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MASTER DEGREE IN ASTROPHYSICS AND COSMOLOGY

MASTER THESIS

**Constraining the AGN contribution to the Cosmic
Star Formation Rate Density up to $z \sim 7$:
the ALMA and JWST synergy**

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Additional resources

GitHub repository web page for notebooks and datasets

https://github.com/CapHarlock27/master_thesis

*A mamma e papà,
per aver creduto in me ancora prima
che imparassi a farlo da solo.*

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Abstract

Understanding the evolution of the cosmic star formation rate density (SFRD) is a central goal of observational galaxy evolution. A major uncertainty in its reconstruction arises from dust-obscured star formation, which can be strongly underestimated by ultraviolet-selected surveys, and from the possible contribution of active galactic nuclei (AGNs) to the infrared emission used as a tracer of star formation. This thesis investigates these effects by revisiting the infrared properties of ALMA-detected galaxies in the COSMOS field using updated multiwavelength information, including recent JWST-based COSMOS2025 data.

The analysis starts from the A³COSMOS catalogue and adopts a blind-like selection designed to minimize the biases associated with targeted ALMA observations. Updated photometry and redshift information are incorporated, giving priority to spectroscopic measurements, followed by COSMOS2025 photometric redshifts and, when necessary, photometric redshifts derived through CIGALE. The final analysis is performed on a sample of 189 galaxies. Their physical properties are derived through panchromatic spectral energy distribution fitting with CIGALE, including stellar emission, dust attenuation and re-emission, and an AGN component. Two different AGN prescriptions, *skirtor2016* and *fritz2006*, are independently employed in order to quantify the dependence of the inferred quantities on the adopted torus model.

The resulting total infrared luminosities are used to reconstruct the infrared luminosity functions through the $1/V_{\text{max}}$ method and, after integration, to estimate the dust-obscured SFRD. The analysis is carried out in two broad redshift intervals, $0.5 \leq z < 3.0$ and $3.0 \leq z \leq 7.0$, while the complete sample is also analysed using the finer redshift subdivision adopted in the previous A³COSMOS study. The two AGN models provide closely consistent infrared luminosities, luminosity functions and full-sample SFRD estimates, indicating that the global dust-obscured star formation history is only weakly affected by the adopted AGN prescription. The recovered evolution shows a high SFRD around Cosmic Noon followed by a decline towards higher redshift, broadly consistent with previous infrared and millimetre determinations.

The role of AGN-hosting galaxies is further investigated by selecting sources with $f_{\text{AGN}} \geq 0.2$ and $f_{\text{AGN}} \geq 0.5$, where f_{AGN} is defined over the rest-frame 5–40 μm interval. Galaxies with moderate AGN contributions account for a substantial fraction of the infrared-derived SFRD, whereas the contribution associated with the most AGN-dominated systems is smaller and significantly more model dependent. This dependence becomes particularly strong at high redshift, where the two AGN prescriptions select substantially different high- f_{AGN} populations. These results show that the total dust-obscured SFRD is relatively robust against the adopted AGN model, while its decomposition according to AGN strength remains a major source of systematic uncertainty.

Introduction

Understanding how galaxies formed and evolved across cosmic time is one of the central goals of modern astrophysics. In the current cosmological framework, galaxies originate from the growth of primordial density fluctuations (Blumenthal et al. 1984) and evolve within dark-matter halos (White & Rees 1978) through a complex interplay of gas accretion, radiative cooling, star formation, chemical enrichment, mergers, and feedback processes (Somerville & Davé 2015; Naab & Ostriker 2017). The relative importance of these mechanisms changes with cosmic epoch and environment, producing the wide diversity of galaxy masses, morphologies, colours, and star-formation properties observed in the local Universe. Reconstructing this evolution therefore requires connecting the present-day galaxy population with increasingly distant systems, whose radiation was emitted when the Universe was substantially younger.

Star formation is one of the fundamental processes driving galaxy evolution. It regulates the progressive conversion of cold gas into stars, determines the build-up of stellar mass, and contributes to the chemical and energetic evolution of the interstellar and circumgalactic media (Kennicutt & Evans 2012). Massive, short-lived stars enrich their surroundings through stellar winds and supernova explosions, while the energy and momentum released by stellar feedback can heat or expel gas and consequently regulate subsequent star formation (Naab & Ostriker 2017). Measuring how efficiently galaxies formed stars at different epochs is thus essential for understanding the evolution of the baryonic component of the Universe.

While the star formation rate (SFR) describes the amount of stellar mass formed per unit time in an individual galaxy (Kennicutt & Evans 2012), the cosmic star formation rate density (SFRD) quantifies the total star formation activity occurring per unit time and per unit comoving volume (Madau & Dickinson 2014). The evolution of the SFRD provides a global view of the assembly of stellar mass and is commonly referred to as the cosmic star formation history. Early measurements based primarily on rest-frame ultraviolet observations revealed that the cosmic SFRD was considerably higher in the past than it is today (Madau et al. 1996; Lilly et al. 1996). Subsequent multiwavelength surveys established a more complete picture, showing that the SFRD increased from the earliest observable epochs, reached a broad maximum around $z \sim 2$, and then declined by approximately one order of magnitude towards the present day (Hopkins & Beacom 2006; Madau & Dickinson 2014). The epoch around the maximum of this relation, often called “Cosmic Noon”, corresponds to a period of intense galaxy growth, during which both star formation and black-hole accretion were substantially more active than in the local Universe (Förster Schreiber & Wuyts 2020).

The overall evolution of the cosmic SFRD is illustrated in Figure 1.

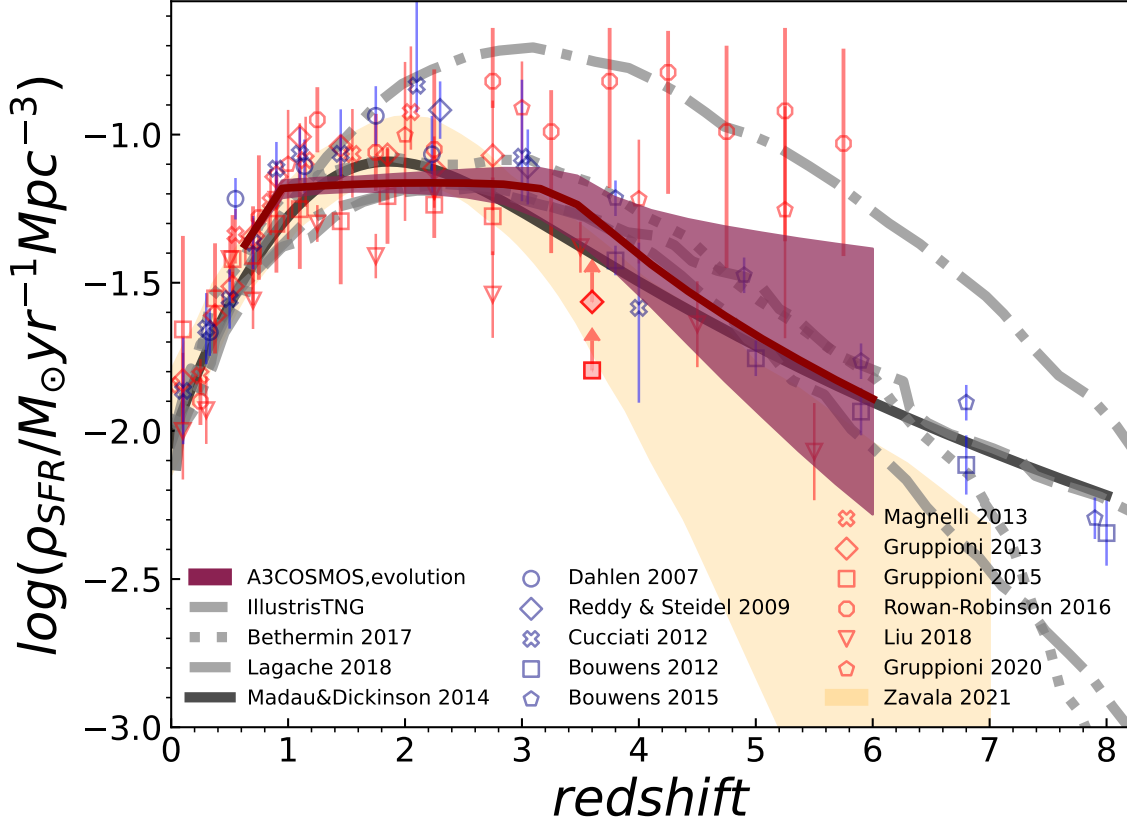


Figure 1: Evolution of the cosmic star formation rate density as a function of redshift. The red diamonds represent the dust-obscured SFRD derived by [Traina et al. 2024](#) through the integration of the infrared luminosity function in individual redshift bins, while the dark-red shaded region shows the evolution obtained from their redshift-dependent luminosity-function fit. Previous infrared and millimetre determinations are shown in red, while ultraviolet-based estimates corrected for dust attenuation are shown in blue. The different curves represent literature determinations and theoretical predictions for the cosmic star formation history. The figure illustrates the broad maximum in the SFRD around Cosmic Noon and its decline towards both lower and higher redshifts. Figure 14 from [Traina et al. 2024](#).

Despite major observational progress, accurately reconstructing the cosmic star formation history remains challenging, particularly at high redshift ([Madau & Dickinson 2014](#)). Star formation cannot be measured directly but must instead be inferred from observable quantities associated with young stellar populations. Ultraviolet radiation is an especially useful tracer because it is predominantly emitted by short-lived, massive stars and is therefore sensitive to recent star formation ([Kennicutt 1998](#); [Kennicutt & Evans 2012](#)). However, ultraviolet photons are efficiently absorbed and scattered by interstellar dust grains ([Calzetti 2001](#); [Draine 2003](#)). As a consequence, the observed ultraviolet luminosity may represent only a fraction of the intrinsic emission produced by young stars, and SFR estimates based exclusively on ultraviolet-selected samples can be severely underestimated in dusty systems.

The energy absorbed by dust at ultraviolet and optical wavelengths is not lost. Dust grains are heated by the surrounding radiation field and re-emit this energy thermally at infrared and submillimetre wavelengths. Infrared observations therefore provide access to the component of star formation that is obscured in the ultraviolet and optical bands

(Sanders & Mirabel 1996; Casey et al. 2014). The total infrared luminosity, commonly integrated over the rest-frame wavelength interval 8–1000 μm , can consequently be used as a tracer of dust-obscured star formation, provided that the contribution from other heating mechanisms is properly taken into account. A complete census of cosmic star formation thus requires a panchromatic approach combining direct stellar emission with the radiation reprocessed by dust.

Infrared surveys have demonstrated that dusty star-forming galaxies contribute substantially to the cosmic SFRD, particularly around its peak at $z \sim 1\text{--}3$ (Le Floch et al. 2005). At higher redshift, however, the magnitude of the obscured contribution remains considerably more uncertain (Gruppioni et al. 2013). This uncertainty is caused by the limited sensitivity and angular resolution of previous far-infrared surveys, the difficulty of identifying counterparts in confused images, and the need to extrapolate poorly sampled spectral energy distributions. Moreover, the increasing luminosity distance and the shifting of the dust emission peak towards longer observed wavelengths make the detection and physical characterisation of high-redshift dusty galaxies particularly demanding (Casey et al. 2014). As a result, the decline of the SFRD beyond $z \gtrsim 3$ is still less securely constrained than its evolution at later cosmic times, and the relative importance of unobscured and obscured star formation remains an active area of research.

An additional complication is introduced by active galactic nuclei (AGNs). Most massive galaxies host a central supermassive black hole (Kormendy & Ho 2013), and the accretion of matter onto these objects can release large amounts of energy over a broad range of wavelengths (Brandt & Alexander 2015). A fraction of the radiation produced by the accretion disc is absorbed by the surrounding dusty material and re-emitted in the infrared, where it may overlap with the emission associated with star formation (Hickox & Alexander 2018). In particular, hot dust heated by the AGN can dominate the mid-infrared spectral energy distribution, while more extended AGN-heated dust may also contribute at longer wavelengths (Lutz 2014).

If the AGN component is not separated from the emission powered by young stars, the infrared luminosity attributed to star formation may be overestimated (Delvecchio et al. 2014). This can affect not only the physical properties derived for individual galaxies but also statistical measurements such as infrared luminosity functions and the integrated SFRD. The bias is expected to be especially relevant at the luminous end of the galaxy population, where the incidence and energetic importance of AGN activity increase (Gruppioni et al. 2013; Delvecchio et al. 2014). At the same time, AGNs are not merely contaminants: the observed connection between black-hole mass and the properties of the host-galaxy bulge suggests that black-hole growth and galaxy evolution are closely related, although the physical mechanisms establishing this connection remain debated (Kormendy & Ho 2013; Heckman & Best 2014). Quantifying the AGN contribution is therefore necessary both to obtain reliable SFR measurements and to investigate the co-evolution of galaxies and their central black holes.

Disentangling the different components of galaxy emission requires broad and sufficiently deep wavelength coverage. The spectral energy distribution (SED) of a galaxy contains the combined emission of its stellar populations, ionised gas, interstellar dust, and possible active nucleus (Walcher et al. 2011). By comparing multiwavelength photometric measurements with physically motivated models, SED-fitting techniques can constrain quantities such as stellar mass, SFR, dust luminosity, attenuation, and AGN

fraction (Conroy 2013). Nevertheless, the reliability of the inferred parameters depends critically on the available photometric coverage, the adopted models, and the treatment of degeneracies among stellar, dust, and AGN components.

The COSMOS field provides an especially suitable environment for this type of analysis. Originally designed as a wide-area survey for studying galaxy evolution and large-scale structure, COSMOS combines deep observations over a field of approximately two square degrees with extensive multiwavelength coverage and spectroscopic follow-up (Scoville et al. 2007). The COSMOS2020 catalogue improved the detection, photometry, and photometric-redshift characterisation of sources in this field by combining a large collection of ground- and space-based observations (Weaver et al. 2022). More recently, the COSMOS-Web programme has extended this legacy through deep James Webb Space Telescope imaging (Casey et al. 2023), leading to the COSMOS2025 catalogue and providing substantially improved constraints on faint and distant galaxy populations (Shuntov et al. 2025).

The James Webb Space Telescope (JWST) has opened a new observational window on galaxy evolution through its sensitivity and angular resolution at near- and mid-infrared wavelengths (Gardner et al. 2023). At high redshift, these observations probe the rest-frame ultraviolet and optical emission of galaxies, improving source detection, photometric-redshift estimates, and measurements of stellar populations. JWST is also particularly effective at identifying red and optically faint systems that may have been missed or poorly characterised by previous surveys (Rigby et al. 2023). However, near- and mid-infrared observations alone generally do not sample the peak of the cold-dust emission and therefore cannot fully constrain the obscured energy budget of galaxies.

The Atacama Large Millimeter/submillimeter Array (ALMA) provides the complementary information required to trace this cold-dust component. Its high sensitivity and angular resolution at millimetre and submillimetre wavelengths enable the detection of dust continuum emission and molecular or atomic gas tracers in distant galaxies (Wootten & Thompson 2009). Within the COSMOS field, the A³COSMOS project has systematically mined the ALMA archive and combined its observations with the extensive ancillary photometry available in the field, producing a valuable sample of millimetre-detected galaxies over a broad redshift range (Liu et al. 2019a). Recent studies based on these data have demonstrated their potential for constraining infrared luminosity functions and the dust-obscured SFRD out to $z \sim 6$ (Traina et al. 2024).

The combination of JWST and ALMA is therefore particularly powerful. JWST constrains the emission from stellar populations and warm dust with unprecedented depth, while ALMA directly probes the longer-wavelength emission associated with cold dust. Their synergy improves the reconstruction of galaxy SEDs, helps identify highly obscured sources, and reduces the degeneracy between stellar and AGN-powered infrared emission. When embedded within the extensive multiwavelength framework of the COSMOS field, these observations offer an opportunity to obtain a more complete census of star formation and nuclear activity during the first few billion years of cosmic history.

The primary aim of this thesis is to constrain the evolution of the dust-obscured cosmic star formation rate density up to $z \sim 7$ and to assess the impact of AGN emission on its determination. The analysis builds upon the blind-like A³COSMOS sample selected by Traina et al. 2024. Its multiwavelength photometry was updated using the COSMOS2025 catalogue and the new JWST observations, while the redshift information was revised

through the compilation of recent spectroscopic catalogues (Merlin et al. 2024; Khostovan et al. 2026) and independent photometric redshift estimates. The updated photometry was modelled through Bayesian SED fitting with CIGALE (Boquien et al. 2019), including stellar, dust, and AGN emission components (Yang et al. 2020; Yang et al. 2022). This makes it possible to estimate the physical properties of the sources and, in particular, to assess the contribution of AGN emission to the SED and its dependence on the adopted nuclear emission model. Several AGN configurations were tested. In particular, the comparison between fritz2006 (Fritz et al. 2006) and skirtor2016 (Stalevski et al. 2016) prescriptions was used to assess the systematic dependence of the inferred physical properties on the description of the nuclear component of the galaxy.

The resulting infrared luminosities are used to reconstruct galaxy luminosity functions in different redshift intervals. Their evolution is modelled through Markov chain Monte Carlo fitting, and the luminosity functions are subsequently integrated to derive the infrared luminosity density and the corresponding SFRD. By comparing measurements obtained with different treatments of the AGN component, this work aims to quantify the fraction of the infrared-derived SFRD associated with galaxies hosting moderate or strong mid-infrared AGN components. The results are finally compared with previous ultraviolet- and infrared-based determinations in order to evaluate the contribution of dusty galaxy populations and investigate whether the high-redshift SFRD may still be underestimated.

The remainder of this thesis develops the theoretical and observational background required for the analysis, beginning with the relevant cosmological framework (Chapter 1) and the physical processes governing galaxy evolution (Chapter 2). The properties of interstellar dust (Chapter 3), infrared emission, and active galactic nuclei (Chapter 4) are then discussed, followed by a detailed description of the datasets (Chapter 5), sample selection, and SED-fitting procedure (Chapter 6). The construction and modelling of the infrared luminosity functions are subsequently presented, together with the derivation of the cosmic SFRD and the analysis of the AGN contribution (Chapter 7). Finally, the main results are discussed in the context of previous studies, and the principal conclusions and future perspectives are summarised.

The interpretation of galaxy observations at cosmological distances requires a framework that connects the measured quantities, such as fluxes and redshifts, to intrinsic physical properties, such as luminosities, stellar masses, star formation rates, and number densities. Since the sources analysed in this thesis span a broad redshift interval, from the relatively nearby Universe to $z \sim 7$, the effects of cosmic expansion must be explicitly taken into account. Redshift determines the epoch at which the observed light was emitted, cosmological distances set the conversion between observed flux and intrinsic luminosity, and comoving volumes provide the normalization required to transform galaxy counts into luminosity functions.

This chapter introduces the basic cosmological quantities used throughout the thesis. The goal is not to provide a complete derivation of modern cosmology, but rather to define the quantities that enter the observational analysis. In particular, the following sections describe the expanding Universe in the context of the standard Λ CDM model, the relation between redshift and cosmic time, the main cosmological distance definitions, and the role of comoving volume in the construction of luminosity functions.

1.1 The expanding Universe, redshift and cosmic time

On sufficiently large scales, the Universe is well described as homogeneous and isotropic. Under these assumptions, its geometry can be represented by the Friedmann–Lemaître–Robertson–Walker metric, in which the expansion of space is encoded in the cosmic scale factor $a(t)$. The scale factor describes how physical distances between comoving observers evolve with cosmic time. The present-day value is conventionally normalized to $a_0 = 1$.

In the standard cosmological model, usually referred to as Λ CDM, the present evolution of the Universe is governed by a combination of cold dark matter, baryonic matter, radiation, and dark energy in the form of a cosmological constant Λ (Carroll et al. 1992; Planck Collaboration et al. 2020). The expansion rate is described by the Hubble parameter

$$H(t) = \frac{\dot{a}(t)}{a(t)} \quad (1.1)$$

where $\dot{a}(t)$ is the time derivative of the scale factor. It is often convenient to express the Hubble parameter as a function of redshift

$$H(z) = H_0 E(z) \quad (1.2)$$

where H_0 is the present-day Hubble constant and $E(z)$ encodes the redshift dependence of the expansion rate. For a general cosmology

$$E(z) = [\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_k(1+z)^2 + \Omega_\Lambda]^{1/2} \quad (1.3)$$

where Ω_m , Ω_r , Ω_k , and Ω_Λ are the present-day density parameters associated with matter, radiation, spatial curvature, and dark energy, respectively.

In most extragalactic studies at redshifts $z \lesssim 7$, the radiation contribution is negligible compared to matter and dark energy. Moreover, observations of the cosmic microwave background are consistent with a nearly flat Universe, for which $\Omega_k \simeq 0$ (Planck Collaboration et al. 2020). In this case, the expansion rate can be approximated as

$$E(z) = [\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2} \quad (1.4)$$

Throughout this thesis, a flat Λ CDM cosmology is assumed, with $H_0 \sim 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.31$ and $\Omega_\Lambda = 0.69$. This assumption provides the basis for converting observed redshifts into distances and comoving volumes, which are required for the reconstruction of the infrared luminosity function and of the cosmic star formation rate density.

Redshift is the primary observable used to locate galaxies in cosmic time. In an expanding Universe, the wavelength of a photon is stretched by the cosmic expansion between the time of emission and the time of observation. The cosmological redshift is defined as

$$1 + z = \frac{\lambda_{\text{obs}}}{\lambda_{\text{em}}} \quad (1.5)$$

where λ_{obs} is the observed wavelength and λ_{em} is the emitted wavelength. Since photon wavelengths scale with the expansion of the Universe, redshift is directly related to the scale factor through

$$1 + z = \frac{a_0}{a(t_{\text{em}})} \quad (1.6)$$

Using the conventional normalization $a_0 = 1$, the scale factor at the time of emission becomes

$$a(t_{\text{em}}) = \frac{1}{1 + z} \quad (1.7)$$

and the corresponding rest-frame wavelength sampled by an observed photometric band is

$$\lambda_{\text{rest}} = \frac{\lambda_{\text{obs}}}{1 + z} \quad (1.8)$$

This relation is central to the analysis performed in this work. The same observed filter probes progressively shorter rest-frame wavelengths as redshift increases.

Redshift is also related to lookback time, defined as the difference between the current age of the Universe and the age of the Universe when the observed light was emitted. The lookback time is given by the integral

$$t_L(z) = \int_0^z \frac{dz'}{(1+z')H(z')} \quad (1.9)$$

and the age of the Universe at redshift z is therefore $t(z) = t_0 - t_L(z)$.

This quantity is particularly useful for interpreting galaxy evolution, because it translates redshift into a temporal sequence. Observing galaxies at increasing redshift corresponds to observing them at progressively earlier stages of cosmic history. Figure 1.1 shows the lookback time and age of the Universe as a function of the redshift.

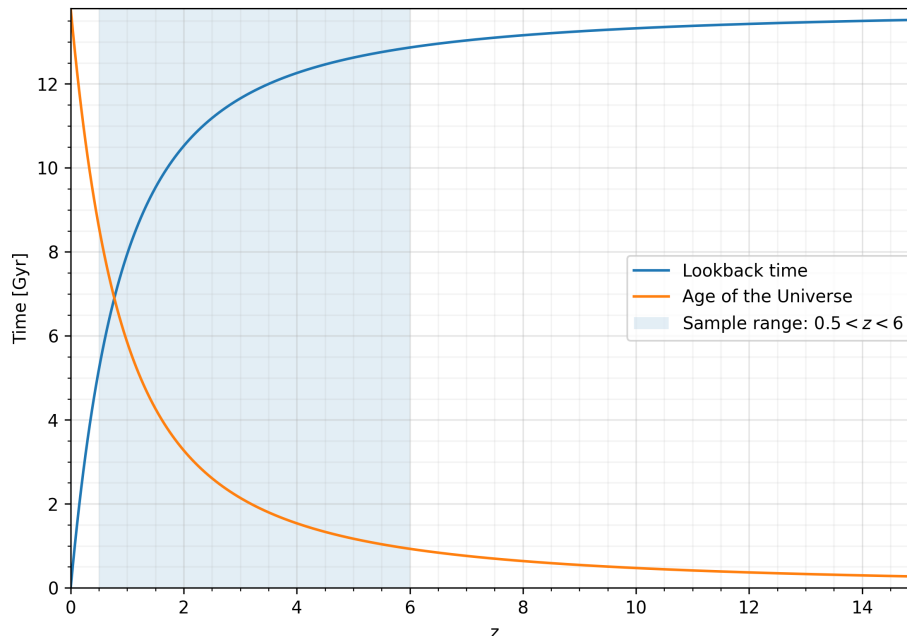


Figure 1.1: Lookback time and age of the Universe as a function of redshift in the adopted flat Λ CDM cosmology. The shaded region highlights the approximate redshift range probed by the galaxy sample analysed in this thesis, $0.5 < z < 6$.

The redshift range considered in this thesis therefore probes a substantial fraction of the history of galaxy formation. The lower-redshift part of the sample traces the Universe after the peak of cosmic star formation activity, while the highest-redshift sources approach the first few billion years after the Big Bang. Since the cosmic star formation rate density evolves strongly over this interval (Madau & Dickinson 2014), dividing the sample into redshift bins allows the evolution of infrared luminosity functions and dust-obscured star formation to be studied as a function of cosmic time.

In practice, redshifts also enter the analysis in several operational ways. It determines which rest-frame wavelengths are sampled by the observed photometric bands, it affects the inferred luminosities through the luminosity distance, and it defines the comoving volume associated with each redshift interval. Reliable redshift estimates are therefore essential for the construction of luminosity functions and for the derivation of the cosmic star formation rate density.

1.2 Cosmological distances and comoving volumes

In an expanding Universe, the concept of distance is not unique. Different definitions are useful depending on the observable quantity under consideration. The most relevant distances for this thesis are the comoving distance, the luminosity distance, and the angular diameter distance. A clear discussion of these distance definitions is given by

Hogg (1999).

The line-of-sight comoving distance to a source at redshift z is defined as

$$D_C(z) = c \int_0^z \frac{dz'}{H(z')} \quad (1.10)$$

where c is the speed of light. Comoving distances factor out the expansion of the Universe and therefore remain fixed for objects that follow the Hubble flow. They are especially useful for describing the large-scale distribution of galaxies and for computing cosmological volumes.

The luminosity distance, D_L , is the distance measure that relates the intrinsic luminosity of a source to the observed flux. For a source of bolometric luminosity L and observed flux Φ , the relation is

$$\Phi = \frac{L}{4\pi D_L^2} \quad (1.11)$$

In a flat Universe, the luminosity distance is related to the comoving distance by

$$D_L(z) = (1+z)D_C(z). \quad (1.12)$$

The additional factor of $(1+z)$ accounts for the redshifting of photon energies and the time dilation of the photon arrival rate.

The angular diameter distance, D_A , relates the physical size of an object to its observed angular size θ

$$\theta = \frac{l}{D_A} \quad (1.13)$$

where l is the physical transverse size and θ is the observed angular size. In a flat Universe, it is related to the comoving distance by

$$D_A(z) = \frac{D_C(z)}{1+z} \quad (1.14)$$

Consequently, the luminosity and angular diameter distances are related by

$$D_L(z) = (1+z)^2 D_A(z) \quad (1.15)$$

The observed photometric fluxes of galaxies must be converted into intrinsic luminosities in order to derive quantities such as the total infrared luminosity, L_{IR} . Although this conversion is performed within the SED-fitting framework, its physical meaning is set by the cosmological relation between flux, luminosity, and distance. Uncertainties in redshift therefore propagate into luminosity estimates through their effect on D_L . This connection is particularly important at high redshift. As redshift increases, the luminosity distance grows rapidly, so that intrinsically luminous galaxies can appear faint in observed flux. The combination of large luminosity distances, dust attenuation, and limited survey sensitivity makes the detection and characterization of high-redshift dusty galaxies observationally challenging. These effects must be considered when interpreting the observed sample and when reconstructing luminosity functions from flux-limited data.

In addition to intrinsic luminosities, the construction of luminosity functions requires

a definition of the cosmological volume sampled by a survey. Since the Universe expands with time, physical volumes evolve with the scale factor. For this reason, galaxy number densities are usually expressed in terms of comoving volume, which factors out the expansion of the Universe and allows galaxy populations observed at different redshifts to be compared within a common reference frame.

For a survey covering a solid angle $d\Omega$, the differential comoving volume element per unit redshift and unit solid angle is given by

$$\frac{dV_c}{dz d\Omega} = \frac{c D_M^2(z)}{H(z)} \quad (1.16)$$

where D_M is the transverse comoving distance. In a spatially flat Universe, D_M is equal to the line-of-sight comoving distance D_C introduced in Equation 1.10 (Hogg 1999). The comoving volume enclosed between two redshifts, z_1 and z_2 , over a survey area Ω , is therefore

$$V_c(z_1, z_2) = \Omega \int_{z_1}^{z_2} \frac{dV_c}{dz d\Omega} dz \quad (1.17)$$

This expression shows that the effective volume probed by a survey depends both on its angular area and on the redshift interval considered. A wide survey samples a larger cosmological volume and is therefore more efficient at detecting rare objects, such as very luminous galaxies, bright quasars or AGNs. Conversely, deep thin surveys cover smaller volumes but can reach fainter flux limits, allowing the study of less luminous populations. The balance between area and depth is therefore a fundamental aspect of survey design and has a direct impact on the range of luminosities and number densities that can be constrained. In the context of this thesis, the situation is more complex than that of a survey with uniform depth. The A³COSMOS sample was constructed from archival ALMA observations obtained at different wavelengths, sensitivities and positions within the COSMOS field.

A further complication arises from the fact that surveys are flux-limited. A galaxy of a given luminosity can only be detected within the redshift range where its observed flux remains above the survey sensitivity limit. Therefore, different galaxies may be observable over different effective volumes. This effect is particularly important for luminosity-function measurements, because faint sources can be detected only over a smaller redshift interval than intrinsically luminous sources. The accessible volume associated with each object is the basis of the classical $1/V_{\text{max}}$ method, which will be discussed in detail in the luminosity-function chapter (Schmidt 1970).

1.3 From observed photometry to luminosity functions

The analysis of distant galaxies begins with observed quantities: fluxes measured in different photometric bands and redshift estimates obtained either spectroscopically or photometrically. These quantities cannot be converted into intrinsic properties by treating each photometric band independently, this because different observed filters probe different rest-frame wavelengths depending on redshift. In addition, the emission of a galaxy results from the superposition of stellar populations, dust heated by star formation and active galactic nuclei.

For a source at redshift z , the luminosity distance determines the conversion between the observed flux and the intrinsic luminosity. In a multiwavelength analysis, this conversion is not performed independently for each band in isolation, but within the broader reconstruction of the spectral energy distribution (SED) (Walcher et al. 2011; Conroy 2013). The observed photometry samples different rest-frame wavelength regions depending on redshift, and SED fitting is used to infer the intrinsic emission of the galaxy across the ultraviolet, optical, infrared, and millimetre regimes. In this thesis, this procedure is used to derive physical quantities such as stellar mass, star formation rate, total infrared luminosity, and AGN fraction.

The total infrared luminosity, L_{IR} , is particularly important for the present work since it traces the energy absorbed by dust at ultraviolet and optical wavelengths and re-emitted in the infrared. It is conventionally defined as the luminosity integrated over the rest-frame wavelength interval

$$L_{\text{IR}} = \int_{8 \mu\text{m}}^{1000 \mu\text{m}} L_{\lambda} d\lambda \quad (1.18)$$

This interval includes most of the thermal radiation emitted by interstellar dust. More detailed information can be found in Chapter 3.

Once an infrared luminosity is derived for each source, the statistical distribution of the galaxy population can be described through the infrared luminosity function (Casey et al. 2014). In general, a luminosity function describes the comoving number density of sources as a function of luminosity

$$\Phi(L) = \frac{dN}{dV_c dL} \quad (1.19)$$

It is often expressed per logarithmic luminosity interval

$$\Phi(L) = \frac{dN}{dV_c d \log_{10} L} \quad (1.20)$$

which is convenient when dealing with galaxy populations spanning several orders of magnitude in luminosity. It is generally reported in units of $\text{Mpc}^{-3} \text{dex}^{-1}$.

The luminosity function therefore combines two cosmological ingredients. First, the luminosity distance is required to infer the intrinsic luminosity of each source from its observed fluxes. Second, the comoving volume is required to convert the number of galaxies in a luminosity bin into a number density. For this reason, luminosity functions are one of the most direct statistical tools for studying the evolution of galaxy populations across cosmic time. The evolution of the infrared luminosity function provides information on the abundance of dusty star-forming systems at different epochs (Gruppioni et al. 2013). Its evolution with redshift reflects changes in the number density and luminosity distribution of galaxies whose star formation is partially or largely obscured by dust. Since ultraviolet observations alone can miss this obscured component, infrared luminosity functions are essential for obtaining a more complete view of the cosmic star formation history.

The infrared luminosity function can also be integrated to obtain the infrared luminosity density

$$\rho_{\text{IR}} = \int L_{\text{IR}} \Phi(L_{\text{IR}}) d\log_{10} L_{\text{IR}} \quad (1.21)$$

This quantity represents the total infrared luminosity emitted per unit comoving volume at a given cosmic epoch. By applying a conversion between infrared luminosity and star formation rate, ρ_{IR} can be transformed into an estimate of the dust-obscured cosmic star formation rate density (Kennicutt 1998; Kennicutt & Evans 2012). This is the quantity ultimately compared with previous determinations of the cosmic star formation history, including the Madau–Dickinson relation (Madau & Dickinson 2014).

Galaxy Formation and the Cosmic Star Formation History

Understanding the evolution of the cosmic star formation rate density requires a physical framework for how galaxies form and evolve across cosmic time. In the standard picture of structure formation, galaxies are not isolated systems, but form within the gravitational potential of dark matter halos. The growth of galaxies is therefore driven by the hierarchical assembly of dark matter structures, by the accretion and cooling of baryonic gas, and by the conversion of this gas into stars. At the same time, feedback from massive stars, supernovae, and active galactic nuclei regulates the efficiency of star formation and shapes the observed properties of galaxies.

The efficiency of this cycle changes with halo mass, redshift and environment. At early stages of cosmic evolution, the rapid growth of dark matter structures and the availability of large gas reservoirs sustain intense star formation. At later times, the cosmological supply of fresh gas decreases, while gas heating, exhaustion and feedback become increasingly effective in limiting the formation of new stars. The combined evolution of these processes produces the characteristic rise and decline of the cosmic star formation rate density.

This chapter introduces the basic physical processes that connect galaxy formation to the cosmic star formation history. The aim is to provide the astrophysical background required to interpret the infrared luminosity functions and the star formation rate density derived in this thesis. After outlining the role of dark matter halos in galaxy formation, the chapter describes the processes of gas accretion, cooling, star formation, and feedback. The final sections will discuss the evolution of the cosmic star formation rate density and the importance of accounting for dust-obscured star formation.

2.1 Galaxy formation in dark matter halos

In the Λ CDM cosmological model, the formation of cosmic structures proceeds hierarchically. Small dark matter perturbations collapse first and subsequently merge to form progressively more massive halos. Galaxies form within these halos, where baryonic matter can cool, condense, and eventually form stars. This framework provides the basis for the modern theory of galaxy formation (White & Rees 1978; Blumenthal et al. 1984; Somerville & Davé 2015). Figure 2.1 shows a simulation of the evolution of galaxy formation in dark matter halos.

Dark matter dominates the gravitational collapse of structures because it does not interact electromagnetically and is therefore not affected by radiative cooling or pressure support in the same way as baryonic matter. As density perturbations grow under

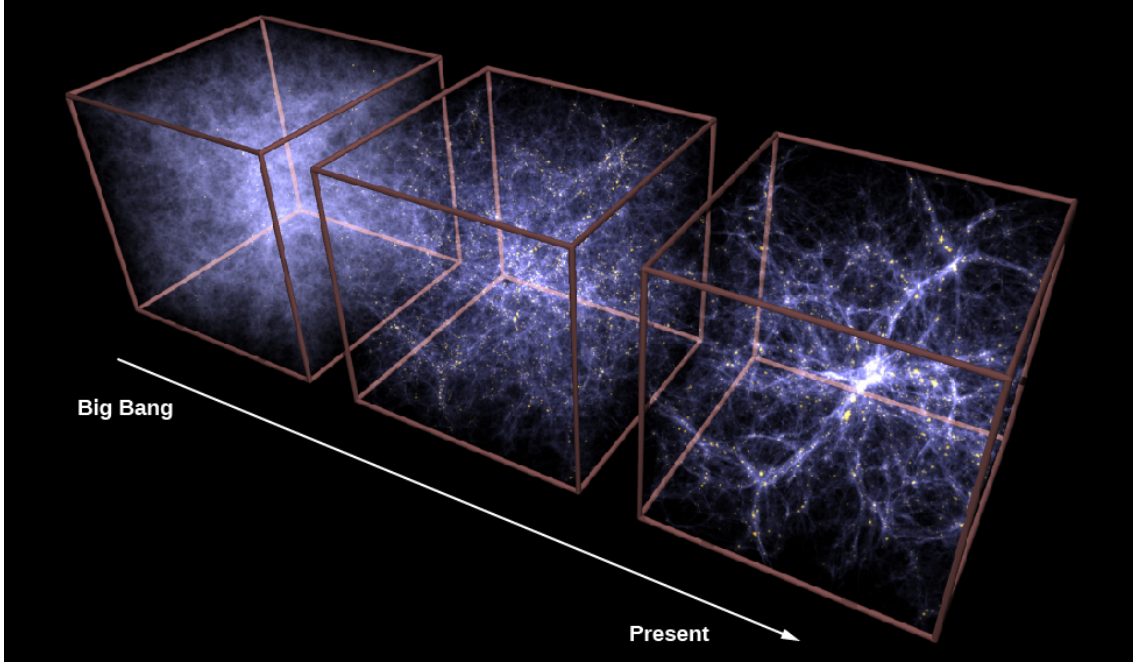


Figure 2.1: Evolution of the large-scale matter distribution from the early Universe to the present day, as reconstructed through cosmological numerical simulations. Initially small density fluctuations grow through gravitational instability, progressively producing dark matter halos and the filamentary network of clusters, filaments and voids known as the cosmic web. Galaxies preferentially form within the densest regions and at the intersections of these filaments. Figure adapted from [Fraknoi et al. 2016](#), original simulation and visualization by V. Springel, MPE, released by NASA/CXC ([Springel 2008](#)).

gravity, dark matter halos provide the potential into which gas can fall. The mass, concentration and assembly history of a halo strongly influence the properties of the galaxy that forms inside it, including its stellar mass, gas content, star formation activity, and merger history. The connection between dark matter halos and galaxies is, however, not simply determined by gravity. While the cosmic baryon fraction sets the maximum amount of baryonic material available within a halo, only a fraction of this gas is converted into stars. Galaxy formation is not determined by gravity alone, but the efficiency of galaxy formation depends on a combination of gas cooling, angular momentum, star formation, feedback, and environmental processes. As a consequence, galaxies represent the visible outcome of a complex interplay between dark matter assembly and baryonic physics. Gas entering a dark matter halo may be heated as it interacts with the halo medium and approaches the virial temperature. At early epochs, the rapid growth of dark matter halos provides the conditions for intense gas accretion and star formation. At later times, the decline in gas accretion rates, the growth of massive halos, and the increasing importance of feedback processes contribute to the observed evolution of the galaxy population and of the cosmic star formation rate density ([Somerville & Davé 2015](#); [Naab & Ostriker 2017](#)).

After cooling, gas can settle into a rotationally supported structure and contribute to the interstellar medium. Gravitational instabilities can lead to the formation of molecular clouds and eventually stars. The connection between the available gas and the resulting star formation activity is commonly described through the Kennicutt–Schmidt relation

$$\Sigma_{\text{SFR}} = A \Sigma_{\text{gas}}^N \quad (2.1)$$

where Σ_{SFR} is the star formation rate surface density, Σ_{gas} is the gas surface density and A is a normalization factor. The value of the exponent depends on the adopted gas tracer and spatial scale but it is of order unity generally, with the classical relation of $N \simeq 1.4$ (Kennicutt 1998; Kennicutt & Evans 2012).

From an observational point of view, the star formation rate is not measured directly, but inferred from tracers associated with young stellar populations. Massive short-lived stars emit strongly in the ultraviolet, while the same radiation can be absorbed by dust and re-emitted in the infrared. As a result, both ultraviolet and infrared emission are key diagnostics of recent star formation. Ultraviolet and infrared observations therefore trace complementary components of recent star formation. The ultraviolet emission probes the fraction of stellar radiation escaping the galaxy without absorption, while the infrared emission traces the radiation reprocessed by dust. However, the relative importance of these tracers depends on the amount of dust obscuration, which becomes especially relevant for dusty star-forming galaxies and for high-redshift sources selected at infrared or millimetre wavelengths. The total infrared luminosity, L_{IR} , is therefore closely connected to star formation in dust-rich systems. In galaxies where young stars are heavily obscured, a significant fraction of the ultraviolet and optical radiation is absorbed by dust grains and reprocessed into infrared emission. This makes infrared observations essential for recovering the obscured component of the star formation activity, which can be missed or underestimated by rest-frame ultraviolet surveys alone.

If gas cooling and gravitational collapse were the only relevant processes, galaxies would convert a much larger fraction of their baryons into stars than is observed. In practice, galaxy formation is inefficient, especially in low-mass and high-mass halos. This inefficiency indicates that feedback processes play a crucial role in regulating the growth of galaxies (Somerville & Davé 2015; Naab & Ostriker 2017).

In low-mass galaxies, feedback from massive stars and supernova explosions can inject energy and momentum into the interstellar medium. These processes heat the gas, drive turbulence, and can launch galactic outflows that remove gas from the star-forming regions. Since low-mass halos have relatively shallow gravitational potentials, part of the gas can be expelled out of galaxy effective radius. Stellar feedback therefore reduces the efficiency of star formation and can delay or suppress the conversion of gas into stars. But the expelled material is not necessarily lost permanently. Depending on the velocity of the outflow and other factors, it may remain bound to the halo and later cool and return to the galaxy.

In massive galaxies, stellar feedback alone is generally not sufficient to explain the suppression of star formation. In these systems, as halos grow, their central galaxies host increasingly bigger black holes, where gas accretion releases large amounts of energy, part of which can couple to the surrounding gas. Feedback associated with active galactic nuclei is thought to play an important role. Energy released by accretion onto supermassive black holes can heat or expel gas, reducing the supply of cold material available for star formation. AGN feedback is therefore often invoked to explain the quenching of star formation in massive galaxies and the observed decline of star-forming activity in the most massive systems (Kormendy & Ho 2013; Heckman & Best 2014). AGN feedback is generally discussed in terms of different operating regimes. At relatively high accretion rates, radiative emission and powerful winds can affect the gas surrounding the nucleus. At lower accretion rates instead, mechanical energy can heat the circumgalactic medium

and prevent gas from cooling efficiently.

Feedback also affects the interpretation of galaxy populations at high redshift. The balance between gas accretion, star formation, dust production, and feedback determines the observed luminosities and spectral energy distributions of galaxies. In dusty systems, part of the stellar radiation is absorbed and re-emitted in the infrared, while the possible presence of an AGN can further contribute to the infrared emission. Separating the contribution of star formation from that of AGN activity is therefore essential when infrared luminosities are used to infer star formation rates.

In the context of this thesis, feedback is relevant in two complementary ways. First, it is a physical mechanism that shapes the evolution of the galaxy population and contributes to the rise and decline of the cosmic star formation rate density. Second, AGN activity can contaminate infrared emission, potentially biasing star formation rate estimates if not properly accounted for. This will motivate the use of SED-fitting models that include both stellar and AGN components, allowing the impact of AGN contamination on infrared luminosity functions and on the derived star formation rate density to be assessed.

2.2 The cosmic star formation rate density

The global evolution of star formation is commonly described through the cosmic star formation rate density, ρ_{SFR} or SFRD. This quantity represents the total mass converted into stars per unit time unit comoving volume and is usually expressed in units of $M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$. Rather than describing an individual galaxy, ρ_{SFR} provides a statistical measure of the average star-forming activity of the Universe as a function of cosmic time. Its evolution reflects changes in the abundance of star-forming galaxies, their typical star formation rates and the distribution of their gas reservoirs.

The reconstruction of the cosmic star formation history has been one of the central achievements of observational extragalactic astronomy. Early star formation rate density was significantly higher in the past than in the local Universe (Madau et al. 1996; Lilly et al. 1996). Subsequent multiwavelength studies extended this picture over a broader redshift interval and combined ultraviolet, optical, infrared and radio tracers, leading to a more complete description of the rise and decline of star formation activity over cosmic time (Hopkins & Beacom 2006). The cosmic star formation rate density is closely connected to the growth of the stellar mass density. A fraction of the mass initially converted into stars is returned to the interstellar medium through stellar winds and supernova explosions. Accounting for this recycled material, the evolution of the cosmic stellar mass density can be written schematically as

$$\frac{d\rho_{\star}}{dt} = (1 - R)\rho_{\text{SFR}}, \quad (2.2)$$

where $\rho_{\star}$ is the stellar mass density and R is the fraction of newly formed stellar mass returned to the interstellar medium. The value of R depends primarily on the stellar initial mass function (IMF) and on the adopted stellar population models. Integrating the star formation rate density over cosmic time therefore provides a prediction for the accumulated stellar mass. Observationally, however, ρ_{SFR} is not measured directly: instead it is inferred from luminosity densities associated with different star formation tracers. For example, as we already mentioned, rest-frame ultraviolet emission traces the light

from young massive stars, while infrared emission traces stellar radiation absorbed and reprocessed by dust. The total star formation rate density can therefore be decomposed into an unobscured component, traced by the ultraviolet, and an obscured component, traced by the infrared.

$$\rho_{\text{SFR}} = \rho_{\text{SFR}}^{\text{UV}} + \rho_{\text{SFR}}^{\text{IR}}. \quad (2.3)$$

This decomposition is particularly important since dust attenuation can strongly affect ultraviolet measurements. In dusty galaxies, a large fraction of the radiation produced by young stars is absorbed by dust grains and re-emitted at infrared wavelengths (this will be explained in detail in Chapter 3). As a result, UV observations alone can underestimate the total star formation activity, especially in massive and dust-rich systems. Infrared and millimetre observations are therefore essential for recovering the obscured component of the cosmic star formation history (Kennicutt 1998; Kennicutt & Evans 2012).

A widely used empirical description of the cosmic star formation history is given by the Madau–Dickinson relation (Madau & Dickinson 2014), which summarizes the observed evolution of ρ_{SFR} from the local Universe to high redshift. In Figure 2.2, the star formation rate density increases from early cosmic times, reaches a maximum at $z \sim 2$, then declines by more than an order of magnitude toward the present day. This evolution reflects the changing balance between gas accretion, star formation, feedback and gas exhaustion across the galaxy population.

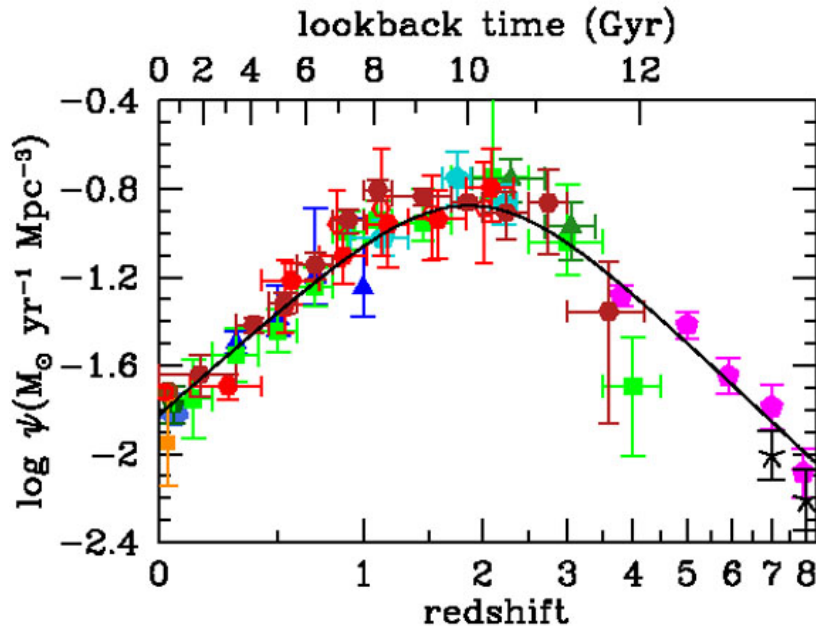


Figure 2.2: Cosmic star formation rate density as a function of redshift. The curve illustrates the characteristic rise of the star formation activity toward Cosmic Noon at $z \sim 2$ and its subsequent decline toward the local Universe. Figure from Madau & Dickinson 2014.

The cosmic star formation history is therefore not only a census of star formation over billions of years, but also a probe of galaxy evolution. Its shape encodes the efficiency with which galaxies accrete gas, form stars or enrich the interstellar medium and regulate their growth through feedback. For this reason, accurate measurements of ρ_{SFR} are essential for testing models of galaxy formation and for understanding the build-up of stellar mass over cosmic time.

The peak of the cosmic star formation rate density at $z \sim 1\text{--}3$ is commonly referred to as Cosmic Noon. During this epoch, the Universe experienced its most intense phase of star formation and black hole growth (see Figure 2.2). During this period galaxies were, on average, more gas-rich and more actively star-forming than in the local Universe, while the number density of luminous infrared galaxies and AGNs was significantly higher than today (Förster Schreiber & Wuyts 2020). After Cosmic Noon, the SFRD declines steadily till present days. This decline is associated with several physical processes: the average gas accretion rate onto galaxies decreases with cosmic time, the gas reservoirs available for star formation are progressively consumed or heated, and feedback processes became increasingly effective in suppressing star formation for massive systems (Heckman & Best 2014). For example, AGN feedback is thought to contribute to the quenching of massive galaxies by heating or expelling gas from regions around it where it could otherwise cool and form stars (Somerville & Davé 2015; Naab & Ostriker 2017). At redshifts above the peak, the decrease in the star formation rate density toward the earliest epochs reflects the progressive build-up of the first galaxy populations. As we previously mentioned in Section 1.2, dark matter halos were less massive and numerous, and galaxies had accumulated less stellar mass. Moreover, measurements become increasingly uncertain at these redshifts because galaxies are fainter and the accessible cosmic time intervals are shorter such that corrections for incompleteness become larger.

Observationally, the Cosmic Noon is also the epoch in which dust-obscured star formation becomes especially important. Many of the most actively star-forming galaxies at $z \sim 1\text{--}3$ emit a large fraction of their bolometric luminosity in the IR. Consequently, IR surveys have shown that dust-obscured galaxies provide a non-negligible contribution to the total SFRD around the Cosmic Noon (Burgarella et al. 2013; Zavala et al. 2021). A complete reconstruction of the cosmic star formation history therefore requires accounting for both unobscured and obscured star formation. While UV emission provides a direct tracer of young stellar populations, it is strongly affected by dust attenuation. In dusty systems, the absorbed light is re-emitted in the IR, making the total IR luminosity a key tracer of obscured star formation (see Chapter 3, Casey et al. 2014). However, the interpretation of the infrared luminosity is not always straightforward. Infrared emission can be powered by star formation, but AGNs can also heat dust and contribute to the mid/far-IR emission (see Chapter 4). If this AGN contribution is not properly accounted for, the IR luminosity attributed to star formation may be overestimated. This is particularly relevant for studies as this one, where systematic biases in L_{IR} can propagate into the derived luminosity functions and integrated SFRD.

Dust, Infrared Emission and Obscured Star Formation

The reconstruction of the cosmic star formation history requires a complete census of both unobscured and obscured star formation. While young and massive stars emit a large fraction of their radiation at ultraviolet wavelengths, this emission can be strongly affected by the interstellar dust. Dust grains can absorb or scatter ultraviolet and optical photons, modifying the observed spectral energy distribution of a galaxy and, in dust-rich systems, it can hide a substantial fraction of the ongoing star formation activity. The absorbed energy is then re-emitted at infrared and submillimetre wavelengths, making infrared observations essential for recovering the obscured component of galaxy growth.

This chapter introduces the physical properties and role of the interstellar dust in galaxies and its impact on the interpretation of star formation tracers. The first section describes the main properties of dust grains and their effect on ultraviolet and optical radiation. The following section then discusses infrared re-emission, the principle of energy balance, and the use of the total infrared luminosity as a tracer of obscured star formation.

3.1 Interstellar dust in galaxies

Interstellar dust is a minor component of the baryonic mass of galaxies, but it has a major impact on their observed emission. For example in the Milky Way, the dust-to-gas mass ratio is of order $\sim 1\%$, although the value can vary with metallicity, environment and galaxy evolutionary stage (Draine 2003; Galliano et al. 2018). Despite this small mass fraction, dust grains interact efficiently with radiation over a broad wavelength range because of their comparable or smaller size than the wavelength. They absorb and scatter ultraviolet and optical photons, contribute to the heating and cooling balance of the interstellar medium itself, and re-emit the absorbed energy in the infrared. As a consequence, dust affects both the observed colours of galaxies and the inferred physical properties derived from their spectra or photometric analyses.

The broad range of observational signatures produced by interstellar dust is summarized in Figure 3.1. Dust affects the emergent spectrum over almost the entire electromagnetic range: it removes stellar radiation at ultraviolet and optical wavelengths, produce characteristic spectral features and re-emits the absorbed energy in the infrared.

A useful way to understand the interaction between dust and radiation is to compare grain radius a with the wavelength of the incoming photon λ . The relevant quantity is the size parameter

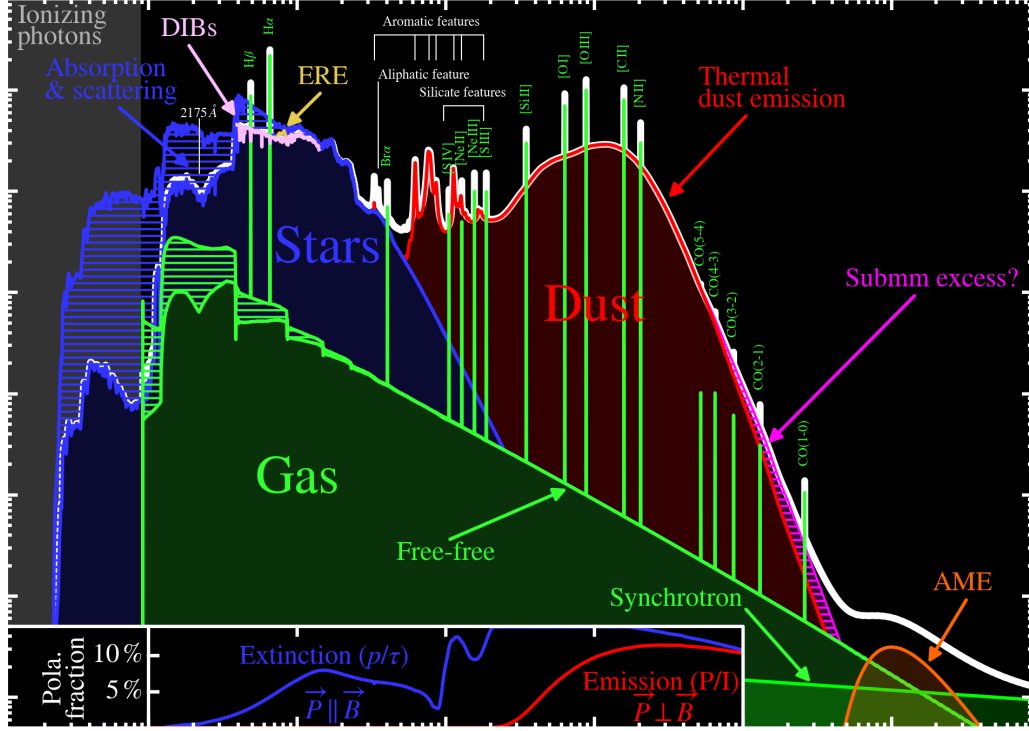


Figure 3.1: Panchromatic representation of the main observational signatures associated with interstellar dust, superimposed on the spectral energy distribution of a typical gas-rich late-type galaxy. At ultraviolet and optical wavelengths, dust removes part of the stellar radiation through absorption and scattering, while the absorbed energy is re-emitted as the broad thermal component dominating the infrared output. The diagram also marks diffuse interstellar bands, extended red emission, aromatic, aliphatic and silicate features, polarized extinction and emission, anomalous microwave emission and several relevant atomic, molecular and non-thermal components. Reproduced from Fig. 2.10 of [Galliano 2022](#); the underlying galaxy SED is based on [Galliano et al. 2018](#).

$$x = \frac{2\pi a}{\lambda} \quad (3.1)$$

When $x \sim 1$, the interaction between the radiation and grains is particularly efficient. Since typical interstellar grains have radii from a few nanometers to a few microns, they interact strongly with ultraviolet and optical photons. This explains why dust attenuation is generally stronger at shorter wavelengths and why rest-frame ultraviolet observations are especially sensitive to dust obscuration.

The physical properties of dust are determined by size, composition, temperature and spatial distribution of the grains. A classical description of the interstellar dust from [Mathis et al. 1977](#) assumes a population of grains with the MRN distribution (Mathis, Rumpl & Nordsieck distribution), in which the number of grains per unit radius follows a power law

$$n(a) da \propto a^{-3.5} da \quad (3.2)$$

extending from very small particles ($a \sim 0.005 \mu\text{m}$) to larger grains with sizes ($a \sim$

0.25 μm). More recent and detailed models such as [Weingartner & Draine 2001](#) or [Draine & Li 2007](#) include mixtures of carbonaceous grains, silicates and polycyclic aromatic hydrocarbons, whose relative abundance and size distribution determine how the extinction curve behaves and the shape of the infrared emission spectrum. Properties of the dust and their abundances can vary significantly between different galaxies and different phases of the interstellar medium. Although modern dust models are more complex, this relation illustrates an important point: most of the grain mass is carried by large grains, while the total surface area, and therefore the number of possible interactions with radiation, can be affected by smaller grains. This is why the grain-size distribution can directly influence both the shape of the extinction curve and the infrared emission spectrum.

The absorption or scattering cross-section of a grain can be written as:

$$C_{\text{abs/sca}}(\lambda, a) = \pi a^2 Q_{\text{abs/sca}}(\lambda, a) \quad (3.3)$$

where $Q_{\text{abs/sca}}$ is the absorption or scattering efficiency, while the geometrical factor πa^2 represents the projected area of the grain. For this reason, two galaxies with the same dust mass can show significantly different attenuation curves if their grain populations or dust geometries are different.

Interstellar dust is not composed of a single type of grain: it generally includes silicate and carbonaceous grains or very small polycyclic aromatic hydrocarbons, commonly called PAHs ([Draine & Li 2007](#)). In detail:

- *Silicate grains* are mainly composed of oxygen-rich refractory material. They absorb and emit efficiently in the infrared and are associated with broad absorption features around 9.7 μm and 18 μm ([Draine 2003](#)).
- *Carbonaceous grains* are primarily composed of carbon in graphite-like or amorphous structures. They absorb efficiently in the ultraviolet and optical wavelengths and therefore contribute significantly to the extinction of stellar light. In models such as [Weingartner & Draine 2001](#), carbonaceous grains are responsible for the ultraviolet extinction bump at 2175 Å. Their infrared behaviour depends strictly on their size: while small grains can be heated by photons and emit in near- and mid-IR, larger grains can reach approximate thermal equilibrium and contribute to the broader infrared continuum.
- *Polycyclic aromatic hydrocarbons* are very small carbon-based molecules composed by aromatic rings. Because of their small size, PAHs can undergo stochastic heating from the absorption of ultraviolet photons, producing prominent emission bands in the mid-IR, for example near 6.2, 7.7 and 8.6 μm . These bands are strong in star-forming galaxies, where PAHs are excited by ultraviolet photons.

Figure 3.2 shows electron-microscopy images of presolar grains from primitive meteorites as an example.

Dust grains are also part of a continuous life cycle. They can form in atmospheres of evolved stars, supernova ejecta and through accretion in dense molecular clouds (grain growth). At the same time, they can be destroyed or modified in size by shocks, intense radiation fields and grain-grain collisions ([Galliano et al. 2018](#)). The dust content of a galaxy therefore depends on lots of factors: galaxy star formation history, metal abundances and enrichment, gas content and interstellar medium conditions.

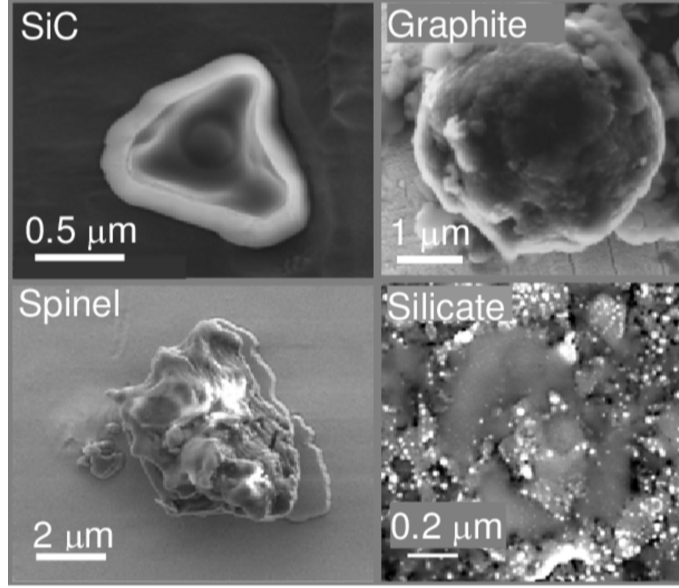


Figure 3.2: Electron-microscopy images of presolar grains isolated from primitive meteorites, including silicon carbide, graphite, spinel and silicate grains. Their submicron-to-micron sizes and heterogeneous morphologies illustrate the diversity of refractory solids produced in stellar environments. Their presolar origin is established primarily from anomalous isotopic abundances rather than from morphology alone. Images from [Hoppe 2010](#), courtesy of the Max Planck Institute for Chemistry, as reproduced in [Galliano 2022](#).

Besides their nature, their effect on radiation can be summarized through the concept of optical depth. Along a given line of sight, the optical depth τ at wavelength λ is:

$$\tau_\lambda = \int \kappa_\lambda \rho_{\text{dust}} ds \quad (3.4)$$

where κ_λ is the dust mass absorption coefficient, ρ_{dust} is the dust mass density and ds is the path length through the dusty medium. For a simple uniform slab, this can be approximated as

$$\tau_\lambda \simeq \kappa_\lambda \Sigma_{\text{dust}} \quad (3.5)$$

where Σ_{dust} is the dust surface density. This expression shows that dust obscuration depends both on the amount of dust and on its wavelength-dependent opacity. Since κ_λ is generally larger in the ultraviolet than in the optical or near-IR, the same dust column can have much stronger effects on young stellar light (UV emission) rather than on older stellar populations. Figure 3.3 shows a multiwavelength view of the Andromeda galaxy as an example of multiwavelength emission.

In summary, from an observational point of view, dust acts both as an obstacle and as a diagnostic. It is an obstacle because it can hide young stars and bias estimates of star formation, based on ultraviolet luminosities. At the same time, it is a diagnostic because the absorbed energy is re-emitted at infrared wavelengths, where it can be used to recover the obscured component of star formation. This dual role is crucial for this thesis.

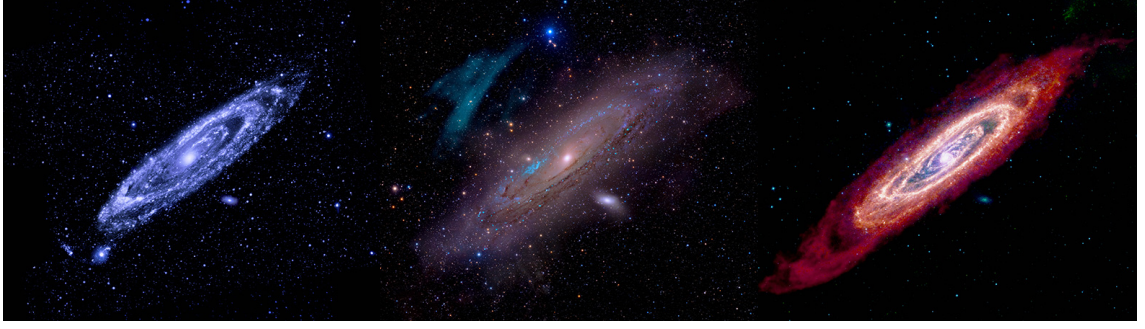


Figure 3.3: Multiwavelength view of the Andromeda galaxy (M31). From left to right: ultraviolet emission with GALEX (Martin et al. 2005), tracing young and unobscured stellar populations; optical emission from ground-based imaging, dominated by the integrated light of stellar populations; infrared emission from dust, traced by facilities such as Spitzer (Werner et al. 2004), COBE (Boggess et al. 1992), Planck (Planck Collaboration et al. 2011) and Herschel (Pilbratt et al. 2010). The comparison illustrates how different wavelength regimes trace different physical phenomena in a galaxy.

3.2 Dust attenuation and star formation obscuration

The impact of dust on the observed stellar emission is commonly described using the two concepts of extinction and attenuation. Extinction describes the absorption and scattering of light along a single line of sight, as in the case of a background source observed through a foreground dust screen. Attenuation describes the net modification of the integrated emission of a galaxy, where stars and dust are mixed (Calzetti 2001; Salim & Narayanan 2020).

A direct visual example of extinction by foreground material is provided by dark nebulae. In these systems, the dust cloud is located between the observer and a dense background stellar field. Absorption and scattering remove optical photons from the line of sight, making the cloud appear as a dark region even though it does not correspond to a physical absence of background stars. The Ink Spot Nebula shown in Figure 3.4, closely illustrates the foreground-screen geometry used in the simplest extinction model.

For a simple foreground uniform screen, the relation between intrinsic and observed flux is

$$\Phi_{\lambda,\text{obs}} = \Phi_{\lambda,\text{int}} e^{-\tau_{\lambda}} \quad (3.6)$$

where $\Phi_{\lambda,\text{int}}$ is the intrinsic flux, $\Phi_{\lambda,\text{obs}}$ is the observed one and τ_{λ} is the optical depth. The attenuation in magnitudes is therefore

$$A_{\lambda} = -2.5 \log_{10} \left(\frac{\Phi_{\lambda,\text{obs}}}{\Phi_{\lambda,\text{int}}} \right) = 1.086 \tau_{\lambda} \quad (3.7)$$

This simple relation is useful because it connects the physical optical depth of the dust to the observable dimming of the galaxy light. However, this is just an observable simplification, since real galaxies are more complex than a foreground uniform screen: the star distribution can vary within the galaxy.

The wavelength dependence of attenuation is usually described through an attenuation curve, whose common definition is

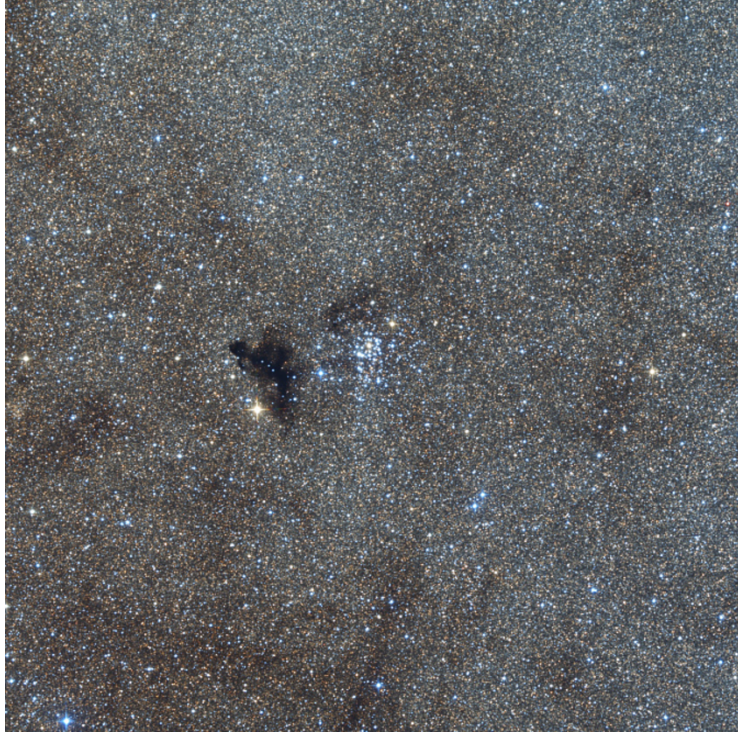


Figure 3.4: Optical image of the Ink Spot Nebula, Barnard 86, observed in projection against the dense stellar background of the Milky Way. The apparent deficit of stars inside the dark region is produced by a foreground interstellar cloud whose dust absorbs and scatters the optical radiation emitted by background sources. The object therefore provides a direct visual example of interstellar extinction in an approximately foreground-screen geometry. Image credit: Gábor Tóth Astrophotography; reproduced via [Galliano 2022](#).

$$k(\lambda) = \frac{A_\lambda}{E(B - V)} \quad (3.8)$$

where $E(B - V) = A_B - A_V$ is the colour excess. The shape of k_λ determines how strongly different wavelengths are attenuated. In general, the attenuation is stronger in the ultraviolet rather than in the optical, which means that the youngest stellar populations are the most affected observationally. Empirical attenuation curves, such as the Calzetti law ([Calzetti 2001](#)), are therefore widely used to correct the ultraviolet and optical emission of stars. In this context, since the targets of this thesis are extragalactic sources, the observer measures the integrated light from many stellar populations and many dusty regions within the galaxy. The observed attenuation depends not only on the grain properties we described, but also on galaxy inclination, dust-star geometry, clumpiness of the medium, spatial distribution of stars (see Fig. 3.5). Consequently, an attenuation law is not a universal property of dust itself, but a description of how it relates to the environment ([Salim & Narayanan 2020](#)).

A useful observational diagnostic of dust obscuration is the infrared excess, usually defined as

$$\text{IRX} = \log_{10} \left(\frac{L_{\text{IR}}}{L_{\text{UV}}} \right) \quad (3.9)$$

where L_{IR} measures the observed infrared luminosity and L_{UV} the ultraviolet one.

In this context L_{IR} is the dust-reprocessed luminosity, while L_{UV} is the escaped ultra-violet emission. High values of IRX indicate that most of the recent star formation is obscured and then re-emitted in the infrared. Relations between IRX and the ultraviolet continuum slope have been widely used to estimate dust attenuation in star-forming galaxies, although their applicability depends on galaxy type (i.e. spiral, elliptical) and star formation history (Meurer et al. 1999).

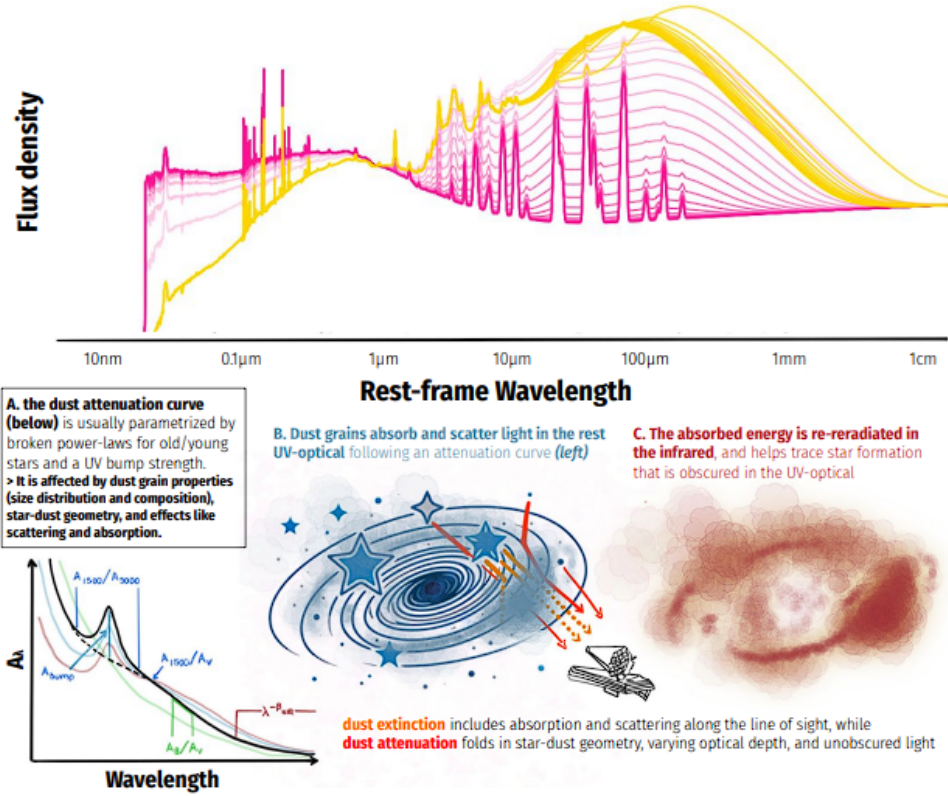


Figure 3.5: Schematic illustration of the effects of dust on galaxy emission. Top: a galaxy spectrum with varying levels of attenuation (pink) and with varying parameters for dust re-emission (yellow). Bottom: the dust attenuation curve parameters based on Salim & Narayanan 2020 and a schematic showing dust attenuation. Figure adapted from Iyer et al. 2025.

3.3 Infrared emission and total infrared luminosity

The absorption of ultraviolet and optical radiation by dust is not simply a loss of information. As we already mentioned, dust grains are heated by the absorbed photons and the energy is re-emitted at longer wavelengths, mainly in the infrared and sub-millimetre regimes. This process produces the characteristic infrared bump observed in the spectral energy distributions of dusty galaxies or AGNs. The shape of this emission depends on the distribution of dust temperatures, on the grain composition and size and on the intensity of the radiation field heating the grains.

For relatively large grains in approximate thermal equilibrium, the dust temperature is given by the balance between the absorbed and emitted power. In simple terms, this condition can be written as

$$\int_0^\infty C_{\text{abs}}(\nu) J_\nu d\nu = \int_0^\infty C_{\text{abs}}(\nu) B_\nu(T_{\text{dust}}) d\nu \quad (3.10)$$

where $C_{\text{abs}}(\nu)$ is the absorption cross-section of the grain, J_ν is the mean intensity of the radiation field, $B_\nu(T_{\text{dust}})$ is the Planck function and T_{dust} is the equilibrium temperature of the dust. This expression shows that dust temperature is not an intrinsic property of the grain alone, but depends on the local radiation field too. Dust close to young massive stars is generally warmer, rather than dust in the diffuse interstellar medium, which is colder.

At far-infrared and sub-millimetre wavelengths, the emission from large grains is often approximated as a modified blackbody

$$L_\nu \propto \nu^\beta B_\nu(T_{\text{dust}}) \quad (3.11)$$

where β is the dust emissivity index. The factor ν^β accounts for the fact that dust grains do not radiate as perfect blackbodies, but have a frequency-dependent emissivity (Hildebrand 1983). Typical values are $\beta \sim 1\text{--}2$, although the exact value depends on grain properties and on the modelling assumptions. This approximation is especially useful to describe the dusty peak and the Rayleigh–Jeans tail of the dust SED. The position of the thermal peak is mainly controlled by the dust temperature: a warmer dust component peaks at shorter wavelengths, while colder peaks at longer wavelengths. If we assume pure blackbody emission, Wien’s displacement law gives

$$\lambda_{\text{peak}} T \simeq 2.9 \times 10^3 \mu\text{m K} \quad (3.12)$$

Although real galaxy SEDs are broader than a single blackbody because they contain dust at different temperatures (multicolour-blackbodies), this relation proves us what we mentioned earlier: dust at $T_{\text{dust}} \sim 30\text{--}50$ K emits most strongly in the far-infrared, while colder dust contributes significantly to the submillimetre and millimetre emission.

A central assumption in many panchromatic SED-fitting methods is energy balance. In other words, the energy removed from the stellar emission by dust attenuation must be all re-emitted in the infrared. Schematically, this can be written as

$$L_{\text{abs}} = \int [L_\lambda^{\text{int}} - L_\lambda^{\text{att}}] d\lambda \simeq L_{\text{dust}} \quad (3.13)$$

where L_λ^{int} is the intrinsic stellar luminosity, L_λ^{att} is the attenuated luminosity emerging from the galaxy and L_{dust} is the luminosity re-emitted by the dust. This principle provides the physical link between dust attenuation and infrared re-emission.

We can define the total infrared luminosity L_{IR} as the integrated luminosity over the rest-frame wavelength range $8\text{--}1000 \mu\text{m}$. In other words

$$L_{\text{IR}} = \int_{8 \mu\text{m}}^{1000 \mu\text{m}} L_\lambda d\lambda \quad (3.14)$$

This wavelength interval is chosen to include most of the dust emission, from the mid-infrared regime to the far-infrared and sub-millimetre regimes. Figure 3.6 shows an example of a spectral energy distribution fit of a dusty galaxy.

The conversion between the total infrared luminosity and star formation rate depends

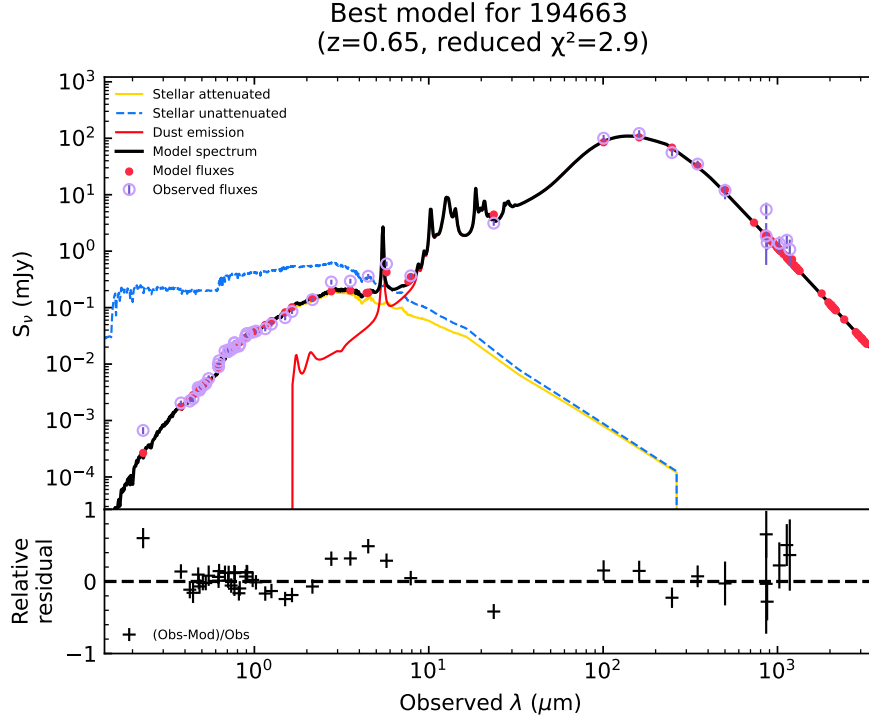


Figure 3.6: Example of a panchromatic spectral energy distribution of a dusty galaxy fit. The prominent far-infrared peak illustrates the reprocessing of ultraviolet and optical stellar radiation by interstellar dust, while the attenuated and unattenuated stellar emission curves show the effects of dust attenuation on stellar emission. Lower panel shows relative residuals. This example is one of the sources used in this thesis, as it will be explained in Chapter 5.

on assumptions about the stellar initial mass function, the star formation history and the timescale over which young stars dominate the dust heating. For a fully obscured and continuously star-forming population, the conversion can be written as

$$\text{SFR}_{\text{IR}} = K_{\text{IR}} L_{\text{IR}} \quad (3.15)$$

where K_{IR} is a calibration factor that depends on the adopted IMF and stellar population model (Kennicutt 1998; Kennicutt & Evans 2012). This relation allows the dust reprocessed luminosity to be translated into star formation rate but it should not be interpreted as universally exact for each galaxy. Its validity depends on the assumption that the infrared emission is mainly powered by young stellar populations; in reality, the interpretation of L_{IR} can be affected by different factors. For example, older stellar population can contribute to the heating of diffuse dust, especially in galaxies with low specific star formation rates and limited infrared wavelength coverage can make the extrapolation of the full 8–1000 μm luminosity uncertain. In this sense, L_{IR} is fundamentally a tracer of dust heating, while it becomes a tracer of star formation only when the dominant heating source is associated with recently formed stars.

Robust measurements of L_{IR} therefore require both broad multiwavelength photometry and reliable constraints on the far-infrared or submillimetre emission. At high redshift, the far-infrared dust peak is shifted to longer observed wavelengths (see Chapter 1). Long-wavelength observations are therefore crucial for constraining the cold dust component and for reducing the dependence on assumed SED templates.

The previous chapter introduced interstellar dust as a physical component able to absorb ultraviolet and optical radiation and re-emit the absorbed energy in the infrared. This mechanism makes infrared luminosity a powerful tracer of dust-reprocessed emission but it also raises an important question: which physical source is responsible for heating the dust? In star-forming galaxies, dust heating is often dominated by young stellar populations; however, galaxies can also host active galactic nuclei (AGN), whose radiation is powered by accretion onto a central supermassive black hole (SMBH). This chapter introduces the physical structure and emission mechanisms of AGNs with particular attention to the origin of their infrared emission.

4.1 The unified model of active galactic nuclei

Active Galactic Nuclei are compact and extremely luminous regions located at the centres of galaxies. Their emission cannot be explained only by stellar processes but instead is powered by the accretion of gas onto a supermassive black hole. The masses of supermassive black holes in galactic nuclei typically range from about 10^6 to $10^{10} M_{\odot}$, depending on the host galaxy and on the evolutionary stage of the system (Kormendy & Ho 2013). Because accretion onto a black hole can convert gravitational potential energy into radiation with relatively high efficiency, AGNs can easily outshine the stellar emission of their host galaxies, especially in the most luminous quasars.

The unified model of AGNs provides a framework in which many observational differences between AGN classes are interpreted in terms of geometry, orientation and intrinsic luminosity rather than completely distinct physical objects (Antonucci 1993; Urry & Padovani 1995). The basic picture assumes that the central engine is composed of a supermassive black hole surrounded by an accretion disk. Such disk produces intense ultraviolet and optical radiation, which can photoionize gas clouds located at different distances from the nucleus. Gas moving rapidly close to the black hole gives rise to broad emission lines, forming the Broad Line Region (BLR), while more extended and lower-density gas produces narrower forbidden and permitted lines, forming the Narrow Line Region (NLR) (Netzer 2015). In addition, a dusty circumnuclear structure surrounds the central regions and can obscure the direct view of the accretion disk and BLR for some lines of sight. Figure 4.1 shows a schematic representation of the main physical components of an Active Galactic Nucleus.

The main physical components of an AGN can be summarized as follows:

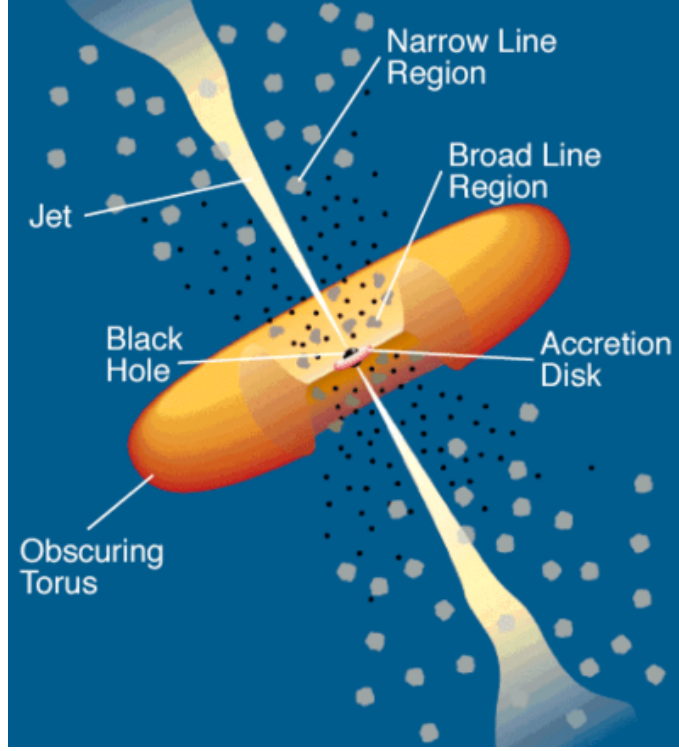


Figure 4.1: Schematic representation of the main physical components of an active galactic nucleus, adapted from Urry & Padovani 1995. The central supermassive black hole is surrounded by an accretion disk and by a compact X-ray emitting corona. Gas clouds close to the nucleus form the Broad Line Region, while dust located farther out can survive in a circumnuclear obscuring structure, often referred to as dusty torus. On larger scales, lower-density gas produces the Narrow Line Region and in some cases, relativistic jets can be launched along the polar axis.

- *Supermassive black hole.* The central supermassive black hole is the compact object that defines the gravitational potential of the nuclear region and powers the AGN through accretion. Its mass is typically in the range of $M_{\text{SMBH}} \sim 10^6\text{--}10^{10} M_{\odot}$, although the exact value depends on the host galaxy and on the growth history of the system (Kormendy & Ho 2013). A useful length scale is the gravitational radius, defined as

$$r_g = \frac{GM_{\text{SMBH}}}{c^2} \quad (4.1)$$

which sets the characteristic scale of the innermost accretion flow. For a black hole of $10^8 M_{\odot}$, this corresponds to $r_g \simeq 1.5 \times 10^{13} \text{ cm}$.

- *Accretion disk.* Gas with angular momentum settles into an accretion disk around the black hole. In the standard picture, viscosity transports angular momentum outward and allows matter to move inward, converting gravitational energy into radiation (Shakura & Sunyaev 1973). The accretion disk emits mainly in the optical and ultraviolet, producing the so-called “big blue bump” observed in many unobscured quasars and Seyfert 1 galaxies (Elvis et al. 1994; Richards et al. 2006).
- *X-ray corona.* A compact region of hot electrons is thought to surround the inner accretion flow. Ultraviolet photons from the disk can be inverse-Compton scattered by this hot plasma, producing X-ray emission. This X-ray component is one of the most direct tracers of accretion power and is widely used to identify AGNs (Rees

1984; Netzer 2015).

- *Broad Line Region*. The Broad Line Region is composed of dense gas clouds located relatively close to the central engine. Their high velocities, produced by the strong gravitational field, generate broad permitted emission lines with widths of thousands of km s^{-1} . The BLR is visible in Type 1 AGNs, where the line of sight to the central engine is not strongly obscured.
- *Dusty torus*. At larger radii than the BLR, dust can survive and form a circumnuclear obscuring structure often referred to as the dusty torus. This component absorbs part of the optical and ultraviolet radiation from the accretion disk and re-emits it in the infrared (see Chapter 3). The torus plays a central role in the distinction between Type 1 and Type 2 AGNs (Fritz et al. 2006; Nenkova et al. 2008a; Nenkova et al. 2008b).
- *Narrow Line Region*. The Narrow Line Region is located on larger scales than the BLR and torus. Its gas has lower characteristic velocities and produces narrow permitted and forbidden emission lines. Since the NLR extends beyond the dusty torus, it can be visible both in Type 1 and Type 2 AGNs.
- *Relativistic jets*. In radio-loud AGNs, collimated relativistic jets can be launched from the innermost regions of the system, probably connected to the black hole spin, magnetic fields and the accretion flow. Jets emit strongly through synchrotron radiation at radio wavelengths and can also contribute at higher energies through inverse-Compton processes. When a relativistic jet is oriented close to the line of sight, Doppler boosting can make the source appear as a blazar (Urry & Padovani 1995; Padovani et al. 2017).

AGN classes are usually defined according to different observational properties. These classifications do not necessarily correspond to completely different physical objects, rather they often have differences in luminosity, viewing angle, obscuration, accretion state or jet orientation with the line of sight. The most common categories can be summarized as follows:

- *Type 1 and Type 2 AGNs*. This classification is based mainly on optical spectroscopy. Type 1 AGNs show both broad and narrow emission lines since the observer has a direct view of the BLR and the central continuum engine. Type 2 AGNs show only narrow emission lines, because the BLR and the accretion disk are obscured along the line of sight by the dusty torus.
- *Seyfert galaxies*. Seyfert galaxies are relatively low- to moderate-luminosity AGNs usually found in nearby galaxies. Their host galaxy is often still visible. Seyfert 1 and Seyfert 2 galaxies correspond broadly to the Type 1 and Type 2 categories, respectively.
- *Quasars*. Quasars are the most luminous radiatively efficient AGNs. In these systems, the nuclear emission can outshine the stellar light of the host galaxy, making them visible up to very high redshift. Their bolometric luminosities are typically of order $L_{\text{bol}} \sim 10^{45}\text{--}10^{48} \text{ erg s}^{-1}$.
- *Radio-quiet and radio-loud AGNs*. AGNs can also be divided according to the relative strength of their radio emission. Most AGNs are radio-quiet, meaning that their radio output is weak compared to their optical or X-ray emission. A smaller fraction are radio-loud and produce powerful relativistic jets, whose synchrotron radiation can dominate the radio emission and extend to larger scales in the form of radio lobes.

- *Radio galaxies.* Radio galaxies are radio-loud AGNs in which the jet is generally observed at a relatively large angle with respect to the line of sight.
- *Blazars.* Blazars are radio-loud AGNs whose relativistic jet is oriented close to the observer's line of sight. Because of relativistic Doppler boosting, the jet emission is strongly amplified, producing high apparent luminosities, rapid variability and emission across a broad range of wavelengths, from radio to gamma rays. Blazars are commonly divided into BL Lac objects and flat-spectrum radio quasars, depending on the strength of their emission lines (Urry & Padovani 1995; Padovani et al. 2017).

These categories show that the observed appearance of an AGN depends on several factors at the same time. Orientation determines whether the central engine and broad line region are directly visible. Obscuration determines how much of the nuclear radiation is absorbed and reprocessed. Luminosity and accretion rate determine whether the source appears as a low-luminosity nucleus, a Seyfert galaxy or a quasar. Finally, the presence and orientation of a relativistic jet determine whether the AGN is radio-quiet, radio-loud, a radio galaxy or a blazar (see Figure 4.2).

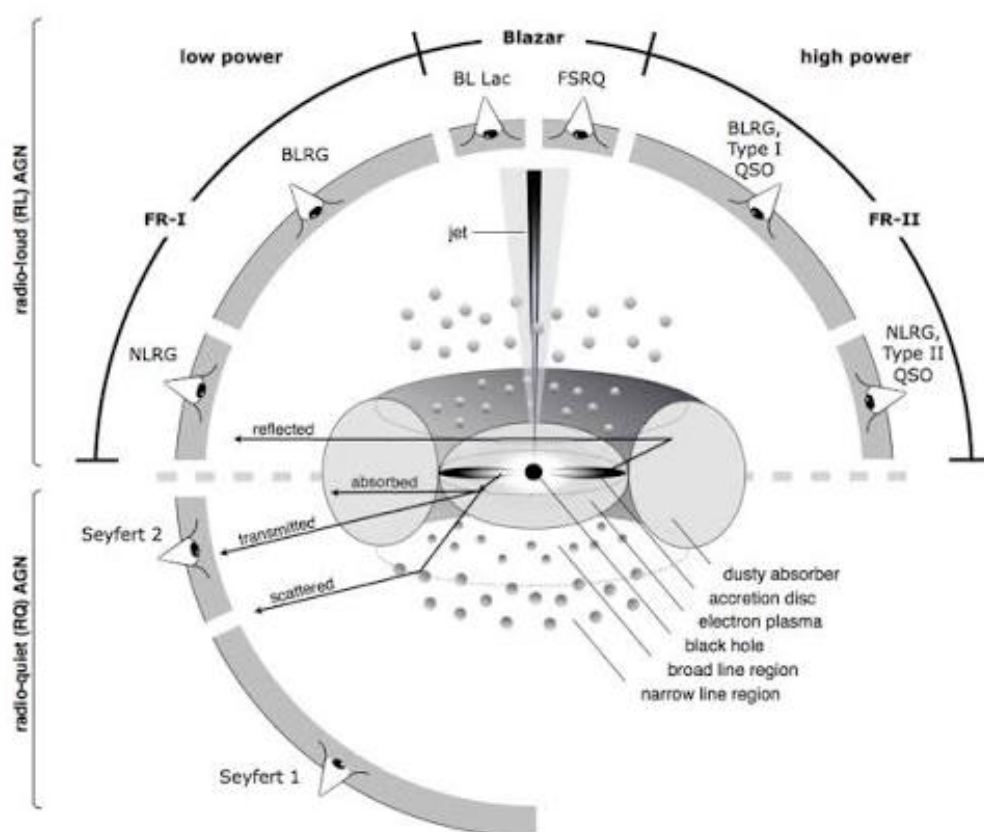


Figure 4.2: Schematic view of the main observational classes of Active Galactic Nuclei in the framework of the unified model. When the observer has a direct view of the accretion disk and BLR, the source is classified as Type 1 AGN; when these inner regions are hidden by the dusty torus, only the NLR is visible directly and the source appears as a Type 2 AGN. Differences in intrinsic luminosity distinguish lower-luminosity Seyfert galaxies from more luminous quasars, while the presence and orientation of relativistic jets define radio galaxies and blazars. Figure adapted from Zackrisson 2005.

4.2 Accretion process and multiwavelength AGN emission

The diversity of AGN classes described in the previous section is ultimately connected to a common physical origin: the release of gravitational energy by gas accreting onto a central supermassive black hole. If matter is accreted at a rate $\dot{M}_{\text{acc}}$, then the bolometric luminosity can be written as

$$L_{\text{bol}} = \eta \dot{M}_{\text{acc}} c^2 \quad (4.2)$$

where η is the radiative efficiency and c is the speed of light. For a radiatively efficient accretion disk, typical values are of order $\eta \sim 0.1$, although the exact value depends on the black hole spin and accretion geometry (Salpeter 1964; Lynden-Bell 1969; Shakura & Sunyaev 1973). This high efficiency explains why AGNs can reach luminosities comparable to, or greater than, those of their host galaxies.

A useful reference scale is the Eddington luminosity, L_{Edd} , defined as the luminosity at which the outward radiation pressure on the ionized gas balances the inward gravitational force. In other words, it is given by

$$L_{\text{Edd}} = 1.26 \times 10^{38} \left(\frac{M_{\text{SMBH}}}{M_{\odot}} \right) \text{erg s}^{-1} \quad (4.3)$$

This relation shows that the maximum characteristic luminosity of an accreting black hole scales linearly with its mass. For this reason, more massive black holes can sustain larger luminosities before radiation pressure becomes dynamically important. Some representative values are listed in Table 4.1.

Table 4.1: Typical Eddington luminosities for different supermassive black-hole masses. The values illustrate how the characteristic luminosity scale of an AGN increases linearly with black-hole mass.

M_{SMBH}	L_{Edd}	$L_{\text{Edd}}/L_{\odot}$
$10^6 M_{\odot}$	$1.3 \times 10^{44} \text{ erg s}^{-1}$	$3.3 \times 10^{10} L_{\odot}$
$10^8 M_{\odot}$	$1.3 \times 10^{46} \text{ erg s}^{-1}$	$3.3 \times 10^{12} L_{\odot}$
$10^{10} M_{\odot}$	$1.3 \times 10^{48} \text{ erg s}^{-1}$	$3.3 \times 10^{14} L_{\odot}$

Even a black hole accreting at only a fraction of its Eddington luminosity can produce an output comparable to, or larger than, the integrated stellar emission of the entire galaxy. For example, a $10^8 M_{\odot}$ black hole radiating at 10% of its Eddington luminosity would have $L_{\text{bol}} \sim 10^{45} \text{ erg s}^{-1}$, which is already in the regime of luminous Seyfert galaxies and quasars.

Furthermore, the ratio between the bolometric luminosity and the Eddington luminosity

$$\lambda_{\text{Edd}} = \frac{L_{\text{bol}}}{L_{\text{Edd}}} \quad (4.4)$$

is called the Eddington ratio and provides a measure of how rapidly the black hole is accreting relative to this theoretical limit. Low-luminosity AGNs can have $\lambda_{\text{Edd}} \lesssim 10^{-3}$ – 10^{-2} , while Seyfert galaxies and quasars are often found at higher values, typically $\lambda_{\text{Edd}} \sim 10^{-2}$ up to 1. Values close to unity correspond to rapidly accreting systems in which radiation pressure becomes important, while very low values indicate weak

accretion relative to the black hole mass. Figure 4.3 shows a multiwavelength view of AGN emission components.

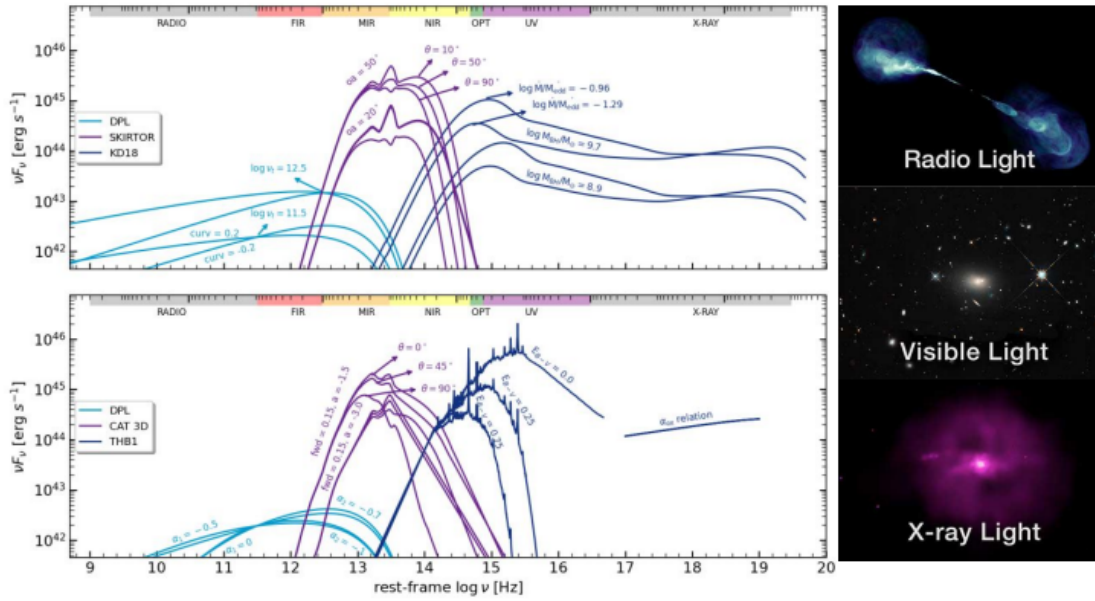


Figure 4.3: Multiwavelength view of AGN emission components. The left panel shows representative models of the AGN spectral energy distribution, including the accretion disk and X-ray emission, the hot nuclear dust emission from the torus and the radio synchrotron component. The right panel illustrates how AGN activity can be observed at different wavelengths using the radio galaxy Hercules A as an example. The figure highlights that AGN emission is intrinsically multi-component. Figure adapted from [Iyer et al. 2025](#), the SED models in the left panel are adapted from [Martínez-Ramírez et al. 2024](#).

The radiation produced by the accretion process does not emerge in a single wavelength regime. Instead, the observed AGN SED is the result of several physical components that dominate different parts of the electromagnetic spectrum ([Netzer 2015](#)). The primary source of energy is the accretion disk. In the standard geometrically thin and optically thick disk picture ([Shakura & Sunyaev 1973](#)), gas loses angular momentum through viscous processes and gradually moves inward. The gravitational energy released at each radius is locally converted into thermal radiation. Since the temperature increases toward smaller radii, the disk behaves approximately as a superimposition of blackbodies with different temperatures rather than as a single-temperature emitter. As a result, the accretion disk emits mainly in the optical and ultraviolet. The hottest inner regions dominate the ultraviolet output, while colder outer regions contribute more strongly in the optical wavelengths. In unobscured AGNs, this produces the characteristic “big blue bump”, which is one of the clearest signatures of radiatively efficient accretion, especially in Type 1 AGNs and quasars, where the line of sight allows a direct view of the central engine.

Closer to the inner accretion flow, a compact region of very hot electrons, commonly referred as the X-ray corona, modifies part of the disk radiation. Ultraviolet photons emitted by the accretion disk interact with these energetic electrons and gain energy through inverse-Compton scattering. This process produces a non-thermal X-ray continuum, usually modelled as a power law. The observed X-ray spectrum can then be further modified by absorption from gas along the line of sight, by scattering and reflection of dense mate-

rial close to the nucleus. Reflection can also produce characteristic spectral features, such as the iron $K\alpha$ line, making X-ray band a powerful probe of the innermost AGN regions (Rees 1984).

The ultraviolet and X-ray radiation from the central engine can also photoionize the gas surrounding the black hole. When ionized gas recombines, or also when electrons collisionally excite ions that later de-excite, emission lines are produced. The Broad Line Region is dense and close to the black hole, so the gas is moving at high velocities and produces broad permitted lines. The Narrow Line Region is located farther out, where the gas has lower characteristic velocities and lower densities, producing narrower permitted and forbidden lines. Therefore, emission lines are not an independent energy source, but merely the reprocessing of the ionizing continuum by the gas distributed around the nucleus.

At larger radii, dust can survive because the temperature drops below the sublimation limit of dust grains. This dusty torus absorbs part of the optical and ultraviolet radiation produced by the accretion disk and converts it into infrared emission. The hottest dust, located closer to the sublimation radius, emits mainly in the near-infrared, while the colder dust farther from the nucleus contributes at the mid-infrared wavelengths. The detailed shape of this infrared spectral component depends on the dust composition, geometry, optical depth, clumpiness and viewing angle (Fritz et al. 2006; Stalevski et al. 2016).

In radio-loud AGNs, an additional non-thermal component is produced by relativistic jets. Charged particles accelerated in the jet spiral around magnetic field lines and emit synchrotron radiation, which usually dominates the radio regime. The resulting spectrum is typically non-thermal and can extend to higher energies depending on the particle distribution, magnetic field strength and radiative losses. In some sources, inverse-Compton processes can further boost low-energy photons to X-ray or gamma-ray energies. If the jet is oriented close to the line of sight, relativistic beaming amplifies the observed emission, producing the extreme luminosities and variability typical of blazars (Padovani et al. 2017).

This multi-component nature makes AGNs identifiable across the electromagnetic spectrum, but it also complicates the interpretation of galaxy-integrated photometry. This complication is particularly important for this work in the infrared. Dust emission in galaxies is often used as a tracer of obscured star formation, but dust heated by an AGN can contribute to the same wavelength range, especially in the near- and mid-infrared regimes.

4.3 Separating AGN and star-formation infrared emission

Through Chapter 3 and in Section 4.2 it has been shown that both stellar populations and active galactic nuclei can heat dust and contribute to the infrared emission of a galaxy. The relevant observational problem is therefore not simply to establish whether an AGN is present, but also to determine how the total infrared output is distributed among the different physical components of the system. This distinction is essential because the infrared luminosity can be interpreted as a tracer of obscured star formation only after the contribution powered by the active galactic nucleus has been accounted for. For an unresolved galaxy, the measured spectral energy distribution is the sum of all emitting

components contained within the observational aperture. A simplified decomposition can be written as

$$\Phi_{\nu}^{\text{obs}} = \Phi_{\nu}^{\text{stars}} + \Phi_{\nu}^{\text{dust,SF}} + \Phi_{\nu}^{\text{AGN}} \quad (4.5)$$

where $\Phi_{\nu}^{\text{stars}}$ is the stellar continuum, $\Phi_{\nu}^{\text{dust,SF}}$ represents dust emission associated predominantly with stellar heating and Φ_{ν}^{AGN} includes the direct and reprocessed emission related to the active galactic nucleus. In real galaxies this decomposition is more complex since diffuse dust may also be heated by evolved stellar populations and because an AGN can illuminate material beyond the compact nuclear region. The main possibility for separating star formation and AGN activity arises from the different distributions of dust temperature produced by the two heating sources. Dust associated with the interstellar medium of star-forming galaxies is generally characterized by temperatures of a few tens of kelvin. Its far-infrared emission is often approximated by an optically thin modified blackbody

$$L_{\nu}^{\text{dust}} \propto \nu^{\beta} B_{\nu}(T_{\text{dust}}) \quad (4.6)$$

where $B_{\nu}(T_{\text{dust}})$ is the Planck function and β is the dust emissivity index, commonly with values in the range $\beta \sim 1.5\text{--}2$. For characteristic temperatures of $T_{\text{dust}} \sim 20\text{--}60$ K, the thermal emission reaches its maximum in the far-infrared, approximately between tens and more than one hundred micrometres in the rest frame (Draine 2011).

By contrast, dust exposed to the intense and concentrated radiation field of an AGN spans much wider and generally hotter temperature distribution. Dust near the sublimation boundary can reach temperatures of approximately 1000–1500 K, while material located further away can remain at temperatures of a few hundred kelvin. The superimposition of these temperatures produces a broad continuum extending from the near- to the mid-infrared (Hönig & Kishimoto 2017) (see Figure 4.4). Therefore, AGN-dominated systems often display a relatively smooth and rising infrared continuum at wavelengths of a few micrometers, whereas star-forming systems exhibit a more prominent far-infrared peak.

This difference does not generate a sharp boundary between the two components. Star-forming regions also contain warm dust close to young massive stars, which contributes in the mid-infrared. At the same time, AGN radiation can heat colder dust at larger distances from the nucleus and may therefore contribute beyond the torus-dominated wavelength range. The observed infrared SED is consequently formed by overlapping temperature distributions rather than by two isolated peaks. A few single measurements cannot generally determine which heating source dominates the integrated observed infrared luminosity (Mullaney et al. 2011).

Spectral features provide additional information because they respond differently to star formation, nuclear radiation and dust geometry. Among the most important diagnostics are the emission bands associated with polycyclic aromatic hydrocarbons (see Section 3.1), particularly those near 6.2, 7.7, 8.6 and 11.3 μm . Their diagnostic power is affected by the underlying continuum. The equivalent width of a PAH feature can be written as

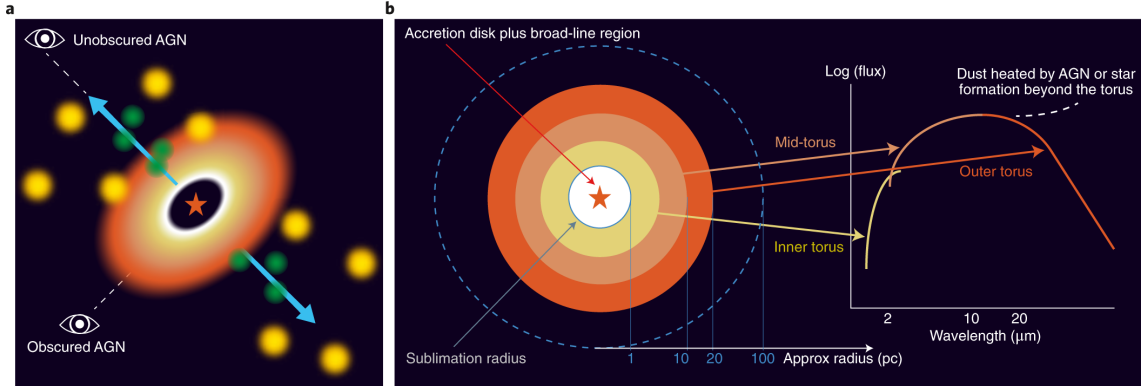


Figure 4.4: Schematic representation of the geometry and infrared emission of the dusty torus in an AGN. Panel (a) illustrates how a non-uniform distribution of dust can produce unobscured and obscured lines of sight toward the central engine. Panel (b) shows the radial temperature stratification of the dusty region: material close to the sublimation radius reaches the highest temperatures and contributes mainly to the near-infrared emission, while progressively cooler dust at larger radii dominates at longer wavelengths. Beyond the classical torus, the infrared emission may include contributions from dust heated either by the AGN or by star formation in the host galaxy, making the two components increasingly difficult to separate. Reproduced from Fig. 1 of [Lacy & Sajina 2020](#).

$$EW_{\text{PAH}} = \int_{\lambda_1}^{\lambda_2} \frac{\Phi_{\lambda} - \Phi_{\lambda,\text{cont}}}{\Phi_{\lambda,\text{cont}}} d\lambda \quad (4.7)$$

where $\Phi_{\lambda,\text{cont}}$ is the estimated continuum beneath the feature. If an AGN adds a strong and smooth mid-infrared continuum, the value of $\Phi_{\lambda,\text{cont}}$ increases and the measured equivalent width decreases, even if the absolute PAH luminosity associated with star formation remains unchanged. Weak PAH equivalent widths can therefore indicate that a continuum source dilutes them, rather than that there is a complete absence of star formation. In addition, hard radiation fields and shocks close to the nucleus may alter the charge state or size distribution of the aromatic grains, further modifying the relative strengths of the PAH bands ([Diamond-Stanic & Rieke 2010](#)).

The silicate features near 9.7 and $18 \mu\text{m}$ probe a different aspect of the system. These features arise from vibrational modes in silicate grains and can appear both in emission and absorption. Their strength is commonly described as

$$S_{\text{sil}} = \ln \left[\frac{\Phi_{\nu}(\lambda_{\text{feature}})}{\Phi_{\nu,\text{continuum}}(\lambda_{\text{feature}})} \right] \quad (4.8)$$

Positive values correspond to emission and negative to absorption. Silicate absorption indicates that warm infrared-emitting material is viewed through a substantial dust column, whereas emission can occur when directly illuminated dust surfaces are visible. However, the feature is not determined just by orientation. Its shape and strength also depend on optical depth, clumpiness, grain composition and relative spatial distribution of the emitting and absorbing material. For this reason, the silicate feature constrains the geometry and obscuration of the nuclear region, but does not provide a unique measurement of the AGN luminosity ([Feltre et al. 2012](#)).

The separation between AGN and stellar formation emission is also influenced by spatial resolution. The AGN-emitting region is typically more compact than the stellar

and interstellar components of its host galaxy. However, for distant objects, photometric measurements usually integrate the nuclear emission, circumnuclear star formation and the extended host within the same aperture. The observed SED therefore does not directly identify the physical size of the emitting region. At the same time, a luminous mid-infrared source may correspond to a compact AGN, an intense nuclear starburst or a combination of both. High angular resolution observations can reduce this ambiguity, but for large extragalactic samples the decomposition is generally performed using spectral shape rather than spatial information.

For our purpose, a quantitative AGN contribution must therefore be defined over a specific wavelength interval. A general definition is

$$f_{\text{AGN}}^{[\lambda_1, \lambda_2]} = \frac{\int_{\lambda_1}^{\lambda_2} L_{\lambda}^{\text{AGN}} d\lambda}{\int_{\lambda_1}^{\lambda_2} (L_{\lambda}^{\text{AGN}} + L_{\lambda}^{\text{dust, SF}}) d\lambda} \quad (4.9)$$

This definition makes clear that f_{AGN} is not an intrinsic number independent of wavelength. As we already said, since AGN-heated dust contributes more strongly at shorter infrared wavelengths, a fraction measured in the near- or mid-infrared is generally larger than the fraction obtained by integrating the total infrared emission from 8 to 1000 μm . Reliable AGN fractions must be determined from rest-frame SED coverage rather than from fixed observed colours alone.

Based on what we said earlier, the total infrared luminosity can be written as

$$L_{\text{IR}}^{\text{obs}} = L_{\text{IR}}^{\text{SF}} + L_{\text{IR}}^{\text{AGN}} \quad (4.10)$$

where all quantities must refer to the same integration interval. If the AGN fraction is defined over this interval, then

$$L_{\text{IR}}^{\text{SF}} = (1 - f_{\text{AGN}}) L_{\text{IR}}^{\text{obs}} \quad (4.11)$$

This correction has direct impact on all computations that include the L_{IR} , as the star formation rate. For a fixed Initial Mass Function (IMF) and calibration

$$\text{SFR}_{\text{IR}} = K_{\text{IR}} L_{\text{IR}}^{\text{SF}} \quad (4.12)$$

where K_{IR} depends on the assumed IMF, stellar population and star-formation timescale (Kennicutt 1998; Kennicutt & Evans 2012). If the entire observed infrared luminosity is instead attributed to star formation, the ratio between the uncorrected and corrected estimates is

$$\frac{\text{SFR}_{\text{IR}}^{\text{uncorrected}}}{\text{SFR}_{\text{IR}}^{\text{true}}} = \frac{1}{1 - f_{\text{AGN}}} \quad (4.13)$$

The relation is non-linear. An AGN fraction of $f_{\text{AGN}} = 0.2$ produces a 25% overestimate of the true SFR, while $f_{\text{AGN}} = 0.5$ causes the SFR to be overestimated by a factor 2. If $f_{\text{AGN}} = 0.8$, only 20% of the luminosity is associated with star formation and the uncorrected SFR is 5 times higher than the corrected value. As an illustrative example, a

source with $L_{\text{IR}}^{\text{obs}} = 10^{12} L_{\odot}$ and a $f_{\text{AGN}} = 0.4$ has

$$L_{\text{IR}}^{\text{SF}} = 6 \times 10^{11} L_{\odot}$$

and using the approximate conversion

$$\text{SFR}_{\text{IR}} \simeq 10^{-10} \left(\frac{L_{\text{IR}}^{\text{SF}}}{L_{\odot}} \right) M_{\odot} \text{ yr}^{-1}$$

the uncorrected luminosity would imply an SFR of approximately $100 M_{\odot} \text{ yr}^{-1}$, while the corrected luminosity would imply approximately $60 M_{\odot} \text{ yr}^{-1}$. This discrepancy does not arise from the star-formation calibration itself, but from assigning AGN-powered luminosity to stellar heating.

In practice, the decomposition is constrained by combining wavelength regions that respond differently to the physical components. Ultraviolet, optical and near-infrared photometry constrains the stellar continuum and attenuation. Mid-infrared data constrain the hot-dust continuum, PAH emission and silicate features. Far-infrared and submillimetre observations constrain the cold-dust peak. Removing any of these wavelength regions increases the degeneracy among stellar emission, dust temperature and AGN contribution (Ciesla et al. 2015).

The objective is not to exclude every source in which an AGN is detected. The presence of an active galactic nucleus does not imply that the host galaxy has no star formation or that its total infrared luminosity is AGN-dominated. Removing all AGN hosts would therefore eliminate genuine star-forming systems and introduce additional kind of biases. The physically meaningful approach is to retain the sources and determine, within the uncertainties allowed by the photometric coverage and adopted models, how their observed energy output is divided between nuclear activity and stellar heating.

This motivates the panchromatic SED-fitting analysis presented in the following chapters. By modelling the stellar, dust and AGN components simultaneously and by explicitly defining the wavelength interval over which the AGN fraction is measured, it becomes possible to quantify the nuclear contribution without discarding the star-forming emission of the host galaxy.

Observational Data and Sample Construction

Previous chapters introduced the cosmological and astrophysical framework required to interpret the infrared emission of distant galaxies. The present chapter describes the observational data used in this work and the construction of the galaxy sample analysed through spectral energy distribution fitting. Particular attention is devoted to the origin of the parent catalogue, to the addition of the new JWST observations from COSMOS-Web and to the choice of the redshift adopted for each source. The analysis builds upon the A³COSMOS study of Traina et al. 2024, which reconstructed the infrared luminosity function and the dust-obscured cosmic star formation rate density from $z = 0.5$ up to $z = 6$. The present work updates that analysis using the COSMOS2025 catalogue, revises the photometric and redshift information of the sources and introduces a more detailed assessment of how the adopted AGN model affects the inferred infrared luminosities.

5.1 The COSMOS field and the A³COSMOS reference study

The Cosmic Evolution Survey, commonly referred to as COSMOS (Scoville et al. 2007), was designed to study the formation and evolution of galaxies over a broad range of cosmic epochs and environments. The field covers an area of approximately 2 deg^2 centred close to the celestial equator, a location that makes it accessible from both northern and southern observatories. Its combination of area and depth was chosen to sample a cosmological volume sufficiently large to contain rare and luminous objects while still allowing sensitive observations of more typical galaxy populations. One of the main advantages of COSMOS is its broad and characterized multiwavelength coverage. Over time, the field has been observed in the X-ray, ultraviolet, optical, near-infrared, mid-infrared, far-infrared, submillimetre, millimetre and radio regimes. These observations were obtained with facilities including *Chandra*, XMM–Newton, GALEX, HST, Subaru, CFHT, VISTA, *Spitzer*, *Herschel*, JCMT, IRAM, VLA and ALMA, among others (Scoville et al. 2007). More recently, the COSMOS-Web programme has added extensive JWST/NIRCam and MIRI coverage, further improving the characterization of faint and high-redshift sources. This panchromatic coverage makes it possible to constrain different physical components of the same galaxy. The large angular area is also important from a statistical perspective. A small deep field can identify intrinsically faint sources, but it probes relatively limited cosmological volumes and it is consequently more affected by cosmic variance. On the contrary, a wider field contains a larger and more representative amount of environments and increases the probability of detecting rare systems, such as luminous infrared galaxies, massive high-redshift galaxies and quasars. COSMOS therefore provides an

appropriate observational basis for constructing luminosity functions and studying the evolution of galaxy populations over cosmic time. Figure 5.1 shows a reduced-resolution HST view of the full COSMOS field.



Figure 5.1: Reduced-resolution mosaic of the full COSMOS field observed with the Advanced Camera for Surveys Wide Field Channel onboard the *Hubble Space Telescope*. The image was obtained in the F814W filter, approximately corresponding to the broad I band, and was constructed from 575 adjacent and partially overlapping pointings. The mosaic illustrates the large area and high surface density of sources covered by COSMOS, which enable statistical studies of galaxy evolution over a broad range of redshifts and environments. The original full-resolution image contains $100\,800 \times 100\,800$ pixels. Image credit: NASA, ESA, and A. Koekemoer (STScI). See [Koekemoer et al. 2007](#) for a detailed description of the HST/ACS observations and data processing.

The millimetre component of the data set used in this thesis originates from the Automated Mining of the ALMA Archive in COSMOS project, also referred to as A³COSMOS ([Liu et al. 2019a](#); [Liu et al. 2019b](#)). The project was initiated in 2017 as a collaboration between the Argelander-Institut für Astronomie and the Max-Planck-Institut für Astronomie. Its objective is not only to maximize the scientific use of existing ALMA observations, but also to provide the astronomical community with consistently processed

images, continuum photometry and derived galaxy properties. The resulting database enables the study of dust, gas and star formation across large samples that would be difficult through a single dedicated ALMA programme. In other words, rather than being a single observing programmes with uniform depth and wavelength coverage, A³COSMOS is based on the systematic mining of public available ALMA observation within the COSMOS field. Importantly, the resulting galaxy sample is selected through its ALMA continuum detections rather than through a single ancillary optical or infrared reference band. Although the prior catalogue adopted in this work uses optical/near-infrared positions to guide the source extraction, inclusion in the catalogue still requires a significant ALMA continuum detection. The sample can therefore be regarded as ALMA-selected, while the multiwavelength COSMOS observations provide the ancillary photometry required for source identification and SED characterization (Liu et al. 2019a; Liu et al. 2019b; Traina et al. 2024). Moreover, since the archival observations were obtained in different ALMA bands, no single observing wavelength defines the selection of the catalogue. The project systematically retrieves the publicly available ALMA observations located within the COSMOS field and processes them through a common pipeline. In this way, data originally obtained by many independent observing programme can be transformed into a homogeneous collection of continuum images, source measurements and metadata associated with them. As a new ALMA project becomes public, the archive-mining procedure can be repeated and the database progressively updated. ALMA itself provides exceptional sensitivity and angular resolution at submillimetre and millimetre wavelengths, but its instantaneous field of view is small compared with the angular extent of COSMOS. According to the A³COSMOS project estimate, mapping the entire 2 deg² field homogeneously to an RMS depth of approximately 0.1 mJy at 1.24 mm would require about 13 742 pointings and roughly 500 hours of observing time (A³COSMOS Collaboration 2026). This is why a conventional uniform ALMA survey of the complete field would therefore be extremely demanding.

The construction of the A³COSMOS database involves several successive steps (Ad-scheid et al. 2024) (see Figure A.1 in the Appendix A). The public ALMA archive is first queried and the relevant observations are downloaded together with their calibration information. The raw interferometric data are then re-calibrated and imaged using the Common Astronomy Software Applications package (CASA, McMullin et al. 2007), producing continuum maps through a consistent processing strategy. Sources are extracted from these maps and after that, ALMA detections are linked to multiwavelength information available in COSMOS. The reliability of the proposed counterparts is assessed using positional offsets, source morphology, image information and quality-control procedures (Adscheid et al. 2024).

As illustrated in Figure 5.2, the archival pointings do not form a regular and uniformly sampled mosaic. They differ in observing wavelength, angular resolution, sensitivity, depth, spatial coverage and most importantly, several regions are covered by overlapping observations. Moreover, most ALMA programmes were designed to observe specific targets rather than to perform an unbiased survey of a randomly selected sky area. Therefore, the resulting catalogue cannot be treated directly as a conventional blind survey. This distinction is particularly important for the derivation of lot of properties. In a blind survey, the probability of detecting a source is primarily determined by the survey area coverage and sensitivity. The probability of observing one kind of source

rather than another is therefore just given by the luminosity functions. In an archival compilation as A³COSMOS instead, the central regions of many pointings contain objects that were deliberately selected for observation because of their known and expected properties. Keeping those targets without any correction would therefore affect and artificially increase the number of particular classes of objects and would bias the inferred number densities.

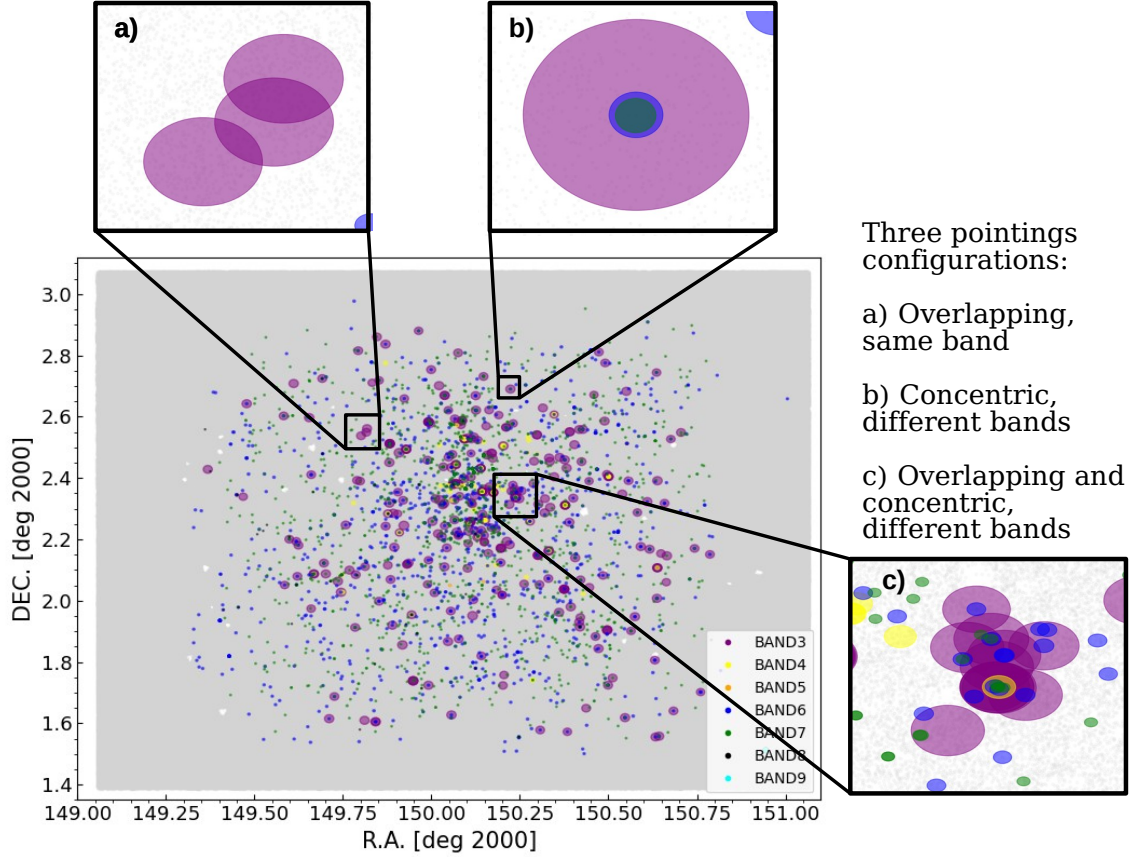


Figure 5.2: Spatial distribution of the archival ALMA observations included in the A³COSMOS database. Individual pointings are colour-coded according to their observing band. The enlarged regions illustrate representative configurations, including partially overlapping observations in the same band, concentric observations obtained in different bands and more complex regions covered by several overlapping pointings. The figure highlights both the large number of available ALMA observations and the spatial and spectral inhomogeneity of the archival coverage. Reproduced from Figure 2 of Traina et al. 2024.

5.1.a Homogenization of the observing wavelengths.

This problem is illustrated in Figure 5.3. The pointings included in the reference analysis span ALMA Bands 3–9, although most of the observations are centred in Bands 6 and 7. Since the observed continuum flux density of a dusty galaxy varies with wavelength and redshift, an RMS value measured in one ALMA band cannot be compared directly with an RMS value measured in another. Therefore, before the effective area can be computed, all pointings must be expressed at a common reference wavelength.

To homogenize the different observing setups, Traina et al. 2024 selected an observed reference wavelength of $\lambda_{\text{ref}} = 1200 \mu\text{m}$, which lies in ALMA Band 6. The objective was

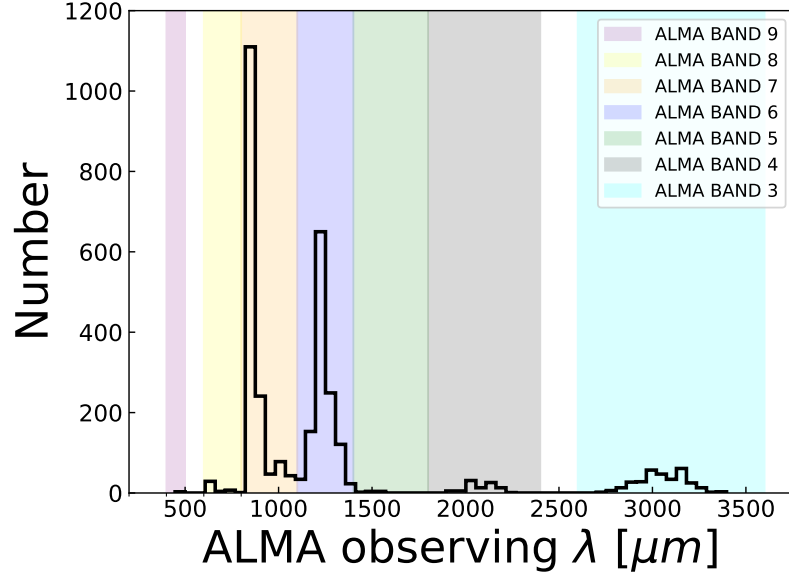


Figure 5.3: Number of archival ALMA pointings included in the A³COSMOS database as a function of observed wavelength. The shaded regions indicate the wavelength coverage of ALMA bands 3–9. Most of the observations are concentrated in Bands 6 and 7, while a smaller number of pointings were obtained at shorter and longer wavelengths. This heterogeneous observing frequency motivates the conversion of all sensitivities to a common reference wavelength before computing the effective survey area. Image reproduced from Figure 1 of [Traina et al. 2024](#).

not to modify the measured flux for each source, but to determine the sensitivity that every observation would have had if it had been observed at the reference wavelength. For a source observed at a wavelength λ_{obs} , the required conversion factor can be expressed as

$$R(\lambda_{\text{obs}}, z) = \frac{\Phi_{\nu}(1200 \mu\text{m})}{\Phi_{\nu}(\lambda_{\text{obs}})} \quad (5.1)$$

where the two flux densities are derived from the observed best-fitting SED at the redshift of the source. Therefore, the equivalent RMS at the reference wavelength is then

$$\sigma_{1200} = R(\lambda_{\text{obs}}, z) \sigma_{\text{obs}} \quad (5.2)$$

where σ_{obs} is the local RMS of the original pointing. The conversion is redshift dependent because, as we already said in Chapter 1, a fixed observed wavelength is shifted based on the redshift value of the source. Consequently, the ratio between the flux at 1.2 mm and that in another ALMA band changes as the thermal dust peak moves through the observed wavelength range. To account for this effect, the reference study divided the source sample into 5 redshift intervals

$$z < 1.5, \quad 1.5 < z < 2.5, \quad 2.5 < z < 3.5, \quad 3.5 < z < 4.5, \quad z > 4.5$$

and computed the median flux-density ratio for each sufficiently populated observing band and redshift bin. The resulting conversion curves are shown in Figure 5.4. At wavelengths close to the 1200 μm reference value, the flux-density ratio approaches unity by construction. At shorter wavelengths the ratio becomes increasingly dependent on redshift while at longer wavelengths the ratio increases as the observed bands move farther along the Rayleigh–Jeans side of the dust SED.

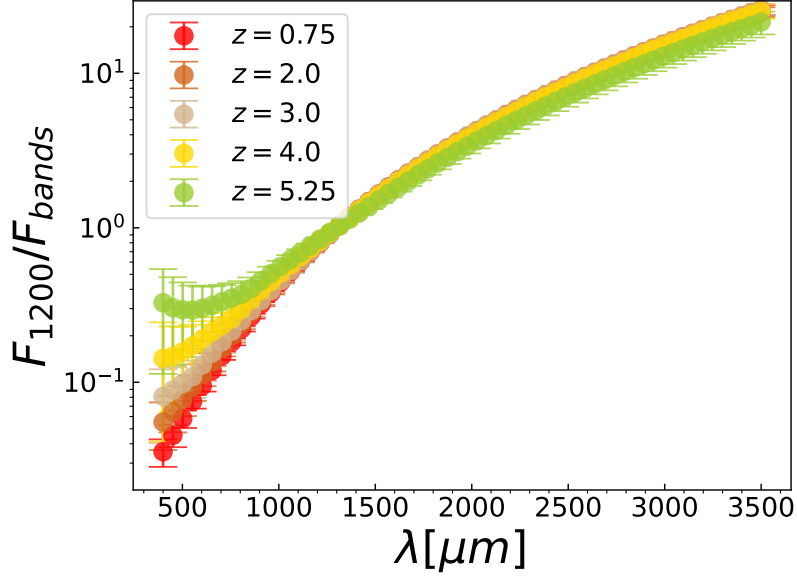


Figure 5.4: Median conversion curves used to express observations obtained at different ALMA wavelengths in terms of an equivalent flux density at the reference wavelength of $1200\mu\text{m}$. Reproduced from Figure 7 of [Traina et al. 2024](#).

5.1.b Primary-beam correction and radial sensitivity.

The wavelength conversion alone is not sufficient because the sensitivity within an individual ALMA pointing is not spatially uniform. The response of the interferometric observation is highest at the pointing centre and decreases radially because of the primary beam. In the work of [Traina et al. 2024](#), the primary beam response has been approximated as a Gaussian function,

$$\text{PB}_{\text{corr}}(d) = \exp\left(-\frac{d^2}{2\sigma_{\text{PB}}^2}\right) \quad (5.3)$$

where d is the angular distance from the pointing centre and

$$\sigma_{\text{PB}} = \frac{\text{FWHM}_{\text{PB}}}{2.35}$$

Only the region in which the primary beam response was larger than 0.2 was retained. Within this boundary, the equivalent RMS at 1.2 mm was then corrected pixel by pixel as

$$\sigma_{1200}^{\text{corr}}(d) = \frac{\sigma_{1200}}{\text{PB}_{\text{corr}}(d)}$$

which shows that the noise is lowest at the pointing centre and increases toward the adopted primary beam boundary. The local detection threshold was subsequently obtained by applying the signal-to-noise criterion used for the prior catalogue. In other words

$$S_{\text{lim}}(d) = 4.35 \sigma_{1200}^{\text{corr}}(d) \quad (5.4)$$

Each pointing was therefore converted into a map in which every spatial pixel was associated with an equivalent limiting flux at 1.2 mm.

5.1.c Treatment of overlapping pointings.

An additional issue arises when two or more pointings overlap (see Figure 5.5). The common region must not be counted multiple times, since it corresponds to the same area of the sky. At the same time, the available sensitivity in that region is determined by the deepest observation. Following the approach of [Avni & Bahcall 1980](#), the limiting flux assigned to an overlapping pixel was therefore

$$S_{\text{lim}}^{\text{overlap}} = \min [S_{\text{lim},1}, S_{\text{lim},2}, \dots, S_{\text{lim},N}] \quad (5.5)$$

In other words, the common area was included only once and was assigned the sensitivity of the deepest pointing covering that position.

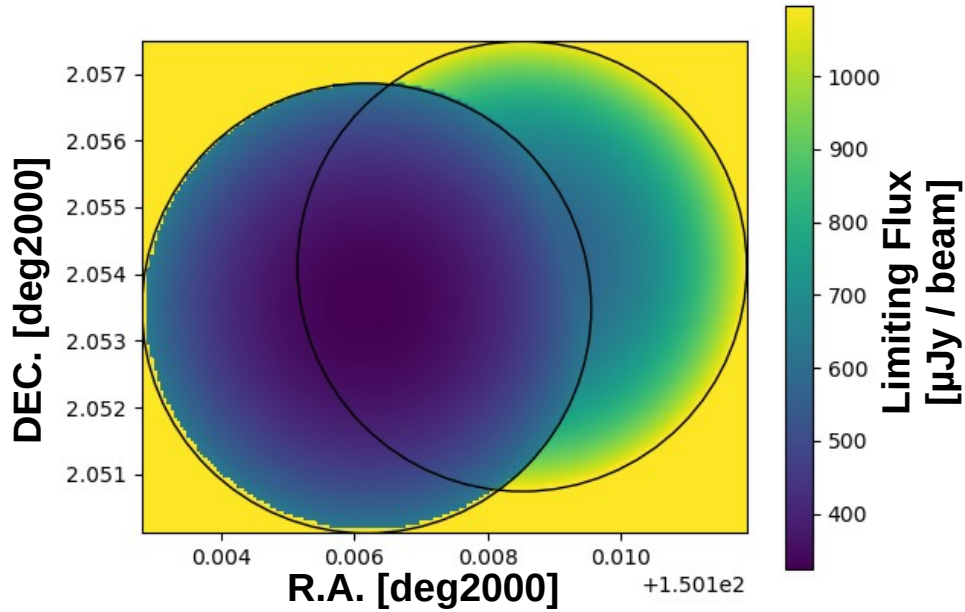


Figure 5.5: Example of two partially overlapping ALMA pointings in ALMA Band 6. The colour scale shows the local limiting flux after converting the sensitivity to the reference wavelength and correcting for the radial primary beam response. The black circles indicate the adopted boundary corresponding to $PB_{\text{corr}} = 0.2$. Within the overlapping region, the area is counted only once and the lower limiting flux, corresponding to the deepest observation, is kept. Reproduced from Figure 8 of [Traina et al. 2024](#).

5.1.d Turning the A³COSMOS selection into a blind-like survey

The corrections described above define how heterogeneous sensitivity in the ALMA archive can be treated consistently. However, they do not remove the second major source of bias, which is the targeted nature of the original observations. The A³COSMOS database considered by [Traina et al. 2024](#) contained 3215 ALMA pointings in the COSMOS field and a prior based catalogue of 1620 sources detected above the adopted peak signal-to-noise ratio threshold of 4.35σ . Since these pointings originated from independent scientific programmes, most of them were centred on a previously selected object. The central target of each observation cannot therefore be treated as a serendipitous detection. Its inclusion would transfer the properties of the selection criteria of the original observing programme in the statistical sample. For instance, observations originally designed to

see known submillimetre galaxies would artificially increase the abundance of bright and dusty systems if their targets were to be retained.

Before removing those targets, it was necessary to identify them reliably. The nominal pointing centre does not always coincide exactly with the final ALMA position of the source. Positional offsets of several arcseconds may occur in these cases. Consequently, a source located away from the exact phase centre could still be the intended target of the observation rather than an independent serendipitous detection. For this reason, Traina et al. 2024 searched for the target within the central $10''$ of every pointing. If the source could be securely identified inside this region, the entire pointing was therefore excluded from the statistical dataset. Without an identifiable target, it would not have been possible to determine which detections should be removed as selected objects inside the pointing. For this reason, the central targets were identified in 2060 of the original 3215 pointings, therefore the number of points retained for the blind-like analysis was 1155. Only these 1155 pointings contributed to the cumulative area-depth relation (in Section 5.1.e) and to the accessible volume used in future luminosity function analysis (in Chapter 7).

However, removing the central target was not sufficient since other sources within the same pointing could be physically associated with the same target and therefore belong to the same group, overdensity or large-scale structure. To reduce this environmental bias, the redshift of every source, z_{source} , was compared with the redshift of the target, z_{target} . Using the criterion from Weaver et al. 2022, two sources were considered potentially associated when

$$|z_{\text{source}} - z_{\text{target}}| < 0.04(1 + z_{\text{target}}) \quad (5.6)$$

The factor $1 + z_{\text{target}}$ accounts approximately for the redshift dependence of the uncertainty associated with photometric redshift estimates. Using this criterion, 104 of the 1620 catalogue sources were classified as potentially associated with the corresponding target and were removed.

The final statistical catalogue was obtained by combining the pointing selection, the removal of the identified targets and the exclusion of 104 potentially clustered sources. The resulting blind-like sample contained 189 galaxies. This value of 189 galaxies is therefore the result of applying the complete set of pointing, target and redshift based selection criteria.

5.1.e Construction of the cumulative area–depth relation.

After all pointings had been converted and combined, the effective area of the survey was derived by counting the number of pixels observable below a given limiting flux. The cumulative areal coverage can be written as

$$A(< S_{\text{lim}}) = \sum_i \Delta\Omega_i \mathcal{H}[S_{\text{lim}} - S_{\text{lim},i}] \quad (5.7)$$

where $\Delta\Omega_i$ is the solid angle of the i -th pixel, $S_{\text{lim},i}$ is its limiting flux and $\mathcal{H}$ is the Heaviside function. This relation gives the total sky area over which a source brighter than a specified flux could have been detected. The cumulative area–depth relation obtained from the selected A³COSMOS pointings is shown in Figure 5.6. As expected, the effective survey area decreases toward fainter limiting fluxes, because only the deepest

pointings and the regions closest to their centres are sensitive enough to detect such weak sources. In contrast, brighter sources can be detected over a much larger fraction of the survey.

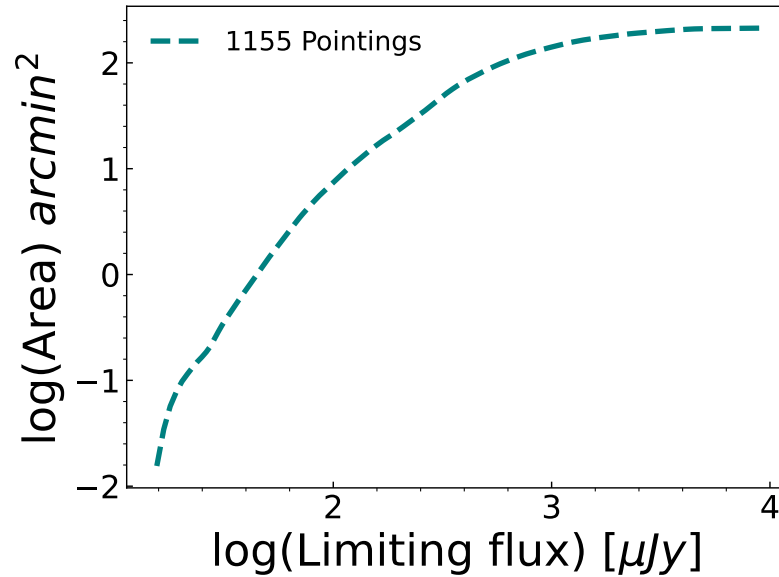


Figure 5.6: Cumulative effective area of the blind-like A³COSMOS survey as a function of the limiting flux converted to the reference wavelength of 1200 μm . The curve quantifies the sky area over which a source of a given flux density could have been detected after accounting for the heterogeneous observing wavelengths, primary-beam attenuation and overlapping pointings. Bright sources are detectable over a larger effective area, whereas faint sources are accessible only in the deepest region of the survey. This area–depth relation is the key ingredient used to determine the accessible volume of each galaxy in the luminosity-function analysis. Reproduced from Figure 9 of Traina et al. 2024.

This resulting area–depth relation is essential to link the ALMA archive and the luminosity function analysis. For each galaxy, the fitted SED can be shifted across its redshift bin to predict the observed 1.2mm flux as a function of the redshift itself. The area corresponding to that flux is then read from the cumulative coverage curve and combined to determine the volume over which the source would have remained detectable. The detailed implementation of this computation will be presented in Section 7.1.

5.2 Photometric update with COSMOS2025

The photometric catalogue used in this thesis was reconstructed starting from the complete parent catalogue adopted by Traina et al. 2024, containing 1620 sources. The update was applied to the complete catalogue rather than directly to the 189 source blind-like sample in order to preserve both the original source identifiers and the statistical selection defined in the reference study, while revising the multiwavelength information associated with each object. Only after the reconstruction of the full catalogue were the 189 sources used for the luminosity function analysis extracted again.

The principal new dataset used for this update is COSMOS2025, the definitive galaxy catalogue produced from the COSMOS-Web survey (Shuntov et al. 2025). COSMOS-Web is a 255 h JWST programme designed to provide deep and wide-area near- and mid-infrared observations of the central COSMOS field. Its imaging includes four

NIRCam broad-band filters, F115W, F150W, F277W and F444W over approximately 0.54 deg^2 , together with MIRI/F770W observations over a non-contiguous area of approximately 0.2 deg^2 . These data extend the high spectral resolution coverage of COSMOS from approximately 1.15 to $7.7 \mu\text{m}$. The COSMOS2025 catalogue combines the JWST measurements with previous HST and ground-based observations and provides photometry, morphological measurements, photometric redshifts and derived physical parameters for more than 7×10^5 galaxies. The catalogue was constructed using both fixed-aperture and profile-fitting measurements, with the latter providing a homogeneous multi-band characterization over 37 bands between approximately 0.3 and $8 \mu\text{m}$. The version used in this work was the official COSMOS-Web DR1 master catalogue `COSMOSWeb_mastercatalog_v1.1.fits` downloaded from the COSMOS2025 data-release website (COSMOS-Web Collaboration 2026).

The association between the original catalogue and COSMOS2025 was performed using the equatorial coordinates of the COSMOS2020 counterparts already assigned to the A³COSMOS detections (Weaver et al. 2022) (see Figure 5.7). The right ascension and declination of each COSMOS2020 source were compared with those of the objects contained in COSMOS2025. A source was considered associated with a COSMOS2025 counterpart when $\Delta\theta \leq 0.5''$.

This small matching radius was adopted to take advantage of the high astrometric accuracy of the two COSMOS catalogues and to limit the probability of associating an A³COSMOS source with an unrelated galaxy. A total of 755 sources in the complete parent catalogue were associated with a COSMOS2025 counterpart. For every successful association, the photometric information available in COSMOS2025 was transferred to the corresponding source in the parent catalogue. The new JWST measurements were added as independent photometric constraints. In addition, all pre-existing photometric bands for which an updated COSMOS2025 measurement was available were replaced with their new values. When instead no updated value was available, the photometric measurement inherited from the original catalogue was retained. The flux densities and uncertainties imported from COSMOS2025 were provided in μJy so, before their inclusion in the final catalogue, both quantities were converted to mJy . The same unit convention was adopted for all photometric measurements in the final catalogue. The resulting catalogue provides broad photometric coverage from the GALEX FUV band at an effective wavelength of approximately $0.153 \mu\text{m}$ to the longest available ALMA continuum measurement at approximately $3325.2 \mu\text{m}$. The complete set contains 54 non-ALMA filters and up to 330 monochromatic ALMA filters. Each ALMA filter represents the effective observing wavelength of an individual archival continuum measurement. Consequently, a single galaxy may contain more than one ALMA flux density obtained at different wavelengths.

Table 5.1 lists the filters included in the updated catalogue. Only the shortest- and longest-wavelength filters are reported in the table to indicate the full wavelength range. The complete list of exact filter identifiers adopted by CIGALE is provided in Appendix B.1.

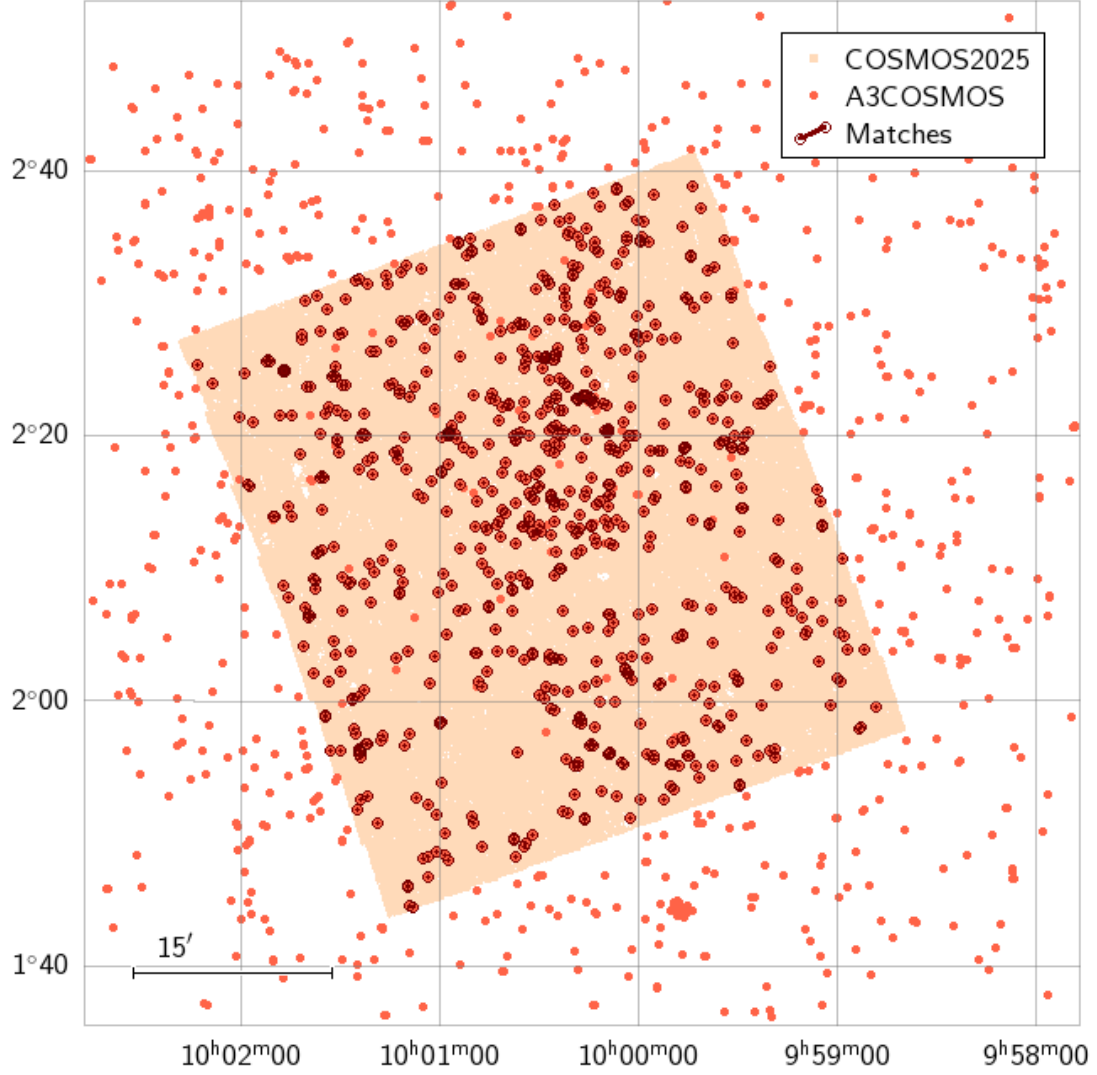


Figure 5.7: Sky distribution of the positional associations between the A³COSMOS sources of Traina et al. 2024 and the objects contained in the COSMOS2025 catalogue (Shuntov et al. 2025). The cross-match was performed using equatorial coordinates, and counterparts were accepted within a maximum angular separation of $\Delta\theta \leq 0.5''$. The COSMOS2025 photometry associated with the successfully matched sources was subsequently used to update the multiwavelength parent catalogue, including the addition of the new JWST measurements. The image was produced with TOPCAT (Taylor 2005).

Table 5.1: Facilities and instruments contributing to the photometric catalogue used in this work. The wavelength intervals correspond to the minimum and maximum effective wavelengths of the adopted filters, rather than to the complete instrumental transmission ranges. The full list of individual filters, including all monochromatic ALMA filters and their corresponding CIGALE identifiers, is reported in Table B.1 in Appendix B.

Facility/instrument	# of filters	λ_{eff} range [μm]	Spectral regime
GALEX	2	0.153–0.231	UV
CFHT/MegaCam– MegaPrime	2	0.368–0.379	UV/optical
Subaru/Suprime-Cam	26	0.427–0.998	Optical–NIR
HST/WFC3–ACS	2	0.804–0.805	Optical/NIR

Continued on next page

Table 5.1 – continued from previous page

Facility/instrument	Number of filters	λ_{eff} range [μm]	Spectral regime
VISTA/VIRCAM	4	1.02–2.15	NIR
JWST/NIRCam	4	1.15–4.40	NIR
Spitzer/IRAC	4	3.55–7.88	NIR/MIR
JWST/MIRI	1	7.64	MIR
Spitzer/MIPS	1	23.59	MIR
Herschel/PACS	2	100.65–160.98	FIR
Herschel/SPIRE	3	248.29–500.38	FIR/submillimetre
ALMA	Up to 330	446.5–3325.5	Submillimetre/mm
JCMT/SCUBA-2	1	861.3	Submillimetre
IRAM 30-m/AzTEC	1	1100	Millimetre
IRAM 30-m/MAMBO	1	1200	Millimetre

The addition of JWST observations is particularly important for the characterization of high-redshift sources. As previously said in Chapter 1, from $z \gtrsim 2$, the NIRCam bands progressively sample the rest-frame optical continuum, which contains information on the accumulated stellar population, stellar masses and other spectral features. For example, the Balmer break is shifted into the NIRCam wavelength range at high redshift and this improved sampling can therefore reduce degeneracies among redshift, stellar age, dust attenuation and other features.

After the photometric association and conversion had been completed, the full updated catalogue was retained as a separate data product.

5.3 Redshift update, compilation and selection

Accurate determination of the source redshift is essential for the physical interpretation of a spectral energy distribution. As previously said in Chapter 1, redshift determines the correspondence between observed and rest-frame wavelengths, the luminosity distance and the comoving volume associated with each galaxy. An incorrect value can therefore affect both the physical parameters derived for an individual source and its contribution to the infrared luminosity function.

The redshift information associated with A³COSMOS catalogue was consequently revised after updating the photometry with COSMOS2025. Spectroscopic and photometric estimates were collected from two independent catalogues: the COSMOS Spectroscopic Redshift Compilation of [Khostovan et al. 2026](#) and the spectroscopic information reported in the ASTRODEEP-JWST catalogue of [Merlin et al. 2024](#). The redshifts previously adopted by [Traina et al. 2024](#) and those reported in COSMOS2020 [Weaver et al. 2022](#) were also retained for comparison. The external catalogues were associated with A³COSMOS sources by comparing their right ascension and declination. As for the photometric cross-match done in Section 5.2, a maximum angular separation of $\Delta\theta \leq 0.5''$ was adopted. This cross-match was done for all the 1620 sources in the updated parent catalogue, while further adjustments were instead done for the 189 sources in the final blind-like sample. The redshift adopted for each galaxy was selected through a hierarchical procedure.

5.3.a Spectroscopic redshift

When only one spectroscopic redshift was available, that value was adopted directly with priority over all photometric estimates. This is because spectroscopic measurements are generally more reliable than broad-band photometric solutions because they are based on the identification of individual emission or absorption features rather than on the overall shape of the SED. In a limited number of cases, however, two or three different spectroscopic values were associated with the same source. For some there were no differences between one redshift estimate and another; for others instead, discordances were greater and additional assessment was required. These discordances could arise from different counterpart assignments, different spectral-line identifications or measurements obtained by independent observing programmes. For each source with multiple spectroscopic redshift candidates, a separate input catalogue was constructed for every available value. The photometry (updated as for Section 5.2) was kept identical in all runs, while the redshift was fixed in turn to the value reported by [Traina et al. 2024](#), [Khostovan et al. 2026](#) or [Merlin et al. 2024](#). Consequently, the alternative runs differed just in the redshift assigned to the source, while the grid of physical models and all other fitting assumptions were kept unchanged.

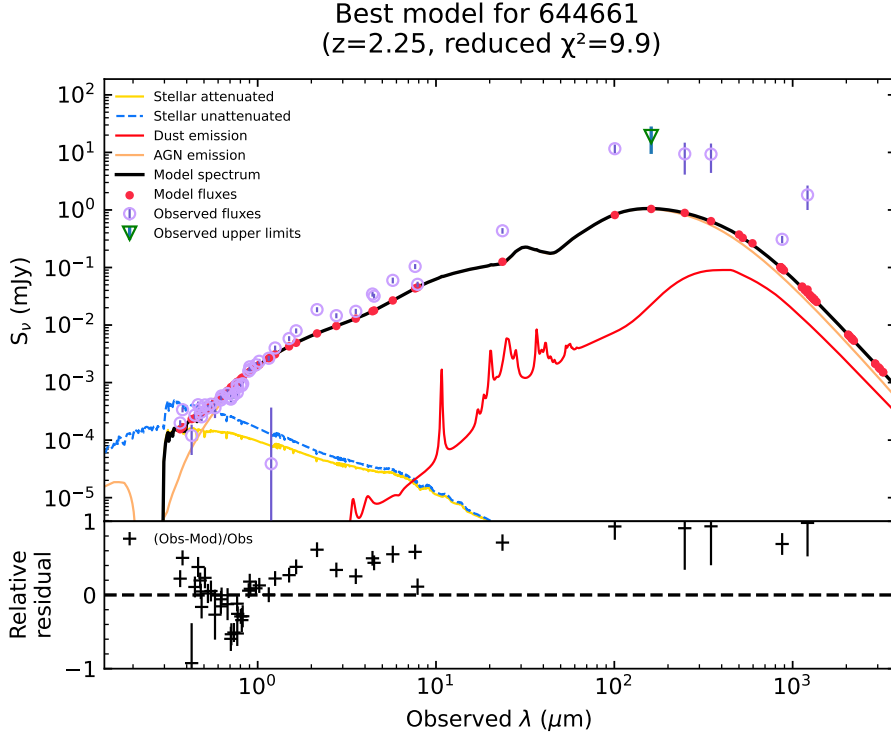
The diagnostic runs employed the `skirtor2016` AGN library ([Stalevski et al. 2016](#)), with the AGN fraction defined over the rest-frame wavelength interval of 5–40 μm . This configuration was adopted as the reference model for the redshift comparison. The main settings of these diagnostic runs are summarized in Table 6.1, while the complete model grid and the physical meaning of the individual parameters are discussed in Chapter 6.

For every candidate redshift, the resulting best-fitting SED was visually inspected and the corresponding reduced χ^2 was recorded. For this purpose, the reduced χ^2 can be written as

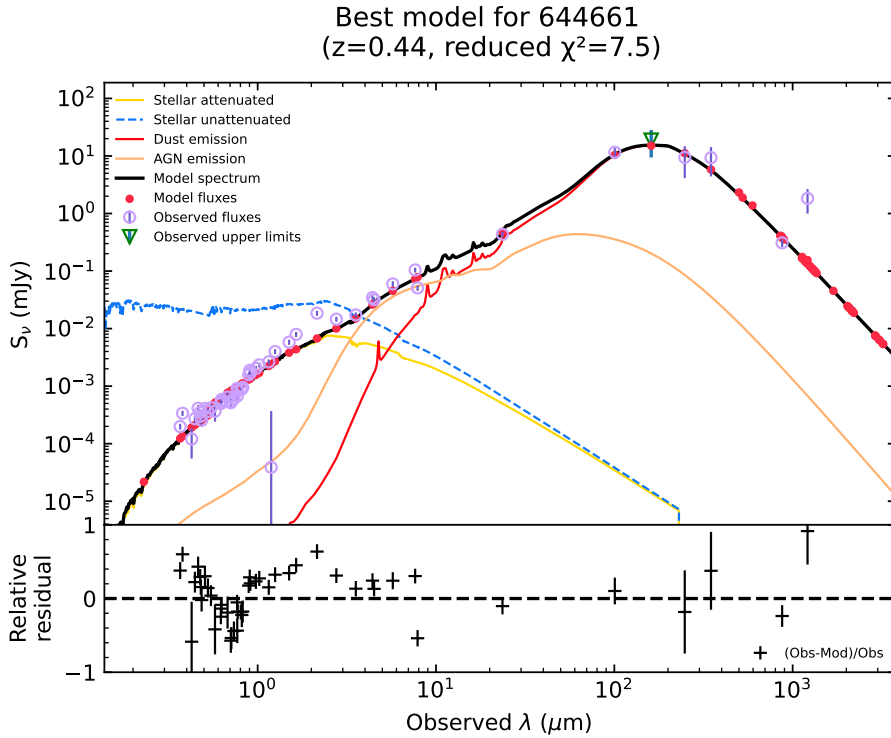
$$\chi_{\text{red}}^2 = \frac{1}{N_{\text{dof}}} \sum_{j=1}^{N_{\text{bands}}} \left[\frac{\Phi_{\nu,j}^{\text{obs}} - \Phi_{\nu,j}^{\text{model}}}{\sigma_j} \right]^2, \quad (5.8)$$

where $\Phi_{\nu,j}^{\text{obs}}$ and $\Phi_{\nu,j}^{\text{model}}$ are respectively the observed and modelled flux densities in the j th band, σ_j is the corresponding uncertainty and N_{dof} is the number of degrees of freedom. The spectroscopic candidate producing the lowest value of χ^2 was adopted as the final redshift. A total of 296 sources were associated with at least one valid spectroscopic redshift. Among these, a smaller subset was associated with multiple spectroscopic measurements and required the additional comparison described above.

Figure 5.8 shows an example of the procedure for the source ID 644661 with discordant spectroscopic measurements. Since the input photometry and model grid are identical, the differences between the fits are produced exclusively by the redshift adopted. Shifting the source to an incorrect redshift changes the rest-frame position of the spectral features and can prevent the same model from simultaneously reproducing the optical, near-infrared and far-infrared observations.



(a) SED fit obtained using A³COSMOS redshift estimate



(b) SED fit obtained using Khostovan et al. 2026 redshift estimate

Figure 5.8: Example of the diagnostic SED-fitting procedure used for a source associated with two different spectroscopic redshift candidates. Each panel shows a CIGALE fit obtained using the same updated photometry and model grid, while fixing the redshift to one of the available catalogue values. The first panel shows the fit obtained using the redshift adopted in the original A³COSMOS analysis, while the second panel shows the fit obtained using the spectroscopic redshift reported by Khostovan et al. 2026. The adopted solution is the second one, providing the lowest reduced χ^2 together with a visual inspection.

5.3.b Photometric redshift

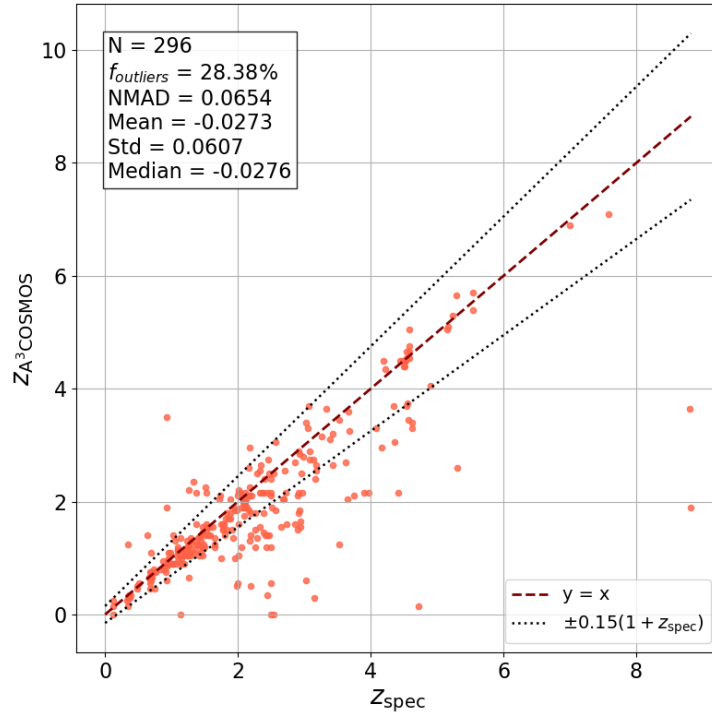
The 296 sources with an adopted spectroscopic redshift were subsequently used as a control sample to assess the reliability of the alternative redshift estimates available for galaxies without spectroscopy. The purpose of this comparison was not to replace the spectroscopic measurements, but to determine which redshift estimator should be preferred for the remaining objects in the parent catalogue.

Three alternative redshift solutions were considered. The first was the redshift previously adopted by Traina et al. 2024, the second was the photometric redshift provided by COSMOS2025 (Shuntov et al. 2025), while the third was independently derived in this work by running CIGALE with redshift as a free parameter. To perform the latter, it was used the updated parent catalogue for the photometry and the same physical model configuration adopted for the fixed-spectroscopic redshift (see Section 5.3.a). In this case, however, redshift was allowed to vary over the grid 0–10 with steps of $\Delta_z = 0.05$.

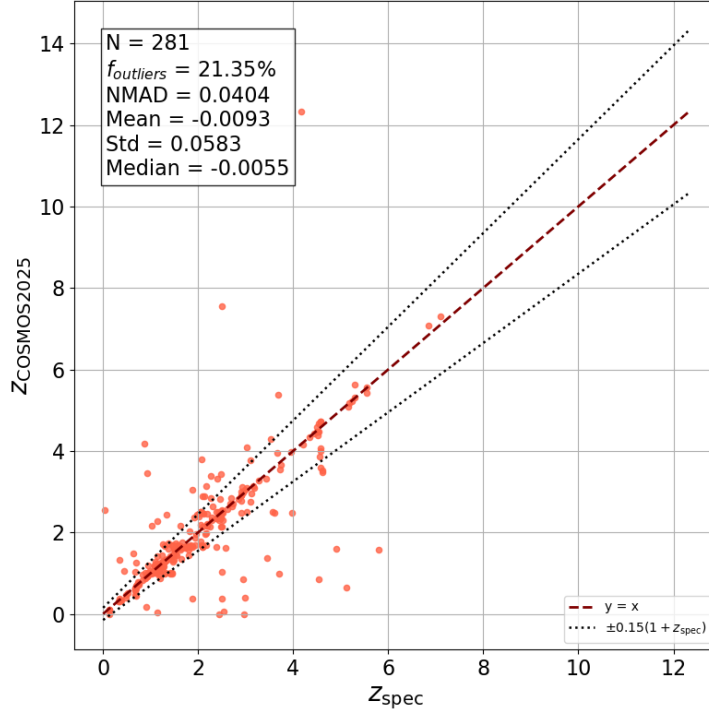
Each of the three estimates was compared with the adopted spectroscopic redshift of the corresponding source (see Figures 5.9a, 5.9b and 5.9c). The normalized redshift difference was defined as

$$\Delta z_{\text{norm}} = \frac{z_{\text{fit}} - z_{\text{spec}}}{1 + z_{\text{spec}}} \quad (5.9)$$

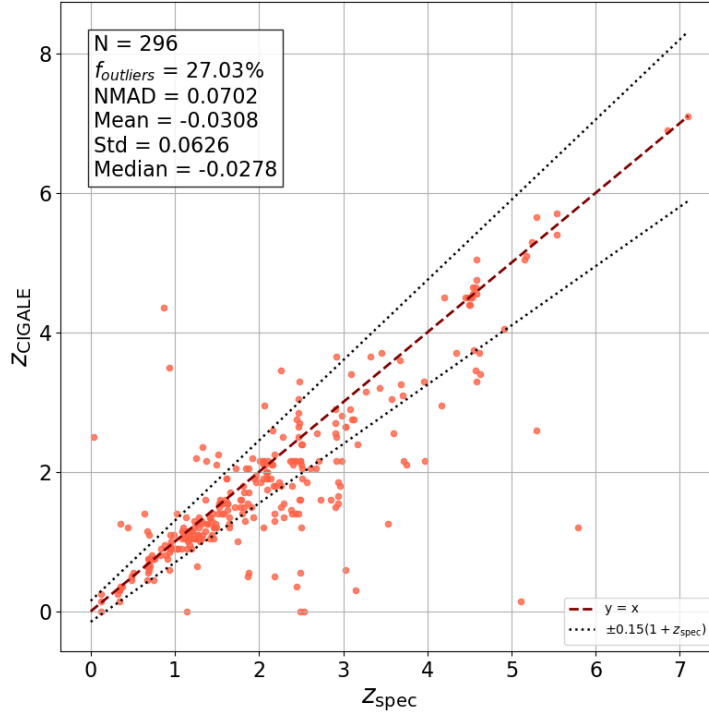
where z_{fit} represents in turn the redshift adopted by the A³COSMOS and COSMOS2025 catalogues, or the value derived through the free-redshift CIGALE run.



(a)



(b)



(c)

Figure 5.9: Comparison between the adopted spectroscopic redshifts and the other catalogues. From top to bottom: panel (a) for redshifts adopted by Traina et al. 2024, panel (b) for COSMOS2025 photometric redshifts and panel (c) for photometric redshifts independently derived in this work using CIGALE and the updated photometry. The dashed line represents the 1:1 relation. Each panel reports the number of sources included and the corresponding outlier fraction.

The main statistic used to compare the three solutions was the outlier fraction, defined as

$$f_{\text{out}} = \frac{N(|\Delta z_{\text{norm}}| > 0.15)}{N} \quad (5.10)$$

In addition to the outlier fraction, the distribution of sources around the 1:1 relation was visually examined. Not all 296 spectroscopic sources have a valid counterpart (and therefore a photometric redshift estimate) in the COSMOS2025 catalogue. Therefore, the number of galaxies included in the three comparisons is not necessarily identical.

Among the alternatives, the COSMOS2025 photometric redshifts show the lowest outlier fraction and the closest visual agreement with the spectroscopic reference values. This result supports their adoption as the preferred solution for sources lacking a spectroscopic measurement.

The comparison with the redshift adopted by [Traina et al. 2024](#) requires additional care. The corresponding catalogue column contains a mix of photometric and spectroscopic redshift measurements and therefore does not represent a pure photometric redshift sample. Despite this difference, the outlier fraction obtained using the redshifts adopted by [Traina et al. 2024](#) was found to be similar to that measured for the new CIGALE photometric solutions. The two sets of estimates show a comparable visual dispersion around the 1:1 relation. Therefore, for sources without either a spectroscopic measurement or a valid COSMOS2025 photometric redshift, the redshift independently derived in this work was retained.

After completing this validation, the redshift hierarchy was applied to the complete catalogue of 1620 sources. Only after assigning a final redshift to the complete updated parent catalogue, the same 189 source identifiers selected by [Traina et al. 2024](#) were extracted. The final blind-like sample contains 60 sources with spectroscopic redshift, 99 with a COSMOS2025 photometric redshift and 30 with a redshift derived through the CIGALE independent run. Finally, Figure 5.10 compares the redshift distribution of the 189 blind-like sources before and after the redshift update described in this section.

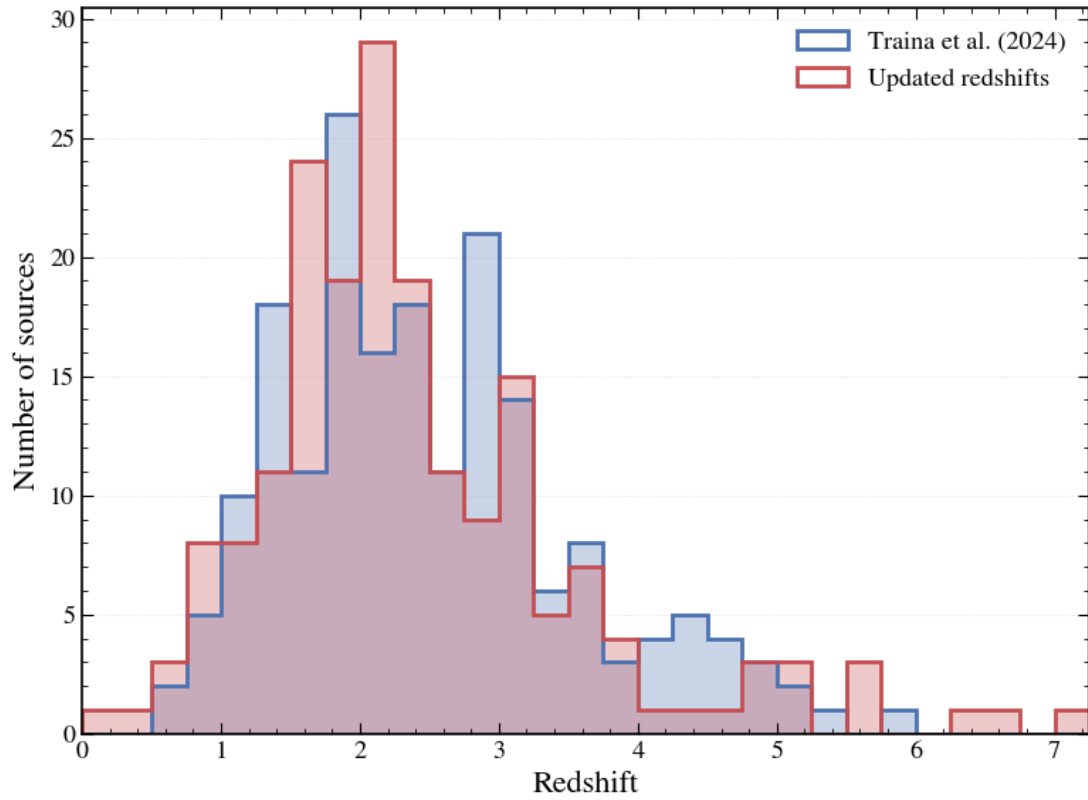


Figure 5.10: Redshift distribution of the 189 sources of the blind-like sample before and after the redshift update. The two histograms refer to the same set of sources and therefore highlight exclusively the effect of the revised redshift assignments.

This chapter presents the SED fitting methodology adopted in this work. The general CIGALE pipeline and the physical modules used to construct the model SEDs are first introduced (Section 6.1). The photometric fine-tuning performed before the final runs is then described, together with the procedure used to identify filters showing systematic discrepancies between observed and modelled photometric points. The following sections will discuss the limitations affecting individual sources and assess the influence of the wavelength interval over which the AGN fraction is defined.

6.1 CIGALE configuration and photometric fine-tuning

6.1.a SED fitting setup

The SED fitting was performed using version 2025.0 of the Code Investigating GALaxy Emission, CIGALE (Boquien et al. 2019). CIGALE is a modular code that combines independent prescriptions for the star formation history, stellar populations, nebular emission, dust attenuation, dust re-emission and AGN activity. Each combination of the input parameters produces a model spectrum, which is convolved with the transmission curves of the filters available for the source and compared with the observed flux densities. One of the principal assumptions underlying the code is the energy-balance condition. The stellar radiation absorbed by dust at ultraviolet and optical wavelengths is required to be totally re-emitted in the infrared. This approach allows observations obtained at different wavelengths to constrain the same physical model. The observations from ultraviolet to near-infrared primarily provide information on the stellar populations and dust attenuation, whereas the mid-infrared, far-infrared and millimetre data constrain the reprocessed emission from dust. The modular structure of CIGALE therefore permits the total SED to be decomposed into its components, although the reliability of this decomposition depends strongly on the wavelength coverage and photometric quality available for each source.

For every galaxy, CIGALE evaluates a grid of models at the redshift assigned through the procedure described in Section 5.3. All final SED fits were performed on the blind-like sample of 189 sources, with redshifts kept fixed.

The agreement between the observed and modelled flux densities is quantified through the χ^2 statistic. The best-fitting SED corresponds to the model producing the minimum value of χ^2_{red} and provides a direct representation of the model combination that most closely reproduces the observed photometry. In addition to the best-fitting solution,

CIGALE performs a likelihood-based analysis over the complete model grid. Each model is assigned a statistical weight $w \propto \exp\left(-\frac{\chi^2}{2}\right)$ from which the probability distribution of each physical parameter is derived. The resulting Bayesian estimates therefore use the information contained in all models compatible with the observations rather than relying exclusively on the single minimum- χ^2 model.

The adopted configuration was based on the general fitting strategy used by Traina et al. 2024. Upper limits were treated using the nonscaling option, where they contributed to the evaluation of the goodness of the fit without modifying the normalization applied to the models. Moreover, a relative systematic uncertainty of 10% was also added in quadrature to the flux density errors in order to account approximately for residual calibration uncertainties and for possible systematic differences among measurements collected from heterogeneous instruments and surveys. The statistical analysis was performed through the pdf_analysis module, while the model SED was constructed using the modules:

- sfhdelayed. The star formation history was described using a delayed model with optional recent bursts where the main stellar component follows

$$\text{SFR}(t) \propto \frac{t}{\tau_{\text{main}}^2} \exp\left(-\frac{t}{\tau_{\text{main}}}\right) \quad (6.1)$$

where τ_{main} controls the characteristic timescale of the main star formation episode.

- bc03. The stellar spectra were generated using the population-synthesis models of Bruzual & Charlot 2003, assuming a Chabrier initial mass function (Chabrier 2003) and solar metallicity. The stellar populations were separated into young and old components at an age of 10 Myr, allowing the contribution of recently formed stars to be treated separately within the adopted attenuation model.
- dustatt_modified_CF00. Dust attenuation was described using the modified Charlot and Fall prescription (Charlot & Fall 2000). In this model, young stellar populations can be attenuated both by their birth clouds and by the diffuse interstellar medium, while older populations are affected only by the latter. The attenuation curves of the two components were represented by power laws with slope -0.7 . The grid explored different values of V-band attenuation and of the fraction of the total attenuation associated with the diffuse interstellar medium.
- dl2014. The infrared emission produced by interstellar dust was modelled using the Draine et al. 2014 templates. The grid varies the mass fraction of PAHs and the minimum intensity of the interstellar radiation field U_{min} . A fraction γ of the dust mass is exposed to a distribution of stronger radiation fields described by a power-law index α . Together, these parameters control the shape and normalization of the infrared dust component and therefore contribute to the determination of the infrared luminosity.
- skirtor2016. This AGN component was modelled using the library of Stalevski et al. 2012; Stalevski et al. 2016. The skirtor2016 module describes radiative transfer through a two-phase dusty medium composed primarily of dense clumps embedded in a lower-density diffuse clump component.
- fritz2006. This AGN component was modelled using the library of Fritz et al. 2006. The model describes radiative transfer through a smooth dusty torus with a flared-disc geometry, in which graphite and silicate grains are continuously distributed around the central illuminating source.

The complete parameter grid for the final SED fitting runs is reported in Table 6.1.

Table 6.1: Physical modules and parameter values adopted for the SED-fitting runs. The stellar, attenuation and dust emission modules are common for both configurations, while the AGN component is modelled using either `skirtor2016` or `fritz2006` modules. Most of the adopted parameters refer to the configuration used by Traina et al. 2024.

Module	Parameter	Adopted values	Description
sfhdelayed	τ_{main} [Myr]	500, 1000, 2000, 5000, 7000	Main SFH timescale
	age_{main} [Myr]	500, 1000, 3000, 5000, 8000, 11000	Main population age
	τ_{burst} [Myr]	10000	Burst timescale
	$\text{age}_{\text{burst}}$ [Myr]	1, 10, 100, 300	Burst age
	f_{burst}	0.00, 0.15, 0.30	Burst mass fraction
	sfr_A	1.0	SFH normalization
	normalise	True	Unit-mass normalization
bc03	imf	1 (Chabrier)	Initial mass function
	metallicity	0.02	Stellar metallicity
	separation_age [Myr]	10	Young/old separation
dustatt	A_V^{ISM} [mag]	0.3, 1.7, 2.8, 3.3	Diffuse ISM attenuation
_modified	μ	0.3, 0.5, 0.8, 1.0	Diffuse attenuation fraction
_CF00	slope_ISM	−0.7	ISM attenuation slope
	slope_BC	−0.7	Birth-cloud attenuation slope
dl2014	q_{PAH} [%]	0.47, 2.5, 3.9	PAH mass fraction
	U_{min}	5, 10, 25, 40	Minimum radiation field
	α	2.0	Radiation-field slope
	γ	0.02	PDR dust fraction
skirtor2016	t	3, 7	Optical depth at $9.7 \mu\text{m}$
	p1	1.0	Radial density exponent
	q	1.0	Angular density exponent
	oa [deg]	40	Torus opening angle
	$R_{\text{out}}/R_{\text{in}}$	20	Torus radial extent
	M_{cl}	0.97	Dust fraction in clumps
	i [deg]	30, 70	Viewing angle
	disk_type	1	Accretion-disc spectrum
	δ	0	Disc-slope modification
	f_{AGN}	0.00, 0.20, 0.40, 0.60, 0.80, 0.99	AGN luminosity fraction
	$\lambda_{\text{fracAGN}} [\mu\text{m}]$	5/40	AGN-fraction interval
	law	0 (SMC)	Polar-dust extinction law
	$E(B - V)_{\text{polar}}$ [mag]	0.03, 0.15, 0.30	Polar-dust reddening
	T_{polar} [K]	100	Polar-dust temperature
	ϵ	1.6	Dust emissivity index
fritz2006	r_ratio	60	Torus radial extent
	$\tau_{9.7}$	0.6, 1.0, 3.0	Optical depth at $9.7 \mu\text{m}$

Continued on next page

Table 6.1 – continued from previous page

Module	Parameter	Adopted values	Description
	β	-0.5	Radial density exponent
	γ	0.0	Angular density exponent
	opening_angle [deg]	100	Torus full opening angle
	ψ [deg]	0.001, 30.100, 89.990	Viewing angle
	disk_type	1	Accretion-disc spectrum
	δ	-0.36	Disc-slope modification
	f_{AGN}	0.00, 0.20, 0.40, 0.60, 0.80, 0.99	AGN luminosity fraction
	lambda_fracAGN [μm]	5–40	AGN-fraction interval
	law	0 (SMC)	Polar-dust extinction law
	$E(B - V)_{\text{polar}}$ [mag]	0.03, 0.15, 0.30	Polar-dust reddening
	T_{polar} [K]	100	Polar-dust temperature
	ϵ	1.6	Dust emissivity index
pdf_analysis	additionalerror	0.10	Additional relative error
	lim_flag	noscaling	Upper-limit treatment

6.1.b Photometric fine-tuning

Although the updated catalogue provides extensive wavelength coverage, as we already mentioned in Chapter 5, it combines measurements obtained with different instruments, angular resolutions, depths and photometric coverages. Systematic inconsistencies between individual bands may consequently affect the SED decomposition and bias the physical parameters derived from the fit. Therefore, before performing the final runs, a dedicated fine-tuning procedure was applied to identify filters whose flux densities could not be reproduced consistently by the adopted model configuration. The diagnostic was performed using the 296 sources for which an adopted spectroscopic redshift was available. This control sample was selected because it was statistically larger than the final blind-like sample and therefore provided a more statistically significant comparison. In addition, the use of only spectroscopic redshifts reduced the possibility that systematic discrepancies between observed and modelled photometric points were caused by an incorrect redshift rather than by the photometric measurements themselves.

This preliminary run employed the `skirtor2016` module with the AGN fraction defined between 5 and 40 μm . For each source, CIGALE generated mock flux densities from the best-fitting SED and re-analysed the resulting artificial observations. These mock measurements were then compared with the original input photometry. For the i th source and the j th filter, the agreement between the mock and the observed point was quantified by the normalized flux-density ratio

$$R_{i,j} = \frac{\Phi_{i,j}^{\text{mock}} - \Phi_{i,j}^{\text{obs}}}{\Phi_{i,j}^{\text{obs}}} \quad (6.2)$$

where $\Phi_{i,j}^{\text{mock}}$ and $\Phi_{i,j}^{\text{obs}}$ are respectively the mock and observed flux densities. A value of $R_{i,j} = 0$ indicates exact agreement between the two quantities, while positive or

negative values indicate that the mock flux density is respectively higher or lower than the observed one. Missing measurements and non-finite ratios were excluded from the statistical calculation. This procedure was done for each filter in each source and their mean value was computed as $\langle R_f \rangle = \frac{1}{N_f} \sum_{i=1}^{N_f} R_{i,j}$ where N_f is the number of valid measurements available for each filter. The corresponding dispersion was instead quantified through the standard deviation. A filter was considered acceptable when the absolute value of its mean relative residual satisfied

$$|\langle R_j \rangle| < 1.3 \quad (6.3)$$

The value of 1.3 was adopted as an empirical quality-control threshold rather than as a formally derived statistical confidence limit. The individual custom ALMA filters were excluded from this diagnostic. Each filter corresponds to the effective observing wavelength of a specific archival continuum measurement and is therefore generally populated by only one or a very small number of sources. A filter-by-filter mean and dispersion would not provide a statistically meaningful assessment. For this reason, all ALMA flux densities were retained in the final SED fitting analysis.

The fine-tuning run identified seven filters whose mean mock versus observed flux ratio did not satisfy the adopted acceptance criterion. These filters were therefore removed from the final photometric input: `cfht.megacam.u`, `hst.acs.wfc.F814W`, `paranal.vircam.NB118`, `spitzer.irac.I4`, `subaru.suprime.IB464`, `subaru.suprime.IB574` and `subaru.suprime.g`. The diagnostic distribution is shown in Figure 6.1.

The resulting cleaned photometric selection was then applied to the final blind-like sample of 189 galaxies and was kept unchanged in all subsequent SED-fitting configurations.

6.2 SED fitting runs and physical results

As already mentioned in this work, the final SED-fitting analysis was performed using two alternative modules for the AGN component, `skirtor2016` and `fritz2006`, while keeping the remaining modules, input photometry and adopted redshifts unchanged. In both configurations, the AGN fraction was defined over the rest-frame wavelength interval 5–40 μm . This approach allows the physical properties inferred from each model to be first examined independently (Subsection 6.2.a) and subsequently compared on a source-by-source analysis (Subsection 6.2.b).

6.2.a Physical results of the `skirtor2016` and `fritz2006` runs

The final SED fitting was performed using two alternative prescriptions for the AGN emission, the `skirtor2016` and `fritz2006` modules. The corresponding parameter grids are reported in Table 6.1. Apart from the AGN module, the input photometry, redshifts and remaining physical components were kept unchanged between the two runs. The distributions of the main physical quantities derived with the two configurations are shown in Figures 6.2 and 6.3. In particular, these are stellar masses, star formation rates, total infrared luminosity and AGN fractions.

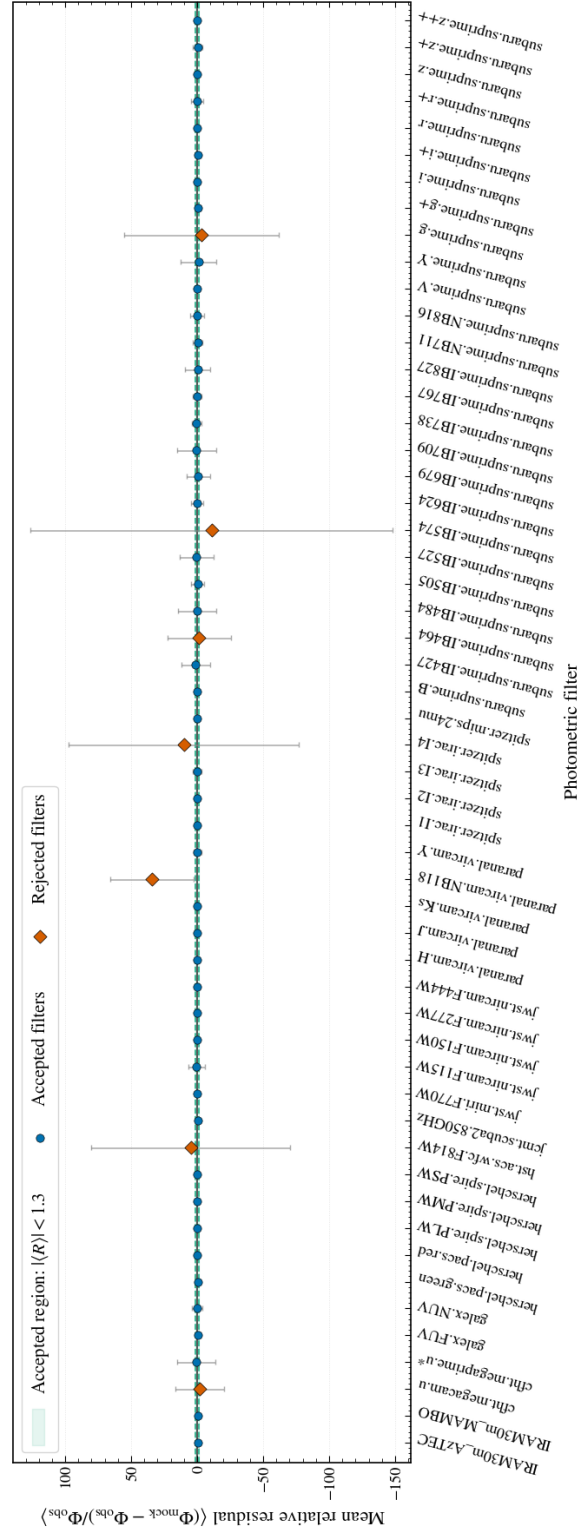


Figure 6.1: Mean relative residuals between the CIGALE mock and observed flux densities for each non-ALMA photometric filter. The points show the mean residual obtained for each filter, while the error bars represent the standard deviation of the source by-source distribution. The horizontal central line indicates perfect agreement, whereas the outer lines show the adopted acceptance interval $|\langle R_j \rangle| < 1.3$. The diagnostic was performed using the 296 sources with an adopted spectroscopic redshift. Individual ALMA filters were excluded because each is populated by too few sources to provide a statistically meaningful filter-level distribution. The filters rejected from the final input are highlighted in the figure.

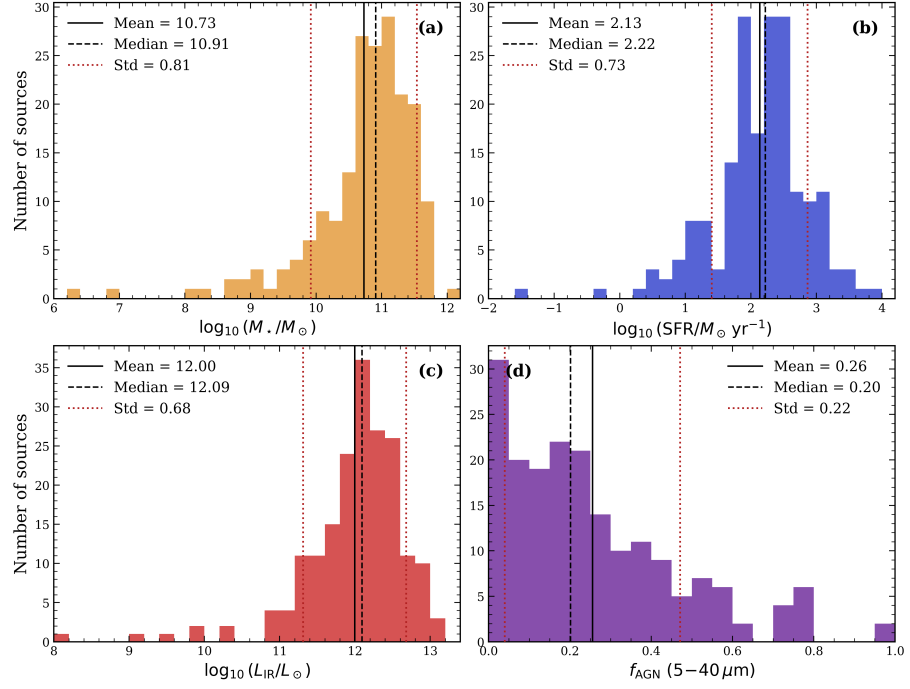


Figure 6.2: Distributions of the physical properties derived from the *skitor2016* SED fit for the 189 sources in the blind-like sample. From top left to bottom right: stellar mass, star formation rate, total infrared luminosity and AGN fraction evaluated over the rest-frame interval 5–40 μm . The solid, dashed and dotted lines indicate respectively the mean, median and standard deviation of each distribution.

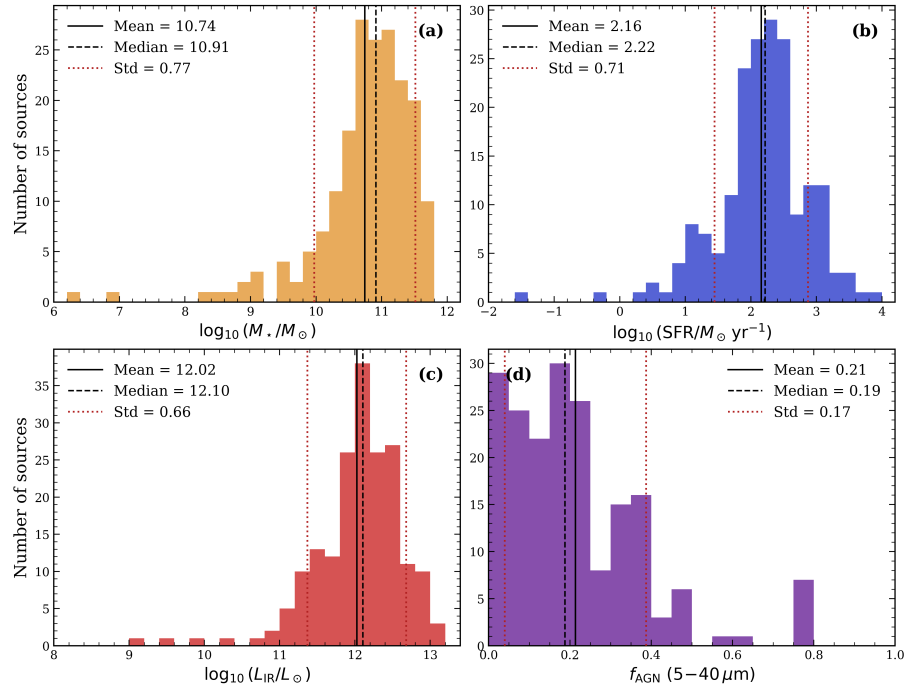


Figure 6.3: Distributions of the physical properties derived from the *fritz2006* SED fit for the 189 sources in the blind-like sample. From top left to bottom right: stellar mass, star formation rate, total infrared luminosity and AGN fraction evaluated over the rest-frame interval 5–40 μm . The solid, dashed and dotted lines indicate respectively the mean, median and standard deviation of each distribution.

- *Stellar mass.* Both runs recover a stellar mass with a distribution which is centred around $\log_{10}(M_*/M_\odot) \sim 11$. For the `skirtor2016` run, the mean, median and standard deviation are 10.73, 10.91 and 0.81, respectively. The `fritz2006` run gives corresponding values of 10.74, 10.91 and 0.77. In both cases, the bulk of the sample is therefore composed of massive galaxies, as expected for the ALMA-selected population considered in this work. The small difference between the mean and median values is produced by a tail extending towards lower stellar masses.
- *Star formation rate.* Similarly to the stellar mass, also the star formation rate shows a little deviation between the mean and median value for both runs. The `skirtor2016` run gives a mean $\log_{10}(\text{SFR}/M_\odot \text{ yr}^{-1}) = 2.13$, a median of 2.22 and a standard deviation of 0.73 dex. The corresponding values obtained with `fritz2006` are instead 2.16, 2.22 and 0.71 dex, respectively. This confirms that the sample is predominantly composed of highly star-forming systems.
- *Total infrared luminosity.* In both configurations, the total infrared luminosity shows a considerably more concentrated distribution around the luminous infrared regime. The `skirtor2016` fit gives a mean $\log_{10}(L_{\text{IR}}/L_\odot) = 12.00$, while the median is 12.09 and the standard deviation is 0.68 dex. The corresponding values obtained with `fritz2006` are 12.02, 12.10 and 0.66 dex. In particular, 113 of the 189 sources in the `skirtor2016` run and 115 in the `fritz2006` run have $\log_{10}(L_{\text{IR}}/L_\odot) \geq 12.00$, indicating that a substantial fraction lies in the ultraluminous infrared galaxy regime, independently of the adopted AGN module.
- *AGN fraction.* The largest differences between the global distributions are found in the AGN fraction. The `skirtor2016` run gives $\langle f_{\text{AGN}} \rangle = 0.26$, a median of 0.20 and a standard deviation of 0.22, whereas the `fritz2006` run gives a mean of 0.21, a median of 0.19 and a standard deviation of 0.17. Both distributions are weighted towards relatively low and intermediate AGN fractions, although the former distribution presents a more extended tail towards larger values. These distributions differ from that presented in Figure 4 of Traina et al. 2024, shown here in Figure 6.4.

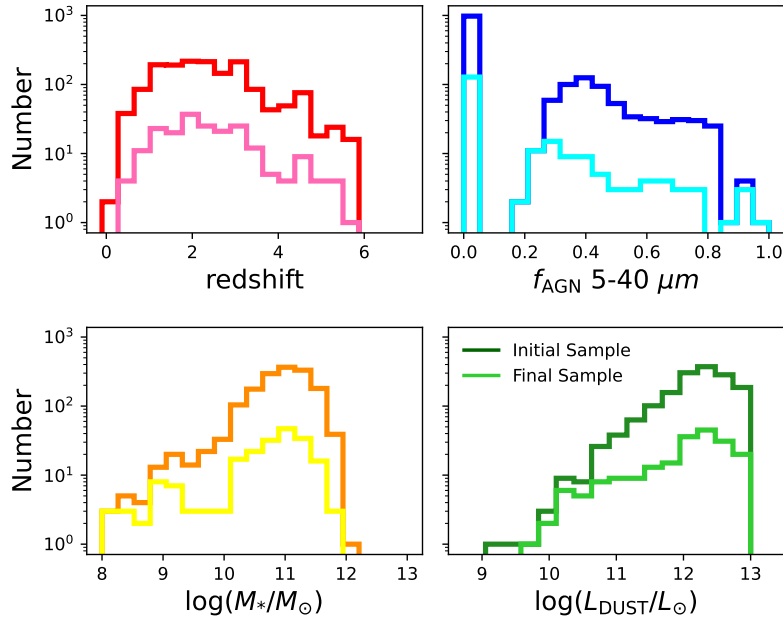


Figure 6.4: Distribution of the AGN fraction obtained by Traina et al. 2024 for the original A³COSMOS analysis.

These differences can be attributed as a consequence of the updated photometry and redshifts adopted in the present analysis.

The quality of individual fits was subsequently investigated following the criterion also used by Traina et al. 2024. Sources with $\chi^2_{\text{red}} > 10$ were individually inspected to assess whether the high statistical value was associated with a poor SED fit. Five objects satisfy this criterion in the *skirtor2016* run, with IDs 304861, 732014, 860387, 1202794 and 1372795. Four of these sources, IDs 304861, 732014, 860387 and 1372795, also exceed the same threshold in the *fritz2006* run, while source 1202794 lies slightly below it. Still, the *fritz2006* SED fit of this source is also included in Figure 6.5 in order to provide direct comparison between the two AGN prescriptions. Visual inspection leads to the same general conclusion for both configurations. The high χ^2_{red} values are primarily driven by a limited group of ultraviolet and optical photometric measurements likely affected by blending or contamination. The specific bands involved differ from source to source, moreover the remaining photometric measurements are generally well reproduced by both SED fitting models. Therefore, the large statistical values do not indicate a globally unsuccessful reconstruction of the SED, but rather reflect the presence of a limited number of discrepant photometric points and for this reason, these sources were retained.

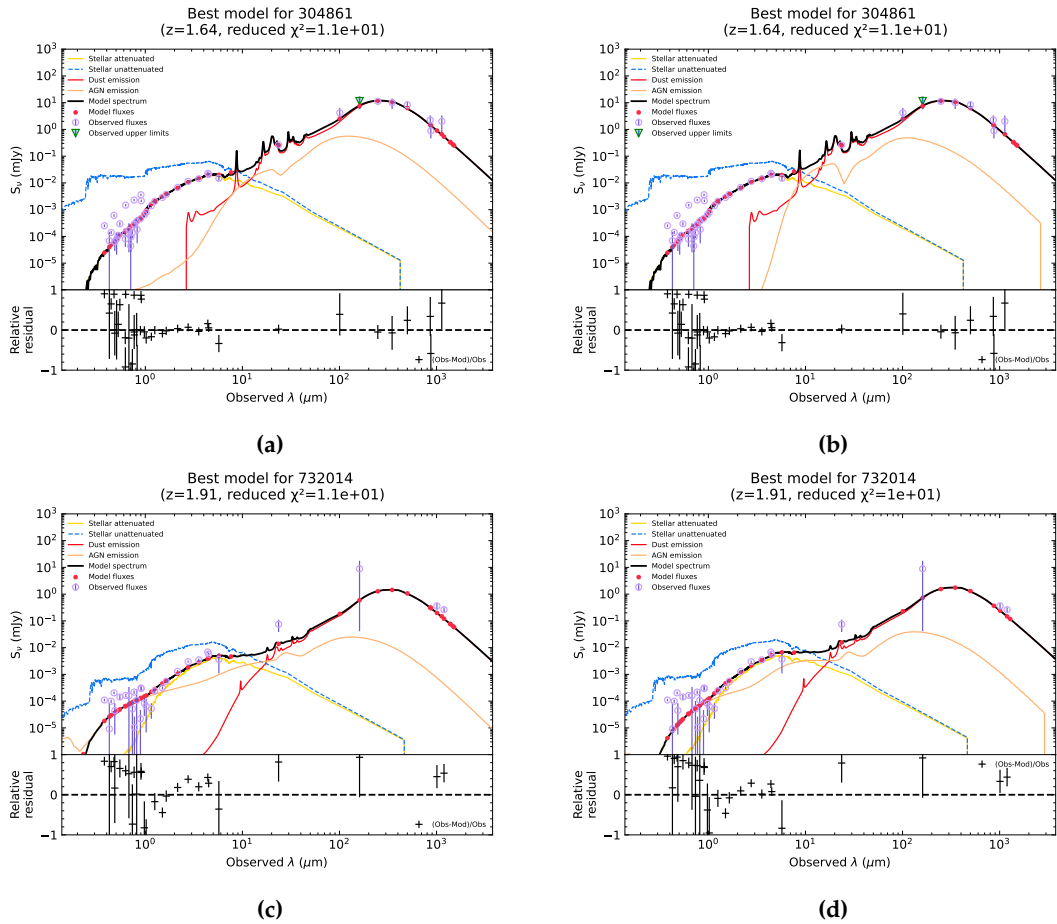


Figure 6.5: Comparison between the *skirtor2016* (left) and *fritz2006* (right) SED fits for the five sources identified as problematic in the two runs. In both configurations, the large χ^2_{red} values are mainly driven by a limited number of discrepant ultraviolet and optical photometric measurements, while the overall SEDs remain reasonably well reproduced.

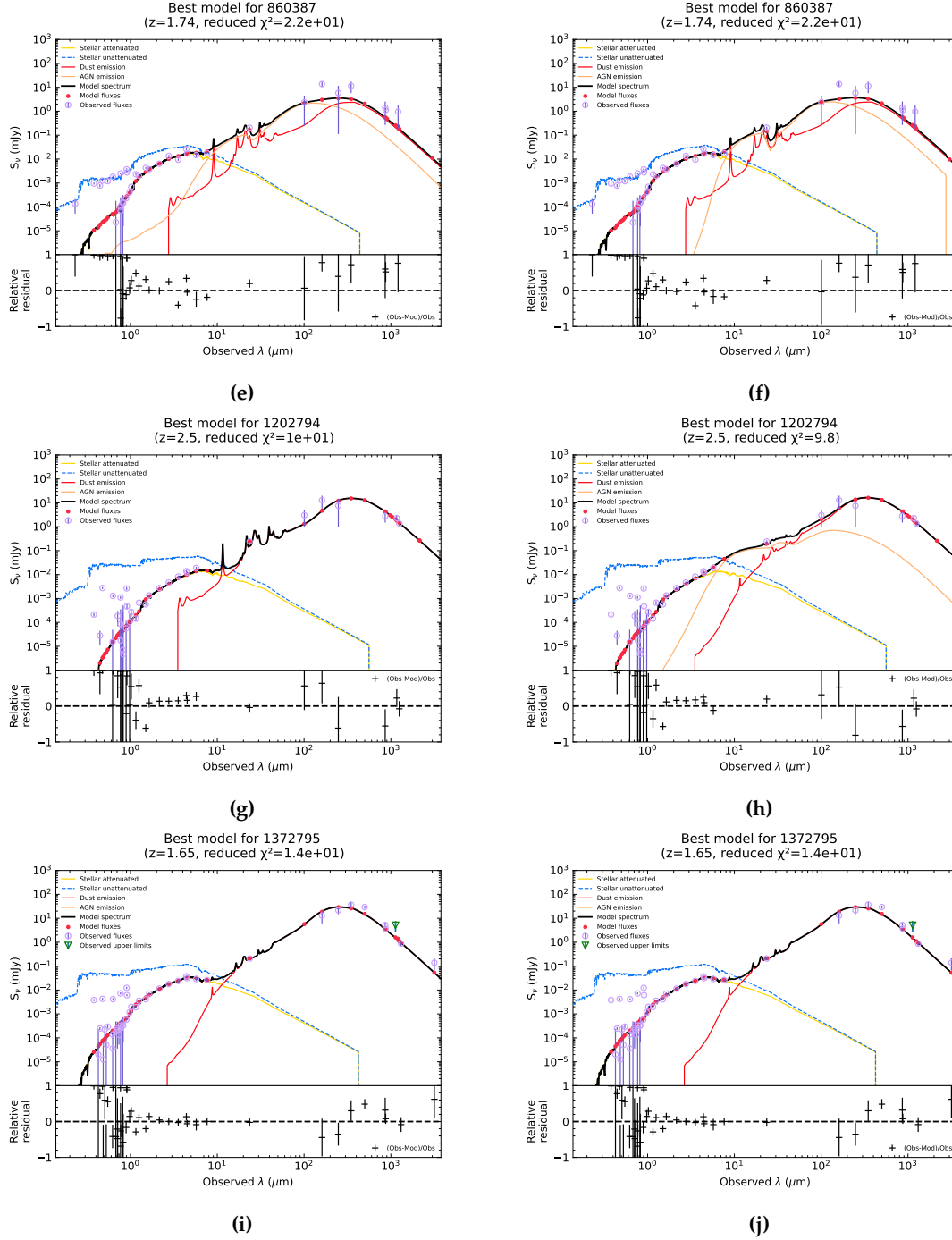


Figure 6.5: Problematic SED fits obtained with *skirtor2016* and *fritz2006* modules (continued).

A different limitation affects sources with extremely sparse multiwavelength detections. Six objects can be identified for which the available detections included in the fit are exclusively associated with ALMA measurements. This limitation is independent of the AGN module. In particular, for sources with IDs 1835469, 1836951, 1837465, 1855033, 1878550 and 1896090, all detected photometric measurements included in the fit are associated with ALMA observations only. The absence of detections outside the millimetre regime strongly limits the possibility of independently constraining the different physical components of the SED. The main uncertainty comes from the choice of the redshift: since

the photometry is based on few sub-millimetre observations only, it is difficult to obtain a precise and realistic value of it. Consequently, quantities as stellar mass, star formation rate and AGN fraction are expected to be considerably less constrained for these sources than for other objects. The six corresponding spectral energy distribution fits are shown in Figures 6.6a–6.6f.

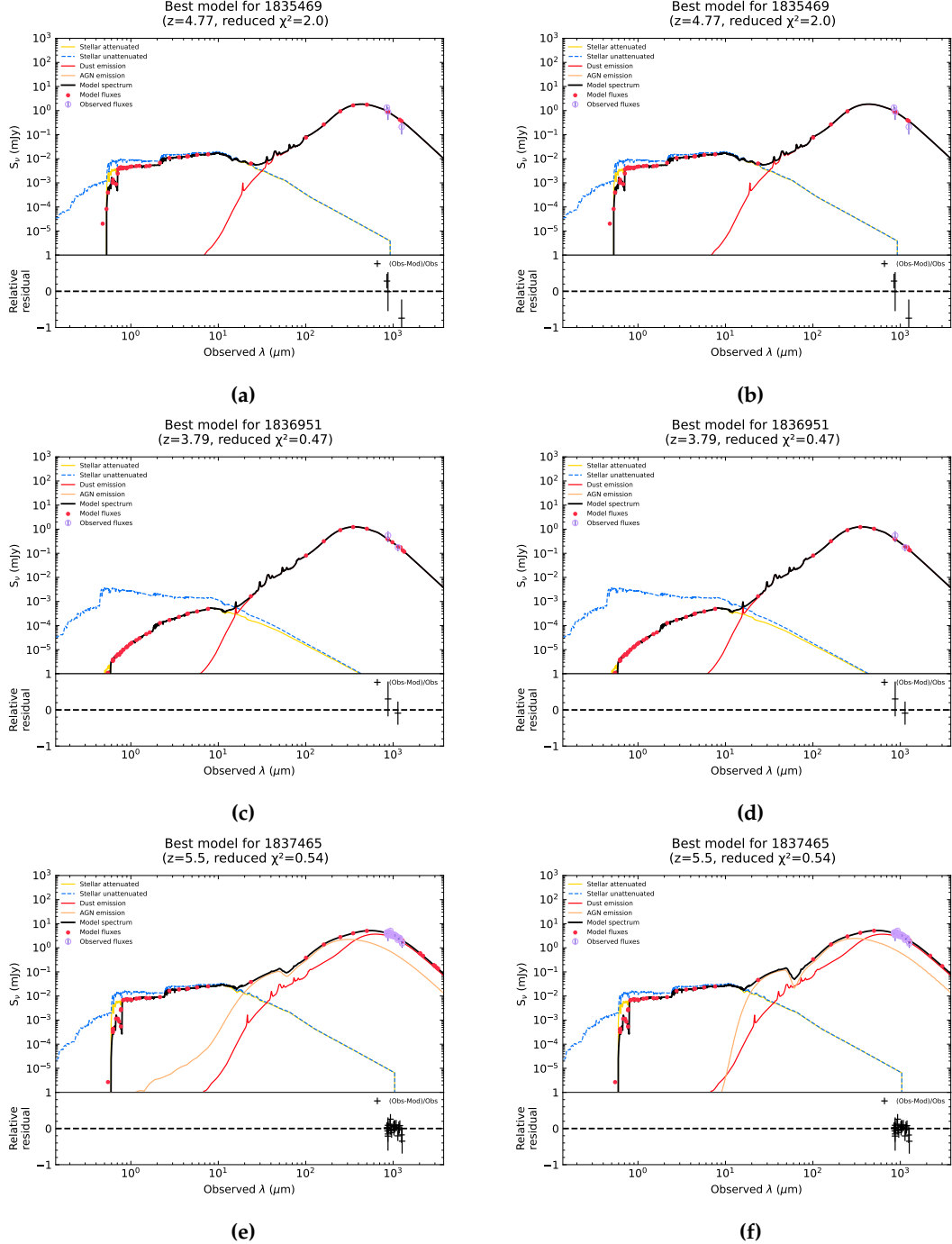


Figure 6.6: SED fits of the six sources for which the detected photometric information is restricted to ALMA measurements, with IDs: 1835469, 1836951, 1837465, 1855033, 1878550 and 1896090, for both *skirtor2016* (left) and *fritz2006* (right) runs. The limited wavelength coverage provides constraints on the long-wavelength dust emission but does not independently sample the stellar and mid-infrared components of the SED.

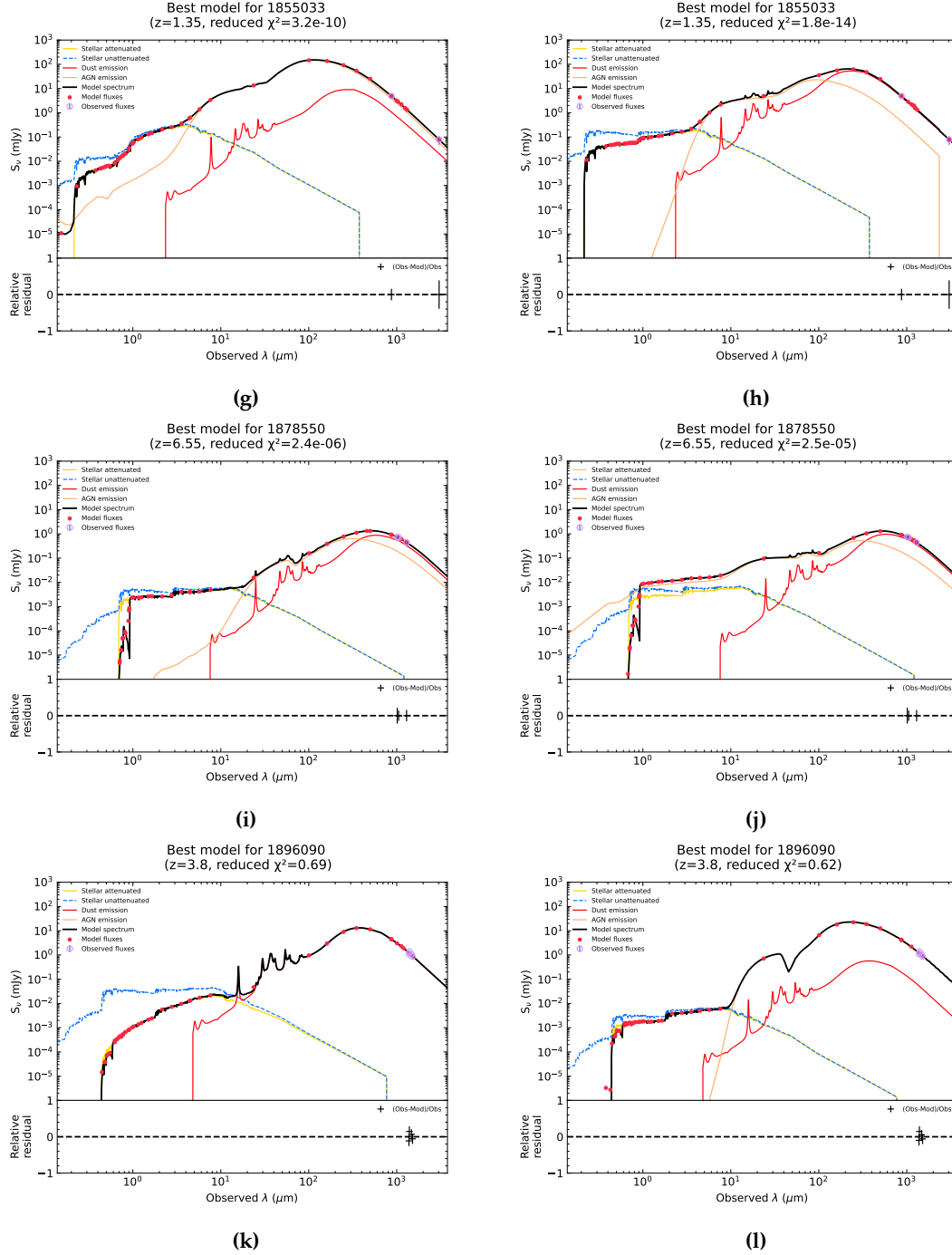


Figure 6.6: SED fits for sources with ALMA-only detections (continued).

Overall, the `skirtor2016` and `fritz2006` runs recover very similar global distributions for stellar mass, star formation rate and total infrared luminosity, whereas a larger dependence on the adopted AGN prescription is visible for the AGN fraction.

6.2.b Comparison between `skirtor2016` and `fritz2006` module results

Although the global distributions derived with the two AGN modules are broadly similar, this does not necessarily imply that the physical properties inferred for each individual galaxy are equally stable. A direct source-by-source comparison was therefore performed

between the results for all 189 sources in the blind-like sample.

The comparison focuses on the same four physical quantities considered in Section 6.2.a: stellar mass, star formation rate, total infrared luminosity and AGN fraction. Figures 6.7a–6.7d show the values obtained with `skirtor2016` against those derived with `fritz2006` for stellar mass, star formation rate, total infrared luminosity and AGN fraction, respectively. In each panel the quantities derived with `skirtor2016` are shown on the horizontal axis, while the values obtained with `fritz2006` are reported on the vertical axis. Sources lying on the dashed line have therefore identical values in the two runs, points above indicate larger values obtained with `fritz2006`, while points below correspond to larger values derived with `skirtor2016`. A first visual inspection already reveals crucial details. Stellar mass shows the tightest relation between the two runs, with a large majority of sources closely following the 1:1 relation for several orders of magnitudes. A similar result is visible for the star formation rate and the total infrared luminosity, although a small number of sources show significantly larger deviations. In contrast, the AGN fraction presents a broader scatter around the 1:1 relation, particularly at intermediate and high values of f_{AGN} . This behaviour suggests that the decomposition of the infrared emission in the 5–40 μm interval between the AGN and other SED components is sensitive to the adopted AGN model, as already noted in Figure 6.2 and Figure 6.3.

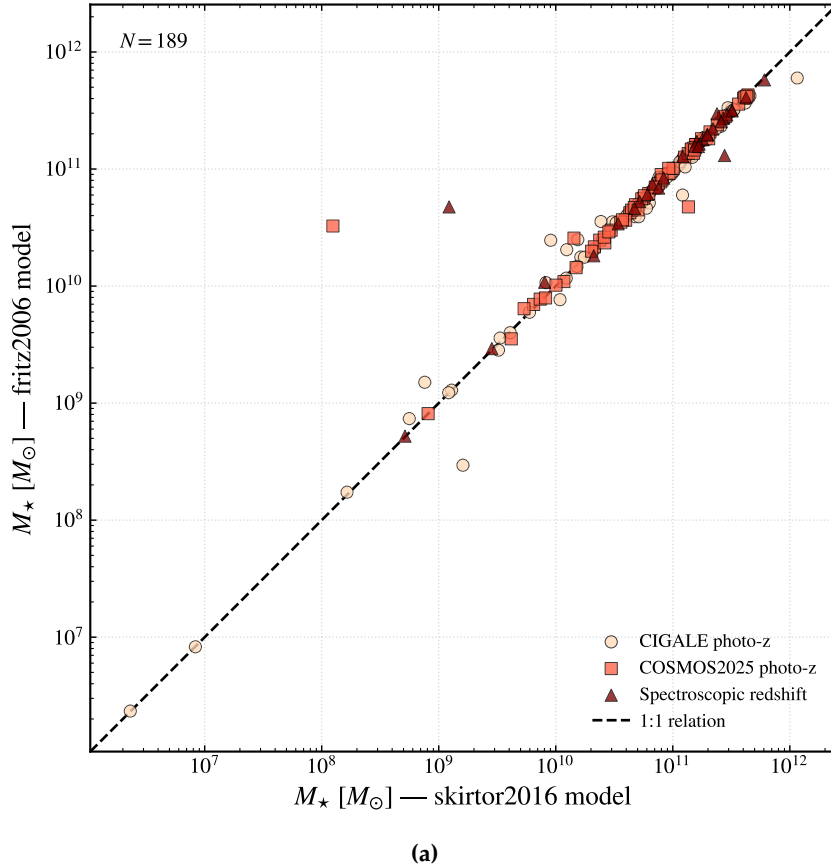
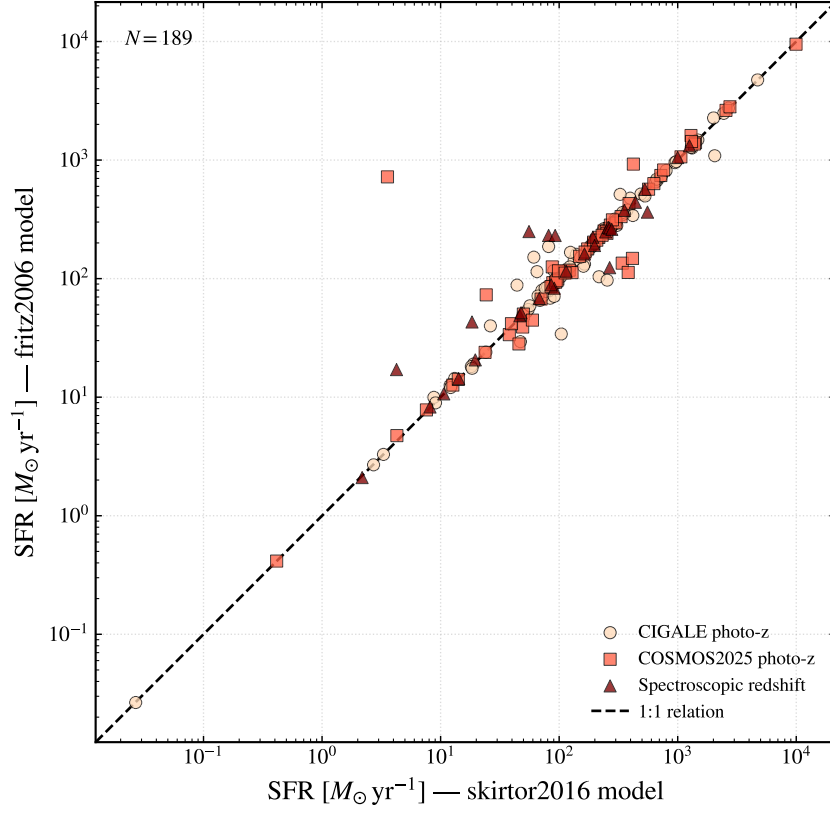
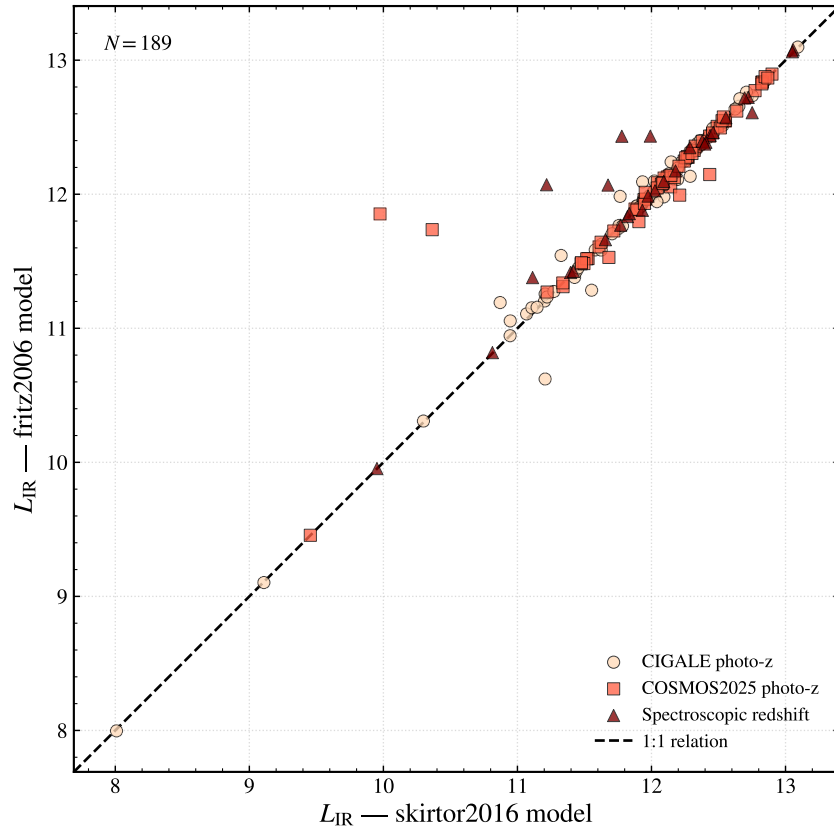


Figure 6.7: Source by source comparison of the physical properties derived with `skirtor2016` and `fritz2006`. From top to bottom: panel (a) for stellar mass, panel (b) for star formation rate, panel (c) for total infrared luminosity and panel (d) for AGN fraction. The dashed black line represents the 1:1 relation. Circles, squares and triangles identify sources with CIGALE photometric, COSMOS photometric and spectroscopic redshifts, respectively.



(b)



(c)

Figure 6.7: Comparison of the physical properties derived with `skirtor2016` and `fritz2006` (continued).

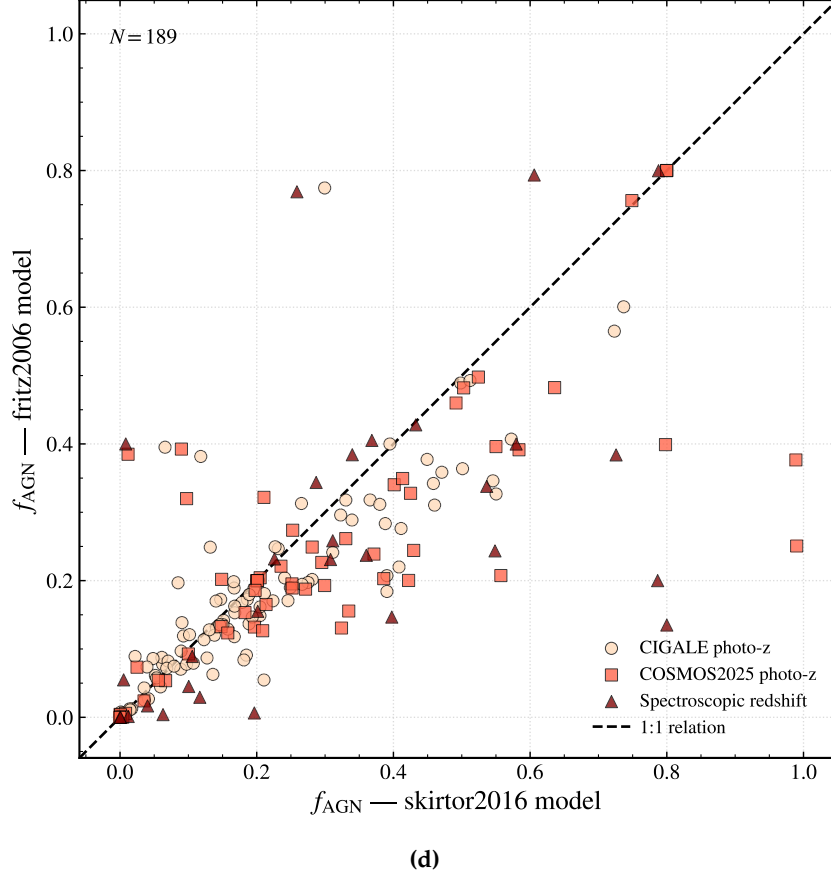


Figure 6.7: Comparison of the physical properties derived with `skirtor2016` and `fritz2006` (continued).

To quantify the differences, for each physical parameter the residual was defined as $\Delta X = X_{\text{Fritz}} - X_{\text{Skirtor}}$ where logarithmic quantities are expressed in dex. The resulting statistics are summarized in Table 6.2.

Table 6.2: Statistics of the source by source differences between the `fritz2006` and `skirtor2016` results. The first three quantities are expressed in dex, while f_{AGN} is dimensionless. The Spearman coefficient ρ quantifies the correlation between the values obtained with the two models.

Parameter	$\langle \Delta X \rangle$	Median(ΔX)	$\sigma_{\Delta X}$	ρ
$\log_{10}(M_{\star}/M_{\odot})$	+0.014	−0.000	0.230	0.987
$\log_{10}(\text{SFR}/M_{\odot} \text{ yr}^{-1})$	+0.023	+0.002	0.219	0.938
$\log_{10}(L_{\text{IR}}/L_{\odot})$	+0.029	+0.002	0.203	0.972
f_{AGN}	−0.042	−0.015	0.148	0.818

- *Stellar mass.* As expected, the strongest agreement is found for the stellar mass. The median difference between the two configurations is essentially zero, and 170 out of 189 sources, which corresponds to nearly 90% of the sample, differ by less than 0.1 dex. The very high Spearman correlation coefficient of $\rho = 0.987$ further indicates that the stellar mass estimates are generally insensitive to the adopted AGN prescription.
- *Star formation rate.* A similarly good agreement is obtained for the star formation rate. The median difference is only 0.002 dex, while 157 sources ($\sim 83\%$ of the

sample) have differences smaller than 0.1 dex. Therefore the correlation remains strong, with $\rho = 0.938$, with the two modules producing only a minor variation in the inferred SFR.

- *Total infrared luminosity.* The total infrared luminosity is also as stable as the former two quantities. The median difference is 0.002 dex and 168 out of 189 sources ($\sim 89\%$) differ by less than 0.1 dex. The corresponding Spearman correlation coefficient is $\rho = 0.972$. This result is particularly relevant for this work, since it indicates that the inferred luminosities derived for the sample are not strongly dependent on the adopted AGN module.
- *AGN fraction.* A larger model dependence is instead observed for the AGN fraction. The mean difference is $\langle \Delta f_{\text{AGN}} \rangle = -0.042$, indicating that the `fritz2006` results tend on average to return slightly lower AGN fractions than `skirtor2016`. The median difference is smaller, -0.015 , showing that the offset is mainly enhanced by a limited number of objects with substantially different solutions. Also the correlation coefficient decreases to $\rho = 0.818$, while 139 sources ($\sim 74\%$) agree within $\Delta f_{\text{AGN}} = 0.1$. The different behaviour of f_{AGN} becomes clearer when the sample is divided according to different AGN fraction thresholds. The numbers of sources exceeding $f_{\text{AGN}} = 0.2, 0.3, 0.5$ in the two runs are reported in Table 6.3.

Table 6.3: Number of sources classified above different AGN-fraction thresholds according to the `skirtor2016` and `fritz2006` results. The “Common” column reports the number of sources satisfying the corresponding criterion in both configurations.

Threshold	<code>skirtor2016</code>	<code>fritz2006</code>	Common
$f_{\text{AGN}} \geq 0.2$	97	83	75
$f_{\text{AGN}} \geq 0.3$	62	49	38
$f_{\text{AGN}} \geq 0.5$	27	9	7

The difference becomes progressively more evident towards large f_{AGN} values. In particular, 27 sources reach $f_{\text{AGN}} \geq 0.5$ with `skirtor2016`, compared with only 9 using `fritz2006`, of which 7 are common to both configurations. Therefore, it can be said that the classification of strongly AGN dominated objects is considerably more sensitive to the adopted AGN module.

Most of the dispersion reported in Table 6.2 is produced by a small number of sources showing much stronger model dependence than the others in the sample. Four particularly relevant examples are IDs 410371, 682011, 690264 and 1394965. Their SEDs are therefore shown in Figure 6.8.

Their physical parameters differ substantially between the two configurations although their χ^2_{red} values do not indicate particularly poor fits. Overall, the comparison indicates that stellar mass, star formation rate and the total infrared luminosity are robust against the choice between the two adopted AGN modules for the large majority of the sample. The AGN fraction is instead more sensitive to the adopted model, particularly for sources with a large inferred AGN contribution.

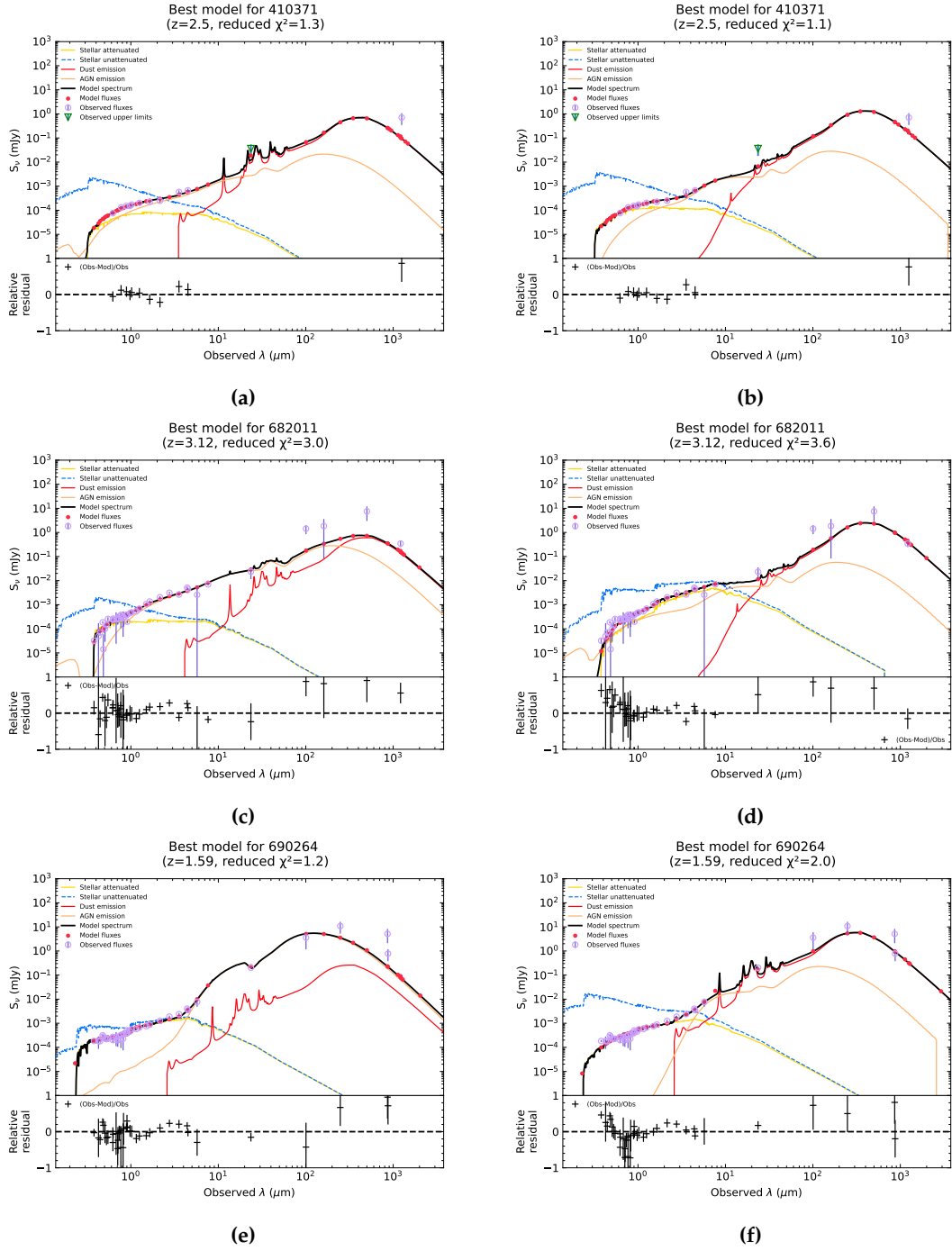


Figure 6.8: Comparison between the *skirtor2016* (left) and *fritz2006* (right) fits for four example sources showing particularly large differences in the recovered physical parameters.

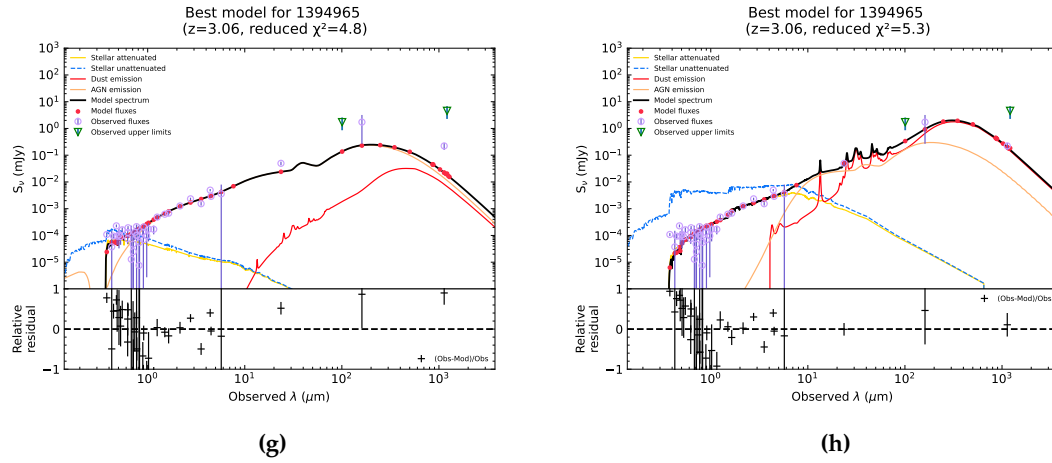


Figure 6.8: Example of sources showing large differences between the two runs (continued).

Infrared Luminosity Functions and Cosmic Star Formation Rate Density

7.1 Infrared luminosity functions

The SED fitting analysis presented in Chapter 6 provided an estimate of the total infrared luminosity L_{IR} integrated over the rest-frame 8–1000 μm interval for each galaxy in the final blind-like sample. While these measurements describe the properties of individual sources, a statistical characterization of the population requires accounting for the different cosmological volumes over which galaxies of different luminosities could have been detected. This is provided by the infrared luminosity function, which describes the comoving number density of galaxies per logarithmic luminosity interval

$$\Phi(L_{\text{IR}}) = \frac{dN}{dV_c d\log_{10} L_{\text{IR}}} \quad (7.1)$$

and is generally expressed in units of $\text{Mpc}^{-3} \text{dex}^{-1}$. As discussed in Chapter 1, the construction of a luminosity function therefore combines the intrinsic luminosity of each galaxy with the cosmological volume over which that source could have entered the observed sample. The infrared luminosity functions that will be presented were reconstructed following the same procedure adopted by Traina et al. 2024 for the original A³COSMOS analysis. Particular care is required because of the nature of the A³COSMOS catalogue. The blind-like selection and the cumulative area–depth relation introduced in Section 5.1.e were specifically constructed to account for its heterogeneous observing strategy. The luminosity function was derived using the $1/V_{\text{max}}$ method of Schmidt 1970, following the implementation described by Traina et al. 2024. The basic principle is that each galaxy contributes to the luminosity function according to the maximum comoving volume over which it would have remained detectable. Bright sources can generally be observed over a larger volume, while intrinsically fainter objects are detectable only in the deepest portions of the survey. In a given luminosity interval, the luminosity function can therefore be written as

$$\Phi(L_{\text{IR}}) = \frac{1}{\Delta \log_{10} L_{\text{IR}}} \sum_i \frac{1}{V_{\text{max},i}} \quad (7.2)$$

where the sum extends over the galaxies contained in the corresponding luminosity and redshift bins.

For each source, the best-fit SED obtained with CIGALE was shifted across the corresponding redshift interval in steps of $dz = 0.02$. At each step, the SED was K-corrected and used to predict the observed flux density at the common reference wavelength of

1200 μm . This flux was then associated with the effective area over which a source of the same brightness could have been detected by interpolating the cumulative area–depth relation shown in Figure 5.6. The accessible area was combined with the comoving volume element at each redshift step to determine the total volume sampled by galaxies. This volume can be expressed as $V_{\text{max}} = V_{z_{\text{max}}} - V_{z_{\text{min}}}$ where z_{max} is either the upper boundary of the redshift bin or the maximum redshift at which the source remains detectable, given the survey sensitivity. The resulting V_{max} values were also corrected for the completeness and spurious-source fractions associated with the A³COSMOS source extraction, following the same prescription adopted in the reference analysis. The individual $1/V_{\text{max}}$ contributions were finally combined in luminosity bins of width 0.5 dex.

The original analysis of Traina et al. 2024 divided the sample into eight narrow redshift intervals between $0.5 \leq z \leq 6$. In the present work, two complementary redshift binnings were adopted. The main analysis was performed using two broader intervals $0.5 \leq z < 3.0$ and $3.0 \leq z \leq 7.0$. These intervals contain comparable numbers of sources and preserve sufficient statistics when progressively restricting the sample according to the AGN fraction. This becomes particularly important for the two adopted selections of $f_{\text{AGN}} \geq 0.2$ and $f_{\text{AGN}} \geq 0.5$. Moreover, the updated redshift compilation places two sources at $z > 6$, which are included in the second broad redshift interval. For the complete sample, the luminosity function calculation was additionally repeated using exactly the same eight redshift intervals adopted by Traina et al. 2024. The binned luminosity functions were subsequently described using the same modified Schechter function adopted by Traina et al. 2024, originally introduced by Saunders et al. 1990

$$\Phi(L) d\log_{10} L = \Phi^* \left(\frac{L}{L^*} \right)^{1-\alpha} \exp \left[-\frac{1}{2\sigma^2} \log_{10}^2 \left(1 + \frac{L}{L^*} \right) \right] d\log_{10} L \quad (7.3)$$

where L^* represents the characteristic luminosity associated with the knee of the luminosity function, Φ^* its normalization, α determines the faint-end slope and σ controls the shape of the bright end decline. The modified Schechter function behaves approximately as a power law below L^* , while it approaches a Gaussian dependence in logarithmic luminosity at the bright end. Following the configuration adopted by Traina et al. 2024, the shape parameters were fixed to $\alpha = 1.2$ and $\sigma = 0.5$, while L^* and Φ^* were instead constrained through a Markov chain Monte Carlo analysis. The resulting posterior distributions provide both the best-fitting luminosity function and its upper and lower uncertainties. The procedure was performed independently using the total infrared luminosities obtained from the skitor2016 and fritz2006 SED fitting runs. In addition to the full sample of 189 galaxies, the luminosity function calculations were repeated after applying two selections to the AGN fraction derived from the SED fitting. Three populations were therefore considered for each AGN model: the complete sample with $f_{\text{AGN}} \geq 0.0$, the sources with $f_{\text{AGN}} \geq 0.2$ and the sources with $f_{\text{AGN}} \geq 0.5$. The two thresholds are used to isolate populations characterized by progressively stronger mid-infrared AGN contributions. The MCMC fitting procedure was performed independently in each redshift bin. The prior ranges adopted for the free parameters were therefore selected separately for each interval, in order to remain representative of the luminosity-function regime sampled at the corresponding redshift. This approach avoids adopting a single excessively broad prior range for all redshift intervals, which could introduce additional dispersion in the posterior distributions in regions of parameter space that are poorly

representative of the IR luminosity function in a given bin.

Before considering the broader redshift subdivision adopted for the AGN-selected analysis, the full-sample analysis was done using the redshift intervals adopted by Traina et al. 2024. The resulting luminosity functions for both models are shown in Figure 7.1, while the corresponding measurements and uncertainties are reported in Table 7.1. In this case, no selection in AGN fraction was applied and all 189 sources were considered.

Table 7.1: Binned infrared luminosity function measurements obtained for the complete sample using the eight redshift intervals adopted by Traina et al. 2024. The reported values correspond to $\log_{10}(\Phi/\text{Mpc}^{-3} \text{ dex}^{-1})$ and the associated Poissonian uncertainties. A dash indicates that no luminosity-function measurement is available in the corresponding bin.

Redshift range	$\log_{10}(L_{\text{IR}}/L_{\odot})$	skirtor2016	fritz2006
$0.5 \leq z < 1.0$	11.75	-3.85 ± 1.00	-3.85 ± 1.00
	12.25	-4.15 ± 0.71	-4.12 ± 0.71
$1.0 \leq z < 1.5$	11.75	-2.95 ± 0.35	-2.94 ± 0.38
	12.25	-4.11 ± 0.45	-4.18 ± 0.45
	12.75	–	-4.68 ± 0.71
	13.25	-4.99 ± 1.00	–
$1.5 \leq z < 2.0$	11.75	-3.78 ± 0.29	-4.21 ± 0.30
	12.25	-3.73 ± 0.23	-3.67 ± 0.22
	12.75	-4.11 ± 0.38	-4.20 ± 0.41
$2.0 \leq z < 2.5$	11.75	-3.53 ± 0.33	-4.55 ± 0.50
	12.25	-3.74 ± 0.27	-3.67 ± 0.24
	12.75	-3.72 ± 0.22	-3.69 ± 0.22
$2.5 \leq z < 3.0$	11.75	-4.16 ± 1.00	-4.53 ± 0.58
	12.25	-3.87 ± 0.29	-3.84 ± 0.29
	12.75	-4.29 ± 0.41	-4.53 ± 0.50
$3.0 \leq z < 3.5$	11.75	–	-4.40 ± 1.00
	12.25	-3.71 ± 0.32	-3.67 ± 0.33
	12.75	-4.24 ± 0.45	-4.07 ± 0.41
$3.5 \leq z < 4.5$	11.75	-4.72 ± 0.58	-4.70 ± 0.58
	12.25	-4.74 ± 0.71	-4.81 ± 0.71
	12.75	-4.49 ± 0.45	-4.57 ± 0.50
	13.25	-5.11 ± 0.71	-4.88 ± 0.58
$4.5 \leq z < 6.0$	11.75	-2.87 ± 0.58	-3.34 ± 0.58
	12.25	-4.40 ± 0.50	-4.41 ± 0.50
	12.75	-4.91 ± 0.58	-4.91 ± 0.58
	13.25	-5.45 ± 1.00	-5.45 ± 1.00

In the luminosity range above the completeness limit, the skirtor2016 and fritz2006 measurements remain generally consistent within their Poissonian uncertainties across the eight intervals. The same behaviour is even more evident when considering the fitted luminosity functions: the two best-fitting curves are remarkably similar over most of the luminosity range effectively constrained by the data, and their uncertainty regions largely overlap in all redshift intervals. This indicates that the overall shape and normalization

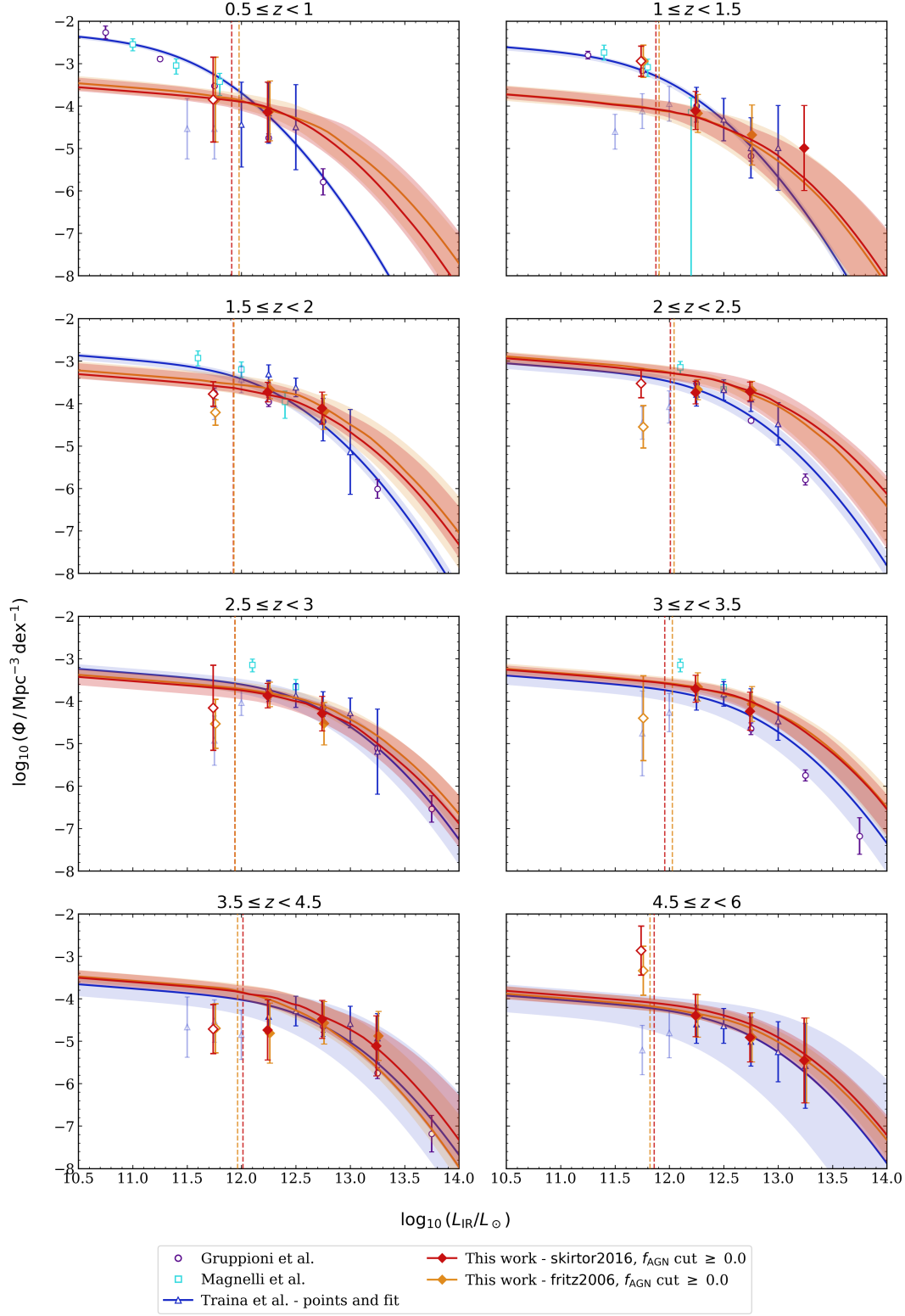


Figure 7.1: Infrared luminosity functions obtained for the complete sample using the eight redshift intervals adopted by Traina et al. 2024. The skirtor2016 and fritz2006 measurements derived in this work are shown together with the corresponding best-fitting modified Schechter functions. The results are compared with the measurements of Gruppioni et al. 2013 and Magnelli et al. 2013, and with the reference fit and measurements of Traina et al. 2024. The vertical dashed lines indicate the infrared luminosity completeness limits for skirtor2016 and fritz2006. Filled diamonds correspond to measurements above the respective completeness limit, while open diamonds indicate luminosity bins below it.

of the reconstructed IR luminosity function are only weakly affected by the choice of AGN torus prescription, as expected from previous considerations on inferred infrared luminosities (see Figure 6.7c).

The most evident differences between the two runs occur instead in the lowest-luminosity points of some bins, particularly at $1.5 \leq z < 2.0$, $2.0 \leq z < 2.5$, and $4.5 \leq z < 6.0$. These measurements lie close to, or below, the corresponding completeness limits and are generally based on a small number of sources, therefore providing substantially weaker constraints on the luminosity function. Once the comparison is restricted to the luminosity regime above the completeness thresholds, the agreement between the two models becomes considerably stronger.

A comparison with the luminosity function of Traina et al. 2024 also shows that the agreement is generally strongest around the luminosity range directly sampled by the present data, approximately around the knee of the luminosity function. Larger differences can appear toward the faint and bright ends, where the fitted curves are increasingly driven by extrapolation and the statistical uncertainties become larger. This effect becomes particularly evident at the highest redshifts, where the smaller number of available sources produces broader confidence regions and consequently weaker constraints on the bright-end slope. Overall, the combined comparison of the individual measurements and of the fitted luminosity functions confirms that the reconstruction of the bright portion of the infrared luminosity function for the complete sample is robust against the adopted AGN torus model. The differences between skirtor2016 and fritz2006 are mainly confined to luminosity bins affected by incompleteness or limited source statistics, rather than representing a systematic difference between the two SED-fitting prescriptions.

Having verified the behaviour of the complete sample using the finer redshift subdivision, we now turn to the two broader redshift intervals adopted for the comparison between the complete and AGN-selected populations. The resulting luminosity functions are analysed separately for the three adopted selections in AGN fraction. For each case, the skirtor2016 and fritz2006 results are shown together in order to assess the dependence of the inferred luminosity function on the adopted AGN prescription, in Figures 7.2, 7.3 and 7.4. The corresponding binned measurements are also reported explicitly in Tables 7.2, 7.3 and 7.4. The uncertainties associated with the individual luminosity bins are Poissonian, following the same convention adopted by Traina et al. 2024. As in the analysis performed with the finer redshift subdivision, model-dependent luminosity completeness limits are determined separately for the skirtor2016 and fritz2006 samples and are shown as vertical dashed lines in the corresponding colours. Measurements below these limits are represented by open diamonds and should be interpreted with caution, whereas filled diamonds indicate luminosity bins above the corresponding completeness threshold. Since f_{AGN} is independently inferred by the two AGN modules (see Figure 6.7d), the sources satisfying a given threshold are not necessarily identical in the two runs. This distinction becomes increasingly relevant as more restrictive selections are applied, as already mentioned in Table 6.3.

We first consider the complete sample, corresponding to $f_{\text{AGN}} \geq 0.0$ and therefore including all 189 sources (Figure 7.2 and Table 7.2).

The full-sample luminosity function shows the expected decrease in number density towards increasingly luminous infrared sources. In the lower-redshift interval, the agreement between the two AGN prescriptions is very good over the luminosity range above

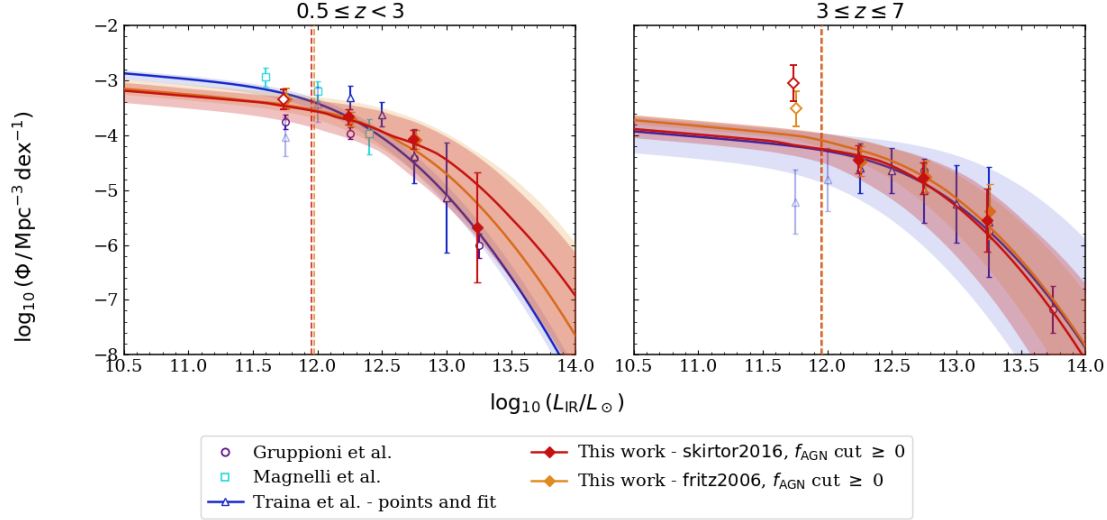


Figure 7.2: Infrared luminosity functions obtained for the complete sample, corresponding to $f_{\text{AGN}} \geq 0.0$, in the two broad redshift intervals $0.5 \leq z < 3.0$ and $3.0 \leq z \leq 7.0$. The solid curves and the corresponding shaded regions represent the modified Schechter fits obtained in this work and their uncertainties for *skirtor2016* and *fritz2006*. The vertical dashed lines indicate the model-dependent infrared luminosity completeness limits, with filled diamonds that correspond to measurements above such threshold, while open diamonds indicate bins below it. The results are compared with the measurements of [Gruppioni et al. 2013](#) and [Magnelli et al. 2013](#), and with the measurements and reference modified Schechter fit of [Traina et al. 2024](#).

Table 7.2: Binned infrared luminosity function measurements obtained for the complete sample. The reported values correspond to $\log_{10}(\Phi/\text{Mpc}^{-3} \text{dex}^{-1})$, with their Poissonian uncertainties. A dash indicates that no LF point is available in the corresponding luminosity bin.

redshift range	$0.5 \leq z < 3.0$		$3.0 \leq z \leq 7.0$	
$\log(L_{\text{IR}}/L_{\odot})$	<i>skirtor2016</i>	<i>fritz2006</i>	<i>skirtor2016</i>	<i>fritz2006</i>
11.75	-3.34 ± 0.18	-3.34 ± 0.19	-3.04 ± 0.33	-3.51 ± 0.32
12.25	-3.66 ± 0.14	-3.71 ± 0.13	-4.44 ± 0.26	-4.47 ± 0.27
12.75	-4.07 ± 0.17	-4.08 ± 0.17	-4.78 ± 0.29	-4.75 ± 0.29
13.25	-5.68 ± 1.00	–	-5.55 ± 0.58	-5.39 ± 0.50

the corresponding completeness limits. In particular, between $\log_{10}(L_{\text{IR}}/L_{\odot}) \simeq 12.25$ and 12.75 , the *skirtor2016* and *fritz2006* measurements differ by only ~ 0.05 dex, well below the corresponding Poissonian uncertainties. The lowest-luminosity point lies below the completeness threshold and therefore provides a weaker constraint on the faint end, while the additional *skirtor2016* measurement at $\log_{10}(L_{\text{IR}}/L_{\odot}) = 13.25$ is affected by a large uncertainty and only weakly constrains the extreme bright end.

A similar behaviour is observed in the high-redshift interval. Above the completeness limits, the two models remain closely consistent across the luminosity range sampled by the data. The largest difference appears in the lowest-luminosity bin, where the two inferred number densities differ more significantly. However, both measurements lie below their respective completeness thresholds and should therefore be interpreted with caution. At higher luminosities, the differences are much smaller and remain well within the statistical uncertainties.

The agreement between the two SED-fitting prescriptions is also evident from the fitted luminosity functions. In both redshift intervals, the *skirtor2016* and *fritz2006* best-

fitting curves remain very close over the luminosity range directly constrained by the observations, with largely overlapping uncertainty regions. A comparison with Traina et al. 2024 also shows a generally good agreement over the luminosity range effectively sampled by the present data. At high redshift, the luminosity functions derived in this work closely follow the reference relation, whereas somewhat larger differences in shape are visible in the lower-redshift interval, particularly towards the bright end. These differences should not necessarily be interpreted as a physical discrepancy, since the present analysis adopts a different luminosity binning and independently derived infrared luminosities, while the fitted modified Schechter function is also sensitive to the limited number of sources constraining the brightest bins.

As already discussed by Traina et al. 2024, the A³COSMOS sample primarily constrains the bright portion of the infrared luminosity function. Restricting the comparison to the luminosity range above the completeness thresholds, both models indicate a lower number density at $3 \leq z \leq 7$ than at $0.5 \leq z < 3$ for a fixed infrared luminosity. Most importantly for the comparison between the SED-fitting prescriptions, both the individual measurements and the fitted luminosity functions confirm that the full-sample infrared luminosity function is largely insensitive to the adopted AGN module. This is consistent with the close agreement in L_{IR} found between the two runs in Section 6.2.b.

The second selection retains only sources with $f_{\text{AGN}} \geq 0.2$ (Figure 7.3 and Table 7.3).

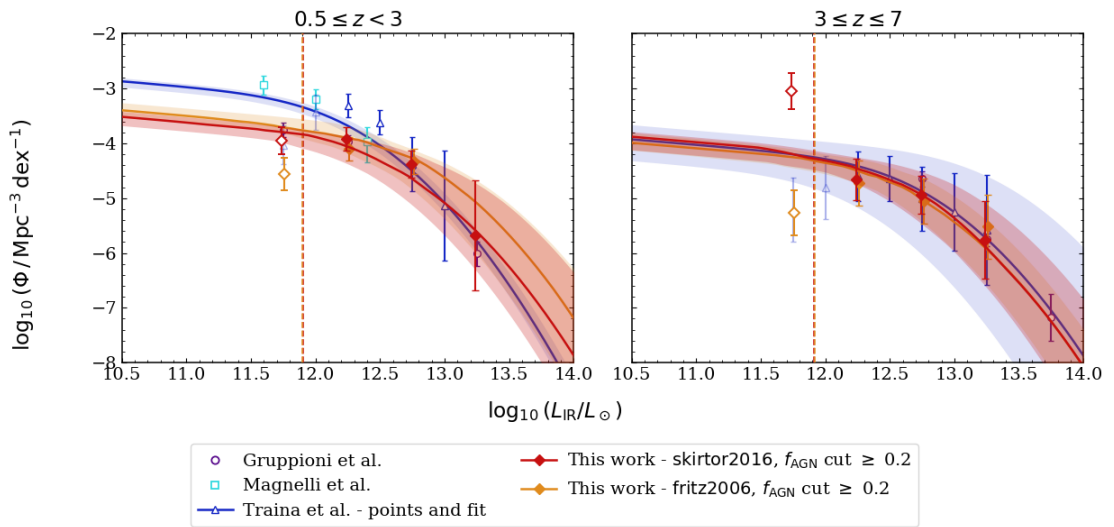


Figure 7.3: Infrared luminosity functions obtained after selecting sources with $f_{\text{AGN}} \geq 0.2$, in the two broad redshift intervals $0.5 \leq z < 3.0$ and $3.0 \leq z \leq 7.0$. The *skirtor2016* and *fritz2006* measurements are shown together in each panel for direct comparison, together with the corresponding best-fitting modified Schechter functions and uncertainty regions. The model-dependent completeness limits are indicated by vertical dashed lines. Symbols, literature measurements, reference fits, and the convention adopted to distinguish complete and incomplete luminosity bins are the same as in Figure 7.2.

Applying the $f_{\text{AGN}} \geq 0.2$ selection produces the expected decrease in the normalization of the luminosity function with respect to the complete sample, since only galaxies with a non-negligible AGN contribution are retained. At $0.5 \leq z < 3$, the reduction is already visible over the luminosity range directly constrained by the data. Around $\log_{10}(L_{\text{IR}}/L_{\odot}) = 12.25\text{--}12.75$, the number density decreases by approximately 0.2–0.4 dex relative to the complete sample, depending on the adopted AGN module. The rela-

Table 7.3: Binned infrared luminosity function measurements obtained after selecting sources with $f_{\text{AGN}} \geq 0.2$. The reported values correspond to $\log_{10}(\Phi/\text{Mpc}^{-3} \text{ dex}^{-1})$, with their Poissonian uncertainties. A dash indicates that no LF point is available in the corresponding luminosity bin.

redshift range $\log(L_{\text{IR}}/L_{\odot})$	$0.5 \leq z < 3.0$		$3.0 \leq z \leq 7.0$	
	skirtor2016	fritz2006	skirtor2016	fritz2006
11.75	-3.95 ± 0.25	-4.56 ± 0.30	-3.04 ± 0.33	-5.27 ± 0.41
12.25	-3.92 ± 0.21	-4.10 ± 0.22	-4.66 ± 0.38	-4.73 ± 0.41
12.75	-4.38 ± 0.25	-4.33 ± 0.23	-4.94 ± 0.35	-5.06 ± 0.41
13.25	-5.68 ± 1.00	–	-5.76 ± 0.71	-5.52 ± 0.58

tively modest reduction indicates that sources with at least a moderate AGN contribution still constitute a significant fraction of the infrared population in this luminosity regime.

The comparison between the two torus prescriptions remains generally good above the corresponding completeness limits. In the lower-redshift interval, the *skirtor2016* and *fritz2006* measurements differ by less than ~ 0.2 dex over the main luminosity range, and are fully consistent within their Poissonian uncertainties. A larger difference is present in the lowest-luminosity bin, but this measurement lies below the completeness threshold for both models and therefore provides a weaker constraint on the luminosity function.

The same behaviour becomes even more evident at high redshift. Above the completeness limits, the two determinations remain broadly consistent throughout the luminosity range sampled by the data, despite the larger statistical uncertainties associated with the reduced number of selected sources. In contrast, the lowest-luminosity bin shows a much larger difference between the two models, exceeding 2 dex. Since both measurements lie below their respective completeness limits, this discrepancy should not be interpreted as a robust difference in the underlying luminosity function. In both redshift intervals, the *skirtor2016* and *fritz2006* best-fitting curves remain close over the luminosity range effectively constrained by the observations, with substantially overlapping uncertainty regions. At $0.5 \leq z < 3$, some difference in normalization is visible towards lower luminosities. At $3 \leq z \leq 7$, the agreement between the two fitted functions is particularly good above the completeness limit, while the confidence regions broaden towards the bright end as a consequence of the smaller number of available sources.

Compared with the reference luminosity function of [Traina et al. 2024](#), the AGN-selected functions naturally lie at lower number densities over much of the sampled luminosity range, since they represent only the subset of sources with $f_{\text{AGN}} \geq 0.2$. The difference is more apparent at lower redshift, while at high redshift the fitted relations remain closer to the reference luminosity function over part of the observed bright-end regime. This suggests that the relative incidence of sources with a moderate AGN contribution may become increasingly important towards higher redshift, although the larger statistical uncertainties prevent a strong conclusion from the luminosity functions alone.

Overall, the $f_{\text{AGN}} \geq 0.2$ selection therefore preserves the broad agreement between the two AGN prescriptions in the luminosity regime where the sample is complete, while making the luminosity function more sensitive to the model-dependent classification of individual sources.

The final luminosity functions were obtained by requiring $f_{\text{AGN}} \geq 0.5$, therefore selecting only sources with a strong contribution from the AGN to the rest-frame infrared emission (Figure 7.4 and Table 7.4).

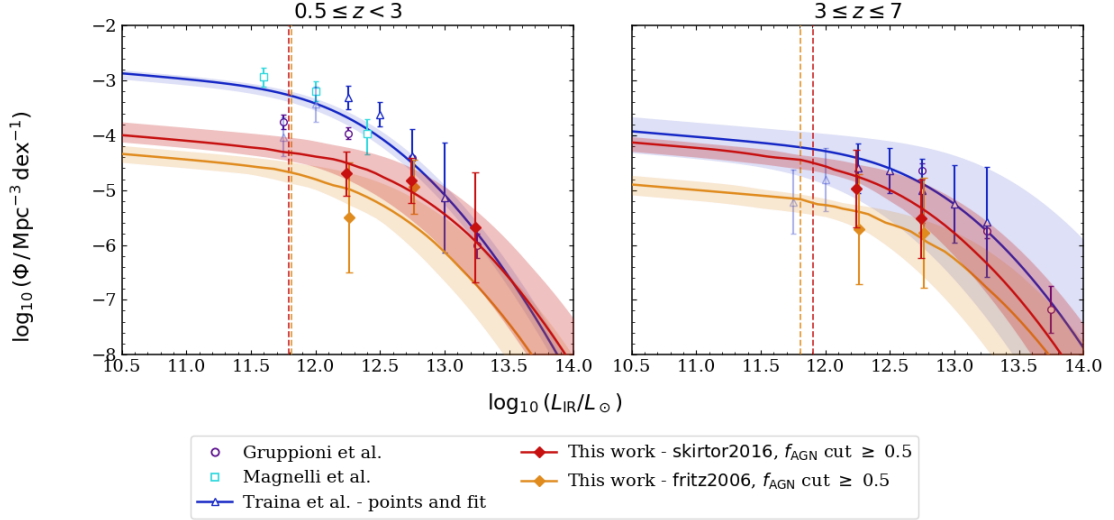


Figure 7.4: Infrared luminosity functions obtained after selecting sources with $f_{\text{AGN}} \geq 0.5$, in the two broad redshift intervals $0.5 \leq z < 3.0$ and $3.0 \leq z \leq 7.0$. The *skirtor2016* and *fritz2006* measurements are shown together in each panel, together with the corresponding best-fitting modified Schechter functions and uncertainty regions. The model-dependent completeness limits are indicated by vertical dashed lines. Symbols, literature measurements, reference fits, and the convention adopted to distinguish complete and incomplete luminosity bins are the same as in Figure 7.2.

Table 7.4: Binned infrared luminosity function measurements obtained after selecting sources with $f_{\text{AGN}} \geq 0.5$. The reported values correspond to $\log_{10}(\Phi/\text{Mpc}^{-3} \text{ dex}^{-1})$, with their Poissonian uncertainties. A dash indicates that no LF point is available in the corresponding luminosity bin.

redshift range	$0.5 \leq z < 3.0$		$3.0 \leq z \leq 7.0$	
$\log(L_{\text{IR}}/L_{\odot})$	<i>skirtor2016</i>	<i>fritz2006</i>	<i>skirtor2016</i>	<i>fritz2006</i>
11.75	—	—	—	—
12.25	-4.70 ± 0.41	-5.50 ± 1.00	-4.97 ± 0.71	-5.71 ± 1.00
12.75	-4.82 ± 0.41	-4.94 ± 0.50	-5.52 ± 0.71	-5.78 ± 1.00
13.25	-5.68 ± 1.00	—	—	—

The latter selection substantially changes the situation. No luminosity-function measurements remain at $\log_{10}(L_{\text{IR}}/L_{\odot}) = 11.75$ for either model or redshift interval, while the surviving measurements are concentrated at $\log_{10}(L_{\text{IR}}/L_{\odot}) \gtrsim 12.25$. The population selected with $f_{\text{AGN}} \geq 0.5$ is therefore restricted to the ULIRG luminosity regime. Unlike the lowest-luminosity measurements discussed for the previous selections, the remaining points lie above the corresponding completeness limits. The dominant limitation in this case is instead the reduced number of selected sources (see Table 6.3), as reflected by Poissonian uncertainties of approximately 0.4–1 dex.

At $0.5 \leq z < 3$, the two models remain consistent within these large uncertainties, although their differences are more pronounced than for the less restrictive selections. A similar behaviour is observed at $3 \leq z \leq 7$, where only two luminosity bins remain populated and the statistical uncertainties are comparable to, or larger than, the differences between the two models.

The increased model dependence is also visible in the fitted luminosity functions. In both redshift intervals, the *fritz2006* fit tends to lie below the *skirtor2016* solution over much of the luminosity range, indicating a lower inferred number density of strongly

AGN-dominated sources. The separation is most evident towards lower luminosities, while the two fitted functions become closer towards the bright end.

Considering the three selections together reveals two main trends. First, progressively increasing the AGN-fraction threshold systematically lowers the normalization of the luminosity function and reduces the number of populated luminosity bins. The effect is strongest for $f_{\text{AGN}} \geq 0.5$, for which only the most infrared-luminous sources remain and the statistical uncertainties become correspondingly larger. Second, the dependence on the adopted AGN model increases as the f_{AGN} cut becomes more restrictive. This behaviour is consistent with the fact that the selection itself is based on a model-dependent quantity. The growing difference between the two luminosity functions therefore primarily reflects differences in the classification of strongly AGN-dominated sources rather than a comparable systematic disagreement in the total infrared luminosities recovered by the two SED-fitting runs.

7.2 Dust-obscured star formation rate density

Once the infrared luminosity functions have been reconstructed, their integration provides a direct estimate of the total infrared luminosity emitted per unit comoving volume. Following the same procedure adopted by Traina et al. 2024, the inferred luminosity density was obtained in each redshift bin by integrating the corresponding best-fitting luminosity function over the interval $8 \leq \log_{10}(L_{\text{IR}}/L_{\odot}) \leq 14$ as follows

$$\rho_{\text{IR}}(z) = \int_8^{14} \Phi(\log_{10} L_{\text{IR}}, z) L_{\text{IR}} d\log_{10} L_{\text{IR}} \quad (7.4)$$

where ρ_{IR} is expressed in $L_{\odot} \text{ Mpc}^{-3}$. The lower integration limit follows the choice of Traina et al. 2024 and allows the resulting values to be consistently compared with previous determinations of the cosmic star formation rate density. The infrared luminosity density was then converted into a dust-obscured SFRD using the Kennicutt 1998 relation, rescaled to the Chabrier 2003 initial mass function adopted throughout the analysis.

$$\rho_{\text{SFR}} = 1.09 \times 10^{-10} \rho_{\text{IR}} \quad (7.5)$$

where ρ_{SFR} is expressed in $M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$. As in the reference analysis, the total infrared luminosity integrated over 8–1000 μm was used without subtracting the AGN contribution before computing the SFRD. At this stage, the derived quantity therefore provides the reference infrared-based SFRD of the complete sample. The possible effect associated with galaxies hosting progressively stronger AGN components is analysed separately in Section 7.3. In the computation of the integral of Equation 7.4, it is important to note that it extends over a luminosity range considerably broader than the region directly sampled by the ALMA-selected galaxies. As shown in Section 7.1, the measurements predominantly constrain the luminous and bright end of the luminosity function. The contribution from lower luminosity galaxies therefore relies on the fitted modified Schechter function, with fixed parameters for the faint-end. Uncertainties on ρ_{SFR} were propagated from the uncertainties of the luminosity function fits.

For the complete sample, the SFRD was first independently derived using the eight narrower redshift intervals adopted by Traina et al. 2024. As for the luminosity functions,

this narrower subdivision was not applied to the different f_{AGN} subsamples, therefore the full sample of 189 sources was used. The evolution obtained using the narrower redshift subdivision is shown in Figure 7.5, together with the corresponding numerical values reported in Table 7.5.

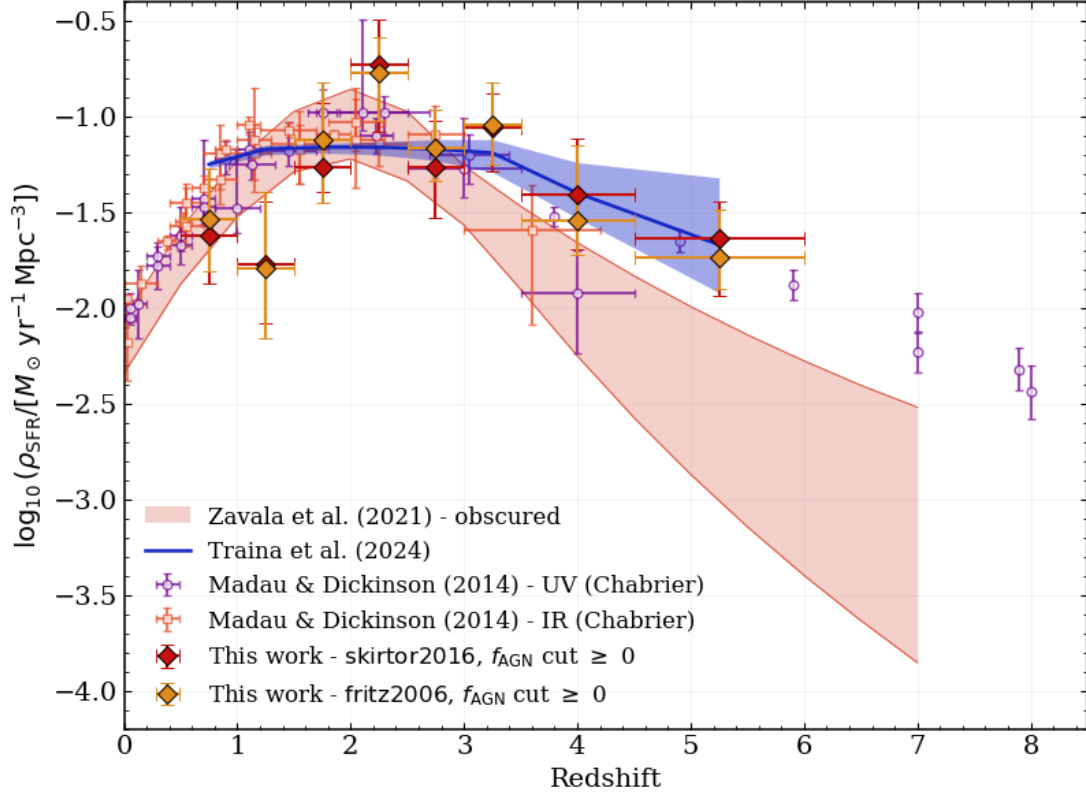


Figure 7.5: Dust-obscured star formation rate density obtained for the complete sample using the eight redshift intervals adopted by Traina et al. 2024. The red and orange diamonds represent the measurements derived in this work using the skitor2016 and fritz2006 models, respectively, while the horizontal and vertical error bars indicate the redshift intervals and the asymmetric uncertainties propagated from the luminosity-function fits. The comparison includes the obscured SFRD of Zavala et al. 2021, the A³COSMOS determination of Traina et al. 2024, and the UV- and IR-based cosmic star formation histories of Madau & Dickinson 2014, as reference.

The higher-resolution reconstruction provides two main results. First, the agreement between the two AGN models remains strong when the sample is divided into narrower redshift intervals. In most bins, the skitor2016 and fritz2006 determinations differ only modestly and remain consistent within their uncertainties. This confirms that the dust-obscured star formation rate density derived for the complete sample is only weakly dependent on the adopted AGN torus model, in agreement with the behaviour already found for the infrared luminosity functions.

Second, the use of the same redshift subdivision adopted by Traina et al. 2024 enables a direct comparison with the original A³COSMOS determination. The general evolutionary behaviour is preserved: the SFRD increases from low redshift up to a maximum around Cosmic Noon, approximately at $z \sim 2-3$, and then declines towards earlier cosmic epochs. In the redshift range around the peak, the measurements derived in this work are in some cases higher than the reference A³COSMOS values, although the overall trend remains

Table 7.5: Dust-obscured SFRD obtained for the complete sample using the eight redshift intervals of Traina et al. 2024. The two central columns report the results obtained in this work with the skirtor2016 and fritz2006 models, while the final column reports the original A³COSMOS determination of Traina et al. 2024. Values are expressed as $\log_{10}(\rho_{\text{SFR}}/[M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}])$.

Redshift range	skirtor2016	fritz2006	Traina et al. 2024
0.5 – 1.0	$-1.620^{+0.346}_{-0.250}$	$-1.538^{+0.270}_{-0.272}$	$-1.25^{+0.02}_{-0.02}$
1.0 – 1.5	$-1.769^{+0.324}_{-0.309}$	$-1.796^{+0.402}_{-0.361}$	$-1.17^{+0.02}_{-0.03}$
1.5 – 2.0	$-1.268^{+0.339}_{-0.129}$	$-1.120^{+0.298}_{-0.334}$	$-1.16^{+0.02}_{-0.03}$
2.0 – 2.5	$-0.731^{+0.237}_{-0.346}$	$-0.773^{+0.186}_{-0.251}$	$-1.16^{+0.03}_{-0.04}$
2.5 – 3.0	$-1.264^{+0.241}_{-0.266}$	$-1.168^{+0.206}_{-0.167}$	$-1.17^{+0.05}_{-0.06}$
3.0 – 3.5	$-1.057^{+0.179}_{-0.227}$	$-1.044^{+0.219}_{-0.205}$	$-1.19^{+0.07}_{-0.10}$
3.5 – 4.5	$-1.411^{+0.298}_{-0.280}$	$-1.542^{+0.393}_{-0.182}$	$-1.40^{+0.16}_{-0.13}$
4.5 – 6.0	$-1.636^{+0.192}_{-0.299}$	$-1.735^{+0.250}_{-0.164}$	$-1.67^{+0.35}_{-0.25}$

compatible within the broader uncertainties of the present reconstruction. At higher redshift, however, the agreement with Traina et al. 2024 becomes markedly better, with both the skirtor2016 and fritz2006 results returning to values much closer to the A³COSMOS relation. This behaviour is fully consistent with the comparison already seen in the infrared luminosity functions, where the high-redshift luminosity functions were also found to follow the Traina et al. 2024 reference more closely. The comparison with the literature therefore confirms the expected overall evolution of the dust-obscured star formation rate density, with high values around Cosmic Noon followed by a decline towards higher redshift. This is an important result, since it shows that the improved consistency at high redshift is not tied to the specific choice of AGN module, but is independently recovered with both skirtor2016 and fritz2006.

After having established the redshift evolution of the complete sample using the narrower subdivision, we now analyse the two broader redshift intervals adopted in the previous section. The resulting full sample star formation rate densities are shown in Figure 7.6, while the corresponding numerical values are reported in Table 7.6. For visualization, fixed horizontal uncertainties of $\Delta z = 1.0$ and $\Delta z = 1.5$ were assigned to the two broad-bin measurements, respectively.

The two AGN models provide a consistent picture of the evolution of the dust-obscured star formation rate density. At $z = 2$ the skirtor2016 and fritz2006 modules differ only by ~ 0.07 dex, with $\log_{10} \rho_{\text{SFR}} = -1.18$ and -1.26 , respectively. This difference is considerably smaller than the uncertainties associated with either measurement. The agreement remains similarly good at $z = 4.5$, where the two estimates differ by approximately 0.13 dex. In this case fritz2006 gives a slightly higher SFRD than skirtor2016, but the two measurements remain fully compatible within their uncertainties. The choice between the two AGN torus modules therefore has only a minor effect on the SFRD obtained when the complete source sample is considered. Moreover, both models also recover the expected decrease in the star formation activity beyond Cosmic Noon. For skirtor2016, the central value decreases by approximately 0.73 dex between $z = 2$ and $z = 4.5$, corresponding to a factor of about 5. The fritz2006 results show a smaller decrease of approximately 0.52 dex, corresponding to a factor of about 3. Given the size and overlap of the uncertainties, the difference between the two evolutionary rates should not be interpreted as significant.

Instead, both results consistently indicate a decline in the contribution of the infrared luminous population towards higher redshifts, as expected from the literature.

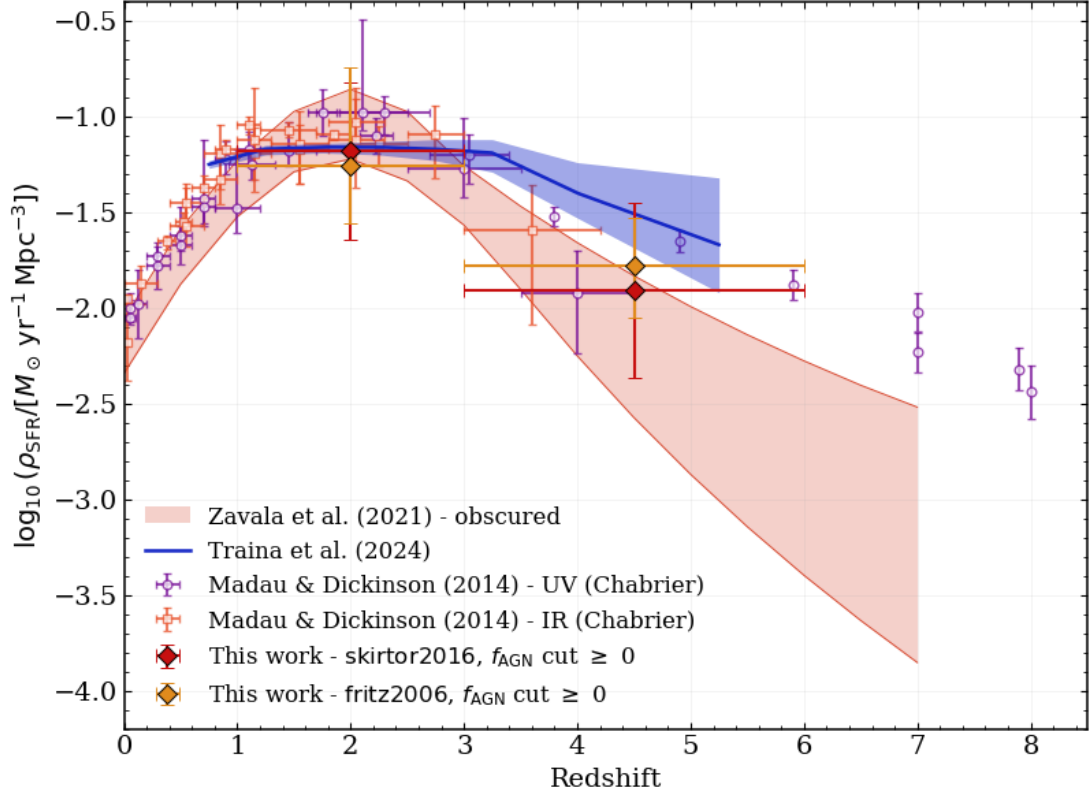


Figure 7.6: Dust-obscured star formation rate density obtained for the complete sample in the two broad redshift intervals adopted in this work. The red and orange diamonds represent the measurements derived with the *skirtor2016* and *fritz2006* models, respectively, allowing a direct comparison between the two AGN prescriptions. Literature measurements and reference evolutionary trends are the same as those introduced in Figure 7.5.

Table 7.6: Dust-obscured SFRD obtained for the complete sample, corresponding to $f_{\text{AGN}} \geq 0.0$, in the two broad redshift intervals adopted in this work. The *skirtor2016* and *fritz2006* columns report the SFRD derived using the corresponding AGN models. Values are expressed as $\log_{10}(\rho_{\text{SFR}}/[M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}])$.

Redshift range	skirtor2016	fritz2006
0.5 – 3.0	$-1.182^{+0.361}_{-0.464}$	$-1.256^{+0.511}_{-0.299}$
3.0 – 7.0	$-1.909^{+0.456}_{-0.455}$	$-1.777^{+0.247}_{-0.276}$

7.3 Contribution of AGN-dominated sources to the obscured SFRD

The full sample broad bins SFRD derived in Section 7.2 provides the reference against which the role of galaxies hosting a significant AGN component can be investigated. To this aim, the luminosity functions derived after imposing the two thresholds $f_{\text{AGN}} \geq 0.2$ and $f_{\text{AGN}} \geq 0.5$ were integrated over the same luminosity interval adopted for the complete sample. As discussed in Section 7.1, these selections were performed independently for the *skirtor2016* and *fritz2006* runs, since the AGN fraction assigned to an individual galaxy depends on the adopted AGN module. It is important to clarify the physical meaning of this comparison. The quantity f_{AGN} used for the selection measures the AGN contribution over the rest-frame 5–40 μm interval, while the luminosity functions and the resulting SFRD are based on the total 8–1000 μm infrared luminosity. Consequently, the star formation rate density obtained for an AGN-selected subsample should not be interpreted as the star formation rate density produced by AGNs themselves. Rather, it quantifies the fraction of the infrared-derived SFRD associated with galaxies whose SEDs contain a moderate to strong mid-infrared AGN component. It therefore provides a measure of how strongly the dust-obscured SFRD is associated with AGN-hosting systems. For each AGN threshold, this ratio was quantified relative to the complete sample SFRD as

$$R_{\text{AGN}}(z; f_{\text{AGN}} \geq f_{\text{th}}) = \frac{\rho_{\text{SFR}}(f_{\text{AGN}} \geq f_{\text{th}})}{\rho_{\text{SFR}}(f_{\text{AGN}} \geq 0.0)} \quad (7.6)$$

Since the SFRD values are reported in logarithmic form, the ratios cannot be obtained directly from the tabulated values. Each logarithmic SFRD was first converted back to linear units, equivalently computing the ratio as $10^{\Delta \log_{10} \rho_{\text{SFR}}}$.

The effect of progressively selecting sources with a larger AGN contribution is shown in Figures 7.7 and 7.8 for the *skirtor2016* and *fritz2006* models, respectively. In each figure, the SFRD obtained for the complete sample is shown together with the results for the $f_{\text{AGN}} \geq 0.2$ and $f_{\text{AGN}} \geq 0.5$ selections, in order to see directly the effect of the change of the AGN-fraction threshold. Measurements are represented at $z = 2.0$ and $z = 4.5$, corresponding to the two broad redshift intervals adopted for the AGN-selected analysis. The numerical results for both selections and their fractions relative to the complete sample are summarized in Table 7.7. The full sample measurements are the same as those in Table 7.6.

We first consider the moderate AGN selection, corresponding to $f_{\text{AGN}} \geq 0.2$. Here, both SED fitting modules indicate that galaxies hosting a non-negligible AGN component account for a substantial fraction of the infrared-derived SFRD. At $z = 2.0$, *skirtor2016* gives $\log_{10} \rho_{\text{SFR}} = -1.36$, compared with -1.18 for the complete sample. The difference of 0.18 dex corresponds to approximately 66.5% of the full sample SFRD. The *fritz2006* selection gives a lower value of $\log_{10} \rho_{\text{SFR}} = -1.62$ corresponding to approximately 43.3% of its complete sample estimates. At $z = 4.5$, the relative contribution increases for both modules. The *skirtor2016* value of $\log_{10} \rho_{\text{SFR}} = -2.03$ corresponds to approximately 75.9% of the total SFRD obtained with the same model, while the *fritz2006* result of -1.97 represents approximately 63.8%. Therefore, despite the differences in the absolute fraction assigned by the two AGN models, both indicate that a large part of the infrared-

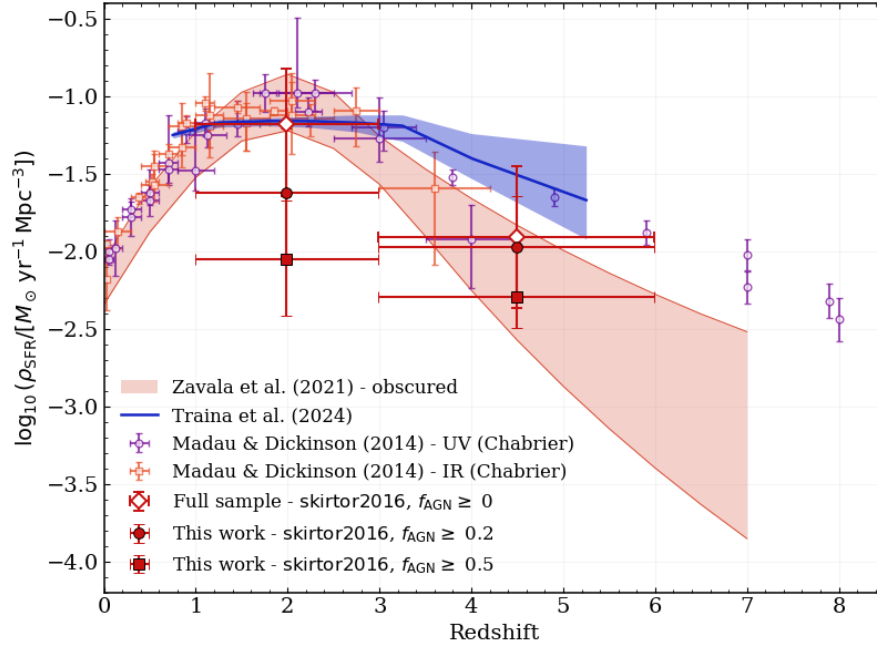


Figure 7.7: Dust-obscured star formation rate density obtained with the *skitor2016* model in the two broad redshift intervals adopted for the AGN-selected analysis. Red diamonds show the complete sample ($f_{\text{AGN}} \geq 0.0$), while circles and squares represent the progressively more restrictive $f_{\text{AGN}} \geq 0.2$ and $f_{\text{AGN}} \geq 0.5$ selections, respectively. The comparison therefore illustrates directly how the inferred SFRD changes as sources with increasingly strong AGN contributions are selected. Literature measurements are the same as those introduced previously in Figure 7.5.

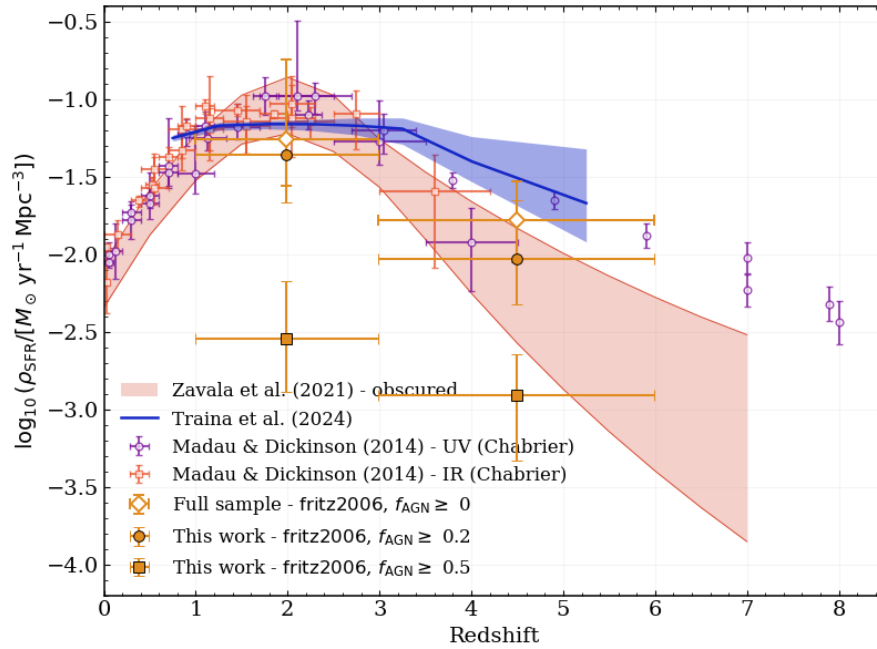


Figure 7.8: Dust-obscured star formation rate density obtained with the *fritz2006* model in the two broad redshift intervals adopted for the AGN-selected analysis. The complete sample and the $f_{\text{AGN}} \geq 0.2$ and $f_{\text{AGN}} \geq 0.5$ selections are represented by diamonds, circles, and squares, respectively. Literature measurements are the same as those introduced previously in Figure 7.5.

Table 7.7: Dust-obscured SFRD obtained for the complete sample and for the two AGN-selected populations. SFRD values are expressed as $\log_{10}(\rho_{\text{SFR}}/[M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}])$. The columns labelled R_{AGN} report the central SFRD of each AGN-selected population as a percentage of the corresponding complete-sample SFRD derived with the same AGN model.

Model	z	$f_{\text{AGN}} \geq 0.0$	$f_{\text{AGN}} \geq 0.2$	$R_{0.2}$	$f_{\text{AGN}} \geq 0.5$	$R_{0.5}$
skirtor2016	2.0	$-1.182^{+0.361}_{-0.464}$	$-1.358^{+0.263}_{-0.307}$	66.5%	$-2.052^{+0.381}_{-0.366}$	13.5%
skirtor2016	4.5	$-1.909^{+0.456}_{-0.455}$	$-2.029^{+0.381}_{-0.293}$	75.9%	$-2.291^{+0.334}_{-0.200}$	41.5%
fritz2006	2.0	$-1.256^{+0.511}_{-0.299}$	$-1.620^{+0.414}_{-0.397}$	43.3%	$-2.545^{+0.369}_{-0.346}$	5.1%
fritz2006	4.5	$-1.777^{+0.247}_{-0.276}$	$-1.972^{+0.327}_{-0.359}$	63.8%	$-2.911^{+0.265}_{-0.417}$	7.4%

derived star formation rate density is associated with galaxies for which the SED fitting requires at least a moderate mid-infrared AGN component. The central estimates also suggest that this association becomes stronger in the higher redshift interval.

A considerably different picture emerges when the more restrictive $f_{\text{AGN}} \geq 0.5$ criterion is imposed. As shown in Figures 7.7 and 7.8, increasing the threshold further reduces the SFRD associated with the selected population and makes the differences between the two AGN prescriptions more evident. For $f_{\text{AGN}} \geq 0.5$, the inferred contribution becomes both substantially smaller and considerably more dependent on the AGN model. At $z = 2.0$, the skirtor2016 selected population accounts for approximately 13.5% of the corresponding full sample SFRD, while the fritz2006 selection accounts for only 5.1%. The difference becomes particularly pronounced in the higher redshift interval. At $z = 4.5$, galaxies satisfying $f_{\text{AGN}} \geq 0.5$ in the skirtor2016 run retain approximately 41.5% of the complete sample SFRD, compared with only 7.4% for fritz2006. This divergence is consistent with the behaviour already observed in the luminosity functions obtained for the high- f_{AGN} selection. It does not originate primarily from a large disagreement in the total infrared luminosities recovered by the two SED fitting runs, which were found to be very similar for the complete sample. Instead, the main difference arises from the model dependence of f_{AGN} itself. As the threshold becomes more restrictive, comparatively small differences in the decomposition of the mid-infrared SED determine whether individual galaxies are included or excluded from the selected population. For instance, the number of sources available for the $f_{\text{AGN}} \geq 0.5$ analysis is also considerably smaller, as shown in Table 6.3, increasing the statistical uncertainty of both the luminosity functions and their integrated star formation rate densities. The high threshold fractions should therefore be regarded as substantially less robust than those obtained for the complete sample or for the moderate AGN selection.

These results show that the impact of AGN modelling on the total dust-obscured SFRD is relatively small, while its impact on the decomposition of that SFRD according to AGN strength is significantly larger. For the moderate $f_{\text{AGN}} \geq 0.2$ selection, both models associate a substantial fraction of the infrared-derived star formation rate densities with galaxies hosting an AGN component, although the exact percentage remains model dependent. For the more restrictive $f_{\text{AGN}} \geq 0.5$ selection, this dependence becomes dominant, particularly at high redshift, where skirtor2016 and fritz2006 models lead to different ratios.

Conclusions

The aim of this thesis was to investigate the dust-obscured component of the cosmic star formation history and to assess how the presence and modelling of active galactic nuclei affect infrared-based estimates of the cosmic star formation rate density. To this purpose, the analysis of the A³COSMOS ALMA-selected population was revisited by incorporating updated multiwavelength and redshift information, with particular attention to the recent COSMOS2025 data and to the improved near- and mid-infrared constraints provided by the James Webb Space Telescope.

Starting from the A³COSMOS catalogue, a blind-like sample was constructed in order to minimize the biases associated with targeted ALMA observations. Updated photometric information and a revised redshift hierarchy were then adopted, prioritizing spectroscopic redshifts whenever available, followed by COSMOS2025 photometric estimates and, when necessary, redshifts derived through CIGALE. The final scientific analysis was performed on 189 galaxies, corresponding to the same blind-like source population considered in the reference study. The physical properties of the galaxies were derived through multiwavelength spectral energy distribution fitting with CIGALE. Particular attention was devoted to the reliability of the input photometry, allowing problematic bands to be identified and excluded before the final fits. Two independent active galactic nuclei models, *skirtor2016* and *fritz2006*, were adopted in order to quantify the systematic uncertainty associated with the modelling of the nuclear infrared component. Despite the substantially different physical descriptions of the dusty torus implemented by the two AGN modules, the derived global galaxy properties were found to be remarkably consistent. Stellar masses, star formation rates and total infrared luminosities show only small differences between the two runs. This agreement indicates that the reconstruction of the overall 8–1000 μm emission is relatively robust against the adopted AGN module when the complete galaxy sample is considered. Larger differences emerge instead in the inferred AGN fraction, demonstrating that the decomposition of the infrared emission into host galaxy and nuclear components remains significantly more model dependent.

The infrared luminosities derived from the SED fitting were then used to reconstruct the infrared luminosity functions through the $1/V_{\text{max}}$ method, accounting for the heterogeneous sensitivity and effective area of the A³COSMOS observations. For the complete sample, the luminosity functions were first reconstructed using the eight redshift intervals adopted by Traina et al. 2024, allowing a direct comparison with the previous A³COSMOS analysis. The calculation was then repeated in the two broader intervals $0.5 \leq z < 3.0$ and $3.0 \leq z \leq 7.0$, which preserve sufficient statistics for the progressively AGN-selected subsamples. The luminosity functions obtained with *skirtor2016* and

fritz2006 are in very good agreement over the luminosity range directly constrained by the data. Their fitted luminosity functions also remain closely consistent, confirming that the reconstruction of the complete infrared population is only weakly dependent on the adopted AGN torus prescription. The finer redshift subdivision preserves the main evolutionary behaviour recovered by *Traina et al. 2024*, including the decline in the abundance of infrared-luminous galaxies towards the highest redshifts. When progressively more restrictive AGN selections are applied, the number density decreases and the dependence on the adopted AGN model becomes more evident, particularly for $f_{\text{AGN}} \geq 0.5$, where differences in the inferred AGN fraction increasingly affect which sources enter the selected population.

The integration of the best-fitting luminosity functions provides the corresponding dust-obscured star formation rate density. The finer redshift reconstruction confirms that the two AGN models provide closely consistent SFRD estimates across the full redshift range and recover the expected increase towards Cosmic Noon followed by a decline at higher redshift. The comparison obtained using the same redshift subdivision of *Traina et al. 2024* is particularly informative. Although some differences are present around the peak of the cosmic star formation history, the agreement with the original A³COSMOS determination improves considerably towards high redshift. The same general behaviour is recovered when the complete-sample is grouped into the two broader redshift intervals. In this case, *skirtor2016* gives $\log_{10} \rho_{\text{SFR}} \simeq -1.18$ at $z = 2$ and -1.91 at $z = 4.5$, while *fritz2006* gives approximately -1.26 and -1.78 , respectively. The differences between the two AGN models remain considerably smaller than the uncertainties of the individual measurements, further confirming that the total dust-obscured SFRD of the complete sample is only weakly sensitive to the adopted AGN torus prescription.

The final part of this work investigated how the inferred SFRD changes when galaxies are selected according to their mid-infrared AGN contribution. Two thresholds were considered independently for the two AGN models: $f_{\text{AGN}} \geq 0.2$ and $f_{\text{AGN}} \geq 0.5$. The moderate selection shows that a substantial fraction of the infrared-derived SFRD is associated with galaxies whose SEDs contain a non-negligible AGN component. For *skirtor2016*, these galaxies account for approximately 66.5% of the complete-sample SFRD at $z = 2$ and 75.9% at $z = 4.5$, while the corresponding *fritz2006* fractions are approximately 43.3% and 63.8%, respectively. A much stronger model dependence appears when the more restrictive threshold is adopted. The corresponding fractions decrease to approximately 13.5% and 41.5% for *skirtor2016* at $z = 2$ and $z = 4.5$, while *fritz2006* yields only about 5.1% and 7.4%. This difference does not primarily reflect a disagreement in the total infrared luminosities recovered by the two models, which remain closely consistent, but rather the different decomposition of the mid-infrared emission and therefore the different galaxies selected by a fixed f_{AGN} threshold. These fractions should not be interpreted as the fraction of the cosmic SFRD physically produced by AGNs. The AGN fraction used in the selection is defined over the rest-frame 5–40 μm interval, while the SFRD is inferred from the total 8–1000 μm infrared luminosity. The result instead quantifies the fraction of the infrared-derived SFRD associated with galaxies hosting increasingly important mid-infrared AGN components. This distinction is particularly important for the $f_{\text{AGN}} \geq 0.5$ subsamples, for which the limited number of objects and the strong dependence of the classification on the adopted torus model introduce considerable uncertainty.

Overall, the results of this thesis indicate that the reconstruction of the total dust-obscured cosmic star formation history from the A³COSMOS population is relatively robust against the choice of the AGN model. Both `skirtor2016` and `fritz2006` recover consistent infrared luminosities, luminosity functions and complete-sample SFRD estimates. The principal systematic uncertainty associated with AGN modelling instead emerges when attempting to separate galaxies according to the strength of their nuclear infrared emission. In this regime, the inferred AGN fraction becomes increasingly model dependent and directly affects the population selected for the luminosity function and SFRD analyses.

Several limitations remain. The ALMA-selected nature of the sample primarily constrains the luminous end of the infrared luminosity function, while the computation of the total luminosity density required an extrapolation towards luminosities below those directly probed by the observations. The statistical uncertainties also increase rapidly when the sample is divided according to the AGN fraction, particularly for $f_{\text{AGN}} \geq 0.5$ at high redshift. Furthermore, although the updated redshift compilation considerably improves the characterization of the sample, spectroscopic confirmation is still unavailable for a fraction of the sources.

Future developments should primarily address the observational and modelling limitations identified in this work. A first important step will be to increase the size and depth of the ALMA-selected sample. The present A³COSMOS population mainly constrains the luminous and bright end of the infrared luminosity function, while the total SFRD still depends on the extrapolation of the fitted function towards luminosities that are not directly sampled. Deeper and more homogeneous ALMA observations would allow the faint end to be constrained more directly, reducing the dependence of the integrated SFRD on the assumed functional form and providing a more complete census of the dust-obscured galaxy population. A second priority concerns the redshift information. Although the updated redshift compilation adopted in this thesis improves the characterization of the sample, spectroscopic measurements are still unavailable for part of the population, particularly at high redshift. Increasing the spectroscopic completeness would improve the determination of the physical properties of individual galaxies and reduce uncertainties in the construction of the luminosity functions and in the corresponding V_{max} estimates. Finally, the results obtained from the AGN-selected subsamples show that improving the decomposition of star formation and nuclear emission remains particularly important. While the total infrared luminosities and the complete-sample SFRD are relatively insensitive to the adopted AGN module, the inferred f_{AGN} becomes increasingly model dependent for sources with a strong nuclear contribution. A further development will be to derive an AGN-decontaminated SFRD by subtracting the AGN-powered contribution from the total infrared luminosity before converting it into a star formation rate density, in this way it can be isolated more directly the infrared emission associated with star formation. A more complete sampling of the rest-frame mid-infrared emission, in particular through JWST/MIRI observations, will provide stronger constraints on the shape of the AGN-heated dust component and help reduce the degeneracy between the nuclear and star-forming emission. Combined with ALMA measurements of the cold-dust emission, these data will allow the relation between obscured star formation and black hole accretion to be characterized more robustly across cosmic time.

Appendix: A³COSMOS archive-mining workflow

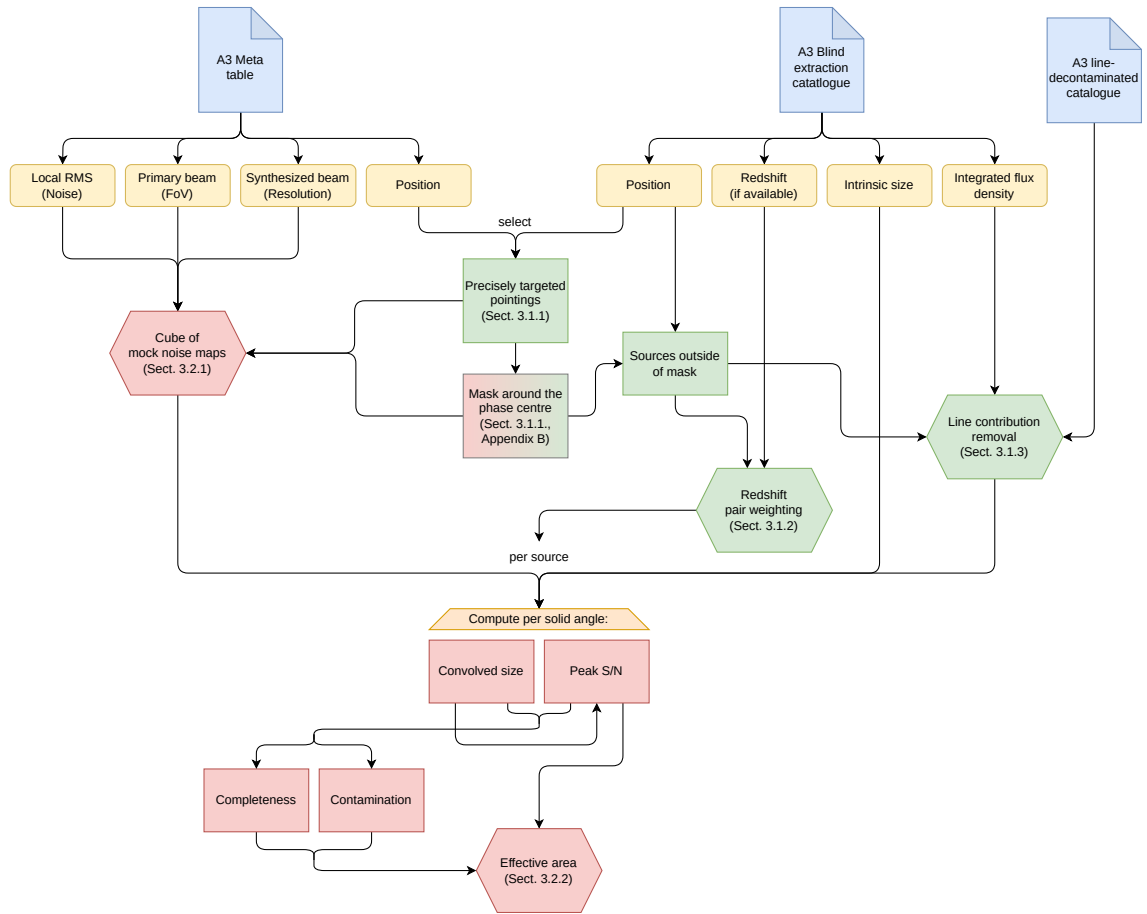


Figure A.1: Schematic representation of the A³COSMOS workflow. Public ALMA observations in the COSMOS field are retrieved from the archive. The ALMA measurements are combined with ancillary photometry and redshift information to construct panchromatic SEDs and derive physical properties of the detected galaxies. Image adapted from [Liu et al. 2019a](#).

B

Appendix: CIGALE Filters list

Table B.1: Complete list of the photometric filters adopted in the CIGALE analysis. The last column indicates whether a filter was excluded after the fine-tuning procedure described in Section 6.1.b.

Filter name	λ_{eff} [μm]	Region	Removed
galex.FUV	0.153	UV	✓
galex.NUV	0.231	UV	✓
cfht.megacam.u	0.368	UV/optical	✗
cfht.megaprime.u*	0.379	UV/optical	✓
subaru.suprime.IB427	0.427	optical	✓
subaru.suprime.B	0.445	optical	✓
subaru.suprime.IB464	0.464	optical	✗
subaru.suprime.g+	0.476	optical	✓
subaru.suprime.g	0.480	optical	✗
subaru.suprime.IB484	0.484	optical	✓
subaru.suprime.IB505	0.505	optical	✓
subaru.suprime.IB527	0.527	optical	✓
subaru.suprime.V	0.550	optical	✓
subaru.suprime.IB574	0.574	optical	✗
subaru.suprime.r	0.622	optical	✓
subaru.suprime.IB624	0.623	optical	✓
subaru.suprime.r+	0.628	optical	✓
subaru.suprime.IB679	0.679	optical	✓
subaru.suprime.IB709	0.709	optical	✓
subaru.suprime.NB711	0.711	optical	✓
subaru.suprime.IB738	0.738	optical	✓
subaru.suprime.i+	0.767	optical	✓
subaru.suprime.IB767	0.768	optical	✓
subaru.suprime.i	0.773	optical	✓
hst.acs.wfc.F814W	0.805	optical/NIR	✗
subaru.suprime.NB816	0.816	optical	✓
subaru.suprime.IB827	0.827	optical	✓
subaru.suprime.z	0.891	optical/NIR	✓
subaru.suprime.z+	0.903	optical/NIR	✓
subaru.suprime.z++	0.910	optical/NIR	✓

Continued on next page

Table B.1 – continued from previous page

Filter name	λ_{eff} [μm]	Region	Status
subaru.suprime.Y	0.998	optical/NIR	✓
paranal.vircam.Y	1.020	NIR	✓
jwst.nircam.F115W	1.150	NIR	✓
paranal.vircam.NB118	1.190	NIR	✗
paranal.vircam.J	1.250	NIR	✓
jwst.nircam.F150W	1.500	NIR	✓
paranal.vircam.H	1.640	NIR	✓
paranal.vircam.Ks	2.150	NIR	✓
jwst.nircam.F277W	2.760	NIR	✓
spitzer.irac.I1	3.550	NIR	✓
jwst.nircam.F444W	4.400	NIR	✓
spitzer.irac.I2	4.500	NIR	✓
spitzer.irac.I3	5.720	MIR	✓
jwst.miri.F770W	7.640	MIR	✓
spitzer.irac.I4	7.880	MIR	✗
spitzer.mips.24mu	23.590	MIR	✓
herschel.pacs.green	100.650	FIR	✓
herschel.pacs.red	160.980	FIR	✓
herschel.spire.PSW	248.290	sub-mm	✓
herschel.spire.PMW	348.440	sub-mm	✓
herschel.spire.PLW	500.380	sub-mm	✓
jcmt.scuba2.850GHz	861.300	sub-mm	✓
IRAM30m_AzTEC	1100.000	mm	✓
IRAM30m_MAMBO	1200.000	mm	✓
ALMA_446p5 to ALMA_3325p5	446.5–3325.5	sub-mm/mm	✓

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