# Starburst activity in the host galaxies of high redshift sources

## The case of the z=2.58 QSO J1409+5628

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# Outline

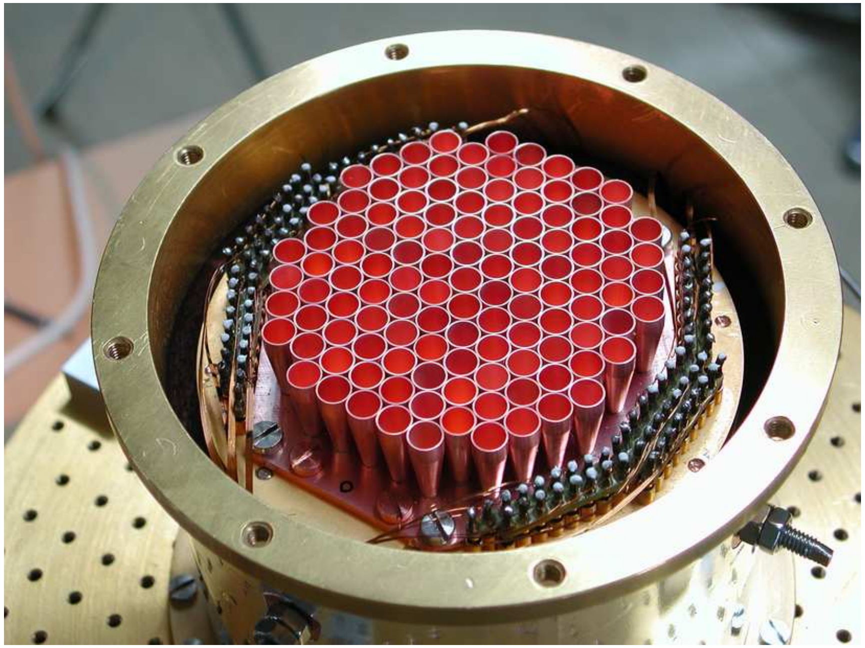
- Introduction
- Starburst & Massive Black Holes
- Molecular Gas in J 1409+5628
- Star Formation Efficiencies of High-$z$ objects
- Conclusions

# Collaborators

- *Pierre Cox* (IAS, Orsay)
- Alain Omont, Niruj Mohan, Patrick Petitjean (IAP)
- Frank Bertoldi (MPIfR)
- Chris Carilli (NRAO)
- Jérôme Pety, Roberto Neri, Axel Weiss (IRAM)
- Xiaohui Fan (Princeton Univ)
- Andreea Petric (Columbia Univ.)
- Dominic J. Benford (NASA/GSFC)

# Instruments

- MAMBO 2 @ IRAM 30-m



# Instruments

- PLATEAU DE BURE INTERFEROMETER

# Instruments

- VERY LARGE ARRAY

# Introduction

Questions :

- How the galaxies was formed and evolved ?
- What is the star formation history of the Universe ?
- Is there a relationship between star formation and massive black hole ?
- What are the physical conditions of the molecular gas in the high-$z$ Universe ?

Approach :

- Deep Field surveys
- Pointed observations

# Deep Field surveys

Strategy

- select a blank field in the sky
- observe it as deep as possible
- identify sources

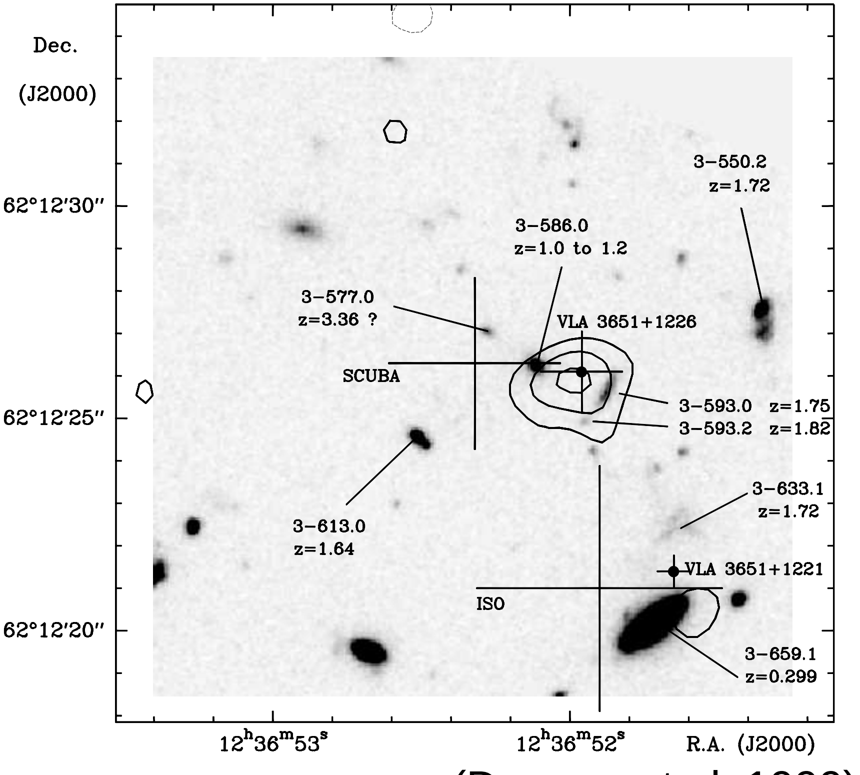
Submm Deep Fields :

- $> 200$ detected sources
- $\approx 50$ optically identified
  - $\approx 10$ CO confirmed

(Chapman et al. 2003; Neri et al. 2003)

Problems :

- Larges beam
- Extinction
- Spectroscopic information




(Downes et al. 1999)

# Pointed (sub) mm Observations

Strategy :

- Select QSOs and Gal. from optical/radio/X-ray surveys
- Observe them in the (sub-)mm wavelength window
- Follow-up of some of them for molecular lines

Advantages

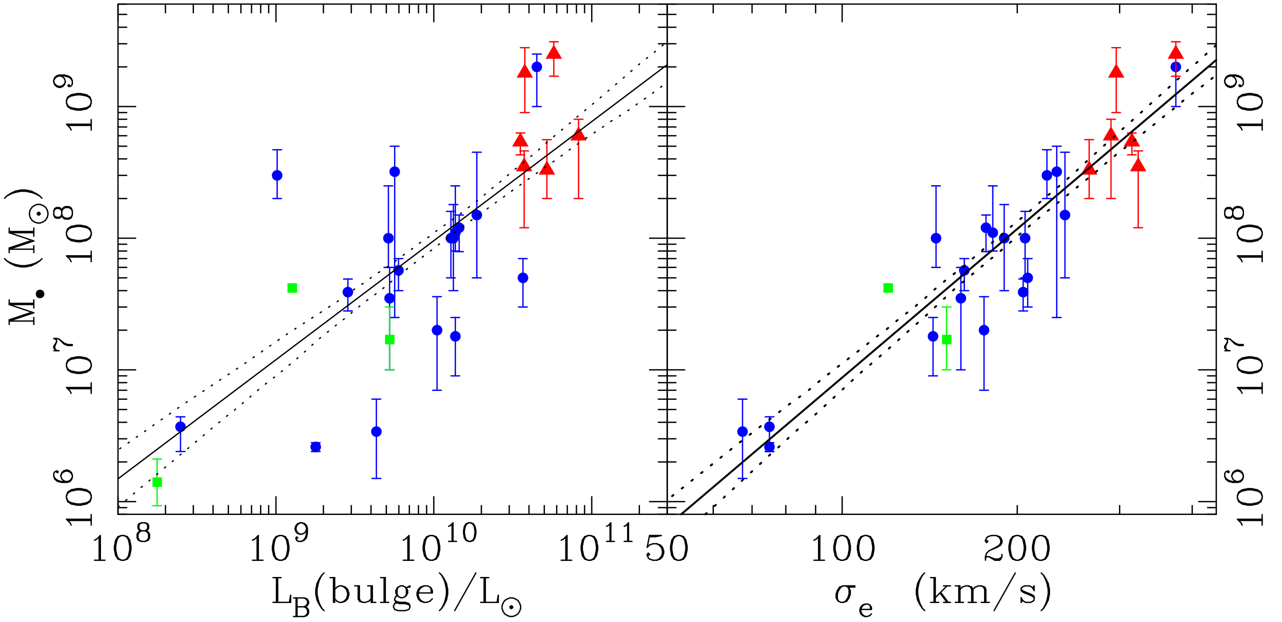
- known position and redshift

History :

- First detection at high-$z$ in 1992 (Brown & vanden Bout 1992)
- First detection $z > 4$ in 1994 (McMahon et al. 1994)
- First "survey" in 1996 (Omont et al. 1996)
- Significant surveys (Omont et al. 2001, 2003; Carilli et al. 2001)
- Highest-$z$ sources *see P. Cox talk tomorrow*

# Massive black holes and their host galaxies

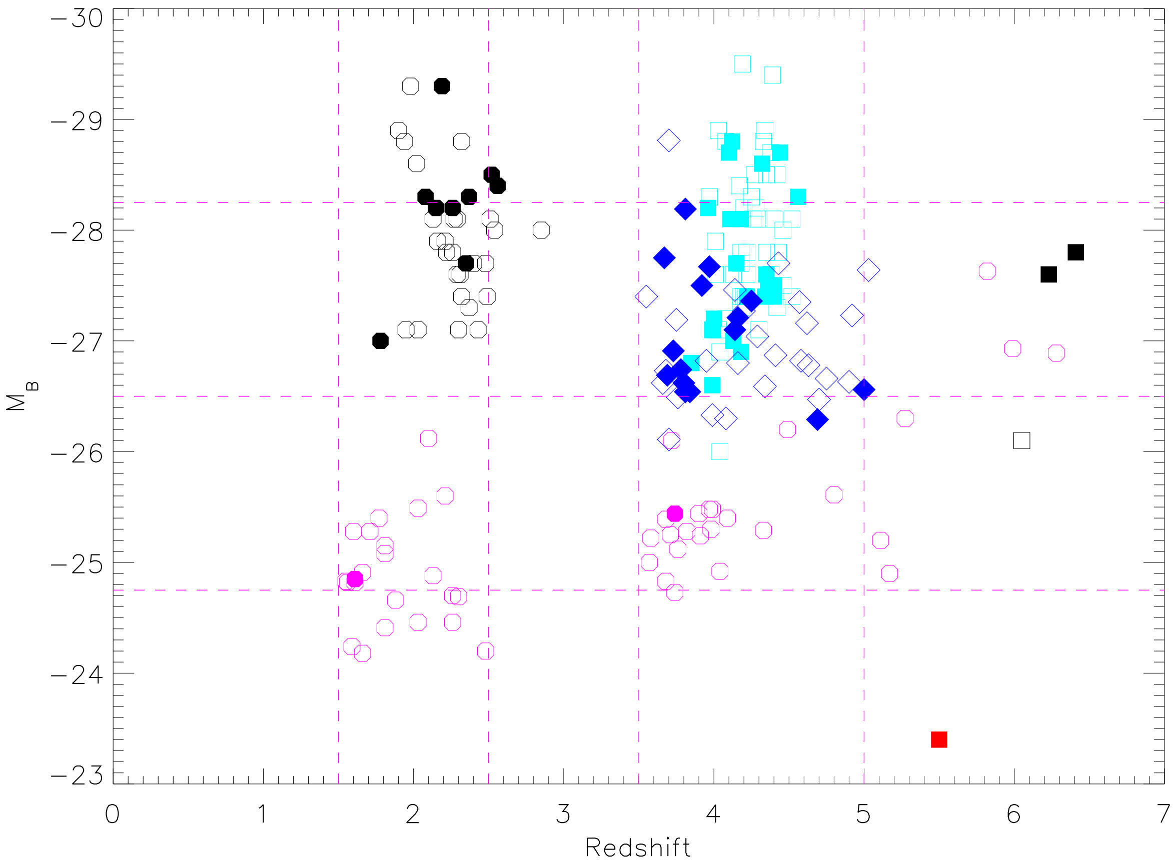
- Spheroidal Galaxies in local universe contain massive black holes
- QSOs contain black holes with $M_{\rm BH} > 10^9$ $M_\odot$
- Black Hole are related to the bulge of their host galaxies




(Gebhardt et al. 2000)

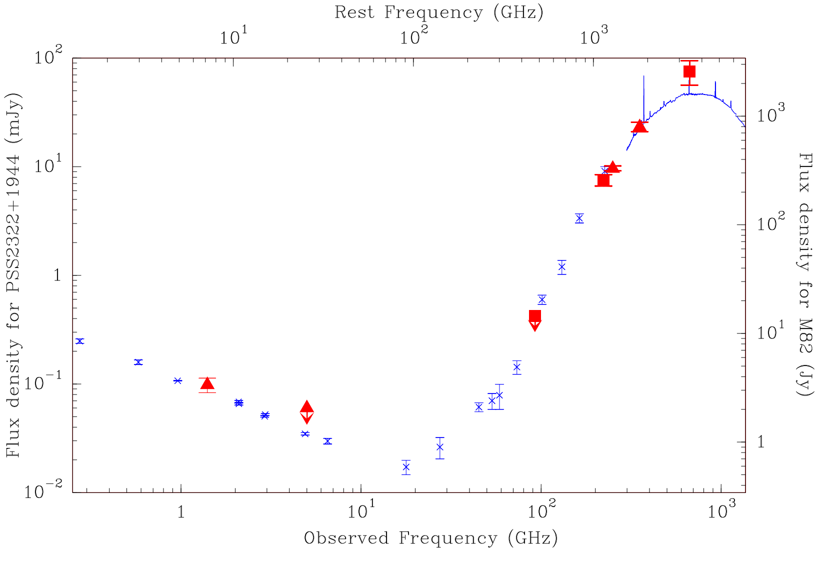
# What about High-$z$ QSOs

- MAMBO 1.25 mm survey of High-$z$ QSOs
- $\approx 200$ optically luminous, radio-quiet QSOs
- PSS (Omont et al. 2001, 2003), SDSS (Carilli et al. 2001)



# Dust in High-$z$ QSOs

- Evidence for dust emission and starburst
  - PSS 2322+1944 (Cox et al. 2002)
  - BRI 1335-0417



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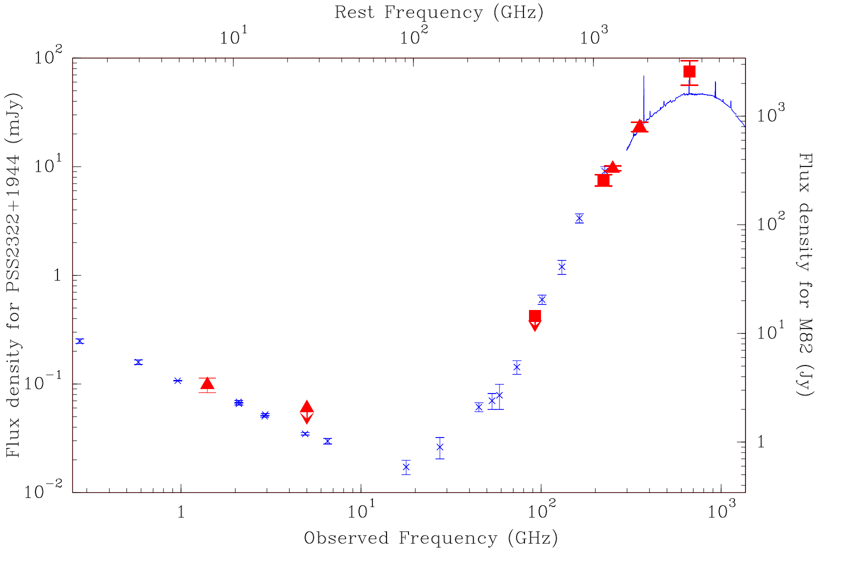
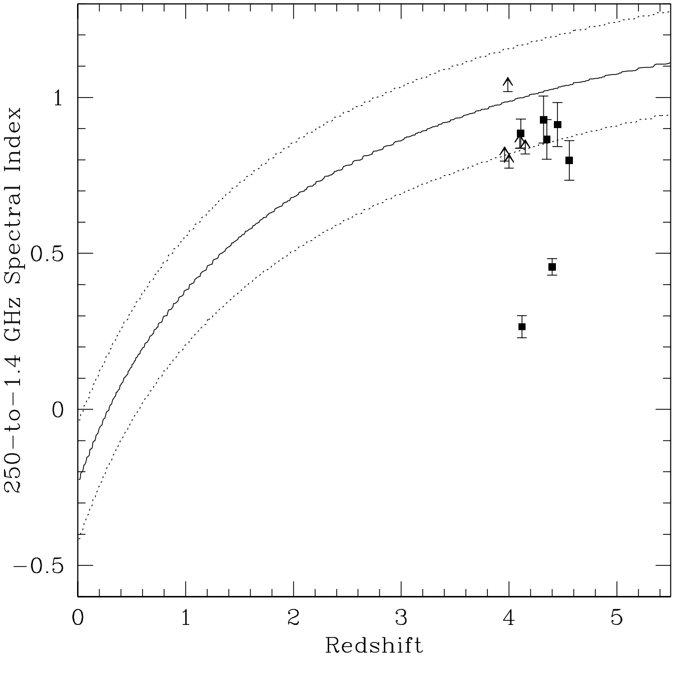
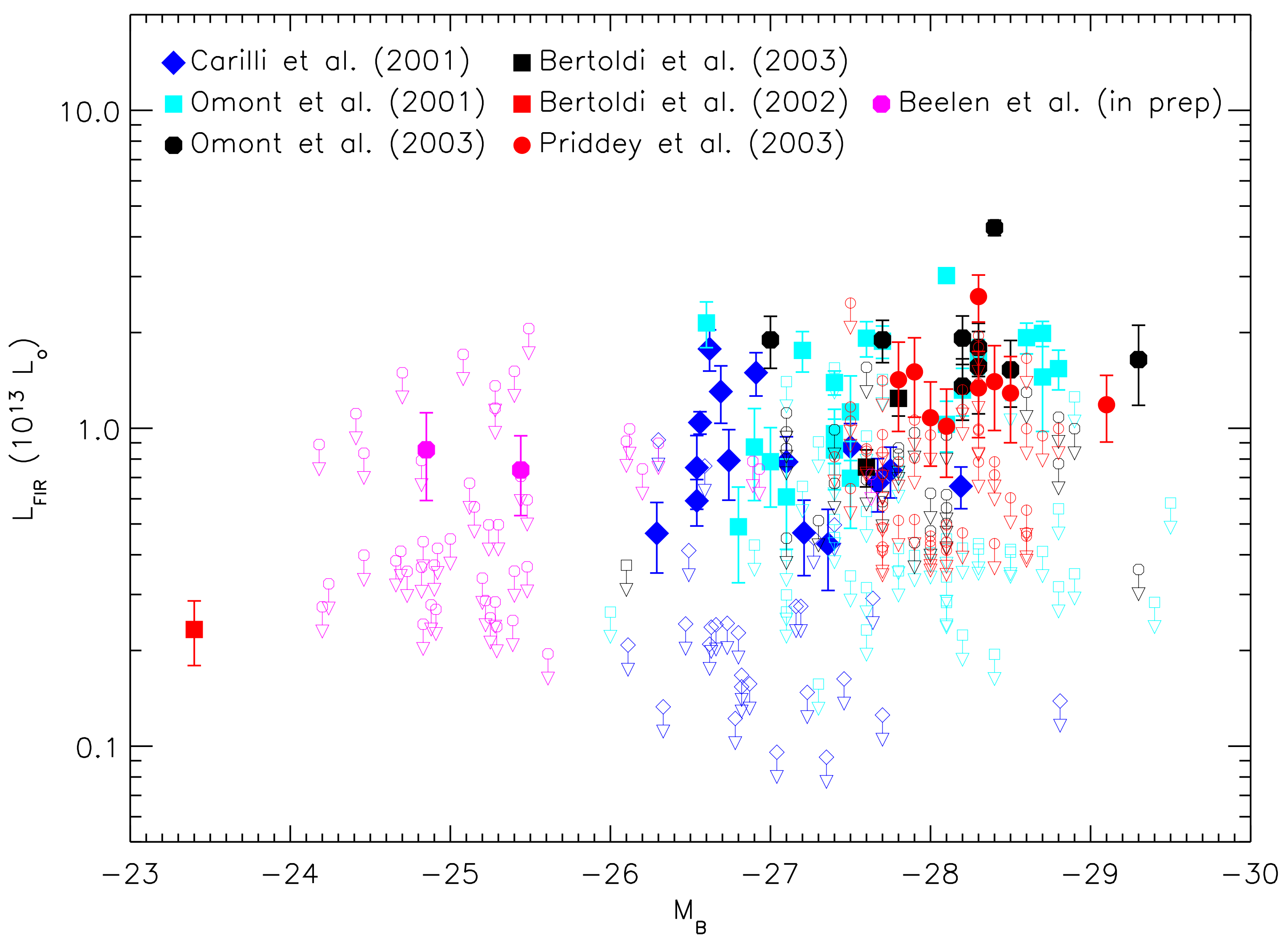



- Radio-Infrared correlation (Condon et al. 1991; Yun et al. 2001)
  - 98% of the IRAS REDSHIFT SURVEY sources
  - extend over 4 decades
- Radio-millimeter relation in High-$z$ QSOs (Carilli et al. 2001)
  - $\alpha_{\mathrm{mm-radio}} \approx \alpha_{\mathrm{starburst}}$

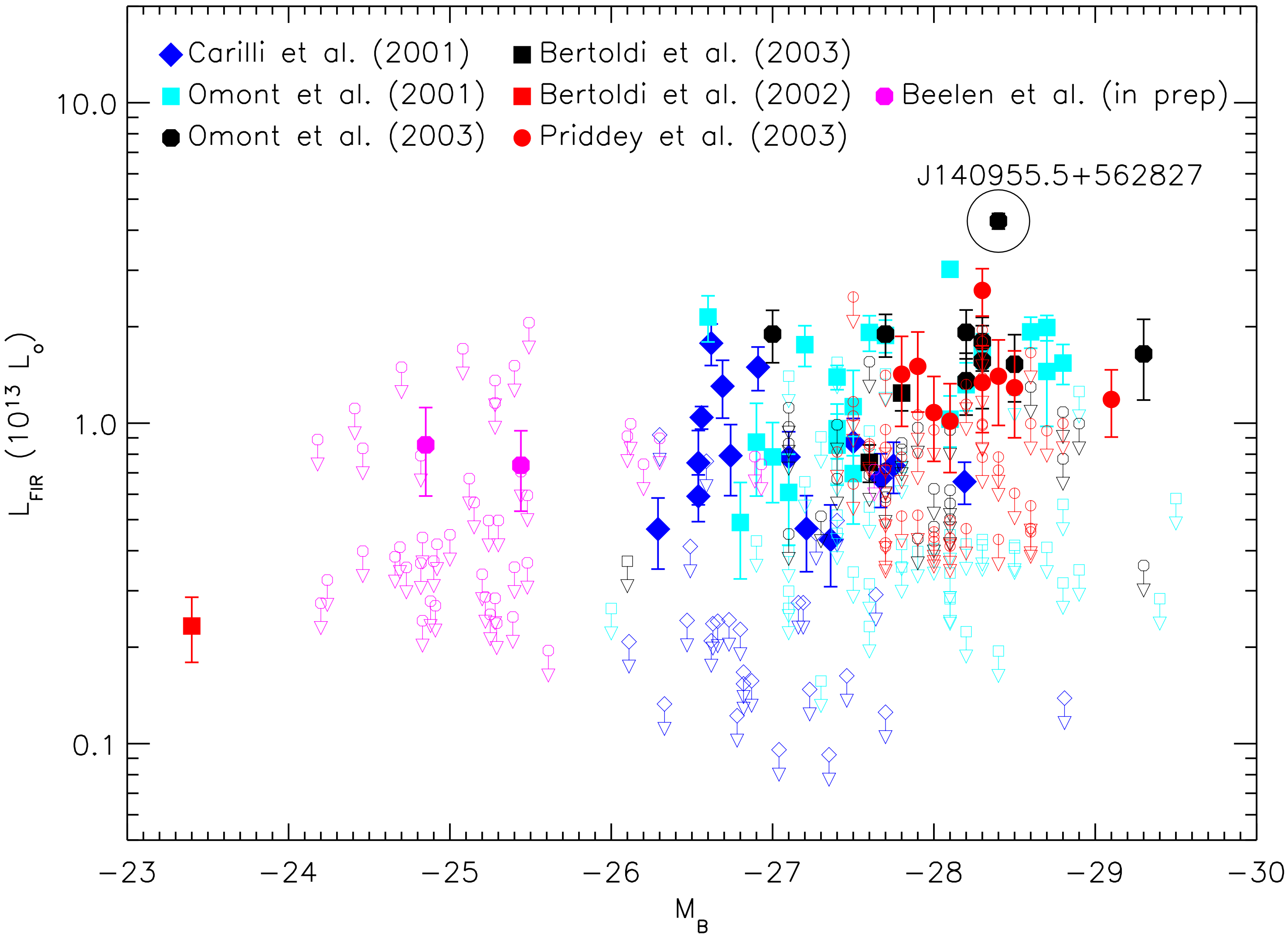


# Starburst vs AGN




Weak correlation ? (Omont et al. 2003)

# Starburst vs AGN




Weak correlation ? (Omont et al. 2003)

# Molecular Gas in J 1409+5628

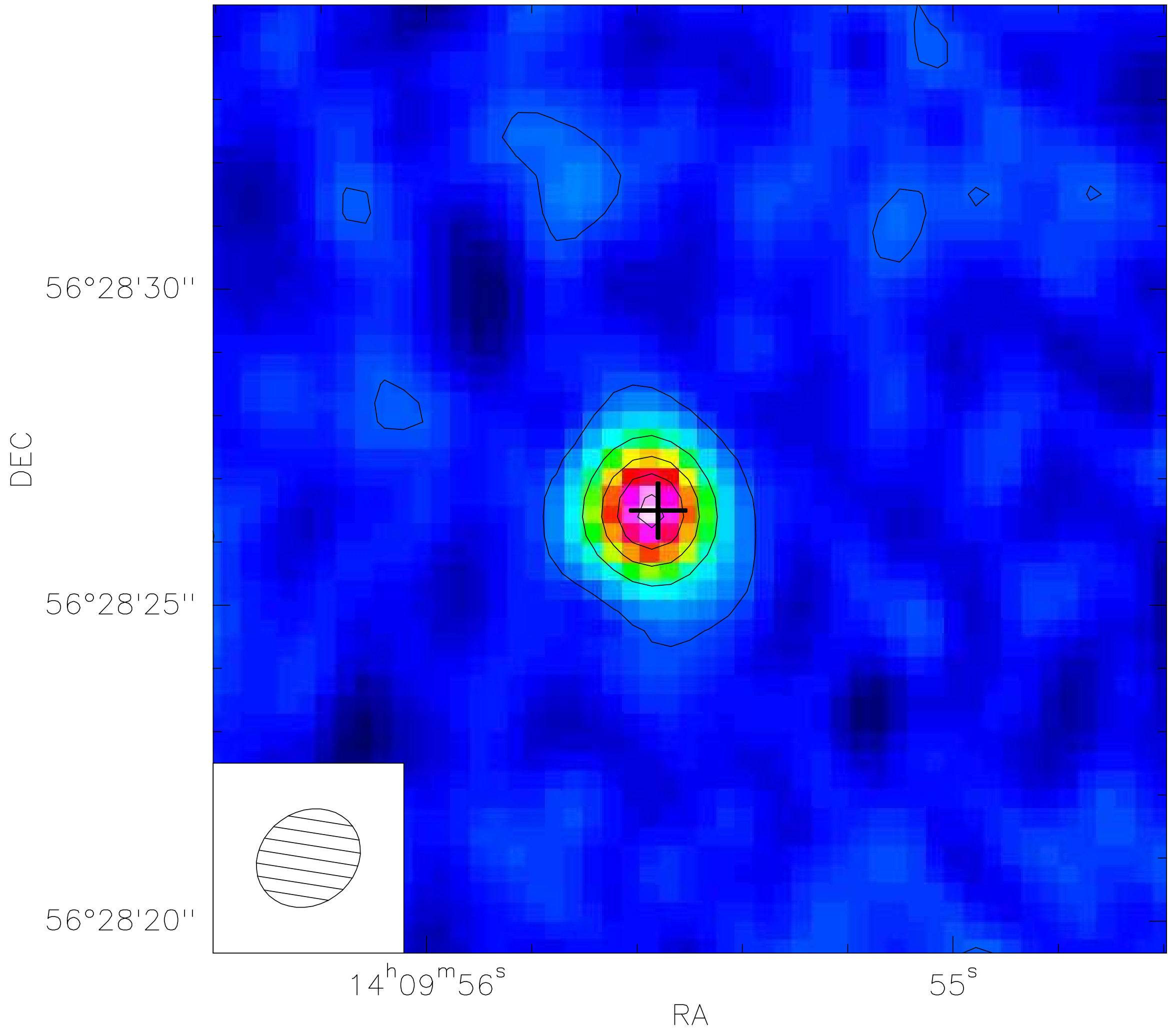
[VV96] J140955.5+562827

- detected at 1.25 mm by Omont et al. (2003)
  - $L_{\rm FIR} = (4.3 \pm 0.2) \times 10^{13}$ L$_\odot$
  - $SFR = \delta_{\rm MF}\, L_{\rm FIR} = 6 \times 10^{3}$ M$_\odot$ yr$^{-1}$
- No evidence for lensing

- Search for radio counterpart with the VLA
  - test the starburst hypothesis

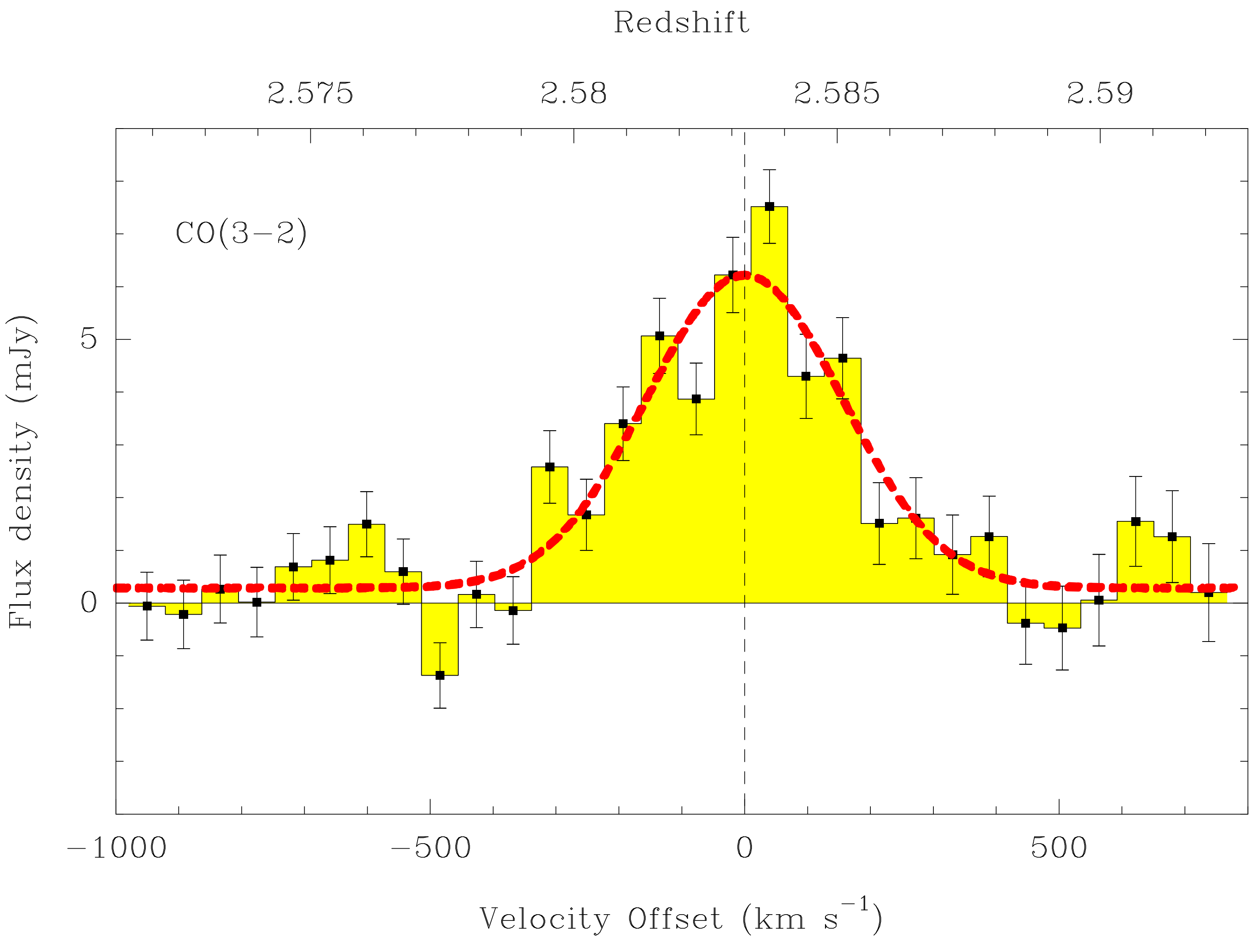
- Search for CO(3→2) emission line with the PdB
  - Broad Absorption Line QSO (Barlow & Junkkarinen 1994)
    - optical shows C IV bal and nal assoc. Lyman $\alpha$ abs.
    - $2.548 < z < 2.583$
  - 9 individual sessions in 2002 & 2003
  - 4 to 6 antennas in D or B configuration

# VLA **1.4 GHz observations of J 1409+5628**

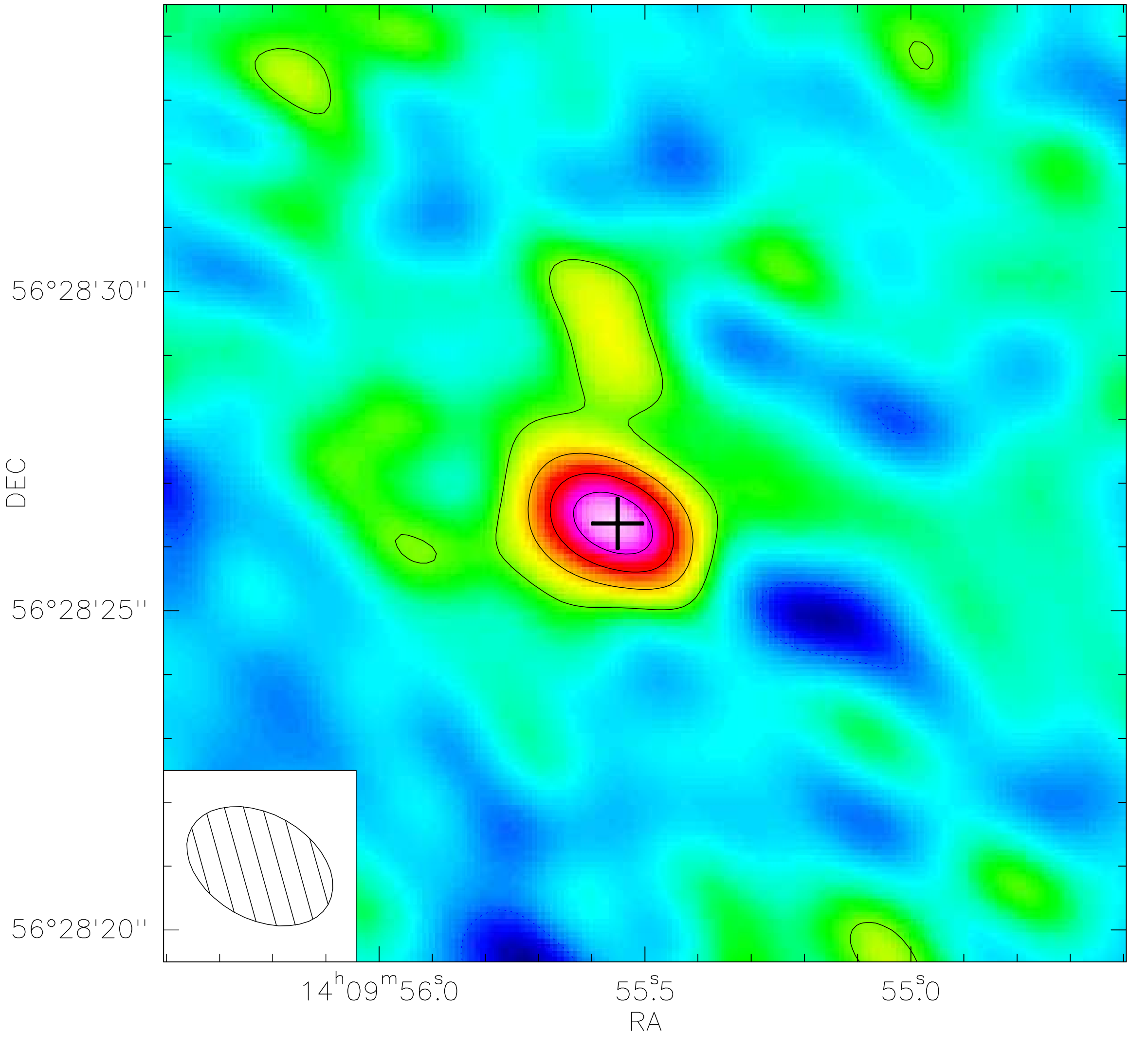



$\alpha_{\mathrm{mm-radio}}$ compatible with a starburst

# CO(3→2) spectrum of J 1409+5628



# CO(3→2) map of J 1409+5628



# CO(3→2) properties of J 1409+5628

- Source is unresolved at $2.44'' \times 1.65'' \approx 20 \times 13$ kpc
- CO position coincides with optical position from 2MASS
  - $z_{\mathrm{CO}} = 2.5832 \pm 0.0001$
  - integrated flux $I_{\mathrm{CO}} = 2.3 \pm 0.2$ Jy km s$^{-1}$
    - $L'_{\mathrm{CO}(3\rightarrow2)} = (8.2 \pm 0.6) \times 10^{10}$ K km s$^{-1}$
    - $L_{\mathrm{CO}(3\rightarrow2)} = (1.1 \pm 0.1) \times 10^{8}$ L$_\odot$
    - $M_{\mathrm{H}_2} = X_{\mathrm{CO}}\, L'_{\mathrm{CO}(1\rightarrow0)} \approx 6.6 \times 10^{10}$ M$_\odot$

- $SFE = SFR/\mathrm{M}_{\mathrm{H}_2} = \frac{\delta_{\mathrm{MF}}}{X_{\mathrm{CO}}} \frac{L_{\mathrm{FIR}}}{L'_{\mathrm{CO}}} = 10^{-7}$ yr$^{-1}$
  - All the gas would be depleted in 10 Myr ! !
    - Continuous Gas infall
    - Cannot extrapolate local IMF to massive stars

# **All $z > 1$ CO detections** *to date*

XML database :

- source position
- nature of the source
- magnification factor
- all CO detections and non-detection
  - transition / frequency / wavelength / redshift
  - integrated flux
  - peak flux / line width
- all photometric observations

Soon available on the web...

# **All $z > 1$ CO detections** *to date*

| | | | CO emission line | | $\approx 1$ mm Cont. | | |
|---|---|---|---|---|---|---|---|
| Source Name | $z$ | transition | flux | width | $\lambda$ | $S_\nu$ | Ref. |
| | | | [$\mathrm{Jy\,km\,s^{-1}}$] | [$\mathrm{km\,s^{-1}}$] | [mm] | [mJy] | |
| HR10 | 1.44 | **2** ( 1 5 ) | 1.40 | 400 | 1.35 | $2.13 \pm 0.63$ | [1,2] |
| FIRAS 10214+4724† | 2.29 | **3** ( 6 ) | $4.10 \pm 0.90$ | $230 \pm 30$ | 1.20 | $9.60 \pm 1.40$ | [3] |
| SMM J16358+4057 | 2.39 | **3** ( 7 ) | $2.30 \pm 0.20$ | $840 \pm 110$ | 1.30 | $2.50 \pm 0.40$ | [4] |
| 53W002 | 2.39 | **3** | $1.51 \pm 0.20$ | $540 \pm 100$ | 1.30 | $1.70 \pm 0.40$ | [5,6] |
| SMM J04431+0210† | 2.51 | **3** ( *7* ) | $1.40 \pm 0.20$ | $350 \pm 60$ | 1.30 | $1.10 \pm 0.30$ | [4] |
| H1413+117 (The Cloverleaf)† | 2.56 | **3** ( 4 5 7 ) | $9.90 \pm 0.60$ | $362 \pm 23$ | 1.34 | $7.50 \pm 0.60$ | [7,8] |
| SMM J14011+0252 | 2.57 | **3** | $2.40 \pm 0.30$ | $200 \pm 40$ | 1.35 | $6.06 \pm 1.46$ | [9,10] |
| MG 0414+0534† | 2.64 | **3** | 2.60 | 580 | 1.30 | $20.70 \pm 1.30$ | [11,12] |
| cB58 | 2.73 | **3** | $0.37 \pm 0.08$ | $174 \pm 43$ | 1.20 | $1.06 \pm 0.35$ | [13,14] |
| Q 1230+1627B | 2.74 | **3** | $0.80 \pm 0.26$ | | 1.35 | $3.33 \pm 0.52$ | [15] |
| SMM J02399-0136† | 2.81 | **3** | $3.10 \pm 0.40$ | $> 1100$ | 1.35 | $5.70 \pm 1.00$ | [16,17] |
| B3 J2330+3927 | 3.09 | **4** | $1.30 \pm 0.30$ | 500 | 1.20 | $4.80 \pm 1.20$ | [18] |
| MG 0751+2716† | 3.20 | **4** | $5.96 \pm 0.45$ | $390 \pm 38$ | 1.30 | $6.70 \pm 1.30$ | [19,12] |
| SMM J09431+4700† | 3.35 | **4** ( *9* ) | $1.10 \pm 0.10$ | $420 \pm 50$ | 1.30 | $2.30 \pm 0.40$ | [4] |
| TN J0121+1320 | 3.52 | **4** | $1.20 \pm 0.40$ | 700 | 1.29 | $< 2.70$ | [20] |
| 6C 1909+722 | 3.53 | **4** | $1.62 \pm 0.30$ | $530 \pm 70$ | 1.25 | $< 3.00$ | [21] |
| 4C 60.07 | 3.79 | **4** | $2.50 \pm 0.43$ | $> 1000$ | 1.25 | $4.50 \pm 1.20$ | [21] |
| APM 08279+5255† | 3.91 | **4** ( 1 9 ) | $3.70 \pm 0.50$ | $480 \pm 35$ | 1.40 | $17.00 \pm 0.50$ | [22] |
| PSS 2322+1944† | 4.12 | **4** ( 1 *10* 2 5 ) | $4.21 \pm 0.40$ | $375 \pm 41$ | 1.20 | $9.60 \pm 0.50$ | [23,24] |
| BR 1335-0415 | 4.41 | **5** ( 2 ) | $2.80 \pm 0.30$ | $420 \pm 60$ | 1.25 | $10.30 \pm 1.35$ | [25] |
| BRI 0952-0115† | 4.43 | **5** | $0.91 \pm 0.11$ | $230 \pm 30$ | 1.25 | $2.78 \pm 0.63$ | [15] |
| BR 1202-0725 | 4.70 | **5** ( 2 4 7 ) | $2.70 \pm 0.41$ | $< 222$ | 1.25 | $10.50 \pm 1.50$ | [26,27] |
| SDSS J114816.64+525150.3 | 6.42 | **6** ( *1* 3 7 ) | $0.64 \pm 0.12$ | $232 \pm 63$ | 1.20 | $5.00 \pm 0.60$ | [28,29] |

Notes – † Source is known to be lensed. Column 3: each number corresponds to the upper level of the observed CO transition; the values in bold face are the ones for which the CO line flux and line width are listed in columns 4 and 5, respectively; the transitions in bracketts list all the transitions which have been observed, italics indicating that the transition was not detected.

References – [1] Andreani et al. (2000) [2] Dey et al. (1999) [3] Solomon et al. (1992) [4] Neri et al. (2003) [5] Scoville et al. (1997) [6] Alloin et al. (2000) [7] Barvainis et al. (1997) [8] Weiß et al. (2003) [9] Frayer et al. (1999) [10] Ivison et al. (2000) [11] Barvainis et al. (1998) [12] Barvainis & Ivison (2002) [13] Baker (2003) [14] Baker et al. (2001) [15] Guilloteau et al. (1999) [16] Genzel et al. (2003) [17] Ivison et al. (1998) [18] De Breuck et al. (2003) [19] Barvainis et al. (2002) [20] de Breuck et al. (2003) [21] Papadopoulos et al. (2000) [22] Downes et al. (1999) [23] Cox et al. (2002) [24] Omont et al. (2001) [25] Guilloteau et al. (1997) [26] Ohta et al. (1996) [27] Omont et al. (1996) [28] Bertoldi et al. (2003) [29] Bertoldi et al.

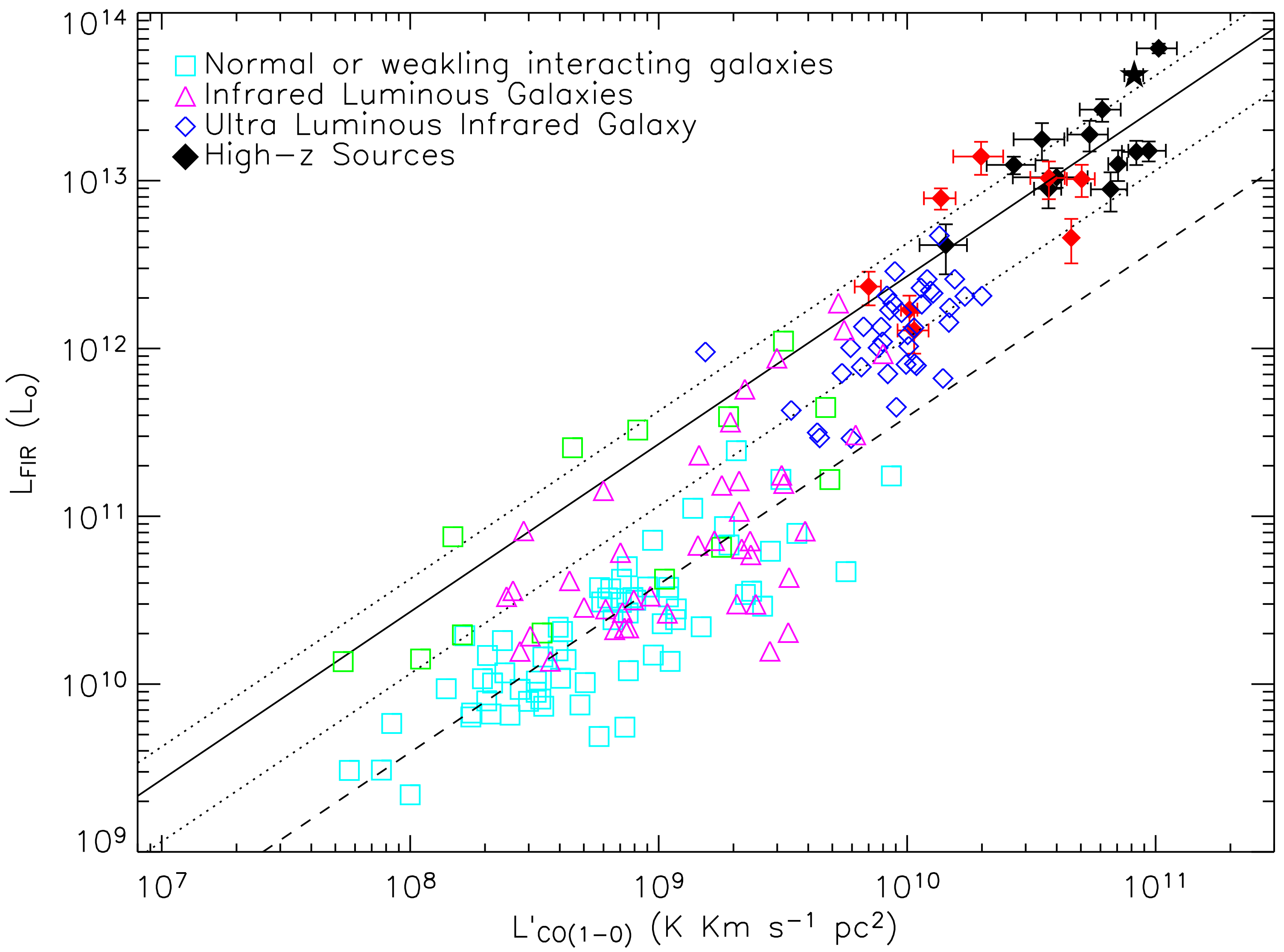
# Comparison with other sources

Local Sources :

- Normal and Weakly Interacting Galaxies (Solomon & Sage 1988)
- Luminous Infrared Galaxies (Dunne et al. 2000; Yao et al. 2003)
- Ultra Luminous Infrared Galaxies (Solomon et al. 1992)

- Common cosmology
- Common $L'_{\rm CO}$ definition
- Common $L_{\rm FIR}$ definition
  - PSS 2322+1944 or BRI 1335-0417 as templates
    - $T = 45$ K & $\beta = 1.5$
  - # photometric data points available
    - $1$ : fix $\beta$ and $T$
    - $2$ : fix $\beta$
    - $> 3$ : $\chi^2$ fit with $\beta$ fixed when necessary

# The infrared-CO luminosities relation



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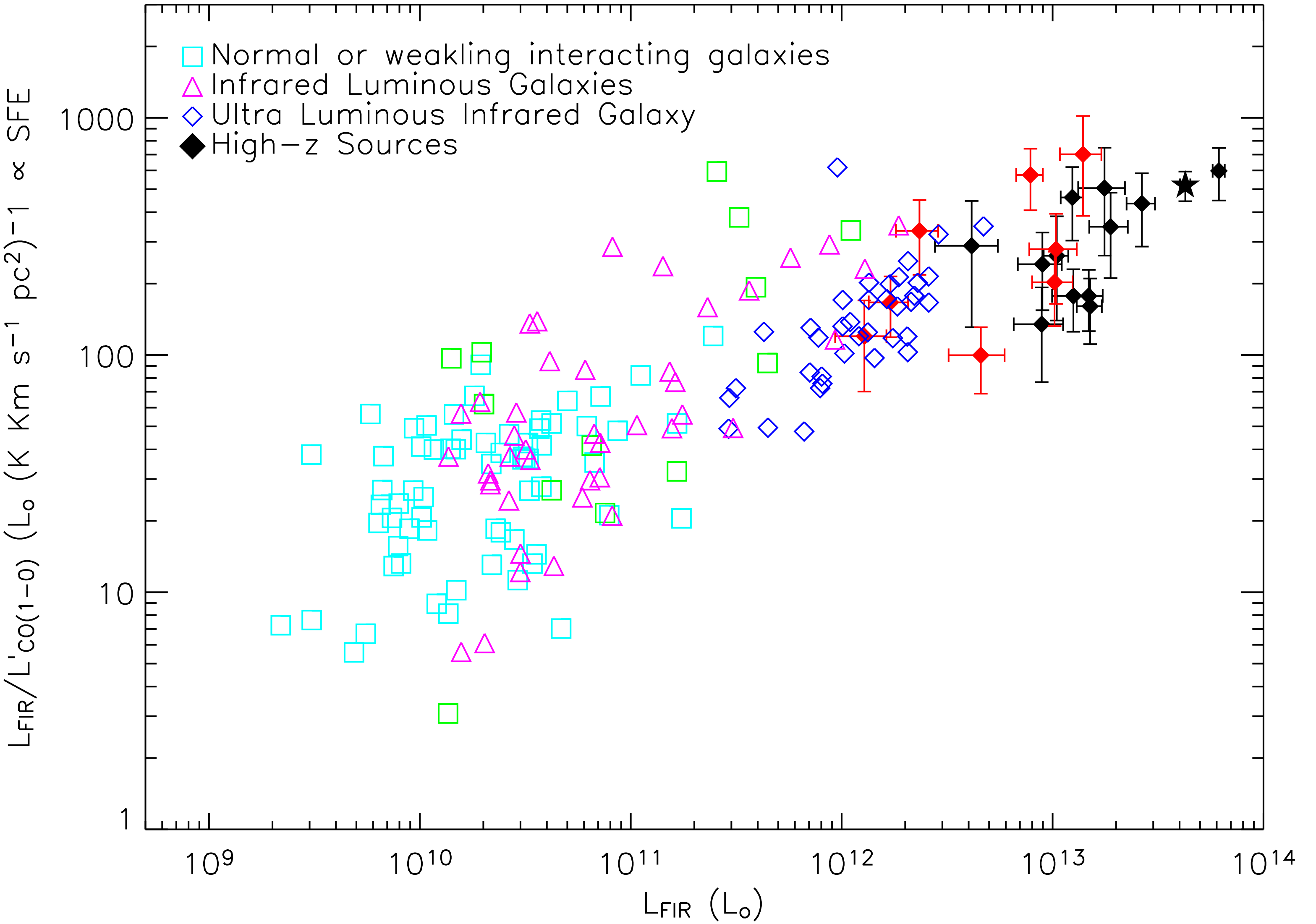

# Star Formation Efficiencies at High-$z$

- High-$z$ objects have the same SFE than local ones
  - but higher $L_{\mathrm{FIR}}$ due to dust heated by the AGN
- High-$z$ objects have higher SFE than local ones
  - need a lot of gas to sustain such efficiencies

# Star Formation Efficiencies at High-$z$

- ~~High-$z$ objects have the same SFE than local ones~~
  - ~~but higher $L_{\mathrm{FIR}}$ due to dust heated by the AGN~~

- High-$z$ objects have higher SFE than local ones
  - need a lot of gas to sustain such efficiencies

# Conclusions

- Most QSOs show strong thermal dust emission predominantly heated by starburst
- "Weak" correlation between star formation and black hole activity in High-$z$ QSOs

- J 1409+5628 is my favorite source
- Molecular gas detections allow us to make detailed studies of ISM at cosmological distance
- Star Formation Efficiencies was higher at $z > 1$ than locally by an order of magnitude

# *Future*

- Observations next month with SHARCK at the CSO
  - Dust temperature vs. redshift
- Observations next winter with MAMBO
  - further study the link btw. black hole & starburst activity

- Use SIRTF to constrain the SEDs of High-$z$ objects
- Search for other molecular (HCN, $H_2 0$) or atomic ([CI], [CII]) emission line to better constrain the ISM
- Modelisation of the ISM in High-$z$ objects
  - dust formation
  - PDRs lines

- Waiting for ALMA. . .

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