Molecular Gas in High-*z* QSO Host Galaxies

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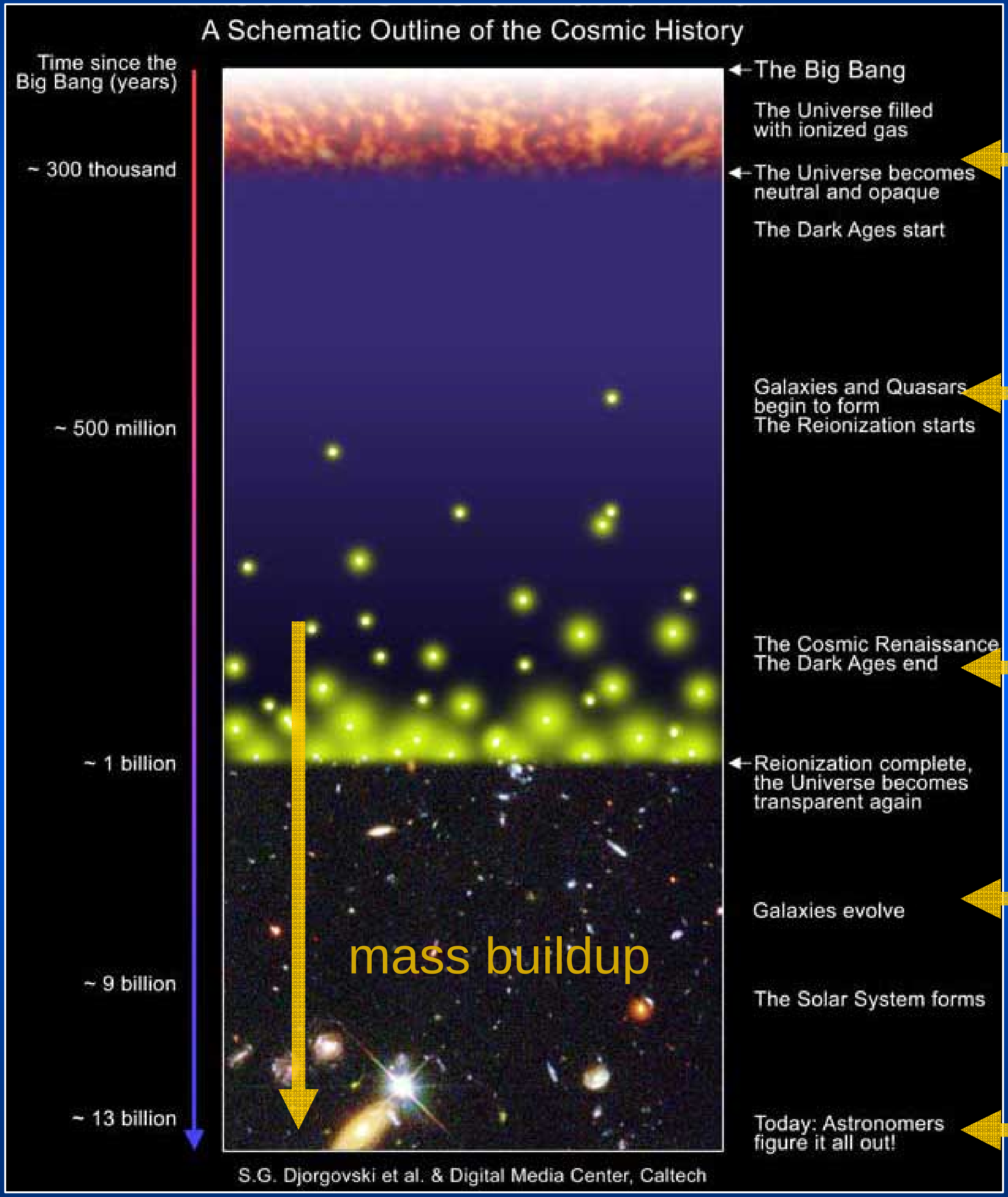
History of the Universe



Recombination (z~1000)

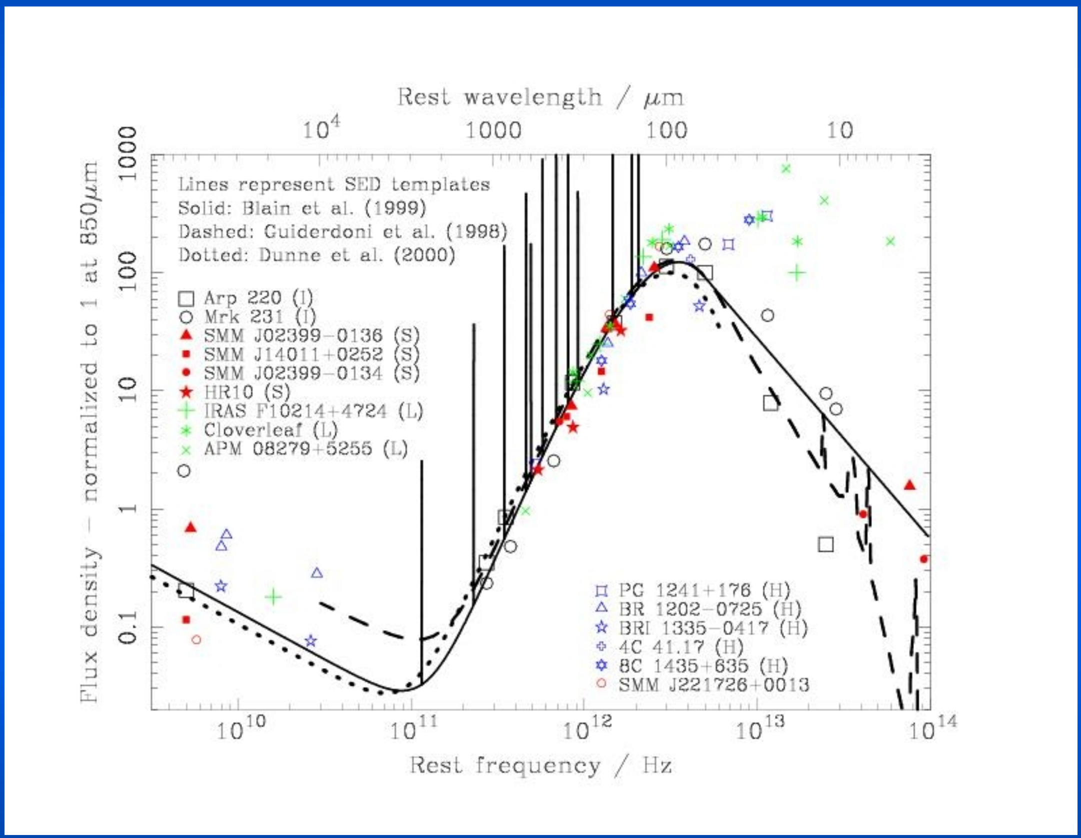
Cosmic 'Dark Ages' - no stars/quasars

Epoch of re-ionization (6<z<20)

Peak of activity QSOs & submm galaxies (z~2.5)

Galaxies today

The spectrum of a ULIRG: a `field guide'



From Blain (2003)

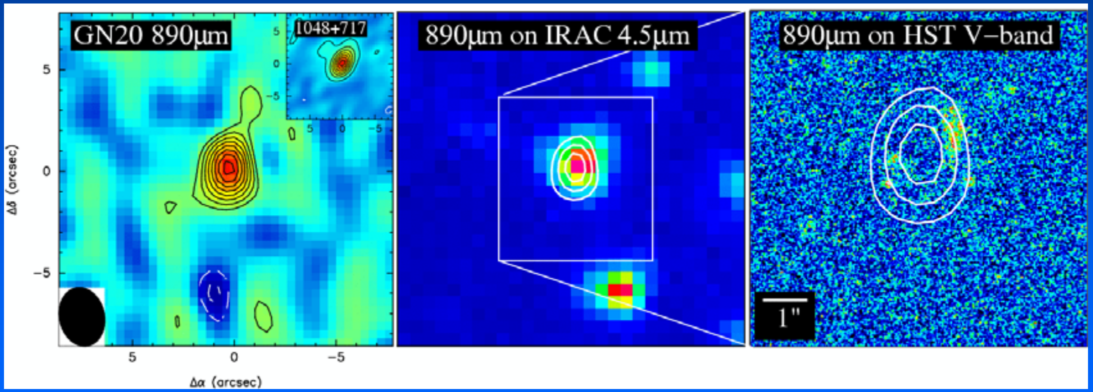
- **Non-thermal radio**
- **Thermal dust**
  - **- Dominated luminosity**
  - **- Hotter in AGN**
  - **- Mid-IR spectral features (missing in AGN)**
- **Molecular and atomic lines**
  - ***- mm CO/HCN***
  - ***- far-IR: C/N/O***
  - **- mid-IR: C-C/C=C/H_2**

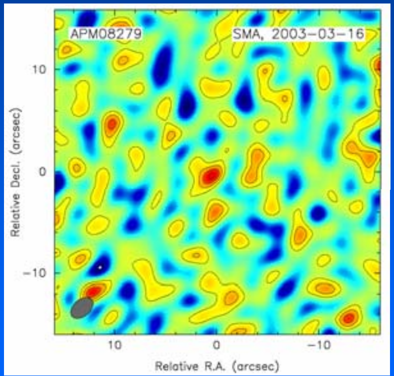
Luminosities involved:

$3 \times 10^{11} < L/L_{sun} < 10^{14}$

Deep Field Sources

15"/10"
SCUBA/
MAMBO



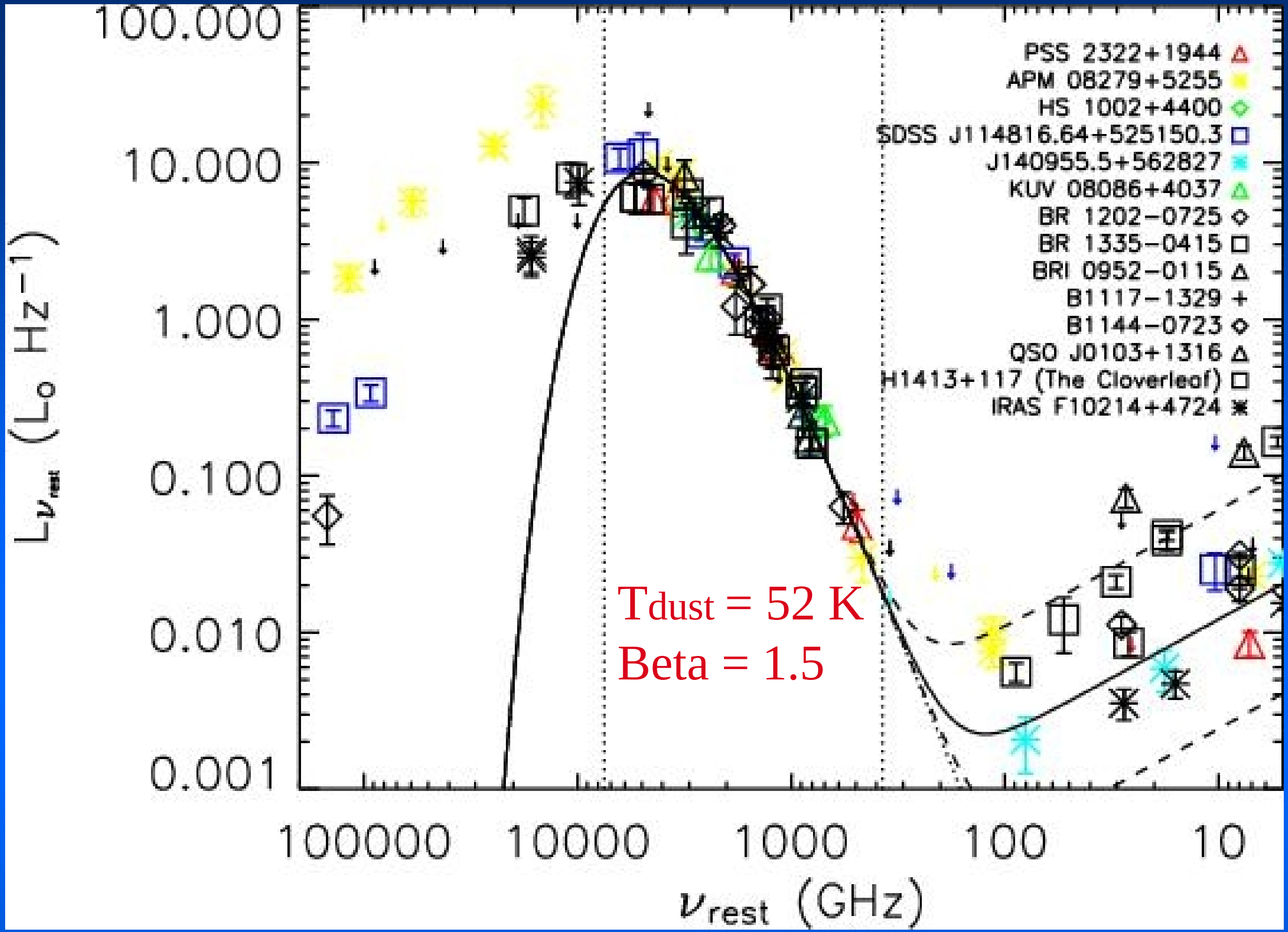


Source identification critical (usually through RC, Chapman et al. 2004)

Pointed Observations

- Sources selected from optical (SDSS) and radio (VLA):
Quasars **(radio-quiet), radio-galaxies**
- Position well known; redshifts known

-> poster



L_FIR = 4x10^{12} x S_{250}(mJy) L_sun for z=0.5 to 8

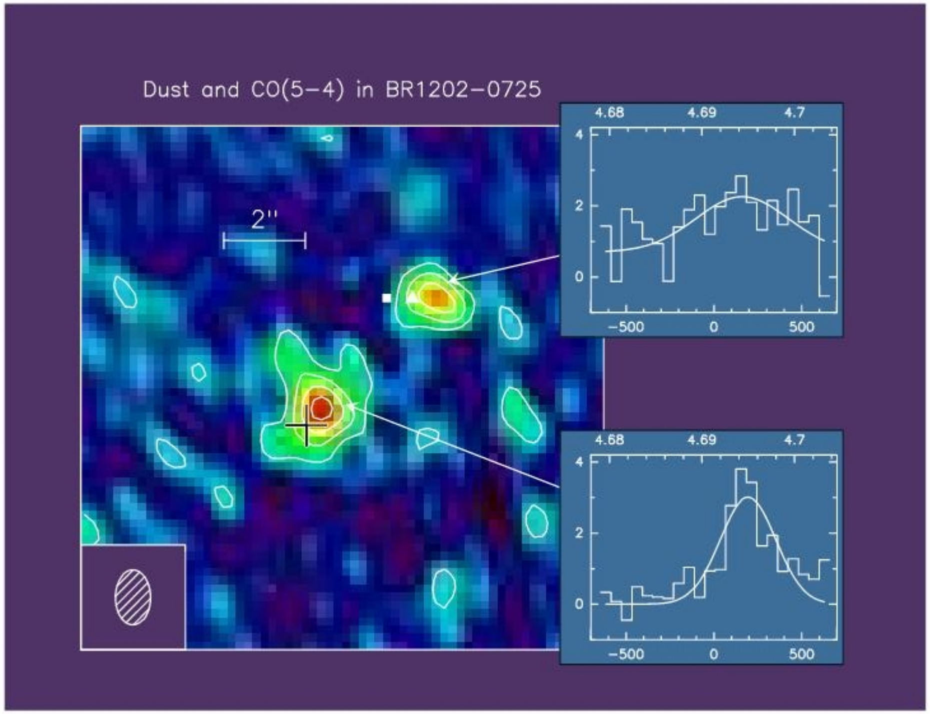
SFR = 1400 x S_{250}(mJy)M_sun/yr (very high)

M_dust = 1.4x10^{8} x S_{250}(mJy) M_sun

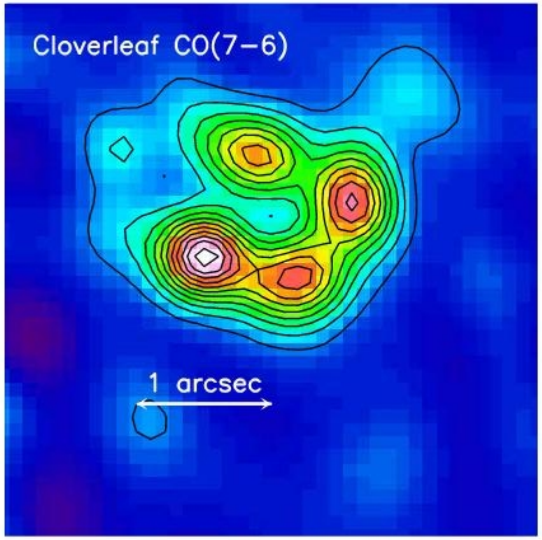
Beelen et al. 2005

QSOs: First Detections of CO at High-*z*

BR1202-0725 at z=4.12



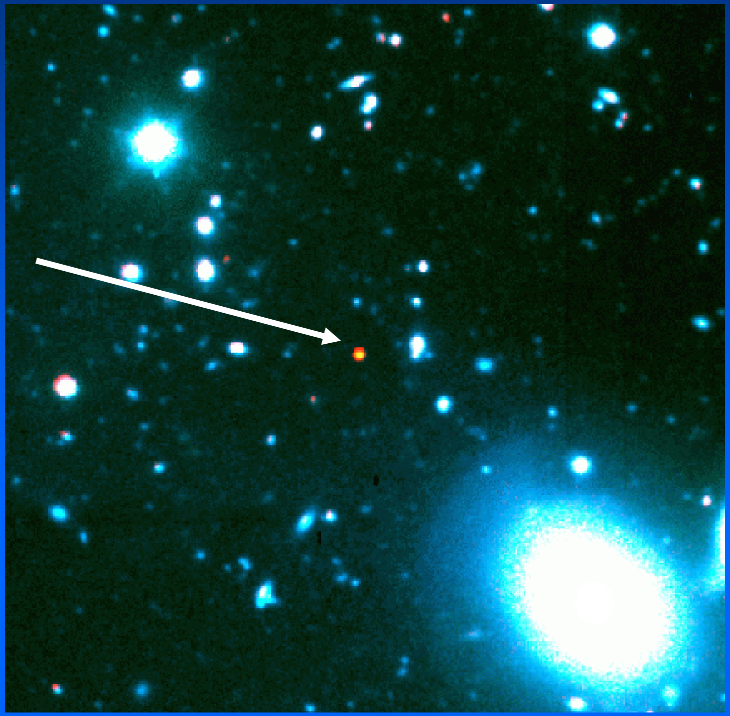
Cloverleaf at z=2.6



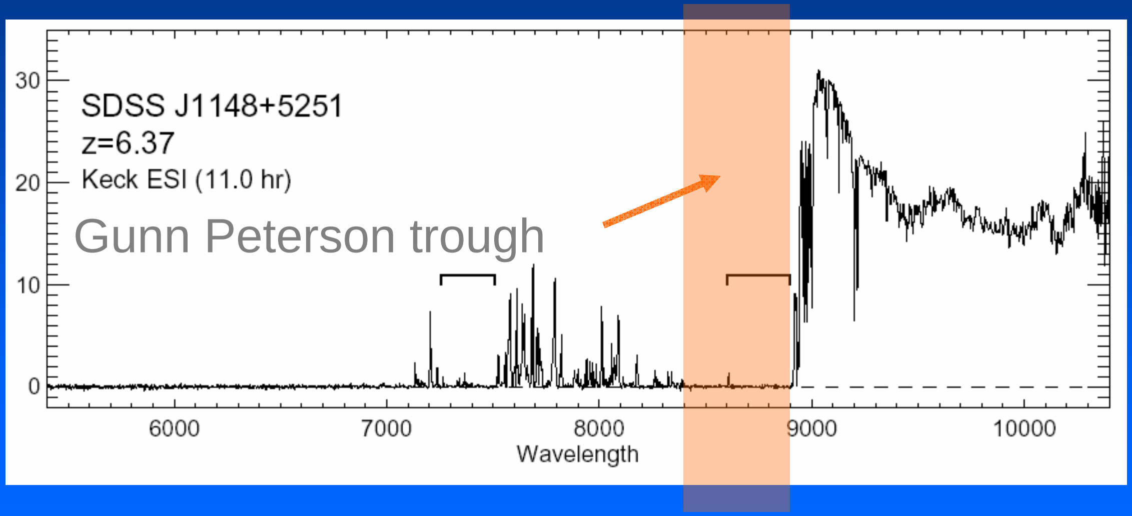
High z Sources detected in CO - August 2005

Source Name	z	Telescopes	line	CO Line [Jy km s^{-1}]	1.2 mm Cont. [mJy]	Ref.
IRAS 10214+4724	2.28	12-m; 30-m	3−2	4.1±0.9	9.6±1.4	[1,2]
Cloverleaf	2.56	PdB; 30-m	3−2	9.9±0.6	18±2	[3]
BR 1202−0725	4.69	PdB; NRO	5−4	2.4±0.3	12.6±2.3	[4,5]
BRI 1335−0417	4.41	PdB	5−4	2.8±0.3	10.3±1.0	[6]
53W002	2.39	OVRO; PdB	3−2	1.20±0.15	1.7±0.4	[7,8]
MG 0414+0534	2.64	PdB	3−2	2.6±0.4	40±2†	[9]
SMM J02399−0136	2.80	OVRO; PdB	3−2	3.1±0.4	7.0±1.2	[10,11]
APM 08279+5255	3.91	PdB	4−3	3.7±0.5	17.0±0.5	[12]
BRI 0952−0115	4.43	PdB	5−4	0.91±0.11	2.8±0.6	[13]
Q1230+1627B	2.74	PdB	3−2	0.80±0.26	2.7±0.6	[13]
SMM J14011+0252	2.57	OVRO	3−2	2.4±0.3	≈ 3	[14]
4C60.07	3.79	PdB	4−3	2.50±0.43	4.5±1.2	[15]
6C1909+722	3.53	PdB	4−3	1.62±0.30	$<$ 3	[15]
HR 10	1.44	PdB	5−4	1.35±0.20	4.9±0.8	[16]
MG 0751+2716	3.20	PdB	4−3	5.96±0.45	6.7±1.3	[17]
PSS 2322+1944	4.12	PdB	4−3	4.21±0.40	9.6±0.5	[18]
B3 J2330+3927	3.09	PdB	4−3	1.3±0.3	4.2±0.6	[19]
TN J0121+1320	3.52	PdB	4−3	1.2±0.4		[20]
J 1409+5628	2.56	PdB	3−2	3.28±0.36	10.7±0.6	[21]
J 1148+5251	6.42	VLA & PdB	3−2	0.18±0.04	5± 0.6	[22,23]
SMM J04431+0201	2.51	PdB	3−2	1.4±0.2	1.1±0.3	[24]
SMM J09431+4700	3.34	PdB	4−3	1.1±0.1	2.3±0.4	[24]
SMM J16358+4057	2.38	PdB	3−2	2.3±1.2	2.6±0.2	[24]
cB58	2.73	PdB	3−2	0.37±0.08	1.06±0.35	[25]
Q0957+561	1.41	PdB	2−1	1.20±0.06	5.7±1.8†	[26,27]
RX J0911+0551	2.79	OVRO	3−2	2.9±1.1	10.2±1.8	[28]
SMM J04135+1027	2.84	OVRO	3−2	5.4±1.3	7±1	[28]
B3 J2330+3927	3.08	PdB	4−3	1.3±0.3	4.8±1.2	[29]
4C41.17	3.79	PdB	4−3	1.8±0.2	3.8±0.4	[30]
TNJ0121+1320	3.52	PdB	4−3	1.2±0.4	–	[31]
TNJ0924−2201	5.19	ATCA	1−0	0.52±0.11	–	[32]
SMM J02396−0134	1.06	PdB	2−1	3.4±0.3	–	[33]
SMM J13120+4242	3.41	PdB	4−3	1.7±0.3	–	[33]
SMM J16366+4105	2.45	PdB	3−2	1.8±0.3	–	[33]
SMM J16371+4053	2.38	PdB	3−2	1.0±0.2	–	[33]
SMM J22174+0015	3.09	PdB	3−2	0.8±0.2	–	[33]
SMM J16359+6612	2.51	PdB & OVRO	3−2	5.75±0.25	3.0±0.7	[34]

J1148+5251 - The Most Distant QSO at z=6.42

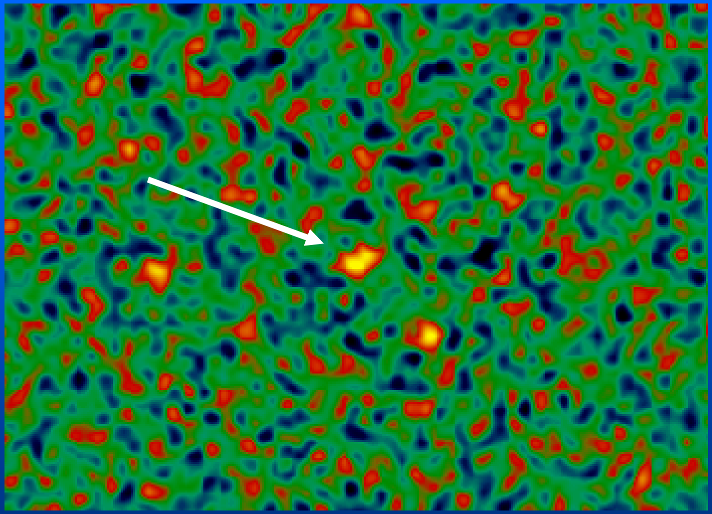


z-band (Keck – Djorgovski et al.)

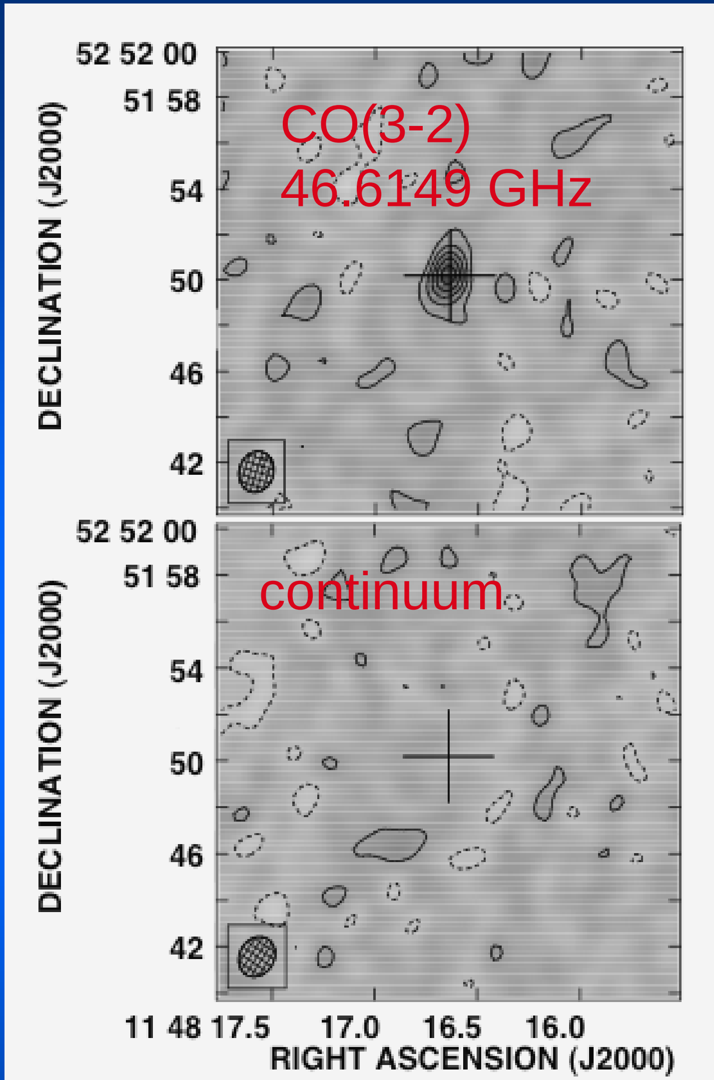


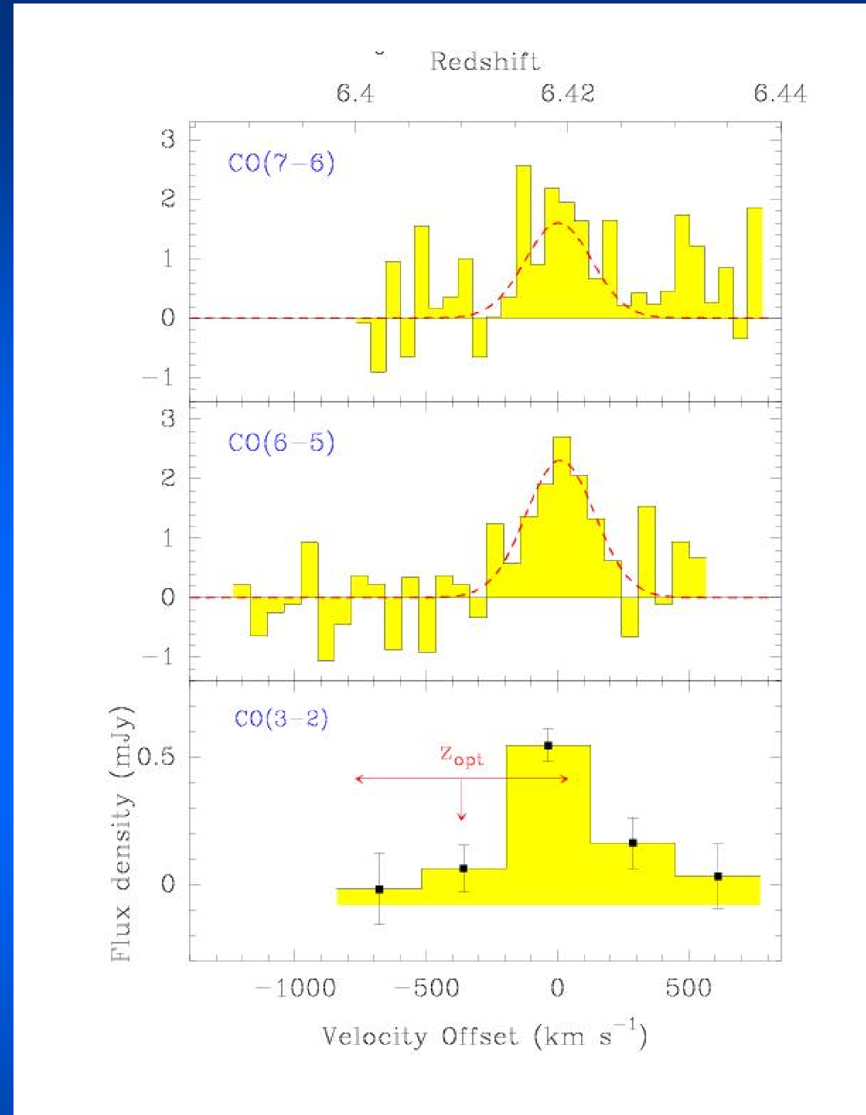
Fan et al. 2003; White et al. 2003

- **z=6.42; age~870 Myr**
- **one of the first luminous sources**
- **M_{BH} ~ 1-5 x 10^9 M_{sun} (Willot et al. 2003)**
- **M_{dust} ~ 10^8 M_{sun} (Bertoldi et al. 2003)**



Dust continuum at 1.2 mm





PdBI

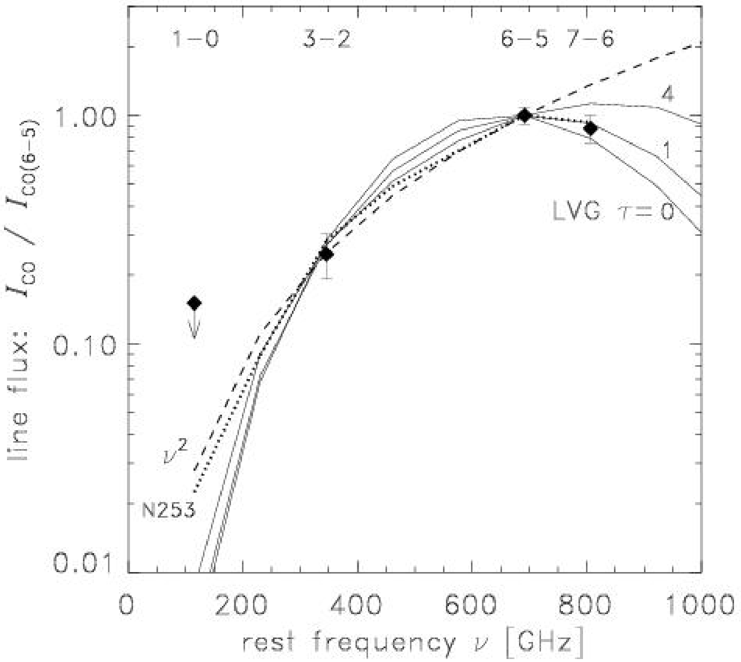
VLA

Walter et al. 2003
Bertoldi et al. 2003

CO excitation in J1148+5251 (filled circles), compared to NGC 253 (dashed)

LVG Model:

T_{kin}= 100K, n_{H2}=7x10^4 cm^{-3}



- **Mass:**

  M_{H2} = 2 x 10^{10} M_{sun}

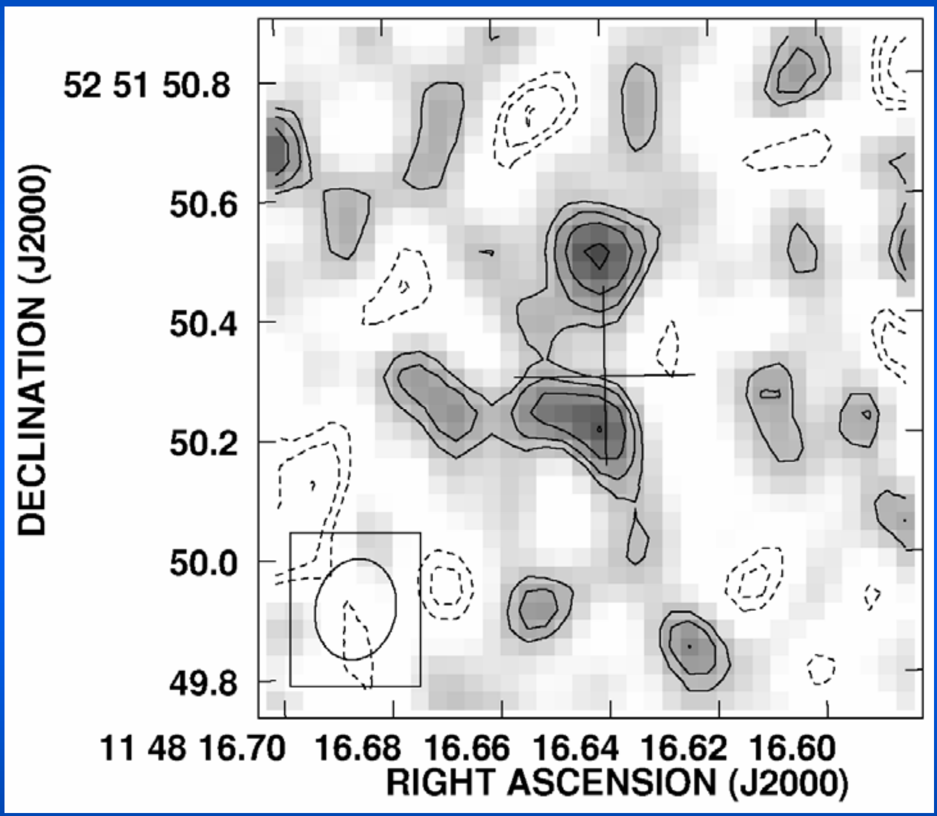
  M_{dyn} = 3 x 10^9 sin^{-2}(i) M_{sun}

- **Mass in C and O: ~3x10^7 M_{sun}**

Bertoldi et al. (2003)

Resolving the CO emission in J1148+5251

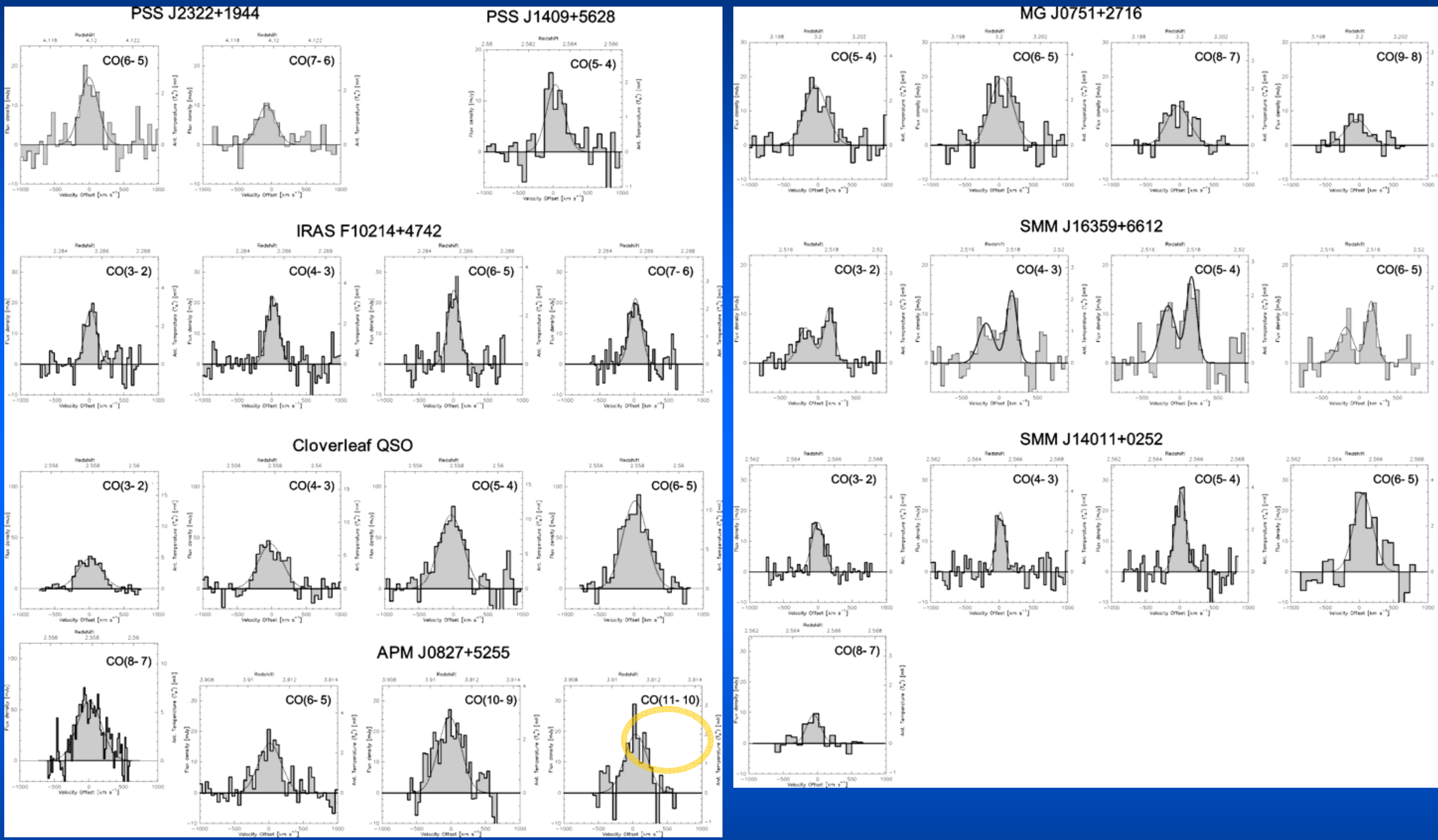
VLA A+B + C array; res.: 0.15” (~1 kpc)



Walter et al. 2004

- Two sources separated by 0.3” (1.7 kpc at z=6.4) containing each 5 x 10^9 M_{sun}
- Not likely to be amplified
- If gravitationally bound,
  M_{Dyn}=4.5x10^{10} M_{sun}

Multiple CO Lines



IRAM 30m CO multiline survey **(1, 2, 3mm bands)** **Weiss et al. (2006)**

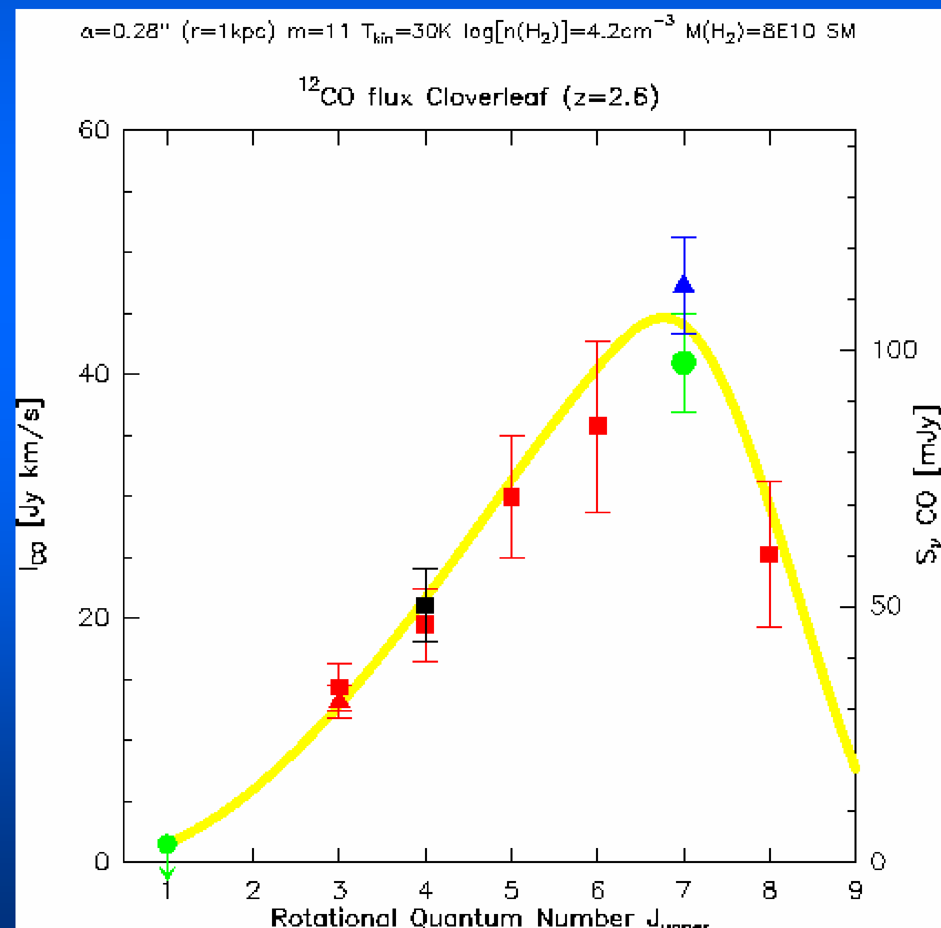
LVG solution Cloverleaf

T_{ex} (CI) ~ low J T_{ex} (CO) [similar critical densities]

CO LVG solution:
Disk radius: 1 kpc
excellent agreement with lens models !
$\log(n(H_2)) = 4.2\ cm^{-3}$
$T_{kin} = 30$ K

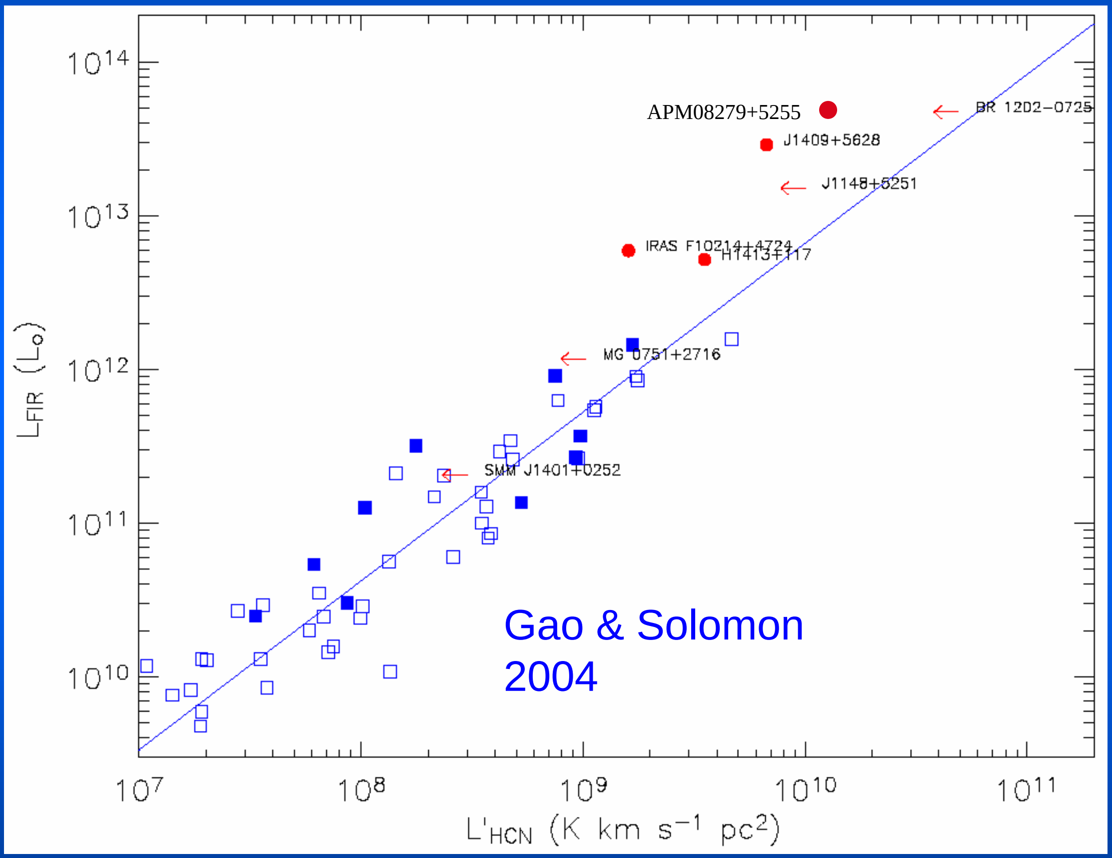
$M(H_2) = 8\ 10^{10}\ M_\odot$
$L'_{CO(1-0)} = 4.4\ 10^{10}$ K km/s pc^2
$X_{co} = 1.8\ M_\odot$/ K km/s pc^2

Neutral Carbon:
$M(CI) = 3\ 10^7\ M_\odot$
[CI]/[H_2] = $6\ 10^{-5}$
($\sim 4\ 10^{-5}$ local starbursts)



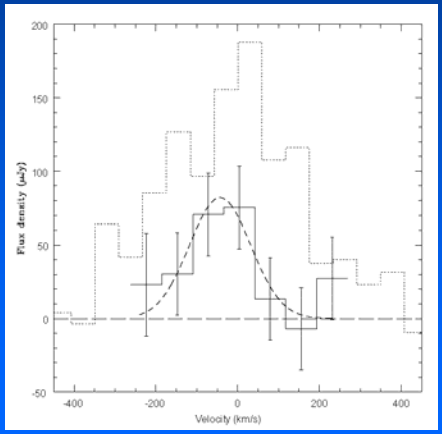
High Density Tracer: HCN

High density tracer in starbursts: n_{H2} > 10(5) cm(-3)

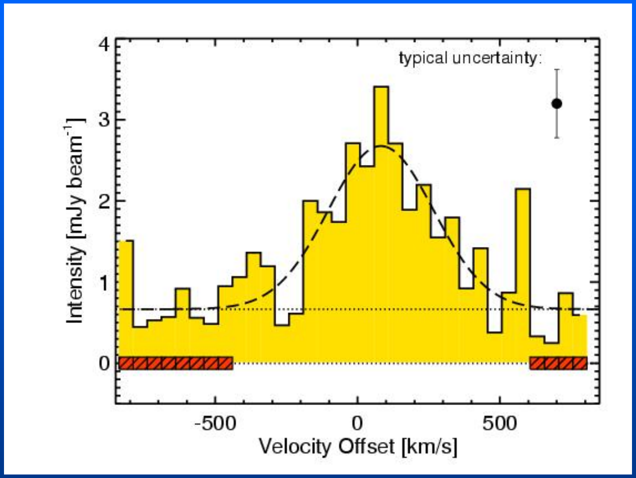


Carilli et al. 2004

J1409+5628 (z=2.56)



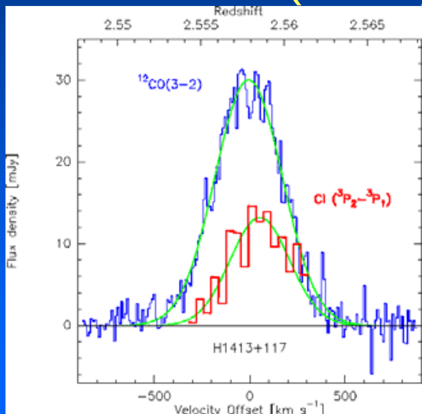
APM08279+5255 (z=3.91)

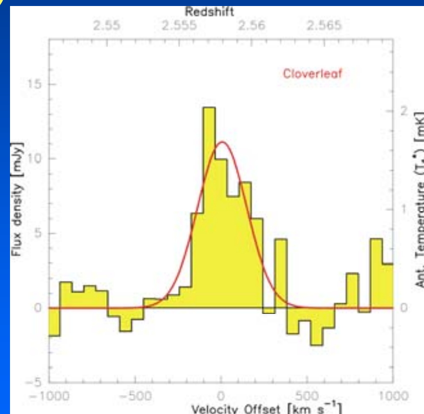


Wagg et al. 2005

Search for Neutral Carbon [CI]

Cloverleaf (z=2.3)

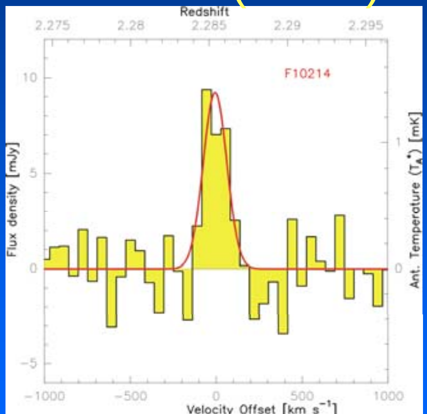




CI ($^3P_2$-$^3P_1$) PdBI

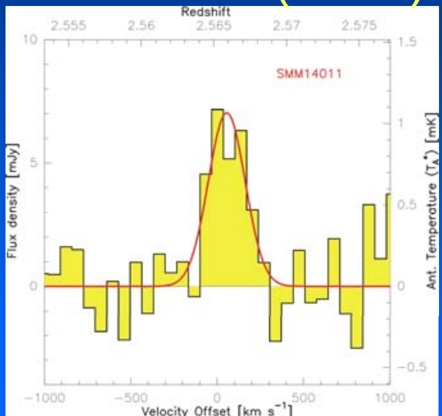
CI ($^3P_1$-$^3P_0$) 30m

F10214 (z=2.3)



CI ($^3P_1$-$^3P_0$) 30m

SMM 14011 (z=2.5)

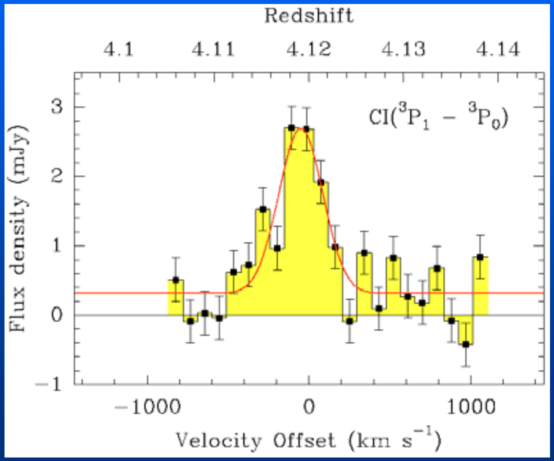


CI ($^3P_1$-$^3P_0$) 30m

2nd extra galactic CI ratio

$L'_{CI(21)}$ / $L'_{CI(10)}$ = 0.5, T_{ex} = 30 K

[CI]/H2 ~ 3 x 10(-5)



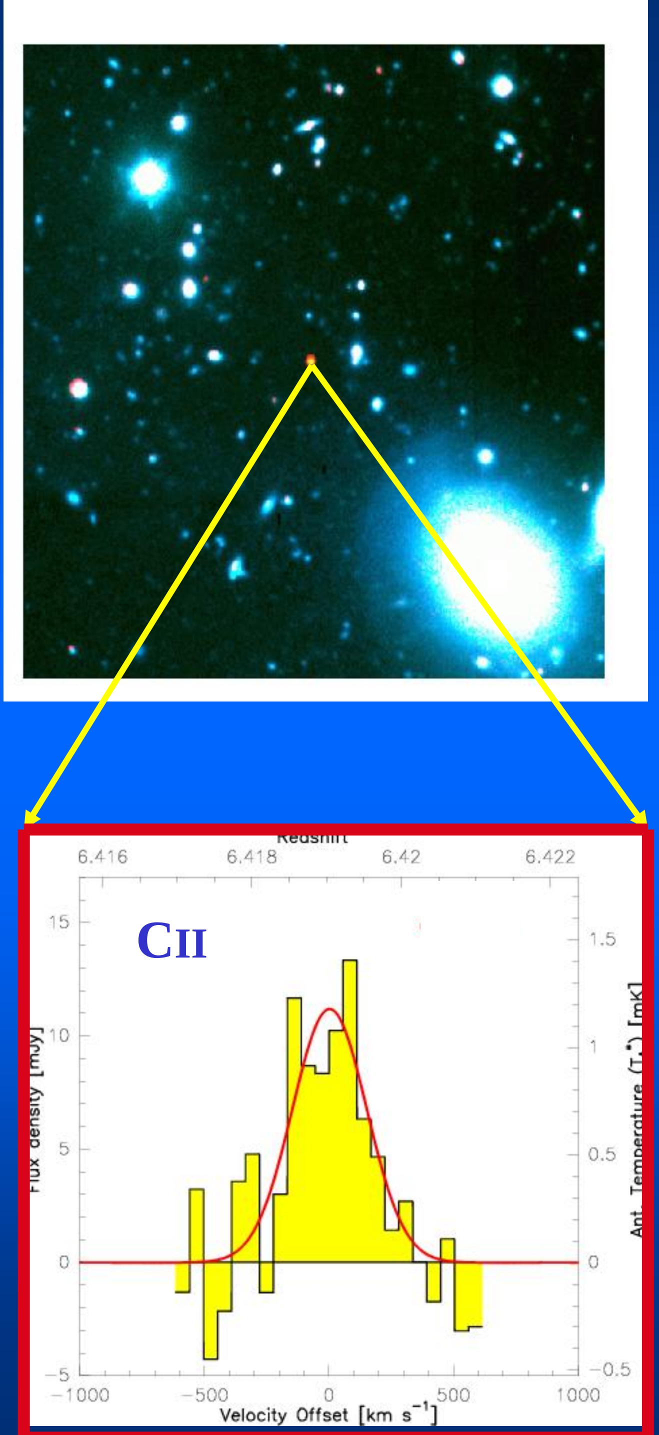
PSS2322 (z=4.12)

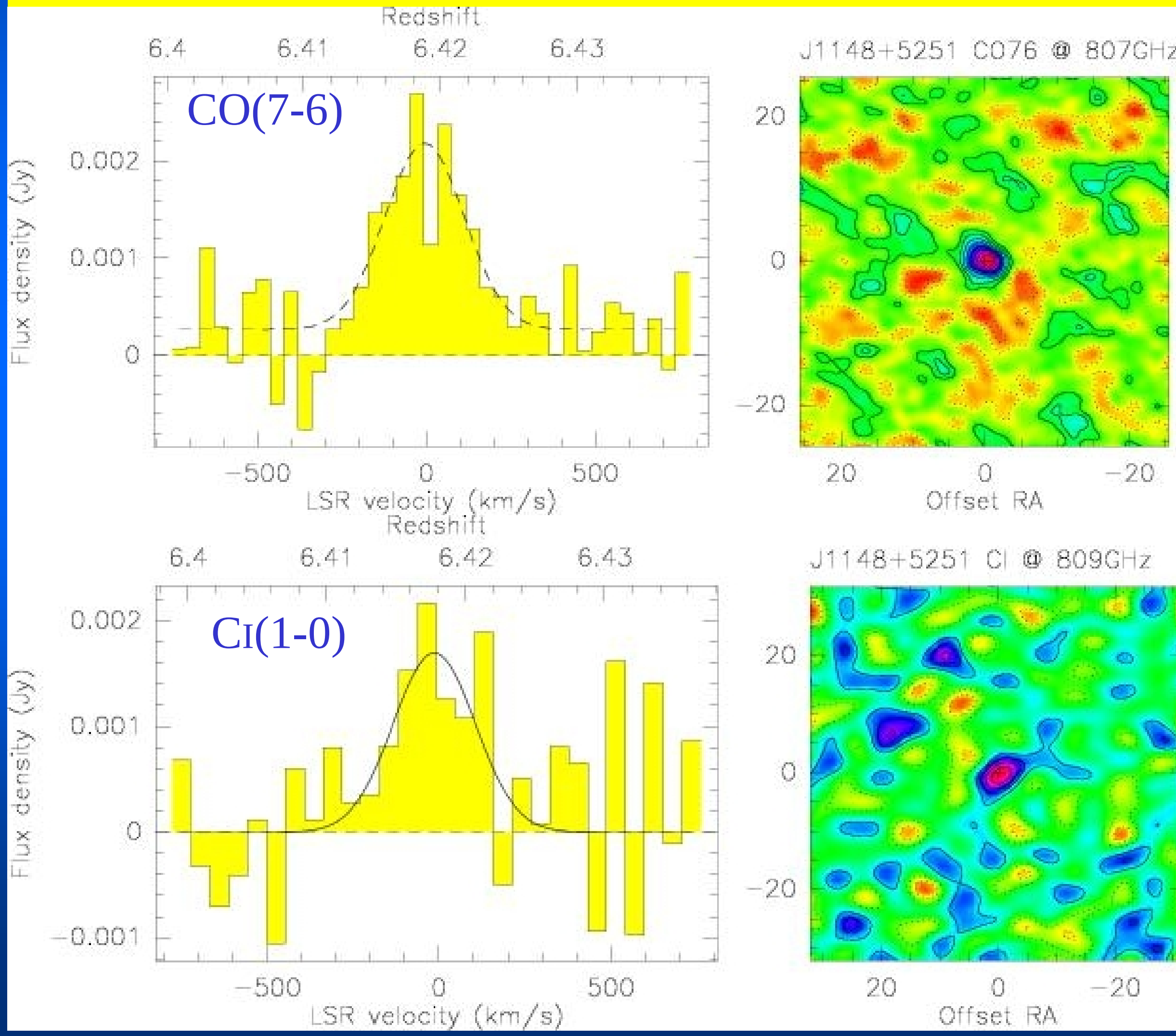
CI ($^3P_1$-$^3P_0$) PdBI

Barvainis et al. 1997;
Weiss et al. 2003, 2004;
Pety et al. 2004

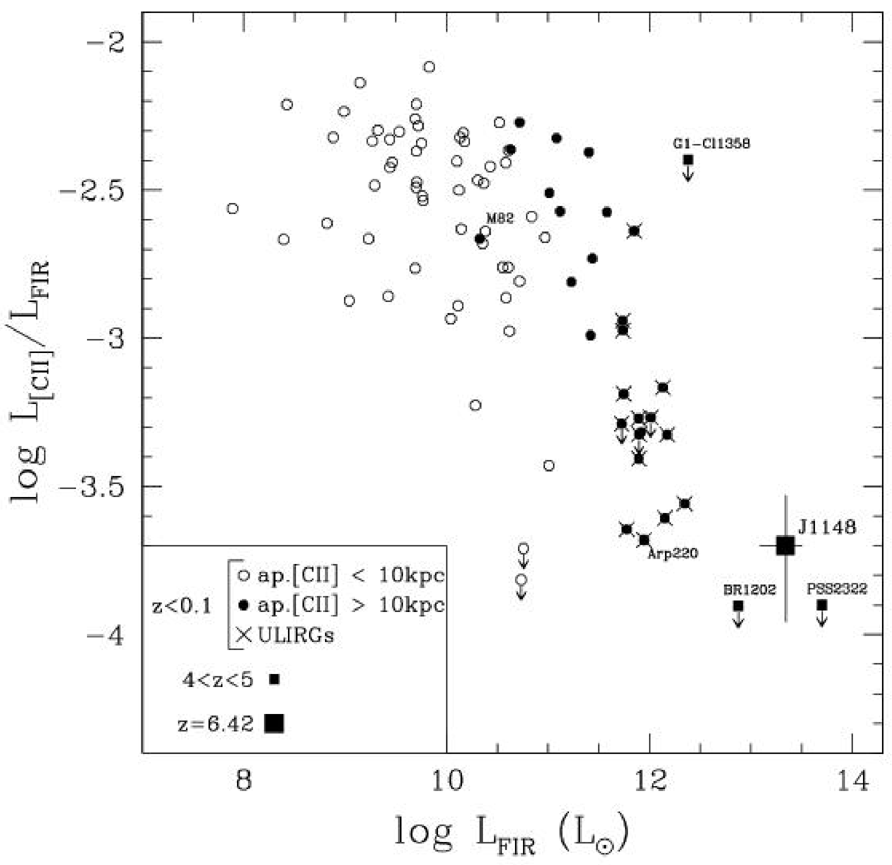
[[CII] 158 microns emission line detected in J1148+5251 at z=6.42

Probing the physics of a PDR at the end of the re-ionisation epoch





[CII] in J1148+5251



- **Done at the 30-meter**
- **Massive starburst (2000 Msun/yr)**
- **Significant metal enrichment**
- **The ratio of the [CII] line luminosity to the total far-infrared luminosity is about 0.06%, i.e. an order of magnitude smaller than has been observed locally**
- *One of the 3 key scientific goals of the ALMA project.*

Maiolino, Cox et al. (2005)

Conclusions

- **From 'imagery' to physics and (chemistry) of the ISM in the early Universe – *QSOs are prime targets***
- **CO measurements ➔ physical conditions of the dense, warm (40-100 K) gas in star-forming galaxies at high redshifts: massive** (10^{10} $M_\odot$), compact (~ 1kpc), dense (10^4 **cm**$^{-3}$) and enriched (abundances ~ solar)
- **Detection of species other than CO: HCN, [CI] and [CII]**
- **Some sources have been resolved with 1 kpc (~0.2")**
- **Studies in the very early universe (< 1 Gyr):**
  - **Metal enrichment**
  - **Dynamical masses**