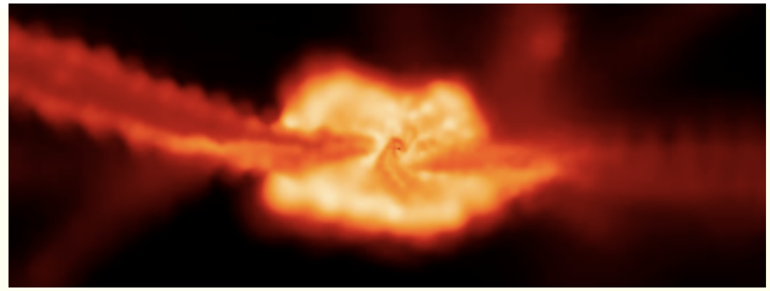






# The first galaxies with ALMA

Françoise Combes
**Observatoire de Paris**

8 Mars 2010

# Capacities of ALMA

➔50 x 12m, bases from 200m to 14km, 3mm to 0.3mm
(factor ~6 in surface with respect to IRAM-PdB)
+ 4 antennae of 12m + 12 antennae of 7m ACA (Japan)
➔4 frequency bands at the beginning
84-116 GHz, 211-275 GHz, 275-370 GHz, 602-720 GHz
Large bandwidth of 8GHz/polar

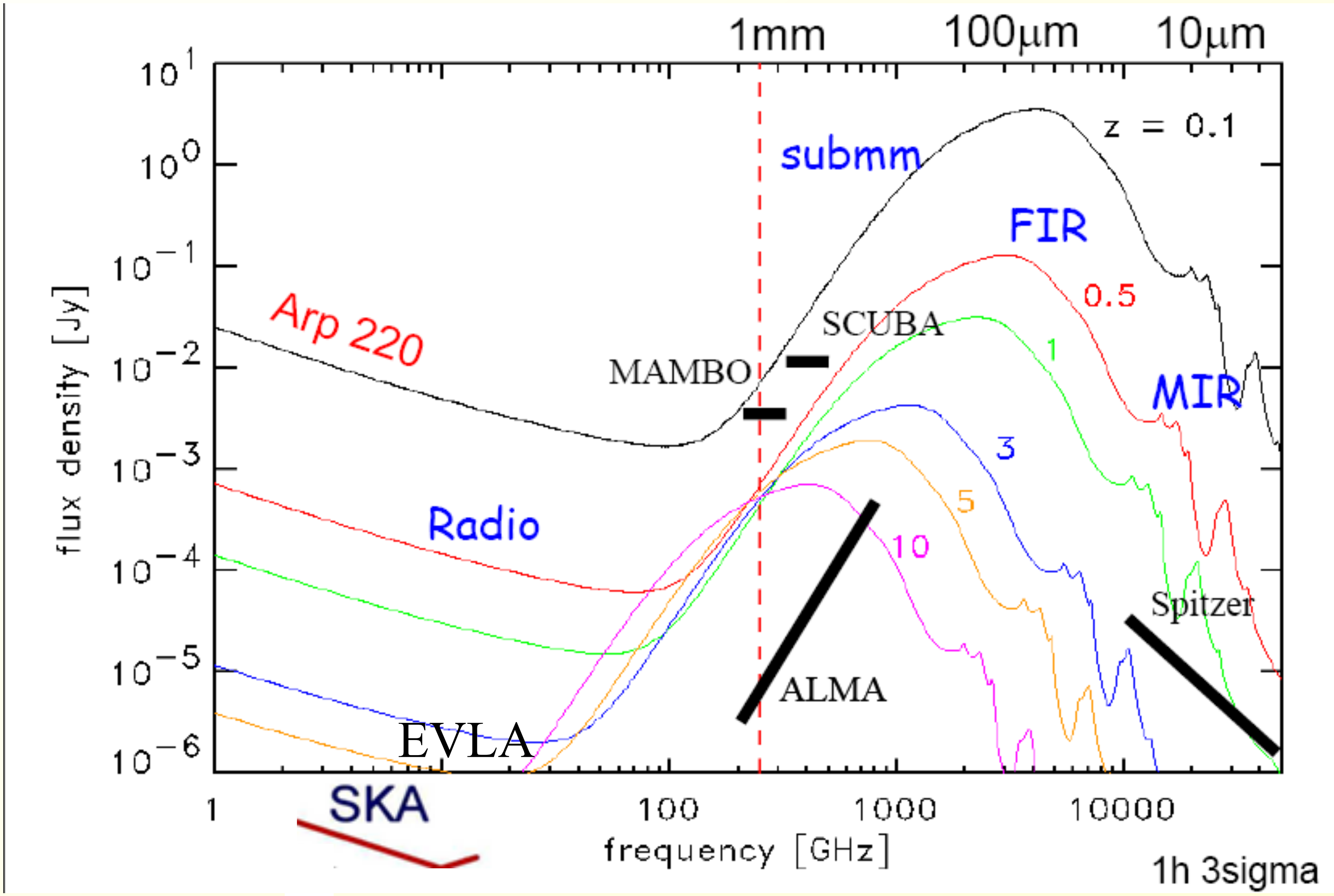
Spatial resolution, up to 10mas,
Spectral resolution up to R=$10^8$
Dynamical range from 128x128 to 8192x8192 pixels

**Small field of view:** from 1arcmin (3mm) to 6 arsec (0.3mm)
Possibility of mosaics

**Early Science 2011?** **In 2012-3:** Full Operation

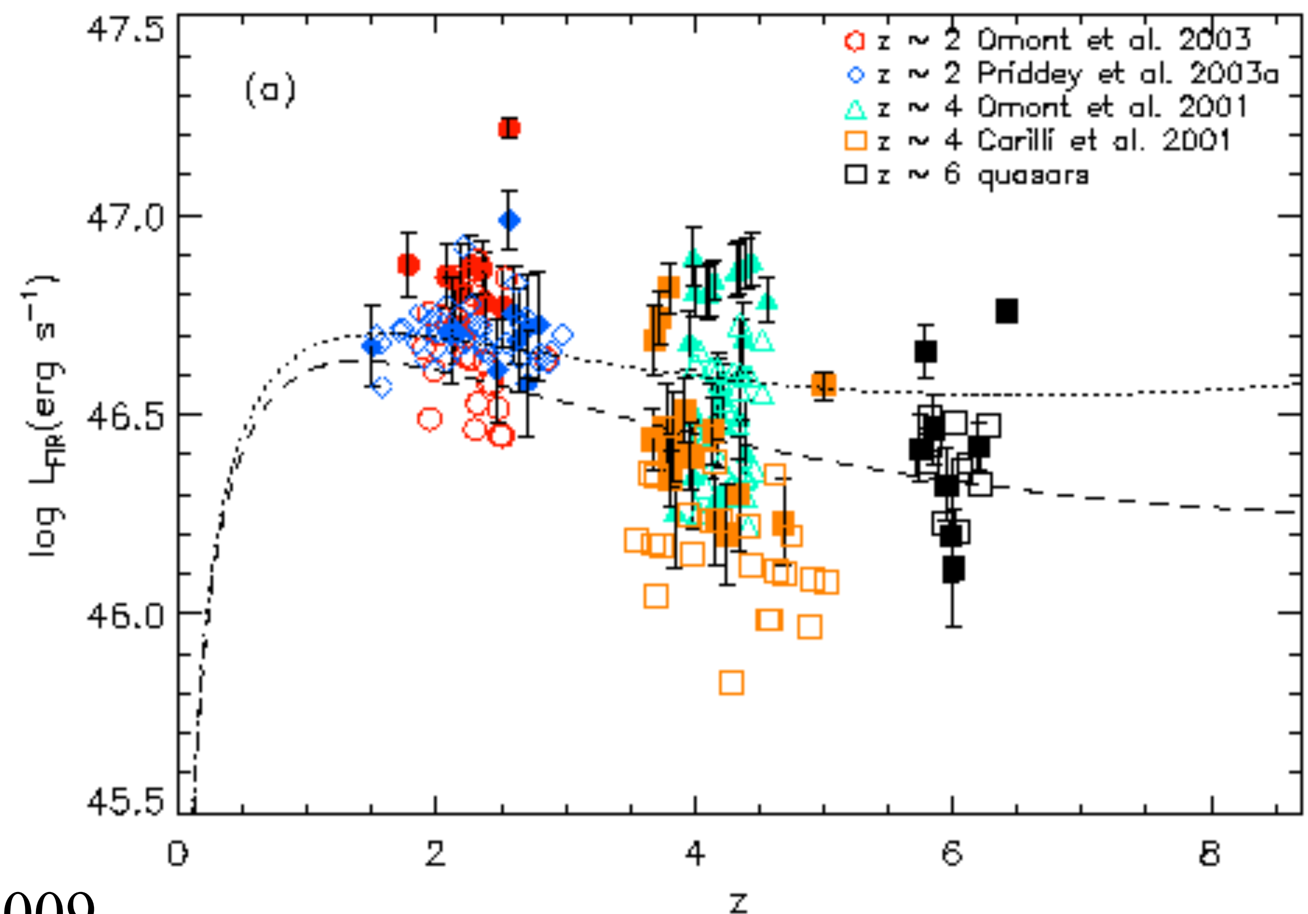
# Main privilege of the mm/submm domain

**Negative K-correction:** example of Arp 220



# Continuum detections

**30% Quasars @ z=6 detected in continuum ➔ HLIRG > $10^{13}$Lo**
**Mdust ~ $10^8$ Mo, means that dust forms early in the universe**




Omont 2009

# Detecting CO in galaxies at high redshift with ALMA

➔For high z galaxies, go to low frequencies
z=6 CO(7-6) at 3mm

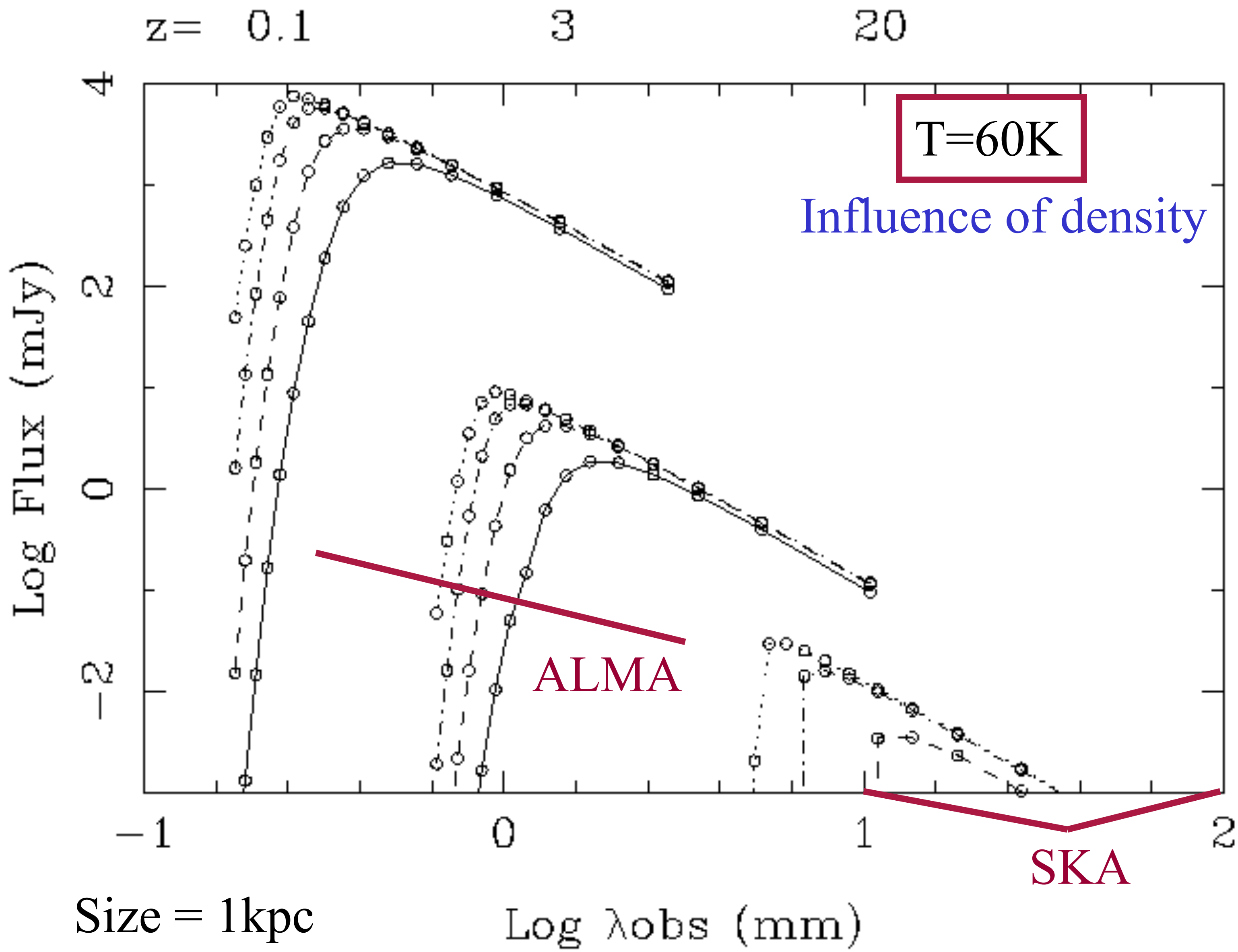
➔At 3mm (115GHz), field of 1 arcmin x 1 arcmin
Most frequently 300x 300 = 90 000 pixels/spectra

**Bandwidth 2x 8GHz ~ 16%, or ~50 000km/s**
**Possibility to have several lines from the Rotational ladder of CO, or other molecules..**

**@z =6, the spacing between CO lines is of 16 GHz.**
**With 2 tunings, one obtains a « redshift-machine »**

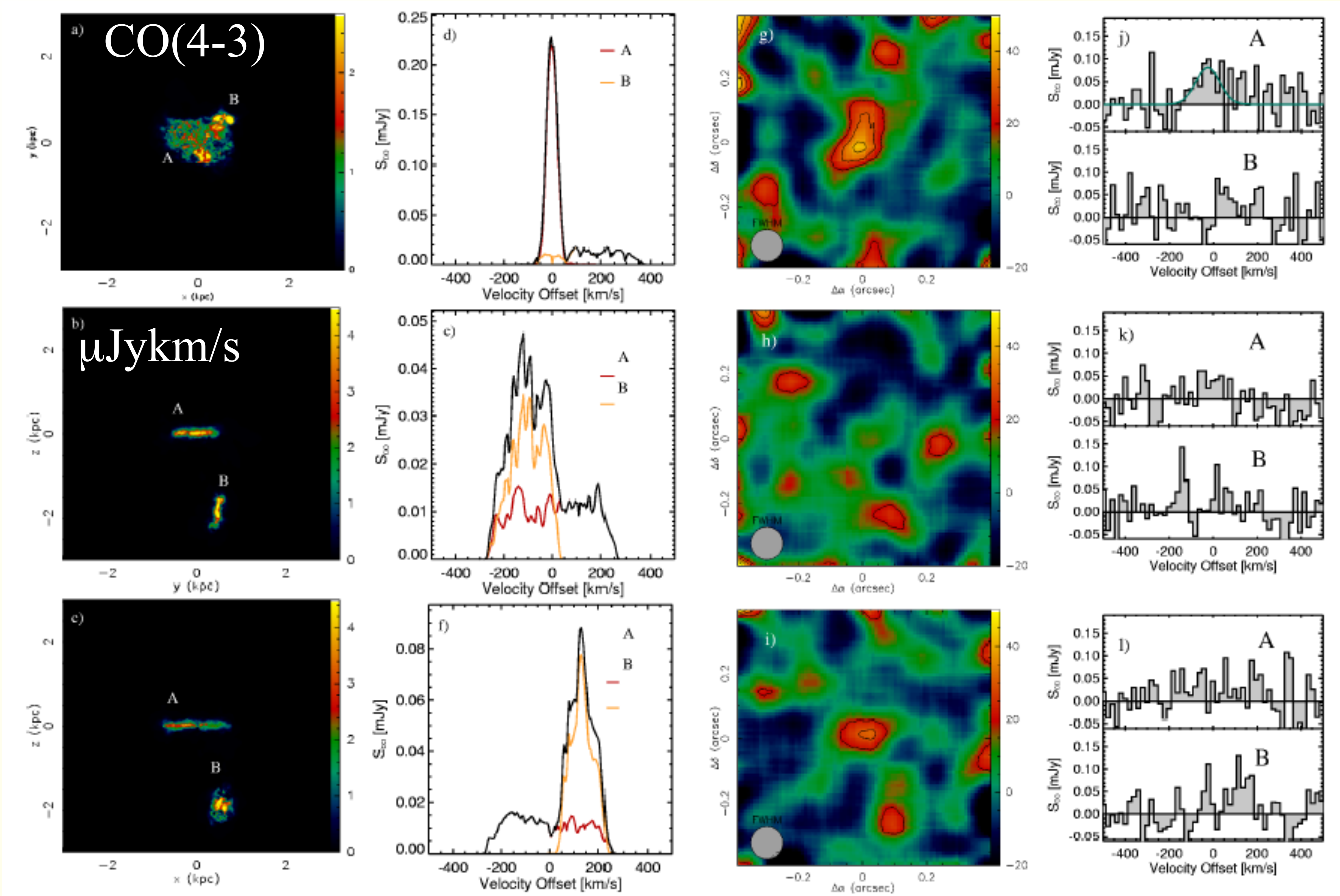
# Z=3 ULIRGs easy to detect with ALMA

$M(H_2) = 6\ 10^{10} Mo$, $N(H_2) = 3.5\ 10^{24}\ cm^{-2}$, $CO/H_2 \sim 10^{-4}$




Size = 1kpc

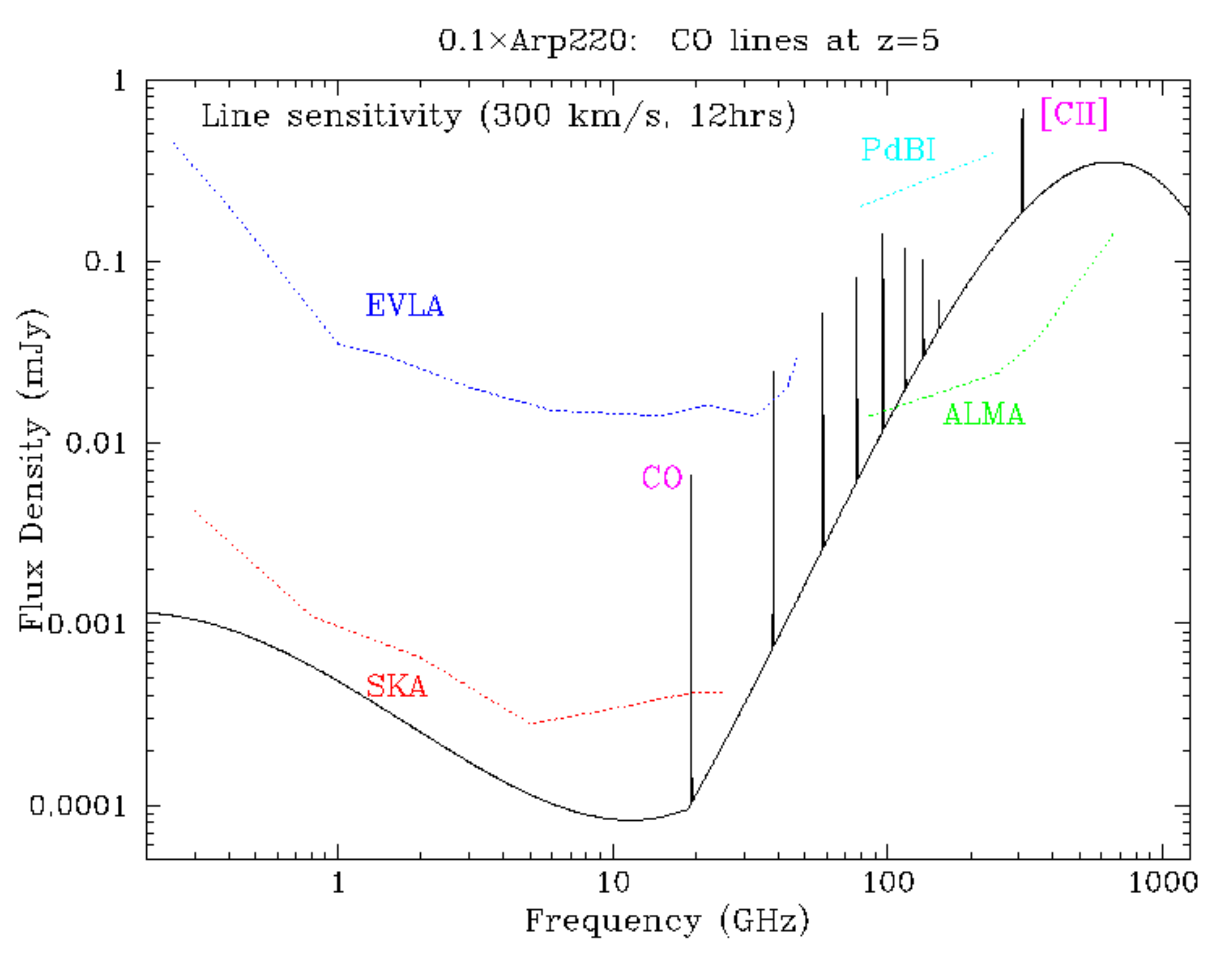
# Predictions for LBG at z~3: ALMA 24h, 0.1"




Greve & Sommer-Larsen 2008

rms=10 μJy/beam (2-3 σ)

# Predictions Line sensitivity z=5



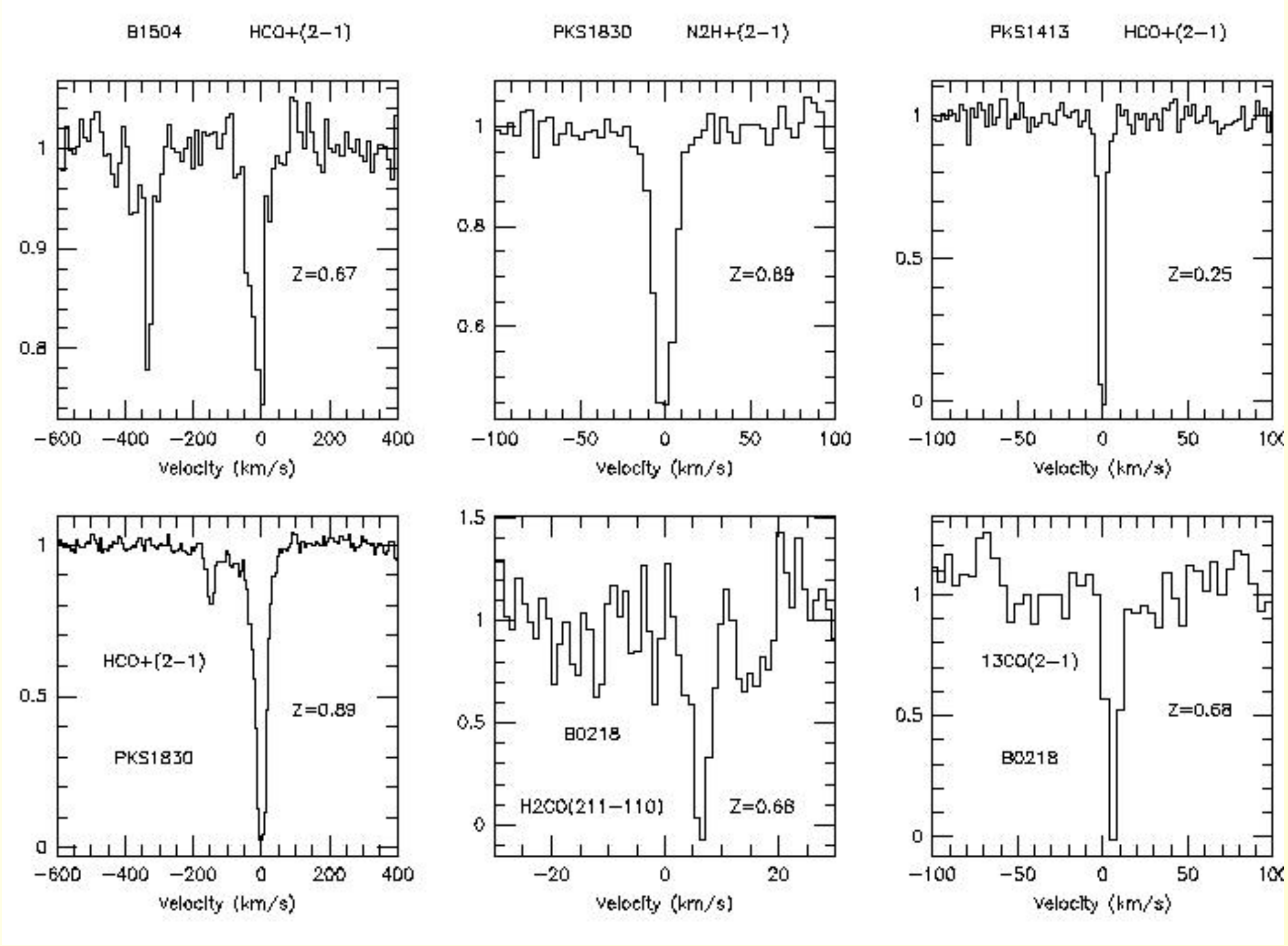

Carilli 2006

# Molecular Absorptions (mm & cm)

Up to now, only 5 systems: PKS1413, B3 1504 (self-abs)
B0218, PKS1830, PMN J0134 (OH): gravit lenses
+ local: CenA, 3C293 (0.045), 4C 31.04 (0.06)

**Chemistry @highz**
**Variations of cst**

~ 30-100 times more sources with ALMA?




Combes & Wiklind 1998

# Cosmic evolution of the CO-LF

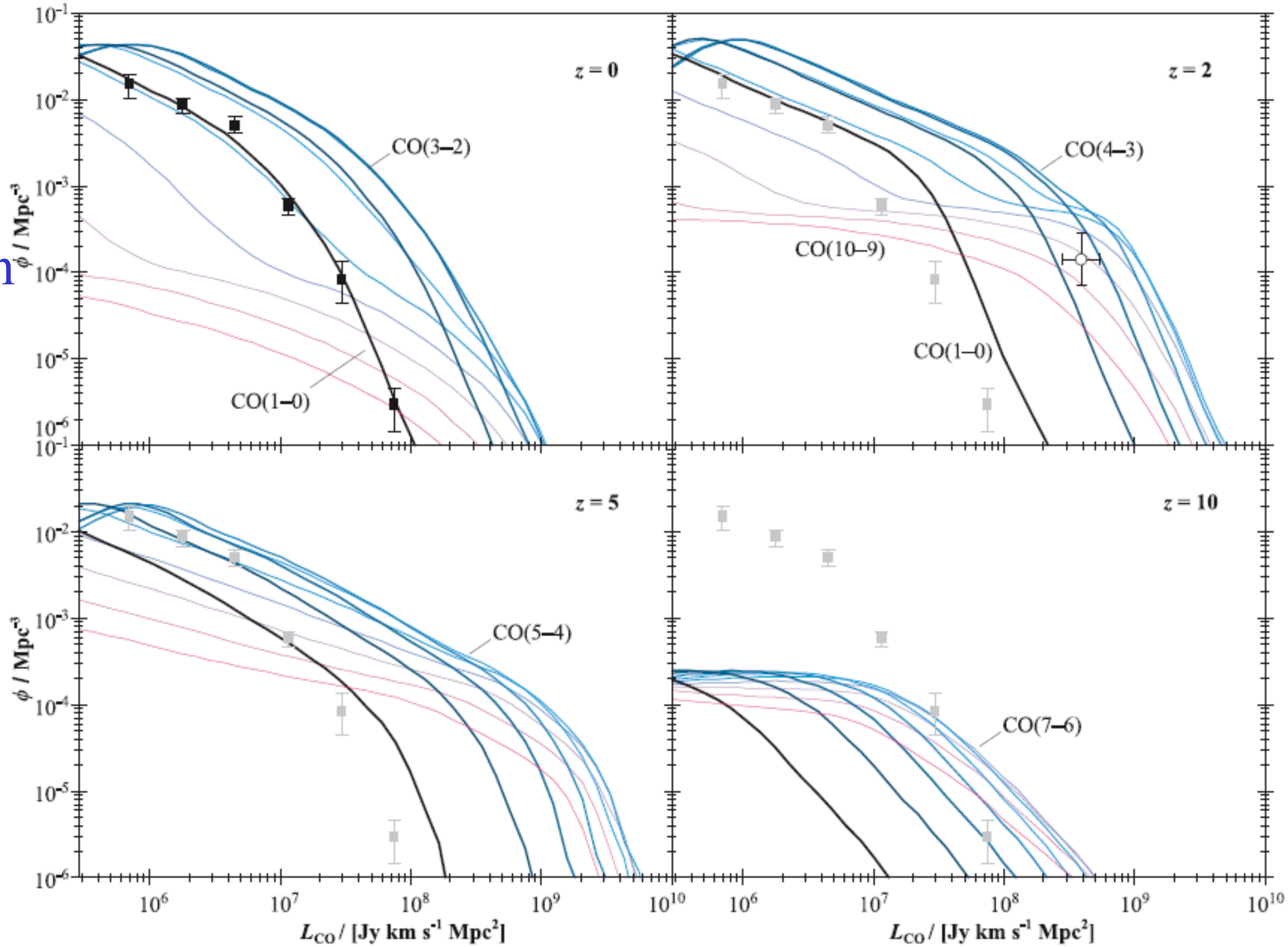
With some hypothesis, about the H2/HI ratio in galaxies

More H2, due to more compact and gaseous galaxies

Heating by SB
AGN, CMB

Metals, smooth
or clumpy

Overlap of
clouds, etc..




Obreschkow
et al 2009

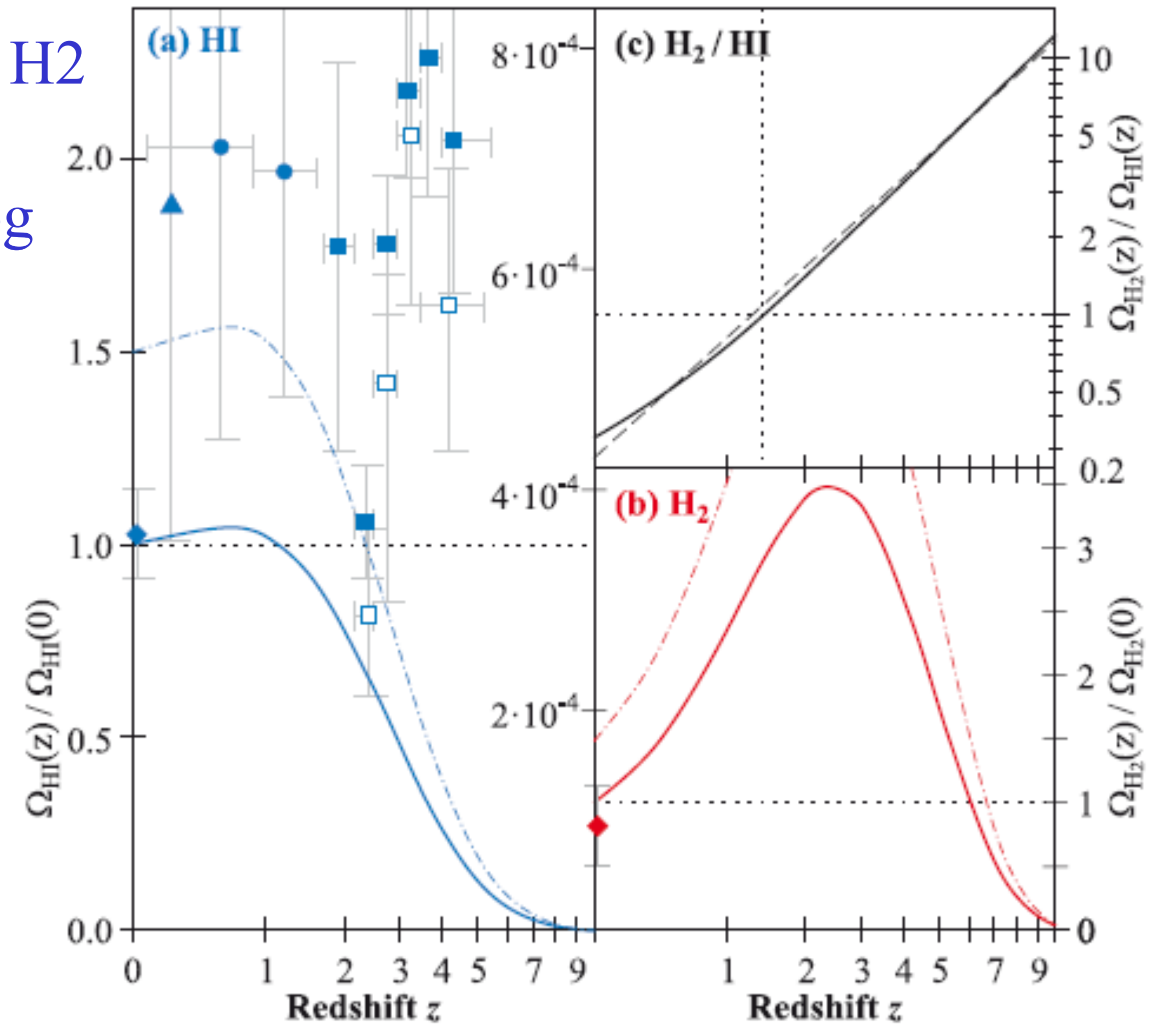
# Cosmic evolution of H2/HI

The HI evolution is taken from absorbants, but could be biased

Pressure-based model for H2

Simulations from a catalog of Millenium, + SAM

H2/HI ~$(1+z)^{1.6}$

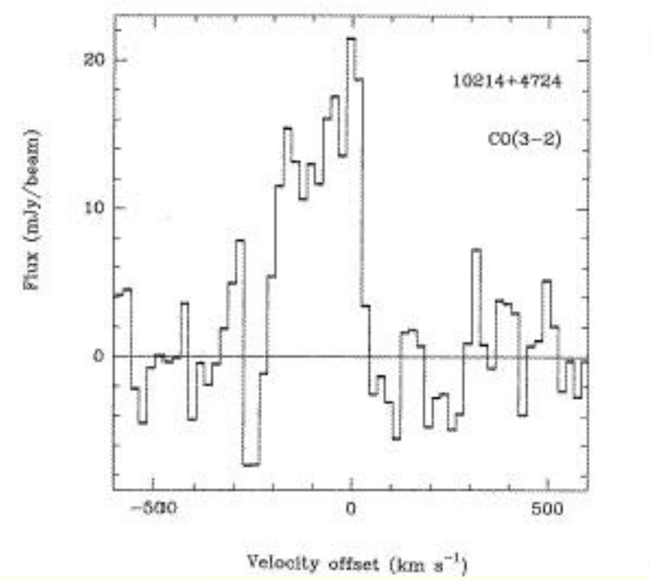


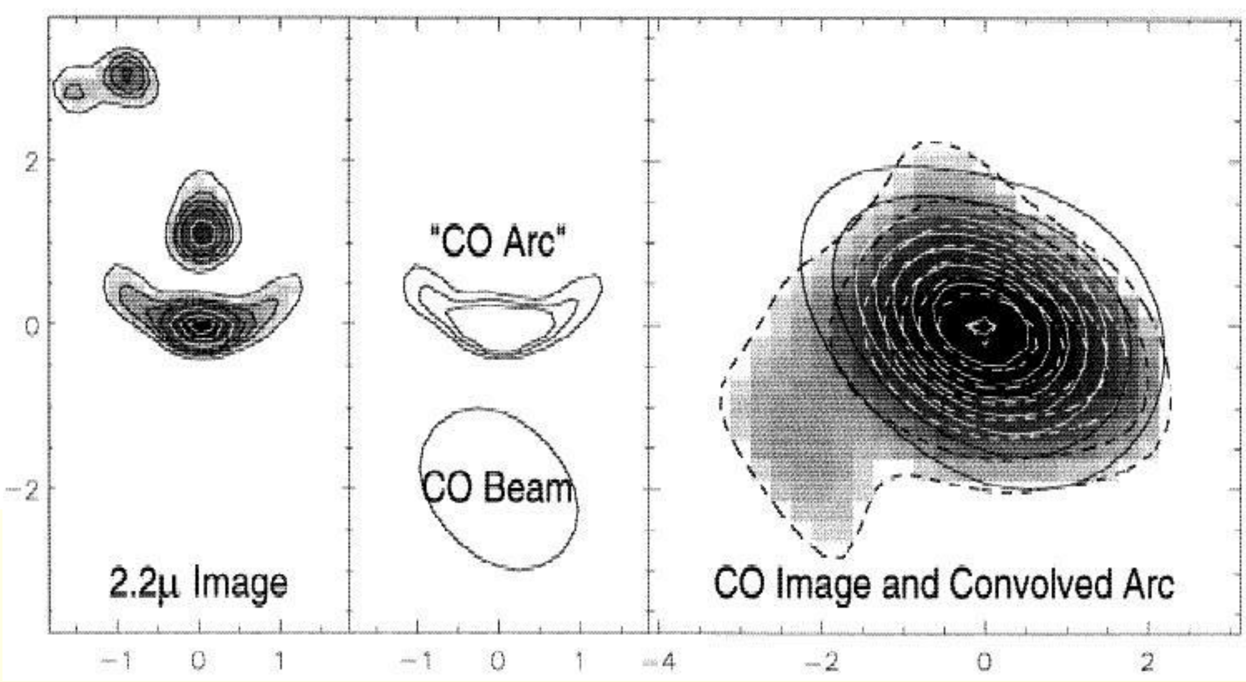

Obreschkow & Rawlings 2009

# Observations of CO lines

**CO emission: ~70 sources at high z (2010)**

**1st historical detection**: Faint IRAS source F10214+4724 à z=2.3 (Brown & van den Bout 92, Solomon et al 92)

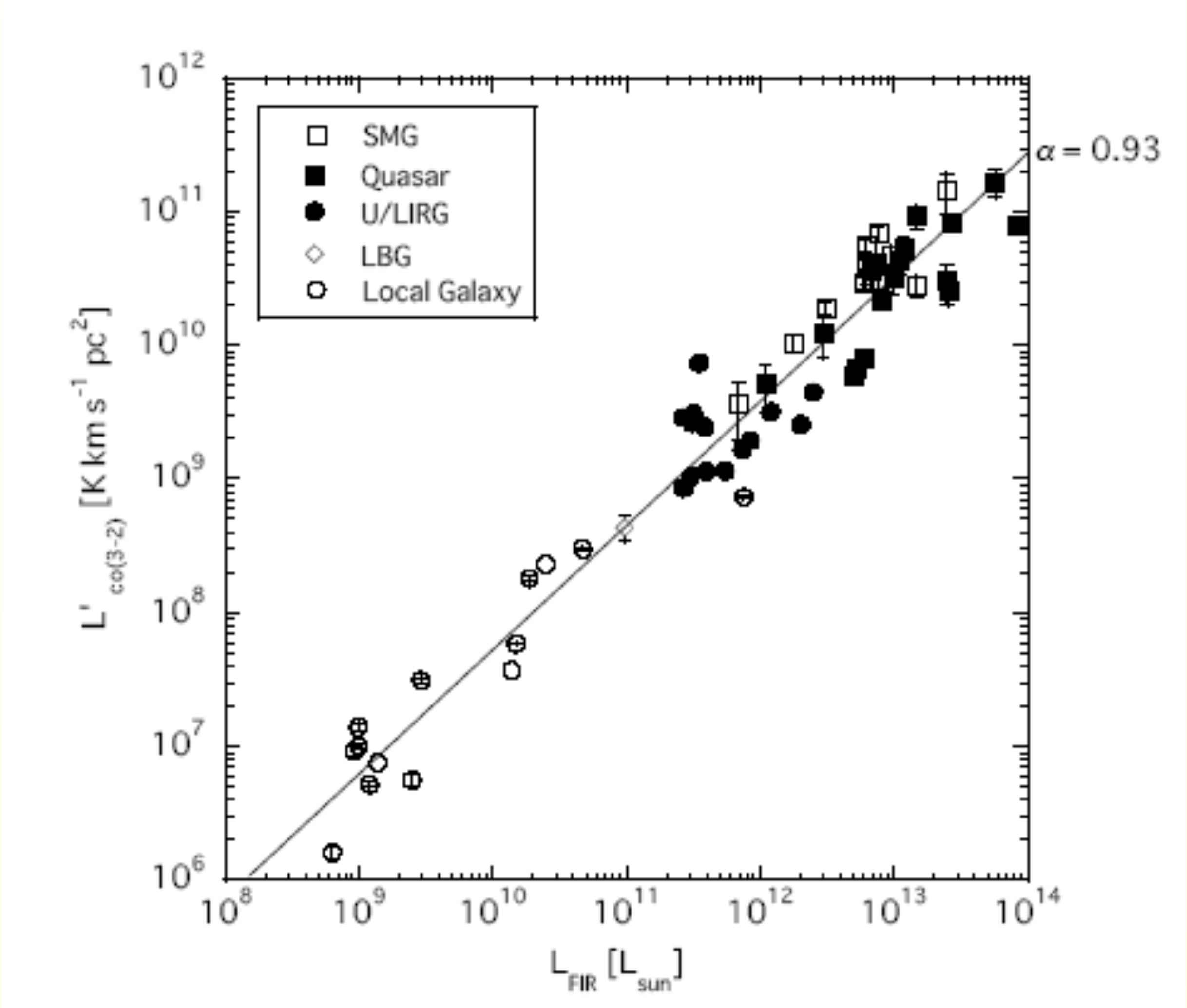



Downes et al 95

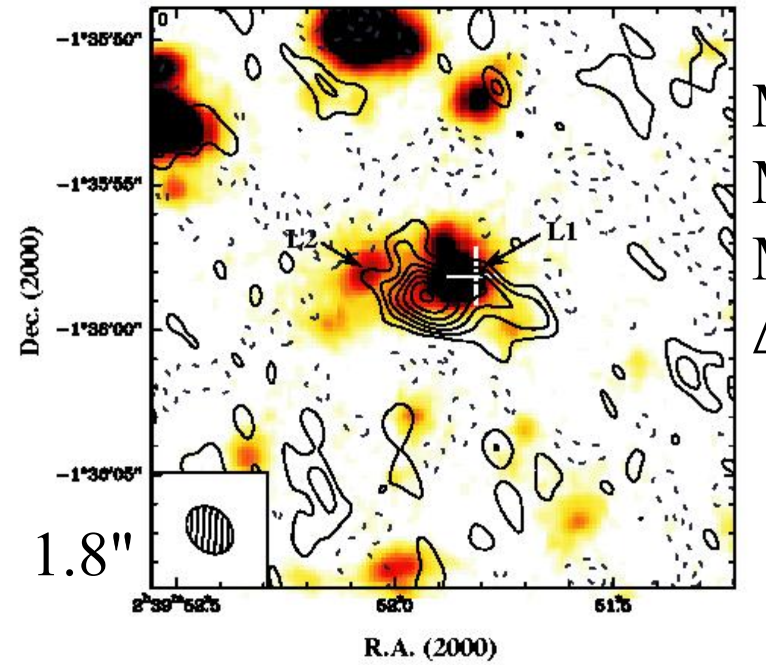
# Properties of high-z galaxies

Iono et al 2009 Good correlation LFIR/LCO (even for QSO)

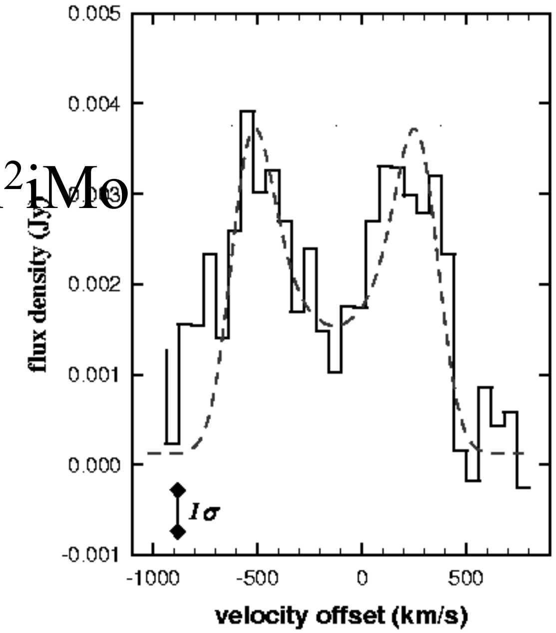


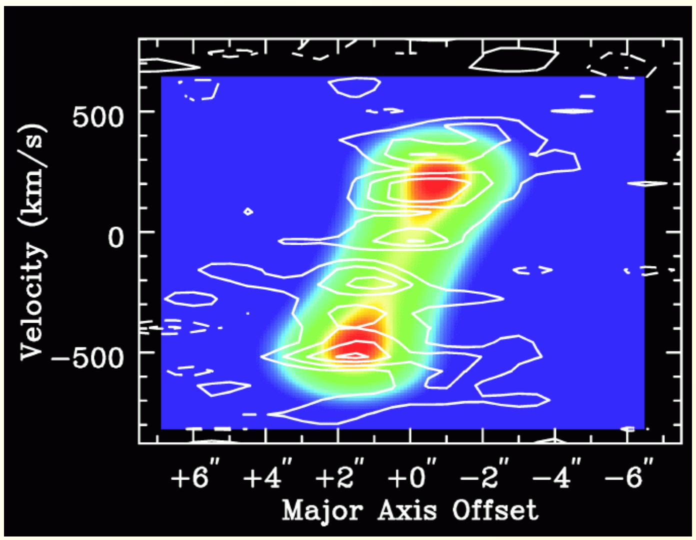
# Kinematics and mass

CO on red



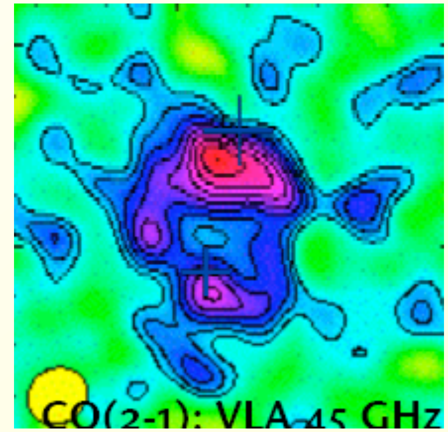

$MH_2 = 6\ 10^{10}$Mo
Mdyn = 3.0 $10^{11}$ /$\sin^2 i$Mo
Mbh = 6 $10^8$Mo?
$\Delta V$ = 1100km/s




SMM J2399-0136
Frayer et al (1998) CO(3-2)
z=2.808
Genzel et al (2003) IRAM-PdB
Amplification of 2.5

# z> 4 galaxies in CO

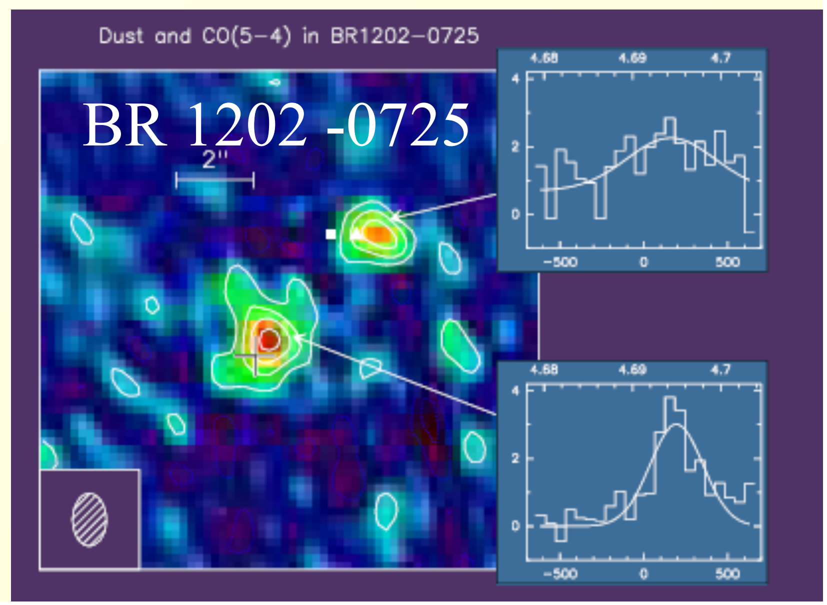



PSS J2322 +1944

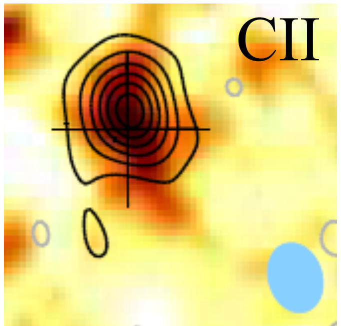
Almost all amplified !

| | | z |
|---|---|---|
| PSS J2322 +1944 | QSO | 4.12 |
| BRI 1335 -0417 | QSO | 4.41 |
| BRI 0952 -0115 | QSO | 4.43 |
| BR 1202 -0725 | QSO | 4.69 |
| TN J0924 -2201 | QSO | 5.19 |
| SDSSJ1148+5251 | QSO | 6.419 |

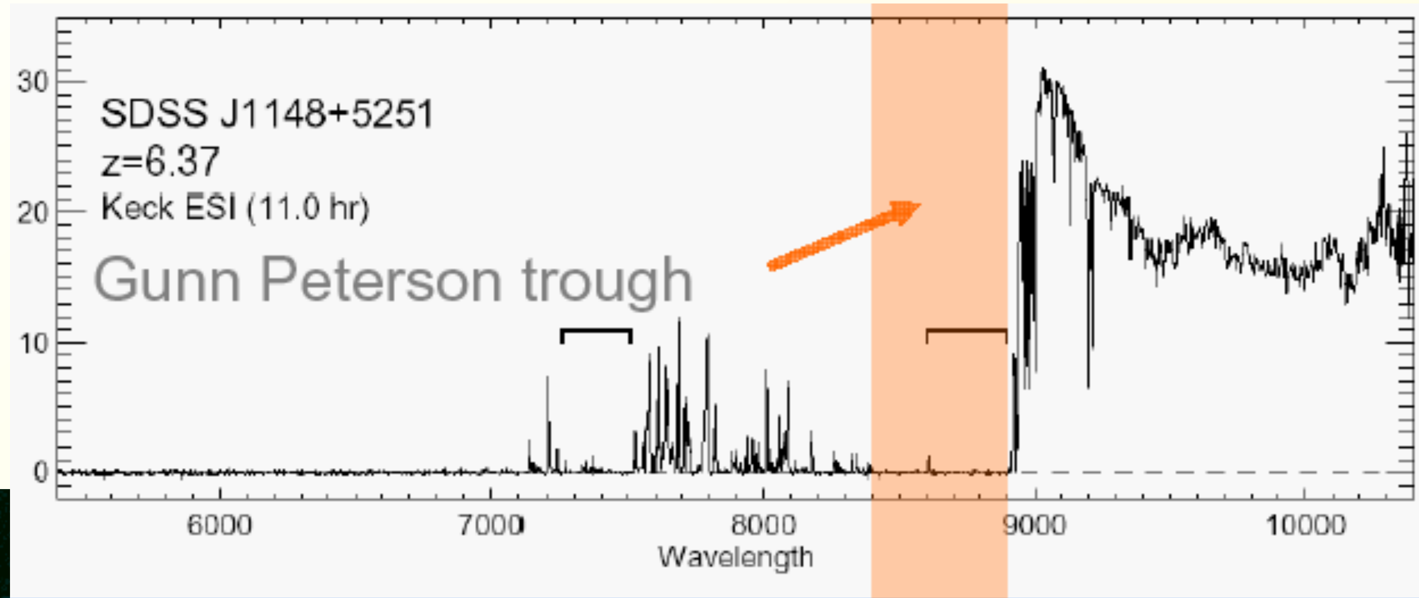
+ 6 z=6 QSO (Wang et al 2010)



# The most distant QSO at z=6.4



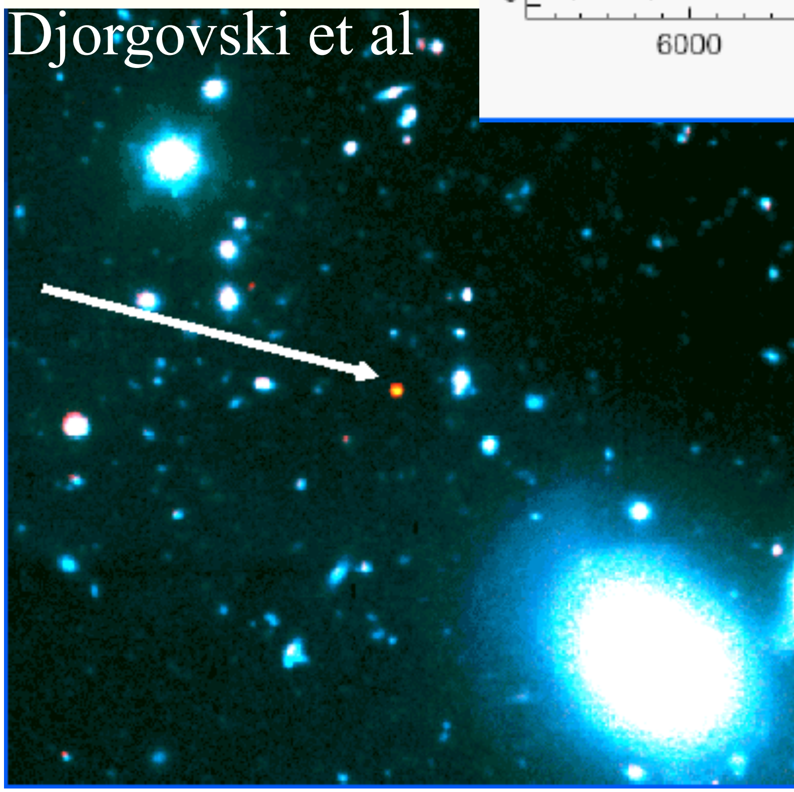

Beam 0.3" PdB




Age ~ 1 Gyr

Keck z-band

Djorgovski et al



Fan et al 2003, White et al 2003

$M_{dust}$ ~$10^8$Mo (Bertoldi et al 2003)

$M_{BH}$ = 1.5 $10^9$Mo (Willot et al 2003)

No HCN detected

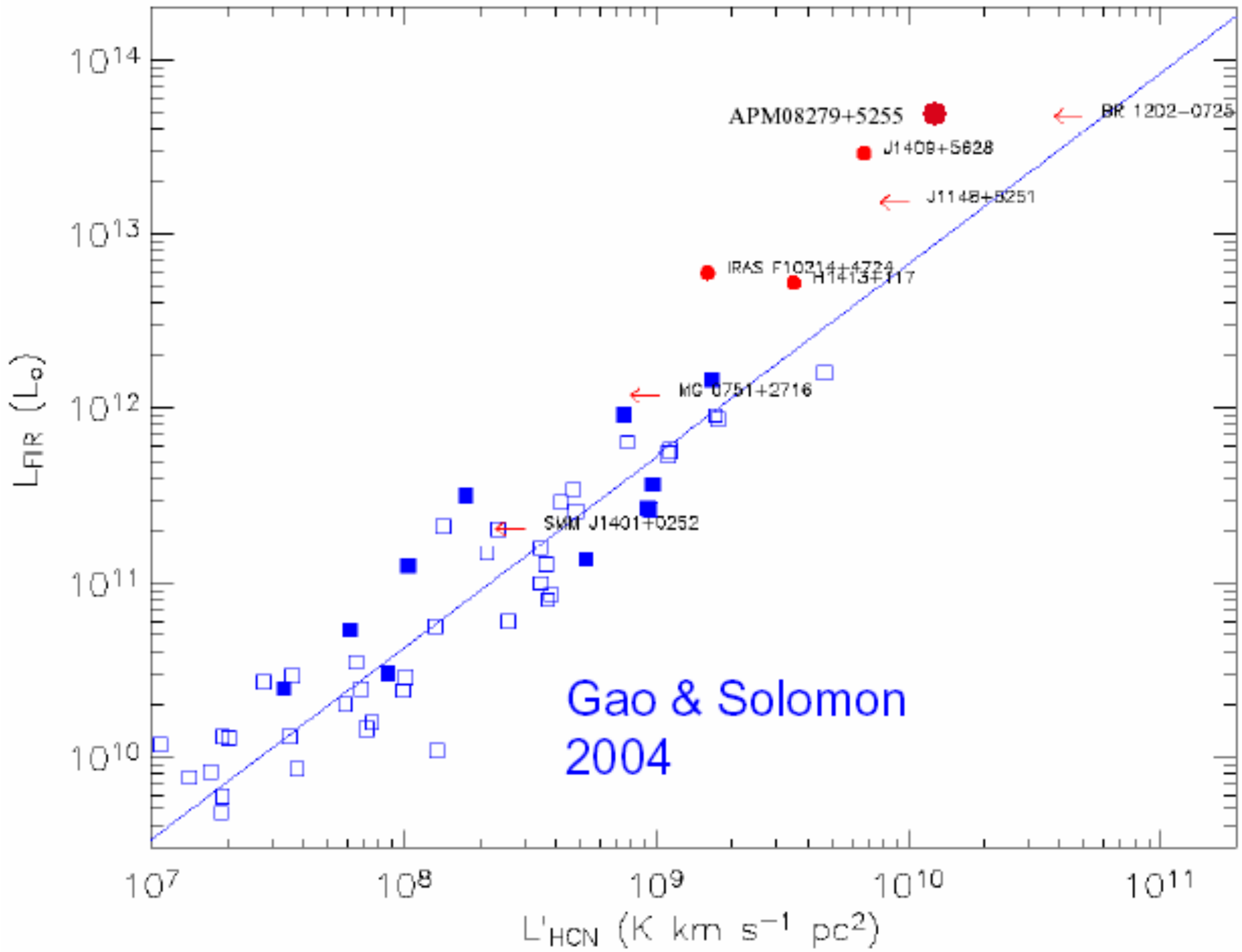
CII, Walter et al 2009

1kpc scale starburst, 1000Mo/yr/kpc$^2$

# High density tracers

HCN appears better correlated to star formation than CO

CI is detected, CII is proportionally weaker in ULIRGs



# Molecular gas at >kpc scale

Gas-rich **mergers** of galaxies, 1.4 Gyr after the Big-Bang

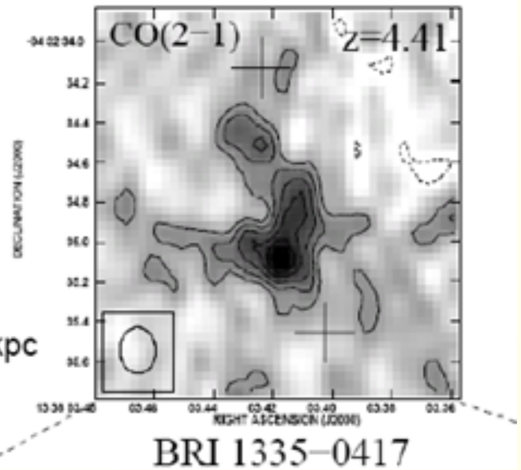
5kpc extent >> local ULIRG

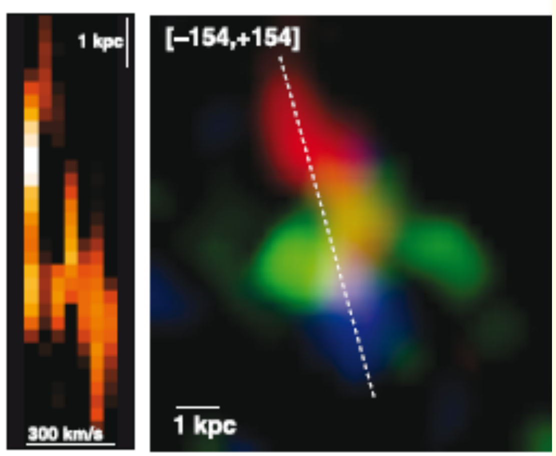
$MH_2$ = 9.2 $10^{10}$Mo

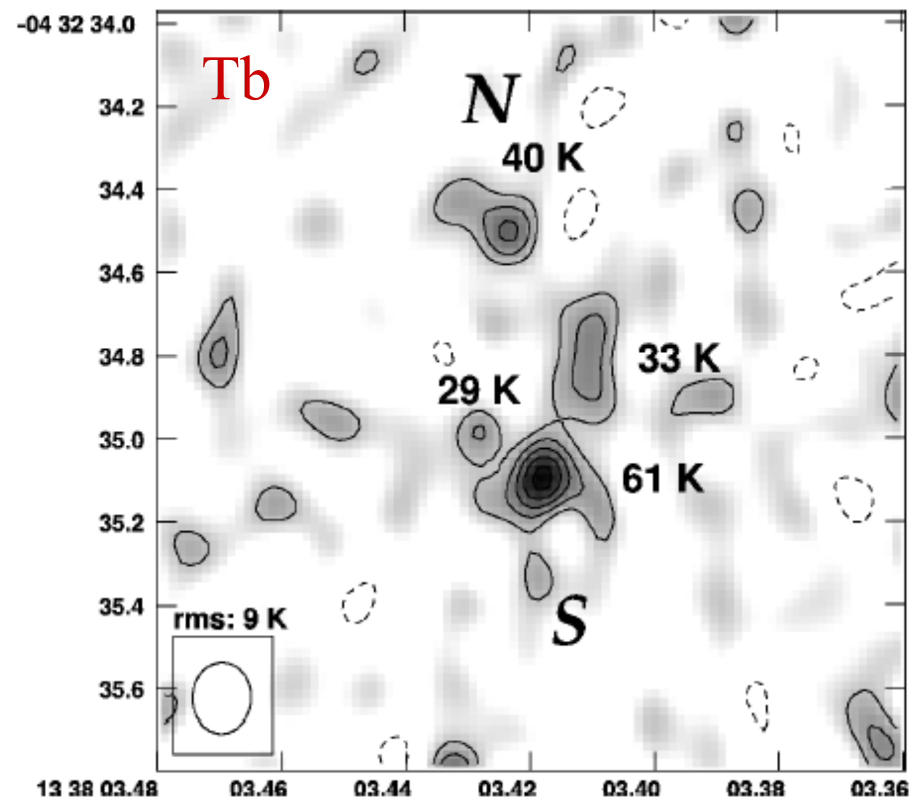
Mdyn = 1.0 $10^{11}$ /$\sin^2 i$Mo

Mbh = 6 $10^9$Mo (Edd limit)

z=4.41



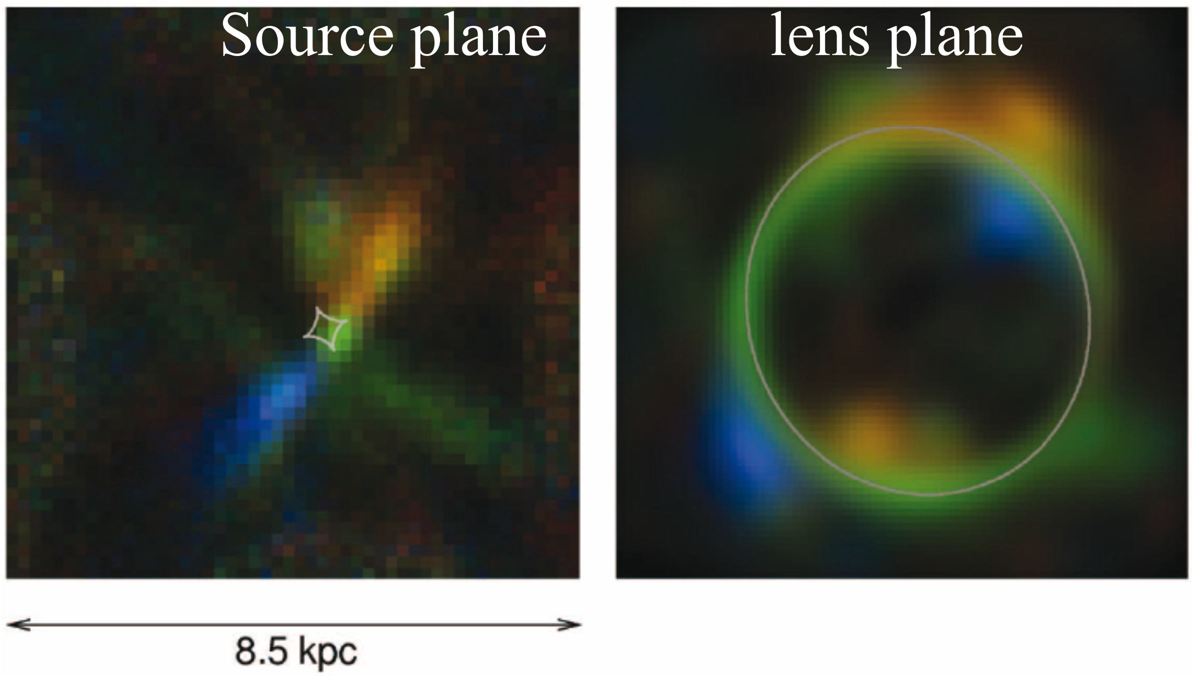

VLA, CO(2-1) Riechers et al 2008

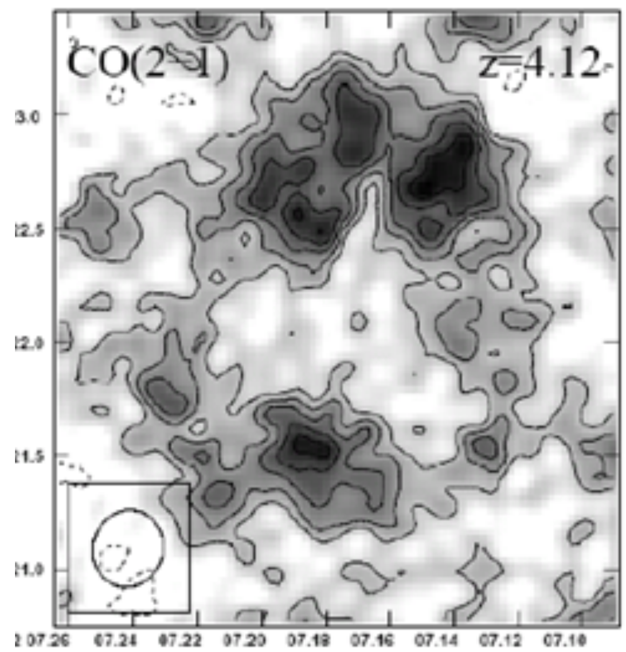
# Molecular gas in Einstein ring

Gas-rich mergers of galaxies

z=4.12, 5kpc extent
BH offset

$MH_2 = 1.7\ 10^{10}$ Mo
Mdyn = 4.4 $10^{10}$ /$\sin^2$iMo
Mbh = 1.5 $10^9$Mo (Edd limit)



PSS J2322+1944 (Einstein Ring)

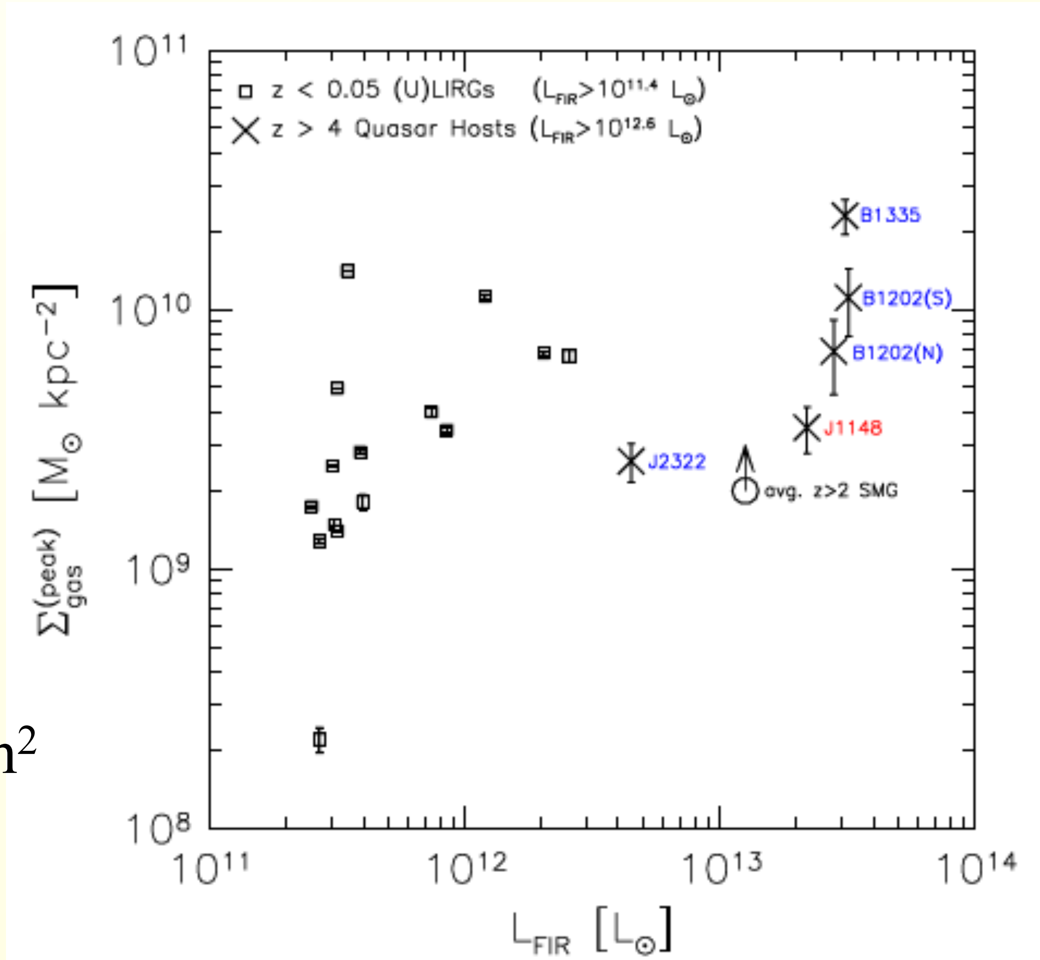
VLA, CO(2-1), SFR= 680 Mo/yr

Riechers et al 2008

Mbulge = 30 Mbh
Too high BH masses!

# Eddington limited star formation

SFR ~500-1000 Mo/yr/kpc$^2$




z> 4 QSO hotsts, 5kpc scale

Dust opacity limited Σdisk SFR

Comparable to local ULIRGs

GMC ~200Mo/pc$^2$ = $10^{22}$ $H_2$/cm$^2$
~2 $10^8$Mo/kpc$^2$

$NH_2$~ $10^{24}$cm$^{-2}$
$nH_2$ ~$10^4$ cm$^{-3}$

Riechers et al 2009

# Moderate SFR: Cosmic eye

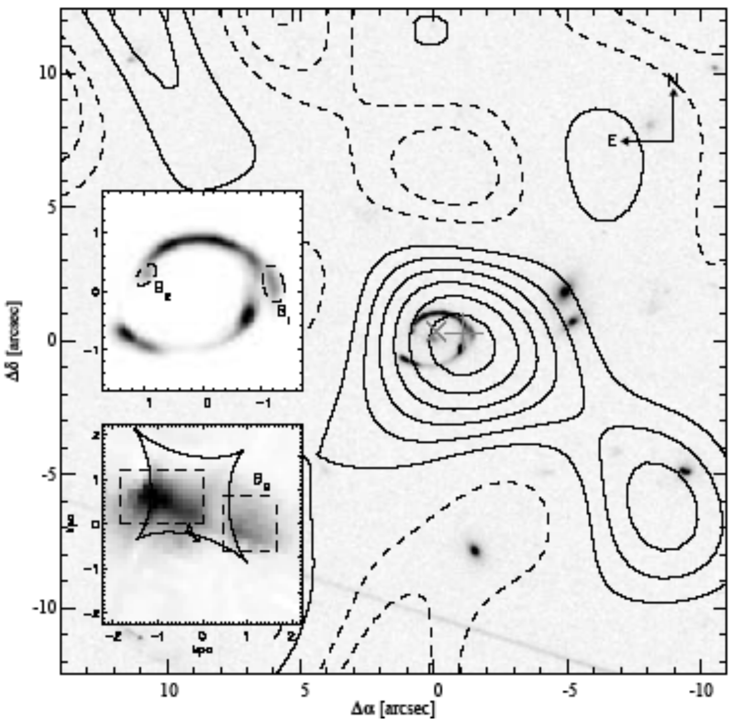
LBG @**z=3.07** P de Bure CO(3-2) detection
(only the 2nd LBG, after cB58)
MH2 = 2.4 $10^9$ Mo M* = 6 $10^9$ Mo (Spitzer mid-IR)

SFR = 60Mo/yr life-time =40Myr
High-z analog of LIRGs

Magnification of **28**
2 UV components, 3kpc apart
Coppin et al 2007

Dynamical mass ~$10^{10}$ Mo
But inclination uncertain

HST ACS

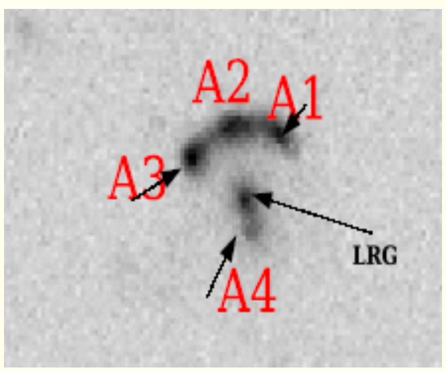


# Star formation rate in LBGs

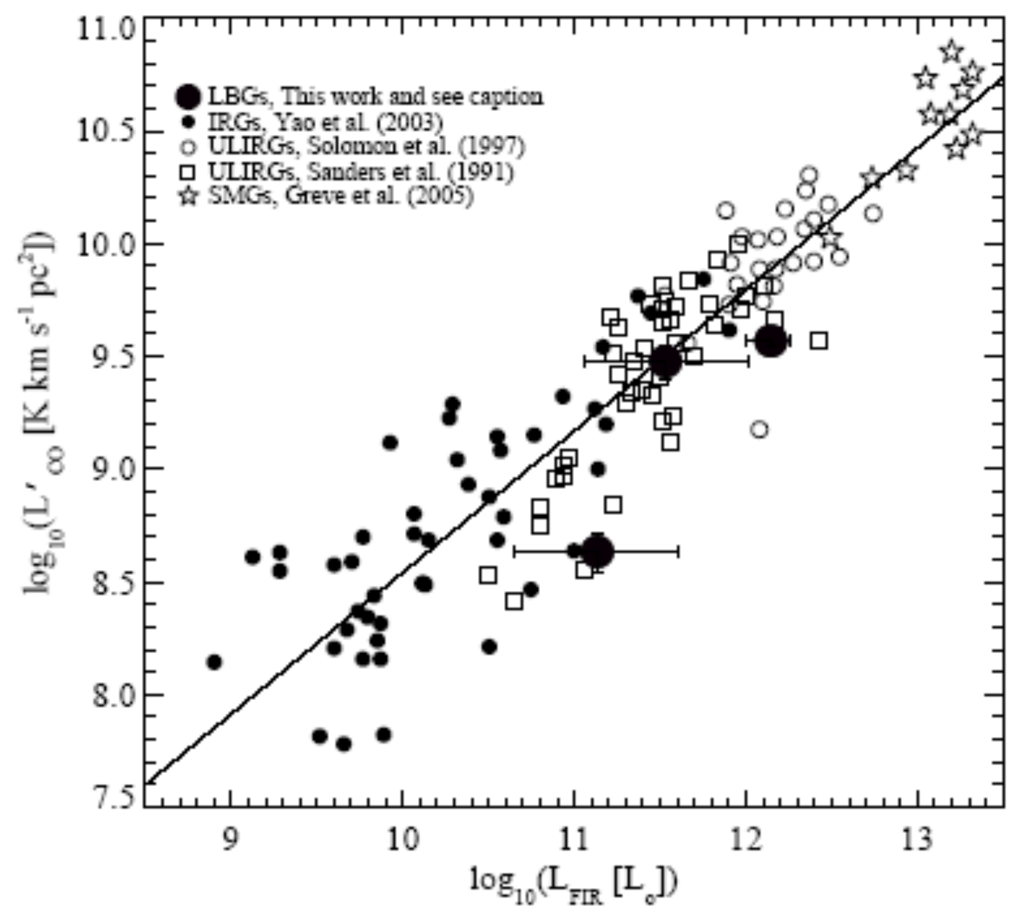
SFE ~140 Mo/Lo

LCO & gas mass
7 times higher than cB58

**z=2.73**

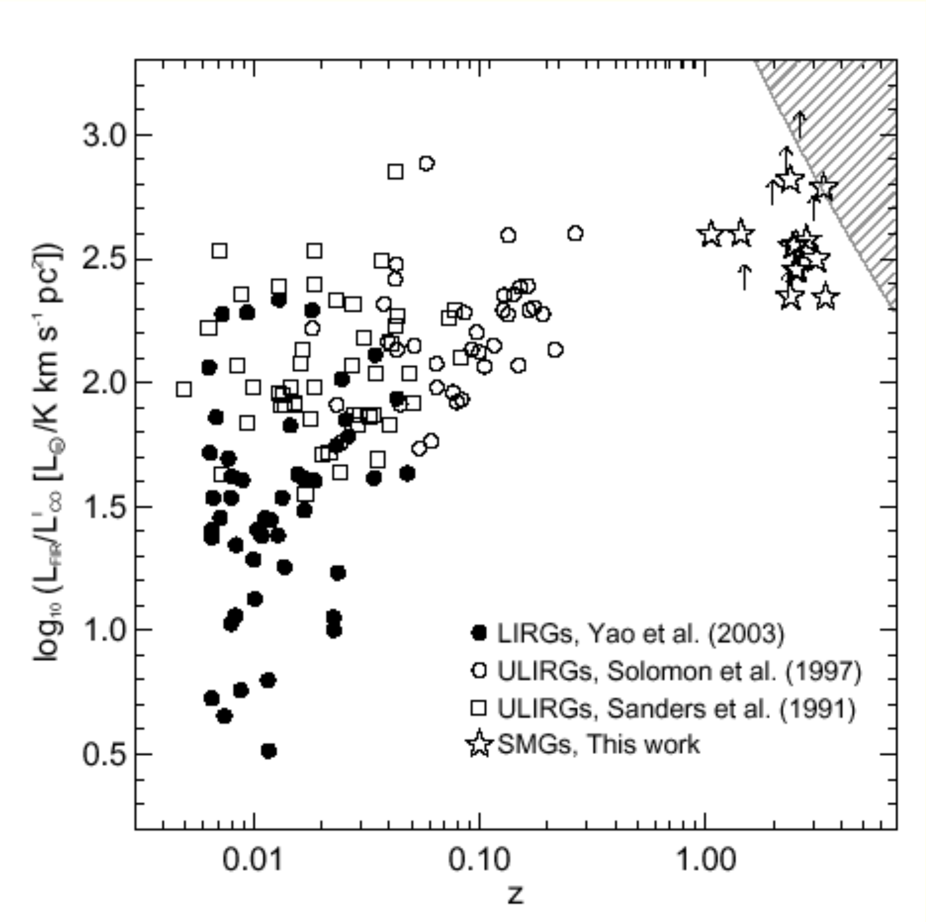



8 o'clock arc
Allam et al 2007



# SMGs: Submillimeter Galaxies
# Star formation efficiency $L_{IR}/L'_{CO}$ vs z

Greve et al 2005




6 SMGs not detected in CO

40- 200 Myr SB phase
SFR ~700 Mo/yr
More efficient than ULIRGs

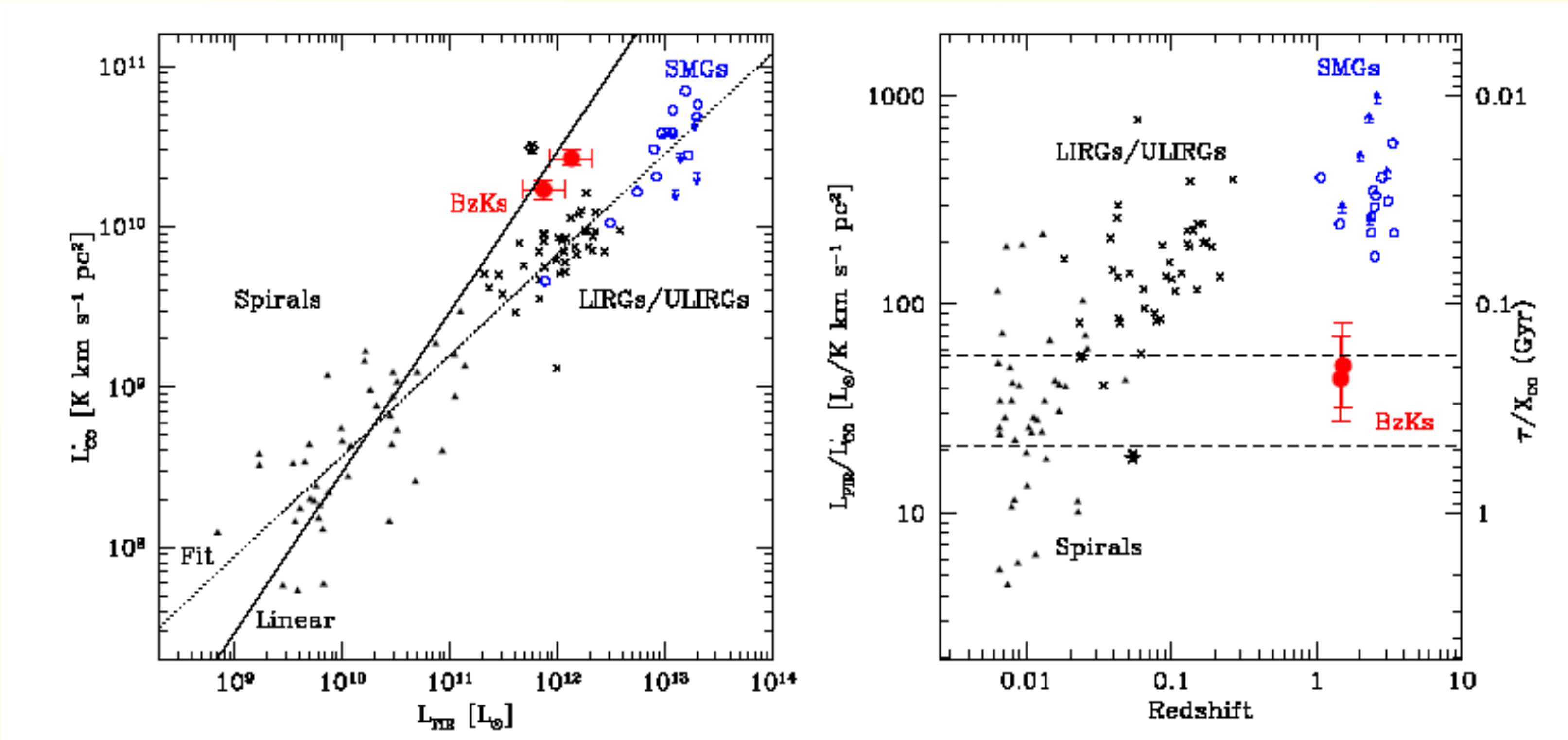
Mergers without bulges?

Total masses ~0.6 $M_*$

# Low efficiency of star formation

In BzK galaxies, much more CO emission detected than expected
Massive galaxies, CO sizes 10kpc? L(FIR) ~$10^{12}$ Lo
Normal SFR, M(H2) ~ 2 $10^{10}$ Mo $\tau$ ~2 Gyr
➔ Much larger population of gas rich galaxies at high z

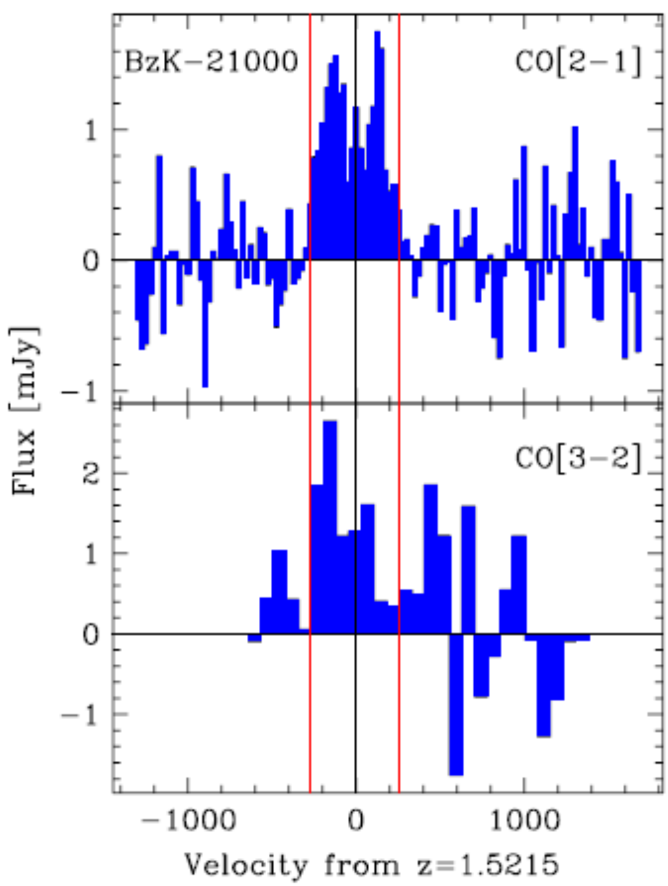
Daddi et al 2008

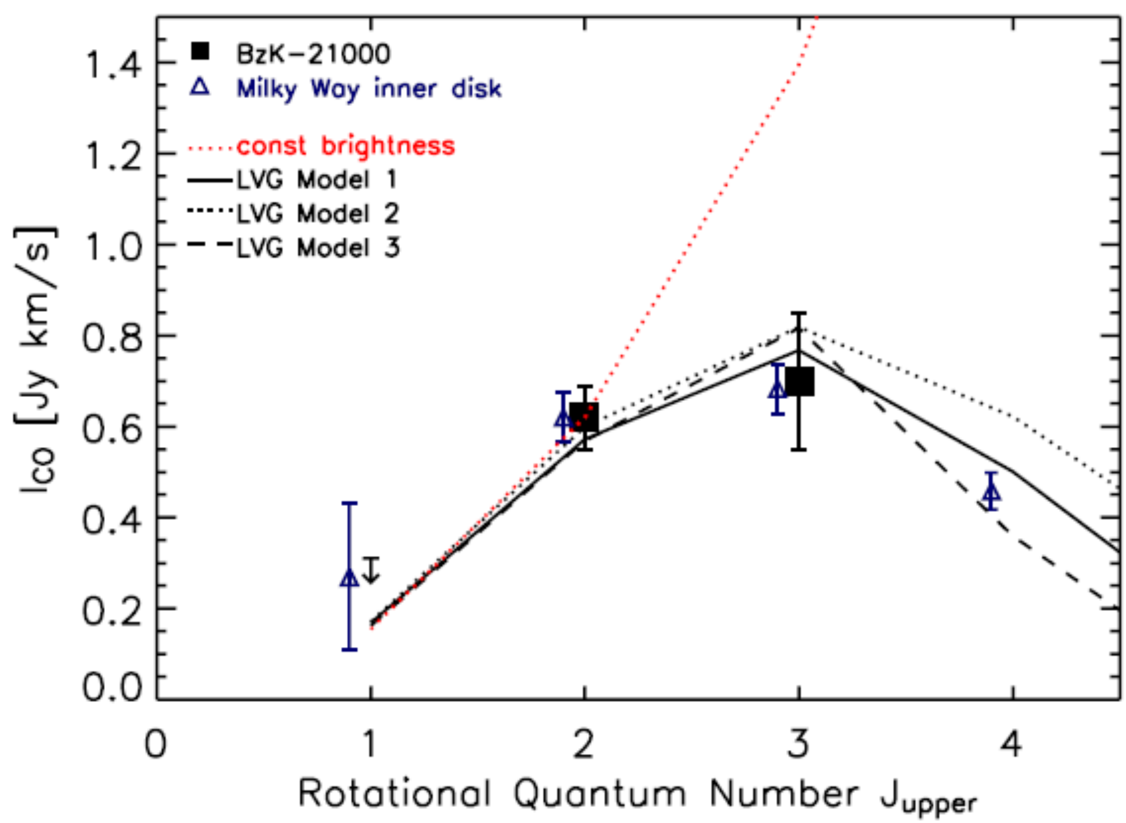


# Low excitation, MW-like

In BzK-21000, z=1.52, weak CO(3-2)

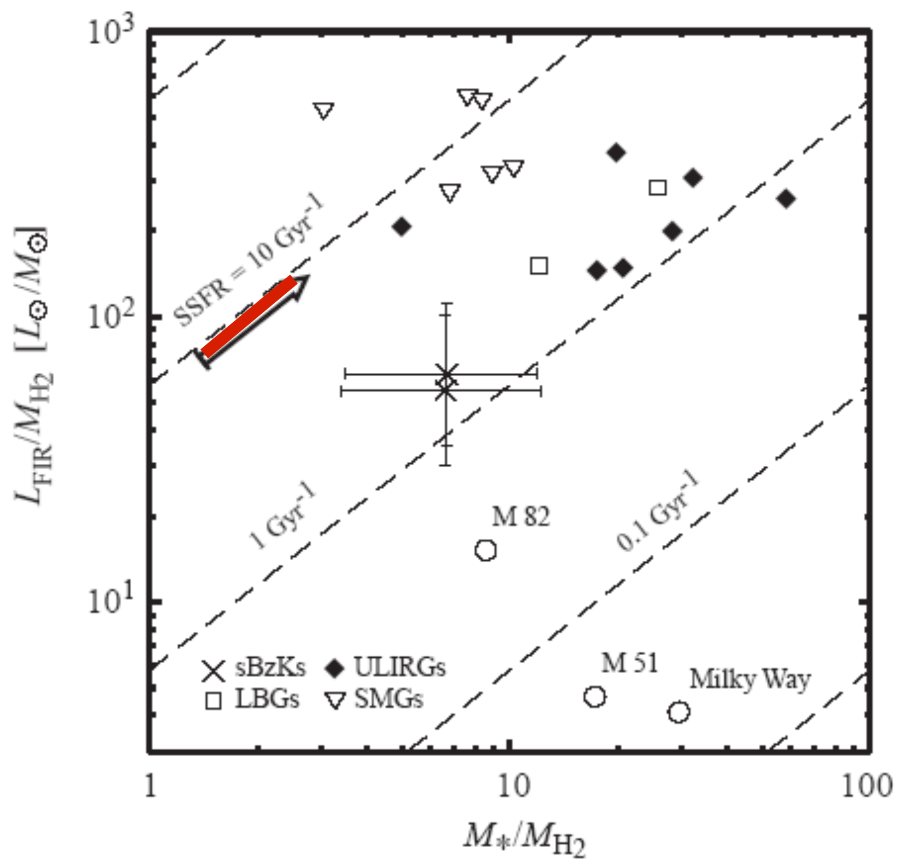
➔ CO conversion factor 4.5 x that of ULIRGS (MH2/LCO)



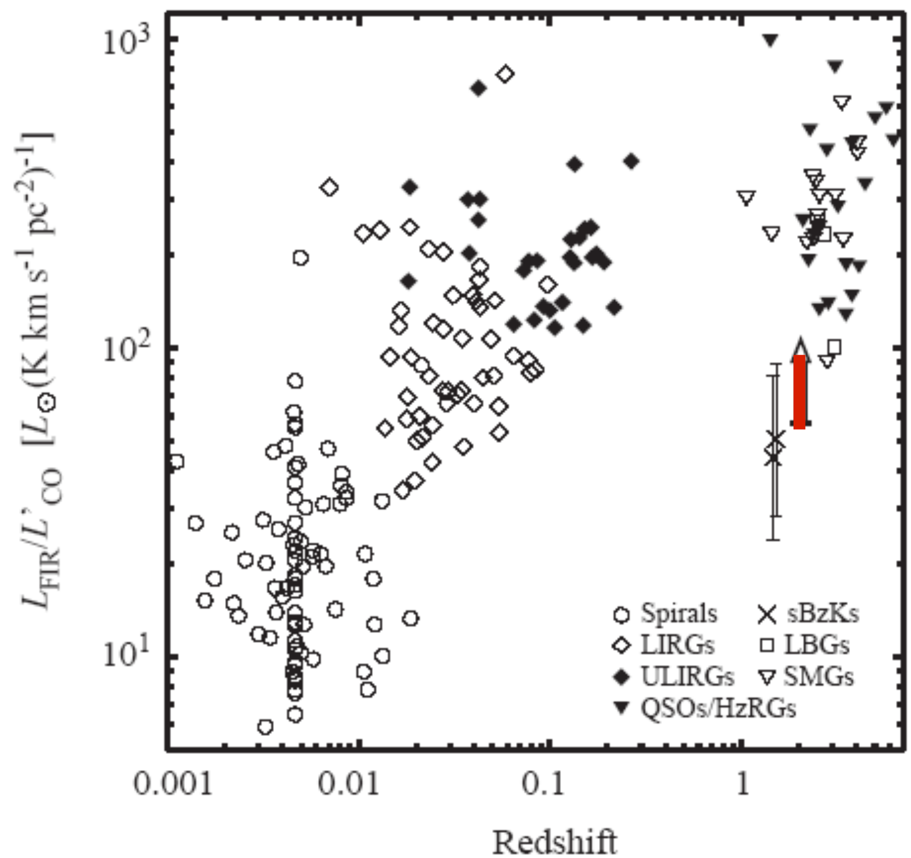




Dannerbauer et al 2009

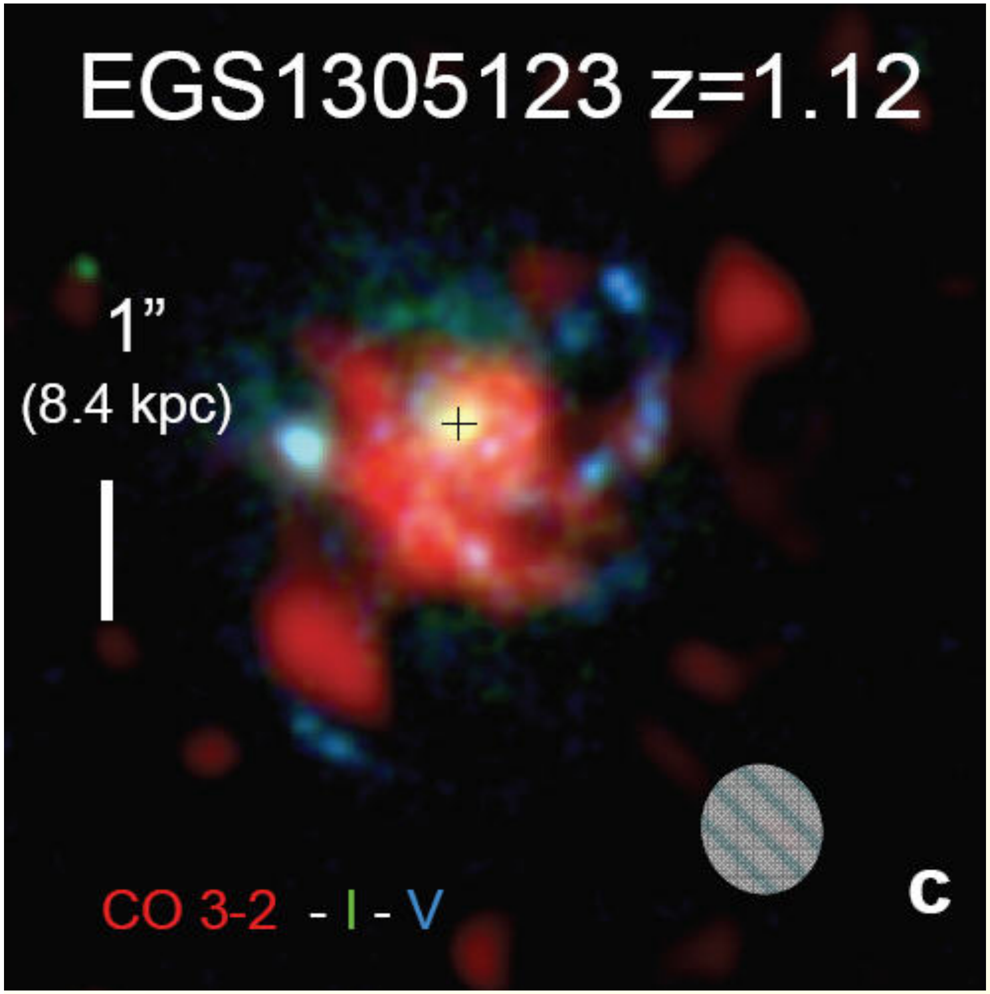
# Large range in BzK galaxies




Another SF BzK not detected in CO: wide range of properties

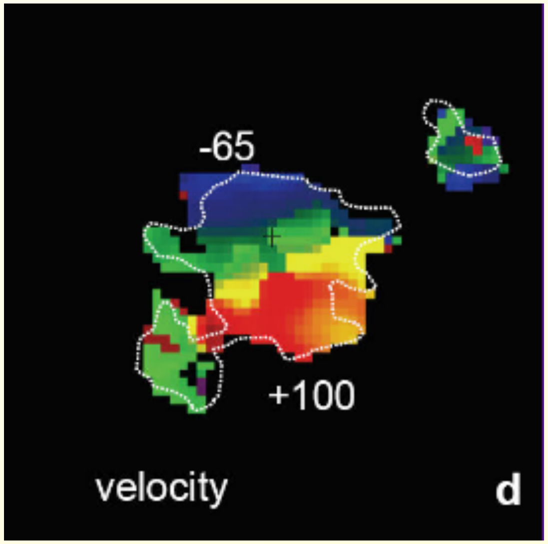



Hatsukade et al 2009




# AEGIS galaxies (1)

19 galaxies observed at IRAM,
10 at z~2.3 and 9 at z~1.2



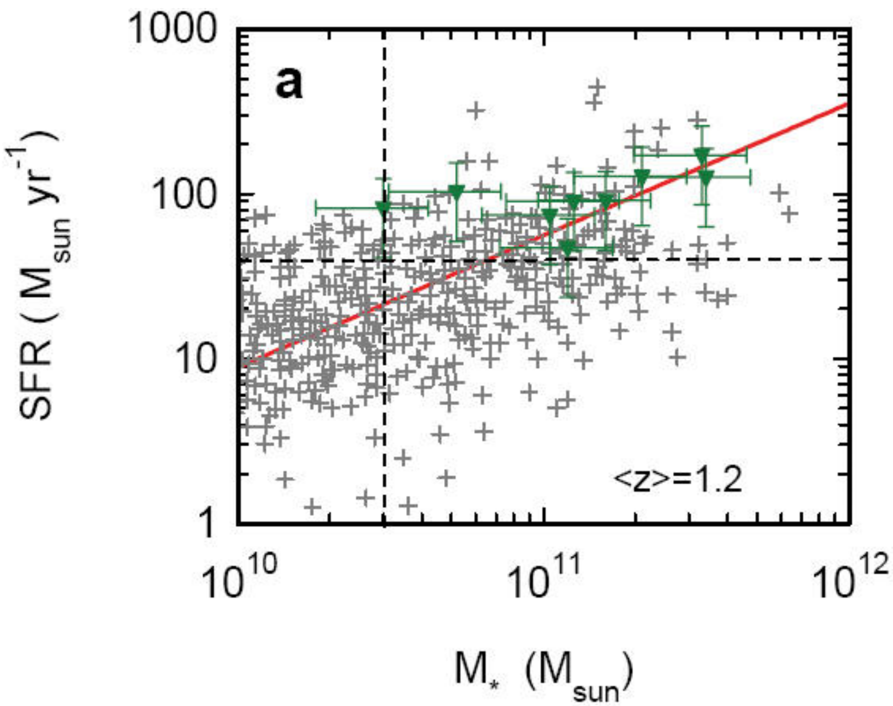

High detection rate >75%, in these « normal » massive Star Forming Galaxies (SFG)

Gas content ~34% and 44% in average at z=1.2 and 2.3 resp.

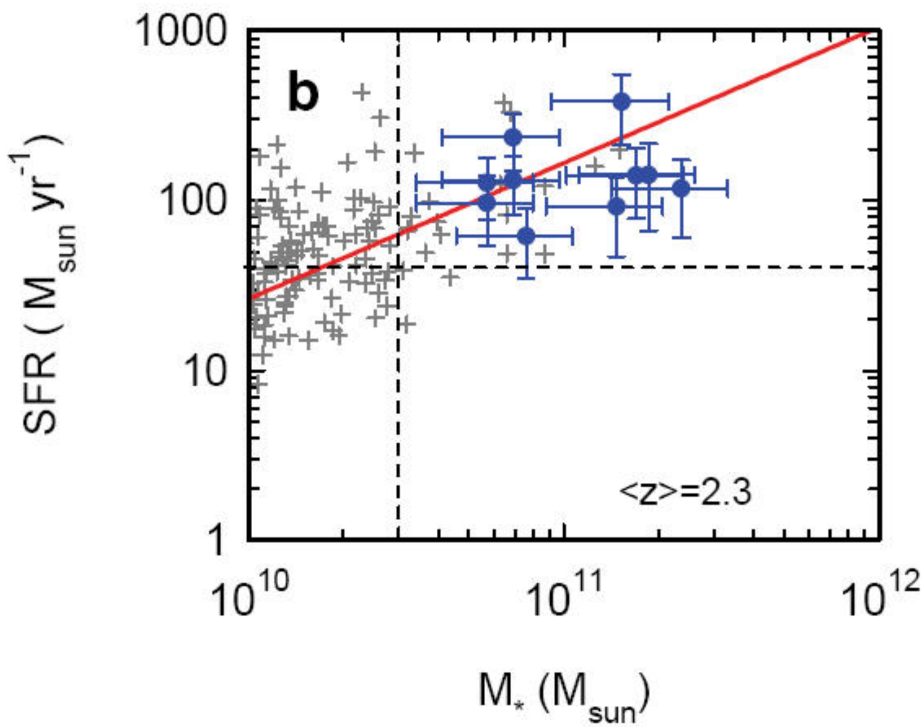


Tacconi et al 2010, Nature

# AEGIS galaxies (2)




**If SFR higher in the past**
**➔ Due to higher gas fraction**




SFR proportional to $M_*^{0.8} (1+z)^{2.7}$

And also a little bit from a higher SF efficiency with redshift

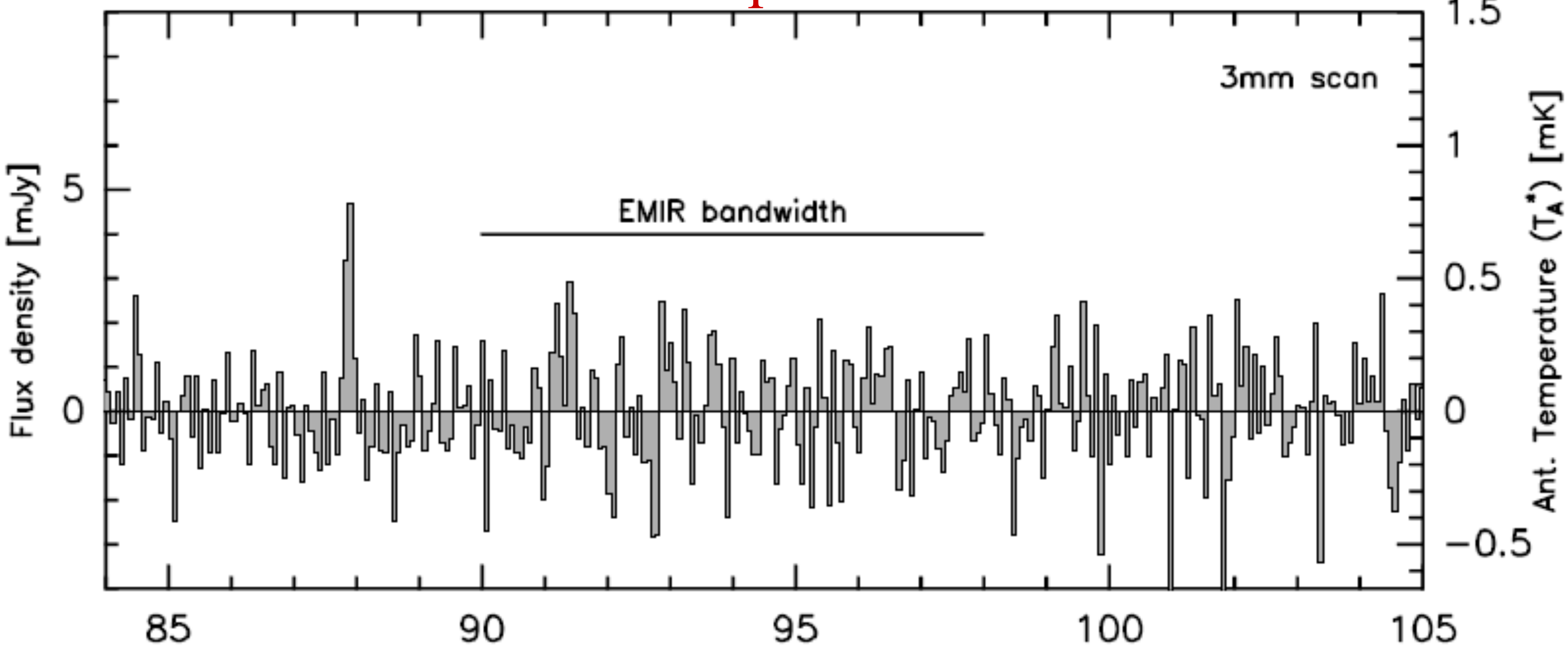
➔ Galaxies must continuously accrete mass

Tacconi et al 2010, Nature

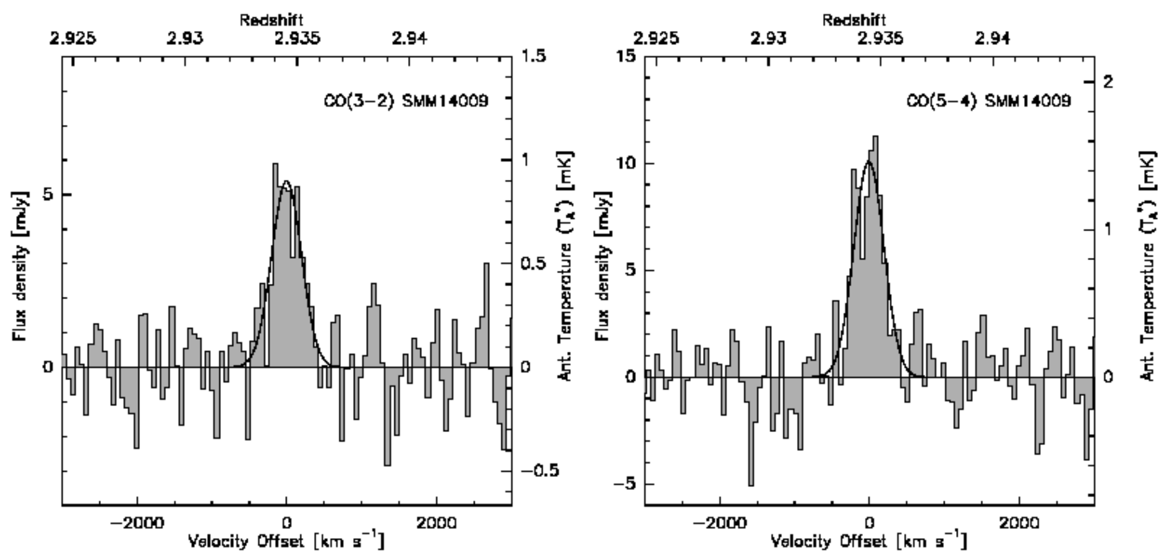
# Redshift Machine

Always a line in 80-116Ghz, if z>2.2

Difference between 2 lines depend on J

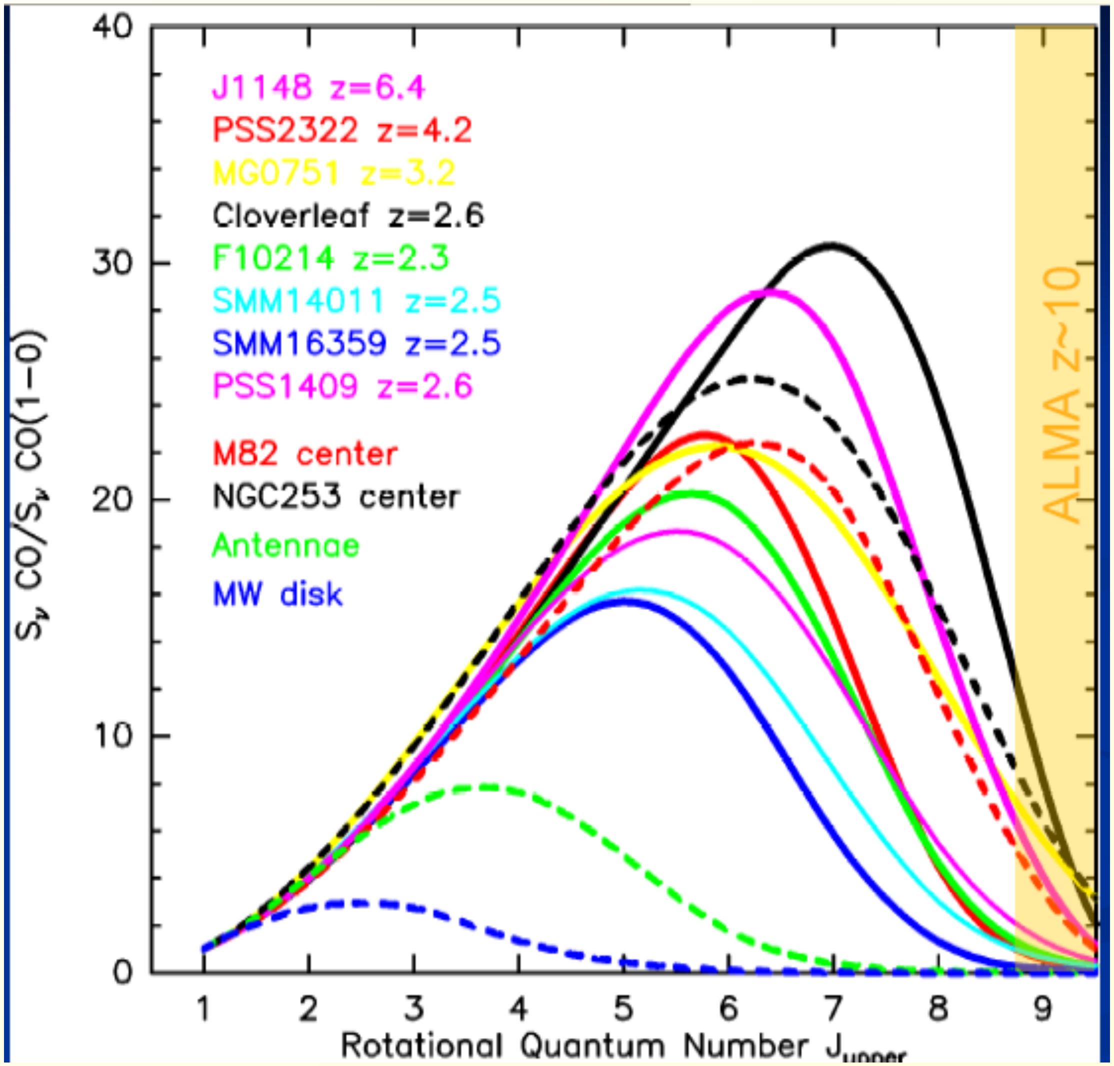



SMMJ14009+0252.



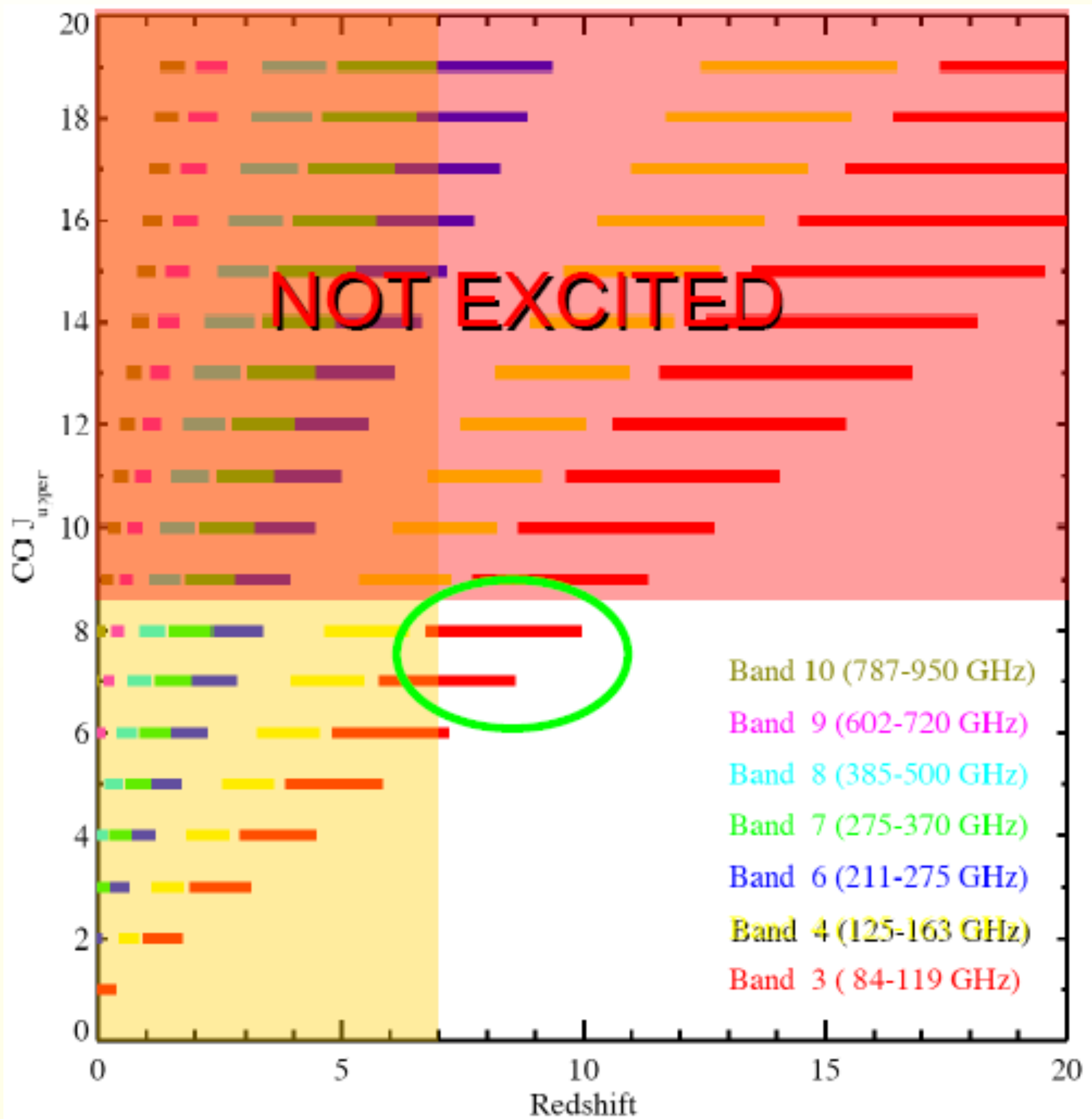

Weiss et al 2009

# Excitation in high-z starbursts




Weiss et al 2007

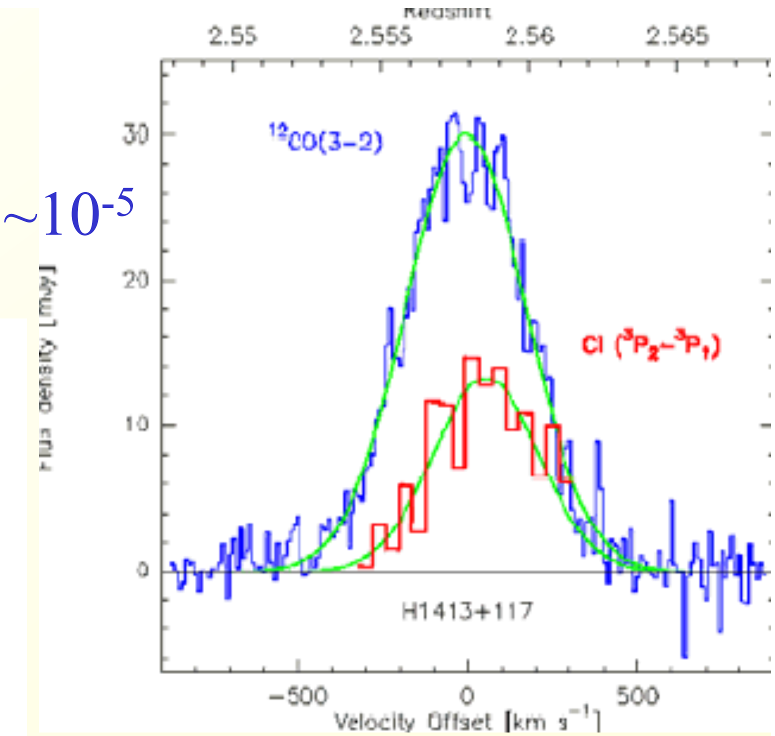
# z> 7 sources: ALMA CO discovery space




*Walter & Carilli 2007*

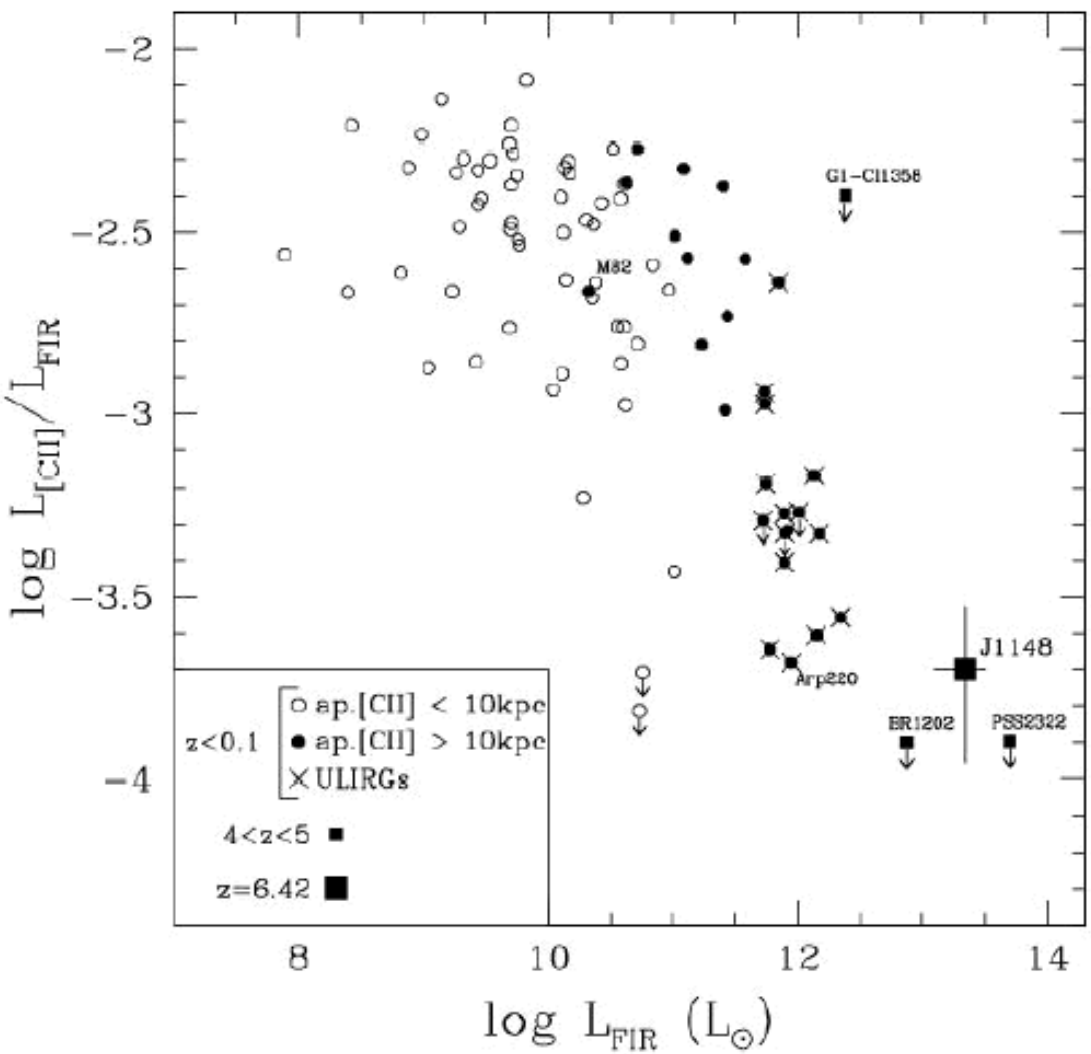
# Other lines CII 158μ, CI, NII…

CI/$H_2$ ~$10^{-5}$




Cloverleaf

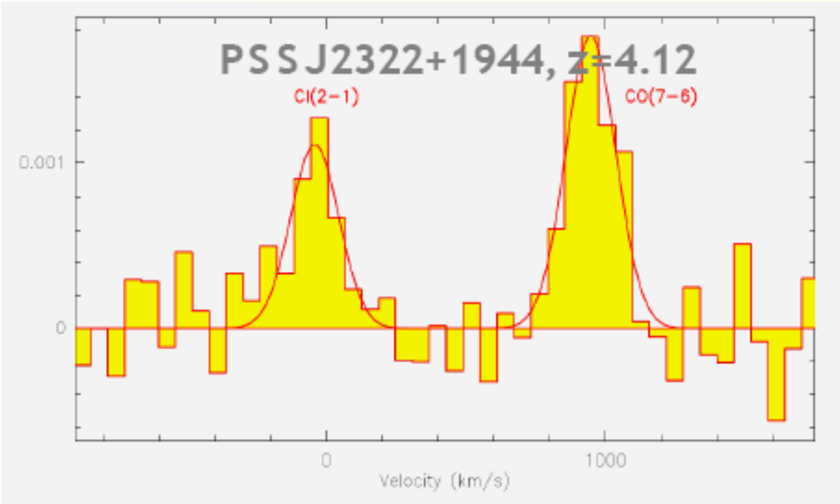
CII/LFIR ~0.06%,
10 times less than locally



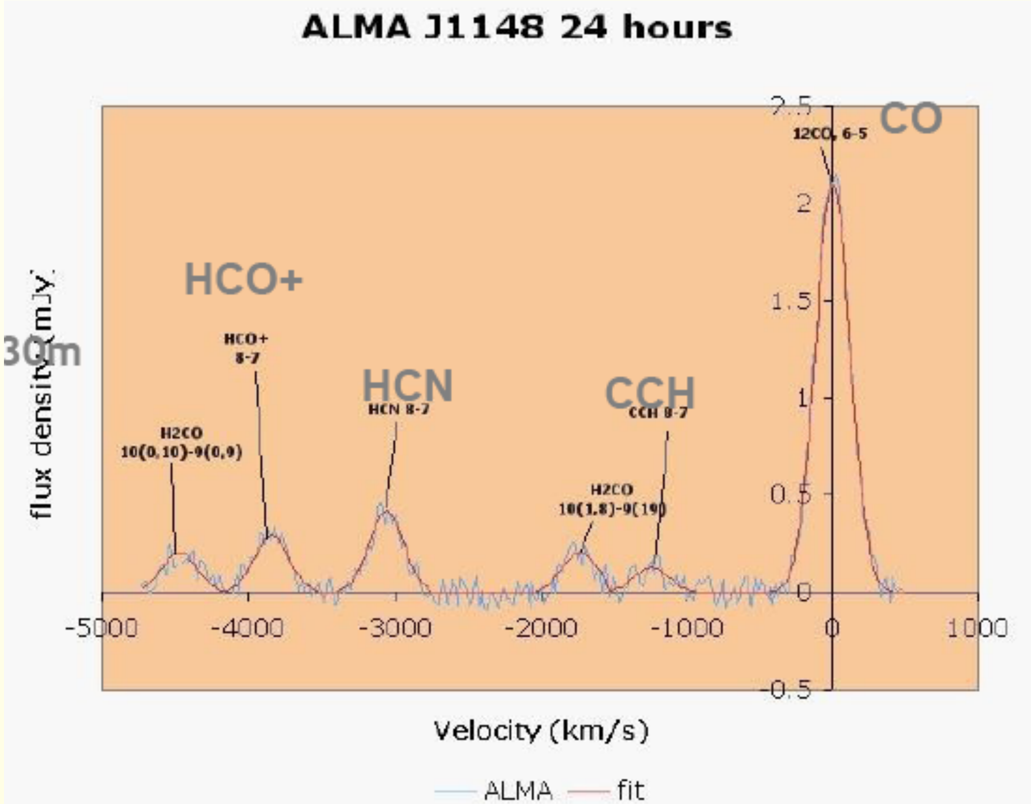

CII detected in
J1148 QSO at IRAM

# Molecular surveys

TODAY




TOMOROW

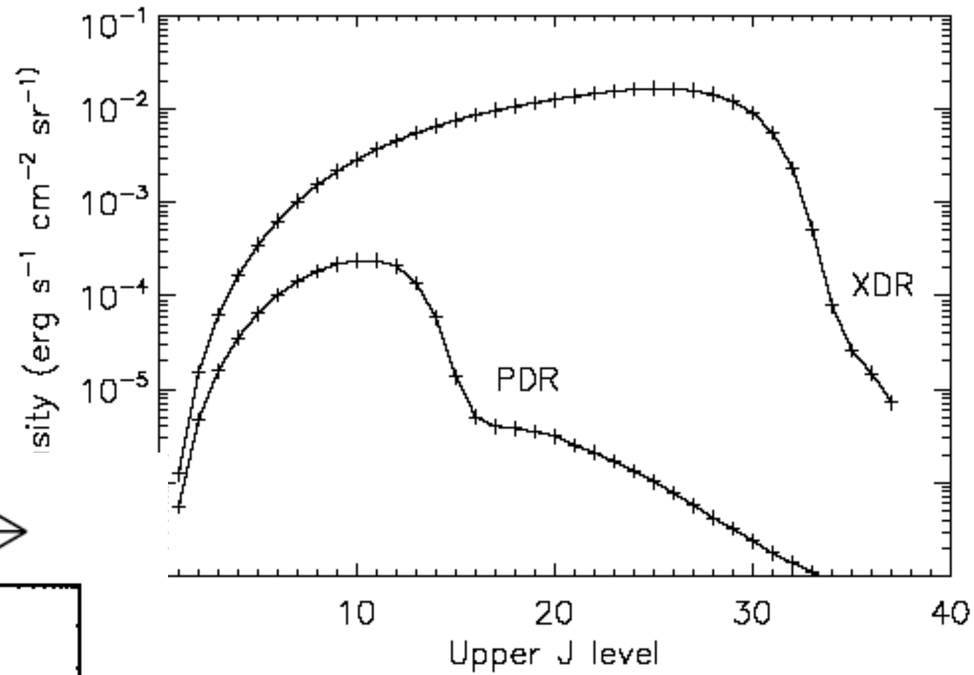


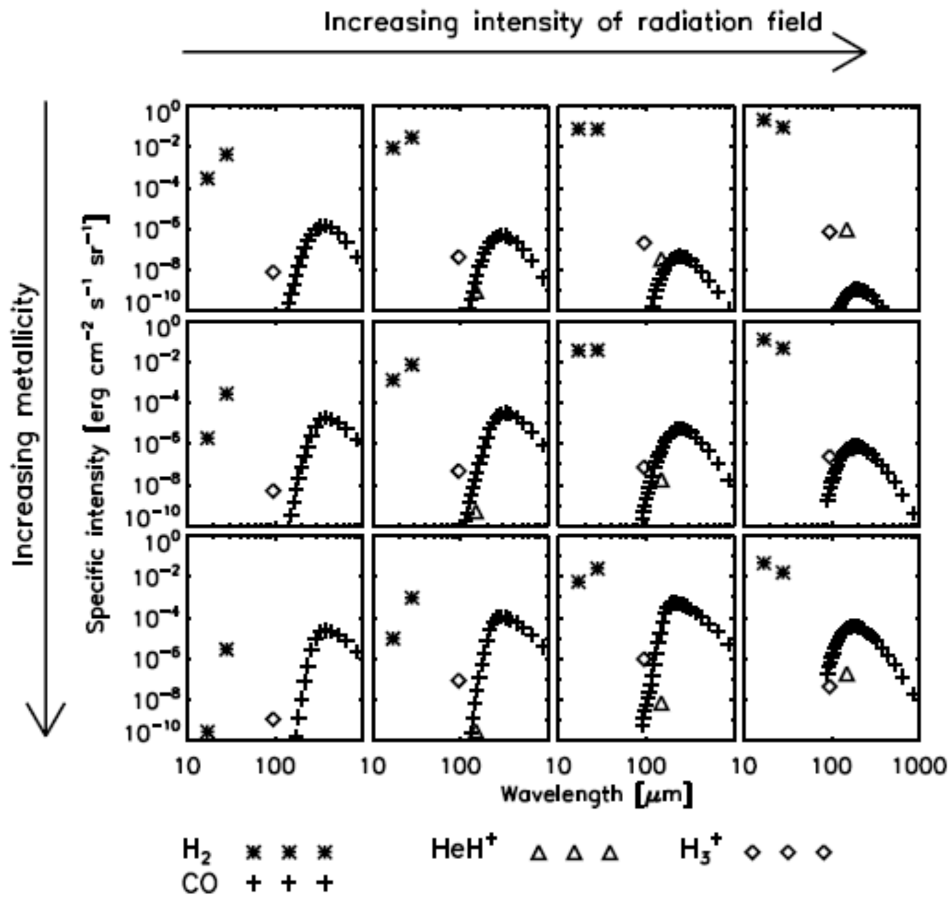

ALMA prediction

# CO & $H_2$ lines for AGN at z ~10

Spaans & Meijerink 2008

$H_3^+$ 95μm, $HeH^+$ 149μm




100K < Tgas < 1000K

Eddington limit for AGN > $10^6 M_o$

CO from J=15 (170μm)

$H_2$ S(0) 28μm, S(1) 17μm

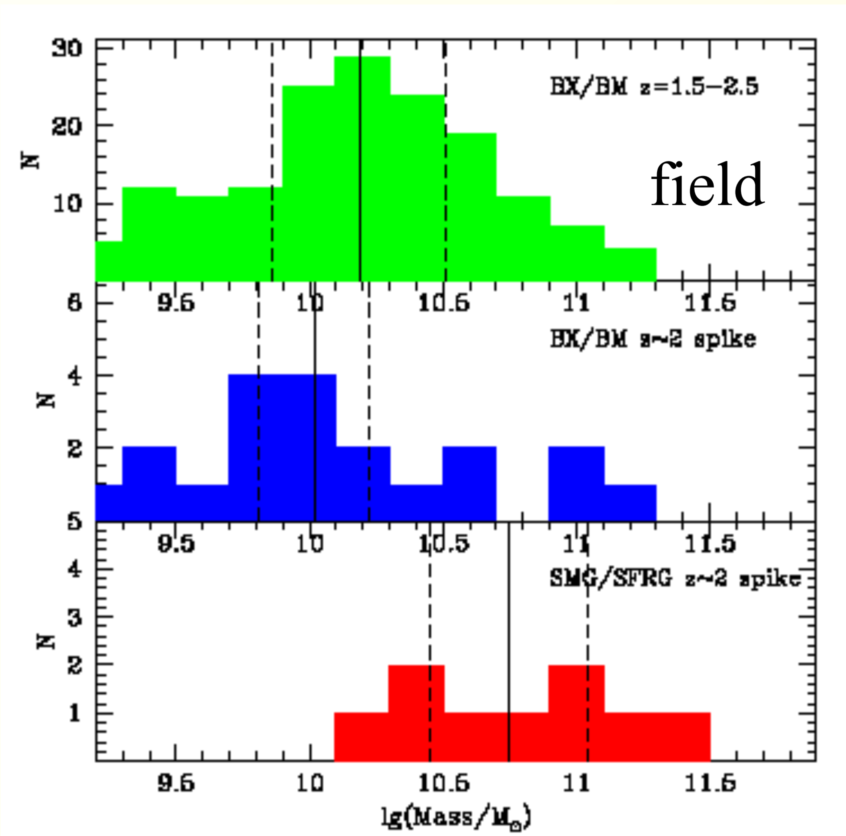
5 < z < 20

$10^{22}$-$10^{24}$ $cm^{-2}$

n ~$10^3$-$10^5$ $cm^{-3}$

# Do SMG actually trace massive haloes?

In the GOODS-N field, cluster of RG and SMG at z=1.99
The strongest known association of SMG *(Chapman et al 2009)*
Overdensity of 10. But only 2 in UV-selected galaxies
➔ Only a mild overdensity, experiencing brief and strong starburst

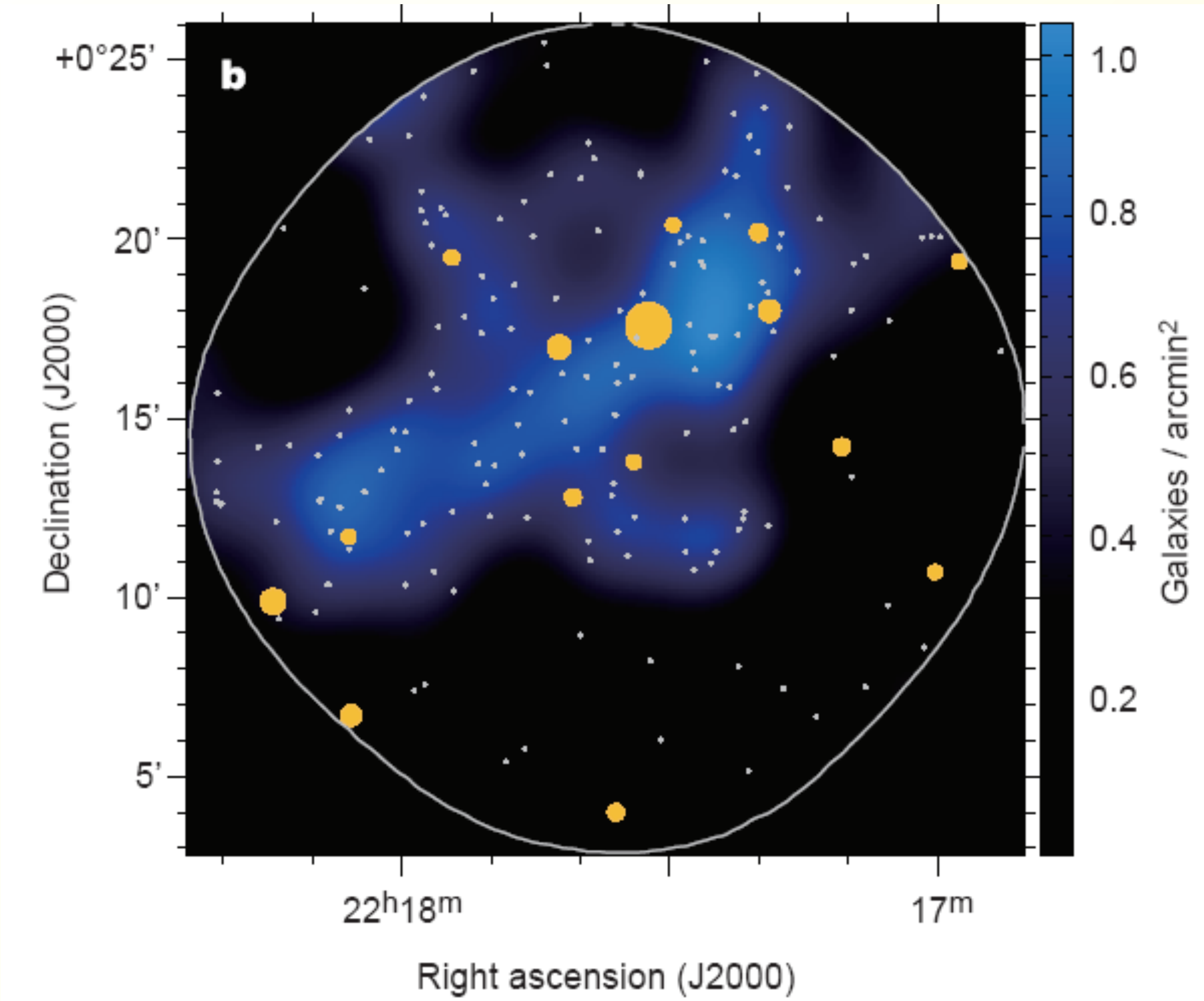



Highly active merger periods in modest mass structures

➔Merger bias

Herschel and ALMA could probe a large range of environments

# SMG in filaments traced by LAE




SSA22
Protocluster region
z=3.1

Filament colour from LAE

SMG 1,1mm from AzTEC on ASTE

S > 2.7 mJy
Size∝ flux

Tamura et al 2009

# APM08279+5255 z=3.9 lensed QSO
# **Influence of AGN feedback on CO emission?**

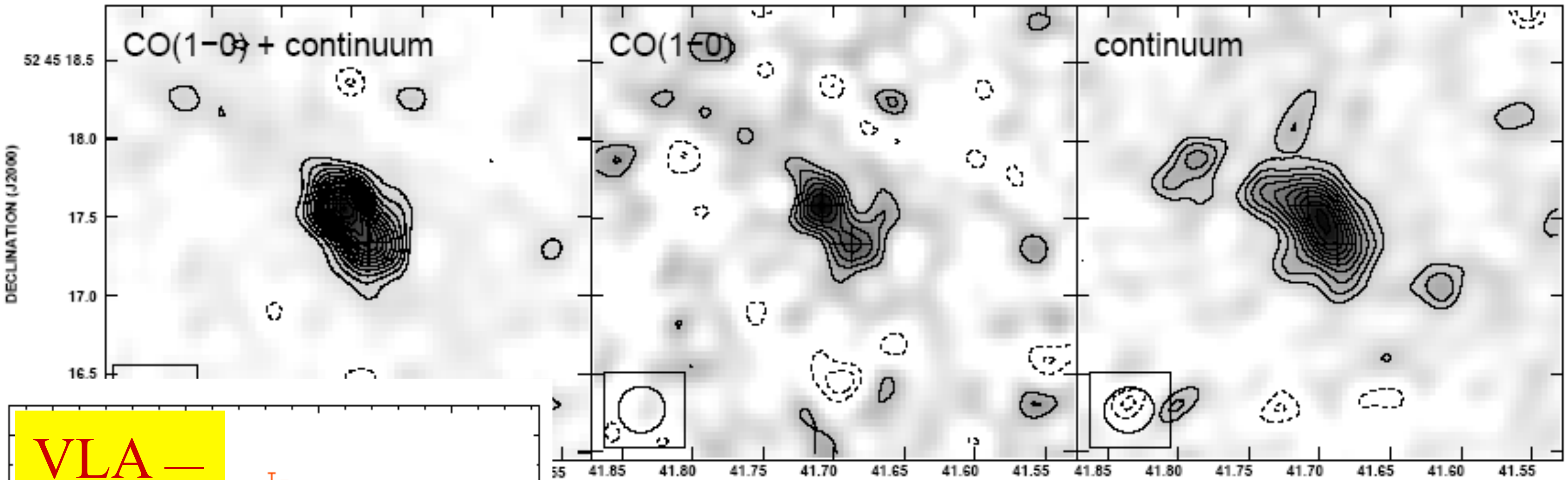
This object is one of the brightest in the sky, and has been observed with mm and cm telescopes (amplification factor ~50)
CO(1-0) to CO(11-10) detected
Recent 0.3" resolution CO(1-0) mapping with VLA *(Riechers + 2009)*

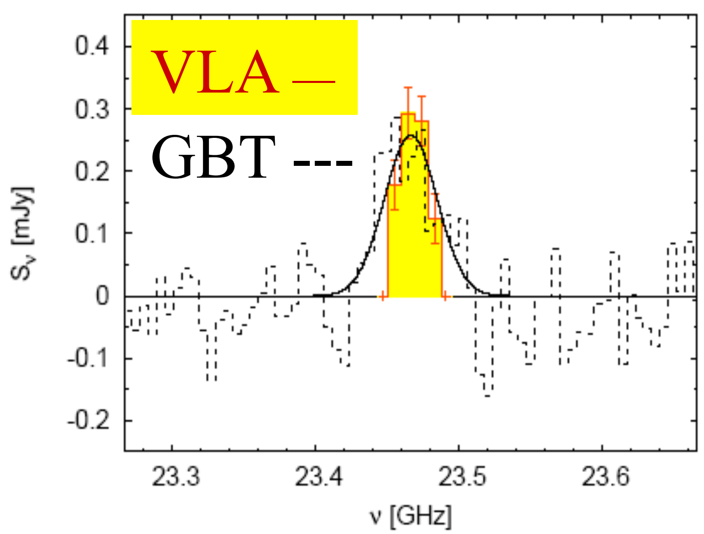
Previously believed to be extended, CO emission is in 2 peaks,
Co-spatial with optical/NIR, may be less amplified than thought (4?)

CO is in a circumnuclear disk of 550 pc radius, inclined by 25°
Mgas ~1.3 $10^{11}$ Mo (ΔV = 556km/s!)
MBH = 2.3 $10^{10}$Mo, bulge 10x less massive than the MBH-σ relation

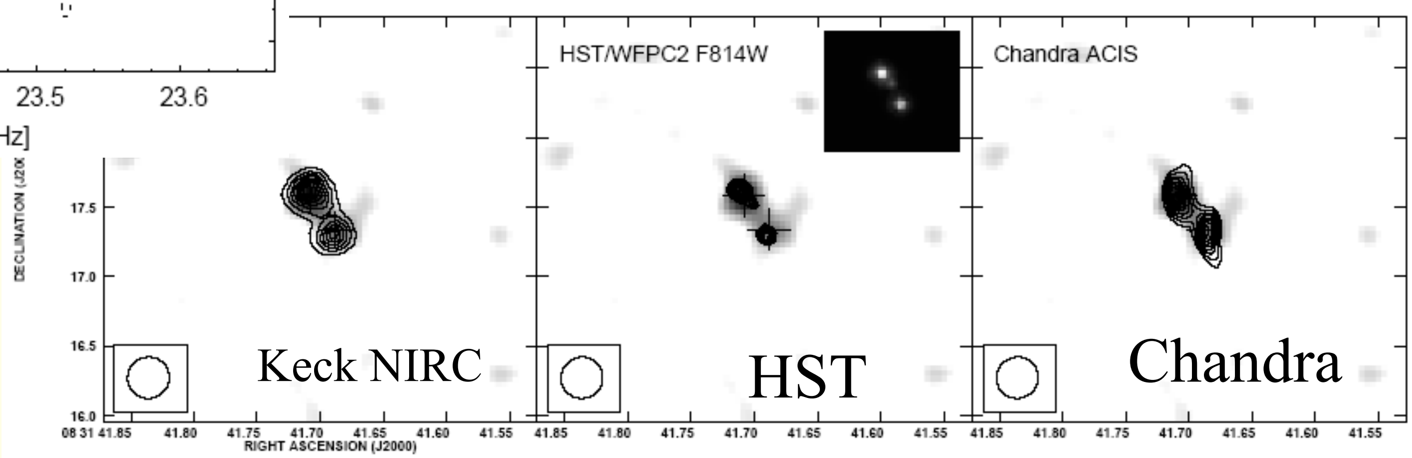
➔No hint of the influence of the AGN feedback…

# APM08279+5255, Riechers et al 09

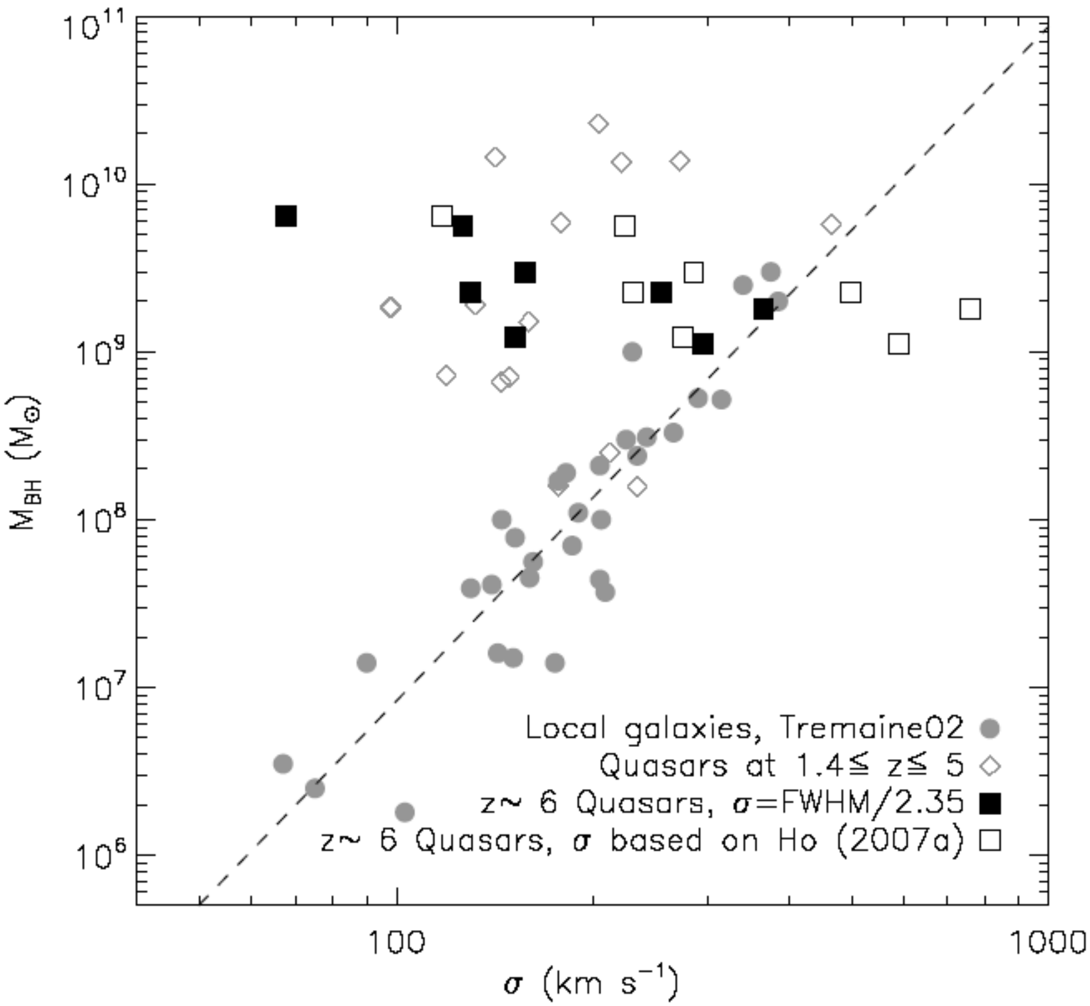



Magnification revised to 4 (100 before!)
CO co-spatial to optical, close to AGN
$MH_2 = 1.3\ 10^{11}$Mo



# MBH/Mbulge, Wang et al 2010




QSO at z=6

➔An order of magnitude higher MBH than expected

**But:**

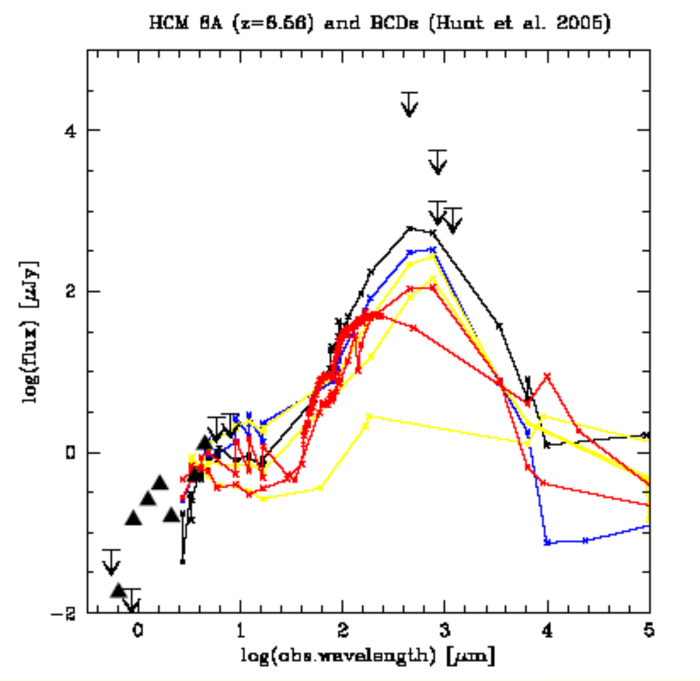
**Unknown inclination**

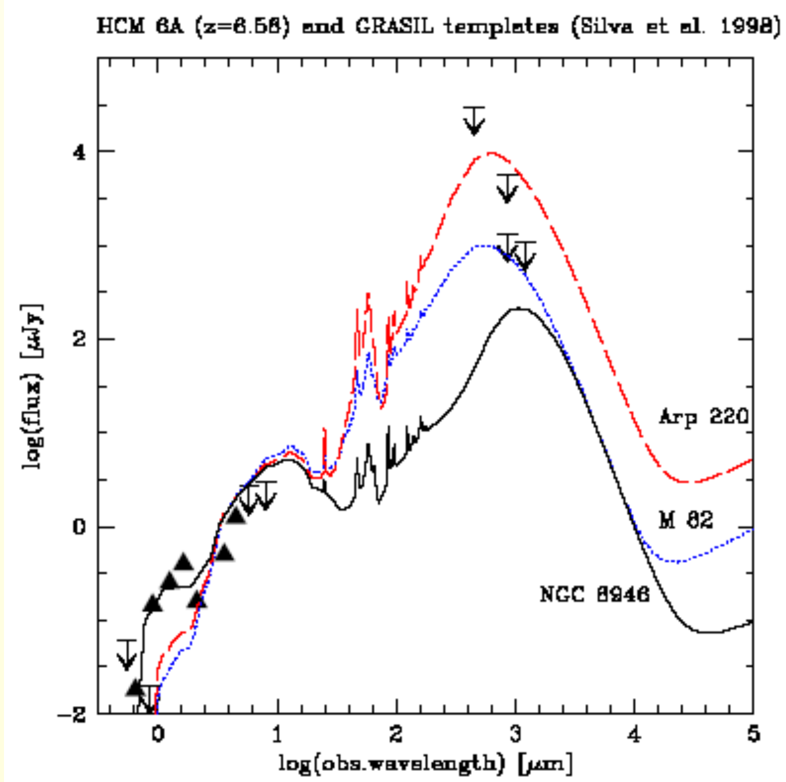
Could be a bias in CO width too small due to a detection bias ?

➔ ALMA will resolve the morphology, and find actual inclinations

# Upper limits for LAE z> 6

HCM6A, at $z$=6.56 behind the Abell 370 cluster   S < 1 mJy at 3σ
dust mass < 5.3 × $10^7$ $M_\odot$, SFR < 35 $M_\odot$ /yr. **Boone et al 2007**
No CO detected $M(H_2) < 5\ 10^9$Mo, if X-factor =0.8 **Wagg et al 2009**




Amplification factor 4.5
+ X  factor 4.5 also ➔ 20
➔ ALMA will have difficulties

# Summary of present work

➔SMG in continuum

➔About 70 systems detected in CO at high z

➔May be dominated by selection effects
ULIRGs very efficient SFE, compact and highly excited
Or more extended gas, with normal SFE and life-times

➔Bias of lensing magnification

➔Quasars and Starburst intimately linked
AGN does not quench SF?

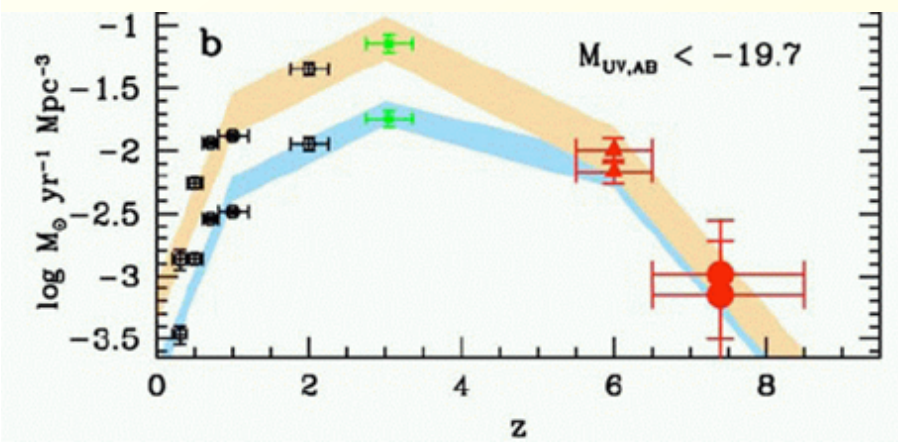
# Perspective with ALMA

•ALMA deep field in continuum: N(S), SFR (z) and SFH

•the CO lines will be intensively observed at high z with ALMA and determined for « **normal** » **systems**
➔ efficiency of star formation (z), and the kinematics, Mdyn

**➔If CO not excited, either CII, or go to GBT, EVLA and SKA precursors to detect the low-J CO lines**

Galaxies at high z, SFH




➔ SFH + MH2 ➔ SFE