National Radio Astronomy Observatory

Molecules at High Redshift
(CO in Spitzer and Herschel-selected High-z Samples)

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Background

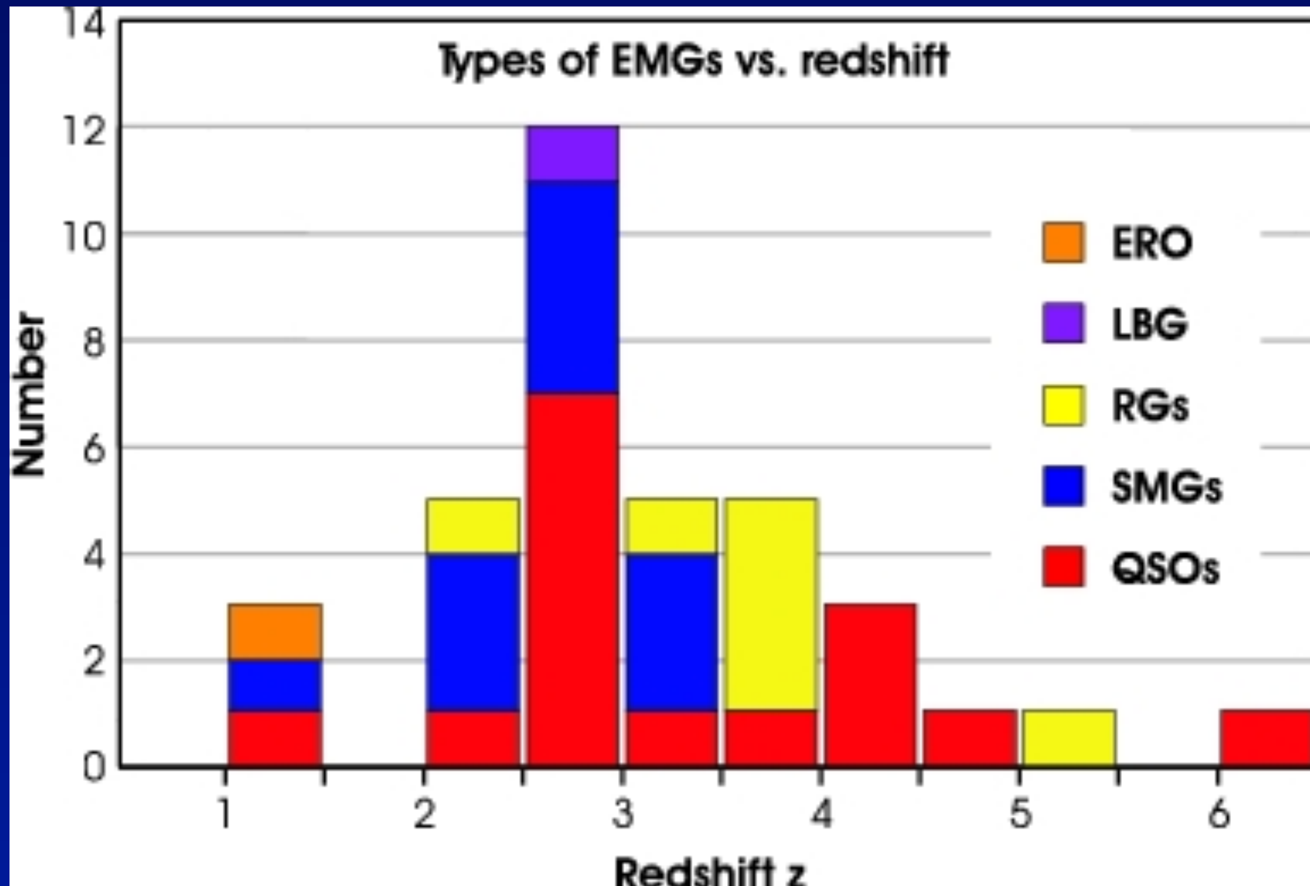
- IRAS ULIRG/LIRGs showed good correlation between L(FIR) and L'(CO) (i.e., FIR {large cold dust grains} ⇔ CO {cold molecular gas})
- CO key tracer for M(H2)
- SCUBA revolutionized the field ➔ Sub-mm galaxies (SMGs) contribute significantly to the total SFR at high-z
- Spitzer 24um (extremely deep in mid-IR) uncovered large samples of LIRGs/ULIRGs at high-redshift
- Herschel enables the accurate measurements of FIR peak of the SEDs

Molecules at High-z?

- Massive stars forming in merger events enrich the ISM rapidly (only need ~1-3x10^8 years to enrich ISM to ~solar metallicity) → massive amounts CO and dust
- Expect peak in L(IR) and L'(CO) luminosities for gas fractions of Mgas/(Mstars+Mgas) ~0.2-0.4 with ~solar metallicity, nearly independent of simple chemical evolutionary models (Frayer & Brown 1997)

Pre-Spitzer: 36 total high-z CO sources at time of Solomon & Vanden Bout 2005 review

- 16 QSOs
- 11 SMGs
- 7 radio galaxies
- 1 ERO-selected (HR10)
- 1 LBG selected (cb58)

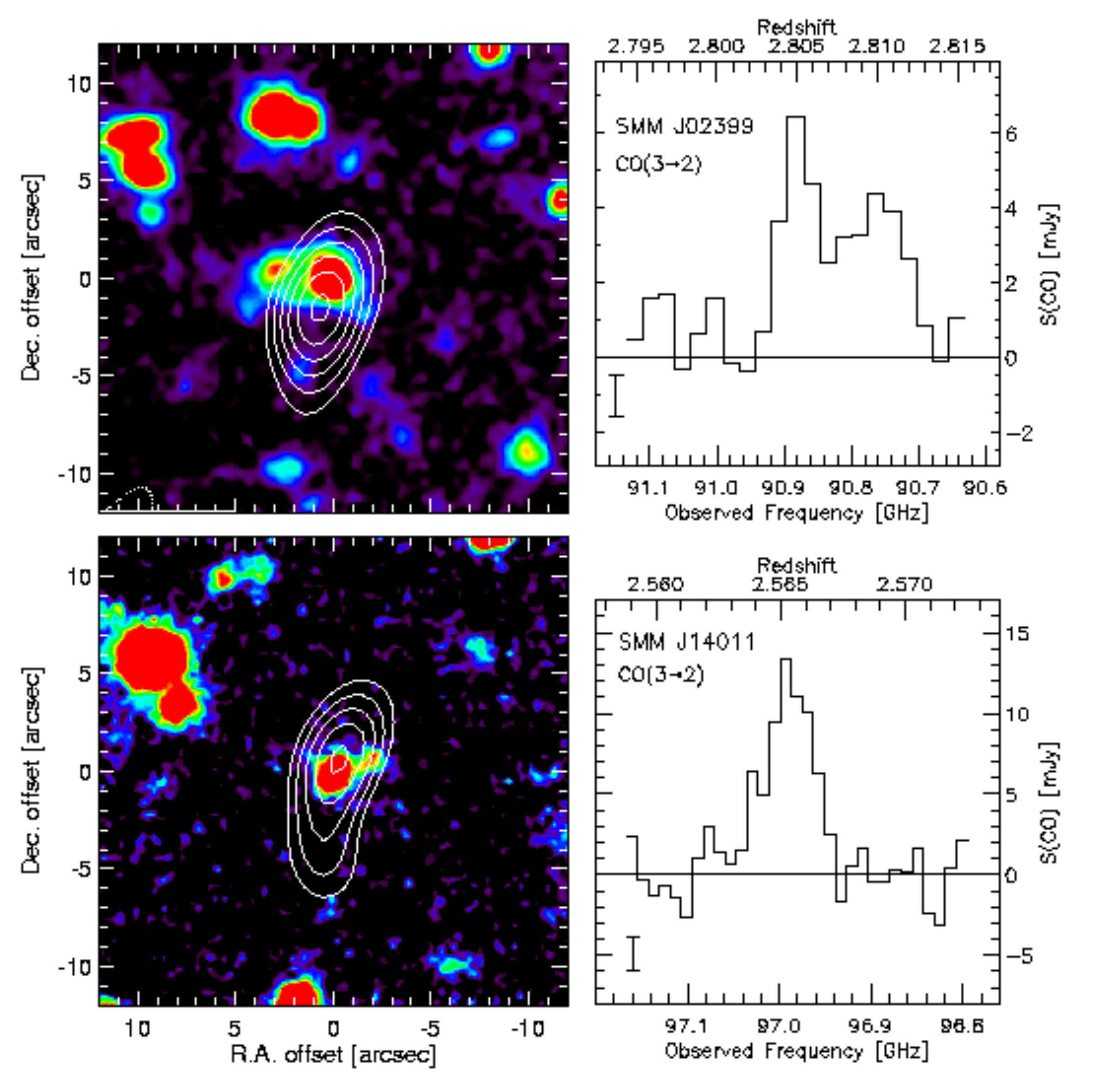


Started with IRAS F10214 in 1991/1992 (Brown & Vanden Bout)

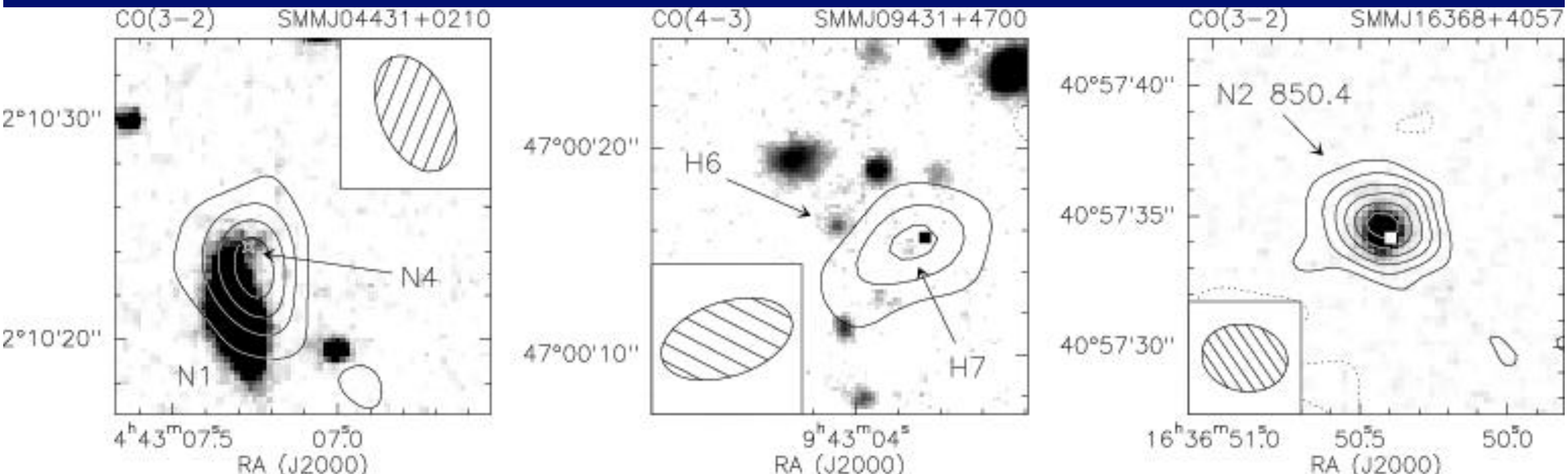
First SMG CO Detections (OVRO, Frayer et al. 1998, 1999)

SMGs:

- $M(H_2) \sim 10^{10-11}$ M(sun) -- enough gas to fuel the star formation implied by $L(FIR) \sim 10^{12-13}$ L (sun)
- Similar CO/FIR/radio luminosity ratios as local ULIRGs
- SMGs ~ scaled-up ULIRGs with slightly cooler Td and more extended than ULIRGs



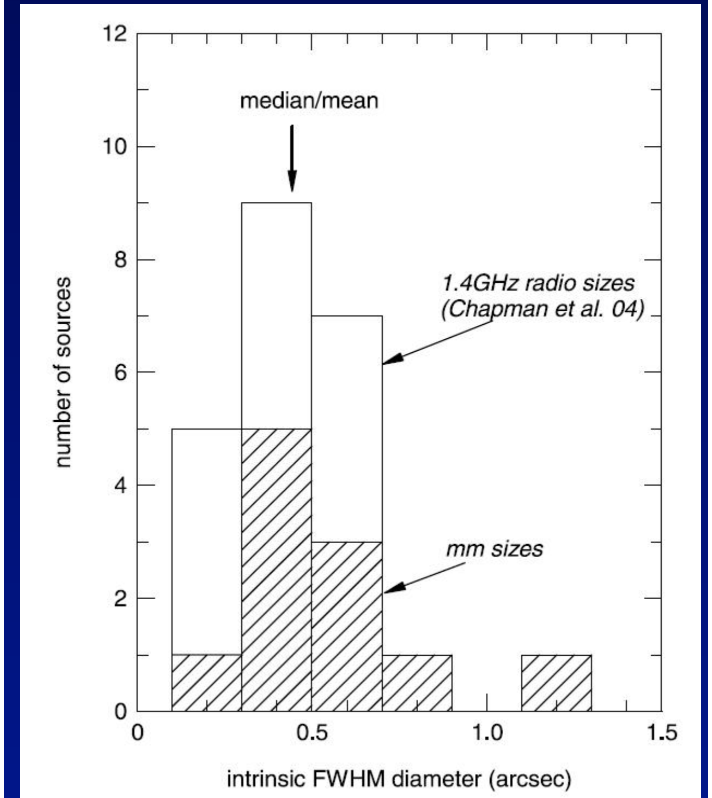
Initial PdBI SMG CO Detections

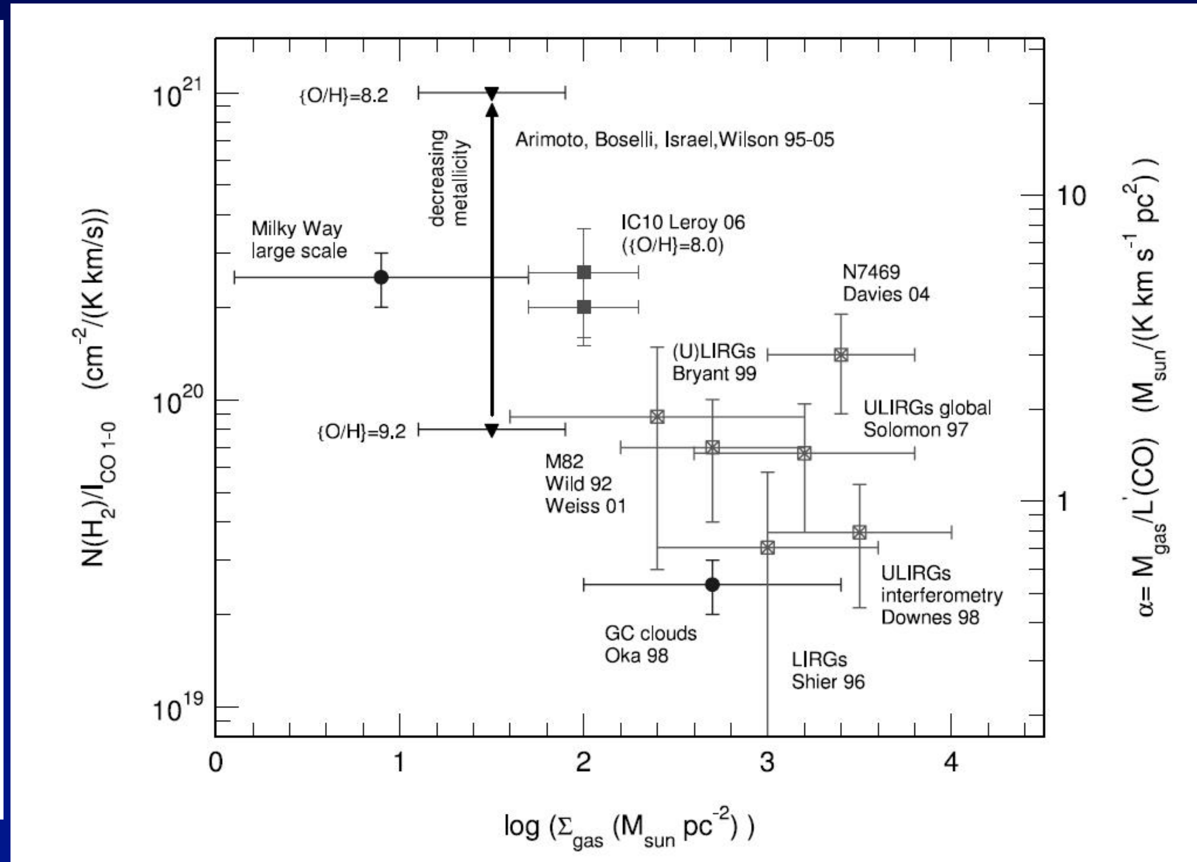


SMG ERO-N4

Neri et al. 03

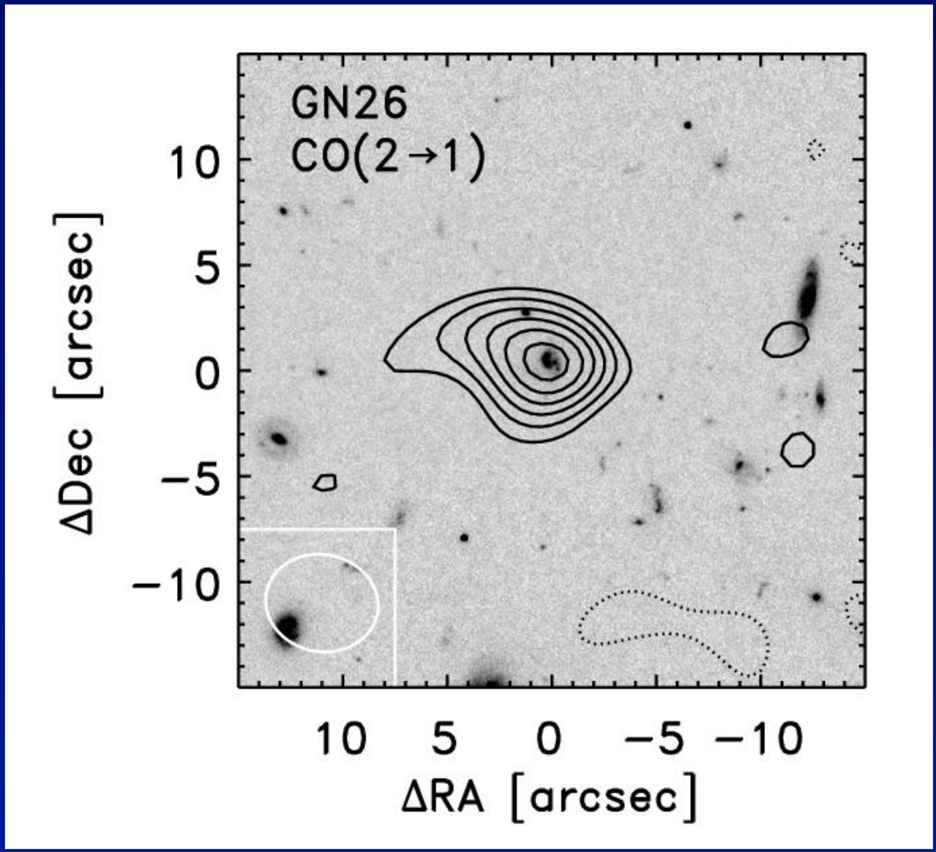
Greve et al. 2005 provided a compilation of 12 SMGs detected in CO

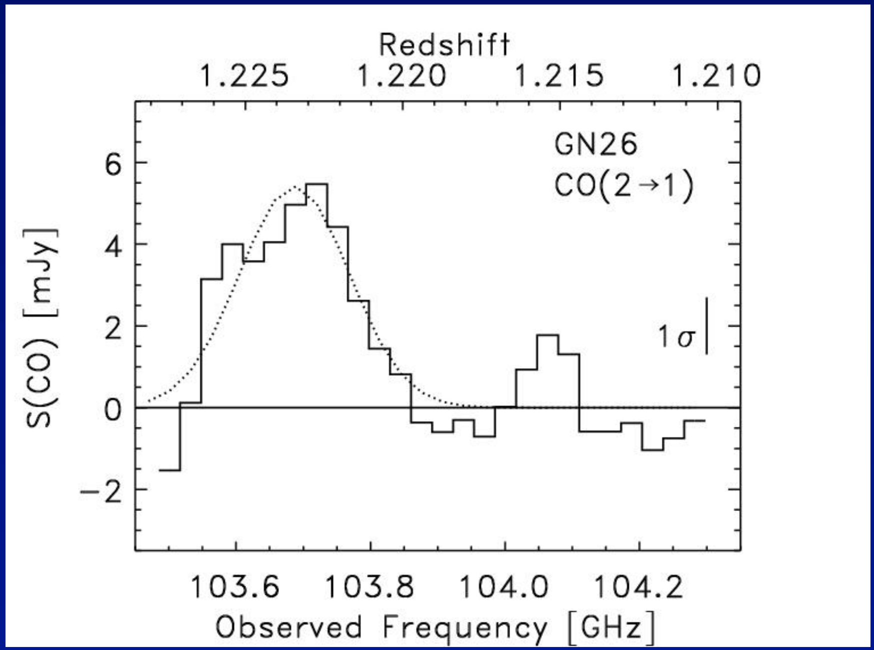




Tacconi et al. 2006, 2008 PdBI high-resolution CO imaging of SMGs find similar mm sizes as radio (CO on kpc scales, not sub-kpc scale as local ULIRGs) and argues for similar CO to H_2 conversion factors (alpha~0.8 Msun (K km/s pc^2)^-1 typically assumed for SMGs and ULIRGs but still unknown by factors of 2 or more).

Spitzer FIR selection based on 70+160um ➔ 1st High-Redshift CO Detection with CARMA

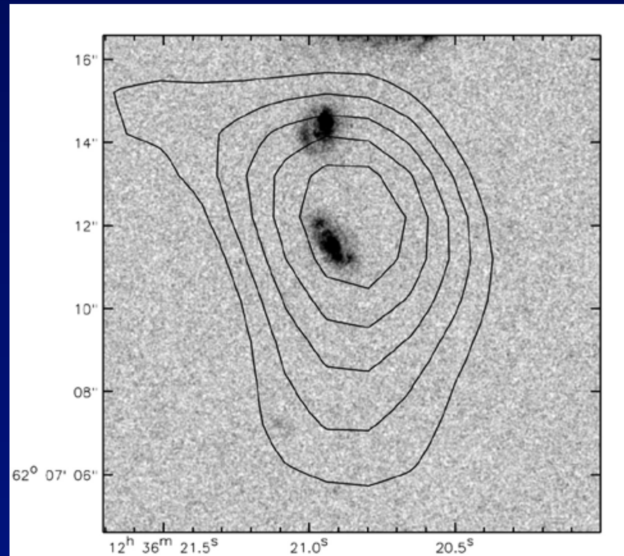




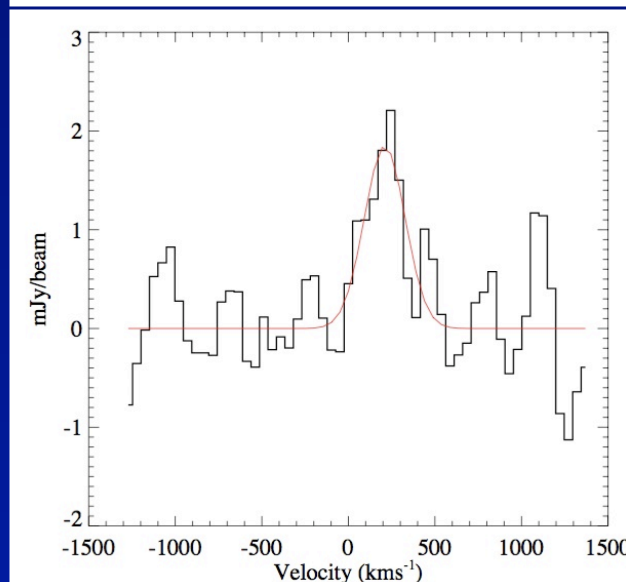
Frayer et al. 2008

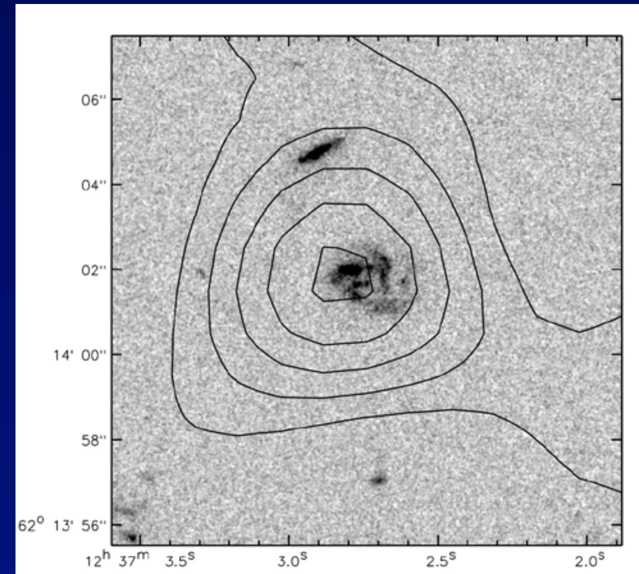
GN26 is the brightest 70&160um high-redshift (z>1) source within the GOODS-North (GO-1); Note: almost missed the source due to the inaccurate (wrong) optical redshift and small 3mm bandwidth.

Pope et al. PdBI CO (2-1) program (2010, in prep): GOODS-N Spitzer 70um sources with strong IRS PAH features

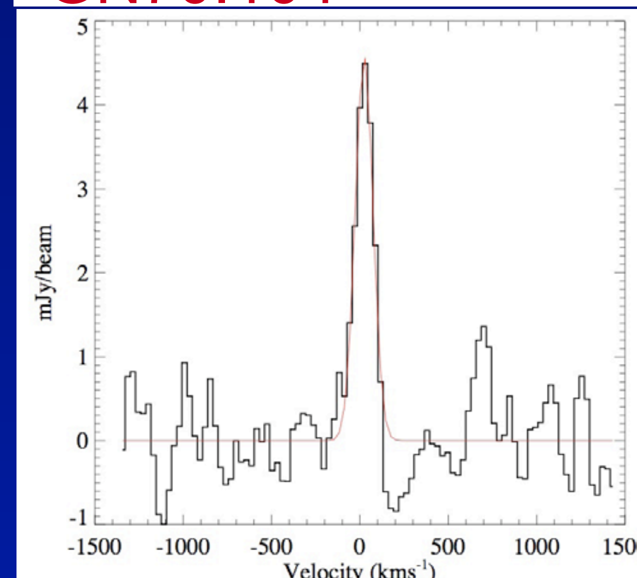


GN70.8





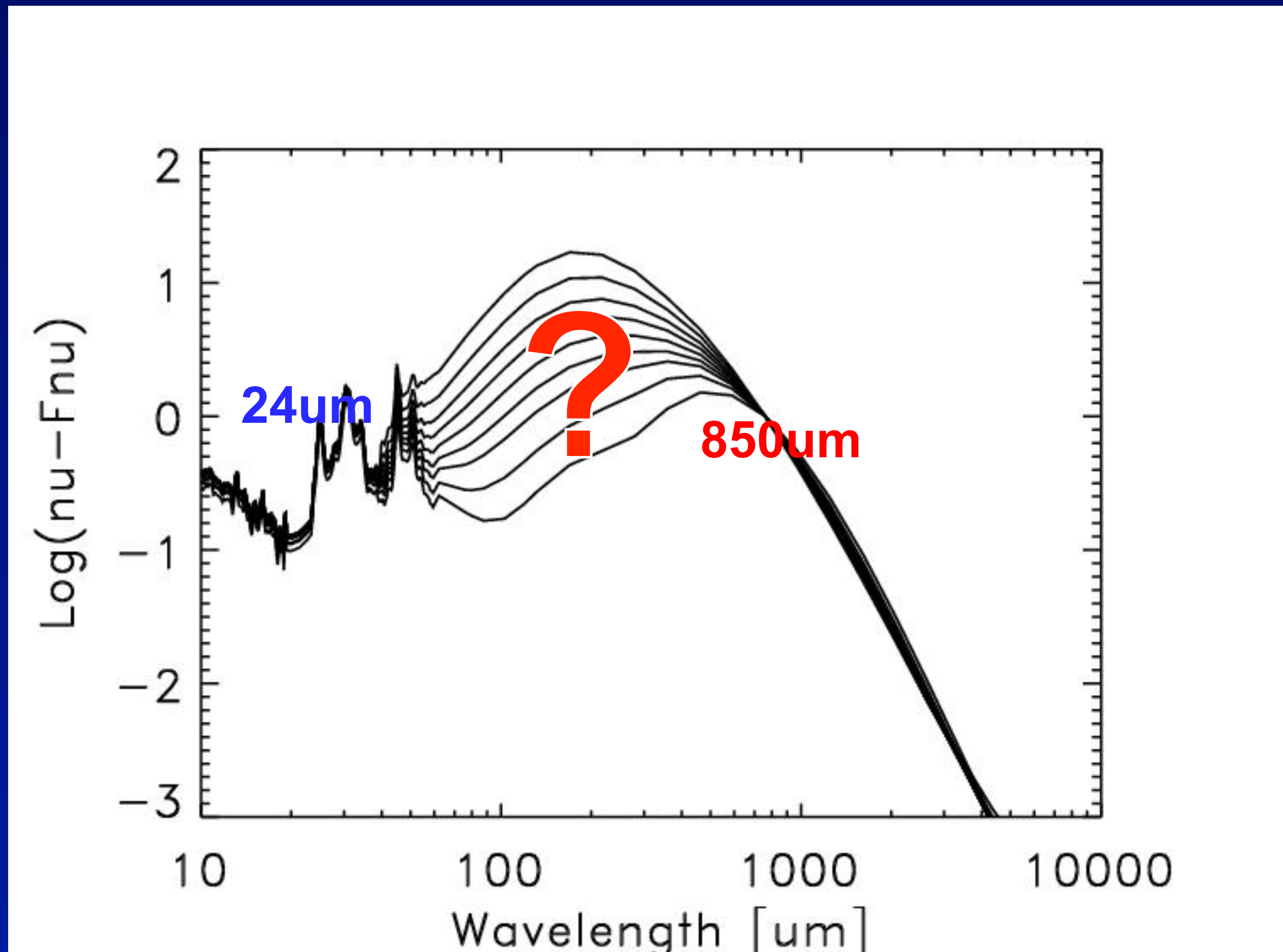
GN70.104



Need FIR measurements near peak!! → Herschel

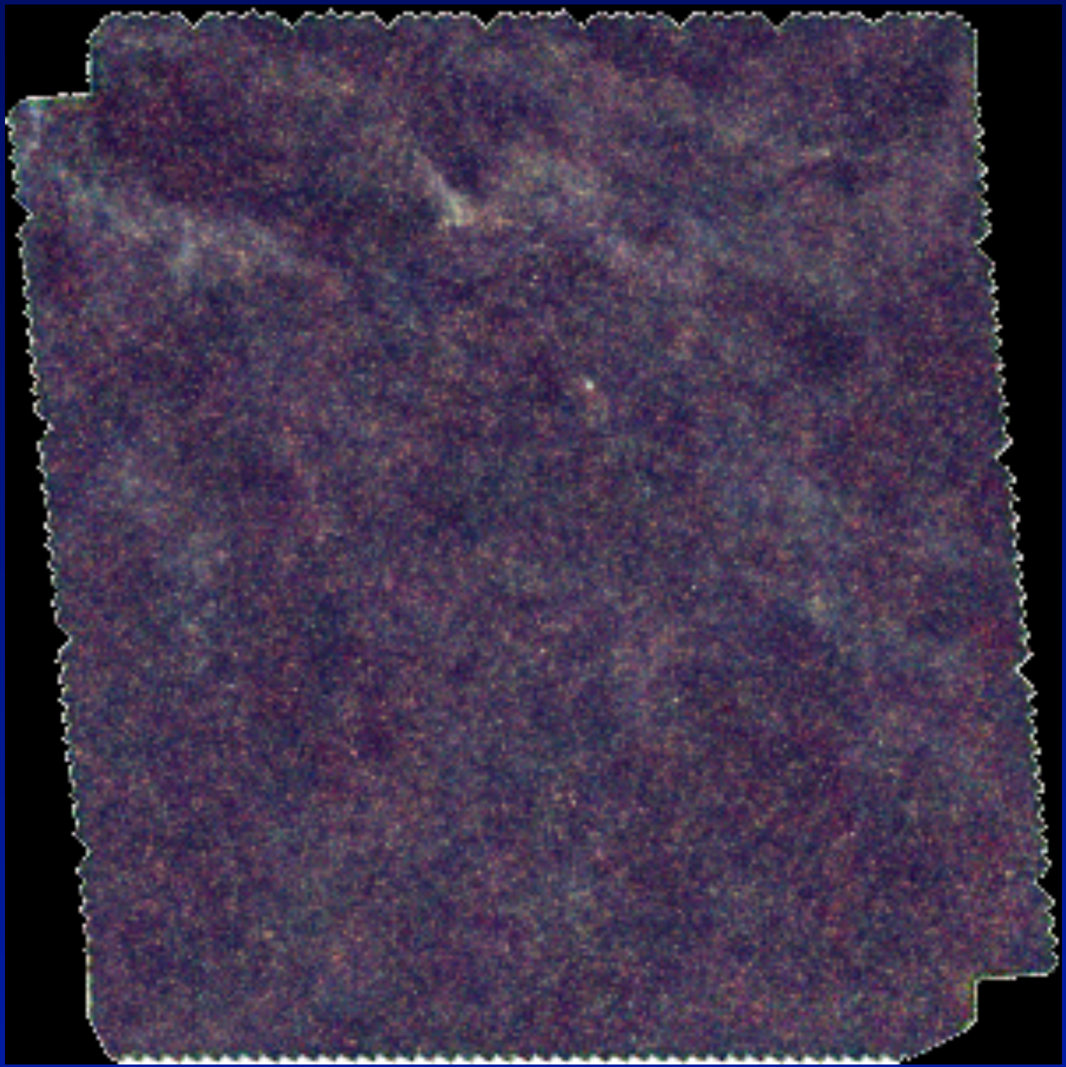
Dale and Helou SEDs at z=3 and normalized at 850um observed-frame.

Most high-z CO sources observed to date are based on 850um and Spitzer 24um selection.
→Uncertain L(IR).



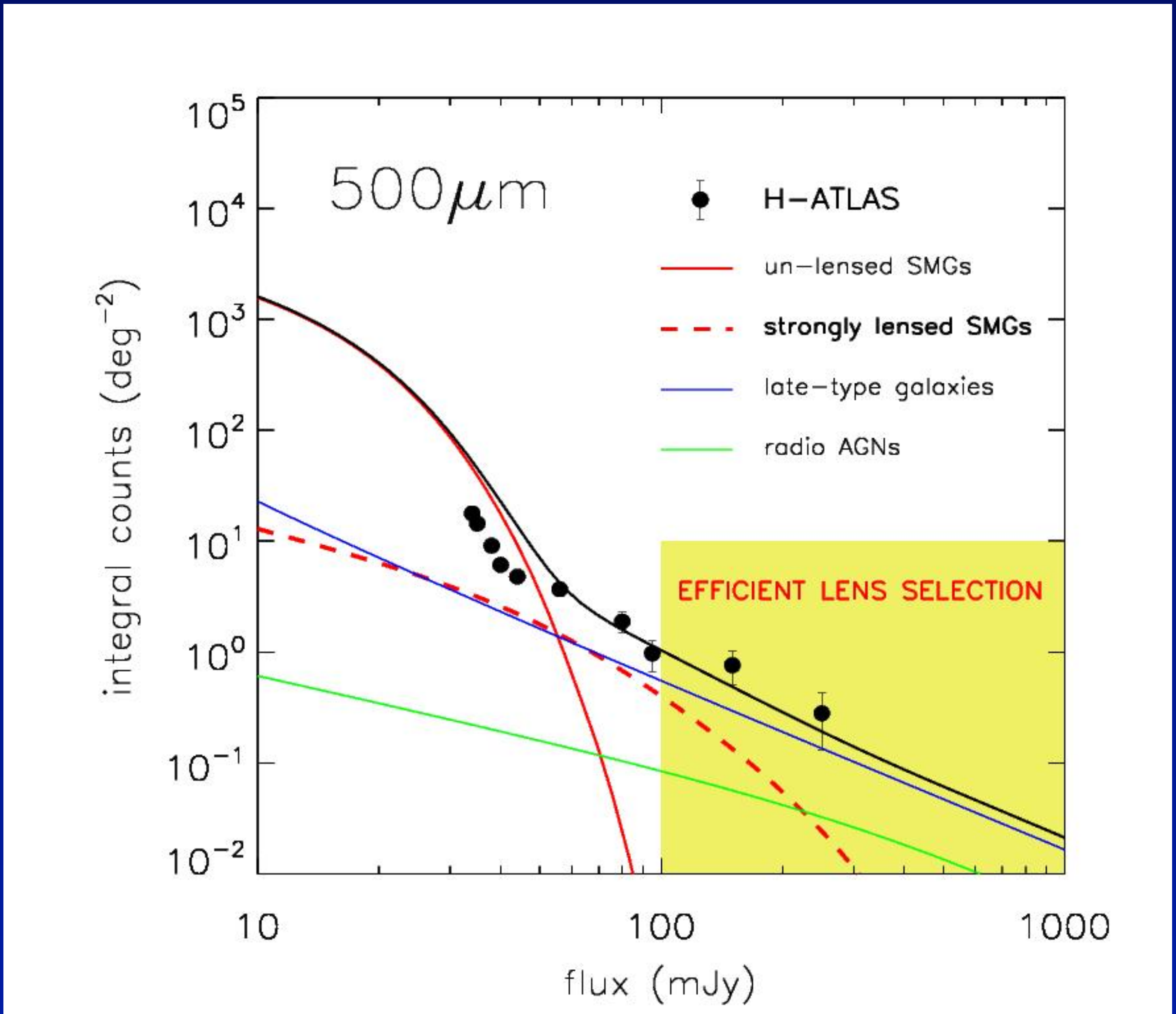
Herschel-ATLAS Survey (Eales et al.)

- Wide-area sub-mm survey: 570 sq-deg (over several fields)
- 100, 160, 250, 350, 500um bands
- rms~10mJy level (confusion limited at longer wavelengths)
- Ancillary optical data
- Right: SDP Gama-9hr field 4deg x 4deg tile (250+350+500um color image)

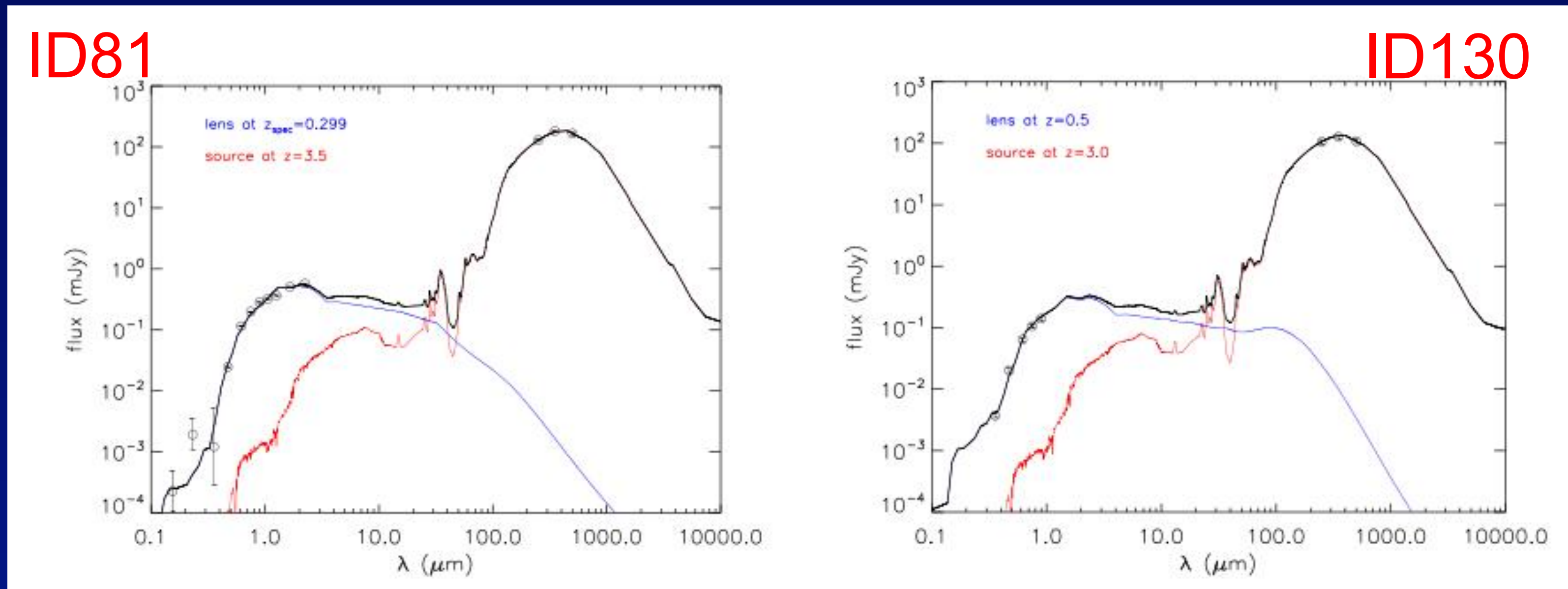


Herschel data shows the upturn in the bright source counts expected from lensed sub-mm sources

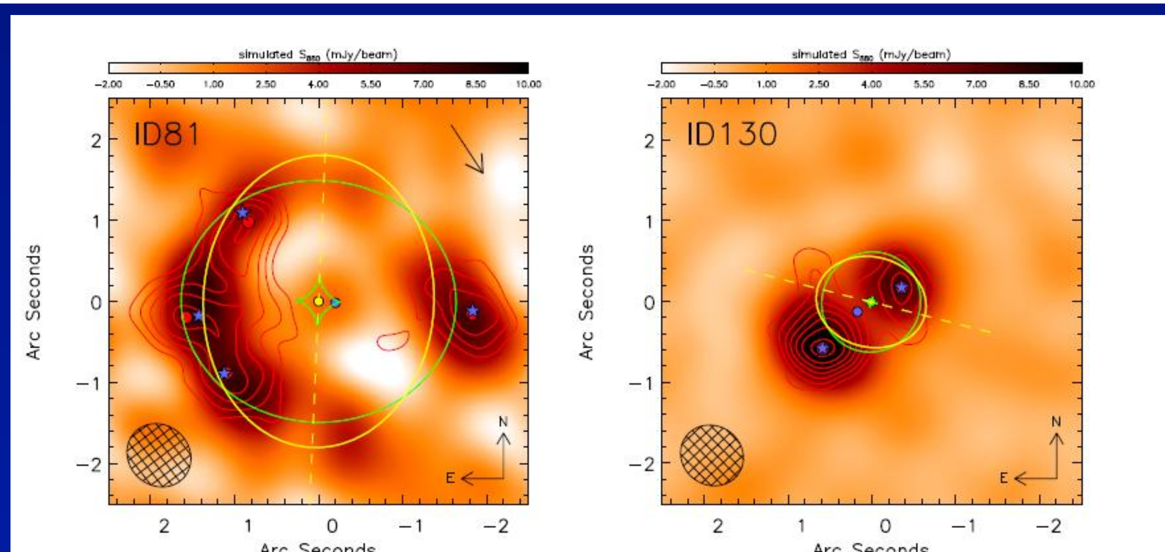
M. Negrello et al. (2010) with H-ATLAS Herschel/ SPIRE data.



Lensed Candidates: Bright 350um “Peakers”

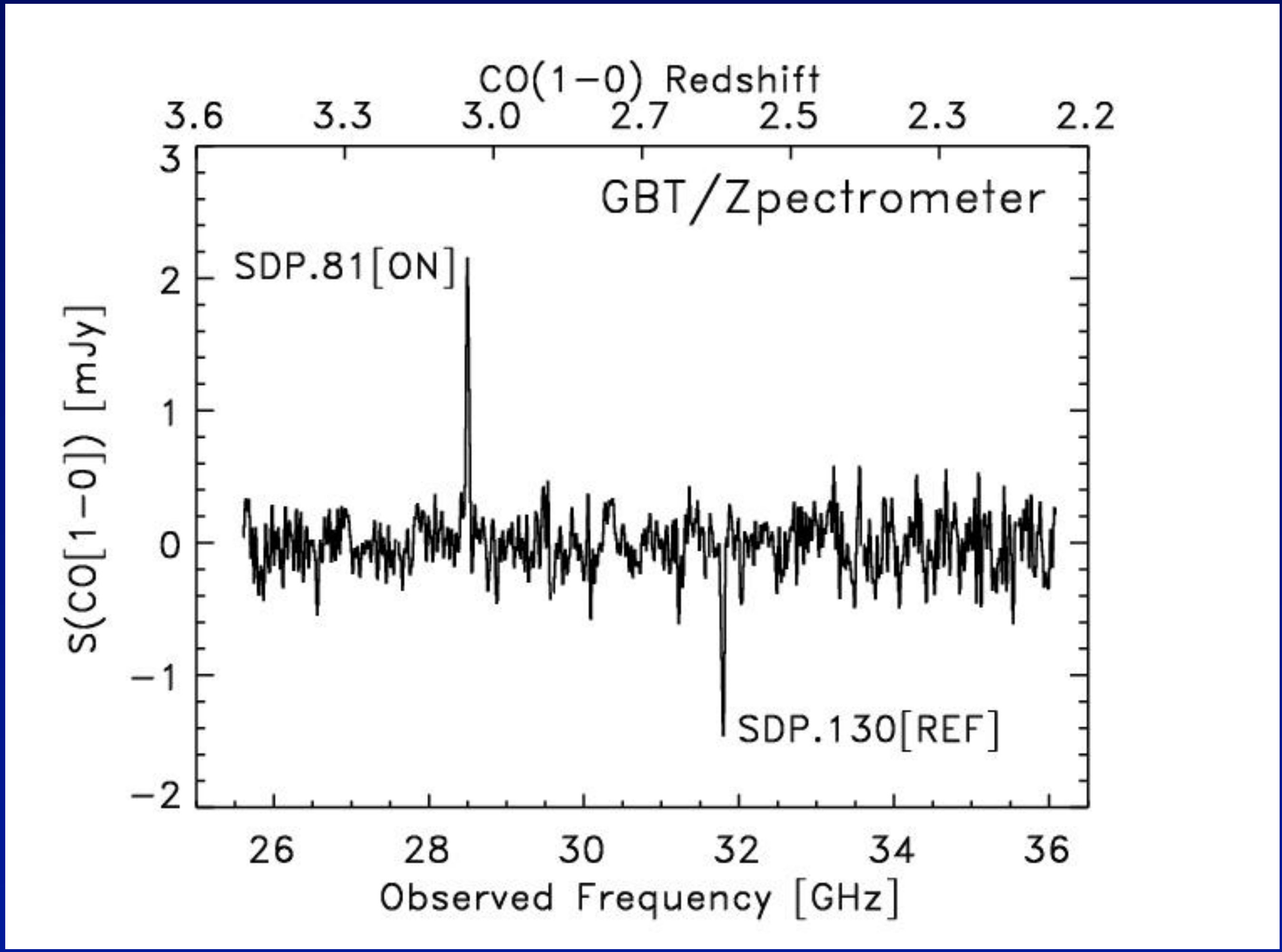


Strong far-infrared background sources -- Sources that peak at 350um are at z~2-3.5 and are ideal targets for GBT/ Zpectrometer redshift measurements using CO (1-0)



SMA imaging

GBT/Zpectrometer (Frayer et al. 2010)

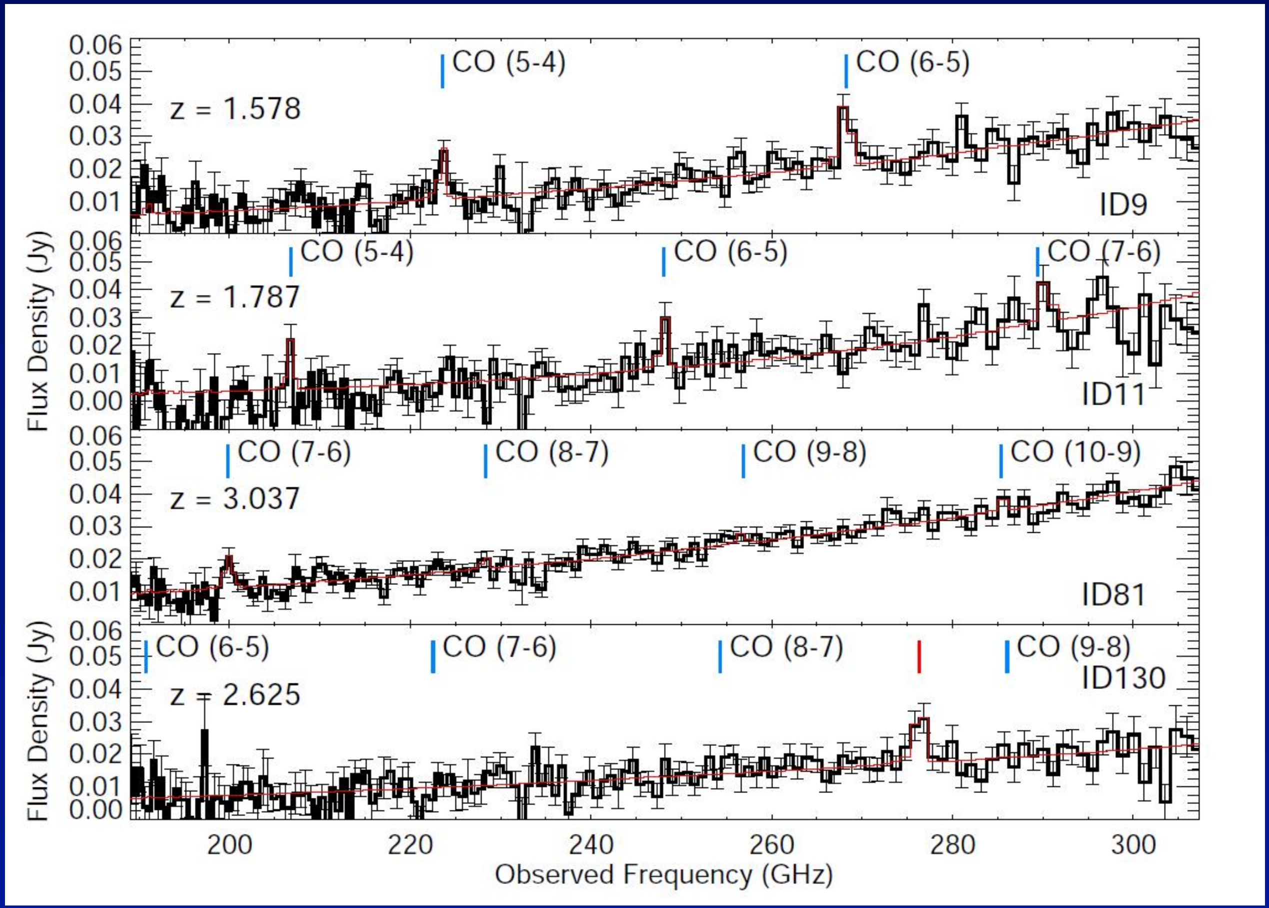


SDP.81(ON)+SDP.130 (REF, negative): CO(1-0) redshifts measured. Confirms sources are background lensed galaxies [only 1.15hr integration time per source]. Both sources confirmed with PdBI CO(3-2) data.

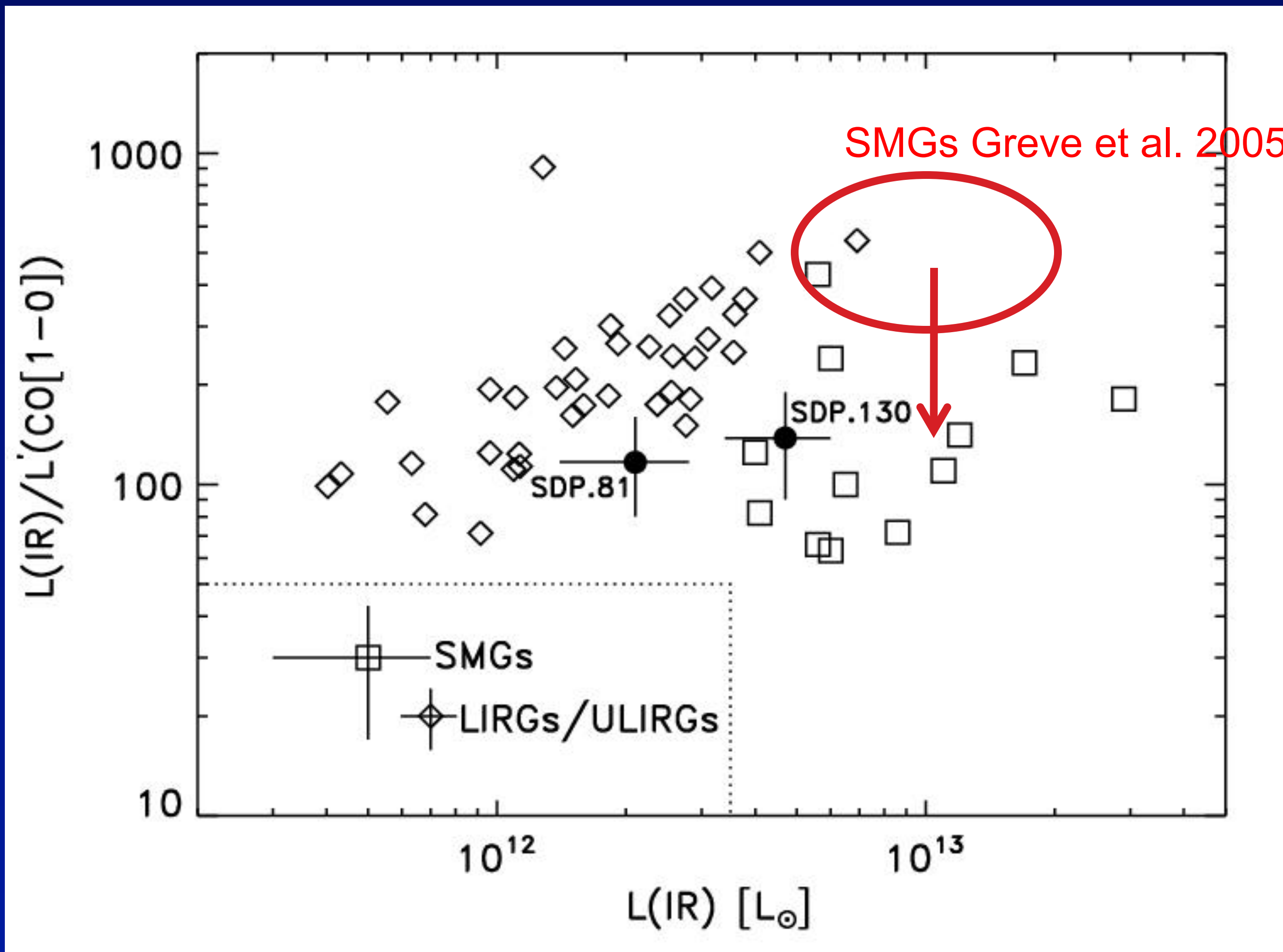
CSO/Z-Spect:

Lupu et al. (2010) searching for redshifts using the high-J CO lines.

Herschel SMGs ➔ Lots of ongoing GBT, CSO, SMA, PdBI, CARMA, IRAM-30m, and eVLA observations.



Results: SMGs have similar L(IR)/L'(CO) ratios and similar L'(CO[3-2])/L'(CO[1-0])~0.6 as the local ULIRGs



Previous SMG results assumed warmer dust (40K) which overestimated Lir by ~2x for the measured SMG Td~35K and the adopted L'CO(3-2)/L'CO (1-0) = 1, underestimated L'CO(1-0) by 1.7

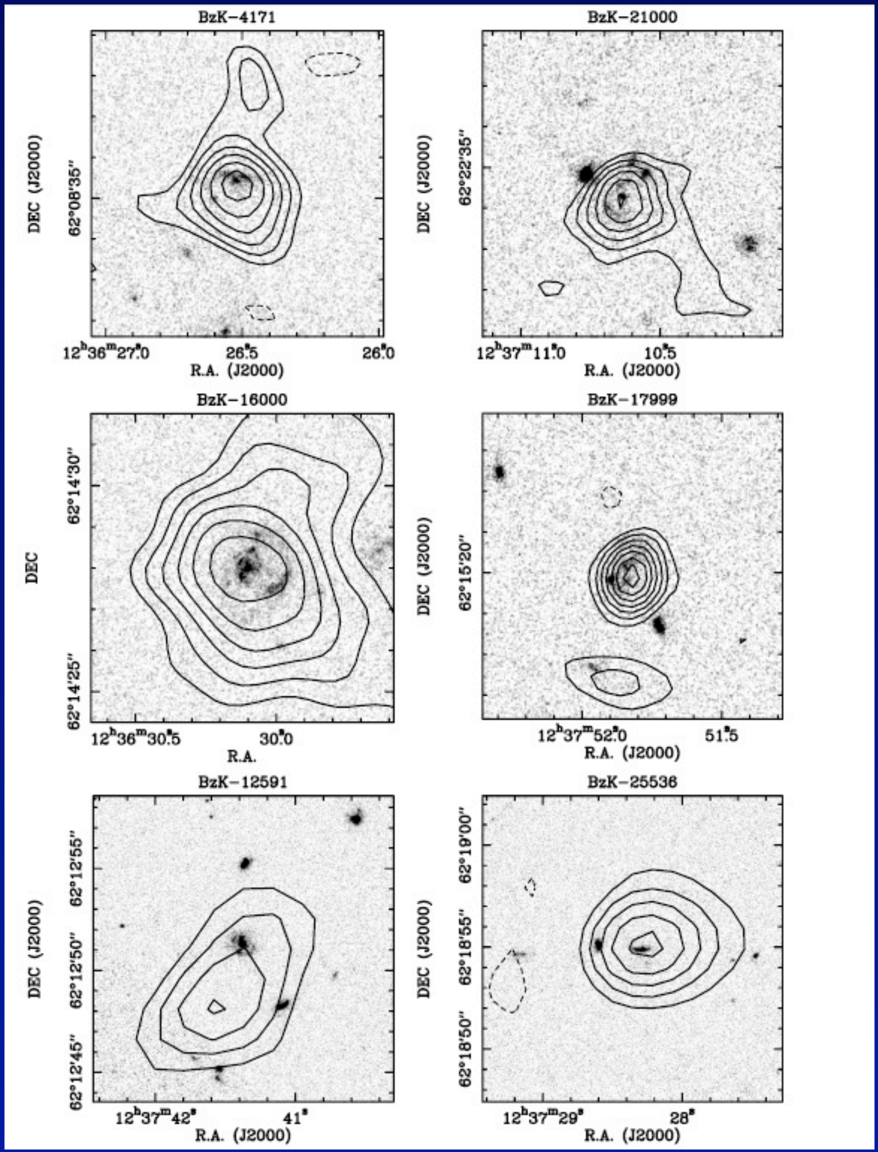
Key: Good FIR measurements with CO(1-0)

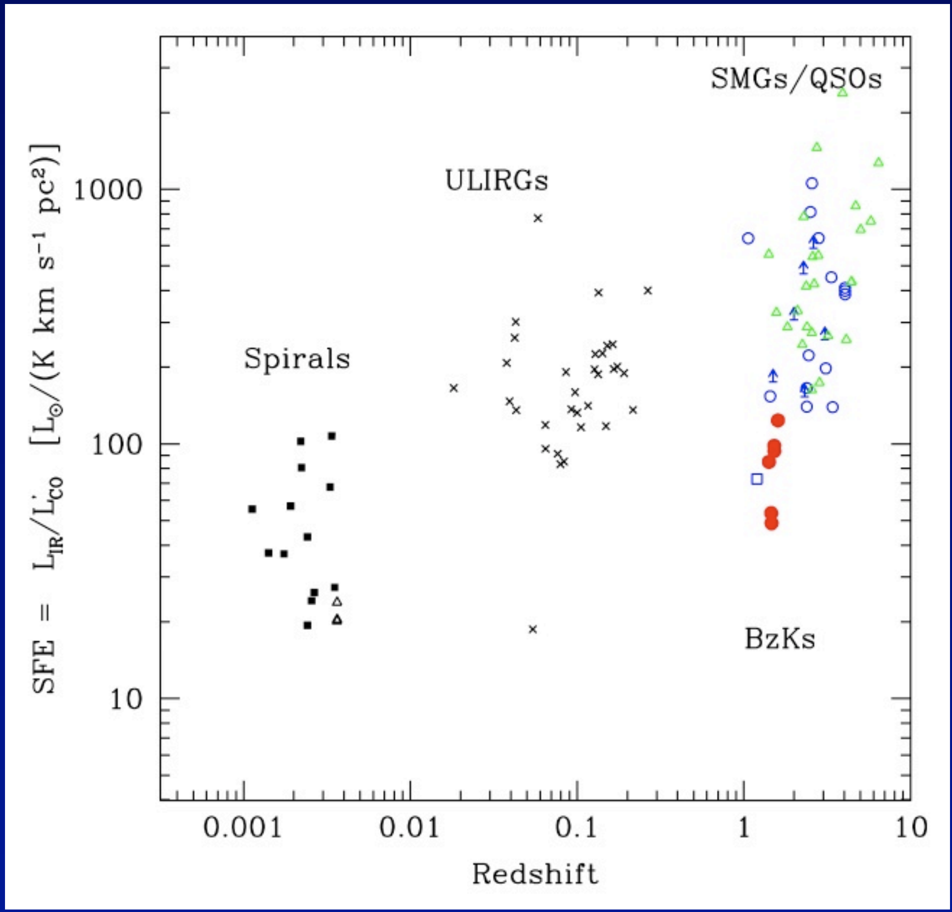
Frayer et al. 2010

Open Questions

- Disk vs merger "modes" of star formation
- alpha – CO to H_2 conversion factors
- Spatial extent and relative strengths of different ISM components: CO(low-J), CO(high-J), HCN, HCO+, CI, C+
- Fraction of high-redshift z >4 IR-luminous starbursts (mm/sub-mm without counterparts) vs "typical" z~1-3 sources studied to date ➔ 500um "peakers" with Herschel probes higher-z

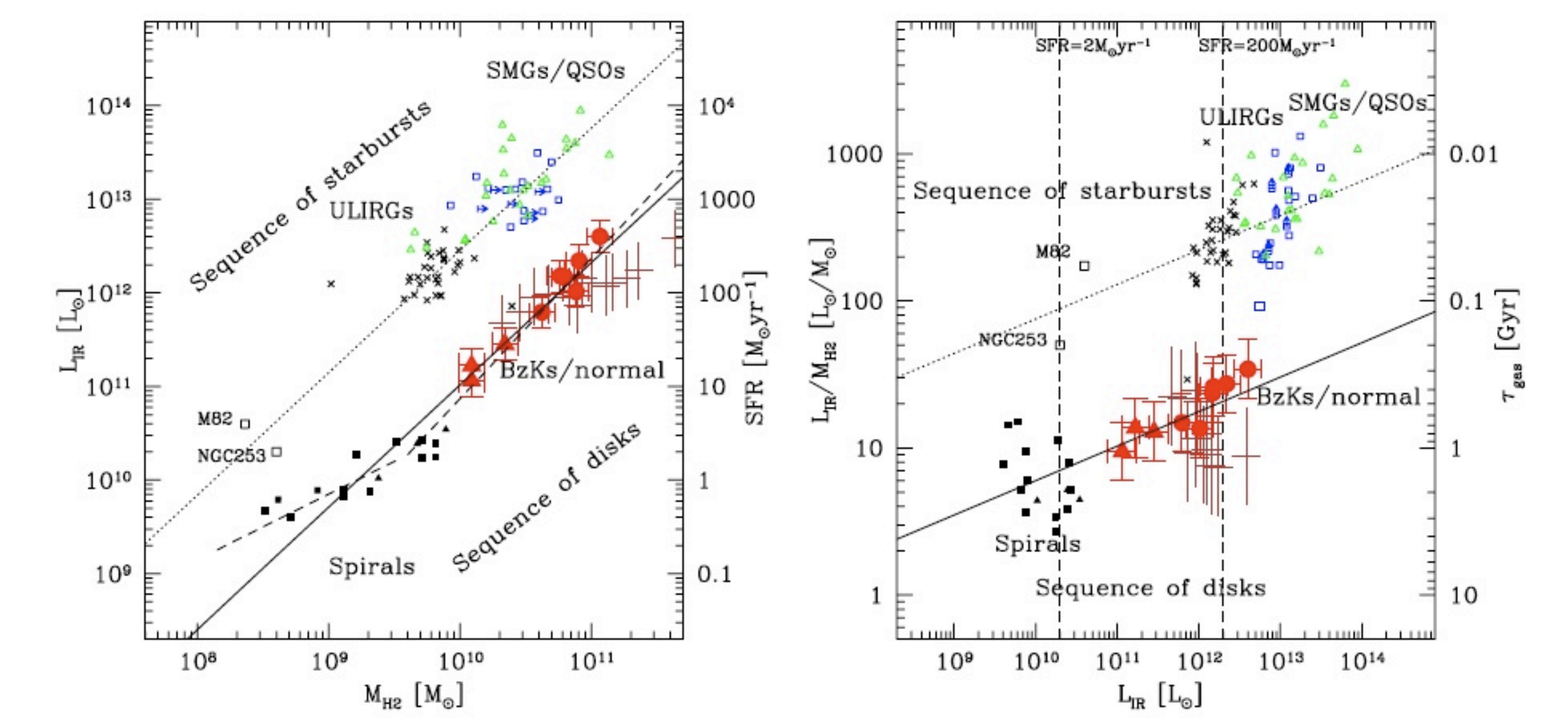
BzKs (24um-selected) "young disks?"





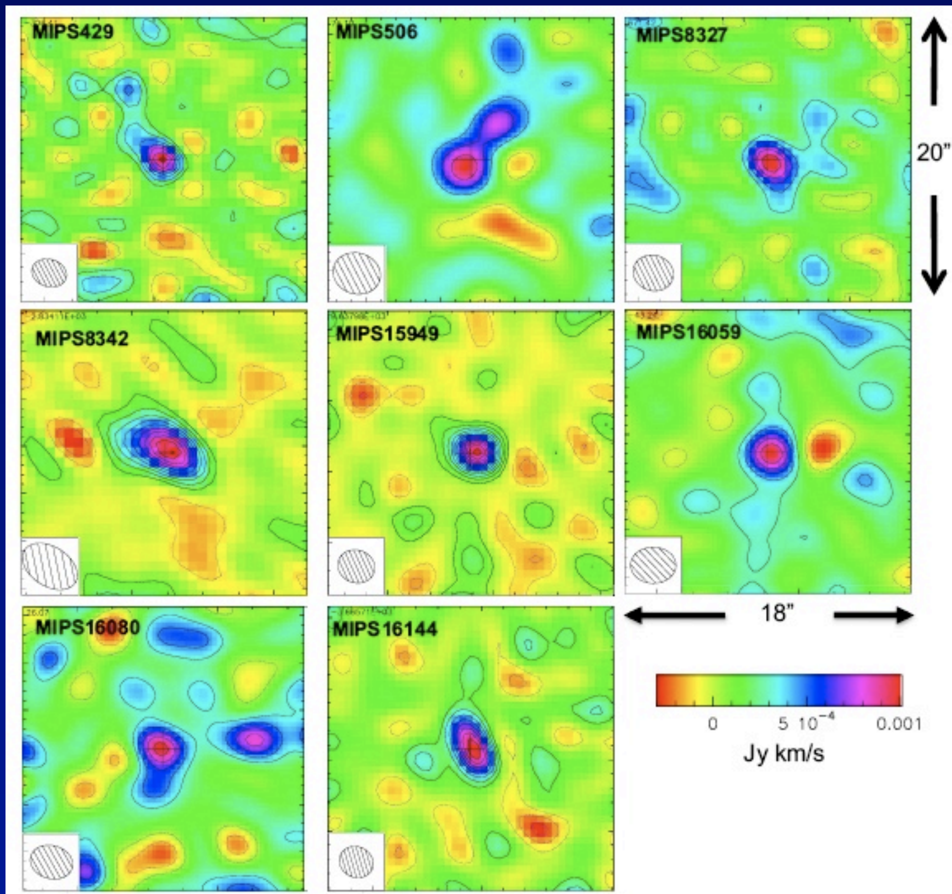
(Daddi et al. 2009, 2010a)

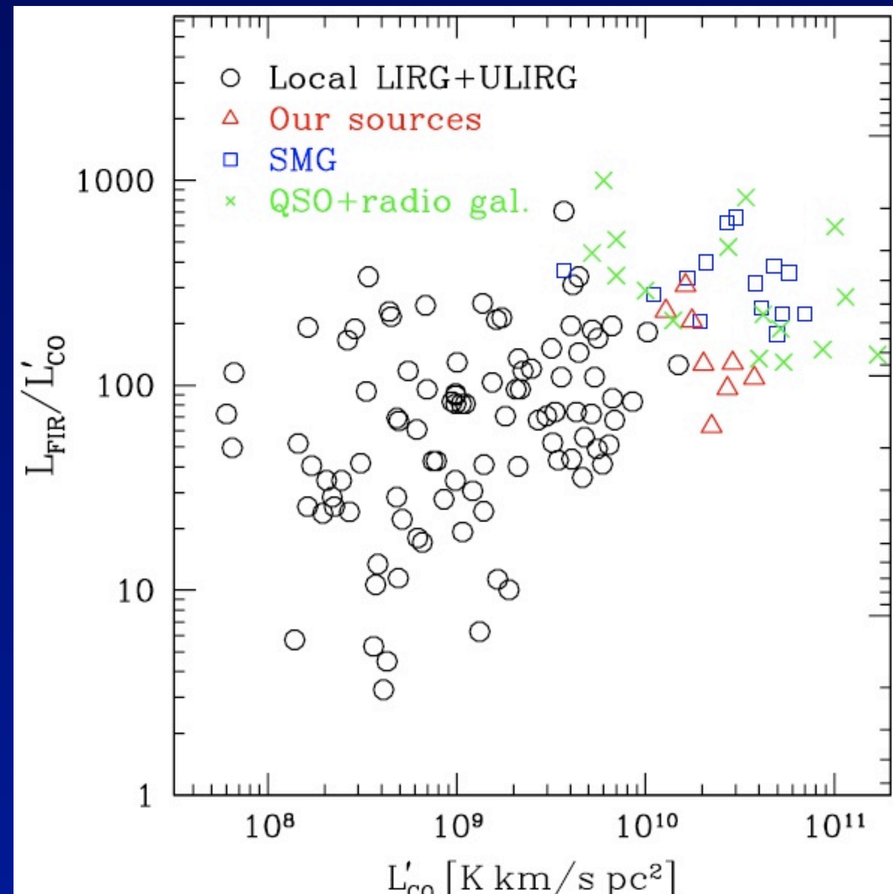
Disks vs Merger Starbursts



(Daddi et al. 2010b) Separation of BzKs from SMGs mostly due to different adopted values of alpha. (Tacconi et al. 2010 disk selected sample roughly similar Lir/L'co as BzKs)

Bright Spitzer 24um XFLS Sources

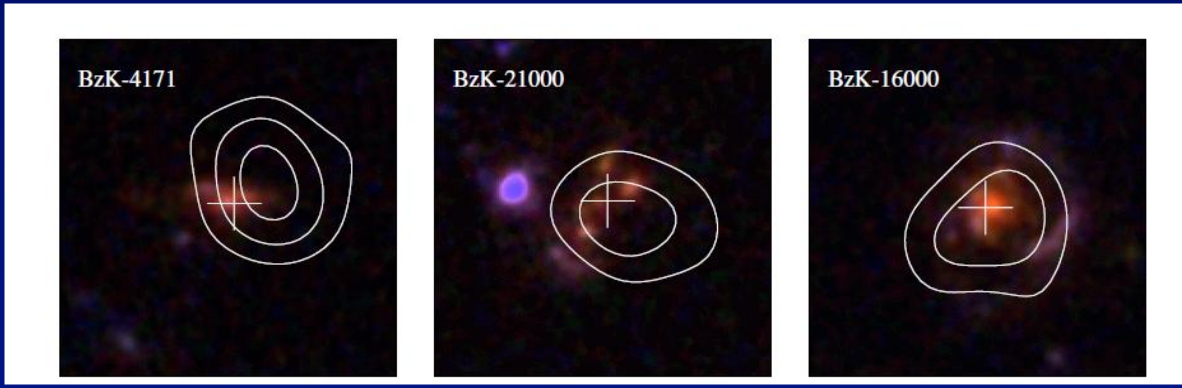




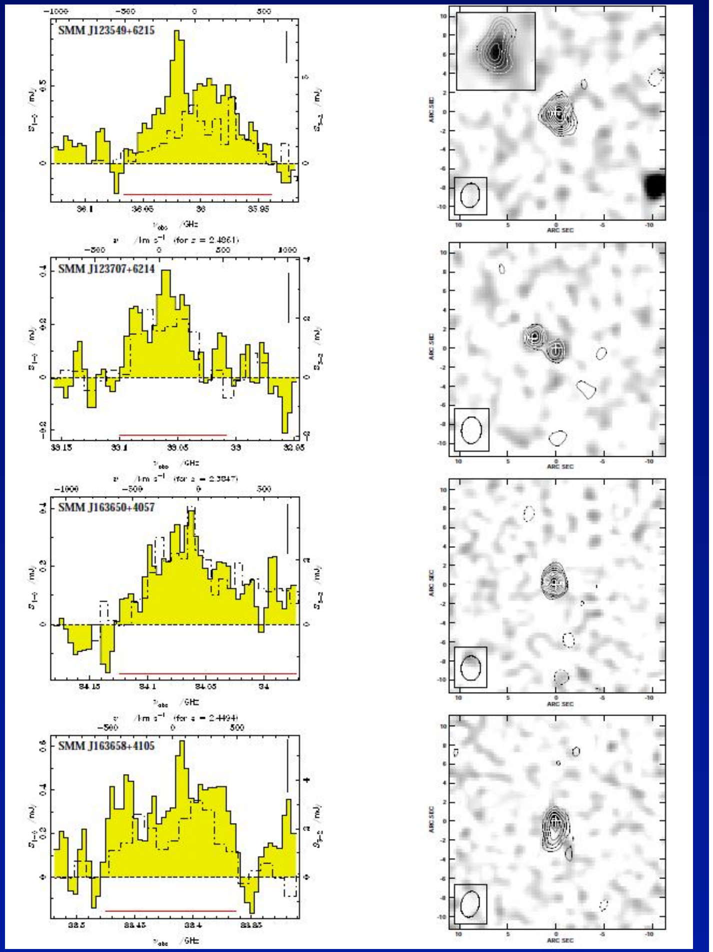
Yan et al. (2010) 24um sources with mm detections. Similar L(IR)/L'CO ratios as SMGs; would be interested to know the (3-2)/(1-0) ratios. May expect 24um-selected sources to be more AGN-dominated with QSO Lir/ L'co and (3-2)/(1-0) ratios ~1 (need CO studies of DOGs).

VLA/eVLA

BzKs (Aravena et al. 2010):



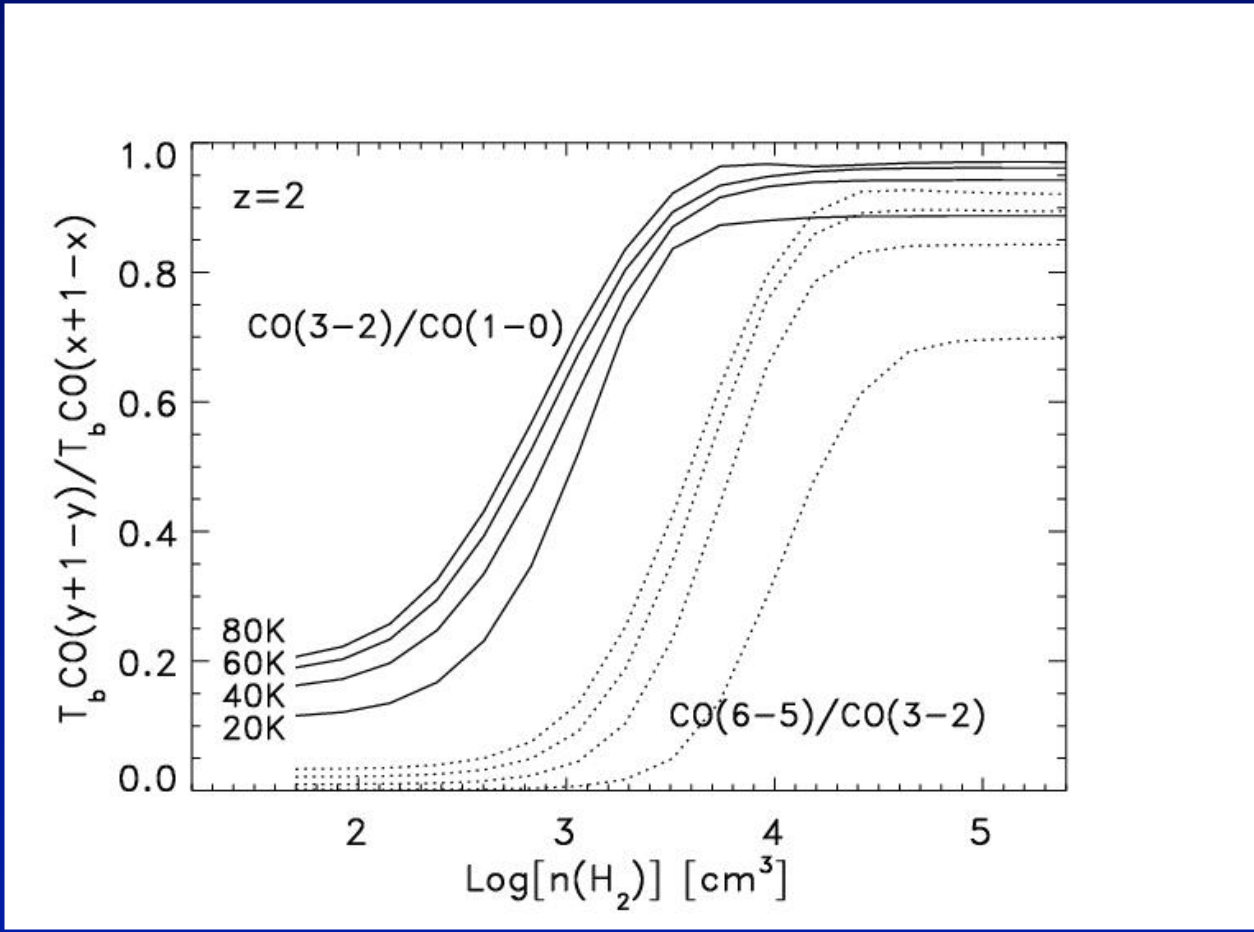
SMGs (Ivison et al. 2010):

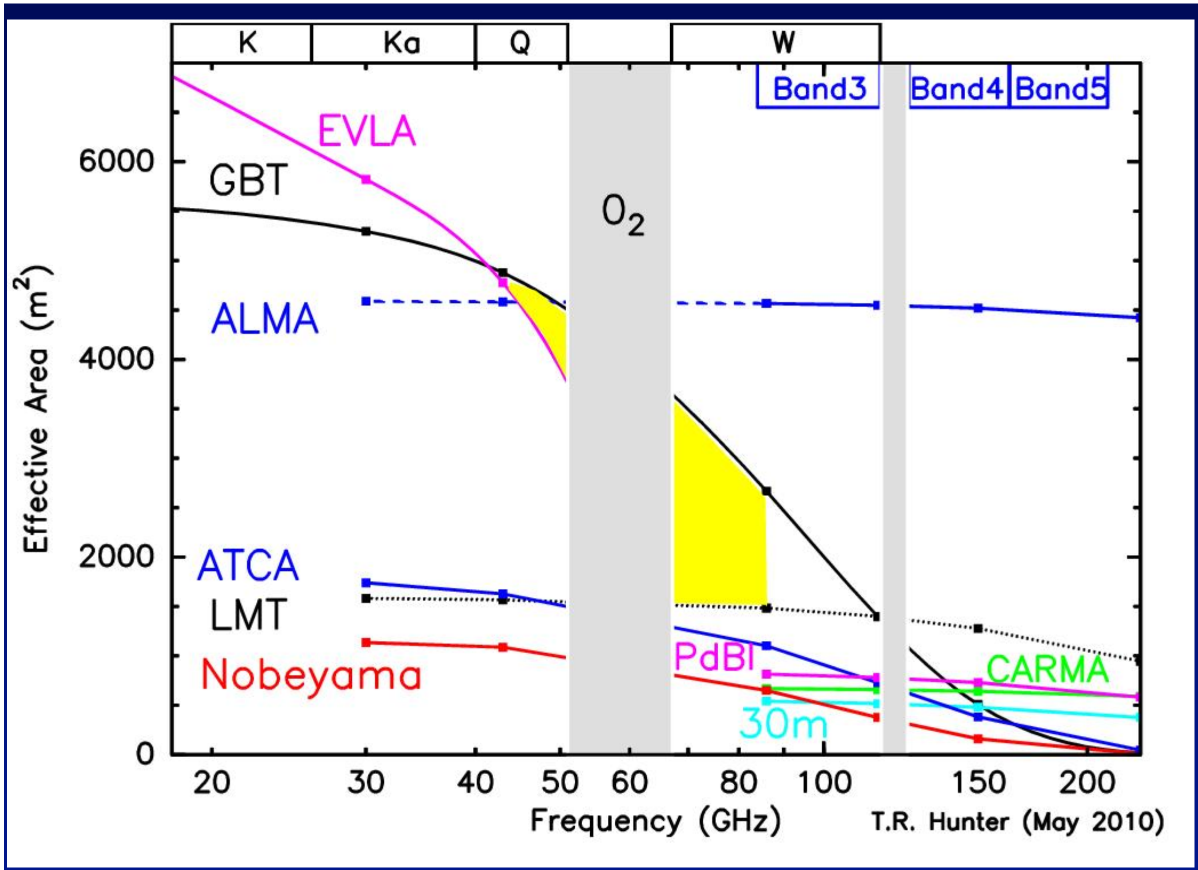


Observations suggest low-CO excitation for both the BzK's and SMG samples➔ extended cold CO(1-0)!? Very extended or just separated clumps ➔ ALMA

Different transitions probe different regions. Need imaging of many transitions. Low-J CO, high-J CO, dense HCN, atomic CI, C+, ect… (alpha not known very well for ULIRGs, let alone SMGs, BzKs, QSOs at high-z). Simple one component models fail to explain the observations.

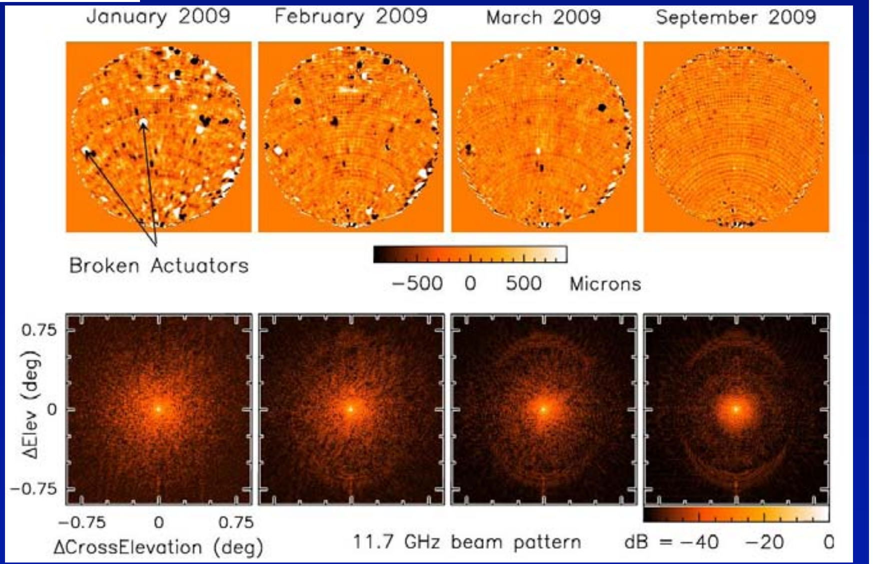
LVG models:





Robert C. Byrd Green Bank Telescope

Given recent surface improvements, the GBT has the largest effective area at Q and W-low (ALMA band2), and there about 1000 hr per year with good weather conditions for 90 GHz at Green Bank.



Concluding Remarks

- Next decade will greatly advance mm/submm studies of galaxy evolution (ALMA, eVLA, PdBI, GBT, LMT, CCAT -- CO Redshift machines on single dishes and detailed CO, HCN, CI, and C+ imaging with interferometers)
- Low-J CO important
- Wide-spectrometer backends permit CO/ISM studies at high-z without the need for optical/NIR redshifts

Table 2: Instruments for CO Redshift Searches

Telescope	Instrument	Frequency Range	Bandwidth	Sensitivity (5σ)[a]
GBT	Zpectrometer	25.6 – 36.1 GHz	34%	0.9 mJy (this work)
CSO	Z-Spec	190 – 305 GHz	46%	100 mJy (Lupu et al. 2010)
CSO	ZEUS[b]	632 – 710 GHz	4%	300 mJy (Ferkinhoff et al. 2010)
IRAM 30m	EMIR[b]	83 – 117 GHz	8%	20 mJy (Weiß et al. 2010)
PdBI	WideX[b]	80 – 116 GHz	3.6%	3.7 mJy (Daddi et al. 2009)
CARMA[b,c]		85 – 116 GHz	8%	13 mJy (web calculator)
EVLA[c]	WIDAR	12 – 50 GHz	40–18%	0.2–0.4 mJy (project page)
LMT[d]	RSR	74 – 111 GHz	40%	1 mJy (estimated)
ALMA[b,d]		84 – 116 GHz	8%	0.4 mJy (web calculator)

Backup slides

Theoretical Motivation

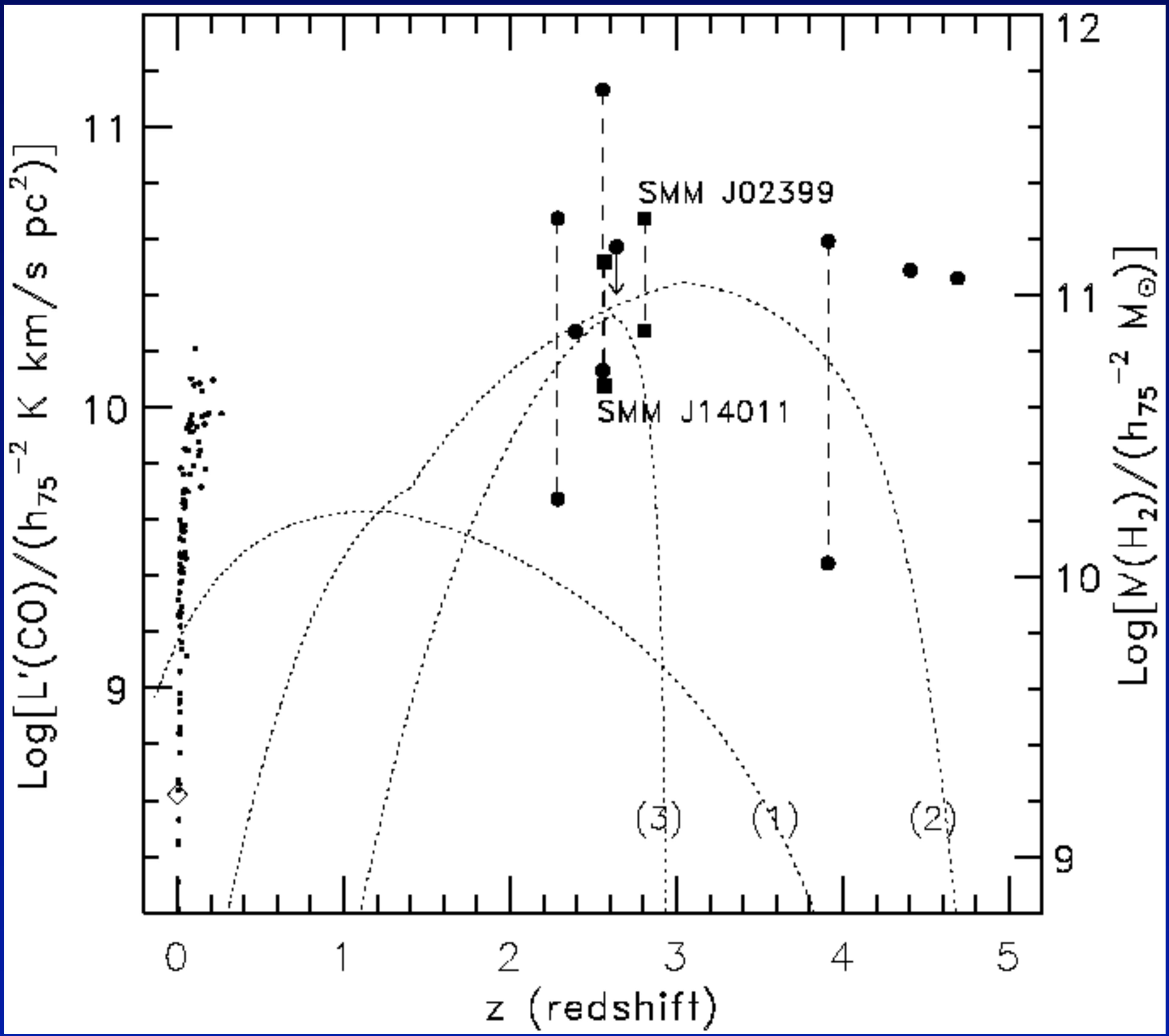
More CO and dust in the past for massive galaxies!!

(1) Spiral Disk model

(2) Elliptical Model

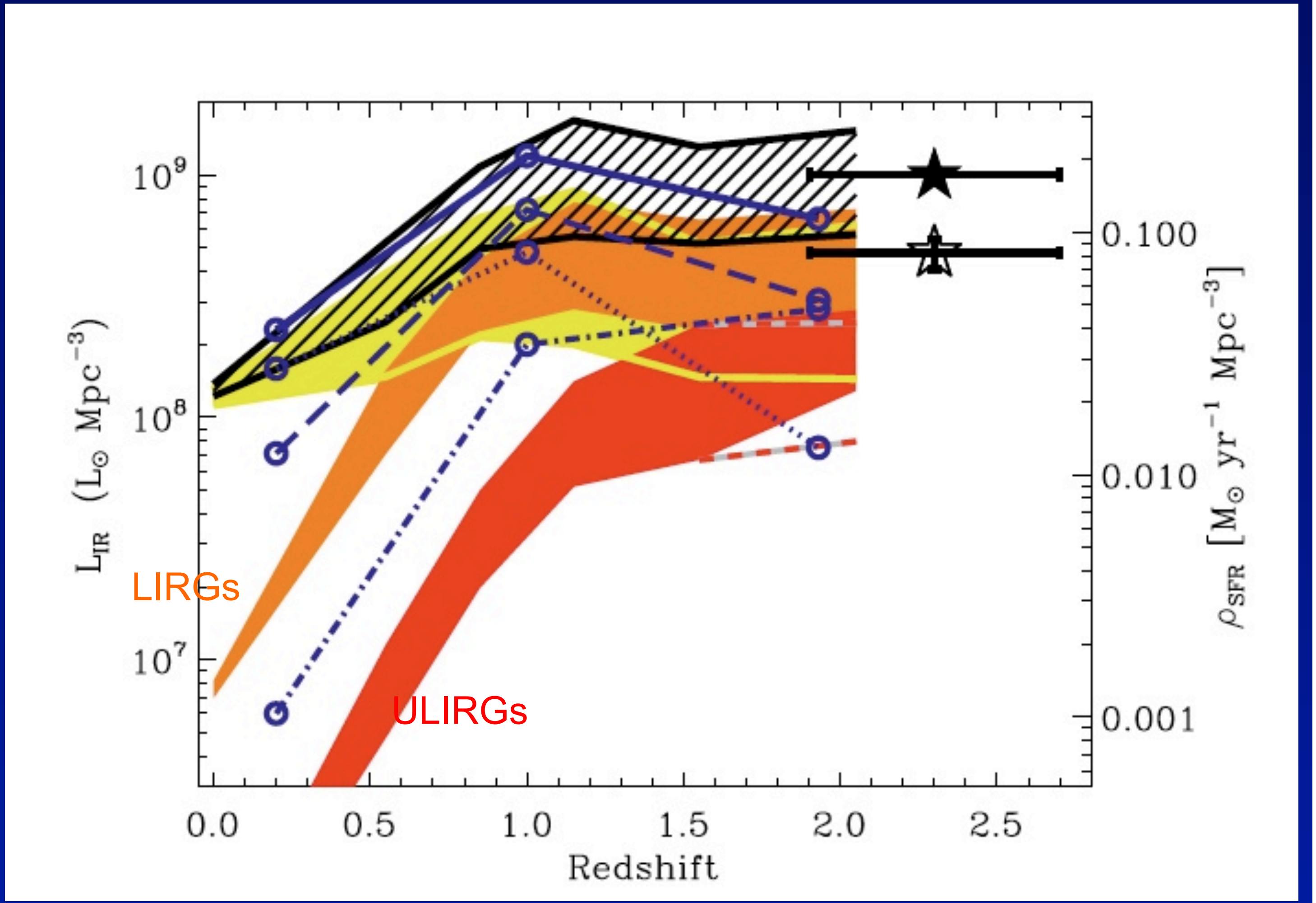
(3) Major Merger Model

Models based on Frayer & Brown 1997



Star-Formation History (FIDEL-70um)

Spitzer reinforced SCUBA/SMG results that ULIRGs are important contributors of the total amount of SFR at high-z



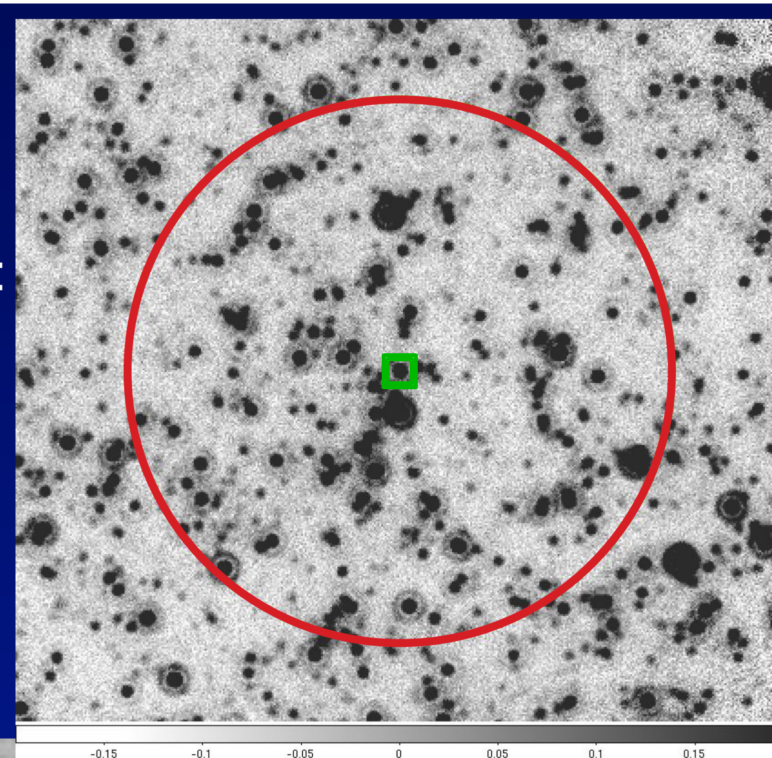
Magnelli, et al. 2009

Spitzer example of finding the brightest-FIR ULIRG in GOODS-North

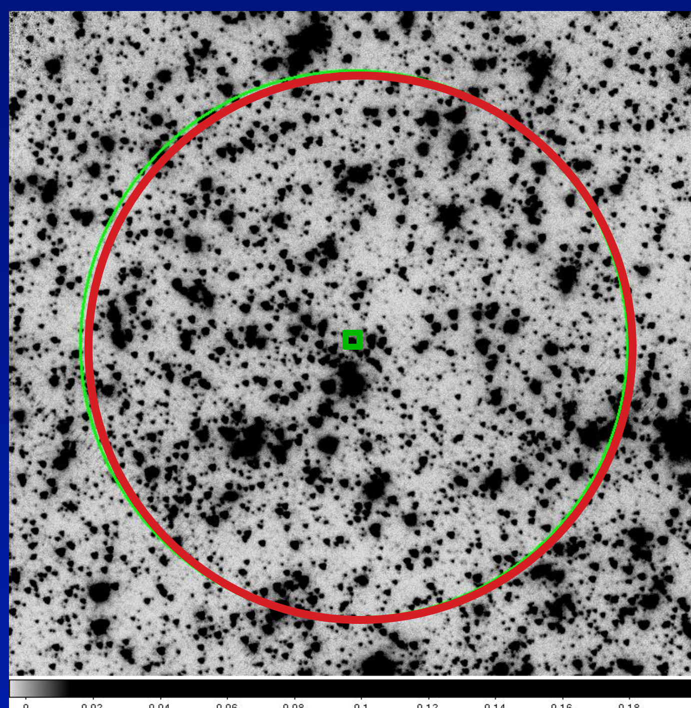
GOODS-N cutouts centered on GN26 for IRAC-3.6, MIPS-24&70um bands (6-arcmin diameter circle). Green Box shows GN26.

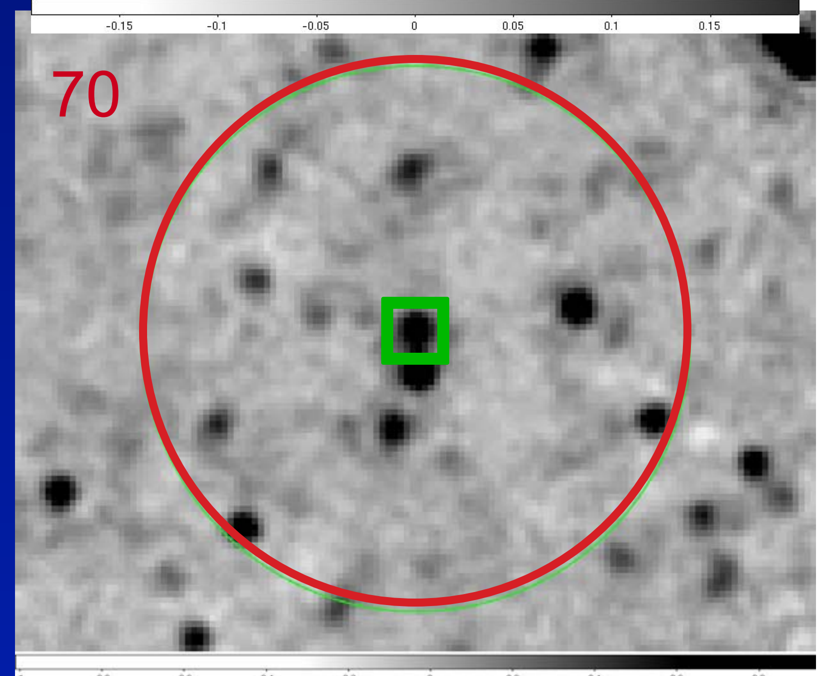
24,70,160um beams =6”, 18.5”, 40”.

24um:



IRAC 3.6um:





Chapman et al. 2005 radio-seleted SMG sample with Keck redshifts

Red=observed distribution

Blue=corrected distribution for completness at high-z due to the radio selection and for the redshift-desert at z~1.5