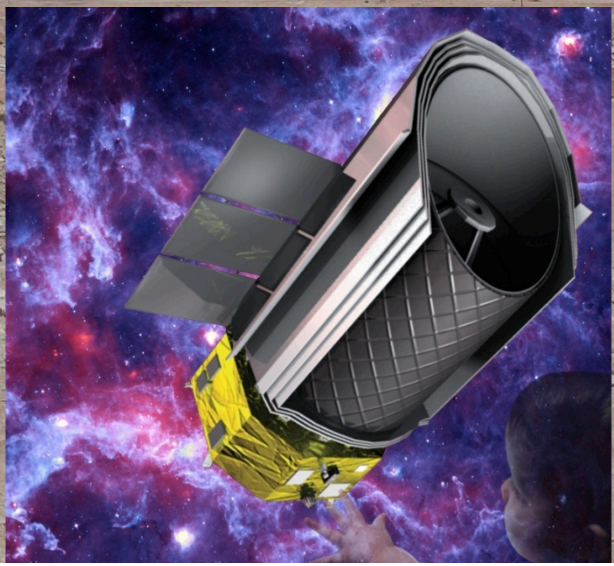
Formation and evolution of galaxies explored with SPICA and ALMA



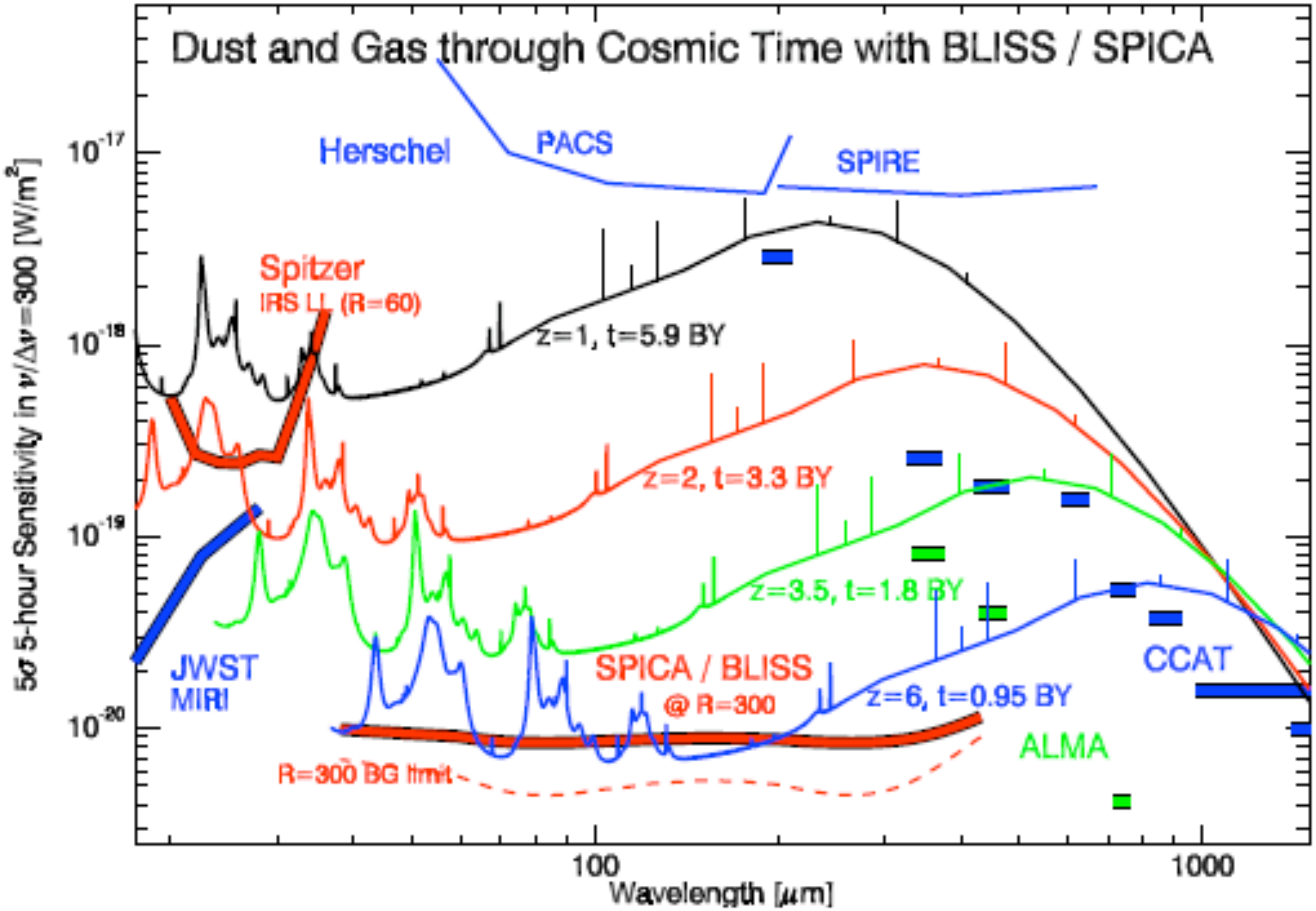
Kotaro KOHNO
（Univ. of Tokyo）

December 16-17, 2010, NAOJ, Mitaka, Japan

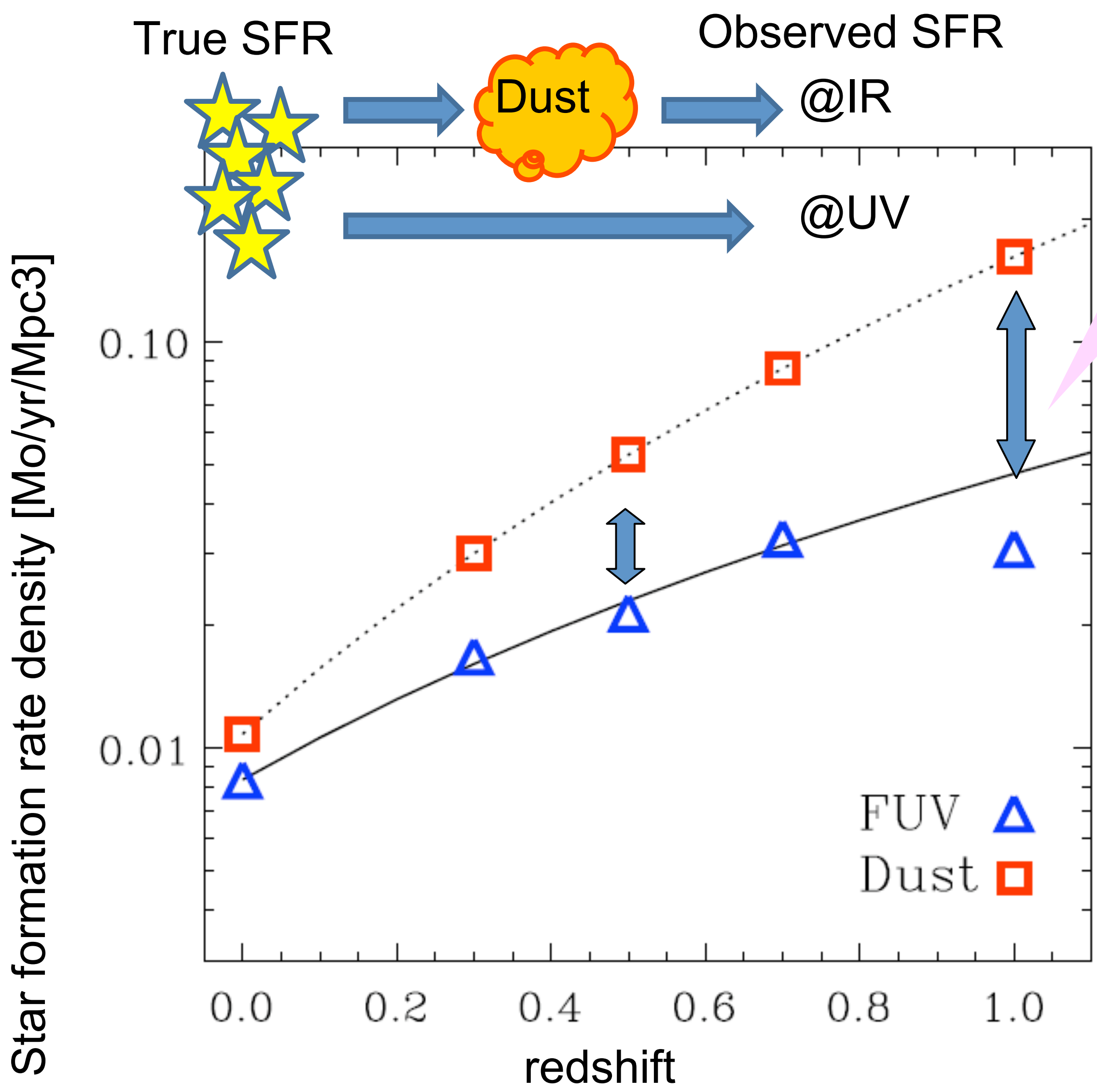
SAFARI+BLISS+ALMA strategy

- Blind imaging-spectroscopic survey with SAFARI: up to z~2 ULIRGs/SMGs
  - Best suited for z~2 cluster studies
- Targetted sensitive spectroscopy with BLISS: up to z~4 ?? ULIRGs/SMGs   we need BLISS !
  - Physical properties of ionized gas (PDRs, HII regions, coronal regions) with FIR fine structure lines
  - Very high-J CO
- Detailed (subarcsec or better resolution) imaging study of spectroscopically confirmed high-z ULIRGs/SMGs + molecular gas

Sensitivity is the issue for high-z !!!



A large portion of the cosmic star formation is obscured by dust

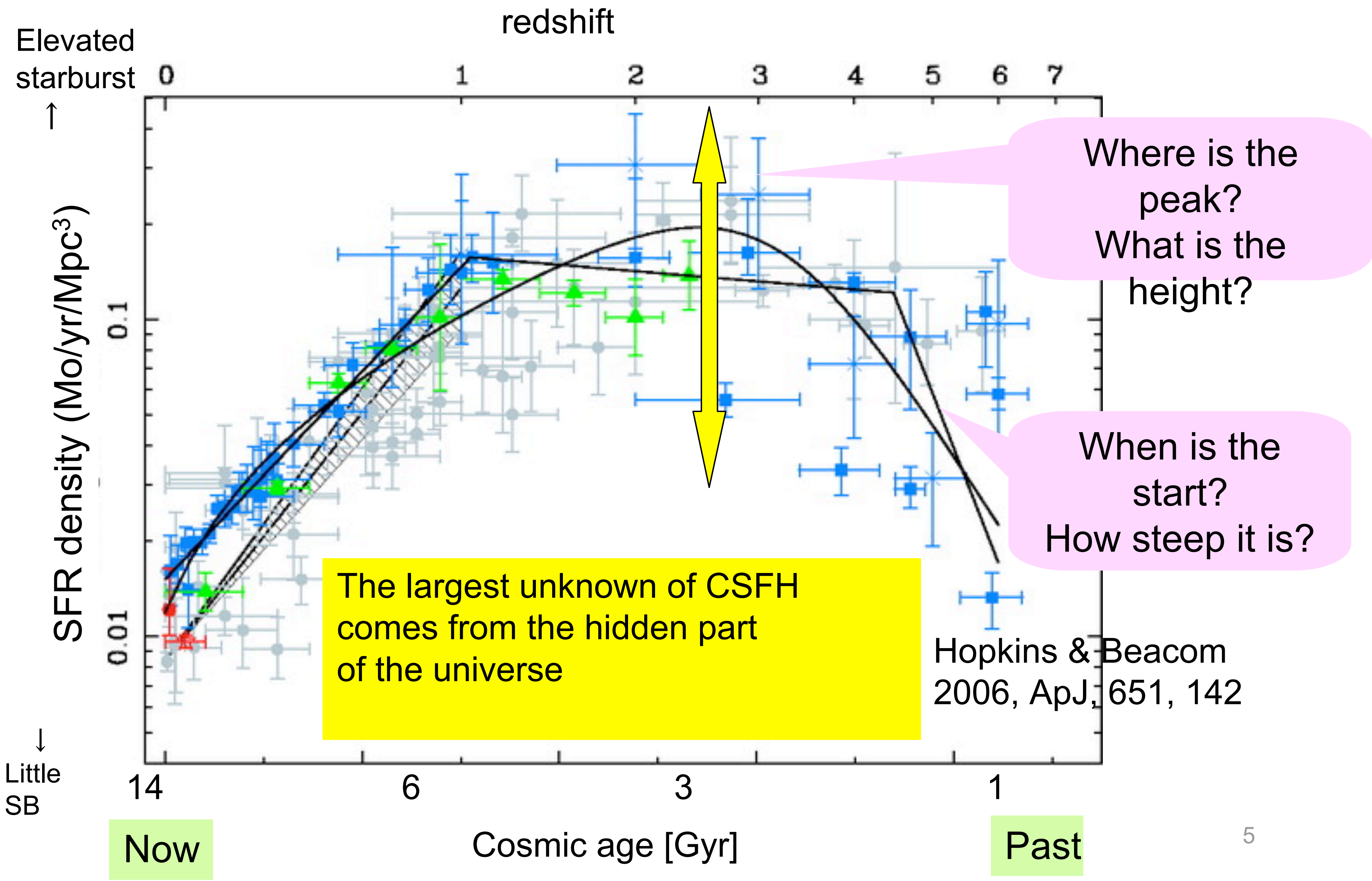


More hidden star formation @higher redshift (>70% at z~1)

Based on the comparison of lum. functions at FUV with GALEX & IR with IRAS/Spitzer

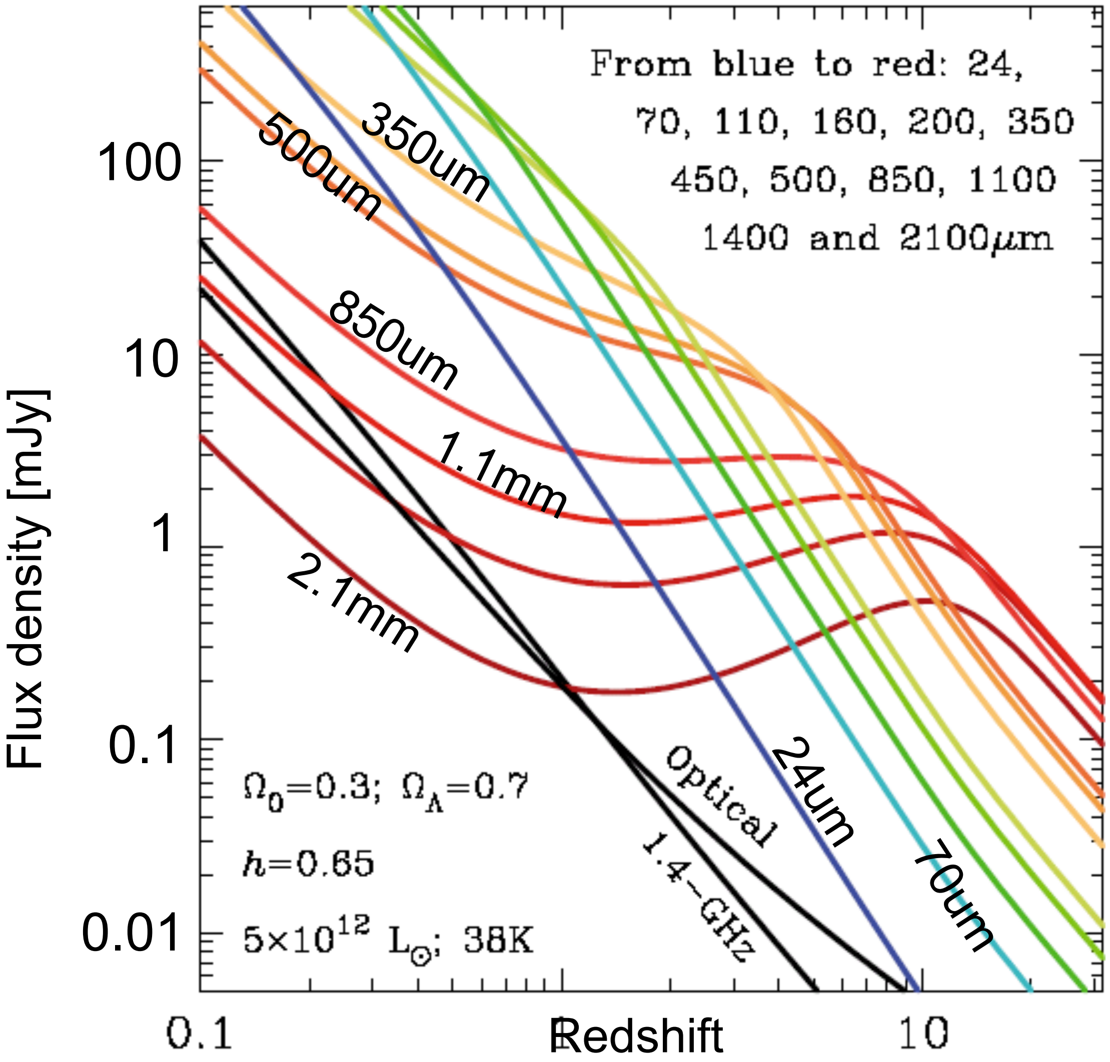
Takeuchi, Buat, & Durgarella 2005, A&A, 440, L17

Cosmic star formation history



Mm/submm is the best to uncover distant dusty extreme starbursts

- Almost constant flux for ~1 < z < ~10
  at 850um/1.1mm
  due to strong negative K correction



Blain et al., 2002, Physics Reports, 369, 111-176

Current situation on SMG study

- Flood of source detections !!!
  - From space: Herschel 250-500 um [mainly z<3]
  - From ground: MAMBO, AzTEC, Laboca, SCUBA2, SPT, etc. 2mm – 350 um [1mm~850um deep surveys are already sensitive enough to z>5 ULIRGs] ※slow mapping speed from ground
- Redshift determination is a nightmare !
- Power source diagnostics is another difficulty (and much more challenging)

AzTEC-ASTE 1.1 mm deep surveys

- wide (~1.6 deg^2) & deep (1σ ~ 0.4 – 1.2 mJy ⇔ ULIRGs @z>1) surveys of blank fields: yielding >750 robust detections

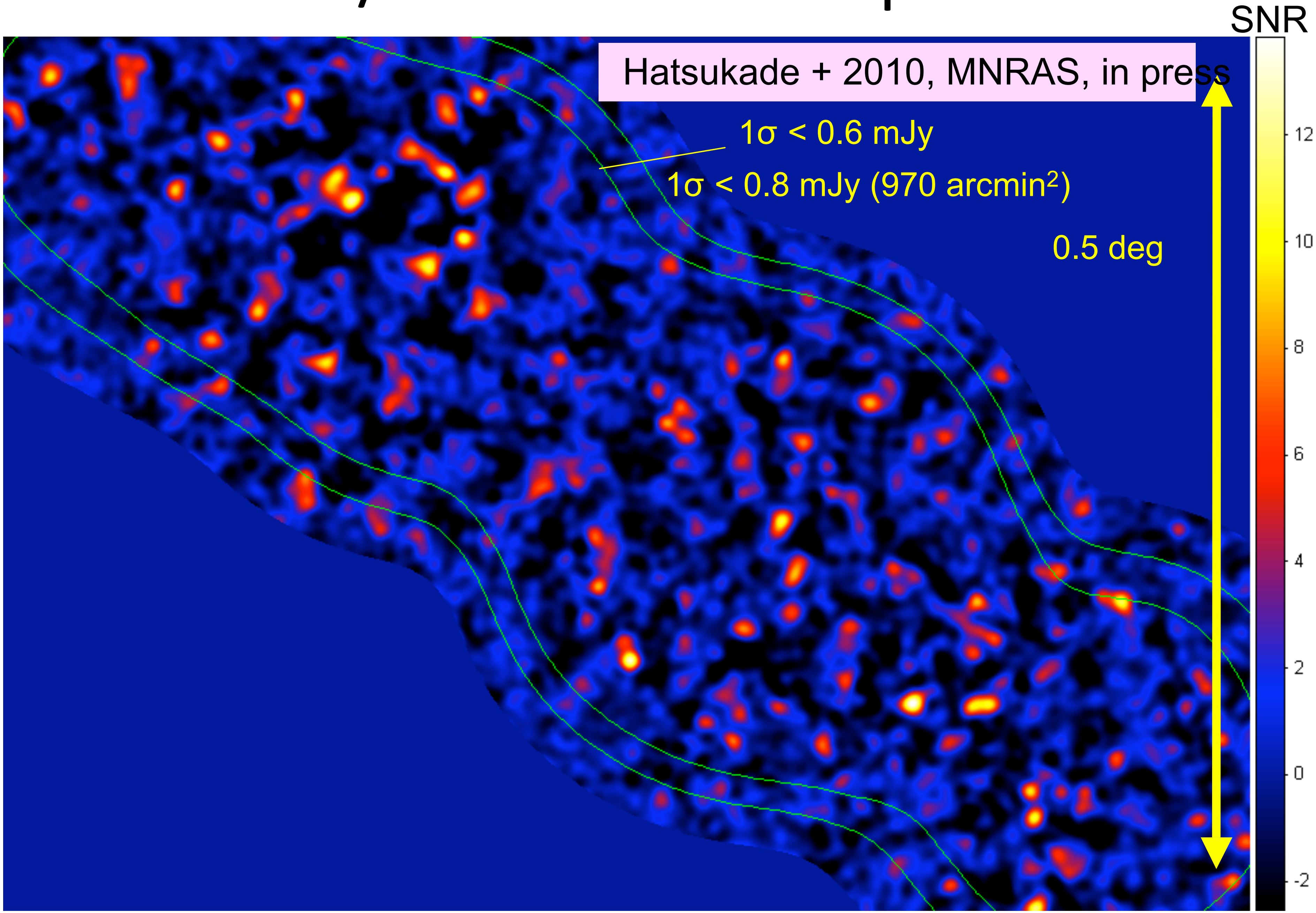
Field name	Survey area (30-50% coverage)	Noise level (1 sigma)	Num. of sources (S/N > 3.5)
SXDF	960 $arcmin^2$	0.5 – 0.9 mJy	174
SSA22	810 $arcmin^2$	0.6 – 1.2 mJy	113
ADF-S	970 $arcmin^2$	0.4 – 0.8 mJy	191
SDF	210 $arcmin^2$	0.7 – 1.0 mJy	25
SXDF z=5.7 clump	300 $arcmin^2$	~ 0.8 mJy	30
COSMOS	2700 $arcmin^2$	~ 1.1 mJy	193
GOODS-S	270 $arcmin^2$	0.5 – 0.7 mJy	48

(+ HDF-S, ECDF-S)

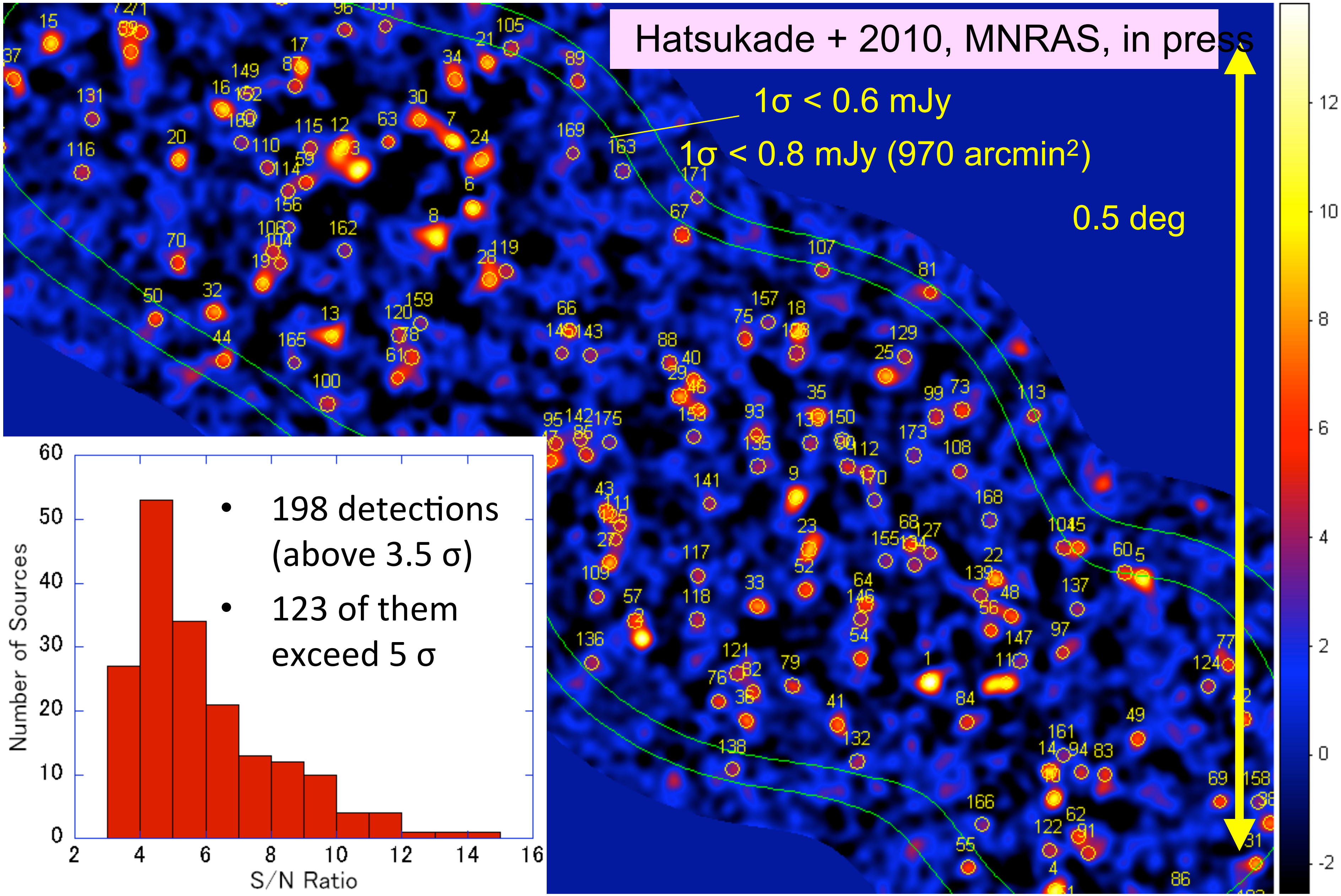
- Biased regions survey: ~1 deg^2, >680 detections
  - High-z radio galaxies, X-ray and optically selected proto-clusters; ~160 $arcmin^2$ x ~40 fields:

>1400 detections in total, the largest ~1mm selected SMG sample

AzTEC/ASTE 1.1mm map of ADF-S



AzTEC/ASTE 1.1mm map of ADF-S

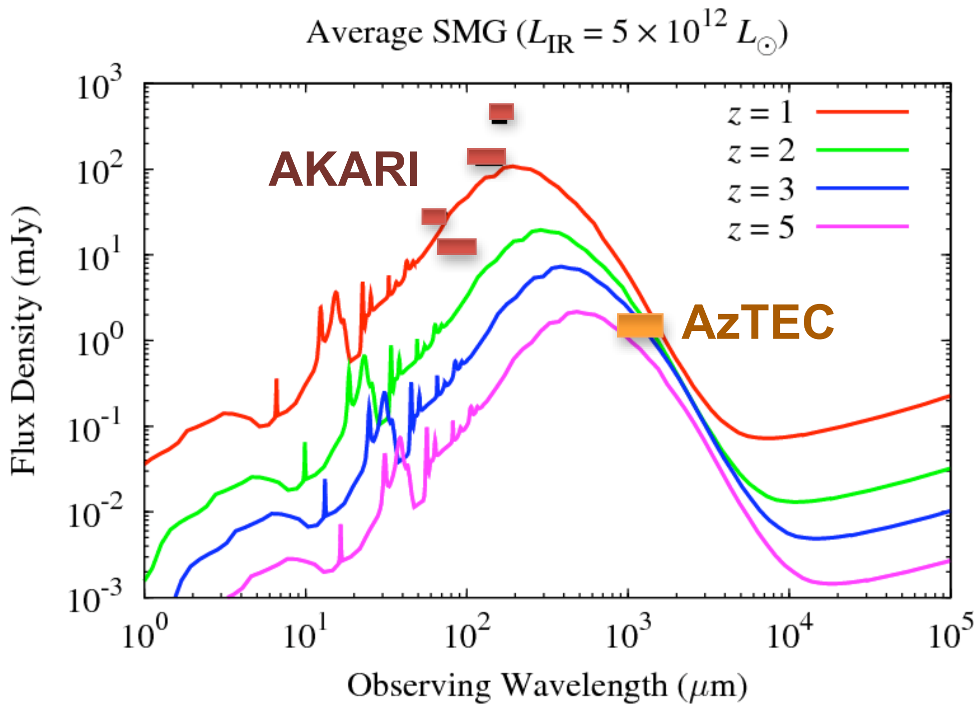


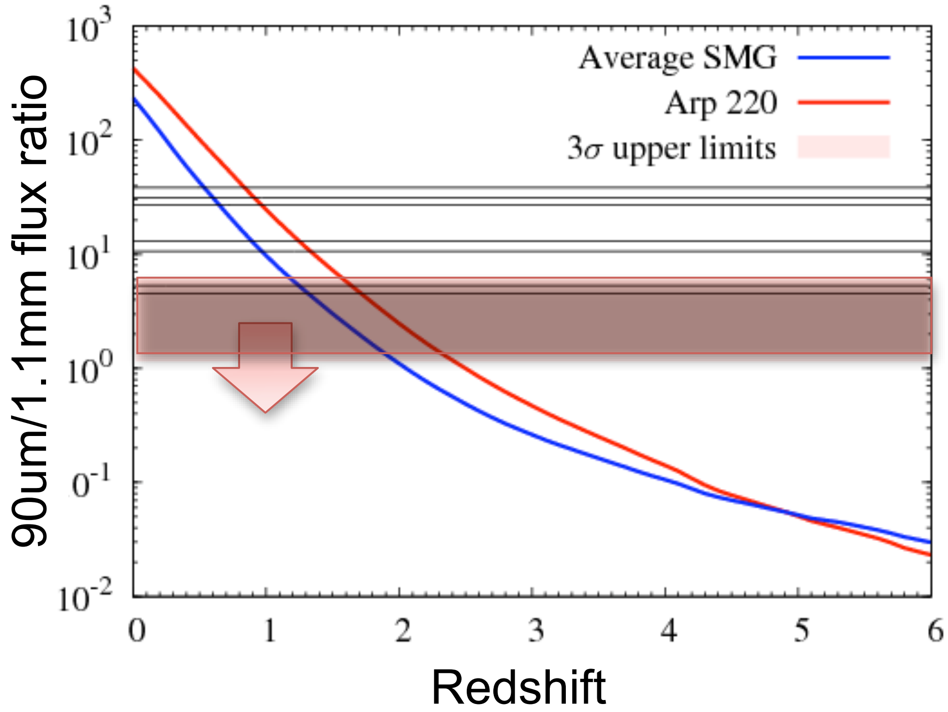
- 198 detections (above 3.5 σ)
- 123 of them exceed 5 σ

Constraints on redshifts of AzTEC/ASTE sources in ADF-S

Hatsukade + 2010, MNRAS, in press

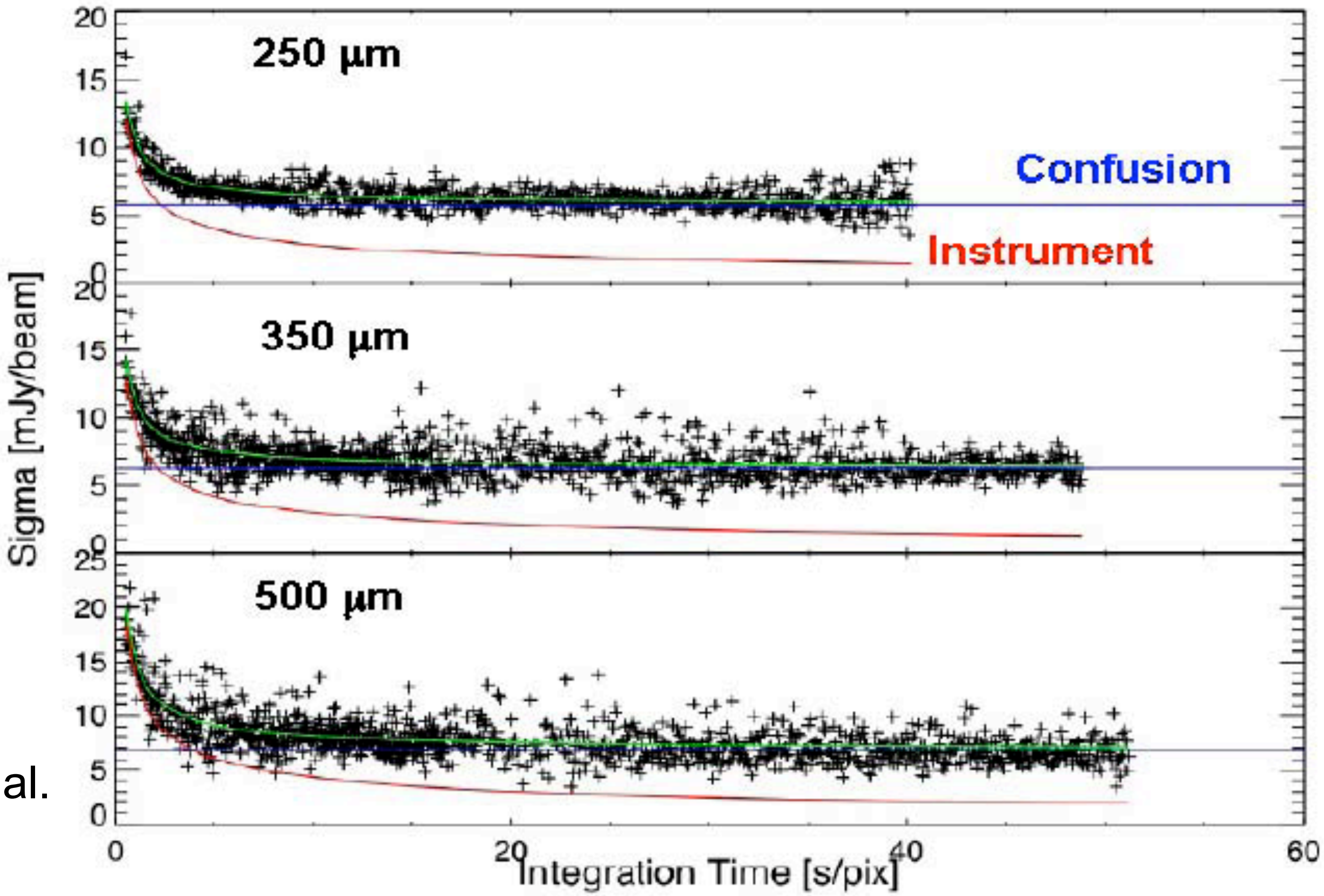
- 90um/1.1mm flux ratio
  ➔ most of the AzTEC sources (196 of 198) : z > 1
  - AKARI 90um sources : low-z, AzTEC 1.1mm sources: high-z
- L(FIR) ~ (3-14) x 10^{12} Lo, SFR ~ 500-2400 Mo/yr





Herschel/SPIRE noise performance: instrumental noise vs confusion noise

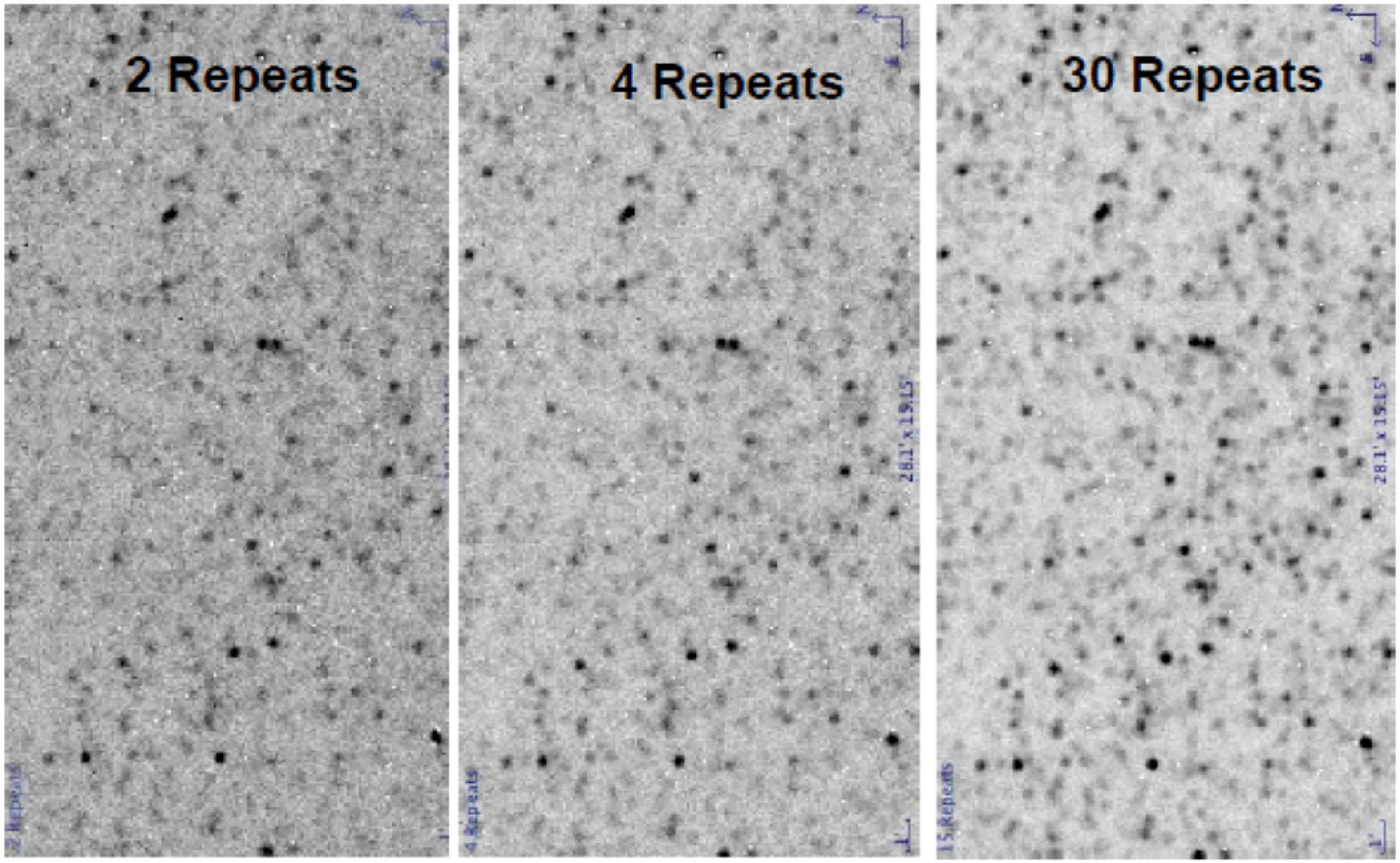
- Reaching a confusion limit very quickly!

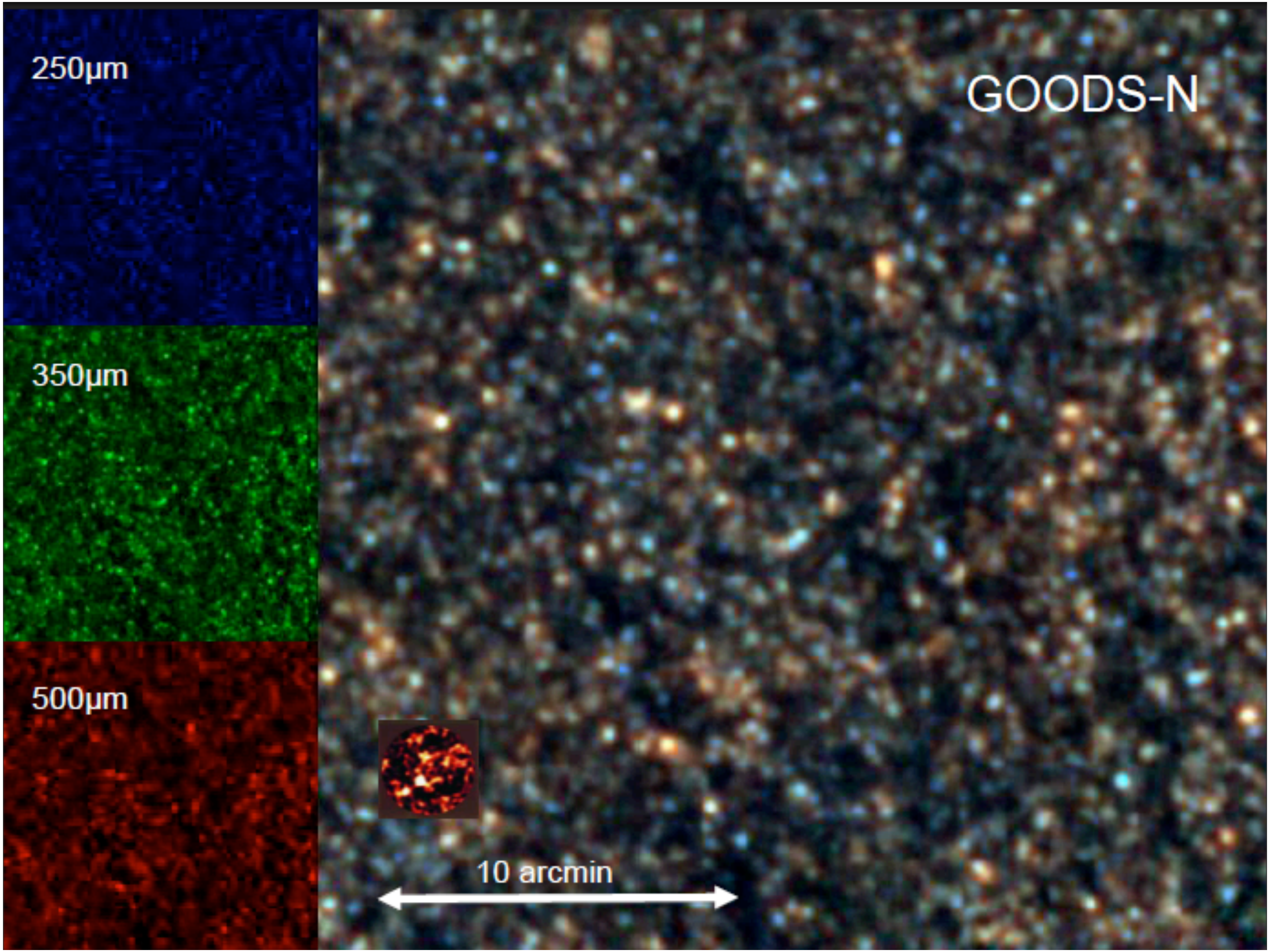


W. Gear et al. 2010

SPIRE deep imaging examples

- This is indeed a confusion limited survey !




250μm
350μm
500μm
GOODS-N
10 arcmin

Current situation on SMG study

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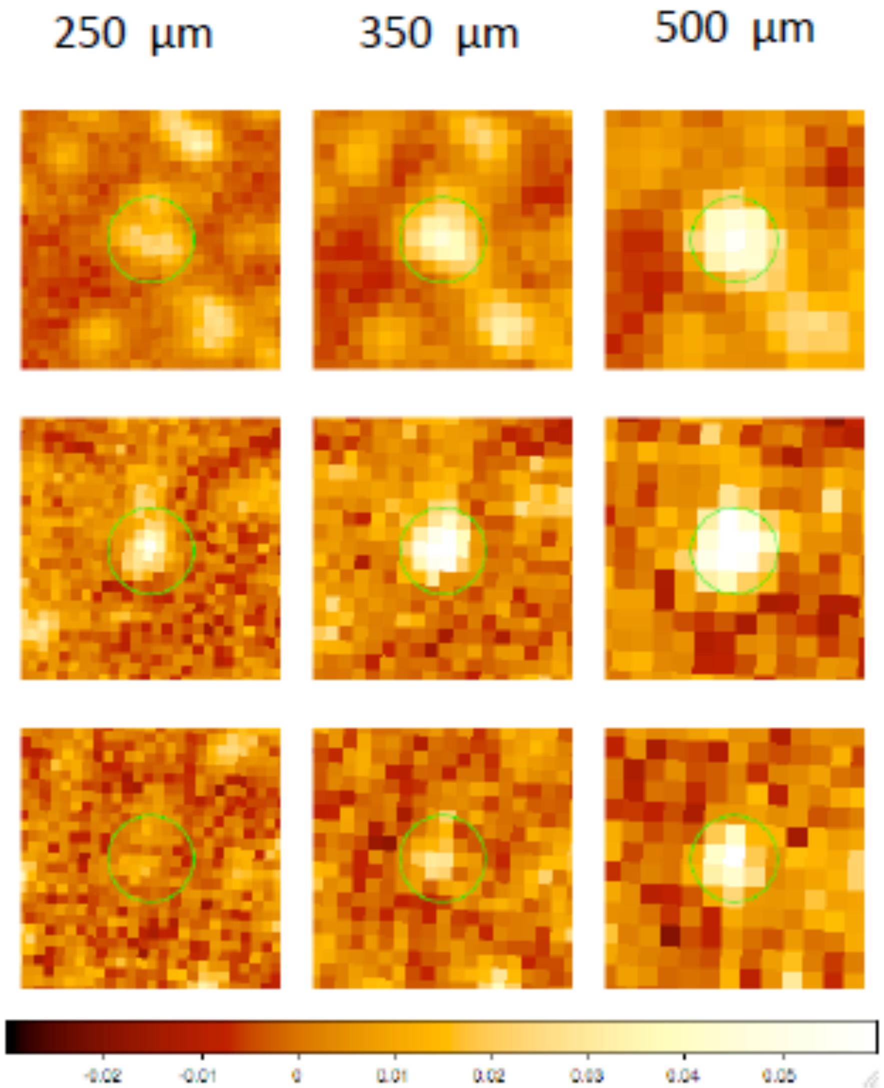
  - From space: Herschel 250-500 um [mainly z<3]
  - From ground: MAMBO, AzTEC, Laboca, SCUBA2, SPT, etc. 2mm – 350 um [1mm~850um deep surveys are already sensitive enough to z>5 ULIRGs] ※slow mapping speed from ground
- Redshift determination is a nightmare !
- Power source diagnostics is another difficulty (and much more challenging)

“500 um risers” as very high-z (z>4) SMG candidates

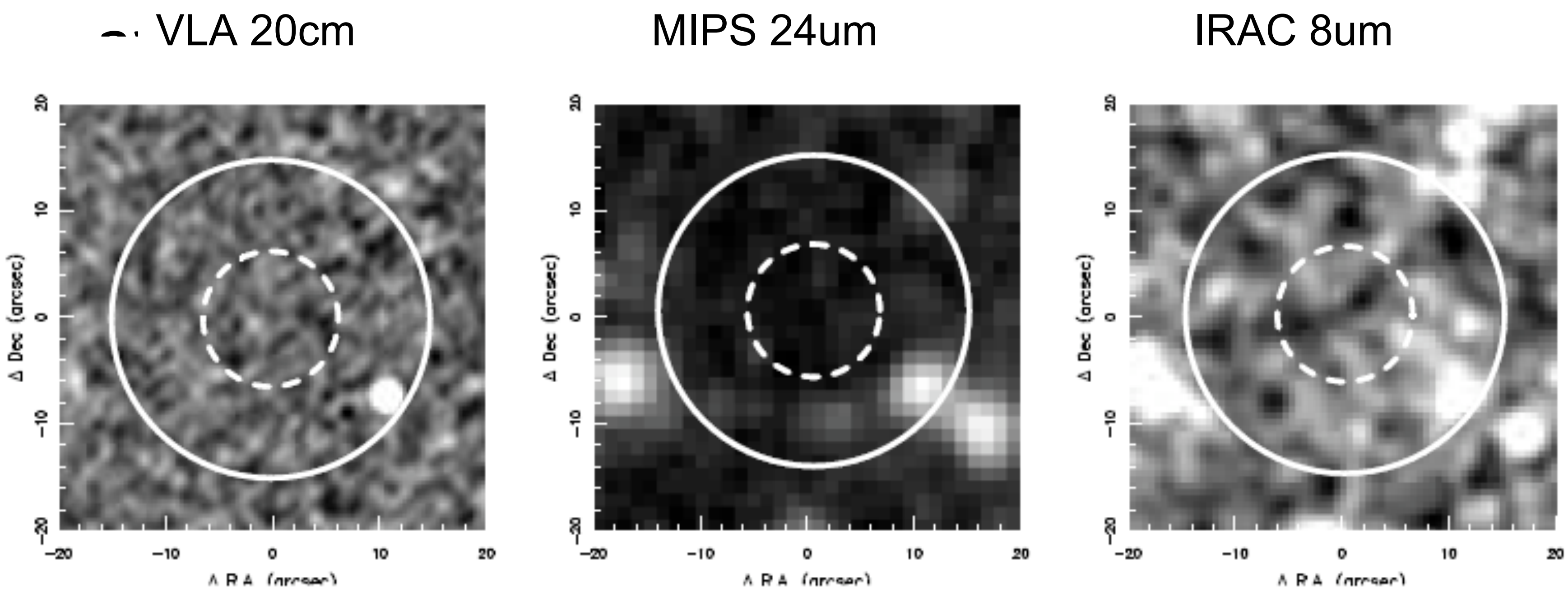
- Higher redshift ➔ SED peak of dust emission goes into the SPIRE bands; redder one in SPIRE color can be a high-z SMG candidate



Dowell et al. 2010

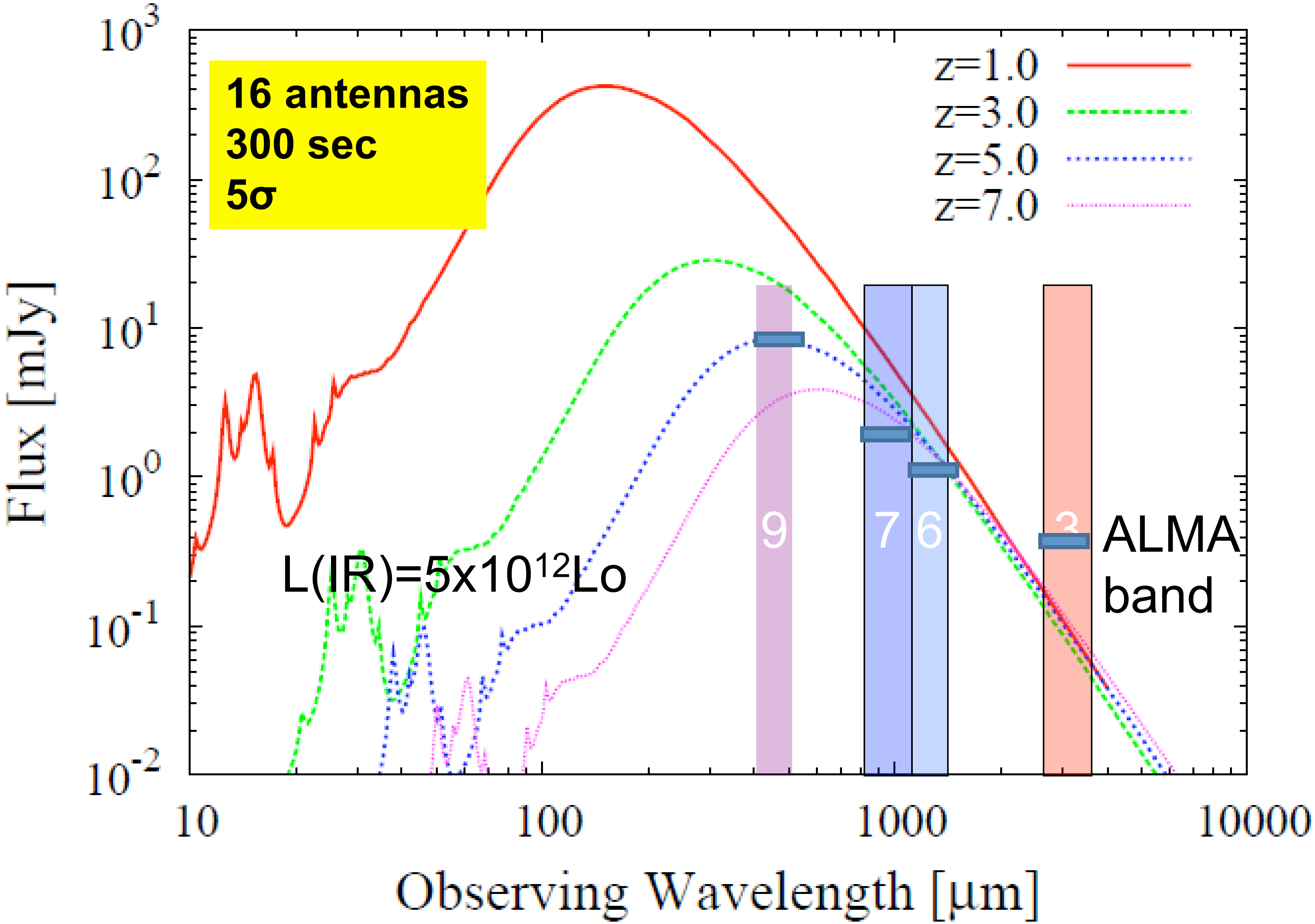
High-z (z > 5 !?) SMG candidates from AzTEC/ASTE

- SXDF, deep 20cm/24um/8um/etc… are

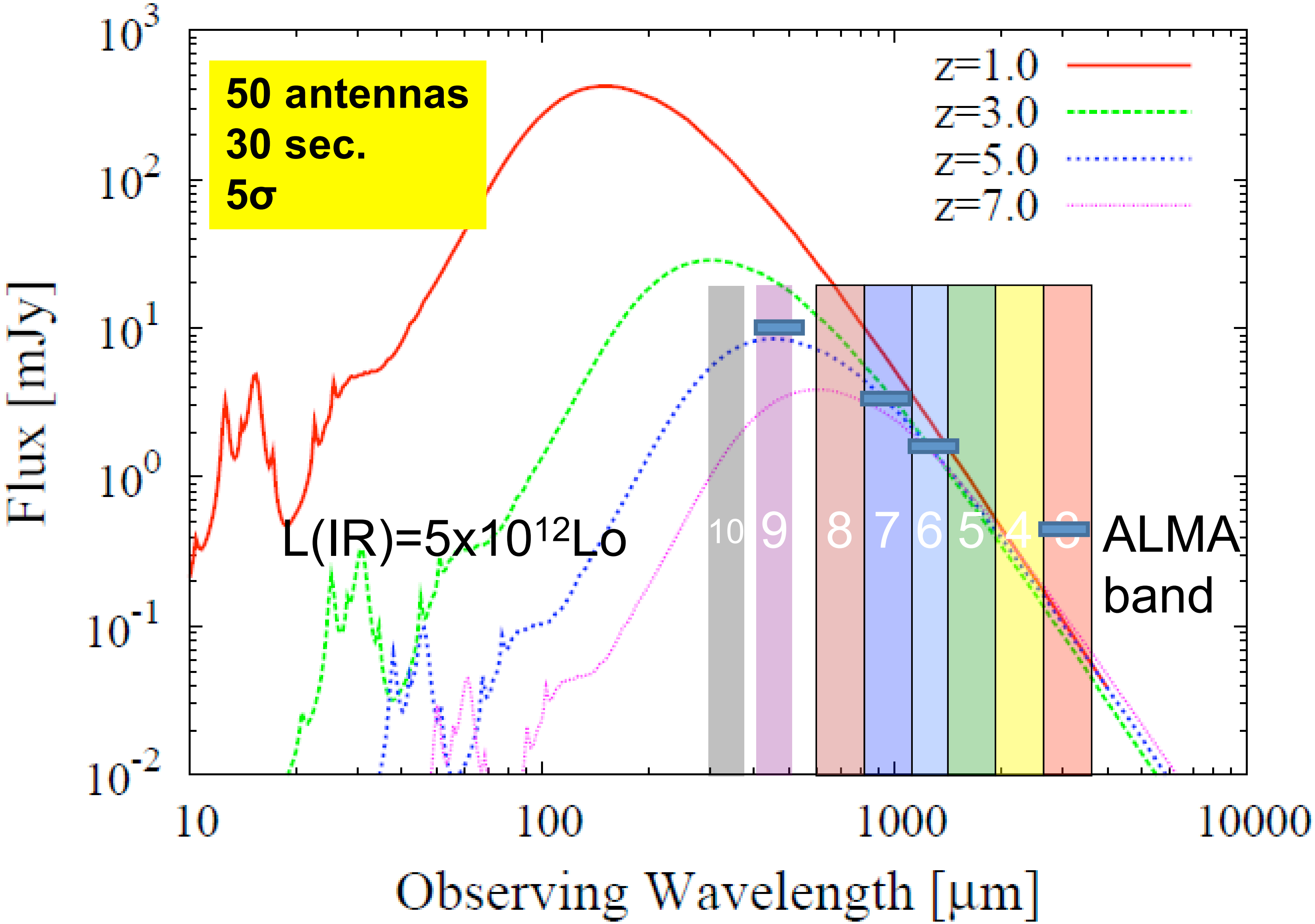


Ikarashi et al., in prep.

Submm Photometric redshift with ALMA early science



Submm photo-z with ALMA full operation



ALMA capability of SMGs

dust cont.@870um
2 < z < 10

L(IR)	10^{13} Lo	10^{12} Lo	10^{11} Lo	10^{10} Lo
SFR	1700 Mo/yr	170 Mo/yr	17 Mo/yr	1.7 Mo/yr
870um flux (2<z<10)	10 mJy	1 mJy	0.1 mJy	0.01 mJy
Integ. time 50 ant.	0.62 sec	62 sec	1.7 hrs	170 hrs
Integ. time 16 ant.	6.3 sec	10 min	18 hrs	1800 hrs

← HLIRGs ULIRGs LIRGs normal? IRGs

Currently known SGMs

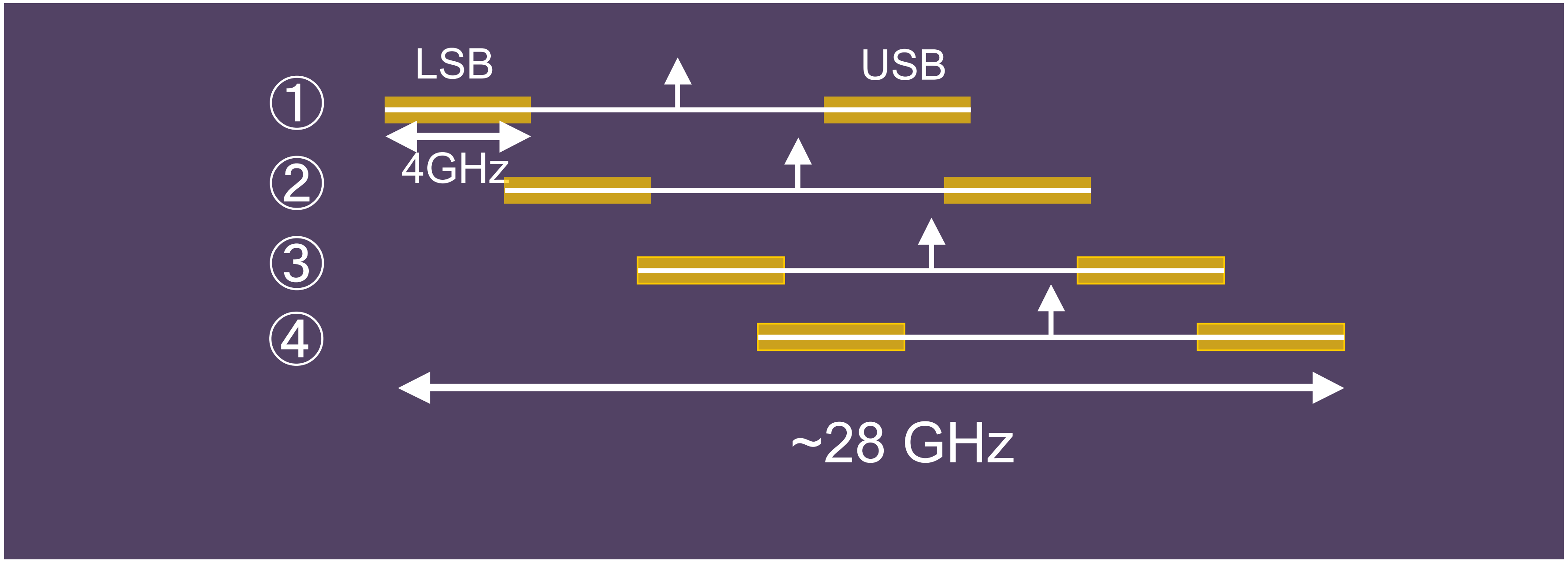
sBzKs
NIR-selected galaxies

LAEs
Lyman alpha line emitters

※ Tdust = 40 K, β = 1.5

ALMA as a redshift machine

- CO line frequency interval = 115 GHz/(1+z)
  - Detections of two lines yield z_{CO}
- ALMA band width = 8 GHz (IF=4-8, USB+LSB)
  - Multiple frequency setup (e.g., 4 different sets will be able to cover 28 GHz width)



Time Estimation

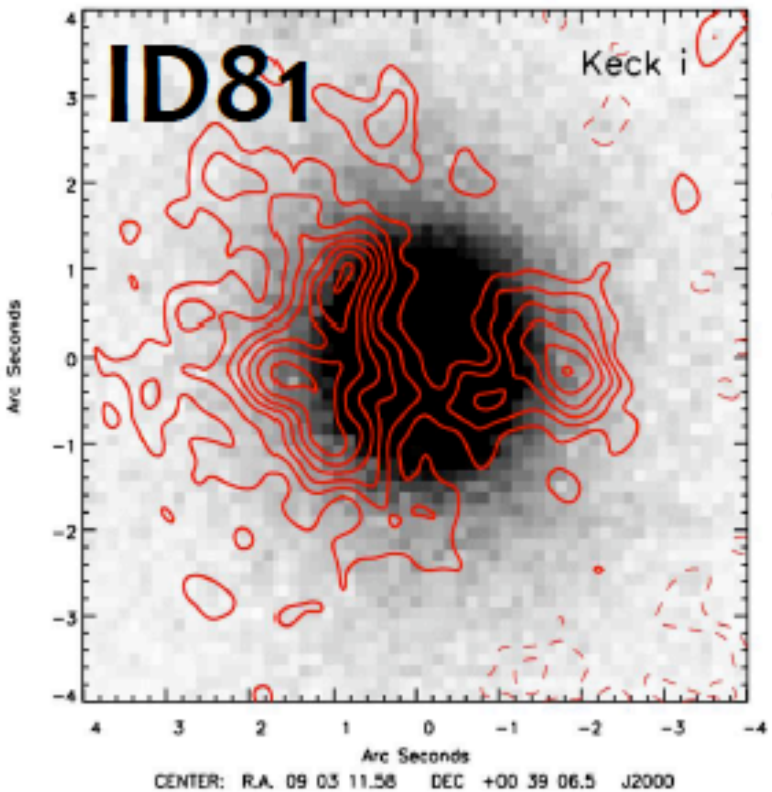
- M_{gas} = 3 x 10^{10} Mo ⇔ L(IR) = 10^{13} Lo
  - CO-H_2 conversion factor α_{CO}= 0.8 Mo/(K km/s pc^2)
  - velocity width = 300 km/s
  - velocity resolution = 50 km/s

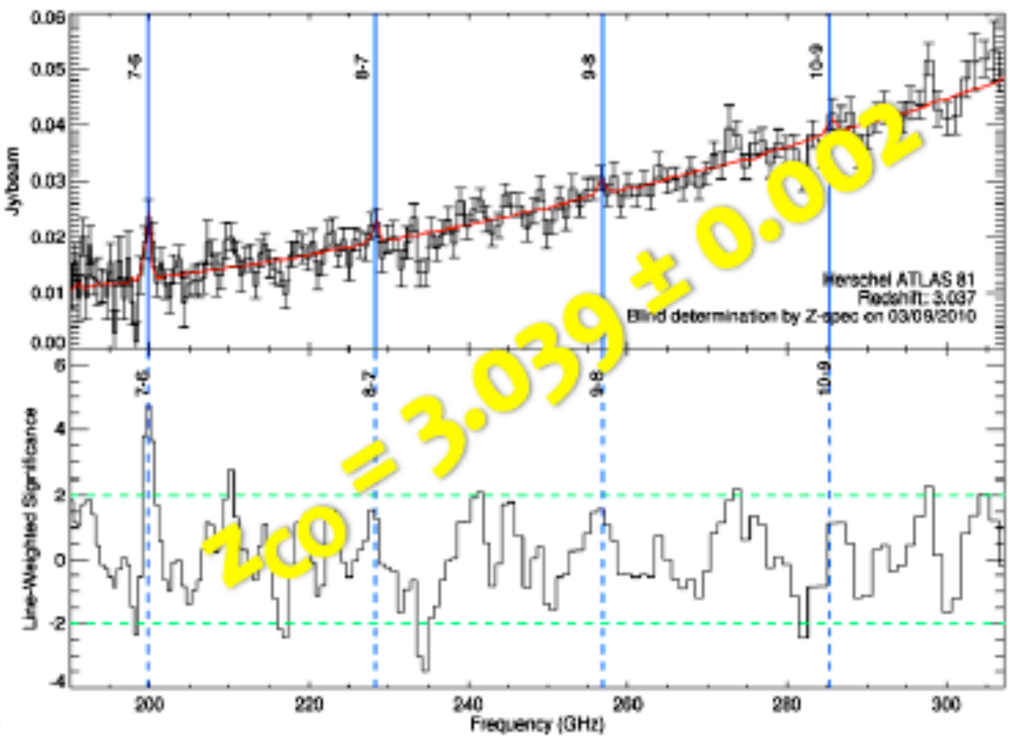
CO	z	v_{obs}	time for 5σ detection [min]	
		[GHz]	50 antennas	16 antennas
CO(3-2)	2.5	100	10/set	100/set

– With rough estimate of redshift (photo-z or dust-z), one night run will be sufficient to spec-z derivation for a few 10 bright SMGs (around z~2)

GRAVITATIONAL LENS CANDIDATES ID81

CSO/Z-spec blind redshift determination for **ID81** (March 09 2010) from observations of the **CO ladder**



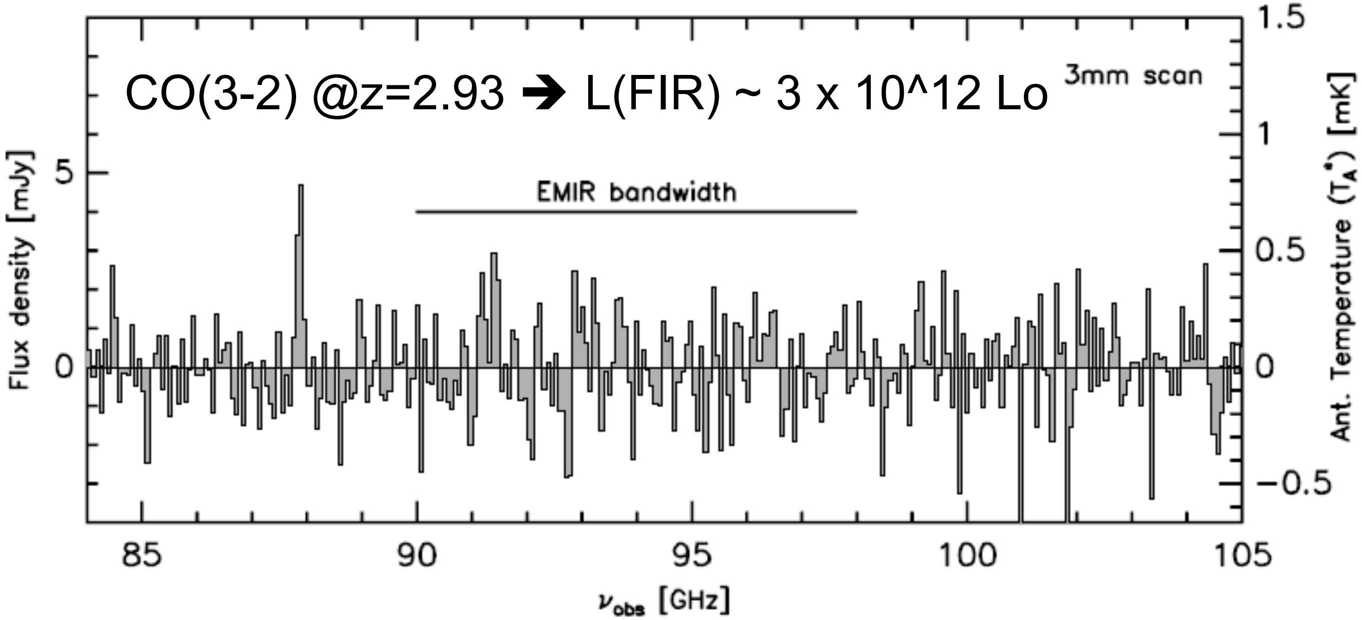


Credit: The Zspec team

Power of ultra-wide band spectrometers

Weiss et al. 2009, ApJ, 705, L45

- EMIR on IRAM 30m; SMM J14009+0252, S_{850um} = 16 mJy



5 tunings
x 2 hours
= 10 hours

+ further
Integ (?? hr)

- New ultra-wide band spectrometer (32 GHz) at 3 mm band, for NRO 45 m telescope, is now under commissioning (Iono et al, in prep.)

Current situation on SMG study

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  - From space: Herschel 250-500 um [mainly z<3]
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- Redshift determination is a nightmare !
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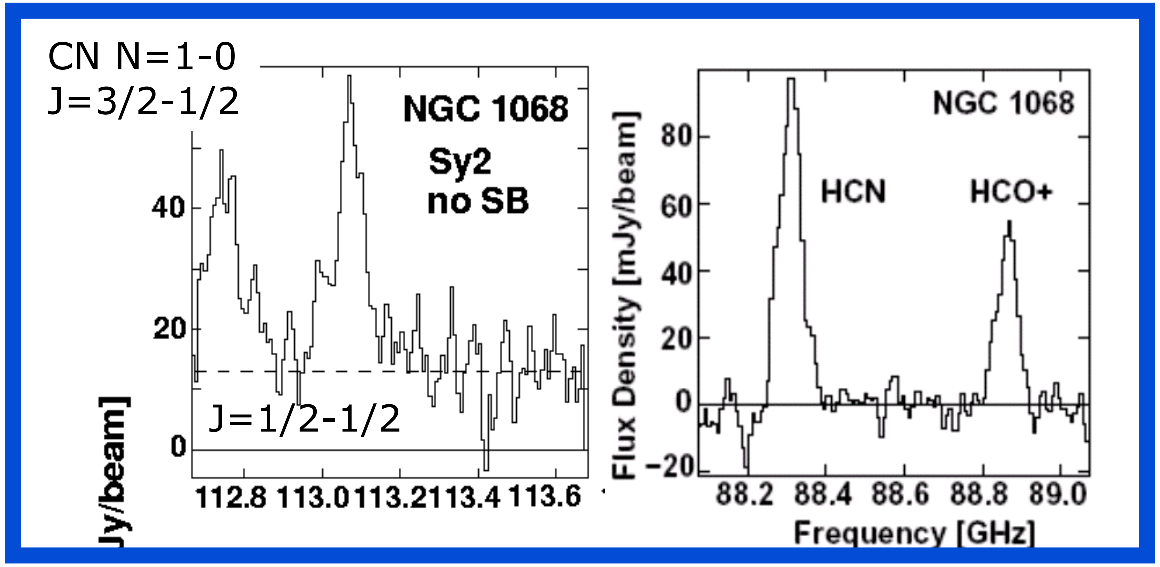
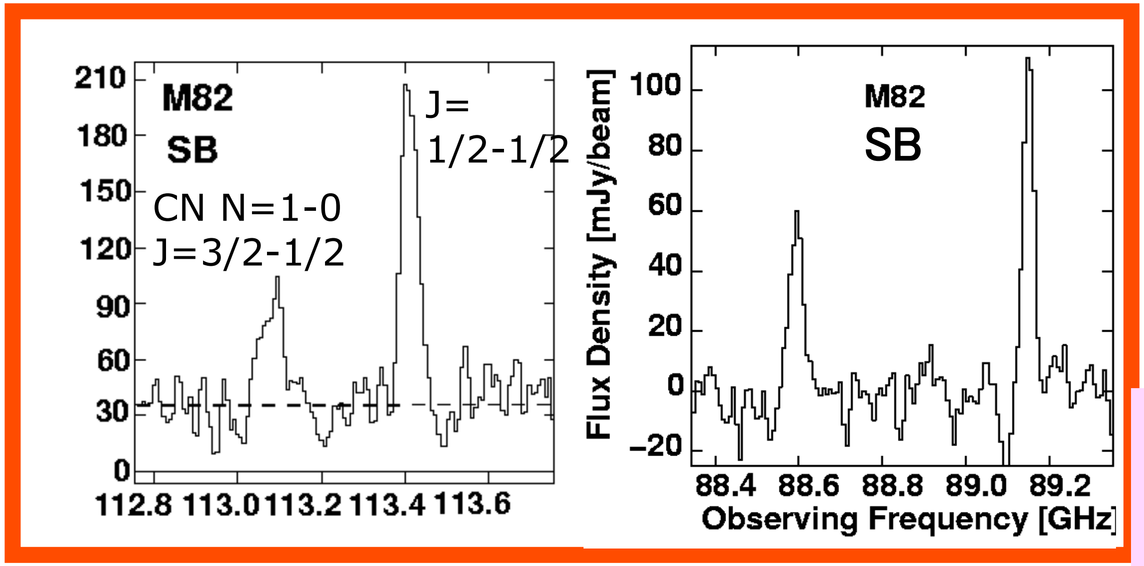
Millimeter-wave molecular spectroscopy as a new diagnostic of nuclear energy source





AGN:

- **HCN/HCO^+ >2-3**
- $CN(J={}^3/_2-{}^1/_2)$ $/(J={}^1/_2-{}^1/_2)\sim1$?

➔XDR chemistry?

MIR pumping? Maser?

Starburst:

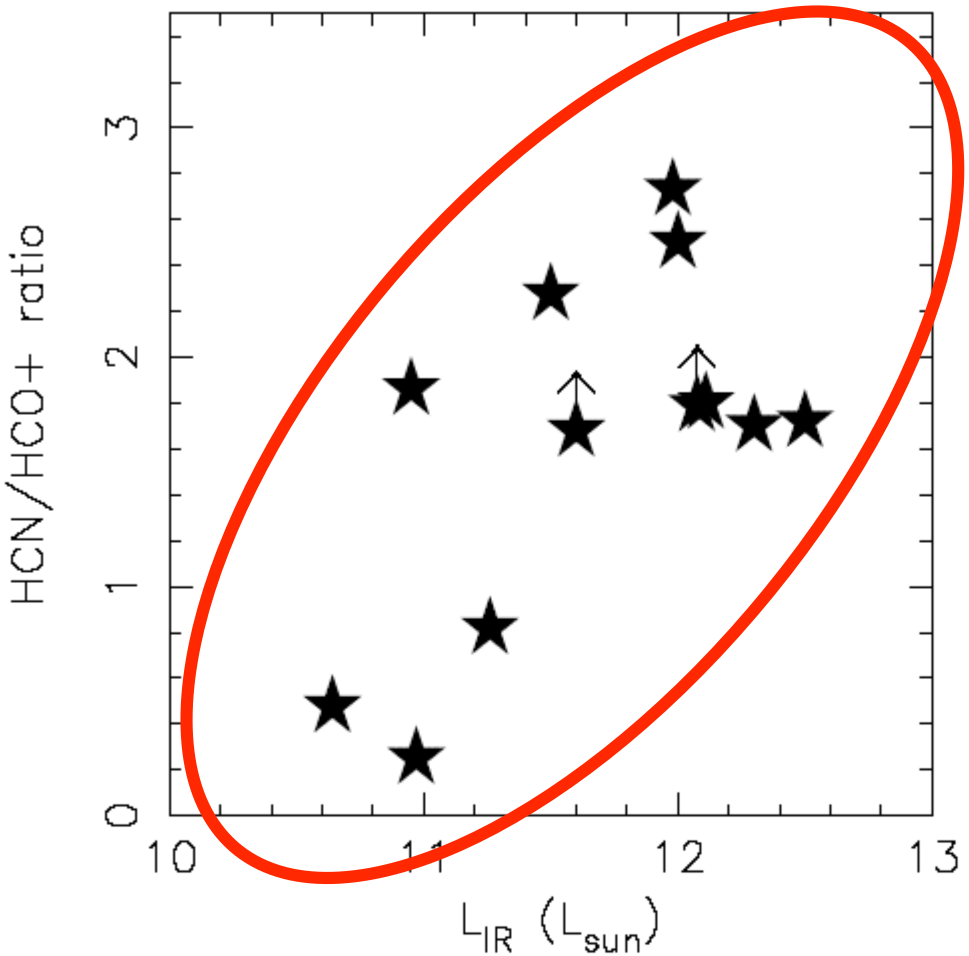
- **$HCN/HCO^+\sim1$**
- $CN(J={}^3/_2-{}^1/_2)$ $/(J={}^1/_2-{}^1/_2)\sim0.3$

➔PDR chemistry?

Nobeyama Millimeter Array
Kohno et al. 2001, 2005,
Kohno et al. 2008, ApSS, 313, 279

Larger AGN contribution to more luminous IR galaxies ?

- Local LIRGs/ULIRGs
- HCN/HCO$^+$ ratios vs L(FIR) ➔ trend?➔ larger contribution of AGN in more luminous IR galaxies?
- What is going on @HyLIRGs～SMGs?



Imanishi, et al.
2007, AJ, 124, 2366

ALMA spectroscopy of dusty starbursts can probe heavily obscured, growing AGN?

SPICA is the ultimate FIR spectrometer

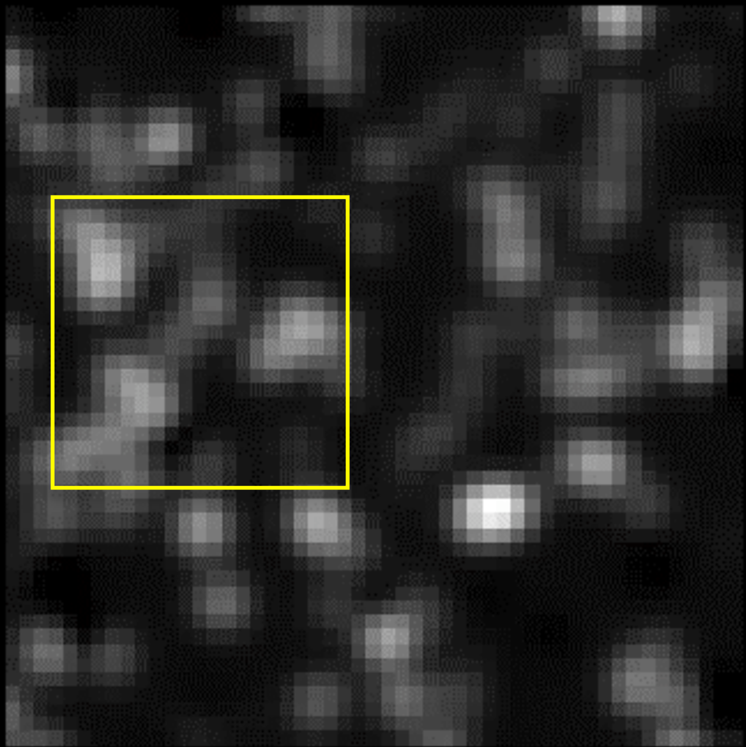
- For photometry: distant FIR galaxies are ubiquitous ! We will be immediately reach the confusion limit at SAFARI wavelengths
  - SPICA is smaller than Herschel; worse in terms of confusion
- The uniqueness of SPICA＠FIR: spectroscopy capability !
  - Make the best use of the cooled telescope + excellent detector technology

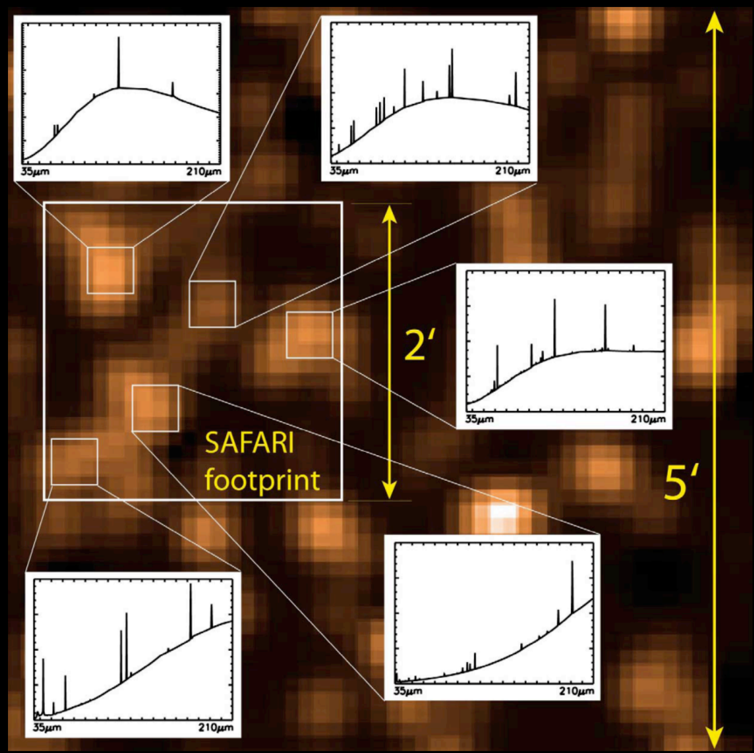
SAFARI+BLISS+ALMA strategy

- Blind imaging-spectroscopic survey with SAFARI: up to z~2 ULIRGs/SMGs
  - Best suited for z~2 cluster studies (Koyama-san +)
- Targetted sensitive spectroscopy with BLISS: up to z~4 ?? ULIRGs/SMGs
  - Physical properties of ionized gas (PDR, HII regions, coronal region) with FIR fine structure lines
- Detailed (subarcsec or better resolution) imaging study of spectroscopically confirmed high-z ULIRGs/SMGs + molecular gas component

The Multiplex Advantage

Looking closer at the SPIRE background sources

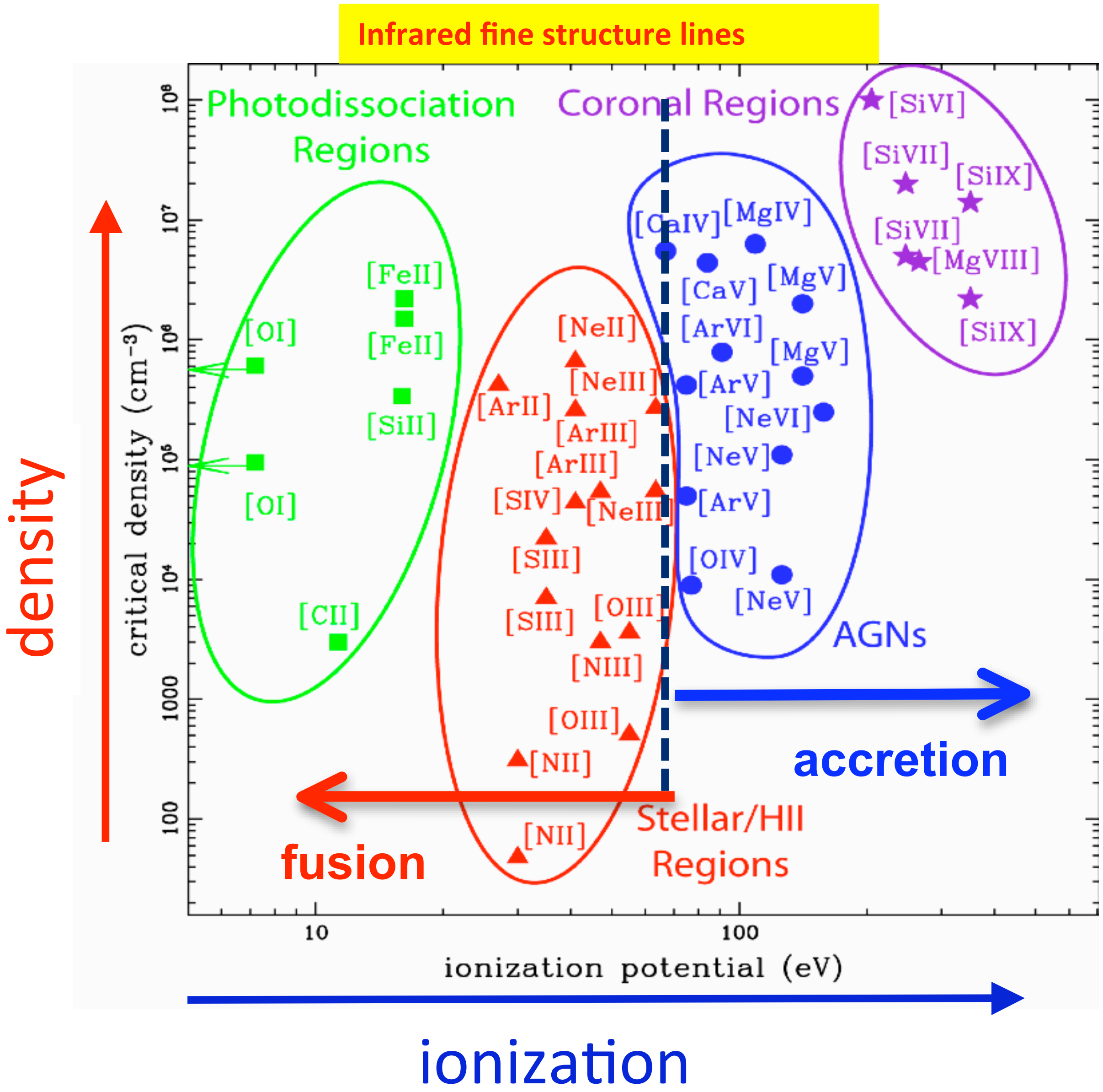




SPICA FIR FTS will take spectra of 7-10 sources/field

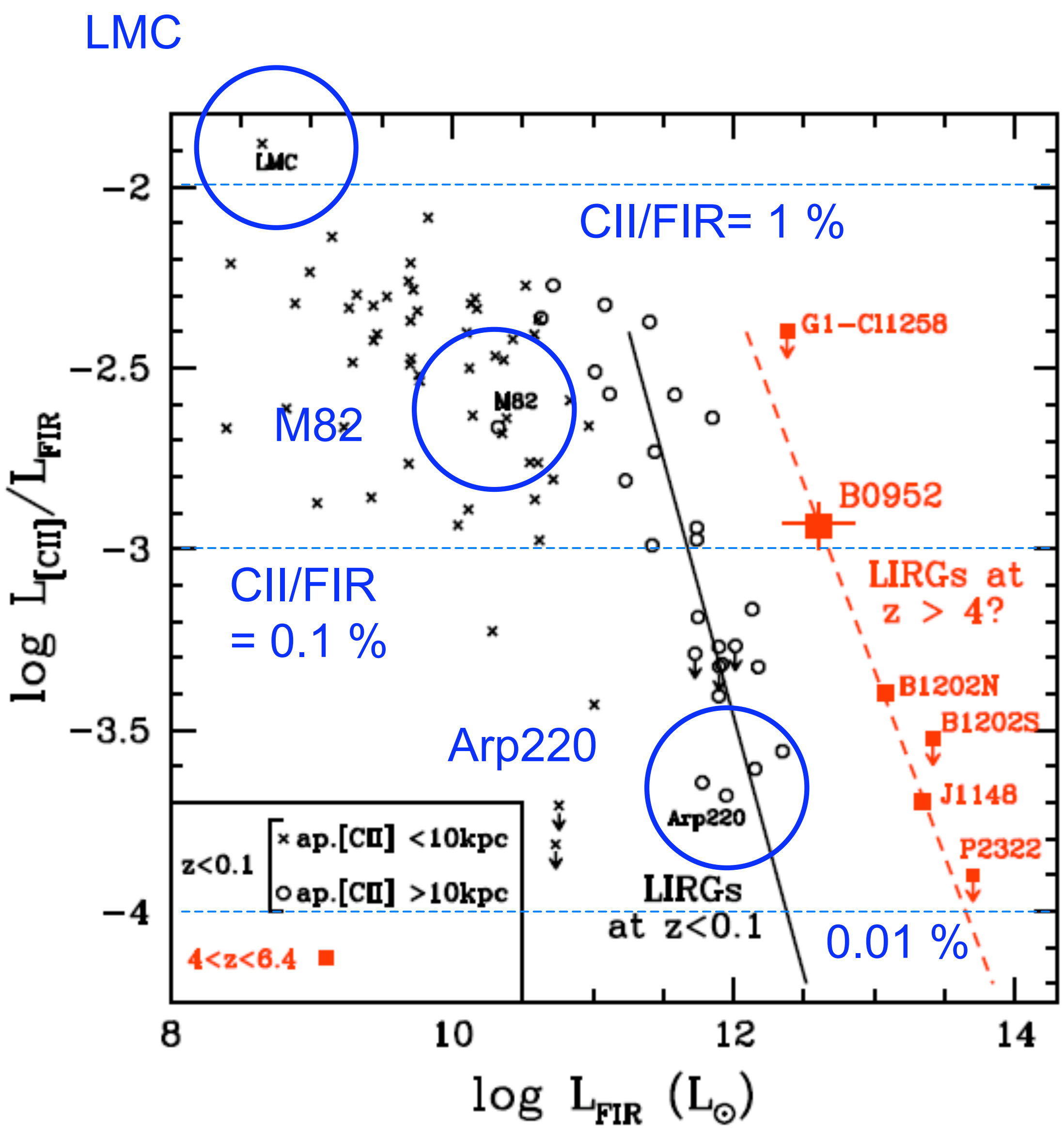
Images Rosenbloom, Oliver, Smith, Raab private communication

MIR-to-FIR fine structure lines as a powerful diagnostic of energy sources of dusty galaxies



- Can penetrate deep into the dusty ISM !

Can we see [CII] in SMGs?

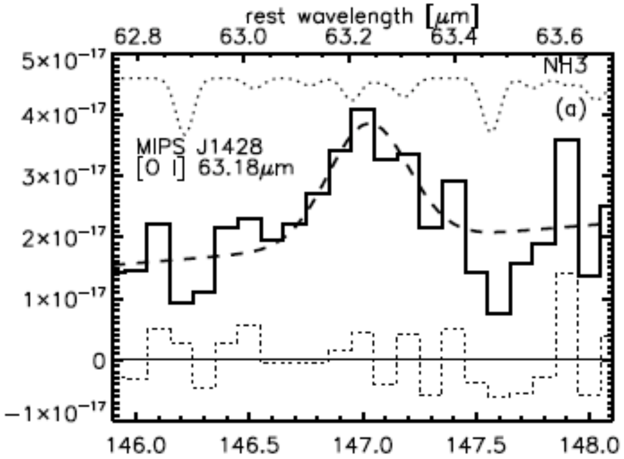


In general, FIR fine Structure lines are weak..

How about SMGs?

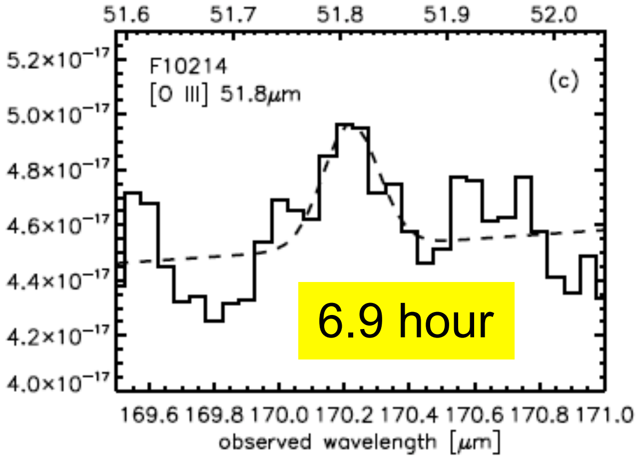
Maiolino et al., 2009, A&A, 500, L1

Encouraging results from Herschel: 1st detection of fine structure lines from high-z extreme starbursts

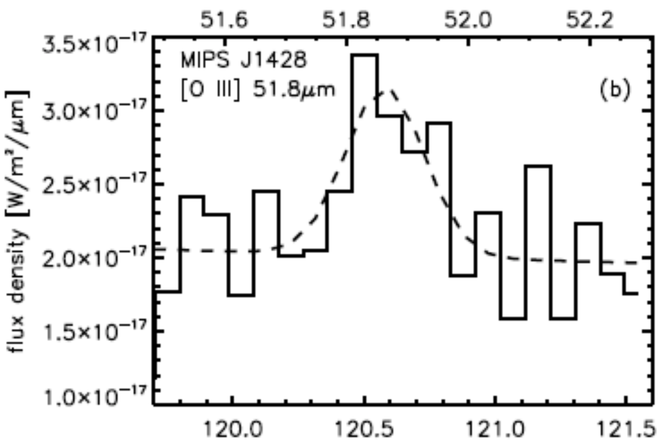


89 min.

[OIII] 88um
Undetected
5 hour integ.



6.9 hour



46 min.

IRAS F10214+4724
z = 2.286,
L(FIR) = 8 x 10^13 Lo

MIPS J1428+3526
z = 1.325,
L(FIR) = 1.3 x 10^13 Lo

[OIV] 26um
Undetected
6.9 hour integ.

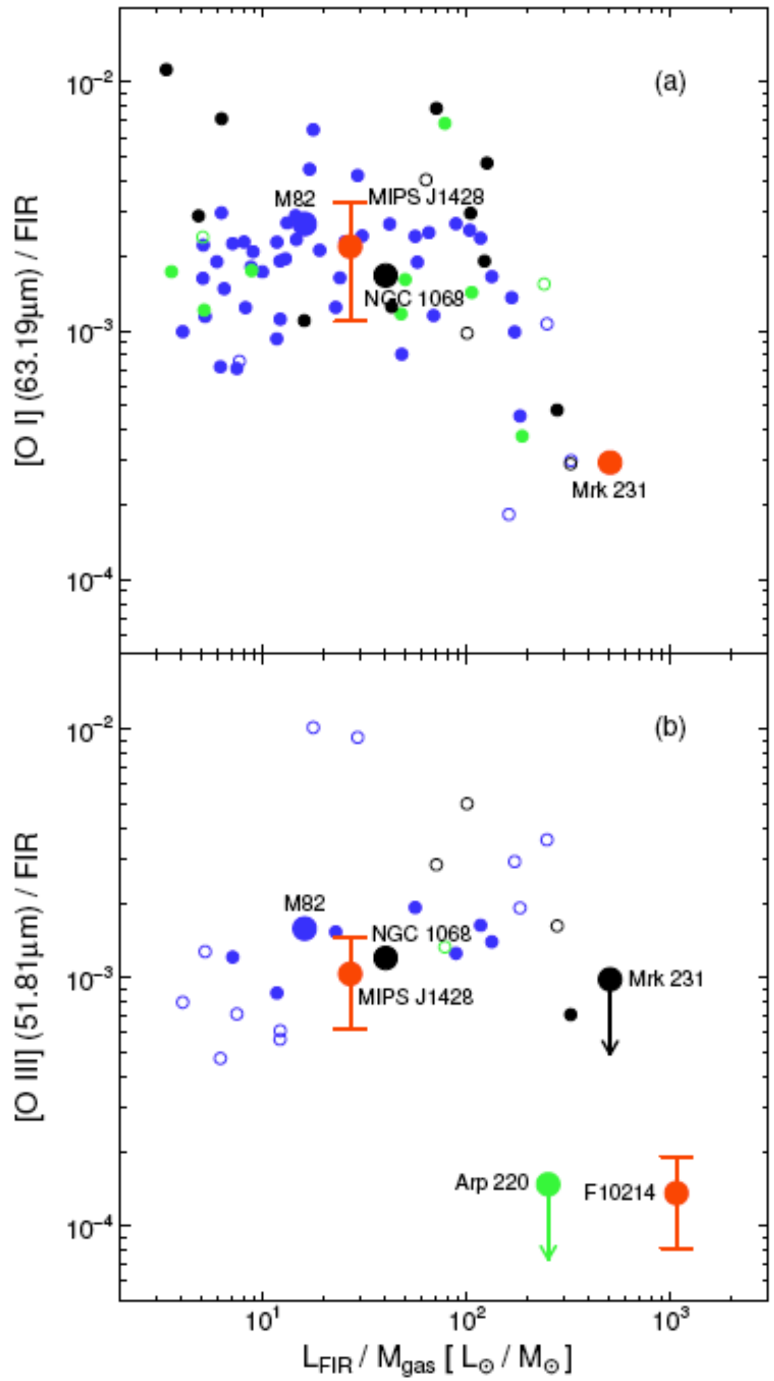
Observed wavelength [um]

Sturm et al. 2010, A&A, 518, L36

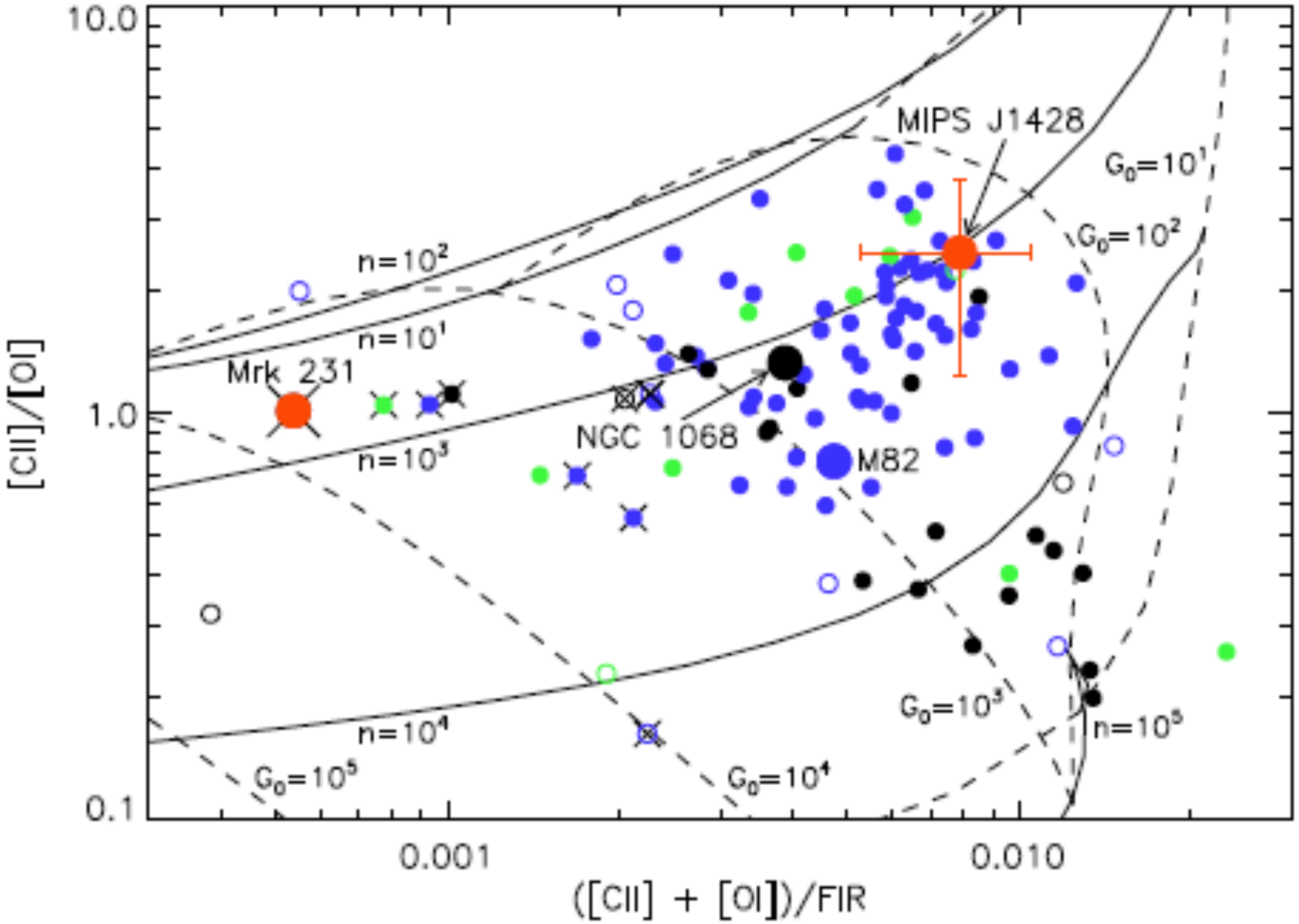
Variation among SMGs

- MIPS J1428, a starburst-dominated system: NO [OI]/FIR DEFICIENT !!!
  - The far-UV flux G_0 and gas density n (PDR models), and the star formation efficiency (from CO and FIR) ➔ similar to normal or starbursts
- F10214 has stringent upper limits on [O IV] and [S III], and an [O III]/FIR ratio
- at least an order of magnitude lower than local starbursts or AGN, similar to local ULIRGs.

Sturm et al. 2010, A&A, 518, L36



Local starburst like SMGs without CII/OI deficient !



● AGN, ULIRGs with AGN

● HII galaxies

● LINERs

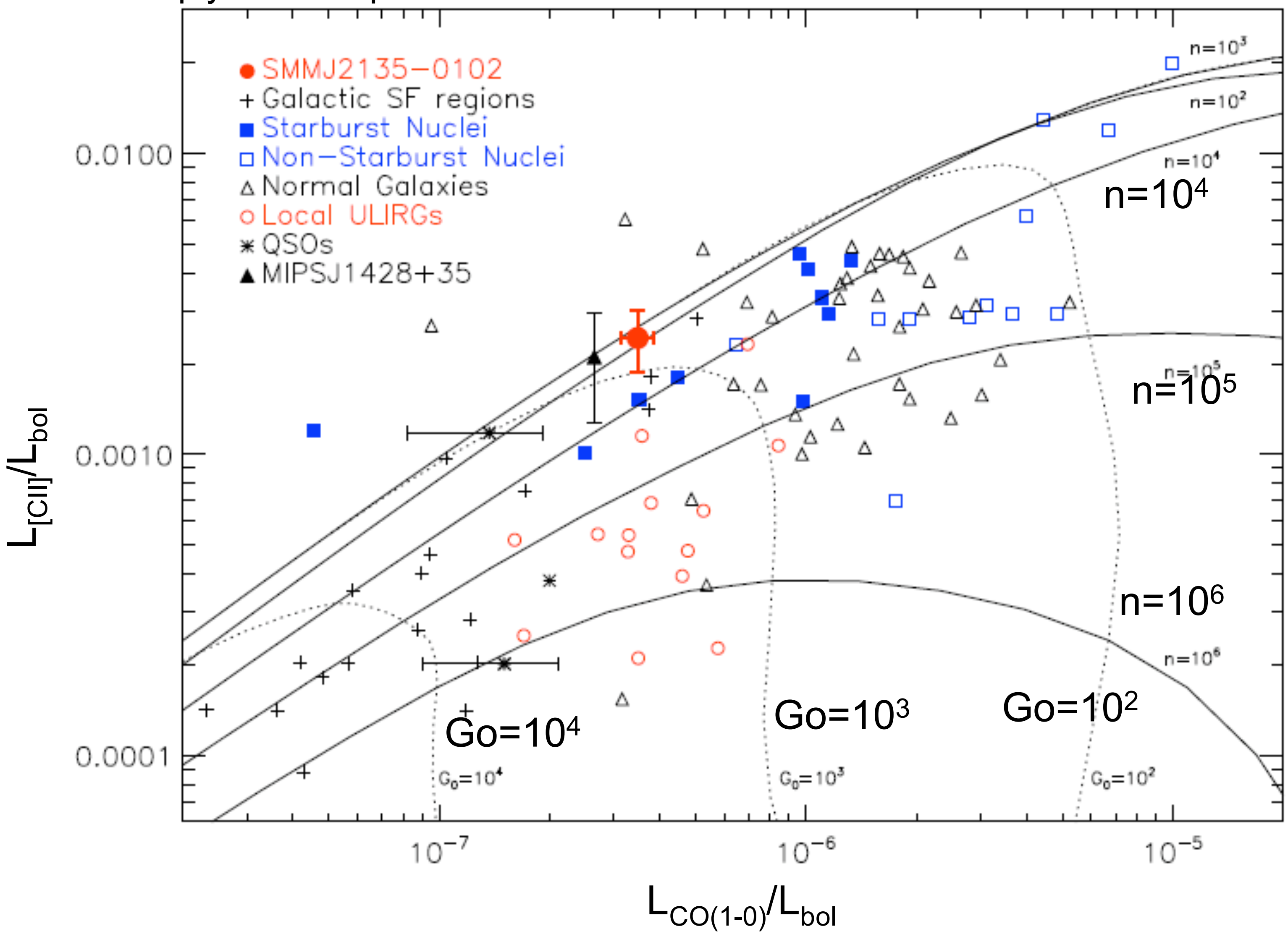
Open ➔ upper limits

Sturm et al. 2010, A&A, 518, L36

Ivison et al. 2010, A&A 518, L35

SMGs ~ local SF regions, ≠ ULIRGs?

L[CII]/Lbol is higher than in local ULIRGs
but similar to local star-forming/starburst galaxies
➔ powered by starburst clumps distributed ~2 kpc,
SMGs are not simply scaled-up ULIRGs



[OIII] 88.356 um line

- 35 eV ➔ hot stars (Teff > 36,000 K) required
- 164 K above ground level
- Critical density ~ 500 cm^-3

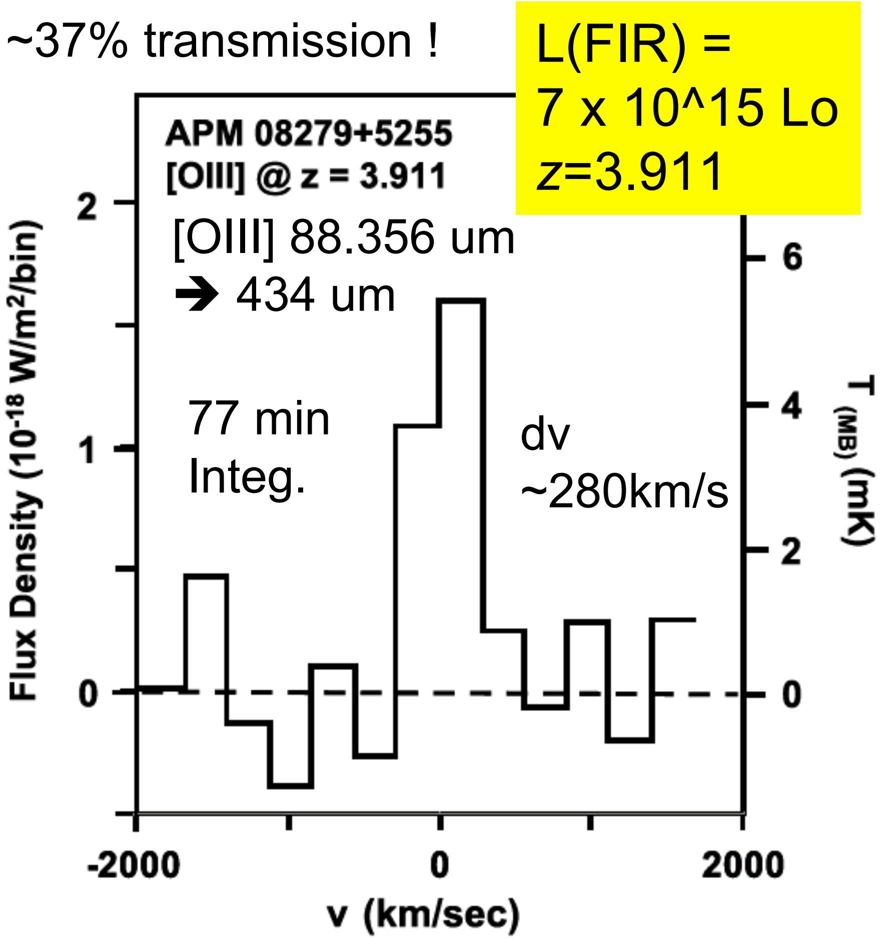
FIR extragalactic spectral line survey with ISO

- 88 galaxies (z<0.05) observed, 75% detected
- 2^{nd} or 3^{rd} brightest line (after [CII]and [OI])
- L_[OIII]/L_FIR ratio: 0.03 to 2%, median ~0.2%

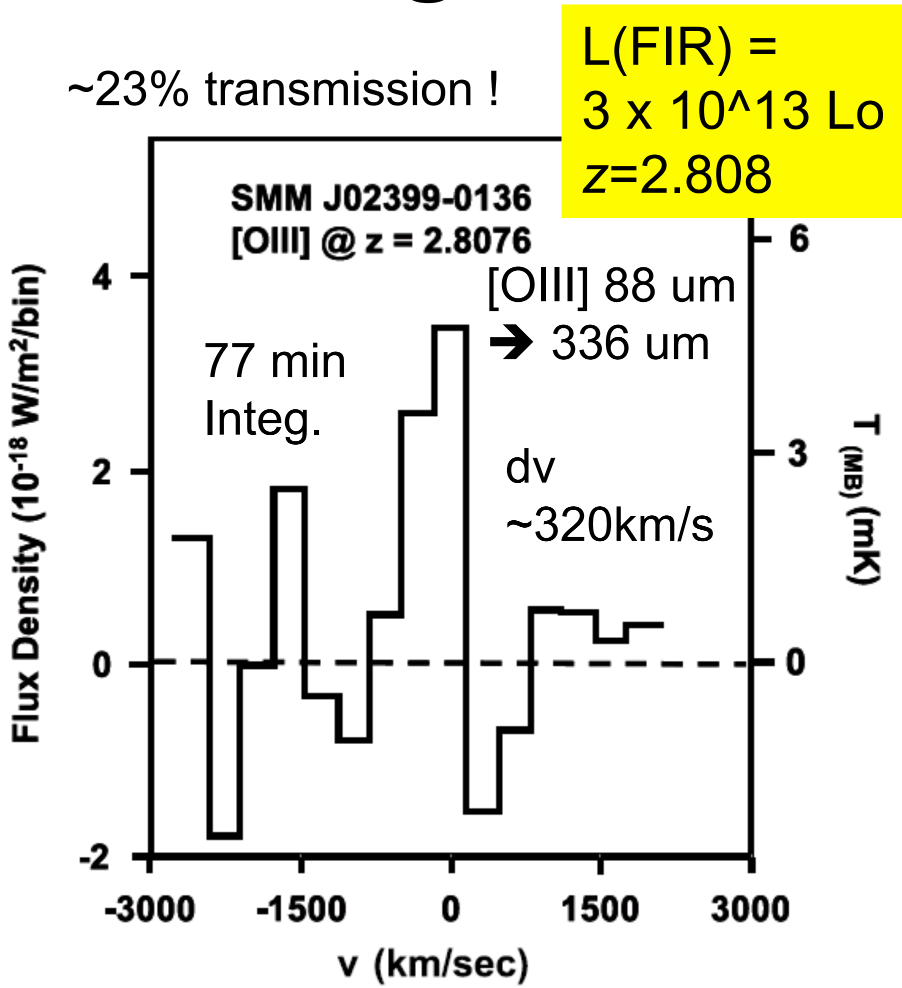
(Malhotra et al. 2001; Negishi et al. 2001; Brauher et al. 2008)

Another efforts from the ground

~37% transmission !



~23% transmission !

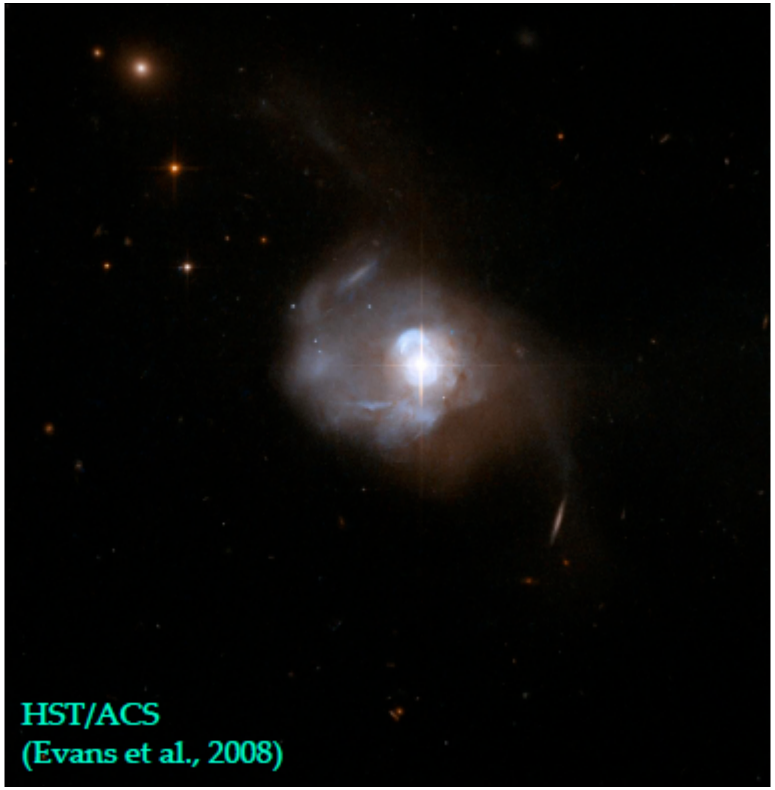


CSO 10 m + ZEUS
echelle grating spectrometer
with 1x32 pix linear bolometer array
for 350 and 450 um windows

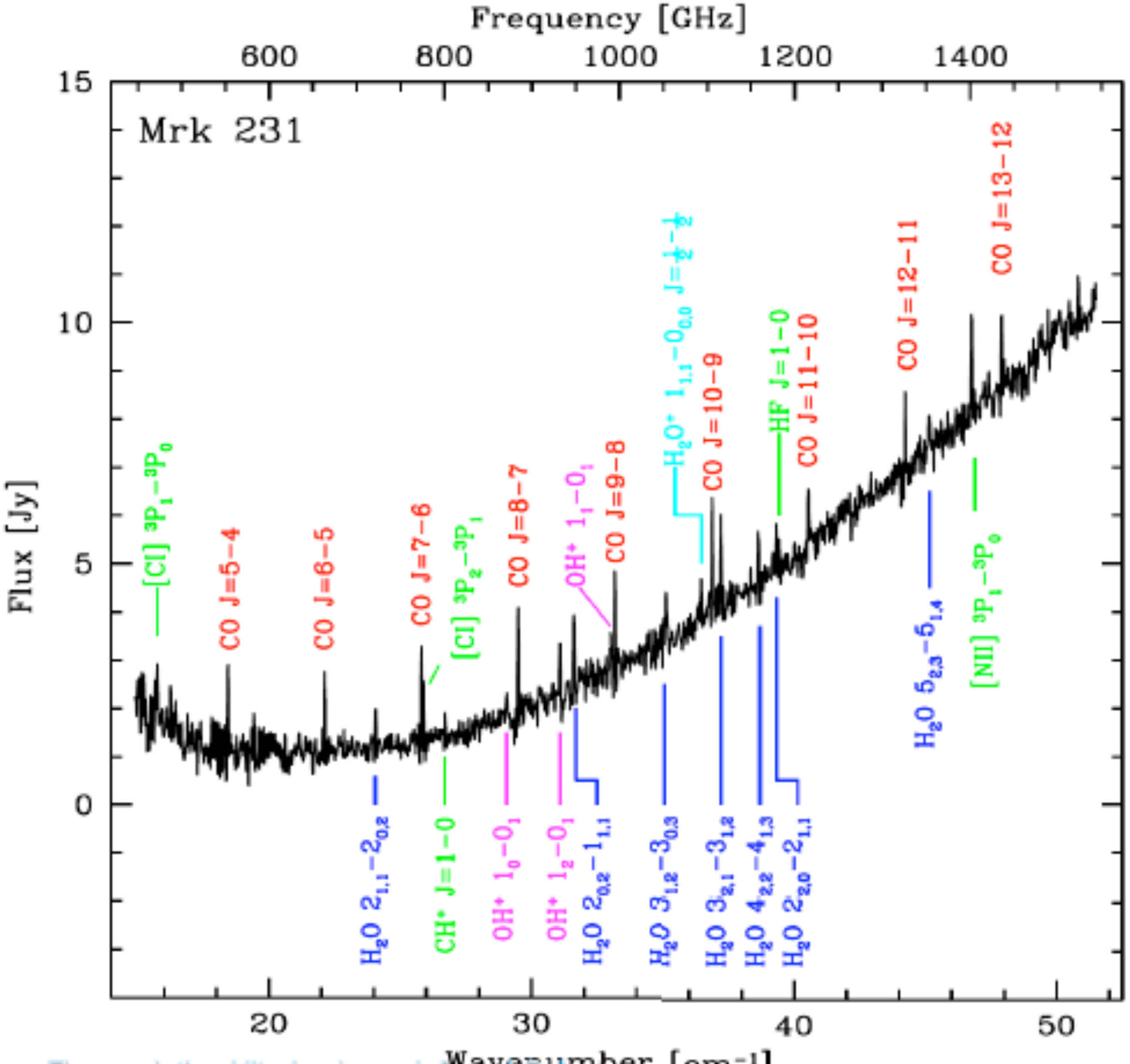
Ferkinhoff et al. 2010,
ApJ, 714, L147

Mkn 231: AGN-dominated ULIRG

- z=0.042 (DL=192 Mpc); one of the closest quasars
- L(IR)=4×10^{12}Lo, the most luminous ULIRG in the IRAS Revised Bright Galaxy Sample
- Warm infrared colors
- Star-forming disk (radius ~ 500 pc) + absorbed X-ray nucleus
- Face-on, massive molecular gas disk, M(H2) ~ 5×10^{9} Mo

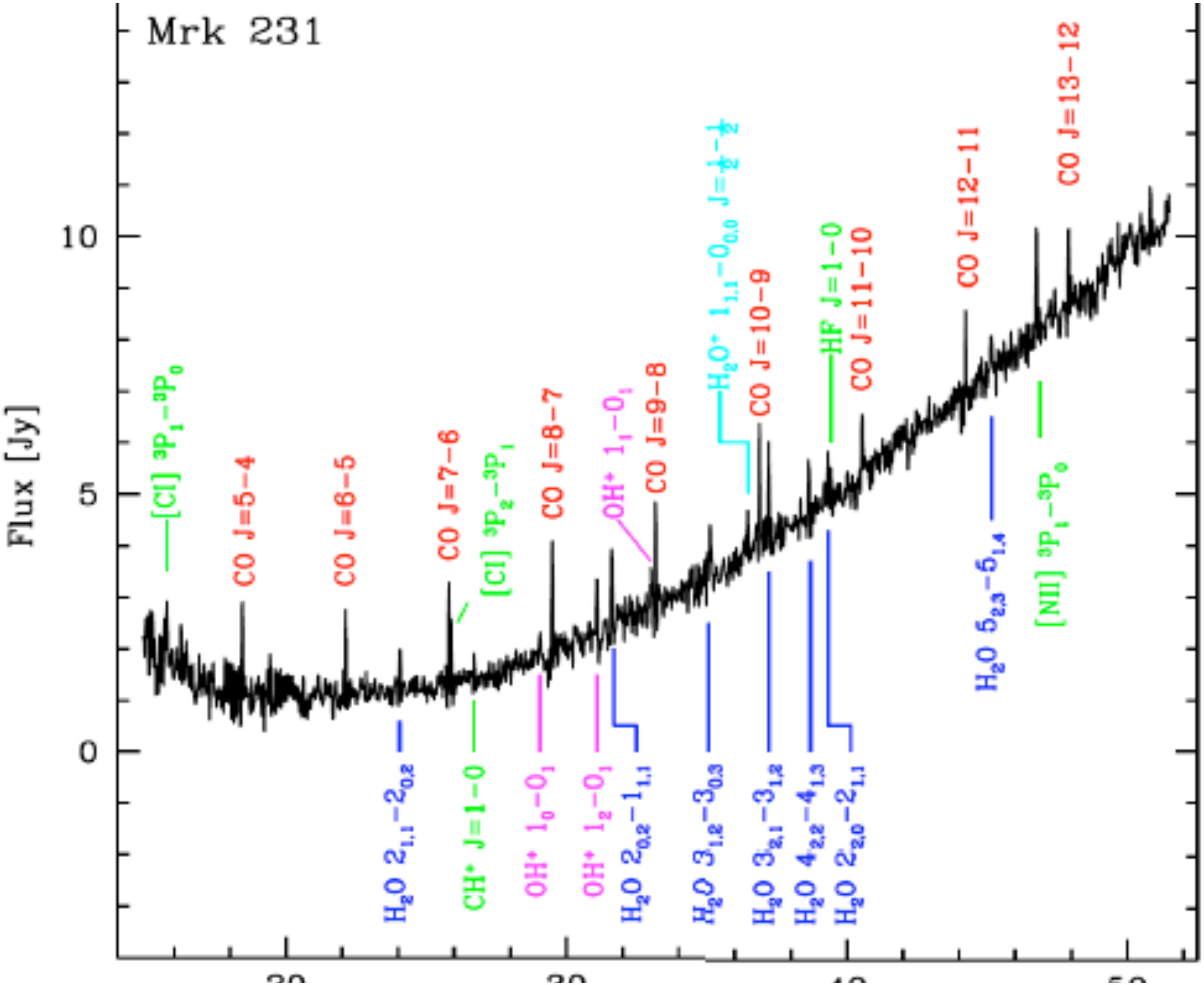


Mkn 231 SPIRE-FTS spectrum



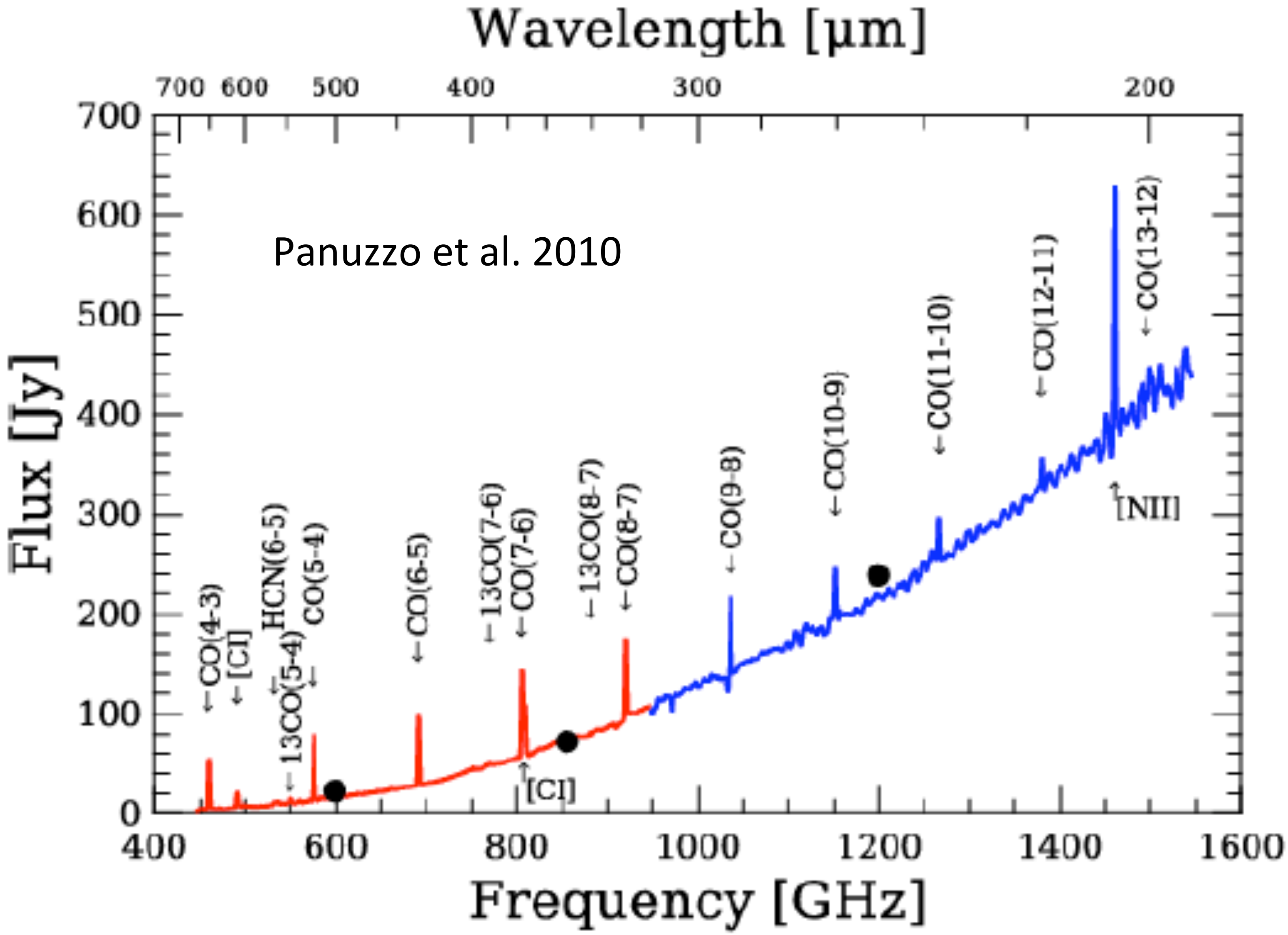
- Very high-J CO lines up to J=13-12 are still well excited !
- Very rich in species; many bright H_2O, H_2O^+, OH^+ lines

Van der Werf et al. 2010



Mrk 231
Flux [Jy]
10
5
0
[CI] 3P1−3P0
CO J=5−4
CO J=6−5
CO J=7−6
[CI] 3P2−3P1
CO J=8−7
OH+ 11−01
CO J=9−8
H2O+ 11,1−00,0 J=1/2−1/2
CO J=10−9
HF J=1−0
CO J=11−10
CO J=12−11
CO J=13−12
H2O 52,3−51,4
[NII] 3P1−3P0
H2O 21,1−20,2
CH+ J=1−0
OH+ 10−01
OH+ 12−01
H2O 20,2−11,1
H2O 31,2−30,3
H2O 32,1−31,2
H2O 42,2−41,3
H2O 22,0−21,1

SPIRE-FTS spectrum of M82, a pure starburst galaxy, is dominated by CO, no H_2O

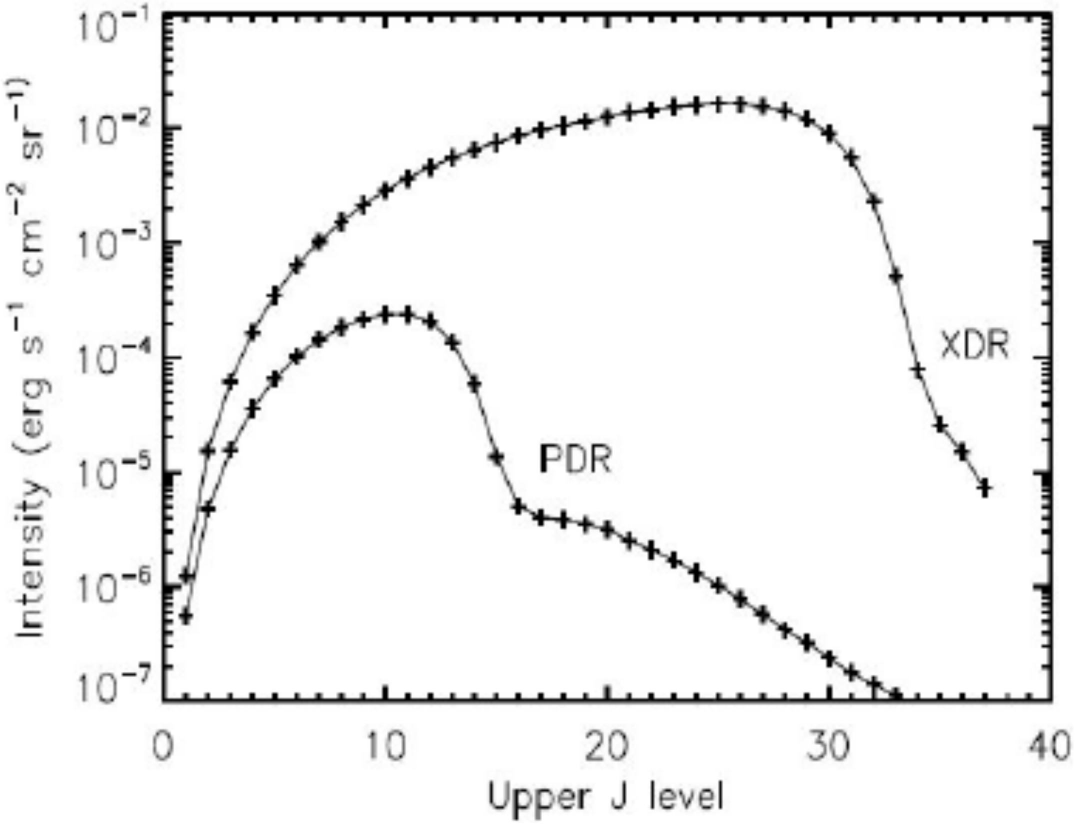


PDR vs XDR: 4 major differences

- X-ray penetrate much larger column densities than UV photons
- Gas heating efficiency in XDRs is very high (10-50 %), compared to PDRs (< 1%)
- Dust heating much more efficient in PDRs than in XDRs
- High ionization levels in XDRs drive ion-molecule chemistry over large column density

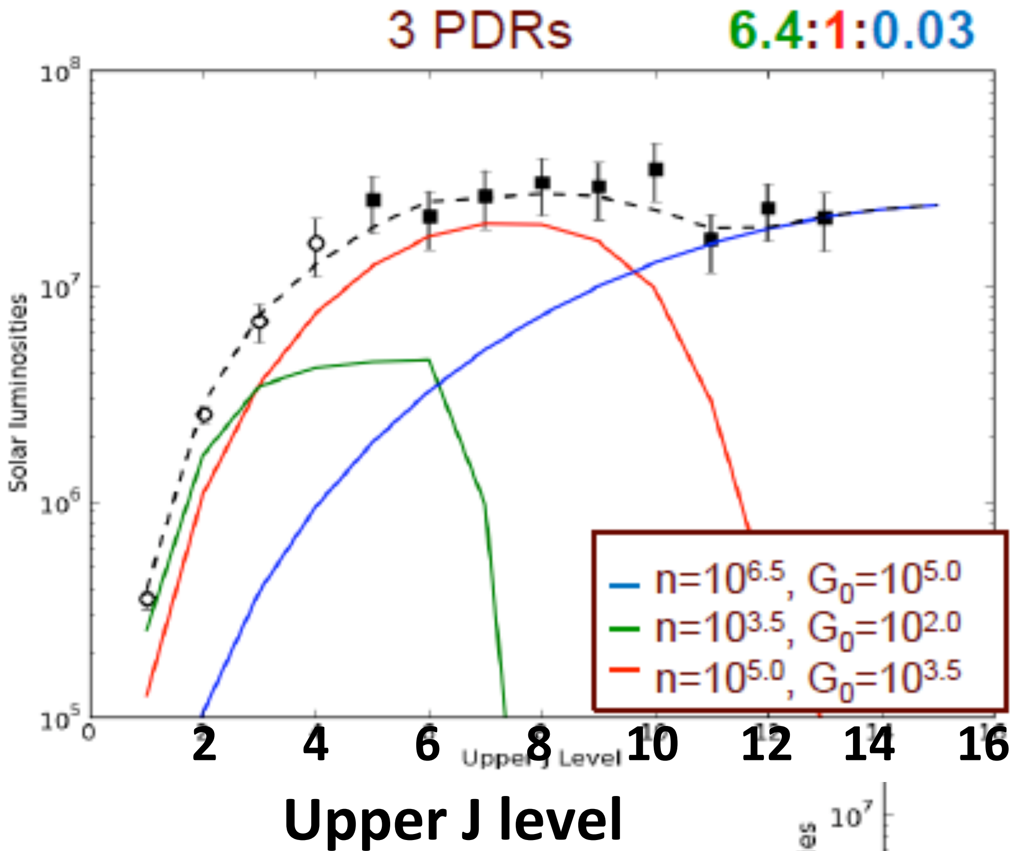
Heating source modeling: XDR vs PDR

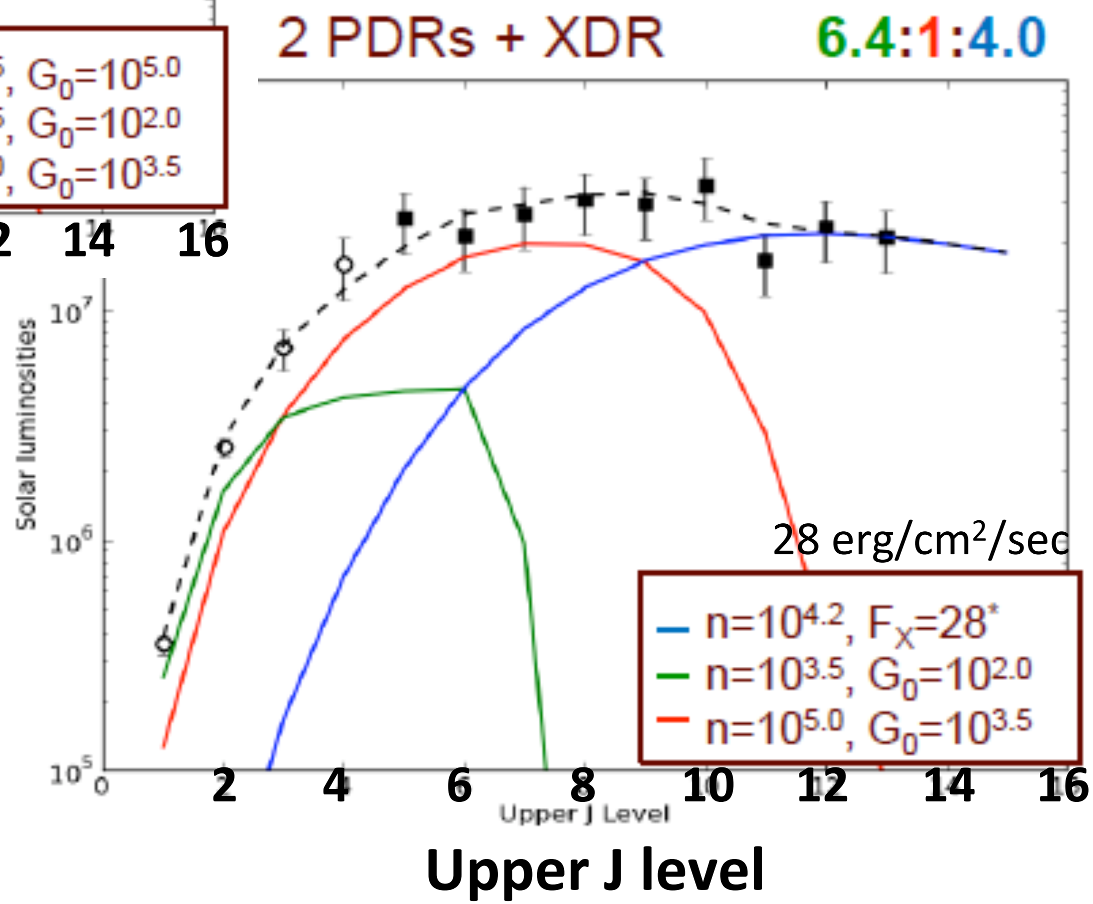
- XDRs produce larger column densities of warmer gas
- Identical incident energy densities give very different CO spectra
- Very high-J CO lines are excellent XDR tracers
- Need good coverage of CO ladder



Spaans & Meijerink 2008

Modeling CO ladder: XDR vs PDR



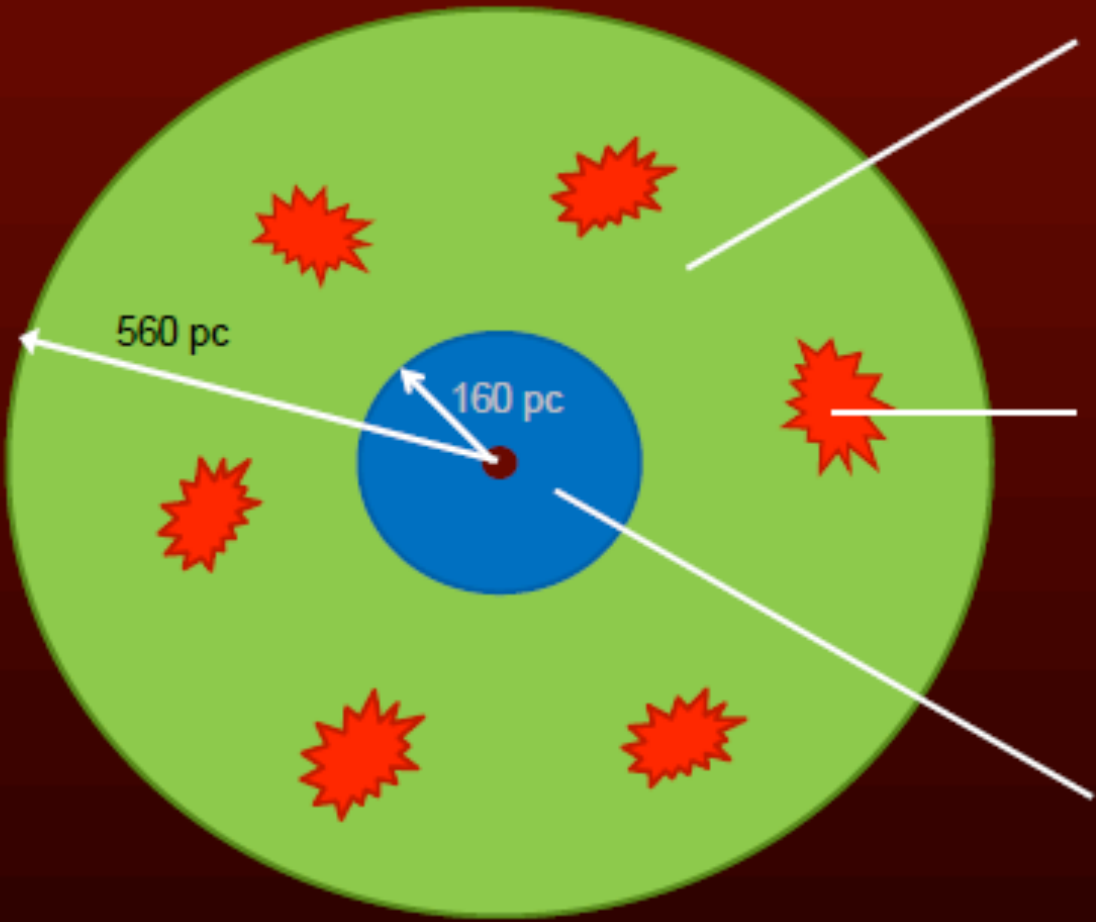


Can PDRs explain the CO ladder too?

- High-J CO lines can also be produced by PDRs, but with $n=10^{6.5}$ cm^{-3} and $G_0=10^5$, containing half of the molecular gas mass
- $G_0=10^5$ only out to 0.3 pc from O5 star; then we must have half of the molecular gas and dust in 0.7% of volume
- With $G_0=10^5$, 50% of the dust mass would be at 170 K
- $[OH^+]$ and $[H_2O^+] > 10^{-9}$ in dense gas requires efficient and penetrative source of ionization; PDR abundance factor 100 – 1000 lower

➔ XDR strongly favoured

PDR/XDR model

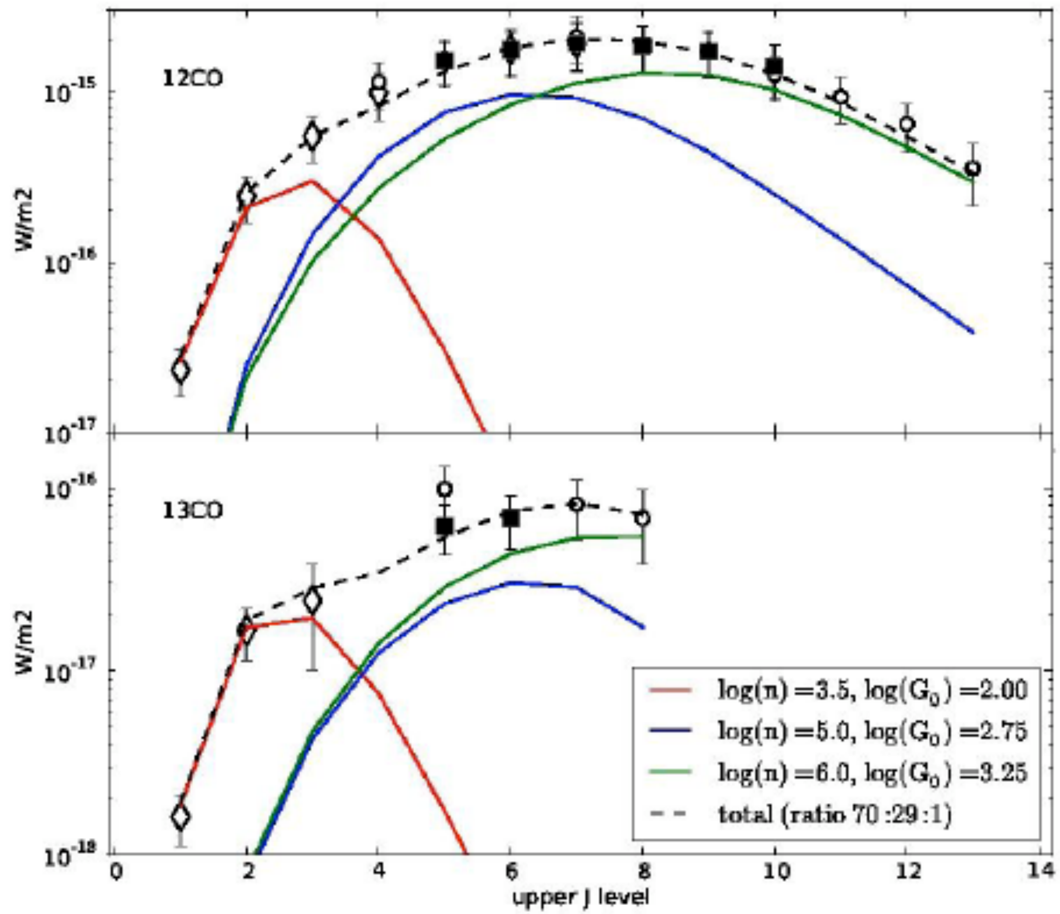


- PDR 1:
  - $n=10^{3.5}$, $G_0=10^2$, R~500pc
  - Large scale molecular gas
  - → Low-J CO, low H_2O lines
- PDR 2:
  - $n=10^5$, $G_0=10^{3.5}$
  - Small, dense SF clumps
  - → mid-J CO lines
- XDR:
  - $n=10^{4.2}$, $F_X=28$, R~150pc
  - Circumnuclear XDR disk
  - → High-J CO, OH^+, H_2O^+, high H_2O lines

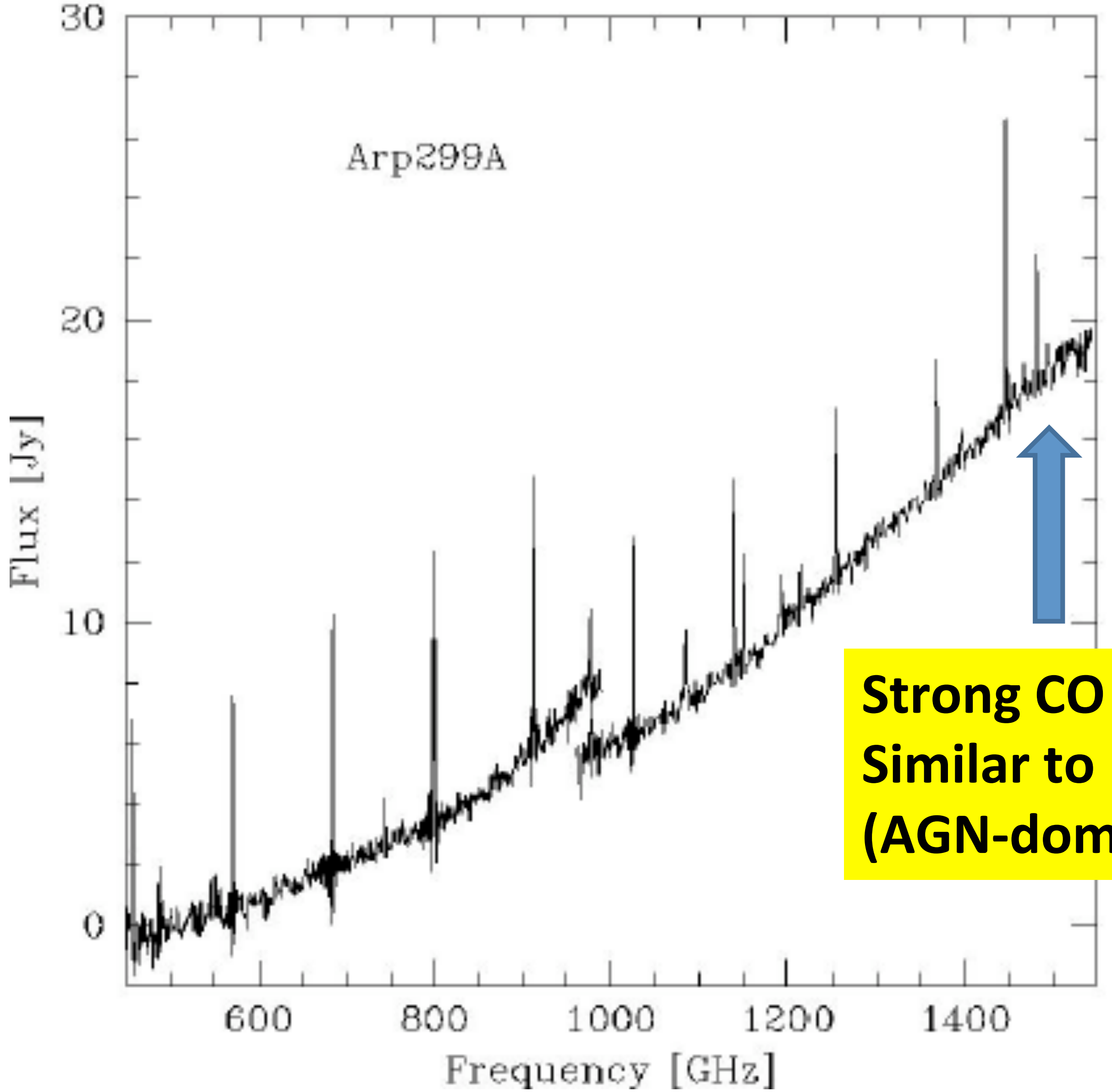
A pure PDR model explains CO ladder in M82

- CO ladder drops at high J
- Combination of PDRs accounts for both the 12CO and 13CO lines
- Highest excitation component can be identified in line profiles

Loenen et al. 2010



More to come; Arp299A FTS spectrum



Strong CO J=13-12 line, Similar to Mkn 231 (AGN-dominated one)

Summary: SAFARI+BLISS+ALMA

- Blind imaging-spectroscopic survey with SAFARI: up to z~2 ULIRGs/SMGs
  - Best suited for z~2 cluster studies
- Targetted sensitive spectroscopy with BLISS: up to z~4 ?? ULIRGs/SMGs we need BLISS !
  - Physical properties of ionized gas (PDRs, HII regions, coronal regions) with FIR fine structure lines
  - Very high-J CO
- Detailed (subarcsec or better resolution) imaging study of spectroscopically confirmed high-z ULIRGs/SMGs + molecular gas