

SCHOOL OF SCIENCE
Department of Physics and Astronomy
Master Degree Programme in Astrophysics and Cosmology

HIDE AND SEEK:
**Cosmic evolution of the Inter Stellar
Medium and its implications for nuclear
obscuration**

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"Astrophysics is a satisfying activity."
Why do we do astrophysics? (Hogg 2026)

Abstract

Recent observations carried out with the *Atacama Large Millimeter/ submillimeter Array* (ALMA) show that the density of the galaxies' interstellar medium (ISM) increases toward earlier cosmic epochs, evolving approximately as $(1+z)^{3.3}$. This implies that at $z > 3$, the gas column density towards galactic nuclei can exceed by more than two orders of magnitude the typical values observed in local galaxies, reaching conditions close to the Compton-thick regime at $z \geq 6$. This scenario suggests that the ISM of the host galaxy may also substantially contribute to the obscuration of accreting supermassive black holes in the primordial Universe, hiding them and their properties from the seeker. In this thesis I will discuss the evolution of the ISM column density in galaxy samples at different redshifts, extending the analysis up to $z > 9$. Three methods have been investigated to estimate the ISM column density in these samples, including the analysis of the sub-millimeter continuum emission from cold dust (*Method 1*), the use of line tracers such as [CII] (*Method 2*) and an indirect method based on the Schmidt–Kennicutt relation and its possible evolution with redshift, which allows the gas surface density to be derived from the measured star formation rate (*Method 3*). In all three approaches, the estimate of the gas surface density requires information about the spatial extent of sources, in particular the characteristic size of the gas distribution or of the star-forming region. Observations of objects at high (sub-arcsec) angular resolution were therefore considered, including galaxies and high-redshift quasars from ALMA surveys reported in the literature, and sources selected by the *James Webb Space Telescope* (JWST) within the COSMOS-Web survey area. For each subsample, the ISM density was measured according to the available tracers, allowing a comparison between the different approaches. This comparative analysis made it possible to assess the robustness of the estimates, the main sources of uncertainty, and the impact of the methodological assumptions. The results of this thesis confirm that the gas column density increases with redshift, suggesting that the ISM of the host galaxy may represent a dominant component of obscuration in early Active Galactic Nuclei (AGN). These findings have important implications not only for understanding the growth history of hidden supermassive black holes, but also for constraining the processes that regulate the evolution of galaxies and their interstellar medium in the early Universe.

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Chapter 1

Introduction

1.1 Motivation and context: galaxies far and beyond may hide their nuclei

The desire to know oneself and the surrounding world is innate in human beings. This desire has led humanity, throughout history, to progress ever further in the understanding of the nature and the Universe: curiosity, and a romantic sense of mystery, push mankind to go beyond what is already known, beyond what seems hidden. The scientist attempts to answer these questions, and even more so these deep desires, through the search for order by finding the laws of nature, often through mathematical description. The astrophysicist figure best represents this evolution of humanity and its capacity to quench this thirst for knowledge. Starting from admiring the night sky and seeking order in those luminous points, human beings have come to describe the Universe with increasingly sophisticated instruments, pushing ever further into space and peering ever further back in time.

The astrophysicists today find themselves interpreting data that are not always straightforward, trying, through fragmentary but increasingly precise observations, to reconstruct the "recipe" of the Universe and understand its evolution.

To study the evolution of the Universe, that is by definition its change over time, it is necessary to introduce a fundamental physical quantity that allows us to express the distance of an object not only in space, but also in time: the *redshift*.

The redshift, denoted by z , measures the shift towards longer wavelengths of the radiation coming from an astronomical source and it is defined as:

$$1 + z = \frac{\lambda_{obs}}{\lambda_{em}} \quad (1.1)$$

where λ_{obs} represents the observed wavelength and λ_{em} the wavelength emitted by the source.

In the cosmological context, redshift is primarily due to the expansion of the Universe: as light travels through space, space itself expands, causing the radiation to stretch towards the red region of the electromagnetic spectrum. Consequently, objects characterized by high redshift values are extremely distant. Since light takes finite time to reach us, observing increasingly distant regions of the Universe is equivalent to observing increasingly ancient epochs of its history (Wright 2006).

Without going into the details of the current Λ CDM "concordance" cosmological model — which is not the purpose of this work — table 1.1 lists a series of redshift values and their corresponding cosmic times. In particular, table 1.1 considers the following cosmological parameters:

$$H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}, \quad \Omega_m = 0.3, \quad \Omega_\Lambda = 0.7$$

where H_0 is the Hubble constant and sets the present-day expansion rate of the Universe; Ω_m is the matter density parameter and represents the fractional contribution of matter (baryonic and dark) to the total energy density; Ω_Λ is the dark energy density parameter and it is associated with the cosmological constant driving the accelerated expansion. Throughout the work, this cosmology will be implicitly assumed as the reference theoretical model for the interpretation of observations of objects up to $z = 14$, reaching back the "cosmic dawn".

Redshift z	Lookback time (Gyr from now)	Age of the Universe (Gyr from the Big Bang)
0	0	13.5
1	7.7	5.8
2	10.2	3.2
3	11.4	2.1
4	12.0	1.5
5	12.3	1.2
6	12.6	0.9
8	12.8	0.6
10	13.0	0.5
12	13.1	0.4
14	13.2	0.3

Table 1.1: *Approximate relation between redshift, lookback time and age of the Universe in the Λ CDM cosmological model, computed using the **astropy** package (Astropy Collaboration et al. 2022).*

Observing a given physical quantity at different redshifts allows us not only to study distant objects, but also to implicitly trace their evolution throughout the history of the Universe (see fig. 1.1 for a chronological overview of the evolution of the Universe, including its principal "moments").

By analyzing galaxies observed at different distances, and therefore at different cosmic epochs, it is possible to investigate how their physical properties change over time. Galaxies are gravitationally bound systems composed of stars, interstellar medium (gas and dust), stellar remnants (white dwarfs, neutron stars, black holes), and a large amount of dark matter; they display a wide variety of properties and span a very broad range of luminosities, sizes, and masses. For example, the characteristic sizes of their luminous components are from 0.1 kpc to tens of kiloparsecs, whereas the optical luminosities and stellar masses are in the range $10^3 - 10^{12}$ in solar units; in our Galaxy -the total mass, including dark matter- is $\sim 10^{12} M_\odot$, whereas the stellar and gas masses amount $\sim 5 \times 10^{10} M_\odot$ and $\sim 6 \times 10^9 M_\odot$, respectively (Cimatti,

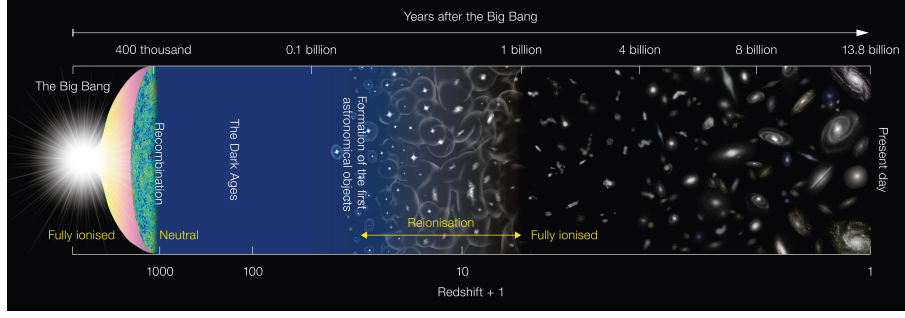


Figure 1.1: *This diagram depicts the major milestones in the evolution of the Universe since the Big Bang, about 13.8 billion years ago. Not to scale (European Southern Observatory 2016). The first luminous objects and proto-galaxies emerged at $z > 9$, starting the reionisation of the Universe (Reionisation Era: $z \sim 6 - 15$).*

Fraternali, and Nipoti 2019). One of the most evident properties of a galaxy is its morphology, i.e. the shape projected on the plane of the sky. The first systematic study of galaxy morphology in the optical waveband dates back to 1926, when the astronomer Edwin Hubble proposed a classification represented in the so-called *tuning fork diagram*, illustrated in fig. 1.2. In this classification, galaxies are divided into three main classes: ellipticals, lenticulars, and spirals, plus a small fraction of irregulars.

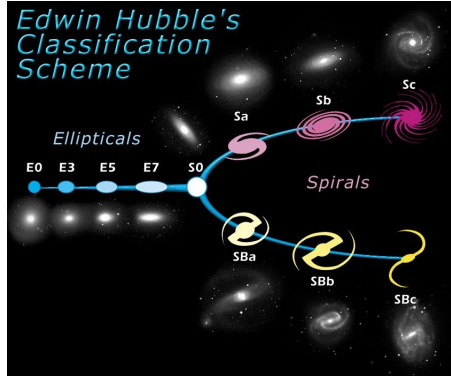


Figure 1.2: *The Hubble tuning fork diagram. On the left, early-type galaxies: ellipticals (E0–E7) and lenticulars (S0). On the right, late-type galaxies: normal spirals (Sa, Sb, Sc) on the upper branch and barred spirals (SBa, SBb, SBc) on the lower branch NASA Science 1999.*

On the left side of the diagram lie *early-type galaxies* (ETGs), which include elliptical (E) and lenticular (S0) galaxies. Ellipticals are further subdivided into subclasses from E0, perfectly spherical, to E7, the most flattened, as a function of their apparent ellipticity. Lenticular galaxies (S0) represent a morphological transition between ellipticals and spirals: they show a dominant central bulge surrounded by a disc, but without spiral arms. On the right side lie *late-type galaxies* (LTGs), whose diagram bifurcates into two branches: the upper branch contains normal spirals (Sa, Sb, Sc), classified according to the decreasing prominence of the bulge relative to the disc, while the lower branch contains barred spirals (SBa, SBb, SBc), which show a

central bar-like structure connecting the bulge to the regions where the spiral arms begin. Galaxies that do not fall into any of the previous classes are classified as irregulars (Irr) (Cimatti, Fraternali, and Nipoti 2019). Unlike ETGs, LTGs typically host ongoing star formation, fuelled primarily by clouds of gas and dust.

However, this classification describes the galaxy population as we observe it today, in the nearby Universe: it represents the result of billions of years of cosmic evolution. At redshift $z \gtrsim 2$, observable galaxies do not always match the galaxy type in the Hubble sequence: they are peculiar, complex, chaotic, and disturbed systems, physically very different from the ellipticals and spirals that populate the local Universe (Conselice 2014).

Observations further show that, at high redshift, galaxies appear on average more compact than their local counterparts and more gas-rich, suggesting a structural evolution over time in which galaxies tend to grow through accretion and merger processes (Conselice 2014; Scoville et al. 2017).

In particular, the amount of cold gas mass, which constitutes most of the interstellar medium (ISM, see section 1.3), grows rapidly toward earlier cosmic epochs, approximately as $M_{\text{gas}} \propto (1+z)^2$ (Scoville et al. 2017; Tacconi et al. 2018; Aravena et al. 2020), see left panel in fig. 1.3, while typical sizes decrease as $r_e \propto (1+z)^{-1}$ (Conselice 2014; Allen et al. 2017), see right panel in fig. 1.3 and fig. 1.4.

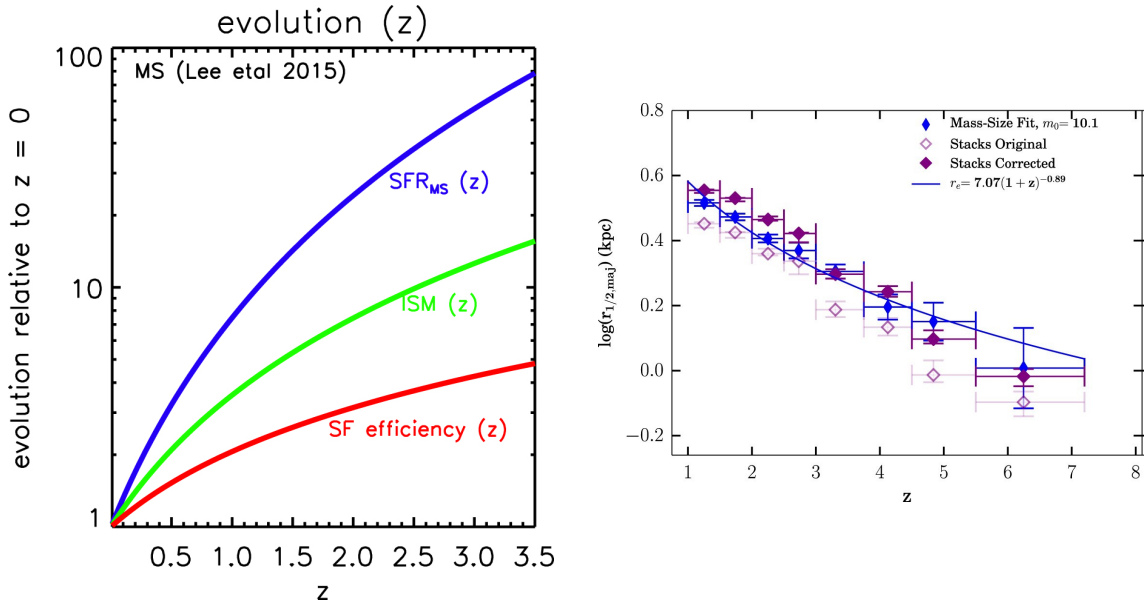


Figure 1.3: *Left panel: The ISM mass grows rapidly toward earlier cosmic epochs. Redshift evolution of the Star Formation Rate – SFR – (blue), ISM mass (green), and star formation efficiency per unit gas mass (red), from Scoville et al. 2017. Right panel: Galaxies are increasingly compact at higher redshifts. Evolution of the average half-light radius of star-forming galaxies from $z \sim 1$ to $z \sim 7$ for a mass-complete sample ($\log(M_*/M_\odot) > 10$), from Allen et al. 2017.*

The large gas content and compactness that characterize high-redshift galaxies have important implications not only for the structural growth of galaxies, but also for the accretion onto the supermassive black hole (SMBH) at their center: the same reservoir of material that fuel the birth of stars can be channeled toward the galactic

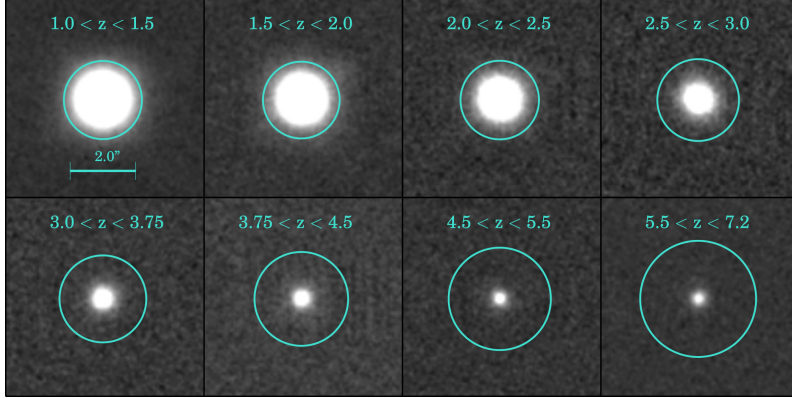


Figure 1.4: *The progressive decrease in size with redshift: stacked HST/F160W images of star-forming galaxies in redshift bins from $z \sim 1$ to $z \sim 7$, from Allen et al. 2017. The circle in each panel has a diameter of 10 kpc at the median redshift of the bin.*

nucleus, to accrete onto the SMBH, thought to be present in all massive galaxies. In the most extreme cases, this accretion process powers an Active Galactic Nucleus (AGN, see section 1.2), which is one of the most luminous objects in the Universe. This connection underlies the so-called *co-evolution* between the SMBH and its host galaxy.

However, the very gas richness and compactness that fuel AGN activity may also hide it: this large amount of gas and dust surrounding the nucleus can absorb and reprocess the AGN radiation over a wide range of wavelengths, making these sources heavily obscured. Understanding how this obscuration occurs and how it affects the observed properties of AGNs is therefore crucial for unveiling the growth of SMBHs across cosmic time.

This chapter is structured as follows: in section 1.2 Active Galactic Nuclei (AGNs) are described, with particular emphasis on obscuration. Section 1.3 describes the properties of InterStellar Medium (ISM), while section 1.4 discusses how the level of obscuration produced by the host galaxy can be quantified through the hydrogen column density. In section 1.5 a review of the current state of the art is also provided, together with the aim of this work.

1.2 The Engine: an overview on AGNs

Understanding the evolution of the interstellar medium — gas and dust in the host galaxy — means understanding also the feeding and accretion mechanisms that awaken the ever-hungry SMBH and give rise to an AGN. With this in mind, we report an overview of AGNs and their main properties.

The term *AGN* (*Active Galactic Nucleus*) was coined in the early 1970s to describe a class of extragalactic objects characterized by peculiar energetic phenomena, including violent motions of gas and dust, excess ultraviolet emission, rapid luminosity variability and the ejection of relativistic jets. Subsequent studies clarified that these

phenomena are associated with highly energetic processes occurring in the central regions of galaxies, with no stellar origin (Peterson 1997). AGNs represent 1–10% of all galaxies and today the term refers to objects whose emission is powered by the accretion of matter onto the SMBH with masses ranging from $10^6 M_\odot$ to $10^{10} M_\odot$ located at the center of those galaxies (Salpeter 1964; Richstone et al. 1998). The physical engine of AGNs is thus the conversion of the gravitational energy of the accreting matter into radiation, with bolometric luminosities¹ that can reach $10^{48} \text{ erg s}^{-1}$, making AGNs among the most luminous sources in the Universe.

The energy scales involved are in fact extremely large: sources with extreme luminosities of the order of $10^{47-48} \text{ erg s}^{-1}$, sustained over characteristic timescales of $\sim 10^7 \text{ yr}$, imply total energies of up to $\sim 10^{61} \text{ erg}$. Through the relation $E = \eta mc^2$, (where η is the radiative efficiency and m is the mass accreted onto the compact object, c the speed of light), it can be shown that the efficiency of thermonuclear fusion is too low to account for the observed luminosities. The only sufficiently efficient mechanism is gravitational accretion onto compact objects. The galaxy hosting this activity in its central regions is referred to as the *host galaxy*.

This accretion process is responsible for emission spanning over twenty orders of magnitude in frequency: thus, while describing AGNs in the next sections, it is useful to keep in mind the broad-band Spectral Energy Distribution (SED) shown in fig. 1.5, where the contributions of all emission components are displayed. Each component plays a leading role on a different stage of the electromagnetic spectrum, contributing to the rich multi-wavelength emission of these sources. Each of this component will be discussed and linked to the corresponding physical substructure of the AGN in the following Sections. A qualitative picture of the AGN structure is also shown in fig. 1.6, which may help in visualizing the geometry and position of the different AGN physical components, described in the next Sections.

¹The bolometric luminosity is the luminosity of a source integrated over all wavelengths.

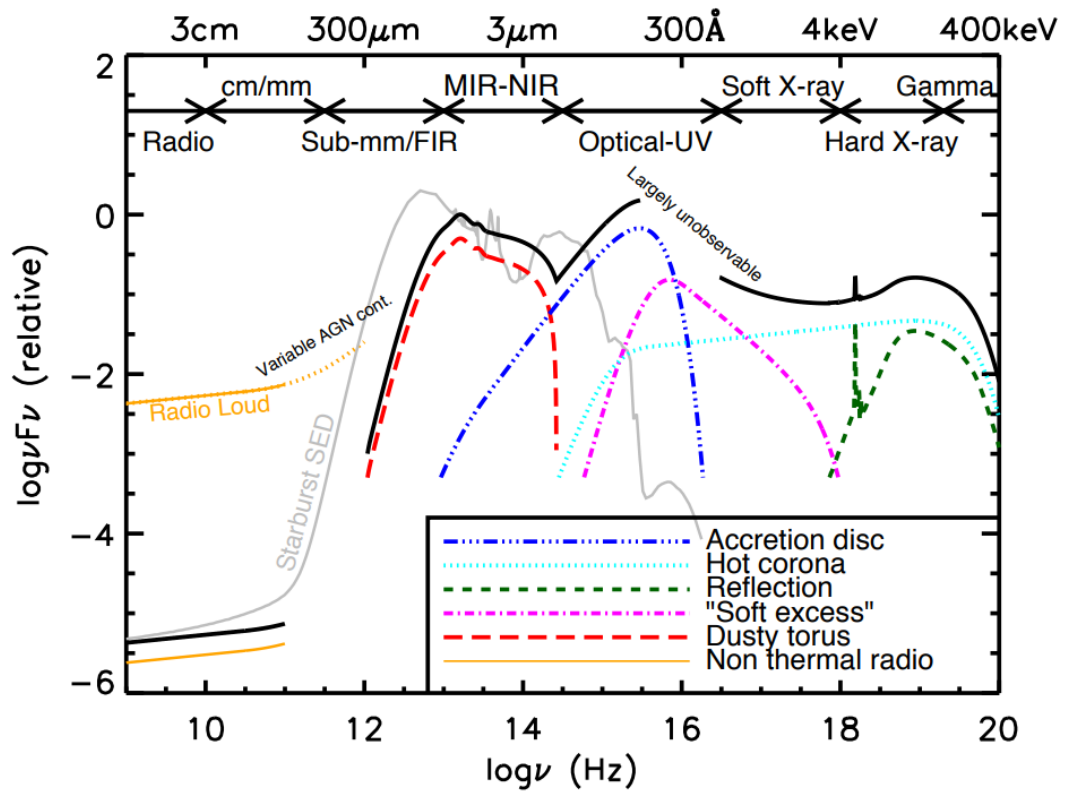


Figure 1.5: *Typical AGN spectral energy distribution, showing the contributions of the main AGN components across the electromagnetic spectrum. From Harrison 2014.*

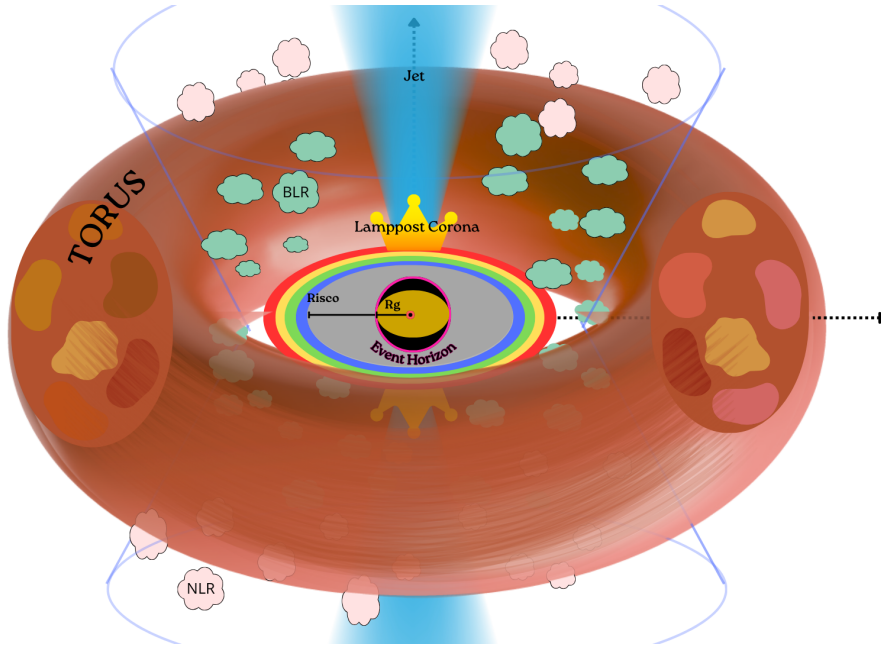


Figure 1.6: *My schematic and qualitative view of the AGN structure and of the Unified Model (see section 1.2.5). The SMBH (black circle) with event horizon, gravitational radius and ISCO radius, surrounded by the accretion disk (colored rings), the lamppost corona (yellow corona), the BLR clouds (green, within the torus), the dusty clumpy-smooth torus (brown/ocra) and the NLR clouds (pink, external to the torus) distributed along the ionization cones (light blue lines); the two relativistic jets along the polar axis (dashed vertical arrow) in blue. Not to scale. Try to imagine the third dimension for a complete understanding of BRL and NRL: the apparent overlap is a projection effect. The dashed horizontal arrow indicates the edge-on line of sight, intercepting the torus and obscuring the BLR.*

1.2.1 The hungry heart: SuperMassive Black Hole

The heart of this engine is the SMBH located at the center of these galaxies. A black hole represents the ultimate singularity in astrophysics: an enormous amount of matter concentrated in an extremely small space, generating extreme density and gravitational attraction. In the case of SMBH this amount of matter is, as mentioned before, of the order of $10^6 M_\odot$ to $10^{10} M_\odot$. According to general relativity, mass and energy curve spacetime; in the case of black holes this curvature becomes so intense that no signal, not even light, can escape their gravitational pull. The boundary of this region is called the *event horizon*. A rigorous description would require a detailed treatment of general relativity, but this is beyond the purpose of this work. However, the main concepts and results are presented here, derived from basic assumptions.

The object is described by the *gravitational radius* r_g :

$$r_g = \frac{GM_{\text{BH}}}{c^2} \quad (1.2)$$

where G is the gravitational constant, c is the speed of light, and M_{BH} is the mass of the central black hole. This characteristic scale represents the distance at which gravitational effects begin to strongly dominate.

In accordance with the so-called "no-hair theorem" (Ruffini and Wheeler 2009), a black hole can be described by only three physical parameters: mass (which consequently give us r_g in eq. (1.2)), angular momentum, and electric charge. Charge is generally assumed to be zero, so the fundamental parameters reduce essentially to mass and angular momentum. The latter is described through the dimensionless spin parameter: $a = \frac{Jc}{GM_{\text{BH}}^2}$ where J is the angular momentum of the black hole. The spin parameter can take values between -1 and 1 : the case $a = 0$ corresponds to a non-rotating (Schwarzschild) black hole, while values $|a| = 1$ describe a maximally rotating (Kerr) black hole. Positive values of a indicate prograde rotation relative to infalling material, while negative values correspond to retrograde rotation.

The *event horizon* represents the boundary beyond which no information can reach an external observer. For a rotating black hole, the horizon radius is given by:

$$r_{\pm} = r_g \left(1 \pm \sqrt{1 - a^2} \right) \quad (1.3)$$

In the non-rotating case ($a = 0$), the solution is called the Schwarzschild radius: $R_s = \frac{2GM_{\text{BH}}}{c^2} = 2r_g$ (also obtainable by equating the escape velocity to the speed of light, derived from conservation of mechanical energy). For a maximally rotating black hole ($a = 1$), the event horizon shrinks to $r_+ = r_g$ ².

Another fundamental scale is the radius of the *Innermost Stable Circular Orbit* (ISCO). Outside the ISCO, matter can orbit stably, forming the accretion disk; below this limit, orbits become unstable and matter inevitably falls toward the black hole. For a non-rotating Schwarzschild black hole, the ISCO is located at:

² r_+ and r_- are the mathematical solutions of the equations, the "true" event horizon is r_+ , while r_- is called the Cauchy solution and represents an inner radius, inside which theoretical solutions are unstable.

$$r_{\text{ISCO}} = 6r_g \quad (1.4)$$

while for a maximally rotating prograde Kerr black hole: $r_{\text{ISCO}} \approx 1.23r_g$. This implies that, as spin increases, matter can approach the central region more closely before crossing the event horizon and can reach stable orbits nearer to the black hole. Figure 1.7 shows the main properties of a BH and its effects on spacetime.

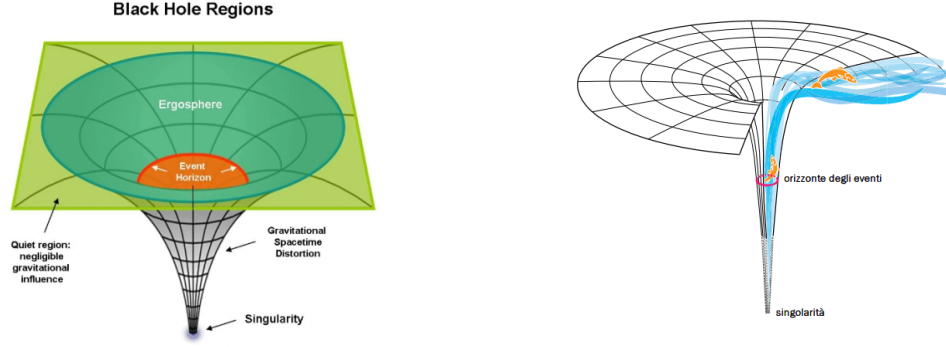


Figure 1.7: *Left: Basic properties of a black hole and its effect on spacetime. The ergosphere is also shown: a region around a rotating black hole where spacetime itself is dragged; from Astronomy Source 2012. Right: Analogy of a fish in a river flowing toward a waterfall. The fish can swim upstream against the current and return to calmer waters only up to the point where the speed of the water approaching the rapids becomes equal to that of the fish. Beyond a certain point, the current becomes too strong and the fish is inevitably dragged over the edge, like matter crossing the event horizon; from Dall’Agata 2013.*

1.2.2 Accretion disc

As mentioned before, the key process powering an AGN is the accretion of material on the SMBH, through which gravitational energy is converted into radiation. The efficiency of this process depends on the radius of ISCO: the smaller r_{ISCO} , the greater the fraction of gravitational energy that can be converted into radiation (Netzer 2015).

Moving away from the black hole, the ISCO marks the inner edge of the accretion disc, a structure of hot, highly luminous gas rotating around the central black hole. Viscous friction between disc layers transfers angular momentum outward, allowing gas to spiral inward while dissipating mechanical energy, heating the gas, and producing intense electromagnetic radiation (Longair 2011).

Expressing the luminosity as the rate of change of gravitational energy gives:

$$L = \frac{GM_{\text{BH}} \dot{M}}{R}, \quad (1.5)$$

where M_{BH} is the black hole mass, $\dot{M} \equiv dM/dt$ is the accretion rate (the rate at which mass flows through the disc onto the black hole), and R is a reference distance.

Choosing r_{ISCO} (thus proportional to eq. (1.2)) as the characteristic distance, the accretion luminosity can be rewritten as:

$$L = \eta \dot{M} c^2, \quad (1.6)$$

where η is the already seen radiative efficiency of the process; for a non-rotating BH $\eta_{\text{Sh}} \sim 0.057$, while for a maximally rotating Kerr BH $\eta_{\text{K}} \sim 0.32$ (Longair 2011). This parameter encapsulates the physical assumptions of the model — the spacetime structure and the black hole spin — which determine r_{ISCO} and, consequently, the emitted luminosity.

The luminosity in eq. (1.6) cannot grow indefinitely: there exists an upper limit known as the Eddington luminosity, L_{Edd} . To derive it, consider ionized hydrogen gas distributed in spherical symmetry around the black hole: each particle will be subjected to two competing forces: the gravitational attraction, which attract the particle toward the black hole, $F_{\text{grav}} = GM_{\text{BH}} m_p / r^2$, and radiation pressure, which pushes the particle away from the black hole, $F_{\text{rad}} = \sigma_T L / (4\pi r^2 c)$, where σ_T is the Thomson cross-section³ and m_p is the proton mass. Imposing equilibrium, $F_{\text{rad}} = F_{\text{grav}}$, yields:

$$L_{\text{Edd}} = \frac{4\pi G M_{\text{BH}} m_p c}{\sigma_T} \simeq 1.26 \times 10^{38} \left(\frac{M_{\text{BH}}}{M_{\odot}} \right) \text{ erg s}^{-1}. \quad (1.7)$$

It is important to emphasize that the Eddington luminosity, although introduced in the context of disc accretion, is a bolometric luminosity, rather than a quantity restricted to a specific spectral band.

Inverting eq. (1.7) through eq. (1.6) it is possible to obtain the Eddington accretion rate:

$$\dot{M}_{\text{Edd}} = \frac{L_{\text{Edd}}}{\eta c^2}. \quad (1.8)$$

While the Eddington limit is derived assuming spherical symmetry, accretion in AGN actually occurs through a disc-like structure on sub-parsec scales. The most widely adopted model is the Shakura & Sunyaev disc (Shakura and Sunyaev 1973): an optically thick, geometrically thin accretion disc. This disc can be thought of as composed of concentric annuli, each emitting as a blackbody (BB, see also section 1.3.3) at a different temperature decreasing with radius. The actual temperature profile $T(r)$ can be derived intuitively by combining the luminosity in the Stefan-Boltzmann law with the Eddington luminosity, procedure that gives:

$$T(r) \simeq 6.3 \times 10^5 M_8^{-1/4} \left(\frac{\dot{M}}{\dot{M}_{\text{Edd}}} \right)^{1/4} \left(\frac{r}{R_s} \right)^{-3/4} \text{ K},$$

where M_8 the black hole mass in units of $10^8 M_{\odot}$. For each annulus a characteristic frequency ν_{peak} can be associated to the peak of the BB emission through the Wien law, which establishes that $\nu_{\text{peak}} \propto T(r)$. Thus the superposition of the annuli contributions produces a power-law spectrum in the UV regime ($300 - 3000 \text{ \AA}$), with flux density $F_{\nu} \propto \nu^{1/3}$. This model successfully accounts for the *big blue bump*

³see also section 1.2.7 for a complete understanding of Thomson cross section.

observed in AGN SEDs (blue curve in fig. 1.5): a thermal continuum peaking in the UV, though its hottest portion in the extreme UV ($\lesssim 912 \text{ \AA}$), remains largely unobservable due to absorption by neutral hydrogen in the interstellar medium.

The maximum temperature is reached at the ISCO. From the $T \propto M_8^{-1/4}$ dependence, it is also possible to assert that less massive black holes produce hotter discs: for AGNs with $M_{\text{BH}} \sim 10^8 M_\odot$ the emission peaks in the UV, whereas for stellar-mass black holes, characterised by masses of tens of $M_\odot$, it shifts to the soft X-ray band⁴.

1.2.3 Hot Corona

Surrounding the innermost regions of the accretion disc is the corona: a plasma of hot electrons at temperatures of $T \sim 10^8\text{--}10^9 \text{ K}$ that extends up to $\sim 10s r_g$ above the disc. Analogously to the solar corona, this component is found at temperatures far exceeding those of the underlying structure, and the heating mechanism remains similarly debated: proposed processes include vertical density gradients in the disc and instabilities in weakly magnetised accretion flows. The geometry is equally uncertain; models include lamppost, toroidal, spherical, and sandwich configurations, with the structure likely non-uniform and clumpy.

Regardless its actual location and structure, the corona is responsible for the X-ray emission observed in AGNs through the mechanism of *inverse Compton scattering*: optical and UV photons produced by the accretion disc are upscattered to higher energies by the hot coronal electrons. In each scattering event, a photon of energy E gains a fractional energy $\Delta E/E$:

$$\frac{\Delta E}{E} \sim \frac{4kT_e}{m_e c^2}, \quad (1.9)$$

where T_e is the electron temperature, k is the Boltzmann constant and m_e is the electron mass. The electron temperature sets a natural upper limit to the process: once the photon energy approaches kT_e , photons and electrons reach thermal equilibrium and no further net energy transfer occurs. The resulting primary X-ray continuum is well described by a power law with a high-energy exponential cutoff, in which the flux density F_ν is proportional to the frequency ν : $F_\nu \propto \nu^{-\alpha} e^{-E/E_c}$, where $E_c \sim kT_e$ marks the upper boundary of the Comptonised spectrum and the photon index α encodes the physical conditions of the corona.

Since the corona radiates isotropically, photons are emitted in all directions: those directed upwards escape freely and constitute the primary X-ray continuum observed (cyan curve in fig. 1.5), while those directed downwards illuminate the disc, where they undergo *reflection*. This interaction produces two characteristic

⁴Since the disc is optically thick, viscous dissipation heats the material and radiation thermalizes before escaping, making the disc radiatively efficient ($\eta \sim 0.1$). Alternative accretion regimes exist depending on the accretion rate. At low rates ($L \ll L_{\text{Edd}}$), the Advection-Dominated Accretion Flow (ADAF) model applies: the disc is geometrically thick and optically thin, most of the dissipated energy is advected into the black hole rather than radiated, and the resulting spectrum is hard and non-thermal. At super-Eddington rates ($L \gtrsim L_{\text{Edd}}$), the *slim* disc model becomes relevant: radiation is partially trapped within the flow, reducing the radiative efficiency ($\eta \sim 0.01$) and driving strong outflows.

spectral signatures: the *iron $K\alpha$ line* at 6.4 keV, arising from fluorescent emission of neutral material in the disc, and the *Compton hump* around 20–30 keV, produced by Compton backscattering of hard X-ray photons off the dense disc atmosphere (dark green curve in fig. 1.5).

The corona may also be responsible for an additional spectral feature observed below ~ 1 keV: the *soft excess* (pink curve in fig. 1.5). One leading interpretation for the soft excess invokes a second, cooler and optically thicker layer of the corona ($T \sim 10^6$ – 10^7 K), which comptonizes disc photons to lower energies than the hot corona discussed above — a warm comptonization scenario (Petrucci et al. 2013). However, the origin of the soft excess remains debated.

1.2.4 Broad Line and Narrow Line Regions

Around the SMBH, disk and corona, it is possible to find clouds of photoionized gas⁵ that define, based on their properties, the Broad Line Region (BLR), located at sub-parsec/parsec scale from the accretion disc, and the Narrow Line Region (NLR), located at larger (up to kpc) distances from the accretion disc.

BLR are characterized by extreme conditions: densities reach $n_e \sim 10^9$ – 10^{11} cm^{−3}, temperatures are $T \sim 10^4$ K, and the clouds move at high velocities, $v \sim 10^3$ – 10^4 km s^{−1}, under the gravitational influence of the SMBH (Peterson 1997). Here forbidden lines are suppressed via collisional de-excitation because of high density: forbidden lines have low probability and the excited atom must wait a relatively long time before emitting a photon; during this waiting time, the atom can alternatively collide with a free electron and transfer its excitation energy into kinetic energy, without emitting any photon. These lines are significantly broadened by the Doppler effect: the observed wavelength of an emission line is Doppler-shifted according to $\lambda_{\text{obs}} = \lambda_0(1 + v_r/c)$, where λ_0 is the rest-frame wavelength and v_r is the radial velocity along the line of sight. The resulting line broadening is therefore $\Delta\lambda/\lambda_0 = v_r/c$, meaning that higher velocities produce wider line profiles. Hence the name *broad* line region.

The NLR are located farther and conditions are less extreme: $n_e \sim 10^4$ – 10^6 cm^{−3}, $T \sim 1$ – 2.5×10^4 K, and velocities are lower, $v \sim 300$ – 1000 km s^{−1}, producing narrower emission lines, hence *narrow* line region (Peterson 1997). The lower density allows forbidden lines — such as [O III], [Ne V], and [Mg VII] — to survive without being collisionally suppressed. Dust is present, as the radiation field is too weak to destroy it (Netzer 2015).

The torus (see below for the details), by blocking radiation in the equatorial direction, allows it to escape only through the polar openings, forming two *ionization cones* along the polar axis. The NLR gas is distributed precisely within these cones, extending from ~ 10 pc to a few kpc from the central source.

⁵The gas is ionized by the UV and X-ray photons emitted by the accretion disk and the hot corona. When electrons recombine with ions, they emit photons at characteristic frequencies, producing these emission lines observed in AGN spectra.

1.2.5 Torus

The accretion disc is in turn surrounded by a toroidal structure of gas and dust, a doughnut-shaped region, extending typically from ~ 1 to ~ 10 pc (Netzer 2015). The inner edge of this structure is defined by the dust sublimation radius R_{sub} , i.e. the minimum distance at which dust can survive without being destroyed by the nuclear radiation:

$$R_{\text{sub}} \simeq 1.3 \left(\frac{L_{\text{UV}}}{10^{46} \text{ erg s}^{-1}} \right)^{1/2} \left(\frac{T_{\text{sub}}}{1500 \text{ K}} \right)^{-2.8} \text{ pc},$$

where L_{UV} is the UV luminosity of the central source and T_{sub} is the sublimation temperature, $T_{\text{sub}} \sim 1000\text{--}2000$ K, depending on dust composition.

The torus lies in the equatorial plane of the system, co-planar with the accretion disc, and exhibits rotational symmetry around the black hole spin axis. Moving outward from the central engine the gas transitions from being partially ionized in the innermost regions, where it is directly exposed to the central radiation, to neutral and molecular phases in the outer zones.

The structure of the torus is described by two classes of models. In the *smooth* model the torus is a homogeneous distribution of gas and dust with temperature decreasing with distance. In the *clumpy* model it is instead composed of discrete clouds, each with its own physical properties: the temperature is therefore not necessarily a function of distance. The clumpy scenario is currently the most widely accepted (Netzer 2015).

The optical-UV radiation is absorbed and reprocessed by the dusty torus, re-emerging in the mid-infrared as a superposition of graybody curves (*red curve* in fig. 1.5; see section 1.3 for dust properties). Soft X-ray photons are instead partially absorbed, while hard X-ray photons can penetrate even through significant amount of gas (see section 1.2.6 and section 1.4). Furthermore, the innermost regions of the torus, partially ionized by the central radiation, produce strong X-ray emission lines — most notably the *iron K α line* at 6.4 keV — and act as a reflective medium for the incident X-ray continuum, contributing to the Compton hump already discussed.

Jets

Jets represent a component that is not always present in the AGN structure. They are extremely collimated outflows of relativistic plasma, produced in the innermost regions of the central engine and oriented along the polar axis, perpendicularly to both the accretion disk and the torus. Although the mechanisms responsible for their formation remain uncertain, they are thought to be related to the spin of the black hole and the accretion disk, coupled with the presence of intense magnetic fields that accelerate and collimate the outflowing plasma. The relativistic electrons composing the jet emit radiation through two main mechanisms. The first is synchrotron emission, in which electrons spiral along magnetic field lines and emit photons predominantly in the radio band. The second is inverse Compton scattering: the same relativistic electrons collide with low-energy photons boosting them to higher energies and contributing to the X-ray and γ -ray emission. An important relativistic effect occurring in jets is *Doppler beaming*: as the jet propagates toward the observer

at velocities close to the speed of light, relativistic effects cause the approaching jet to appear significantly brighter and more energetic. Less powerful jets decelerate already within the host galaxy, while the most powerful ones extend up to Mpc scales (Urry and Padovani 1995). The interaction with the surrounding medium causes the loss of collimation and the formation of diffuse structures: hot spots and large-scale radio lobes.

The zoo of active galactic nuclei and Unified Model

The components described so far are the building blocks of a unified physical picture but, as is often the case in astrophysics (and not only), the same object can appear remarkably different depending on how and from where it is observed. AGNs are a prime example of this: depending on our viewing angle, the structure described in the previous sections can take a completely different appearance. Moreover, the classification of these objects depends on the energy band in which they are observed, on the presence or absence of a relativistic jet, and on the efficiency of the accretion process. Following all these distinctions leads to a rich and sometimes confusing "zoo" of classifications and nomenclatures, whose exhaustive discussion lies beyond the scope of this thesis. To have a hint of it, in fig. 1.8 are reported some of the names and classifications of AGNs, showing that observational differences can be understood within a common physical framework and that the diversity of AGNs classes primarily reflects the orientation of the central engine with respect to the line of sight.

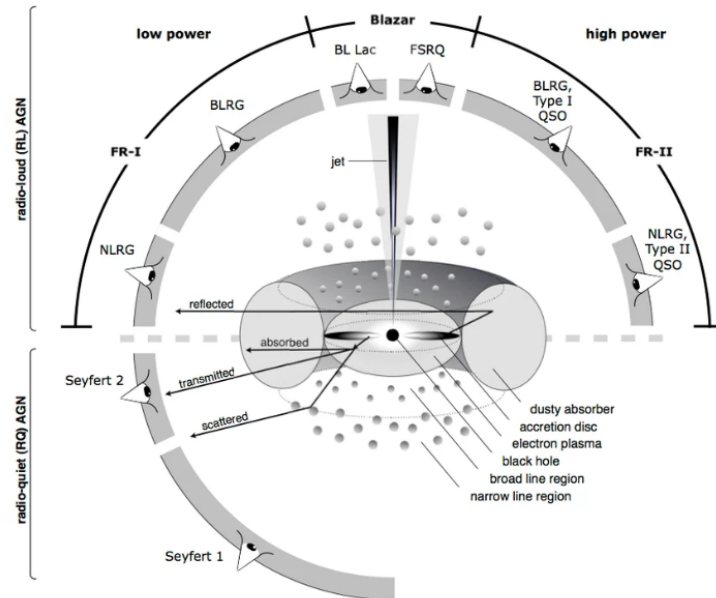


Figure 1.8: *Schematic representation of our understanding of the AGN phenomenon in the unified scheme. The type of object we see depends on the viewing angle, whether or not the AGN produces a significant jet emission, and how powerful the central engine is. Note that radio loud objects are generally thought to display symmetric jet emission. From Beckmann and Shrader 2012.*

For the purpose of this thesis it is important to notice that historically this viewing-angle dependence lies at the basis of the *Unified Model* of AGN (Antonucci 1993). According to this scenario, the central engine of AGN is fundamentally the same in all sources — namely accretion onto a SMBH — while the observed diversity mainly arises from orientation effects and from the presence of **obscuring material** surrounding the nucleus. In that model this obscuration has been associated with the presence of the dusty torus surrounding the central engine and has led to the distinction between *Type 1 and Type 2 AGN*. If the line of sight is "free" — i.e. the system is observed along directions perpendicular to the equatorial plane of the torus — the nuclear regions are directly visible: these are Type 1 AGNs, in which the broad emission lines and the optical/UV continuum can be directly detected. If instead the line of sight intercepts the torus, the innermost regions of the AGN cannot be directly observed, the emission from the accretion disc and from the BLR is heavily absorbed: these are Type 2 AGNs, in which the nuclear emission is partially or completely obscured. The strength of these obscuration effects depends on the viewing angle and on the amount of gas along the line of sight.

1.2.6 Obscured AGNs

While the Unified Model attributes obscuration primarily to the nuclear dusty torus, it is now well established that absorbing material can be present on a wide range of physical scales. In addition to the torus, obscuration can arise from circumnuclear starburst disks on scales of tens to hundreds of parsecs, and — most relevantly at high redshift — from gas and dust distributed on the scale of the entire host galaxy ($> \text{kpc}$) (Hickox and Alexander 2018). In a more general sense, obscuration is defined as anything that absorbs emission and/or scatters a large fraction of it away from the line of sight of the observer. Thus, with *obscured AGNs* are indicated those systems whose emission from accretion disk is not directly detected due to the presence of material between the accretion disk and the observer⁶.

The level of obscuration is commonly quantified through the hydrogen column density N_{H} (see later and section 1.4 for a detailed definition), measured in units of cm^{-2} . In turn, AGNs can be classified according to their column density as follows:

- **Unobscured AGN:** $N_{\text{H}} < 10^{22} \text{ cm}^{-2}$;
- **Compton-thin obscured AGN:** $10^{22} \leq N_{\text{H}} < 10^{24} \text{ cm}^{-2}$, soft X-ray photons ($\lesssim 2 \text{ keV}$) are absorbed, while hard X-ray ($\geq 10 \text{ keV}$) emission remains detectable;
- **Compton-thick (CT) AGN:** $N_{\text{H}} \geq 10^{24} \text{ cm}^{-2}$, the column density is so elevated that also hard X-ray photons ($\geq 10 \text{ keV}$) are suppressed.

Figure 1.9 shows the spectral energy distribution of a heavily obscured AGN ($\log N_{\text{H}} = 24.0$), with a low AGN contribution ($f_{\text{AGN}} = 0.30$, which represents the

⁶A more classical definition of obscured AGN is the absence of BLR in the optical waveband (Antonucci 1993), since the broad lines originate near the nucleus and are obscured by the torus; however, here we focus on obscuration by the host galaxy medium.

intrinsic AGN emission at $1\,\mu\text{m}$) decomposed into its main components: the dusty torus, dominating the mid-IR; the host galaxy, dominating the optical; the AGN accretion disc and its associated emission lines, visible in the optical/soft X-ray range; hot gas together with X-ray binaries, dominating the hard X-ray emission. At such high obscuration levels, the optical/UV emission from the accretion disc is strongly suppressed, while the mid-IR emission reprocessed by the torus is largely unaffected, becoming instead the dominant observable component. In the X-rays, absorption progressively shifts to higher energies as the column density increases. This signature is due to the fact that the obscuring medium is typically composed of dust, which dominates the obscuration at UV–infrared wavelengths (see section 1.3) and/or gas, which dominates the absorption at X-ray energies (Hickox and Alexander 2018).

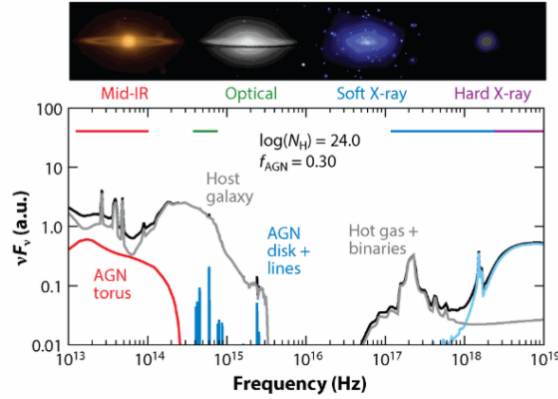


Figure 1.9: *Model spectral energy distribution of a heavily obscured AGN at $\log N_{\text{H}} = 24.0$ and $f_{\text{AGN}} = 0.30$, showing the contributions from the AGN torus (red), the AGN accretion disc and emission lines (blue), the host galaxy (gray), and their combined emission (black). Adapted from Hickox and Alexander 2018. See the text for details.*

Therefore, the common classification just reported is not arbitrary, but arises from a deeper study of the properties of the obscuring material.

1.2.7 "Seeing through" obscuration: optical depth and column density across wavelengths

Understanding this classification requires connecting these observational features to the physical properties of the obscuring material itself — whether dust or gas — and to its distribution along the line of sight within the host galaxy. In a sense, the “small” affects the “large”: the microscopic properties of the interstellar medium shape the observational appearance of some of the most powerful objects in the Universe. However, the connection between these properties and the observed features of obscuration is not always straightforward. This section introduces the two quantities that provide the physical and mathematical framework needed to quantify — and thus to understand — obscuration across wavelengths, and their connection: optical depth and column density. It also serves as a bridge between the description of AGNs just presented and the description of the interstellar medium given in section 1.3.

The quantity that at particle levels quantifies how difficult it is for a photon to

travel through the medium is the optical depth τ_λ (τ_ν) and can be interpreted as the cumulative attenuation offered by the particles that act as shields for the incoming photons. Mathematically, this is expressed as the integral of the product of the number density of particles of a given species n , and their cross-section⁷ σ_λ , along the line of sight:

$$\tau_\lambda = \int_0^s n \cdot \sigma_\lambda dl. \quad (1.10)$$

This expression shows that, at fixed path length, the optical depth is determined by the type of interacting particle (σ_λ) and its number density along the line of sight (n). This leads to a first important consideration: σ_λ depends on the nature of the obscuring material and its interaction with the incoming photons⁸.

If the photon encounters a solid dust grain, the interaction is governed by a classical wave-optical framework and Mie theory (Mie 1908) can be applied, in which the wavelength λ of the incoming photon and the physical size of the dust grain a (see section 1.3) are compared:

- $\lambda \gg a$: the photon wavelength is much larger than the grain — the radiation passes around the grain almost undisturbed. This is the case of radio waves ($\lambda \gg 1$ cm), which are unaffected by dust;
- $\lambda \sim a$: the photon is attenuated (both absorbed and scattered) by the grain (see section 1.3.2). This is the case of UV-optical wavelength ($0.01 - 1 \mu\text{m}$);
- $\lambda \ll a$: the wavelength is much smaller than the grain and the geometrical cross-section becomes negligible. This is the case of X-rays wavelength ($0.01 - 10$ nm).

Anyway, as the energy increases, the wavelength of the photon must be compared to smaller structures, up to atoms, whose interaction can no longer be described geometrically.

The dominant process for soft X-rays is the photoelectric effect: a photon of energy E is absorbed by an atom if E exceeds the ionization (binding) energy E_I of an atomic electron, which is then ejected with kinetic energy $E - E_I$. The cross section for this process is inversely proportional to the energy of the photon: $\sigma_{\text{pe}}(E) \propto E^{-3.4}$ (Longair 2011).

For hard X-rays, which are characterized by higher energies, E greatly exceeds the ionization potential of the atoms. Then, electrons are essentially free and the dominant process becomes the Thomson scattering: the photons are scattered in random directions by the electrons and the cross section of this process is independent on energy, it is the so called Thomson cross section $\sigma_T \simeq 6.65 \times 10^{-25} \text{ cm}^2$.

At even higher energies (γ rays, $E \gtrsim 511 \text{ keV}$), relativistic corrections become important and the Thomson cross-section transitions into the Klein–Nishina regime,

⁷the cross-section of a particle-radiation interaction measures the probability of that interaction to take place.

⁸A photon is a quantum of light, therefore carries energy, which is proportional to its frequency ν and inversely proportional to wavelength λ , according to the relation $E = h\nu = hc/\lambda$, where h is the Planck constant.

where σ decreases with increasing energy (Longair 2011). A detailed treatment of this regime is beyond the scope of this work.

So, soft X-rays are efficiently absorbed by the gas via photoelectric effect, while hard X-rays can be trapped by repeated Thomson scattering off free electrons. These two processes are directly connected to the definition of obscured Compton thin and obscured Compton thick AGNs introduced above, which depends on the value of N_H . The column density in fact is the physical quantity linking the ISM to AGN obscuration: this quantity has the dimensions of cm^{-2} and represents the number of particles per unit area intercepted along a given direction (Longair 2011; Draine 2011). Mathematically, it is defined as the integral of the volume number density n of a given species along the line of sight l :

$$N = \int_0^s n \, dl \quad (1.11)$$

The link between column density and optical depth is enclosed in eq. (1.10), that combined with the above equation gives:

$$\tau_\lambda = N \cdot \sigma_\lambda \quad (1.12)$$

In particular, in the contest of obscuration, column density refers to the *hydrogen column density* N_H :

$$N_H = \int_0^s n_H \, dl \quad (1.13)$$

where n_H is the hydrogen number density and the integral is computed along the line of sight toward the nucleus (see section 1.4 for a more detailed discussion).

Finally, it is possible to better understand the definition of obscured AGNs in the two regimes, previously introduced, by considering that $N_H = \tau_\lambda / \sigma$.

The medium become opaque to radiation when $\tau \sim 1$, therefore:

- **Compton thin:** the medium is opaque to soft X-rays via photoelectric absorption and the cross section can be estimated as $\sigma_{\text{pe}}(1 \text{ keV}) \sim 10^{-22} \text{ cm}^2$ (Longair 2011). Therefore $N_H \sim \frac{1}{\sigma_{\text{pe}}} \sim 10^{22} \text{ cm}^{-2}$
- **Compton thick:** the medium is opaque to hard X-rays via Thomson scattering, with cross-section $\sigma_T = 6.65 \times 10^{-25} \text{ cm}^2$. Therefore $N_H \sim \frac{1}{\sigma_T} \sim 10^{24} \text{ cm}^{-2}$.

With this classification in mind, we can now move forward to the nature of the obscuring material itself, and to the model which allows us to estimate N_H (see section 1.4 and section 2.1).

1.3 The Fuel and the Veil: the InterStellar Medium

The ensemble of gas and dust constitutes in astrophysics the interstellar medium (ISM) and belongs to the component of the galaxy made up of diffuse material (cosmic rays, magnetic fields, radiation fields, gas and dust) located in the space between stars. In galaxies undergoing ongoing star formation, gas and dust represent the primary fuel from which new stars are born and, as mentioned in section 1.1, the

same reservoirs that feed star formation can channel material toward the galactic nucleus, providing the fuel for SMBH accretion and acting as the main agent of nuclear obscuration at high redshift (Gilli et al. 2022).

More fundamentally, the interstellar medium is an enormous and complex environment that can serve as a laboratory for testing our astrophysical knowledge on several levels, since its properties are of considerable importance in many fields of astrophysics (Carroll and Ostlie 2017):

- stellar evolution itself is a cyclic process in which the ISM plays a leading role; a star is born under particular conditions from the interstellar medium and during the final stages of its life, depending on the mass of the star, much of the material composing it may return to the ISM through stellar winds and explosive events;
- the description of the structure, dynamics, and evolution of galaxies requires the study of the ISM in order to better interpret observations carried out with telescopes: when studying an object, whether nearby or distant, we must take into account the presence of the interstellar medium. The ISM absorbs part of the radiation produced by stars and re-emits it at longer wavelengths. It is therefore necessary to consider it in order to obtain a coherent picture of the physical processes occurring inside a galaxy;
- the formation and destruction of dust grains and complex molecules belonging to the ISM requires a detailed understanding of chemistry in an environment that cannot be reproduced in a terrestrial laboratory;
- finally, in the context of nuclear activity, the ISM represents the primary large-scale agent of obscuration toward the galactic nucleus; at high redshift, its column density can reach Compton-thick values, making it the dominant factor in hiding actively accreting supermassive black holes from our view (Gilli et al. 2022).

The mass of the ISM represents a significant fraction of the visible matter in a galaxy: $\sim 10\text{--}15\%$ in the Milky Way, with a composition of 99% gas (present in all its components: ionized, neutral, atomic, molecular) and 1% dust (Karttunen et al. 2007). Defining the baryonic gas fraction as $f_{\text{gas}} = M_{\text{gas}}/(M_{\text{gas}} + M_{\star})$ – where M_{gas} is the gas mass and $M_{\star}$ is the stellar mass – it rises from $\sim 5\%$ in the local Universe to $\sim 50\%$ at $z \gtrsim 3$ (Tacconi et al. 2018).

1.3.1 Phases and composition of the interstellar medium

Considering the gaseous component, it is made up of 70% hydrogen, 28% helium, and the remaining 2% of other metals such as carbon and silicon. Hydrogen is therefore the main element of the gaseous component and may be present in neutral (HI), ionized (HII), and molecular (H₂) form.

Depending on the temperature and density of the gas, different phases of the interstellar medium can be distinguished, located in different galactic environment (Hollenbach and Tielens 1999; Haverkorn and Spangler 2013; Cimatti, Fraternali,

and Nipoti 2019). In table 1.2 are reported typical values of temperature and density for the phases described below.

Property	GMCs	CNM	WNM	WIM	HII regions	HIM
T (K)	$\sim 10 - 100$	~ 100	8000	8000	8000	10^6
ρ (cm^{-3})	$> 10^2$	10-100	0.1-0.5	0.1-0.5	5-10	$\geq 10^{-3}$

Table 1.2: *Main properties of the ISM phases as a function of temperature and density (Haverkorn and Spangler 2013; Cimatti, Fraternali, and Nipoti 2019).*

- **Hot Ionized Medium (HIM)**

This phase is found between 10^6 and 10^7 K and includes regions where the gas has high temperatures and low densities; this phase mainly appears in places where supernova explosions have occurred, during which much of the material of a star is released into the surrounding space. The hydrogen present here is in ionized form. The gas in this phase cools principally via bremsstrahlung emission in X-ray or synchrotron radiation in radio band.

- **Warm Neutral and Warm Ionized Medium(WNM,WIM)**

This phase is found around 10^4 K and, depending on the radiation field, may include hydrogen both in neutral form (WNM) and ionized form (WIM).

WIM is located where young and very hot stars (or X ray binaires/ galactic UV background) are able to ionize the hydrogen present in the ISM. With respect to the HII regions (see below) it has a lower density and it is more diffuse in the galaxy. The WIM primarily cools via UV and optical permitted line emission, such as $H\alpha$, $H\beta$ as well as bremsstrahlung radiation in the radio band. Given the low density environments, high-excitation forbidden lines may also be observed.

WNM has a similar temperature and density of WIM but it is situated in regions shielded, where ionizing photons are not able to penetrate. The principal tracer is the HI 21 cm line, produced by the hyperfine transition of neutral hydrogen: it is a very rare transition (timescale of $\sim 10^7$ yrs) but it can be detected where the abundance of neutral hydrogen in the ISM is very high.

- **HII regions and Photo-Dissociation Regions (PDRs).**

HII regions are zones of ionized gas at temperatures of order 10^4 K, found primarily around young, massive, and very hot stars. In the star formation process, a star is born within the dense core of a molecular cloud; once formed, its intense UV radiation field ionizes the surrounding medium. Photons with energies above 13.6 eV — the Lyman limit — are able to ionize the surrounding hydrogen, creating a Strömgren sphere of nearly fully ionized gas. HII regions emit both in continuum and in lines. The continuum is characterized by bremsstrahlung emission, which at these temperatures falls at radio wavelengths. Emission in lines is characterized by intense hydrogen recombination lines, such

as the Balmer series ($H\alpha$, $H\beta$), and, owing to the low gas density, by forbidden lines of ionized elements such as $[OIII]$ and $[NIII]$.

Moving away from the star, beyond the HII region, it is possible to find the Photo-Dissociation Regions (**PDRs**)

The presence of dust in these regions contributes to the heating processes of gas in PDRs: dust grains and polycyclic aromatic hydrocarbons (PAHs) absorb far ultra violet(FUV) photons and eject electrons through the photoelectric effect that heat the gas collisionally. In the end, PDRs host neutral hydrogen, ionized carbon (C^+), and molecular species simultaneously. The main cooling mechanisms and observational tracers are the fine-structure lines of atomic species — primarily $[CII]$ $158\ \mu m$ and $[OI]$ $63\ \mu m$ — together with molecular line emission from warm gas, particularly CO and H_2 .

- **Cold Neutral Medium (CNM)** This phase is found at temperatures around 100 K and includes gas at the lowest temperatures and highest densities. Hydrogen here is present in neutral atomic form (CNM) – the same chemical state as the WNM but at lower temperature and higher density– and, in the densest regions, in molecular form (H_2). In particular, the molecular form (H_2) is located in the Giant Molecular Clouds (GMCs).
- **Giant Molecular Clouds** This gravitationally bound structure represent the coldest and densest phase of the ISM, with temperature reaching lower than 10 K. They constitute the main environment of the interstellar medium for the development of the solid component of the ISM: dust. These clouds, from which star formation begins, are clouds whose size ranges from 30 pc to 100 pc and whose mass is equal to $10^{5-6}M_\odot$, mainly composed of molecular hydrogen; within these clouds it is possible to identify much smaller regions with higher density, called cores and clumps. The cores, containing a few solar masses, are the actual seeds of star formation. The greater the number of these clouds, the greater the star formation activity.

Although molecular hydrogen H_2 is the most abundant molecule in the Universe, it is extremely difficult to observe directly. Its homonuclear, symmetric structure means it has no permanent electric dipole moment, so only electric quadrupole rotational transitions are allowed, but this transitions are less probable to happen and would require gas temperatures of ~ 500 K to be excited — far above the typical GMC temperature⁹. As a result, H_2 remains in its ground state and does not emit detectable radiation under typical GMC conditions. The molecular gas content is therefore traced by carbon monoxide CO, the second most abundant molecule in the Universe (see section 1.3.4). CO has a strong binding energy (11.1 eV) that allows it to survive in environments with intense UV radiation and cosmic rays; its asymmetric structure gives it a permanent electric dipole moment, enabling efficient rotational transitions observable at radio and millimeter wavelengths (see section 1.3.4, in particular table 1.4).

⁹The rotational energy spacing scales as $\Delta E_{\text{rot}} = \hbar^2(J+1)/I$, where J is the rotational quantum number and I the moment of inertia, which is directly proportional to the molecular mass. H_2 , being the lightest molecule, has energy levels widely spaced that cannot be excited at GMC temperatures.

1.3.2 Dust

In the cold gas (table 1.2), especially in PDRs and in GMCs, it is also possible to identify dust, namely the solid component of the interstellar medium. Dust has several important effects on the surrounding gas and on the radiation propagating through it.

Interstellar dust consists of grains with typical sizes on the order of $0.1\text{--}1\text{ }\mu\text{m}$, mainly composed of silicates and carbon, sometimes enriched with magnesium and iron; in table 1.3 we report the abundances for our Galaxy.

Constituent	Abundance	Atomic weight (a.u.)	M/M_H
C	2.5×10^{-4}	12	0.0030
Mg	4.0×10^{-5}	24	0.0010
Fe	3.4×10^{-5}	56	0.0019
Si	3.8×10^{-5}	28	0.0011
O	4.5×10^{-4}	16	0.0014
Total			0.0084

Table 1.3: *Main constituents of interstellar dust in the Milky Way, where abundance is given relative to the total hydrogen in the ISM, adapted from Cimatti’s lectures.*

The grains exhibit an irregular shape and can exhibit more or less compact porosity; the inner part of the grains is made of rocky material, covered by refractory material (i.e. able to resist to high temperatures without chemically reacting with the materials it is in contact with). When grains are located in a very cold environment, such as in giant molecular clouds, they can present an ice layer on their surface; where the temperature is instead high, the ice sublimates and only the inner part remains (Cimatti, Fraternali, and Nipoti 2019).

We will concentrate on the properties of dust grains, but it is worth remarking that, in addition to the grains, there are other components considered part of interstellar dust: molecules such as PAHs (Polycyclic Aromatic Hydrocarbons), DIBs (Diffuse Interstellar Band carriers)¹⁰, diamonds, ices of different compositions and crystalline silicates. Among these components, the most important are PAHs: they are collections of benzene rings, present throughout the universe. Wherever a spectrum is taken, strong emission bands due to PAHs are always observed, emitting in the mid-IR regime ($\sim 5 - 30\text{ }\mu\text{m}$).

Formation and destruction

Dust grains can form from the gas phase into progressively larger structures thanks to chemical processes: atoms aggregate into molecules and then, through processes we do not yet understand, into grains. Anyway, this process takes a long time and it would not be realistic to account for the observed amount of dust. There exists a

¹⁰They are responsible for some very broad absorption bands present in the spectra of stars located behind the dust cloud; their origin is not yet clear but can be associated with complex molecules and solid particles.

more efficient process, called *nucleation*. Nucleation involves phase transitions: under specific conditions of density and temperature, many atoms are able, through this process, to aggregate into clusters and form "seeds" that give rise to dust grains. The main sources of dust are the final stages of a star's life, during its explosive phases. In these contexts, a large amount of matter is released into the interstellar medium through stellar winds: the ejected gas activates nucleation. Nova and supernova explosions feed this process.

Dust grains are very fragile and are completely destroyed in environments with high temperatures (1000–2000 K), which is why dust is found in the environment of GMCs, together with cold gas. Dust grains can be destroyed by high temperatures and by highly energetic radiation such as UV, X-rays, and γ -rays, but also through processes such as photodesorption (through which the grain's mantle is destroyed while the core remains intact) and gas-phase bombardment (in which, on the surface of the grain — that is located in a very gas-dense region — chemical reactions occur that lead to the destabilization of the grain), collisions with cosmic rays, and also collisions between dust grains themselves (the kinetic energy of the particles is so high that it can lead to their destruction).

The evolution of dust consists of a sort of cycle, triggered by the final stages of stellar evolution: the dust formed here is dispersed into the interstellar medium and preserved in giant molecular clouds, in which other stars will form. With each cycle, the interstellar medium is enriched with heavier elements originating during stellar evolution, and the cycle continues as long as molecular gas is available.

From a physical point of view, dust plays an important role in numerous processes, such as the formation of H_2 and the reprocessing of radiation.

Absorption and emission

Dust grains absorb radiation with wavelengths of the order of their size ($0.1 - 1 \mu\text{m}$), that is, UV/optical radiation, and re-emit it at longer wavelengths in the IR (from $10 \mu\text{m}$ to $200 \mu\text{m}$, depending on the dust temperature itself). The presence of dust can thus be detected either through the absorption of UV/optical light or through emission in the IR bands (Carroll and Ostlie 2017). On average, in present-day galaxies, between 1/4 and 1/3 of stellar radiation is reprocessed into emission by dust. The scattering of radiation by dust also has important effects and produces structures around massive stars known as reflection nebulae. The combined contribution of absorption and scattering, which effectively removes optical/UV radiation along the line of sight, is called *extinction*.

To describe these processes, we consider the radiative transfer equation (eq. (1.20)). It will be particularly remarkable, as the continuum emission of dust in the far infrared band serves as a powerful tracer of the physical conditions of the ISM, encoding information about dust temperature and mass.

Extinction and optical depth

The phenomenon of extinction occurs when between a luminous source and the observer there is interposed some material (in our case dust) capable of absorbing and scattering radiation (fig. 1.10). Through *absorption*, the energy radiated by the

source is re-radiated at wavelengths typical of the infrared; through *scattering*, the propagation direction of the ray is changed, leading to a decrease in intensity along the original direction of propagation. The combined effect of these two phenomena, *extinction*, attenuates the intensity of the original beam; in the following, we will derive an expression for it (Karttunen et al. 2017), in connection to the optical depth seen in section 1.2.6.

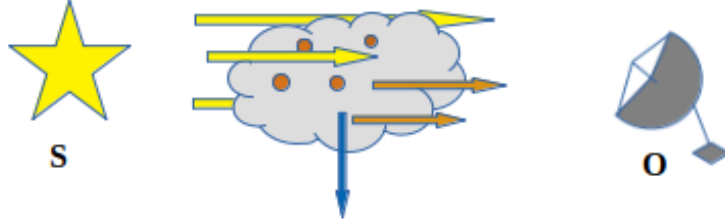


Figure 1.10: A qualitative image representing the light reprocessing through dust clouds. The yellow, blue, and brown rays represent respectively the radiation emitted by the source S , the radiation scattered by the interstellar cloud, and the radiation emitted by the interstellar cloud; O is the observer.

Assuming that the interstellar dust grains are spherical with radius a , their interaction with incoming photons can be characterized by an extinction cross-section C_{ext} (see section 1.2.6), which quantifies the effective area over which a grain intercepts radiation. In the Mie regime ($\lambda \sim a$, relevant for UV-optical wavelengths), C_{ext} is proportional to the geometric cross-section:

$$C_{\text{ext}} = Q_{\text{ext}} \pi a^2, \quad (1.14)$$

where Q_{ext} is the dimensionless extinction efficiency¹¹.

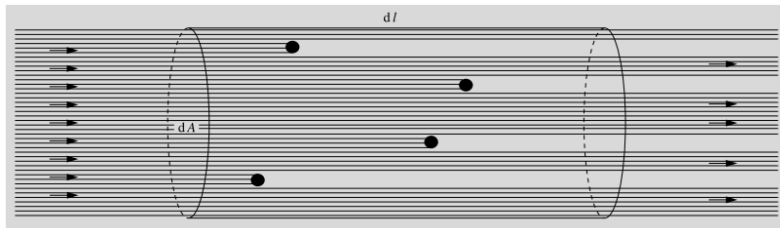


Figure 1.11: Cylinder of interstellar cloud considered to derive a formulation of extinction; from (Karttunen et al. 2017)

As discussed in section 1.2.7, the cross section is strictly linked with the optical depth. A concrete picture of the optical depth of dust grains can be built by considering a small cylinder of interstellar cloud, of length dl and cross-sectional area

¹¹The extinction coefficient is the sum of the absorption and scattering coefficients, $Q_{\text{ext}} = Q_{\text{abs}} + Q_{\text{scat}}$. According to the Mie theory (Mie 1908), (see also section 1.2.6), when the particle radius is much smaller than the wavelength of the incident radiation, absorption is the dominant process.

dA , perpendicular to the direction of propagation, as sketched in fig. 1.11. Further assume that the dust grains inside the cylinder do not overlap each other. If we denote by n the number density of grains, there will be $n dl dA$ grains in the volume element considered, covering a fraction $d\tau_\lambda$ of the area dA :

$$d\tau_\lambda = \frac{n dA dl C_{\text{ext}}}{dA} = n C_{\text{ext}} dl, \quad (1.15)$$

where $d\tau_\lambda$ (or equivalently $d\tau_\nu$, the two notations being interchangeable) is therefore the optical depth of the volume element, consistent with the definition introduced with eq. (1.10).

Over the length dl the radiation intensity will change by

$$dI_\nu = -I_\nu d\tau_\nu. \quad (1.16)$$

Integrating Eq. (1.16) one obtains:

$$I_\nu = I_\nu(0) e^{-\tau_\nu}, \quad (1.17)$$

which expresses the phenomenon of extinction: I_ν denotes the intensity perceived by an observer located beyond the cloud, and $I_\nu(0)$ the intensity emitted by the source.

When $\tau_\nu \gg 1$ the medium is said to be *optically thick* or opaque: photons of frequency ν on average cannot cross the entire medium without being absorbed; when $\tau_\nu \ll 1$ the medium is said to be *optically thin* or transparent: photons of frequency ν can traverse the material without being absorbed.

From the observational point of view, extinction not only affects the apparent magnitude (making a source appear fainter than it should be based on distance alone), but also causes reddening of light: the magnitude of extinction rises for shorter wavelengths (λ). To account for the first effect, the following formula is used:

$$m - M = 5 \log \frac{r}{10 \text{ pc}} + A, \quad (1.18)$$

where $A \geq 0$ represents the extinction in magnitudes due to the intervening material; m is the apparent magnitude, M the absolute magnitude, and r the distance of the object. Knowing the relation between intensity and magnitude, it is possible to derive a relation between A and the optical depth:

$$A = (2.5 \log e) \tau \approx 1.086 \tau^{12}. \quad (1.19)$$

As expected, extinction depends on the optical depth, i.e. on the amount of dust that the radiation must traverse. This reflects what explained in section 1.2.6: reddening (magnitude of extinction increases towards shorter wavelengths) occurs because for $\lambda \sim a$ the interaction between radiation and dust is maximised (Mie scattering regime). Since interstellar grains have typical sizes $a \sim 0.1 \mu\text{m}$, this condition is dominant in the optical and ultraviolet bands.

¹² τ can be expressed as a function of λ or ν interchangeably and the same applies to the extinction expressed in magnitudes.

Radiative Transfer Equation

The radiative transfer equation takes into account not only the absorption due to the matter interposed between source and observer (as described in the previous section), but also the possibility that the material itself emits; the variation of intensity along a specific direction therefore becomes:

$$\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu + j_\nu. \quad (1.20)$$

In this equation j_ν is the emission coefficient for monochromatic emission and is defined as the energy emitted per unit time, solid angle, volume, and frequency, while α_ν is the absorption coefficient and represents the loss of intensity of a beam travelling a distance ds ; by convention α_ν is positive. At a microscopic level, this coefficient is related to the density ρ and opacity κ_ν of the particles i.e. how well the particles can absorb the incident radiation, through $\alpha_\nu = \kappa_\nu \rho$. In particular, the opacity, or mass absorption coefficient, can be defined as the cross-section per unit mass of the absorbing particle (Rybicki and Lightman 1986) and in case of dust grains:

$$\kappa_\nu = \frac{\sigma_\nu}{m_{\text{grain}}}, \quad (1.21)$$

where m_{grain} is the mass of a single dust grain. Opacity depends on the frequency (wavelength) of the incoming photons and can be expressed as:

$$\kappa_\nu = \kappa_0 \left(\frac{\nu}{\nu_0} \right)^\beta, \quad (1.22)$$

where ν_0 is an arbitrary reference frequency, $\kappa_0 = \kappa_{\nu_0}$ is the opacity normalisation at that frequency, and β is the dust emissivity index, typically found to lie in the range $1 \lesssim \beta \lesssim 2$ (Rybicki and Lightman 1986; Dunne et al. 2000).

In this work the opacity is assumed to be

$$\kappa_\nu(\beta) = 0.77 (\nu/352 \text{ GHz})^\beta \text{ cm}^2 \text{ g}^{-1} \quad (1.23)$$

with $\beta = 1.6$, in accord to literature (Dunne et al. 2000; Venemans et al. 2020; Gilli et al. 2022; Wang et al. 2024)

Having defined opacity, the optical depth in eq. (1.10) can equivalently be expressed as the integral along the path dl of the opacity κ_λ , multiplied by the local density of the obscuring material ρ :

$$\tau_\lambda = \int_0^s \kappa_\lambda \cdot \rho \, dl. \quad (1.24)$$

If the medium is homogeneous, κ_λ and ρ are constant along the path s and $\tau_\nu = \kappa_\nu \rho s$.

The radiative transfer equation then takes a particularly simple form when expressed in terms of optical depth. Equation (1.20) then becomes:

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu; \quad S_\nu \equiv \frac{j_\nu}{\alpha_\nu}, \quad (1.25)$$

where S_ν is the source function, defined as the ratio of the emission coefficient to the absorption coefficient; integrating gives:

$$I_\nu = I_\nu(0) e^{-\tau_\nu} + S_\nu (1 - e^{-\tau_\nu}). \quad (1.26)$$

1.3.3 Blackbody Emission

Under conditions of thermodynamic equilibrium between radiation and matter, the source function S_ν coincides with the Planck function:

$$B_\nu(T_d) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT_d} - 1}, \quad (1.27)$$

where $k = 1.38 \times 10^{-16} \text{ erg K}^{-1}$ is the Boltzmann constant, $c = 3 \times 10^{10} \text{ cm s}^{-1}$ the speed of light in vacuum, and $\hbar = 1.055 \times 10^{-27} \text{ erg}\cdot\text{s}$ the reduced Planck constant¹³.

Equation (1.26) thus takes the form:

$$I_\nu = I_\nu(0) e^{-\tau_\nu} + B_\nu(T_d)(1 - e^{-\tau_\nu}), \quad (1.28)$$

where $I_\nu(0) e^{-\tau_\nu}$ is the intensity of the radiation (emitted by the background source) absorbed by the dust grains, and $B_\nu(T_d)(1 - e^{-\tau_\nu})$ is the intensity of the radiation emitted by the heated dust grains.

In thermodynamic equilibrium, the energy absorbed and emitted by the grains are in perfect balance:

$$\int_\nu I_{*,\nu} Q_{\text{abs},\nu}(a) d\nu = \int_\nu B_\nu(T_d) Q_{\text{em},\nu}(a) d\nu. \quad (1.29)$$

The left-hand term contains the amount of energy absorbed, while the right-hand term contains the amount of energy emitted. Both the emission coefficient $Q_{\text{em},\nu}$ and the absorption coefficient $Q_{\text{abs},\nu}$ depend on the grain size (a is the particle radius) and on the frequency ν of the radiation. The temperature dependence T_d is expressed by the Planck function.

We now find an expression for the two coefficients $Q_{\text{abs},\nu}$ and $Q_{\text{em},\nu}$ by separating in the radiative transfer equation eq. (1.28) the stellar (*) and dust (d) contributions at the exit of the cloud (of thickness L):

$$I_{*,\nu}(L) = I_{*,\nu}(0) e^{-\tau_\nu}, \quad \tau_\nu = \alpha_\nu L, \quad (1.30)$$

$$I_{d,\nu}(L) = B_\nu(T_d)(1 - e^{-\tau_\nu}), \quad \tau_\nu = \alpha_\nu L. \quad (1.31)$$

Inside and outside the cloud the source function and the stellar intensity are, respectively, zero. Manipulating eq. (1.30):

$$I_{*,\nu}(0) - I_{*,\nu}(L) = I_{*,\nu}(0)(1 - e^{-\tau_\nu}). \quad (1.32)$$

From these results we observe that eq. (1.31) expresses the intensity of the radiation absorbed by the cloud, which varies as $(1 - e^{-\tau_\nu})$, while eq. (1.32) expresses the intensity of the thermal emission from the dust, which also varies as $(1 - e^{-\tau_\nu})$. These two equations are therefore the integrands of eq. (1.29). We thus obtain:

$$Q_{\text{abs},\nu} = Q_{\text{em},\nu} = (1 - e^{-\tau_\nu}). \quad (1.33)$$

For a perfect blackbody (a body capable of re-emitting all absorbed radiation), the absorption coefficient equals 1 and its brightness is described by the Planck function

¹³In SI units: $k = 1.38 \times 10^{-23} \text{ J K}^{-1}$, $c = 3 \times 10^8 \text{ m s}^{-1}$, and $\hbar = 1.055 \times 10^{-34} \text{ J}\cdot\text{s}$.

(eq. (1.27)). The emission from dust grains (eq. (1.31)) is instead called *greybody* or *modified blackbody* emission.

One can also make explicit the frequency dependence of τ_ν , similarly to eq. (1.22), through the relation (Sommovigo et al. 2021):

$$\tau_\nu = \left(\frac{\nu}{\nu_0} \right)^\beta, \quad (1.34)$$

where β is the dust emissivity index and varies according to the chemical characteristics of the grains (e.g. for metals and crystalline materials $\beta = 2$, and for amorphous materials $\beta = 1$), ν is the rest-frame frequency, and ν_0 is the frequency at which the dust becomes optically thick; when $\nu < \nu_0$ the optically thin regime holds. We also make explicit the dust emission in the two different regimes. In the optically thick case, with $\tau_\nu \gg 1$, eq. (1.31) reduces to the blackbody function (eq. (1.27)). In the optically thin case, with $\tau_\nu \ll 1$ (expanding in a Taylor series), eq. (1.31) becomes:

$$I_{d,\nu}(L) = B_\nu(T_d) \left(\frac{\nu}{\nu_0} \right)^\beta, \quad (1.35)$$

and the emission and absorption coefficients are identified with the optical depth:

$$Q_{\text{abs},\nu} = Q_{\text{em},\nu} = \tau_\nu = \left(\frac{\nu}{\nu_0} \right)^\beta. \quad (1.36)$$

We can now relate these physical properties of dust to the observables. In particular, observations provide access to the flux density S , defined as the product of the intensity I and the solid angle Ω subtended by the source: $S = I\Omega$. By assuming that the intensity is given by the dust thermal emission described in eq. (1.31), the observed flux density can be written as:

$$S_{\nu_{\text{obs}}} = \Omega [B_\nu(T_d) - B_\nu(T_{\text{CMB}})] (1 - e^{-\tau_\nu}) (1 + z)^{-3} \quad (1.37)$$

where B is the Planck function, T_d is the dust temperature, $T_{\text{CMB}} = 2.725(1 + z)$ K is the CMB temperature at redshift z ; ν_{obs} and ν are the observed and rest frequency respectively, linked each other by $\nu = \nu_{\text{obs}}(1 + z)$.

Relation 1.37 will play a key role in the derivation of the dust mass, and, consequently, on the gas mass (see section 2.3).

1.3.4 CO and [CII] emission lines at high redshift

CO emission line

As discussed in the context of Giant Molecular Clouds (GMCs), CO is a good tracer of molecular gas: it is the second most abundant molecule in the Universe and, thanks to its permanent electric dipole moment, it exhibits strong rotational transitions. These transitions are efficiently excited at the low temperatures (~ 10 – 50 K) typical of molecular clouds.

Each rotational transition corresponds to a well-defined change in the rotational quantum number J , and therefore to a specific energy difference between levels. In

molecular clouds, collisions with other particles (mainly H_2) can excite CO to higher rotational states; the molecule subsequently decays to lower levels by emitting a photon with energy $E = h\nu$. The fundamental transition $J = 1 \rightarrow 0$ corresponds to an emission frequency of 115 GHz. The main low- J CO transitions are summarized in table 1.4.

Transition (J)	ν (GHz)	λ (mm)
$J = 1 \rightarrow 0$	115.27	2.60
$J = 2 \rightarrow 1$	230.54	1.30
$J = 3 \rightarrow 2$	345.80	0.87

Table 1.4: *Main rotational transitions of the CO molecule. Each transition corresponds to a change in the rotational quantum number J .*

In terms of observability we have to compare these transitions to the frequency range covered by the Atacama Large Millimeter/submillimeter Array (ALMA), currently the most sensitive interferometric facility at millimeter and submillimeter wavelengths, which operates approximately between 35 and 950 GHz (Bands 1–10, see section 3.1 and table 3.1).

Since the observed frequency is related to the emitted one through $\nu_{\text{obs}} = \frac{\nu_{\text{em}}}{1+z}$, the CO rotational lines are progressively shifted to lower frequencies with increasing redshift. As a consequence, the CO($1 \rightarrow 0$) transition moves out of the ALMA frequency range already at $z \gtrsim 3.3$, while the CO($2 \rightarrow 1$) transition becomes inaccessible for $z \gtrsim 5.6$. Thus, at higher redshift, observations rely on either higher- J CO transitions, which remain within ALMA bands or on alternative tracers. Among these, the [CII] $158\mu\text{m}$ fine-structure line is particularly important.

[CII] emission line

The [CII] line is one of the major coolant of cold ($T \leq 300\text{K}$) gas; it is a fine structure line at $157.74\mu\text{m}$ (1900.5GHz) that arises from the transition between $^2P_{\frac{3}{2}}$ and $^2P_{\frac{1}{2}}$ levels of single ionized carbon (C^+) and it is one of the brightest emission line in star-forming galaxies. As mentioned also in section 1.3.1, since the ionization potential of Carbon is lower than that of Hydrogen (11.3 eV vs 13.6 eV), C^+ can exist in a range of ISM phases, including cold neutral medium (CNM), diffuse ionized gas (HII regions) and Photo-Dissociation Regions (PDRs) - the interfaces between molecular clouds and HII regions, where UV photons from massive young stars or AGN ionize carbon but not hydrogen.

In the recent years [CII] emission line is becoming a workhorse line for the study of the cool atomic gas in distant galaxies (Carilli and Walter 2013). This is basically due to the fact that it traces both the cold neutral medium and ionized gas and its rest frequency emission of 1900.5GHz ($\lambda \sim 158\mu\text{m}$) lies in the detectable range of instruments like ALMA (see section 3.1) for high redshift observations: the [CII] transition at $\nu_{\text{em}} = 1900.5\text{GHz}$ can be detected by ALMA (theoretically) up to $z \gtrsim 20$. In normal Star Forming Galaxies more than 60 – 90% of the total [CII] luminosity arises from these photo-dissociation regions, so most of this luminosity emerges from the molecular phase: and in fact the [CII] line luminosity has been

calibrated and used to estimate the total molecular gas mass (Carilli and Walter 2013; Zanella et al. 2018), by defining a conversion factor $\alpha_{[\text{CII}]} = M_{\text{gas}}/L_{[\text{CII}]}$ between [CII] luminosity $L_{[\text{CII}]}$ and gas mass M_{gas} (see also section 2.4).

1.4 The bridge: the ISM Column Density

As presented in section 1.2.6 the key physical quantity linking the obscuring material to AGN obscuration is the *column density*, which, in the context of obscuration, refers to the *hydrogen column density* N_{H} , for which we recall the definition:

$$N_{\text{H}} = \int n_{\text{H}} dl$$

Hydrogen is the natural reference species because it is the most abundant element in the Universe ($\sim 75\%$ of the baryonic mass) and, as described in the previous sections, it defines the physical phases and composition of the ISM itself, each associated with its own observational tracers (see section 1.3).

The quantity N_{H} includes all hydrogen phases:

$$N_{\text{H}} = N_{\text{HI}} + 2N_{\text{H}_2} + N_{\text{HII}} \quad (1.38)$$

where the factor of 2 in front of N_{H_2} accounts for the two hydrogen atoms per molecule (Wolfire, Vallini, and Chevance 2022). In the massive, high-redshift galaxies considered in this work, the gas is predominantly molecular (Carilli and Walter 2013; D’Amato et al. 2020; Salvestrini et al. 2025; Vallini et al. 2025) so that N_{H} is effectively dominated by the molecular component.

Moreover, when characterizing the obscuration toward an AGN, it is useful to decompose the total column density into its physical contributions:

$$N_{\text{H,tot}} = N_{\text{H,torus}} + N_{\text{H,ISM}} + N_{\text{H,other}} \quad (1.39)$$

Since the ensemble of gas and dust constitutes the obscuring medium — affecting observations both in the X-rays and in the sub-mm, as described in section 1.2.6 — N_{H} is measurable both from X-ray spectroscopy of the AGN and from millimeter observations of the host galaxy ISM. Anyway a clarification must be done: since the X-rays emission comes directly from the AGN, the measured column density in this case is the total one ($N_{\text{H,tot}}$). On the other hand the sub-mm radiation is sourced by the medium on galactic scales, thus the measured column density is the one referred to the ISM itself ($N_{\text{H,ISM}}$). The scope of this work is to quantify the obscuration due to the ISM on galactic scales, thus evaluating $N_{\text{H,ISM}}$; we refer to section 1.5 for a more detailed discussion of the torus contribution. To evaluate $N_{\text{H,ISM}}$ we rely on a recent work by Gilli et al. 2022, in which it has been established that under the approximation of randomly oriented exponential disk, the mean column density toward the nucleus is on average approximately twice the mean gas surface density Σ_{gas} :

$$\boxed{N_{\text{H,ISM}} \approx 2.1 \Sigma_{\text{gas}}} \quad (1.40)$$

We treat in details this derivation in section 2.1 and give in fig. 1.12 a qualitative representation of nuclear obscuration provided by the host galaxy.

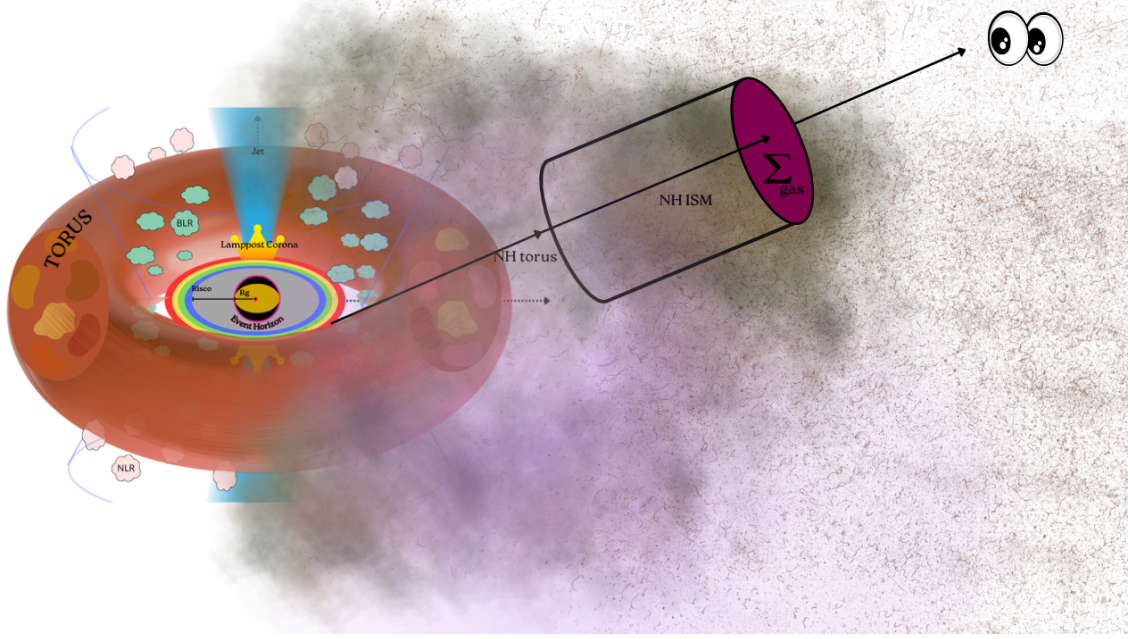


Figure 1.12: *Qualitative representation of AGN obscuration and column density N_H . Moving outward from the central engine, not only the torus but also the host galaxy can contribute to the obscuration of the nucleus. N_H is the integral of the hydrogen number density n_H [cm^{-3}] along the line of sight, while Σ_{gas} is a surface density — the connection between the two will be discussed in section 2.1.*

1.5 State of the art and aim of the thesis

In recent years several observational and theoretical studies have investigated the origin of AGN obscuration and, in particular, the possible contribution of the host galaxy. X-ray observations have revealed that the incidence of obscuration in AGNs increases significantly with redshift (La Franca et al. 2005; Treister and Urry 2006; Vito et al. 2018; Peca et al. 2023). This trend is especially pronounced for the most luminous systems. The fraction of quasars (QSOs) with bolometric luminosities $L_{\text{bol}} \gtrsim 10^{45} \text{ erg s}^{-1}$ obscured by hydrogen column densities $N_H > 10^{23} \text{ cm}^{-2}$ increases from ~ 10 –20% in the local Universe up to $\sim 80\%$ at $z \sim 4$, when the Universe was only ~ 1.5 Gyr old (Vito et al. 2018).

These percentages vary with luminosity, but the trend is clear: the fraction of obscured AGNs increases with redshift, as shown in fig. 1.13.

Figure 1.13 also shows that, at fixed redshift, the obscured fraction decreases with increasing luminosity. A separate study by Trefoloni et al. 2025 investigated instead how the torus covering factor – i.e. the fraction of the solid angle around the nucleus subtended by the circumnuclear obscuring material – correlates with luminosity and redshift. As shown in fig. 1.14, the covering factor anticorrelates with bolometric luminosity at fixed redshift (right panel): this is in agreement with a receding torus scenario, in which radiation pressure from more luminous AGNs reduces the torus covering factor. However, the covering factor shows no significant evolution with redshift at fixed luminosity (left panel). Thus the obscured fraction of AGNs increases with redshift but the torus alone cannot account for this evolution:

an additional contribution to obscuration must therefore arise from the host galaxy.

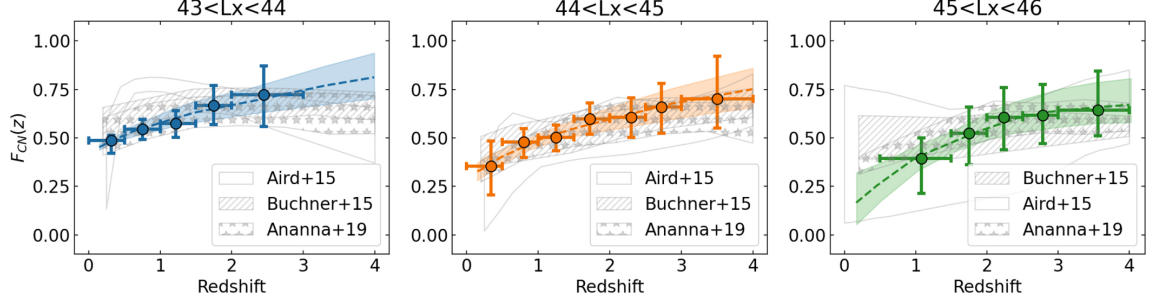


Figure 1.13: *Redshift evolution of the Compton-thin obscured AGN fraction* ($22 \leq \log N_{\text{H}}/\text{cm}^{-2} < 24$), for three X-ray luminosity bins: $43 < \log L_{\text{X}}/\text{erg s}^{-1} < 44$ (left), $44 < \log L_{\text{X}}/\text{erg s}^{-1} < 45$ (middle), and $45 < \log L_{\text{X}}/\text{erg s}^{-1} < 46$ (right), from Peca et al. 2023. Data points are compared to different models (gray regions). The obscured fraction increases with redshift at all luminosities, and decreases with increasing luminosity at fixed redshift.

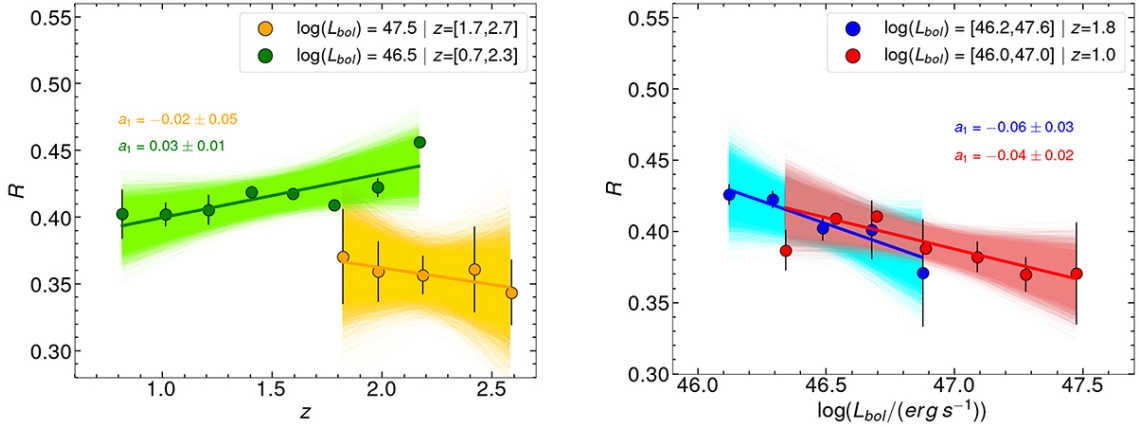


Figure 1.14: *Torus covering factor R as a function of redshift (left panel) and bolometric luminosity (right panel)*, from (Trefoloni et al. 2025). In the left panel, data points at different luminosities (color-coded) show that R is higher at lower luminosities, but no significant evolution with redshift is observed within each luminosity bin. In the right panel, the anticorrelation between R and L_{bol} is clearly detected, and the different redshift bins (color-coded) show consistent slopes and normalizations, confirming the absence of redshift evolution at fixed luminosity.

It makes physical sense if we think at the empirical trend presented in section 1.1: galaxies are more compact at higher redshifts, with sizes scaling as $r \propto (1+z)^{-1}$, and more gas-rich, with gas masses scaling as $M_{\text{gas}} \propto (1+z)^2$. Naively, given these empirical scaling relations and since $N_{\text{H,ISM}} \propto M_{\text{gas}}/r^2$ (eqs. (2.5) and (2.16)), one expects that ISM column density will grow with redshift as $(1+z)^4$. This was investigated quantitatively by Gilli et al. 2022, who combined ALMA observations of massive galaxies (samples of star-forming galaxies and quasar host galaxies with $M_{\star} > 10^{10} M_{\odot}$) across the redshift range $z \sim 0-6$ to investigate the cosmic evolution of the ISM column density and its impact on AGN obscuration. Using dust continuum

and [CII] emission as tracers of the total ISM mass, together with galaxy size measurements, they estimated the average ISM column density toward galaxy centers.

That work confirmed the picture outlined above, of an increase of the ISM column density with redshift up to $z \sim 6$, with a best-fit trend of $N_{\text{H,ISM}} \propto (1+z)^{3.3}$, as shown in fig. 1.15. Moreover Gilli et al. 2022 found that at $z \gtrsim 2$ the ISM column density inferred from ALMA observations becomes comparable to the column densities commonly measured in AGNs X-ray spectra. The average value of $N_{\text{H,ISM}}$ rises from $\langle \log N_{\text{H,ISM}} \rangle \sim 22 \text{ cm}^{-2}$ at $z \sim 0$ to values comparable to those typically measured through X-ray spectroscopy of AGN ($\langle \log N_{\text{H,X}} \rangle \sim 23\text{--}23.5 \text{ cm}^{-2}$) already at $z \gtrsim 1.5\text{--}2$. This result is consistent with the absence of strong redshift evolution in the torus covering factor of Trefoloni et al. 2025, and implies that the ISM of the host galaxy itself becomes a significant — and potentially dominant — contributor to the nuclear obscuration at high redshift (Circosta et al. 2019; D’Amato et al. 2020; Gilli et al. 2022). At $z \gtrsim 6$, the ISM alone may be sufficient to obscure the nucleus up to the Compton-thick regime ($N_{\text{H,ISM}} \gtrsim 10^{24} \text{ cm}^{-2}$).

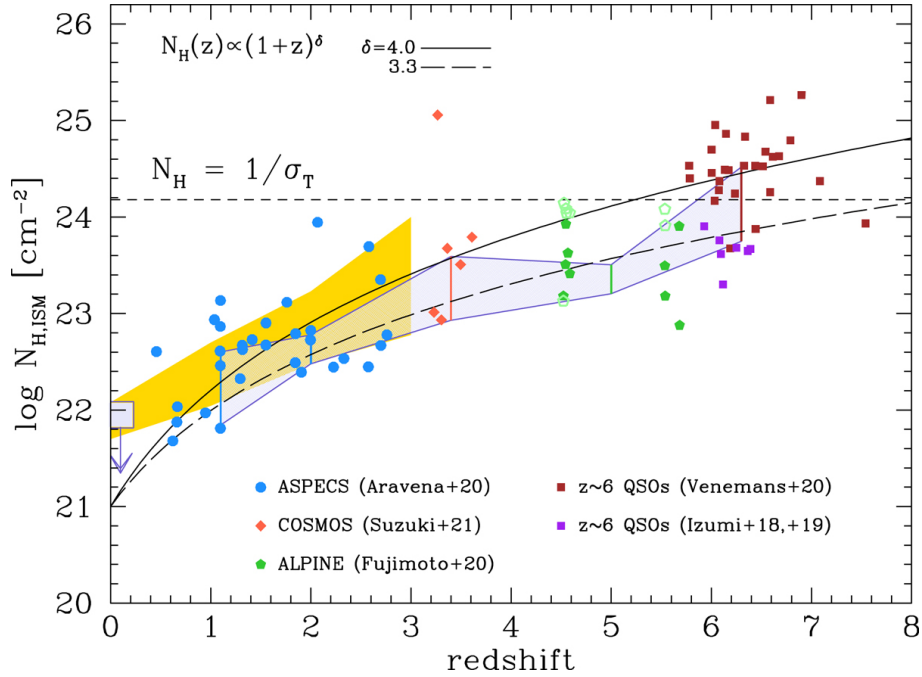


Figure 1.15: *ISM column density $N_{\text{H,ISM}}$ as a function of redshift for samples of star-forming galaxies and quasar host galaxies, from (Gilli et al. 2022). The best-fit trend $N_{\text{H,ISM}} \propto (1+z)^{3.3}$ confirms that the host galaxy ISM provides a contribution to nuclear obscuration at high redshift. The horizontal dashed line marks the Compton-thick threshold, $N_{\text{H}} = 1/\sigma_{\text{T}} \simeq 1.5 \times 10^{24} \text{ cm}^{-2}$, above which the nucleus becomes optically thick to Compton scattering.*

This is where the present work begins: the aim of this thesis is to evaluate the level of nuclear obscuration by extending current predictions to cosmic epochs not yet probed at $z > 6$, providing the first estimate of the column density at $z \sim 7$ and, for selected samples, extending the analysis to the range $z \sim 6\text{--}9$. To this end, three

methods for estimating the column density have been investigated, refining those already employed in the literature and, in part, proposing new approaches.

The thesis is from now on structured as follows:

- Chapter 2 describes the methods used to derive an estimate of the gas surface density and, consequently, of the column density;
- Chapter 3 presents the samples investigated, with particular attention to the sample at the core of this study, at redshift ~ 7 ;
- Chapter 4 presents and discusses the results obtained, providing for the first time an estimate of the column density at redshift ~ 7 and beyond;
- Chapter 5 summarises the work presented in this thesis, draws conclusions arising from it, and discusses their implications for possible future work.

Chapter 2

Methodology

As seen in the introduction (section 1.4), the key parameter that express the nuclear obscuration is the column density, which is in turn related to the gas surface density.

In this work, the gas surface density Σ_{gas} is derived by following three different approaches, depending on the available observables:

1. $\Sigma_{\text{gas},\text{cont}}$ is estimated from the dust continuum emission: we will refer to this approach as *Method 1*;
2. $\Sigma_{\text{gas},[\text{CII}]}$ is estimated from the luminosity of the [CII] emission line: we will refer to this approach as *Method 2*;
3. $\Sigma_{\text{gas},\text{SFR}}$ is derived by inverting a modified Schmidt–Kennicutt relation that is redshift dependent, using the star formation rate as a tracer: we will refer to this approach as *Method 3*.

The first two approaches derive Σ_{gas} directly from its definition, as the ratio of the enclosed gas mass to the emitting area (eq. (2.5)). In both cases, the source size is represented by the circularized effective radius of the respective tracer — dust continuum or [CII] emission — while the gas mass is estimated differently: from continuum observations via an assumed dust-to-gas ratio, from [CII] emission line by assuming a conversion factor. The assumptions and definitions adopted for both the source size and the gas mass are presented in the following sections.

The third approach does not rely on a direct measurement of the gas mass. Instead, Σ_{gas} is inferred by inverting a redshift-dependent Schmidt–Kennicutt-like relation, which requires an estimate of the star formation rate surface density. The source size in this case is defined through the Sérsic radius.

These methods will be applied to the samples presented in chapter 3 to derive their gas column density and will be discussed better in the next sections.

This chapter is structured as follow: in section 2.1 we present the derivation of the relation between N_{H} and Σ_{gas} at the core of this study; section 2.2 presents how the source area is evaluated, with particular attention to beam deconvolution and to a comparison between the sizes associated with different tracers; section 2.3 and section 2.4 present how the gas mass is evaluated starting from the dust continuum emission and from the [CII] emission line, respectively; finally, section 2.5 introduces the star formation rate and discusses how to derive the gas surface density from the star formation rate surface density of galaxies at different redshifts.

2.1 ISM column density: N_{H}

In the following sections we derive $N_{\text{H,ISM}}$ — hereafter simply N_{H} — the parameter quantifying the obscuration toward the nucleus due to the interstellar medium of the host galaxy. The procedure follows that adopted by Gilli et al. 2022, with the intermediate mathematical steps made explicit for clarity.

The geometry assumed throughout this derivation is illustrated in fig. 2.1, which shows an edge-on view of the disk galaxy model adopted in that work. Figure 1.12 shows instead a qualitative representation of obscuration (see also fig. 1.8 for comparison).

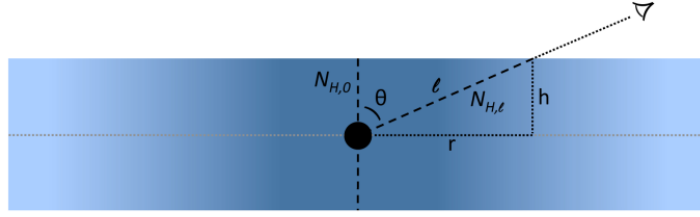


Figure 2.1: *Edge-on sketch of the adopted disk galaxy geometry, from (Gilli et al. 2022). The darker shading reflects the higher ISM density of the assumed exponential profile.*

2.1.1 Exponential disk model

We consider galaxies as disks where both the light surface brightness and the gas density profiles decline exponentially along the radial direction, corresponding to a Sérsic index $n=1$ (see section 2.5.2 for a detailed presentation of the *Sérsic profile*). The surface brightness follows an exponential profile:

$$I(r) = I_0 e^{-r/r_0} \quad (2.1)$$

where I_0 is the central surface brightness and r_0 is the *scale radius*, i.e. the distance over which the brightness decreases by a factor of $1/e$.

Defining the *effective radius* r_e as the radius enclosing half of the total luminosity, is possible to write:

$$\int_0^\infty I(r) 2\pi r dr = 2 \int_0^{r_e} I(r) 2\pi r dr \quad (2.2)$$

Solving both integrals by parts ¹ yields a transcendental equation whose numerical solution gives:

$$r_e = 1.678 r_0 \quad (2.3)$$

The exponential profile can therefore be rewritten in terms of r_e :

$$I(r) = I(r_e) e^{-(r-r_e)/r_0} \quad (2.4)$$

¹ $\int e^{-r/r_0} r dr = -r_0 r e^{-r/r_0} - \int e^{-r/r_0} = \dots = [-r_0 e^{-r/r_0} (r + r_0)]$

2.1.2 Gas surface density

The mean gas surface density within a specific radius is the ratio between the gas mass enclosed in that radius and the area defined by that radius. Considering as the radius the *effective radius* r_e , and a circular area, the mean surface gas density can be written as:

$$\Sigma_{\text{gas}} = \frac{M_{\text{gas}}/2}{\pi r_e^2} \quad (2.5)$$

This is also the quantity that can be estimated observationally, once the total gas mass and the effective radius of the galaxy are known from millimeter/optical observations ². Mathematically it is possible to write $M_{\text{gas}} = 2\pi r_e^2 \Sigma_{\text{gas}}$.

By considering fig. 2.1, working in cylindrical coordinates and assuming no density gradient along the vertical axis z , the gas surface density is obtained by integrating the volume density over the full disk thickness $2h$ ³:

$$\Sigma_{\text{gas}}(r) = \int_0^{2h} \rho(r, z) dz = 2h\rho_0 e^{-r/r_0} = \Sigma_{\text{gas},0} e^{-r/r_0} \quad (2.6)$$

where $\Sigma_{\text{gas},0} = 2h\rho_0$ is the central surface density. The gas surface density follows the same exponential profile as the luminosity, and can equally be written as:

$$\Sigma_{\text{gas}}(r) = \Sigma_{\text{gas}}(r_e) e^{-(r-r_e)/r_0} \quad (2.7)$$

In particular, assuming a disk geometry, the total gas mass can be obtained by summing the contributions from all concentric annuli, from the centre ($r = 0$) to infinity. Mathematically, it can be obtained by integrating the surface density over all disk annuli:

$$M_{\text{gas}} = \int_0^\infty \Sigma_{\text{gas}}(r) 2\pi r dr = 2\pi \Sigma_{\text{gas},0} \int_0^\infty r e^{-r/r_0} dr = 2\pi \Sigma_{\text{gas},0} r_0^2 \quad (2.8)$$

where the last step uses the result $\int_0^\infty r e^{-r/r_0} dr = r_0^2$, obtained by integration by parts. Equating the two expressions for M_{gas} :

$$2\pi r_e^2 \Sigma_{\text{gas}} = M_{\text{gas}} = 2\pi \Sigma_{\text{gas},0} r_0^2 \quad (2.9)$$

it is possible to obtain the relation between the central and mean surface densities:

$$\Sigma_{\text{gas},0} = \left(\frac{r_e}{r_0}\right)^2 \Sigma_{\text{gas}} \approx 2.8 \Sigma_{\text{gas}} \quad (2.10)$$

where it has been used $r_e/r_0 = 1.678$.

Column density toward the nucleus: face-on view and generic orientation

For a galaxy viewed *face-on* ($\theta = 0^\circ$), the column density toward the nucleus equals half the central surface density. Indeed, $\Sigma_{\text{gas},0}$ accounts for all gas above and below

²An alternative observational route is provided by the Schmidt–Kennicutt relation, discussed below.

³Surface density = mass/area = volume density $\times$ height

the galactic plane, whereas photons emitted by the nucleus — located at the disk midplane — traverse only the upper half of the disk before reaching the observer:

$$N_{\text{H},0} = \frac{\Sigma_{\text{gas},0}}{2} \approx 1.4 \Sigma_{\text{gas}} \quad (2.11)$$

This provides an expression for the central column density $N_{\text{H},0}$, and will be used to derive the column density for a generic orientation.

For a generic orientation angle θ between the disk axis and the line of sight, the column density is obtained by integrating the volume density along the optical path ℓ . From the disk geometry (fig. 2.1), the radial coordinate r and the path element are related to θ by:

$$r = z \tan \theta \quad \Rightarrow \quad d\ell = \frac{dr}{\sin \theta} \quad (2.12)$$

The upper integration limit corresponds to the disk surface at $z = h$. Since the density depends only on r , $\rho(r) = \rho_0 e^{-r/r_0}$, the integral becomes:

$$N_{\text{H},\ell} = \int_0^\ell \rho(r, z) d\ell = \int_0^{h \tan \theta} \rho_0 e^{-r/r_0} \frac{dr}{\sin \theta} = \frac{\rho_0}{\sin \theta} \int_0^{h \tan \theta} e^{-r/r_0} dr \quad (2.13)$$

Solving the integral:

$$N_{\text{H},\ell} = \frac{r_0 \rho_0}{\sin \theta} \left[1 - e^{-\frac{h}{r_0} \tan \theta} \right] \quad (2.14)$$

This expression ranges from $h\rho_0$ in the face-on limit ($\theta = 0^\circ$) to $r_0\rho_0$ in the edge-on limit ($\theta = 90^\circ$).

Average column density

For randomly oriented disks, the mean viewing angle is $\langle \theta \rangle = 1 \text{ rad} \approx 57.3^\circ$. Substituting $\theta = 57.3^\circ$ and assuming a characteristic half-scale height $h = 0.15 r_e$ (Elmegreen and Elmegreen 2006; Bouché et al. 2015) into eq. (2.14), one obtains:

$$N_{\text{H}} \approx 0.39 r_0 \rho_0 \quad (2.15)$$

Using $\Sigma_{\text{gas},0} = 2h\rho_0$ (see eq. (2.6)), it is possible to express the N_{H} as function of $\Sigma_{\text{gas},0}$, and consequently, considering $h = 0.15 \cdot 1.678 r_0$, is possible to derive:

$$\boxed{N_{\text{H,ISM}} \approx 1.5 N_{\text{H},0} \approx 2.1 \Sigma_{\text{gas}}} \quad (2.16)$$

Finally the ISM column density towards the nucleus is proportional to the average gas surface density. Thus, to evaluate the column density is sufficient to estimate the gas surface density.

2.2 Source Area

The discussion on the source size is presented first, as it constitutes a common ingredient to all three methods adopted to derive Σ_{gas} .

The source area is commonly assumed to be circular ⁴, and it is therefore defined as:

$$A = \pi R^2 \quad (2.17)$$

where R is assumed to be the effective radius of the source, i.e. the radius enclosing half of the total flux (or mass) of the system. This area enters into the calculation of several physical parameters and must be carefully interpreted as referring to the region containing half of the total emission ⁵.

2.2.1 Effective radius

In this work three different effective radii will be considered:

- R_{cont} : the effective radius associated with the dust continuum emission, tracing the spatial extent of the dust-emitting region;
- $R_{\text{[CII]}}$: the effective radius associated with the [C II] 158 μm line emission, tracing the cold gas reservoir and the partially ionized medium;
- $R_{\text{Sérsic}}$: the effective radius derived from a Sérsic profile fit to the rest-frame UV/optical stellar continuum and associated to the star forming region.

In order to estimate the sizes from observations, it is necessary to recall some basic relations between the distance of the object and its angular size on the sky.

Once the redshift of an object is known and a cosmological model is assumed (ΛCDM), its distance is determined by the cosmological relations. In particular, the angular diameter distance D_A (related to the luminosity distance D_L ⁶) is defined as the ratio between the true transverse size of an object ($\text{size}[kpc]$) and its apparent angular size in the sky ($\theta_{\text{rad}}[\text{radians}]$)

$$D_A = \frac{\text{size}}{\theta} \quad (2.18)$$

For practical purposes, D_A can be computed using tools such as Python (`astropy`, Astropy Collaboration et al. 2022) or Cosmo Calculator (Wright 2006), which implement the standard cosmological relations given a set of cosmological parameters (the ones reported in section 1.1). Once D_A is known, the physical size of a source can be derived directly from its observed angular size $\theta_{\text{arcsec}}[\text{arcsec}]$. Therefore, the physical size of the source can be derived as:

$$\text{size} = \theta_{\text{arcsec}} \cdot \frac{\pi}{180 \times 3600} \cdot D_A \quad (2.19)$$

⁴This assumption is widely adopted in the literature, especially for samples of high-redshift galaxies (Gilli et al. 2022), and is justified by the fact that the derived surface densities are relatively insensitive to moderate deviations from circular symmetry.

⁵For example, in the dust mass calculation through eq. (2.24), only half of the observed flux $S_{\nu_{\text{obs}}}$ must be considered; since R is defined as the effective radius, the total dust mass of the system is therefore $M_{\text{dust,tot}} = 2 M_{\text{dust}}(R_{\text{eff}})$.

⁶ $D_L = (1 + z)^2 D_A$

where the term $\frac{\pi}{180 \times 3600}$ converts the angular size from arcseconds into radians.

However, this simple relation does not immediately provide the intrinsic size of the object. Indeed, when observing the sky with a telescope, and especially with an interferometer such as ALMA, what is measured is not the intrinsic brightness distribution of the source, but rather the convolution of the source emission with the instrumental response, i.e. the beam. At high redshift, the effect of the beam becomes increasingly important, and must be carefully removed by deconvolution.

Deconvolution is typically performed by dedicated software, but the deconvolved sizes are not always reported in the literature. In those cases, by considering that the beam and the observed emission are usually approximated with Gaussian profiles, characterized by their Full Width at Half Maximum (FWHM) and since the convolution of two Gaussians is still a Gaussian, it is possible to derive an approximate deconvolved size as:

$$FWHM_{Dec} = \sqrt{FWHM_{Obs}^2 - FWHM_{Beam}^2} \quad (2.20)$$

Once the deconvolved FWHM values along the major and minor axes are obtained, it is convenient to define a single circularized FWHM as their geometric mean:

$$FWHM_{circ} = \sqrt{FWHM_{maj} \times FWHM_{min}} \quad (2.21)$$

Since the $FWHM_{maj}$ and $FWHM_{min}$ represent the angular dimensions of the Gaussian fit along the major and minor axes, $FWHM_{circ}$ represent a diameter and the corresponding radius is obtained by dividing by two; expressing the circularized physical radius in terms of the observed FWHM values (given in arcseconds):

$$R = \frac{1}{2} \sqrt{FWHM_{maj} \times FWHM_{min}} \cdot \frac{\pi}{180 \times 3600} \cdot D_A \quad (2.22)$$

This circularized radius represents the effective radius, that by definition corresponds to the radius that encloses half of the total mass (or luminosity) of the system⁷.

These conversions can, in principle, be applied to each of the three size definitions considered in this work. A first important consideration regarding [Method 1](#) and [Method 2](#) concerns the extent of the dust continuum and [CII] emission and it is presented in the next section. The Sérsic radius, used for [Method 3](#), is discussed separately in section 2.5.2.

2.2.2 R_{cont} and $R_{[CII]}$

With R_{cont} and $R_{[CII]}$ we refer to the effective circularized radii of the dust continuum and [CII] emission, respectively, derived from data available in literature.

Figure 2.2 shows the continuum and [CII] emission map of a representative source from the high- z QSO sample of Wang et al. 2024 (see section 3.8 for details on the sample). The yellow ellipse in the bottom-left corner of the panel represents the synthesized beam, i.e. the effective angular resolution of the interferometric

⁷For a 2D Gaussian intensity profile $I(r) \propto e^{-r^2/2\sigma^2}$, integrating the flux shows that the radius enclosing 50% of the total volume of the distribution is $\sigma\sqrt{2\ln 2}$, which equals exactly $FWHM/2$.

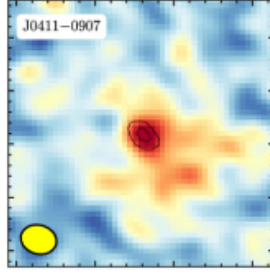


Figure 2.2: Continuum-subtracted [CII] and dust continuum map of a representative source from the $z \sim 7$ quasars sample of Wang et al. 2024. The panel is $5'' \times 5''$ wide, with north up and east to the left. The background color map shows the continuum-subtracted [CII] $158 \mu\text{m}$ line emission, while the solid black contours trace the dust continuum emission. The yellow ellipse in the bottom-left corner represents the synthesized beam of the ALMA observations.

observations. It reflects the response of the antenna array to a point source: any emission on angular scales smaller than the beam cannot be resolved. Since the beam is generally elliptical rather than circular — as clearly visible in the panel — the source size is not uniquely defined by a single axis, as previously described. For this reason, by adopting a circularized effective radius it is possible to establish a single representative measure of the source extent.

In fig. 2.2, the contours reveals that dust continuum emission is more compact than the [CII] emission, consistent with the different physical origins of the two tracers. From a physical point of view, $R_{\text{[CII]}}$ is expected to exceed R_{cont} , because the [CII] $158 \mu\text{m}$ line emission traces both the dense gas in star-forming regions and the more diffuse, extended component of the interstellar medium, whereas the dust continuum emission is more concentrated in the actively star-forming regions where the dust is heated most efficiently (Carilli and Walter 2013).

The sizes of the [CII] and continuum emission were compared for all the $z \sim 7$ sources of Wang et al. 2024: the trend for these sources at $z \sim 7$ is quantified in fig. 2.3, where the ratio between R_{cont} and $R_{\text{[CII]}}$ for the quasars in the sample is shown and on average R_{cont} is half of $R_{\text{[CII]}}$ and only two sources presents $R_{\text{cont}} > R_{\text{[CII]}}$ (see appendix A.1 for the continuum and [CII] emission maps of all sources in the sample).

We present here an important caveat about the choice of tracer used to define the continuum radius, that is well discussed in Gilli et al. 2022. Using the dust continuum emission as a proxy for the gas radius can lead to an underestimate of the true extent of the gas distribution, since dust-based sizes are systematically smaller than those obtained from other tracers. The stellar UV/optical size, for example, is found to be comparable to the size derived from CO emission — widely regarded as the best tracer of the cold molecular gas. For this reason, when a reliable continuum (dust) size is not available, we adopt the stellar size instead. In this case, however, the resulting column density should be regarded as a lower limit, since the dust-based radius tends to be smaller than (and thus would imply a higher column density than) the stellar-based one.

For quasars, the situation is different: because the nuclear emission outshines the

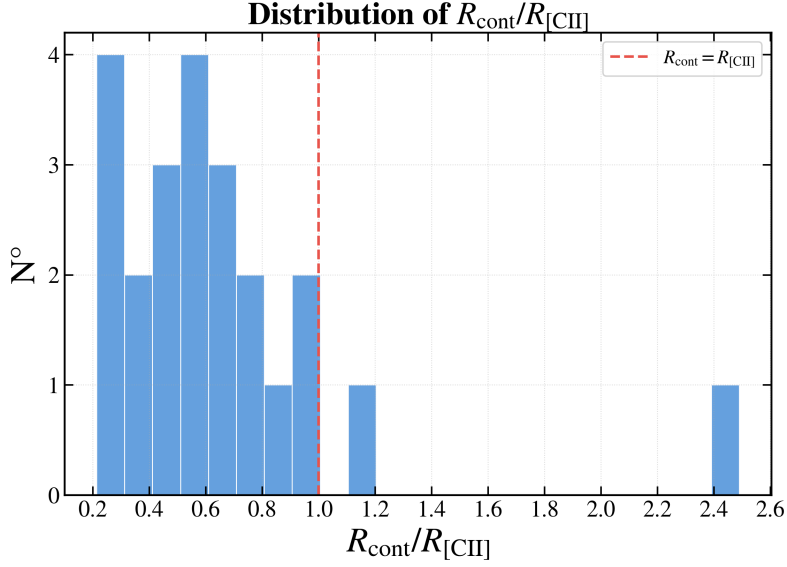


Figure 2.3: *Distribution of the ratio $R_{\text{cont}}/R_{[\text{CII}]}$ for the quasar sample of Wang et al. 2024. Values below unity indicate sources in which the $[\text{CII}]$ emission is more spatially extended than the dust continuum. The dashed red vertical line marks the 1:1 relation. The predominance of sources with $R_{\text{cont}}/R_{[\text{CII}]} < 1$ is consistent with the expectation that $[\text{CII}]$ traces a more diffuse gas component.*

host galaxy at UV/optical wavelengths, no reliable stellar-light size is available, and the dust continuum size is used instead.

2.3 Gas Mass: Dust

The second ingredient needed for the two first methods is the Gas Mass, which can be estimated both from dust continuum or line emission.

The gas to dust ratio

As for the continuum emission, it is possible to derive the gas mass from the dust mass, by adopting a gas to dust ratio, δ_{GDR} :

$$M_{\text{gas}} = \delta_{\text{GDR}} \cdot M_{\text{dust}} \quad (2.23)$$

For high redshift sources the gas to dust ratio chosen in this work is $\delta_{\text{GDR}} = 200$ (Aravena et al. 2020; Gilli et al. 2022).

Therefore, for *Method 1*, all is reduced to obtain a reliable estimate of the dust mass from thermal dust continuum emission. Below we discuss in greater details the methodology used, with particular emphasis on the differences between the optically thin and thick cases and their impact on the temperature and dust estimates.

2.3.1 Thermal continuum emission and dust mass

As seen in section 1.3.2 the radiation emitted by dust grains is well described by a modified black body spectrum; the observable flux produced by dust is described by eq. (1.37). From this equation it is possible to derive the dust mass by considering that the dust optical depth τ_ν is proportional to surface density $\Sigma_d = \rho_d s$, $\tau_\nu = \Sigma_d k_\nu(\beta)$ (see also eq. (1.23)); the surface density is in turn proportional to the dust mass (M_{dust}) and the source physical area A , $\Sigma_d = M_{\text{dust}}/A$ (Gilli et al. 2022). Thus, the dust mass can be expressed as:

$$M_{\text{dust}} = -\ln \left(1 - \frac{(1+z)^3 S_{\nu_{\text{obs}}}}{\Omega [B_\nu(T_d) - B_\nu(T_{\text{CMB}})]} \right) \frac{A}{k_\nu} \quad (2.24)$$

where B_ν is the black body function presented in eq. (1.27), evaluated at the dust temperature T_d and at the CMB temperature $T_{\text{CMB}} = 2.73(1+z)$ K respectively; z is the source redshift; $S_{\nu_{\text{obs}}}$ is the observed flux density, conventionally expressed in Jansky ($1 \text{ Jy} = 10^{-23} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$) and converted to CGS units before use; $A = \pi R_e^2$ is the physical area of the source, with the effective radius R_e conventionally measured in kpc and A consequently expressed in kpc^2 , converted to cm^2 ($1 \text{ kpc} = 3.086 \times 10^{21} \text{ cm}$) before use; $\Omega = A/D_A^2$ is the solid angle subtended by the source, obtained as the ratio between the physical area A and the square of the angular diameter distance D_A , and is therefore dimensionless; k_ν is the dust mass absorption coefficient (eq. (1.23)), expressed in $\text{cm}^2 \text{ g}^{-1}$. All quantities are converted to CGS units (erg, cm, g, s) prior to evaluating eq. (2.24), so that M_{dust} is obtained in grams and subsequently converted to solar masses.

It is important to note that at high redshift ($z > 4$), the Cosmic Microwave Background can significantly contribute to dust heating, simultaneously reducing the contrast between dust emission and the background. Therefore, dealing with sources at high redshift, we cannot ignore the Cosmic Microwave Background, whose temperature increases as $(1+z)$: indeed, dust masses would be underestimated if CMB heating is neglected.

This expression for the dust mass, eq. (2.24), requires that the argument of the natural logarithm must be positive, thus:

$$B_\nu(T_d) > \frac{(1+z)^3 S_{\nu_{\text{obs}}}}{\Omega} + B_\nu(T_{\text{CMB}}) \quad (2.25)$$

where $B_\nu(T) = \frac{2h\nu^3}{c^2} (e^{\frac{h\nu}{k_B T}} - 1)^{-1}$ is the Planck function, which quantifies the dependence of the black body emission on temperature; by solving for dust temperature T_d , it is possible to obtain a lower limit to the dust temperature (Gilli et al. 2022):

$$T_d > T_{\text{min}} \equiv \frac{h\nu}{k_B} \left[\ln \left(1 + \frac{2\Omega h\nu^3}{c^2 (S_{\nu_{\text{obs}}} (1+z)^3 + \Omega B_\nu(T_{\text{CMB}}))} \right) \right]^{-1} \quad (2.26)$$

Optical Depth and Dust Temperature: thick or thin?

An expression for the dust temperature can be obtained directly from eq. (1.37) by explicitly keeping the dependence on the optical depth:

$$T_d = \frac{h\nu}{k_B} \left[\ln \left(1 + \frac{2\Omega h\nu^3 (1 - e^{-\tau})}{c^2 (S_{\nu_{obs}} (1+z)^3 + \Omega B_\nu(T_{CMB}) (1 - e^{-\tau}))} \right) \right]^{-1} \quad (2.27)$$

This expression reduces to eq. (2.26) for $\tau_\nu \gg 1$. Physically, this reflects the fact that in the optically thick regime the observed emission originates primarily from the outer layer of the dust cloud: under this condition, for fixed observational parameters (frequency, size, redshift, nature fundamental constants), there exists a minimum temperature required for the emitted radiation to match the observed flux and the temperature is independent on optical depth. T_{min} is the minimum temperature allowed by a given observed flux and source size in the optically thick regime.

As the optical depth decreases ($\tau \ll 1$), for a fixed dust mass and source size, the emitted flux is suppressed (by a factor $(1 - e^{-\tau_\nu})$ in eq. (1.37)); therefore, a higher temperature is required to reproduce the same observed emission and in this approximation eq. (2.27) takes the form:

$$T_d = \frac{h\nu}{k_B} \left[\ln \left(1 + \frac{2\Omega h\nu^3 \cdot \tau}{c^2 (S_{\nu_{obs}} (1+z)^3 + \Omega B_\nu(T_{CMB}) \cdot \tau)} \right) \right]^{-1} \quad (2.28)$$

Moreover, as will be shown in the next sections, in this optically thin limit the dust mass expression in eq. (2.24) simplifies to the commonly used form:

$$M_{thin} = \frac{S_{\nu_{obs}} D_L^2}{(1+z) k_{\nu_{obs}}(\beta) [B_\nu(T_d) - B_\nu(T_{CMB})]} \quad (2.29)$$

where D_L is the luminosity distance, linked through $D_L = (1+z)^2 D_A$ to the angular diameter, which in turn is linked to the solid subtended by the source and angle and source area, $D_A^2 = A/\Omega$.

Source Area and Dust Mass: thin and thick regime.

The common assumption of an optically thin regime can lead to underestimate the dust mass, even if the source flux is measured at *mm* wavelengths, where the opacity is low (see eq. (1.34)). Indeed by comparing eq. (2.24) and eq. (2.29) it is possible to observe that in the optically thin limit the mass loses its explicit dependence on the source size: an extended and a compact source with the same observed flux and temperature would yield the same dust mass, which is physically unrealistic.

It is possible to quantify this effect analyzing eq. (2.24) from a mathematical point of view, focusing on the dependence of the dust mass on the emitting area (A) of a source with size R . By substituting the solid angle with $D_A^2 = A/\Omega$ in the equation and keeping all the other parameters fixed:

$$M_{dust} = -\frac{A}{k_\nu} \ln \left(1 - \frac{C}{A} \right) \quad (2.30)$$

where $C = \frac{(1+z)^3 S_{\nu_{obs}} D_A}{[B_{\nu}(T_d) - B_{\nu}(T_{CMB})]}$ is a constant that encloses observed flux, frequency, redshift and dust temperature, alias all the parameters that are taken constant in this discussion. Considering that $\ln(1+x) = x - \frac{x^2}{2} + \dots$ for $x \ll 1$, in the case of large emitting areas ($A \gg C$), :

$$M_{\text{dust}} \propto C + \frac{C^2}{2A} + \dots \propto C + \frac{C^2}{2R^2} + \dots \quad (2.31)$$

Therefore, in the limit of extended sources the dust mass approaches a constant value, recovering the optically thin approximation. In contrast, when the emitting regions become more compact ($A \rightarrow C$), the logarithm diverges and the inferred dust mass increases rapidly, reflecting the large optical depths required to reproduce a fixed observed flux from a smaller emitting area.

Physical interpretation

Since the optical depth is proportional to the dust surface density as $\tau_{\nu} = k_{\nu} \Sigma_d$ and $\Sigma_d = M_{\text{dust}}/A$, compact sources are more likely to be in the optically thick regime than extended sources. In the optically thick regime the observed emission originates from the outer layers of the dust distribution, and the dust temperature approaches its minimum value T_{min} derived in eq. (2.26): physically the system behave like a black body whose brightness is set by its surface temperature, rather than by the amount of dust. Conversely, in the optically thin regime all the dust along the line of sight contribute to the observed radiation, not only the dust in the outer layers. For a given flux, a more extended source therefore requires a higher dust temperature (or a larger dust mass) to compensate for the lower surface density (and smaller optical depth). These two regimes highlight a fundamental size-temperature-mass degeneracy.

2.3.2 Minimum Temperature assumption

It is important to note that an optically thick regime does not necessarily imply that the dust temperature is equal to the minimum value T_{min} . In general, optically thick sources can have any temperature. However, for a fixed observed flux and source size, the optically thick limit corresponds to the minimum temperature required to reproduce the observations and assuming a lower temperature would yield to unphysical parameters. Thus, in the computation of the dust mass, eq. (2.24) and eq. (2.29), the temperature entering the blackbody emission is assumed to be $T_{\text{dust}} = \bar{T}$ if $T_{\text{min}} < \bar{T}$ or $T = 1.2T_{\text{min}}$ if $T_{\text{min}} > \bar{T}$, where $\bar{T}$ is a commonly adopted value for the source that is being studied, for example for quasars or high- z galaxies: $\bar{T} = 47K$ (Venemans et al. 2020). This choice follows (Gilli et al. 2022).

The following table summarizes the main results of these considerations, together with the relevant equations. It should be interpreted as follows: eq. (2.24) holds in general, both in the optically thin and optically thick regime. It reduces to eq. (2.29) in the optically thin case, which is more likely to occur for extended sources, where the dust temperature is sufficiently far from its minimum value. Equation (2.24) must instead be used in its general form when the source is optically thick. In this more

extreme regime, the observed emission originates primarily from the outer layers of the source, and the dust temperature therefore tends to approach its minimum value — a condition more commonly found in compact sources.

Regime	τ	Dust Mass	Temperature	Size
Thin	$\ll 1$	M_{thin} (eq. (2.29))	T_{dust} (eq. (2.27)) $\gg T_{\text{min}}$ (eq. (2.26))	Extended
Thick	$\gg 1$	M_{dust} (eq. (2.24))	$T_{\text{dust}} \rightarrow T_{\text{min}}$ (eq. (2.26))	Compact

Table 2.1: *Summary of optically thin and thick regimes. In the thin regime the emission is "volumetric" and the temperature must increase to compensate for the low optical depth. In the thick regime the emission is "surface-dominated": T_{dust} has a lower bound T_{min} . In both regimes, T_{min} represents a lower bound set by the observed flux and size; actual dust temperatures may be higher depending on physical conditions.*

A concrete application of these considerations is presented in section 3.8, where a sample of quasars at $z \sim 7$ serves as a testbed for quantifying the degeneracies that arise when deriving dust masses from continuum observations alone. In particular is discussed the interconnection between the dust mass M_{dust} , the dust temperature T_{dust} , and the optical depth τ_ν , highlighting how an assumption on the optical thin regime can lead to biased — or even unphysical — dust mass estimates. Other considerations about the temperature assumption also find place in section 4.2.2, where it is highlighted how temperature affects the estimate of the column density.

2.4 Gas Mass: [CII]

2.4.1 [CII] Luminosity and conversion factor

As described in section 1.3.4, another important observable that we can use to infer the molecular gas mass is the intensity of [CII] emission line (Carilli and Walter 2013, Zanella et al. 2018). Once the luminosity of the emission line $L_{[\text{CII}]}$ is known, the gas mass M_{gas} can be derived by assuming an appropriate conversion factor $\alpha_{[\text{CII}]} [M_\odot/L_\odot]$:

$$M_{\text{gas}} = \alpha_{[\text{CII}]} \cdot L_{[\text{CII}]} \quad (2.32)$$

The line luminosity is obtained from the observed spectrum: a line profile (typically a Gaussian) is fitted to the spectrum, from which the integrated line flux $F \Delta v$ is measured, where F is the flux density and Δv the velocity width of the line. The luminosity is then computed following a standard relation; as an example, we report the one adopted by Wang et al. 2024:

$$\frac{L_{[\text{CII}]}}{L_\odot} = 1.04 \times 10^{-3} \left(\frac{F_{[\text{CII}]} \Delta v}{\text{Jy km s}^{-1}} \right) \left(\frac{\nu_{\text{obs}}}{\text{GHz}} \right) \left(\frac{D_L}{\text{Mpc}} \right)^2 \frac{1}{1+z}, \quad (2.33)$$

where $F_{[\text{CII}]} \Delta v$ is the total integrated [CII] line flux, ν_{obs} is the observed frequency of the line, and D_L is the luminosity distance. The line profile fitting, together with

the extraction of the flux, the velocity width Δv , and the observed frequency ν_{obs} , is typically carried out with dedicated software (e.g., the `imfit` task within `CASA`); the details of this procedure are beyond the scope of this work. A typical spectrum showing [CII] emission line from the sample of quasars of Wang et al. 2024 is reported in fig. 2.4.

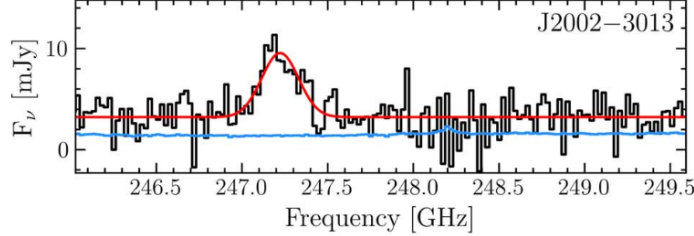


Figure 2.4: *Example of a spectrum used for the estimation of the [CII] luminosity in Wang et al. 2024, see section 3.8). The black histogram shows the observed spectrum, the red curve the best-fit Gaussian profile to the [CII] line, and the blue curve the noise. The y-axis shows the flux density F_ν , while the x-axis shows the observed frequency; the latter is directly related to the velocity through Doppler shift, $v = c(\nu_0 - \nu)/\nu_0$, where ν_0 is the frequency at line center.*

Before going into the details of the conversion factor, it is important to clarify that in this work M_{gas} refers to the *total* gas mass, including both molecular and atomic components: as discussed in section 1.3.4, [CII] is a multiphase tracer whose emission arises from both atomic and molecular gas components, with the majority of its emission expected to originate from photo-dissociation regions associated with molecular clouds. Studies of high-redshift galaxies and quasars by D’Amato et al. 2020 and Wang et al. 2024 show that the molecular component typically accounts for approximately 75 – 80% of the total gas mass.

Motivated by these results, and by the discussion presented in the previous sections, the [CII]-based conversion factor can then be used as a good proxy for the total gas mass of the sources. Further support for this assumption is provided by the models presented in Vallini et al. 2025, which combine spatially resolved simulations with PDR models. In-person discussions with *L. Vallini* helped to further clarify and validate the interpretation that gas associated with molecular regions is the main actor in powering the observed [CII] emission.

Their study moreover predicts that the conversion factor decreases with increasing compactness: physically, this anticorrelation is coherent with the fact that more compact sources have denser ISM regions subjected to more extreme conditions, producing stronger [CII] emission per unit gas mass.

Although [CII] as a gas mass tracer has limitations -dependence on metallicity, dust temperature, radiation field intensity, and its multiphase origin- in this work the relation derived in Vallini et al. 2025 has been adopted, emphasizing that for high-redshift sources the main factor affecting $\alpha_{[\text{CII}]}$ is source compactness, with smaller and denser systems having lower conversion factors.

The relation derived by Vallini et al. 2025 is:

$$\log(\alpha_{[\text{CII}]} / \text{M}_\odot \text{L}_\odot^{-1}) = 0.69 \cdot \log(R_{[\text{CII}]} / \text{kpc}) + 1.17 \quad (2.34)$$

where $R_{[\text{CII}]}$ is the half light radius associated to the $[\text{CII}]$ emission line. The trend for the samples in their work is shown in fig. 2.5.

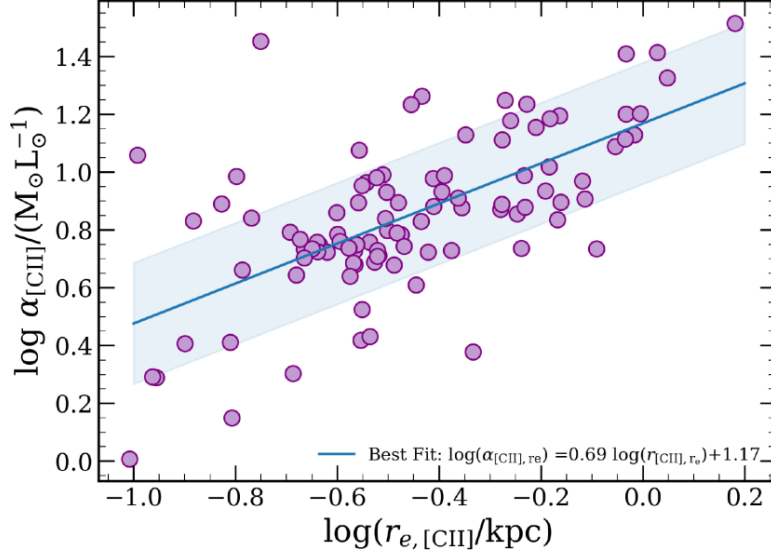


Figure 2.5: Conversion factor ($\alpha_{[\text{CII}]}$) as a function of the $[\text{CII}]$ emission half light radius ($r_{e,[\text{CII}]}$) for the sample considered in (Vallini et al. 2025).

In this work, whenever the gas mass has been derived from $[\text{CII}]$ emission line, this relation has been adopted. It is worth comparing eq. (2.34) with the empirical calibration of Zanella et al. 2018, who studied the $[\text{CII}]$ -to-gas conversion factor in a sample of main-sequence galaxies at $z \sim 2$ with typical sizes $r_e \sim 4\text{--}7$ kpc, finding $\alpha_{[\text{CII}]} \simeq 31 \text{ M}_\odot \text{ L}_\odot^{-1}$ with a dispersion of ~ 0.2 dex. Crucially, Zanella et al. 2018 find this value to be largely independent on redshift, metallicity, and distance from the main sequence, treating it as a universal conversion factor by combining galaxies from different samples without explicitly accounting for their sizes.

The Vallini et al. 2025 models instead show that $\alpha_{[\text{CII}]}$ increases with increasing galaxy size eq. (2.34). Evaluating this relation at the typical size of the Zanella et al. 2018 sample ($r_e \sim 5$ kpc) yields $\alpha_{[\text{CII}]} \approx 45 \text{ M}_\odot \text{ L}_\odot^{-1}$, consistent with the Zanella et al. value of $\alpha_{[\text{CII}]} \approx 31 \text{ M}_\odot \text{ L}_\odot^{-1}$ within the intrinsic dispersion of ~ 0.2 dex ($\sim 1\sigma$). The two calibrations are therefore compatible in the regime of extended, $z \sim 2$ main-sequence galaxies, with the Vallini et al. 2025 relation providing a physically motivated generalization that naturally accounts for the size evolution of galaxies across cosmic time.

This behaviour will be further discussed in connection with the redshift evolution of Σ_{gas} in the following section.

2.5 Gas Surface Density from SFR

Differently from the two first method, which require establishing how to derive the gas mass and its associated emitting region in order to compute the surface gas density "directly" from eq. (2.5) (where the size r_e can be either $R_{[\text{CII}]}$ or R_{cont}), the third method relies on the Schmidt-Kennicutt relation (Kennicutt 1998, fig. 2.6).

This fundamental relation links the Star Formation Rate density Σ_{SFR} to the (total) gas density Σ_{gas} :

$$\Sigma_{SFR} = 2.5 \times 10^{-4} \left(\frac{\Sigma_{gas}}{1 M_{\odot} \text{ pc}^{-2}} \right)^{1.4} M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2} \quad (2.35)$$

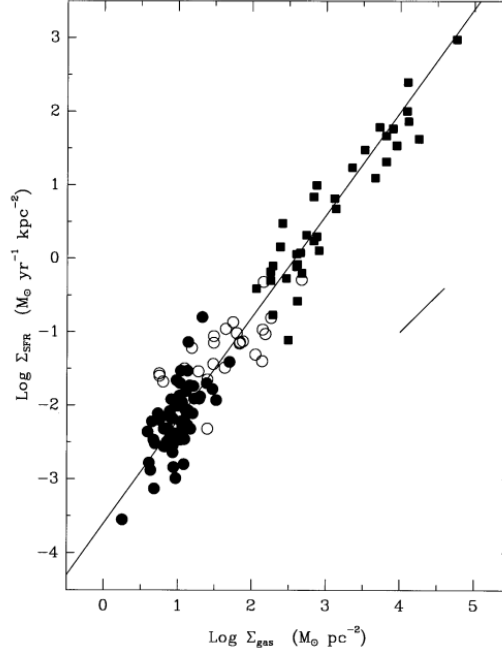


Figure 2.6: *The classical Kennicutt–Schmidt star formation law, from Kennicutt 1998. Filled circles show disk-averaged surface densities for normal spiral galaxies, open circles show the corresponding central values, and filled squares represent circumnuclear starburst galaxies. The solid line is the best-fit power law, $\Sigma_{SFR} \propto \Sigma_{gas}^N$, with $N = 1.40$. The short, diagonal line shows the effect of changing the scaling radius by a factor of 2 (see Kennicutt 1998 for details). Note that Σ_{gas} is expressed in $M_{\odot} \text{ pc}^{-2}$ while Σ_{SFR} is expressed in $M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, following the original convention.*

Before discussing the redshift evolution of this relation, it is important to recall that Σ_{SFR} is given by the ratio between the Star Formation Rate, SFR, and the area of the region associated with the emission (πR^2), whose size R can be evaluated through the Sérsic radius:

$$\Sigma_{SFR} = \frac{\text{SFR}}{2\pi R_{\text{Sérsic}}^2} \quad (2.36)$$

thus some remarks on the SFR and Sérsic radius are required⁸.

⁸The factor of 2 accounts for the fact that, being $R_{\text{Sérsic}}$ the effective radius (see later), half of the total SFR should be associated with the corresponding area, similarly to what explained for eq. (2.5).

2.5.1 Star Formation Rate

The rate at which stars form is a key parameter in astrophysics, as it directly affects, among other things, the spectral classification of galaxies. This parameter is the star formation rate (SFR) and it is usually expressed in solar masses per year ($M_{\odot} \text{ yr}^{-1}$) (Cimatti, Fraternali, and Nipoti 2019). Without going into detail – as this is beyond the scope of this work – it is possible to derive the SFR in different ways. It is not a quantity directly measured, but is instead determined using a variety of indicators, each based on the luminosity (L) of a galaxy component that is sensitive to the presence of young, massive stars:

$$\text{SFR} = C L_{\text{indicator}}, \quad (2.37)$$

where C is a conversion factor calibrated under a specific set of assumptions, and whose value depends on the tracer considered (Cimatti, Fraternali, and Nipoti 2019). The indicators used to estimate the SFR can be of different types, depending on the wavelength range and on the specific tracer considered.

A first category relies on the continuum luminosity. Young, massive O/B stars produce UV radiation, so that the rest-frame UV continuum can be used to obtain a direct estimate of the SFR. However, it is important to note that dust can partially absorb this radiation, and must be taken into account. This same dust, in turn, re-emits the absorbed radiation in the infrared, which can therefore be used as a complementary tracer, or combined with the UV continuum to recover the total (obscured + unobscured) star formation activity. In the case of the infrared, however, some caution is required, since the AGN itself can also heat the surrounding dust, contaminating the tracer (see section 1.2).

A second category is represented by emission lines, arising in the [HII] regions surrounding these young stars: the UV photons they produce ionize the surrounding gas, giving rise to nebular emission. In particular, $\text{H}\alpha$ and [OII] are the main indicators, tracing hydrogen recombination and a forbidden transition of ionized oxygen, respectively.

Other tracers include the radio continuum (synchrotron and free-free emission) and the X-ray luminosity (from high-mass X-ray binaries), both correlated with recent star formation activity.

All of these tracers, however, can be significantly contaminated when an AGN is present: recombination and forbidden lines, as well as the UV continuum, can be enhanced by nuclear emission from the broad- and narrow-line regions, while X-ray and radio luminosities are often dominated by the accreting black hole itself. The far-infrared continuum is comparatively more robust, since the wavelength range probed is dominated by star-formation-heated dust rather than by the hot dust of the AGN torus, in any case also this range is not immune, as said above.

Finally, the SFR can also be derived indirectly through SED fitting, as one of the best-fitting parameters obtained once a star formation history is assumed; also in this case the presence of an AGN can affect the SFR estimate, but several codes have been developed to separate the AGN and stellar contributions (for example CIGALE). This approach will be particularly relevant in our work (see section 3.3, section 3.4, section 3.7).

2.5.2 $R_{\text{Sérsic}}$

Since the star formation rate is traced by stellar emission, it is natural to associate the size of this emitting region with the extent of the stellar light itself. A common and well-established method for describing the surface brightness distribution of galaxies is the Sérsic profile (Sérsic 1968):

$$I_{\lambda}(R) = I_{\lambda,e} \cdot \exp \left\{ -b(n) \left[\left(\frac{R}{R_e} \right)^{1/n} - 1 \right] \right\} \quad (2.38)$$

where $I_{\lambda,e}$ is the surface brightness at wavelength λ at the effective radius R_e , n is the Sérsic index, and $b(n)$ is a numerical constant well approximated by $b(n) \simeq 2n - 1/3 + 4/(405n)$ (Ciotti and Bertin 1999). By definition, R_e encloses half of the total luminosity of the source, consistently with the definition of effective radius adopted throughout this work (section 2.2).

The Sérsic index n controls the shape of the profile: for $n = 1$ the profile reduces to a simple exponential distribution (assumption adopted in section 2.1), while for $n = 0.5$ it becomes Gaussian. As n increases, the profile becomes more centrally concentrated, with a steeper core and shallower outskirts. Different galaxy types are associated with characteristic ranges of n : ellipticals and bulges typically have $2 < n < 10$, discs have $n \approx 1$, and bars are characterised by flat profiles with $n \lesssim 0.5$ (Cimatti, Fraternali, and Nipoti 2019).

With $R_{\text{Sérsic}}$ we indicate the effective radius R_e in eq. (2.38). Since $R_{\text{Sérsic}}$ is derived from the surface brightness profile, when the UV/optical emission of the galaxy is considered, it is reasonable to associate $R_{\text{Sérsic}}$ with the extent of star-forming activity, as this emission arises primarily from young, massive stars (and so in eq. (2.36)).

In practice, $R_{\text{Sérsic}}$ can be obtained through fitting to photometric imaging. In this work the values of $R_{\text{Sérsic}}$ are drawn from the COSMOS-Web catalogue (Shuntov et al. 2025, see also section 3.4), which provides Sérsic profile fits (effective radius, index n , ellipticity, and position angle) derived from high-resolution imaging.

2.5.3 Schmidt Kennicutt: explicit evolution with redshift from simple physical intuition

Once the surface density of the SFR is defined, it is possible to put it in relation with the surface gas density. The surface density of the star formation rate in ?? defines how rapidly stars are formed in a given region. The surface gas density represents instead the gas mass per unit area. From a dimensional point of view, these two quantities are related by a timescale. From a physical point of view, connecting the gas surface density to the star formation rate surface density corresponds to understanding how efficiently gas is converted into stars. It is then reasonable to relate this two quantities with a free fall time (i.e. a timescale associated with gravitational collapse in star forming regions), $\tau_{ff} = \sqrt{\frac{3\pi}{32G\rho}}$, where ρ is the gas volume density. Keeping in mind that only a fraction of the gas is going to form

stars during each collapsing time, it is possible to write:

$$\Sigma_{SFR} \propto \frac{\Sigma_{gas}}{\tau_{ff}} \propto \Sigma_{gas} \cdot \sqrt{\rho} \quad (2.39)$$

By considering that the density is mass over volume and that the surface gas density is mass over area, it is possible to write:

$$\Sigma_{SFR} \propto \Sigma_{gas} \cdot \sqrt{\frac{\Sigma_{gas}}{R}} \propto \Sigma_{gas}^{\frac{3}{2}} \cdot R^{-\frac{1}{2}} \quad (2.40)$$

By remembering that the radius scales with redshift as the inverse of $(1+z)$ (Allen et al. 2017), we have been able to derive a relation between the surface SFR density and the gas surface density with redshift:

$$\Sigma_{SFR} = A \cdot \Sigma_{gas}^{\frac{3}{2}} (1+z)^{\frac{1}{2}} \quad (2.41)$$

Where A is the normalization that takes in account all the constants, efficiency parameters, conversion factors, and must be calibrated.

By inverting this relation is possible to derive the surface gas density by knowing the star formation surface density. The expression utilized in this work to derive the gas surface density is:

$$\Sigma_{gas} = \Sigma_{SFR}^{2/3} \cdot B \cdot (1+z)^{-1/3} \quad (2.42)$$

where $B = A^{-2/3}$ is now the normalization. To calibrate these normalizations, the procedure described below was adopted.

First of all we compare eq. (2.41) with the classical Schmidt–Kennicutt (KS) relation (Kennicutt 1998):

$$\Sigma_{SFR} \approx 10^{-12} \kappa_s \Sigma_{gas}^{1.4}, \quad (2.43)$$

where κ_s is the burstiness parameter quantifying the deviation from the KS relation (Ferrara et al. 2019⁹). Physically, $\kappa_s > 1$, identifies systems forming stars more efficiently than expected from their gas content. Since the goal is to investigate the redshift dependence, κ_s is settled equal 1 (see later for a more detailed discussion).

The two expressions share the same behaviour — Σ_{SFR} as function of Σ_{gas} — but differ in the exact power-law index (1.5 vs 1.4). Matching eq. (2.41) to eq. (2.43) makes it possible to calibrate A (and consequently B), which depends on Σ_{gas} :

$$A \propto 10^{-12} \cdot \Sigma_{gas}^{-0.1} \quad (2.44)$$

The dependence of A on Σ_{gas} is very weak (exponent -0.1), so it is reasonable to treat it approximately constant once evaluated at a representative value of Σ_{gas} . To choose this representative value, we rely on the spatially resolved KS relation at $z \approx 7$ presented by Vallini et al. 2024. As shown in fig. 2.7, the pixel-by-pixel distributions and the global values of five spatially resolved high- z galaxies span $\log(\Sigma_{gas} / M_{\odot} \text{ kpc}^{-2}) \approx 8\text{--}10$, with the most intensely star-forming central regions

⁹The coefficient 10^{-12} arises from expressing Σ_{gas} in units of $M_{\odot} \text{ kpc}^{-2}$ rather than $M_{\odot} \text{ pc}^{-2}$ as in the original Schmidt–Kennicutt formulation.

clustering around $\log(\Sigma_{\text{gas}} / \text{M}_{\odot} \text{ kpc}^{-2}) \approx 8.0\text{--}8.5$. All five sources, together with mock galaxies in the SERRA simulation (see Vallini et al. 2024 for details) lie above the local KS relation, with values of κ_s consistent the starburst regime. Considering that in this work we studied samples of quasar host galaxies as well as star forming galaxies (chapter 3), we adopted the representative value $\log(\Sigma_{\text{gas}} / \text{M}_{\odot} \text{ kpc}^{-2}) = 8$ for the calibration of eq. (2.45), corresponding to the region populated by the global values of the five sources and the SERRA simulated galaxies.

We note that this choice is appropriate for compact, intensely star-forming systems such as quasar hosts; for samples dominated by more quiescent galaxies, a lower representative value of $\log(\Sigma_{\text{gas}} / \text{M}_{\odot} \text{ kpc}^{-2})$ would be more appropriate. In any case, the weak dependence of A on Σ_{gas} (exponent -0.1) ensures that the calibration is robust against such variations: shifting the representative value by ± 0.5 dex changes A by less than 15%, well within the overall uncertainties of the method¹⁰.

The normalization is therefore:

$$A = 10^{-12} \cdot 10^{-8 \times 0.1} = 10^{-12.8}, \quad (2.45)$$

and consequently:

$$B = A^{-2/3} = (10^{-12.8})^{-2/3} = 10^{8.5}, \quad (2.46)$$

so that eq. (2.42) becomes:

$$\Sigma_{\text{gas}} = 10^{8.5} \Sigma_{\text{SFR}}^{2/3} (1+z)^{-1/3}, \quad (2.47)$$

where Σ_{SFR} is in units of $\text{M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ and Σ_{gas} is in units of $\text{M}_{\odot} \text{ kpc}^{-2}$.

By analyzing fig. 2.7 and applying eq. (2.47) to the star-shaped points (the only ones with known redshift, from Vallini et al. 2024), it is possible to recover Σ_{gas} starting from the corresponding Σ_{SFR} , thus verifying that the calibration consistently reproduces the values reported in the plot.

At $z = 0$ our relation in eq. (2.47) well reproduces the classical Schmidt Kennicutt law (eq. (2.35) and eq. (2.43)) for the values of Σ_{gas} most populated at high redshift (see fig. 2.7). Considering $\log(\Sigma_{\text{gas}} / \text{M}_{\odot} \text{ kpc}^{-2}) = 8$, i.e. $\log(\Sigma_{\text{gas}} / \text{M}_{\odot} \text{ pc}^{-2}) = 2$, our relation evaluated at $z = 0$ gives $\log(\Sigma_{\text{SFR}}) = -0.75$, while the classical law gives $\log(\Sigma_{\text{SFR}}) = -0.8$. This good agreement breaks down for values of Σ_{gas} far from the most densely populated one, as a consequence of the dependence of our calibration on Σ_{gas} itself.

We therefore rely on our redshift-dependent Schmidt–Kennicutt law, given the good agreement around the point considered and the physical motivation just exposed.

Physical interpretation

From the physical point of view, eq. (2.47) shows that at higher redshifts *lower* Σ_{gas} are required to sustain the same Σ_{SFR} , compared to what would be needed at lower redshifts. In other words, high redshift galaxies were more efficient at converting gas

¹⁰Specifically, $A = 10^{-12} \cdot \Sigma_{\text{gas}}^{-0.1}$, so a shift of ± 0.5 dex in Σ_{gas} propagates as $\Delta \log A = -0.1 \times (\pm 0.5) = \mp 0.05$ dex, corresponding to a factor of $10^{0.05} \approx 1.12$, i.e. a variation of less than 15%. The numerical values follow as $A = 10^{-12} \cdot 10^{-8 \times 0.1} = 10^{-12.8}$ and $B = A^{-2/3} = 10^{12.8 \times 2/3} = 10^{8.5}$.

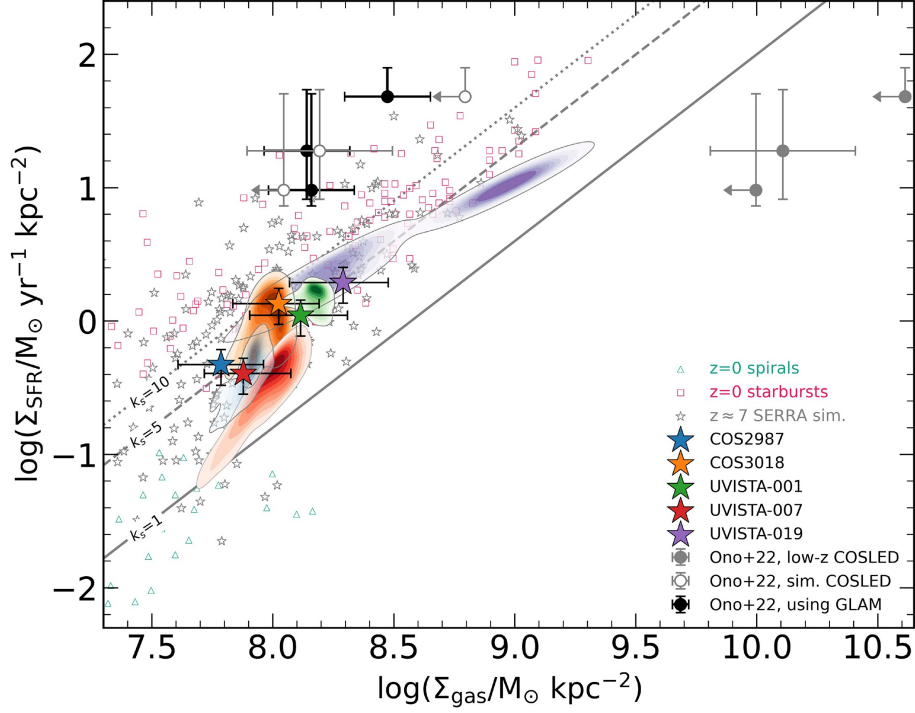


Figure 2.7: *Spatially resolved Kennicutt–Schmidt from (Vallini et al. 2024).* The 2D density distribution of Σ_{SFR} versus Σ_{gas} for five galaxies at $z \sim 7$ analyzed with is shown as shaded colored regions, while colored stars indicate the global values of each source. Simulated galaxies are shown as empty gray stars. The solid, dashed, and dotted lines represent the KS relation for $\kappa_s = 1, 5$, and 10 , respectively. All five sources lie above the local KS relation, with $\kappa_s \approx 3\text{--}10$, consistent with the starburst regime. The representative value $\log(\Sigma_{\text{gas}}/\text{M}_\odot \text{ kpc}^{-2}) = 8$ adopted for the calibration of eq. (2.45) corresponds to the region populated by the global values of the five sources and the SERRA simulated galaxies (see Vallini et al. 2024 for details).

into stars than their low-redshift counterparts of comparable size. This behaviour is consistent with the picture emerging from the previous section. The $\alpha_{[\text{CII}]}$ conversion factor is not universal, but depends on galaxy size: more extended present-day structures can share the same conversion factor as more compact high-redshift systems, with the size evolution with redshift — $r_e \propto (1+z)^{-1}$ — accounted for. In both cases, the evolution is ultimately driven by compactness: smaller galaxies have denser ISM, shorter dynamical timescales, and higher star-formation efficiencies.

A possible interpretation is that both redshift and burstiness trace the same underlying structural evolution of galaxies across cosmic time. Since high-redshift systems are generally more compact and characterized by larger gas surface densities, they are expected to form stars more efficiently, leading to larger effective values of κ_s . In this picture, the explicit $(1+z)^{-1/3}$ dependence in eq. (2.47) may be viewed as an indirect parametrization of the same physical evolution that Vallini et al. 2025 relate to galaxy size via $\alpha_{[\text{CII}]} \propto (1+z)^{-0.69}$ (eq. (2.34)): both relations ultimately reflect the increasing compactness and star-formation efficiency of galaxies at earlier cosmic epochs. The burstiness parameter κ_s in eq. (2.43) fits naturally into this framework: rather than being a fundamental quantity, it may simply reflect the structural compactness of a galaxy. More compact systems — whether at high redshift or in local starbursts — are characterized by higher κ_s values because their denser ISM naturally drives more efficient star formation.

The explicit $(1+z)^{-1/3}$ dependence in eq. (2.47), the size dependence of $\alpha_{[\text{CII}]}$ from Vallini et al. 2025, and the burstiness parameter κ_s are therefore three complementary descriptions of the same underlying physics.

2.6 Summary

The main concepts of the adopted methodology described up to now are summarized in table 2.2. In the following, we summarize the data needed to apply this methodology to the samples studied in our work (described in the next chapter). In particular:

- **Method 1:** Once the **redshifts**, **millimeter fluxes**, and **sizes** are known, we derived the **dust masses** for all sources in the samples using eq. (2.24) in section 2.3, adopting for each source the rest-frame **frequency** $\nu_{\text{em}} = \nu_{\text{obs}}(1+z)$ corresponding to the observed flux.

The **minimum temperature** has been calculated and the dust temperature is evaluated following the discussion in section 2.3.2, assuming $T_{\text{dust}} = 47$ K or, if $T_{\text{min}} > 47$ K, $T_{\text{dust}} = 1.2 T_{\text{min}}$, in agreement with Gilli et al. 2022 (see table 2.1).

Once the dust mass is evaluated, the **gas mass** is derived assuming a **gas-to-dust ratio** $\delta_{\text{GDR}} = 200$, and the gas surface density and consequently the column density are obtained following the methodology summarized in table 2.2.

- **Method 2:** Once the **size** of the region associated [CII] **emission line** is known, it is possible to derive the **conversion factor**, adopting the relation

expressed in eq. (2.34); by knowing the [CII] **luminosity**, the gas mass is then inferred and the gas surface density and consequently the column density are obtained following the methodology summarized in table 2.2.

- **Method 3**: Once the **SFR** and the **Sérsic radius** are known, it is possible to derive the SFR surface density (eq. (2.36)) and, consequently, the gas surface density using the new relation in eq. (2.47). The column density is obtained following the methodology summarized in table 2.2.

The values obtained are then reported in Chapter 4.

$$N_{\text{H}} = 2.1 \Sigma_{\text{gas}}$$

Method	Based on	Size	Key quantities	M_{gas}	Σ_{gas}
Method 1	Dust continuum	R_{cont}	$S_{\nu} \rightarrow M_{\text{dust}}$	$\delta_{\text{GDR}} M_{\text{dust}}$	$\frac{M_{\text{gas}}}{2\pi R_{\text{cont}}^2}$
Method 2	[CII] emission line	$R_{[\text{CII}]}$	$L_{[\text{CII}]}; \alpha_{[\text{CII}]}$	$\alpha_{[\text{CII}]} L_{[\text{CII}]}$	$\frac{M_{\text{gas}}}{2\pi R_{[\text{CII}]}^2}$
Method 3	SFR (SED fitting)	$R_{\text{Sérsic}}$	$\Sigma_{\text{SFR}} = \frac{SFR}{2\pi R_{\text{Sérsic}}^2}$		$10^{8.5} \Sigma_{\text{SFR}}^{2/3} (1+z)^{-1/3}$

Table 2.2: *Recap of the methodology used for the evaluation of Σ_{gas} and, consequently, of the column density $N_{\text{H}} = 2.1 \Sigma_{\text{gas}}$*

Chapter 3

Galaxies and quasars samples

The aim of this thesis is to evaluate the level of nuclear obscuration at redshift $z > 6$. To this end, the methodology described in the previous chapter and summarized in table 2.2 was first applied to lower-redshift samples in order to validate and refine *Method 1*, compare it with *Method 2*, and — for the first time — apply *Method 3*.

The samples investigated in this study consist of massive galaxies ($M_* > 10^{10} M_\odot$) and quasars spanning a wide redshift range up to $z \sim 6$, presented for the first time in Gilli et al. 2022. The analysis was then extended to a sample of quasars with stellar masses of the order of 10^{10} – $10^{11} M_\odot$, at $z \sim 7$, collected by Wang et al. 2024 and to sources with similar redshift from the COSMOS-Web catalogue (Shuntov et al. 2025), characterized, on average, by lower stellar masses ($M_* \sim 10^9 M_\odot$). For both these samples the column density was evaluated for the first time in this work. The quasar sample at $z \sim 7$, presented in Wang et al. 2024, was studied in detail: dust masses were estimated for the first time without assuming the optically thin approximation, and column densities were derived applying *Method 1* and *Method 2*. For sources from the COSMOS-Web catalogue, the column density was estimated for the first time, using *Method 3*.

This Chapter is structured as follows: first of all, section 3.1 describes the main facilities from which the sample data are drawn; then, each section presents the source sample, together with a brief description of the main survey from which it is drawn. In sections 3.2 to 3.5 the data samples discussed in Gilli et al. 2022 are introduced adding also SFRs drawn from COSMOS-Web catalogue. In section 3.6 sanity checks and caveats concerning *Method 1* are presented. Section 3.7 presents sources at $z \sim 7$ with both Sérsic radius and SFR available from JWST observations. Section 3.8 presents a sample of quasars for which dust masses are estimated without the optically-thin approximation, together with an extensive review of their continuum data from the literature.

3.1 Facilities

Before going into the details of the samples, it is useful to give some hints on the main facilities considered in this work, which are the ground-based Atacama Large Millimeter/submillimeter Array (ALMA) and the space-based James Webb Space Telescope (JWST), for which we provide an overview of their main features. The

samples (and the derived data) have also been observed with other telescopes, such as Hubble and Chandra — facilities operating in the optical/near-infrared and X-ray bands, respectively — for which a detailed overview would be superfluous.

ALMA

The Atacama Large Millimeter/submillimeter Array (ALMA) is a radio telescope formed by 66 antennas that work together as a single antenna with a diameter of up to 16 kilometres. It is one of the most powerful astronomical radio observatories in the history of mankind, resulting from a collaboration between Europe, North America, East Asia, and Chile. It is located in this last country, at an altitude of 5000 m (fig. 3.1, right panel), and its operation is based on interferometry. Interferometry is a measurement method that exploits wave interference (of light or radio waves): radio signals are collected by different antennas and are combined to produce an image that is much brighter and sharper than what a single antenna could achieve.

Each parabolic antenna collects the incoming signal over its surface and concentrates it at a single point, called the *focal point*. From there, the signal is channelled to the receivers, located behind the antenna at the so-called *front end*, where it is amplified and digitised for further processing (fig. 3.1, left panel).

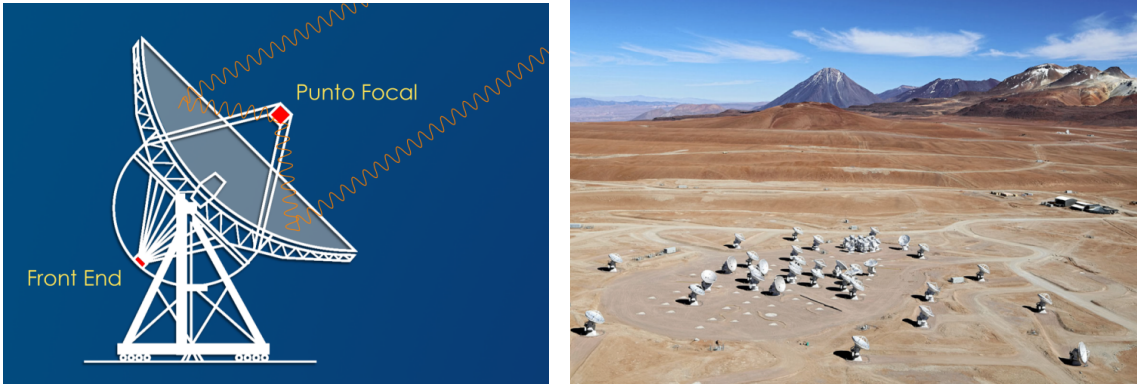


Figure 3.1: *The ALMA telescope. In the left panel is shown a schematic of a parabolic ALMA antenna, showing the incoming radiation (orange) reflected off the main dish toward the focal point (Punto Focal), where the front-end receivers (Front End) collect and process the signal. In the right panel is shown an aerial view of part of the ALMA 12-m Array in the Atacama desert, in Chile. From (Introduction to ALMA 2025)*

Each receiver type is sensitive to a particular "band", or range of wavelengths of the electromagnetic spectrum, and data can only be taken in one band at a time. The observed wavelengths covered by ALMA with interferometry are in the range 30 – 950 GHz, thus covering the (sub-)millimetre regime, see table 3.1.

Thanks to interferometry, if the ensemble of antennas is synchronised to observe the same object and the digitised signals from each antenna are simultaneously combined, the resulting image has a resolution equivalent to that of a single antenna with a diameter equal to the size of the array¹. This combination of signals from the

¹The angular resolution of an interferometer indicates how small a detail can be resolved, and is given by $\theta \approx \lambda/B_{\max}$, where λ is the observed wavelength and $B_{\max}$ is the maximum baseline, i.e.

Band	Wavelength coverage (mm)	Frequency (GHz)
1	6–8.6	35–50
2	2.6–4.5	67–116
3	2.6–3.6	84–116
4	1.8–2.4	125–163
5	1.4–1.8	163–211
6	1.1–1.4	211–275
7	0.8–1.1	275–373
8	0.6–0.8	385–500
9	0.4–0.5	602–720
10	0.3–0.4	787–950

Table 3.1: *ALMA receiver bands: wavelength coverage and frequency range. Adapted from ESO 2026. Nine of the planned ten receivers are installed and operating on each ALMA antenna, with the tenth currently being installed (band 2 receivers have been tested but are not yet fully operational). The coverage is not continuous because of the terrestrial atmosphere: between some bands, atmospheric absorption – mainly due to water vapour and oxygen – is too strong to allow ground-based observations, and these frequency ranges are therefore left uncovered.*

66 antennas is performed by the *correlator* (Introduction to ALMA 2025; ESO 2026; ALMA Observatory 2026). The observations are carried out divided into cycles and, since 2011, 12 cycles have been completed, with Cycle 13 currently in preparation.

At the redshifts considered in this work, ALMA is fundamental for observing both the dust continuum and the [CII] emission line, since both signatures are redshifted into the observed (sub)-millimeter regime². For example, at $z \sim 7$, the [CII] line, whose rest-frame frequency is $\nu_{\text{em}} = 1900.5$ GHz (158 μm), is redshifted to an observed frequency of $\nu_{\text{obs}} \simeq 237.6$ GHz (corresponding to a wavelength of about 1.26 mm), falling within ALMA Band 6. At lower redshift, e.g. $z \sim 3$, the same line is redshifted to $\nu_{\text{obs}} \simeq 475.1$ GHz (about 0.63 mm), falling instead within ALMA Band 8. Thanks to ALMA, numerous surveys have been carried out, several of which target fields also observed by other major observatories, like the *Hubble Space Telescope* (HST) and the *Chandra X-ray Observatory*, allowing a more complete understanding of the objects targeted by these surveys (e.g. see the next sections).

JWST

The James Webb Space Telescope (JWST), with respect to ALMA, observes at shorter wavelengths, covering the near- and mid-infrared range from approximately 0.6 to 28 μm through its four main instruments: Near-InfraRed Camera (NIRCam), Near-InfraRed Spectrograph (NIRSpec), Near-InfraRed Imager and Slitless Spectrograph (NIRISS), and Mid-InfraRed Instrument (MIRI) (fig. 3.2, left panel). Launched in

the largest separation between antennas in the array.

² $\nu_{\text{obs}} = \frac{\nu_{\text{em}}}{1+z}$

December 2021 and placed in orbit around the second Sun–Earth Lagrange point (L2), at ~ 1.5 million km from Earth, JWST employs a 6.5 m segmented primary mirror (fig. 3.2, right panel) – nearly three times the diameter of Hubble’s – resulting in a significantly larger collecting area, i.e. the total reflective surface that gathers incoming light: a larger collecting area means more photons detected per unit time, and therefore the ability to observe fainter and more distant sources, together with improved spatial resolution. Observing from space also allows JWST to overcome the fundamental limitations of ground-based near- and mid-infrared astronomy, such as atmospheric absorption, seeing, and thermal background emission. The four instruments allow JWST not only to image galaxies with high sensitivity and resolution but also to obtain their spectra, enabling spectroscopic confirmation of their redshift through the detection of rest-frame optical emission lines such as [OIII], $H\alpha$, and $Ly\alpha$ ³.

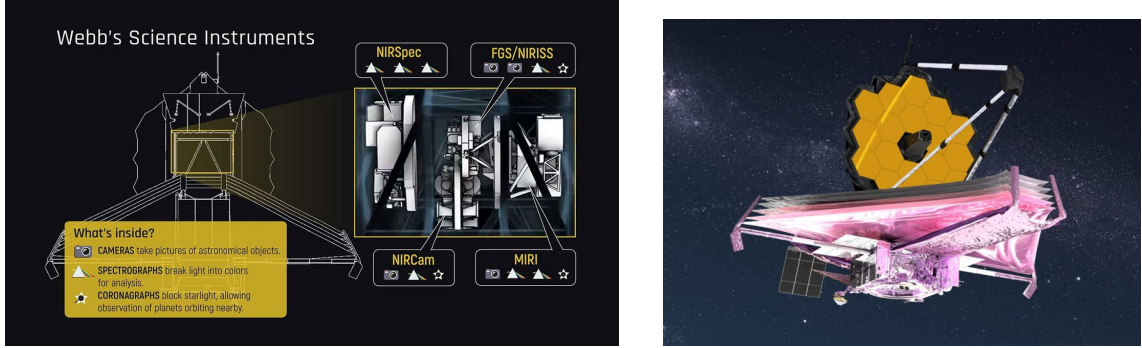


Figure 3.2: *The JWST and its science instruments. Left panel: Schematic of JWST’s four main science instruments – NIRCam, NIRSpec, NIRISS/FGS, and MIRI – housed within the Integrated Science Instrument Module (ISIM). Icons denote each instrument’s observing modes: camera (imaging), spectrograph (spectroscopy), and coronagraph. Credit: NASA. Right panel: artist’s conception of JWST, showing the golden segmented primary mirror (6.5 m) and the five-layer sunshield in the foreground. Credit: NASA.*

At high redshift the synergy between JWST and ALMA allow us to trace both the cold dust and the stellar component: while ALMA probes the cold dust and gas content of galaxies through their rest-frame far-infrared and submillimeter emission, JWST traces their stellar populations and ionised gas, offering complementary information essential for a complete picture of galaxy evolution at high redshift (NASA Science 2026).

3.2 ASPECS: Massive galaxies at $z \sim 0-2$

Survey

The ALMA Spectroscopic Survey in the Hubble Ultra Deep Field is a 3D survey of gas and dust in distant galaxies (Decarli et al. 2019; Aravena et al. 2020; Walter et al.

³NIRCam and NIRISS are primarily dedicated to imaging, while NIRSpec provides multi-object spectroscopy; MIRI extends this capability further into the infrared.

2020): the third dimension corresponds to the frequency axis, so that a full spectrum can be extracted for each pixel on the sky. The survey targets a broader region than what had already been observed at other wavelengths: the Hubble Ultra Deep Field (HUDF, Beckwith et al. 2006), an area of 11 arcmin^2 observed with the Hubble Space Telescope, which observes primarily in the ultraviolet, optical, and near-infrared. Within this field, a smaller region of 4.6 arcmin^2 also benefits from the deepest near-IR observations available, and is known as the Hubble eXtreme Deep Field (XDF). ASPECS roughly overlaps with this region, observing the same 4.6 arcmin^2 area in both Band 3 and Band 6, reaching a continuum depth of $\sim 10 \mu\text{Jy rms}$ through a blind spectral scan, without any pre-selection of targets (fig. 3.3). This field is also located at the center of the Chandra Deep Field South (CDFS), a field that has been observed with the Chandra X-ray Observatory for 7 Ms (Luo et al. 2017).

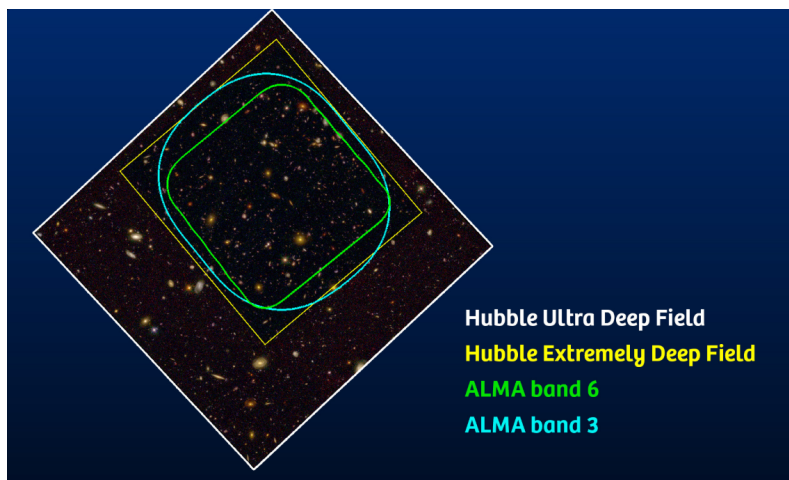


Figure 3.3: *Footprints of the ASPECS survey overlaid on the Hubble Ultra Deep Field. The white and yellow contours show the Hubble Ultra Deep Field (HUDF) and the Hubble eXtreme Deep Field (XDF), respectively; the green and cyan contours show the ALMA Band 6 and Band 3 used by ASPECS. From (Visuals 2026).*

Sample

The sample considered in this work consists of 32 massive galaxies selected by Gilli et al. 2022 from a parent sample of 41 massive galaxies ($M_* > 10^{10} M_\odot$) with spectroscopic redshifts in the range $z = 0.4\text{--}2.8$. The parent sample reduces to 32 galaxies because of size measurements: the angular resolution of ALMA data in ASPECS is $\sim 1.3''$ FWHM, which is not sufficient to provide a reliable estimate of the extent of either dust or molecular gas emission of high-redshift galaxies⁴. Therefore Gilli et al. 2022 considered galaxy sizes estimated from the stellar light in the rest-frame optical bands (see section 2.2.2), using F160W-band photometry from HST, as part of the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey

⁴As an example, at the median redshift of the sample $z = 1.5$, ASPECS would only resolve galaxies with half-light radii $> 5.5 \text{ kpc}$, whereas the typical galaxy radius at that redshift is $\sim 3 \text{ kpc}$ (Allen et al. 2017).

(CANDELS -Grogin et al. 2011; Koekemoer et al. 2011): these size measurements are available from van der Wel et al. 2012, and only the 32 objects with reliable size measurements were considered.

Continuum data and Method 1

We report in table 3.2 the set of observational quantities adopted in this work. Redshifts and the 1.2 mm flux densities, together with their uncertainties, were taken from Aravena et al. 2020; Gilli et al. 2022; the circularized effective radius R_{cont} was derived from the half-light semi-major axis r_{maj} and the axial ratio q reported by van der Wel et al. 2012, together with their uncertainties. Specifically, the circularized effective radius is defined as in eq. (2.22), therefore $R_{\text{cont}} = \sqrt{R_{\text{maj}}^2 q}$, where R_{maj} is r_{maj} expressed in kpc, and q is the ratio between the minor and major axis. The minimum dust temperature was evaluated for each source; since it was found to be always lower than 47 K, the dust masses were derived assuming $T_{\text{dust}} = 47$ K. The derived dust masses values are also listed in table 3.2.

3.3 COSMOS: Star forming galaxies at $z \sim 3$

Survey

The Cosmic Evolution Survey (COSMOS) is one of the largest multiwavelength astronomical surveys, covering a 2 deg^2 equatorial field observed across virtually the entire electromagnetic spectrum, from X-rays to radio, using both space-based (e.g. Hubble, Chandra) and ground-based facilities (Scoville et al. 2007, fig. 3.4). Its main goal is to study the evolution of galaxies, AGNs, and large-scale structure as a function of cosmic time and environment. The data available in this field – including accurate photometric and spectroscopic redshifts, stellar masses, morphologies, and AGN identification – make COSMOS a natural target for deep follow-up programs and observations, both with ALMA and JWST.

Cosmos-Web catalogue

In particular the largest JWST Cycle 1 treasury program give life to COSMOS-Web (Casey et al. 2023). It maps a contiguous $\sim 0.54 \text{ deg}^2$ area at the center of the COSMOS field (fig. 3.4) with NIRCcam in four filters (F115W, F150W, F277W, F444W), complemented by $\sim 0.19 \text{ deg}^2$ of parallel MIRI imaging in F770W. Covering an area roughly 18 times larger than previous surveys at comparable depth, COSMOS-Web was primarily designed to map the spatial distribution, environments, and physical properties of galaxies during the Epoch of Reionization ($6 \lesssim z \lesssim 11$). The COSMOS-Web program has produced the COSMOS2025 catalogue (Shuntov et al. 2025), combining NIRCcam (F115W, F150W, F277W, F444W) and MIRI (F770W) imaging with ancillary HST and ground-based photometry. The catalogue provides spectroscopic and photometric redshifts and physical parameters (stellar mass, star formation rate, star formation history) derived through SED fitting with both LePHARE (*Photometric Analysis for Redshift Estimate*) and CIGALE (*Code Investigating GALaxy Emission*), together with morphological measurements (as

ASPECS: Continuum data

ID	z	$S_{1.2\text{ mm}}$ (μJy)	R_{cont} (kpc)	M_{dust} ($10^7 M_{\odot}$)
C02	1.760	432 ± 10	2.243 ± 0.017	12.6 ± 0.3
C03	1.414	430 ± 23	3.711 ± 0.017	12.8 ± 0.7
C05	1.551	461 ± 28	5.57 ± 0.03	13.7 ± 0.8
C06	2.696	1071 ± 47	3.27 ± 0.11	26.5 ± 1.2
C07	2.580	233 ± 12	1.1 ± 0.6	5.9 ± 0.3
C10	1.997	342 ± 34	4.404 ± 0.015	10 ± 1
C11	2.760	289 ± 21	4.17 ± 0.06	7.1 ± 0.5
C13	1.037	116 ± 16	1.7 ± 0.2	3.3 ± 0.5
C14a	1.999	96 ± 10	1.93 ± 0.17	2.7 ± 0.3
C15	1.317	118 ± 13	3.150 ± 0.007	3.5 ± 0.4
C16	1.095	143 ± 18	4.8 ± 1.4	4.2 ± 0.5
C17	1.848	97 ± 15	2.728 ± 0.008	2.8 ± 0.4
C18	1.845	107 ± 16	3.01 ± 0.06	3.1 ± 0.5
C19	2.574	85 ± 12	2.672 ± 0.013	2.2 ± 0.3
C20	1.093	95 ± 16	2.512 ± 0.006	2.8 ± 0.5
C22	1.097	59 ± 11	4.871 ± 0.012	1.7 ± 0.3
C25	1.098	90 ± 17	1.73 ± 0.07	2.6 ± 0.5
C26	1.552	65 ± 15	1.5 ± 0.4	1.9 ± 0.5
C28	0.662	184 ± 46	8.312 ± 0.007	4.2 ± 1.1
C30	0.458	34 ± 10	0.9560 ± 0.0005	0.57 ± 0.17
C31	2.227	47 ± 12	1.869 ± 0.006	1.3 ± 0.3
C32	0.667	41 ± 10	2.270 ± 0.007	0.9 ± 0.2
C33	0.948	42 ± 10	4.365 ± 0.007	1.2 ± 0.3
FC01	1.315	55.6 ± 13.7	1.8 ± 0.6	1.7 ± 0.4
FC02	2.067	41.7 ± 10.7	0.3740 ± 0.0018	1.2 ± 0.3
FC08	1.906	34.6 ± 9.5	1.8 ± 1.7	1.0 ± 0.3
FC09	2.700	33.3 ± 9.3	1.193 ± 0.014	0.8 ± 0.2
FC12	1.096	33.4 ± 9.8	1.7 ± 0.2	1.0 ± 0.3
FC17	0.622	34.8 ± 9.6	3.553 ± 0.006	0.8 ± 0.2
FC18	1.096	62.5 ± 19.9	1.84 ± 0.07	1.8 ± 0.6
FC20	1.294	85.8 ± 23.8	3.503 ± 0.007	2.6 ± 0.7
FC25	2.330	165.2 ± 54.2	2.79 ± 0.02	4.4 ± 1.4

Table 3.2: *Properties of the 32 ASPECS galaxies derived in this work. Redshifts z and flux densities $S_{1.2\text{ mm}}$ and their uncertainties are from Aravena et al. 2020; Gilli et al. 2022. The circularized effective radius R_{cont} is derived from van der Wel et al. 2012 as described in the text. The dust mass M_{dust} is the total dust mass derived from the 1.2 mm flux density assuming $T_d = 47\text{ K}$.*

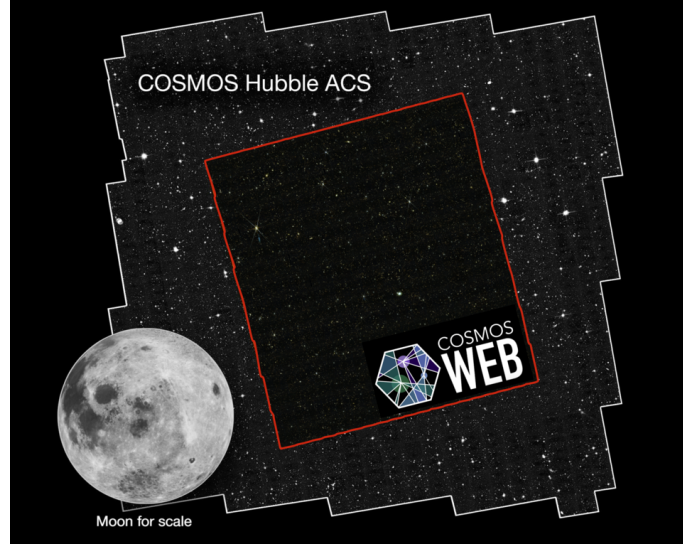


Figure 3.4: *Footprint of the COSMOS-Web JWST survey (red outline, $\sim 0.54 \text{ deg}^2$) overlaid on the original COSMOS field imaged by the Hubble Space Telescope (ACS, white outline) in 2004. The Moon is shown for angular-size comparison. From [IPAC/Caltech press release](#).*

Sérsic profile fits) obtained from the JWST imaging (see Shuntov et al. 2025 for details).

Without entering into the details of the fitting procedure adopted by Shuntov et al. 2025, the structural and physical parameters provided in COSMOS2025 (Sérsic fits, stellar masses, and SFRs) are computed by fixing the redshift to either the spectroscopic or the best-fit photometric value, and then evaluating the position of this adopted redshift relative to the full photometric redshift probability distribution obtained independently from the SED fit. When the adopted redshift lies close to the peak of the probability the resulting fit parameters are well constrained; on the other hand, a significant offset between the two is signal of an unreliable or poorly constrained fit, which can propagate into anomalous structural or physical parameters.

About the SFR we want to highlight that JWST observations allow the SFR to be estimated in several ways, and the COSMOS-Web catalogue provides multiples estimates of SFR, derived independently from LePHARE and CIGALE SED fitting. Among these, we adopt the (total) SFR labelled `sfr_100myr` in the catalogue, i.e. the star formation rate averaged over the last 100 Myr (look-back time), derived with CIGALE SED fitting. This choice is motivated by the physical timescale relevant to the Schmidt-Kennicutt relation, which links the surface density of star formation to the surface density of the gas reservoir being consumed. A SFR averaged over 10 Myr, for example, would be more appropriate for bursty star formation episodes or at very high redshift, where galaxies may not yet have had time to build up 100 Myr of star formation history and where depletion times are shorter.

Sample

The sample considered in this work consists of 6 massive ($M_\star > 10^{10} M_\odot$) star-forming galaxies at $z_{\text{spec}} \sim 3.1\text{--}3.6$ in the COSMOS field, selected from a parent population with near-infrared spectroscopy and reliable gas-phase metallicity measurements, from Suzuki et al. 2021. ALMA Band 6 ($\lambda \approx 1.3$ mm) observations, reaching continuum noise levels of $10\text{--}50 \mu\text{Jy}$, were available for these sources from Gilli et al. 2022.

As for the ASPECS sample, the angular resolution of the ALMA observations is not sufficient to resolve the true extent of dust or molecular gas emission of the sources; Gilli et al. 2022 therefore relied on galaxy sizes estimated from HST photometry (Leauthaud et al. 2007), see section 2.2.2. We will refer to this sample as *Suzuki21*.

Continuum data and Method 1

The data used here are listed in table 3.3. Fluxes and their respective uncertainties, together with redshift are available directly from Gilli et al. 2022 and Suzuki et al. 2021. Sizes are available from both Gilli et al. 2022 and Leauthaud et al. 2007, but uncertainties were available in neither case. Although the uncertainty on the sizes is not explicitly reported in Leauthaud et al. 2007, their analysis of the shape measurement error shows that this error increases systematically for fainter and smaller sources⁵. Following this qualitative trend, we adopt a conservative relative uncertainty of $\sigma_R/R = 20\%$, following also van der Wel et al. 2012, who find that HST-based half-light radii are reliable to $\lesssim 20\%$ accuracy for sources above the relevant magnitude/S–N completeness limit. This choice is also conservative with respect to, and consistent with, the value adopted for the higher-redshift ($z \sim 6$) quasar host sample of Venemans et al. 2020, whose sources are on average more compact than the $z \sim 3.3$ galaxies considered here. For the most marginally resolved sources in our sample a larger uncertainty of $\sim 25\%$ may be more appropriate, though for simplicity and consistency across the sample we adopt a uniform 20% uncertainty throughout.

Also in this case the minimum dust temperature was evaluated for each source; since it was found to be lower than 47 K, the dust masses were derived assuming $T_{\text{dust}} = 47$ K. The derived dust masses are also listed in table 3.3.

Cross-matching with COSMOS2025 and Method 3

We cross-matched the six sources of *Suzuki21* sample with the COSMOS2025 catalogue of Shuntov et al. 2025, in order to obtain structural and physical parameters (Sérsic morphology and SFR) derived from JWST, to apply the third method in recovering the gas surface density. Four out of six sources were recovered, with some clarification:

⁵Point Spread Function (PSF), i.e. the blur that any optical instrument inevitably imposes on the light from even a perfectly point-like source (such as a star), due to diffraction, the telescope’s optics, and (for ground-based observations) atmospheric turbulence (seeing). Corrections become increasingly significant when the galaxy size approaches that of the PSF.

- Source #3, although located within the wider area covered by COSMOS observations, falls outside the $\sim 0.54 \text{ deg}^2$ observations carried out by JWST, and it is therefore not included in the COSMOS2025 catalogue.
- Source 214339 (COSMOS2025 ID 504186) shows an anomalous Sérsic radius, nearly an order of magnitude larger than the other sources in the sample ($\sim 2.2 \text{ arcsec}$, compared to $0.15\text{--}0.4 \text{ arcsec}$)⁶. For this source, we adopted for the size measurement corresponding to the star forming region the size of the dust continuum emission, e.g R_{cont} in table 3.3.
- Source 208681 (COSMOS2025 ID 586884) has no reported SFR or stellar mass in COSMOS2025⁷, so it was not possible to apply *Method 3* to this source.

SUZUKI21: Continuum and COSMOS-Web data

ID	z	$S_{1.3 \text{ mm}}$ (mJy)	R_{cont} (kpc)	M_{dust} ($10^8 M_{\odot}$)	$SFR_{100 \text{ Myr}}$ ($M_{\odot}/\text{yr}$)	$R_{\text{Sérsic}}$ (kpc)
208681	3.267	1.02 ± 0.05	0.67 ± 0.13	2.96 ± 0.16	/	1.18 ± 0.01
214339	3.609	0.30 ± 0.05	1.5 ± 0.3	0.77 ± 0.13	26 ± 6	R_{cont}
406444	3.304	0.12 ± 0.04	2.5 ± 0.5	0.33 ± 0.11	52 ± 3	2.87 ± 0.02
3	3.230	0.11 ± 0.01	2.2 ± 0.4	0.29 ± 0.03	/	/
434585	3.363	0.11 ± 0.03	1.0 ± 0.2	0.31 ± 0.08	69 ± 8	1.14 ± 0.01
192129	3.495	0.05 ± 0.01	0.81 ± 0.16	0.12 ± 0.02	18 ± 1	2.08 ± 0.02

Table 3.3: *Properties of the COSMOS $z \sim 3.3$ star-forming galaxies. Redshifts z , fluxes $S_{1.3 \text{ mm}}$ are drawn from Gilli et al. 2022. R_{cont} is half-light radius from Leauthaud et al. 2007, converted to physical kpc, with a conservative relative uncertainty $\sigma_R/R = 20\%$ adopted as described in the text. The dust mass M_{dust} is the total dust mass derived from the 1.2 mm flux density assuming $T_d = 47 \text{ K}$. SFR and $R_{\text{Sérsic}}$ and associated errors are taken from the COSMOS2025 catalogue, as described in the text.*

A comparison between the column densities obtained by applying *Method 1* and *Method 3*, is reported in Chapter 4.

3.4 ALPINE: massive galaxies at $z \sim 4\text{--}5$

Survey

The ALMA Large Program to INvestigate [CII] at Early Times (*ALPINE*) is a survey targeting 118 typical, main-sequence galaxies at $z_{\text{spec}} \sim 4.4\text{--}4.6$ and $z_{\text{spec}} \sim 5.1\text{--}5.9$ (Le Fèvre et al. 2020; Béthermin et al. 2020). The gap between the two redshift ranges

⁶The Sérsic index ($n \sim 7.3$) is close to the upper bound of the fitting prior ($n \in [0.3, 9]$). Given the degeneracy between Sérsic index and effective radius, this combination is indicative of a poorly constrained morphological fit, and the source was therefore excluded from the sample

⁷This source shows a substantial discrepancy between its adopted redshift ($z = 3.27$, consistent with the spectroscopic redshift of Suzuki et al. 2021) and a photometric redshift estimate from the catalogue ($z \sim 4.25$), despite the spatial cross-match of 0.09 arcsec separation.

is due to an atmospheric opacity window in which the [CII] line is not observable from the ground. Unlike the blind approach of ASPECS, ALPINE observes a sample of pre-selected, UV-selected sources, located within the COSMOS and Extended Chandra Deep Field South (ECDFS, Lehmer et al. 2005) fields, exploiting the extensive multi-wavelength imaging and spectroscopic data already available for these regions. This survey targets the [CII] 158 μm line together with the underlying dust continuum, with the main goals of quantifying the amount of dust-obscured star formation, calibrating the relation between [CII] luminosity and star formation rate, characterising the gas and dust distribution, and investigating the gas kinematics and the role of mergers in early galaxy growth.

Sample

This sample consists of 7 massive ($M_\star > 10^{10} M_\odot$) UV-selected star-forming galaxies drawn from the ALPINE survey. These 7 sources are the subset of the 13 massive ALPINE galaxies detected in dust continuum that also have a reliable size estimate from HST photometry in Fujimoto et al. 2020, and were selected by Gilli et al. 2022 as those for which the ISM column density could be derived from dust mass and UV/optical stellar size. Since these sources are part of the ALPINE program, the [CII] emission line luminosity was also available, along with the size associated with the emission (Fujimoto et al. 2020; Gilli et al. 2022).

Continuum data and Method 1

The data used here are listed in table 3.4. Fluxes, redshift and sizes were drawn from Gilli et al. 2022 and Fujimoto et al. 2020, together with uncertainties. Also in this case the minimum dust temperature was evaluated for each source, using eq. (2.26); since it was found to be lower than 47 K, the dust masses were derived assuming $T_{\text{dust}} = 47$ K. The derived dust masses are also listed in table 3.4.

ALPINE: Continuum data

ID	z	$S_{0.85-1.05}$ (μJy)	R_{cont} (kpc)	M_{dust} ($10^7 M_\odot$)
DC494057	5.540	179 ± 30	0.59 ± 0.17	1.9 ± 0.3
DC683613	5.536	245 ± 54	0.6 ± 0.2	2.6 ± 0.6
DC818760	4.554	1077 ± 130	1.1 ± 0.2	8.3 ± 1.0
DC873756	4.548	1355 ± 76	1.1 ± 0.4	10.5 ± 0.6
vc5100822662	4.524	210 ± 38	1.3 ± 0.3	1.6 ± 0.3
vc5100969402	4.587	327 ± 99	0.59 ± 0.15	2.5 ± 0.8
vc5180966608	4.529	419 ± 84	0.6 ± 0.2	3.2 ± 0.7

Table 3.4: *Properties of the ALPINE sample, where DC = DEIMOS-COSMOS and vc = vuds-cosmos. Redshifts z , dust continuum flux densities $S_{0.85-1.05}$, effective circularized radii R_{cont} are from Fujimoto et al. 2020; Gilli et al. 2022. The total dust masses M_{dust} were obtained from the mm flux densities assuming $T_d = 47$ K.*

[CII] emission and Method 2

As mentioned, for these sources the [CII] emission line luminosity was also available, together with the size of the associated emission region; these values are listed in table 3.5. Given the size and the redshift, it was possible to derive the conversion factor $\alpha_{\text{[CII]}}$ following eq. (2.34) and, consequently, estimate the gas mass, as described in section 2.4. These derived values are also reported in table 3.5.

ALPINE: [CII] emission data

ID	z	$L_{\text{[CII]}}$ ($10^8 L_{\odot}$)	$R_{\text{[CII]}}$ (kpc)	$\alpha_{\text{[CII]}}$ ($M_{\odot}/L_{\odot}$)	M_{gas} ($10^{10} M_{\odot}$)
DC494057	5.540	7.2 ± 0.5	2.5 ± 0.3	27.7 ± 1.9	2.0 ± 0.3
DC683613	5.536	8.0 ± 0.7	1.8 ± 0.3	22.4 ± 2.8	1.8 ± 0.4
DC818760	4.554	43.0 ± 1.7	2.59 ± 0.16	28.5 ± 1.2	12.3 ± 1.0
DC873756	4.548	36.2 ± 1.3	2.36 ± 0.11	26.8 ± 0.9	9.7 ± 0.7
vc5100822662	4.524	7.9 ± 0.7	2.6 ± 0.4	28.5 ± 2.8	2.2 ± 0.4
vc5100969402	4.587	5.2 ± 0.6	1.6 ± 0.3	20.6 ± 2.9	1.1 ± 0.3
vc5180966608	4.529	13.7 ± 1.1	5.1 ± 0.4	45.5 ± 2.6	6.3 ± 0.9

Table 3.5: *Properties of the ALPINE sample, where DC = DEIMOS-COSMOS and vc = vuds-cosmos. Redshifts z , [CII] emission line luminosity $L_{\text{[CII]}}$, circularized effective radius of the [CII] emission $R_{\text{[CII]}}$ are from Fujimoto et al. 2020; Gilli et al. 2022. The conversion factor $\alpha_{\text{[CII]}}$ and gas mass M_{gas} were derived as described in the text.*

Cross-matching with COSMOS2025 and Method 3

As for the $z \sim 3$ sample, we cross-matched the seven sources of the ALPINE sample with the COSMOS2025 catalogue by Shuntov et al. 2025, in order to obtain structural and physical parameters (Sérsic morphology and SFR) derived from JWST, to apply the third method in recovering the gas surface density. Four out of seven sources were recovered, with some clarification:

- Sources #DC494057 and #DC818760, although located within the wider area covered by COSMOS observations in the ALPINE survey, fall outside the $\sim 0.54 \text{ deg}^2$ observations carried out by JWST, therefore these sources are not included in the COSMOS2025 catalogue.
- Source #DC683613 is present in the catalogue, but lacks an estimate of SFR in the catalogue.

The SFR and Sérsic radius drawn from the catalogue are listed in table 3.6.

These quantities allowed us to evaluate the column density using *Method 3*. The corresponding estimates are presented in chapter 4, together with a comparison of the column density estimates obtained with the three different methods.

ALPINE: Cosmos-Web data

ID	$SFR_{100\text{ Myr}}$ ($M_{\odot}\text{ yr}^{-1}$)	$R_{\text{Sérsic}}$ (kpc)
DC494057	—	—
DC683613	/	1.53 ± 0.09
DC818760	—	—
DC873756	50 ± 20	2.11 ± 0.05
vc5100822662	44 ± 2	0.98 ± 0.02
vc5100969402	47 ± 2	0.78 ± 0.03
vc5180966608	12.4 ± 0.6	0.665 ± 0.008

Table 3.6: *Star formation rates and effective Sérsic radii for the ALPINE sample. DC494057 and DC818760 fall outside the COSMOS-Web footprint and lack a match. DC683613 is matched and structurally characterized but lacks a SFR estimate in the catalogue.*

3.5 Quasars at $z \sim 6$

This sample consists of 34 QSO host galaxies at $z \sim 6$, drawn from two complementary programmes targeting UV-bright and UV-faint quasars, respectively. At this redshift, the selection of massive ($M_* > 10^{10-11} M_{\odot}$) galaxies is challenging due to their low space density; QSOs therefore serve as beacons to identify and study their host galaxies with dedicated ALMA follow-up (Gilli et al. 2022).

The first subset consists of 27 UV-bright ($M_{\text{UV}} \lesssim -25$) QSOs at $z > 5.7$ from Venemans et al. 2020, all previously detected in both [CII] and 1.2 mm continuum with $L_{[\text{CII}]} \gtrsim 10^9 L_{\odot}$. ALMA Band 6 observations reach continuum sensitivities of $\text{rms} \sim 50\text{--}200 \mu\text{Jy}$ at an average resolution of $\sim 0.3''$ FWHM, sufficient to spatially resolve both the dust continuum and [CII] emission. We will refer to this first sub sample as *Venemans*.

The second subset comprises 7 UV-faint QSOs from the Subaru High- z Exploration of Low-Luminosity Quasar project (SHELLQs) (Matsuoka et al. 2016; Matsuoka et al. 2019), observed with ALMA by Izumi et al. 2018a; Izumi et al. 2019 at $z = 5.9\text{--}6.4$ and $-22.8 < M_{\text{UV}} < -25.3$. Observations reach a continuum rms of $\sim 20 \mu\text{Jy}$ at 1.2 mm with an average beam of $\sim 0.5''$; all sources are detected in [CII] and 6 out of 7 also in the dust continuum. We will refer to this sub-sample as *Izumi*.

Continuum data and Method 1

Redshifts, fluxes and sizes were compiled in Gilli et al. 2022. The uncertainties on the sizes for the SHELLQs sample were available directly from Izumi et al. 2018a; Izumi et al. 2019, while for the high-luminosity sample they were not reported in the literature; as mentioned previously, we therefore adopted a fiducial error of 20%, based on the analysis reported by Venemans et al. 2020. The data used here are listed in table 3.7. The sources J0842+1218, J2100-1715, and P323+12 are not resolved, so an upper limit was adopted for their size. For J1208-0200 and J2228+0152, the median size of the detected sources was assigned instead; for J2228+0152, an upper

limit on the flux is also reported, due to the non-detection (Gilli et al. 2022). The inferred dust masses for these sources are therefore lower limit of the true masses (see section 2.3).

The minimum temperature $T_{\min}$ was evaluated for all the sources and, for five of them ($P231 - 20$, $J2318 - 3029$, $J2348 - 3054$, $P007 + 04$, and $J2054 - 0005$), it was higher than 47 K. For these sources, a dust temperature of $1.2T_{\min}$ was therefore assumed in the evaluation of the dust mass.

These quantities are listed in table 3.7.

[CII] emission and Method 2

As mentioned, for these sources the [CII] emission line luminosity was also available, together with the size of the associated emission region; these values are listed in table 3.5. Given the size, it was possible to derive the conversion factor $\alpha_{[\text{CII}]}$ following eq. (2.34) and, consequently, estimate the gas mass, as described in section 2.4. These derived values are also reported in table 3.8. As for the continuum data, the uncertainties on the sizes for the SHELLQs sample were available directly from Izumi et al. 2018a; Izumi et al. 2019, while for the high luminous sample we adopted an error of 20%, based on the values reported by Venemans et al. 2020. These values are reported in table 3.8.

3.6 A safety check for Method 1

Before proceeding with the analysis of the new samples, we validated the computation of the dust mass, necessary for our Method 1, by comparing the dust masses obtained in this work with those derived by Gilli et al. 2022, hereafter *G22*.

For each source the dust mass was computed and compared with the ones from *G22*. When the total observed flux is used in eq. (2.24) the two sets of values are in good agreement, confirming the validity of our method. This allowed us to investigate a caveat in the calculation: since the size adopted in eq. (2.24) corresponds to the half-light radius, only half of the total flux should formally be used. This was overlooked in *G22*, whereas this correction should be applied to get physically accurate mass values: the difference between the logarithms of the mass under the two assumptions (half-flux vs total flux in eq. (2.24)) is generally below 0.3 dex (a factor of 2) and this effect becomes more pronounced for the sample of high-redshift, luminous quasars (Venemans), for which the discrepancy is not only larger but also more scattered.

This behaviour arises because the minimum dust temperature $T_{\min}$ – and consequently the temperature assumed in the mass calculation – depends jointly on the source size R and on the observed flux $S_{\nu_{\text{obs}}}$ (eq. (2.26)). Using an overestimated flux in this calculation leads to an overestimated $T_{\min}$, and possibly to an overestimated dust temperature; since the inferred dust mass depends on the assumed temperature, this in turn propagates into an overestimated final mass estimate. We illustrate this effect for one of the sources showing the most pronounced discrepancy, J1048–0109 (fig. 3.5). For this source the minimum temperature computed using the total observed flux is $T_{\min} = 46.98$ K: in this regime the standard assumption of $T_{\text{dust}} = 47$ K

QSO at $z \sim 6$: continuum data

Name	z	$S_{1900 \text{ GHz}}$ (mJy)	R_{cont} (kpc)	M_{dust} ($10^8 M_{\odot}$)
<i>High-luminosity QSOs Venemans et al. 2020</i>				
P009−10	6.0040	3.7 ± 0.4	1.5 ± 0.3	4.7 ± 0.5
J0100+2802	6.3269	1.37 ± 0.09	0.93 ± 0.19	1.94 ± 0.14
J0109−3047	6.7904	0.52 ± 0.08	0.37 ± 0.07	0.90 ± 0.17
J0129−0035	5.7788	2.61 ± 0.06	0.52 ± 0.10	4.0 ± 0.5
J025−33	6.3373	2.49 ± 0.11	0.63 ± 0.13	4.1 ± 0.4
P036+03	6.5405	2.55 ± 0.05	0.5 ± 0.1	3.0 ± 0.4
J0305−3150	6.6139	5.34 ± 0.19	0.81 ± 0.16	10.4 ± 1.6
P065−26	6.1871	1.37 ± 0.11	0.55 ± 0.11	2.0 ± 0.2
J0842+1218	6.0754	0.68 ± 0.06	< 0.72	> 0.89
J1044−0125	5.7846	3.00 ± 0.12	0.46 ± 0.09	5.5 ± 1.5
J1048−0109	6.6759	2.79 ± 0.08	0.56 ± 0.11	5.8 ± 1.1
P167−13	6.5144	0.89 ± 0.12	0.89 ± 0.18	1.31 ± 0.18
J1120+0641	7.0848	0.64 ± 0.05	0.39 ± 0.08	1.23 ± 0.14
P183+05	6.4386	4.79 ± 0.16	1.1 ± 0.2	7.5 ± 0.5
J1306+0356	6.0330	0.74 ± 0.08	0.64 ± 0.13	0.97 ± 0.11
J1319+0950	6.1347	5.1 ± 0.2	1.0 ± 0.2	7.6 ± 0.6
J1342+0928	7.5400	0.34 ± 0.04	0.89 ± 0.18	0.64 ± 0.08
P308−21	6.2355	1.18 ± 0.08	1.6 ± 0.3	1.58 ± 0.11
J2100−1715	6.0807	0.56 ± 0.08	< 0.65	> 0.73
P323+12	6.5872	0.23 ± 0.12	< 0.30	> 0.36
J2318−3113	6.4429	0.36 ± 0.08	1.3 ± 0.3	0.51 ± 0.11
P359−06	6.1719	0.79 ± 0.07	0.94 ± 0.19	1.05 ± 0.10
P231−20	6.5869	4.37 ± 0.15	0.27 ± 0.05	1.2 ± 0.2
J2318−3029	6.1456	3.11 ± 0.07	0.37 ± 0.07	1.9 ± 0.3
J2348−3054	6.9007	2.28 ± 0.07	0.25 ± 0.05	1.9 ± 0.6
P007+04	6.0015	2.33 ± 0.06	0.34 ± 0.07	1.7 ± 0.2
J2054−0005	6.0389	3.15 ± 0.10	0.41 ± 0.08	2.5 ± 0.4
<i>Low-luminosity QSOs Izumi et al. 2018a; Izumi et al. 2019</i>				
J2239+0207	6.2497	1.11 ± 0.03	0.43 ± 0.10	1.75 ± 0.17
J0859+0022	6.3903	0.16 ± 0.02	0.9 ± 0.3	0.22 ± 0.03
J1152+0055	6.3637	0.19 ± 0.03	1.1 ± 0.4	0.26 ± 0.04
J2216−0016	6.0962	0.14 ± 0.03	1.3 ± 0.4	0.17 ± 0.04
J1202−0057	5.9289	0.246 ± 0.012	1.3 ± 0.3	0.300 ± 0.015
J1208−0200	6.1165	0.09 ± 0.02	< 1.01	> 0.11
J2228+0152	6.0805	< 0.05	< 1.01	> 0.06

Table 3.7: Properties of $z \sim 6$ QSO sample. Redshifts z , flux density at 1900 GHz, circularized effective radius R_{cont} , and dust masses M_{dust} . For J1208−0200 and J2228+0152 the continuum size is unresolved: R_e is reported as an upper limit and M_{dust} as the corresponding lower limit. J2228+0152 has also a upper limit for the flux because is undetected. For the high-luminosity QSOs for P231−20, J2318−3029, J2348−3054, P007+04, and J2054−0005, the dust temperature was assumed to be $1.2 T_{\text{min}}$, as explained in section 2.3.2.

QSO at $z \sim 6$: [CII] data

Name	z	$L_{[\text{CII}]}$ ($10^9 L_\odot$)	$R_{[\text{CII}]}$ (kpc)	$\alpha_{[\text{CII}]}$ ($M_\odot/L_\odot$)	$M_{\text{gas},[\text{CII}]}$ ($10^9 M_\odot$)
<i>High-luminosity QSOs Venemans et al. 2020</i>					
P009−10	6.0040	9.1 ± 0.7	2.0 ± 0.4	24 ± 3	220 ± 30
J0100+2802	6.3269	3.76 ± 0.18	1.2 ± 0.2	17 ± 2	63 ± 9
J0109−3047	6.7904	1.87 ± 0.16	0.63 ± 0.13	10.7 ± 1.5	20 ± 3
J0129−0035	5.7788	1.92 ± 0.07	0.86 ± 0.17	13.3 ± 1.8	26 ± 4
J025−33	6.3373	5.7 ± 0.2	1.0 ± 0.2	15 ± 2	86 ± 12
P036+03	6.5405	3.38 ± 0.08	0.96 ± 0.19	14.4 ± 2.0	49 ± 7
J0305−3150	6.6139	5.9 ± 0.4	1.4 ± 0.3	18 ± 3	107 ± 16
P065−26	6.1871	1.71 ± 0.17	2.2 ± 0.4	25 ± 3	43 ± 7
J0842+1218	6.0754	0.75 ± 0.10	0.72 ± 0.14	11.8 ± 1.6	8.8 ± 1.7
J1044−0125	5.7846	1.6 ± 0.2	0.92 ± 0.18	14.0 ± 1.9	23 ± 4
J1048−0109	6.6759	2.10 ± 0.14	0.80 ± 0.16	12.7 ± 1.8	27 ± 4
P167−13	6.5144	5.6 ± 0.3	1.5 ± 0.3	19 ± 3	108 ± 16
J1120+0641	7.0848	1.21 ± 0.11	0.82 ± 0.16	12.9 ± 1.8	16 ± 3
P183+05	6.4386	7.2 ± 0.3	1.7 ± 0.3	21 ± 3	150 ± 20
J1306+0356	6.0330	1.12 ± 0.11	0.99 ± 0.20	15 ± 2	17 ± 3
J1319+0950	6.1347	4.0 ± 0.4	1.3 ± 0.3	18 ± 2	72 ± 12
J1342+0928	7.5400	1.32 ± 0.09	1.4 ± 0.3	19 ± 3	25 ± 4
P308−21	6.2355	3.4 ± 0.2	1.6 ± 0.3	20 ± 3	69 ± 10
J2100−1715	6.0807	1.31 ± 0.14	0.85 ± 0.17	13.2 ± 1.8	17 ± 3
P323+12	6.5872	1.45 ± 0.19	1.0 ± 0.2	15 ± 2	22 ± 4
J2318−3113	6.4429	1.59 ± 0.14	1.7 ± 0.3	21 ± 3	33 ± 5
P359−06	6.1719	2.62 ± 0.14	1.1 ± 0.2	15 ± 2	40 ± 6
P231−20	6.5869	3.5 ± 0.3	0.53 ± 0.11	9.6 ± 1.3	34 ± 5
J2318−3029	6.1456	2.22 ± 0.12	0.63 ± 0.13	10.8 ± 1.5	24 ± 4
J2348−3054	6.9007	1.77 ± 0.18	0.35 ± 0.07	7.2 ± 1.0	13 ± 2
P007+04	6.0015	1.58 ± 0.09	0.64 ± 0.13	10.9 ± 1.5	17 ± 3
J2054−0005	6.0389	3.08 ± 0.14	0.67 ± 0.13	11.2 ± 1.6	35 ± 5
<i>Low-luminosity QSOs Izumi et al. 2018a; Izumi et al. 2019</i>					
J2239+0207	6.2497	1.91 ± 0.17	1.61 ± 0.05	20.6 ± 0.4	39 ± 4
J0859+0022	6.3903	0.92 ± 0.10	1.1 ± 0.4	16 ± 4	15 ± 6
J1152+0055	6.3637	0.76 ± 0.16	1.0 ± 0.4	15 ± 4	11 ± 6
J2216−0016	6.0962	2.04 ± 0.16	1.8 ± 0.4	22 ± 3	45 ± 10
J1202−0057	5.9289	1.24 ± 0.08	1.0 ± 0.4	15 ± 5	18 ± 7
J1208−0200	6.1165	0.54 ± 0.11	1.31 ± 0.17	17.8 ± 1.6	10 ± 3
J2228+0152	6.0805	0.49 ± 0.11	0.73 ± 0.17	11.8 ± 2.0	6 ± 2

Table 3.8: *Properties for $z \sim 6$ QSO sample. Redshifts z , [CII] emission line luminosity $L_{[\text{CII}]}$, circularized effective radius of the [CII] emission $R_{[\text{CII}]}$ from Gilli et al. 2022; Izumi et al. 2018b; Izumi et al. 2019; Venemans et al. 2020 with respective uncertainties, evaluated as described in the text. The conversion factor $\alpha_{[\text{CII}]}$ and gas mass M_{gas} were derived as described in the text.*

happens to be numerically adequate, but it lies right at the edge of the physically allowed temperature range. A more conservative and physically motivated choice, $T_{\text{dust}} = 1.2 T_{\text{min}}$, would have been preferable in this case. The same issue does not arise when the half flux is used: in that case $T_{\text{min}} = 36.6$ K is lower, and the fixed assumption $T_{\text{dust}} = 47$ K remains a safe choice. In the left panel of fig. 3.5 is shown the minimum dust temperature T_{min} as a function of source size R , computed for $S_{\nu_{\text{obs}}}/2$ (cyan) and $S_{\nu_{\text{obs}}}$ (red). At the reference radius $R = 0.562$ kpc (dashed line), T_{min} increases from 36.60 K to 46.98 K when the flux is doubled.

In the right panel is shown the corresponding dust mass, $\log_{10}(M_{\text{dust}}/M_{\odot})$, as a function of R , evaluated at a fixed dust temperature for each case ($T_{\text{dust}} = 47.00$ K for $S_{\nu_{\text{obs}}}/2$, and $T_{\text{dust}} = 1.2 T_{\text{min}}(S_{\nu_{\text{obs}}}) = 56.37$ K for $S_{\nu_{\text{obs}}}$).

The effects of the dust temperature will also be discussed in chapter 4, as an important parameter whose influence extends to the evaluation of the column density as well. This first safety check allowed us to better understand continuum emission, before studying the new quasar sample at redshift 7.

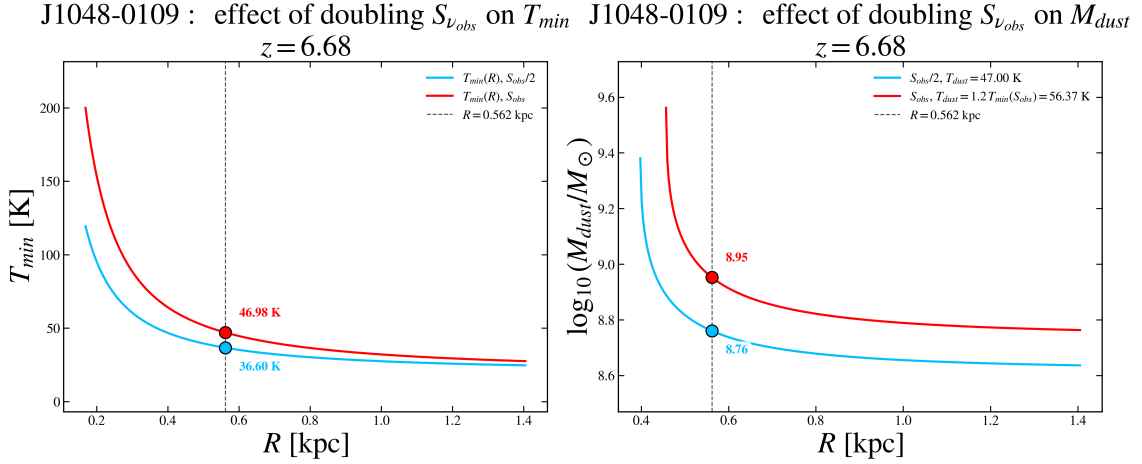


Figure 3.5: *Left: minimum dust temperature T_{min} as a function of the assumed source radius R , for source J1048–0109, computed using the observed flux $S_{\text{obs}}/2$ (cyan) and using S_{obs} (red). Right: corresponding dust mass, expressed as $\log_{10}(M_{\text{dust}}/M_{\odot})$, as a function of R , for two temperature assumptions: $T_{\text{dust}} = 47$ K with the half of observed flux (cyan), and $T_{\text{dust}} = 1.2 T_{\text{min}}(S_{\text{obs}})$ (red). The vertical dashed line marks the source’s effective radius.*

3.7 COSMOS-Web Sources at $z \sim 7$

This sample consists of 23 sources drawn from the COSMOS-Web catalogue (Shuntov et al. 2025) with redshift $z > 6$. Sources are selected only if their spectroscopic redshift has a high confidence level (>90) and if the catalogue’s photometric redshift agrees with the spectroscopic one ($|z_{\text{spec}} - z_{\text{phot}}| < 0.5$). This selection ensures that the physical parameters used in this work –SFR and Sérsic radius– are relatively well constrained from reliable SED fits. From the parent sample obtained by this selection, four sources (IDs 395957, 396600, 589878, 676801) lack SED-derived stellar mass and SFR estimates, and were therefore excluded from this work.

Table 3.9 lists the relevant parameters extracted from the catalogue for the evaluation of the column density with *Method 3*. It is worth noting that, for these sources, the stellar mass is on the order of $10^9 M_\odot$, markedly lower than in the samples considered so far.

COSMOS Web sources at $z \sim 7$

ID	z	$R_{\text{Sérsic}}$ (kpc)	$\text{SFR}_{100 \text{ Myr}}$ ($M_\odot \text{ yr}^{-1}$)	$M_\star$ ($M_\odot$)
696398	6.5818	0.05 ± 0.04	0.8 ± 0.4	1.94×10^8
26432	6.3156	1.4 ± 0.2	2 ± 1	4.50×10^8
697023	6.5830	0.39 ± 0.06	1.4 ± 0.7	5.14×10^8
11501	6.0781	0.40 ± 0.04	3 ± 1	6.74×10^8
24981	6.7020	0.8 ± 0.1	4 ± 2	7.02×10^8
5426	6.0642	0.98 ± 0.09	4 ± 2	7.49×10^8
17173	6.0088	0.6 ± 0.1	4 ± 2	8.51×10^8
468253	6.2210	1.1 ± 0.1	4 ± 1	8.96×10^8
25006	6.7010	0.7 ± 0.1	5 ± 2	9.33×10^8
663999	6.3063	0.36 ± 0.01	4 ± 1	9.55×10^8
710964	6.7751	0.26 ± 0.04	3 ± 2	9.60×10^8
671425	6.0460	1.0 ± 0.2	4 ± 2	1.15×10^9
47123	6.0814	1.46 ± 0.04	13 ± 6	2.84×10^9
14309	6.1987	0.14 ± 0.05	2 ± 2	6.44×10^9
664333	6.8076	2.2 ± 0.1	28 ± 11	6.84×10^9
467074	7.0400	0.15 ± 0.03	5 ± 2	6.92×10^9
358243	7.0900	0.53 ± 0.01	50 ± 5	9.44×10^9
19408	6.8820	0.57 ± 0.02	8 ± 3	1.15×10^{10}
671610	6.8540	0.97 ± 0.04	43 ± 12	1.19×10^{10}
474402	6.6290	1.5 ± 0.1	31 ± 13	1.34×10^{10}
559024	6.9830	0.79 ± 0.02	60 ± 16	1.39×10^{10}
639392	7.1450	0.38 ± 0.04	14 ± 2	2.45×10^{10}
51120	6.0270	0.317 ± 0.005	6.2 ± 0.3	4.39×10^{10}
395957	6.9260	0.59 ± 0.02	...	...
396600	6.9240	0.22 ± 0.03	...	...
589878	6.8140	0.26 ± 0.05	...	...
676801	6.5382	0.15 ± 0.02	...	...

Table 3.9: *Properties of the COSMOS-Web sources at $z > 6$, ordered by increasing stellar mass, with $\text{SFR}_{100 \text{ Myr}}$ and Sérsic radius.*

3.8 Quasars at $z \sim 7$ (*W24* sample)

This sample consists of 27 massive galaxies hosting luminous quasars at redshift ~ 7 , studied by Wang et al. 2024. We will refer to this sample as *W24*. That work aimed to investigate SMBH–galaxy relations at high redshift; to this end, observations of

the [CII] emission line and the underlying far-infrared dust continuum were carried out for these sources using (ALMA) and the NOthern Extended Millimeter Array (NOEMA) at sub-arcsecond resolution. The parent sample of *W24* consists of 31 quasars, from which we excluded the lensed source (J0439+1634) and the sources with only 3σ upper limit on fluxes detection (J0829+4117, J0839+3900, J1216+4519). The FWHM of the major and minor axes of the continuum and [CII]-emitting regions were available in *W24*, allowing us to derive the effective circularized radius, as reported in section 2.2; the associated uncertainty was computed by propagating the error on the major axis reported in the literature. Fluxes, observing frequencies, and [CII] luminosities and associated uncertainties were also taken from the literature.

The approach adopted here was analogous to the previous ones, but this sample served as a testbed for several considerations, on *Method 1* and *Method 2*.

Continuum data and Method 1

The observational continuum data from the literature used in this work are summarized in table 3.10, together with the derived dust masses. The minimum temperature was evaluated for all the sources and for J0319–1008 and J2002–3013 it was found to be higher than 47 K.

[CII] data and Method 2

In addition to the continuum data, [CII] line emission measurements were available for the *W24* sample, specifically the [CII] luminosity and the deconvolved size of that emitting region (and so $R_{\text{[CII]}}$). With the source sizes in hand, the $\alpha_{\text{[CII]}}$ conversion factor was estimated as described in section 2.4, allowing the molecular gas mass to be inferred for each source. These quantities are reported in table 3.11.

Not all sources with detected dust continuum emission also show a [CII] emission line, and not all [CII]-detected sources are spatially resolved. As a result, four sources are excluded in the [CII]-based analysis:

- **J0213–0626** and **J1129+1846** have no detected [CII] emission line, and therefore no measurement of $R_{\text{[CII]}}$ is available;
- **J0837+4929** and **J1135+5011** are observed with NOEMA, whose angular resolution is insufficient to spatially resolve the [CII] emission; consequently, no reliable size measurement can be derived.

The final [CII] sample used in this work therefore consists of 23 sources, all observed with ALMA and spatially resolved.

3.9 Optically thick and optically thin assumption in *W24*

We use the comprehensive information available for the *W24* sample as a testbed to highlight the impact of the optical depth assumption on the derived dust masses. We will do so by comparing estimates obtained under the optically thin approximation

QSO at $z \sim 7$: Continuum data

Name	z	S_{cont} [mJy]	R_{cont} [kpc]	M_{dust} [$10^8 M_{\odot}$]
J0038−1527	7.0340	0.90 ± 0.06	1.25 ± 0.14	1.50 ± 0.10
J0213−0626	6.7214	0.31 ± 0.04	0.7 ± 0.2	0.48 ± 0.06
J0218+0007	6.7700	1.05 ± 0.06	0.93 ± 0.12	1.66 ± 0.10
J0224−4711	6.5222	2.12 ± 0.06	0.99 ± 0.05	3.22 ± 0.10
J0229−0808	6.7249	5.09 ± 0.06	0.57 ± 0.03	9.0 ± 0.8
J0246−5219	6.8876	1.41 ± 0.04	0.70 ± 0.05	2.44 ± 0.08
J0252−0503	7.0006	0.99 ± 0.07	0.92 ± 0.14	1.66 ± 0.12
J0313−1806	7.6422	0.48 ± 0.04	0.88 ± 0.17	0.94 ± 0.08
J0319−1008 ^c	6.8275	0.37 ± 0.06	0.5 ± 0.3	0.60 ± 0.11
J0411−0907	6.8260	0.22 ± 0.06	1.2 ± 0.6	0.34 ± 0.09
J0430−1445	6.7142	0.67 ± 0.09	1.1 ± 0.2	1.02 ± 0.14
J0525−2406	6.5397	3.26 ± 0.06	0.68 ± 0.02	5.90 ± 0.17
J0706+2921	6.6037	0.78 ± 0.05	1.22 ± 0.02	1.16 ± 0.08
J0910+1656	6.7289	0.23 ± 0.05	1.2 ± 0.7	0.35 ± 0.08
J0910−0414	6.6363	3.38 ± 0.04	0.62 ± 0.05	6.9 ± 0.5
J0921+0007	6.5646	0.27 ± 0.08	2.3 ± 0.8	0.39 ± 0.12
J0923+0402	6.6330	0.47 ± 0.11	2.8 ± 0.7	0.69 ± 0.16
J0923+0753	6.6817	0.35 ± 0.08	1.6 ± 0.4	0.52 ± 0.12
J1007+2115	7.5153	1.91 ± 0.07	0.93 ± 0.07	3.84 ± 0.16
J1058+2930	6.5846	0.44 ± 0.08	0.7 ± 0.3	0.65 ± 0.12
J1104+2134	6.7662	1.99 ± 0.04	0.48 ± 0.12	4.2 ± 0.9
J1129+1846 ^a	6.824	0.18 ± 0.08	2.65	0.278
J2002−3013 ^c	6.6876	1.88 ± 0.05	0.30 ± 0.03	2.7 ± 0.5
J2102−1458	6.6645	0.95 ± 0.06	1.0 ± 0.2	1.45 ± 0.10
J2211−6320	6.8449	1.67 ± 0.04	0.50 ± 0.07	3.3 ± 0.3
J0837+4929 ^b	6.6452	0.18 ± 0.03	2.258	0.266
J1135+5011 ^b	6.5851	0.33 ± 0.03	2.256	0.480

Table 3.10: *Properties of the $z \sim 7$ QSOs sample from W24: redshifts z , continuum flux density around the [CII] emission S_{cont} , circularized effective radius R_{cont} , and total dust masses M_{dust} . Notes on individual sources: a: for this source the flux was estimated from the taper image with a beam size of 1 arcsec; b: these are unresolved sources for which the beam size is assumed; in both cases R_e corresponds to an upper limit (beam size) and M_{dust} is correspondingly a lower limit. c: $T_{\text{dust}} = 1.2 T_{\text{min}}$, as explained in section 2.3.2*

QSO at $z \sim 7$: [CII] data

Source	z	$R_{[\text{CII}]}$ (kpc)	α	$L_{[\text{CII}]}$ ($10^9 L_\odot$)	M_{gas} ($10^{10} M_\odot$)
J0038–1527	7.0340	2.3 ± 0.2	26.0 ± 1.7	3.2 ± 0.3	8.3 ± 1.2
J0218+0007	6.7700	1.7 ± 0.4	22 ± 4	1.7 ± 0.4	3.7 ± 1.4
J0224–4711	6.5222	1.36 ± 0.08	18.3 ± 0.7	5.43 ± 0.15	9.9 ± 0.7
J0246–5219	6.8876	1.25 ± 0.10	17 ± 1	3.13 ± 0.18	5.4 ± 0.6
J0252–0503	7.0006	2.5 ± 0.5	28 ± 4	2.7 ± 0.5	8 ± 2
J0313–1806	7.6422	1.2 ± 0.5	16 ± 5	0.60 ± 0.13	1.0 ± 0.5
J0319–1008	6.8275	2.2 ± 0.7	25 ± 5	2.5 ± 0.7	6 ± 3
J0411–0907	6.8260	4.3 ± 1.0	40 ± 7	2.1 ± 0.5	8 ± 3
J0430–1445	6.7142	1.47 ± 0.18	19.3 ± 1.6	2.7 ± 0.3	5 ± 1
J0525–2406	6.5397	1.28 ± 0.04	17.5 ± 0.4	5.48 ± 0.19	9.6 ± 0.5
J0706+2921	6.6037	2.6 ± 0.5	28 ± 4	2.2 ± 0.3	6.3 ± 1.7
J0910+1656	6.7289	2.8 ± 0.5	30 ± 3	1.9 ± 0.3	5.6 ± 1.5
J0910–0414	6.6363	1.44 ± 0.19	19.0 ± 1.7	4.2 ± 0.2	7.9 ± 1.1
J0921+0007	6.5646	2.4 ± 0.3	27 ± 3	1.20 ± 0.14	3.3 ± 0.7
J0923+0402	6.6330	2.4 ± 0.3	27 ± 2	2.0 ± 0.2	5.5 ± 1.1
J0923+0753	6.6817	2.6 ± 0.5	28 ± 3	1.7 ± 0.3	4.8 ± 1.4
J1007+2115	7.5153	0.97 ± 0.18	14.5 ± 1.8	2.8 ± 0.2	4.0 ± 0.8
J1058+2930	6.5846	2.5 ± 0.6	27 ± 5	2.7 ± 0.5	8 ± 3
J1104+2134	6.7662	2.0 ± 0.3	24 ± 3	1.8 ± 0.3	4.3 ± 1.2
J2102–1458	6.6645	1.5 ± 0.2	19 ± 2	1.51 ± 0.14	2.9 ± 0.6
J2211–6320	6.8449	0.93 ± 0.12	14.0 ± 1.2	2.27 ± 0.16	3.2 ± 0.5
J2002–3013	6.6876	1.07 ± 0.17	15.5 ± 1.7	2.2 ± 0.2	3.4 ± 0.7
J0229–0808	6.7249	1.15 ± 0.08	16.3 ± 0.7	4.81 ± 0.19	7.8 ± 0.7

Table 3.11: *Properties of the $z \sim 7$ QSOs sample. Redshifts z , [CII] emission line luminosity $L_{[\text{CII}]}$, from Wang et al. 2024 circularized effective radius of the [CII] emission $R_{[\text{CII}]}$, evaluated as described in the text. The conversion factor $\alpha_{[\text{CII}]}$ and gas mass M_{gas} were derived as described in the text.*

with those from the general formulation, highlighting the conditions under which the two regimes diverge and the thin assumption breaks down.

Most of the considerations discussed in section 2.3 can be summarized in two main degeneracies: the one between optical depth and temperature ($\tau - T$) and the one between mass and size ($M - R$).

Dust Masses

In addition to the observables listed in table 3.10 and table 3.11, Wang et al. 2024 also reported an estimate of the dust mass. The dust masses derived by Wang et al. 2024, here M_{Wang} , were obtained under the optically thin assumption, i.e. using eq. (2.29). In this section we examine how the derived mass changes under the two assumptions (optically thin vs. general treatment)⁸, and the resulting consequences for the inferred column density.

Firstly the dust mass was evaluated using eq. (2.29), M_{thin} and compared with M_{Wang} . The dust temperature was fixed to $T_{\text{dust}} = 47$ K, the emissivity index to $\beta = 1.6$, with the opacity coefficient $\kappa_{\nu}(\beta) = 0.77 (\nu/352 \text{ GHz})^{\beta} \text{ cm}^2 \text{ g}^{-1}$, as assumed in the literature and also in W24. The ratio between the dust masses derived here and those reported in W24 is shown in fig. 3.6: the mean ratio is ~ 0.93 , validating the implementation of eq. (2.29) and the few-percent offset may be attributed to small differences between the exact input values (fluxes, redshifts) adopted by the authors and those available from the published tables in Wang et al. 2024. Having established the consistency of the optically thin calculation, the impact of relaxing the optically thin assumption was studied.

The mass was then estimated using the general formula in eq. (2.24), which we denote here M_{general} to distinguish it from the thin case M_{thin} : fig. 3.7 shows a comparison of the ratio of the dust masses computed with the two assumptions. For 9 sources out of 27 the ratio between M_{general} and M_{thin} is significantly larger than one (i.e., not consistent with unity within the errors), meaning that the approximation of thin case is inadequate to evaluate the dust mass. The values obtained under the different assumptions are listed in table 3.12. Both values were derived assuming the same temperature, as discussed below.

Minimum temperature

In estimating the dust mass in the general case, adopting a temperature of 47 K yield unphysical results for the source J2002–3013: when the optically thin assumption is relaxed, it is not possible to derive a dust mass for this source assuming a temperature $T_{\text{dust}} = 47$ K. This prompted a more detailed analysis of the minimum dust temperature for each source.

The minimum temperature was computed using eq. (2.26), and the resulting values are reported in table 3.12. For most quasars, T_{min} is well below 47 K, validating the adopted temperature. However, for J2002–3013, $T_{\text{min}} = 50.3$ K: a temperature of 47 K is not enough to reproduce the observed flux with the measured size. For J0229–0808 the resulting minimum temperature is 45 K, which is mathematically

⁸Remember that, as seen in section 2.3 if the half-light radius is used in eq. (2.24), then it is necessary to put half of the total observed flux in those equations.

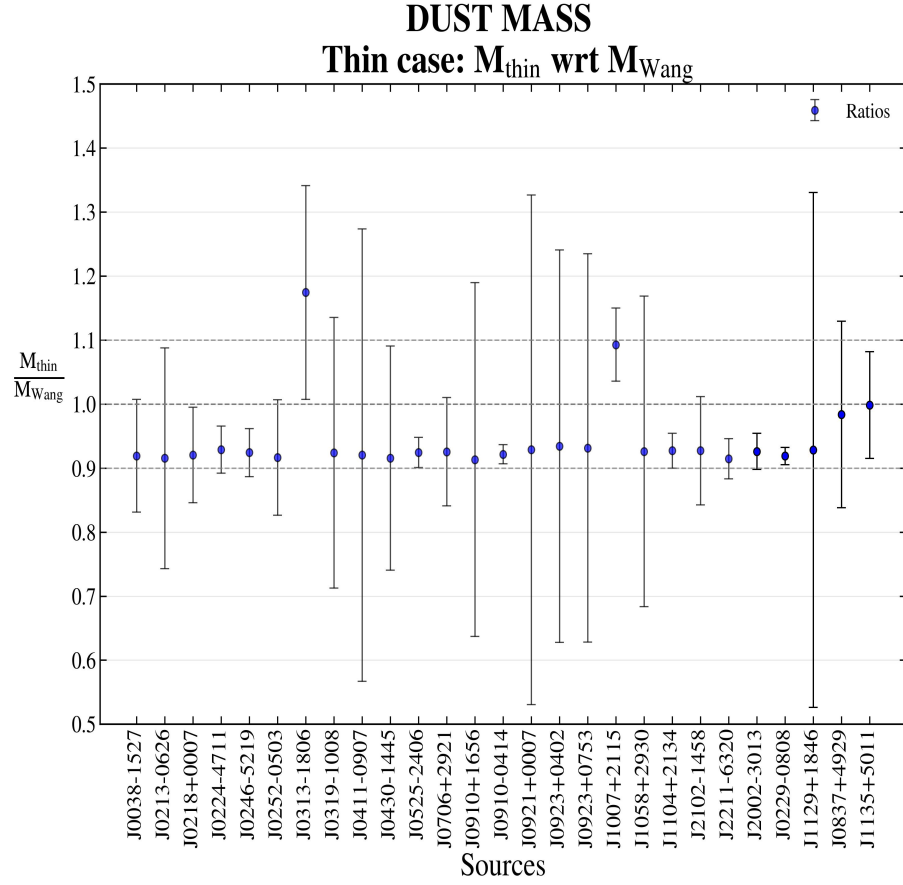


Figure 3.6: *Optically thin case: ratio between the dust mass estimates derived in this work under the optically thin approximation eq. (2.29), M_{thin} , and the dust masses reported by W24 (M_{Wang}), again estimated in the optically thin approximation.*

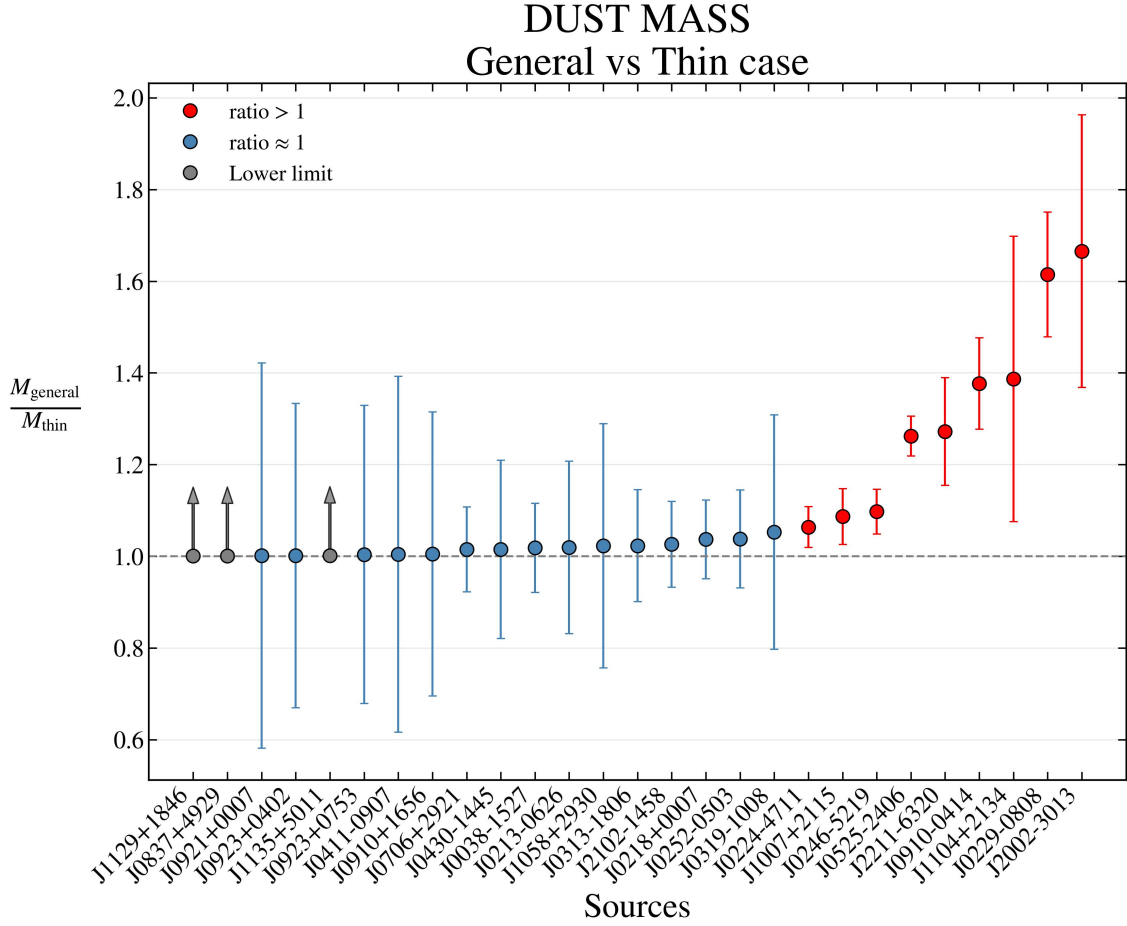


Figure 3.7: Ratio between the dust mass estimated in the general case M_{general} and that derived under the optically thin assumption M_{thin} . Blue points indicate sources whose ratios are consistent with unity within the uncertainties (15 sources), while red points denote sources whose ratios remain significantly larger than unity even accounting for the measurement uncertainties (9 sources). Gray points with upward arrows mark unresolved sources for which only a lower limit on the size is available (3 sources), and thus represent lower limits on the true ratio.

permitted; however given how close this value lies to the reference of 47 K, the dust in this source is likely warmer than this standard assumption would suggest. For these objects, as was similarly done for the *Venemans* sample of quasars, a temperature of $1.2 T_{\min}$ was adopted.

These sources show that neglecting the minimum temperature constraint and assuming optically thin emission can lead to dust mass estimates that differ by a factor of ~ 2 or even unphysical solutions. These examples highlight the necessity to understand how dust temperature, mass, and source size are intrinsically correlated through the optical depth.

Optical depth

Once the dust mass in the general case is determined, the corresponding optical depth can be estimated as $\tau_\nu = k_\nu \cdot M_{\text{dust}}/A$ (Gilli et al. 2022). The obtained values are listed in table 3.12. For completeness, the distributions of the minimum temperature and optical depth are also shown in fig. 3.8: the two sources that have an optical depth larger than 1 and a minimum temperature similar or higher than 47 K corresponds to J0229-0808 and J2002-3013, respectively.

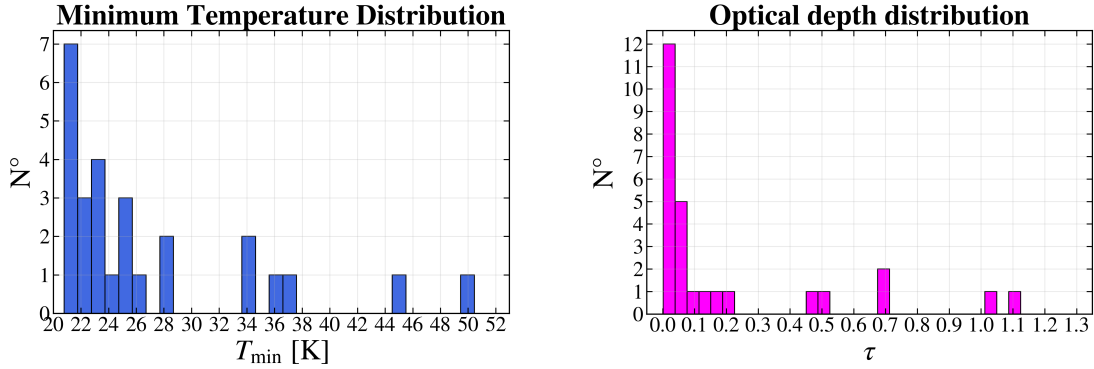


Figure 3.8: *Distributions of minimum temperature (left) and optical depth (right) for W24.*

3.9.1 Optical depth-Temperature degeneracy and Mass-Size degeneracy in W24

At this point to better understand the degeneracies discussed so far and the dependence on size, several plots are introduced.

Figure 3.9 illustrates the effects of optical depth, minimum dust temperature and size, on the ratios between the dust mass computed in the general case using eq. (2.24) and in the optically thin case using eq. (2.29), for each source. The color map in each panel, from top to bottom, corresponds to optical depth, minimum temperature and size (half light radius), respectively. The source IDs are reported on the x-axis, at the bottom. In the colormaps, lighter colors indicate higher values:

Optical depth, minimum temperature, and dust masses under different assumptions for QSOs at $z \sim 7$

Name	τ	$T_{\min}$ [K]	M_{general} [$10^8 M_{\odot}$]	M_{thin} [$10^8 M_{\odot}$]
J0038−1527	0.036 ± 0.008	23.5 ± 0.4	1.50 ± 0.10	1.47 ± 0.10
J0213−0626	0.04 ± 0.02	22.9 ± 1.0	0.48 ± 0.06	0.47 ± 0.06
J0218+0007	0.073 ± 0.019	24.4 ± 0.7	1.66 ± 0.10	1.60 ± 0.09
J0224−4711	0.125 ± 0.013	25.8 ± 0.5	3.22 ± 0.10	3.03 ± 0.09
J0246−5219	0.19 ± 0.03	28.2 ± 0.8	2.43 ± 0.08	2.22 ± 0.06
J0252−0503	0.07 ± 0.02	24.9 ± 0.9	1.66 ± 0.12	1.60 ± 0.11
J0313−1806	0.046 ± 0.018	25.3 ± 0.6	0.94 ± 0.08	0.92 ± 0.08
J0319−1008	0.10 ± 0.12	26 ± 4	0.60 ± 0.11	0.57 ± 0.09
J0411−0907	0.009 ± 0.008	21.8 ± 0.4	0.34 ± 0.09	0.34 ± 0.09
J0430−1445	0.030 ± 0.012	22.5 ± 0.6	1.02 ± 0.14	1.01 ± 0.14
J0525−2406	0.49 ± 0.03	33.7 ± 0.6	5.90 ± 0.17	4.68 ± 0.09
J0706+2921	0.030 ± 0.002	22.27 ± 0.10	1.16 ± 0.08	1.14 ± 0.07
J0910+1656	0.010 ± 0.012	21.6 ± 0.6	0.35 ± 0.08	0.35 ± 0.08
J0910−0414	0.68 ± 0.12	36.4 ± 1.9	6.9 ± 0.5	4.98 ± 0.06
J0921+0007	0.003 ± 0.002	20.78 ± 0.12	0.39 ± 0.12	0.39 ± 0.12
J0923+0402	0.0034 ± 0.0019	20.99 ± 0.11	0.69 ± 0.16	0.69 ± 0.16
J0923+0753	0.008 ± 0.004	21.4 ± 0.2	0.52 ± 0.12	0.52 ± 0.12
J1007+2115	0.17 ± 0.03	28.6 ± 0.7	3.84 ± 0.16	3.53 ± 0.13
J1058+2930	0.05 ± 0.03	23.0 ± 1.5	0.65 ± 0.12	0.64 ± 0.12
J1104+2134	0.7 ± 0.4	37 ± 6	4.2 ± 0.9	3.03 ± 0.06
J2102−1458	0.05 ± 0.02	23.4 ± 0.9	1.45 ± 0.09	1.41 ± 0.09
J2211−6320	0.50 ± 0.15	34 ± 3	3.3 ± 0.3	2.60 ± 0.06
J1129+1846	> 0.0015	21	> 0.278	0.28 ± 0.12
J0837+4929	> 0.0020	21	> 0.266	0.27 ± 0.04
J1135+5011	> 0.0036	21	> 0.480	0.48 ± 0.04
J2002−3013	1.1 ± 0.3	50 ± 4	2.7 ± 0.5	1.57 ± 0.04
J0229−0808	1.05 ± 0.14	45.0 ± 1.9	9.0 ± 0.7	5.55 ± 0.07

Table 3.12: *Optical depth, minimum temperature, and dust masses (general vs. thin case) for the sources in the W24 sample. For J1129+1846, J0837+4929, and J1135+5011, only an upper limit on the size was available; the corresponding τ and M_{general} values should therefore be regarded as lower limits (see text). For J2002−3013 and J0319−1008 a dust temperature of $T = 1.2T_{\min}$ was adopted.*

for optical depth and radius, yellow represents larger values, while for minimum temperature, light blue indicates higher temperatures. It is possible to observe that, as the ratios between the two mass estimates increases, optical depth increases and minimum temperature also increases, while size decreases. These plots clearly show that dust mass cannot be reliably estimated under the optically thin approximation for more compact sources. The general case (eq. (2.24)) holds regardless of whether the source lies in the optically thin regime or not, (eq. (2.24) is size dependent) whereas the thin approximation (eq. (2.29) no size dependence) breaks down for a subset of sources — particularly the most compact ones. As the ratio deviates from 1 the minimum temperature also increases: departing from optically thin regime leads to higher minimum dust temperatures; for compact and optically thick configurations, low-temperature solutions are excluded by the model and in this regime, the minimum dust temperature becomes a strong lower bound imposed by the optical depth and source size.

To better visualize this effects and the dependence of observed flux on optical depth, size, temperature, we show other two plots arranged in two panels, in figs. 3.10 to 3.12. In the top panel, the flux is shown as a function of dust temperature and optical depth, $S_{\nu_{\text{obs}}}(T, \tau)$. In the bottom panel, the flux is shown as a function of dust mass and source size, $S_{\nu_{\text{obs}}}(M, R)$. The plots are shown for three representative sources, selected as particular cases in fig. 3.9: one source with $M_{\text{general}}/M_{\text{thin}} \sim 1$ (J0923+0753), one with $M_{\text{general}}/M_{\text{thin}} \gg 1$ (J1104+2134) and the source with a minimum dust temperature exceeding 47 K (J2002–3013). The plots for all the remaining sources are presented in appendix A.3.

In both panels the color scale represents the continuum flux density as function of the plotted variables. The red curve marks the iso-flux curve corresponding to half of the observed flux density ($S_{\nu_{\text{obs}}}/2$): this choice reflects the fact that the effective radius R_{cont} encloses half of the total continuum emission.

τ -T degeneracy, top panel

The flux is shown as a function of dust temperature and optical depth, for a fixed source size (reported under the plot). The vertical cyan line marks the dust minimum temperature (T_{min} , see also table 3.12). This temperature is not an assumed value, but a physical lower limit set by the requirement of reproducing the observed flux at fixed size: in the plot this line corresponds to the asymptotic limit of the iso-flux line in the optically thick regime.

The blue line indicates the assumed dust temperature to compute the dust mass (47 K for all quasars, except for J0229-0808 and J2002-3013). For a given temperature, the corresponding optical depth (black line) can be inferred from the intersection with the iso-flux curve (red curve).

M-R degeneracy, bottom panel

The flux is shown as a function of the size and dust mass (effective radius and dust mass contained in this size). The red curve shows all the combination of M_{gen} , R , returning half of the observed flux. For a fixed source size R (black vertical line, corresponding to the measured half-light-radius), the dust mass can be inferred

from the intersection with the iso-flux contour. The two horizontal dashed lines represent the dust mass estimated in the optically thin regime (M_{thin} , cyan) and the general formulation (M_{dust} , blue). Both these values correspond to half of the values in table 3.12, consistently with the use of R_{eff} . The value of the optical depth, reported under the plot, rules the regime. When the optical depth is small ($\tau \ll 1$), the two mass estimates coincide and the two horizontal lines overlap: this is the case of J0923+0753, fig. 3.10. As the optical depth increases, the system moves toward the optically thick regime, the optically thin approximation progressively underestimates the true dust mass and the two horizontal lines diverge: this is the case of J1104+2134, fig. 3.12.

These plots together illustrate the intrinsic degeneracies among mass, size, temperature, and optical depth and how to derive and interpret these quantities from continuum observations. The purpose of these plots is to show how the transition between optically thin and optically thick regimes, directly corresponds to the region where the general dust-mass estimate departs from the optically thin approximation. As the system approaches the optically thick limit and the temperature approaches its minimum limit, the thin approximation increasingly underestimates the true dust mass and, consequently, the column density. This concept will be further discussed also in section 4.2.2.

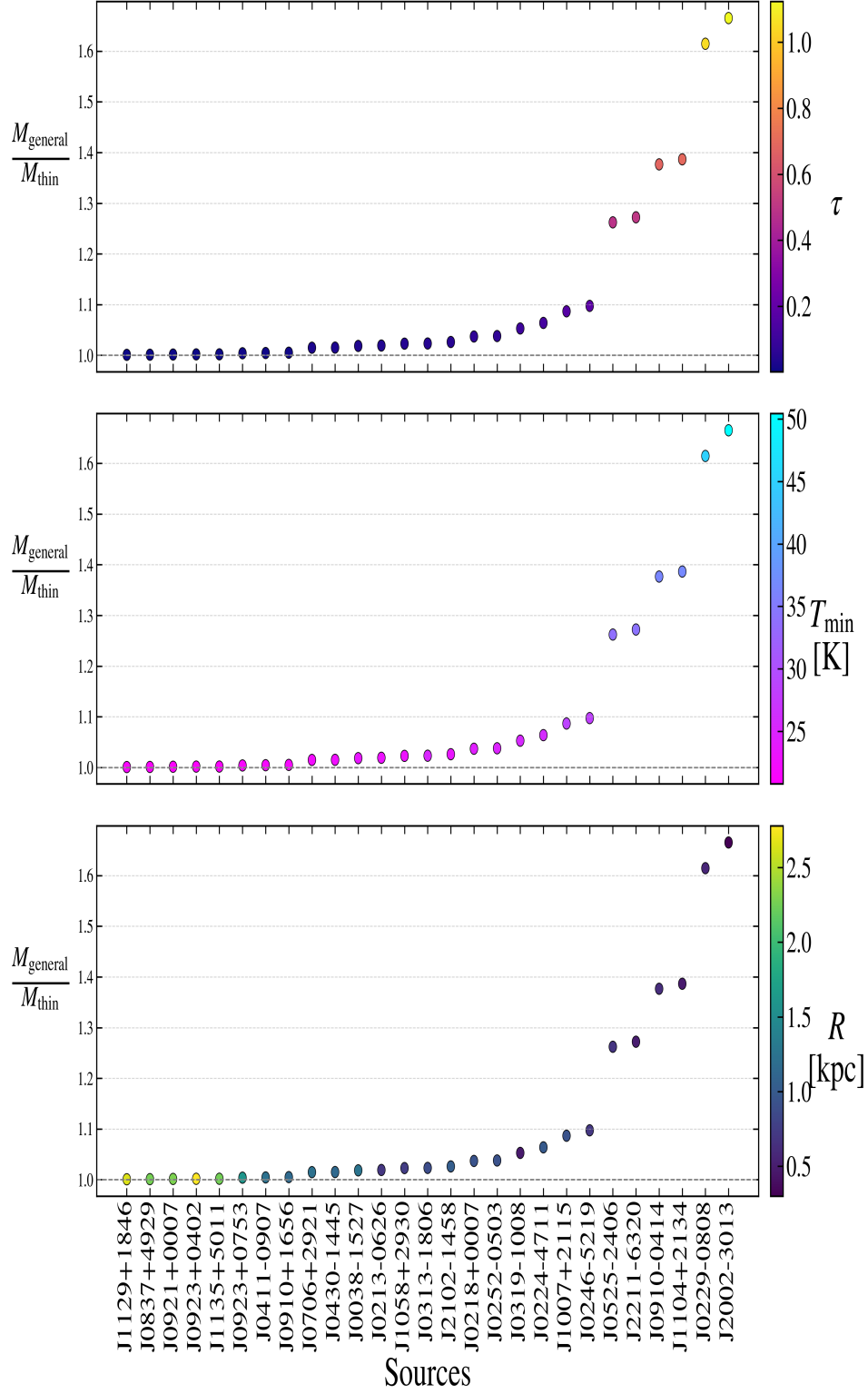


Figure 3.9: Ratios between the dust mass computed in the general case (eq. (2.24)) and under the optically thin approximation (eq. (2.29)) of optical depth, minimum dust temperature, and source size (half-light radius).

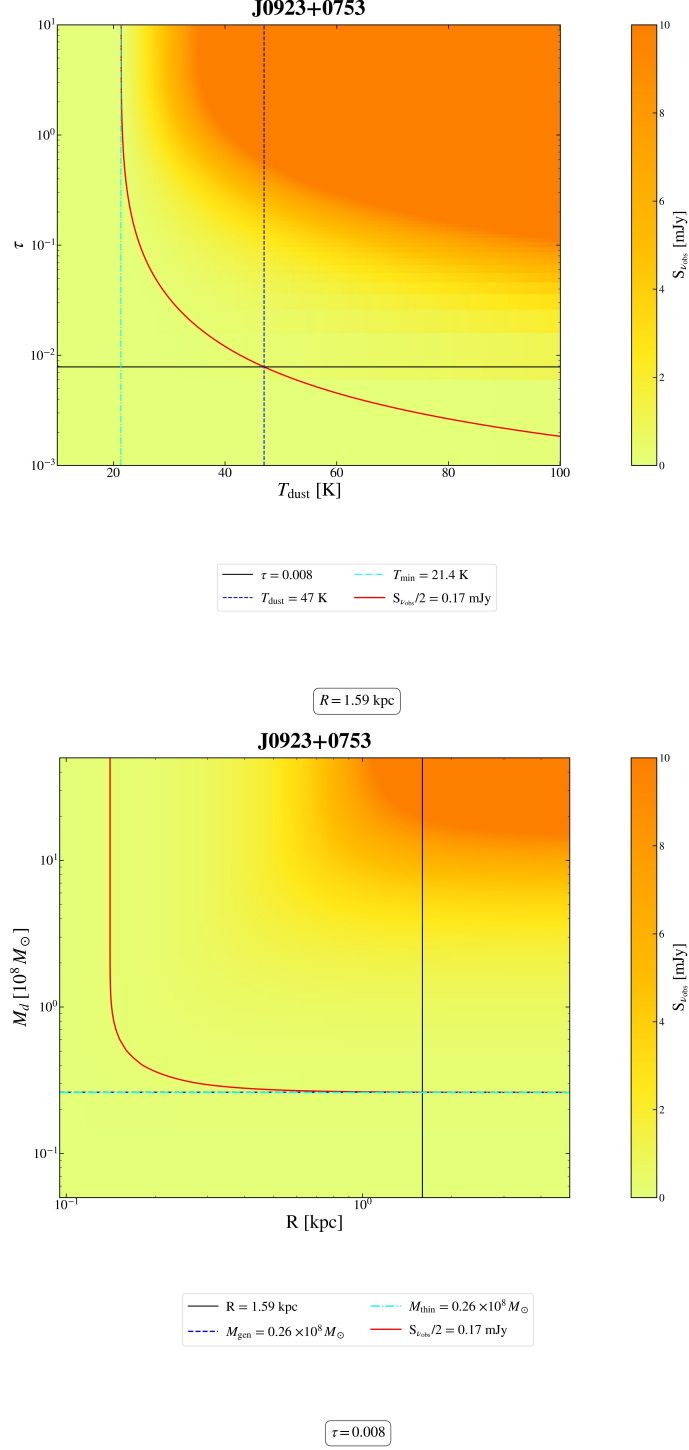
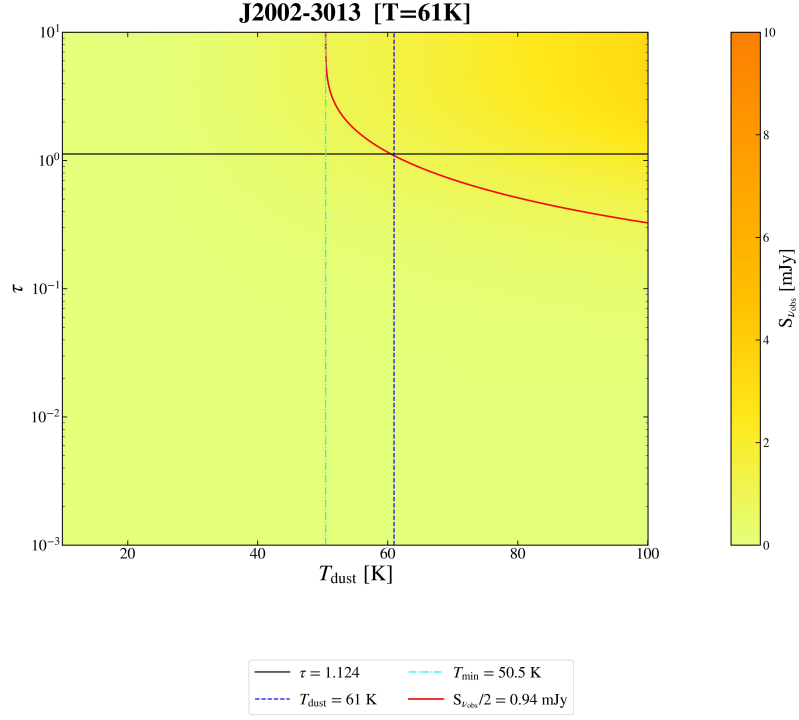
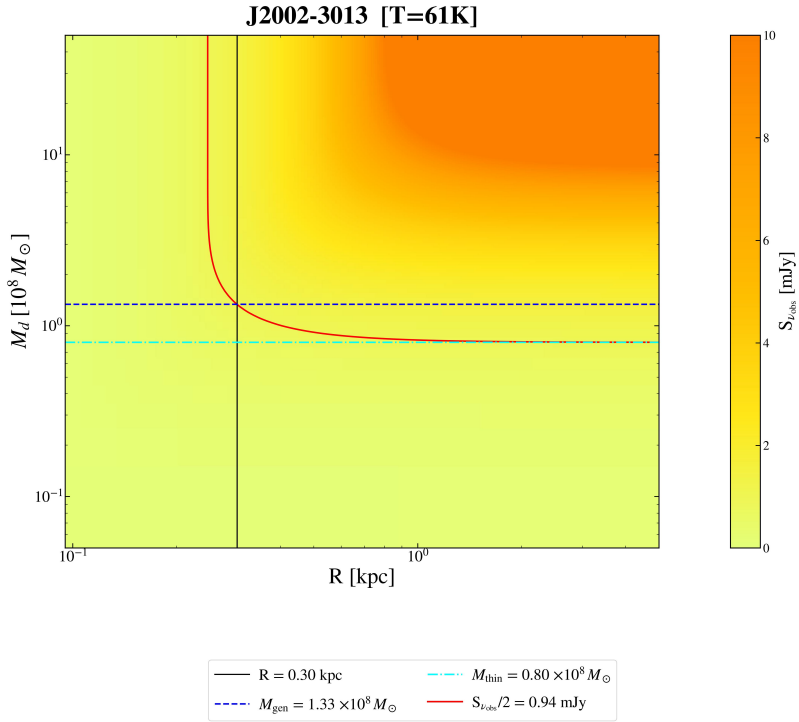


Figure 3.10: Source J0923+0753, with $M_{\text{general}}/M_{\text{thin}} \sim 1$. Upper panel: Flux as a function of optical depth and temperature. The red curve shows the isoflux curve corresponding to half of the observed flux, and the horizontal black line indicates the optical depth for the fiducial dust temperature of 47 K (blue vertical line). The cyan vertical line marks the minimum temperature. Bottom panel: Flux as a function of dust mass and size. The red curve shows the isoflux curve corresponding to half of the observed flux, the horizontal cyan line indicates the mass computed in the optically thin approximation, and the horizontal blue line shows the mass in the general case. The black vertical line marks the source effective radius. Measured values of the quantities are given in the legends, and the color map represents the flux. The two panels are linked through the parameters shown at the bottom of each panel.

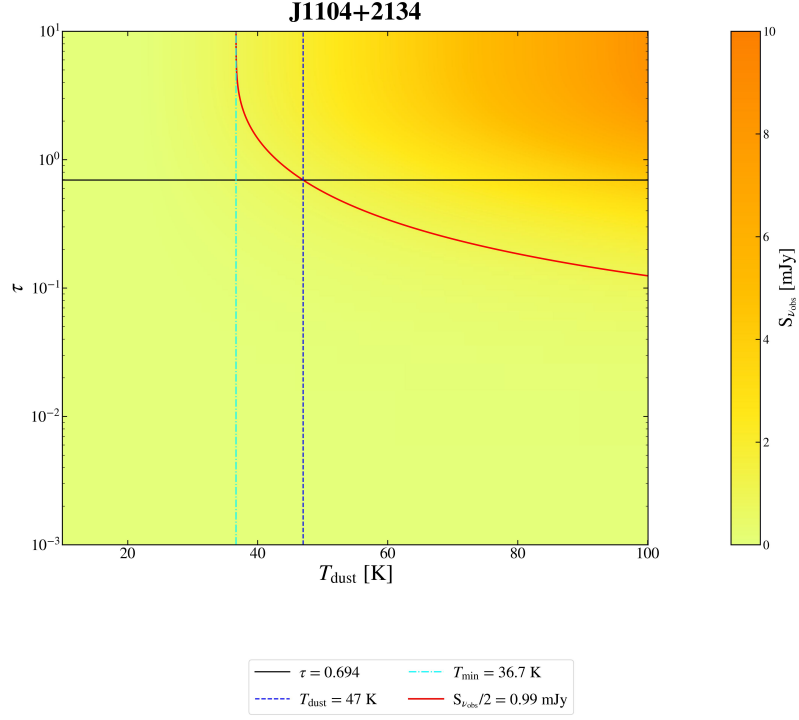


$R = 0.30 \text{ kpc}$

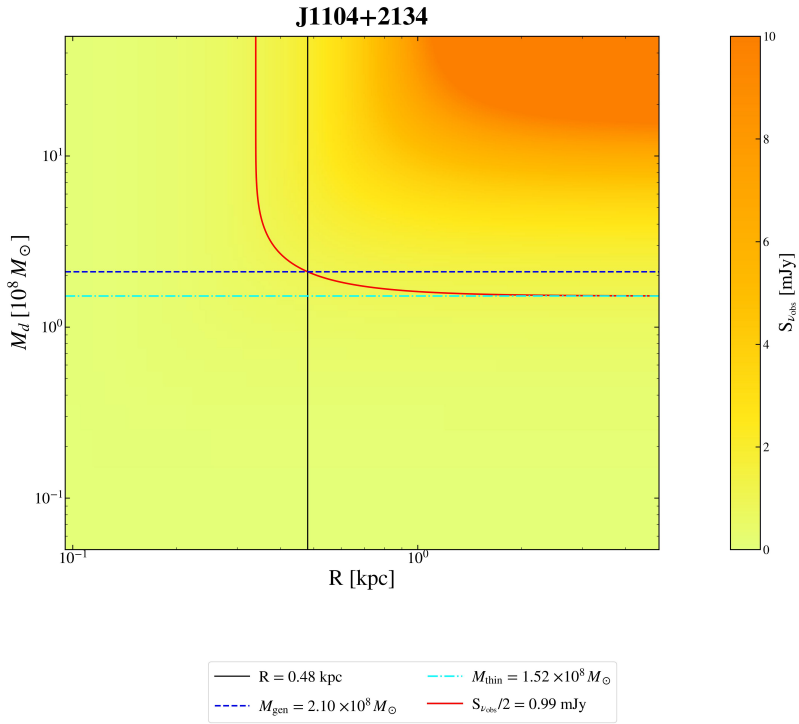


$\tau = 1.124$

Figure 3.11: Same as fig. 3.10, but for the source J2002-3013, with $T_{\min} > 47 \text{ K}$.



$R = 0.48 \text{ kpc}$



$\tau = 0.694$

Figure 3.12: Same as fig. 3.10, but for the source J1104+2134, with $M_{\text{general}}/M_{\text{thin}} \gg 1$ (but $T_{\text{min}} < 47 \text{ K}$).

Chapter 4

Results and discussion

In this chapter we present and discuss the main results of this work that can be drawn from the data presented in chapter 3. In section 4.1 the dust masses estimates are reported for the full compilation of sources that span $z \sim 0 - 7$, including the QSOs sample of *W24*, analyzed here for the first time. We then compare in section 4.2 the column densities obtained from the three different tracers adopted in this work, dust continuum, [CII] emission and SFR-based, assessing their consistency and identifying systematic effects. In particular, when comparing the [CII] and dust-continuum estimates, we examine in detailed the size and gas-mass properties of the new $z \sim 7$ QSOs sample and investigate the compactness of QSOs at $z \sim 6 - 7$ and its connection to the optically thin/thick regimes of dust continuum emission. Finally, in section 4.3 we combine all tracers and samples to study the evolution of N_{H} with redshift up to $z \sim 7$ and beyond, quantifying the nuclear obscuration provided by the ISM.

4.1 Dust masses

Once we have checked *Method 1*, comparing it with Gilli et al. 2022 and having all the degeneracies under control, we re-estimated the dust masses for all the sources presented in chapter 3: 79 sources up to $z \sim 6$ belonging to the ASPECS, *Suzuki21*, ALPINE, *Izumi* and *Venemans*) samples and 27 sources at $z \sim 7$ belonging to the *W24* sample. In total we have assembled 106 sources (the largest compilation assembled so far) for which dust masses have been derived consistently assuming the "*M general*" approach, i.e. applying eq. (2.24) to the observed continuum fluxes reported in literature.

Figure 4.1 shows these values and the two curves corresponding to the minimum mass one can infer assuming a flux density at 1.2 mm of $S_{\nu_{\text{obs}}} = 0.03$ mJy and $S_{\nu_{\text{obs}}} = 0.09$ mJy, respectively, and a dust temperature of $T_{\text{dust}} = 47$ K in eq. (2.29) (the minimum mass is obtained under the thin approximation-size independent relation), following the same assumption adopted by Gilli et al. 2022. These fluxes correspond, respectively, to the 3σ detectability limit for the ASPECS survey and for the *W24* sample, with one key difference: for ASPECS, $\sigma = 10 \mu\text{Jy}$ is the uniform rms reached across the entire blind survey, whereas for *W24* it is simply the smallest flux uncertainty among the individually targeted sources. In both cases, these curves

tell us the dust mass limit probed by each dataset: following the same logic in Gilli et al. 2022, we want to show that dust masses down to $\sim 10^7 M_\odot$ are, in principle, detectable at all redshifts considered, which is what makes it possible to trace the evolution of the ISM column density with z , without that evolution being affected by a redshift-dependent detection bias.

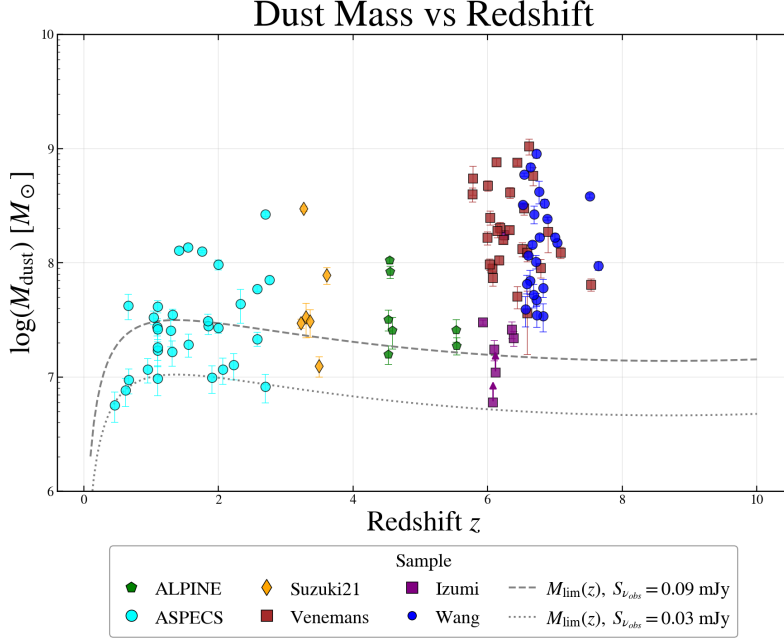


Figure 4.1: *Dust mass as a function of redshift for the galaxy and quasar samples considered in this work: ALPINE, ASPECS, Suzuki21, Venemans and Izumi ($z \sim 6$ quasar hosts), and the newly implemented W24 sample at $z \sim 7$. The dotted line marks the minimum dust mass corresponding to the 3σ continuum sensitivity of the ASPECS survey ($\sigma = 10 \mu\text{Jy}$, i.e., $S_{\nu_{\text{obs}}} = 0.03 \text{ mJy}$). The dashed line marks the minimum dust mass corresponding to the deepest 3σ sensitivity reached among the W24 sources ($\sigma_{\text{min}} = 0.03 \text{ mJy}$, i.e., $S_{\nu_{\text{obs}}} = 0.09 \text{ mJy}$). Both curves assume a dust temperature $T_d = 47 \text{ K}$ in eq. (2.29), following Gilli et al. 2022. Upward arrows mark sources for which only a lower limit on the dust mass could be inferred.*

4.2 Comparison of column densities with different methods

Having derived N_H for all samples following the methodology described in chapter 2 across the three tracers (dust continuum, [CII], and SFR-based inversion of the Kennicutt–Schmidt relation), several considerations can be drawn based on the tracer employed. Thus, before presenting the evolution of N_H with redshift, we first report the comparisons between the column densities obtained from the different tracers, in order to evaluate their consistency and identify any systematic offsets between methods, seeking to understand how the physics underlying each tracer is reflected in a different N_H value.

4.2.1 SFR vs Dust Continuum: springboard for new JWST data

The *Suzuki21* and ALPINE samples present both an estimate of the dust continuum flux (Gilli et al. 2022) and of the SFR (Shuntov et al. 2025). The relevant data are presented in section 3.3 and section 3.4 respectively. We can therefore compare the values of N_{H} obtained with *Method 1* and *Method 3*.

Suzuki21 sample

Table 4.1 shows the values of column densities obtained via the dust-based and SFR-based methods for the massive galaxies at $z \sim 3$ of *Suzuki21*, together with their ratio (four out of six had SFR measurements). A visual comparison of the column densities obtained with the different methods for these 4 sources is provided in fig. 4.2 (left). Given the small sample size, it is not possible to draw firm conclusions. Nonetheless, we note that for sources 434585 and 406444 the two methods yield comparable values. For 214339 and 192129 the two estimates differ moderately, even accounting for the associated uncertainties, with the SFR-based method providing a lower column density. In more detail, source 214339 is the only source for which no *Sérsic radius* is available. In this case, we used the size of the dust continuum emission as a characteristic radius. This choice may partly account for the measured discrepancy. Inspection of the catalogue reveals that source 192129 is flagged with a Chandra detection, suggesting the possible presence of an AGN, which could affect the SFR-based estimate.

Suzuki21* column densities: *Method 1* vs *Method 3

Name	z	$N_{\text{H,dust}} [\text{cm}^{-2}]$	$N_{\text{H,SFR}} [\text{cm}^{-2}]$	$N_{\text{H,SFR}}/N_{\text{H,dust}}$
3	3.230	$(3.7 \pm 1.5) \times 10^{22}$	—	—
208681	3.267	$(3.9 \pm 1.6) \times 10^{24}$	—	—
406444	3.304	$(3.1 \pm 1.6) \times 10^{22}$	$(3.9 \pm 0.6) \times 10^{22}$	1.3 ± 0.7
434585	3.363	$(1.7 \pm 0.8) \times 10^{23}$	$(1.6 \pm 0.3) \times 10^{23}$	0.9 ± 0.5
192129	3.495	$(1.1 \pm 0.5) \times 10^{23}$	$(3.0 \pm 0.5) \times 10^{22}$	0.3 ± 0.1
214339	3.609	$(2.2 \pm 1.0) \times 10^{23}$	$(6 \pm 2) \times 10^{22}$	0.3 ± 0.2

Table 4.1: Comparison of N_{H} estimates from dust continuum and SFR-based methods, with their ratio, for the *Suzuki21* sample of sources at $z \sim 3$.

ALPINE sample

An analogous comparison has been carried out for the *ALPINE* sample: table 4.2 shows the values of column densities obtained with the two different methods, with the corresponding visual representation in the right panel of fig. 4.2.

Of the seven ALPINE sources with a dust-based estimate, only four of them also have a SFR-based one, as explained in section 3.4. The SFR based method underestimates the column density relative to the dust-based one for three sources,

ALPINE column densities: Method 1 vs Method 3

Name	z	$N_{\text{H,dust}} [\text{cm}^{-2}]$	$N_{\text{H,SFR}} [\text{cm}^{-2}]$	$N_{\text{H,SFR}}/N_{\text{H,dust}}$
DC_494057	5.540	$(3.2 \pm 1.9) \times 10^{23}$	—	—
DC_683613	5.536	$(5 \pm 4) \times 10^{23}$	—	—
DC_818760	4.554	$(4.3 \pm 1.8) \times 10^{23}$	—	—
DC_873756	4.548	$(5 \pm 3) \times 10^{23}$	$(5.8 \pm 1.9) \times 10^{22}$	0.12 ± 0.09
vc_5100822662	4.5235	$(5 \pm 3) \times 10^{22}$	$(1.4 \pm 0.2) \times 10^{23}$	2.6 ± 1.4
vc_5100969402	4.5869	$(4 \pm 3) \times 10^{23}$	$(2.0 \pm 0.3) \times 10^{23}$	0.5 ± 0.3
vc_5180966608	4.5293	$(5 \pm 5) \times 10^{23}$	$(1.01 \pm 0.16) \times 10^{23}$	0.18 ± 0.16

Table 4.2: Comparison of N_{H} estimates from dust continuum and SFR-based methods, with their ratio, for the ALPINE sources at $z \sim 4 - 5$.

as already noted for the *Suzuki21* sample. vc_5100822662, shows the opposite behaviour, with the SFR-based estimate exceeding the dust-based one by a factor of ~ 2.6 .

vc_5180966608 has its dust-continuum size measurement flagged as "bad" in Gilli et al. 2022; since $N_{\text{H}} \propto R^{-2}$ in the dust-continuum method, an unreliable size measurement could plausibly contribute to this discrepancy. None of the four sources is flagged with a Chandra detection in the COSMOS catalogue.

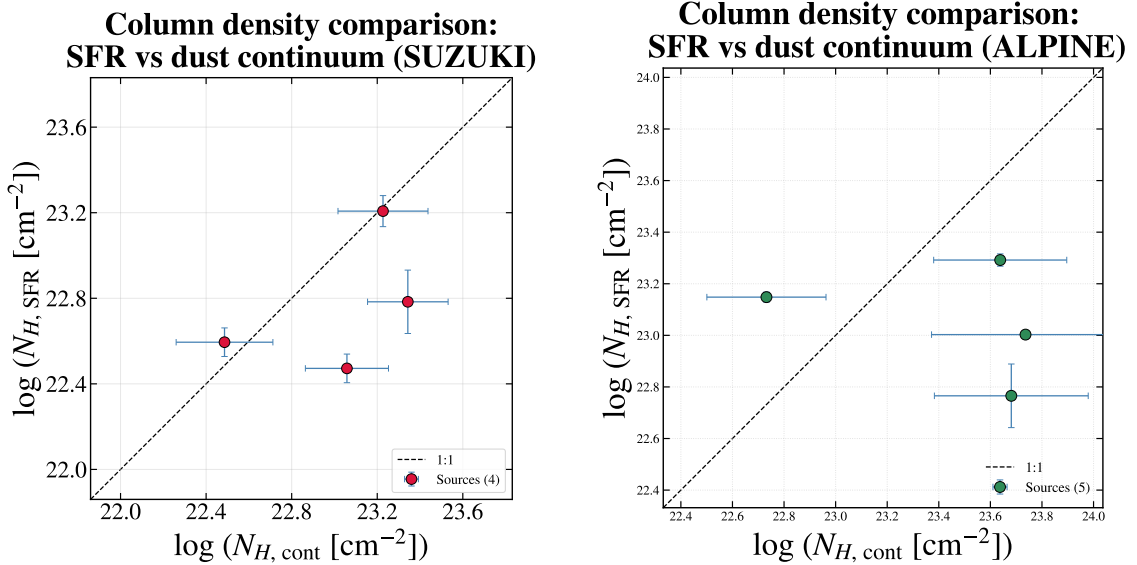


Figure 4.2: Comparison of N_{H} estimates from the SFR-based and dust-continuum methods for the *Suzuki21* (left) and ALPINE (right) samples.

Considering the eight sources in the two samples ($z \sim 3 - 5$) for which both estimates are available, what emerges is that the SFR-based method tends to underestimate the column density with respect to the dust-based method; averaging the ratio in logarithmic space, this amounts to roughly a factor of two:

$$N_{\text{H,SFR}} \simeq 0.55 N_{\text{H,cont}} \quad (4.1)$$

Overall, given the small number of sources with both estimates available, these results should be regarded as suggestive rather than conclusive. Nonetheless, the SFR-based method is the only one currently available for estimating the column density at high redshift, where dust-continuum observations are not easily accessible. With the advent of JWST, which investigates the distant Universe, giving us information about star formation and the structural properties of galaxies at $z \geq 6$ we extended this method at $z \sim 7$ and beyond (see section 3.7), keeping the caveats discussed above in mind.

4.2.2 [CII] vs Dust Continuum: compactness and dust temperature

Here we report a comparison between the values of N_{H} obtained with [Method 1](#) and [Method 2](#). This comparison was possible for the *ALPINE* sample and for the QSOs of *Venemans*, *Izumi* and *W24* at $z \sim 6 - 7$ whose description and data tables are presented in section 3.4, section 3.5 and section 3.8 respectively.

In order to have a complete understanding of the column densities derived from the two estimates and their comparison, we first compared the sizes of the corresponding emission regions and the resulting total gas masses

Size comparison

Firstly, we compared the size $R_{[\text{CII}]}$ and R_{cont} for the ALPINE and QSOs at $z \sim 6 - 7$ sample (fig. 4.3): the [CII]-derived sizes are systematically more extended than the dust continuum ones, reflecting the different physical processes traced by the two emissions: while the continuum emission predominantly probes the dense molecular phase associated with dust, the [CII] emission also arises from PDRs and diffuse neutral gas, thus tracing a more extended and heterogeneous component of the interstellar medium (section 1.3.4). This behaviour is more pronounced for the ALPINE sources ($R_{[\text{CII}]} \sim 3R_{\text{cont}}$) than for the quasars at $z \sim 6$ ($R_{[\text{CII}]} \sim 1.5R_{\text{cont}}$) and the quasars at $z \sim 7$ ($R_{[\text{CII}]} \sim 2R_{\text{cont}}$).

Mass comparison

We then compared the total gas mass estimates derived from the two tracers, which in principle should be consistent with each another, since both the conversion factor $\alpha_{[\text{CII}]}$ and the gas-to-dust ratio δ_{GDR} provide independent methods for estimating the same total gas mass.

For the ALPINE sample, the gas mass computed from the dust continuum assuming a dust temperature of $T_{\text{dust}} = 47$ K, is found to be lower than the gas mass evaluated from the [CII] emission (fig. 4.4, left panel)

By computing the minimum temperature for the ALPINE sample, we find that $T_{\text{min}} \lesssim 20$ K for all sources; a temperature of 25 K can therefore be considered sufficient and more appropriate to reproduce the observed flux. With this temperature, the

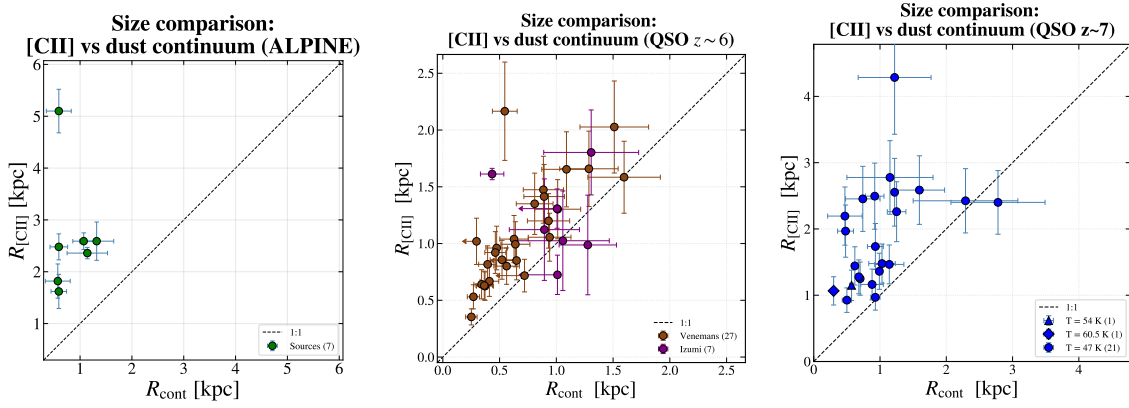


Figure 4.3: Comparison between the effective radius of the $[CII]$ emission and that of the dust continuum emission for the ALPINE sample (left), the QSO sample at $z \sim 6$ (center) from Venemans et al. 2020 (brown) and Izumi et al. 2018b; Izumi et al. 2019 (purple) and for the QSOs from W24 at $z \sim 7$. The dashed line represents the 1:1 relation between $[CII]$ and continuum, while the dots represent the individual sources. Leftward arrows denote upper limits on R_{cont} for sources with unresolved continuum emission. For the W24 sample, studied in detailed for the first time, the sources with an assumed $T_{\text{dust}} > 47$ K, are also indicated with different markers

resulting gas mass inferred from dust continuum increases by a factor of ~ 4 (Gilli et al. 2022, Pozzi et al. 2021). As visible in the right panel of fig. 4.4, the two mass estimates show better agreement, lying closer to the one-to-one relation. Consequently, since Method 1 and Method 2 both use the ratio between the gas mass and the size, the column density derived from the $[CII]$ measurements will turn out to be lower, for same gas mass.

The same comparison was performed for the quasar samples at $z \sim 6$ and $z \sim 7$, whose gas mass comparisons are shown in fig. 4.5. The assumption of 47 K for the dust temperature for the QSOs at $z \sim 6 - 7$ is corroborated by recent findings in the literature. For example, Costa et al. 2026 report an average value of 48 K for a sample of nine quasars at $z \sim 7$. In appendix A.2, we report a comparison of our measurement for minimum dust temperature and those obtained by Costa et al. 2026 for the seven sources in common. We also note that the minimum temperatures derived for these samples are within 20 – 30 K, also consistent with an assumption of 47 K¹. However for the QSOs at $z \sim 7$ some sources show a $[CII]$ -derived gas mass higher than the continuum-derived one, similarly to what is found for the ALPINE sample; assuming a lower temperature would increase the continuum-derived gas mass and, in principle, bringing it back onto the 1:1 line. This relation with temperature is more clearly illustrated in the column density comparison, discussed below.

N_H comparison

Table 4.3 shows the values of N_H of the ALPINE sample, obtained with the dust-based method ($T_{\text{dust}} = 47$ K) and the $[CII]$ -based one, together with their ratio; a

¹We recall that in the evaluation of the dust mass a temperature $T_{\text{dust}} = 47$ K was assumed if $T_{\text{min}} < 47$ K, while for the sources with $T_{\text{min}} \geq 47$ K, a temperature $T_{\text{dust}} = 1.2 T_{\text{min}}$.

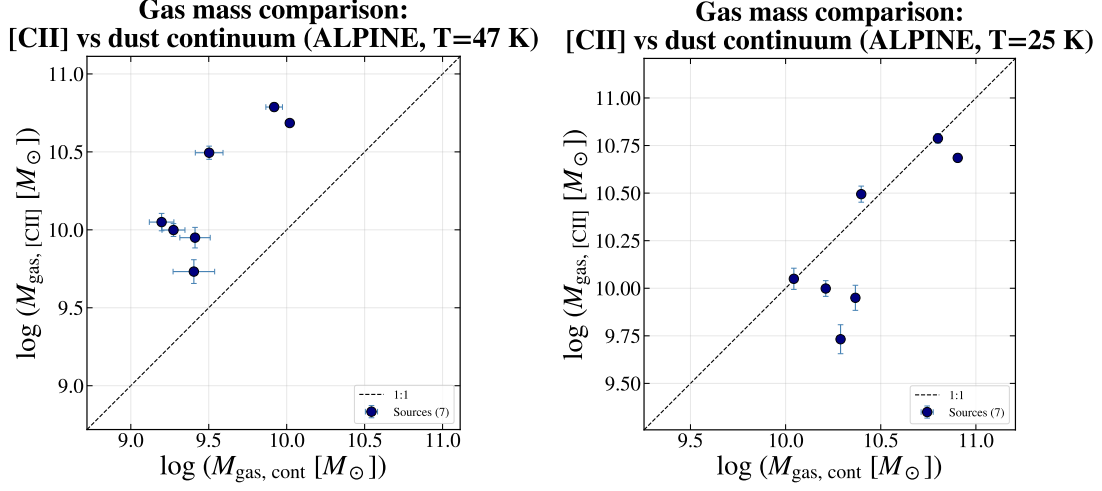


Figure 4.4: Comparison between the total gas mass obtained from $[CII]$ measurements and from dust continuum, assuming a dust temperature of 47 K (left panel) and 25 K (right panel) for the ALPINE sample.

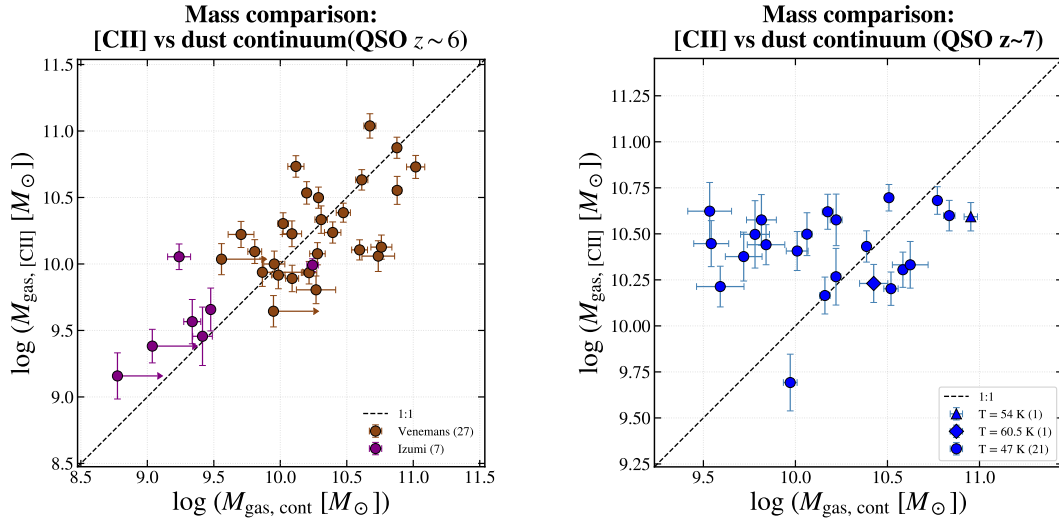


Figure 4.5: Gas mass estimates derived assuming a size-dependent conversion factor for $[CII]$ and a fixed gas-to-dust ratio for the continuum, for the $z \sim 6$ QSO sample (left panel) and for the $z \sim 7$ QSO (right panel). In both panels, the dashed line represents the 1:1 relation, while the dots represent the individual sources. Rightward arrows denote lower limits on $M_{\text{gas,cont}}$ for sources with marginally detected continuum emission. For the W24 sample, studied here in detailed for the first time, are also indicated with different markers the sources with an assumed $T_{\text{dust}} > 47$ K.

visual representation is shown in the left panel of fig. 4.6. In the right panel the same representation is shown under the different dust temperature assumption $T_{\text{dust}} = 25$ K (see fig. 4.6).

ALPINE column densities: Method 1 vs Method 2

Name	z	$N_{\text{H,dust}} [\text{cm}^{-2}]$	$N_{\text{H,[CII]}} [\text{cm}^{-2}]$	$N_{\text{H,[CII]}}/N_{\text{H,dust}}$
DC_494057	5.540	$(3.2 \pm 1.9) \times 10^{23}$	$(1.0 \pm 0.2) \times 10^{23}$	0.30 ± 0.19
DC_683613	5.536	$(5 \pm 4) \times 10^{23}$	$(1.6 \pm 0.6) \times 10^{23}$	0.3 ± 0.3
DC_818760	4.554	$(4.3 \pm 1.8) \times 10^{23}$	$(5.5 \pm 0.7) \times 10^{23}$	1.3 ± 0.5
DC_873756	4.548	$(5 \pm 3) \times 10^{23}$	$(5.2 \pm 0.5) \times 10^{23}$	1.1 ± 0.7
vc_5100822662	4.5235	$(5 \pm 3) \times 10^{22}$	$(1.0 \pm 0.3) \times 10^{23}$	1.8 ± 1.1
vc_5100969402	4.5869	$(4 \pm 3) \times 10^{23}$	$(1.2 \pm 0.5) \times 10^{23}$	0.3 ± 0.2
vc_5180966608	4.5293	$(5 \pm 5) \times 10^{23}$	$(7.2 \pm 1.4) \times 10^{22}$	0.13 ± 0.11

Table 4.3: Comparison of N_{H} estimates from dust continuum and [CII]-based methods, with their ratio, for the ALPINE sources at $z \sim 4 - 5$, $T_{\text{dust}} = 47$ K.

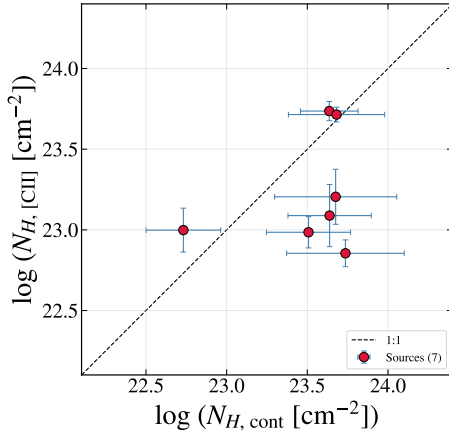
What emerges from this comparison is that, for $T_{\text{dust}} = 47$ K, the two column densities differ on average by a factor of ~ 2 :

$$N_{\text{H,[CII]}} \simeq 0.51 N_{\text{H,cont 47K}} \quad (4.2)$$

In this case, the lower dust-continuum gas mass (relative to the [CII]-based one) compensates for the more extended spatial distribution of the [CII]-emitting gas, so that the two effects act in opposite directions on $N_{\text{H}} = M_{\text{gas}}/R^2$ and partially cancel out. For $T_{\text{dust}} = 25$ K the column density estimates differ by a factor of 30 (~ 1.5 dex):

$$N_{\text{H,[CII]}} \simeq 0.03 N_{\text{H,cont 25K}} \quad (4.3)$$

**Column density comparison:
[CII] vs dust continuum (ALPINE, T=47 K)**



**Column density comparison:
[CII] vs dust continuum (ALPINE, T= 25 K)**

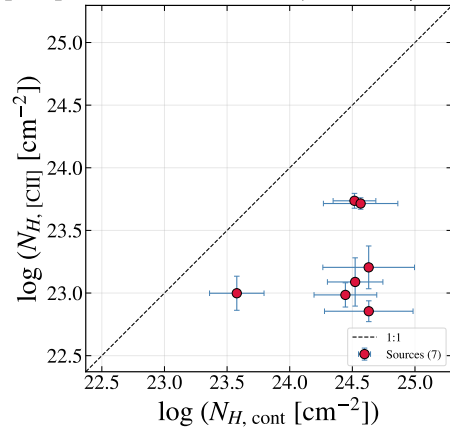


Figure 4.6: Column densities obtained from [CII] measurements and from dust continuum, assuming a dust temperature of 47 K (left panel) and 25 K (right panel).

Also in this case the limited number of sources in the sample does not allow us to draw firm constraints, but considerations regarding the choice of dust temperature and its link with source extension start to emerge.

A similar comparison was done for the QSO samples at $z \sim 6-7$, allowing further tests of the method and a better understanding of the underlying physics. Table 4.4 and table 4.5 show the N_H values obtained with the dust-based method and the [CII]-based one, together with their ratio for the QSOs at $z \sim 6$ (Venemans, Izumi) and for the QSOs at $z \sim 7$ (W24), respectively; the two values are plotted against each other in fig. 4.7.

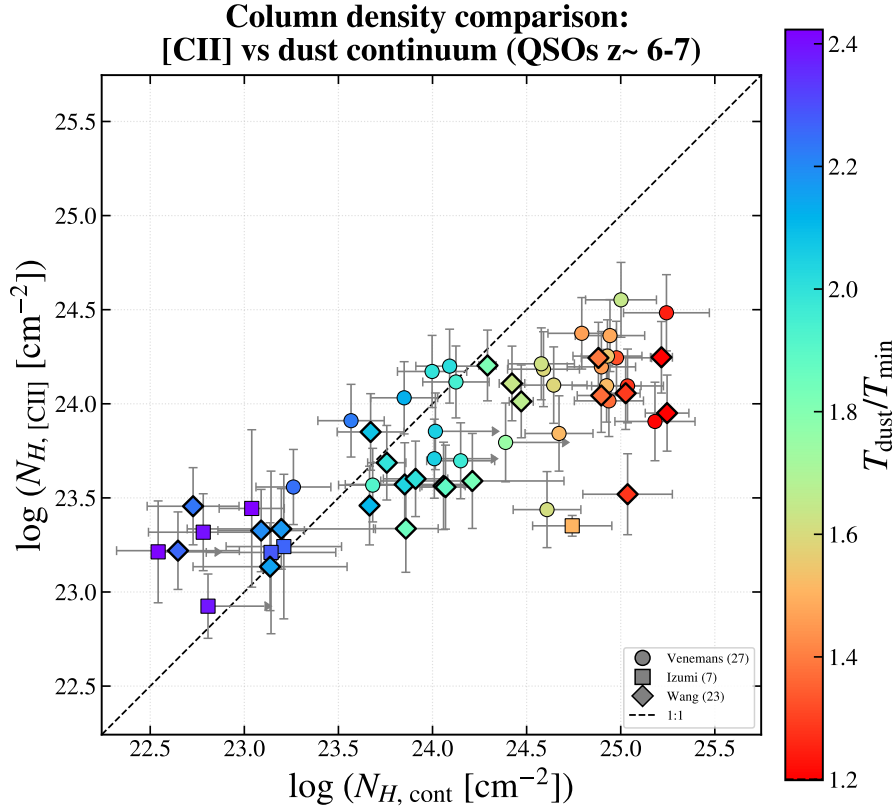


Figure 4.7: Comparison of N_H estimates obtained from the [CII]-based and dust-continuum-based methods for the QSO sample at $z \sim 6-7$ color-coded by the ratio $T_{\text{dust}}/T_{\text{min}}$ between the assumed dust temperature and the minimum temperature.

As discussed before, the [CII]-derived sizes are on average $\sim 1.5 - 2$ times larger than the dust-continuum sizes, whereas the two independent mass estimates are in good agreement (fig. 4.3 central panel and fig. 4.5 left panel). Naively, since $N_H \propto M_{\text{gas}}/R^2$, a larger [CII] radius combined with comparable gas masses would be expected to translate into a systematically lower [CII]-based column density (as for the ALPINE sample). However, fig. 4.7 shows a more structured picture: the two estimates agree well around $\log(N_H) \sim 24$, while $N_{H, [\text{CII}]}$ exceeds $N_{H, \text{cont}}$ at lower column densities and falls below it at higher column densities — a trend that cannot be explained by the size mismatch alone, since the latter would produce a systematic offset in a single direction.

$z \sim 6$ QSO column densities: Method 1 vs Method 2

Name	z	$N_{\text{H,dust}} [\text{cm}^{-2}]$	$N_{\text{H,[CII]}} [\text{cm}^{-2}]$	$N_{\text{H,[CII]}}/N_{\text{H,dust}}$
P007+04	6.002	$(8 \pm 4) \times 10^{24}$	$(1.3 \pm 0.6) \times 10^{24}$	0.15 ± 0.09
P009-10	6.004	$(1.2 \pm 0.5) \times 10^{24}$	$(1.6 \pm 0.7) \times 10^{24}$	1.3 ± 0.8
J0100+2802	6.327	$(1.3 \pm 0.5) \times 10^{24}$	$(1.3 \pm 0.6) \times 10^{24}$	1.0 ± 0.6
J0109-3047	6.790	$(3.9 \pm 1.7) \times 10^{24}$	$(1.5 \pm 0.7) \times 10^{24}$	0.4 ± 0.2
J0129-0035	5.779	$(9 \pm 4) \times 10^{24}$	$(1.0 \pm 0.5) \times 10^{24}$	0.12 ± 0.07
J025-33	6.337	$(6 \pm 3) \times 10^{24}$	$(2.4 \pm 1.0) \times 10^{24}$	0.4 ± 0.2
P036+03	6.540	$(8 \pm 3) \times 10^{24}$	$(1.6 \pm 0.7) \times 10^{24}$	0.20 ± 0.12
J0305-3150	6.614	$(9 \pm 4) \times 10^{24}$	$(1.8 \pm 0.8) \times 10^{24}$	0.19 ± 0.11
P065-26	6.187	$(4.1 \pm 1.7) \times 10^{24}$	$(2.7 \pm 1.3) \times 10^{23}$	0.07 ± 0.04
J0842+1218	6.075	$(1.0 \pm 0.4) \times 10^{24}$	$(5 \pm 2) \times 10^{23}$	0.5 ± 0.3
J1044-0125	5.785	$(1.5 \pm 0.8) \times 10^{25}$	$(8 \pm 4) \times 10^{23}$	0.05 ± 0.04
J1048-0109	6.676	$(1.1 \pm 0.5) \times 10^{25}$	$(1.2 \pm 0.6) \times 10^{24}$	0.11 ± 0.07
P167-13	6.514	$(1.0 \pm 0.4) \times 10^{24}$	$(1.5 \pm 0.7) \times 10^{24}$	1.5 ± 0.9
J1120+0641	7.085	$(4.7 \pm 2.0) \times 10^{24}$	$(7 \pm 3) \times 10^{23}$	0.15 ± 0.09
P183+05	6.439	$(3.8 \pm 1.5) \times 10^{24}$	$(1.6 \pm 0.7) \times 10^{24}$	0.4 ± 0.3
J1306+0356	6.033	$(1.4 \pm 0.6) \times 10^{24}$	$(5 \pm 2) \times 10^{23}$	0.4 ± 0.2
J1319+0950	6.135	$(4.4 \pm 1.8) \times 10^{24}$	$(1.3 \pm 0.6) \times 10^{24}$	0.29 ± 0.18
J1342+0928	7.540	$(5 \pm 2) \times 10^{23}$	$(3.7 \pm 1.7) \times 10^{23}$	0.8 ± 0.5
P231-20	6.587	$(1.0 \pm 0.4) \times 10^{25}$	$(3.6 \pm 1.6) \times 10^{24}$	0.4 ± 0.2
P308-21	6.236	$(3.7 \pm 1.5) \times 10^{23}$	$(8 \pm 4) \times 10^{23}$	2.2 ± 1.3
J2054-0005	6.039	$(9 \pm 4) \times 10^{24}$	$(2.3 \pm 1.0) \times 10^{24}$	0.26 ± 0.16
J2100-1715	6.081	$(1.0 \pm 0.4) \times 10^{24}$	$(7 \pm 3) \times 10^{23}$	0.7 ± 0.4
P323+12	6.587	$(2.4 \pm 1.7) \times 10^{24}$	$(6 \pm 3) \times 10^{23}$	0.3 ± 0.2
J2318-3113	6.443	$(1.8 \pm 0.8) \times 10^{23}$	$(3.6 \pm 1.7) \times 10^{23}$	2.0 ± 1.3
J2318-3029	6.146	$(9 \pm 4) \times 10^{24}$	$(1.8 \pm 0.8) \times 10^{24}$	0.21 ± 0.13
J2348-3054	6.901	$(1.8 \pm 0.9) \times 10^{25}$	$(3.0 \pm 1.4) \times 10^{24}$	0.17 ± 0.12
P359-06	6.172	$(7 \pm 3) \times 10^{23}$	$(1.1 \pm 0.5) \times 10^{24}$	1.5 ± 0.9
J1208-0200	6.117	$> 6.4 \times 10^{22}$	$(8 \pm 3) \times 10^{22}$	< 1.3
J2228+0152	6.080	$> 3.5 \times 10^{22}$	$(1.6 \pm 1.0) \times 10^{23}$	< 4.7
J2239+0207	6.250	$(6 \pm 3) \times 10^{24}$	$(2.3 \pm 0.3) \times 10^{23}$	0.04 ± 0.02
J0859+0022	6.390	$(1.6 \pm 1.2) \times 10^{23}$	$(1.7 \pm 1.5) \times 10^{23}$	1.1 ± 1.2
J1152+0055	6.364	$(1.4 \pm 1.1) \times 10^{23}$	$(1.6 \pm 1.6) \times 10^{23}$	1.2 ± 1.5
J2216-0016	6.096	$(6 \pm 4) \times 10^{22}$	$(2 \pm 1) \times 10^{23}$	3 ± 3
J1202-0057	5.929	$(1.1 \pm 0.4) \times 10^{23}$	$(3 \pm 3) \times 10^{23}$	3 ± 3

Table 4.4: Comparison of N_{H} estimates from dust continuum and [CII]-based methods, with their ratio, for the Venemans and Izumi QSO samples at $z \sim 6$.

$z \sim 7$ QSO column densities: [Method 1](#) vs [Method 2](#)

Name	z	$N_{\text{H,dust}} [\text{cm}^{-2}]$	$N_{\text{H,[CII]}} [\text{cm}^{-2}]$	$N_{\text{H,[CII]}}/N_{\text{H,dust}}$
J0038-1527	7.034	$(5.7 \pm 1.3) \times 10^{23}$	$(5 \pm 2) \times 10^{23}$	0.9 ± 0.4
J0213-0626	6.721	$(6 \pm 4) \times 10^{23}$	—	—
J0218+0007	6.770	$(1.1 \pm 0.3) \times 10^{24}$	$(3.7 \pm 2.0) \times 10^{23}$	0.32 ± 0.19
J0224-4711	6.522	$(2.0 \pm 0.2) \times 10^{24}$	$(1.6 \pm 0.7) \times 10^{24}$	0.8 ± 0.4
J0246-5219	6.888	$(3.0 \pm 0.4) \times 10^{24}$	$(1.0 \pm 0.5) \times 10^{24}$	0.35 ± 0.16
J0252-0503	7.001	$(1.2 \pm 0.4) \times 10^{24}$	$(3.6 \pm 1.9) \times 10^{23}$	0.31 ± 0.19
J0313-1806	7.642	$(7 \pm 3) \times 10^{23}$	$(2.2 \pm 1.2) \times 10^{23}$	0.3 ± 0.2
J0319-1008	6.828	$(1.6 \pm 1.8) \times 10^{24}$	$(4 \pm 2) \times 10^{23}$	0.2 ± 0.3
J0411-0907	6.826	$(1.4 \pm 1.3) \times 10^{23}$	$(1.4 \pm 0.7) \times 10^{23}$	1.0 ± 1.1
J0430-1445	6.714	$(4.7 \pm 1.9) \times 10^{23}$	$(7 \pm 3) \times 10^{23}$	1.5 ± 0.9
J0525-2406	6.540	$(7.6 \pm 0.5) \times 10^{24}$	$(1.8 \pm 0.8) \times 10^{24}$	0.23 ± 0.10
J0706+2921	6.604	$(4.6 \pm 0.3) \times 10^{23}$	$(2.9 \pm 1.4) \times 10^{23}$	0.6 ± 0.3
J0910+1656	6.729	$(1.6 \pm 1.8) \times 10^{23}$	$(2.2 \pm 1.1) \times 10^{23}$	1.4 ± 1.7
J0910-0414	6.636	$(1.06 \pm 0.19) \times 10^{25}$	$(1.1 \pm 0.5) \times 10^{24}$	0.11 ± 0.05
J0921+0007	6.565	$(4 \pm 3) \times 10^{22}$	$(1.7 \pm 0.8) \times 10^{23}$	4 ± 3
J0923+0402	6.633	$(5 \pm 3) \times 10^{22}$	$(2.9 \pm 1.4) \times 10^{23}$	5 ± 4
J0923+0753	6.682	$(1.2 \pm 0.7) \times 10^{23}$	$(2.1 \pm 1.1) \times 10^{23}$	1.7 ± 1.3
J1007+2115	7.515	$(2.6 \pm 0.4) \times 10^{24}$	$(1.3 \pm 0.6) \times 10^{24}$	0.5 ± 0.2
J1058+2930	6.585	$(7 \pm 5) \times 10^{23}$	$(3.7 \pm 1.9) \times 10^{23}$	0.5 ± 0.5
J1104+2134	6.766	$(1.1 \pm 0.6) \times 10^{25}$	$(3.3 \pm 1.6) \times 10^{23}$	0.03 ± 0.02
J2102-1458	6.665	$(8 \pm 3) \times 10^{23}$	$(4.0 \pm 1.8) \times 10^{23}$	0.5 ± 0.3
J2211-6320	6.845	$(8 \pm 2) \times 10^{24}$	$(1.1 \pm 0.5) \times 10^{24}$	0.14 ± 0.08
J1129+1846	6.824	$> 2.4 \times 10^{22}$	—	—
J0837+4929	6.645	$> 3.1 \times 10^{22}$	—	—
J1135+5011	6.585	$> 5.6 \times 10^{22}$	—	—
J0229-0808	6.725	$(1.7 \pm 0.2) \times 10^{25}$	$(1.8 \pm 0.8) \times 10^{24}$	0.11 ± 0.05
J2002-3013	6.688	$(1.8 \pm 0.5) \times 10^{25}$	$(9 \pm 4) \times 10^{23}$	0.05 ± 0.03

Table 4.5: Comparison of N_{H} estimates from dust continuum and [CII]-based methods, with their ratio, for the W24 QSO samples at $z \sim 7$. J0229-0808 and J2002-3013 are the sources for which $T_{\text{min}} > 47 \text{ K}$

Color-coding each point by the ratio of the assumed dust temperature with respect to the minimum temperature, reveals the origin of this behaviour. As seen in section 2.3, the argument of the logarithm in eq. (2.24) must remain below unity for M_{dust} to be defined. This condition sets a minimum temperature which can be interpreted as the temperature a source would have if all of its emission originated from the outer layer (i.e. the optically thick regime). The value adopted for the dust temperature, T_{dust} must be higher than the minimum temperature and directly and non-linearly biases the inferred dust mass, and therefore $N_{H,\text{dust}}$:

- At $\log(N_{H,\text{cont}}) < 24$, the assumed $T_{\text{dust}} = 47 \text{ K}$ is well above the computed T_{min} (blue points, colder T_{min}): M_{dust} is close to its optically-thin value and $N_{H,\text{cont}}$ falls below $N_{H,[\text{CII}]}$.
- Conversely, at $\log(N_{H,\text{cont}}) \gtrsim 24$, T_{dust} is close to T_{min} (red points, hotter T_{min}), where dust approaches the optically thick limit: M_{dust} is close to the optically thick value and $N_{H,\text{dust}}$ exceeds $N_{H,[\text{CII}]}$.

The fact that this change of behaviour occurs at $\log(N_H) = 24$ is not a coincidence: it reflects the same transition between the optically thin and optically thick regimes that also distinguishes obscured from heavily obscured (Compton-thick) AGNs.

When we estimate the minimum temperature condition (eq. (2.26)) we introduce T_{min} as a physical parameter that tracks how the continuum emission moves from one regime to the other. No equivalent constraint is imposed on the [CII]-based estimate, and therefore the derived estimates with this method do not distinguish between the two regimes.

Mathematically the minimum temperature (eq. (2.26)) is set mainly by the surface brightness of the source, i.e. by the ratio between the observed flux ($S_{\nu_{\text{obs}}}$) and the solid angle of the emitting region ($\Omega = A/D_A^2$) in eq. (2.26). This means that more compact sources require higher minimum temperatures. Both the minimum temperature and the surface brightness are tracking the same underlying property: the compactness of the continuum emission.

To better visualize this connection, we color-coded the size, mass, and column density comparisons presented up to now in this section according to two quantities: the ratio between the assumed dust temperature and T_{min} (i.e. how close the source is to the optically thick approximation) in fig. 4.8, and the continuum surface brightness, $S_{\nu_{\text{obs}}}/(\pi R_{\text{cont}}^2)$ in fig. 4.9.

As expected the trend is the same for the two sets of plots, in particular:

- when $T_{\text{dust}}/T_{\text{min}}$ is close to 1 the source is in the optically thick regime. This corresponds to the more compact sources (left panels), with high surface brightness and, consequently, $N_{H,\text{dust}} > N_{H,[\text{CII}]}$. In this regime, part of the gas mass is "hidden" behind the outermost emitting layer.
- when $T_{\text{dust}}/T_{\text{min}}$ is far from 1 the source is in the optically thin regime. This corresponds to less compact sources, with lower surface brightness and $N_{H,\text{dust}} \leq N_{H,[\text{CII}]}$. We can see through the outermost layer, and the emission from the innermost gas contributes as well.

Finally we explored any dependence on $[\text{CII}]$ luminosity, by color coding the sources by $L_{[\text{CII}]}$: fig. 4.10 shows the dependence on $L_{[\text{CII}]}$ is weaker than the dependence on either surface brightness or the $T_{\text{dust}}/T_{\text{min}}$ ratio.

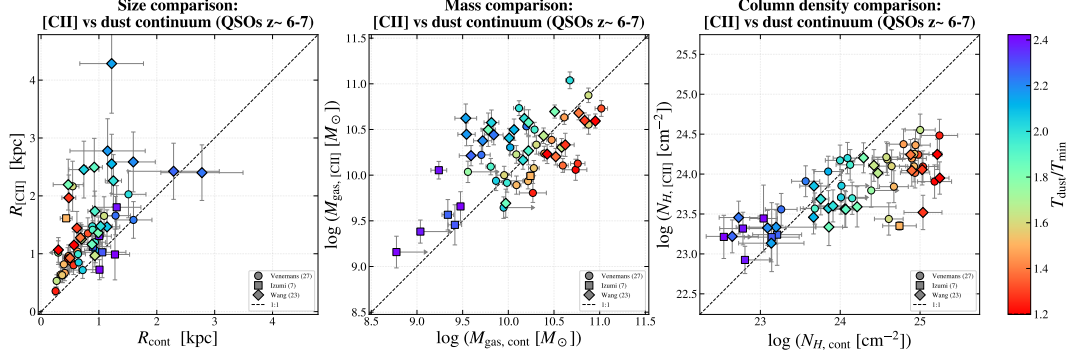


Figure 4.8: Comparison between $[\text{CII}]$ and dust continuum emission: sizes, masses, column densities, color coded by $T_{\text{dust}}/T_{\text{min}}$. The right panel is identical to fig. 4.7, but we report it also here for a direct comparison with fig. 4.9 and fig. 4.10

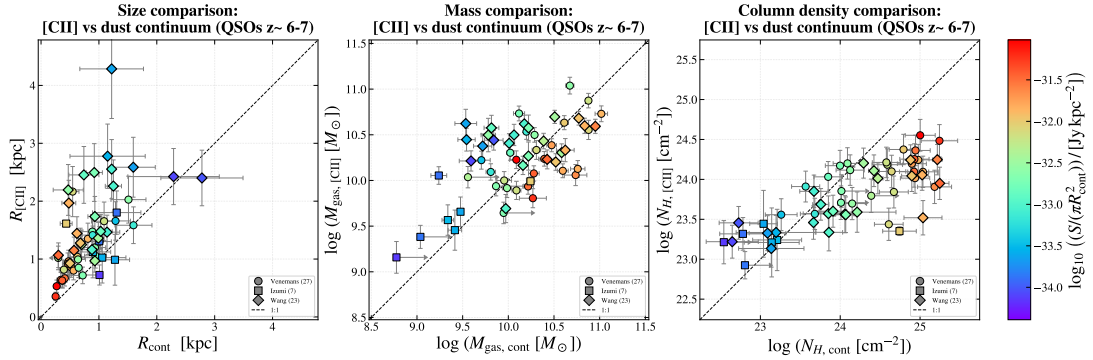


Figure 4.9: Comparison between $[\text{CII}]$ and dust continuum emission: sizes, masses, column densities, color coded by surface brightness.

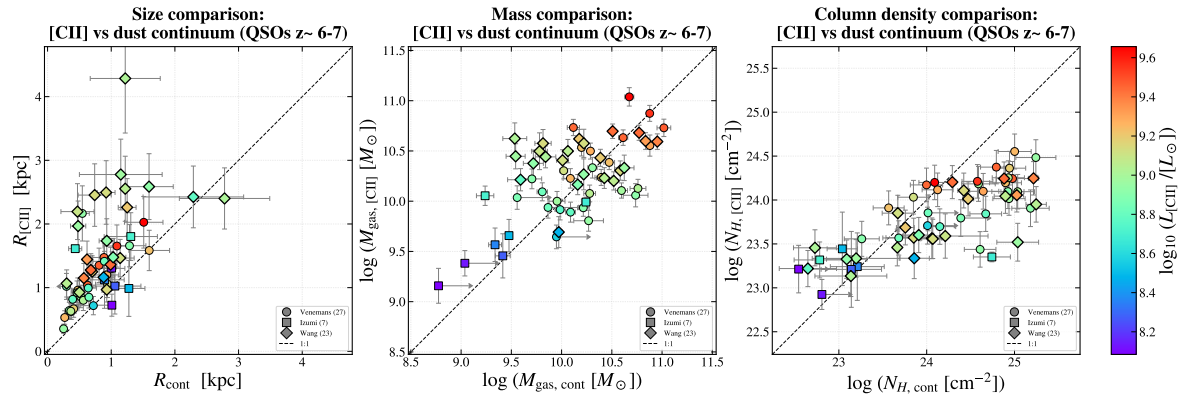


Figure 4.10: Comparison between $[\text{CII}]$ and dust continuum emission: sizes, masses, column densities, color coded by $[\text{CII}]$ luminosity.

What is found on average for the total sample of QSOs is:

$$N_{\text{H},[\text{CII}]} \simeq 0.45 N_{\text{H,cont}}, \quad (4.4)$$

similarly to the ALPINE sample. When the sample is divided according to luminosity, a clear difference emerges. The less luminous quasars (*Izumi*) have a characteristic ratio:

$$N_{\text{H},[\text{CII}]} \simeq 1.16 N_{\text{H,cont}}, \quad (4.5)$$

whereas for the more luminous quasars (*Venemans + Wang*) show:

$$N_{\text{H},[\text{CII}]} \simeq 0.39 N_{\text{H,cont}}. \quad (4.6)$$

This is consistent with the trend shown in fig. 4.7: the more luminous QSOs (*Venemans + Wang*) have T_{dust} closer to T_{min} that causes the continuum-based method to saturate with respect to [CII] based method, hence $N_{\text{H,cont}} > N_{\text{H},[\text{CII}]}$ in the subsample. The less luminous quasars (*Izumi*) remain in a regime where the continuum-based method is not constrained by T_{min} , and the two tracers agree more closely, with $N_{\text{H},[\text{CII}]}$ even slightly exceeding $N_{\text{H,cont}}$. This can be associated to the so called [CII] deficit in FIR powerful galaxies (e.g. see Narayanan and Krumholz 2016; Ebagezio et al. 2024).

4.3 Evolution of ISM Column Density with redshift

The main goal of this thesis is to determine the evolution of nuclear obscuration, expressed by the parameter N_{H} , evaluated at each z of the sources.

The state of the art up to $z \sim 6$ has been evaluated in Gilli et al. 2022 and expressed in Section 1.5. The result of the work presented in chapter 2 and chapter 3 permit to extend the study up to $z \sim 7$ and beyond.

Once the methods had been compared, we evaluated N_{H} for all the sources discussed so far, for which N_{H} had been estimated with at least one of the three proposed *Methods*, and examined how N_{H} evolves with redshift. Motivated by the expected increase $N_{\text{H}} \propto (1+z)^4$ (see section 1.5), we modelled the trend as $N_{\text{H}} = A(1+z)^\alpha$, fitted in linearized form as

$$\log_{10} N_{\text{H}} = \log_{10} A + \alpha \log_{10}(1+z). \quad (4.7)$$

The fit was always performed with a non-linear least-squares routine² and sources for which only a lower limit on N_{H} was available were excluded from the fit.

First, we fitted 101³ sources for which dust continuum measurements were available, including the $z \sim 7$ sources from *W24* (this work). The trend is shown in fig. 4.11 and the best fit gives:

$$N_{\text{H}} \propto (1+z)^{2.95 \pm 0.28} \quad (4.8)$$

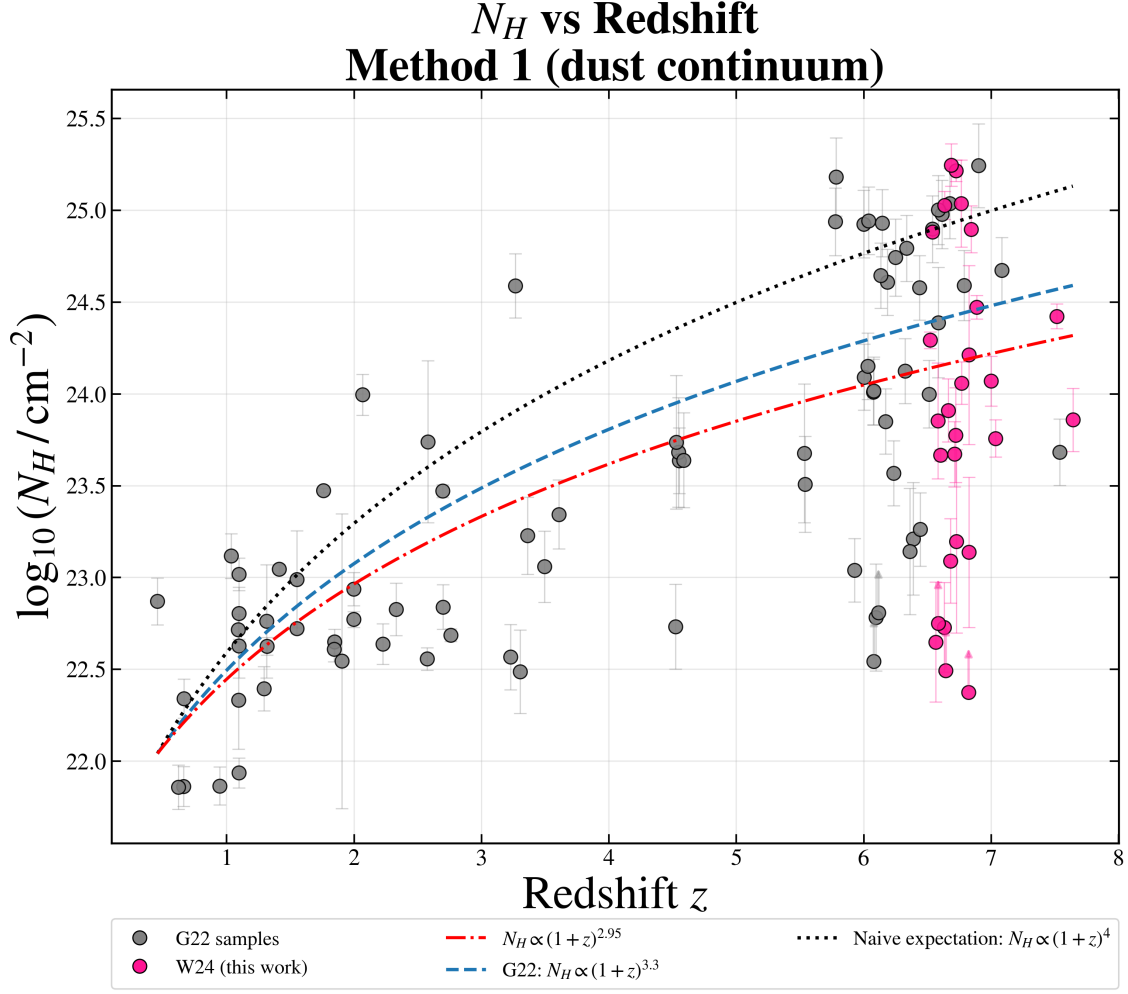


Figure 4.11: N_H as a function of redshift for sources with dust continuum measurements: G22 samples (grey circles) and W24, this work, (pink circles). Upward arrows denote lower limits. The red dash-dotted line shows the best-fit power law found in this work $N_H \propto (1+z)^{2.95}$; the blue dashed line the relation from G22, $N_H \propto (1+z)^{3.3}$; the black dotted line shows the naive expectation, $N_H \propto (1+z)^4$.

consistent with the results of Gilli et al. 2022, $N_H \propto (1+z)^{3.3}$ and close to what is expected from the simple, empirical arguments discussed in section 1.5, $N_H \propto (1+z)^4$.

We then included the CosmosWeb sources at $z \sim 7$ adding to the fit the 6 sources in the highest stellar-mass bin ($\log M_* \geq 10$, labeled as "m10" in fig. 4.12), while the remaining 17 sources of this sample in the lower-mass bins (labeled "m8, m9" in fig. 4.12) are shown for completeness but excluded from the fit. Figure 4.12 shows the result and the best for the 101 (*Method 1*) + 6 (*Method 3*, COSMOS-Web) sources gives:

$$N_H \propto (1+z)^{2.73 \pm 0.29} \quad (4.9)$$

²`scipy.optimize.curve_fit`

³We estimated N_H with *Method 1* for 106 sources, but we didn't consider in the fit the 3 sources of W24 and the 2 of *Izumi* with lower limits.

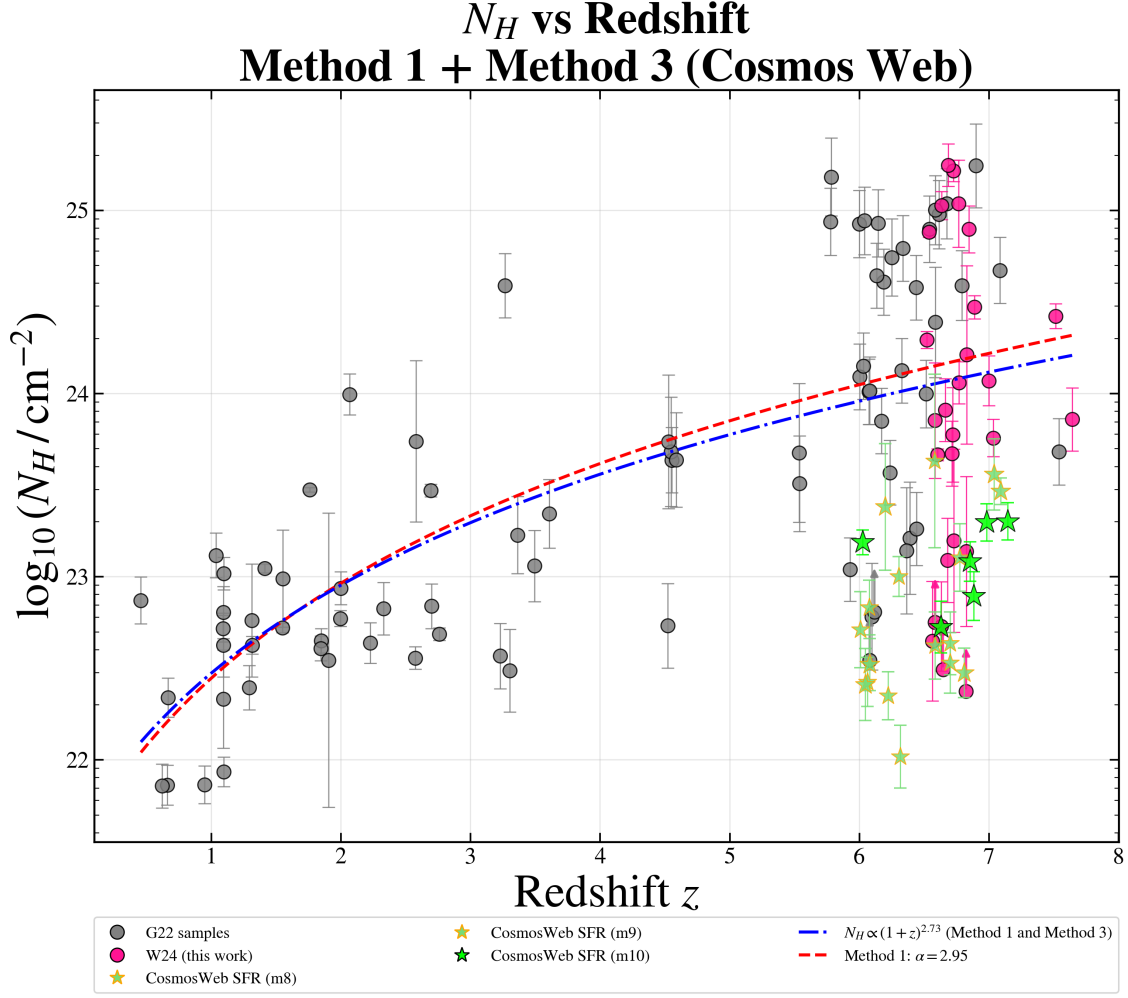


Figure 4.12: Same as Figure 4.11, with the *CosmosWeb* SFR-based sources added (m8, m9, m10 mass bins; green/yellow stars). Only the m10 bin ($\log M_\star \geq 10$) is included in the fit, which gives $N_H \propto (1+z)^{2.73 \pm 0.29}$.

consistent, within the uncertainties, with the dust-continuum-only fit obtained above.

As shown in chapter 3, for the ALPINE (section 3.4), and QSOs samples at $z \geq 4$ (section 3.5, section 3.8), [CII] measurements were available. We then considered a dataset comprised by N_H estimated from the dust continuum *Method 1* for the sources at $z < 4$ (ASPECS and *Suzuki21*, a total of 38 sources) and N_H computed through *Method 2* for the sources at $z > 4$ (7 from the ALPINE sample, 34 from *Venemans, Izumi*, 23 from *W24*). This dataset is reported in fig. 4.13 and the different symbols represent different N_H origin ([CII], dust continuum, SFR). We performed the fit with these 95 sources and the trend with redshift is lowered to $\alpha = 2.18 \pm 0.19$ (cyan curve in fig. 4.13).

Moved by curiosity we decided to extend the SFR-based method to a sample of high- z galaxies studied by Calabrò et al. 2024 to get a preliminary sense of how the column density evolution might extend up to $z \sim 9$. The sample of Calabrò et al. 2024 consists of 230 galaxies for which the authors studied the evolution of the SFR

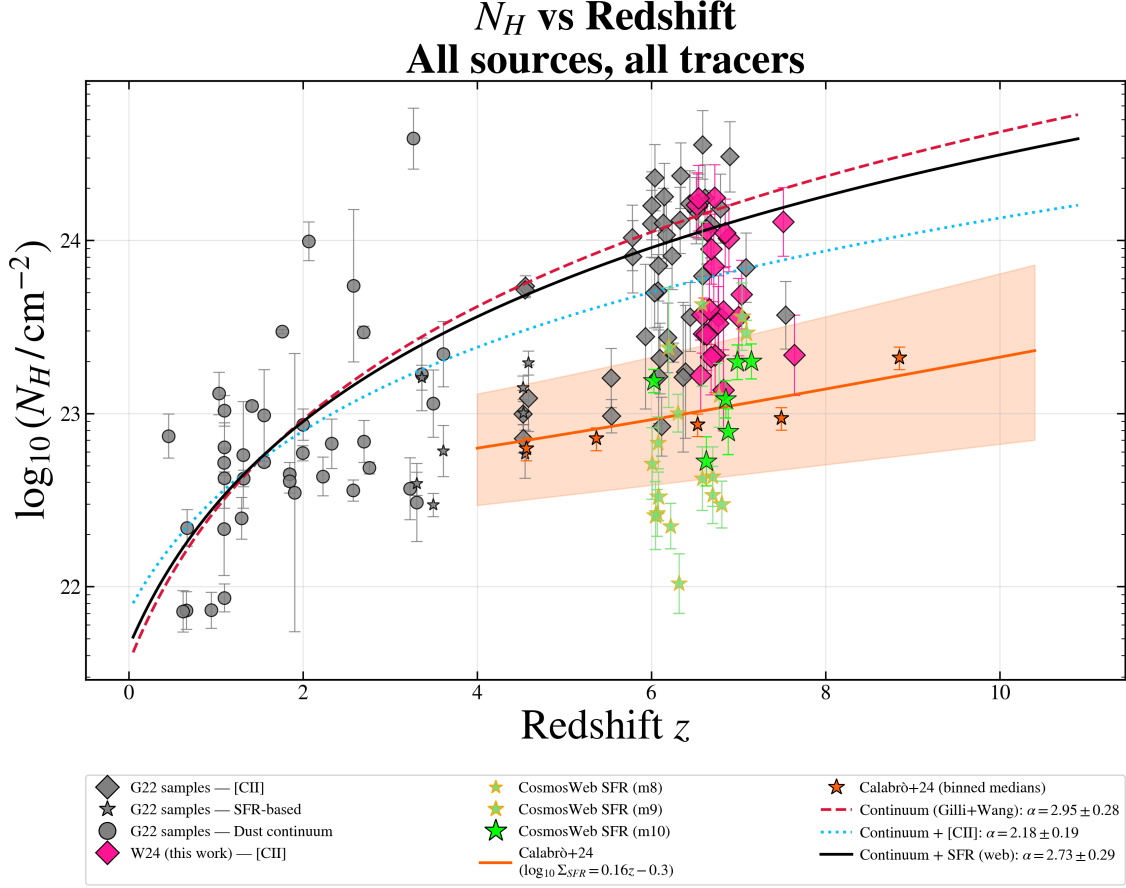


Figure 4.13: N_H as a function of redshift for all sources and different tracers combined, including the high-redshift galaxies of Calabrò et al. 2024. The three curves show the best-fit power laws obtained with different tracer/sample combinations, as discussed in the text.

surface density. These sources are JWST/NIRSpec-confirmed galaxies at $4 < z < 10$ from spectroscopic surveys, including 11 objects at $z \geq 8$. The sample was divided into redshift bins(4-5,5-6,6-7,7-8,8-10) and for each bin the authors report the median Σ_{SFR} as a function of the median redshift. We adopted the five median Σ_{SFR} values corresponding to these bins, recovering them graphically from the published figure (see Fig.2 Calabrò et al. 2024 for details). The inferred values are listed in table 4.6. These values are not individual sources, but representative of the bulk population at each epoch.

We then used eq. (2.47) to evaluate the Σ_{gas} and consequently the column density. These values are plotted in fig. 4.13 (orange stars). In addition to the representative points, we show in fig. 4.13 also the best-fit relation found by the authors, $\log_{10} \Sigma_{\text{SFR}} = 0.16z - 0.3$, which directly translates into a relation between N_H and z (solid orange curve, with shaded area that accounts for both the uncertainty on the best-fit parameters reported by the authors and the systematic uncertainty of our Method 3).

We did not include these sources in any of our fits, since the SFRs for this sample were derived from emission lines rather than SED fitting over a ~ 100 Myr timescale,

as done for the COSMOS sources. Moreover, the stellar masses considered in Calabrò et al. 2024 span a range of 10^7 – $10^{10.5} M_\odot$, with a median $\log_{10}(M_\star/M_\odot) = 8.7$, lower than the stellar masses considered in this work and implemented in the fit. Nonetheless, the column density inferred starting from the relation found by Calabrò et al. 2024 provides an independent test of our results: despite the different SFR estimate and the fact that these sources were not used in the fit, it yields column densities that are consistent with the SFR-based points shown in fig. 4.13 (G22 SFR-based and COSMOS-Web SFR sources).

z (bin median)	$\log \Sigma_{\text{SFR}}$ [$M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$]	Σ_{SFR} [$M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$]	Σ_{gas} [$M_\odot \text{ kpc}^{-2}$]	N_H [cm^{-2}]
4.56	0.36	2.30	3.4×10^8	$(6.3 \pm 0.9) \times 10^{22}$
5.37	0.48	3.01	3.8×10^8	$(7.2 \pm 1.1) \times 10^{22}$
6.53	0.64	4.32	4.6×10^8	$(8.7 \pm 1.3) \times 10^{22}$
7.49	0.72	5.21	5.0×10^8	$(9.4 \pm 1.4) \times 10^{22}$
8.84	1.27	18.78	1.1×10^9	$(2.11 \pm 0.32) \times 10^{23}$

Table 4.6: *Redshift-binned Σ_{SFR} values from Calabrò et al. 2024 (Fig. 2), converted to Σ_{gas} and N_H following Method 3 section 2.5.3.*

Chapter 5

Conclusions and Further Directions

With the purpose of investigating the evolution of nuclear obscuration provided by the ISM, we obtained a series of results, which we summarize below. We assembled 106 galaxies and quasars spanning $z \sim 0$ to $z \sim 7$ – including the $z \sim 7$ *W24* quasars, analyzed here for the first time. These sources are not only distributed continuously across this entire redshift range, allowing us trace the evolution of the ISM column density, but they also span a consistent stellar-mass range ($\log M_*/M_\odot \sim 10$ – 11). For a significant fraction of them, multiple independent tracers – dust continuum (*Method 1*), [CII] (*Method 2*), and, in some cases, SFR-based (*Method 3*) estimates – are available for the same objects. This aspect made it possible to compare the different methods and uncover systematic differences between them. As discussed in section 4.2.2, comparing continuum- and [CII]-based estimates for the same sources revealed a connection between compactness, minimum dust temperature, and the optically thick/thin regimes. We extended the analysis to COSMOS-web galaxies at $z \sim 7$ and to galaxies at $z \sim 9$ as a preliminary exploration, and outline how it may be pushed further in future work.

5.1 Dust masses: handle with care

In this work we investigated in detail how to correctly evaluate the dust mass of a source, starting from the general expression presented in section 2.3, which we report here, eq. (2.24):

$$M_{\text{dust}} = -\ln \left(1 - \frac{(1+z)^3 S_{\nu_{\text{obs}}}}{\Omega [B_\nu(T_d) - B_\nu(T_{\text{CMB}})]} \right) \frac{A}{k_\nu},$$

We highlighted, from a mathematical point of view, the explicit dependence of this expression on the source size, and showed that, in the optically-thin regime, eq. (2.24) reduces to eq. (2.29):

$$M_{\text{thin}} = \frac{S_{\nu_{\text{obs}}} D_L^2}{(1+z) k_{\nu_{\text{obs}}}(\beta) [B_\nu(T_d) - B_\nu(T_{\text{CMB}})]},$$

a formula widely adopted in the literature, but that does not carries the dependence on the source size.

This behaviour is mathematically evident from the expansion reported in eq. (2.31):

$$M_{\text{dust}} \propto C + \frac{C^2}{2A} + \dots \propto C + \frac{C^2}{2R^2} + \dots,$$

where the leading-order term C corresponds to the size-independent, optically-thin mass, while the higher-order correction, scaling as R^{-2} , becomes increasingly important as the source size decreases – that is, precisely in the compact, optically-thick regime where the thin approximation breaks down.

The general case makes no a priori assumption on the optical depth of the dust emission: it accounts for the possibility that the source is optically thick, $\tau_\nu \gtrsim 1$, in which case part of the emitted radiation is reprocessed and trapped within the source before escaping. For this reason, whenever spatially resolved size measurements are available eq. (2.24) is the only formula that can be considered robust to compactness effects, and should be regarded as the correct choice over eq. (2.29).

The practical consequence of using the wrong formula is illustrated by the $z \sim 7$ quasar sample analyzed in this work, drawn from the *W24* compilation. Comparing the dust masses obtained from eq. (2.24) (hereafter $M_{\text{dust}}^{\text{general}}$) with those obtained from eq. (2.29) shows that, for one third of the sources, adopting the optically-thin approximation would underestimate the true dust mass, with the discrepancy being largest for the most compact sources (fig. 3.9).

In summary, $M_{\text{dust}}^{\text{general}}$ is the correct choice whenever source sizes are available, while M_{thin} should only be regarded as a proxy for the true dust mass in the absence of size information, keeping in mind that it may underestimate the mass, particularly for the most compact sources.

5.2 [CII] versus dust continuum: minimum temperature as a symptom of thickness

The fact that our samples comprised 64 sources with gas mass estimated from both *Method 1* and *Method 2* (see sections 3.4, 3.5 and 3.8), permitted a comparison between the column densities derived through the two methods. This allowed us not only to establish how much the two estimates differ, but also to investigate the physical nature of this difference.

On average the [CII]-derived column density is lower than the continuum-derived one, which is, in principle, consistent with the fact that the [CII] emission is more extended. However, this size mismatch alone should shift the two estimates in the same direction across the whole sample. A closer inspection instead reveals a more complex pattern, particularly among the quasars (section 4.2.2). Sources with higher surface brightness turn out to be the most compact, and for these the ratio between the assumed and the minimum dust temperature approaches unity (see fig. 4.8, fig. 4.9). In this sense, the minimum temperature is simply the other side of the same coin: the most compact sources are naturally driven towards the optically thick regime, which corresponds to a dust temperature close to T_{min} .

All of the observed emission arises from the outermost layer, while the emission from the inner regions is reprocessed and trapped before it can escape. The high

values of minimum temperature found for these sources can therefore be regarded as a symptom of thickness.

5.3 A redshift-dependent Schmidt–Kennicutt relation: a new probe of column density

Starting from basic physical assumptions, we derived a new relation to estimate the gas surface density directly from the star formation rate, with an explicit dependence on redshift (section 2.5.3). Equation (2.47):

$$\Sigma_{\text{gas}} = 10^{8.5} \Sigma_{\text{SFR}}^{2/3} (1+z)^{-1/3},$$

offers a physical explanation for the increase of the burstiness parameter observed at high redshift with respect to the classical Schmidt–Kennicutt law: high-redshift sources are more compact, and this compactness indicates that they are intrinsically more efficient at converting gas into stars.

This method also makes it possible to extend the study of the evolution of $N_{\text{H,ISM}}$ with redshift to $z > 7$ thanks to the availability of reliable SFR and sizes measurements provided by JWST observations (see fig. 4.12, fig. 4.13 and below).

5.4 Compton-thick obscured AGNs at $z \sim 7$

With this work, the increase of $N_{\text{H,ISM}}$ discussed in the introduction and previously constrained up to $z \sim 6$ by Gilli et al. 2022 is extended up to $z \sim 7$. The dust-continuum-only fit gives $N_{\text{H,ISM}} \propto (1+z)^{2.95 \pm 0.28}$ (see fig. 4.11), consistent within the uncertainties with the slope of Gilli et al. 2022 ($\alpha = 3.3$) and close to the simple theoretical expectation $N_{\text{H}} \propto (1+z)^4$. Including the CosmosWeb sources at $z \sim 7$ in the highest stellar-mass bin ($\log M_{\star} > 10$) yields a consistent, slightly shallower slope of $\alpha = 2.73 \pm 0.29$ (see fig. 4.12).

The column densities derived in this work quantify to which extent the interstellar medium of the host galaxy alone can obscure the active nucleus. N_{H} at $z \sim 7$ reach values of the order of $5 \times 10^{23} - 10^{24} \text{cm}^{-2}$ (see fig. 4.11, fig. 4.12, fig. 4.13) approaching the Compton-thick threshold ($N_{\text{H}} \gtrsim 1.5 \times 10^{24} \text{cm}^{-2}$), indicating that at these redshifts the host-galaxy ISM alone can substantially obscure the central engine, regardless of the torus contribution. This trend is confirmed even when different tracers are included in the analysis: although combining continuum with [CII] measurements yields a lower slope, $\alpha \sim 2.2$, the overall increase of N_{H} with redshift is preserved.

Finally, extending the SFR-based method to galaxies up to $z \sim 9$ (Calabrò et al. 2024) provides a preliminary, qualitative indication that this increasing trend may persist up to $z \sim 9$, although these points were not included in our fits given the different SFR-derivation method.

5.5 How well hidden? Extending the $N_{\text{H}}-z$ relation to $z > 9$

Method 3 allows the column density – and hence the degree of nuclear obscuration – to be evaluated directly from the SFR and the size of the star-forming region. As a final test in this work, we applied this method to four sources at $z > 9$ (fig. 5.1), among the best studied, newly discovered JWST-selected galaxies and AGN reported in the literature. The four sources and the quantities required to apply *Method 3*, are reported in table 5.1, together with the corresponding reference. As in the case of the sources of Calabrò et al. 2024, the SFR values collected here are not homogeneous with those adopted in the lower redshift samples (10 Myr or emission lines instead than 100 Myr). These sources lie at $z \sim 9-14$, corresponding to an epoch only about half a billion years after the Big Bang, so a more careful treatment of the SFR determination – and, more generally, of the applicability of Method 3 in this regime – will be required before any quantitative conclusion can be drawn. In addition, their stellar masses are lower than those of the galaxies studied in the rest of this work.

Name	z	SFR [$M_{\odot} \text{ yr}^{-1}$]	R_{eff} [kpc]	$\log(M_{\star}/M_{\odot})$	Reference
JADES-GS-z9-0	9.4327	5.5	0.110	8.2	Curti et al. (2025)
GN-z11	11.00	21	0.064	9.1	Tacchella et al. (2023)
Maisie’s Galaxy	11.44	2	0.340	8.5	Finkelstein et al. (2022)
JADES-GS-z14-0	14.32	19	0.26	8.6	Carniani et al. (2024)

Table 5.1: *Literature sources at $z \gtrsim 9$ added to populate the ultra-high-redshift regime of the SFR-based N_{H} estimate (Method 3). These sources are shown in Figure 5.1 (which reproduces and extends fig. 4.13) but excluded from the fits.*

The inclusion of these sources is not meant to yield firm conclusions; rather, it offers a first look into the ultra-high-redshift Universe.

5.6 Keep this in mind while playing hide-and-seek

There are several aspects worth keeping in mind when extending this kind of analysis to even higher redshifts. In particular:

- The gas-to-dust ratio (GDR) was assumed to be constant across the sample. A higher or lower value would rescale linearly the column density inferred from continuum measurements. The GDR could also be allowed to vary from source to source – for instance as a function of metallicity or stellar mass (see Calura et al. 2016 and references therein) – rather than being fixed to a single value; this would require an independent, source-by-source calibration.
- The SFR averaged over a 100 Myr timescale is physically well motivated up to $z \sim 7$, but becomes increasingly difficult to apply at higher redshifts, corresponding to a younger Universe where alternative SFR indicators, sensitive to shorter timescales, should be considered.

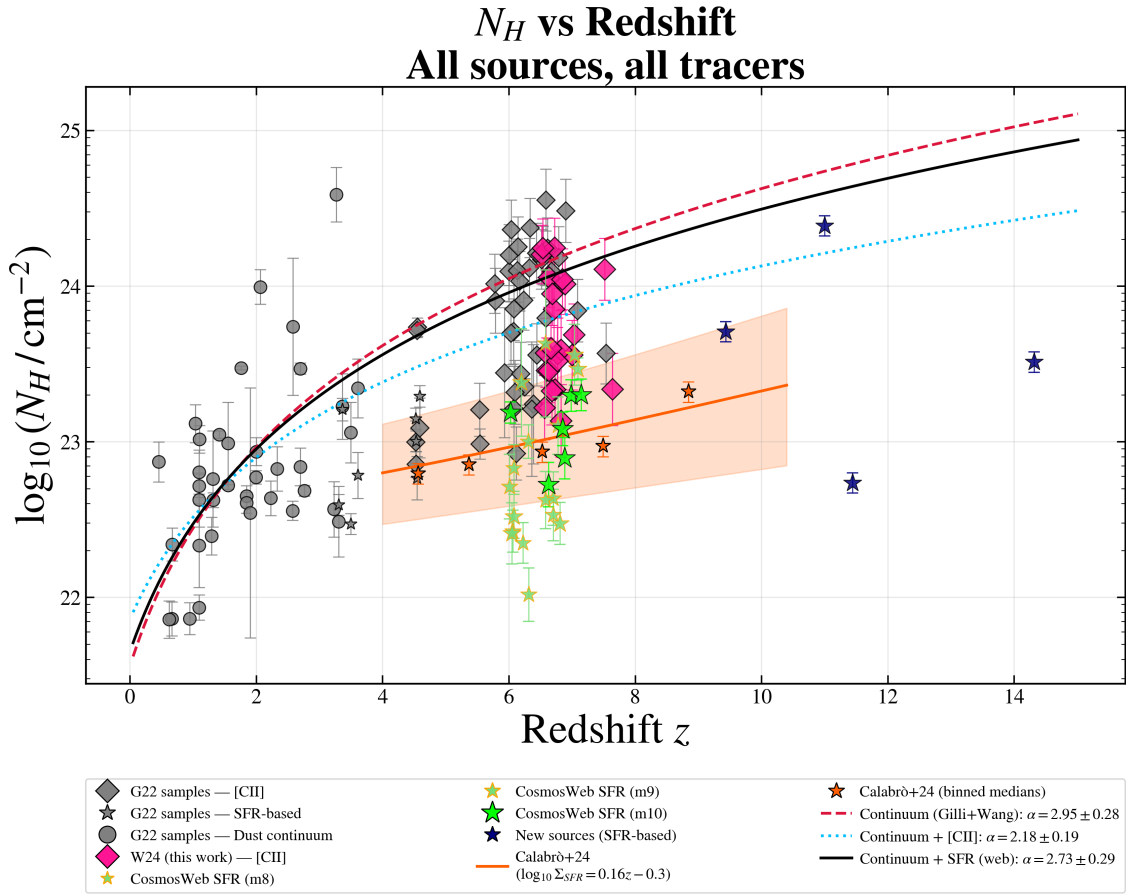


Figure 5.1: Same as fig. 4.13, but with the implementation of ultra high redshift sources (see table 5.1)

- The dust temperature assumed for each source directly affects the inferred dust mass and, consequently, the derived column density. As for the GDR, a source-by-source determination of the dust temperature (e.g. via FIR continuum SED fitting) would in principle provide more accurate individual estimates.
- The [CII]-to-gas conversion factor, although calibrated on source size, can still vary significantly from source to source and depends on mass and metallicity as well.
- At redshifts preceding the reionization era, the gas is expected to be predominantly atomic rather than molecular, a regime that would require a different treatment of the gas mass estimate.
- The sources populating the highest-redshift end of our analysis – such as the COSMOS-Web galaxies, the Calabrò et al. 2024 sample, and the additional literature sources at $z \gtrsim 9$ – are systematically less massive than the galaxies and quasars of our sample at $z \lesssim 7$. Extending the $N_{\text{H}}-z$ relation to lower stellar masses, and verifying whether it still holds in that regime, is therefore an important direction for future work.
- Future analysis of X-ray observations for these sources will help in comparing the obscuration due to the nuclear torus with that provided by the host galaxy’s ISM.

Nonetheless, the methodology presented in this work provides a springboard for future observations and the only viable way to estimate nuclear obscuration by the host galaxy at high redshift: this first game of hide-and-seek has allowed us to investigate where these sources hide, and to characterize the hiding place provided by the host galaxy.

Appendix

A.1 [CII] and continuum contours in the *W24* sample

Figure A.1 shows the dust continuum maps for the full *W24* sample, revealing the compactness of the continuum emission relative to the more extended [CII] emission discussed in section 2.2.2 (see fig. 2.2).

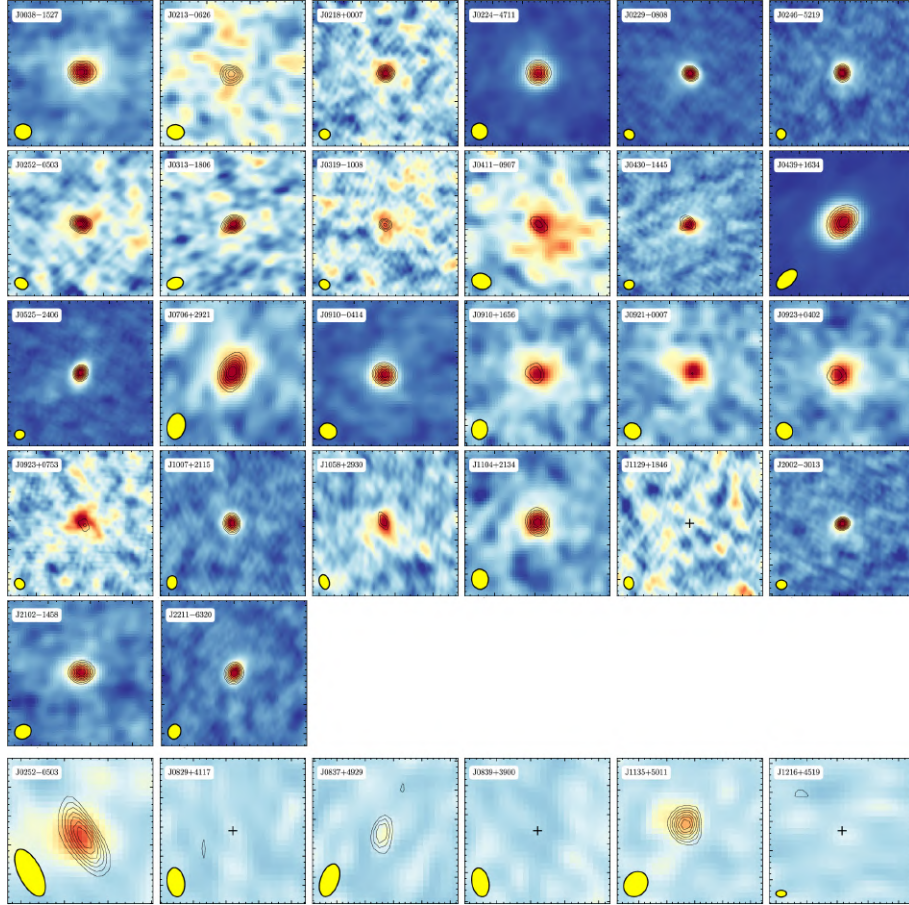


Figure A.1: *ALMA* (top 26 panels) and *NOEMA* (bottom 6 panels) thumbnails from *W24*. See caption in fig. 2.2 and Wang et al. 2024 for details.

A.2 Minimum temperature as symptom of thickness: comparison with literature

Seven of the *Venemans* sources were studied in detailed by Costa et al. 2026, who inferred the dust temperature through SED fitting of the infrared continuum emission. In that work the dust SED was modeled as a single-temperature modified blackbody, combining new ALMA Band 8 observations with archival photometry in other submm/mm bands. We therefore compared the minimum temperature $T_{\min}$ obtained in this work with the dust temperature T_{dust} they derived. The comparison is presented in table A.1. For six out of seven sources the two values agree closely and only for PJ009-10 the temperature inferred from SED fitting is higher than the minimum temperature. Besides the slightly different assumption on the calculations, the closeness of the true dust temperature to the minimum one is a symptom of thickness.

For PJ009-10 the derived T_{dust} is significantly higher than $T_{\min}$, indicating that this source lies in the optically thin regime – consistent with the low optical depth reported by Costa et al. 2026: $\tau_{1900} = 0.02^{+0.02}_{-0.01}$. This is also the most extended source in the sample, with an effective radius of the continuum emission a factor of ~ 3 –4 larger than the others.

PJ231-20 shows the largest uncertainty on $T_{\min}$ among the sample, and is also the source with the highest optical depth ($\tau_{1900} = 0.6^{+0.2}_{-0.2}$) reported by Costa et al. 2026. This is also the most compact source.

Dust temperature and size of the QSO sample from Costa et al. 2026, plus Pōniuāēna (Feruglio et al. 2023, Yang et al. 2020).

Source	$T_{\min}$ [K]	T_{dust} [K]	R [kpc]
	this work	Costa et al. 2026	this work
J0305-3150	35 ± 4	37^{+6}_{-3}	0.81 ± 0.16
J2318-3029	50 ± 9	52^{+20}_{-8}	0.37 ± 0.07
J2348-3054	67 ± 14	65^{+5}_{-4}	0.25 ± 0.05
PJ007+04	46 ± 8	48^{+20}_{-7}	0.34 ± 0.07
PJ009-10	23 ± 1	50^{+29}_{-13}	1.5 ± 0.3
PJ036+03	39 ± 5	44^{+2}_{-2}	0.47 ± 0.09
PJ231-20	86 ± 21	63^{+7}_{-5}	0.27 ± 0.05
Feruglio et al. 2023			
J1007+2115 [†]	29 ± 1	50 (fixed)	0.93 ± 0.07

Table A.1: *Sources in this work studied also by Costa et al. 2026 and for which the actual the dust temperature was derived by sed fitting at infrared emission. Source J1007+2115 is also reported as part of different works and encountered several times during my university study [†]Pōniuāēna means unseen spinning source of creation, surrounded with brilliance.*

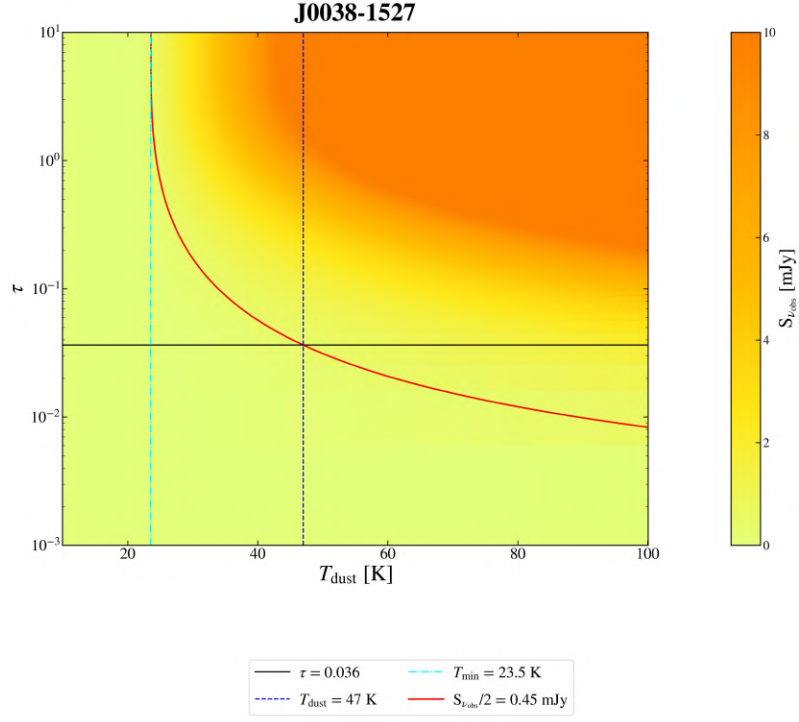
We also report the quasar J1007+2115, known as Pōniuāēna¹, as a further well-studied source for comparison with our results. The dust mass we infer for this source, $M_{\text{dust}} = (3.84 \pm 0.16) \times 10^8 M_{\odot}$, is a factor of ~ 2 higher than the value reported by Feruglio et al. 2023, $M_{\text{dust}} = (1.7 \pm 0.6) \times 10^8 M_{\odot}$. This discrepancy can be attributed to the different convention adopted for the source size: in this work, R_{dust} is defined as a half-light radius, so the total dust mass is obtained as $M_{\text{dust,tot}} = 2 M_{\text{dust}}(R_{\text{eff}})$ (sections 2.2 and 2.3), whereas Feruglio et al. 2023 treat the (nearly identical, $\sim 1.0 \times 1.0 \text{ kpc}^2$, still unresolved as of 2023) synthesized-beam size as the total emitting area, applying the full observed flux without any additional factor. Indeed, half of our value, $1.92 \times 10^8 M_{\odot}$, agrees with their result within the quoted uncertainties, confirming that the two estimates are consistent once the size convention is accounted for.

No fitted dust temperature is reported for this source: Feruglio et al. 2023 fixes $T_{\text{dust}} \sim 50 \text{ K}$ as an assumed value. Comparing this assumed temperature to the minimum temperature we derive, $T_{\text{min}} = 29 \pm 1 \text{ K}$, suggest that the dust continuum emission of this source is consistent with the optically thin regime.

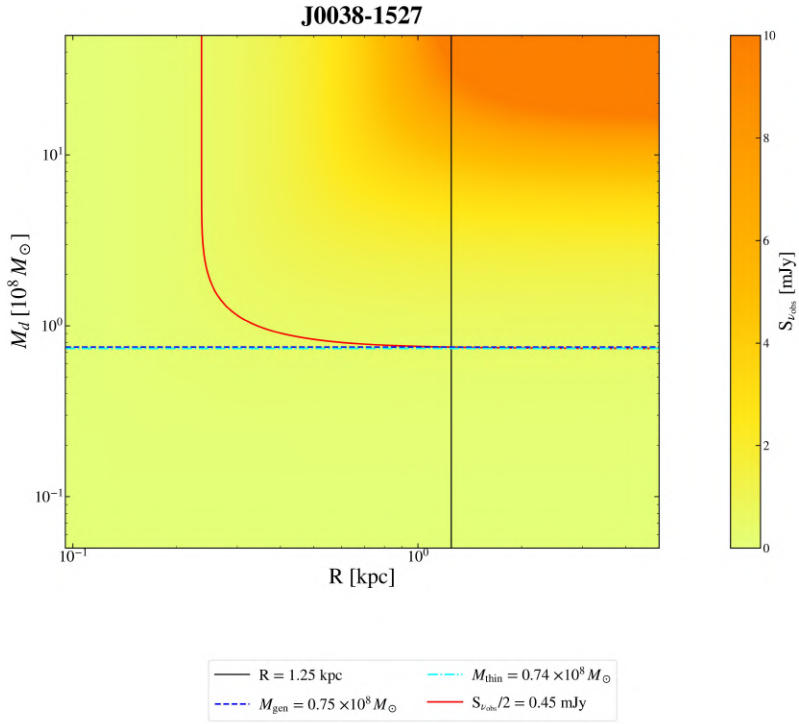
A.3 Degeneracy plots for the *W24* sample

In the next pages we present the plots illustrating the degeneracies between optical depth and temperature (τ – T) and between dust mass and size (M – R), discussed in section 3.9.1 and shown there for three representative sources in figs. 3.10 to 3.12. The caption of fig. 3.10 applies to all the figures reported here. See also fig. 3.9 for a complete overview of the degeneracy and for the identification of individual sources. Sources named with "upper limit" correspond to those with a tapered map or unresolved emission, labeled "a" and "b" in table 3.10.

¹The name means “unseen spinning source of creation, surrounded with brilliance” in Hawaiian. I encountered this source in several works during my university studies

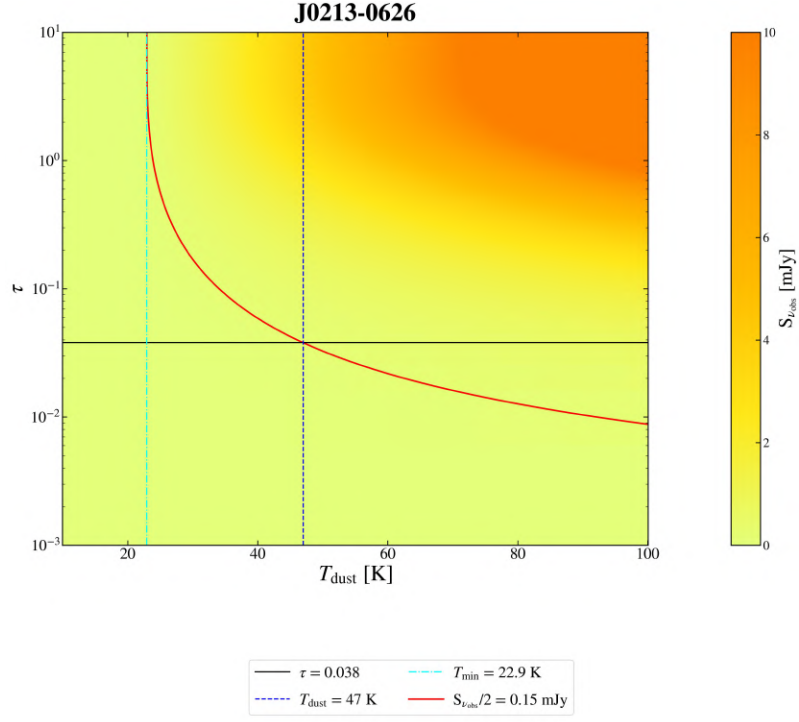


$R = 1.25 \text{ kpc}$

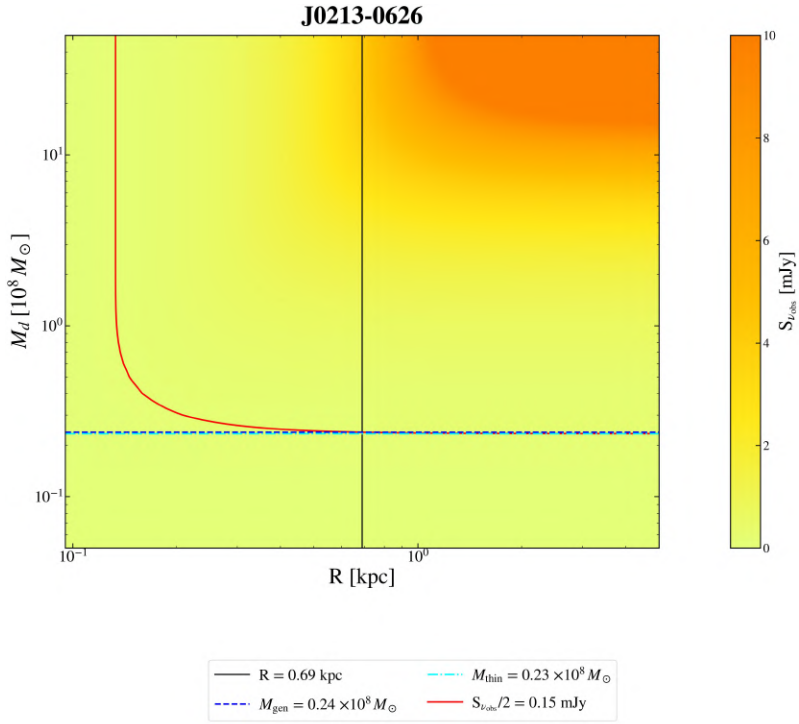


$\tau = 0.036$

Figure A.2: *Source J0038-1527.*



$R = 0.69 \text{ kpc}$



$\tau = 0.038$

Figure A.3: *Source J0213-0626.*

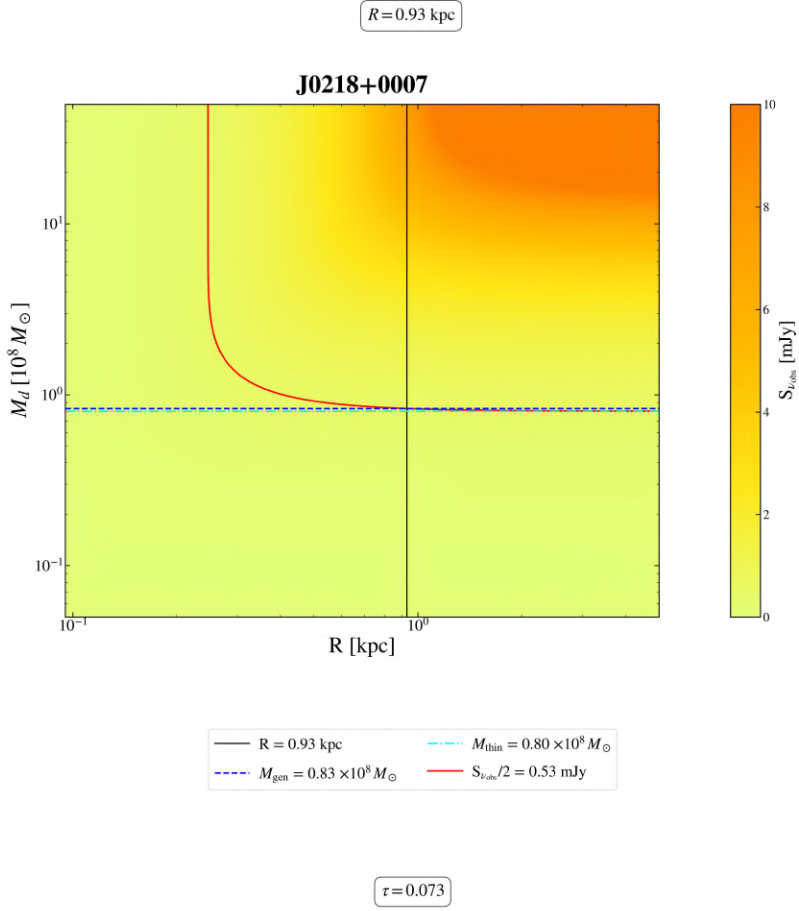
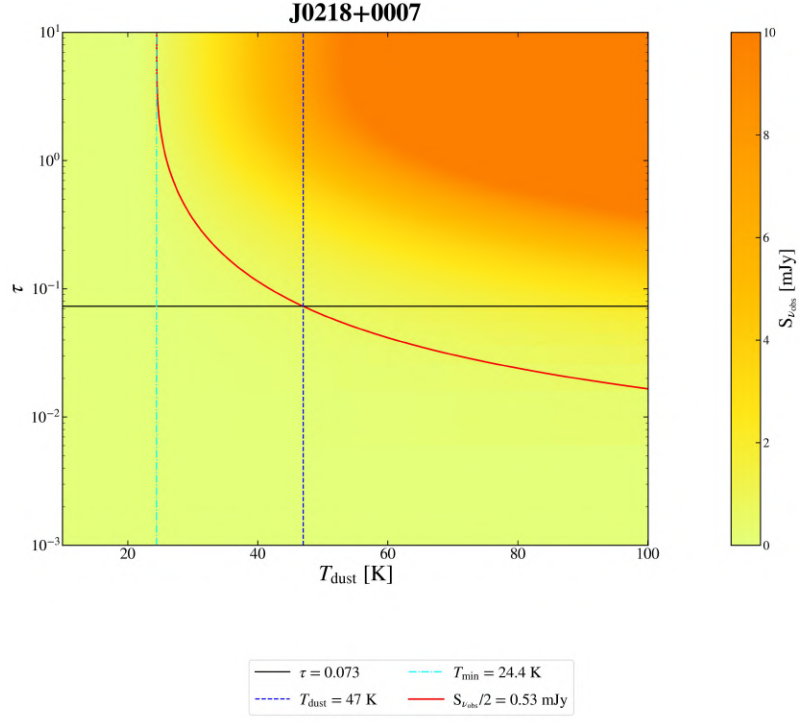


Figure A.4: *Source J0218+0007.*

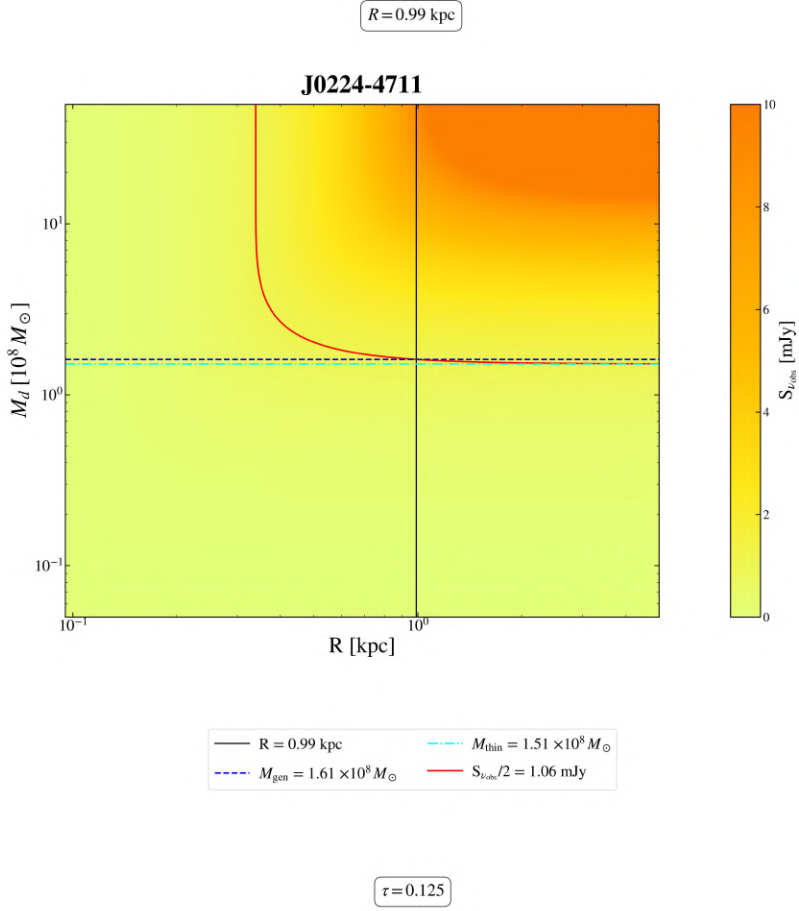
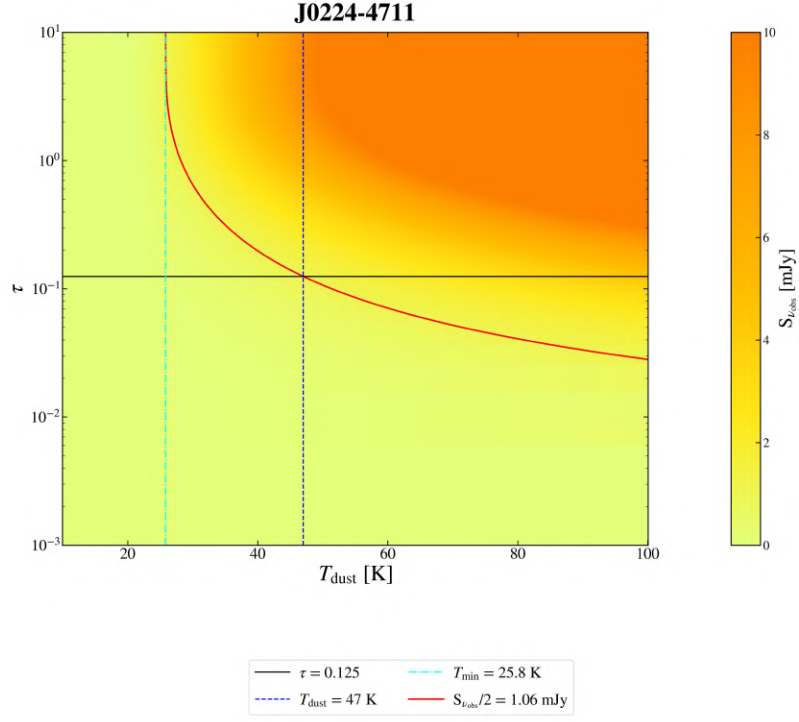
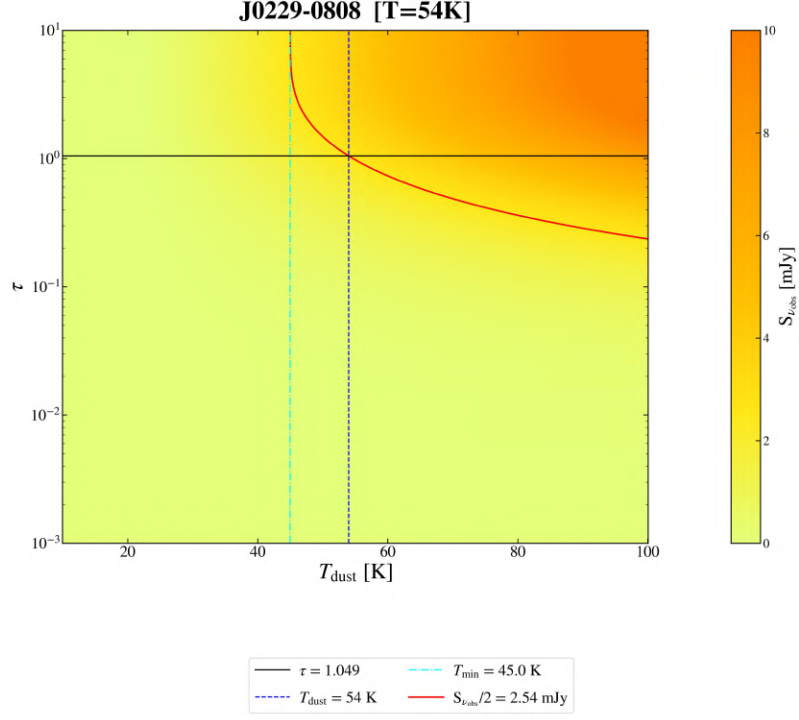
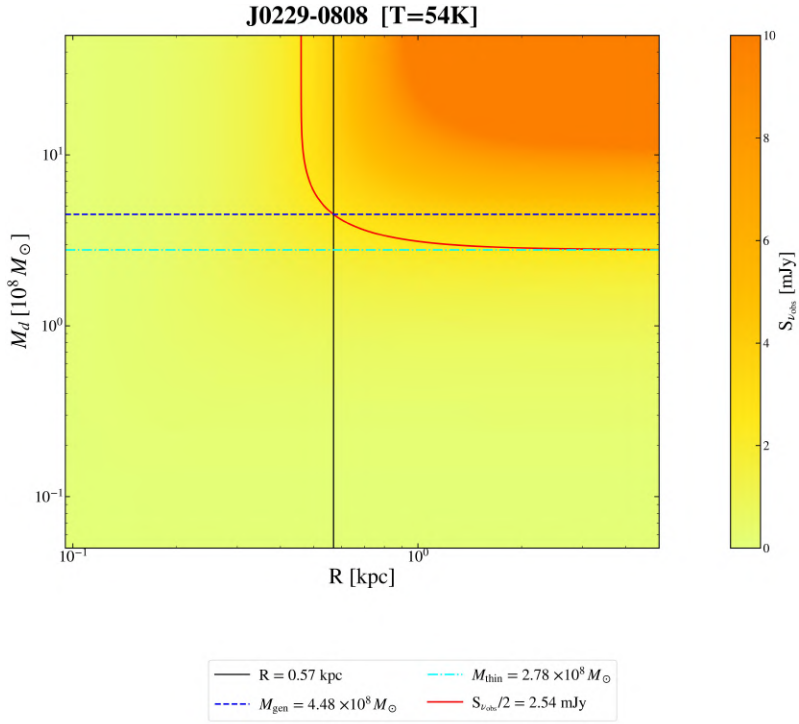


Figure A.5: *Source J0224-4711.*



$R = 0.57 \text{ kpc}$



$\tau = 1.049$

Figure A.6: *Source J0229-0808, with $T_{\min} > 47 \text{ K}$.*

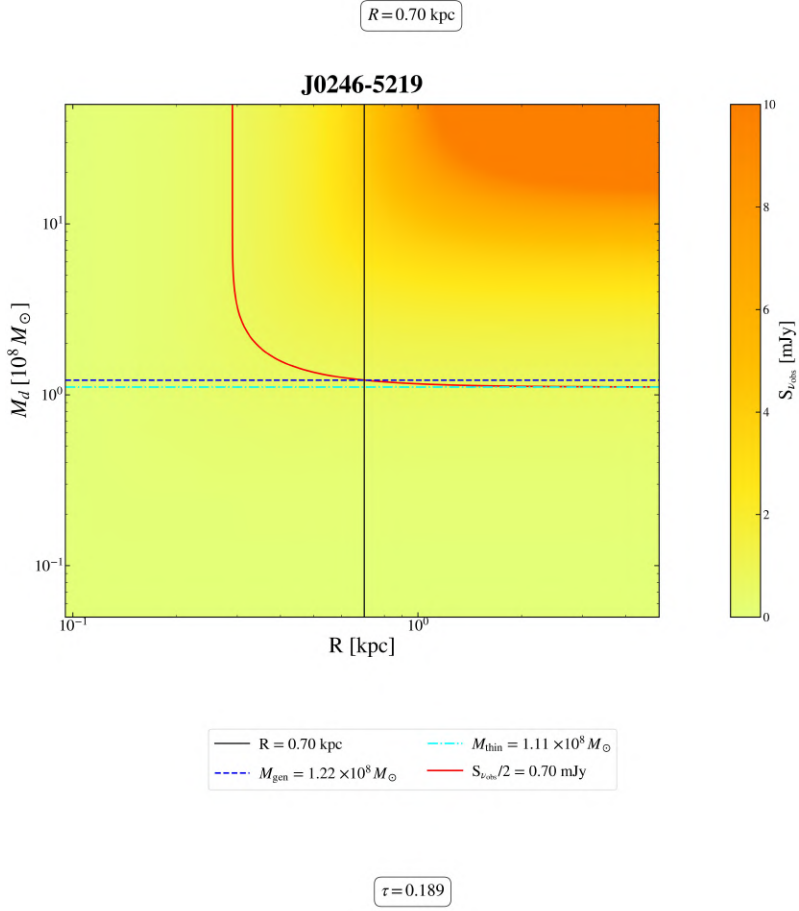
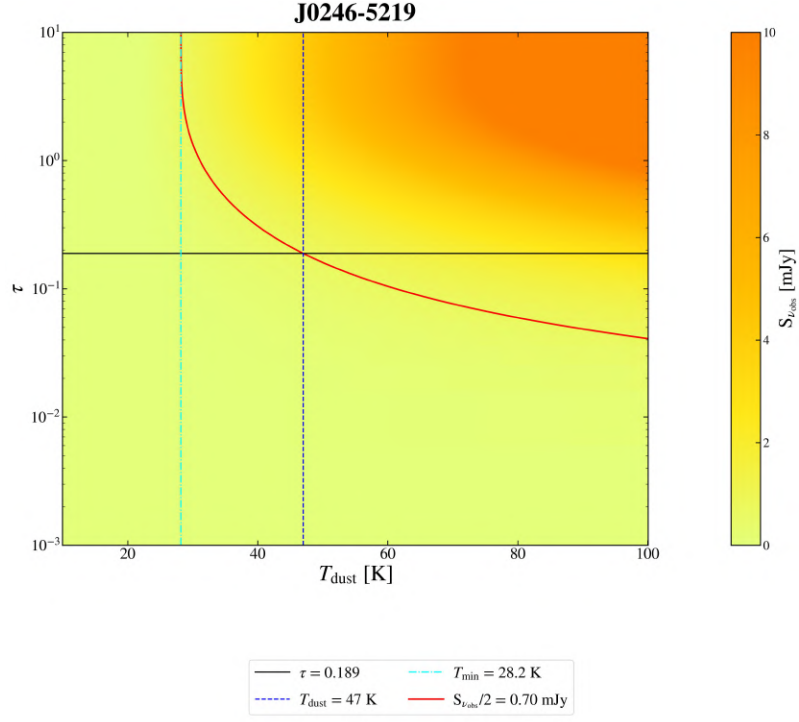
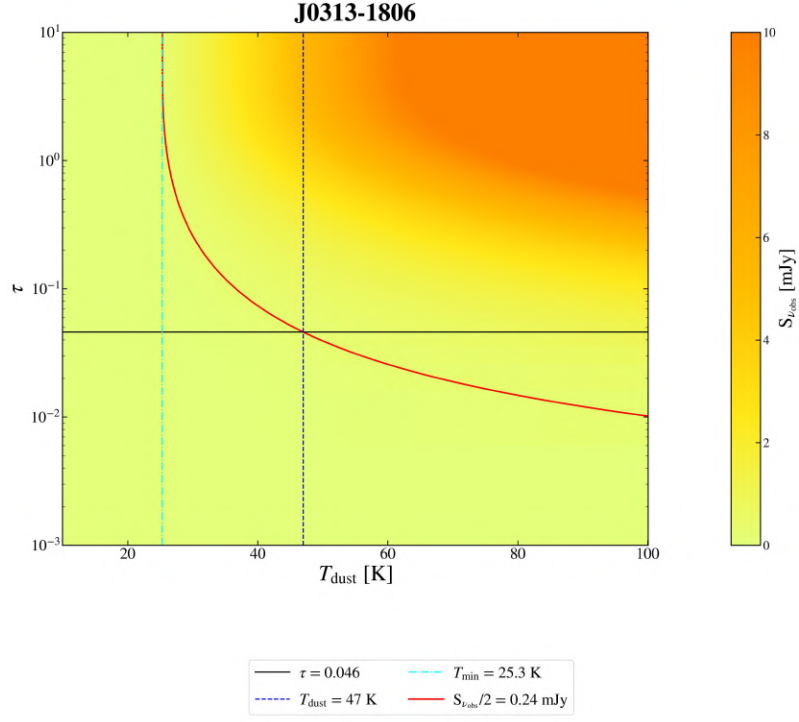
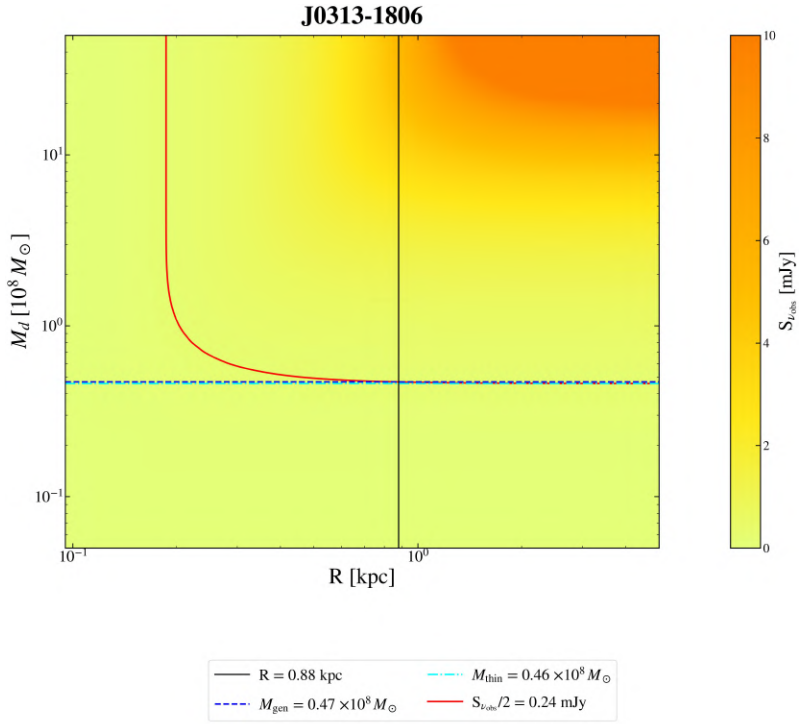


Figure A.7: *Source J0246-5219.*

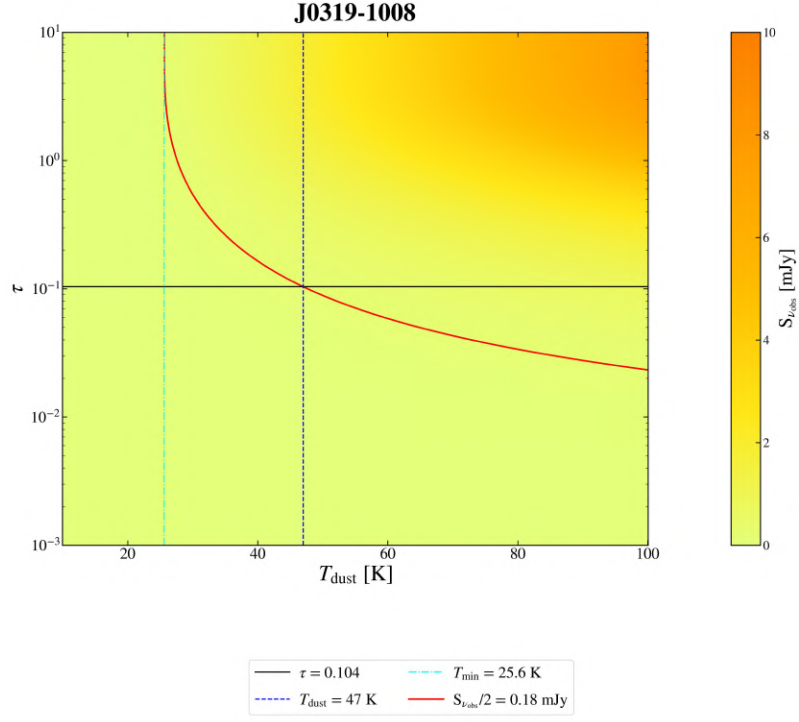


$R = 0.88 \text{ kpc}$

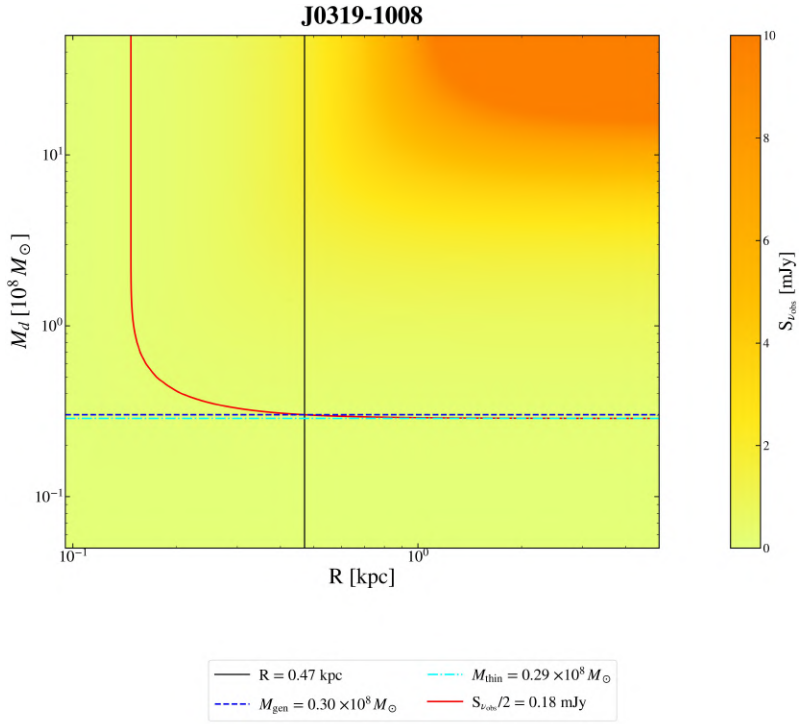


$\tau = 0.046$

Figure A.8: *Source J0313-1806.*

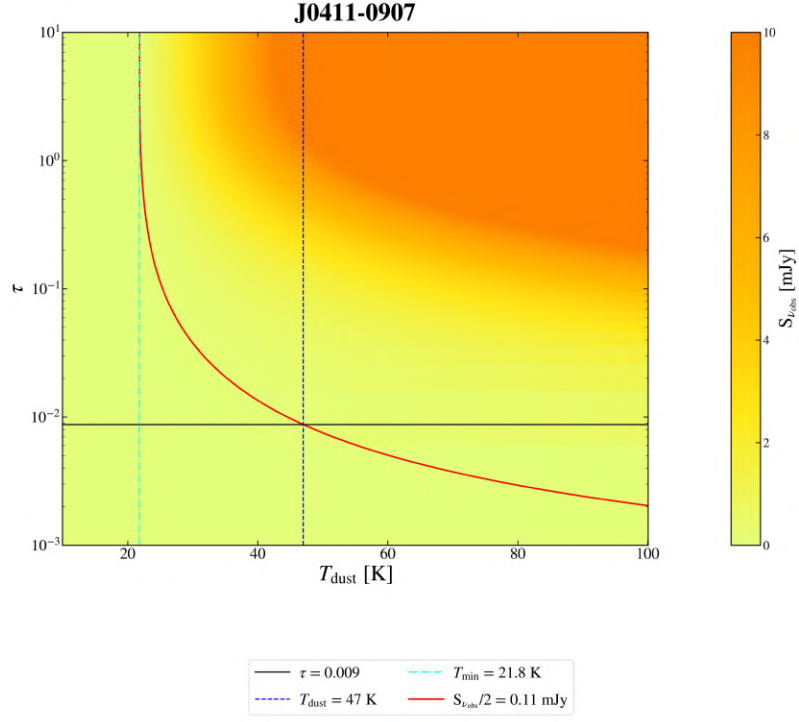


$R = 0.47 \text{ kpc}$

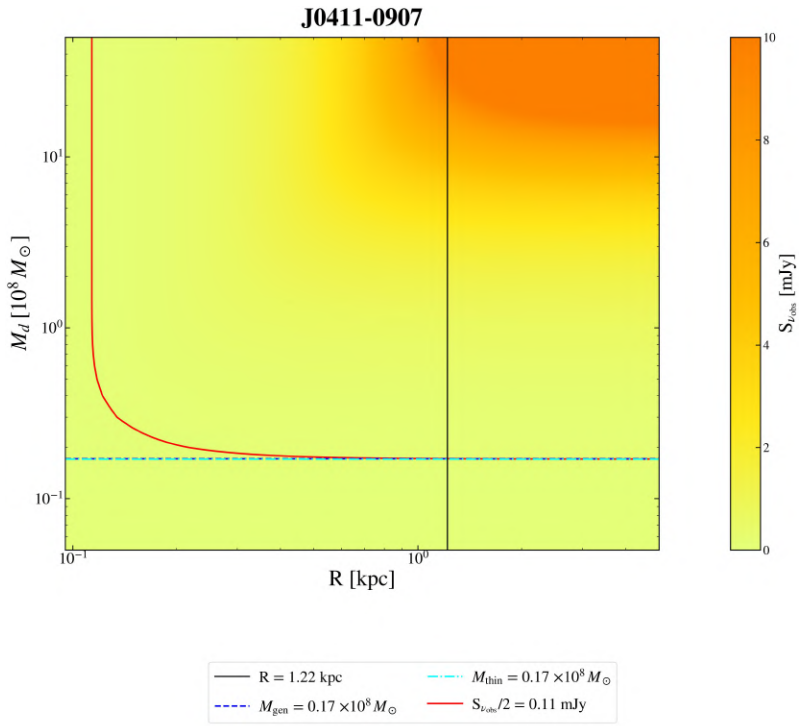


$\tau = 0.104$

Figure A.9: *Source J0319-1008.*

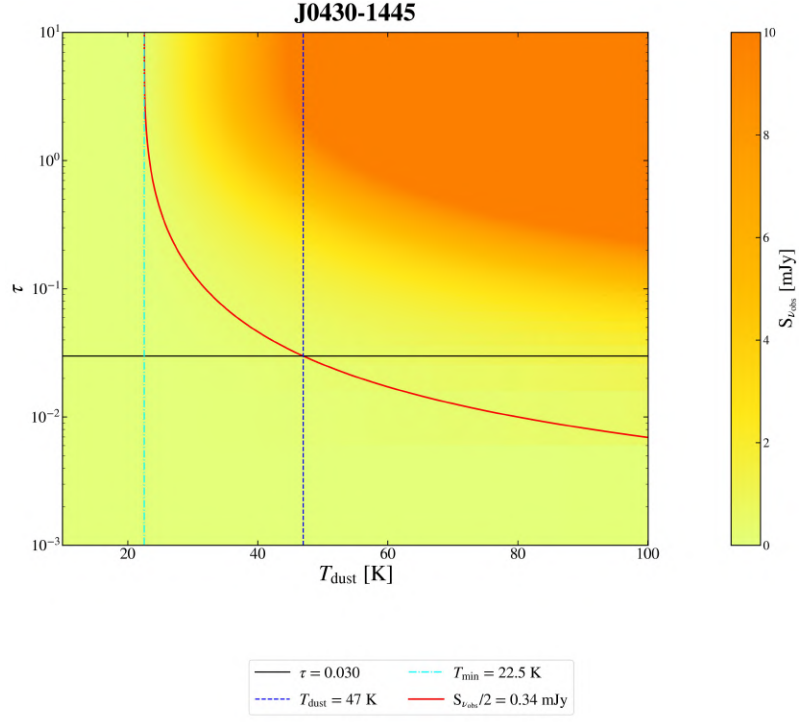


$R = 1.22 \text{ kpc}$

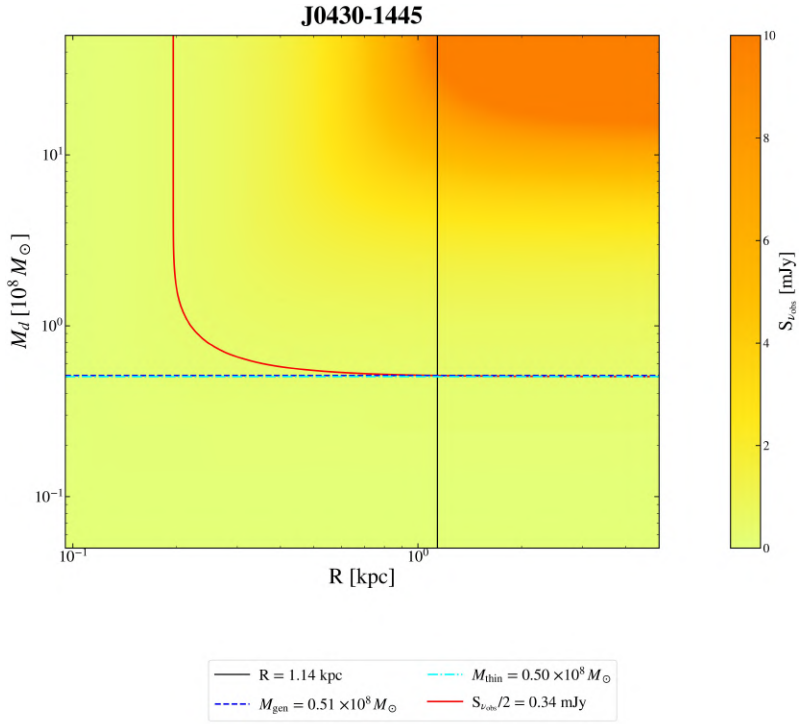


$\tau = 0.009$

Figure A.10: *Source J0411-0907.*



$R = 1.14 \text{ kpc}$



$\tau = 0.030$

Figure A.11: *Source J0430-1445.*

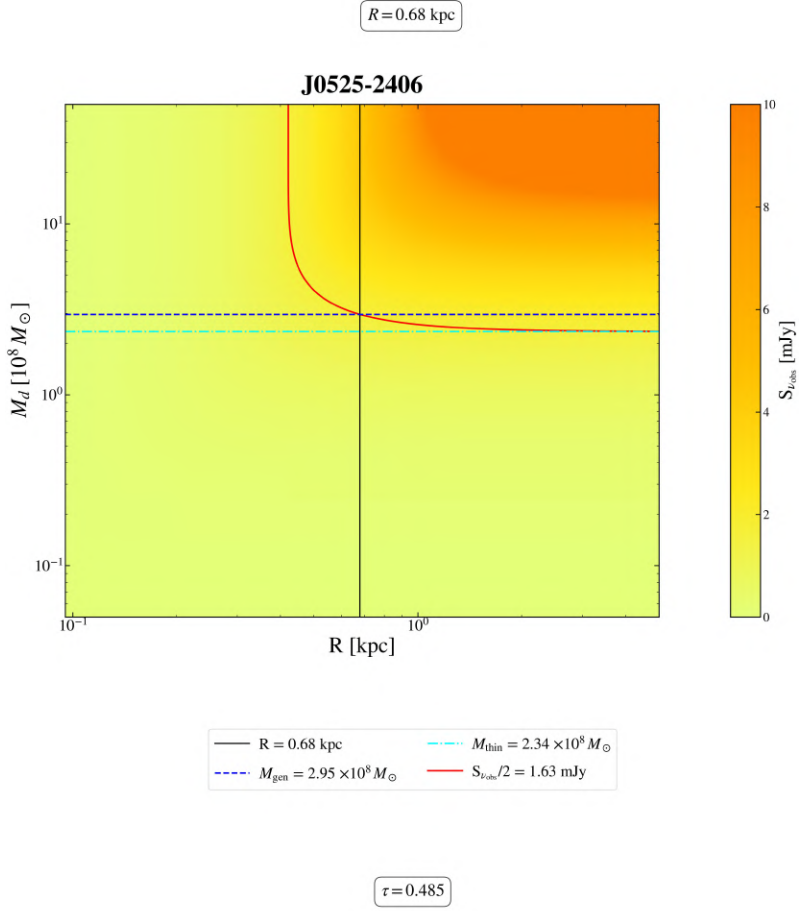
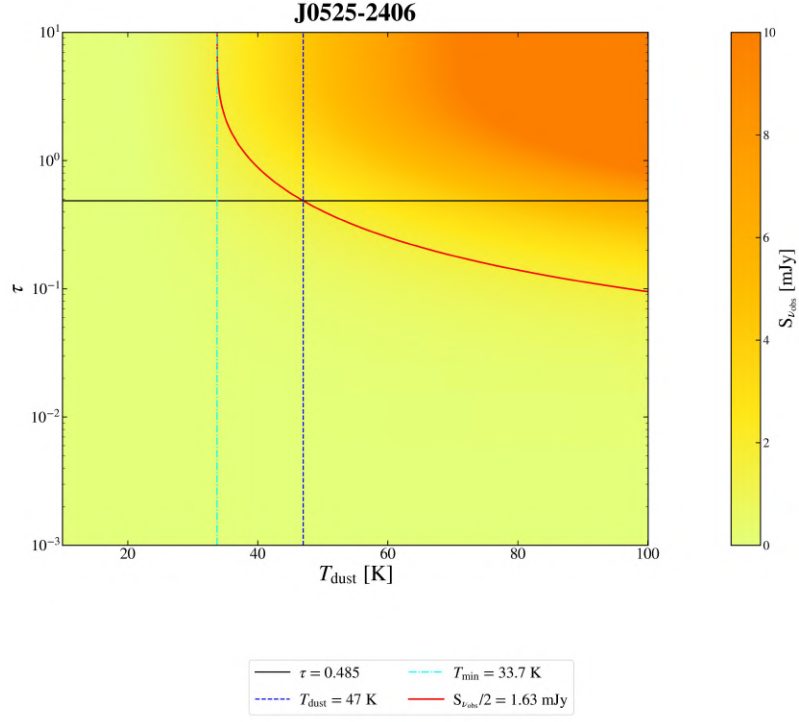


Figure A.12: *Source J0525-2406.*

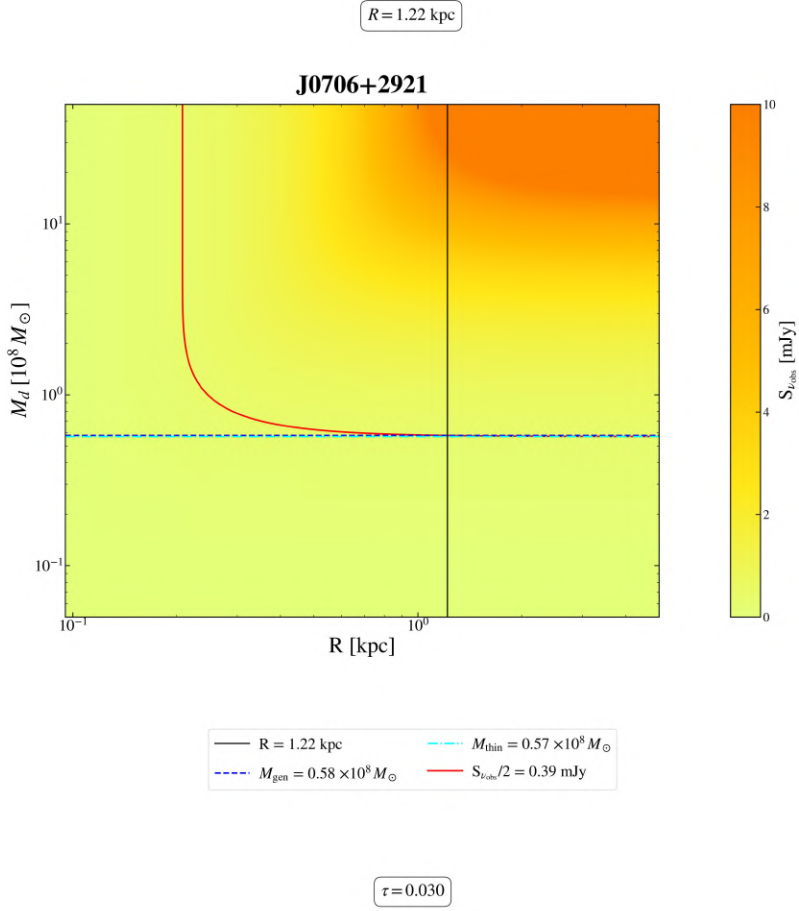
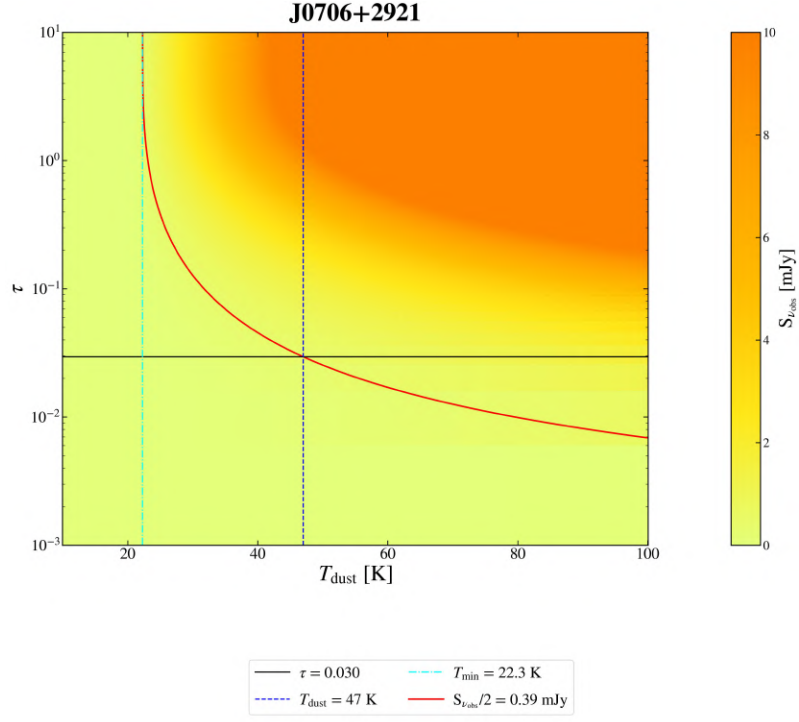


Figure A.13: *Source J0706+2921.*

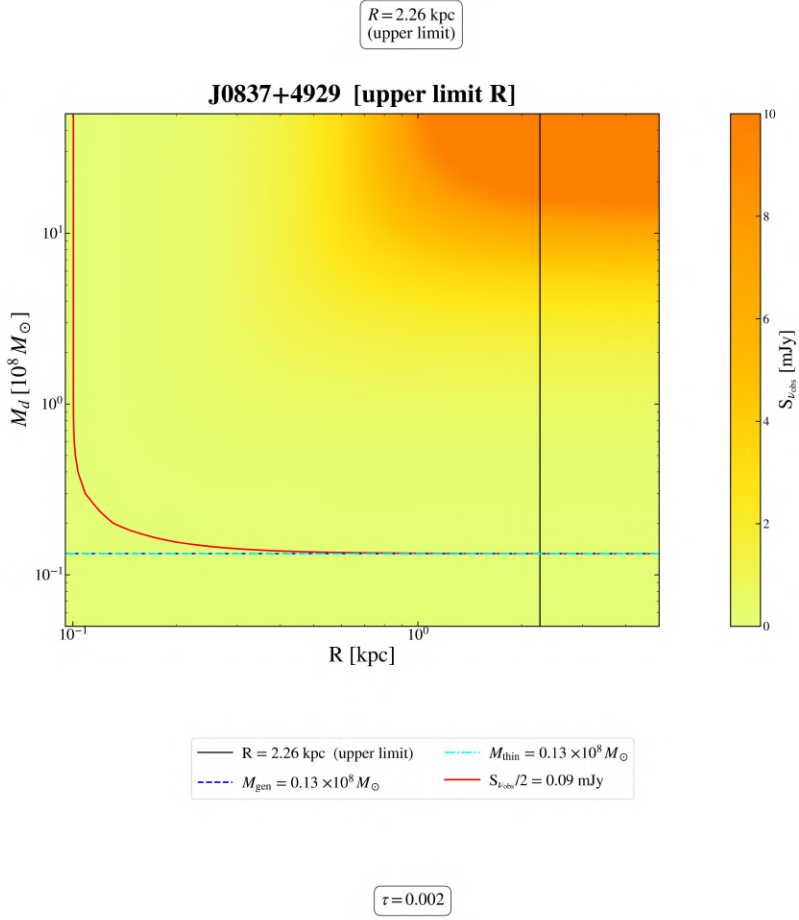
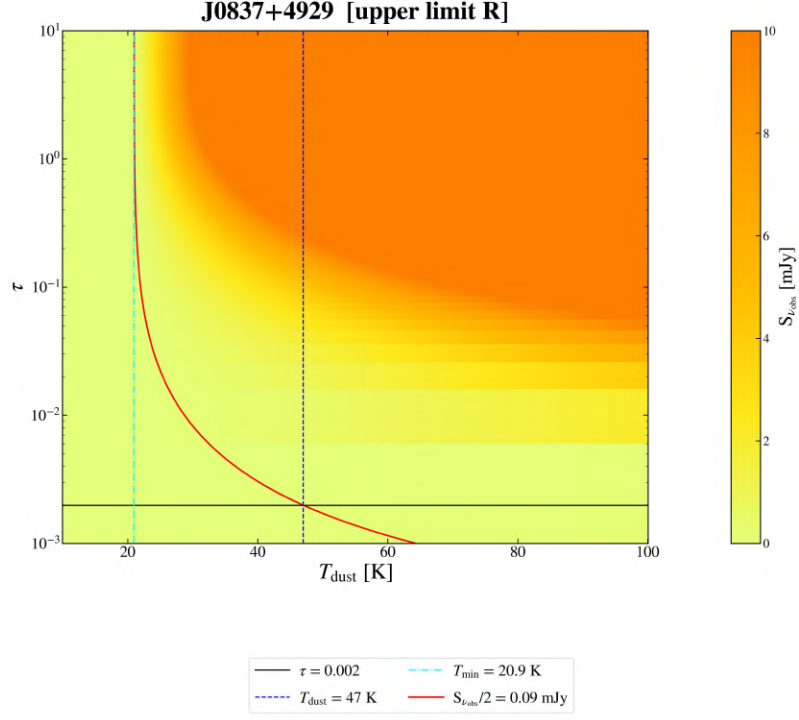
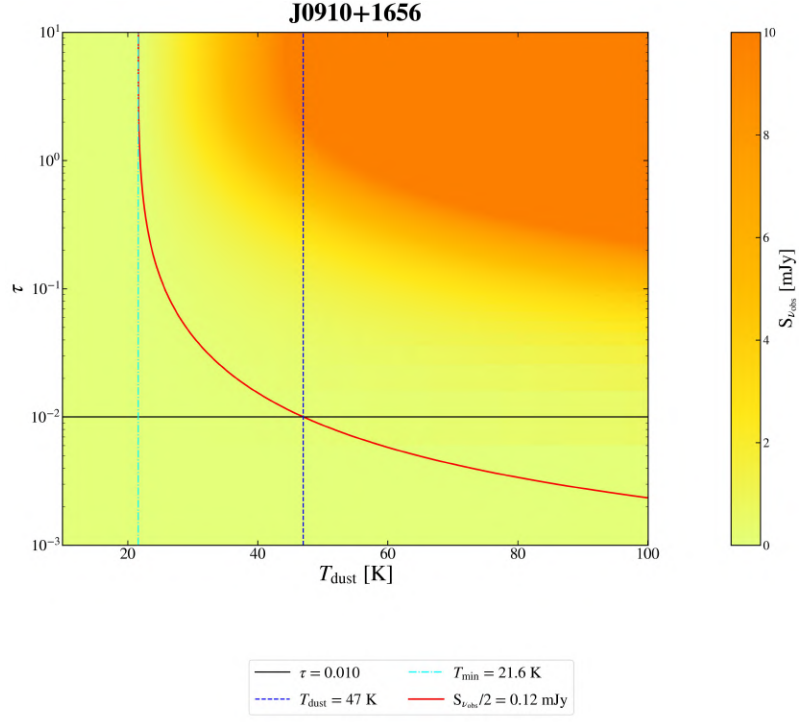
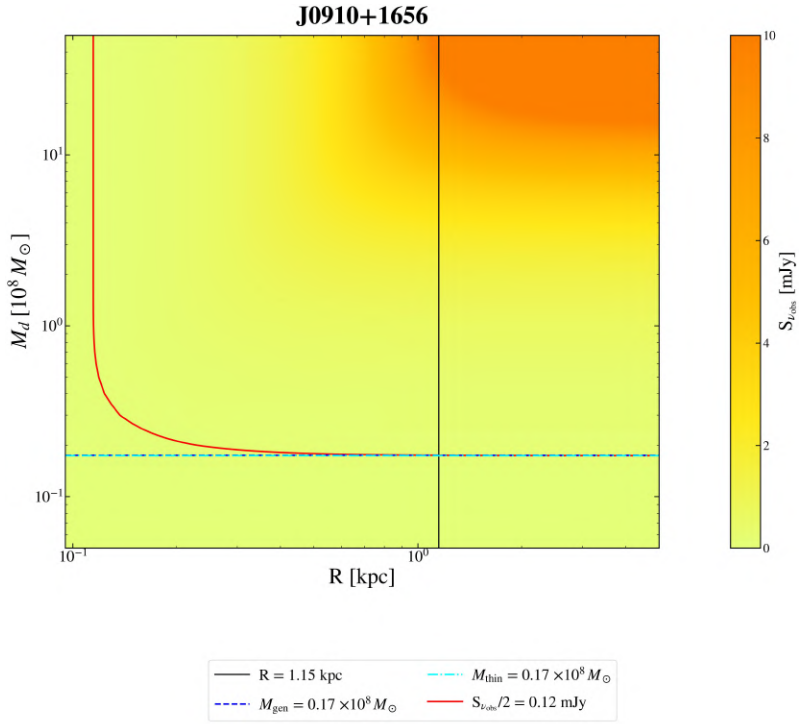


Figure A.14: Source J0837+4929, for which the size given as an upper limit.

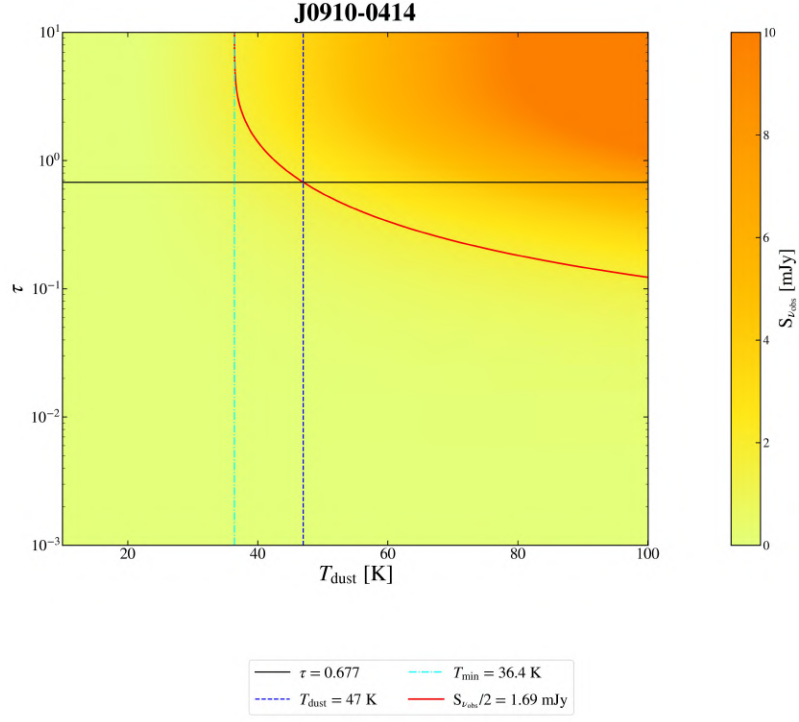


$R = 1.15 \text{ kpc}$

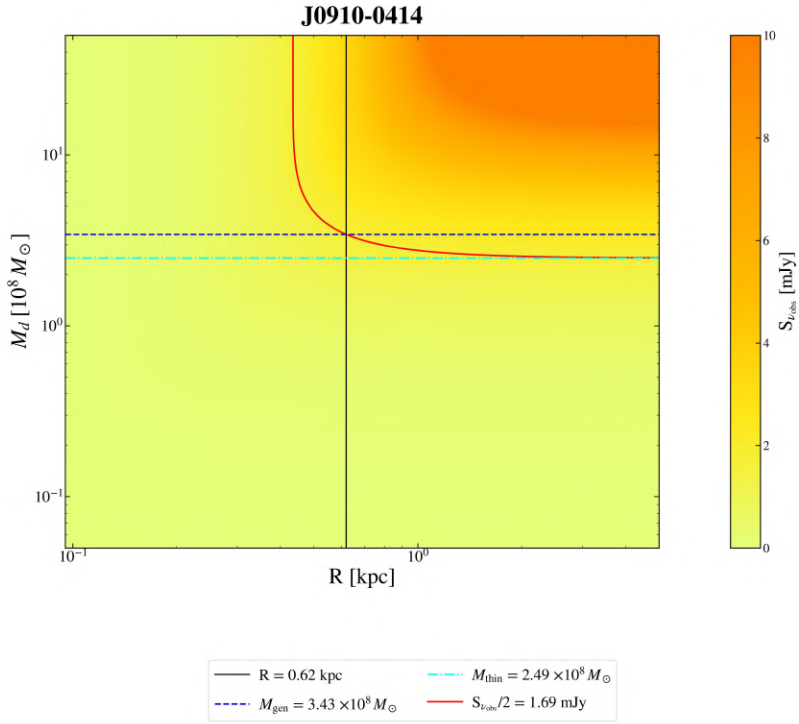


$\tau = 0.010$

Figure A.15: *Source J0910+1656.*

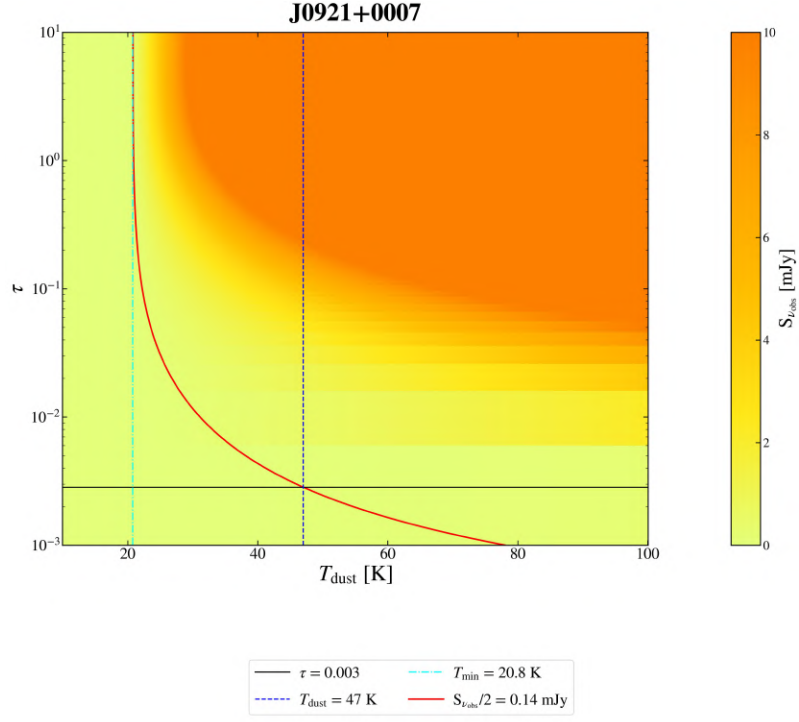


$R = 0.62 \text{ kpc}$

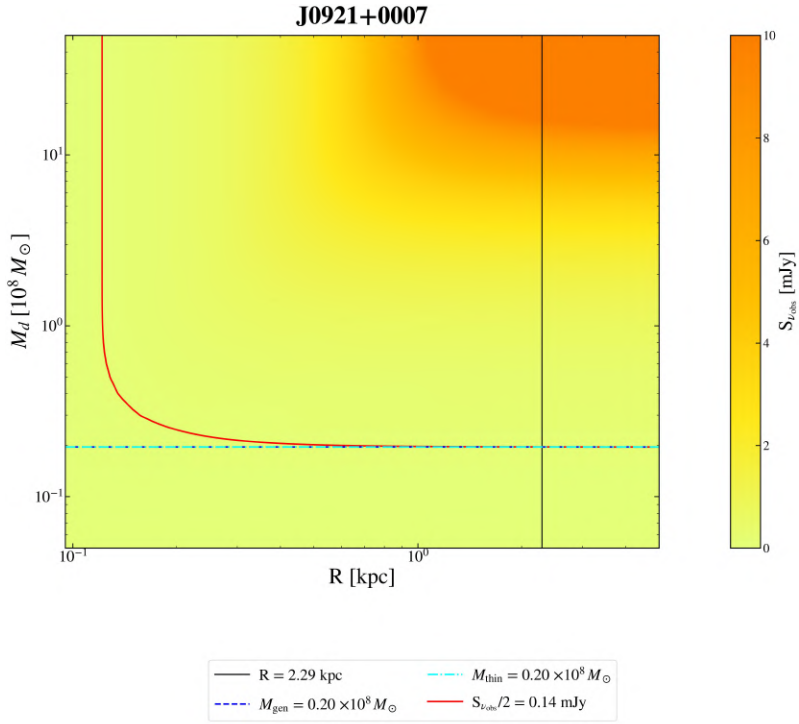


$\tau = 0.677$

Figure A.16: *Source J0910-0414.*



$R = 2.29 \text{ kpc}$



$\tau = 0.003$

Figure A.17: *Source J0921+0007.*

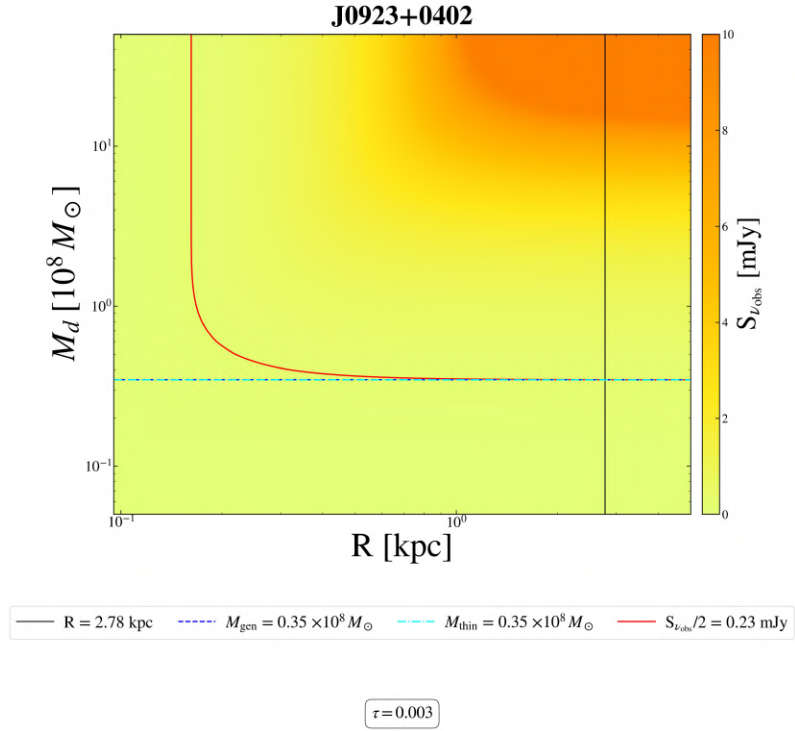
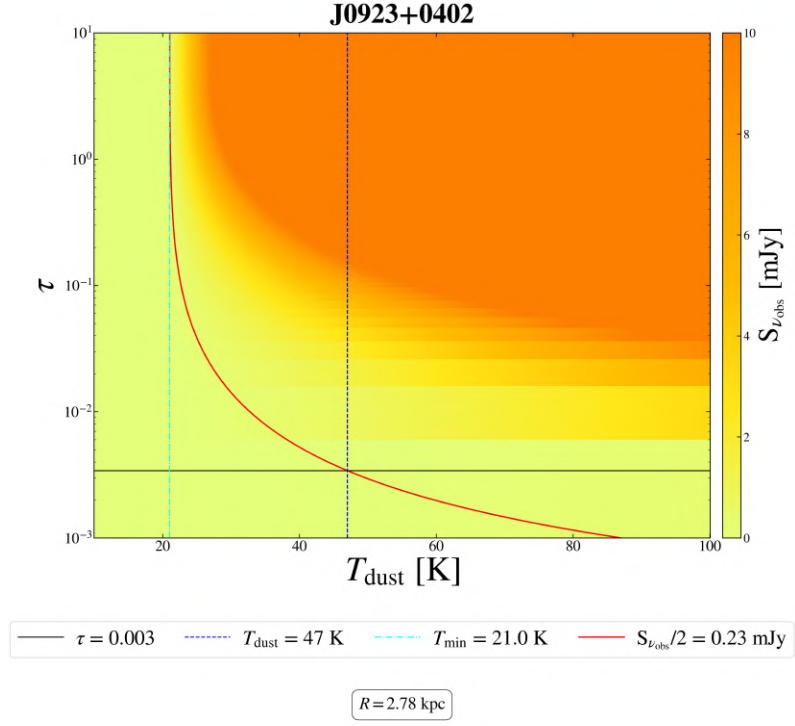


Figure A.18: *Source J0923+0402.*

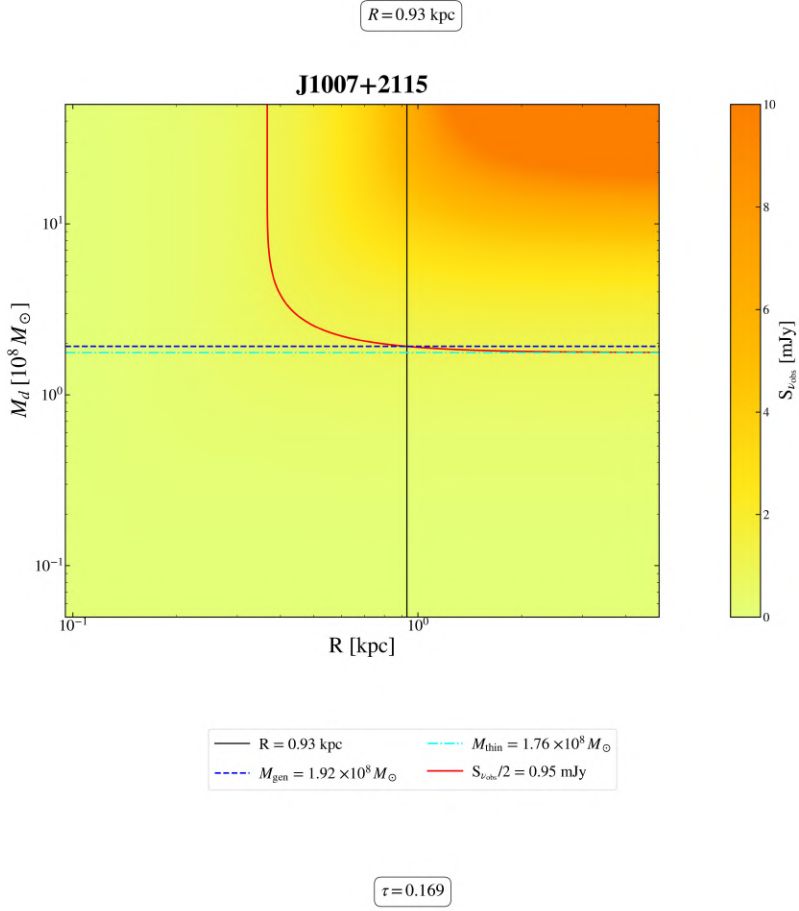
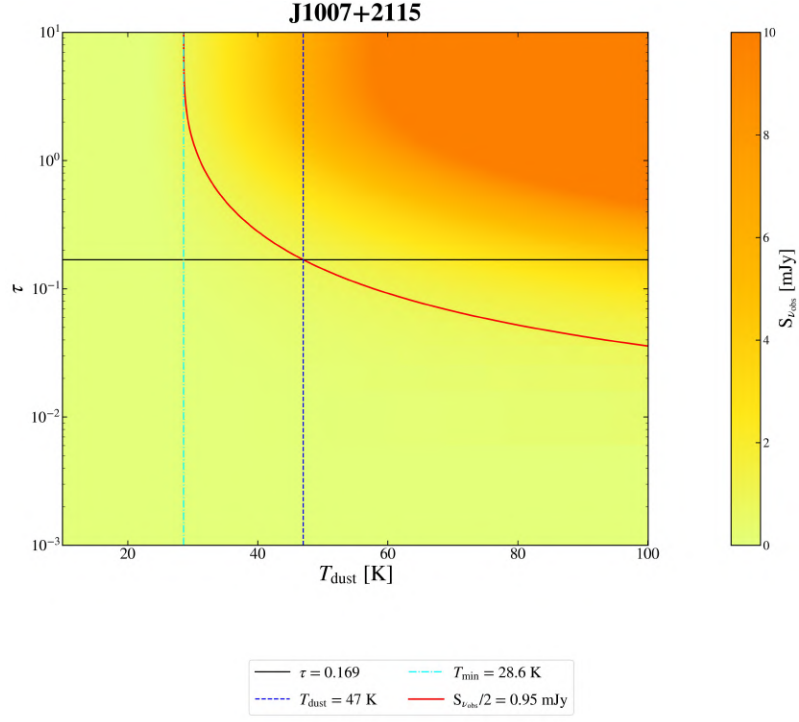


Figure A.19: *Source J1007+2115.*

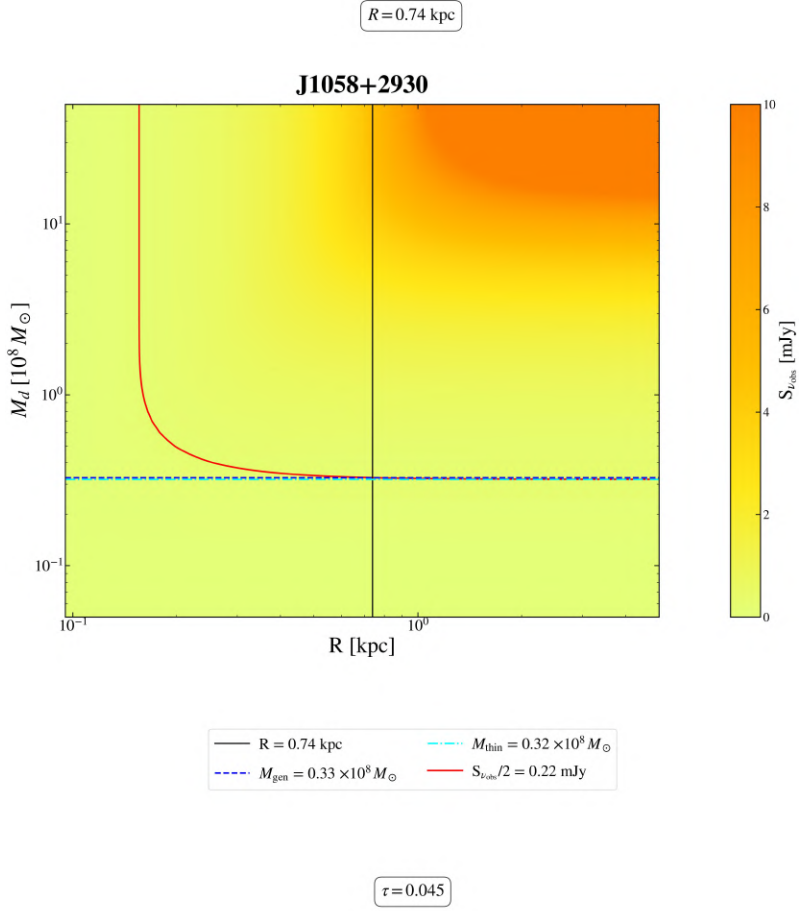
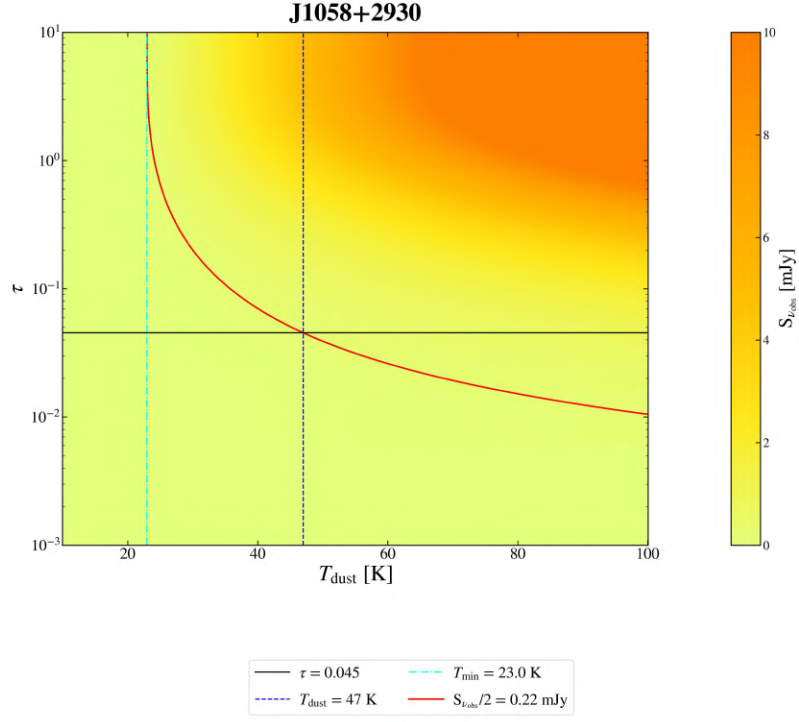
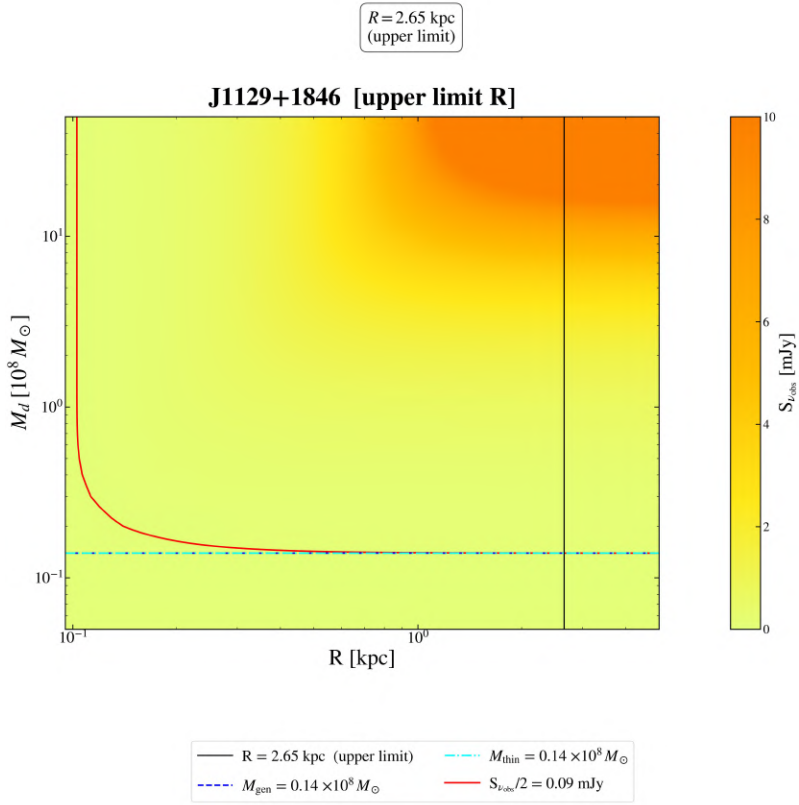
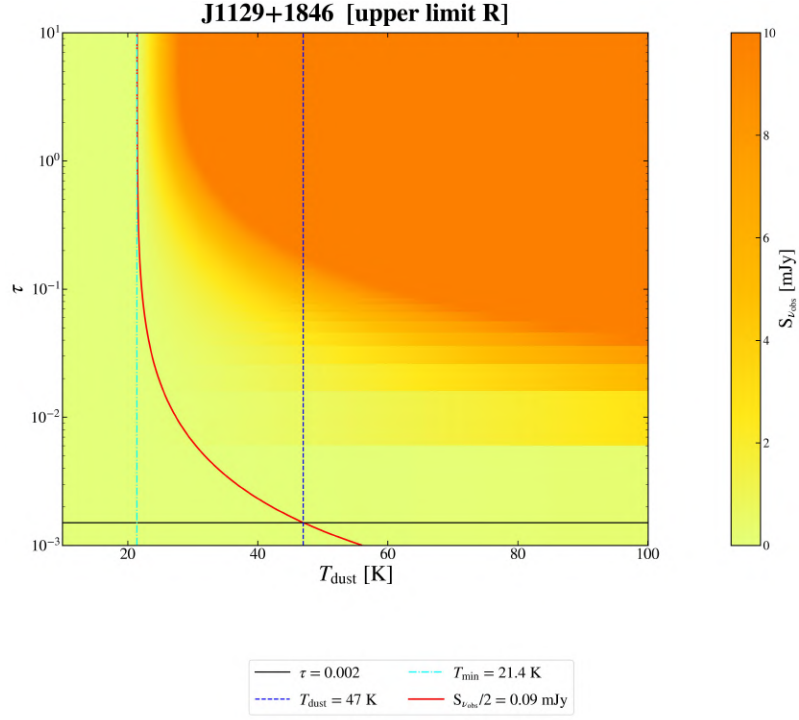


Figure A.20: *Source J1058+2930.*



$\tau = 0.002$

Figure A.21: Source J1129+1846, for which the size is given as an upper limit.

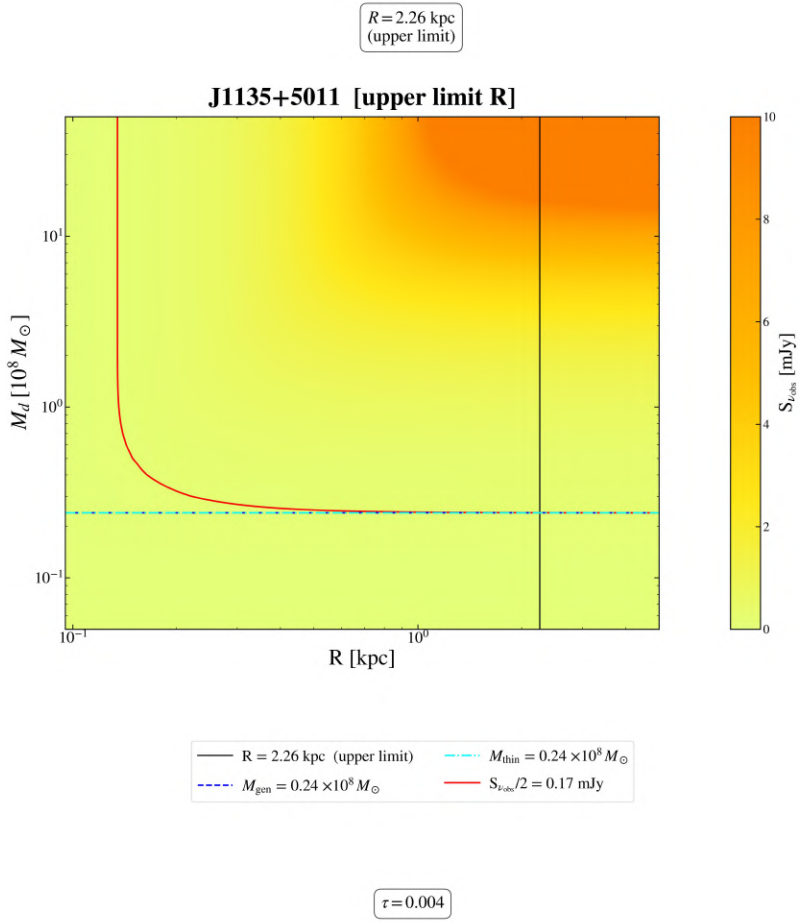
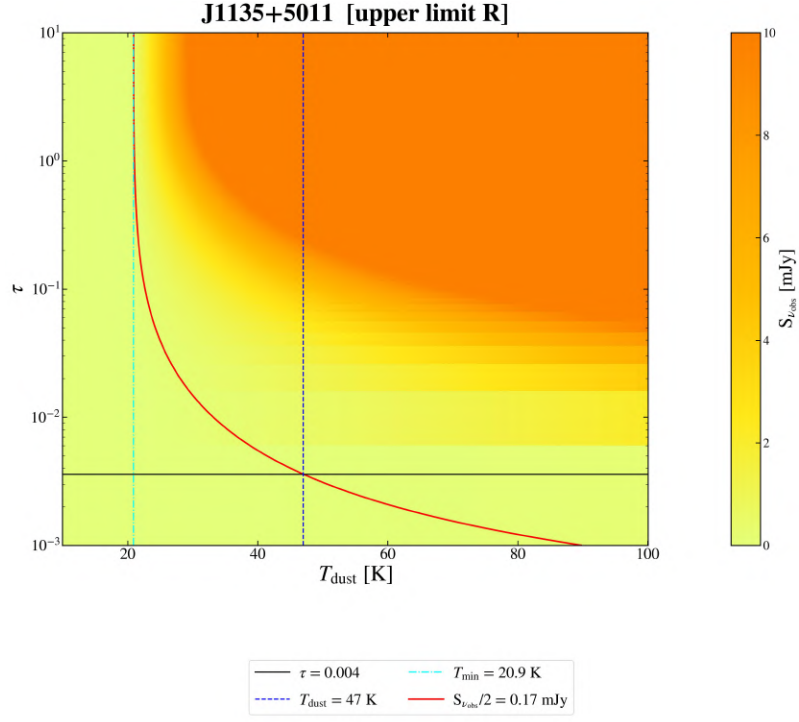
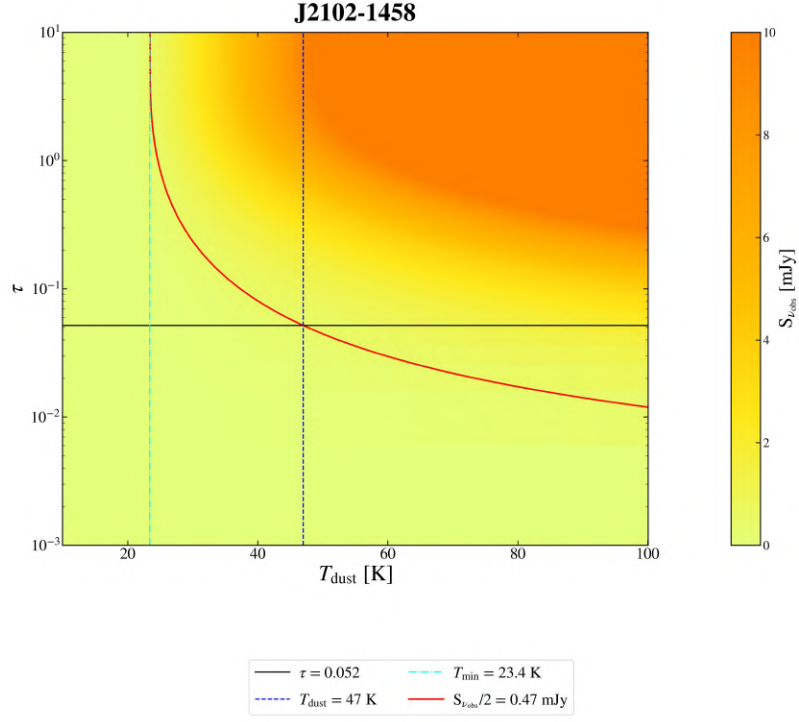
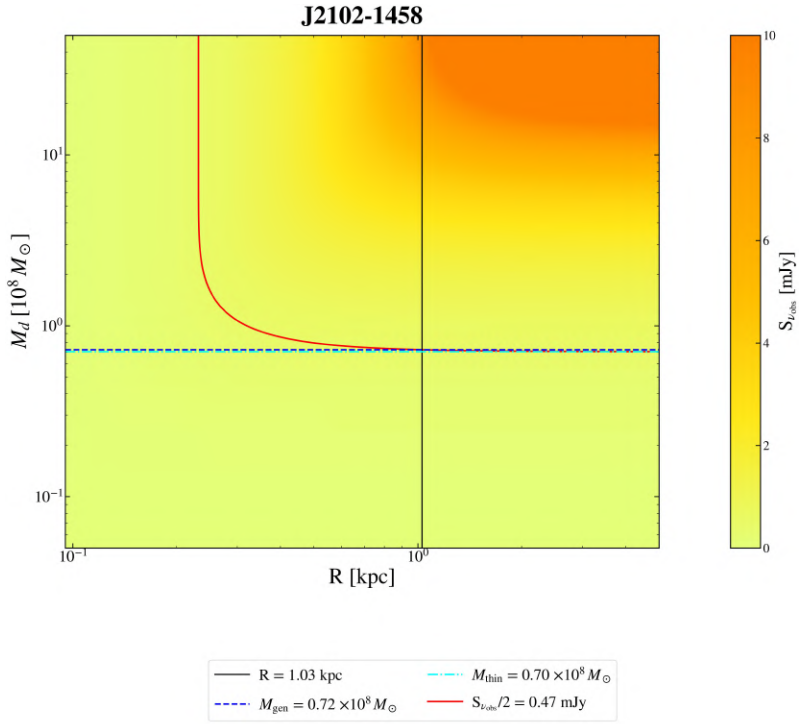


Figure A.22: Source J1135+5011, for which the size is given as an upper limit.



$R = 1.03 \text{ kpc}$



$\tau = 0.052$

Figure A.23: *Source J2102-1458.*

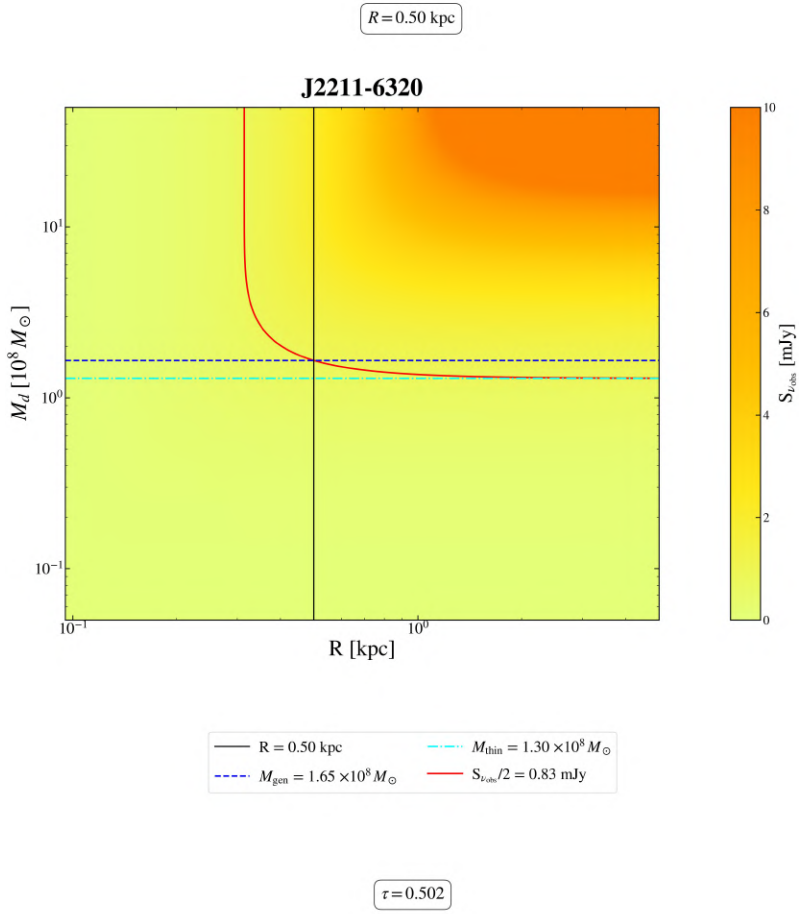
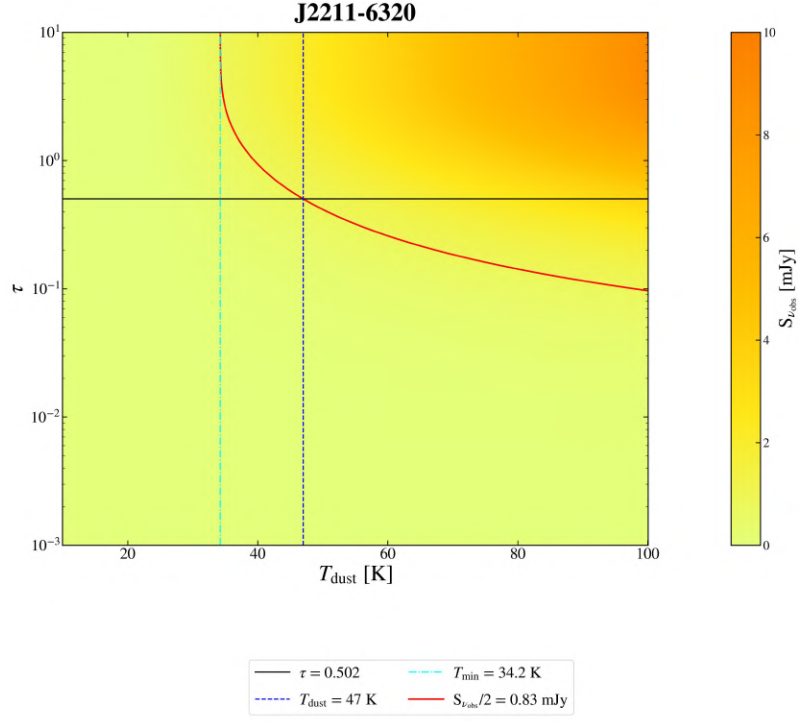


Figure A.24: *Source J2211-6320.*

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