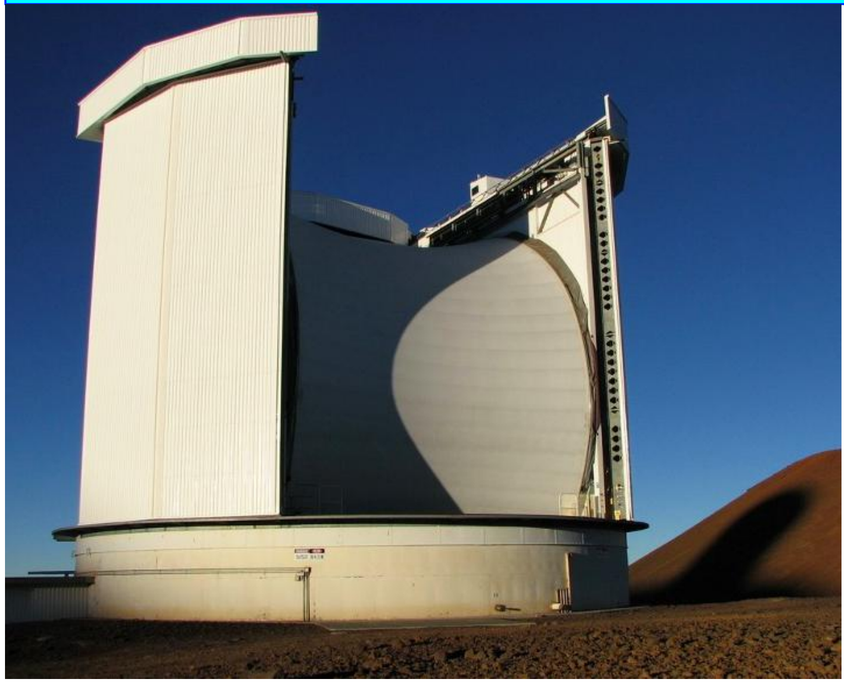
The Star Formation Laws in Galaxies Near & Far



Yu GAO

Purple Mnt. Obs

Aug. 8th, 2017@SFDE17: from local clouds to distant gals.

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***+13/16; 6 Xu+14/15; 7 Lu+14/15; 8 Zhao+16/17; 9 Tan, Gao+

Star formation (SF) laws

(Schmidt 59, 63; Kennicutt 89, 98; Wong & Blitz 02; Heyer+04; Gao & Solomon 04; Krumholz & McKee 05; Krumholz & Thompson 07; Bigiel+08; Robertson & Kravtsov 08; Gnedin+09; Krumholz+09; Daddi+10; Gnedin & Kravtsov 10; Ostriker+10; Schruba+10; Genzel+10; Gnedin & Kravtsov 11; Narayanan+11; Bigiel+11; **Shi+11**; **Liu+11**; Rahman+11,12; Feldmann+11,12,13; Lada+12; Liu & Gao 12; Shetty+13).

- Schmidt (1959): SFR~density(HI)^n,

  n=1-3, mostly 2-3 in ISM of our Galaxy.
- Kennicutt (1989): total gas

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

  n is not well constrained. ~1-3, wide spread.
- Kennicutt (1998): n=1.4 ?

  Total gas (HI + H2) vs. molecular gas
- Gao & Solomon (2004): n=1 in dense gas

  (Hubble law and H_0 analogy)

Hubble law

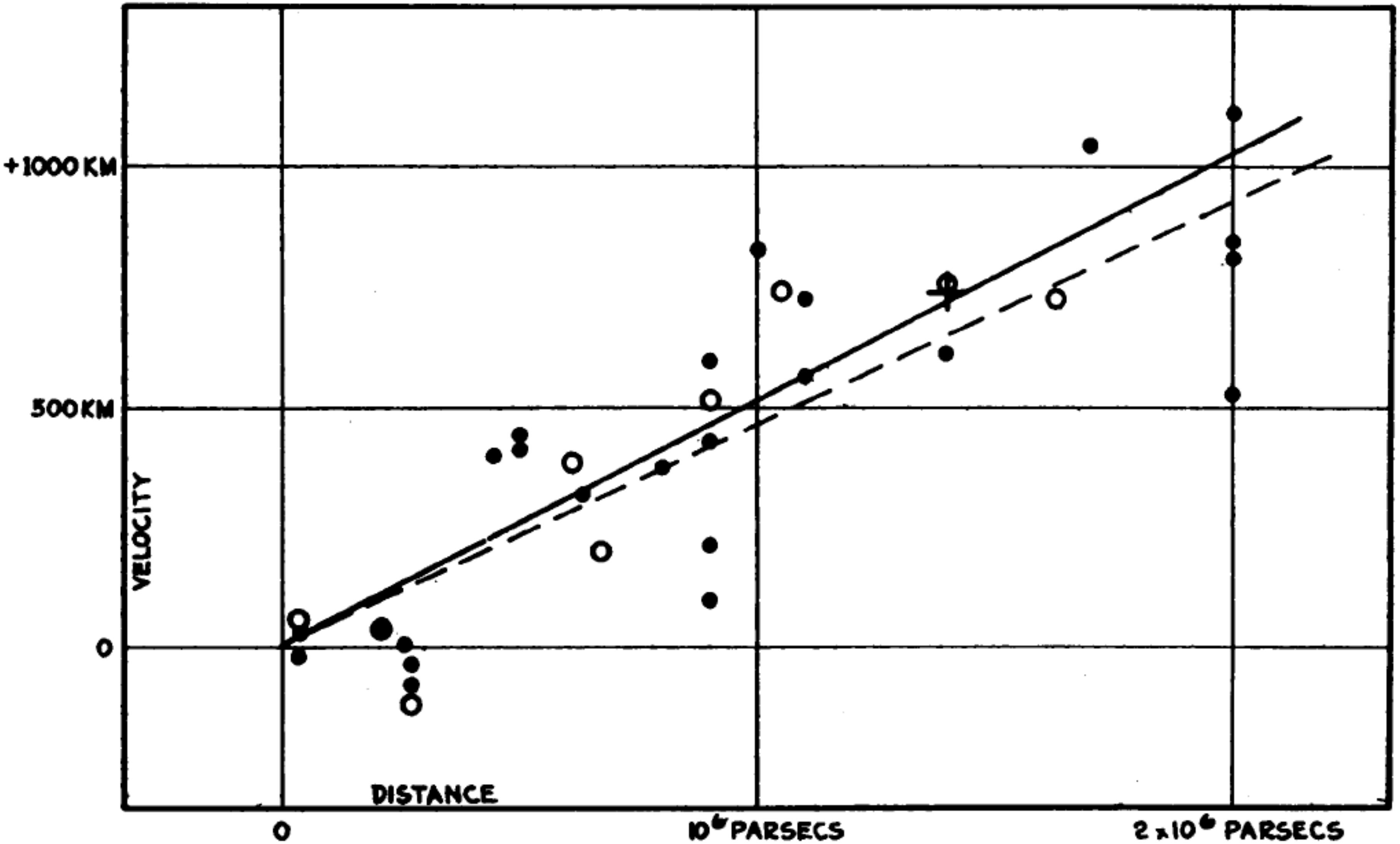
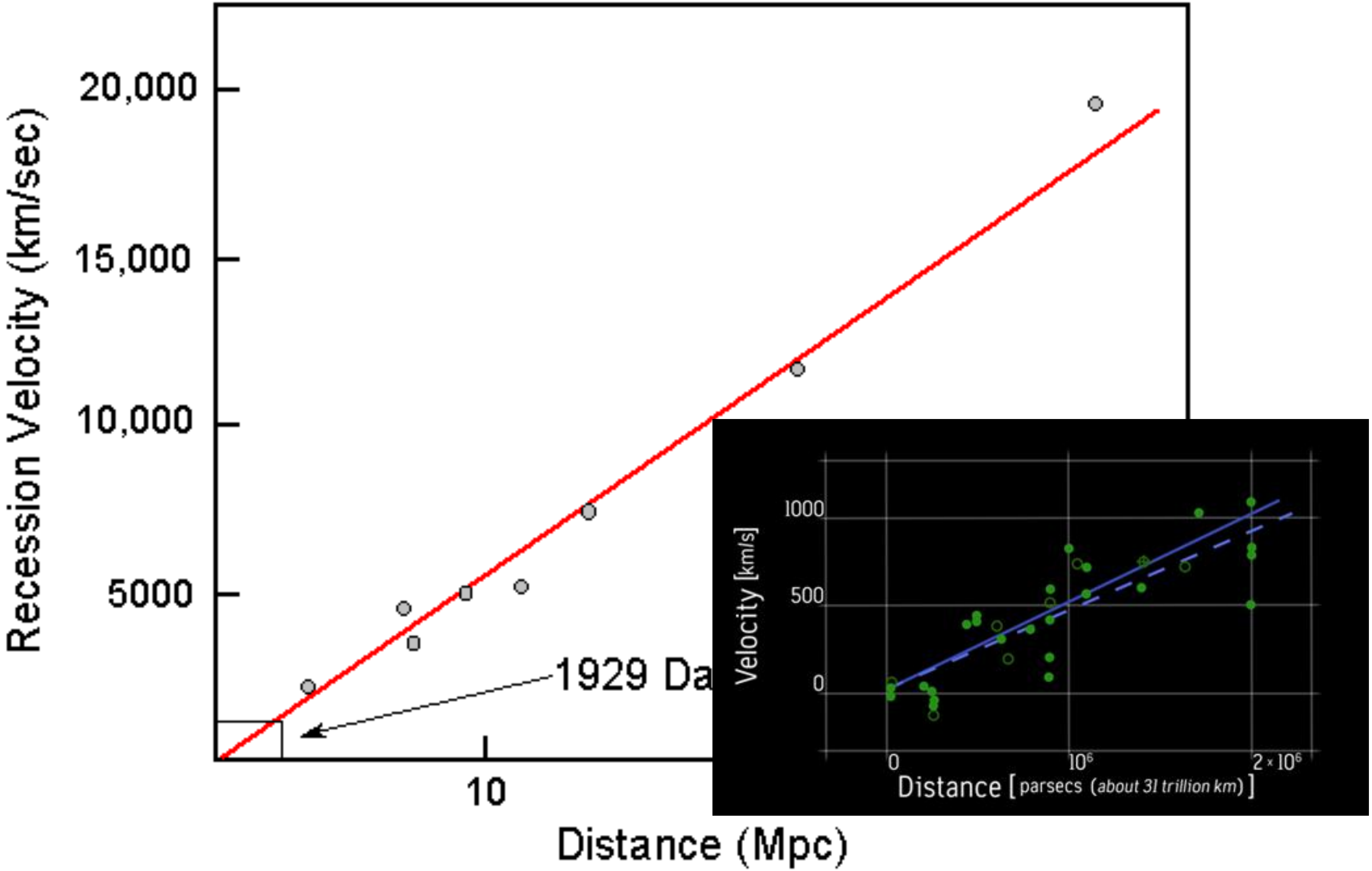


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Hubble & Humason (1931)



Hubble law vs. SF law

- Hubble: 1 of 2 variables directly observed
- It's a linear relationship!
- Yet >~70yrs H_0 measurements (wars)!!

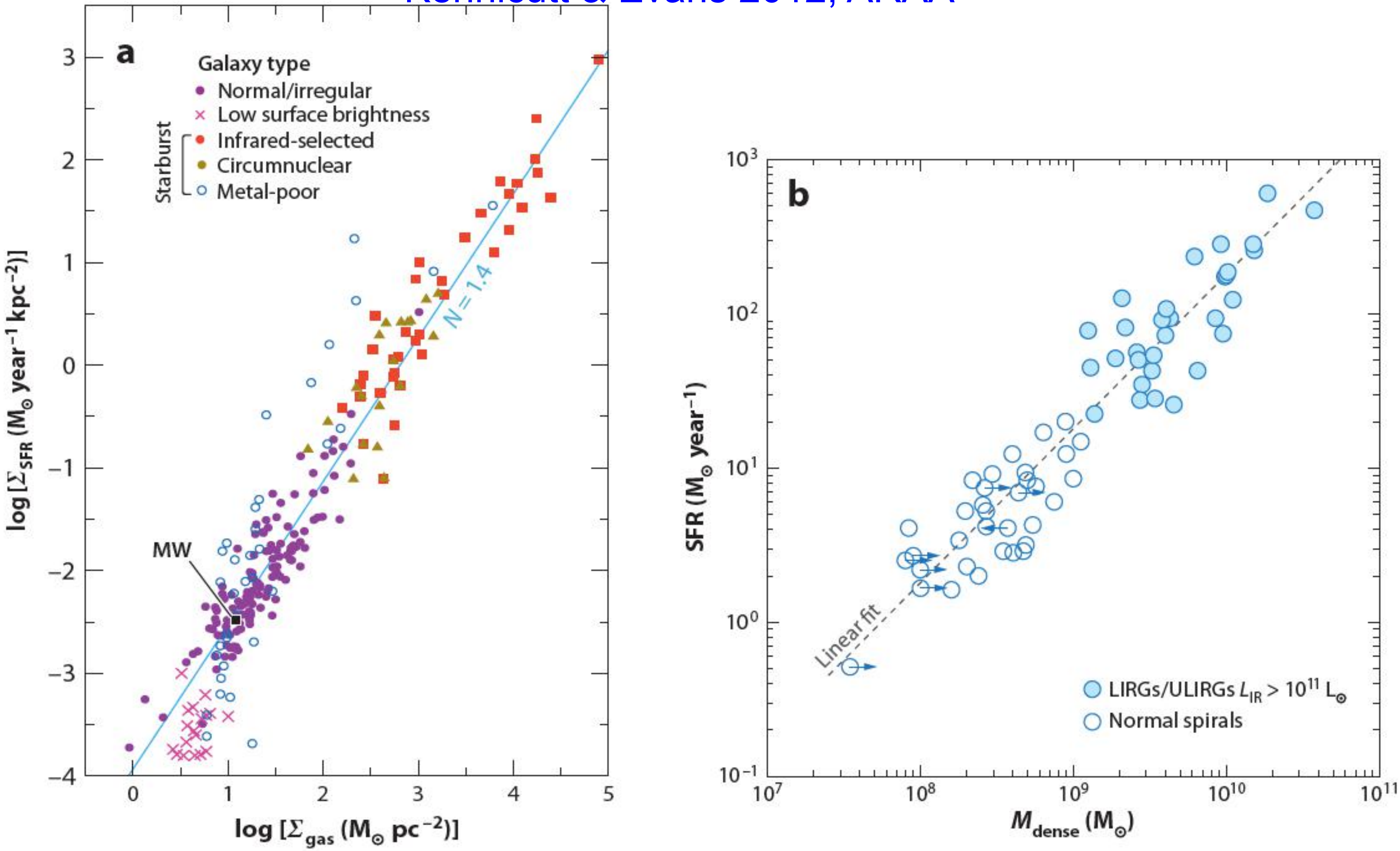
?! SF: SFR a factor of 2-3 accuracy (much worse @ high-z)

?? Star-forming gas? HI, total, H_2 or dense H_2 (~10 uncertainties, troubles?! ALMA!)

?! Might not be an exact linear relationship (even though FIR-HCN/CS linear!)

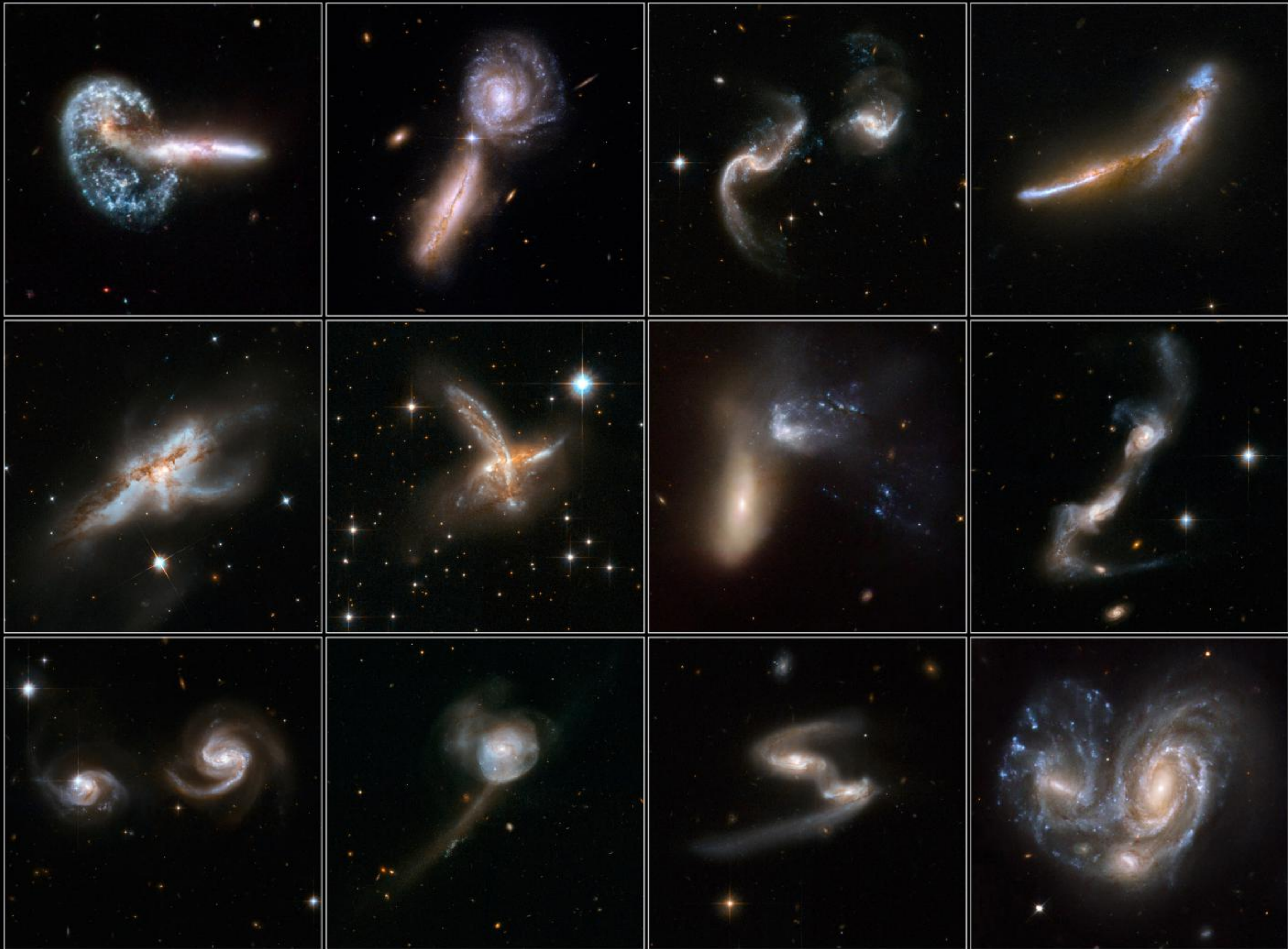
?? SF constant (SF law is still @infancy)

Kennicutt & Evans 2012, ARAA



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

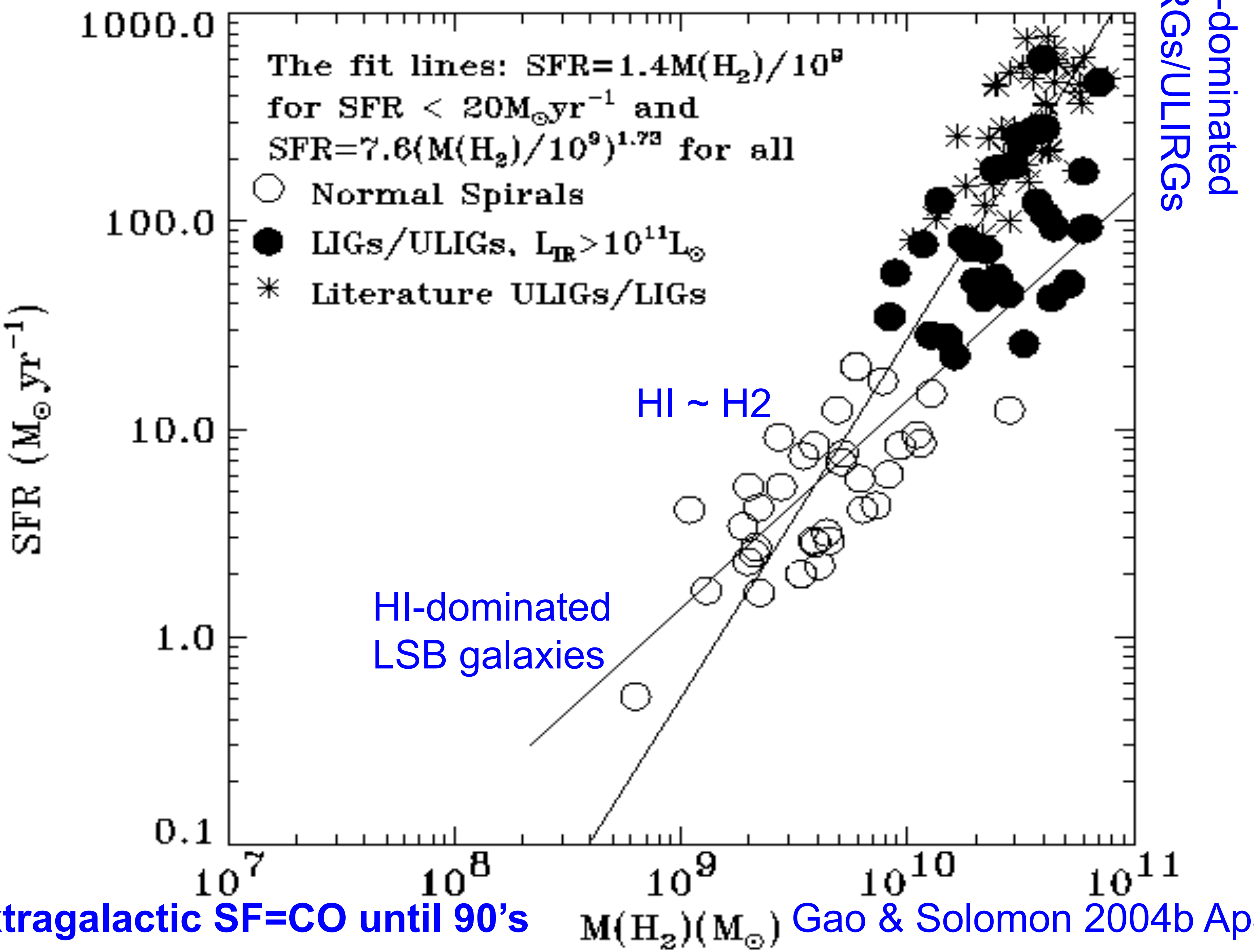
Interacting Galaxies *Hubble Space Telescope* • ACS/WFC • WFPC2



NASA, ESA, the Hubble Heritage (AURA/STScI)-ESA/Hubble Collaboration, and
A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University)

STScI-PRC08-16a

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



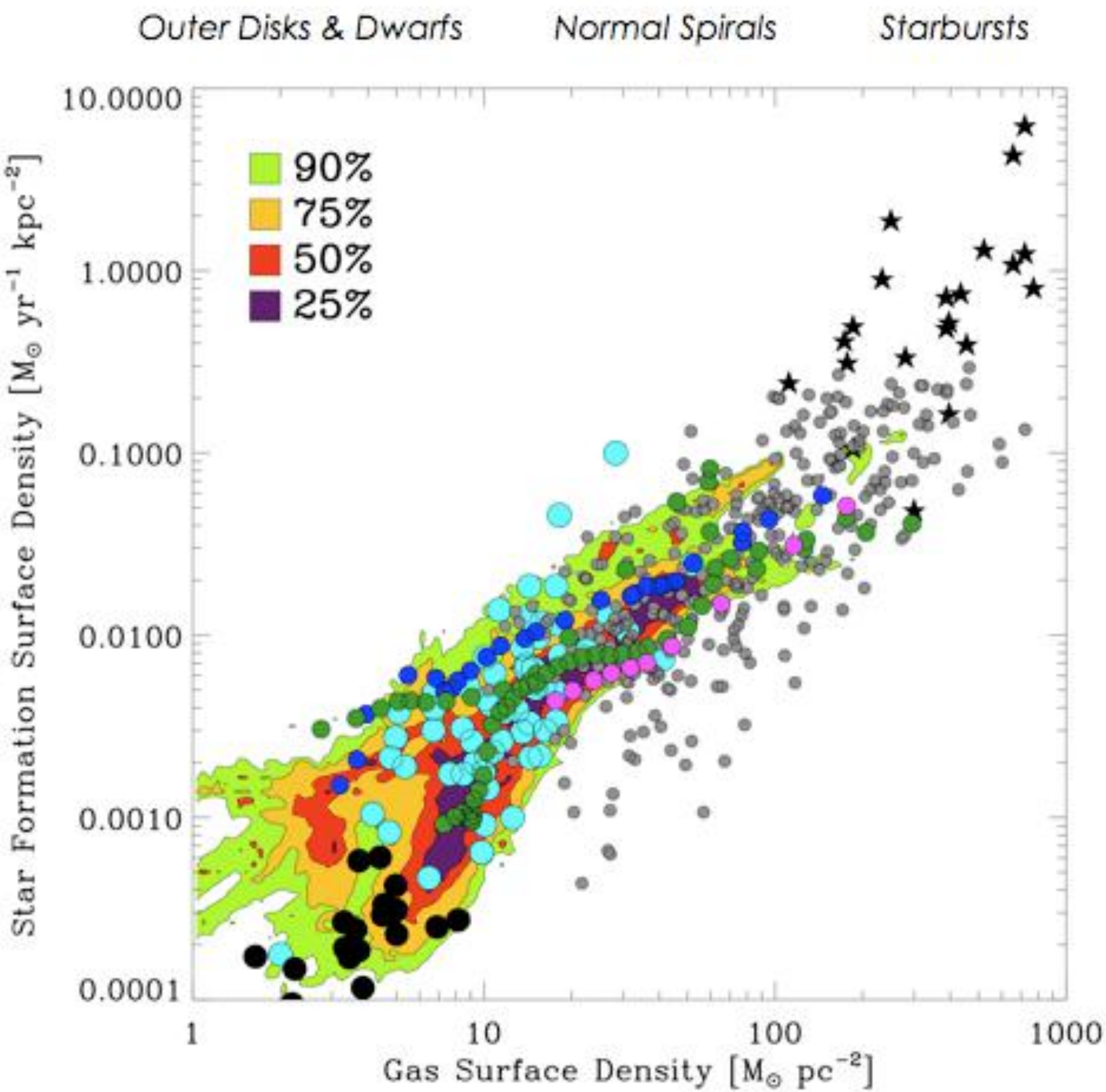
Extragalactic SF=CO until 90's

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)

- Kennicutt-Schmidt Relation (Kennicutt et al. 1998):

$$\Sigma_{\mathrm{SFR}} \propto (\Sigma_{\mathrm{gas}})^{1.4 \pm 0.15}$$

- Silk-Elmegreen Relation (Silk 1997; Elmegreen 1997):

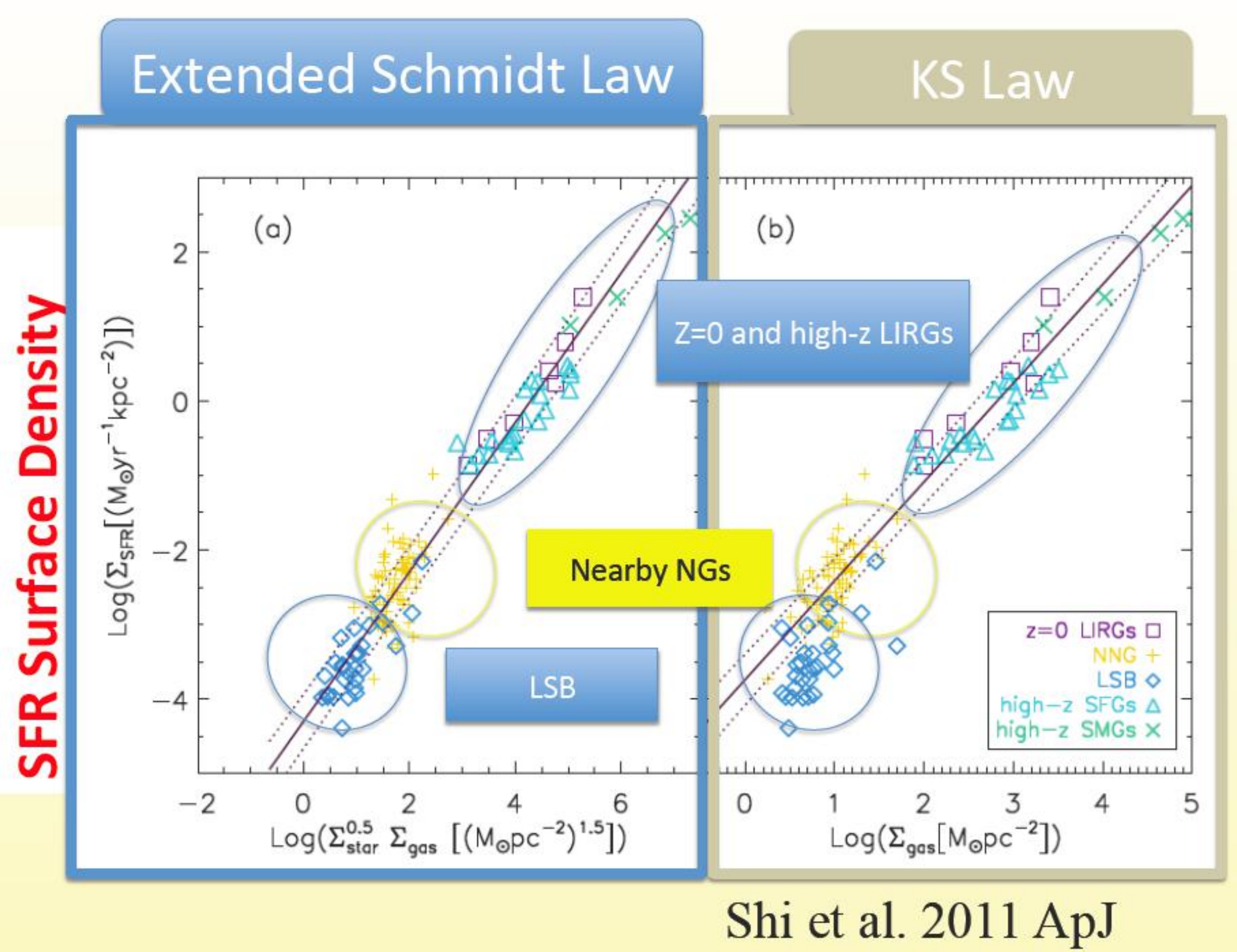
$$\Sigma_{\mathrm{SFR}} \propto \frac{\Sigma_{\mathrm{gas}}}{\tau}; \tau = \text{orbital timescale}$$

Σ_{SFR} as a function of Σ_{gas} and Σ_{star}

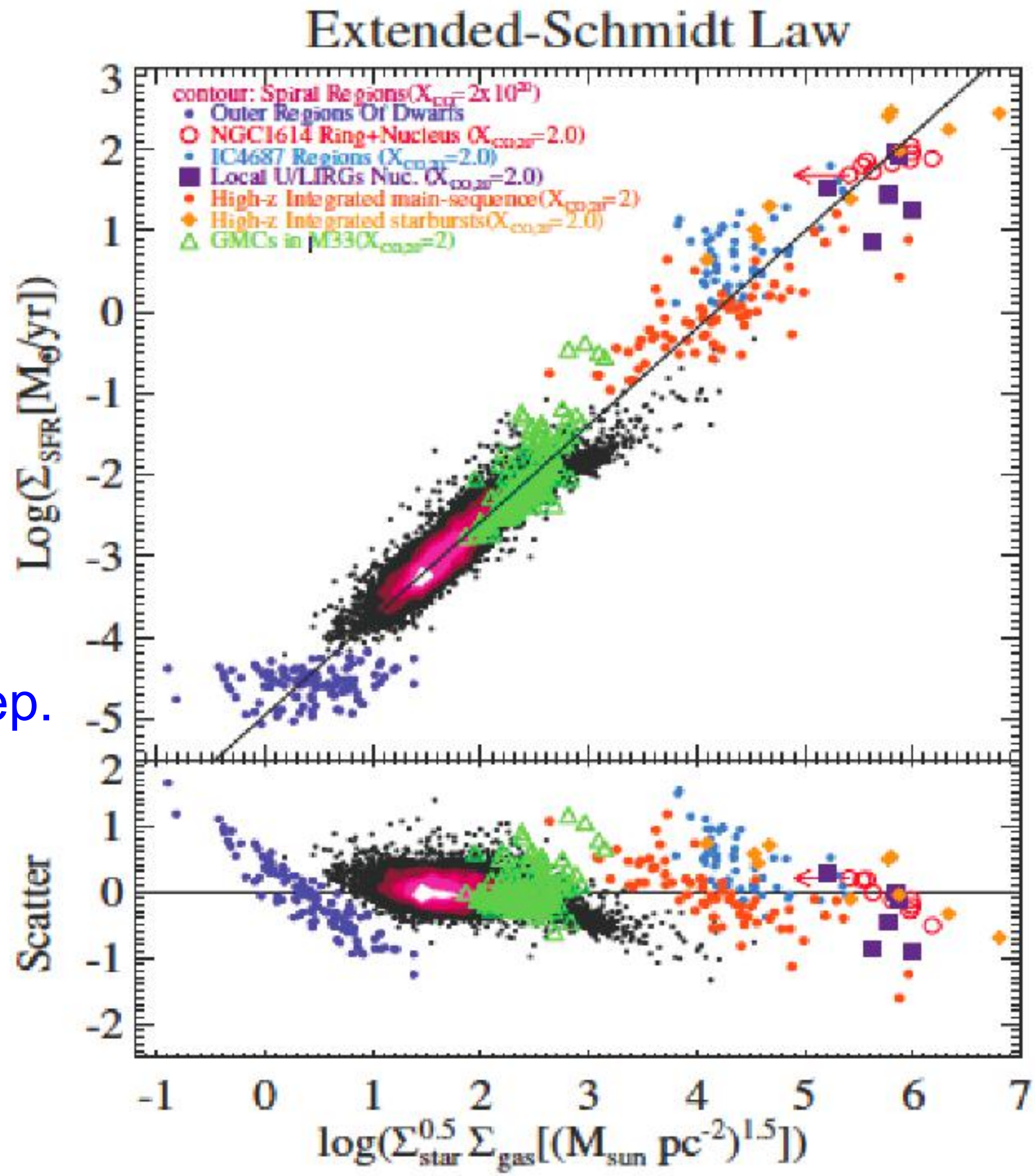
$$\Sigma_{SFR} \propto \Sigma_{gas}^{0.98\pm0.06} \Sigma_{star}^{0.48\pm0.06}$$

A *unity* index on Σ_{gas} gives a clear physical implication of the relation:

Star-Formation-Efficiency (SFE)=SFR/M_{gas} is a function of the stellar density, i.e., the stellar density controls how efficient new stars form.

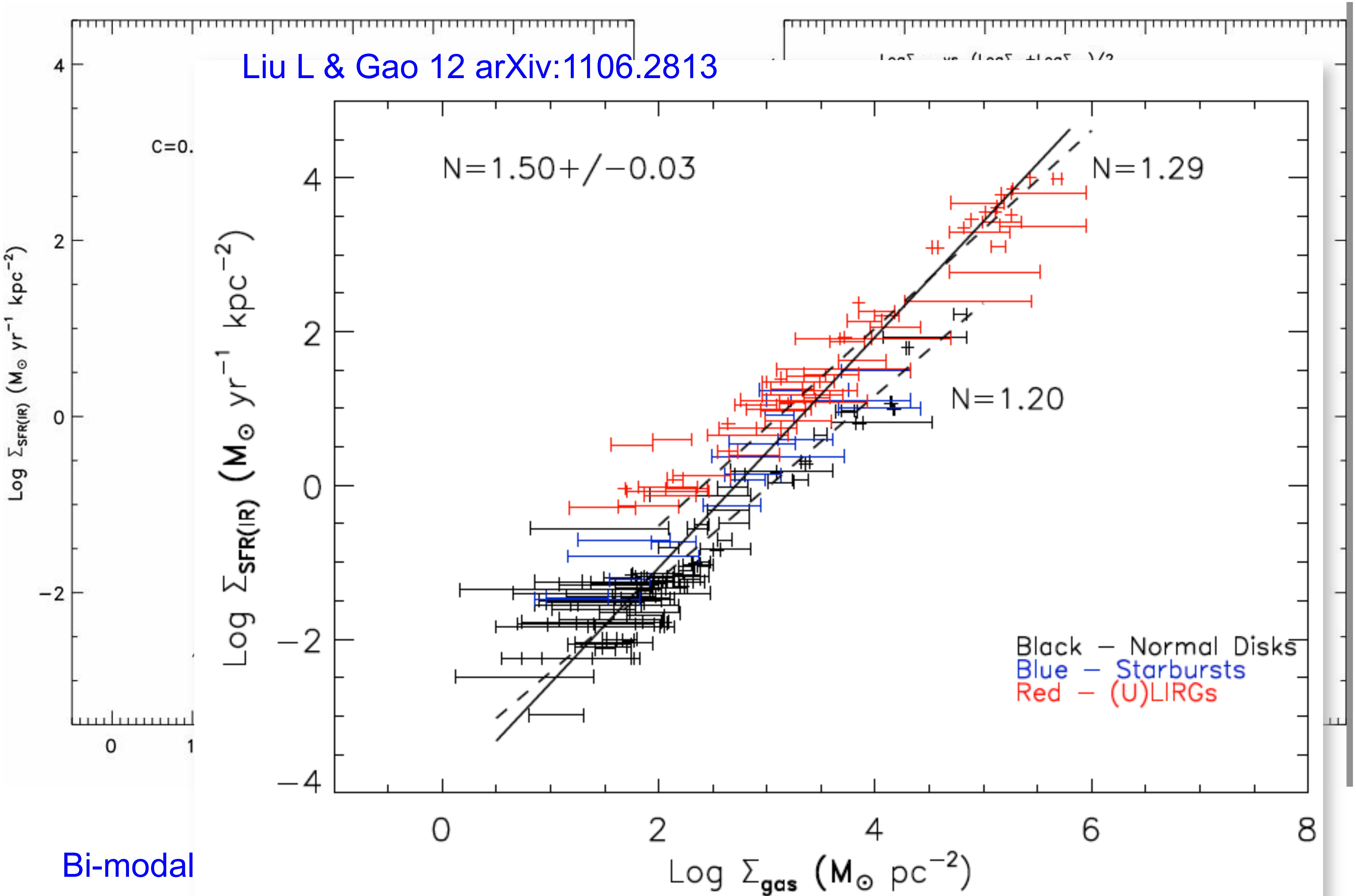


Extended Schmidt Law
KS Law
SFR Surface Density
(a)
(b)
Z=0 and high-z LIRGs
Nearby NGs
LSB
Log(Σ_SFR[(M⊙yr⁻¹kpc⁻²)])
Log(Σ^0.5_star Σ_gas [(M⊙pc⁻²)^1.5])
Log(Σ_gas[M⊙pc⁻²])
z=0 LIRGs
NNG
LSB
high−z SFGs
high−z SMGs
Shi et al. 2011 ApJ



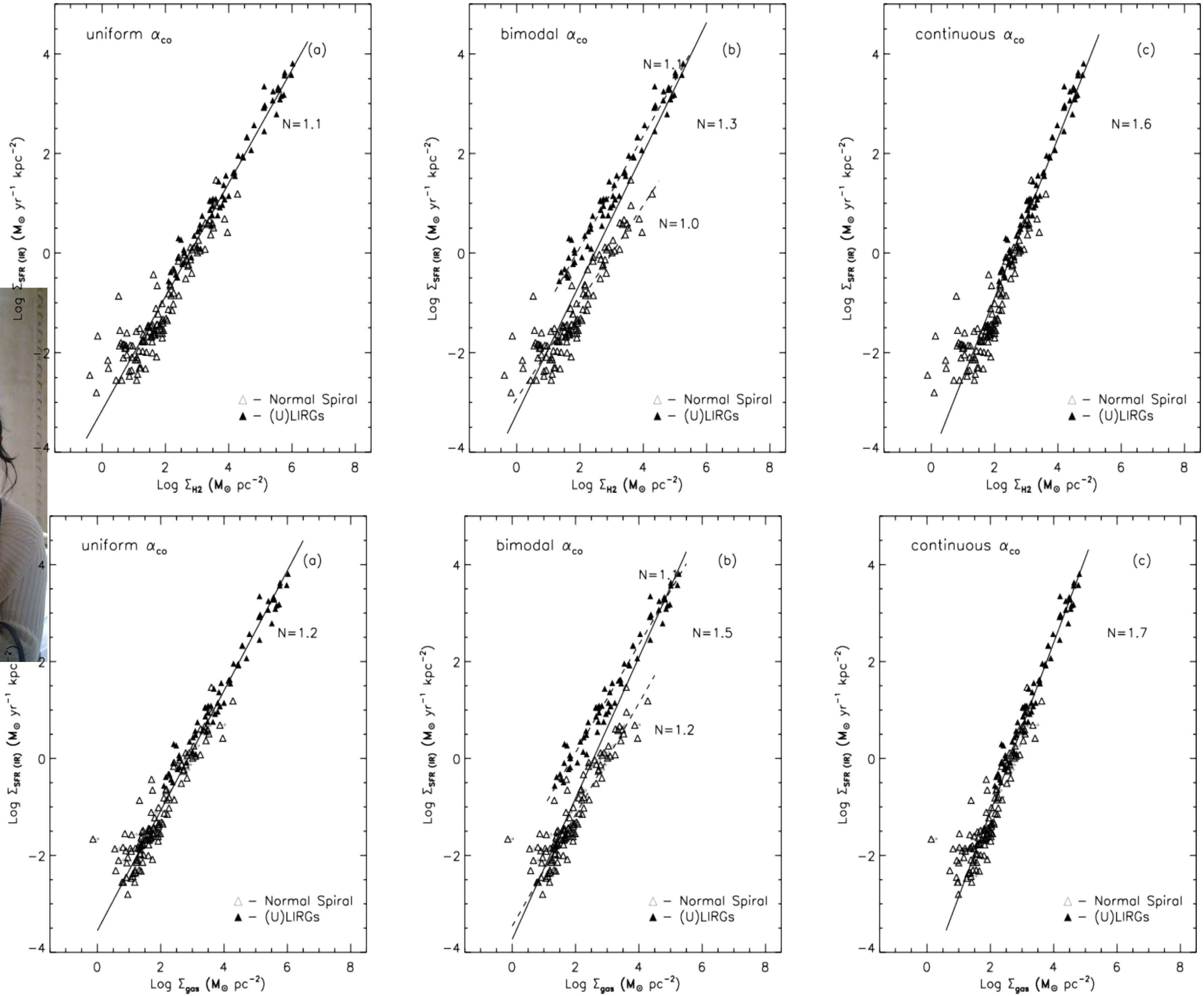
Shi+17 in prep.

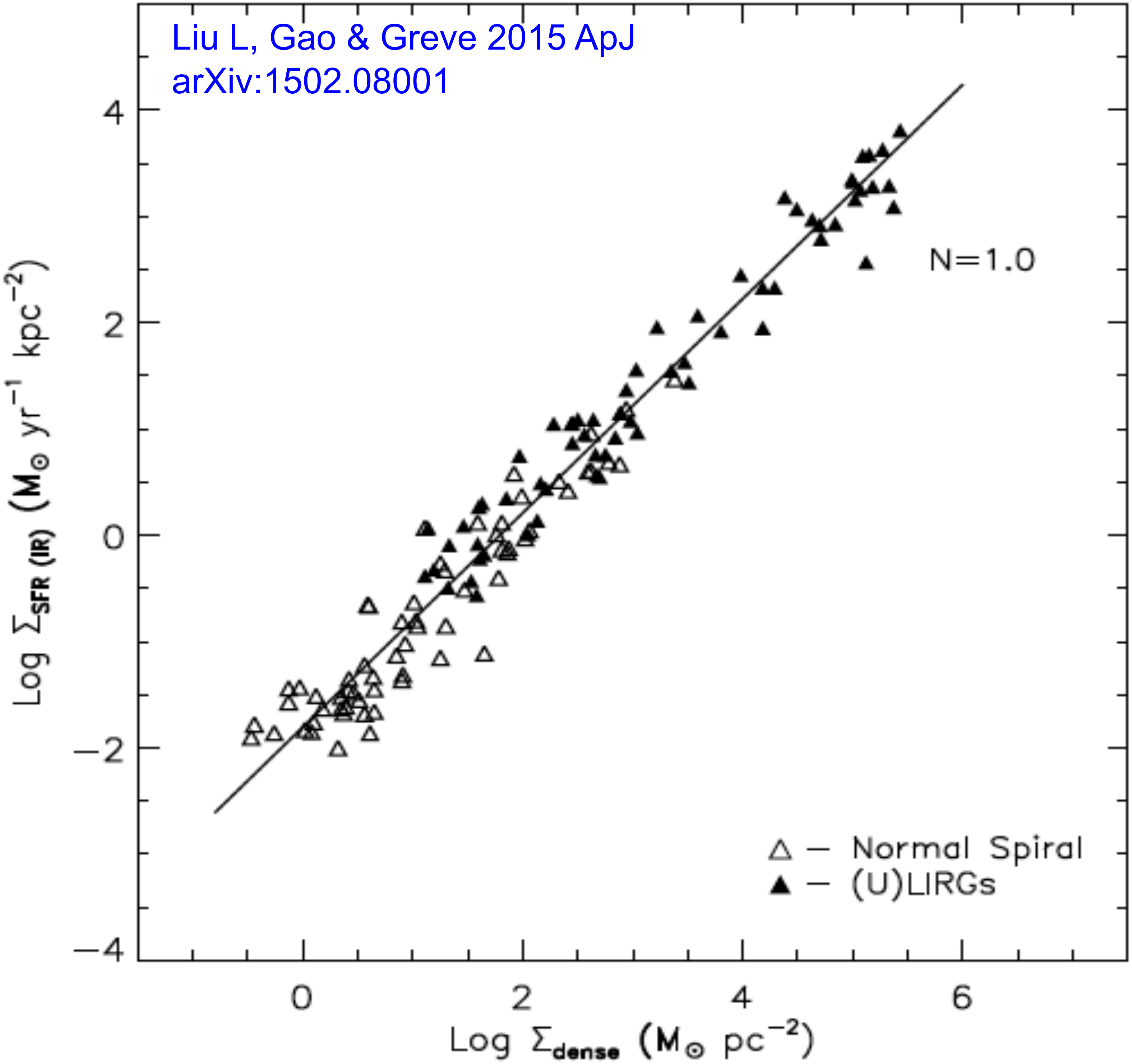
Liu L & Gao 12 arXiv:1106.2813



Bi-modal

Liu L, Gao & Greve 2015 ApJ 805, 31

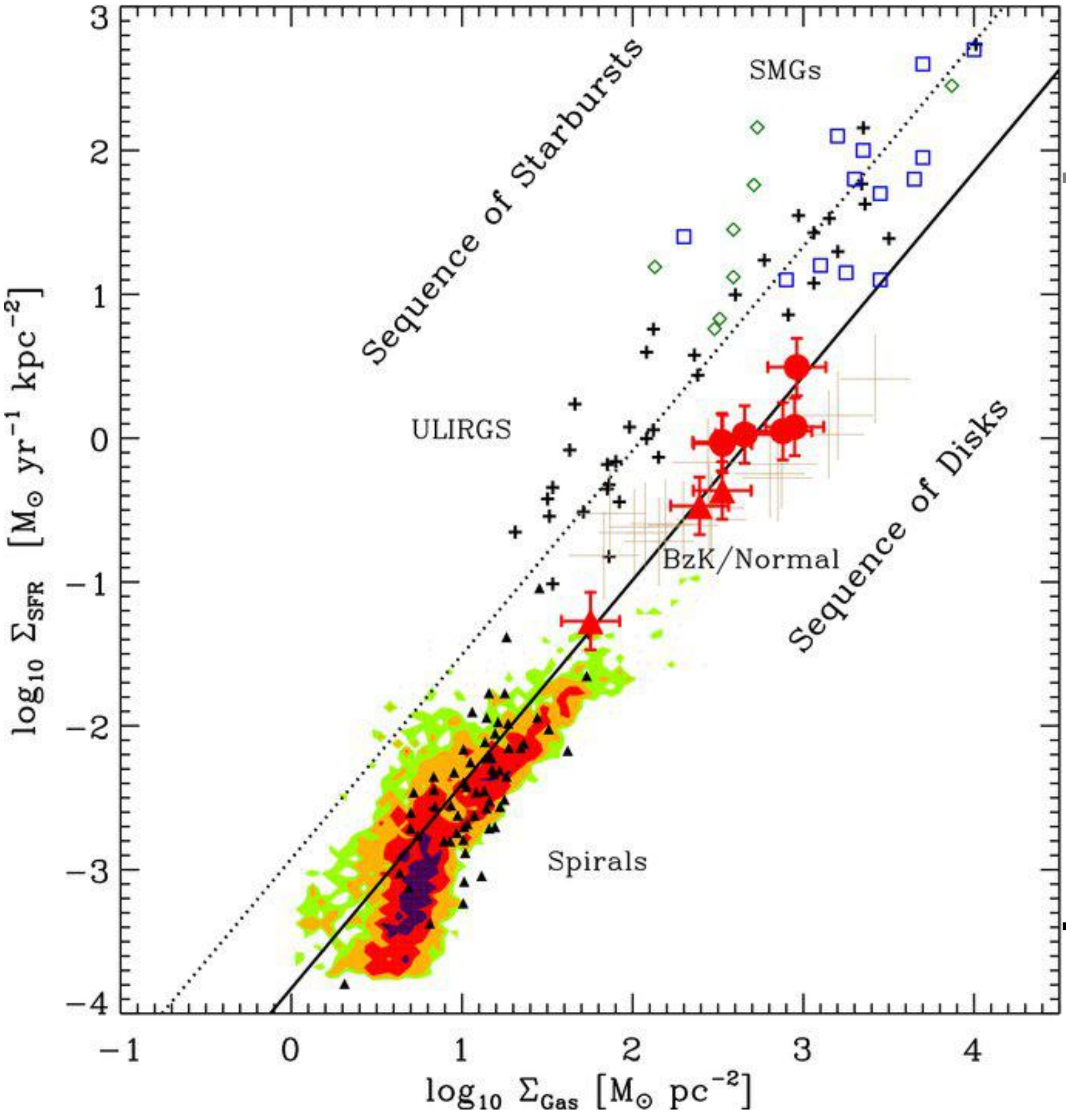

uniform α_{co}
(a)
N=1.1
bimodal α_{co}
(b)
N=1.1
N=1.3
N=1.0
continuous α_{co}
(c)
N=1.6
Normal Spiral
(U)LIRGs
Log Σ_{H2} ($M_\odot$ pc^{-2})
Log $\Sigma_{SFR\,(IR)}$ ($M_\odot$ yr^{-1} kpc^{-2})
uniform α_{co}
(a)
N=1.2
bimodal α_{co}
(b)
N=1.1
N=1.5
N=1.2
continuous α_{co}
(c)
N=1.7
Log Σ_{gas} ($M_\odot$ pc^{-2})



Liu L, Gao & Greve 2015 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

K-S SF Law in high-redshift galaxies

Daddi et al. 2010; Genzel+2010



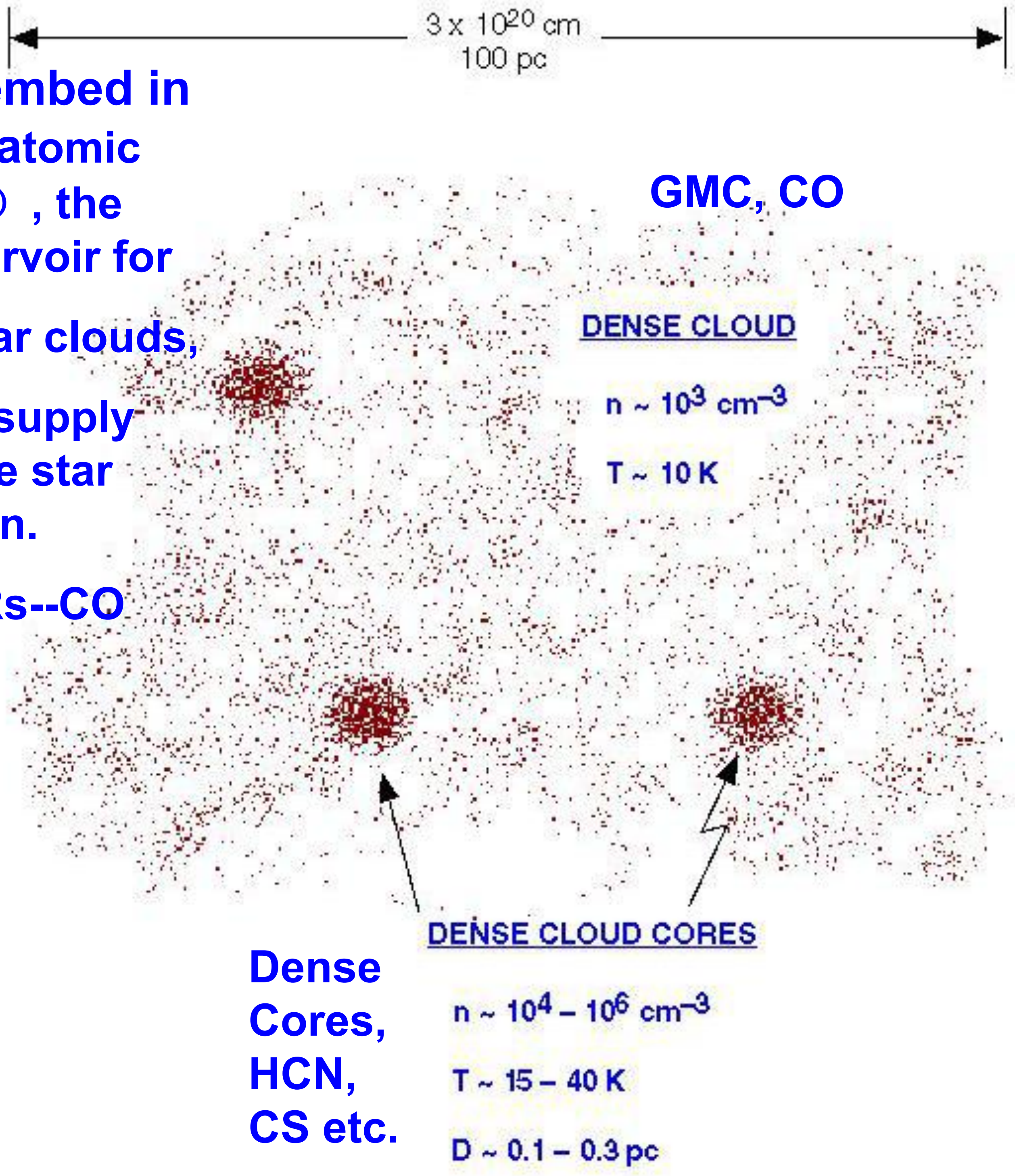
Two major SF modes:
1. a long-lasting mode for disks (local spirals and BzKs)
2. a rapid starburst for LIRGs ULIRGs & SMGs/QSOs

CO->H2 conversion factor
?? α_{CO} (Msun (K km/s pc^2)$^{-1}$:
 4.6 for local spirals
 3.6 ± 0.8 for BzKs
 0.8 for LIRGs/SMGs/QSOs
* Papadoupolos+2012,ApJ?!

GMCs embed in diffuse atomic gas（HI）, the gas reservoir for molecular clouds, and the supply for future star formation.

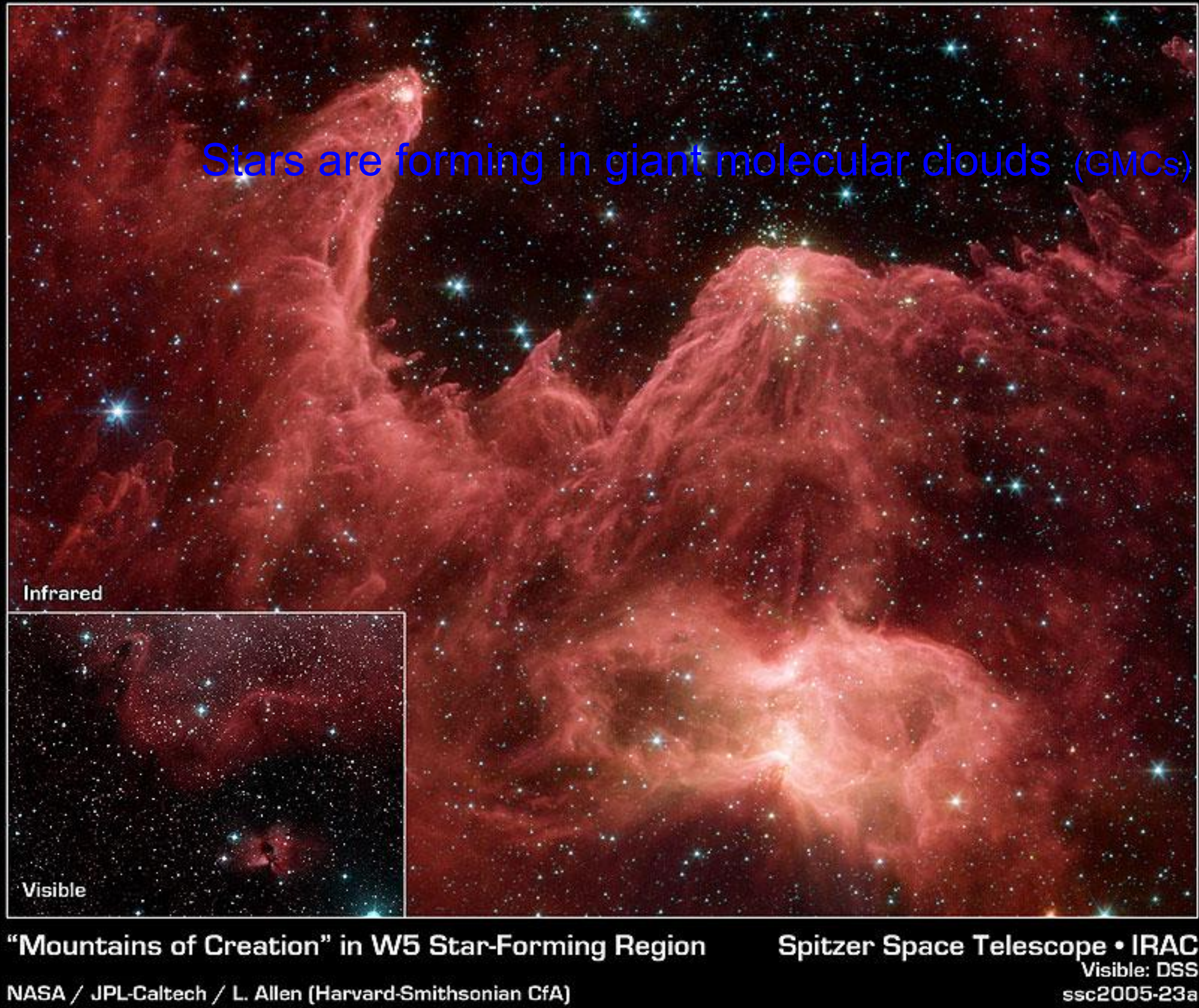
HI—PDRs--CO

GMC, CO



Dense Cores, HCN, CS etc.

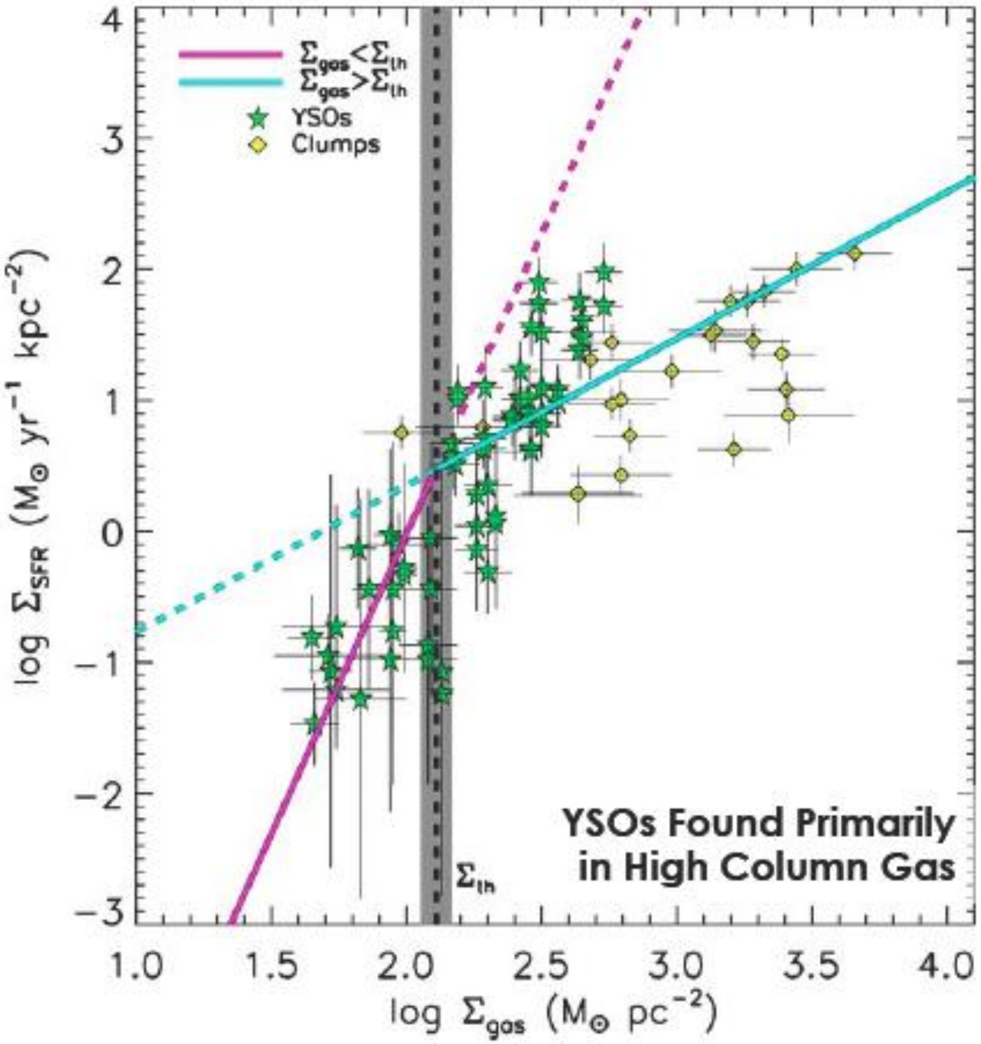
Stars are forming in giant molecular clouds (GMCs)



Dense Gas

Stars Form in Dense Gas

Inside local molecular clouds, young stellar objects (tracing recent star formation) are found within the specifically high column density regions. High density gas forms stars.



Leroy's talk at Sexten 17

HEIDERMAN ET AL. (2010), EVANS ET AL. (2014), LADA ET AL. (2010, 2012) – C.F. FILAMENTS IN ANDRE ET AL. (2014)

High Density Tracers

Merging/interactions trigger gas infall to nuclear regions

Nuclei of Galaxies should possess denser molecular gas

as GMCs have to survive to **tidal forces (must be denser)**

*

Critical density: the radiating molecule (eg, CO) suffers collisions at the rate: n(H2) sigma v = A

(Einstein coefficient A ~ nu^3 mu^2)

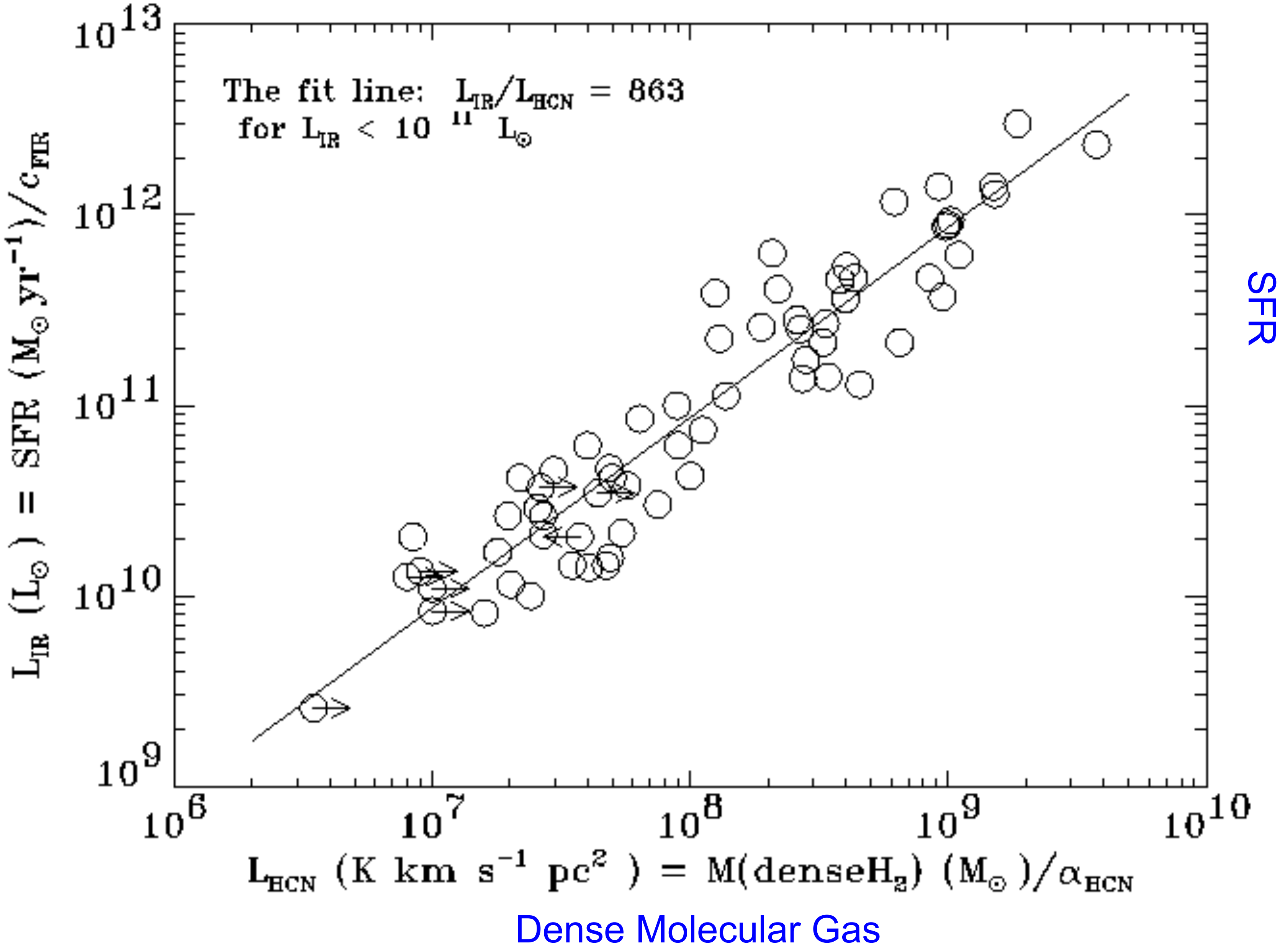
* High-J **(>~4)** levels of CO (nu ~ J) → n(H2) >~10^4cm^{-3}

Need higher critical density to excite: n(H2) >~10^4cm^{-3}

* & high dipole moment molecules

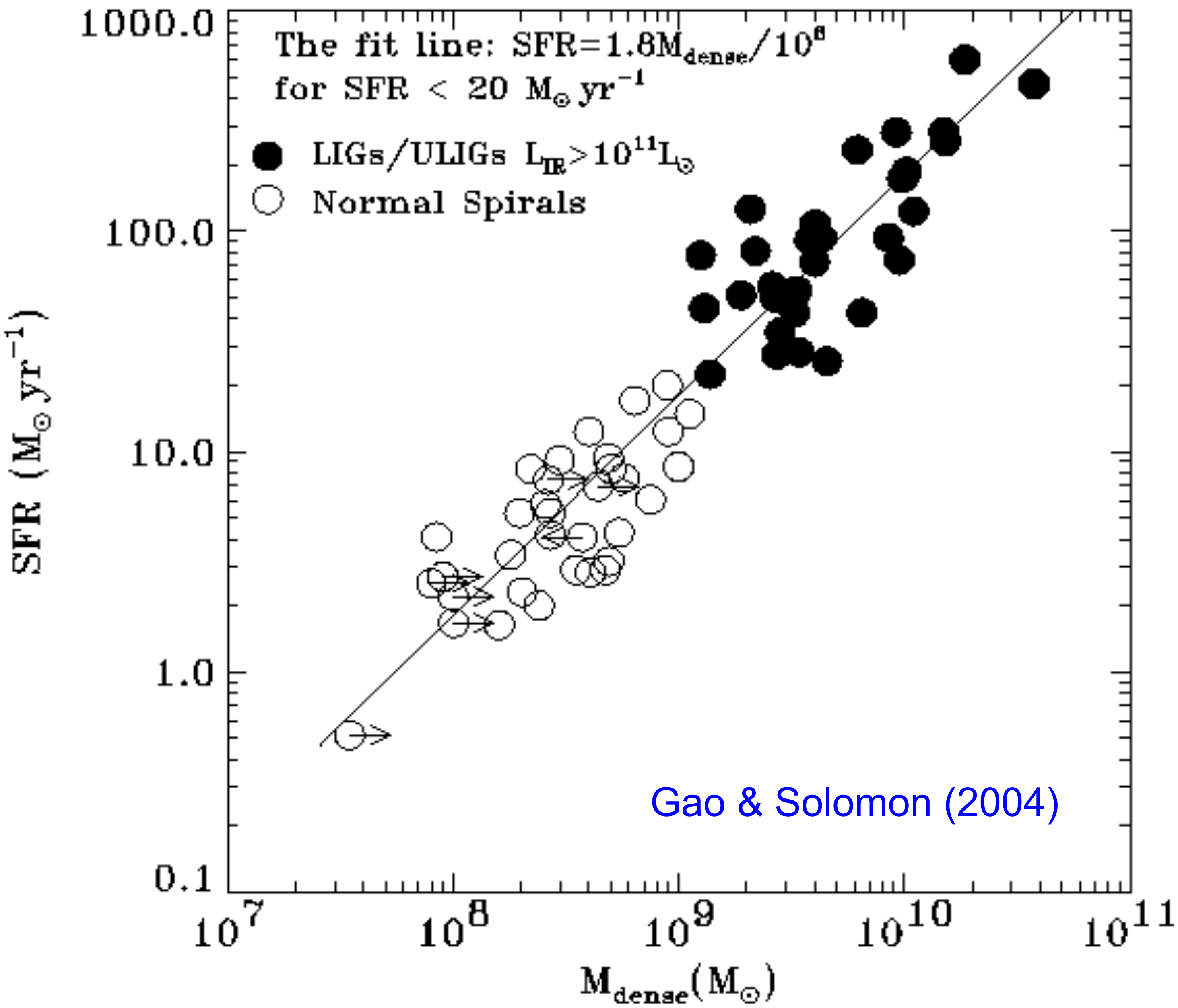
HCN, HNC, HCO+, CS (mu ~ 30x > CO), n(H2) >~10^5cm^{-3}

* X factors ? CO-to-H2, HCN-to-DenseH2 conversions



The fit line: L_{IR}/L_{HCN} = 863
for $L_{IR} < 10^{11} L_\odot$
L_{IR} ($L_\odot$) = SFR ($M_\odot$ yr^{-1})/c_{FIR}
L_{HCN} (K km s^{-1} pc^2) = M(denseH_2) ($M_\odot$)/α_{HCN}
10^6
10^7
10^8
10^9
10^{10}
10^9
10^{10}
10^{11}
10^{12}
10^{13}
SFR
Dense Molecular Gas

SFR vs. M_dense(H2): linear correlation

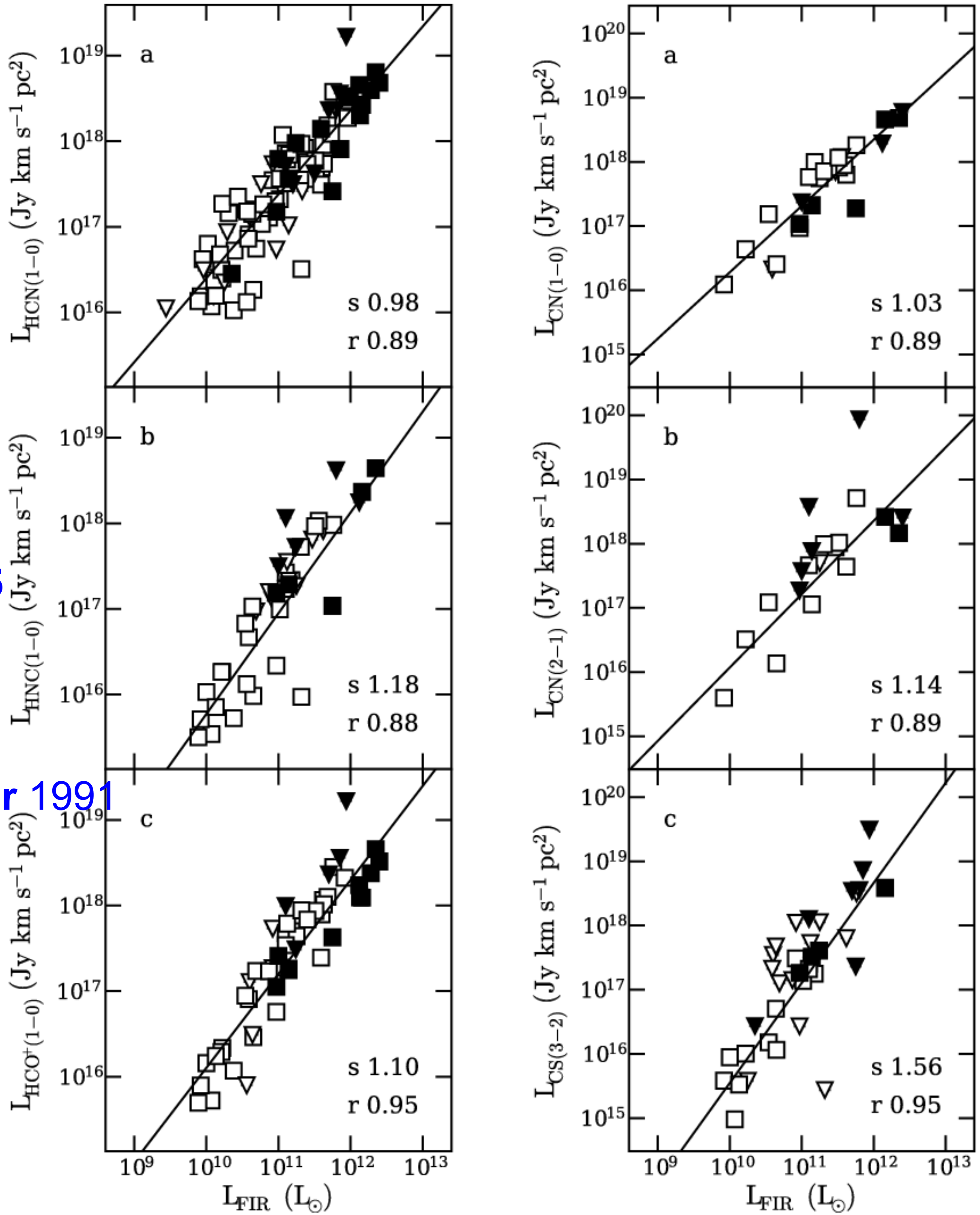


Baan, Henkel, Loenen + 2008

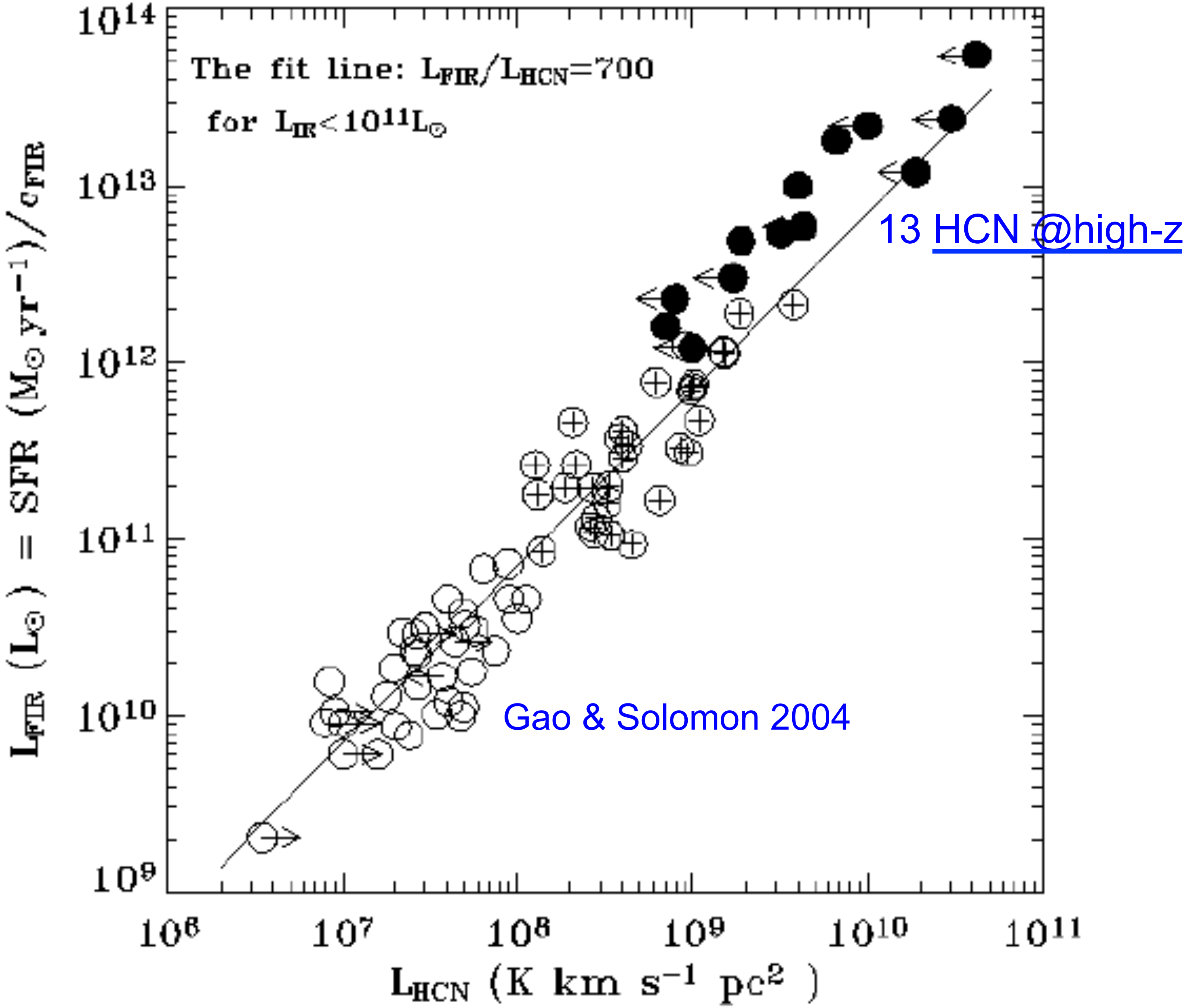
HCN,CS,HNC etc. in SF gals.

- **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

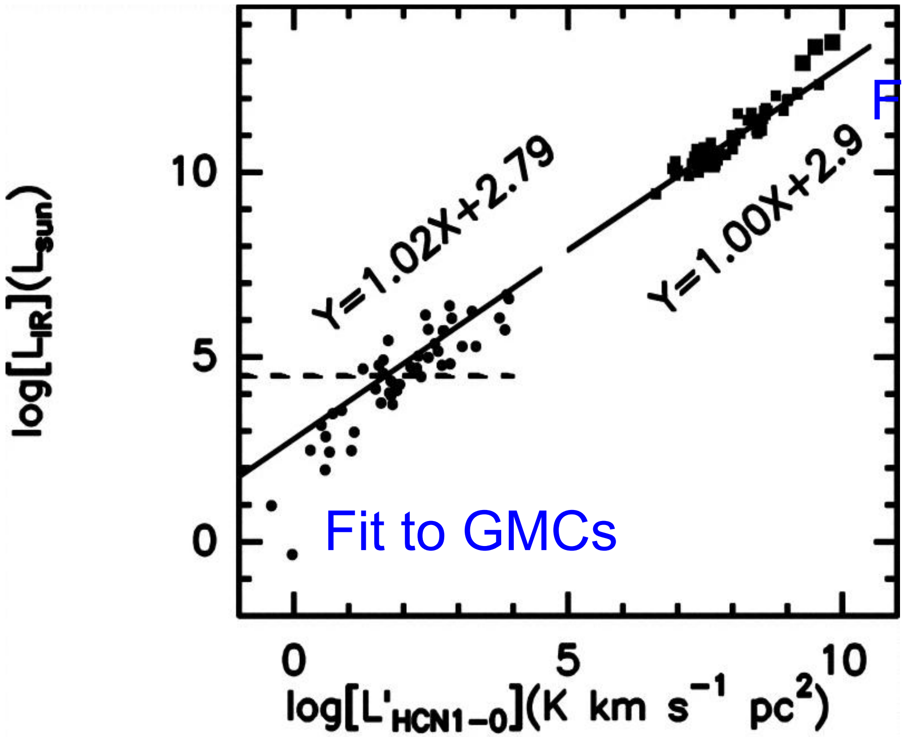
Best case studies:
Arp 220 & NGC 6240
(Greve + 2009)



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

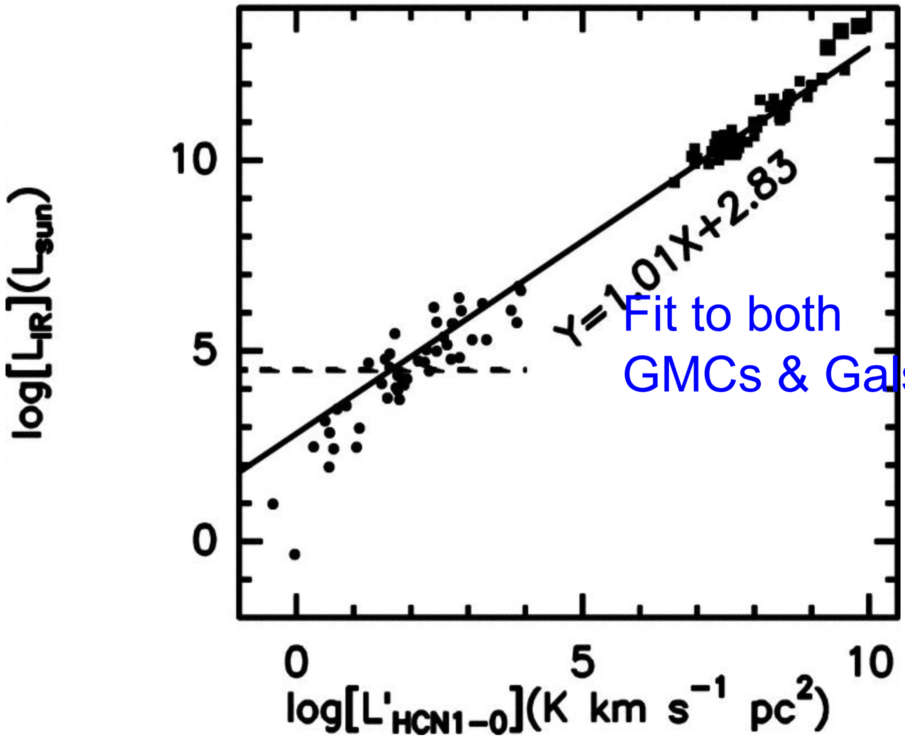


Wu, Evans, Gao et al. 2005 ApJL



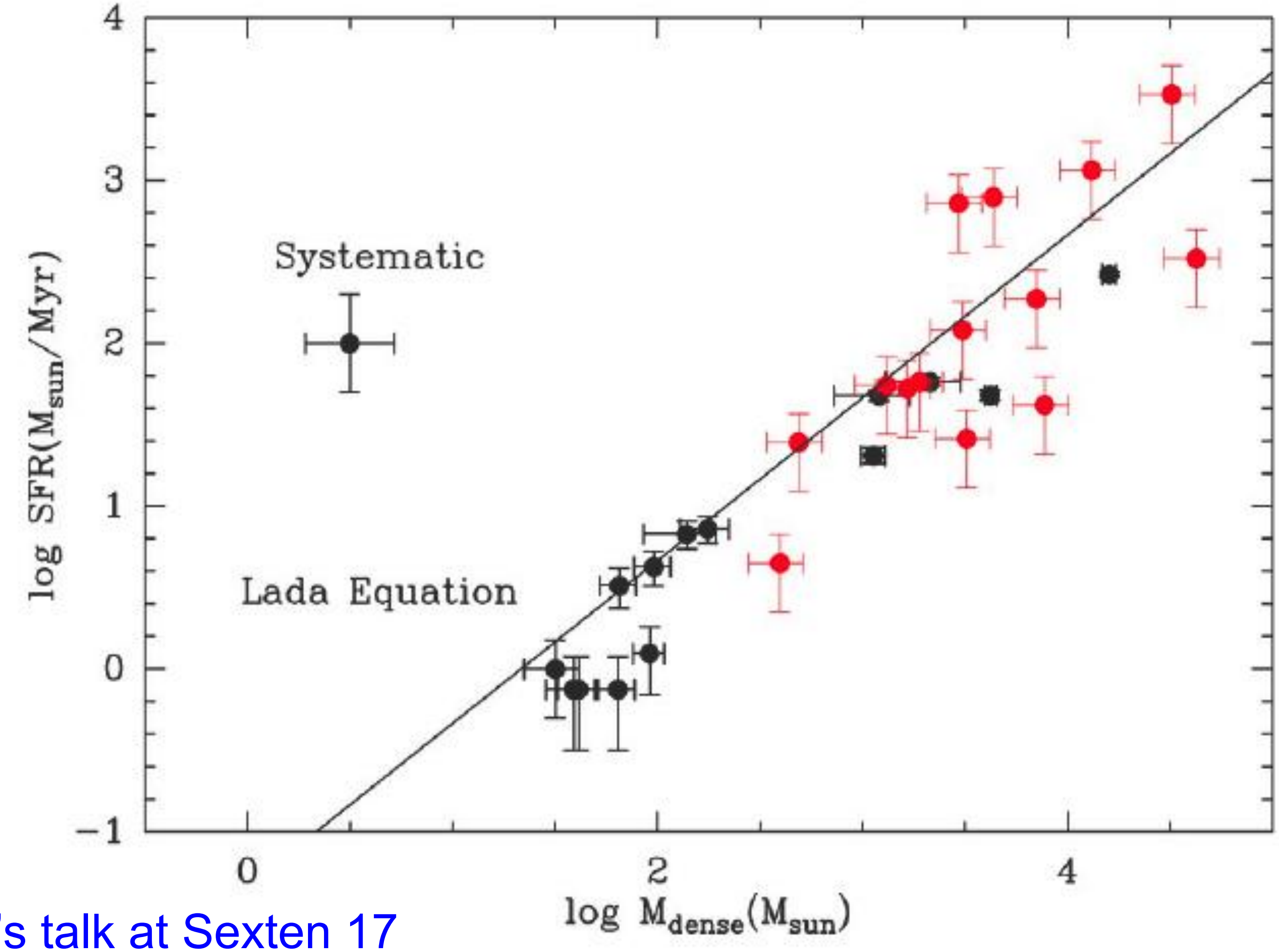
Fit to Galaxies

Wu+2010



Fit to both GMCs & Gals..

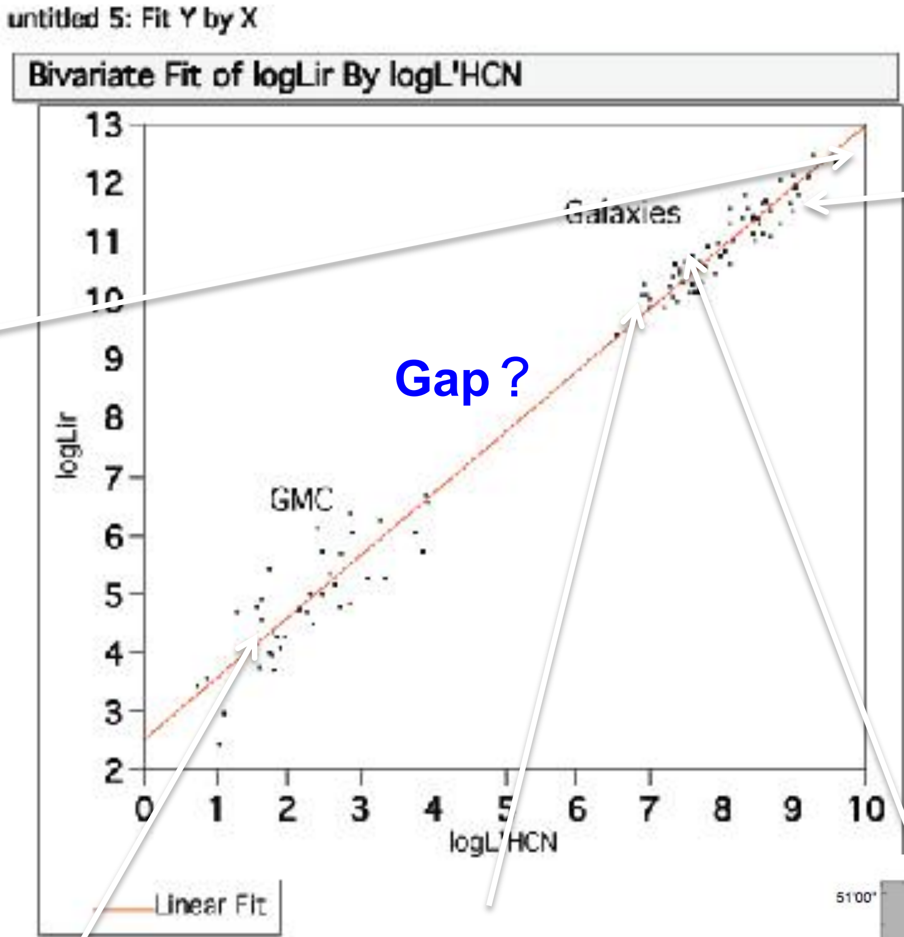
Several studies of the Milky Way find that the amount of dense gas (from a column density threshold or defined by as gas emitting in some high critical density line) is the best predictor of star formation in a given molecular cloud.

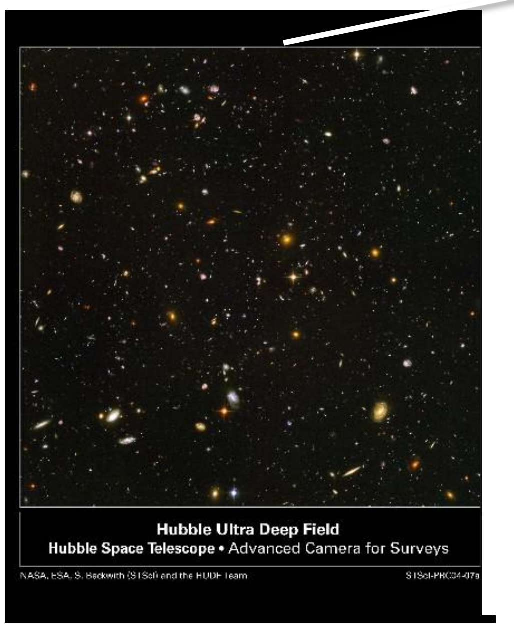


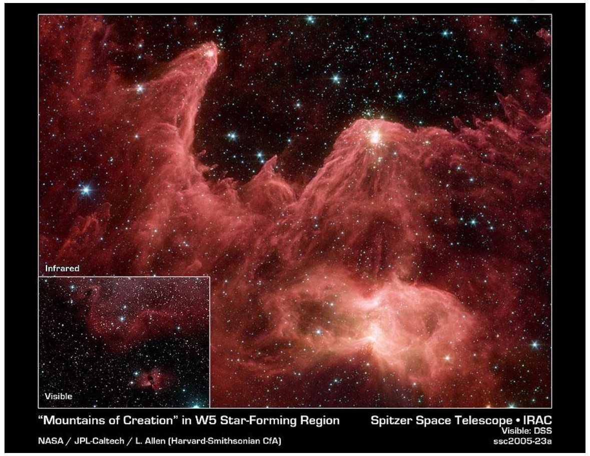
Leroy's talk at Sexten 17

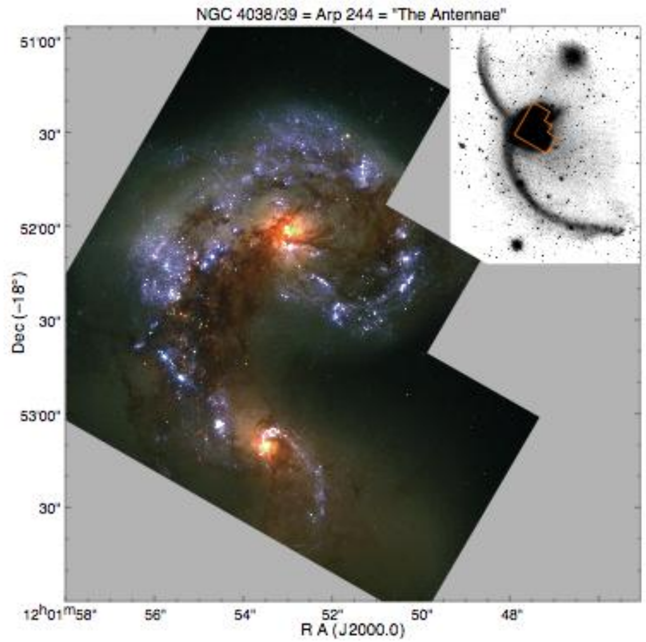
EVANS ET AL. (2014), VUTISALCHAVAKUL ET AL. (2016), LADA ET AL. (2010, 2012), WU ET AL. (2005, 2010)

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

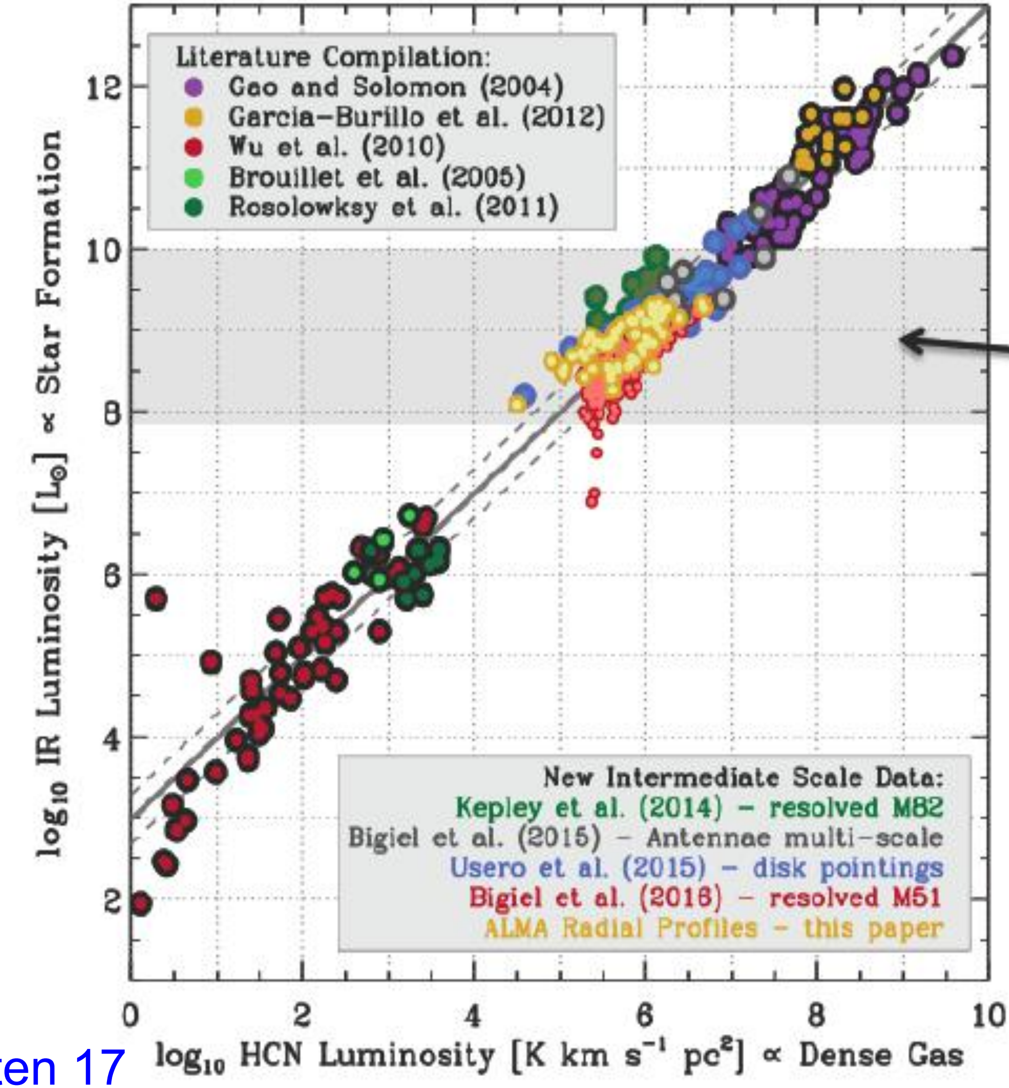








These new surveys do fill in the luminosity range between whole galaxies and individual clouds. The HCN-IR (dense gas-SFR) correlation holds in broad brush.



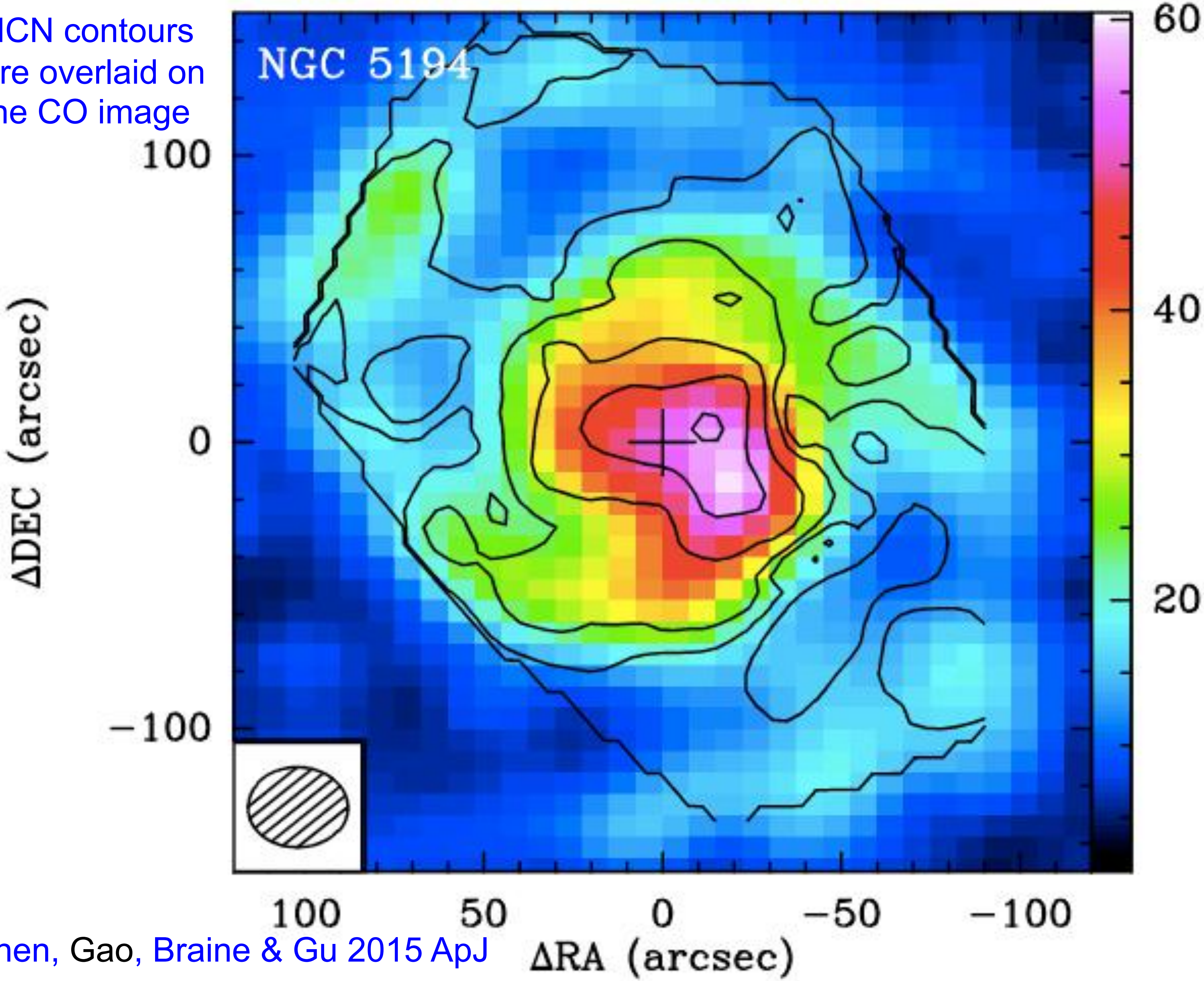
New surveys:

Disk pointings
M51 pixels
M82 regions
Antenna pointings
ALMA disk profiles

Leroy's talk at Sexten 17

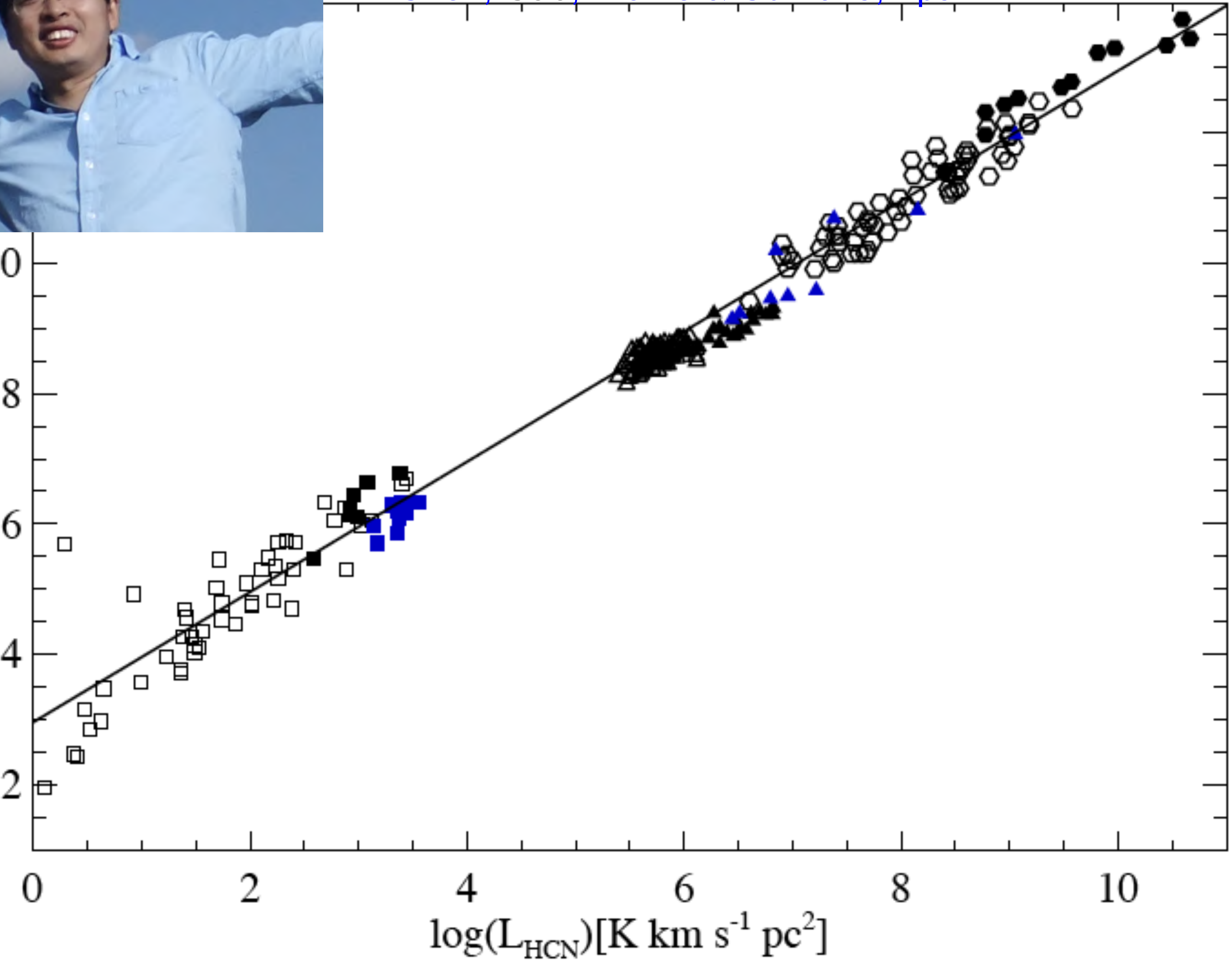
MOLLY GALLAGHER, LEROY ET AL. (SUBMITTED), BIGIEL ET AL. (2016), USERO ET AL. (2015)

HCN contours are overlaid on the CO image

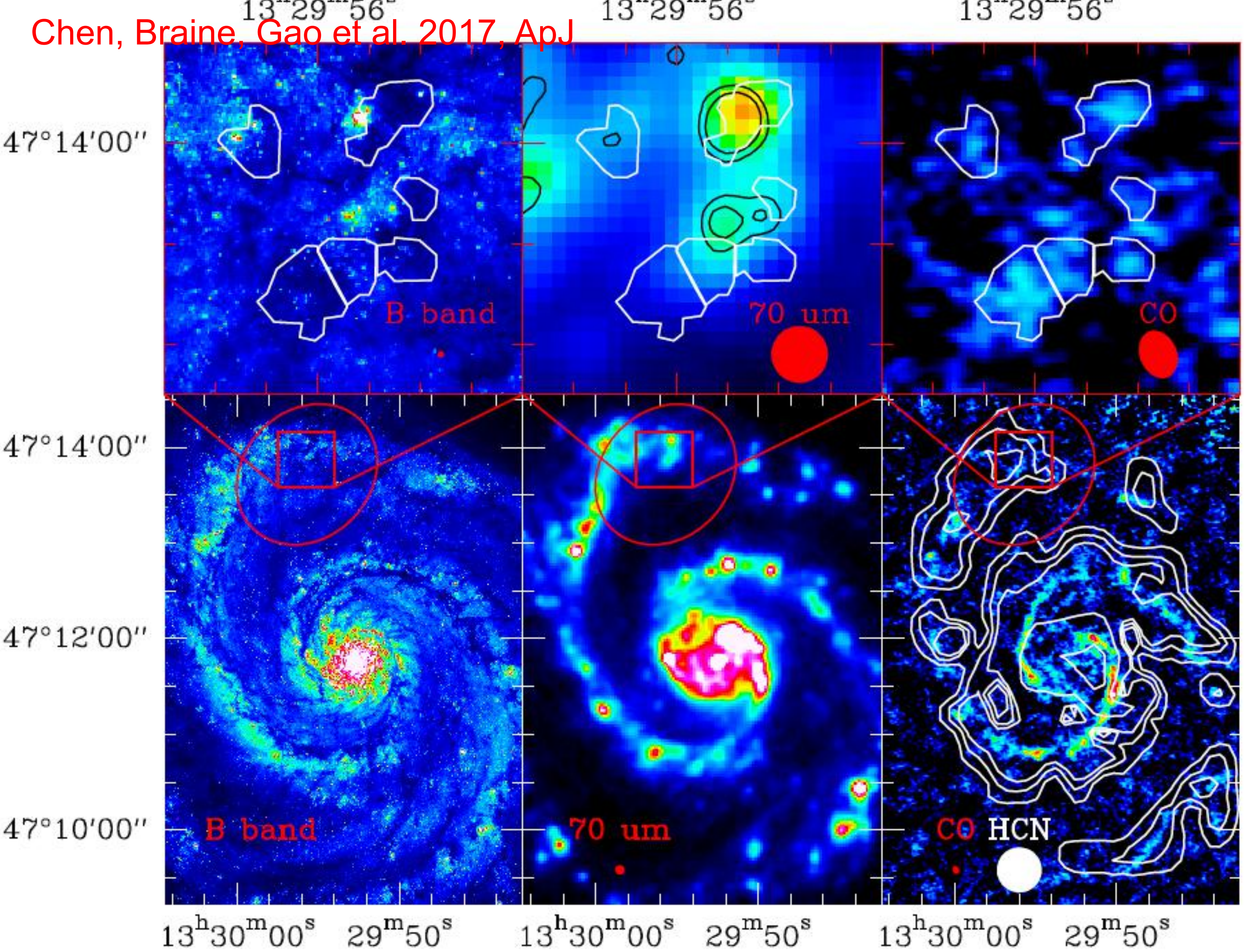


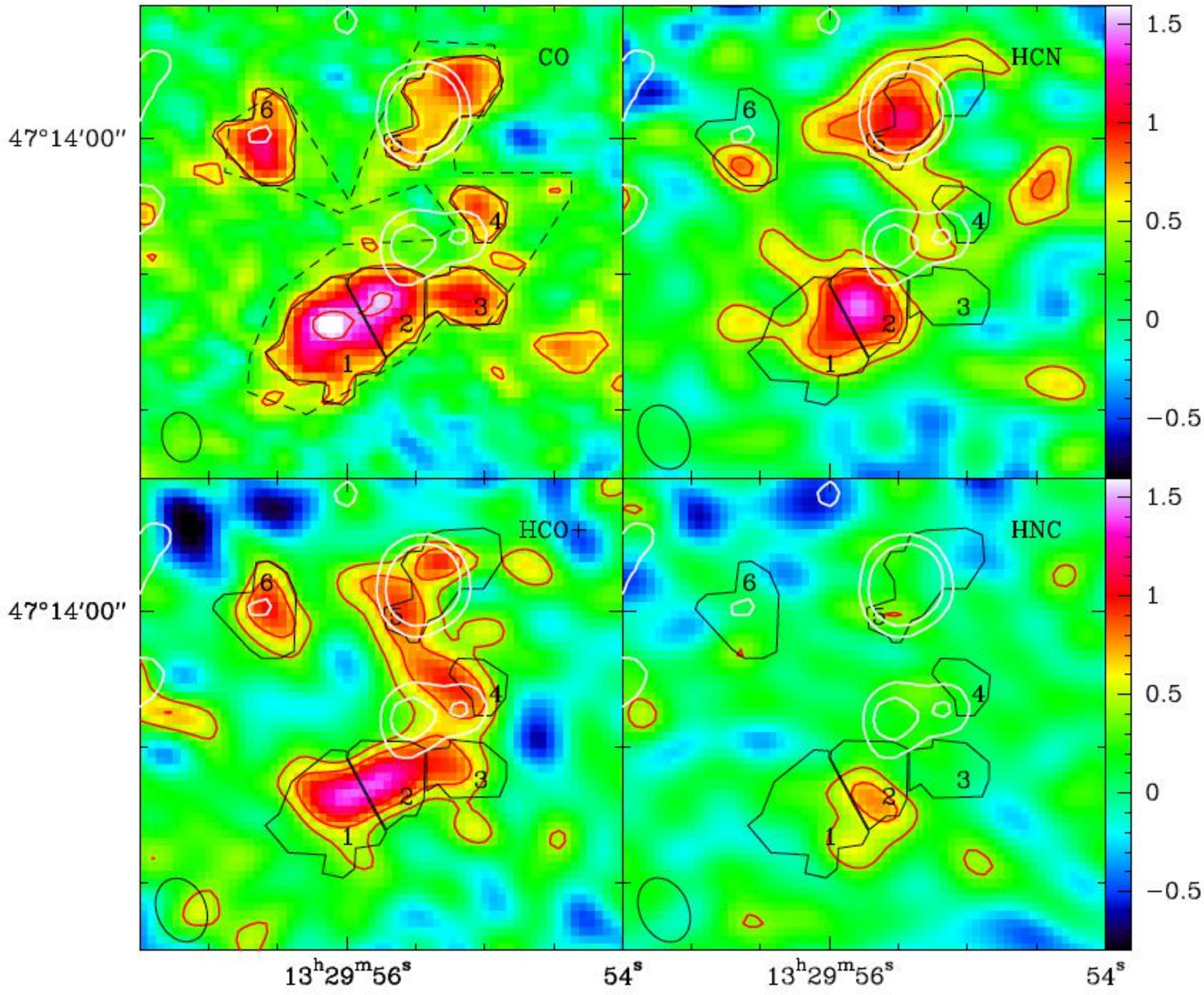
Chen, Gao, Braine & Gu 2015 ApJ

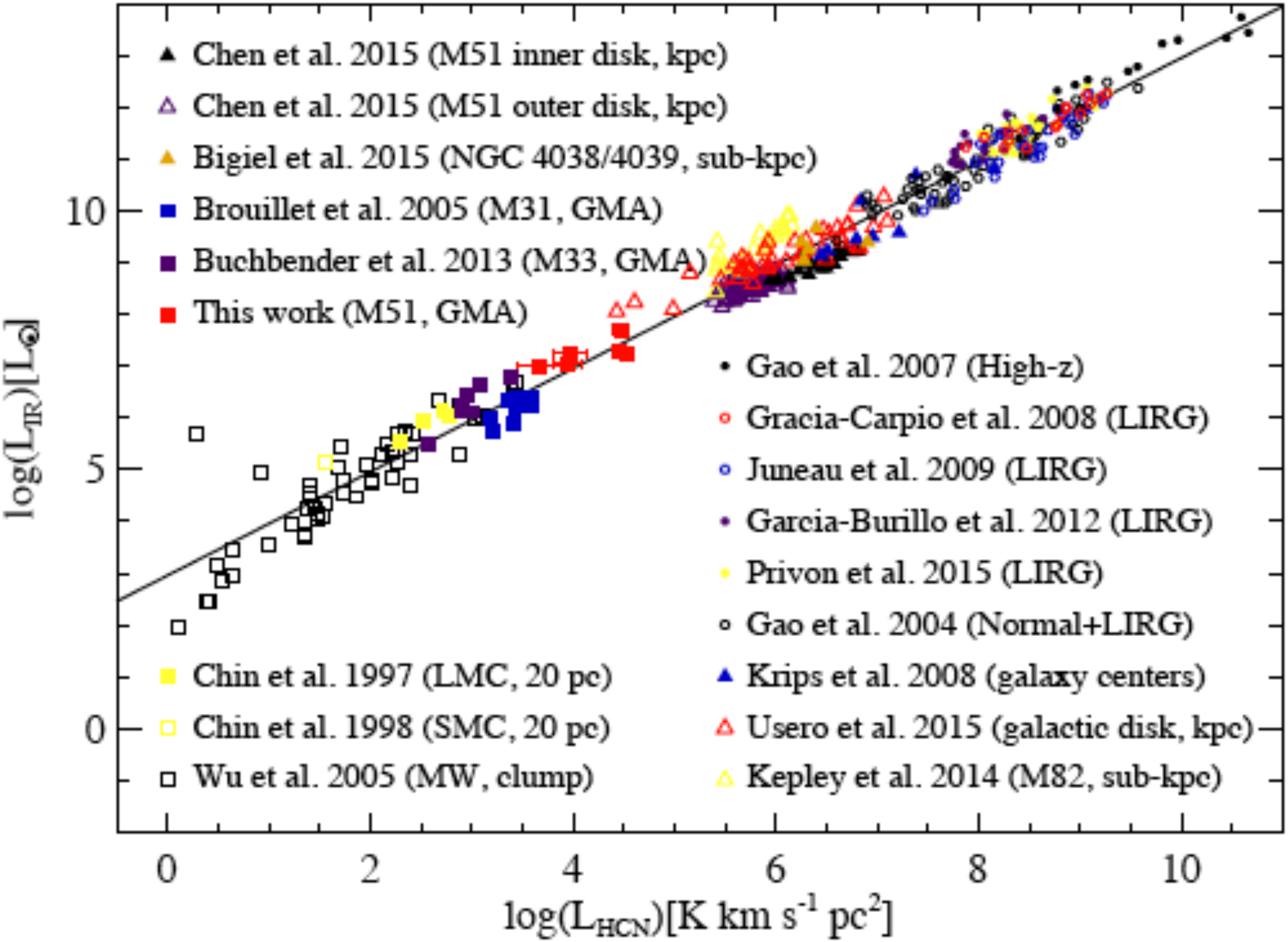
Chen, Gao, Braine & Gu 2015, ApJ



Chen, Braine, Gao et al. 2017, ApJ




CO
HCN
HCO+
HNC
47°14′00″
47°14′00″
$13^h29^m56^s$
54^s
$13^h29^m56^s$
54^s
1.5
1
0.5
0
−0.5
1.5
1
0.5
0
−0.5
1
2
3
4
5
6



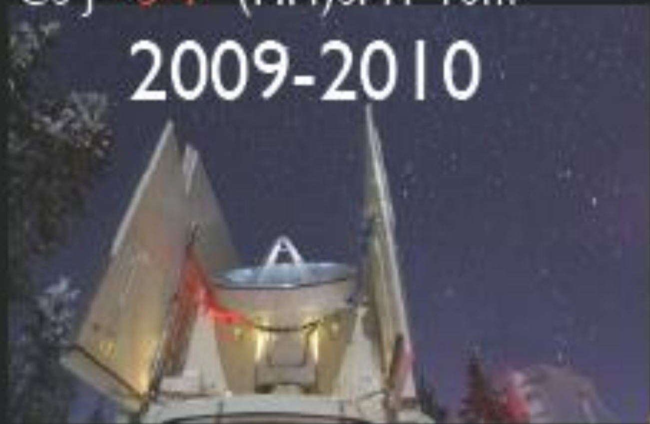
Chen et al. 2015 (M51 inner disk, kpc)
Chen et al. 2015 (M51 outer disk, kpc)
Bigiel et al. 2015 (NGC 4038/4039, sub-kpc)
Brouillet et al. 2005 (M31, GMA)
Buchbender et al. 2013 (M33, GMA)
This work (M51, GMA)
Gao et al. 2007 (High-z)
Gracia-Carpio et al. 2008 (LIRG)
Juneau et al. 2009 (LIRG)
Garcia-Burillo 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)
$\log(L_{IR})[L_\odot]$
$\log(L_{HCN})[\mathrm{K\ km\ s^{-1}\ pc^2}]$
0
2
4
6
8
10
0
5
10

Multiple-J CS survey

Multiple transition from J=1-0 to 7-6 of CS lines towards ~ 50 nearby normal galaxies, starburst, and (U)LIRGs

CS J= 2-1/3-2/5-4 IRAM 30m

CS J= 5-4 (HH)SMT 10m



CS J= 7-6 APEX 12m

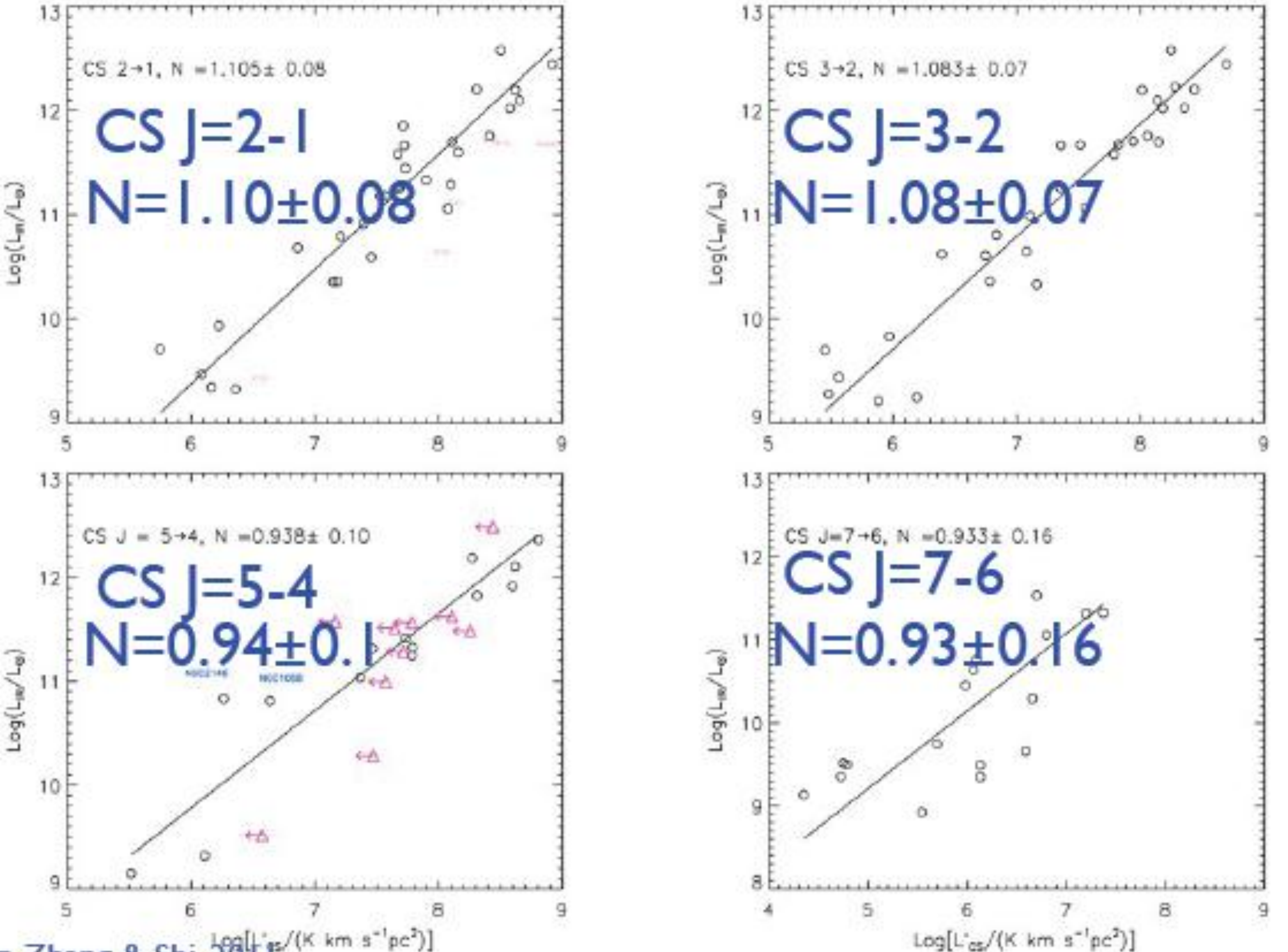
CS J= 1-0 GBT 100m

CS J= 1-0 EVLA

PMO, Zhi-Yu Zhang

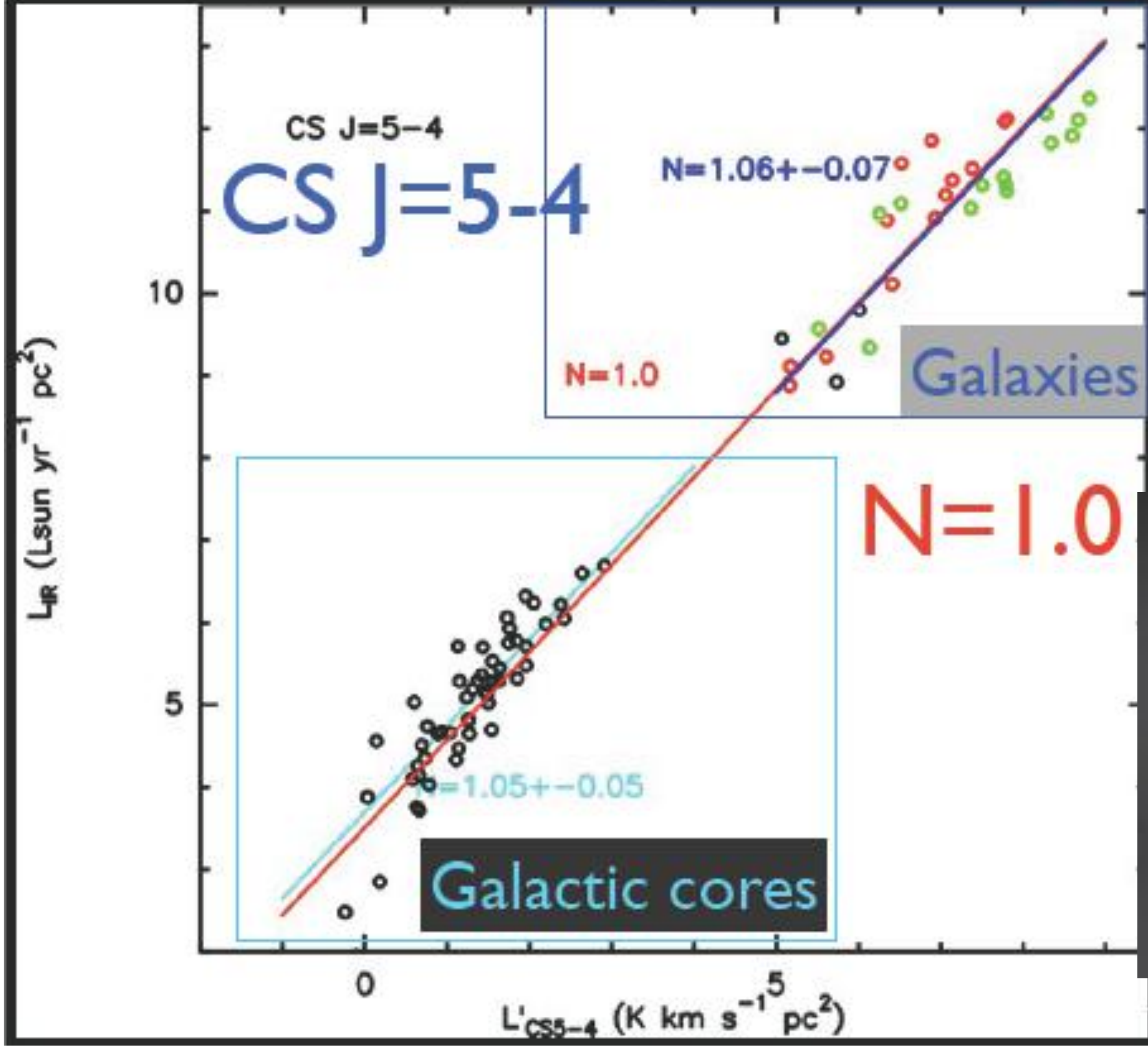
L'CS-LIR correlations

CS: better tracer of dense gas than HCN!



Wang, Zhang & Shi, 2011

Connecting with Galactic CS study ~ 10 orders of magnitude

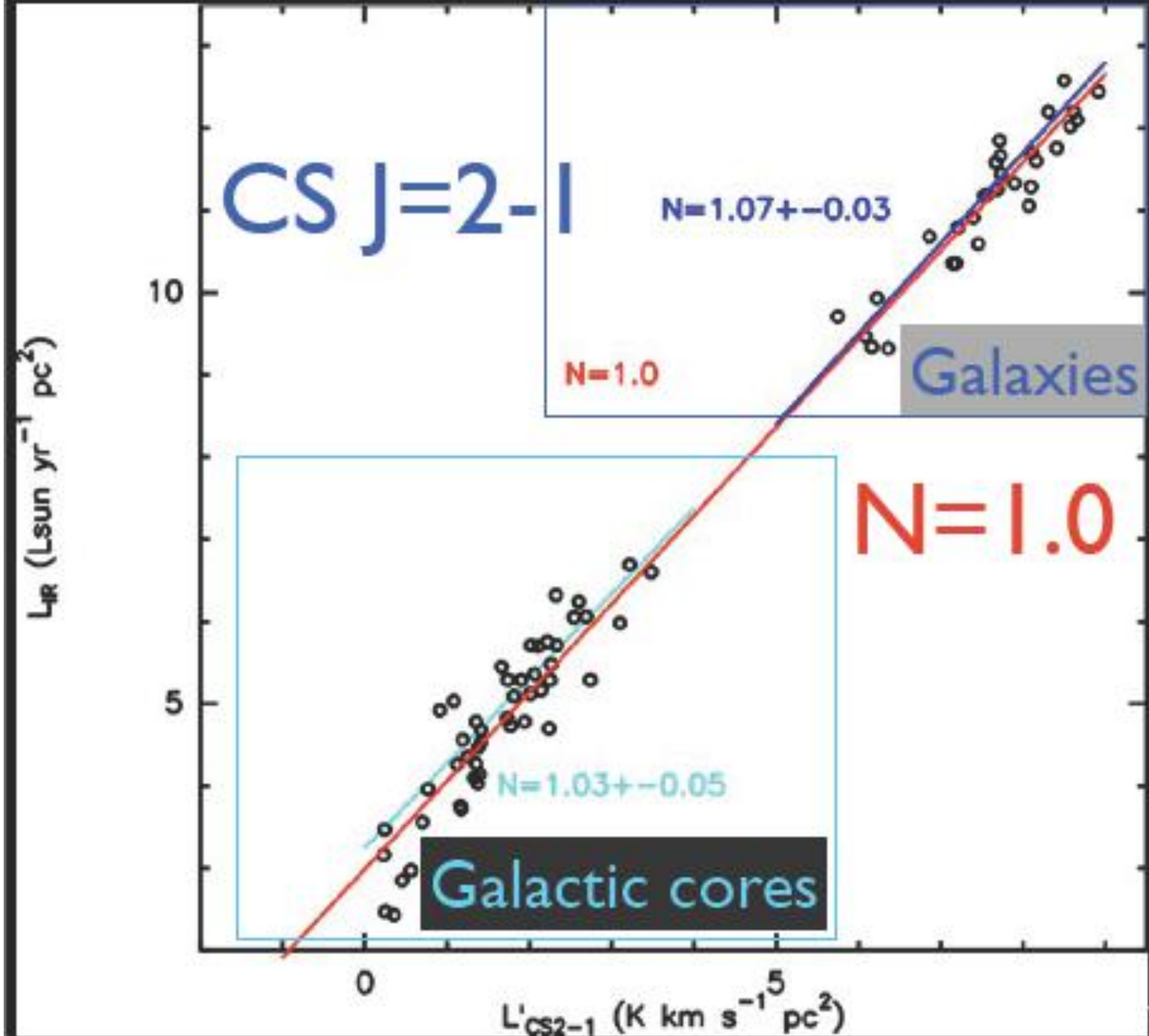


SMT 10m

IRAM 30m

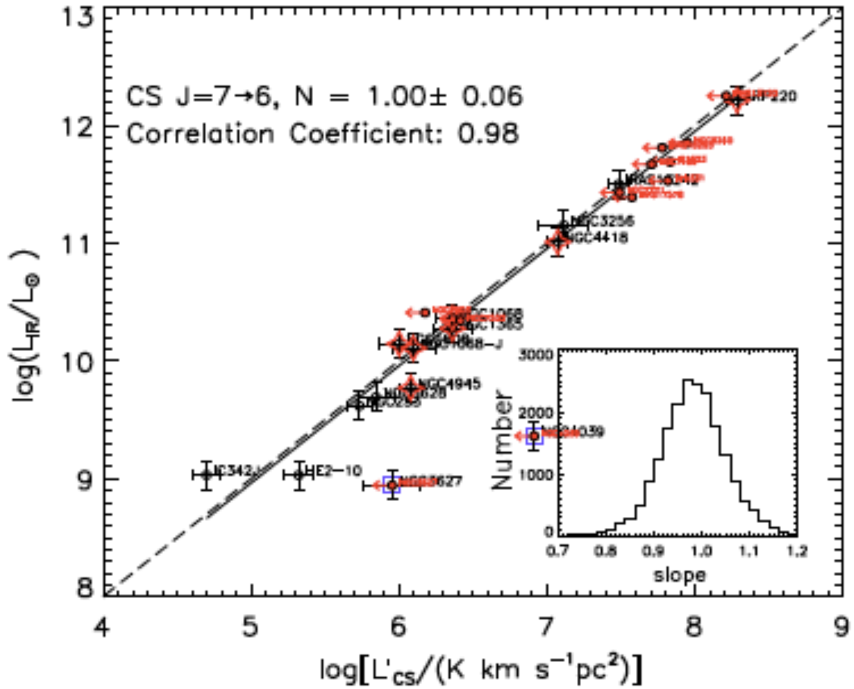
Baan + 2008

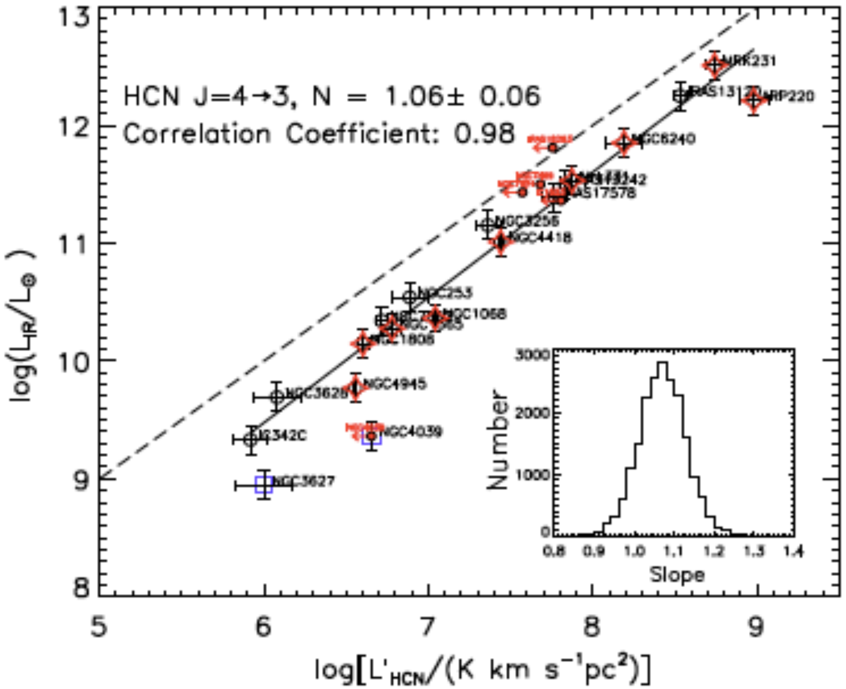
Connecting with Galactic CS study ~ 10 orders of magnitude



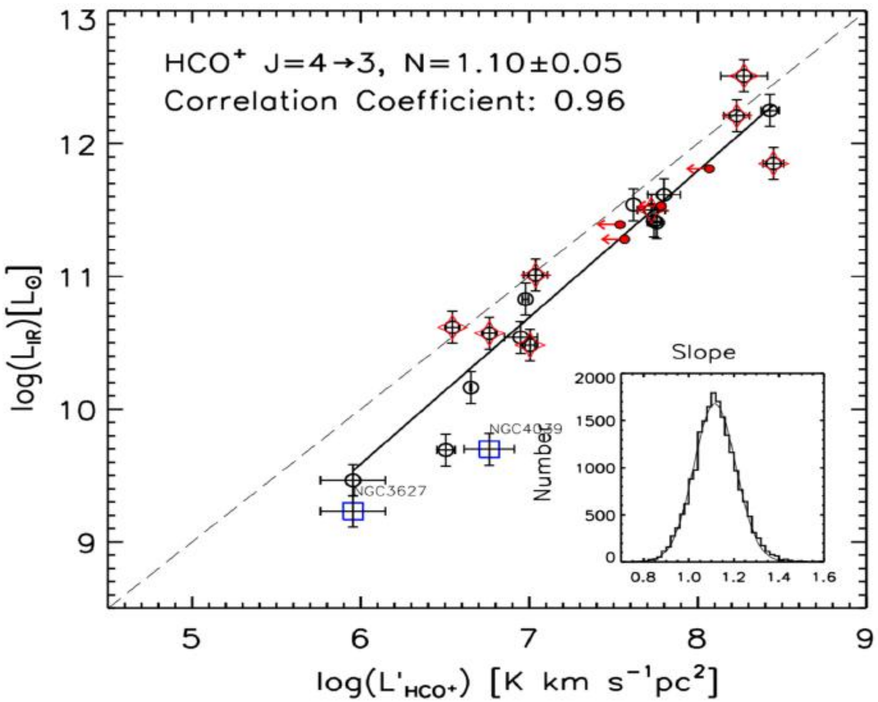
- ○ IRAM 30m

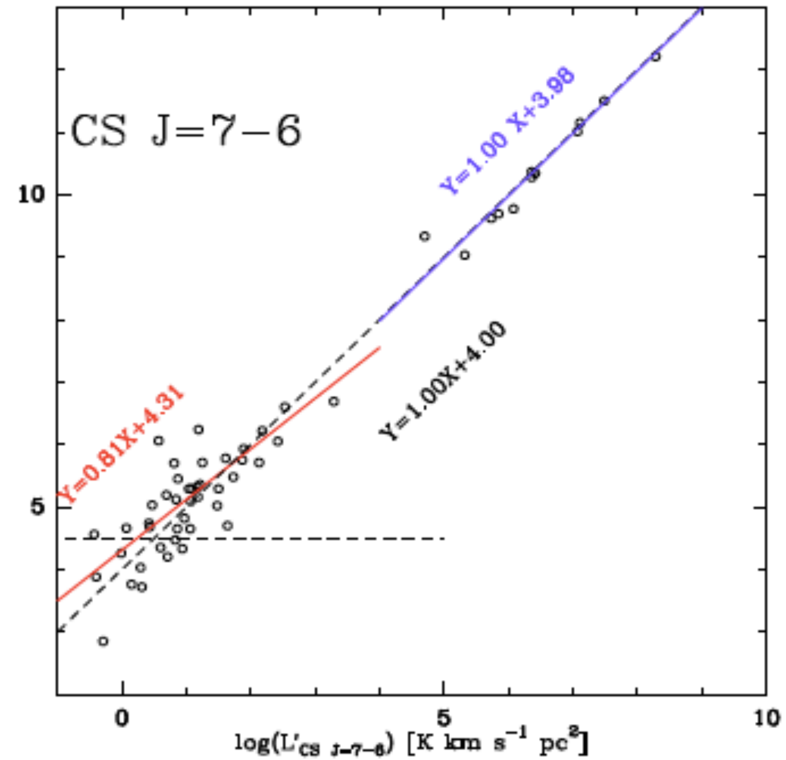
Wu+2010

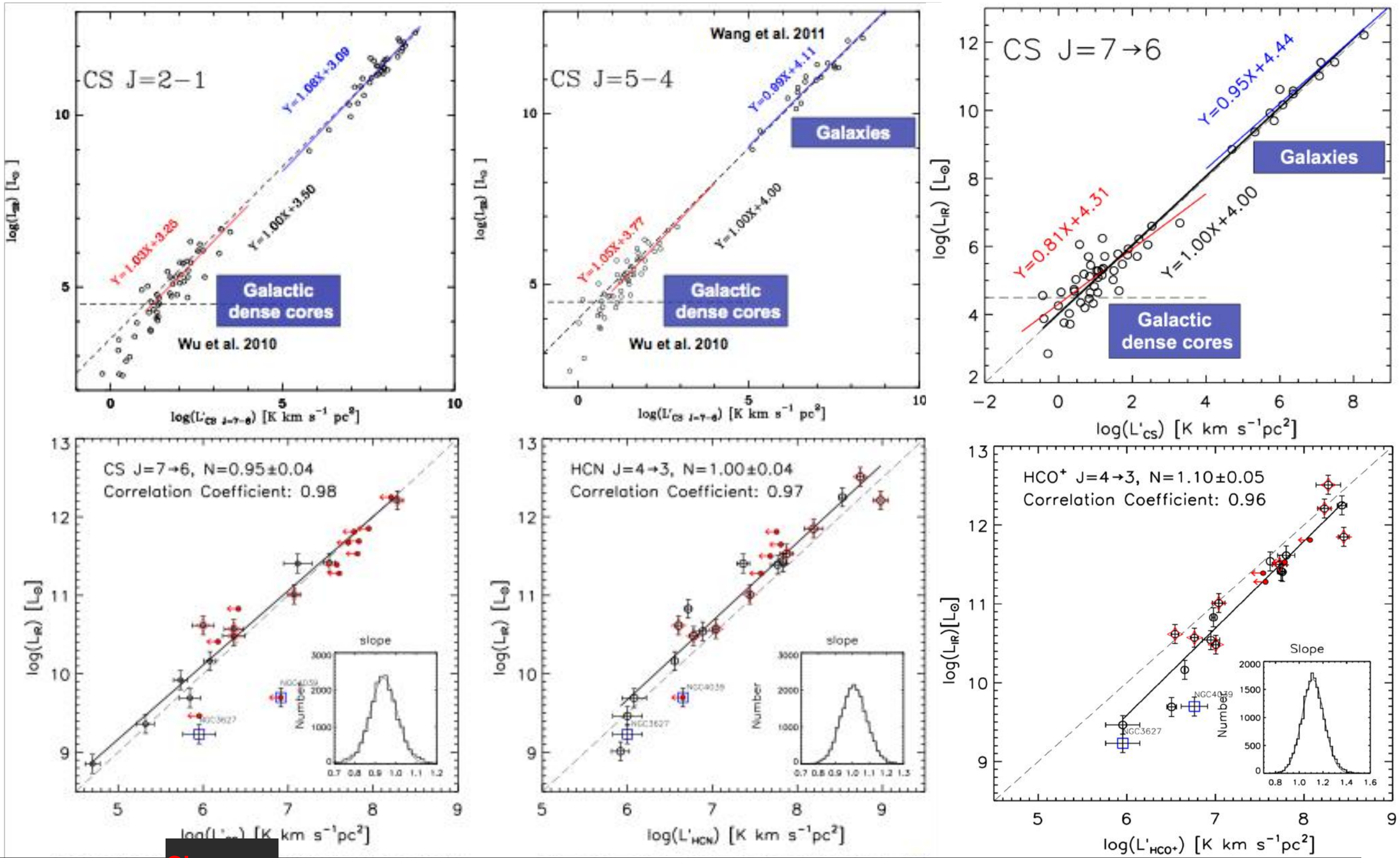




Zhang, Gao, Henkel et al. 2014

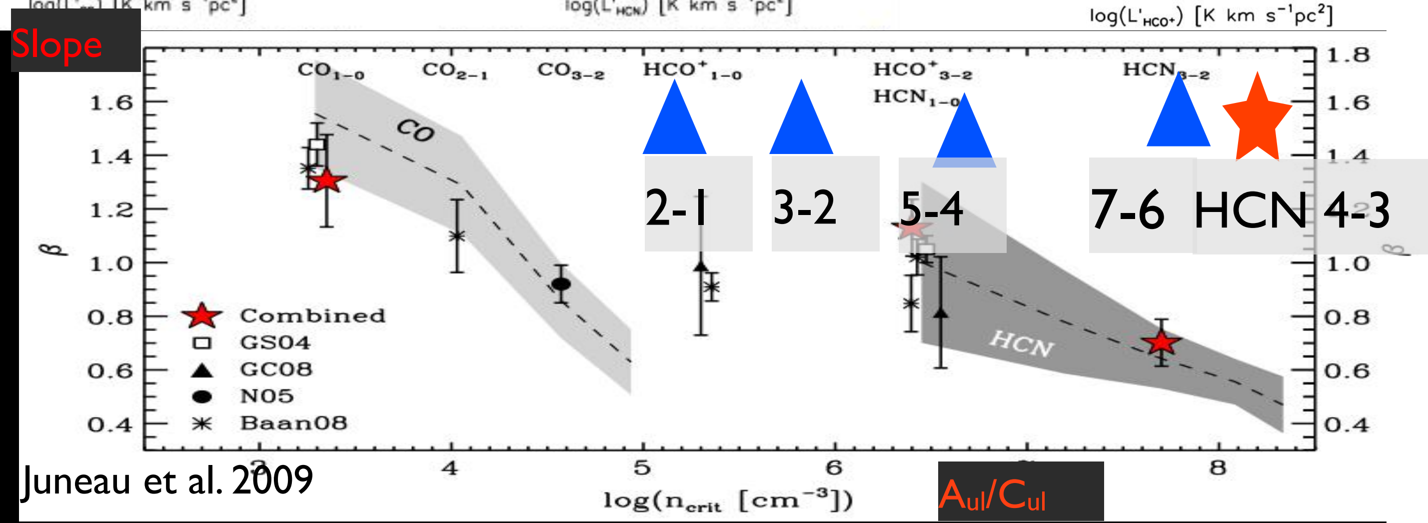


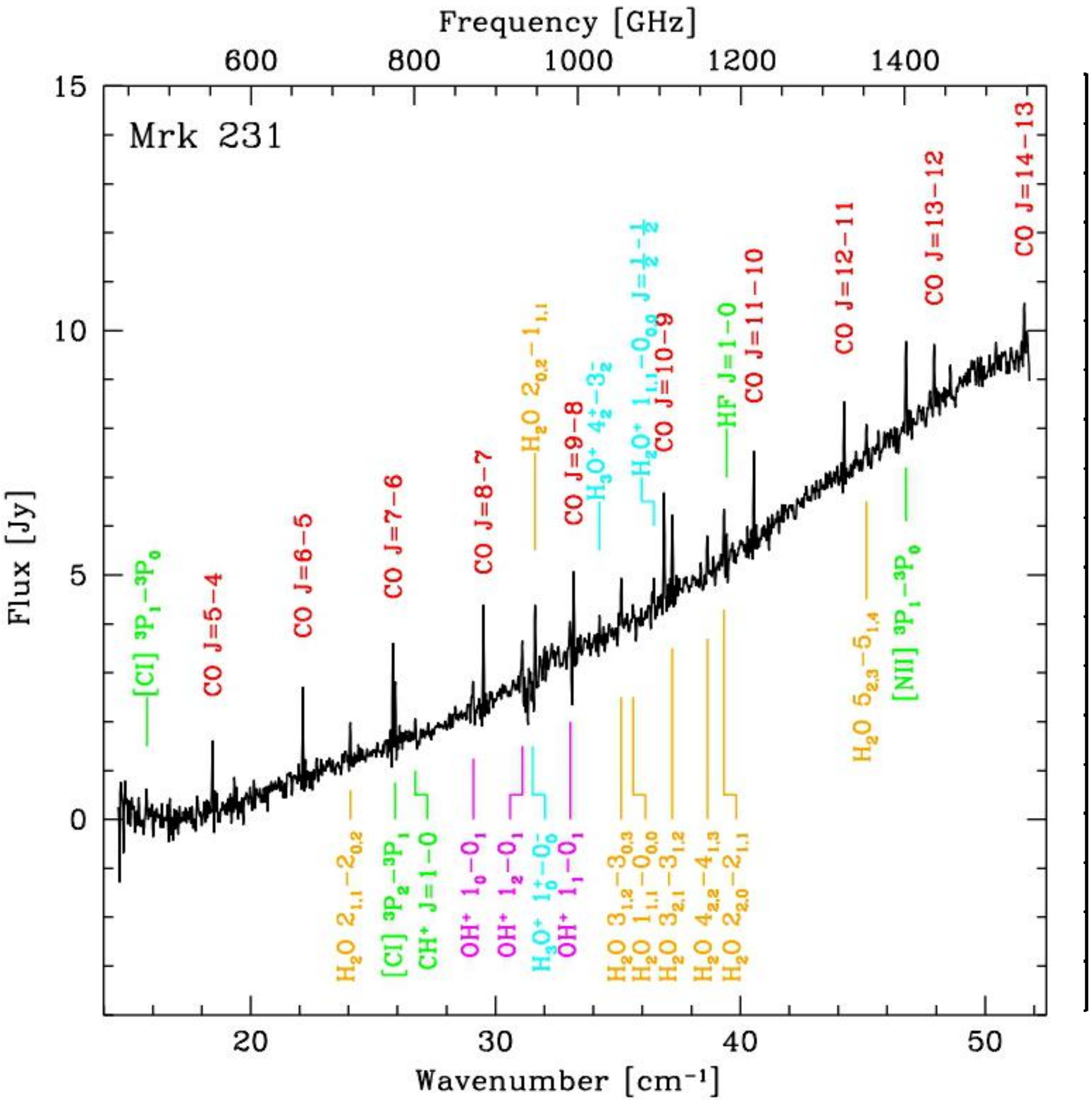




Zhang+2014, ApJL

All linearly correlated with IR luminosity.





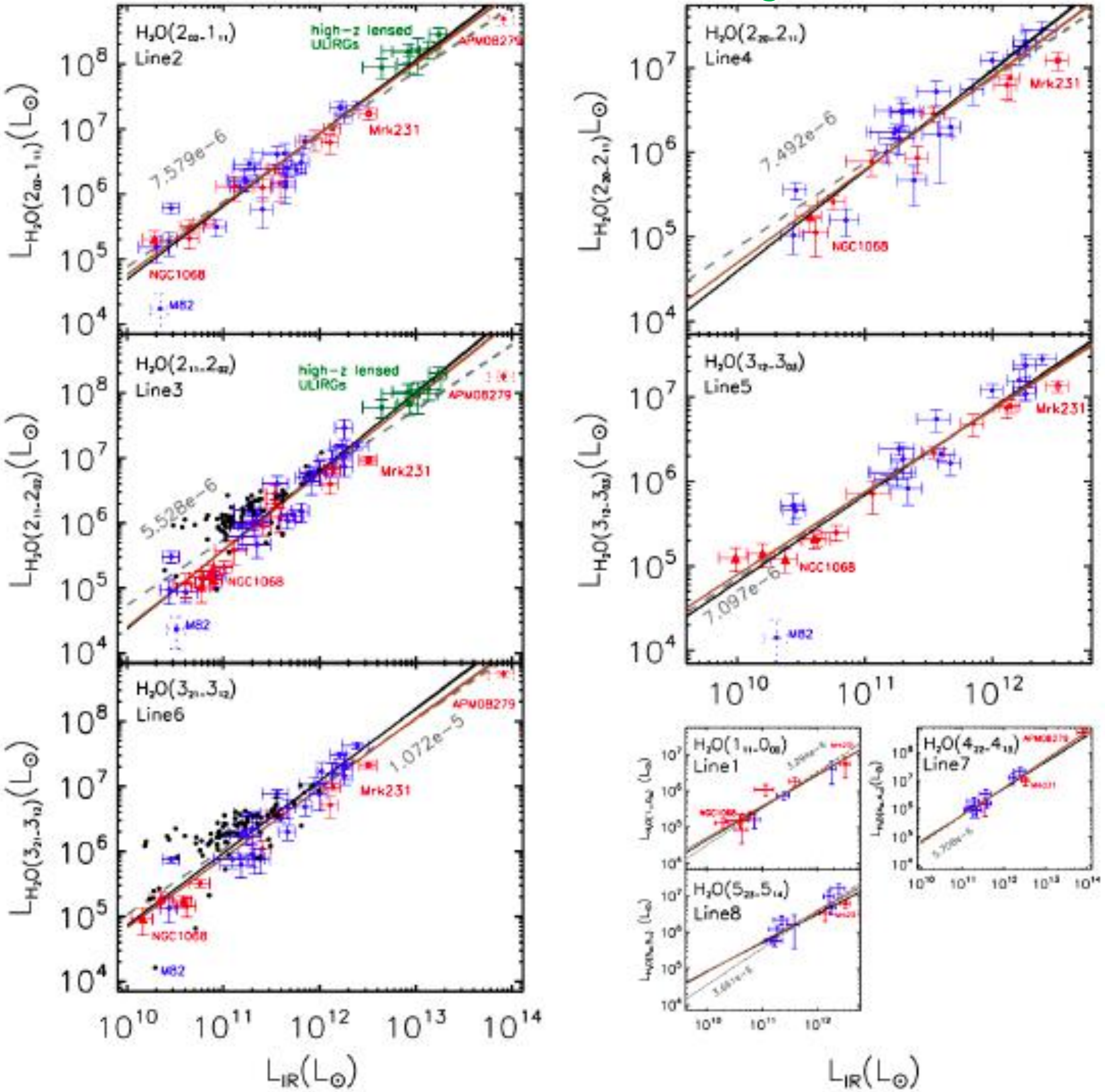
Mrk231 SPIRE FTS

Van der Werf + 10

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.



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

- 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 $L_{H_2O\text{-}a}/L_{H_2O\text{-}b}$
- Detection of H_2O^+ and $H_2{}^{18}O$ lines.

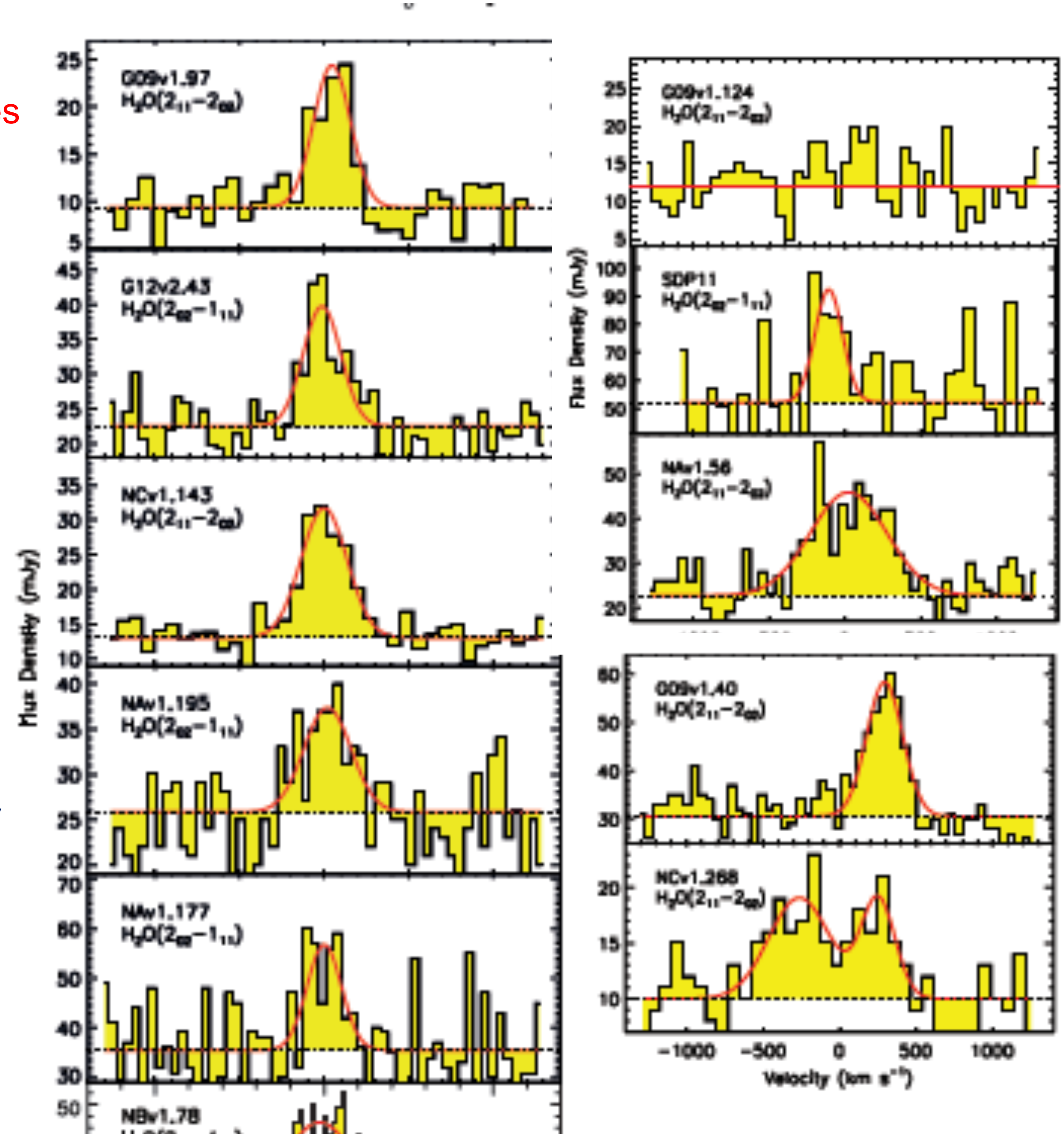
H_2O in H-ATLAS lenses

Step 1:
Additional detections
9/10 (16/17 in total)
Yang et al. 2016.
and poster

H_2O is strong in most high-z ULIRGs

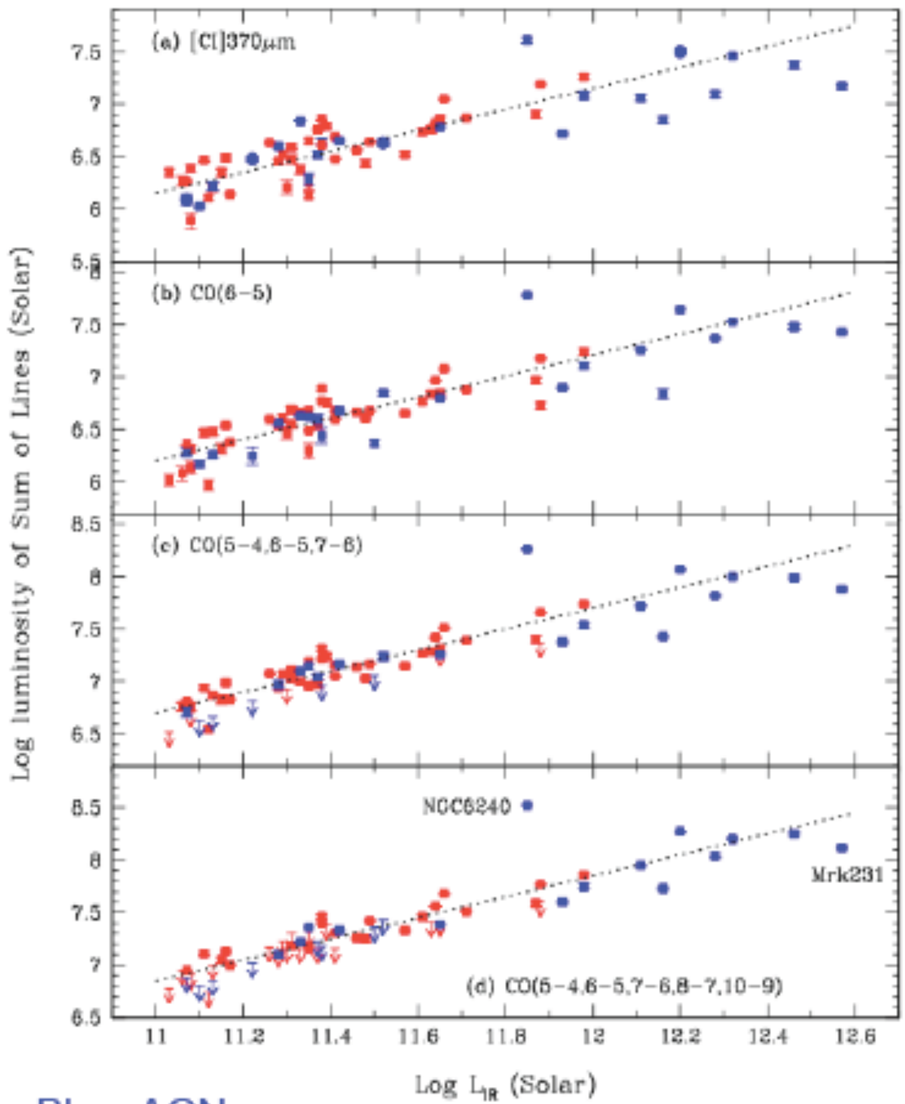
→ detectable in all lenses with PdBI

→ strongest molecular lines besides CO



Dust and Molecular Gas Heating

Linear fits with a fixed slope of 1

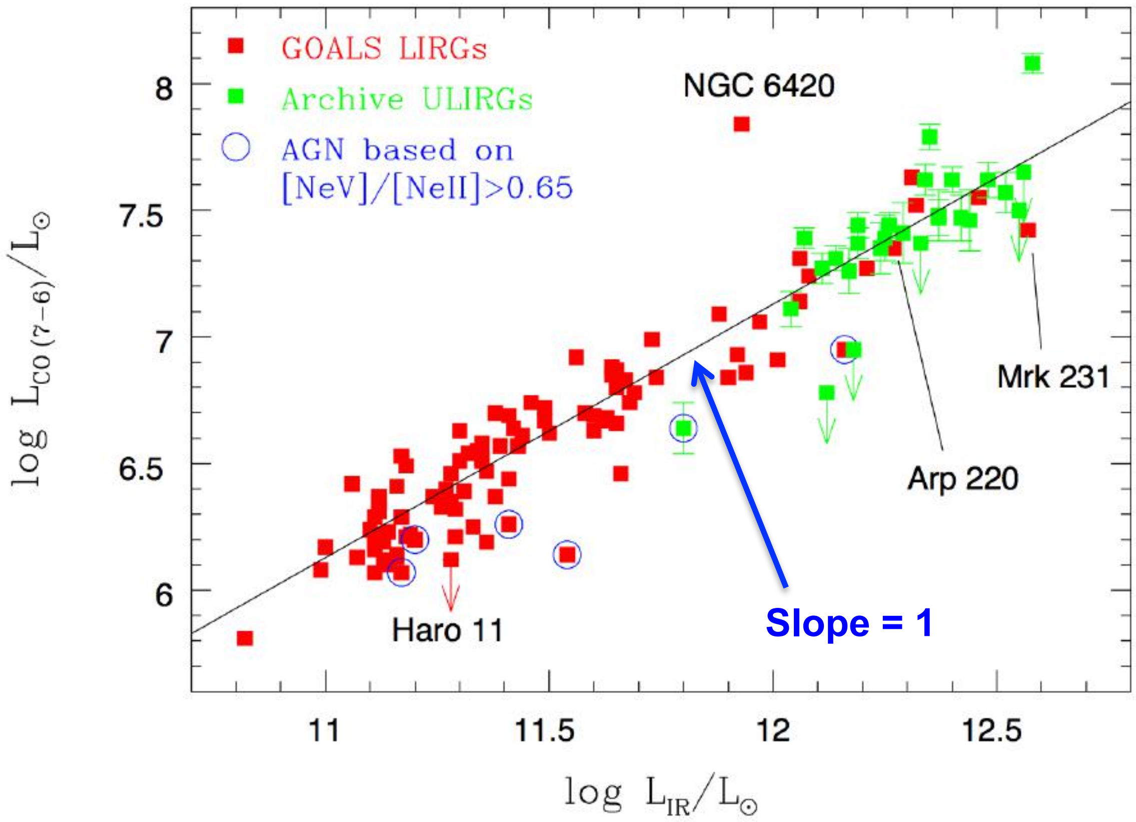


Blue: AGN;
Red: non AGN.

Lu + 2014

- While [CI] 370 μm [or low-J CO lines such as CO(4-3)] correlate apparently with L_{IR}, CO(6-5) is more tightly correlated with L_{IR}, even at the "low luminosity" end.
  - ➤ There is a relative cold gas component that is not or less directly associated with SFR.
- Combining a few mid-J CO lines improves the scatter, at both low and high luminosity ends, leading to a better one-to-one correlation with L_{IR}.
  - ➤ This well-defined one-to-one correlation traces mainly the PDR gas/dust heating.

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}:

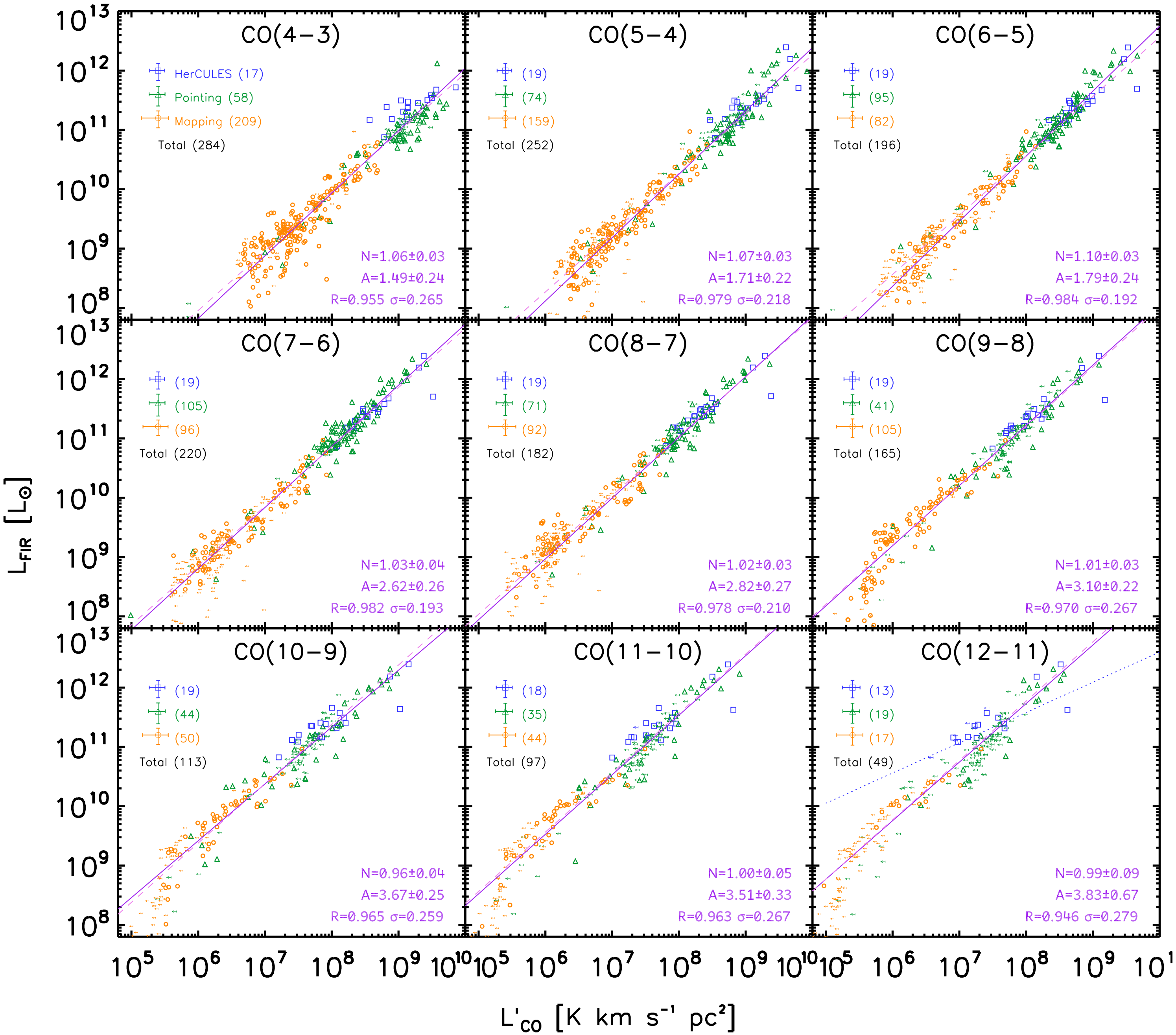
- Not much contaminated by AGN (Lu et al. 2014)
- Easier to measure in the ALMA era, i.e., only need one line measurement in principle

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



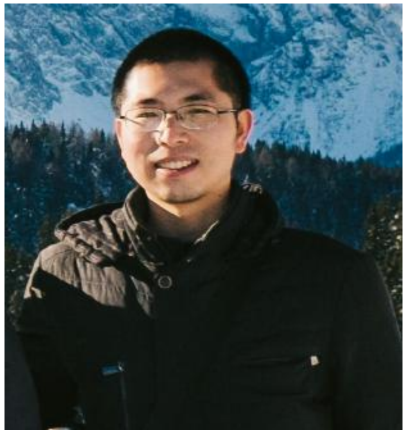
All are not far from linear
– dense gas law

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

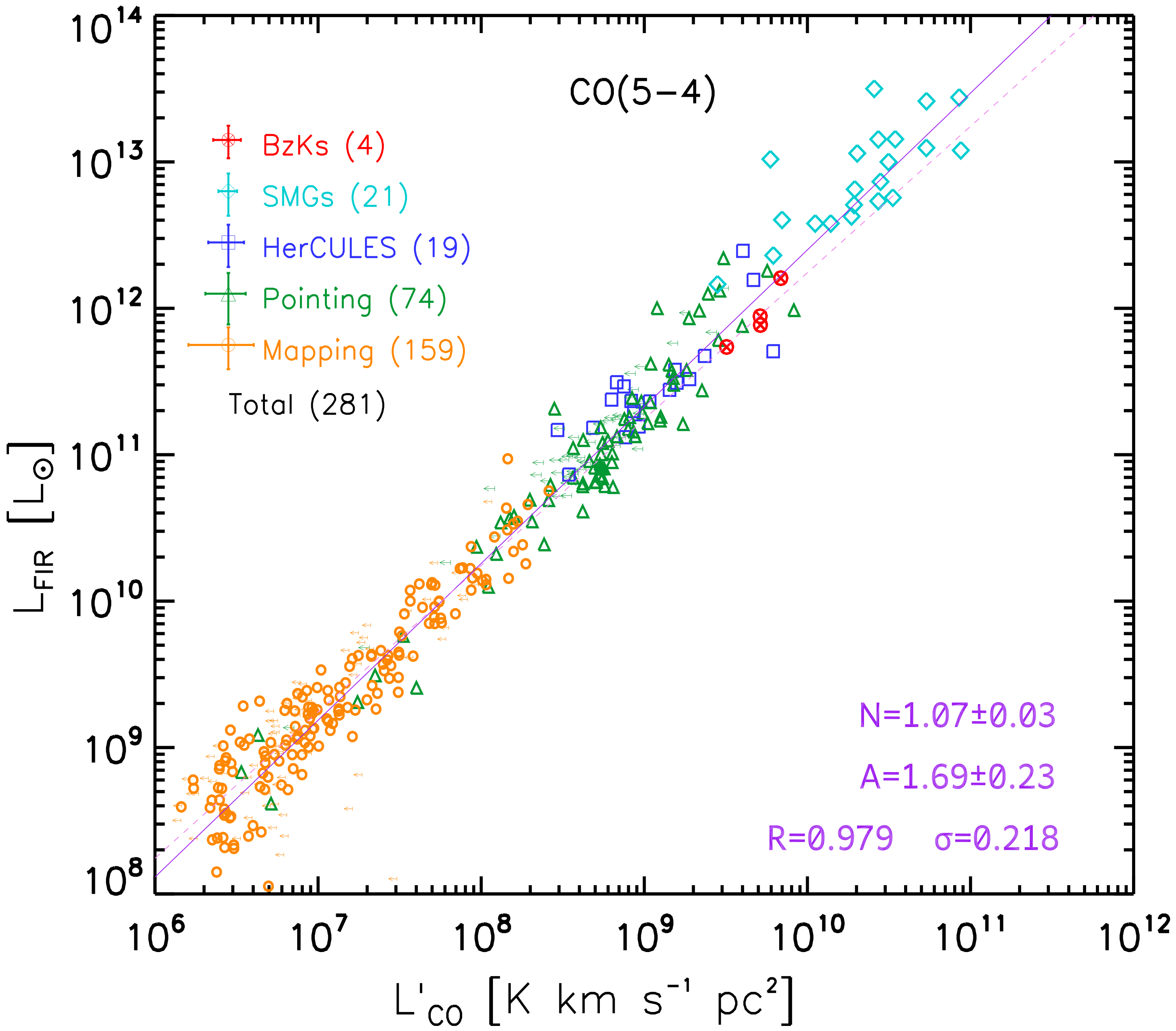
Slightly super-linear at J≤6 – K-S law

High-J CO better tracers dense gas!

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



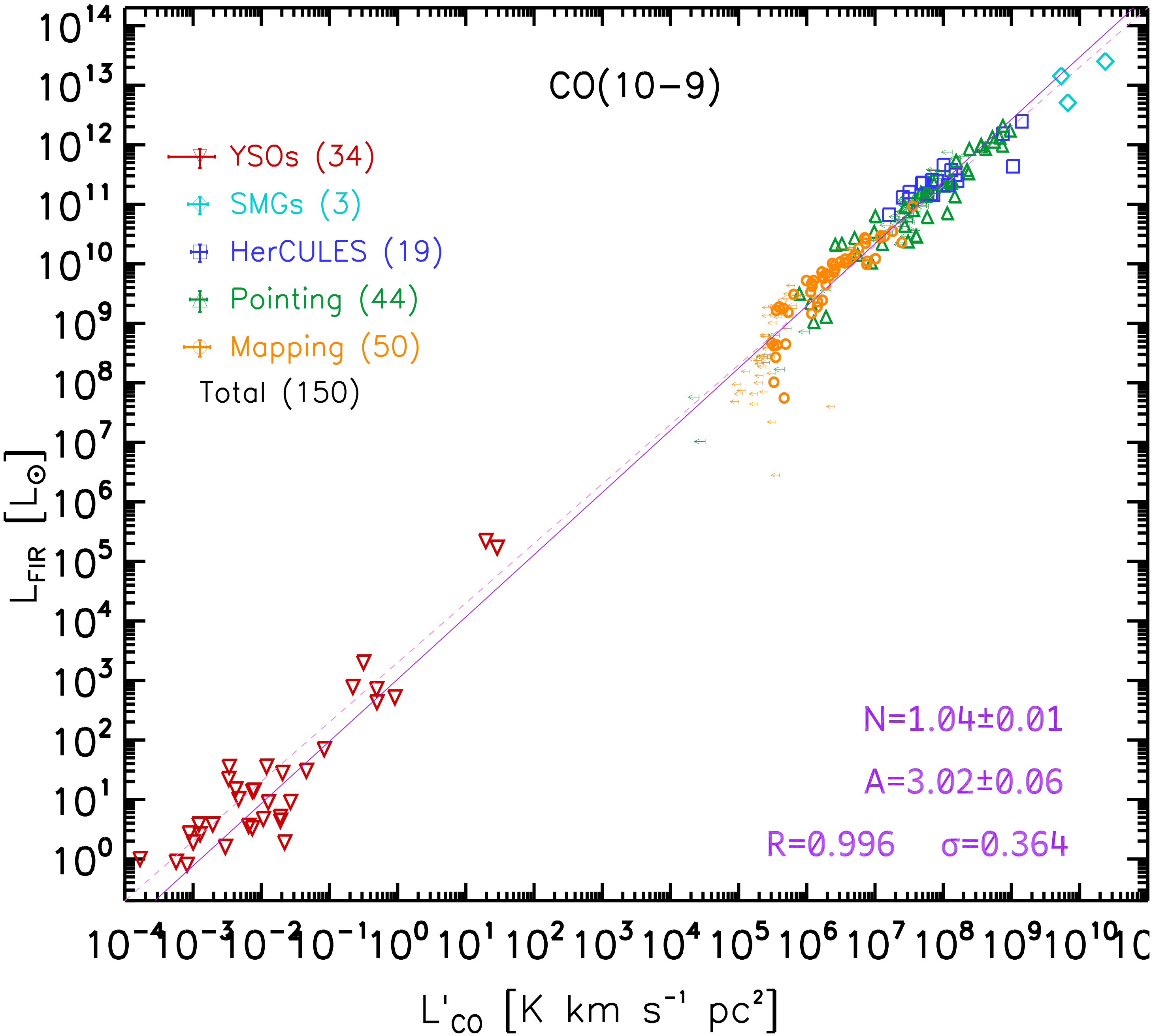
CO(5-4) – FIR from Local to High-z



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

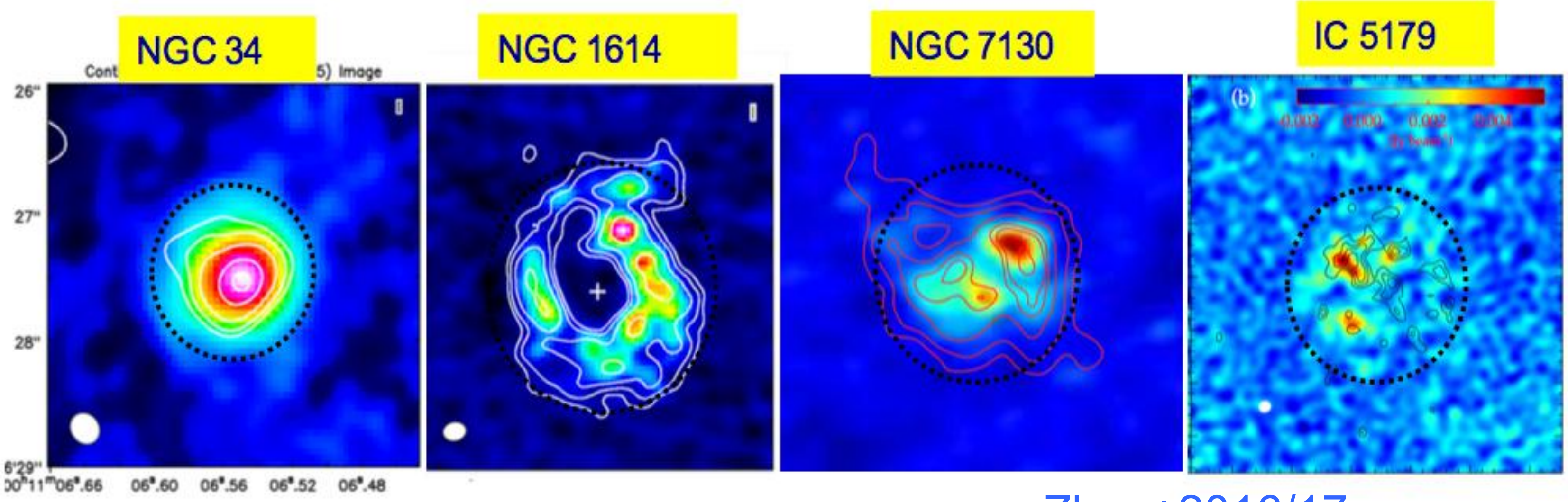


$CO10\text{-}9+H_2O3_{12}\text{-}2_{21}$
Herschel FTS + HIFI
Galactic + Galaxies
SanJose-Garcia et al. 2013

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

A universal SF law over 15 orders of magnitude

Comparison of the 4 Nuclei in CO(6-5)



Xu+2014/15 Zhao+2016/17

	NGC 34	NGC 1614	NGC 7130	IC 5179
Resolution (pc):	106 x 94	85 x 66	70 x 49	37 x 32
Log $L_{IR}/L_{\odot}$:	11.49	11.65	11.42	11.24
FIR color:	1.01	0.94	0.65	0.52
Gas configuration:	Rotating disk (r < 200 pc)	Rotating ring (100 < r < 350 pc)	Co-rotating clouds (r ~ 175 pc)	Co-rotating clouds (r ~ 185 pc)
$CO(6\text{-}5)_{nucleus}$: (in terms of SFR in $M_{\odot}$/yr)	56 (=19x3)	32	17	3
$CO(6\text{-}5)_{nucleus}/CO(6\text{-}5)_{totol}$:	1.0 (=6x0.16)	0.63	0.34	0.16

New Star Formation Law

- 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

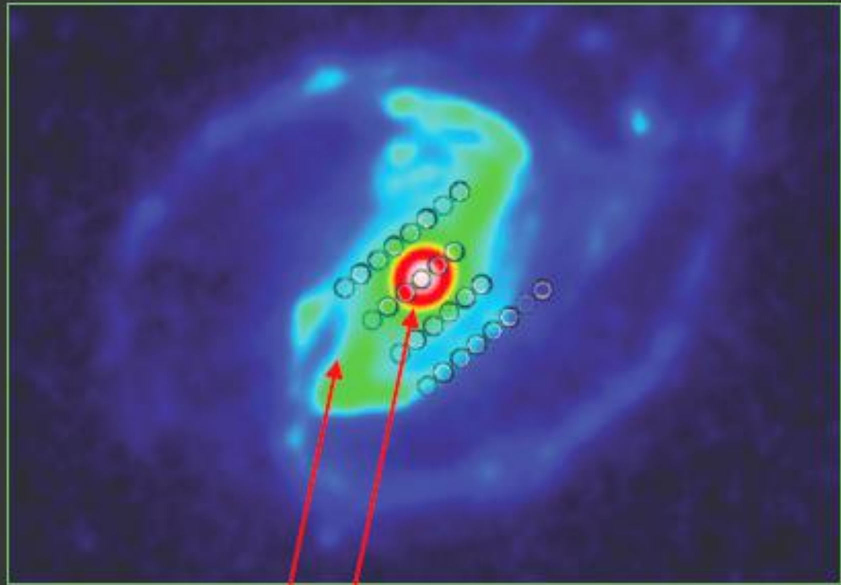
Gao & Solomon: Dense H_2 (fuel !!) → Stars

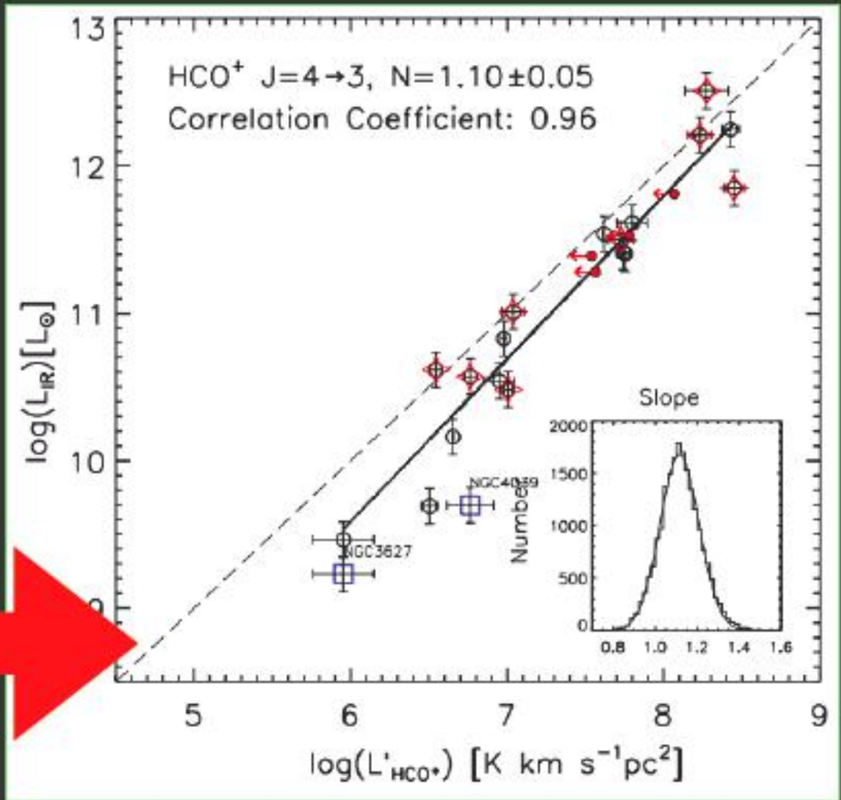
from Cores to High-z: Dense Gas→Massive SF

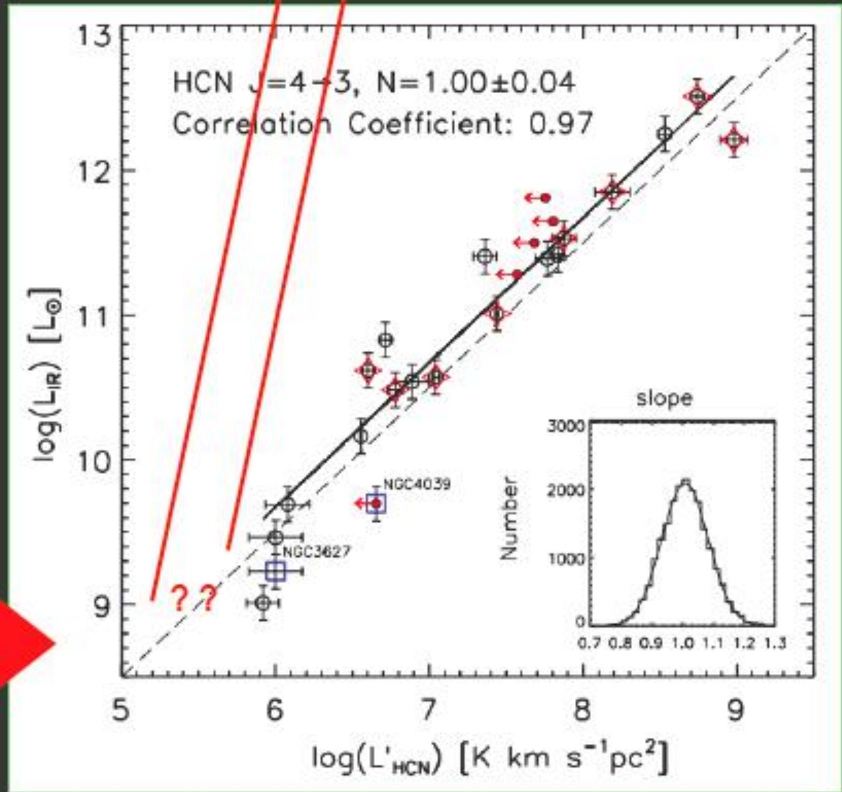
HI=gas reservoir (FAST) is an excellent tracer of galaxy interactions: kinematics/morphology; evolution & environments (not SF). H2 OK for SF, X-factor? yet dense H2 best (e.g., EAO/JCMT; ALMA/NOEMA)!

SCIENCE GOALS

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

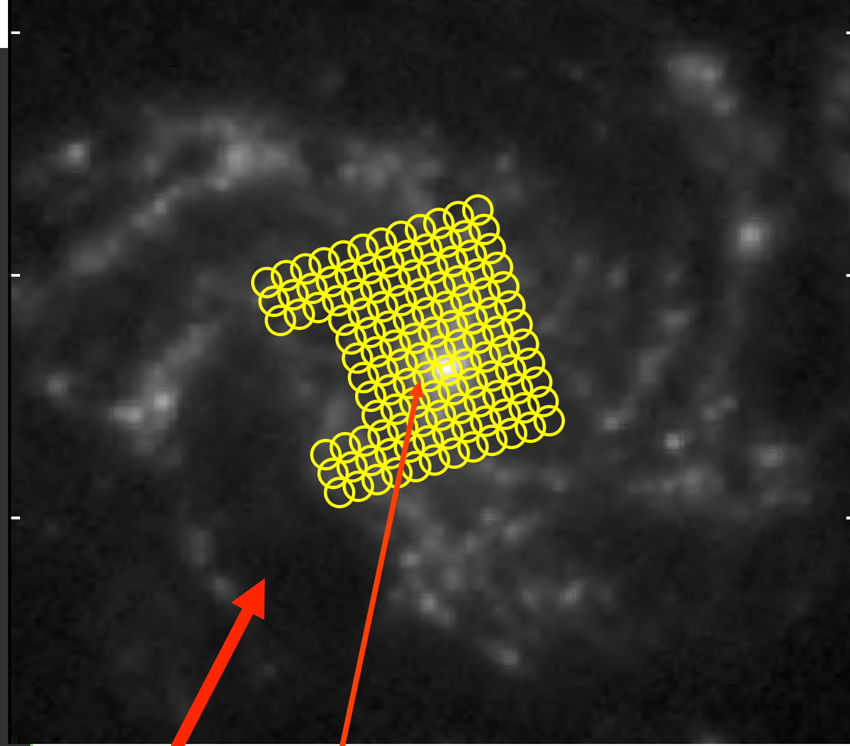


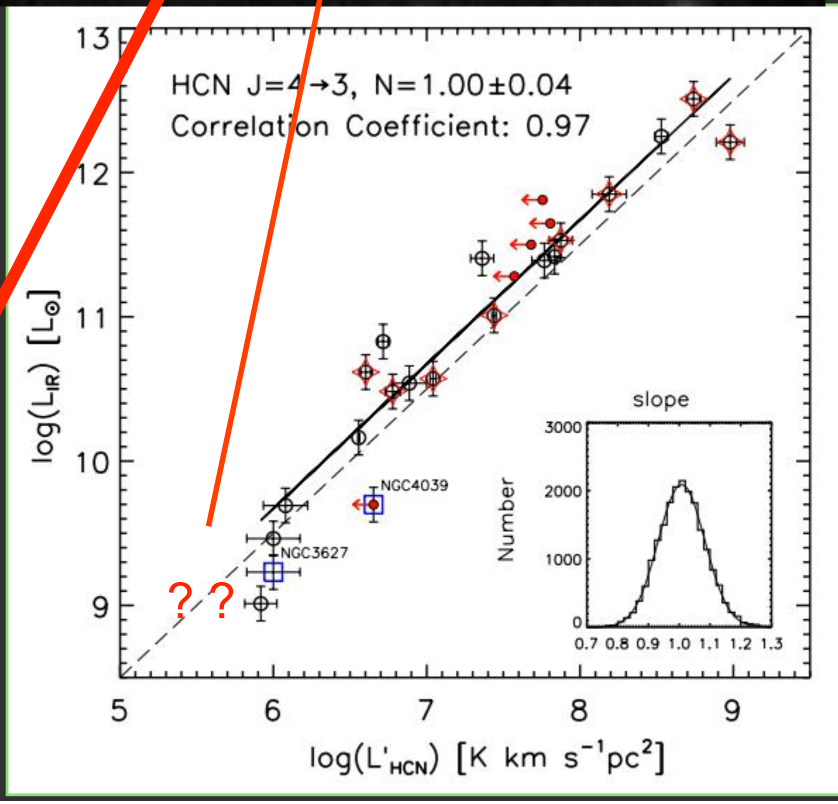


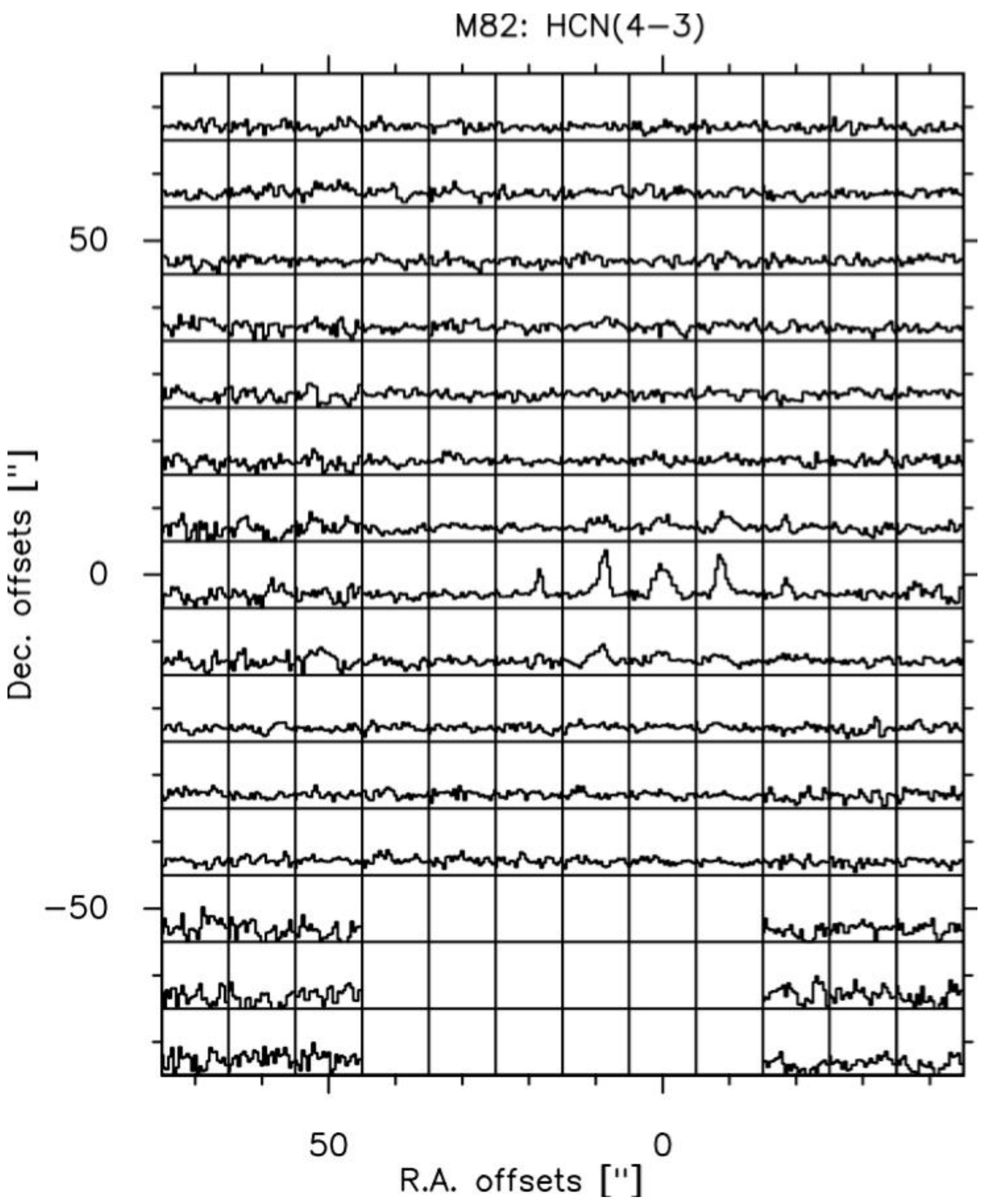


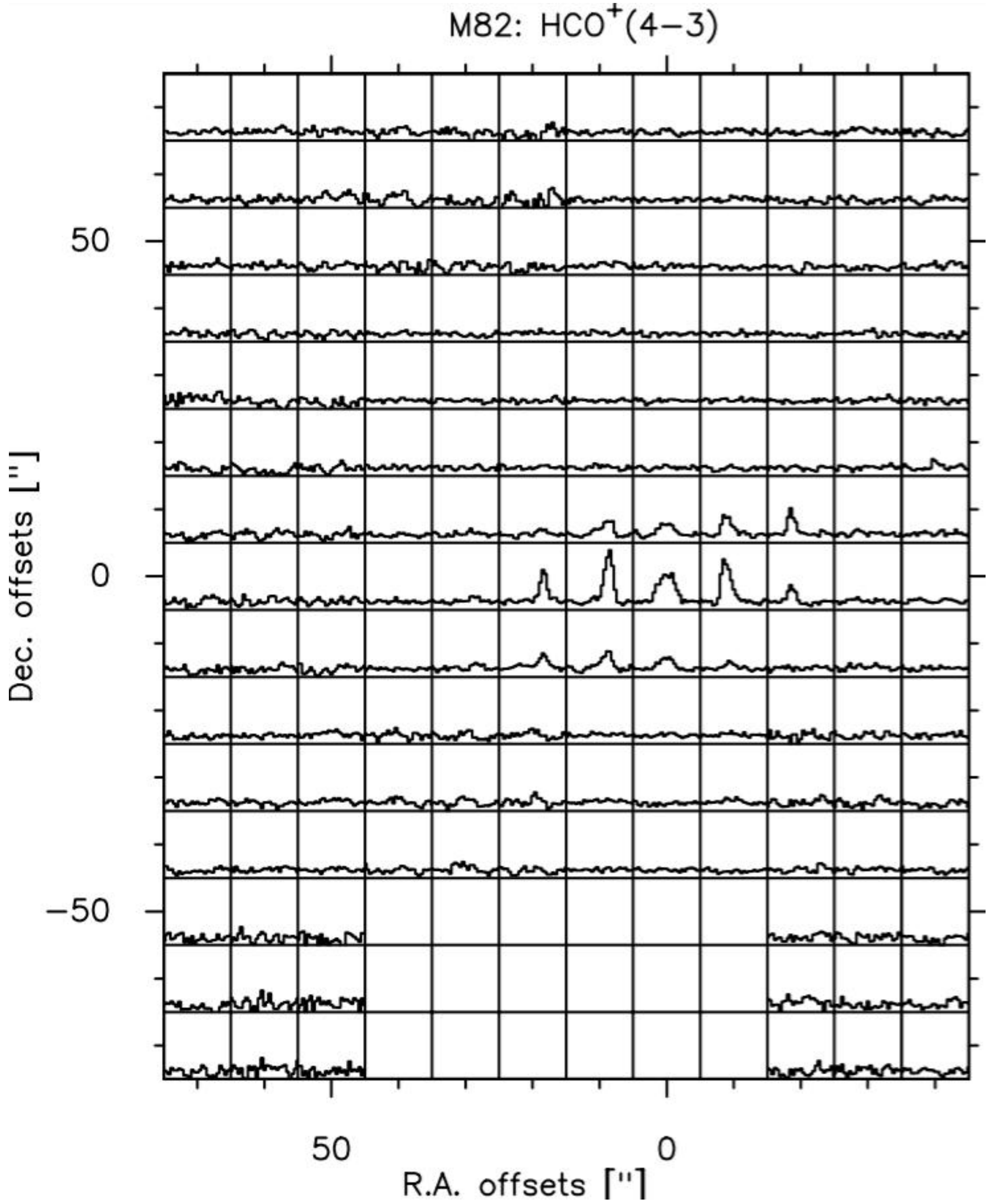
PROJECT AND SCIENCE GOALS

- *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 ~5×10⁶M☉ 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*



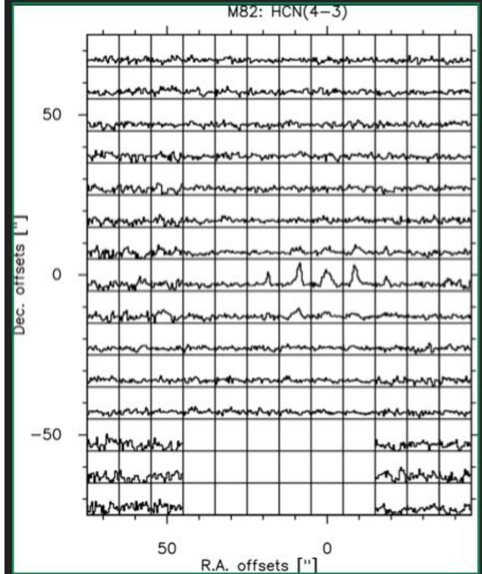


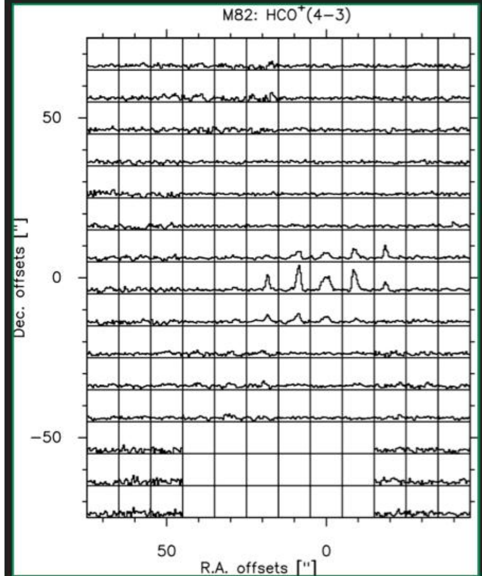

M82: HCN(4−3)
Dec. offsets ["]
50
0
−50
R.A. offsets ["]
50
0


M82: HCO^+(4−3)
Dec. offsets ["]
50
0
−50
R.A. offsets ["]
50
0

FIRST RESULTS

Jiggle-mapping:
2 arcmin central region

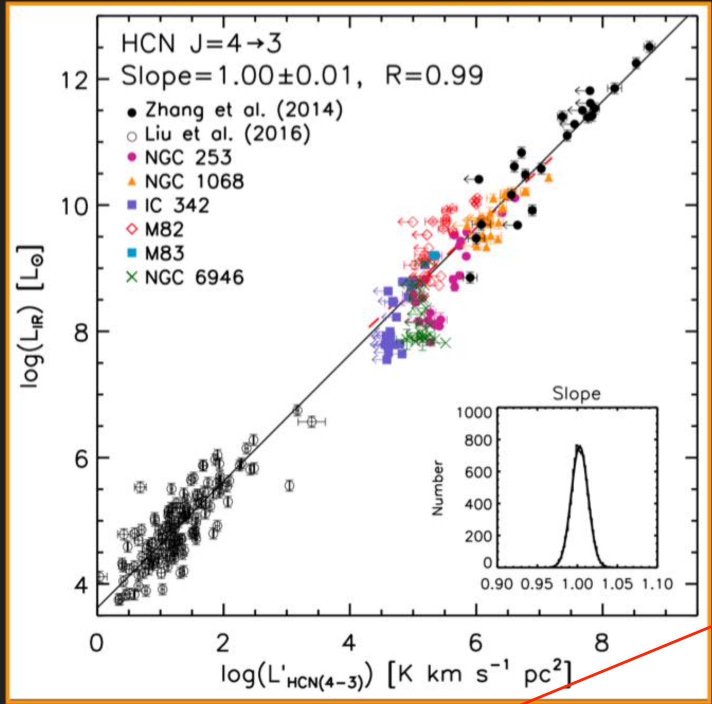


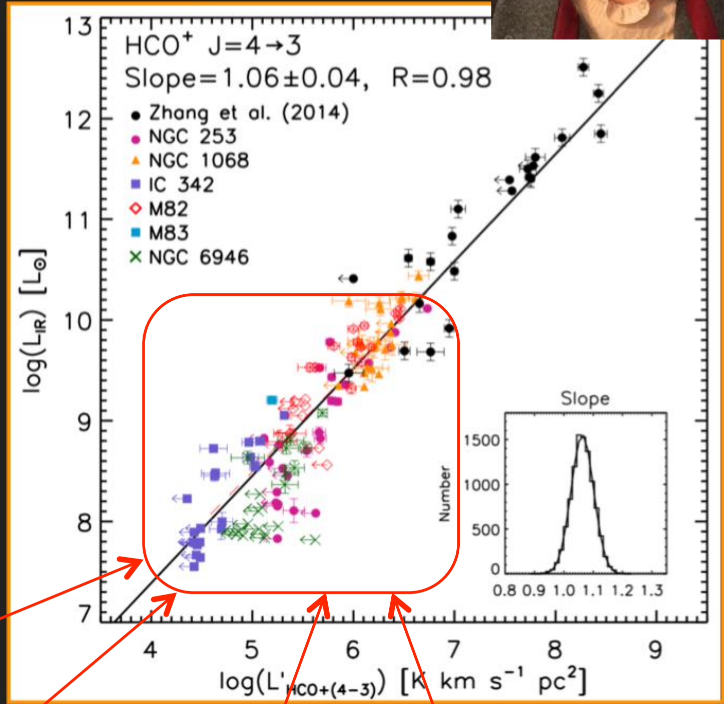


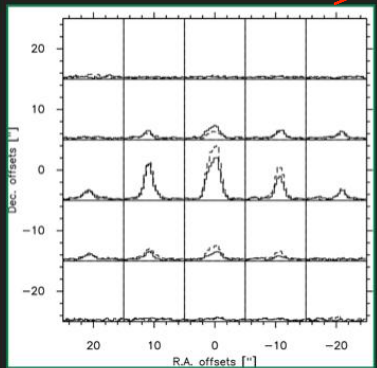
L_{IR} vs. $L'_{HCN(4-3)}$

Tan, Gao+ in prep

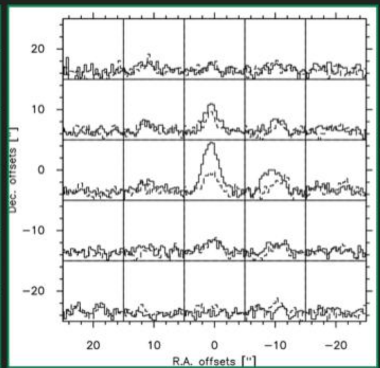
L_{IR} vs. $L'_{HCO+(4}$



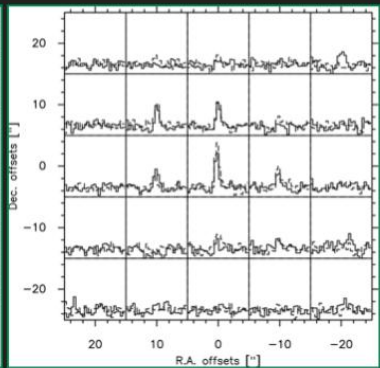




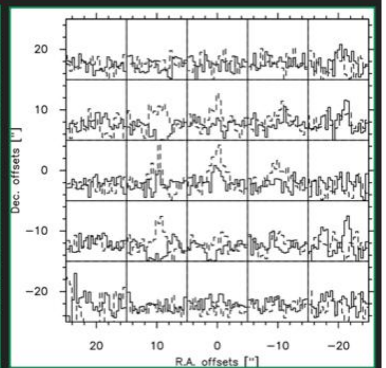
NGC 253



NGC 1068



IC 342



NGC 6946

THANK YOU

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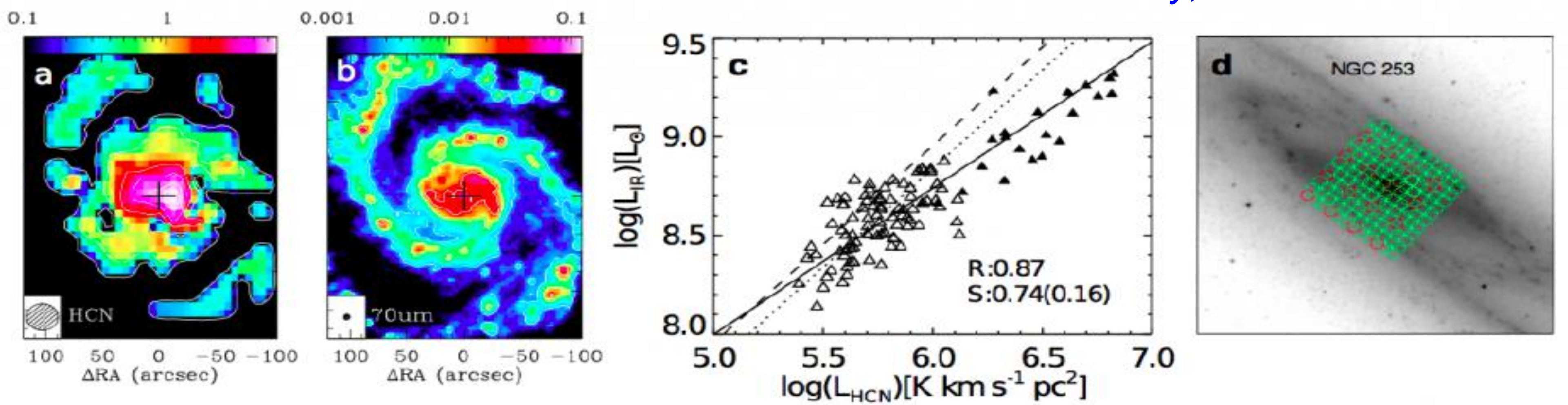
Satoki Matsushita; Aeree Chung;
Erik Rosolowsky; Kohno Kotaro



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} – $L'_{HCNJ=1-0}$ 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.