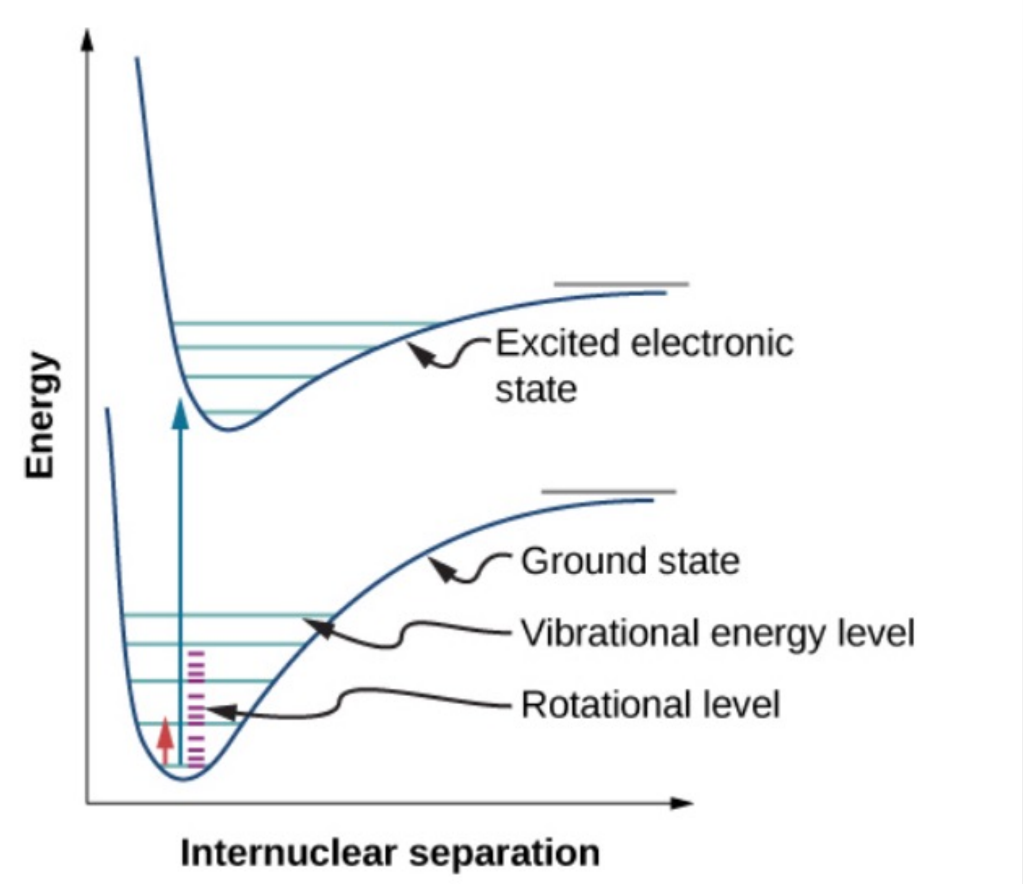
Linda Tacconi, Reinhard Genzel &
Amiel Sternberg
2020, ARA&A, 58, 157

The evolution of the star-forming interstellar medium across cosmic time.

Resources/other reviews:
Carilli & Walter (2013) - older ARA&A review of the high z ISM
Solomon & vanden Bout (2005) – even older ARA&A review of the high z ISM
Bolatto, Wolfire & Leroy (2013) – ARA&A review of α_{CO}

Observing the molecular medium – a recap



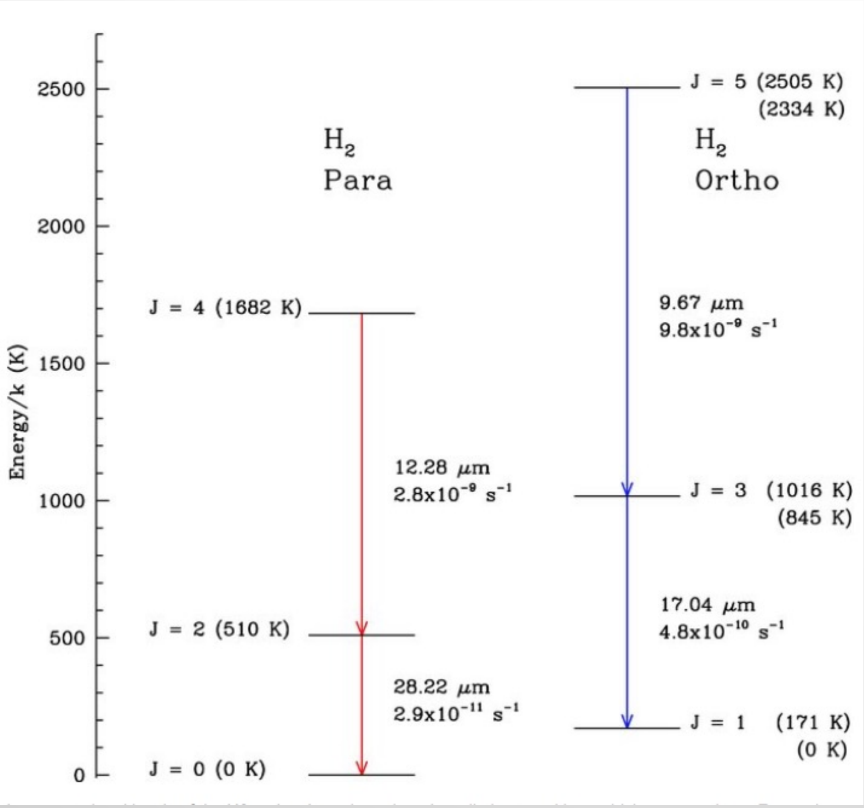
Molecules not only have electronic, but also rotational and vibrational transitions.

- Electronic transitions in UV.
- Vibrational transitions in the mid-IR.
- Rotational transitions in the mm/radio

Of these, the rotational transitions are those most readily accessible from the ground (and brightest).

Problems with using H_2

- No dipole moment – rotational dipole transitions are forbidden.

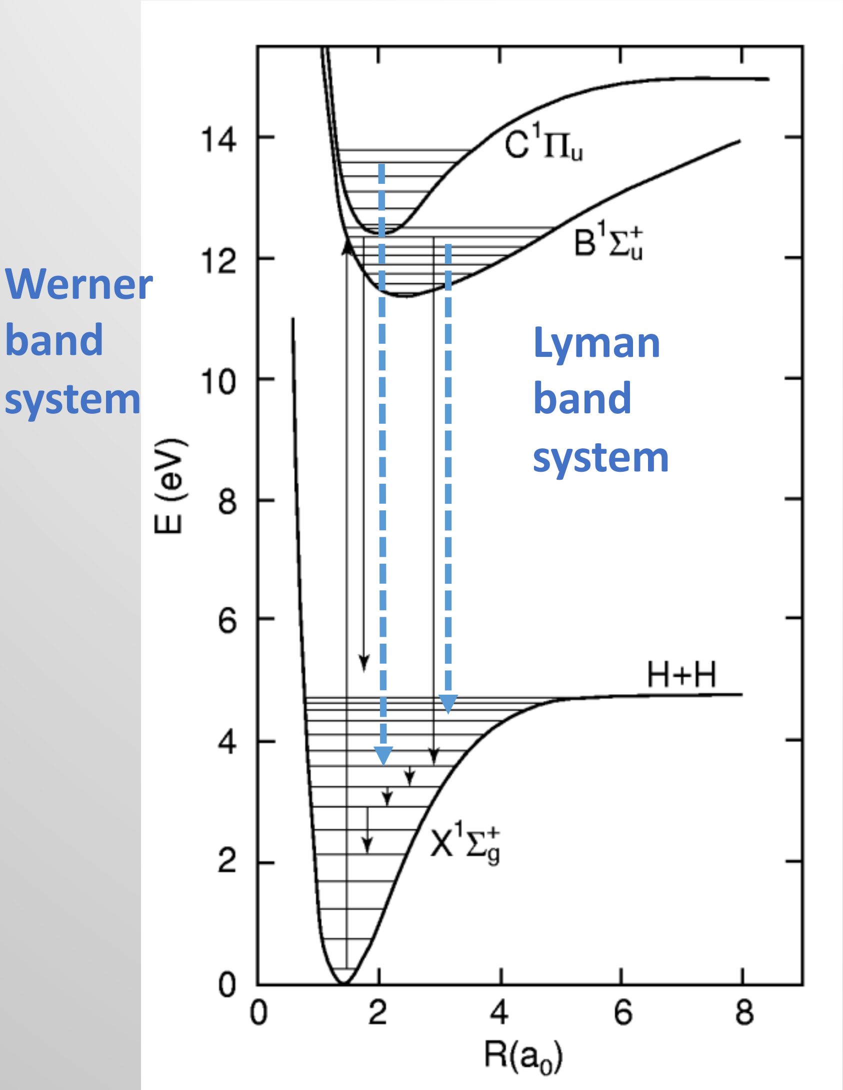


- Rotational quadrupole transitions (ΔJ = +- 2) are allowed but …
- the lowest energy transition is very weak due to long spontaneous decay time (~100 years).
- Inconvenient wavelength (28 microns) in far-IR
- Requires excitation temperature of 510K (most molecular clouds are not this warm).

- Lowest vibrational state at 2.2 microns is even harder to excite, E/k ~ 6500 K.

At high z H_2 can be observed in absorption

(not covered in this review – included here for interest)



Electronic states are labelled as Σ, π, … equivalent to s, p … in atomic spectroscopy.

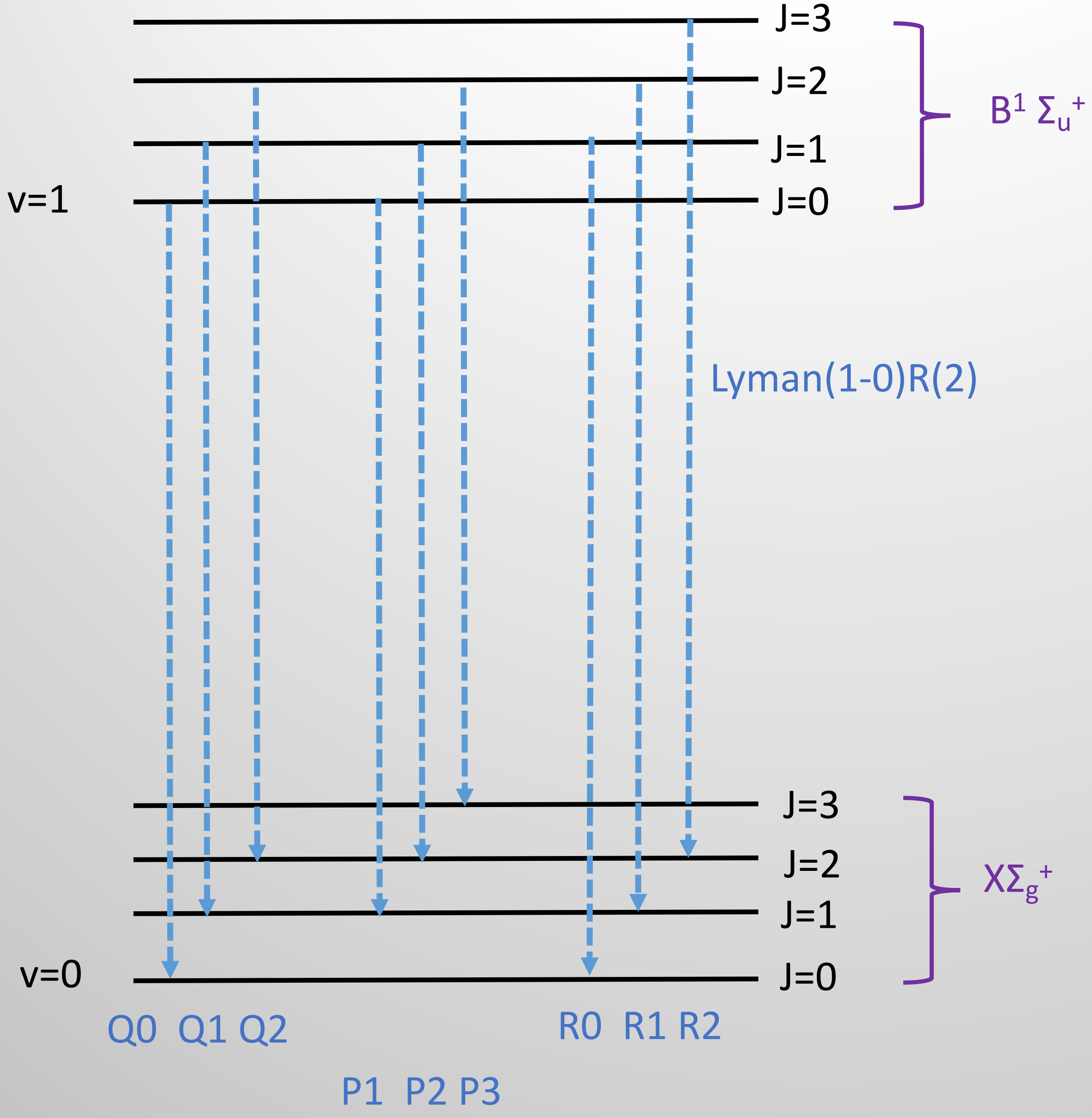
Transitions between one electronic band system and another labelled, e.g. Lyman (any transitions between $B^1\ \Sigma_u^+$ and $X\Sigma_g^+$) and Werner (any transitions between $C\ \pi_u$ and $X\Sigma_g^+$).

Specific lines follow similar convention as for ro-vib lines:

$(v_{up} - v_{low})$ P/Q/R (J_{low})

P branch is for ΔJ = +1
Q branch is for ΔJ = 0
R branch is for ΔJ = -1

Example – Lyman Band



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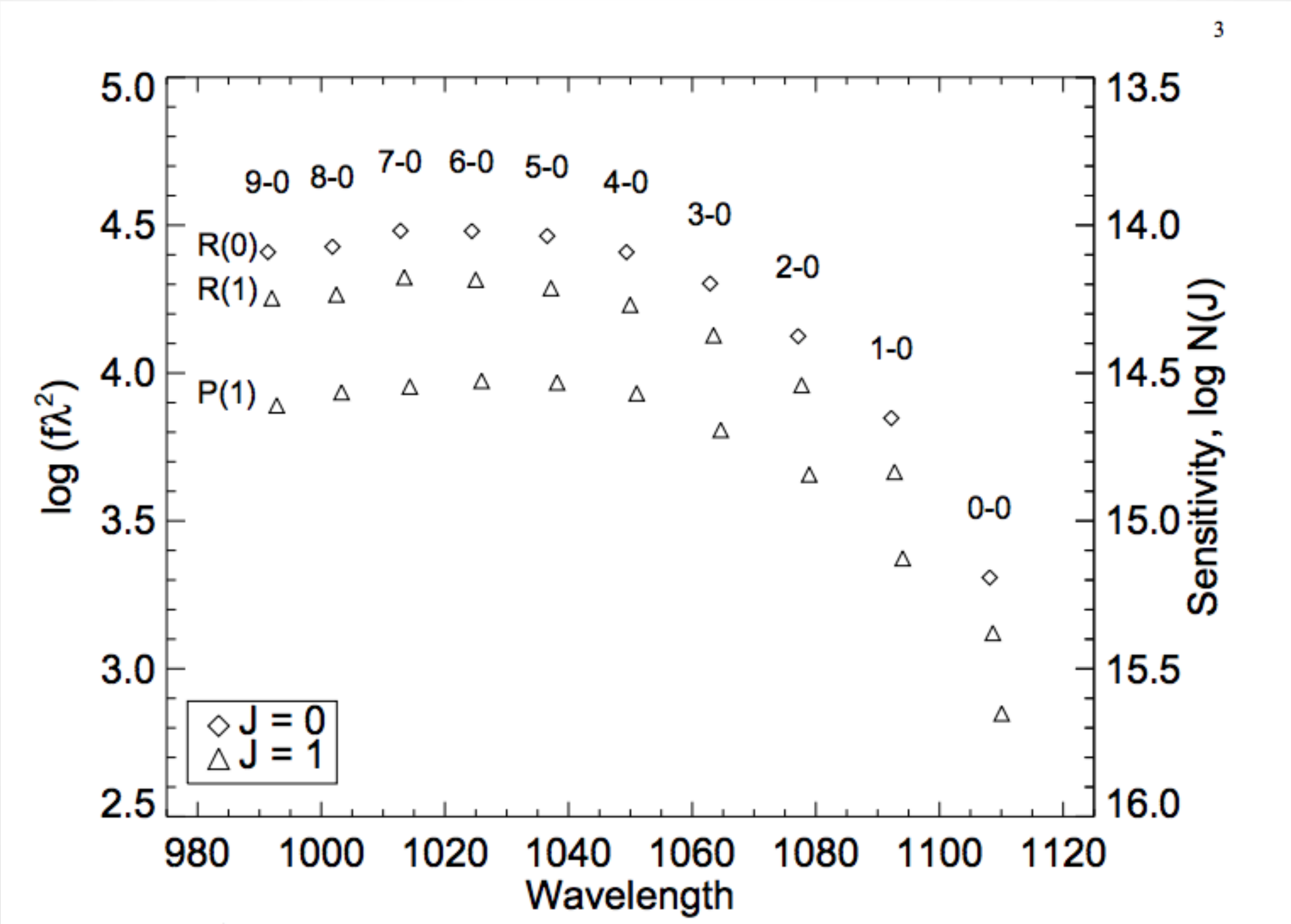
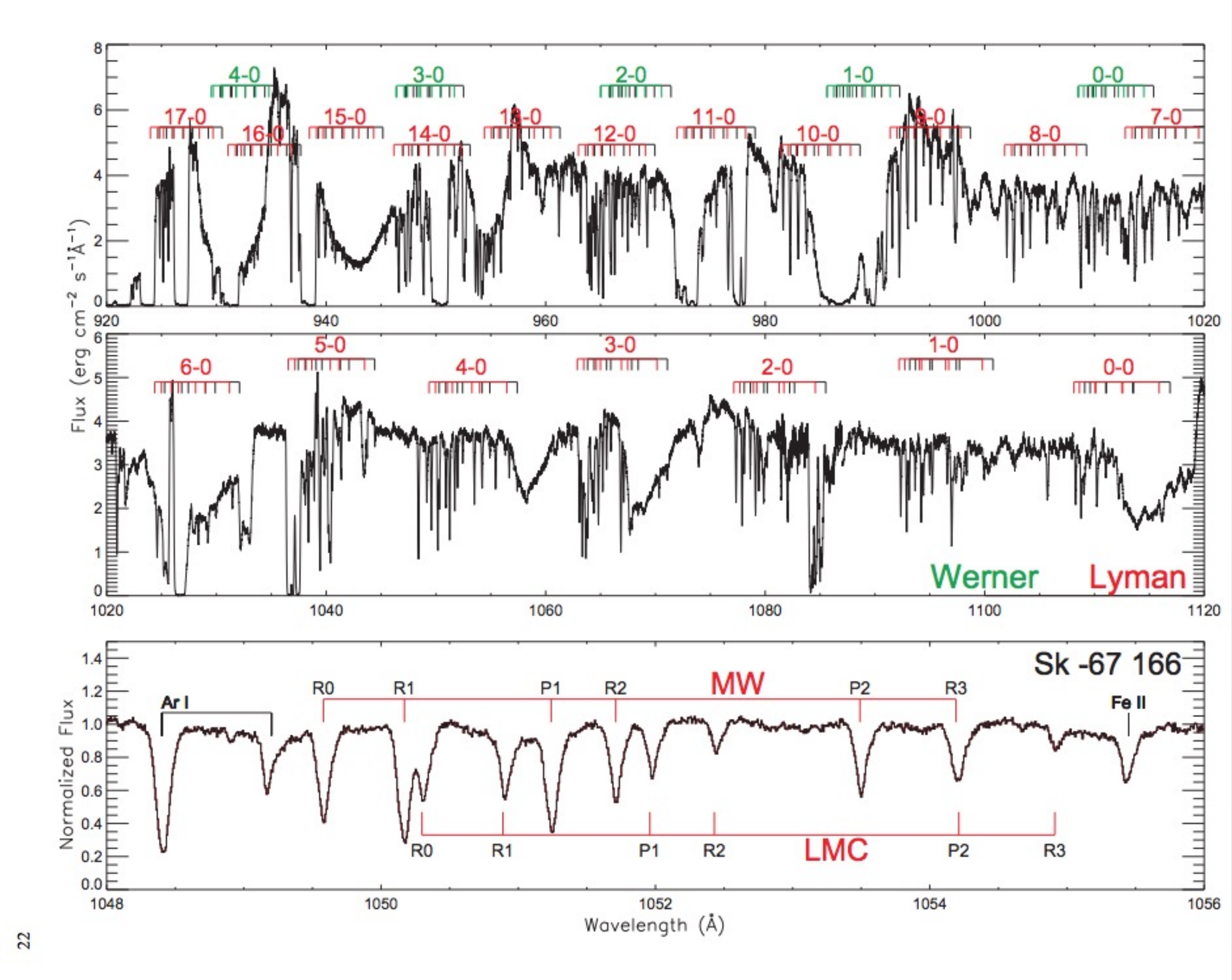


Tumlinson et al. (2002)

Rest frame UV shifted into the optical at z>2 (or observe at low z with UV telescope)

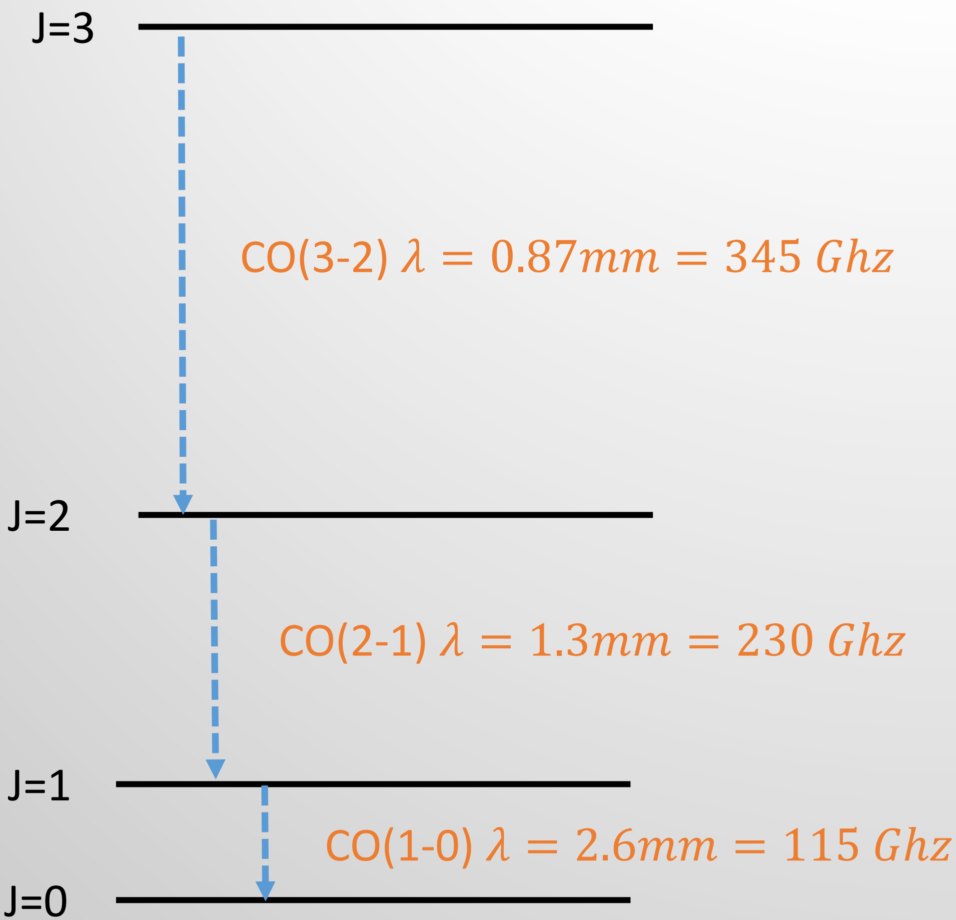
Study in absorption using background stars (local) or QSOs (high z)



Tumlinson et al. (2002)

Complex spectra – require high resolution spectroscopy (usually echelle)

CO as an alternative to H_2



J=3

CO(3-2) $\lambda = 0.87mm = 345\ Ghz$

J=2

CO(2-1) $\lambda = 1.3mm = 230\ Ghz$

J=1

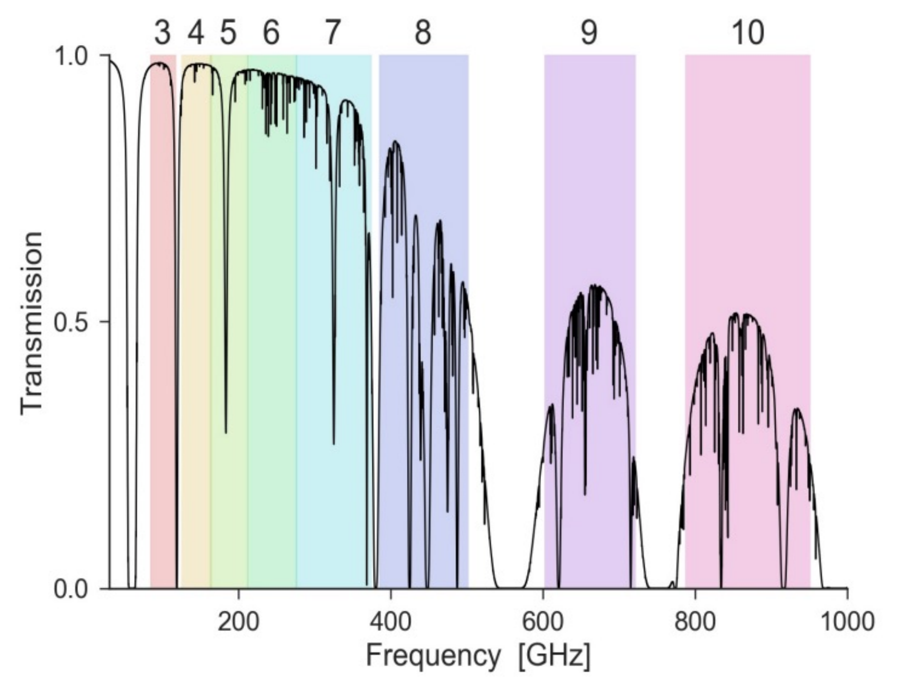
CO(1-0) $\lambda = 2.6mm = 115\ Ghz$

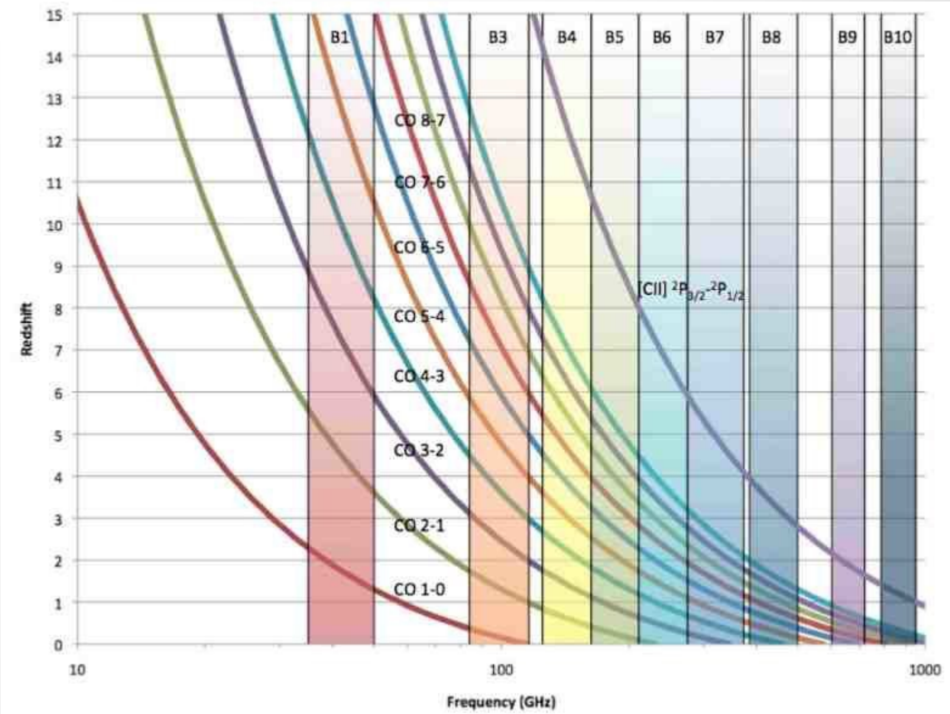
J=0

Benefits of CO

- Has a permanent dipole moment (rotational dipole transitions allowed)
- Lowest energy level in a convenient atmospheric window.
- Lowest energy level corresponds to E/k ~ 5K (easily excited)
- Low critical density of ~ 2000 cm^{-3}

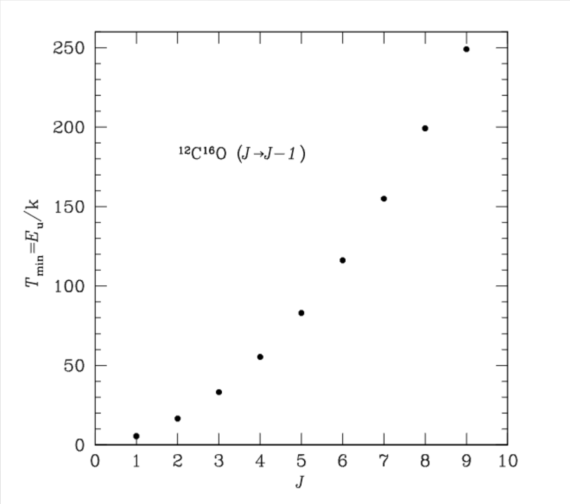
Atmospheric transmission and ALMA bands (Band 1 & 2 in development)





High z surveys tend to use CO(2-1) or CO(3-2), still at reasonably low excitation temperatures:

$$\Delta E = \frac{h^2 J(J+1)}{4\,\pi^2 I}$$



Measuring the molecular mass – a recap

The CO line luminosity is usually seen expressed in one of two ways:

$$L_{CO} = 1.04 \times 10^{-3}\, S_{CO}\; \nu_{obs}\, D_L^2 \qquad \text{in units of } L_\odot$$

Where S_{CO} is the velocity integrated line flux in Jy km/s, D_L is the luminosity distance in Mpc and $\nu_{obs} = \nu_{rest}/(1+z)$ is the observed frequency in GHz.

Perhaps more commonly, the line luminosity is often written as a product of the source brightness (radio astronomers like to use temperature units for this) per area:

$$L'_{CO} = 3.25 \times 10^{7}\, S_{CO}\; \nu_{obs}^{-2}\, D_L^2\, (1+z)^3 \qquad \text{in units of K km/s pc}^{-2}$$

See Solomon & vanden Bout (2005) for more details

Measuring the molecular mass – a recap

Next we need to convert the CO line luminosity to an H_2 mass by using a “conversion factor” that is expressed in one of two ways, with conversion factors of different units and assigned either α_{CO} or X_{CO} to distinguish them.

1). Most commonly we want the total mass of molecular gas so use

$M(H_2) = \alpha_{CO}\ L'_{CO}$

Where α_{CO} has units of $M_\odot$ (K km/s $pc^{-2})^{-1}$ and $M(H_2)$ has units of $M_\odot$. “Galactic” value of $\alpha_{CO} = 4.3\ M_\odot$ (K km/s $pc^{-2})^{-1}$ (accounts for 36% correction for He and metals; otherwise $\alpha_{CO} = 3.2\ M_\odot$ (K km/s $pc^{-2})^{-1}$).

2) Alternatively, for column densities we can use

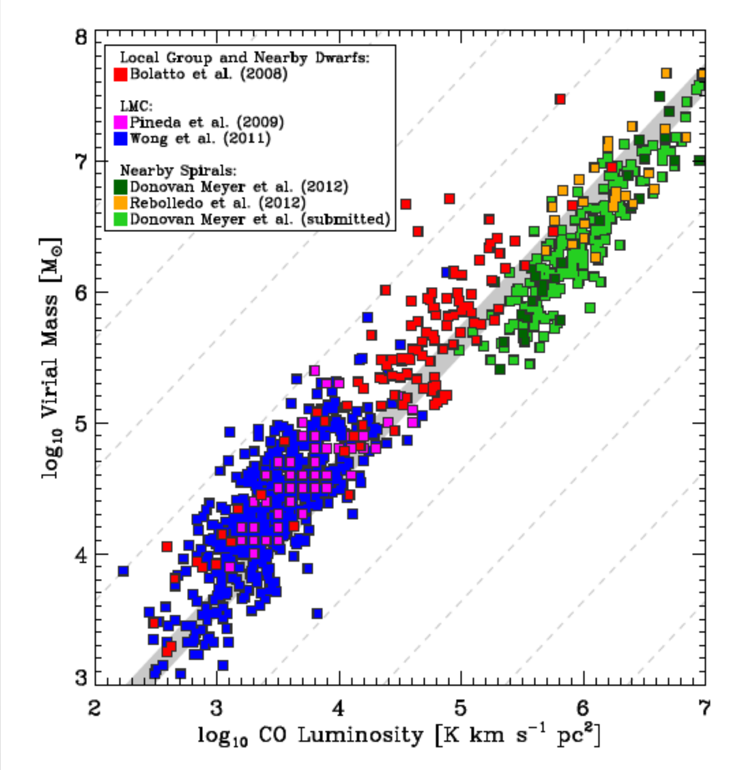
$N(H_2) = X_{CO}\ I_{CO}$

Where I_{CO} is the integrated intensity in units of K km/s (compared with a the L'_{CO} luminosity that has units of K km/s pc^{-2}), X_{CO} has units of (K km/s$)^{-1}cm^{-2}$ and $N(H_2)$ has units of cm^{-2}. “Galactic” value of $X_{CO} = 2 \times 10^{20}$ (K km/s$)^{-1}cm^{-2}$.

Measuring the CO-to-H_2 conversion factor

Fundamentally this requires measuring L_{CO} and comparing to an independent estimate of H_2 mass. Most of these methods only tractable at very low z.

- Virial masses of molecular cloud determined from measurements of resolved GMCs, obtained from measurements of size and velocity dispersion.



Dashed lines show values of constant α_{CO}

Bolatto et al. (2013)

Considerable variation amongst nearby galaxies (despite the commonly used approach of a constant conversion factor).

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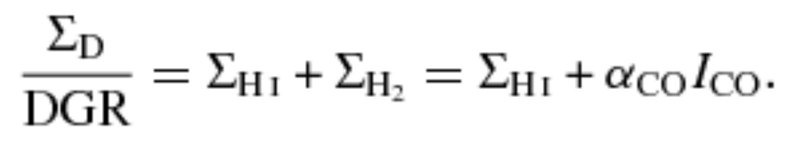
- Virial masses of molecular cloud determined from measurements of resolved GMCs, obtained from measurements of size and velocity dispersion.

- Extinction maps. We have previously seen that A_V tracks total N_H:

$$N_H = N(HI) + 2N(H_2) \sim 2 \times 10^{21} A_V$$

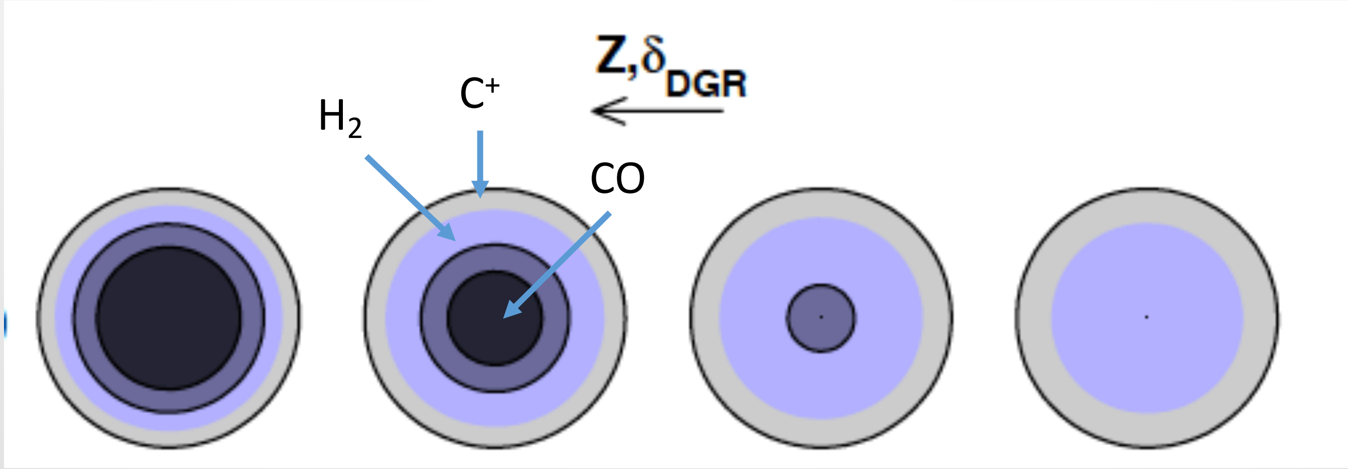
- Emission from dust then assume a dust-to-gas ratio (more on this later). Determine dust-to-gas ratio (DGR) in regions dominated by HI.



$$\frac{\Sigma_{\mathrm{D}}}{\mathrm{DGR}} = \Sigma_{\mathrm{H\,I}} + \Sigma_{\mathrm{H_2}} = \Sigma_{\mathrm{H\,I}} + \alpha_{\mathrm{CO}} I_{\mathrm{CO}}.$$

See Bolatto et al. (2013) for more details

Conversion factor headaches – low metallicity



Bolatto et al. (2013)

High metallicity

Low metallicity

At low metallicity there is less C and O. However, CO emission is optically thick so its emission depends (to first order) on the surface area and velocity width (not on its actual abundance). The ratio of CO/H_2 therefore depends on relative sizes of these regions.

At low metallicity the decrease in dust shielding means that dissociating radiation penetrates further into the cloud and destroys CO (H_2 is self shielded).

This affects 1) high z galaxies (more metal-poor at fixed M*) and 2) local low mass galaxies (mass-metallicity relation).

Jargon alert: Optically thin/thick

Recall the definition of optical depth from an earlier lecture:

The optical depth (**τ**) is related to the column density (N) of intervening material and its absorption cross section (**σ**):

$$\tau(\nu) = \int_0^{+\infty} n\sigma(\nu)\, ds = N\sigma(\nu),$$

Written as a function of the measured flux compared to the initial flux: $F/F_0 = e^{-\tau}$

Optical depth can also be thought of as the number of mean free paths. Typically we therefore only see photons into an emitting region to $\tau \sim 1$.

- If $\tau \ll 1$ we say that the medium is optically thin -> all the photons get out
- If $\tau \gg 1$ we say the medium is optically thick -> most photons do not escape and we only see the "skin" of the cloud
- Self-shielding occurs when the gas is optically thick so absorbs dissociating photons

An Aside

But if CO is optically thick, why is it used as a tracer of total mass?

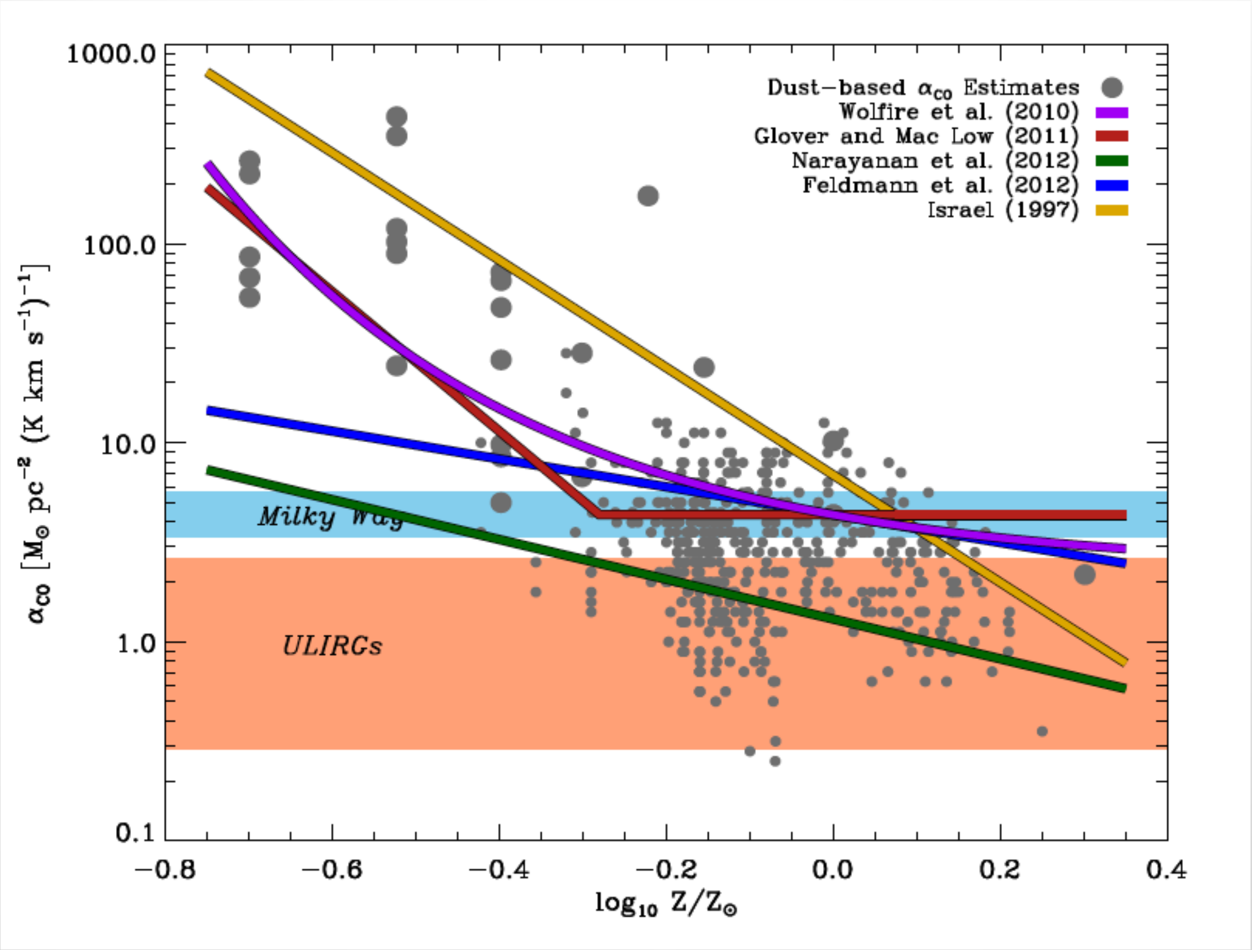
Assume that:

- GMCs are virialized (velocity width traces mass)
- Observed emission is the superposition of some number of virialized clouds

Total mass information is therefore contained in line width.

See Section 2 of Bolatto et al. (2013) for more information and a detailed derivation.

Conversion factor headaches – low metallicity



Bolatto et al. (2013)

Various α_{CO} prescriptions available that include a metallicity dependence.
E.g. Sun et al. (2020)

$$\alpha_{CO} = 4.35\, Z'^{-1.6}\ M_\odot\, \mathrm{pc}^{-2}\, (\mathrm{K\,km\,s^{-1}})^{-1}$$

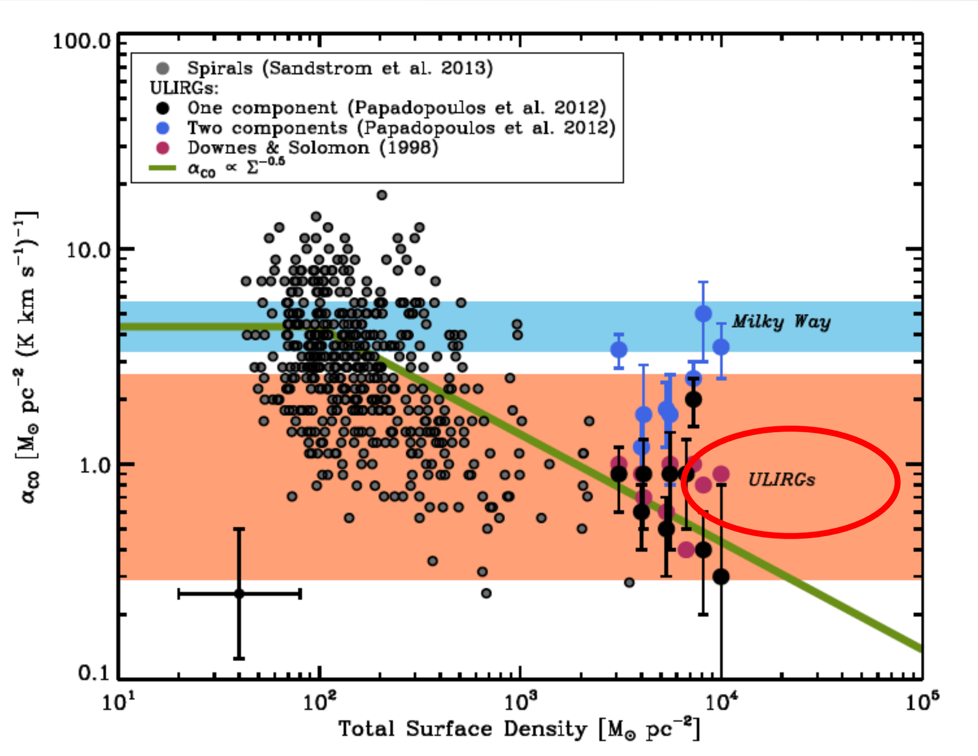
Conversion factor headaches – ISM conditions

From theoretical expectations (see Section 2 of Bolatto et al. 2013):

$$\alpha_{\rm CO} \equiv \frac{M_{mol}}{L_{\rm CO}} \approx 6.1\, L_{\rm CO}{}^{-0.2}\, T_B^{-0.8}\, \Sigma_{\rm GMC}{}^{0.6}.$$

Jargon alert: ULIRG

In starburst galaxies we expect higher temperatures and densities; at some level these changes cancel out, but starbursts are still known to have lower conversion factors. Since high z galaxies have high SFRs, measuring starburst alpha is relevant.

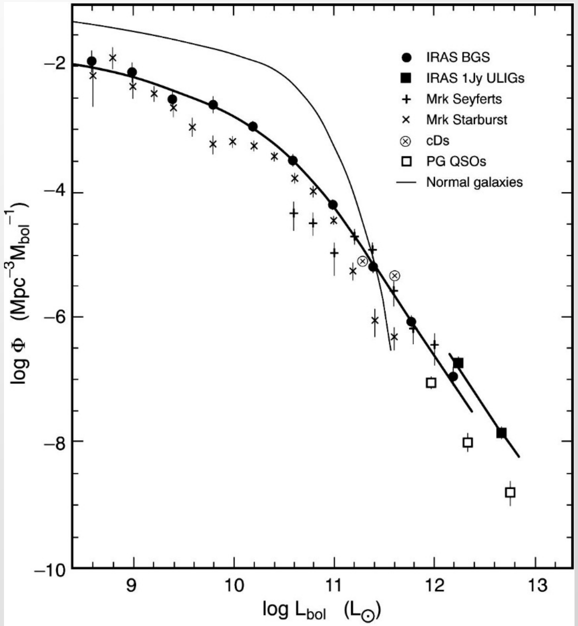


Bolatto et al. (2013)

Jargon alert: (U)LIRG = (Ultra) Luminous Infra-Red Galaxy

Galaxies with high IR luminosities discovered after the launch of the IRAS satellite in 1983.

A ULIRG has $L_{IR} > 10^{12}\ L_\odot$
A LIRG has $L_{IR} > 10^{11}\ L_\odot$

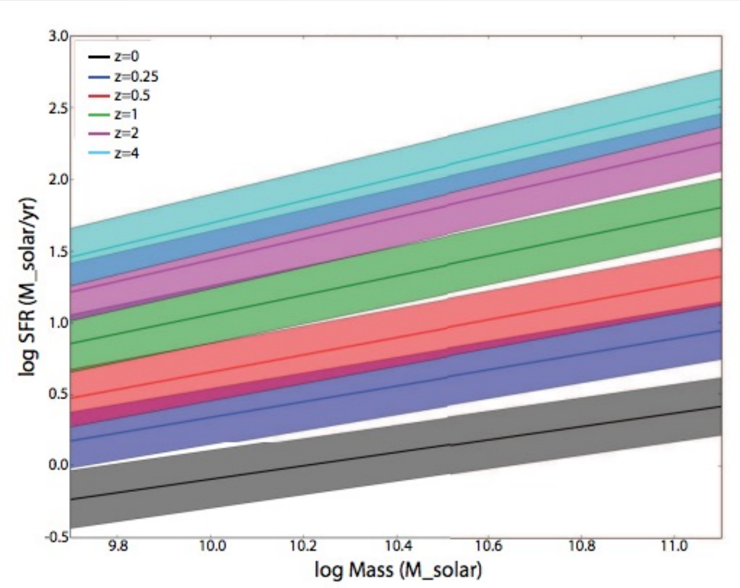


L_{IR} is usually defined from 8-1000 microns.

$1\ L_\odot = 3.85 \times 10^{33}$ erg/s

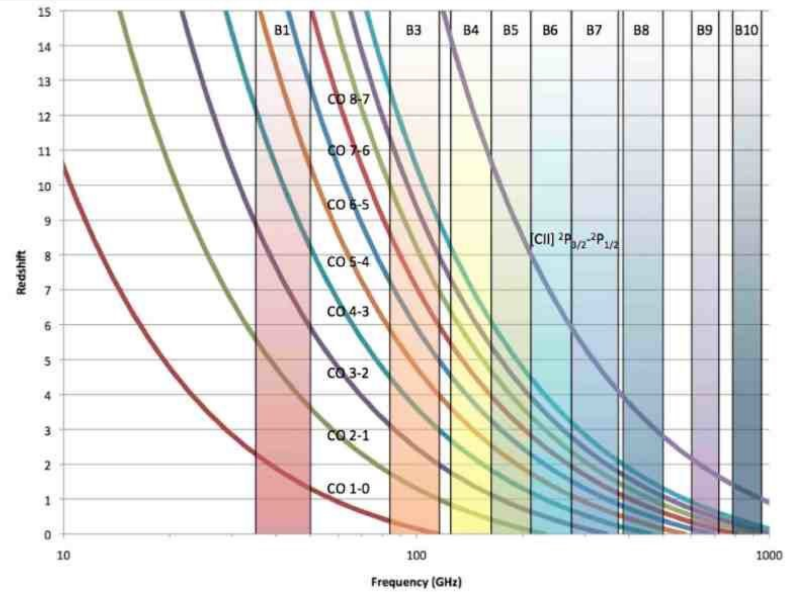
If powered by star formation, SFR in ULIRGs is over 150 $M_\odot$ /year.

Speagle et al. (2014)

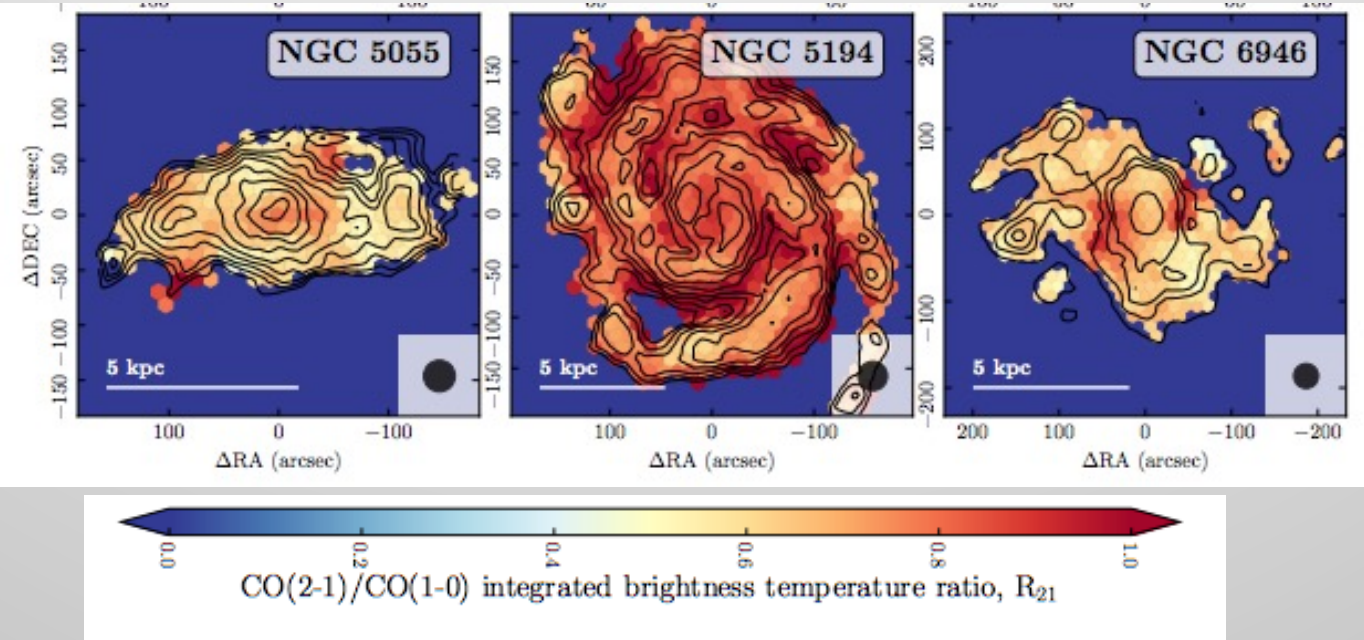


(U)LIRGs very rare in local universe, but the evolving SFMS means they are increasingly common at high z (i.e. LIRGs correspond to "normal" SFRs of mid-mass galaxies).

Conversion factor headaches – Different J lines



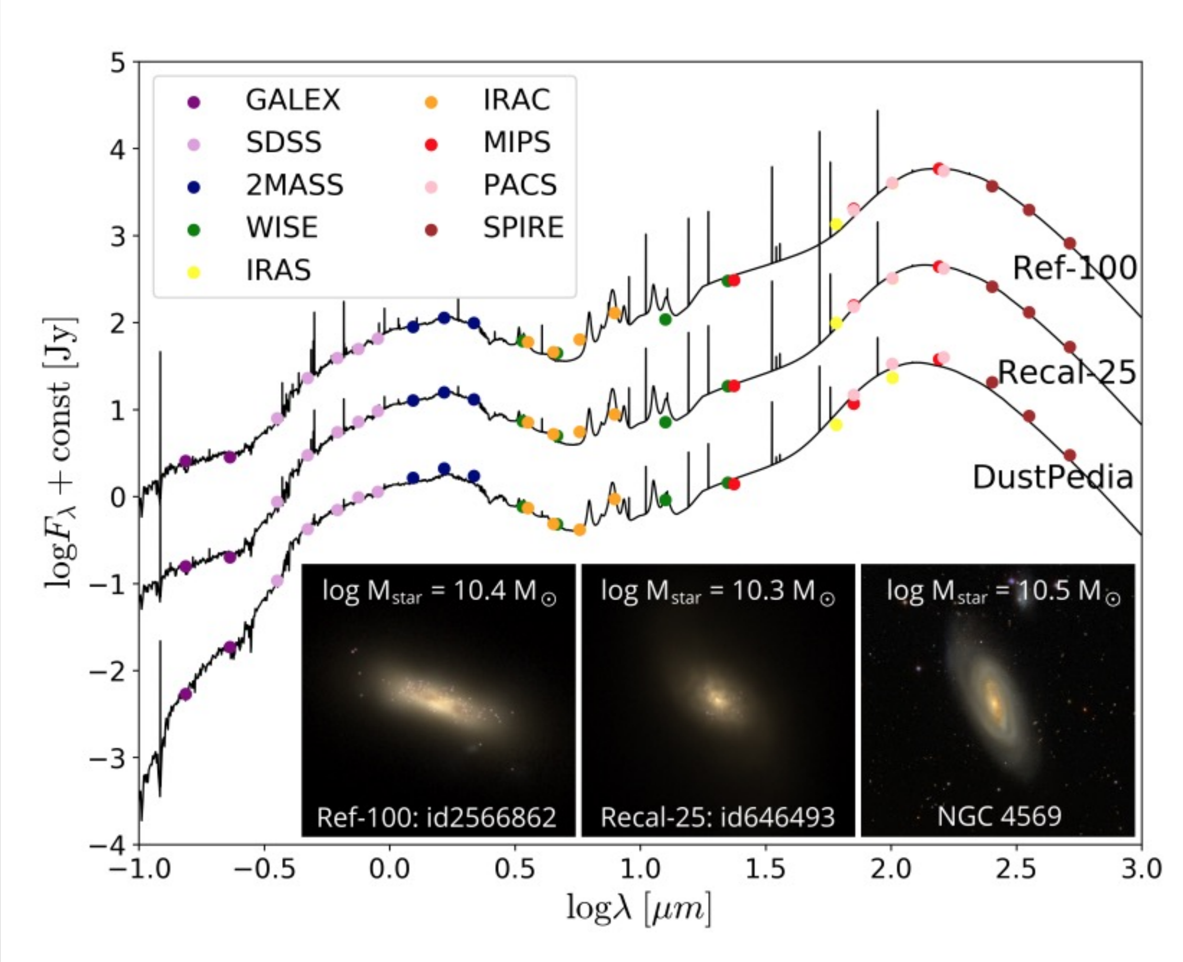
High z surveys tend to observe higher J lines. First need to convert from, e.g. L_{CO} (2-1) to L_{CO} (1-0) (which has uncertainty) and then convert to H_2 mass (which has uncertainty).



Den Brok et al (2021)

Molecular gas from dust measurements – SED fitting

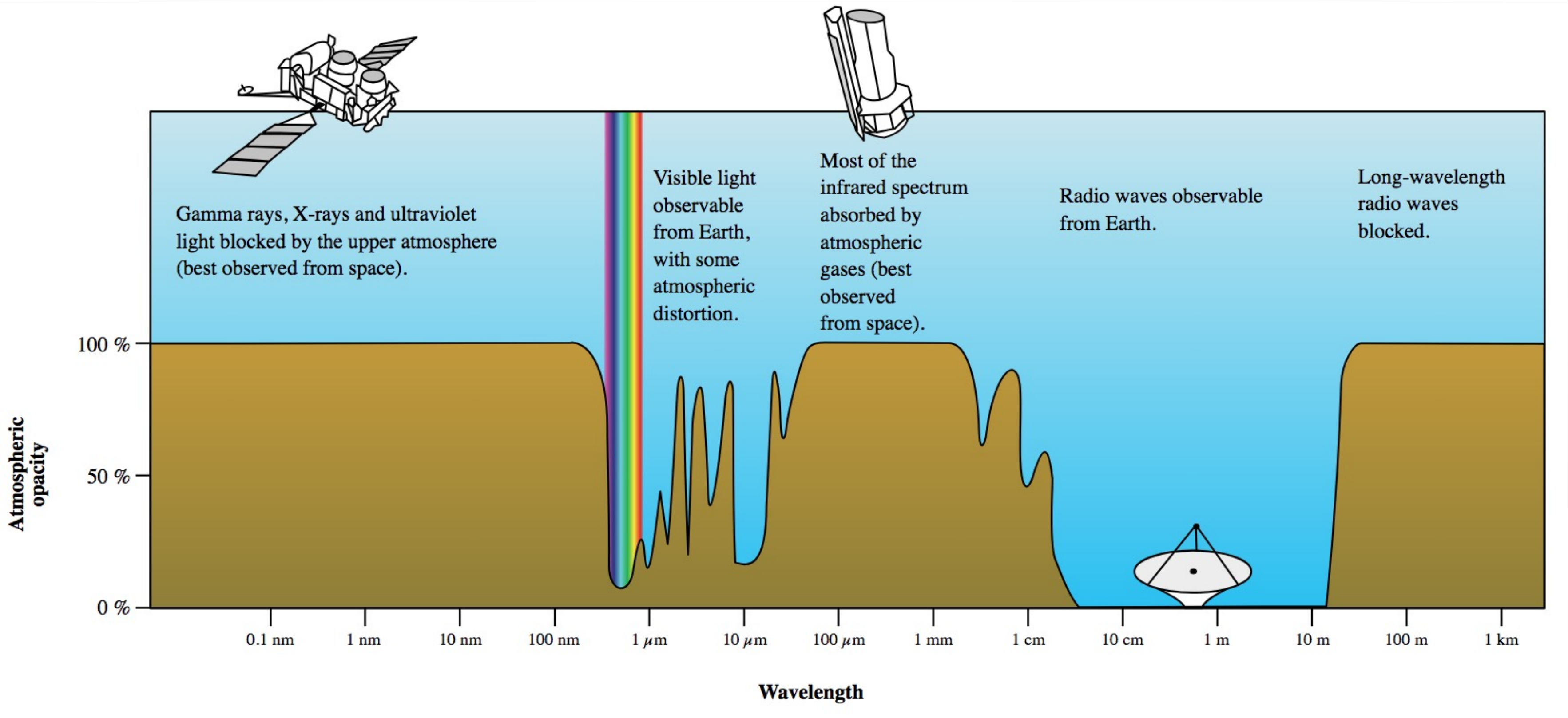
Spectral energy distribution (SED) fitting allows to get dust mass, which can be converted to gas mass if we know the dust-to-gas ratio. Good option for high z when (low J) CO lines are harder to observe.



Trcka et al (2020)

Molecular gas from dust measurements

Need to be in space to observe in the far-IR.



Molecular gas from dust measurements

Need to be in space to observe in the far-IR. The ability to fit SEDs and characterize the dust emission revolutionized by Herschel, which uniquely probed beyond 200 microns.

SOURCE: ESA

Space telescopes only [edit]

Name	Effective aperture cm (in)	Wavelength Coverage	Year	Refs
James Webb (JWST)	650 cm	0.6-28.5 μm	2021-	
Herschel Obs.	350 cm (138″)	60-672 μm	2009 - 2013	[2]
Hubble WFC3	240 cm	0.2-1.7 μm	2009 -	
Euclid NISP	120 cm	0.92-2.02 μm	2023 -	
Spitzer	85 cm	3-180 μm	2003 - 2020	[4]
Akari	68.5 cm	2-200 μm	2006 -2011	[4]
ISO	60 cm	2.5-240 μm	1995-1998	[4]
IRAS	57 cm	5-100 μm	1983	[4]
NEO Surveyor	50 cm	4–5.2 & 6–10 μm	2028 (planned)	[9]
WISE/NEOWISE	40 cm	3-25 μm	2009-2011 & 2013 -	[4]
MSX	33 cm	4.3-21 μm	1996 - 1997	
Spacelab IRT	15.2 cm	1.7-118 μm	1985 Aug	[10]
Human Eye †	~1 cm	0.39-0.75 μm	-	

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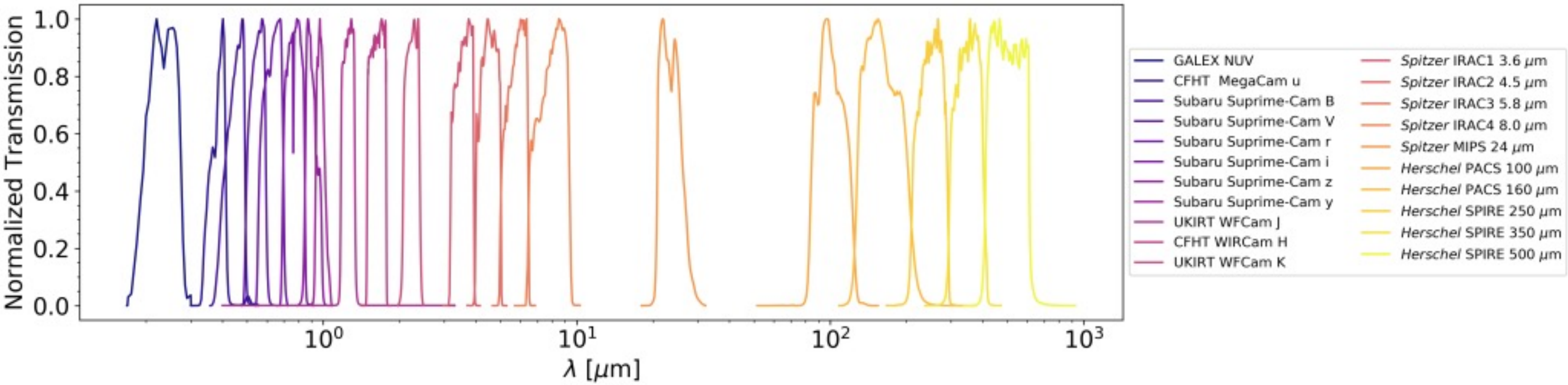
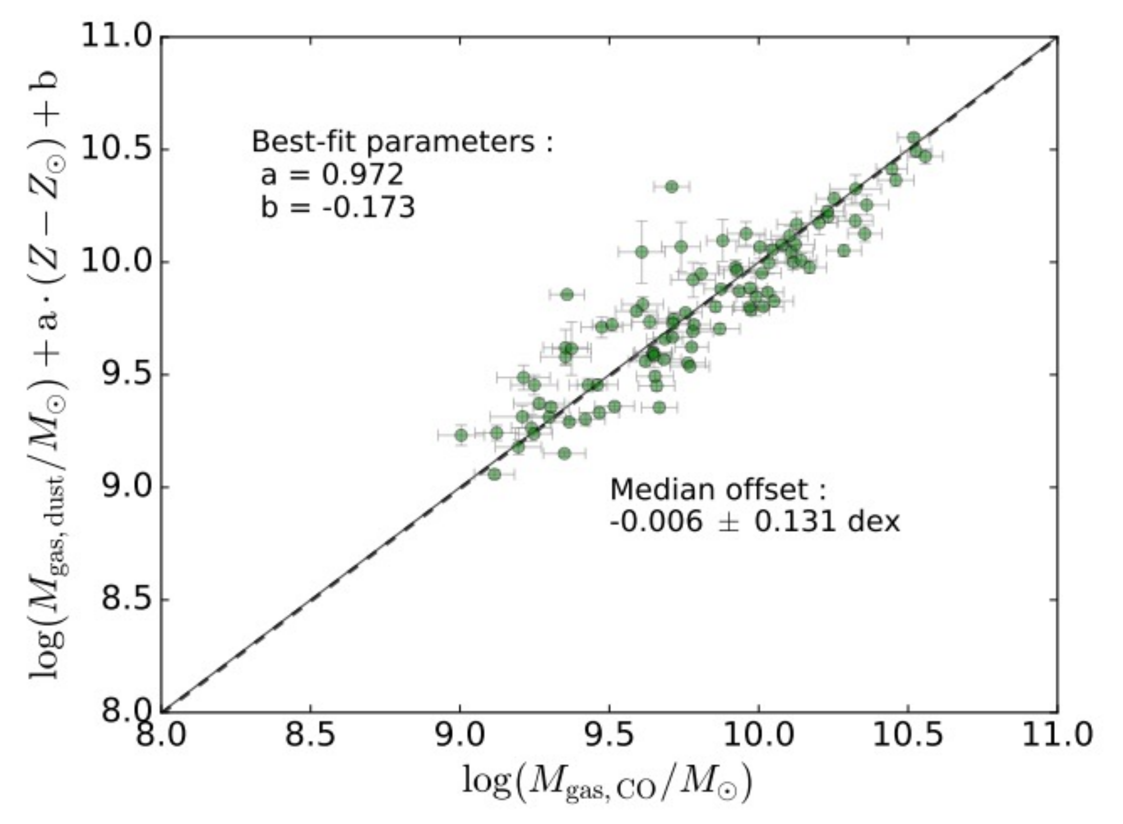


Villa-Velez et al. (2021)

Molecular gas from dust measurements – gas-to-dust ratio

Converting from the derived dust mass to a gas mass requires assuming or calibrating a gas-to-dust ratio (δ_{gd}).

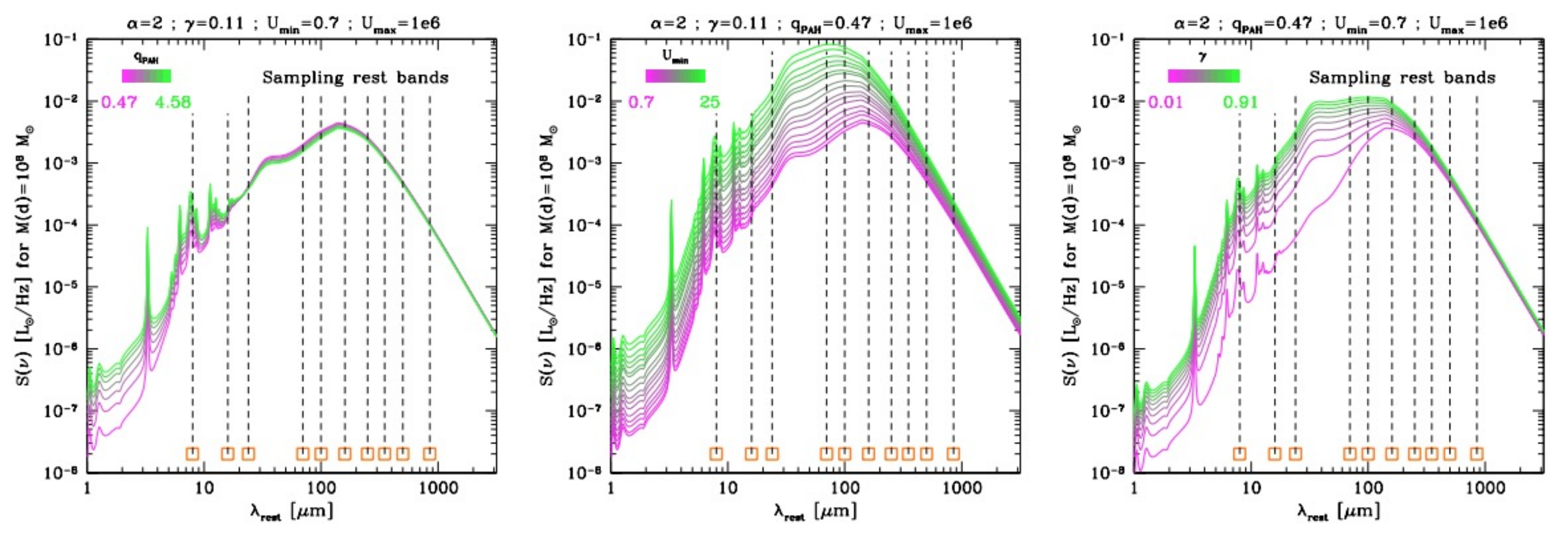


Bertemes et al. (2018)

Molecular gas from dust measurements – mm continuum

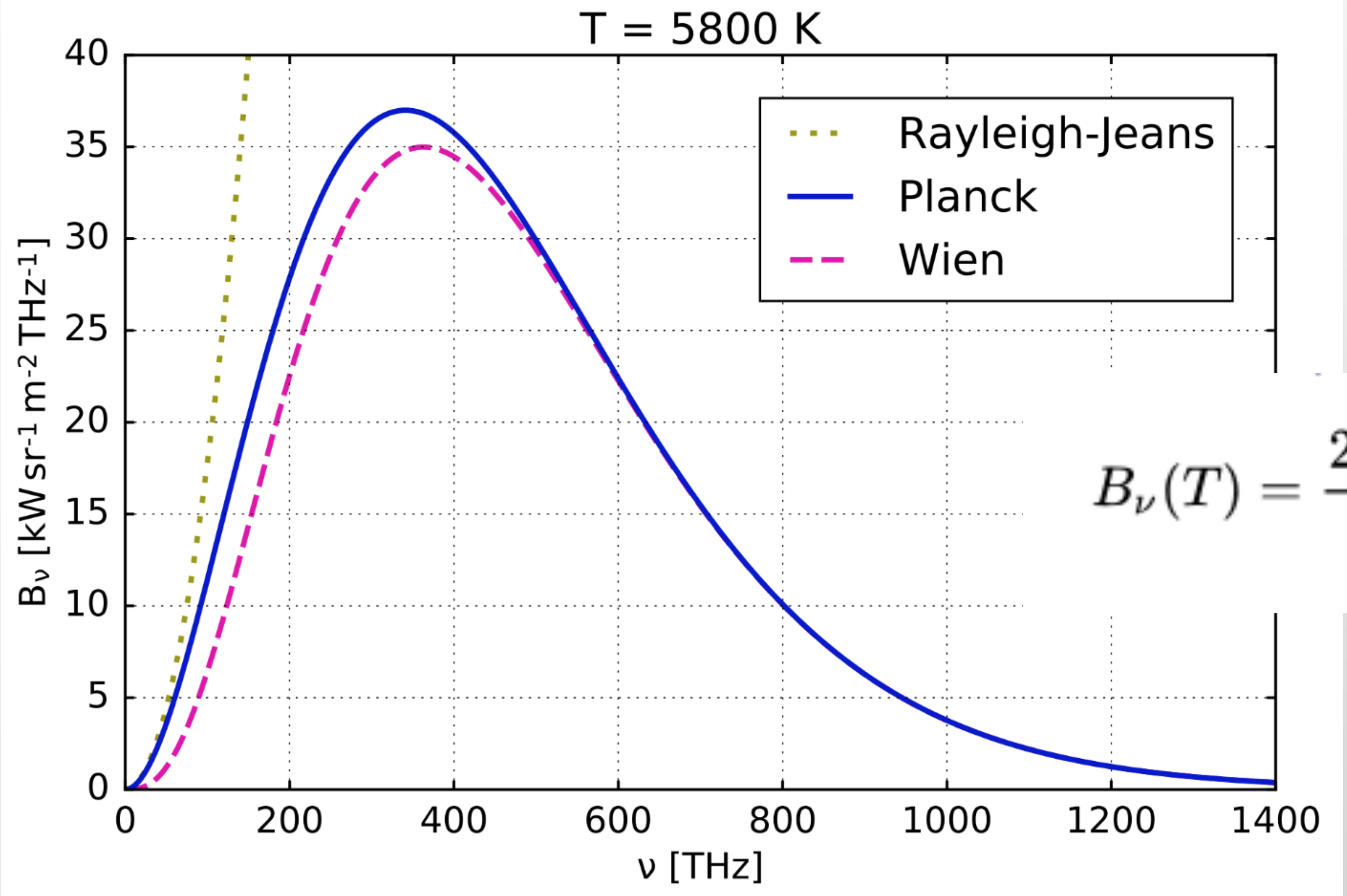
Rather than fitting an entire SED, an alternative is to just sample the SED once, in the Rayleigh-Jeans tail, e.g at 1mm. This is reasonable as long as the emission is optically thin and the dust temperature doesn't change much. Under these conditions dust emission ~ dust mass (see Section 4 of Scoville et al. 2017).

$$S_\nu \propto \kappa_D(\nu) T_{\rm D} \nu^2 \frac{M_{\rm D}}{d_L^2}$$



Berta et al. (2016) showed that dust masses can be obtained robustly (i.e. not too sensitive to parameter choices) as long as the long wavelengths are sampled.

Jargon alert: Rayleigh-Jeans tail



$$B_\nu(T) = \frac{2\nu^2 k_B T}{c^2}.$$

The Rayleigh-Jeans law is a classical approximation of blackbody irradiance. It agrees with the Planck function only at low frequencies (**kT/hν >> 1**), i.e. long wavelengths.
Aside: Wien's approximation works at the other extreme, at high frequencies.

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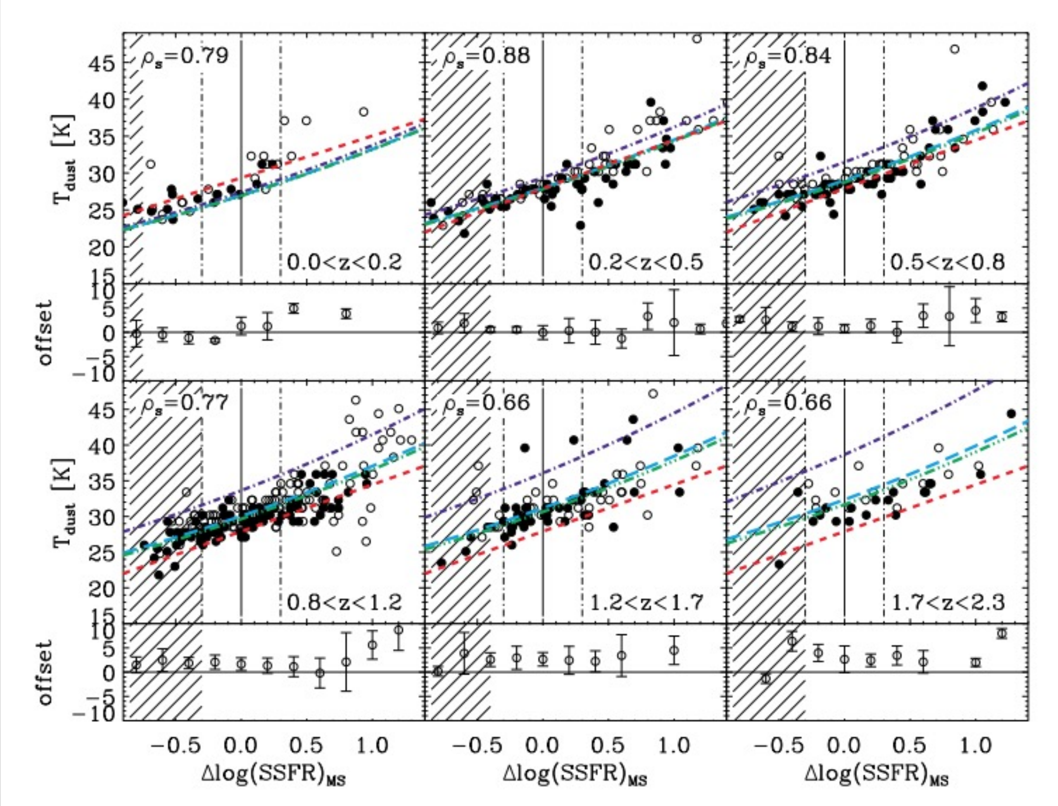

Magnelli et al. (2014) show that dust temperatures change as SFRs move away from the SFMS, but it is mild, even at z~2.

Molecular gas from dust measurements – mm continuum

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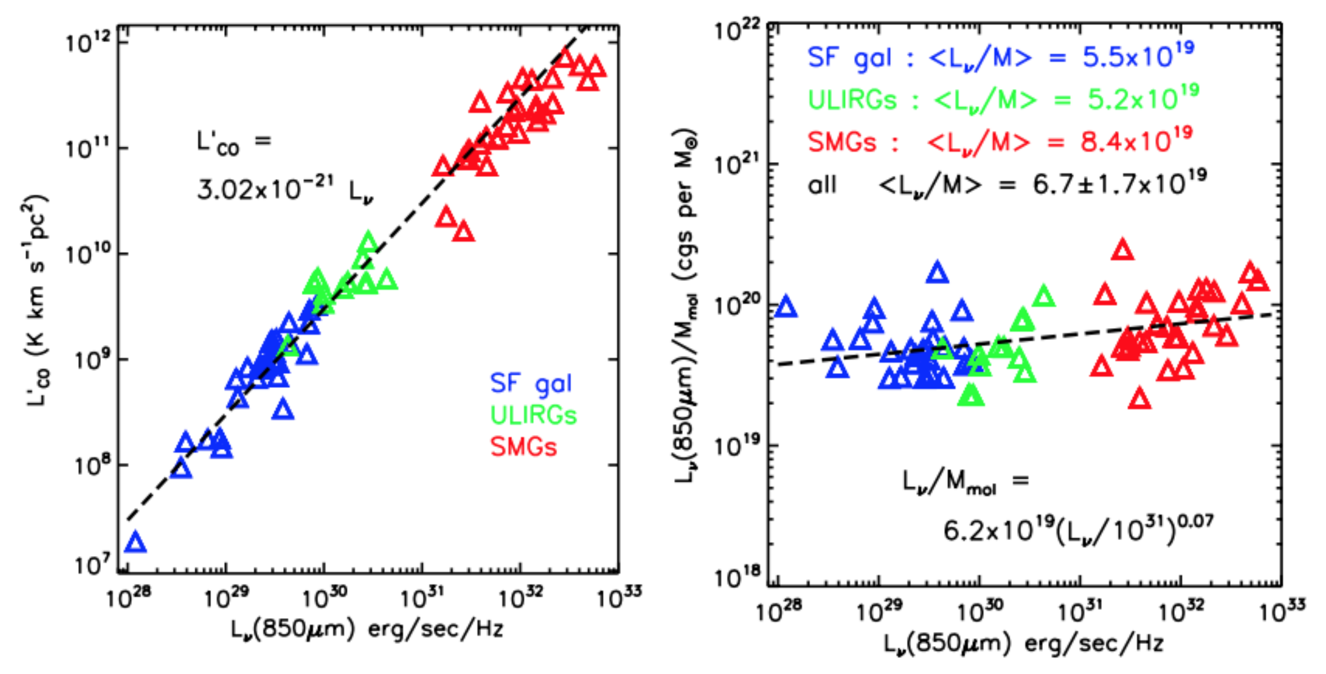
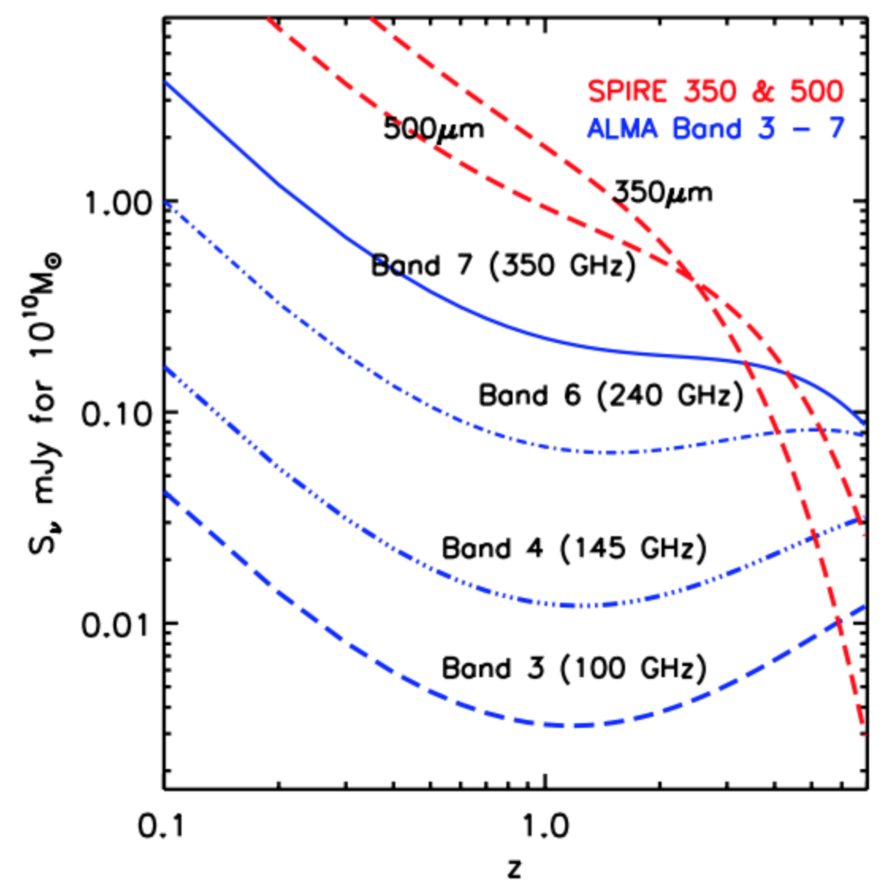


Calibration by Scoville et al. (2016)

Molecular gas from dust measurements – mm continuum

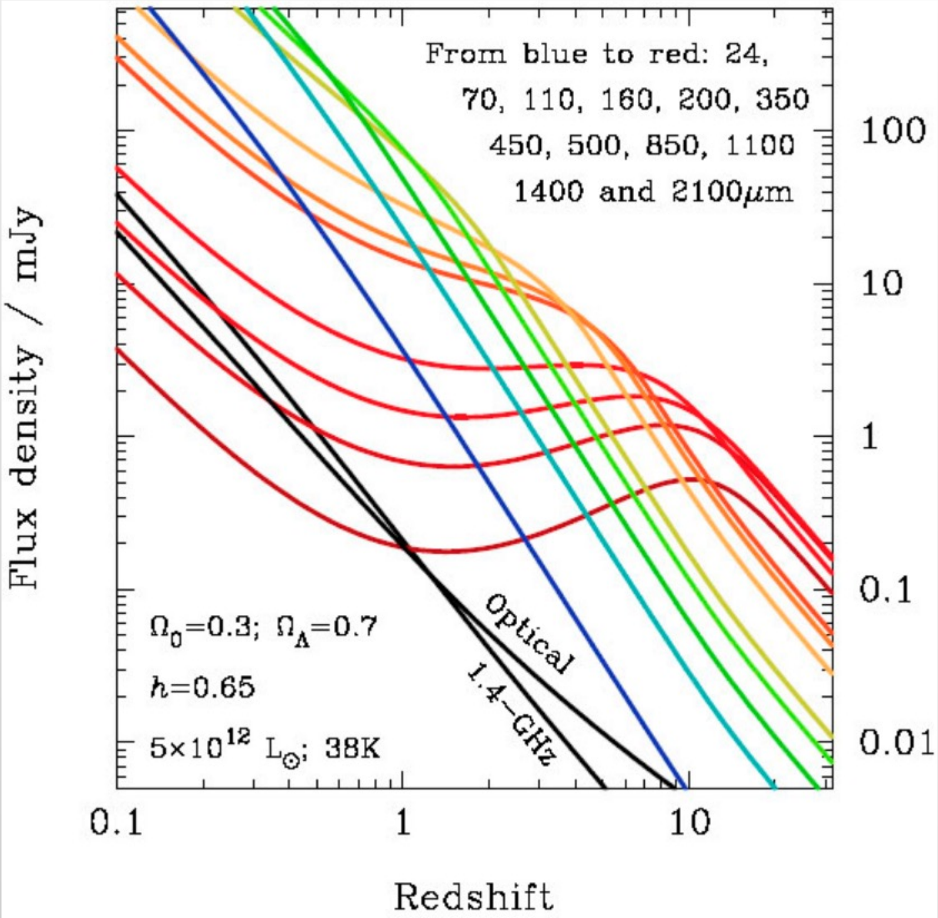
The dust continuum method is particularly useful at high z where ALMA can make detections in short integrations and the emission is well placed in Bands 3-7.



Scoville et al. (2016)

Observations of dusty galaxies in the sub-mm is helped by a negative k-correction.

Jargon alert: negative k-correction



Blain et al. (2002)

Objects get fainter the further away they are.

But there is an additional term in computing the observed flux from a redshifted object called the “k-correction”.

In general, the term “k-correction” refers to the change in brightness due to redshifting a spectrum through different photometric bands.

Due to the shape of a dusty SED, long wavelength emission actually gets brighter between z~1 and z~10. This is referred to as a negative k-correction.

Summary

- Although H_2 can be studied at high z thanks to electronic band systems shifting into the optical, this is only practical in absorption when there is a background QSO. Therefore observing H_2 directly is as challenging at high z as at low z.

- There are significant uncertainties in converting from CO line emission to H_2 mass. These are compounded for high z work by different ISM conditions and the use of high J lines.

- Dust-based gas estimates are a good option for high z, although still have to calibrate/assume a dust-to-gas ratio.

- The Herschel far-IR telescope revolutionized our ability to measure dust at long wavelengths, but is now defunct.

- ALMA is the new critical observatory, being able to access low J CO lines, and mm continuum.