# The Dust and Gas Content of Quasars and Galaxies in the Early Universe

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# Collaborators

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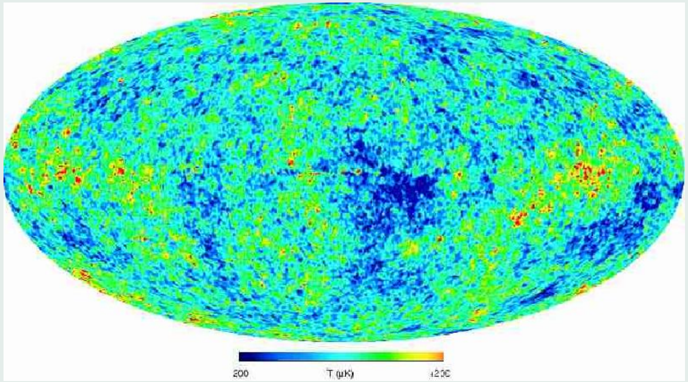
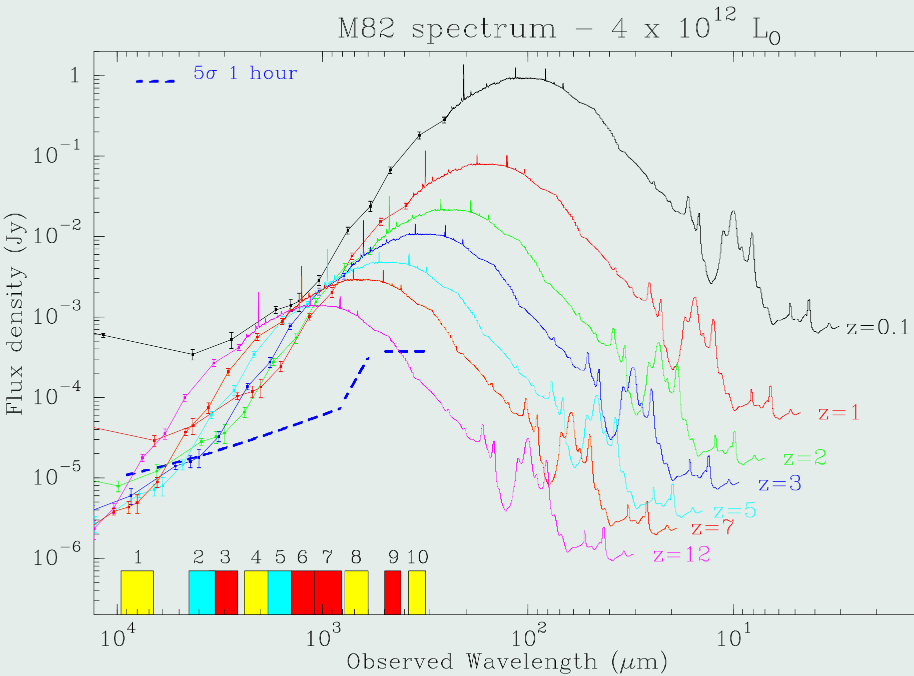
# Origins: How were galaxies formed?




- **Smooth hot Universe 300,000 years after Big Bang**
- **⇒ 12 billion years later, a highly structured Universe of galaxies, containing stars, & planets**
- When was the 'first light' in the Universe?
- How and when are the different components of galaxies (disks and spheroids) formed?
- What physics controls the formation of stars in young galaxies?
- How do galaxies exchange material with their surroundings?
- **How is the formation of a galaxy linked to the formation of the black hole at the center?**

# ULIRG Spectrum and Negative K-correction

## The submillimeter/millimeter & radio domains




- Non-thermal radio
- Thermal dust
  - Dominates luminosity
  - Hotter in AGN?
  - Mid-IR flatter 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/$H_2$
- **Magnification**

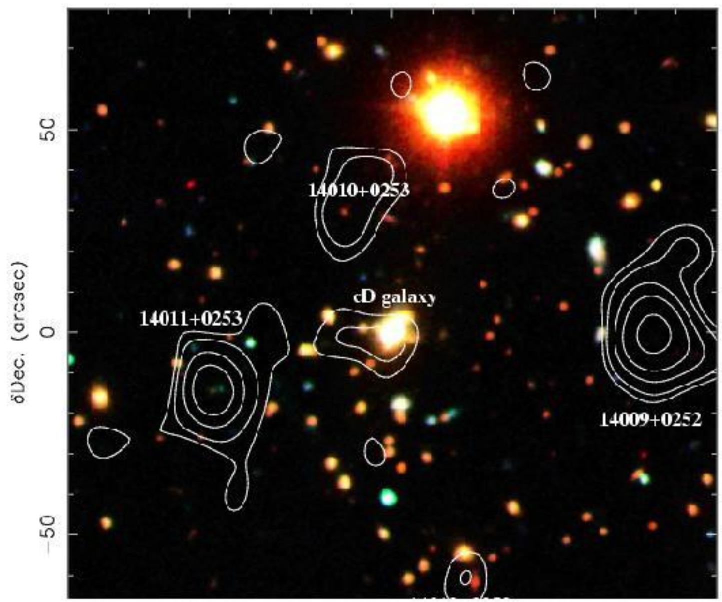
# The IRAM Instruments

# The Very Large Array

# The galaxy cluster A 1835

## Deep Fields; Optical & Submm Observations

- SCUBA image at 850 $\mu$m superimposed on an optical image (Ivison et al. 2000). **Complementary** informations on the cluster: the submm sources are weak in the optical and viceversa.
- **100-200 Deep submm field Sources known**
- **Only a few (until last year) for which redshift is measured**
- **Hence CO follow-up observations are/were difficult**

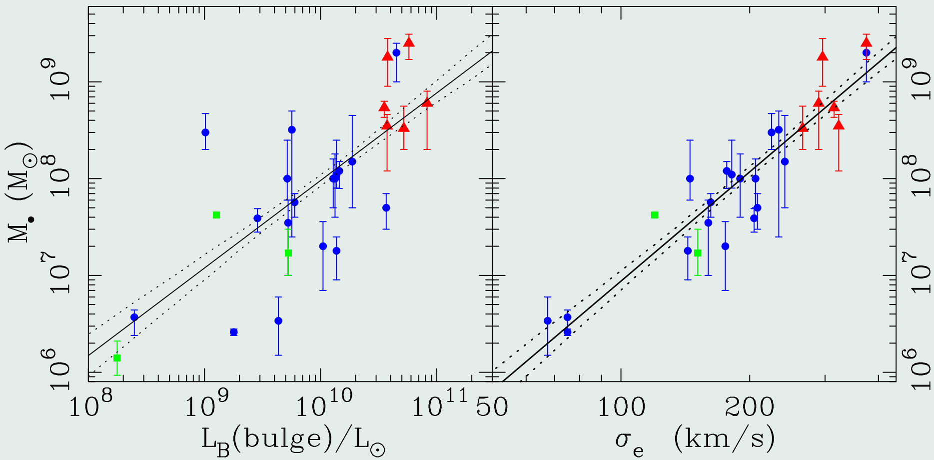


# Why study Quasars at high redshift?

- **Coeval formation of massive black holes and stars**
- Spheroidal Galaxies in Local Universe contain Massive Black Holes
  - $M_{\rm BH} \propto M_{\rm Spheroid}$
  - $M_{\rm BH} \propto \Delta(V_{\rm Spheroid})$
- QSOs contain Black Holes with $M_{\rm BH} > 10^9\, M_\odot$
  - Associated with Massive Galaxies: $M > 10^{11}\, M_\odot$
- Strong metal emission lines and dust: Rapid Enrichment

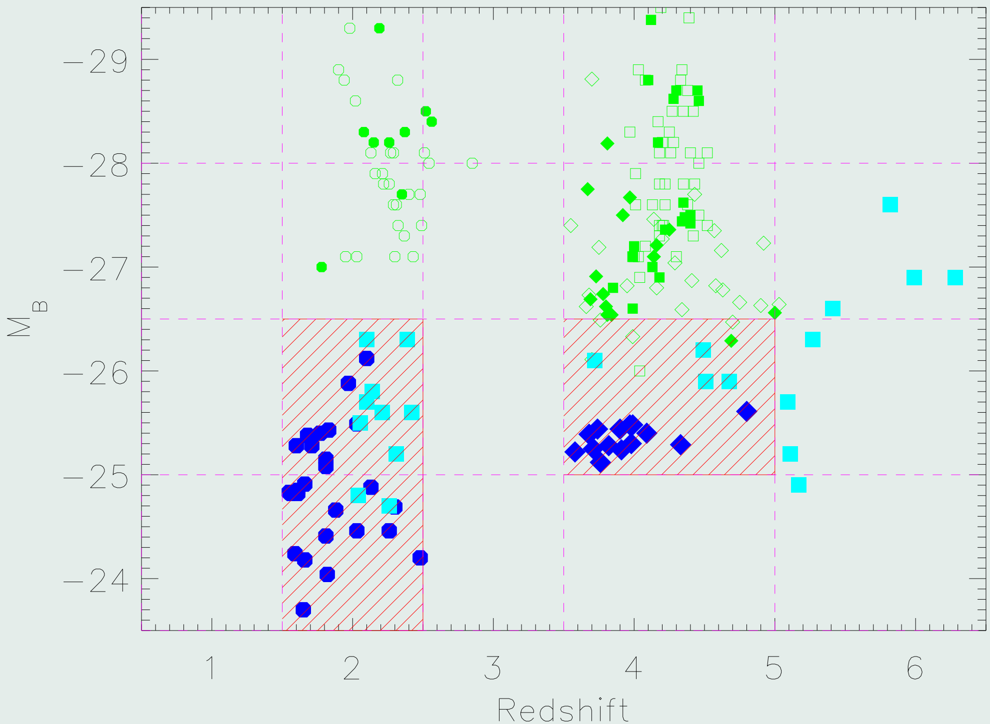
# Relationship between $M_{BH}$ and $\sigma_e$

- $M_{BH} = 1.2 \pm 02 \times 10^8\,\mathrm{M}_\odot(\sigma_\mathrm{e}/200\mathrm{km\,s}^{-1})^{3.75\pm0.3}$
- Small scatter in $M_{BH}$ at fixed $\sigma_e$
- Implies that the central black hole masses is closely related to properties of the host galaxy's bulge
- **Consistent with the idea that the growth of supermassive black holes and massive bulges occured simultaneously**



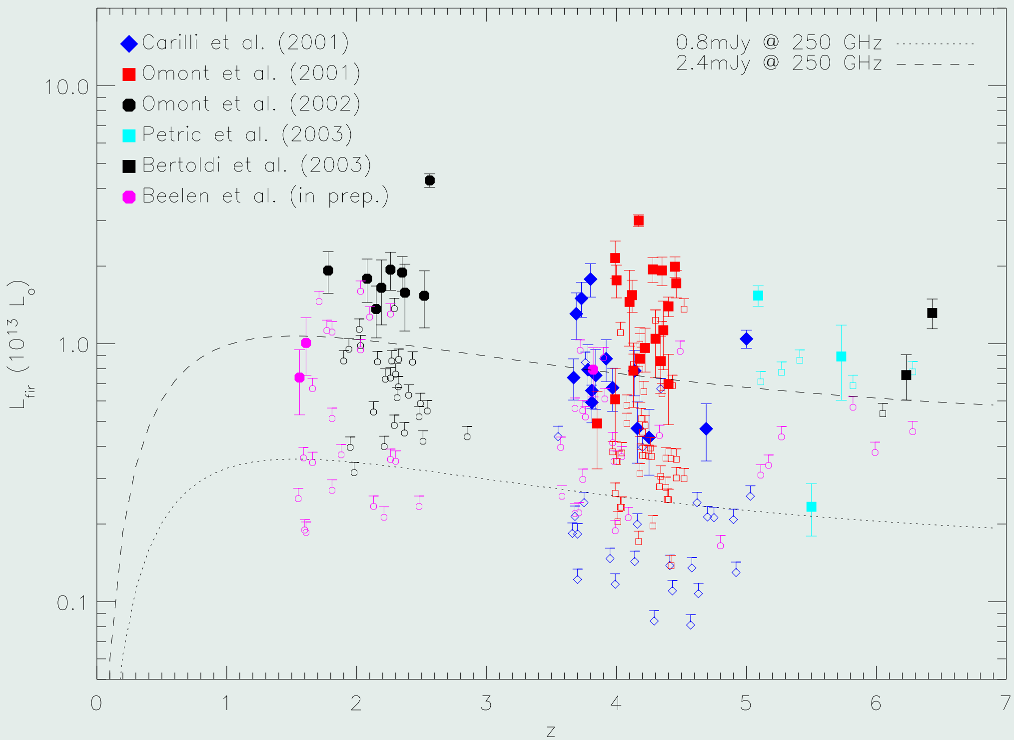

Gebhardt et al. (2000); Shields et al. (2003)

# Sample of high-$z$ Quasars observed at 1.25 mm



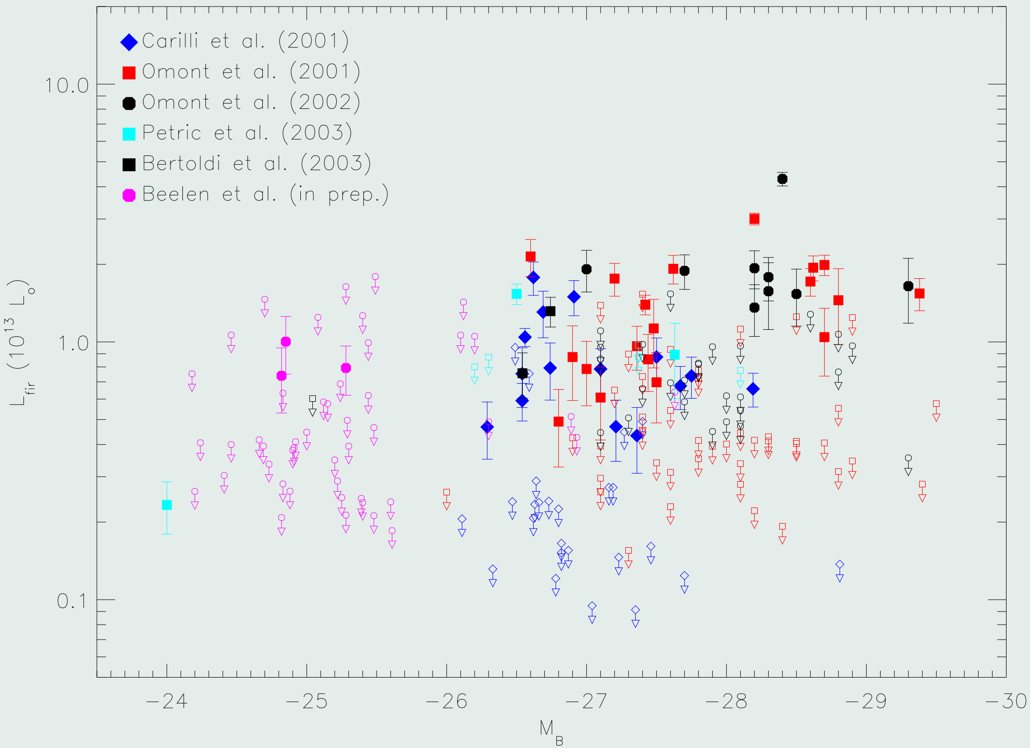

**$\approx 200$ optically selected, luminous, radio-quiet QSOs (from SDSS, PSS, PG) at $1 < z < 6.4$ to study dust (1.25 mm) and molecular gas**

# Infrared Luminosity of High-$z$ Quasars




**30% Detection Rate at $z > 1.8$**

# Optical & Infrared Luminosities of Quasars

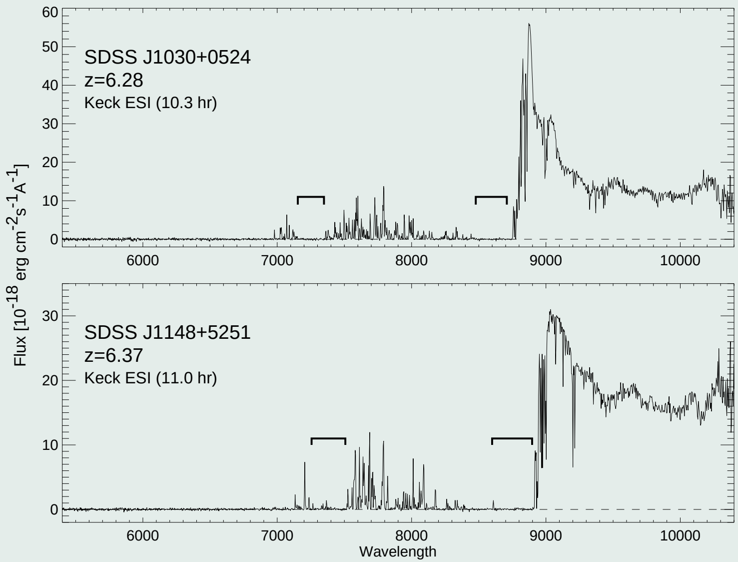


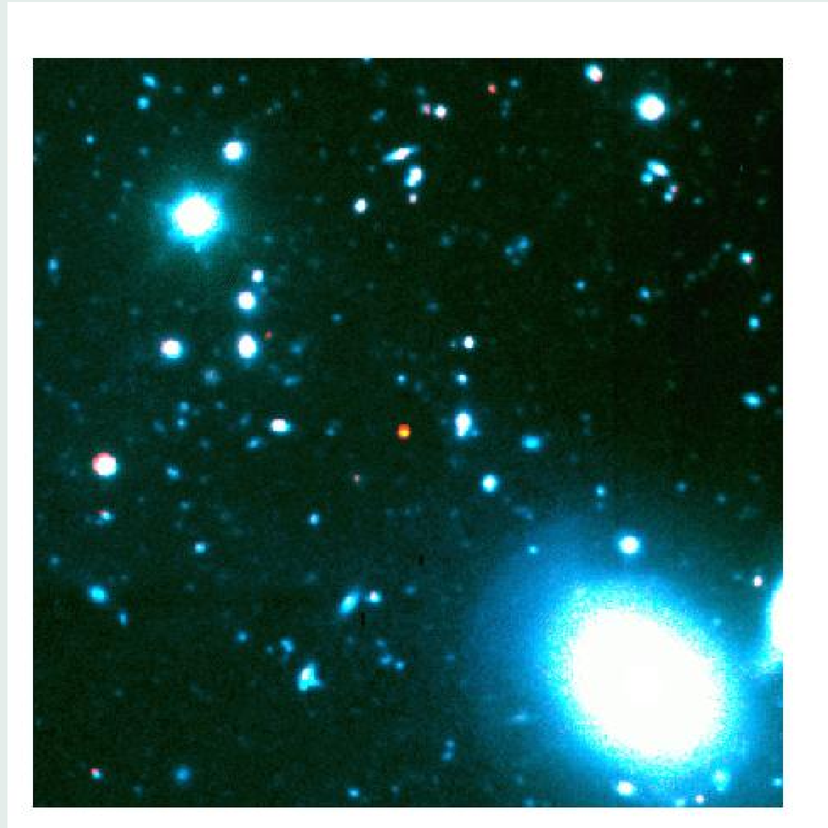

**Weak correlation of $L_{FIR}$ vs $M_B$?**

$M_B > -26 \Rightarrow$ 10% detected; $M_B < -26 \Rightarrow$ 30% detected

Omont et al. (2003) A&A 398, 857; Beelen et al. (2004)

# $z > 6$ Quasars: Probing the End of Reionisation

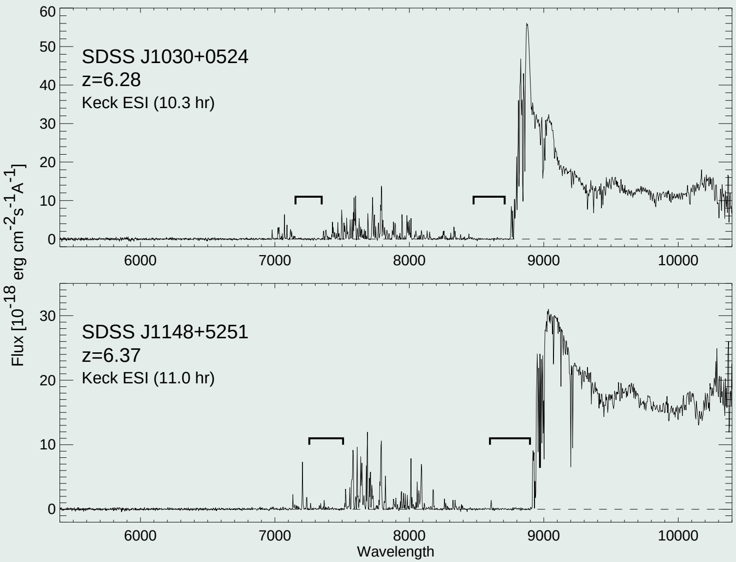


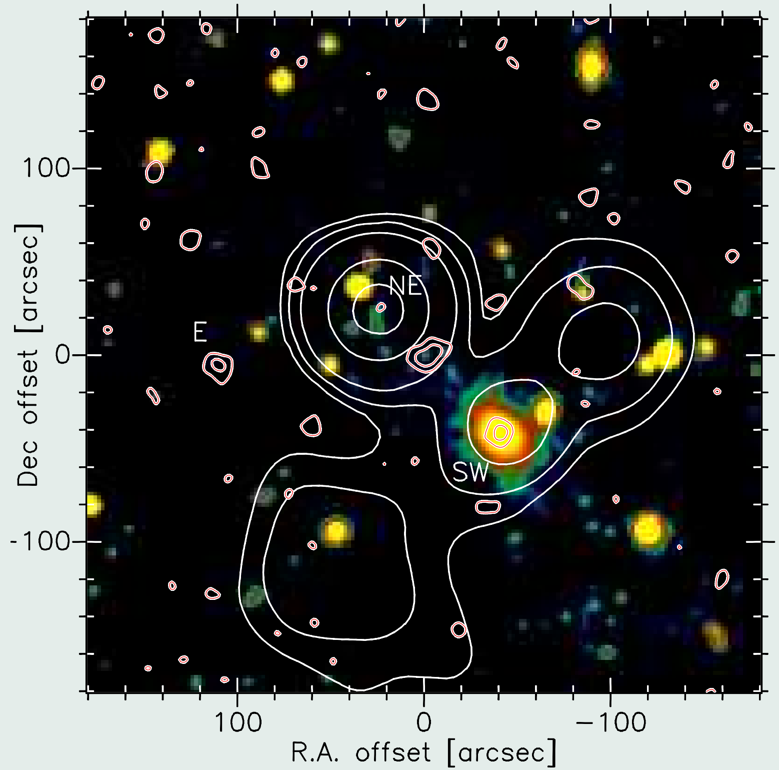



**J1148+5251: most distant QSO known**

Fan et al. (2003); White et al. (2003); Djorgovski et al. (2003)

# Dust in $z > 6$ Quasars

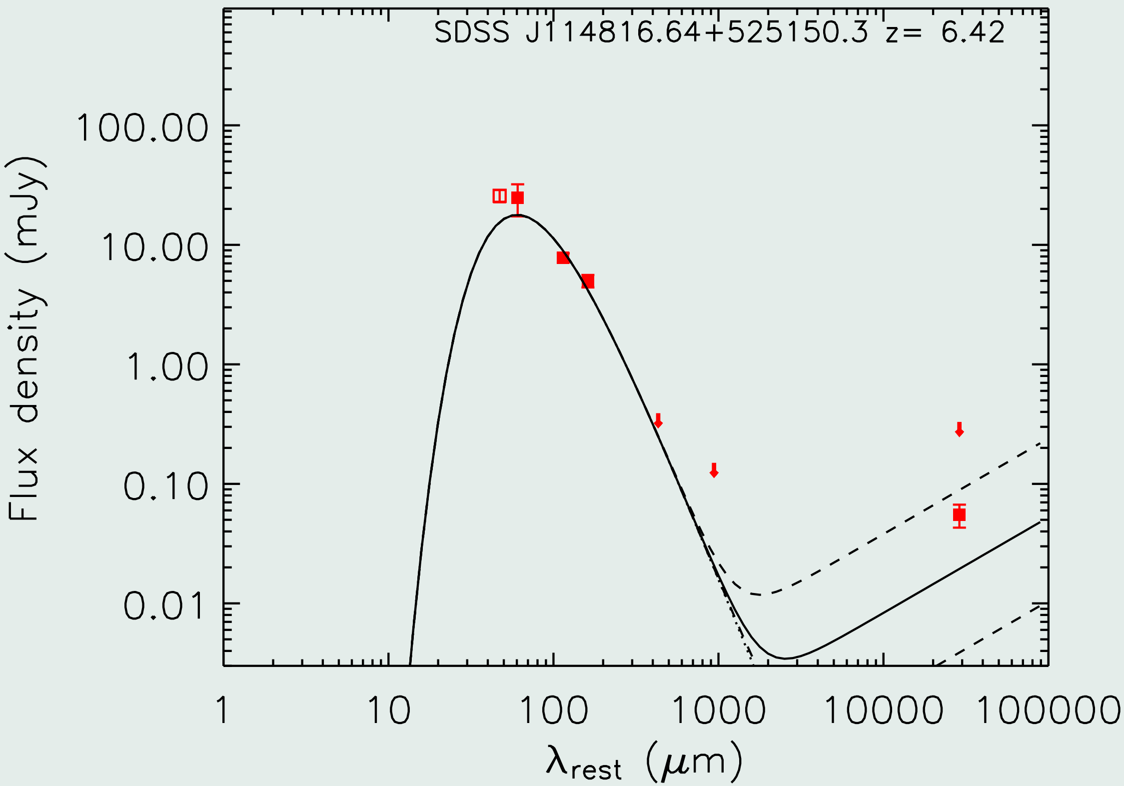



**J1148+5251: MAMBO 1.2 mm map**

Fan et al. (2003); White et al. (2003); Bertoldi, Carilli, Cox al. (2003)

# Spectrum J1148+5251 at $z = 6.42$




Beelen, Benford, Cox et al. (2004)

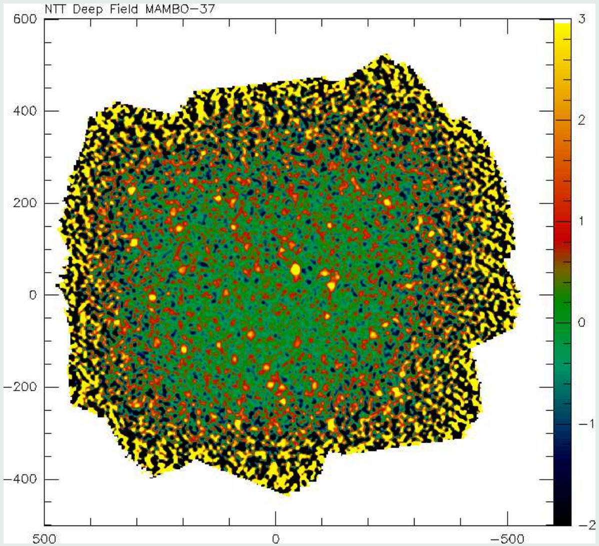
# Properties of the $z = 6.42$ QSO J1148+5251

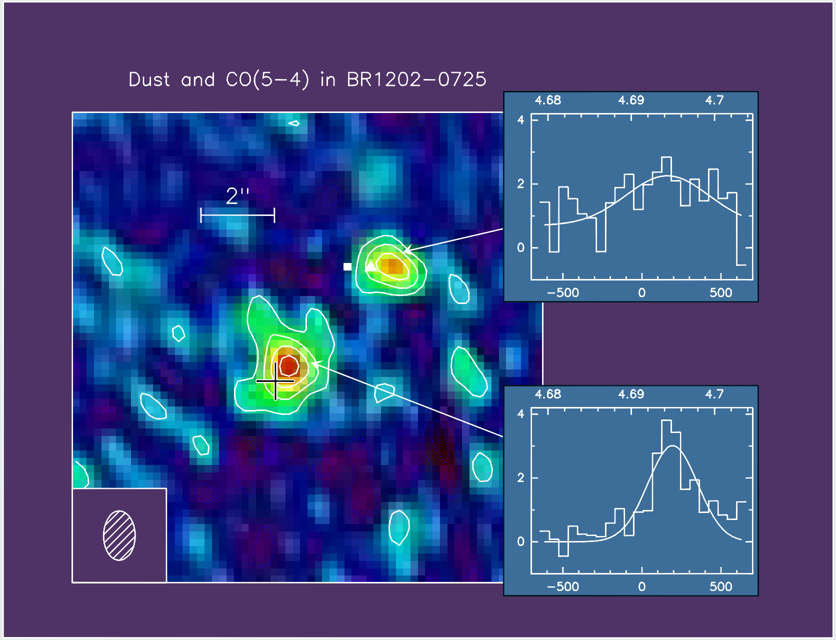
- Distance
  - $z = 6.42$ – most distant QSO known, $\approx 850$ million years after Big Bang
- Optical Properties (Black Hole) – Fan et al. (2003); Willott et al. (2003)
  - $M_{1450} = -27.8$, $L_{bol} \sim 10^{14}\,L_\odot$
  - $M_{BH} \approx 3 \times 10^9\,M_\odot \quad \Rightarrow \quad M_{bulge} \approx 10^{13}\,M_\odot$
- Millimeter (Bertoldi et al. 2003) & Radio Measurements (Carilli et al. 2003)
  - $S_{250} = 5.0 \pm 0.6\,\mathrm{mJy}$
  - $S_{1.4} = 55 \pm 12\,\mu\mathrm{Jy} \quad \Rightarrow$ Radio/FIR relation
- Derived Properties
  - $L_{\rm FIR} = 1.2 \times 10^{13}\,L_\odot$ (for $T_{\rm dust} = 45K$ and $\beta = 1.5$)
  - $\mathbf{M_{\rm dust} = 7 \times 10^8\,M_\odot}$ (adopting $\kappa_{230} = 7.5\,\mathrm{cm^2\,g^{-1}}$)
  - $\dot{M}_{\rm SF} \approx 2000\,M_\odot\,\mathrm{yr}^{-1} \Rightarrow$ **Large Reservoirs of molecular gas are needed!**

# Some Constraints on the Dust Formation

- Time available to form dust at $z = 6.42$
  - If epoch of early reionization is at $z \approx 17$ (*WMAP* results), $z = 6.42$ corresponds to $\Delta t \approx 0.7\,\mathrm{Gyr}$. At a constant formation rate, this implies a *net* dust production rate of $\approx 1 M_\odot\,\mathrm{yr}^{-1}$
- Stellar Dust Factories
  - $\Delta t \approx 0.7\,\mathrm{Gyr}$ is too short to produce refractory grains in winds of low-mass ($\leq 8\,M_\odot$) stars. If product of stellar processes, dust condensation in type II SNRs, and perhaps in winds of high-mass ($\geq 40\,M_\odot$) which are thought to have dominated the early phase of star formation (e.g., Bromm & Loeb 2003).
- Consequences on the dust properties
  - If above is true, dust composition must then be composed of silicates and perhaps oxides If production in the winds of high-mass stars is important, carbon dust might have been formed as well
  - Consequences on the dust properties (mass absorption coefficient): extinction curve, mass absorption coefficient etc...

# Dust & CO in BR 1202–0725 at z = 4.7




Bertoldi et al. (2002); Omont et al. (1996)

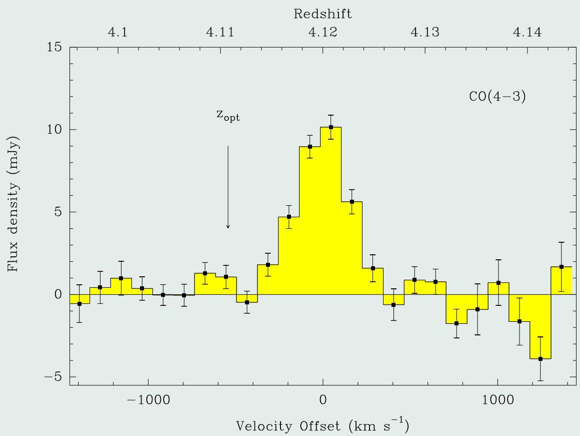
# High $z$ Sources detected in CO - May 2004

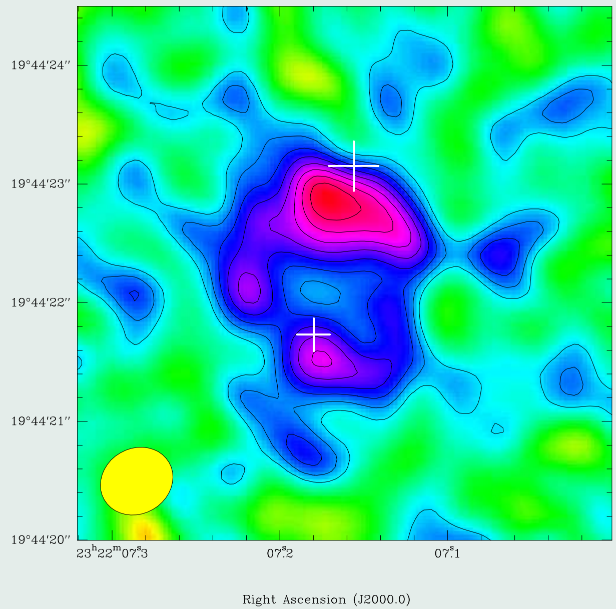
| Source Name | $z$ | Telescopes | CO Line | | 1.2 mm Cont. | Ref. |
|---|---|---|---|---|---|---|
| | | | line | [Jy km $s^{-1}$] | [mJy] | |
| IRAS 10214+4724 | 2.28 | 12-m; 30-m | 3→2 | 4.1±0.9 | 9.6±1.4 | [1,2] |
| Cloverleaf | 2.56 | PdB; 30-m | 3→2 | 9.9±0.6 | 18±2 | [3] |
| BR 1202−0725 | 4.69 | 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 | $40\pm2^{\dagger}$ | [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; 30-m | 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 | $\approx 3$ | [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] |

References – [1] Brown & van den Bout (1992); [2] Solomon et al. (1992); [3] Barvainis et al. (1994); [4] Omont et al. (1996a); [5] Ohta et al. (1996); [6] Guilloteau et al. (1997); [7] Scoville et al. (1997); [8] Alloin et al. (2000); [9] Barvainis et al. (1998); [10] Frayer et al. 1998); [11] Genzel et al. (2002); [12] Downes et al. (1999); [13] Guilloteau et al. (1999); [14] Frayer et al. (1999); [15] Papadopoulos et al. (2000); Andreani et al. (2000); [17] Barvainis, Alloin & Bremer (2002); [18] Cox et al. (2002); [19] de Breuck et al (2003a); [20] de Breuck et al. (2003b); [21] Beelen et al. (2003); [22] Walter et al. (2003); [23] Bertoldi et al. (2003a, b); [24] Neri et al. (2003); [25] Baker et al. (2003).

Sources in blue are known to be lensed $^{\dagger}$ Non-thermal emission

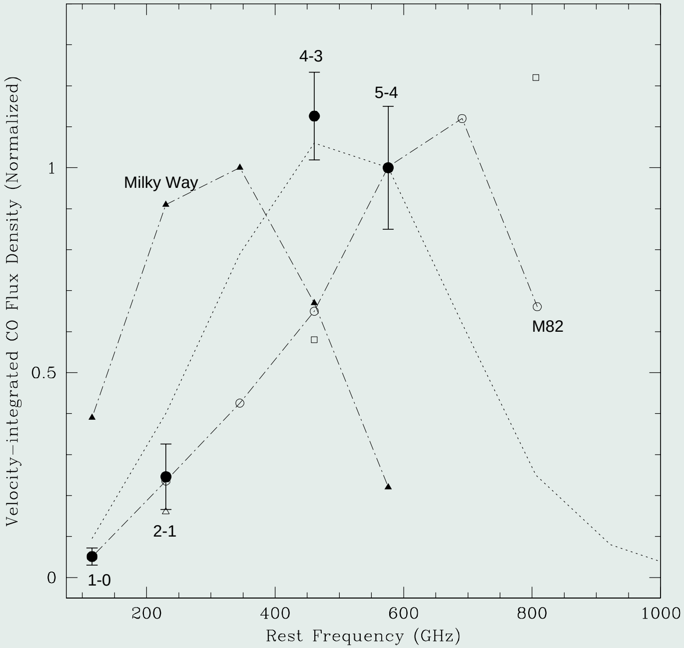
# Disk of Star Formation in PSS2322+1944 at $z = 4.12$




Cox et al. (2002); Carilli et al. (2003)

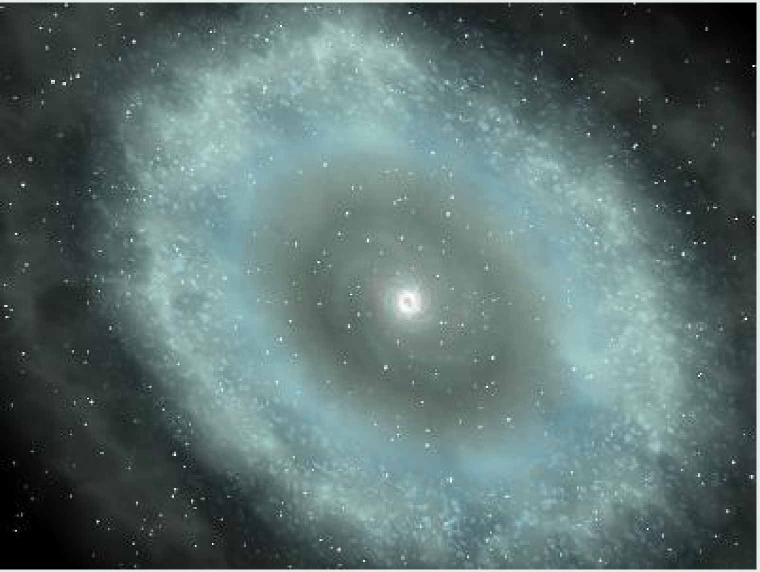
# CO Excitation in PSS2322+1944




- CO excitation in PSS 2322+1944 (filled circles), compared to
  - BRI 1202–0725 at $z = 4.7$ (filled squares)
  - BRI 1335–0417 at $z = 4.4$ (open squares)
  - Milky Way from *COBE* (solid triangles)
  - Starburst M 82 (open circles)
- LVG model for PSS 2322+1944
  - $\mathbf{T_{kin} = 47K}$
  - $\mathbf{n(H_2) = 5 \times 10^3\ cm^{-3}}$

Carilli, Cox et al. (2002)

# Properties of PSS2322+1944

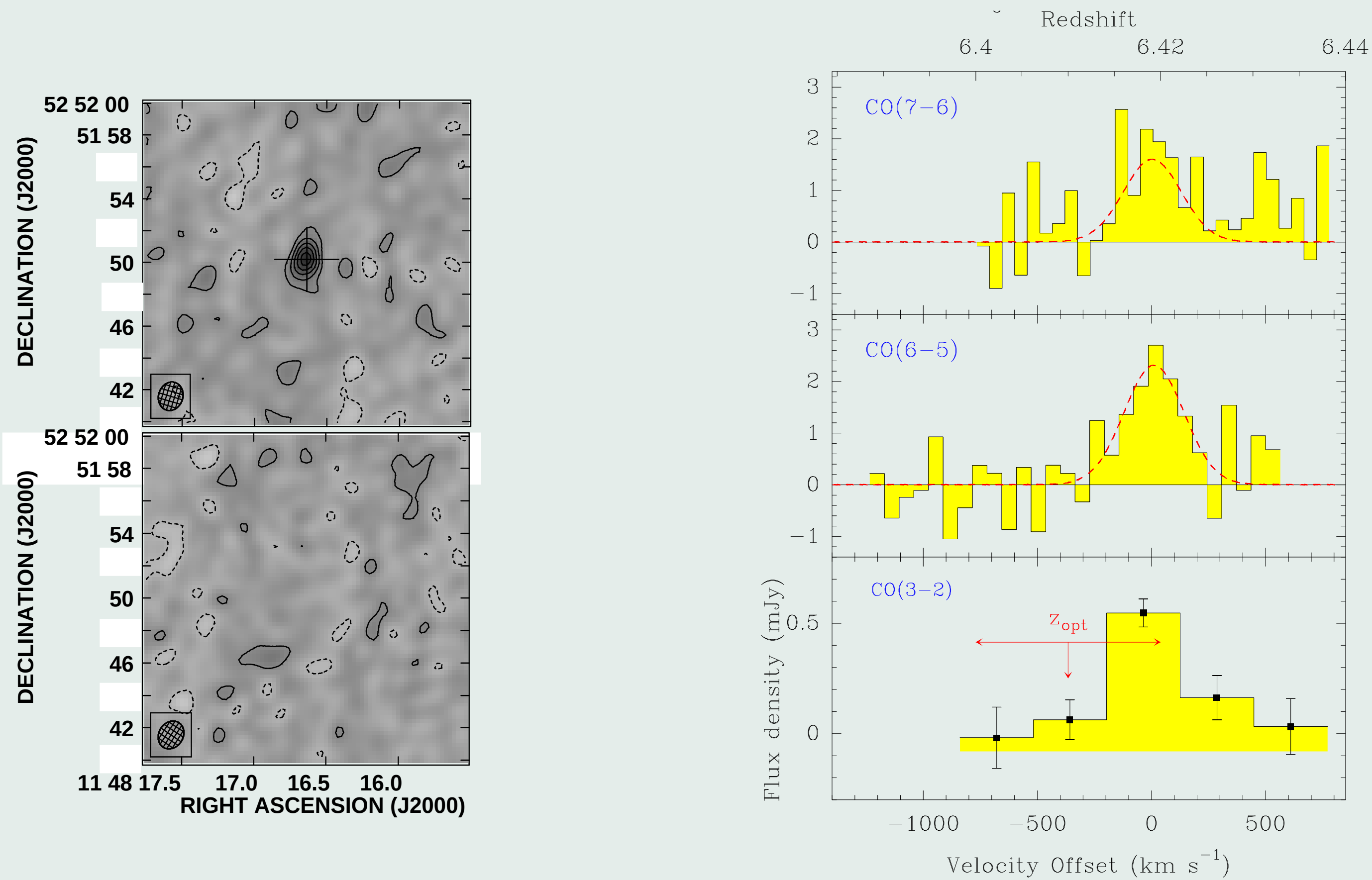


- 2 kpc Radius inclined disk with $115\,\mathrm{km\,s^{-1}\,kpc^{-1}}$
- Mass is $\sim 3 \times 10^{10}\,\sin^{-2} i\, M_{\odot}$
- Lensing Galaxy at $z \approx 1$
- AGN between inner and outer caustic

Carilli et al. (2003)

# Molecular Gas in J1148+5251 ($z = 6.42$)

13




**Walter et al. (2003) Nature 424, 406; Bertoldi et al. (2003) A&A 409, L47**

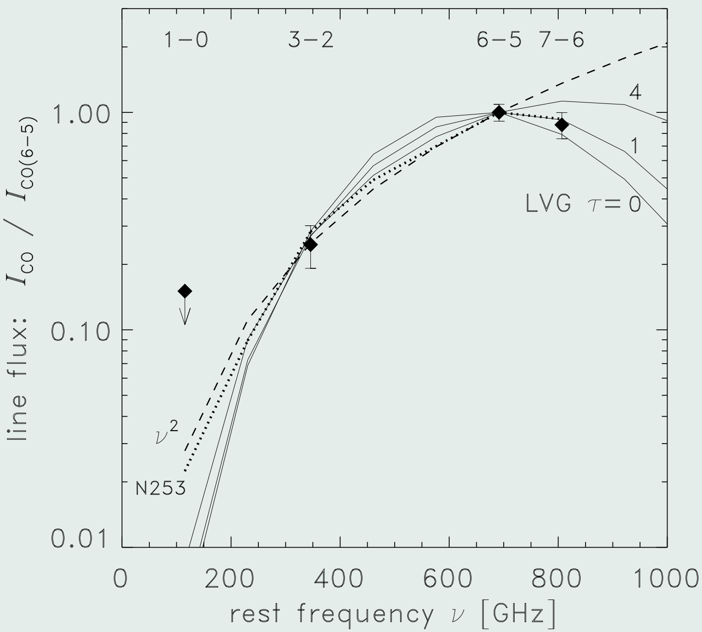
# Properties of the CO lines in J1148+5251

| Line | $\nu_{\rm rest}$ [GHz] | $\nu_{\rm obs}$ [GHz] | $z_{\rm CO}$ | peak int. [mJy] | $\Delta v_{\rm FWHM}$ [$\rm km\,s^{-1}$] | $I_{\rm CO}$ [Jy km s$^{-1}$] | $L'_{\rm CO}$ [$10^{10}$ K km s$^{-1}$ pc$^2$] | $L_{\rm CO}$ [$10^8\,L_\odot$] |
|---|---|---|---|---|---|---|---|---|
| CO (7→6) | 806.651 | 108.729 | 6.4192±0.0009 | 2.14 | 258±69 | 0.64±0.09 | $1.73 \pm 0.24$ | $2.92 \pm 0.40$ |
| CO (6→5) | 691.473 | 93.204 | 6.4187±0.0006 | 2.45 | 262±63 | 0.73±0.07 | $2.69 \pm 0.24$ | $2.86 \pm 0.25$ |
| CO (3→2)$^\dagger$ | 345.795 | 46.610 | 6.419±0.004 | 0.6 | 320$^\dagger$ | 0.18±0.04 | $2.68 \pm 0.27$ | $0.35 \pm 0.04$ |
| CO (1→0) | 115.271 | 15.537 | – | $< 0.36$ | – | $< 0.11^\ddagger$ | $< 14.2^\ddagger$ | $< 0.07^\ddagger$ |

NOTE. – For J1148+5251, the apparent CO line luminosity (see Solomon et al. 1997) is given by $L'_{\rm CO} = 3.2 \times 10^4 I_{\rm CO} \nu_{\rm obs}^{-2}$, the intrinsic line luminosity $L_{\rm CO} = 4.2 \times 10^6 I_{\rm CO} \nu_{\rm obs}$, in the units given above. All upper limits correspond to $3\sigma$. $^\dagger$ From Walter et al. (2003) – the line width corresponds to the 50 MHz channel width of the VLA 46.6 GHz observations; $^\ddagger$ $3\sigma$ upper limit, adopting a line width of $260\,\rm km\,s^{-1}$.

Bertoldi et al. (2003)

# CO Excitation in J1148+5251

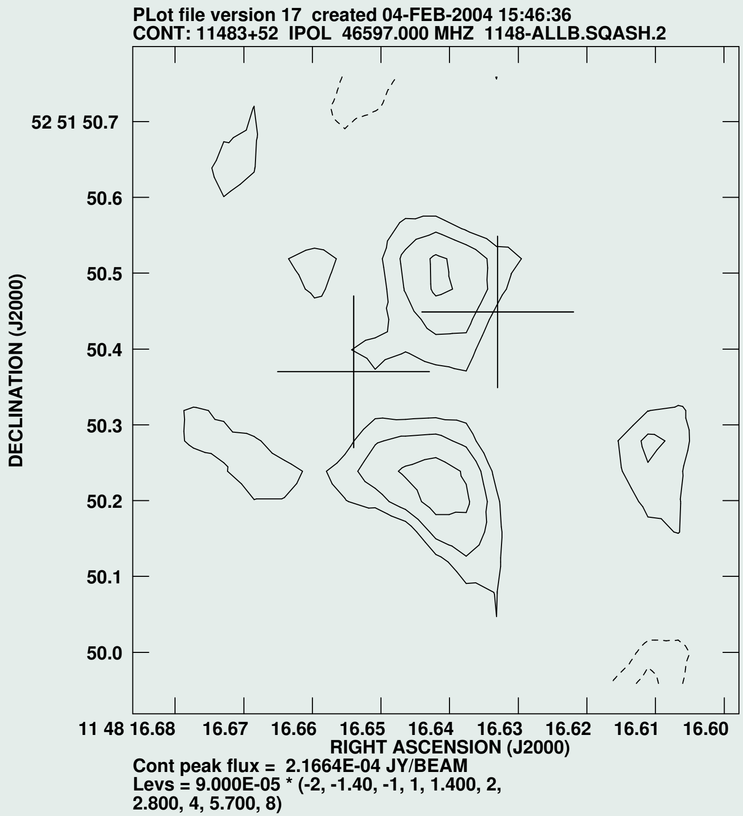



- CO excitation in J1148+5251 (filled circles), compared to NGC 253 (dashed)
- LVG model for J1148+5251 (with different $\tau_{CO}$)
  - $\mathbf{T_{kin} = 100\ K}$
  - $\mathbf{n(H_2) = 7 \times 10^4\ cm^{-3}}$
- $M_{H_2} \approx 2 \times 10^{10}\, M_\odot$
- $M_{dyn} \approx 3 \times 10^9 \sin^{-2}(i)\, M_\odot$
- $M_{BH} \approx (1 - 5) \times 10^9\, \mathrm{M}_\odot$
- $M_{Bulge} \approx (0.5{-}2.5) \times 10^{12}\, \mathrm{M}_\odot$

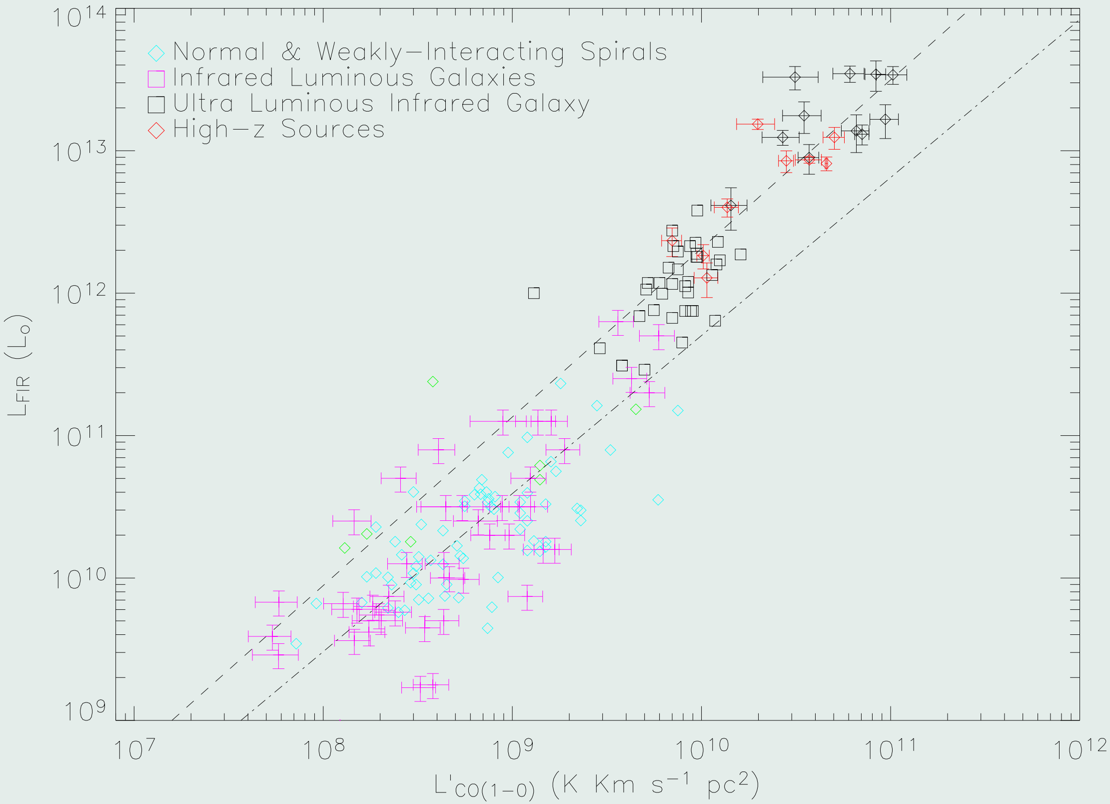
Bertoldi et al. (2003); Walter et al. (2003)

# Molecular Gas in J1148+5251: RESOLVED

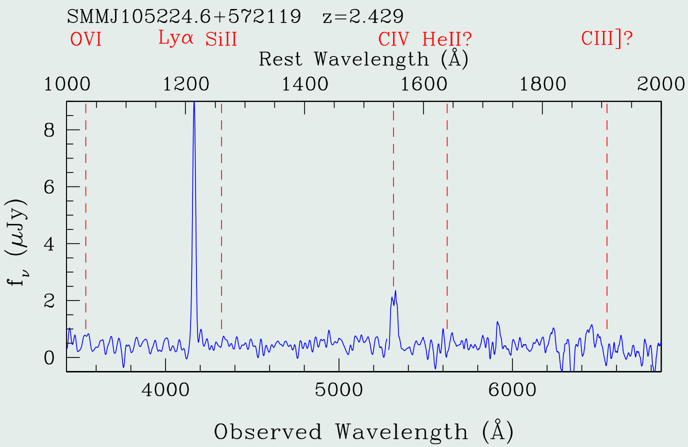
- **CO(3–2)** emission as seen at $0.15''$ resolution seen with the VLA. Two sources separated by $0.3''$ or 1.8 kpc at $z = 6.4$
- Crosses show QSO position using SDSS and Keck astrometry
- Consistent within $0.1''$
- QSO associated with northern source: Merger?
- QSO between two CO sources
- Similar to BR1202?

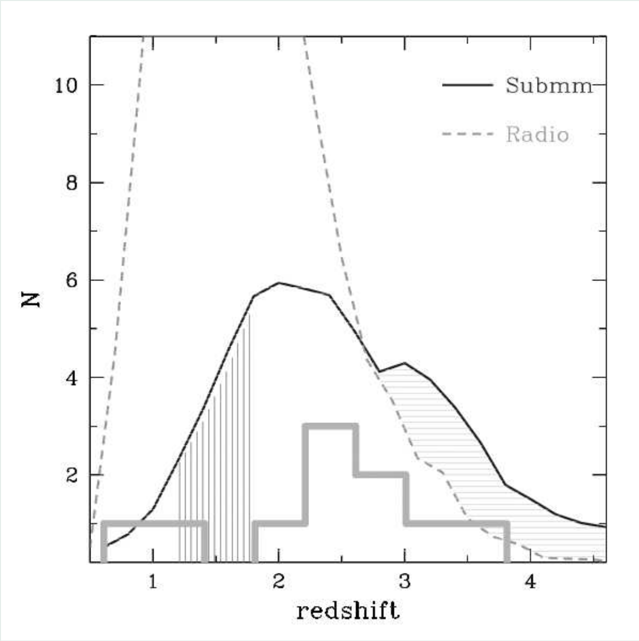


# Relation between $L_{FIR}$ and $L'_{CO(1\rightarrow0)}$: SFE

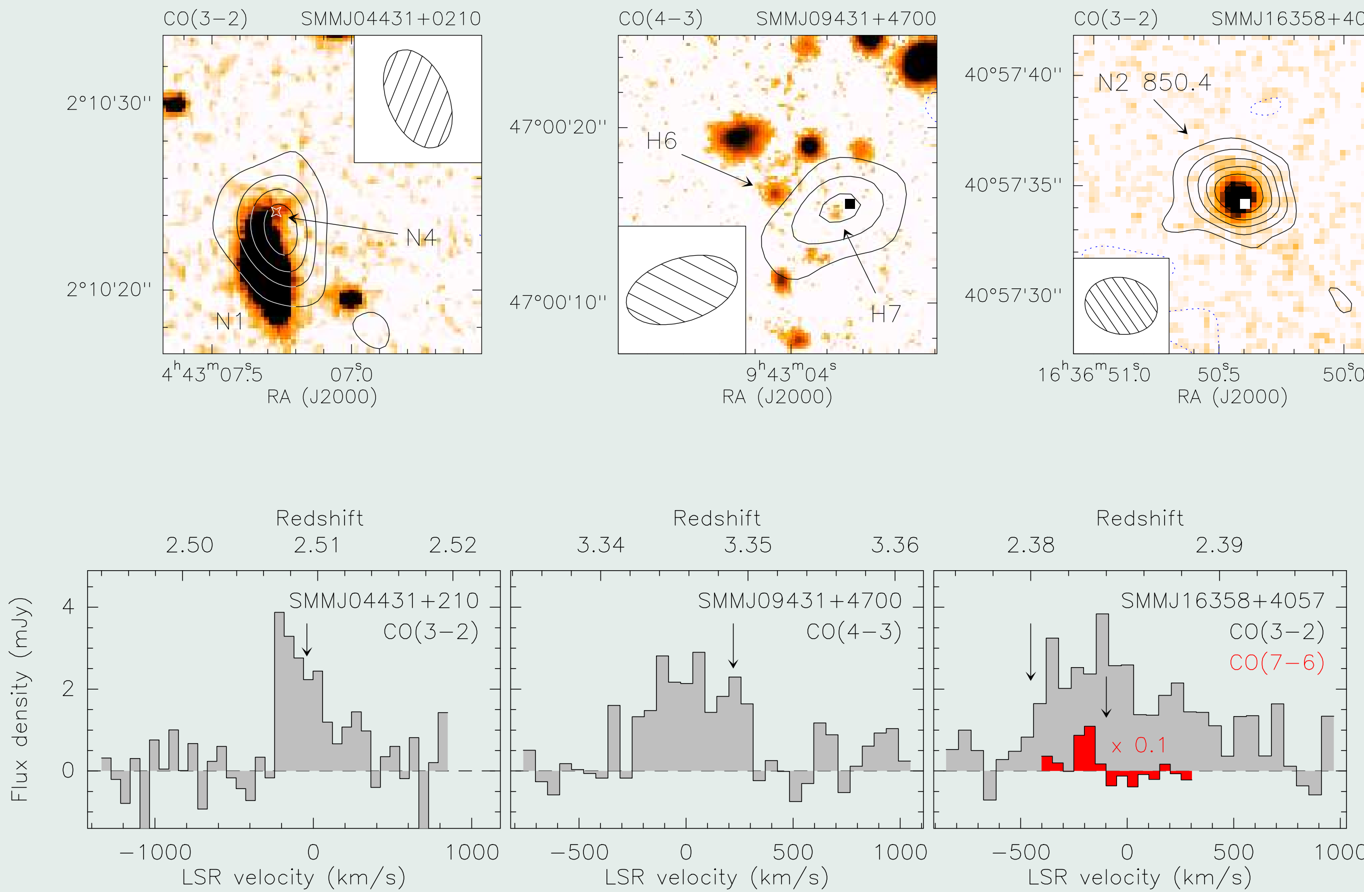


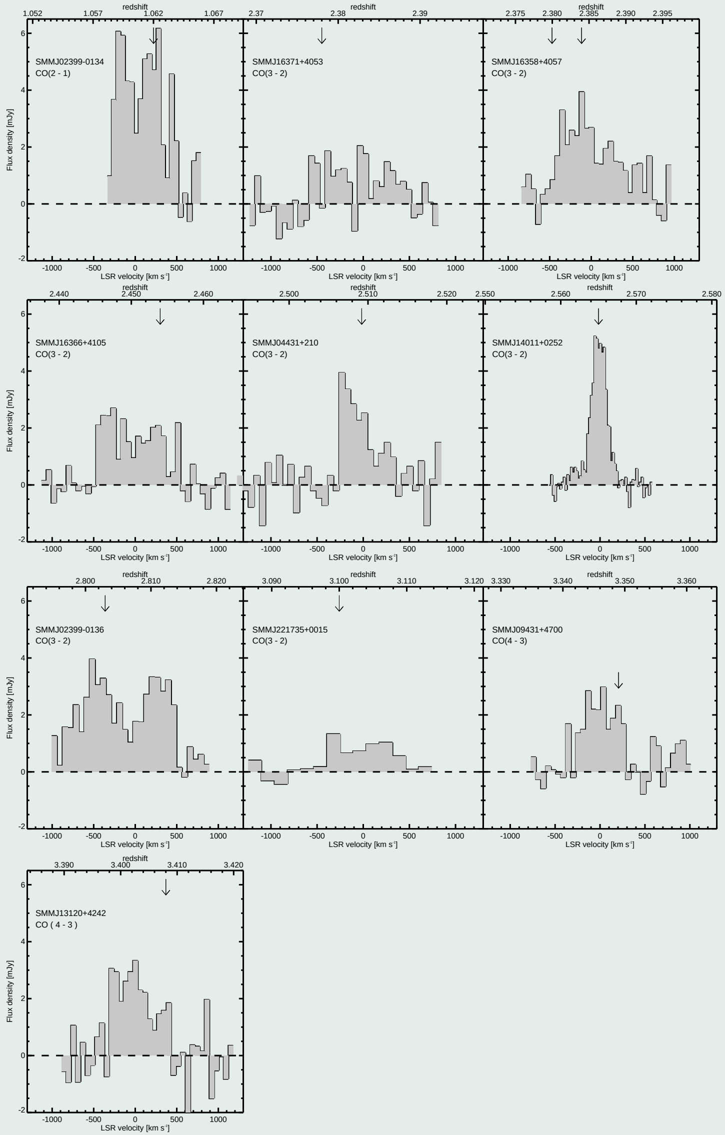
# Uncovering the $z$ distribution of Submm Galaxies




Chapman et al. (2003)


CO(3−2)
SMMJ04431+0210
2°10'30''
2°10'20''
N4
N1
4h43m07.5s
07.0s
RA (J2000)
CO(4−3)
SMMJ09431+4700
47°00'20''
47°00'10''
H6
H7
9h43m04s
RA (J2000)
CO(3−2)
SMMJ16358+4057
40°57'40''
40°57'35''
40°57'30''
N2 850.4
16h36m51.0s
50.5s
50.0s
RA (J2000)
Redshift
2.50
2.51
2.52
Redshift
3.34
3.35
3.36
Redshift
2.38
2.39
Flux density (mJy)
SMMJ04431+210
CO(3−2)
SMMJ09431+4700
CO(4−3)
SMMJ16358+4057
CO(3−2)
CO(7−6)
x 0.1
−1000
0
1000
−500
0
500
1000
−500
0
500
1000
LSR velocity (km/s)
LSR velocity (km/s)
LSR velocity (km/s)


SMMJ02399-0134
CO(2 - 1)
SMMJ16371+4053
CO(3 - 2)
SMMJ16358+4057
CO(3 - 2)
SMMJ16366+4105
CO(3 - 2)
SMMJ04431+210
CO(3 - 2)
SMMJ14011+0252
CO(3 - 2)
SMMJ02399-0136
CO(3 - 2)
SMMJ221735+0015
CO(3 - 2)
SMMJ09431+4700
CO(4 - 3)
SMMJ13120+4242
CO ( 4 - 3 )
redshift
Flux density [mJy]
LSR velocity [km s⁻¹]

# Properties of the Submm Galaxies

| Name | Line | $z$ | $I_{\rm CO}$ [Jy km s$^{-1}$] | $\Delta v_{FWHM}$ [km s$^{-1}$] | $M_{\rm H_2}$ [$10^{10}\,M_\odot$] |
|---|---|---|---|---|---|
| SMM J04431+0210 | CO (3→2) | 2.5094±.0002 | 1.4±0.3 | 350±60 | 1.0 |
| SMM J09431+4700 | CO (4→3) | 3.3460±.0001 | 1.1±0.2 | 420±50 | 2.7 |
| SMM J16358+4057 | CO (3→2) | 2.3853±.0014 | 2.3±0.4 | 630±110 | 6.9 |

- The CO line observations confirm the rest-frame UV/optical redshifts from Chapman et al. (2003)
- More than double the number of confirmed redshifts of the faint submm population thus **proving their high-$z$ nature**
- **The gas masses are large** ($3 \times 10^{10}\,M_\odot$)
- In two cases, part of interacting systems
- **The submm-population consists of gas rich and massive, composite starburst/AGN systems, which are going a major burst of star formation and are evolving into** $\mathrm{m}^*$**-galaxies**
- **SO FAR 10 DETECTED OUT OF 13**

Neri et al. (2003); Greve et al. (2004)

# Submm/Far-IR Bright Galaxies: a Timeline

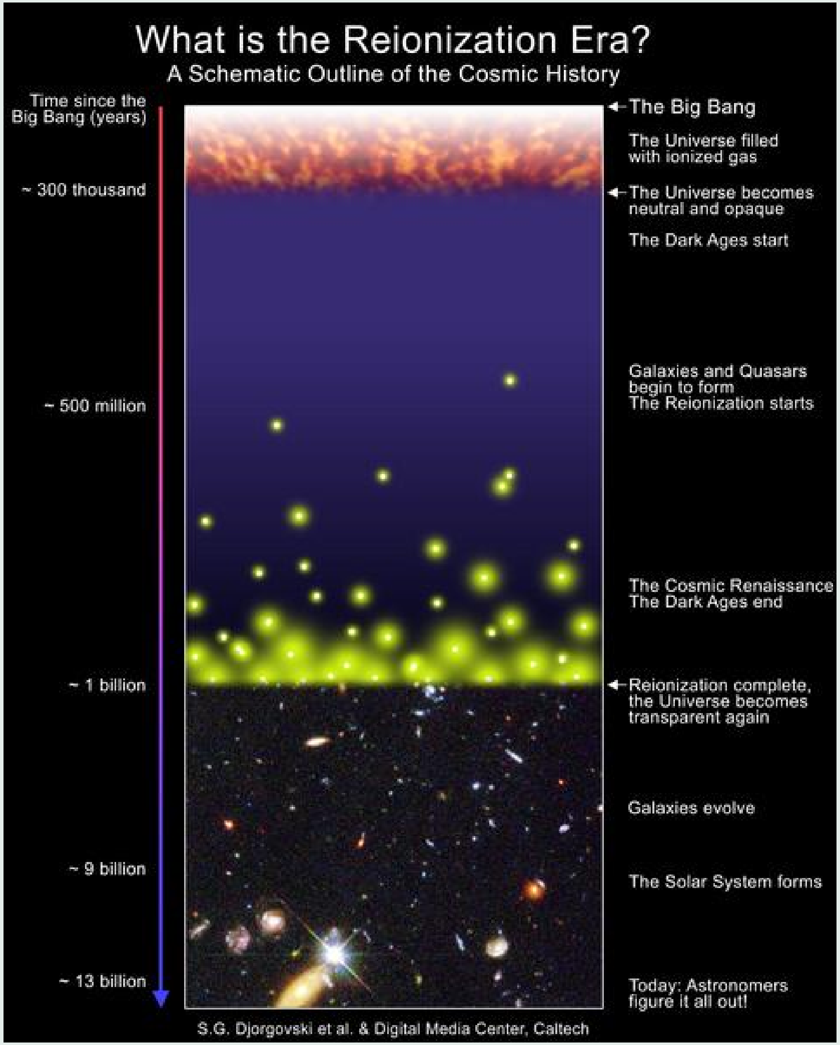
- 1984: IRAS
  - Similar far-IR and optical luminosities for most local galaxies
  - **Some galaxies are MUCH more luminous in far-IR**
- Mid-1990's
  - **ISO** extended limits of knowledge in mid/far-IR to $z \sim 1$
  - Pointed submm/mm detections of some high-$z$ QSOs/radio galaxies
  - First CO detections in high-$z$ ($z \sim 2.5$) IRAS galaxies
- 1995-2004
  - First sensitive 2D camera find previously unknown high-$z$ galaxies at 1.3 and 0.85 mm (**SCUBA & Mambo I/II**)
  - Further detections of CO in high-$z$ galaxies and quasars, mostly with **PdBI**
  - Detection of the Infrared Background Emission (*COBE*)
  - *WMAP* Results
  - Keck LRIS-B redshifts for significant numbers ($> 70$) $z \sim 2.5$ submm galaxies and follow-up CO observations at PdBI
  - SPITZER
    - Will map large ($\sim 100 \mathrm{deg}^2$) fields far deeper than ISO's $< 1\,\mathrm{deg}^2$
    - Yield accurate SEDs for the most luminous dusty galaxies to $z \approx 2$
- Future: Near & Far
  - From space: **Herschel & Planck; JWST**
  - **Large aperture far-IR space telescope; IR/submm space interferometer**
    - APEX, PdB$^+$ & CARMA
    - **ALMA** will resolve images of faint high-$z$ galaxies
    - **ELT** & **OWL**: first stars?
    - **SKA** surveys

# ALMA in 2012 - an Artist's View

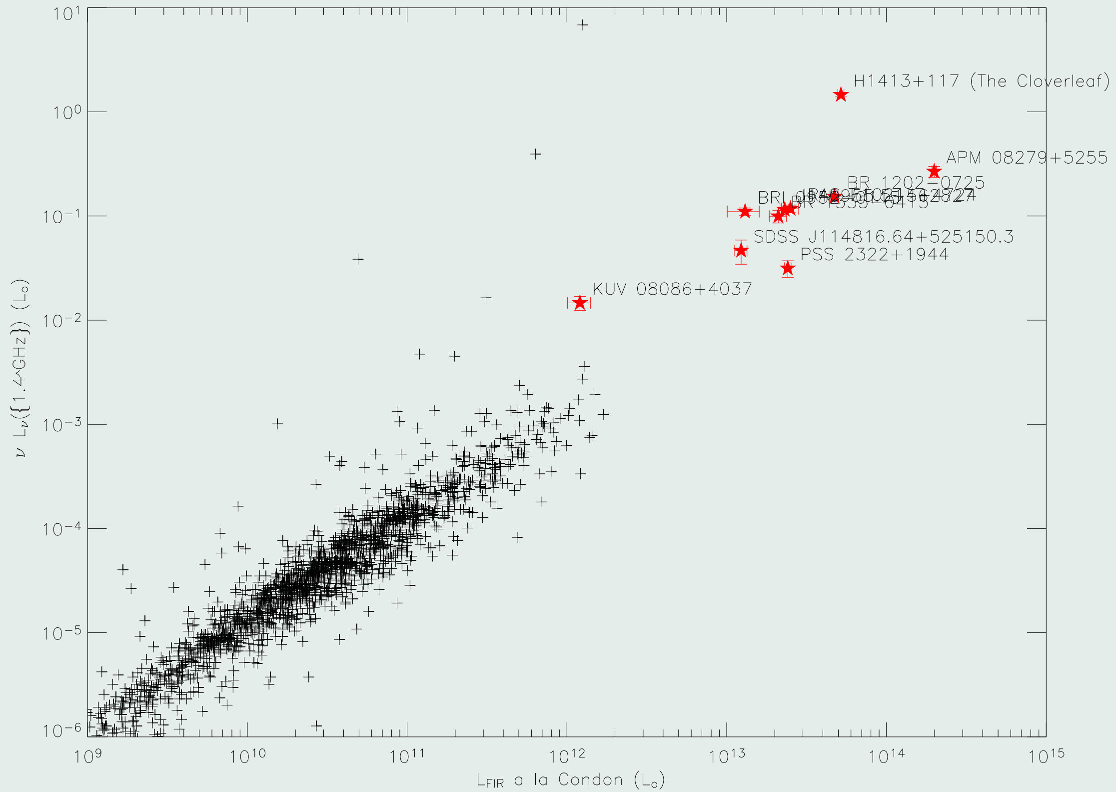
# The High-$z$ Universe & ALMA

- Deep field surveys in the mm/submm continuum: high sensitivity, **NO CONFUSION**
  - Identification of high-$z$ objects, i.e. $\Rightarrow z \approx 20$**, i.e. Reionization**
  - Images of gravitational lenses
  - Kinematics: **estimates of dynamical masses**
- Spectra between 85 & 720 GHz
  - Redshift estimate ($z$)
  - Search for proto-galaxies in molecular gas (CO)
  - Search of species other than CO, e.g., HCN, CN, $HCO^+$, isotopes, [CII], etc........
  - **Physics & Chemistry**
- Cosmic Background
- Unexpected Results
- **A NEW ERA IN COSMOLOGY**

# The history of the Universe



# Radio to Far-infrared Relation




Yun, Reddy & Condon (2001); Beelen et al. (2004)