) full radiative-transfer (RT) models informed by geometry and dust physics. Template-based methods use population synthesis models such as those of Bruzual and Charlot (2003) or Maraston (2005), and semi-empirical SED templates, as discussed in detail in Polletta et al.

(2007) and Michałowski et al. (2010). Models that include stellar populations, dust attenuation curves, and re-emission in the FIR. By altering star-formation histories (SFHs), metallicities, and dust laws, such as **CIGALE**, **MAGPHYS**, and **LePhare**, we used a Bayesian method to match observed photometry across multiple wavelengths and to estimate the actual physical properties. Even though these methods work well, degeneracies between age, extinction, and metallicity remain a significant issue. For the dust-dominated regime FIR – submillimeter, reduced parametric models are often used. A single-temperature modified blackbody is often assumed, with emissivity β and temperature T_{dust} as free parameters. However, because real galaxies contain dust at a range of temperatures, multi-component or power-law models are sometimes required to capture the full SED (Casey, 2012). These choices differ in how they treat optical depth, mid-IR continuum, and AGN contamination, and each entails known degeneracies (e.g., $T_{\text{dust}}-z$) that must be addressed using priors or ancillary data. A comprehensive overview of these trade-offs for DSFGs is provided in the review by Casey et al. (2014), which discusses optical-depth effects and mid-IR treatment.

1.3.2 Extracting physical properties of galaxies from SED

Typically, we can extract physical properties such as L_{IR} (8–1000 μm), SFR, T_{dust} , and M_{dust} from SED fittings of FIR/submillimeter. However, this may be limited by constraints on AGN fractions. Theoretically, L_{IR} is calculated by integrating the best-fit of SED. Those results, followed by a $L_{\text{IR}} \rightarrow \text{SFR}$ calibration (with IMF-dependent scaling). The dust temperature is often reported as the characteristic temperature of the fitted greybody, given its sensitivity to optical depth assumptions and the adopted β . The dust mass M_{dust} is calculated using the long-wavelength (optically thin) formula, which states that the spectral flux, $S_{\nu} \propto \kappa_{\nu} M_{\text{dust}} B_{\nu}(T_{\text{dust}})/D_L^2$, where κ_{ν} is the dust opacity and D_L is the luminosity distance; uncertainties in κ_{ν} and β dominate systematics. These methodologies and caveats are summarized in Casey et al. (2014), including the impact of AGN on mid-IR continuum and the need for additional data to decouple components.

Fitting to models:

SED fitting takes actual measured photometry data and compares it to sets of predicted SED models in order to find the best fit. Fit templates are, in general, built by means of software for the synthesis of stellar populations such as the ones used by Bruzual and Charlot (2003) or Maraston (2005), which include initial mass function (IMF), star formation history (SFH) and metallicity codes. Dust attenuation is applied using empirical or theoretical extinction curves, and re-emission in the infrared is modelled to conserve energy. Several widely used codes have been developed for this purpose. **CIGALE** (Noll et al., 2009; Boquien et al., 2019) combines the emissions from stars in the UV to near-infrared range with the attenuation caused by dust and the re-emission from dust in the far-infrared. **MAGPHYS** (Da Cunha et al., 2011) is a technique that relates the quantity of UV absorbed to dust-reprocessed heat. LePhare (Arnouts and Ilbert, 2011) is one of the popular approaches for photometric redshift (photo- z) and stellar mass estimation.

Fitting to modified blackbody functions:

A widely used parametric form for the far-IR/submillimeter is a modified blackbody (MBB),

$$S_\nu \propto (1 - e^{-\tau_\nu}) B_\nu(T_{\text{dust}}), \quad \tau_\nu = \left(\frac{\nu}{\nu_0} \right)^\beta, \quad (1.3)$$

which reduces to $S_\nu \propto \nu^\beta B_\nu(T_{\text{dust}})$ in the optically thin approximation. S_ν is the flux density at ν for a given temperature T in units of $\text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}$ or Jy, $\tau(\nu)$ is the optical depth defined by $\tau(\nu) = \kappa_\nu \Sigma_{\text{dust}}$ and is commonly represented as $\tau(\nu) = (\nu/\nu_0)^\beta$, where β is the spectral emissivity index and ν_0 is the frequency where the optical depth equals unity. The choice between using a model with finite optical depth and optically thin alters the results for dust temperature and L_{IR} . Incorporating a mid-infrared power-law component can improve consistency of the results when the data are reliable, particularly at wavelengths $\lesssim 100 \mu\text{m}$. Casey et al. (2014)) examines these different types and the usual range of parameters for DSFGs.

1.3.3 Acquiring redshifts

Redshifts play a critical role in our understanding of the universe, particularly in measuring distances to galaxies. By analysing these redshifts, we can convert the observed fluxes into the intrinsic luminosities of these galaxies and gain insights into their positions. However, determining spectroscopic redshifts for submillimeter galaxies has been difficult due to their faintness and dust interference. As a result, researchers have been exploring alternative methods to overcome these challenges.

- **Optical and near-infrared photometric redshifts** utilize broadband SED fitting of the stellar components, typically based on deep multi-wavelength images, such as those from CANDELS, COSMOS or UltraVISTA. Although effective, the degeneracies between dust reddening and age can bias the results. As in Koprowski (2015) derived optical photometric redshifts for SCUBA-2 sources, finding a median $z \sim 2.5$.
- Long-wavelength photometric redshifts use the ratio of submillimeter to radio flux, which is based on the strong correlation between far-infrared and radio emissions (Helou et al., 1985; Condon, 1992). Because dust SEDs have a negative K-correction, the submillimeter flux stays almost the same across a broad range of redshifts, but the radio flux drops off quickly. This allows the flux ratio to act as a crude redshift indicator (Carilli and Yun, 1999). Also, Koprowski (2015) demonstrated this technique using AzTEC 1.1 mm and VLA 1.4 GHz data.
- Spectroscopic redshifts remain the most reliable method, but they are challenging to apply to very faint sources. ALMA now allows for scanning the CO line, which helps to get accurate redshift measurements for dusty galaxies, though these are observationally expensive.

1.3.4 Redshifts distribution

The redshift distribution of submillimeter galaxies is the key to when dusty star formation peaked. Redshifts from spectroscopy can be challenging to obtain because

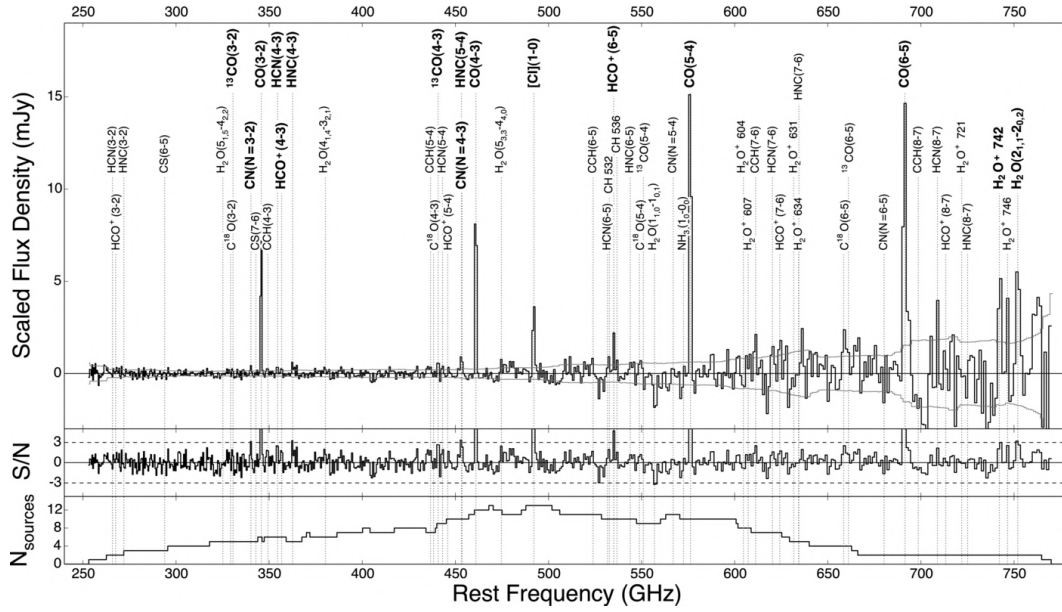


Figure 1.6: A combined continuum-subtracted spectrum in the rest-frame range of $0.4 - 1.2\text{ mm}$ high-redshift submillimeter galaxies has been created from 22 SPT SMGs, displayed at a resolution of 500 km s^{-1} . Notable CO and CI lines, among others, are distinctly observable. The middle panel illustrates the signal-to-noise ratio (SNR) corresponding to the top panel. This figure is taken from Spilker et al. (2014).

of the optical faintness of the sources. However, with improvements in millimeter-wave spectroscopy (e.g., CO/[CII]) and photometric methods over optical–IR bands, the distributions are becoming more consistent. Much larger samples show that the median redshift of bright galaxies selected with submillimeter selection is ($z \sim 2.5$), corresponding to the peak in cosmic star formation activity (Koprowski, 2015; Casey et al., 2014). Sources at higher $z > 3$ are generally brighter, which is the result of both selection effects and intrinsic evolution. The data we have gathered indicate that submillimeter galaxies are not just a transient, low-redshift population. Instead, they appear to play a significant role during a key phase of star formation in the early Universe, characterised by substantial dust content. Additionally, redshift distributions are crucial for calibrating luminosity functions and for linking observed flux densities to physical quantities (e.g., stellar mass, star formation rates).

1.4 Stacking method

1.4.1 Basic definition

The stacking method is crucial for understanding dusty star-forming galaxies (DSFGs) and high-redshift masses. Most importantly, these galaxies are too faint to be detected individually in current far-infrared and submillimeter surveys across much of the early Universe. The large single-dish beams (e.g., *Herschel*, SCUBA-2) generate a confusion noise floor, so that sources can only be detected if they are sufficiently bright to overcome this level, i.e., the most extreme starbursts. But these bright ones are only the so-called “tip of the iceberg” of cosmic star formation. Beyond the confusion limit, most activity is driven by fainter (“normal”) star-forming galaxies. Through stacking, we can statistically determine the average flux from these sources that are not detected individually. By co-adding and averaging individual submillimeter images at the locations of optically or near-IR selected galaxies, the dust emission signals accumulate while random noise cancels out. Thus, stacking effectiveness depends on the number of sources we stacked ($\sqrt{N}$) and enables measurements of the mean flux densities, star-formation rates (SFRs), and dust properties of populations that would usually be too faint to detect on their own (Koprowski et al., 2017; Casey et al., 2014; Dole et al., 2006).

1.4.2 Confusion Noise

in which the telescope beam encompasses flux from several faint, confusion, where the telescope beam encompasses flux from several faint unresolved sources. This creates a noise floor that is unaffected by instrumental sensitivity and can be significant for flux densities in the few mJy range of SCUBA-2 850 μm maps (Nguyen et al., 2010; Koprowski, 2015). Confusion introduces biases that favor higher fluxes (flux-boosting) and increases uncertainty in counterpart identification. Stacking provides a statistical method to mitigate confusion by averaging over multiple lines of sight, which enables the recovery of mean properties when individual detections are not feasible. For these measurements, it is crucial to apply rigorous corrections for clustering and flux-boosting biases.

1.5 Molecular gas and Star formation

1.5.1 Detection of Molecular gas

Studying of molecular gas reservoirs in galaxies has achieved significant progress using interferometric telescopes over the past decades. These studies have shown that cool molecular gas plays a critical role in galaxy evolution, serving as the primary fuel for star formation (Gao et al. (2023)). Molecular clouds are self-gravitating and exhibit an internal pressure that is approximately an order of magnitude greater than that of other phases of gas. As a result, these clouds are not in pressure equilibrium with the surrounding components. As hydrogen is the most common element in the Universe (Oklopčić and Hirata (2013)), we will not be able to observe emission lines of its molecular form, H_2 , since the baricenter of dipole moment is placed in center of charges. as a result, the transition between the levels 1 and 0 ($J=1-0$) is forbidden. However, with quadruple interactions, higher-order transitions can occur. These higher-order transitions require temperatures of around 500 K, which are typically absent in molecular clouds. Although molecular hydrogen has not been detected, we can trace it through the second most abundant molecule in the universe, carbon monoxide (CO). The CO molecule produces emission lines that correspond to transitions between its rotational states, as described by Equation 1.4.

$$E = J(J + 1) - J, \quad (1.4)$$

where E is a rotational energy in ergs, J is an orbital angular momentum. Molecular gas is easily detected via emission of CO, as CO has a weak permanent magnetic dipole moment, which is the reason why the dipole transition $J = 1 - 0$ is allowed.

1.5.2 Deriving conversion factor of CO-to- H_2

Astronomers commonly use CO emission to estimate the masses of molecular gas. The usual technique involves correlating CO intensity with the column density of the molecular gas, creating a straightforward relationship (Bolatto et al. (2013)).

$$N(H_2) = X_{CO} W(J = 1 \rightarrow 0)({}^{12}C^{16}O \quad J = 1 \rightarrow 0), \quad (1.5)$$

where $N(H_2)$ is measured in cm^{-2} , $W(CO)$ is expressed in standard radio astronomy units, specifically K km s^{-1} , and X_{CO} refers to the conversion factor, also known as α_{CO} . For clarity, we will refer to the most common isotopologue, ${}^{12}C^{16}O$, simply as CO Bolatto et al. (2013), unless stated otherwise. This discussion pertains to the ground rotational transition $J = 1 \rightarrow 0$. The relationship described has an analogy that arises from integrating the emission area and adjusting for the mass contributions of heavier elements found in the molecular gas (Bolatto et al. (2013)). Furthermore, α_{CO} converts CO line luminosity to the total gas mass;

$$M_{\text{mol}} = \alpha_{CO} L'_{CO}, \quad (1.6)$$

where units of M_{mol} and L_{CO} are measured in $M_{\odot}$ and $\text{km pc}^2 \text{s}^{-1}$. Alternatively, the mass-to-light conversion factor is denoted as α_{CO} . According to cosmic abundances, helium contributes a 36% correction to the mass contribution of heavy elements. The conversion factor from CO to H_2 is referred to as X_{CO} and α_{CO} Bolatto et al. (2013). For $X_{CO} = 2 \times 10^{20} \text{ cm}^{-2} (\text{K km/s})^{-1}$, the corresponding α_{CO} is $4.3 M_{\odot} (\text{K km/s pc}^{-2})^{-1}$ Bolatto et al. (2013). In addition, the Milky Way and Local Group (excluding the Small Magellanic Cloud), the conversion factor exhibits a surprisingly narrow range of $X_{CO} \sim 2 - 4 \times 10^{20} \text{ cm}^{-2} / \text{K km s}^{-1}$ or ($\alpha_{CO} \sim 3 - 6 M_{\odot} \text{ pc}^{-2} (\text{K km s}^{-1})^{-1}$) (Delahaye et al. (2011); Bloemen et al. (1986); Leroy et al. (2011); Reipurth et al. (2007))

1.5.3 CO-Excitation ladder

The investigation of CO line emission across different rotational transitions provides a powerful diagnostic of the physical conditions within the interstellar medium (ISM). The so-called CO excitation ladder, or spectral line energy distribution (SLED), provides information on how the intensity of CO radiation varies with J , and gives us an estimate for gas temperature, density, and excitation mechanisms (for example, see Fig. 1.7 in Carilli and Walter (2013)). In modest SF galaxies, the

condition of low excitation in molecular gas was still noticeable because lower- (J) transitions were dominant. In the Milky Way, the carbon monoxide spectral line energy distribution (CO SLED) peaks at rotational levels $J = 3\text{--}4$. Similarly, disk-like star-forming galaxies on the main sequence at high redshift, which contribute significantly to the cosmic star-formation rate density (SFRD), display CO ladders similar to those of local spiral galaxies, with emission concentrated at low rotational levels ($J \leq 3$; Aravena et al. (2010, 2014); Dannerbauer et al. (2009)). As the level of star formation and gas excitation increases, these SLEDs become steeper and peak at higher transitions, typically between $(J \sim 4)$ and $(J \sim 6)$ (Daddi et al. (2015)). In contrast, very active starburst galaxies in which strong radiation fields and dense molecular gas are present show much more excited ladders that peak between $(4 < J < 8)$ (Bothwell et al. (2013); Daddi et al. (2015); Magdis et al. (2012)). Therefore, the evolution of these excitation patterns is a sensitive probe to how energy and density conditions in the ISM depend on galaxy types and cosmic epochs.

There is an essential difference between quasars (QSOs) and SMGs. QSOs can be represented as possessing a primary high-excitation gas component, with molecular gas emissions arising from a concentrated area at the center of the quasars host (Riechers et al. (2011)). Compared to other types, SMGs are more accurately described by a model that features both a concentrated high-excitation phase and a more spread-out interstellar medium (ISM) (Ivison et al. (2011); Riechers et al. (2011)). The most intense levels of excitation, reaching around $J \sim 8$ or higher, indicate that we are likely observing some of the hottest and densest environments, which are commonly associated with regions dominated by X-rays (Van der Wel et al. (2009)). These extreme conditions are often associated with active galactic nuclei (AGN), which exhibit considerable activity and produce cosmic rays.

1.5.4 Molecular gas mass & CO line Luminosity

As outlined in Carilli and Walter (2013) and Solomon and Vanden Bout (2005), to estimate molecular gas mass from observed CO higher transitions, we need to follow two key steps. First, we must find the ratio between these higher CO transitions and

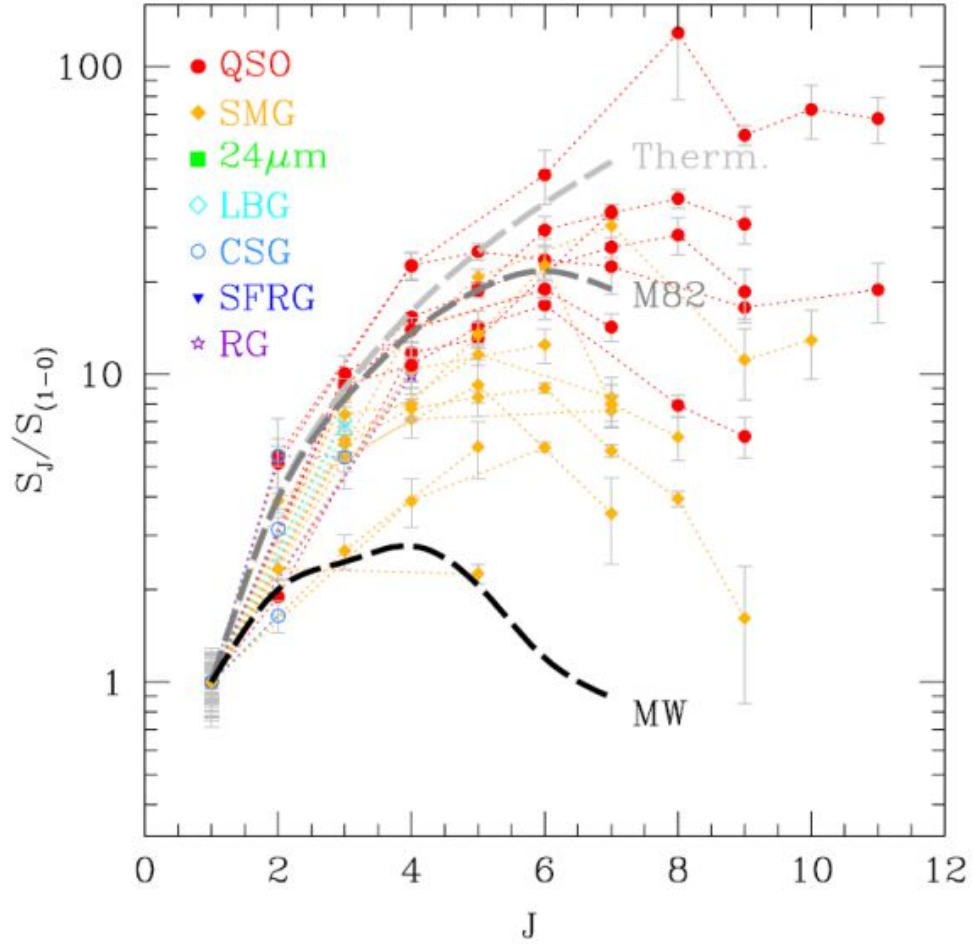


Figure 1.7: CO excitation ladder, i.e. the CO line flux $S_{J-(J-1)}$ as a function of J and normalized to $S_{1\rightarrow 0}$, are colored for different source types and connected for individual objects. The dashed gray line shows constant brightness temperature on the R-J scale, i.e. $S \propto \nu^2$. Image extracted from the Carilli and Walter (2013).

the CO(1–0) line. As shown in Figure 1.7, this ratio is affected by excitation conditions, which can differ significantly from galaxy to galaxy. This variability makes it difficult to accurately deduce the emissions from CO(1–0) based on the observations from CO(5–4) (Carilli and Walter (2013); Daddi et al. (2007)). Secondly, we need to understand the conversion of the luminosity of CO(1–0) into a meaningful estimate of the molecular gas mass (see the review of Carilli and Walter (2013)). In general, observed emission lines from a galaxy is known as line luminosity (Casey et al. (2014); Solomon and Vanden Bout (2005)). In this example, we will focus on carbon monoxide (CO) as the emitting molecular line, though other molecular species could be used instead. Line luminosities are defined as either L_{CO} or L'_{CO} . The equations are (Solomon and Vanden Bout (2005)):

$$\frac{L_{\text{CO}}}{[L_{\odot}]} = 1.04 \times 10^{-3} \times \frac{S_{\text{CO}}\Delta\nu}{[\text{Jy km s}^{-1}]} \times \frac{\nu_{\text{rest}}(1+z)^{-1}}{[\text{GHz}]} \frac{D_L^2}{\text{Mpc}^2}, \quad (1.7)$$

where $S_{\text{CO}}\Delta\nu$ is the integrated flux of the CO velocity in units of Jy km s^{-1} , ν_{rest} and D_L^2 are the rest-frame frequency in GHz and the luminosity distance in Mpc, respectively. L_{CO} is the total energy output from the CO line in units of $L_{\odot}$. Similarly, the integrated line of CO luminosity is denoted as L'_{CO} ,

$$\frac{L_{\text{CO}}}{[\text{K km s}^{-1} \text{ pc}^2]} = 3.25 \times 10^7 \times \frac{S_{\text{CO}}\Delta\nu}{[\text{Jy km s}^{-1}]} \times \frac{D_L^2}{\nu_{\text{obs}}^2(1+z)^3} \frac{[\text{GHz}]}{\text{Mpc}^2}, \quad (1.8)$$

In general, we use L'_{CO} to convert the luminosity of CO to a H_2 gas mass (Casey et al. (2014); Carilli and Walter (2013)).

1.5.5 Molecular gas fraction and gas consumption

The process of star formation in galaxies is closely linked to the amounts of molecular gas they contain. An important measure in understanding how galaxies evolve is the molecular gas fraction, which is the ratio of the mass of molecular gas to the total baryonic content, basically the sum of both stars and gas ($M_{\text{H}_2} + M_{\star}$).

$$f_{\text{gas}} = \frac{M_{\text{H}_2}}{M_{\text{H}_2} + M_{\star}}. \quad (1.9)$$

Research indicates that the amount of molecular gas in galaxies has changed significantly over cosmic history. In the local universe, massive galaxies typically contain only 5% to 10% of molecular gas. However, when we look back at galaxies from a time when the universe was younger (around $z \sim 1$ and higher), we discover much higher gas fractions, sometimes jumping up to 20% or even as much as 80% (Daddi et al. (2010); Tacconi et al. (2010); Geach et al. (2011); Tacconi et al. (2013)). This is especially true for large galaxies that are actively forming new stars.

A closely related concept is the gas depletion (or consumption) timescale, which characterises how long a galaxy could continue forming stars at its present rate before exhausting its molecular reservoir:

$$\tau_{\text{dep}} = \frac{M_{\text{mol}}}{\text{SFR}}. \quad (1.10)$$

For main-sequence galaxies in the nearby Universe, this timescale is relatively long, typically $\tau_{\text{dep}} \sim 1 - 2$ Gyr. At higher redshifts ($z \geq 2$), however, it decreases substantially, to a few $\times 10^8$ yr (Daddi et al. (2010); Genzel et al. (2010)). In harsh environments, such as dusty star-forming galaxies (DSFGs) and submillimeter galaxies (SMGs), depletion times can be very brief, often less than approximately 100 million years. This quick depletion is indicative of their vigorous starburst activity (Bothwell et al. (2013); Carilli and Walter (2013)).

1.6 Physical properties & Galaxy Evolution

1.6.1 Stellar masses

When the redshifts are available for any galaxies, we can determine their physical properties. One of the primary and fundamental physical properties is the estimate of stellar mass, $M_{\star}$. However, depending on the methods to derive $M_{\star}$, it can be varied (Hainline et al. (2011); Michałowski et al. (2012)). Estimates generally use SED fitting in the rest-frame near-IR, where the emission originates from the older stellar activity and is less attenuated by dust obscuration. However, input parameters that affect the SED fitting (like SFH, SSP model, and IMF) are the

main cause of uncertainty when estimating stellar masses (Bruzual and Charlot, 2003; Hainline et al., 2011; Thomas et al., 2005). Different models can lead to significantly different results. The main types of models used are:

Star formation history

First, the assumed star formation history (SFH) plays an important role in these results. These models span from a single short burst to ongoing star formation or more complex multi-component histories. A single burst (τ model) generally generates lower stellar masses, as all stars need to be young in order to reproduce the observed UV flux. Instead, a single o- or multi-component history allows for an older underlying stellar population, which may result in masses up to several times larger than estimated otherwise (Wang et al. (2011)).

Stellar population synthesis (SPS)

Another major issue is the selection of a stellar population synthesis (SPS) model, which introduces substantial uncertainty. With an IMF that describes the number of stars at each mass and a star-formation history, all stars are placed along the correct isochrones in the Hertzsprung-Russell (HR) diagram. When we observe them, the shape of the SED comes from the combined light of these stars, including the effects of dust absorption. The main question is whether to use models in which the thermally pulsating asymptotic giant branch (TP-AGB) has a strong influence, as in Maraston (2005), or models in which the TP-AGB has little effect, as in Bruzual and Charlot (2003). Application of these models to identical datasets can yield stellar mass estimates that differ by up to 50%, underscoring a significant systematic uncertainty in the field.

Initial mass function (IMF)

The initial mass function (IMF) plays a critical role in estimating stellar mass, yet it is subject to considerable uncertainty. For instance, adopting the standard Salpeter (1955) IMF rather than the Chabrier (2003) IMF changes the estimated stellar mass

by approximately a factor of 1.8. This uncertainty arises from ongoing debates regarding possible variations in the IMF, including the possibility of a more top-heavy distribution in extreme starburst environments (Bastian et al. (2010)). These factors collectively introduce substantial systematic uncertainties, thereby complicating precise measurements of stellar masses in distant, dust-obscured galaxies.

1.6.2 Star formation rates

The star formation rate is the total mass of gas converted into stars per unit time (typically $M_{\odot}/\text{yr}$) and is a vital driver of galaxy evolution. It is the primary process responsible for assembling stellar mass, chemically enriching the Interstellar Medium (ISM) with heavy elements, and driving the growth of cosmic structures. Understanding the Star Formation Rate (SFR) is essential for constructing a comprehensive picture of the Star Formation Rate Density (SFRD) throughout cosmic history. Measuring this apparently straightforward parameter with accuracy is quite difficult, as the process of star formation is seldom directly observed. In general, the SFR is assessed across the full range of the electromagnetic spectrum, from X-rays to radio waves, and includes both emission lines and continuum tracers (Reddy et al. (2012); Kennicutt Jr and Evans (2012)). Although the results of these methods can vary, the primary target is to detect emissions that trace recently formed stars (10–100 Myr). Additionally, we strive to avoid evolved stars and lines contaminated by AGN.

In the subsections below, I will briefly discuss the methods we can use to estimate the SFR.

Ultraviolet (UV) Continuum Tracer

The ultraviolet (UV) emission of galaxies directly traces the light from young massive O and B-type stars in the range of $\sim 0.150\text{--}0.280\ \mu\text{m}$, and this is the best range to investigate the star formation time scale around $\sim 100\text{--}300\ \text{Myr}$, and thus provides a nearly instantaneous measure of star formation. The calibration is typically expressed as Kennicutt Jr and Evans (2012):

$$\text{SFR}_{\text{UV}} (\text{M}\odot, \text{yr}^{-1}) = 1.4 \times 10^{-28} L_{\nu, \text{UV}} (\text{erg s}^{-1} \text{Hz}^{-1}), \quad (1.11)$$

where $L_{\nu, \text{UV}}$ is the monochromatic luminosity at 1500 Å and 2500 Å. However, UV light is strongly attenuated by dust, making corrections essential when estimating SFRs from this tracer alone.

Infrared (IR) / Far-Infrared (FIR) Tracer

As we know, UV light is emitted by young massive stars and is absorbed by dust, which then re-emits it in the FIR regime. This process is known as dust obstruction (Kennicutt Jr and Evans (2012)). The dust particles are more responsive to UV light, as their cross-section for absorbing UV stellar radiation is greater compared to that of optical light. As a result, dust that is heated by young stars emits more intense radiation and reaches its peak emission at shorter wavelengths, around 60 μm . Also, dust heated by low-mass and evolved stars emits at longer wavelengths, typically between 100 μm and 150 μm . This distinction is one of the main arguments for using bolometric IR emission (which spans from roughly 8 μm to 1000 μm) as a proxy for SFR. The relationship is often expressed as: (Kennicutt Jr (1998)):

$$\text{SFR}_{\text{IR}} (\text{M}\odot, \text{yr}^{-1}) = 4.5 \times 10^{-44} L_{\text{IR}} (\text{erg s}^{-1}), \quad (1.12)$$

where L_{IR} is the total infrared luminosity integrated over 8–1000 μm .

Ionized Gas Emission Lines (e.g., H_α)

Ionised emission lines are emitted by hot, massive young stars that function as sources of energetic photons. Moreover, these ionised gases absorb indirect electrons and radiate light in characteristic frequencies. This causes it to produce a variety of distinct nebular lines. Among these lines, H_α (0.6563 μm) and H_β (0.4861 μm) are the most common observed and play a crucial role in astrophysics. Also, other recombination lines, such as P_α , P_β , Br_α and Br_γ are noteworthy. The intensities of the emission lines that occur beyond the Lyman limit directly correlates with the total luminosity of the stars, making them valuable indicators for studying star

formation.

The strength of the ionising flux is mostly contributed by the most massive and short-lived stars, such as $M_{\odot} > 10$ and $\tau_{\text{MS}} < 20$ Myr, and this method traces SFR. To estimate SFR, we need to consider the conversion factor between ionising photons and the SFR. Also, the ionising factor depends on the evolutionary synthesis models. As an example, using IMF Kroupa (2001), we can find SFR (Calzetti (2013)), and it is,

$$\text{SFR}(Q(H^o)) = 7.4 \times 10^{-54} Q(H^o), \quad (1.13)$$

where $\text{SFR}(Q(H^o))$ is the star formation rate in $M_{\odot} \text{ yr}^{-1}$, $Q(H^o)$ is the ionising photons rate in s^{-1} , and the luminosity of H_{α} can be calculated by following relation (Osterbrock and Ferland (2006)):

$$L_{(H_{\alpha})} = 1.37 \times 10^{-12} Q(H^o). \quad (1.14)$$

In order to obtain a direct relation between SFR and H_{α} , we need to assume constant electron temperature $T_e = 10000$, K and density $n_e = 100, \text{ cm}^{-3}$. By substituting Equation 1.13 and 1.14, we obtain,

$$\text{SFR}_{H_{\alpha}} = 5.5 \times 10^{-42} L(H_{\alpha}). \quad (1.15)$$

The main advantage of this method is the direct link with SFR and the nebulae emission, and the main disadvantage is we have to assume IMF and extinction factors.

Since each of the methods overviewed above has its limitations (e.g., dust attenuation in UV/ H_{α} , AGN contamination in the IR, calibration uncertainty in radio), we combine those measurements to alleviate this limitation as much as possible in present studies. For instance “UV+IR” includes both the unobscured and obscured star formation (Hirashita et al. (2003); Bell et al. (2003)):

$$\text{SFR}_{\text{tot}} = \text{SFR}_{\text{UV,corr}} + \text{SFR}_{\text{IR}}. \quad (1.16)$$

This combination provides the most comprehensive census of star formation, particularly in dusty, high-redshift systems.

1.6.3 Cosmical Infrared Background

The Cosmic Infrared Background (CIB) is an integrated measure of light reprocessed by dust from stars throughout cosmic history. Therefore, it contains a rich amount of information about where and when star formation occurred under obscuration in the history of the Universe within a single diffuse signal. Initially detected as an all-sky excess at extragalactic [far-IR/submillimeter] wavelengths, the CIB is now being studied both in its mean (absolute) intensity and, importantly, also in its spatial fluctuations (anisotropies), since they trace the large-scale distribution of dusty, star-forming galaxies (DSFGs) over an extensive range in redshift and hence connect galaxy physics to cosmic structure (Planck/IRAS/large-scale CIB studies; Lenz et al. (2019); Mak et al. (2017)). In practice, much of the constraining power comes from two complementary observables: the total CIB intensity (which constrains the integral of obscured star formation) and the angular power spectrum/cross correlations with other tracers of CIB maps (which break that integral into redshift- and halo-mass contributions) (Lim et al., 2023; Mak et al., 2017).

1.6.4 Specific Star formation rates and the main sequence

The specific star formation rate (sSFR) is defined as the efficiency of star formation in a galaxy, and it can be calculated by taking the ratio of the SFR to the galaxy's stellar mass ($M_\star$):

$$sSFR = \frac{SFR}{M_\star}. \quad (1.17)$$

It measures the relative growth rate of a galaxy's stellar population, essentially how quickly the stellar mass doubles under ongoing star formation. However, it yields roughly the same sSFR at a given redshift, despite differences in stellar mass.

Observations indicate that high sSFRs are associated with galaxies that are

rapidly accumulating stellar mass, whereas low sSFRs suggest systems evolving more slowly or already quenched. Observations show that typical sSFRs increase with redshift, reflecting more active growth of galaxies in the early Universe (Noeske et al. (2007); Daddi et al. (2007); Whitaker et al. (2012)).

Closely related to this concept is the star-forming main sequence (MS): the tight correlation between SFR and stellar mass observed in the majority of star-forming galaxies. This relation holds across a broad range of redshifts, with only modest scatter (~ 0.3 dex), and can be parameterised as:

$$\text{SFR} \propto M_{\star}^{\alpha}, \quad (1.18)$$

where $\alpha \sim 0.6 - 1.0$ depending on redshift and sample (Speagle et al. (2014); Brinchmann et al. (2004); Daddi et al. (2007)). Sources with SFRs much higher than the MS are classified as starbursts, while those with SFRs below the MS are classified as quiescent/passive. Also, MS galaxies at high redshifts have a higher star formation rate than the current universe (a decrease in sSFR by a factor of ~ 20 from $z \sim 2$ to $z = 0$) (Santini et al. (2009)). See Figure 1.8.

In combination, sSFR and the main sequence provide a framework for interpreting galaxy evolution. By measuring the sSFR, one measures how quickly galaxies form stars in relation to their size. Instead, the main sequence represents the “typical” star-forming mode as a function of cosmic era.

1.6.5 Calibration of IRX- β and IRX- $M_{\star}$

.

One of the key challenges in observational cosmology is measuring the star formation rate while accounting for the effects of dust. The presence of dust grains absorbs UV photons from young massive stars and re-emits the radiation in the infrared (IR), as discussed in the previous sections (Madau and Dickinson (2014); McLure et al. (2018)). Due to dust obscuration, we must treat L_{IR} and L_{UV} separately, and consider the ratio of infrared to UV luminosity, known as the infrared excess (IRX).

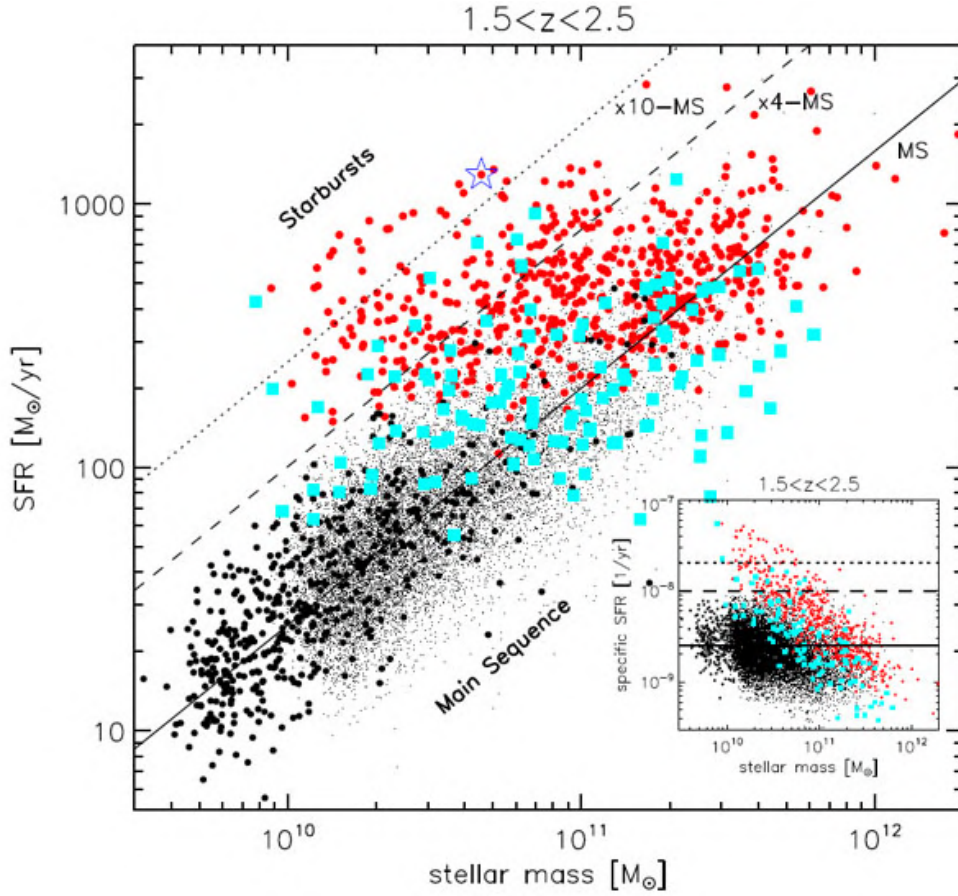


Figure 1.8: The plot represents the SFR- $M_{\odot}$ relation for SFGs ($1.5 < z < 2.5$) observed in PACS/*Herschel* from COSMOS and GOODS fields. The solid black line shows the main sequence (MS) of these galaxies at a mean redshifts $z \sim 2$, according to Daddi et al. (2007). Above this line we have the starburst region, as shown by the dashed and dotted lines. The image is drawn from (Rodighiero et al. (2011)).

$$\text{IRX} = \frac{L_{\text{IR}}}{L_{\text{UV}}}. \quad (1.19)$$

We introduce calibrations such as $\text{IRX}-\beta$ and $\text{IRX}-M_{\star}$ as indirect methods. Most of the SFR at cosmic noon is dominated by obscured SFR (Dunlop et al. (2017); Bowler et al. (2020)), and beyond $z > 4$ the UV SFR is more dominant due to the limited sensitivity in FIR detections. This is one reason for introducing indirect methods.

IRX- β relation

The UV spectral slope is one of the most widely used diagnostics of dust attenuation, which is related to IRX. The relation with β is defined by a power-law fit to the UV continuum, $f_\lambda \propto \lambda^\beta$. Several methods for determining the UV spectral slope are described by Rogers et al. (2013). Meurer et al. (1999) originally calculated β by fitting a power-law function to the ten continuum rest-frame (125 - 250 nm) bands from Calzetti and Kinney (85). The previous research of Meurer et al. (1999) showed a tight relation between IRX and β for local starburst galaxies, often referred to as the Meurer relation. The reddest UV slopes indicate higher dust attenuation and AGN contamination. Moreover, this could raise the IRX values. However, recent work has found that high-redshift galaxies frequently do not follow this local calibration (e.g., Reddy et al. (2011); Casey et al. (2014); Koprowski et al. (2017)), reflecting differences in dust geometry, metallicity, and star formation history.

IRX- $M_\star$ relation

As an alternative approach, we can use the stellar mass relation to avoid the effect of dust on the UV slope. More recently, Whitaker et al. (2014); McLure et al. (2018) have found a strong correlation between IRX and stellar mass. More massive galaxies generally have greater dust obscuration and are also more gas-rich and metal-rich. The relationship between IRX and $M_\star$ is beneficial at high z , because photometric errors and absorption from the intergalactic medium can make it hard to estimate β . Stellar mass gives a stable measure of the cumulative star formation history of a galaxy (e.g., Speagle et al. (2014); Whitaker et al. (2014)). In contrast, the UV slope is more susceptible to the effects of recent star formation episodes and dust obscuration

1.6.6 Luminosity function

The luminosity function (LF) is a fundamental statistical tool in observational cosmology that quantifies the number of sources with a given rest-frame luminosity per unit volume. It is the most effective way to present the statistics of the galaxy pop-

ulation. One of the simplest ways to study this is by looking at relationships like the UV and IR luminosity functions (LF; e.g., Gruppioni et al. (2013); Koprowski et al. (2017, 2026)) and the star formation rate density (ρ_{SFR} ; e.g., Madau and Dickinson (2014); Dunlop et al. (2017)). After the cosmic infrared background was discovered, many studies began to focus on how much IR contributes to the total ρ_{SFR} , which is determined by integrating the relevant luminosity function (e.g., Magnelli et al. (2013); Gruppioni et al. (2013); Madau and Dickinson (2014); Dunlop et al. (2017); Liu et al. (2026)). The luminosity function (ϕ_L) describes how many galaxies there are in a given volume for each luminosity range. Formally, the comoving number density of galaxies with luminosities between L and $L + dL$ is given by $\phi_L dL$ (e.g., (Hopkins et al. (2006))). Integrating the luminosity function reveals the total number density of galaxies and describes its evolution over cosmic time. For DSFGs, the most critical measure is the infrared luminosity function. The infrared luminosity function is the most important quantity for DSFGs. This function describes the number of galaxies as a function of their total IR luminosity, which is usually integrated from 8 to 1000 μm and bands that straddle that region, due to its strong and relatively clean calibrations for the SFR in very obscured systems via conversions similar to those found by Kennicutt Jr (1998). Consequently, the infrared luminosity function enables us to trace the evolution of the cosmic star formation rate density (SFRD) and understand the contribution of obscured versus unobscured star formation to the accumulation of stellar mass throughout cosmic history. However, observationally, the infrared LF is challenging to constrain. In general, the most common method to calculate LF is the $1/V_{\text{max}}$ estimator (Schmidt, 1968), defined as:

$$\int_{L_1}^{L_2} \phi(L) dL = \sum_{i=1}^{n_{\text{obs}}} \frac{1}{V_{\text{max}}(i)}, \quad \text{where} \quad V_{\text{max}}(i) \equiv \int_{\Omega} \int_{z_{\text{min}}(i)}^{z_{\text{max}}(i)} \frac{d^2V}{d\Omega dz} dz d\Omega, \quad (1.20)$$

where, $V_{\text{max}}(i)$ is the maximum comoving volume within which a galaxy i could still be detected given the survey's flux limit and its luminosity. The shape of the LF is controlled by its analytical form. For instance, the bright-end tail of

LF for ultraluminous galaxies (ULIRGs) is typically described by either a modified Schechter function or a double power-law (Saunders et al., 1990).

$$\phi(L) = \frac{dn}{dL} = \phi_{\star} \left(\frac{L}{L_{\star}} \right)^{1-\alpha} \exp \left(-\frac{1}{2\sigma^2} \log^2 \left[1 + \frac{L}{L_{\star}} \right] \right), \quad (1.21)$$

where $\phi_{\star}$ is the overall normalization, $L_{\star}$ is the characteristic luminosity marking the transition between the faint-end power-law slope and the exponential cutoff at the bright end, and α and σ control the slopes.

Studies from the past two decades have shown a strong correlation between the infrared luminosity function and redshift, as illustrated in Figure 1.9. In addition, previous data from *Spitzer* 24 μm data (Le Floc'h and et al., 2005; Caputi et al., 2007) shows that gradually increasing of characteristic luminosity $L_{\star}$ from $z \sim 0$ to $z \sim 2$. This was later confirmed and extended to higher redshifts ($z \sim 3.6$) with *Herschel* data, which probed the peak of the dust emission directly (Magnelli et al., 2011, 2013; Gruppioni et al., 2013; Casey et al., 2014). Results suggest that the galaxies dominating the cosmic SFRD shift from "norm" spiral galaxies at low- z to luminous and ultraluminous infrared galaxies (LIRGs and ULIRGs) at their peak around $z \sim 1\text{--}2.5$ (see Fig. 1.10).

1.6.7 Star formation rate density

The cosmic star formation rate density (SFRD) is an essential concept in observational cosmology, based on the luminosity function. On the other hand, SFRD describes the cosmic history of star formation, and it represents the total mass of stars $M_{\odot}$ formed per unit time per unit comoving volume of the Universe at a given redshift (Madau et al., 1998; Hopkins et al., 2006). To understand the overall picture of star-forming activity in the universe, we must first understand the energy balance between the energy emitted by young, massive stars and the fraction of that energy absorbed by dust and re-radiated at FIR wavelengths. For the local Universe, this is relatively straightforward because of the abundance of high-resolution images, but at high redshift ($z > 2$) the impact of interstellar dust becomes harder to assess

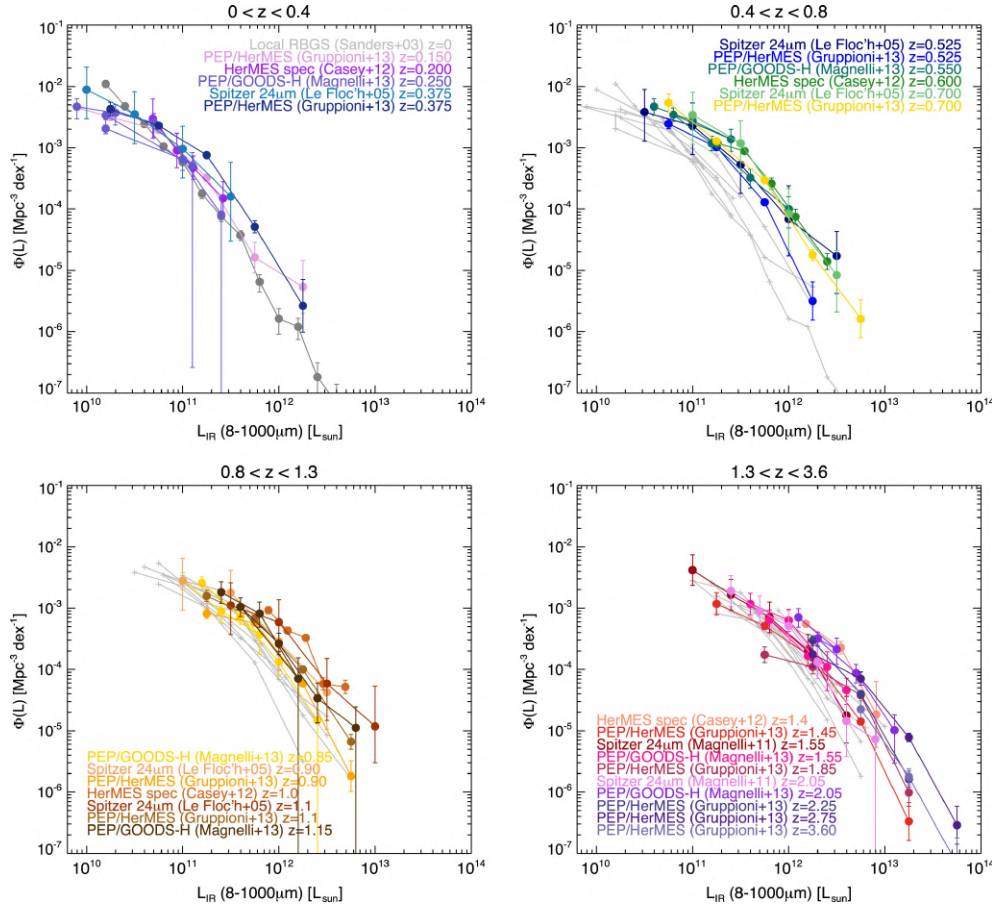


Figure 1.9: The evolution of the integrated infrared (8–1000 μm) luminosity function across redshift, showing a strong increase in the characteristic luminosity $L_\star$ with lookback time. Adapted from Casey et al. (2014).

(Madau and Dickinson, 2014).

$$\dot{\rho} \ast (z) = \int_0^\infty \psi, \phi(\psi, z), d\psi, \quad (1.22)$$

where ψ is the star formation rate of a galaxy and $\phi(\psi, z)$ is the SFR function. In practice, for flux-limited surveys, the $1/V_{\text{max}}$ estimator is commonly used to compute this integral while accounting for observational biases.

The UV-based dust-uncorrected SFRs are relatively easy to estimate out to very high redshifts due to the superior depth of the UV/optical data. However, the correction from the observed UV-based SFRD to the intrinsic value is very difficult and is a subject of an ongoing debate (see Madau & Dickinson 2014 for details)

The SFRs that are calculated without correcting for dust using UV light are

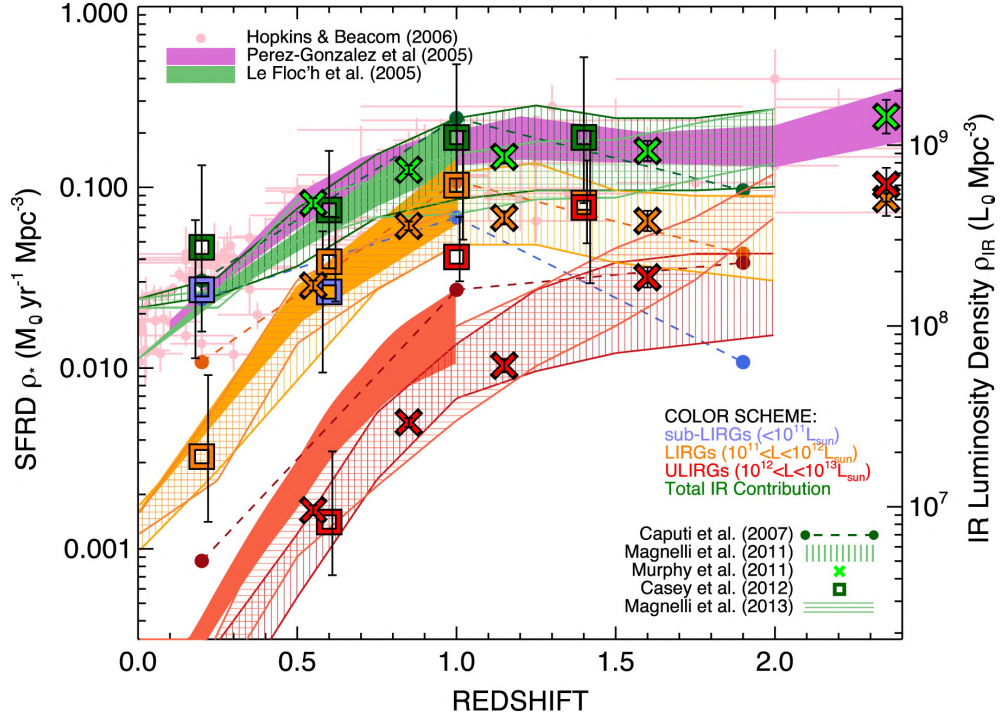


Figure 1.10: The contribution of infrared luminosity-binned (sub-LIRGs, LIRGs, & ULIRGs) galaxies to the total cosmic SFR density, showing the preeminent role of LIRGs at $z \sim 1$ and ULIRGs at $z \gtrsim 1.5$. Adapted from Casey et al. (2014).

easier to estimate even at very high redshifts because the UV and optical data are detailed and deep. However, correcting the observed UV-based star formation rate density to its actual value is not easy, and there is still much discussion about how to do it correctly (see Madau and Dickinson (2014) for more information). As established in Madau and Dickinson (2014) and the previous sections, a significant portion of star formation, especially at its peak epoch ($z \sim 2-3$), occurs within dusty, optically thick environments. Therefore, a complete census of the SFRD requires a multi-wavelength approach (see, Figure 1.11):

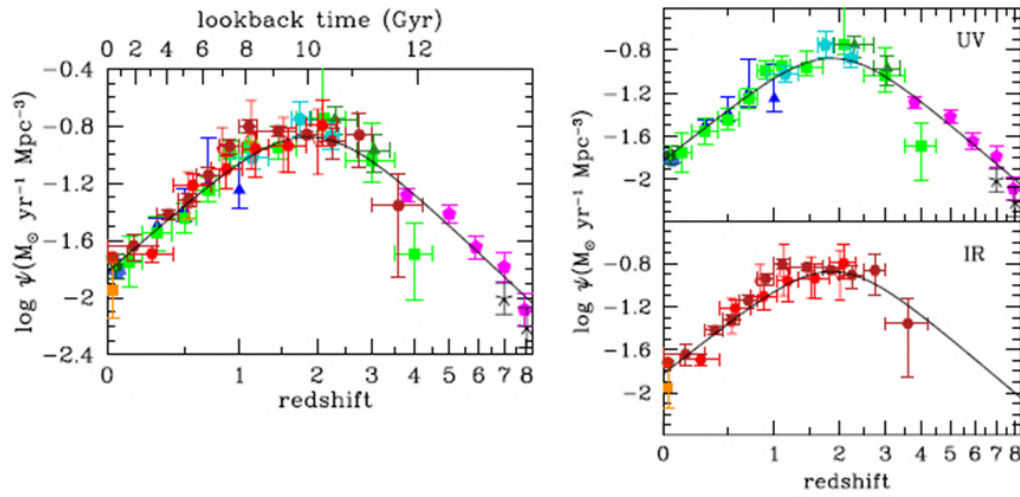


Figure 1.11: The evolution of the cosmic star formation rate density with redshift (a “Lilly–Madau” plot). The left panel shows the total SFRD (UV + IR) from numerous studies, revealing a rise from high redshift to a peak at $z \sim 2-3$, followed by a sharp decline to the present day. The UV (panel top right) and IR (panel bottom right) based star formation rate densities. Adapted from Madau and Dickinson (2014).

References

- Aravena, M., Carilli, C., Daddi, E., Wagg, J., Walter, F., Riechers, D., Dannerbauer, H., Morrison, G. E., Stern, D., and Krips, M. (2010). Cold molecular gas in massive, star-forming disk galaxies at $z=1.5$. *The Astrophysical Journal*, 718(1):177.
- Aravena, M., Hodge, J. A., Wagg, J., Carilli, C. L., Daddi, E., Dannerbauer, H., Lentati, L., Riechers, D. A., Sargent, M., and Walter, F. (2014). Co (1–0) line imaging of massive star-forming disc galaxies at $z=1.5$ –2.2. *Monthly Notices of the Royal Astronomical Society*, 442(1):558–564.
- Arnouts, S. and Ilbert, O. (2011). Lephare: Photometric analysis for redshift estimate. *Astrophysics Source Code Library*, pages ascl–1108.
- Ashby, M. L., Dye, S., Huang, J.-S., Eales, S., Willner, S., Webb, T., Barmby, P., Rigopoulou, D., Egami, E., McCracken, H., et al. (2006). Mid-infrared identifications of scuba galaxies in the cudss 14 hour field with the spitzer space telescope. *The Astrophysical Journal*, 644(2):778.
- Barger, A., Cowie, L., Sanders, D., Fulton, E., Taniguchi, Y., Sato, Y., Kawara, K., and Okuda, H. (1998). Submillimetre-wavelength detection of dusty star-forming galaxies at high redshift. *Nature*, 394(6690):248–251.
- Bastian, N., Covey, K. R., and Meyer, M. R. (2010). A universal stellar initial mass function? a critical look at variations. *Annual Review of Astronomy and Astrophysics*, 48:339–389.

- Bell, E. F., McIntosh, D. H., Katz, N., and Weinberg, M. D. (2003). A first estimate of the baryonic mass function of galaxies. *The Astrophysical Journal*, 585(2):L117.
- Bloemen, J., Strong, A., Mayer-Hasselwander, H., Blitz, L., Cohen, R., Dame, T., Grabelsky, D., Thaddeus, P., Hermsen, W., and Lebrun, F. (1986). The radial distribution of galactic gamma rays. iii-the distribution of cosmic rays in the galaxy and the co-h₂ calibration. *Astronomy and Astrophysics (ISSN 0004-6361)*, vol. 154, no. 1-2, Jan. 1986, p. 25-41., 154:25–41.
- Bolatto, A. D., Wolfire, M., and Leroy, A. K. (2013). The co-to-h₂ conversion factor. *Annual Review of Astronomy and Astrophysics*, 51(1):207–268.
- Boquien, M., Burgarella, D., Roehlly, Y., Buat, V., Ciesla, L., Corre, D., Inoue, A., and Salas, H. (2019). Cigale: a python code investigating galaxy emission. *Astronomy & Astrophysics*, 622:A103.
- Bothwell, M., Smail, I., Chapman, S., Genzel, R., Ivison, R., Tacconi, L., Alaghband-Zadeh, S., Bertoldi, F., Blain, A., Casey, C., et al. (2013). A survey of molecular gas in luminous sub-millimetre galaxies. *Monthly Notices of the Royal Astronomical Society*, 429(4):3047–3067.
- Bowler, R., Jarvis, M., Dunlop, J., McLure, R., McLeod, D., Adams, N., Milvang-Jensen, B., and McCracken, H. (2020). A lack of evolution in the very bright end of the galaxy luminosity function from $z \sim 8$ to 10. *Monthly Notices of the Royal Astronomical Society*, 493(2):2059–2084.
- Brinchmann, J., Charlot, S., White, S. D., Tremonti, C., Kauffmann, G., Heckman, T., and Brinkmann, J. (2004). The physical properties of star-forming galaxies in the low-redshift universe. *Monthly notices of the royal astronomical society*, 351(4):1151–1179.
- Bruzual, G. and Charlot, S. (2003). Stellar population synthesis at the resolution of 2003. *Monthly Notices of the Royal Astronomical Society*, 344(4):1000–1028.
- Calzetti, D. (2013). Star formation rate indicators. *Secular Evolution of Galaxies*, 419.

- Calzetti, D. and Kinney, A. (1985). L., & storchi-bergmann, t. 1994. *ApJ*, 429:582.
- Caputi, K. I., Lagache, G., Yan, L., Dole, H., Bavouzet, N., Le Floch, E., Choi, P., Helou, G., and Reddy, N. (2007). The infrared luminosity function of galaxies at redshifts $z=1$ and $z\sim 2$ in the goods fields. *The Astrophysical Journal*, 660(1):97.
- Carilli, C. and Walter, F. (2013). Cool gas in high-redshift galaxies. *Annual Review of Astronomy and Astrophysics*, 51(1):105–161.
- Carilli, C. and Yun, M. S. (1999). The radio-to-submillimeter spectral index as a redshift indicator. *The Astrophysical Journal*, 513(1):L13.
- Casey, C. M. (2012). Far-infrared spectral energy distribution fitting for galaxies near and far. *Monthly Notices of the Royal Astronomical Society*, 425(4):3094–3103.
- Casey, C. M., Narayanan, D., and Cooray, A. (2014). Dusty star-forming galaxies at high redshift. *Physics Reports*, 541(2):45–161.
- Chabrier, G. (2003). The galactic disk mass function: reconciliation of the hubble space telescope and nearby determinations. *The Astrophysical Journal*, 586(2):L133.
- Chen, C.-C., Cowie, L. L., Barger, A. J., Casey, C. M., Lee, N., Sanders, D. B., Wang, W.-H., and Williams, J. P. (2012). Faint submillimeter galaxy counts at $450\ \mu\text{m}$. *The Astrophysical Journal*, 762(2):81.
- Condon, J. (1992). Radio emission from normal galaxies. *In: Annual review of astronomy and astrophysics. Vol. 30 (A93-25826 09-90), p. 575-611.*, 30:575–611.
- Cowie, L. L., Songaila, A., Hu, E. M., and Cohen, J. (1996). New insight on galaxy formation and evolution from keck spectroscopy of the hawaii deep fields. *arXiv preprint astro-ph/9606079*.
- Da Cunha, E., Charlot, S., Dunne, L., Smith, D., and Rowlands, K. (2011). Magphys: a publicly available tool to interpret observed galaxy seds. *Proceedings of the International Astronomical Union*, 7(S284):292–296.

- Daddi, E., Bournaud, F., Walter, F., Dannerbauer, H., Carilli, C., Dickinson, M., Elbaz, D., Morrison, G., Riechers, D., Onodera, M., et al. (2010). Very high gas fractions and extended gas reservoirs in $z=1.5$ disk galaxies. *The Astrophysical Journal*, 713(1):686.
- Daddi, E., Dannerbauer, H., Liu, D., Aravena, M., Bournaud, F., Walter, F., Riechers, D., Magdis, G., Sargent, M., Béthermin, M., et al. (2015). Co excitation of normal star-forming galaxies out to $z=1.5$ as regulated by the properties of their interstellar medium. *Astronomy & Astrophysics*, 577:A46.
- Daddi, E., Dickinson, M., Morrison, G., Chary, R., Cimatti, A., Elbaz, D., Frayer, D., Renzini, A., Pope, A., Alexander, D., et al. (2007). Multiwavelength study of massive galaxies at $z \sim 2$. i. star formation and galaxy growth. *The Astrophysical Journal*, 670(1):156.
- Daddi, E., Renzini, A., Pirzkal, N., Cimatti, A., Malhotra, S., Stiavelli, M., Xu, C., Pasquali, A., Rhoads, J. E., Brusa, M., et al. (2005). Passively evolving early-type galaxies at $1.4 \leq z \leq 2.5$ in the hubble ultra deep field. *The Astrophysical Journal*, 626(2):680.
- Dannerbauer, H., Daddi, E., Riechers, D., Walter, F., Carilli, C., Dickinson, M., Elbaz, D., and Morrison, G. (2009). Low milky-way-like molecular gas excitation of massive disk galaxies at $z=1.5$. *The Astrophysical Journal*, 698(2):L178.
- Delahaye, T., Fiasson, A., Pohl, M., and Salati, P. (2011). The gev-teV galactic gamma-ray diffuse emission-i. uncertainties in the predictions of the hadronic component. *Astronomy & Astrophysics*, 531:A37.
- Dole, H., Lagache, G., Puget, J.-L., Caputi, K. I., Fernandez-Conde, N., Le Floc'h, E., Papovich, C., Pérez-González, P. G., Rieke, G. H., and Blaylock, M. (2006). The cosmic infrared background resolved by spitzer-contributions of mid-infrared galaxies to the far-infrared background. *Astronomy & Astrophysics*, 451(2):417–429.

- Dunlop, J., McLure, R. J., Biggs, A. D., Geach, J. E., Michałowski, M. J., Ivison, R., Rujopakarn, W., van Kampen, E., Kirkpatrick, A., Pope, A., et al. (2017). A deep alma image of the hubble ultra deep field. *Monthly Notices of the Royal Astronomical Society*, 466(1):861–883.
- Dye, S., Eales, S. A., Aretxaga, I., Serjeant, S., Dunlop, J., Babbedge, T., Chapman, S., Cirasuolo, M., Clements, D., Coppin, K., et al. (2008). The scuba half degree extragalactic survey (shades)–vii. optical/ir photometry and stellar masses of submillimetre galaxies. *Monthly Notices of the Royal Astronomical Society*, 386(2):1107–1130.
- Eales, S., Dunne, L., Clements, D., Cooray, A., De Zotti, G., Dye, S., Ivison, R., Jarvis, M., Lagache, G., Maddox, S., et al. (2010). The herschel atlas. *Publications of the Astronomical Society of the Pacific*, 122(891):499.
- Elbaz, D., Daddi, E., Le Borgne, D., Dickinson, M., Alexander, D., Chary, R.-R., Starck, J.-L., Brandt, W., Kitzbichler, M., MacDonald, E., et al. (2007). The reversal of the star formation-density relation in the distant universe. *Astronomy & Astrophysics*, 468(1):33–48.
- Gao, Y., Gu, Q., Liu, G., Zhang, H., Shi, Y., Dou, J., Li, X., and Kong, X. (2023). Merger-induced star formation in the low-metallicity dwarf galaxy ngc 4809/4810. *Astronomy & Astrophysics*, 677:A179.
- Geach, J. E., Smail, I., Moran, S. M., MacArthur, L. A., Lagos, C. d. P., and Edge, A. C. (2011). On the evolution of the molecular gas fraction of star-forming galaxies. *The Astrophysical Journal Letters*, 730(2):L19.
- Genzel, R., Tacconi, L., Gracia-Carpio, J., Sternberg, A., Cooper, M., Shapiro, K., Bolatto, A., Bouché, N., Bournaud, F., Burkert, A., et al. (2010). A study of the gas–star formation relation over cosmic time. *Monthly notices of the royal astronomical Society*, 407(4):2091–2108.
- Gruppioni, C., Pozzi, F., Rodighiero, G., Delvecchio, I., Berta, S., Pozzetti, L., Zamorani, G., Andreani, P., Cimatti, A., Ilbert, O., et al. (2013). The herschel

- pep/hermes luminosity function–i. probing the evolution of pacs selected galaxies to $z \approx 4$. *Monthly Notices of the Royal Astronomical Society*, 432(1):23–52.
- Hainline, L. J., Blain, A., Smail, I., Alexander, D., Armus, L., Chapman, S., and Ivison, R. (2011). The stellar mass content of submillimeter-selected galaxies. *The Astrophysical Journal*, 740(2):96.
- Hatsukade, B., Iono, D., Akiyama, T., Yoshikawa, M., Dunlop, J., Ivison, R., Peck, A., Ikarashi, S., Biggs, A., Ezawa, H., et al. (2010). Unveiling the nature of submillimeter galaxy sxdf 850.6. *The Astrophysical Journal*, 711(2):974.
- Helou, G., Soifer, B., and Rowan-Robinson, M. (1985). Thermal infrared and non-thermal radio-remarkable correlation in disks of galaxies. *Astrophysical Journal, Part 2-Letters to the Editor (ISSN 0004-637X)*, vol. 298, Nov. 1, 1985, p. L7-L11. *NASA-supported research.*, 298:L7–L11.
- Hezaveh, Y., Marrone, D., Fassnacht, C., Spilker, J., Vieira, J., Aguirre, J., Aird, K., Aravena, M., Ashby, M., Bayliss, M., et al. (2013). Alma observations of spt-discovered, strongly lensed, dusty, star-forming galaxies. *The Astrophysical Journal*, 767(2):132.
- Hirashita, H., Buat, V., and Inoue, A. K. (2003). Star formation rate in galaxies from uv, ir, and $\text{H}\alpha$ estimators. *Astronomy & Astrophysics*, 410(1):83–100.
- Hodge, J., Karim, A., Smail, I., Swinbank, A., Walter, F., Biggs, A., Ivison, R. J., Weiss, A., Alexander, D., Bertoldi, F., et al. (2013). An alma survey of submillimeter galaxies in the extended chandra deep field south: source catalog and multiplicity. *The Astrophysical Journal*, 768(1):91.
- Hopkins, P. F., Somerville, R. S., Hernquist, L., Cox, T. J., Robertson, B., and Li, Y. (2006). The relation between quasar and merging galaxy luminosity functions and the merger-driven star formation history of the universe. *The Astrophysical Journal*, 652(2):864.
- Ivison, R., Papadopoulos, P., Smail, I., Greve, T., Thomson, A., Xilouris, E., and Chapman, S. (2011). Tracing the molecular gas in distant submillimetre galaxies

- via co (1–0) imaging with the expanded very large array. *Monthly Notices of the Royal Astronomical Society*, 412(3):1913–1925.
- Iverson, R., Smail, I., Le Borgne, J.-F., Blain, A., Kneib, J.-P., Bezecourt, J., Kerr, T., and Davies, J. (1998). A hyperluminous galaxy at $z=2.8$ found in a deep sub-millimetre survey. *Monthly Notices of the Royal Astronomical Society*, 298(2):583–593.
- Karim, A., Swinbank, A., Hodge, J., Smail, I., Walter, F., Biggs, A., Simpson, J., Danielson, A., Alexander, D., Bertoldi, F., et al. (2013). An alma survey of sub-millimetre galaxies in the extended chandra deep field south: high-resolution 870 μm source counts. *Monthly Notices of the Royal Astronomical Society*, 432(1):2–9.
- Kennicutt Jr, R. C. (1998). Star formation in galaxies along the hubble sequence. *Annual Review of Astronomy and Astrophysics*, 36(1):189–231.
- Kennicutt Jr, R. C. and Evans, N. J. (2012). Star formation in the milky way and nearby galaxies. *Annual Review of Astronomy and Astrophysics*, 50(1):531–608.
- Koprowski, M., Dunlop, J., Michałowski, M. J., Cirasuolo, M., and Bowler, R. (2014). A reassessment of the redshift distribution and physical properties of luminous (sub-) millimetre galaxies. *Monthly Notices of the Royal Astronomical Society*, 444(1):117–128.
- Koprowski, M., Dunlop, J. S., Michałowski, M. J., Coppin, K., Geach, J., McLure, R. J., Scott, D., and van der Werf, P. (2017). The evolving far-ir galaxy luminosity function and dust-obscured star formation rate density out to $z \approx 6$. *Monthly Notices of the Royal Astronomical Society*, 471(4):4155–4169.
- Koprowski, M., Wijesekera, J., Dunlop, J., Lisiecki, K., McLeod, D., McLure, R., Michałowski, M., and Solar, M. (2026). Evolution of the infrared luminosity function and its corresponding dust-obscured star formation rate density out to $z \approx 6$. *Astronomy & Astrophysics*, 706:A345.
- Koprowski, M., Wijesekera, J., Dunlop, J., McLeod, D., Michałowski, M., Lisiecki,

- K., and McLure, R. (2024). Charting the main sequence of star-forming galaxies out to redshifts $z \leq 5.7$. *Astronomy & Astrophysics*, 691:A164.
- Koprowski, M. P. (2015). (sub) millimetre-selected galaxies and the cosmic star-formation history.
- Kroupa, P. (2001). On the variation of the initial mass function. *Monthly Notices of the Royal Astronomical Society*, 322(2):231–246.
- Le Floc’h, E. and et al. (2005). Infrared luminosity functions from the chandra deep field-south: The spitzer view on the history of dusty star formation at $0 < z < 1$. *The Astrophysical Journal*, 632(1):169–190.
- Lenz, D., Doré, O., and Lagache, G. (2019). Large-scale maps of the cosmic infrared background from planck. *The Astrophysical Journal*, 883(1):75.
- Leroy, A. K., Bolatto, A., Gordon, K., Sandstrom, K., Gratier, P., Rosolowsky, E., Engelbracht, C. W., Mizuno, N., Corbelli, E., Fukui, Y., et al. (2011). The co-to-h2 conversion factor from infrared dust emission across the local group. *The Astrophysical Journal*, 737(1):12.
- Lim, S., Hill, R., Scott, D., van Waerbeke, L., Cuillandre, J.-C., Carlberg, R. G., Chisari, N. E., Dvornik, A., Erben, T., Gwyn, S., et al. (2023). Constraints on galaxy formation from the cosmic-far-infrared-background–optical-imaging cross-correlation using herchel and unions. *Monthly Notices of the Royal Astronomical Society*, 525(1):1443–1478.
- Liu, F.-Y., Dunlop, J. S., McLure, R. J., McLeod, D. J., Barrufet, L., Carnall, A. C., Begley, R., Pérez-González, P. G., Donnan, C. T., Ellis, R. S., et al. (2026). Jwst primer: a deep jwst study of all alma-detected galaxies in primer cosmos–dust-obscured star formation history back to $z \approx 7$. *Monthly Notices of the Royal Astronomical Society*, 545(2):staf1961.
- Lonsdale, C. J., Farrah, D., and Smith, H. E. (2006). Ultraluminous infrared galaxies. *Astrophysics Update 2*, pages 285–336.

- Madau, P. and Dickinson, M. (2014). Cosmic star-formation history. *Annual Review of Astronomy and Astrophysics*, 52(1):415–486.
- Madau, P., Pozzetti, L., and Dickinson, M. (1998). The star formation history of field galaxies. *The Astrophysical Journal*, 498(1):106.
- Magdis, G. E., Daddi, E., Bethermin, M., Sargent, M., Elbaz, D., Pannella, M., Dickinson, M., Dannerbauer, H., da Cunha, E., Walter, F., et al. (2012). The evolving interstellar medium of star-forming galaxies since $z=2$ as probed by their infrared spectral energy distributions. *The Astrophysical Journal*, 760(1):6.
- Magnelli, B., Elbaz, D., Chary, R., Dickinson, M., Le Borgne, D., Frayer, D., and Willmer, C. (2011). Evolution of the dusty infrared luminosity function from $z=0$ to $z=2.3$ using observations from spitzer. *Astronomy & Astrophysics*, 528:A35.
- Magnelli, B., Popesso, P., Berta, S., Pozzi, F., Elbaz, D., Lutz, D., Dickinson, M., Altieri, B., Andreani, P., Aussel, H., et al. (2013). The deepest herchel-pacs far-infrared survey: number counts and infrared luminosity functions from combined pep/goods-h observations. *Astronomy & Astrophysics*, 553:A132.
- Mak, D. S. Y., Challinor, A., Efstathiou, G., and Lagache, G. (2017). Measurement of cib power spectra over large sky areas from planck hfi maps. *Monthly Notices of the Royal Astronomical Society*, 466(1):286–319.
- Maraston, C. (2005). Evolutionary population synthesis: models, analysis of the ingredients and application to high- z galaxies. *Monthly Notices of the Royal Astronomical Society*, 362(3):799–825.
- McLeod, D., McLure, R., Dunlop, J., Cullen, F., Carnall, A., and Duncan, K. (2021). The evolution of the galaxy stellar-mass function over the last 12 billion years from a combination of ground-based and hst surveys. *Monthly Notices of the Royal Astronomical Society*, 503(3):4413–4435.
- McLure, R., Dunlop, J., Cullen, F., Bourne, N., Best, P., Khochfar, S., Bowler, R., Biggs, A., Geach, J., Scott, D., et al. (2018). Dust attenuation in $2 < z < 3$

- star-forming galaxies from deep alma observations of the hubble ultra deep field. *Monthly Notices of the Royal Astronomical Society*, 476(3):3991–4006.
- Meurer, G. R., Heckman, T. M., and Calzetti, D. (1999). Dust absorption and the ultraviolet luminosity density at $z \approx 3$ as calibrated by local starburst galaxies. *The Astrophysical Journal*, 521(1):64.
- Michałowski, M. J., Dunlop, J. S., Cirasuolo, M., Hjorth, J., Hayward, C. C., and Watson, D. (2012). The stellar masses and specific star-formation rates of submillimetre galaxies. *Astronomy & Astrophysics*, 541:A85.
- Michałowski, M. J., Watson, D., and Hjorth, J. (2010). Rapid dust production in submillimeter galaxies at $z > 4$? *The Astrophysical Journal*, 712(2):942.
- Nguyen, H., Schulz, B., Levenson, L., Amblard, A., Arumugam, V., Aussel, H., Babbedge, T., Blain, A., Bock, J., Boselli, A., et al. (2010). Hermes: The spire confusion limit. *Astronomy & Astrophysics*, 518:L5.
- Noeske, K., Weiner, B., Faber, S., Papovich, C., Koo, D., Somerville, R., Bundy, K., Conselice, C., Newman, J., Schiminovich, D., et al. (2007). Star formation in aegis field galaxies since $z = 1.1$: the dominance of gradually declining star formation, and the main sequence of star-forming galaxies. *The Astrophysical Journal*, 660(1):L43.
- Noll, S., Burgarella, D., Giovannoli, E., Buat, V., Marcillac, D., and Munoz-Mateos, J. (2009). Analysis of galaxy spectral energy distributions from far-uv to far-ir with cigale: studying a sings test sample. *Astronomy & Astrophysics*, 507(3):1793–1813.
- Oklopčić, A. and Hirata, C. M. (2013). $\text{Ly}\alpha$ heating of inhomogeneous high-redshift intergalactic medium. *The Astrophysical Journal*, 779(2):146.
- Oliver, S., Bock, J., Altieri, B., Amblard, A., Arumugam, V., Aussel, H., Babbedge, T., Beelen, A., Béthermin, M., Blain, A., et al. (2012). The herschel multi-tiered extragalactic survey: Hermes. *Monthly Notices of the Royal Astronomical Society*, 424(3):1614–1635.

- Osterbrock, D. E. and Ferland, G. J. (2006). *Astrophysics Of Gas Nebulae and Active Galactic Nuclei*. University science books.
- Polletta, M., Tajer, M., Maraschi, L., Trinchieri, G., Lonsdale, C., Chiappetti, L., Andreon, S., Pierre, M., Le Fevre, O., Zamorani, G., et al. (2007). Spectral energy distributions of hard x-ray selected active galactic nuclei in the xmm-newton medium deep survey. *The Astrophysical Journal*, 663(1):81.
- Reddy, N., Dickinson, M., Elbaz, D., Morrison, G., Giavalisco, M., Ivison, R., Papovich, C., Scott, D., Buat, V., Burgarella, D., et al. (2011). Goods-herschel measurements of the dust attenuation of typical star-forming galaxies at high redshift: observations of ultraviolet-selected galaxies at $z \sim 2$. *The Astrophysical Journal*, 744(2):154.
- Reddy, N. A., Pettini, M., Steidel, C. C., Shapley, A. E., Erb, D. K., and Law, D. R. (2012). The characteristic star formation histories of galaxies at redshifts $z \sim 2$ –7. *The Astrophysical Journal*, 754(1):25.
- Reipurth, B., Jewitt, D., and Keil, K. (2007). *Protostars and planets V*. University of Arizona Press.
- Riechers, D. A., Hodge, J., Walter, F., Carilli, C. L., and Bertoldi, F. (2011). Extended cold molecular gas reservoirs in $z \sim 3.4$ submillimeter galaxies. *The Astrophysical Journal Letters*, 739(1):L31.
- Rodighiero, G., Daddi, E., Baronchelli, I., Cimatti, A., Renzini, A., Aussel, H., Popesso, P., Lutz, D., Andreani, P., Berta, S., et al. (2011). The lesser role of starbursts in star formation at $z \sim 2$. *The Astrophysical journal letters*, 739(2):L40.
- Rogers, A., McLure, R., and Dunlop, J. (2013). The unbiased measurement of ultraviolet spectral slopes in low-luminosity galaxies at $z \sim 7$. *Monthly Notices of the Royal Astronomical Society*, 429(3):2456–2468.
- Salpeter, E. E. (1955). The luminosity function and stellar evolution. *Astrophysical Journal*, vol. 121, p. 161, 121:161.

- Sanders, D. and Mirabel, I. (1996). Luminous infrared galaxies. *Annual Review of Astronomy and Astrophysics*, 34(1):749–792.
- Santini, P., Fontana, A., Grazian, A., Salimbeni, S., Fiore, F., Fontanot, F., Boutsia, K., Castellano, M., Cristiani, S., De Santis, C., et al. (2009). Star formation and mass assembly in high redshift galaxies. *Astronomy & Astrophysics*, 504(3):751–767.
- Saunders, W., Rowan-Robinson, M., Lawrence, A., et al. (1990). The 60-micron and far-infrared luminosity functions of iras galaxies. *Monthly Notices of the Royal Astronomical Society*, 242(2):318–337.
- Schechter, P. (1976). An analytic expression for the luminosity function for galaxies. *Astrophysical Journal*, Vol. 203, p. 297–306, 203:297–306.
- Schmidt, M. (1968). Space distribution and luminosity functions of quasi-stellar radio sources. *Astrophysical Journal*, vol. 151, p. 393, 151:393.
- Smail, I., Ivison, R., and Blain, A. (1997). A deep submillimeter survey of lensing clusters: A new window on galaxy formation and evolution. *The Astrophysical Journal*, 490(1):L5.
- Solomon, P. and Vanden Bout, P. A. (2005). Molecular gas at high redshift. *Annu. Rev. Astron. Astrophys.*, 43(1):677–725.
- Speagle, J. S., Steinhardt, C. L., Capak, P. L., and Silverman, J. D. (2014). A highly consistent framework for the evolution of the star-forming “main sequence” from $z = 0$ –6. *The Astrophysical Journal Supplement Series*, 214(2):15.
- Spilker, J., Marrone, D., Aguirre, J., Aravena, M., Ashby, M., Béthermin, M., Bradford, C., Bothwell, M., Brodwin, M., Carlstrom, J., et al. (2014). The rest-frame submillimeter spectrum of high-redshift, dusty, star-forming galaxies. *The Astrophysical Journal*, 785(2):149.
- Tacconi, L., Genzel, R., Neri, R., Cox, P., Cooper, M., Shapiro, K., Bolatto, A., Bouché, N., Bournaud, F., Burkert, A., et al. (2010). High molecular gas frac-

- tions in normal massive star-forming galaxies in the young universe. *Nature*, 463(7282):781–784.
- Tacconi, L., Neri, R., Genzel, R., Combes, F., Bolatto, A., Cooper, M., Wuyts, S., Bournaud, F., Burkert, A., Comerford, J., et al. (2013). Phibss: molecular gas content and scaling relations in $z = 1-3$ massive, main-sequence star-forming galaxies. *The Astrophysical Journal*, 768(1):74.
- Thomas, D., Maraston, C., Bender, R., and De Oliveira, C. M. (2005). The epochs of early-type galaxy formation as a function of environment. *The Astrophysical Journal*, 621(2):673.
- Van der Wel, A., Bell, E. F., Van den Bosch, F. C., Gallazzi, A., and Rix, H.-W. (2009). On the size and comoving mass density evolution of early-type galaxies. *The astrophysical journal*, 698(2):1232.
- Wang, W., Lu, J., Luo, Z., Yang, Z., Hua, H., and Chen, Z. (2011). Galaxy evolution: infrared to millimeter wavelength perspective. *Galaxy Evolution: Infrared to Millimeter Wavelength Perspective*, 446.
- Wardlow, J. L., Smail, I., Coppin, K., Alexander, D., Brandt, W., Danielson, A., Luo, B., Swinbank, A., Walter, F., Weiß, A., et al. (2011). The laboca survey of the extended chandra deep field-south: a photometric redshift survey of submillimetre galaxies. *Monthly Notices of the Royal Astronomical Society*, 415(2):1479–1508.
- Weiß, A., Kovács, A., Coppin, K., Greve, T., Walter, F., Smail, I., Dunlop, J., Knudsen, K., Alexander, D., Bertoldi, F., et al. (2009). The large apex bolometer camera survey of the extended chandra deep field south. *The Astrophysical Journal*, 707(2):1201.
- Whitaker, K. E., Franx, M., Leja, J., Van Dokkum, P. G., Henry, A., Skelton, R. E., Fumagalli, M., Momcheva, I. G., Brammer, G. B., Labbé, I., et al. (2014). Constraining the low-mass slope of the star formation sequence at $0.5 < z < 2.5$. *The Astrophysical Journal*, 795(2):104.

- Whitaker, K. E., Van Dokkum, P. G., Brammer, G., and Franx, M. (2012). The star formation mass sequence out to $z=2.5$. *The Astrophysical Journal Letters*, 754(2):L29.

Publications constituting the dissertation

The primary aim of this thesis is to investigate the cosmic history of star formation, tracing its evolution back to epochs when the Universe was less than 10% of its present age. This work aims to broaden our understanding of how and when galaxies formed their stars by including the entire population of both bright and faint, dusty star-forming systems over a wide range of redshifts. To address these tasks, this thesis employs a twofold approach, utilizing state-of-the-art observational data and advanced analysis (stacking). Particular emphasis is placed on techniques that enable investigation below the classical detection limits to estimate the IR luminosities and, consequently, the SFRs of galaxies too faint to be detected individually. The latter novelties allow for a more detailed reconstruction of the dust-obscured SFH at high- z .

The publications are presented in three articles, referred to as articles A, B, and C.

- **Article A:** - In this article, we provide a new characterisation of the star-forming main sequence (MS) over $0 < z \lesssim 5.7$. With a subset of around 100,000 K -band-selected galaxies from the COSMOS and the UDS fields, we stacked far-infrared data in both *Herschel* and SCUBA-2. We fit modified blackbody models to obtain average infrared luminosities and star formation rates in stellar mass and redshift bins. The fit confirmed a steep dependence of star-formation rate on stellar mass at low masses, followed by a saturation of the relation at high masses. We found that the MS normalisation evolves

exponentially with redshift; the dust temperature rises from typically 20 K to about 50 K at $z \approx 5$. The analysis also showed that the obtained main-sequence evolution self-consistently recovers the observed growth rate of the galaxy stellar mass function. However, a mild excess of low-mass galaxies is predicted at high redshifts. These results represent one of the tightest empirical constraints on the SFMS and significantly enhance the calibration of dust-based star formation diagnostics in young galaxies.

- **Article B:** - Here, we investigate the evolution of dust attenuation in main-sequence galaxies by exploring the $\text{IRX}-\beta$ relation as a function of stellar mass ($M_\star$) from $z \approx 0.5 - 5.7$. The analysis is based on $\sim 100,000$ K -band-selected galaxies in the UKIDSS UDS and COSMOS fields, for which we perform SED modelling of rest-frame UV-NIR photometry (including *Herschel* and JCMT/SCUBA-2 far-infrared measurements). Stacking was carried out to obtain average IR fluxes, and SEDs were modelled with **CIGALE** for estimates of intrinsic UV slopes and bolometric correction values. Our $\text{IRX}-\beta$ relation is well described by a Calzettian attenuation curve and reveals a mild dependence of the attenuation on redshift; effectively, our derived extinction is systematically greater at $z > 2.5$ than would be expected from its low-redshift counterpart. Our findings also demonstrate that the stellar mass is a better predictor of dust attenuation than β , as it reduces scatter and reveals a constant flattening of IRX at high masses, which is associated with dust saturation processes and feedback. These findings provide crucial empirical constraints on dust evolution and the interpretation of obscured star formation in the first five billion years of cosmic history.
- **Article C:** - This article investigates the evolution of the far-infrared luminosity function (IR LF) and the corresponding dust-obscured star formation rate density (SFRD) out to $z \approx 6$. Using deep SCUBA-2 $850\,\mu\text{m}$ from the S2CLS survey, ALMA follow-up with AS2UDS and large-area *Herschel* imaging, the work constrains both the bright and faint end of the IR LF via direct detections and stacking analysis of mass-complete galaxy samples. The charac-

teristic luminosity ($L^\star$) evolves roughly as $(1+z)^{1.4\pm0.1}$ while the characteristic density ($\Phi^\star$) is roughly constant out to $z \approx 2$, and then drops off rapidly towards higher redshifts. Fitting an evolving IR LF gives the dust-obscured SFRD which peaks at $z \approx 2 - 3$ and drops rapidly toward higher redshifts, contributing less than $\sim 25\%$ of the total cosmic SFRD at $z = 6$. These results suggest that dust-obscured star formation comprises 100% of the population at “cosmic noon” and becomes progressively sub-dominant towards earlier times, indicating a transition from optimal to UV-visible SF in the first billion years of galaxy evolution.

Author Contribution statement

This thesis consists of three papers. In the first paper A, I was a co-author. In the second paper B, I am the first author, and it is available as a pre-print on arXiv. In the third paper, C, I am a co-author, and it is available as a pre-print on arXiv.

Hereby, I declare that my contributions to the paper A are as follows:

M. Koprowski, **J. Wijesekera**, J. Dunlop, et al. (2024). *Charting the main sequence of star-forming galaxies out to redshifts $z \lesssim 5.7$. Astronomy & Astrophysics*, 691, A164. doi: 10.1051/0004-6361/202449948.

Impact factor: 6.1, **MNiSW points:** 140, Q1,

consisted of:

- helping with parts of the analysis, namely the stacking procedure and the visualization of the results, constituting 15% of the total workload.

Hereby, I declare that my contributions to paper B are as follows:

J. Wijesekera, M. Koprowski, J. Dunlop, et al. (2024). *Charting the main sequence of star-forming galaxies out to redshifts $z \lesssim 5.7$. Astronomy & Astrophysics*, 691, A164. doi: 10.1051/0004-6361/202449948.

Impact factor: 6.1, **MNiSW points:** 140, Q1,

As the first author, I used COSMOS and UDS catalogues to calibrate IRX- β and IRX- $M_\star$ relations for MS galaxies. CIGALE was used to derive physical parameters from each redshift bin, such as the UV slope (β), Bolometric Correction for 1600, intrinsic UV slope (β) and UV luminosity at 150 nm. Furthermore, L_{IR} were derived by following the Casey et al. (2014) function. By reviewing the previous articles, I was able to calibrate the IRX- β - β and IRX- $M_\star$ relations using Meurer et al. (1999) and McLure et al. (2018). Finally, the bootstrapping method was used to calculate the errors for each IRX value.

Hereby, I declare that my contributions to paper C are as follows:

J. Wijesekera, M. Koprowski, J. Dunlop, et al. (2025). *“Evolution of the infrared luminosity function and its corresponding dust-obscured star formation rate density out to $z \sim 6$. arXiv e-prints, arXiv–2509, 2025.*

Impact factor: 6.1, **MNiSW points:** 140, Q1.

consisted of:

- helping with parts of the analysis, namely the stacking procedure and the visualization of the results, constituting 15% of the total workload.

The tasks of the PhD project

The main tasks of the doctoral thesis were to:

- Charting the Star-Forming Main Sequence Across Cosmic Time. A comprehensive analysis of how galaxies build their stellar mass from the local Universe to redshift $z \lesssim 5.7$.
- Determine the star formation rate from the UV continuum tilt when direct IR detection is not available via the so-called IRX- β relation, and determine the relationship between IR luminosity and galaxy mass (IRX- $M_\star$).
- Determination of the direct contribution of the brightest IR sources in the sky to the total star formation rate density in the Universe.

Papers

1.7 Article A

Charting the main sequence of star-forming galaxies
out to redshifts $z \lesssim 5.7$

Charting the main sequence of star-forming galaxies out to redshifts $z \lesssim 5.7$

M. P. Koprowski^{1,★}, J. V. Wijesekera¹, J. S. Dunlop², D. J. McLeod², M. J. Michałowski^{3,2},
K. Lisiecki^{1,4}, and R. J. McLure²

¹ Institute of Astronomy, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziądzka 5, 87-100 Toruń, Poland

² Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh EH9 3HJ, UK

³ Astronomical Observatory Institute, Faculty of Physics, Adam Mickiewicz University, ul. Słoneczna 36, 60-286 Poznań, Poland

⁴ National Centre for Nuclear Research, Pasteura 7, 093 Warsaw, Poland

Received 12 March 2024 / Accepted 25 September 2024

ABSTRACT

We present a new determination of the star-forming main sequence (MS), obtained through stacking 100k *K*-band-selected galaxies in the far-infrared (FIR) *Herschel* and *James Clerk Maxwell* Telescope (JCMT) imaging. By fitting the dust emission curve to the stacked FIR photometry, we derive the IR luminosities (L_{IR}), and hence the star formation rates (SFRs) out to $z \lesssim 5.7$. The functional form of the MS is found, with the linear $\text{SFR}-M_*$ relation that flattens at high stellar masses and the normalization that increases exponentially with redshift. We derive the corresponding redshift evolution of the specific star formation rate (sSFR) and compare our findings with the recent literature. We find our MS to be exhibiting slightly lower normalization at $z \lesssim 2$ and to flatten at somewhat larger stellar masses at high redshifts. By deriving the relationship between the peak dust temperature (T_d) and redshift, where T_d increases linearly from ~ 20 K at $z = 0.5$ to ~ 50 K at $z = 5$, we conclude that the apparent inconsistencies in the shapes of the MS are most likely caused by the different dust temperatures assumed when deriving SFRs in the absence of FIR data. Finally, we investigate the derived shape of the star-forming MS by simulating the time evolution of the observed galaxy stellar mass function (GSMF). While the simulated GSMF is in good agreement with the observed one, some inconsistencies persist. In particular, we find the simulated GSMF to be slightly overpredicting the number density of low-mass galaxies at $z \gtrsim 2$.

Key words. dust, extinction – galaxies: evolution – galaxies: high-redshift – galaxies: ISM – galaxies: star formation

1. Introduction

The increasing amount of multiwavelength data, obtained as part of wide-field and deep surveys, enables a progressively detailed examination of large samples of galaxies. Substantial advancements in determining important physical properties of galaxies (e.g., photometric redshifts, stellar masses, dust attenuation curves) have enabled the identification (in the rest-frame color-color space) of two separate types of galaxy populations: star-forming ones and quiescent ones (SFGs and QGs; e.g., Labbé et al. 2005; Wuyts et al. 2007; Ilbert et al. 2010). The main difference between these two distinct populations of galaxies is their star formation activity; it has been shown that the star formation rate (SFR) and stellar mass (M_*) of the SFGs follow a tight correlation out to the highest redshifts probed – the so-called star-forming main sequence (MS; e.g., Speagle et al. 2014; Tomczak et al. 2016; Daddi et al. 2022; Popesso et al. 2023). Most commonly, the $\text{SFR}-M_*$ relation can be parameterized with a simple power law:

$$\log(\text{SFR}/M_\odot \text{ yr}^{-1}) = \alpha \log(M_*/M_\odot) + \beta, \quad (1)$$

where α and β represent the slope and normalization of the MS, respectively. While the normalization has been shown to increase in redshift, with galaxies exhibiting higher SFRs at earlier epochs, the slope of the MS has been found to be

close to unity, mostly independent of redshift, with values ranging between ~ 0.8 and 1.3 (e.g., Lee et al. 2015; Tomczak et al. 2016; Popesso et al. 2023). More recently, a number of studies have found that the star-forming MS flattens at higher masses (e.g., Lee et al. 2015; Schreiber et al. 2015; Leslie et al. 2020; Leja et al. 2022; Popesso et al. 2023), reaching an asymptotic value of the SFR.

The exact shape and evolution of the MS is still widely discussed in the literature, with many studies presenting somewhat different perspectives. The sources of the discrepancies are many, including the assumed initial mass function (IMF), stellar population synthesis modeling, star formation histories (SFHs), and dust extinction curves. Most importantly, different techniques used for the estimation of the total SFRs can affect the results significantly. Since part of the UV emission coming from young stars gets absorbed by the interstellar dust, it is crucial to be able to properly quantify this effect. Measuring the dust attenuation from the rest-frame UV/optical data alone produces very uncertain results, because of the degeneracy between the age (different SFHs) and reddening (different metallicities, extinction curves). The advent of the *Herschel* Space Observatory (Pilbratt et al. 2010) allowed for the direct detection of the energy being re-emitted by dust in the far-infrared (FIR), and therefore a more reliable determination of the total (UV+IR) SFRs. However, since *Herschel* FIR data suffers from a relatively low resolution, only the most IR-luminous sources can be detected at high redshifts, and hence samples of SFGs studied

★ Corresponding author; drelkopi@gmail.com

with *Herschel* tend to be incomplete, often biasing the results toward large values of the SFRs. [Speagle et al. \(2014\)](#) and, more recently, [Popesso et al. \(2023\)](#) compiled various studies in the literature in order to convert them to the same absolute calibrations in an attempt to solve some of the issues listed above. While they carefully address all the inconsistencies caused by different modeling assumptions, the uncertainties associated with the various total SFR indicators, as well as the completeness of samples compiled, remain a concern.

In this work, we make use of the sample of $\sim 100k$ K -band-selected galaxies from the ground-based UV+optical+near-IR $\sim 2\text{deg}^2$ imaging of the UKIDSS Ultra Deep Survey (UDS) and COSMOS fields ([McLeod et al. 2021](#)). Galaxies are stacked in bins of redshift and stellar mass in the FIR *Herschel* and the *James Clerk Maxwell Telescope* (JCMT) SCUBA-2 ([Holland et al. 2013](#)) maps, in order to determine the shape and redshift evolution of the star-forming MS out to $z \lesssim 5.7$. The stacking approach, used by several authors before (e.g., [Tomczak et al. 2016](#); [Leslie et al. 2020](#); [Mérida et al. 2023](#)), has several advantages. The sample of galaxies stacked is mass-complete, assuring that the resulting values of the IR luminosity (and SFR) are not biased due to selection effects. In addition, thanks to the inclusion of the SCUBA-2 $850\mu\text{m}$ data, our stacked photometry maps the Rayleigh-Jeans portion of the dust emission spectrum, allowing for the precise determination of the dust temperatures, and thus the SFRs.

The paper is structured as follows. In Sect. 2, the data used in this work is described. We outline the stacking procedure and the star-forming sample selection process in Sect. 3. Section 4 explains the methodology used in the determination of the star-forming MS for our sample. We discuss the results of this work in Sect. 5. In particular, the shape and evolution of the star-forming MS and its relation to the so-called Schmidt-Kennicutt relation (SK relation; [Schmidt 1959](#); [Kennicutt 1998](#)) is explained in Sect. 5.1, followed by a discussion of the variations in the peak dust temperature with IR luminosity and redshift in Sect. 5.2 and a comparison to other works in Sect. 5.3. In Sect. 5.4, we attempt to interpret some of the discrepancies between the different shapes of the MS found in the literature, by “growing” the observed galaxy stellar mass function (GSMF) in time. Finally, we summarize our conclusions in Sect. 6. Throughout the paper, we use the [Chabrier \(2003\)](#) stellar IMF with an assumed flat cosmology of $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70\text{ km s}^{-1}\text{ Mpc}^{-1}$.

2. Data

2.1. Optical/near-IR catalogs

We started with the optical/near-IR catalogs of the UKIDSS Ultra Deep Survey (UDS) and COSMOS fields. The details of the data used, galaxies selection process and determination of photometric redshifts and stellar masses are presented in [McLeod et al. \(2021\)](#), with the shortened description given below.

2.1.1. Imaging

For the UKIDSS UDS field ([Lawrence et al. 2007](#)), we included UDS DR11 imaging (Almaini et al., in prep.) in the near-IR *JHK* bands, with *Y*-band imaging from the VISTA VIDEO DR4 release over XMM-LSS ([Jarvis et al. 2013](#)). We complemented this with UV imaging in *u**-band from CFHT MegaCam, and optical imaging in *BVRiz'* from Subaru Suprime-Cam

([Furusawa et al. 2008](#)). We also employed imaging in the narrowband NB921 ([Koyama et al. 2011](#)) and the refurbished Suprime-Cam *z*-band (z'_{new} ; [Furusawa et al. 2016](#)). To extend our wavelength coverage into the mid-infrared, we utilized *Spitzer* IRAC imaging in $3.6\mu\text{m}$ and $4.5\mu\text{m}$, combining the SEDS ([Ashby et al. 2013](#)), S-CANDELS ([Ashby et al. 2015](#)), and SPLASH (PI Capak; see [Mehta et al. 2018](#)) programs. The effective area of the overlapping UDS imaging was 0.69 deg^2 , after masking for bright stars.

For the COSMOS field, we combined near-IR *YJHK_s* imaging from UltraVISTA DR4 ([McCracken et al. 2012](#)) with UV/optical *u*griz* imaging from the CFHTLS-D2 T0007 data release ([Hudelot et al. 2012](#)). We confine our study to the 1 deg^2 overlapping area covered by these data sets. After masking, this reduced to an effective area of 0.86 deg^2 . As with the UDS, we also included Subaru Suprime-Cam z'_{new} imaging. There is a wealth of *Spitzer* IRAC imaging available in $3.6\mu\text{m}$ and $4.5\mu\text{m}$ over the COSMOS field. The programs we combined include S-COSMOS ([Sanders et al. 2007](#)), SPLASH (PI Capak), SEDS ([Ashby et al. 2013](#)), S-CANDELS ([Ashby et al. 2015](#)) and SMUVS ([Ashby et al. 2018](#)).

2.1.2. Photometric redshifts and stellar masses

As is explained in detail in [McLeod et al. \(2021\)](#), the parent multiwavelength catalogs were constructed by running SOURCE-EXTRACTOR ([Bertin & Arnouts 1996](#)) in dual-image mode, with the K -band as the detection image. Photometry was measured in 2-arcsec diameter apertures on the PSF-homogenized UV to near-IR images. For the lower resolution *Spitzer* IRAC 3.6 and $4.5\mu\text{m}$ data, the photometry was measured using the software TPHOT ([Merlin et al. 2015](#)).

For each object in the catalog, the photometric redshift we assigned was the median of six SED fitting runs, employing three different software codes. With LEPHARE, we included runs with the [Bruzual & Charlot \(2003\)](#), PEGASE ([Fioc & Rocca-Volmerange 1999](#)) and COSMOS ([Ilbert et al. 2009](#)) template libraries. We also included two EAZY ([Brammer et al. 2008](#)) runs, using the PCA and PEGASE templates, and one further run with the BPZ code ([Benítez 2000](#)), using the [Coleman et al. \(1980\)](#) templates. The resulting values of σ_z , defined as $1.483 \times \text{MAD}(dz)$, where MAD is the median absolute deviation and $dz = (z_{\text{phot}} - z_{\text{spec}})/(1 + z_{\text{spec}})$, for COSMOS and UDS fields were found to be equal to 0.019 and 0.022, respectively ([McLeod et al. 2021](#)).

Stellar masses were measured for each object by fixing the photometric redshift to z_{med} , and re-fitting the SED using LEPHARE with the [Bruzual & Charlot \(2003\)](#) library. This template set included a [Chabrier \(2003\)](#) IMF, a [Calzetti et al. \(2000\)](#) dust attenuation law and IGM absorption as in [Madau \(1995\)](#). The values were found to be in excellent agreement with those derived by the CANDELS team (see Table 2 of [McLeod et al. 2021](#)), with a tight 1:1 relation and a typical scatter of ± 0.05 dex. The resulting catalogs were then cleaned of stars, AGN, artifacts and objects with contaminated photometry. Finally, a further $\chi^2 < 40$ goodness-of-fit cut was implemented on the catalogs.

2.2. Far-infrared

For the extraction of the stacked FIR flux densities in the COSMOS and UDS fields we used the *Herschel* ([Pilbratt et al. 2010](#)) Multi-tiered Extragalactic Survey (HerMES; [Oliver et al. 2012](#)) and the Photodetector Array Camera and Spectrometer (PACS;

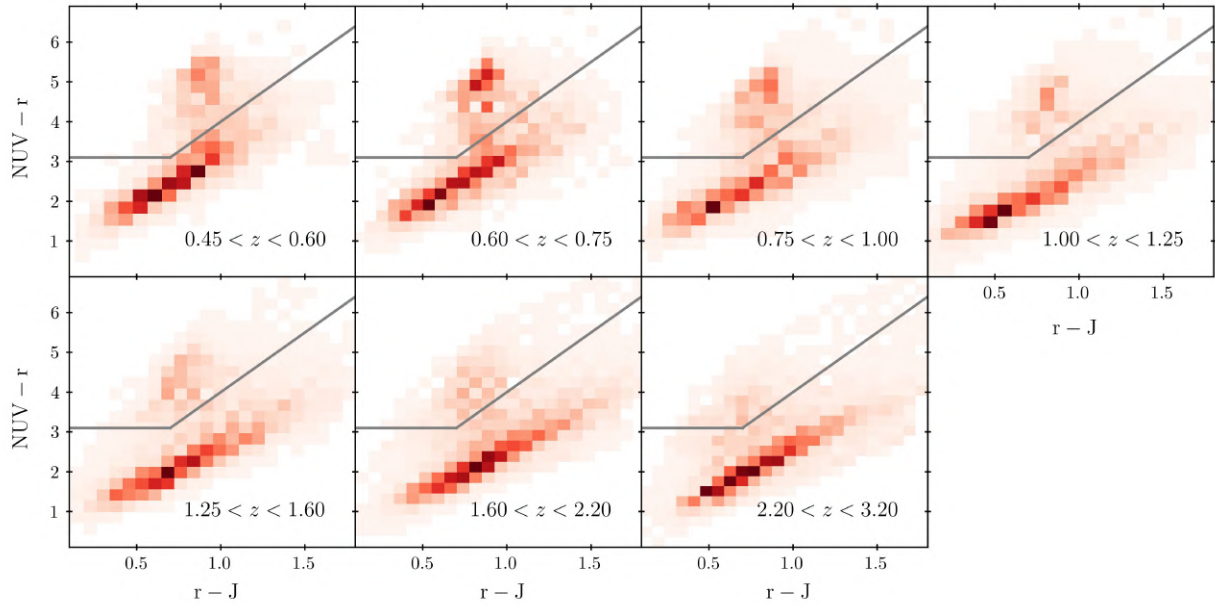


Fig. 1. Results of the $NUVrJ$ color-color selection results, defined in Eq. (2) shown for redshift bins adopted in this work. The $NUVrJ$ colors (Ilbert et al. 2013) are used in order to distinguish between sources reddened due to the lack of star formation (quiescent galaxies – upper left section of the plots) from those where red colors are caused by dust extinction (SFGs – main locus in the plots).

Poglitsch et al. 2010) Evolutionary Probe (PEP; Lutz et al. 2011) data obtained with the Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al. 2010) and PACS instruments. We utilized Herschel maps at 100, 160, 250, 350 and 500 μm with beam sizes of 7.39, 11.29, 18.2, 24.9, and 36.3 arcsec, and 5σ sensitivities of 7.7, 14.7, 24.0, 27.5, and 30.5 mJy, respectively.

In order to constrain the Rayleigh-Jeans tail of the dust emission curve, we have also included the data collected as a part of the SCUBA-2 Cosmology Legacy Survey (S2CLS; Geach et al. 2017), with the UKIDSS-UDS and COSMOS 850 μm imaging covering $\approx 0.9 \text{ deg}^2$ with a 1σ noise of 0.9 mJy and $\approx 1.3 \text{ deg}^2$ with the 1σ noise of 1.6 mJy, respectively.

3. Stacking

3.1. Sample selection

For the purpose of successful stacking (i.e., to maximize the number of sources in each stack), we designed each redshift bin to encompass ~ 1 billion years of Universe evolution, ranging from 1 to 9 billion years after the Big Bang (with the corresponding redshift bins of [0.45, 0.6, 0.75, 1.0, 1.25, 1.6, 2.2, 3.2, 5.7]; see Table A.1). We also made sure that the sample we stacked is mass-complete. The procedure for estimating the mass completeness in the UDS and COSMOS fields is explained in McLeod et al. (2021). In brief, the completeness was estimated using simulations, in which K -band imaging was produced by injecting a set of artificial galaxies with a wide range of physical properties. Adopting the original setup, the corresponding photometry catalogs were then constructed using SEXTRACTOR. In order to determine the 90% mass-completeness limit, the relation from Pozzetti et al. (2010) was used to derive the limiting stellar mass for each object in our sample. The 90% mass completeness limit, below which 90% of the limiting stellar masses lie, could then be derived as a function of redshift. The resulting redshift and stellar mass bins adopted in this work are listed in Table A.1.

In order to derive the $\text{SFR}-M_*$ relation for the star-forming sample, we first needed to separate it from the quiescent population. Here, we adopted the selection based on the $NUVrJ$ colors (Ilbert et al. 2013):

$$\begin{aligned} (NUV - r) &> 3 \times (r - J) + 1; \\ (NUV - r) &> 3.1, \end{aligned} \quad (2)$$

where NUV , r and J rest-frame magnitudes were generated from the best-fit SEDs. The advantage of this method is that it is able to separate sources for which reddening is caused by aging from those for which it is produced by dust extinction, thereby decreasing the chance of contaminating the dust-enshrouded star-forming sample with quiescent galaxies. Because at high redshifts the rest-frame J -band can no longer be traced by the photometry available in this work, the $NUVrJ$ color-color selection was performed out to $z \sim 4$, as is depicted in Fig. 1.

To avoid overestimating the SFRs at the high-mass end of the MS, we further detected and removed the starburst galaxy population from our stacking sample. To identify starbursts, we used the ALMA-detected sources in the COSMOS (Liu et al. 2019) and UDS (Stach et al. 2019) fields, with associated stellar masses and SFRs, as has been found by Liu et al. (2019) and Dudzevičiūtė et al. (2020), respectively. Following Elbaz et al. (2018), starbursts are defined as galaxies with $\text{SFR}/\text{SFR}_{\text{MS}} > 3$, where SFR_{MS} is the corresponding MS value, given the redshift and stellar mass of each ALMA-detected source, with the functional form of the star-forming MS of Popesso et al. (2023).

3.2. Far-infrared fluxes

Since current FIR/submillimeter surveys struggle to reach the (sub-)millijansky depths necessary for the detection of the dust emission in typical SFGs, we have resorted here to the well-known method of stacking (e.g., Whitaker et al. 2014; Schreiber et al. 2015; Tomczak et al. 2016; Koprowski et al. 2018). In order to determine the FIR fluxes at a given band, we cut a square stamp around the position of each source, with

the size of approximately $3\times$ the full width at half maximum (FWHM) of the corresponding beam. The average FIR fluxes at each pixel were then evaluated following the inverse-variance weighting:

$$S_v = \frac{\sum_i S_{v,i}/\sigma_i^2}{\sum_i 1/\sigma_i^2}, \quad (3)$$

where $S_{v,i}$ is the flux density of the i th source and σ_i is the 1σ instrumental noise, extracted at each pixel in a given source's stamp. The error on the mean stacked fluxes for each pixel was calculated according to

$$\sigma_{\text{stack}}^2(S_v) = \frac{1}{\sum_i 1/\sigma_i^2}, \quad (4)$$

with the example $500\mu\text{m}$ stamps for each redshift and stellar mass bin given in Data availability.

The stacked average FIR flux densities at each bin were then extracted from the nonlinear least squares best fits to the light profiles derived from corresponding stamps. The reason for this is that, at the *Herschel* 250, 350, and $500\mu\text{m}$ SPIRE bands, due to the relatively large beam sizes, the clustering of objects associated with the stacked sources is seen to significantly contribute to the mean flux. Figure 2 shows the light profile and the best fits for the sample of *Herschel* SPIRE $500\mu\text{m}$ sources at $1.25 < z < 1.75$ with stellar masses between $10.25 < \log(M_*/M_\odot) < 10.5$. As can be seen, the stacked flux (red line) consists of the average flux from the stacked sample (dashed blue line) and the background flux from the associated sources (dotted green line), both of which can be modeled with a Gaussian function. In cases when a double Gaussian (beam + background) gives better fits than a single Gaussian (beam), the background is subtracted and the resulting average flux density of the stacked sample is extracted from a beam component of the best fit.

The errors on the stacked FIR fluxes, which are related to the redshifts, stellar masses, and the *NUVrJ* quiescent galaxy selection procedure uncertainties, were estimated using the bootstrapping method. In each step, a mock catalog was constructed by drawing, at random and with replacement, a sample of sources from the original mass-complete dataset. The stacking procedure, described above, was then applied and the average fluxes were extracted. The process was repeated 1000 times and the uncertainties on the FIR fluxes, $\sigma_{\text{bootstrap}}$, taken to be the standard deviation of the resulting simulated values. In addition, the contribution to the final stacked FIR fluxes errors from the uncertainties related to the functional fits to the light profiles, σ_{fit} , described above, as well as the errors related to the individual observed FIR fluxes from Eq. (4) were included, with the final errors on the stacked values equal to

$$\sigma(S_v) = \sqrt{\sigma_{\text{bootstrap}}^2 + \sigma_{\text{fit}}^2 + \sigma_{\text{stack}}^2}. \quad (5)$$

4. The star formation rate–stellar mass relations

4.1. Star formation rate measurements

A total SFR consists of the UV and IR components, where the rest-frame UV light is sensitive to the young massive stars and is therefore a good tracer of recent, unobscured star formation, while the IR emission accounts for the stellar emission that has been absorbed by the interstellar dust. Here, we followed the recent calibration of Kennicutt & Evans (2012), where

$$\text{SFR}_{\text{tot}} = 1.71 \times 10^{-10} (L_{\text{FUV}} + 0.46 \times L_{\text{IR}}). \quad (6)$$

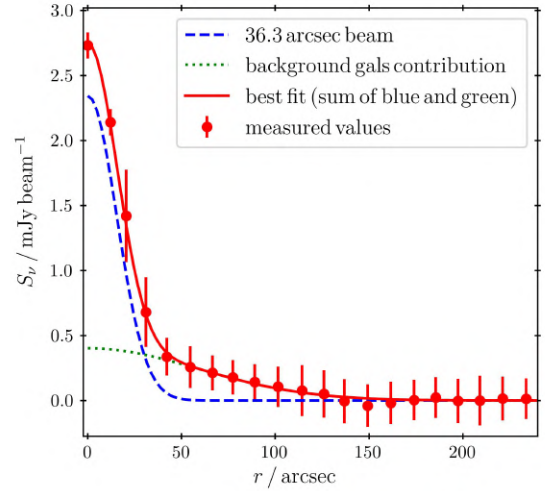


Fig. 2. $1.25 < z < 1.75$, $10.25 < \log(M_*/M_\odot) < 10.5$ light profile derived at $500\mu\text{m}$. The red points represent mean values of the flux densities derived from stacked images as a function of distance from the image center. The dashed blue, dotted green, and solid red lines represent the corresponding beam, the contribution from background sources, and the sum of the two, respectively. For *Herschel* SPIRE bands, the contribution from background sources is significant and must therefore be subtracted from the overall light profile, when deriving stacked flux densities (see Sect. 3.2).

The far-UV (FUV) part of the SFR was derived from the FUV luminosity measured at 150 nm , where $L_{\text{FUV}} = \nu L_\nu$, with FUV SFRs calculated for each galaxy and then the mean value evaluated at each redshift or stellar mass bin.

In order to find the IR luminosity, L_{IR} , the dust emission curve of Casey (2012) was fit to the available FIR photometry using the nonlinear least squares analysis. The adopted dust emission curve, described in Table 1 of Casey (2012), can be approximated as a classic single-temperature gray-body function at FIR wavelengths, with the addition of the power law fit at mid-IR wavelengths. The data was initially fit with both the single gray-body and the power law gray-body curves and it was found that the latter gives better fits to the data at mid-IR bands. The power law gray-body curve has four free parameters – the mid-IR power law slope, α , the emissivity index, β , the effective dust temperature, $T_{\text{d}}^{\text{eff}}$, and the overall normalization, N . Since, at $z \gtrsim 2$, the available photometry redward of the dust emission peak consists only of the 850 and $500\mu\text{m}$, with the $500\mu\text{m}$ being affected by blending (see Fig. 2), we decided to fix β at 1.96. Similarly, due to the lack of photometry at a rest-frame wavelength of $\lambda \lesssim 80\mu\text{m}$, we also fixed α at 2.3. Values of α and β were fixed according to the recommendations of Drew & Casey (2022). The curve was then integrated between 8 and $1000\mu\text{m}$ and the errors were estimated from the corresponding covariance matrix. The stacked photometry and the best fits for the whole (star-forming and quiescent) and star-forming subsamples are given in Data availability. The resulting best-fit values of the total SFR at each redshift or stellar mass bin for the whole and star-forming subsamples are listed in the top and bottom panels of Table A.1, as well as being depicted as color points with error bars in the left and right panels of Fig. 3, respectively.

4.2. Fitting the star formation rate–stellar mass function

Since the SFR- M_* relation was shown to exhibit a turnover at high masses (e.g., Lee et al. 2015; Popesso et al. 2023), we

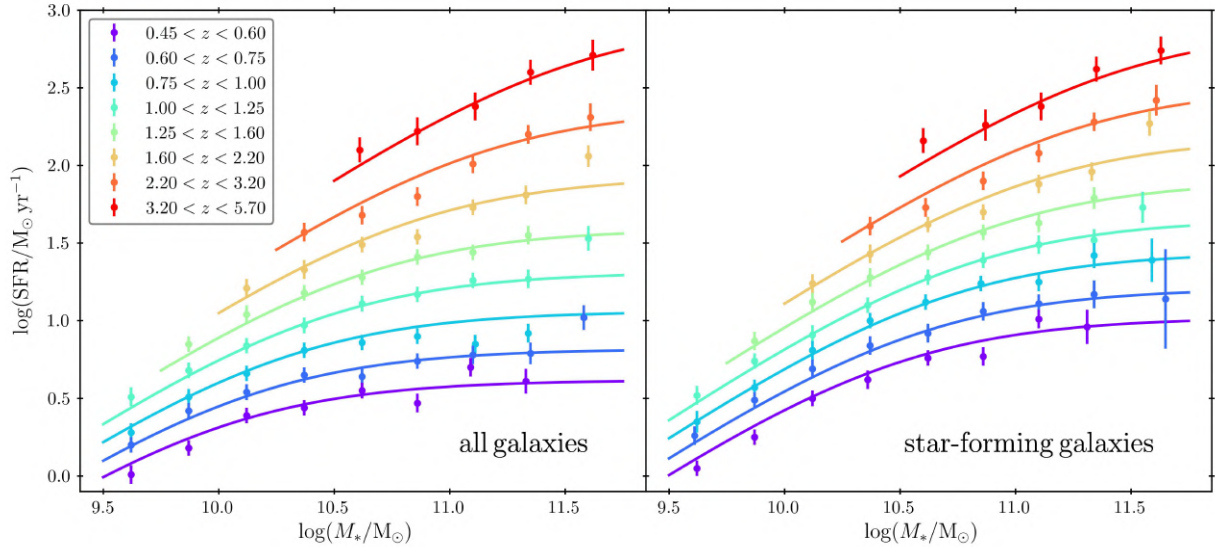


Fig. 3. SFR- M_* relations derived in Sect. 4 for the whole (star-forming and quiescent – left panel) and the star-forming (MS – right panel) galaxy samples. The best-fit lines, color-coded with redshift, were derived according to Eq. (8).

Table 1. Best-fit values to parameters from Eq. (9) for the star-forming galaxies and for all galaxies (both star-forming and quiescent).

Parameter	All galaxies	SF galaxies
a1	3.28 ± 0.32	2.97 ± 0.20
a2	-3.36 ± 0.26	-2.62 ± 0.14
a3	0.46 ± 0.08	0.59 ± 0.10
b1	11.73 ± 0.73	11.38 ± 0.39
b2	-2.06 ± 0.62	-1.14 ± 0.30
b3	0.37 ± 0.23	0.50 ± 0.36

used the functional form of the SFR- M_* relation from Lee et al. (2015):

$$\text{SFR} = \text{SFR}_{\text{max}} / (1 + (M_*/M_0)^{-\gamma}), \quad (7)$$

where the SFR transitions from a power law with slope γ at masses below M_0 to an asymptotic value, SFR_{max} , at $M_* \gg M_0$. The slope, γ , has been shown to vary with redshift, with values between $0.8 \lesssim \gamma \lesssim 1.3$ (e.g., Lee et al. 2015; Tomczak et al. 2016). Because of the low dynamic range in M_* , particularly at high redshift, we decided to fix γ . With the best-fit value of $\gamma = 1.0$, adopted from Popesso et al. (2023), Eq. (7) becomes

$$\text{SFR} = \text{SFR}_{\text{max}} / (1 + (M_0/M_*)). \quad (8)$$

We find that the most accurate fits to the SFR- M_* relation are produced when the logarithm of the free parameters of Eq. (8) are assumed to follow an exponential evolution with redshift, where

$$\begin{aligned} \log(\text{SFR}_{\text{max}}/M_\odot \text{ yr}^{-1}) &= a_1 + a_2 \times e^{-a_3 z} \\ \log(M_0/M_\odot) &= b_1 + b_2 \times e^{-b_3 z}. \end{aligned} \quad (9)$$

The functional form of Eq. (8) was fit to the stacked data (Table A.1) using the nonlinear least square fitting, where, initially, the fits were performed for the whole sample, including both star-forming and quiescent galaxies. The best-fit curves can be seen in the left panel of Fig. 3 and the best-fit parameters from Eq. (9) for the whole sample are listed in Table 1.

As can be seen in Fig. 3, the SFR- M_* relation shows a clear turnover at high stellar masses, represented in Eq. (8) by the parameter M_0 . However, since the whole sample consists of both the star-forming and quiescent galaxies, the apparent turnover may simply be a consequence of the increasing population of quiescent galaxies at low redshifts. We therefore repeated the procedure for the SFGs only. The corresponding best SFR- M_* fits are shown in the right panel of Fig. 3, with the best-fit parameters listed in Table 1. As can be seen, the turnover is still visible at low redshifts, albeit slightly less pronounced.

5. Discussion

5.1. Evolution of the star-forming main sequence

As has been discussed in previous studies (e.g., Santini et al. 2014; Wang et al. 2022), the shape of the star-forming MS is controlled by the relationship between the molecular gas mass and SFR surface densities – the SK relation. After stacking a mass-complete sample of $0.4 \lesssim z \lesssim 3.6$, $M_* > 10^{10} M_\odot$ MS galaxies, Wang et al. (2022) found that all the MS galaxies lie on the stellar mass and redshift independent MS-only SK relation, with the slope of ~ 1.13 . For comparison, at high ΣM_{gas} , starburst galaxies exhibit two to three times higher star-forming efficiencies, producing the SK relation with slightly higher normalization (e.g., Daddi et al. 2010; Kennicutt & De Los Reyes 2021). In addition, Wang et al. (2022) showed that the FIR sizes of all the MS galaxies do not vary with stellar mass or redshift, with the mean half-light radius of ~ 2.2 kpc, implying the so-called integrated SK law, where $\text{SFR} \propto M_{\text{gas}}^{1.13}$. The star-forming MS stellar mass and redshift evolution is therefore driven by the shape of the integrated SK relation and galaxy molecular gas content (f_{gas}). The molecular gas fraction, $f_{\text{gas}} \equiv M_{\text{gas}}/M_*$, on the other hand, is driven by many processes, including the star formation efficiency ($\text{SFE} \equiv \text{SFR}/M_{\text{gas}}$), gas cooling, feedback, and the merger rate. As has been shown by Santini et al. (2014), the redshift and stellar mass evolution of the molecular gas content in SFGs, together with the redshift-independent SK relation, give rise to the fundamental $f_{\text{gas}}-M_*$ -SFR three-dimensional surface. Santini et al. (2014) stacked GOODS-S, GOODS-N and the COSMOS SFGs out to $z = 2.5$ in *Herschel* bands to show

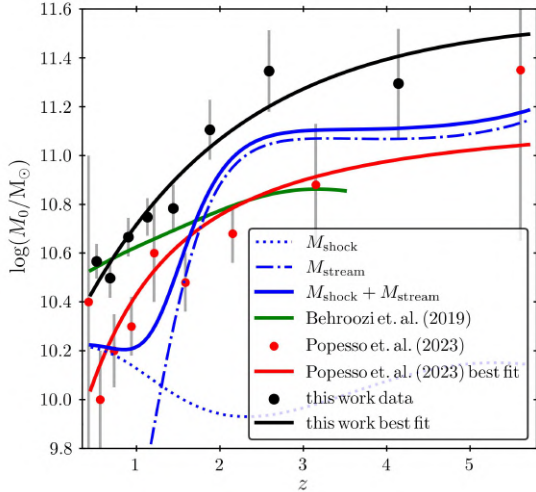


Fig. 4. M_{shock} and M_{stream} boundaries, above which the star formation is theoretically expected to be quenched, as is described in Sect. 5.1, shown in blue, where halo masses were converted to stellar masses using the prescription of Behroozi et al. (2013). The empirical curve of Behroozi et al. (2013) is also shown with a solid green line. For comparison, the results of this work are plotted in black. Red data represents the M_0 redshift evolution found in Popesso et al. (2023).

that the molecular gas fraction at given stellar mass and SFR does not depend on redshift. The projection of the $f_{\text{gas}}-M_*$ -SFR surface onto the M_* -SFR plane, given f_{gas} variations with stellar mass and redshift, produces the evolution of the star-forming MS.

From the best-fit function describing the MS evolution below the bending mass M_0 (Eqs. (7) and (9)) at any given redshift, the SFR dependence on the stellar mass is close to linear ($\gamma \sim 1$), consistent with the constancy of the low-mass power law slope of the stellar mass function of $\alpha \sim 1.5$ (e.g., Tomczak et al. 2014, although see Sect. 5.4). Since, from the MS-only integrated SK relation, $\text{SFR} \propto M_{\text{gas}}^{1.13}$, a linear dependence of the SFR on stellar mass implies that at a given redshift and below M_0 , the gas fraction should decrease with stellar mass, as was indeed found in previous works (e.g., Schreiber et al. 2016; Wang et al. 2022). Similarly, since $\text{SFR} \propto M_*$ below M_0 and the gas fraction decreases with stellar mass, the star-forming efficiency ($\equiv \text{SFR}/M_{\text{gas}}$) will increase with M_* . On the other hand, for a given stellar mass, increasing the SFR with redshift (evolution of the MS normalization) should also increase the molecular gas mass (MS-only SK relation). For a given stellar mass, the gas fraction must therefore increase with redshift, which is consistent with previous findings (e.g., Geach et al. 2011; Wang et al. 2022).

At masses $> M_0$, the MS flattens. As has been suggested (e.g., Daddi et al. 2022; Popesso et al. 2023), the SFR- M_* turnover is most likely caused by the phasing out of cold accretion. Based on theoretical scenarios, the cold gas can accrete freely for dark matter halos with $M_{\text{DM}} < M_{\text{shock}}$, where $M_{\text{shock}} (\approx 10^{11.8} M_{\odot})$ independent of redshift) marks the mass above which shocks can efficiently heat incoming baryons. Above M_{shock} , the cold accretion can still occur at higher redshifts through cold, collimated streams for halos with $M_{\text{DM}} < M_{\text{stream}}$, with M_{stream} boundary evolving with redshift from $\sim 10^{12.5} M_{\odot}$ at $z = 2$ to $\sim 10^{13.5} M_{\odot}$ at $z = 3$. Converting from halo to stellar masses using the prescription of Behroozi et al. (2013), we plot the redshift evolution of the $M_{\text{shock}}-M_{\text{stream}}$ boundary in Fig. 4, with the M_{shock} , M_{stream} and $M_{\text{shock}} + M_{\text{stream}}$ boundaries shown in dotted, dash-

dotted, and solid blue lines, respectively. We also plot the results of this work in black, where it can be seen that the boundary is in good agreement with the redshift evolution of the SFR- M_* turnover mass M_0 (increasing exponentially toward higher redshifts; Eq. (9)). For comparison, the results of Behroozi et al. (2013) and Popesso et al. (2023) are also shown. This suggests that the flattening of the SFR- M_* relation, at a given redshift, is most likely caused by the suppression of the cold-gas feeding of the galaxy, which effectively decreases its molecular gas fraction. At the same time, Daddi et al. (2022) points out that this process is not equivalent to quenching, describing galaxies with very low SFRs, for which additional processes are required, the most likely candidates of which include mergers and AGNs.

Flattening of the MS at $M_* > M_0$ gives a relatively small increase in SFR for a large increase in stellar mass. Provided that MS galaxies lie on the integrated SK relation, a small increase in SFR gives a small increase in molecular gas mass, causing the molecular gas fractions above M_0 to decrease significantly, consistent with the above scenario. However, Schreiber et al. (2016) found that flattening of the star-forming MS at $z \sim 1$ is caused not by the decrease in the molecular gas fraction but rather by the significant drop in the star-forming efficiency, with only a small change in f_{gas} . For galaxy stellar masses above the bending mass, the large increase in M_* gives only a small increase in SFR. A small change in f_{gas} would imply that the corresponding molecular gas mass should also significantly increase. This is inconsistent with the finding of Wang et al. (2022) that all the SFGs lie on the SK relation, where $\text{SFR} \propto M_{\text{gas}}^{1.13}$, since a small increase in the SFR above M_0 for MS galaxies should give similarly small rise in the molecular gas mass (and hence large decrease in f_{gas}). A near-constant gas fraction above M_0 would therefore suggest that the MS galaxies at these large masses should lie below the SK relation. More work, with larger samples, is clearly required to resolve this inconsistency.

5.2. Temperature-redshift relation

The evolution of the dust temperature with redshift has been debated numerous times in the literature. There are three main sets of claims that can be distinguished – those that argue that, at fixed L_{IR} , T_d is lower at higher redshifts (e.g., Chapman et al. 2002; Pope et al. 2006; Magnelli et al. 2014), those that claim T_d to be increasing with z (e.g., Schreiber et al. 2018; Faisst et al. 2020), and those that show no evolution at all (e.g., Dudzevičiūtė et al. 2020; Reuter et al. 2020; Drew & Casey 2022). As has been shown by Drew & Casey (2022), the apparent increase in the dust temperature in lower-redshift galaxies is often caused by the bias, whereby colder systems had been fit with warmer-temperature SEDs due to the lack of long wavelength data (and hence no photometric constraints on the Rayleigh-Jeans tail of the dust emission curve). A number of works that have found no evolution of T_d with redshift are based on brightest sources selected at (sub-)mm wavelengths, not necessarily representative of the bulk of the star-forming galaxy population on the MS (e.g., Dudzevičiūtė et al. 2020; Reuter et al. 2020). Drew & Casey (2022) have found that for the sample of $z < 2$ galaxies, the IR luminosity anti-correlates with the dust emission rest-frame peak wavelength (and hence correlates with the luminosity-weighted dust temperature). They have also determined that the $z < 2$ T_d-L_{IR} relation does not evolve with redshift. Given that the SFRs (and L_{IR}) for star-forming MS galaxies, at fixed stellar mass, increase with redshift, the redshift-independent correlation of L_{IR} and T_d produces hotter SEDs at higher z 's.

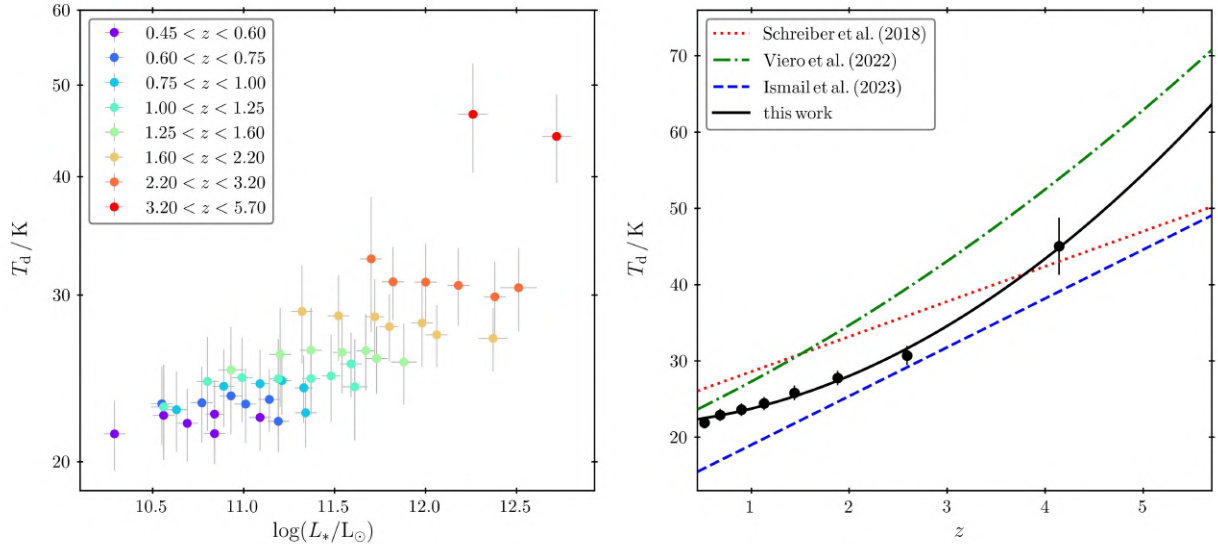


Fig. 5. Evolution of peak dust temperature found in this work. Left panel: The peak dust temperatures, T_d , as a function of the IR luminosity, L_{IR} , color-coded with redshift. It can be seen that while T_d increases with L_{IR} between $z = 0.45$ – 5.7 , it does not seem to significantly vary at any given redshift. Right panel: Since T_d variations with L_{IR} at any given redshift remain small, we plot the average peak dust temperature as a function of redshift as black points, with the best-fit solid black line. For comparison, we show the relations of Schreiber et al. (2018), Viero et al. (2022) and Ismail et al. (2023) as dotted red, dash-dotted green, and dashed blue lines, respectively. For discussion see Sect. 5.2.

In the left panel of Fig. 5 we plot the peak dust temperatures (derived from best-fit SEDs given in Data availability using Wien’s law) for the star-forming sample of galaxies as a function of the IR luminosity, color-coded with redshift. We can see that, as in the case of Drew & Casey (2022), T_d clearly correlates with L_{IR} (even when confining our sample to sources at $z < 2$). However, at any given redshift, we do not find any evolution of the dust temperature with L_{IR} . If anything, similarly to Schreiber et al. (2018), we can see a minor decline of T_d at highest IR luminosities at $z \lesssim 2$. As is discussed in Liang et al. (2019), the differences in dust temperatures are caused mainly by the variations in the specific star formation rate (sSFR; see the right panel of Fig. 6). In this scenario, higher sSFR systems have more young ($t \lesssim 10$ Myrs) star clusters, which heat the dust to higher temperatures, producing more emission in mid-IR wavelengths and hence increasing the values of the effective peak temperatures. This is consistent with the slight decrease in T_d at the highest stellar masses and the increase with redshift seen in the left panel of Fig. 5. Since, at any given redshift, the dust temperature variations are small, we plot the mean values of T_d as a function of z (black dots) in the right panel of Fig. 5. We find that the data can be well fit with the quadratic equation, where

$$T_d^{\text{MS}}/\text{K} = (1.13 \pm 0.17) \times z^2 + (0.88 \pm 0.78) \times z + (21.74 \pm 0.70). \quad (10)$$

For comparison, the results of Schreiber et al. (2018), Viero et al. (2022) and Ismail et al. (2023) are shown as dotted red, dash-dotted green, and dashed blue lines, respectively. It can be seen that our results, as well as the relation of Schreiber et al. (2018), give slightly higher temperatures at low redshifts than Ismail et al. (2023). This is most likely caused by the fact that both in this work and in the work of Schreiber et al. (2018), the emissivity index, β , has been fixed at constant value (1.96 and 1.5, respectively). As is shown in Ismail et al. (2023), β correlates with dust temperature, where

warmer SEDs are characterized by lower emissivity values. At low redshifts, where T_d is ~ 20 K, β is expected to vary between 2.5 and 3.5. Fixing β at lower values will naturally increase the best-fit dust temperatures. The effect is stronger for lower assumed values of emissivity, which can be seen in the figure. Comparing to Viero et al. (2022), we can see that our results also point toward slightly hotter dust in the early Universe. As is explained in Viero et al. (2022), however, assuming hotter dust at higher redshifts is necessary in order to explain a number of observations, like the lack of dusty objects in the early Universe (Sommovigo et al. 2020), inconsistencies in the high- z IRX- β relation (Bouwens et al. 2016), or unusually high dust masses (Bakx et al. 2020).

5.3. Comparison to the literature

In Fig. 7, we show the comparison of the SFR- M_* relation for SFGs (star-forming MS) found in this work (solid black lines) with those found by Speagle et al. (2014), Tomczak et al. (2016) and Popesso et al. (2023), plotted with dashed blue, dash-dotted green, and dotted red lines, respectively. The lines represent the best-fit functions at the central value of each redshift bin studied in this work. The first feature that can be seen is the lack of the turnover for the SFR- M_* relation of Speagle et al. (2014). As has been pointed out by Popesso et al. (2023), this was likely caused by the fact that the sample studied in Speagle et al. (2014) was mostly confined to sources with stellar masses below $10^{11} M_{\odot}$.

At low redshifts, for stellar masses $\log(M_*/M_{\odot}) \lesssim 10.5$, our values of the SFR are lower than those of Tomczak et al. (2016) and Popesso et al. (2023). This is most likely caused by fitting our IR data with colder SEDs, where dust temperatures of ~ 20 K were assumed (see Fig. 5). At $z > 2$ and $\log(M_*/M_{\odot}) \gtrsim 11$, our values of SFR tend to be slightly larger than those of Tomczak et al. (2016) and Popesso et al. (2023). As is explained in Sect. 3.1, all the starburst galaxies that were detected with ALMA in COSMOS and UDS fields were excluded from the sample of this work. However, because the relatively long

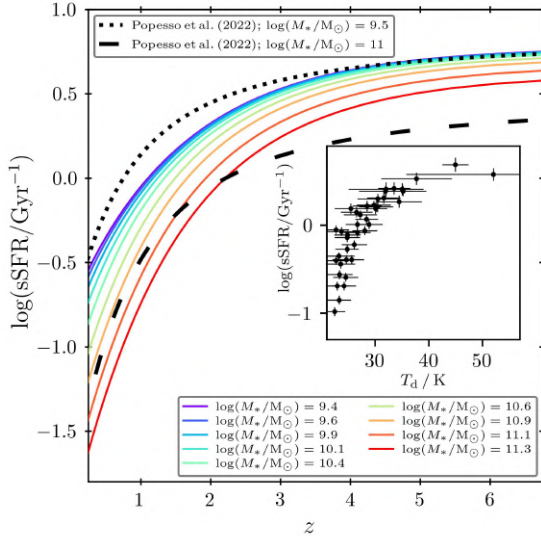


Fig. 6. Logarithm of the sSFR, derived from the best-fit functional forms of the star-forming MS found in this work, plotted as a function of redshift and color-coded with stellar mass. The shape of the relations is consistent with the redshift evolution of the molecular gas fraction in SFGs, as is discussed in Sect. 5.3. For comparison, we show the findings of Popesso et al. (2023) at two stellar mass regimes. The inset plot shows the relation between the sSFR and peak dust temperature. The similar shapes of the sSFR evolution with z and T_d is consistent with the scenario, presented in Liang et al. (2019), in which different dust temperature are mainly driven by the variations in the sSFR (see Sect. 5.2).

wavelength of ALMA observations tends to miss hot dust sources (e.g., Chen et al. 2022), we likely failed to identify a fraction of a high-mass starburst population that, due to its high SFRs, would boost the average stacked values. In addition, the determination of the high-mass end of the MS at high redshifts is based on a handful of sources. Looking at Fig. 3 of Popesso et al. (2023), it can be seen that at the highest redshift both the bending and the normalization of the MS are underpredicted by the adopted functional forms.

In Fig. 6, we show the corresponding evolution of the sSFR with redshift, color-coded with the stellar mass. A clear turnover can be seen at $z \sim 2$, which is a direct consequence of the bending of the normalization of the MS with redshift (Eq. (9)). This, on the other hand, as is explained in Sect. 5.1, is likely caused by the increase in the molecular gas fraction, which was found by Wang et al. (2022) to be exponentially increasing with redshift. The sSFR- z relation exhibits lower normalization at higher stellar masses, since at masses $\gtrsim M_0$ the MS flattens, decreasing the resulting sSFR. In the inset plot, the evolution of the sSFR with the peak dust temperature can be seen. Similar shapes of the sSFR relation with both redshift and dust temperature are consistent with the suggestion (Liang et al. 2019) that the increase in the dust temperature with redshift, found in Sect. 5.2, is indeed caused by the corresponding increase in the sSFRs.

For comparison, the relation of Popesso et al. (2023) for $\log(M_*/M_\odot) \approx 10.0$ and 11.5 are shown as dotted and dashed black lines, respectively. The inconsistencies at low and high redshifts come from different normalizations of the corresponding MSs, as was explained above. In order to investigate those further, in the following section we explore how the evolution of the MS found in this work and the works of Speagle et al. (2014), Tomczak et al. (2016) and Popesso et al. (2023) affects the “growth” of the GSMF.

5.4. Growth of the galaxy stellar mass function

The star-forming MS effectively quantifies the stellar mass growth of a galaxy with time. We can therefore compare the evolution of the GSMF as implied by any given MS with the observed one. The procedure is described in detail in Leja et al. (2015) and can be summarized as follows. At each redshift, the stellar mass for a given GSMF is being grown assuming the SFR from the MS, causing the GSMF to shift toward higher masses. Additionally, mainly due to winds and outflows, a fraction of the mass is ejected from a stellar population, a careful treatment of which has been presented in Moster et al. (2013). The stellar mass growth with time can therefore be expressed as

$$\dot{M}(M, z) = \text{SFR}(M, z) \times (1 - R), \quad (11)$$

where R is the fraction of the mass lost during passive stellar evolution, starting at 0 and reaching 0.36 after ~ 10 Gyr, assuming the Chabrier IMF. However, since most of the mass loss happens during the first 100 Myr, following Leja et al. (2015), we assume it to be instantaneous and fix R at 0.36.

We start the procedure with the observed star-forming stellar mass function of McLeod et al. (2021). The stellar mass at any given redshift is evolved according to Eq. (11) assuming different star-forming MSs. In Fig. 8 we show the results of this exercise, with the observed star-forming GSMF at the final redshift shown in gray. The stellar mass function, produced by evolving the observed GSMF between redshifts listed in the upper right corner of each panel, for the MS of Speagle et al. (2014), Tomczak et al. (2016) and Popesso et al. (2023) are plotted with dashed blue, dash-dotted green, and dotted red lines, respectively. The results from this work are shown with a solid black line. It can be seen that the evolved GSMFs differ at both low and high-mass ends, which is due to the differences in the shapes of the corresponding MSs. At low redshifts and stellar masses the MS found in this work predicts lower values of the SFR, which causes the GSMF to grow more slowly in mass and hence the shift toward higher masses is in this case smaller than those produced by Speagle et al. (2014), Tomczak et al. (2016) and Popesso et al. (2023). Similarly, at high redshift and stellar masses, the stellar mass shifts are slightly larger (except for the case of Speagle et al. 2014, where no bending was assumed). The most striking feature of Fig. 8 is the inconsistency of all the evolved functions with the observed GSMF. There are two main reasons for that. Firstly, the mass evolution of the GSMF is going to be affected by galaxy mergers, where mergers are expected to decrease the number density and contribute to the mass growth of galaxies. As is shown by Leja et al. (2015), however, including mergers will change the evolved GSMF at low masses by only 0.1–0.2 dex between redshifts 2.25 and 0.5. The second reason is the fact that, as GSMF evolves in time, a fraction of SFGs will transform into passive sources, effectively shifting the evolved stellar mass function down toward lower densities.

In order to account for this effect, we additionally evolve the GSMF, where both star-forming and passive galaxies have been included. In order to extend this exercise to higher redshifts, we adopt the stellar mass function of Davidzon et al. (2017), where $z \approx 6$ has been reached. The SFR- M_* relation used in this case includes all galaxies (star-forming and quiescent) and is shown in the left panel of Fig. 3. The resulting evolved GSMF at different redshifts is compared to the observed one in Fig. 9 (thin black and thick gray lines, respectively). Since Speagle et al. (2014) and Popesso et al. (2023) did not publish the SFR- M_* relations for the galaxy samples that include the quiescent sources, we compare our results with Tomczak et al. (2016) only (dashed

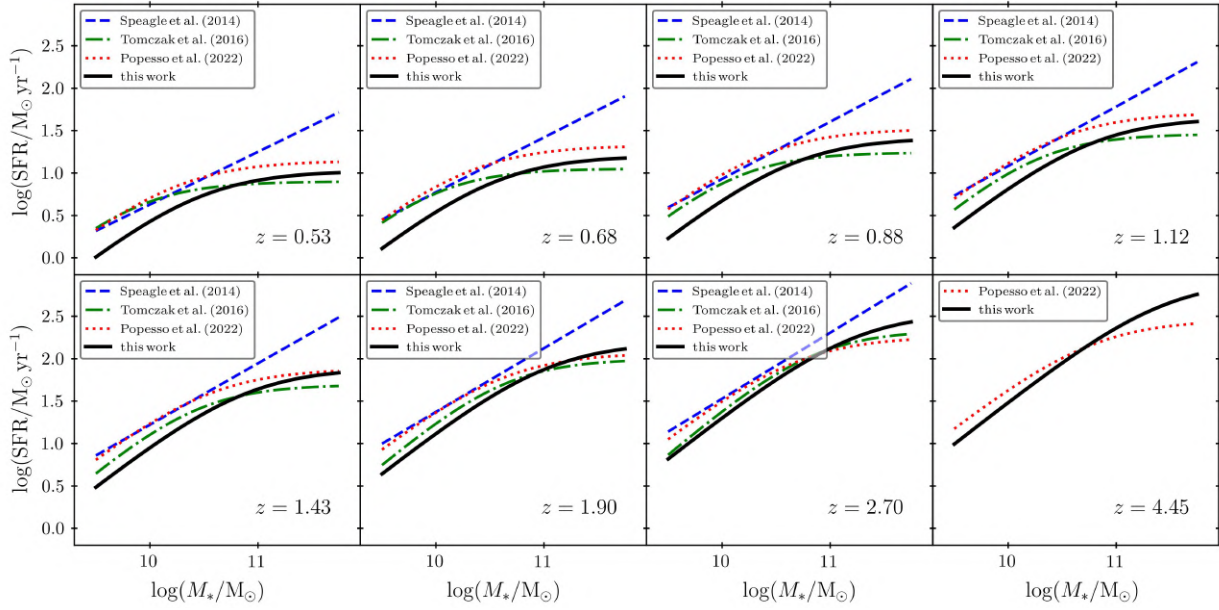


Fig. 7. Best-fit star-forming MS shown at each redshift bin studied in this work as the solid black line. For comparison, we show the relations of Speagle et al. (2014), Tomczak et al. (2016) and Popesso et al. (2023), plotted with dashed blue, dash-dotted green, and dotted red lines, respectively. While all the functions tend to roughly agree with each other, some inconsistencies can clearly be seen, discussion of which is presented in Sect. 5.3.

green line). It is clear from Fig. 9 that the obvious shift in galaxies number density between the observed and simulated functions, apparent in Fig. 8, is no longer present. This confirms that the inconsistency in the star-forming GSMFs is caused by the decrease in density due to the fraction of SFGs transforming into passive sources. For low masses at $z \gtrsim 2$ the low-mass end of the simulated stellar mass functions tends to be steeper than the observed ones. This is caused by the low-mass slope of the observed GSMF undergoing the evolution in redshift toward higher values. In order for our SFR- M_* relation to produce results consistent with this, the low-mass slope, γ , from Eq. (7) would also need to evolve. However, as is explained in Sect. 4.2, since our data does not probe low stellar masses at high redshifts, γ was assumed to be constant. The fact that the constant γ gives steeper low-mass slopes of the GSMF at high z 's indicates that the power law slope of the SFR- M_* relation for all galaxies (star-forming and quiescent) should increase in redshift. Similarly, since the low-mass slope of the star-forming GSMF, found in both Davidzon et al. (2017) and McLeod et al. (2021), increases at $z \gtrsim 2$, the slope of the star-forming MS should also evolve. At $z \gtrsim 3$ the high-mass end of the simulated GSMF overpredicts the number of galaxies. While the errors on the observed high-redshift stellar mass function at these masses are significantly large (~ 1 dex), it is also possible that the high-mass end of the SFR- M_* relations in this work, and hence the growth of the stellar masses, is contaminated by the presence of starburst galaxies.

6. Summary

We have stacked $\sim 100k$ K -band selected COSMOS and UDS galaxies in the IR *Herschel* and JCMT bands in bins of stellar mass and redshift in order to investigate the SFR evolution out to $z \sim 7$. Inverse variance stacking was used, where, for the *Herschel* SPIRE bands, background sources were found to contribute significantly to the stacked fluxes. After removing the background sources' contribution (fitted with the Gaussian

function), the IR luminosities, and hence the SFRs, were determined and the functional forms of the SFR evolution with stellar mass and redshift found. This was done for both the star-forming and whole (star-forming and quiescent) galaxy samples, where the quiescent sources were selected using the UVJ color-color space. The main findings of this work can be summarized as follows:

- (i) The SFR of SFGs populating the MS exhibits a nearly linear growth with stellar mass at any given redshift at low masses. Above the so-called bending mass, M_0 , the MS flattens toward an asymptotic value of the SFR. At constant stellar mass, the SFR also increases with redshift – the redshift evolution of the normalization of the MS. This behavior is consistent with the scenario in which the evolution of the star-forming MS is driven by the position of the galaxy on the integrated SK relation, given its molecular mass fraction (e.g., Santini et al. 2014; Wang et al. 2022). We find that the redshift evolution of the bending mass, M_0 , is exponential, increasing sharply from $z \sim 0.5$ to $z \sim 2$ and flattening at $z > 2$. The similarity to the shape of the relation between the stellar mass, above which shocks can efficiently heat incoming baryons, and redshift, found in Daddi et al. (2022), suggests that the flattening of the MS is likely caused by the phasing out of the cold accretion.
- (ii) We investigated the evolution of the peak dust temperature with IR luminosity and redshift, by fitting the stacked photometry with the dust emission curve of Casey (2012). Similarly to Drew & Casey (2022), an increase in T_d with IR luminosity was found. However, when confined to any given redshift, our data does not show any significant evolution with L_{IR} . We conclude that the increase in T_d with IR luminosity is driven by the evolution of the L_{IR} with redshift for the MS galaxies. We find that the dust temperature increases quadratically with redshift, consistent with the scenario in which higher values of T_d for SFGs are driven by the increase in their sSFRs (e.g., Liang et al. 2019).

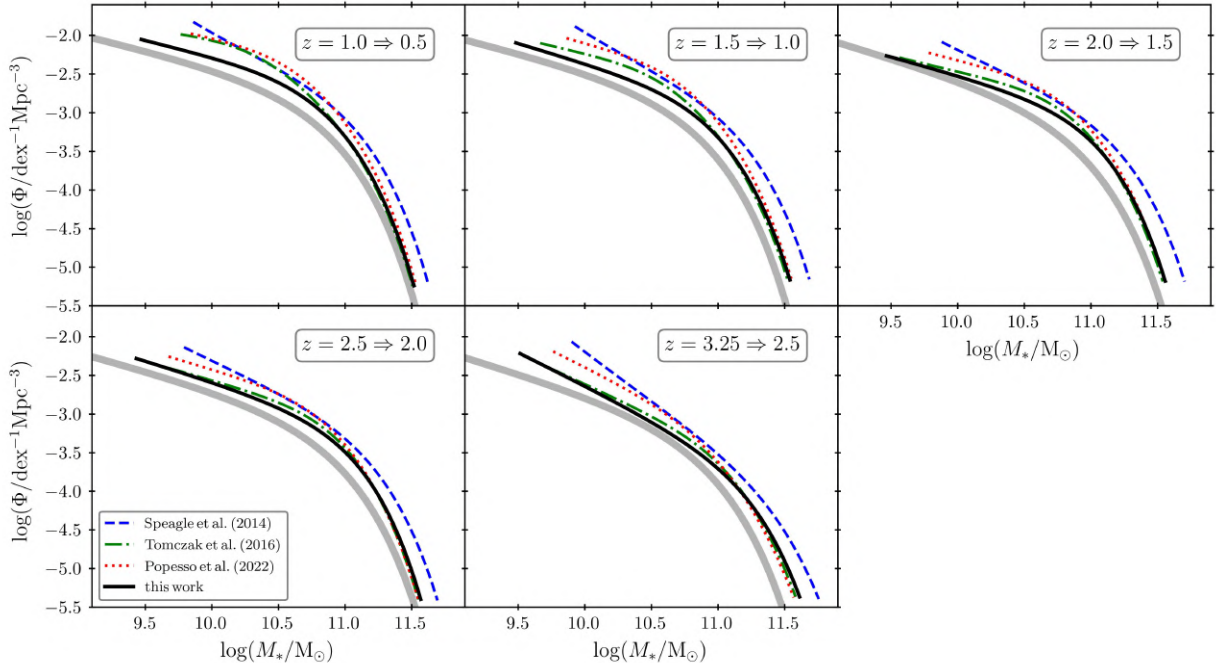


Fig. 8. Comparison between the observed and simulated star-forming GSMFs. The simulated GSMFs are constructed by “growing” the observed function of [McLeod et al. \(2021\)](#), between the redshifts listed in the upper right corner of each panel, according to Eq. (11). The mass evolution resulting from assumed star-forming MSs of [Speagle et al. \(2014\)](#), [Tomczak et al. \(2016\)](#) and [Popesso et al. \(2023\)](#), are plotted with dashed blue, dash-dotted green, and dotted red lines, respectively. The simulated function constructed using the results of this work are presented in solid black, while the thick solid gray line represents the observed GSMF at the final redshift of each simulation. The inconsistencies at low- and high-mass ends of the simulated GSMFs come from differences in the corresponding shapes of the MSs involved (Fig. 7). The significant shift in densities between the observed and simulated GSMFs is caused by the fraction of SFGs, simulated between the redshifts in question, entering a quiescent mode, as is discussed in Sect. 5.4.

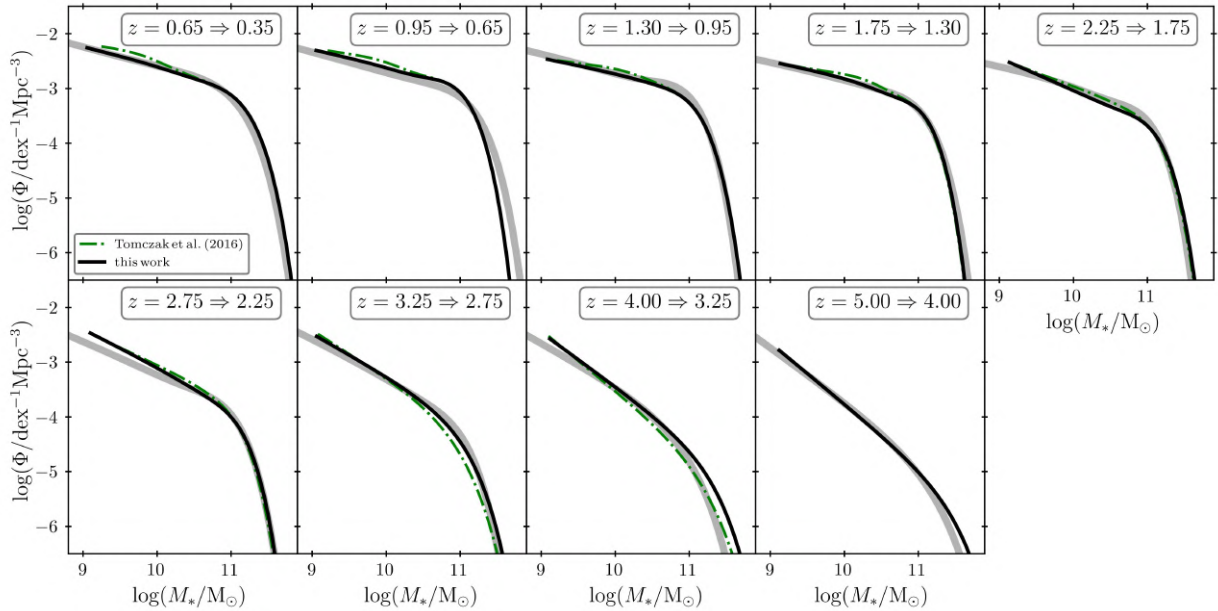


Fig. 9. Comparison between the observed and simulated GSMFs, where both star-forming and quiescent galaxies are considered. To extend the redshift range, the simulated GSMFs are constructed by “growing” the observed function of [Davidzon et al. \(2017\)](#), between the redshifts listed in the upper right corner of each panel, according to Eq. (11). The mass evolution results from assuming the SFR- M_* relation characteristic of galaxy samples including both the star-forming and quiescent sources, where we compare our results, shown in solid black, with those of [Tomczak et al. \(2016\)](#), depicted with a dash-dotted green line. The thick solid gray line represents the observed GSMF at the final redshift of each simulation. It can be seen that the significant gap in densities, apparent in Fig. 8, is no longer present, indicating that, indeed, the inconsistencies were caused by the fraction of sources evolving into quiescent mode, as is discussed in Sect. 5.4. The low-mass slope of simulated GSMFs at $z \gtrsim 2$ is inconsistent with the observed function, indicating that the corresponding slope of the SFR- M_* relations most likely evolves toward steeper values toward earlier epochs.

- (iii) The evolution of the MS found in this work was compared with the relations of [Speagle et al. \(2014\)](#), [Tomczak et al. \(2016\)](#) and [Popesso et al. \(2023\)](#). We find that the normalization of our MS at $z \lesssim 2$ for masses below the bending mass, M_0 , is slightly lower, while the SFRs above M_0 at high redshifts exhibit larger values (except for the MS of [Speagle et al. 2014](#), where no MS bending was found). We attribute these inconsistencies to the dust temperatures assumed, when fitting the IR data. As was found in this work, T_d increases from ~ 20 K to ~ 60 K between redshifts 0.5 and 5.5, and hence assuming dust temperatures at the level of ~ 30 K, as is often done in the absence of the FIR data, will correspondingly affect the determined IR luminosities (and hence the SFRs). We also note that the higher values of the SFRs at high redshifts for $M_* > 10^{11} M_\odot$ could be, at least in part, caused by the contamination of the MS sample by starburst galaxies.
- (iv) Adopting different shapes of the SFR- M_* relation, we simulated the time evolution for the observed GSMFs of [Davidzon et al. \(2017\)](#) and [McLeod et al. \(2021\)](#). For the star-forming sample, we find that the GSMF “grows” too fast, producing simulated relations significantly above the observed ones. By performing the simulations using the SFR- M_* relation, found using both star-forming and quiescent galaxies, we confirm that the overprediction of SFG number densities is caused by a significant fraction of sources evolving into the quiescent phase and thereby leaving the star-forming MS. In addition, we find the simulated low-mass end of the GSMF gives higher number densities at high z , indicating that the low-mass slope of the MS likely evolves toward steeper values with redshift. However, due to the significant uncertainties, more detailed analysis based on larger high- z samples is required.

Data availability

Example stacked image and best-fit SEDs are available [here](#).

Acknowledgements. This research was funded in whole or in part by the National Science Center, Poland (grant no. 2020/39/D/ST9/03078). For the purpose of Open Access, the author has applied a CC-BY public copyright license to any Author Accepted Manuscript (AAM) version arising from this submission. JSD acknowledges the support of the Royal Society through a Research Professorship. MJM acknowledges the support of the National Science Centre, Poland through the SONATA BIS grant 2018/30/E/ST9/00208 and the Polish National Agency for Academic Exchange Bekker grant BPN/BEK/2022/1/00110. DJM acknowledges the support of the Science and Technology Facilities Council. KL acknowledges the support of the Polish Ministry of Education and Science through the grant PN/01/0034/2022 under ‘Perły Nauki’ program.

References

- Ashby, M. L. N., Willner, S. P., Fazio, G. G., et al. 2013, *ApJ*, **769**, 80
 Ashby, M. L. N., Willner, S. P., Fazio, G. G., et al. 2015, *ApJS*, **218**, 33
 Ashby, M. L. N., Caputi, K. I., Cowley, W., et al. 2018, *ApJS*, **237**, 39
 Bakx, T. J. L. C., Tamura, Y., Hashimoto, T., et al. 2020, *MNRAS*, **493**, 4294
 Behroozi, P. S., Wechsler, R. H., & Conroy, C. 2013, *ApJ*, **770**, 57
 Benítez, N. 2000, *ApJ*, **536**, 571
 Bertin, E., & Arnouts, S. 1996, *A&AS*, **117**, 393
 Bouwens, R. J., Aravena, M., Decarli, R., et al. 2016, *ApJ*, **833**, 72
 Brammer, G. B., van Dokkum, P. G., & Coppi, P. 2008, *ApJ*, **686**, 1503
 Bruzual, G., & Charlot, S. 2003, *MNRAS*, **344**, 1000
 Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, *ApJ*, **533**, 682
 Casey, C. M. 2012, *MNRAS*, **425**, 3094

- Chabrier, G. 2003, *PASP*, **115**, 763
 Chapman, S. C., Smail, I., Ivison, R. J., et al. 2002, *ApJ*, **573**, 66
 Chen, Y. Y., Hirashita, H., Wang, W. H., & Nakai, N. 2022, *MNRAS*, **509**, 2258
 Coleman, G. D., Wu, C. C., & Weedman, D. W. 1980, *ApJS*, **43**, 393
 Daddi, E., Elbaz, D., Walter, F., et al. 2010, *ApJ*, **714**, L118
 Daddi, E., Delvecchio, I., Dimauro, P., et al. 2022, *A&A*, **661**, L7
 Davidzon, I., Ilbert, O., Laigle, C., et al. 2017, *A&A*, **605**, A70
 Drew, P. M., & Casey, C. M. 2022, *ApJ*, **930**, 142
 Dudzevičiūtė, U., Smail, I., Swinbank, A. M., et al. 2020, *MNRAS*, **494**, 3828
 Elbaz, D., Leiton, R., Nagar, N., et al. 2018, *A&A*, **616**, A110
 Faisst, A. L., Fudamoto, Y., Oesch, P. A., et al. 2020, *MNRAS*, **498**, A192
 Fioc, M., & Rocca-Volmerange, B. 1999, arXiv e-prints [arXiv:astro-ph/9912179]
 Furusawa, H., Kosugi, G., Akiyama, M., et al. 2008, *ApJS*, **176**, 1
 Furusawa, H., Kashikawa, N., Kobayashi, M. A. R., et al. 2016, *ApJ*, **822**, 46
 Geach, J. E., Smail, I., Moran, S. M., et al. 2011, *ApJ*, **730**, L19
 Geach, J. E., Dunlop, J. S., Halpern, M., et al. 2017, *MNRAS*, **465**, 1789
 Griffin, M. J., Abergel, A., Abreu, A., et al. 2010, *A&A*, **518**, L3
 Holland, W. S., Bintley, D., Chapin, E. L., et al. 2013, *MNRAS*, **430**, 2513
 Hudelot, P., Cuillandre, J. C., Withington, K., et al. 2012, VizieR Online Data Catalog: **II/317**
 Ilbert, O., Capak, P., Salvato, M., et al. 2009, *ApJ*, **690**, 1236
 Ilbert, O., Salvato, M., Le Floch, E., et al. 2010, *ApJ*, **709**, 644
 Ilbert, O., McCracken, H. J., Le Fèvre, O., et al. 2013, *A&A*, **556**, A55
 Ismail, D., Beelen, A., Buat, V., et al. 2023, *A&A*, **678**, A27
 Jarvis, M. J., Bonfield, D. G., Bruce, V. A., et al. 2013, *MNRAS*, **428**, 1281
 Kennicutt, J. R. C. 1998, *ApJ*, **498**, 541
 Kennicutt, J. R. C., & De Los Reyes, M. A. C. 2021, *ApJ*, **908**, 61
 Kennicutt, R. C., & Evans, N. J. 2012, *ARA&A*, **50**, 531
 Koprowski, M. P., Coppin, K. E. K., Geach, J. E., et al. 2018, *MNRAS*, **479**, 4355
 Koyama, Y., Kodama, T., Nakata, F., Shimasaku, K., & Okamura, S. 2011, *ApJ*, **734**, 66
 Labbé, I., Huang, J., Franx, M., et al. 2005, *ApJ*, **624**, L81
 Lawrence, A., Warren, S. J., Almaini, O., et al. 2007, *MNRAS*, **379**, 1599
 Lee, N., Sanders, D. B., Casey, C. M., et al. 2015, *ApJ*, **801**, 80
 Leja, J., van Dokkum, P. G., Franx, M., & Whitaker, K. E. 2015, *ApJ*, **798**, 115
 Leja, J., Speagle, J. S., Ting, Y. S., et al. 2022, *ApJ*, **936**, 165
 Leslie, S. K., Schinnerer, E., Liu, D., et al. 2020, *ApJ*, **899**, 58
 Liang, L., Feldmann, R., Kereš, D., et al. 2019, *MNRAS*, **489**, 1397
 Liu, D., Lang, P., Magnelli, B., et al. 2019, *ApJS*, **244**, 40
 Lutz, D., Poglitsch, A., Altieri, B., et al. 2011, *A&A*, **532**, A90
 Madau, P. 1995, *ApJ*, **441**, 18
 Magnelli, B., Lutz, D., Saintonge, A., et al. 2014, *A&A*, **561**, A86
 McCracken, H. J., Milvang-Jensen, B., Dunlop, J., et al. 2012, *A&A*, **544**, A156
 McLeod, D. J., McLure, R. J., Dunlop, J. S., et al. 2021, *MNRAS*, **503**, 4413
 Mehta, V., Scarlata, C., Capak, P., et al. 2018, *ApJS*, **235**, 36
 Mérida, R. M., Pérez-González, P. G., Sánchez-Blázquez, P., et al. 2023, *ApJ*, **950**, 125
 Merlin, E., Fontana, A., Ferguson, H. C., et al. 2015, *A&A*, **582**, A15
 Moster, B. P., Naab, T., & White, S. D. M. 2013, *MNRAS*, **428**, 3121
 Oliver, S. J., Bock, J., Altieri, B., et al. 2012, *MNRAS*, **424**, 1614
 Pilbratt, G. L., Riedinger, J. R., Passvogel, T., et al. 2010, *A&A*, **518**, L1
 Poglitsch, A., Waelkens, C., Geis, N., et al. 2010, *A&A*, **518**, L2
 Pope, A., Scott, D., Dickinson, M., et al. 2006, *MNRAS*, **370**, 1185
 Popesso, P., Concas, A., Cresci, G., et al. 2023, *MNRAS*, **519**, 1526
 Pozzetti, L., Bolzonella, M., Zucca, E., et al. 2010, *A&A*, **523**, A13
 Reuter, C., Vieira, J. D., Spilker, J. S., et al. 2020, *ApJ*, **902**, 78
 Sanders, D. B., Salvato, M., Aussel, H., et al. 2007, *ApJS*, **172**, 86
 Santini, P., Maiolino, R., Magnelli, B., et al. 2014, *A&A*, **562**, A30
 Schmidt, M. 1959, *ApJ*, **129**, 243
 Schreiber, C., Pannella, M., Elbaz, D., et al. 2015, *A&A*, **575**, A74
 Schreiber, C., Elbaz, D., Pannella, M., et al. 2016, *A&A*, **589**, A35
 Schreiber, C., Elbaz, D., Pannella, M., et al. 2018, *A&A*, **609**, A30
 Sommovigo, L., Ferrara, A., Pallottini, A., et al. 2020, *MNRAS*, **497**, 956
 Speagle, J. S., Steinhardt, C. L., Capak, P. L., & Silverman, J. D. 2014, *ApJS*, **214**, 15
 Stach, S. M., Dudzevičiūtė, U., Smail, I., et al. 2019, *MNRAS*, **487**, 4648
 Tomczak, A. R., Quadri, R. F., Tran, K. V. H., et al. 2014, *ApJ*, **783**, 85
 Tomczak, A. R., Quadri, R. F., Tran, K. V. H., et al. 2016, *ApJ*, **817**, 118
 Viero, M. P., Sun, G., Chung, D. T., Monceli, L., & Condon, S. S. 2022, *MNRAS*, **516**, L30
 Wang, T. M., Magnelli, B., Schinnerer, E., et al. 2022, *A&A*, **660**, A142
 Whitaker, K. E., Franx, M., Leja, J., et al. 2014, *ApJ*, **795**, 104
 Wuyts, S., Labbé, I., Franx, M., et al. 2007, *ApJ*, **655**, 51

Appendix A: Additional table

Table A.1. Stacked values of the SFR (in $M_{\odot} \text{ yr}^{-1}$) for all the galaxies (star-forming and quiescent; top panel) and SFGs (bottom panel) between redshifts 0.45 and 5.7. The first column lists the mass bins, where $M \equiv \log_{10}(M_{*}/M_{\odot})$.

	$0.45 \leq z < 0.60$	$0.60 \leq z < 0.75$	$0.75 \leq z < 1.00$	$1.00 \leq z < 1.25$	$1.25 \leq z < 1.60$	$1.60 \leq z < 2.20$	$2.20 \leq z < 3.20$	$3.20 \leq z < 5.70$
	log(SFR)	log(SFR)	log(SFR)	log(SFR)	log(SFR)	log(SFR)	log(SFR)	log(SFR)
$9.25 \leq M < 9.50$	0.01 ± 0.06	0.20 ± 0.05	0.28 ± 0.06	0.51 ± 0.06				
$9.50 \leq M < 9.75$	0.18 ± 0.05	0.42 ± 0.05	0.51 ± 0.05	0.68 ± 0.05	0.85 ± 0.05			
$9.75 \leq M < 10.00$	0.39 ± 0.05	0.54 ± 0.05	0.66 ± 0.05	0.84 ± 0.05	1.04 ± 0.06	1.21 ± 0.06		
$10.00 \leq M < 10.25$	0.44 ± 0.05	0.65 ± 0.05	0.81 ± 0.05	0.97 ± 0.05	1.18 ± 0.05	1.33 ± 0.06	1.57 ± 0.06	
$10.25 \leq M < 10.50$	0.55 ± 0.05	0.64 ± 0.06	0.86 ± 0.05	1.11 ± 0.05	1.28 ± 0.05	1.49 ± 0.05	1.68 ± 0.06	2.10 ± 0.08
$10.50 \leq M < 10.75$	0.47 ± 0.06	0.74 ± 0.05	0.90 ± 0.05	1.17 ± 0.05	1.41 ± 0.05	1.54 ± 0.05	1.80 ± 0.06	2.22 ± 0.09
$10.75 \leq M < 11.00$	0.70 ± 0.06	0.78 ± 0.06	0.85 ± 0.06	1.26 ± 0.05	1.44 ± 0.05	1.73 ± 0.05	2.01 ± 0.06	2.38 ± 0.09
$11.00 \leq M < 11.25$	0.61 ± 0.08	0.79 ± 0.07	0.92 ± 0.06	1.27 ± 0.06	1.55 ± 0.06	1.81 ± 0.06	2.20 ± 0.06	2.60 ± 0.08
$11.25 \leq M < 11.50$	–	1.02 ± 0.08	–	1.53 ± 0.08	–	2.06 ± 0.07	2.31 ± 0.09	2.71 ± 0.10
$9.25 \leq M < 9.50$	0.05 ± 0.05	0.26 ± 0.06	0.35 ± 0.07	0.52 ± 0.06				
$9.50 \leq M < 9.75$	0.25 ± 0.05	0.49 ± 0.05	0.57 ± 0.05	0.74 ± 0.05	0.87 ± 0.06			
$9.75 \leq M < 10.00$	0.50 ± 0.05	0.69 ± 0.06	0.81 ± 0.06	0.91 ± 0.06	1.12 ± 0.06	1.24 ± 0.06		
$10.00 \leq M < 10.25$	0.62 ± 0.06	0.84 ± 0.06	1.00 ± 0.05	1.10 ± 0.05	1.28 ± 0.06	1.43 ± 0.06	1.61 ± 0.06	
$10.25 \leq M < 10.50$	0.76 ± 0.05	0.92 ± 0.06	1.12 ± 0.05	1.28 ± 0.05	1.44 ± 0.05	1.62 ± 0.05	1.73 ± 0.06	2.16 ± 0.08
$10.50 \leq M < 10.75$	0.77 ± 0.06	1.06 ± 0.06	1.24 ± 0.05	1.39 ± 0.05	1.57 ± 0.05	1.70 ± 0.05	1.90 ± 0.06	2.26 ± 0.10
$10.75 \leq M < 11.00$	1.01 ± 0.06	1.11 ± 0.06	1.25 ± 0.06	1.49 ± 0.06	1.63 ± 0.06	1.88 ± 0.06	2.08 ± 0.06	2.38 ± 0.09
$11.00 \leq M < 11.25$	0.96 ± 0.11	1.17 ± 0.09	1.42 ± 0.08	1.52 ± 0.07	1.79 ± 0.07	1.96 ± 0.06	2.28 ± 0.06	2.62 ± 0.08
$11.25 \leq M < 11.50$	–	1.14 ± 0.32	1.39 ± 0.14	1.73 ± 0.10	–	2.27 ± 0.08	2.42 ± 0.10	2.74 ± 0.09

1.8 Article B

Evolution of dust attenuation in star-forming galaxies with UV slope, stellar mass, and redshift out to $z \sim 5$

Evolution of dust attenuation in star-forming galaxies with UV slope, stellar mass, and redshift out to $z \sim 5$

J. V. Wijesekera¹, M. P. Koprowski¹, J. S. Dunlop², K. Lisiecki^{1,3}, D. J. McLeod², R. J. McLure²,
M. J. Michałowski^{2,4}, and M. Solar⁴

¹ Institute of Astronomy, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziądzka 5, 87-100 Toruń, Poland, drelkopi@gmail.com

² Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh EH9 3HJ, UK

³ National Centre for Nuclear Research, Pasteura 7, 093, Warsaw, Poland

⁴ Astronomical Observatory Institute, Faculty of Physics and Astronomy, Adam Mickiewicz University, ul. Słoneczna 36, 60-286 Poznań, Poland

Received September 15, 1996; accepted March 16, 1997

ABSTRACT

Context. In order to reliably constrain the dust-obscured portion of star formation across cosmic time, an accurate calibration of the so-called infrared excess ($\text{IRX} \equiv L_{\text{IR}}/L_{\text{UV}}$) and its dependence on intrinsic galaxy properties is required. While the local $\text{IRX}-\beta$ relation (where $F_{\lambda} \propto \lambda^{\beta}$) has been widely used to correct for the effects of dust absorption and scattering, many recent high-redshift works show significant inconsistencies, being most likely caused by differences in the assumed attenuation curves, dust temperatures and galaxies' star-to-dust relative morphology.

Aims. We derive a dependence of the IRX on UV slope β , stellar mass M_* , and redshift out to $z \simeq 5$, and establish consistent functional relations that can be used for correcting the UV/optical-selected galaxy samples for the effects of dust absorption.

Methods. This work is based on a K -band selected sample of $\sim 10^5$ star-forming galaxies detected in the UDS and COSMOS fields. Quiescent sources and known starbursts are removed, and the IR luminosities are established through stacking in FIR *Herschel* and JCMT maps. UV slopes are found from SED fits and stacked IRX values are derived by taking the median of individual IRX measurements in bins of β , M_* and redshift.

Results. While our best-fit $\text{IRX}-\beta$ relation is consistent with a Calzetti-like attenuation curve at $\beta \gtrsim -1$, at bluer values the IRX seems to increase with redshift due to different mass-completeness limits imposed. When deriving the $\text{IRX}-\beta$ relation in stellar-mass bins, a systematic trend is found, where the effective slope of the attenuation law becomes progressively shallower with increasing mass. We incorporate this into the $\text{IRX}-\beta$ relation through the slope of the underlying reddening law, $dA_{1600}/d\beta$, being a quadratic function of $\log(M_*/M_{\odot})$. Expressing IRX as a function of the stellar mass we find a tight correlation, with IRX rising monotonically with mass but exhibiting a clear high-mass turnover at $z \lesssim 2-3$, consistent with suppressed cold-gas accretion and dust growth in massive systems.

Key words. dust, extinction – galaxies: evolution – galaxies: high-redshift – galaxies: ISM

1. Introduction

The accurate determination of the cosmic star-formation rate density (ρ_{SFR}) across cosmic time remains a fundamental objective of observational cosmology. To build a complete picture of the star-formation activity in the Universe, one must account for all the energy produced by young, massive stars, which includes both the direct rest-frame ultraviolet (UV) emission that escapes the host galaxy and the fraction absorbed by the interstellar medium (ISM) and re-emitted at far-infrared (FIR) wavelengths. While this task is relatively straightforward in the local Universe due to the wealth of the available high-resolution imaging, at high redshifts ($z > 2$) the impact of the interstellar dust becomes harder to assess (Madau & Dickinson 2014 and references therein).

One of the commonly used methods for quantifying the dust-obscured fraction of the stellar light is through the so-called infrared excess ($\text{IRX} \equiv L_{\text{IR}}/L_{\text{UV}}$) and its relationship with galaxies' optical properties, like the UV slope (β) or the stellar mass (M_*). Historically, the relationship between IRX and β has been used as a primary proxy for dust attenuation (e.g., Calzetti et al. 2000; Reddy et al. 2012; Bouwens et al. 2016; Fudamoto et al.

2020b). Originally established by Meurer et al. (1999), this relationship describes a tight empirical correlation for local starburst galaxies, with a relatively flat, Calzetti-like attenuation law assumed, where the reddening of a galaxy's UV color between the rest-frame 125-250 nm can be used to predict its total dust obscuration. For over a decade, this relation was often used for correcting UV-selected samples at high redshifts. However, with more deep-field surveys producing increasing amount of high-redshift imaging, it became evident that 'normal' star-forming galaxies (SFGs) differ significantly from the starburst sequence in terms of the dust content (e.g., Reddy et al. 2010, 2012). These deviations have been suggested to arise from a combination of varying stellar population ages, metallicity effects, and complex dust-to-star geometries that are not accounted for by the local Meurer et al. (1999) data (e.g., Narayanan et al. 2018; Salim & Narayanan 2020).

The high-resolution imaging produced by the Atacama Large Millimeter/submillimeter Array (ALMA) has further complicated this picture. Initial FIR observations of Lyman-break galaxies (LBGs) at $z \sim 5-6$ reported surprisingly low IRX values

(Capak et al. 2015; Bouwens et al. 2016), representing a departure from the local Calzetti-like attenuation law typically applied to star-forming systems. This suggested that high-redshift galaxies are potentially more consistent with the Small Magellanic Cloud (SMC)-like extinction law. In addition, wrongly measured or assumed temperature of the interstellar dust (T_d) was also shown to play a role in the derived values of the IR luminosities. A number of works established T_d to be an increasing function of redshift (e.g., Viero et al. 2022; Ismail et al. 2023; Koprowski et al. 2024), with the apparent ‘IRX deficit’ potentially being an artifact of underestimating the FIR luminosity of warm-dust systems.

Furthermore, the IRX- β relationship has recently been found to also depend on the stellar masses of the galaxy samples (Álvarez-Márquez et al. 2019; Bouwens et al. 2020). It has been found that while low-mass systems at high redshifts appear ‘IR-faint’ for a given value of beta, more massive galaxies, $\log(M_*/M_\odot) > 10$, are often consistent with the local Calzetti-like attenuation curves. This mass dependence suggests that as galaxies grow, they rapidly accumulate dust and develop the complex, multi-component ISM structures seen in local starbursts (e.g., van der Wel et al. 2025; Gebek et al. 2025; Lisiecki et al. 2025). Recent JWST observations (e.g., Fisher et al. 2025; Shivaei et al. 2025) further indicate that the scatter in the IRX- β plane is amplified by ‘bursty’ star-formation histories, where high UV luminosities can ‘decouple’ from the dust-obscured regions, resulting in dusty sources possessing relatively blue values of the UV slope.

Beyond the complications related to the physical evolution of galaxies, a significant challenge lies in the selection of both rest-frame UV/optical and FIR-based samples. Most high-redshift ALMA studies, for instance, are biased toward the most IR-luminous sources, potentially missing the ‘normal’ population of star-forming galaxies, while samples selected at the rest-frame UV/optical bands are often incomplete in terms of the stellar mass. To overcome this, we utilize a K -band selected sample of approximately 100,000 galaxies from the UKIDSS Ultra Deep Survey (UDS) and COSMOS fields, covering a combined area of nearly 2 deg² (McLeod et al. 2021). In order to reach beyond the detection limits of typical FIR observations, we resort to a well-known method of stacking. This approach is critical for ensuring mass completeness and accounting for the selection effects that often plague individual FIR detections studies. By stacking individual infrared excess values of galaxies in distinct UV slope, stellar mass and redshift bins, we were able to establish a consistent relationship between the IRX, UV slope, stellar mass and redshift for star-forming galaxies out to $z \sim 5$.

This paper is structured as follows. In Section 2 we describe the data used in this work. The star-forming galaxies’ sample selection process and methods used to derive the physical properties and the stacked IRX values are presented in Section 3. In Section 4 the results are presented and discussed, where the high-redshift IRX- β relation is derived in Section 4.1, the stellar mass dependence through the slope of the reddening law is introduced into the IRX- β relationship in Section 4.2, followed by the comparison with recent literature in Section 4.3. The IRX- M_* function and its evolution with redshift is presented, discussed and compared with other studies in Sections 4.4 and 4.5. We summarize in Section 5. Throughout the paper, we use the Chabrier (2003) stellar IMF with an assumed flat cosmology of $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. Data

2.1. Optical/near-IR catalogs

In order to determine how the IRX varies across cosmic time, we stack the optical/near-IR star-forming galaxies’ samples of the UKIDSS Ultra Deep Survey (UDS) and COSMOS fields (McLeod et al. 2021) in the FIR *Herschel* and James Clerk Maxwell Telescope (JCMT) maps. The details of the data used, the selection process, catalogs construction and the determination of photometric redshifts and stellar masses are presented in McLeod et al. (2021), with a short summary given below.

The UKIDSS UDS field (Lawrence et al. 2007) includes UDS DR11 imaging (Almaini et al., in preparation) in the near-IR JHK bands, Y-band imaging from the VISTA VIDEO DR4 (Jarvis et al. 2013), UV imaging in u^* -band from CFHT MegaCam (Gwyn 2012), optical imaging in BVRiz’ from Subaru Suprime-Cam (Furusawa et al. 2008) and the mid-infrared *Spitzer* IRAC imaging in 3.6 μm and 4.5 μm , combining the SEDS (Ashby et al. 2013), S-CANDELS (Ashby et al. 2015), and SPLASH (PI Capak; see Mehta et al. 2018) programs. The effective area of the overlapping UDS imaging was 0.69 deg², after masking for bright stars. For the COSMOS field, near-IR $YJHK_s$ imaging from UltraVISTA DR4 (McCracken et al. 2012) with UV/optical u^*griz imaging from the CFHTLS-D2 T0007 data release are combined. As with the UDS, the data also includes the *Spitzer* IRAC imaging available in 3.6 μm and 4.5 μm , covering the area of 0.86 deg².

The optical/near-IR data available for each galaxy were fit with a number of spectral energy distribution (SED) codes, where the final redshift was taken to be the median of individual values, z_{med} . The precision was assessed using the available spectroscopic data, with the values of σ_z , defined as $1.483 \times \text{MAD}(dz)$, where MAD is the median absolute deviation and $dz = (z_{\text{med}} - z_{\text{spec}})/(1 + z_{\text{spec}})$, for the COSMOS and UDS fields, found to be equal to 0.019 and 0.022, respectively (McLeod et al. 2021).

Stellar masses were measured for each object by fixing the photometric redshift to z_{med} , and re-fitting the SED using LE-PHARE with the Bruzual & Charlot (2003) library, a Chabrier (2003) IMF, a Calzetti et al. (2000) dust attenuation law and IGM absorption as in Madau (1995). The resulting values were checked against masses found by the CANDELS team, where a tight 1:1 relation and a typical scatter of ± 0.05 dex was found.

2.2. Far-infrared

Two different stacking procedures have been used. For the stacked IRX values in bins of UV slope, stellar mass and redshift, FIR flux densities in the COSMOS and UDS fields were extracted using the SCUBA-2 Cosmology Legacy Survey (S2CLS; Geach et al. 2017) 850 μm imaging, as explained in Section 3.4. In order to determine the functional form of the IRX- β relationship, however, our sample was additionally stacked in the *Herschel* (Pilbratt et al. 2010) Multi-tiered Extragalactic Survey (HerMES; Oliver et al. 2012) and the Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al. 2010) Evolutionary Probe (PEP; Lutz et al. 2011) maps obtained with the Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al. 2010) and PACS instruments (Section 4.1).

3. Methods

3.1. Sample selection

We binned our data in equal redshift intervals spanning $0.5 < z < 5.0$ with a step size of $\Delta z = 0.5$, with the exception of the highest-redshift bin, where the bin width was set to $\Delta z = 1.0$ to improve the detection rate. For the analysis of the IRX- β relation, we set the lowest redshift to 2.0, since at lower values the available photometry does not cover the rest-frame UV slope interval of 125–250 nm. Additionally, we restricted our sample to sources exceeding the 90% stellar mass completeness limit established by McLeod et al. (2021). This results in lower mass thresholds of $\log(M_*/M_\odot) = [9.50, 9.50, 9.50, 9.50, 9.75, 9.75, 10.00, 10.25]$ across the respective redshift bins defined by $z = [0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0]$, with a total of 135596 galaxies.

Quiescent galaxies were excluded based on the *NUVrJ* color-color selection criteria of Ilbert et al. (2013):

$$\begin{aligned} (NUV - r) &> 3 \times (r - J) + 1; \\ (NUV - r) &> 3.1, \end{aligned} \quad (1)$$

where *NUV*, *r* and *J* AB magnitudes are determined from spectral energy distribution (SED) fitting (see Section 3.2). This method separates sources whose reddening results from the aging of the stellar population (ie., quiescent galaxies) from the dusty star-forming sample. The *NUVrJ* color-color selection was limited to redshifts less than 4, as the rest-frame *J*-band becomes progressively difficult to trace at higher redshifts with the available photometry, with a total of 18958 (14%) sources identified as quiescent.

Similarly to Koprowski et al. (2024), we also identified and removed 479 starburst galaxies, using the ALMA-selected samples in the COSMOS (Liu et al. 2019) and UDS (Stach et al. 2019) fields, with stellar masses and SFRs from Liu et al. (2019) and Dudzevičiūtė et al. (2020), respectively. Following Elbaz et al. (2018), starbursts were defined as galaxies with $\text{SFR}/\text{SFR}_{\text{MS}} > 3$, with SFR_{MS} being the corresponding main-sequence value (Koprowski et al. 2024).

3.2. SED fitting

Spectral energy distribution fitting was performed in order to determine the rest-frame *NUV*, *r* and *J* absolute magnitudes used for quiescent galaxies selection (Eq. 1), UV slopes, UV luminosities necessary for the derivation of the stacked IRX values and the IRX- β relationship functional form parameters (Section 4.1). We used the Code Investigating GALaxy Emission (CIGALE; Boquien et al. 2019), with the stellar models of Bruzual & Charlot (2003), Chabrier (2003) initial mass function, Calzetti et al. (2000) dust attenuation law and the IGM absorption of Meiksin (2006). Simple exponential star-formation history models, $\text{SFH} \propto \exp(-t/\tau)$, were assumed, with τ values of 0.1, 0.3, 1, 2, 3, 5, 10 and 15 Gyr and the dust attenuation, A_V , ranging between 0 and 2.8 in steps of 0.05. The *NUVrJ* magnitudes and the UV luminosities were found for each source by CIGALE from the best-fit SEDs. The procedure for deriving the UV slopes is described in Section 3.3, while the determination of the IRX- β relationship functional form parameters is explained in Section 4.1.

3.3. UV slopes

A number of methods have been used for determining the UV spectral slope β , a comprehensive review of which is presented in Rogers et al. (2013). Originally, Meurer et al. (1999) calculated β by fitting a power-law function to the ten continuum rest-frame 125–250 nm bands of Calzetti et al. (1994). Most often, however, only a few photometric points are available in this wavelength range and, hence, the resulting β 's are burdened with significant uncertainties. As explained by McLure et al. (2018), these uncertainties can bias the stacked values of the IRX, flattening the corresponding IRX- β relationship. Therefore, we derived the UV slopes by fitting the power-law function to the best-fit SEDs in the rest-frame wavelength range of 125–250 nm, where $S_\lambda \propto \lambda^\beta$. As recently shown by Morales et al. (2024), SED-based values exhibit lower scatter and reduced biases than those derived from photometric power-law fitting.

To estimate the UV slope uncertainties for each source, the photometry was randomly sampled from normal distributions, with the means and standard deviations corresponding to the catalog values and their associated errors and the resulting value of β_i derived from the best-fit SED. The procedure was repeated 1000 times and the final errors were taken to be the standard deviations of the individual values of β_i . Due to the diminishing quality of the photometry with redshift, the mean values of β_i are increasing from 0.15 at $z \sim 2$ to 0.55 at $z \sim 5$.

3.4. Stacked IRX values

For about 600k star-forming galaxies in our optical/near-IR catalogs, only ~ 2000 sources were directly detected in the S2CLS 850 μm survey (Geach et al. 2017). In order to get reliable estimates of the IR luminosity, and hence the IRX, we, therefore, resorted to the well-known method of stacking (e.g., Tomczak et al. 2016; Leslie et al. 2020; Mérida et al. 2023; Koprowski et al. 2024). Because it is not clear how does L_{IR} couple with L_{UV} , the stacked values of the IRX were taken to be equal to the median of the individual values of the infrared excess found for each source in the stack. For this to work, individual values of both, the UV and the IR luminosity for each source had to be found. While the UV luminosities were established from the SED fitting to the available UV/optical photometry, as described in Section 3.2, the determination of individual values of L_{IR} is difficult, due to the relatively shallow depth of the FIR observations. The FIR *Herschel* and JCMT SCUBA-2 flux densities extracted at each source's position are well below the noise level and, therefore, extracting IR luminosities requires the assumptions to be made on the value of the dust temperature. Therefore, to derive stacked IRX values in bins of β , M_* , and redshift, we relied on a single FIR photometry band. Specifically, we extracted the SCUBA-2 850- μm flux density at each source's position, converted it to IR luminosity, and divided it by the corresponding UV luminosity. L_{IR} was found by integrating the best-fit dust emission curve of Casey (2012) between 8–1000 μm rest frame, with the emissivity and the mid-IR power-law slope set to 1.96 and 2.3, respectively, as per recommendations of Drew & Casey (2022). To determine the dust temperature, we applied the T_d - z relation from Koprowski et al. (2024), which was derived from a stacking analysis of the exact same sample used in this work. In each bin, the corresponding stacked values of the UV slope, stellar mass and redshift were also derived by taking the median of all the individual numbers.

The impact of redshift and stellar-mass uncertainties on the stacked values of the IRX, β , M_* and redshift was quantified using

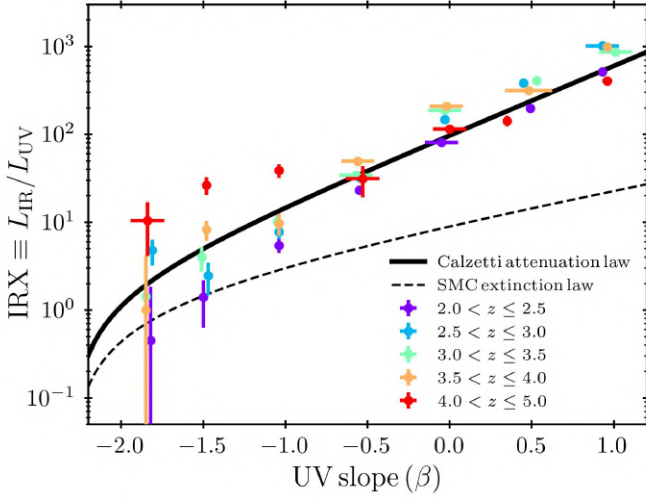


Fig. 1. IRX- β relationship for $2.0 < z \leq 5.0$ sample studied in this work. The color points with error bars show the stacked values of the IRX in bins of β , summarized in Table A.1. The black solid line represents the best-fit functional form (Equation 9), with $dA_{1600}/d\beta = 1.97$ being consistent with the attenuation curve of Calzetti et al. (2000). The scatter at $\beta \lesssim -1$ is caused by different stellar mass completeness limits imposed at each redshift bin (see Section 4.1 for details). For reference, the SMC curve is plotted in dashed line.

a bootstrap method. At each iteration, a mock catalog was generated by randomly drawing, with replacement, a set of sources from the original mass-complete dataset, for which a stacked value was found, following the procedure described above. The process was repeated 1000 times and the errors, $\delta_{\text{bootstrap}}$, were then taken to be the median absolute deviation of the resulting simulated values. In addition, to account for uncertainties in the UV luminosity and UV slope, we performed simple Monte Carlo simulations in which, in each of 1000 runs, the values of L_{UV} and β were randomly drawn from Gaussian distributions with standard deviations set to their respective 1σ uncertainties. The corresponding errors, δ_{MC} , were taken to be equal to the median of the individual values found in each run. The final uncertainties were then determined, where:

$$\delta = \sqrt{\delta_{\text{bootstrap}}^2 + \delta_{\text{MC}}^2}. \quad (2)$$

4. Analysis & Discussion

4.1. IRX- β in bins of UV slope

In order to find the evolution of the infrared excess with the UV slope and redshift, we stacked our mass-complete sample following the procedure explained in Section 3.4. The redshift and β bins and the mass-completeness limits, adopted from McLeod et al. (2021), with the corresponding IRX- β median values are summarized in Table A.1 and plotted in Figure 1 as color points with error bars.

The functional form was adopted from Meurer et al. (1999):

$$\text{IRX} = (10^{0.4A_{1600}} - 1) \times B, \quad (3)$$

where A_{1600} is the attenuation at the rest-frame 1600Å and B is the ratio of two correction factors:

$$B = \frac{\text{BC}(1600)}{\text{BC}(\text{FIR})}. \quad (4)$$

Since, in the original work of Meurer et al. (1999), the FIR luminosity, measured using IRAS data, was defined as $L_{\text{FIR}} = 1.25(L_{60} + L_{100})$ and the UV luminosity was determined at the rest-frame 1600Å, corrections were required in order to convert into bolometric luminosities. In this work, the IR luminosity is found by integrating the best-fit dust emission curve between 8-1000 μm (Section 3.4), so the FIR correction factor is by definition equal to 1. BC(1600), on the other hand, can be found once the intrinsic stellar emission curve is known. The attenuation at the rest-frame 1600Å is defined as:

$$A_{1600} = \frac{dA_{1600}}{d\beta} (\beta_{\text{obs}} - \beta_{\text{int}}), \quad (5)$$

with β_{obs} and β_{int} being the UV slopes of the observed and the intrinsic stellar emission spectra, respectively.

In order to establish the best-fit functional form of the IRX- β relation (i.e. the best-fit values of BC(1600) and A_{1600}), it is first required to find the underlying shapes of the intrinsic and observed UV-FIR SEDs. Following previous works (e.g. McLure et al. 2018; Koprowski et al. 2018) and our stacked results from Figure 1, we assumed the IRX- β relation not to evolve significantly with redshift and, therefore, derive our SEDs for the whole $2.0 < z < 5.0$ sample combined. In order to deal with non-detections, in the UV/optical bands we adopted median stacked values. For the FIR *Herschel* and JCMT SCUBA-2 bands the stacking analysis was performed, following the procedure explained in Section 3.2 of Koprowski et al. (2024). In brief, an inverse-variance weighting stacking method was utilized to derive average fluxes in a given band. For each source a square stamp was extracted with a side length approximately three times the full width at half maximum (FWHM) of the corresponding beam. The average stacked FIR flux densities were subsequently determined by applying nonlinear least squares best fits to the resulting light profiles. Because source clustering contributes significantly to the mean flux in the larger *Herschel* SPIRE bands, a double Gaussian profile was often utilized to accurately model and subtract this background contamination. Finally, the uncertainties on these stacked FIR fluxes were estimated using a bootstrapping method that incorporated instrumental noise and functional fit errors. The corresponding best-fit observed and intrinsic SEDs were then found by fitting to the stacked UV-FIR photometry using CIGALE, as explained in Section 3.2, with the slope of the dust reddening law, $dA_{1600}/d\beta$, set as a free parameter. The intrinsic stellar emission curve was then used to calculate the intrinsic UV slope and the bolometric correction factor, BC(1600):

$$\begin{aligned} \beta_{\text{int}} &= -2.30 \pm 0.10, \\ \text{BC}(1600) &= 1.51 \pm 0.11, \end{aligned} \quad (6)$$

with the resulting best-fit IRX- β relationship functional form plotted as black solid line in Figure 1. Because our sample contains significantly more sources at lower redshifts, stacking all galaxies across the $2.0 < z < 5.0$ range biases the resulting fits toward low- z data. However, when stacking was performed in separate redshift bins, the derived IRX- β relations showed only a slight variation at $\beta < -2.0$, with the lower-redshift fits yielding slightly higher intrinsic UV slopes and BC(1600) values, reflecting the older average ages of their underlying stellar populations.

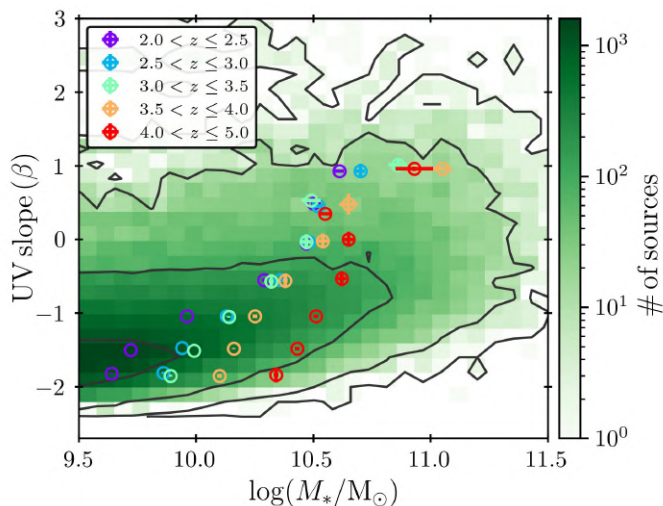


Fig. 2. Relationship between the UV slope and the stellar mass for the sample presented in Figure 1. Green background image shows a 2D histogram of the β - M_* distribution, with 1, 10, 100 and 1000 sources contours displayed with black curves. It can be seen that due to different mass-completeness limits imposed at each redshift bin (Table A.1), the median stellar masses at bluest β bins increase with redshift, which in turn drives the scatter in Figure 1 (see Section 4.1 for details).

In order to estimate the errors, we performed simple Monte Carlo simulations, where in each of 1000 realizations, the photometry was randomly sampled from the Gaussian distribution with the means and standard deviations equal to the catalog's values and their errors, respectively. The best-fit SEDs were found and the bolometric correction, $BC(1600)$, and β_{int} calculated for each run. The final errors were then set to be equal to the median of all the individual values. The best-fit slope, $dA_{1600}/d\beta = 1.97$, is consistent with the Calzetti et al. (2000) reddening law, where the values of:

$$dA_{1600}/d\beta = 1.97 \quad \text{and} \quad dA_{1600}/d\beta = 0.91, \quad (7)$$

for the Calzetti attenuation law and SMC extinction curve were assumed, respectively (McLure et al. 2018). Accordingly, our best-fit IRX- β relation is hereafter referred to as a Calzetti-like attenuation law.

It can be seen in Figure 1 that at $\beta > -1.0$ our IRX- β relation is in agreement with the Calzetti et al. (2000) attenuation curve across all redshift bins. At bluer β 's, however, the values of the IRX seem to be increasing with redshift. In Figure 2 the median values of the UV slope and stellar mass, corresponding to the stacked data of Figure 1, color-coded with redshift are plotted. The green background image shows a 2D histogram of the $\beta_{\text{obs}}-M_*$ distribution, with the black contours corresponding to the values of 1, 10, 100 and 1000. It can be seen that at bluer β 's the median stellar masses are significantly larger at higher redshifts, reflecting different stellar mass completeness limits imposed in each redshift bin (Table A.1). This aligns with recent results indicating that IRX correlates with stellar mass, such that, at fixed β , systems with higher stellar masses exhibit larger values of the infrared excess (e.g., Álvarez-Márquez et al. 2019; Bouwens et al. 2020). In order to investigate this further, in the next section we stack individual values of the infrared excess in bins of the stellar mass.

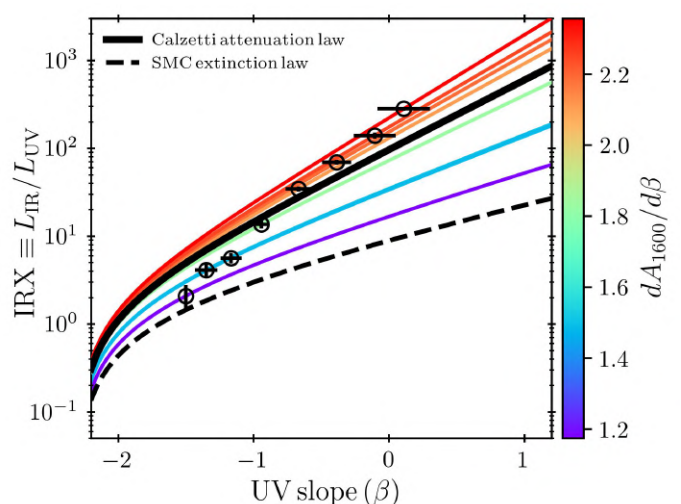


Fig. 3. IRX- β relationship in bins of stellar mass. The black circles show the stacked data (Table 1), with a clear correlation between the stellar mass and the slope of the reddening law, $dA_{1600}/d\beta$. Adopting Equation 9, with $dA_{1600}/d\beta$ set as free parameter, best-fit values for the reddening slope were found (last column in Table 1), with the corresponding correlation with the stellar mass derived in Section 4.2 and plotted in Figure 4. For reference, this work's best-fit relationship (consistent with the Calzetti curve), together with the SMC curve are plotted in solid and dashed lines, respectively.

4.2. IRX- β in bins of stellar mass

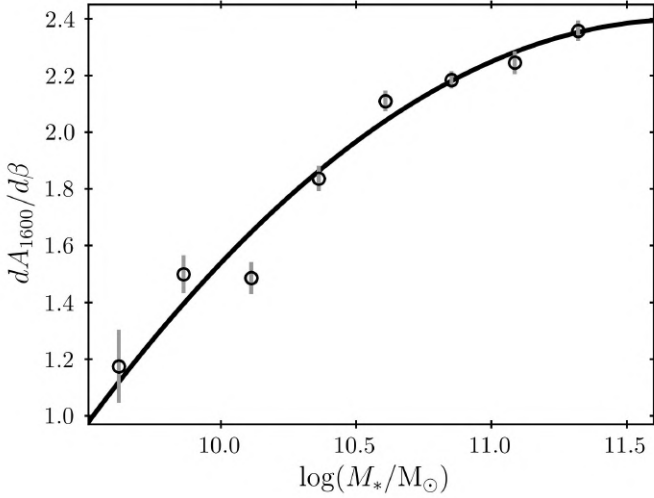
Following the procedure explained in Section 3.4, the stacked median values of the infrared excess were found in bins of the stellar mass for all the sources between redshifts 2.0 and 5.0, where in each stellar mass bin the corresponding UV slope was assumed to be the median of all the individual β 's. The results of this exercise are presented in Figure 3 with black open circles and summarized in Table 1. For reference, the best-fit functional form of the IRX- β relation found in Section 4.1 (consistent with the Calzetti et al. 2000 curve) and the SMC-like relation are plotted as black solid and dashed lines, respectively. It can be clearly seen that the position of a given IRX- β stacked data point relative to the best-fit relation correlates with the median stellar mass.

As explained in a number of recent works (e.g., Narayanan et al. 2018; Koprowski et al. 2018; Salim & Narayanan 2020), the scatter in the IRX- β plane is mainly caused by the variations in the slopes of the underlying attenuation laws, where galaxies affected by flatter (grayer) curves are shifted towards bluer UV slopes. Salim & Narayanan (2020) show that the attenuation curves slopes correlate strongly with effective optical opacity (i.e. the dust column density), with dusty and more massive galaxies having, on average, grayer curves. They attribute this relationship primarily to the combined effects of radiative transfer processes (scattering and absorption) and local geometry (clumpiness of dust). In this framework, a fraction of the rest-frame UV light, originating from young massive stars, escapes the galaxy through gaps in the dust distribution and via scattering processes, causing the effective attenuation curve to flatten.

It has been shown that galaxies at high redshifts exhibit a large variety of dust attenuation laws (e.g., Kriek & Conroy 2013; Lo Faro et al. 2017; Salmon et al. 2016; Cullen et al. 2018). Álvarez-Márquez et al. (2019) investigated a sample of high-redshift LBGs and found more massive sources to be affected by grayer attenuation curves. Similar trend was found by Bouwens et al. (2020). More recently, Shivaeei et al. (2025) inves-

Table 1. Physical properties for the $2.0 < z \leq 5.0$ sample stacked in Section 4.2 and plotted in Figure 3.

	β	M_*	$\log(\text{IRX})$	$dA_{1600}/d\beta$
$9.50 < \log(M_*/M_\odot) \leq 9.75$	-1.50 ± 0.00	9.62	$0.32^{+0.09}_{-0.12}$	1.17 ± 0.13
$9.75 < \log(M_*/M_\odot) \leq 10.00$	-1.35 ± 0.01	9.86	$0.61^{+0.05}_{-0.05}$	1.50 ± 0.07
$10.00 < \log(M_*/M_\odot) \leq 10.25$	-1.17 ± 0.01	10.11	$0.75^{+0.04}_{-0.05}$	1.49 ± 0.06
$10.25 < \log(M_*/M_\odot) \leq 10.50$	-0.94 ± 0.00	10.36	$1.13^{+0.04}_{-0.04}$	1.84 ± 0.05
$10.50 < \log(M_*/M_\odot) \leq 10.75$	-0.67 ± 0.02	10.61	$1.54^{+0.03}_{-0.03}$	2.11 ± 0.04
$10.75 < \log(M_*/M_\odot) \leq 11.00$	-0.39 ± 0.02	10.85	$1.84^{+0.03}_{-0.03}$	2.18 ± 0.03
$11.00 < \log(M_*/M_\odot) \leq 11.25$	-0.11 ± 0.03	11.09	$2.15^{+0.04}_{-0.04}$	2.25 ± 0.04
$11.25 < \log(M_*/M_\odot) \leq 11.50$	0.11 ± 0.04	11.32	$2.45^{+0.03}_{-0.03}$	2.36 ± 0.04

**Fig. 4.** Relationship between the dust reddening slope, $dA_{1600}/d\beta$, and the stellar mass for the sample plotted in Figure 3, where a clear correlation can be seen, with more massive systems being characterized by flatter attenuation curves. The functional form of the relation is derived and discussed in Section 4.2 and summarized in Equation 9.

tigated a spectroscopic sample from three JWST/NIRCam grism surveys and found the slopes of the attenuation curves to become shallower at higher values of the dust attenuation. Given that the dust attenuation is positively correlated with the stellar mass (i.e. more massive galaxies tend to be more dusty; Figure 2, but also McLure et al. 2018; Bouwens et al. 2020), higher-mass sources are systematically expected to be characterized by grayer attenuation curves.

We, therefore, proceed to establish the functional form of the relationship between the stellar mass and the slope of the underlying attenuation law using data from Figure 3. For practical reasons, the attenuation curve for a given stellar mass bin is quantified with the dust reddening slope of Equation 5, $dA_{1600}/d\beta$. A steeper attenuation curve leads to greater relative attenuation toward the edges of the UV wavelength range over which the UV slope β is measured (i.e., 125–250 nm in the rest frame). That means that, for a fixed attenuation, the steeper curve will produce redder β , shifting the galaxy to the right on the IRX- β plane. Consequently, steeper attenuation curves cause β to redden more rapidly as attenuation increases, giving rise to shallower reddening slopes, $dA_{1600}/d\beta$.

Assuming the median intrinsic stellar SED parameters, BC(1600) and β_{int} , found in Section 4.1 for our $2.0 < z \leq 5.0$ sample, $dA_{1600}/d\beta$ was established for each IRX- β stacked point in Figure 3 from Equation 3 using the χ^2 minimization method. The resulting values are summarized in Table 1 and plotted in Figure 4 with open circles, with the corresponding functional forms of the IRX- β relation depicted in Figure 3 with solid color lines. The correlation between the slope, $dA_{1600}/d\beta$, and the stellar mass was then found using the χ^2 minimization method (solid curve in Figure 4), where:

$$\begin{aligned}
 dA_{1600}/d\beta &= aM^2 + bM + c, \\
 a &= -0.30 \pm 0.07, \\
 b &= 7.06 \pm 1.40, \\
 c &= -38.8 \pm 7.5,
 \end{aligned} \tag{8}$$

with $M = \log(M_*/M_\odot)$ and the errors estimated from the corresponding co-variance matrix. Therefore, the infrared excess becomes a function of both the UV slope and the stellar mass, where the later enters the equation through its effect on the slope of the reddening law, $dA_{1600}/d\beta$, with the corresponding functional forms summarized in Table 2. The comparison between the functional form found in this work and the ones determined in Álvarez-Márquez et al. (2019) and Bouwens et al. (2020) are presented in Sections 4.4 and 4.5.

4.3. IRX- β – comparison to previous studies

We plot our stacked data in Figure 5. The gray circles represent median values of the infrared excess resulting from stacking all the sources between redshifts 2.0 and 5.0 (Table A.2), adopting stellar mass limits from Table A.1. For reference, this work’s best-fit relationship (consistent with the Calzetti curve), together with the SMC curve are plotted in solid and dashed lines, respectively. It can be seen that our median data is still slightly below the best-fit curve at blue UV slopes. This is caused by the variations in the corresponding stellar masses, with bluer bins having slightly lower median values of M_* .

For comparison, in the top panel of Figure 5 we plot the recent literature results of Heinis et al. (2013); Reddy et al. (2018); McLure et al. (2018); Koprowski et al. (2018); Álvarez-Márquez et al. (2019); Fudamoto et al. (2020b) and Bouwens et al. (2020). The stacked data found in this work seem to be in a reasonable agreement with the works of McLure et al. (2018); Koprowski et al. (2018); Álvarez-Márquez et al. (2019) and Fudamoto et al. (2020b), with the slightly elevated values found in Koprowski

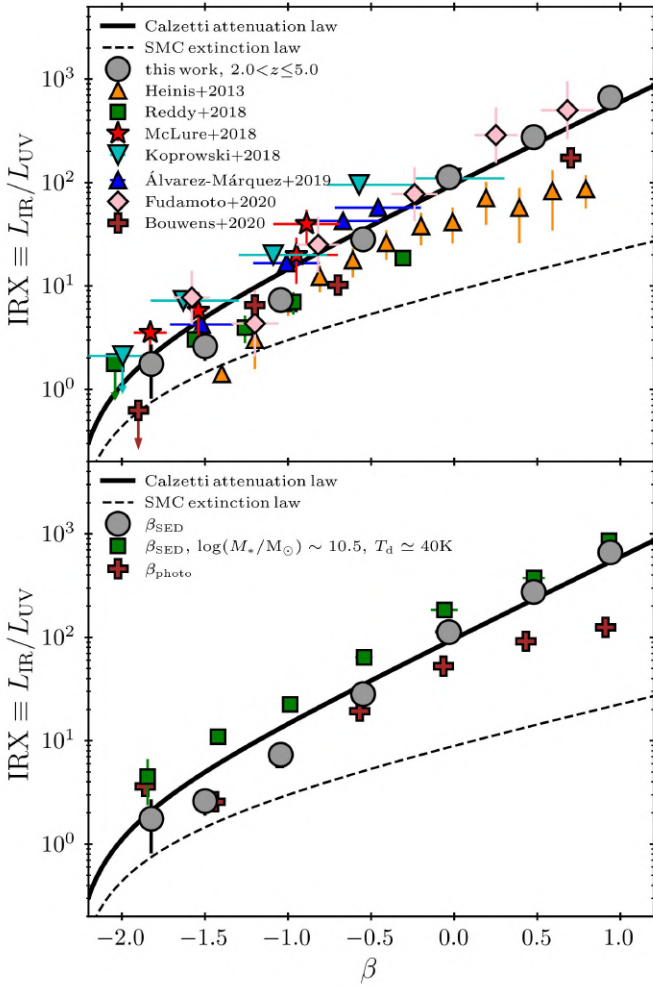


Fig. 5. IRX- β relationship derived for the $2.0 < z \leq 5.0$ sample of this work (gray circles; Table A.2). **Top panel.** Our median data lying slightly below the best-fit curve at blue UV slopes is driven by variations in the corresponding median stellar masses. We compare our data with the recent literature results of Heinis et al. (2013); Reddy et al. (2018); McLure et al. (2018); Koprowski et al. (2018); Álvarez-Márquez et al. (2019); Fudamoto et al. (2020b) and Bouwens et al. (2020). For reference, this work’s best-fit relationship and the SMC-like curve are plotted in solid and dashed lines, respectively. **Bottom panel.** To investigate the literature scatter, we highlight how varying data treatment methodologies alters our results (gray circles). Adopting a dust temperature of $T_d = 40$ K with a restricted stellar mass of $\log(M_*/M_\odot) \sim 10.5$ (green squares), or deriving UV slopes via photometric power-law fitting instead of best-fit SEDs (red crosses), radically changes the shape and normalization of the relation, mirroring the scatter seen in the top panel. See Section 4.3 for details.

et al. (2018) most likely caused by the higher dust temperature assumed when deriving their IR luminosities. The numbers presented in Heinis et al. (2013); Reddy et al. (2018) and Bouwens et al. (2020) are slightly below our stacked data. However, due to the variety of methods employed to measure both UV slopes and IRX, the direct comparison between these works is difficult.

The discrepancies between different data sets can be attributed to several methodological choices. These factors include the techniques used to calculate UV slopes, the procedures for de-blending FIR flux densities (particularly in the low-resolution *Herschel* SPIRE bands), the assumed profiles of dust emission curves, the specific stacking methods applied, and the apparent

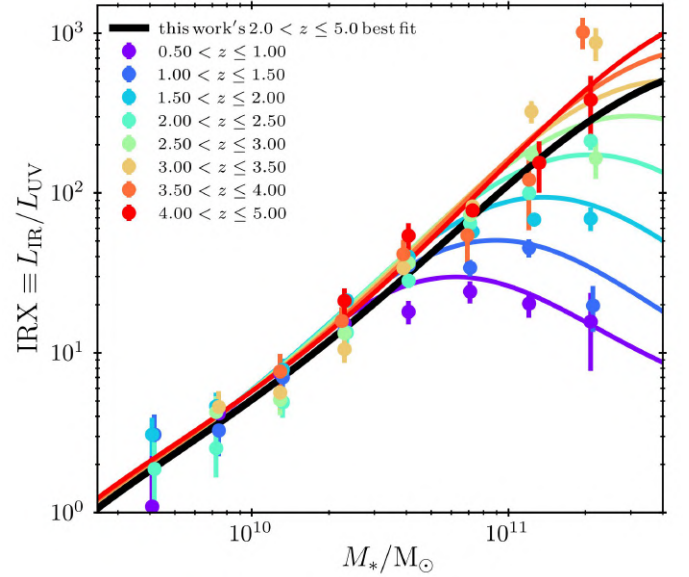


Fig. 6. IRX values median-stacked in bins of M_* and redshift (color points with error bars; Table A.3). The black line shows the best-fit functional form for the $2.0 < z \leq 5.0$ sample of Figure 3, while the color solid lines depict the functional forms found at the individual redshift bins, as explained in detail in Section 4.4.

dependence of IRX values on stellar mass. We illustrate the effects that some of these choices have on the resulting IRX- β relation in the bottom panel of Figure 5. The gray circles, as in the top panel, depict the results of this work. Limiting our sample to sources with the stellar mass of $\log(M_*/M_\odot) \sim 10.5$ and setting the dust temperature to the value adopted in Koprowski et al. (2018) of $T_d = 40$ K, our stacking procedure produces the results presented with green squares. On the other hand, when the UV slopes are derived by fitting a power-law to the available photometry between rest-frame 125–250 nm (as oppose to fitting to the best-fit SEDs), we can see the resulting relationship to flatten with β , consistent with the findings presented in McLure et al. (2018). Variations in the assumed dust temperature, stellar mass range and the method of deriving the UV slope alone can produce discrepancies (0.5 dex at blue end to ~ 1 dex at red end), that are similar in magnitude to the ones seen in the top panel of Figure 5.

4.4. IRX- M_*

Since measurements of the UV slope, β , are often burdened with significant uncertainties, causing additional scatter in the corresponding IRX values, it is often preferable to express the infrared excess as a function of stellar mass. We, therefore, stacked our full $0.5 < z \leq 5.0$ sample in bins of redshift and M_* , as summarized in Table A.3, with the resulting median values plotted in Figure 6 with color points. In order to find the functional form, we started with the IRX- β relationship found in Section 4.1 (Equations 9 summarized in Table 2), with the functional form of the stellar mass evolution of the reddening law, $dA_{1600}/d\beta$, found in Section 4.2 (Equations 10 summarized in Table 2). To express the IRX as a sole function of stellar mass, we converted the observed UV slope, β_{obs} , into stellar mass, M_* . This was done using data corresponding to the stacked points of Figure 3, plotted as black open circles in the top panel of Figure 7, by fitting a Gaussian function (black solid line in Figure 7), using non-linear

Table 2. Functional form of the IRX- β - M_* - z relationship.

IRX- β relationship found in Section 4.1	
$\text{IRX} = (10^{0.4A_{1600}} - 1) \times B$	
$A_{1600} = \frac{dA_{1600}}{d\beta} (\beta_{\text{obs}} - \beta_{\text{int}})$	(9)
$B = 1.51 \pm 0.11$	
$\beta_{\text{int}} = -2.30 \pm 0.10$	
$dA_{1600}/d\beta$ dependence on the stellar mass found in Section 4.2	
$\frac{dA_{1600}}{d\beta} = a\mathcal{M}^2 + b\mathcal{M} + c$	
$\mathcal{M} = \log(M_*/M_\odot)$	
$a = -0.30 \pm 0.07,$	(10)
$b = 7.06 \pm 1.40,$	
$c = -38.8 \pm 7.5$	
$\beta_{\text{obs}}-M_*$ relationship evolution with redshift established in Section 4.4	
$\beta_{\text{obs}} = a + b \times \exp\left(-\frac{(\mathcal{M} - c)^2}{2d^2}\right)$	
$\mathcal{M} = \log(M_*/M_\odot)$	
$a = -1.78 \pm 0.03$	(11)
$b = (0.45 \pm 0.04) \times z + (0.56 \pm 0.07)$	
$c = (0.40 \pm 0.04) \times z + (10.33 \pm 0.06)$	
$d = (0.16 \pm 0.03) \times z + (0.44 \pm 0.07)$	

least squares with the errors estimated from the corresponding co-variance matrix. The resulting relation can be written as:

$$\beta = a + b \times \exp\left(-\frac{(\mathcal{M} - c)^2}{2d^2}\right), \quad (12)$$

with $\mathcal{M} = \log(M_*/M_\odot)$ and:

$$\begin{aligned} a &= -1.78 \pm 0.03 \\ b &= 2.24 \pm 0.14 \\ c &= 12.00 \pm 0.13 \\ d &= 1.16 \pm 0.07. \end{aligned} \quad (13)$$

For comparison, in the top panel of Figure 7, the similar relationships found in McLure et al. (2018); Álvarez-Márquez et al. (2019) and Bouwens et al. (2020) are plotted with yellow, red and blue solid lines, respectively. An excellent agreement between our relationship and the one found in McLure et al. (2018) can clearly be seen. The results of Álvarez-Márquez et al. (2019) are based on a sample of $2.5 < z < 3.5$ COSMOS field Lyman Break Galaxies. Since LBGs are selected at the rest-frame UV bands, a fraction of red sources will likely be missed, underestimating the resulting stacked values of the UV slopes. Data investigated in Bouwens et al. (2020), on the other hand, shows elevated β 's at high stellar masses. The source of this inconsistency can be attributed to a slightly different method of deriving the best-fit β - M_* relation. In this work, the stacked points in the top panel of Figure 7 were found by taking median values of individual UV slopes in each stellar mass bin, with the best-fit function found from non-linear least squares (similarly to McLure

et al. 2018). In Bouwens et al. (2020), however, the number of sources on each side of the best-fit function was minimized, which produces slightly different results.

By combining Equation 12 with Equations 9 and 10, we obtain the best-fit IRX- M_* relationship shown as the black solid line in Figure 6. While it is in agreement with the low-mass stacked data, at higher stellar masses large inconsistencies can clearly be seen. Moreover, the disagreement between the best-fit function and the stacked data seems to increase towards lower redshifts, where the IRX- M_* data exhibits a clear turnover. This behavior, which has been detected in previous works (e.g., Whitaker et al. 2014; Pannella et al. 2015), can also be seen in the shape of the star-forming galaxies main sequence (e.g., Tomczak et al. 2016; Popesso et al. 2023; Koprowski et al. 2024). As discussed by Daddi et al. (2022), the turnover in the star-forming main sequence can be caused by phasing out of the cold gas accretion. At this turnover mass, supersonic shocks heat infalling molecular gas and halt cold accretion, effectively starving the galaxy of the fuel needed for sustained, dust-obscured star formation. Since the cold gas accretion is more efficient at higher redshifts, through cold collimated streams traveling along the dark matter filaments, the turnover of the main sequence, and hence the infrared excess, shifts towards higher masses at high redshifts, consistent with the Figure 6 data.

The decreasing IRX past the turnover stellar mass indicates that, during this starvation phase, the dust-obscured star formation (L_{IR}) undergoes a more rapid reduction relative to the unobscured star formation (L_{UV}). This is because the infrared luminosity predominantly traces the youngest massive stars ($\lesssim 10$ Myr) deeply embedded within dense molecular birth clouds, while the unobscured UV luminosity is sensitive to slightly older stellar populations (up to ~ 100 Myr) residing in the more diffuse in-

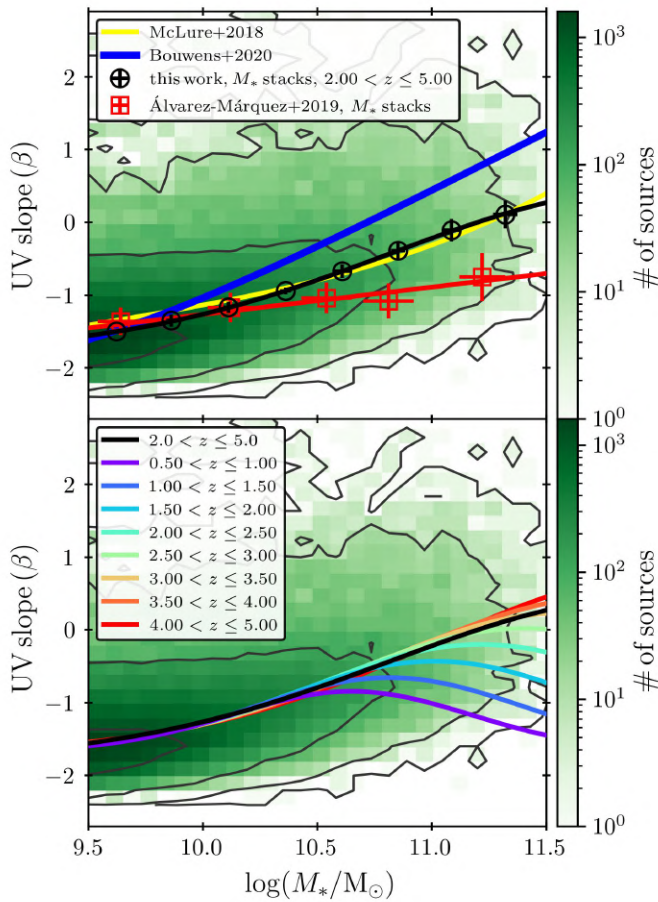


Fig. 7. The relationship between the observed UV slope and stellar mass for the $2.0 < z \leq 5.0$ sample of this work. Green background image represents a 2D histogram of the β - M_* distribution, with 1, 10, 100 and 1000 sources contours displayed with thin black curves. **Top panel.** Black circles with error bars show median values of β in bins of M_* (Table 1), with the thick black solid curve depicting the best-fit functional form of Equation 12. For comparison, the relationships found in McLure et al. (2018); Álvarez-Márquez et al. (2019) and Bouwens et al. (2020) are shown. **Bottom panel.** Black curve as in the top panel with the color curves determined for individual redshift bins, following the procedure explained in Section 4.4.

terstellar medium (e.g., Calzetti et al. 2010; Kennicutt & Evans 2012). At the turnover mass, when supersonic shocks heat the incoming gas, the dense molecular reservoirs are rapidly consumed by star formation or dispersed by feedback, decreasing L_{IR} . The UV emission from longer-lived stars, however, persists, resulting in the rapid decline of the corresponding IRX. As the lack of new gas prevents the further accumulation of dust in these massive systems, we expect this decrease in the IRX to be accompanied by a ‘blueing’ of the corresponding UV slope.

We, therefore, expect the β - M_* relation of Figure 7 to also exhibit a turnover at high stellar masses, mimicking the behavior of the IRX- M_* stacked data plotted in Figure 6. Since UV slopes cannot be reliably established using our data at redshifts ≤ 2 , where the IRX- M_* turnover is most prominent, we derived the corresponding redshift evolution of the β - M_* relation indirectly. IRX- M_* relation of this work is derived from the best-fit IRX- β curve (Eq. 9), with the stellar mass evolution of the reddening law given by Eq. 10, and β translated into M_* using the appropriate form of the β - M_* relationship. Motivated by the arguments pre-

sented above, we assume that the position and redshift evolution of the high-mass IRX- M_* turnover is driven by the evolution of the corresponding β - M_* curve. We, therefore, fitted the stacked IRX- M_* data (color points in Figure 6) with Equations 9 and 10, allowing the β - M_* relation of Eq. 12 to vary. The derived best-fit evolution for the free parameters of the β - M_* function, found using non-linear least squares, is given by:

$$\begin{aligned} a &= -1.78 \pm 0.03 \\ b &= (0.45 \pm 0.05) \times z + (0.56 \pm 0.13) \\ c &= (0.40 \pm 0.05) \times z + (10.33 \pm 0.08) \\ d &= (0.16 \pm 0.03) \times z + (0.44 \pm 0.08), \end{aligned} \quad (14)$$

which we summarized in Equation 11 of Table 2 and plotted in the bottom panel of Figure 7 with color solid lines. The corresponding evolution of the best-fit IRX- M_* relationship for our stacked median data are depicted with solid color lines in Figure 6. Because our relation is derived from stacked measurements, the small uncertainties on our best-fit β - M_* relation parameters represent the precision of the median relation. Individual galaxies, however, exhibit a substantial intrinsic physical scatter of $\sigma_{\beta, \text{intr}} \approx 0.3$ at $\log(M_*/M_\odot) = 9.5$ increasing to $\sigma_{\beta, \text{intr}} \approx 0.7$ at $\log(M_*/M_\odot) = 11.5$ around this median track.

It is also important to consider whether alternative factors, such as variations in the dust temperature (T_d) or dust SED, could be responsible for the high-mass IRX turnover. In this work, a redshift-dependent T_d relation from Koprowski et al. (2024) was adopted, with no stellar mass dependence at a given redshift. However, the dust temperature was found to increase with the specific SFR (e.g., Magnelli et al. 2014; Liang et al. 2019). Because the sSFR for star-forming galaxies with masses above the turnover mass decreases, their dust temperatures are expected to be lower than the average population. As we derived our IRX values from the 850 μm flux density on the Rayleigh-Jeans tail of the dust emission curve, the L_{IR} is highly sensitive to the assumed temperature. Applying a more realistic, mass-dependent (colder) T_d to the highest-mass bins would result in lower extrapolated L_{IR} (and IRX) values. Therefore, our assumption of a mass-independent T_d provides a conservative upper limit on the corresponding values of the IRX. Assuming lower T_d at high-mass end would cause the observed IRX turnover to become even more pronounced.

4.5. IRX- M_* – comparison to previous studies

The comparison of our data with the recent literature results of Whitaker et al. (2014); Heinis et al. (2014); Pannella et al. (2015); McLure et al. (2018); Koprowski et al. (2018); Álvarez-Márquez et al. (2019), Bouwens et al. (2020) and Fudamoto et al. (2020a) is shown in Figure 8. Our $0.5 < z \leq 5.0$ median-stacked values are presented with black filled circles, with the best-fit functional forms, produced by combining Equations 9, 10 and 11 (summarized in Table 2) depicted with black solid lines. A good agreement with most of the works can be seen, with the exception of the low-redshift Whitaker et al. (2014) and Heinis et al. (2014) data and the results of Álvarez-Márquez et al. (2019) and Fudamoto et al. (2020a). A clear high-mass turnover at low redshifts, discussed in previous section, was also detected in the works of Whitaker et al. (2014); Heinis et al. (2014) and Pannella et al. (2015), with Whitaker et al. (2014) and Heinis et al. (2014) finding somewhat elevated values of the IRX at low stellar masses. As explained in Section 4.3, these may arise from a number of different assumptions, most likely our choice of lower

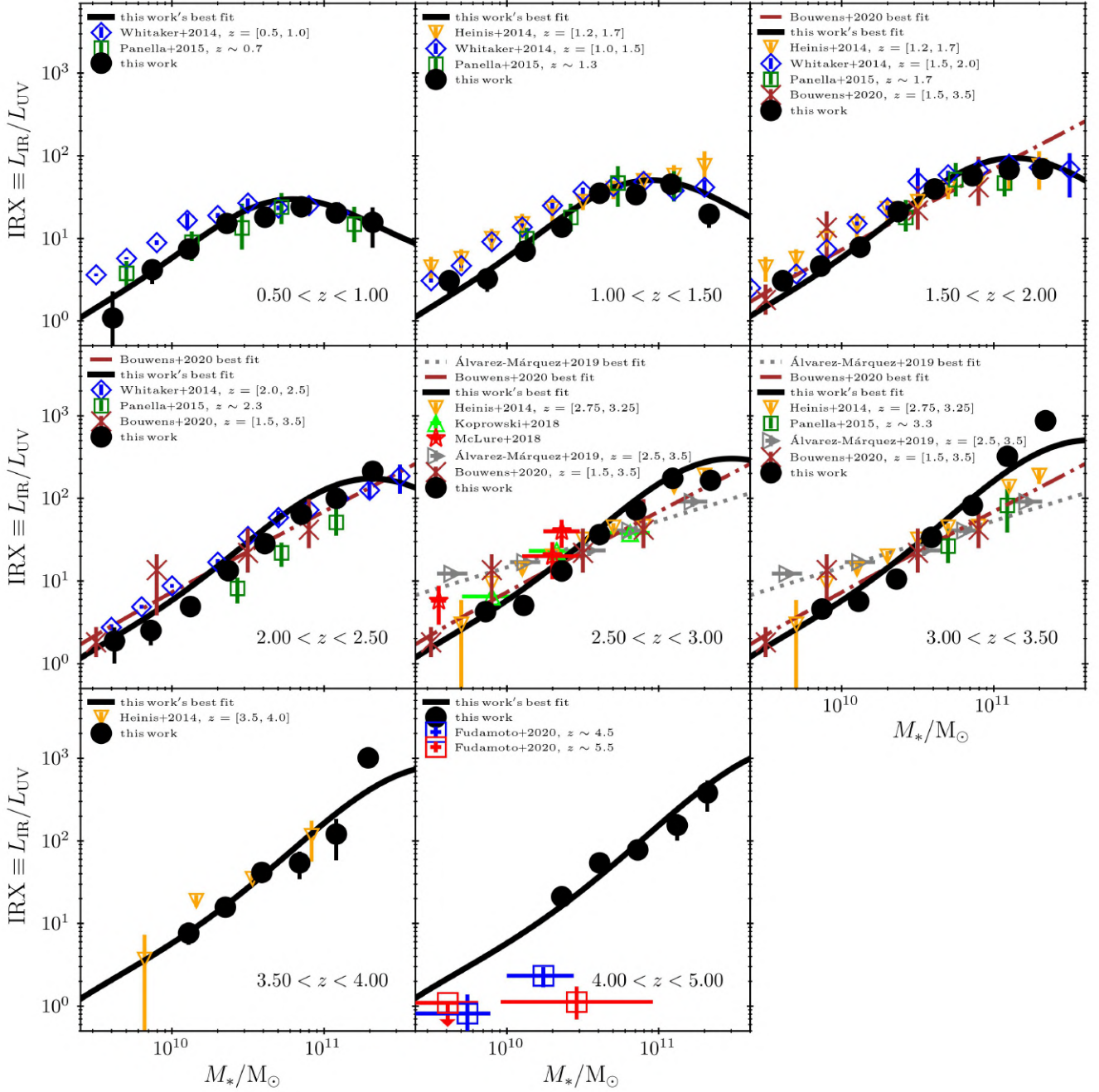


Fig. 8. IRX- M_* relationship for the $0.5 < z \leq 5.0$ sample of this work. The black circles with error bars show IRX values median-stacked in bins of M_* (Table A.3; same as color points in Figure 6). The black curves show corresponding best-fit functional forms summarized in Table 2 (same as color curves in Figure 6). For comparison, recent literature data of Whitaker et al. (2014); Heinis et al. (2014); Pannella et al. (2015); McLure et al. (2018); Koprowski et al. (2018); Álvarez-Márquez et al. (2019), Bouwens et al. (2020) and Fudamoto et al. (2020a) are also plotted, the discussion of which is presented in Section 4.5.

dust temperature at low redshifts, guided by the T_d - z relation of Koprowski et al. 2024. Assuming a single SED template for the dust emission, with $T_d = 30$ K, our lowest-redshift low-mass stacked IRX data shift towards higher values by ~ 0.3 dex.

The IRX- M_* data found in Álvarez-Márquez et al. (2019) follows a significantly flatter relationship. As the authors explain in Álvarez-Márquez et al. (2019), the inconsistencies at low stellar masses are most likely caused by the incompleteness of their LBGs sample in terms of M_* . Assuming the dependence of the stellar mass on the IRAC 3.6 μm flux density, the mass complete-

ness at $\log(M_*/M_\odot) < 10$ is between 80% and 50%, with lower-IRX sources missed from the sample. The IRX- M_* data and the corresponding functional form found in Bouwens et al. (2020) is in a very good agreement with our results, with some inconsistencies at high stellar masses. At the highest redshift bin we can see the reported IRX stacked values of Fudamoto et al. (2020a) lying significantly below our data, likely due to the selection effects. As explained in Fudamoto et al. (2020a), the UV-selected samples at $z > 4$ may be missing a significant population of UV-undetected, massive galaxies (e.g., Wang et al. 2019; Alcalde Pampiega et al.

2019). Because the parent ALPINE sample of Fudamoto et al. (2020a) is UV-selected ($M_{UV} < -20.2$), it inherently excludes a fraction of highly dust-obscured galaxies from their stacks. This selection bias explains why the discrepancy with our stacked values becomes more pronounced at higher stellar masses, where such heavily dusty sources constitute a larger fraction of the population. Between redshifts 3.0 and 4.0 at the highest mass bins our analysis produced somewhat elevated values of the IRX. We attribute these discrepancies to the fact that we were not able to remove all the starbursts from our sample. As explained in Section 3.1, starbursts were identified using the available ALMA data, which is not only incomplete in the COSMOS field, but is also biased against detecting sources with low dust masses and high dust temperatures. Since starbursts are known to exhibit very high dust content (e.g., Koprowski et al. 2018), their presence in the high-mass sample is expected to boost the resulting IRX values.

5. Summary

In this work we investigated a K -band selected, mass-complete sample of 135,596 star-forming galaxies (spanning stellar masses of $9.5 \leq \log(M_*/M_\odot) \leq 11.5$) from the UDS and COSMOS fields. The sample spans a combined $\sim 2 \text{ deg}^2$ with extensive UV–near-IR coverage and FIR/sub-mm imaging from *Herschel* and JCMT. We established the quantitative dependence of IRX on UV slope, stellar mass, and redshift out to $z \sim 5$ to provide functional prescriptions suitable for the dust correction of high-redshift galaxy samples. We adopted the available photometric redshifts and stellar masses from McLeod et al. (2021) and removed quiescent systems and ALMA-identified starbursts where possible. IR luminosities were obtained via inverse-variance stacking at $850 \mu\text{m}$ adopting Casey (2012) SEDs and a redshift-dependent dust temperature relation from Koprowski et al. (2024). UV slopes were derived from SED fits in the rest-frame 125–250 nm range, and the IRX was computed as the median of individual IRX values. The main results and key quantities can be summarized as follows:

(i) Stacking in the UV slope bins reveals that, at $\beta \gtrsim -1.0$, the IRX– β relation is consistent with a Calzetti-like attenuation law, yielding a best-fit dust-reddening slope of $dA_{1600}/d\beta = 1.97$, a bolometric correction $BC(1600) = 1.51 \pm 0.11$, and an intrinsic UV slope of $\beta_{\text{int}} = -2.30 \pm 0.10$. At bluer UV slopes, however, the stacked values of the IRX increase with redshift. We found this systematic trend to be a direct consequence of the different mass-completeness limits imposed in each redshift bin, with higher- z data effectively probing higher-mass galaxies at a given β .

(ii) Stacking in stellar-mass bins between $2.0 < z \leq 5.0$, we found the IRX to systematically increase, at a given β , with mass relative to the nominal Calzetti-like IRX– β relation. This behavior demonstrates that dust-rich, massive systems are characterized by flatter (grayer) attenuation curves, likely driven by the combined effects of radiative transfer processes and increasingly disturbed dust-star relative morphologies. We explicitly quantify this through the effective slope of the reddening law, finding it follows a tight quadratic dependence on stellar mass: $dA_{1600}/d\beta = (-0.30 \pm 0.07)M^2 + (7.06 \pm 1.40)M - (38.8 \pm 7.5)$, where $M = \log(M_*/M_\odot)$, making IRX a bivariate function of β and M_* .

(iii) Expressing IRX directly as a function of M_* yields a monotonic rise with mass out to $z = 5.0$. However, at $z \lesssim 2 - 3$, a clear high-mass turnover is detected. This turnover indicates a rapid reduction in dust-obscured star formation (L_{IR} , tracing

young stars $\lesssim 10 \text{ Myr}$) relative to unobscured star formation (L_{UV} , tracing older populations up to $\sim 100 \text{ Myr}$), most likely driven by supersonic shocks halting cold-gas accretion and starving massive galaxies of the fuel needed for dust growth. Accounting for a sSFR-dependent dust temperature would push our high-mass, low-redshift stacked IRX values lower, making the IRX– M_* turnover even more pronounced. While our derived β – M_* track tightly constrains the median behavior of this relation, individual galaxies exhibit a substantial intrinsic physical scatter around this median, widening from $\sigma_{\beta, \text{intr}} \approx 0.3$ at $\log(M_*/M_\odot) = 9.5$ to $\sigma_{\beta, \text{intr}} \approx 0.7$ at $\log(M_*/M_\odot) = 11.5$.

(iv) The results of this work broadly agree with previous stacking-based measurements (e.g., McLure et al. 2018; Álvarez-Márquez et al. 2019; Bouwens et al. 2020) while providing a comprehensive framework that resolves many literature inconsistencies. Much of the discrepancy in recently published relations can be largely resolved by incorporating the stellar-mass dependence of the reddening law and a careful SED-based estimation of β . Some of the remaining differences can be attributed to the dust emission curve modeling, where adopting a fixed dust temperature (e.g., $T_d = 30 \text{ K}$) shifts our low-redshift stacked IRX values higher by ~ 0.3 dex, and the selection effects, with purely UV-selected samples missing a substantial fraction of dust-obscured galaxies at high stellar masses, resulting in significantly lower reported IRX values.

Acknowledgements. This research was funded in whole or in part by the National Science Center, Poland (grant no. 2020/39/D/ST9/03078 and 2023/49/B/ST9/00066). For the purpose of Open Access, the author has applied a CC-BY public copyright license to any Author Accepted Manuscript (AAM) version arising from this submission. JSD, DIM acknowledge the support of the Royal Society through the award of a Royal Society University Research Professorship to JSD. KL acknowledges the support of the National Science Centre, Poland, through the PRELUDIUM grant UMO-2023/49/N/ST9/00746. This paper used data from project MJLSC02 on the James Clerk Maxwell Telescope, which is operated by the East Asian Observatory on behalf of The National Astronomical Observatory of Japan, Academia Sinica Institute of Astronomy and Astrophysics, the Korea Astronomy and Space Science Institute, the National Astronomical Observatories of China and the Chinese Academy of Sciences (Grant No. XDB09000000), with additional funding support from the Science and Technology Facilities Council of the United Kingdom and participating universities in the United Kingdom and Canada. This work is based in part on data products from observations made with ESO Telescopes at the La Silla Paranal Observatory under ESO programme ID 179.A-2005 and ID 179.A-2006 and on data products produced by CALET and the Cambridge Astronomy Survey Unit on behalf of the UltraVISTA and VIDEO consortia. This work is based in part on data obtained as part of the UKIRT Infrared Deep Sky Survey. UKIRT is owned by the University of Hawaii (UH) and operated by the UH Institute for Astronomy; operations are enabled through the cooperation of the East Asian Observatory. When (some of) the data reported here were acquired, UKIRT was supported by NASA and operated under an agreement among the University of Hawaii, the University of Arizona, and Lockheed Martin Advanced Technology Center; operations were enabled through the cooperation of the East Asian Observatory. When (some of) the data reported here were acquired, UKIRT was operated by the Joint Astronomy Centre on behalf of the Science and Technology Facilities Council of the U.K. This work is also based in part on observations made with the *Spitzer Space Telescope*, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under NASA contract 1407. This work is based in part on observations obtained with MegaPrime/MegaCam, a joint project of CFHT and CEA/IRFU, at the Canada-France-Hawaii Telescope (CFHT) which is operated by the National Research Council (NRC) of Canada, the Institut National des Sciences de l'Univers of the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii.

References

- Alcalde Pampliega, B., Pérez-González, P. G., Barro, G., et al. 2019, *ApJ*, **876**, 135
- Álvarez-Márquez, J., Burgarella, D., Buat, V., Ilbert, O., & Pérez-González, P. G. 2019, *A&A*, **630**, A153
- Ashby, M. L. N., Willner, S. P., Fazio, G. G., et al. 2015, *ApJS*, **218**, 33

- Ashby, M. L. N., Willner, S. P., Fazio, G. G., et al. 2013, *ApJ*, 769, 80
- Boquien, M., Burgarella, D., Roehlly, Y., et al. 2019, *A&A*, 622, A103
- Bouwens, R., González-López, J., Aravena, M., et al. 2020, *ApJ*, 902, 112
- Bouwens, R. J., Aravena, M., Decarli, R., et al. 2016, *ApJ*, 833, 72
- Bruzual, G. & Charlot, S. 2003, *MNRAS*, 344, 1000
- Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, *ApJ*, 533, 682
- Calzetti, D., Kinney, A. L., & Storchi-Bergmann, T. 1994, *ApJ*, 429, 582
- Calzetti, D., Wu, S.-Y., Hong, S., et al. 2010, *ApJ*, 714, 1256
- Capak, P. L., Carilli, C., Jones, G., et al. 2015, *Nature*, 522, 455
- Casey, C. M. 2012, *MNRAS*, 425, 3094
- Chabrier, G. 2003, *PASP*, 115, 763
- Cullen, F., McLure, R. J., Khochfar, S., et al. 2018, *MNRAS*, 476, 3218
- Daddi, E., Delvecchio, I., Dimauro, P., et al. 2022, *A&A*, 661, L7
- Drew, P. M. & Casey, C. M. 2022, *ApJ*, 930, 142
- Dudzevičiūtė, U., Smail, I., Swinbank, A. M., et al. 2020, *MNRAS*, 494, 3828
- Elbaz, D., Leiton, R., Nagar, N., et al. 2018, *A&A*, 616, A110
- Fisher, R., Bowler, R. A. A., Stefanon, M., et al. 2025, *MNRAS*, 539, 109
- Fudamoto, Y., Oesch, P. A., Faisst, A., et al. 2020a, *A&A*, 643, A4
- Fudamoto, Y., Oesch, P. A., Magnelli, B., et al. 2020b, *MNRAS*, 491, 4724
- Furusawa, H., Kosugi, G., Akiyama, M., et al. 2008, *ApJS*, 176, 1
- Geach, J. E., Dunlop, J. S., Halpern, M., et al. 2017, *MNRAS*, 465, 1789
- Gebek, A., Diemer, B., Martorano, M., et al. 2025, *A&A*, 695, A90
- Griffin, M. J., Abergel, A., Abreu, A., et al. 2010, *A&A*, 518, L3
- Gwyn, S. D. J. 2012, *AJ*, 143, 38
- Heinis, S., Buat, V., Béthermin, M., et al. 2013, *MNRAS*, 429, 1113
- Heinis, S., Buat, V., Béthermin, M., et al. 2014, *MNRAS*, 437, 1268
- Ilbert, O., McCracken, H. J., Le Fèvre, O., et al. 2013, *A&A*, 556, A55
- Ismail, D., Beelen, A., Buat, V., et al. 2023, *A&A*, 678, A27
- Jarvis, M. J., Bonfield, D. G., Bruce, V. A., et al. 2013, *MNRAS*, 428, 1281
- Kennicutt, R. C. & Evans, N. J. 2012, *ARA&A*, 50, 531
- Koprowski, M. P., Coppin, K. E. K., Geach, J. E., et al. 2018, *MNRAS*, 479, 4355
- Koprowski, M. P., Wijesekera, J. V., Dunlop, J. S., et al. 2024, *A&A*, 691, A164
- Kriek, M. & Conroy, C. 2013, *ApJ*, 775, L16
- Lawrence, A., Warren, S. J., Almaini, O., et al. 2007, *MNRAS*, 379, 1599
- Leslie, S. K., Schinnerer, E., Liu, D., et al. 2020, *ApJ*, 899, 58
- Liang, L., Feldmann, R., Kereš, D., et al. 2019, *MNRAS*, 489, 1397
- Lisiecki, K., Donevski, D., Man, A. W. S., et al. 2025, *arXiv e-prints*, [arXiv:2509.10117](https://arxiv.org/abs/2509.10117)
- Liu, D., Lang, P., Magnelli, B., et al. 2019, *ApJS*, 244, 40
- Lo Faro, B., Buat, V., Roehlly, Y., et al. 2017, *MNRAS*, 472, 1372
- Lutz, D., Poglitsch, A., Altieri, B., et al. 2011, *A&A*, 532, A90
- Madau, P. 1995, *ApJ*, 441, 18
- Madau, P. & Dickinson, M. 2014, *ARA&A*, 52, 415
- Magnelli, B., Lutz, D., Saintonge, A., et al. 2014, *A&A*, 561, A86
- McCracken, H. J., Milvang-Jensen, B., Dunlop, J., et al. 2012, *A&A*, 544, A156
- McLeod, D. J., McLure, R. J., Dunlop, J. S., et al. 2021, *MNRAS*, 503, 4413
- McLure, R. J., Dunlop, J. S., Cullen, F., et al. 2018, *MNRAS*, 476, 3991
- Mehta, V., Scarlata, C., Capak, P., et al. 2018, *ApJS*, 235, 36
- Meiksin, A. 2006, *MNRAS*, 365, 807
- Mérida, R. M., Pérez-González, P. G., Sánchez-Blázquez, P., et al. 2023, *ApJ*, 950, 125
- Meurer, G. R., Heckman, T. M., & Calzetti, D. 1999, *ApJ*, 521, 64
- Morales, A. M., Finkelstein, S. L., Leung, G. C. K., et al. 2024, *ApJ*, 964, L24
- Narayanan, D., Conroy, C., Davé, R., Johnson, B. D., & Popping, G. 2018, *ApJ*, 869, 70
- Oliver, S. J., Bock, J., Altieri, B., et al. 2012, *MNRAS*, 424, 1614
- Pannella, M., Elbaz, D., Daddi, E., et al. 2015, *ApJ*, 807, 141
- Pilbratt, G. L., Riedinger, J. R., Passvogel, T., et al. 2010, *A&A*, 518, L1
- Poglitsch, A., Waelkens, C., Geis, N., et al. 2010, *A&A*, 518, L2
- Popesso, P., Concas, A., Cresci, G., et al. 2023, *MNRAS*, 519, 1526
- Reddy, N., Dickinson, M., Elbaz, D., et al. 2012, *ApJ*, 744, 154
- Reddy, N. A., Erb, D. K., Pettini, M., Steidel, C. C., & Shapley, A. E. 2010, *ApJ*, 712, 1070
- Reddy, N. A., Oesch, P. A., Bouwens, R. J., et al. 2018, *ApJ*, 853, 56
- Rogers, A. B., McLure, R. J., & Dunlop, J. S. 2013, *MNRAS*, 429, 2456
- Salim, S. & Narayanan, D. 2020, *ARA&A*, 58, 529
- Salmon, B., Papovich, C., Long, J., et al. 2016, *ApJ*, 827, 20
- Shivaei, I., Naidu, R. P., Rodríguez Montero, F., et al. 2025, *arXiv e-prints*, [arXiv:2509.01795](https://arxiv.org/abs/2509.01795)
- Stach, S. M., Dudzevičiūtė, U., Smail, I., et al. 2019, *MNRAS*, 487, 4648
- Tomczak, A. R., Quadri, R. F., Tran, K.-V. H., et al. 2016, *ApJ*, 817, 118
- van der Wel, A., Martorano, M., Marchesini, D., et al. 2025, *A&A*, 701, A30
- Viero, M. P., Sun, G., Chung, D. T., Moncelsi, L., & Condon, S. S. 2022, *MNRAS*, 516, L30
- Wang, L., Pearson, W. J., Cowley, W., et al. 2019, *A&A*, 624, A98
- Whitaker, K. E., Franx, M., Leja, J., et al. 2014, *ApJ*, 795, 104

Appendix A: Additional tables

Table A.1. IRX values median-stacked in bins of β and redshift.

M_{lim}		$-2.25 < \beta \leq -1.75$		$-1.75 < \beta \leq -1.25$		$-1.25 < \beta \leq -0.75$		$-0.75 < \beta \leq -0.25$		$-0.25 < \beta \leq 0.25$		$0.25 < \beta \leq 0.75$		$0.75 < \beta \leq 1.25$	
		$\log(\text{IRX})$ (β)		$\log(\text{IRX})$ (β)		$\log(\text{IRX})$ (β)		$\log(\text{IRX})$ (β)		$\log(\text{IRX})$ (β)		$\log(\text{IRX})$ (β)		$\log(\text{IRX})$ (β)	
2.0 < $z \leq 2.5$	9.50	$-0.35^{+0.30}_{-inf}$		$0.15^{+0.19}_{-0.35}$		$0.74^{+0.07}_{-0.09}$		$1.36^{+0.04}_{-0.04}$		$1.91^{+0.03}_{-0.04}$		$2.30^{+0.03}_{-0.03}$		$2.71^{+0.02}_{-0.02}$	
		(-1.82 ± 0.01)		(-1.50 ± 0.01)		(-1.04 ± 0.01)		(-0.55 ± 0.01)		(-0.05 ± 0.10)		(0.49 ± 0.01)		(0.93 ± 0.01)	
2.5 < $z \leq 3.0$	9.75	$0.68^{+0.12}_{-0.17}$		$0.39^{+0.15}_{-0.23}$		$0.89^{+0.07}_{-0.08}$		$1.51^{+0.04}_{-0.04}$		$2.17^{+0.04}_{-0.04}$		$2.58^{+0.02}_{-0.02}$		$3.01^{+0.01}_{-0.01}$	
		(-1.81 ± 0.02)		(-1.47 ± 0.01)		(-1.04 ± 0.01)		(-0.55 ± 0.01)		(-0.03 ± 0.01)		(0.45 ± 0.01)		(0.93 ± 0.10)	
3.0 < $z \leq 3.5$	9.75	$0.16^{+0.30}_{-inf}$		$0.60^{+0.12}_{-0.16}$		$1.01^{+0.07}_{-0.08}$		$1.54^{+0.04}_{-0.05}$		$2.27^{+0.02}_{-0.02}$		$2.61^{+0.02}_{-0.02}$		$2.94^{+0.01}_{-0.01}$	
		(-1.85 ± 0.01)		(-1.51 ± 0.01)		(-1.05 ± 0.01)		(-0.57 ± 0.10)		(-0.03 ± 0.10)		(0.53 ± 0.01)		(1.01 ± 0.10)	
3.5 < $z \leq 4.0$	10.00	$0.00^{+0.30}_{-inf}$		$0.92^{+0.10}_{-0.13}$		$0.99^{+0.11}_{-0.14}$		$1.70^{+0.05}_{-0.06}$		$2.32^{+0.02}_{-0.03}$		$2.50^{+0.03}_{-0.03}$		$3.00^{+0.02}_{-0.02}$	
		(-1.85 ± 0.02)		(-1.48 ± 0.01)		(-1.04 ± 0.01)		(-0.56 ± 0.10)		(-0.02 ± 0.10)		(0.48 ± 0.14)		(0.96 ± 0.02)	
4.0 < $z \leq 5.0$	10.25	$1.02^{+0.21}_{-0.41}$		$1.42^{+0.09}_{-0.11}$		$1.59^{+0.07}_{-0.08}$		$1.50^{+0.14}_{-0.21}$		$2.06^{+0.04}_{-0.04}$		$2.15^{+0.06}_{-0.07}$		$2.61^{+0.02}_{-0.02}$	
		(-1.84 ± 0.10)		(-1.48 ± 0.01)		(-1.04 ± 0.02)		(-0.53 ± 0.10)		(0.00 ± 0.10)		(0.35 ± 0.02)		(0.96 ± 0.03)	

Notes. Data corresponding to color points of Figure 1, with M_{lim} being the mass-completeness limit at each redshift bin, where $M = \log(M_*/M_\odot)$. Median values of β in each bin are listed in the brackets.

Table A.2. IRX values median-stacked in bins of β .

M_{lim}		$-2.25 < \beta \leq -1.75$		$-1.75 < \beta \leq -1.25$		$-1.25 < \beta \leq -0.75$		$-0.75 < \beta \leq -0.25$		$-0.25 < \beta \leq 0.25$		$0.25 < \beta \leq 0.75$		$0.75 < \beta \leq 1.25$	
		$\log(\text{IRX})$ (β)		$\log(\text{IRX})$ (β)		$\log(\text{IRX})$ (β)		$\log(\text{IRX})$ (β)		$\log(\text{IRX})$ (β)		$\log(\text{IRX})$ (β)		$\log(\text{IRX})$ (β)	
2.0 < $z \leq 5.0$	As in Table A.1	$0.25^{+0.19}_{-0.34}$		$0.42^{+0.11}_{-0.14}$		$0.87^{+0.04}_{-0.05}$		$1.45^{+0.03}_{-0.03}$		$2.05^{+0.02}_{-0.02}$		$2.44^{+0.02}_{-0.02}$		$2.82^{+0.01}_{-0.01}$	
		(-1.82 ± 0.01)		(-1.50 ± 0.01)		(-1.04 ± 0.01)		(-0.55 ± 0.03)		(-0.03 ± 0.08)		(0.48 ± 0.03)		(0.94 ± 0.04)	

Notes. Same as in Table A.1 but without binning in redshift.

Table A.3. IRX- M_* stacked values.

	$9.50 < \mathcal{M} \leq 9.75$	$9.75 < \mathcal{M} \leq 10.00$	$10.00 < \mathcal{M} \leq 10.25$	$10.25 < \mathcal{M} \leq 10.50$	$10.50 < \mathcal{M} \leq 10.75$	$10.75 < \mathcal{M} \leq 11.00$	$11.00 < \mathcal{M} \leq 11.25$	$11.25 < \mathcal{M} \leq 11.50$
	$\log(\text{IRX})$ ($\mathcal{M}$)	$\log(\text{IRX})$ ($\mathcal{M}$)	$\log(\text{IRX})$ ($\mathcal{M}$)	$\log(\text{IRX})$ ($\mathcal{M}$)	$\log(\text{IRX})$ ($\mathcal{M}$)	$\log(\text{IRX})$ ($\mathcal{M}$)	$\log(\text{IRX})$ ($\mathcal{M}$)	$\log(\text{IRX})$ ($\mathcal{M}$)
$0.5 < z \leq 1.0$	$0.04^{+0.30}_{-0.17}$ (9.61)	$0.62^{+0.12}_{-0.17}$ (9.87)	$0.87^{+0.08}_{-0.10}$ (10.11)	$1.18^{+0.07}_{-0.08}$ (10.36)	$1.26^{+0.07}_{-0.08}$ (10.61)	$1.38^{+0.06}_{-0.08}$ (10.85)	$1.31^{+0.07}_{-0.09}$ (11.08)	$1.20^{+0.18}_{-0.31}$ (11.32)
$1.0 < z \leq 1.5$	$0.49^{+0.12}_{-0.17}$ (9.62)	$0.51^{+0.12}_{-0.16}$ (9.87)	$0.85^{+0.07}_{-0.08}$ (10.12)	$1.14^{+0.06}_{-0.07}$ (10.36)	$1.55^{+0.04}_{-0.05}$ (10.61)	$1.53^{+0.05}_{-0.06}$ (10.85)	$1.66^{+0.05}_{-0.06}$ (11.08)	$1.30^{+0.12}_{-0.17}$ (11.33)
$1.5 < z \leq 2.0$	$0.49^{+0.10}_{-0.14}$ (9.61)	$0.67^{+0.08}_{-0.10}$ (9.86)	$0.90^{+0.07}_{-0.08}$ (10.12)	$1.33^{+0.04}_{-0.04}$ (10.37)	$1.60^{+0.03}_{-0.04}$ (10.61)	$1.76^{+0.03}_{-0.04}$ (10.86)	$1.83^{+0.04}_{-0.04}$ (11.10)	$1.84^{+0.07}_{-0.08}$ (11.32)
$2.0 < z \leq 2.5$	$0.27^{+0.17}_{-0.27}$ (9.62)	$0.40^{+0.13}_{-0.18}$ (9.86)	$0.69^{+0.08}_{-0.10}$ (10.12)	$1.13^{+0.06}_{-0.08}$ (10.37)	$1.45^{+0.04}_{-0.05}$ (10.61)	$1.81^{+0.04}_{-0.05}$ (10.85)	$2.00^{+0.04}_{-0.04}$ (11.08)	$2.33^{+0.05}_{-0.06}$ (11.32)
$2.5 < z \leq 3.0$	...	$0.63^{+0.10}_{-0.13}$ (9.86)	$0.71^{+0.08}_{-0.10}$ (10.11)	$1.12^{+0.05}_{-0.06}$ (10.36)	$1.56^{+0.06}_{-0.07}$ (10.61)	$1.86^{+0.05}_{-0.06}$ (10.85)	$2.24^{+0.05}_{-0.06}$ (11.09)	$2.22^{+0.10}_{-0.13}$ (11.34)
$3.0 < z \leq 3.5$	...	$0.66^{+0.10}_{-0.13}$ (9.87)	$0.75^{+0.08}_{-0.11}$ (10.11)	$1.02^{+0.07}_{-0.08}$ (10.36)	$1.53^{+0.06}_{-0.07}$ (10.59)	$1.92^{+0.07}_{-0.08}$ (10.86)	$2.51^{+0.06}_{-0.07}$ (11.09)	$2.94^{+0.09}_{-0.12}$ (11.34)
$3.5 < z \leq 4.0$	...	...	$0.88^{+0.11}_{-0.14}$ (10.11)	$1.20^{+0.08}_{-0.10}$ (10.35)	$1.62^{+0.09}_{-0.11}$ (10.59)	$1.74^{+0.14}_{-0.20}$ (10.84)	$2.08^{+0.18}_{-0.32}$ (11.08)	$3.01^{+0.09}_{-0.11}$ (11.29)
$4.0 < z \leq 5.0$	...	...	...	$1.33^{+0.08}_{-0.10}$ (10.36)	$1.73^{+0.08}_{-0.09}$ (10.61)	$1.89^{+0.09}_{-0.11}$ (10.86)	$2.19^{+0.13}_{-0.19}$ (11.12)	$2.58^{+0.15}_{-0.23}$ (11.32)

Notes. Data corresponding to color points of Figure 6 and black circles of Figure 8, with $\mathcal{M} = \log(M_*/M_\odot)$. Median values of $\mathcal{M}$ in each bin are listed in the brackets.

1.9 Article C

Evolution of the infrared luminosity function and its corresponding dust-obscured star formation rate density out to $z \sim 6$

Evolution of the infrared luminosity function and its corresponding dust-obscured star formation rate density out to $z \sim 6$

M. P. Koprowski^{1,*}, J. V. Wijesekera¹, J. S. Dunlop², K. Lisiecki^{1,4}, D. J. McLeod², R. J. McLure²,
M. J. Michałowski^{3,2}, and M. Solar³

¹ Institute of Astronomy, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziądzka 5, 87-100 Toruń, Poland

² Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh EH9 3HJ, UK

³ Astronomical Observatory Institute, Faculty of Physics and Astronomy, Adam Mickiewicz University, ul. Słoneczna 36, 60-286 Poznań, Poland

⁴ National Centre for Nuclear Research, Pasteura 7, 093 Warsaw, Poland

Received 1 October 2025 / Accepted 3 January 2026

ABSTRACT

We present a new determination of the evolving far-infrared (FIR) galaxy luminosity function (LF) and the resulting inferred evolution of dust-obscured star-formation rate density (ρ_{SFR}) out to redshift $z \sim 6$. To establish the evolving comoving number density of FIR-bright objects, we made use of AS2UDS, a high-resolution ALMA follow-up study of the JCMT SCUBA-2 Cosmology Legacy Survey (S2CLS) submillimeter imaging in the UKIDSS UDS survey field. In order to estimate the contributions of faint and low-mass sources, we implemented a method in which the faint-end of the IR LF is inferred by stacking (in stellar mass and redshift bins) the optical and near-infrared samples of star-forming galaxies into the appropriate FIR Herschel and submillimeter JCMT maps. Using this information we determined the faint-end slope of the FIR LF in two intermediate redshift bins (where it can be robustly established) and then adopted this result at all other redshifts. The evolution of the characteristic luminosity of the galaxy FIR LF, L_* , is found to increase monotonically with redshift, evolving as $L_* \propto z^{1.38 \pm 0.07}$, while the characteristic number density, Φ_* , is well fit by a double power-law function; it is constant at $z < 2.24$ and declines as $z^{-4.95 \pm 0.73}$ at higher redshifts. We then calculated the evolution of the corresponding dust-obscured star-formation rate density and compared it with the results from a number of recent studies in the literature. Our analysis confirms that dust-obscured star formation activity dominates ρ_{SFR} at cosmic noon but then becomes progressively less important with increasing redshift. While dusty star-forming galaxies are still found out to the highest redshifts explored here, UV-visible star formation dominates at $z > 4$, and dust-obscured activity contributes less than 25% to the star formation rate density by $z \sim 6$.

Key words. galaxies: evolution – galaxies: high-redshift – galaxies: ISM – galaxies: luminosity function, mass function – galaxies: star formation

1. Introduction

One of the main goals of modern extragalactic astronomy is to describe the evolution of star formation (SF) throughout cosmic history. The most direct way of achieving this goal is through the calibration of various relationships that characterize how SF in galaxies evolves with time. The most important examples of such relationships are the ultraviolet (UV) and infrared (IR) luminosity function (LF; e.g., Gruppioni et al. 2013; Koprowski et al. 2017; Wang et al. 2019; Bouwens et al. 2021; Fujimoto et al. 2024) and the star formation rate density (ρ_{SFR} ; e.g., Madau & Dickinson 2014; Dunlop et al. 2017; Traina et al. 2024; Liu et al. 2026; Barrufet et al. 2025).

Since the discovery of the cosmic infrared background (Puget et al. 1996; Hauser et al. 1998), the IR contribution to the total ρ_{SFR} , determined through the integration of the corresponding luminosity function, has been the primary focus of numerous studies (e.g., Magnelli et al. 2013; Gruppioni et al. 2013; Madau & Dickinson 2014; Rowan-Robinson et al. 2016; Koprowski et al. 2017; Dunlop et al. 2017; Wang et al. 2019;

Gruppioni et al. 2020; Traina et al. 2024; Magnelli et al. 2024; Fujimoto et al. 2024; Sun et al. 2025; Liu et al. 2026). While most of the results seem to be consistent out to $z \sim 2 - 3$, where the SF activity of the Universe reaches its peak, at $z \gtrsim 4$ the derived values disagree by over an order of magnitude.

The accurate assessment of the evolution of SF in the early Universe is essential for evaluating current galaxy evolution models. Thanks to the sensitivity of the rest-frame UV observations, the unobscured portion of the SF in galaxies has been investigated out to redshifts as high as ~ 11 (e.g., Bouwens et al. 2014; Laporte et al. 2016; Harikane et al. 2024; McLeod et al. 2024; Donnan et al. 2024). Due to the time required for the formation of the interstellar dust, the unobscured SF is thought to dominate the total budget at such high redshifts. Since it is now well known that by cosmic noon ($z \sim 2 - 3$) the vast majority of stellar emission in the UV gets absorbed by interstellar dust and reemitted in the IR, we expect ρ_{SFR} to transition from being UV dominated to IR dominated. However, because of the observational limitations in the infrared (see Casey et al. 2014 for details), the exact redshift of this transition is yet to be determined.

* Corresponding author: drelkopi@gmail.com

The contribution of the dust-enshrouded stellar emission to the total SF budget in the early Universe has primarily been assessed through the most extreme IR sources, known as submillimeter galaxies (e.g., [Smail et al. 1997](#); [Hughes et al. 1998](#)) or more broadly as dusty star-forming galaxies (DSFGs; [Casey et al. 2014](#)), which have very large IR luminosities ($L_{\text{IR}} \gtrsim 10^{12} L_{\odot}$; e.g., [Chapman et al. 2005](#); [Michałowski et al. 2017](#)) and extremely high SF rates ($\text{SFR} \gtrsim 100 M_{\odot} \text{ yr}^{-1}$; e.g., [Swinbank et al. 2014](#); [Koprowski et al. 2016](#)). Observations conducted using NASA’s *Spitzer Space Telescope* and ESA’s *Herschel Space Observatory* enabled the determination of the infrared luminosity functions out to $z \simeq 2 - 4$ (e.g., [Le Floc’h et al. 2005](#); [Caputi et al. 2007](#); [Rodighiero et al. 2010](#); [Patel et al. 2013](#); [Magnelli et al. 2013](#); [Gruppioni et al. 2013](#); [Rowan-Robinson et al. 2016](#); [Wang et al. 2019](#)). However, only the most extreme DSFGs have been detected at $z \gtrsim 2$, which necessitated significant extrapolations to account for fainter objects, leading to uncertain and often inconsistent results.

[Koprowski et al. \(2017\)](#) utilized a sample of the James Clerk Maxwell Telescope (JCMT) 850- μm -selected sample to construct the IR luminosity function out to $z \sim 4$. While the submillimeter wavelengths benefit from the negative K -correction, allowing for the observation of IR galaxies out to very high redshifts, surprisingly low numbers of sources were detected at $z \gtrsim 2$. Similarly, due to the very limited areas observed, the high-resolution ALMA blank-sky surveys conducted in recent years also struggled to detect any sources at very high redshifts (e.g., [Walter et al. 2016](#); [Dunlop et al. 2017](#); [Bouwens et al. 2020](#)). [Gruppioni et al. \(2020\)](#) made use of the ALMA sources serendipitously detected as a part of the ALMA Large Program to INvestigate CII at Early Times (ALPINE) in order to derive the IR LF out to $z \sim 6$. [Fujimoto et al. \(2024\)](#) reached similar redshifts utilizing the ALMA Lensing Cluster Survey (ALCS) data, with faint objects detected through lensing. Most recently, [Magnelli et al. \(2024\)](#), [Traina et al. \(2024\)](#), and [Liu et al. \(2026\)](#) determined the contribution of IR sources to the total ρ_{SFR} in the early Universe using the somewhat inhomogeneous sample of individual ALMA pointings collected as a part of the A³COSMOS survey ([Liu et al. 2019](#); [Adscheid et al. 2024](#)). Due to the limited sensitivity of the IR data, the corresponding faint-end slope of the IR LF reported in these works ranges between -0.2 and -1.0 , with errors approaching 0.5 . In addition, [Dudzevičiūtė et al. \(2020\)](#) analyzed a high-resolution ALMA follow-up study (AS2UDS; [Stach et al. 2019](#)) of the JCMT SCUBA-2 submillimeter survey of the UKIDSS UDS field ([Geach et al. 2017](#)). As a part of their analysis, [Dudzevičiūtė et al. \(2020\)](#) derived photometric redshifts, IR luminosities, IR luminosity functions, and the corresponding star formation rate densities down to the $870 \mu\text{m}$ flux limit of 3.6 mJy , later extrapolating their results down to a flux limit of 1 mJy using the ALMA number counts of [Hatsukade et al. \(2018\)](#). They found that the contribution of submillimeter galaxies to the total star formation rate density in the Universe peaks at $z \sim 3$, with a contribution of $\sim 15\%$ for sources with $S_{870} > 3.6 \text{ mJy}$ and $\sim 60\%$ for $S_{870} > 1 \text{ mJy}$, indicating that roughly half of the ρ_{SFR} at that redshift comes from ultra luminous IR galaxies (ULIRGs)-luminosity sources.

The aim of this study is to add to the existing knowledge by deriving the evolution of the IR LF, including its faint-end slope, up to $z \sim 6$. In order to include the contribution from the faintest galaxies, we adopted an indirect approach, where the faint-end portion of the LF is determined through stacking of the optically selected mass-complete sample of star-forming galaxies in the far-IR (FIR) maps of *Herschel* and JCMT maps,

with the stellar mass used as a proxy for the IR luminosity. The paper is structured as follows. We present the data in Section 2. In Section 3.1.1 we explain the details behind our derivation of the IR LF faint-end slope. In Section 3.1.2 we describe how we used data from AS2UDS, a high-resolution ALMA follow-up study of all the SCUBA-2 sources detected within the S2CLS map of the UKIDSS UDS field ([Geach et al. 2017](#); [Stach et al. 2019](#)), to construct the bright end of our IR LF. In Section 3.1.3 we construct the functional form of the IR LF and quantify its evolution with redshift out to $z \sim 6$, discuss the results, and compare them with recent literature. The corresponding star formation rate density is derived, discussed, and compared with other works in Section 3.2. We provide a summary of this work in Section 4. Throughout the paper we assume a flat cold dark matter cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$.

2. Data

The faint end of the infrared luminosity function was established via stacking the optical/near-IR catalogs of the UKIDSS Ultra Deep Survey (UDS) and COSMOS fields ([McLeod et al. 2021](#)) following the methodology outlined in [Koprowski et al. \(2024\)](#), where the stellar masses of galaxies were used as a proxy for the IR luminosity. For the purpose of extracting the stacked FIR flux densities, we used the *Herschel* ([Pilbratt et al. 2010](#)) Multi-tiered Extragalactic Survey (HerMES; [Oliver et al. 2012](#)) and the Photodetector Array Camera and Spectrometer (PACS; [Poglitsch et al. 2010](#)) Evolutionary Probe (PEP; [Lutz et al. 2011](#)) data obtained with the Spectral and Photometric Imaging Receiver (SPIRE; [Griffin et al. 2010](#)) and PACS instruments, where *Herschel* maps at $100, 160, 250, 350$, and $500 \mu\text{m}$ were utilized. In order to constrain the Rayleigh–Jeans tail of the dust emission curve, we also include the data collected as part of the SCUBA-2 Cosmology Legacy Survey (S2CLS; [Geach et al. 2017](#)).

The bright end of the IR LF (Section 3.1.2) was derived using high-resolution ALMA follow-up data (AS2UDS; [Stach et al. 2019](#); [Dudzevičiūtė et al. 2020](#)) of the S2CLS UKIDSS UDS field ([Geach et al. 2017](#)). The original SCUBA-2 map encompasses an area of 0.96 square degrees, with a noise level of less than 1.3 mJy and a median sensitivity of $\sigma_{850} = 0.88 \text{ mJy beam}^{-1}$, where 716 sources were detected. As explained in [Geach et al. \(2017\)](#), the SCUBA-2 source detection completeness for the UDS field was determined by the recovery rate of artificial sources injected into the jackknife maps as a function of input flux.

A detailed description of the ALMA observations and data reduction and the construction of the catalog can be found in [Stach et al. \(2019\)](#). In summary, all 716 SCUBA-2 sources were observed using ALMA Band 7 during Cycles 1, 3, 4, and 5. All the maps were tapered to 0.5 arcsec for source detection purposes, with the resulting AS2UDS catalog consisting of 708 individual ALMA-identified submillimeter galaxies ($\sigma_{870} > 4.3$). Based on $60\,000$ simulated ALMA observations, the sample was found to be complete at $S_{870} \gtrsim 4 \text{ mJy}$.

The associated photometric redshifts and FIR luminosities for all AS2UDS sources were adopted from [Dudzevičiūtė et al. \(2020\)](#). In short, the available photometry spans a wavelength range from the u -band to radio, with low-resolution *Herschel* SPIRE data deblended using the procedure explained in [Swinbank et al. \(2014\)](#). Photometric redshifts as well as IR luminosities were found using the updated MAGPHYS spectral energy distribution modeling code ([da Cunha et al. 2015](#); [Battisti et al.](#)

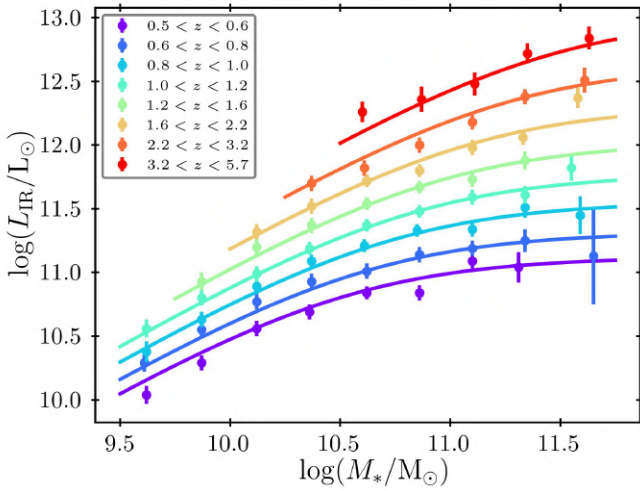


Fig. 1. Infrared luminosity-stellar mass relation determined through stacking the optical/near-IR mass-complete samples of McLeod et al. (2021) in the FIR *Herschel* and JCMT maps, adopted from Koprowski et al. (2024). The stacked L_{IR} values were used to determine the faint-end portion of the IR LF, as explained in Section 3.1.1.

2019), along with the stellar models from Bruzual & Charlot (2003), the initial mass function of Chabrier (2003), and the dust attenuation model of Charlot & Fall (2000). The resulting photometric redshifts were tested against the available spectroscopic data, yielding a median offset – defined as $(z_{\text{spec}} - z_{\text{phot}})/(1 + z_{\text{spec}})$ – of -0.005 ± 0.003 , with a dispersion of 0.13.

The corresponding dust temperatures were found by Dudzevičiūtė et al. (2020) using MAGPHYS and the modified blackbody curve:

$$S \propto (1 - e^{-\tau_{\text{rest}}}) \times B(\nu_{\text{rest}}, T), \quad (1)$$

where $B(\nu_{\text{rest}}, T)$ is the Planck function and the optical depth defined is as $\tau_{\text{rest}} \equiv (\nu_{\text{rest}}/\nu_0)^\beta$, with the emissivity index β set to 1.8. As explained in Dudzevičiūtė et al. (2020), the corresponding temperatures for both MAGPHYS and the modified blackbody fits were found to be in a very good agreement, with a typical fractional difference of $(T_d^{\text{MBB}} - T_d^{\text{MAGPHYS}})/T_d^{\text{MBB}} = -0.28 \pm 0.01$.

3. Analysis and discussion

3.1. Infrared luminosity function

3.1.1. Faint end

The IR luminosities for the galaxies constituting the faint-end portion of the luminosity function were extracted indirectly by stacking the optical/near-IR samples in the FIR *Herschel* and JCMT maps and using the stellar mass as proxies. The rationale behind this approach is that the IR luminosities of the star-forming galaxies are tightly correlated with their stellar masses via the so-called main sequence (e.g., Speagle et al. 2014; Tomczak et al. 2016; Daddi et al. 2022; Popesso et al. 2023; Koprowski et al. 2024). The stacking procedure was performed by Koprowski et al. (2024), and we adopted their results in this work (Figure 1 with the individual L_{IR} values listed in Table B.1). The redshift bins were designed to encompass the approximately 1 billion years of Universe evolution, ranging from 1 to 9 billion years after the Big Bang (with the corresponding redshift bins of [0.45, 0.6, 0.75, 1.0, 1.2, 1.6, 2.2, 3.2, 5.7]).

As we consider a sample of star-forming galaxies here, our assessment of the faint end of the IR luminosity function in effect excludes both quiescent and starburst galaxies (see Koprowski et al. 2024 for details). This is warranted, as passive sources are much less numerous than the active galaxies, and they exhibit significantly lower IR luminosities at a given stellar mass, rendering their contribution to the resulting LF negligible. Starbursts, on the other hand, are much more luminous in the IR, and their contribution to the LF is therefore assessed using the ALMA data, as explained in Section 3.1.2.

Since the $L_{\text{IR}}-M_*$ relation, similarly to the star-forming main sequence, exhibits a turnover at high masses, the functional form of Lee et al. (2015) was adopted:

$$L_{\text{IR}} = L_{\text{IR}}^{\text{max}} / (1 + (M_*/M_0)^{-\gamma}), \quad (2)$$

with the slope, γ , set to one. As explained in Koprowski et al. (2024), the most accurate fits to the $L_{\text{IR}}-M_*$ relation are produced when the logarithm of the free parameters of Eq. (2) are assumed to follow an exponential evolution with redshift, where

$$\begin{aligned} \log(L_{\text{IR}}^{\text{max}}/M_\odot \text{yr}^{-1}) &= a_1 + a_2 \times e^{-a_3 z} \\ \log(M_0/M_\odot) &= b_1 + b_2 \times e^{-b_3 z}. \end{aligned} \quad (3)$$

Eq. (2) was fit to the stacked data (Table B.1) using nonlinear least square fitting. The best-fit curves are shown in Figure 1, with the best-fit parameters of Eq. (3) listed in Table 2.

Because of the lack of ALMA detections (IR LF bright end) at low redshifts (Section 3.1.2), we limited our analysis to the redshift bins of [1.2, 1.6, 2.2, 3.2, 5.7]. In addition, we only considered $z-M_*$ bins with stellar masses below the main-sequence bending mass, M_0 , at which point the $L_{\text{IR}}-M_*$ relationship leaves the power-law regime ($M_0/M_\odot \sim 10^{11.0}$ at $1.2 < z < 2.2$ rising to $M_0/M_\odot \sim 10^{11.2}$ at $z > 2.2$). The IR luminosity for each $z-M_*$ bin was extracted from the $L_{\text{IR}}-M_*$ best-fit relation (Equations (2) and (3) with the best-fit parameters from Table 2). In order to determine the corresponding IR luminosity function, a standard $1/V_{\text{max}}$ method (Schmidt 1968) was used:

$$\Phi(L, z) = \frac{1}{\Delta \log L} \sum_i \frac{1}{V_i}. \quad (4)$$

The width of the L_{IR} bin in log space, $\Delta \log L$, was taken from the best-fit $L_{\text{IR}}-M_*$ functional form of Equation (2). Given that the width of the stellar mass bin is $\Delta \log(M_*/M_\odot) = 0.25$ and the slope, γ , in Equation (2) was set to one, $\Delta \log L$ below the bending mass, M_0 , is also ≈ 0.25 . The number of sources in each bin, i , is listed at the bottom panel of Table B.1, and V_i is the comoving volume available to the i th source.

The resulting values for the faint-end portion of the IR LF are listed in Table 1 and depicted as black points in Figure 2. To assess the errors on the number of sources in each bin, the bootstrapping method was used. In each step, a mock catalog was constructed by drawing, at random and with replacement, a sample of sources from the original mass-complete dataset. The process was repeated 1000 times, and the uncertainties on the number of sources in each $z-M_*$ bin were taken to be the standard deviation of the resulting simulated values. The errors on the average stacked values of L_{IR} , listed in Table B.1, are from Koprowski et al. (2024). The errors on the IR LF faint-end data points are driven by the errors on the number of sources in each bin (Bottom panel of Table B.1), and as can be seen in Figure 2 and Table 1, they are significantly smaller than the errors on the L_{IR} .

3.1.2. Bright end

The bright end of the IR LF was determined using high-resolution ALMA follow-up data of all the S2CLS UKIDSS UDS sources from AS2UDS (Stach et al. 2019; Dudzevičiūtė et al. 2020). The main advantage of the ALMA data is the high resolution of the observations, which allow for robust optical counterpart identification. Each source has two values of completeness associated with it – one from the original S2CLS survey (Geach et al. 2017) and one from the ALMA follow-up observations (Stach et al. 2019). To make sure the data used here are flux complete, we limited the ALMA sample to sources with fluxes $S_{870} > 4$ mJy, for which the completeness in the ALMA maps was established to be close to 100%. Since, as stated in Stach et al. (2019), for SCUBA-2 sources above $S_{850} \sim 3.5$ mJy all the single-dish flux in ALMA maps, on average, has been recovered, we can treat ALMA $S_{870} > 4$ mJy sources as a flux-complete ($>80\%$ completeness in the original S2CLS SCUBA-2 UDS map of Geach et al. 2017) homogeneous sample.

As discussed briefly in Section 2, the IR luminosities were taken from Dudzevičiūtė et al. (2020), where in order to get reliable values of L_{IR} , we limited our sample to sources with at least one *Herschel* SPIRE detection. We therefore required our sample to be 870 μm flux complete ($S_{870} > 4$ mJy) and have at least one SPIRE detection. The median dust temperature of the sources in the AS2UDS sample was estimated by Dudzevičiūtė et al. (2020) to be ~ 30 K (with a 68th percentile range of 25.7–37.3 K). Adopting the modified blackbody curve of Equation (1), with the 870 μm flux of 4 mJy and the dust temperature of 37.3 K (upper 68th percentile), we arrived at the conservative IR luminosity completeness limit of $\log(L_{\text{IR}}/L_{\odot}) = 12.5$ at $z < 1.6$, respectively rising to 12.75 and 13.00 at $z < 3.2$ and < 5.7 (Table 3).

The IR luminosity function was found using the $1/V_{\text{max}}$ method (Schmidt 1968), where

$$\Phi(L, z) = \frac{1}{\Delta \log L} \sum_i \frac{1 - \text{FDR}}{w_i \times V_i}, \quad (5)$$

with $\Delta \log L$ being the width of the luminosity bin in log space and V_i as the comoving volume available to the i th source, while the false detection rate (FDR) and the completeness, w_i , are from the original SCUBA-2 survey (Geach et al. 2017). As explained in Geach et al. (2017), a fraction of low signal-to-noise ratio sources may be missed by the source detection algorithm due to them residing in the noise valleys. For the purpose of the sample completeness, the fraction of missed galaxies was therefore quantified in the form of the source completeness, w_i . Similarly, false sources may be identified due to statistical fluctuations expected from Gaussian noise, as quantified by FDR. In both cases, as described in Geach et al. (2017), the jackknife noise-only map was populated with artificial sources, after which the source extraction algorithm was applied. The ratio between the recovered and the injected numbers were then used to determine w_i and FDR for each source in the parent SCUBA-2 sample of Geach et al. (2017), which were then adopted in our calculations of the IR LF of Equation (5). The resulting values are summarized in Table 3 and depicted as color points with gray error bars in Figure 2. In order to assess the errors, we conducted Monte Carlo simulations in which redshifts and infrared luminosities were randomly sampled from normal distributions, with the means and standard deviations corresponding to the catalog values and their associated errors. The 1σ uncertainties associ-

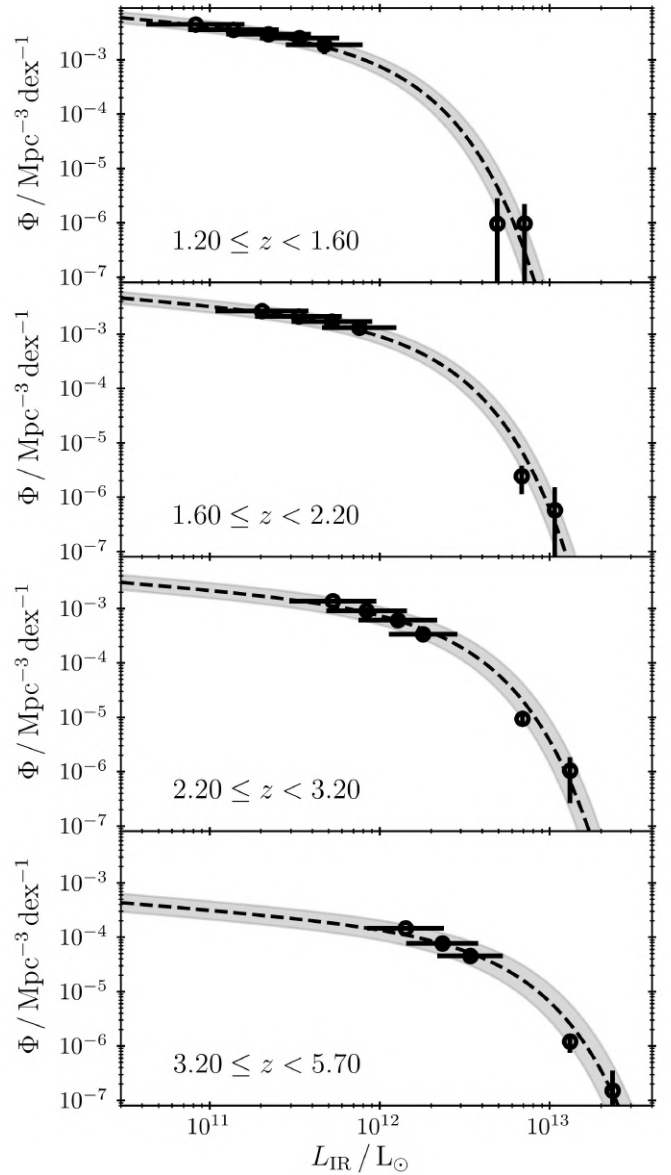


Fig. 2. Infrared luminosity function found in this work at different redshift bins, as indicated in the plot. The faint-end data (Table 1), determined through stacking (see Section 3.1.1 for details), are depicted by black points with horizontal error bars. The remaining bright-end data (Table 3) found using the ALMA follow-up data of the S2CLS UKIDSS UDS sources (AS2UDS; Stach et al. 2019) are also shown (Section 3.1.2). The best-fit Schechter functions of Equation (6) are represented by dashed black lines, with the gray area representing 1σ uncertainties. The faint-end slope was determined at two low redshift bins, and the more accurate result, $\alpha = -0.26 \pm 0.11$, was adopted at all the remaining redshifts, as explained in Section 3.1.3.

ated with the stacked IR LFs were then obtained by computing the standard deviations of the simulated data.

We note that our derived form of the bright end of the IR LF closely resembles that presented in Dudzevičiūtė et al. (2020). The only notable distinctions are that we have assumed slightly different redshift binning and included the completeness and false detection rate values of the original S2CLS sample of Geach et al. (2017) in our $1/V_{\text{max}}$ analysis. However, given that the initial SCUBA2 sample has been determined to be nearly flux complete for $S_{850} > 4$ mJy, incorporating them did not have

Table 1. Infrared luminosity comoving volume density for the faint-end of the IR LF.

	$\log(\Phi/\text{Mpc}^{-3} \text{ dex}^{-1})$					
	$9.75 \leq \mathcal{M} < 10.00$	$10.00 \leq \mathcal{M} < 10.25$	$10.25 \leq \mathcal{M} < 10.50$	$10.50 \leq \mathcal{M} < 10.75$	$10.75 \leq \mathcal{M} < 11.00$	$11.00 \leq \mathcal{M} < 11.25$
$\bar{z} = 1.44$	$(\mathcal{L} = 10.91 \pm 0.29)$ $-2.35^{+0.03}_{-0.03}$	$(\mathcal{L} = 11.14 \pm 0.27)$ $-2.45^{+0.04}_{-0.04}$	$(\mathcal{L} = 11.35 \pm 0.25)$ $-2.53^{+0.06}_{-0.08}$	$(\mathcal{L} = 11.53 \pm 0.23)$ $-2.60^{+0.08}_{-0.10}$	$(\mathcal{L} = 11.67 \pm 0.23)$ $-2.73^{+0.12}_{-0.18}$	–
$\bar{z} = 1.88$	–	$(\mathcal{L} = 11.31 \pm 0.27)$ $-2.58^{+0.03}_{-0.03}$	$(\mathcal{L} = 11.52 \pm 0.26)$ $-2.67^{+0.05}_{-0.05}$	$(\mathcal{L} = 11.72 \pm 0.24)$ $-2.77^{+0.08}_{-0.09}$	$(\mathcal{L} = 11.88 \pm 0.22)$ $-2.88^{+0.10}_{-0.13}$	–
$\bar{z} = 2.59$	–	–	$(\mathcal{L} = 11.72 \pm 0.26)$ $-2.86^{+0.04}_{-0.04}$	$(\mathcal{L} = 11.92 \pm 0.24)$ $-3.04^{+0.06}_{-0.06}$	$(\mathcal{L} = 12.11 \pm 0.23)$ $-3.21^{+0.08}_{-0.10}$	$(\mathcal{L} = 12.25 \pm 0.20)$ $-3.47^{+0.11}_{-0.15}$
$\bar{z} = 4.14$	–	–	–	$(\mathcal{L} = 12.15 \pm 0.23)$ $-3.83^{+0.04}_{-0.05}$	$(\mathcal{L} = 12.37 \pm 0.21)$ $-4.11^{+0.06}_{-0.07}$	$(\mathcal{L} = 12.53 \pm 0.19)$ $-4.34^{+0.09}_{-0.11}$

Notes. $\mathcal{M} \equiv \log(M_*/M_\odot)$ and $\mathcal{L} \equiv \log(L_{\text{IR}}/L_\odot)$. For each stellar mass bin, the corresponding IR luminosity at a given redshift is shown in the brackets. Details are provided in Section 3.1.1.

Table 2. Best-fit values to parameters from Eq. (3).

Parameter	Best-fit values
a1	2.97 ± 0.20
a2	-2.62 ± 0.14
a3	0.59 ± 0.10
b1	11.38 ± 0.39
b2	-1.14 ± 0.30
b3	0.50 ± 0.36

a substantial impact on our results. The comparison with the IR LF and the ρ_{SFR} values found in [Dudzevičiūtė et al. \(2020\)](#) is presented in Sections 3.1.3 and 3.2.

3.1.3. IR LF functional form

Following previous works, we fit the IR LF with the Schechter function:

$$\Phi(L, z) = \Phi_\star \left(\frac{L}{L_\star} \right)^\alpha \exp\left(\frac{-L}{L_\star} \right), \quad (6)$$

where $\Phi_\star$ is the normalization parameter, α is the faint-end slope, and $L_\star$ is the characteristic luminosity that marks the border between the power law and the exponential fits (for comparison purposes, the modified Schechter fits are presented in Appendix A). Due to the relatively shallow depth of IR observations, the faint-end slope is usually determined only at redshifts $z \ll 1$ (e.g., [Gruppioni et al. 2013](#)) and then fixed at higher redshifts, with the exception of [Koprowski et al. \(2017\)](#), where α was found using the ALMA survey of Hubble Ultra Deep Field ([Dunlop et al. 2017](#)) at $z \approx 2$. Here, we fit the faint-end slope at the two lowest redshift bins ($1.2 \leq z < 1.6$ and $1.6 \leq z < 2.2$), finding $\alpha = -0.26 \pm 0.11$ and -0.23 ± 0.18 , respectively, and we adopted a more accurate $1.2 \leq z < 1.6$ value of -0.26 at all redshift bins.

The faint- and bright-end data from Figure 2 were fit at each redshift using Equation (6) (solid black curves in Figure 2), with α set to -0.26 and using the nonlinear least squares analysis with the errors estimated from the corresponding covariance matrix. The resulting values of $\Phi_\star$ and $L_\star$ are summarized in Table 4 and depicted as black points with error bars in Figure 3. The functional form for the redshift dependence for each parameter

(black solid curves in Figure 3) was then found, where

$$\Phi_\star / \text{Mpc}^{-3} \text{ dex}^{-1} = \Phi_{\star,0} \left[\left(\frac{z}{z_0} \right)^{a_1} + \left(\frac{z}{z_0} \right)^{a_2} \right]^{-1}$$

$$L_\star / L_\odot = b_1 \times z^{b_2} \quad (7)$$

and

$$\begin{aligned} \Phi_{\star,0} &= (1.22 \pm 0.20) \times 10^{-3} \\ z_0 &= 2.24 \pm 0.23 \\ a_1 &= \text{fixed} \\ a_2 &= 4.95 \pm 0.73 \\ b_1 &= (5.26 \pm 0.30) \times 10^{11} \\ b_2 &= 1.38 \pm 0.07, \end{aligned} \quad (8)$$

with a_1 fixed at 0.0 following [Casey et al. \(2018\)](#).

In the top panel of Figure 3 we present the redshift evolution of the characteristic number density, $\Phi_\star$, as a solid black line. The steep evolution found here, where $\log \Phi_\star \propto (1+z)^{-4.95}$ is close to the dust-poor model of [Casey et al. \(2018\)](#), who assumed $\log \Phi_\star \propto (1+z)^{-5.9}$. The redshift evolution of the characteristic luminosity, $L_\star$, is shown in the bottom panel of Figure 3 with a solid black line. The increasing evolution of $L_\star$ with redshift is consistent with the downsizing scenario ([Thomas et al. 2010](#)) in which the more luminous (and more massive) galaxies formed earlier than their fainter counterparts (this is also apparent in Figure 4).

In Figures 5 and 6, we present a comparison of our functional form of the IR LF with other data and their corresponding best-fit functions from the literature ([Magnelli et al. 2013](#); [Gruppioni et al. 2013](#); [Koprowski et al. 2017](#); [Casey et al. 2018](#); [Dudzevičiūtė et al. 2020](#); [Traina et al. 2024](#); [Fujimoto et al. 2024](#)). Figure 5 shows that our results agree (within the errors) with the majority of the studies shown here, with notable exceptions being the *Herschel*-selected samples from [Gruppioni et al. \(2013\)](#) and the inhomogeneous ALMA COSMOS data presented by [Traina et al. \(2024\)](#). Previous works include discussion of the discrepancies between submillimeter-selected and *Herschel*-selected samples (e.g., [Koprowski et al. 2017](#)), where the low-resolution *Herschel* data from [Gruppioni et al. \(2013\)](#) is affected by blending issues, which likely leads to an overestimation of the infrared luminosity values, where for the brightest *Herschel* sources the 250 μm flux may be overestimated by around 150% ([Scudder et al. 2016](#)) and is also prone to active galactic nucleus contamination. The ALMA data used in [Traina et al. \(2024\)](#) consists of the publicly available COSMOS data and is therefore

Table 3. Infrared luminosity comoving volume density for the bright end of the IR LF.

	$\log(\Phi/\text{Mpc}^{-3} \text{ dex}^{-1})$			
	$12.50 \leq \mathcal{L} < 12.75$	$12.75 \leq \mathcal{L} < 13.00$	$13.00 \leq \mathcal{L} < 13.25$	$13.25 \leq \mathcal{L} < 13.50$
$\bar{z} = 1.44$	$-6.02^{+0.46}_{-\text{inf}}$	$-6.01^{+0.34}_{-\text{inf}}$	...	...
$\bar{z} = 1.88$	...	$-5.61^{+0.20}_{-0.38}$	$-6.24^{+0.40}_{-\text{inf}}$	...
$\bar{z} = 2.59$	...	$-5.07^{+0.07}_{-0.08}$	$-5.98^{+0.24}_{-0.59}$	...
$\bar{z} = 4.14$	...	...	$-5.92^{+0.11}_{-0.15}$	$-6.82^{+0.34}_{-\text{inf}}$

Notes. $\mathcal{L} \equiv \log(L_{\text{IR}}/L_{\odot})$. Details are provided in Section 3.1.2.

Table 4. Schechter function (Equation (6)) best-fit parameters.

$\langle z \rangle$	$\log(\Phi_{\star}/\text{Mpc}^{-3} \text{ dex}^{-1})$	$\log(L_{\star}/L_{\odot})$
1.44	-2.98 ± 0.10	11.93 ± 0.05
1.88	-3.13 ± 0.11	12.13 ± 0.04
2.59	-3.33 ± 0.14	12.28 ± 0.05
4.14	-4.23 ± 0.16	12.55 ± 0.06

Notes. The values were calculated at the center value of each redshift bin studied in this work (see Section 3.1.3 for details).

inhomogeneous in terms of observing wavelength and depth. In addition, ALMA observations tend to target the most luminous IR sources, and hence, due to clustering, the IR LFs constructed from such data are likely biased toward larger number densities. Traina et al. (2024) aimed at fixing the clustering bias of their sample by excluding central sources in all of their ALMA pointings. However, the ALMA data, by selection, target relatively dense regions in the field, likely boosting the resulting values of the IR LF. The works of Magnelli et al. (2013) and Fujimoto et al. (2024) largely agree with our results (within errors), with the exception of the brightest L_{IR} bin at $z \sim 2$. In the case of Magnelli et al. (2013), the sample was selected at the *Herschel* PACS wavelength, with the *Herschel* fluxes affected by blending and the PACS selection bands likely contaminated by the active galactic nuclei. In the case of Fujimoto et al. (2024), the sample studied was based on the 180 dust continuum sources identified in 33 massive cluster fields and hence can also likely be biased toward larger number densities at the bright end. On the other hand, the 850 μm selection of this work will potentially miss low-dust mass, high-dust temperature sources. Although we tried to account for this effect in our completeness calculations, some sources with a low dust mass and relatively high dust temperature may still be missed in our sample.

In Figure 5 we also plot the results of Dudzevičiūtė et al. (2020) with green crosses, where the IR LF values were determined at IR luminosities above the limit corresponding to the S_{870} flux of 3.6 mJy and the median temperature of the AS2UDS sample of ~ 30 K without the requirement of at least one SPIRE detection. Since we assumed a more conservative dust temperature value of 37.3 K, we effectively limited our analysis to the most luminous IR bins (Section 3.1.2). As the submillimeter flux roughly traces the dust mass of the galaxies (M_d ; e.g., Dudzevičiūtė et al. 2020), our lower-limit IR luminosity bins will statistically miss a small fraction of sources with $\log(M_d/M_{\odot}) \sim 9.0$ ($S_{870} \sim 4$ mJy) and $T_d > 37.3$ K (increasing to higher dust temperatures at $z \gtrsim 4$ due to SPIRE detection requirement). Assuming a lower dust temperature produces less luminous IR lower limits, which become increasingly less complete. The small differences at the highest L_{IR}

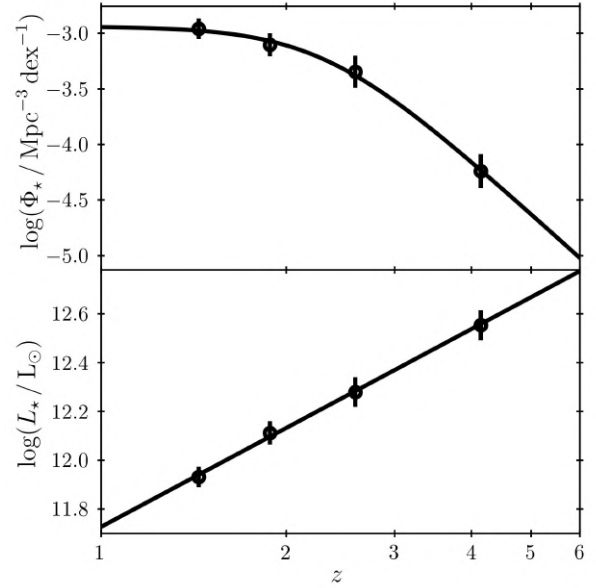


Fig. 3. Redshift evolution of the Schechter function parameters found in this work. The values determined at each redshift (Table 4) are shown as black points, with the best-fit functions (Equations (7) and (8)) depicted by black solid lines. (For details see Section 3.1.3.)

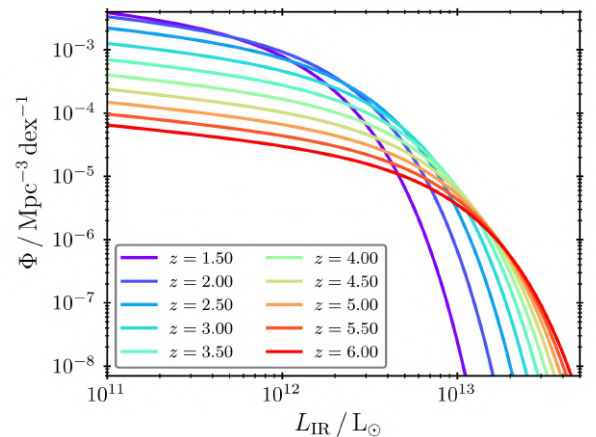


Fig. 4. Redshift evolution of the functional form of the IR LF found in this work (Equations (6), (7) and (8)).

bins between both works can mainly be attributed to the different redshift bins adopted but also to the fact that the sample used in Dudzevičiūtė et al. (2020) included sources without any *Herschel* SPIRE detections and did not adopt the completeness

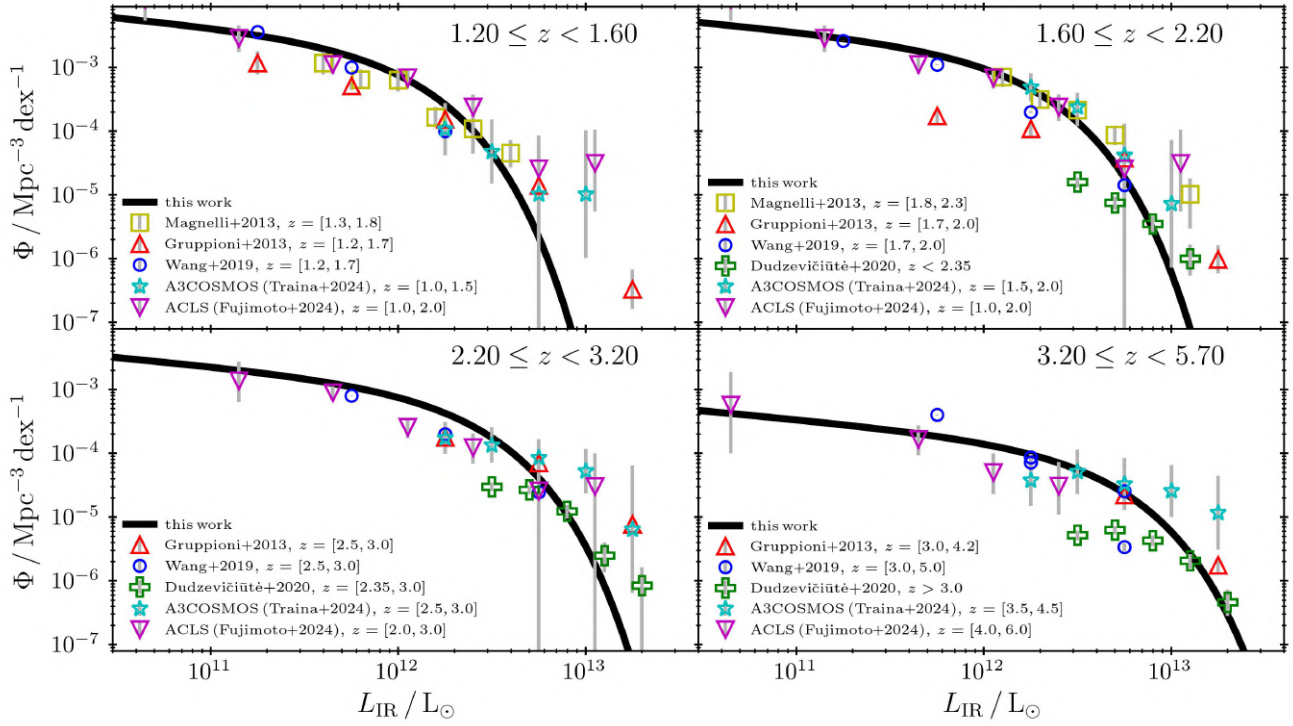


Fig. 5. Functional form of the infrared luminosity function found in this work (black solid line). For comparison we show the individual data found in other literature studies (Magnelli et al. 2013; Gruppioni et al. 2013; Wang et al. 2019; Dudzevičiūtė et al. 2020; Traina et al. 2024, and Fujimoto et al. 2024). (For a detailed discussion, see Section 3.1.3.)

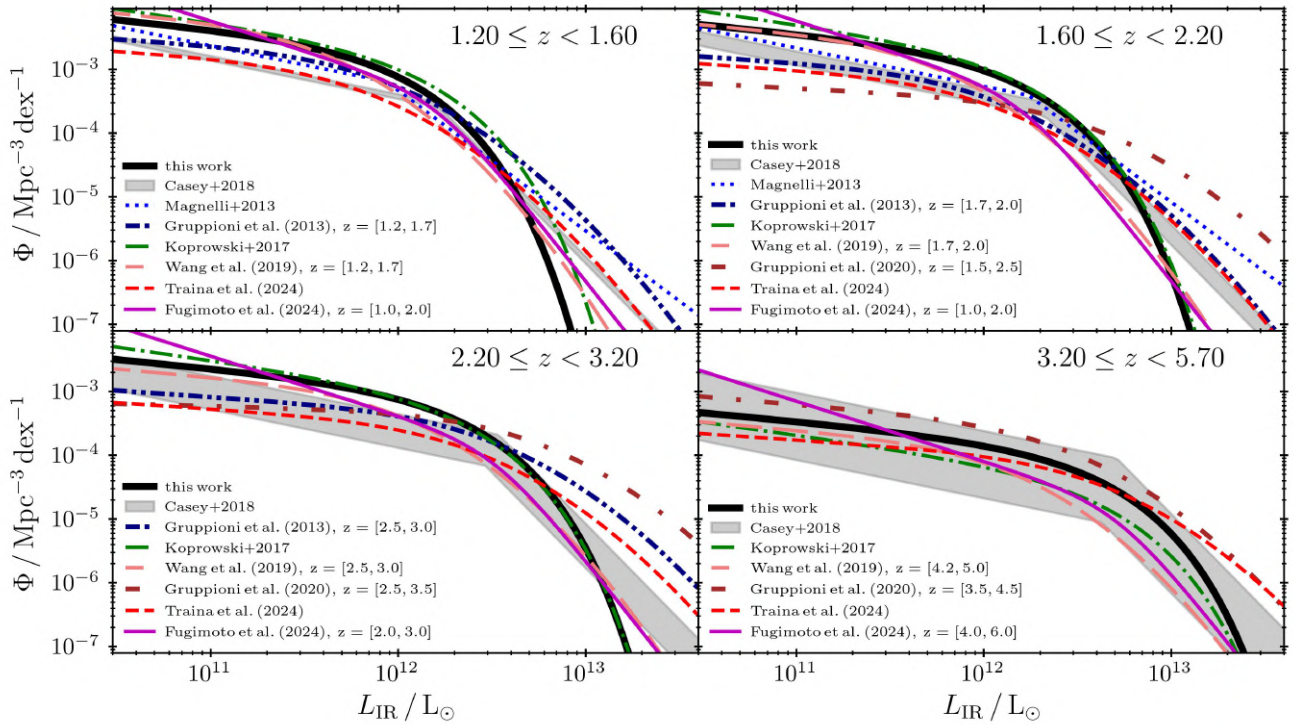


Fig. 6. Functional form of the infrared luminosity function found in this work (black solid line). Other IR LFs found in the literature are also shown for comparison (Magnelli et al. 2013; Gruppioni et al. 2013; Koprowski et al. 2017; Wang et al. 2019; Gruppioni et al. 2020; Traina et al. 2024, and Fujimoto et al. 2024). It can be seen that while at the faint end our results seem to be mostly consistent with other works (see Figure 5), the assumed value of the faint-end slope causes the corresponding functions to differ significantly. The shaded region represents the regime bounded at the bottom by the dust-poor models and at the top by the dust-rich models of the early Universe postulated by Casey et al. (2018). (For a detailed discussion, see Section 3.1.3.)

Table 5. Star formation rate density values at the redshift bins studied in this work.

z_{center}	$\log(\rho_{\text{SFR}}/\text{M}_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3})$
1.44	-1.04 ± 0.07
1.88	-0.98 ± 0.08
2.59	-1.07 ± 0.09
4.14	-1.71 ± 0.13

corrections of Equation (5) from the original SCUBA-2 sample of Geach et al. (2017).

The IR LF functional forms corresponding to the data from Figure 5 presented in Figure 6 show the impact of the assumed faint-end slope on the resulting form of the IR LF. Even though, as can be seen in Figure 5, the literature data are mostly consistent with our findings at the faint end, the assumed α impacts the resulting functional form significantly, which in turn slightly affects the corresponding values of the star formation rate density, ρ_{SFR} , which we discuss in the next subsection.

3.2. Cosmic star formation history

In order to find the comoving volume density of the IR luminosity, ρ_{IR} , at redshift z_i , we followed

$$\rho_{\text{IR}}(z_i) = \int_{\log(L_{\min})}^{\log(L_{\max})} \Phi(L, z_i) \times L \text{dlog}(L), \quad (9)$$

where Φ is the Schechter function of Equation (6), with the best-fit parameters at z_i listed in Table 4. Following previous works (e.g., Koprowski et al. 2017; Gruppioni et al. 2013; Traina et al. 2024), we integrate Equation (9) between $8.0 < \log(L_{\text{IR}}/L_{\odot}) < 14.0$. To find the star formation rate density, we then followed Kennicutt (1998):

$$\rho_{\text{SFR}} = \rho_{\text{IR}} \times \mathcal{K}_{\text{IR}} \times 0.63, \quad (10)$$

with $\mathcal{K}_{\text{IR}} = 1.73 \times 10^{-10} \text{ M}_{\odot} \text{ year}^{-1} L_{\odot}^{-1}$ and an additional multiplicative factor of 0.63 to convert from a Salpeter to a Chabrier IMF. The resulting values are summarized in Table 5 and depicted as red circles with error bars in Figure 7. The red solid line depicts the redshift evolution of the star formation rate density derived from the best-fit functions of Figure 3 between the redshifts considered in this work ($1.2 < z < 5.7$). In order to estimate the errors on ρ_{SFR} at each redshift listed in Table 4, we performed Monte Carlo simulations, where in each of the 1000 realizations, the IR luminosities and their corresponding IR LF values listed in Tables 1 and 3 were randomly sampled from a Gaussian distribution with the mean and the variance equal to the calculated values and their errors, respectively. In each of the realizations, the best-fit Schechter function was found (Equation (6)), and the corresponding ρ_{SFR} was determined following Equations (9) and 10. The final errors on ρ_{SFR} at each redshift were then taken to be equal to the standard deviations of all the individual values.

In the top panel of Figure 7, we compare our results with those presented in Dudzevičiūtė et al. (2020). The blue line (with 1σ errors represented by the shaded area) depicts the results presented in Dudzevičiūtė et al. (2020) down to the S_{870} flux limit of 3.6 mJy, while the orange line shows the derived values extrapolated down to the S_{870} flux limit of 1.0 mJy, where the ALMA number counts of Hatsukade et al. (2018) were used.

The green line gives the evolution of ρ_{SFR} found in this work down to the IR luminosity detection limits of our IR faint sample presented in Section 3.1.1 (Table 1), and the red circles with 1σ error bars represent the integrated values down to $\log(L_{\text{IR}}/L_{\odot}) = 8.0$, with the red solid line produced from the evolution of the best-fit Schechter function parameters, presented in Section 3.1.3. The increasing values of ρ_{SFR} at $z \lesssim 3$ for each of the samples are simply a consequence of different lower L_{IR} limits adopted, where S_{870} fluxes from Dudzevičiūtė et al. (2020) of 3.6 and 1.0 mJy correspond to a $\log(L_{\text{IR}}/L_{\odot})$ of ~ 12.4 and ~ 11.7 , respectively. For the sample of this work represented by the green line in the figure, the IR LF lower limit is set to a $\log(L_{\text{IR}}/L_{\odot})$ of ~ 10.9 at $z \sim 1.4$, rising to ~ 12.0 at $z > 4$ (Table 1), while the red circles were produced by integrating the best-fit Schechter functions down to $\log(L_{\text{IR}}/L_{\odot}) = 8.0$. Interestingly, the differences in the derived ρ_{SFR} values for each sample decrease toward higher redshifts, which indicates the growing contribution of the most IR luminous sources to the total star formation rate density toward earlier epochs (which is also apparent in Figure 4).

In the bottom panel of Figure 7, we compare our findings with a range of recent results from the literature, where whenever possible, the conversion from L_{IR} to SFR was recalibrated using Equation (10). It can be seen that the numbers found in this work are in a good agreement with those determined in Dunlop et al. (2017), Wang et al. (2019), Magnelli et al. (2024), and Liu et al. (2026). In the case of Dunlop et al. (2017) and Liu et al. (2026), the cosmic star formation rate density was derived from individual ALMA detections. In order to account for sources that went undetected by ALMA, Dunlop et al. (2017) performed stacking down to the stellar mass limit of $\sim 10^{9.3} \text{ M}_{\odot}$, while Liu et al. (2026) included the contribution from the ALMA-undetected galaxies down to $M_{*} > 10^{10} \text{ M}_{\odot}$. Magnelli et al. (2024) estimated the ρ_{SFR} at $z \sim 4.5$ by uv -plane stacking COSMOS sources in the available ALMA data down to $M_{*} = 10^{9.5} \text{ M}_{\odot}$. These lower limits are consistent with the recent findings in which no dust was detected in high-redshift galaxies with stellar masses below $M_{*} \sim 10^{9.5} \text{ M}_{\odot}$ (e.g., Pannella et al. 2015; McLure et al. 2018; Koprowski et al. 2018).

It can also be seen in Figure 7 that our results are somewhat lower than those of Traina et al. (2024), Fujimoto et al. (2024), Sun et al. (2025) and significantly lower than the results found in Rowan-Robinson et al. (2016) and Gruppioni et al. (2020) at $z \gtrsim 3$. At high redshifts, the selected 350 μm and 500 μm *Herschel* sample of Rowan-Robinson et al. (2016) consists only of the sources with the most extreme S/N ($S/N > 5$), and the sources have IR luminosities considerably higher than the knee of the corresponding LF. Gruppioni et al. (2020), as can be seen in Figure 6, predicts bright-end number densities that are significantly larger than what was found in this work. In fact, their IR LF suggests approximately ten times more sources at the bright end than what is predicted by the somewhat extreme case of the dust-rich early Universe scenario of Casey et al. (2018).

The shaded region in Figure 7 depicts the ρ_{SFR} theoretical regime bounded from the bottom by the dust-poor scenario and from the top by the dust-rich scenario of the early Universe, as calibrated by Casey et al. (2018). In the dust-poor model, the UV-bright sources (dotted blue line in Figure 7; Dunlop 2016) dominate star formation at $z \gtrsim 3.5$, where the dust-formation timescale, driven primarily by asymptotic giant branch (AGB) stars and supernovae, is expected to be longer than the time it takes to form the first UV-bright galaxies. The dust-rich model, on the other hand, predicts the cosmic star formation to be dominated by the dusty star forming galaxies between $1.5 < z < 6.5$.

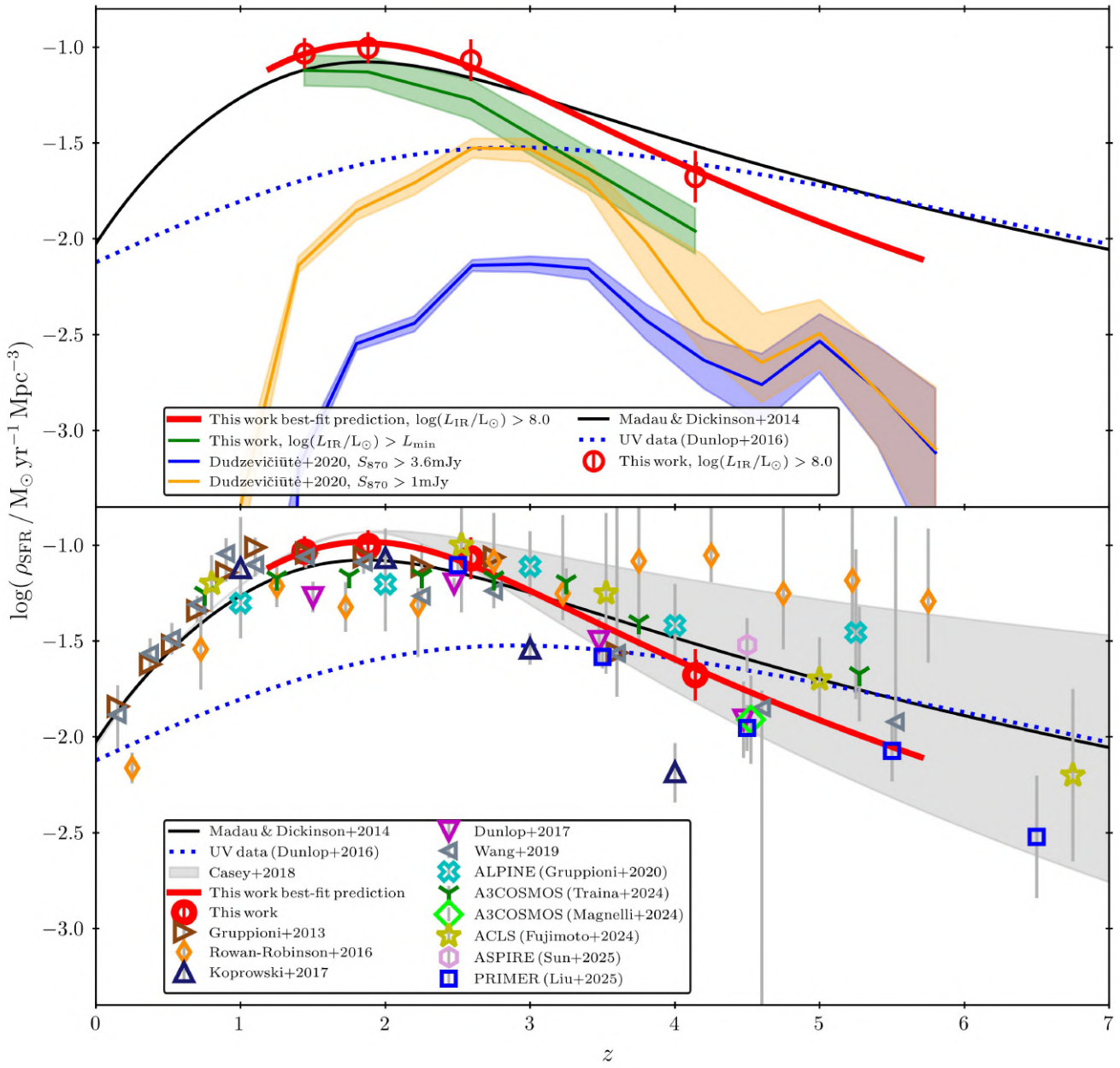


Fig. 7. Star formation rate density for four redshift bins studied in this work (Table 5), depicted with red circles with error bars, found by integrating the corresponding IR LFs between $8.0 < L_{\text{IR}}/L_{\odot} < 14.0$. The solid red line represents the redshift evolution of the star formation rate density derived from the best fits to the Schechter function parameters of Figure 3 between redshifts considered in this work ($1.2 < z < 5.7$). The solid black line represents the IR ρ_{SFR} evolution found in Madau & Dickinson (2014), while the dotted blue line shows the evolution of the UV ρ_{SFR} of Dunlop (2016). *Top:* Comparison of our results with those presented in Dudzevičiūtė et al. (2020), where the blue and orange lines depict the contribution to ρ_{SFR} from 870 μm sources above 3.6 mJy and 1.0 mJy (extrapolated using ALMA number counts of Hatsukade et al. 2018), respectively. The shaded areas represent 1σ errors. The green line shows the evolution down to the IR luminosity detection limits of our IR faint sample presented in Section 3.1.1. The differences in the derived values of the ρ_{SFR} at a specific redshift across the samples arise from the different L_{IR} limits adopted (see Section 3.2). At $z \gtrsim 4$, these differences decrease, which can be attributed to the growing contribution of bright submillimeter galaxies to the ρ_{SFR} . *Bottom:* Comparison of ρ_{SFR} found in this work with the most recent results from the literature plotted with color symbols (Gruppioni et al. 2013; Rowan-Robinson et al. 2016; Koprowski et al. 2017; Dunlop et al. 2017; Wang et al. 2019; Gruppioni et al. 2020; Traina et al. 2024; Magnelli et al. 2024; Fujimoto et al. 2024; Sun et al. 2025; Liu et al. 2026). The shaded region shows the results of Casey et al. (2018) bounded at the bottom by the dust-poor models and at the top by the dust-rich models of the early Universe. It can be seen that our results are in a good agreement with the results of Dunlop et al. (2017), Wang et al. (2019), Magnelli et al. (2024), and Liu et al. (2026). Also, some inconsistencies with other works are apparent, the discussion of which is presented in Section 3.2. Considering the shaded region of Casey et al. (2018), it can be seen that the results of this work point toward the dust-poor early Universe scenario, where the IR sources are expected to dominate the total ρ_{SFR} out to $z \sim 4$.

As noted by Casey et al. (2018), the dust-rich model is somewhat extreme, as very few DSFGs have been found at $z \gtrsim 5$, mainly due to observational limitations (see Casey et al. 2014 for details). Indeed, from Figure 7 it can be seen that the IR LF found in this work predicts number densities of DSFGs that are similar to the dust-poor model and consistent with the low-detection rates at high redshifts, placing our results in a dust-poor early Universe regime, where the IR sources seem to dominate the star formation rate density at least out to $z \sim 4$.

4. Summary

We have probed the low-luminosity regime of the IR luminosity function out to $z = 5.7$ by stacking the optical/near-IR catalogs of McLeod et al. (2021) in the FIR *Herschel* and JCMT maps, using stellar mass as a proxy, where the $L_{\text{IR}}-M_*$ relationship of Koprowski et al. (2024) was used. Together with the ALMA follow-up data of the S2CLS UKIDSS UDS sources (AS2UDS; Stach et al. 2019; Dudzevičiūtė et al. 2020), we have established the evolution of the functional form of IR LF between redshifts 1.2 and 5.7. We fit the data at four redshift bins (Table 4) with the Schechter function of Equation (6), and we established a value of the faint-end slope; the redshift evolution of the characteristic luminosity, L_* ; and the characteristic number density, Φ_* . By integrating the best-fit functions, we have determined the values of the comoving volume density of star formation, ρ_{SFR} . The main results of this work can be summarized as follows:

1. The faint end of the IR luminosity function values of $\alpha = -0.26 \pm 0.11$ and -0.23 ± 0.18 were determined at two low-redshift bins of $1.2 \leq z < 1.6$ and $1.6 \leq z < 2.2$, respectively, and the more accurate $1.2 \leq z < 1.6$ value of -0.26 was adopted at all remaining redshift bins. The characteristic number density at $z \gtrsim 2$ is a steeply declining function of redshift, where $\Phi_* \propto z^{-4.95}$, and it is very similar to the predicted evolution for the dust-poor model of the early Universe investigated in Casey et al. (2018). The redshift evolution of the characteristic luminosity was found to be a power-law function, where $L_* \propto z^{1.38}$, supporting the downsizing scenario (Thomas et al. 2010), where most luminous galaxies form before their less luminous counterparts.
2. When comparing the functional form of the IR LF with the results from the recent literature, we found our faint-end slope to be in agreement with most of other calibrations. At the bright end, we predict relatively small number densities of sources, which aligns with recent studies struggling to detect high-redshift galaxies in the FIR (Dunlop et al. 2017; Aravena et al. 2020). A small number of previous studies found significantly more high- L_{IR} sources, which we attribute to the low resolution of the FIR observations and/or the methodology adopted when dealing with inhomogeneous FIR samples.
3. Finally, the redshift evolution of the star formation rate density, ρ_{SFR} , was established by integrating the corresponding IR LFs at the four redshift bins investigated in this work. The resulting ρ_{SFR} peaks at $z \simeq 2$ and later declines with redshift from $z \sim 2$ out to $z \sim 6$, with the high-redshift values significantly lower than those presented in Madau & Dickinson (2014). Our data are in very good agreement with the recent works of Dunlop et al. (2017), Wang et al. (2019), Magnelli et al. (2024), and Liu et al. (2026), but they are somewhat below the numbers derived in Traina et al. (2024), Fujimoto et al. (2024) and Sun et al. (2025). The most striking differences are between our results and those established by Rowan-Robinson et al. (2016) and Gruppioni et al. (2020), who significantly larger number densities have been found at the bright end. Considering the two extreme cases of a dust-rich and a dust-poor early Universe presented in Casey et al. (2018), the ρ_{SFR} redshift evolution found in this work places our findings in the dust-poor scenario, where we predict that the IR sources will dominate the total density of star formation in the Universe out to $z \sim 4$.

Acknowledgements. This research was funded in whole or in part by the National Science Center, Poland (grants no. 2020/39/D/ST9/03078, 2023/51/B/ST9/01479, 2023/49/B/ST9/00066 and 2024/53/N/ST9/00350). For the purpose of Open Access, the author has applied a CC-BY public copyright license to any Author Accepted Manuscript (AAM) version arising from this submission. JSD and DJM acknowledge the support of the Royal Society through a Research Professorship awarded to JSD. KL acknowledges the support of the National Science Centre, Poland, through the PRELUDIUM grant UMO-2023/49/N/ST9/00746. Supported by the Foundation for Polish Science (FNP).

References

- Adscheid, S., Magnelli, B., Liu, D., et al. 2024, *A&A*, **685**, A1
 Aravena, M., Boogaard, L., González-López, J., et al. 2020, *ApJ*, **901**, 79
 Barrufet, L., Dunlop, J. S., Begley, R., et al. 2025, *ArXiv e-prints* [arXiv:2508.05740]
 Battisti, A. J., da Cunha, E., Grasha, K., et al. 2019, *ApJ*, **882**, 61
 Bouwens, R. J., Bradley, L., Zitrin, A., et al. 2014, *ApJ*, **795**, 126
 Bouwens, R., González-López, J., Aravena, M., et al. 2020, *ApJ*, **902**, 112
 Bouwens, R. J., Oesch, P. A., Stefanon, M., et al. 2021, *AJ*, **162**, 47
 Bruzual, G., & Charlot, S. 2003, *MNRAS*, **344**, 1000
 Caputi, K. I., Lagache, G., Yan, L., et al. 2007, *ApJ*, **660**, 97
 Casey, C. M., Narayanan, D., & Cooray, A. 2014, *Phys. Rep.*, **541**, 45
 Casey, C. M., Zavala, J. A., Spilker, J., et al. 2018, *ApJ*, **862**, 77
 Chabrier, G. 2003, *PASP*, **115**, 763
 Chapman, S. C., Blain, A. W., Smail, I., & Ivison, R. J. 2005, *ApJ*, **622**, 772
 Charlot, S., & Fall, S. M. 2000, *ApJ*, **539**, 718
 da Cunha, E., Walter, F., Smail, I. R., et al. 2015, *ApJ*, **806**, 110
 Daddi, E., Delvecchio, I., Dimauro, P., et al. 2022, *A&A*, **661**, L7
 Geach, J. E., Dunlop, J. S., Halpern, M., et al. 2017, *MNRAS*, **465**, 1789
 Griffin, M. J., Abergel, A., Abreu, A., et al. 2010, *A&A*, **518**, L3
 Gruppioni, C., Pozzi, F., Rodighiero, G., et al. 2013, *MNRAS*, **432**, 23
 Gruppioni, C., Béthermin, M., Loiacono, F., et al. 2020, *A&A*, **643**, A8
 Harikane, Y., Nakajima, K., Ouchi, M., et al. 2024, *ApJ*, **960**, 56
 Hatsukade, B., Kohno, K., Yamaguchi, Y., et al. 2018, *PASJ*, **70**, 105
 Hauser, M. G., Arendt, R. G., Kelsall, T., et al. 1998, *ApJ*, **508**, 25
 Hughes, D. H., Serjeant, S., Dunlop, J., et al. 1998, *Nature*, **394**, 241
 Kennicutt, R. C., Jr 1998, *ApJ*, **498**, 541
 Koprowski, M. P., Dunlop, J. S., Michałowski, M. J., et al. 2016, *MNRAS*, **458**, 4321
 Koprowski, M. P., Dunlop, J. S., Michałowski, M. J., et al. 2017, *MNRAS*, **471**, 4155
 Koprowski, M. P., Coppin, K. E. K., Geach, J. E., et al. 2018, *MNRAS*, **479**, 4355
 Koprowski, M. P., Wijesekera, J. V., Dunlop, J. S., et al. 2024, *A&A*, **691**, A164
 Laporte, N., Infante, L., Troncoso Iribarren, P., et al. 2016, *ApJ*, **820**, 98
 Le Floch, E., Papovich, C., Dole, H., et al. 2005, *ApJ*, **632**, 169
 Lee, N., Sanders, D. B., Casey, C. M., et al. 2015, *ApJ*, **801**, 80
 Liu, D., Lang, P., Magnelli, B., et al. 2019, *ApJS*, **244**, 40
 Liu, F. Y., Dunlop, J. S., McLure, R. J., et al. 2026, *MNRAS*, **545**, staf1961
 Lutz, D., Poglitsch, A., Altieri, B., et al. 2011, *A&A*, **532**, A90
 Madau, P., & Dickinson, M. 2014, *ARA&A*, **52**, 415
 Magnelli, B., Popesso, P., Berta, S., et al. 2013, *A&A*, **553**, A132
 Magnelli, B., Adscheid, S., Wang, T.-M., et al. 2024, *A&A*, **688**, A55
 McLeod, D. J., McLure, R. J., Dunlop, J. S., et al. 2021, *MNRAS*, **503**, 4413
 McLeod, D. J., Donnan, C. T., McLure, R. J., et al. 2024, *MNRAS*, **527**, 5004
 McLure, R. J., Dunlop, J. S., Cullen, F., et al. 2018, *MNRAS*, **476**, 3991
 Michałowski, M. J., Dunlop, J. S., Koprowski, M. P., et al. 2017, *MNRAS*, **469**, 492
 Oliver, S. J., Bock, J., Altieri, B., et al. 2012, *MNRAS*, **424**, 1614

- Pannella, M., Elbaz, D., Daddi, E., et al. 2015, [ApJ](#), **807**, 141
- Patel, H., Clements, D. L., Vaccari, M., et al. 2013, [MNRAS](#), **428**, 291
- Pilbratt, G. L., Riedinger, J. R., Passvogel, T., et al. 2010, [A&A](#), **518**, L1
- Poglitsch, A., Waelkens, C., Geis, N., et al. 2010, [A&A](#), **518**, L2
- Popesso, P., Concas, A., Cresci, G., et al. 2023, [MNRAS](#), **519**, 1526
- Puget, J. L., Abergel, A., Bernard, J. P., et al. 1996, [A&A](#), **308**, L5
- Rodighiero, G., Vaccari, M., Franceschini, A., et al. 2010, [A&A](#), **515**, A8
- Rowan-Robinson, M., Oliver, S., Wang, L., et al. 2016, [MNRAS](#), **461**, 1100
- Saunders, W., Rowan-Robinson, M., Lawrence, A., et al. 1990, [MNRAS](#), **242**, 318
- Schmidt, M. 1968, [ApJ](#), **151**, 393
- Scudder, J. M., Oliver, S., Hurley, P. D., et al. 2016, [MNRAS](#), **460**, 1119
- Smail, I., Ivison, R. J., & Blain, A. W. 1997, [ApJ](#), **490**, L5
- Speagle, J. S., Steinhardt, C. L., Capak, P. L., & Silverman, J. D. 2014, [ApJS](#), **214**, 15
- Stach, S. M., Dudzevičiūtė, U., Smail, I., et al. 2019, [MNRAS](#), **487**, 4648
- Sun, F., Wang, F., Yang, J., et al. 2025, [ApJ](#), **980**, 12
- Swinbank, A. M., Simpson, J. M., Smail, I., et al. 2014, [MNRAS](#), **438**, 1267
- Thomas, D., Maraston, C., Schawinski, K., Sarzi, M., & Silk, J. 2010, [MNRAS](#), **404**, 1775
- Tomczak, A. R., Quadri, R. F., Tran, K.-V. H., et al. 2016, [ApJ](#), **817**, 118
- Traina, A., Gruppioni, C., Delvecchio, I., et al. 2024, [A&A](#), **681**, A118
- Walter, F., Decarli, R., Aravena, M., et al. 2016, [ApJ](#), **833**, 67
- Wang, L., Pearson, W. J., Cowley, W., et al. 2019, [A&A](#), **624**, A98

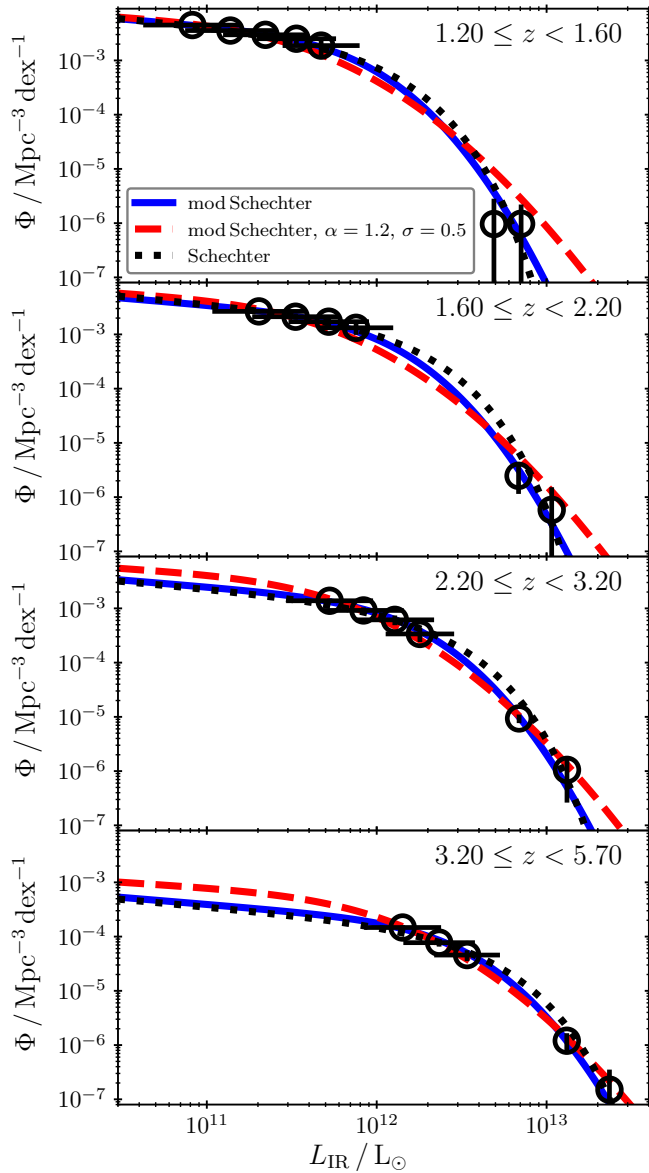


Fig. A.1. Infrared LF binned data of Figure 2 (black circles with error bars) with the best-fit functional forms overlaid. The modified Schechter fits with α and σ parameters (Equation A.1) allowed to vary freely are depicted with blue solid line. Fixing α and σ at the recent literature values of -0.2 and 0.5 , respectively (Gruppioni et al. 2013; Wang et al. 2019; Gruppioni et al. 2020; Traina et al. 2024), produces the modified Schechter function presented with the red dashed line, while the best-fit classical Schechter curve (Equation 6) derived in this work is shown with the black dotted line.

Appendix A: Modified-Schechter fits

Since a number of recent works have adopted a modified version of the Schechter function (e.g., Gruppioni et al. 2013; Wang et al. 2019; Gruppioni et al. 2020; Traina et al. 2024), in this appendix we present an alternative IR LF functional fits and the corresponding star formation rate density calculations following the original work of Saunders et al. (1990), where

$$\Phi(L) = \Phi_* \left(\frac{L}{L_*} \right)^\alpha \exp \left[-\frac{1}{2\sigma^2} \log_{10}^2 \left(1 + \frac{L}{L_*} \right) \right]. \quad (\text{A.1})$$

The free parameters Φ_* and L_* mark the so-called knee of the luminosity function, with $L \ll L_*$ behaving as a power-

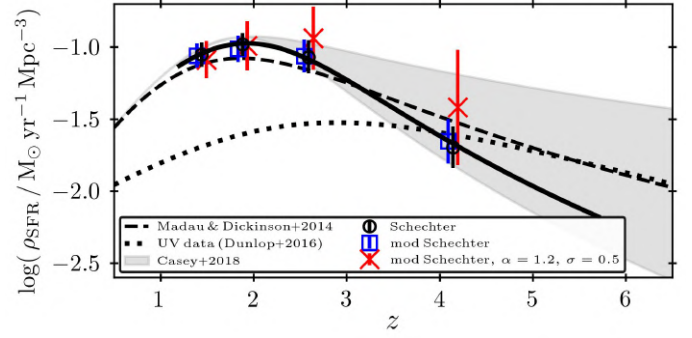


Fig. A.2. Star formation rate density found by integrating the best-fit curves of Figure A.1 between $8.0 < L_{\text{IR}}/L_{\odot} < 14.0$. Similarly to Figure 7, the black solid line represents the IR ρ_{SFR} evolution found in Madau & Dickinson (2014), while the blue dotted line shows the evolution of the UV ρ_{SFR} of Dunlop (2016). The shaded region shows the results of Casey et al. (2018), bounded at the bottom by the dust-poor models and at the top by the dust-rich models of the early Universe. The black circles with the solid curve represent this work's results found in Section 3.2. Values of ρ_{SFR} corresponding to the modified Schechter fits (Equation A.1) with the best-fit α and σ parameters of -0.26 and 0.31 , respectively, are shown with blue squares. Data found from modified Schechter fits with α and σ fixed at recent literature $z \ll 1$ values of -0.2 and 0.5 , respectively, are depicted with red crosses. It can be seen that, while using the modified Schechter function with all the parameters allowed to vary freely produces results almost identical to the classical Schechter results of this work, setting α and σ at the $z \ll 1$ best-fit values if Gruppioni et al. (2013), produces significantly larger numbers at highest redshift bins.

law and $L \gg L_*$ following a Gaussian curve. This function has proven to be useful, since it allows the control of the shape of the bright-end portion of the curve through the σ parameter. While the classical Schechter function adopted in this work does not require any modifications at the bright end, it is interesting to investigate whether the modified version produces different results in terms of ρ_{SFR} . In most of the high-redshift studies (e.g., Gruppioni et al. 2013; Wang et al. 2019; Gruppioni et al. 2020; Traina et al. 2024), both α and σ are fixed at $z \ll 1$ best-fit values of -0.2 and 0.5 , respectively. In Figure A.1 we show the binned data of Figure 2 with black circles with the best-fit classical Schechter function found in this work depicted with black dotted lines. The modified Schechter fits, where α and σ are fixed at -0.2 and 0.5 , respectively, are presented with red dashed lines, while the similar fits with α and σ set as free parameters are shown with blue solid lines. It can be seen that fixing α and σ at $z \ll 1$ values produces very poor fits at two lowest redshift bins, where the faint-end portion of the curve is best traced by the data. Allowing those parameters to vary (blue solid lines in Figure A.1) given significantly better fits, with the best-fit values of $\alpha = -0.26$ and $\sigma = 0.31$.

The corresponding star formation rate densities are shown in Figure A.2, with the black circles and the solid black line representing the results of this work presented in Section 3.2. The blue squares, showing the ρ_{SFR} values derived from the modified Schechter fits with α and σ set as free parameters (blue solid lines in Figure A.1), are in an excellent agreement with the classical Schechter fits adopted in this work, while the data corresponding to the $z \ll 1$ low-resolution *Herschel* modified Schechter parameters found in Gruppioni et al. (2013), give significantly higher values of ρ_{SFR} at high-redshift bins.

Appendix B: Additional table

Table B.1. $L_{\text{IR}}/L_{\odot}$ stacking results.

	$0.45 \leq z < 0.60$	$0.60 \leq z < 0.75$	$0.75 \leq z < 1.00$	$1.00 \leq z < 1.25$	$1.25 \leq z < 1.60$	$1.60 \leq z < 2.20$	$2.20 \leq z < 3.20$	$3.20 \leq z < 5.70$
	$\log(L_{\text{IR}}/L_{\odot})$	$\log(L_{\text{IR}}/L_{\odot})$	$\log(L_{\text{IR}}/L_{\odot})$	$\log(L_{\text{IR}}/L_{\odot})$	$\log(L_{\text{IR}}/L_{\odot})$	$\log(L_{\text{IR}}/L_{\odot})$	$\log(L_{\text{IR}}/L_{\odot})$	$\log(L_{\text{IR}}/L_{\odot})$
$9.25 \leq M < 9.50$	10.04 ± 0.07	10.29 ± 0.07	10.38 ± 0.08	10.56 ± 0.07	10.93 ± 0.07			
$9.50 \leq M < 9.75$	10.29 ± 0.06	10.55 ± 0.06	10.63 ± 0.06	10.80 ± 0.06	11.20 ± 0.06			
$9.75 \leq M < 10.00$	10.56 ± 0.06	10.77 ± 0.06	10.89 ± 0.06	10.99 ± 0.06	11.37 ± 0.06			
$10.00 \leq M < 10.25$	10.69 ± 0.06	10.93 ± 0.06	11.09 ± 0.05	11.19 ± 0.05	11.54 ± 0.05	11.52 ± 0.06	11.70 ± 0.06	
$10.25 \leq M < 10.50$	10.84 ± 0.05	11.01 ± 0.06	11.21 ± 0.05	11.37 ± 0.05	11.67 ± 0.05	11.72 ± 0.05	11.82 ± 0.05	12.26 ± 0.08
$10.50 \leq M < 10.75$	10.84 ± 0.06	11.14 ± 0.06	11.33 ± 0.05	11.48 ± 0.05	11.73 ± 0.06	11.80 ± 0.05	12.00 ± 0.06	12.36 ± 0.10
$10.75 \leq M < 11.00$	11.09 ± 0.06	11.19 ± 0.06	11.34 ± 0.06	11.59 ± 0.06	11.73 ± 0.06	11.98 ± 0.06	12.18 ± 0.06	12.48 ± 0.09
$11.00 \leq M < 11.25$	11.04 ± 0.12	11.25 ± 0.09	11.51 ± 0.08	11.61 ± 0.07	11.88 ± 0.07	12.06 ± 0.06	12.38 ± 0.06	12.72 ± 0.08
$11.25 \leq M < 11.50$	–	11.13 ± 0.38	11.45 ± 0.15	11.82 ± 0.10	–	12.37 ± 0.08	12.51 ± 0.10	12.84 ± 0.09
	N of sources	N of sources	N of sources	N of sources	N of sources	N of sources	N of sources	N of sources
$9.25 \leq M < 9.50$	1287 ± 36	1868 ± 40	3983 ± 56	4647 ± 69	4347 ± 63			
$9.50 \leq M < 9.75$	1033 ± 32	1415 ± 37	2967 ± 51	3378 ± 51	3237 ± 56			
$9.75 \leq M < 10.00$	769 ± 26	983 ± 27	2172 ± 46	2503 ± 49	2442 ± 55	4259 ± 61		
$10.00 \leq M < 10.25$	507 ± 22	719 ± 24	1637 ± 40	1916 ± 44	1768 ± 39	3137 ± 58	3691 ± 55	825 ± 31
$10.25 \leq M < 10.50$	351 ± 20	437 ± 20	1084 ± 32	1371 ± 38	1050 ± 33	2237 ± 48	2216 ± 46	384 ± 19
$10.50 \leq M < 10.75$	138 ± 11	223 ± 13	554 ± 23	714 ± 25	388 ± 20	1424 ± 37	1273 ± 37	189 ± 13
$10.75 \leq M < 11.00$	47 ± 6	82 ± 9	150 ± 12	278 ± 16	86 ± 9	646 ± 23	558 ± 24	68 ± 9
$11.00 \leq M < 11.25$	7 ± 2	9 ± 3	22 ± 5	56 ± 8	–	154 ± 12	153 ± 13	21 ± 5
$11.25 \leq M < 11.50$	–	2 ± 1	2 ± 1	8 ± 3	–	14 ± 3	14 ± 3	

Notes. Stacked results for star-forming galaxies between redshifts 0.45 and 5.7 (top panel) with the number of stacked optical/near-IR sources in each bin (bottom panel). The first column lists the mass bins, where $M \equiv \log_{10}(M_*/M_{\odot})$.

Co-author contribution statements

1.10 Article A

Charting the main sequence of star-forming galaxies
out to redshifts $z \lesssim 5.7$

Toruń, March 2, 2026

dr hab. Maciej Koprowski
Institute of Astronomy
Faculty of Physics, Astronomy and Informatics
Nicolaus Copernicus University
Gagarina 11
87-100 Toruń, Poland

**Astronomy Discipline Council
Nicolaus Copernicus University
Toruń**

Author contribution statement

I hereby declare that my contribution to the work:

'Charting the main sequence of star-forming galaxies out to redshifts $z \leq 5.7$ '

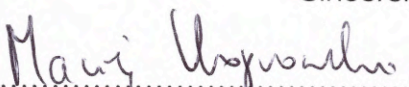
A&A, Volume 691, November 2024, A164

consisted of:

- conducting the follow-up analysis of the stacked main sequence of galaxies,
- directing the work during the project and writing most of the paper,

constituting 65% of the total workload.

Sincerely,


.....
dr hab. Maciej Koprowski

Toruń, March 2, 2026

mgr Jude Vijayanga Wijesekera
Institute of Astronomy
Faculty of Physics, Astronomy and Informatics
Nicolaus Copernicus University
Gagarina 11
87-100 Toruń, Poland

**Astronomy Discipline Council
Nicolaus Copernicus University
Toruń**

Author contribution statement

I hereby declare that my contribution to the work:

'Charting the main sequence of star-forming galaxies out to redshifts $z \leq 5.7$ '

A&A, Volume 691, November 2024, A164

consisted of:

- stacking galaxies' sample in FIR maps and deriving the main sequence,
- writing the corresponding part of the paper,

constituting 15% of the total workload.

Sincerely,



.....
mgr Jude Vijayanga Wijesekera

Toruń, March 2, 2026

Prof. James Dunlop
School of Physics and Astronomy
University of Edinburgh
Blackford Hill, Edinburgh EH9 3HJ, UK

**Astronomy Discipline Council
Nicolaus Copernicus University
Toruń**

Author contribution statement

I hereby declare that my contribution to the work:

'Charting the main sequence of star-forming galaxies out to redshifts $z \lesssim 5.7$ '

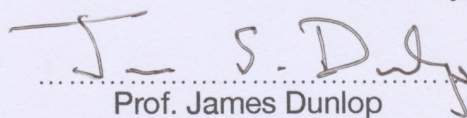
A&A, Volume 691, November 2024, A164

consisted of:

- helping with addressing the issues raised during the project,
- providing useful comments,

constituting 5% of the total workload.

Sincerely,


Prof. James Dunlop

Toruń, March 2, 2026

Dr. Derek McLeod
School of Physics and Astronomy
University of Edinburgh
Blackford Hill, Edinburgh EH9 3HJ, UK

**Astronomy Discipline Council
Nicolaus Copernicus University
Toruń**

Author contribution statement

I hereby declare that my contribution to the work:

'Charting the main sequence of star-forming galaxies out to redshifts $z \leq 5.7$ '

A&A, Volume 691, November 2024, A164

consisted of:

- provision of multi-wavelength/SED-fitted catalogues,
- addressing the issues raised during the project,
- helping with the text,

constituting 10% of the total workload.

Sincerely,



Dr. Derek McLeod

Toruń, March 2, 2026

dr hab. Michał Michałowski
Instytut Obserwatorium Astronomiczne
Wydział Fizyki
Uniwersytet im. Adam Mickiewicz w Poznaniu
ul. Słoneczna 36
60-286 Poznań, Polska

**Astronomy Discipline Council
Nicolaus Copernicus University
Toruń**

Author contribution statement

I hereby declare that my contribution to the work:

'Charting the main sequence of star-forming galaxies out to redshifts $z \lesssim 5.7$ '

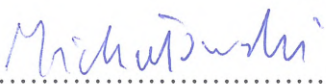
A&A, Volume 691, November 2024, A164

consisted of:

- helping with addressing the issues raised during the project,
- providing useful comments,

constituting 5% of the total workload.

Sincerely,


.....
dr hab. Michał Michałowski

1.11 Article B

Evolution of dust attenuation in star-forming galaxies with UV slope, stellar mass, and redshift out to $z \sim 5$

Toruń, March 2, 2026

mgr Jude Vijayanga Wijesekera
Institute of Astronomy
Faculty of Physics, Astronomy and Informatics
Nicolaus Copernicus University
Gagarina 11
87-100 Toruń, Poland

**Astronomy Discipline Council
Nicolaus Copernicus University
Toruń**

Author contribution statement

I hereby declare that my contribution to the work:

'Evolution of dust attenuation in star-forming galaxies with UV slope, stellar mass, and
redshift out to $z \sim 5$ '

arXiv:2602.04765, submitted to A&A

consisted of:

- conducting most of the analysis - stacking the IRX values in FIR maps and deriving functional forms of the IRX-beta and mass relations,
- directing the work during the project and writing large parts of the paper,

constituting 50% of the total workload.

Sincerely,



.....
mgr Jude Vijayanga Wijesekera

Toruń, March 2, 2026

dr hab. Maciej Koprowski
Institute of Astronomy
Faculty of Physics, Astronomy and Informatics
Nicolaus Copernicus University
Gagarina 11
87-100 Toruń, Poland

**Astronomy Discipline Council
Nicolaus Copernicus University
Toruń**

Author contribution statement

I hereby declare that my contribution to the work:

'Evolution of dust attenuation in star-forming galaxies with UV slope, stellar mass, and
redshift out to $z \sim 5$ '

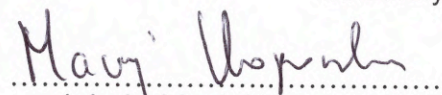
arXiv:2602.04765, submitted to A&A

consisted of:

- helping with the analysis and with the interpretation of the results,
- helping with the final writing of the introduction and discussion parts of the paper,

constituting 30% of the total workload.

Sincerely,


.....
dr hab. Maciej Koprowski

Toruń, March 2, 2026

Prof. James Dunlop
School of Physics and Astronomy
University of Edinburgh
Blackford Hill, Edinburgh EH9 3HJ, UK

Astronomy Discipline Council
Nicolaus Copernicus University
Toruń

Author contribution statement

I hereby declare that my contribution to the work:

'Evolution of dust attenuation in star-forming galaxies with UV slope, stellar mass, and
redshift out to $z \sim 5$ '

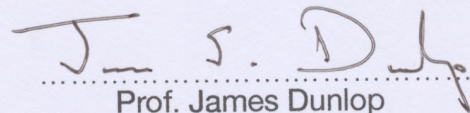
arXiv:2602.04765, submitted to A&A

consisted of:

- providing useful comments and editing parts of the final text,

constituting 5% of the total workload.

Sincerely,


Prof. James Dunlop

Toruń, March 2, 2026

Dr. Derek McLeod
School of Physics and Astronomy
University of Edinburgh
Blackford Hill, Edinburgh EH9 3HJ, UK

**Astronomy Discipline Council
Nicolaus Copernicus University
Toruń**

Author contribution statement

I hereby declare that my contribution to the work:

'Evolution of dust attenuation in star-forming galaxies with UV slope, stellar mass, and
redshift out to $z \sim 5$ '

arXiv:2602.04765, submitted to A&A

consisted of:

- provision of multi-wavelength/SED-fitted catalogues,
- editing small parts of the final text,

constituting 5% of the total workload.

Sincerely,


.....
Dr. Derek McLeod

Toruń, March 2, 2026

mgr Krzysztof Lisiecki
Departament Badań Podstawowych
Narodowe Centrum Badań Jądrowych
ul. Pasteura 7
02-093 Warszawa

**Astronomy Discipline Council
Nicolaus Copernicus University
Toruń**

Author contribution statement

I hereby declare that my contribution to the work:

'Evolution of dust attenuation in star-forming galaxies with UV slope, stellar mass, and
redshift out to $z \sim 5$ '

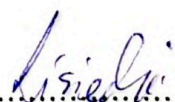
arXiv:2602.04765, submitted to A&A

consisted of:

- providing useful comments in the final stages of the project,

constituting 5% of the total workload.

Sincerely,


.....
mgr Krzysztof Lisiecki

1.12 Article C

Evolution of the infrared luminosity function and its corresponding dust-obscured star formation rate density out to $z \sim 6$

Toruń, March 2, 2026

dr hab. Maciej Koprowski
Institute of Astronomy
Faculty of Physics, Astronomy and Informatics
Nicolaus Copernicus University
Gagarina 11
87-100 Toruń, Poland

**Astronomy Discipline Council
Nicolaus Copernicus University
Toruń**

Author contribution statement

I hereby declare that my contribution to the work:

'Evolution of the infrared luminosity function and its corresponding dust-obscured star
formation rate density out to $z \sim 6$ '

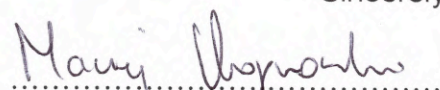
A&A, Volume 706, February 2026, A345

consisted of:

- conducting the analysis of the bright-end of the luminosity function and calculating final star-formation rate density,
- directing the work during the project and writing most of the paper,

constituting 45% of the total workload.

Sincerely,


.....
dr hab. Maciej Koprowski

Toruń, March 2, 2026

mgr Jude Vijayanga Wijesekera
Institute of Astronomy
Faculty of Physics, Astronomy and Informatics
Nicolaus Copernicus University
Gagarina 11
87-100 Toruń, Poland

**Astronomy Discipline Council
Nicolaus Copernicus University
Toruń**

Author contribution statement

I hereby declare that my contribution to the work:

'Evolution of the infrared luminosity function and its corresponding dust-obscured star
formation rate density out to $z \sim 6$ '

A&A, Volume 706, February 2026, A345

consisted of:

- stacking galaxies' sample in FIR maps, deriving the faint-end of the luminosity function and helping with the rest of the analysis,
- writing the corresponding parts of the paper,

constituting 35% of the total workload.

Sincerely,



.....
mgr Jude Vijayanga Wijesekera

Toruń, March 2, 2026

Prof. James Dunlop
School of Physics and Astronomy
University of Edinburgh
Blackford Hill, Edinburgh EH9 3HJ, UK

**Astronomy Discipline Council
Nicolaus Copernicus University
Toruń**

Author contribution statement

I hereby declare that my contribution to the work:

'Evolution of the infrared luminosity function and its corresponding dust-obscured star
formation rate density out to $z \sim 6$ '

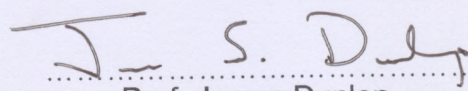
A&A, Volume 706, February 2026, A345

consisted of:

- helping with addressing the issues raised during the project,
- providing useful comments,

constituting 5% of the total workload.

Sincerely,


Prof. James Dunlop

Toruń, March 2, 2026

Dr. Derek McLeod
School of Physics and Astronomy
University of Edinburgh
Blackford Hill, Edinburgh EH9 3HJ, UK

**Astronomy Discipline Council
Nicolaus Copernicus University
Toruń**

Author contribution statement

I hereby declare that my contribution to the work:

'Evolution of the infrared luminosity function and its corresponding dust-obscured star
formation rate density out to $z \sim 6$ '

A&A, Volume 706, February 2026, A345

consisted of:

- provision of multi-wavelength/SED-fitted catalogues,
- providing final text comments,

constituting 5% of the total workload.

Sincerely,


.....
Dr. Derek McLeod

Toruń, March 2, 2026

mgr Krzysztof Lisiecki
Departament Badań Podstawowych
Narodowe Centrum Badań Jądrowych
ul. Pasteura 7
02-093 Warszawa

**Astronomy Discipline Council
Nicolaus Copernicus University
Toruń**

Author contribution statement

I hereby declare that my contribution to the work:

'Evolution of the infrared luminosity function and its corresponding dust-obscured star
formation rate density out to $z \sim 6$ '

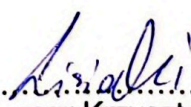
A&A, Volume 706, February 2026, A345

consisted of:

- initial help with stacking in FIR maps,
- providing useful comments,

constituting 5% of the total workload.

Sincerely,


.....
mgr Krzysztof Lisiecki

Summary and future projects

1.13 Summary

1.13.1 Summary

Throughout my PhD thesis I have presented a detailed investigation into the evolution of star-forming galaxies (SFGs) over the last 12.5 billion years of cosmic history ($z \approx 0 - 6$). By leveraging deep multi-wavelength datasets and advanced statistical techniques, we have addressed three fundamental questions in extragalactic astronomy: the evolution of the star-forming main sequence (MS), the cosmic history of dust-obscured star formation, and the physical drivers of dust attenuation.

The Star-Forming Main Sequence out to $z \sim 6$:

In order to investigate the SFR evolution out to $z \sim 7$, we stacked $\sim 100,000$ K -band selected COSMOS and UDS galaxies in IR imaging from *Herschel* and JCMT bands in bins of stellar mass and redshift. Inverse-variance stacking was used, and for the *Herschel* SPIRE bands, background sources were found to have stacked fluxes. After removing the background source contribution from each stacking stamp, we calculated the IR luminosities, derived the SFRs, and determined the functional forms of SFR evolution with stellar mass and redshift. This was done for both the MS galaxies and the whole galaxy sample. The main findings of the first project are as follows:

- We established that the star-forming MS exhibits a linear relationship between $\log(SFR)$ and $\log(M_*)$ that flattens at high stellar masses ($M_* > 10^{10.5} M_\odot$)

across all studied redshifts.

- The normalization of the MS was found to increase exponentially with redshift, reflecting the significantly higher star-formation activity in the early Universe.
- We found that peak dust temperature (T_d) increases quadratically with redshift, rising from ~ 20 ,K at $z = 0.5$ to ~ 60 ,K at $z = 5.5$. We concluded that many discrepancies in previous MS studies were likely due to the assumption of incorrect, constant dust temperatures.
- Simulations of the galaxy stellar mass function (GSMF) based on our derived MS revealed a slight overprediction of low-mass galaxies at $z \geq 2$, hinting at the need for more complex star-formation duty cycles or "bursty" star formation.

Evolution of the Infrared Luminosity Function out to $z \sim 6$

Building upon our MS analysis, we sought to map the total energy output of the dust-obscured Universe. To do this, we probed the low-luminosity regime of the IR luminosity function (LF) out to $z = 5.7$. This was achieved by stacking optical/near-IR galaxy catalogs within FIR *Herschel* and JCMT maps, using stellar mass as a proxy and applying the $L_{IR} - M_*$ relationship derived in our previous work (Koprowski et al., 2024). By supplementing this stacked sample with high-resolution ALMA follow-up data from the AS2UDS survey, we established the evolution of the functional form of the IR LF between $z = 1.2$ and 5.7. The main results of this work include:

- The characteristic luminosity (L_*) of the FIR LF evolves as $L_* \propto z^{1.38 \pm 0.07}$, while the characteristic number density (Φ_*) remains constant until $z \approx 2.24$ before declining sharply at higher redshifts.
- We confirmed that dust-obscured star formation dominates the total cosmic star-formation rate density (ρ_{SFR}) at "cosmic noon" ($z \sim 2 - 3$).

- A critical transition occurs at $z \sim 4$, where UV-visible star formation begins to dominate the total budget. By $z \sim 6$, dust-obscured activity contributes less than 25% to the total star-formation rate density.

Evolution of Dust Attenuation out to $z \sim 5$

The final component of this thesis investigated the physical drivers of dust attenuation using a K -band selected sample of $\sim 100,000$ star-forming galaxies from the UDS and COSMOS fields. We established the dependence of the infrared excess ($IRX \equiv L_{IR}/L_{UV}$) on the UV slope (β), stellar mass, and redshift out to $z \sim 5$ to provide functional prescriptions suitable for dust correction of high-redshift galaxy samples. We adopted the photometric redshifts and stellar masses from McLeod et al. (2021) and removed quiescent systems and ALMA-identified starbursts where possible. IR luminosities were obtained via stacking at $850\,\mu\text{m}$, adopting Casey (2012) SEDs and our previously derived redshift-dependent dust temperature relation. The main results of this study are as follows:

- The $IRX - \beta$ relation is consistent with a Calzetti-like attenuation curve at $\beta \geq -1$, yielding a best-fit dust-reddening slope of $dA_{1600}/d\beta = 1.97$, a bolometric correction $BC(1600) = 1.51 \pm 0.11$, and an intrinsic UV slope of $\beta_{\text{int}} = -2.30 \pm 0.10$. At bluer UV slopes, however, the stacked values of the IRX increase with redshift.
- We developed a new, mass-dependent $IRX - \beta$ calibration where the reddening law slope is a quadratic function of $\log(M_*)$. We explicitly quantify this through the effective slope of the reddening law, finding it follows a tight quadratic dependence on stellar mass: $dA_{1600}/d\beta = (-0.30 \pm 0.07)\mathcal{M}^2 + (7.06 \pm 1.40)\mathcal{M} - (38.8 \pm 7.5)$, where $\mathcal{M} = \log(M_*/M_\odot)$, making IRX a bivariate function of β and M_* .
- We identified a tight $IRX - M_*$ correlation that rises monotonically with mass but exhibits a significant turnover at the highest masses for $z \leq 2 - 3$, consistent with the suppression of gas accretion and dust growth in the most massive systems.

Together, these studies provide a self-consistent framework for understanding how galaxies grow their stellar populations and accumulate dust over most of cosmic time.

1.13.2 Future work

For my future work, I plan to use the latest COSMOS-Web catalogue and CANDELS data, managing its $\sim 700,000$ sources to extend my PhD research on Main Sequence (MS) galaxies and dust attenuation. To ensure a robust census of star-forming systems, I use $\text{NUV}-r-J$ colour-colour selections to remove passive galaxies from absolute magnitudes derived via CIGALE. In the future, I aim to leverage this expertise to characterise the physical properties of massive galaxies across cosmic time, bridging the gap between JWST's near-infrared view and the LMT's millimetre perspective.

Furthermore, I will work on Radio/FIR Correlations (FIRC) and Thermal Radio Decomposition. While the FIRC is remarkably tight in the local Universe, observations suggest that the relation evolves (with the q parameter declining) at high redshift. It remains widely debated whether this evolution is intrinsic, driven by mass-dependent magnetic field strengths or by changes in the radio emission mechanisms, or a systematic effect due to low-luminosity AGN contamination. A major theoretical puzzle is the effect of the Cosmic Microwave Background (CMB) at $z > 2$: the high CMB energy density should, in principle, suppress non-thermal synchrotron emission via Inverse Compton scattering, making galaxies "radio-quiet", yet empirical data often contradict this.

To address this problem, I will aim to **decompose the total radio flux into its thermal (free-free) and non-thermal (synchrotron) components**. I will try to access deep **VLA maps in the COSMOS field** and measure the radio spectral index by stacking Main Sequence galaxies across multiple VLA bands (e.g., 1.4, 3, and 10 GHz). I will use **NUV- r - J colour cuts** to rigorously remove passive and AGN-contaminated systems. Because observing at 3 GHz at $z \sim 3$ probes rest-frame ~ 12 GHz, the flat-spectrum thermal component contributes a much larger fraction of the observed flux. By fitting a two-component model to these stacked, multi-band

radio SEDs, I will derive the average thermal fraction as a function of stellar mass and redshift. This will allow me to directly test whether CMB quenching is actively suppressing non-thermal emission at high- z and to establish whether the thermal radio continuum can serve as a robust, dust-unbiased star formation rate indicator to complement ALMA and LMT observations.

Finally, I plan to bridge theory and observations using the SIMBA simulation. During my internship at the NCBJ, I used the **CAESAR** package to extract intrinsic galaxy properties from SIMBA simulations to analyse the SFMS across different redshift bins. Because this extraction did not use radiative transfer (RT), I saw significant discrepancies at higher redshifts between the intrinsic SIMBA results and my empirical, dust-attenuated results from the COSMOS-Web catalog.

To check these discrepancies, I want to run **comprehensive Radiative Transfer post-processing on the entire SIMBA simulation volume** using PowderDay. I will utilize the latest iteration of SIMBA, which tracks advanced physical properties including detailed dust geometry, production mechanisms, and grain size distributions. By applying RT to this highly realistic dust framework, I aim to construct a **state-of-the-art mock catalog mirroring COSMOS-Web**. This will provide the community with a robust dataset of synthetic photometry coupled with known physical properties, which is invaluable for calibrating SED fitting tools and testing selection biases. Because applying high-resolution RT across a large cosmological volume requires vast computational resources and is key to the success and scalability of this project, I require a **High-Performance Computing (HPC) system** from my next postdoc stop.