Prospects for studies of the ISM in high-redshift galaxies

Jeff Wagg
ESO Fellow - Santiago

Chris Carilli (NRAO), Fabian Walter (MPIA), Ran Wang (NOAO)
Dominik Riechers (Caltech), Frank Bertoldi (U. Bonn), Karl Menten (MPIfR)
Pierre Cox, Roberto Neri (IRAM), David Wilner (CfA)
Nissim Kanekar (NCRA)

ALMA spectroscopy, Victoria
January 15, 2011

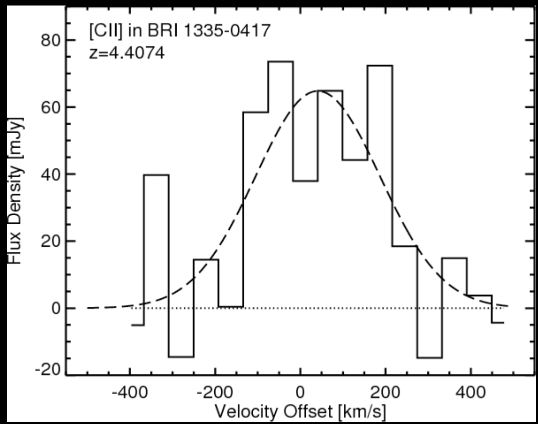
Outline

• CO and cold molecular gas in starburst galaxies at AGN at z < 4: estimating total molecular gas masses

• CO line emission in quasar host and star-forming galaxies during the epoch of reionization: molecular and dynamical gas masses of the first galaxies

• HCN, HCO+ line emission and the dense molecular gas in high-redshift galaxies

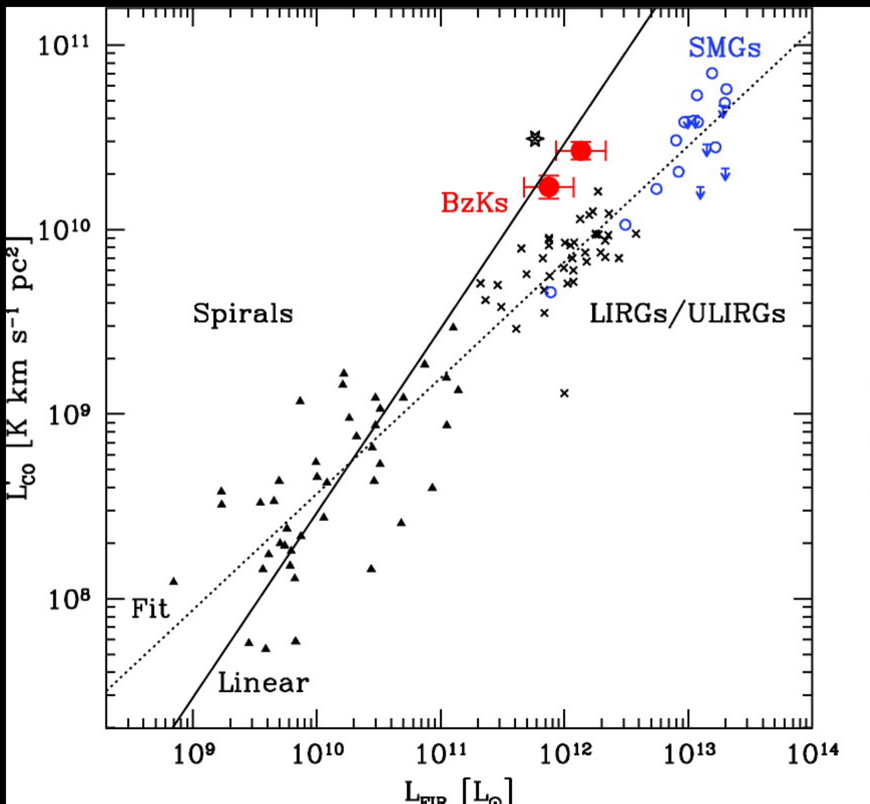
• C+ line emission at z > 4: first observations with ALMA

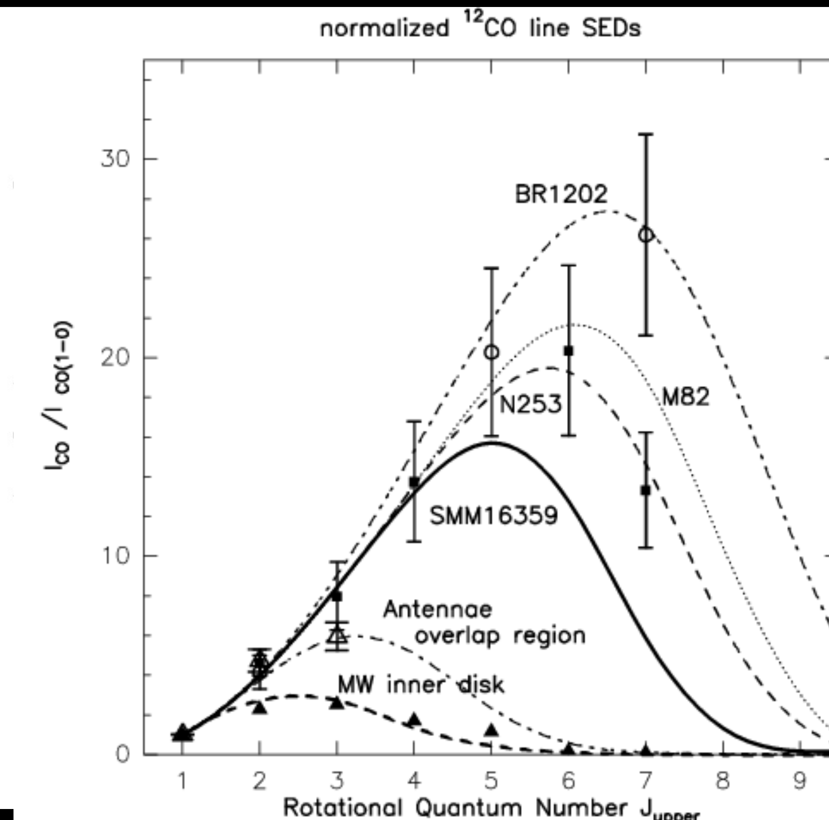


APEX 350 GHz; Wagg et al. 2010

CO line emission as a tracer of molecular gas at high-redshift: fueling star-formation and AGN activity

Molecular gas mass





Obscured star-formation rate

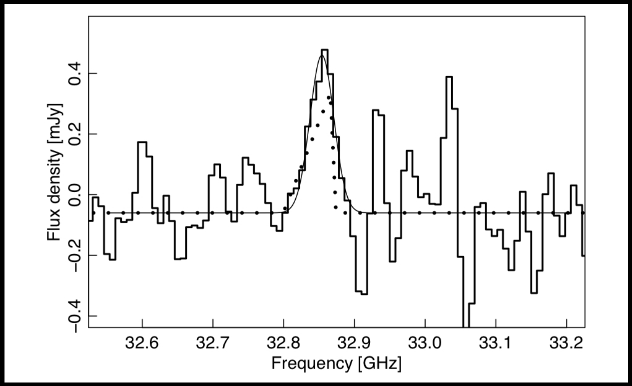
High-z: Solomon & Vanden Bout 2005; Greve et al 2005; Riechers et al 2006; Daddi et al. 2008

$M_{H2} \sim 0.8\ L'_{CO}$ [M_{sun}] ULIRGS (Downes & Solomon 1998)

$M_{H2} \sim 4.6\ L'_{CO}$ [M_{sun}] Milky Way (e.g. Solomon & Barrett 1991)

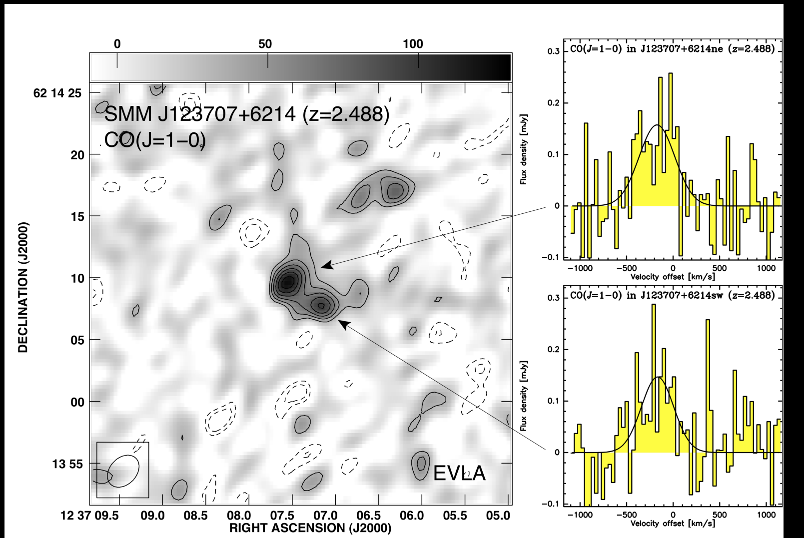
EVLA and GBT: cold molecular gas at high-redshift

CO J=1-0 in z=1.8 to 3.4 submm galaxies



SMMJ04431 z=2.5
GBT - Zspectrometer

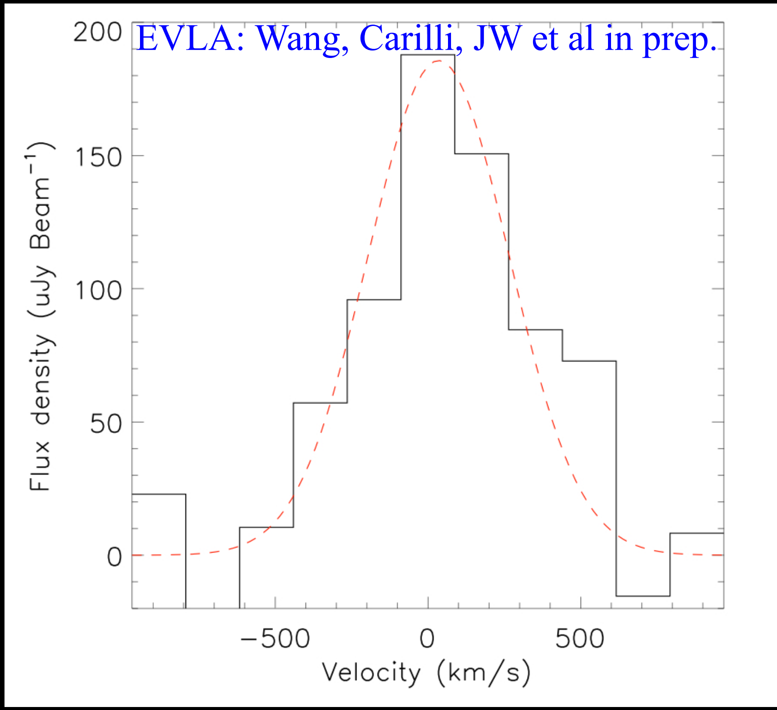
Harris et al 2010



Riechers, Walter, Carilli & JW 2010

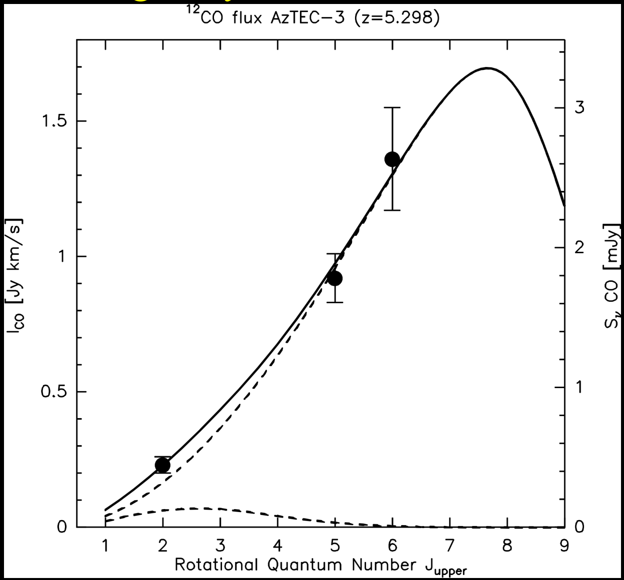
see also Ivison et al 2010

CO J=2-1 in z > 5.7 quasar host galaxies



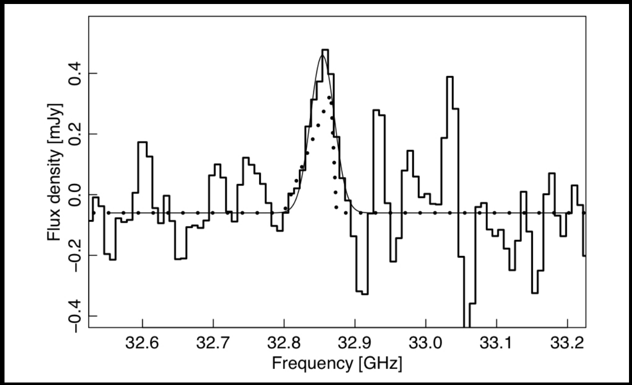
CO J=2-1 in a z=5.3 submm galaxy

Riechers et al 2010



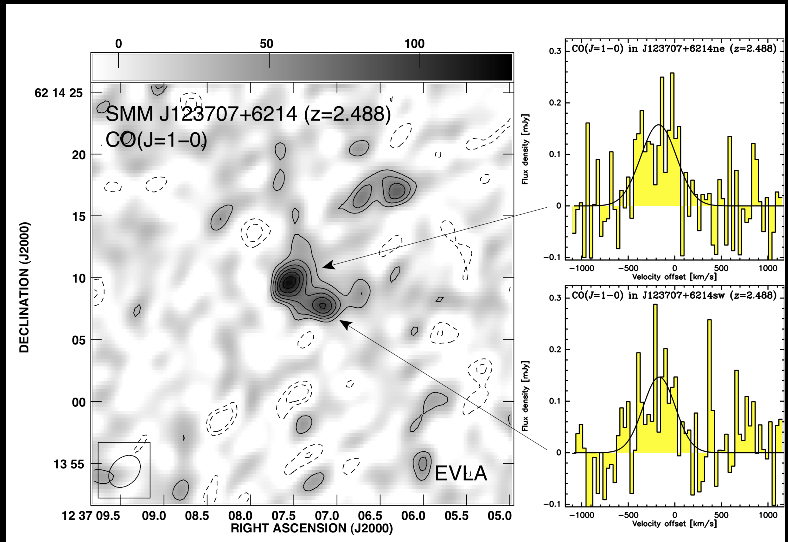
EVLA and GBT: cold molecular gas at high-redshift

CO *J*=1-0 in z=1.8 to 3.4 submm galaxies



SMMJ04431 z=2.5
GBT - Zspectrometer

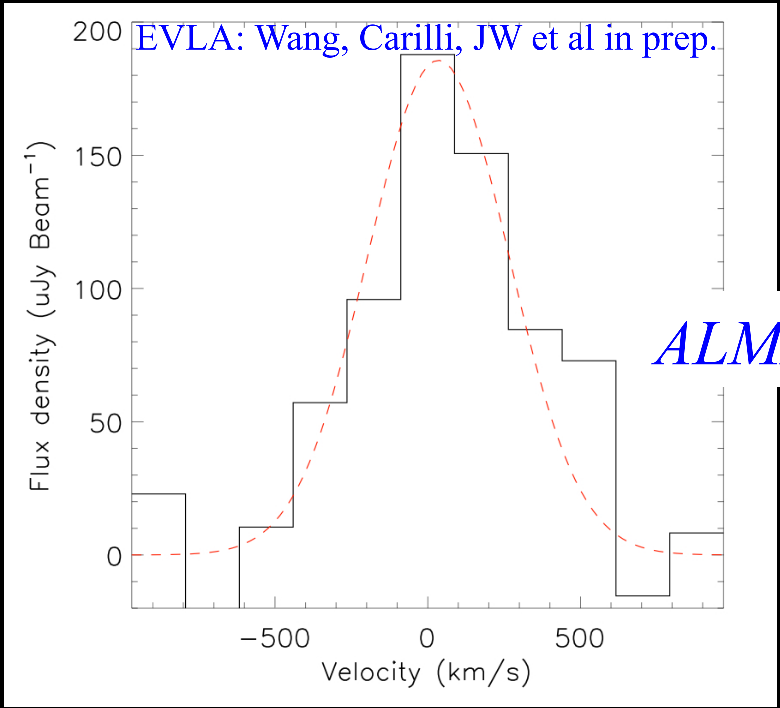
Harris et al 2010



Riechers, Walter, Carilli & JW 2010

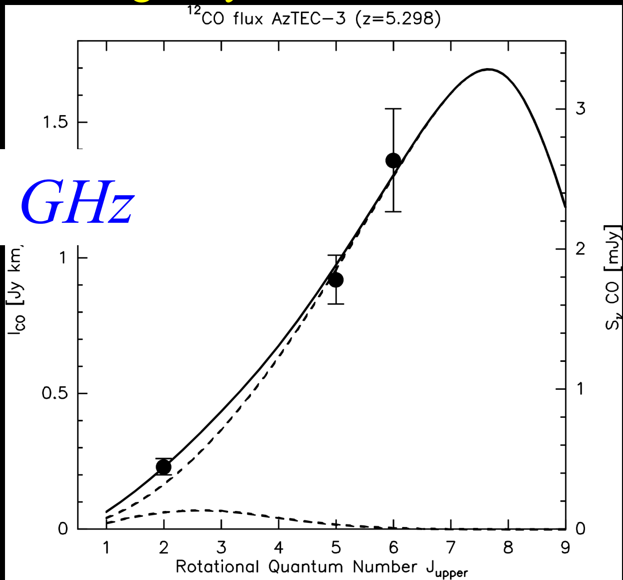
see also Ivison et al 2010

CO *J*=2-1 in z > 5.7 quasar host galaxies



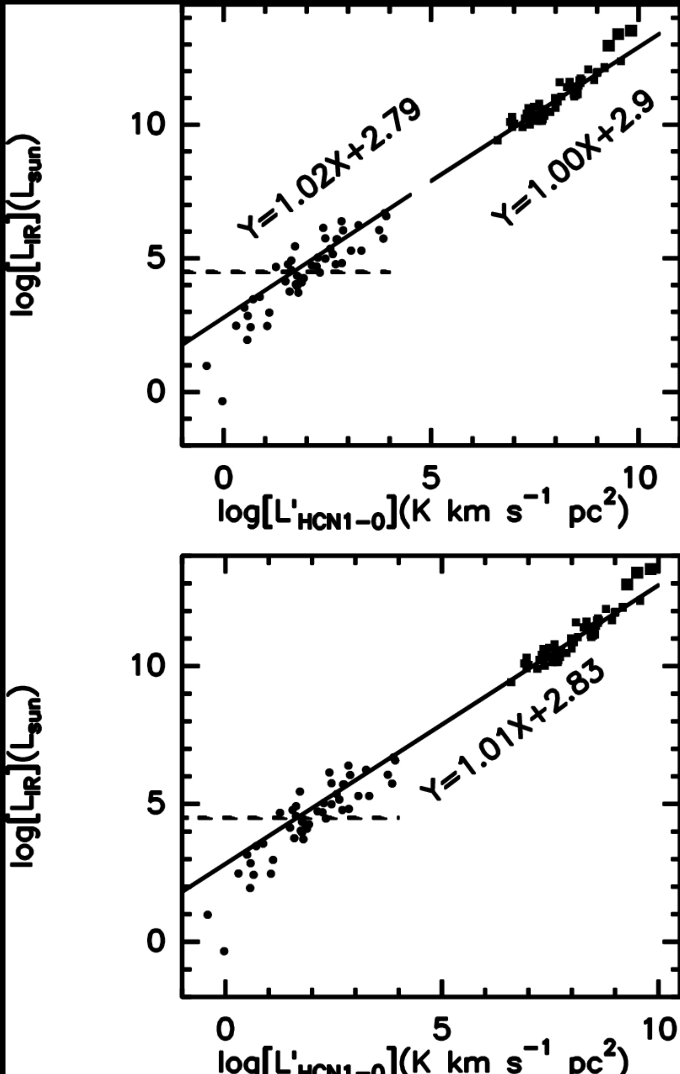
CO *J*=2-1 in a z=5.3 submm galaxy

Riechers et al 2010



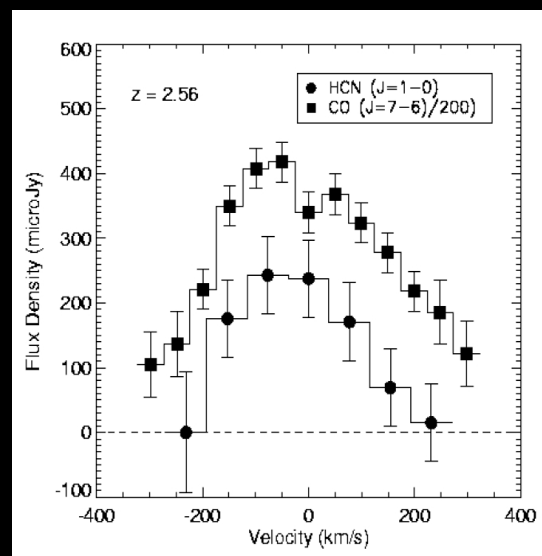
ALMA Band 1: 31-45 GHz

Dense gas tracers: HCN and HCO+



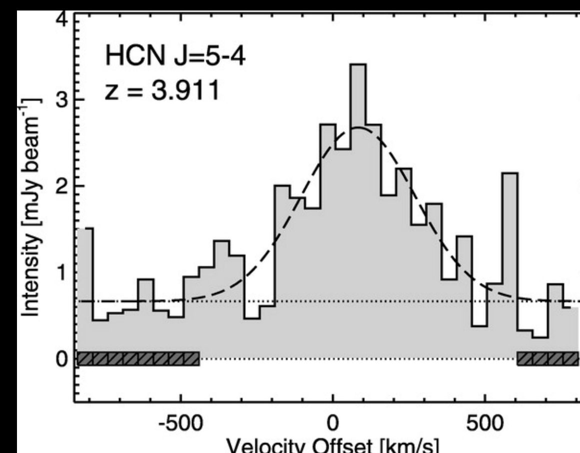
Galactic cores - Wu et al. 2005

- HCN in the Galaxy, selectively traces the dense gas (>1e4 cm^{-3}) responsible for star-formation
- correlation between L_{IR} and L_{HCN} over ~8 orders in magnitude for L_{IR} (from Galactic cores to ULIRGs) (Gao & Solomon 2004; Wu et al. 2005)
- only five known high-redshift objects (z > 2) are bright enough to have been detected in low-*J* HCN/HCO+

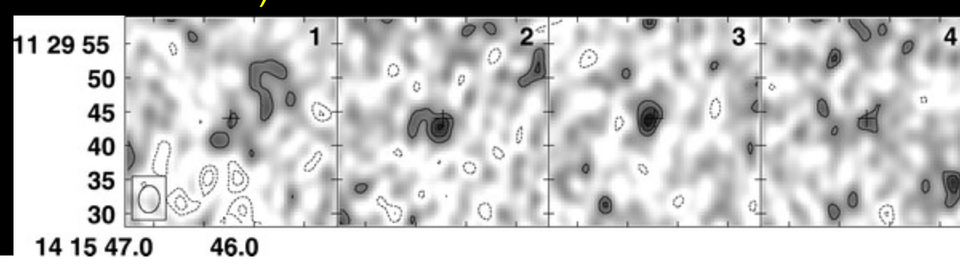


Cloverleaf at z=2.56: HCN *J*=1-0
(Solomon et al. 2003)

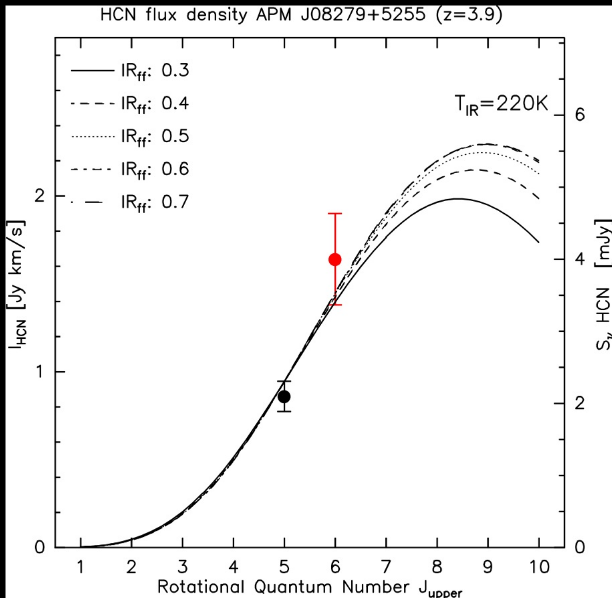
APM08279 at z=3.9: HCN *J*=5-4
(Wagg et al. 2005; Weiss et al 2007)



Cloverleaf at z=2.56: HCO+ *J*=1-0/4-3
(Riechers et al. 2006, 2010)

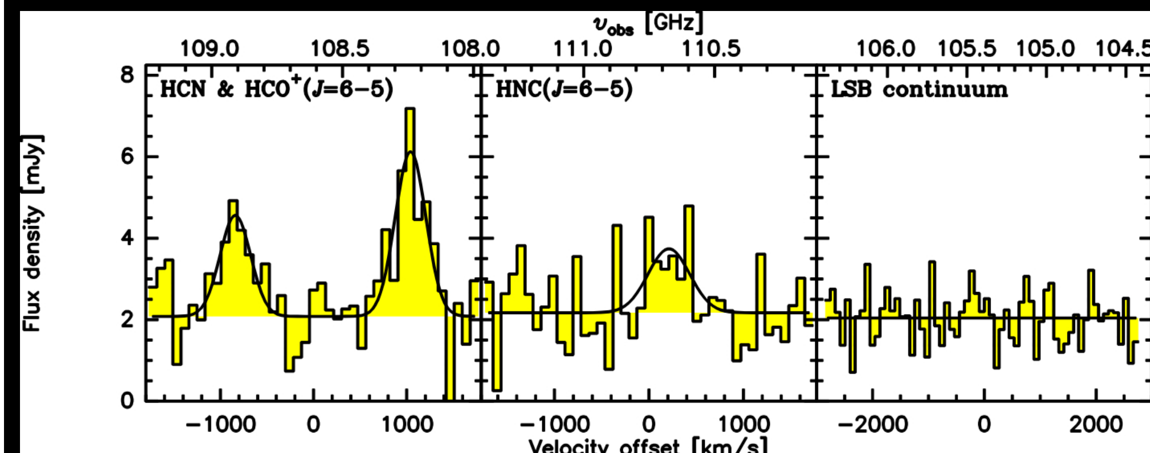


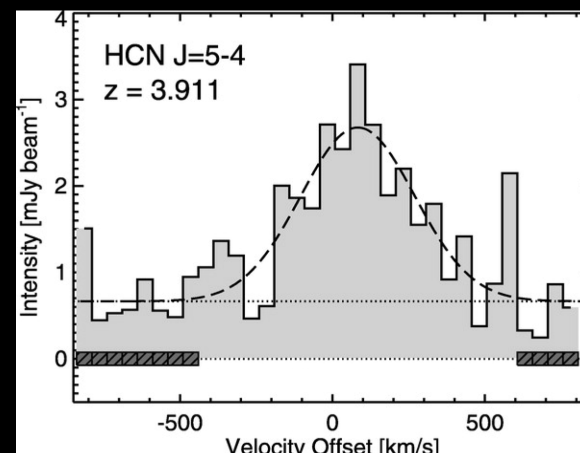
Dense gas tracers: high-*J* HCN, HNC and HCO+



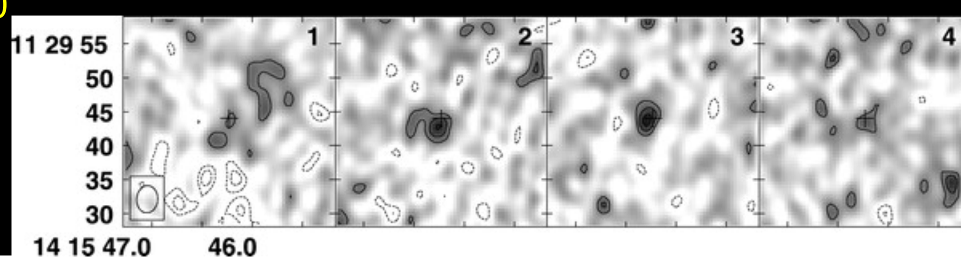
- HCN in the Galaxy, selectively traces the dense gas (>1e4 cm^{-3}) responsible for star-formation
- correlation between L_{IR} and L_{HCN} over ~8 orders in magnitude for L_{IR} (from Galactic cores to ULIRGs) (Gao & Solomon 2004; Wu et al. 2005)
- only five known high-redshift objects (z > 2) are bright enough to have been detected in low-*J* HCN/HCO+

APM08279 at z=3.9: HCN *J*=5-4
(Wagg et al. 2005; Weiss et al 2007)



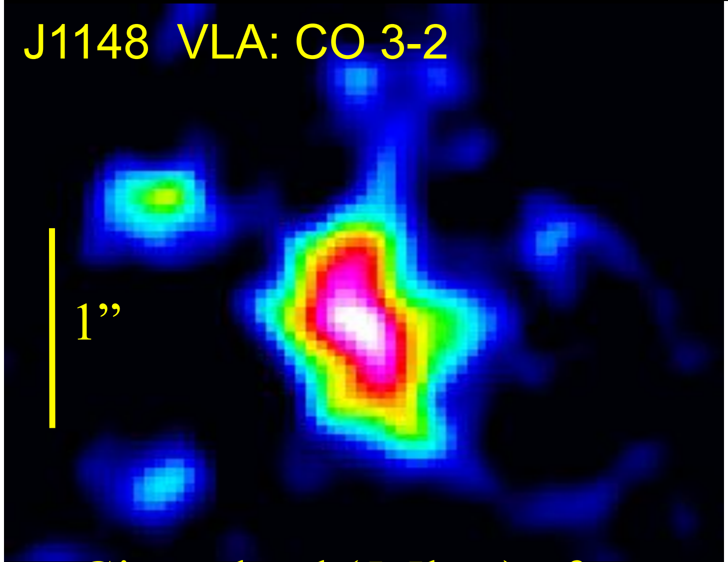


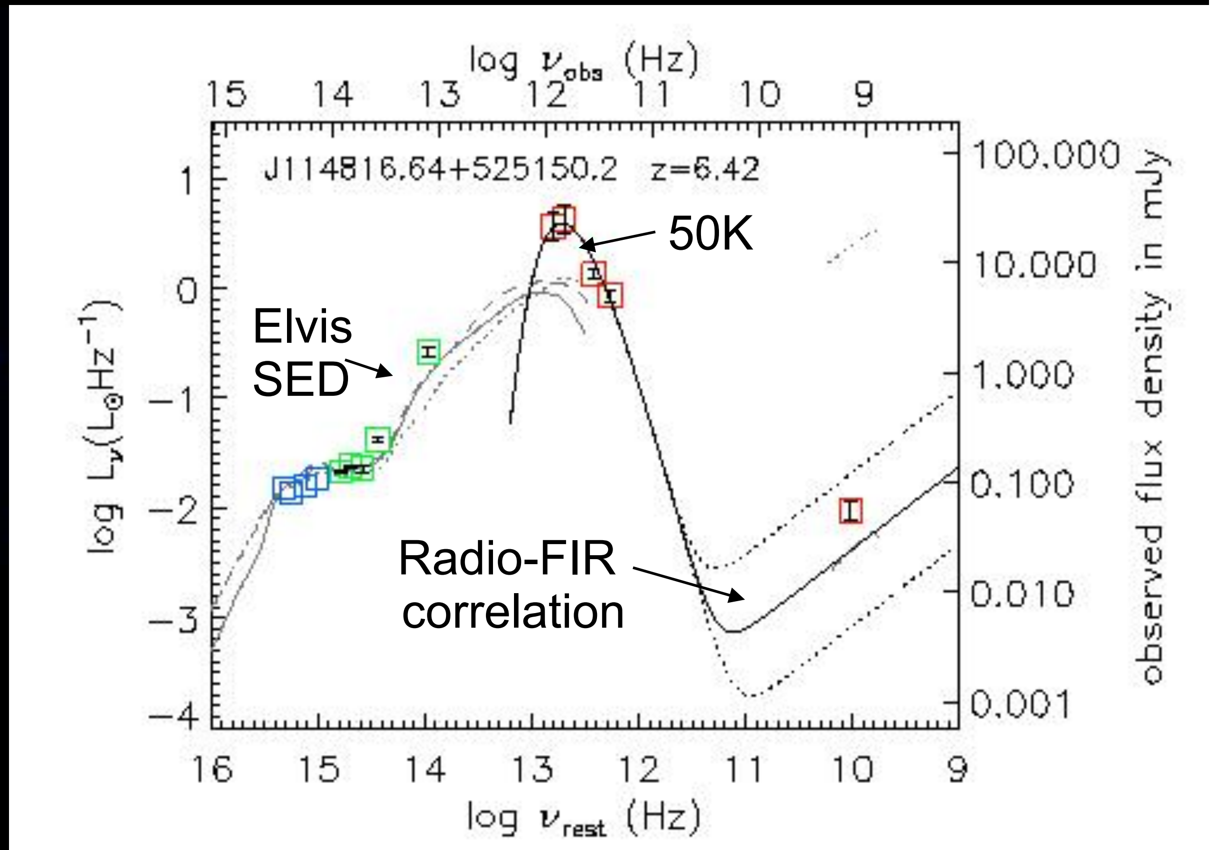
APM08279 at z=3.9 -Riechers, Weiss, Walter & JW 2010



Cloverleaf at z=2.56: HCO+ *J*=1-0/4-3
(Riechers et al. 2006, 2010)

SDSS J1148+5251: Dust and molecular gas into cosmic reionization





- Giant cloud (5.5kpc) of gas and dust:

  7e8 M_o in dust

  2e10 M_o in gas

- Hyper luminous IR galaxy (FIR=1e13 L_o)
- Follows Radio-FIR correlation: SFR = 3000 M_o/yr

- Early enrichment of heavy elements ($z_{sf} > 8$)
- Dust formation by massive stars:

  Cass-A (e.g. Rho et al 2008)

Molecular gas in galaxies during reionization: CO in z > 5.7 quasars

- MAMBO 1.2mm: 30% of optical quasars at z>5.7 hyperluminous in FIR, $5\text{-}10\times10^{13}$ Lsun (Bertoldi et al. 2003; Petric et al. 2003; Wang et al. 2007)

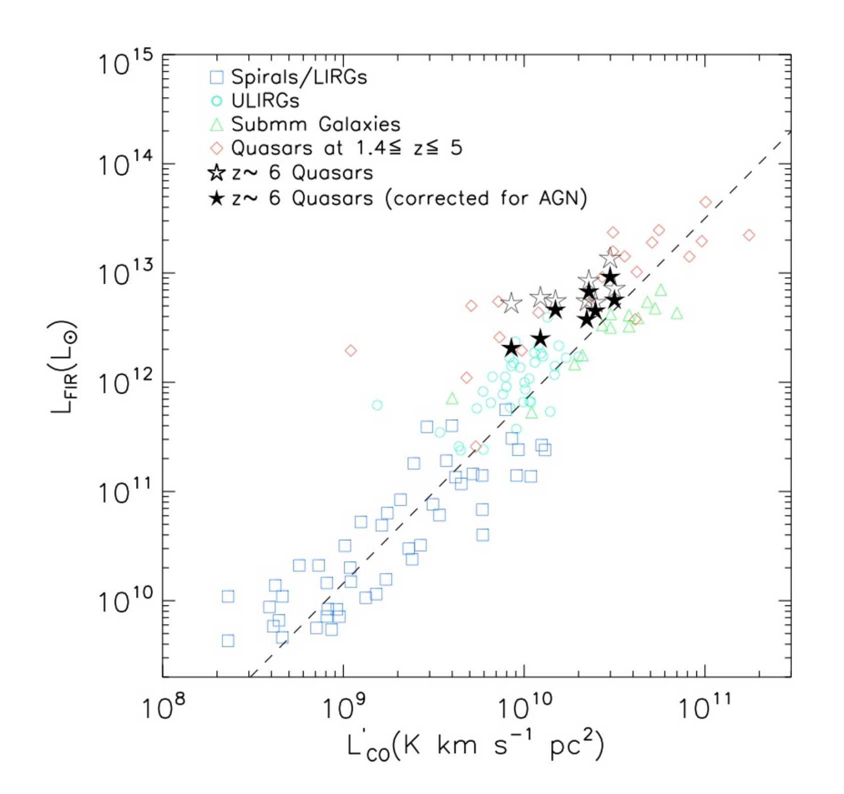
- T_{dust} ~ 40-60 K (Beelen et al 2006; Wang et al 2008)

- PdBI survey of high-*J* CO line emission (*J*=6-5, 5-4) detects 8/8 sources (Bertoldi et al 2003, Carilli et al 2007; Wang et al. 2010)

- molecular gas masses: $0.7\text{-}2.6\times10^{10}$ Msun

- line FWHM: 160 –830 km/s

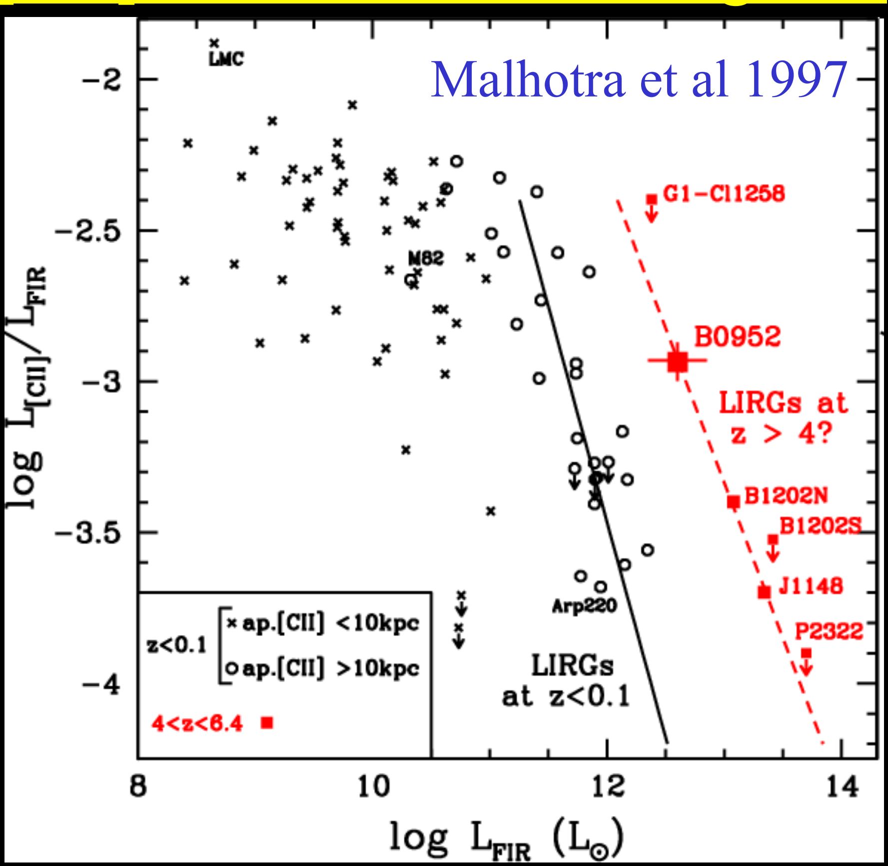
Ran Wang (Jansky Fellow), Carilli, Neri, Cox, Walter, Wagg, Riechers, Bertoldi, Menten, Omont, Strauss & Fan, 2010



- gas excitation? (e.g. Wagg et al. 2008, GBT memo #256; Wang, CC, JW et al in prep.)

- CO in low luminosity AGN at z~6? (Wang, Wagg, CC et al. submitted)

[CII] atomic ISM cooling line



High-z detections - see Maiolino et al 2009; Stacey et al 2010

- [CII] fine structure line (157.7um)
- star-formation rate indicator
- [CII] contributes high fraction of LFIR:

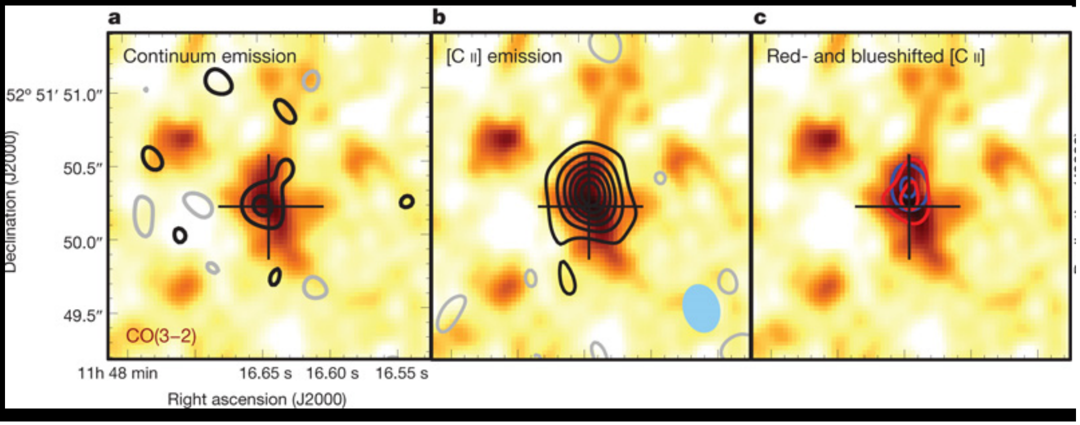
  Dwarf galaxies: 1%

  star-forming galaxies: 0.5%

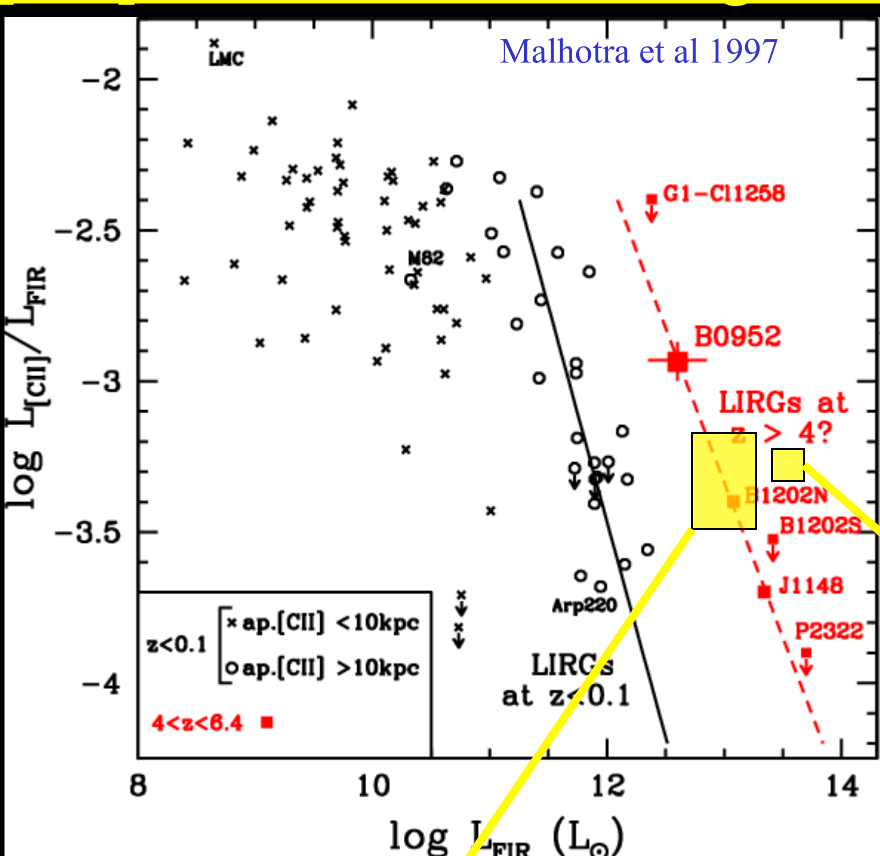
  ULIRGs: 0.05%

- Redshifts and galaxy dynamics during reionization (e.g. Walter & Carilli 2008)

[CII] line emission in J1148 at z=6.42
(PdBI; Walter et al. 2009):
Starburst on kiloparsec scales



[CII] atomic ISM cooling line



High-z detections - see Maiolino et al 2009; Stacey et al 2010

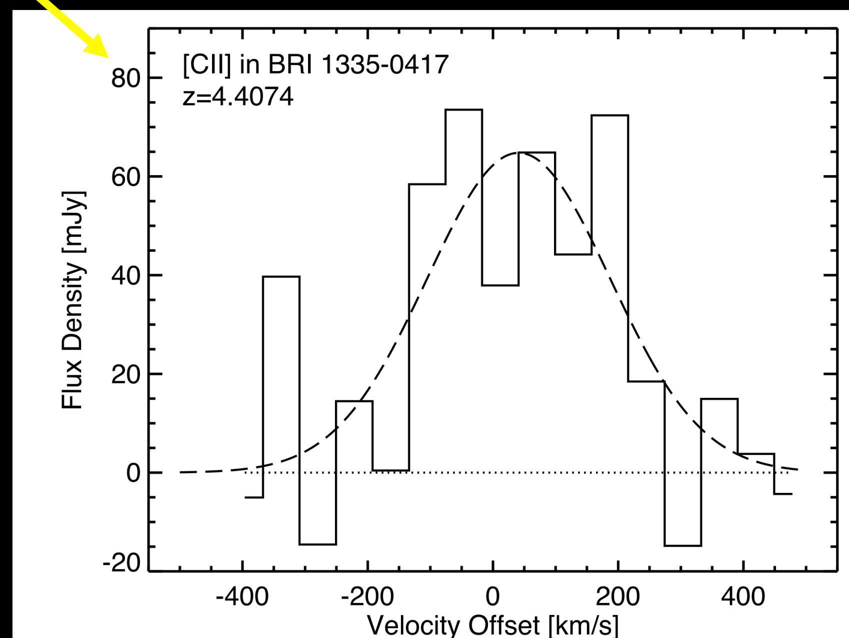
Starburst galaxy at z=4.5 (SMA; Wagg et al. in prep.)

- [CII] fine structure line (157.7um)
- star-formation rate indicator
- [CII] contributes high fraction of LFIR:

  Dwarf galaxies: 1%

  star-forming galaxies: 0.5%

  ULIRGs: 0.05%

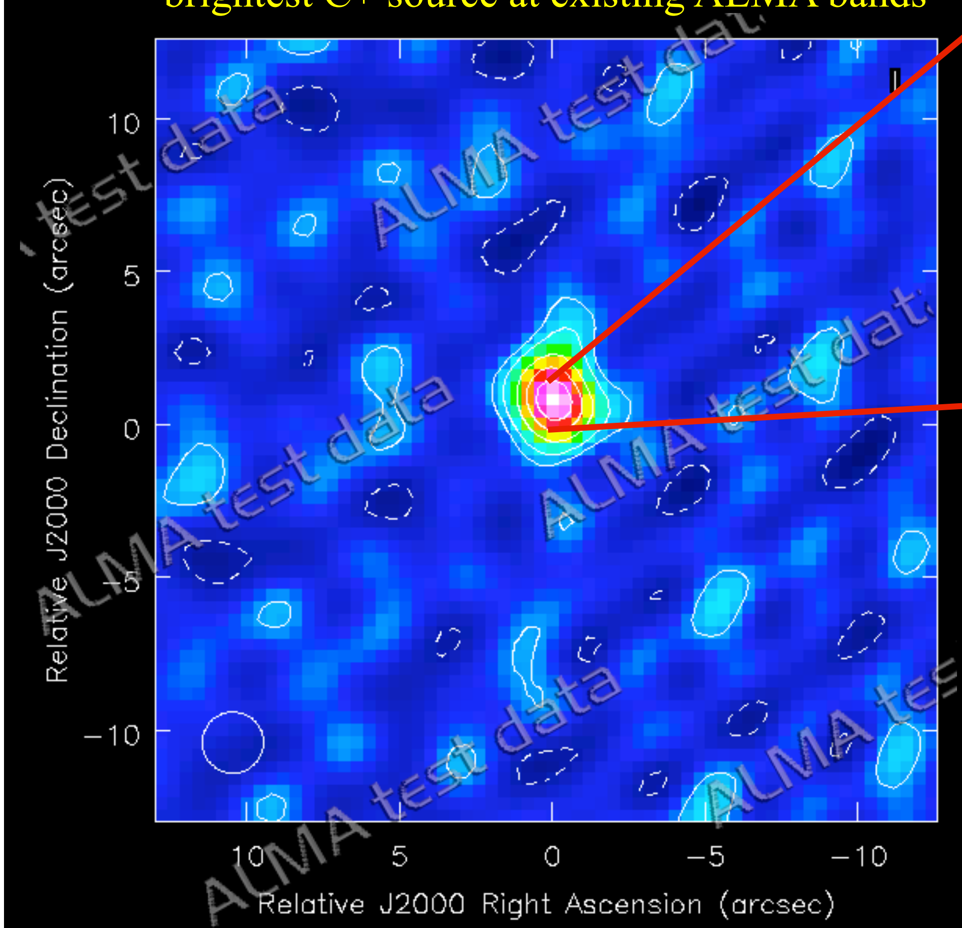


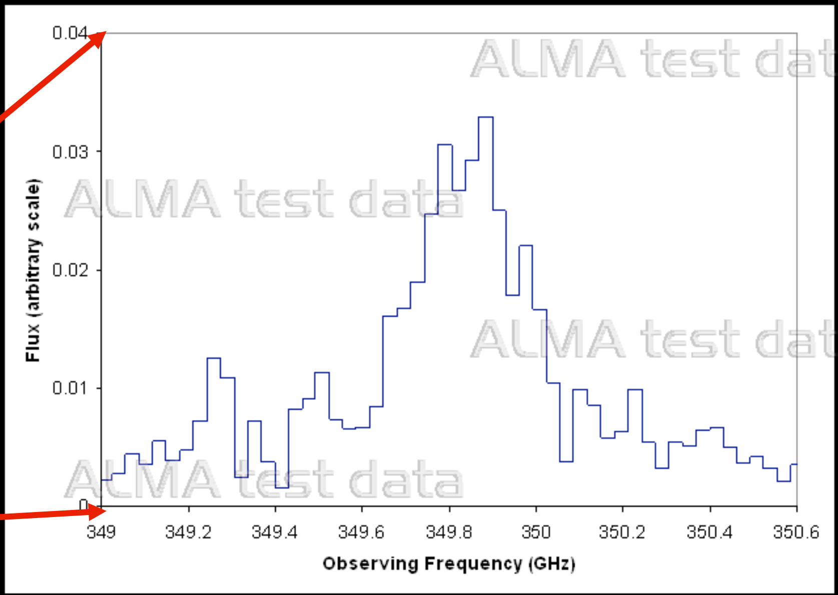
[CII] line emission in BRI1335-0417 at z=4.4 (APEX; Wagg et al. 2010):

ALMA observations of [CII] line emission at z=4.4

BRI0952-0115 – lensed quasar host galaxy at z=4.4

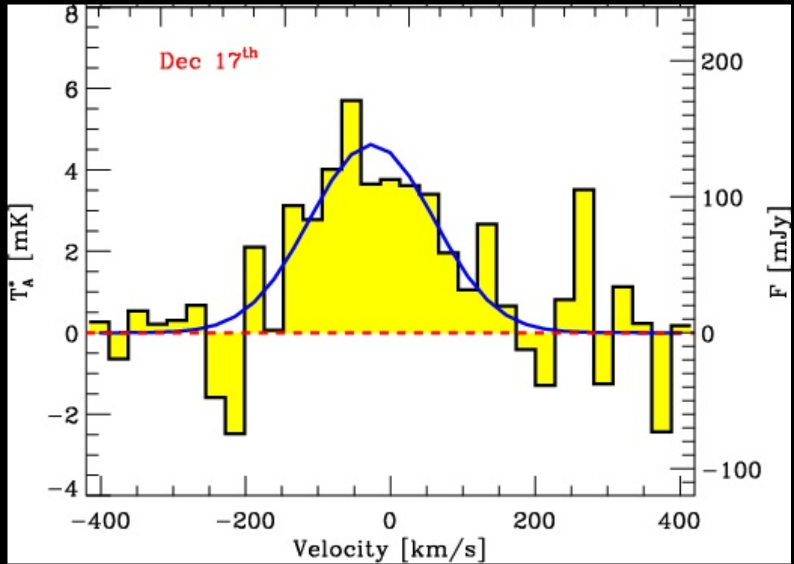
- brightest C+ source at existing ALMA bands





ALMA (6 antennas), Band 7, 350GHz – 1 hour total
PI: Wagg reduction: Villard & Fomalont

Special thanks to all of those involved in the ALMA project: JAO, NAASC, ESO, ASIAA, NAOJ



APEX spectrum – 20 hours total
Maiolino et al. (2009)


An ESO Workshop on
Multiwavelength Views of the ISM in High-redshift Galaxies
June 27-30, 2011
Santiago, Chile
gas2011@eso.org
SOC:
Andrew Baker
Chris Carilli
Carlos De Breuck (co-Chair)
Leopoldo Infante
Rob Ivison
Roberto Maiolino
Alison Peck
Dominik Riechers
Linda Tacconi
Jeff Wagg (Chair)
Fabian Walter
Tommy Wiklind
Min Yun
LOC:
Carlos De Breuck
Diego Garcia-Appadoo
Maria Eugenia Gomez
Paulina Jiron
Sergio Martin
Alison Peck
Jeff Wagg
ESO
http://www.eso.org/sci/meetings/2011/gas2011.html

Summary

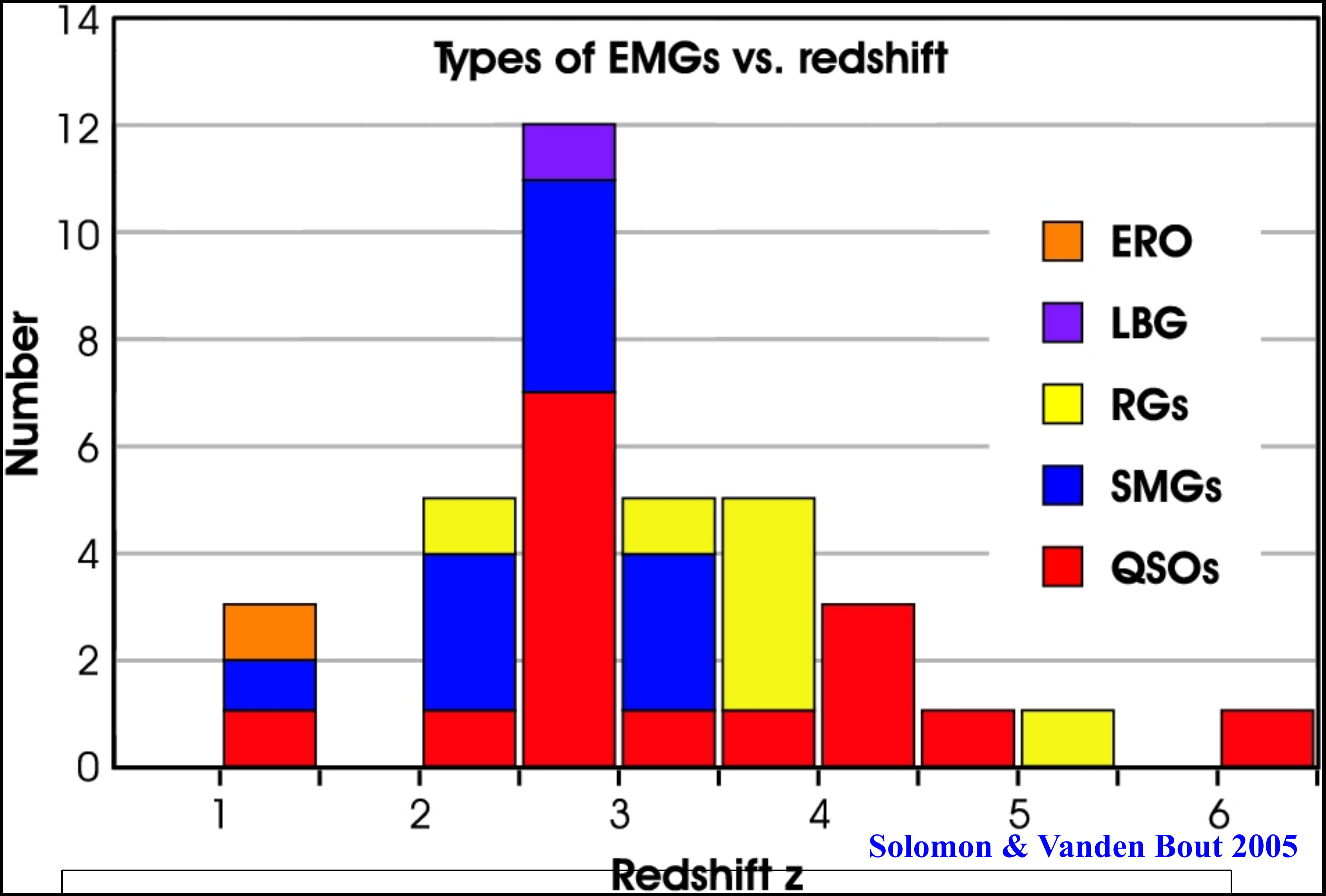
• observations of high-*J* CO line emission (*J*=3-2) misses 20-50% of the molecular gas mass in starburst galaxies at z > 1, more in the case of lower excitation BzK star-forming galaxies: GBT, EVLA and ALMA Band 1

• CO *J*=6-5/5-4 observations with the PdBI measure molecular gas masses for 8 quasar host galaxies at z > 5.7 – consistent with the EVLA *J*=2-1 line intensity

• measuring dense molecular gas masses using low-*J* HCN and HCO+ lines with the EVLA and GBT is limited by sensitivity: ALMA?

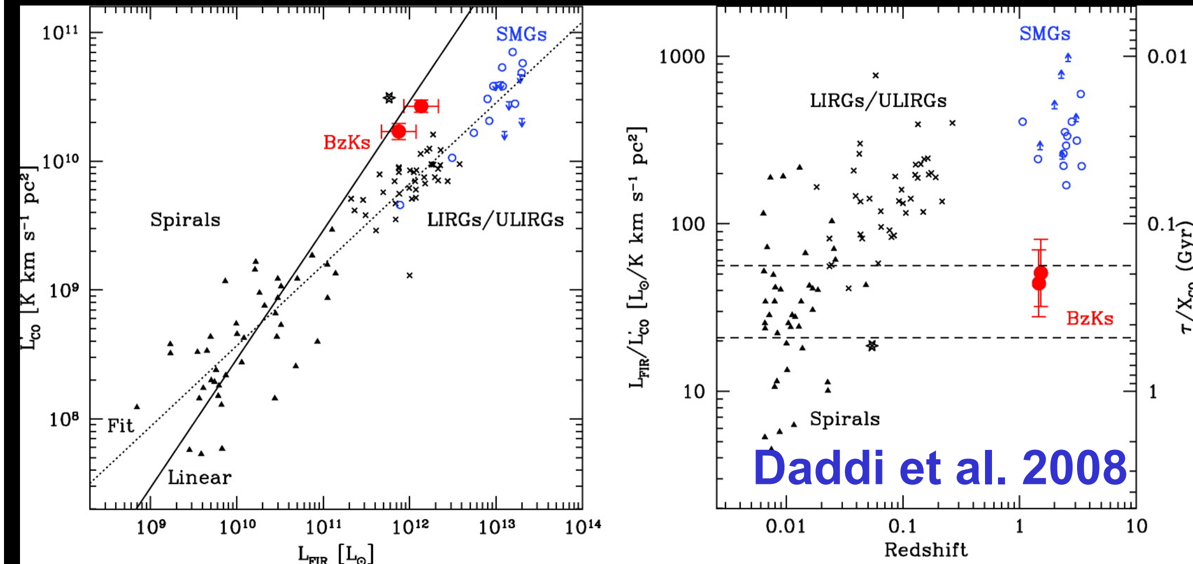
• C+ line emission will be the preferred means of studying the ISM and measuring dynamical masses for z > 4 galaxies with ALMA

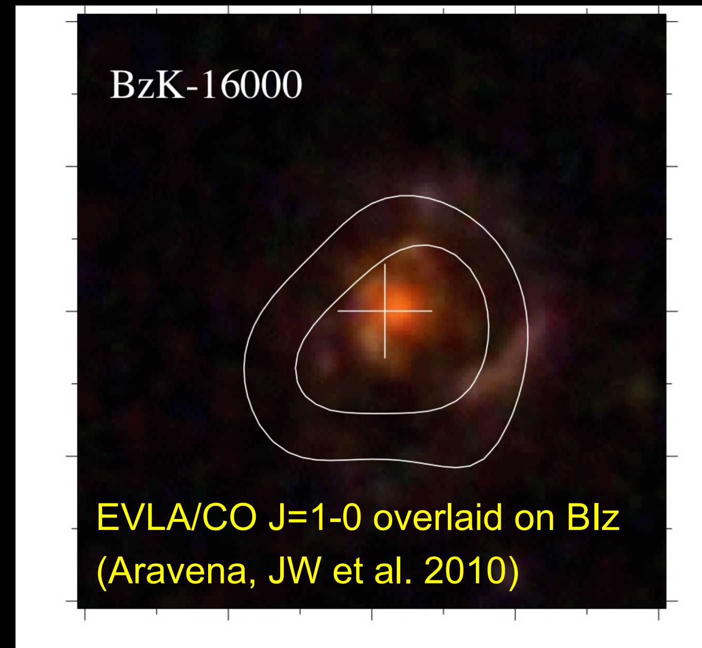
Summary of high-z CO line detections

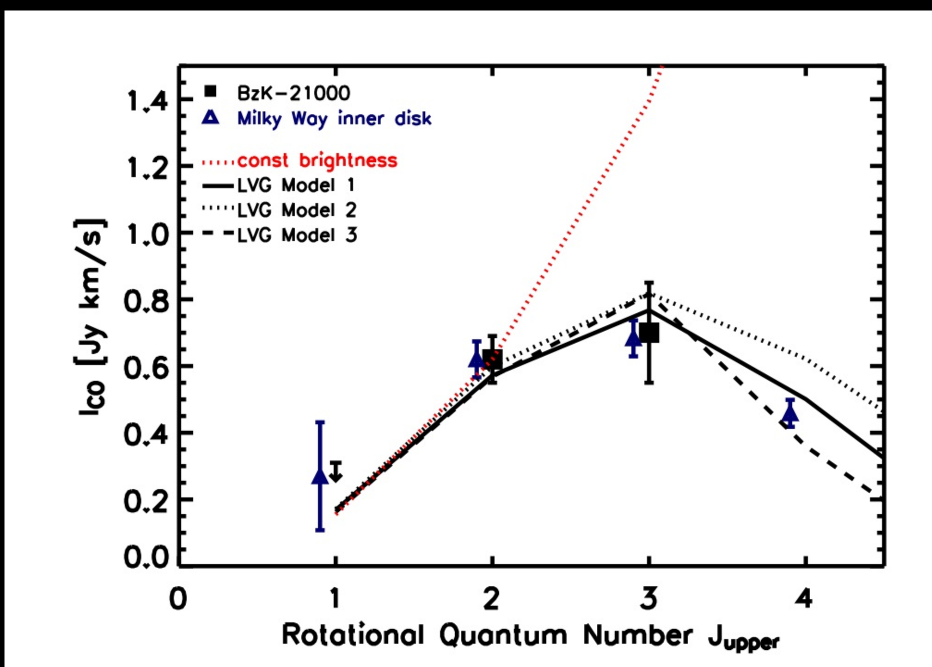


- nearly 80 objects at 1.0 < z < 6.4 detected in CO line emission
- most detected in high-*J* transitions, less than 10 detections of CO *J*=1-0

Low excitation molecular gas in disk galaxies at z~1.5







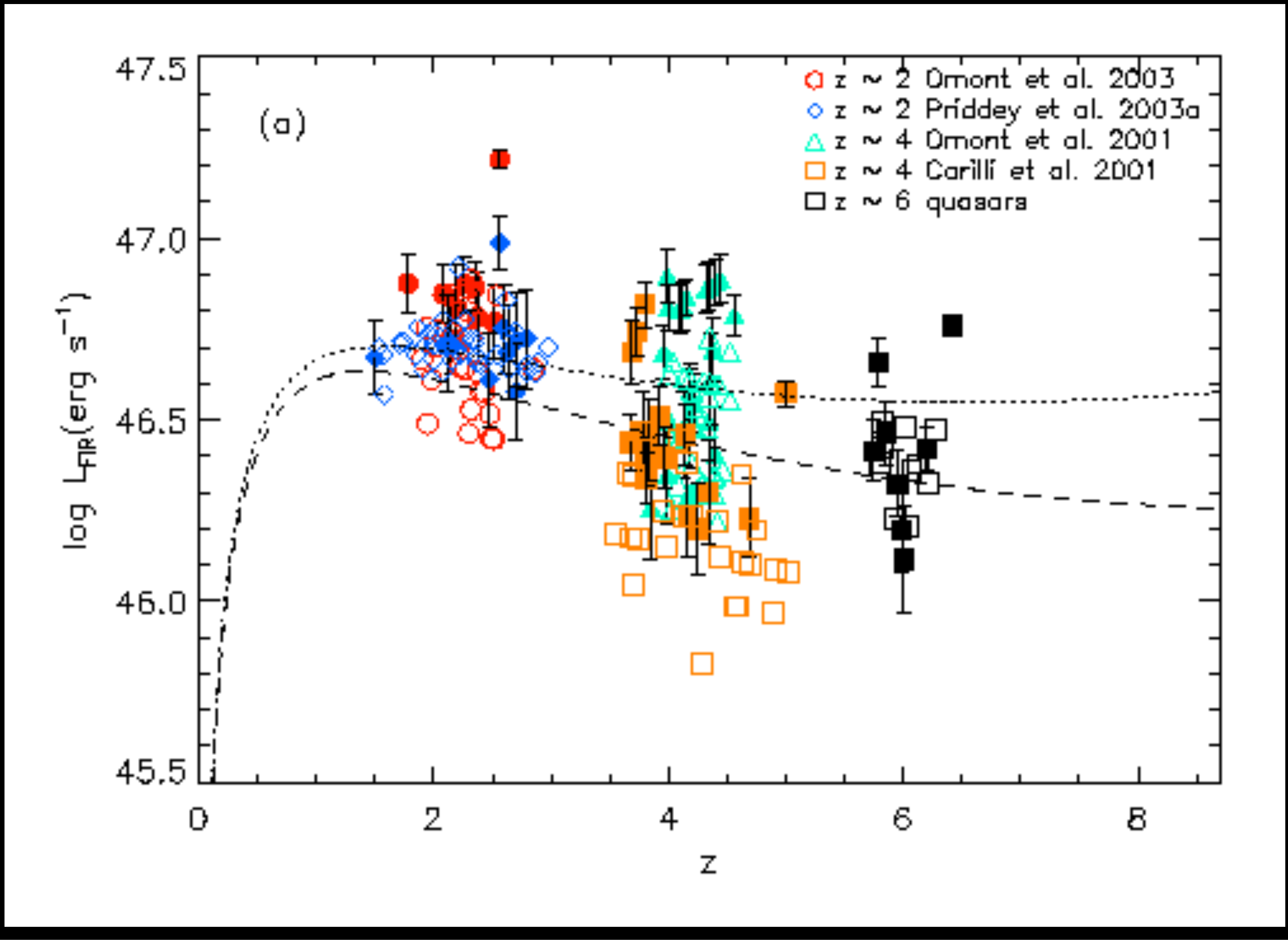
- BzK galaxies: star-forming galaxies identified in (B-z) vs. (z-K) diagram (eg Daddi et al. 2004)

- CO *J*=2-1 with PdBI: large masses of molecular gas (10^{10} Msun) forming stars with low efficiency (~100 Msun/yr)

Dannerbauer et al. in 2009

Dust in the host galaxies of high-redshift quasars

- 30% of z~6 QSO host galaxies = Hyper-lum. IR galaxies: L_{FIR} ~ 1e13 L_o
- M_{dust} ~ 1e8 M_o (e.g. Wang et al 2007)
- t_{univ} < 1Gyr => Dust formation in massive stars during SNII?

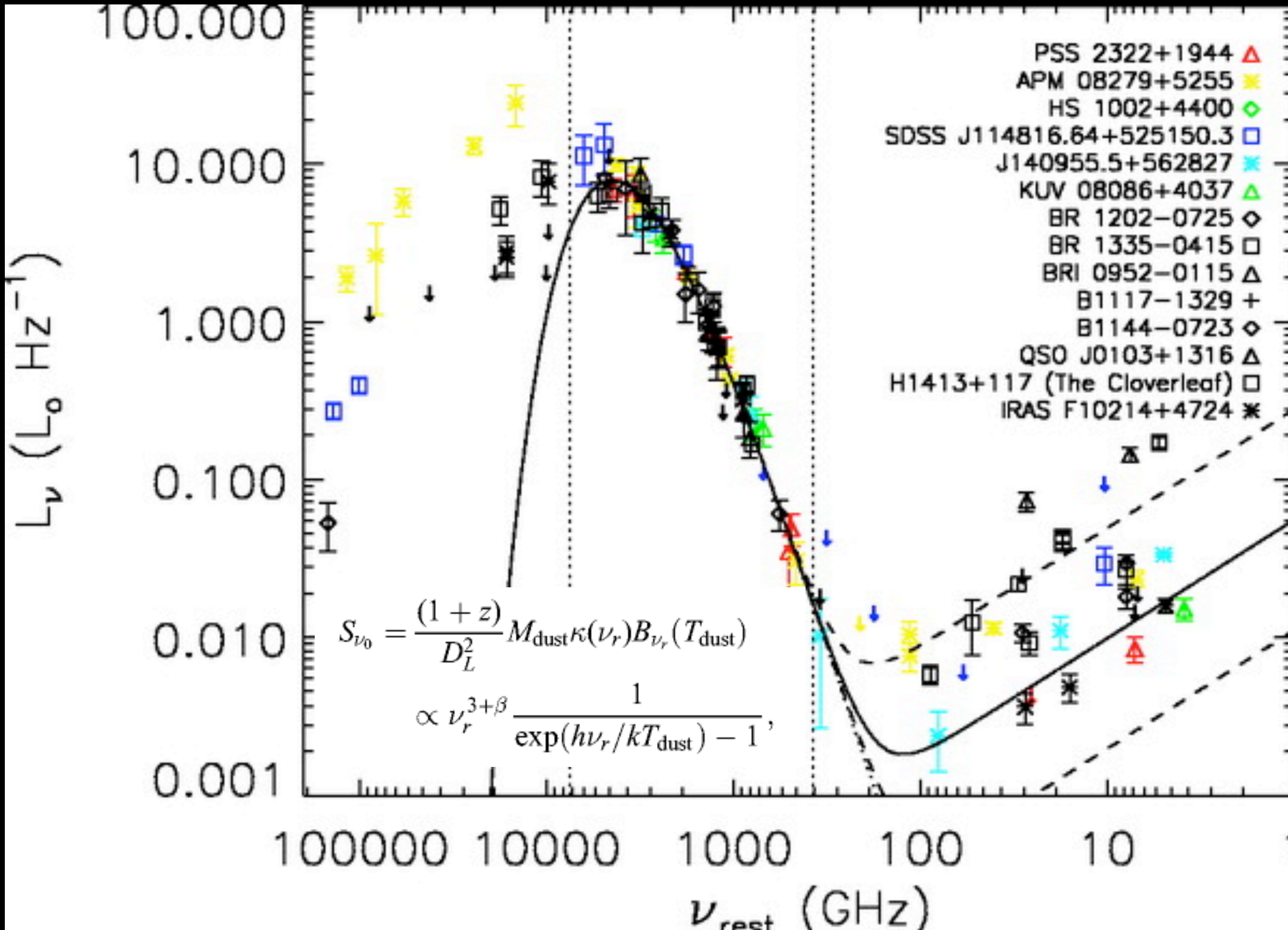


3-σ detection limit

$S_{1.2mm}$ = 3mJy

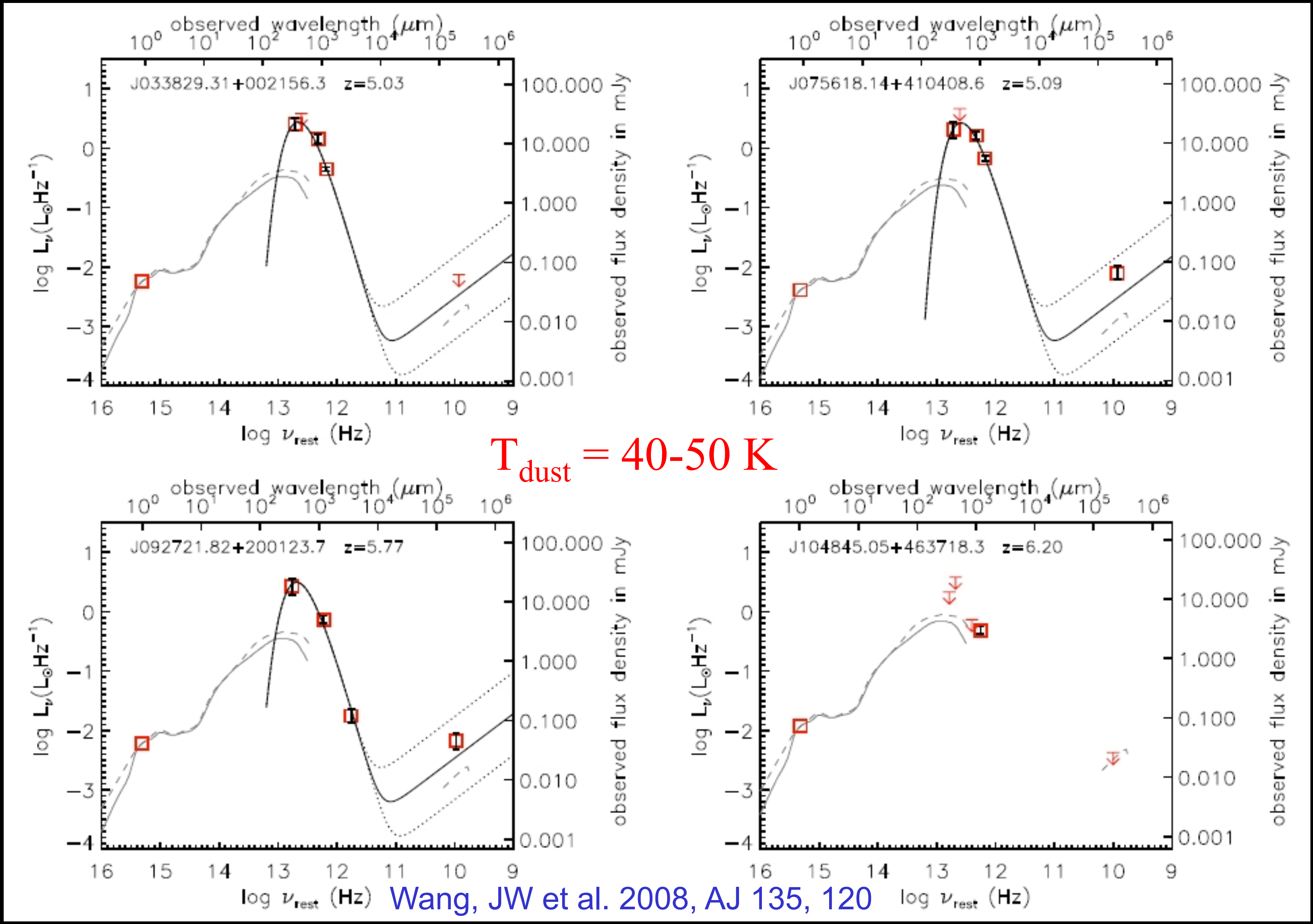
Wang et al (2007)

Dust temperatures: 350um continuum emission from high-redshift quasars



Beelen et al. 2006

Dust temperatures: 350um continuum emission from high-redshift quasars



Breakdown MBH - Mbulge relation at high z: SMBH forms first?

CO =>

Mgas = 2e10 Mo

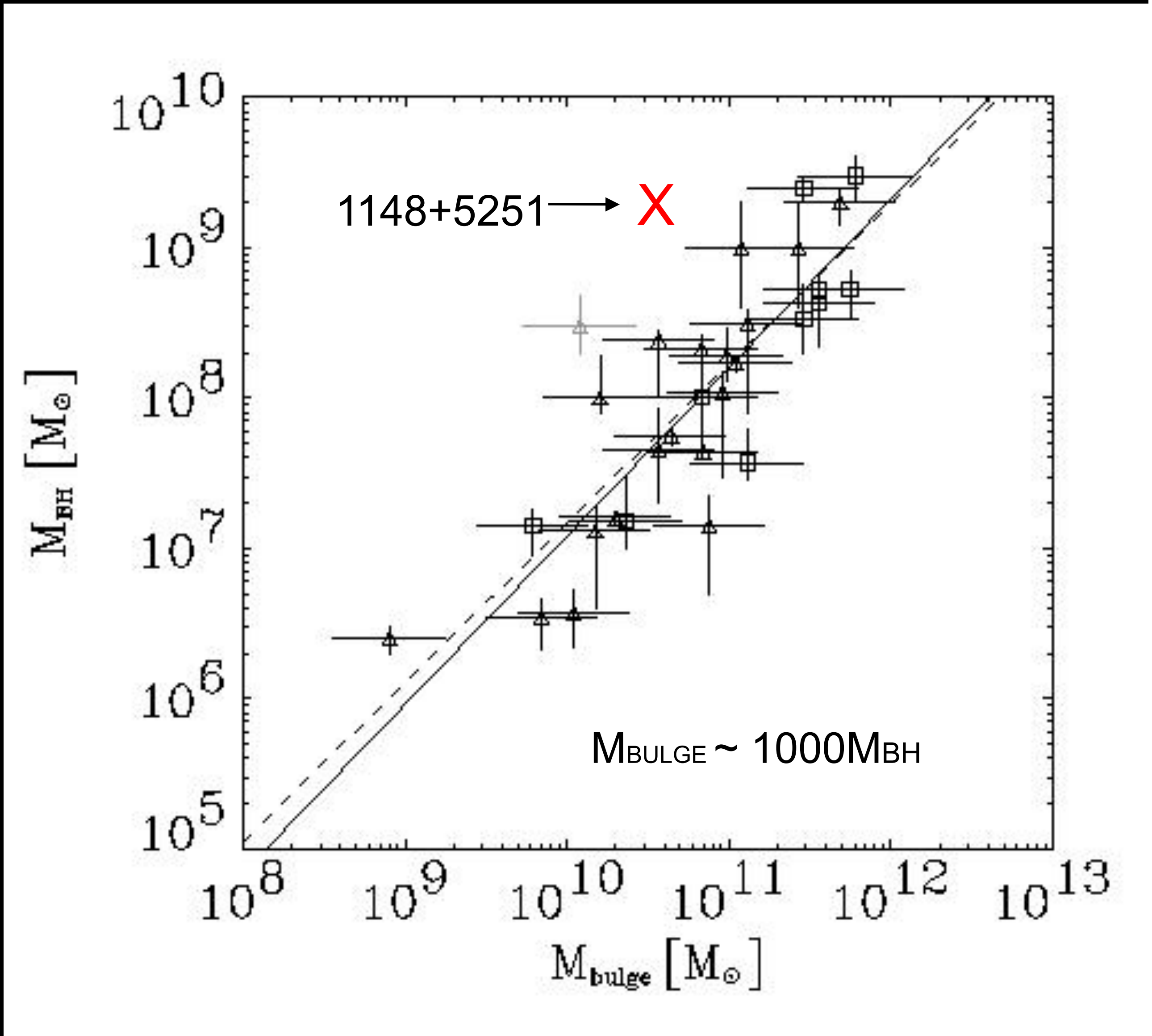
Mdyn = 5e10 (<2.5kpc)

Optical =>

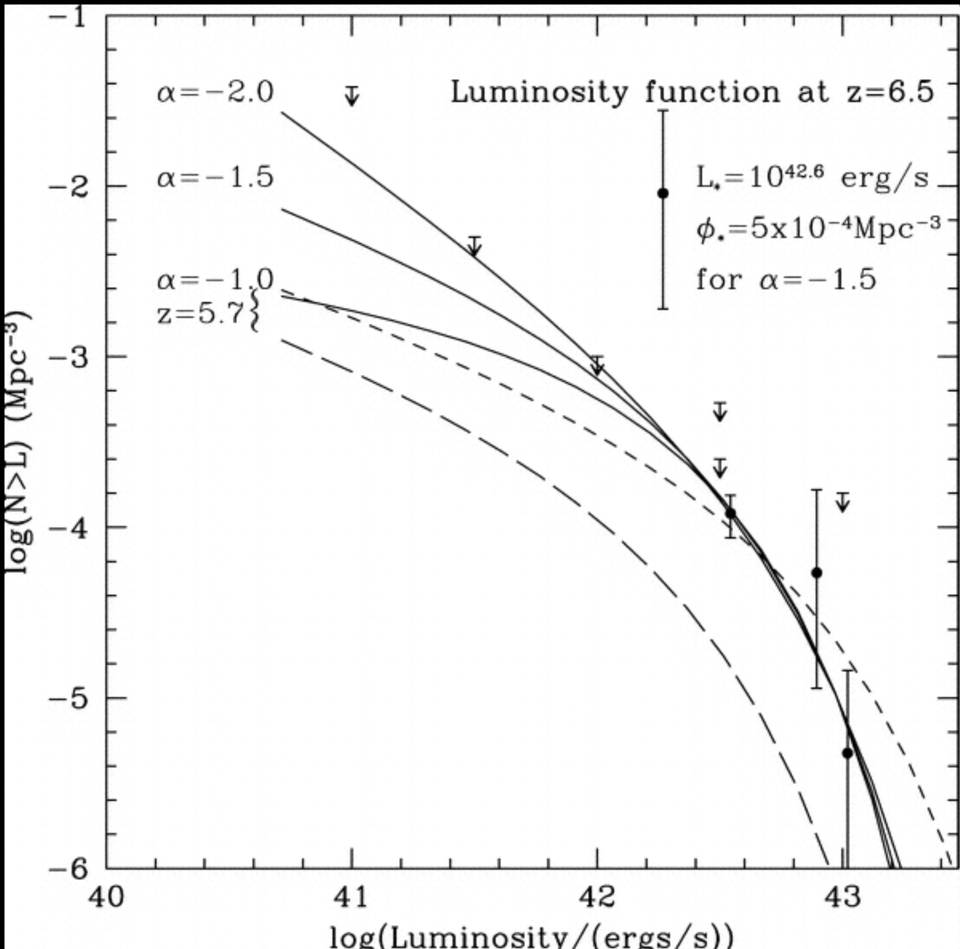
MBH = 2e9

(Willott et al 2003)

=> Mbulge = 1e12



High-redshift Lyα emitters and galaxy evolution



Malhotra & Rhoads 2004

- LAEs at z~6: star-forming galaxies: reionization? (e.g. Yan & Windhorst 2004)

- stellar masses: 10^{8-10} Msun
- ages 5 – 500 Myr (e.g. Lai et al 2007; Finkelstein et al. 2009)

- SFRs: 3 – 140 Msun/yr (e.g. Hu et al. 2002; Taniguchi et al. 2005; Chary et al. 2005)

- dusty? (e.g. Stanway et al. 2004; Chary et al. 2005; Finkelstein et al 2009)

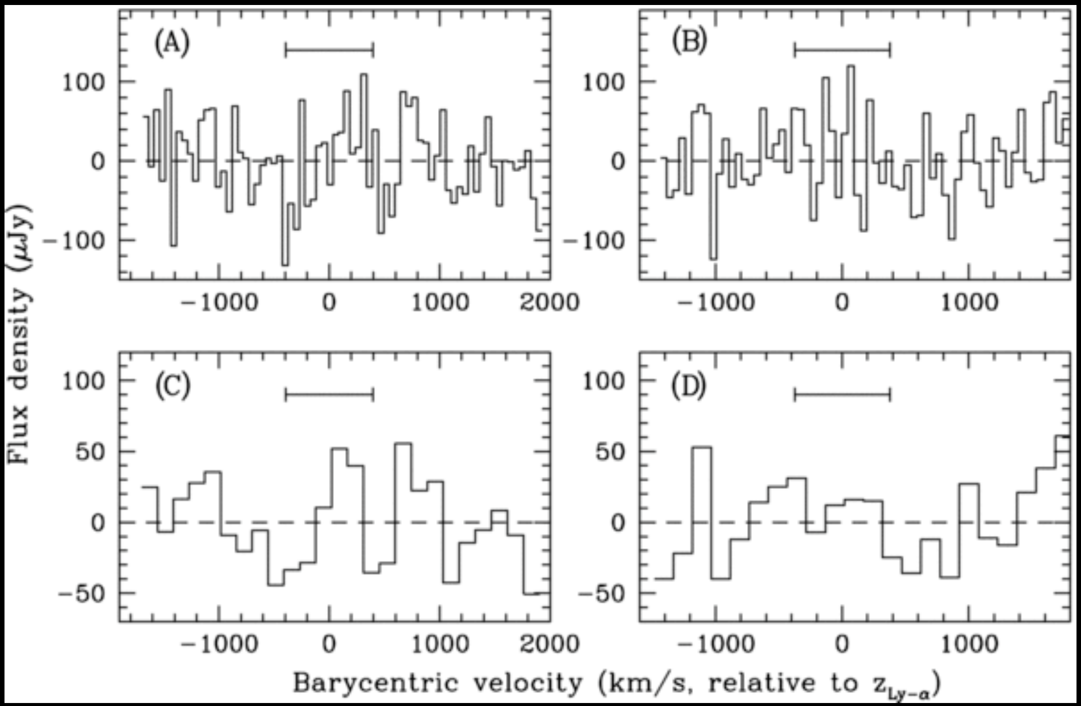
What are the molecular gas masses of LAEs?

Molecular gas in galaxies during reionization: CO in Lyα emitters

Wagg, Kanekar & Carilli 2009, ApJL, 697, 33

HCM 6A
z=6.56 Hu et al 2002

IOK-1
z=6.96 Iye et al 2006



CO J=1-0 GBT Ku-band

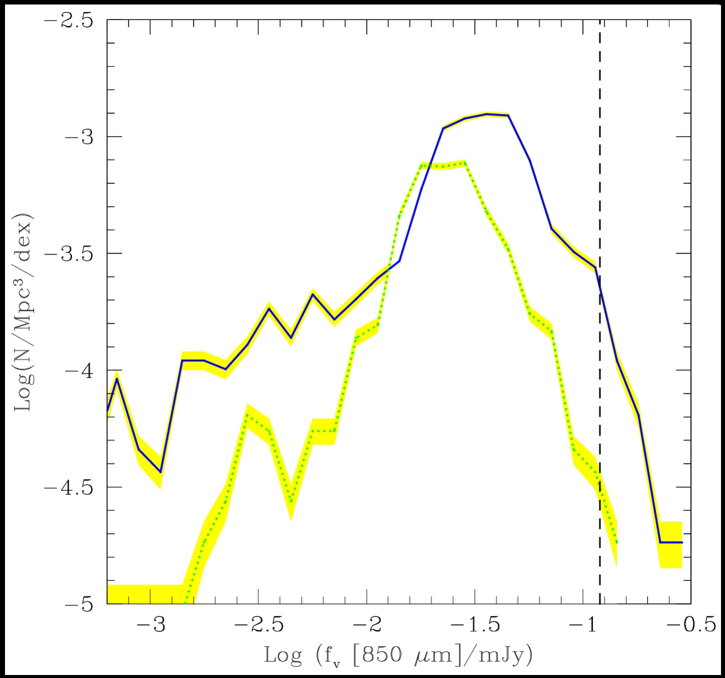
- two LyA emitters at z>6.5
- SFR ~ 10-140 Msun/yr
- 25hrs per source with the 100m NRAO Green Bank Telescope, 200 MHz BW
- Tsys~25 K at 15GHz
- typical rms: 20μJy per 300km/s chan

- No CO J=1-0 detected with GBT - HCM6A: L'CO < 6.1E+9 $(dV/300)^{1/2}$ K km/s pc^2
  M_{H2} < 4.9E+9 $(dV/300)^{1/2}$ $(X_{CO}/0.8)$ Msun

- Only sensitive constraints on the presence of molecular gas in LAEs

Cold dust and atomic gas in Lyα emitters: HCM6A at z=6.56

submm/mm emission in LAEs: Finkelstein et al 2009; Dayal et al 2009



Simulated density of LAEs detectable by ALMA (Dayal ea)

Star-formation in HCM6A

- lensing factor =4.5 (Hu et al. 2002)
- SFR inferred from UV: ~9Mo/yr (Hu et al. 2002)
- SFR from Hα: >~140 Mo/yr (Chary et al. 2005)
- $L_{FIR} < 2.1\times10^{11}$ Lsun, for Td = 36 K: SFR < 33 Mo/yr (Boone et al 2007)

New PdBI observations

- Observed C+ and 250 GHz continuum emission in HCM6A at z=6.56
- 2 tracks (20 hrs) with 5 PdBI antennas, 1GHz BW
- No C+ or 250 GHz continuum emission

- typical rms: 1.27 mJy per 50 km/s ch (convolved with 4″ Gaussian)
- $L_{[CII]} < 4.3\times10^{8}$ Lsun
- 250 GHz continuum < 0.17 mJy
- $L_{FIR} < 1\times10^{11}$ Lsun, for Td = 36 K, SFR < 16 Mo/yr