Characterize Star Formation and Gas Properties in QSOs and SMGs at z > 4 via Sub-millimeter Line Spectroscopy

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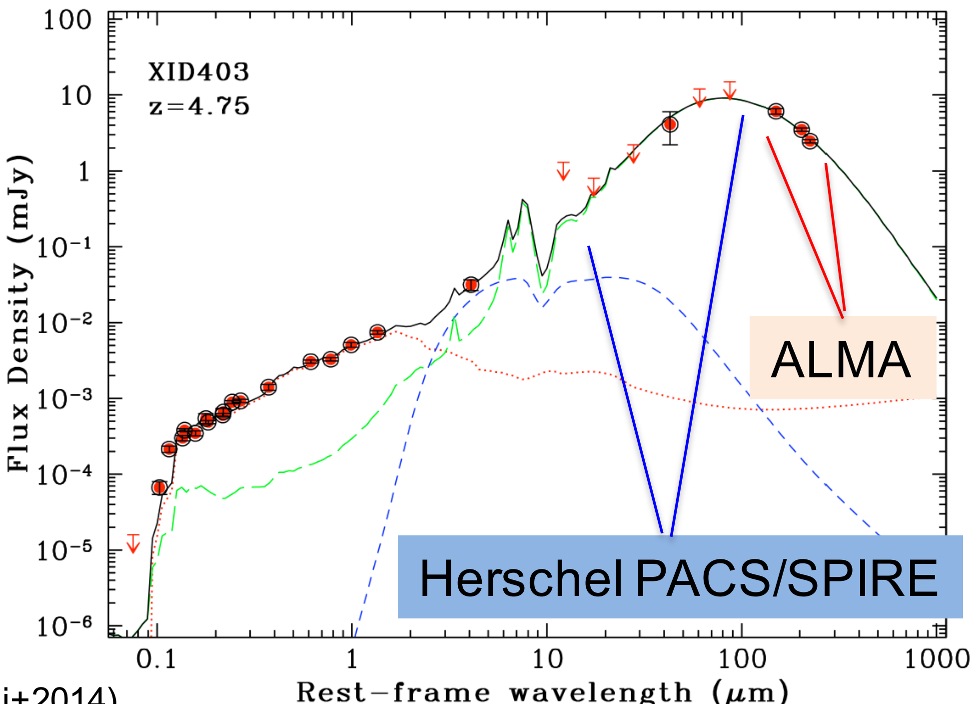
+ More

Talk Outline

- Challenges in characterizing the star formation (SF) in galaxies at high *z*
- Introducing a new, efficient spectroscopic approach for **ALMA**
- Some application examples at $4 < z < 5$
- Summary

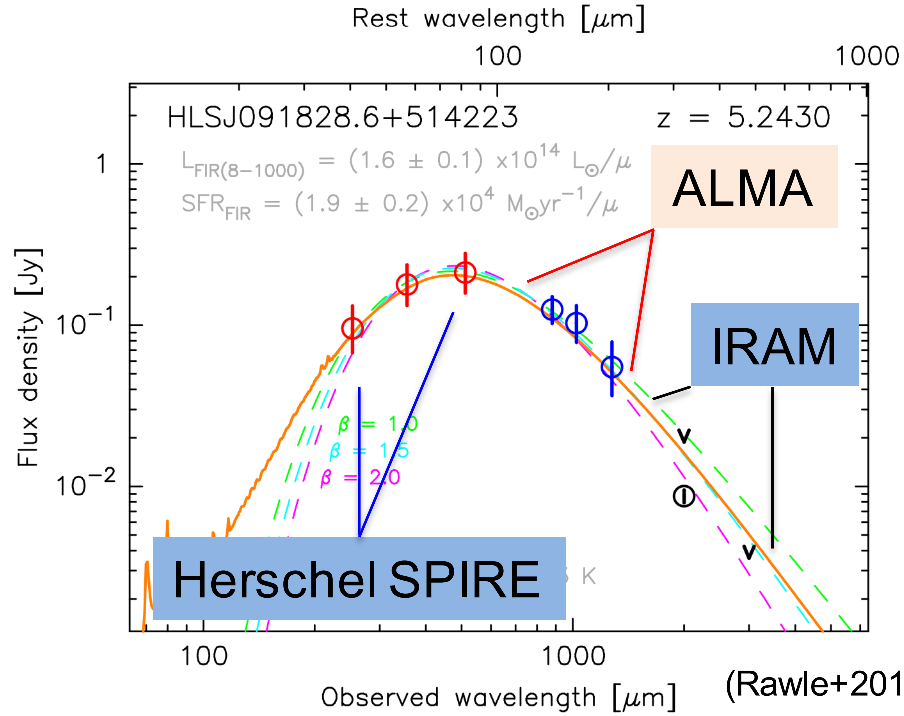
Conventional Approach: Full Dust SED Analysis

LESS J033229.4-275619 (z = 4.75)



(Gilli+2014)

HLSJ091828.6+514223 (z = 5.24)



(Rawle+2014)

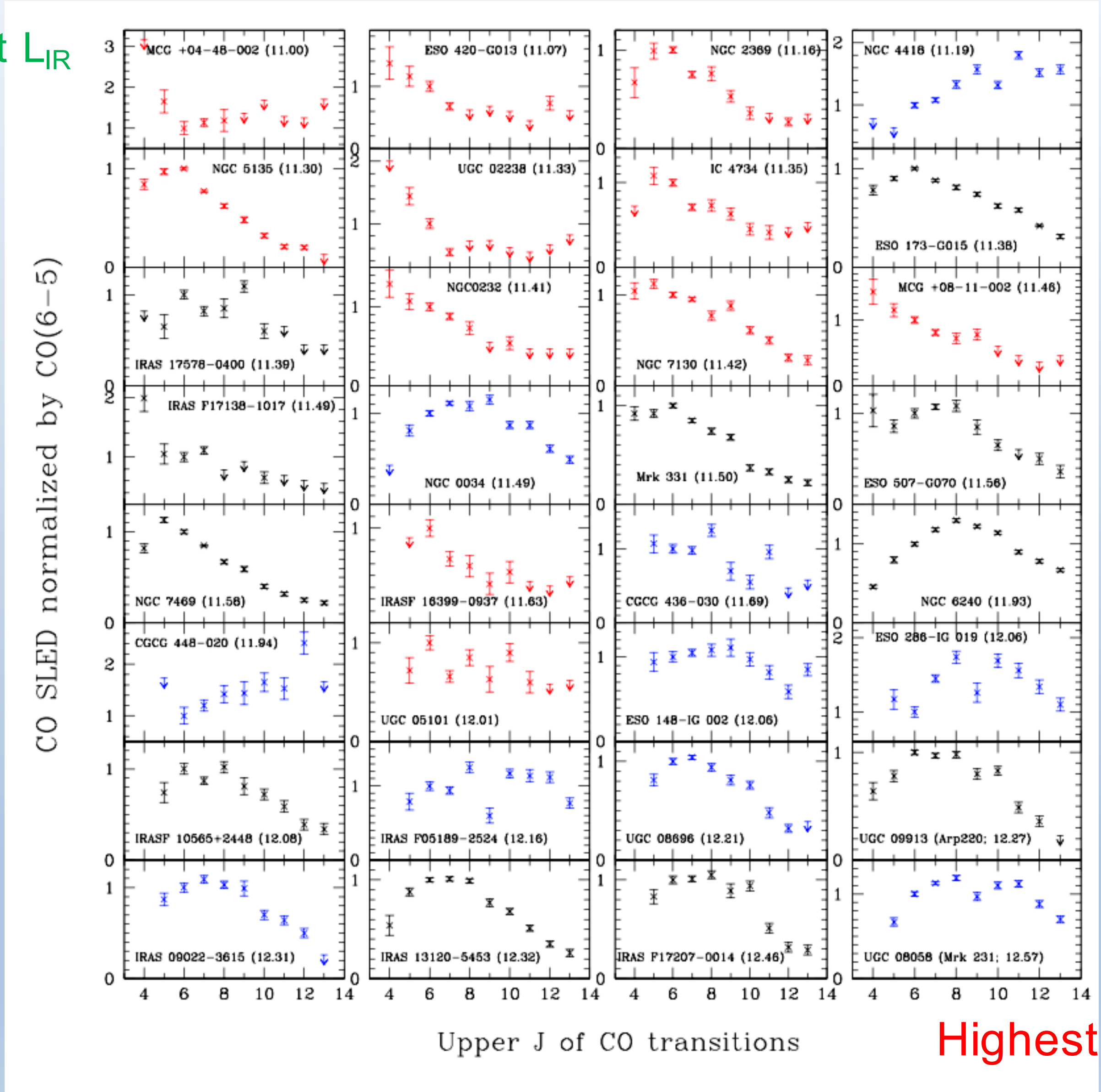
L_{IR} = (5.9+/-0.9) x 10^{12} $L_\odot$
C(60um/100um)$_{rest}$ = 0.9

L_{IR} = (160+/-10) x 10^{12} $L_\odot$
C(60um/100um)$_{rest}$ = 1.0

Reasonably accurate L_{IR} and T_{dust} often require observations with multiple facilities; also, continuum measurements are against brighter CMB at high *z* (da Cunha+2013)

CO Spectral Line Energy Distribution (SLEDs)

Lowest L_{IR}



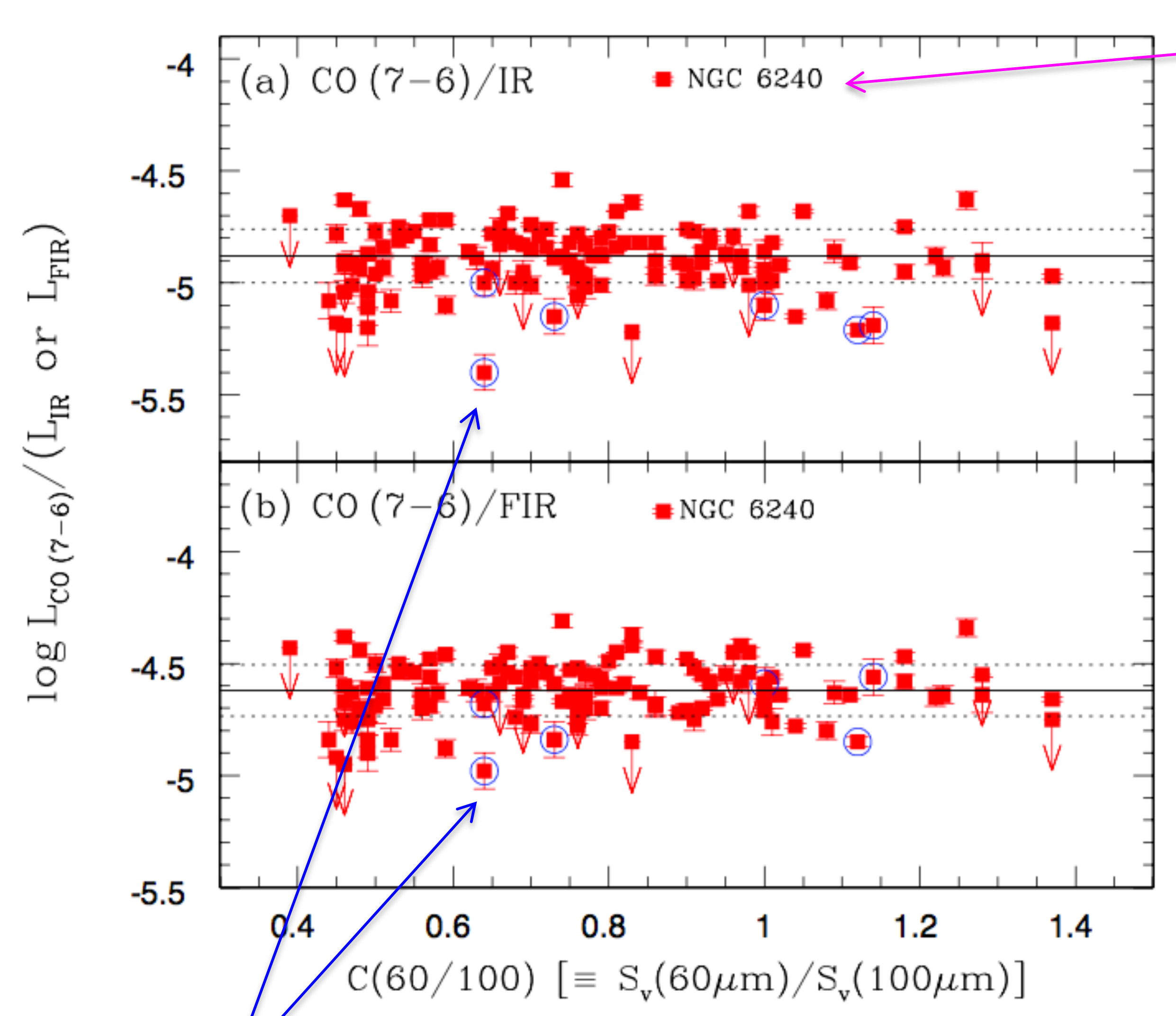
Highest L_{IR}

Lu+14,17a:
Herschel/SPIRE 200-700 um spectroscopy of 125 LIRGs from GOALS sample

CO SLED shape depends on FIR color C(60/100) [$\equiv S_{\upsilon}(60\mu m)/S_{\upsilon}(100\mu m)$]:

- Red: relatively cold
- Black: Intermediate
- Blue: warm

Mid-J CO Line Emission Traces SF Rate (SFR)



A rare case (see Lu+14)

$L_{CO(7\text{-}6)}$ / L_{IR} is

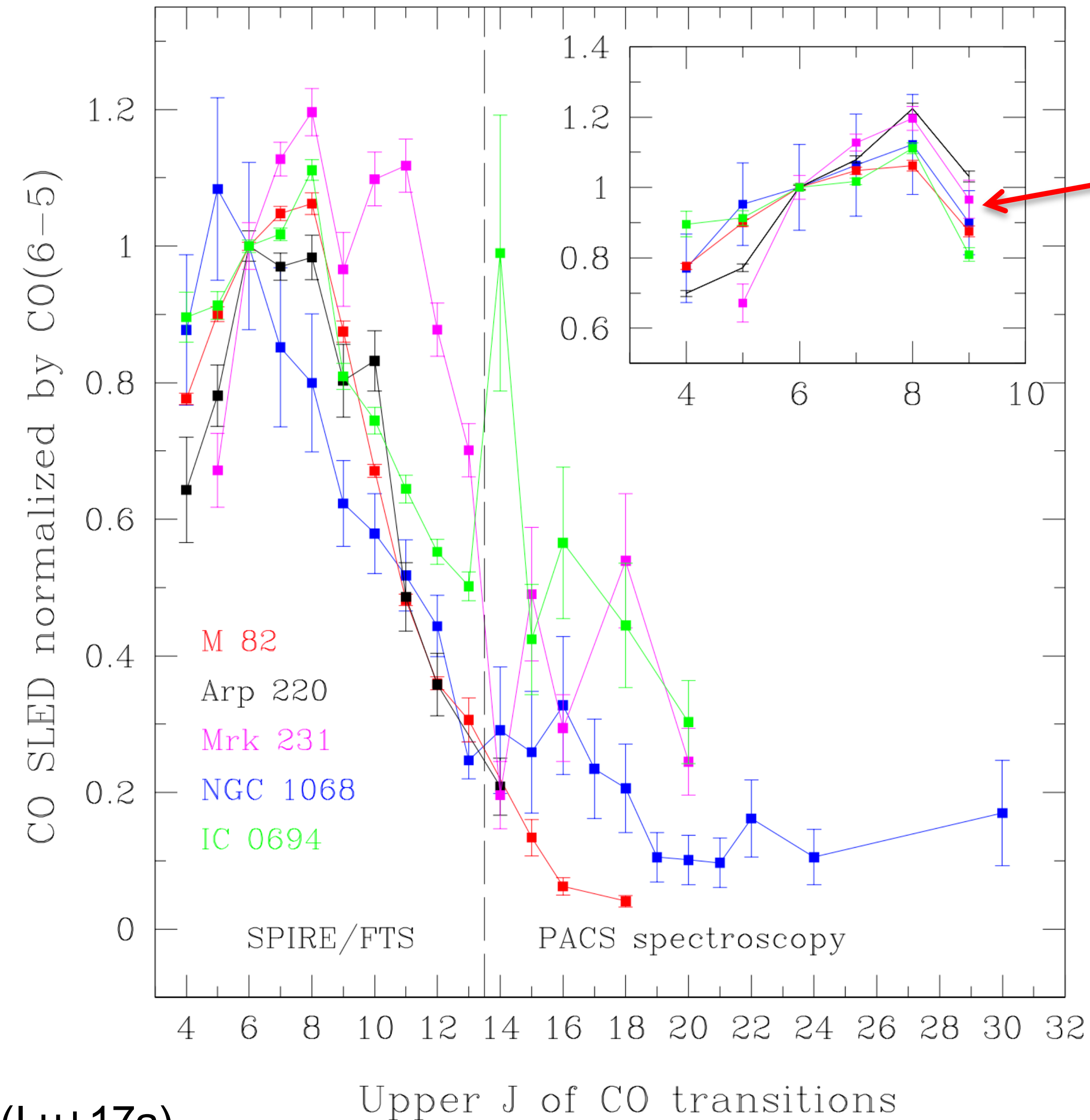
- independent of FIR color to within 30% for SF-dominated LIRGs;
- however lower for AGNs due to AGN contamination to L_{IR}, i.e., vertically offset by log (1 – L_{AGN}/L_{IR})

IR luminosity of the AGN

- Circled in blue: 6 dominant AGNs (i.e., >50% of L_{IR} is from AGN)

(Lu+14,15,17a)

AGN Gas Heating Impacts CO Lines at J > 10



(Lu+17a)

After adjustment for the dependence of the mid-J SLED shape on the FIR color for SF-dominated LIRGs (Lu+2017a)

Color Coding

starbursts:	M82; Arp 220
dominant AGNs:	Mrk231; NGC 1068
possible dominant AGN:	IC 0694 (=Arp 299A)

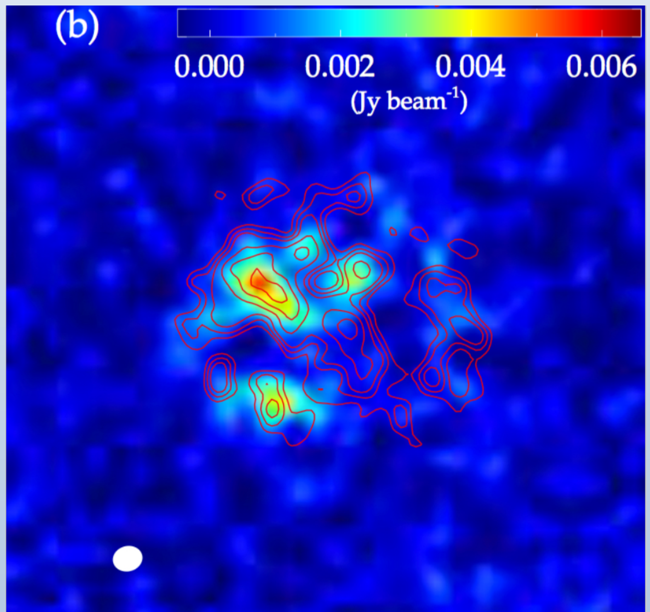
ALMA Cases: SF *vs.* AGN

IC 5179: Starburst

(log L_{IR} = 11.24; FIR color = 0.52)

Image: continuum @434 um

Contours: CO (6-5) @0.14: res (35 pc)



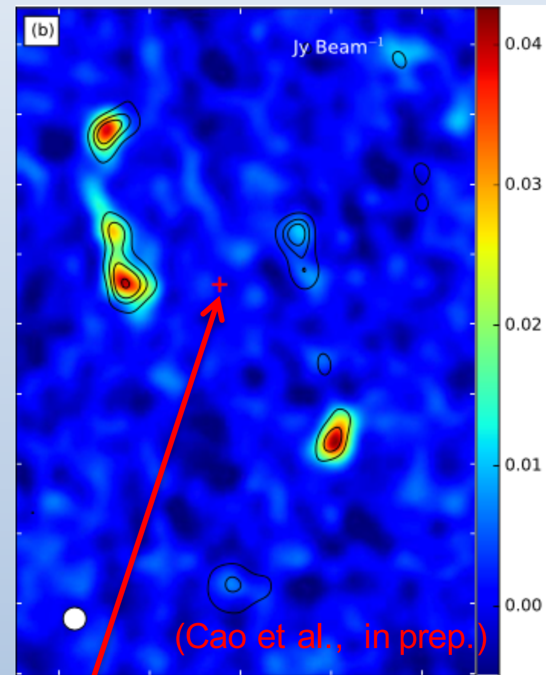
(Zhao et al. 2017.)

NGC 5135 : Seyfert 2

(log L_{IR} = 11.30; FIR color = 0.54)

Image: continuum @434 um;

contours: CO (6-5) @0.4" res. (120 pc)



CO (6-5) not detected at the AGN position

In both cases, CO (6-5) / S_ν(434 um) varies between ~1,000 and ~4,000 km s^{-1}

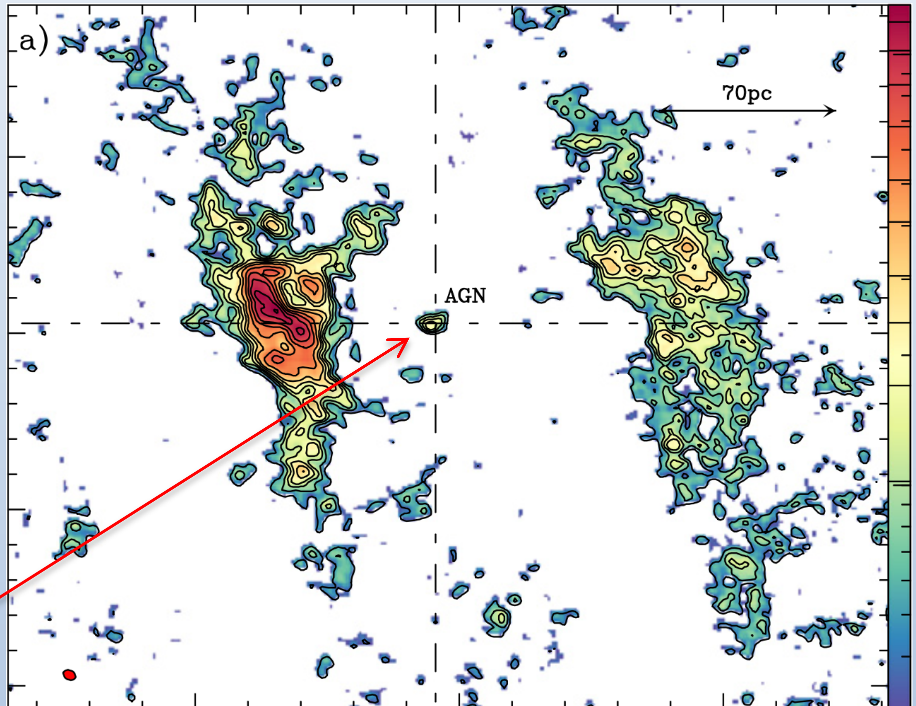
➔ Similar heating mechanism for CO (6-5) in both cases: most likely to be SN-powered shock heating

Another ALMA AGN Example: NGC 1068

(log L_{IR} = 11.4, FIR color = 0.76; Seyfert 2)

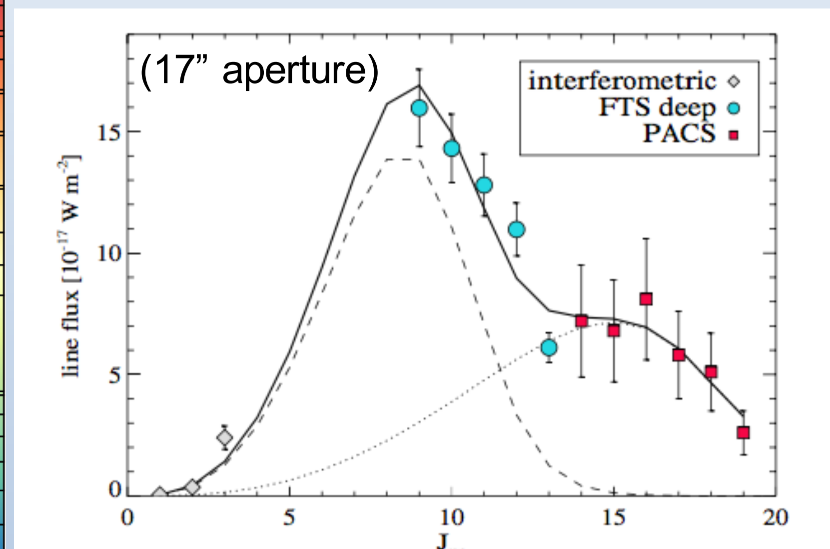
Image & contours: ALMA CO (6-5) at 4 pc resolution

AGN torus (r ~ 5 pc)



(Garcia-Burillo et al. 2016)

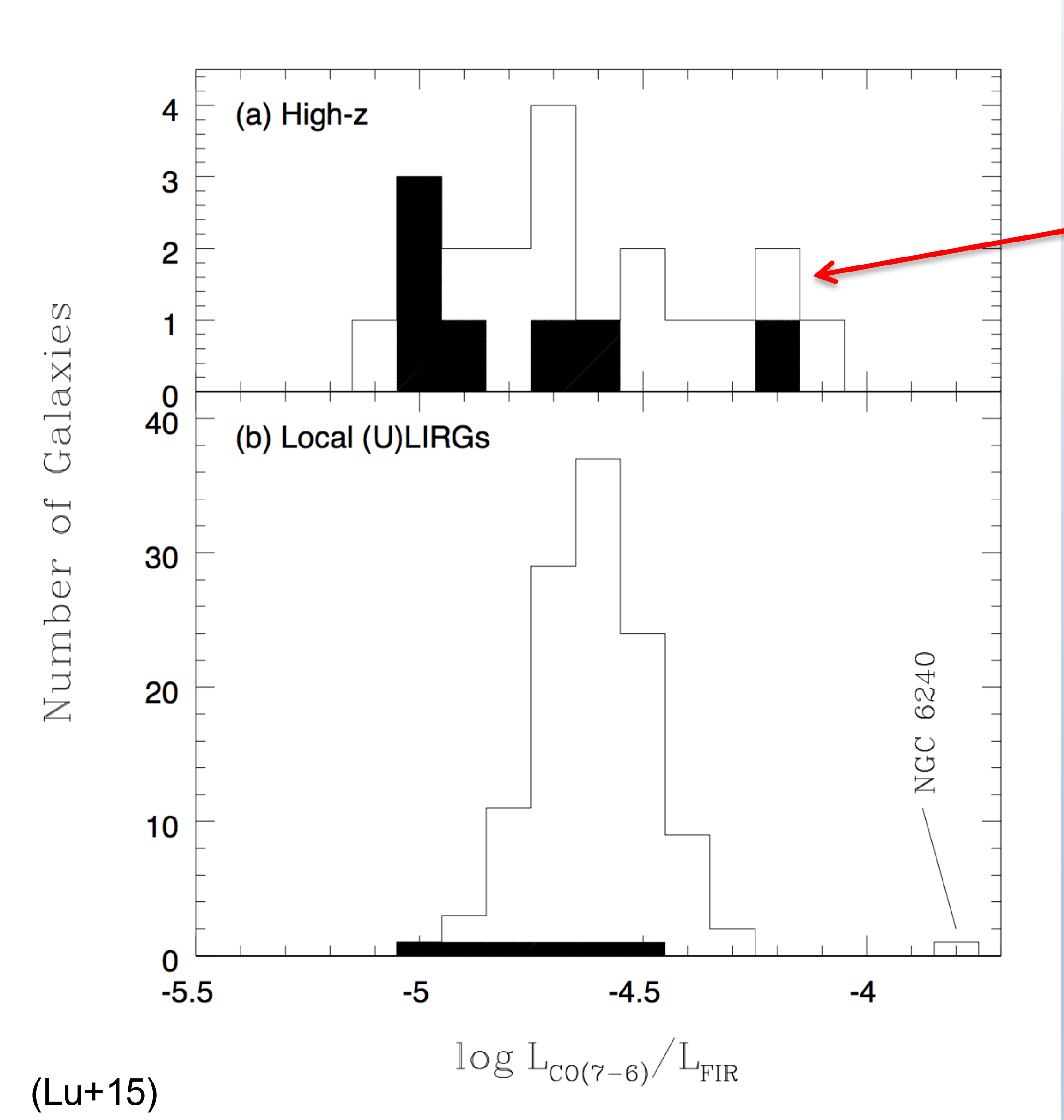
SPIRE/FTS: CO SLED of CND



(Spinoglio et al. 2012)

- The AGN torus has a much smaller ratio of $F_{CO\,(6\text{-}5)}$ / S_ν(434 um) ~ 370 km s^{-1}
- CO (6-5) of the circum-nuclear disk (CND) is likely associated with SF

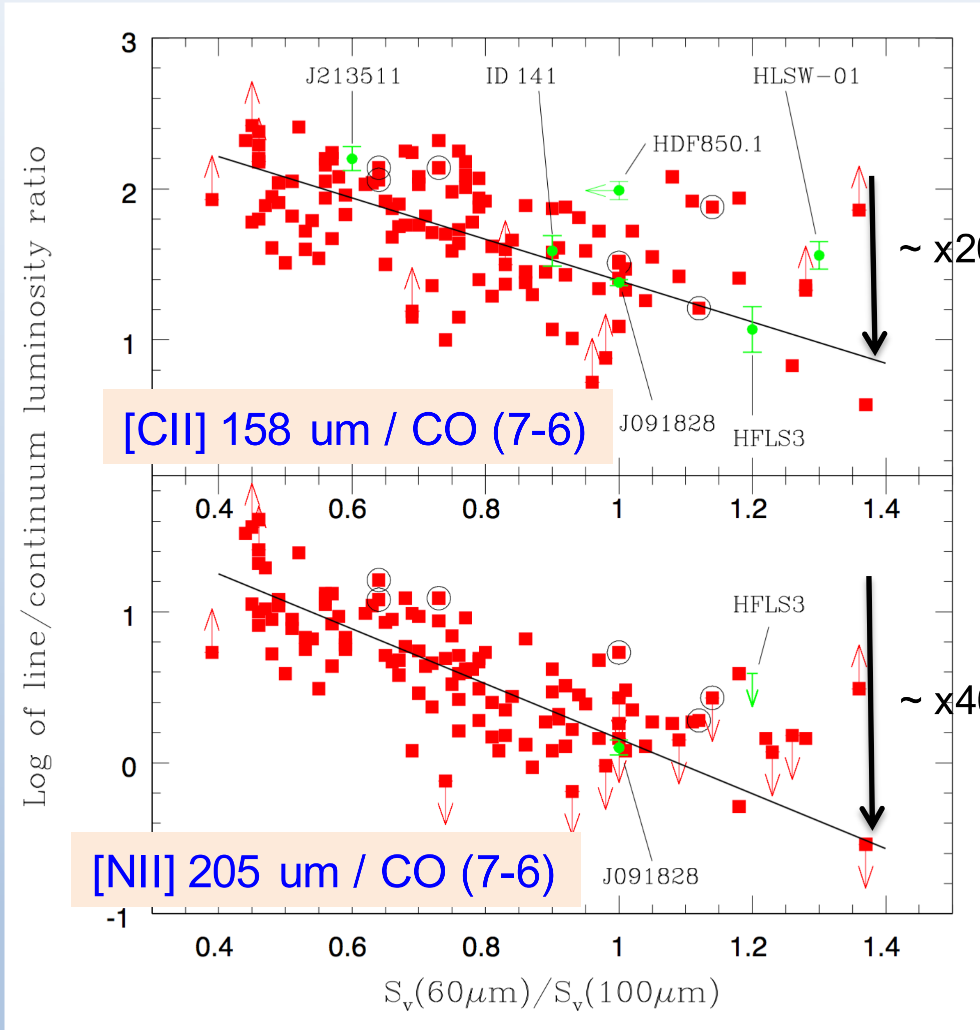
CO (7-6) as SFR Tracer: Local vs. high z

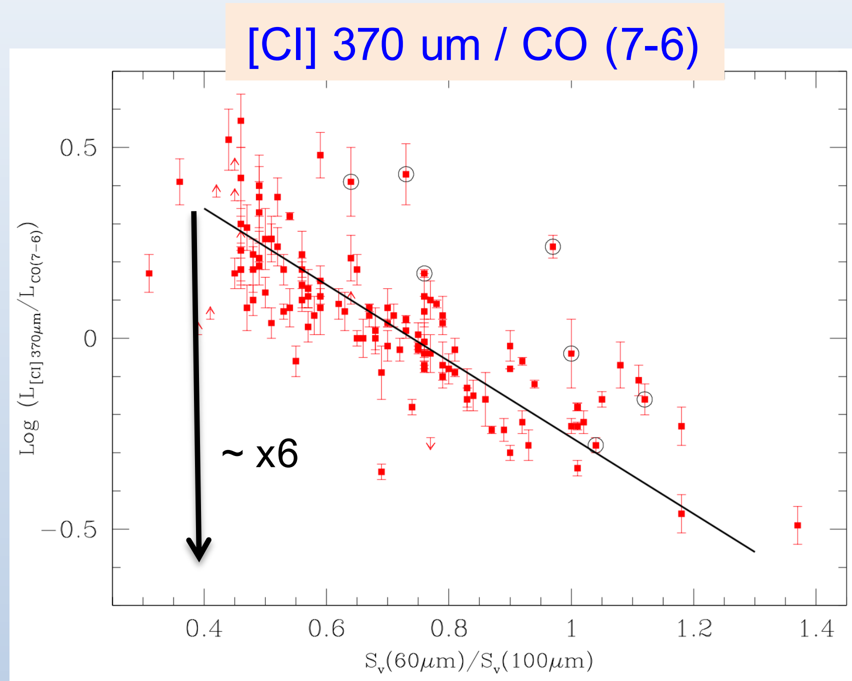


SMGs and QSO (shaded histogram) at z > 2 with CO (7-6) measurements in the literature prior to 2015 (Lu+2015)

Wider histogram likely due to less accurate L_{FIR} values in the literature

In Contrast, Most Atomic/ionic Gas Cooling Lines Suffer "Energy Deficiency"





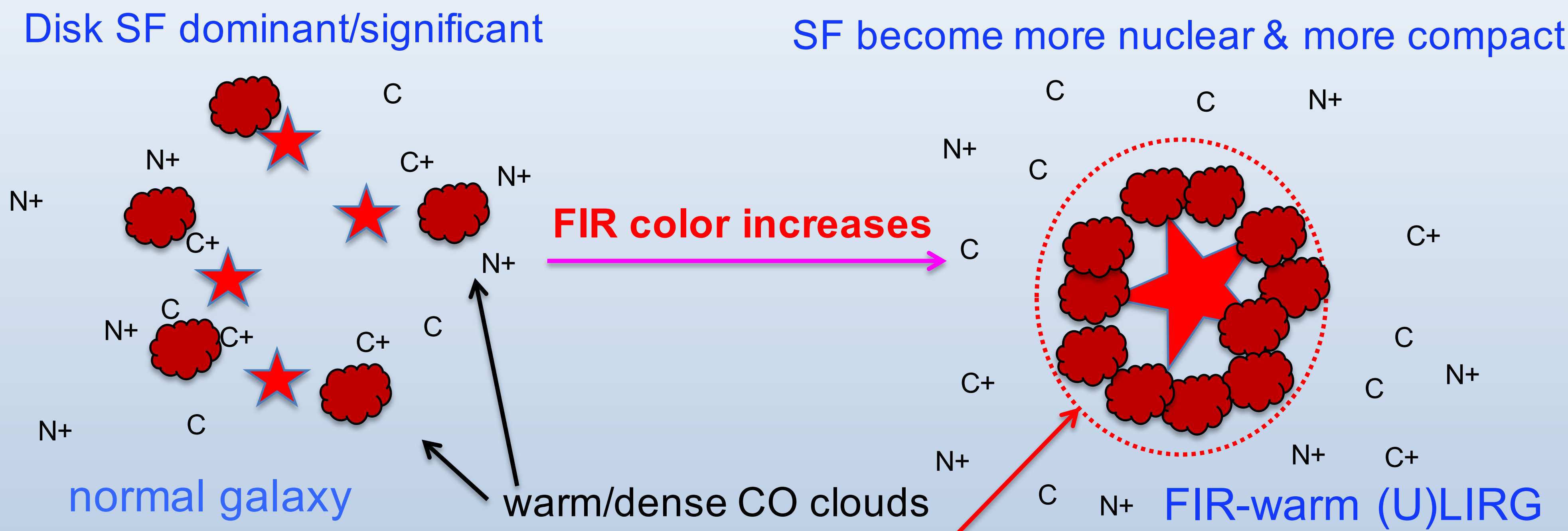
The dominant AGNs (circled) here have somewhat higher line luminosity ratios on average, particularly for [CI] 370um,

but the AGN sample is still small.

Red: local LIRGs;
Green: available high-z galaxies

(see Lu et al. 2015, 2017a)

Cartoon Model: Normal Galaxies to ULIRGs



- Highly obscured & high gas density nuclear SF, best probed by L_{IR}
- A gas cooling line is under-represented here if it has a low n_{crit} or/and if it is associated with photon gas heating (because dust is very effective in UV photon absorption ➔ L_{IR}),
  i.e., $L_{[NII]\ 205um}$ / L_{IR} , $L_{[CII]\ 158um}$ / L_{IR}, …., all drop as the FIR color increases
- A mid-J CO line, e.g., CO (6-5) or CO (7-6), competes well against L_{IR}, due to its high n_{crit} and being associated with shock gas heating (thus not impacted by the dust presence),
  therefore, $L_{CO(6-5)}$ / L_{IR} or $L_{CO(7-6)}$ / L_{IR} remains constant as the FIR color increases

A Pilot ALMA Spectral Line Snapshot Survey of SMGs and QSOs at z > 4

ULIRGs:

- Observing, in CO (7-6), [CI] 370 um, and/or [NII] 205 um, all 8 galaxies between $4 < z < 5$, $\delta < -10^{o}$, and with a prior [CII] 158 μm detection (see Carilli & Walter 2013). All are ULIRGs ($L_{IR} > 10^{12}\ L_{\odot}$)
- 1" beam, ~100 km/s resolution
  - Targeting mainly line fluxes

L* class galaxies (LIRGs): Also observing in [NII], 4 galaxies (with $L_{IR} \sim 10^{11}\ L_{\odot}$) at z ~ 5.5 with prior [CII] detections in Capak+2015

We hope to infer for each target:

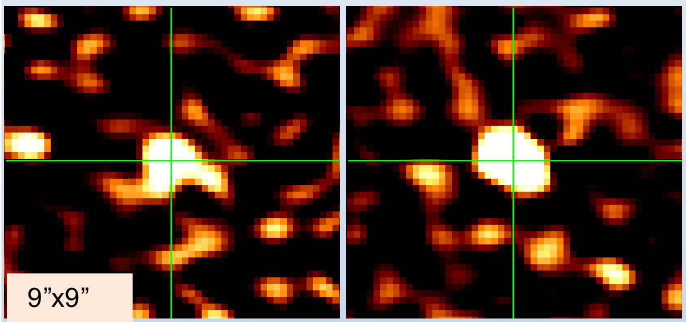
Parameter	Uncertainty*	Estimator	Reference
SFR	~30%	CO(7-6)	Lu+14,15
M_{H2}	~ x2	S_{ν} (372μm) (or [CI] 370um)	Scoville+16 Jiao+17
SFE	~ x2	SFR/M_{H2}	N/A
**			
T_{dust} (or FIR color)	~ 2 K	e.g., [NII]/CO(7-6)	Lu+15
Σ_{SFR} (SF surf. density)	~ x4	T_{dust} or FIR color	Liu+15; Lutz+16
SF size	~ x2	$(SFR/\ \Sigma_{SFR})^{1/2}$	N/A

Bonus: kinematic/dynamic information if enough spectral/spatial resolution is acquired

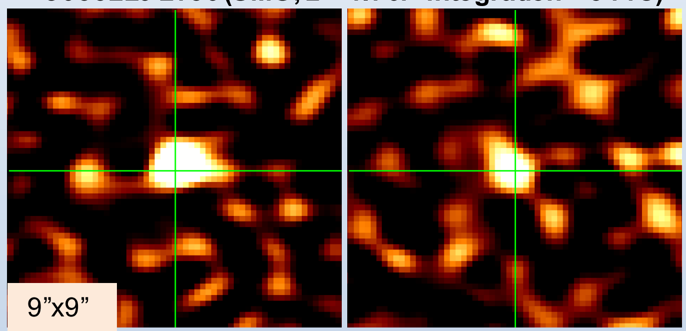
CO(7-6) Imaging Examples: Continuum at 372 μm and Line

On-target integration time of 5 to 15 min should be adequate (S/N > 10)

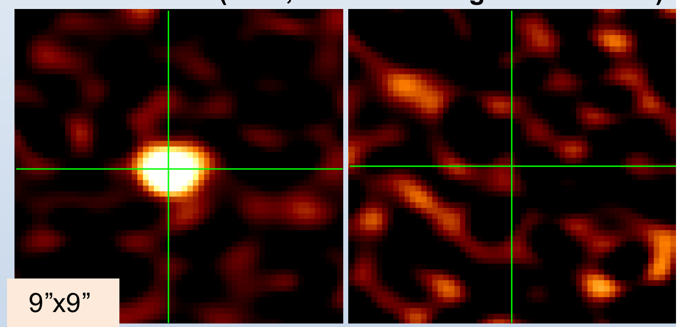
BRI 0952-0115 (QSO; z = 4.43: integration = 302 s)



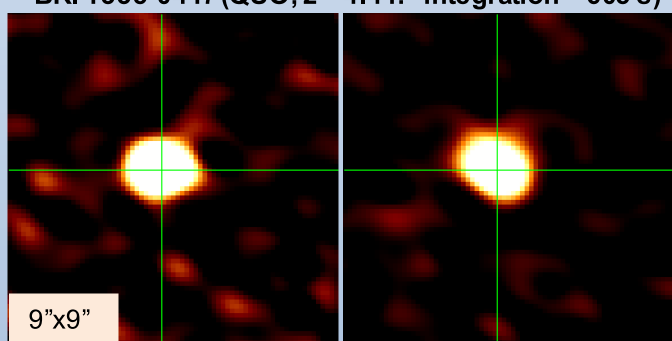
J033229-2756 (SMG; z = 4.76: integration = 544 s)



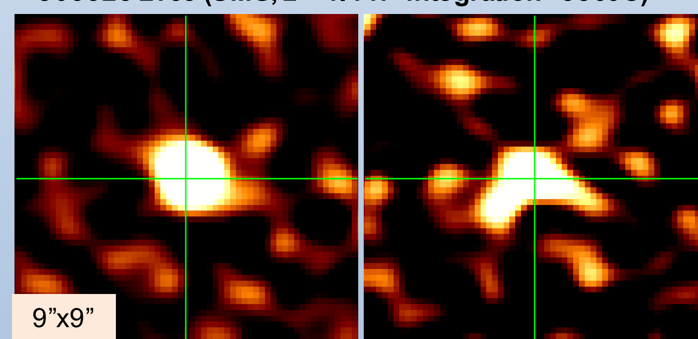
J03324-2800 (SMG; z = 4.42: integration= 1875 s)



BRI 1335-0417 (QSO; z = 4.41: integration = 605 s)



J03325-2735 (SMG; z = 4.44: integration= 5866 s)



Continuum

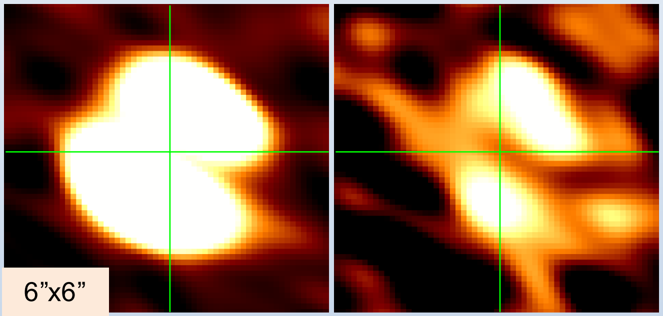
CO(7-6) 100 km/s channel at line frequency

CO(7-6) undetected because the published redshift is incorrect

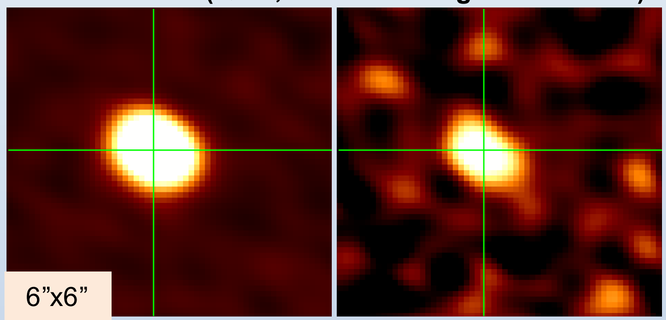
[NII] 205 μm Imaging examples: Continuum and Line

On-target integration time of 10 to 20 min should be adequate (S/N > 10)

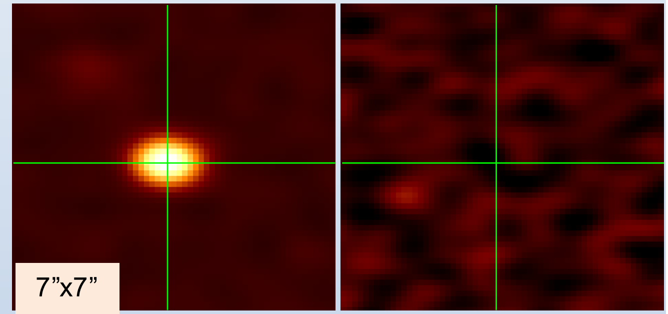
ID 141 **(SMG; z = 4.24: integration = 302 s)**



BRI 1335-0417 (QSO; z = 4.41: integration = 302 s)

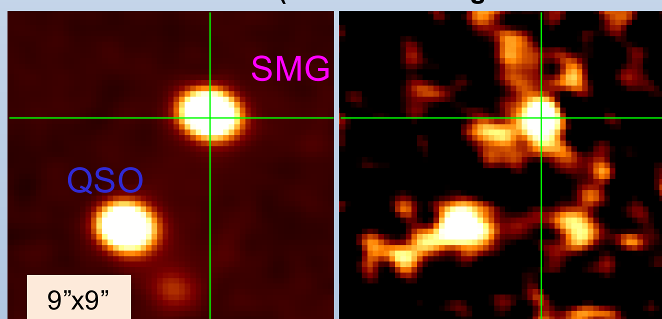


J03324-2800 (SMG; z = 4.42: integration = 3084 s)

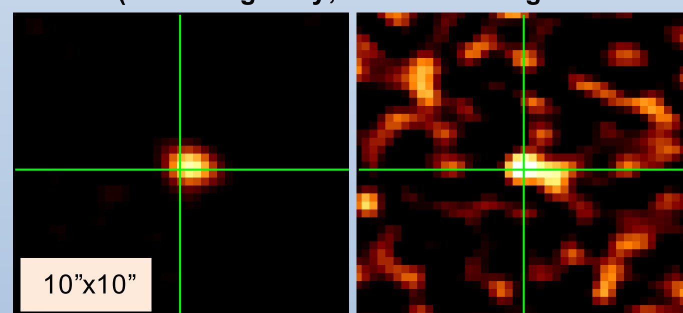


(Cheng+2017)

BRI 1202-0725 **(z = 4.24: integration = 2419 s)**



HZ 10 (L*-class galaxy; z = 5.66: integration= 1966 s)



Continuum

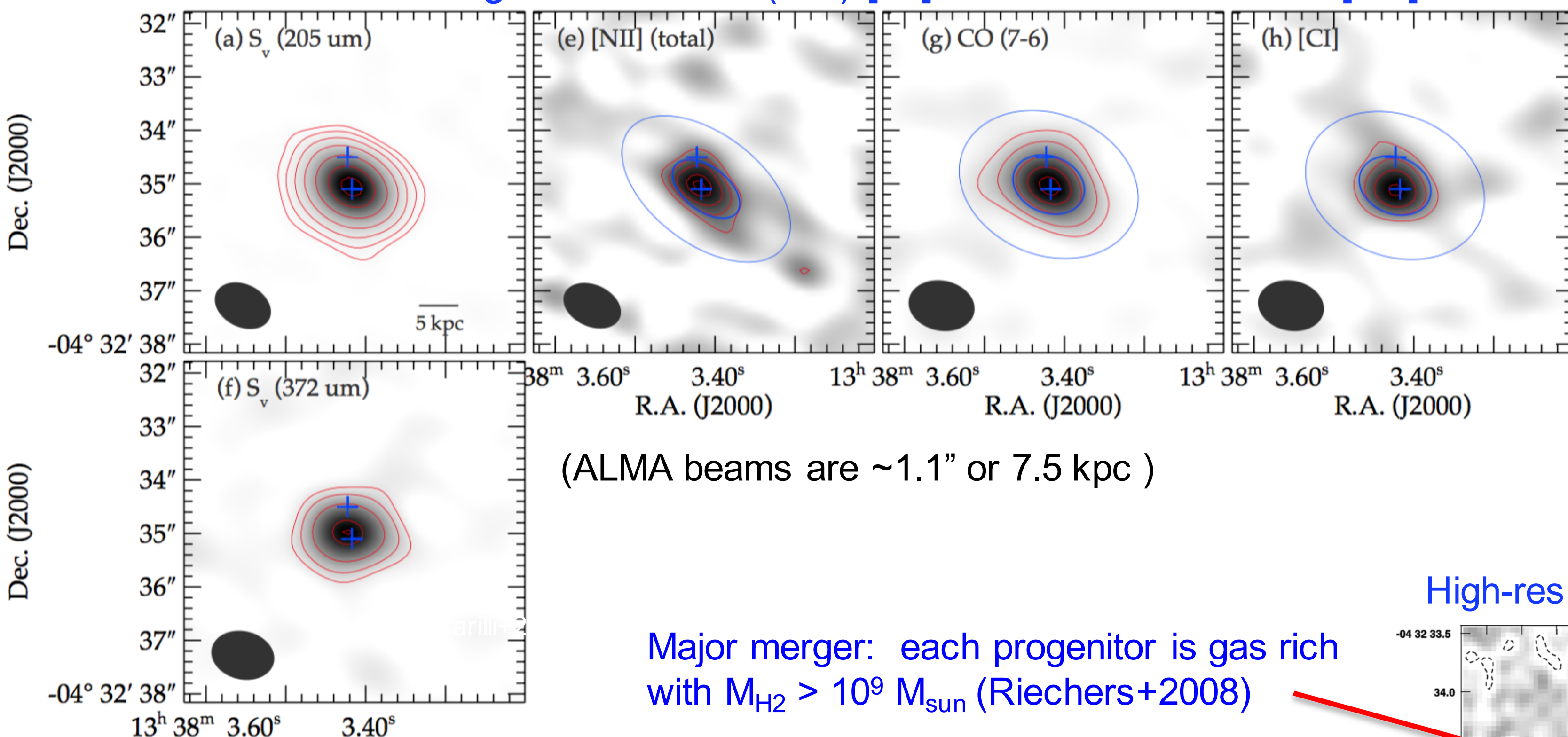
[NII] 100 km/s channel at line frequency

(see Lu+2017b)

[NII] 205 um undetected because the published redshift is incorrect

BRI 1335-0417, a QSO and Merger at $z = 4.4$

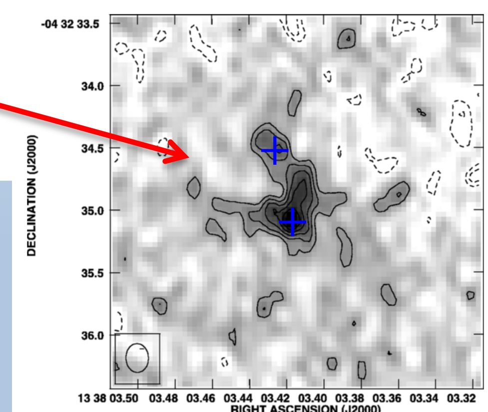
ALMA: 10 min integration on CO (7-6)/[CI] 370 um + 5 min on [NII] 205 um



(ALMA beams are ~1.1" or 7.5 kpc)

Major merger: each progenitor is gas rich with $M_{H2} > 10^9$ M_{sun} (Riechers+2008)

High-res VLA: CO (2-1)

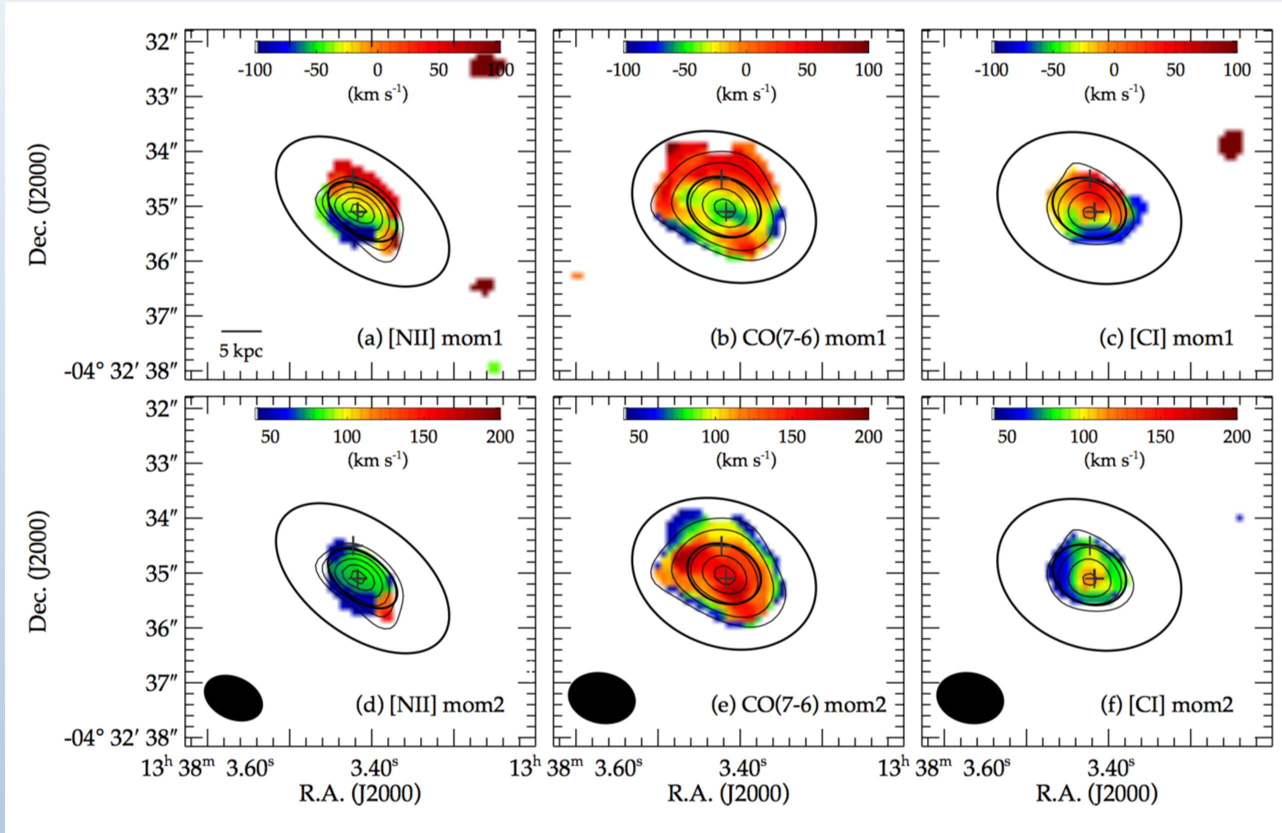


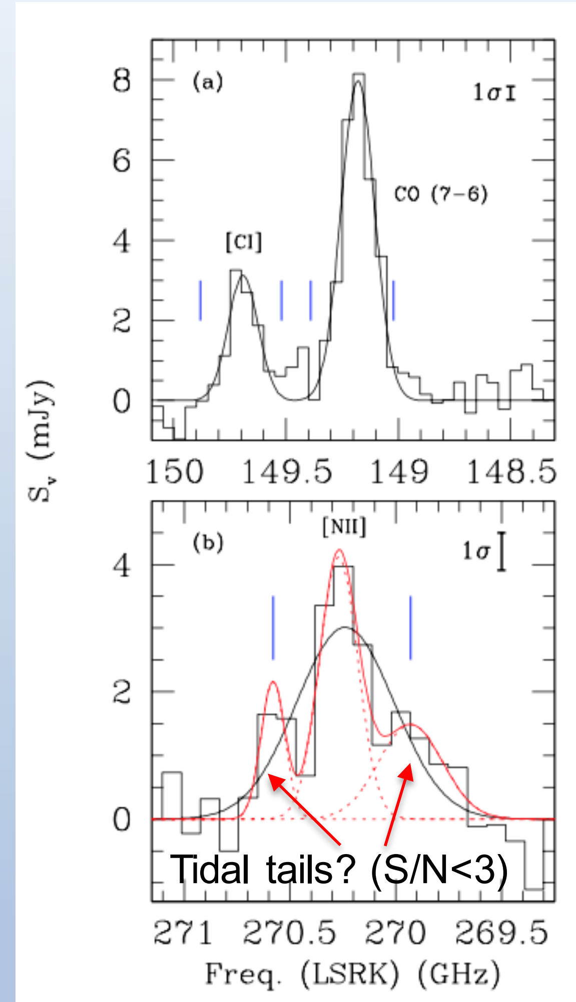
Measured sizes (after beam de-convolution) vary systematically:

- Dust continuum and CO (7-6) (unresolved to barely resolved)
- [CI] 370 um is marginally resolved: d_{deconv}~ 5 kpc
- [NII] 205 um is well resolved: d_{deconv}~ 9 kpc

(Lu et al, in prep)

BRI 1335-0417: Line Moments and Profile



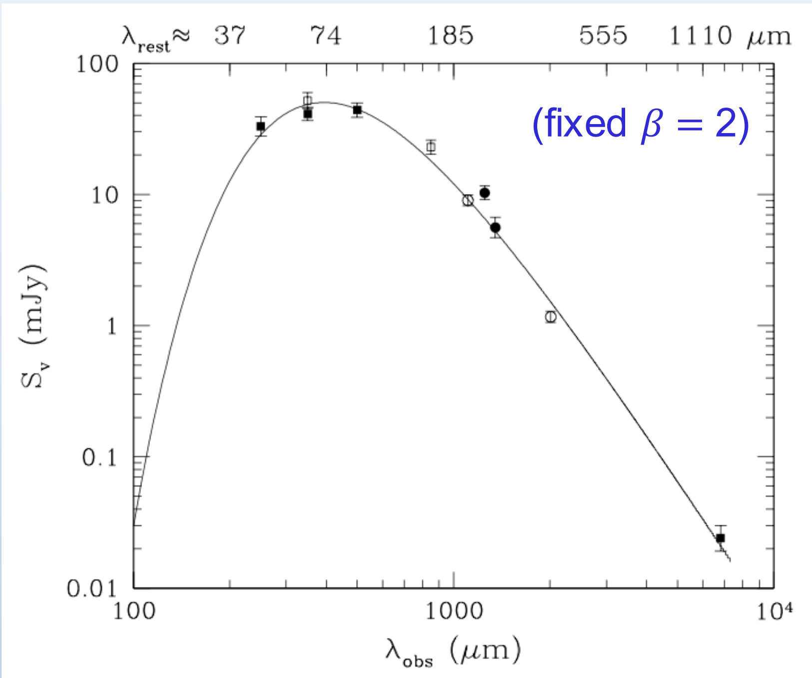


Between three lines:

- Similar velocity fields (-100 to +100 km/s), but
- Significantly larger velocity dispersion for CO (7-6) (up to 200 km/s) than for [CI] or [NII] (only up to 80 to 100 km/s), due to the merger?

(Lu et al, in prep)

BRI 1335-0417, a QSO/Merger at z = 4.4



SED fit: T_{dust} = 41.5 K or C(60/100) ~ 1.1

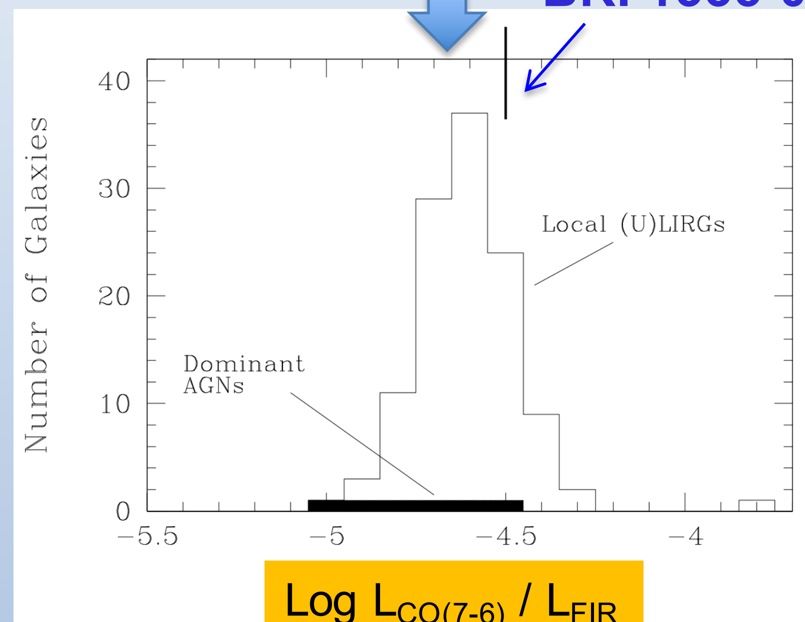
Line luminosity ratio (1)	Value (2)	$C(60/100)^a$ (3)	Ref[b] (4)
log ([N II]$_{core}$/CO (7−6))	$-0.21(\pm0.06)^c$	1.20 (±0.15)	(1)
log ([N II]$_{total}$/CO (7−6))	$+0.06(\pm0.06)^c$	1.06 (±0.15)	(1)
log ([C II]/CO (7−6))	$+1.30(\pm0.09)^c$	1.04 (±0.15)	(1)
log ([C I]/CO (7−6))	$-0.47(\pm0.04)^d$	1.20 (±0.11)	(2)
CO (7−6)/CO (5−4)[e]	$+1.30(\pm0.15)^c$	>1.0	(2)

Line ratios ➔ C(60/100) = 1.1±0.1

L_{FIR} (QSO) = 2.0 (±0.1) x 10^{13} $L_\odot$

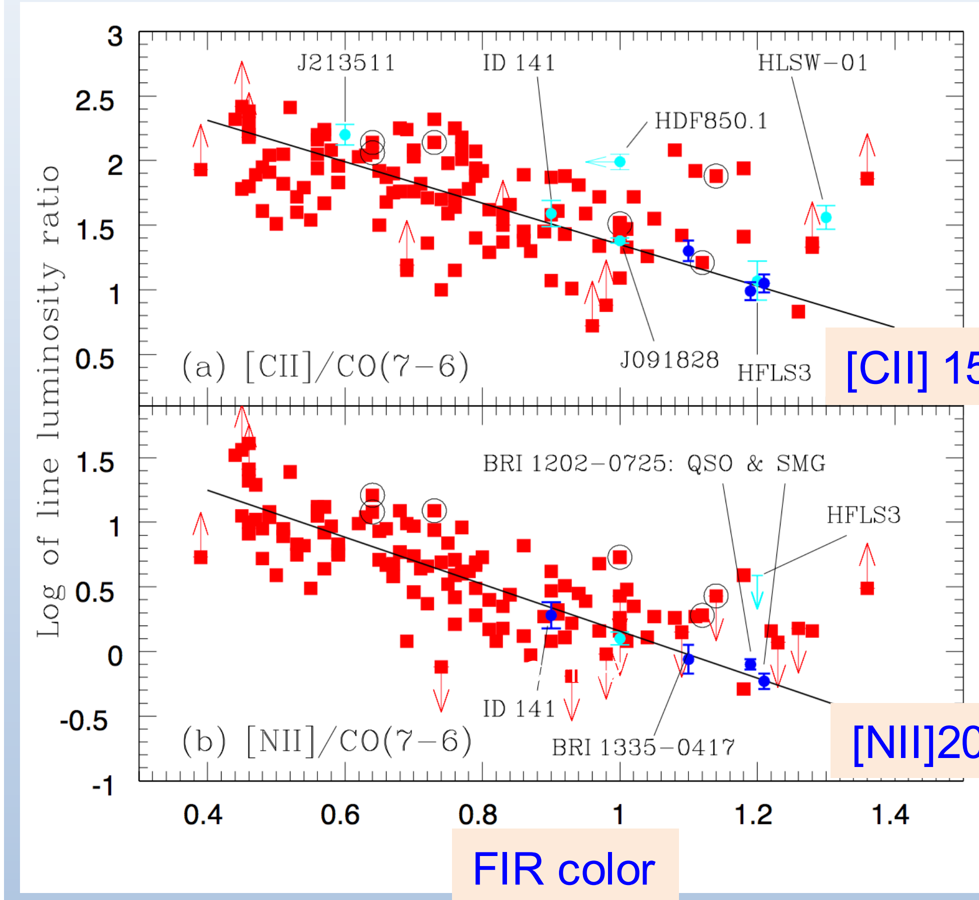
log $L_{CO(7\text{-}6)}$ / L_{FIR} ≈ −4.50 ±0.05

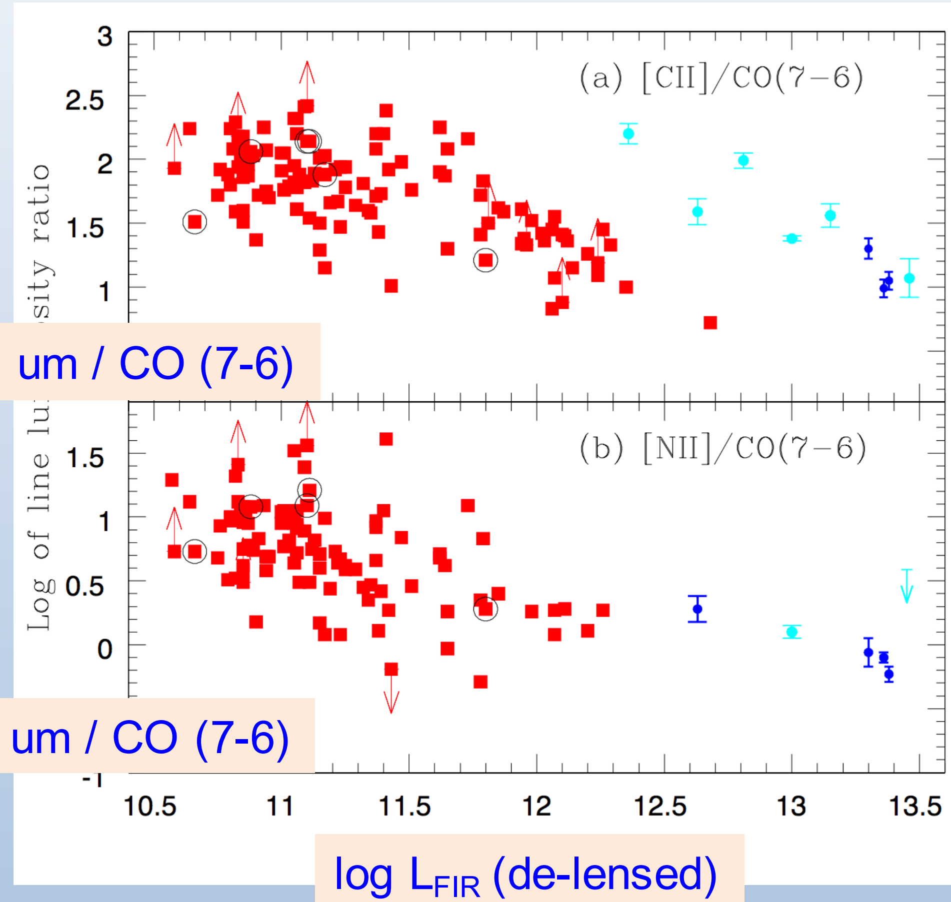
BRI 1335-0417



- SFR ~ 5.1(1±30%) × 10^3 M_{sun} yr^{-1}
- M_{gas} ~ 5 x 10^{11} M_{sun}
- SF region diameter ~ 1.7 kpc
- SF surface density ~ 1 x 10^3 M_{sun} yr^{-1} kpc^{-2}

Star Formation: Local vs. High Redshifts





- Red: local LIRGs
- Cyan: high-z LIRGs from the literature
- Blue: some high-z LIRGs from our own ALMA observations

➔ High-z ULIRGs: a larger SF region rather than a higher SF surface density

Summary

- Base on *Herschel* observations, the flux of a mid-J CO line, such as CO (7-6), is a robust and accurate tracer of SFR for luminous galaxies, where
  - "robustness": largely free from AGN contamination, independent of whether the SF is dominated by disk or nuclear SF
  - "accuracy": ~30% accuracy
- In contrast, many atomic/ionic gas cooling lines, e.g., [CII] 158 um and [NII] 205 um, are poor SF tracers of the SFR, their significant anti-correlation with SFR as the FIR color (or T_{dust}) of a galaxy increases can be used to infer T_{dust} (or SFR surface density)
- A dual line snapshot strategy is proposed for and experimented with ALMA, involving the CO (7-6) line, plus any one of the following: [NII] 205um, [CII] 158 um and [CI] 370 um
- Our analysis shows that the increased SFR in the brightest LIRGs at z > 4 is primarily due to a larger star forming region rather than a higher SF surface density

END