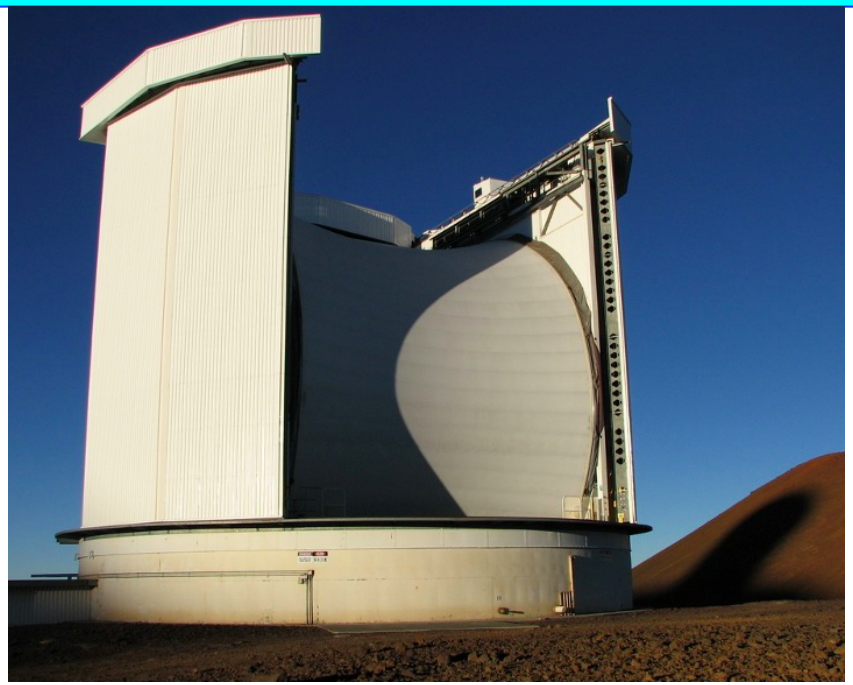
The far-IR and HCN correlations from molecular cloud cores to global galaxies



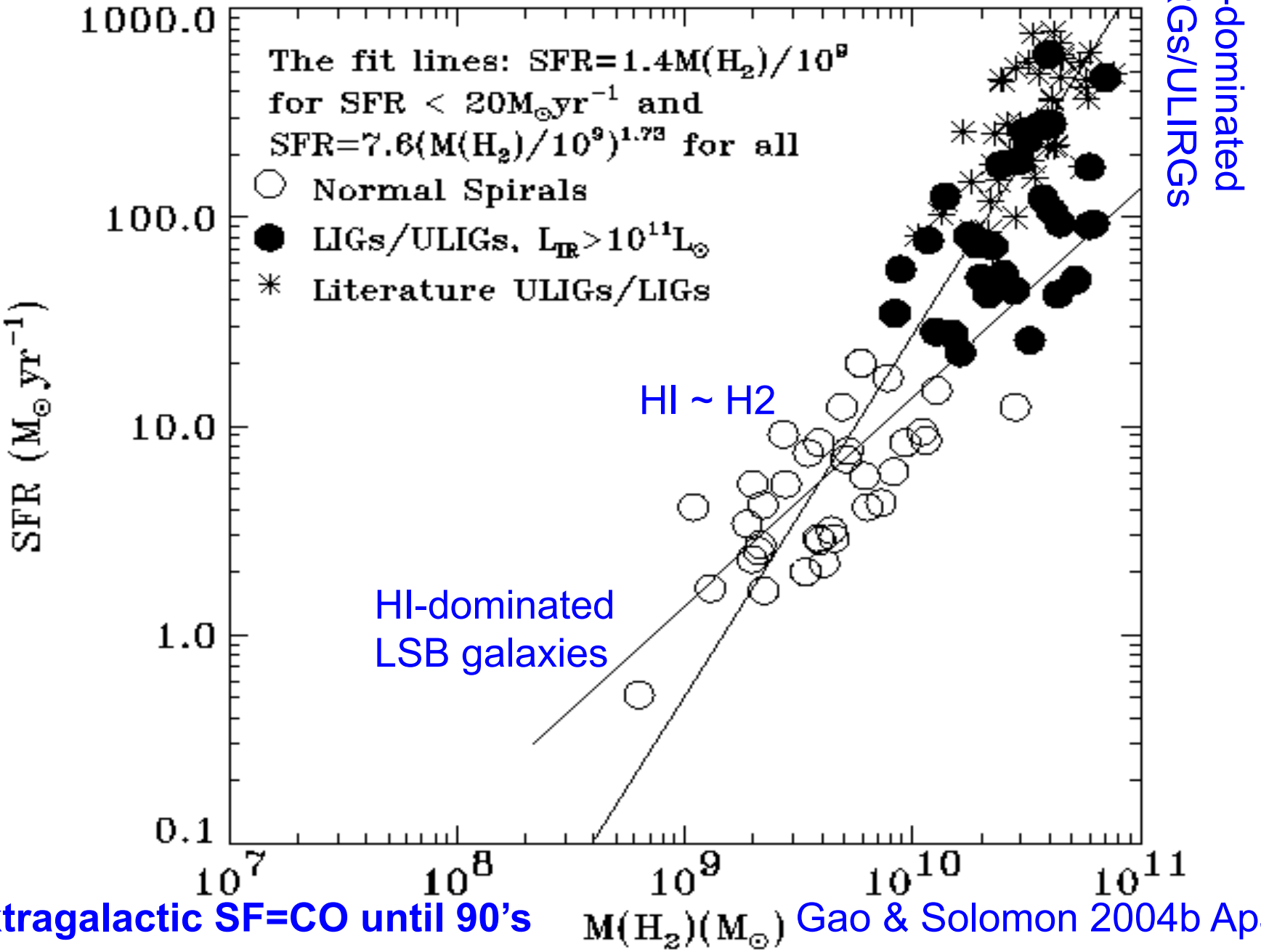
Yu GAO

Purple Mountain Observatory

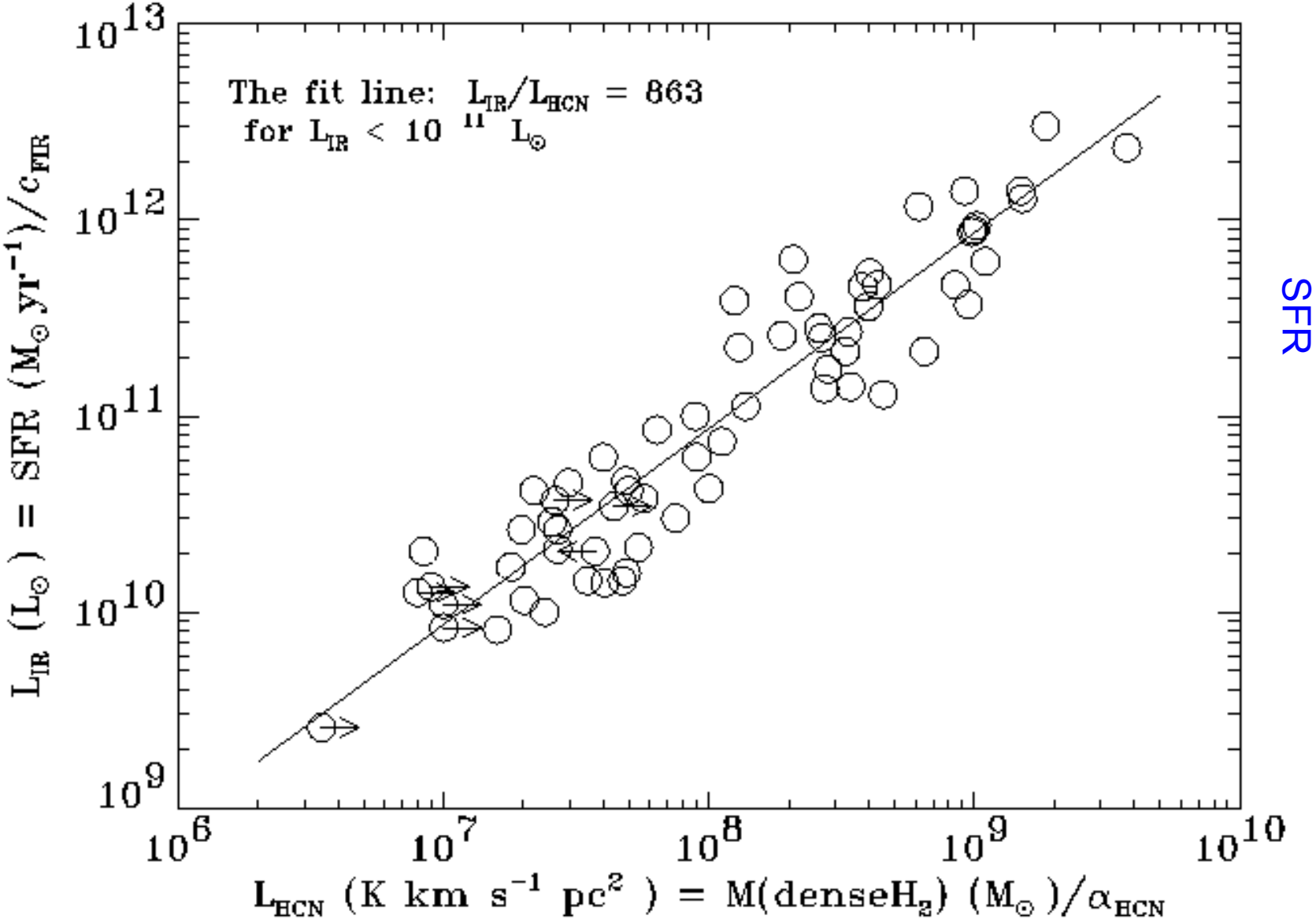
Mar.27th@Bamberg,ISM2018

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 ***Yang***+2013/2016/2017; 6 Tan, Gao+ 2018 ApJ re-sub.

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



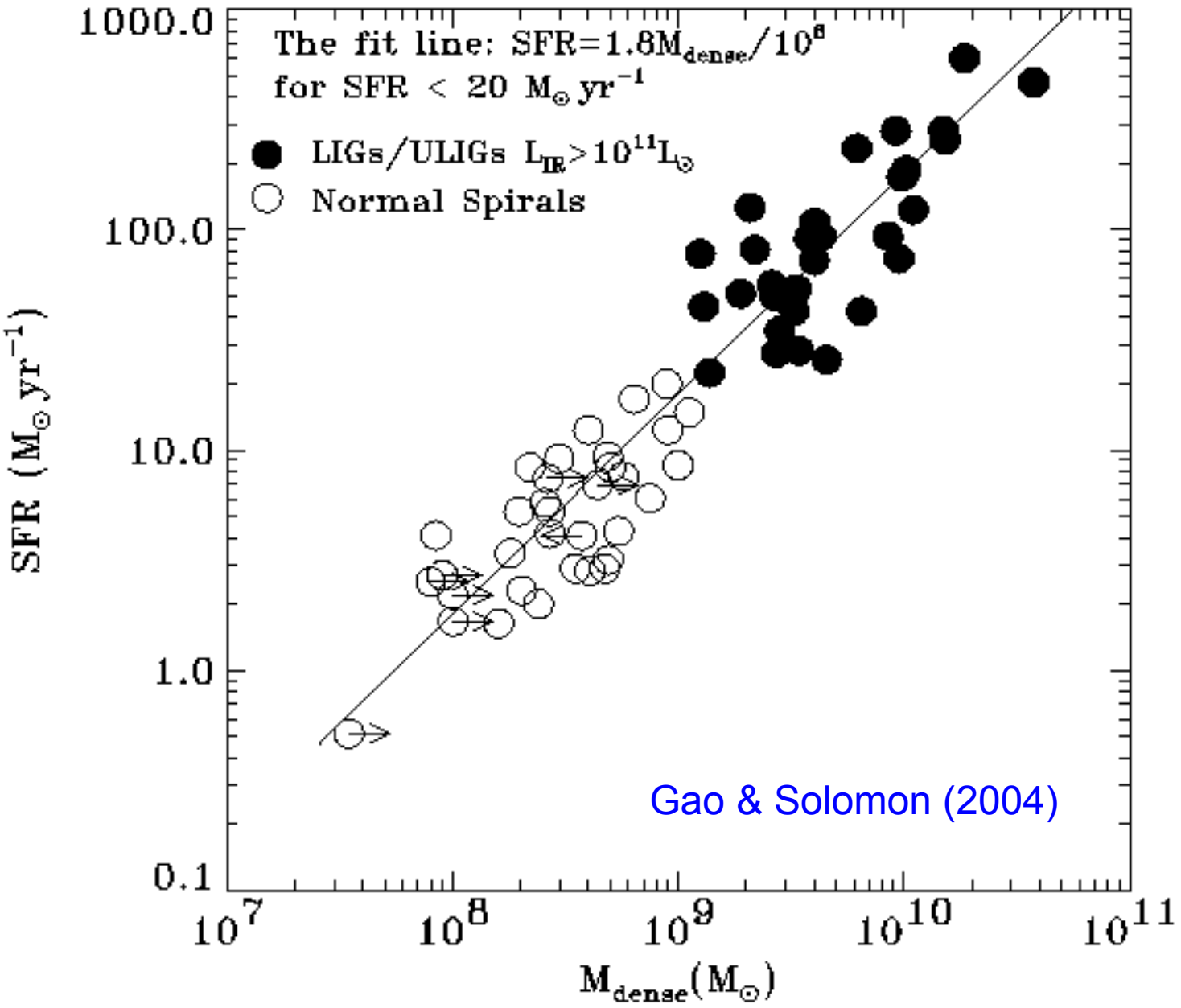
Extragalactic SF=CO until 90's Gao & Solomon 2004b ApJ



SFR

Dense Molecular Gas

SFR vs. M_dense(H2): linear correlation

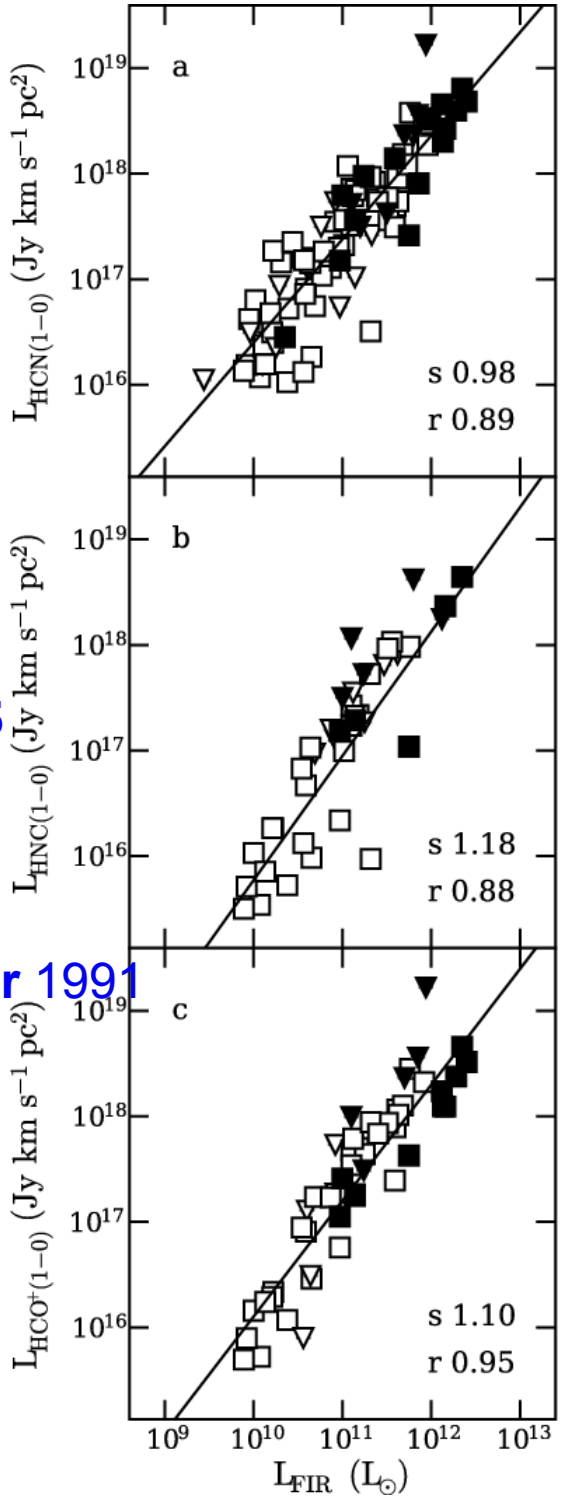


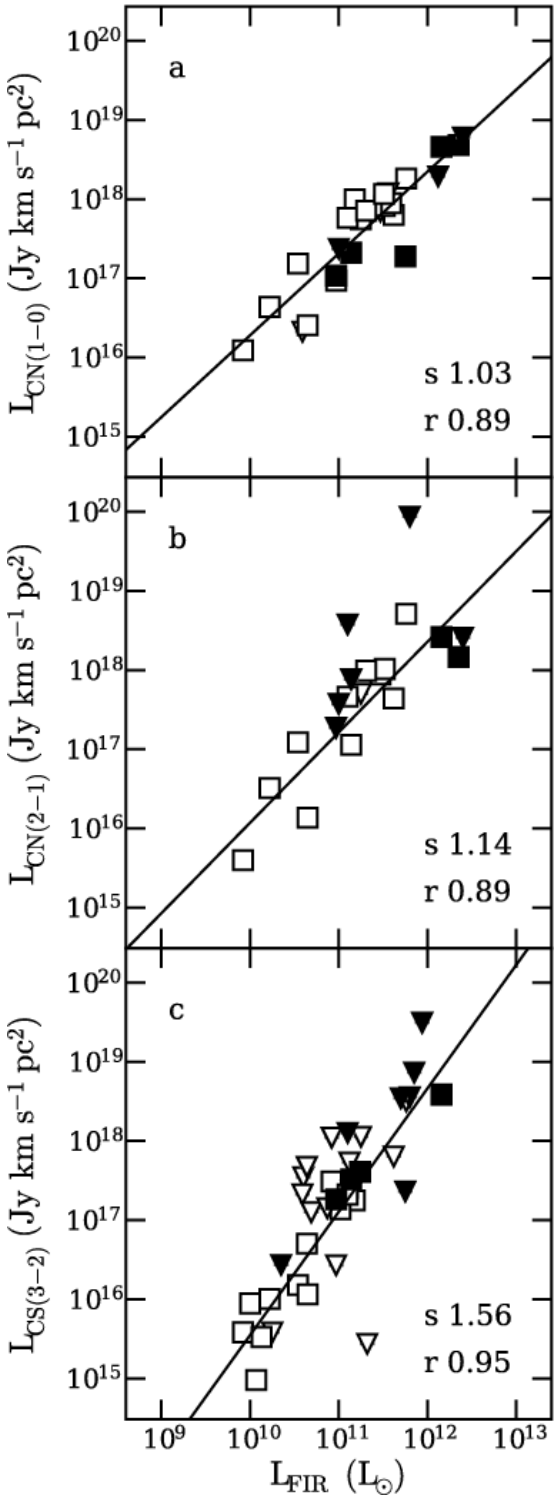
Baan, Henkel, Loenen + 2008

HCN,CS,HNC etc. in SF gals.

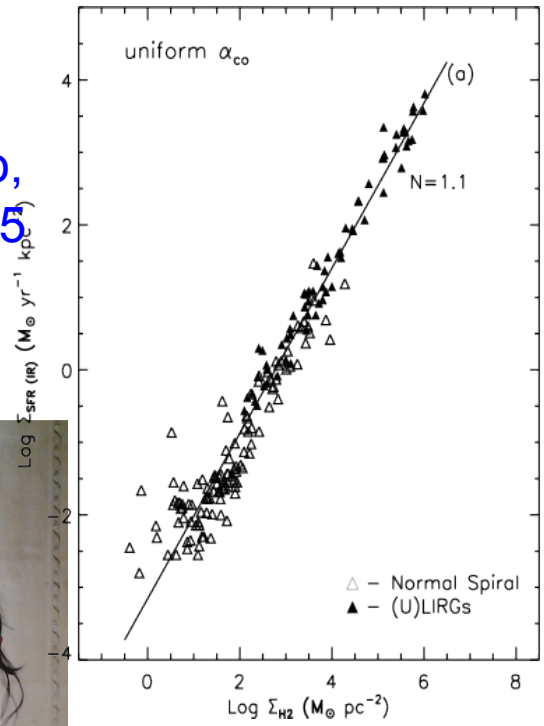
- **Baan et al. (2008)**
- **Kohno 2007, et al. (2003)**
- **Imanishi 2006, et al. 2009, 2013, 2016a,b**
- **Aalto et al. 2007, 2002, 1995**
- **Solomon et al. 1992**
- **Nguyen** et al. 1992
- **Henkel et al. 1990**
- **Henkel, Baan, Mauersberger** 1991

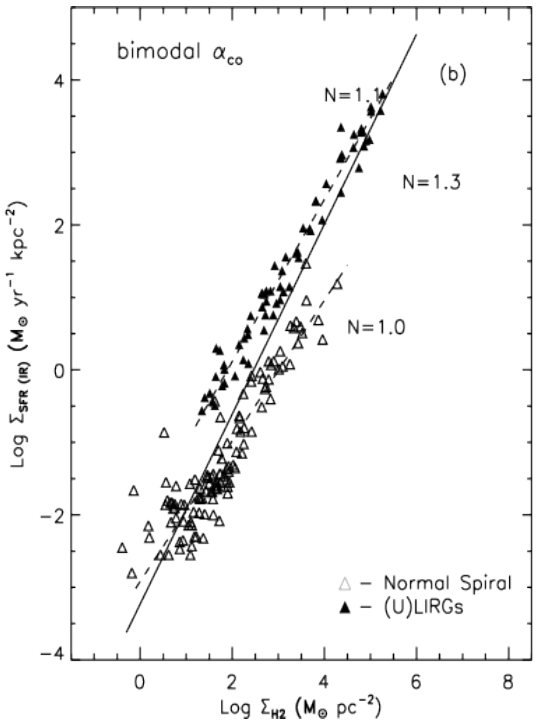
Best case studies:
Arp 220 & NGC 6240
(Greve + 2009)

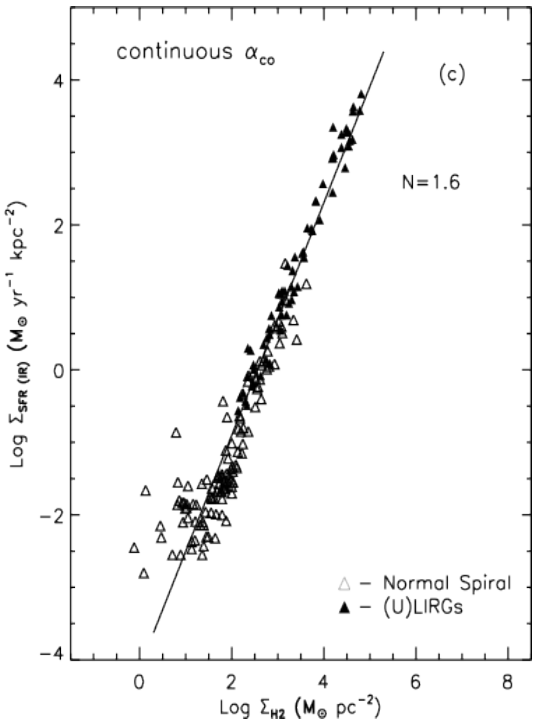


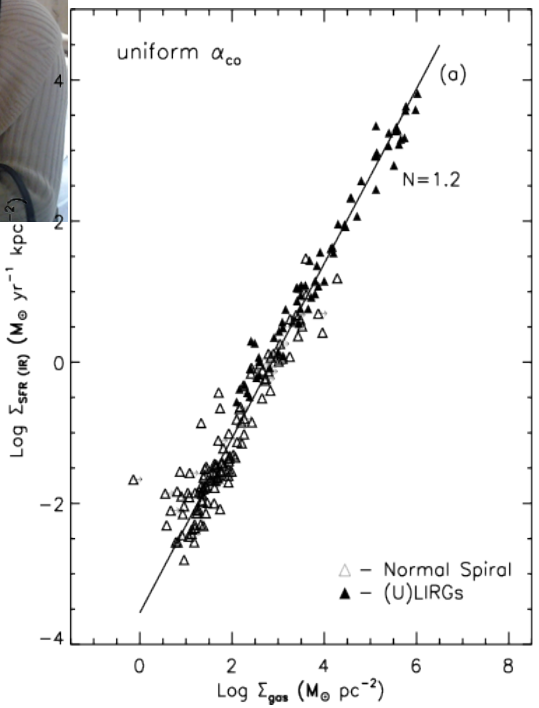


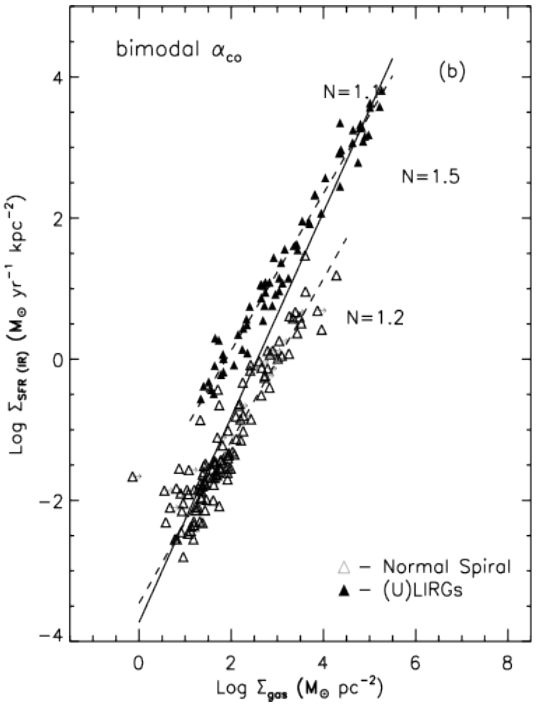
Liu, Gao, Greve 15

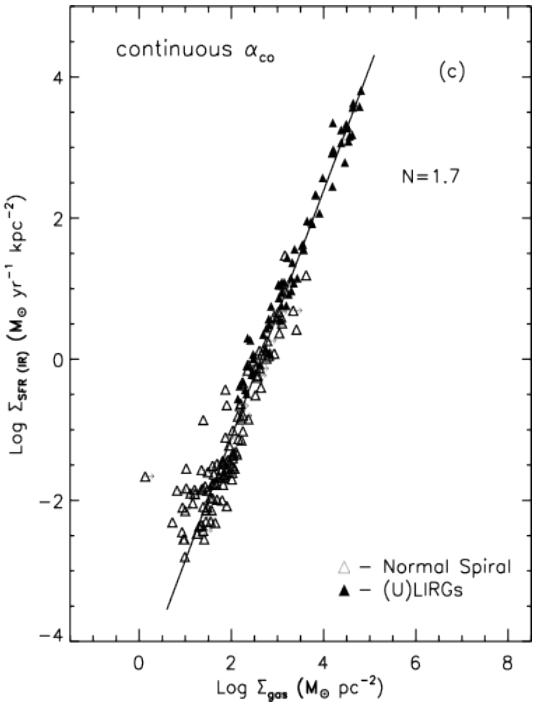


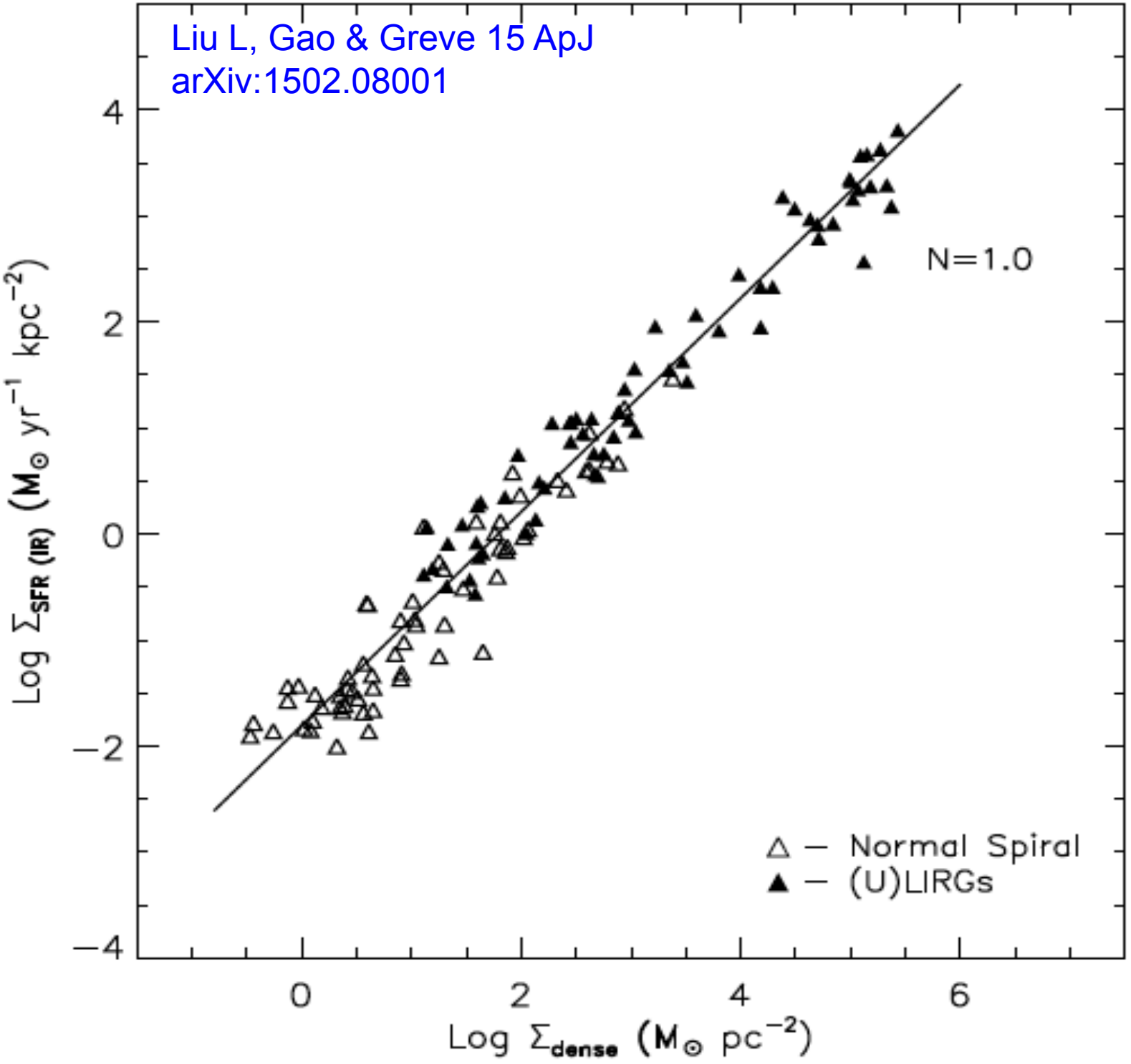




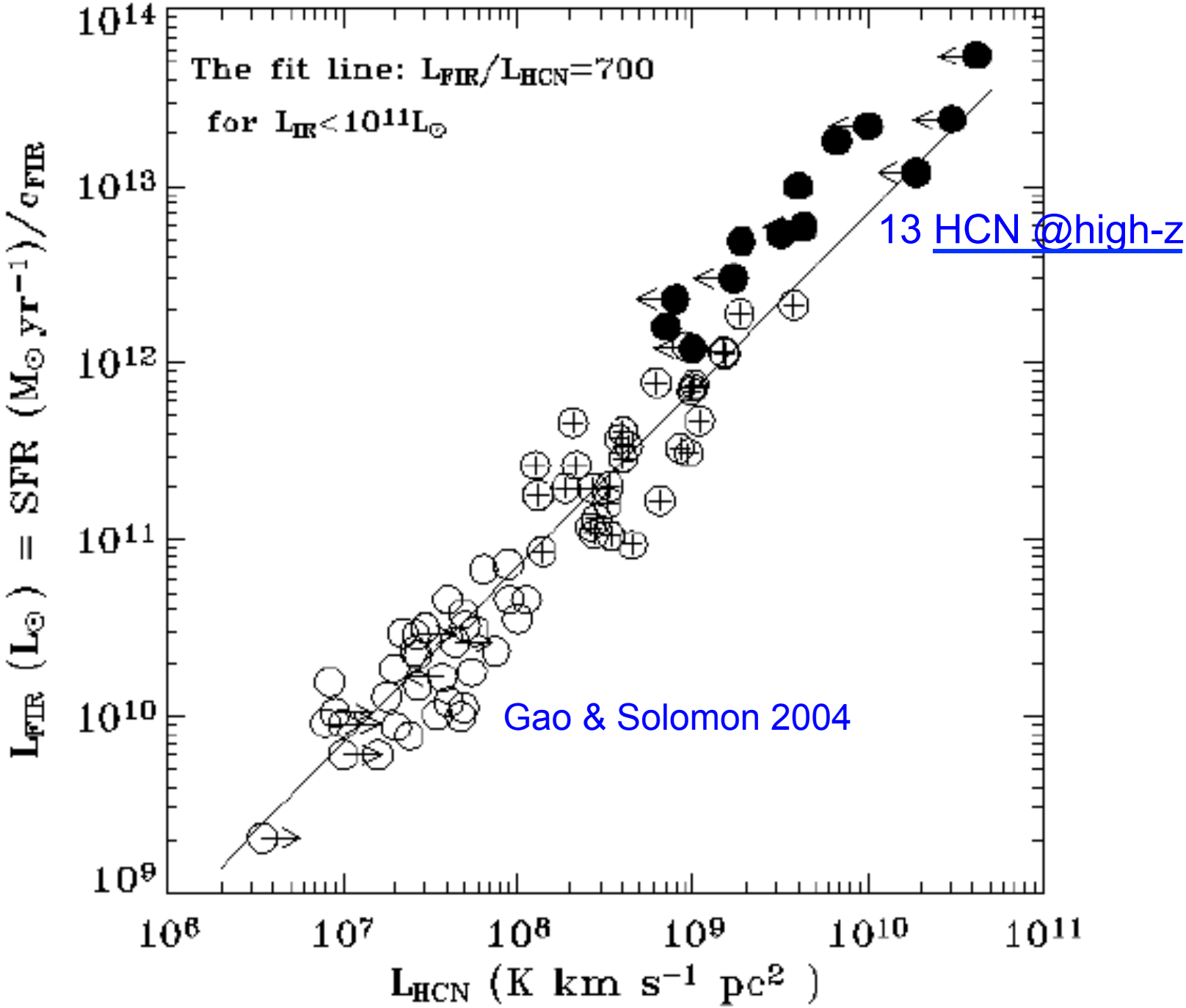







Liu L, Gao & Greve 15 ApJ
arXiv:1502.08001
N=1.0
△ — Normal Spiral
▲ — (U)LIRGs
Log $\Sigma_{SFR\ (IR)}$ ($M_\odot$ yr^{-1} kpc^{-2})
Log Σ_{dense} ($M_\odot$ pc^{-2})
4
2
0
−2
−4
0
2
4
6

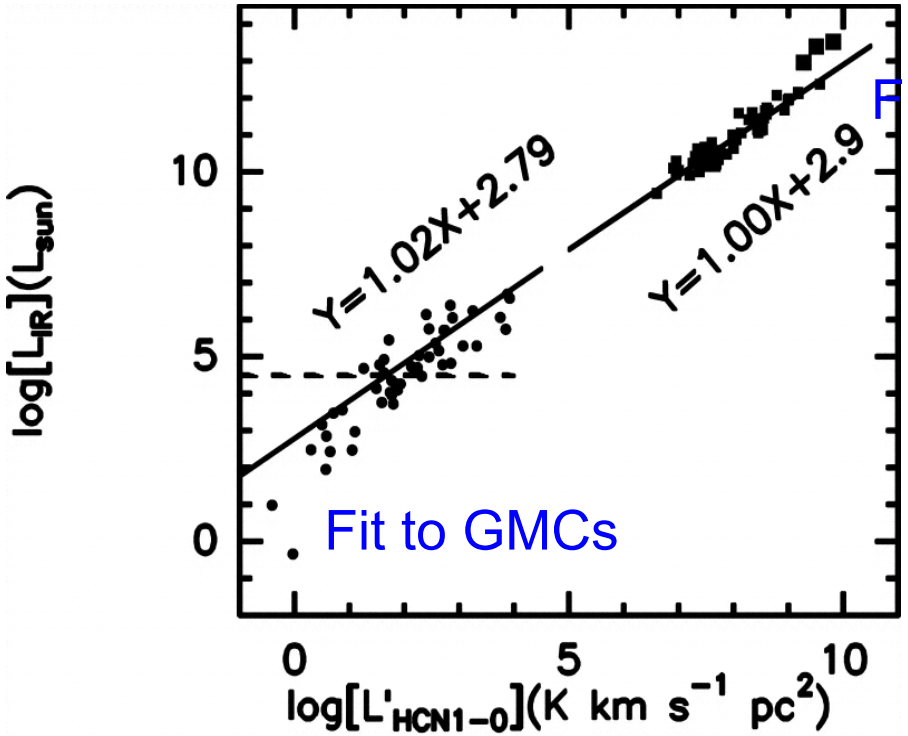
Gao, Carilli, Solomon & Vanden Bout 2007 ApJ, 660, L93



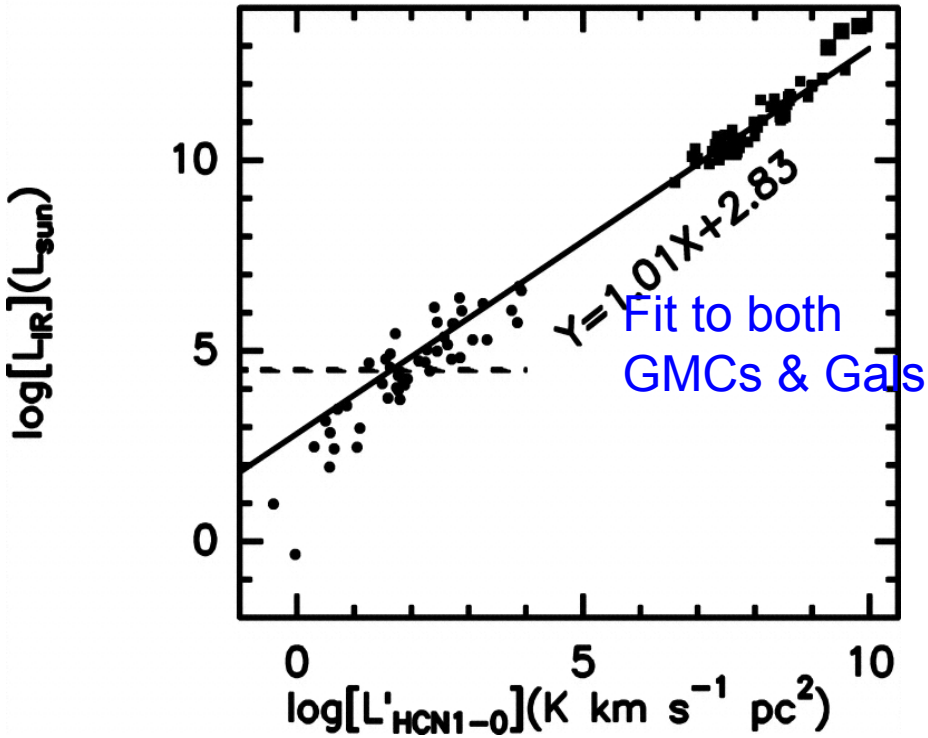
13 HCN @high-z

Gao & Solomon 2004

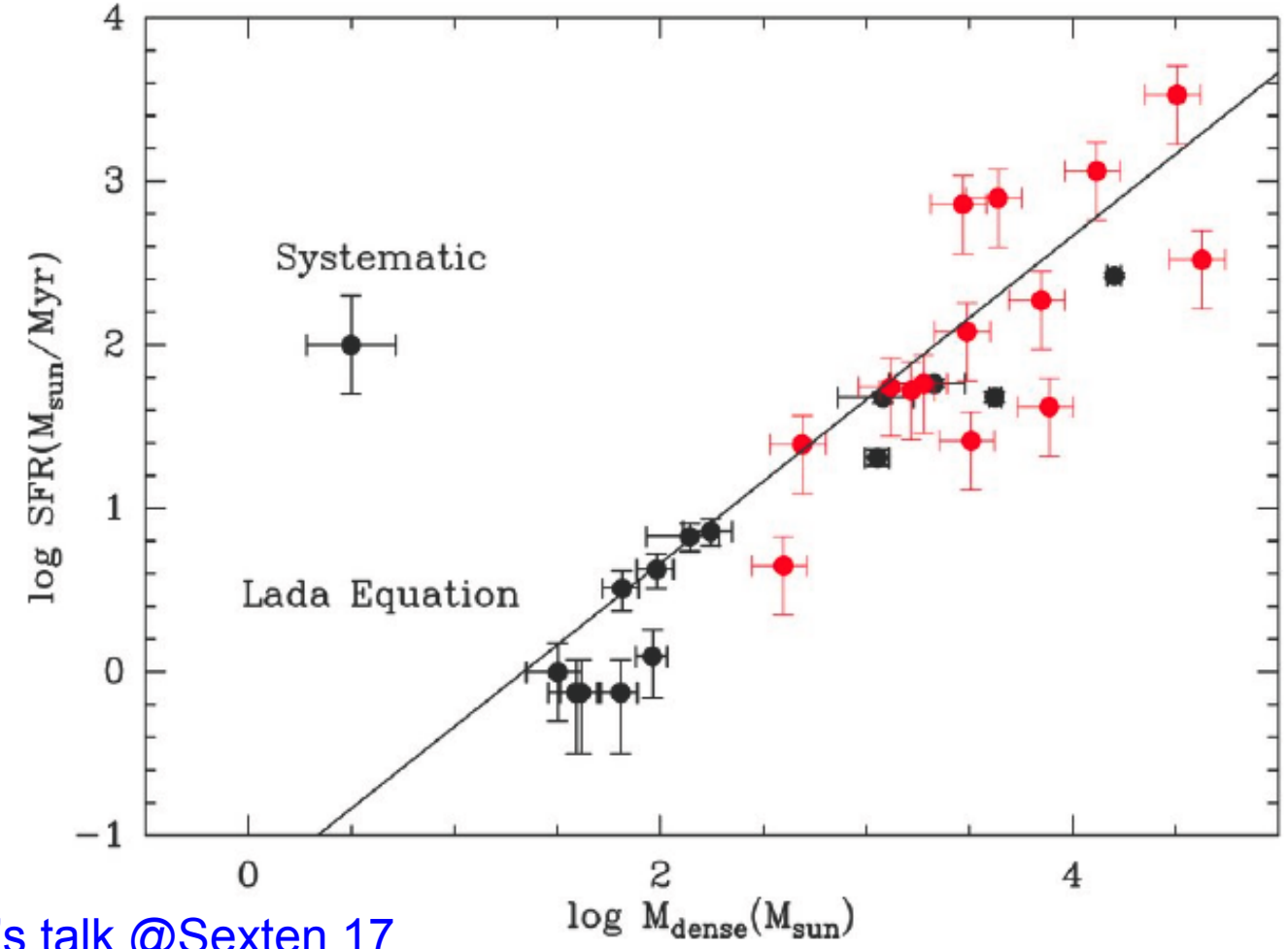
Wu, Evans, Gao et al. 2005 ApJL



Wu+2010



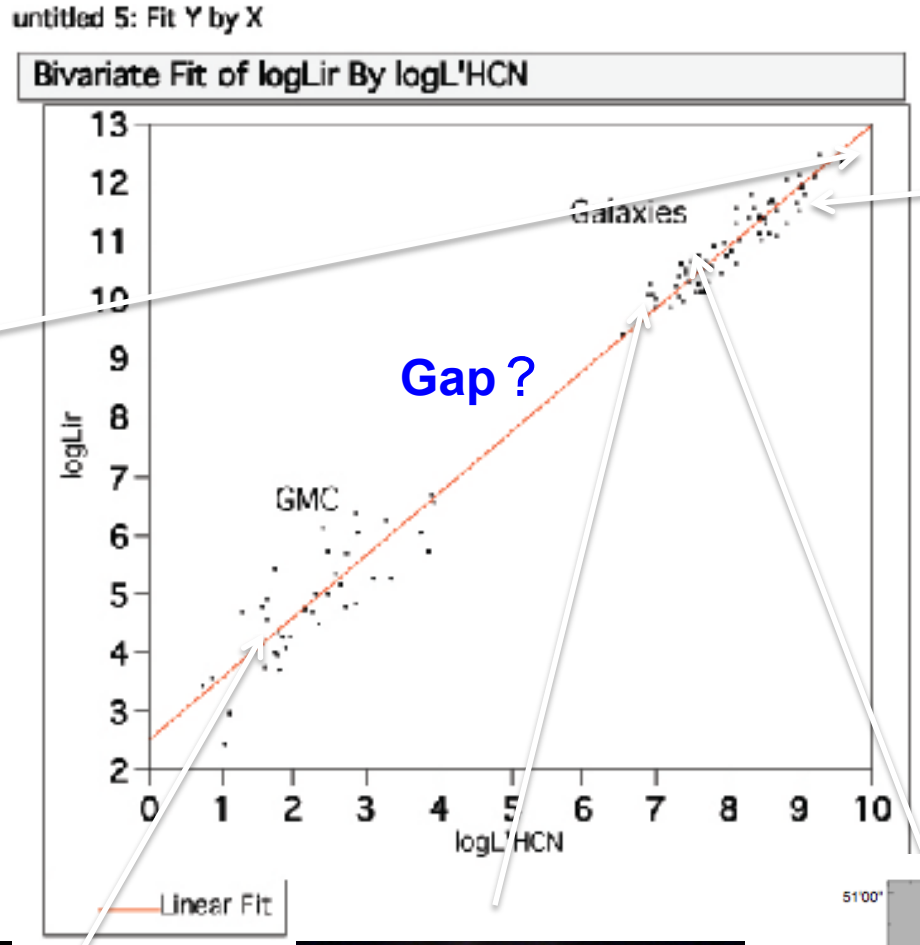
Several studies of the Milky Way find that the amount of dense gas (from a column density threshold or defined by as gas emitting in some high critical density line) is the best predictor of star formation in a given molecular cloud.

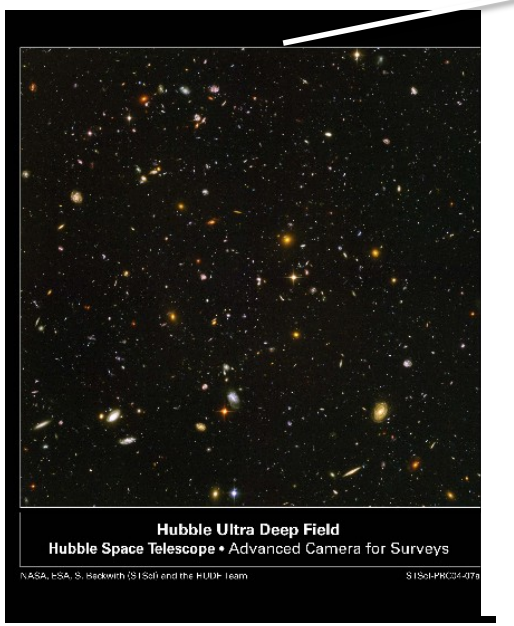


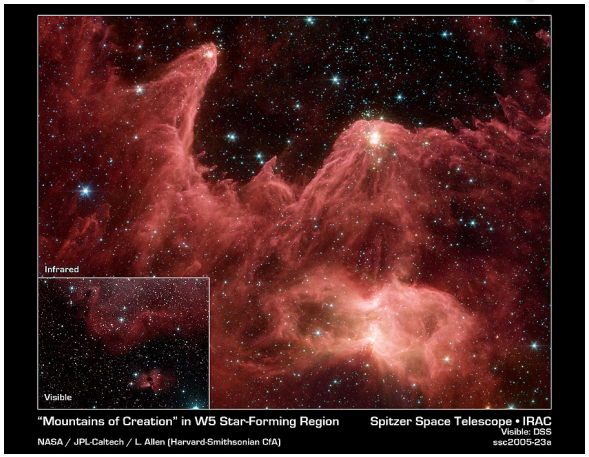
Leroy's talk @Sexten 17

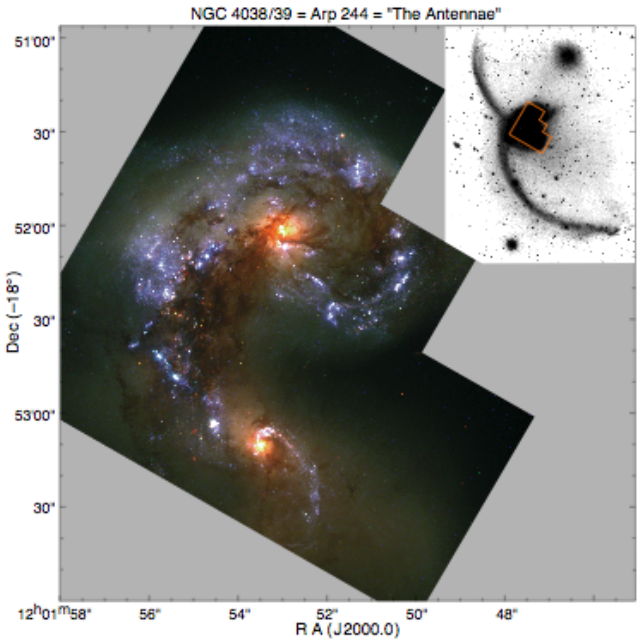
EVANS ET AL. (2014), VUTISALCHAVAKUL ET AL. (2016), LADA ET AL. (2010, 2012), WU ET AL. (2005, 2010)

Can dense cores in galaxies fill in the gap in FIR-HCN corr.?

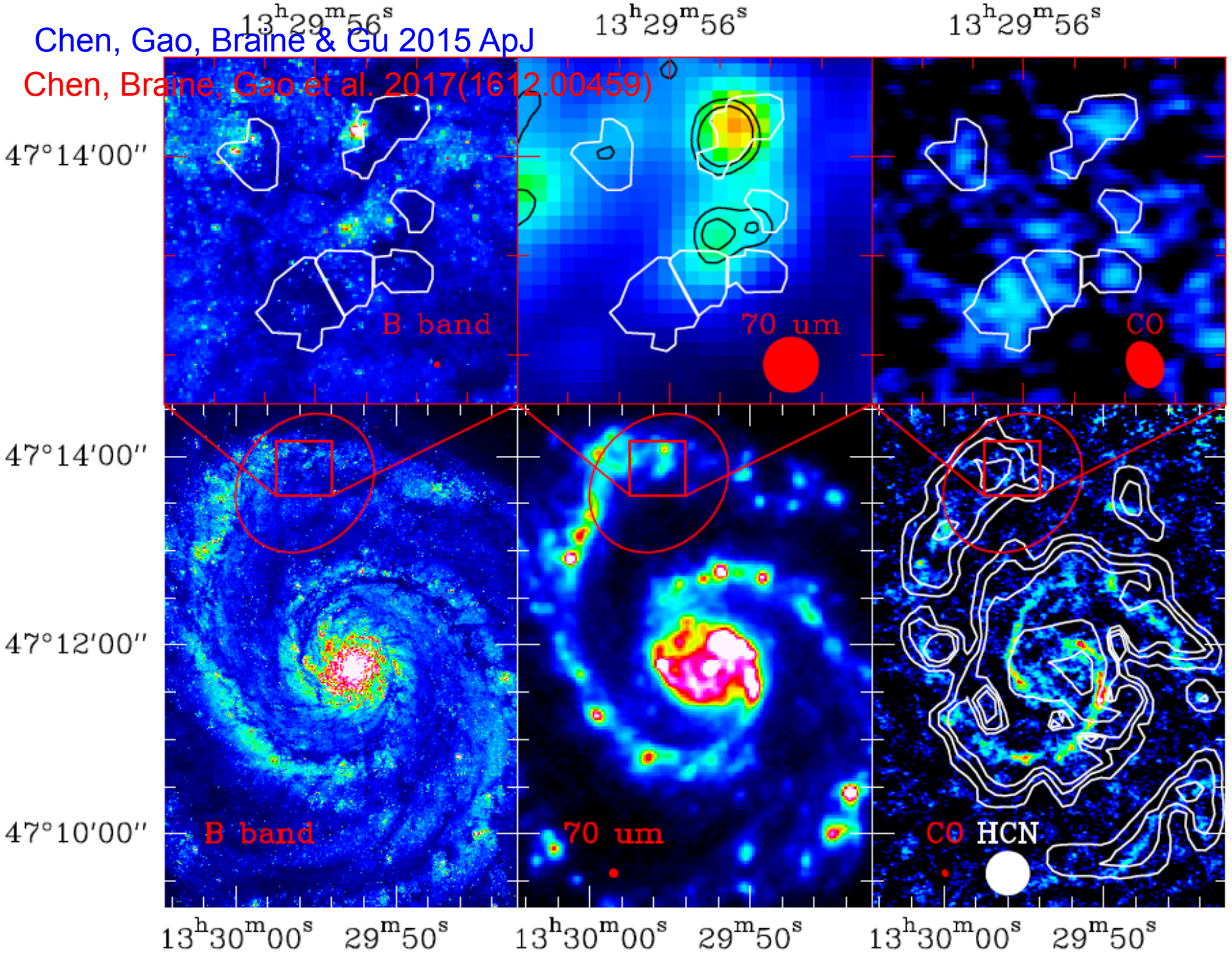


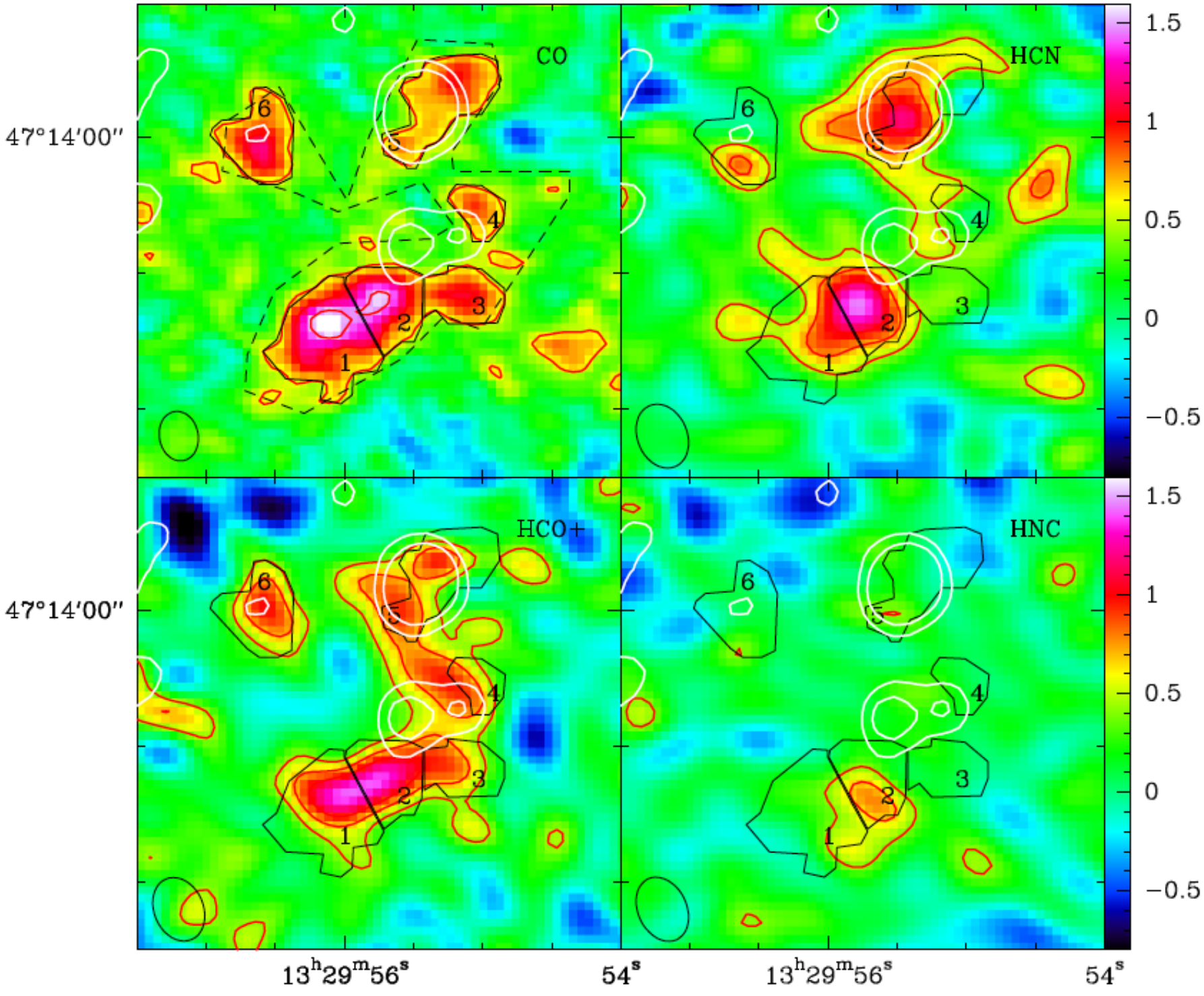


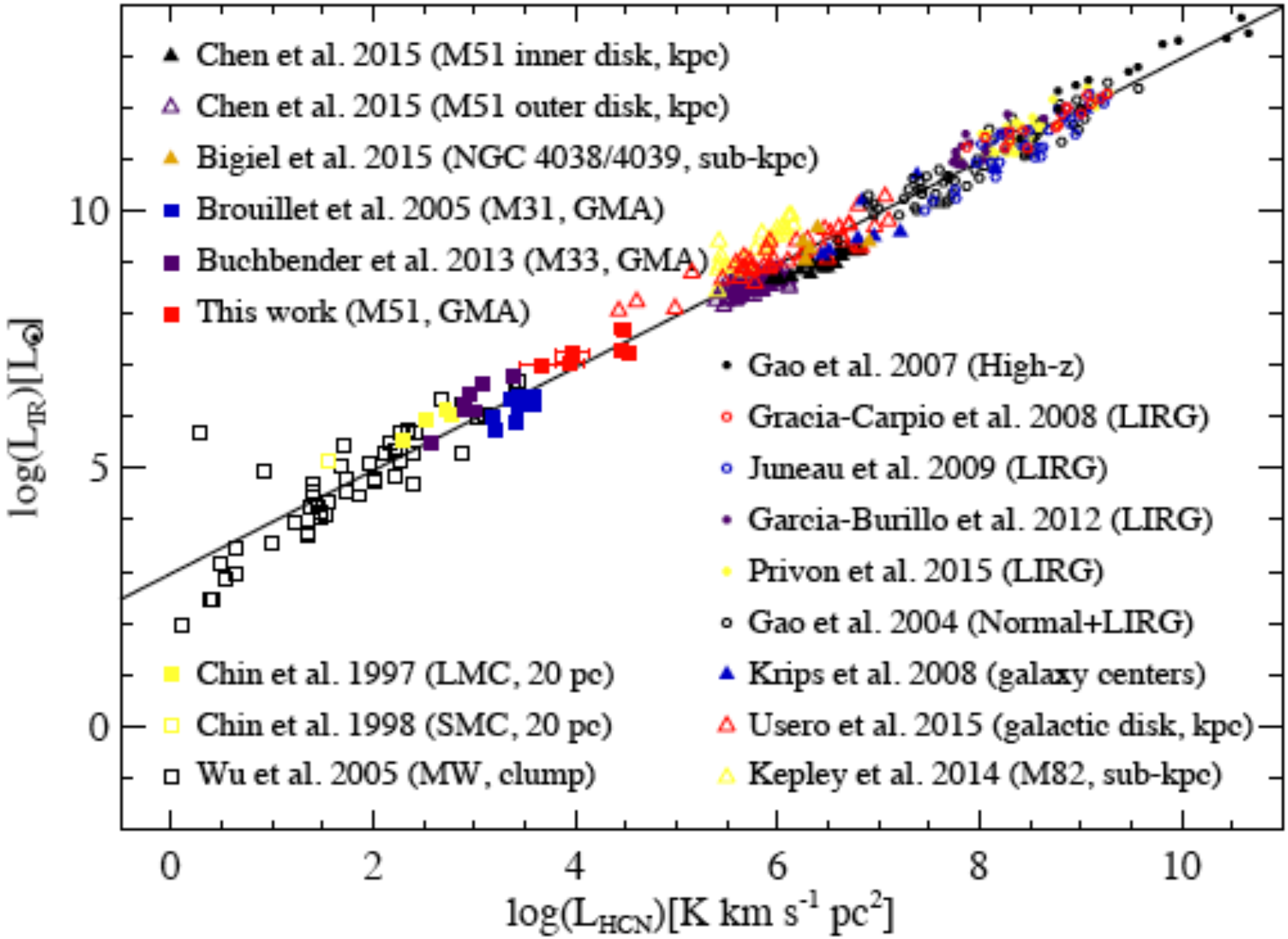




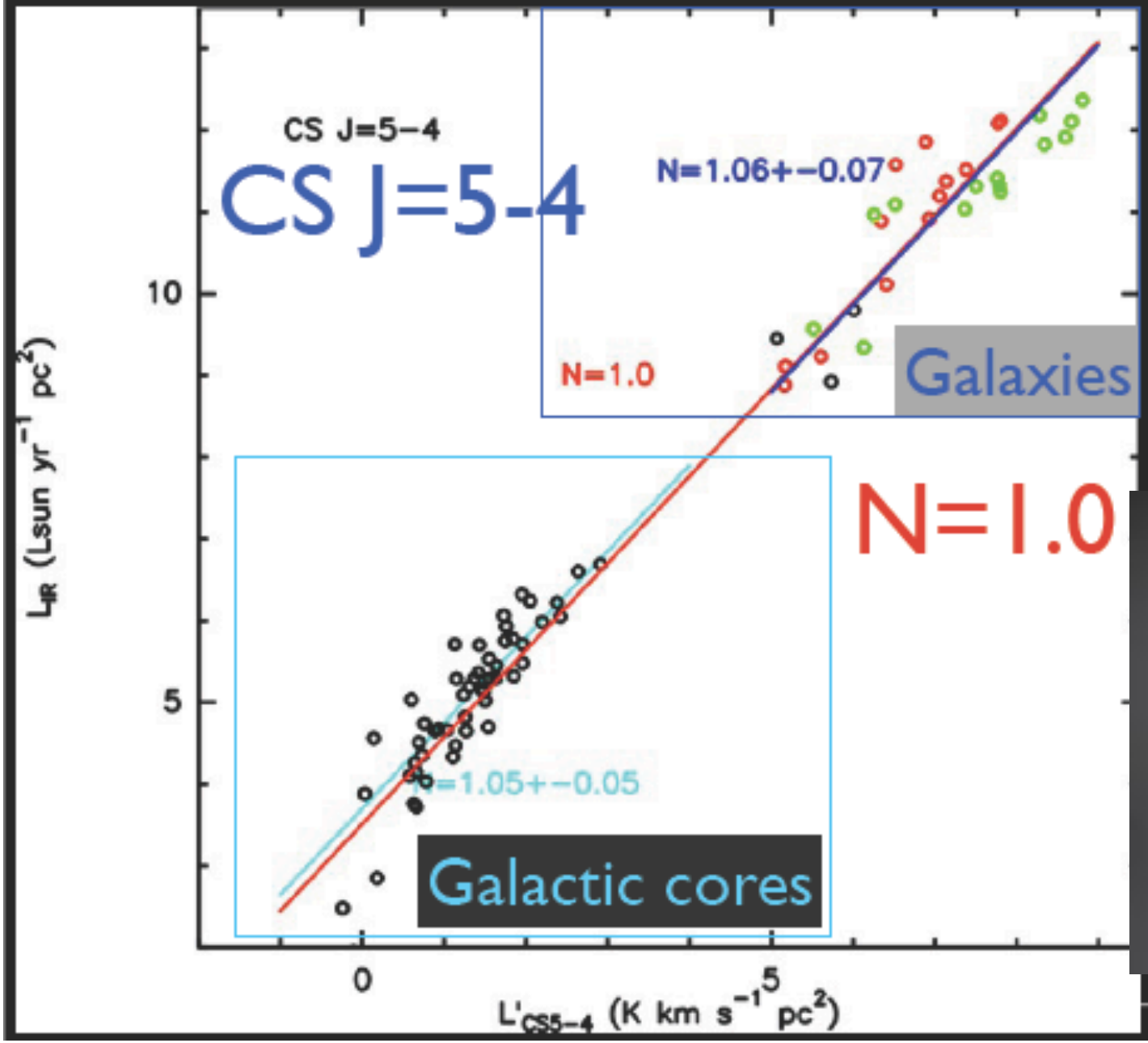
Chen, Gao, Braine & Gu 2015


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


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


Chen et al. 2015 (M51 inner disk, kpc)
Chen et al. 2015 (M51 outer disk, kpc)
Bigiel et al. 2015 (NGC 4038/4039, sub-kpc)
Brouillet et al. 2005 (M31, GMA)
Buchbender et al. 2013 (M33, GMA)
This work (M51, GMA)
Gao et al. 2007 (High-z)
Gracia-Carpio et al. 2008 (LIRG)
Juneau et al. 2009 (LIRG)
Garcia-Burillo et al. 2012 (LIRG)
Privon et al. 2015 (LIRG)
Gao et al. 2004 (Normal+LIRG)
Krips et al. 2008 (galaxy centers)
Usero et al. 2015 (galactic disk, kpc)
Kepley et al. 2014 (M82, sub-kpc)
Chin et al. 1997 (LMC, 20 pc)
Chin et al. 1998 (SMC, 20 pc)
Wu et al. 2005 (MW, clump)
log(L_IR)[L_⊙]
log(L_HCN)[K km s^-1 pc^2]
0
5
10
0
2
4
6
8
10

Connecting with Galactic CS study ~ 10 orders of magnitude

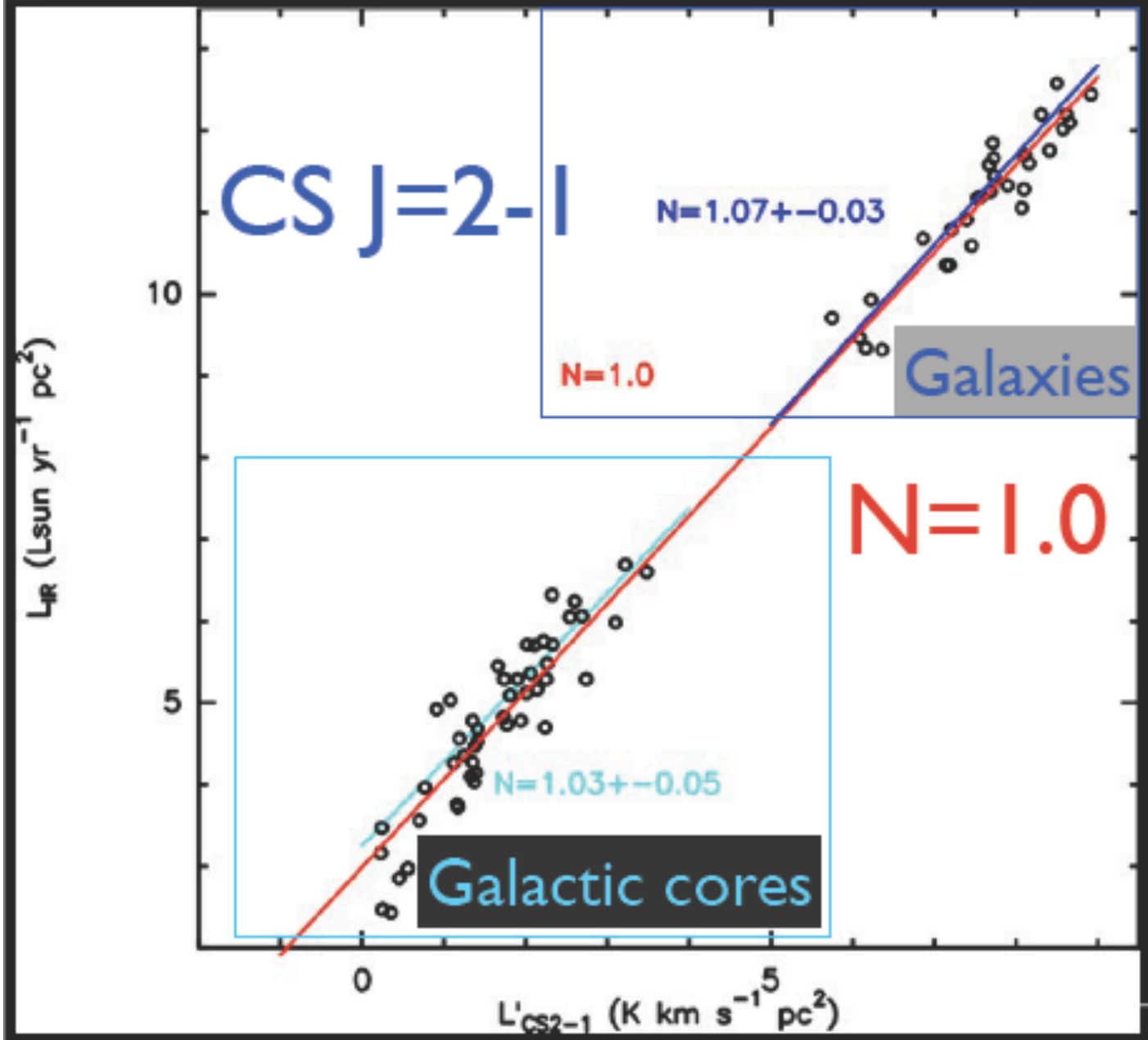


SMT 10m

IRAM 30m

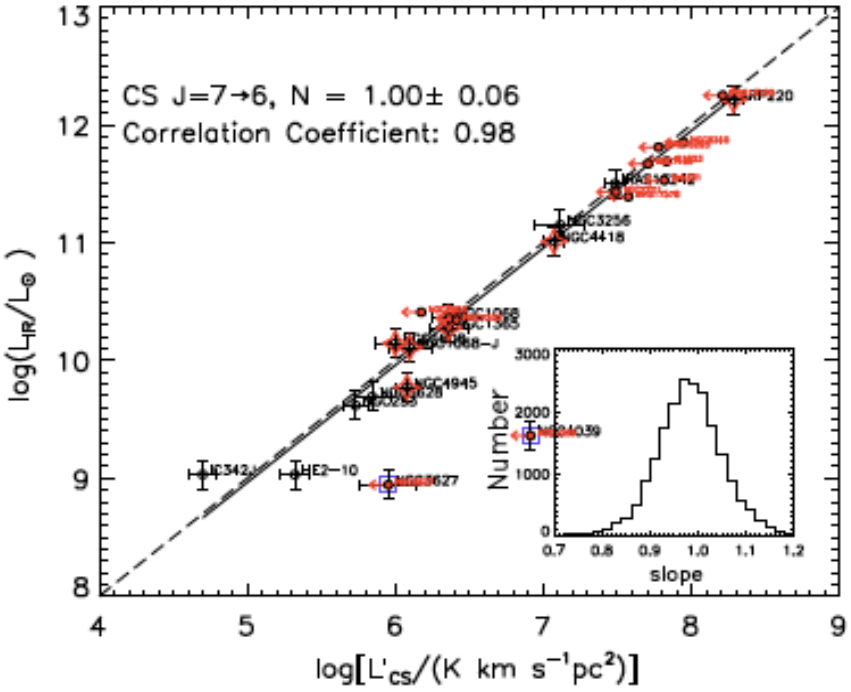
Baan + 2008

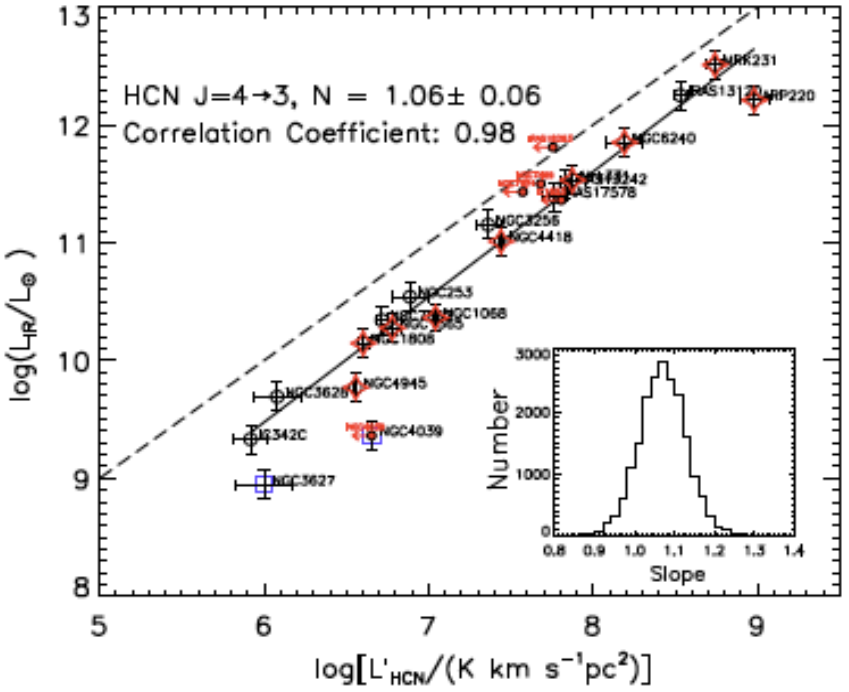
Connecting with Galactic CS study ~ 10 orders of magnitude



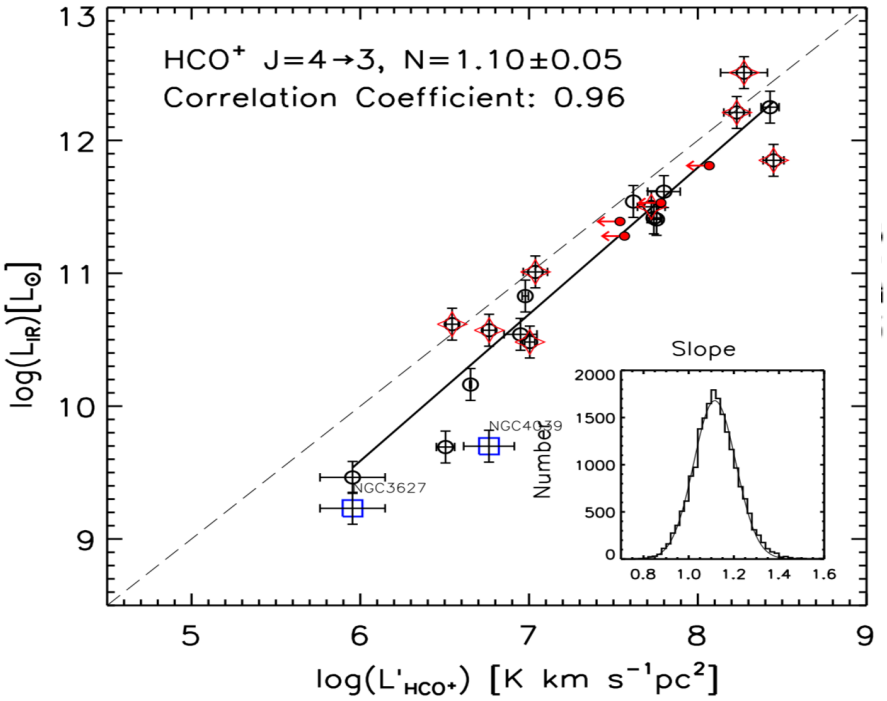
- IRAM 30m

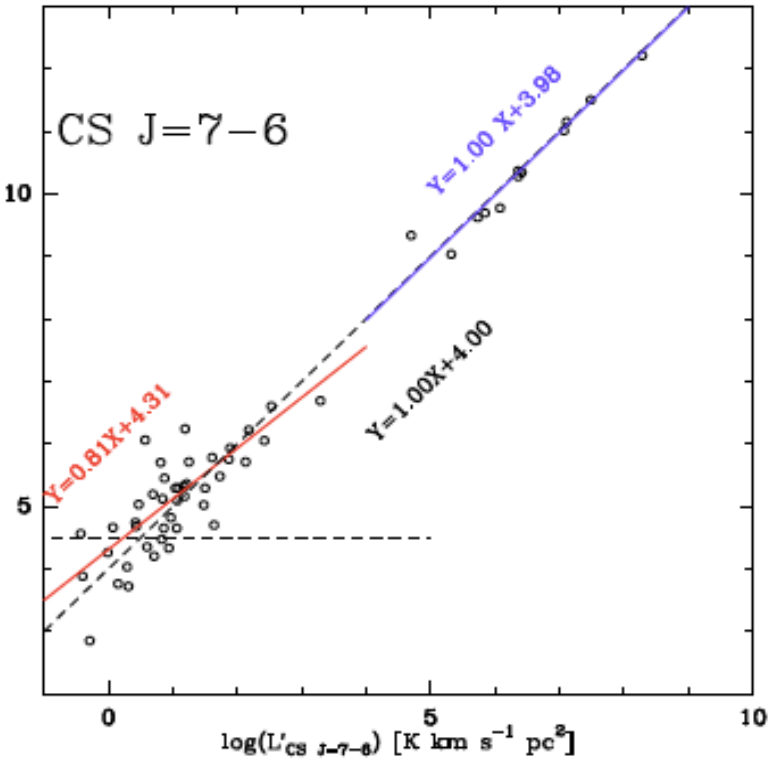
Wu+2010

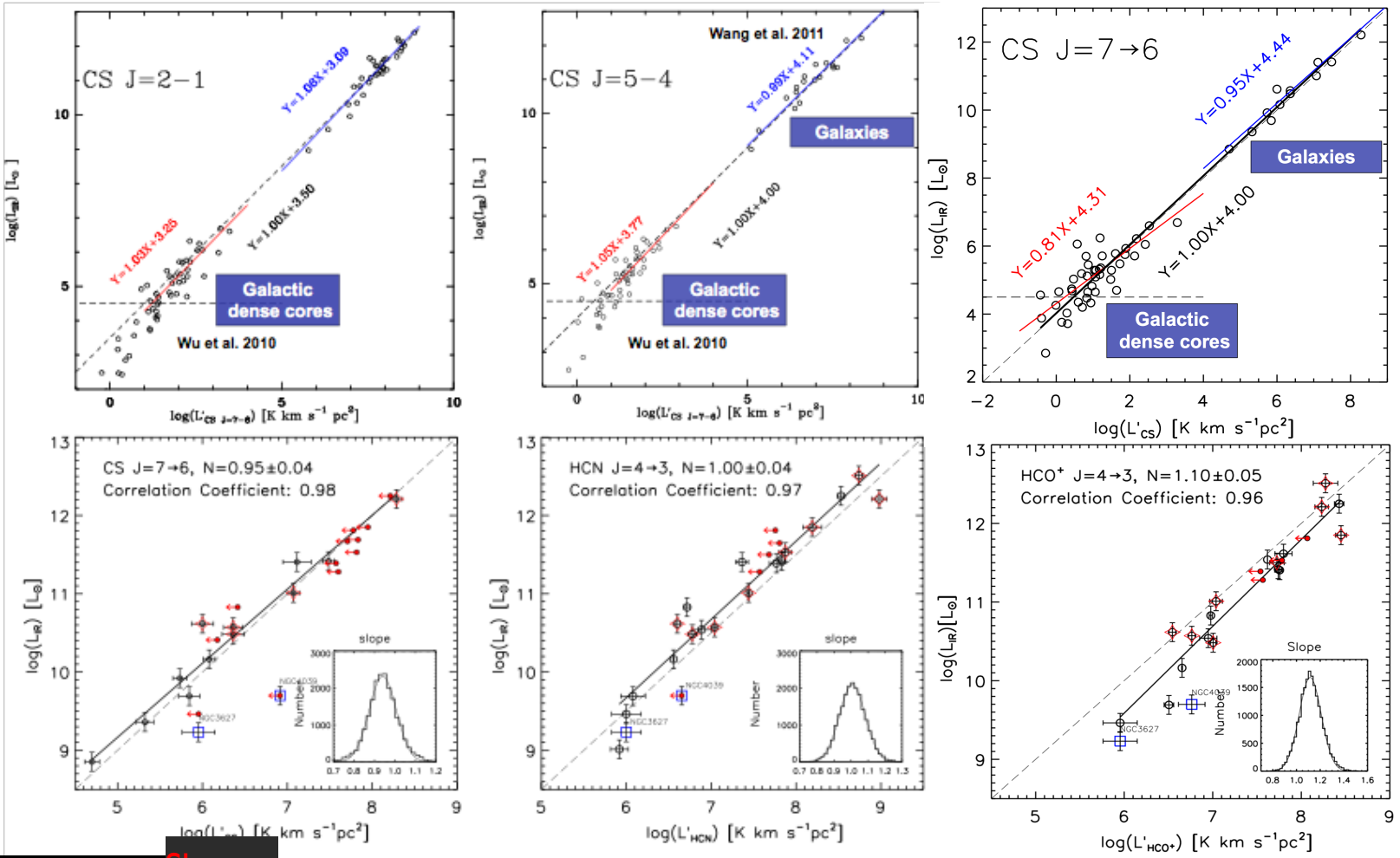




Zhang, Gao, Henkel et al. 2014

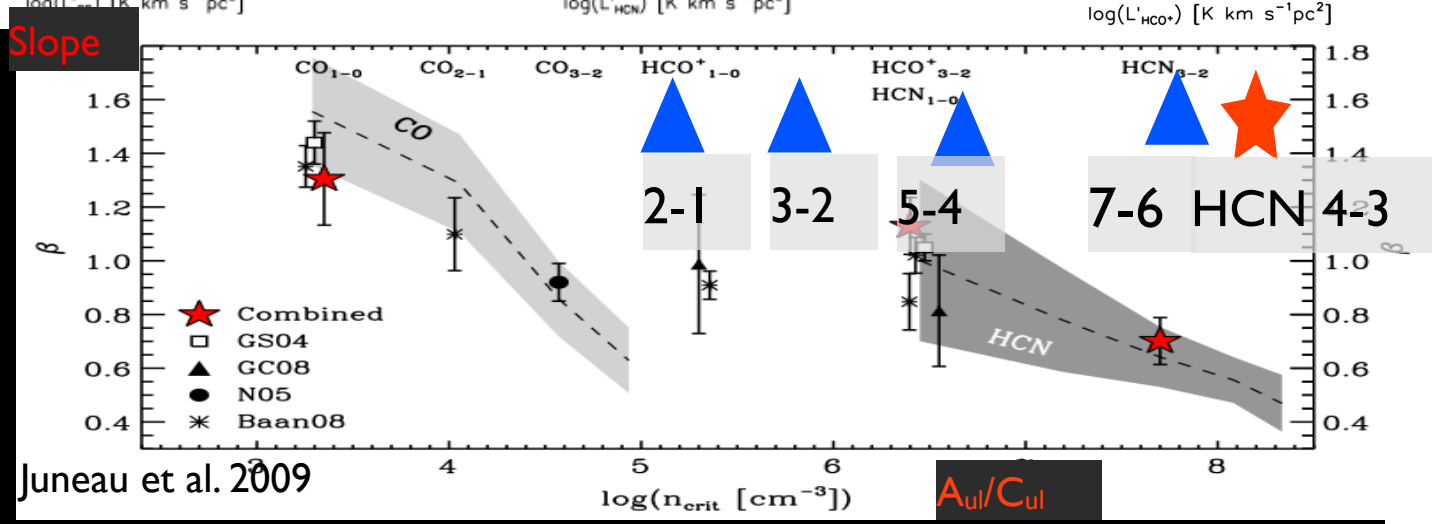






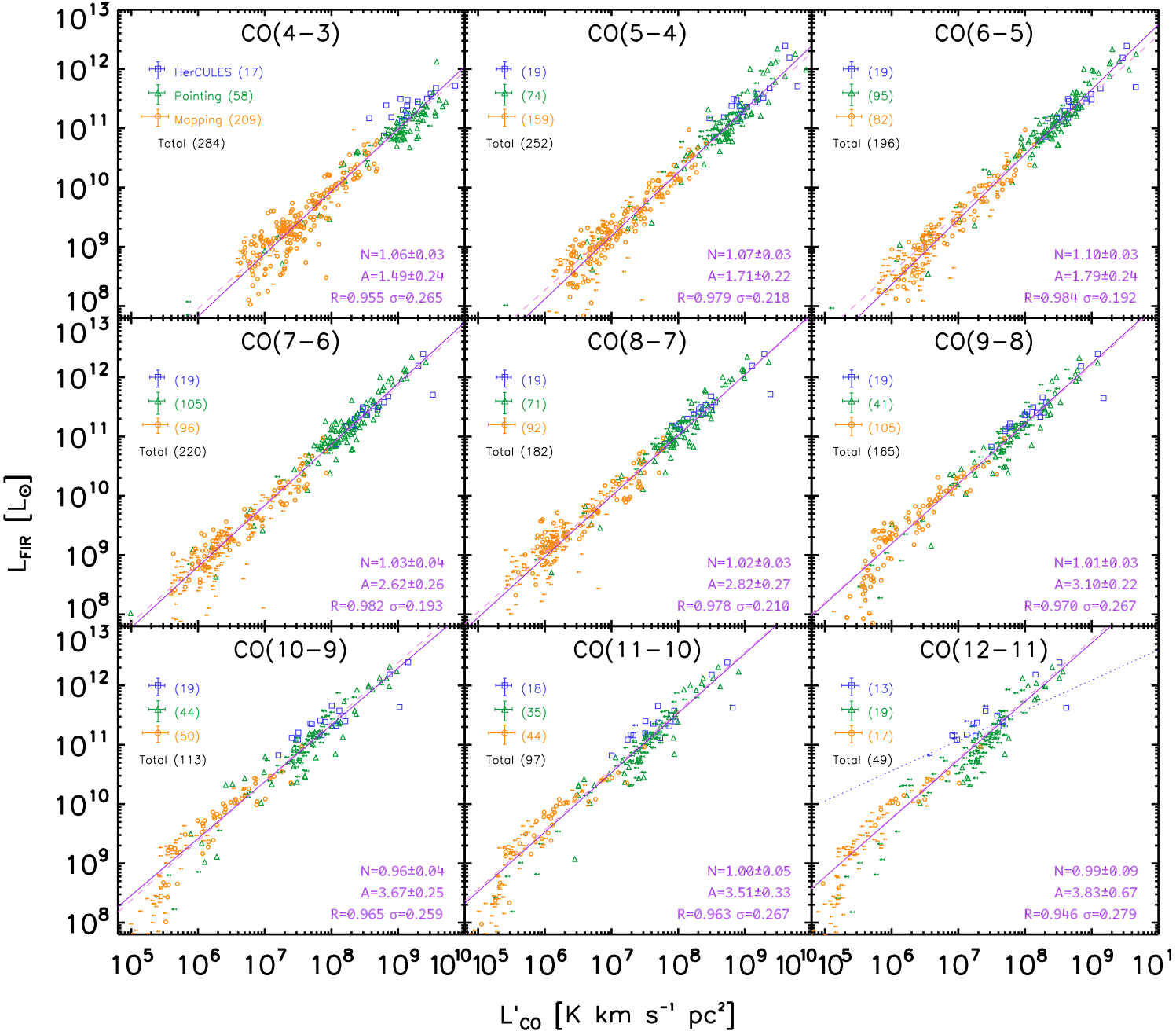
Zhang+2014, ApJL

All linearly correlated with IR luminosity.



Juneau et al. 2009

High-J CO--IR Correlation in Local Universe



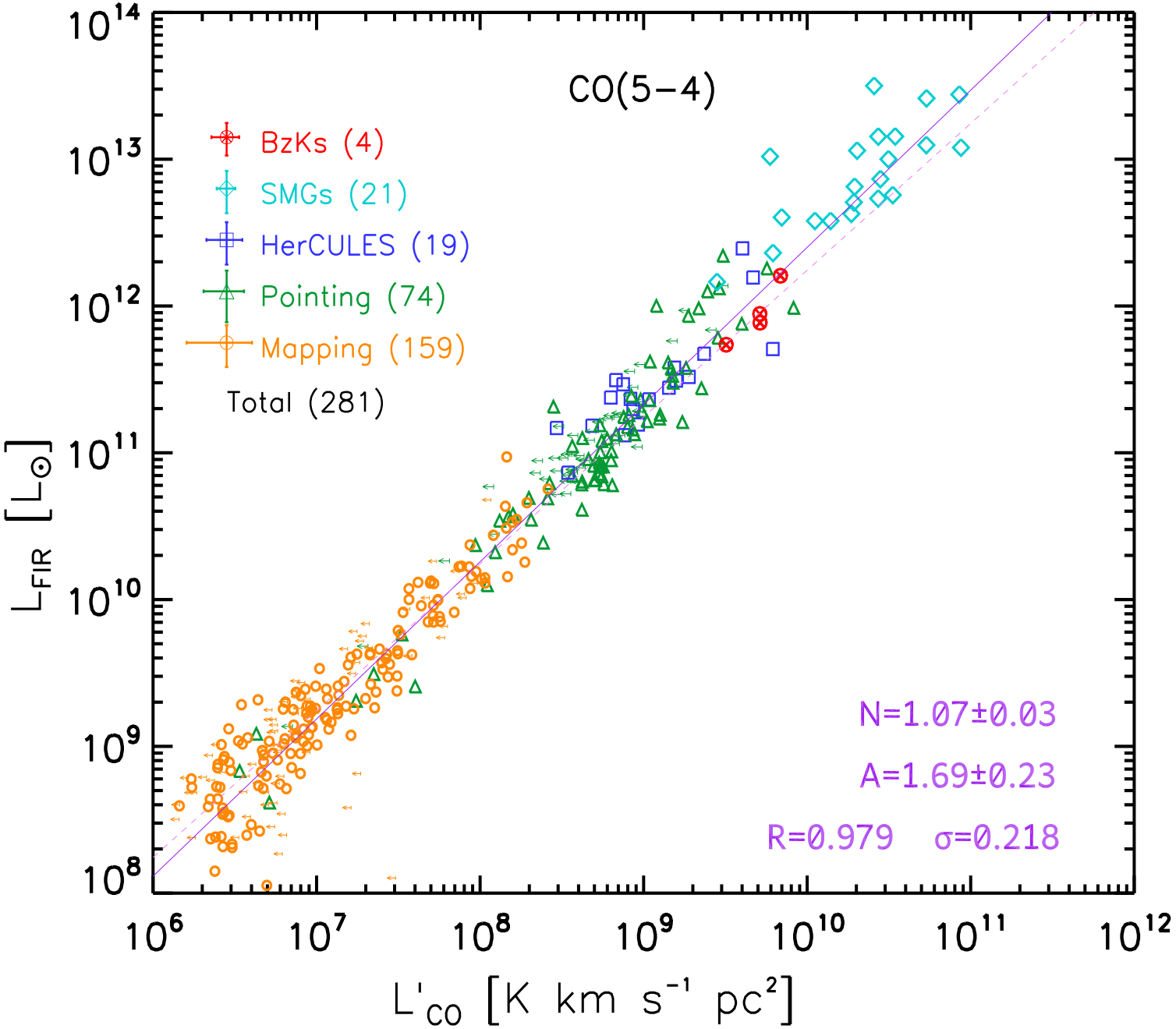
All are not far from linear
– dense gas law

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

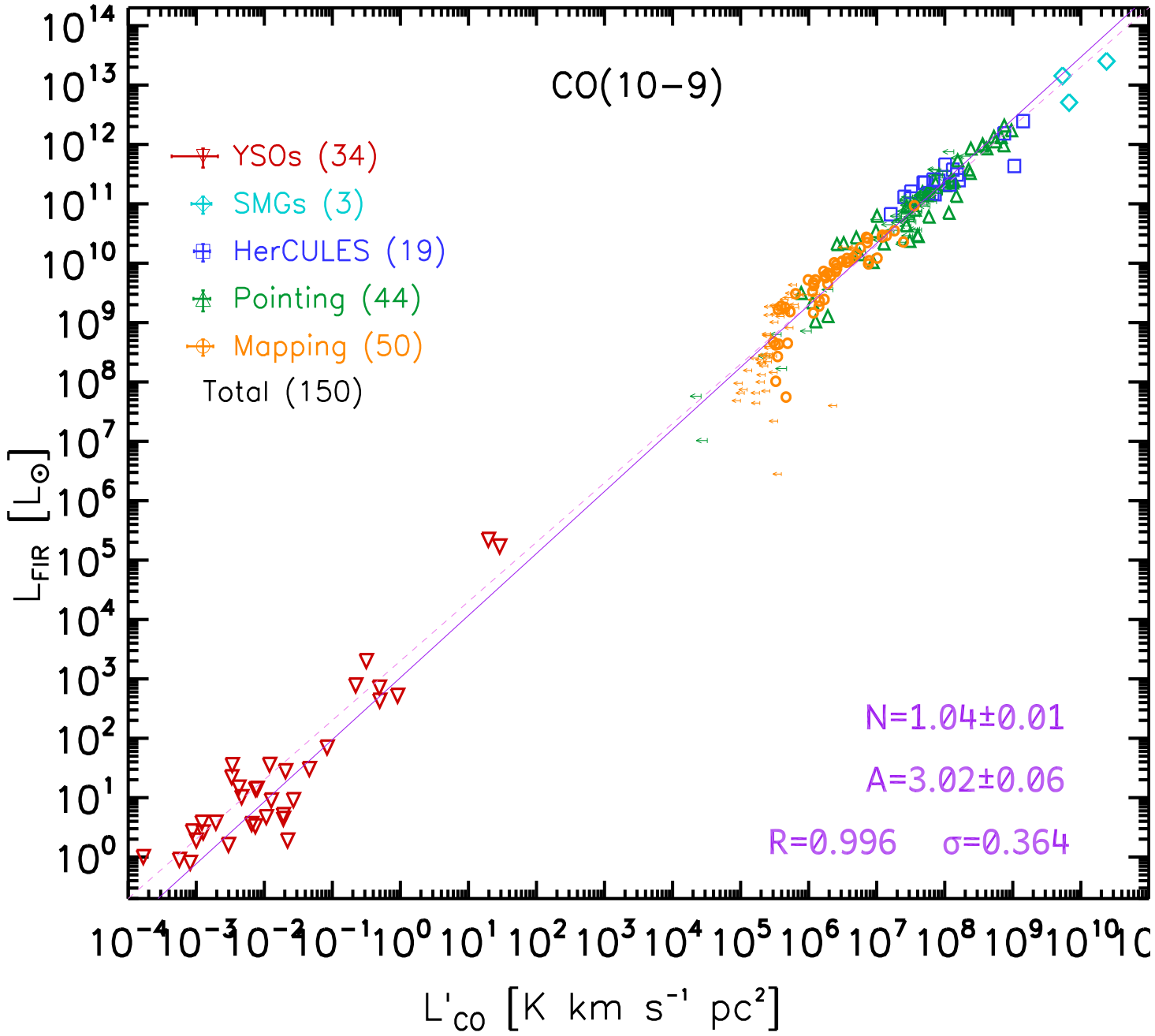
BzK

– normal SFG with moderate SFR – steady evolution

SMG

– starburst with very high SFR – merger evolution

– note that IR are poorly determined so far



CO10-9+H_2O3_{12}-2_{21}
Herschel FTS + HIFI
Galactic + Galaxies
SanJose-Garcia et al. 2013

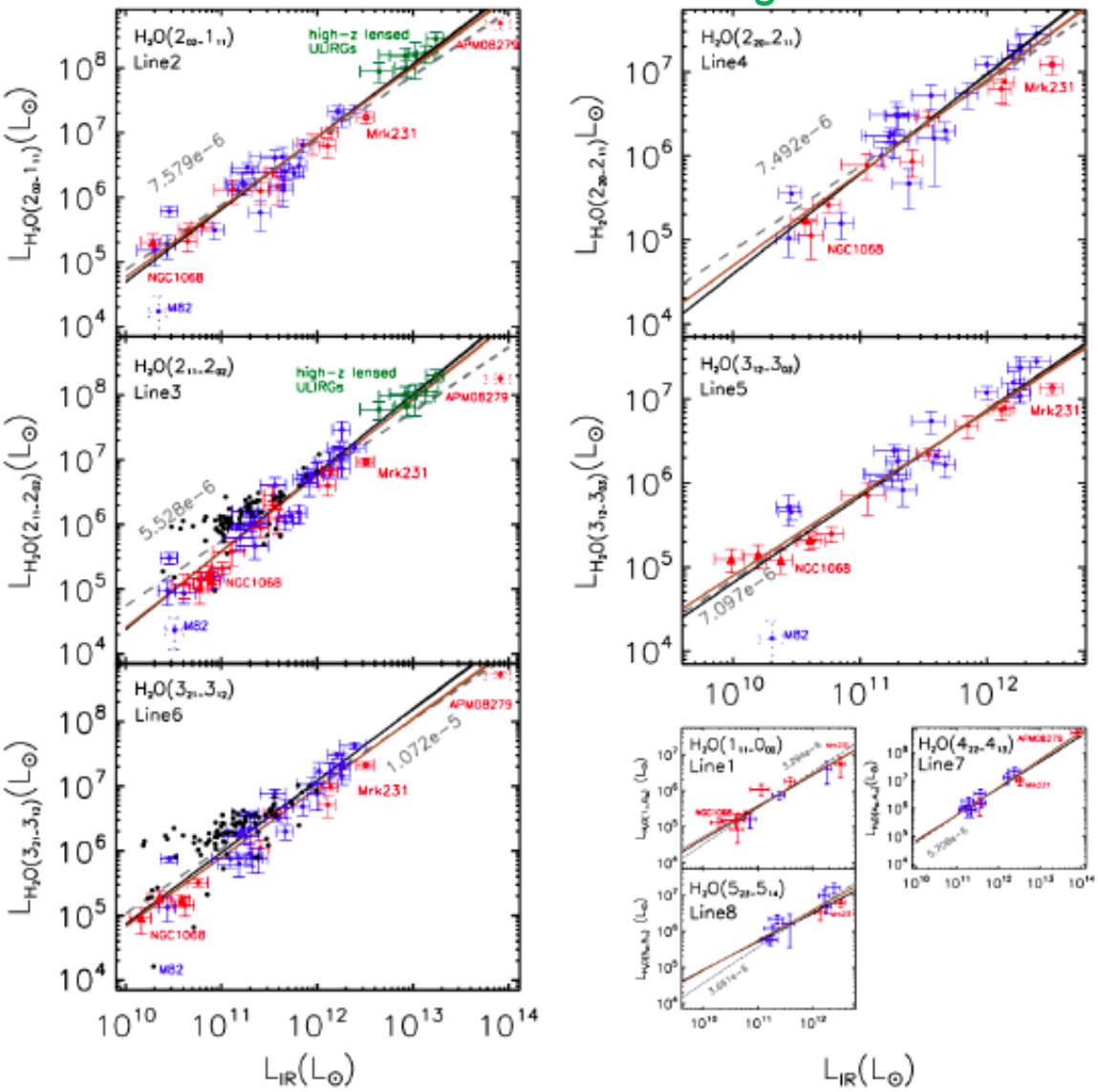
YSOs/protostars
– pc scale SF
SMGs
– high-z starbursts
HerCULES
– local starbursts
Pointing
– local SFGs
Mapping
– local normal disks

A universal SF law nearly 15 orders of magnitude

Submm H_2O and far-Infrared relation in galaxies

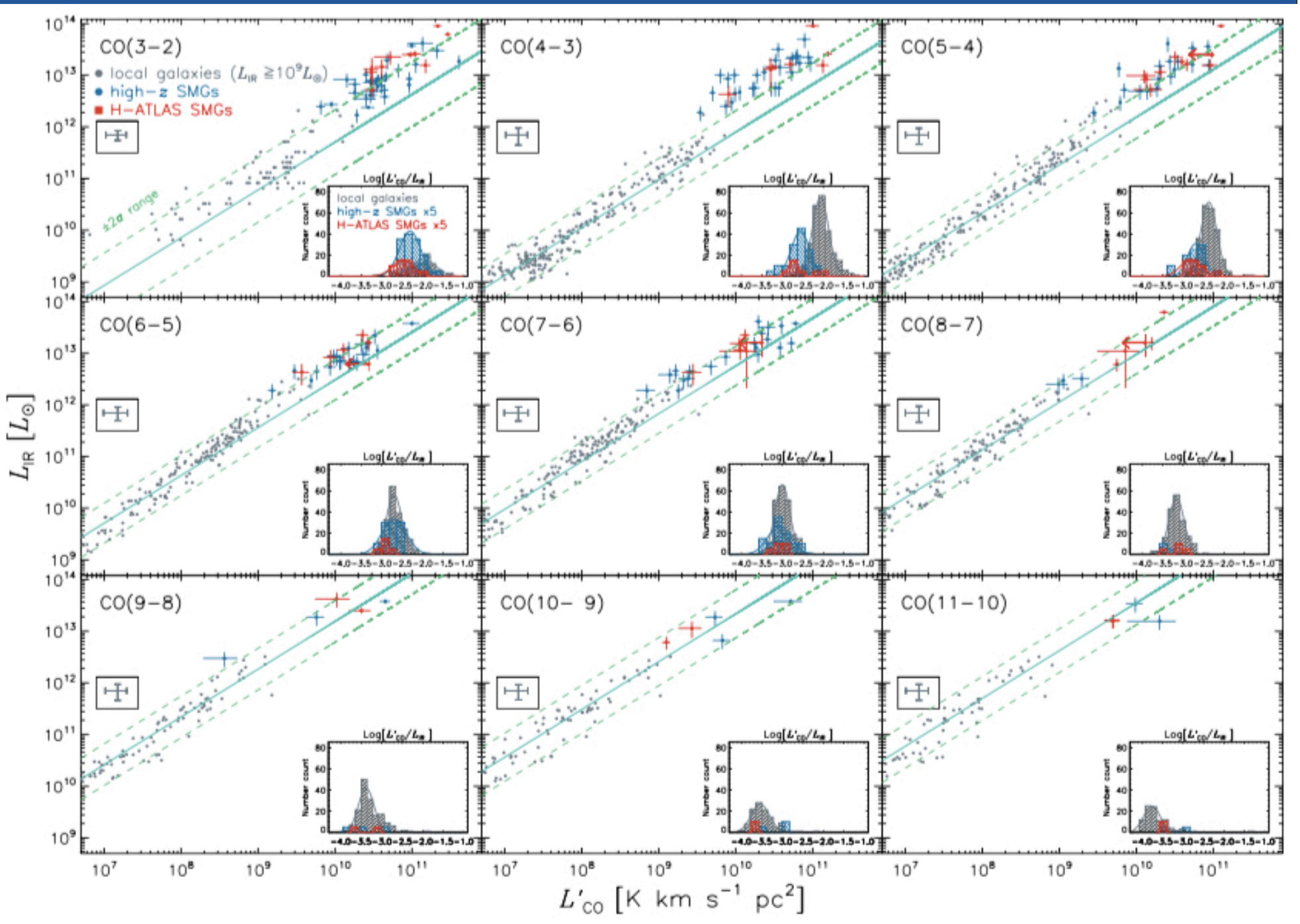
- First systematic study of submm H_2O emission near and far

Yang et al. 2013/16.



H_2O is an efficient and important tracer of compact, dense warm gas and IR sources.

- Submm H_2O rotational lines (*Herschel*) to be the second strongest lines after high-J CO in LIRGs & ULIRGs.
- H_2O luminosity grows with total infrared luminosity near-linearly, correlate strongly with star formation.
- IR-pumping may play important role in H_2O excitation, especially high-lying lines.
- T_d ~ 110K dust contribute little to H_2O excitation. L_{H_2O}/L_{IR} - $f_{25\mu m}/f_{60\mu m}$
- There's no difference between AGN and starburst dominate galaxies, AGN is not necessary for H_2O excitation.
  - L_{H_2O}/L_{IR} and L_{H_2O}-a/L_{H_2O}-b
- Detection of H_2O^+ and $H_2{}^{18}O$ lines.

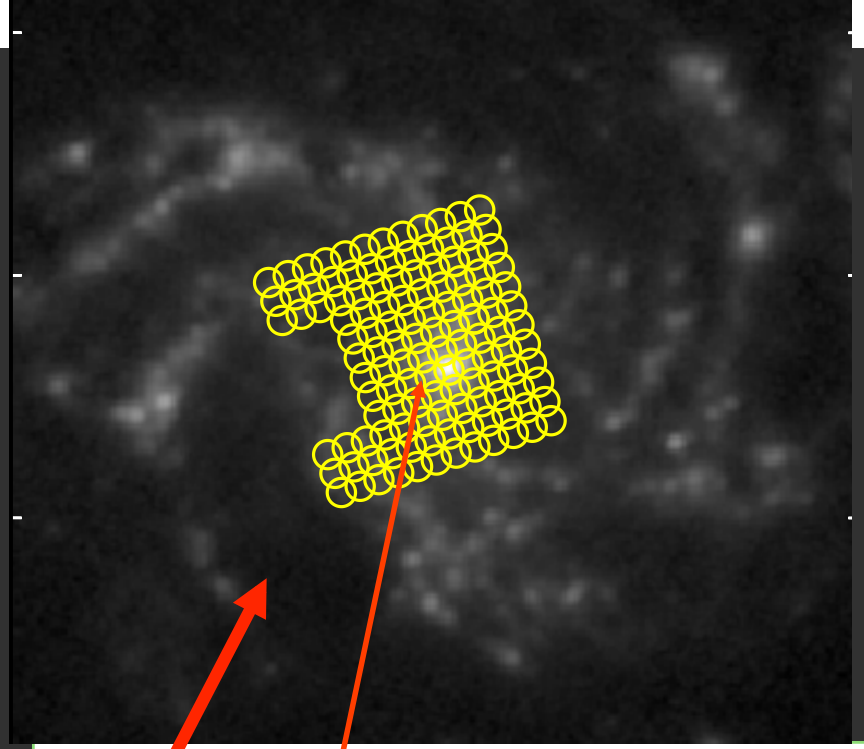

CO(3−2)
CO(4−3)
CO(5−4)
CO(6−5)
CO(7−6)
CO(8−7)
CO(9−8)
CO(10− 9)
CO(11−10)
local galaxies ($L_{IR} \geq 10^9 L_\odot$)
high−z SMGs
H−ATLAS SMGs
±2σ range
local galaxies
high−z SMGs x5
H−ATLAS SMGs x5
Number count
L_{IR} [$L_\odot$]
L'_{CO} [K km s^{-1} pc^2]

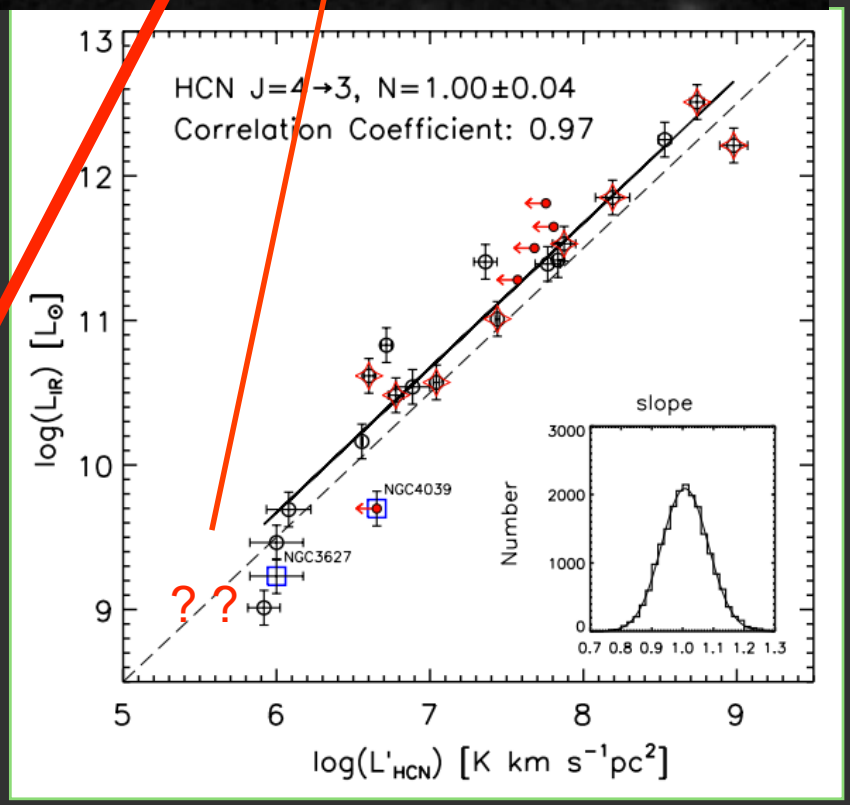
PROJECT AND SCIENCE GOALS

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 ~5×10^{6}M$_\odot$ and scales ~0.2-2.8kpc in other galaxies*
- *Bridge the gap between and Galactic observations*

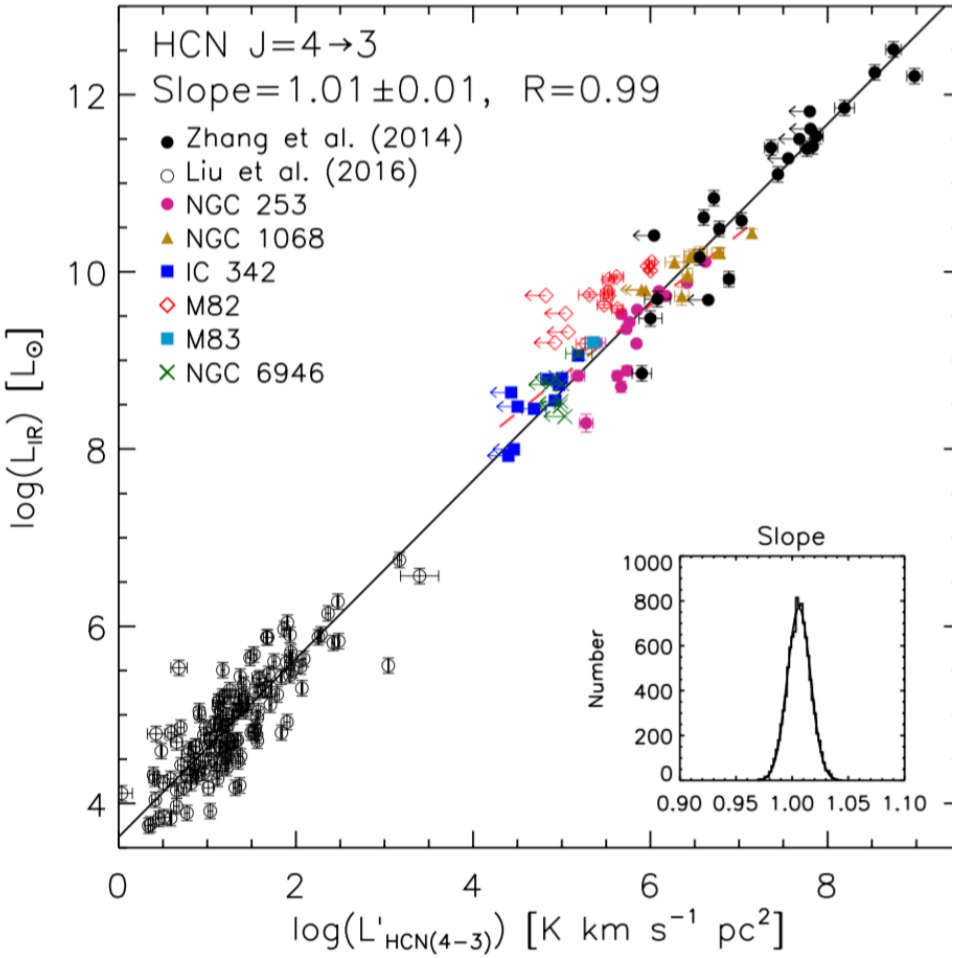
- *Resolved dense gas star formation relations*
- *Intermediate scales/luminosities*
- *Different environments: nuclear vs. disk*
- *Radial distribution of dense gas and SF efficiency*



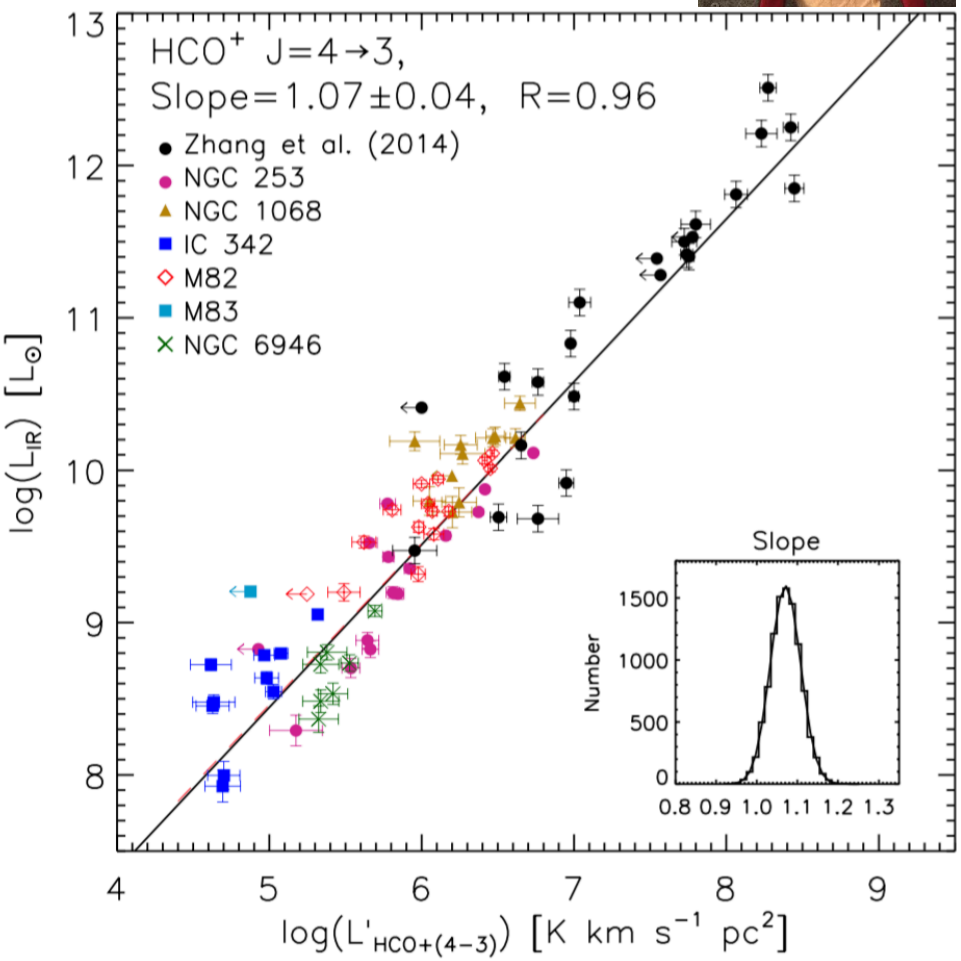


Tan, Gao, Zhang+2018

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

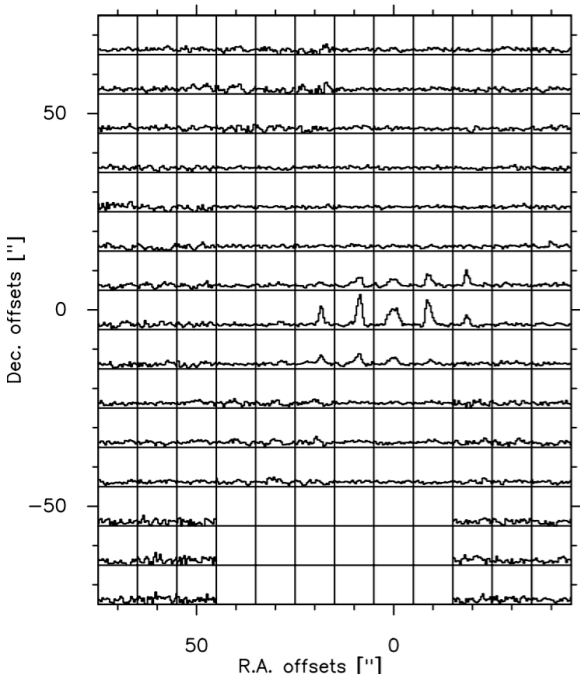


L_{IR} vs. $L'_{HCO+(4-3)}$



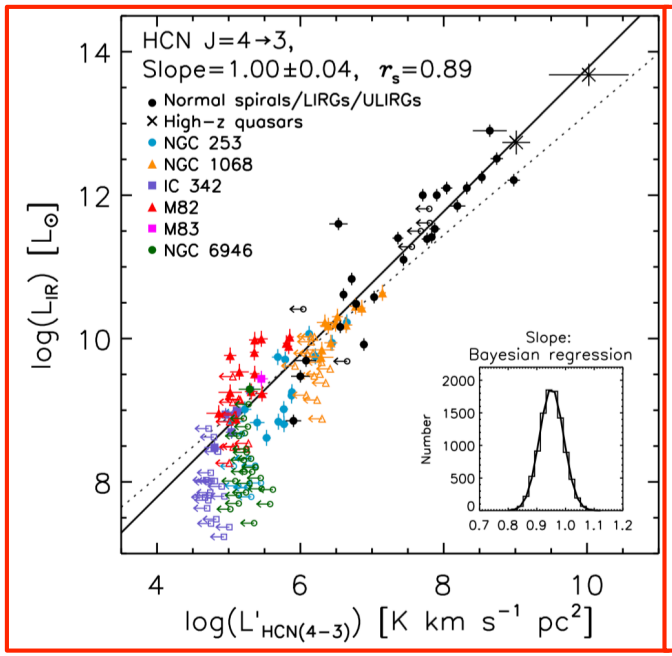
The MALATANG Survey: the L_{gas} – L_{IR} correlation on sub-kiloparsec scale in six nearby star-forming galaxies

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

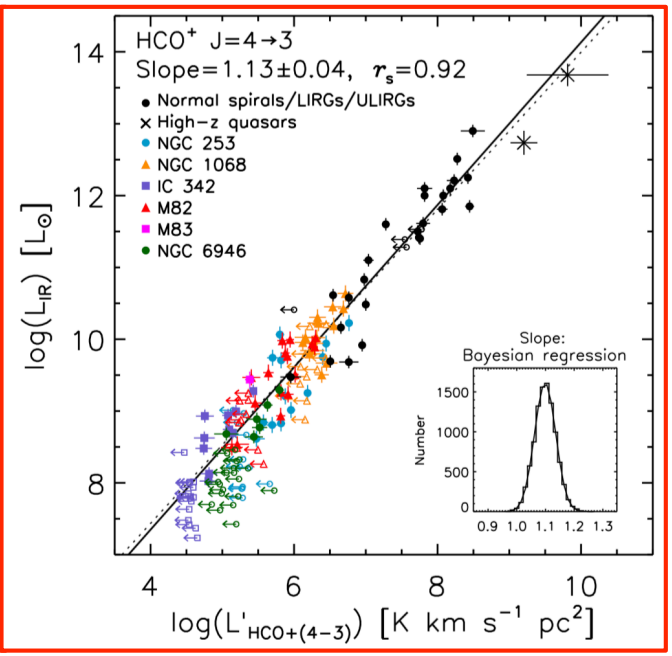


(Tan et al. 2018, submitted)

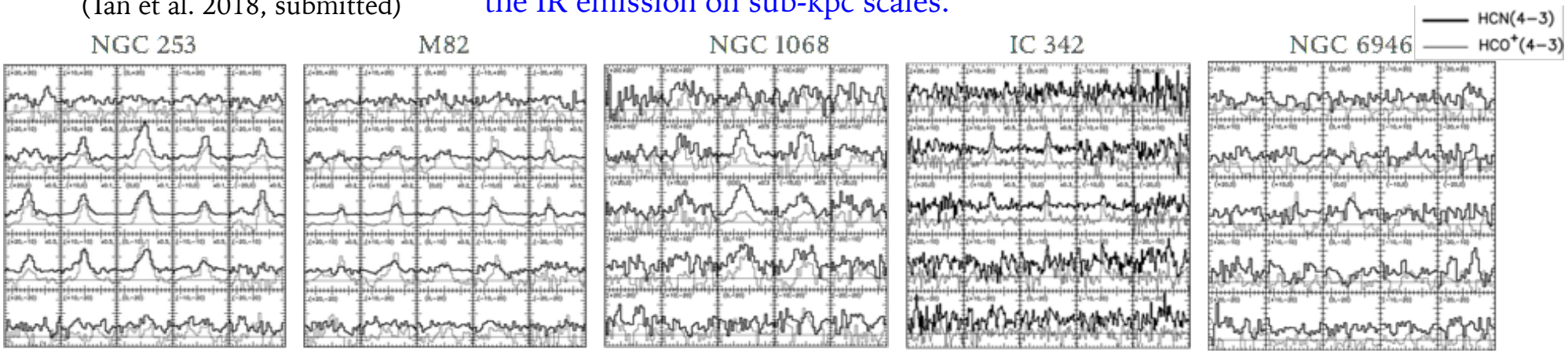
L_{IR} vs. $L_{HCN(4-3)}$



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



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



Concluding remarks

- Dense Molecular Gas → High Mass Stars
- SFR ~ M(DENSE), **linear?!** dense gas
- Dense gas tracers (e.g. HCN, CS, HCO+ COJ>3, H2O… 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

HI=gas reservoir (FAST) is an excellent tracer of galaxy interactions: kinematics/morphology; evolution & environments (not SF). H2 OK for SF, X-factor? yet dense H2 best (e.g., EAO/JCMT; ALMA/NOEMA)!