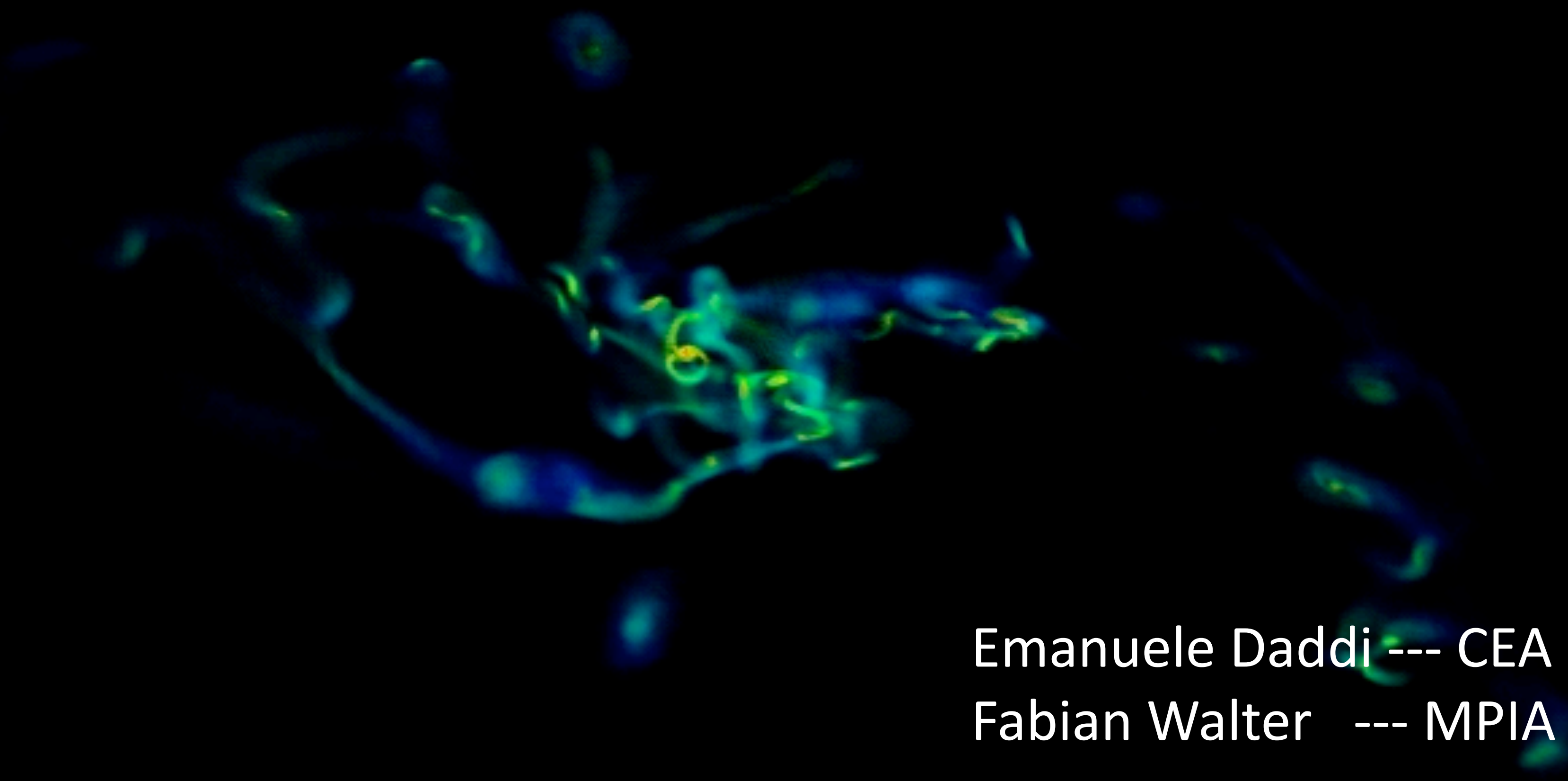
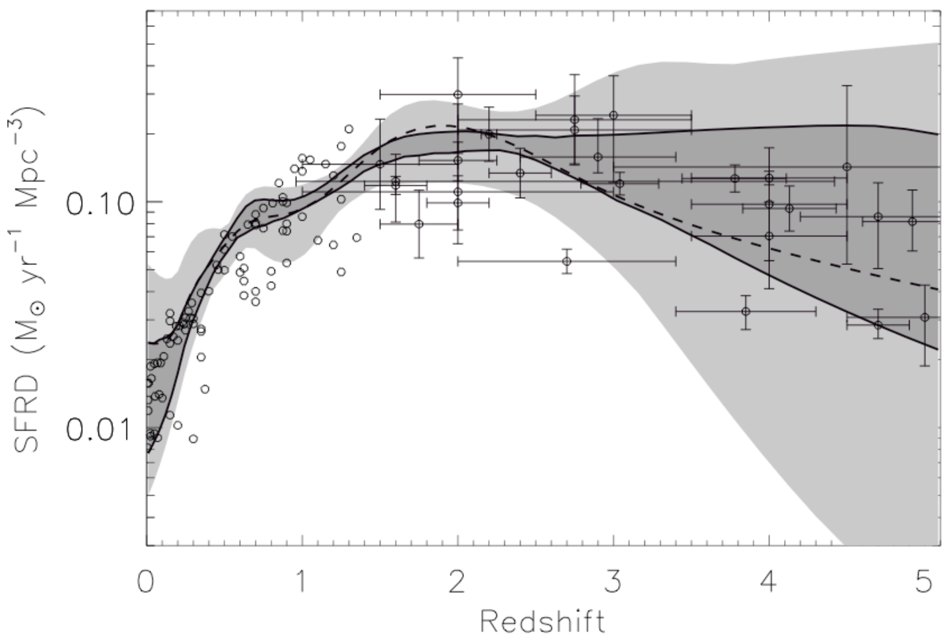
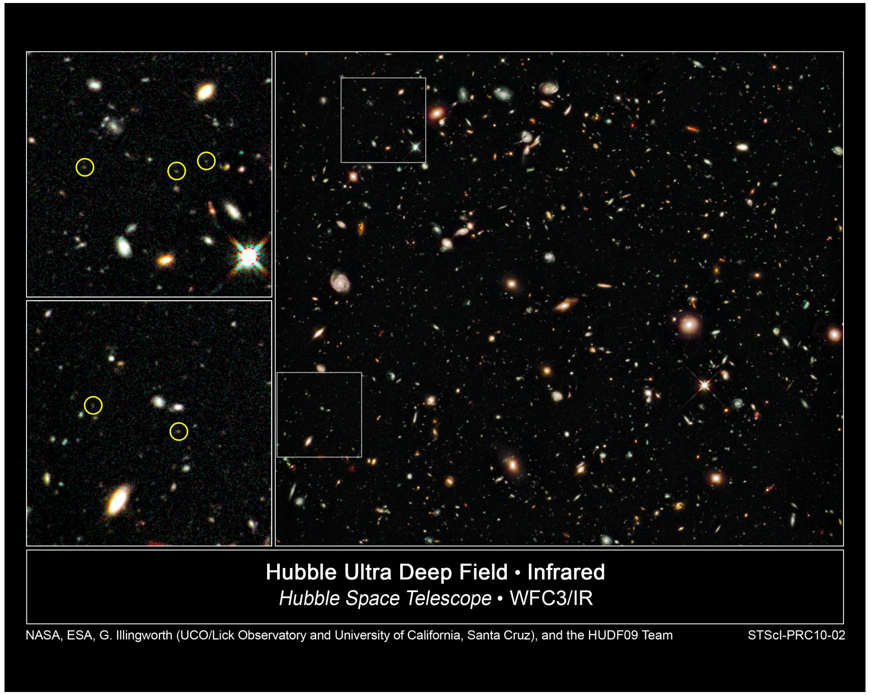
Galaxy formation with ALMA



Emanuele Daddi --- CEA
Fabian Walter --- MPIA

Cosmic evolution of star formation in galaxies since the highest redshifts

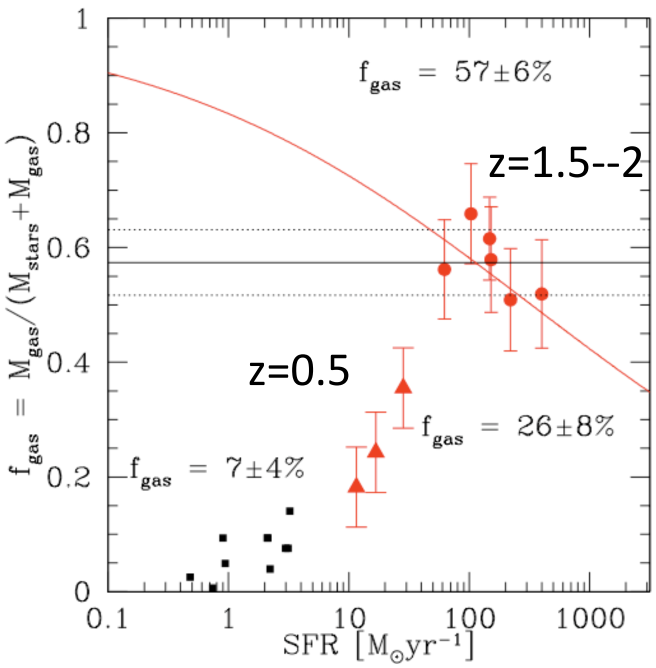




We want to study high-z star formation from the far-IR

Obtain probes comparable in depth to UV rest frame studies (e.g., UDF)

Cosmic evolution of the molecular gas content in galaxies since the highest redshifts



Daddi et al 2008; 2010 (see also Tacconi et al 2010)

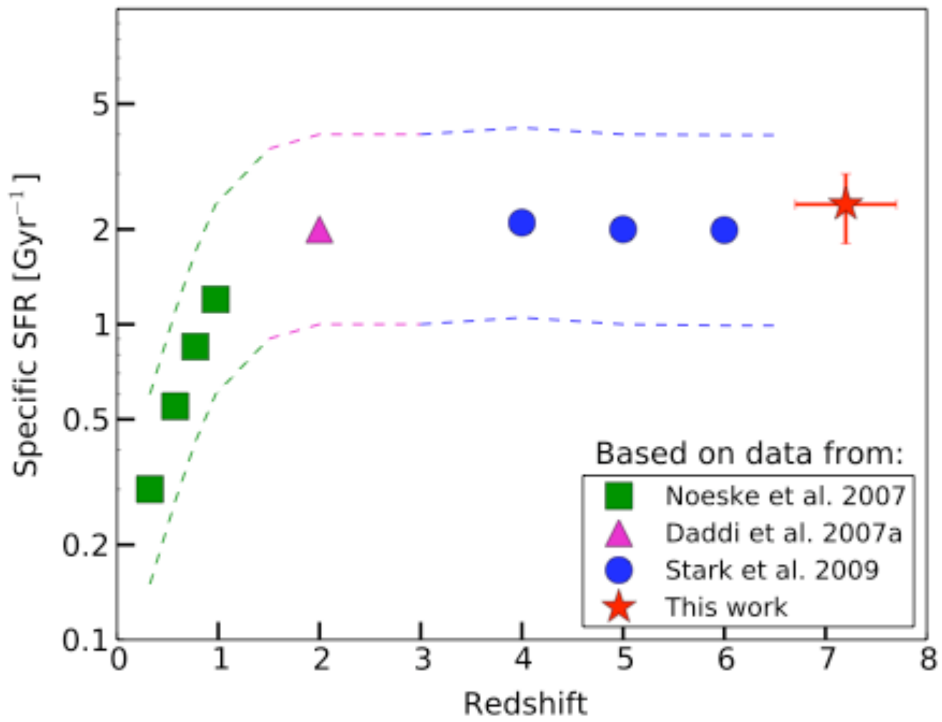
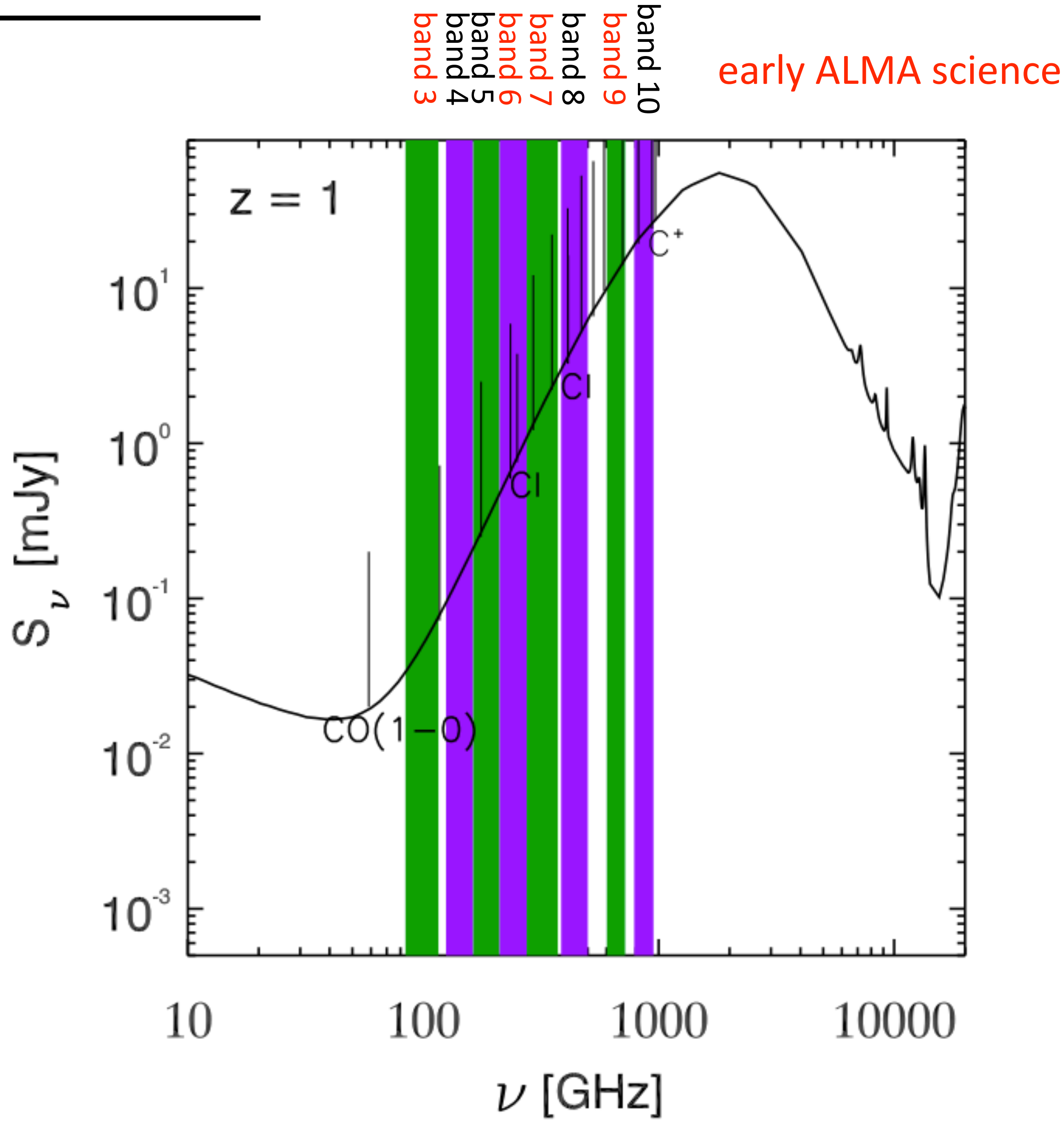


Figure from Gonzalez et al 2010

What's the role and content of molecular gas in early galaxy assembly ?

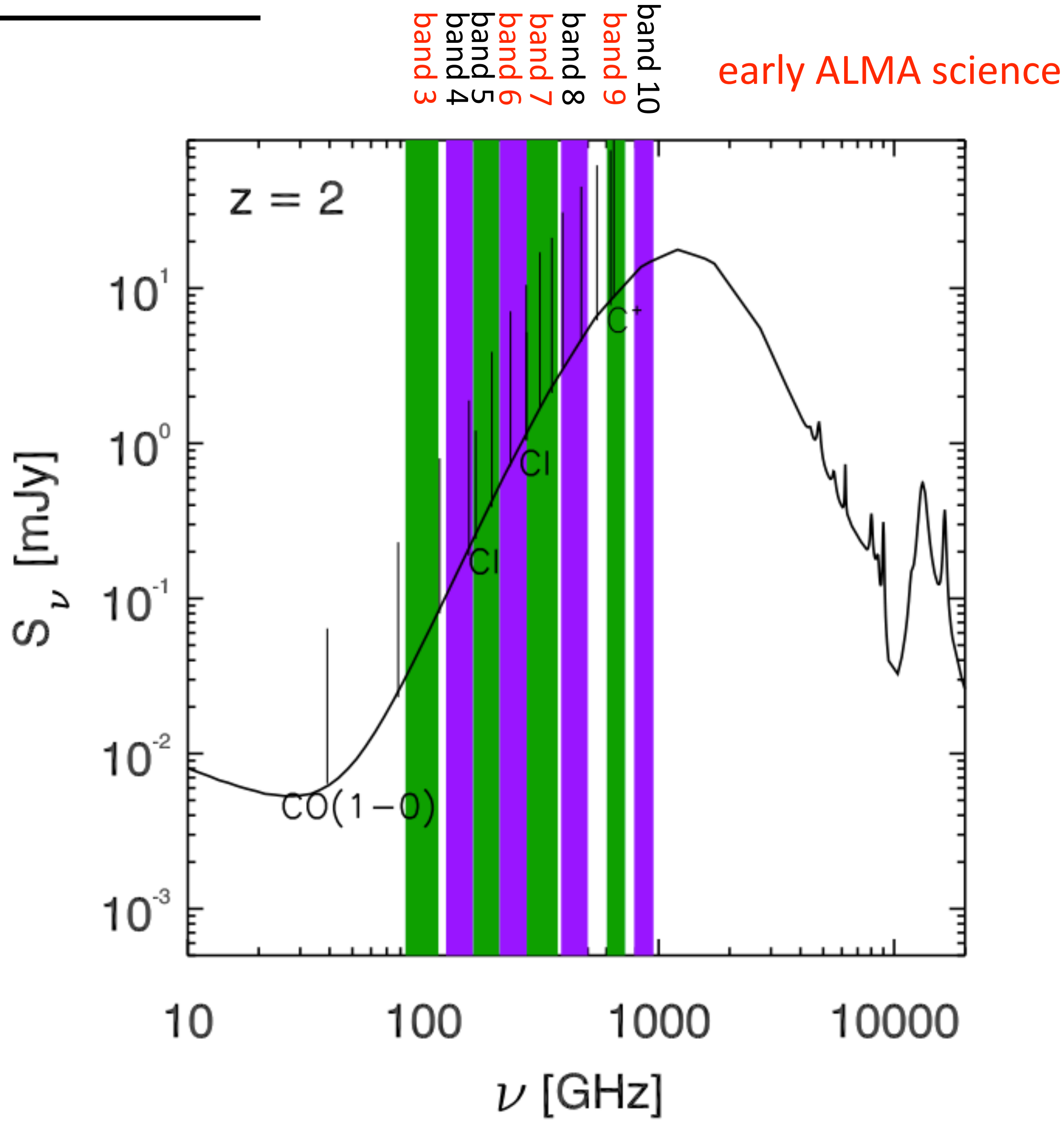
What ALMA will enable: Detailed studies of Dust and Mol. Gas

- detection
- resolved imaging
- excitation
- high-density tracer
- atomic lines



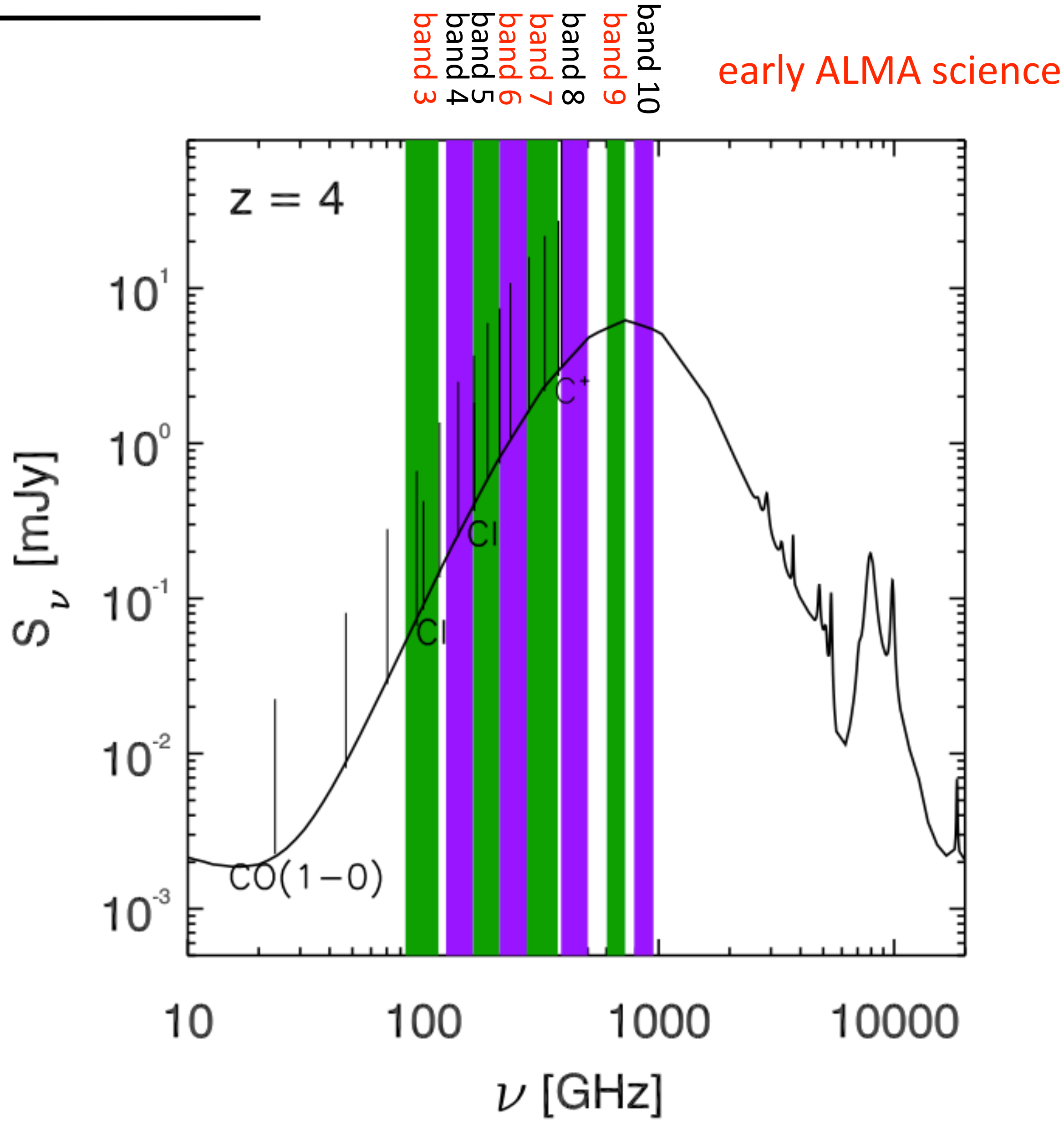
What ALMA will enable: Detailed studies of Dust and Mol. Gas

- detection
- resolved imaging
- excitation
- high-density tracer
- atomic lines



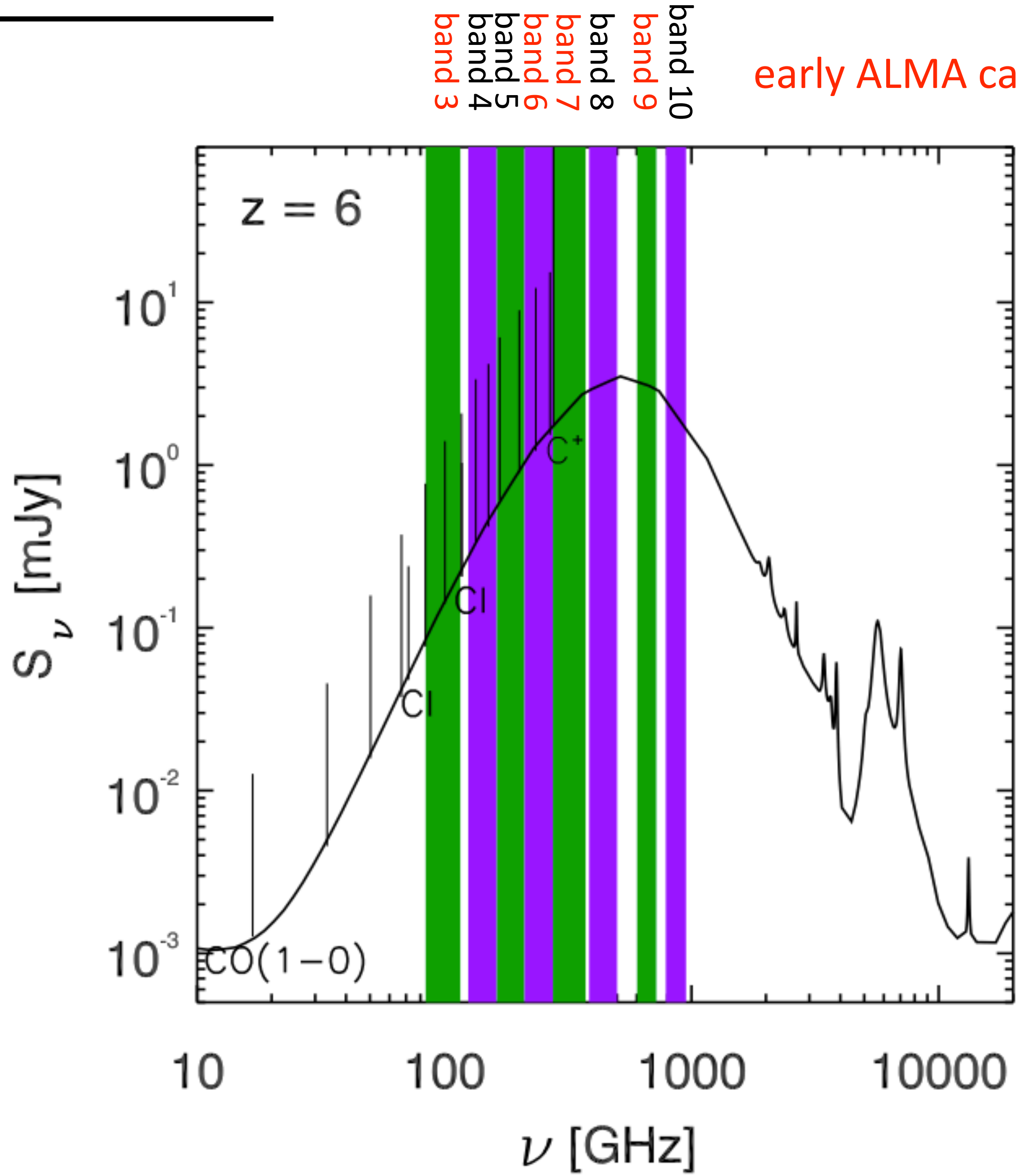
What ALMA will enable: Detailed studies of Dust and Mol. Gas

- detection
- resolved imaging
- excitation
- high-density tracer
- atomic lines



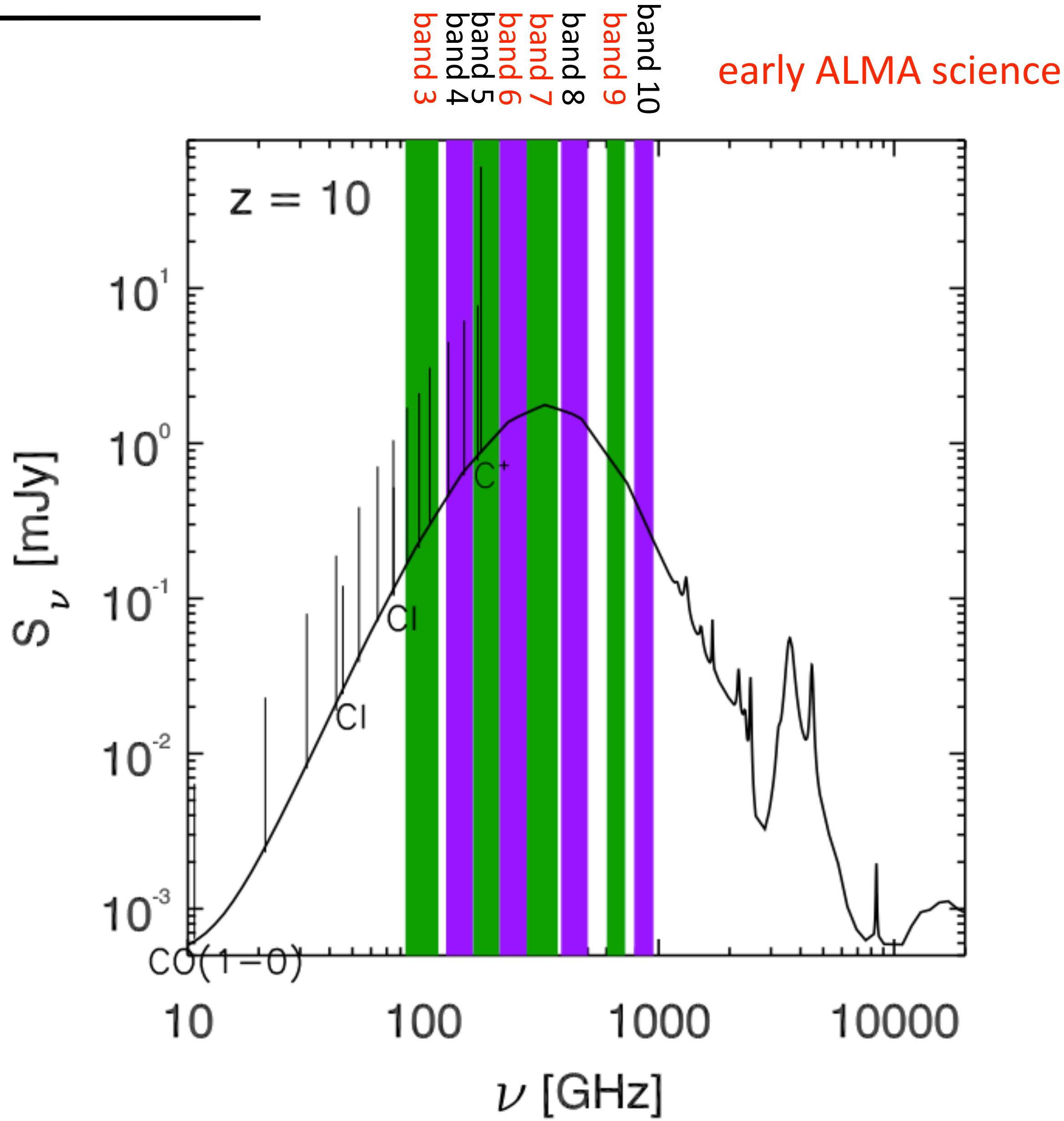
What ALMA will enable: Detailed studies of Dust and Mol. Gas

- detection
- resolved imaging
- excitation
- high-density tracer
- atomic lines



What ALMA will enable: Detailed studies of Dust and Mol. Gas

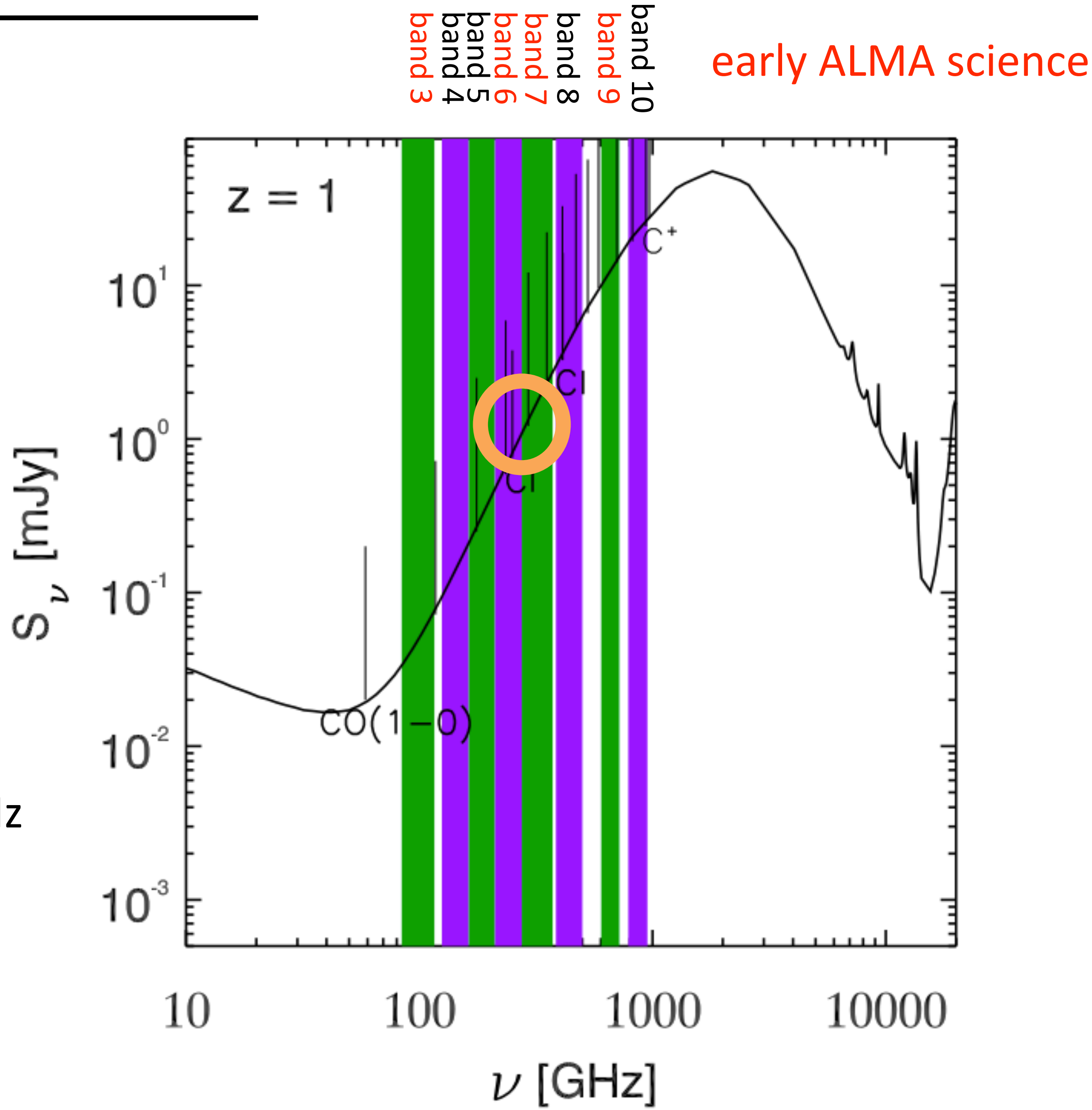
- detection
- resolved imaging
- excitation
- high-density tracer
- atomic lines



What ALMA will enable: Detailed studies of Dust and Mol. Gas

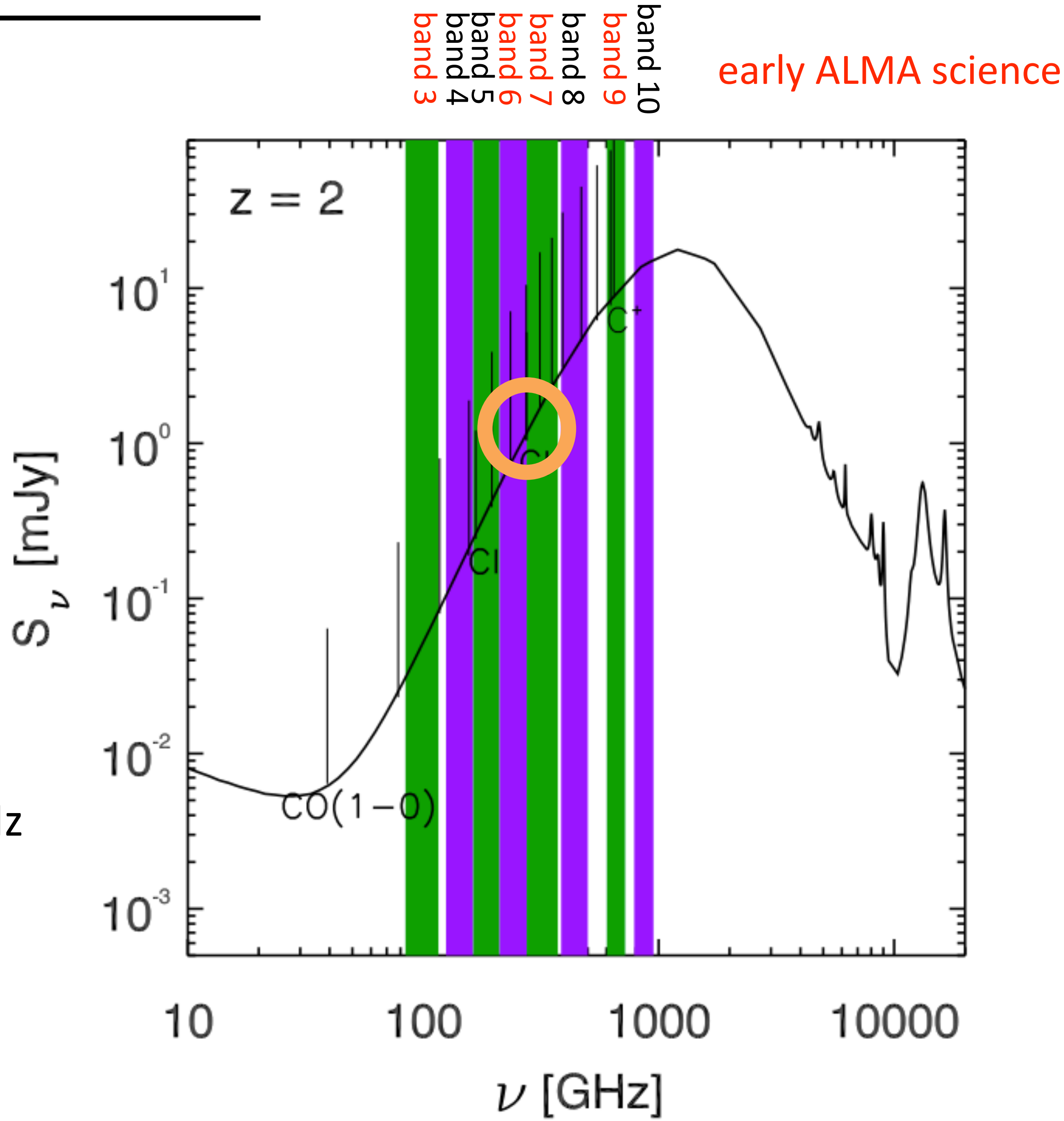
- detection
- resolved imaging
- excitation
- high-density tracer
- atomic lines

Flux at 230/345 GHz
~ constant as f(z)



What ALMA will enable: Detailed studies of Dust and Mol. Gas

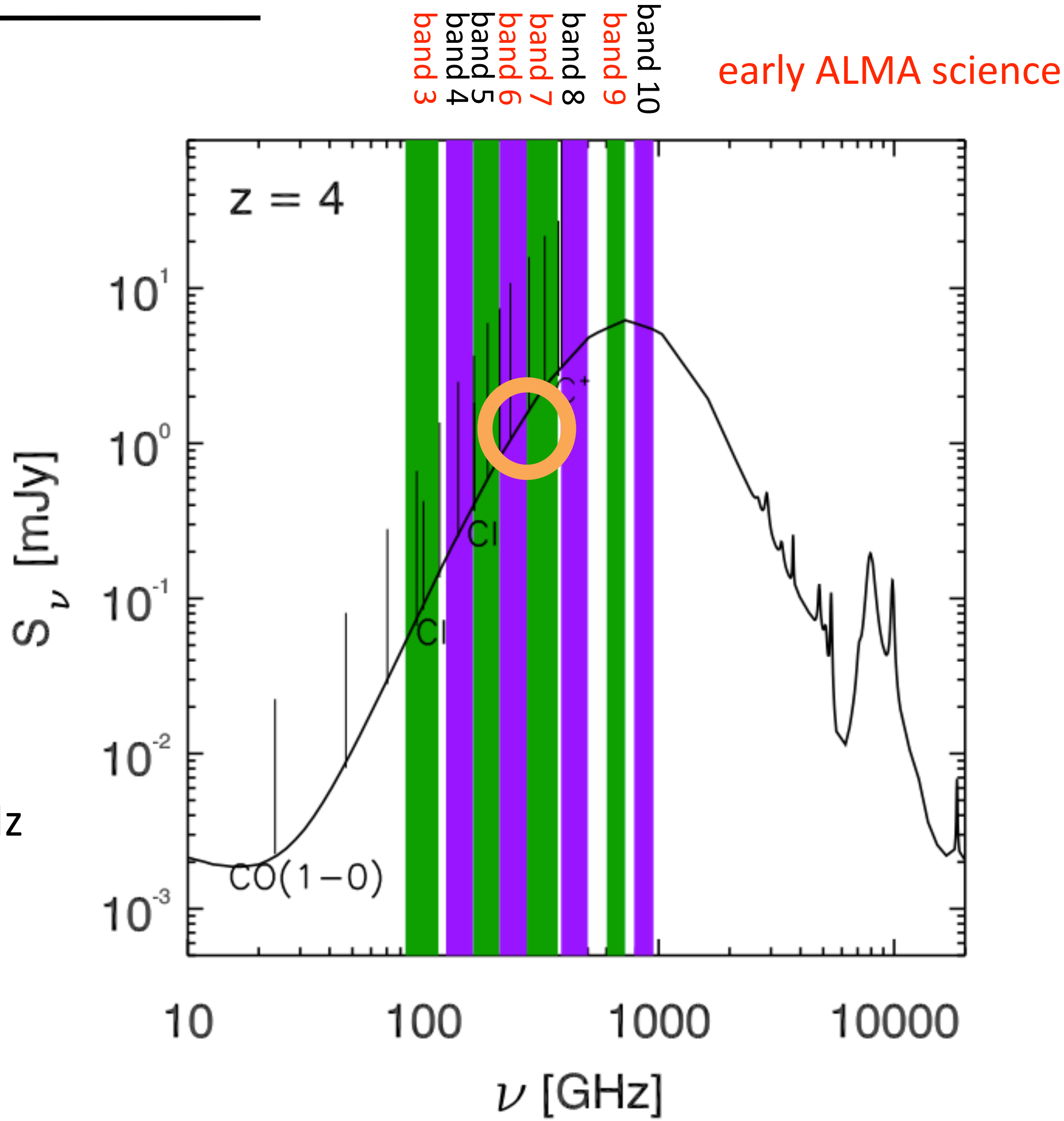
- detection
- resolved imaging
- excitation
- high-density tracer
- atomic lines



Flux at 230/345 GHz
~ constant as f(z)

What ALMA will enable: Detailed studies of Dust and Mol. Gas

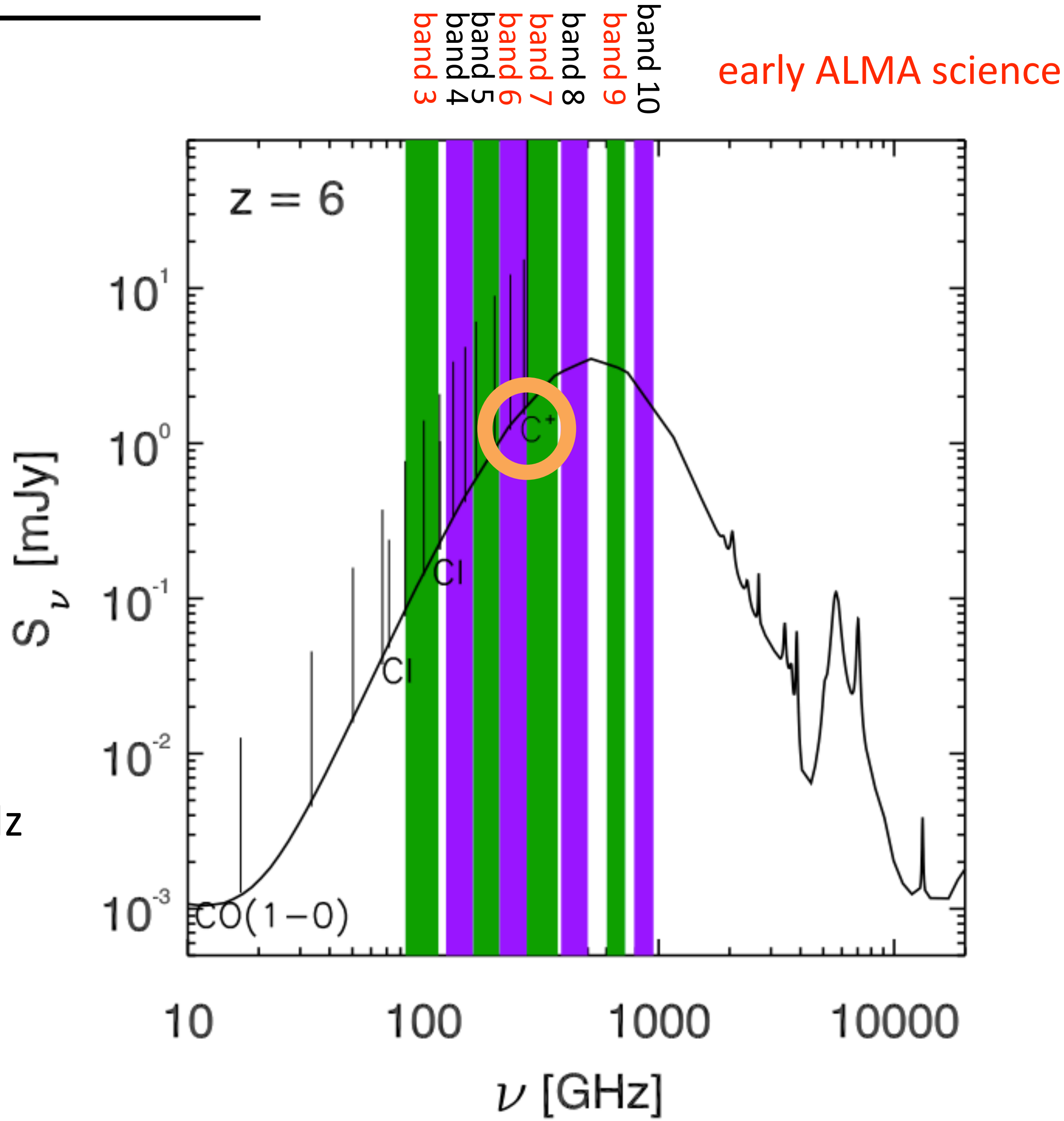
- detection
- resolved imaging
- excitation
- high-density tracer
- atomic lines

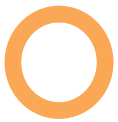


Flux at 230/345 GHz
~ constant as f(z)

What ALMA will enable: Detailed studies of Dust and Mol. Gas

- detection
- resolved imaging
- excitation
- high-density tracer
- atomic lines

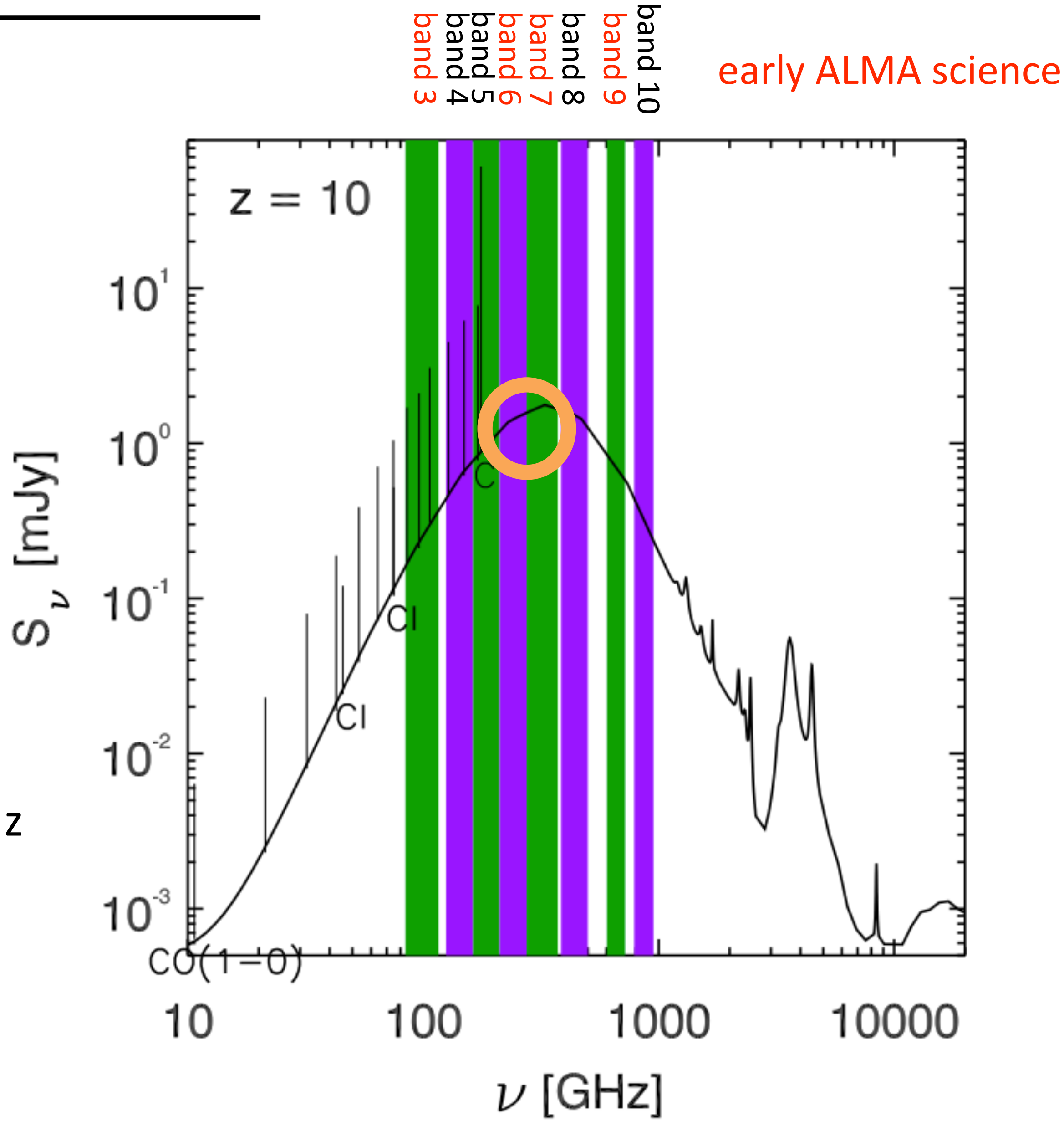




Flux at 230/345 GHz
~ constant as f(z)

What ALMA will enable: Detailed studies of Dust and Mol. Gas

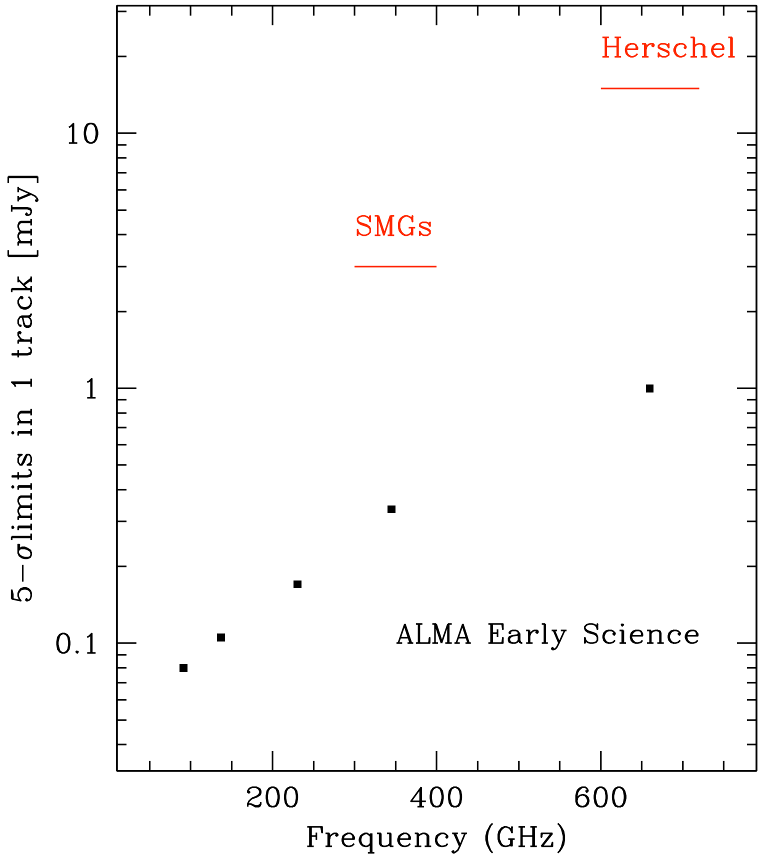
- detection
- resolved imaging
- excitation
- high-density tracer
- atomic lines



Flux at 230/345 GHz
~ constant as f(z)

How deep we can go with ALMA now and then: continuum

Early Science: 16 antennas and 2 GHz full polarization bandwidth
(case for unresolved emission, compact configuration, **1 track of 8h**)



It takes **minutes** of integration times
To detect any Herschel source or any
SMG known to date
(already in early science)

In 1 track: 0.3mJy@850um, 1mJy@450um

ALMA final: 50 antennas and 8 GHz full polarization bandwidth:

→ continuum: 6.3 times deeper at fixed t_{INT}, 40 times faster to a given f_{ν}

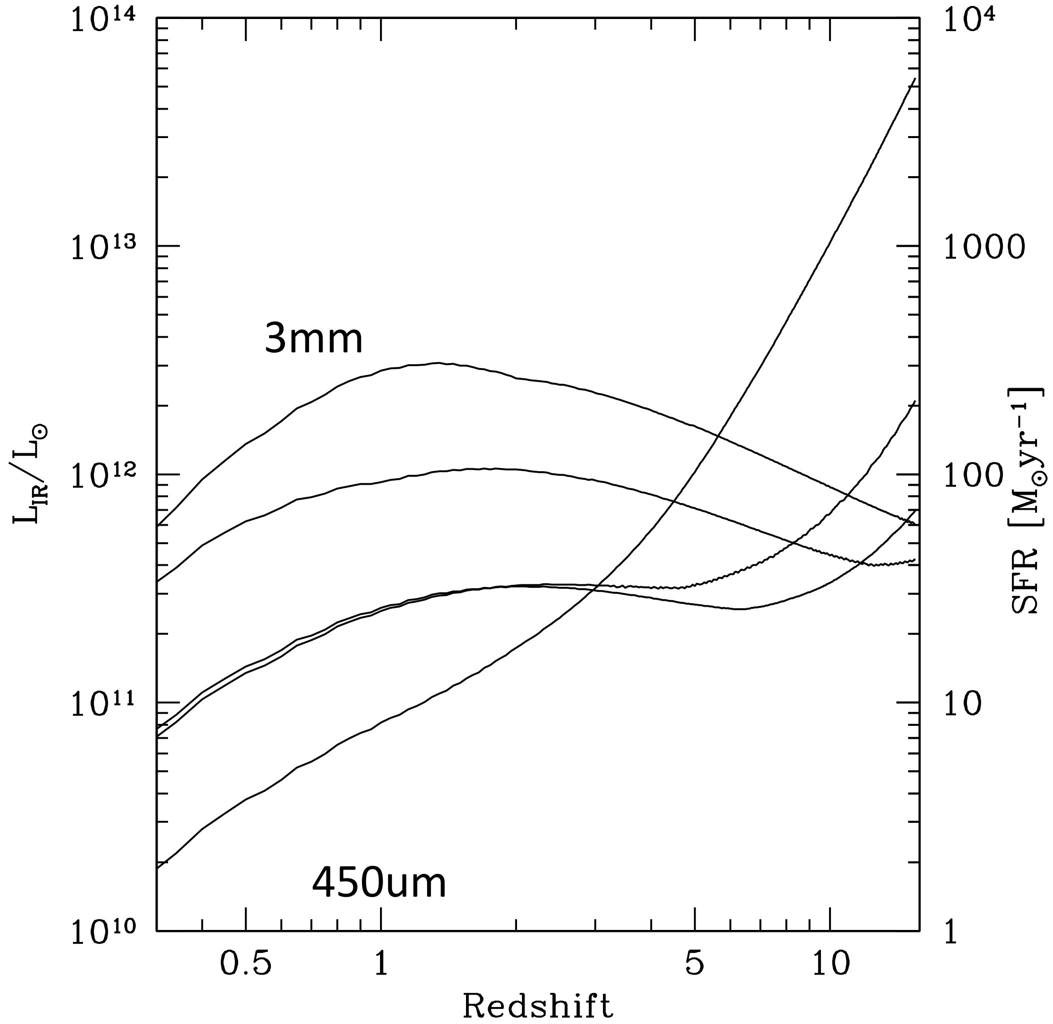
→ lines: 3 times deeper at fixed t_{INT}, 10 times faster to a given f_{ν}

How deep we can go with ALMA: SFRs/L_{IR}

Early Science: 16 antennas and 2 GHz full polarization bandwidth

(case for unresolved emission, compact configuration, **1 track of 8h**

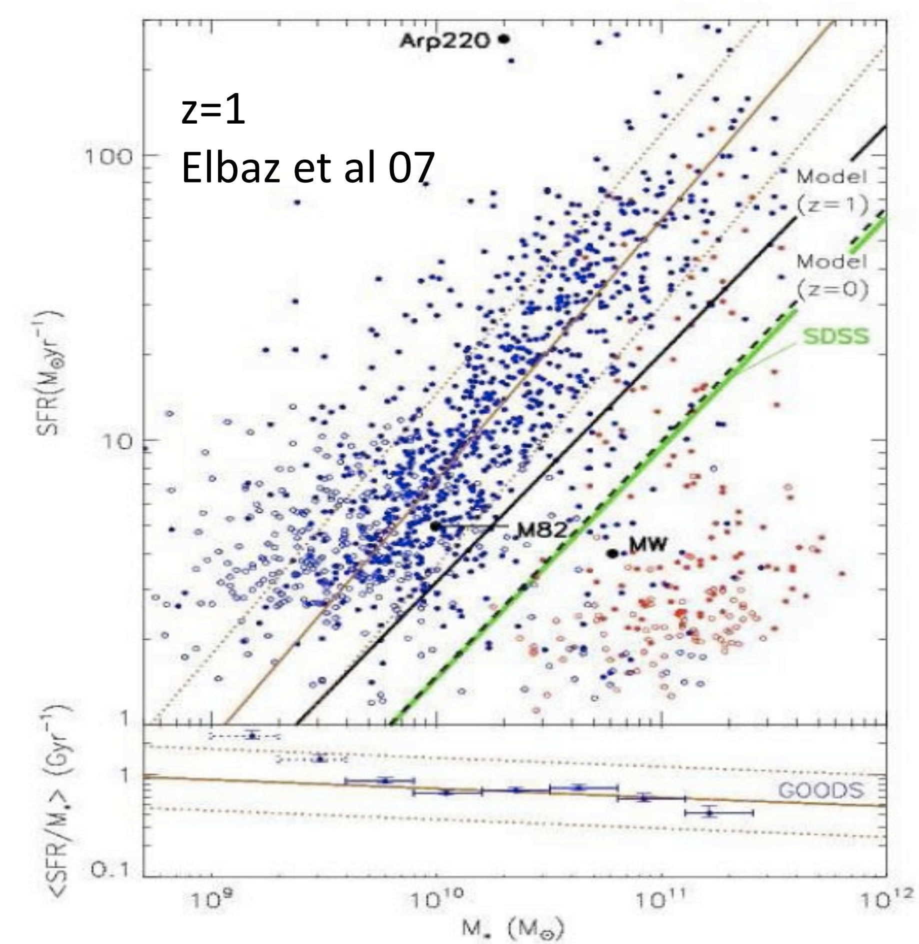
Use Chary & Elbaz template shape for $L_{IR} = 10^{11}\ L_{\odot}$)

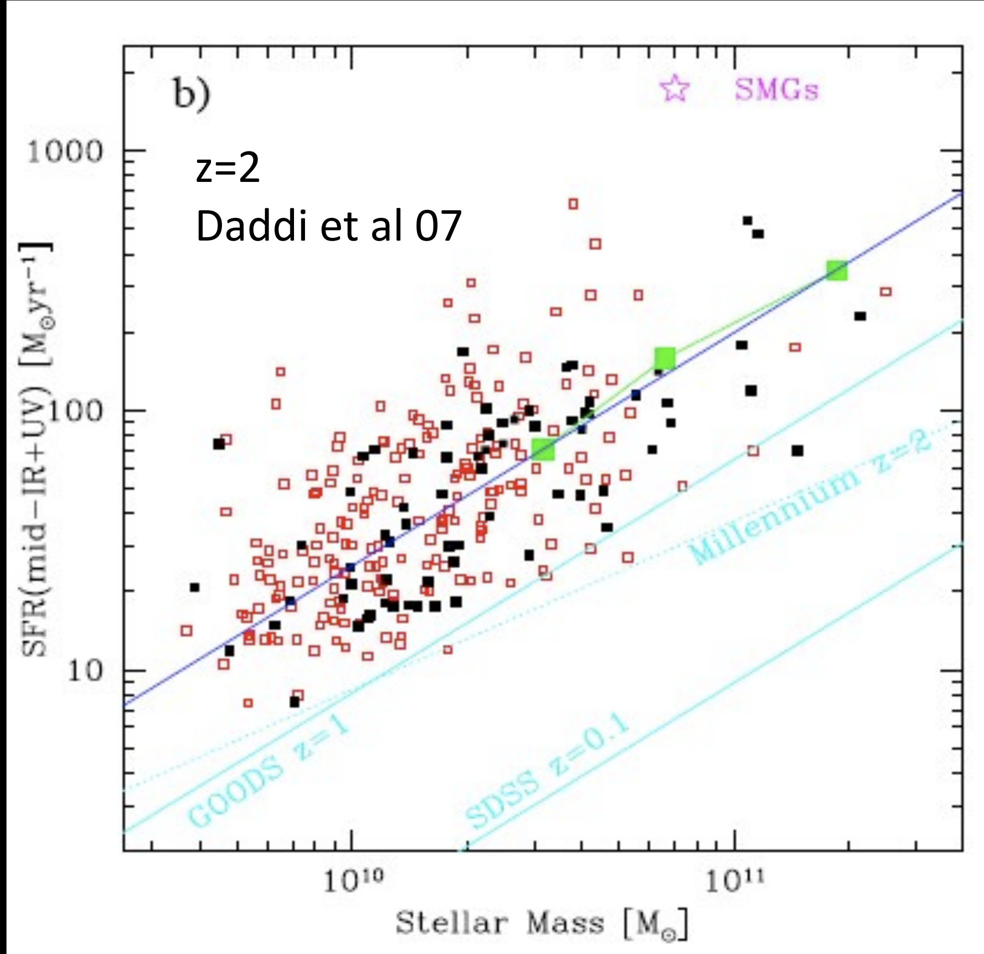


Shortest wavelengths 450/850um are the best up to intermediate z (but at z>5 also 1-2mm bands similar)

SFR = 30 $M_{\odot} yr^{-1}$ in 1 track to z=10

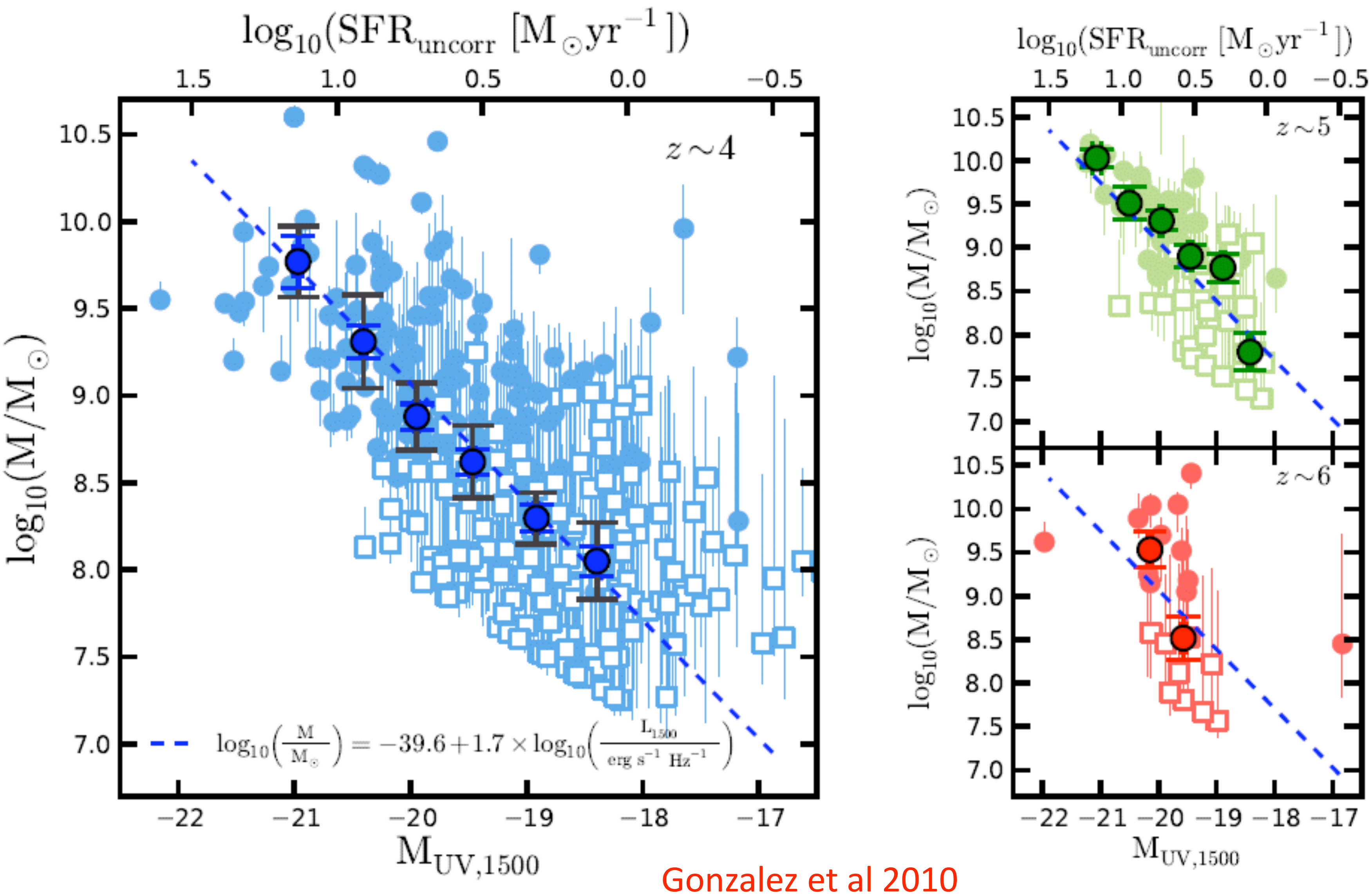
To z=1—2 most of the optical/near IR selected galaxies are within reach in 1 track





Down to a few 10^10 Msun for disk galaxies on the ‘main sequence’ (mass-SFR correl.)

Similar mass limit applies to higher-z, but massive galaxies are not there!



Gonzalez et al 2010

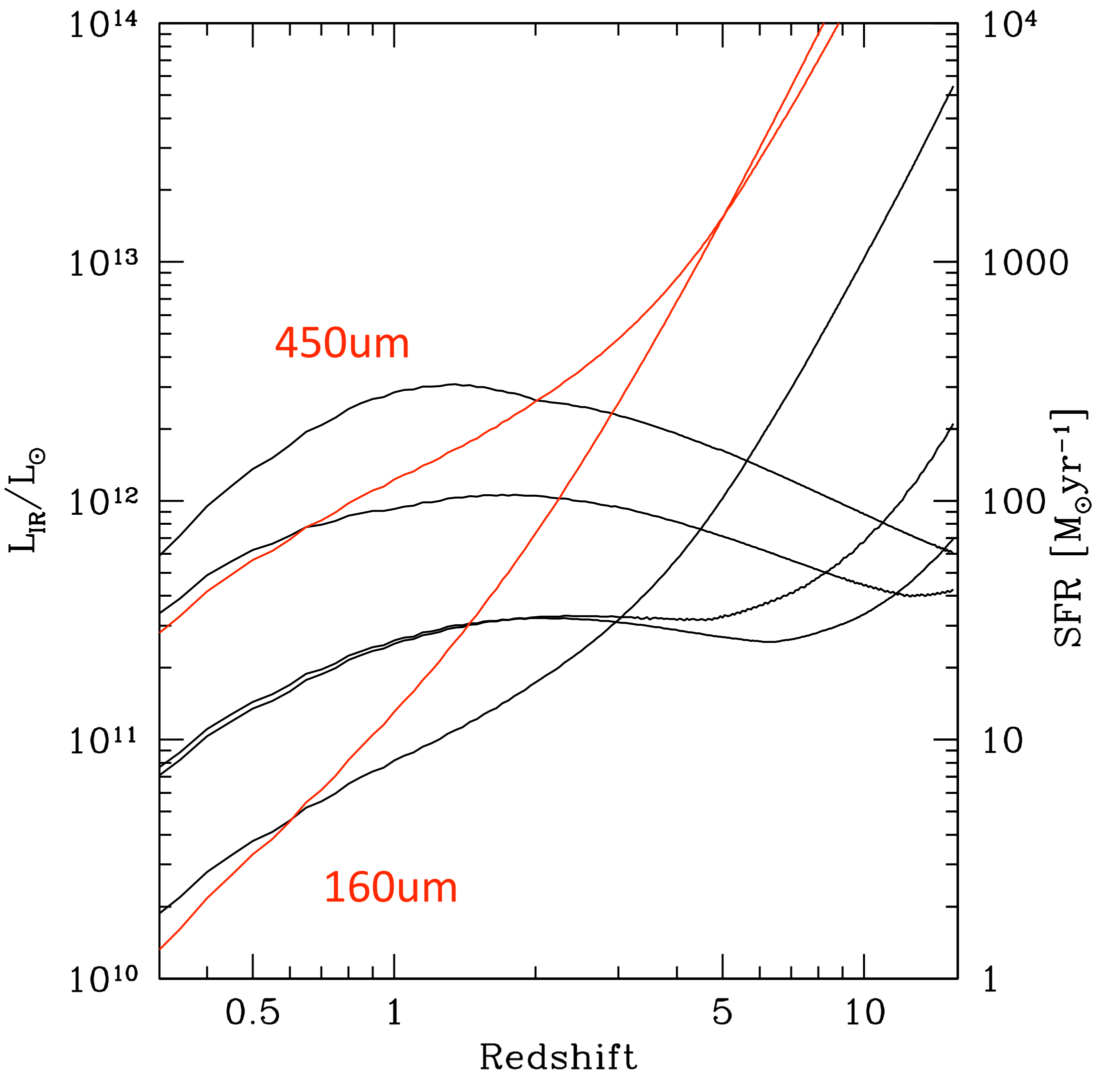
Detecting the z~6—7 LBGs will definitely need the full ALMA

How deep we can go with ALMA: SFRs/L_{IR}

Early Science: 16 antennas and 2 GHz full polarization bandwidth

(case for unresolved emission, compact configuration, **1 track of 8h**

Use Chary & Elbaz template shape for $L_{IR} = 10^{11}\ L_{\odot}$)

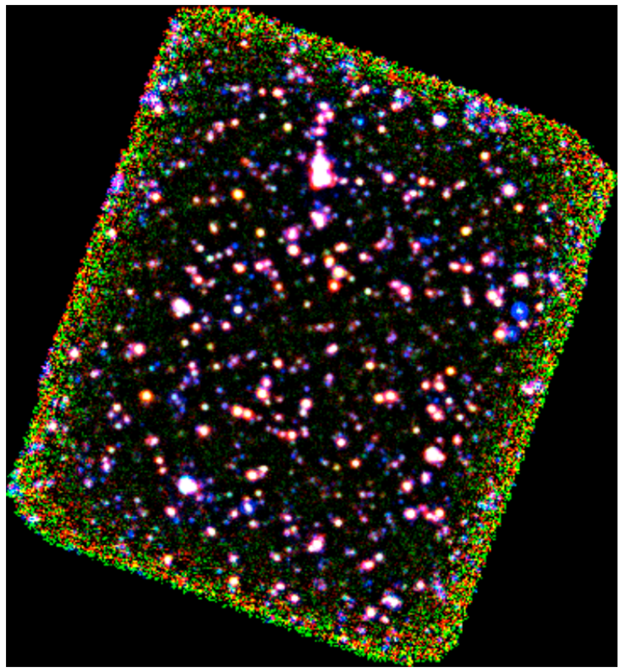


Herschel confusion limits

3mJy@160um   15mJy@450um

Submm detection of any HSO source

In less than 1 track (Early Science)



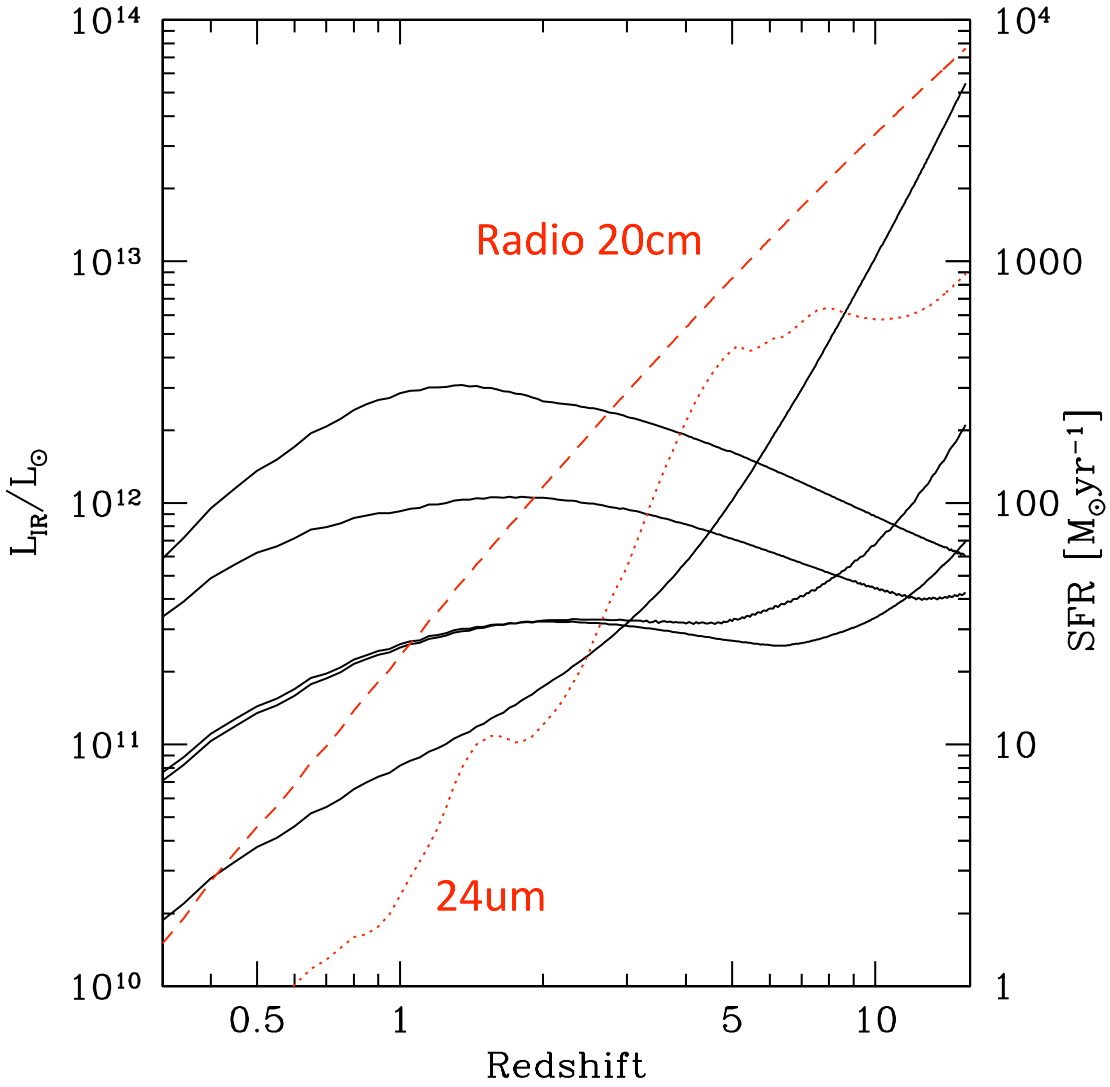
H-GOODS (PI Elbaz)

How deep we can go with ALMA: SFRs/L_{IR}

Early Science: 16 antennas and 2 GHz full polarization bandwidth

(case for unresolved emission, compact configuration, **1 track of 8h**

Use Chary & Elbaz template shape for $L_{IR} = 10^{11}\ L_\odot$)



GOODS depth radio/24um

20uJy@24um 15uJy@1.4GHz

Most sources easily within reach

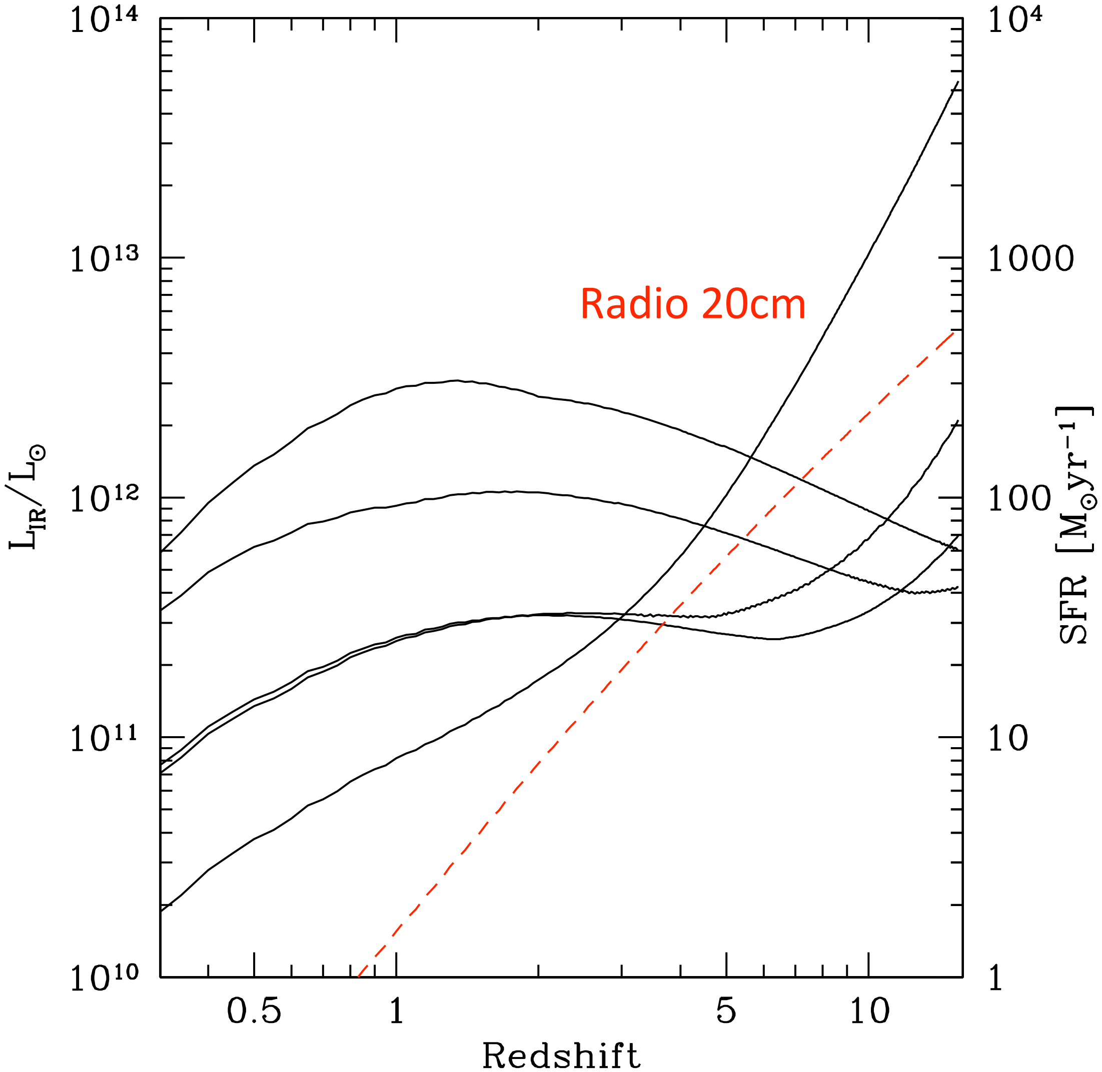
Expecially at high-z

How deep we can go with ALMA: SFRs/L_{IR}

Early Science: 16 antennas and 2 GHz full polarization bandwidth

(case for unresolved emission, compact configuration, **1 track of 8h**

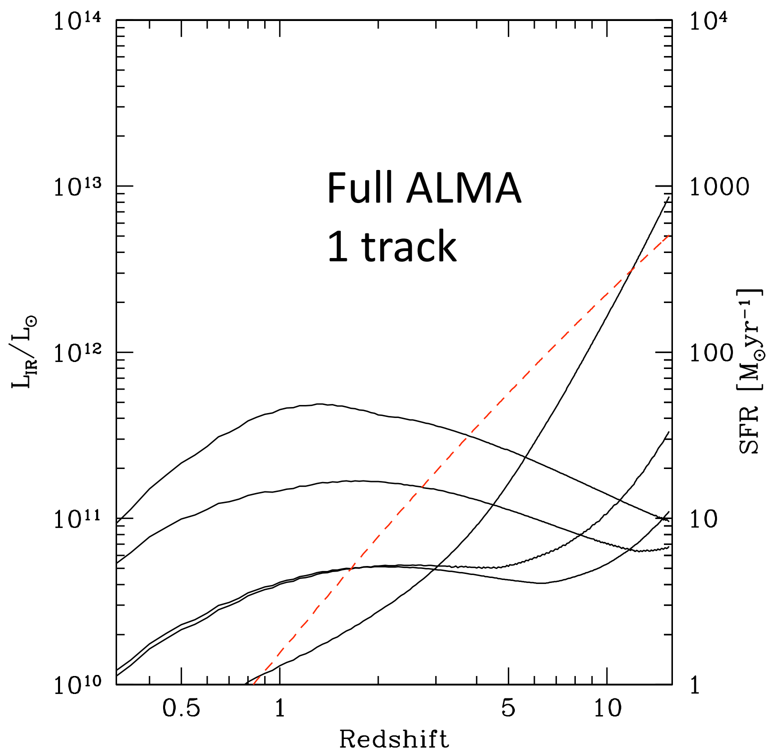
Use Chary & Elbaz template shape for $L_{IR} = 10^{11}\ L_{\odot}$)



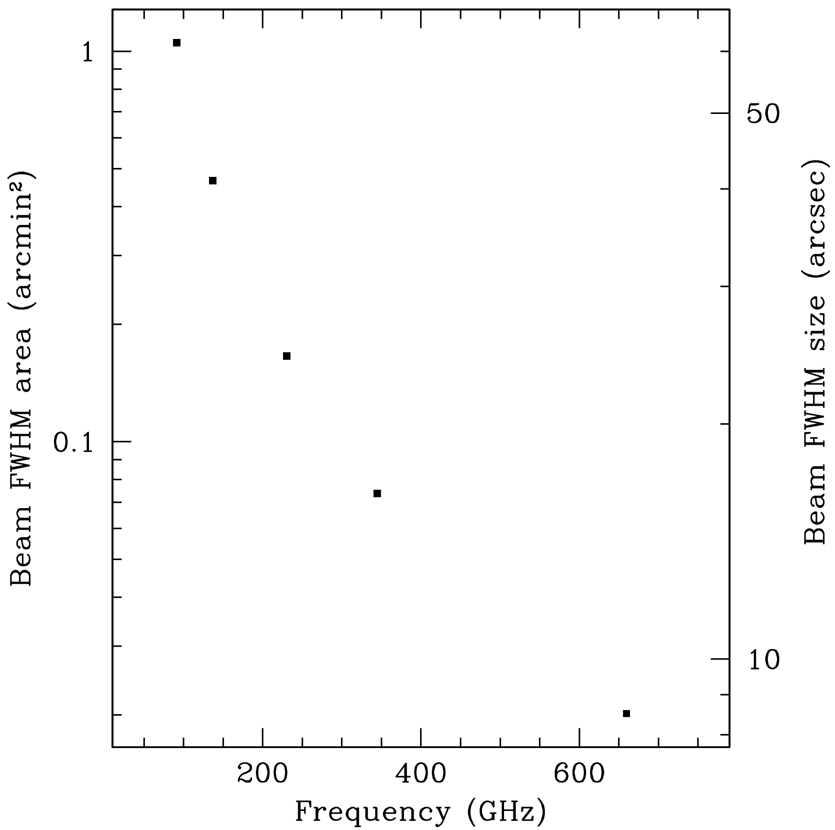
EVLA (full capability)

1uJy@1.4GHz

Deeper than ALMA Early Science capabilities



How wide we can go with ALMA: not a survey machine (?)



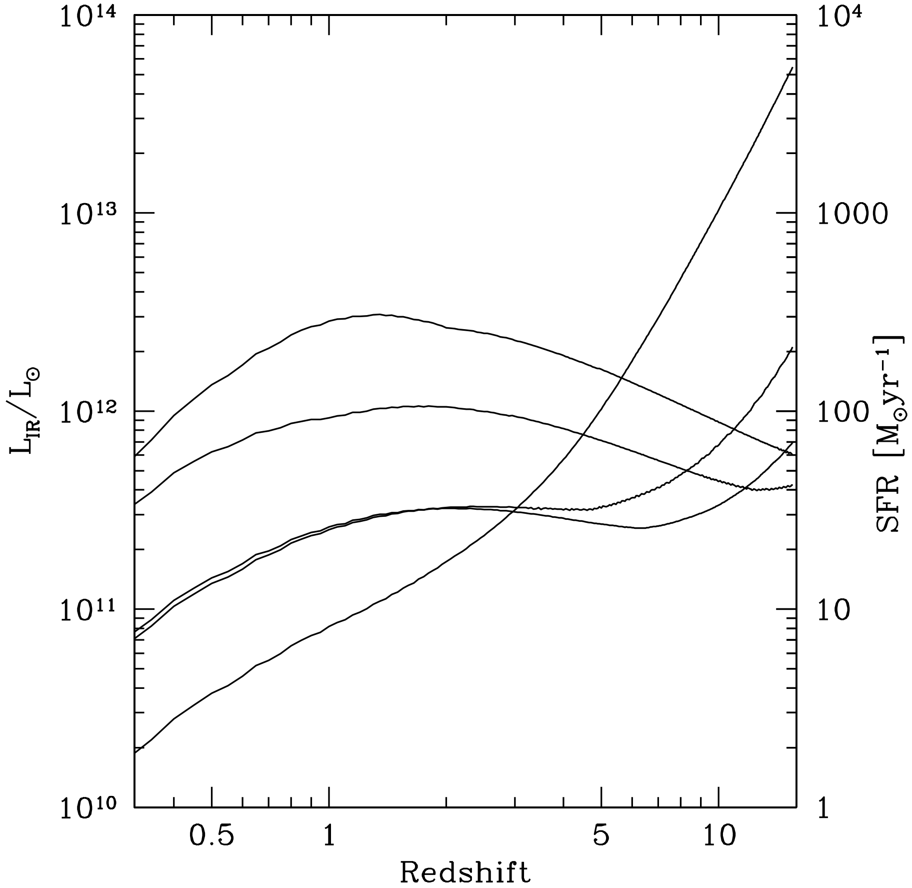
Number of Pointings	90 GHz (3mm)	345 GHz (850um)
UDF 10 arcmin^2	10	150
GOODS 300 arcmin^2	300	4500
COSMOS 2 deg^2	7200	10^5

But, e.g., full GOODS-S field to 20mJy@450 (all Herschel-SPIRE sources above confusion):
→~150h of integration time with 16 antennas (and subarcsec resolution versus 30" Herschel)
→ <10h with 50 antennas

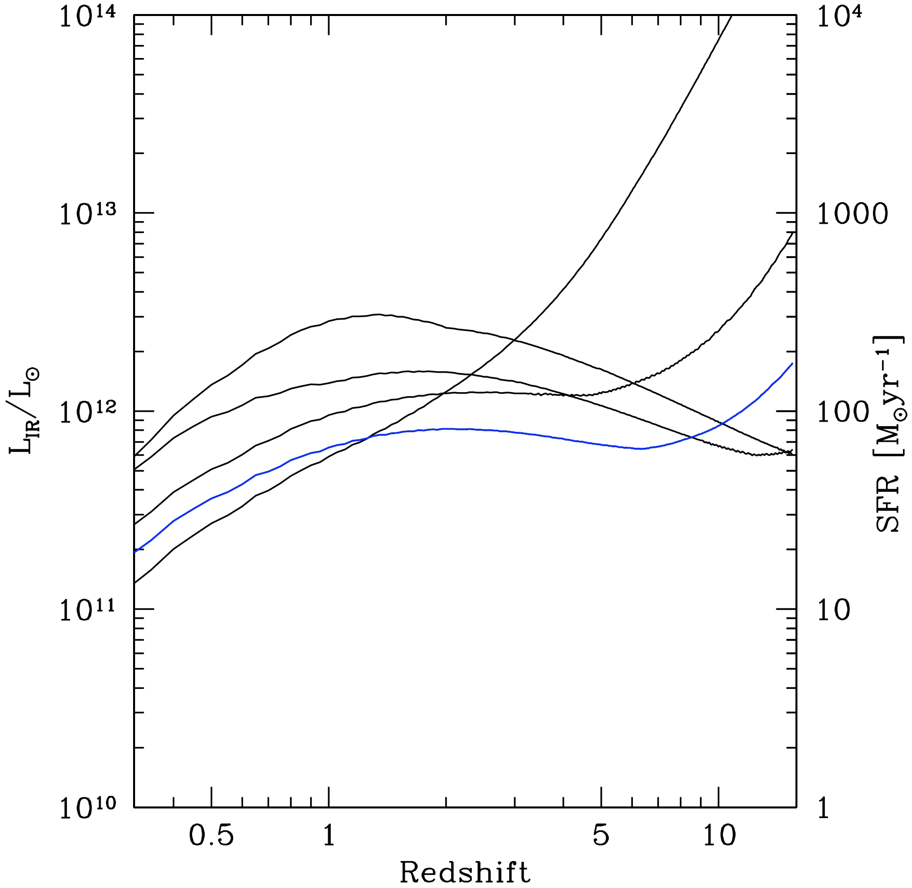
How wide we can go with ALMA: not a survey machine (?)

Which is the best band for continuum surveys ?

1 track / 1 pointing



1 track / 1 arcmin^2



Most efficient band for surveys: 1mm (or 450um at z<1). All ULIRGs any z, 1track/1arcmin^2

But overall, differences are not big, at z>2 850um to 3mm are comparable

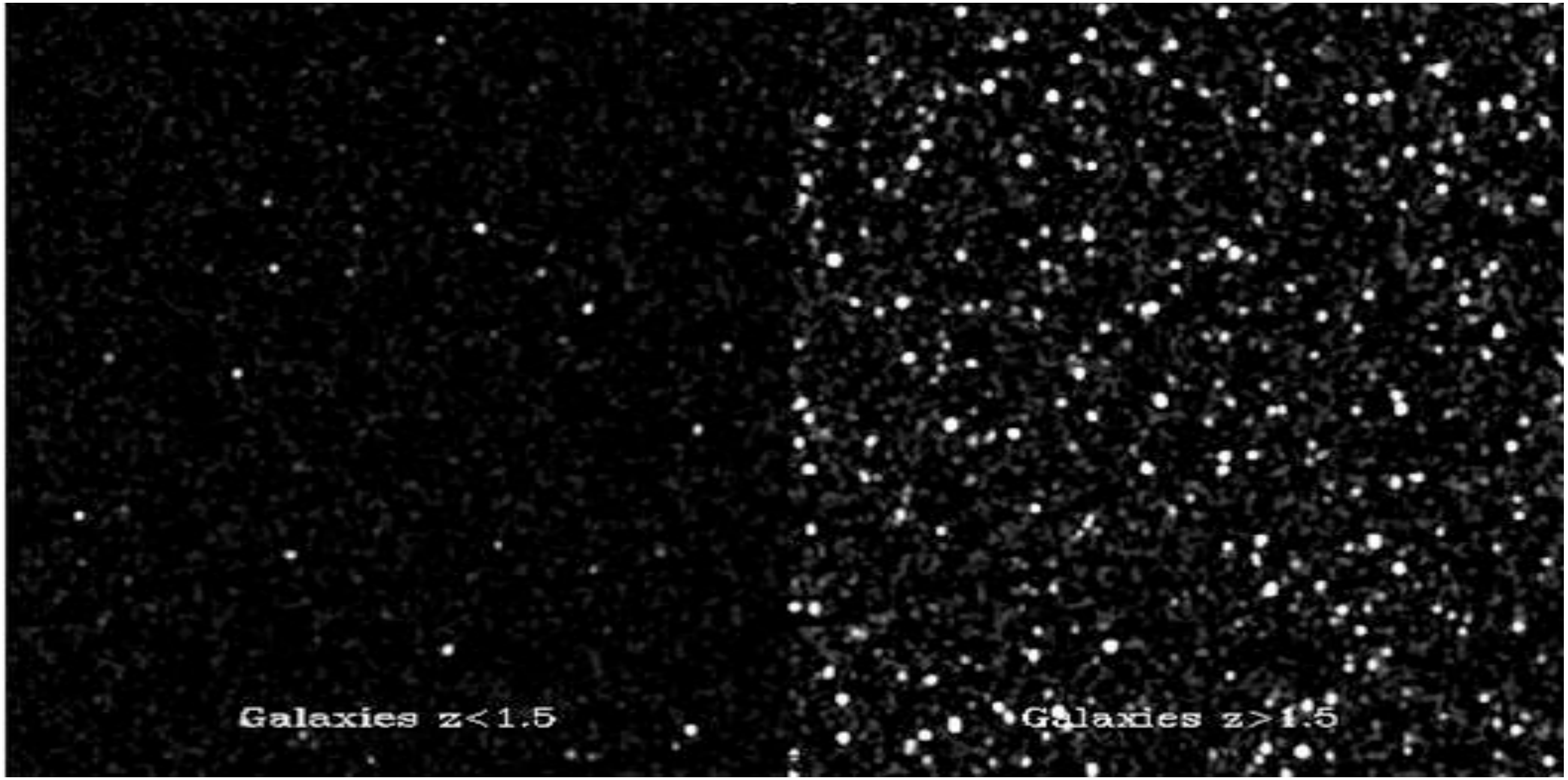
→ Multiband surveys should provide redshift sensitive informations for reasonable fraction

Optical Deep Field

z<1.5

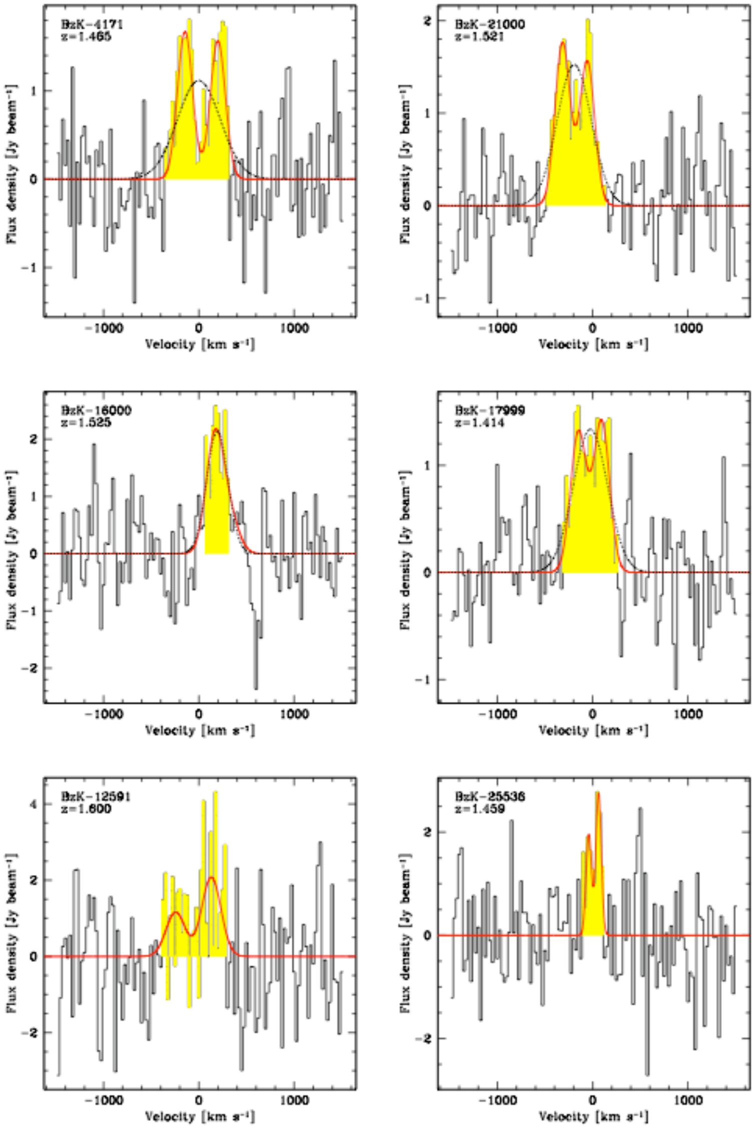
z>1.5

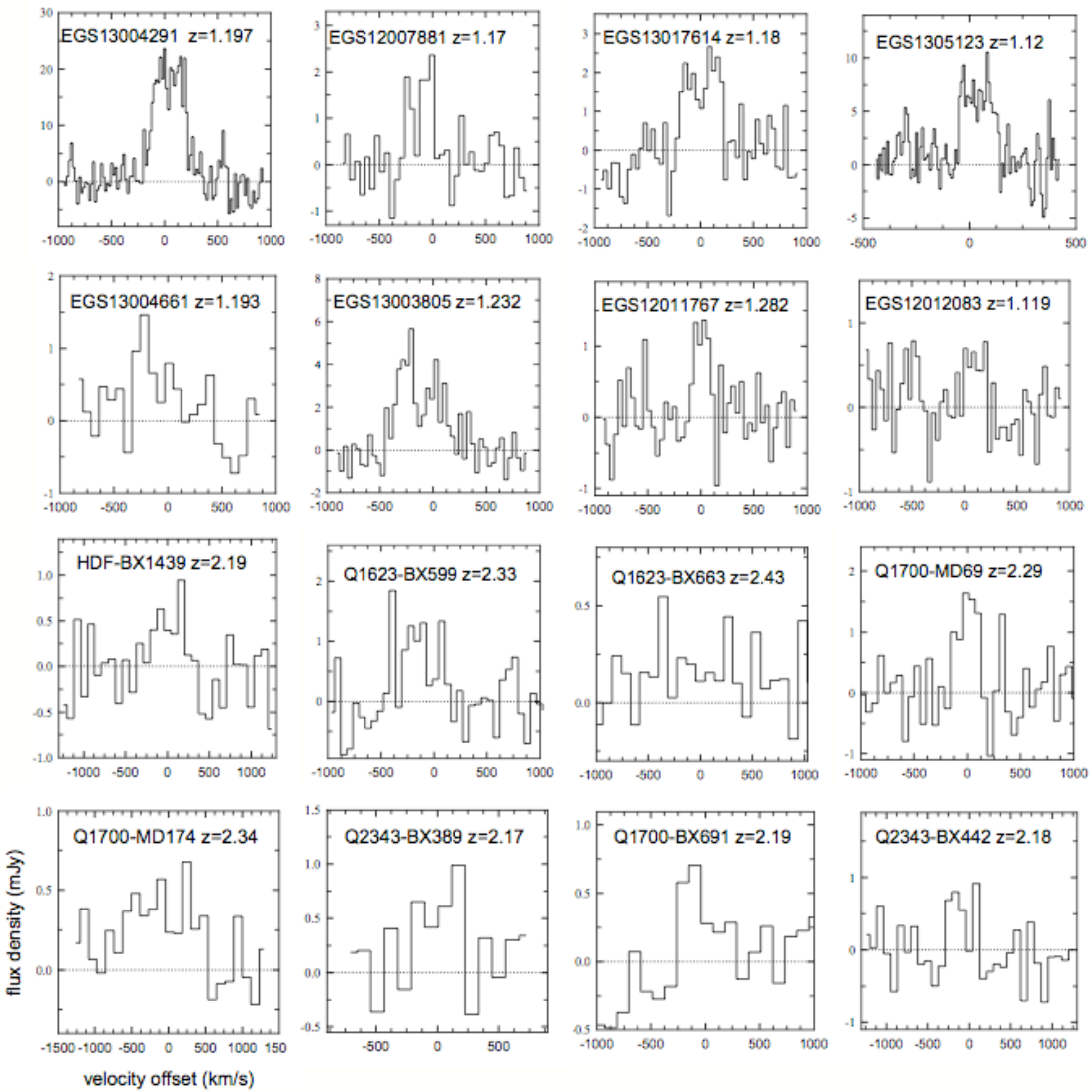
(Hypothetical) Submillimeter Deep Field



z<1.5 z>1.5

Molecular gas in massive galaxies at z=1.5-2.5





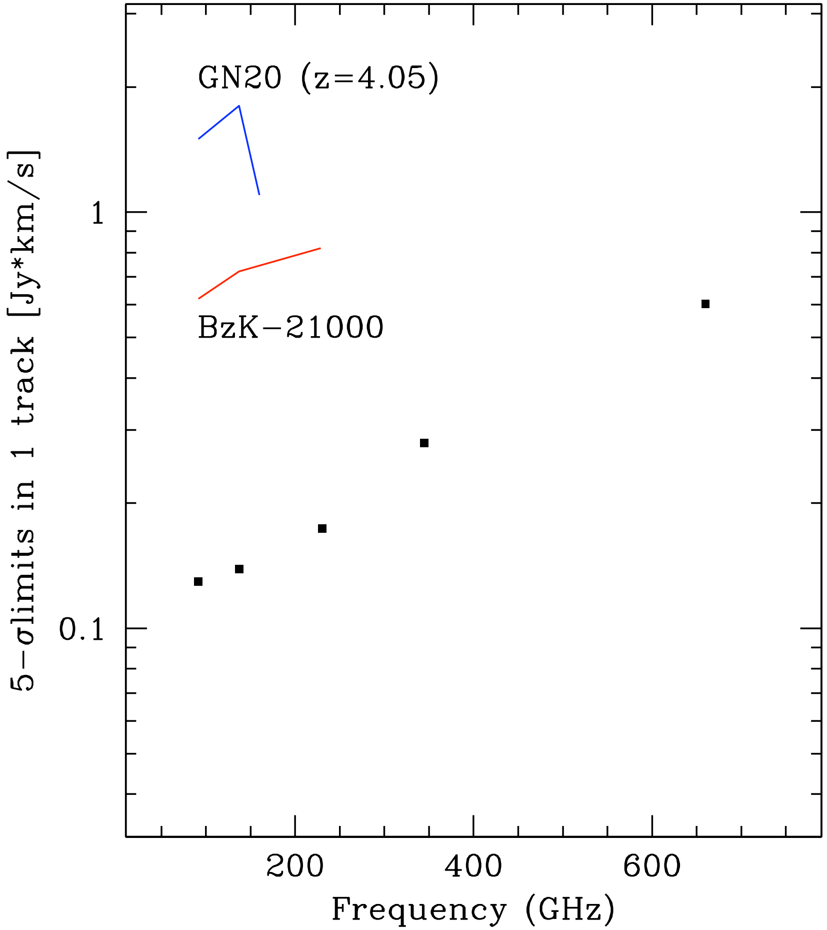
Daddi et al. 2008; 2010

Tacconi et al. 2010

How deep we can go with ALMA: Molecular lines

<u>Early Science: 16 antennas and 2 GHz full polarization bandwidth</u>

(case for unresolved emission, compact configuration, **1 track of 8h)**

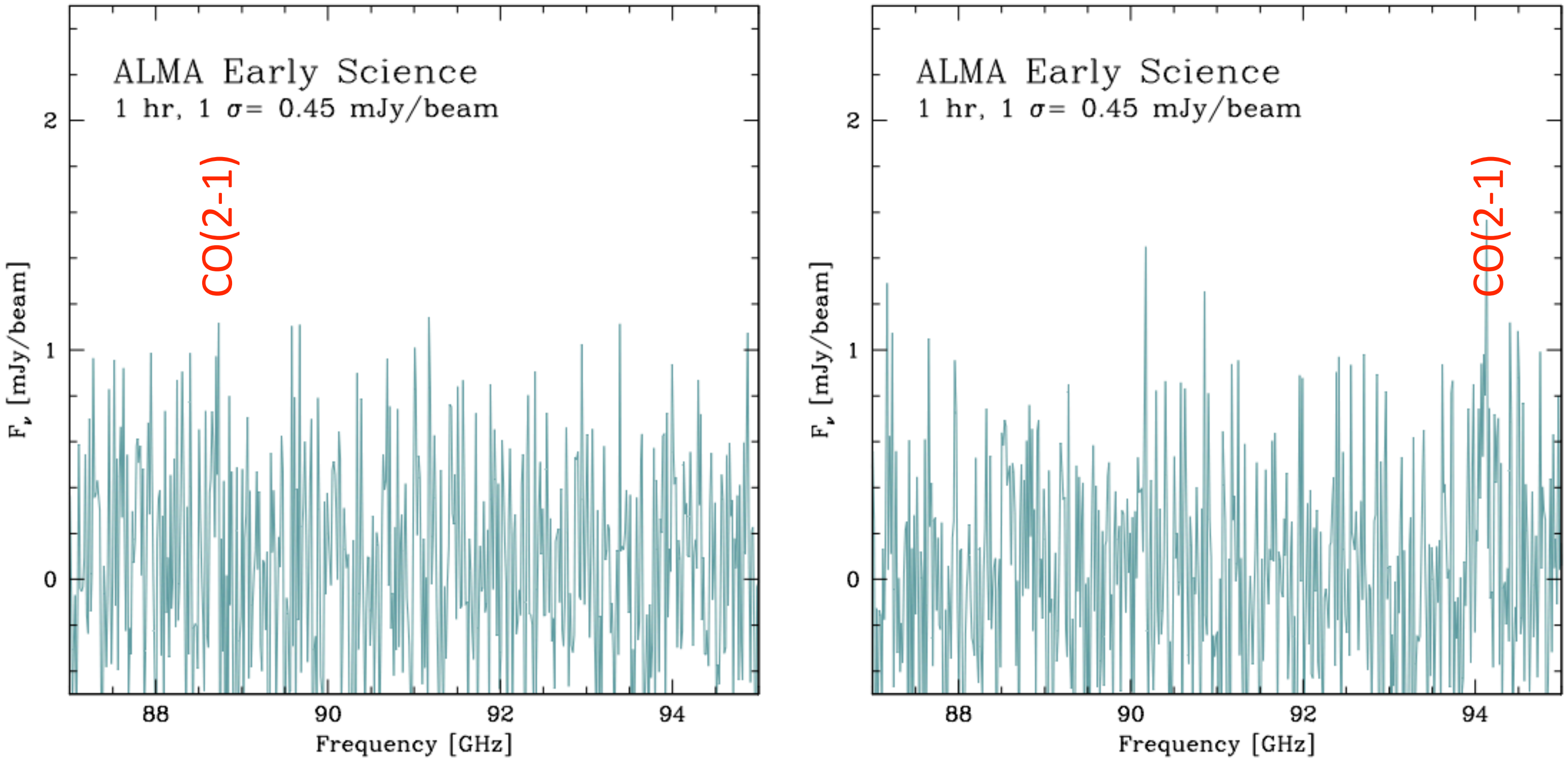


Reach ~0.1-0.2 Jy*km/s at 1—3mm
0.5 Jy*km/s at 450um

Objects studied so far will be easy to detect

Massive Galaxies at z=1.5-2.5 --- ALMA simulations

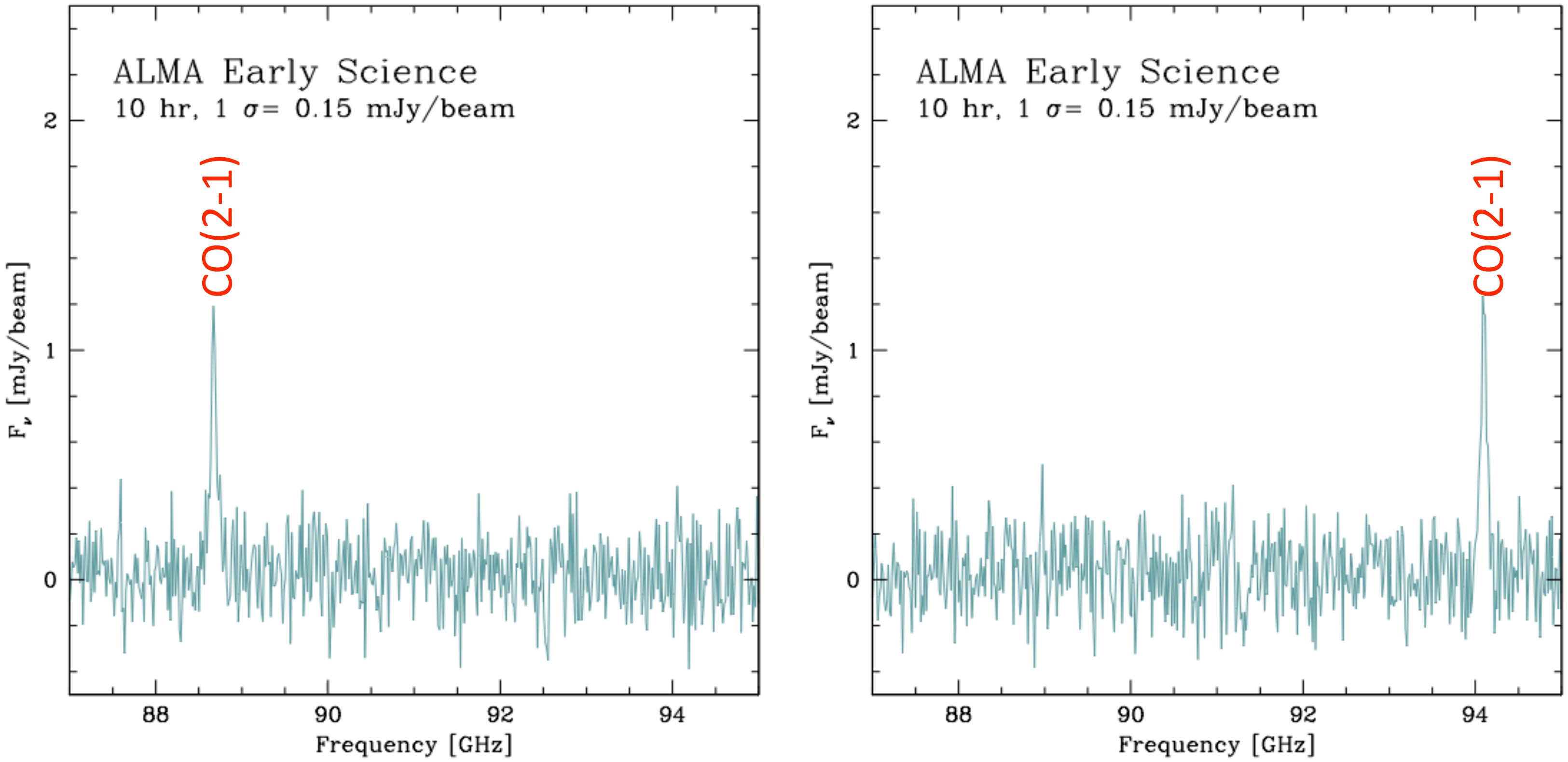
input: BzK galaxy at z~1.5 with CO(2-1) peak: 1mJy
[typical values in Daddi, Tacconi for BzK galaxy with SFR~100$M_{sun}yr^{-1}$]



2-3 sigma detection in 1h (2-3 times faster than PdBI)

Massive Galaxies at z=1.5-2.5 --- ALMA simulations

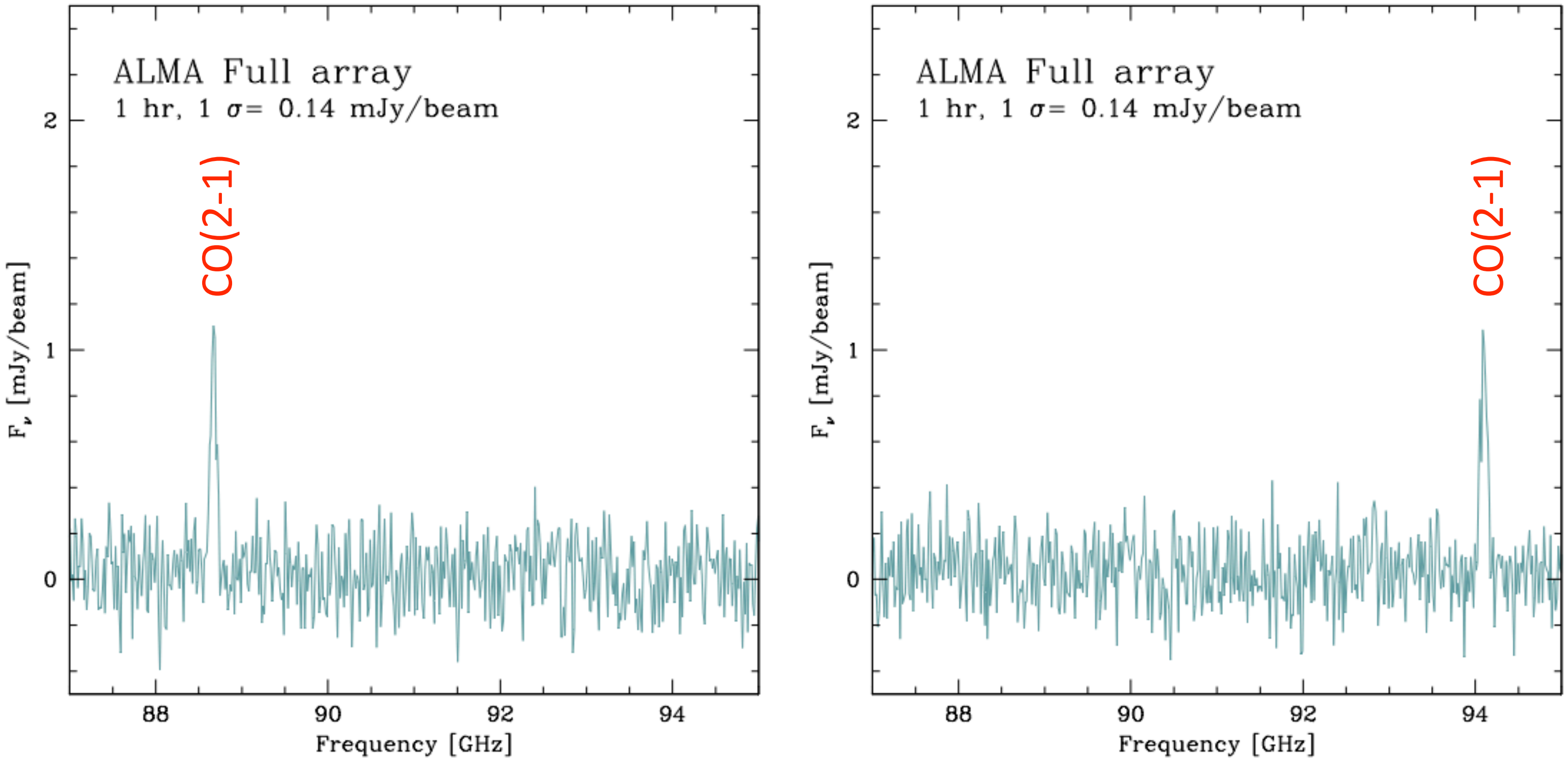
input: BzK galaxy at z~1.5 with CO(2-1) peak: 1mJy
[typical values in Daddi, Tacconi for BzK galaxy with SFR~100$M_{sun}yr^{-1}$]



10 sigma detection in 1 track

Massive Galaxies at z=1.5-2.5 --- ALMA simulations

input: BzK galaxy at z~1.5 with CO(2-1) peak: 1mJy
[typical values in Daddi, Tacconi for BzK galaxy with SFR~100$M_{sun}yr^{-1}$]

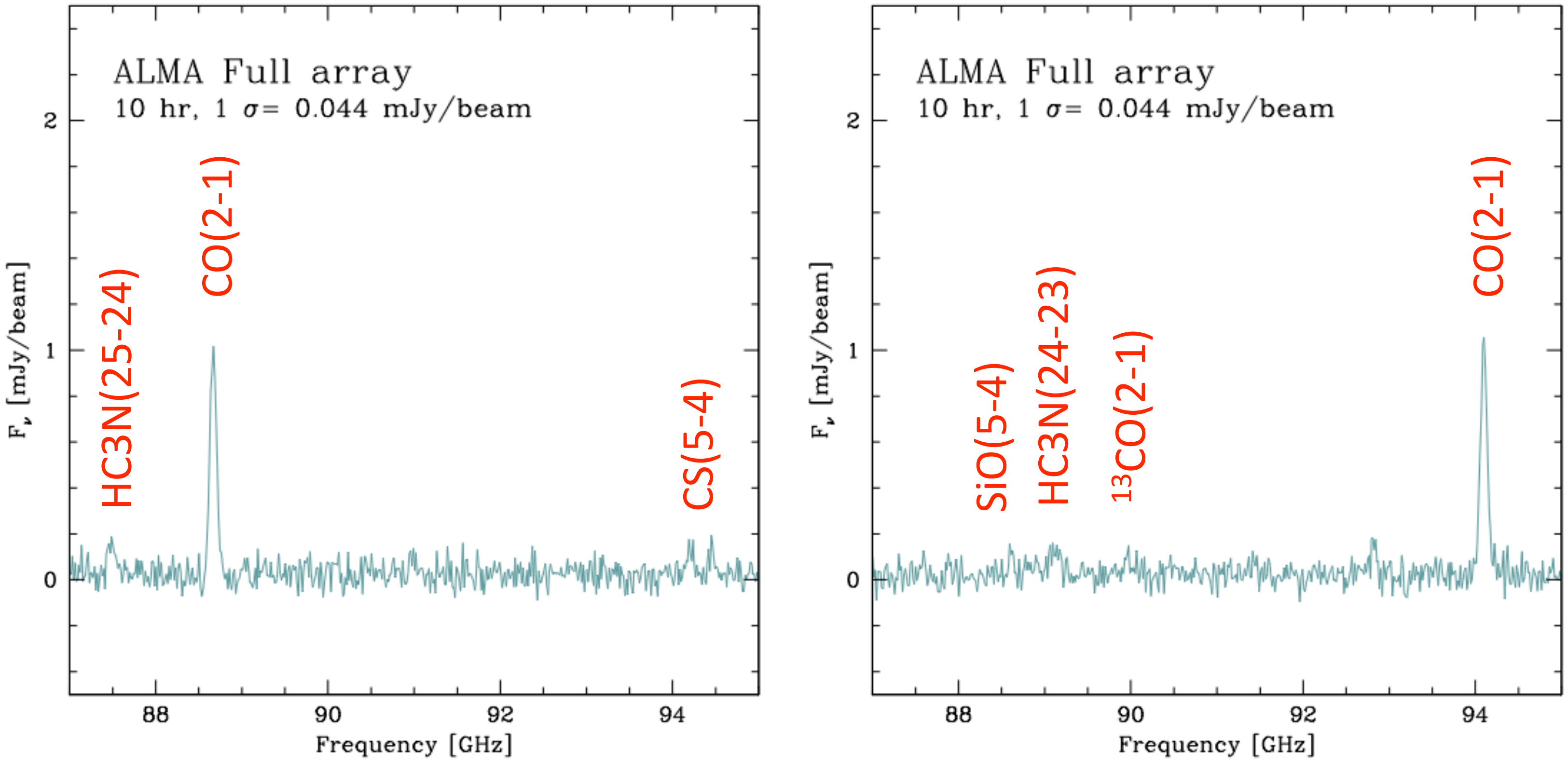


10 sigma detection in 1 hour (20-30 times faster than PdBI)

Massive Galaxies at z=1.5-2.5 --- ALMA simulations

input: BzK galaxy at z~1.5 with CO(2-1) peak: 1mJy

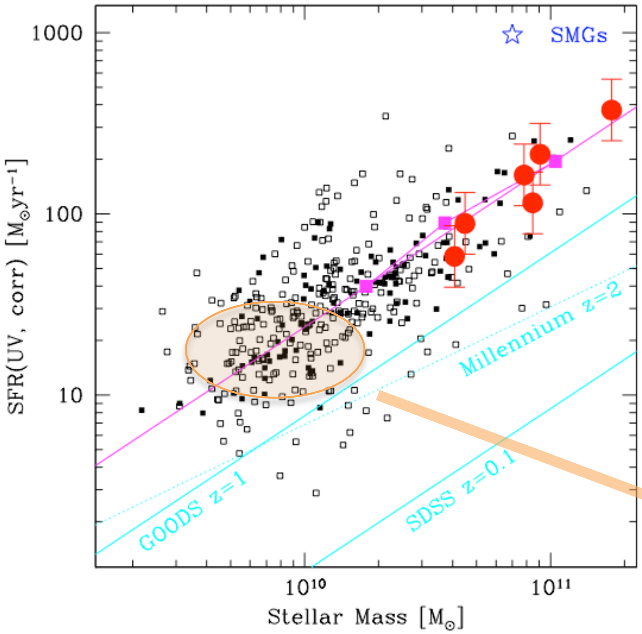
[typical values in Daddi, Tacconi for BzK galaxy with SFR~100$M_{sun}yr^{-1}$, M_{H2}~ few 10^{10} M_{sun}]



10h with full ALMA → multiple serendipitous CO detections in any field of view !!

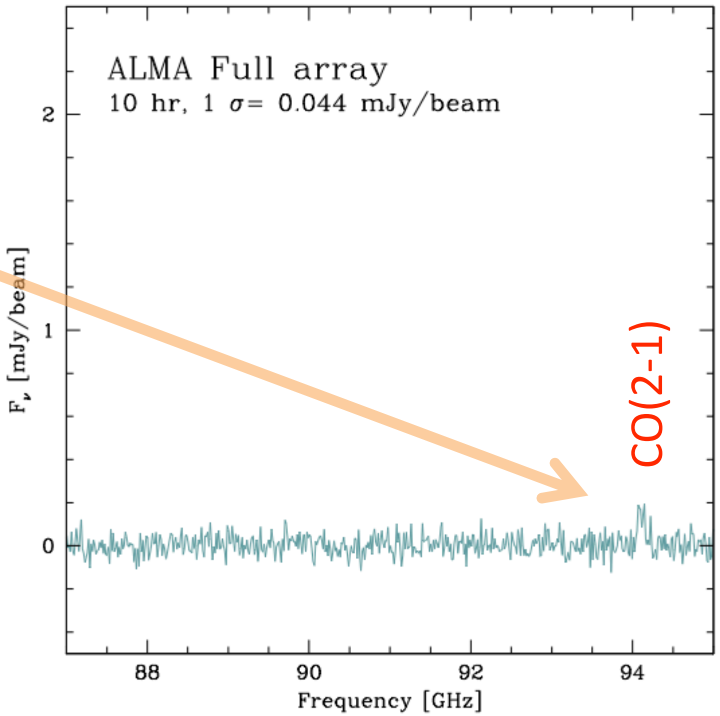
Less massive Galaxies at z=1.5-2.5 --- ALMA simulation

so far, only the brightest BzKs have been looked at:



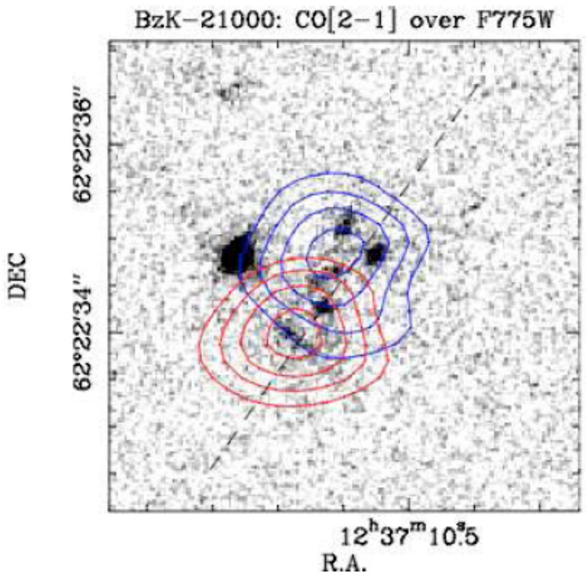
Daddi et al. 2010

input: same as before, but
SFR~20 M_{sun} yr^{-1}, M_{H2}=few x 10^9 M_{sun}

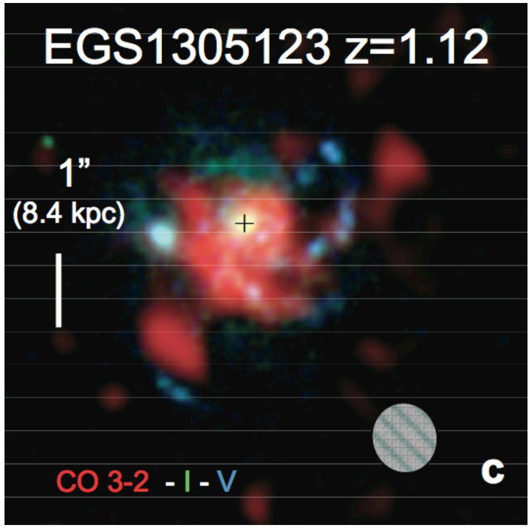


Massive Galaxies at z=1.5-2.5 --- Resolving the Gas

science drivers: resolved dynamical analysis – resolved star formation law
-- evidence for interaction



Daddi et al. 2010

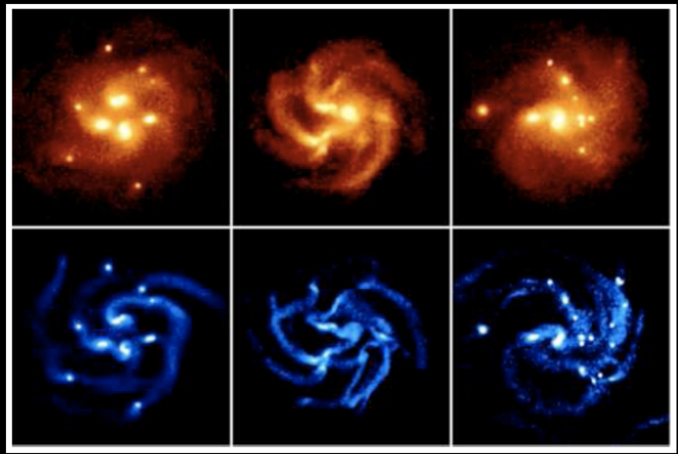


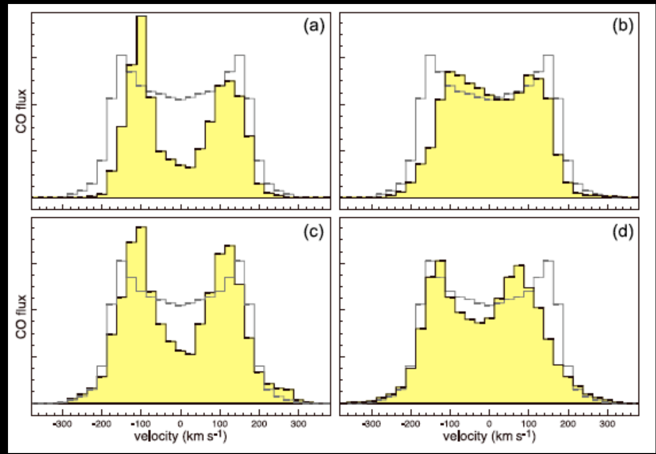
Tacconi et al. 2010

Sources are extended on ~1” scales.
1kpc resolution (0.15”) → ~50 independent beams

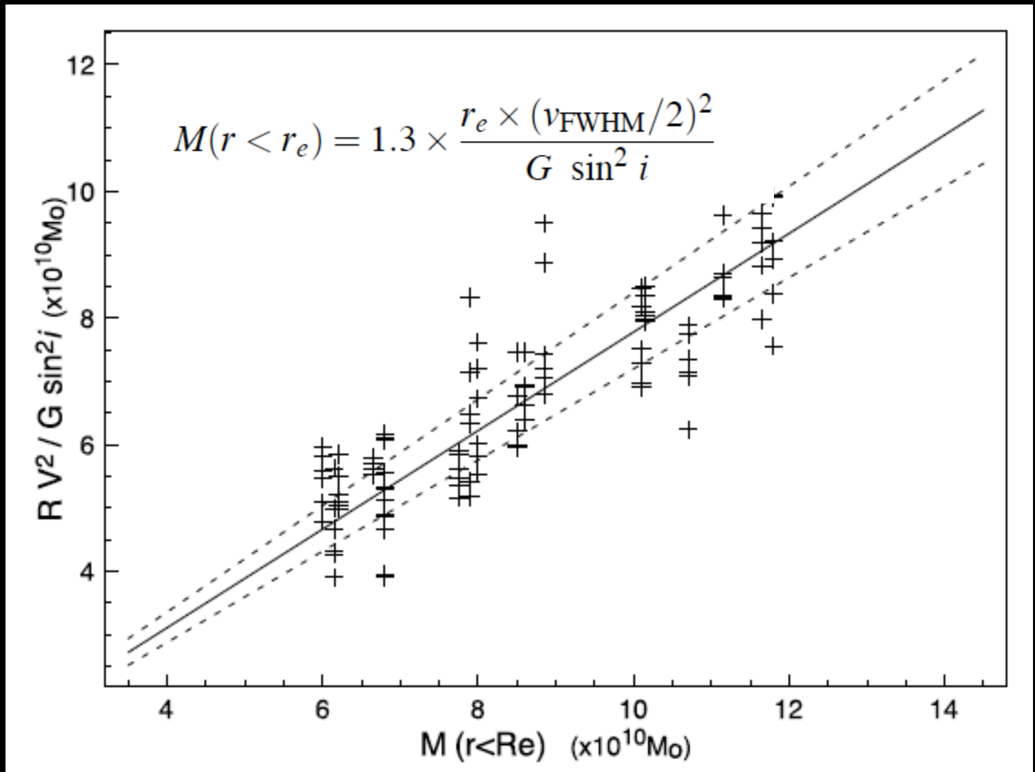
previous example: S/N=25 in 50 km/s channel for the full source.

Calibrating Mdyn/α_{CO} estimate through clumpy disks simulations (Daddi et al 2010)





Bournaud
Elmegreen
Elmegreen
2007

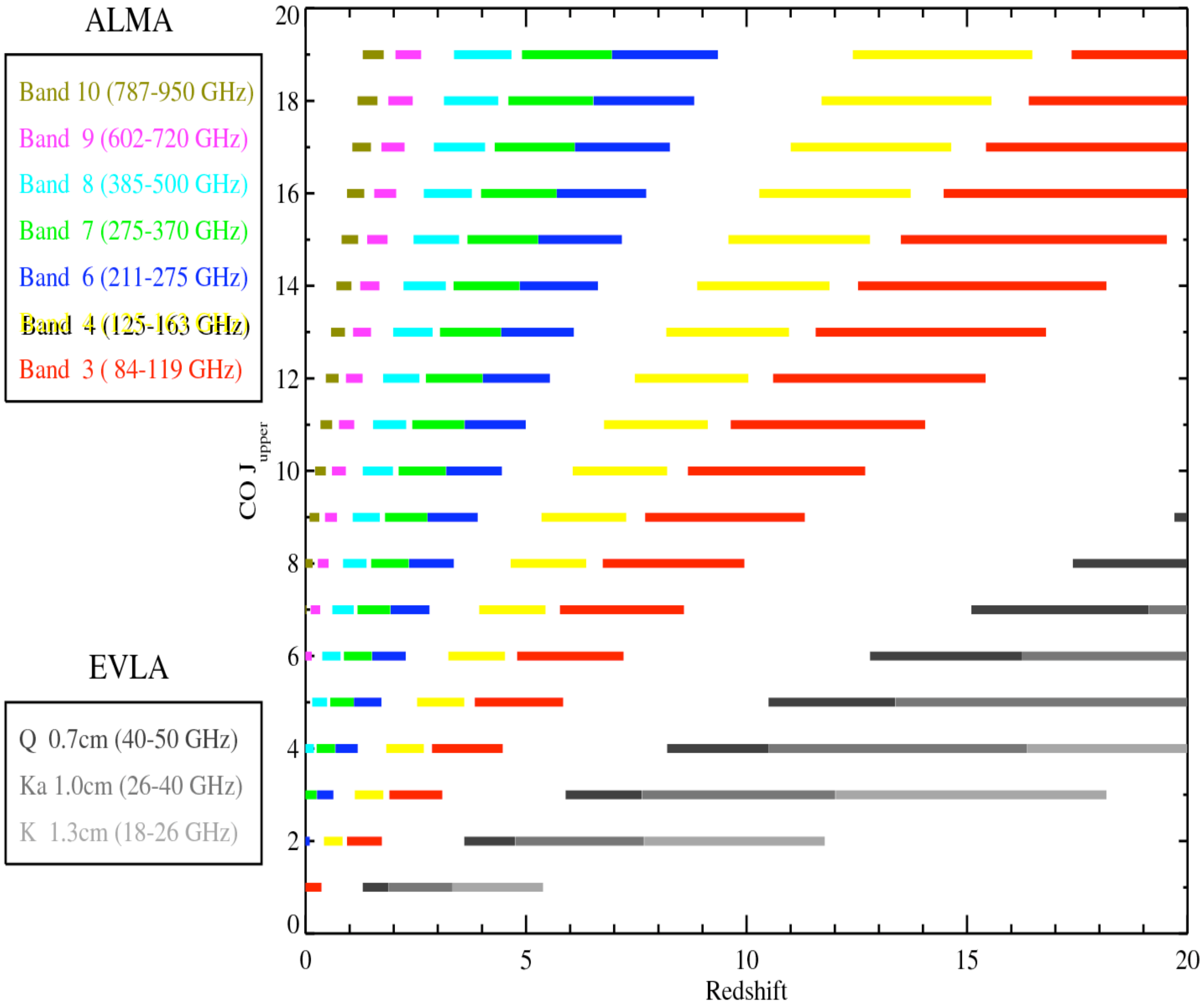


We ‘observed’ the models as the real data

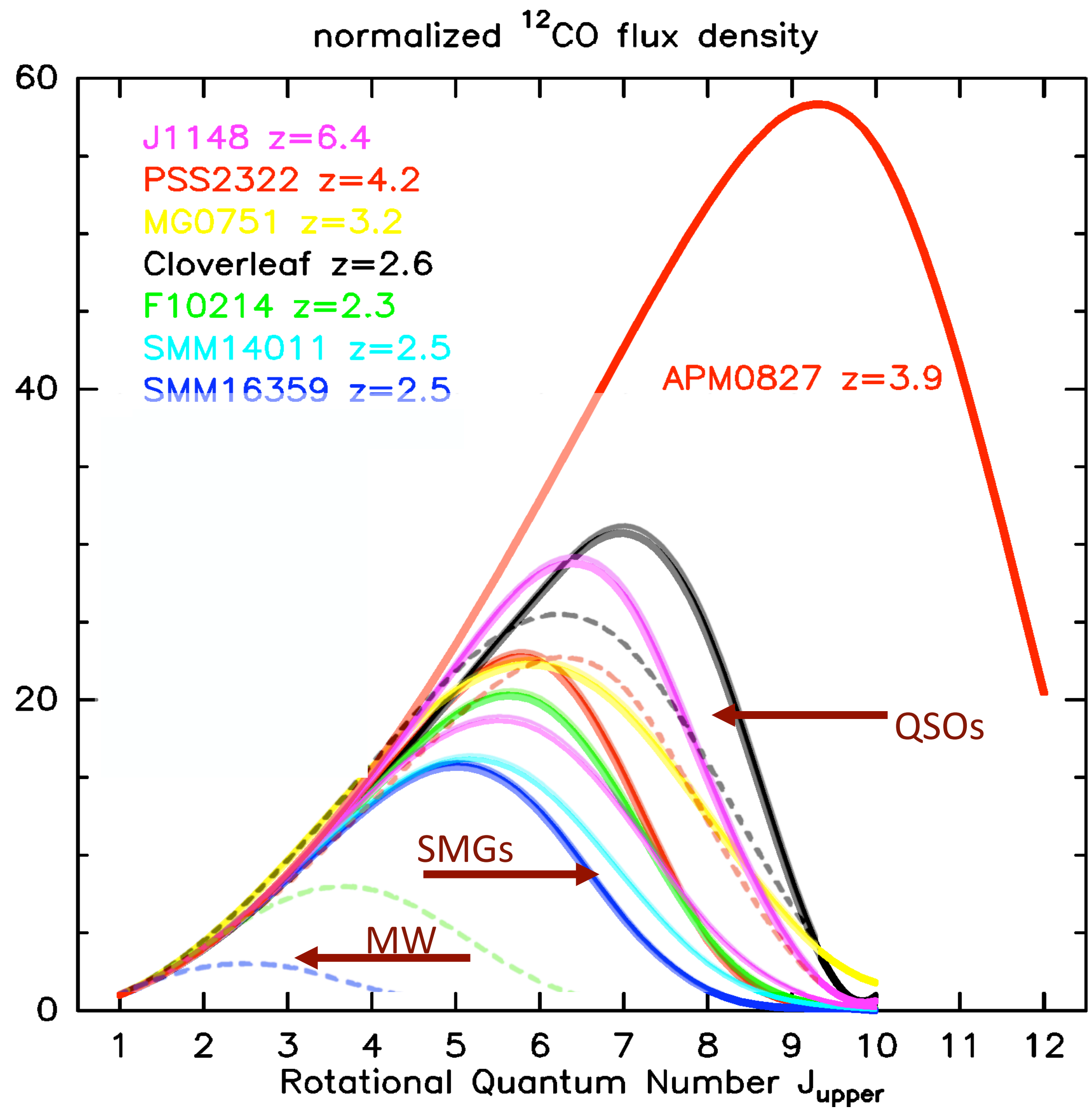
r_e/sin i through Sersic fits
v_{FWHM} (2-gaussian fits)

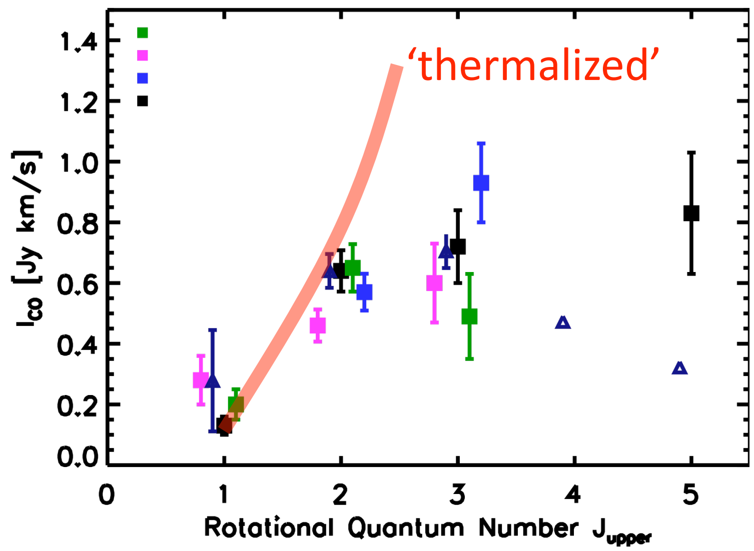
Account for dispersion 12%

CO Line redshift coverage for ALMA and EVLA



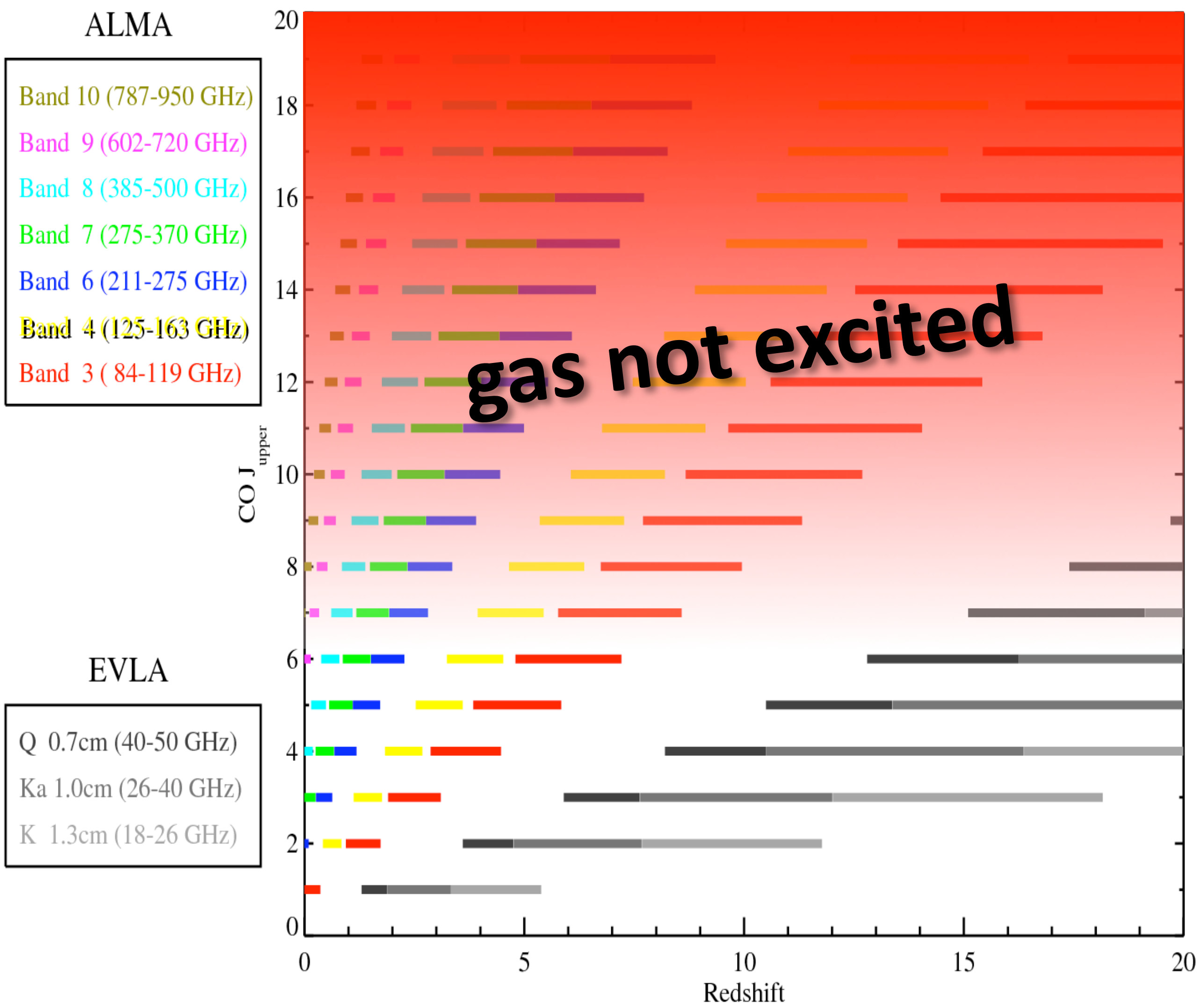
Excitation is important



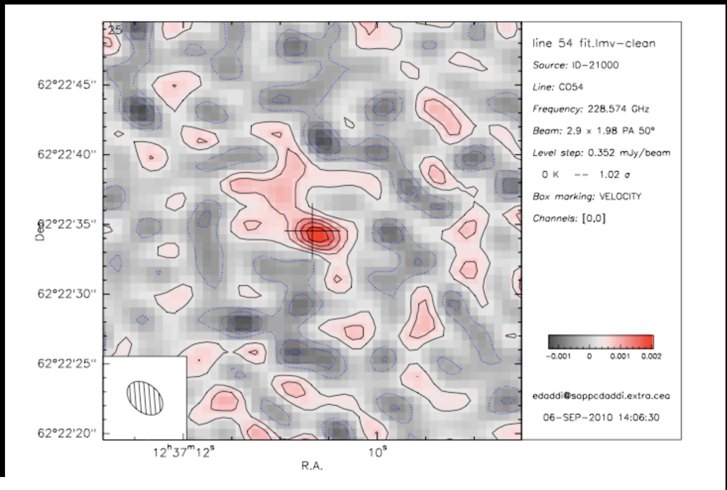


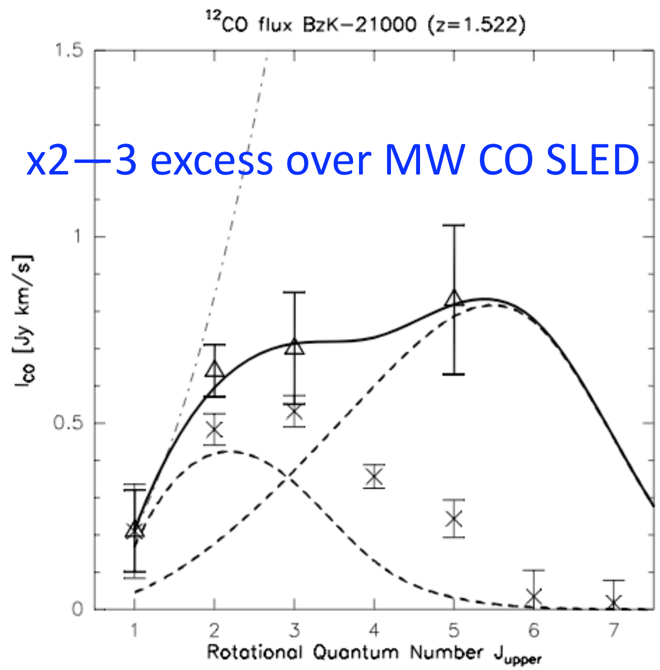
BzK excitation (Dannerbauer et al. 2009; and in preparation)

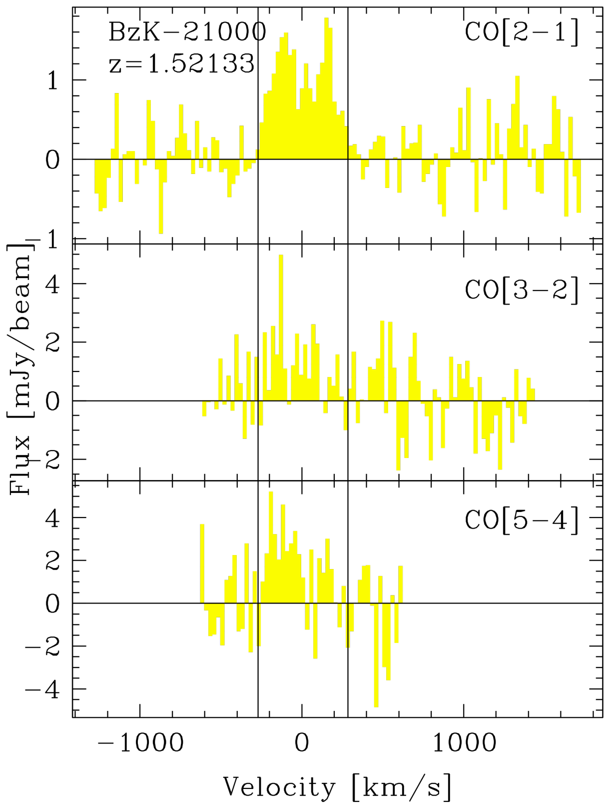
CO Line redshift coverage for ALMA and EVLA



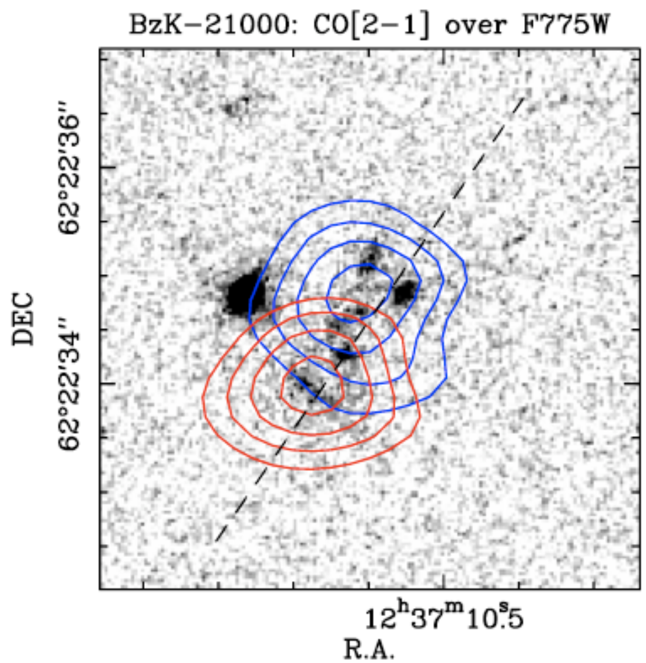
BzK-21000 z=1.521 we tried to look at CO54, detected!







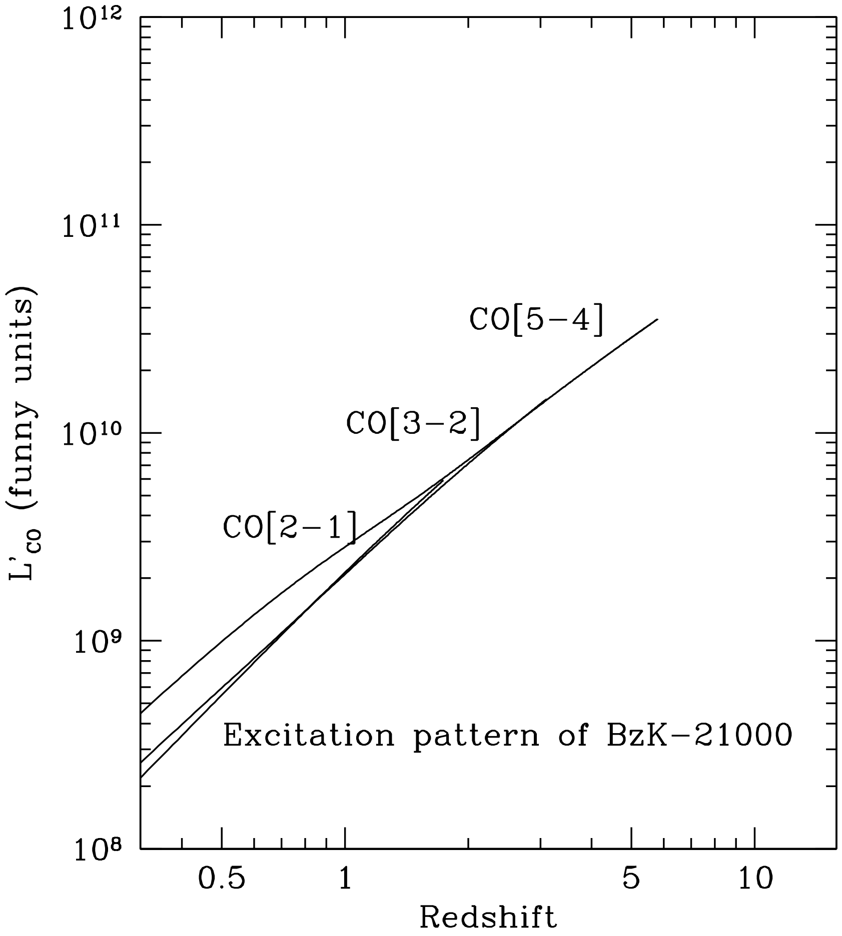
Likely we are detecting
The dense gas in the
clumps

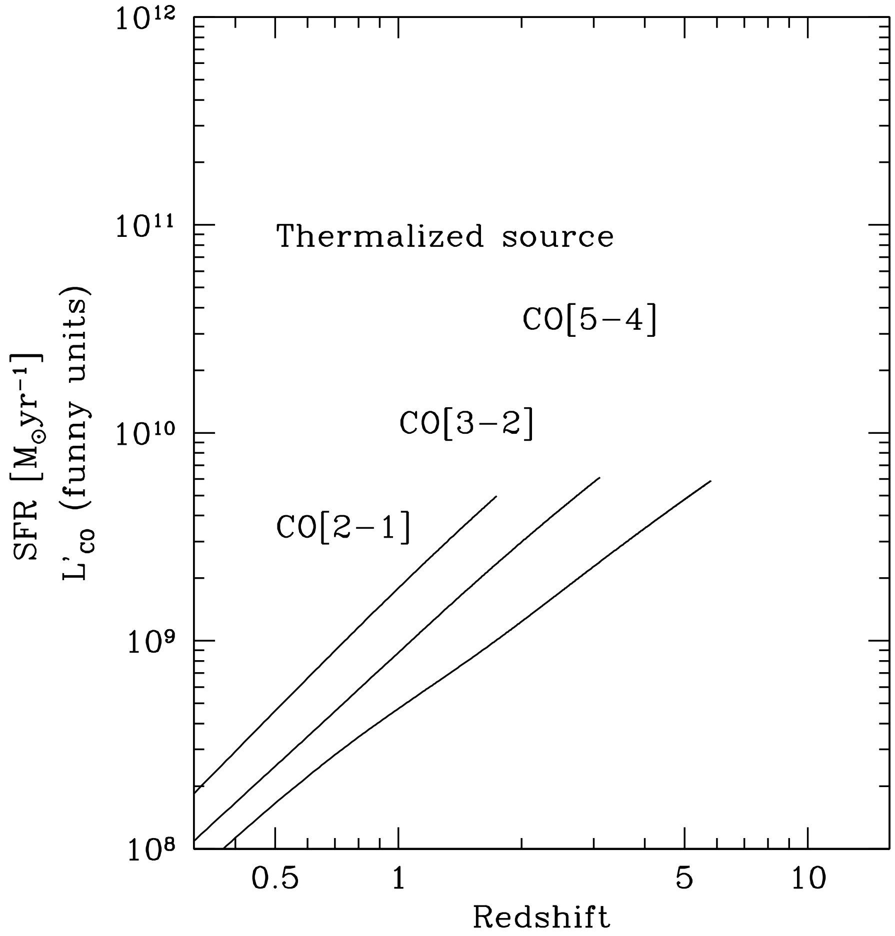


How deep we can go with ALMA: Molecular lines

Early Science: 16 antennas and 2 GHz full polarization bandwidth

(case for unresolved emission, compact configuration, **1 track of 8h)**

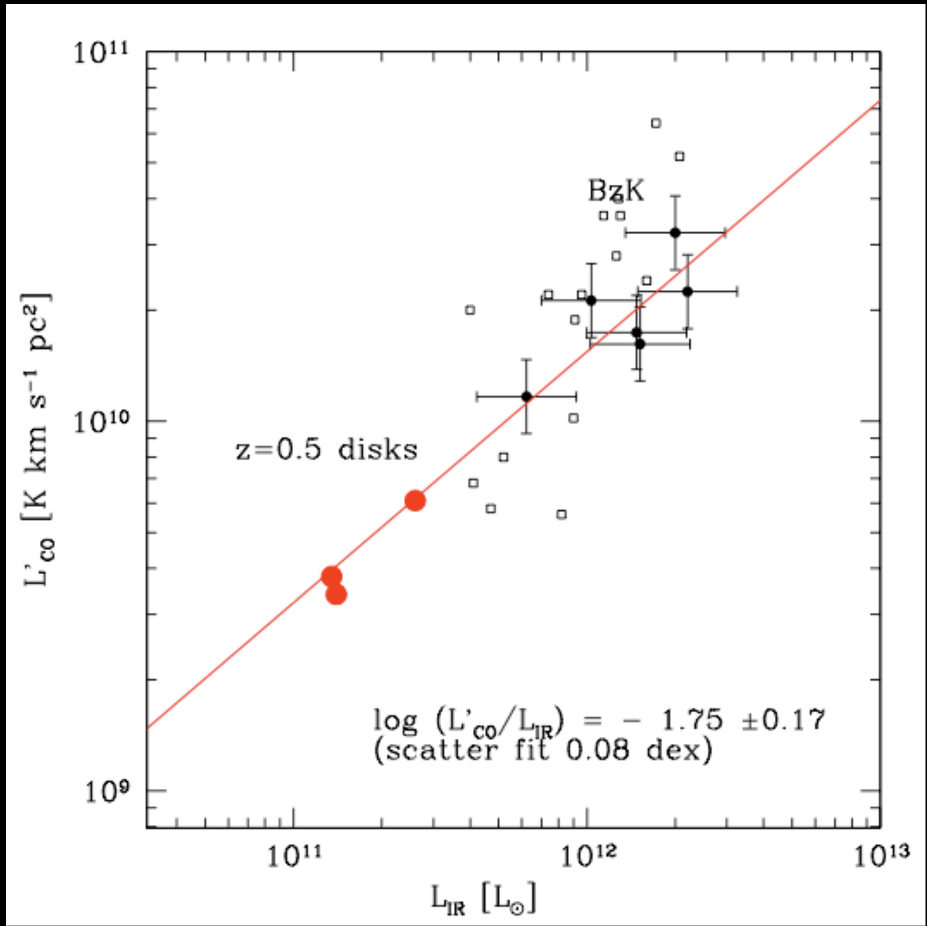




Normal galaxies might be hard to detect at high redshift z>3 (due to the low excitation)

Full ALMA will get us 3x deeper at fixed time → 3×10^{10} in $M_\odot$ gas at z=5 in 1 track

Amazing regularity in the gas luminosity



Detections from Tacconi et al., Genzel et al., are consistent (when correcting for a x2 excitation term as derived by Dannerbauer et al (2009; and in preparation)

→Normal high-z galaxies are luminous in CO and gas rich

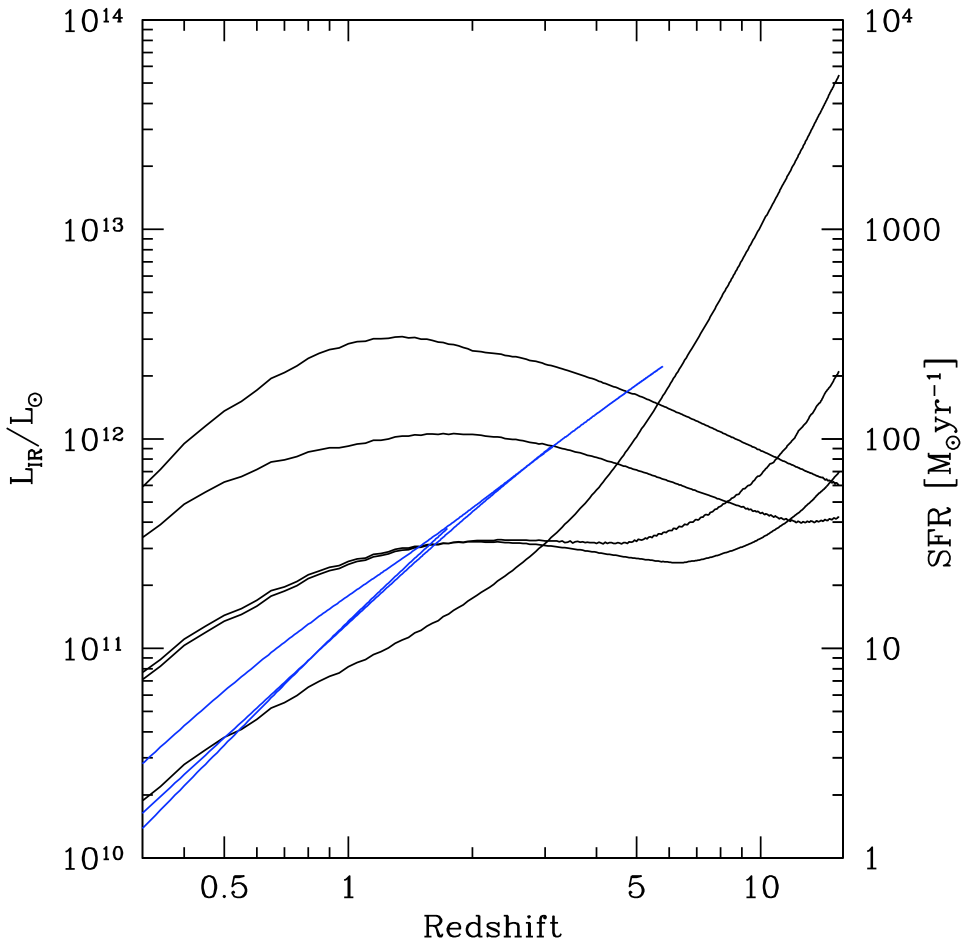
But notice: both axis require a factor to convert to physical props: α_{CO} (L'_{CO}->M_{gas}) and IMF (L_{IR}-> SFR)

Small scatter → both vary little in relative terms

How deep we can go with ALMA: Molecular lines

Early Science: 16 antennas and 2 GHz full polarization bandwidth

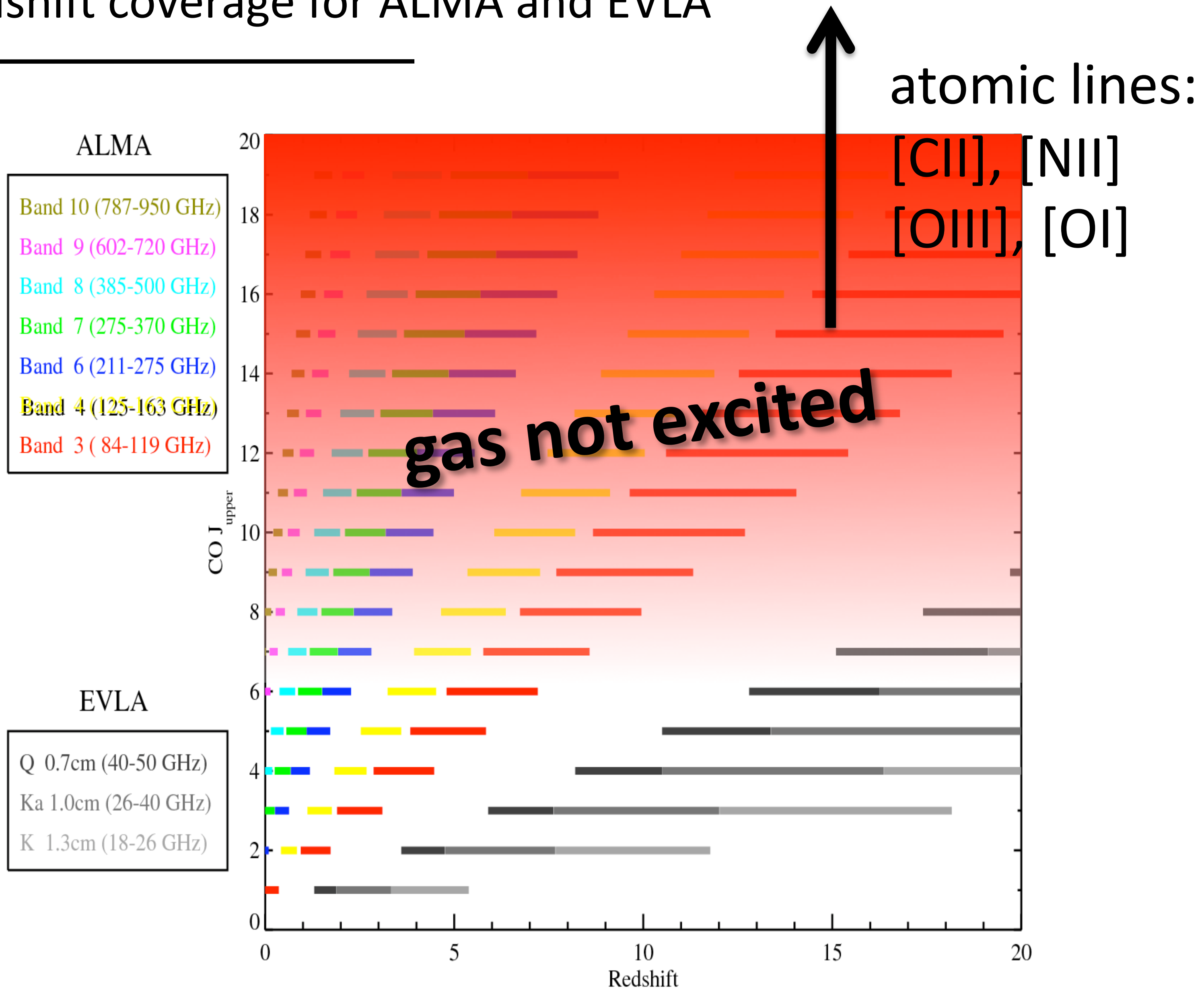
(case for unresolved emission, compact configuration, **1 track of 8h)**



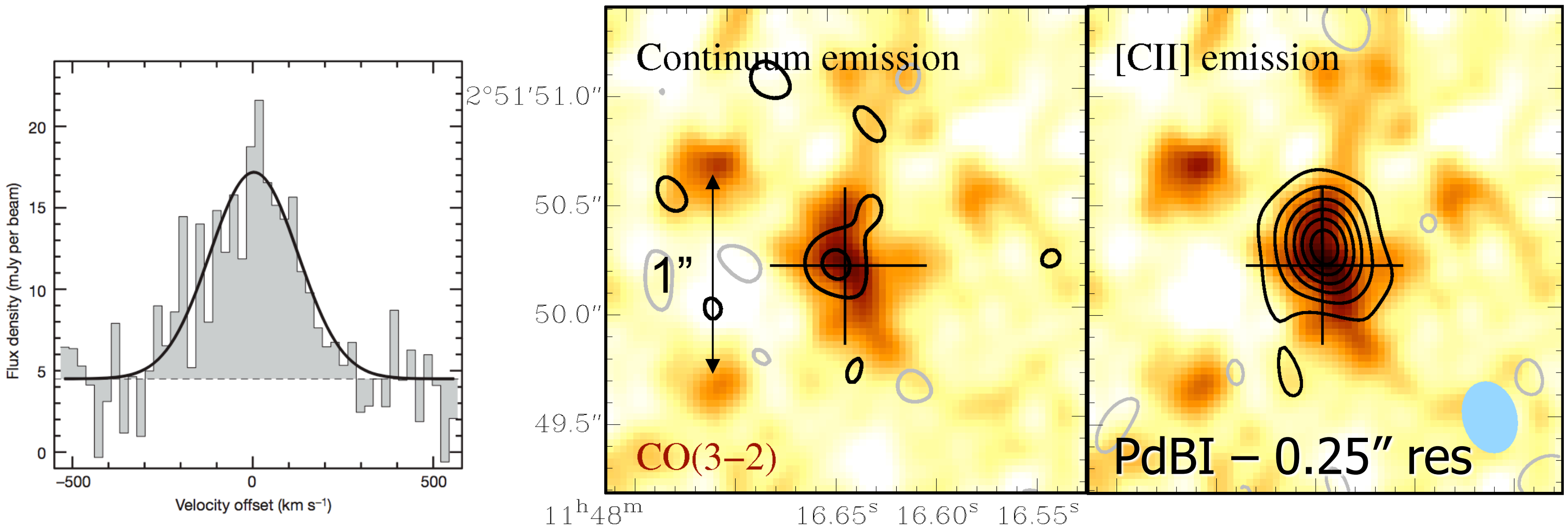
Up to z~2 we'll be able to detect CO
In most sources that can be seen
In the continuum (need specz)

At z>3 continuum much easier than lines

CO Line redshift coverage for ALMA and EVLA



[CII] to the rescue at z>6



FIR continuum [CII]

Maiolino ea 2005, Walter ea. 2009

- [CII] size ~ 1.5 kpc => SFR/area ~ 1000 M_o yr^{-1} kpc^{-2}
- Maximal starburst: (Thompson, Quataert, Murray 2005)
  - ➢ Self-gravitating gas disk, Vertical support: radiation pressure
  - ➢ 'Eddington limited' SFR/area ~ 1000 M_o yr^{-1} kpc^{-2}

ALMA Early Science and galaxy formation and evolution

- Early Science with 16 antennas already powerful for galaxy formation
- detect SFR>30$M_\odot$ yr^{-1} up to very high-z (3 $M_\odot$ yr^{-1} full ALMA)
- ALMA will not be a wide-field survey machine (but survey capabilities exist)
- big improvement in CO studies over existing state of the art
- low excitation of CO and uncertainties in α_{CO} will pose problems
- at z<2 CO easier; at z>3 continuum easier (for normal galaxies)
- other molecular/atomic tracers will become detectable/important (CII/etc)