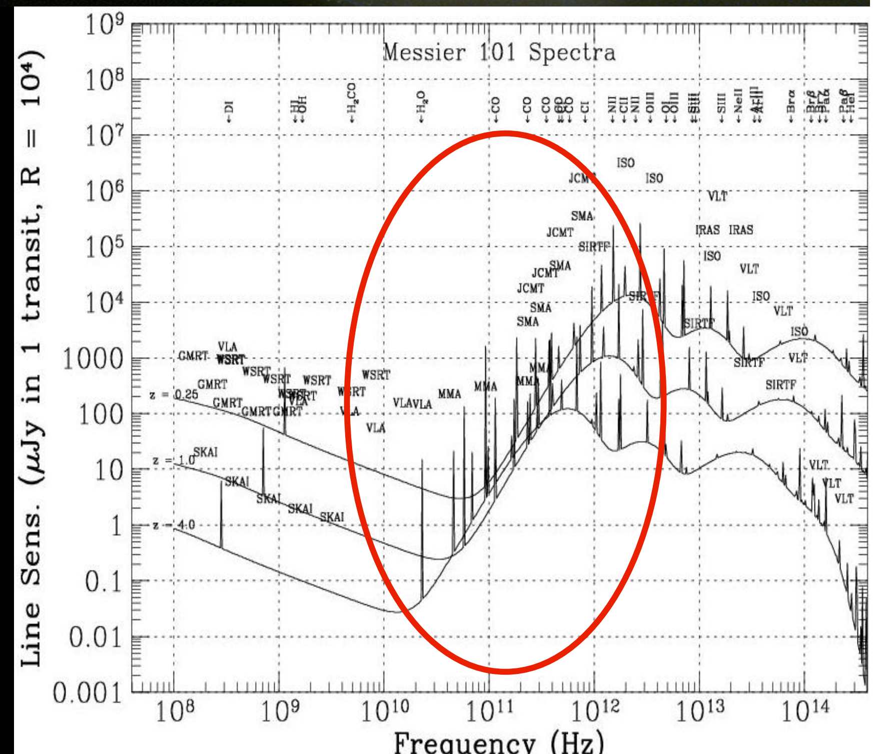
1^{st} galaxies: cm/mm observations – fuel for galaxy formation

- mm continuum: thermal emission from warm dust => star formation
- mm lines: high order molecular lines, atomic fine structure lines => ISM physics
- cm lines: low order molecular lines => gas mass, dynamics
- cm continuum: synchrotron emission => star formation, AGN



Carilli, Wang, Riechers, Walter, Wagg, Bertoldi, Menten, Cox, Fan

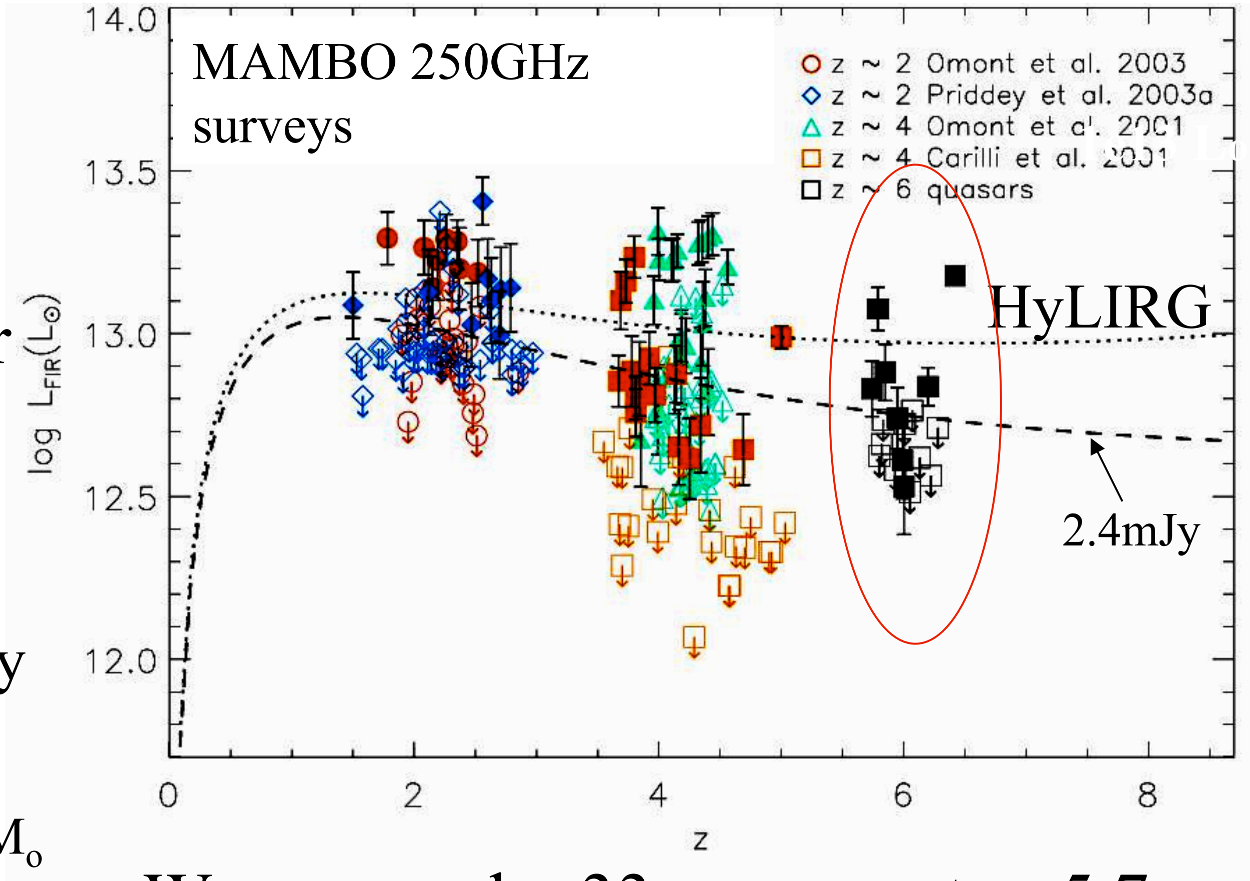
Massive galaxy formation at z~6: gas, dust, star formation in quasar hosts

Why quasar hosts?

▪ probe massive galaxy formation:

$L_{bol} \sim 10^{14} L_o \Rightarrow M_{BH} \sim 10^9 M_o$
$\Rightarrow M_{bulge} \sim 10^{12} M_o$

▪ Spectroscopic z

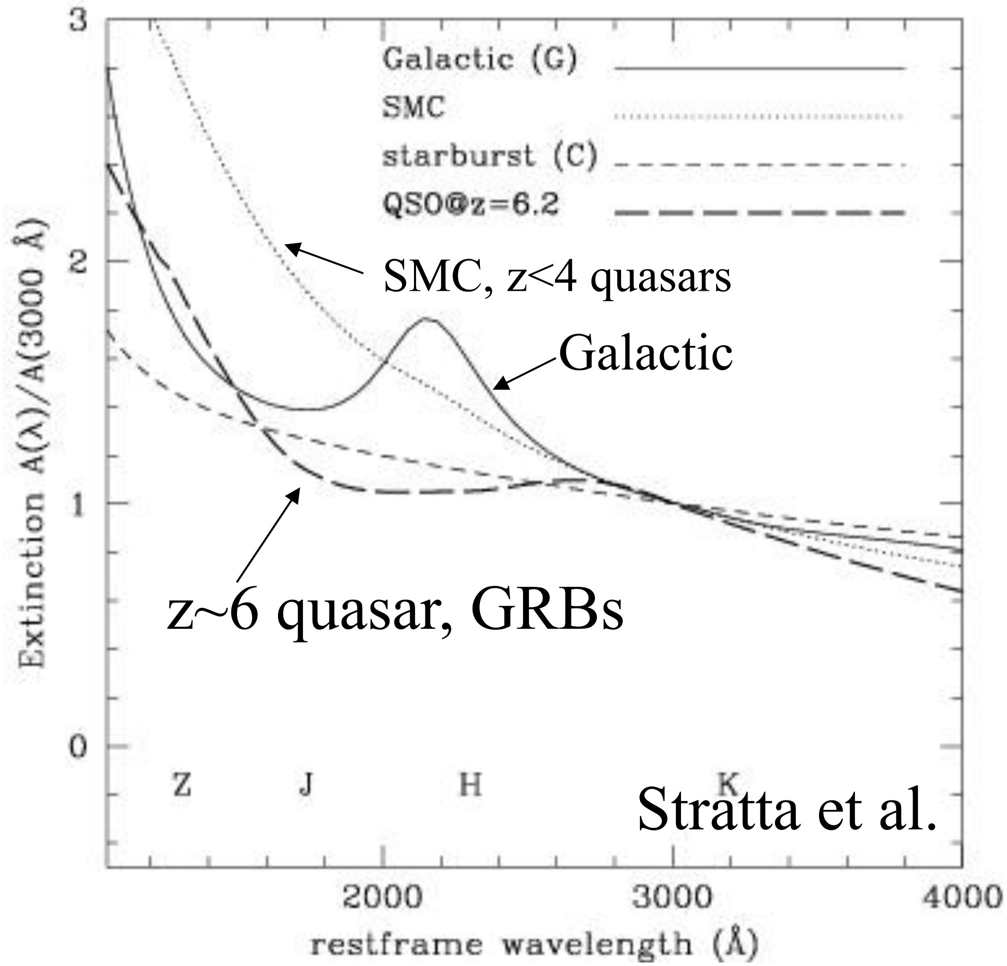


Wang sample: 33 quasars at z>5.7

- 1/3 of z>2 quasars have S_{250} > 2mJy
- $L_{FIR} \sim 0.3$ to $1.3 \times 10^{13}\ L_o$ (47K, $\beta = 1.5$)
- $M_{dust} \sim 1.5$ to $5.5 \times 10^8\ M_o$

Dust formation at t_{univ}<1Gyr?

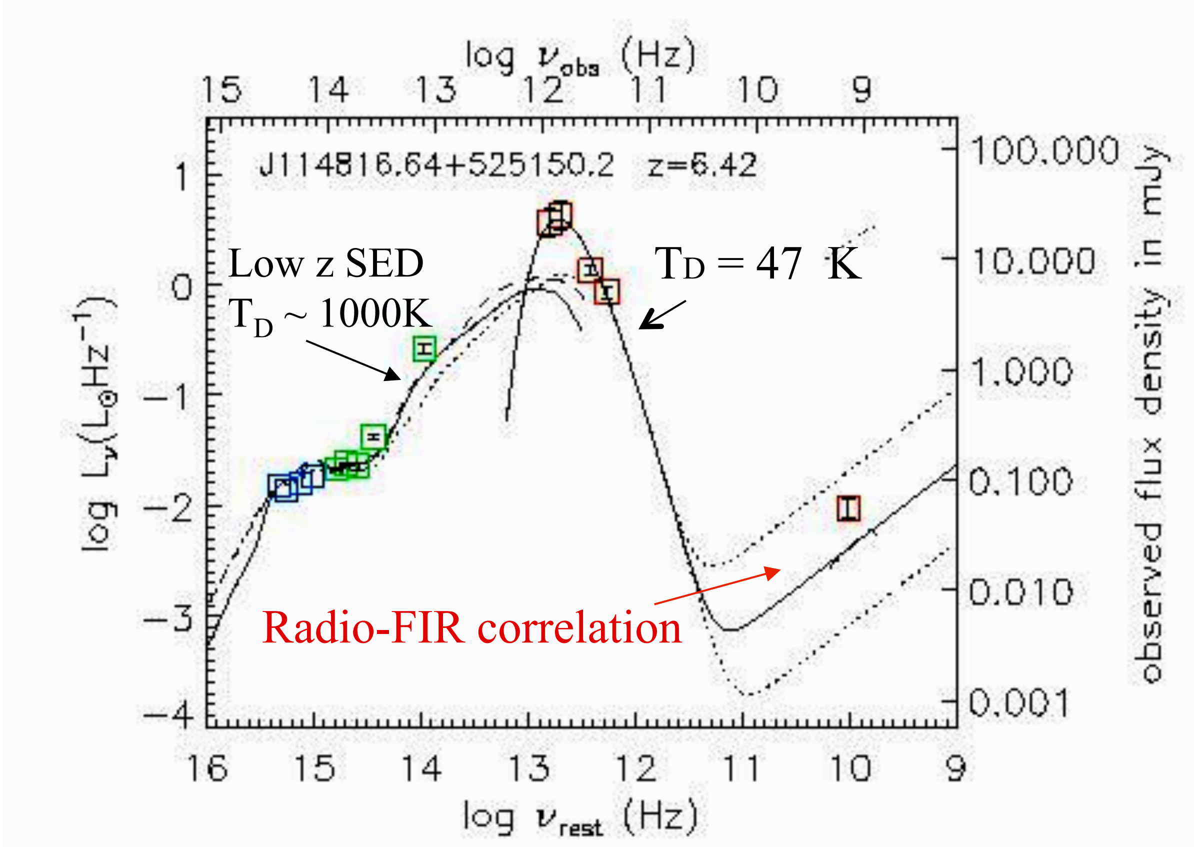
- AGB Winds ≥ 1.4e9yr
  - ➢ High mass star formation? (Dwek, Anderson, Cherchneff, Shull, Nozawa)
  - ➢ 'Smoking quasars': dust formed in BLR winds (Elvis)
- Extinction toward z=6.2 QSO and z~6 GRBs => different mean grain properties (Perley, Stratta)
  - ➢ Larger, silicate + amorphous carbon dust grains formed in core collapse SNe vs. eg. graphite

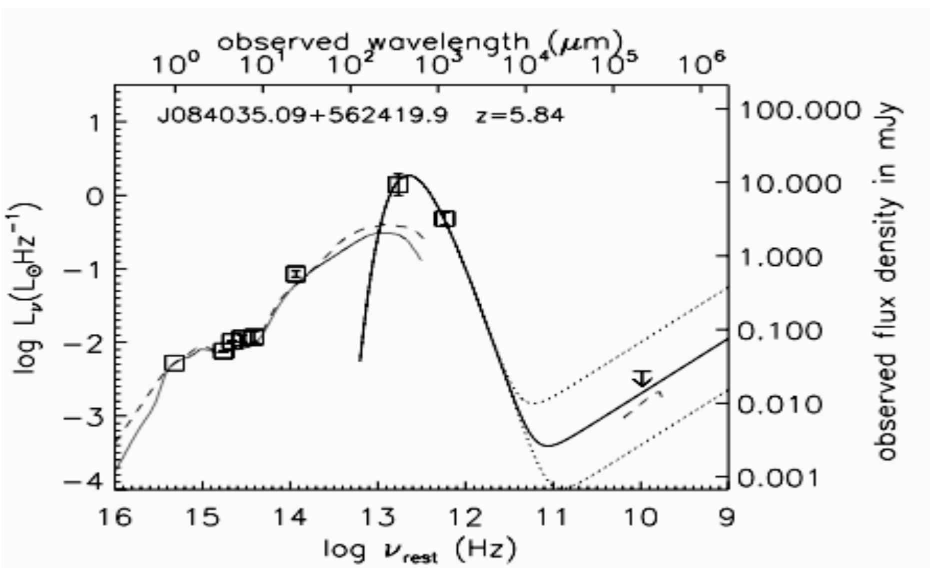


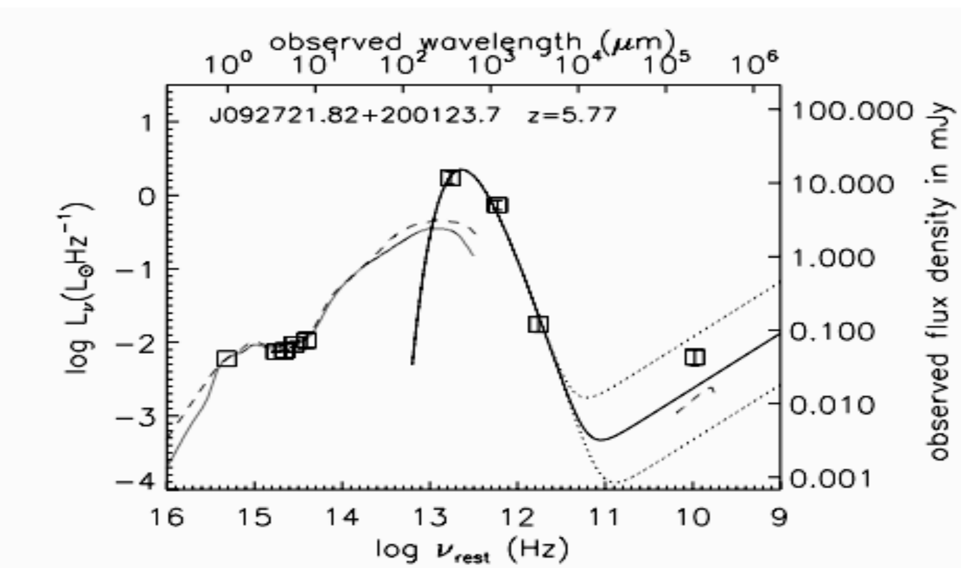
Dust heating? Radio to near-IR SED

- FIR excess = 47K dust
- SED consistent with star forming galaxy:

SFR ~ 400 to 2000 M_o yr^{-1}

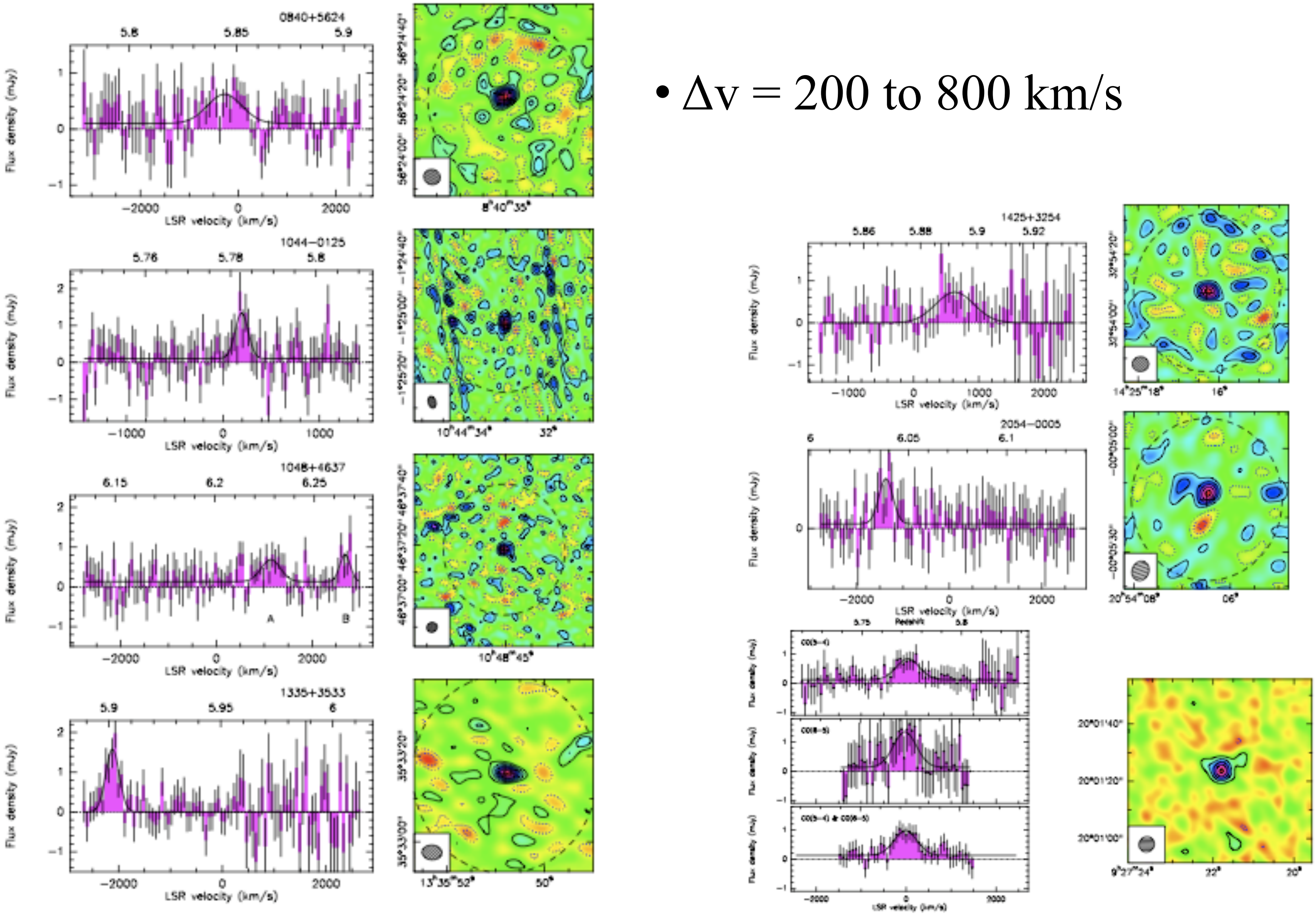




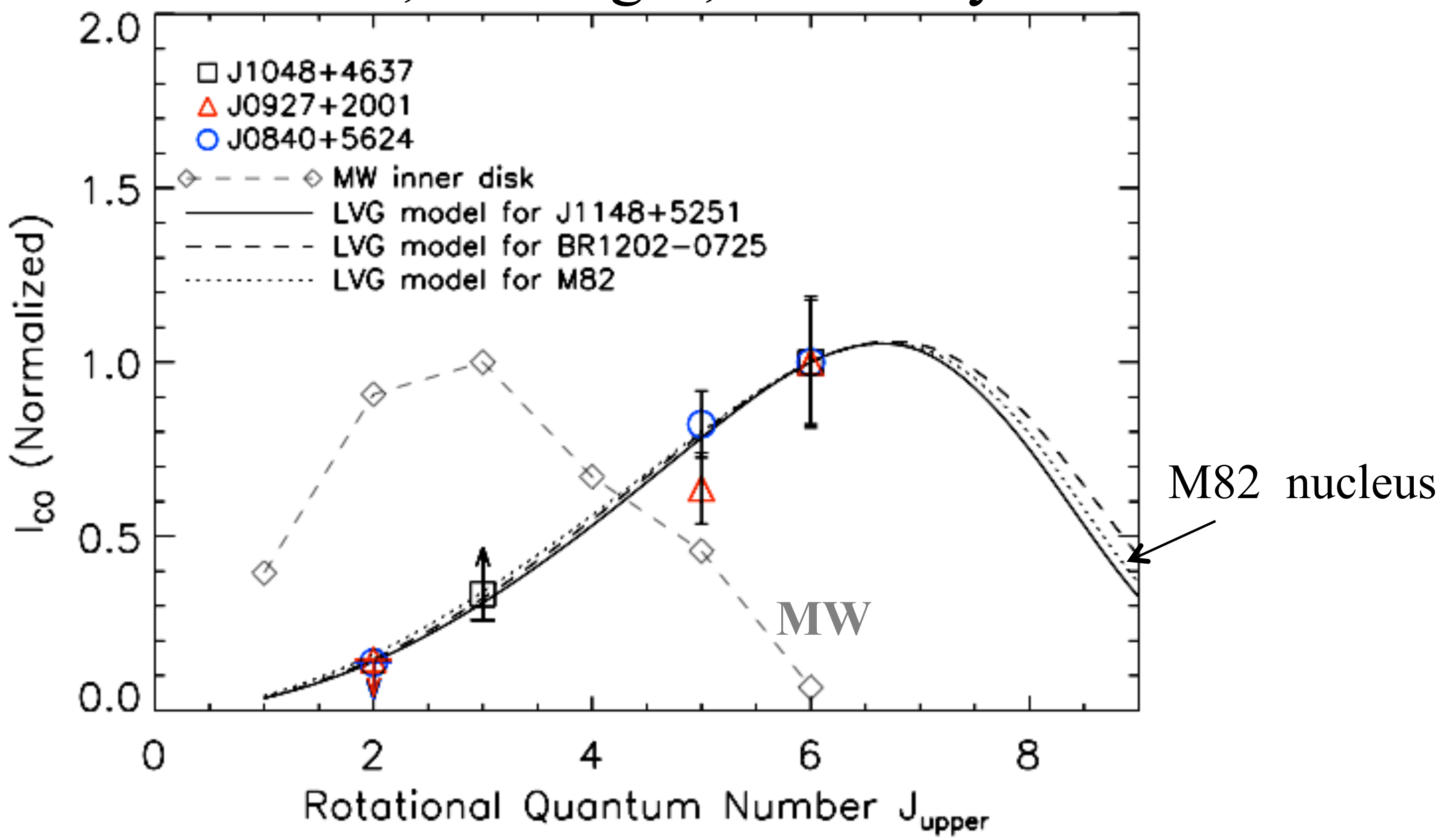


Fuel for star formation? Molecular gas: 8 CO detections at z ~ 6 with PdBI, VLA

- $M(H_2) \sim 0.7$ to 3×10^{10} M_o
- $\Delta v = 200$ to 800 km/s

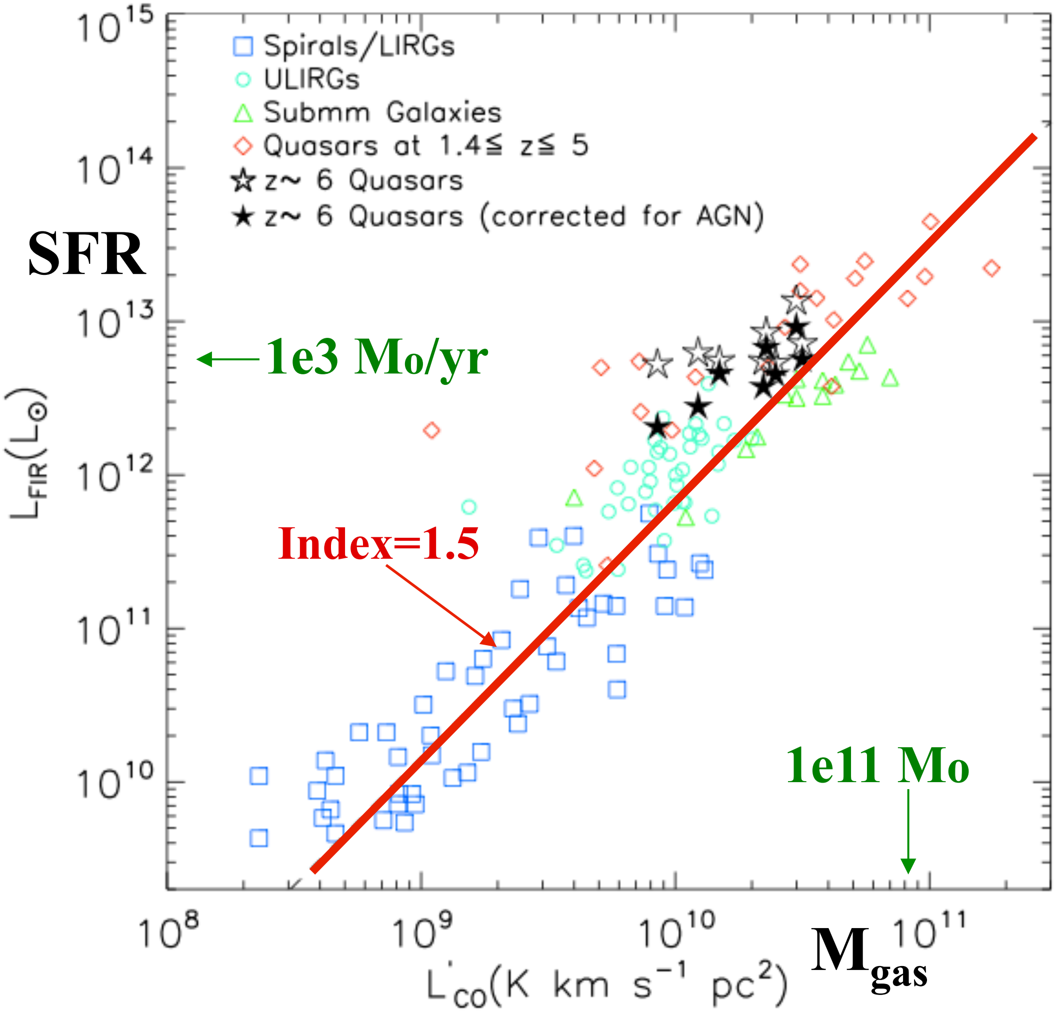


CO excitation: Dense, warm gas, thermally excited to 6-5



- LVG model => T_k = 50K, $n_{H2} = 2x10^4$ cm^{-3}
- Giant Molecular Cloud (50pc): $n_{H2}\sim 10^2$ to 10^3 cm^{-3}
- GMC cores (≤1pc): $n_{H2}\sim 10^4$ cm^{-3}

LFIR vs L’(CO): ‘integrated Kennicutt-Schmidt law’

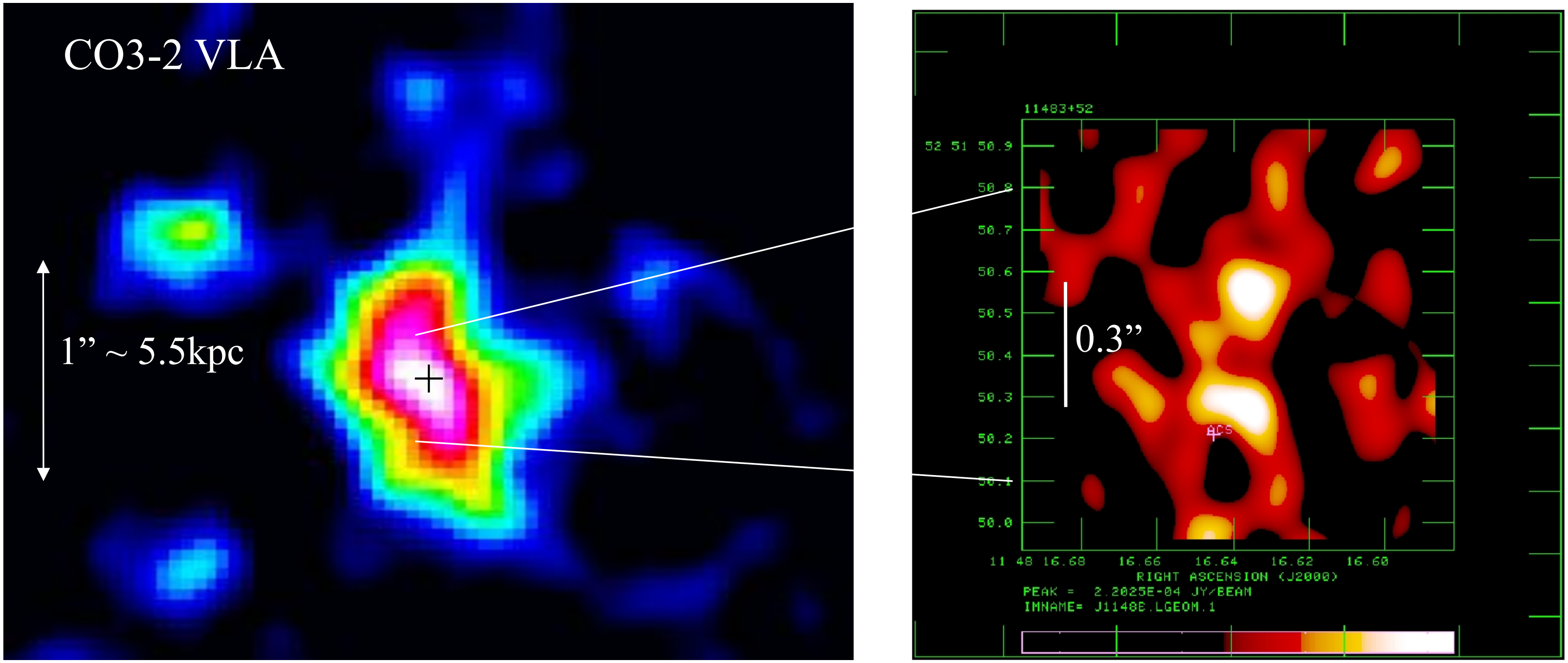


- Further evidence for star formation
- Gas consumption time (M_{gas}/SFR) decreases with SFR

FIR ~ 10^{10} Lo/yr => t_c~10^8yr
FIR ~ 10^{13} Lo/yr => t_c~10^7yr

=> Need gas re-supply to build giant elliptical

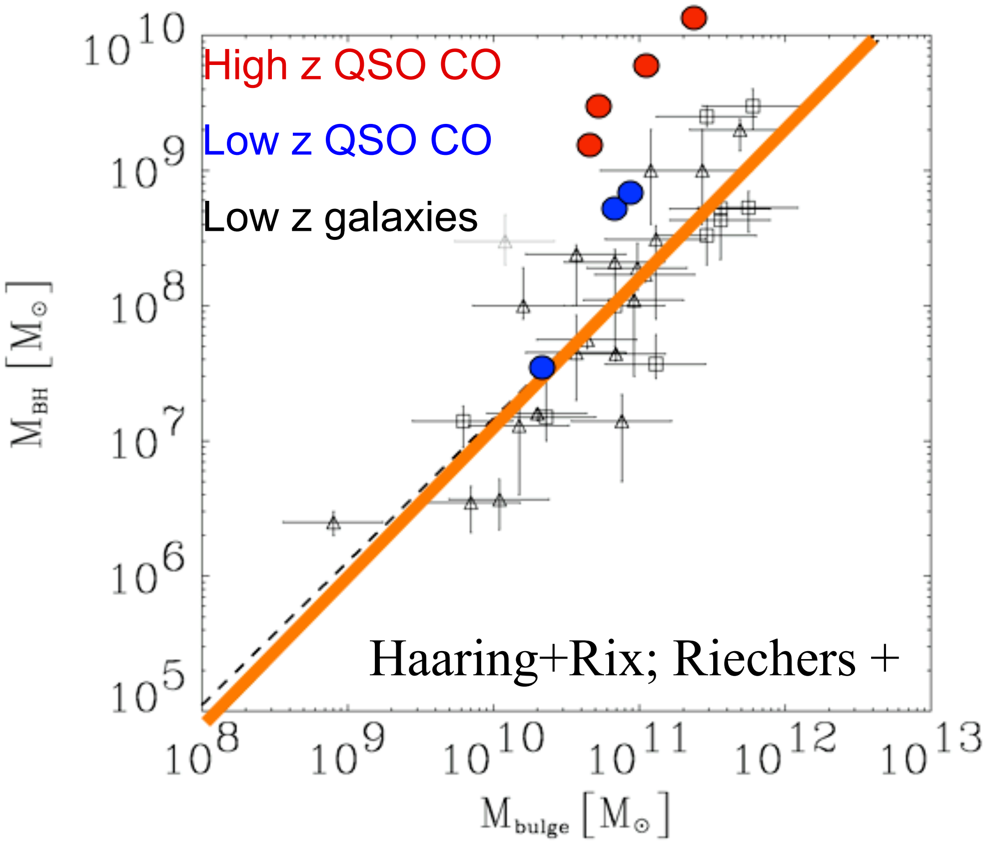
1148+52 z=6.42: VLA imaging at 0.15” resolution

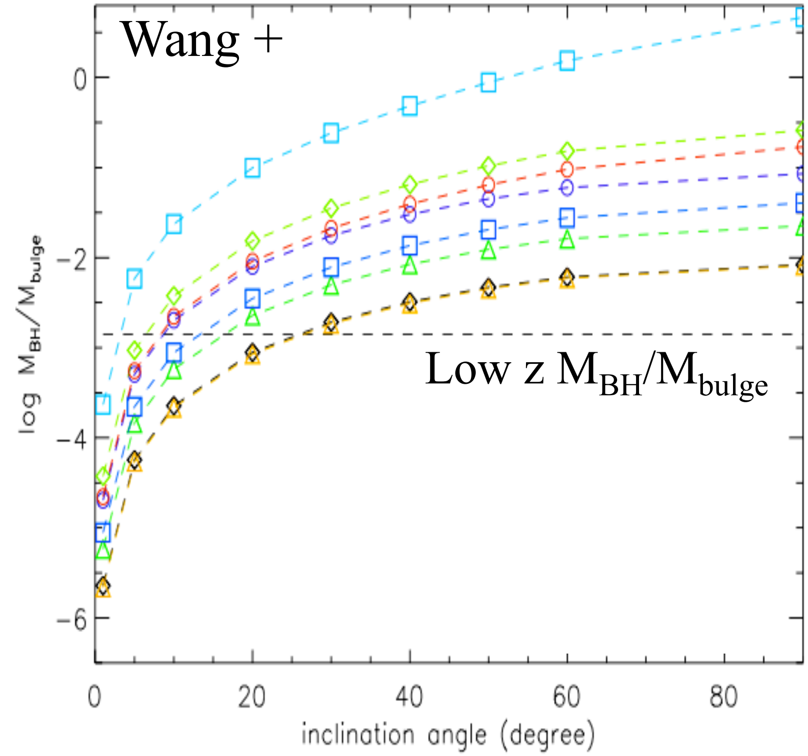


- Size ~ 6 kpc
- Double peaked 2kpc separation, each ~ 1kpc, $M(H_2) \sim 5 \times 10^9\ M_o$
- $T_B \sim 35$ K ~ starburst nuclei

Gas dynamics => ‘weighing first galaxies’

Break-down of M_{BH} -- M_{bulge} relation at very high z

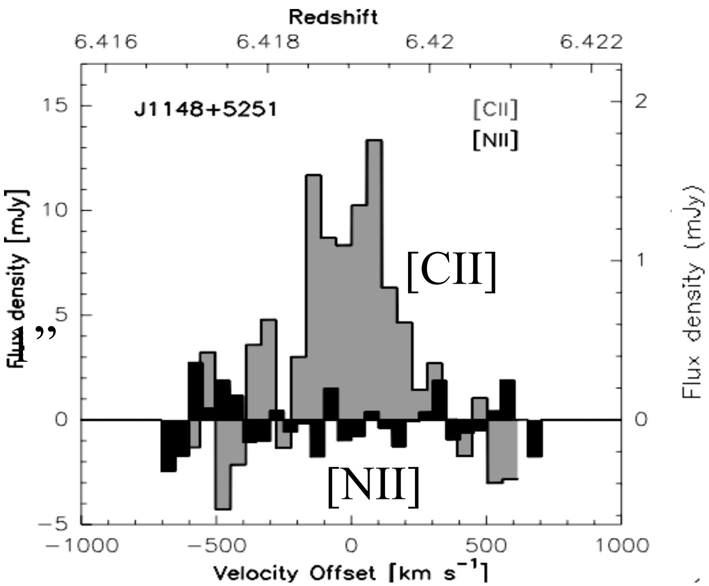


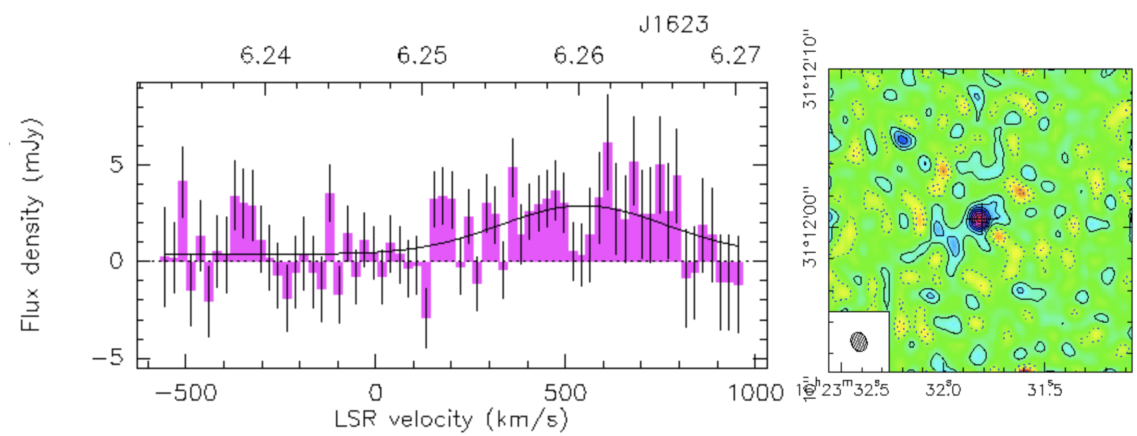


- $\langle M_{BH}/M_{bulge}\rangle = 15 \times$ low z => Black holes form first?
- All highly inclined: $i < 20^{o}$
- Lauer Bias for optically selected quasars

[CII] 158um search in z > 6.2 quasars

- Dominant ISM gas cooling line
- Traces CNM and PDRs
- [CII] strongest (factor 10!) cm to FIR line in MW ~ 1% L_{Gal}
- z>4 => FS lines observed in (sub)mm bands; z>6 => Bure!





- $S_{[CII]}$ = 3mJy
- S_{250GHz} < 1mJy

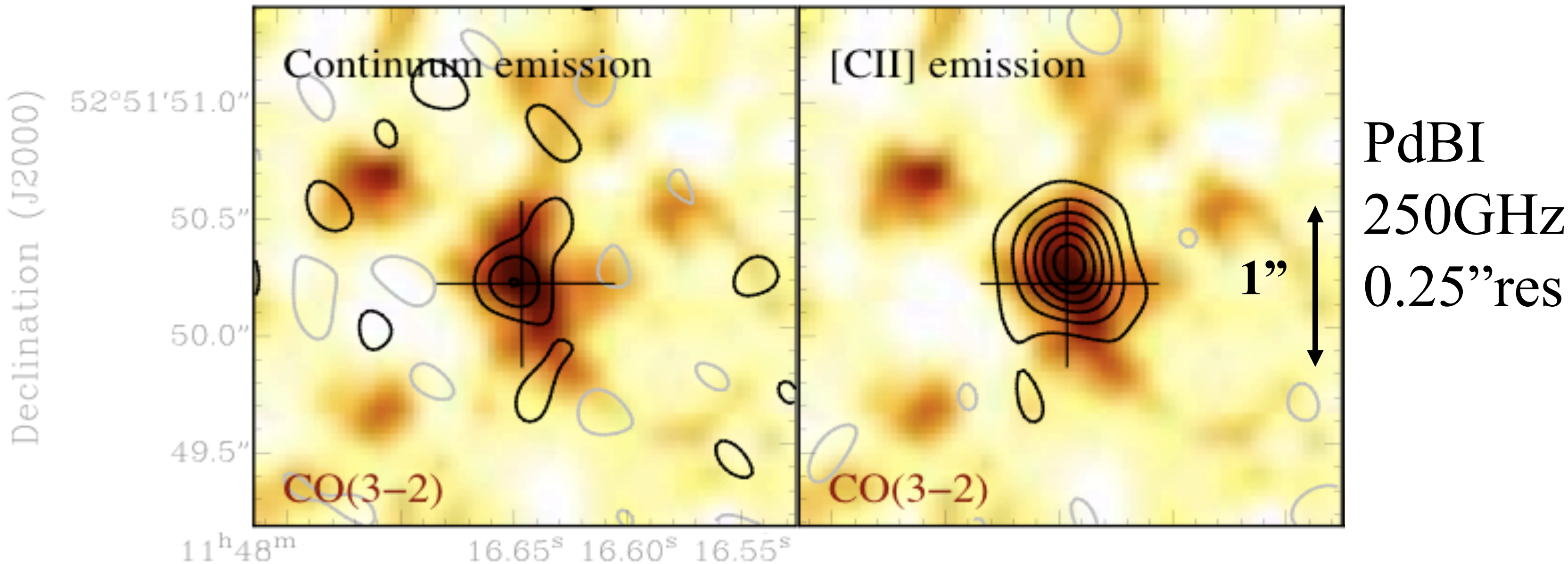
•$L_{[CII]} = 4\text{x}10^9\, L_o$ ($L_{[NII]} < 0.1 L_{[CII]}$)

•S_{250GHz} = 5.5mJy

•$S_{[CII]}$ = 12mJy

Kundsen, Bertoldi, Walter, Maiolino +

1148+53 z=6.42:'Maximal star forming disk' (Walter + 2009)

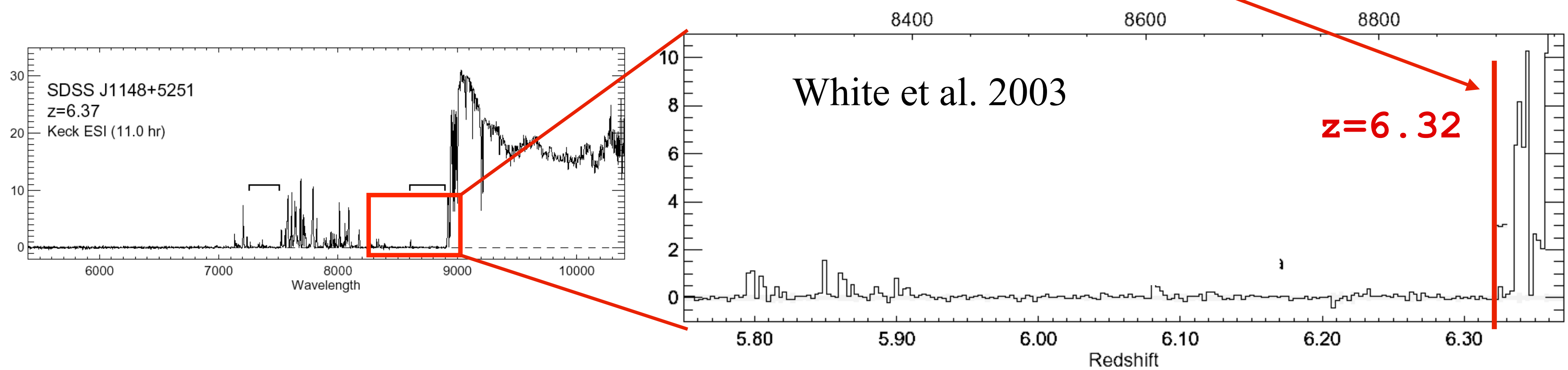


- [CII] size ~ 1.5 kpc => SFR/area ~ 1000 M_o yr^{-1} kpc^{-2}
- Maximal starburst (Thompson, Quataert, Murray 2005)
  - ➢ Self-gravitating gas disk
  - ➢ Vertical disk support by radiation pressure on dust grains
  - ➢'Eddington limited' SFR/area ~ 1000 M_o yr^{-1} kpc^{-2}
  - ➢ eg. Arp 220 on 100pc scale, Orion SF cloud cores < 1pc

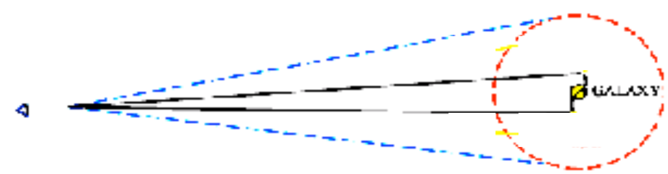
Quasar Near Zones

• Accurate host redshift from CO: z=6.419+/0.001 (typical optical redshifts Δz~0.02)

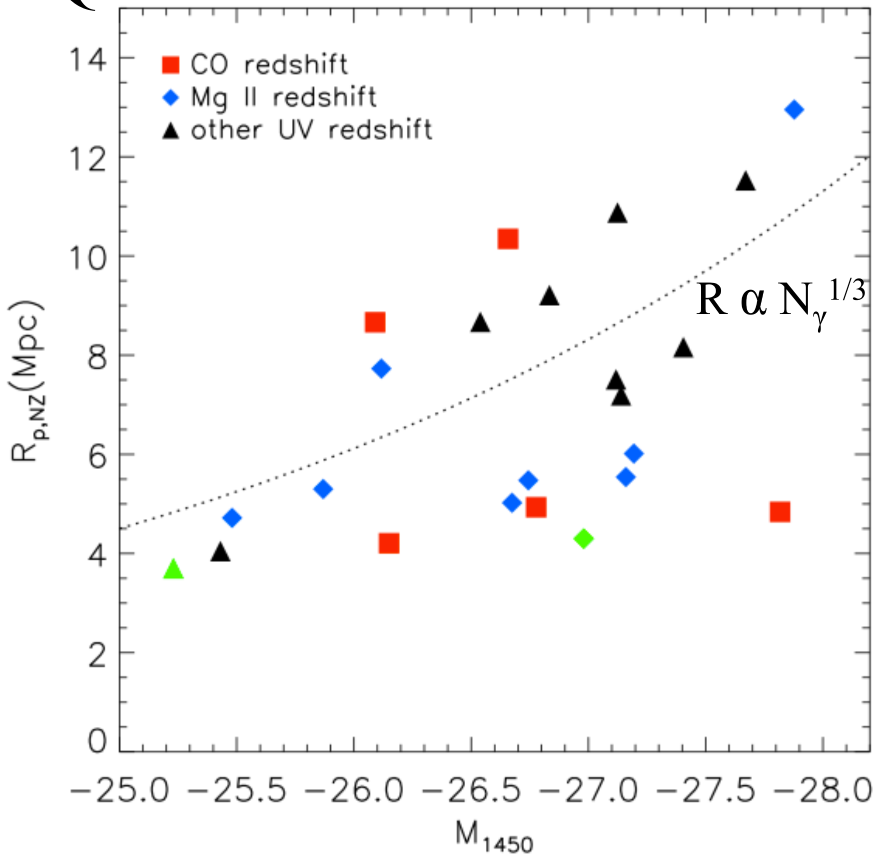
• Quasar near zone: photons leaking down to z=6.32

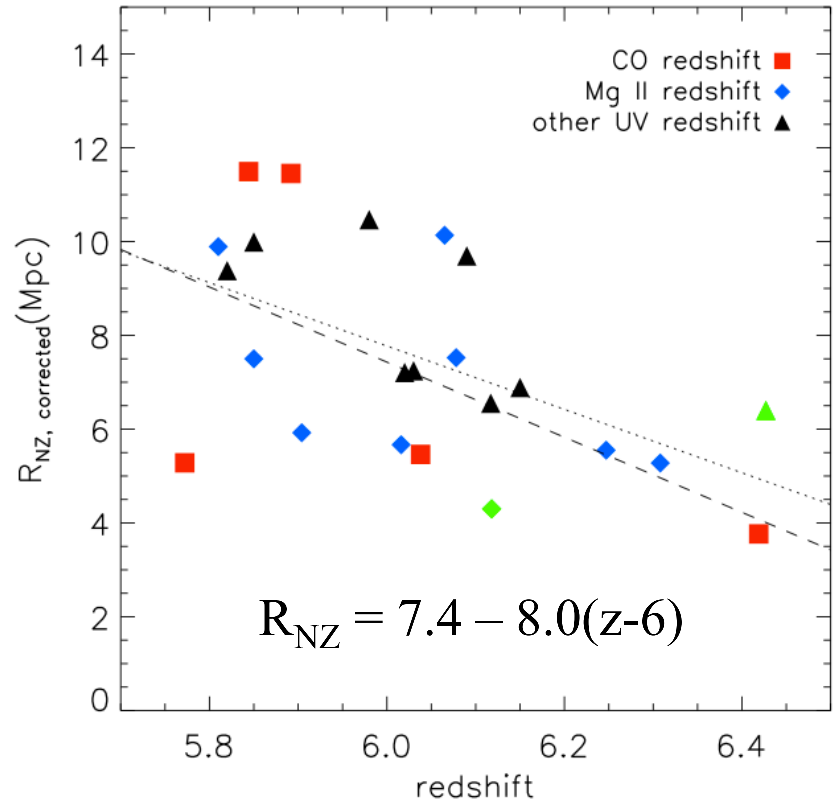


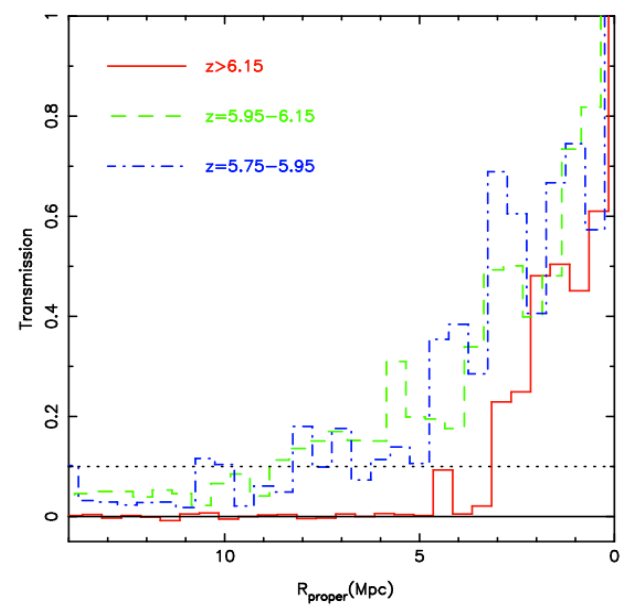
‘time bounded’ Stromgren sphere:
R = 4.7 Mpc (Haiman +; Wyithe +)



Quasar Near-Zones: Fan revisited





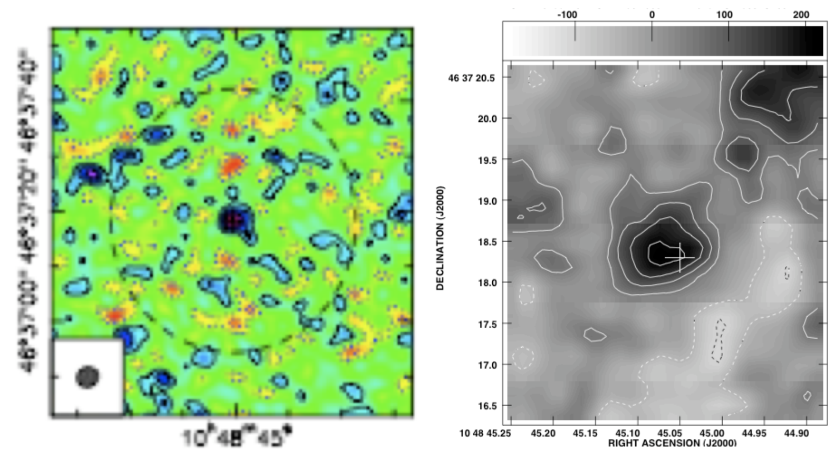


• f(HI) decreases by factor 9 from z=6.4 to 5.7 or

• Rapid increase in background ionization rate and mfp at end of overlap (Bolton+)

• Either way, suggestive of something interesting occurring in IGM at z ~ 6.5

Summary cm/mm observations of 33 quasars at z~6: only direct probe of the host galaxies

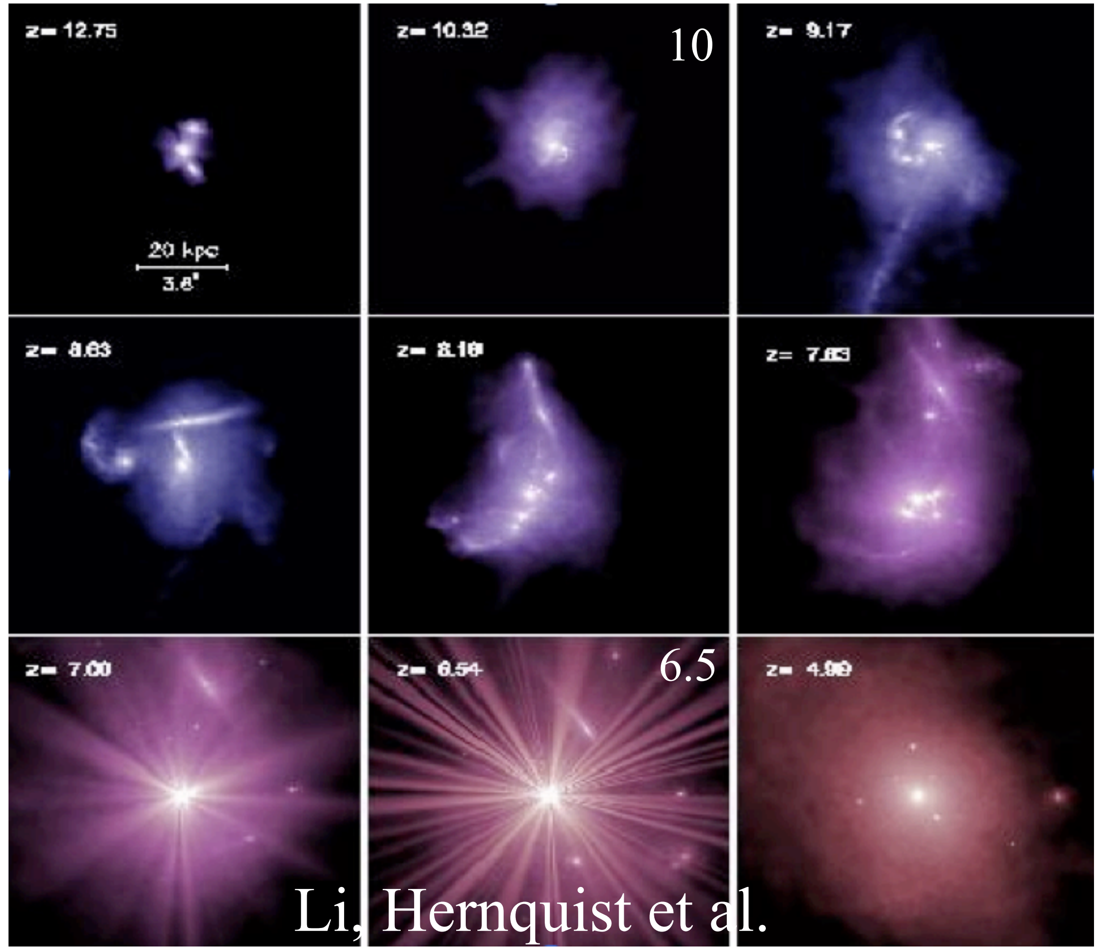


J1048 z=6.23 CO w. PdBI, VLA

- 11 in mm continuum => $M_{dust} \sim 10^8\ M_o$: Dust formation in SNe?
- 10 at 1.4 GHz continuum: Radio to FIR SED => SFR ~ 1000 M_o/yr
- 8 in CO => $M_{gas} \sim 10^{10}\ M_o$: Fuel for star formation in galaxies
  - High excitation ~ starburst nuclei
  - Follow KS Star formation law: $t_c \sim 10^7$ yr
- 3 in [CII] => maximal star forming disk: 1000 $M_o\ yr^{-1}\ kpc^{-2}$
- Confirm decrease in R_{NZ} with increasing z

Building a giant elliptical galaxy + SMBH at t_{univ}< 1Gyr

- Multi-scale simulation isolating most massive halo in 3 Gpc^3
- Stellar mass ~ 1e12 Mo forms in series (7) of major, gas rich mergers from z~14, with SFR ≥ 1e3 Mo/yr
- SMBH of ~ 2e9 Mo forms via Eddington-limited accretion + mergers
- Evolves into giant elliptical galaxy in massive cluster (3e15 Mo) by z=0



- Rapid enrichment of metals, dust in ISM
- Rare, extreme mass objects: ~ 100 SDSS z~6 QSOs on entire sky
- Goal: push to normal galaxies at z > 6

What is ALMA? Tenfold improvement (or more), in all areas of (sub)mm astronomy, including resolution, sensitivity, and frequency coverage.

•antennas: 54x12m, 12x7m antennas

•frequencies: 80 GHz to 720 GHz

•res = 20mas res at 700 GHz

•rms = 13uJy in 1hr at 230GHz

What is the EVLA? similar ten-fold improvement in most areas of cm astronomy

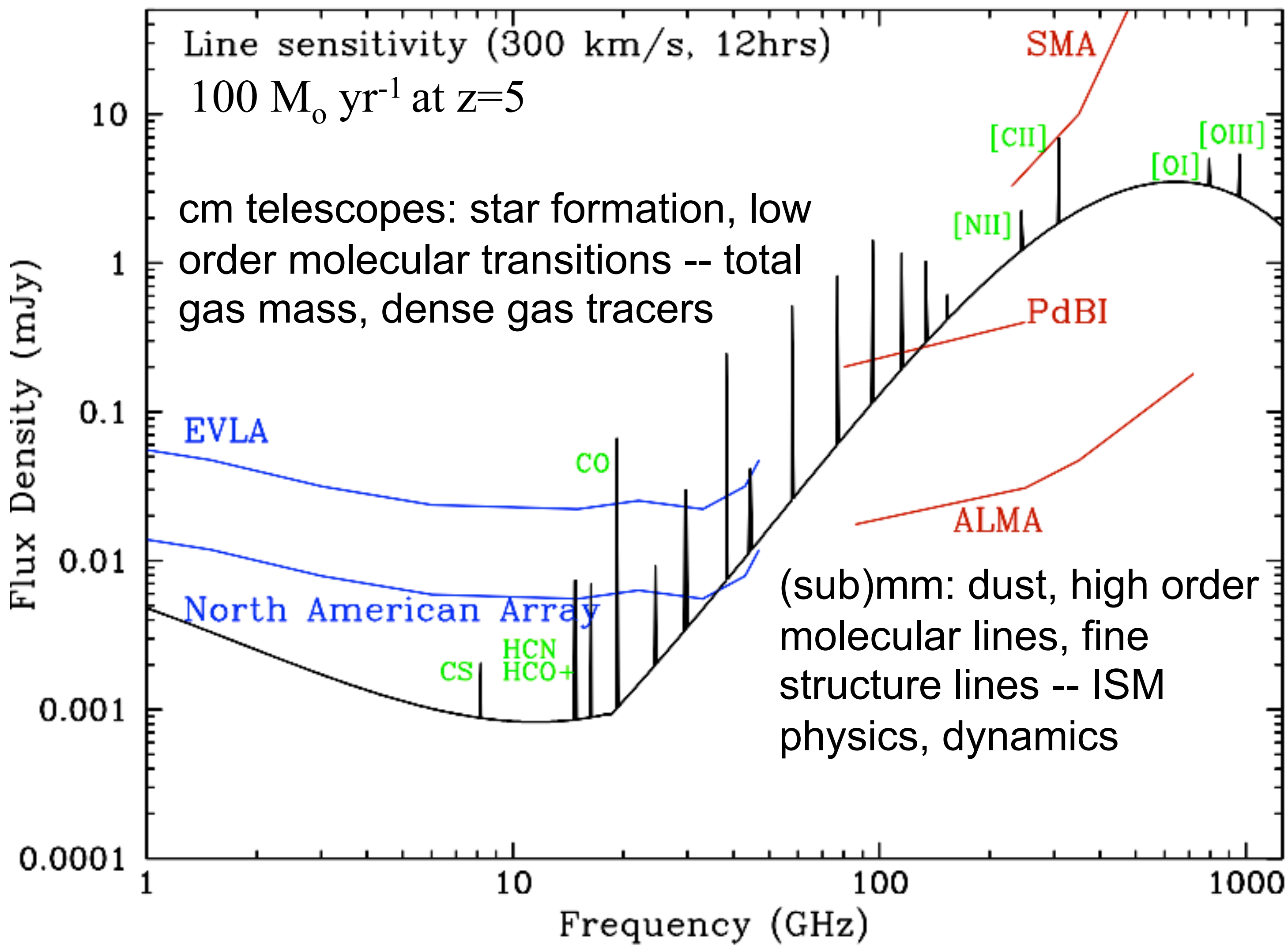
•frequencies = 1 to 50 GHz

•8 GHz BW => 80x old

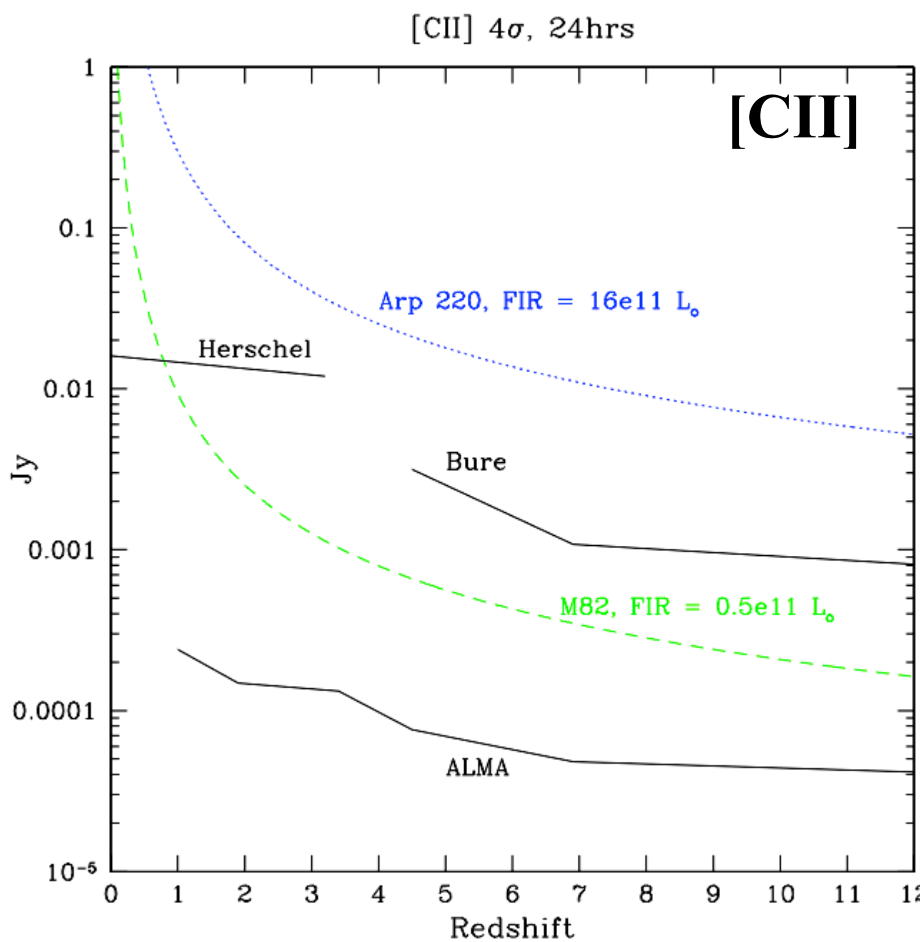
•res = 40mas res at 43GHz

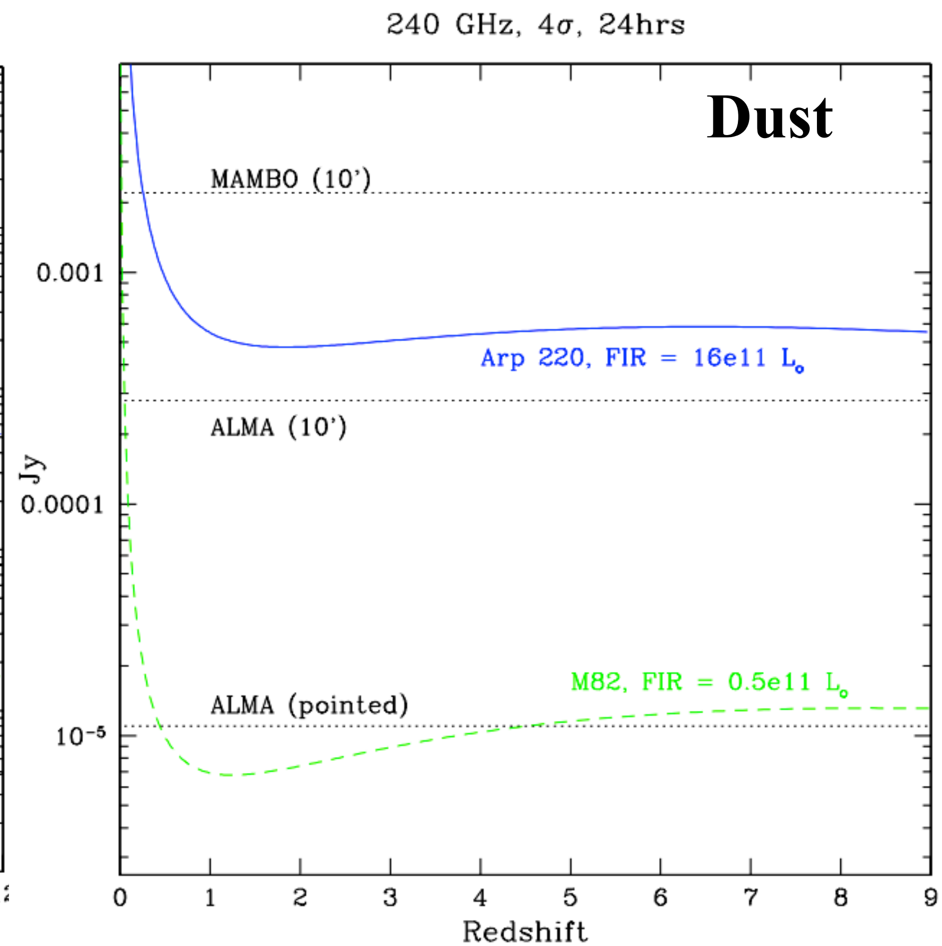
•rms = 6uJy in 1hr at 30GHz

Pushing to normal galaxies at high z

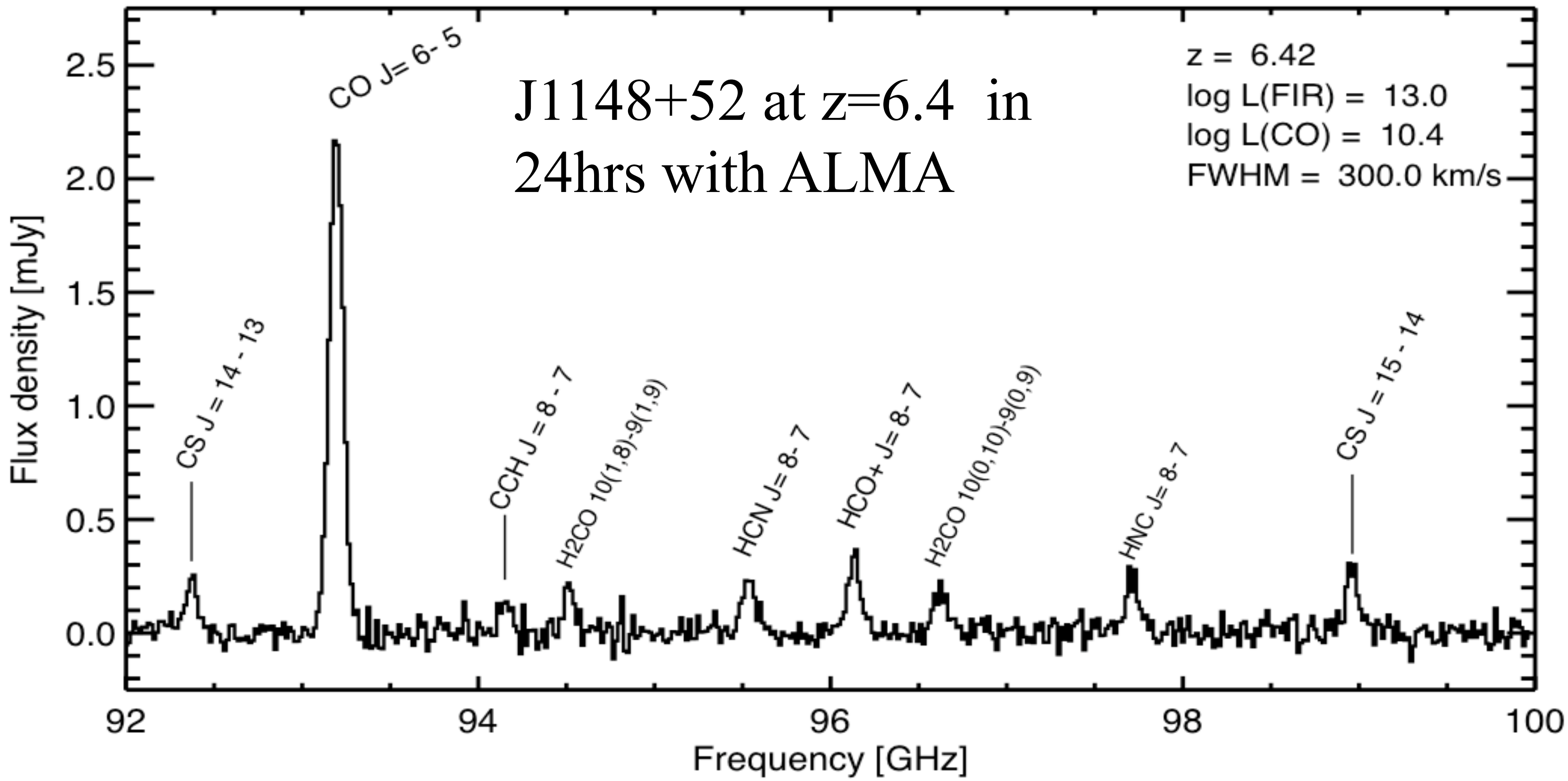


ALMA and first galaxies





Wide bandwidth spectroscopy



- ALMA: Detect multiple lines, molecules per 8GHz band
- EVLA at 32GHz (CO2-1 at z=6): Δz =1.8 => large cosmic volume searches

ALMA Status

•Antennas, receivers, correlator in production: best submm receivers and antennas ever!

•Site construction well under way: Observation Support Facility, Array Operations Site, 3 Antenna interferometry at high site!

• Early science call Q1 2011

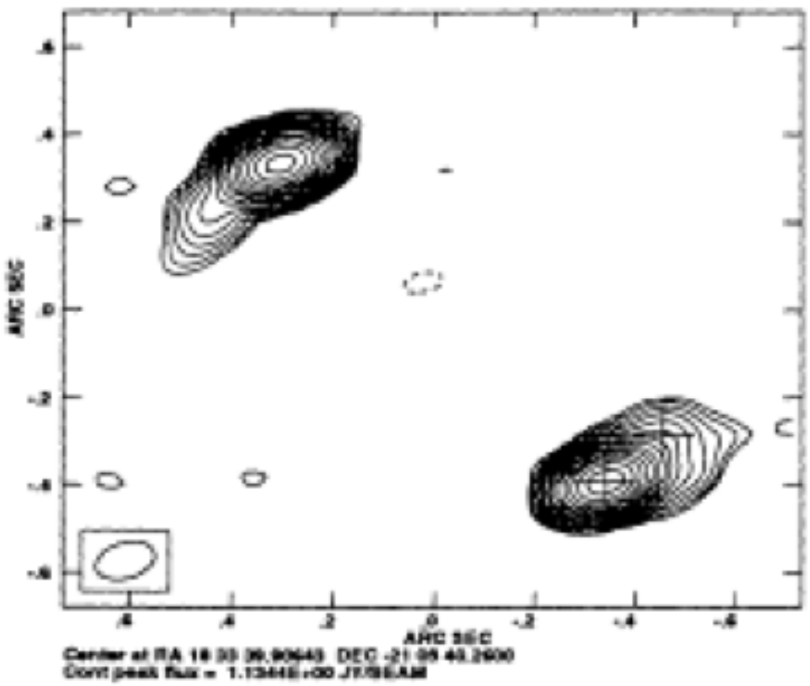
EVLA Status

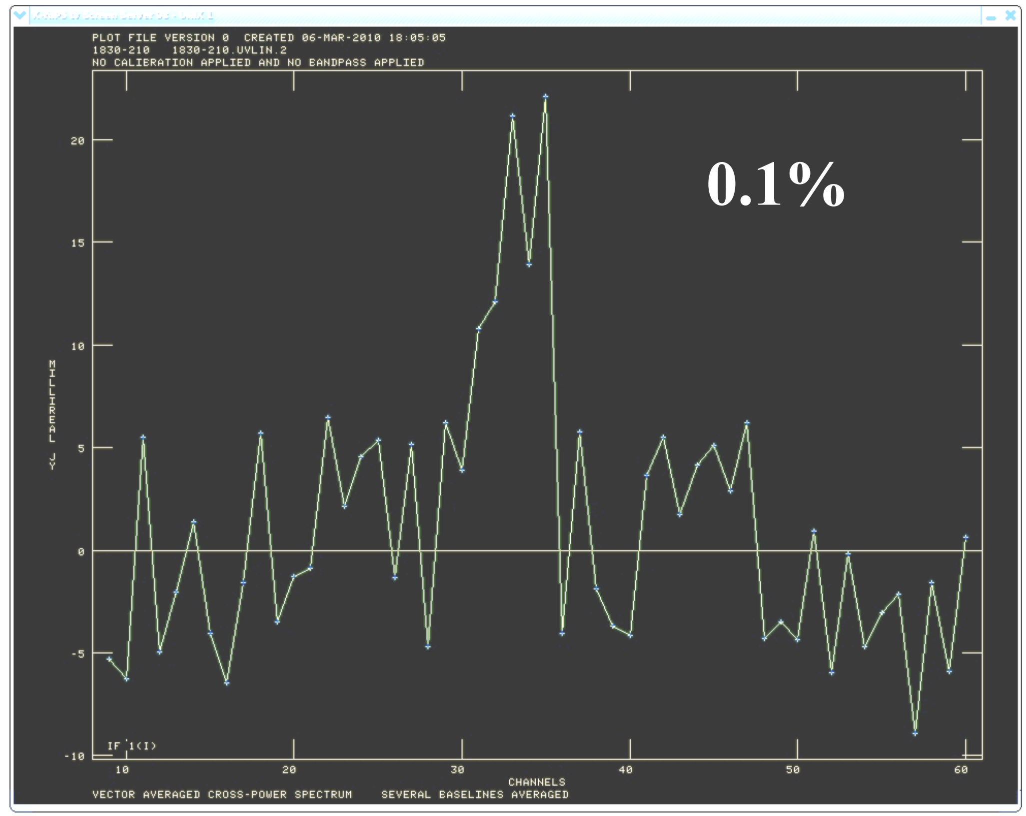
•Antenna retrofits 70% complete (100% at $\nu \geq$ 18GHz).

•Early science in March 2010 using new correlator (2GHz)

•Full receiver complement completed 2012 + 8GHz

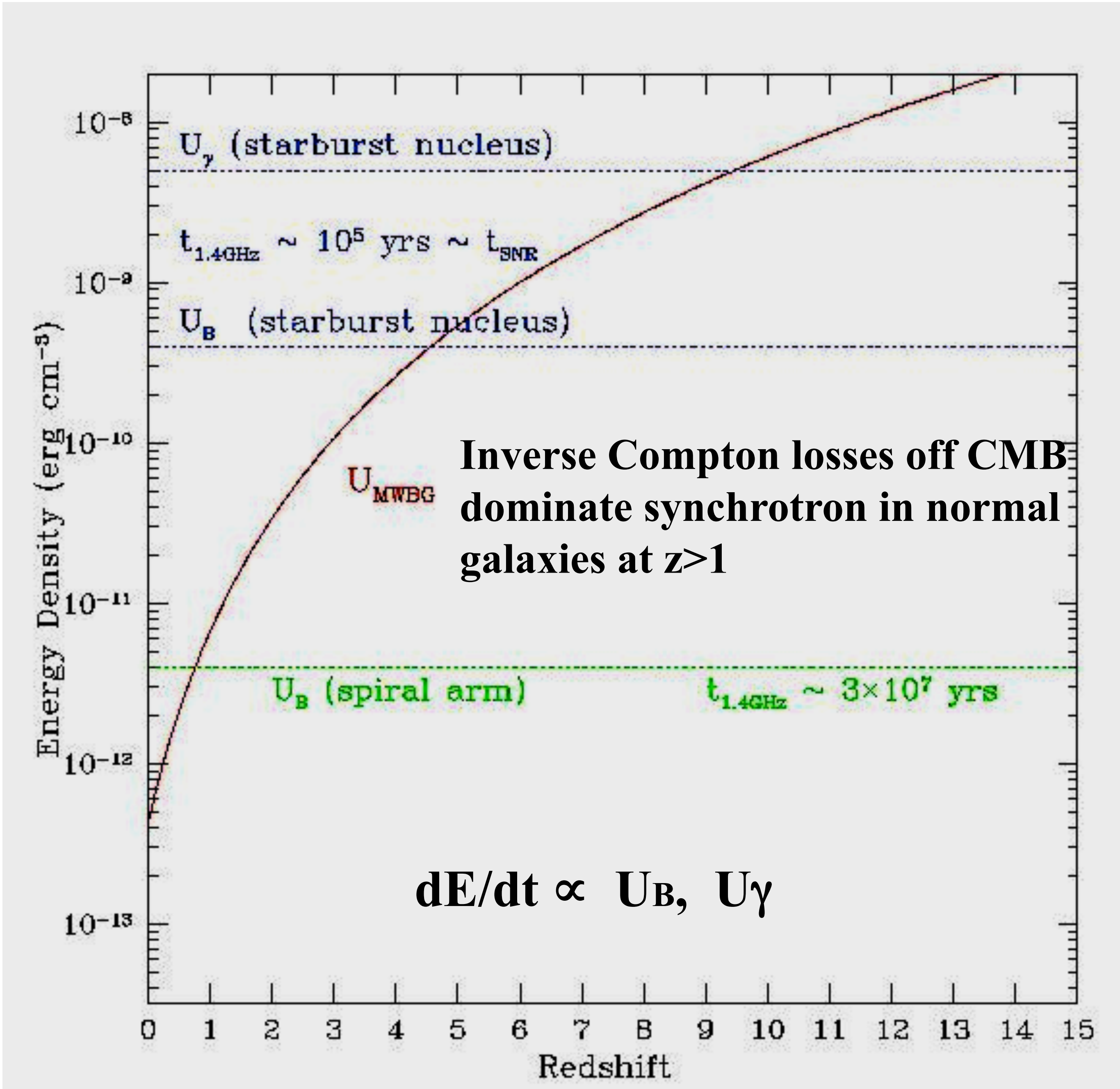
CH stimulated emission at z=0.9 by GMC in lensing galaxy toward PKS1830-211





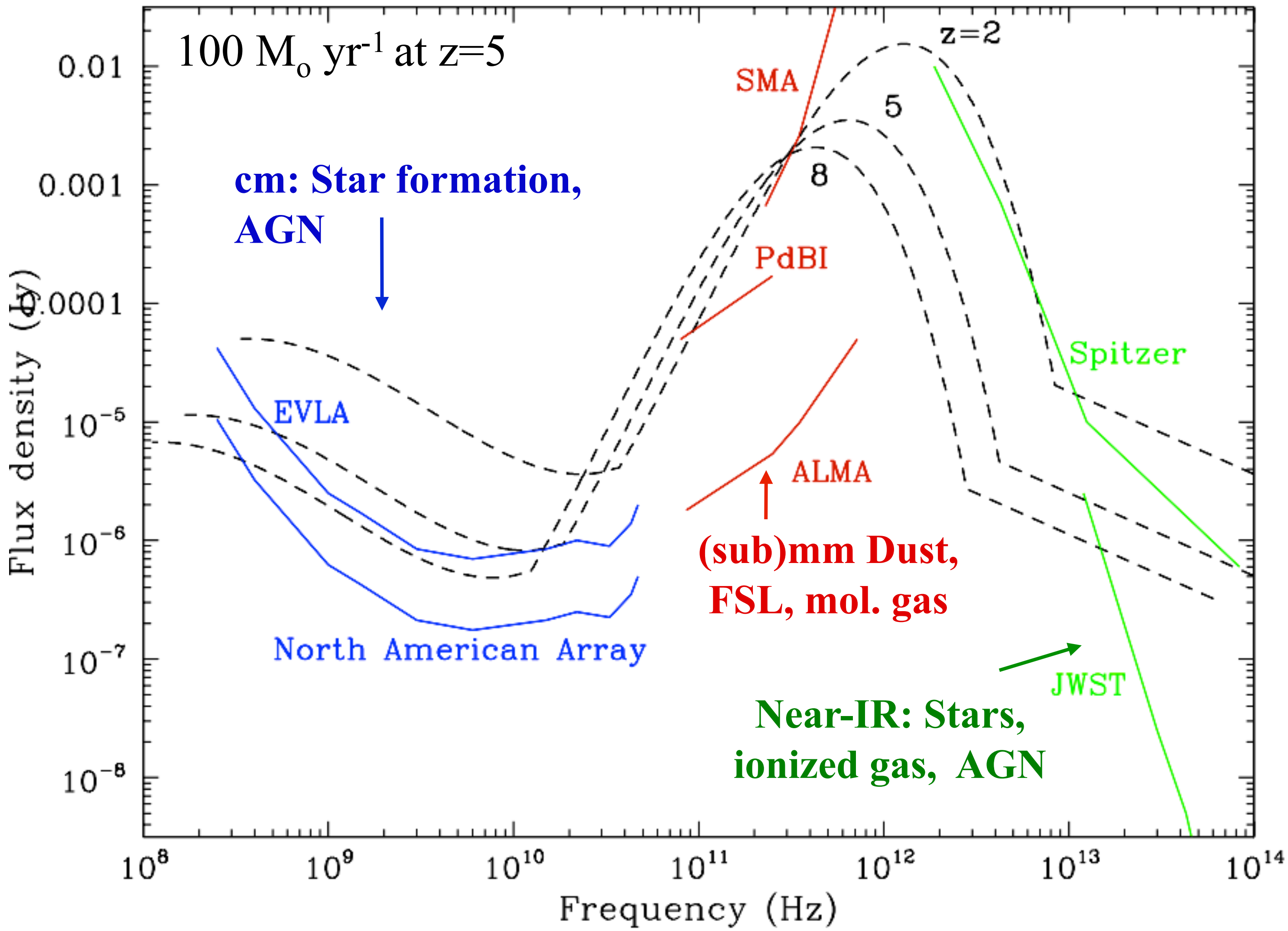

END
ESO

Radio-FIR correlation: how can it work?



Pushing to normal galaxies: continuum

A Panchromatic view of 1st galaxy formation



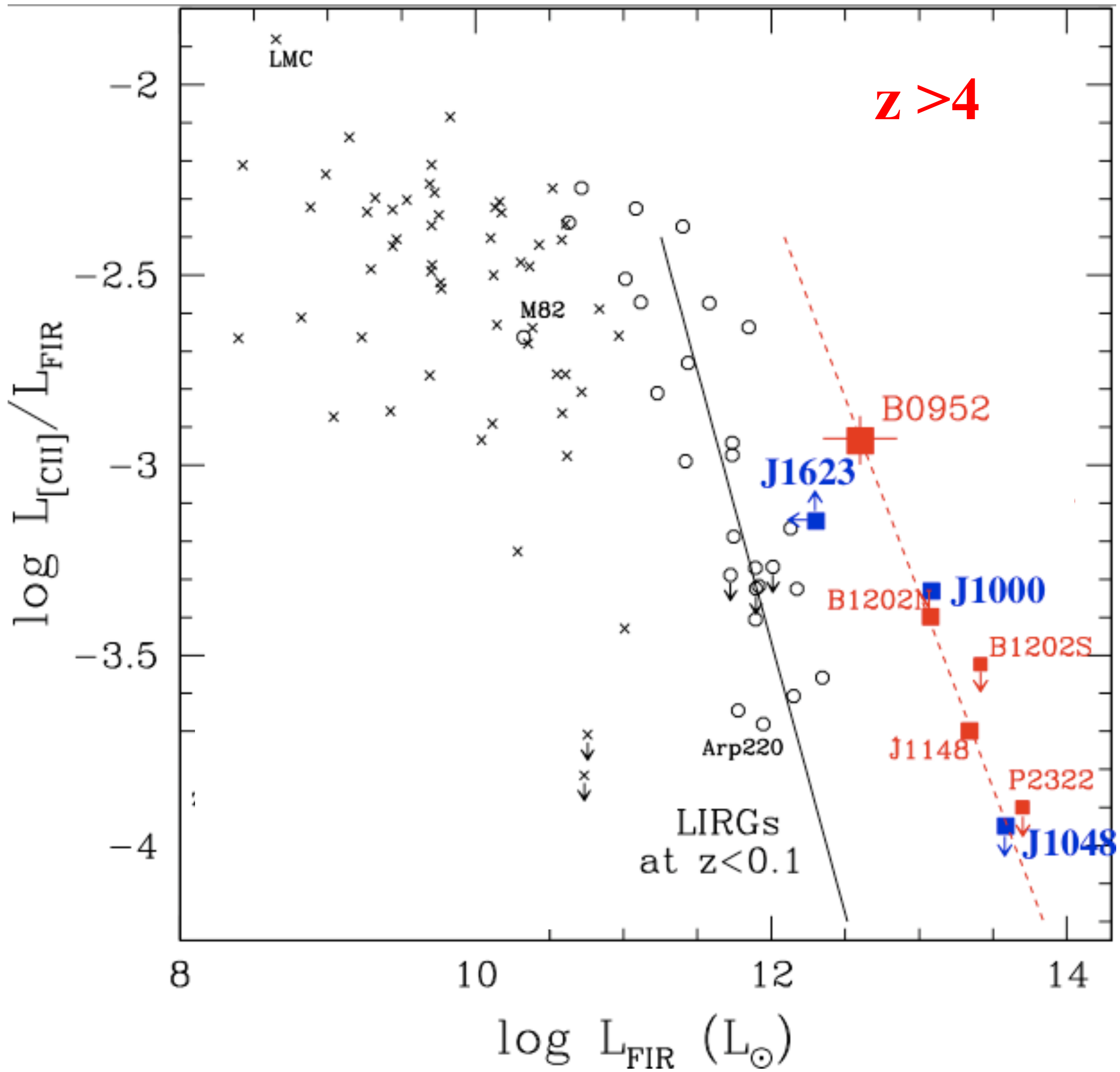
[CII]

• [CII]/FIR decreases with L_{FIR} = lower gas heating efficiency due to charged dust grains => luminous starbursts are still hard to detect in C+

• Normal star forming galaxies are not much harder to detect

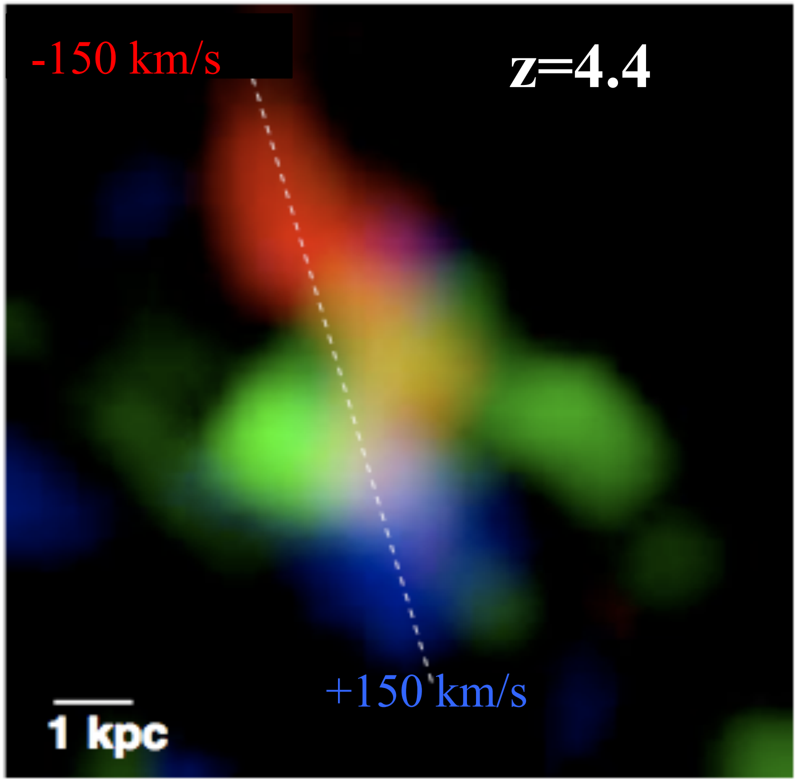
• HyLIRG at z> 4: no worse than low z ULIRG

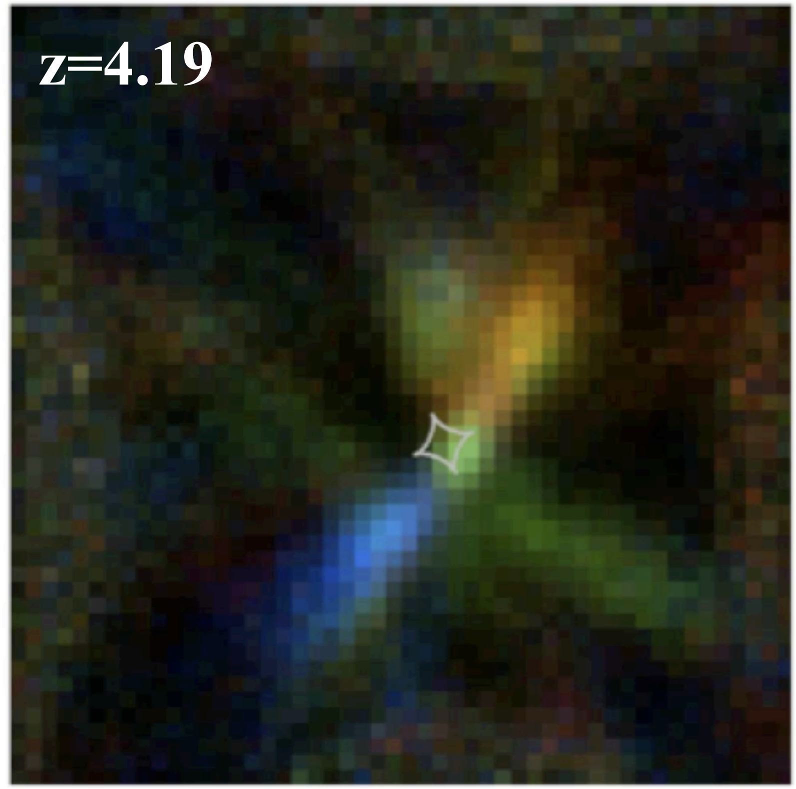
•Don’t pre-select on dust



Malhotra, Maiolino, Bertoldi, Knudsen, Iono, Wagg…

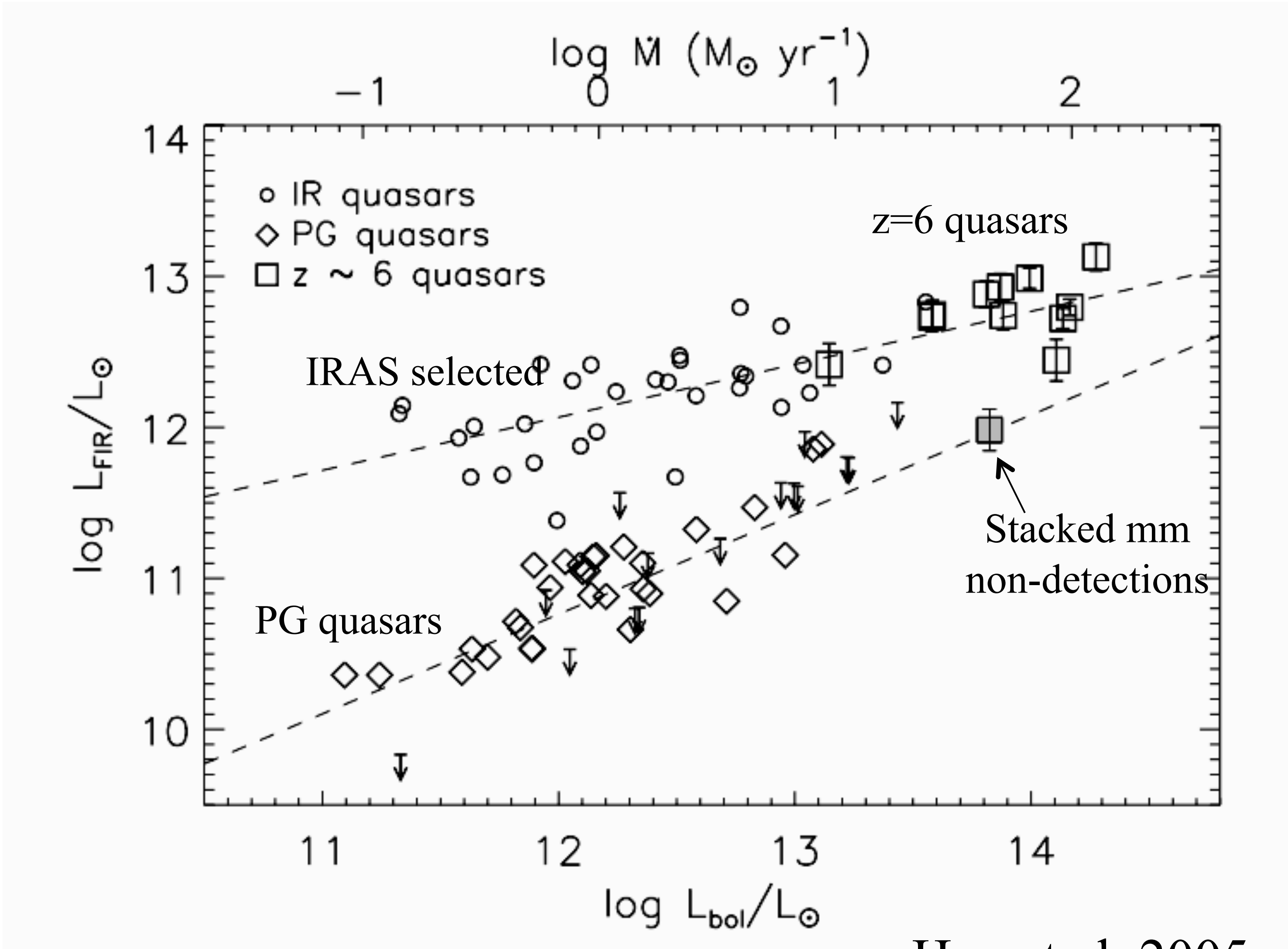
Gas dynamics: CO velocities



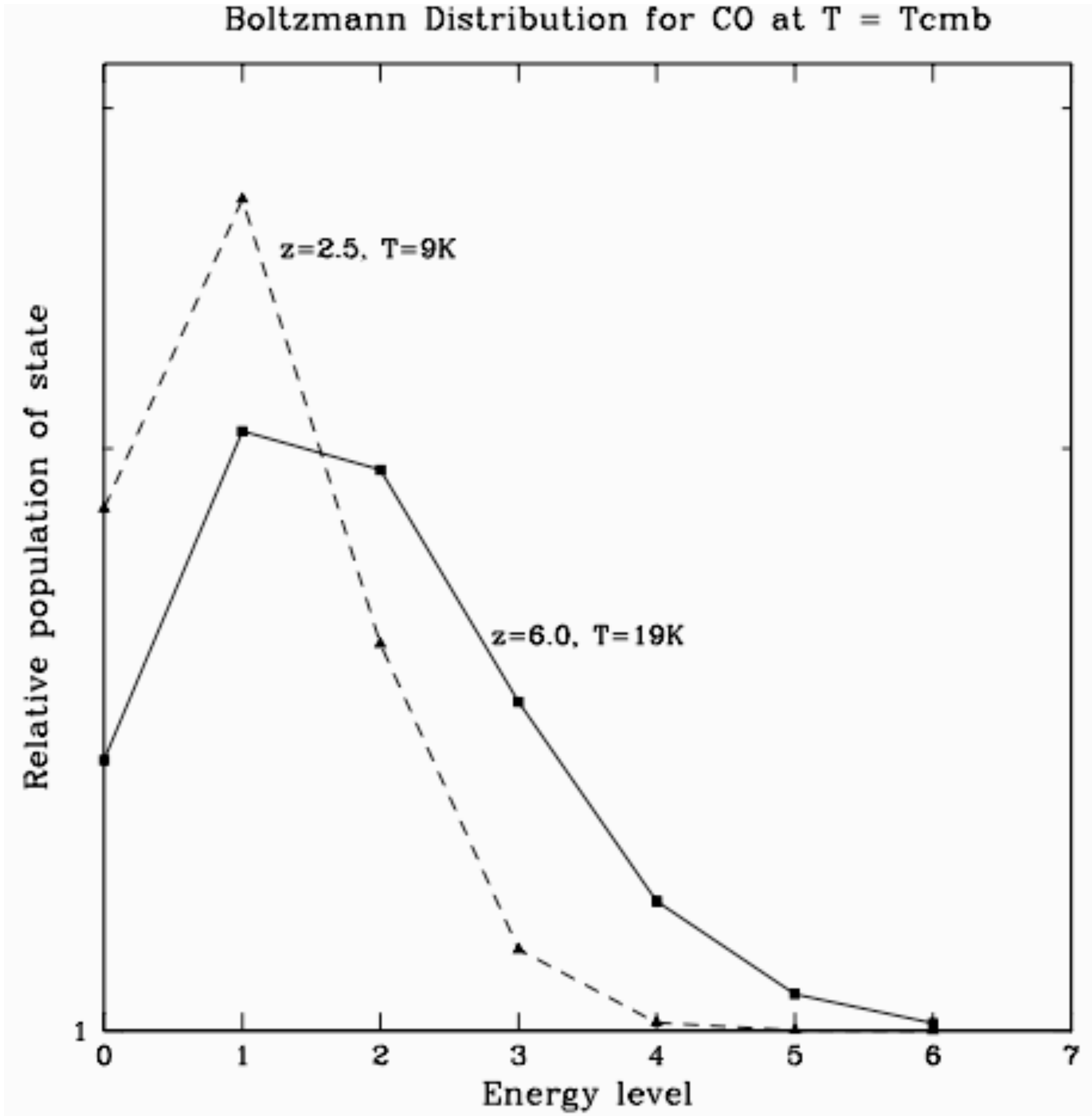


- Dynamical mass (r < 3kpc) ~ 0.4 to 2 x10^{11} M_o
- $M(H_2)/M_{dyn} \geq 1/2$

Comparison to low z quasar hosts



Hao et al. 2005



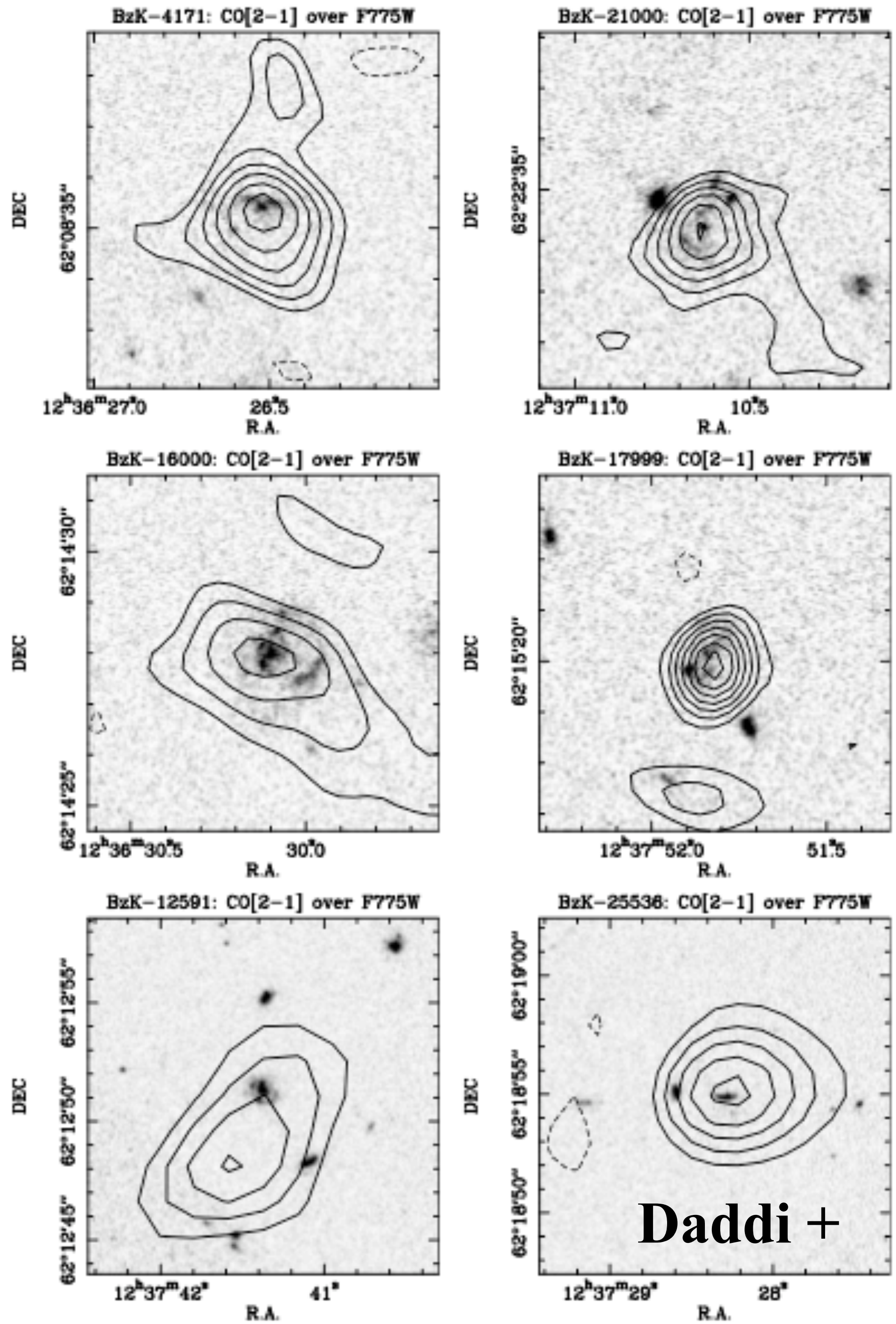
Boltzmann Distribution for CO at T = Tcmb
z=2.5, T=9K
z=6.0, T=19K
Relative population of state
Energy level
1
0
1
2
3
4
5
6
7

Gas dominated, normal galaxies at z~2

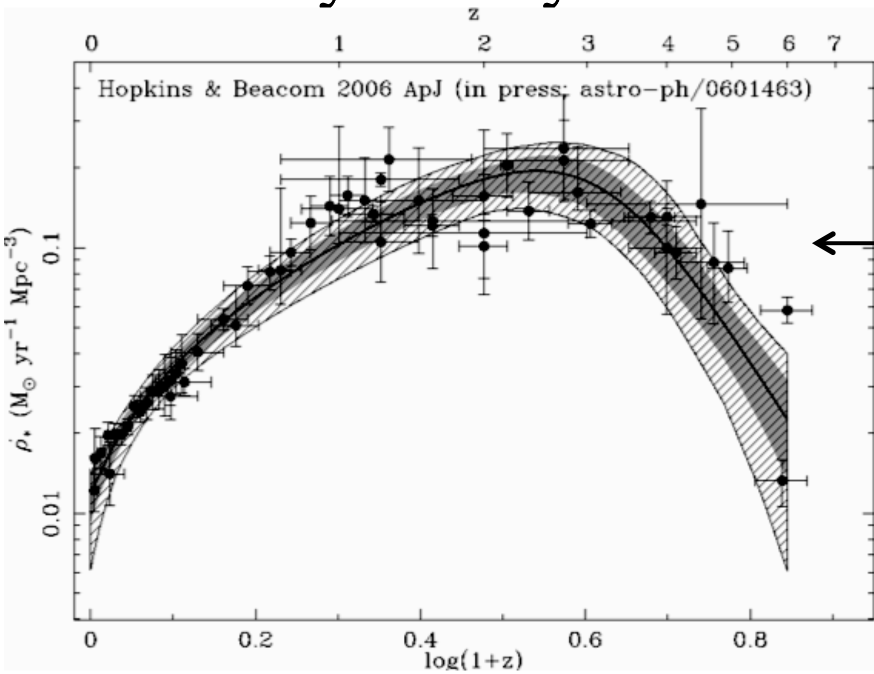
- sBzK z~2: normal star forming galaxies (SFR ~ 10 to 100 M_o/yr)
- 6 of 6 detected in CO
- Gas masses > 10^{10} $M_o \geq$ stellar masses
  - CO excitation ~ Milky Way
  - Gas depletion timescales > few x10^8 yrs

⇒ Secular galaxy evolution during the epoch of galaxy assembly

(see also Tacconi et al. 2010)



Gas density history of the Universe



SF law

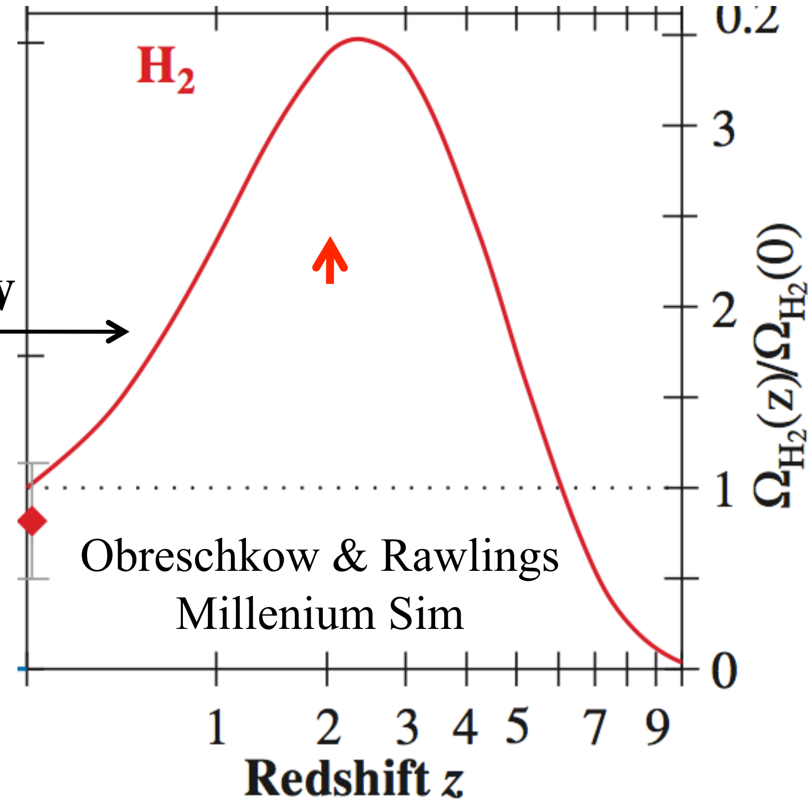


Table 1: EVLA (30-38GHz), ALMA (90-98GHz), 1000hrs, 50arcmin^2

	Tansition	z_{range}	Number of Galaxies
ALMA	CO 1-0	0.17 to 0.27	40
ALMA	CO 2-1	1.3 to 1.6	389
EVLA	HCN 1-0	1.3 to 2.0	7
EVLA	HCO^+ 1-0	1.3 to 2.0	7
EVLA	CO 1-0	2.0 to 2.8	130
ALMA	CO 3-2	2.5 to 2.8	122
ALMA	CO 4-3	3.7 to 4.1	66
ALMA	CO 5-4	4.9 to 5.4	24
EVLA	CO 2-1	5.0 to 6.7	13
ALMA	CO 6-5	6.0 to 6.7	7
ALMA(250GHz)	[CII] 158μm	6.36 to 6.6	110
ALMA(250GHz)	Continuum	$z < 10$	5000

<u>EVLA/ALMA deep fields</u>

- 100s of galaxies z=0.2 to 6.7 in CO, HCN, HCO+…
- $M(H_2) > 2e10\ M_o$ at z>1
- 100 in [CII] z ~ 6.5
- 5000 in dust continuum