Redshifted far-infrared/submm dust emission from high-z QSOs

Alain Omont (IAP)

160-400 µm emission observed at 1.2 mm (z = 2-6.4)

OUTLINE

DUST MM EMISSION IN HIGH Z QSOs (z = 2 – 6.4)

- **Background : high z SCUBA/MAMBO ULIRGs**

- **IRAM-30m/MAMBO 1.2 mm Observations of bright QSOs**

- **Results : 55 detections. Statistics → z & L_{bol} dependence**
  Prominent sources at z > 6 and others

- **Properties and Origin of Dust Emission**
  Evidence for dust emission
  Dust temperature and mass
  Heating : starburst or QSO. Evidence for starburst
  Implications

FUTURE : ALMA etc.

COLLABORATION

General   P. Cox , A. Beelen   IAS, Orsay
F. Bertoldi (+ E. Kreysa)   MPIfR, Bonn
C. Carilli   NRAO

QSO samples
SDSS z > 6 : X.Fan, M. Strauss
PSS : G. Djorgovski

SCUBA 850μm
R. McMahon, K. Isaak, R. Priddey   Cambridge

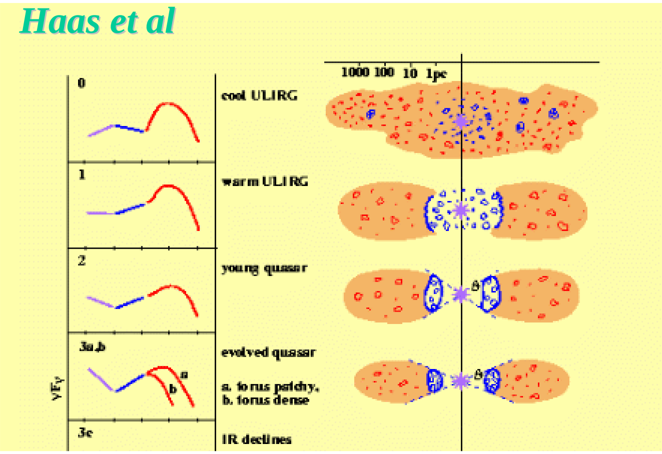
CSO 350μm   D. Benford, T. Phillips   Caltech

Radio VLA   C. Carilli, A. Petric, F. Walter   NRAO

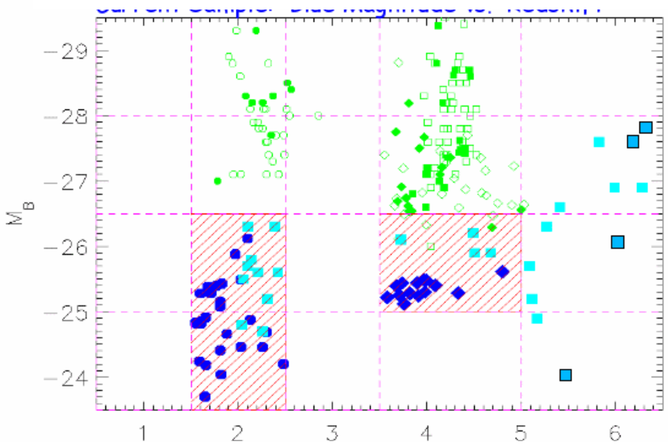
PARALLEL WORKS
Radioquiet QSOs SCUBA Isaak, Priddey, Mc Mahon et al. ; Willot et al., etc.
Radioloud QSOs SCUBA Willott et al.
Radiogalaxies : SCUBA Archibald et al., Ivison et al., etc.
IRAM   De Breuck et al., etc.
Etc
→ X AGN

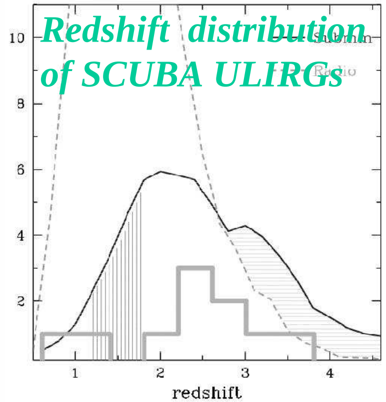
Highlights

- *AGN (10^{13}- 10^{14} Lo) + ULIRG (10^{12}- 10^{13} Lo)*
- *Massive star formation at less than 1 Gyr*
  (where SCUBA/MAMBO galaxies not yet identifed at z>4)
- *Large mass of dust → Heavy elements enrichment + dust formation*
- *Coeval Bulge/Black-Hole evolution → Massive Ellipticals*
- *Dust heating combines starburst + AGN*
- *First step → CO detection → ΔV → mapping + V structure with ALMA*

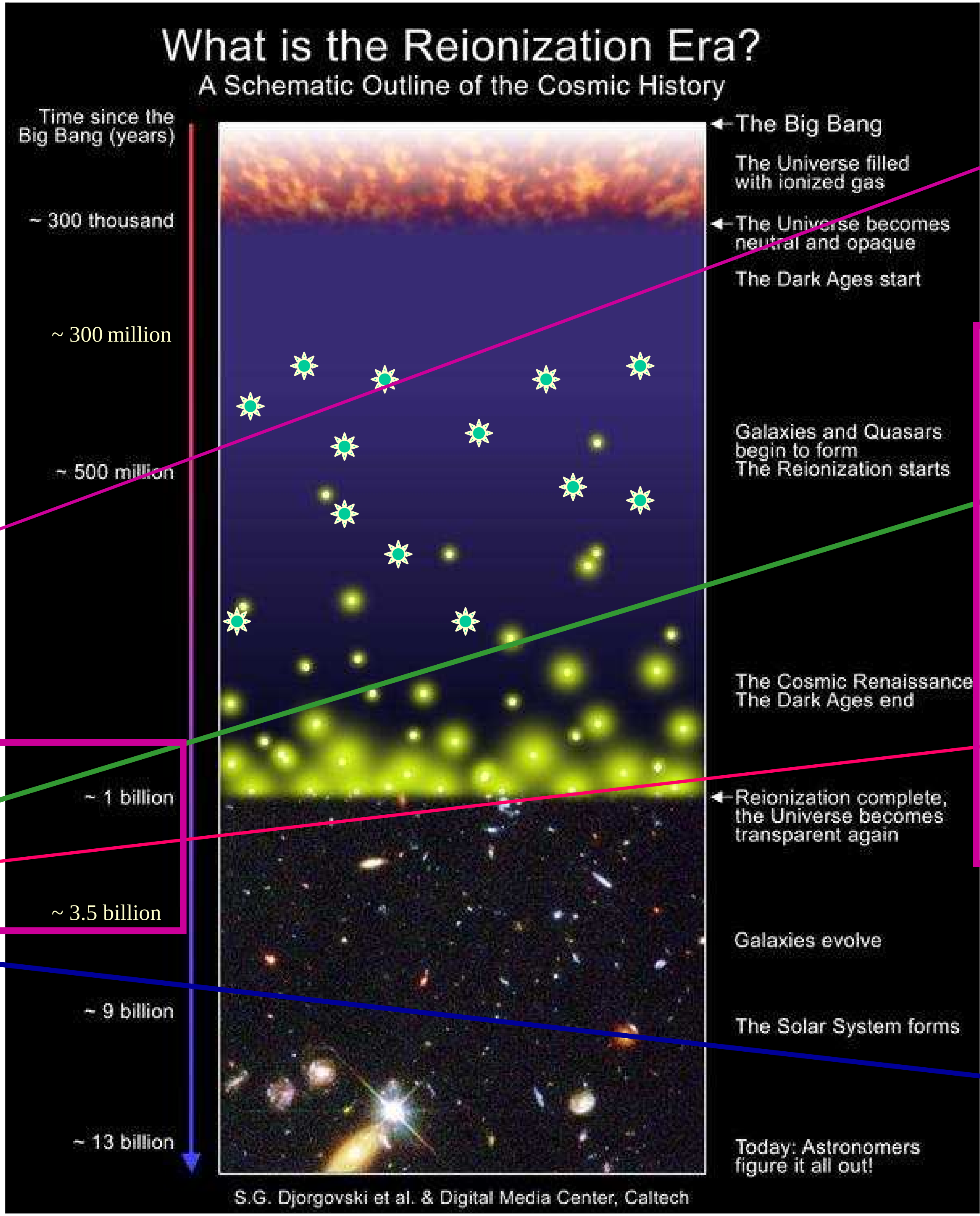


Redshifts of studied QSOs





z	D_{phot} (Gpc)
1000	
20	230
12	130
z= 6	60
z=2	16
0.5	3
0	



z ~ 7 – 20 ?
- Reionization
PopIII stars +1st galaxies
- Formation of 1st galaxies
Pop. II stars
- First AGN

z ~ 4 – 7 :
Current frontier
- Galaxies and QSOs detection
- End of reionization

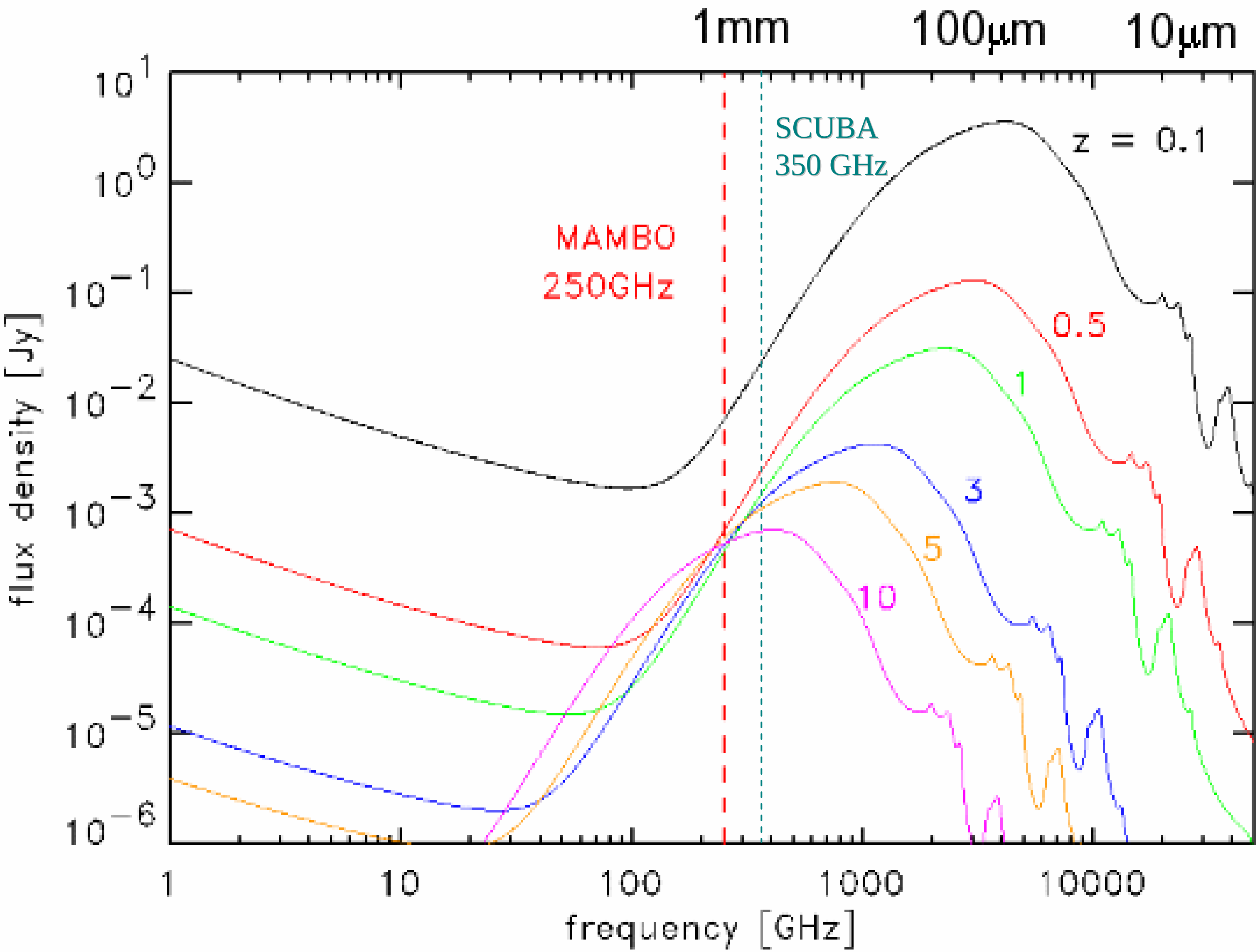
z ~ 1.5 -4:
- Peak of star formation
submm sources + LBGs
- Peak of QSO activity
Proto-cluster formation

z ~ 0.5-1.5 :
Final phase of active star formation
- ISOCAM sources
- Weak X-ray AGN
- Cluster formation

The high z mm-submm window

Very steep submm SED of ULIRGs

→ Sensitivity at ~1mm independent of z for 0.5 < z < 10 !



SCUBA(-MAMBO) census of high-z ULIRGs

- *Take advantage of steep submm spectrum*
- *Account for the whole submm background*
- *z at Keck for radio ones (~60%) (weak AGN ?)*

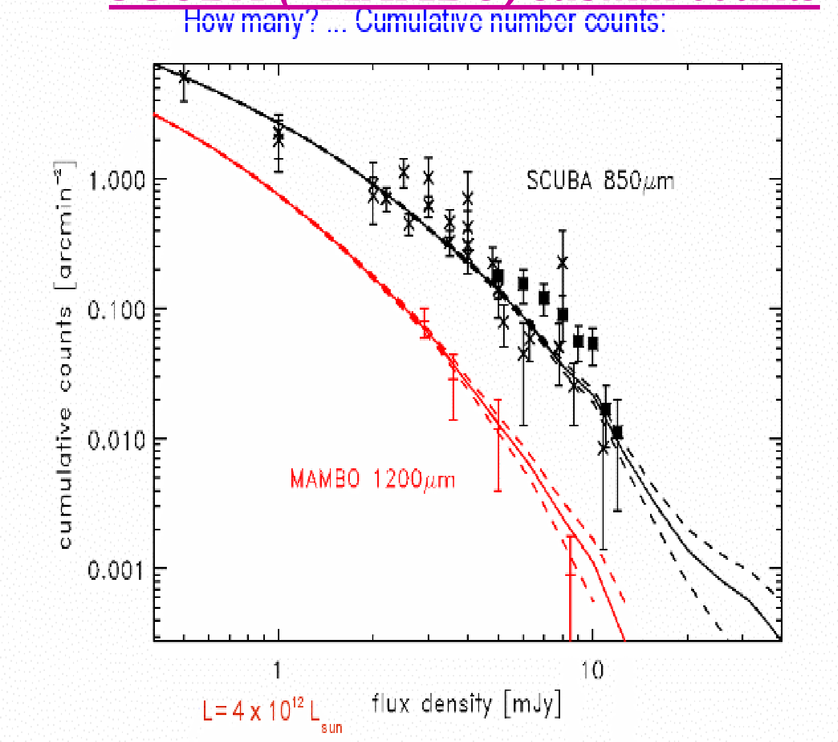
→ History of star formation up to z~3-4

- *Small but uncertain number at z>4*

→CO detected at IRAM-PdB in 8-10

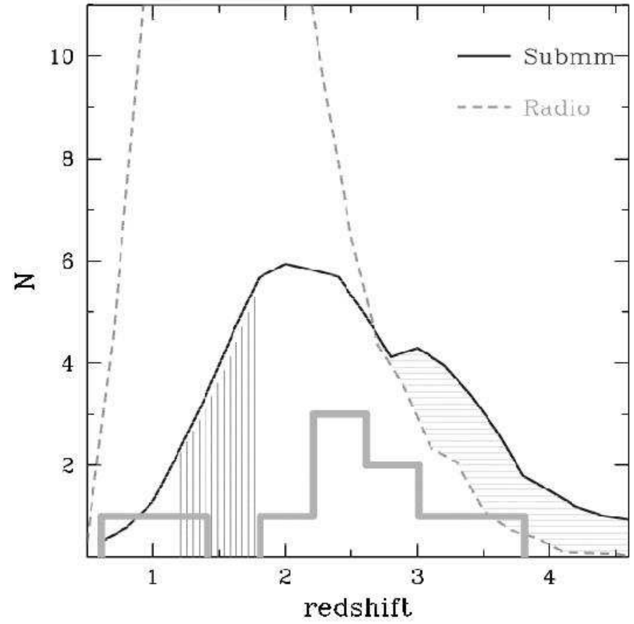
(Neri et al 2003)

SCUBA (+MAMBO) submm counts

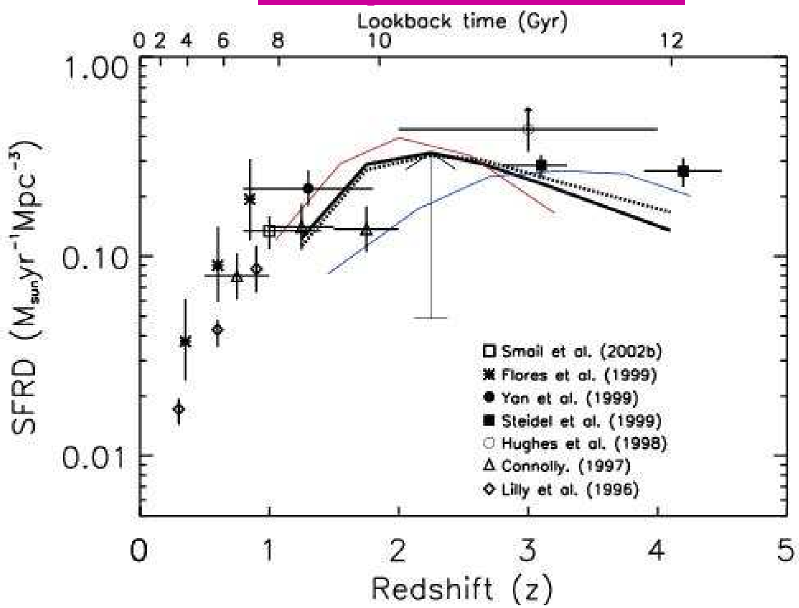


SCUBA(-radio) redshift distribution

Chapman, Blain, Ivison, Smail 2003



Star-formation rate



IRAM-30m/MAMBO 1.2 mm observations of bright high-z QSOs

1. Aims

- **Correlations between major starbursts and black-holes at high z**

  → black-hole/spheroid mass correlation

- **Easiest way to find (biased) cases of ULIRGs at very high z**

  Redshifts of SCUBA/MAMBO sources are difficult to determine and practically unknown at z > 4

  Better to search similar sources around known objects: (bright) QSOs or radiogalaxies *(Archibald et al. 2001)*

IRAM-30m/MAMBO 1.2 mm Observations of bright high-z QSOs

2. Sample

(Bright) QSOs (L_{bol} ~ 10^{13} -10^{14} Lo) with z~2-6, from optical surveys : PSS, SDSS, etc.

Range of redshifts : large sample at z>4 ; comparison at z~2 ; largest redshifts identified → z=6.4

Range of luminosities : M_B ~ -24 -28

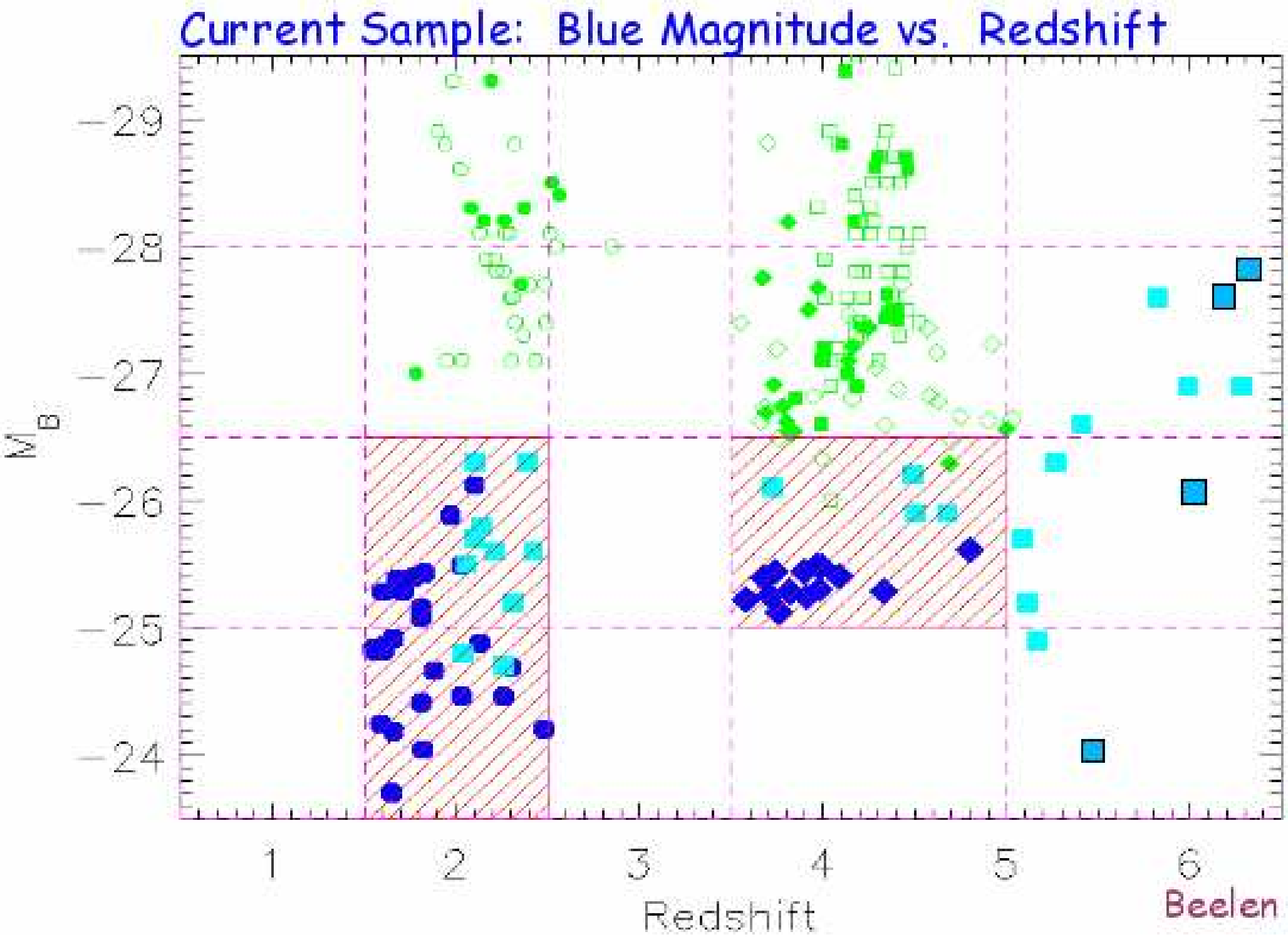
→

Omont et al. 1996 (+McMahon et aL. 1994) **small sample (20) APM etc.**
Carilli et al. 2001 **deep SDSS sample (41) at z > 4**
Omont et al. 2001 **bright PSS sample (62) at z > 4**
Omont et al. 2003 **bright sample (35) at z ~ 2**
Bertoldi et al. 2003 (+ Bertoldi & Cox 2002, Petric et al. 2003) **(6) highest z → 6.4**
Beelen et al. 2004 **extension to fainter luminosities (40) at z ~ 2 & z > 4**

Total ~ 200 observed sources

(Parallel studies with SCUBA: series of papers by *Priddey, Isaak, McMahon et al.*)

MAMBO survey: ~200 optically selected SDSS, PSS, PG quasars at z=1-6 to study dust and molecular gas.



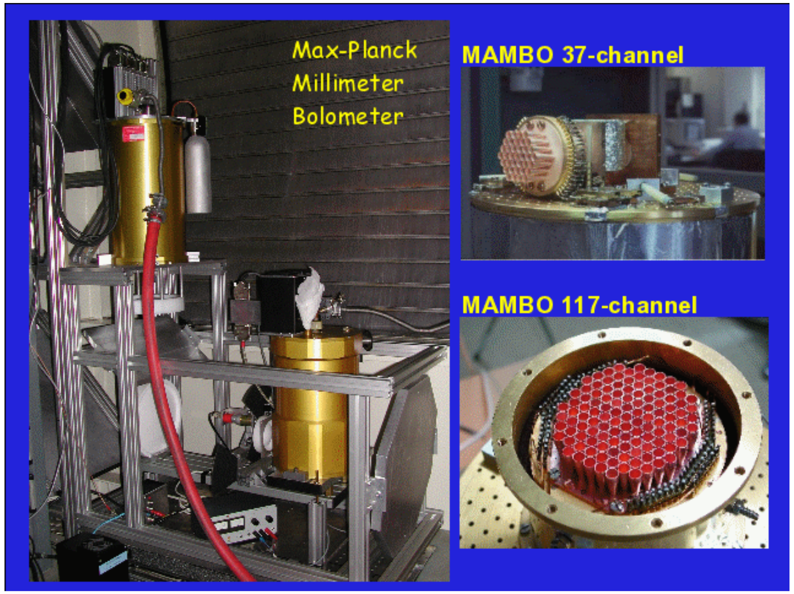
Beelen et al. 2002

IRAM-30m/MAMBO 1.2 mm Observations of high-z bright QSOs

3. Observations

IRAM 30m Telescope
Pico Veleta (Granada, Spain)
11'' beam
Reasonably good pointing accurracy ~2''
Wobbling secondary mirror

MAMBO bolometer cameras
Built at MPIfR Bonn *(E. Kreysa group)*
37 → 117 channels
Pointed observations on central channel
Good sky substraction with other channels
(MOPSI software Zylka, Bertoldi, etc.)



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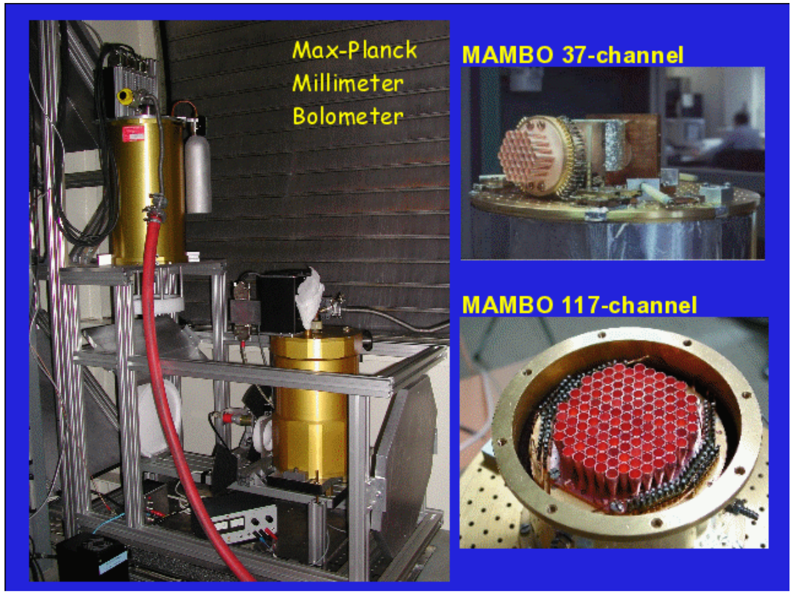


rms ~ 30 mJy in 1 sec.
Average rms ~0.6-0.7 mJy → 2h per source
Several hundreds of hours of observation

IRAM-30m/MAMBO 1.2 mm Observations of bright QSOs

4. Summary of results

High rate of detection : ~55 sources detected→ ~ 25%

Strong propensity to the presence of interstellar matter (dust) around active massive black holes → fuel of QSO activity, black-hole/bulge coeval growth

→ → →

- **No significant dependence on z**
- **Small dependence on L_{opt}**
- **Evidence for DUST emission**
- **Starburst or AGN dust heating ?**
- **Arguments for substantial contribution from starburst**

→→→

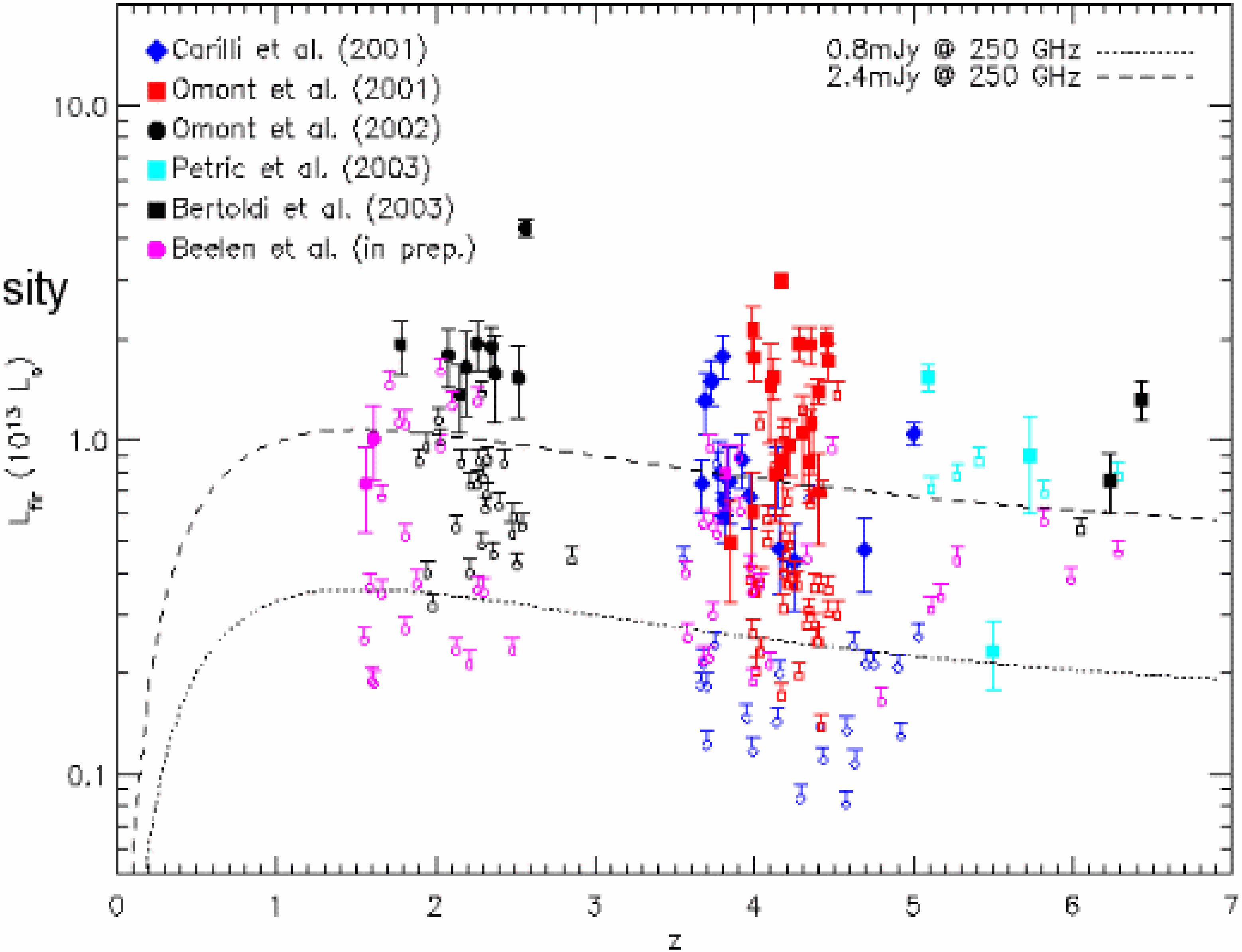
Prominent sources: BR 1202-725 z=4.7, PSS 2322 z=4.1, SDSS J1148 z=6.4, etc.

(→→→

CO search at IRAM or VLA → C. Carilli)

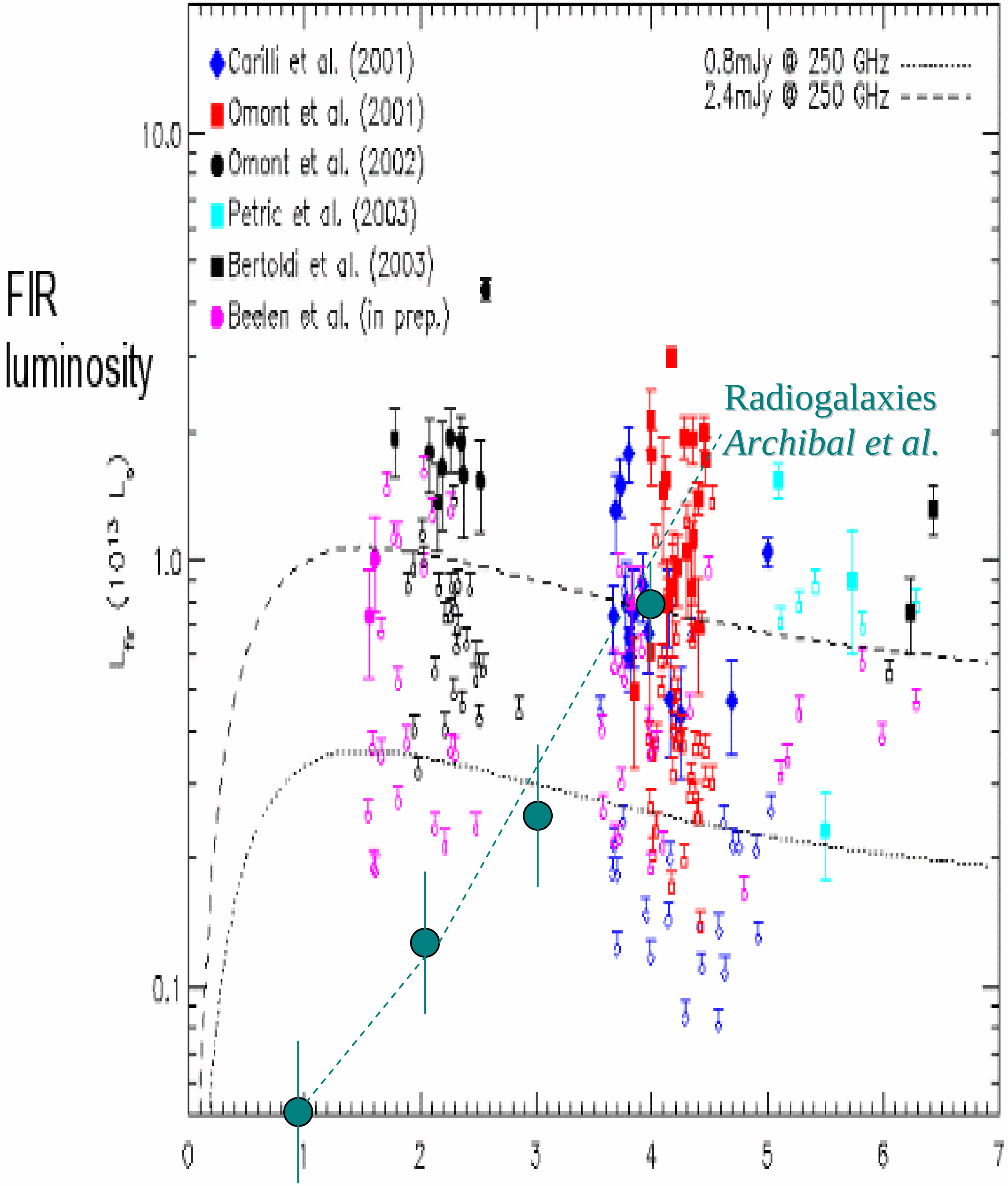
FIR flux (estimated) vs. redshift

FIR luminosity



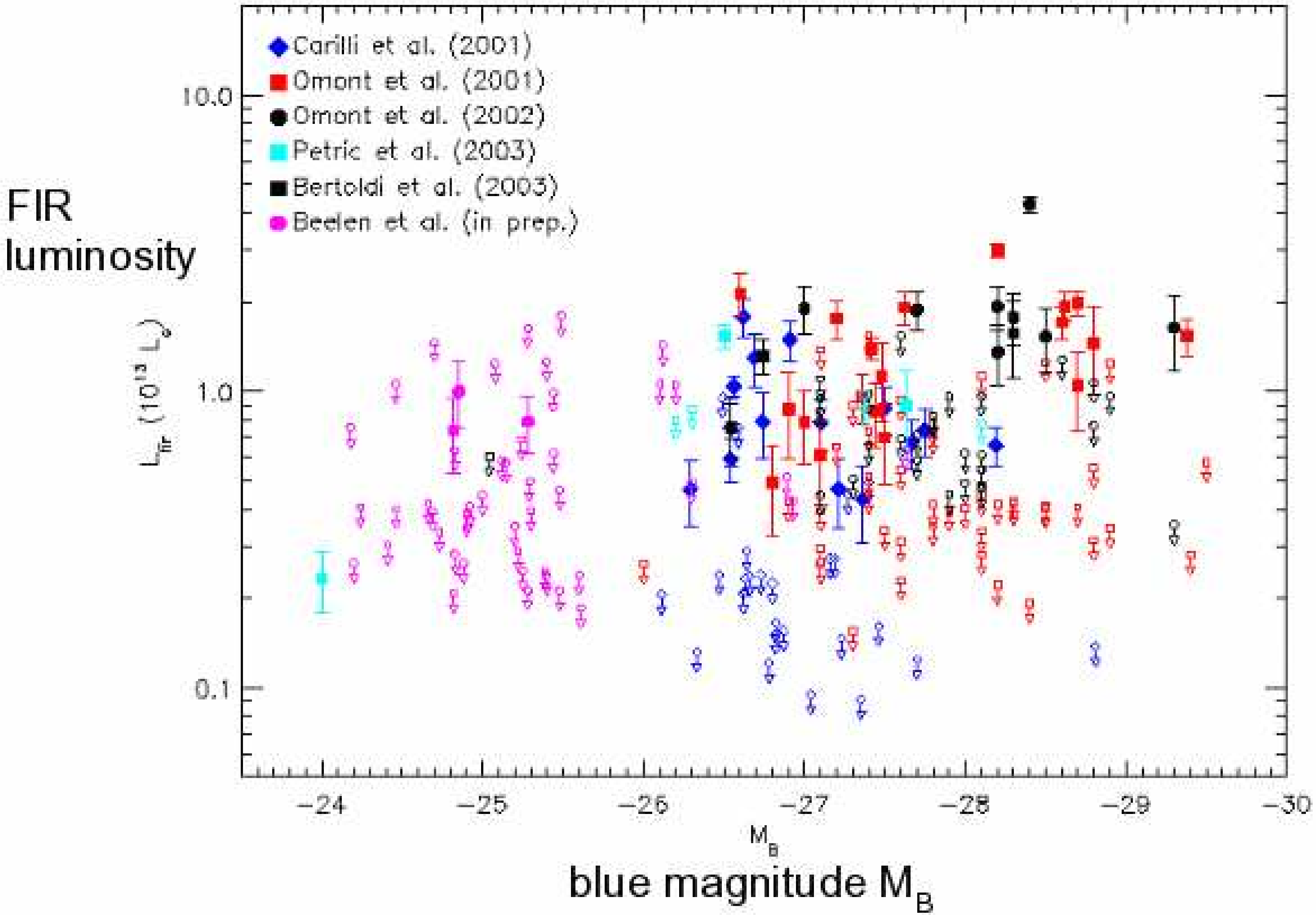
redshift

No significant dependence on redshift

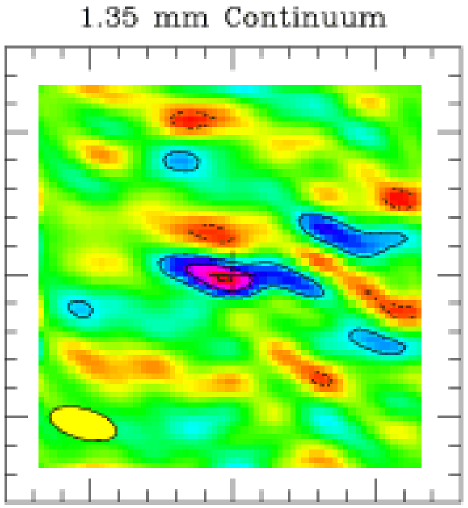


The redshift behavior of L_{FIR} is very different from radiogalaxies where a strong increase with z is observed by Archibald et al.2001

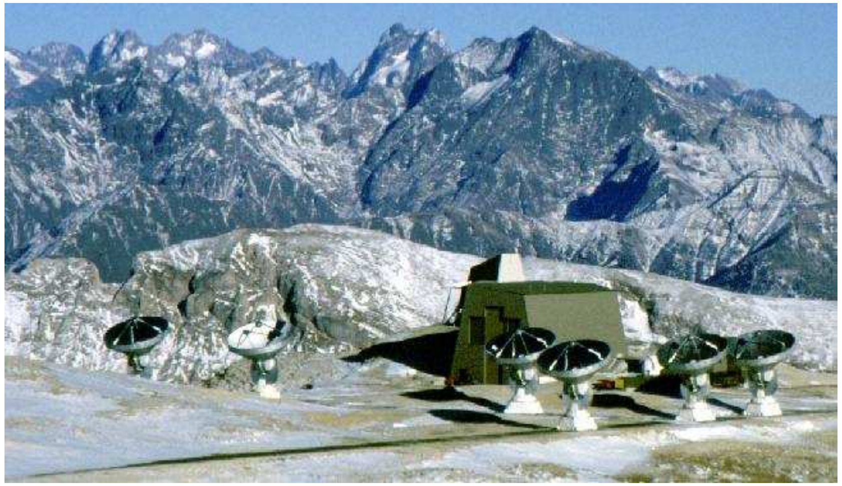
FIR is ~~not~~ weakly correlated with rest-UV



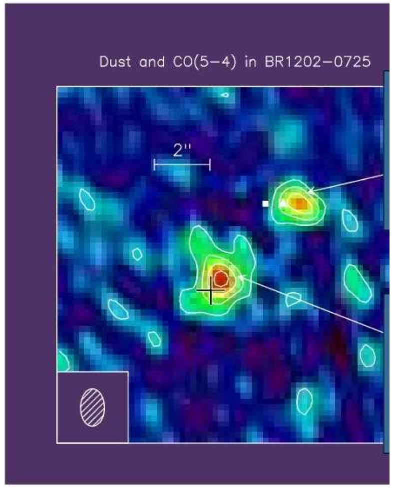
Information from high angular resolution 1.3 mm dust observation



PSS 2322



IRAM Plateau de Bure Interferometer



BR1202-0725

- **1.3 mm dust detection at IRAM interferometer in more than 10 high z QSOs**
- **In most cases emission not resolved with 1-2'' resolution (or not detected)**
  In some cases PdB intensity significantly smaller than MAMBO-30m intensity
  → weak emission partially extended vs 2'' ??
- **A few resolved lensed objects:**
  - Spectacular : Cloverleaf, APM0855 ….
  - Marginally extended : BR0952, PSS2322 *(Cox et al. 2002)* ….
- **The unique case of BR1202-0725 with 2 strong sources 4'' apart *(Omont et al. 1996)***
  → (complex) lens or two (merging) ULIRGs ??

Dust emission from the most distant quasars

Bertoldi et al. 2003

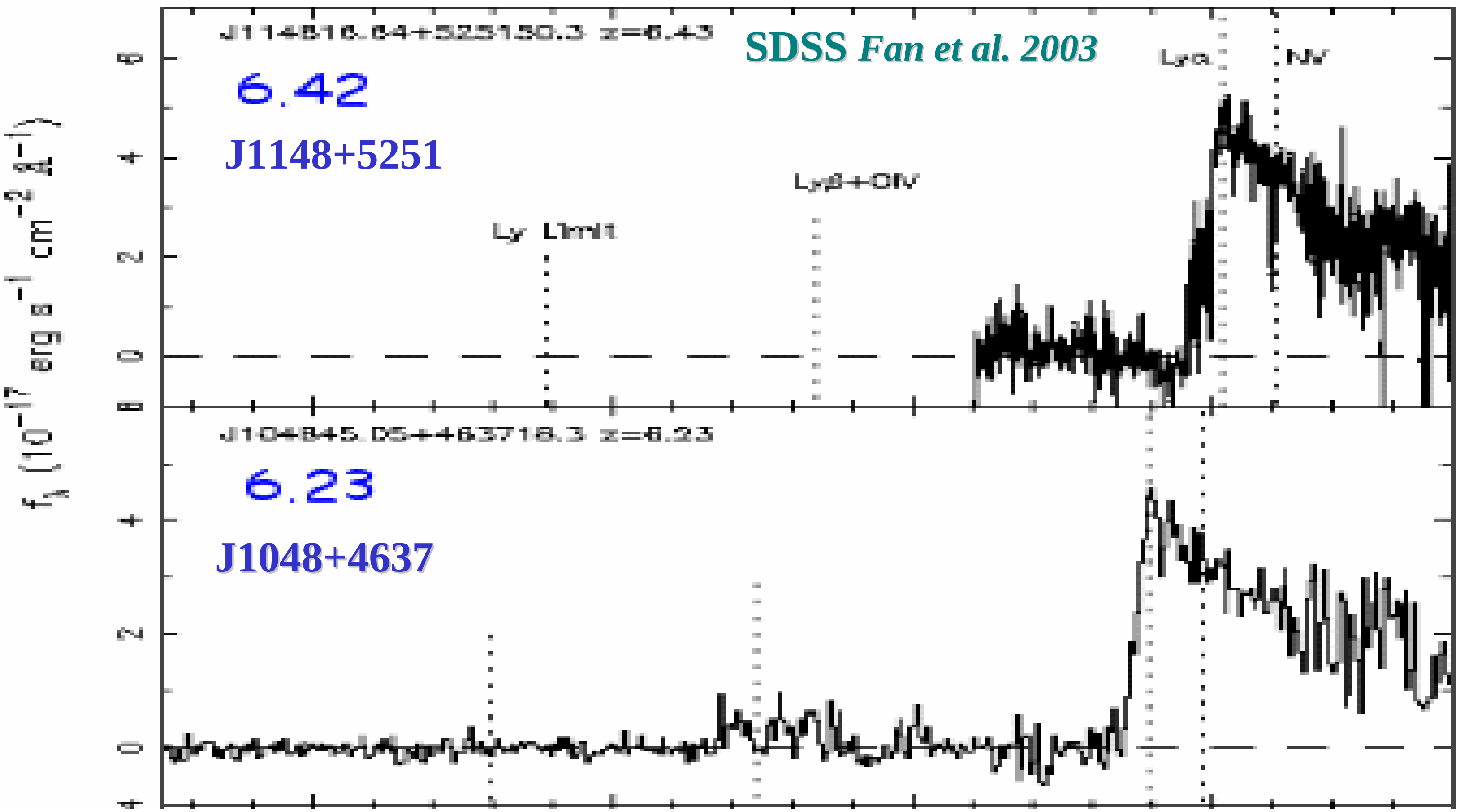
S_{250GHz} = 5.0 & 3.0 mJy

→ L_{FIR} ~ 10^{13} Lo (uncorrected for possible moderate lensing)

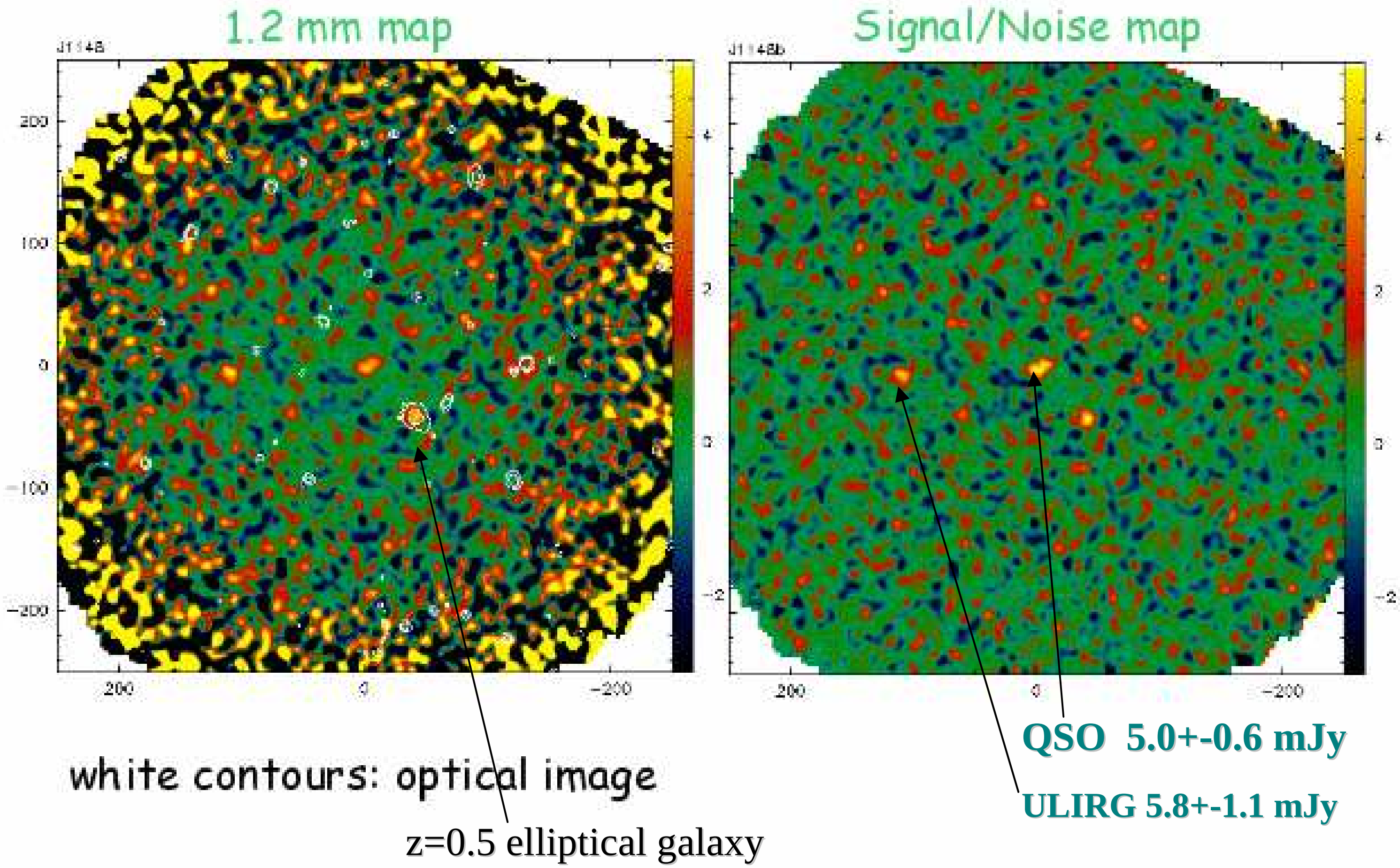
→ M_{dust} ~ 10^{8} Mo at t ~ 0.8 Gyr → Rapid metal enrichment

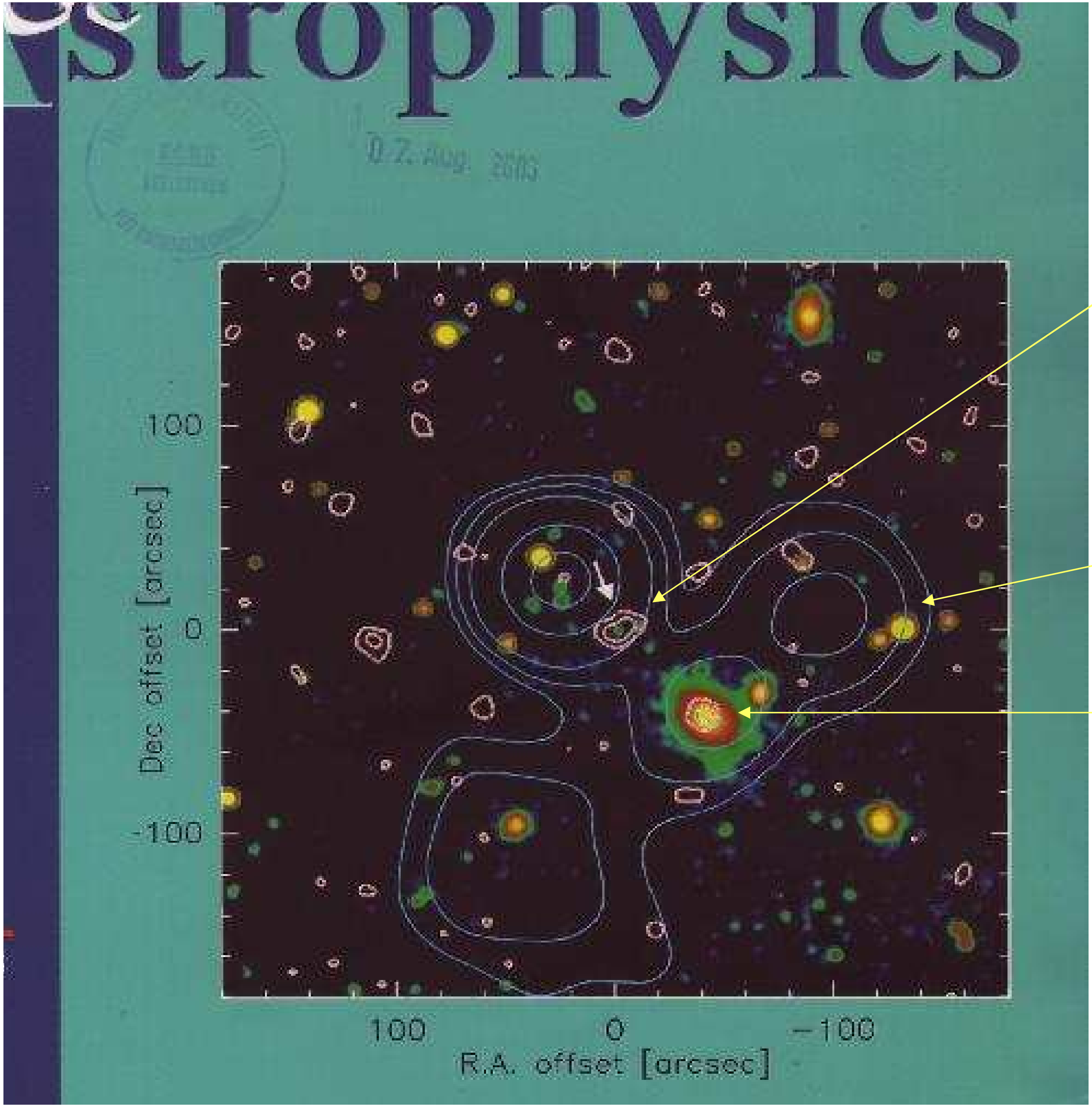
→ Dust formation in supernovae or Pop III stars

+ CO detection (→ C. Carilli)



MAMBO imaging observation of J1148





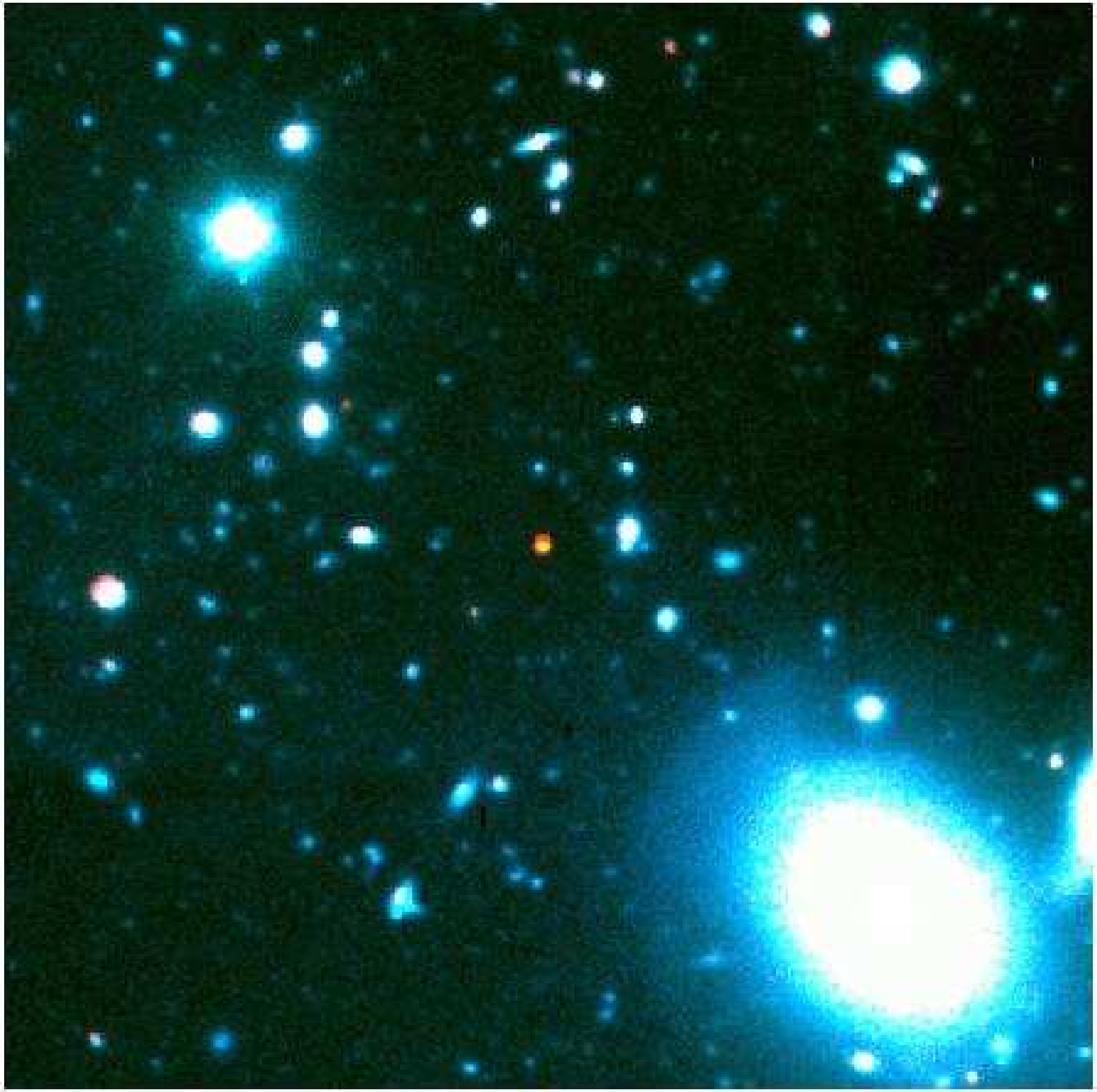
SDSS J1148+5251

Mambo 1.2mm (contours) on z' SLOAN image

Dust at z=6.42 !

1.4 GHz radio VLA-NVSS

Elliptical galaxy at z = 0.05



Keck K'

CONFIRMATION OF DUST ORIGIN OF THE EMISSION

- **Flux ratios 850 μm / 1.2 mm characteristic of dust**

SCUBA : Isaak et al. 2002, Priddey et al. 2003

- **Flux ratios FIR / radio comparable to local ULIRGs**

VLA : Carilli et al. 2001, Petric et al. 2004, Beelen et al. 2004

- **Many are confirmed as radio quiet from deep VLA observations**

Carilli et al. 2001, Petric et al. 2004, Beelen et al. 2004

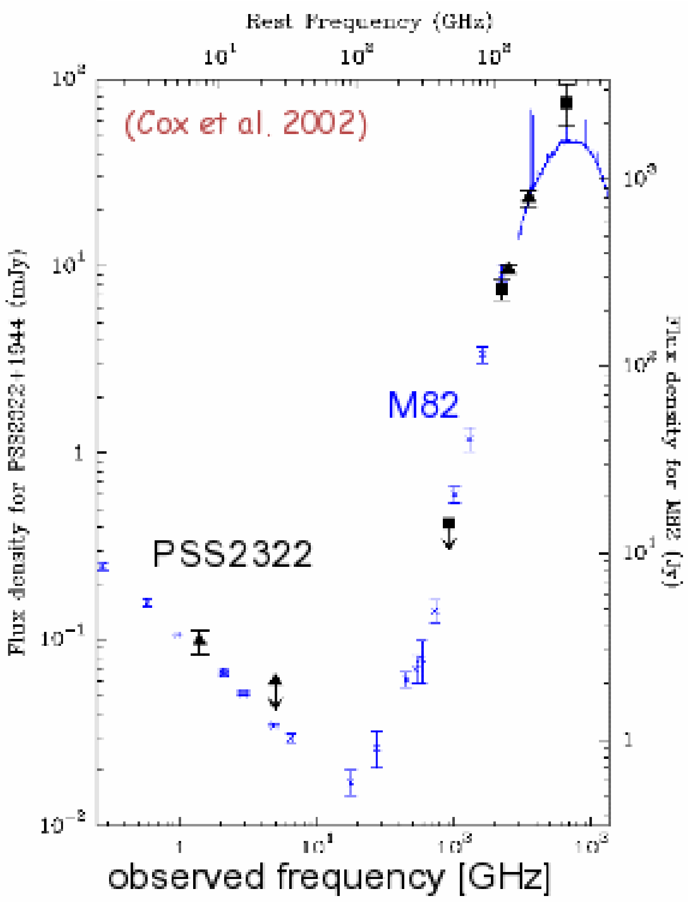
- **A few are found weakly radio loud, but dust emission confirmed**

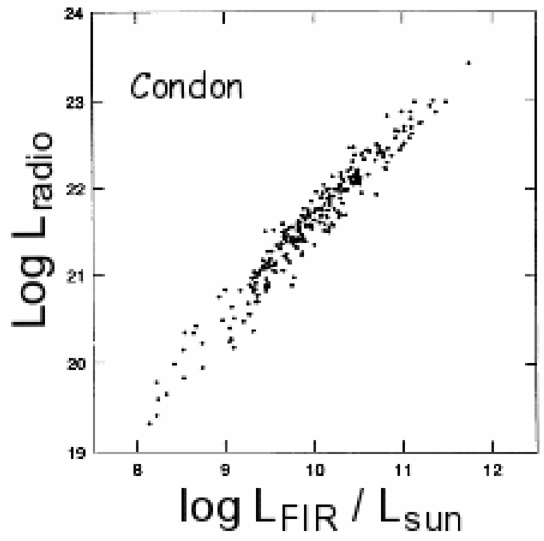
Carilli et al. 2001

- **Radio to mm Spectral Energy Distribution (SED) very comparable to templates of starburst dust emission : M 82, etc.**

Cox et al. 2002

SED from radio to submm of bright QSO PSS2322 at z=4.1 is in good agreement with standard SED of the template local Luminous IR Galaxy M 82



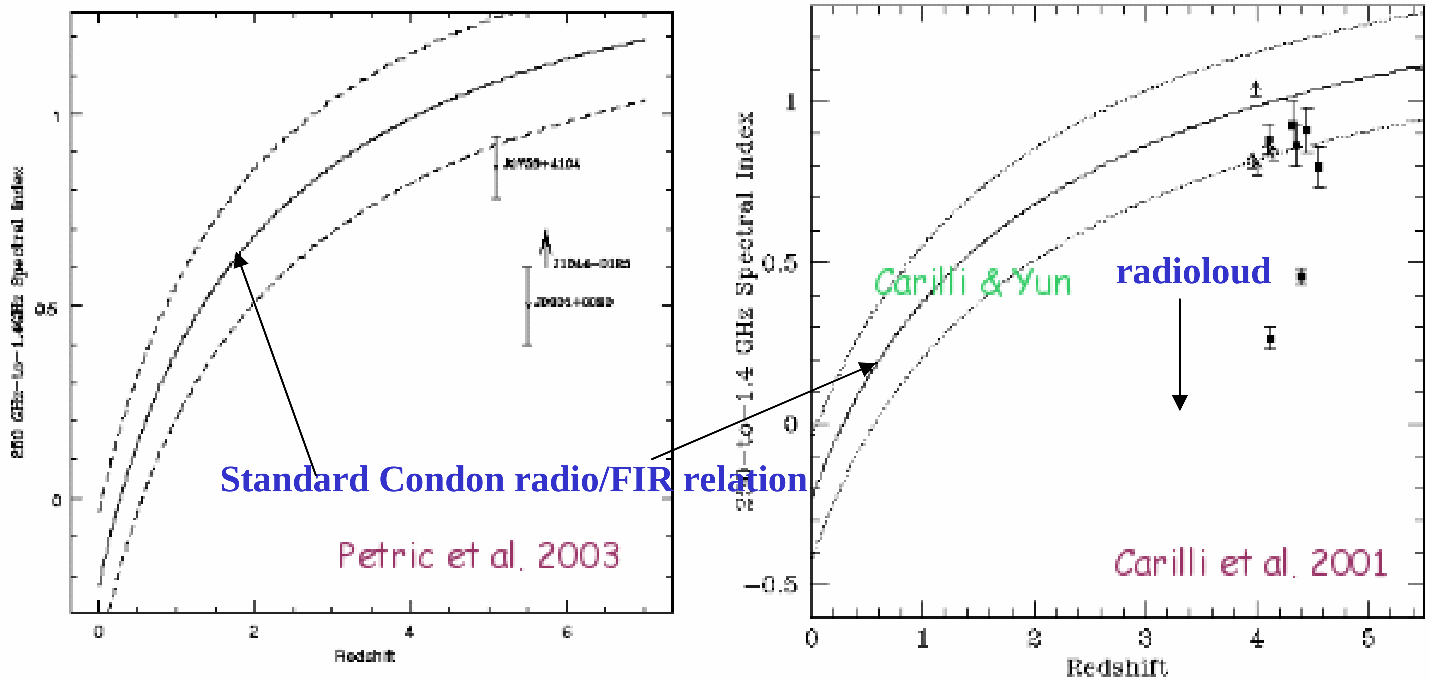


Proportionality of radio (synchrotron) and far-IR (dust) luminosities of star forming regons/galaxies on 4 orders of magnitude

Radio to mm relation at z > 4

	radio-loud	50-100 μJy	<100 μJy
Carilli et al. 2001: 12 QSO at z = 4-5	2	5	5
Petric et al. 2003: 10 QSO at z = 5-6.3	2	2	8
	4	7	13

250 GHz to 1.4 GHz spectral index



DUST TEMPERATURE & FAR-INFRARED LUMINOSITY

mm/submm emission dominated by cold dust at 30-50 K

(Benford et al. 1999, Priddey & McMahon 2001)

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mm/submm emission dominated by cold dust at 30-50 K

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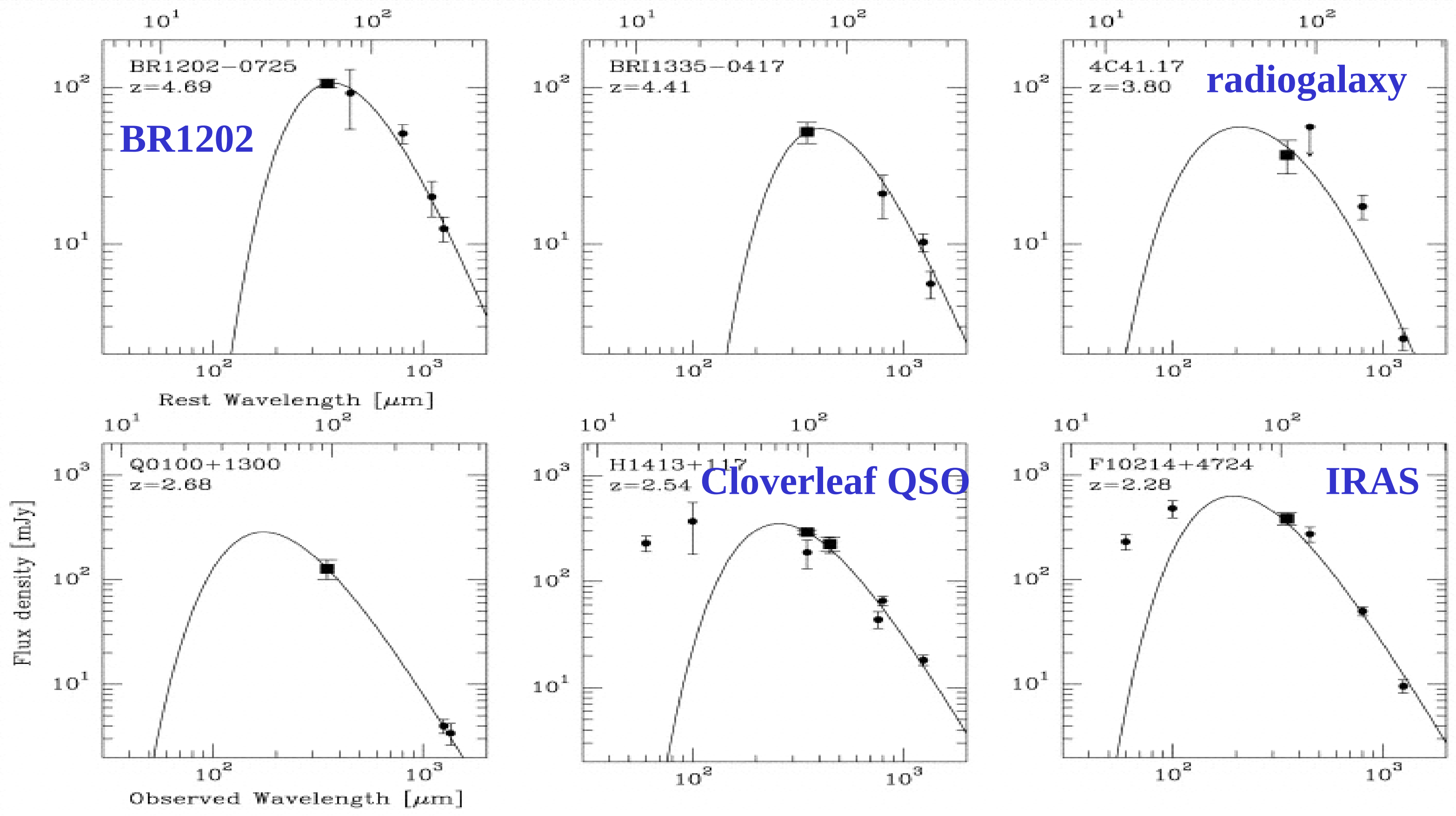
FIR-submm Spectral Energy Distribution of high-z AGN

Benford et al. 1999 **→ T_{dust} ~ 40-50 K (→ 100 K)**

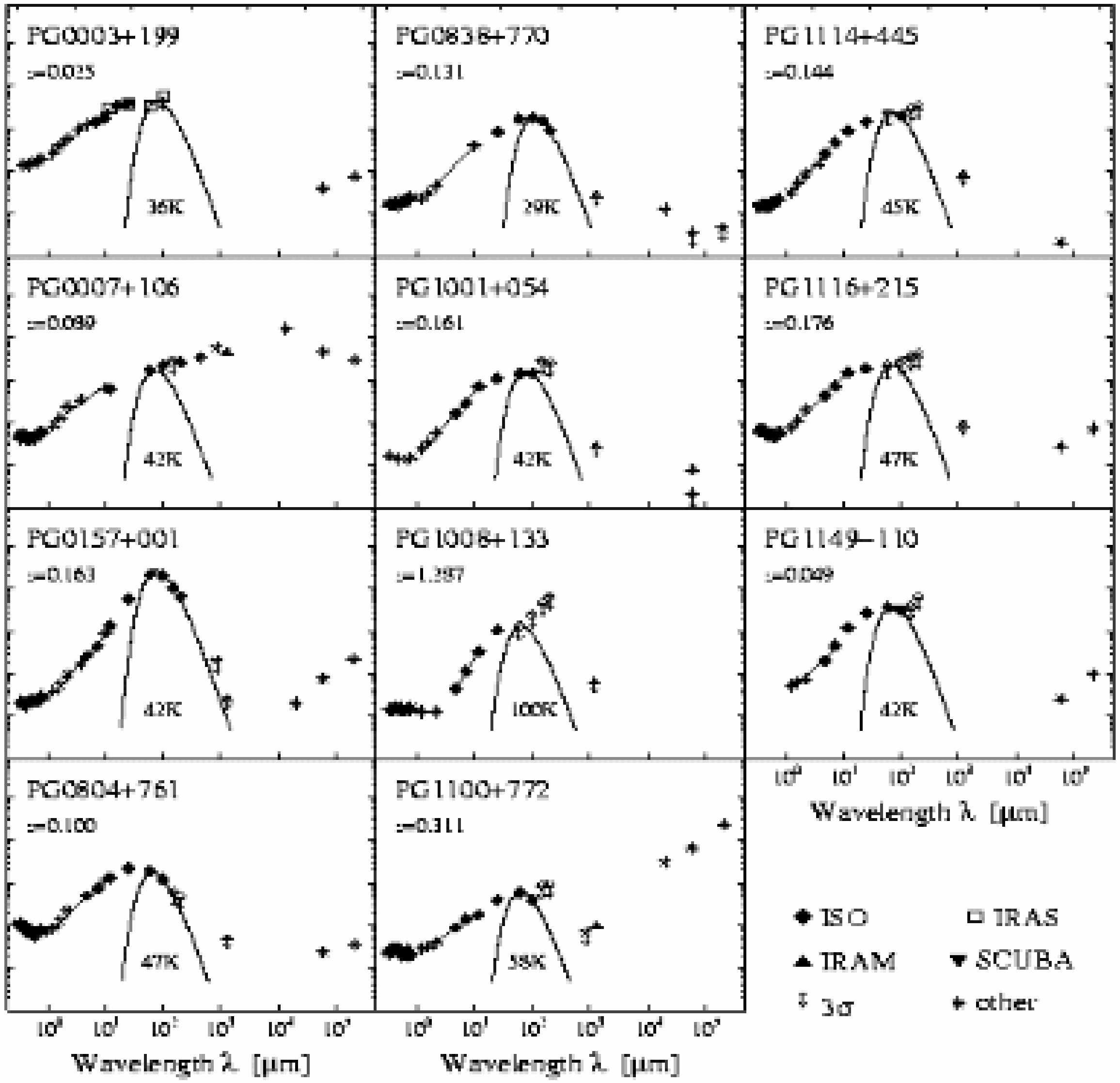


mparison

SED of QSOs and Radio Galaxies *(local)*

n & cold dust

Haas et al. 2003



Haas et al. 2003

DUST TEMPERATURE & FAR-INFRARED LUMINOSITY

mm/submm emission dominated by cold dust at 30-50 K
(Benford et al. 1999, Priddey & McMahon 2001)

→ L_{FIR} ~ 3-4 10^{12} ($S_{1.2mm}$ / mJy) Lo → ~ 10^{13} Lo

- Comparable to brightest SCUBA sources
- Typically ~ 0.1 L_{opt}

- Probably at a few 100 pc to ~1 kpc from the center
- (no direct relation with AGN obscuration by very close dust)

- (possibility of :
  - warmer closer dust component : seen in mid-IR *Haas et al., Freudling et al.,etc.*
  - colder dust component, farther out)

MASS OF DUST

- Typically ~ 10^8 Mo
- But inversely proportional to uncertain dust emissivity
- → M_{H2} ~ a few 10^{10} Mo

WHICH HEATING FOR COLD DUST ?
→ FAR-IR LUMINOSITY ?

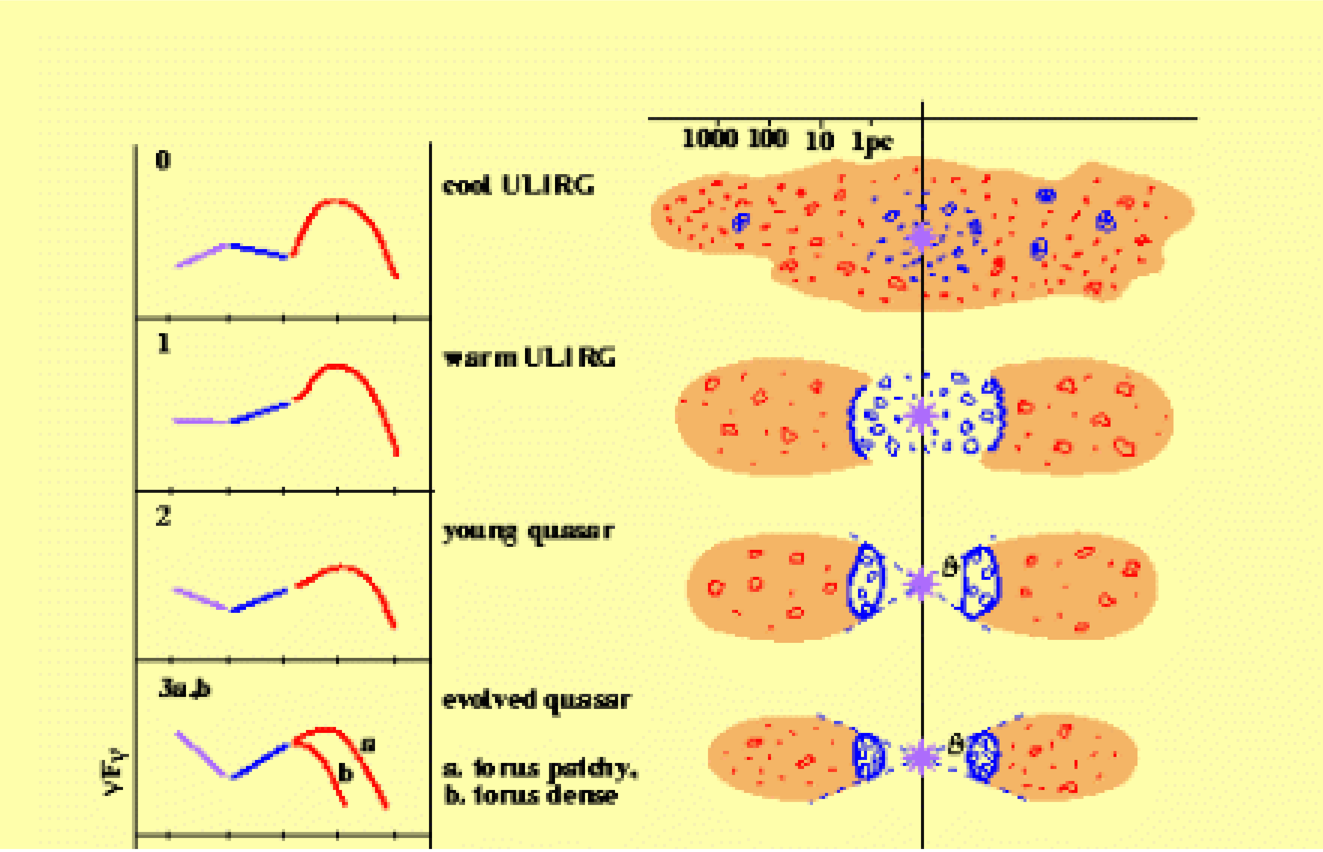
STARBURST OR AGN ?

Both are viable :

- **For AGN heating :**

(see e.g. Sanders et al. 1989, Andreani et al. 1999, Willott et al. 2002, Haas et al. 2003, Freudling et al. 2003, etc.)

- **L_{FIR} is only a tiny fraction of L_{bol} (~0.1)**
- **Possible to imagine adequate geometry/ UV radiative transfer**
- **Higher T (>~100 K) dust detected in far/mid-IR must be heated by the AGN**



Models of AGN strong dust emission by Haas et al. 2003

Haas et al. 2003

• <u>Starburst powering of dust heating</u>

• Is known to dominate in most local and high z ULIRG's (where $L_{FIR} \sim 10^{12}$ Lo) :

- ISO spectroscopy (Genzel et al., etc.)
- Correlation of L_{FIR} with CO and with radio
- No X-Ray detection of most SCUBA sources

• Extension to $L_{FIR} \sim 10^{13}$ Lo is possible in exceptional objects : central collapse or major merging in massive ellipticals ?

• → Arguments for a <u>substantial starburst contribution</u> to heating of cold dust in millimeter detected high z QSOs :

- Correlation with CO in strong sources above CO detection limit
- Correlation with radio intensity seems rather general
- Large starbursts are needed to quickly synthesize stars and metals

WHICH HEATING FOR COLD DUST ?
→ FAR-IR LUMINOSITY ?

STARBURST OR AGN ?

Conclusions

- **Both are viable**

- **Probably a combination of both in various proportions**

- **Proportions may depend on redshift, with more starburst at z > 4 than at z ~ 2 ? as for radio-quasars/radiogalaxies** ***(Willott et al. 2002)***

- **But some starburst probably always present in 1.2mm detected sources**

FRACTION OF TYPE I QSOs AMONG SCUBA/MAMBO SOURCES

- Density of SCUBA/MAMBO sources with $S_{1.2mm}$ > 2 mJy : ~ 1000/deg^2

- Density of SCUBA/MAMBO AGN with $S_{1.2mm}$ > 2 mJy : >~ 100 - 150 /deg^2 ?

- Density of detectable (25%) QSOs with M_B < -26.5 : ~ 0.5 /deg^2

- Detection rate smaller at M_B ~ -24 –25

→ Density of all detectable Type I QSOs with M_B < -23 uncertain but smaller than SCUBA AGN density

PROPECTS : IMMEDIATE FUTURE

SCUBA, MAMBO → SMA, APEX, SIRTF
→ CARMA, E-IRAM, LMT, BLAST…

Systematic characterisation of highest z AGN (sub)mm emission

- **Cold Dust : → tracer of molecular gas**
- **(+ CO : → confirmation of starburst, ΔV, T_{gas} → *C. Carilli*)**
- **→ parallel growth of Bulge & Black Hole**

→ Cold dust in classical optical QSOs

- **Improve statistics on whole range of M_B down to ~ -23**
- **Peculiar classes: (BAL *Willott*), red, weakly radioloud**
- **Further studies at z<~1 (+radio *Mohan*)**
- **SEDs with SIRTF**

→ Cold dust in X-ray AGN, various classes:
Optical, Obscured, Type 2, …

→ CO in most luminous dust emitters


APEX: the Atacama Pathfinder Experiment
12 m modified ALMA prototype, built by Vertex
18 μm surface accuracy
18" resolution @ 870 μm
0.5° maximum field of view
first light soon
Max-Planck-Institut für Radioastronomie
ONSALA RYMDOBSERVATORIUM
CHALMERS TEKNISKA HÖGSKOLA
ESO
ASTRONOMISCHES INSTITUT

FARTHER FUTURE

New Facilities: ASTRO-F, HERSCHEL, (WIDE) ...

DOMINATED BY ALMA

- 64 movable 12-meter antennas in submm site
- Sensitivity gain ~ 100 / existing equipment
- >~1000 in imaging speed

ALMA at Chajnantor

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New Facilities: ASTRO-F, HERSCHEL, (WIDE) ...

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- 64 movable 12-meter antennas in submm site
- Sensitivity gain ~ 100 / existing equipment
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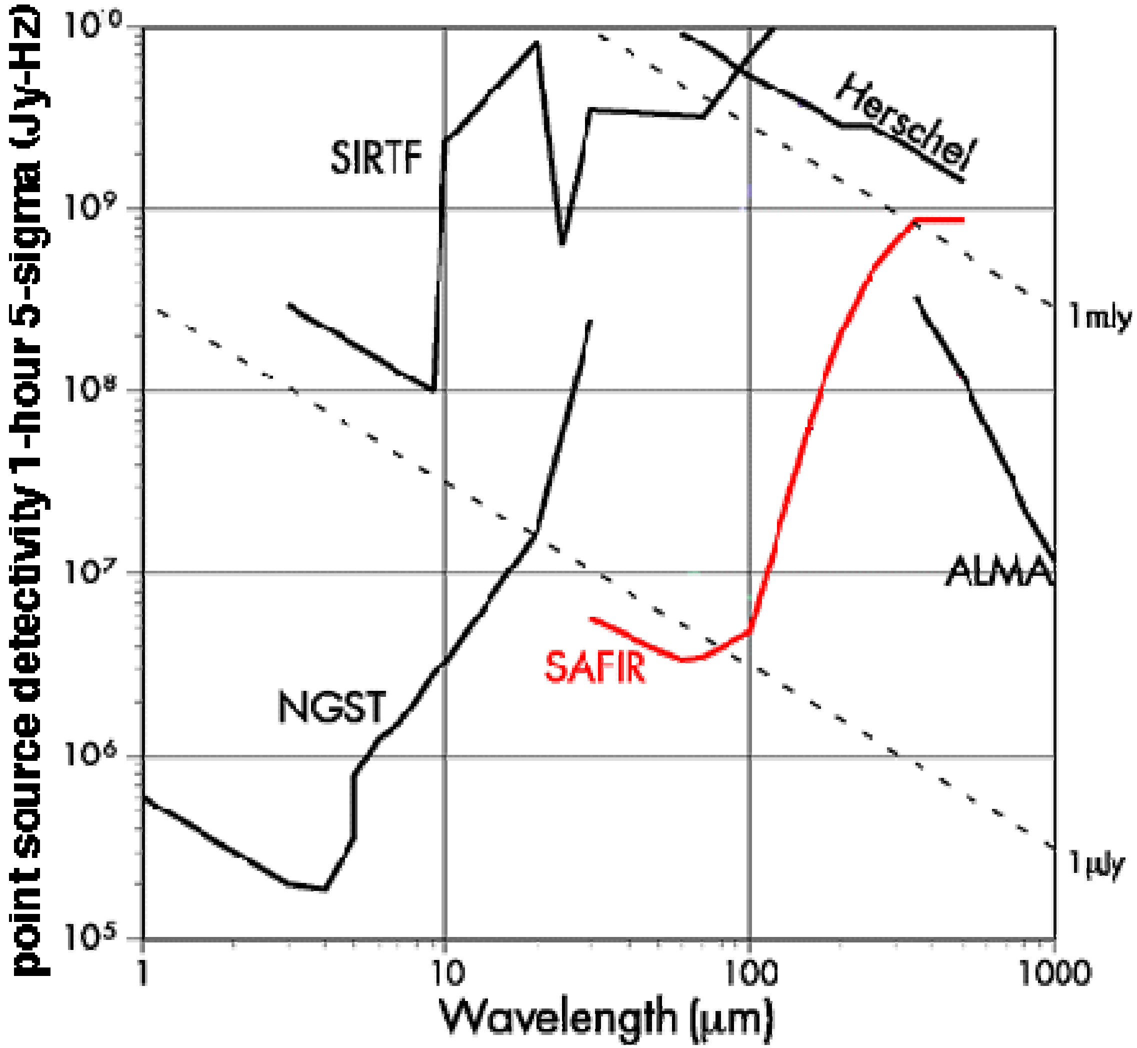
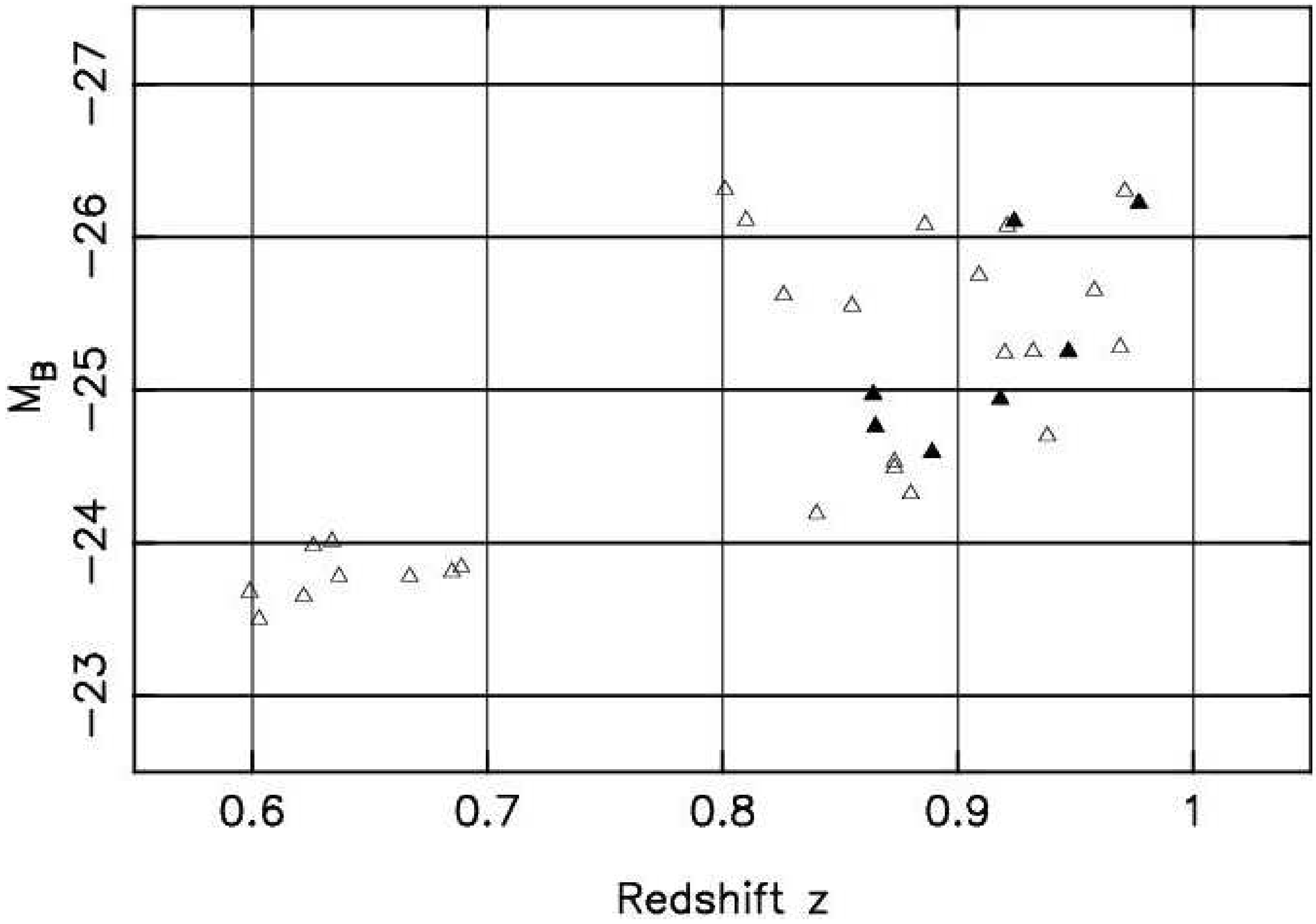
- Higher frequency → T_{DUST}
- CO + Dust detection in ALL QSOs & radiogalaxies → highest z
- C^+, CI and other molecules
- Spatially resolved / Velocity
- Companions, proto-clusters
- Lensing


point source detectivity 1-hour 5-sigma (Jy-Hz)
10¹⁰
10⁹
10⁸
10⁷
10⁶
10⁵
1
10
100
1000
Wavelength (μm)
SIRTF
Herschel
1 mJy
1 μJy
ALMA
NGST
SAFIR



−27
−26
−25
−24
−23
M_B
0.6
0.7
0.8
0.9
1
Redshift z