GBT and EVLA Results and Opportunities on the Evolution of Gas in Luminous Infrared Galaxies: GBT Observations of Molecular Gas in High Redshift ULIRGs and Neutral Hydrogen Gas in Local U/LIRGS

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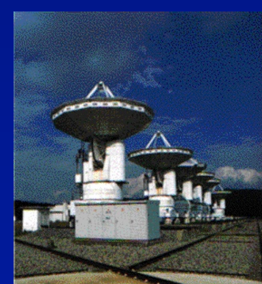
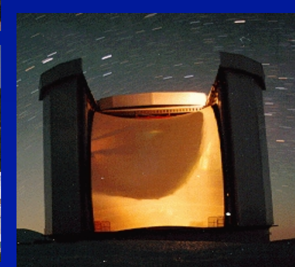
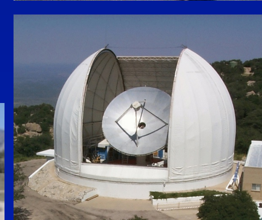
Zpectrometer
Ultra-wideband analog cross-correlator spectrometer for the Green Bank Telescope





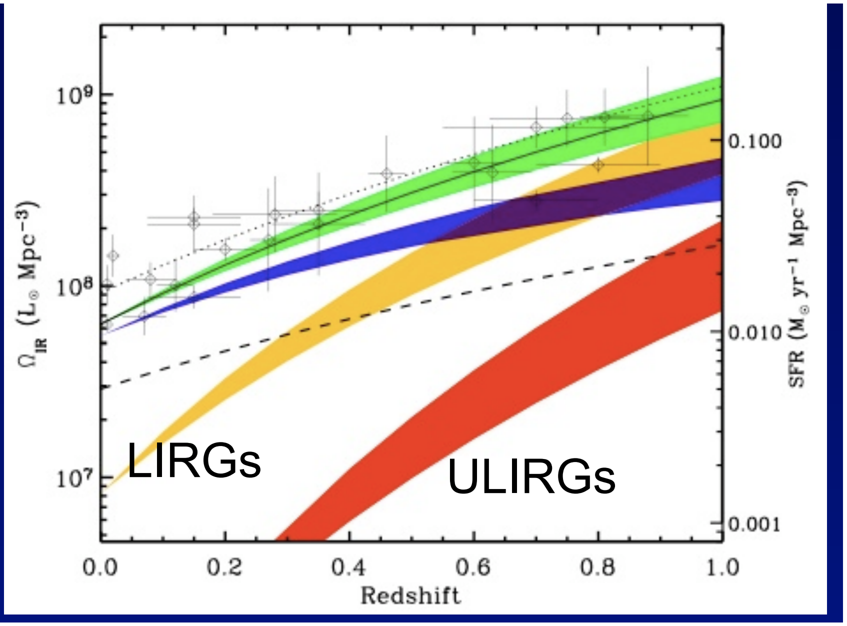


Ultra-Luminous Infrared Galaxies

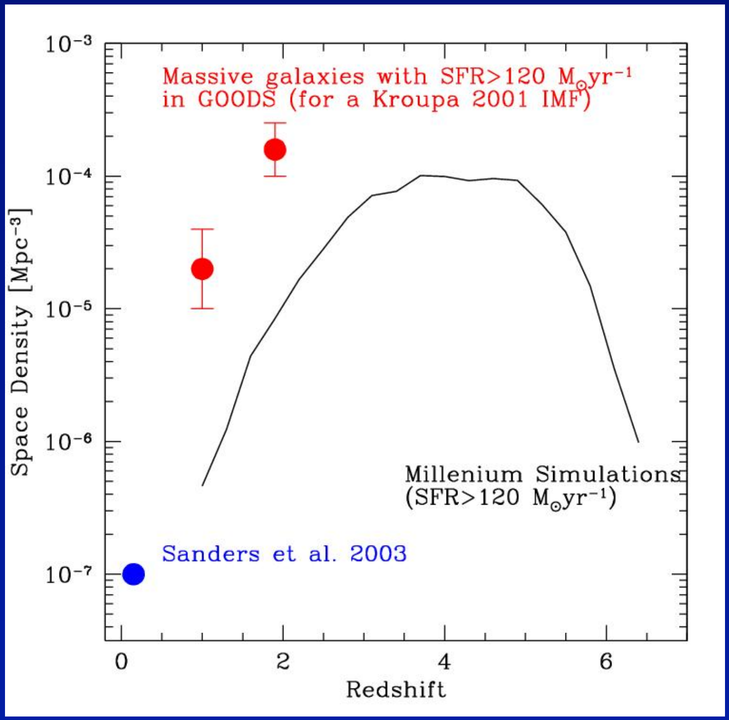
- Discovered by IRAS in the mid-80’s
- ULIRGs: L(IR) > 10^12 Lsun {~>100x more luminous in the in the infrared (IR) than “normal” spiral galaxies}
- LIRGs: L(IR) > 10^11 Lsun
- Associated with galaxy mergers/interactions (locally – at high-z ➔disks?)
- Powered by extreme starbursts and AGN
- Relatively rare in local universe, but numbers increase dramatically at high-z

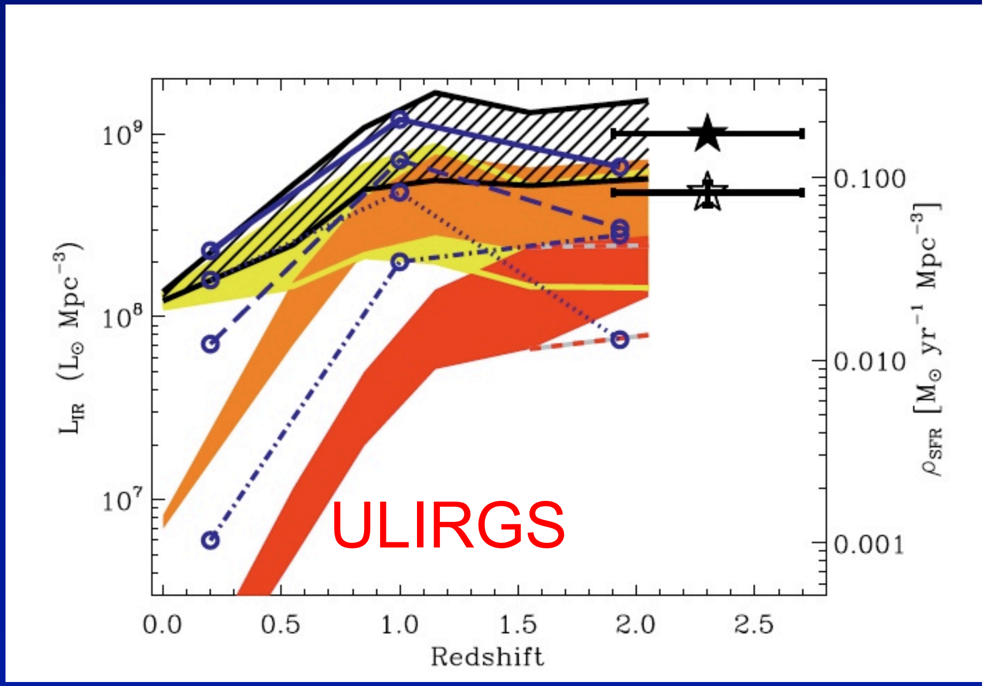
ULIRG numbers increase dramatically at z~2

Le'Floch et al. 2005:



Daddi et al. 2007





Magnelli, et al. 2009

High-Redshift CO

- IRAS ULIRG/LIRGs showed good correlation between L(FIR) and L'(CO) (i.e., **Far-IR {large cold dust grains} ⇔ CO {cold molecular gas}**)

Solomon et al. 1997

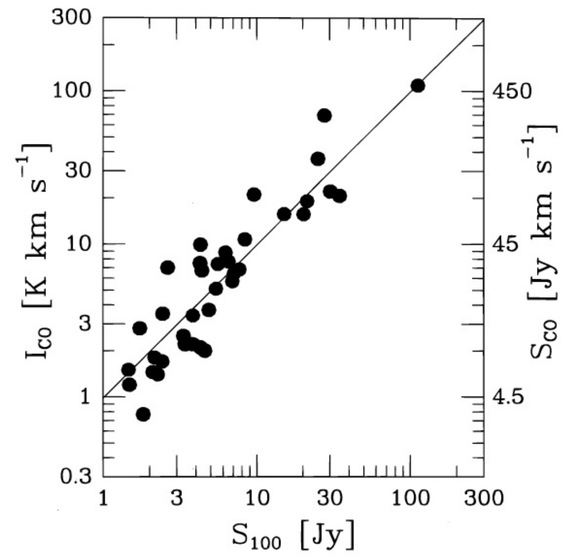
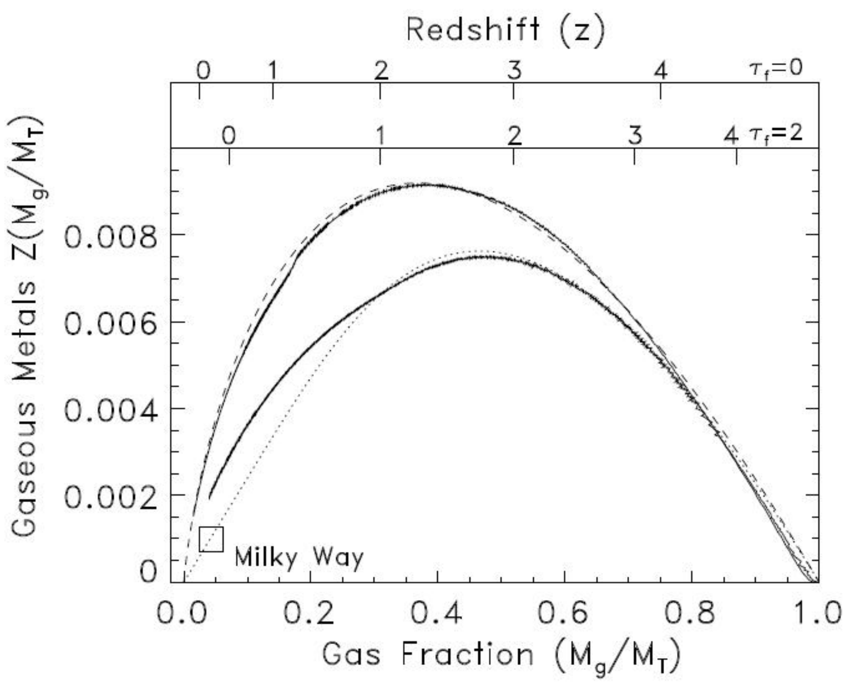


FIG. 4.—Integrated CO(1–0) line intensity, I_{CO}, in K_{mb} km s^{-1}, vs. *IRAS* 100 μm flux density, in Jy, for the ultraluminous galaxies in our sample. The solid line corresponds to the relation $I_{CO} = 1.0 \times S_{100}$.

➔Study the evolution of galaxies via the molecular gas (major goal in the upcoming decade for mm/sub-mm research)

Since H_2 has no rotational transitions, CO which is the 2nd most abundant molecule is used as a proxy for H_2.

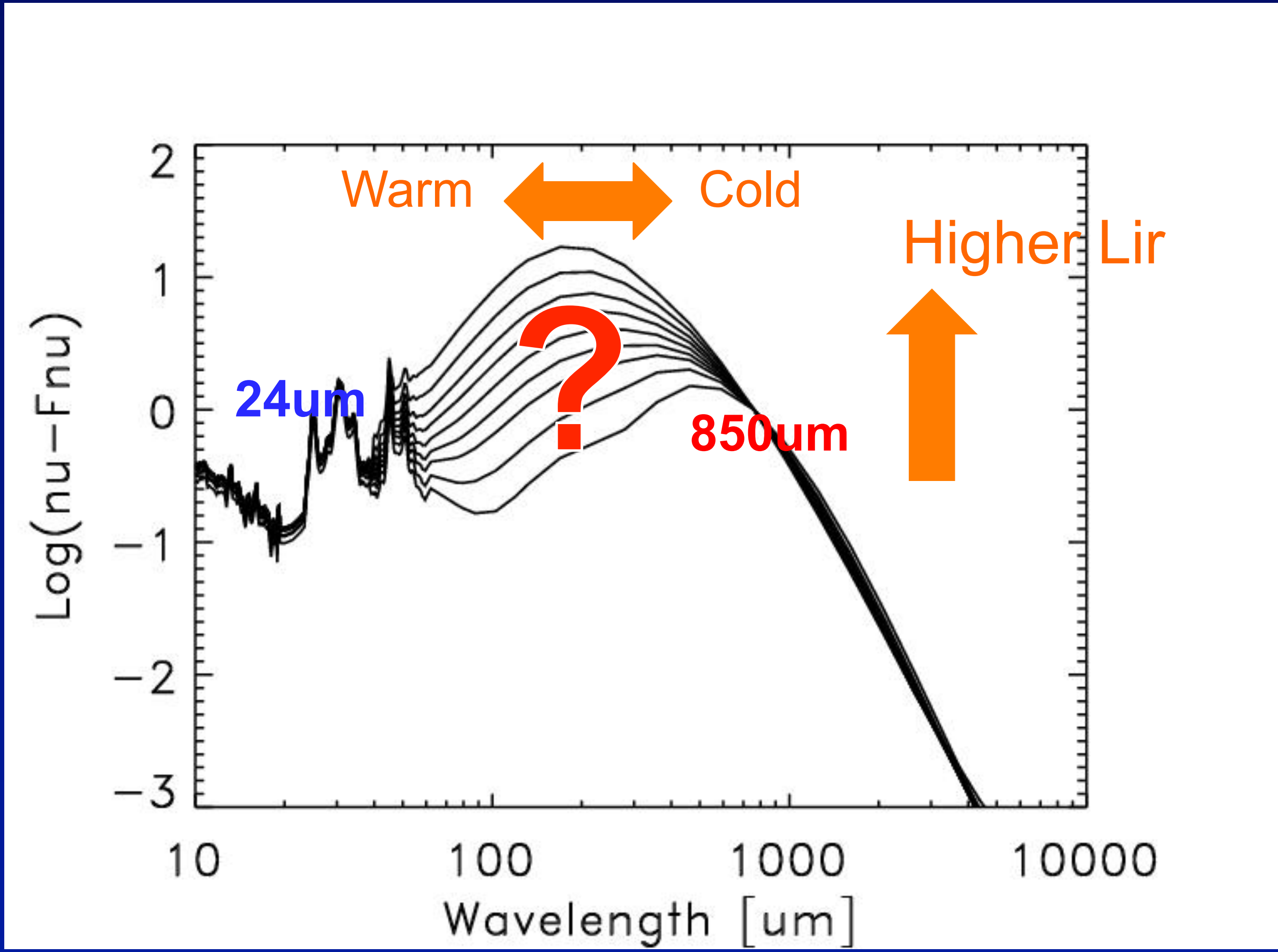


Frayer & Brown 1997

FIR measurements near peak ➔ **Herschel**

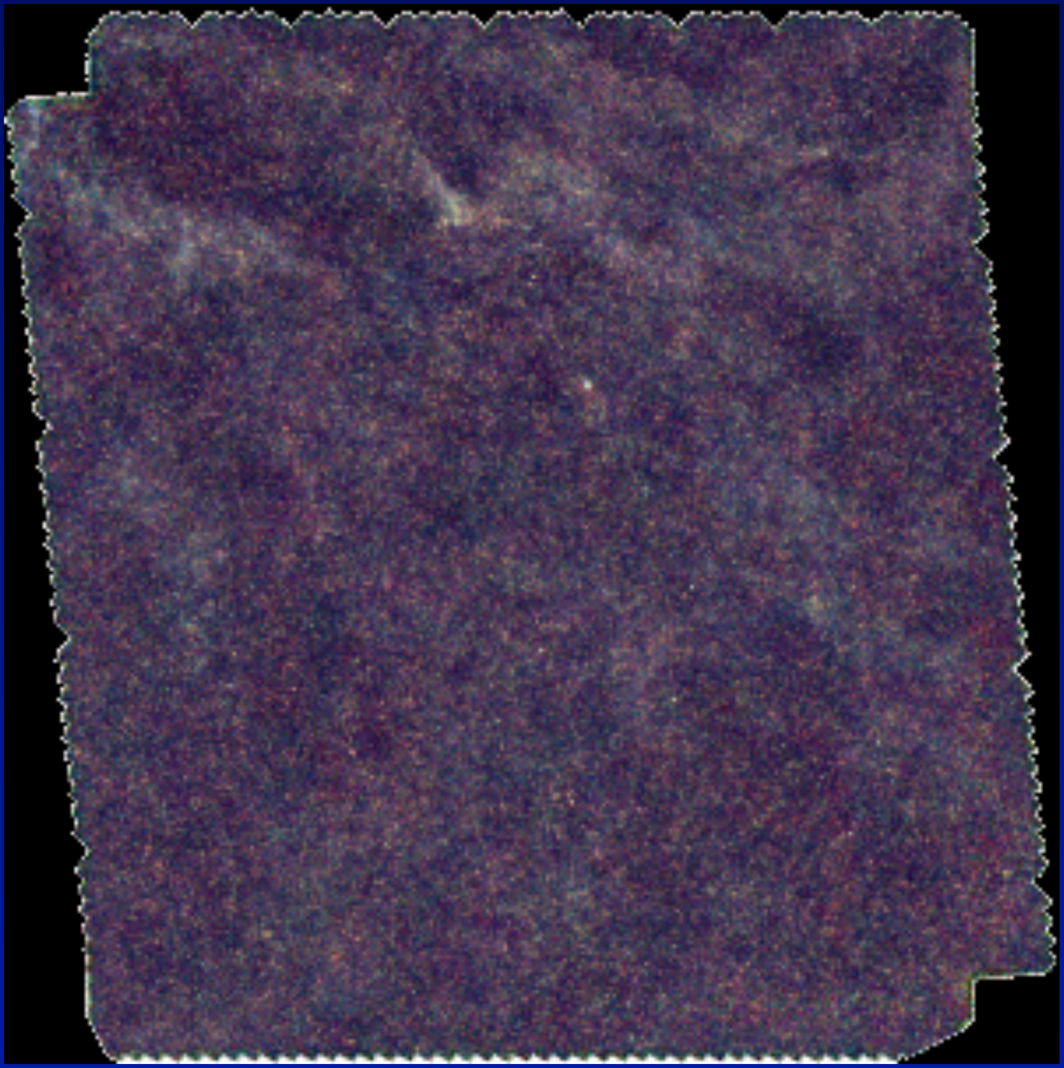
Dale and Helou SEDs at z=3 and normalized at 850um observed-frame.

Pre-Herschel, most high-z based on 850um and Spitzer 24um selection ➔Uncertain L(IR) and Td



Herschel-ATLAS Survey (Eales et al.)

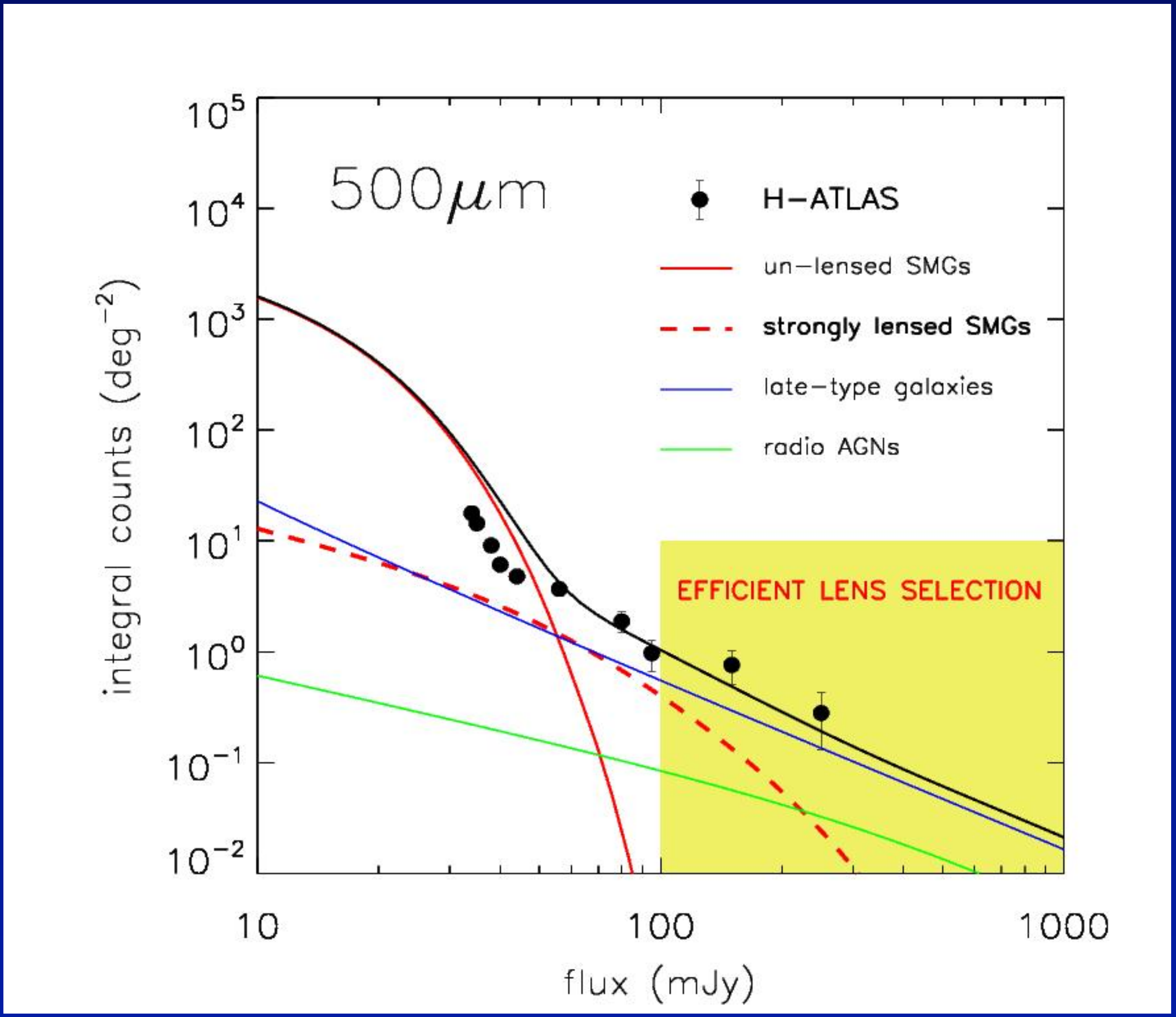
- Wide-area sub-mm survey: 570 sq-deg (over several fields)
- 100, 160, 250, 350, 500um bands
- rms~10mJy level (confusion limited at longer wavelengths)
- Ancillary optical data
- Right: SDP Gama-9hr field 4deg x 4deg tile (250+350+500um color image) -- picked a field with galactic cirrus?!?



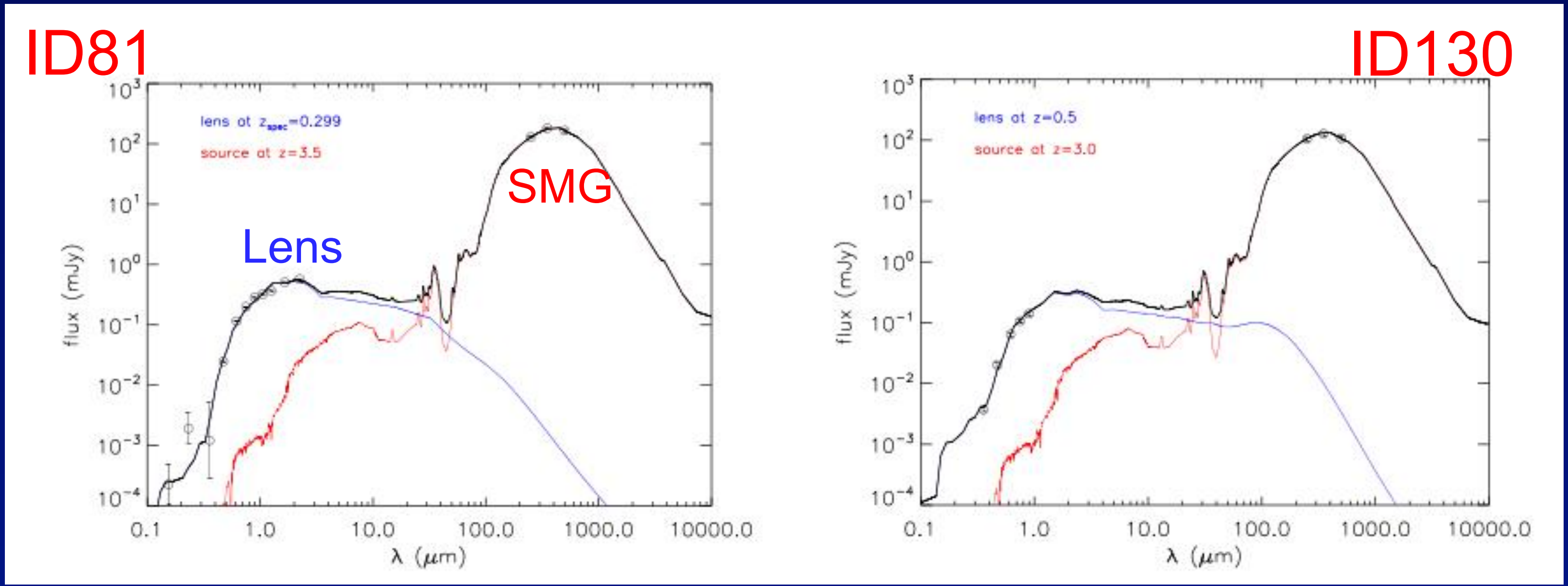
Herschel data shows the upturn in the bright source counts expected from lensed sub-mm galaxies (SMGs)

M. Negrello et al. (2010) H-ATLAS SPIRE results➔ Bright sub-mm sources not at low-z are lensed high-z SMGs.

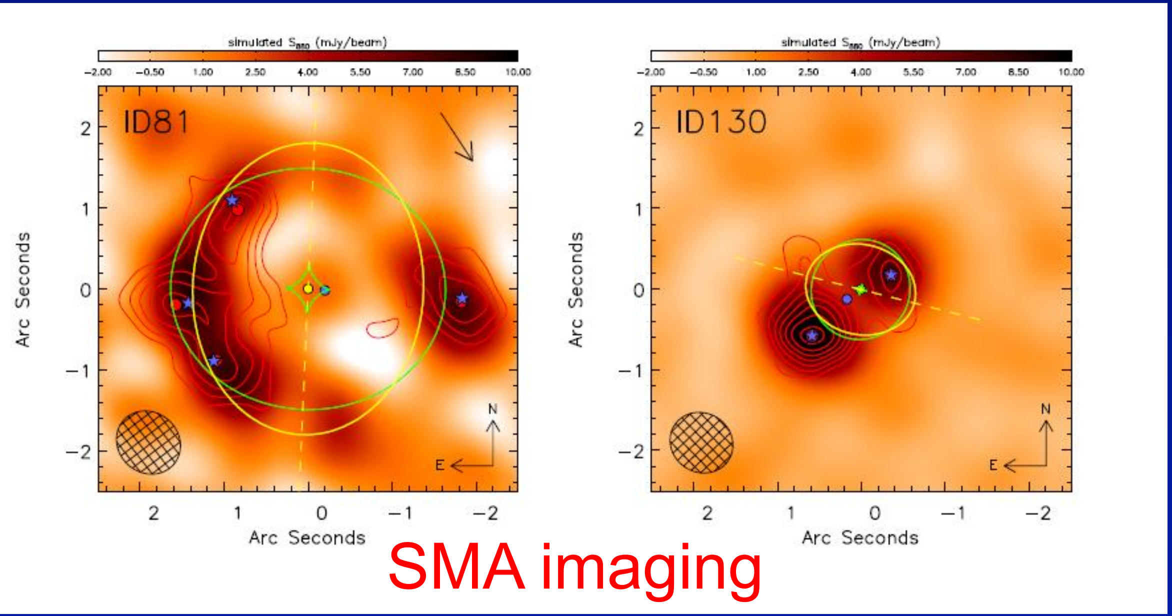
(e.g., Asantha's talk)



Lensed Candidates: Bright 350um "Peakers"



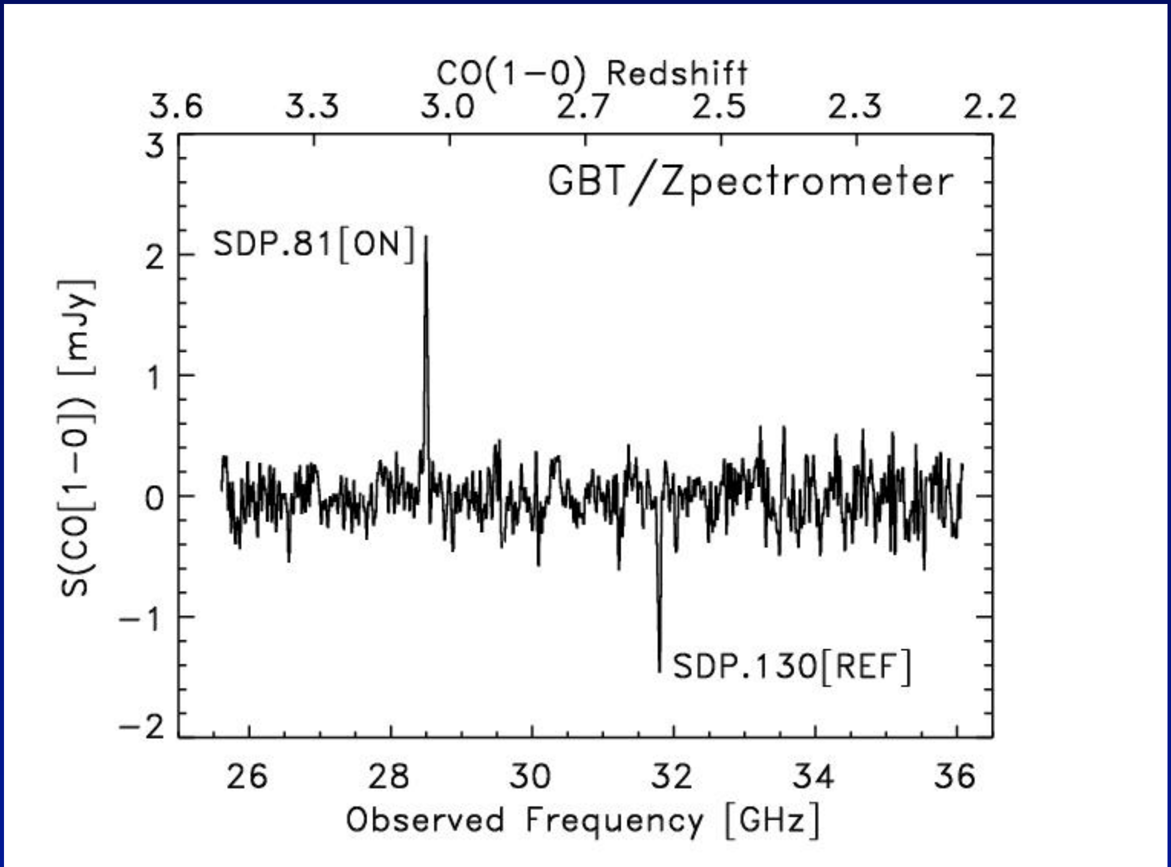
Strong far-infrared background sources -- Sources that peak at 350um are at z~2-3.5 and are ideal targets for GBT/ Zpectrometer -- Redshift measurements using CO (1-0) (2.6mm line => ~1cm)



GBT/Zpectrometer CO(1-0) (Frayer et al. 2011)

➔Now can directly search for CO at the Herschel positions of candidate high-z sources

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.



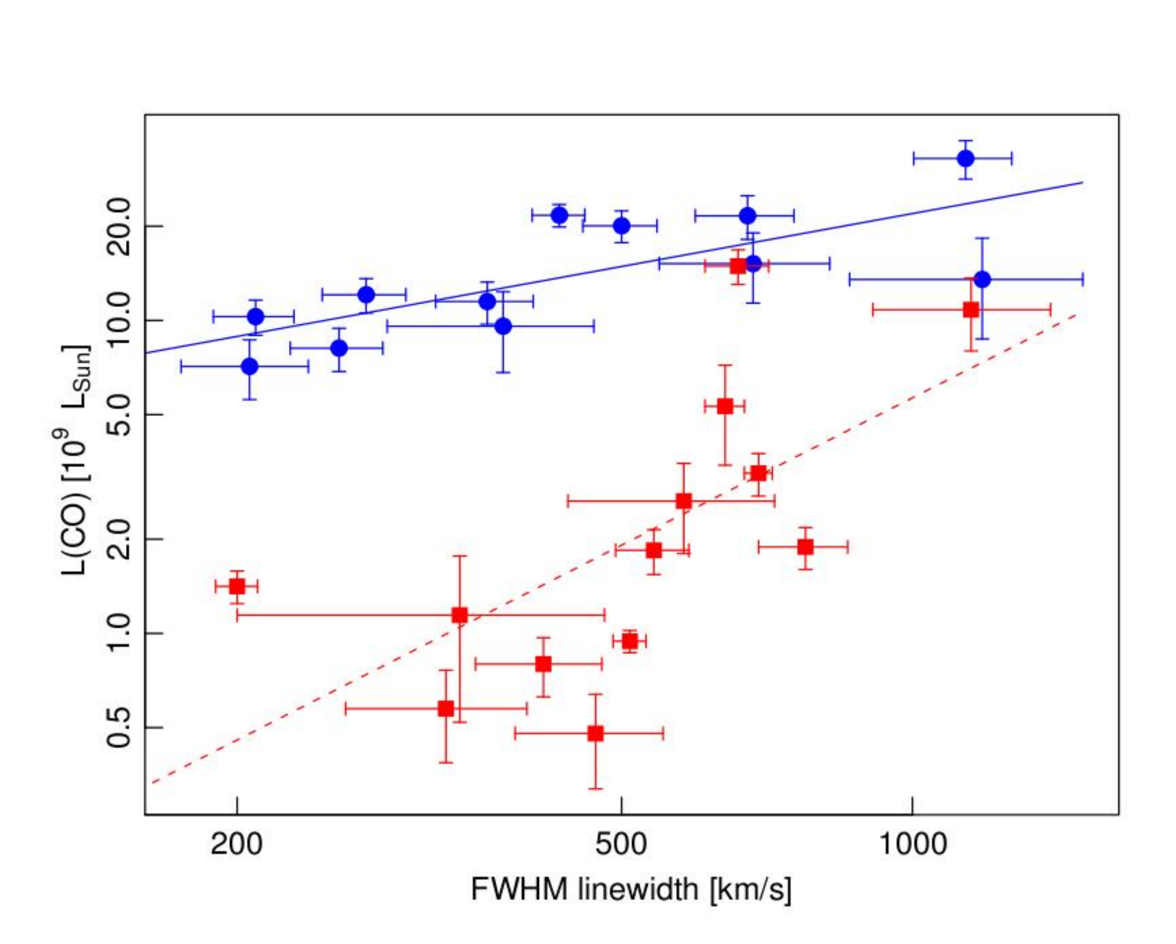
12 GBT detections from last season (summarized in Andrew’s talk), and Zpectrometer just went back up on the GBT☺

Line-width -- Luminosity Relationship (Tully-Fisher) ➔ estimates of magnification

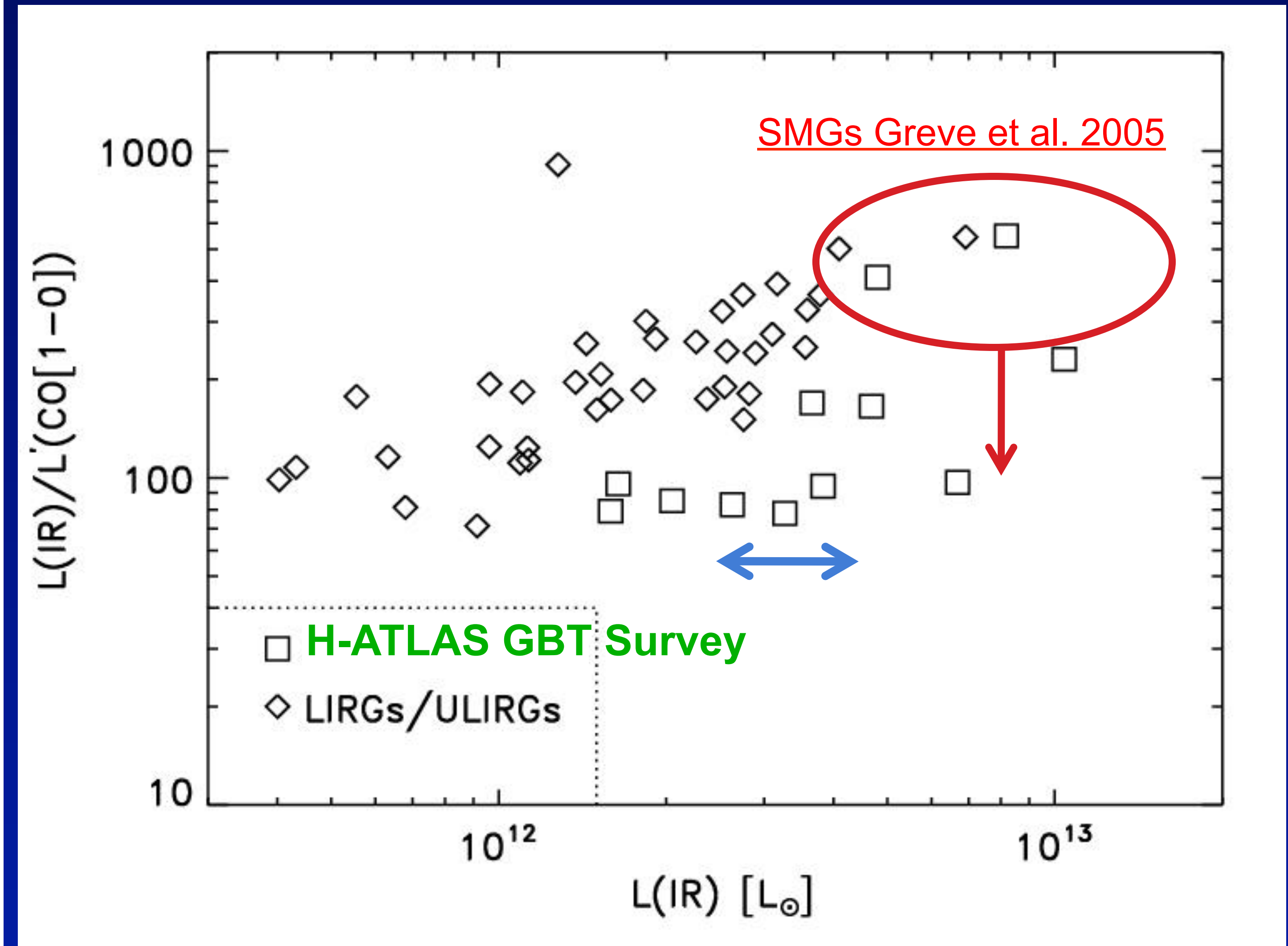
Blue= GBT sample (un-corrected for lensing)

Red = high-z sample in literature corrected for lensing (based on the work from Bothwell et al., in prep)

➔Empirical statistical relationship:
mag ~ 3900/ FWHM.
Magnification factors of 3-19 (Harris et al. in prep.)



SMGs have slightly lower L(IR)/L'(CO) ratios in comparison to local ULIRGs



Previous SMG results overestimated Lir by ~2x via 850um extrapolation and adopted L'CO(3-2)/ L'CO(1-0) = 1 which underestimated L'CO(1-0) by 1.7

Key: Good FIR measurements with CO(1-0) from the H-ATLAS GBT Survey

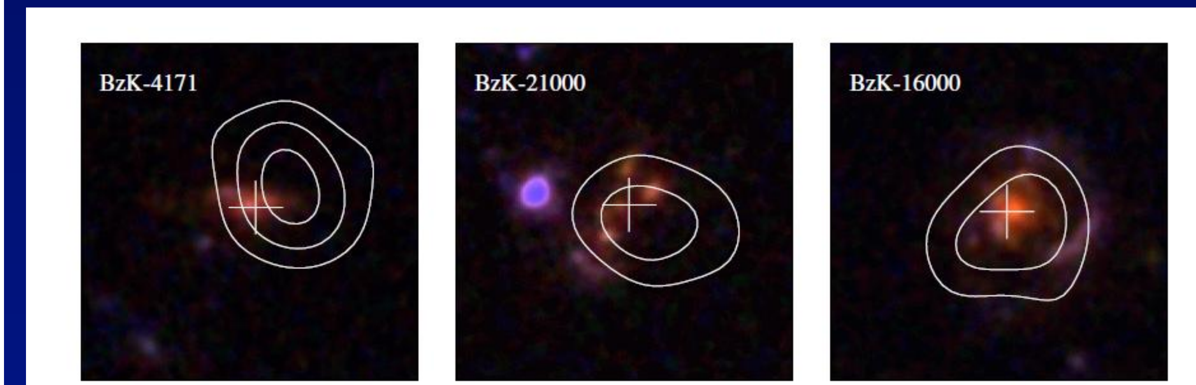
GBT H-ATLAS CO Results

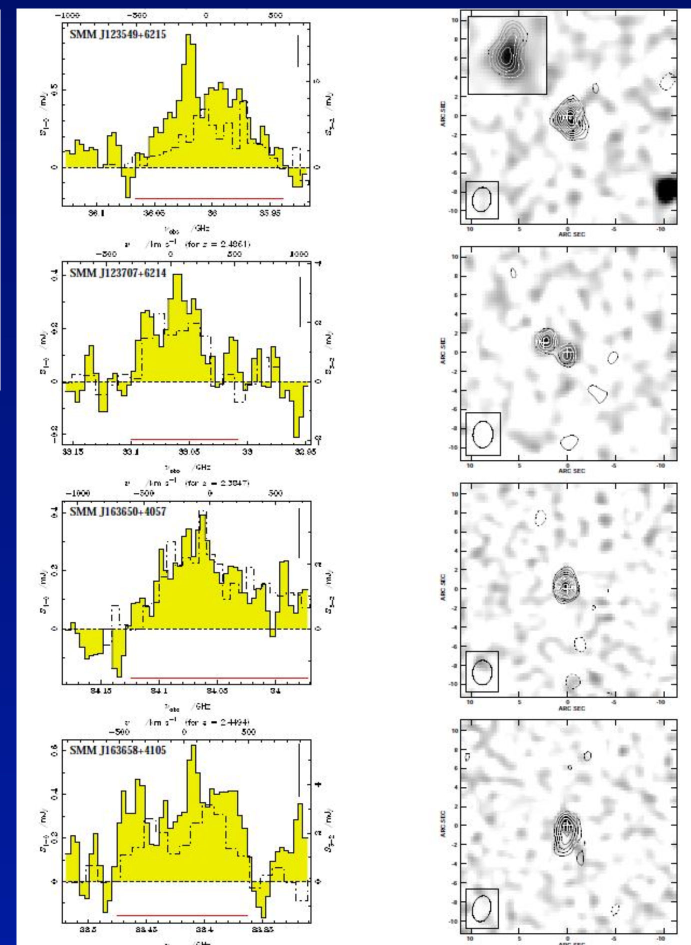
- 12 detections of CO(1-0) for the H-ATLAS SMGs to date (a few more with the GBT for HerMES and other samples)
- Avg/Median Td~35 K (30—45 K range of Td) (~5 K lower on average than local ULIRGs)
- Median L(IR)/L'(CO) ~ 100 Lsun (K km/s pc^2)^-1 (~2x lower than local ULIRGs)
- CO(3-2)/CO(1-0) ~0.8 (Andrew's talk)
- Average redshift <z> ~2.5 (Andrew's talk)
- ??alpha – CO to H_2 conversion factors??➔?? SFE??

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

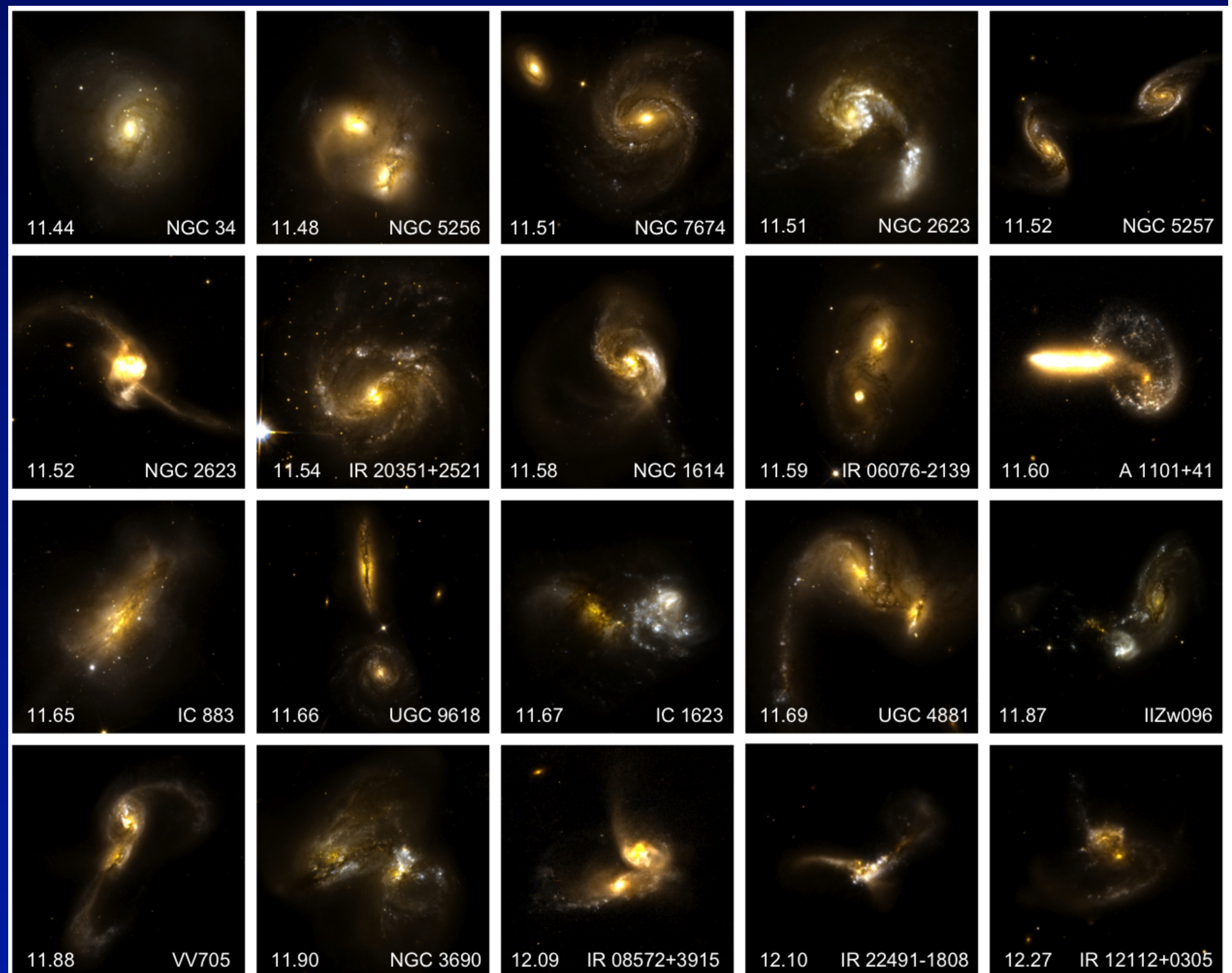
EVLA 8 GHz of bandwidth will allow CO(1-0) searches from z~1.5—8.5

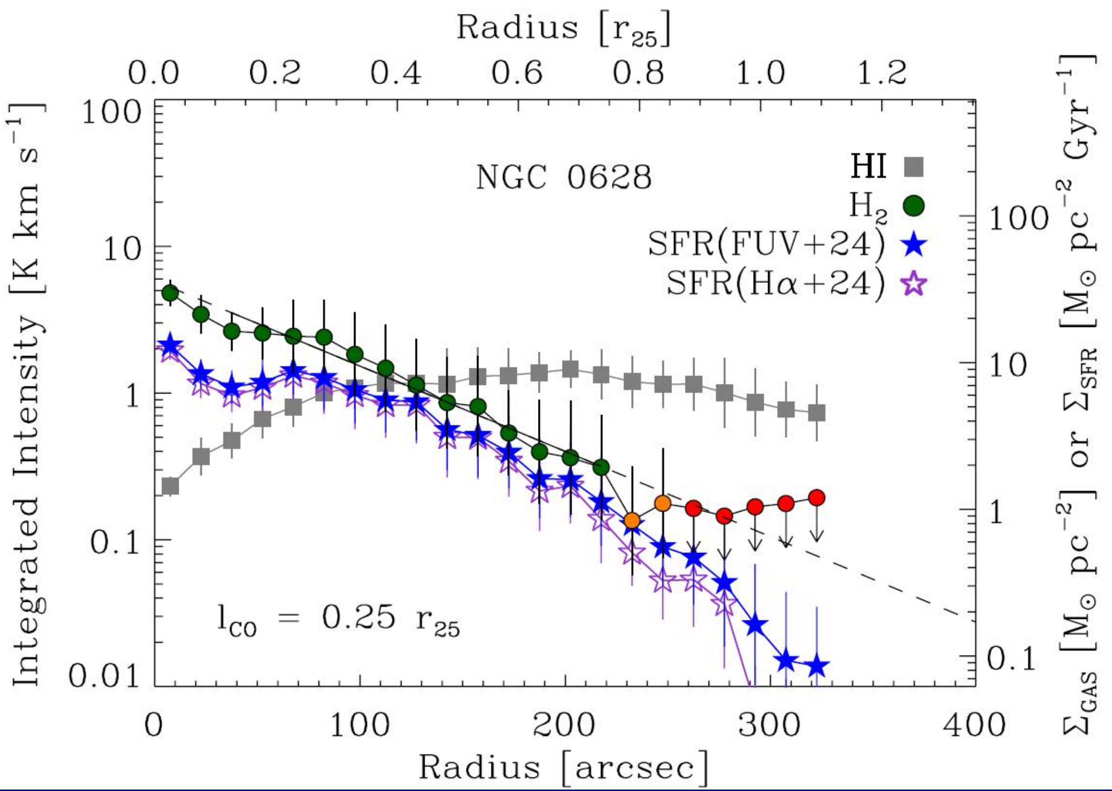
The Great Observatories All-sky LIRG Survey

GBT-GOALS HI Observations

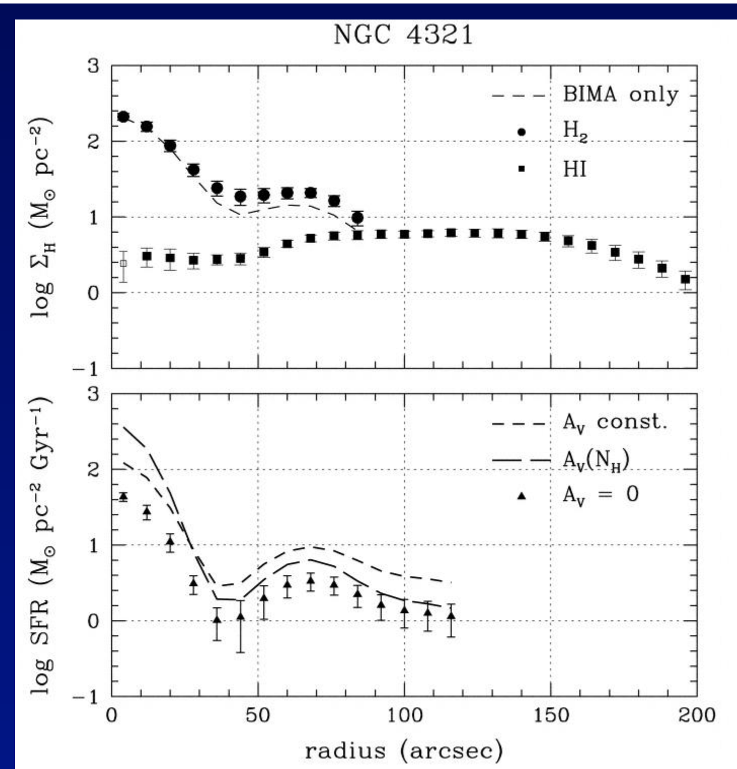
- Observed all 162 LIRGs at dec>-35 deg in the GOALS sample (brightest extragalactic IRAS sources with L(IR)>10^11 Lsun, z<0.1)

- 180 hours of GBT observations (30 min – 3 hr per source)
- L-band (1400 MHz, 21cm, 9’ beam)



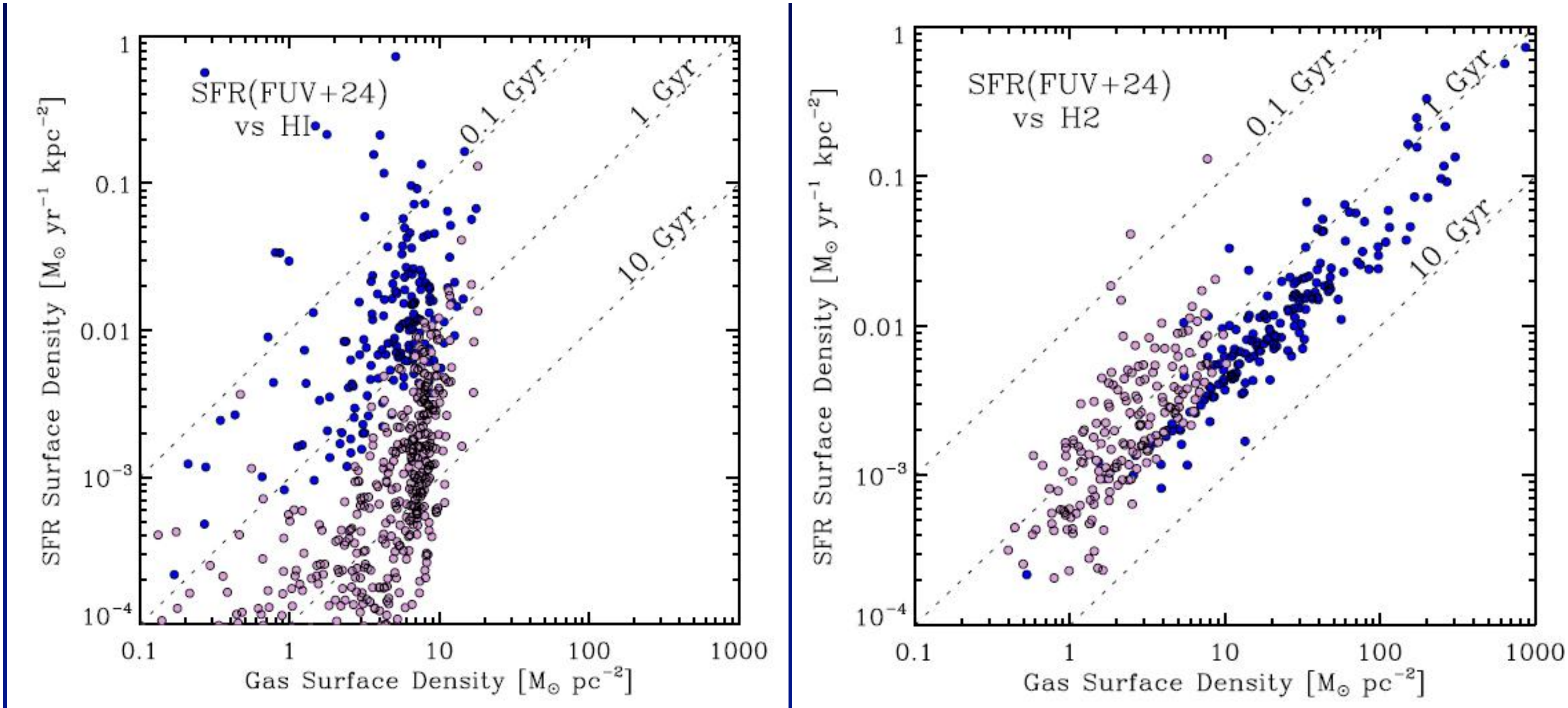


Schruba et al. 2011



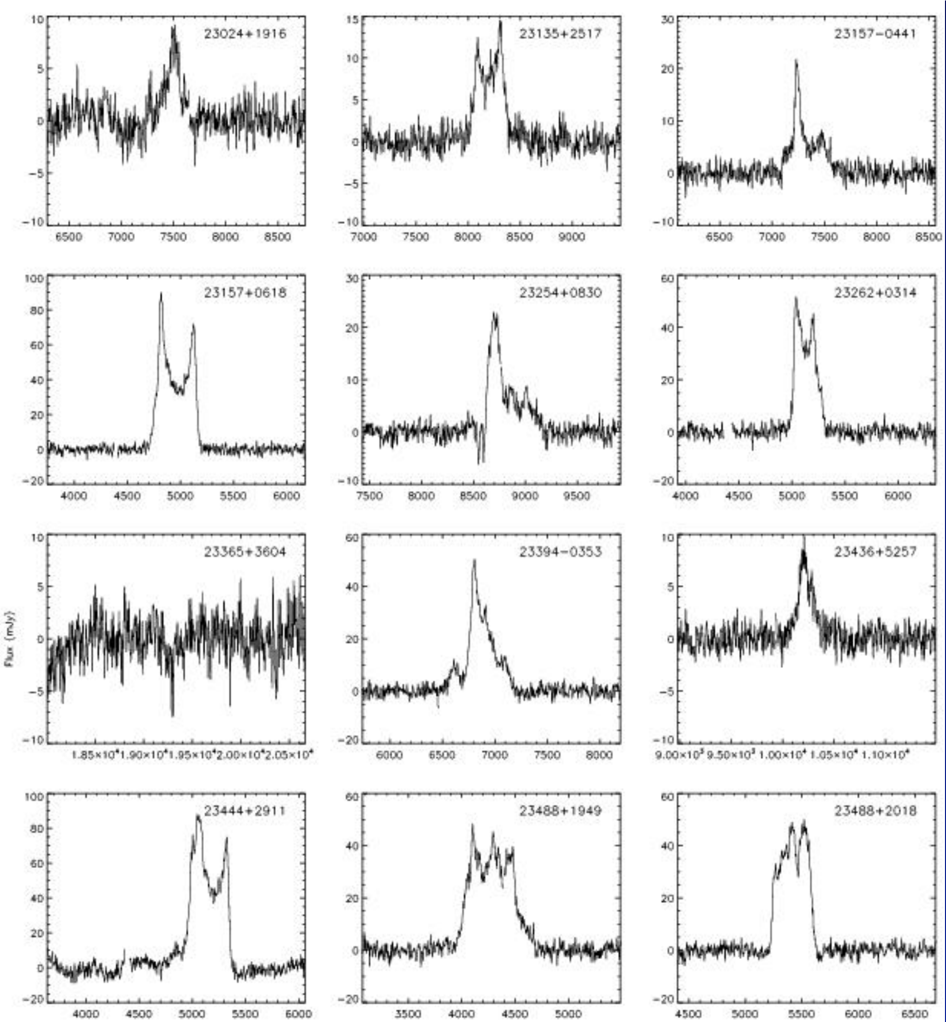
Wong & Blitz 2002

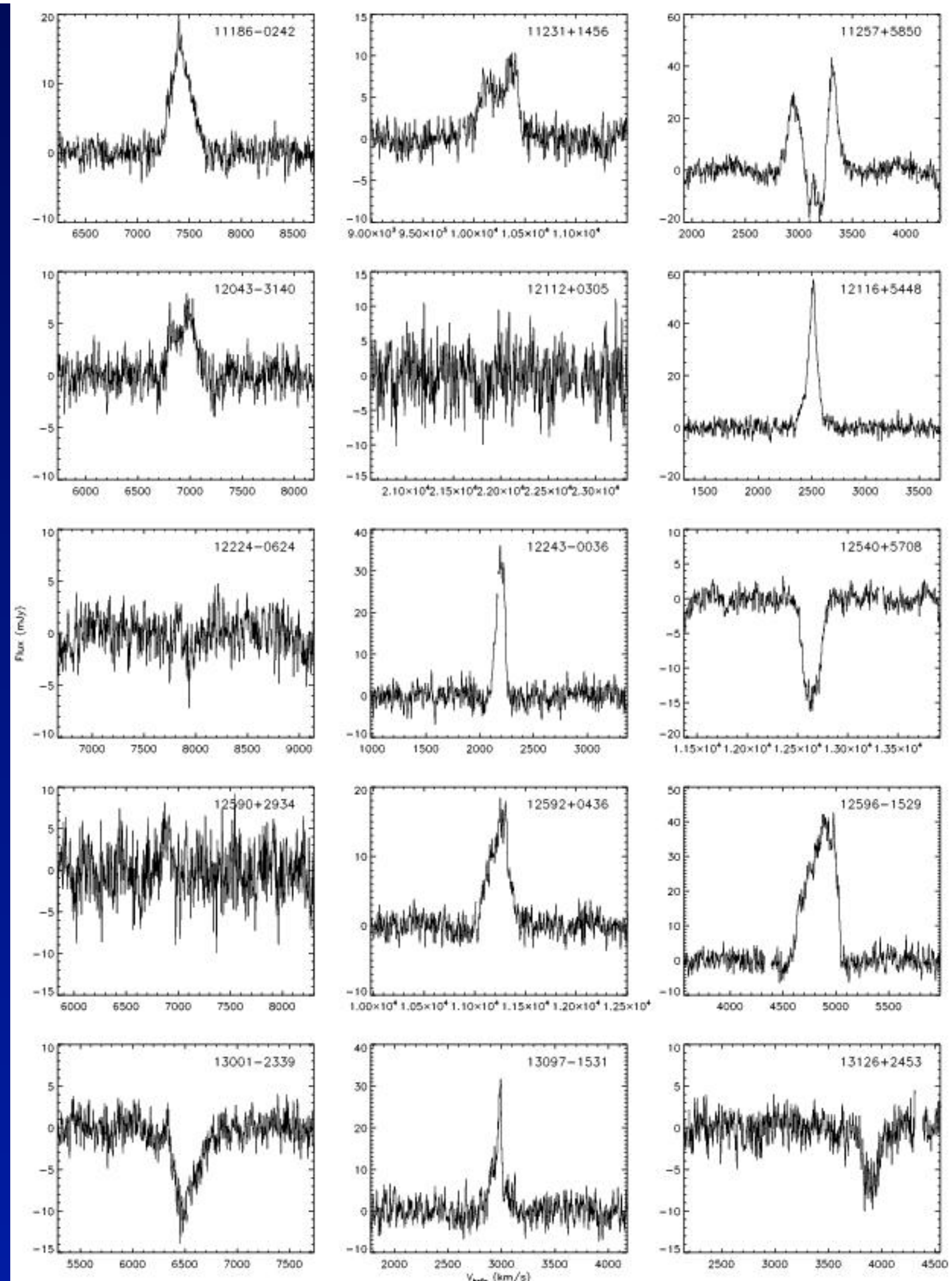
- HI radial profiles ~flat in spiral galaxies
- CO is centrally concentrated and traces SFR
- Total M(H2) ~ M(HI) in spirals



Schruba et al. 2011

- HI not correlated with SFR in spirals.
- At >~10 Msun pc^-2, HI➔ H_2.





Wide-Variety of HI profiles:

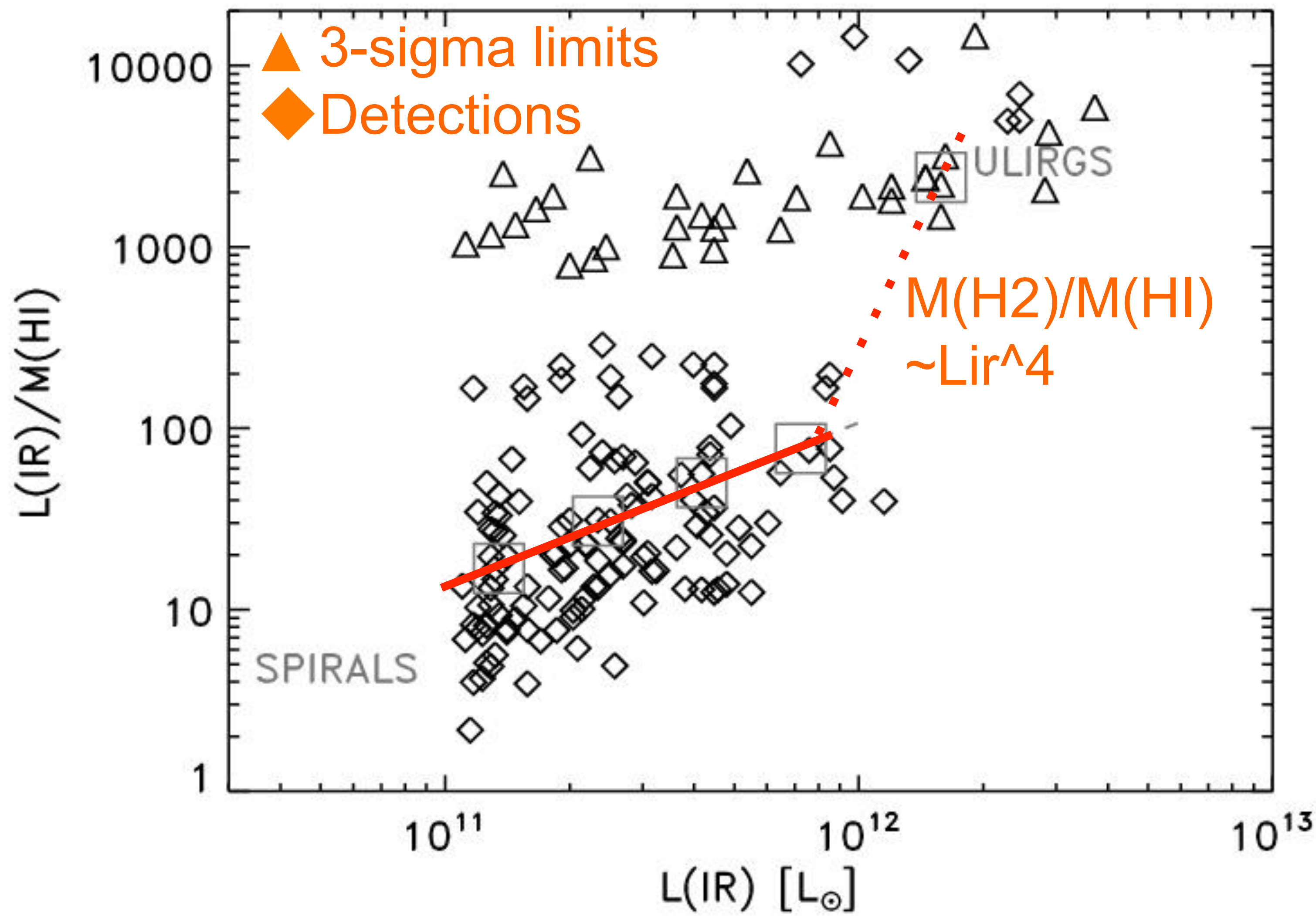
- Double horns: Spiral galaxies
- Gaussian, Strong Asymmetries
- Multiple components
- Strong absorption

M(HI) trend for LIRGS

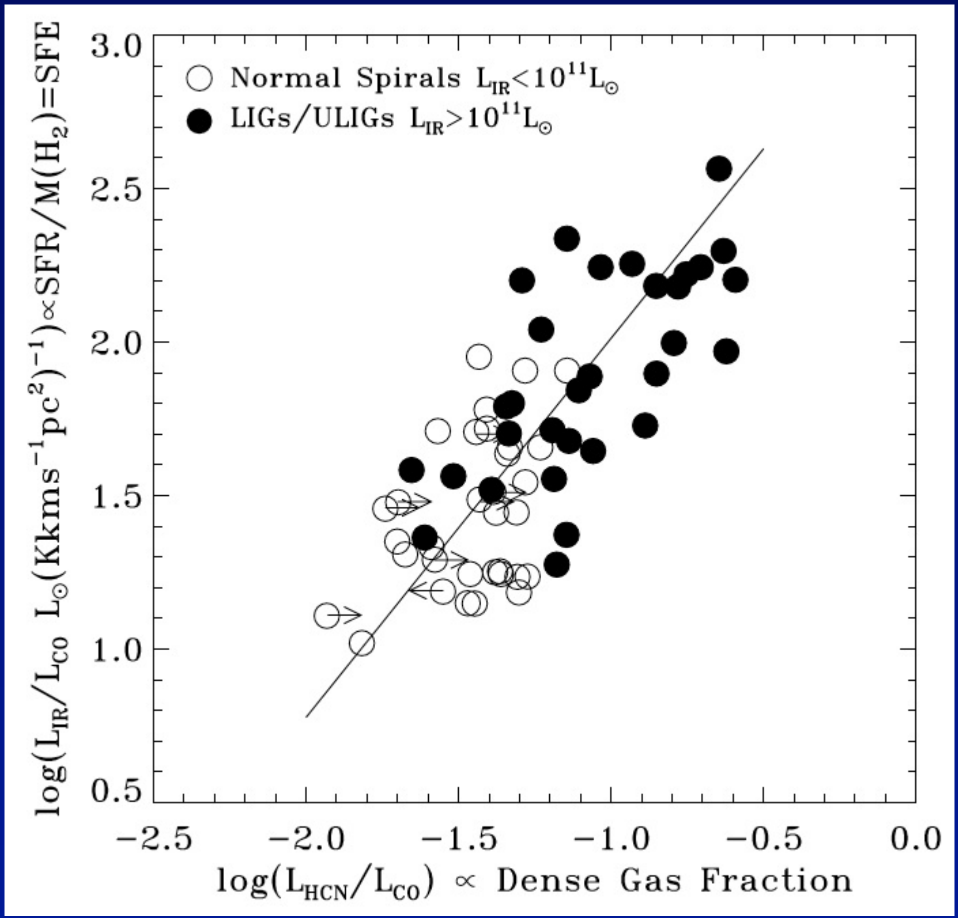
Boxes (median of each bin)

Diana Windemuth's (undergrad) REU project

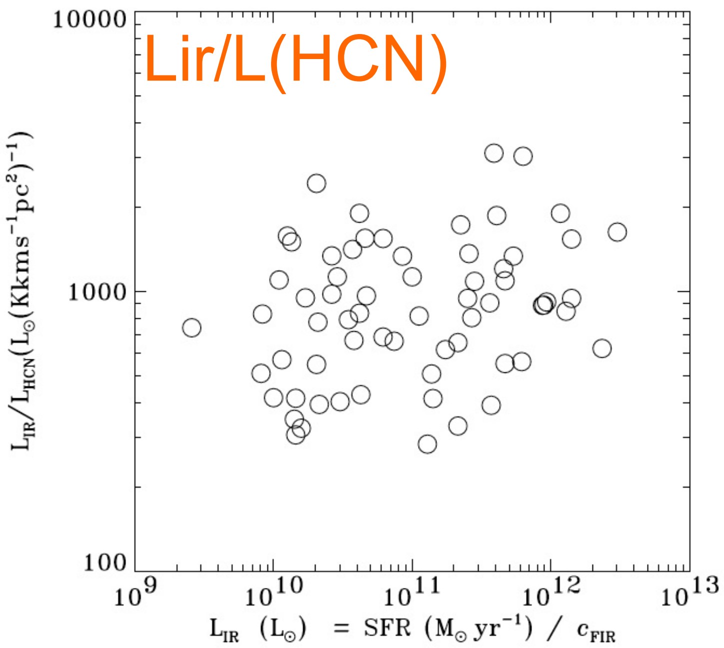
Sabrina Stierwalt (IPAC postdoc) looking into HI trends with GOALS ancillary data

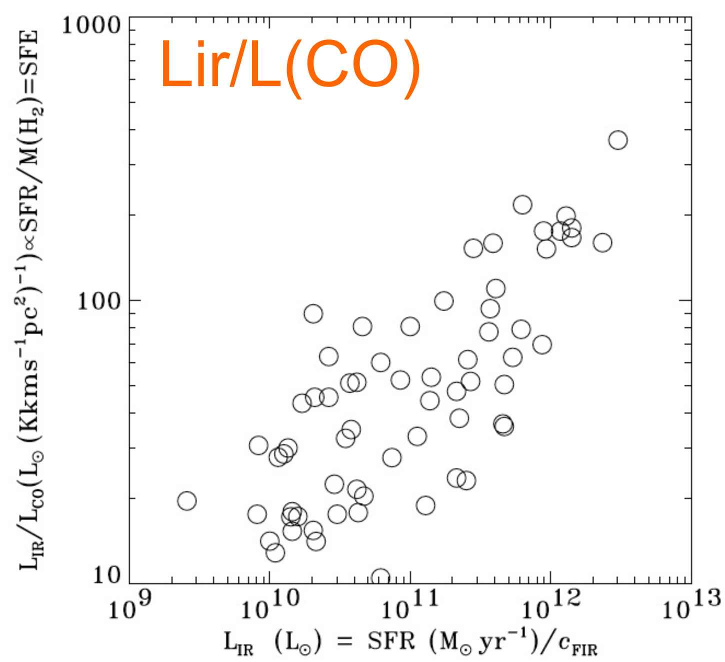


Dense Molecular Gas



Gao & Solomon 2004

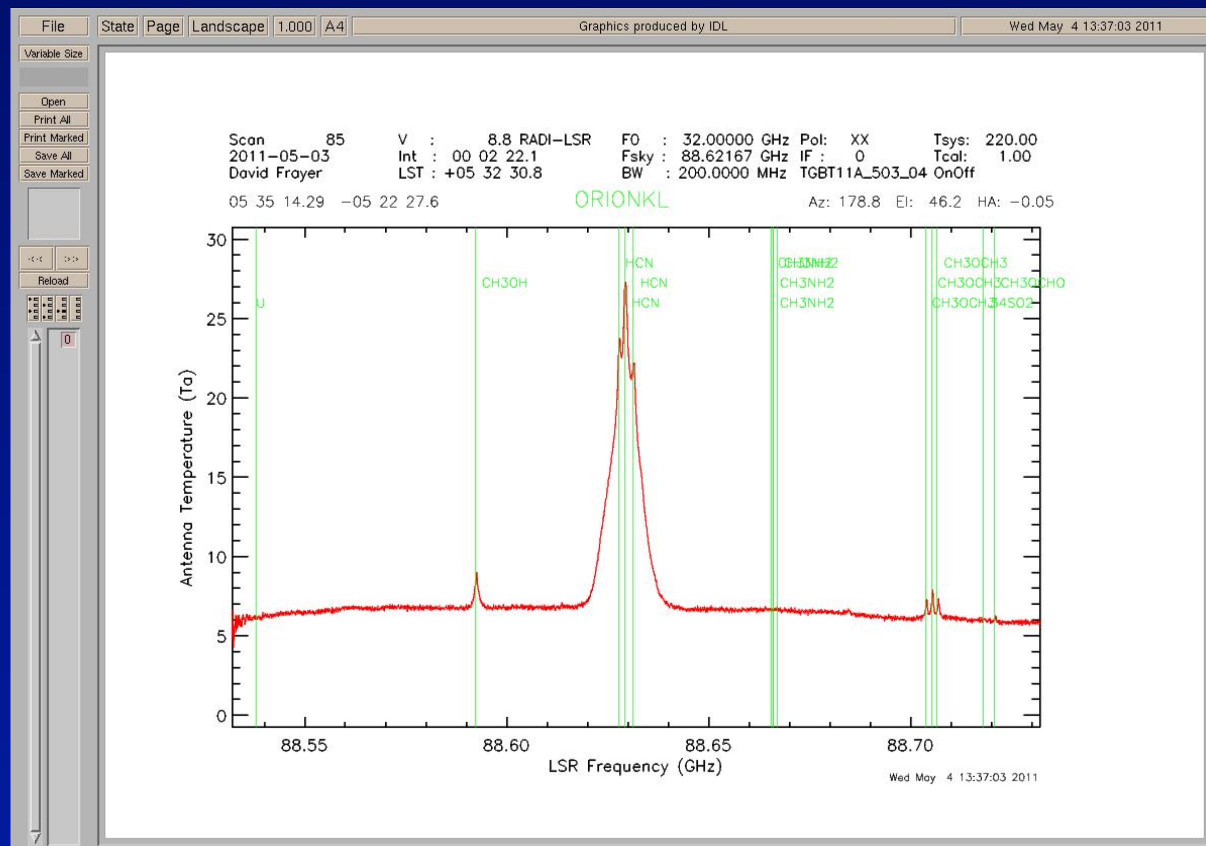




Need HCN+CO for larger sample ➔ GBT for HCN

GBT 4mm Receiver (68-92 GHz)
First Light, May 2011: HCN in Orion-KL

Commissioning
2011 Nov/Dec



See http://www.gb.nrao.edu/4mm for more details.

Concluding Remarks

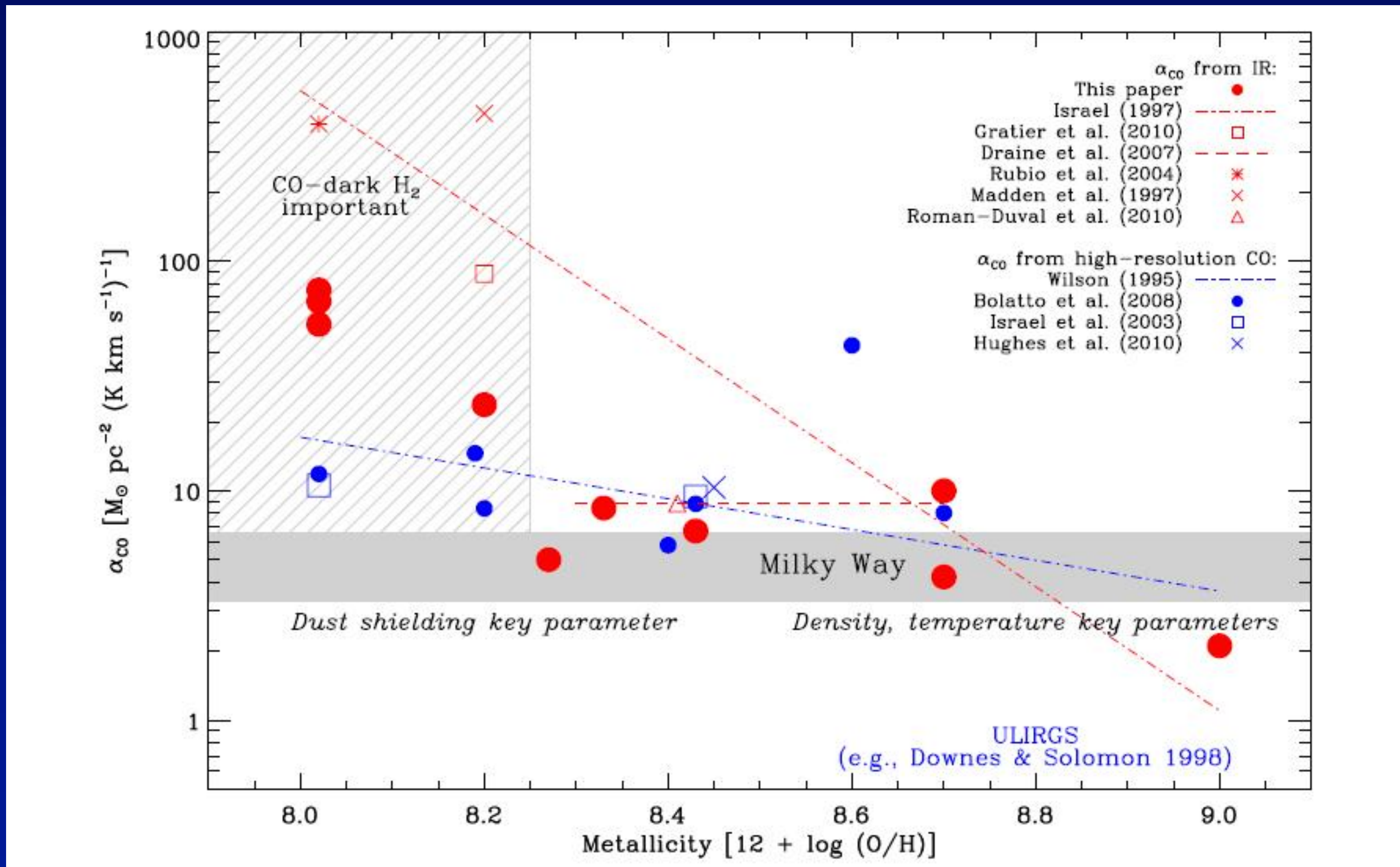
- Next decade will greatly advance mm/submm studies of galaxy evolution {ALMA, eVLA, PdBI, CARMA, SMA, GBT, IRAM-30m, SPT, LMT, CCAT -- CO Redshift machines on single dishes and detailed CO, HCN, CI, and C+ imaging with interferometers}
- Low-J CO important (total molecular gas mass)
- Wide-spectrometer backends permit CO/ISM studies at high-z without the need for prior optical/NIR redshifts
- Local ULIRGs show extreme HI "deficiencies" (rapid conversion of HI into H2)

➢ Combination of HI+CO+HCN data in GOALS LIRGs to test models of gas evolution (both large single-dish surveys and detailed imaging)

➢ High-z CO, HCN, CI, C+ follow-up work on Herschel/SMG samples

Backup Slides

CO-to-H2 conversion factor



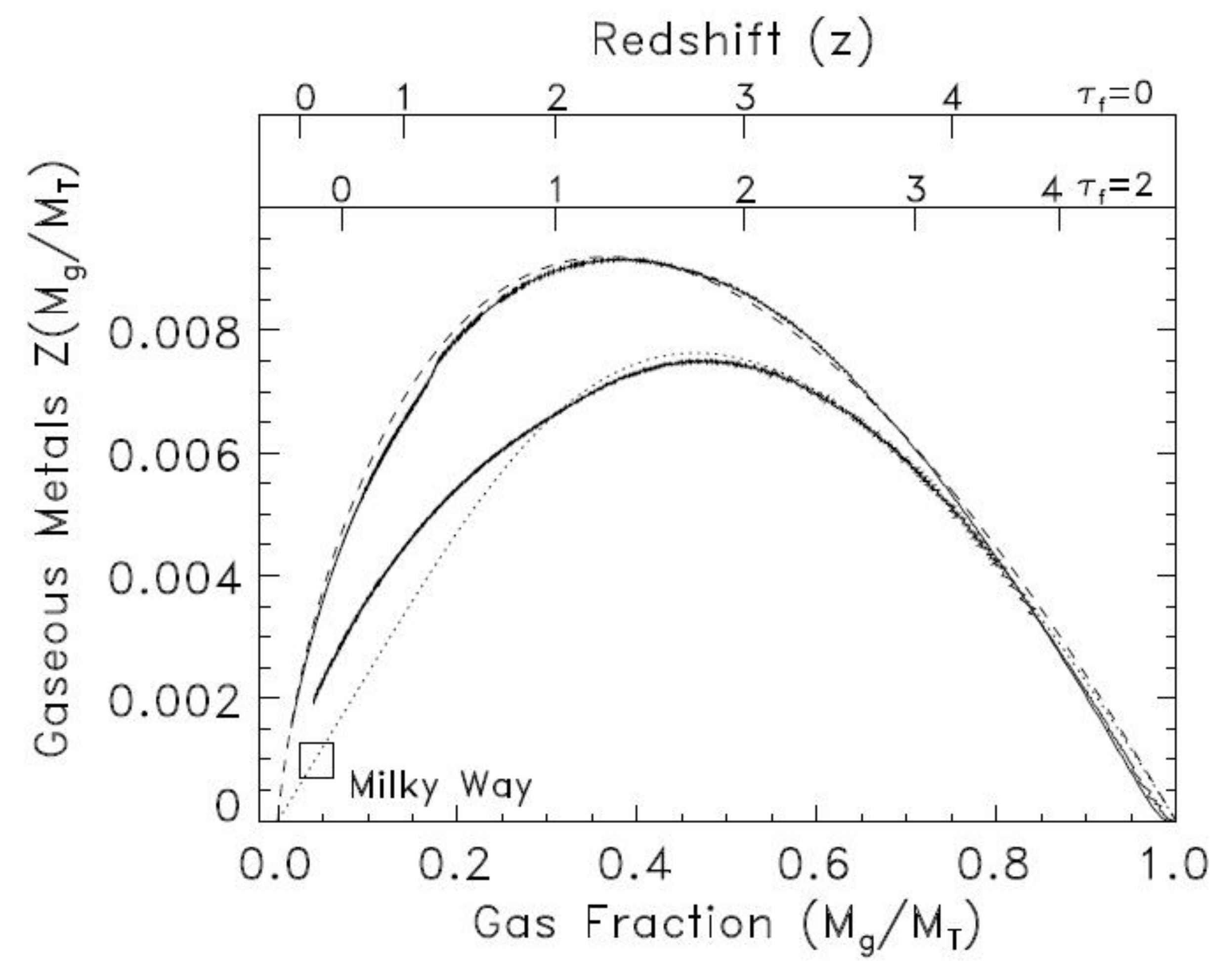
Leroy et al. 2011

Theoretical Motivation

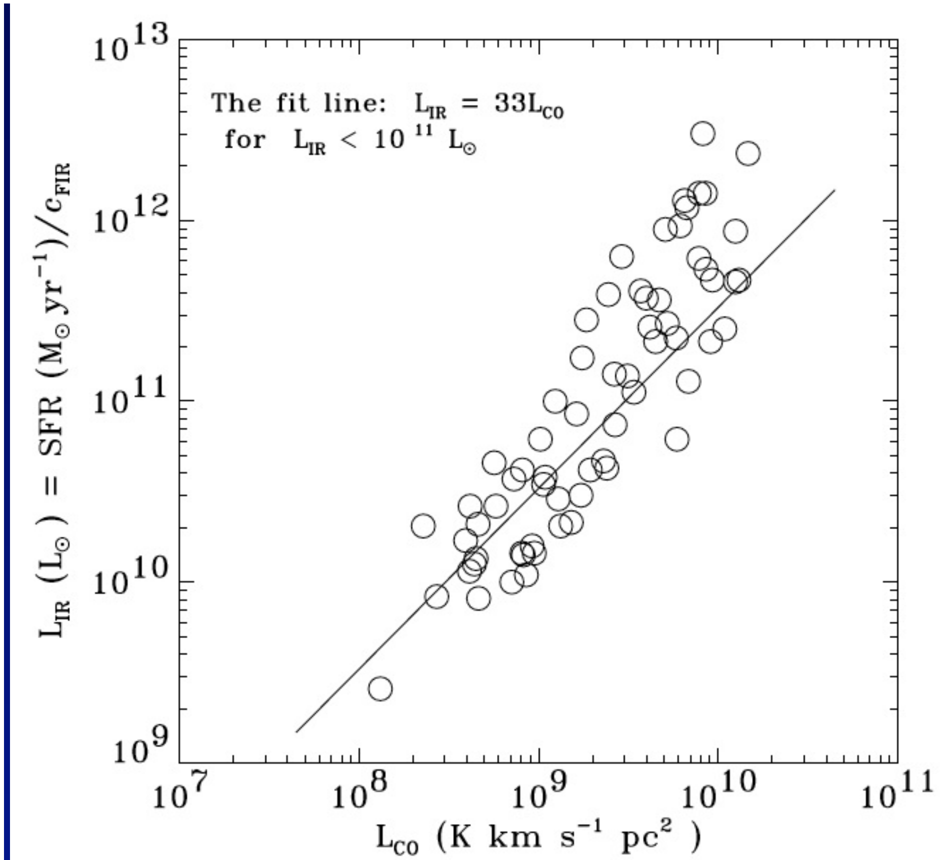
More CO and dust in the past for massive galaxies!!

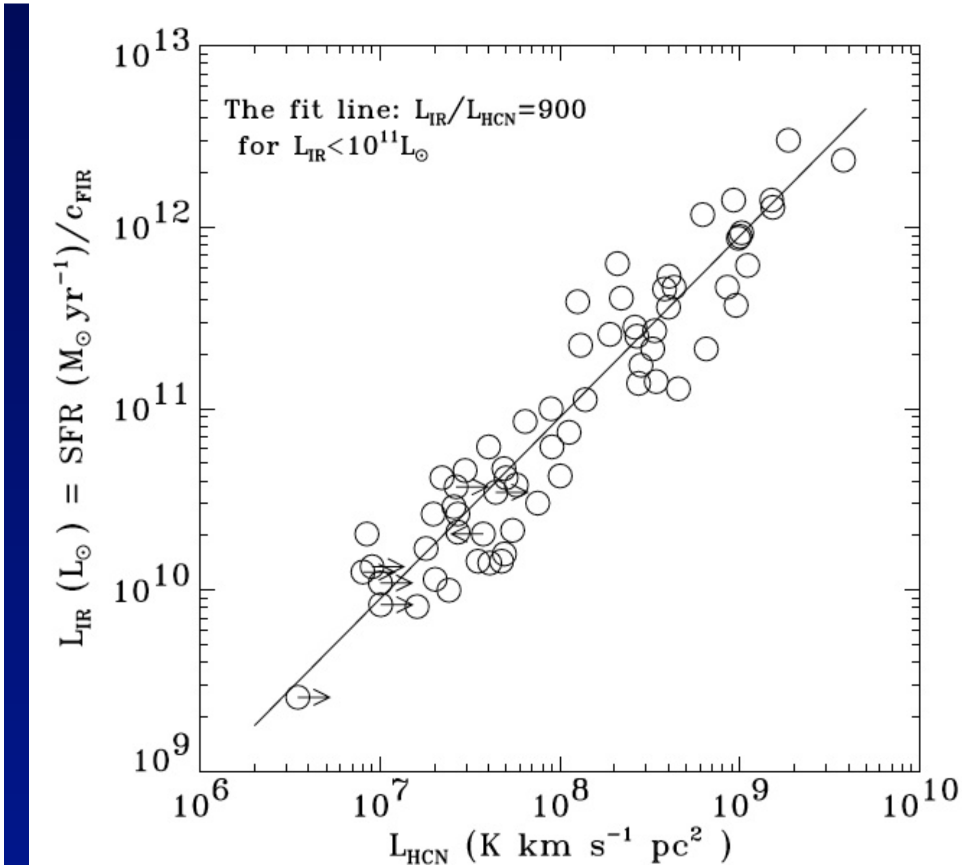
Peak of gaseous metals (Z*Mgas) occurs for gas fractions of 0.3-0.5.

Metals (Z) = everything not H and He



Models from Frayer & Brown 1997





CO

Gao & Solomon 2004

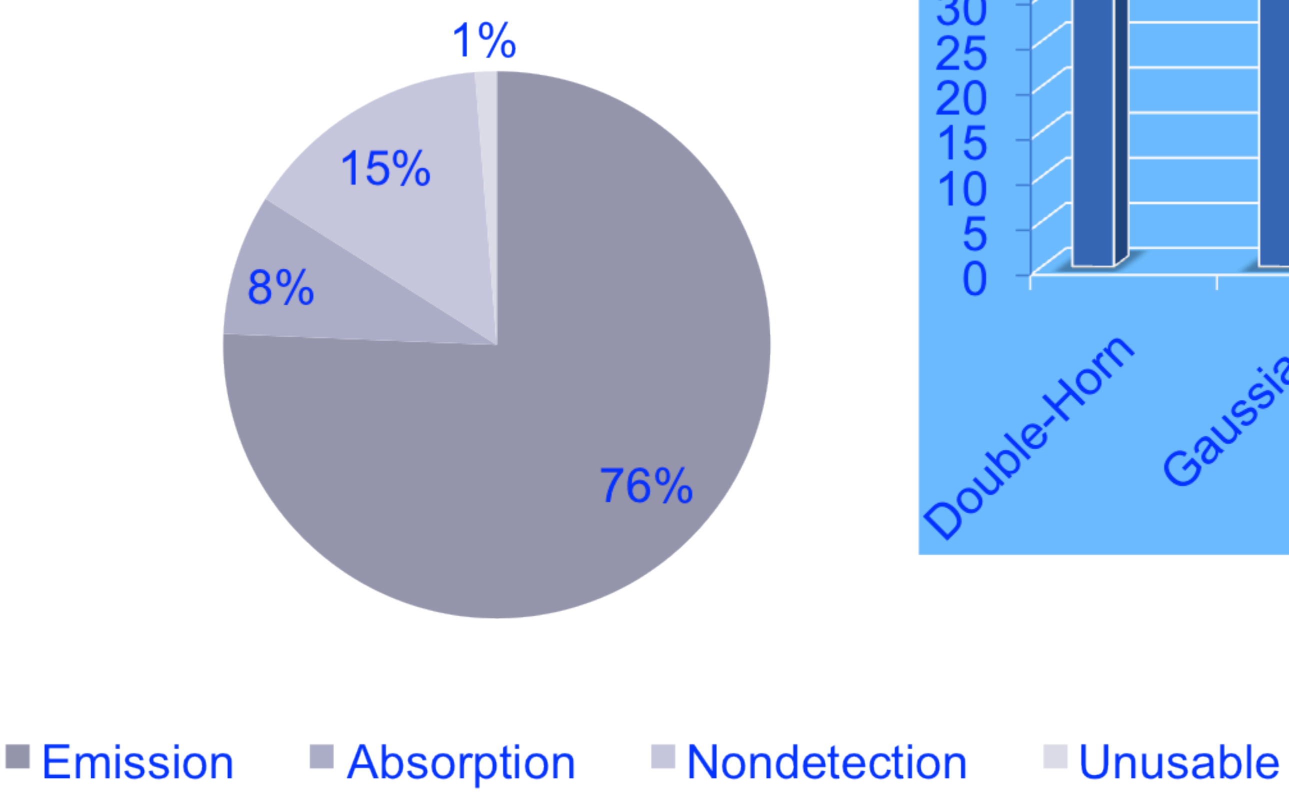
HCN

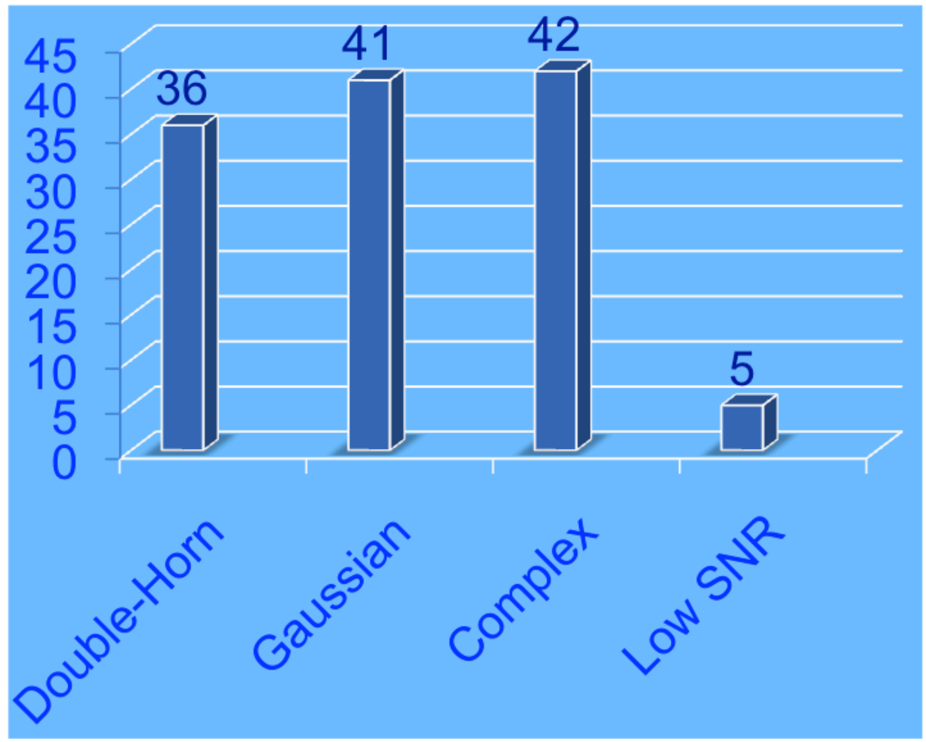
HCN correlates 1-to-1 with Lir, significantly better than CO.
Dense gas (traced by HCN) better correlated with SFR.

Density: HI ~ 100 cm^-3
CO ~ 1000 cm^-3
HCN ~ 10^5 cm^-3

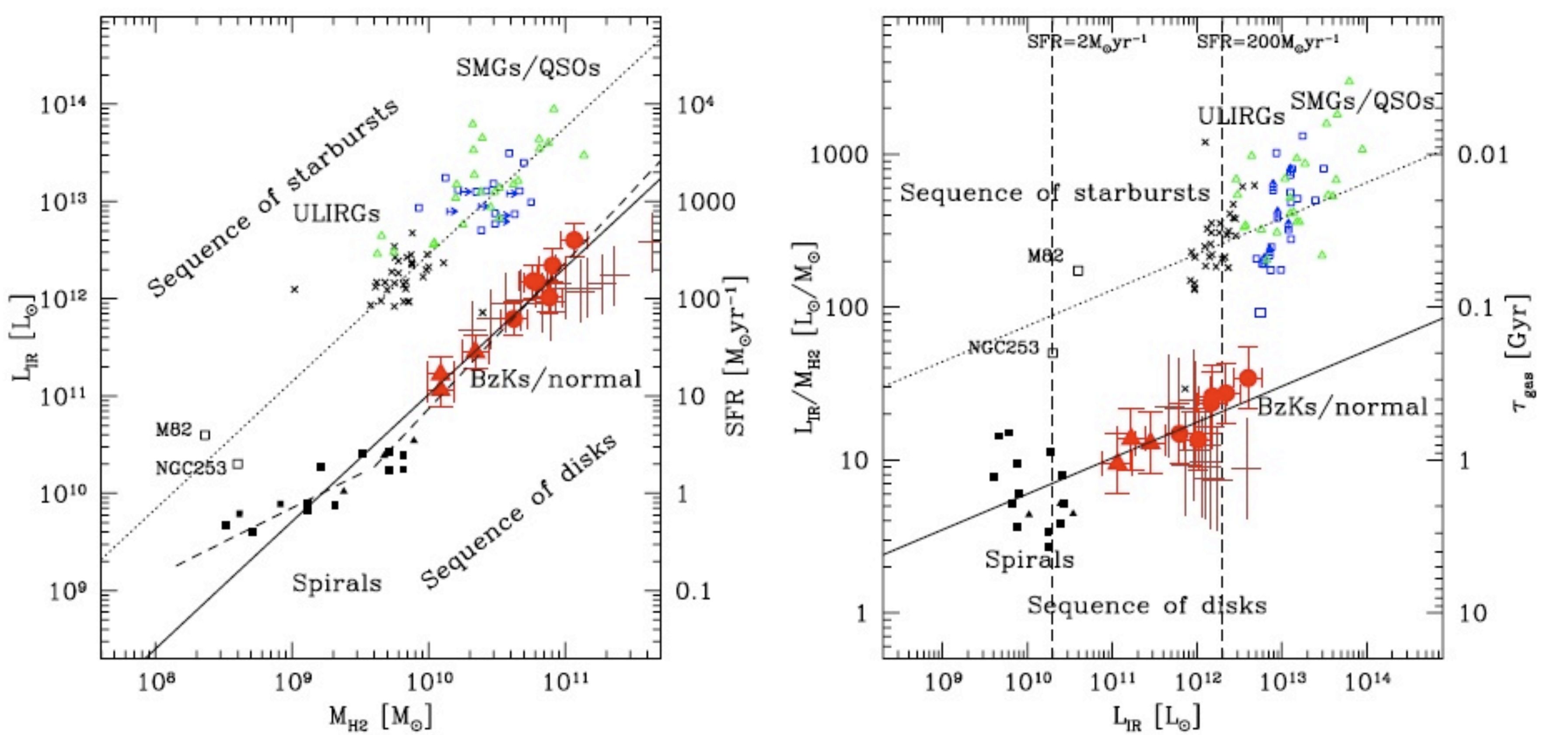
Detection Rate and Profile Types

Diana Windemuth's classification





Disk vs Starburst "Sequence"



(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)

LIRGS:

Lir/M(HI)~ Lir^0.8 => M(HI)~Lir^0.2

Lir/M(H2)~ Lir^0.5 => M(H2)~Lir^0.5

➔M(H2)/M(HI)~Lir^0.3

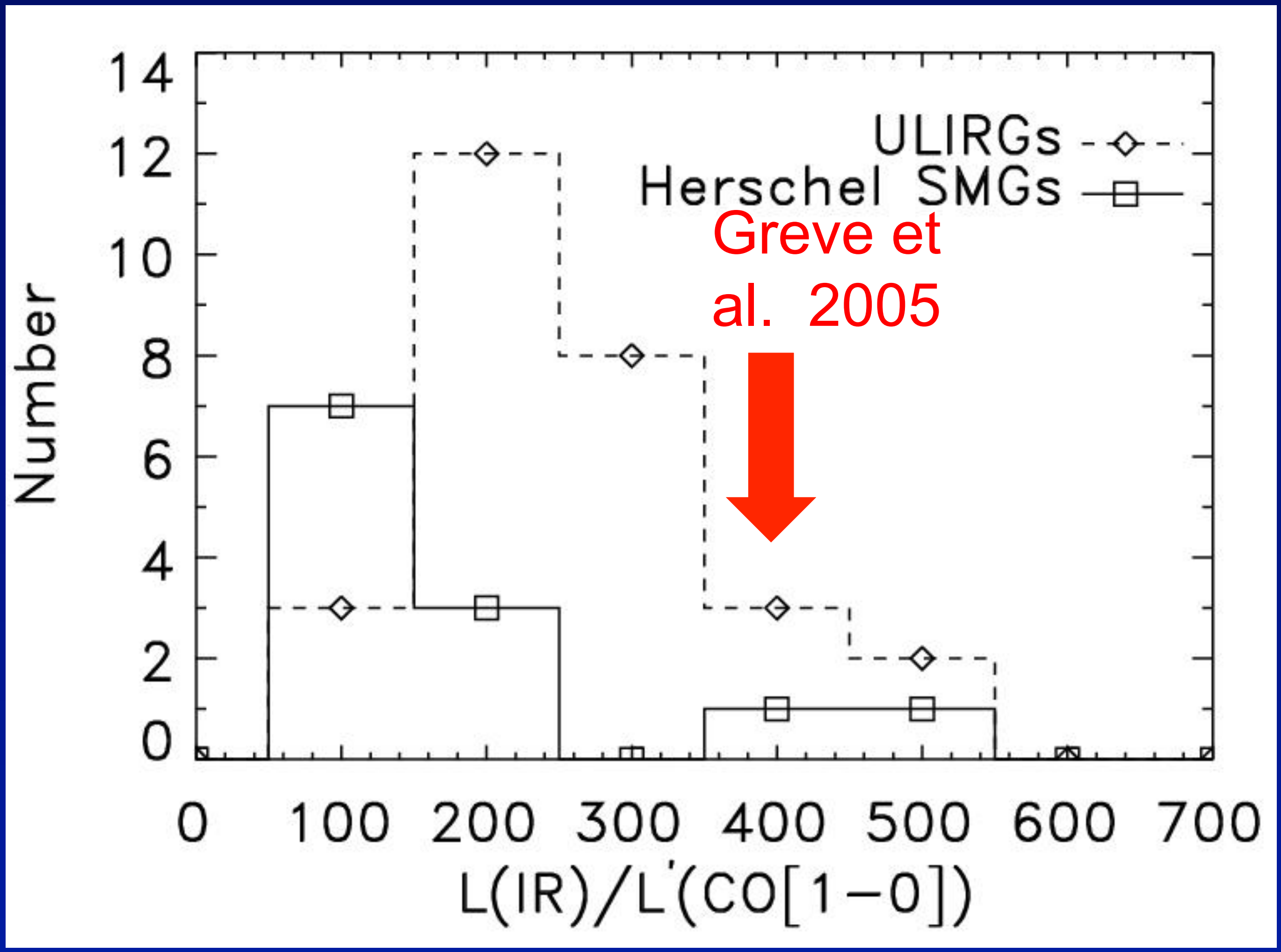
ULIRGs:

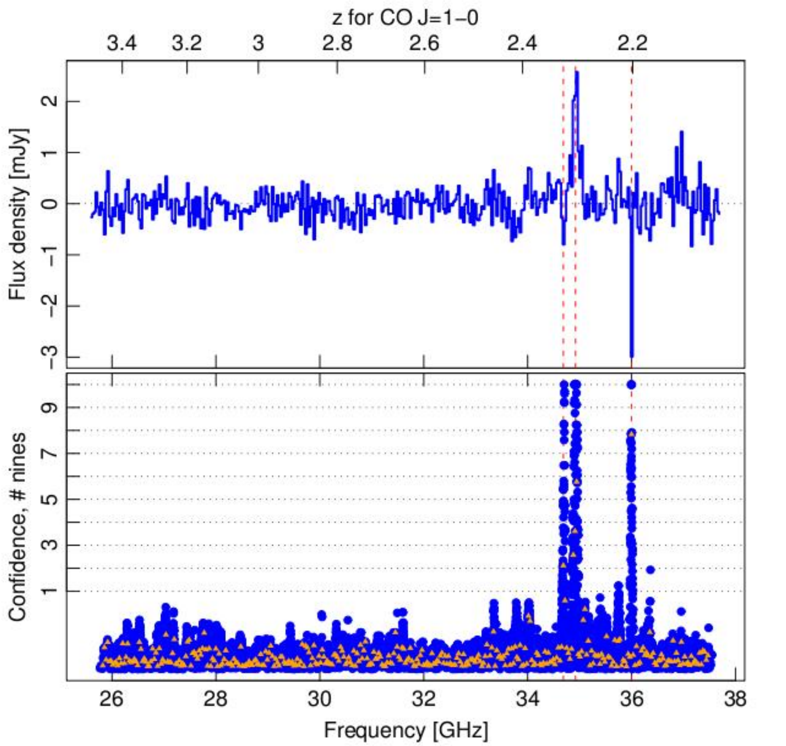
Lir/M(HI)~ Lir^(~4.5) => M(HI)~Lir^(~-3.5)

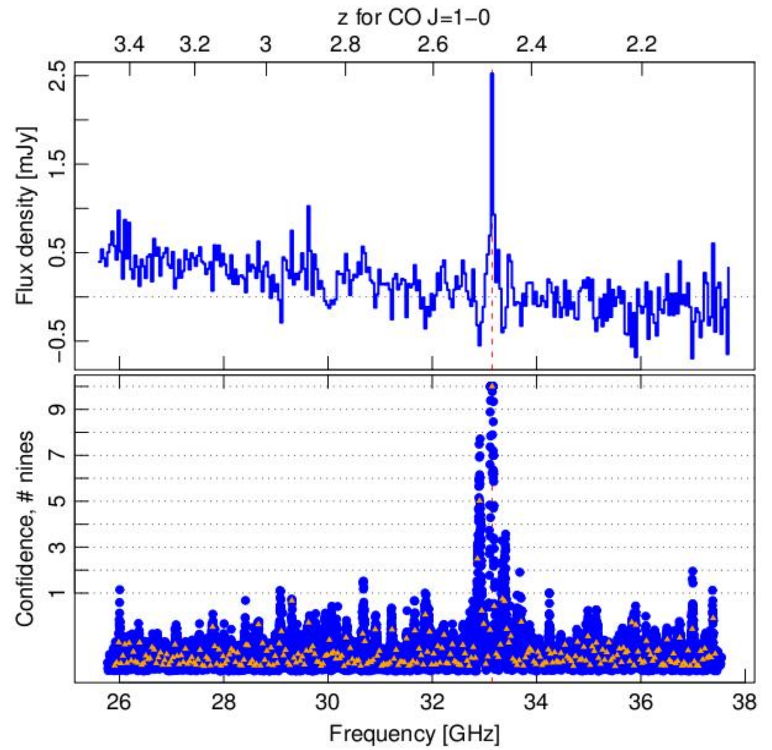
Lir/M(H2)~ Lir^0.5 => M(H2)~Lir^0.5

➔M(H2)/M(HI)~Lir^(~4)

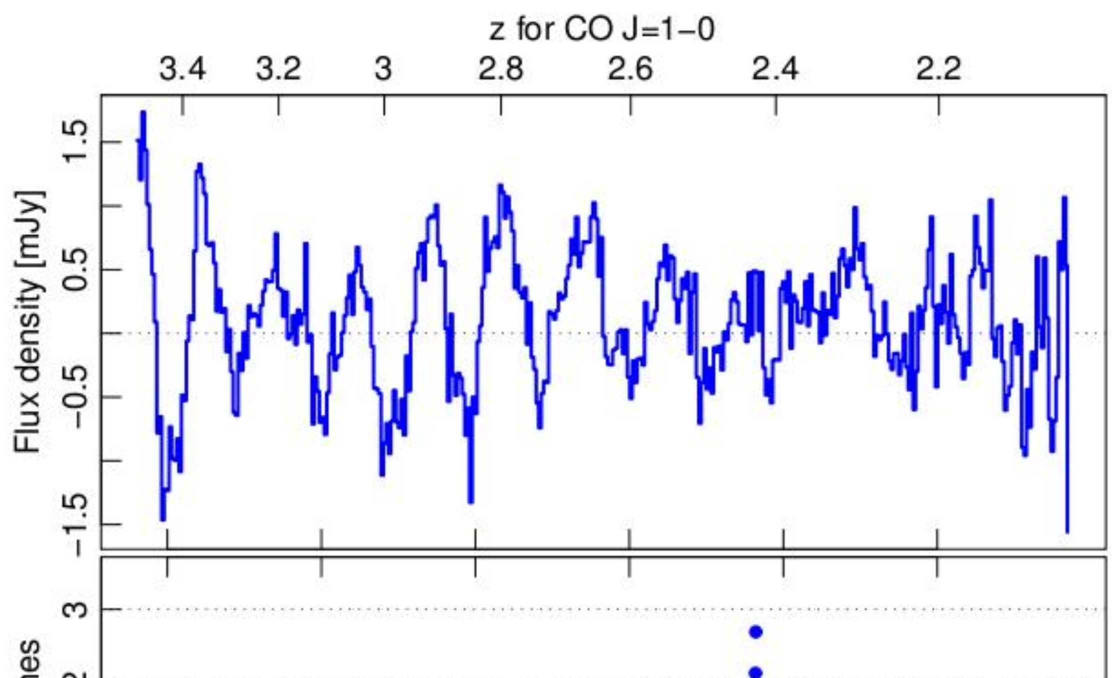
(rapid conversion of HI into H2 in ULIRGs)


ULIRGs
Herschel SMGs
Greve et al. 2005
Number
L(IR)/L'(CO[1–0])
0
2
4
6
8
10
12
14
0
100
200
300
400
500
600
700



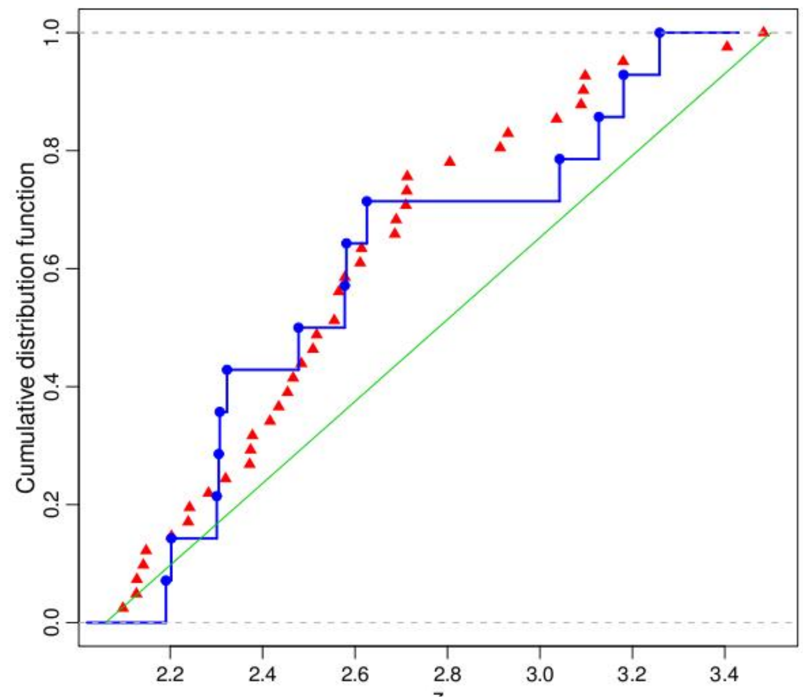


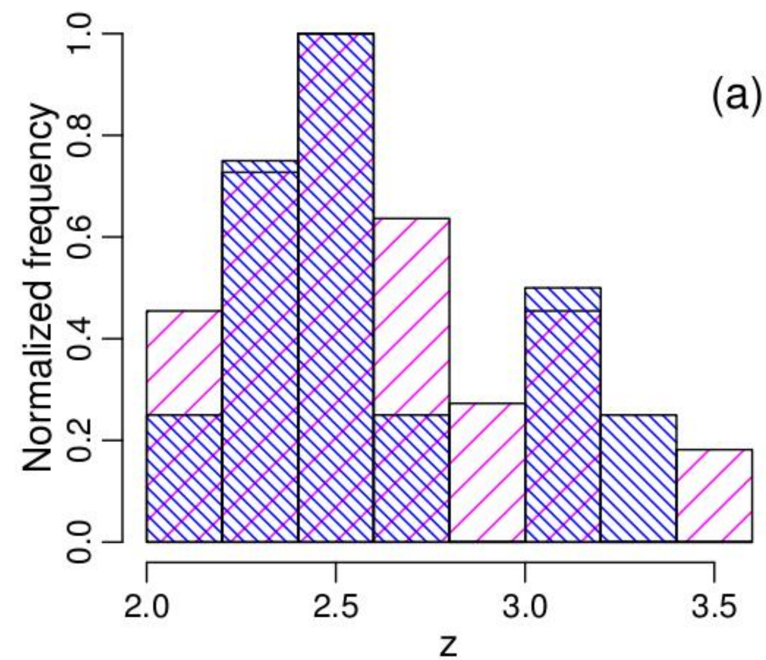
Example bad data:



Redshift Distribution
SMGs <z>~2.5

- Green Line =uniform distribution of redshifts
- Blue = Observed redshift distribution of H-ATLAS SMGs (based on 12 GBT CO detections)
- Red = Observed SMG distribution from Chapman et al. 2005



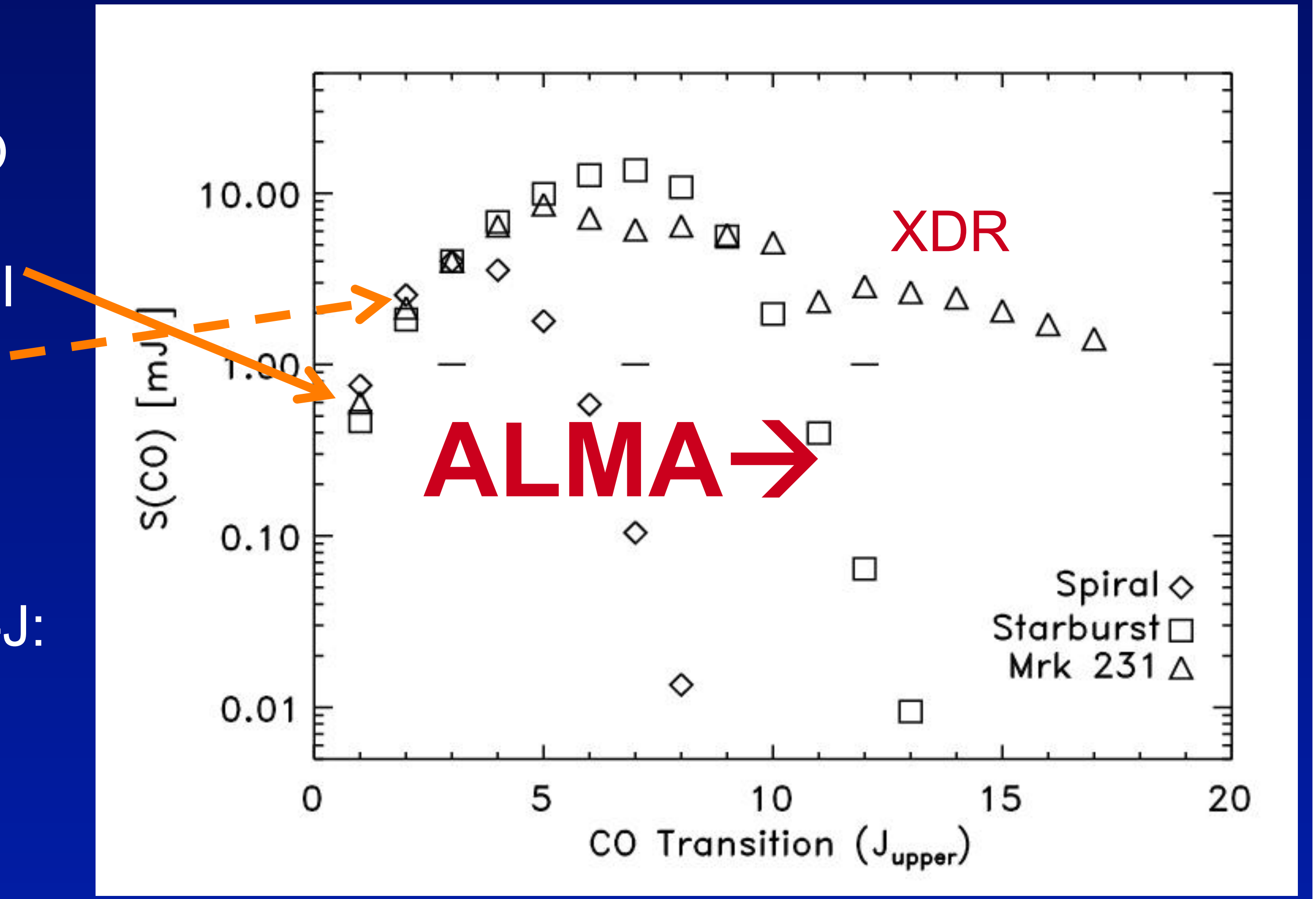


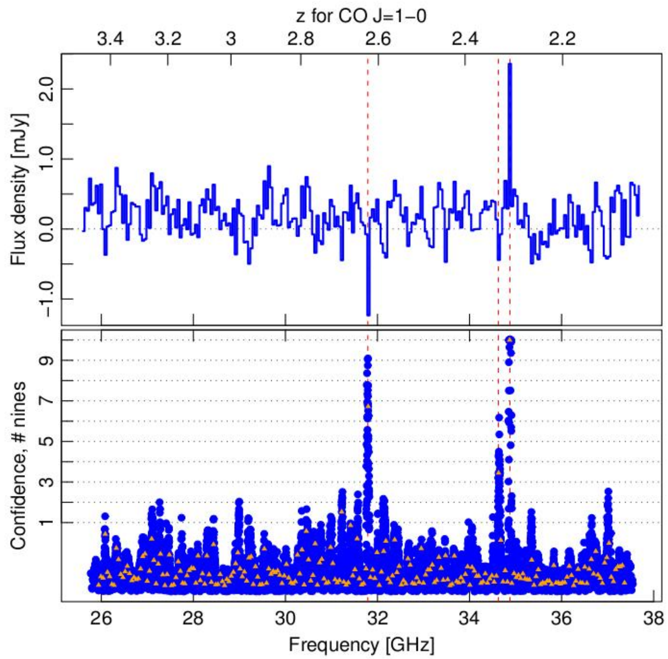
Harris et al., in prep

High-z CO

GBT+EVLA measures CO (1-0) ground-state and total M(H2) {and (2-1) at highest-z}

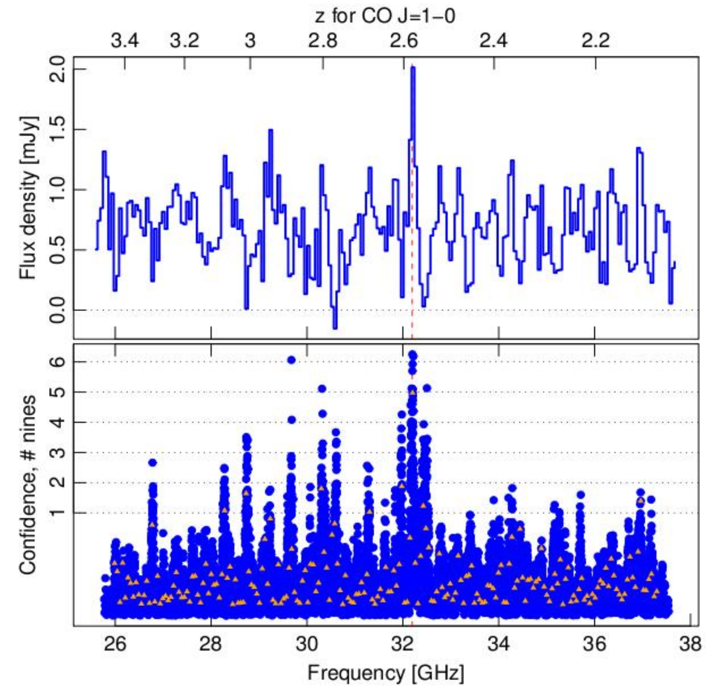
ALMA higher-J: Spirals vs Starbursts vs AGN

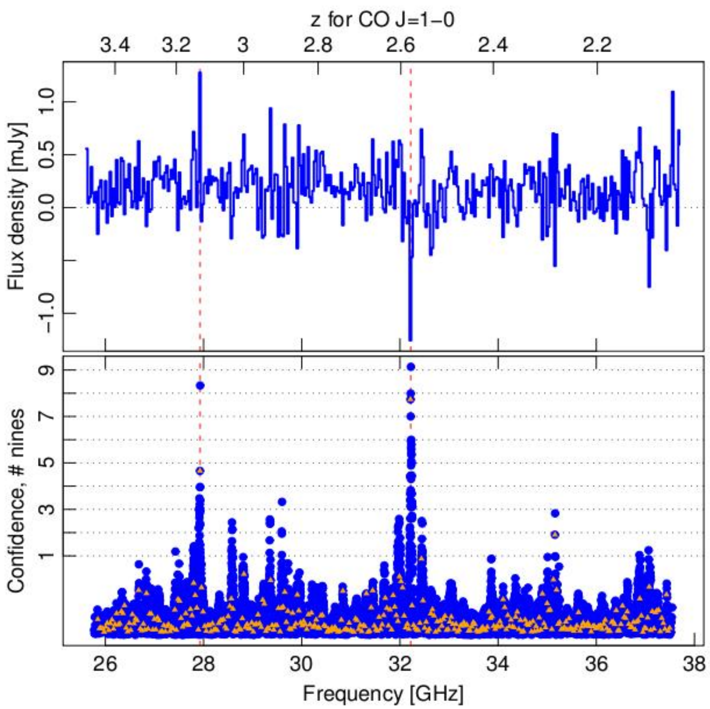


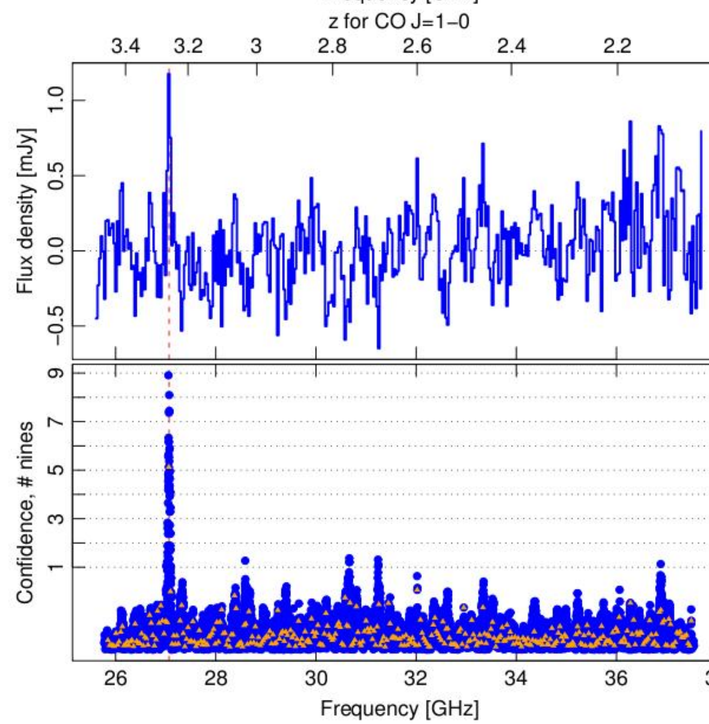


Some example GBT CO(1-0) Zpectrometer data from last season – 12 detections to date from H-ATLAS

Zpectrometer just went back up on the GBT☺







Obtaining CO detections for SCUBA SMGs before current generation of wide-bandwidth spectrometers was time consuming…

1. Crude submm position (15")
2. Radio/mm map for accurate position (1")
3. Accurate NIR/optical redshift of candidate counterpart(s) with large optical telescopes (cannot be too obscured)
4. Finally CO redshift searches (7 years between first CO detections Frayer et al. 1998,99 in SMGs and SMG-CO survey Greve et al. 2005)

➔Now can directly search for CO at the Herschel positions of candidate high-z sources

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 30 m	EMIR[b]	83–117 GHz	8%	9 mJy (IRAM documentation)
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%	4 mJy (32 m), 1.5 mJy (50 m)[e]
ALMA[b,d]		84–116 GHz	8%	0.4 mJy (Web calculator)