

Cool Gas in High Redshift Galaxies

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Abstract

Over the last decade, observations of the cool interstellar medium in distant galaxies via molecular and atomic fine structure line emission has gone from a curious look into a few extreme, rare objects, to a mainstream tool to study galaxy formation, out to the highest redshifts. Molecular gas has now been observed in close to 200 galaxies at $z > 1$, including numerous AGN host-galaxies out to $z \sim 7$, highly starforming sub-millimeter galaxies (median redshift $z \sim 2.5$), and increasing samples of ‘main-sequence’ color-selected star forming galaxies at $z \sim 1.5$ – 2.5 . Studies have moved well beyond simple detections, to dynamical imaging at kpc-scale resolution, and multi-line, multi-species studies that determine the physical conditions in the interstellar medium in early galaxies. Observations of the cool gas are the required complement to studies of the stellar density and star formation history of the Universe, as they reveal the phase of the interstellar medium that immediately preceeds star formation in galaxies. Current observations suggest that the order of magnitude increase in the cosmic star formation rate density from $z \sim 0$ to 2 is commensurate with a similar increase in the gas to stellar mass ratio in star forming disk galaxies. Progress has been made on determining the CO luminosity to H_2 mass conversion factor at high- z , and the dicotomy between high versus low values for main sequence versus starburst galaxies, respectively, appears to persist with increasing redshift, with a likely dependence on metallicity and other local physical conditions. Studies of atomic fine structure line emission are rapidly progressing, with some tens of galaxies detected in the exceptionally bright [C II] $158\mu\text{m}$ line to date. The [C II] line is proving to be a unique tracer of galaxy dynamics in the early Universe, and, together with other atomic fine structure lines, has the potential to be the most direct means of obtaining spectroscopic redshifts for the first galaxies during cosmic reionization.

CONTENTS

Introduction	2
<i>Motivation</i>	2
<i>Galaxy formation and the need for cool gas observations</i>	3
Concepts of observing cool gas	6
<i>Heating and cooling of the starforming ISM in galaxies</i>	6
<i>Tracing molecular gas: observable frequencies</i>	7
<i>Gas Temperatures & Critical Density</i>	7
<i>Brightness Temperature and line luminosities</i>	8
<i>CO luminosity to total molecular gas mass conversion factor</i>	9

<i>Modeling the line excitation</i>	11
<i>Water lines</i>	12
<i>Atomic Fine Structure lines</i>	13
<i>Relation to far-infrared emission and SFRs</i>	14
<i>Role of CMB</i>	15
Molecular gas at high redshift	16
<i>Introduction</i>	16
<i>Quasars</i>	17
<i>Submillimeter galaxies</i>	17
<i>Radio Galaxies</i>	19
<i>Color Selected Star-Forming Galaxies (CSG)</i>	19
<i>MIPS/24 micron-selected Galaxies</i>	20
<i>Lyman-Break Galaxies, Lyα Emitters, and Lyα Blobs</i>	20
<i>Table of all high-z ISM detections</i>	21
<i>Historical note</i>	21
Observational diagnosis of the cool ISM in distant galaxies	21
<i>Molecular gas excitation</i>	21
<i>CO luminosity to total molecular gas mass conversion</i>	23
<i>Atomic Fine Structure lines</i>	26
<i>Dense gas tracers and other molecules at high redshift</i>	28
<i>Star formation laws and gas consumption</i>	29
<i>Imaging of the molecular gas in early galaxies</i>	32
<i>Outflows</i>	34
Dense Gas History of the Universe	35
<i>Gas dominated disks during the epoch of galaxy assembly</i>	35
<i>First Galaxies</i>	38
<i>Spectral Deep Fields and the Dense Gas History of the Universe</i>	39
Summary Points / Concluding Remarks	41
Future directions	42

1 Introduction

1.1 Motivation

The last few years have seen remarkable progress in the study of the cool, molecular gas content of galaxies, using centimeter and (sub-)millimeter telescopes. The cool gas content is a critical parameter in galaxy evolution, serving as the immediate fuel for star formation in galaxies. The state of the field in 2005 was reviewed by Solomon & vanden Bout (2005; see also Omont 2007). At that point, only a few handful of extreme starburst galaxies and luminous active galactic nuclei (AGN) host galaxies had been detected in molecular gas emission at significant lookback times, hardly anything was known about the gas excitation, and there were no detections of atomic fine structure lines. Research in recent years has resulted in an explosion in the number and type of galaxies detected in molecular line emission, as well as in atomic fine structure line emission, in the distant Universe. Detailed multi-transition, multi-species follow-up has been performed to determine the physical conditions of the gas in some of the brightest high-redshift systems known. The results are proving extremely telling for our understanding of galaxy formation and evolution and suggest that the molecular gas content of galaxies increases significantly with look-back time.

It is a good time to review the field of molecular line observations of high redshift galaxies for two reasons. First is the dramatic advance that has been made over the last decade, both in the number of galaxies detected, as well as the characterization of the molecular properties of these galaxies through followup observations. Second is the imminent full operation of revolutionary telescopes, the Atacama Large Millimeter/Submillimeter Array, ALMA (Wootten & Thompson 2009; Andreani 2010), and the Karl J. Jansky Very Large Array, JVL (Perley et al. 2011), both of which promise to explore this evolution of the universal molecular gas content to an order of magnitude greater level of detail and sensitivity than previously possible. This review of the field, at this temporal cusp of knowledge, captures the current state of the field, and frames the fundamental questions that will be addressed with the next generation instruments.

1.2 Galaxy formation and the need for cool gas observations

Galaxy evolution has been the subject of many reviews in recent years (e.g. Shapley 2011, Renzini 2006, Giavalisco 2002, Silk & Mamon 2012) and the last decade has seen dramatic advances in our understanding of cosmic structure formation. Cosmic geometry, the mass-energy content of the Universe, and the initial density fluctuation spectrum, are now known to better than 10% (Spergel et al. 2007, Komatsu et al. 2011). Structure formation through gravitational instabilities has been calculated in exquisite detail through numerical studies (e.g. Springel et al. 2005, Klypin et al. 2011), and observationally verified through studies of galaxy distributions (e.g., Peacock et al. 2001, Reid et al. 2010). And the cosmic star formation rate density (the ‘star formation history of the Universe’, SFHU), and stellar mass build-up, have been quantified back to first light and cosmic reionization (e.g. Bouwens et al. 2011a, Coe et al. 2013), within 1 Gyr of the Big Bang. Studies of galaxy formation are now turning attention to the evolution of the cool gas, the fuel for star formation in galaxies. In this section, we briefly summarize some of the general conclusions on galaxy formation that are relevant to our subsequent review of the gaseous evolution of galaxies.

Three main epochs have been identified in the SFHU, starting with a steady rise during cosmic reionization from $z \sim 10$ to 6 (e.g. Bouwens et al. 2011b; Bouwens et al. 2012, Coe et al. 2013), corresponding to the epoch when light from the first galaxies reionizes the neutral intergalactic medium (IGM) that pervaded the Universe (Fan et al. 2006, Finkelstein et al. 2012). The comoving cosmic star formation rate density then peaks at $z \sim 1$ to 3. This range is known as the ‘epoch of galaxy assembly,’ during which about half the stars in the present day Universe form (Shapley 2011; Marchesini et al. 2009; Reddy et al. 2008). Last comes the order of magnitude decline in the comoving cosmic star formation rate density from $z \sim 1$ to the present (e.g. Lilly et al. 1996, Madau et al. 1996).

The study of galaxy formation takes on the challenge to explain this observed star formation history of the universe in the context of Λ CDM, the hierarchical dark matter halo model. To understand galaxy formation we must investigate how stars and star formation are distributed over dark matter halos with different masses as a function of time. The most important feature of our current understanding of the field is that star and galaxy formation is inefficient: only $\sim 5\%$ of all baryons (i.e. atoms of all kind) are in stars and dark stellar remnants at redshift zero (e.g., Fukugita & Peebles 2004).

Galaxies with a baryonic mass of slightly more than that of the Milky Way

($\sim 5 \times 10^{10} M_{\odot}$) are most efficient in converting the available baryons into stars ($\sim 15 - 20\%$, e.g. Moster et al. 2010). One key observational result is that this ‘typical’ galaxy mass has not greatly changed since $z \sim 3$ (e.g., Marchesini et al. 2009, Ilbert et al. 2010). Dark matter halos and their baryon content, on the other hand, have grown by two orders of magnitude over that time span (e.g. Springel et al. 2005). It appears that dark matter halos with a total mass of $\sim 10^{12} M_{\odot}$ are, at all cosmic times, the most efficient star formation factories. For such halos, the star formation rate at different epochs is observed to roughly follow the cosmological accretion rate as predicted by Λ CDM: star-formation rates are observed to increase systematically with redshift, in a regular fashion such that a galaxy ‘main sequence’ (defined below) is established, with a relatively small scatter in star formation rate for a given galaxy stellar mass (e.g. Noeske et al. 2007). At $z \sim 0$, the cosmic star formation rate density is dominated by galaxies with star formation rates $\leq 10 M_{\odot} \text{ yr}^{-1}$ (FIR luminosities $\leq 10^{11} L_{\odot}$). By $z \sim 2$, the dominant contribution shifts to galaxies forming stars at $\sim 100 M_{\odot} \text{ yr}^{-1}$ (Murphy et al. 2011; Magnelli et al. 2011). Once the halo and the galaxy grow beyond this mass, further growth through star formation is marginal (e.g. Peng et al. 2010) and accretion of other galaxies (merging) becomes the dominant evolutionary channel (van der Wel et al. 2009).

Massive galaxies with low star formation activity, if any, are observed at all redshifts $z \leq 3$ (e.g. Franx et al. 2003, Kriek et al. 2006) and their existence remains a puzzle as there is no trivial mechanism that prevents gas from cooling and forming stars in more massive halos. Many ideas abound: shock heating of in-falling gas (Kereš et al. 2005, Dekel & Birnboim 2006), feedback from active galactic nuclei (AGN, Croton et al. 2006; Bell et al. 2012), motivated by ubiquitously observed super-massive black holes in massive galaxies and the coincidence of the peak of QSO and star-formation activity at $z \sim 2$ (Hopkins et al. 2006), and stabilization of gaseous disks as a result of bulge formation (Martig et al. 2009). Feedback by AGN-driven winds appears to be required to explain the evolution of young star forming galaxies into red, bulge-dominated galaxies at intermediate redshift (e.g., Feruglio et al. 2010), while powerful radio jets from AGN may be needed to heat the intercluster gas around massive galaxies at late cosmic epochs, thereby inhibiting further late-time growth of massive galaxies (Fabian 2012; McNamara & Nulsen 2007).

We briefly clarify our use of the terms ‘starburst’ and ‘main sequence’ (MS) for star forming galaxies in this review. These classifications have arisen in two, parallel situations. First, studies find that the majority of starforming galaxies at both high and low redshifts define a ‘main sequence’, in which there is a relatively tight distribution (dispersion $< 0.3\text{dex}$) in specific star formation rate ($\text{sSFR} = \text{SFR}/\text{stellar mass}$) versus stellar mass. The sSFR is typically a slowly decreasing function of increasing stellar mass, and, at a given stellar mass, the sSFR increases by a factor 20 from $z=0$ to 2 for these MS galaxies (Sargent et al. 2012; Rodighiero et al. 2011). However, at all redshifts the distribution function in sSFR requires a second component at a factor 4 to 10 times higher SFR than the nominal main sequence. This ‘starburst’ component constitutes a few percent of the distribution by number, and about 10% in terms of the contribution to the cosmic star formation rate density.

Second, as presented in Sec. 4.5, there also appears to be a parallel dual-sequence in the Far-IR to CO luminosity ratio, with factor few higher ratios for starburst versus main sequence galaxies. The implied gas consumption timescales

may be an order of magnitude, or more, shorter in starburst systems than in main sequence galaxies (modulo the conversion factor, see Sec. 4.2). There is some evidence to support the notion that starbursts are associated with major gas rich mergers, although this remains an area of open investigation. These two sequences of star forming galaxies are in addition to early-type galaxies discussed above, which are typically higher stellar mass, and show an order of magnitude, or more, lower sSFR.

In order to understand why star formation efficiency peaks at a certain halo mass and then declines for more massive systems, the interplay between gas accretion, cooling, star formation and feedback must be understood. Most of our current understanding of galaxy formation, as briefly summarized above, is based on studies of the stars, star formation, and ionized gas. There remains a major gap in our knowledge, namely, observations of the cool gas: the fuel for star formation in galaxies. Put simply, current studies probe the products of the process of galaxy formation, but miss the source. If we can trace the presence of cold gas and its distribution in different galaxies and halos over cosmic time, the puzzle of the efficiency of star and galaxy formation can be unraveled. Numerous observational and theoretical papers have pointed out this crucial need for observations of the cool molecular gas feeding star formation in galaxies (Dressler et al. 2009; Genzel et al. 2008, Obreschkow & Rawlings 2009a; Bauermeister et al. 2010).

We review the current status of observations of the cool gas content of galaxies, as measured via the rotational transitions of common interstellar molecules, and via the atomic fine structure line transitions, predominantly [C II]. Our focus is on results since the reviews of Solomon & vanden Bout (2005) and Omont (2007). Our review is primarily observational. We present tools and concepts of studying the interstellar medium in distant galaxies (Sec. 2), then summarize observational results for different galaxy types at high redshift (Sec. 3). We then discuss implications of the recent observations (Sec. 4) and what they tell us about conditions in early galaxies and galaxy formation in general (Sec. 5). We end by raising some of the key questions that can be addressed with new facilities: the JVLA and ALMA (Sec. 6 and Sec. 7).

We only consider molecular and fine structure line emission in this review. For a review of the few rotational molecular absorption line systems seen at high redshift to date, see Combes (2008) and Carilli & Menten (2002).

SIDEBAR: Over the last two decades, the star formation history of the universe, and the build up of stellar mass, has been well quantified as a function of galaxy environment and luminosity, back to cosmic reionization ($z \sim 10$). It is clear that massive galaxies form most of their stars early, and that the majority of star formation occurs at $z > 1$. The dominant contribution to the cosmic star formation rate density shifts to higher star formation rate galaxies with redshift. The next major step in the study of galaxy formation is the delineation of the cool gas content of galaxies, and, in particular, the molecular interstellar medium (ISM) out of which stars forms, as a function of cosmic time.

2 Concepts of observing cool gas

2.1 Heating and cooling of the starforming ISM in galaxies

At high redshift, the ionized ISM can be studied through a combination of optical emission lines (e.g. $\text{Ly}\alpha$, $\text{H}\alpha$) and far-infrared (FIR) atomic fine structure lines (e.g. $[\text{C II}]$, $[\text{N II}]$, $[\text{O III}]$). The neutral medium can be studied with FIR atomic fine structure lines (e.g. $[\text{O I}]$, $[\text{C I}]$, $[\text{C II}]$). Unfortunately, HI 21cm emission from galaxies cannot be studied at redshifts $z > 0.5$ due to limited sensitivity, and must await the full square kilometer array (Carilli & Rawlings 2003). The atomic phase in high redshift systems can also be studied through absorption measurements through individual lines-of-sights (Wolfe et al. 2005).

In the molecular medium, the high gas densities protect molecules against UV photodissociation, because of the shielding by dust and self-shielding of H_2 (Tielens 2005, Lequeux 2005, Dyson & Williams 1980). The molecular gas phase is thought to immediately precede star formation (e.g. Leroy et al. 2008, Schruba et al. 2011) and this phase is thus most relevant to study a galaxy's potential to form new stars. The other phases of the ISM cannot form stars directly (but see, e.g., Glover & Clark 2012), unless they cool sufficiently to form cold and dense molecular gas. The processes in the ISM are highly dynamic, with new gas being accreted (e.g. through mergers or cold mode accretion, CMA, Sec. 5.1.2) and gas being lost through both stellar and black hole feedback processes (Sec. 4.7).

The temperature and density of the ISM is a result of environment, and is determined by a balance of heating and cooling. There are several mechanisms that lead to the heating of the molecular gas (e.g. Goldsmith 1978). Deep within dark molecular clouds, the main heating source is through cosmic rays (i.e. protons and electrons accelerated to GeV energies). Cosmic rays ionize H_2 molecules, and the free electrons then transfer excess kinetic energy to other H_2 molecules.

In molecular clouds associated with active star formation, UV heating is also invoked to explain molecular gas heating. In this picture, O and B stars that dominate the radiation in starforming regions (mostly in the far-UV, $6.0\text{ eV} < E < 13.6\text{ eV}$, recall that $1\text{ eV} \sim 10^4\text{ K}$ ($1\text{ eV} = 11605\text{ K}$)), turn their interface with the molecular clouds into photon dominated regions (PDRs; also historically known as photo-dissociation regions; Hollenbach and Tielens 1997). On the very surface, the CO is dissociated by UV radiation, and the dominant emission comes from atomic fine structure lines and H_2 rovibrational lines, as well as dust continuum and PAH emission. Further into the region, dust-shielding and self-shielding allows for the persistence of CO, with the gas heated mainly by electrons that are released from the surfaces of dust grains due to UV absorption.

Related to the UV heating in PDRs is the heating that occurs through X-ray emission (X-ray dominated region, or XDR) emerging from AGN and/or hot plasmas heated by SNe, where the harder input spectrum of the X-rays penetrates further into the molecular clouds than the UV radiation (e.g. Meijerink et al. 2006). Both PDR and XDR regions are discussed in Sec. 2.6.2. Mechanical shock models have also been invoked to explain the extreme excitation conditions in nuclear starburst or other dense regions (e.g. Flower & Pineau des Forets 2003, Kristensen et al. 2008, Meijerink et al. 2013; Stacey et al. 2010; Nikola et al. 2010).

In terms of gas cooling, atomic fine structure lines have long been noted as being

the dominant coolant of interstellar gas in star forming galaxies (Spitzer 1978), in particular, in cooler regions where permitted lines of Hydrogen cannot be excited ($< 10^4$ K; Sec. 2.8). As forbidden transitions, the lines are typically optically thin, and hence avoid line trapping (resonant scattering) in high column density regions. A few lines have ionization potentials that are higher than hydrogen (13.6 eV) and are thus cooling lines of the ionized medium only (e.g. [N II], [O III]). Others have lower ionization potentials, and thus also trace the neutral ISM (e.g., [C II] [O I], [C I]). Up to a few percent of the FUV energy from star formation in galaxies can go to gas heating via photo-electrons, which is reradiated by fine structure lines, principally the [C II] $158\mu\text{m}$ line (and in some cases [O I]). The majority of the stellar radiation goes into dust heating that is balanced through FIR emission, or is radiated directly into the Universe, in roughly equal proportions (depending on geometry and dust content, e.g., Elbaz 2002).

2.2 Tracing molecular gas: observable frequencies

The molecular gas mass in galaxies is dominated by molecular hydrogen, H_2 . Given the lack of a permanent dipole moment, the lowest ro-vibrational transitions of H_2 are both forbidden, and perhaps more importantly, have high excitation requirements (the first quadropole line lies 500 K above the ground, significantly higher than temperatures in giant molecular clouds). As a consequence, only a very small fraction of the cool molecular gas can be studied through H_2 emission in the infrared. This is the reason that historically, emission from tracer molecules have been used to detect molecular gas in galaxies, and from which the total molecular gas mass is then deduced. The molecule of choice has traditionally been carbon monoxide, CO, since it is the most abundant molecule after H_2 , has low excitation requirements (~ 5 K for first excited state, see Sec. 2.3), and is easily observed from the ground (3 mm band) in its ground transition.

In general, tracer molecules show quantized rotational states populated based on collisions and the radiation field. For a linear polar molecule of moment of inertia, I , the orbital angular momentum is given by (Townes & Schalow 1975) $L = n\hbar$ and the corresponding rotational energy is $E_{\text{rot}} = \frac{L^2}{2I} = \frac{n^2\hbar^2}{2I} = \frac{J(J+1)\hbar^2}{2I}$ with $\Delta J = \pm 1$ (conservation of angular momentum). The energy released from level J to $J-1$ is: $\Delta E_{\text{rot}} = [J(J+1) - (J-1)J]\frac{\hbar^2}{2I} = \frac{\hbar^2 J}{I} = h\nu_{\text{line}}$.

In reality this approximation is not strictly valid, as centrifugal forces will increase with J so that the bond (distance between atoms) will stretch, which in turn changes I . This effect leads to frequencies that are slightly lower than the first harmonic, eg. for CO, the line-spreading via rotational stretching of higher order transitions is of order 10 MHz to 15 MHz, or effectively 20 to 30 km s^{-1} , allowing for unique redshift determinations based on just two transitions (e.g., Weiß et al. 2009). Depending on molecule, there can be other additional fine and hyperfine structures overlaid (i.e., magnetic and electrostatic interactions within the molecule; e.g., Riechers et al. 2007a for the case of CN).

2.3 Gas Temperatures & Critical Density

The kinetic temperature of the H_2 molecules, T_{kin} is determined by the velocity distribution of the molecules following the Maxwell-Boltzmann distribution. The excitation of other tracer molecules, such as CO, is mostly determined by the number of collisions with H_2 molecules as they are very abundant, massive and

have a high cross section. It is often assumed that this kinetic gas temperature equals the temperature of the dust T_{dust} at high densities. However it should be noted that the heating and cooling processes of the dust and molecular gas phases are quite different and therefore thermal balance is not required.

Typically, rotational transitions are expressed as a function of critical density, n_{crit} , ie. the density at which collisional excitation balances spontaneous radiative deexcitation: $n_{crit} = A/\gamma$ where A is the Einstein coefficient for spontaneous emission, $A \propto \mu^2 \times \nu^3$ in units of s^{-1} , γ is the collision rate coefficient in units of $cm^3 s^{-1}$, and μ is the dipole moment of the molecular transition under consideration in the $J=1$ state.

The Einstein coefficient A (see Tab. 7) is determined entirely by the physical properties of the molecule and is proportional to the frequency cubed (i.e. higher- J transitions have higher deexcitation rates). The collision rate coefficient γ however depends on the temperature of the gas ($\gamma = \langle \sigma \times v \rangle$ where σ is the collision cross section and v is the velocity of the particle). Collision rate coefficients for the excitation of CO by H_2 are given by Flower et al. (1985) and Yang et al. (2010), and are typically ~ 3 to $10 \times 10^{-11} cm^3 s^{-1}$ for the low- J transitions and temperatures of 40–100 K.

Stars are created in cores of molecular clouds that have much higher densities than the bulk of the gas traced by CO(1–0). This is the reason why molecules with significantly higher dipole moments (leading to a higher A coefficient as $A \propto \mu^2$ and thus higher critical density) are typically observed. Typical dense gas tracers and their dipole moments are: CS: 1.958 D [Debye], HCO^+ : 3.93 D, HCN: 2.985 D, for comparison CO has a dipole moment of 0.110 D (Schöier et al. 2005). The downside of choosing these high density tracer molecules is their low abundance and resulting faint line fluxes (as discussed in Sec.4.4).

As an example, Tab. 7 summarizes the Einstein coefficients for the different transitions of CO and HCN. The critical density for these molecules is given in the last column of the table. It is obvious that higher- J transitions need increasingly high critical densities to be visible. Einstein coefficients and collision rates for other molecules can be found in Schöier et al. (2005).

2.4 Brightness Temperature and line luminosities

Historically, radio astronomers express the surface brightness of a source as a Rayleigh–Jeans (RJ) brightness temperature for a blackbody at given temperature through Planck’s law. Measurements of brightness temperature and surface brightness are thus equivalent measurements. Rather than expressing the temperature in terms of the Planck temperature, radio astronomers have traditionally used the low frequency (Rayleigh-Jeans) limit ($\frac{kT}{h\nu} \gg 1$):

$$B_\nu = \frac{2h\nu^3}{c^2} \times \frac{1}{\exp(\frac{h\nu}{kT}) - 1} \sim \frac{2kT\nu^2}{c^2}$$

In this limit: $T_B^{obs} = \frac{c^2}{2k\nu_{obs}^2} I_\nu$, where I_ν is the surface brightness. The RJ approximation is valid at centimeter wavelengths. However in the millimeter and particular submillimeter regime $\frac{kT}{h\nu} = 0.7[\lambda/1mm][T/10K]$, the RJ approximation is no longer valid in many regions of astrophysical interest, and RJ brightness temperatures can no longer be interpreted as a physical temperature. If one is interested in true temperatures, full Planck temperatures should be derived

instead.

At high redshift, there are two commonly used ways to express line luminosities. One, L_{line} is expressed as the source luminosity in L_{\odot} or other rational units. The second, L'_{line} , is expressed via the (areal) integrated source brightness temperature, in units of $\text{K km s}^{-1} \text{ pc}^2$. The following equations can be used to derive these two luminosities (Solomon et al. 1992):

$$L'_{line} = 3.25 \times 10^7 \times S_{line} \Delta v \frac{D_L^2}{(1+z)^3 \nu_{obs}^2} \text{ K km s}^{-1} \text{ pc}^2$$

$$L_{line} = 1.04 \times 10^{-3} \times S_{line} \Delta v D_L^2 \nu_{obs} L_{\odot}$$

where $S_{line} \Delta v$ is the measured flux of the line in Jy km s^{-1} , D_L is the luminosity distance in Mpc, and ν_{obs} is the observed frequency. Solving for $S \Delta v$ and equating leads to: $L_{line} = 3 \times 10^{-11} \nu_r^3 L'_{line}$ where ν_r is the rest frequency of the line. Note that L'_{line} is directly proportional to the surface brightness T_B , i.e. the L'_{line} ratio of two lines give the ratio of their intrinsic, source-average surface brightness temperatures T_B . If the molecular gas emission were to come from thermalized, optically thick regions, L'_{line} is constant for all J levels.

SIDEBAR: The question often arises which quantity to quote in a paper, L_{line} or L'_{line} ? Both have their justification: e.g. if one is interested in comparing the power that is being emitted through a given line to calculate the cooling capability (e.g. in relation to the FIR luminosity, L_{line}/L_{FIR}) one uses the L_{line} definition. The L'_{line} is commonly used to translate measured CO luminosities to H_2 masses using the conversion factor α . Also, for thermalized molecular gas emission L'_{line} is approximately constant for all transitions. It is good advice to give both quantities in a paper, but in all cases also the measured integrated fluxes of the lines $S_{line} \Delta v$ (in units of Jy km s^{-1}).

2.5 CO luminosity to total molecular gas mass conversion factor

The conversion factor relating CO(1–0) luminosity to total molecular gas mass (dominated by H_2) in the nearby Universe has been reviewed recently by Bolatto et al. (2013). We briefly summarize the main points in this section.

Molecular gas in the Milky Way and nearby galaxies is predominantly in giant molecular clouds with overall sizes up to 50 pc. Hence, early work on the conversion factor focused on GMCs. In nearby systems (including the Milky Way) the clouds can typically be spatially resolved, and hence the conversion factor considered, X_{CO} , is the ratio of column density (H_2 molecules per cm^2) to CO velocity integrated surface brightness (K km s^{-1}), while for distant galaxies spatially integrated quantities are usually measured, and the conversion factor α_{CO} is then the ratio of total mass (in M_{\odot}) to total CO line luminosity ($\text{K km s}^{-1} \text{ pc}^2$). The ratio, $X/\alpha = 4.6 \times 10^{10} \text{ pc}^2 \text{ cm}^{-2} M_{\odot}^{-1}$ = the number of hydrogen molecules per solar mass, converted to the appropriate units and corrected by a factor 1.36 for Helium.

Numerous techniques have been used to determine the conversion factor in GMCs, including: (i) a comparison of CO columns derived from isotopic measurements to H_2 columns derived from optical extinction measurements using a standard dust-to-gas ratio (Dickman 1978; 1975; Dame et al. 2001), (ii) a comparison of γ -ray emission to CO surface brightness, where the γ -rays result from

the interaction between cosmic rays with H_2 molecules (Strong & Mattox 1996, Bloemen 1989, Hunter et al 1997), and (iii) modeling GMCs as self-gravitating clouds. In the latter case, a key discovery was the correlation between line width and cloud size, with line width increasing as the square root of cloud size (the ‘Larson relations’; Larson 1981). This functional form implies a constant surface density $\sim 100 \text{ M}_\odot \text{ pc}^{-2}$ for GMCs (Solomon et al. 1987), and that the CO luminosity is linearly proportional to cloud virial mass. Indeed, this relationship provides the theoretical underpinning of the use of CO luminosity to derive total gas mass in the case of optically thick emission (Solomon et al. 1987; Dickman et al. 1986), where luminosity is dictated principally by line width. Bolatto et al. (2013) summarize these results, and conclude that a value of $X_{\text{CO}} = 2 \times 10^{20} \text{ H}_2 \text{ molecules per cm}^{-2} / (\text{K km s}^{-1})$, or $\alpha_{\text{CO}} \sim 4 \text{ M}_\odot / (\text{K km s}^{-1} \text{ pc}^2)$, is appropriate for GMCs in the MW and nearby spiral galaxies, with a factor two (0.3 dex) scatter.

Draine et al. (2007) hypothesized that, if the abundance of the elements can be assumed to be proportional to the Oxygen abundance, and adopting a Milky-Way fraction of elements tied up in grains, then $M_{\text{dust}}/M_{\text{gas}} = 0.010[(\text{O}/\text{H})]/[(\text{O}/\text{H})_{\text{MW}}]$. Using observations of nearby galaxies, they showed that the gas columns derived from the IR thermal dust emission are consistent with $X_{\text{CO}} = 4 \times 10^{20} \text{ cm}^{-2} / (\text{K km s}^{-1})$ and metallicities between 0.3 and 1 solar for their galaxy sample. Leroy et al. (2011) use an empirical dust-to-gas ratio approach in nearby galaxies and obtain similar results, showing that the lowest metallicity galaxies clearly have much higher conversion factors. They suggest that decreased dust shielding in low metallicity environments leads to CO-free, but still H_2 rich, cloud envelopes (see also Schrubba et al. 2012; Sandstrom et al. 2013).

A different picture has emerged for nearby nuclear starburst galaxies, including the nuclei of dwarf starbursts like M82 and NGC 253, corresponding to Luminous Infrared Galaxies, or LIRGs ($L_{\text{IR}} \sim 10^{11} L_\odot$), and ultraluminous infrared galaxies (ULIRGs) such as Arp 220 ($L_{\text{IR}} \sim 10^{12} L_\odot$). It was noted early-on that a Milky Way conversion factor leads to a molecular gas mass larger than the dynamical mass in some of these systems (Bryant et al. 1999). In their seminal analysis of CO radiative transfer and gas dynamics in starburst nuclei of ULIRG on scales $< 1 \text{ kpc}$, Downes & Solomon (1998) find a characteristic value of $\alpha_{\text{CO}} \sim 0.8 \text{ M}_\odot / (\text{K km s}^{-1} \text{ pc}^2)$ in these systems. The lower value of α implies more CO emission per unit molecular gas mass. They hypothesize that much of the CO emission is not from virialized GMCs, but from an overall warm, pervasive molecular inter-cloud medium. In this case the linewidth, and hence line luminosity (for optically thick emission), is determined by the total dynamical mass (gas and stars), as well as ISM pressure. Narayanan et al. (2012) show that the lower α value in starbursts is due to warm gas that is heated by dust (at densities $> 10^4$, such energy exchange is efficient), as well as large, non-virial line widths from the GMCs. More recently, Papadopoulos et al. (2012) suggest that the molecular gas heating processes in nuclear starbursts may be very different than is typically assumed for PDRs, with cosmic rays and turbulence dominating over photons.

In general, the value of α is likely a function of local ISM conditions, including pressure, gas dynamics, and metallicity, and remains an active area of research for nearby galaxies (Ostriker & Shetty 2011; Narayanan et al. 2012; Narayanan & Hopkin 2012; Papadopoulos et al. 2012, Leroy et al. 2013, Schrubba et al. 2012, Sandstrom et al. 2013). We note that the conversion factor has been calibrated

using observations of CO(1–0) in nearby galaxies. These low order transitions redshift to centimeter wavelengths at $z > 2$.

2.6 Modeling the line excitation

Many observations of galaxies at high-redshift are unresolved, and studies of the global CO excitation play an important role in constraining their average molecular gas properties. This CO excitation, i.e. the relative strengths of the observed rotational transitions, is sometimes referred to ‘CO spectral line energy distributions’, ‘CO SLEDs’ or ‘CO excitation ladder’. We here use the term ‘CO ladder’, as the measured quantity is the emission of a given rotational transition J . We note that some authors also chose to plot spectral power distributions (i.e. plotting L instead of $S_\nu \times dV$ as a function of rotational number J).

The excitation temperature determines the population of the molecular levels through the Boltzmann distribution. Under the assumption of local thermodynamical equilibrium (LTE) this excitation temperature will be equal to the kinetic temperature of the gas. ‘Thermal’ excitation means that the population of all levels is according to the Boltzmann distribution. The excitation is ‘sub-thermal’ if the population of the high levels is less than that given the kinetic temperature of the gas, as occurs in lower density environments where collisional excitation cannot balance spontaneous emission rates. We briefly discuss the commonly used techniques to model the excitation of the various levels of molecular line emission.

2.6.1 ESCAPE PROBABILITY/LVG MODELS One basic tool commonly used to model the excitation of the molecular gas emission is the large velocity gradient (LVG) method (e.g. Young & Scoville 1991). In the following we will discuss this model for the CO molecule, but the same modeling can be done for any molecule. The model calculates for a given temperature T_{kin} , H_2 density, CO abundance ($[CO]/[H_2]$), and velocity gradient dv/dr , how the various levels of the CO are populated through collisional excitation with H_2 . Some models and their dependence on temperature and density are illustrated in Fig. 3 (see also Figures in van der Tak et al. 2007). Since the CO emission is optically thick (at least in the low- J transitions) the emission would have difficulties escaping the cloud, which is why a velocity gradient is introduced in the model that describes how many photons can eventually leave the cloud. The justification for implementing such a gradient is that in reality the molecular medium is turbulent which enables CO photons to escape their parental clouds. The LVG codes also take the redshift of the source into account which dictates the temperature of the cosmic microwave background (CMB, Sec. 2.10). Once the occupation numbers of the different levels are calculated, the optical depths τ for the transitions as well as the Rayleigh–Jeans brightness temperatures T_B (which would be constant in LTE) and the resulting line intensities are derived.

In this way, for a given set of parameters, the expected line intensities for any molecule can be derived (assuming certain abundances of the molecule under consideration). In principle, the measurement of the line emission ladder of a number of different molecules thus puts tight constraints on the temperature and density of the gas. This assumes that these lines probe the same volume, which may not hold for those molecules tracing very high densities (e.g. HCO^+ and HCN). Of particular interest is adding different isotopomers, such as ^{13}CO or $C^{18}O$ as these are more optically thin than the $^{12}C^{16}O$ emission, and are thought

to originate from the same volume as $^{12}\text{C}^{16}\text{O}$, at least on GMC scales.

2.6.2 PDR AND XDR MODELS In PDR (Photo-dominated regions) and XDR (X-ray dominated regions) models a cloud is exposed to a radiation field from which the temperature and density distribution of the H_2 molecules is derived. With the resulting values for T_{ex} and density a code similar to LVG is then run to calculate the line intensities of the rotational transitions of the molecules under consideration. A difference with respect to the LVG models is that abundances of species are calculated based on the radiation field and the gas column density. The main difference between the PDR and XDR codes is that PDRs only exist at the surface of clouds (where they emit fine structure lines of [C I], [C II] and [O I], and rotational lines of CO in the submillimeter). In the XDR phase (further inside the cloud) the [O I], [C II], and [S III] lines are main coolants in the sub-millimeter regime (Meijerink & Spaans 2005). One limitation of most PDR / XDR models is that they are based on (one-dimensional) infinite slabs – i.e. they do not have a confined volume. As a consequence no mass estimates are typically given by the codes. The gas temperatures calculated in PDR/XDR models are still quite uncertain and depend on the code used, especially in the high-density, high-UV case (e.g., Röllig et al. 2007). Given the high excitation measured in nearby galaxies based on Herschel data (up to $J \sim 30$, Hailey-Dunsheath et al. 2012), shock heating is also invoked to explain extreme CO excitation (see also Meijerink et al. 2013).

One complication in all the models above is that it is now established that the high- J rotational transitions of some molecules, e.g. HCN, are not only excited through collisions (as the critical densities of some of the detected high- J lines are extremely high, $\sim 10^9 \text{ cm}^{-3}$, i.e. they are not even being reached in the cores of GMCs). One potential mechanism to excite the observed high- J HCN rotational modes is through the infrared stretching and bending modes of HCN at 3, 5 and 14 microns (this is referred to as ‘infrared pumping’ of the rotational levels, e.g. Weiß et al. 2007a). Similar pumping may be in place even in the case of CO emission and may explain the very high- J excitation seen in some local galaxies (above references, and Harris et al. 1991 for radiative trapping leading to enhanced mid- J CO emission).

2.7 Water lines

Water is thought to be one of the most abundant molecules in galaxies, present predominantly in icy mantels of dust grains in cold environments (Tielens et al. 1991; Hollenbach et al. 2008). In warmer environments, water in the gas phase is thought to play an important role in cooling (Neufeld & Kaufmann 1993, Neufeld et al. 1995). The rotational transitions of water have high Einstein A values, and thus very high critical densities ($> 10^8 \text{ cm}^{-3}$), i.e. collisional excitation can only happen in the very centres of dense cloud cores and other excitation mechanisms, in particular infrared pumping, are typically invoked.

Naturally, water lines at low redshift are very difficult to observe from the ground given the Earth’s atmosphere. Herschel Space Observatory observations enabled the first detections of submillimeter lines of H_2O in nearby galaxies, other than Masers (Mrk 231: Van der Werf et al. 2010, Gonzales-Alfonso et al. 2010, M82: Weiß et al. 2010). These observations have yielded very different results between the objects: Mrk 231 revealed a rich spectrum of H_2O lines but the ground-state lines remained undetected (Van der Werf et al. 2010). In M 82 no

highly excited emission was found (Panuzzo et al. 2010) but many low-excitation lines (Weiß et al. 2010). Generally speaking, the water emission line spectrum is very complex and not straightforward to interpret if only one or a few lines are measured (Gonzalez-Alfonso et al. 2010). We discuss recent high-redshift detections of water lines in Sec. 4.4.

2.8 Atomic Fine Structure lines

The atomic fine structure lines (FSLs) are major coolants of cooler interstellar gas (Section Sec. 2.1). Table 7 summarizes key parameters of important sub-millimeter atomic fine structure lines.

2.8.1 SINGLY IONIZED CARBON: [C II] is the strongest line from star forming galaxies at radio through FIR wavelengths (eg. [C II] line fluxes are typically $> 10^3$ times stronger than CO(1–0) in star forming galaxies), and in particular, [C II] $158\mu\text{m}$ is the strongest line from the cooler gas in galaxies ($< 10^4$ K).

The ratio of [C II]/FIR luminosity for the Milky Way is 0.003, and this value holds in nearby disk galaxies, with a relatively large scatter (factor three; e.g. Malhotra et al. 1997, 2001). However, the ratio appears to drop significantly at FIR luminosities above $10^{11} L_{\odot}$. One explanation for this drop is a reduction in the heating efficiency by photoelectric emission from dust grains in high radiation environments due to highly charged grains. This explanation is supported by the fact that the [C II]/FIR ratio is also a decreasing function of increasing dust temperature (e.g., Malhotra et al. 2001, Luhman et al. 2003). High dust opacity/absorption at $158\mu\text{m}$ may also decrease the [C II]/FIR ratio in high luminosity systems.

[C II] has a lower ionization potential than H I (11.3 eV vs. 13.6 eV), hence [C II] traces both the cold neutral medium (CNM) and ionized gas. This makes [C II] less easy to interpret, in particular if the emission cannot be resolved spatially. The [C II] luminosity is not a simple function of star formation rate, nor is there a simple dependence between [C II] luminosity and the total mass of the ISM. In an early study, Stacey et al. (1991) argue that roughly 70% of the total [C II] emission from nearby spiral galaxies comes from PDRs, and recent Herschel observations shows a possible correlation between the [C II] luminosity and the $11.3\mu\text{m}$ PAH feature, suggesting a close correlation between PDRs and [C II] emission (Sargsyan et al. 2012). Herschel imaging has also shown significant differences in the spatial distribution of the [C II] emission and CO emission on scales ≤ 300 pc in nearby galaxies (Mookerjee et al. 2011; Rodrigues-Fernandez et al. 2006) (see also Cormier et al. 2010).

A clear trend for increasing [C II]/FIR ratio with decreasing metallicity has been established (Cormier et al. 2010; Isreal & Mahoney 2011). Lower metallicity leads to lower dust and higher UV mean free paths. The decreased dust-shielding in PDR regions leads to deeper photo-dissociation into the molecular clouds and increased photo-electric heating efficiencies leading to higher [C II] luminosities relative to the FIR. High-redshift observations of [C II] are discussed in Sec. 4.3.2.

2.8.2 ATOMIC CARBON: [C I] Because the ^3P fine-structure system of atomic carbon forms a simple three-level system, detection of both optically thin carbon lines, $\text{C I}(^3P_1 \rightarrow ^3P_0)$ and $\text{C I}(^3P_2 \rightarrow ^3P_1)$ enables one to derive the excitation temperature, neutral carbon column density and mass, independent of any other information (e.g., Ojha et al. 2001, Weiß et al. 2003, Walter et al.

2011). A combination of this method (using [C I]) with the aforementioned CO excitation ladder is particularly powerful as it eliminates some of the degeneracy frequently found in CO radiative transfer models under the assumption that [C I] traces the same regions as CO (see discussion in Sec. 4.1).

Studies of atomic carbon in the local universe have been carried out in molecular clouds of the galactic disk, the galactic center, M82 and other nearby galaxies (e.g., White et al. 1994; Stutzki et al. 1997; Gerin & Phillips 2000; Ojha et al. 2001; Israel & Baas 2002; Israel 2005). These studies have shown that [C I] is closely associated with the CO emission independent of environment. Since the critical density for the $\text{C I}(^3P_1 \rightarrow ^3P_0)$ and CO(1–0), lines are both $n_{\text{cr}} \approx 10^3 \text{ cm}^{-3}$, this suggests that the transitions arise from the same volume and share similar excitation temperatures (e.g. Ikeda et al. 2002). We discuss high-redshift detections of [C I] in Sec. 4.3.1.

2.8.3 OTHER FINE STRUCTURE LINES: [N II], [O I], [O III] Beyond [C II] and [C I], there are a number of other far-infrared fine structure lines that are potentially important physical diagnostics for the ISM, in particular the lines from [O I]63 μm , [O III]52 μm and 88 μm , and [N II]122 μm and 205 μm . While typically 10 times weaker than [C II], the oxygen line strengths increase dramatically with the hardness of the radiation field, such that in AGN environments the [O III]88 μm can be stronger than [C II] (Spinoglio et al. 2012; Spinoglio & Malkan 1992; Genzel & Cesarsky 2000, Stacey et al. 2010). Most of these lines are at even higher frequencies than [C II] and are thus difficult to observe even in the high-redshift universe.

The ionization potential of carbon, oxygen, and nitrogen are 11.3 eV, 13.6 and 14.5 eV, respectively. Hence, [C II] traces both the neutral and ionized medium, while oxygen and nitrogen trace the ionized medium only (except for [O I]). The [N II]122 μm / [O III]88 μm ratio is a sensitive measure of hardness of the radiation field since these two lines have similar critical densities for excitation (~ 300 to 500 cm^{-3}), but very different ionization potentials (35 eV for [O II]). [C II] 158 μm and [N II] 205 μm have essentially the same critical density for thermal excitation ($\sim 45 \text{ cm}^{-3}$), hence the ratio of [C II]₁₅₈/[N II]₂₀₅ indicates the fraction of [C II] emission from ionized gas, assuming only a gas phase C/N abundance (Oberst et al. 2006, Walter et al. 2009a, Decarli et al. 2012, Ferkinhoff et al. 2010, 2011). In this case, the [C II]₁₅₈/[N II]₂₀₅ ratio for ionized gas ranges between 3 and 4 (Fig. 2 in Oberst et al.). Oberst et al. (2006) show that the [N II]122 μm / [N II]205 μm ratio is a densitometer, with a value of ~ 0.5 for densities below 10^2 cm^{-3} , rising to 10 for densities greater than 10^3 cm^{-3} .

2.9 Relation to far-infrared emission and SFRs

In this review, we concentrate on the molecular gas properties of high redshift galaxies. To put the physical properties of the ISM into perspective, we will also use the far-infrared (FIR) emission and star formation rates in galaxies. For reference we here give the equations that are commonly used to derive IR/FIR luminosities and star formation rates from single-band FIR continuum measurements. We stress that the numbers that follow are appropriate for ‘dusty’ SEDs typically found at high redshift, but that the relations will be a strong function of galaxy properties, such as the star formation activity and dust optical depth. The following equations are to first order independent of redshift for $z > 1$, given the inverse K-correction in the sub-millimeter regime (e.g. Blain et al. 2002;

Kennicutt & Evans 2012).

The IR luminosity L_{IR} is defined from 8–1000 μm , whereas the FIR luminosity L_{FIR} is commonly defined from 40–400 μm (Sanders et al. 2003). L_{IR} is typically $\sim 30\%$ higher than L_{FIR} for ‘dusty’ SEDs. Some authors also define FIR from 42–122 μm (Helou et al. 1985) – this latter definition gives L_{FIR} that are 20–30% smaller than the L_{FIR} definition above.

In measured flux densities at 250 GHz and 350 GHz (850 μm), the following relations are commonly used: $L_{\text{FIR}}[L_{\odot}] \sim 1.2 \times 10^{12} S_{350\text{GHz}}[\text{mJy}]$ (e.g. Genzel et al. 2010, Pope et al. 2006, Magnelli et al. 2010), $L_{\text{FIR}}[L_{\odot}] \sim 3 \times 10^{12} S_{250\text{GHz}}[\text{mJy}]$ (e.g. Bertoldi et al. 2003, Omont et al. 2001), with significant dependencies on the actual shape of the SED. As Scoville (2012) points out, a continuum measurement around 1 mm wavelengths (observed frame) is not suited to give good estimates of L_{IR} given the unknown intrinsic dust SED, at least for redshifts $z < 4$. However, it gives a good estimate on the dust mass (given that the dust is optically thin, and that the dust temperatures are not found to vary greatly).

The SFR can be calculated from the IR luminosities following: $\text{SFR} \sim \delta_{\text{MF}} \times 1.0 \times 10^{-10} L_{\text{IR}}$ where δ_{MF} depends on the stellar population (this assumes that the galaxy is dusty i.e. that all of the power radiated by young stars is absorbed by dust and re-emitted in the infrared; also that there is no contribution of the AGN to the FIR emission). For a range of metallicities, starburst ages (< 100 Myr) and initial mass functions (IMFs) Omont et al. (2001) find: $0.8 < \delta_{\text{MF}} < 2$. Typically a $\delta_{\text{MF}} = 1.8$ is appropriate for a Salpeter IMF (e.g. Kennicutt et al. 1998), and $\delta_{\text{MF}} \sim 1.0$ for a Chabrier IMF.

We adopted FIR luminosities for all high-redshift sources in which line emission has been detected (Tab. 3). These FIR luminosities have been derived using various different methodologies and therefore should be treated with caution. Wherever available, we adopted the FIR luminosities given by individual studies but caution that not all authors have adopted the same ‘FIR’ definition. E.g. L_{FIR} is frequently adopted to go from 8–1000 μm , whereas strictly speaking this is the definition of the IR luminosity (see above). For the purpose of this review we simply set $L_{\text{FIR}} \sim L_{\text{IR}}$. For each source in the table we have computed the FIR luminosities as follows: 1) if a L_{FIR} value is already reported in the literature (e.g., based on dust SED fitting of multiple photometric information) we use the most up-to-date estimate available; 2) for a number of color-selected galaxies, only an estimate of the SFR is available. In this case, we convert it into dust luminosity using the relation $\log L_{\text{FIR}} = \log \text{SFR} - \log(1.3) + 10$, where L_{FIR} is in solar units and SFR is in solar masses per year (see Genzel et al., 2010). 3) If only a continuum estimate is available, we use the 850 μm flux to infer continuum luminosity, assuming the Arp 220 template by Silva et al. (1998) and integrating from 8 μm – 1000 μm . To first order, $\log L_{\text{FIR}} \approx \log(1.2 \times F_{\nu}(850 \mu\text{m})) + 12$, where $F_{\nu}(850 \mu\text{m})$ is the flux density at 850 μm , expressed in mJy. If 850 μm measurements are not available, we use the 1200 μm measurement instead (in this case, $\log L_{\text{FIR}} \approx \log(F_{\nu}(1200 \mu\text{m})) + 12.36$).

2.10 Role of CMB

The temperature of the CMB at redshift z is given by: $T_{\text{CMB}}(z) = 2.73 \times (1 + z)$. At a redshift of $z = 6$, $T_{\text{CMB}} = 19.1$ K, meaning it is warmer than the dust temperature of Milky Way at present. As the dust will always be heated by photons of the CMB (through absorption), the minimum dust temperature

will be that of the CMB (and the kinetic temperature of the gas will equal the thermal dust temperature at high enough densities, da Cunha et al. 2013). As brightness temperature measurements are by definition always done with respect to the background (i.e. the CMB) it will be increasingly difficult to detect cold dust emission at high redshift.

The molecular gas is affected in two ways by the CMB: First, the higher temperature of the CMB will lead to an increase of the line excitation, and thus the line luminosities (e.g., Obreschkow et al. 2009a, da Cunha et al. 2013). Second, the observing background against which the line is measured also increases. The relative effect of the CMB will depend on the intrinsic excitation temperature of the gas (Combes et al. 1999, Obreschkow et al. 2009a, da Cunha et al. 2013). For example, for molecular gas at a temperature much higher than the CMB, the relative decrease in line flux will be much lower than in a case where the molecular gas temperature is almost equal to the CMB. As a result of this, the shape of the observed CO ladder for a source with given temperature and density will also change as a function of redshift: The peak of the SED will shift to higher-J values as the lower-J transitions are most easily affected by the effects of the CMB (da Cunha et al. 2013). A suppressed measurement of the CO lines also implies that the conversion factor α will change as a function of CMB temperature.

SIDEBAR: It should be noted that all CO detections at very high redshift ($z > 5$), i.e. where T_{CMB} is significant, are to date from galaxies that harbor hyper-star forming environments (e.g. the $z \sim 6$ quasars and the few known SMGs at $z > 5$ have SFRs of $\sim 1000 M_{\odot} \text{ yr}^{-1}$) with accompanying high temperatures of the ISM, ranging from 35–50 K, or at least a factor two warmer than the CMB. However it is clear that in lower temperature environments, more typical of lower luminosity star forming galaxies, the consequences of the CMB will be significant: the lowest-J lines will be faint at $z > 4$, and other cool ISM tracers may be required, such as [C II].

3 Molecular gas at high redshift

3.1 Introduction

Historically, different groups have been focusing on different selection techniques in their searches for molecular gas in high redshift systems. This has lead to different source categories and types which we will broadly follow for simplicity. But it is important to point out that there is major overlap in the properties of the sources discussed in the following. Many high-redshift quasars are found to be bright in the submillimeter regime, but they are classified as ‘quasars’ not ‘submillimeter galaxies’ as they have been originally selected as being quasars. Likewise, ‘submillimeter galaxies’ (hereafter: SMGs) have typically been selected in blind submm surveys of the sky, but some show signatures of a quasar. However they are still typically referred to as SMGs as they have been discovered as such (e.g., Ivison et al. 1998; Alexander et al. 2005).

Considering telescopes, most work has been done the IRAM Plateau de Bure interferometer (PdBI), the Very Large Array (VLA) and its successor (EVLA/JVLA), the Owen’s Valley Radio Observatory (OVRO) and its successor CARMA (Combined Array for Research in Millimeter Astronomy), the Australia Telescope Compact Array (ATCA), and the IRAM 30 m, James Clerk Maxwell Telescope

(JCMT), 100 m MPIfR Effelsberg, NRAO Green Bank (GBT) and Nobeyama Radio Observatory (NRO) single dish telescopes. These facilities have undergone a series of improvements in receiver and antenna performance, as well as correlator upgrades leading to dramatic improvements in bandwidth. The latter has been particularly important in detecting the often broad lines seen in high-redshift galaxies in the absence of precise redshifts. Also, customized receivers on single-dish telescopes have been built with very large bandwidths to blindly detect CO emission in high-redshift galaxies, eg. the ZSPEC on the CSO (Gromke et al. 2002), and the ZSPECTROMETER on the GBT (Harris et al. 2010). These systems have led to successful blind searches, aided in part by strong lensing of galaxies discovered in recent very wide-field Herschel surveys.

Figure 1 shows a plot of the frequency coverage for CO and other molecules for some available telescopes, with all actual measurements superposed. This plot emphasizes the complementarity of the centimeter and millimeter telescopes to probe a broad range in molecular gas and atomic fine structure transitions, providing a detailed diagnostic suite to study the ISM in early galaxies.

3.2 Quasars

Quasars were the first targets for submm continuum observations at high redshift (e.g. Omont et al. 1996). Extensive subsequent work has shown that 1/3 of optically selected quasars are detected in submm continuum observations with mJy sensitivity, and this fraction remains roughly constant from $z \sim 1$ to 6 (e.g., Wang et al. 2008a,b; Beelen et al. 2006; Priddey et al. 2003). Searches for CO emission have systematically detected CO in submm-detected quasar samples. More recently, [C II] is now being detected in quasar host galaxies, including the most distant quasar known with a spectroscopic redshift at $z = 7.1$ (Venemans et al. 2012).

As we shall see below (Sec. 4.1), of all objects detected at high redshifts, quasar host galaxies show the highest excitation for the molecular gas (Barvainis et al. 1997, Weiß et al. 2007b, Riechers et al. 2009a) and, in the few cases where the emission could be resolved, the CO is distributed in compact (\leq few kpc) gas reservoirs (Walter et al. 2004, Riechers et al. 2008a, 2008b, 2009b, 2011a; Carilli et al. 2002). The resulting star formation rate surface densities can thus be very high ($\sim 1000 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, Walter et al. 2009b). This suggests the presence of a coeval starburst with the SMBH growth (Walter et al. 2004, Wang et al. 2010, Coppin et al. 2008). Typically the gas excitation in the quasar host galaxies can be modeled with one gas component only, and there is no evidence for extended molecular gas reservoirs around these objects (Weiss et al. 2007a, 2007b, Riechers et al. 2009, Riechers 2011a).

The molecular medium in quasar host galaxies is amongst the best studied at high redshift, and typical molecular gas masses are a few $\times 10^{10} (\alpha/0.8) \text{ M}_{\odot}$, with resulting short implied gas consumption times $\sim 10^7 \text{ yr}$ (Sec. 4.5). Evidence for molecular outflows in quasars has recently been presented in two cases (Sec. 4.7).

3.3 Submillimeter galaxies

Submillimeter galaxies were classically selected from the (sub-)millimeter maps obtained at $850 \mu\text{m}$ by SCUBA at the JCMT and at 1.2 mm with MAMBO at the IRAM 30m (e.g. Smail et al. 1997, Hughes et al. 1998, Ivison et al. 2000,

2007, Dannerbauer et al. 2004). Given the sensitivities of the sub-millimeter cameras of typically ≥ 1 mJy, detections are by definition Hyperluminous infrared galaxies (HyLIRGs), with $L_{\text{FIR}} \sim 10^{13} L_{\odot}$, implying star formation rates $\sim 1000 M_{\odot} \text{ yr}^{-1}$. Early searches for molecular gas emission then revealed large gas reservoirs (Frayser et al. 1998, Frayer et al. 1999 using OVRO) and extensive campaigns, in particular done at the PdBI (Neri et al. 2003, Greve et al. 2005, Tacconi et al. 2006, 2008, Engel et al. 2010, Bothwell et al. 2010, 2013) have characterized the molecular interstellar medium in exquisite detail. In a few cases the molecular reservoirs could be resolved (Ivison et al. 2010a, 2011, Riechers et al. 2011b, Carilli et al. 2011, Hodge et al. 2012), leading to substantial sizes of ~ 10 kpc in a number of galaxies, although compact CO emission has been seen in a few cases as well (Carilli et al. 2002a; Tacconi et al. 2008). In all cases, a common trait for SMGs is extremely high optical extinction in the main regions of star formation traced by CO and thermal dust emission. This trait is accentuated by the case of the first SMG discovered in a submm deep field, HDF 850.1 (Hughes et al. 1998), which still remains unidentified in the deepest optical and near-IR images (Walter et al. 2012a).

The average excitation of the molecular gas in SMGs is less extreme than in the quasars (e.g. Weiß et al. 2007b, see Sec. 4.1), which may be attributed to the fact that the star formation in some SMGs proceeds on more extended scales than in the compact quasar hosts. Typical gas reservoir masses are of order a few $\times 10^{10} (\alpha/0.8) M_{\odot}$ which implies that the gas consumption times are short, of order $\sim 10^7$ yr (similar to the quasars). Even though the redshift distribution of SMGs is thought to peak around $z \sim 2.5$ (Chapman et al. 2003), there is a significant tail towards higher redshift (Schinnerer et al. 2008, Daddi et al. 2009a, Riechers et al. 2010a, 2013; Coppin et al. 2009, Walter et al. 2012a; Younger et al. 2007; Yun et al. 2012).

FIR-bright galaxies have recently also been blindly detected by large areal mapping with Herschel (sometimes referred to as ‘Herschel-selected galaxies’ or HSGs) at shorter wavelengths than in the original SCUBA/MAMBO selection (Negrello et al. 2010) and thus have a different selection function (either warmer dust temperatures or lower redshifts) than the traditional SMG selection (see also Greve et al. 2008). The Herschel selected galaxies are also typically a factor few lower in FIR luminosity than classical (SCUBA-selected) SMGs. These galaxies have also been shown to harbor massive reservoirs of gas (Cox et al. 2011, Combes et al. 2012a, Riechers et al. 2011a, Harris et al. 2012). A significant fraction of the brightest HSGs are gravitationally lensed.

The SMG surveys and related work showed a 1000-fold increase in the space density of ULIRGs from $z=0$ to $z \sim 2.5$ (Hughes et al. 1998, Blain et al. 2002). Like in the case of the quasar host galaxies, it has been proposed that the SMGs pinpoint the formation of a massive galaxy at high redshift (Swinbank et al. 2006, Daddi et al. 2009a,b, Hickox et al. 2012).

Like low- z ULIRGs, QSOs and SMGs lie significantly above the so-called SFR- M_{\star} ‘main sequence’ (Sec. 4.5, Sec. 1.2)), however, they have other properties that are often dissimilar to nearby nuclear starbursts, such as more extended gas disks in many cases (Sec. 4.6), cooler average dust and gas temperatures, and disk-like fine structure line ratios (Sec. 4.3). Overall, SMGs are certainly extreme starbursts, but they are likely a heterogeneous population, including compact starbursts in gas-rich major mergers, massively accreting disk galaxies, and enhanced star formation likely due to gravitational harassment in dense

proto-cluster regions (Hayward et al. 2012; Hodge et al. 2012).

3.4 Radio Galaxies

Radio galaxies are identified in wide-field radio surveys at cm wavelengths, and the radio emission is related to AGN jet activity, typically on scales $> 10\text{kpc}$. Radio galaxies were the first very high redshift galaxies discovered, and they remain the best beacons to massive, clustered galaxy formation at high redshift (Miley & de Breuck 2008). In the standard AGN unification model, radio galaxies are simply radio loud quasars seen with the jets closer to the sky plane, such that the broadline region is obscured by the accreting dusty torus (so-called type-II AGN).

Radio galaxies were also among the first high-redshift sources in which molecular gas was detected (Scoville et al. 1997, Papadopoulos et al. 2000, De Breuck 2003a,b, 2005, Greve et al. 2004). Like some quasars, radio galaxies are often bright in (sub)millimeter continuum emission and have similar gas masses to the quasars and SMGs. CO imaging of radio galaxies often reveals multiple components on tens of kpc scales, likely indicating major gas-rich mergers (De Breuck 2003a,b, 2005, Emonts et al. 2011). The most recent imaging study by Ivison et al. (2012) shows multiple, gas rich components over tens of kpc, indicating a merging, starburst proto-cluster environment.

3.5 Color Selected Star-Forming Galaxies (CSG)

Major progress was achieved in recent years in star forming galaxies selected via their optical or near-IR colors at $z \sim 1.5$ to 3. These galaxies have been selected in three different ways. The first strategy was through the near-IR BzK color selection, which selects galaxies by their 4000\AA break (Daddi et al. 2004). In 2008, Daddi et al. demonstrated that this color selection successfully selects gas-rich galaxies. Daddi et al. (2010) then used this selection technique to target 6 sBzK galaxies with stellar masses $> 10^{10} M_{\odot}$, that were also detected in the radio (but not the sub-millimeter). All galaxies were detected in CO emission, implying large reservoirs of molecular gas in galaxies that are not forming stars at the extreme rates seen in quasars and SMGs (Daddi et al. 2008; 2010).

A second color-selected sample is the rest-frame UV color selection technique, the BM/BX selection (Steidel et al. 2004). Tacconi et al. (2010) used this technique to identify a sample of CSG at $z \sim 2$ for CO observations. They also detect large gas reservoirs in the majority of their sample. In the following we use the term CSG (color-selected star forming galaxies) for both the BzK and BM/BX, and related, color selection techniques.

A third color-selected sample is the Star-Forming Radio-selected Galaxies (SFRGs). These objects are rest-frame UV-color selected to be $z > 1$ galaxies, and then further identified as 20 cm radio continuum sources of ~ 50 to $100\mu\text{Jy}$ but are not detected in the sub-millimeter. Chapman et al. (2008) and Casey et al. (2011) detected molecular gas reservoirs with masses of $\sim 10^{10} M_{\odot}$ in about half their sample (which includes a few BzK galaxies studied by Daddi et al. 2008). Indeed, it has been found that there is significant overlap between the various color selection techniques (Grazian et al. 2007).

The term ‘normal star forming galaxies’ at high redshift is often used for these CSG. The intrinsic star formation rates are high, $\geq 100 M_{\odot} \text{yr}^{-1}$ (Daddi et al.

2010, Tacconi et al. 2010), however, these galaxies follow a similar CO to FIR luminosity ratio as low redshift spirals (Sec. 4.5), and they lie on the sSFR ‘main sequence’, and as described in Sec. 1.2. Moreover, galaxies of this FIR luminosity make a dominant contribution to the overall cosmic SFR during the epoch of galaxy assembly (Sec. 1.2).

Further studies of the CSG galaxy population has shown that they are extended on 10 kpc scales in gas and stars (Daddi et al. 2010, Tacconi et al. 2010; Tacconi et al. 2012; Sec. 4.6) and that they have gas excitation that is lower than what is found in quasar hosts or SMGs (Dannerbauer et al. 2009; Aravena et al. 2011; see Sec. 4.1). However, such measurements are currently restricted to low-J lines only (up to $J=3$).

3.6 MIPS/24 micron–selected Galaxies

Spitzer 24 μm –selected galaxies at $z\sim 2$ have been studied in molecular gas emission by Yan et al. (2010). At the typical redshift of the sample, the 8 μm PAH feature, a tracer for star formation, is shifted in the 24 micron band. Even though these sources are bright at 24 μm and are thus forming stars at high rates, they are mostly undetected at 1.2 mm using MAMBO. Still they often have CO luminosities comparable to SMGs. These sources often show evidence for mergers, and some host dust–obscured AGNs (Yan et al. 2010, see also Iono et al. 2006a). This population is likely a hodgepodge of sources, including type 2 quasars, SMGs and hot dust sources.

3.7 Lyman–Break Galaxies, Ly α Emitters, and Ly α Blobs

Progress has been made on detecting CO emission from strongly lensed LBGs, corresponding to color-selected galaxies at $z \geq 3$. Baker et al. (2004) and Coppin et al. (2007) detected CO 3-2 emission in two LBGs at $z \sim 3$ that are lensed by a factor of 30. Riechers et al. (2010b) detect CO 1-0 emission in these two systems, and find relatively low excitation, and gas masses $\sim 4 \times 10^9 (\alpha/4) M_\odot$, after correcting for lensing. The first detection of a more massive, unlensed LBG at $z = 3.2$ has been reported in Magdis et al. (2012a).

CO emission has also been searched for in high- z Ly α emitting galaxies (LAE) and Ly α emitting ‘blobs’. Observations of one strongly lensed LAE at $z = 6.5$ resulted in a stringent upper limit to the gas mass of $4.9 \times 10^9 (\alpha/0.8) M_\odot$ (Wagg et al. 2009). Ly α blobs are typically large (tens of kpc), and their exact origin remains uncertain, possibly being the remnants of radio–mode feedback as seen in the Ly- α halos around powerful radio galaxies (Miley & De Breuck 2008), or even representing cooling gas in dense filaments from the IGM (Dekel et al. 2009). Searches for CO emission have led to non-detections at $z \sim 3$ (Yang et al. 2012), and $z = 6.6$ (Wagg & Kanekar 2012), with gas mass limits of order $10^{10} (\alpha/0.8) M_\odot$.

The advent of ALMA early science has opened the very real and exciting prospect of detecting [C II] 158 μm emission from typical LBGs and LAEs at very high ($z > 6$) redshift. Even with limited capabilities (1/3 of the final array), a number of typical LBGs and LAEs have already been detected with relative ease in [C II] at $z \sim 5$ (Riechers et al. 2013; Wagg et al. 2012; Carilli et al. 2012; Sec. 4.3.2).

3.8 Table of all high- z ISM detections

We have compiled a table of all high-redshift ($z > 1$) detections of the molecular interstellar medium. Most of the detections are of the CO line, but there are also detections of higher-density molecular gas tracers (observed only in quasar hosts), such as CN, HCN, HNC and HCO^+ and the CO isotopomer ^{13}CO . For many sources, multiple-J CO detections are available. The table also includes measurements of the atomic fine structure lines, most notably [C II], but also [N II], [O III] and [C I]. For convenience we have also added the FIR luminosities of these sources, derived through heterogenous ways (see footnotes in the table), following the equations in Sec. 2.9. The table will be available online through the homepage of the Annual Reviews in Astronomy and Astrophysics.

In total, the interstellar medium has now been detected in close to 200 sources at $z > 1$. In the following we summarize the basic observational parameter space (CO line luminosities and excitation, full width half maximum, sub-millimeter continuum emission, redshift distribution) through some key plots to interpret this rich set of observational data. In all plots we use the same color coding for different groups of galaxies (as defined in Sec. 3). These are the QSOs (quasars), SMGs (submillimeter-selected galaxies, including one Extremely Red Object (ERO) and Herschel-selected galaxies, HSG), CSGs (color-selected star forming galaxies, selected through BzK and BM/BX selection techniques), RG (radio galaxies), SFRG (star forming radio galaxies), Spitzer $24\mu\text{m}$ selected galaxies and LBG (Lyman-break galaxies). The classification is therefore entirely based on the selection technique, not on the actual physical properties.

3.9 Historical note

Since the earliest detection of molecular gas in the $z = 2.28$ quasar IRAS F 10214 by Brown & Vanden Bout (1992) and Solomon et al. (1992) there has been a steady increase in the number of line detections at high redshift. This is illustrated in the left panel of Figure 2 where the cumulative number of detections is presented as a function of discovery year. From this plot it is clear that over the first decade or so, the detections were dominated by quasars, with SMGs picking up in larger numbers around the turn of the millennium. Only recently have CSG been added to the list in significant numbers. The right panel of Figure 2 shows the redshift distribution of all galaxies with a line detection.

4 Observational diagnosis of the cool ISM in distant galaxies

4.1 Molecular gas excitation

As noted in Sec 2.6 the excitation of molecular gas in high-redshift galaxies provides important information regarding the average physical properties of the gas, in particular its temperature and density. This is illustrated in Fig. 3 where the expected CO excitation is shown as a function of density and temperature. One important caveat is that typically only galaxy-integrated line fluxes can be measured at high redshift. These measurements are then fed into LVG (Sec. 2.6.1) or PDR/XDR (Sec. 2.6.2) models that assume that the line emission is emerging from the same cloud/volume (i.e. that they share the same physical conditions). The validity of this assumption is questionable, as it is known that the different rotational transitions have different critical densities: the higher-J

transitions need much higher densities than the low- J ones to be excited. This situation complicates further if unresolved measurements of high-density tracers (e.g. HCN, HCO^+) are added to the ‘single component’ models. Another caveat is that the molecular gas excitation measurements in high redshift galaxies are typically restricted to the mid- J levels of CO emission.

With these caveats in mind there are a number of important results emerging from high-redshift CO excitations analyses. The main result is that the different source populations at high redshift show distinctly different excitation (see compilation of all high-redshift CO excitation in Fig. 4). The CO excitation of quasar host galaxies can in essentially all cases be modeled by a simple model with one temperature and density out to the highest- J CO transition with a typical gas density of $\log(n(\text{H}_2)[\text{cm}^{-3}]) = 3.6\text{--}4.3$, and temperatures of $T_{\text{kin}} = 40\text{--}60$ K. A prominent example is the highly excited quasar host APM08279+5255 (Weiß et al. 2007a). Measurements of the CO ground transition in a number of quasar host galaxies (Riechers et al. 2011a) have shown that the measured CO(1-0) flux is what was expected based on a single-component extrapolation from higher- J CO transitions, i.e. there is no excess of CO(1-0) emission in these sources (Riechers et al. 2006a, 2011a). One interpretation of this finding is that the molecular gas emission comes from a very compact region in the centre of the quasar host, which is confirmed by the few (barely) resolved measurements of quasar hosts (Sec. 4.6). It should be noted though that there is recent evidence that an additional high-excitation component, likely related to the AGN itself, is needed to explain the elevated high- J line fluxes in some sources, e.g. PSS 2322+1944 (Weiß et al., in prep.) and J1148+5251 (Riechers et al., in prep.).

The submillimeter galaxies, on the other hand, show (i) less excited molecular gas, and (ii) excess emission in the CO(1-0) ground transition. This is again illustrated in Fig. 4, where the orange symbols of the SMGs are on average at lower fluxes compared to the quasars (red symbols). On average, the typical density of SMGs is $\log(n(\text{H}_2)[\text{cm}^{-3}]) = 2.7\text{--}3.5$, and temperatures are in the range of $T_{\text{kin}} = 30\text{--}50$ K. Observations in the CO(1-0) line of a few SMGs have furthermore demonstrated that an additional cold component is needed to explain the observed excitation (Ivison et al. 2011, Riechers et al. 2011b). This implies that the total gas mass of the SMGs is underestimated if mid- J CO transitions are used to calculate masses assuming constant brightness temperature (see Sec. 4.2). A few SMGs have been resolved spatially and show more extended emission in the ground transition than in higher transitions (Ivison et al. 2011; although cf. Hodge et al. 2012).

Up to the mid- J measurements available for high redshift sources the CO excitation of the SMGs and QSOs roughly follow those of the centres of nearby starburst galaxies (e.g., M82: Mao et al. 2000; Ward et al. 2003, see dashed line in Fig. 4; NGC 253: Bradford et al. 2003; Bayet et al. 2004, and Henize 2-10: Bayet et al. 2004). It should be noted that the excitation in Galactic molecular cloud cores can be equally high (e.g. Habart et al. 2010, Leurini et al. 2012; van Kempen et al. 2010, Manoj et al. 2012). However, in Galactic clouds such very high excitation is only seen in pc scales cloud cores, while in nearby starburst nuclei high excitation is seen on scales of order 100 pc scales, and for high-redshift galaxies the scale can extend to a few kpc.

As stated in Sec. 3, the separation between SMGs and QSO host galaxies is largely due to historical selection effects and there are sources that fulfill both definitions. The different excitation conditions in the two groups however

argue that broadly speaking gas-rich quasars and SMGs represent different stages of galaxy evolution, with the quasars being more compact and harboring more highly excited gas than the SMGs. In a simplistic picture, the quasars could be the result of a merger, in which the molecular gas concentrates in the centre of the potential well, while the SMGs would then constitute merging systems that have not fully coalesced. The latter is supported by the fact that high-resolution observations of many SMGs show multiple emission components (e.g. Engel et al. 2010, Tacconi et al. 2010). SMGs and quasars also show similar clustering properties (Hickox et al. 2012).

To date, only a few excitation measurements exist for the CSGs (Dannerbauer et al. 2009; Aravena et al. 2010), and only up to CO 3-2. In the case of BzK-21000 Dannerbauer et al. (2009) showed that the $J=3$ emission must be significantly subthermally excited, resembling more that of the Milky Way than the higher-excitation systems discussed above. These CSGs have lower star formation rates than found in the quasars and SMGs, and have large (~ 10 kpc) sizes – the combination of these apparently leads to a less extreme gas excitation than found in the hyper-starburst galaxies at high redshift. Observations of higher order CO transitions are required in these systems.

Bothwell et al. (2012) suggest that there is a correlation between CO luminosity and line width in high redshift starbursts, likely relating to baryon-dominated gas dynamics within the regions probed. In Fig. 5, we plot the CO line widths (FWHM) vs. CO luminosity for a broader range of CO detected distant galaxy types. Considering only the hyperstarbursts (SMGs and quasar hosts), both occupy similar parameters space in this diagram, and there is no significant correlation between CO luminosity and linewidth. However, the CSG clearly segregate to smaller line widths relative to SMGs, by about a factor \sim two, and, while the scatter is large, the median CO luminosity for CSGs is smaller by a similar factor.

4.2 CO luminosity to total molecular gas mass conversion

Until a few years ago, the standard practice for high redshift galaxies was to use the starburst conversion factor to derive gas masses. This practice was justified in part on the extreme luminosities, high inferred gas densities based on CO excitation, and in some cases on the direct observation of compact star forming regions (scales $\sim 2 - 4$ kpc; Tacconi et al. 2008, Momjian et al. 2007, Ivison et al. 2010a, 2012, Carilli et al. 2002, Walter et al. 2009). Also, in some cases it appeared that, like nearby nuclear starbursts, the gas mass exceeded the dynamical mass when using a Milky Way conversion factor (Solomon et al. 1997, Tacconi et al. 2008, Carilli et al. 2010, Walter et al. 2004, Riechers et al. 2008, 2009).

As other populations of galaxies are now being detected in CO emission at high redshift, such as color-selected star forming galaxies (Sec. 3.5), the question of the conversion factor has become paramount. The last few years have seen a few attempts at the first direct measurements of the CO luminosity to gas mass conversion factor.

A minimum α can be derived assuming optically thin emission, and adopting a Boltzmann distribution for the population of states. In this case, the CO(1-0) luminosity, $L_{\text{CO}(1-0)}$, simply counts the number of molecules in the $J=1$ state via: $N_{J=1} = L_{\text{CO}(1-0)} / (A \times h\nu)$, where A is the Einstein A coefficient ($6 \times 10^{-8} \text{ s}^{-1}$), and $\nu = 115 \text{ GHz}$. The total number of CO molecules is then determined by the partition function, ie. the relative fraction in the $J=1$ state, which we designate

f. For example at $T = 10, 20$, and 40 K, $f = 0.47, 0.31$, and 0.19 , respectively. One can then convert to total number of H_2 molecules assuming a CO/H_2 abundance ratio, which for Galactic GMCs is 10^{-4} . Multiplying by the mass of an H_2 molecule, and including a factor 1.36 for the Helium abundance, leads to the total gas mass. Converting to the relevant units, leads to: $\alpha = (0.09/f) M_\odot [K km s^{-1} pc^2]^{-1}$, at $z = 0$.¹

Tacconi et al. (2008) use spatially resolved spectral imaging to derive either virial or rotational masses for a sample of SMGs and color selected galaxies. Galaxy sizes are estimated from the CO imaging and/or optical or near-IR imaging (see also Neri et al. 2003; Thomson et al. 2012). Tacconi et al. compare the dynamical masses with the sum of the gas mass (modulo α) and stellar mass (derived from near-IR photometry), including a small correction (10% to 20%) for dark matter. They conclude that for the SMGs, the value of α is most likely close to the starburst value ($\alpha \sim 1$), while for the CSG a value $\alpha \sim 4.8$ is favored.

Daddi et al. (2010) have performed a similar analysis on CSGs, based on (marginally) spatially resolved imaging with the PdBI of CO 2–1 emission of a sample of three $z \sim 1.5$ sBzK galaxies. Their dynamical analysis is guided by numerical simulations of clumpy, turbulent disks, to allow for significant non-circular motions (Bournaud et al. 2009). They find that the measurements are consistent with $\alpha_{CO} = 3.6 \pm 0.8 M_\odot / (K km s^{-1} pc^2)$.

The best rotational dynamical analysis of an SMG to date is the JVLA observation of GN 20 at $z = 4.0$ (Fig. 7) by Hodge et al. (2012; see Sec. 4.6). They show that the CO(2–1) emission is well characterized by a rotating disk of 7 kpc radius with a large rotation velocity of $575 \pm 100 km s^{-1}$ and internal velocity dispersion of $100 km s^{-1}$. They derive a dynamical mass of $5.4 \pm 2.4 \times 10^{11} M_\odot$. Subtracting the stellar mass, including a 15% dark matter contribution leads to $\alpha \sim 1 M_\odot / (K km s^{-1} pc^2)$.

The main uncertainties in the dynamical analysis are the current crude estimates of the dynamical masses based on marginally resolved imaging data, and the standard pit-falls in estimating the stellar masses based on SED fitting, in particular for starburst-type systems (Ivison et al. 2011).

Magdis et al. (2011) use a metallicity-dependent dust-to-gas ratio approach to estimate α_{CO} . They analyze two galaxies in the GOODS-N deep field with excellent rest-frame IR SEDs, one SMG (GN 20), and one CSG (BzK 21000). From these, and using the Draine & Li (2007) dust models, they derive a dust mass for each source. Metallicities are derived from the stellar mass – metallicity relation for the CSG (Erb et al. 2006), and a starburst model for GN 20. They then use the Solomon et al. (1997) metallicity dependent dust to gas relation to obtain an estimate of the gas masses of $9 \times 10^{10} M_\odot$ for the CSG and $1.5 \times 10^{11} M_\odot$ for the SMG. Comparing these masses to the CO(1–0) luminosities leads to $\alpha \leq 1.0$ for the SMG, while for the CSG they find $\alpha \sim 4$, consistent with earlier estimates. These results have been generalized in the more comprehensive study by Magdis et al. (2012b).

Ivison et al. (2011) take two different approaches to derive molecular gas masses, and hence infer α in SMGs. First, they propose a model in which some fraction of the CO emission occurs at the ‘Eddington limit’ in dense star forming regions (a ‘maximal starburst’), ie. a self-gravitating disk supported by

¹Including a correction for the relative contribution of the CMB increases these values by about 35% at $z = 2.5$ (Ivison et al. 2011).

starburst-driven radiation pressure on the dust grains (Thompson et al. 2005; Thompson 2009; Krumholz & Thompson 2012). Thompson (2009) derive a maximum star formation efficiency in this case of: $\text{SFE}_{\text{max}} \equiv L_{\text{IR}}/M_{\text{gas}} < 500 L_{\odot} M_{\odot}^{-1}$, and an areal star formation rate density of $1000 M_{\odot} \text{yr}^{-1} \text{kpc}^{-2}$. This maximum surface density is seen to hold on scales from star forming cloud cores in GMCs ($\sim 1\text{pc}$) to the nuclear starburst regions of low- z ULIRGs.

Iverson et al. then make a correction to the total gas for the fraction of cold, quiescent gas not involved in active star formation based on the CO excitation. Under these assumptions, the molecular gas mass can be estimated from the IR luminosity. For 4 of their 5 SMGs, the values are between $\alpha = 0.4$ and 0.7 , while for the last source the value is 3.7 . This latter source also has by far the lowest CO excitation.

Second, Iverson et al. (2011) use radiative transfer modeling to derive physical conditions within the clouds, and infer gas masses in a manner analogous to the low redshift ULIRG analysis of Downes & Solomon (1998). Unfortunately, LVG models have a fundamental degeneracy between density, temperature, and non-virial gas kinematics, when using just CO excitation (Sec. 2.6.1). They find the CO SEDs are consistent with either $\alpha \sim 4.5$ in cold, dense gas with large non-virial motions, or $\alpha \sim 1$ in warm, more diffuse gas closer to virial dynamics.

Genzel et al. (2012) consider the effect of metallicity on the conversion factor α in a sample of CSG at $z \sim 1$ to 2 . They have obtained estimates for the metallicities from optical $[\text{NII}]/\text{H}\alpha$ measurements. They find that galaxies with similar sizes, SFRs, and dynamical masses, but different metallicities (and stellar masses; Erb et al.), show very different star formation efficiencies, with the CO to FIR luminosity ratio decreasing dramatically with decreasing metallicity, at fixed FIR luminosity. If α is the same in each system, then this would imply a much shorter gas consumption timescale (gas mass/SFR) in low metallicity galaxies vs. high metallicity galaxies.

Alternatively, Genzel et al. (2012) propose adopting a standard star formation efficiency relating gas mass to star formation rate (Sec. 4.5). In this case, the decrease in CO luminosity is not due to a lower gas mass but an increase in α at low metallicity. Such a trend is expected and observed at low metallicity in nearby galaxies (Sec. 2.5), since dust shielding becomes less efficient, and CO in molecular cloud envelopes are photo-dissociated much more deeply into the cloud (Leroy et al. 2011; Bolatto et al. 2013; Schruba et al. 2012). Genzel et al. 2012; Stacey et al. 1991) derive the empirical relationship: $\log(\alpha_{\text{CO}}) = 12 - 1.3 \times [12 + \log(\text{O}/\text{H})]$. The implication is that stars can form in CO-poor molecular gas, and that the expected CO luminosities of low metallicity galaxies at high redshift are lower than previously predicted based on standard α values (Glover & Clark 2012; Papadopoulos & Pelupessy 2010).

Magnelli et al. (2012) perform a similar analysis of the conversion factor based on dust-to-gas ratios, for a mixed sample of SMGs and CSG at $z = 1$ to 4 . They adopt a similar dust mass calculation based on the FIR luminosity, and a metallicity-dependent dust-to-gas ratio as in Genzel et al. (2012). Their results are consistent with a low value of α for starbursts, and a factor five higher value for CSG. They also find a trend of decreasing α with increasing dust temperature, and while the trend may be continuous, they recommend that for a dust temperatures $< 30\text{K}$, a Milky Way conversion factor is appropriate, while for higher dust temperatures the starburst value should be used, at least for solar metallicity systems.

SIDEBAR: Many conclusions in astronomy are not based on a single, absolutely compelling direct measurement, but on a series of measurements, modeling, and consistency arguments from which the weight of evidence leads to a ‘concordance model’. This approach applies to the the CO-to-gas mass conversion factor in distant galaxies. The current measurements of α_{CO} are principally based on dynamical imaging and modeling, dust-to-gas measurements, radiative transfer modeling, and most recently, on star formation efficiencies. These measurements suggest a nuclear starburst value $\sim 0.8 \text{ M}_{\odot}/(\text{K km s}^{-1} \text{ pc}^2)^{-1}$ for SMGs and quasar hosts, and a Milky Way GMC value of $\alpha_{\text{CO}} \sim 4 \text{ M}_{\odot}/(\text{K km s}^{-1} \text{ pc}^2)^{-1}$ in CSG, with a likely further increase in low metallicity galaxies. These values are consistent with the generally extended, clumpy disk-like CO distribution, lower CO excitation, and Milky Way CO/FIR (FIR derived from SFR) ratios in CSG, compared to the often (although not exclusively) more compact, merger-like morphologies, higher excitation, and starburst CO/FIR ratios in SMGs and quasars.

4.3 Atomic Fine Structure lines

4.3.1 ATOMIC CARBON: [C I] In a recent study, Walter et al. (2011) summarize the [C I] observations of 13 high-redshift galaxies (this compilation included work by Barvainis et al. 1997, Weiß et al. 2003, 2005a, Pety et al. 2004, Wagg et al. 2006, Ao et al. 2005, Riechers et al. 2009a, Casey et al. 2009, Lestrade et al. 2010, Danielson et al. 2011). These systems studied in [C I] are amongst the brightest emitters both in the submillimeter regime and in CO line emission, and many of them are lensed. The main finding was that the [C I] properties of high-redshift systems do not differ significantly to what is found in low-redshift systems, including the Milky Way. In addition, there are no major differences in [C I] properties between the QSO- and SMG-selected samples. The $L'_{\text{CI}(1-0)}/L'_{\text{CO}}$ ratios (0.29 ± 0.12) are similar to low- z galaxies (e.g., 0.2 ± 0.2 , Gerin & Phillips 2000).

As argued in Sec. 2.8, measurements of both [C I] lines can constrain gas excitation temperatures of the molecular gas, independent of radiative transfer modeling. For the available sample, a carbon excitation temperature of $29.1 \pm 6.3 \text{ K}$ was derived (Walter et al. 2009). This temperature is lower than what is typically found in starforming regions in the local universe despite the fact that the sample galaxies have star formation rate surface densities on kpc scales of 100’s of $\text{M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$. However, the temperatures are roughly consistent with published dust temperatures of high-redshift starforming galaxies (Beelen et al. 2006, Kovács et al., 2006, 2010, Harris et al. 2012). Low carbon excitation as well as low dust temperatures could indicate that the measurements include a significant amount of gas/dust unaffected by star formation.

The [C I] abundances in the current high- z galaxy sample of $(X[[\text{C I}]]/X[\text{H}_2]) = (8.4 \pm 3.5) \times 10^{-6}$ are comparable, within the uncertainties, to what is found in local starforming environments (Walter et al. 2009). The [C I] lines are a negligible coolant (average $L_{\text{CI}}/L_{\text{FIR}} = (7.7 \pm 4.6) \times 10^{-6}$). There is tentative evidence that this ratio may be elevated in the SMGs by a factor of a few compared to the QSOs (Walter et al. 2009).

4.3.2 IONIZED CARBON: [C II] The [C II] $158\mu\text{m}$ line is rapidly becoming a work-horse line for the study of the cool atomic gas in distant galaxies. The

number of [C II] detections at high redshift has increased substantially in the last few years using the CSO, PdBI, APEX and the SMA (Maiolino et al. 2009; Stacey et al. 2010; Iono et al. 2006b, Hailey–Dunsheath et al. 2010, Wagg et al. 2010; Walter et al. 2012; Cox et al. 2011; De Breuck et al. 2011; Gallerani et al. 2012), as well as a few detections in strongly lensed galaxies with Herschel (Ivison et al. 2010b, Valtchanov et al. 2011). To date, there have been about two dozen [C II] detections from galaxies at $z > 1$, including a number at $z > 6$ (see Sec. 5.2). ALMA during early science has already demonstrated the ability to detect [C II] emission from relatively normal star forming galaxies at high redshift (LBGs, LAEs) in [C II] emission (Wagg et al. 2012; Carilli et al. 2012; Riechers et al. 2013).

Fig. 6 shows a broad scatter in the [C II]/FIR ratio at $z > 1$. Note that the high- z galaxy sample all have FIR luminosities $\geq 10^{12} L_{\odot}$. However, there is a trend for luminous AGN to have the lowest ratios, and star-formation dominated galaxies (eg. SMGs) to have ratios closer to that of the Milky Way (e.g., Stacey et al. 2010).

Stacey et al. (2010) use the CO, FIR, and [C II] emission to argue that the [C II] emission is dominated by PDRs in the star forming galaxies. From these observations, they derive the physical conditions in the PDRs in high redshift galaxies, finding gas densities of order a few $\times 10^4 \text{ cm}^{-3}$, and the strength of the FUV radiation field: $G \sim 10^3 \times 1.6 \times 10^{-3} \text{ erg cm}^{-2} \text{ s}^{-1}$, where $1.6 \times 10^{-3} \text{ erg cm}^{-2} \text{ s}^{-1}$ is the local Galactic interstellar radiation field (ISRF, ‘Habing field’). They find a further factor 10 higher G for the AGN dominated systems. Their modeling also implies that the scale of the PDRs is \geq few kpc, much larger than for GMCs or nuclear starburst galaxies at low redshift. The fraction of molecular gas mass associated with PDRs is between 20% and 100% in their sample.

Swinbank et al. (2012) detect likely [C II] $158\mu\text{m}$ emission in two SMGs using ALMA, from which they derive redshifts of $z \sim 4.4$ and 4.2 . They suggest that the bright-end of the [C II] luminosity function increases dramatically with redshift, with close to a thousand-fold increase in the number density of galaxies with $L[\text{C II}] > 10^9 L_{\odot}$ from $z = 0$ to 4 . We discuss [C II] detections in a number of $z > 6$ galaxies in Sec. 5.2.

4.3.3 OTHER FINE STRUCTURE LINES There have been only a few detections of fine structure lines other than [C II] at high redshift to date, mostly in strongly lensed systems using principally the PdBI and Herschel. We summarize some of the physical diagnostics that have been achieved with such observations.

In their Herschel study of SMGs at $z \sim 1.4$, Coppin et al. (2012) find that the [O I] $63\mu\text{m}$ /FIR ratio is comparable to spiral galaxies nearby, and much higher than what is seen in low- z nuclear starbursts. Similar results were found by Ferkinhoff et al. 2010 and Sturm et al. (2010) in their [O I] $63\mu\text{m}$, [O III] $52\mu\text{m}$, and [C II] $158\mu\text{m}$ study of a strongly lensed ULIRG at $z = 1.3$ (see also Hailey–Dunsheath et al. 2010). The interesting conclusion is that, although these systems are intrinsically ULIRG or HyLIRGs, they do not show a deficit in the major PDR cooling lines as seen in nearby ULIRGs. A similar conclusion has been reached based on [C II] and [N II] observations of lensed SMGs (Nagao et al. 2012; De Breuck et al. 2011). In particular, the compilation of Decarli et al. (2012) shows a mean value for $[\text{N II}]122\mu\text{m}/\text{FIR} \sim 3 \times 10^{-4}$, close to that seen in low z disk galaxies, although admittedly the scatter is large.

Conversely, Valtchanov et al. (2011) and Ferkinhoff et al. (2010; 2011) perform

PDR analyses of lensed SMGs at $z \sim 3$, using FIR, CO, [O III], [N II] and/or [C II] measurements. They find mean densities of order 2000 cm^{-3} , FUV radiation field of $G=200$, and sizes for the emitting region $\sim 0.6 \text{ kpc}$. The relatively strong [O III] implies that the radiation field must be very hot (35,000K), either dominated by O9.5 stars or an AGN NLR-like radiation field.

SIDEBAR: The [C II] $158\mu\text{m}$ line is realizing its potential in the study of the cooler atomic gas in distant galaxies. This strong line will be a workhorse-line for redshift determinations in the first galaxies, and in the study of galaxy dynamics at the highest redshifts. However, the interpretation of [C II] emission is not straightforward, since [C II] traces both the neutral as well as the ionized medium, and it appears to be suppressed in high-density regions. Likewise, multi-fine structure line diagnostics at high redshift have tremendous potential to probe the physical conditions in the ISM in high z galaxies, but studies are in their infancy. The current observations reflect the heterogeneous nature of SMGs, with many showing spiral galaxy-like FSL properties, and a few showing evidence for an AGN-like component.

4.4 Dense gas tracers and other molecules at high redshift

Emission from high dipole molecules, such as HCN and HCO^+ , comes only from highest density regions in molecular clouds ($n_{\text{CR}} > 10^4 \text{ cm}^{-3}$), corresponding to regions directly associated with active star formation. These lines are typically an order of magnitude weaker than the integrated CO emission from star forming galaxies, although the higher dense gas fraction in nuclear starbursts can lead to line strengths up to 25% of CO (Riechers et al. 2011c). To date, there remain just a handful of detections at high redshift, mostly from strongly lensed hyper-starbursts (Riechers et al. 2006b, 2010c; 2011c; García-Burillo et al. 2006, Danielson et al. 2011). The two strongly lensed hyper-starburst/AGN, APM 0827+5255 at $z=3.91$ and the Cloverleaf quasar (H1413+117; Barvainis et al. 1994) at $z=2.56$ play an analogous role to the Galactic molecular cloud SgrB2, as high- z ‘molecule factories’. These are the only sources with multiple transitions detected from molecules and isotopes other than ^{12}CO , including HCN, HNC, HCO^+ , H_2O , CN, ^{13}CO . We briefly review the recent results on these sources.

For APM 0827+5255, strong emission from very high order transitions is seen (Weiß et al. 2007a; Riechers et al. 2010c). Formally, the critical densities for excitation for the higher order HCN and HCO^+ transitions are $> 10^8 \text{ cm}^{-3}$. The excitation suggests emission from a region with a radius $\sim 200 \text{ pc}$ around the AGN, where IR pumping (Sec. 4.4) plays a dominant role in molecular excitation. The $J=6$ isomer ratio of $\text{HNC}/\text{HCN}=0.5$ is consistent with the IR pumping model (Riechers et al. 2010c).

For the Cloverleaf quasar, low and high order emission from HCN and HCO^+ , and CN have been detected (Solomon et al. 2003; Riechers 2006b, 2007a, 2011c; Barvainis et al. 1997; Wilner et al. 1995). Modeling including the multiple CO transitions implies collisional excitation by gas with a mean kinetic temperature of 50 K and density of $10^{4.8} \text{ cm}^{-3}$, in a molecular region with a radius $\sim 0.8 \text{ kpc}$ (Riechers et al. 2011c). Hence, in contrast to APM 0827–5255, the Cloverleaf is consistent with collisional excitation in a hyperstarburst region with a radius of order 1 kpc.

The only detection of rare isotopic emission at high redshift is ^{13}CO 3–2 emission from the Cloverleaf (Henkel et al. 2010). The isotopic luminosity ratio for the $J=3$ emission is 40, eight times larger than that seen in Milky Way GMCs. The only nearby galaxy with a ratio approaching that of the Cloverleaf is the merging ULIRG NGC 6240, where Greve et al. (2009) obtain a lower limit of 30. Henkel et al. (2010) conclude that the large isotope ratio in the Cloverleaf likely reflects a real ^{13}C abundance deficit, by a factor of four or so relative to Milky Way GMC value of 40 to 90 (Henkel et al. 1993).

Progress has recently been made on detecting thermal emission from (rest frame) FIR ro–vibrational transitions of water at high redshift (van der Werf et al. (2011), Omont et al. 2011; Combes et al. 2012a). In APM 0827–5255, van der Werf et al. show that the lower level transitions (rest frame frequencies below 1 THz) likely arise in collisionally excited gas with kinetic temperatures of 100 K, and clump densities of order $3 \times 10^6 \text{ cm}^{-3}$. The higher order transitions require radiative excitation by IR radiation on a scale of a few hundred parsecs around the AGN, with conditions similar to the nuclear regions of the low redshift starburst/AGN galaxy, Mrk 231 (van der Werf et al. 2010). They argue for distributed gas heating, as expected for a star–formation heated PDR, and not an AGN dominated XDR.

We note that a linear relation between $L'_{\text{HCN}(1-0)}$ and L_{FIR} has been found for local galaxies, including spirals and ULIRGs (Gao & Solomon 2004a, 2004b), unlike the non-linear relationship between $L'_{\text{CO}(1-0)}$ and L_{FIR} . It has been shown that this relation extends even to the dense cores of galactic clouds (Wu et al. 2005). One interpretation of this finding is that the dense molecular phase traced by HCN is immediately preceeding the onset of star formation. However, Riechers et al. (2007b) have shown that this linear relationship appears to break down in the high–redshift systems studied to date, i.e. that they have lower HCN luminosities than expected based on a linear extrapolation from the low–redshift (and Galactic) measurements. This finding may indicate even higher average gas densities in the highest–redshift systems compared to dense environments found locally. It may also hint at an increased star formation efficiency (or both, Riechers et al. 2007b).

SIDEBAR: Progress on dense gas tracers at high redshift has been limited to strongly lensed, extremely luminous systems, due to the limited sensitivity of existing telescopes. The results thus far indicate a mixture of PDR/XDR heating and collisional excitation in compact extreme starburst regions. Given the very high average densities in dense starbursts at high redshift, cosmic ray heating and related modeling will play an increasingly important role. In the future, much progress is expected from much broader bandwidths, as they will in almost all cases yield ‘involuntary line surveys’ of dense gas tracers.

4.5 Star formation laws and gas consumption

Quantifying the relationship between star formation rate (SFR) and gas density (the so–called ‘star formation law’, ‘Schmidt law’, ‘Schmidt–Kennicutt law’ or ‘K–S law’) has been a key goal in observational astrophysics over the last 50 years, starting with Schmidt (1959). Any relationship between SFR and gas surface densities has important implications for our understanding of galaxy formation and evolution as it describes how efficiently galaxies turn their gas into stars.

Such a ‘law’ would also serve as essential input to hydrodynamical simulations (and other models) of galaxy evolution that start with dark matter halos that are being fed by gas infall. It should be noted that the term ‘law’ (in a sense of a physical law) is not appropriate to describe an empirical relationship. However, we stick to this nomenclature as it is now common practice to refer to the SFR–gas relationship. This relationship has been reviewed recently for nearby galaxies by Kennicutt & Evans (2012). Herein we focus on $z > 1$ galaxies.

The relation between star formation rate and gas density is typically expressed in terms of surface densities ($\Sigma_{SFR} \sim \Sigma_{gas}^n$). One complication is that the measurement of surface densities requires resolved measurements of galaxies. In the compilation by Kennicutt (1998a, 1998b) the integrated star formation rates and gas masses were averaged over entire galaxy disks to derive an average surface density for a given galaxy. Observational capabilities have improved since, and spatially resolved measurements of the star formation rate and gas surface densities are now available for a number of nearby galaxies (e.g., Kennicutt 2007, Bigiel et al. 2008, 2011, Leroy et al. 2008, 2013, Rahman et al. 2011, 2012, Liu et al. 2011). These spatially resolved measurements typically have resolutions of one kiloparsec or slightly better, i.e. they still average over many individual giant molecular clouds that are typically ~ 50 pc in size. It is clear from Galactic studies that the relationship $\Sigma_{SFR} \sim \Sigma_{gas}^n$ must break down on very small scales: e.g. a star forming region will ionize its immediate surrounding, thus destroying any relationship that may be present on larger scale. This has been quantified by Schruba et al. (2010) and Onodera et al. (2010) who have shown that in the case of M33 the star formation law on large/galactic scales breaks down on scales below ~ 300 pc. There is now largely consensus that the star formation law is ‘molecular’, i.e. that the equation above becomes: $\Sigma_{SFR} \sim \Sigma_{H_2}^n$. H I does not appear to be intimately linked to the star formation process through such a simple description, even though it is clear that H I is needed to form H₂ to begin with (Kennicutt & Evans 2012).

Measuring the star formation law at high redshift is significantly complicated by the fact that few resolved CO measurements exist, and dust and/or AGN emission confuses determination of optical sizes. The recent comprehensive study of Tacconi et al. (2013) shows that, where both the size of the SF disk as well as the size of the CO emission could be measured, reasonable agreement between the quantities was found (see also Daddi et al. 2010a). However, typically only global measurements of SFR and molecular gas are plotted in high redshift research.

Unlike in the local universe, where L'_{CO} luminosities and H₂ masses can be calculated from the CO(1–0) or CO(2–1) transitions (Sec. 2.5), the majority of high-redshift measurements are done using higher J transitions. To put all high-redshift systems on the same plot, the L'_{CO} luminosity of the CO(1–0) transition needs to be estimated, assuming the typical excitation of the galaxy under consideration. Narayanan et al. (2010a) discusses how the slope of the star formation law could change if different transitions of CO are used and if the different line ratios are not accounted for properly. We consider the excitation ladder in Sec. 4.1, and in the analysis below, we adopt a set of canonical values for different galaxy types, based on the (admittedly limited) available data (Tab. 2).

Two further complications are involved when comparing derived quantities, such as gas mass and star formation rate. First is CO luminosity to gas mass conversion factor, α . As discussed in detail in Sec. 4.2, different source populations likely have different values of α . And second is derivation of the SFR from

observed SEDs. Methods include: SED fitting of UV/optical/IR data for CSGs, FIR luminosities for SMGs and AGN after correction for hot dust heated by the AGN (Jiang et al. 2010, Leipski et al. 2010, 2013, Riechers 2011, Genzel et al. 2010), and radio luminosities assuming the radio–FIR correlation (Condon 1992).

To avoid the above complications, we focus on the empirical relationship between the observables, L_{FIR} and $L'_{\text{CO}(1-0)}$, for all high-redshift galaxies detected to date in Figure 9. Most of the galaxies detected at high redshift have luminosities (both FIR and CO) that are much higher than typical systems seen in the local universe (grey/black data points). At the highest luminosities, the SMGs and quasar host galaxies dominate. The entire distribution can be fit with a power law of the form

$$\log(L_{\text{IR}}) = 1.37(\pm 0.04) \times (\log L'_{\text{CO}}) - 1.74(\pm 0.40)$$

with a slope that is consistent with the power law found when looking at the integrated properties of nearby galaxies only (including ULIRGs, Kennicutt 1998a). However, it is also apparent that the CSGs have higher CO luminosities for a given L_{FIR} (or SFR) compared to the QSO/SMG population (Daddi et al. 2008; 2010; Tacconi et al. 2010; 2013). Genzel et al. (2010) and Daddi et al. (2010b) argue that there are in fact 2 sequences visible in this plot, one ‘starburst’ sequence (red dashed line) and one ‘main sequence’/CSG relation (grey dashed line). For the latter, Daddi et al. (2010b) and Genzel (2010) derived:

$$\log(L_{\text{IR}}) = 1.13 \times (\log L'_{\text{CO}}) + 0.53$$

with L'_{CO} in units of $\text{K km s}^{-1} \text{pc}^2$, L_{IR} in units of L_{\odot} . The values given here are from Daddi (2010b), but the relation derived by Genzel et al. (2010) is very similar.

Both Genzel et al. (2010) and Daddi et al. (2010b) proceed to calculate molecular gas masses from the CO luminosities using a molecular gas conversion factors α that is about five times higher in the case of the CSGs relative to SMGs, based on the arguments in Sec. 4.2. This then leads to an increased gap between the CSG population and the SMGs/QSOs with an offset of roughly 1 dex in L_{FIR} . This strengthens the presence of two different star formation regimes, one highly-efficient star formation mode for starburst (presumably triggered by mergers and/or other interactions) and one less-efficient and thus longer-lasting mode for the CSGs (‘main-sequence’ galaxies).

The different star formation efficiencies, defined as $\text{SFE} = L_{\text{FIR}}/L'_{\text{CO}}$ (in units of $L_{\odot}/(\text{K km s}^{-1} \text{pc}^2)^{-1}$), are further highlighted in the right panel of Fig. 9. It is immediately obvious from this plot that the SFE of the CSG is lower compared to the high-redshift quasars and SMGs by a factor of few, and that the CSGs reach values that are similar to what is found in local galaxies. The offset between the two sequences becomes even more pronounced when different α conversion factors are used for the two high-redshift galaxy populations.

The gas consumption timescale is defined simply as: $\tau_c = M_{\text{gas}}/SFR$, i.e. the time it would take to use up the available molecular gas reservoir given the current star formation rate. The right hand of axis of Fig. 9 shows these timescales, assuming the two different conversion factors relevant to SMGs and CSGs (Sec. 4.2). The gas consumption timescale in CSGs is of order 10^8 to 10^9 years (Daddi et al. 2008, 2010a,b, Genzel et al. 2010, Tacconi et al. 2010, 2013), comparable to that in low redshift disk galaxies (Bolatto et al. 2012).

For comparison, the SMGs and other HyLIRGs galaxies have extremely short consumption timescales $\leq 10^7$ yr.

In the local universe it has been shown by Kennicutt (1998a,b) that if the dynamical timescale is taken into account (i.e. Σ_{SFR} is plotted as a function of Σ_{gas}/τ_{dyn} and not only as a function of Σ_{gas}), all galaxies fit on one relation with slope ~ 1 . Both Genzel et al. 2010 and Daddi et al. 2010 showed that this trend also continues at high-redshift, i.e. that a ‘universal’ star formation law is obtained, with no separation between the two star forming sequences. The dynamical timescale τ_{dyn} is here defined to be the rotational period at the last measured point in a galaxy (typically taken to be the half-light radius). We note that the latter is not easily determined given current observations at high redshift, and that a physical interpretation of this finding is not straightforward. In a sense it is puzzling that the global properties of a galaxy (τ_{dyn}) appear to be related to local star formation process. Krumholz et al. (2011) perform a similar analysis, only using an estimate of the local gas free-fall time, and conclude that all systems, from local molecular clouds to distant galaxies (starburst and main-sequence), fall on a single star formation law in which the star formation rate is simply $\sim 1\%$ of the molecular gas mass per local free-fall time.

As a general comment, it should be kept in mind that there are significant selection effects that may contribute to the apparent functional behavior in the ‘SF law’ plot. For example, as essentially all galaxies have been pre-selected based on their star formation activity, it is conceivable that large molecular gas reservoirs exist at low L_{FIR} ; they have simply not yet been looked at.

SIDEBAR: Constraining the ‘star formation law’, i.e. relating the star formation rate to the available gas reservoir, has been the focus of many studies at low and high redshift in the past decade. Even though it is not a ‘law’ in a physical sense, this empirical relation has the potential power to predict one quantity from the other, sheds light on the star formation process, and serves as vital input in numerical simulations and galaxy formation models. At high redshift there is a clear relation between the main observables, $\log(L_{IR})$ and $\log(L'_{CO})$. Once translated into physical quantities (SFR and H_2 mass) there is now good evidence for two sequences of star formation, one ‘starburst’ sequence, with very short consumption times, 10^7 – 10^8 yr (local ULIRGs, SMGs and QSOs) and a ‘normal, quiescent’ sequence, $\sim 10^9$ yr (local spirals, CSG, ‘main sequence’ galaxies).

4.6 Imaging of the molecular gas in early galaxies

The last few years has seen tremendous progress in high resolution imaging of the molecular gas in high redshift galaxies, mainly by the VLA and the IRAM PdBI. Imaging of CO emission has been performed on the brighter sources with a spatial resolution comparable to that of the HST ($\sim 0.15''$), or roughly 1 kpc at $z > 1$. Following we highlight a few of the best examples to date (see Fig. 7).

4.6.1 A TYPICAL CSG In their ground breaking studies of CSG, Tacconi et al. (2010) and Daddi et al (2010a) find gas rich disks without extreme starbursts (see also Tacconi et al. 2012; Sec. 3.5). The best imaging study to date of a CSG is that of the CO(3–2) emission from EGS1305123 using the PdBI at $0.6''$ resolution by Tacconi et al. (2010) (Fig. 7). The H_2 mass is $1.3 \times 10^{11} (\alpha/3.2) M_\odot$, distributed in a rotating disk with a radius of 8kpc, and a terminal rotation

velocity of 200 km s^{-1} . While clearly rotating, the disk also has a high internal velocity dispersion $\geq 20 \text{ km s}^{-1}$, implying substantial disk turbulence.

The disk is punctuated by high brightness temperature clumps with radii $\leq 2 \text{ kpc}$ and masses $\sim 5 \times 10^9 M_\odot$. The gas surface densities are $\sim 500 M_\odot \text{ pc}^{-2}$, a factor few larger than for Galactic GMCs, and they hypothesize that these clumps are conglomerates of a number of Galactic-type GMCs rather than a single giant GMC, due to the relatively low internal velocity dispersions ($\sim 20 \text{ km s}^{-1}$) Daddi et al. (2010a) obtain similar imaging results for a few CSG at $z \sim 1.5$, although at somewhat lower spatial resolution.

These imaging observations of CO in $z \sim 1$ to 3 CSG have been critical to the interpretation that the CSG are gas-dominated, rotating disk galaxies undergoing steady, high levels of star formation (see Sec. 3.5). They also helped to constrain the conversion factor α for these systems through dynamical arguments (Sec. 4.2).

4.6.2 BRI 1335–0417: TIDALLY DISTURBED GAS SURROUNDING A LUMINOUS QUASAR BRI 1335–0417 at $z = 4.4$ was among the first optically selected, very high- z quasars to be identified with a hyper-luminous FIR host galaxy, implying an accreting SMBH with mass $\sim 10^9 M_\odot$ coeval with an extreme starburst (SFR $\sim 1000 M_\odot \text{ yr}^{-1}$) (Guilloteau et al. 1997). The host galaxy has been detected in CO line emission, with an implied $M(\text{H}_2) \sim 8 \times 10^{10} (\alpha/0.8) M_\odot$ (Carilli et al. 2002a), as well as strong [C II] emission (Wagg et al. 2010). BRI 1335–0417 is a broad absorption line quasar, indicating AGN outflow. Fig. 7 (middle) shows the CO images from the of BRI 1335–0417 from the VLA (Riechers et al. 2008b). These are the highest quality CO images of any non-lensed high- z quasar to date. The system shows complex morphology in the gas on a scale of $\sim 1''$. The molecular gas shows multiple components distributed over $\sim 7 \text{ kpc}$, with a pronounced tail extending to the north, peaking in a major CO clump $\sim 0.7''$ from the quasar, and with a few other streams connecting to the quasar from other directions. While there is an overall north-south velocity gradient, the general velocity field appears chaotic.

Riechers et al. interpret the complex gas structure in BRI 1335–0417 as tidal remnants from a late-stage, gas-rich (‘wet’) merger. The merger drives gas accretion onto the main galaxy, fueling the hyper-starburst and the luminous AGN, generally consistent with the high molecular excitation seen in quasar hosts (Sec. 4.1). For comparison, the SMG-quasar pair BRI 1202–0725 at $z \sim 4.7$ shows a distinct SMG and quasar, possibly corresponding to an early-stage merger, before galaxy coalescence (Salome et al. 2012, Carilli et al. 2012).

4.6.3 GN 20: AN SMG WITH A GAS RICH DISK The galaxy GN 20 is the brightest SMG in the GOODS-North field (Pope et al. 2006), and the host galaxy is heavily obscured at optical wavelengths. Daddi et al. (2009a) made a serendipitous redshift determination of $z = 4.05$ from CO emission using the PdBI (by targeting a nearby CSG). Two other SMGs at this redshift have been detected in CO and dust continuum emission about $20''$ to the west (Carilli et al. 2010; Hodge et al. 2013), and there is a clear over-density of galaxies in this field, with 15 LBGs with $z_{\text{phot}} \sim 4$ within a radius of $25''$ of GN 20 (Daddi et al. 2009).

A long observation using the JVLA in early science of the CO (2–1) emission (Hodge et al. 2012) shows that the CO is distributed in a disk with a diameter $\sim 14 \text{ kpc}$ (Fig. 7, right). The regions emitting in CO and dust continuum are mostly obscured in the HST I-band image. The only tracable optical emission is seen at the edges of the source (Hodge et al. 2012). Such heavy obscuration in

the optical is characteristic of SMGs.

The GN 20 disk dynamics are consistent with a standard ‘tilted-ring’ gas rotation model, with a dynamical mass of $5.4 \pm 2.4 \times 10^{11} M_{\odot}$. Observations at 1 kpc resolution reveal that 30% to 50% of the gas is in giant clumps with gas masses of a few $\times 10^9 (\alpha/0.8) M_{\odot}$, brightness temperatures between 16 K and 31 K, and line widths of order 100 km s^{-1} (Hodge et al. 2012). A dynamical analysis suggests the clumps could be self-gravitating. The gas surface densities of the clumps are $\sim 4000 (\alpha/0.8) M_{\odot} \text{ pc}^{-2}$, more than an order of magnitude larger than typical GMCs. An analysis of the overall galaxy dynamics has been used to determine the value of α in GN 20 (see Sec. 4.2).

The apparent disk in GN 20 suggests that not all HyLIRGs at very high redshift result from an ongoing major merger. This conclusion has also been reached for a few other SMGs at lower redshift, where low order CO observations show large, disk-like gas reservoirs similar to GN 20 (Ivison et al. 2011; Riechers et al. 2011; Greve et al. 2003, Ivison et al. 2010a,b).

In GN 20, the clumpy disk is consistent with that expected in the cold mode accretion model (e.g. Keres et al. 2005, Dekel et al. 2006, 2009), only now scaled up by almost an order of magnitude in FIR luminosity relative to typical CSG (Sec. 5.1.2). It is possible that the star formation in this gas rich disk has been enhanced due to gravitational harassment by the other SMGs and smaller galaxies in the proto-cluster.

SIDEBAR: Spatially resolving the molecular gas emission in high redshift galaxies is to date restricted to very few, bright, sources. Imaging the molecular and cool atomic gas a few selected high redshift galaxies has revealed 10 kpc-scale, clumpy and turbulent, but apparently rotating disks in CSG and some SMGs, as well as strongly tidally disturbed gas distributions in some SMGs and quasar hosts.

4.7 Outflows

Theoretical models without negative feedback (negative feedback = ejection of material due to either star formation or AGN activity) predict both a higher gas content in massive galaxies in the nearby Universe, and a larger population of star forming massive galaxies today, than observed. At high galactic masses, including AGN feedback mitigate these problems in simulations, both driving gas out of the immediate ISM of the host galaxy via AGN winds, and suppressing further gas accretion from the IGM via large-scale radio jets (Fabian 2012). Direct evidence for feedback has been seen in nearby galaxies, including outflows seen in OH far-IR lines, molecular emission lines, optical lines, and atomic fine structure lines (e.g., in the case of M 82: Strickland & Heckman 2009, Walter et al. 2002, Martin et al. 1998). The fact that old, gas-poor massive galaxies have now been seen at redshifts of 2 and beyond suggest that feedback must be an important process even earlier.

Recent observations have detected evidence for feedback on kpc-scales in very early galaxies. One of the best examples of AGN feed-back are the broad line wings of the [C II] emission from the $z=6.4$ quasar J1148-5251 by Maiolino et al. (2012). They derive an outflow velocities of 1300 km s^{-1} , an outflow rate of $\dot{M}_{outfl} \sim 3500 M_{\odot} \text{ yr}^{-1}$, and kinetic power of: $P_K \sim 1.9 \times 10^{45} \text{ erg s}^{-1}$. This is roughly 0.6% of the quasar bolometric luminosity, well below the theoretical upper limit to a radiatively driven quasar outflow of 5% of the bolometric luminosity

(Lapi et al. 2005), but it is barely consistent with the maximum kinetic power that can be driven by the associated starburst in the quasar host (Veilleux et al. 2005). Likewise, theoretical models indicate that star formation driven winds reach a maximum velocity of $\sim 600 \text{ km s}^{-1}$ (Thacker et al. 2006). Maiolino et al. (2012) argue that the outflow is most likely AGN-driven. The gas consumption timescale for the outflow is comparable to that due to star formation, of order 10^7 yr .

Other systems show varying degrees of feedback in the cooler gas. The BRI 1202–0725 quasar–SMG galaxy pair does show evidence for a broad wing in the quasar host galaxy [C II] $158\mu\text{m}$ spectrum, but the outflow kinetic energy is well below that of J1148+5251, and star formation likely dominates gas depletion in the galaxy (Wagg et al. 2012; Carilli et al. 2012). Weiß et al. (2012) detect a 250 km s^{-1} outflow in a $z = 2.8$ quasar in both CO and [C I]. They derive a lower limit to the mass outflow rate of $180 \text{ M}_{\odot} \text{ yr}^{-1}$, which is slightly larger than the star formation rate in the host galaxy.

SIDEBAR: Molecular Outflows have only very recently been detected in a few high-redshift systems. Given that they feature (by definition) broad and faint line wings they remained undetected by past observations, both due to missing sensitivity and insufficient bandwidth. Quantifying the kinetic energy and masses associated with such outflows will provide important input in galaxy simulations in which feedback by stellar (or AGN) activity is a key driver for galaxy evolution.

5 Dense Gas History of the Universe

5.1 Gas dominated disks during the epoch of galaxy assembly

5.1.1 GAS FRACTION One of the most striking results from the study of CSG is the remarkably high detection rate (between 50–100%) in CO emission (Daddi et al. 2010a; Tacconi et al. 2010; Tacconi et al. 2012). The line strengths are comparable to those seen in the hyperstarbursts, but the star formation rates are almost an order of magnitude smaller (Sec. 4.5). Moreover, these galaxies have a space density more than an order of magnitude larger than SMGs (10^{-4} Mpc^{-3} down to $M_{\text{stars}} = 10^{10} \text{ M}_{\odot}$), and they represent the galaxies that dominate the integrated cosmic star formation rate during the ‘epoch of galaxy assembly’ (Sec. 1.2).

A series of measurements and consistency arguments lead to a value of $\alpha_{\text{CO}} \sim 4$ in CSG (Sec. 3.5). The implied H_2 masses range from 3×10^{10} to $10^{11} \text{ M}_{\odot}$. Interestingly, these gas masses are comparable to, or even larger than, the stellar masses in these galaxies, as first pointed out by Daddi et al. (2010a) and Tacconi et al. (2010). This ratio is very different with respect to large disk galaxies at low redshift, where the stellar masses are close to an order of magnitude larger than the cool gas masses.

In Fig. 10 we plot a compilation of the latest measurements of the gas fraction, defined as $f_{\text{gas}} \equiv M_{\text{gas}}/M_{\text{stars}}$, out to $z \sim 4$, where M_{gas} corresponds to the molecular component, including a 1.36 factor for Helium. At all redshifts, the galaxies were selected to be star forming disk galaxies with stellar masses $> 10^{10} \text{ M}_{\odot}$.

While the scatter in Fig. 10 at any given redshift is large, there is a clear trend

for increasing gas fraction with redshift in massive disk galaxies. The mean value at $z \sim 0$ is: $M_{\text{gas}}/M_{\text{stars}} \sim 0.1$, which increases to $M_{\text{gas}}/M_{\text{stars}} \sim 1$ at $z > 1.5$. A functional form of $f_{\text{gas}} \sim 0.1 \times (1+z)^2$ fits the data reasonable (see also Magdis et al. 2012a; Geach et al. 2011). Note that the high- z CSG CO samples tend to be at the upper end of the mass range for CSGs, but are typical of main sequence galaxies in all other respects (eg. Daddi et al. 2010). Moreover, the recent large study of Tacconi et al. (2012) suggests that the gas fraction in CSGs may increase with decreasing galaxy mass, thereby excentuating the results in Fig. 10.

We note that all points in Fig. 10 are for large disk galaxies (stellar masses $> 10^{10} M_{\odot}$), and that the same value of $\alpha \sim 4 M_{\odot}/(\text{K km s}^{-1} \text{ pc}^2)^{-1}$ was used for all sources. Moreover, while stellar masses are nominally based on full SED-fitting, the outcome is predominantly dictated by the observed near-IR data, corresponding to roughly rest frame R band (Daddi priv. comm.). Hence, the ratio on the ordinate of Fig. 10 can be considered approximately empirical, and $\propto L'_{\text{CO1-0}}/R_{\text{mag}}^{\text{rest}}$.

Narayanan et al. (2012) consider the question of the increasing gas fraction in galaxies with redshift, including SMGs and CSG, and conclude that some of the effect might be attributed to a changing value of α , with α decreasing with redshift due to higher velocity dispersions and gas temperatures in high redshift galaxies.

Overall, the CO measurements of CSG suggest that the peak epoch of cosmic star formation also corresponds to an epoch when molecular gas masses dominates over stellar masses in common star forming galaxies (see also Swinbank et al. 2013; Geach et al. 2011; Magdis et al. 2012a). This fundamental change in the baryon content of disk galaxies with redshift likely has definitive consequences on the nature of star formation in early galaxies (Sec. 5.2).

Of course, we must keep in mind that the CSG at high redshift may not evolve into low redshift disk galaxies, and demographics suggests that subsequent mergers can lead to substantial morphological evolution. For instance, the space density and clustering of the CSG at $z \sim 2$ is consistent with their evolution into early-type galaxies at $z \sim 0$ (Shapley 2011; Tacconi et al. 2008).

SIDEBAR: The gas fraction of molecular gas versus stars in massive disk galaxies increases by an order of magnitude from $z = 0$ to $z \sim 2$. Hence, the peak epoch of cosmic star formation ($z \sim 2$) corresponds to the epoch when typical star forming disk galaxies were dominated by cool gas, not stars.

5.1.2 GAS ACCRETION Gas resupply for star formation in galaxies has become an important issue at both low and high redshift. The most extreme situations are the gas consumption times in QSO host galaxies and SMGs, which are always extremely short, in some cases as short as 10 Million years (Sec. 4.5). However, even CSGs have gas consumption timescales substantially less than the Hubble time (Tacconi et al. 2012). This point is emphasized by Bauermeister et al. (2010), where they conclude based on the short molecular gas consumption timescales in high z galaxies and the lack of evolution of the cosmic HI mass density (from study of damped Ly α absorption systems), that ultimately the gas must be accreted from the IGM.

The clear need for substantial gas resupply over cosmic time has led to a change in thinking on the gas supply to early galaxies. As opposed to either cooling of virialized, hot halo gas (White & Rees 1978), or major, gas-rich mergers

(Robertson et al. 2006), the dominant mode of star formation during the epoch of galaxy assembly may be driven by cold mode accretion (CMA), aka stream-fed galaxy formation. A convergence of observations, simulations, and analytic studies suggest that gas accretion in early galaxies occurs along cold streams ($T \sim 10^4\text{K}$) from the filamentary IGM that never shock-heat, but stream onto the galaxy at close to the free-fall time (Elmegreen & Burkert 2010; Dekel et al. 2009a,b; Bournaud et al. 2009; Keres et al. 2005, 2009). This cool gas may form a thick, turbulent, rotating disk (Genzel et al. 2011, 2008, 2006; Daddi et al. 2010). The disks are marginally Toomre-unstable (Swinbank et al. 2011; Tacconi et al. 2010), leading to rapid fragmentation into a few kpc-scale clumps which very efficiently form stars. These clumps can be 100 times larger than Galactic GMCs, and 10^7 times more luminous (Swinbank et al. 2010). The star forming regions could then migrate to the galaxy center via dynamical friction and viscosity, forming compact stellar bulges (Genzel et al. 2008; Dekel et al. 2009a; Keres et al. 2009). The process leads to relatively steady, active ($\sim 100 M_\odot \text{ yr}^{-1}$) star formation in galaxies over timescales of order 1 Gyr, and has been termed ‘rapid secular galaxy evolution’ (Genzel et al. 2008).

In these models, the process slows down dramatically as gas supply decreases, and the halo mass increases, generating a virial shock in the accreting gas. Subsequent dry (gas-poor) mergers at $z < 2$ lead to continued total mass build up, and morphological evolution, but little star formation in such models (Hopkins et al. 2010; Naab et al. 2009, Kereš et al. 2009). In this picture the majority of stars in spheroidal galaxies are thought to form via CMA at $z \sim 2$ to 3.

Dave et al. (2010) suggest that the CMA phenomenon may even scale up to HyLIRGs, and that a substantial fraction of high- z SMGs could be fed primarily by CMA, and not major mergers. Hydrodynamical simulations show that quite high gas accretion rates can be achieved in large halos at early epochs, and SFR can be elevated over the average accretion rate by a factor 2 to 3 via (common) minor mergers and general gravitational harassment in the dense environments of SMGs (see also Finlator et al. 2006, Narayanan et al. 2010b).

Physically, there may be a continuum of accretion processes, from relatively continuous CMA, through ‘clumpy’ accretion of small satellites, to the rare major gas rich merger. However, current modeling and observations favor a model in which most of the accretion occurs relatively continuously over timescales $\geq 10^9$ years (Dekel et al. 2009; Guo & White 2008).

We emphasize that clumpy, turbulent but rotating gas disks are simply a consistency argument for CMA (Shapiro et al. 2008), and they do not conclusively rule out gas-rich mergers. Robertson & Bullock (2008) have shown that ordered rotation of an extended gas disk can be reestablished shortly after a major merger. Some recent observations detected low-metallicity gas near high-redshift galaxies; the properties of this gas have been argued to be consistent with a CMA picture (e.g. Ribaud et al. 2011, Kacprzak et al. 2012). The few single detections to date are however not sufficient to conclusively proof the existence of CMA from an observational perspective.

SIDEBAR: The current evidence for gas accretion through cold mode accretion at $z > 1$ is circumstantial, based on the similarity between the predicted and observed morphologies of gas-dominated disks in CSG. Low ionization quasar absorption lines may provide the best means by which to prove the existence of these flows.

5.2 First Galaxies

Deep fields at near-IR wavelengths, and narrow band near-IR surveys, are now systematically detecting galaxies at $z \sim 6$ to 10, corresponding to the tail-end of cosmic reionization when the Universe was less than 1 Gyr old (Bouwens et al. 2012a,b; Pentericci et al. 2011, Bradac et al. 2012; Coe et al. 2013). Reionization represents the epoch when light from the first galaxies acted to reionize the neutral intergalactic medium that pervaded the Universe after recombination (e.g., Fan et al. 2006). Current studies suggest that the typical star forming galaxies at these redshifts have lower dust content than similar luminosity galaxies at lower redshift (Bouwens et al. 2010).

The search for dust and cool gas into cosmic reionization has focused predominantly on the host galaxies of luminous quasars with good spectroscopic redshifts. One of the most distant, and best studied, of the molecular gas detections remains the quasar SDSS J1148+5251 at $z = 6.42$ (Walter et al. 2003; 2004, 2009; Riechers et al. 2009a Wang et al. 2013). This (and similar) system represent the coeval formation of massive galaxies and supermassive black holes within 1 Gyr of the Big Bang. Large scale cosmological simulations show that massive galaxies and SMBH can form at $z \sim 6$ via gas rich mergers, driving extreme starbursts, and rapid accretion onto the black holes, with subsequent black hole mergers (Li et al. 2007). Such systems are thought to evolve into large galaxies in rich clusters at low- z . More recent simulations suggest that cold accretion from the IGM may also play a role in, and possibly even dominate, the gas resupply (Khandai et al 2012). As the SMBH builds, feedback from the AGN expels gas from the galaxy, and hinders further accretion, thereby terminating star formation in the galaxy (Maiolino et al. 2012).

Exciting results have been obtained via imaging of the [C II] 158 μ m line in $z > 6$ galaxies, as demonstrated in Fig. 8. Imaging of [C II] emission from the highest redshift SDSS quasars ($z \sim 6$) show velocity gradients indicative of rotation, with disk scales of order a few kpc (Wang et al. 2013). In once case, a ‘maximal starburst disk’ is seen on a scale ~ 1 kpc (Walter et al. 2009; Sec. 4.2). [C II] has also been detected in the most distant quasar with a spectroscopic redshift known, the quasar J 1120+0641 at $z = 7.08$ (Venemans et al. 2012).

The gas dynamics in distant quasar host galaxies allows for a study of the evolution of the black hole – bulge mass relation. Wang et al. (2010) present the most detailed analysis to date out to $z \sim 6$. In this study, the black hole masses are based on standard line-width relations of ionized gas, and are consistent with simple Eddington arguments. They find that the median black hole–bulge mass ratio is 15 times higher at $z \sim 6$ than today, although the scatter is close to an order of magnitude (see also Shields et al. 2006; Coppin et al. 2008). These results suggest that SMBH may assemble before the mass in their host galaxies. Such a deviation has been predicted in hydrodynamical simulations of very early SMBH and massive galaxy formation (Khandai et al. 2012).

As pointed out in Sec. 4.3.2, the [C II]/FIR increases with decreasing metallicity. Hence, even if the dust content of star forming galaxies at the highest redshifts were indeed to decrease (Bouwens et al 2010cb, Walter et al. 2012b), the [C II] line may remain strong, and will be a key redshift determinant, and a primary means to image gas dynamics in the first galaxies, since it traces both PDRs and the CNM.

SIDEBAR: The presence of detectable CO, [C II] (and dust) emission

at redshifts out to $z=7$ was almost inconceivable a little more than 10 years ago. At these redshifts, the age of the universe was < 1 Gyr, and there has been little time to enrich the interstellar medium with carbon and oxygen, and then cool to form dust and molecules. The detection of molecular emission and fine structure line emission at $z > 6$ currently remains limited to hyperluminous infrared galaxies. These results reveal the coeval formation of massive galaxies and supermassive black holes in extreme starburst events within 1 Gyr of the Big Bang. Given the difficulties of detecting CO at the highest redshifts, [C II] and other fine structure lines will likely play the dominant role in the study of the starforming ISM at the earliest epochs.

5.3 Spectral Deep Fields and the Dense Gas History of the Universe

Most observations of the molecular gas phase in the universe have been restricted to galaxy populations that were pre-selected in the UV/optical/IR/FIR, i.e. based on their star formation properties. However, in order to obtain an unbiased census of the molecular gas content in primeval galaxies, there is a clear need for a blind search of molecular gas down to mass limits characteristic of the normal star forming galaxy population, i.e. a CO deep field. Such a CO deep field has been out of reach given past instrumentation, both in terms of sensitivity and instantaneous bandwidth. However, this situation is now dramatically changing with the advent of new observational facilities. Clearly, fields with the best photometric supporting data are preferred, for rapid follow-up identification, as well as dense spectroscopic coverage, for possible ‘3D-stacking’.

As an aside, we note that a number of authors have successfully used frequency scans to obtain redshifts from CO emission for sources that were very bright in the FIR, but that had no easily identifiable counterpart in the optical, and therefore no redshift determination (Weiss et al. 2009; Lestrade et al. 2010; Walter et al. 2012; Cox et al. 2011; Combes et al. 2012a, Riechers 2011, Scott et al. 2011). A good example of such a redshift search using CO is the recent GBT spectroscopic survey of Herschel-discovered SMGs, for which redshifts were determined for 11 of 24 galaxies observed (Harris et al. 2012). Recent ALMA observations by Swinbank et al. (2012) have shown the power of the [CII] $158\mu\text{m}$ line as a redshift determinant at $z \geq 4$.

Cosmological simulations have been used to predict the cosmic evolution of the dense gas history of the universe. Most of these models and simulations start with dark-matter simulations, such as the Millenium simulations (Springel et al. 2005). The dark matter halos are then populated with model galaxies and these evolve according to simple rules (‘semi-analytical modeling’). In this modeling, each galaxy today has a well-defined history of growing and merging galaxies. Obreschkow et al. (2009b) applied post-processing to these galaxies to subdivide their cold gas masses into the atomic and molecular gas phases, by assuming that the ISM pressure (Leroy et al. 2008, 2013) sets the phase balance between these two phases. As discussed in Sec. 4.2, an important complication is the CO luminosity to gas mass conversion factor. In a follow-up paper, Obreschkow et al. (2009a) predicted the CO luminosity functions for the various transitions of CO, including a number of effects, such as heating by starbursts and CMB, and metallicity dependence. Power et al. (2010) compared a number of currently favored

semi-analytical galaxy models (again applying them to the Millenium simulation). Lagos et al. (2011) used a similar methodology, but a different galaxy formation model to separate the atomic and molecular gas phases of the interstellar medium. Lagos et al. (2012) then refined their model through modeling the various rotational transitions of CO using a PDR code. All these models are scaled such that the CO(1–0) luminosity function at $z=0$ is matched (Keres et al. 2003).

An independent approach to predicting CO and H₂ luminosity functions as well as the cosmic evolution of the H₂/CO density is presented in Sargent et al. (2013). They separate the contributions of main-sequence and starburst galaxies to the IR luminosity functions of galaxies at various redshifts, and use the relation between CO luminosities and IR luminosities for these two populations to predict CO luminosities (Sec. 4.5). They also use a metallicity-dependent conversion factor to go from predicted CO luminosities to H₂ masses (Sec. 4.2). Other calculations of this type include those by Geach & Papadopoulos (2012) and Carilli & Blain (2002).

Figure 11 summarizes the various predictions put forward to date. The top panel shows the predicted CO luminosities in 5 redshift bins, including $z=0$. The CO luminosity function has to date only been measured at $z=0$ (see datapoints in top left panel by Keres et al. 2003). The luminosity functions for all other redshift bins are essentially unconstrained.

The integral under each of the luminosity curves gives the total CO luminosity which can then, under the assumption of a given conversion factor α , be translated to total molecular gas for each galaxy population. The summed density of this quantity is plotted in Fig. 12, for the models discussed above. We note that the cosmic density in H I determined through studies of damped Ly α absorption line systems, appears to show little evolution at least through the epoch of galaxy assembly (Wolfe et al. 2005).

The number of high- z detections of molecular gas in CSG remains limited, and to date no truly deep, wide field spectral search has been performed. However, we are reaching a point where it may be possible to set limits on the evolution of the cosmic density of molecular gas. We here take a very simple approach, based on the measured stellar to gas mass ratios in existing (admittedly limited, e.g. Aravena et al. 2012) samples, and the cosmic stellar mass densities of these populations.

For five sBzK galaxies at $z \sim 1.5$ to 2, Daddi et al. (2010) find a mean value of $M_{\text{gas}}/M_{\text{stars}} = 1.15$. For ten BX/BM galaxies at $z \sim 2$ to 2.5, Tacconi et al. (2010) find $M_{\text{gas}}/M_{\text{stars}} = 0.79$. Tacconi et al. (2012) reach similar conclusions for CSGs at $z = 1.2$ and 2.2. Riechers et al. (2010b) measure a mean of $M_{\text{gas}}/M_{\text{stars}} = 1.4$ for two lensed LBGs at $z \sim 3$. In all cases, a value of $\alpha \sim 4 + / - 0.4$ was assumed (see also Magdis et al. 2012a). In all cases the scatter in the ratio is close to a factor 2, and so for simplicity, we adopt $M_{\text{gas}}/M_{\text{stars}} \sim 1$ in all cases. Note that we focus on CSG, since their space density is more than an order of magnitude higher than for HyLIRG, such as quasar hosts and SMGs, and their gas masses appear comparable (although there is a question of duty cycle in the latter samples). In this sense, these calculations represent lower limits.

Grazian et al. (2007) tabulate the total cosmic stellar mass density in different types of galaxies at different redshifts. They also quantify the substantial overlap between populations selected with the different techniques. At $z \sim 1.8$, they find the sBzK galaxies dominate the stellar mass density of the star forming galaxy

population (we assume only star forming galaxies contribute to the cosmic gas density), with comoving stellar mass density of $\rho_{stars} = 5.9 \times 10^7 \text{ M}_\odot \text{ Mpc}^{-3}$. Likewise for BX/BM/LBG at $z \sim 2.5$, for which they find $\rho_{stars} = 2.8 \times 10^7 \text{ M}_\odot \text{ Mpc}^{-3}$, and at $z \sim 3.3$, with $\rho_{stars} = 1.2 \times 10^7 \text{ M}_\odot \text{ Mpc}^{-3}$.

Assuming unity ratio with the gas mass we can then establish lower limits to the cosmic gas mass density at the respective epochs, plotted in Fig. 12. We also include the $z=0$ measurement of Keres et al. (2003). Interestingly, the sBzK limit is already pushing the cosmic density into the modeled regime based on e.g., the star formation history of the universe and star formation laws.

We emphasize that this analysis is mainly illustrative, with very substantial uncertainties. First, we assume the unity gas-to-stellar mass ratios hold for galaxies well below the masses of those current observed in CO. In particular, the galaxies in the Daddi et al. (2010) and Tacconi et al. (2010) samples were typically at the high-mass end of the CSG distribution, although having ‘main-sequence’ properties otherwise (eg. sSFR, gas consumption timescales). Interestingly, the larger sample of Tacconi et al. (2012) shows a trend for increasing gas fraction with decreasing stellar mass, which would increase the cosmic gas densities in Fig. 12. Second, we adopt a standard GMC value of α , when in fact this value could increase dramatically with e.g. decreasing metallicity, such that the GMC value radically underestimates the total gas mass (e.g., Genzel et al. 2012). And third, we currently cannot rule-out a population of lower-mass, gas rich galaxies that do not appear in any optical survey.

SIDEBAR: Studies of the molecular medium at high redshift have been restricted to galaxies that have been pre-selected in the optical or infrared wavebands through their star formation activity. This could potentially lead to a biased view of the molecular gas properties of high-redshift galaxies. A promising way forward is through observations of molecular deep fields, i.e. complete frequency scans towards regions in the sky that have superb multi-wavelength observations available. Such observations were prohibitive given the sensitivity and bandwidth of past facilities; a situation that will be changing with ALMA and the JVLA. The principal remaining uncertainty in determining the cosmic space density of molecular gas ($\Omega_{H_2}(z)$) will be the calibration of the conversion factor, α .

6 Summary Points / Concluding Remarks

Over the last decade, observations of the cool ISM in distant galaxies via molecular line and atomic fine structure line emission has gone from a curious look into a few extreme, rare objects, to a mainstream tool in the study of galaxy formation, out to the highest redshifts ($z \sim 7$). Molecular gas has now been observed in close to 200 galaxies, including numerous AGN host-galaxies, extreme starburst SMGs, and increasing samples of ‘main-sequence’ CSG. Studies have moved well beyond simple detection, to dynamical imaging at kpc-scale resolution, and multi-line, multi-species studies of the ISM in early galaxies. Study of atomic fine structure line emission is also rapidly accelerating, with some tens of galaxies detected in [C II] $158\mu\text{m}$, and other species, at $z > 1$, including detection of the most distant quasar with a spectroscopic redshift ($z = 7.08$).

The results of these studies are extremely telling for models of galaxy formation,

providing the required complement to studies of the stars and star formation in early galaxies. One of the most exciting empirical result is the discovery that CSG have CO luminosities approaching those of SMGs and quasar hosts, but FIR luminosities close to an order of magnitude less. The higher space density of the CSG galaxies provides a rich hunting ground for molecular line studies of distant galaxies. Observations suggest that the gas fraction ($M_{\text{gas}}/M_{\text{stars}}$) in massive disk galaxies increases by an order of magnitude from $z \sim 0$ to $z \geq 1.5$. Hence, the epoch of peak cosmic star formation density corresponds to an epoch of gas-dominated disks.

For the rarer, hyper-starburst galaxies, the quasar hosts and powerful radio galaxies show the most extreme gas properties, in terms of gas excitation, star formation ‘efficiency’, and compact although complex, gas morphologies. These results indicate compact, hyper-starbursts coeval with Eddington-limited AGN accretion. Submm galaxies are a mixed bag of gas rich mergers and extended, gas rich disks in dense cosmic environments.

Current measurements suggest that the hyper-starbursts have a low CO luminosity to gas mass conversion factor, $\alpha \sim 0.8$, consistent with the extreme dense ISM conditions seen in nearby nuclear starbursts. The CSG are consistent with a Milky Way GMC value of $\alpha \sim 4$. There is increasing evidence that α increases with decreasing metallicity in galaxies, and in general, there may be a continuum of values of α , depending on ISM pressure, dynamics, and metallicity. The correlation between CO and FIR luminosity suggests two populations: starburst galaxies with rapid gas consumption timescales of a few $\times 10^7$ years, and main sequence galaxies with gas consumption timescales an order of magnitude longer.

The strong ISM gas cooling line from [C II] is proving to be a key tool in the study of the dynamics of the earliest galaxies. [C II] imaging of $z > 4$ galaxies has already revealed a ‘maximal starburst disk’ on sub-kpc scales, likely rotating disks on few to 10 kpc-scales, and possible tidal structures on even larger scales. ALMA has already demonstrated the ability to detect [C II] emission from LAEs and LBGs at high redshift.

We have made a first attempt at quantifying the dense gas history of the Universe, based on current observations. While admittedly gross, these measurements are consistent with modeling based on large scale cosmological simulations, and on empirical models based on assumed star formation laws.

7 Future directions

We re-emphasize that we stand at a cusp in knowledge, with the breath-taking promise of the ALMA and JVLA poised to revolutionize the study of the cool gas in early galaxies, and we have presented some of the early science results from these telescopes herein. Later in the decade, telescopes such as CCAT and NOEMA will also make important contributions.

We are no longer limited by numbers of high- z sources to study – there are thousands of CSG, quasars, and SMGs from cosmological deep fields. These populations have been delineated in terms of their space density, cosmic environment, and redshift distribution in remarkable detail. At this stage, we feel it is the high resolution imaging capabilities of ALMA and the JVLA that will be most incisive for unraveling the complex processes involved in early galaxy formation. Some of the key questions that need to be addressed include:

- For interpreting CO observations, the key uncertainty remains the conversion factor, especially in low metallicity systems where lack of dust shielding may dramatically reduce the CO content. We expect calibrating this relationship will follow the current path using multiple methods, including dynamics, radiative transfer modeling, and dust-to-gas modeling, leading to a concordance of estimates, and likely multi-parameter models involving eg. metallicity.
- Spatially resolved imaging (sub-kpc) of multiple CO transitions, as well as of the thermal dust continuum emission, is needed to study the relative distribution and excitation of the fuel for star formation with respect to regions of active star formation. Such imaging also allows for a study of star formation laws as a function of surface brightness, and not integrated quantities.
- Observations of high dipole moment molecules, and other complex molecules, will allow for detailed astrochemical modeling of the dense gas immediately involved in active star formation in distant galaxies.
- An inventory of fine structure lines is required to set the ISM gas cooling budget, AGN versus star formation indicators, and for metallicity determinations.
- We expect that studies of the [C II] $158\mu\text{m}$ line will play an important role in the determination of redshifts and dynamics of the first galaxies, well into cosmic reionization.

The new telescopes coming on-line open up the very real possibility of performing blind, deep field surveys for molecular gas, and atomic fine structure line emission, from distant galaxies. Over the next few years, we expect that the dense gas history of the Universe diagram will be fully populated, as the CO luminosity functions and conversion factors are quantified out to the highest redshifts. Coupled with the near-IR through X-ray studies of stars, star formation, and AGN, such pan-chromatic deep fields will provide a complete picture of the conversion of gas into stars over the history of the Cosmos.

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Acronyms

- AGN: Active galactic nucleus
- CMA: Cold mode accretion
- CMB: Cosmic microwave background
- CSG: Color-selected starforming galaxy (BzK-, BM/BX-selected)
- DGHU: Dense gas history of the universe
- FIR: Far-infrared
- FSL: (Atomic) fine structure line
- GMC: Giant Molecular Clouds
- ISM: Interstellar Medium
- LTE: Local thermodynamic equilibrium
- LVG: Large velocity gradient
- PDR: Photon dominated region (aka: Photodissociation region)
- SMBH: Supermassive black hole
- SMG: Submillimeter Galaxy
- QSO: Quasi-stellar object, or quasar
- XDR: X-ray dominated region

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Table 1: Fundamental parameters for frequently observed molecules and fine structure lines. Numbers for the atomic fine structure constants are taken from Stacey et al. (2011). Einstein A coefficients, rest frequencies and collision rates γ are taken from the Leiden Atomic and Molecular Database (Schöier et al. 2005). Column E.P. is the excitation potential of the upper level above ground. The critical density is the density at which the rate of the collisional depopulation of a quantum level equals the spontaneous radiative decay rate. We note that definition of the critical density used here is $n_{crit} = A\gamma$ (Sec. 2.3). This is not the proper definition which includes the summation of all collisional transitions to the lower level – such a treatment will lower the critical densities presented here. The critical densities also decrease if the lines are optically thick. For species occurring in neutral gas clouds, the collision partners are H and H₂ (assumed $T_{gas}=100$ K). For species occurring in ionized gas regions, the collision partners are electrons (marked with a $[\star]$ in the last column). For details see Stacey et al. 2011.

species	trans.	E.P. K	λ μm	ν GHz	Einstein A s^{-1}	n_{crit} cm^{-3}
[O I]	$^3P_1 \rightarrow ^3P_2$	228	63.18	4744.8	9.0×10^{-5}	4.7×10^5
	$^3P_0 \rightarrow ^3P_1$	329	145.53	2060.1	1.7×10^{-5}	9.4×10^4
[O III]	$^3P_2 \rightarrow ^3P_1$	440	51.82	5785.9	9.8×10^{-5}	$3.6 \times 10^3 [\star]$
	$^3P_1 \rightarrow ^3P_0$	163	88.36	3393.0	2.6×10^{-5}	510 $[\star]$
[C II]	$^3P_{3/2} \rightarrow ^3P_{1/2}$	91	157.74	1900.5	2.1×10^{-6}	2.8×10^3 50 $[\star]$
[N II]	$^3P_1 \rightarrow ^3P_2$	188	121.90	2459.4	7.5×10^{-6}	310 $[\star]$
	$^3P_1 \rightarrow ^3P_0$	70	205.18	1461.1	2.1×10^{-6}	48 $[\star]$
[C I]	$^3P_2 \rightarrow ^3P_1$	63	370.42	809.34	2.7×10^{-7}	1.2×10^3
	$^3P_1 \rightarrow ^3P_0$	24	609.14	492.16	7.9×10^{-8}	470
CO	J=1–0	5.5	2601	115.27	7.2×10^{-8}	2.1×10^3
	J=2–1	16.6	1300	230.54	6.9×10^{-7}	1.1×10^4
	J=3–2	33.2	867	345.80	2.5×10^{-6}	3.6×10^4
	J=4–3	55.3	650.3	461.04	6.1×10^{-6}	8.7×10^4
	J=5–4	83.0	520.2	576.27	1.2×10^{-5}	1.7×10^5
	J=6–5	116.2	433.6	691.47	2.1×10^{-5}	2.9×10^5
	J=7–6	154.9	371.7	806.65	3.4×10^{-5}	4.5×10^5
	J=8–7	199.1	325.2	921.80	5.1×10^{-5}	6.4×10^5
	J=9–8	248.9	289.1	1036.9	7.3×10^{-5}	8.7×10^5
	J=10–9	304.2	260.2	1152.0	1.0×10^{-4}	1.1×10^6
HCN	J=1–0	4.25	3383	88.63	2.4×10^{-05}	2.6×10^6
	J=2–1	12.76	1691	177.26	2.3×10^{-04}	1.8×10^7
	J=3–2	25.52	1128	265.89	8.4×10^{-04}	6.8×10^7
	J=4–3	42.53	845.7	354.51	2.1×10^{-03}	1.8×10^8
	J=5–4	63.80	676.5	443.12	4.1×10^{-03}	3.8×10^8
	J=6–5	89.32	563.8	531.72	7.2×10^{-03}	7.1×10^8
	J=7–6	119.09	483.3	620.30	1.2×10^{-02}	1.2×10^9
	J=8–7	153.11	422.9	708.88	1.7×10^{-02}	1.8×10^9
	J=9–8	191.38	375.9	797.43	2.5×10^{-02}	2.5×10^9
	J=10–9	233.90	338.4	885.97	3.4×10^{-02}	3.3×10^9

Table 2: Factors to calculate $L'_{\text{CO}(1-0)}$ from higher-J transitions up to $J = 5$. For the SMGs and QSOs average values are quoted based on all available literature estimates. For the CSG the ratio is taken from Dannerbauer et al. (2009) and Aravena et al. (2010); their LVG model 1. The values for the Milky Way and the centre of M82 are from Weiß et al. (2005b) ‘-’ indicates that no well-constrained value is available. We assume the same excitation as for the CSG for the LBGs, SFRGs. We adopt QSO excitation for the RGs and SMG excitation for the $24\mu\text{m}$ and ERO sources.

source	SMG	QSO	CSG	MW	M82
$L'_{\text{CO}(2-1)}/L'_{\text{CO}(1-0)}$	0.85	0.99	0.97	0.5	0.98
$L'_{\text{CO}(3-2)}/L'_{\text{CO}(1-0)}$	0.66	0.97	0.56	0.27	0.93
$L'_{\text{CO}(4-3)}/L'_{\text{CO}(1-0)}$	0.46	0.87	0.2	0.17	0.85
$L'_{\text{CO}(5-4)}/L'_{\text{CO}(1-0)}$	0.39	0.69	–	0.08	0.75

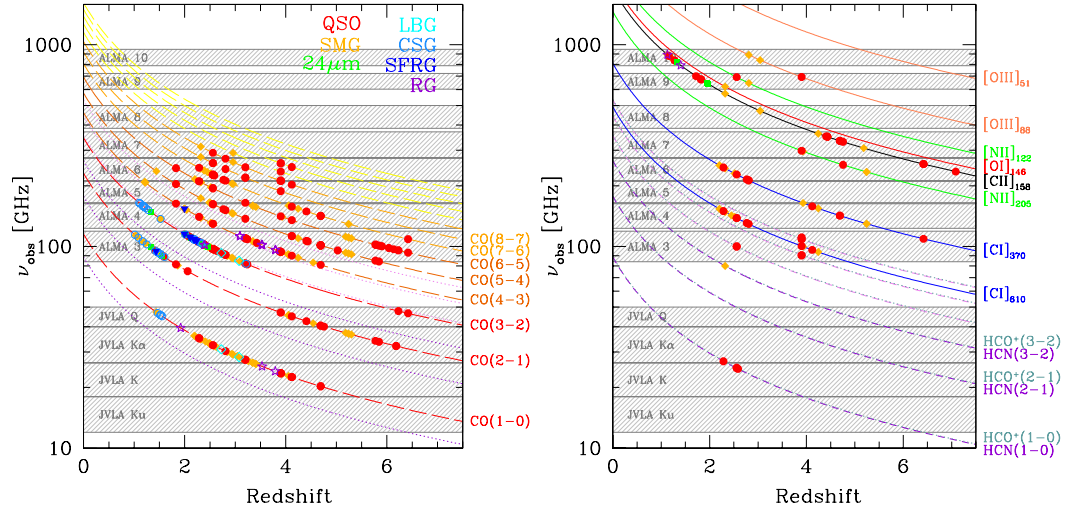


Figure 1: Redshifted frequencies ν_{obs} of CO transitions (left) and other key tracers of the starforming ISM (right) as a function of redshift z , following $\nu_{\text{obs}} = \nu_{\text{rest}}/(1+z)$. The shaded areas indicate the frequency bands covered by various telescopes. Highlighted are the ALMA frequency bands as well as the ‘high-frequency’ bands of the JVL A. The colored points indicate detection of all high redshift ($z > 1$) lines. The color of the points refer to the different source types, as explained in the left panel.

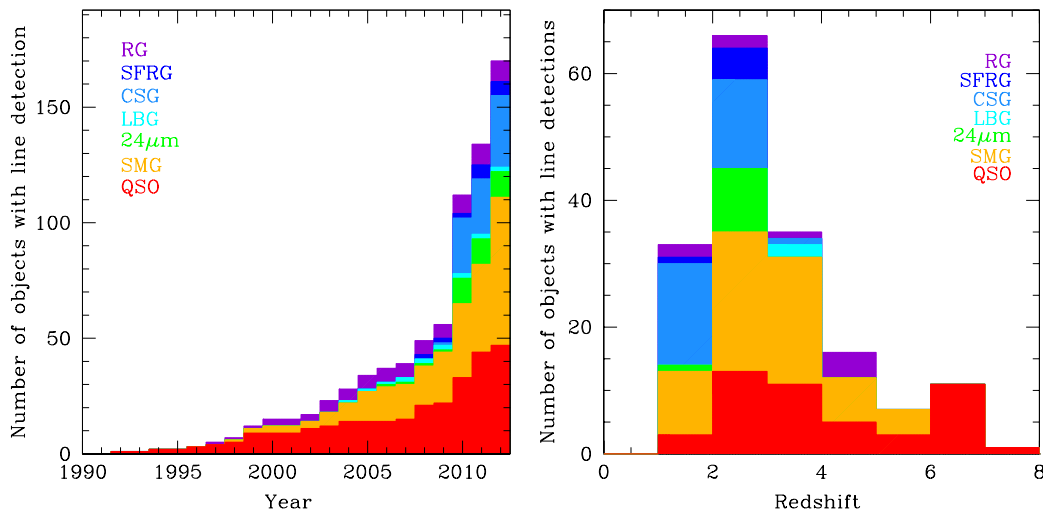


Figure 2: *Left*: Discovery history of high-redshift ($z > 1$) line detections. The cumulative number of detections is shown, and the different colors indicate the different galaxies populations. Historically, QSOs (Sec. 3.2), SMGs (Sec. 3.3) and radio galaxies (Sec. 3.4) have been the focus of most studies. In recent years, these have been complemented by observations of ‘main sequence’ starforming galaxies (CSG, Sec. 3.5). To date close to 200 galaxies have been detected in line emission at $z > 1$. *Right*: Redshift distribution of all sources for all $z > 1$ line detections. The highest redshift sources $z > 5$ detected are the QSOs, with a growing contribution from SMGs.

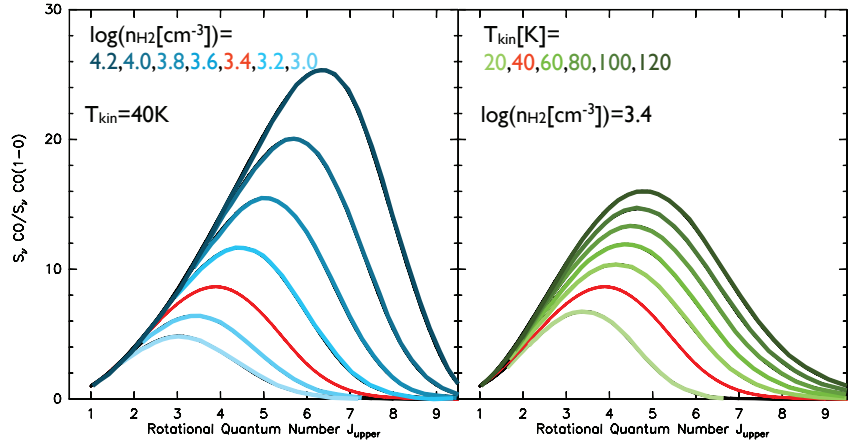


Figure 3: This figure illustrates how the measured CO emission ladder changes as a function of temperature and density (adopted from Weiß et al. (2007)). The left panel shows the effect of changing density at fixed temperature ($T_{kin} = 40$ K). The right panel shows the effect of varying kinetic temperatures for a fixed density ($\log(n(\text{H}_2)) = 3.4$). Both panels have been normalized to the CO(1–0) transition. High CO excitation is achieved through a combination of high kinetic temperature and high density. Given the typically sparsely sampled CO excitation and large error bars in high redshift observations, this degeneracy can not be easily broken observationally. Additional information, such as independent estimates of the kinetic temperature through [C I] or dust measurements can help to break this degeneracy. Note that increased temperatures lead to a broader CO emission ladder, as more and more high- J levels are populated following the Boltzmann distribution.

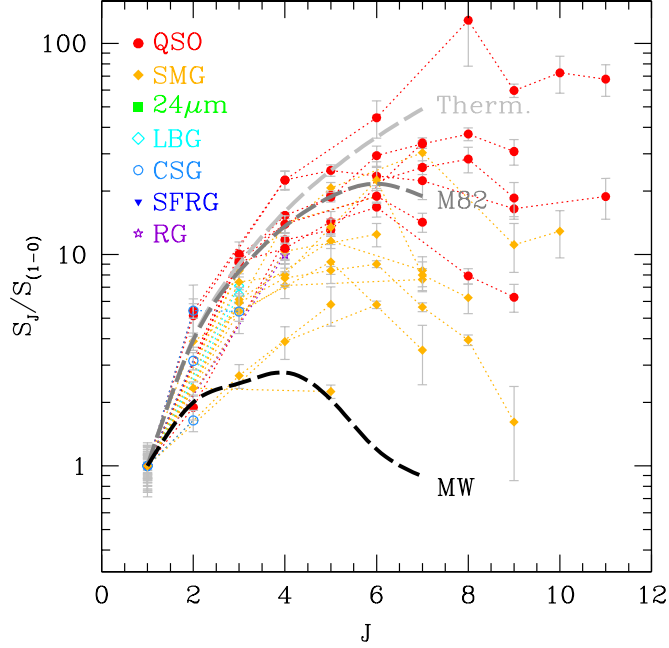


Figure 4: CO emission ladder of all sources where the CO(1–0) line has been measured. The CO line flux is shown as a function of rotational quantum number and the colors indicate the different source types. Measurements for individual sources are connected by a dashed line. The line fluxes have been normalized to the CO(1–0) line. The QSOs are the most excited systems found, with an average peak of the CO ladder at around $J \sim 6$. This is consistent with the high star formation rate and compact emission regions in their host galaxies. The SMGs are slightly less excited on average, and their CO emission ladder peak around $J \sim 5$. The dashed thick lines indicate template CO emission ladders for the Milky Way (black) and M82 (grey). The dashed dark grey line shows constant brightness temperature on the Rayleigh–Jeans scale, i.e. $S \sim \nu^2$ (note that this approximation is not valid for high J).

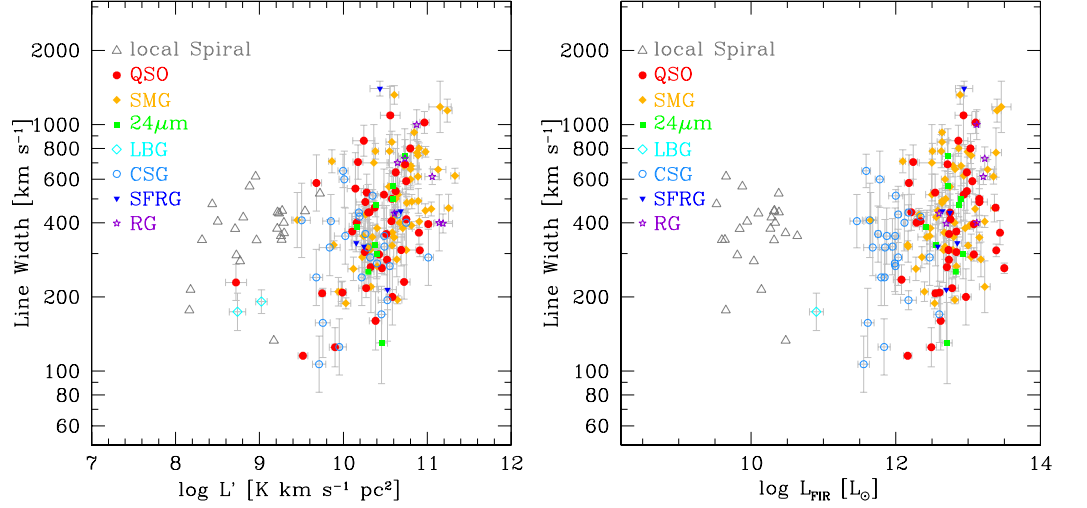


Figure 5: The CO line width (FWHM) versus CO line luminosity (left) and versus the FIR luminosity (right panel). Note that the CSG show systematically lower line widths for a given CO line luminosity than the hyper-starburst quasar hosts and SMGs (we have corrected the $v_{\text{rot,max}}$ values given in Tacconi et al. (2010) to give accurate FWHM values). The grey datapoints show local spiral galaxies (with stellar masses $>10^{10} M_{\odot}$ from the HERACLES/THINGS surveys (Leroy et al. 2009, Walter et al. 2008). The local FWHM values are corrected for inclination, the high- z values are not (in the absence of unknown inclinations).

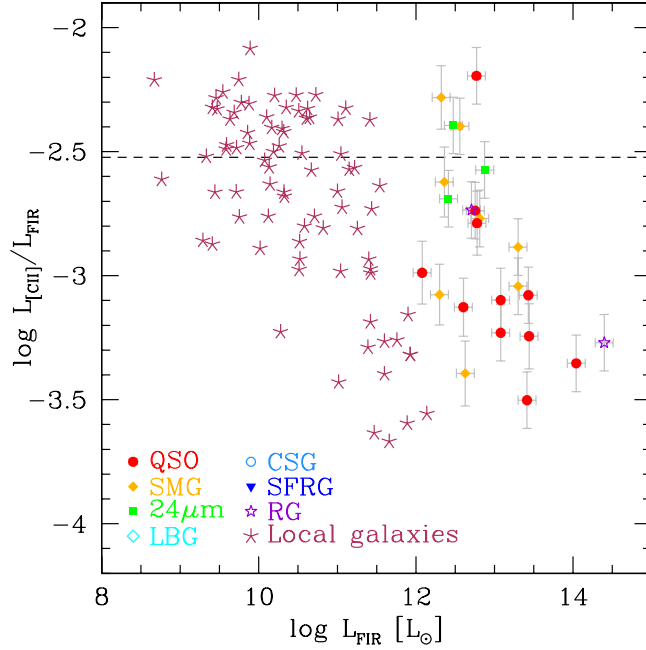


Figure 6: The ratio $L_{\text{CII}}/L_{\text{FIR}}$ as a function of L_{FIR} (data from Table 3). The dashed horizontal line indicates a value of $3 \times 10^{-3} \sim$ Milky Way value. The L_{FIR} measurements are corrected for lensing (where known).

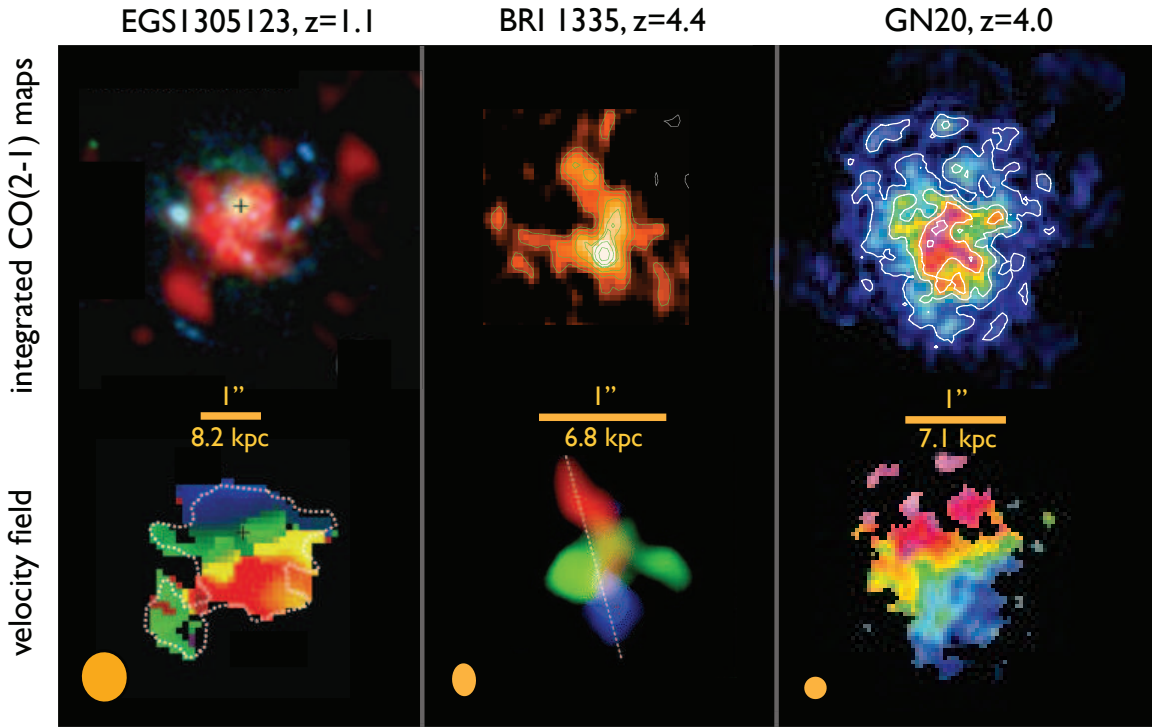


Figure 7: Best examples of resolved molecular line emission at high redshift from which gas kinematics can be derived. These are (from left to right): The CSG EGS 1305123 (Tacconi et al. 2010), the QSO BRI 1335 (Riechers et al. 2008b) and the SMG GN 20 (Hodge et al. 2012). The top row shows the integrated CO(2–1) maps of the targets. The bottom row shows the velocity fields of the targets; here the color indicates the velocity at which gas is moving a given position on the sky. The velocity scale ranges from (blue to red): -65 to $+100$ km s^{-1} , -154 to $+154$ km s^{-1} , -300 to 300 km s^{-1} , respectively. The beamsizes are given in the bottom left of each galaxy; the bar indicates $1''$ on the sky (size in kpc is also given at the respective redshift).

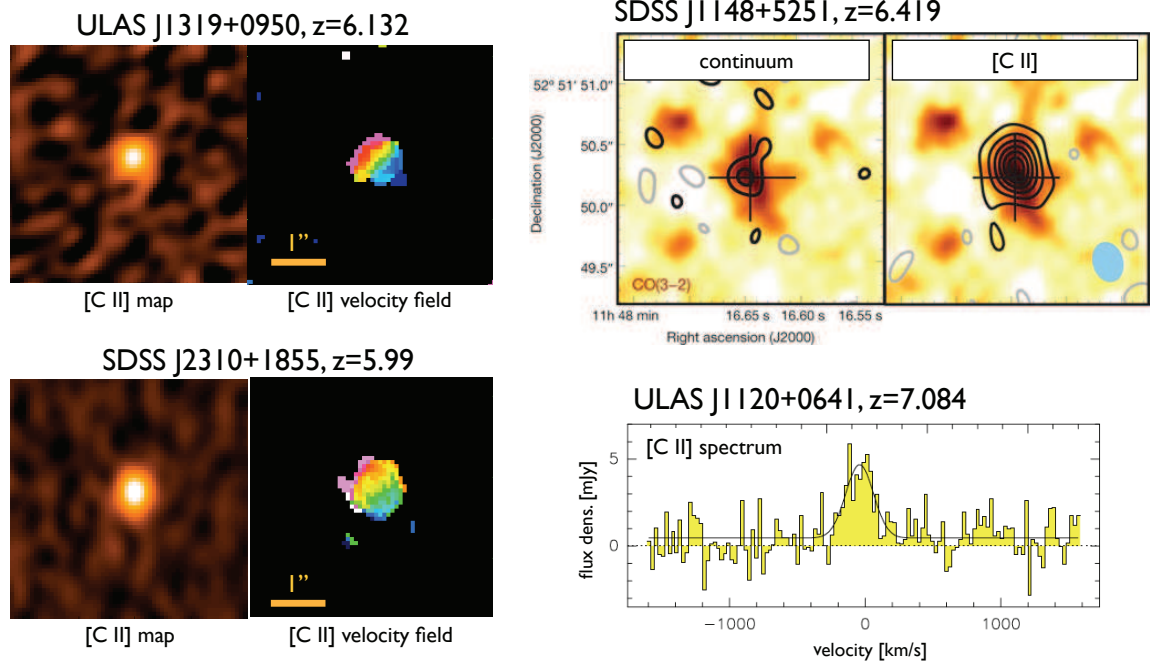


Figure 8: Results from observations of $[\text{C II}]$ $158\mu\text{m}$ emission from $z \geq 6$ quasars. Left shows ALMA images of the total intensity plus the intensity weighted mean gas velocity for two SDSS quasars (Wang et al. 2013). The velocity range in the top figure is $\pm 300 \text{ km s}^{-1}$ (red to blue), while that in the bottom frame is $\pm 100 \text{ km s}^{-1}$. Note the clear velocity gradients, consistent with gas rotation on scales ~ 7 kpc ($\sim 1''$ at $z \sim 6$). The upper right shows the VLA CO images of the $z = 6.42$ SDSS quasar, J1148+5251, as color scale in both frames. The contours on the left show the 250 GHz continuum emission, and those on the right show the $[\text{C II}]$ $158\mu\text{m}$ emission imaged by the PdBI (from Walter et al. 2009a). The lower right shows the PdBI $[\text{C II}]$ $158\mu\text{m}$ spectrum of the most distant spectroscopic redshift quasar known, a quasar at $z = 7.08$ (Venemans et al. 2012).

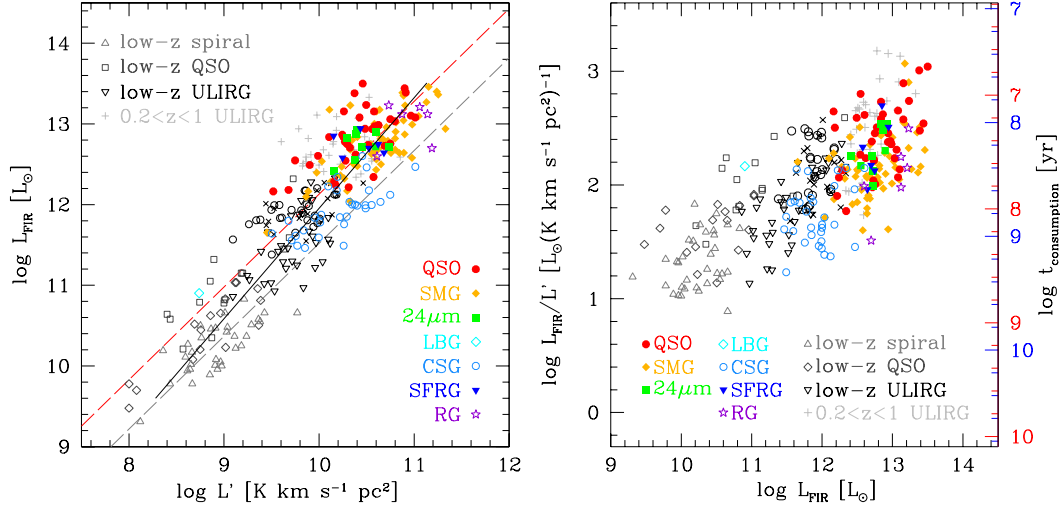


Figure 9: *Left:* L'_{CO} as a function of L_{FIR} for all systems detected at $z > 1$ (colored points). L'_{CO} was calculated using the lowest available J-measurement and assuming the excitation correction tabulated in Tab. 2 (see table caption for details on different source populations). The grey symbols represent $z < 1$ measurements: the $0.2 < z < 1$ ULIRG sample by Combes et al. 2011 and 2012b (crosses), low- z quasars from the Hamburg-ESO QSO survey (diamonds, Bertram et al. 2007), PG quasars (squares, Evans et al. 2001, Evans 2006, Scoville et al. 2003), nearby spiral galaxies (upward triangles), low- z spirals, starburst galaxies, and ULIRGs (downward and upward triangles, Gao& Solomon 2004a,b), the $z < 0.2$ IR QSO sample by Xia et al. (2012) and $0.04 < z < 0.11$ ULIRG sample by Chung et al. (2009, open circles). The full line is a fit to all data points which gives a slope of 1.35 ± 0.04 . The dashed lines indicate the best fits for the main sequence galaxies (grey dashed) and starburst galaxies (red dashed) derived by Genzel et al. (2010) and Daddi et al. (2010). *Right:* The right hand panel shows the logarithmic ratio $L_{\text{FIR}}/L'_{\text{CO}}$ as a function of L_{FIR} . $L_{\text{FIR}}/L'_{\text{CO}}$ is a measure for the star formation efficiency in an object, and under the assumption of a conversion factor is the inverse of the consumption time $\tau_{\text{consumption}}$. The consumption time is plotted on the right hand side of the panels for two different values of α , Galactic (red labels) and ULIRG (blue labels). The consumption time for nearby galaxies and the CSG are ~ 1 Gyr, assuming a Galactic α . The consumption times for the most actively star forming systems are only a few $\times 10^7$ yr under the typical assumption of a ULIRG α .

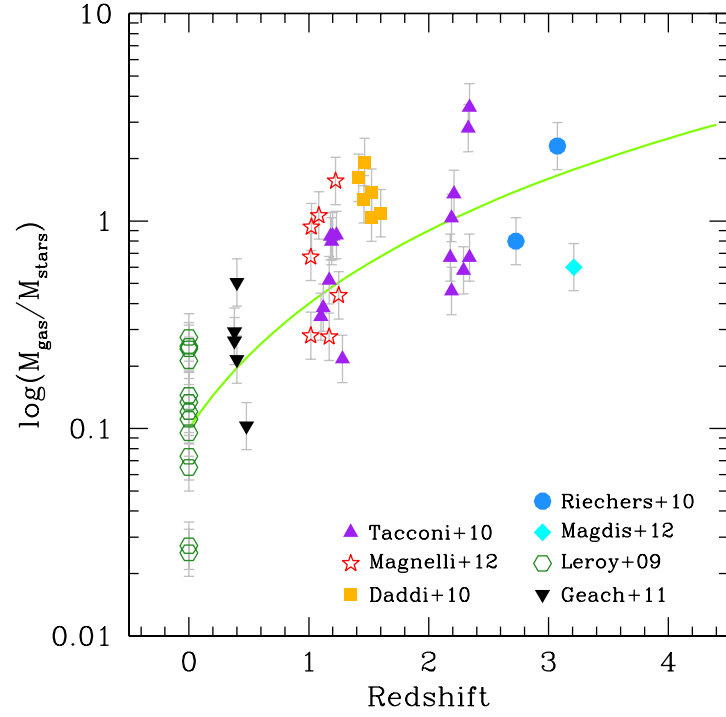


Figure 10: The ratio of gas mass to stellar mass ($M_{\text{gas}}/M_{\text{stars}}$), for various galaxy samples. The green circles are from the $z=0$ HERACLES nearby galaxy sample (Leroy et al. 2009) where we only include galaxies with stellar masses $> 10^{10} M_{\odot}$, to be consistent with the high- z samples plotted. All the points plotted assume $\alpha \sim 4$. The green curve follows $M_{\text{gas}}/M_{\text{stars}} = 0.1 \times (1+z)^2$ (e.g. Geach et al. 2011).

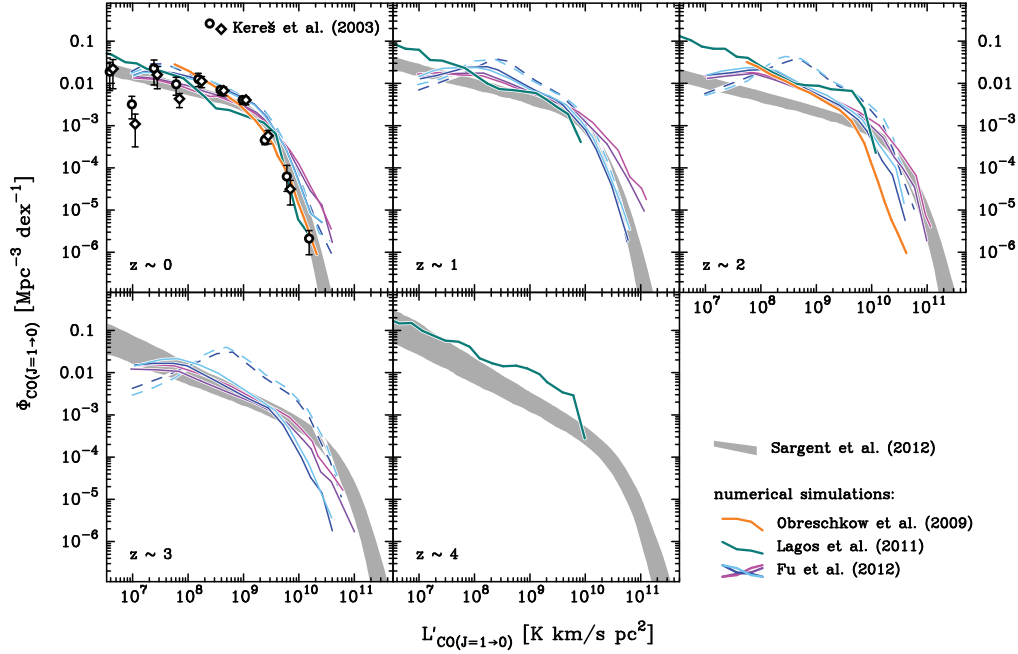


Figure 11: Models for the evolution of the CO luminosity function based on semi-analytical cosmological models plus ‘recipes’ to relate gas mass to CO luminosity (colored lines). The grey shading is from Sargent et al. (2013) and shows the indirectly inferred redshift evolution of the CO(1–0) luminosity function (grey shading) based on (1) the evolution of the stellar mass function of star-forming galaxies, (2) the redshift evolution of the specific SFR of main-sequence galaxies, (3) the distribution of main-sequence and star-bursting galaxies in the SFR- M_* -plane (Sargent et al. 2012), (4) distinct prescriptions of the star formation efficiency of main-sequence and star-bursting galaxies, and (5) a metallicity-dependent conversion factor α_{CO} . The CO luminosity function includes contributions both from ‘main-sequence’ and starbursts, where the latter is characterised by a more than 10-fold increase of the star-formation efficiency. In the upper left panel the observational constraints on the local CO LF reported in Kereš et al. (2003) are also shown (see Sargent et al. 2013 for details).

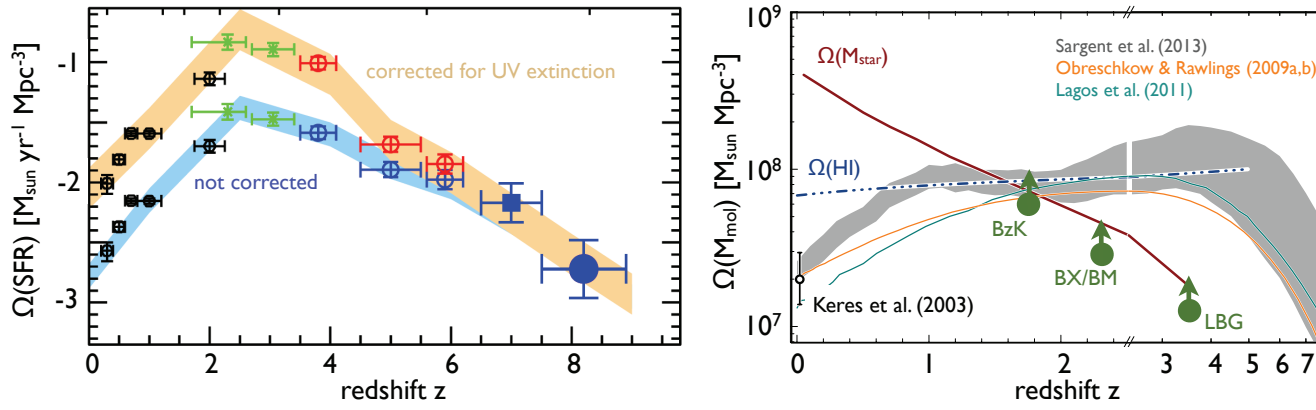


Figure 12: *Left:* Representation of the evolution of the cosmic star formation rate density (adopted from the compilation shown in Bouwens et al. 2010). *Right:* The evolution of the cosmic cool gas mass density (from Sargent et al. 2013), including predictions from semi-analytical cosmological models (Obreschkow & Rawlings 2009a,b, Lagos et al. 2011) as well as the models by Sargent et al. (2013). The latter shows the evolution inferred from the integration of the indirectly inferred molecular gas mass functions underlying the CO luminosity distributions of Fig. 11. Also included are some admittedly extremely rough limits based on what is known about known galaxy populations at $z > 1$. (see text for details). These points are shown to illustrate the potential impact of molecular deep field (‘blind’) surveys.