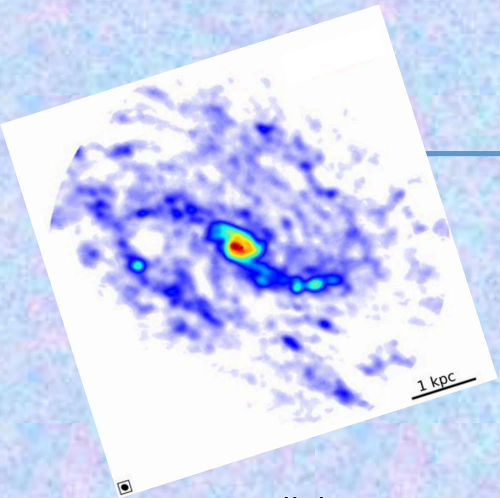
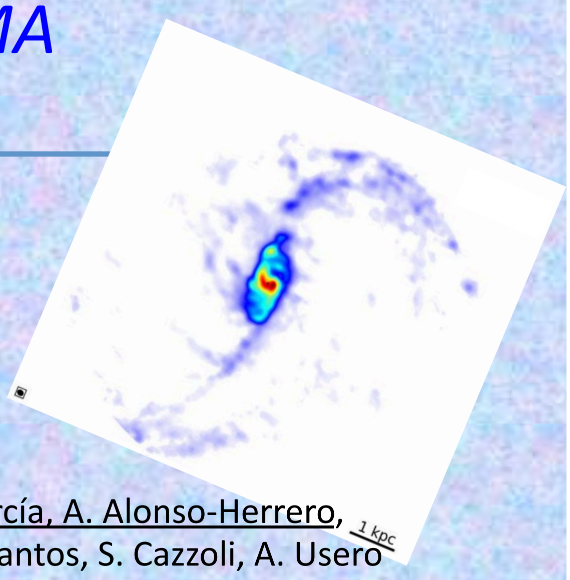
Local Luminous InfraRed Galaxies as the most compact galaxies among low- and high-z system observed at sub-kpc scale with ALMA





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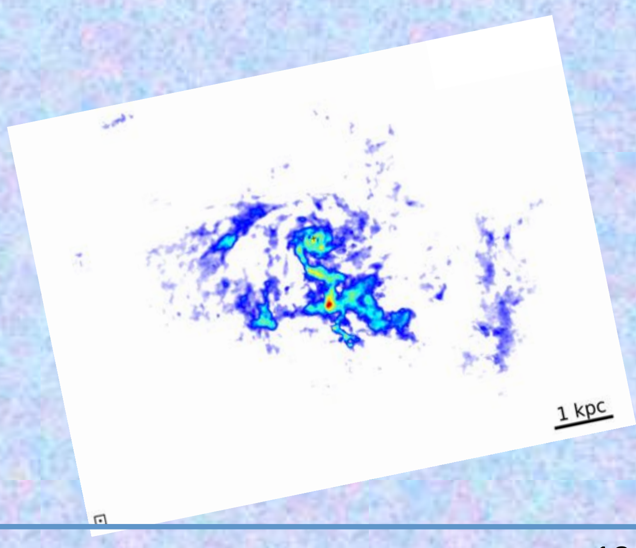


EXCELENCIA MARÍA DE MAEZTU

talento cm Programa de atracción de talento investigador Comunidad de Madrid

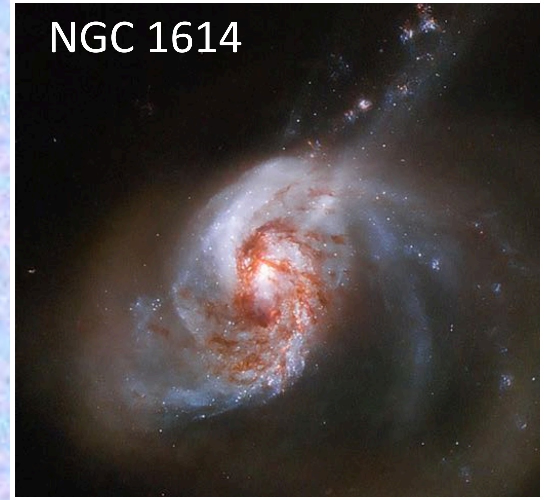
18-20 May 2022, XIII ESTALLIDOS WORKSHOP

(Ultra) Luminous Infrared Galaxies

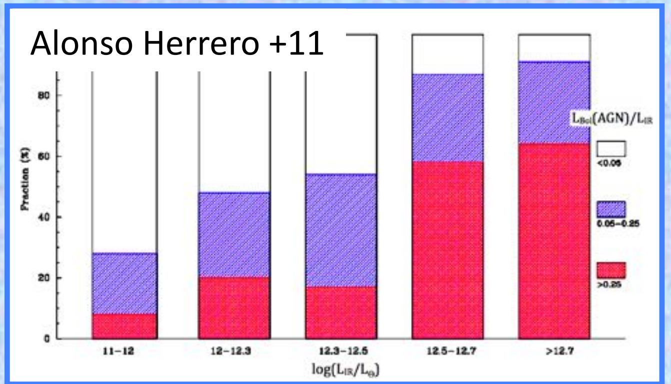
LIRG: $10^{11} \leq L_{IR} < 10^{12}\ L_{\odot}$

ULIRG: $10^{12} \leq L_{IR} < 10^{13}\ L_{\odot}$

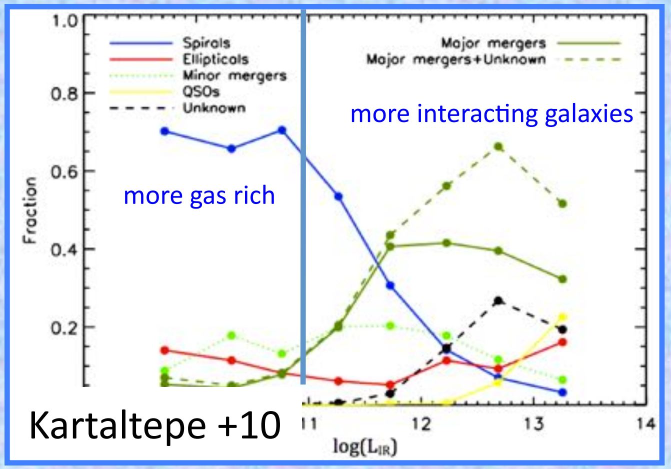
- host the most extreme SF events in the present universe
- IR emission mainly powered by Star formation and/or AGN



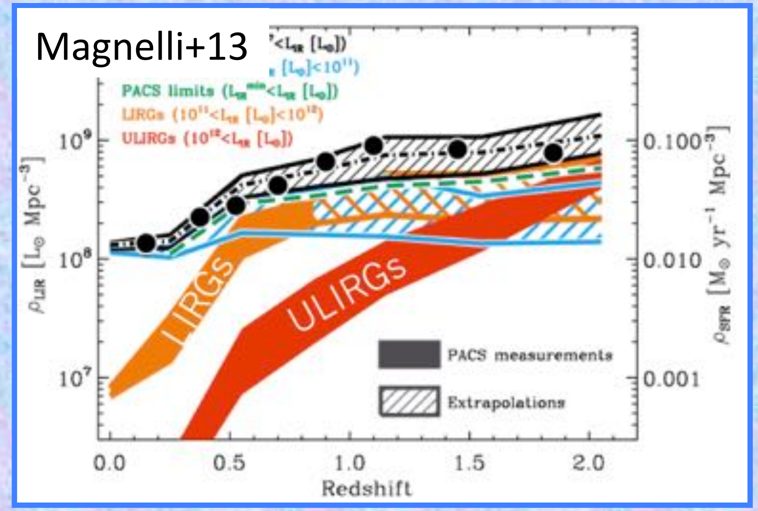
✓ AGN contribution increases with L_{IR}



✓ More Interacting galaxies at high L_{IR}

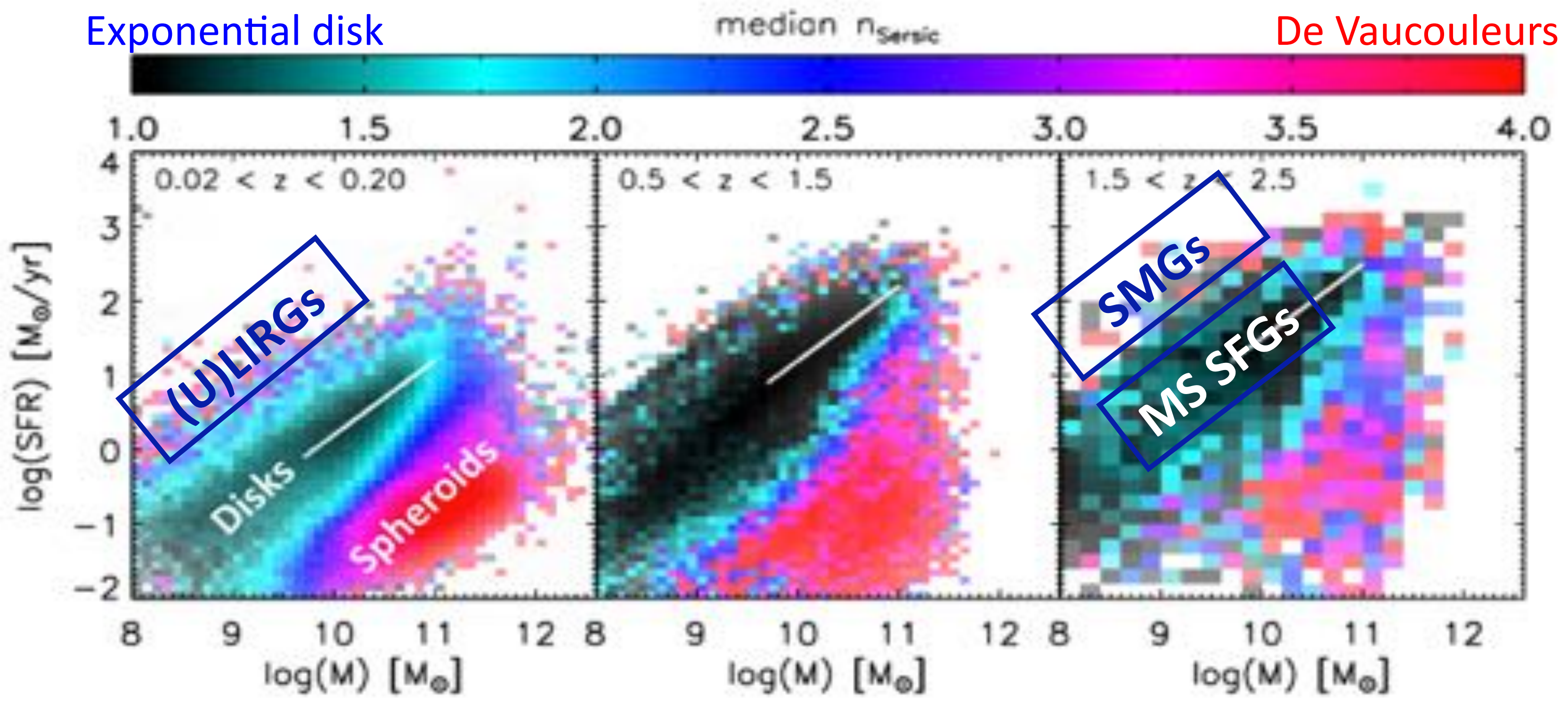


✓ Relevant contributors to the whole past SF z > 1 but they are rare locally



(U)LIRGs: Clues about galaxy evolution

Stellar mass – SFR relation: the *Main Sequence*



Wuyts +11

Local (U)LIRGs cover similar SFR than high-z MS SFGs

- To clarify the interpretation of high-z data using high S/N & high spatial resolution
- To constrain different evolutionary scenarios

The project:

New CO(2-1) observations of a representative sample of local LIRGs at high spatial resolution (<100 pc) from ALMA to provide detailed measurements of their molecular size

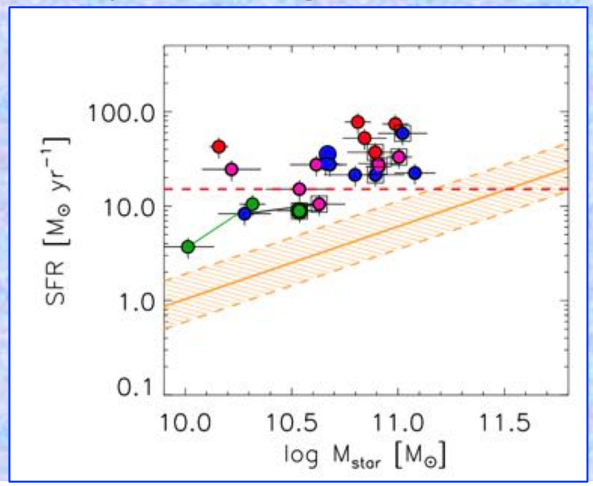
Main goals:

- ✧ to test, for the first time, the relation among the spatial extent (R_{eff}) of the different tracers (*molecular, stellar and ionized gas*) in a sample of local LIRGs;
- ✧ to compare their sizes with those observed *locally in Spirals, ETGs and ULIRGs* as well as in *high-z* systems (*MS SFGs and SMGs*)

The LIRG sample

- Representative sample of 24 individual local (z< 0.02) LIRGs observed with ALMA
- $L_{IR} = 10^{11}$-$10^{11.7}$ $L_{\odot}$ (covers a uniform distribution)
- Different ionization types (most of them HII ; a few Seyfert, LINERs) → ~1/3 show the presence of AGN, which does not dominate the galaxy emission
- Different dynamical phases (morphological types: isolated galaxies “0”, pre-colaescence phase “1” and mergers “2”, classified using *Spitzer*/IRAC and *HST* images) + kinematic information from Hα (Arribas+12, Bellocchi +13, +16) and CO maps (“0RD”, “0PD”, “1” and “2”)
- 2/3 of the sample show the presence of interaction or past merger activity in their morphology and/or kinematics
- LIRGs lie <u>above</u> Main-Sequence (MS) with

  $M_{star} = 10^{10}$-10^{11} $M_{\odot}$ and SFR~30 $M_{\odot}$/yr

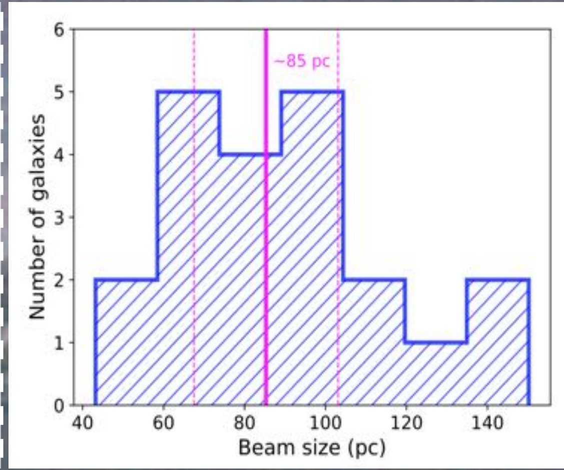


The observations:

- ALMA (band 6)

CO(2-1) and 1.3 mm (247 GHz) continuum:

- ✓ synthetized (FWHM) beam =0.2”-0.4” (~90 pc) → similar to GMCs
- ✓ Total integration time per source 20-30 min
- ✓ FOV = 5-8 kpc^2 up to 10-17 kpc^2 (mosaic, NGC3256)
- ✓ Sensitivity (1σ) → CO(2-1) 0.4-1.2 mJy/beam
  247 GHz 0.02-0.1 mJy/beam



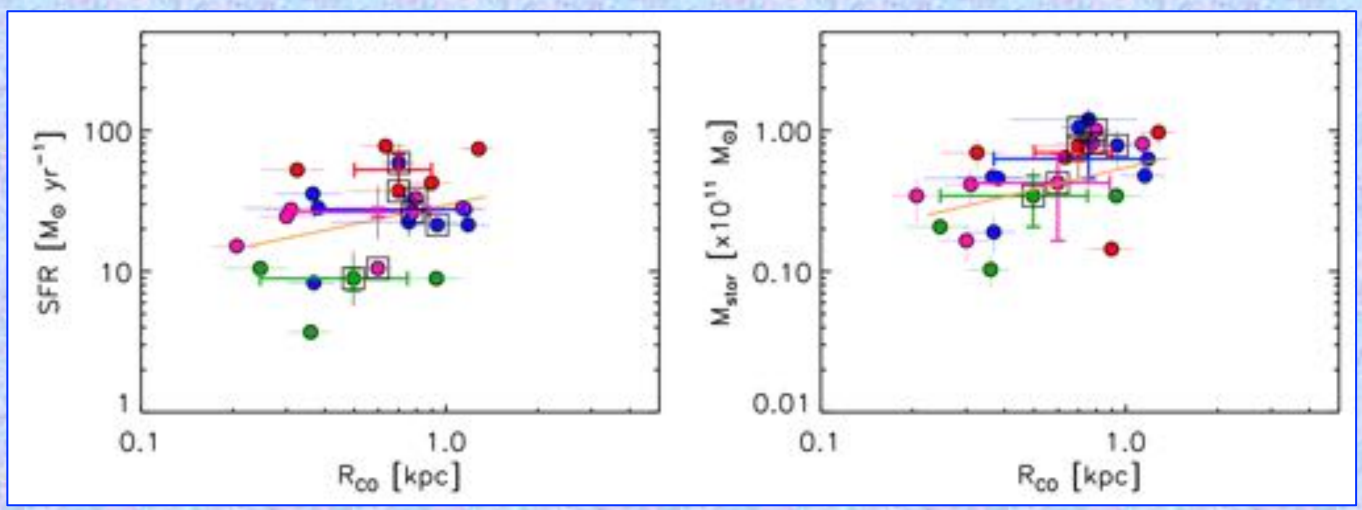
Ancillary data & method

- VIMOS/VLT: ionized (Hα) size (Arribas et al. 2012)
- 2MASS (K band): stellar size (Bellocchi et al. 2013)

→ R_{eff} estimation using the Curve-of-growth (CoG) method → R_{circ} =√(A/2)/π

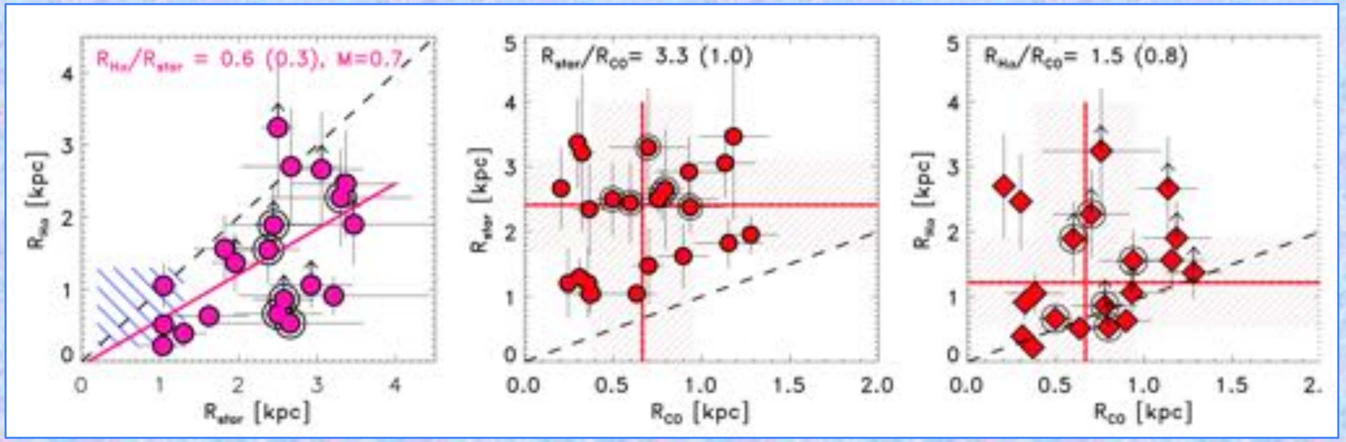
Results in local LIRGs:

SFR-R_{CO} & M_{star}- R_{CO}



Slight tendency for the galaxies with higher SFR and stellar mass to have larger R_{CO} (R_{CO} < 1 kpc)

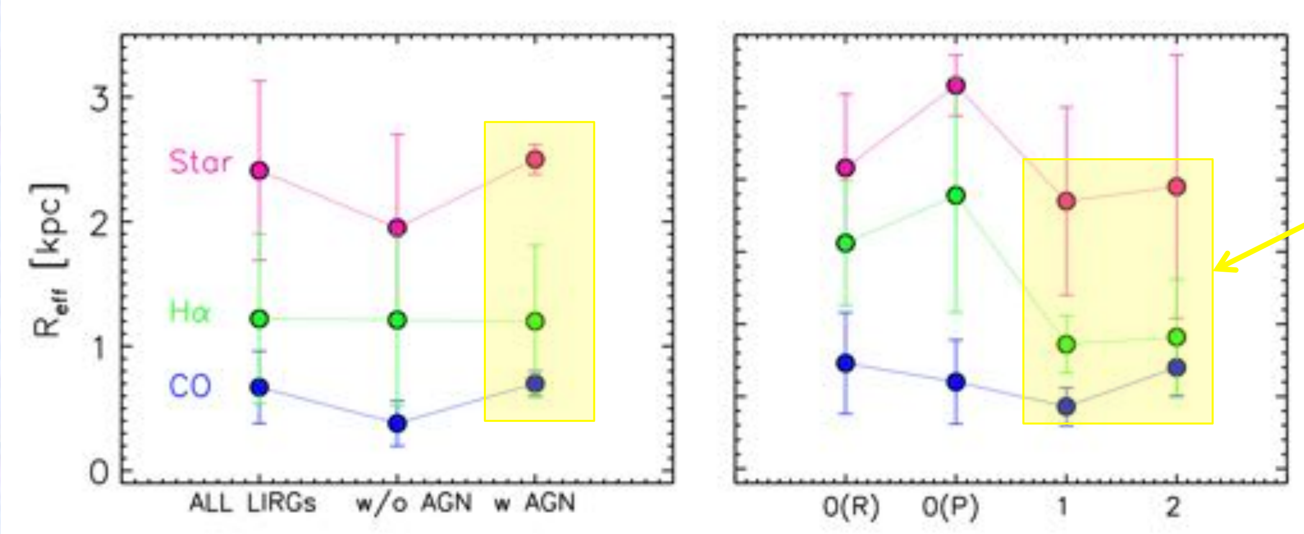
R_{CO} *versus* R_{ion} and R_{star}



$R_{ion} \approx R_{CO} \times 2$

$R_{star} \approx R_{CO} \times 3$

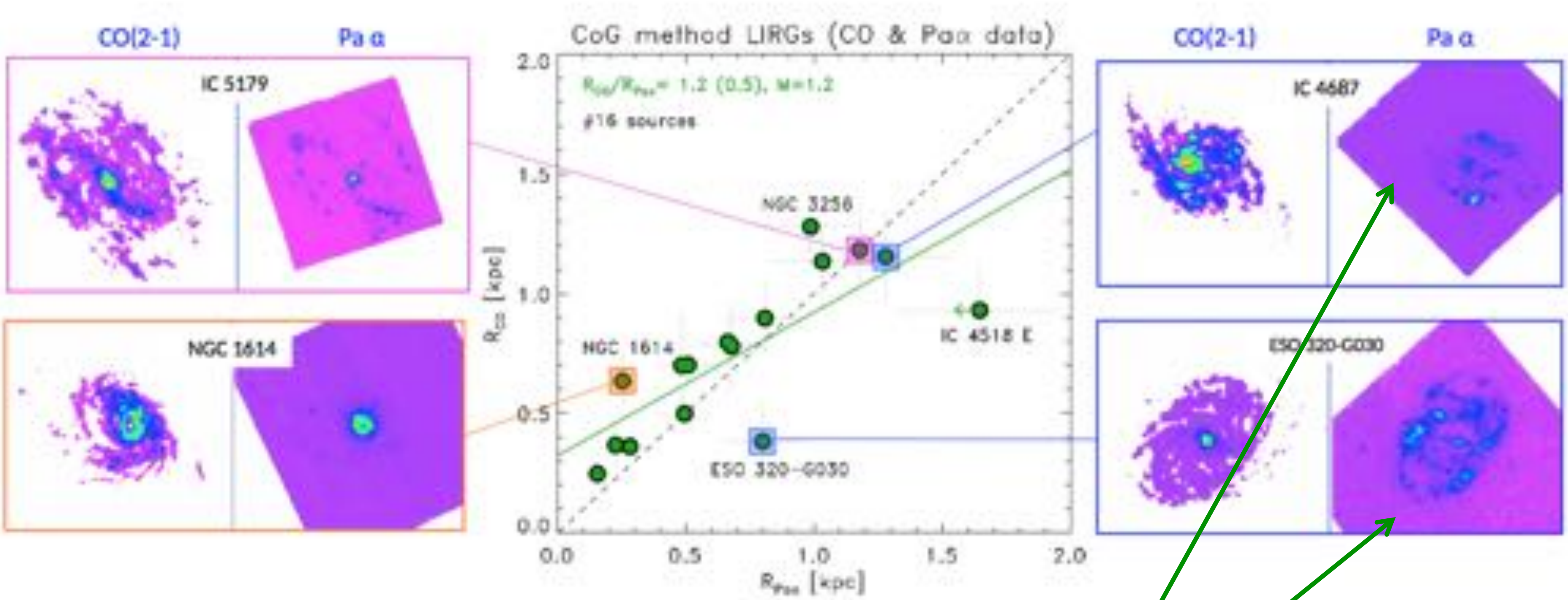
The impact of AGN on the molecular gas



Sample (1)	# (2)	R_{CO} [kpc] (3)	R_{cont} [kpc] (4)	R_{star} [kpc] (5)	$R_{H\alpha}$ [kpc] (6)
All LIRGs	24	0.66 ± 0.33 (0.67 ± 0.29)	0.37 ± 0.31 (0.29)	2.21 ± 0.81 (2.41 ± 0.72)	1.42 ± 0.89 (1.22 ± 0.68)
LIRGs w/o AGN	17	0.64 ± 0.38 (0.38 ± 0.18)	0.37 ± 0.34 (0.24)	2.12 ± 0.88 (1.95 ± 0.75)	1.48 ± 0.97 (1.21 ± 0.69)
LIRGs w AGN	7	0.72 ± 0.14 (0.70 ± 0.10)	0.38 ± 0.20 (0.40)	2.44 ± 0.62 (2.50 ± 0.12)	1.29 ± 0.71 (1.20 ± 0.60)
0 RD	8	0.73 ± 0.34 (0.73 ± 0.35)	0.46 ± 0.40 (0.38)	2.00 ± 0.83 (2.08 ± 0.50)	1.59 ± 1.00 (1.56 ± 0.43)
0 PD	7	0.59 ± 0.34 (0.60 ± 0.29)	0.31 ± 0.23 (0.31)	2.58 ± 0.65 (2.65 ± 0.21)	1.64 ± 1.03 (1.89 ± 0.81)
1	4	0.51 ± 0.30 (0.43 ± 0.13)	0.34 ± 0.35 (0.18)	1.96 ± 0.89 (1.85 ± 0.65)	0.86 ± 0.28 (0.86 ± 0.20)
2	5	0.77 ± 0.35 (0.70 ± 0.20)	0.37 ± 0.26 (0.26)	2.22 ± 0.99 (1.95 ± 0.91)	1.14 ± 0.71 (0.91 ± 0.40)

→ LIRGs with AGN show larger (median) molecular radii by x2 wrt w/o AGN: maybe due to the presence of high surface brightness CO emission in extra-nuclear regions

The impact of extinction



High extinction A_V ~ 3 mag in the central regions in Paα maps

→ Tight correlation between the molecular and ionized gas: $R_{CO} \sim R_{Pa\alpha} = 0.75$ kpc

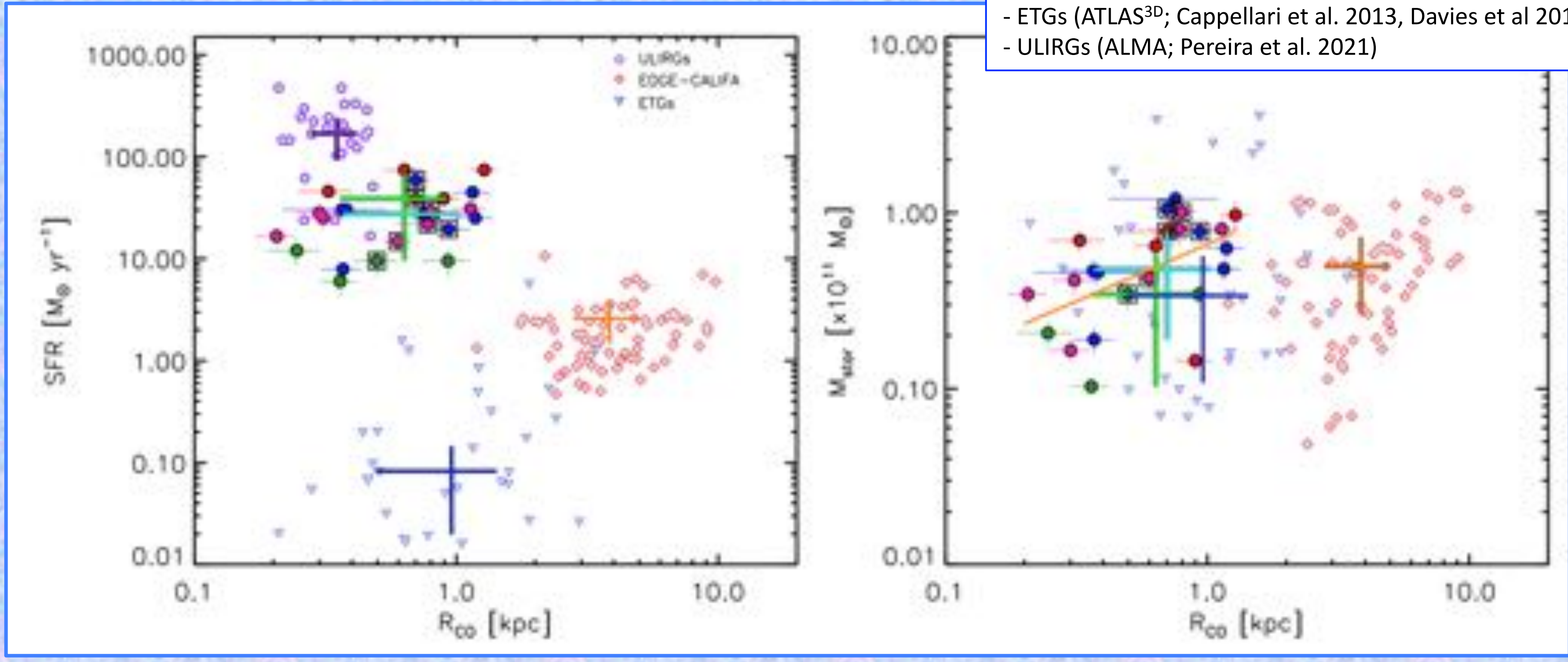
→ Larger Hα size than Paα tracer are derived as a result of the extinction

Comparison with @low-z and high-z systems

Sample (1)	z (2)	# (3)	R_{CO} [kpc] (4)	R_{cont} [kpc] (5)	R_{star} [kpc] (6)	$R_{H\alpha}$ [kpc] (7)	M_{star} [$\times10^{10}$] $M_\odot$ (8)	Ref. (9)
LIRG	≲0.02	24	0.66 ± 0.33 (0.67)	0.37 ± 0.31 (0.29)	2.21 ± 0.81 (2.41)	1.42 ± 0.89 (1.37)	5.6 ± 3.2 (4.8)	this work
E-S0	0.02	258 (49 [a])	1.15 ± 0.77 (1.01)	…	2.74 ± 1.98 (2.20)	…	7.3 ± 9.6 (3.8)	C13, D13, D14
Spiral	≲0.03	68	4.37 ± 1.97 (3.86)	…	…	…	7.6 ± 5.0 (7.1)	Bo17
MS SFG	<0.004	90	…	…	3.45 ± 1.41 (3.40)	–	2.9 ± 2.8 (2.3)	L21
ULIRG	<0.17	30 (7, 23 [b])	0.33 ± 0.09 (0.36)	0.12 ± 0.10 (0.11)	3.45 ± 1.79 (3.80)	2.02 ± 1.55 (1.58)	…	P21, A12, B13
SFG	1–1.7	82 (72 [c])	1.95 ± 1.23 (1.67)*	…	3.43 ± 1.49 (3.10)	…	7.9 ± 7.9 (5.7)	V20, Pu21
cSFG	2	45	…	…	1.26 ± 0.88 (1.00)	…	8.1 ± 5.5 (10.8)	Ba14
SFG	2	3	4.90 ± 1.31 (5.50)	4.83 ± 4.18 (3.90)	6.93 ± 1.76 (7.90)	…	20.0 ± 9.5 (19.0)	K20
SFG	2	11	…	1.5 ± 1.2 (1.2)	3.7 ± 1.5 (3.1)	…	15.6 ± 6.2 (11.7)	T17
SFG	2	38	…	…	3.82 ± 2.20 (3.20)	…	4.3 ± 6.1 (2.2)	FS18
SFG	2	4	…	4.63 ± 0.65 (4.80)	5.20 ± 0.62 (5.20)	3.43 ± 1.46 (3.90)	12.7 ± 13.3 (8.3)	Cheng20
SFG	0.7–2.7	280	…	…	3.39 ± 1.63 (3.14)	4.26 ± 2.74 (3.43)	…	W20
SMG	2	14	…	1.74 ± 0.51 (1.95)	5.03 ± 1.48 (4.75)	…	18.6 ± 16.0 (13.2)	L19
SMG	2	1	6.6 ± 0.9	1.2 ± 0.1	6.4 ± 0.5	6.6 ± 0.9	20.0	Chen17
SMG	2	(6) m	…	1.82 ± 0.31 (1.85)	…	3.80 ± 1.40 (3.95)	16.0	Chen20
cSFG	2.5	6	…	0.90 ± 0.30 (0.81)	1.8 ± 0.93 (1.57)	…	…	Ba16
SFG	2–2.5	6	…	…	…	4.18 ± 1.58 (3.85)	3.7 ± 2.5 (2.5)	H21
SMG	2.5	(4) m	3.8 ± 0.1	1.7 ± 0.1	4.0 ± 2.0	…	8.0	CR18
SMG	2.5	(16) m	…	1.8 ± 0.2	4.1 ± 0.8	…	8.0 ± 1.0	H16
QG	3–4	16	…	…	0.98 ± 0.86 (0.58)	…	8.2 ± 3.9 (7.6)	S15
SFG	3–4	14	…	…	2.79 ± 2.49 (2.09)	…	5.5 ± 2.0 (4.6)	S15
SMG	4–5	4	–	1.13 ± 0.18 (1.05)	…	…	…	G18
SFG	4–6	18 (7 [c])	…	…	0.98 ± 0.14 (0.94)	…	0.9 ± 0.5 (0.8)	F20, Fa20

Comparison with local Spirals, ETGs and ULIRGs

- Spirals (EDGE-CALIFA; Bolatto et al. 2017)
- ETGs (ATLAS^{3D}; Cappellari et al. 2013, Davies et al 2014)
- ULIRGs (ALMA; Pereira et al. 2021)



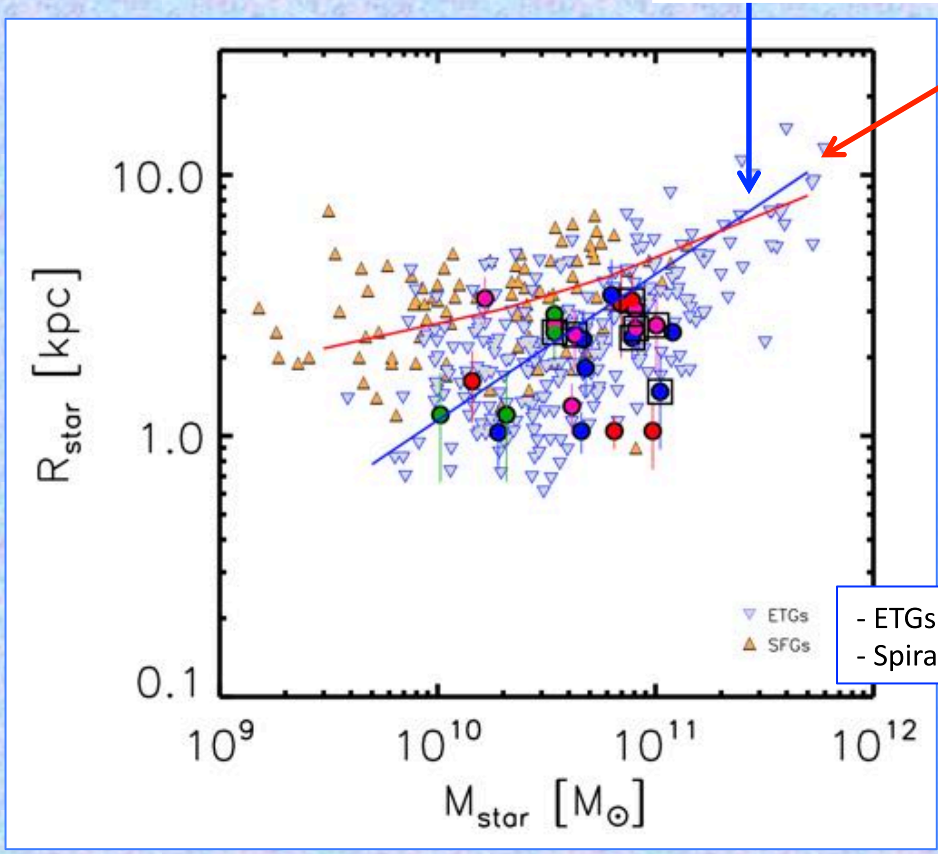
- LIRGs have x6 smaller R_{CO} than local Spirals: $R_{Spirals}$ ~ R_{LIRGs} x 6;
- LIRGs show similar molecular size than ETGs (≤ 1 kpc): R_{ETGs} ~ R_{LIRGs};
- ULIRGs are x2 more compact than local LIRGs: R_{LIRGs} ~ R_{ULIRGs} x2 ;

→ *interactions may have an important role in the compaction of the molecular size*

- LIRGs cover similar M_{star} than ETGs and Spirals (10^{10} - 10^{11} $M_{\odot}$), but forming stars at rates a factor of ≥ 10 above Spirals

M_{star}- R_{star} plane at low-z:

From Shen et al. 2003:
Mass-size relation for late-type galaxies and early-type galaxies at low-z.



- ETGs (Cappellari et al. 2013)
- Spirals (PHANGS-ALMA; Leroy et al 2021)

LIRGs share similar M_{star} and R_{star} with ETGs (~2.5 kpc), being more compact (x1.5) and more massive (x2) than local Spirals (MS SFGs; Leroy+2021)

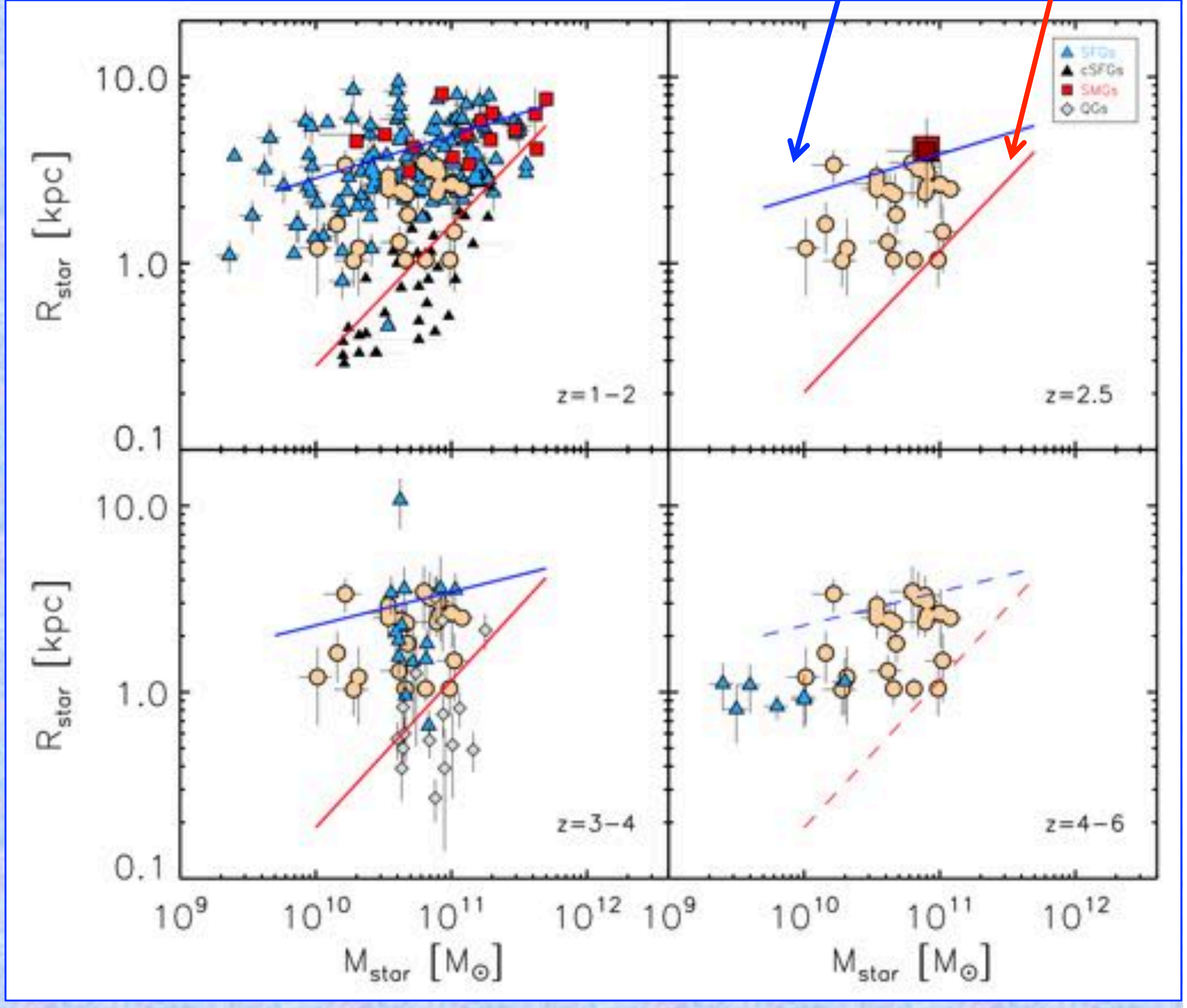
→ (U)LIRGs can transform gas-rich spirals into intermediate-stellar mass ETGs through merger events (Genzel+2001, Kawakatu+2006, Cappellari+2013a)

M_{star}- R_{star} plane at high-z:

From van der Wel et al. 2014: 3D-HST+CANDELS
Mass-size relation for late-type galaxies and
early-type galaxies at each corresponding z

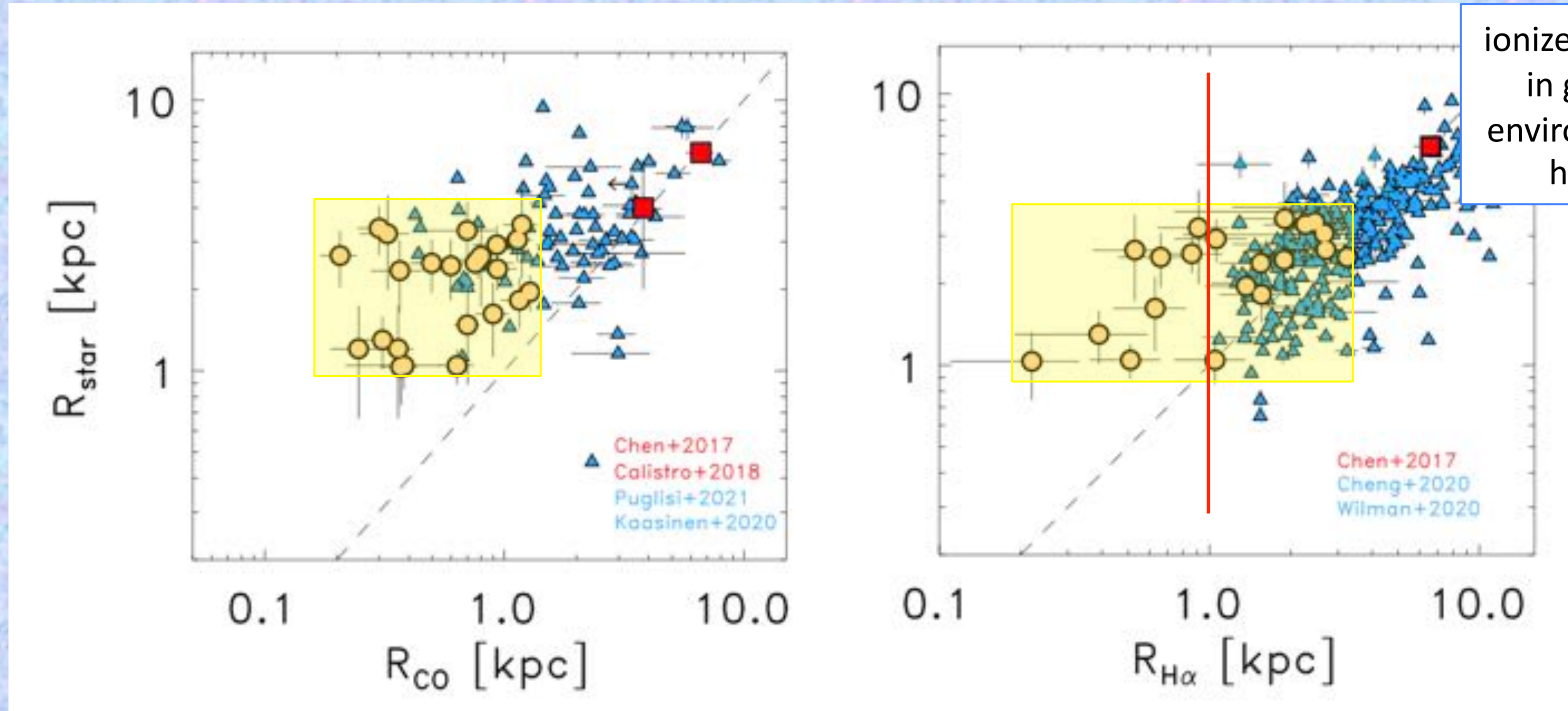
Stellar mass in high-z systems in the range 10^{10}-$2x10^{11}$ $M_{\odot}$ while their stellar host in high-z SFGs and SMGs:

i) compact host (<1 kpc)
ii) intermediate host (1-4 kpc)
iii) extended host (4-10 kpc)



- LIRGs share similar stellar mass and stellar size with MS SFGs at z~1-4;
- SMGs stellar hosts are x3 more massive than local LIRGs and more extended (x2);

Different tracers among local LIRGs and high-z systems



ionized nebulae in gas-rich environment at high-z?

- high-z SFGs tend to be close to the 1:1 relation between R_{star}- R_{CO};
- LIRGs appear as more compact than high-z SFGs in their molecular gas distribution (x2.6; x8 more compact than SMGs);

- $R_{star} \sim R_{ion}$ in high-z systems: half of the LIRGs show R_{ion} < 1 kpc, while high-z SFG show R_{ion} > 1 kpc

→ High-z systems form stars in regions distributed over the entire galaxy host, while in LIRGs it is concentrated in smaller central regions

Conclusions

Local LIRGs

- The molecular gas distribution in LIRGs is compact (R_{CO} ~ 0.7 kpc);
- their stellar host and ionized gas are larger (x3.5 and x2) than CO;

Comparison with local systems:

- LIRGs are indistinguishable from ETGs in the M_{star}-R_{star} plane: M_{star} (10^{10} - 10^{11} $M_{\odot}$), R_{star} (~2.5 kpc) and R_{CO} (~1 kpc);
- LIRGs show R_{star} more compact (x1.5) than local Spirals and x6 more compact R_{CO} than in local Spirals of similar M_{star}

→ good agreement with the evolutionary scenario in which LIRGs can transform Spirals into ETGs

Comparison with high-z systems using different tracers:

- LIRGs share similar stellar mass and size with MS SFGs at z~1-4;
- high-z SFGs tend to be close to the 1:1 relation between R_{star}- R_{CO} & R_{star}~ R_{ion} (but not LIRGs…)

→ Regions of current SF (traced by the ionized gas) and of potential SF (traced by molecular gas) are substantially smaller in LIRGs

https://arxiv.org/pdf/2204.02055.pdf Bellocchi et al. 2022 (A&A)