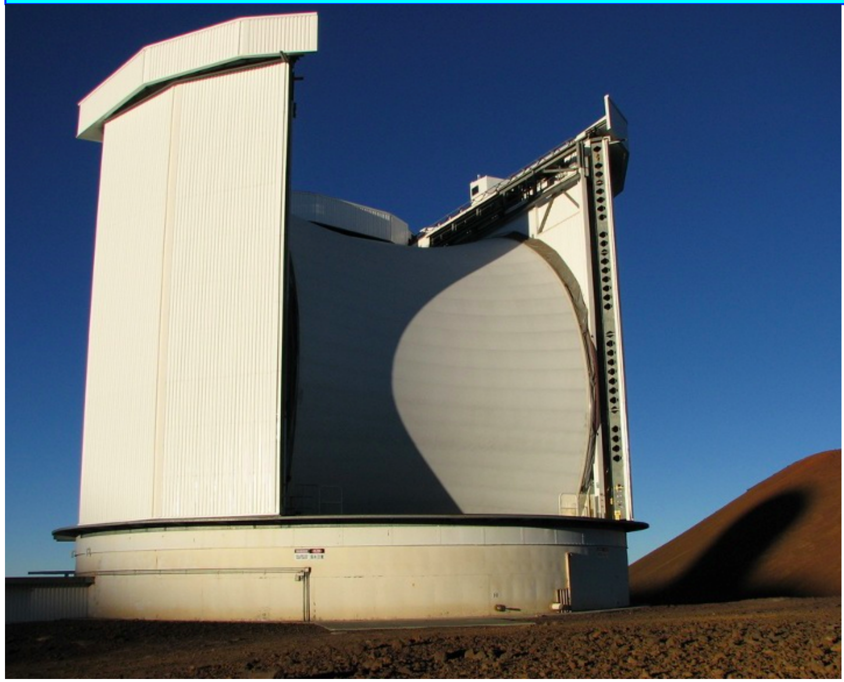
MALATANG project updates: the far-infrared and HCN correlations



Yu GAO (高煜)

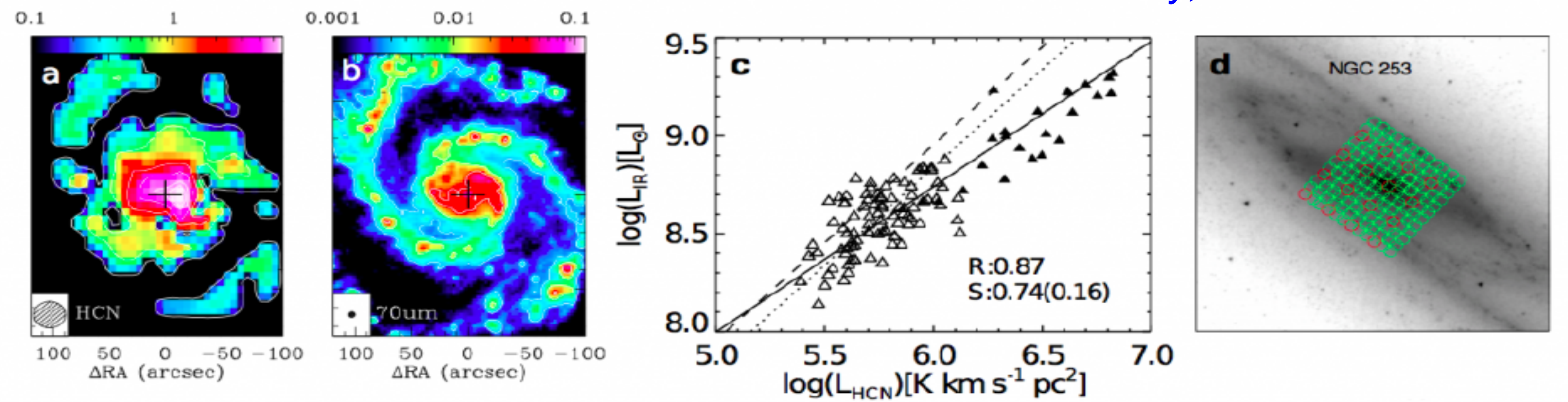
Purple Mountain Observatory

Chinese Academy of Sciences

***1 Chen,* Gao *& Braine*+*2015/17 ApJ (1507.08506,*1612.00459); 2 Liu,D, Gao & Isaak+2015 ApJL (1504.05897); 3 Liu,L Gao & Greve 2015 ApJ (1502.08001); *4 Zhang,* Gao *& Henkel+2014 ApJL*; 5 Lu +2017; 6 Tan, Gao+ 2018 ApJ; 7 Jiang+2019; 8 Zhang+2020**

MALATANG
Project update

Contact:
Yu Gao (yugao@pmo.ac.cn)
Zhiyu Zhang (zzhang@eso.org)
Thomas Greve (t.greve@ucl.ac.uk)
Satoki Matsushita; Aeree Chung;
Erik Rosolowsky; Kohno Kotaro



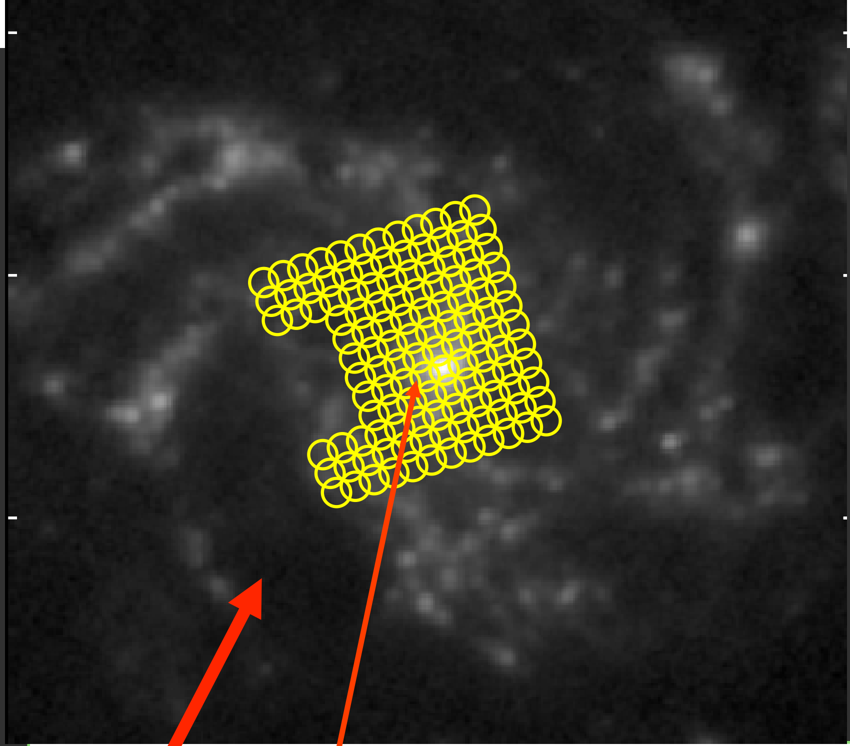
MALATANG in a nutshell: here illustrated by a study of M51 (Chen et el 2015). a) Moment 0 map of the HCN J= 1 – 0 emission towards M 51 (contours at: 0.1, 0.6, 1.9, 3.4, 4.9, 5.4 K km/s on the Tmb scale). b) Herschel/PACS 70 μm image tracing the IR dust continuum (contours at: 3, 9, 27, 81 mJy/pixel. c) The resolved $L_{IR} – L'_{HCN J=1-0}$ relation observed towards M 51, with each symbol representing a region ~1 kpc in size. The solid and dashed lines show the best log-linear fits to the nuclear (filled triangles) and disk (open triangles) regions combined and to the disk regions only, respectively. The combined correlation is seen to be shallower than the galaxy-integrated linear relation observed by Gao & Solomon (2004) (illustrated by the dashed line). d) Schematic of a HARP-B jiggle mode observations of a MALATANG target (NGC 253). With a beam spacing of 1000 , the shown 3 x 3 jiggle pattern will result in fully sampled HCN and HCO+ J = 4 -3 maps that probe dense molecular gas across a range of environments, from inter-arm regions to the central starburst nuclei.

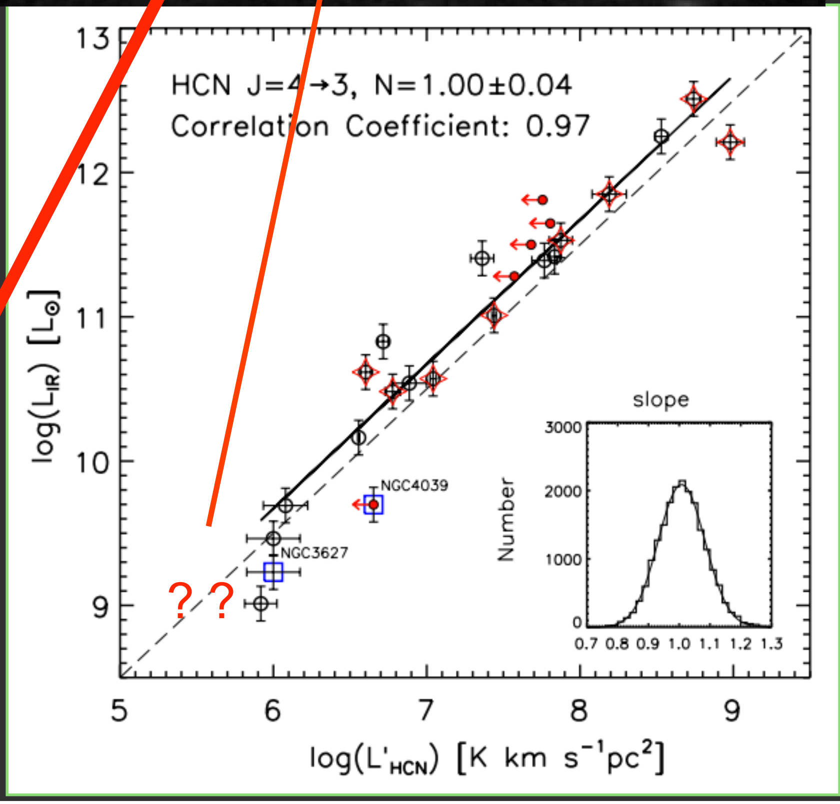
PROJECT AND SCIENCE GOALS

MALATANG

- *390hr JCMT-HARP program: map HCN and HCO+ J=4-3 in 23 of the nearest and IR-brightest galaxies beyond the Local Group*
- *First attempt at systematically map the distribution of dense gas out to large galactocentric distances in a statistically significant sample*
- *dense gas vs. star formation relationship down to gas masses of ~$5\times10^6 M_\odot$ and scales ~0.2-2.8kpc in other galaxies*
- *Bridge the gap between and Galactic observations*

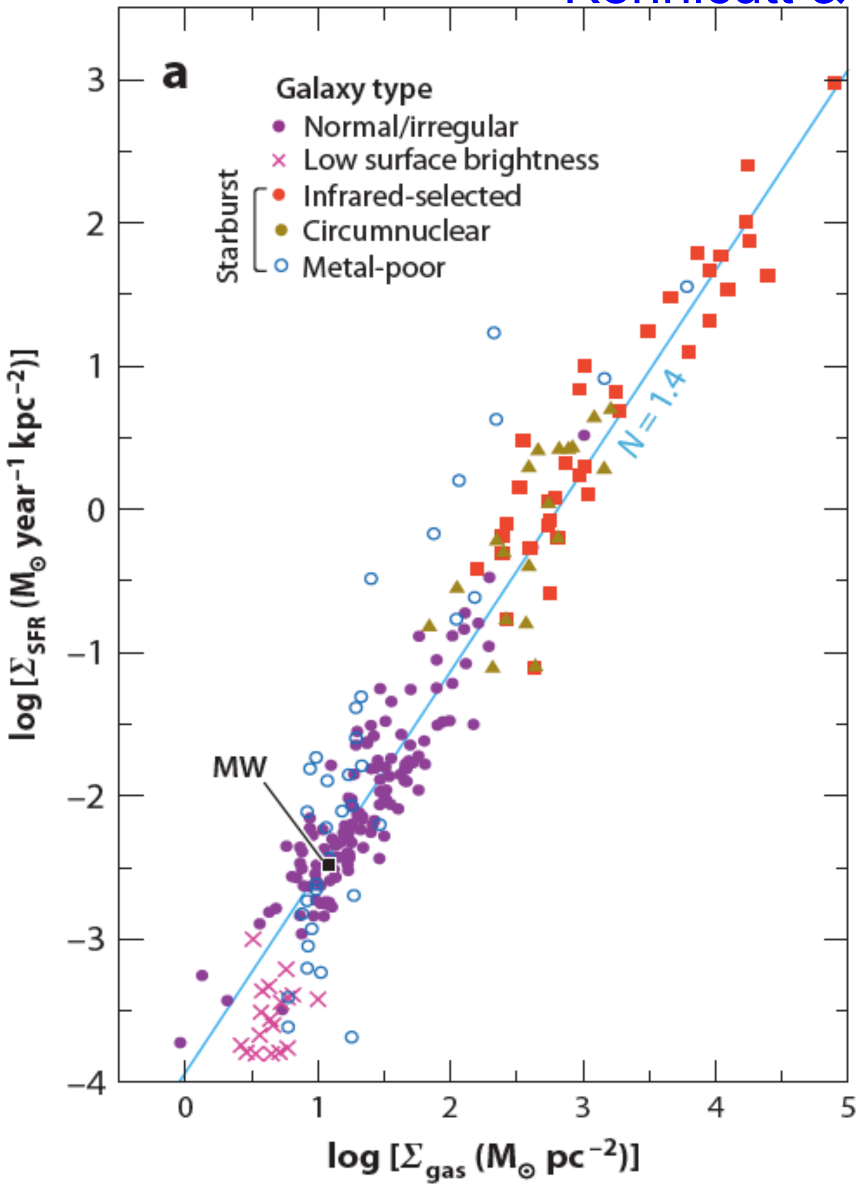
- *Resolved dense gas star formation relations*
- *Intermediate scales/luminosities*
- *Different environments: nuclear vs. disk*
- *Radial distribution of dense gas and SF efficiency*



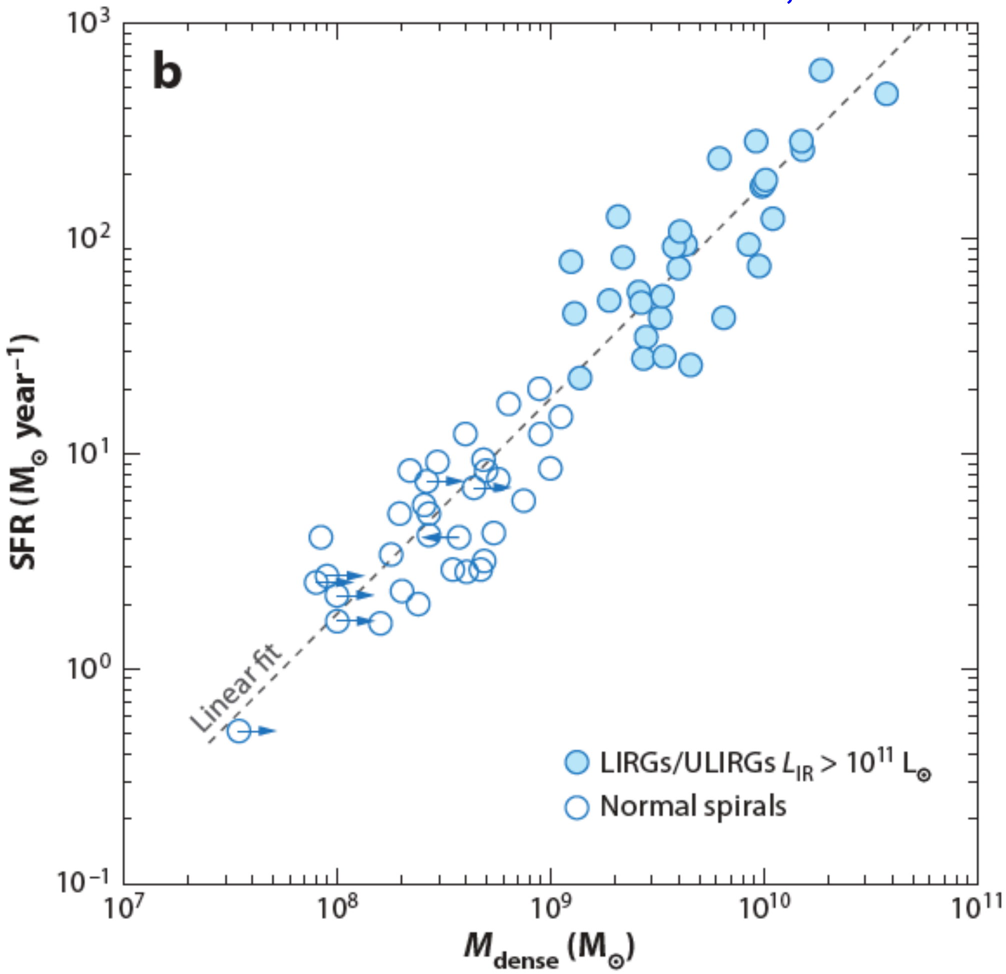


Motivation

Kennicutt & Evans 2012, ARAA

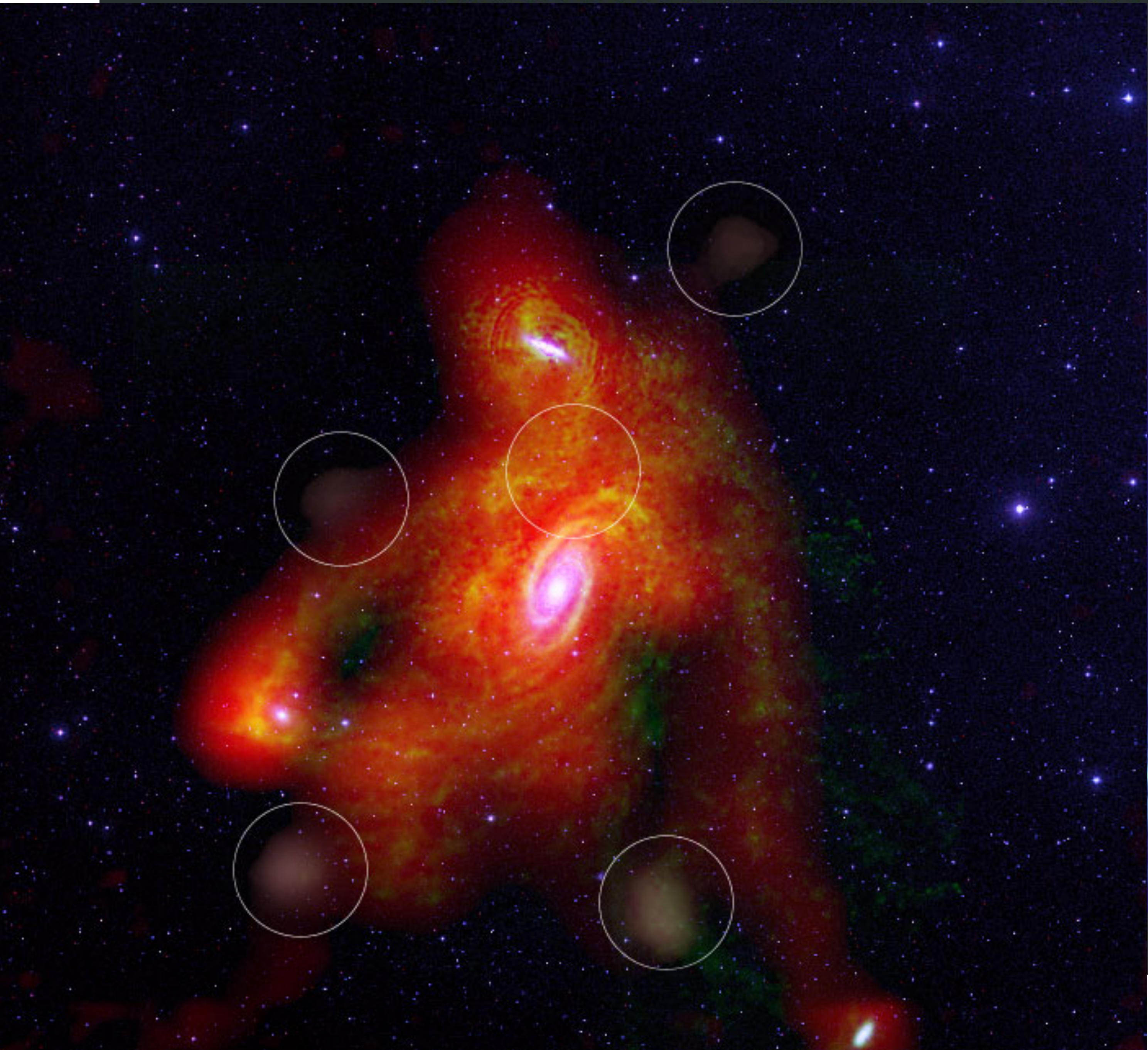


Gao & Solomon 2004a,b

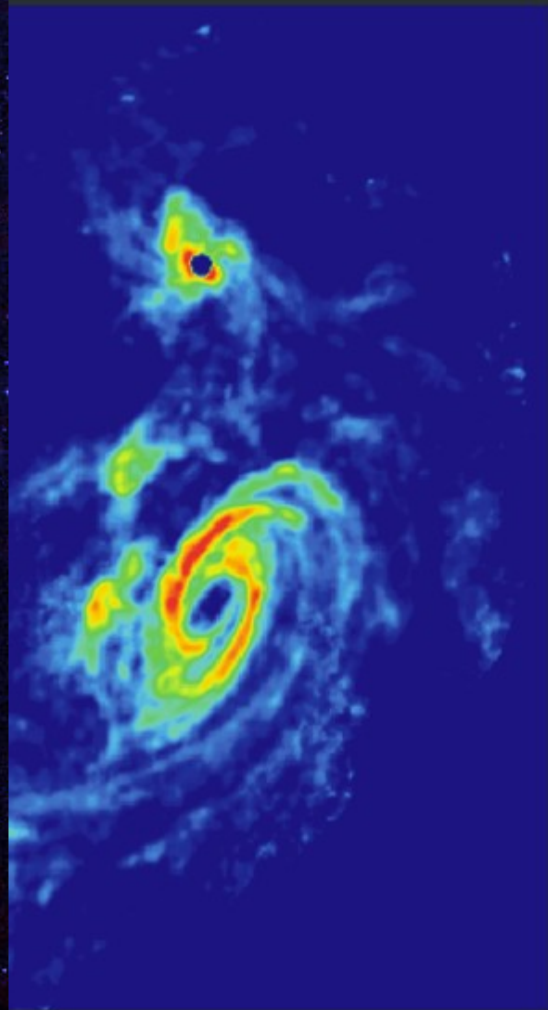


Disk-average [SFR~ density(HI+H2)^1.4]

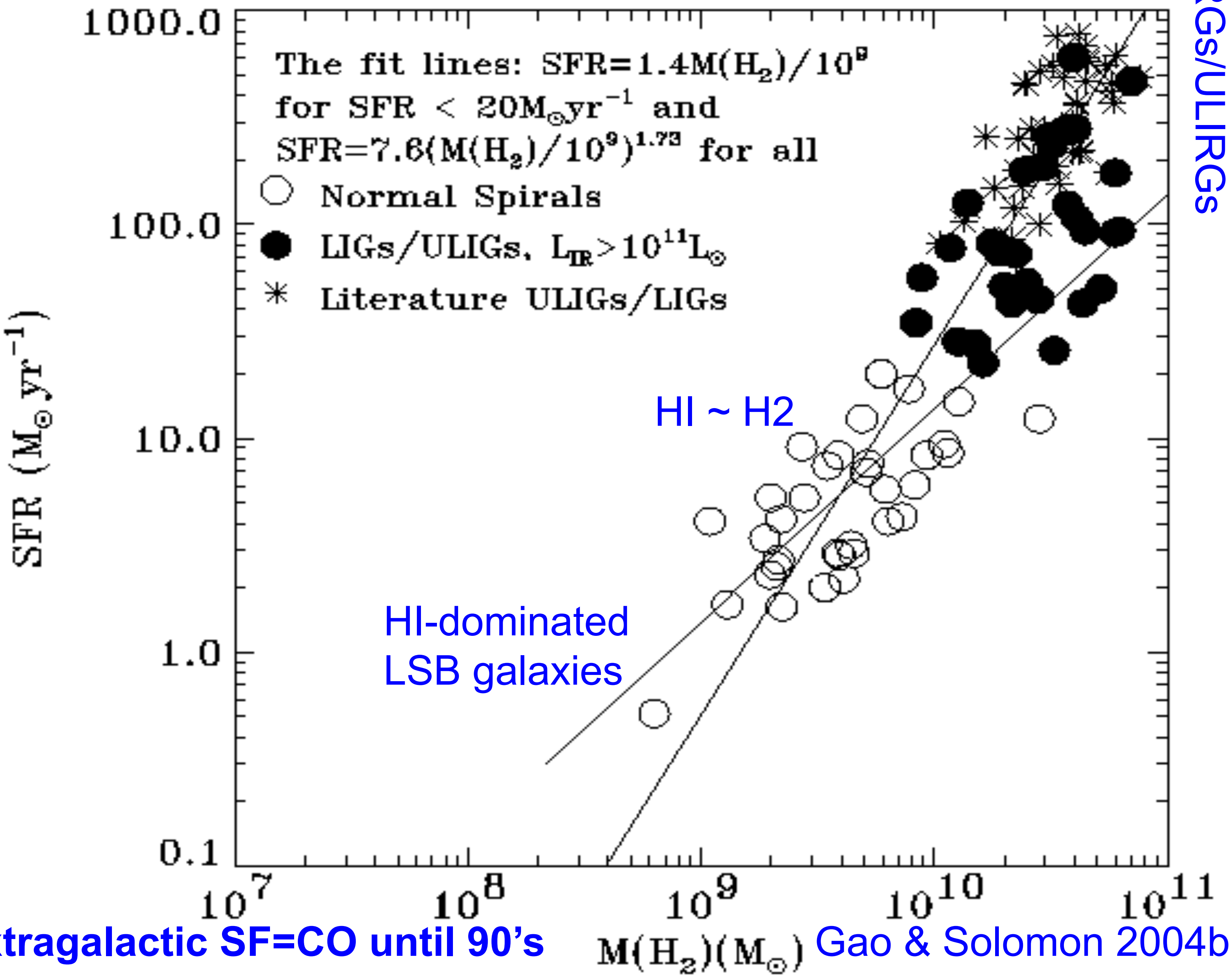
TIDAL INTERACTIONS IN M81 GROUP



HI Distribution



SFR vs. M(H2): No Unique Slope:1, 1.4, 1.7?



H2-dominated
LIRGs/ULIRGs

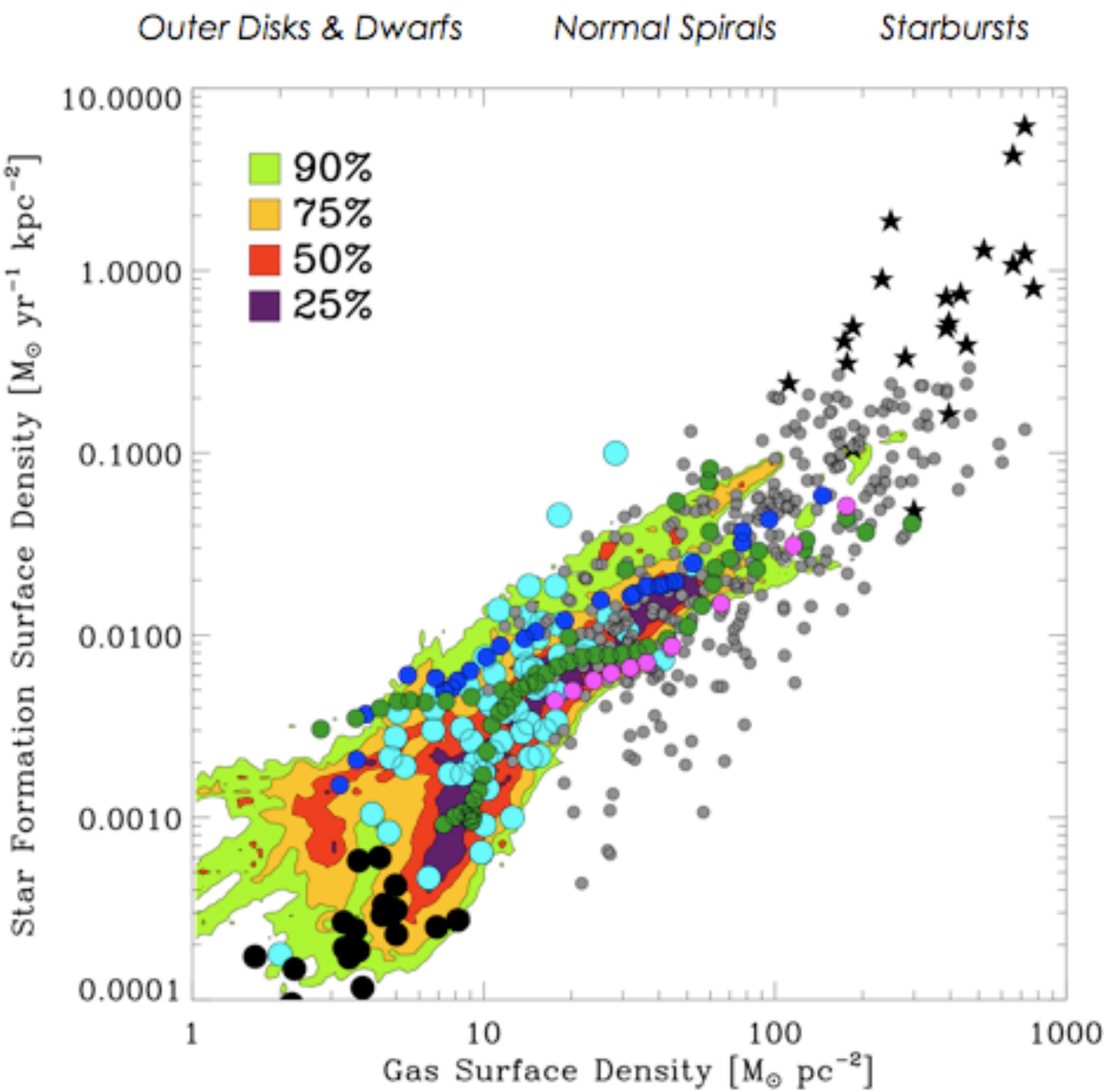
Extragalactic SF=CO until 90's

Gao & Solomon 2004b ApJ

SF thresholds may simply reflect the change of the dominant cold gas phase in galaxies from HI ->H2 & from H2->denseH2 -->dense cores (DCs) →super-star clusters (SSCs)

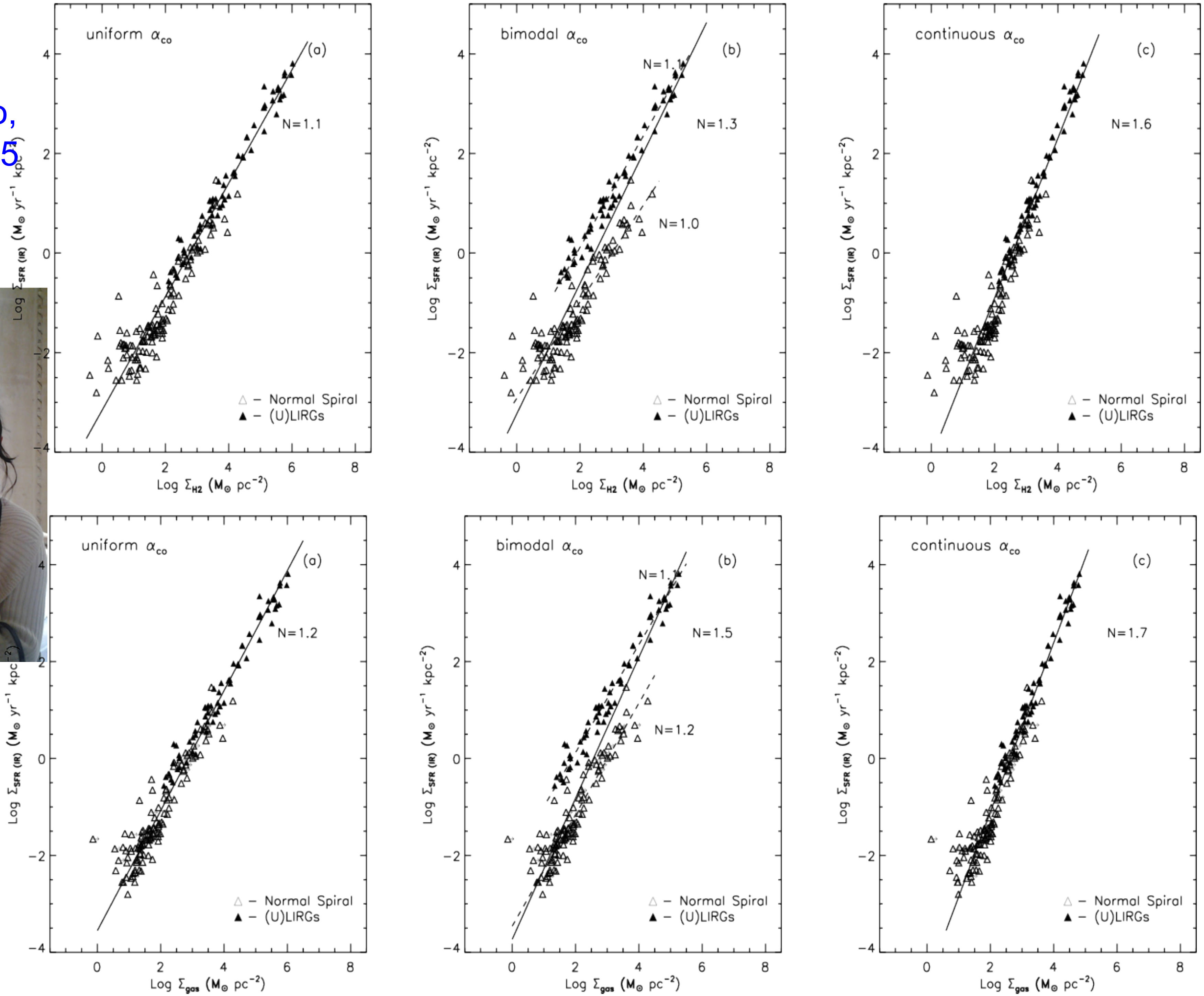
Schruba+2011 ~linear in H2!

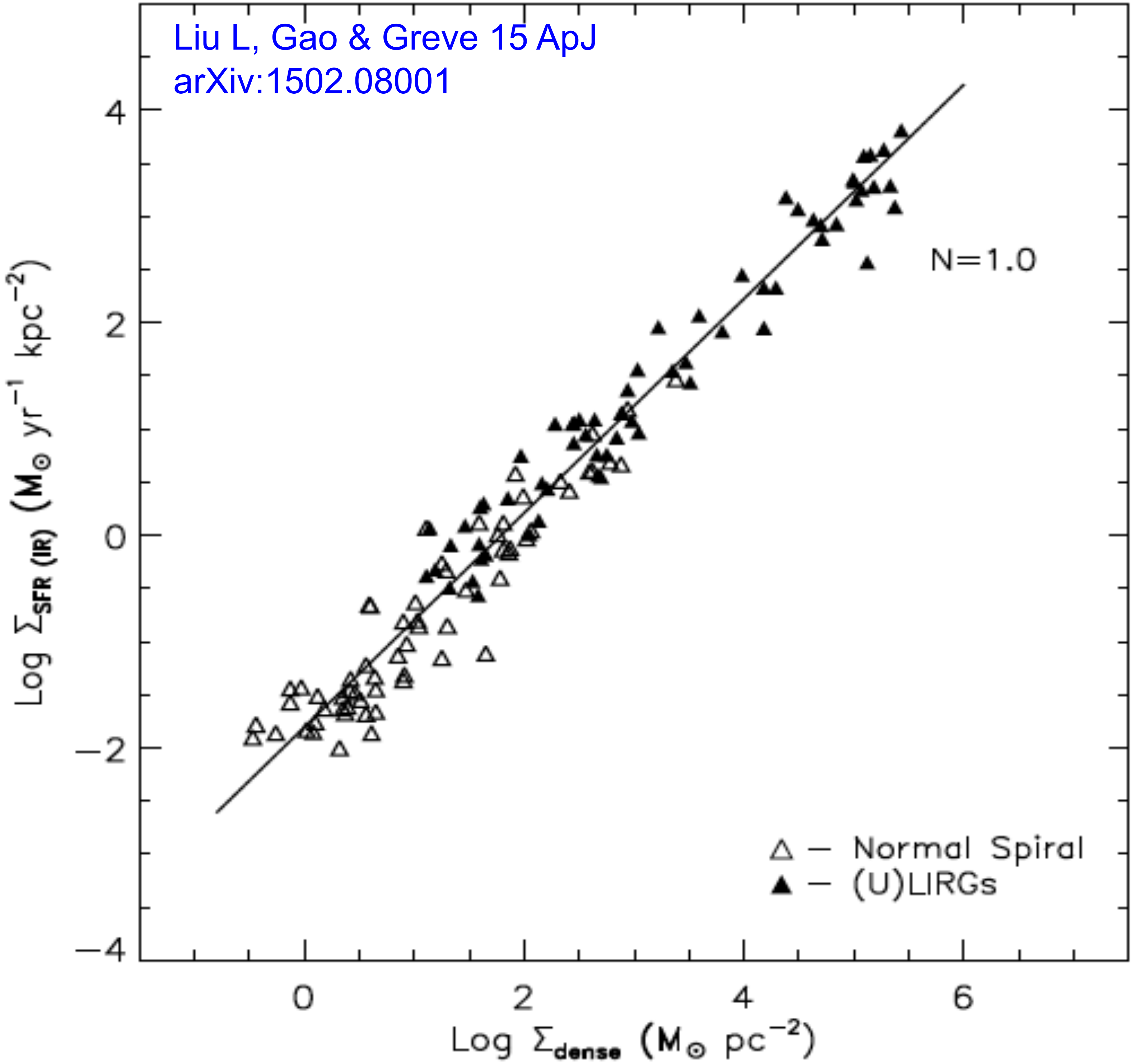
Bigiel's talk @SFR50



Kennicutt (1998) spirals and ★bursts; Wong & Blitz (2002); Schuster et al. (2007) Wyder et al. (2007); Kennicutt et al. (2007); Crosthwaite & Turner (2007)

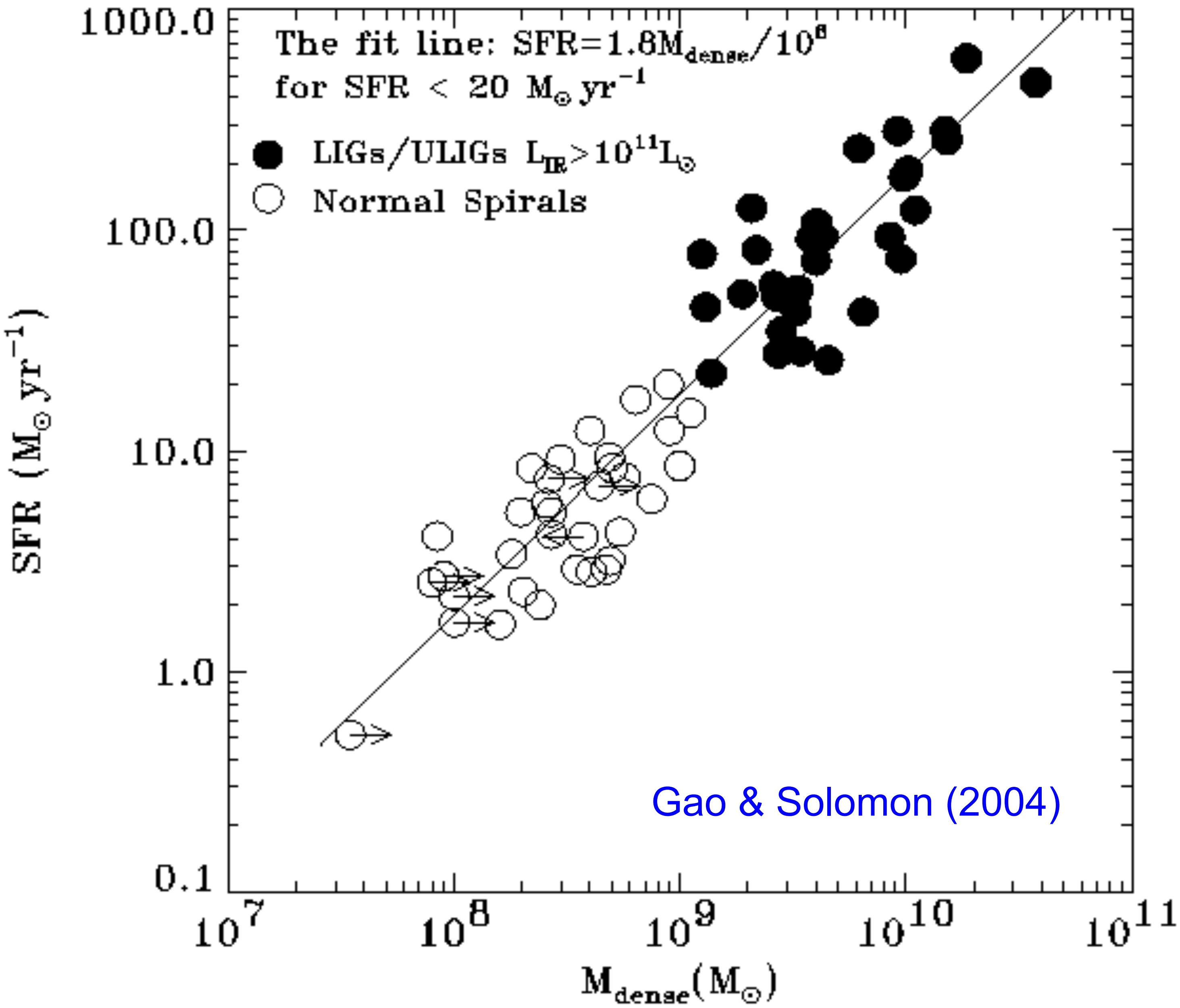
Liu, Gao, Greve 15





Liu L, Gao & Greve 15 ApJ
arXiv:1502.08001
N=1.0
△ – Normal Spiral
▲ – (U)LIRGs
Log $\Sigma_{SFR\ (IR)}$ ($M_\odot$ yr^{-1} kpc^{-2})
Log Σ_{dense} ($M_\odot$ pc^{-2})
4
2
0
−2
−4
0
2
4
6

SFR vs. M_dense(H2): linear correlation



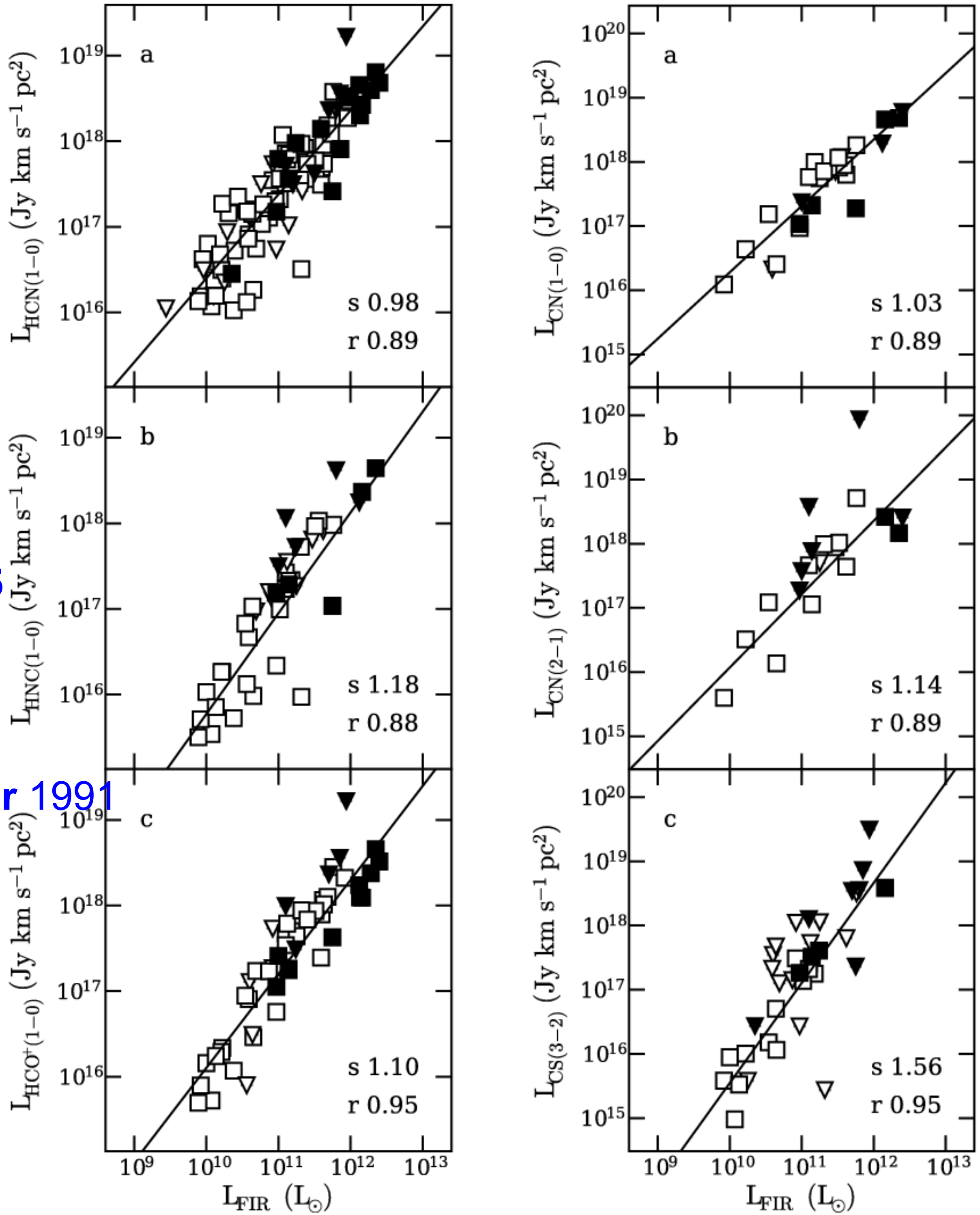
Gao & Solomon (2004)

Baan, Henkel, Loenen + 2008

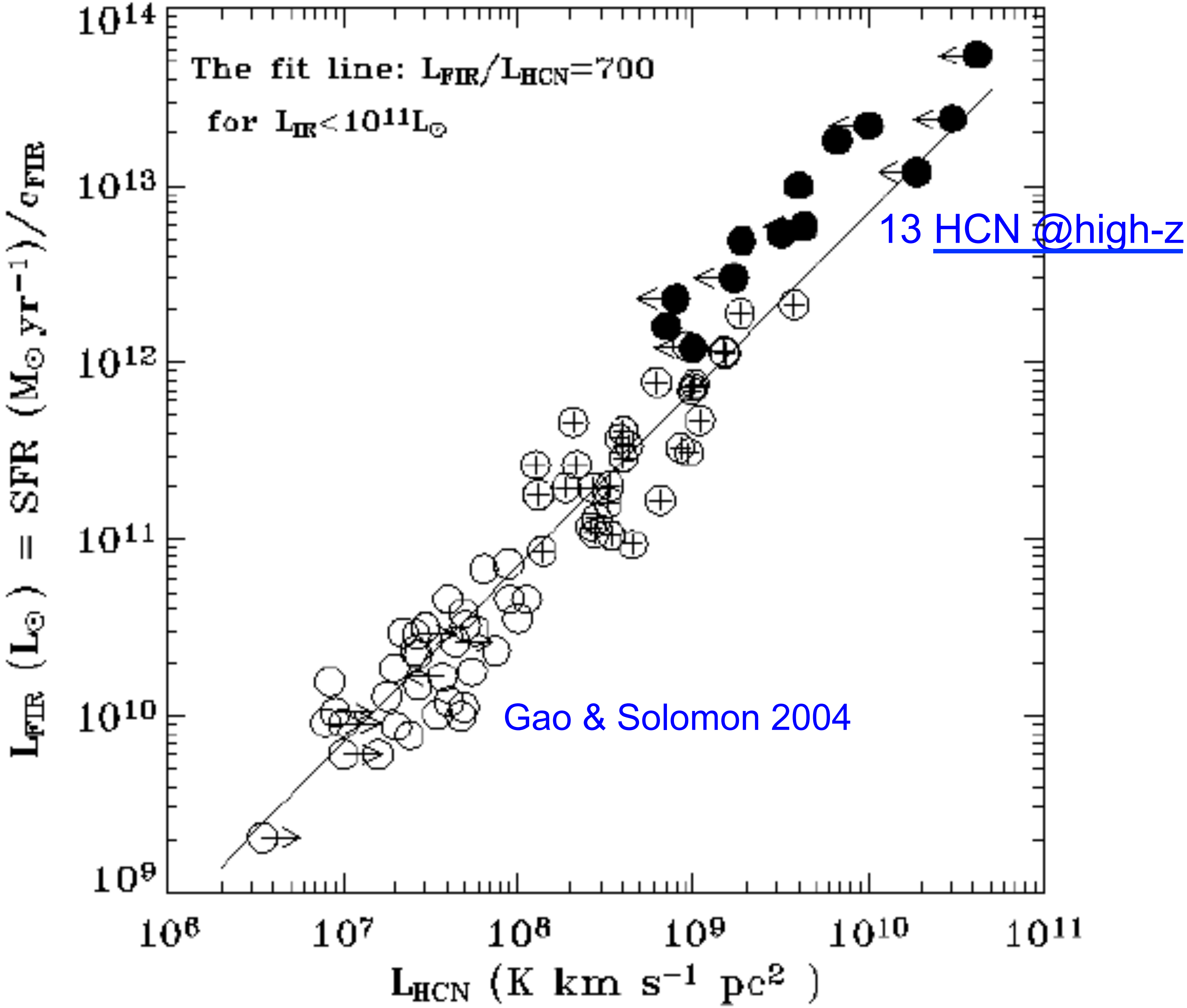
HCN,CS,HNC etc. in SF gals.

- **Baan et al. (2008)**
- **Kohno 2007, et al. (2003)**
- **Imanishi 2006, et al. 2009, 2013, 2016a,b**
- **Aalto et al. 2007, 2002, 1995**
- **Solomon et al. 1992**
- **Nguyen** et al. 1992
- **Henkel et al. 1990**
- **Henkel, Baan, Mauersberger** 1991

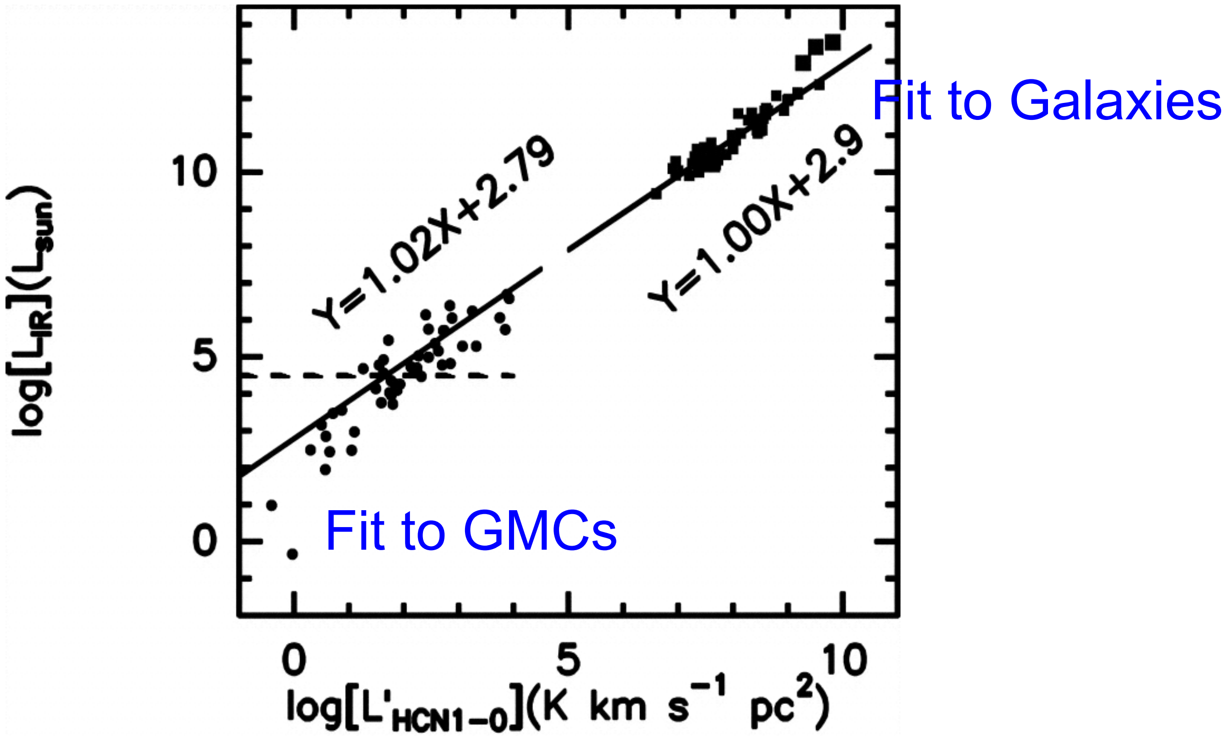
Best case studies:
Arp 220 & NGC 6240
(Greve + 2009)



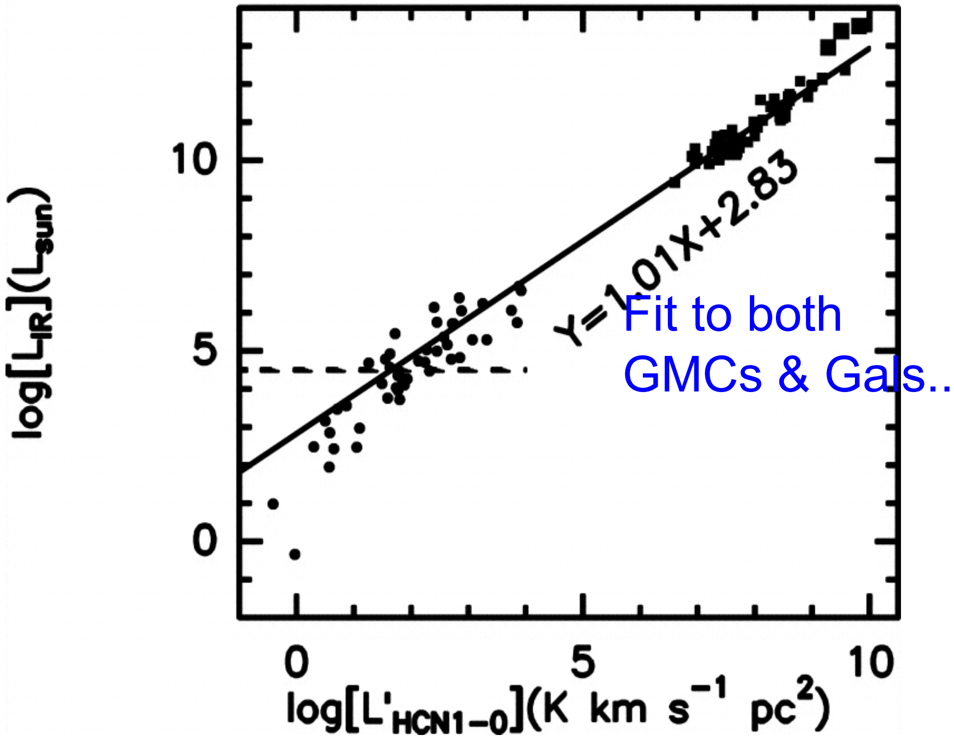
Gao, Carilli, Solomon & Vanden Bout 2007 ApJ, 660, L93

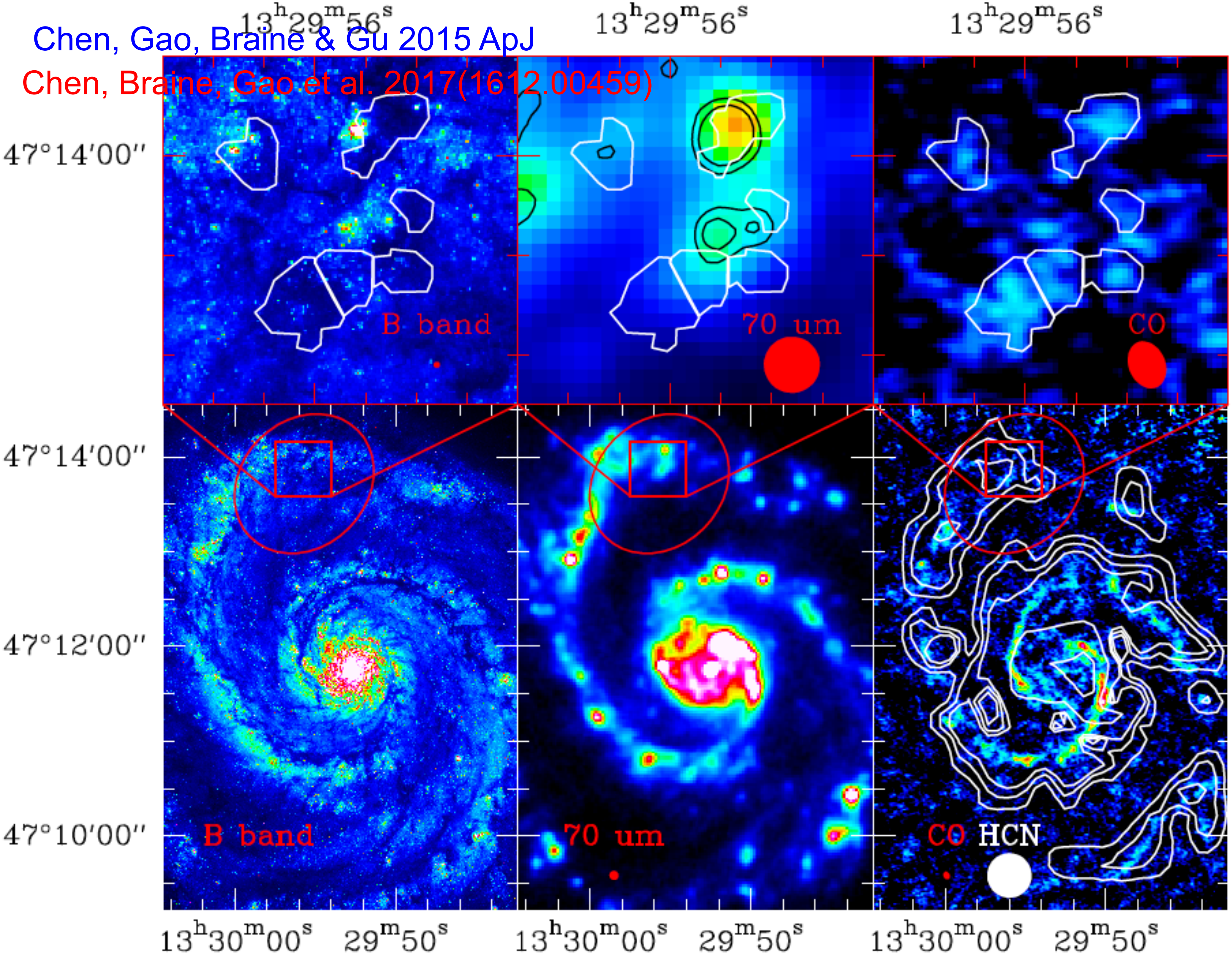


Wu, Evans, Gao
et al. 2005 ApJL



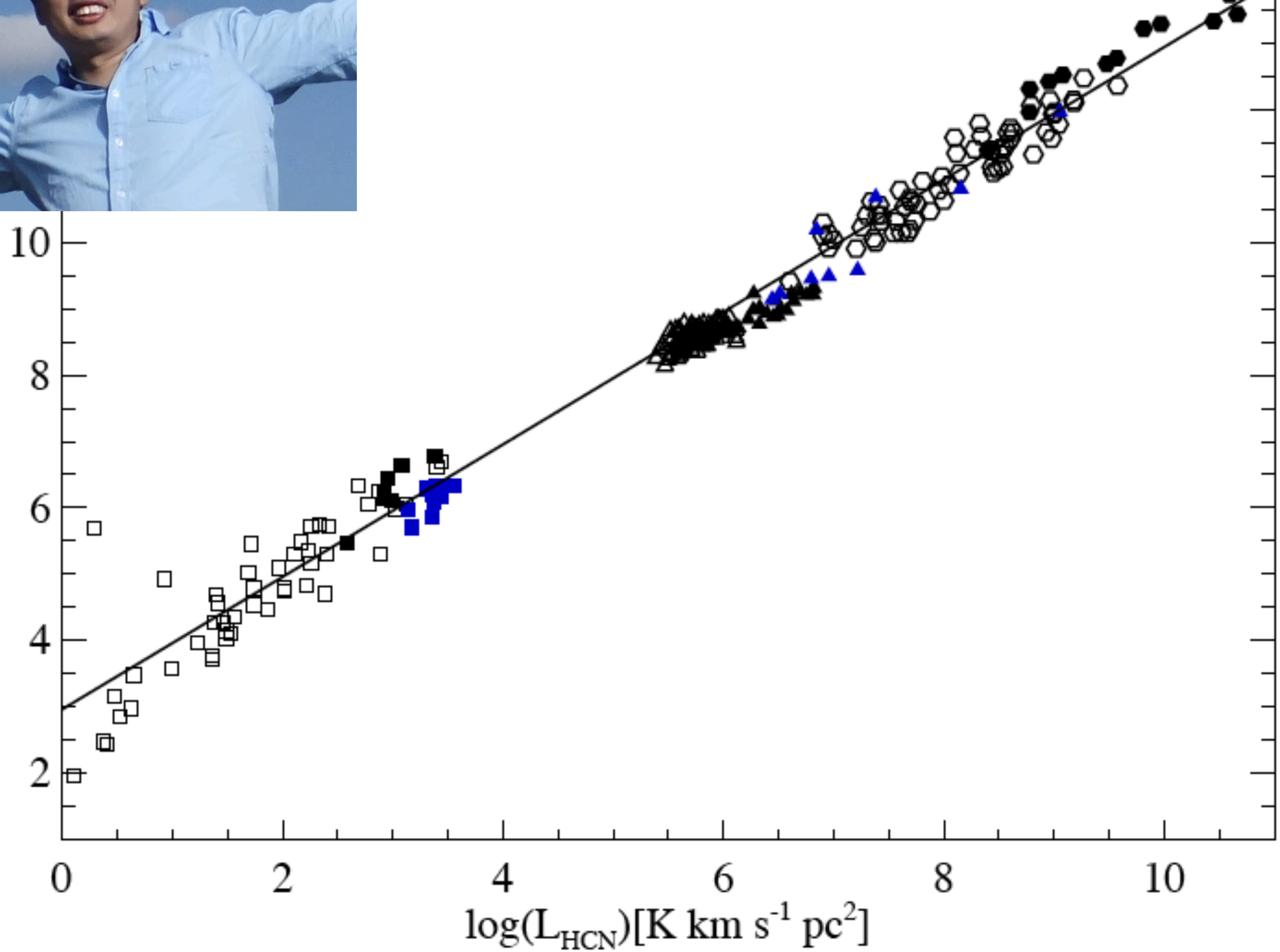
Wu+2010

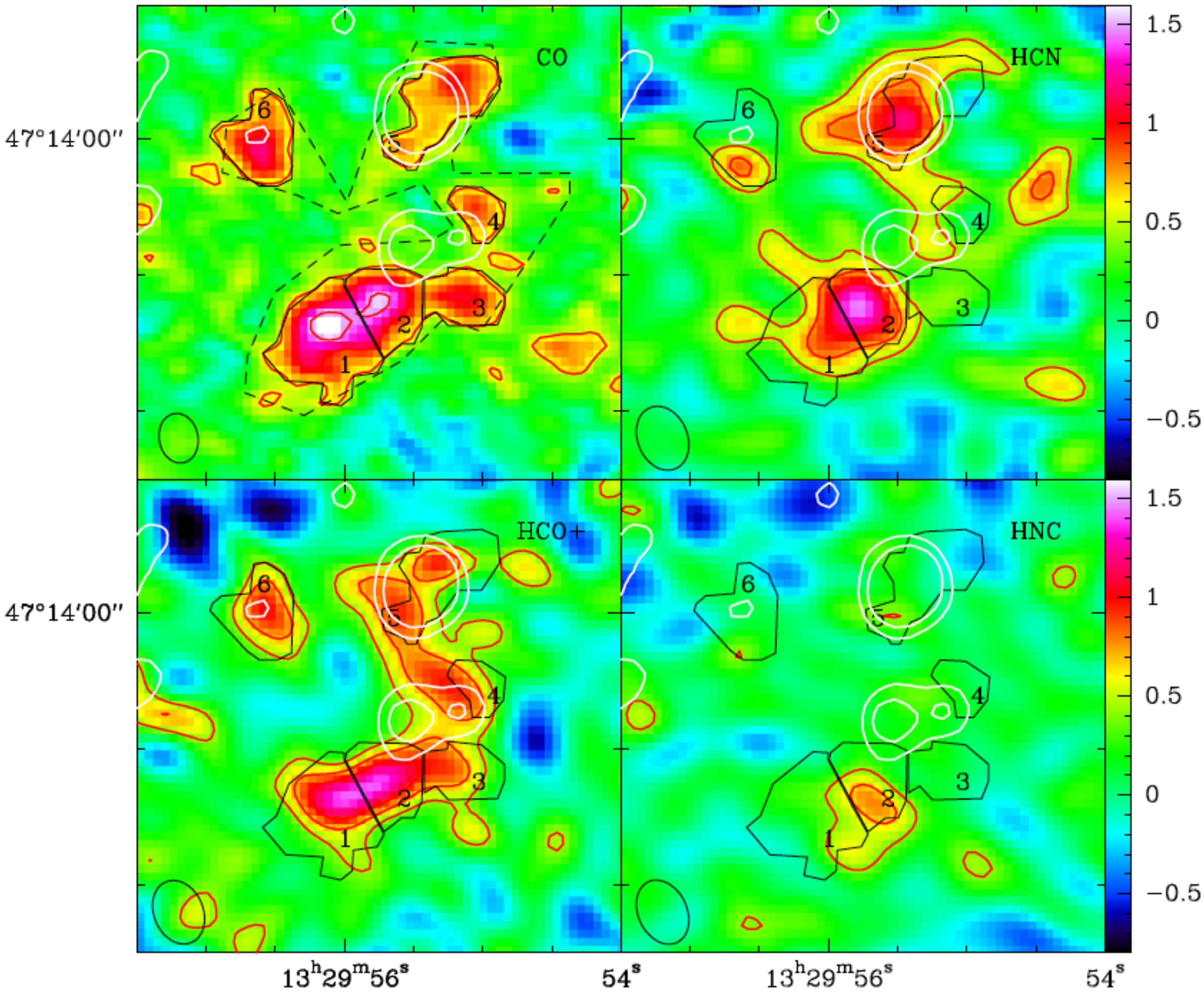




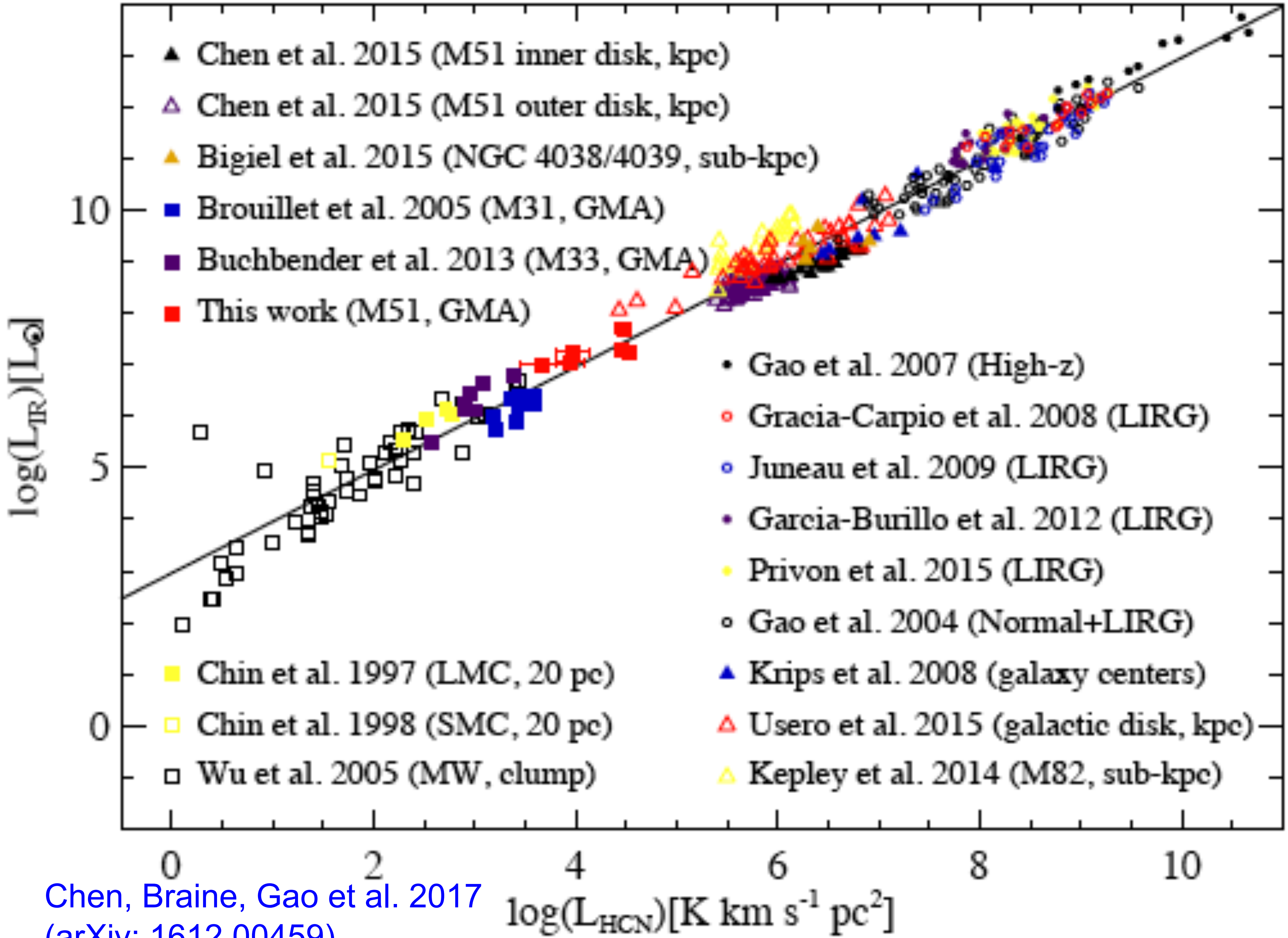
Chen, Gao, Braine & Gu 2015 ApJ
Chen, Braine, Gao et al. 2017(1612.00459)
13h29m56s
13h29m56s
13h29m56s
47°14′00″
B band
70 um
CO
47°14′00″
47°12′00″
47°10′00″
B band
70 um
CO HCN
13h30m00s
29m50s
13h30m00s
29m50s
13h30m00s
29m50s

Chen, Gao, Braine & Gu 2015

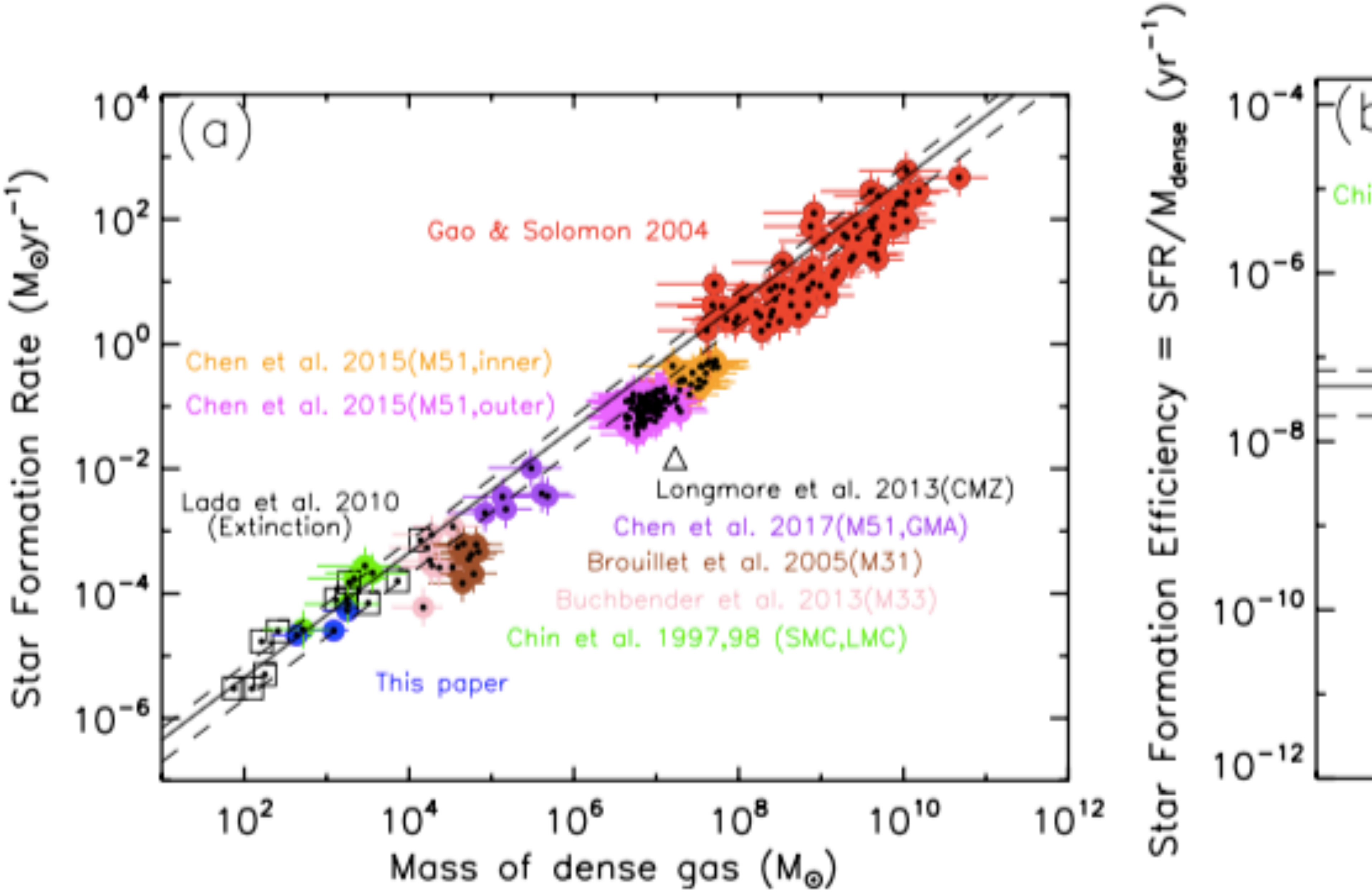




CO
HCN
HCO+
HNC
1
2
3
4
5
6
47°14′00″
13h29m56s
54s
1.5
1
0.5
0
−0.5

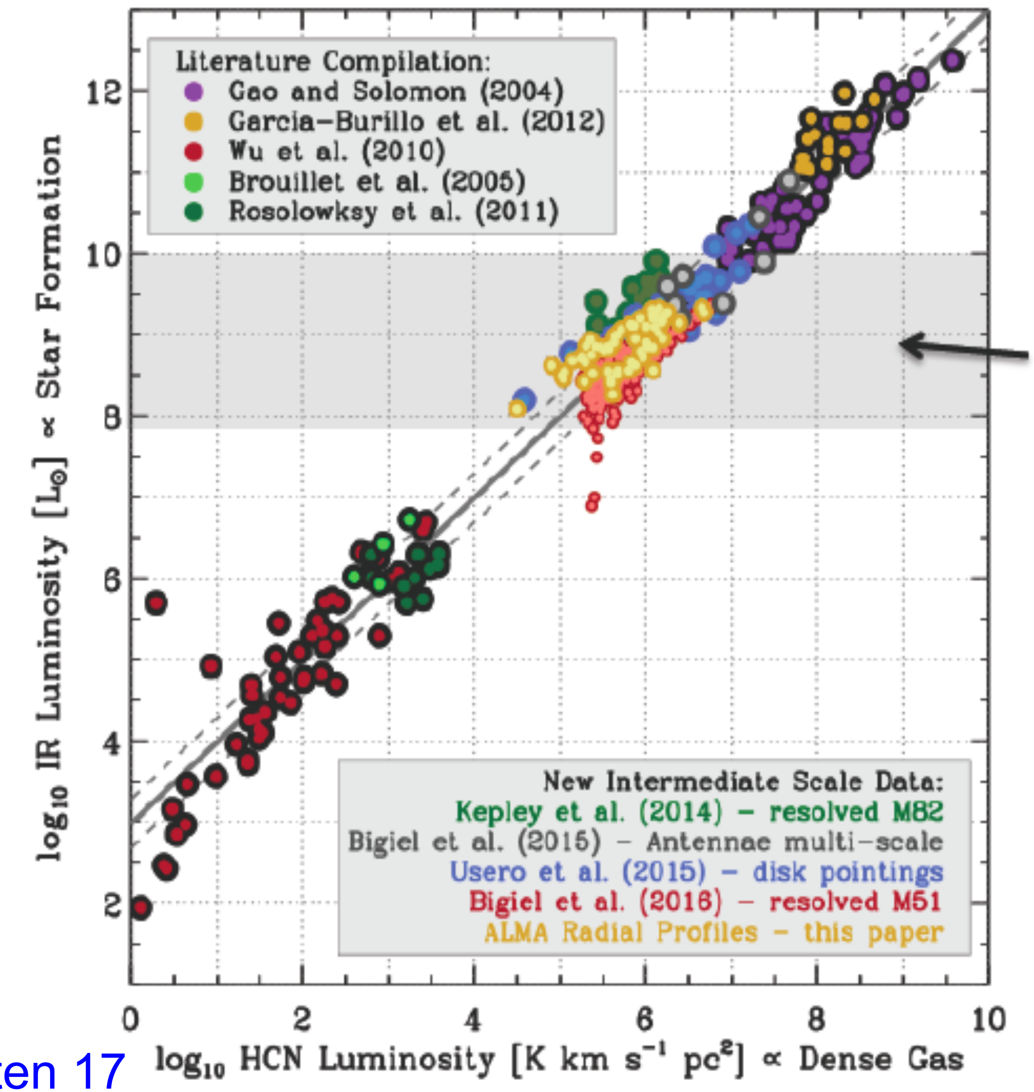


Chen, Braine, Gao et al. 2017
(arXiv: 1612.00459)



Shimajiri + 2017

These new surveys do fill in the luminosity range between whole galaxies and individual clouds. The HCN-IR (dense gas-SFR) correlation holds in broad brush.



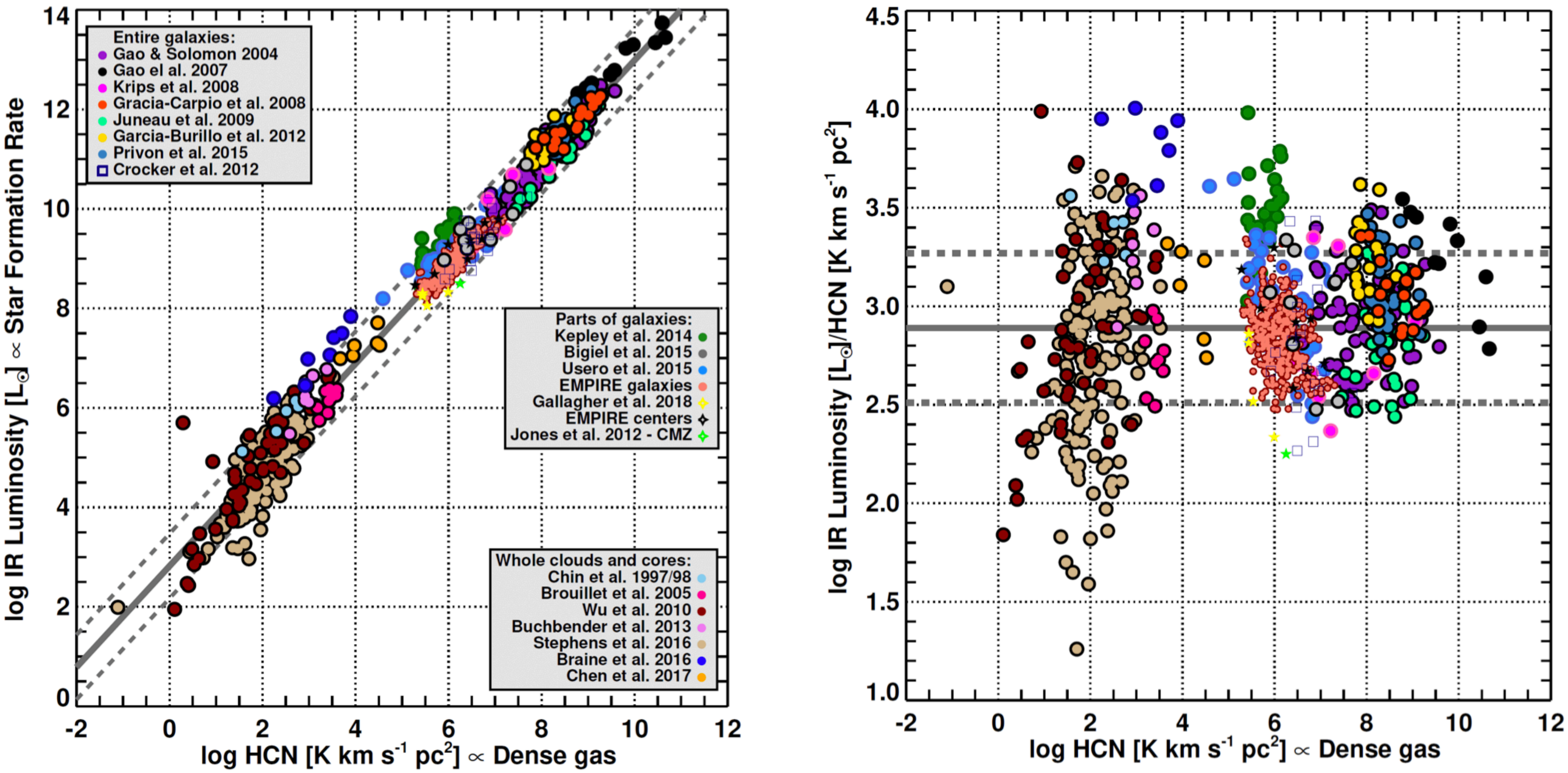
New surveys:

Disk pointings
M51 pixels
M82 regions
Antenna pointings
ALMA disk profiles

Leroy's talk at Sexten 17

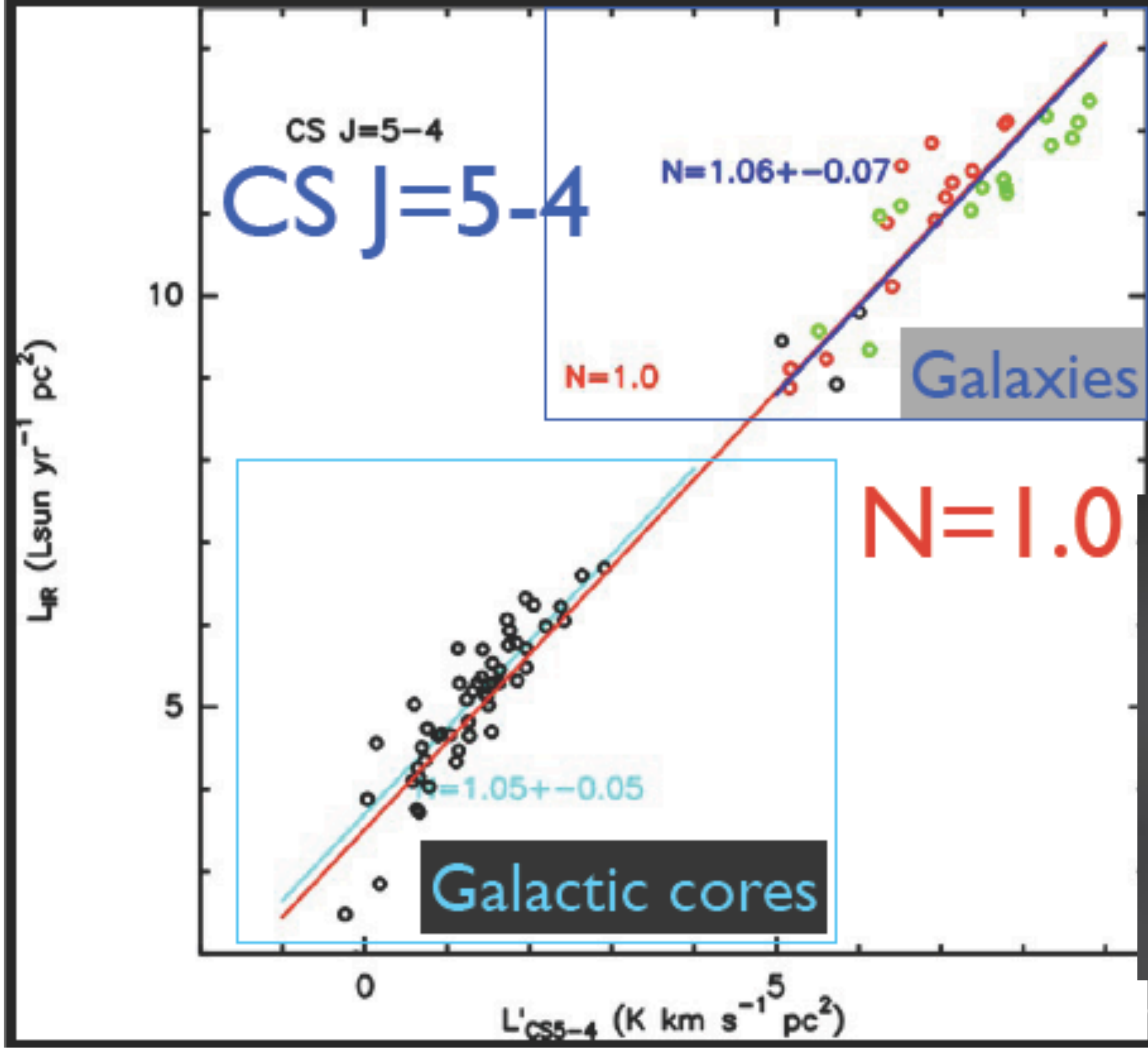
MOLLY GALLAGHER, LEROY ET AL. (SUBMITTED), BIGIEL ET AL. (2016), USERO ET AL. (2015)

EMPIRE Result



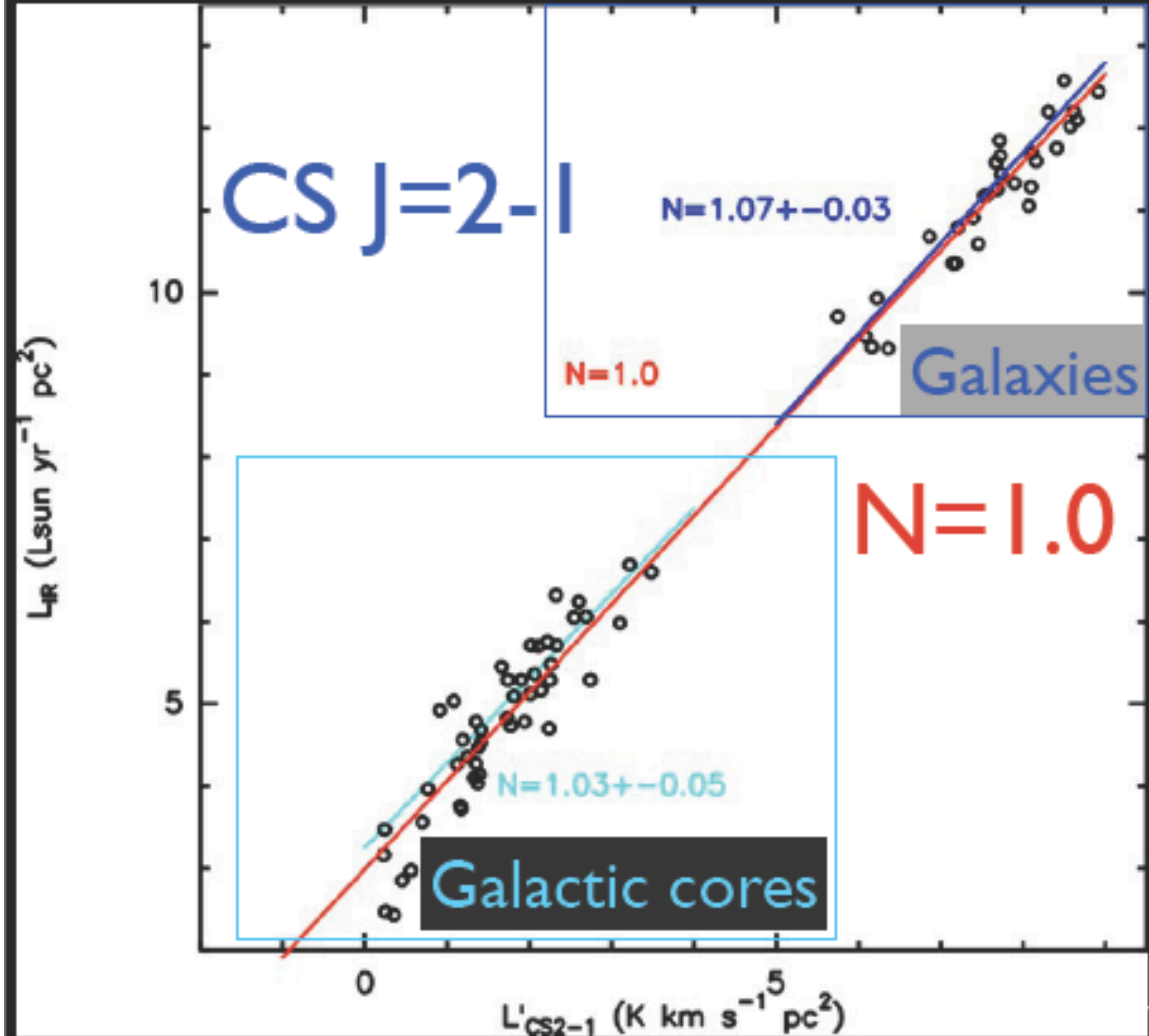
Jiménez-Donaire et al. 2019

Connecting with Galactic CS study ~ 10 orders of magnitude



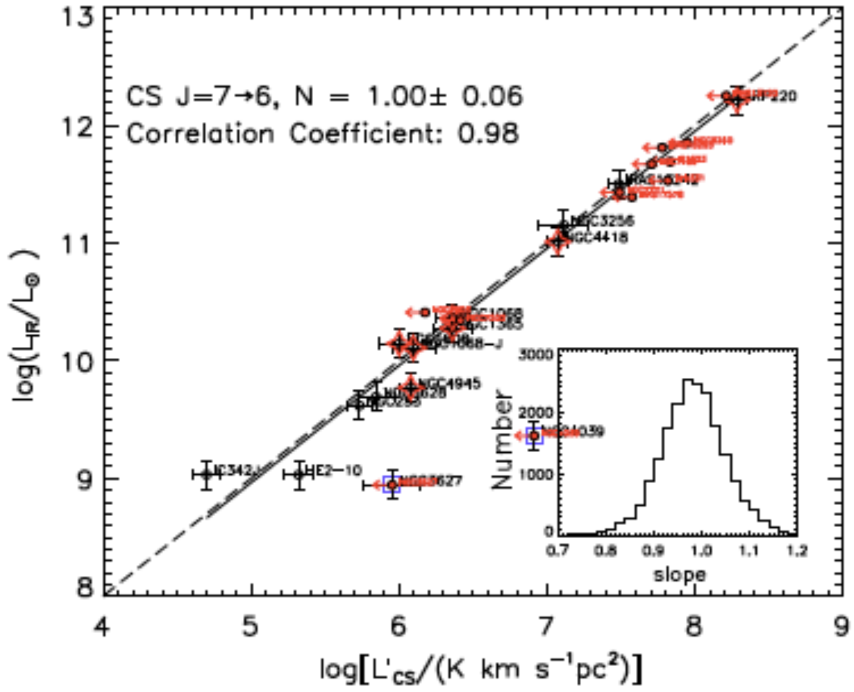
SMT 10m
IRAM 30m
Baan + 2008

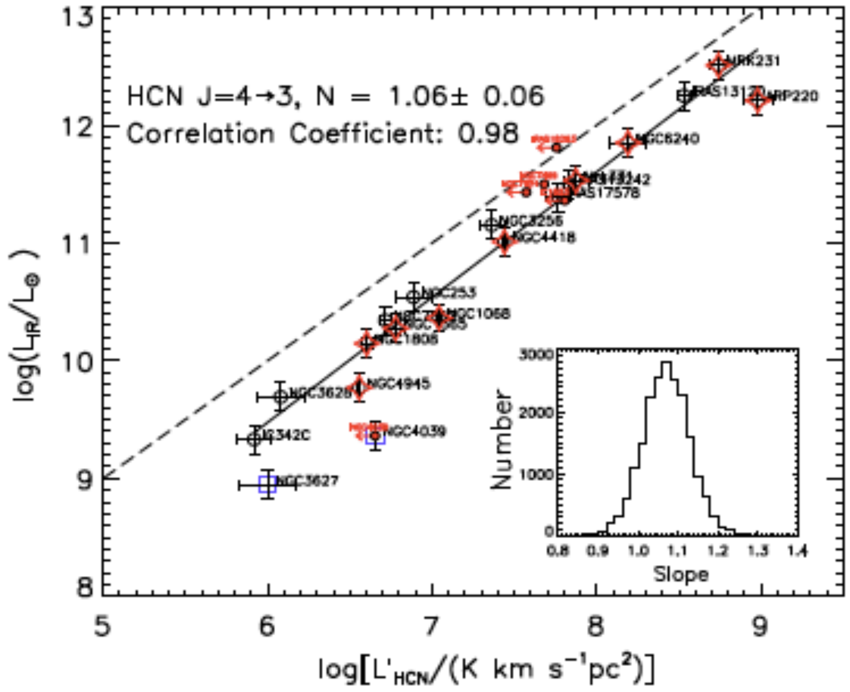
Connecting with Galactic CS study ~ 10 orders of magnitude



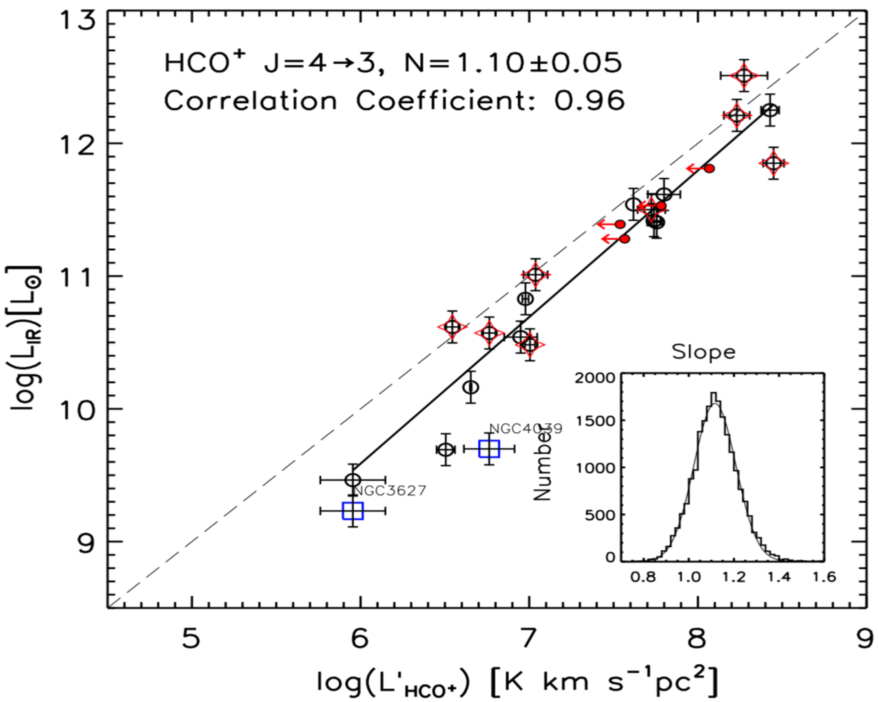
- IRAM 30m

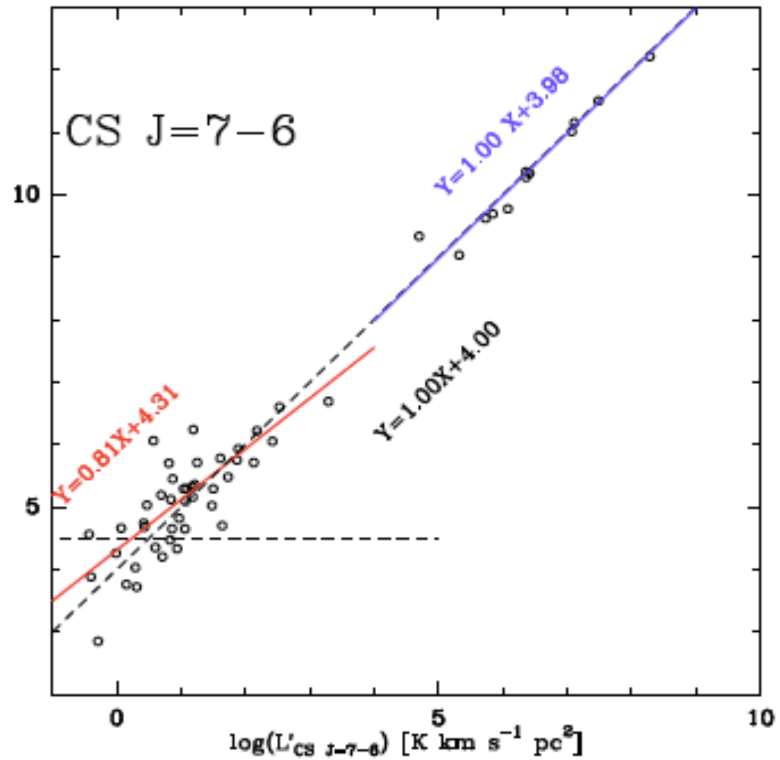
Wu+2010



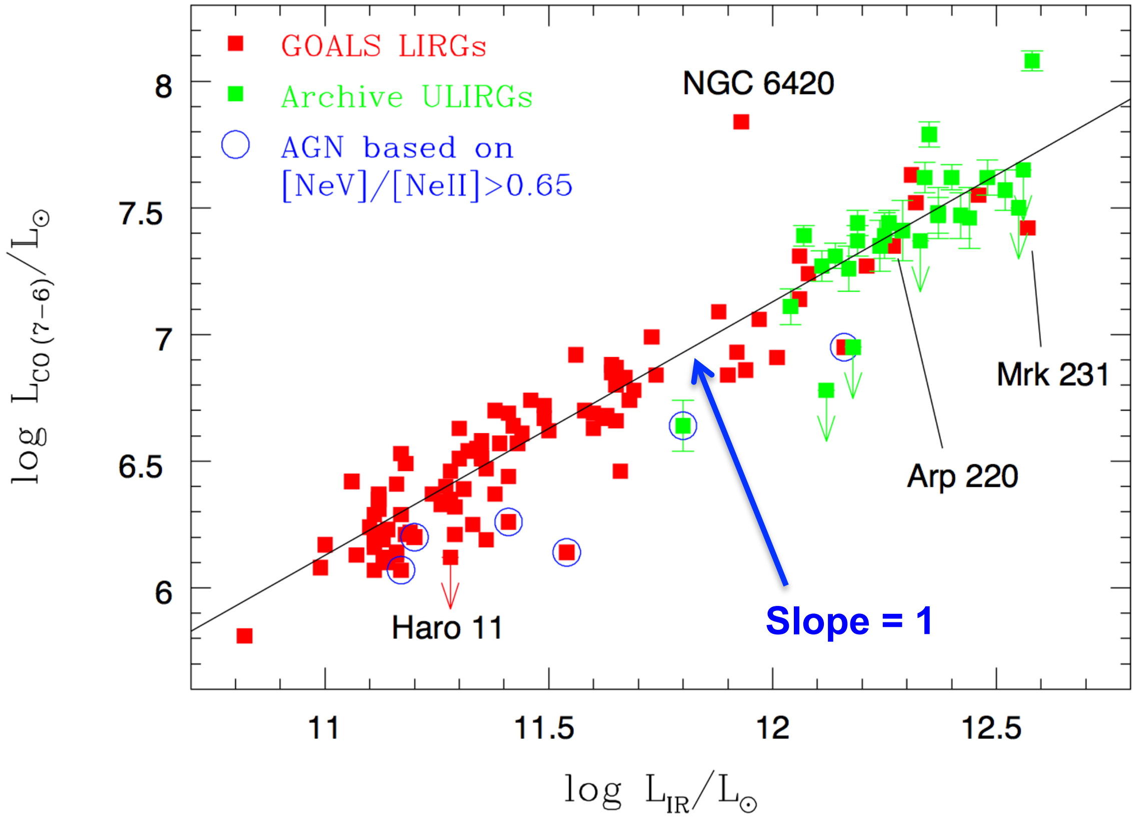


Zhang, Gao, Henkel et al. 2014





Warm CO Gas Emssion as a SFR Tracer



$SFR/(M_\odot\ yr^{-1}) = 1.34 \times 10^{(-5\pm0.12)}\ (L_{CO(7-6)}/L_\odot)$

(based on Kennicutt 1998)

Advantages over L_{IR}:

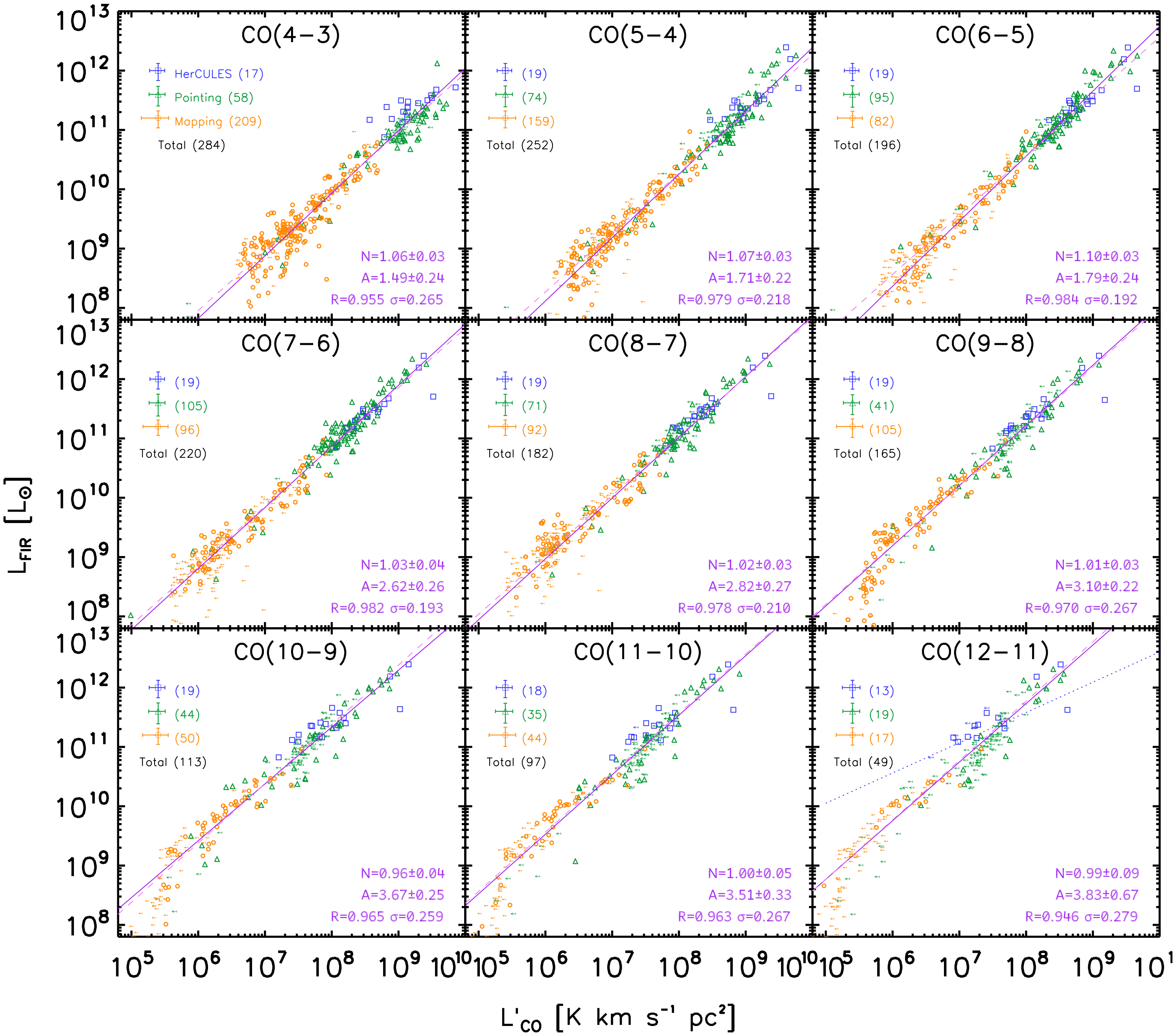
- Not much contaminated by AGN (Lu et al. 2014)
- Easier to measure in the ALMA era, i.e., only need one line measurement in principle

Possible caveats:

- NGC 6240-like objects. But they are quite rare.
- Low metallicity combined with low gas density may lead to low CO abundance due to a more severe UV photo-dissociation.

(Note: only plotted the 102 GOALS LIRGs with at least 85% of the 70um flux within the 30" FTS beam)

High-J CO--IR Correlation in Local Universe



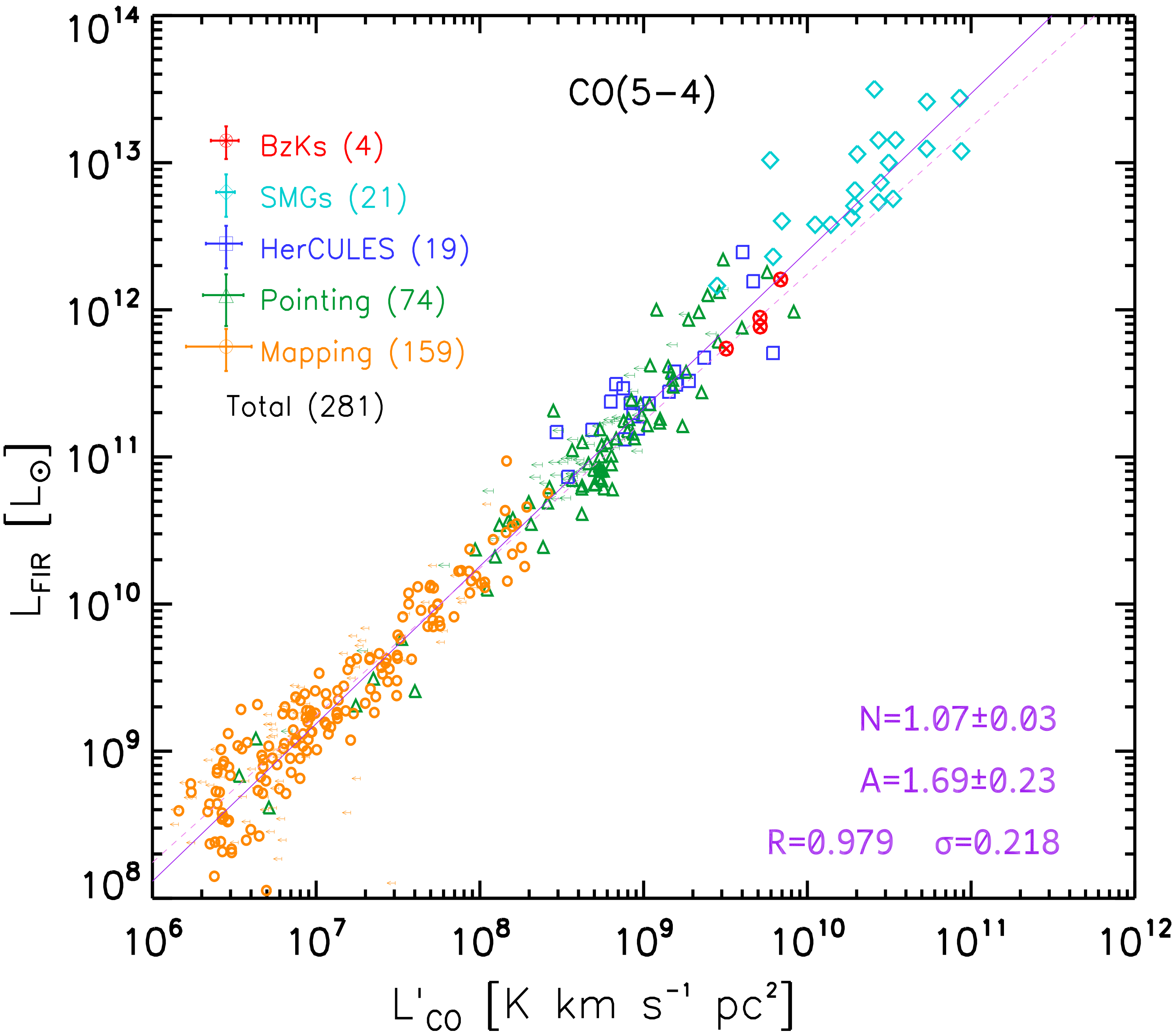
All are not far from linear
– dense gas law

CO J~6-7 are the tightest
– best SF tracer

Slightly super-linear at J≤6 – K-S law

High-J CO better tracers dense gas!

D. Liu, Y. Gao, K. Isaak, et al. 2015



CO(5-4) a most detected high-J CO line at high-z

– deepest CO toward normal SFG at z~1.5 Daddi et al. 2015

BzK

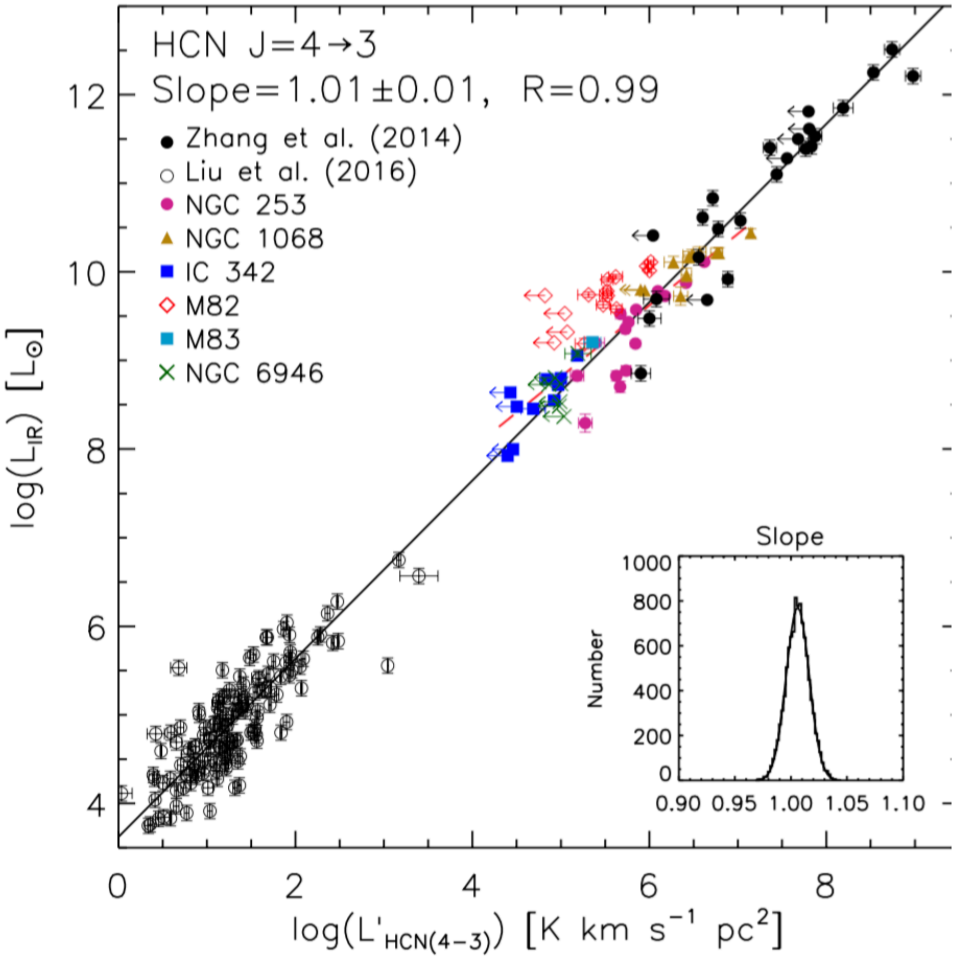
– normal SFG with moderate SFR – steady evolution

SMG

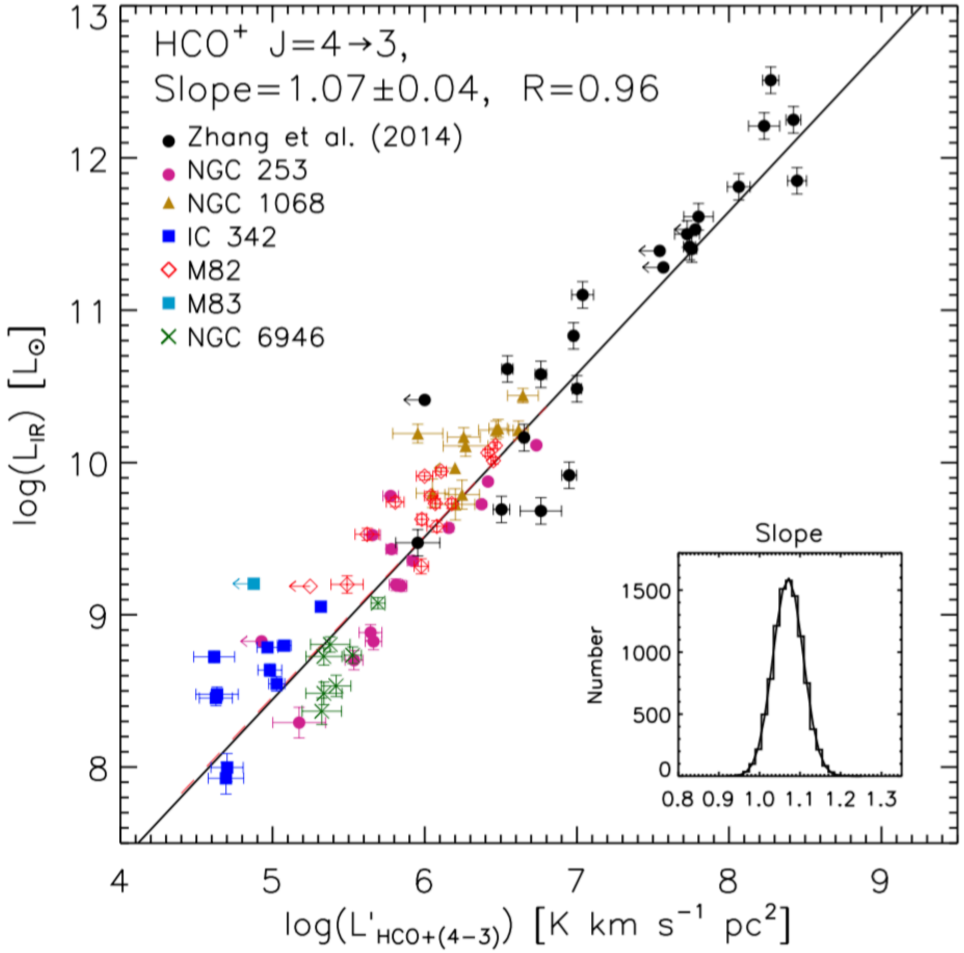
– starburst with very high SFR – merger evolution – note that IR are poorly determined so far

Tan, Gao, Zhang+2018

L_{IR} vs. $L'_{HCN(4-3)}$

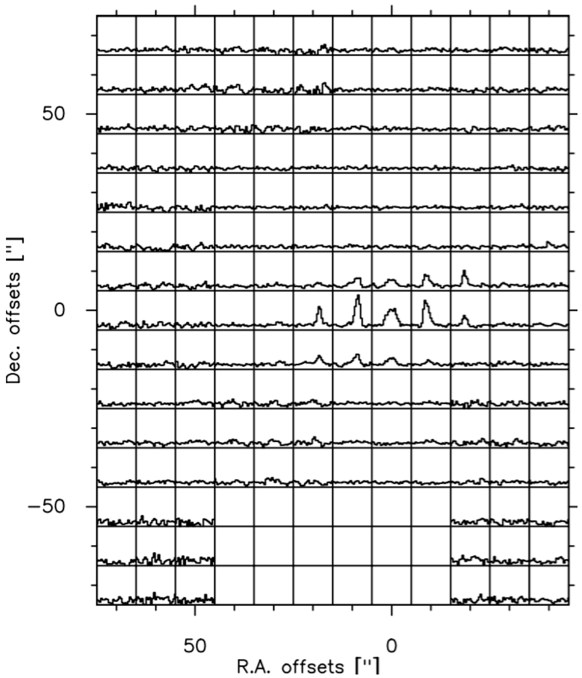


L_{IR} vs. $L'_{HCO+(4-3)}$



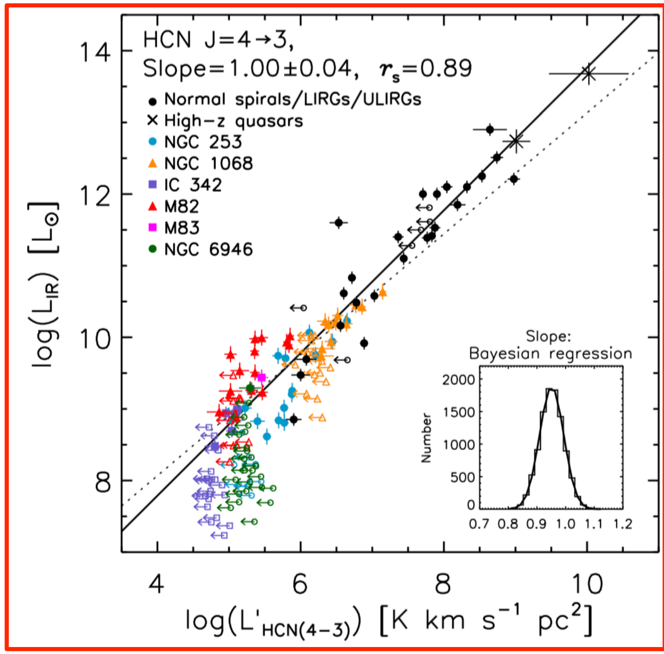
The MALATANG Survey: the $L_{gas} - L_{IR}$ correlation on sub-kiloparsec scale in six nearby star-forming galaxies

Jiggle-mapping:
2×2 arcmin^2 central region

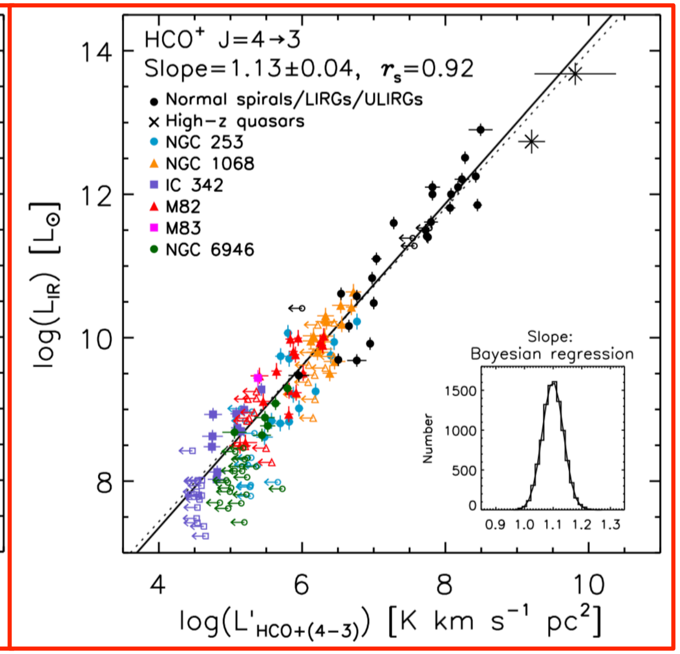


(Tan et al. 2018, ApJ)

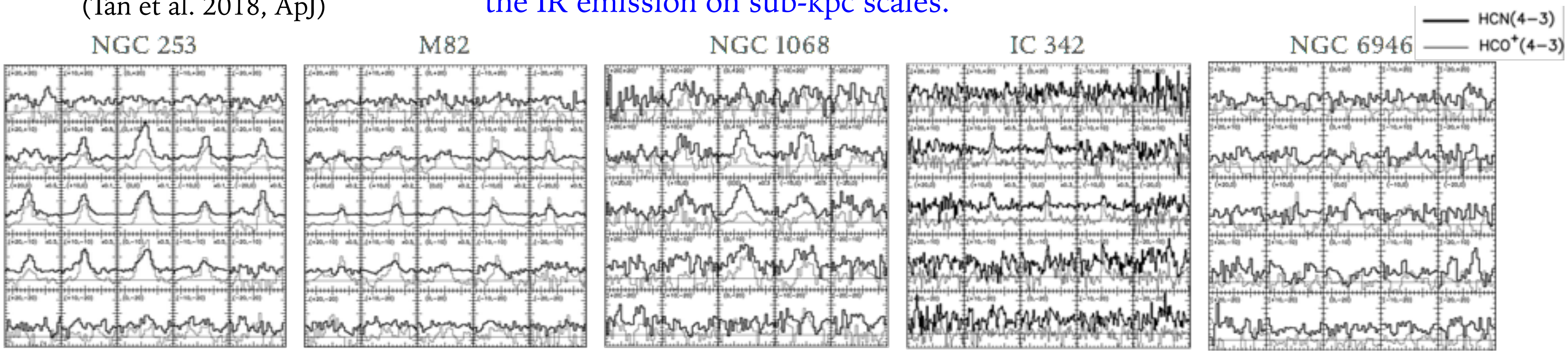
L_{IR} vs. $L_{HCN(4\text{-}3)}$



L_{IR} vs. $L_{HCO^+(4\text{-}3)}$

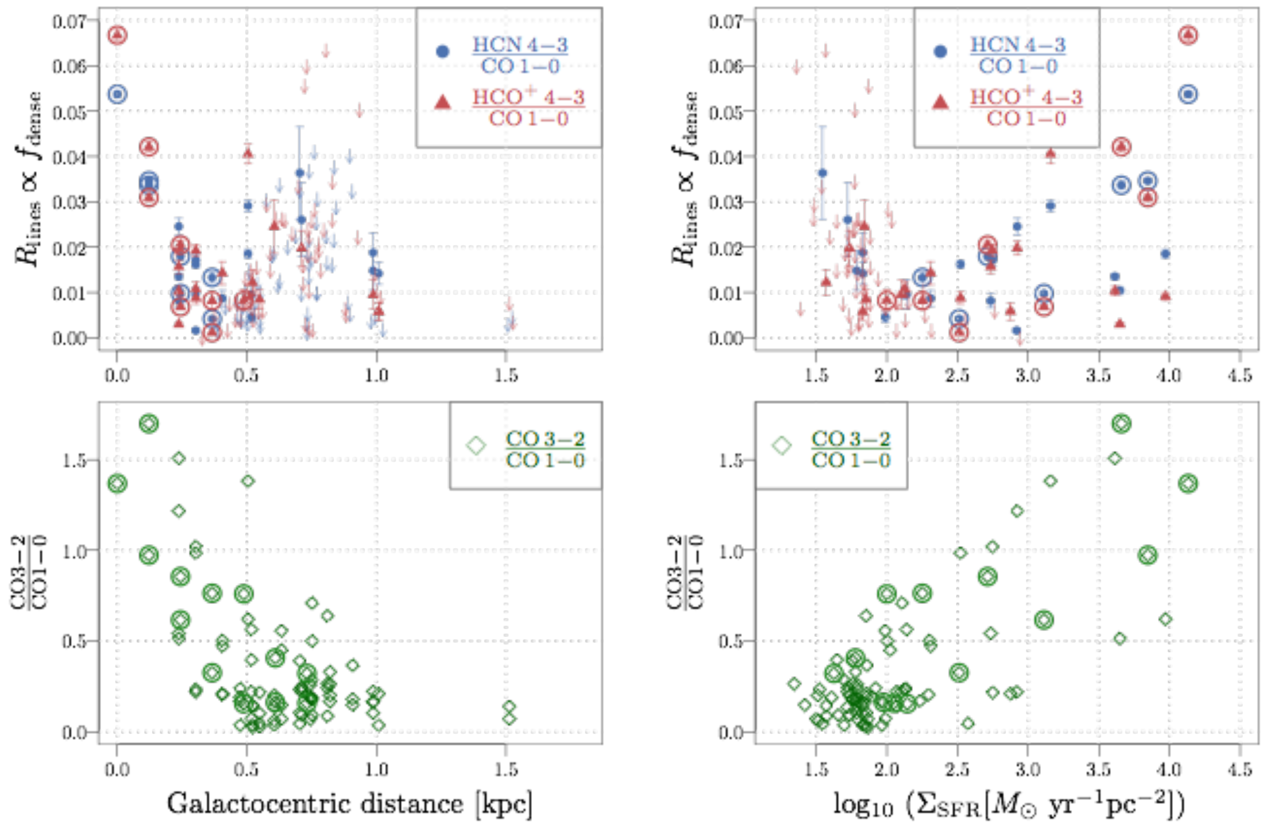


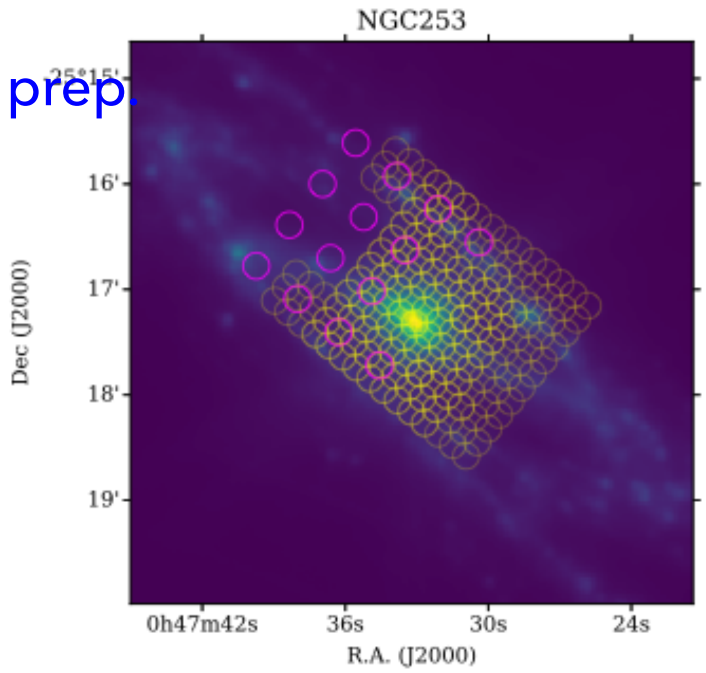
The dense gas traced by HCN(4-3) and HCO$^+$(4-3) is linearly correlated with the IR emission on sub-kpc scales.



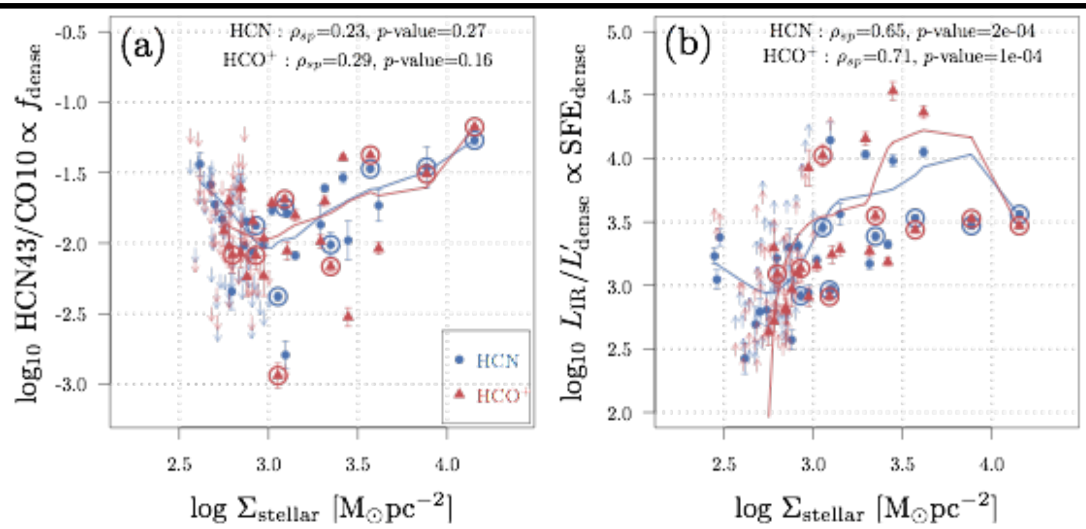
MALATANG – NGC 253

Jiang+19 in prep.





1. higher f_{dense} in NGC253 center and in higher Σ_{SFR}

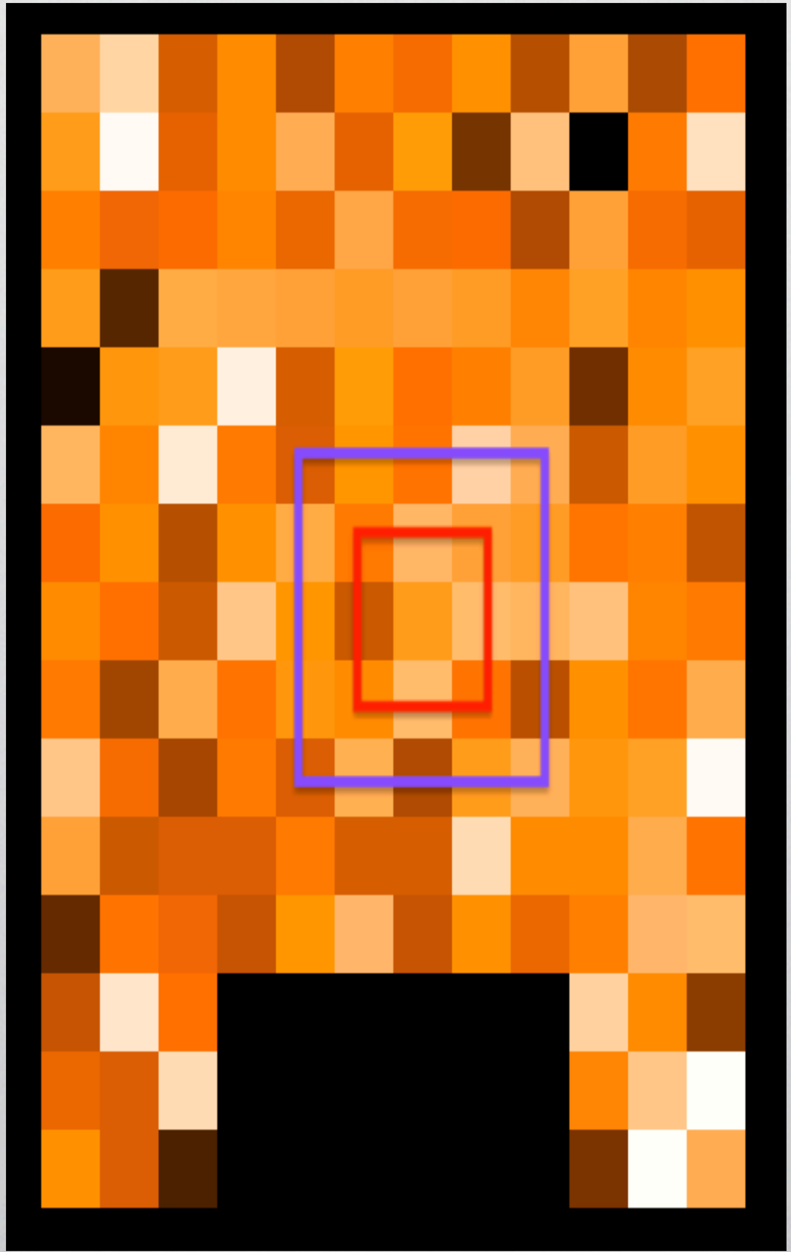


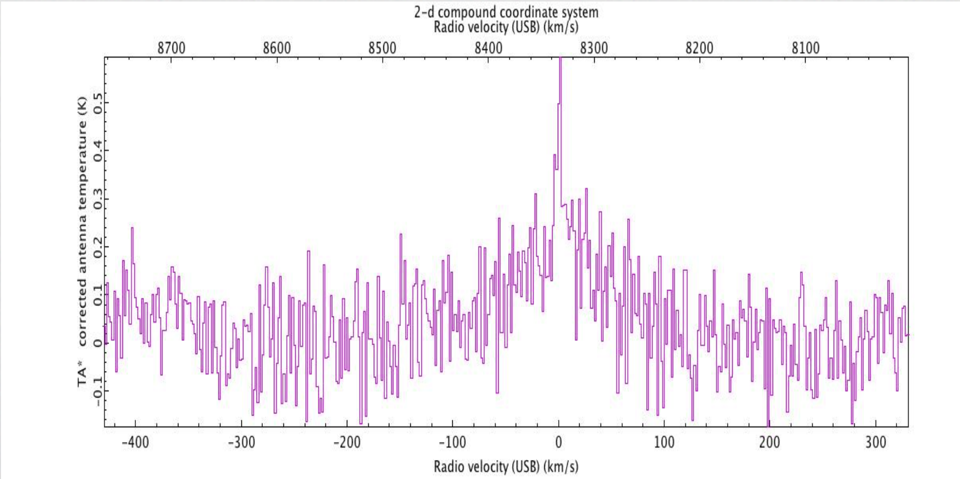
2. SFE vs. Σ_{star} seems different from Bigiel+06 (explanation: n_{crit} of 4-3 is 100 times higher than n_{crit} of 1-0. Hence tracing denser gas)

Stacking in M82
Wang, J (MS thesis)

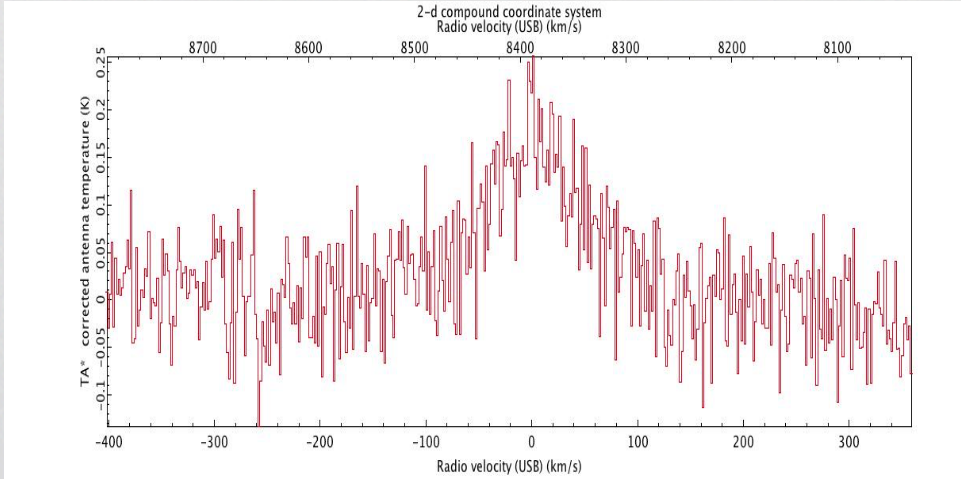
345471.66	345468	345480.21	345509.93	345587.97
345448.53	345444.17	345460.83	345517.07	345620.78
345445.96	345440.42	**345462.9**	345530.33	345624.26
345519.47	345467.47	345440.1	345470.36	345563.52
345542.24	345574.5	345478.3	345520.94	345591.76

CO J=3-2 central frequency (MHz)

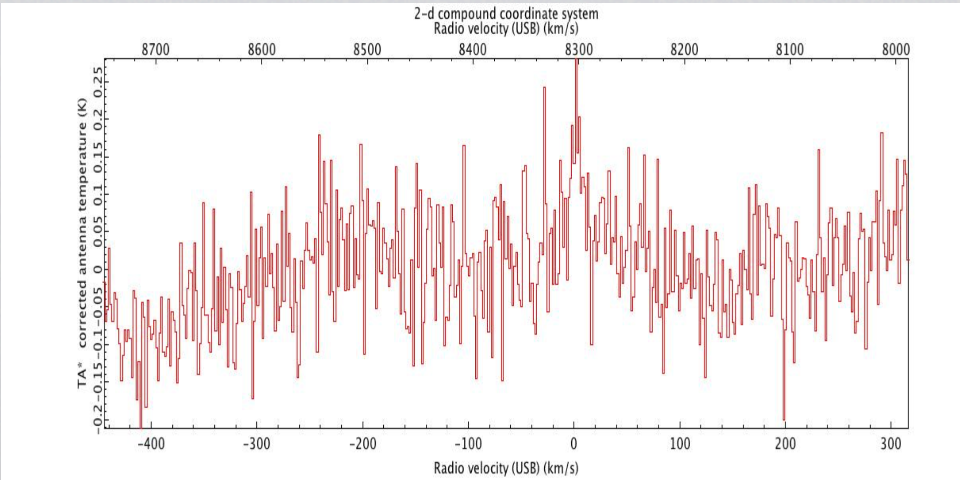


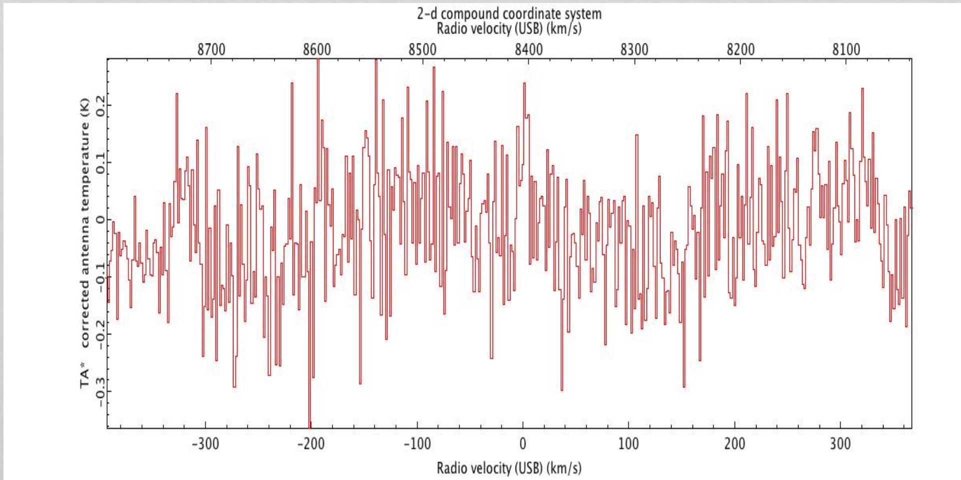


center-5x5



R1

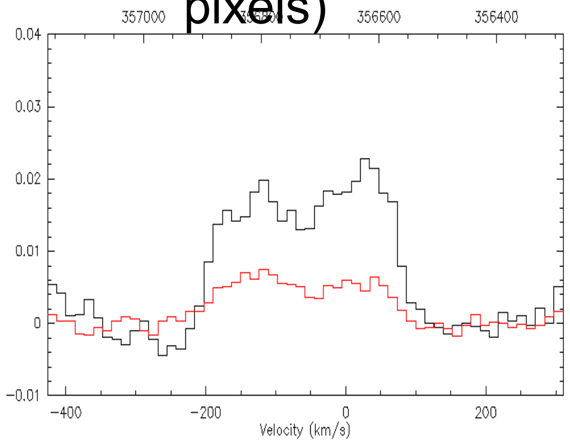




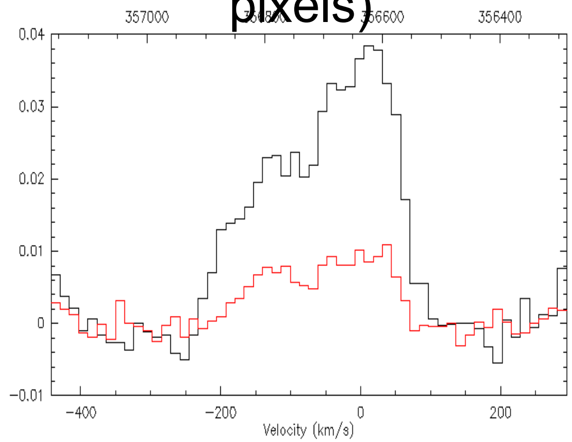
R2

R4

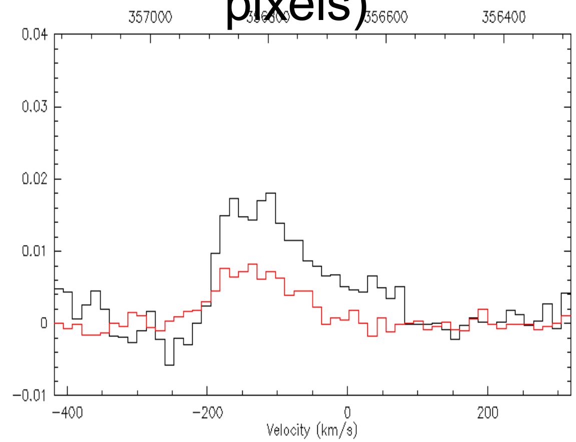
center (25 pixels)



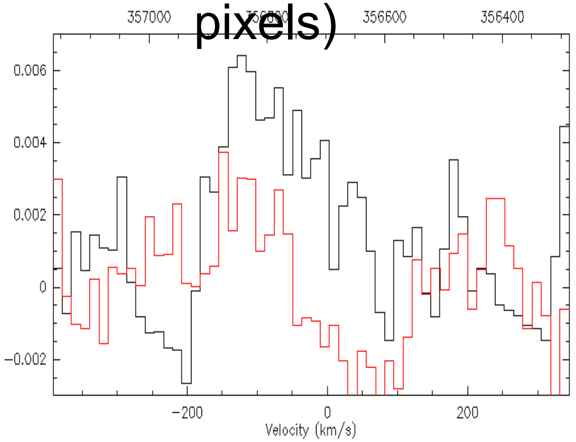
R1(8 pixels)



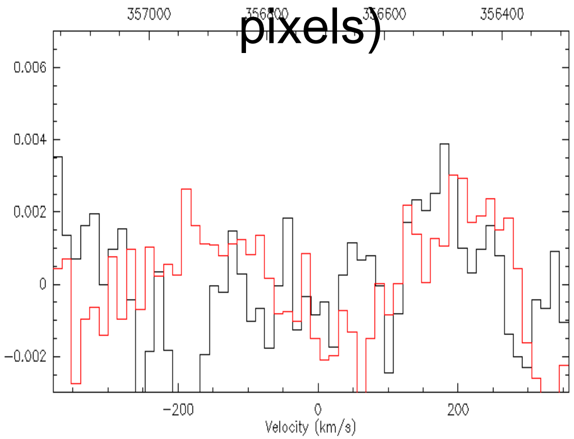
R2 (16 pixels)



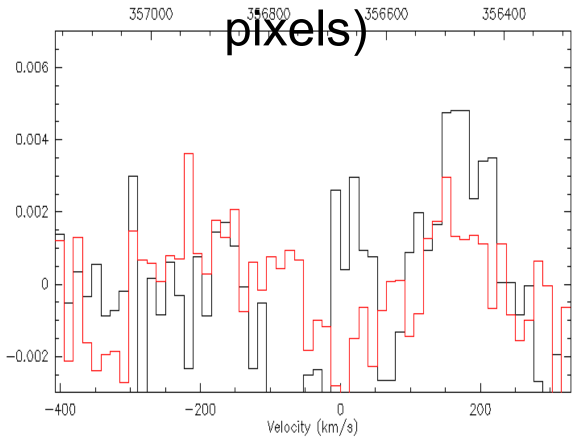
R3 (24 pixels)



R4 (30 pixels)

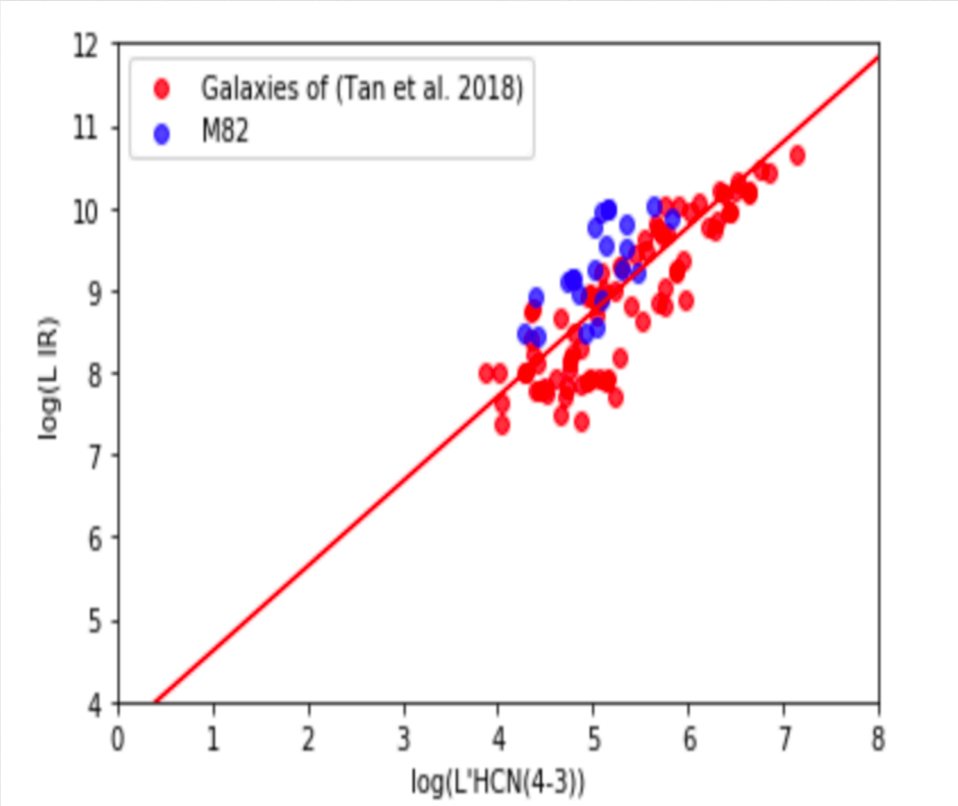


R5 (24 pixels)

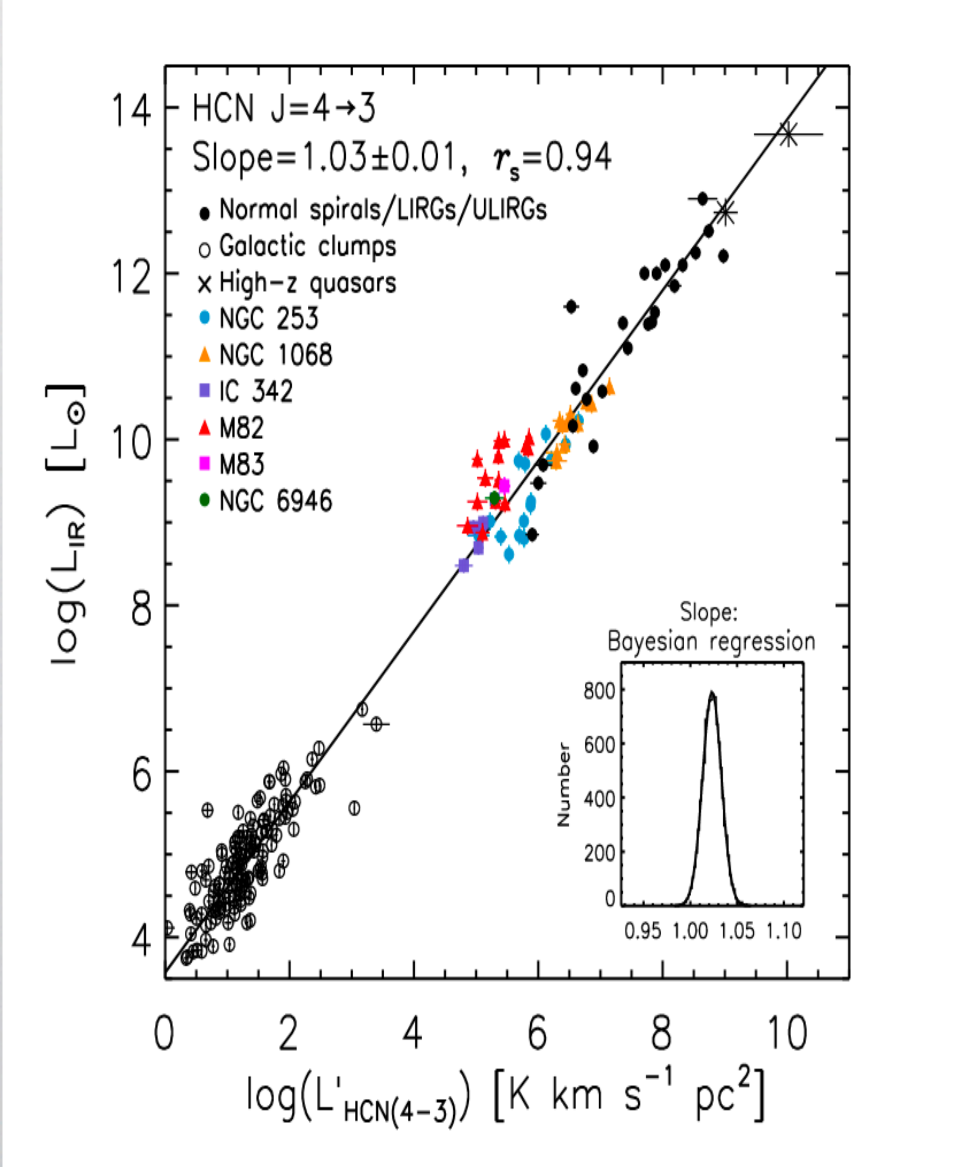


HCO^+ HCN

L'_{dense} - L_{IR} relation



This work



Tan et al. 2018

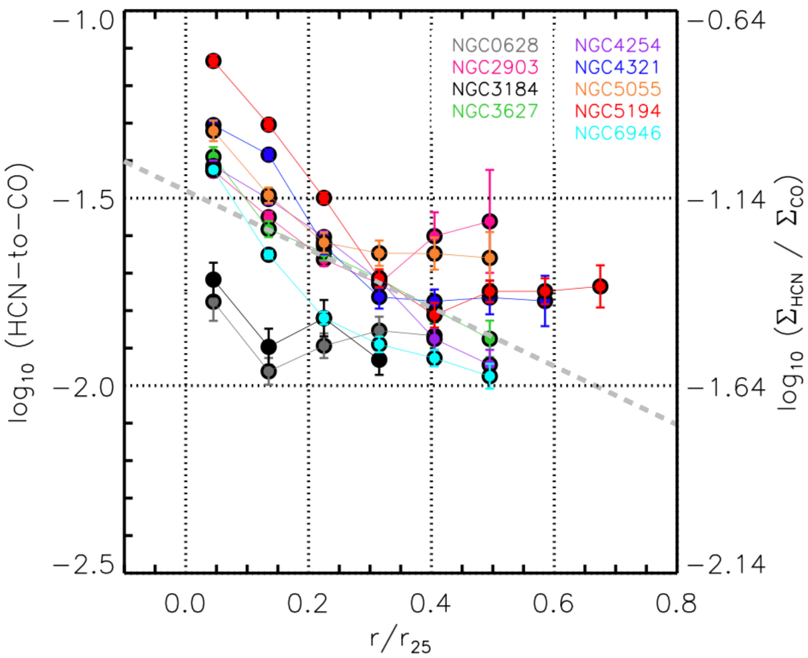
EMPIRE Galaxy Sample

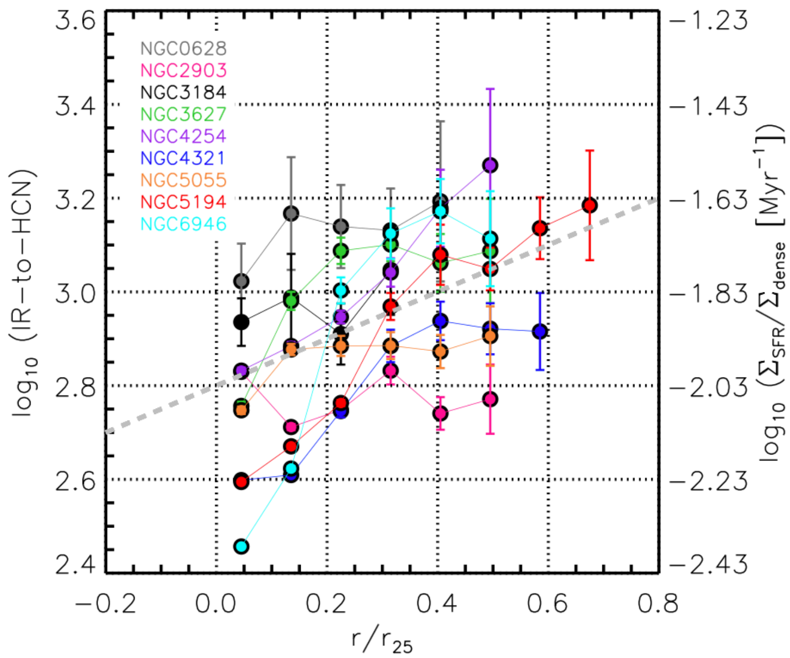
Galaxy	RA (EQ 2000) hh mm ss.s	DEC (EQ 2000) dd mm ss	i (^{o})	P.A. (^{o})	r_{25} (')	D (Mpc)	V_{hel} (km s^{-1})	Metal. 12+log(O/H)	Morph.	$\langle\Sigma_{SFR}\rangle$ ($M_\odot$ $yr^{-1}kpc^{-2}$)	$\log_{10}(M_*)$ $\log_{10}(M_\odot)$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
NGC 628	01:36:41.8	15:47:00	7	20	4.9	9.0	659.1	8.35	SAc	4.0×10^{-3}	10.0
NGC 2903	09:32:10.1	21:30:03	65	204	5.9	8.5	556.6	8.68	SABbc	5.7×10^{-3}	10.1
NGC 3184	10:18:17.0	41:25:28	16	179	3.7	13.0	593.3	8.51	SABcd	2.8×10^{-3}	10.2
NGC 3627	11:20:15.0	12:59:30	62	173	5.1	9.4	717.3	8.34	SABb	7.7×10^{-3}	10.5
NGC 4254	12:18:50.0	14:24:59	32	55	2.5	16.8	2407.0	8.45	SAc	18×10^{-3}	10.5
NGC 4321	12:22:55.0	15:49:19	30	153	3.0	15.2	1571.0	8.50	SABbc	9.0×10^{-3}	10.6
NGC 5055	13:15:49.2	42:01:45	59	102	5.9	8.9	499.3	8.40	SAbc	4.1×10^{-3}	10.5
NGC 5194	13:29:52.7	47:11:43	20	172	3.9	8.4	456.2	8.55	SAbc	20×10^{-3}	10.5
NGC 6946	20:34:52.2	60:09:14	33	243	5.7	7.0	42.4	8.40	SABcd	21×10^{-3}	10.5

Jiménez-Donaire et al. 2019

- EMPIRE used the IRAM 30-m telescope to map multiple molecular lines of nine nearby, face-on massive spiral galaxies. The J=1→0 transitions of HCN, HCO+, HNC, CO, 13CO, C18O, and other fainter lines were covered.
- Three EMPIRE galaxies have been also observed in MALATANG (NGC 2903, NGC3627, NGC6946).
- The EMPIRE survey spent about 70 hours per galaxy and achieved an r.m.s. noise level of 2-3 mK (T_{MB}),

EMPIRE Result





Jiménez-Donaire et al. 2019

New JCMT Proposal

N	Source Name	R.A.	Decl.	Distance	Diameter	$f_{60\mu m}$	$f_{100\mu m}$	$\log L_{FIR}$	$\log \Sigma_{SFR}$	$T_{peak}^{(HCN10)}$	$T_{peak}^{(HCN43)}$	$T_{disk}^{(HCN43)}$	$t_{obs-band3}^{(HCN43)}$	$t_{obs-band2(4)}^{(HCN43)}$
		(J2000)	(J2000)	(Mpc)	(arcmin)	(Jy)	(Jy)	($L_\odot$)	($M_\odot yr^{-1} kpc^{-2}$)	(mK)	(mk)	(mk)	(hrs)	band-2(4)(hrs)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
1	**Maffei 2**[a]	02 41 55.0	59 36 15	2.8	5.82×1.57	135	225	10.00	0.42	150	14[a]	10	10	5(23)
2	**M 83**[a]	13 37 00.9	−29 51 56	3.7	12.9×11.5	265.84	524.09	9.94	-1.44	23[b]	10[a]	5	46	23(120)
3	∗**M 51**	13 29 52.7	47 11 43	7.6	11.2×6.9	97.42	221.21	10.31	-1.78	30	21	5	30	17(68)
4	∗**NGC 0628**	01 36 41.8	15 47 00	9.0	12.0×12.0	21.54	54.45	9.82	-2.47	8	6	4	35	21(74)
5	∗**NGC 6946**[a]	20 34 52.3	60 09 14	5.5	11.5×9.8	129.78	290.69	10.01	-1.68	45	10[a]	4.5	46	25(112)
6	∗NGC 2903[a]	09 32 10.1	21 30 03	6.2	12.6×6.0	60.54	130.43	10.05	-1.22	10	3[a]	2	35	21(75)
7	∗NGC 3184	10 18 17.0	41 25 28	13.0	8.5×7.8	8.72	28.58	9.72	-2.55	6	4	3.5	14	8(29)
8	∗NGC 3627[a]	11 20 14.9	12 59 30	8.1	9.1×4.2	66.31	136.56	10.24	-1.43	12	5[a]	3	18	11(37)
9	∗NGC 4254	12 18 50.0	14 24 59	16.8	5.7×4.7	37.46	91.86	10.42	-1.54	12	8	3.5	12	8(24)
10	∗NGC 4321	12 22 55.0	15 49 19	15.2	6.8×5.8	26.00	68.37	10.28	-1.6	15	10	3.5	12	7(25)
11	∗NGC 5055	13 15 49.3	42 01 45	7.5	12.6×7.2	40.00	139.82	10.01	-1.63	11	8	5	8	5(17)

- We have proposed to extend the MALATANG to map HCN J=4→3 and HCO+ J=4→3 in all EMPIRE galaxies including 5 JIGGLE maps with JCMT.
- We need a total of 476 hours band 3 time to reach an r.m.s. noise level of 2-3 mK (T_A).

New APEX Proposal

Source Name	R.A. (J2000)	Decl. (J2000)	Distance (Mpc)	Diameter (arcmin)	$f_{60\mu m}$ (Jy)	$f_{100\mu m}$ (Jy)	$\log L_{FIR}$ ($L_\odot$)	$T_{peak}^{(HCN43)}$ (mK)	Sampling (pixels)	$T_{disk1}^{(HCN43)}$ (mk)	$T_{disk2}^{(HCN43)}$ (mk)	$t_{obs}^{(HCN43)}$ (hrs)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
NGC 3256[a]	10 27 52.4	−43 54 25	35.4	1.8×1.3	102.63	114.31	11.43	10	3×1	5.8, 3.4[c]	...	5.0(0.68+1.09+3.25)
NGC 4945[a]	13 05 27.6	−49 28 09	3.9	26.0×6.0	625.46	1329.70	10.41	130	5×5	7.3	1.5	28.5(0.004+0.074*8+1.745*16)
NGC 5128	13 25 27.6	−43 01 12	4.0	6.0×5.0	213.29	411.89	9.94	78[b]	5×5	32.3	8.9	13.5(0.011+0.065*8+0.811*16)
NGC 7552[a]	23 16 09.5	−42 35 09	21.4	1.8×0.8	77.37	102.92	10.88	14	3×3	5.6	...	16.5(0.34+2.0*8)
NGC 7582	23 18 22.2	−42 22 19	21.3	2.6×0.7	52.20	82.86	10.73	42[b]	3×3	8.7	...	7.5(0.038+0.89*8)

- We have proposed to use the SEPIA345 receiver on APEX to map the HCN (4-3), HCO+ (4-3), CS (7-6), and CO (3-2) simultaneously along the major axes of five nearest/ brightness Southern galaxies with declination < -40 degree.
- We need a total of 79 hours under the weather condition of 1.0mm pwv.

Summary

- Dense Molecular Gas → High Mass Stars
- SFR ~ M(DENSE), **linear?!** dense gas
- Dense gas tracers (e.g. HCN, CS, HCO+ COJ>3, H_2O… density >~10^5 cc), linear!
- HI → H_2 → DENSE H_2 → Stars

Schmidt law : HI(gas reservoir) → Stars X

Kennicutt : HI(gas reservoir) + H_2(fuel ?!)→ Stars X

Gao & Solomon: Dense H_2 (fuel !!) → Stars!?

from Cores to High-z: Dense Gas→Massive SF

*HCN/HCO+(4-3) still the linear correlation with far-IR: globally and resolved regions provided by MALATANG

*Variations and scatters in the linear correlations: physics!

*Sino-German collaboration grants: synergy empire/malatang/paws