Dense gas tracers and star formation laws:

Multiple transition CS survey in nearby active star-forming galaxies

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Dense gas really matters.

Collaborators:

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Karl Menten (MPIfR)
et al.

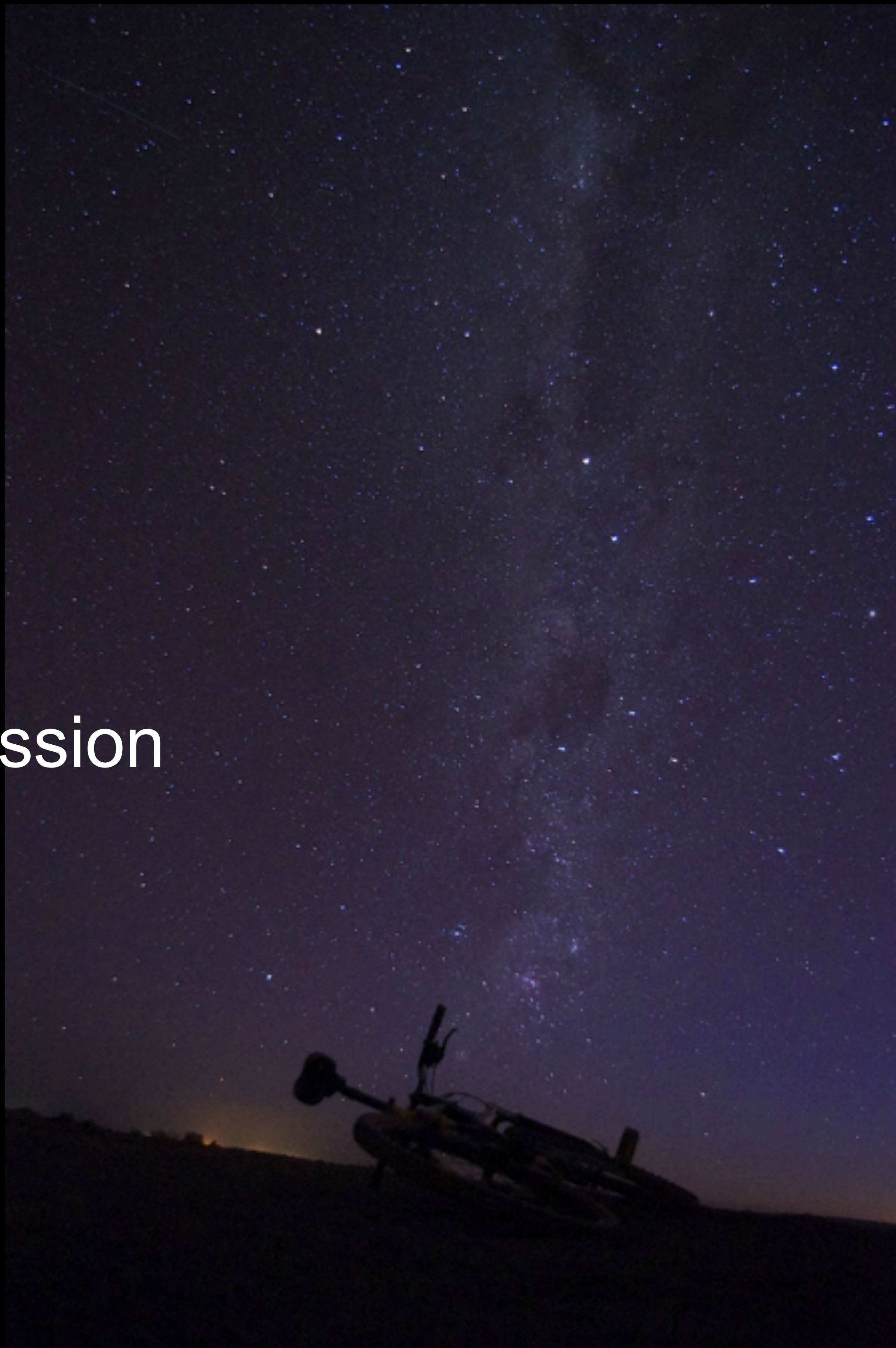
Outline

- Background
- Gas tracers and Star formation
- Star formation laws

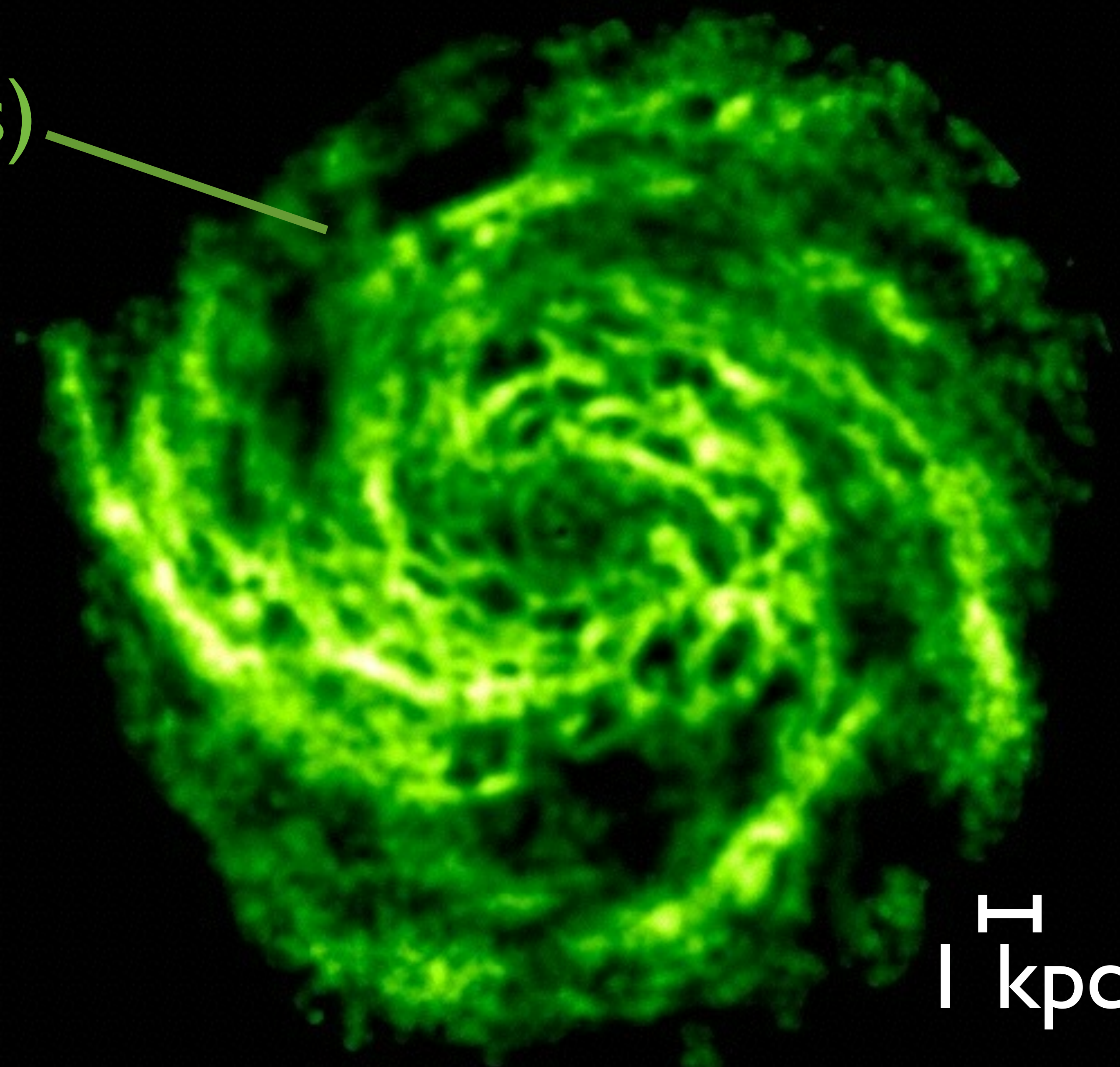
- Surveys and Results
- Multiple-J CS surveys in galaxies
- Star formation vs. dense gas emission

- MALATANG and more.

- Summary



Which gases are forming stars?

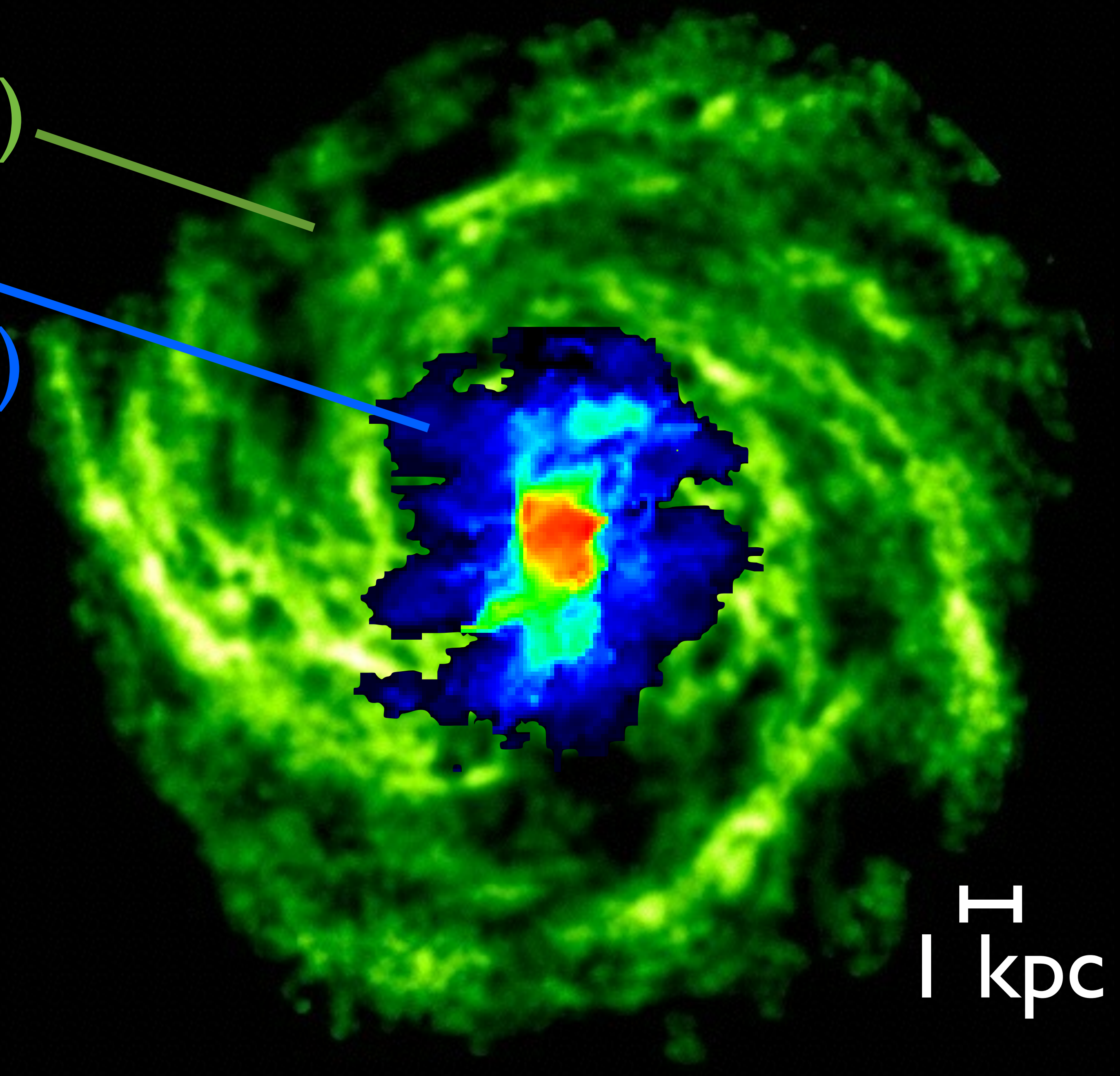


Which gases are forming stars?

IC 342

HI (atomic gas)

^{12}CO J=1-0 (molecular gas)



THINGS

NRAO 12m

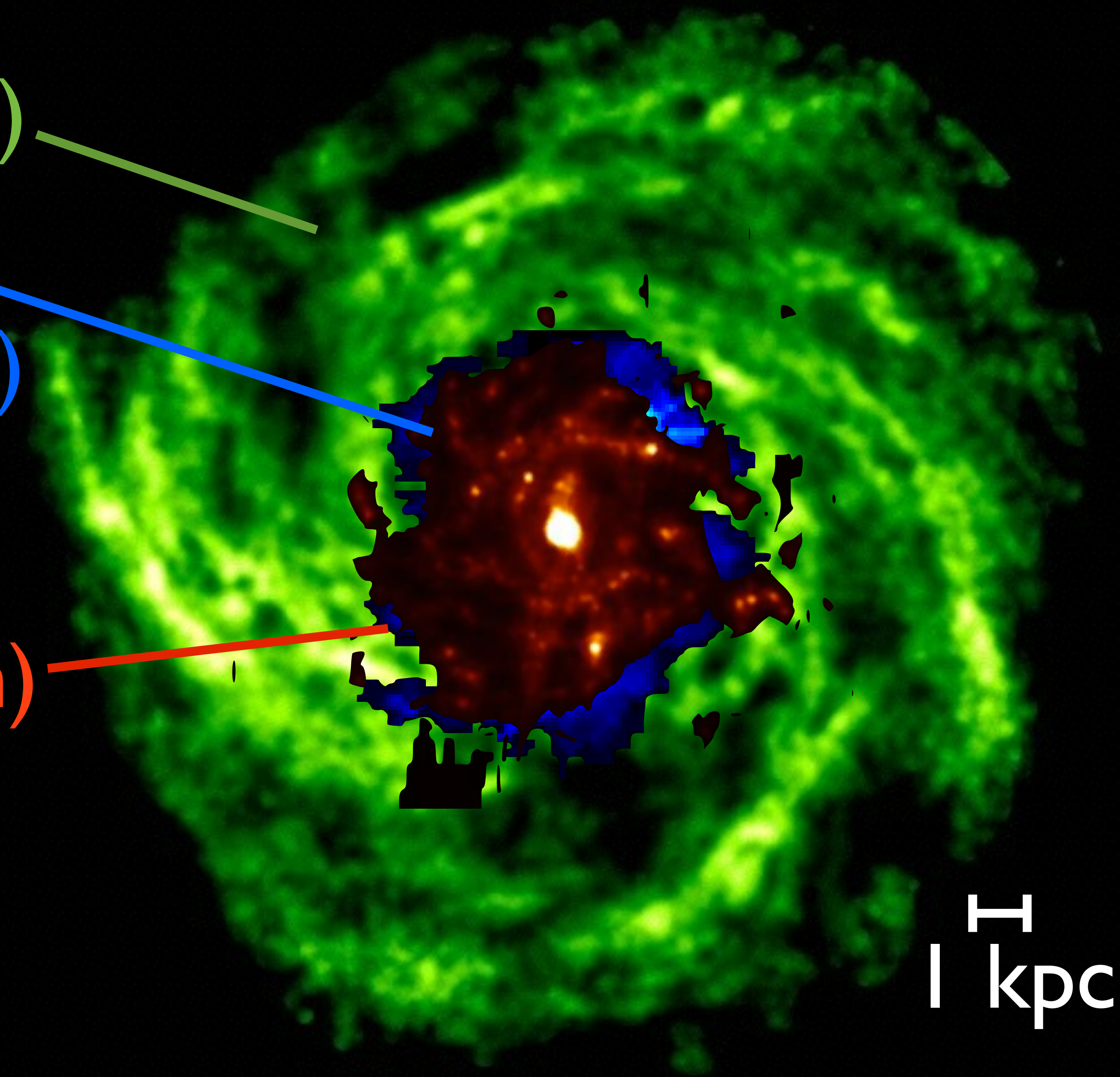
Which gases are forming stars?

IC 342

HI (atomic gas)

^{12}CO J=1-0 (molecular gas)

IR emission (star formation)



THINGS

NRAO 12m

Spitzer 70um

On kpc scales, SFR is more related to H_2 gas, rather than to HI.

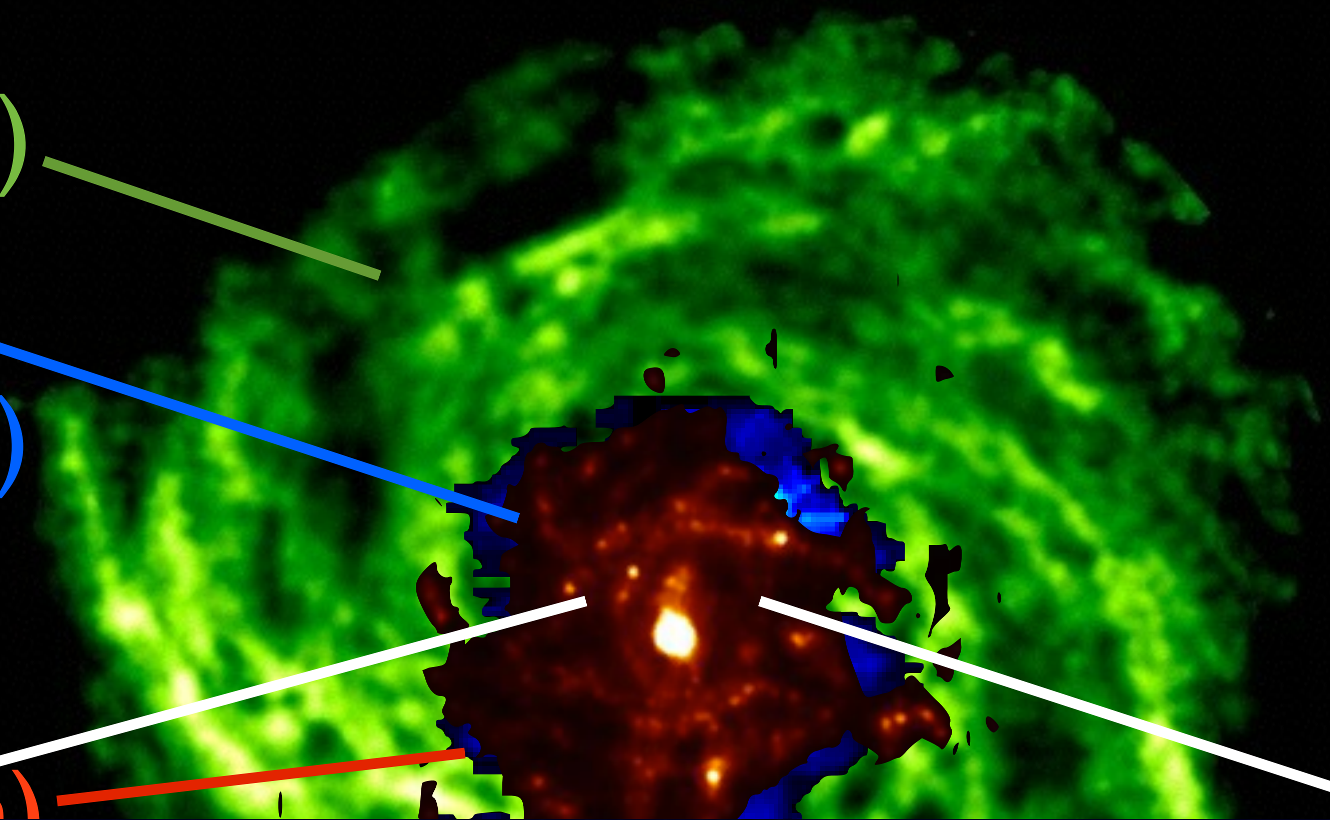
Which gases are forming stars?

IC 342

HI (atomic gas)

^{12}CO J=1-0 (molecular gas)

IR emission (star formation)



THINGS

NRAO 12m

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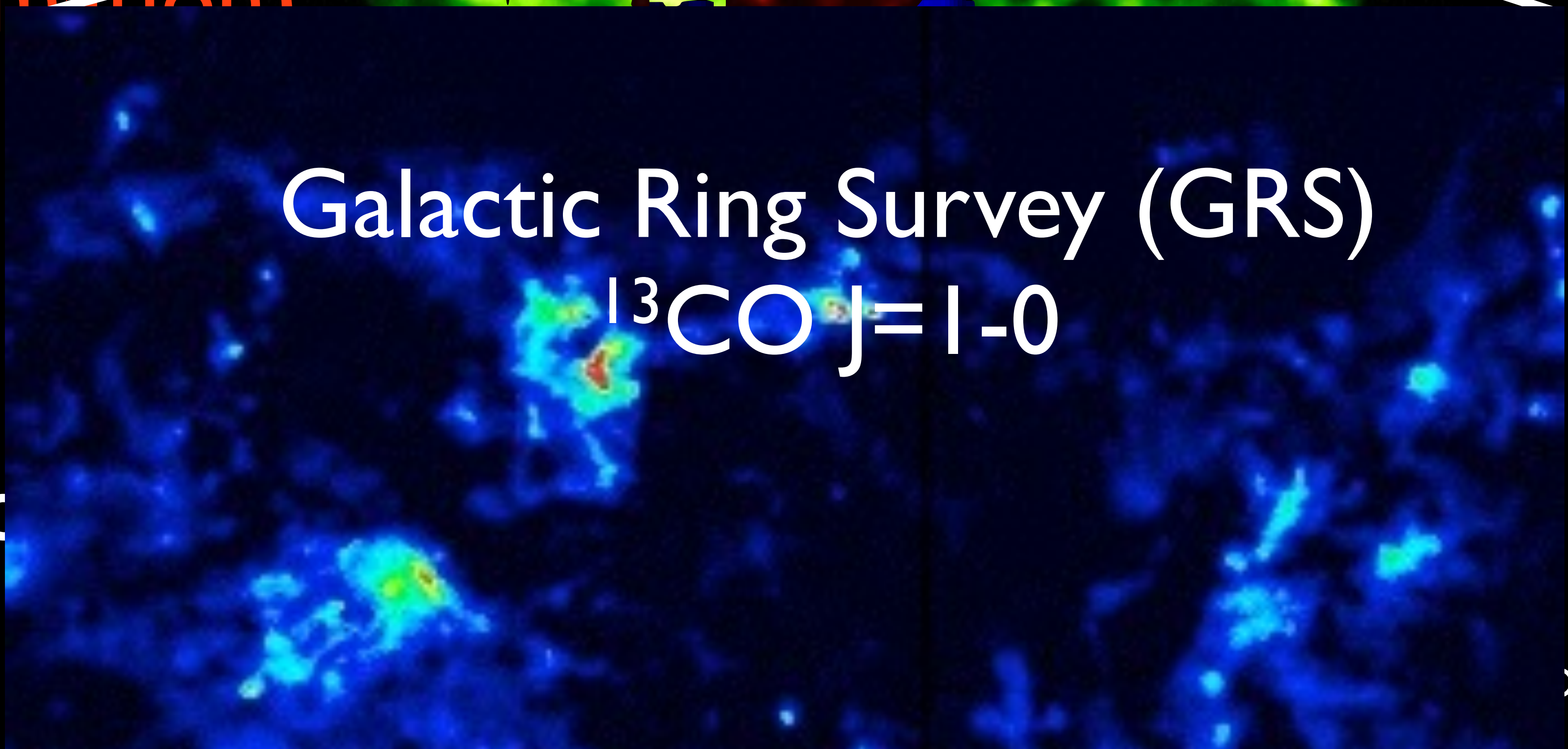
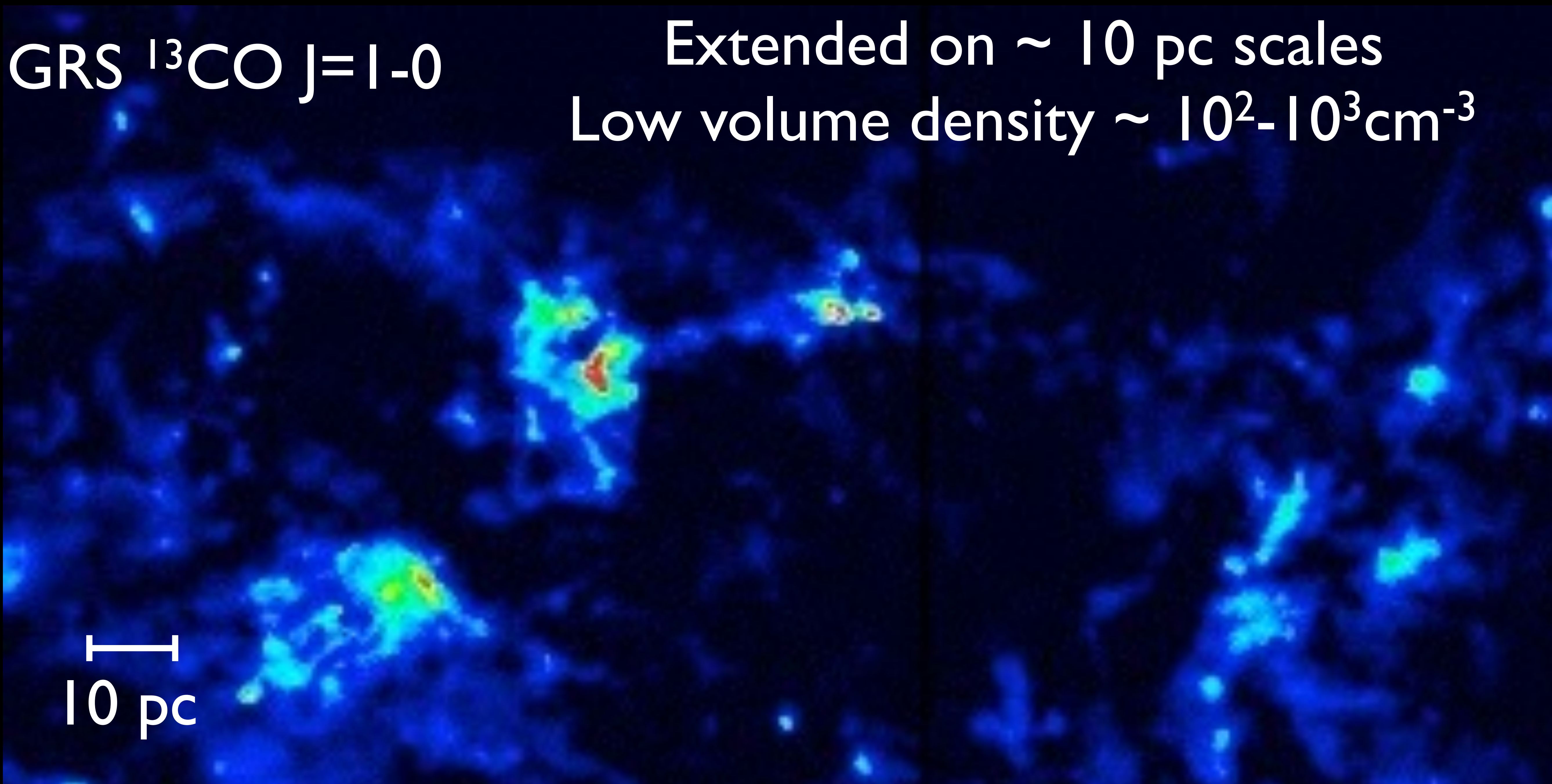


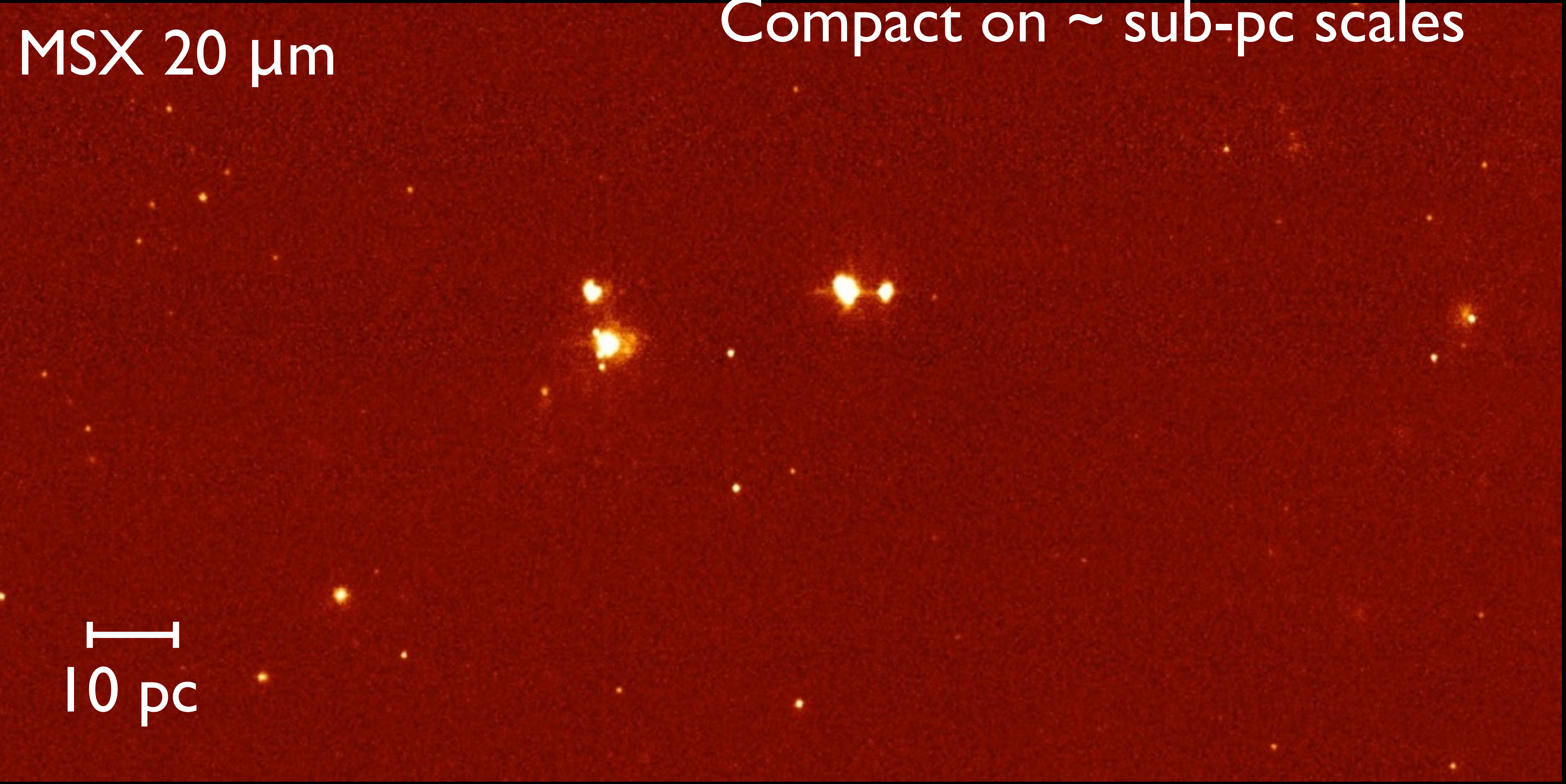
On kpc … than HI

…), Zhi-Yu Zhang

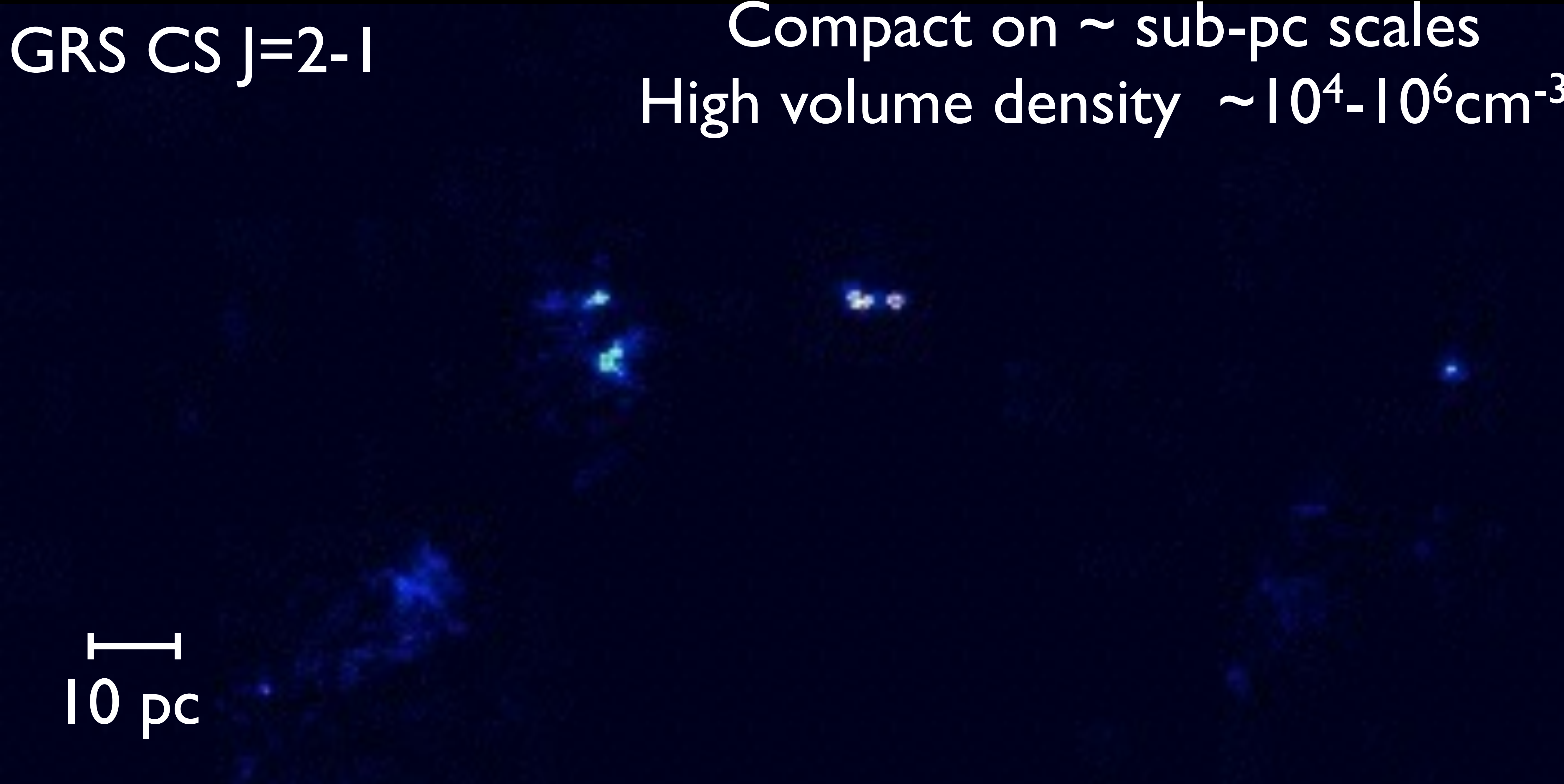
Which gases are forming stars? - Galactic view



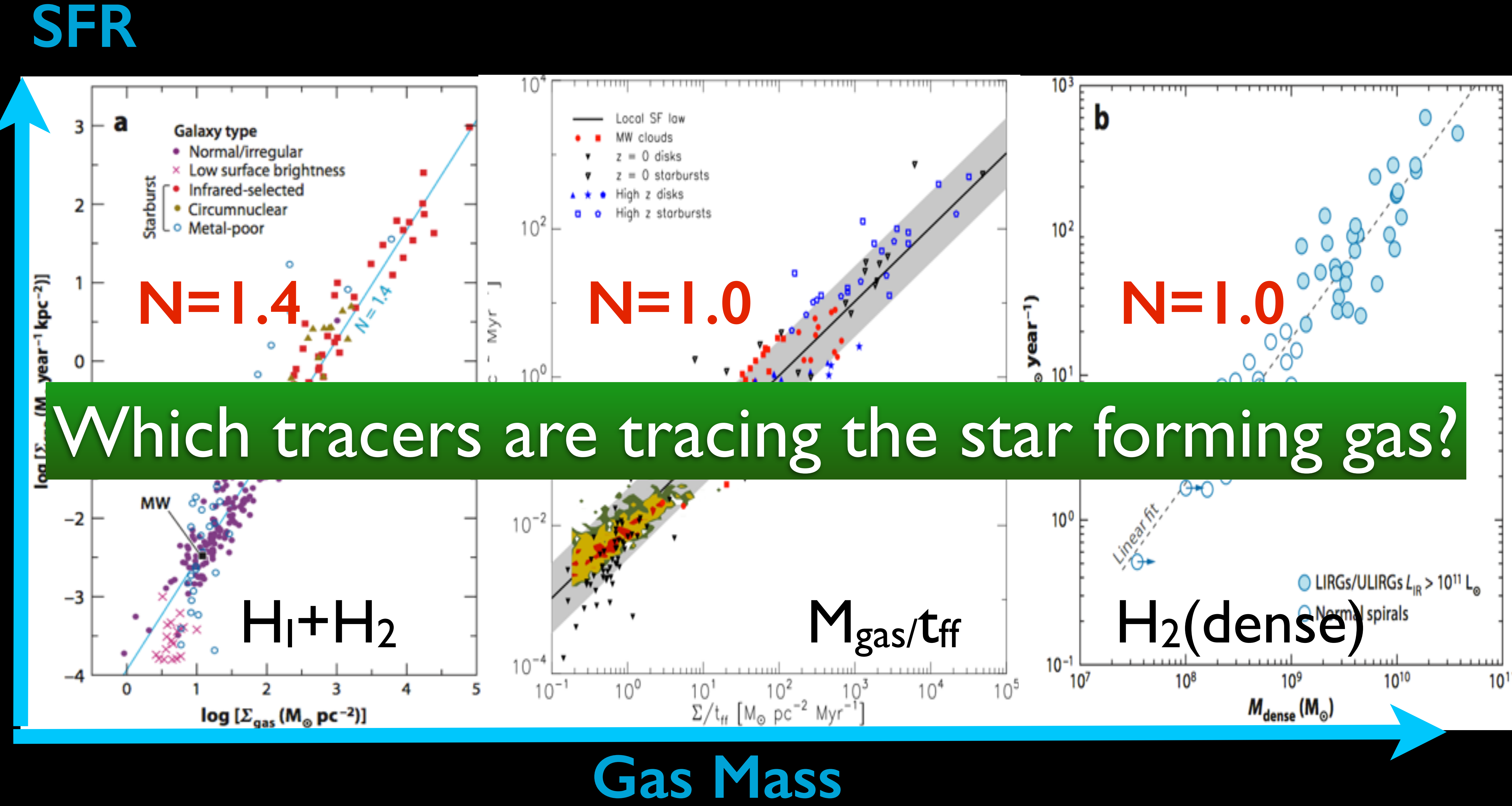
Which gases are forming stars? - Galactic view



Which gases are forming stars? - Galactic view



Star Formation Laws: Gas - SFR relations

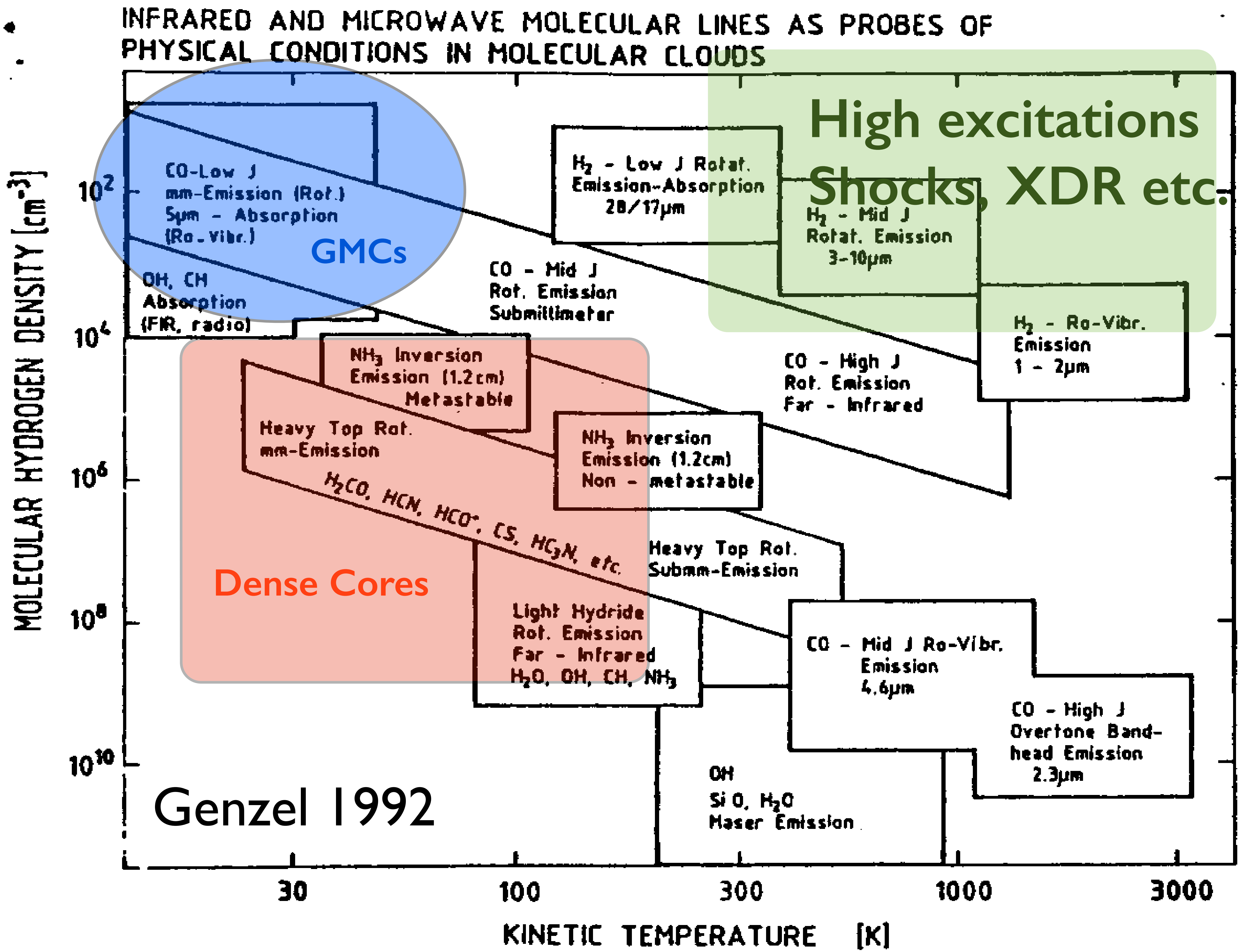


Kennicutt 1998

Krumholz et al. 2012

Gao & Solomon 2004

Tracers of Physical Conditions in Molecular Clouds



Dense gas tracers $n_{crit} > 10^4 cm^{-3}$

When $n(H_2) > n_{crit}$:
Collisional excitation dominant.
Easily be thermalised.

$$n_{crit} = \frac{\Sigma_{l<u} A_{ul}}{\Sigma_{l\neq u} C_{ul}}$$

$n_{crit}(HCN)$: $10^4 \sim 10^7 cm^{-3}$

$n_{crit}(HCO^+)$: $10^4 \sim 10^6 cm^{-3}$

$n_{crit}(CO)$: $10^2 \sim 10^5 cm^{-3}$

$n_{crit}(CS)$: $10^4 \sim 10^6 cm^{-3}$

HCN : IR-pumping, XDR, chemistry on T_{kin}.

e.g. Weiss et al. 2008; Graci-Carpio et al. 2006; Lintott & Viti 2006; Baan et al. 2008

HCO^+ : Shock, ionisation fields, etc.

e.g. Dickinson et al. 1980; Dickmann et al. 1992; Papadopolous et al. 2007

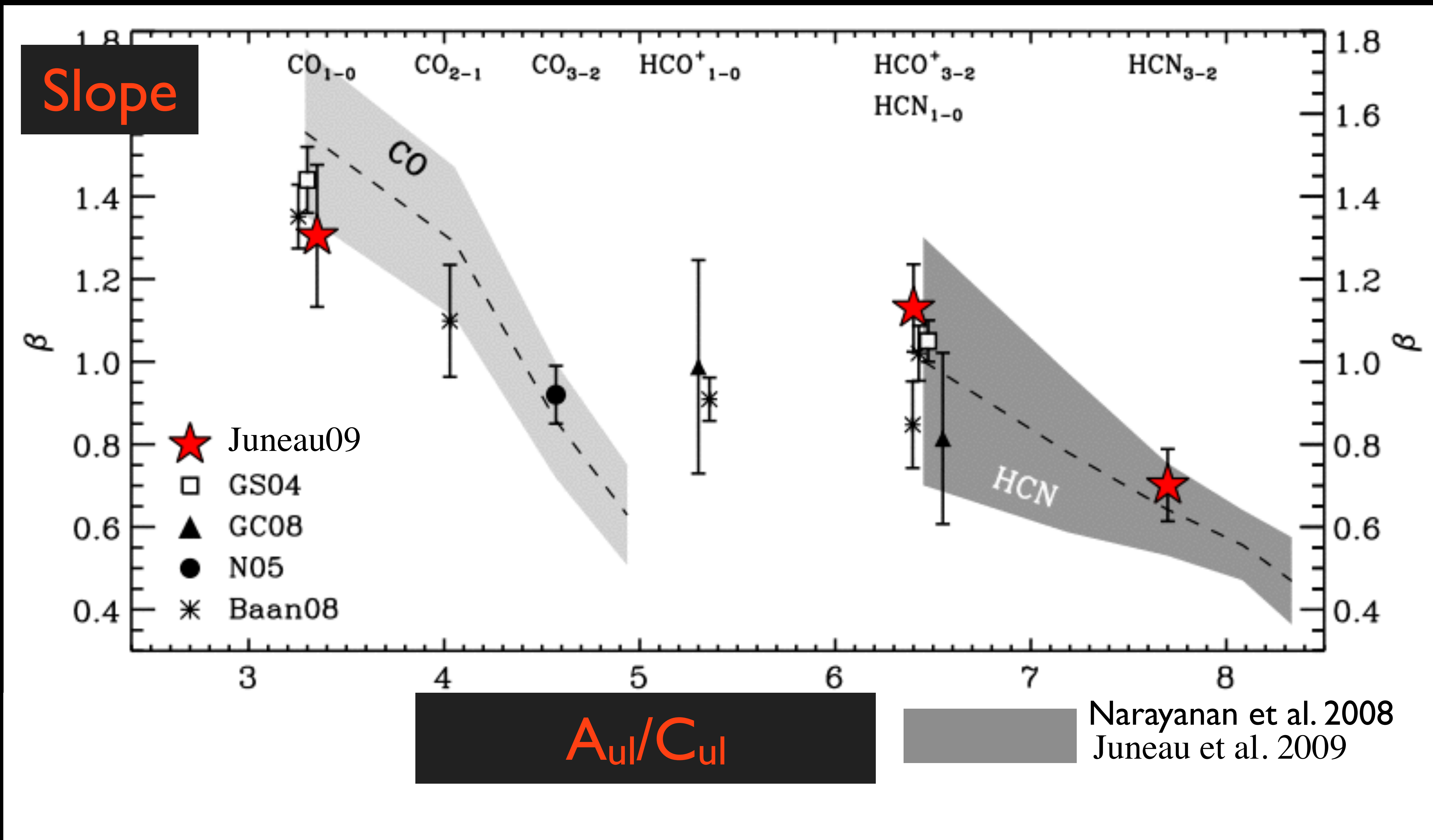
High-J CO: Warm gas.

CS : Weak (~1/4 of HCN intensity), chemically stable?

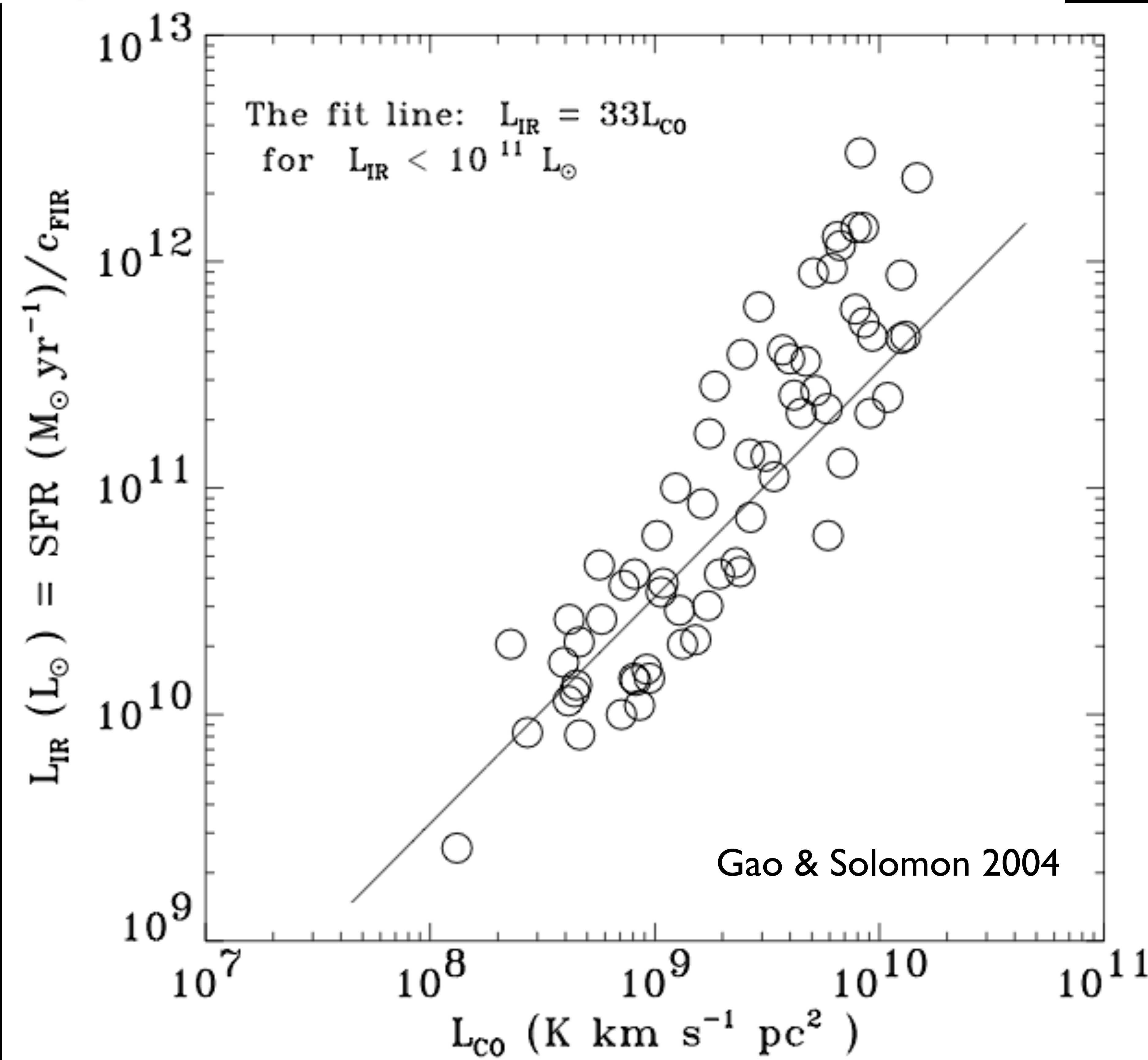
e.g. Charnley 1997; Martín et al. 2008;2009

Simulations of star formation laws

higher transitions/densities have lower slope indices?



L'$_{gas}$-L$_{IR}$ correlations -- CO 1-0 (n_{crit}~ 4 x10^2 cm^{-3})

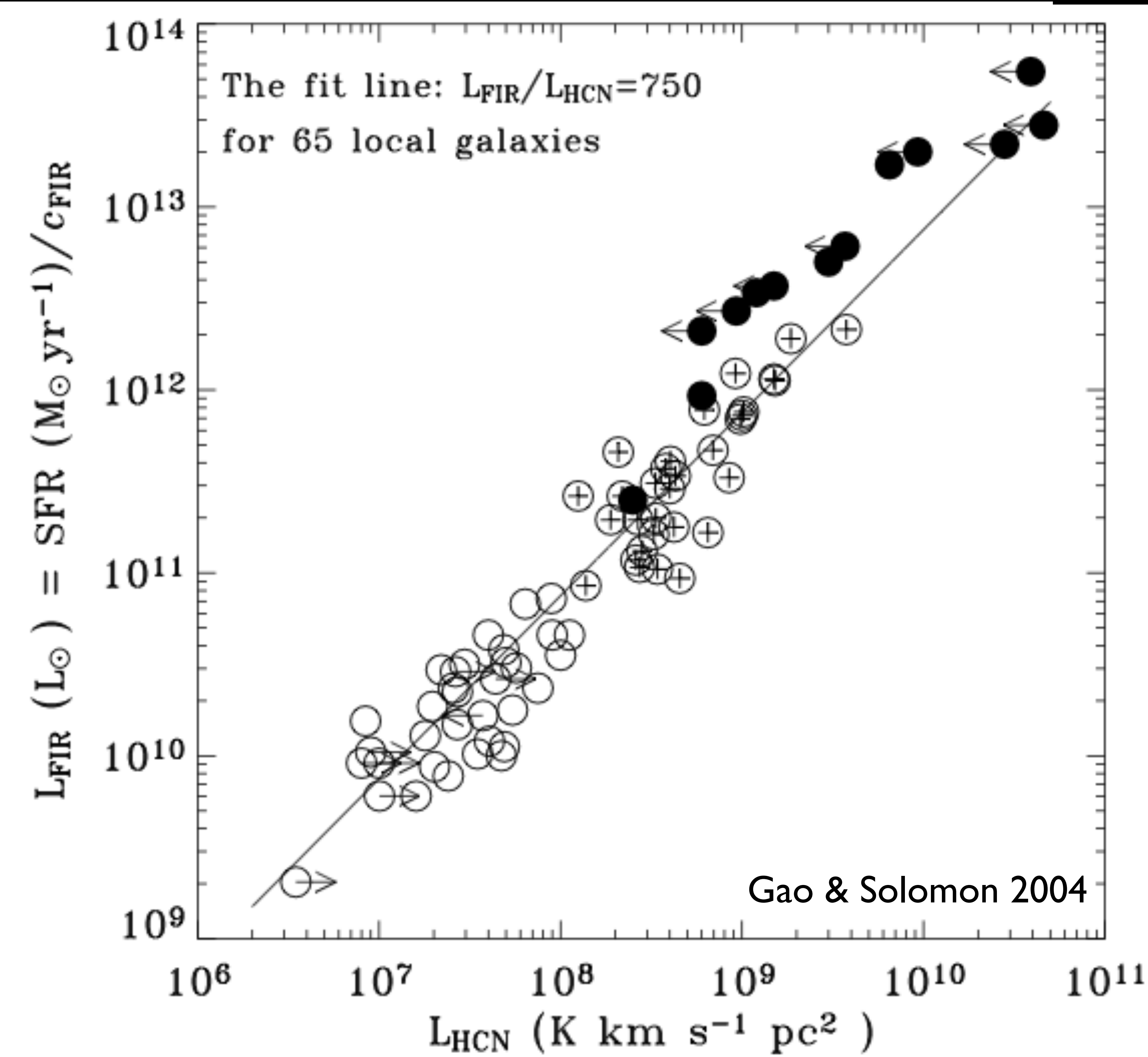


Slope~1.4

L'$_{gas}$ -- M$_{gas}$

L$_{IR}$ -- SFR

L'_{gas}-L_{IR} correlations -- HCN 1-0 (n_{crit}~ 2 x10^5 cm^{-3})

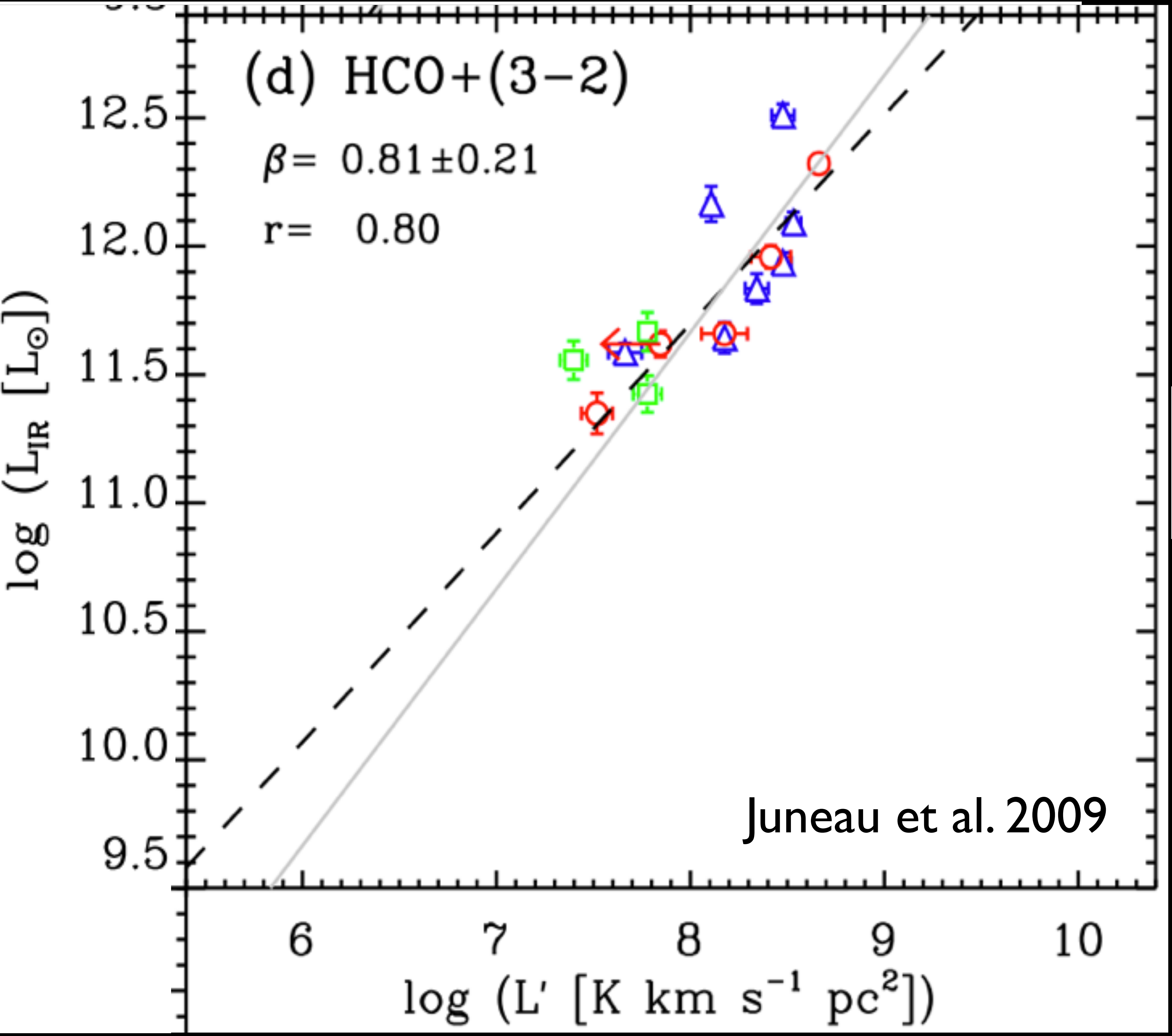


Slope=1

L'_{gas} -- M_{gas}

L_{IR} -- SFR

L'_{gas}-L_{IR} correlations -- HCO^+ 3-2 (n_{crit}~ 1 x10^6 cm^{-3})

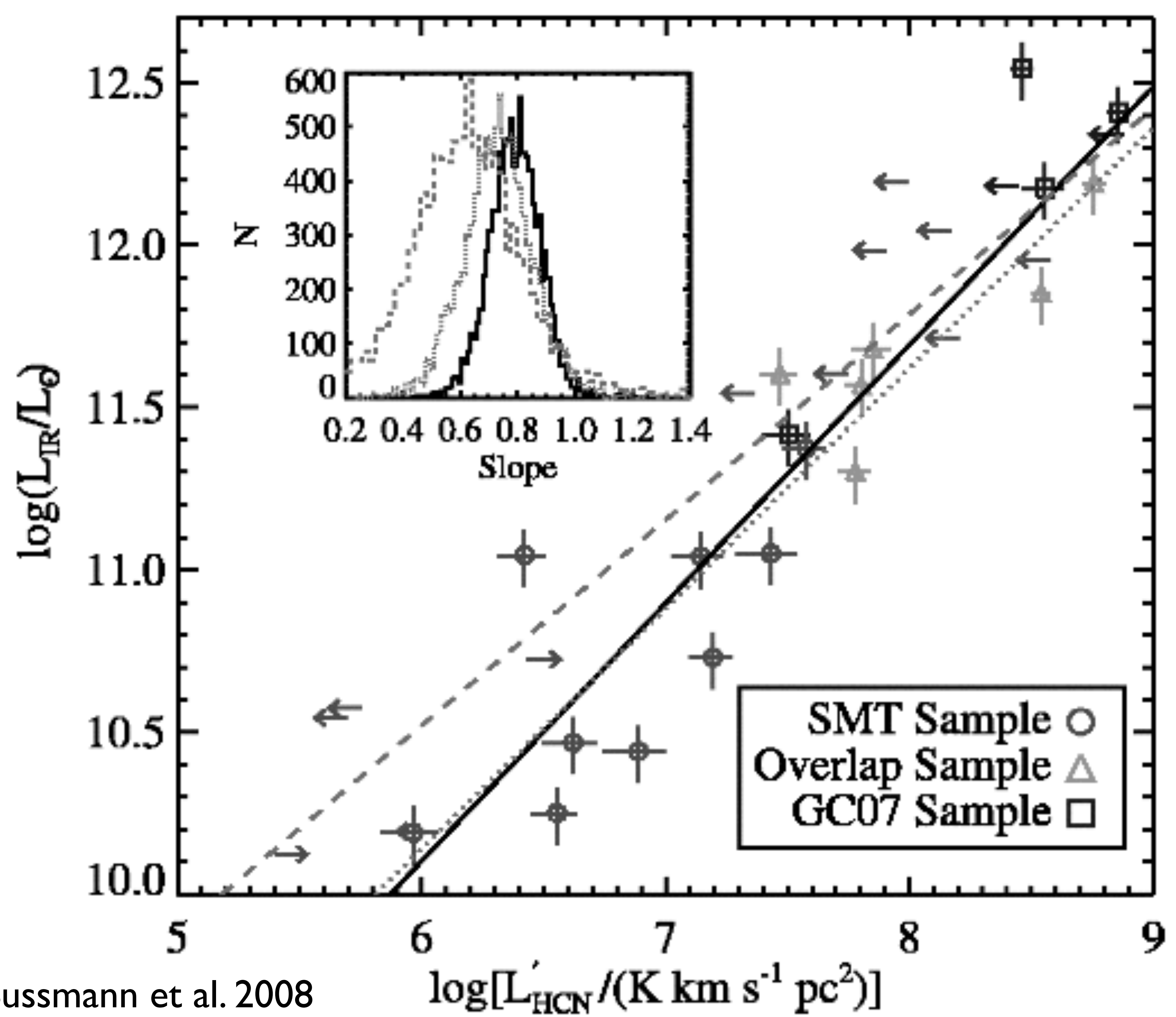


Slope=0.8

L'_{gas} -- M_{gas}

L_{IR} -- SFR

L'$_{gas}$-L$_{IR}$ correlations -- HCN 3-2 (n_{crit}~ 5 x10^6 cm^{-3})



Bussmann et al. 2008

N~0.7

L'$_{gas}$ -- M$_{gas}$
L$_{IR}$ -- SFR

Galactic CS & HCN studies

CS 2–1:

Least squares : $\log(L_{IR}) = 1.03(\pm 0.05) \times \log(L'_{CS2-1}) + 3.25(\pm 0.11); r = 0.80$

Robust fit : $\log(L_{IR}) = 0.87 \times \log(L'_{CS2-1}) + 3.56$

1.03(0.05)

CS 5–4:

Least squares fit : $\log(L_{IR}) = 1.05(\pm 0.05) \times \log(L'_{CS5-4}) + 3.77(\pm 0.08); r = 0.86$

Robust fit : $\log(L_{IR}) = 0.86 \times \log(L'_{CS5-4}) + 3.90$

1.05(0.05)

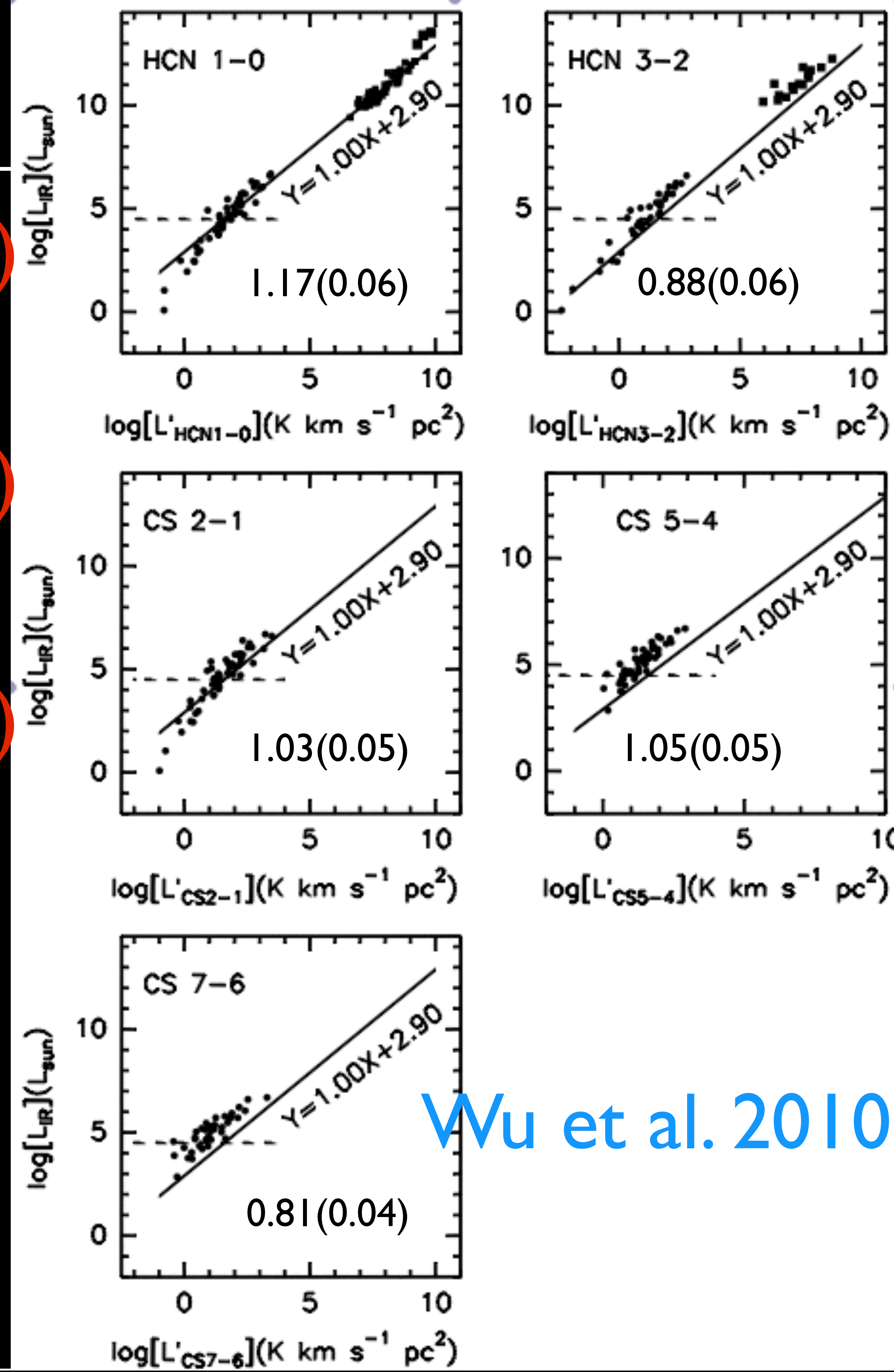
CS 7–6:

Least squares fit : $\log(L_{IR}) = 0.81(\pm 0.04) \times \log(L'_{CS7-6}) + 4.31(\pm 0.06); r = 0.81$

Robust fit : $\log(L_{IR}) = 0.64 \times \log(L'_{CS7-6}) + 4.58$

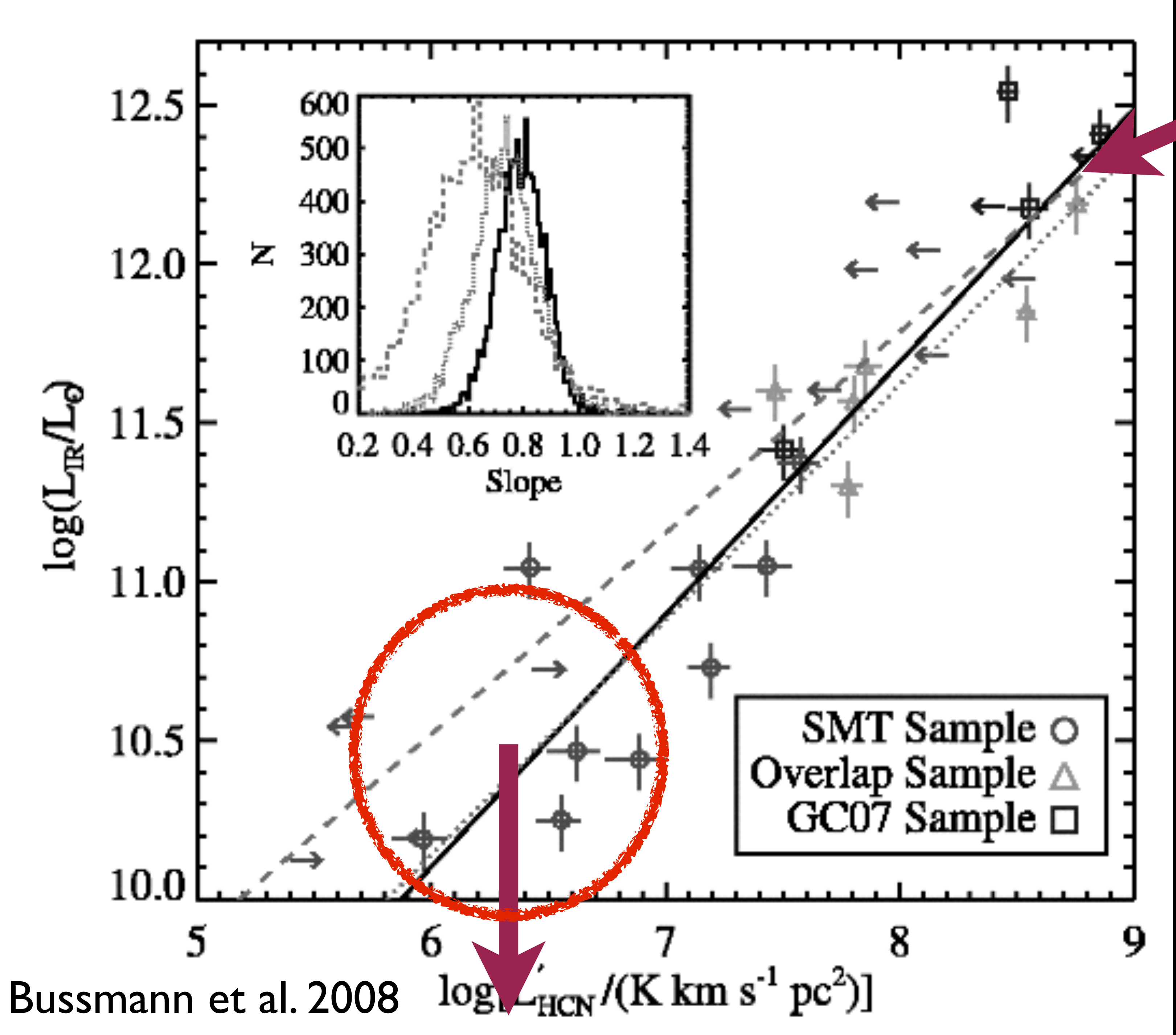
0.81(0.04)

The average density determined from CS excitation of the massive clumps in our sample is about $10^{5.9}$ cm^{-3} (Plume et al. 1997), less than the critical density of all the tracers in this study except for the CS 2–1 line (Table 9), but greater than the effective density (Table 9) and the density that was found to contribute most to the HCN 1–0 line in the simulations of Krumholz & Thompson (2007). In fact, a density derived from excitation analysis is biased toward the densest regions and the mean density of the clumps in the sense of mass divided by volume is generally less (e.g., Shirley et al. 2003). As noted above, the relations we find do not support the suggestions by Krumholz & Thompson (2007) or Narayanan et al. (2008).



Wu et al. 2010

Issues in observational results



Bussmann et al. 2008

IR pumping ?
Chemistry?

Stable tracers need.

IR size > beamsize

Either to map gas emission
or
to match IR with beam

To test the above models in galaxies, multiple transition surveys of chemically clean dense tracers, e.g. CS lines, are needed.

Sample Selection:

1. IRAS Revised Bright Galaxies sample (IRAS RBGs, Sanders 2003).
   Flux cutoff: F_{100um} >100 Jy, F_{60um} >50 Jy.

2. Rich detections of CO and HCN lines.

3. A large range of L_{IR}, and galaxy types:
   Nearby normal galaxies, starburst, LIRGs, and ULIRGs.

~ 50 galaxies are selected

Multiple-J CS survey

~ 280 hours in total

Multiple transitions (J=1-0 to 7-6) of CS lines towards ~ 40 nearby normal galaxies, starburst, and (U)LIRGs

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

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

CS J= 5-4/7-6 APEX 12m

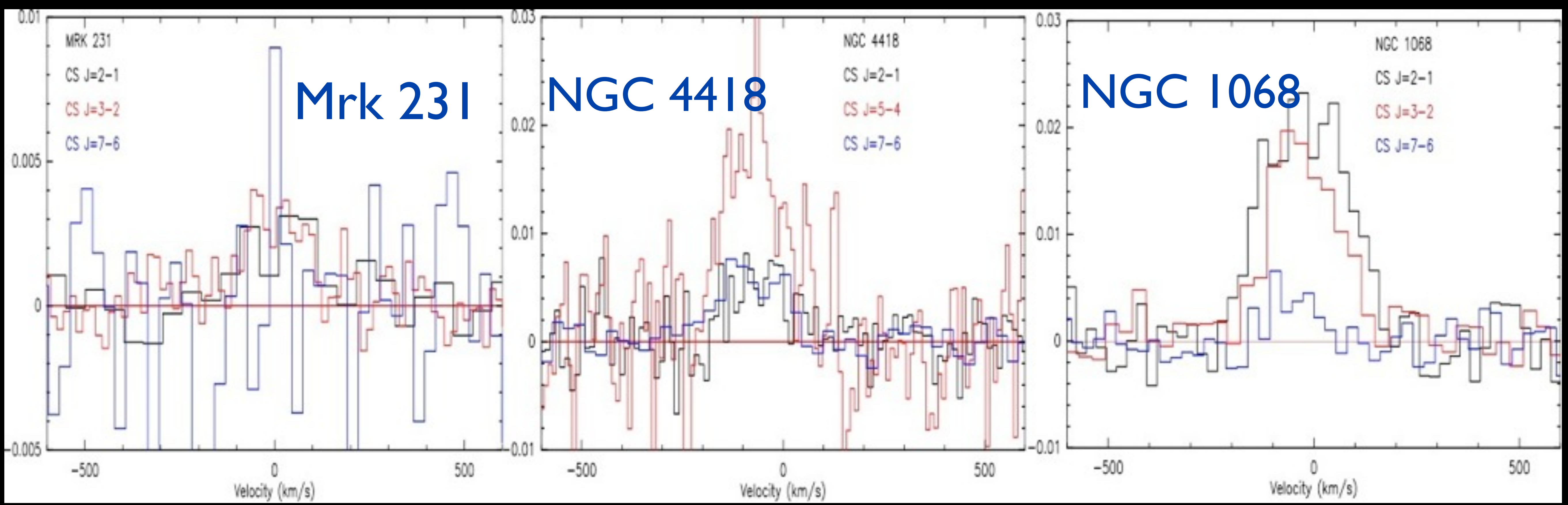
CS J= 1-0 GBT and the EVLA

Samples and Detections

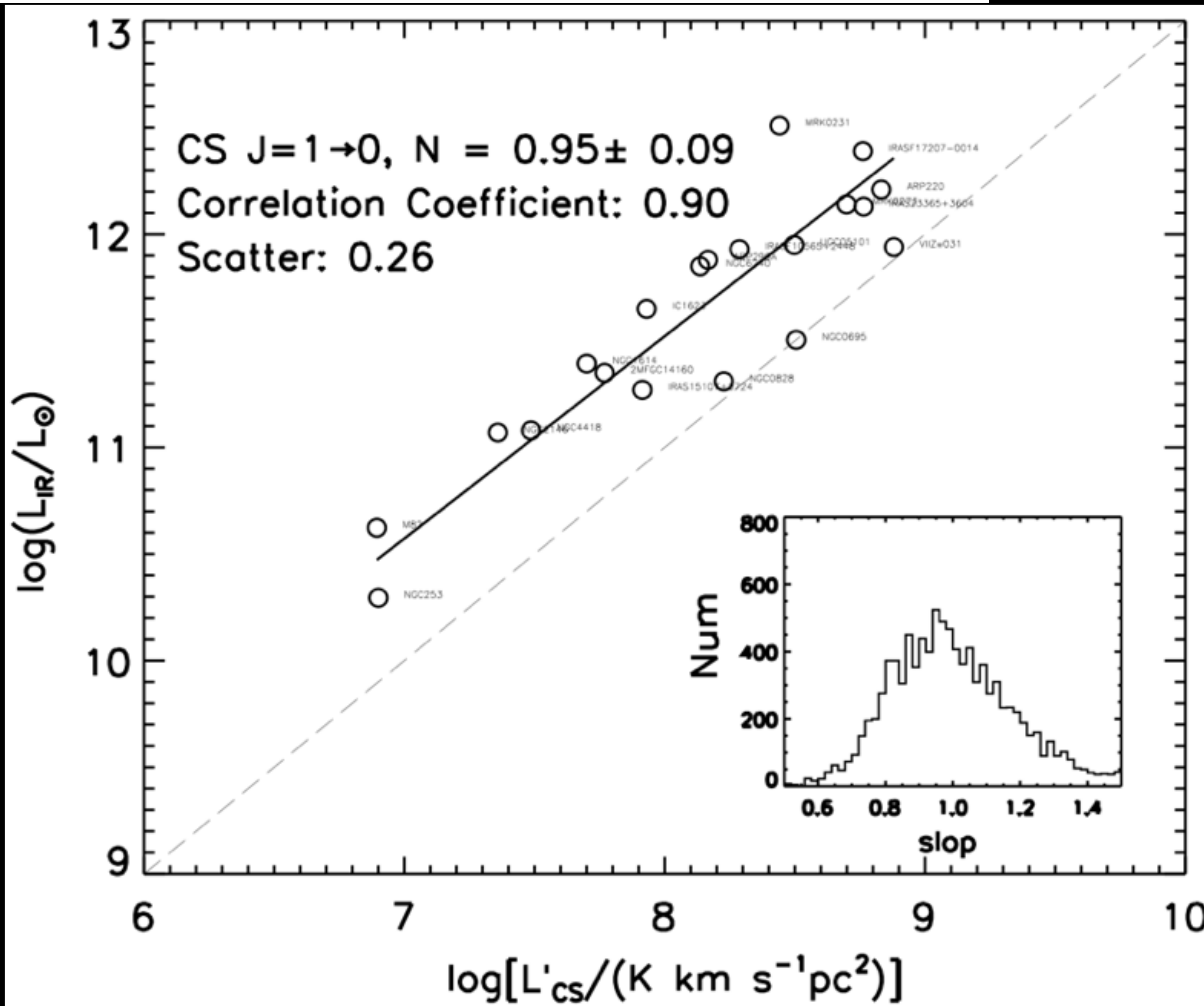
CS J=1-0 : 20/24 galaxies
CS J=2-1 : 41/47 galaxies
CS J=3-2 : 30/41 galaxies
CS J=5-4 : 21/40 galaxies
CS J=7-6 : 11/20 galaxies
$C^{34}S$ J=2-1: 5 detections

+ CS detections in literatures

HCN/HCO^+ J=4-3 simultaneously

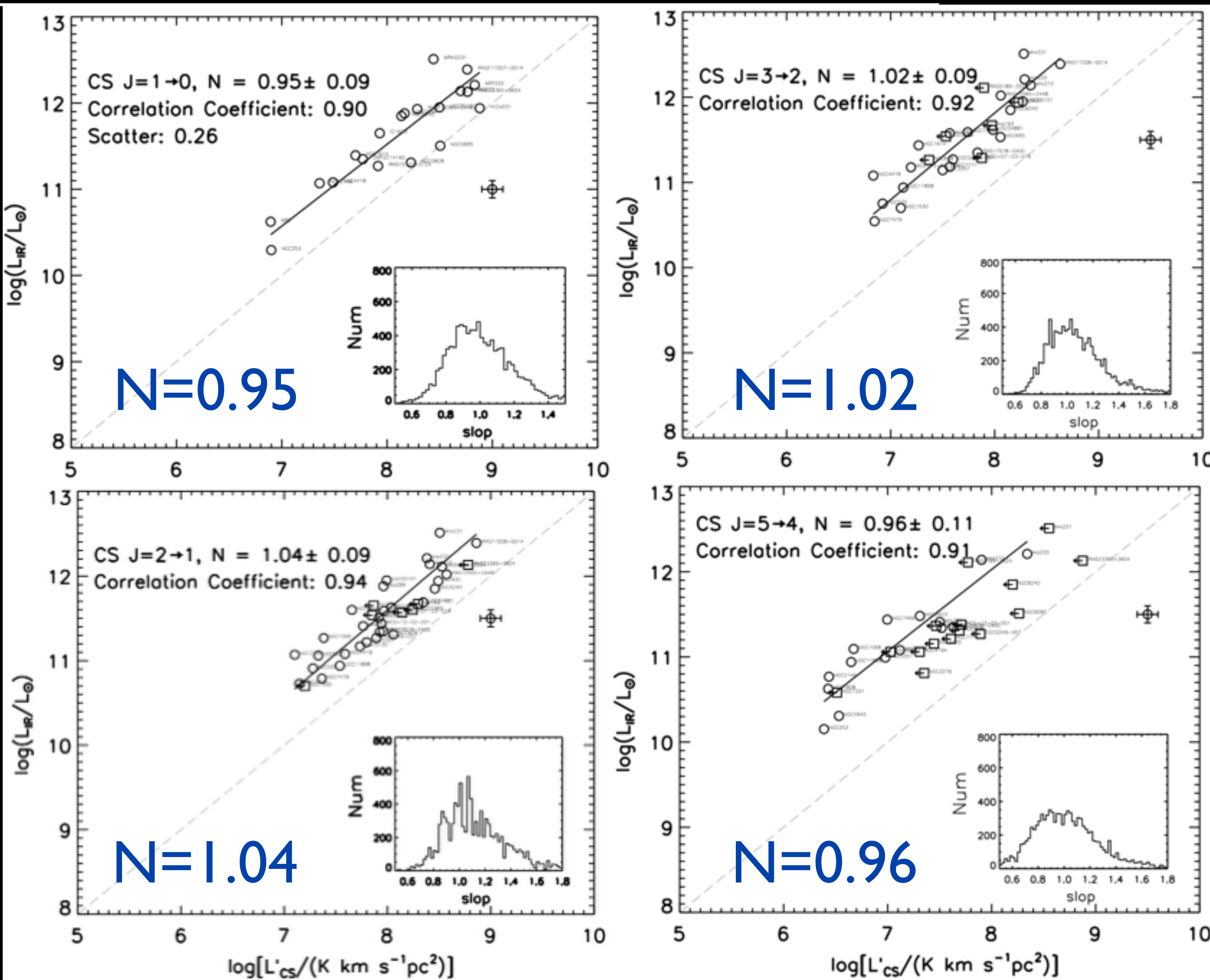


L'$_{gas}$-L$_{IR}$ (small targets)   CS J=1-0 n_{crit}~ $1\times10^4 cm^{-3}$



AO, Zhi-Yu Zhang

L'_{gas}-L_{IR} (small targets) CS J=1-0 to J=5-4



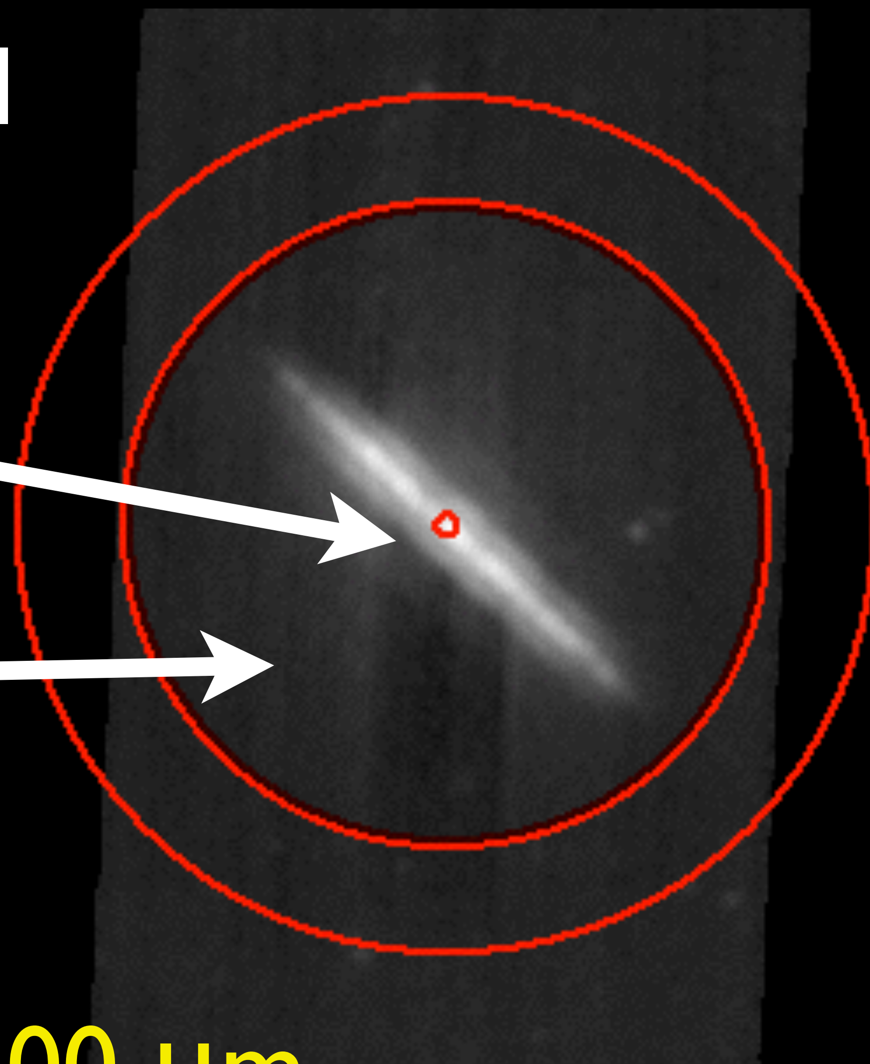
hi-Yu Zhang

Beam matching photometry for extended targets

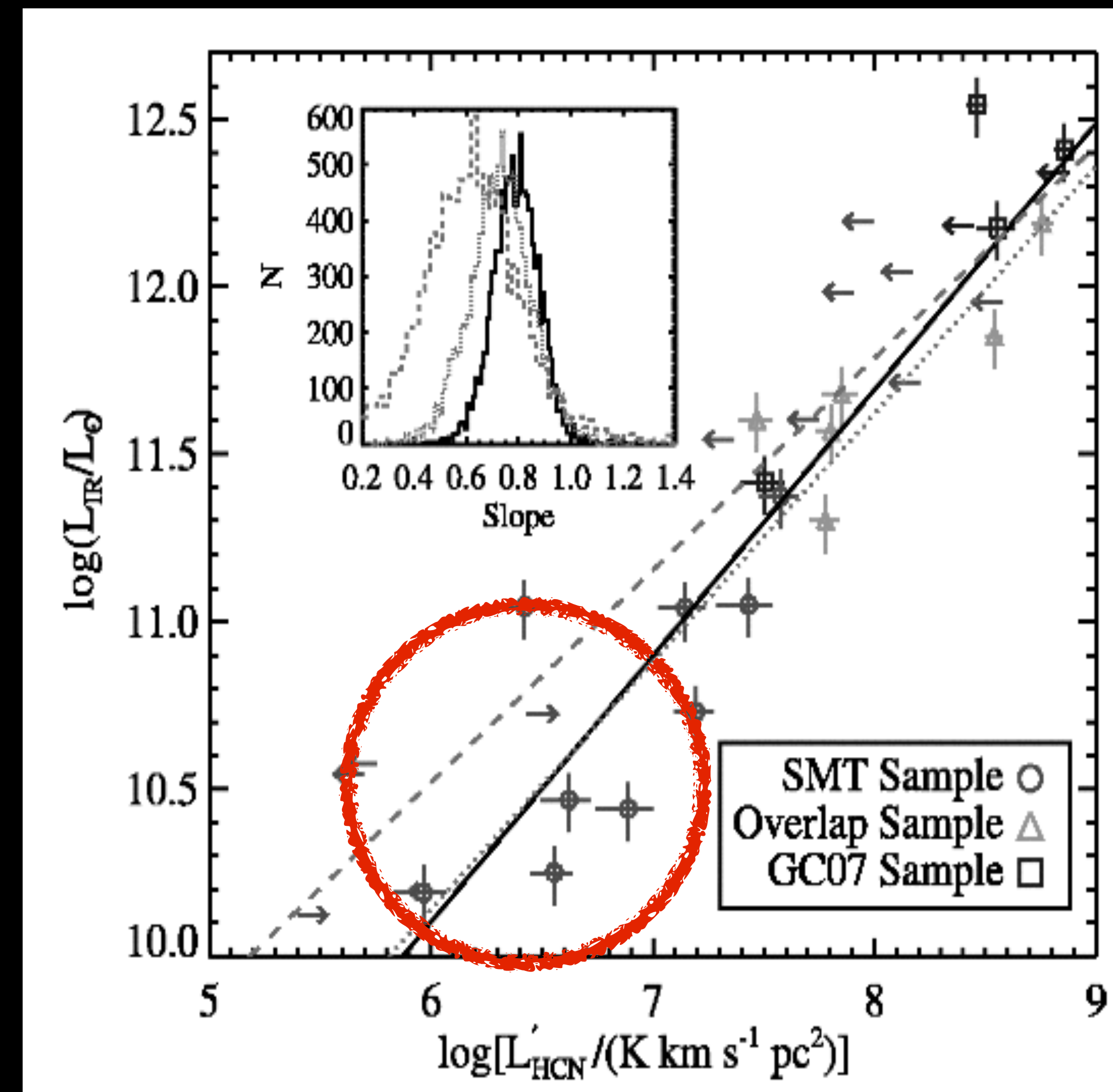
NGC 891

Beam

Whole



Herschel 100 μm



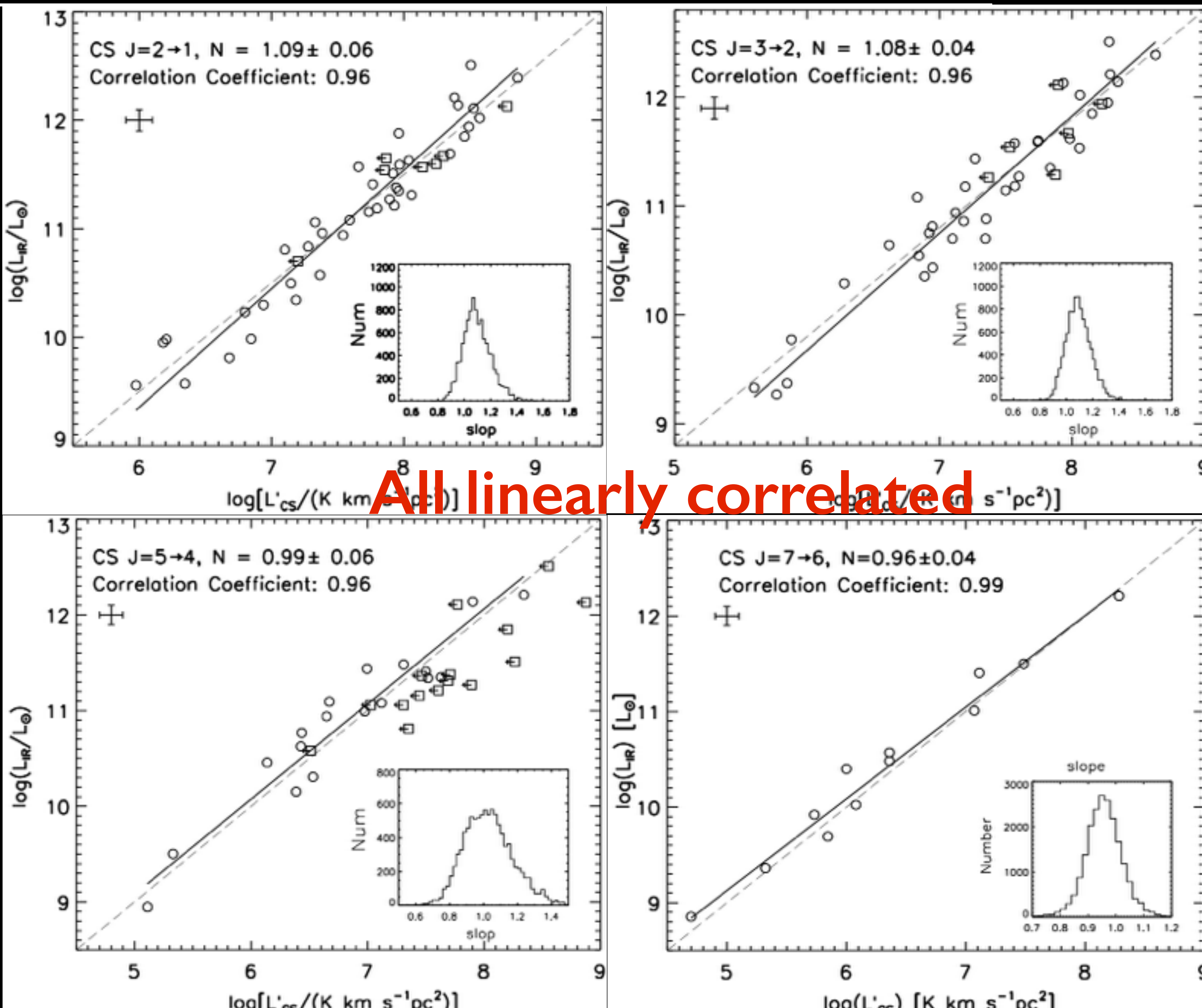
Bussmann et al. 2008

$$L_{SD} = R_{SD} \times L_{TIR}(IRAS)$$

$R_{SD}=F_{beam}/F_{total}$ varies at different bands

Assuming whole galaxy share one IR SED.

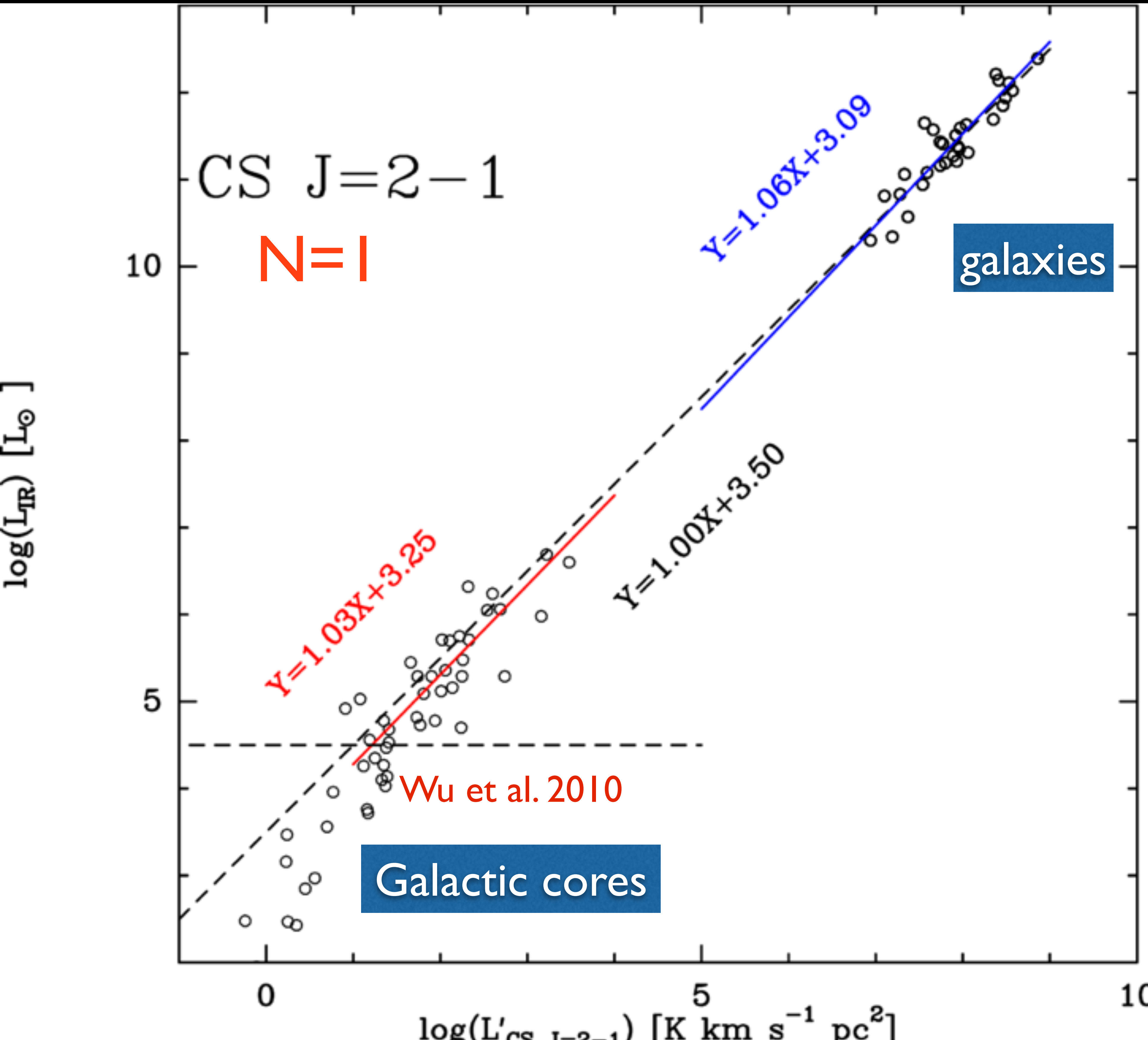
L'cs-LIR correlations Beam matching correction



All linearly correlated

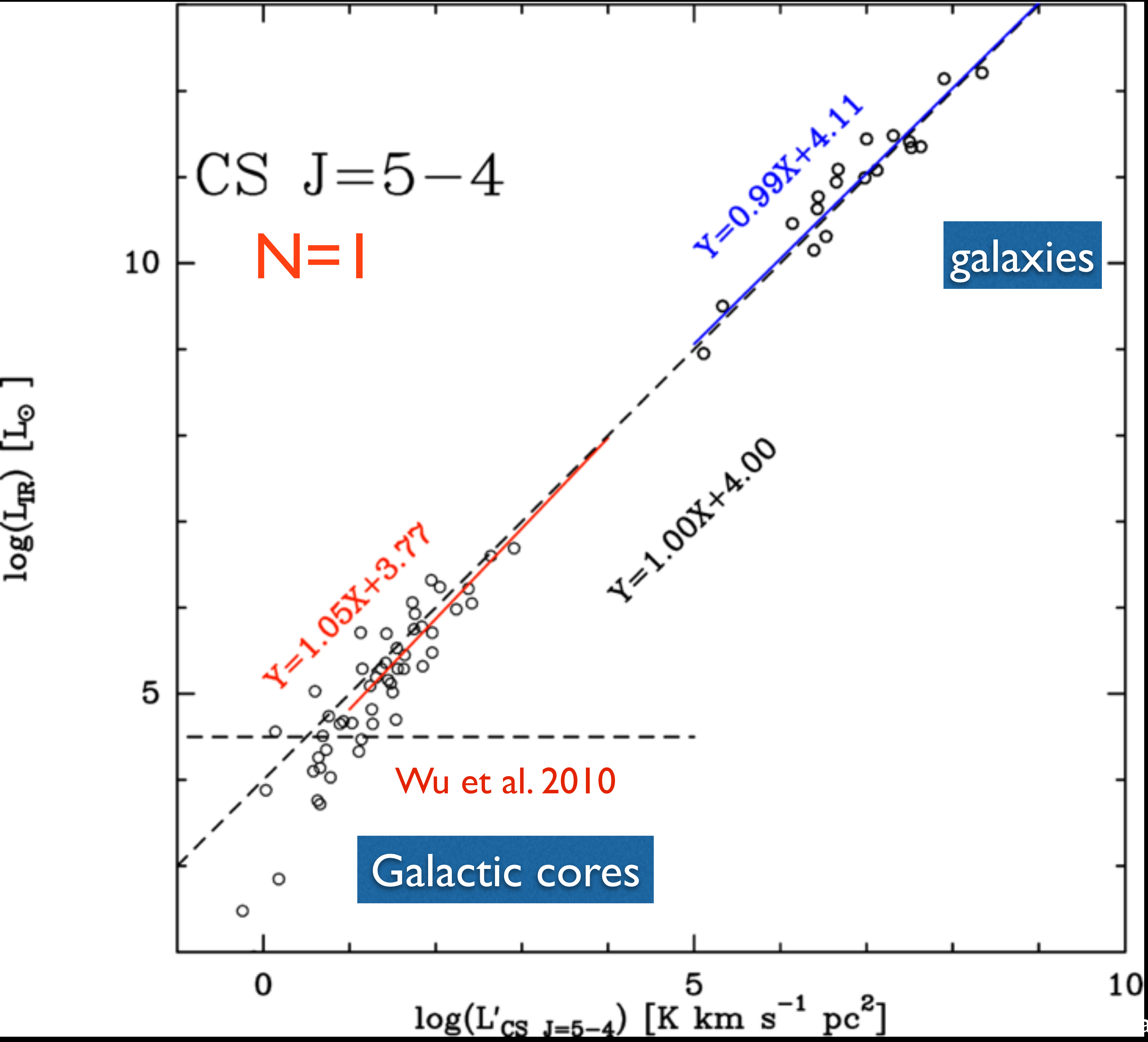
EAO, Zhi-Yu Zhang

L'_{CS}-L_{IR} correlations ~ 8 orders of magnitude



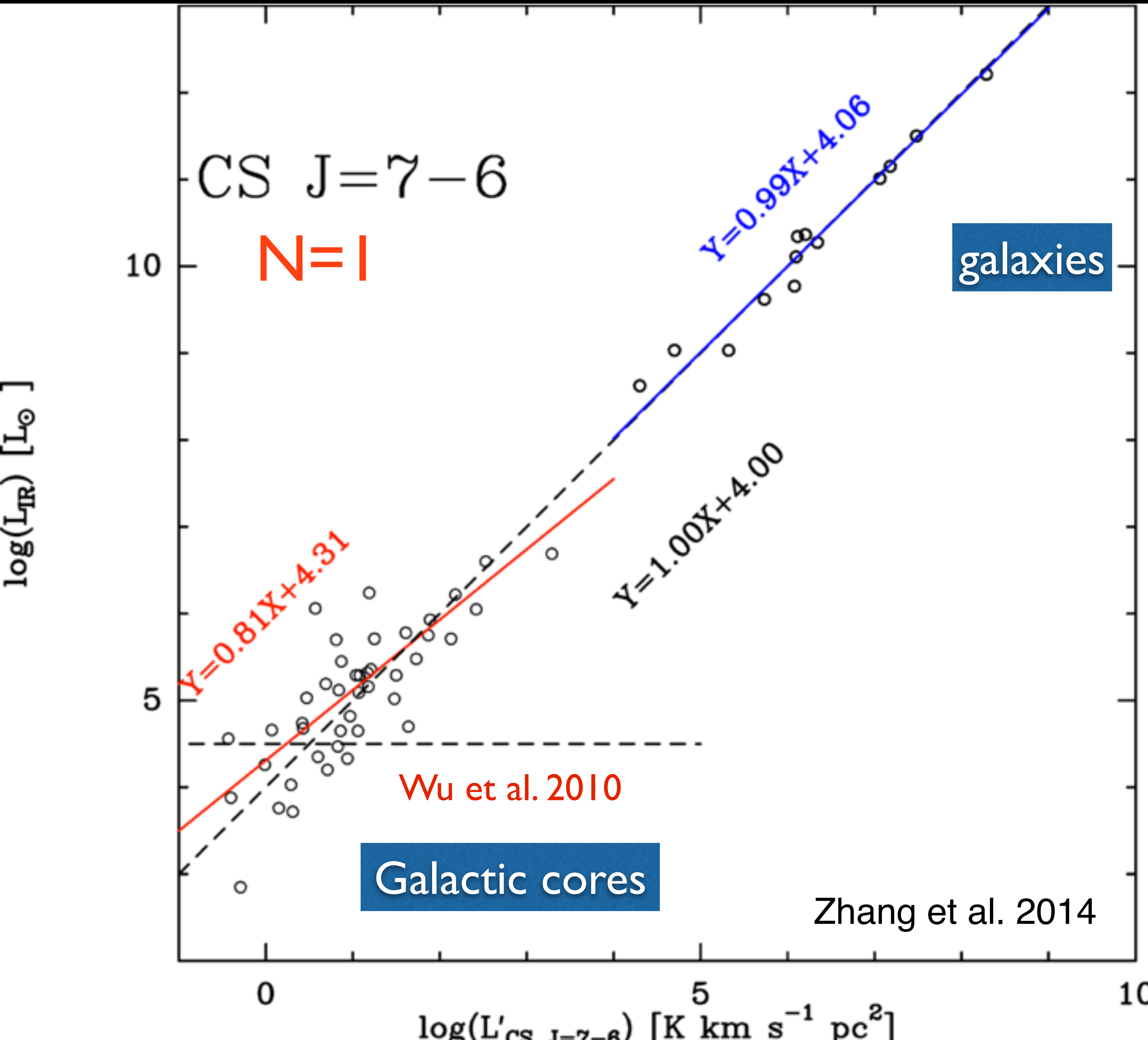
$n_{crit} \sim 1 \times 10^5\ cm^{-3}$

L'cs-LIR correlations ~ 8 orders of magnitude



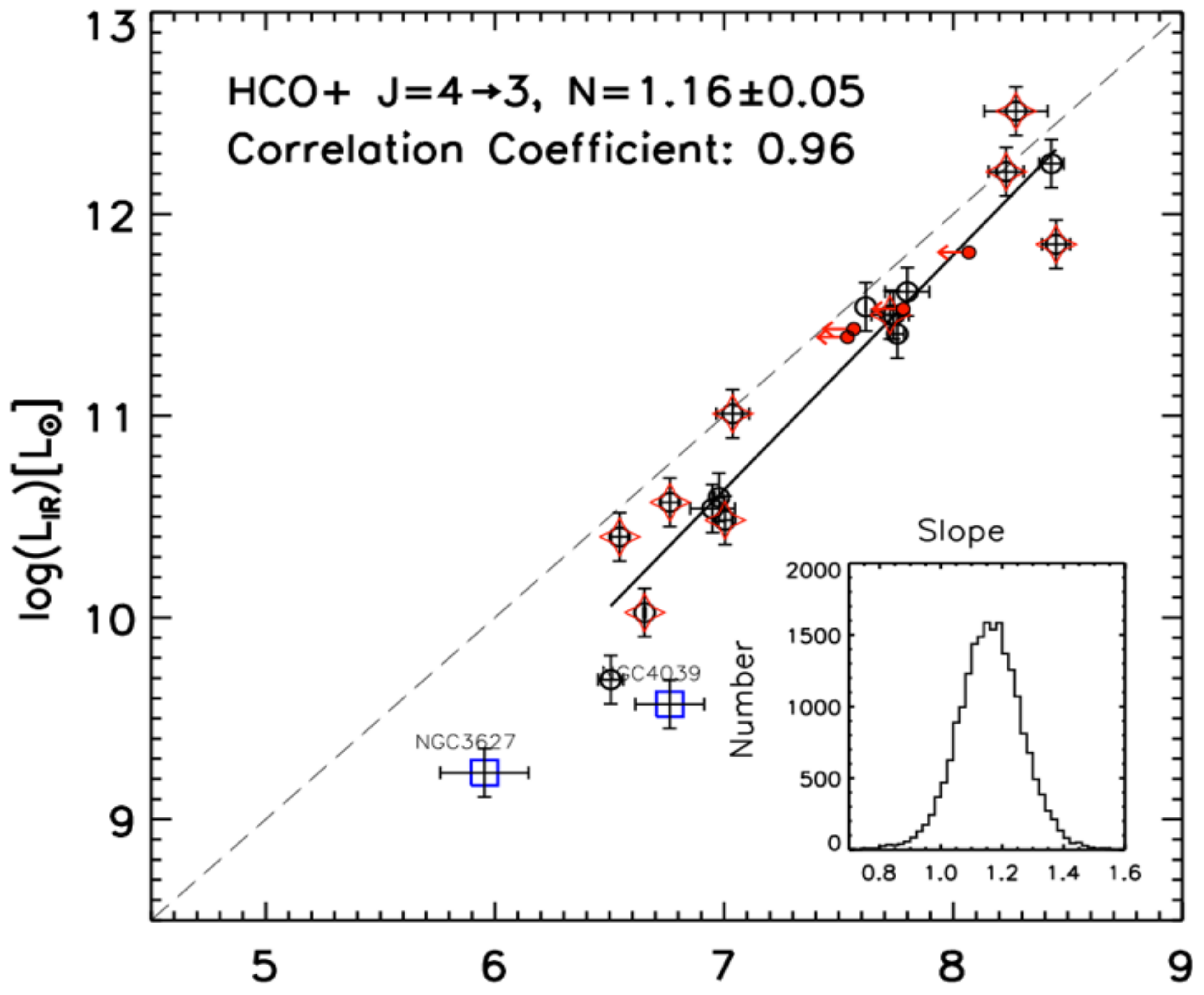
n_{crit}~ $2x10^6$ cm^{-3}

L'CS-LIR correlations ~ 8 orders of magnitude



n_{crit}~ 5×10^6 cm^{-3}

HCO^+ J=4-3 -- observed simultaneously with CS J=7-6

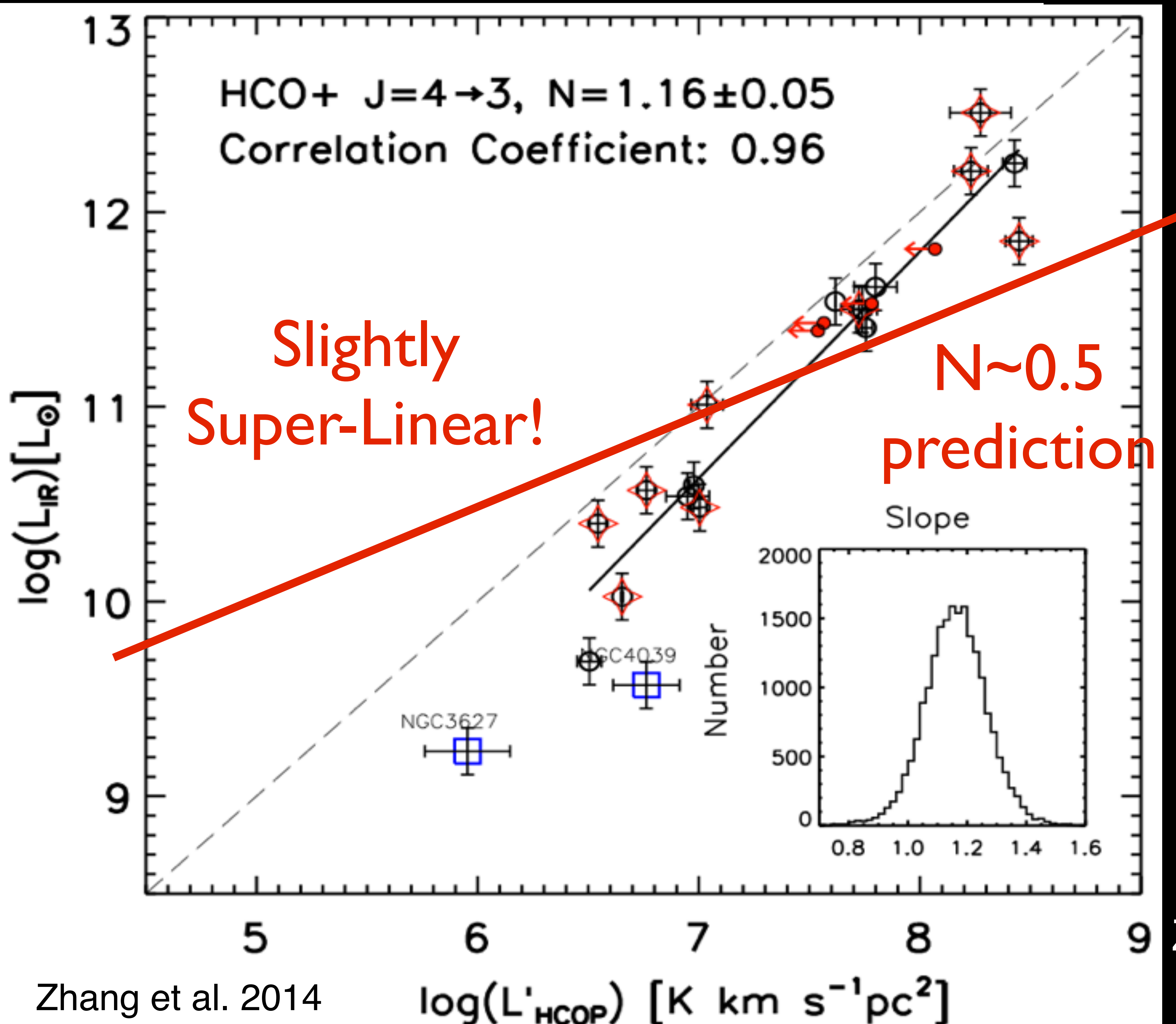


Zhang et al. 2014

$n_{crit} \sim 2 \times 10^6\ cm^{-3}$

Zhang et al. 2014

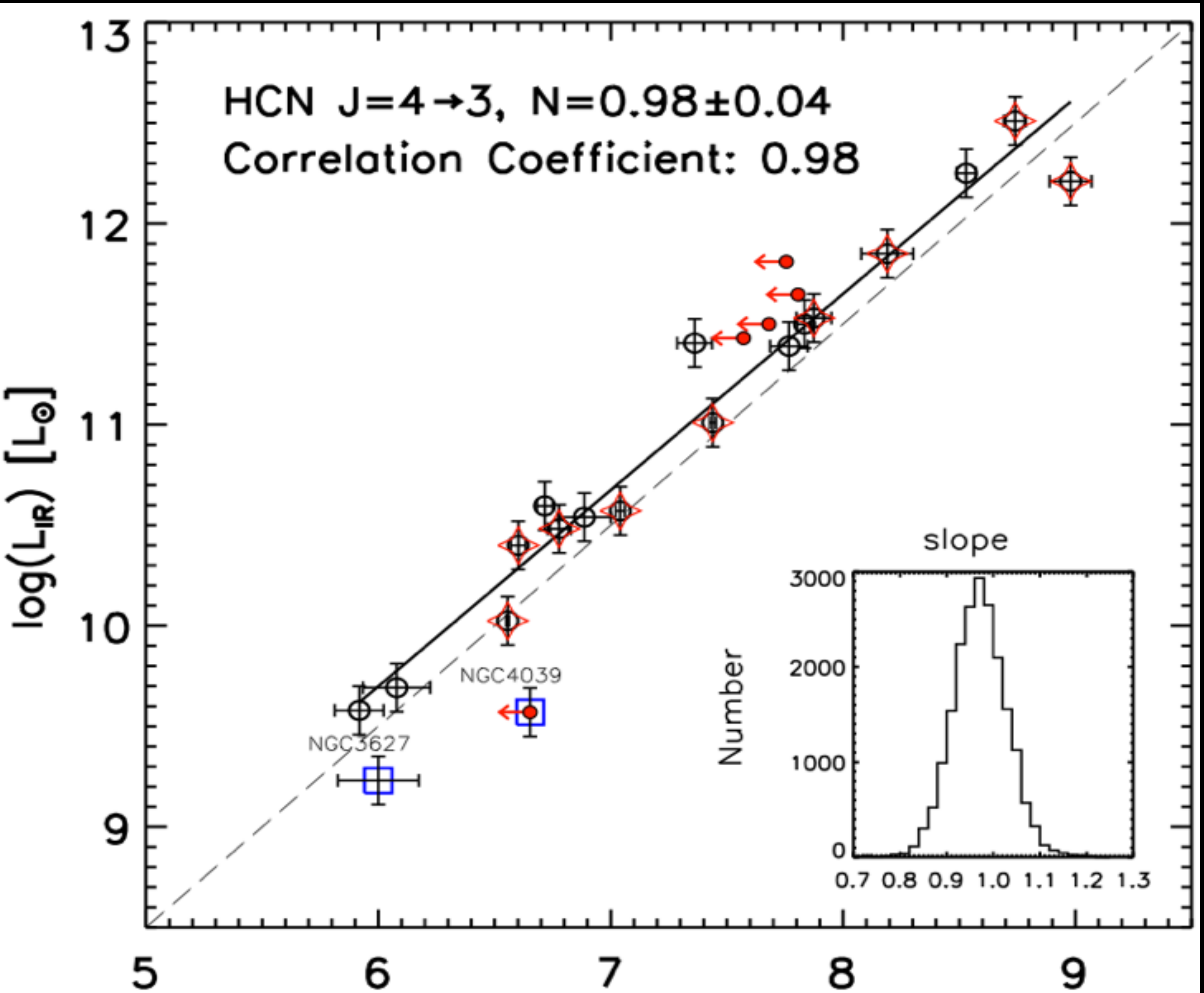
HCO$^+$ J=4-3 -- observed simultaneously with CS J=7-6



n_{crit}~ $2x10^6$ cm^{-3}

Zhang et al. 2014

HCN J=4-3 -- observed simultaneously with CS J=7-6

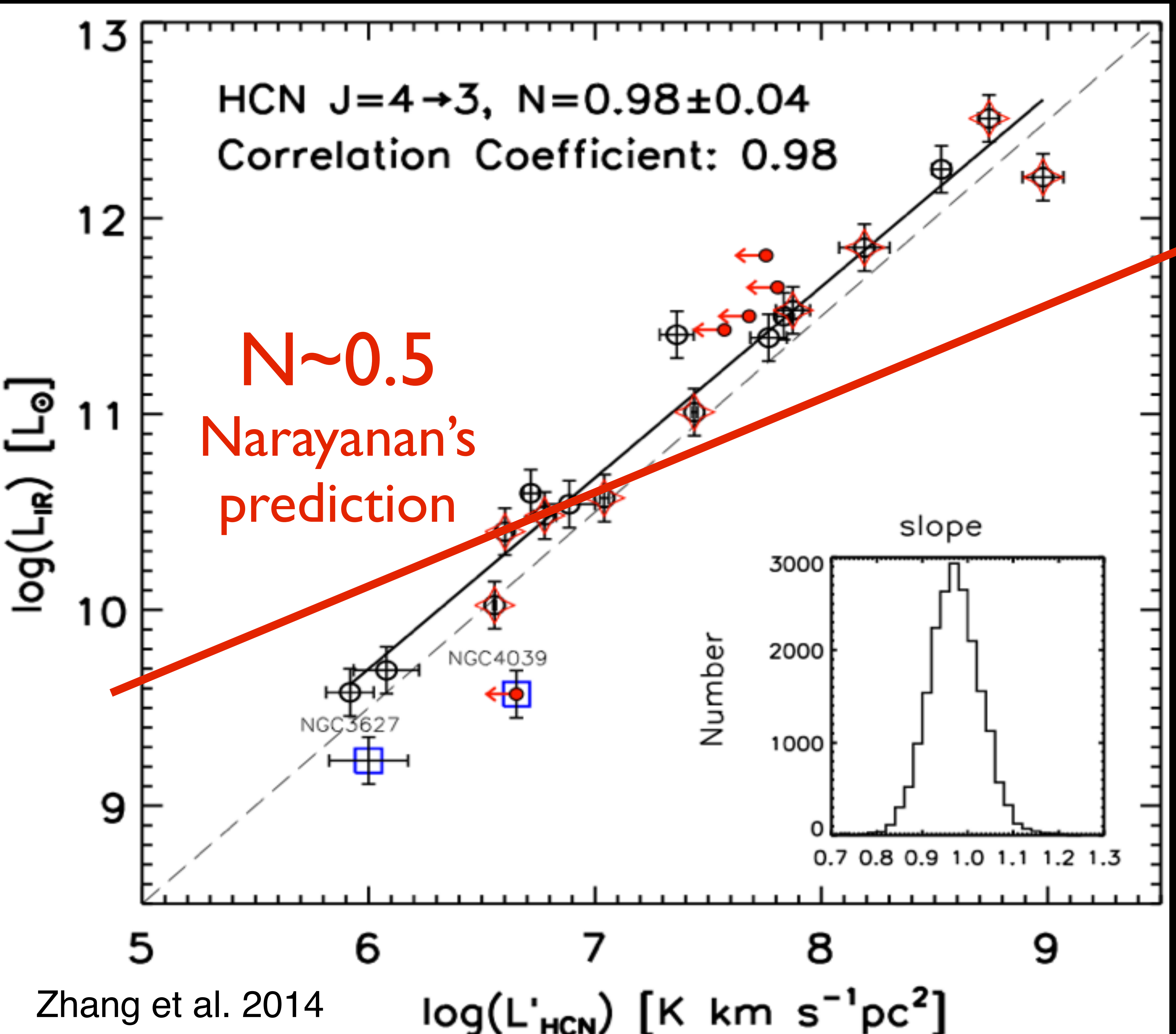


Zhang et al. 2014

$n_{crit} \sim 1 \times 10^7\ cm^{-3}$

Zhang et al. 2014

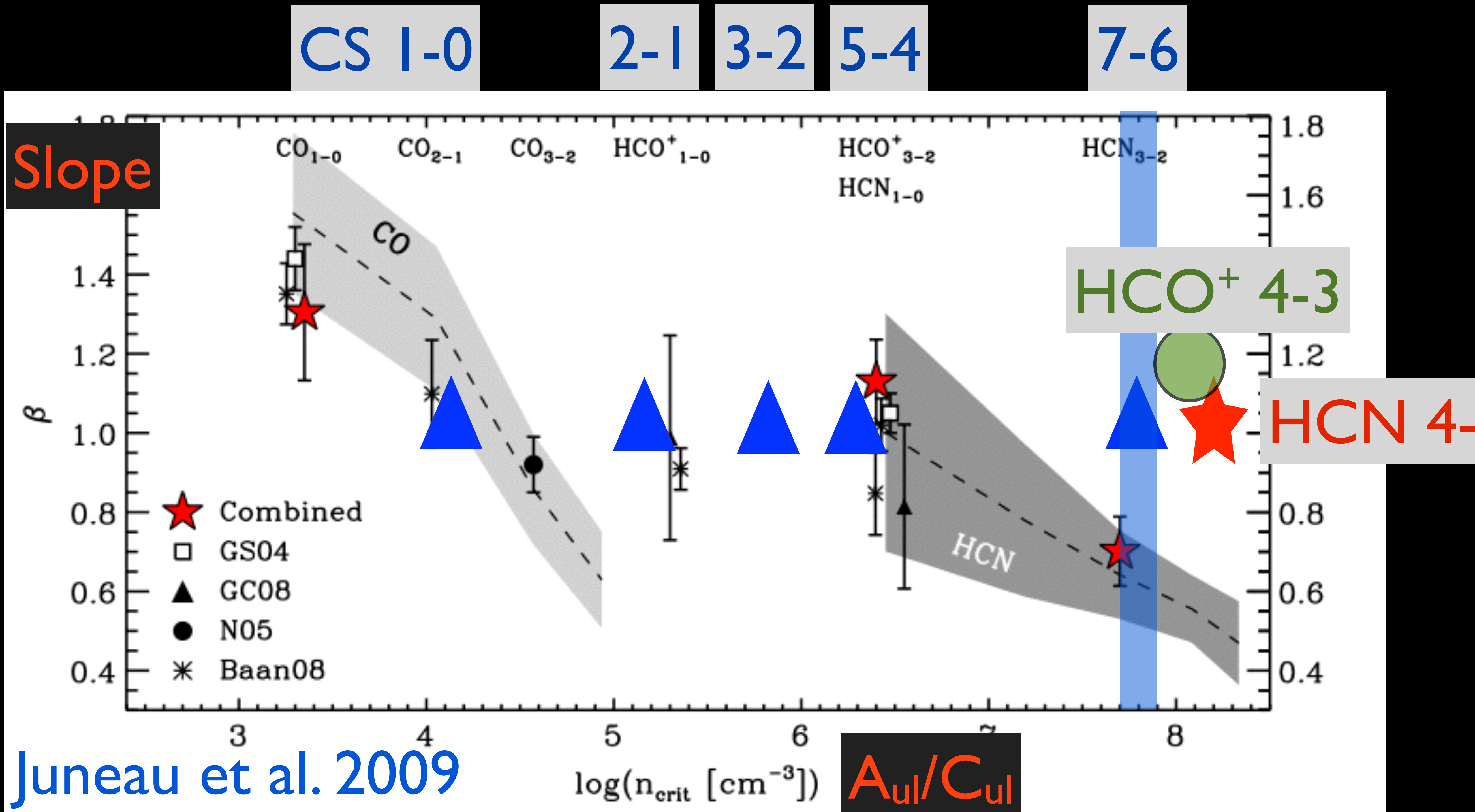
HCN J=4-3 -- the highest n_{crit} tracer



$n_{crit} \sim 1 \times 10^7 cm^{-3}$

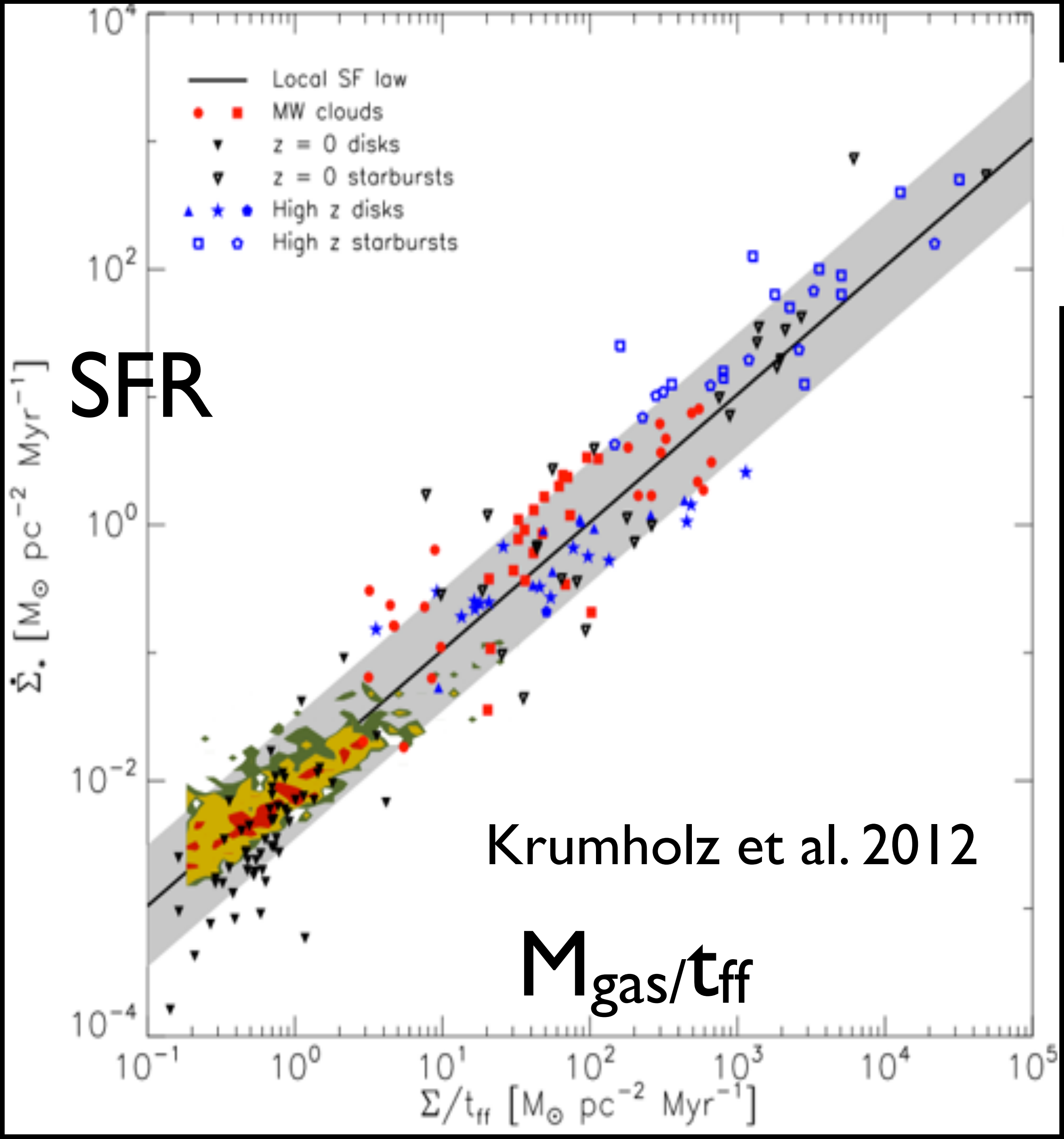
Zhang et al. 2014

Dense gas tracers with n_{crit} ~10^4 -10^8 cm^{-3}



Dense gas tracers have linear correlations irrespective to n_{crit}, universally over 8 orders of luminosity magnitudes.

Does time scale matter? -- For Dense gas: probably No.



$$\dot{\rho}_* = f_{H_2}\epsilon_{ff}\frac{\rho}{t_{ff}} = f_{H_2}\epsilon_{ff}\sqrt{\frac{32G\rho^3}{3\pi}}$$

f_{H2} : H_2 fraction

ϵ_{ff} : constant, dimensionless measure of SFR

$$t_{ff} \propto \rho^{-1/2}$$

If $L_{IR} = (L'_{dense})^N/t_{ff}$, N will decrease with n_{crit}.

This will be contradictory to our observed results.

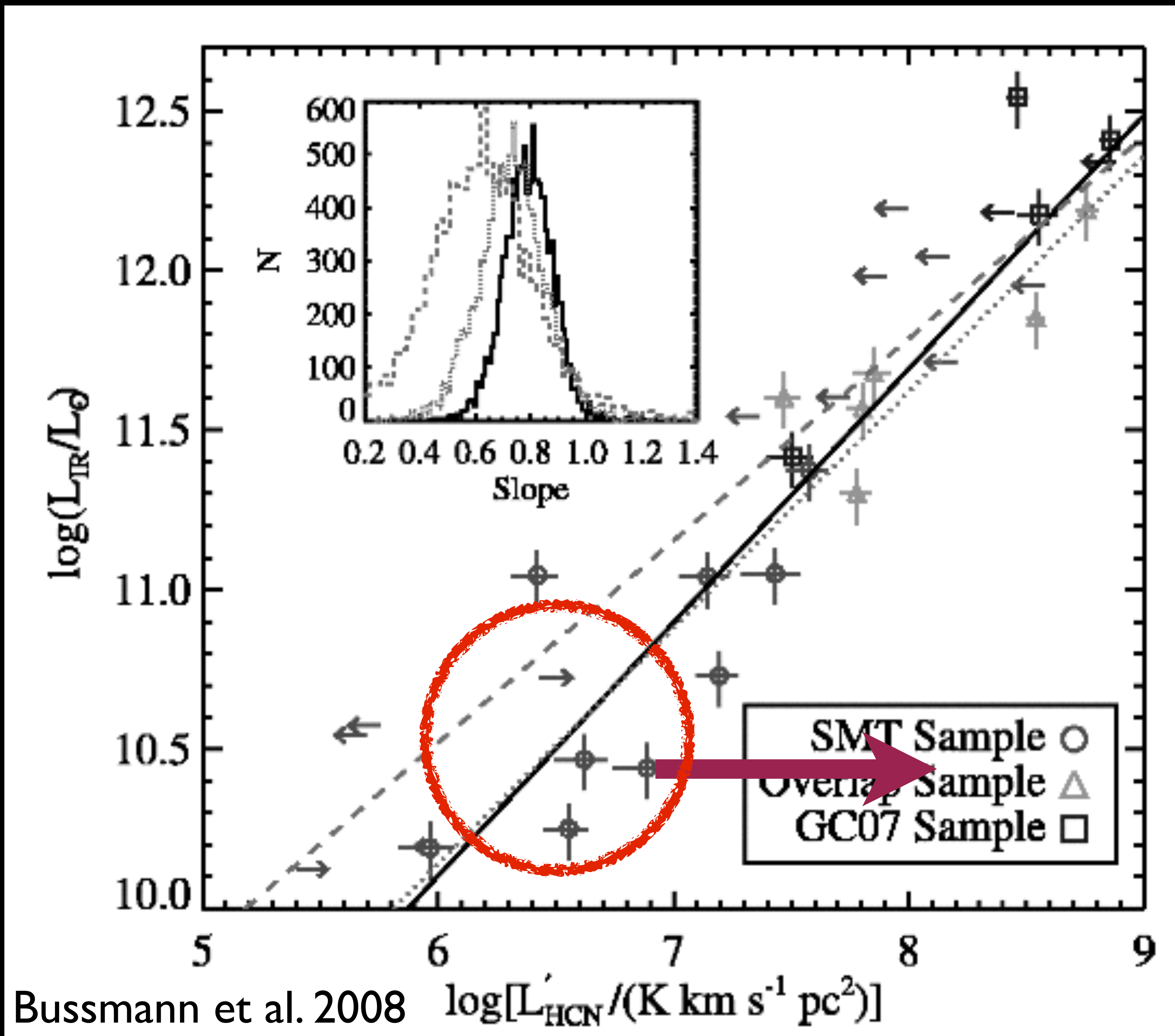
Short summary

1) Dense molecular gas ($n(H_2)$~> 10^4 cm^{-3}) is the star-forming gas.

2) How much dense gas, how much star-formation —linear correlations.

3) L'_{dense}-L_{IR} universally stays linear from Galactic cores to galaxies, irrespective to critical density, once it is > 10^4 cm^{-3}.

The other half of the story

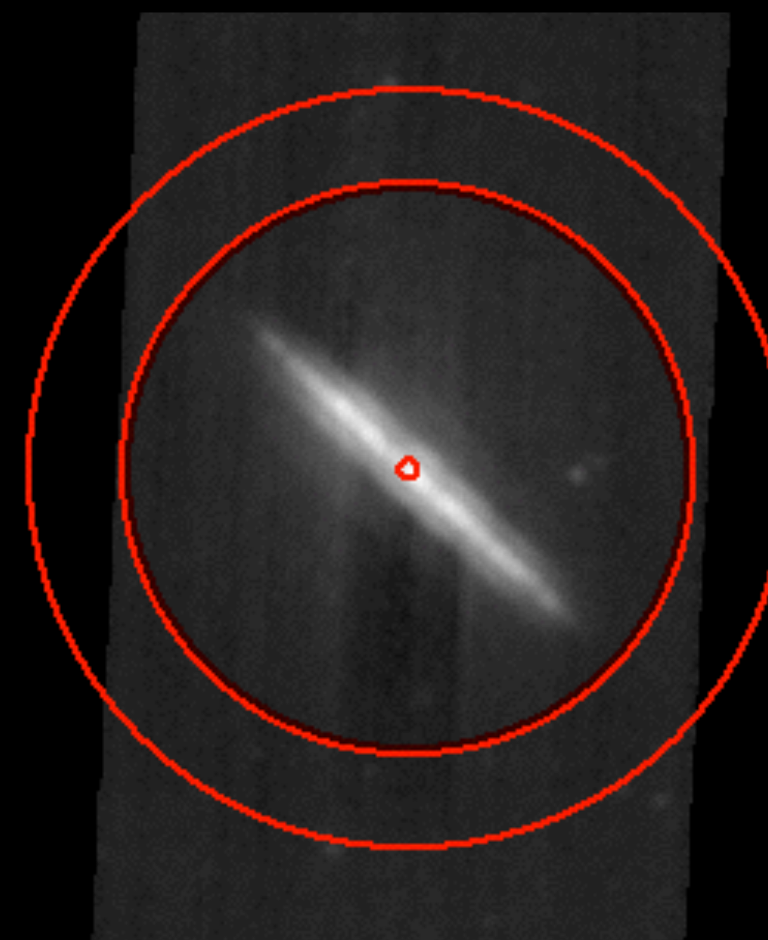


Bussmann et al. 2008

Either to map gas emission

or

to match IR with beam



MALATANG

co-PI: Yu Gao, Zhiyu Zhang, Thomas Greve

JCMT 390 hrs large program

Mapping HCN/HCO+ J=4-3 in ~20 nearby star-forming galaxies.

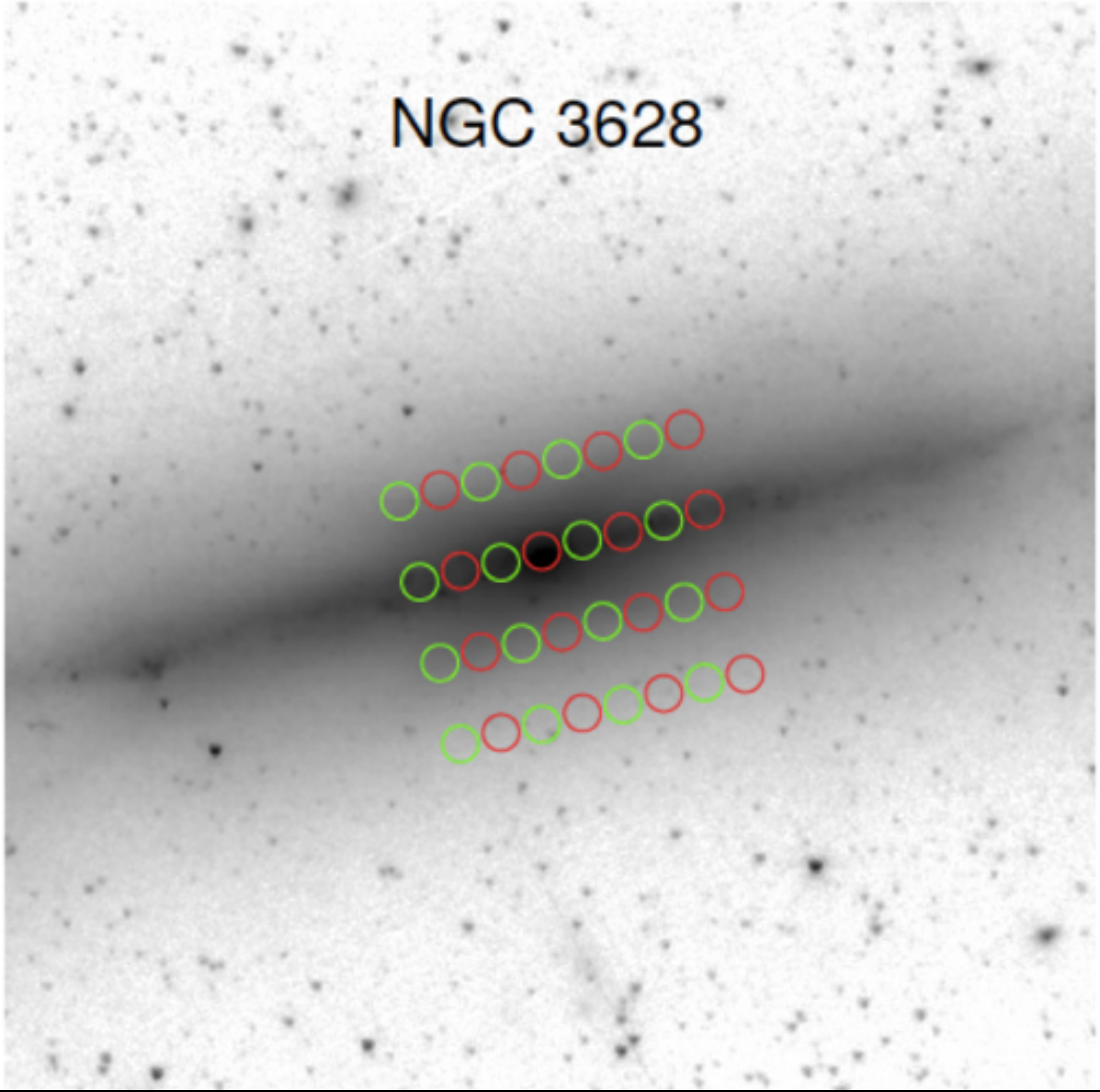
Synergy with Herschel FTS high-J CO and excitation modelling.

Characterising the physical/chemical conditions and excitations of the SF units probed by HCN/HCO+

Dense gas emission on disks and arms.

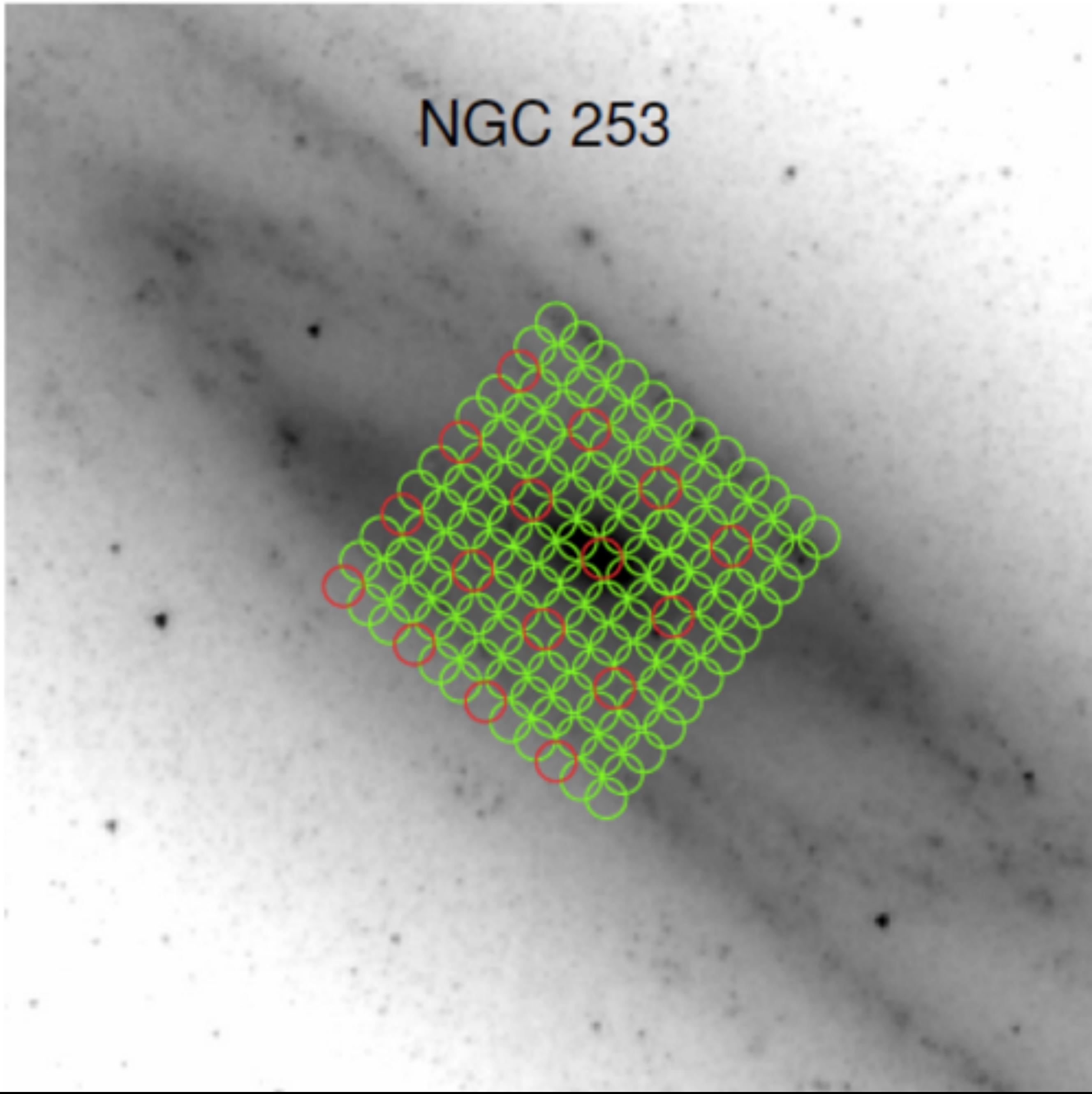
Grid mode

Mostly for edge-on galaxies

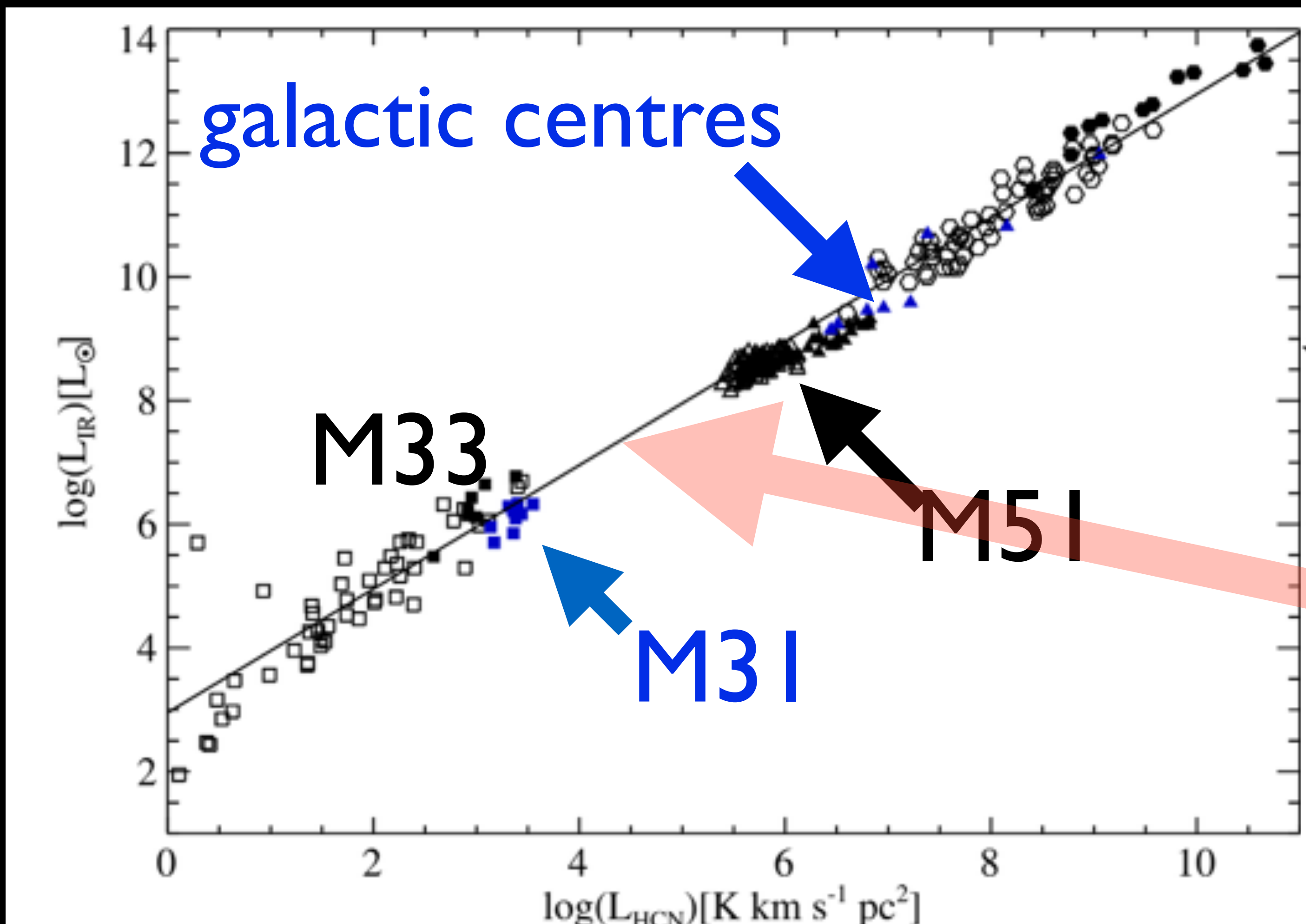


Jiggle mode

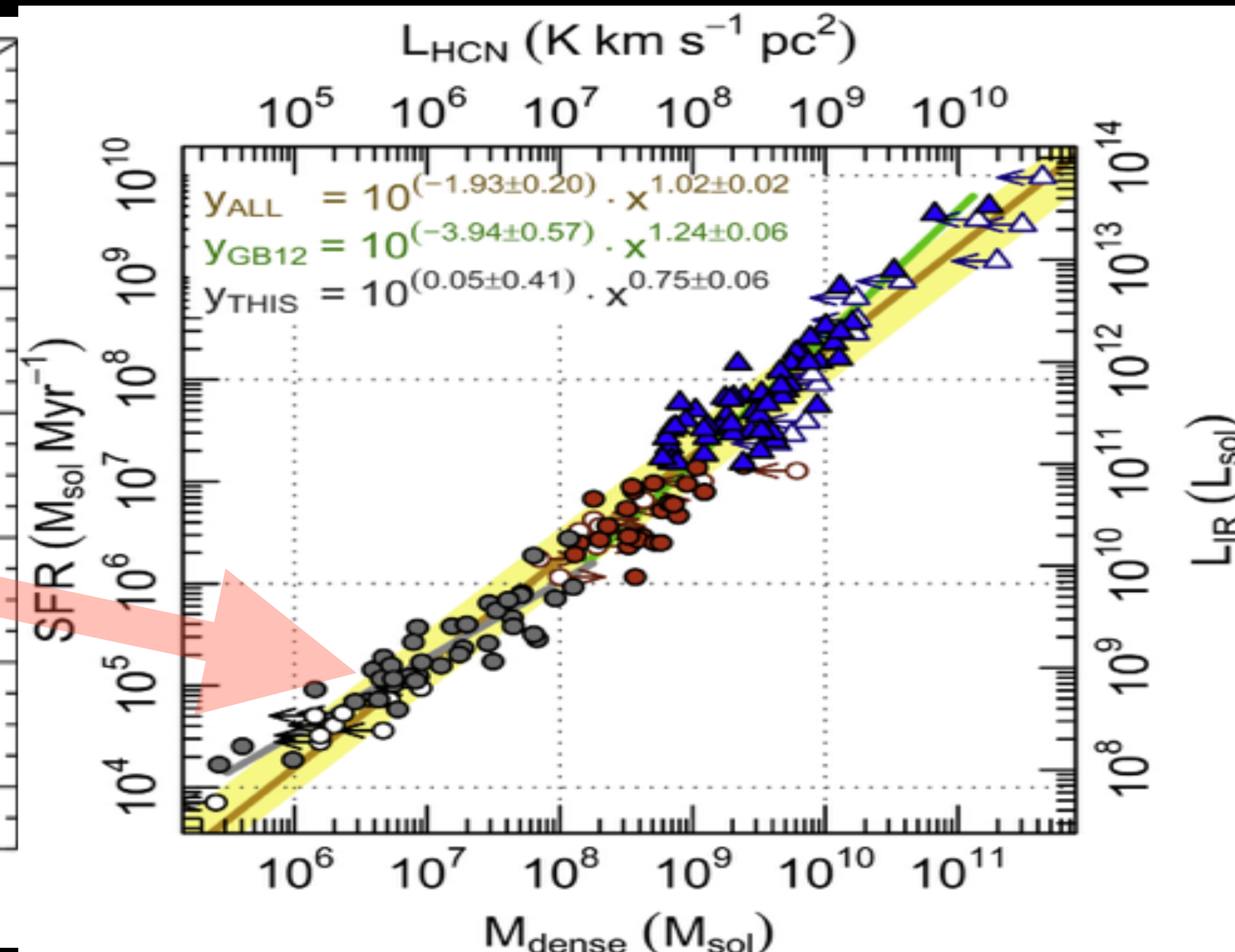
Mostly for face-on/large galaxies



Different mode of star formation on disks?



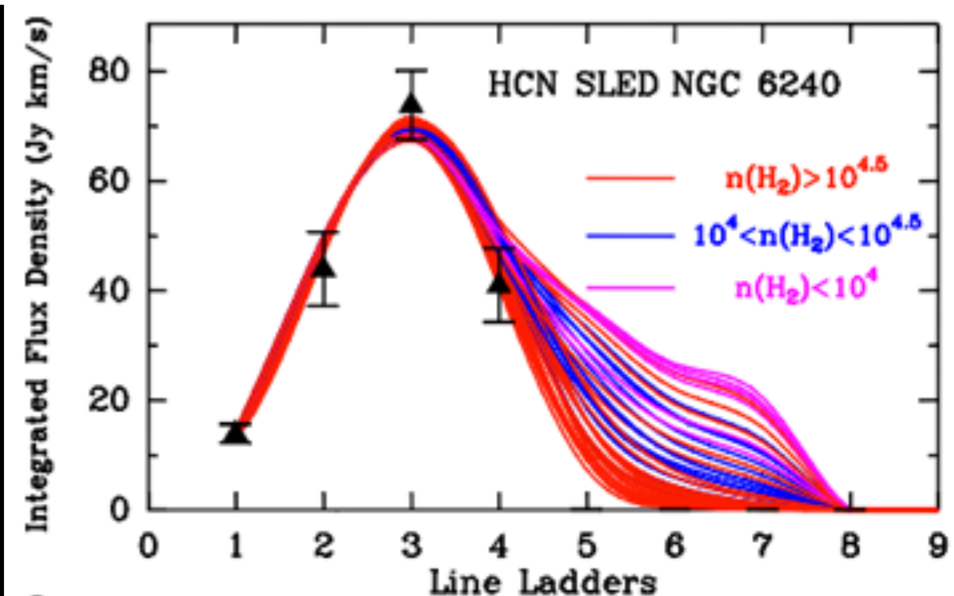
Chen et al. 2015

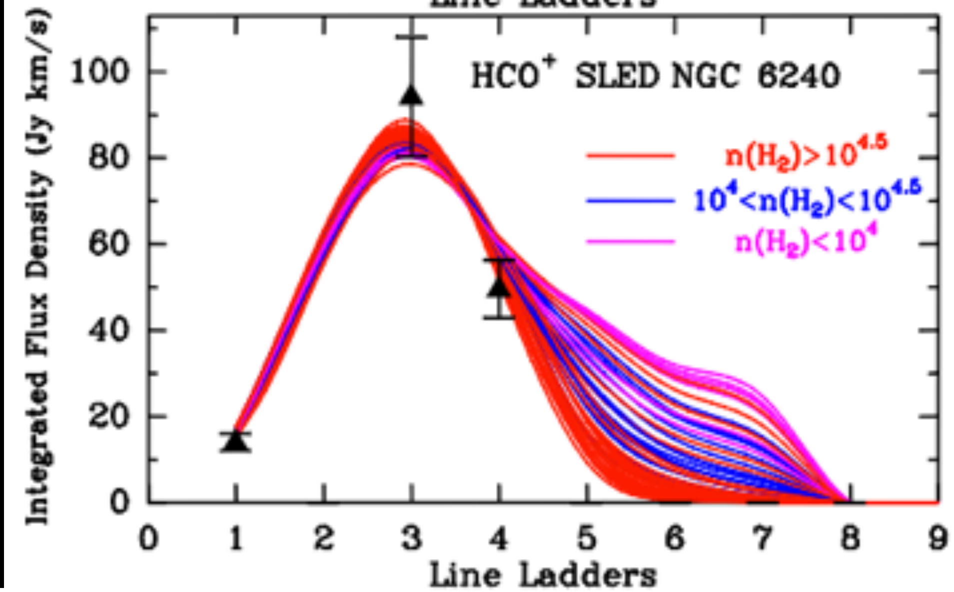


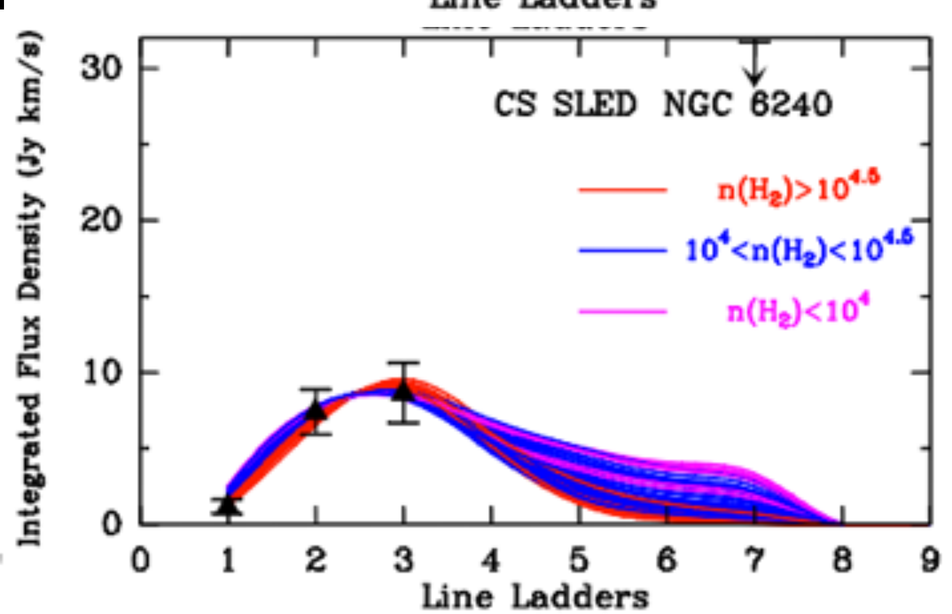
Usero et al. 2015

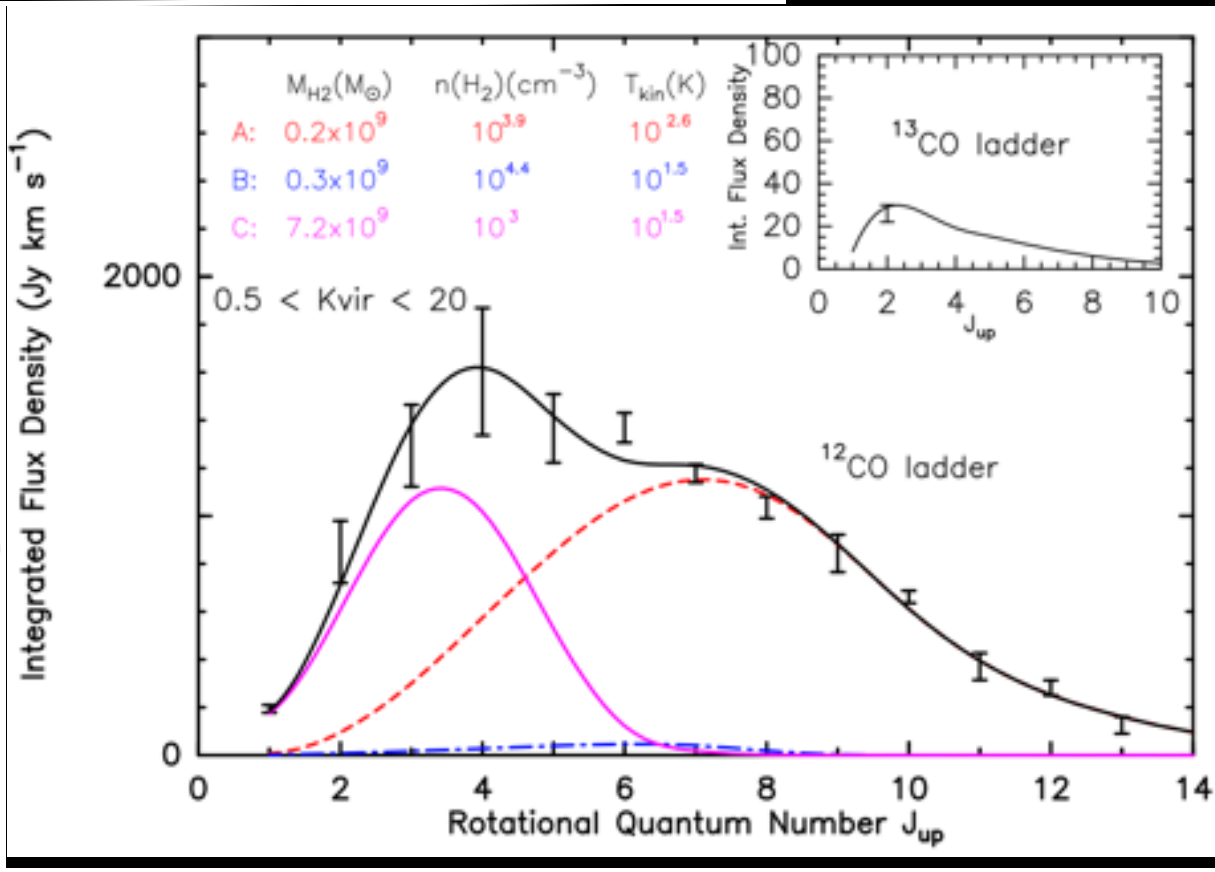
MALATANG will give the answers.

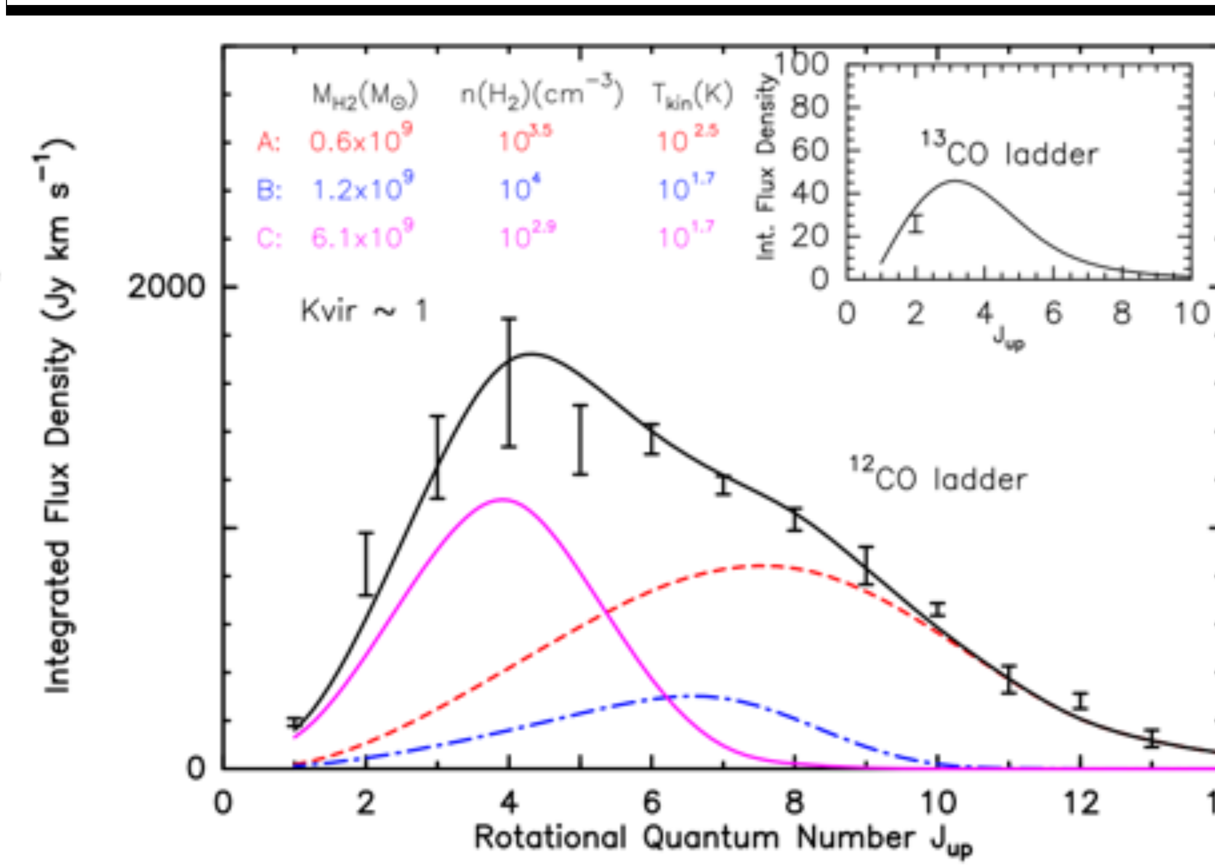
Synergy the HCN/HCO+ SLEDs with CO











Papadopoulos + 2014


Thank you!

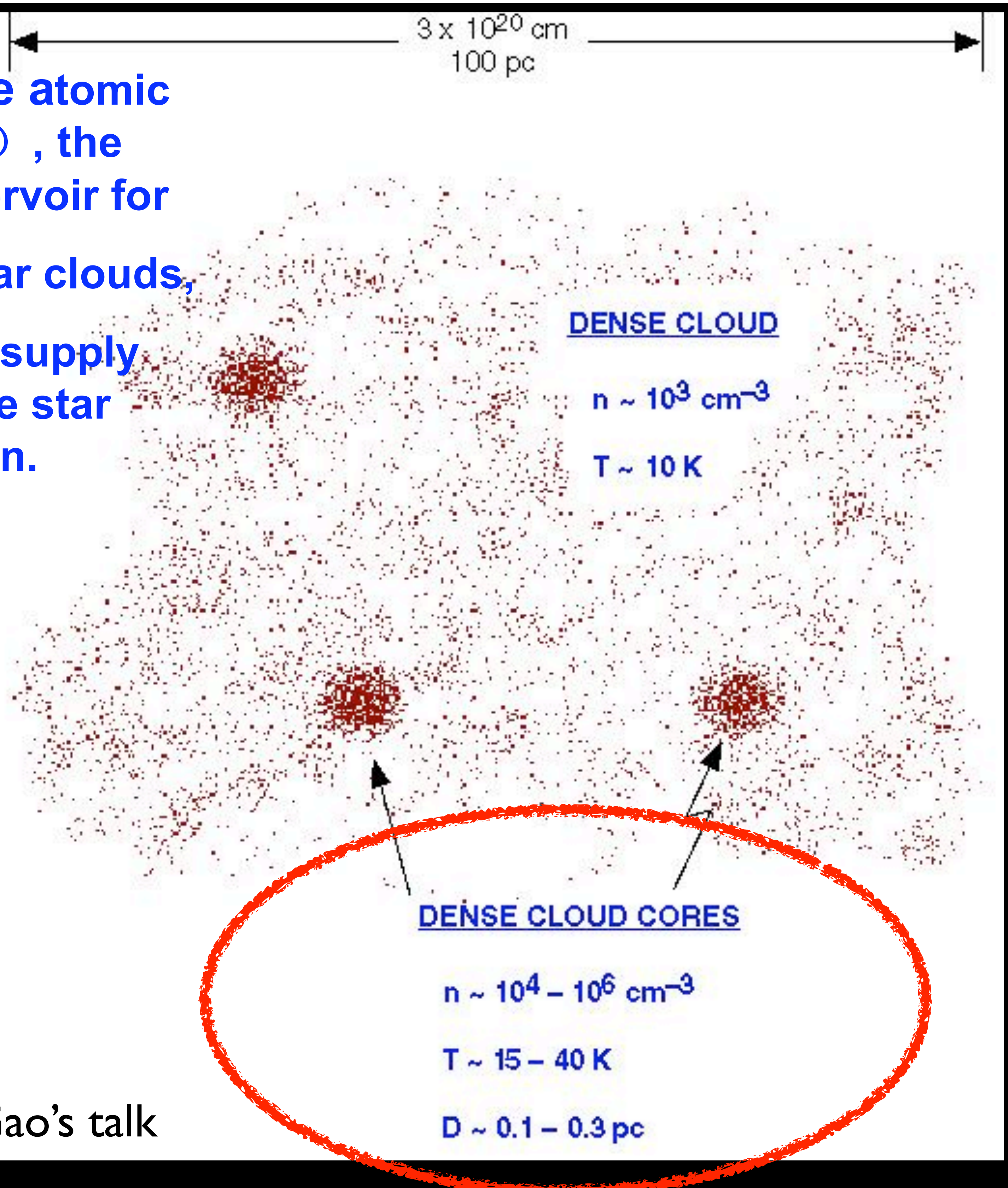
Background: Gymnastic music

ALMA will be helpful!

Stars are forming in dense molecular gas cores

Diffuse atomic gas（HI）, the gas reservoir for molecular clouds, And the supply for future star formation.

PDRs



from Y. Gao’s talk

GMCs:

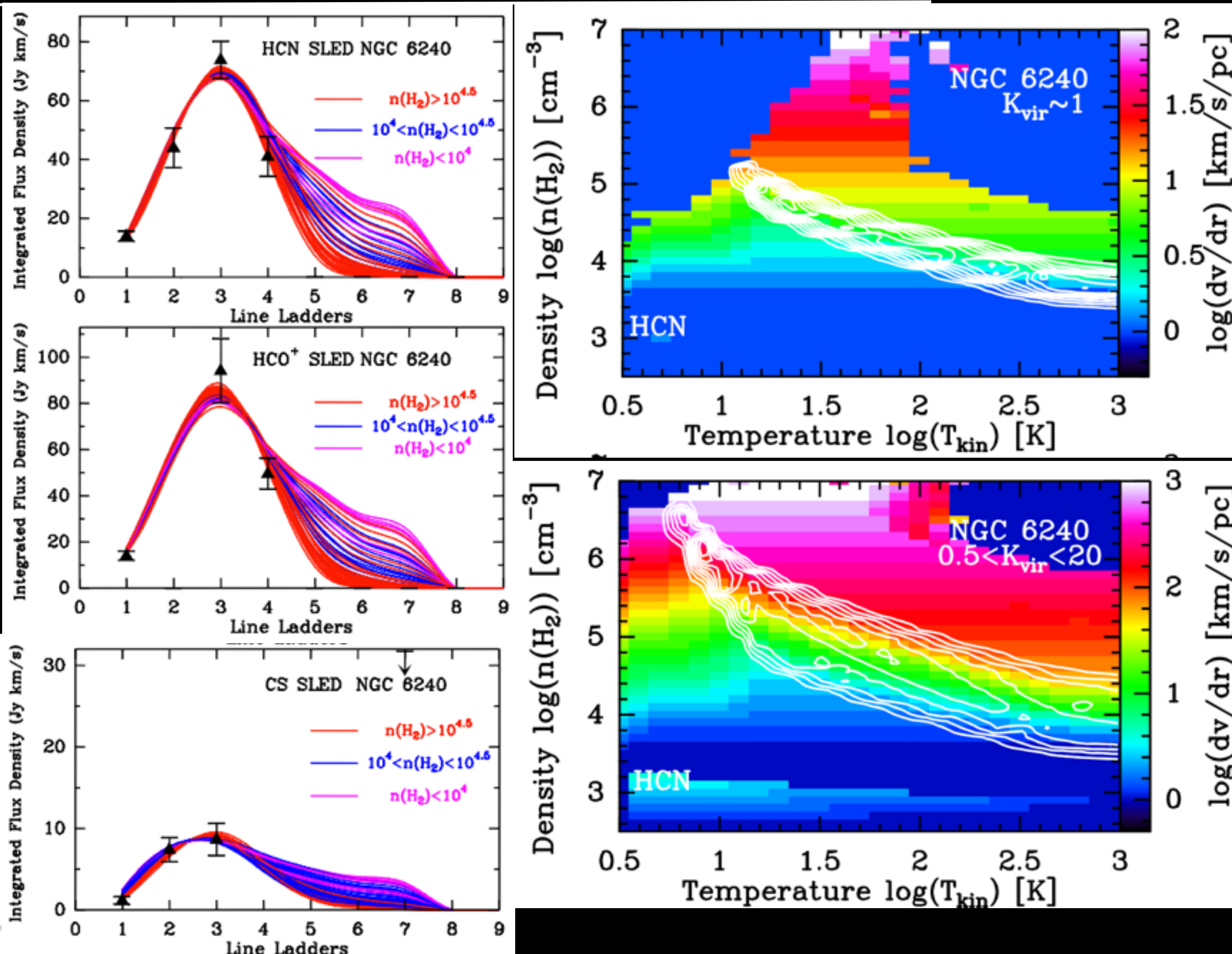
$n(H_2)$ ~ 10^2-10^3 cm^{-3}
T_{kin} ~ 10 - 20 K
D ~ 10- 100 pc

Dense cores:

$n(H_2)$ ~ 10^4-10^6 cm^{-3}
T_{kin} ~ 15 - 100 K
D ~ 0.1- 0.3 pc
self-gravity bound

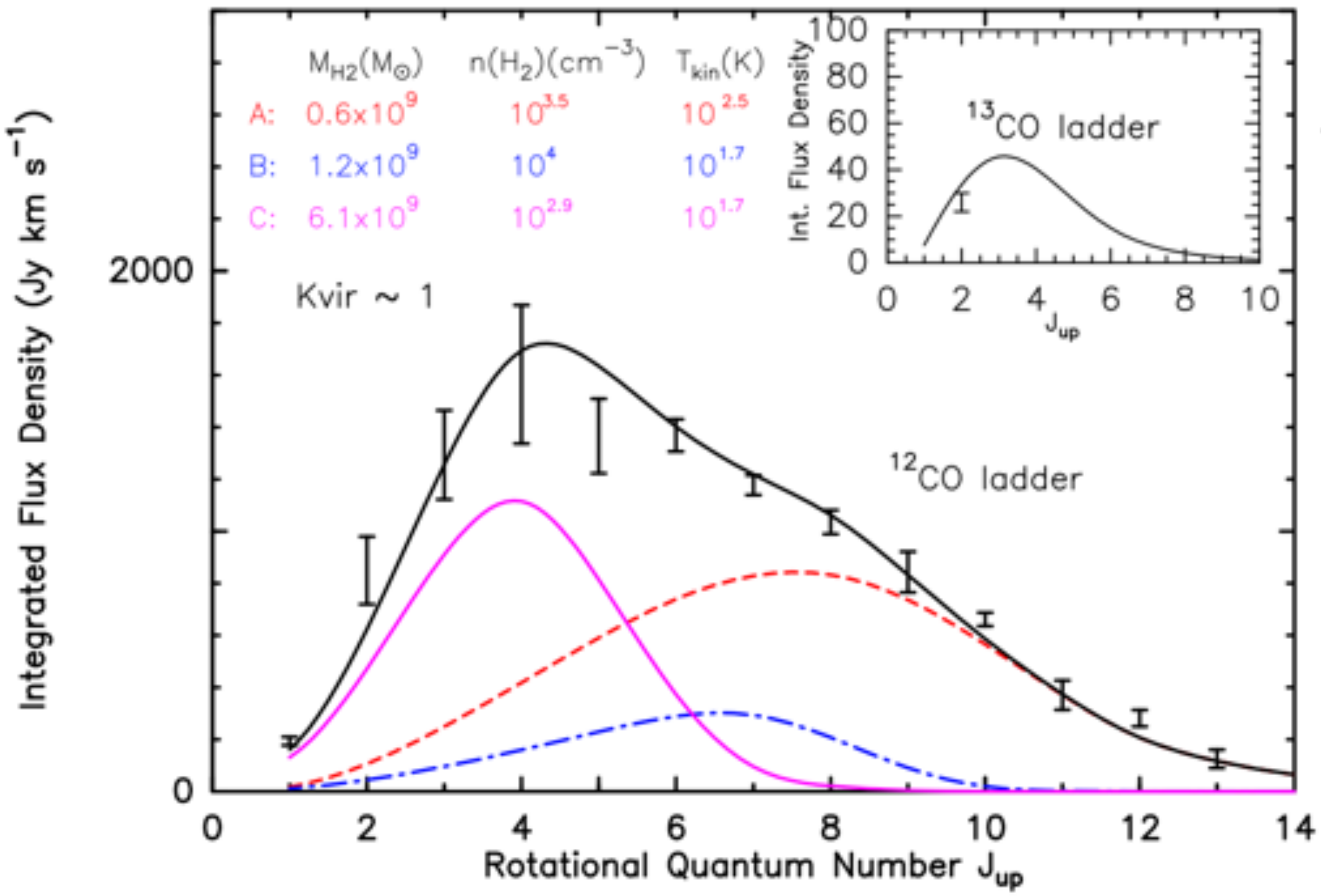
Backup Slides

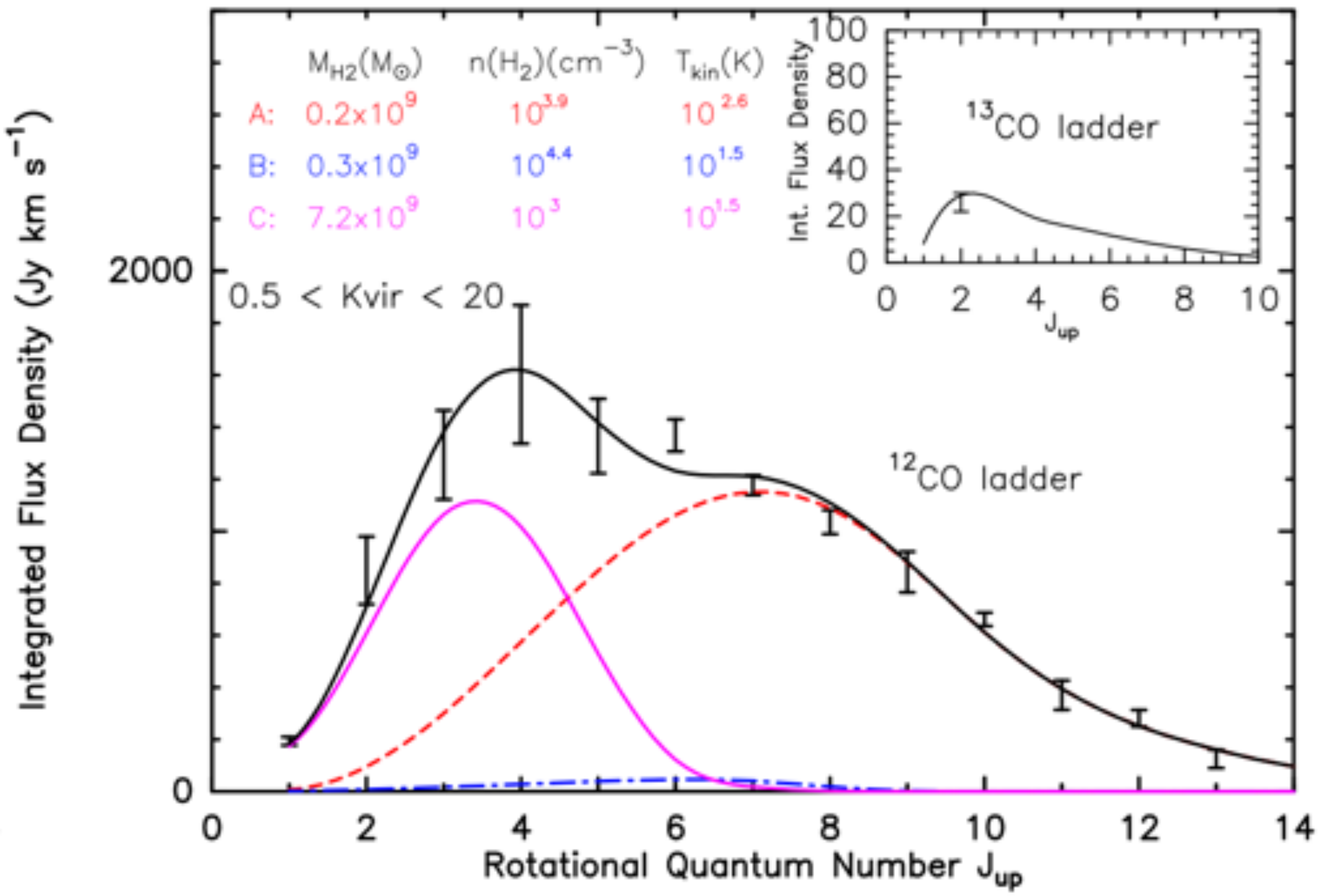
LVG+ML/Bayesian Modelling with dense gas tracers and CO



Papadopoulos + 2014

Model high-J CO using LVG results of HCN (NGC 6240)





~60-70% of the molecular gas is in dense gas phase. The thermal state of molecular gases can not be maintained by FUV from PDRs.

Detailed LVG analysis will be done for the whole sample.

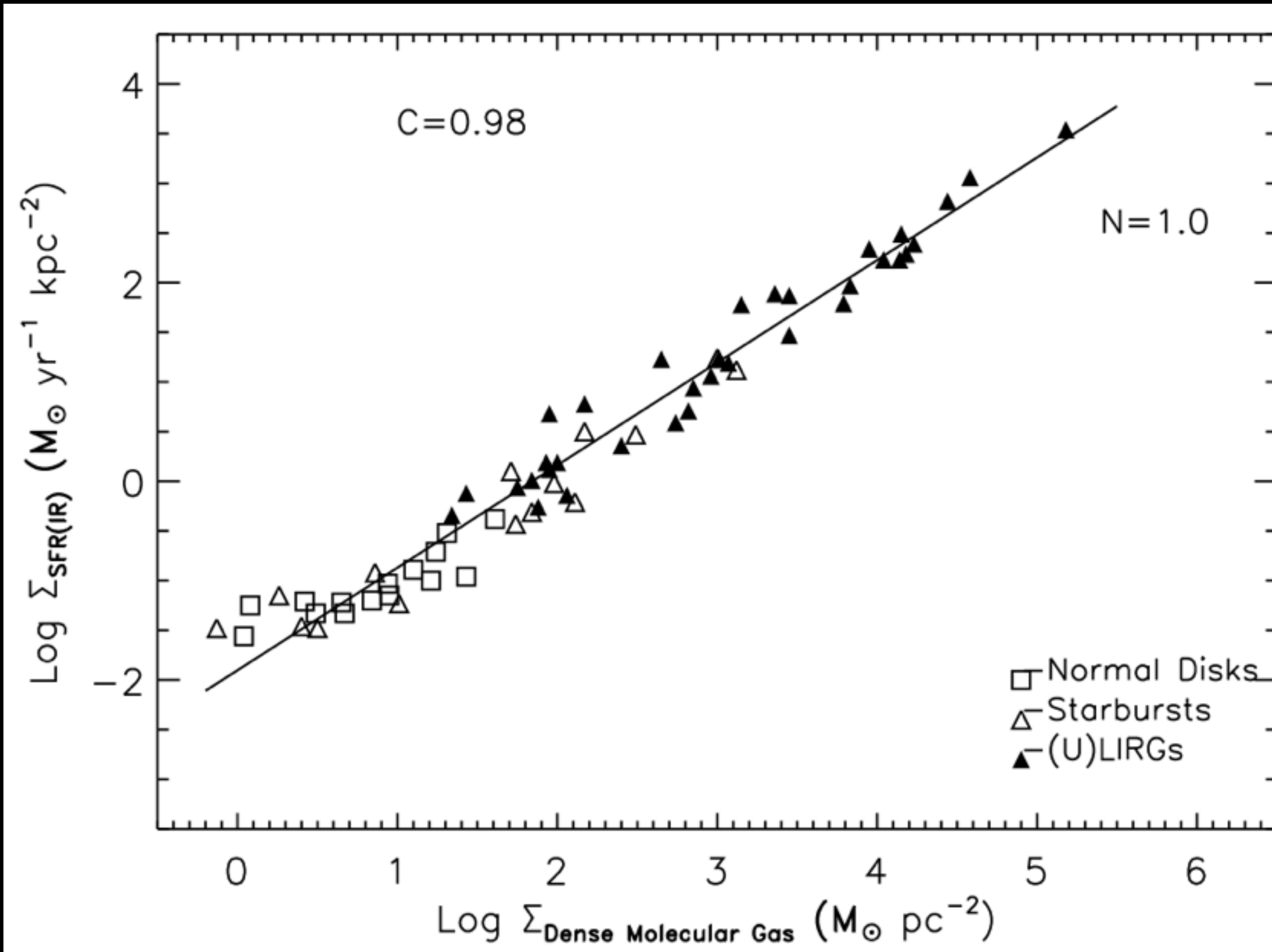
Caveats

L'_{dense} is a first order approximation of M_{dense}.

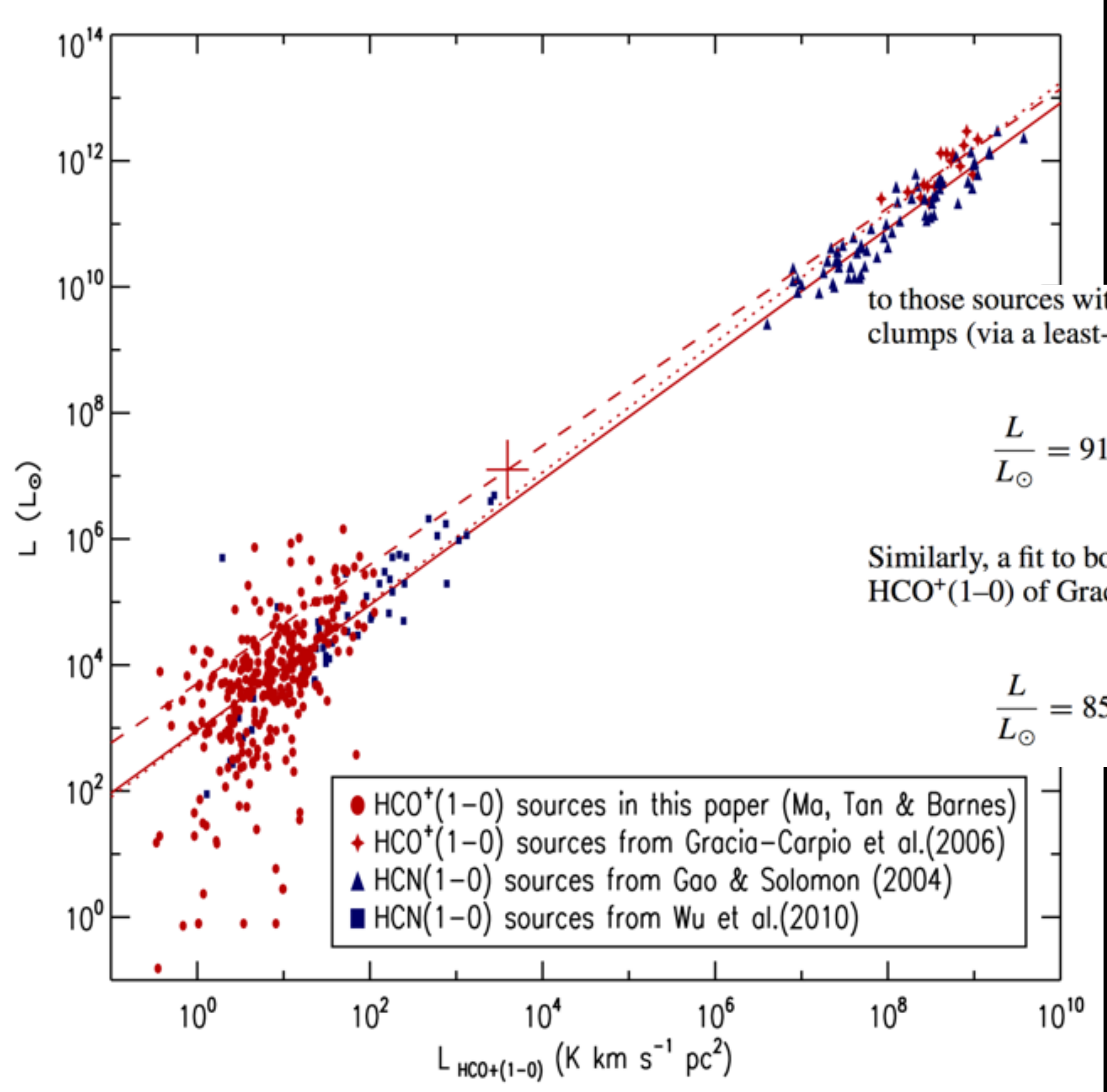
Detections of high n_{crit} lines do not necessarily mean that the gas densities are above n_{crit}, because they can be sub-thermally excited.

Analysis on excitation conditions is needed.

Surface density correlation of HCN -10



HCO+ J=1-0



to those sources with $L > 10^{1.5} L_\odot$). Only fitting to the CHaMP clumps (via a least-squares fit in log L) yields

$$\frac{L}{L_\odot} = 917\left(^{+208}_{-170}\right)\left(\frac{L_{\mathrm{HCO^+(1-0)}}}{\mathrm{K\ km\ s^{-1}pc^2}}\right)^{1.00\pm0.09}. \qquad (41)$$

Similarly, a fit to both the CHaMP sample and the extragalactic HCO+(1–0) of Graciá-Carpio et al. (2006) yields

$$\frac{L}{L_\odot} = 857\left(^{+105}_{-93}\right)\left(\frac{L_{\mathrm{HCO^+(1-0)}}}{\mathrm{K\ km\ s^{-1}pc^2}}\right)^{1.03\pm0.02}. \qquad (42)$$

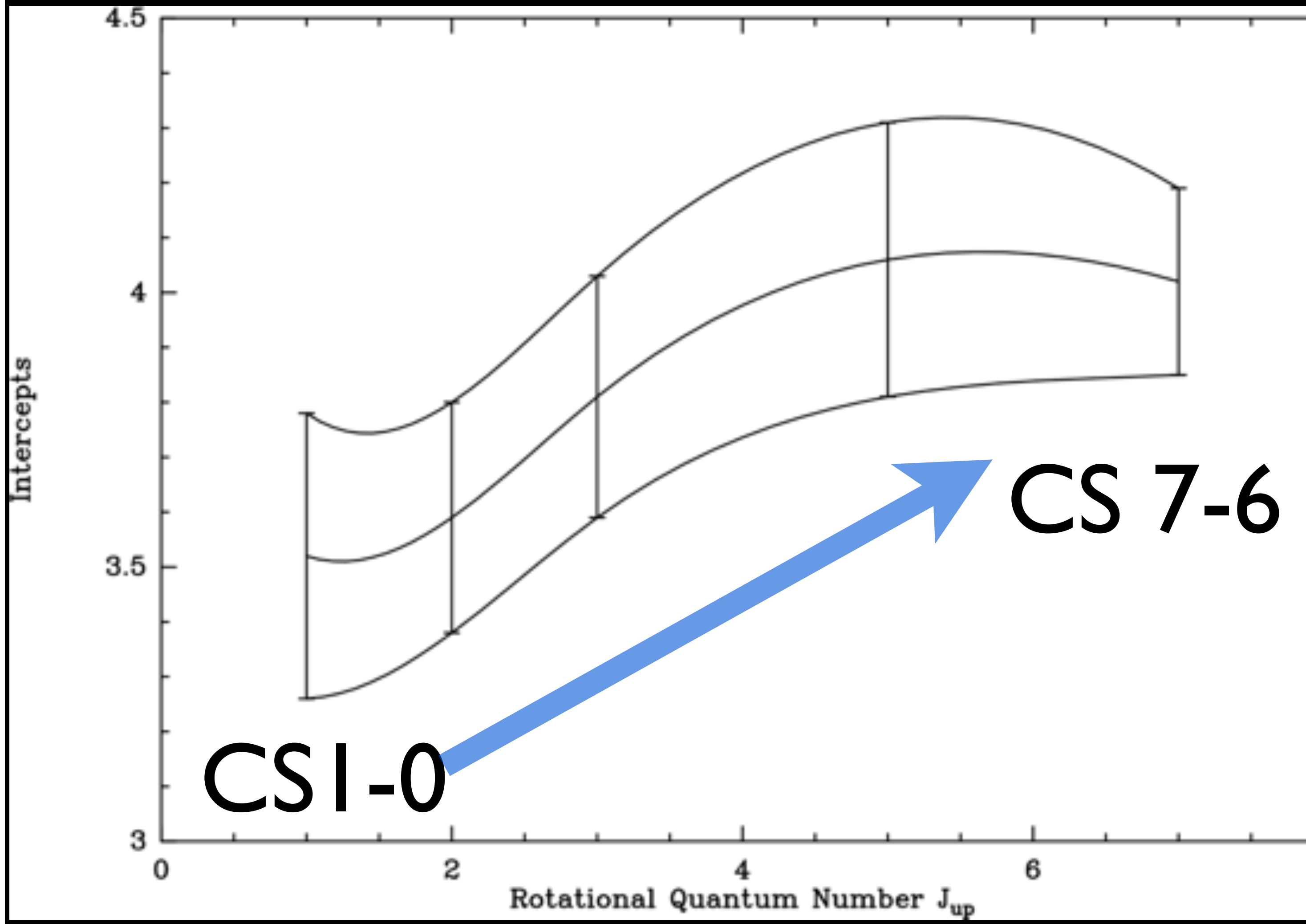
Ma et al. 2013

Fitting results

Table 3.8: Fitting parameters of the correlations of L'_{CS}-L_{IR}

Transition	Slope index	Intercepts	r^a	s^b
fitting without beam match correction				
CS J=1→0	0.71(0.10)	5.99(0.76)	0.82	0.31
CS J=2→1	0.88(0.05)	4.57(0.40)	0.94	0.24
CS J=3→2	0.83(0.05)	5.17(0.34)	0.93	0.26
CS J=5→4	0.69(0.06)	6.40(0.42)	0.91	0.25
CS J=7→6	0.68(0.08)	6.60(0.56)	0.89	0.33
fitting with beam match correction				
CS J=1→0	0.94(0.07)	3.96(0.52)	0.93	0.24
CS J=2→1	1.20(0.06)	1.95(0.44)	0.96	0.27
CS J=3→2	1.13(0.05)	2.80(0.34)	0.96	0.25
CS J=5→4	0.99(0.06)	4.11(0.44)	0.96	0.24
CS J=7→6	0.99(0.06)	4.06(0.43)	0.98	0.17
fitting with only point sources				
CS J=1→0	0.95(0.09)	3.93(0.69)	0.90	0.26
CS J=2→1	1.04(0.09)	3.30(0.72)	0.94	0.22
CS J=3→2	1.02(0.09)	3.67(0.69)	0.92	0.22
CS J=5→4	0.96(0.11)	4.33(0.80)	0.91	0.24

Intercept vs. J



sub-linear slope indices for uncorrected targets

linear correlations for point targets and beam matched targets

Aperture Correction -- beams are small

6: Parameters of the photometry.

Source name	CS2-1 (25″) 24Ratio	24Apercor	70Ratio	70Apercor	CS 3-2 (17″) 24Ratio	24Apercor	70Ratio	70Apercor
[illegible]	[illegible]	1.17	0.060	[illegible]	[illegible]	[illegible]	0.033	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	1.17	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
NGC3628	0.390	1.17	0.146	1.819	0.299	1.53	0.081	2.67
NGC3079	0.068	1.17	0.182	1.819	0.052	1.53	0.103	2.67
NGC0520	0.763	1.17	0.359	1.819	0.600	1.53	0.206	2.67
NGC7479	0.697	1.17	0.228	1.819	0.550	1.53	0.134	2.67
NGC1530	1.	1.	1.	1.	1.	1.	1.	1.
NGC7771	0.465	1.17	0.201	1.819	0.364	1.53	0.110	2.67
NGC7469	1.	1.	1.	1.	1.	1.	1.	1.
NGC1614	1.	1.	1.	1.	1.	1.	1.	1.
NGC828	0.740	1.17	0.373	1.819	0.530	1.53	0.213	2.67
ARP193	1.	1.	1.	1.	1.	1.	1.	1.
UGC02369	1.	1.	1.	1.	1.	1.	1.	1.
NGC0695	1.	1.	1.	1.	1.	1.	1.	1.
M[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
M[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
U[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
U[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
M[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
IR[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
IR[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
IRAS10565	1.	1.	1.	1.	1.	1.	1.	1.
VIIZW31	1.	1.	1.	1.	1.	1.	1.	1.
IRAS23365	1.	1.	1.	1.	1.	1.	1.	1.

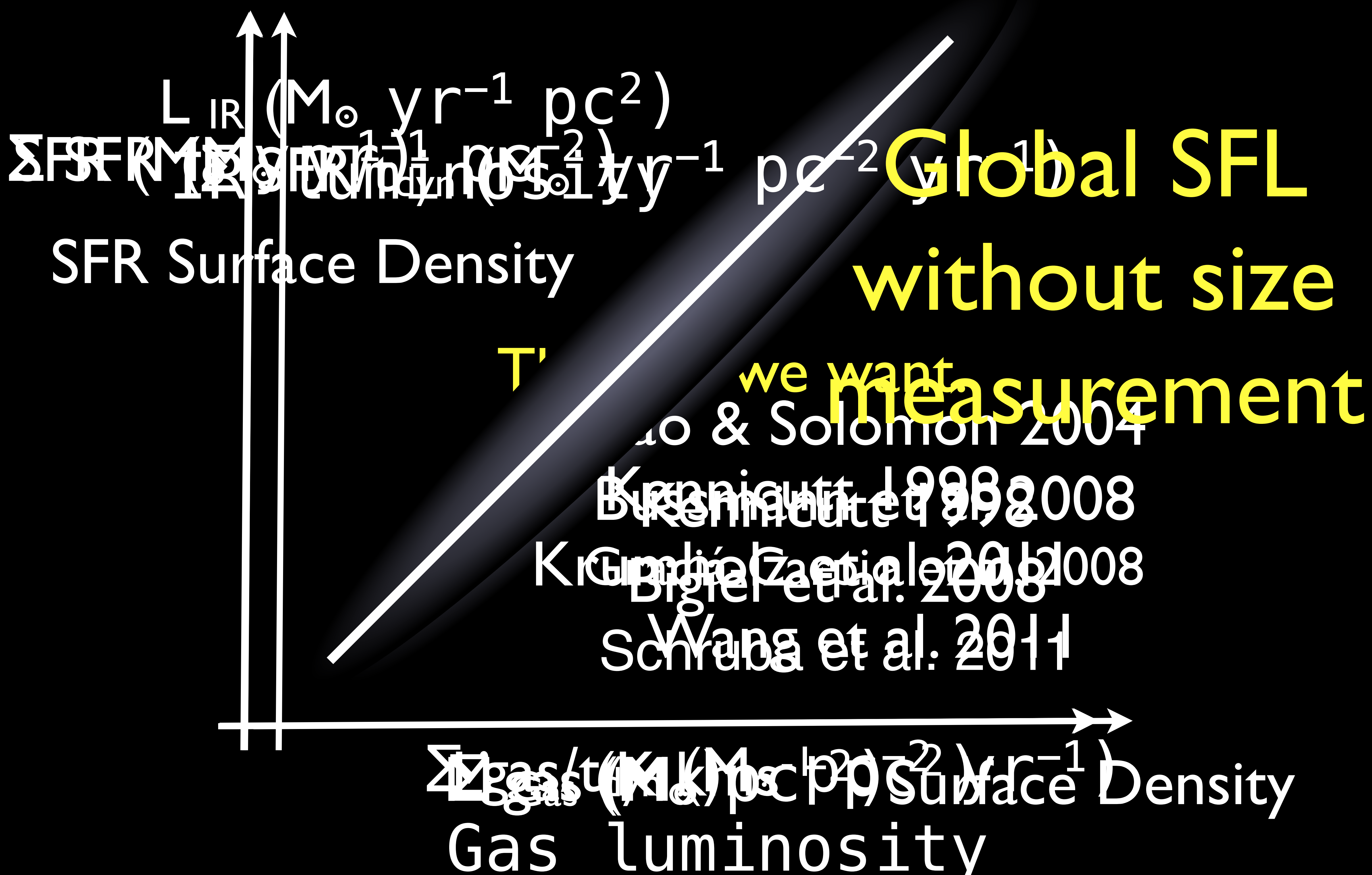
Convolution → Photometry → Aperture correction → Final flux

50K blackbody PSF

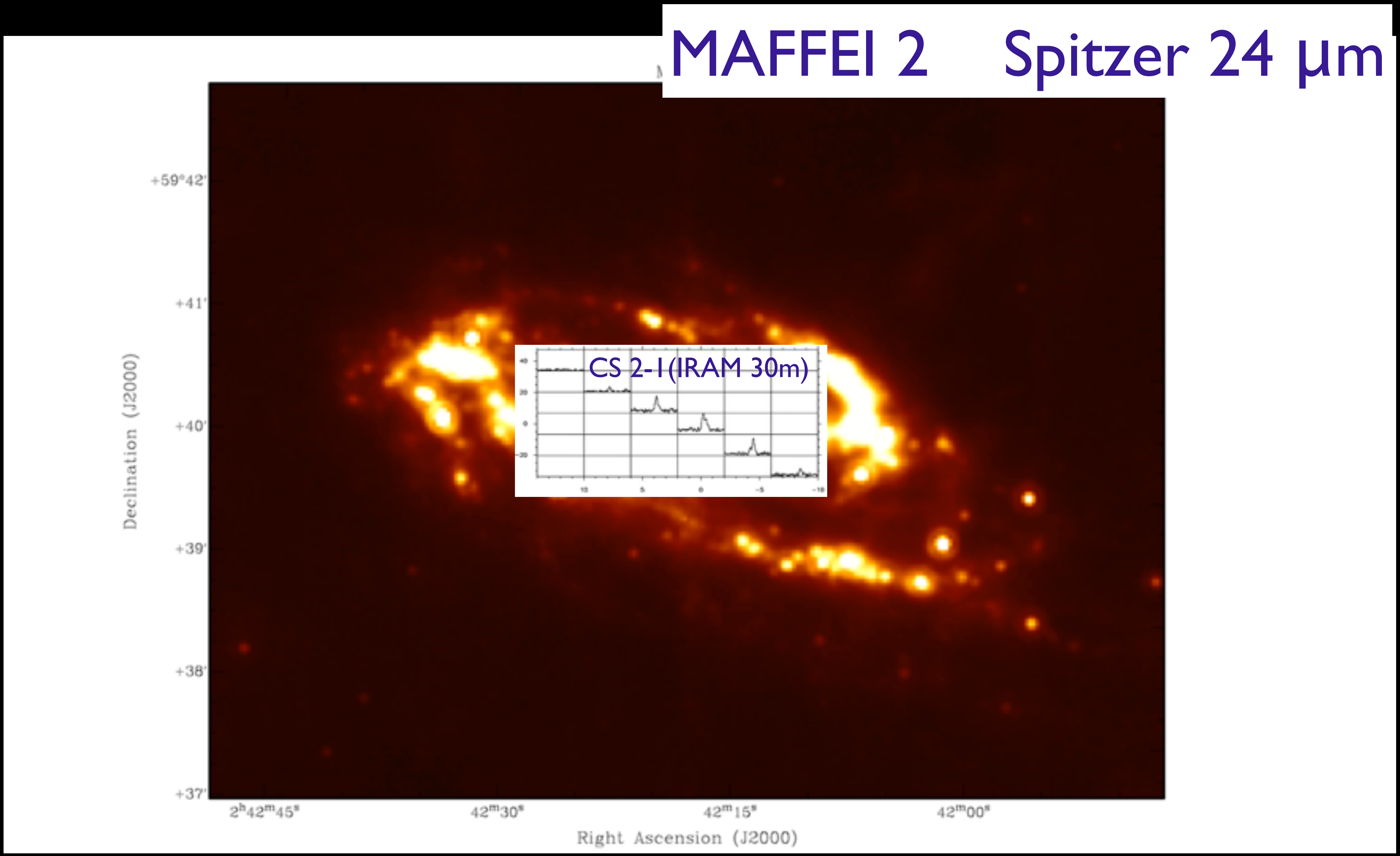
$$Flux_{beam}=F_{total} \times R_{beam/total} \times Aper_{corr}$$

The IR flux corresponding to CS beams are calculated with $Flux_{beam} = Flux_{gal} \times R_{beam/gal} \times Aper$, where $Flux_{beam}$ is the IR flux with in the CS beam, $Flux_{gal}$ is the IRAS flux of the total galaxies, $R_{beam/gal}$ is the ratio of the flux inside CS beam to the flux of the whole galaxies measured in the Spitzer MIPS 24μm or 70 μm images, and Aper is the aperture correction factor measured on the Spitzer MIPS PSF of a 50K blackbody for the corresponding beamsizes.

Star Formation Law (Units)



Extended CS emission on the disk



Dense gas tracers

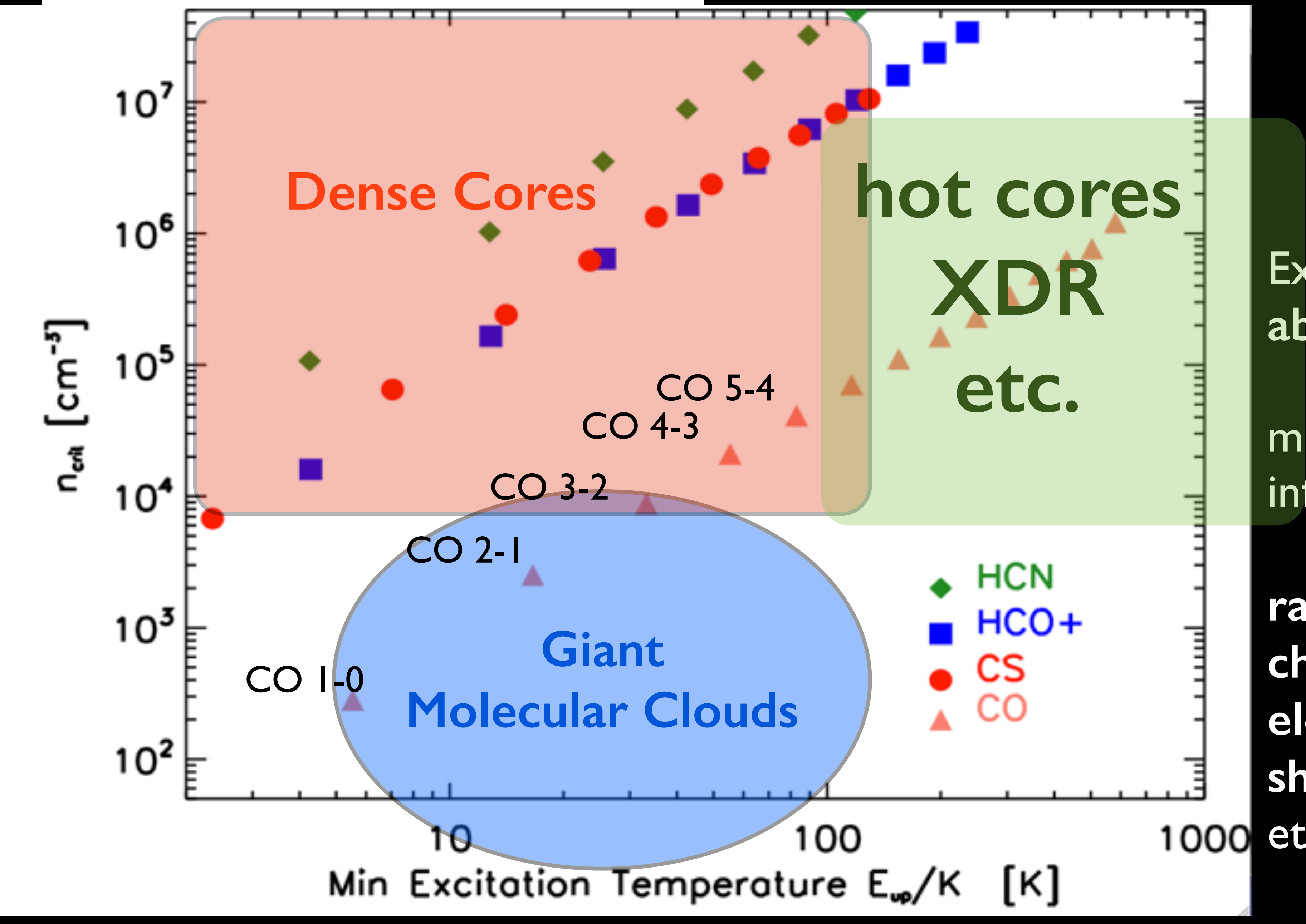
Critical Density:

$$n_{\rm crit} = \frac{\Sigma_{\rm l<u} A_{\rm ul}}{\Sigma_{\rm l\neq u} C_{\rm ul}}$$

Rotational transitions of heavy molecules

HCN, HCO+, CS, high-J CO etc.

Dense gas tracer: $n_{crit} > 10^4 cm^{-3}$

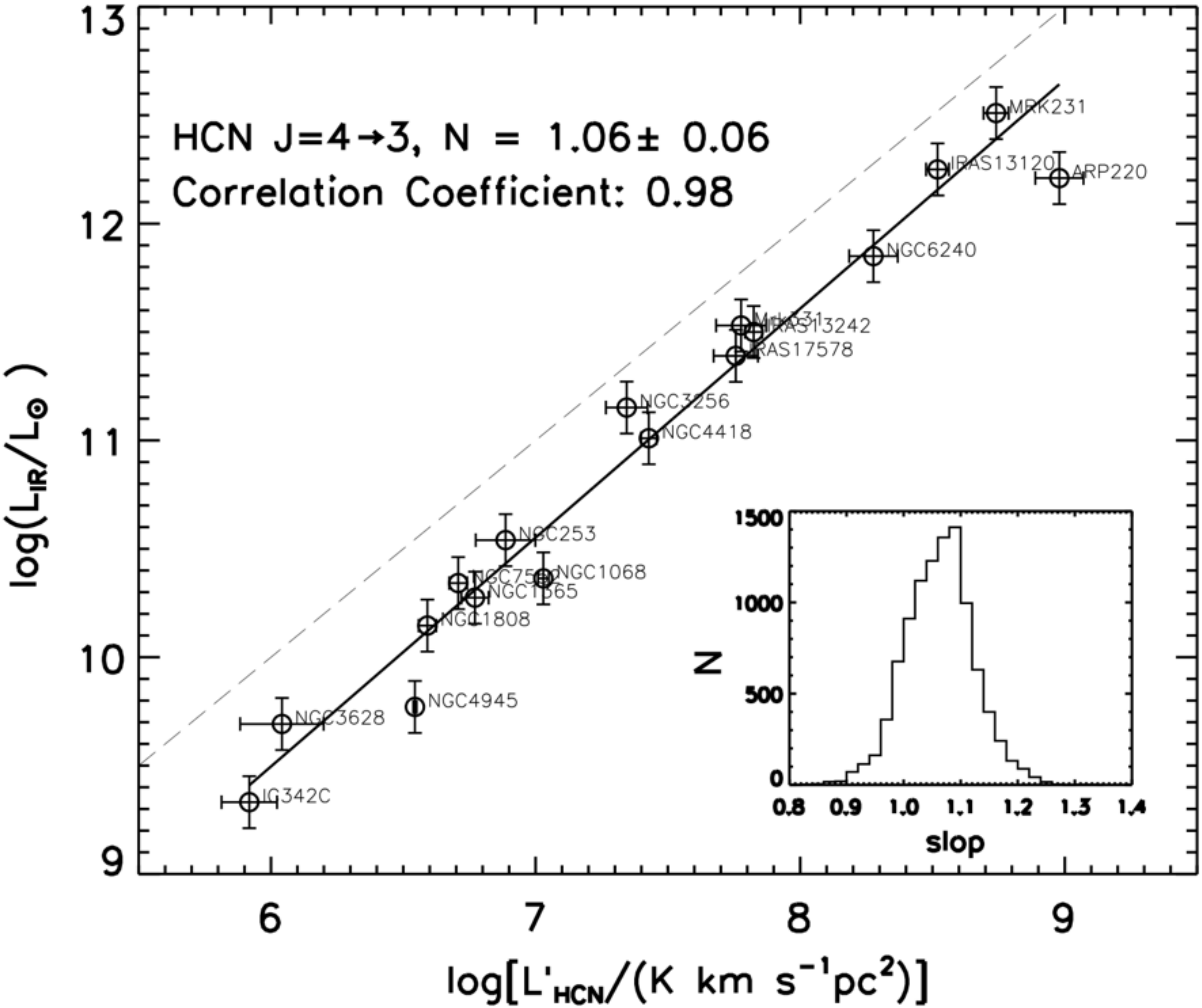


Except for
abundance and excitation,

molecular emissions can be influenced by:

radiative pumping,
chemistry,
electron density,
shock dissociation,
etc.

Molecule	Transitions J	Frequency (GHz)	E_{upper} (K)	$n_{\mathrm{crit}}(100\ \mathrm{K})$ ($\mathrm{cm^{-3}}$)	$A_{\mathrm{ul}}/\Gamma_{\mathrm{ul}}(100\ \mathrm{K})$ ($\mathrm{cm^{-3}}$)	$n_{\mathrm{crit}}(20\ \mathrm{K})$ ($\mathrm{cm^{-3}}$)	$A_{\mathrm{ul}}/\Gamma_{\mathrm{ul}}(20\ \mathrm{K})$ ($\mathrm{cm^{-3}}$)
CO	1→0	115.2711912	5.53	2.1×10^{2}	2.1×10^{3}	4.4×10^{2}	2.2×10^{3}
	2→1	230.5379938	16.60	1.9×10^{3}	2.2×10^{4}	3.6×10^{3}	2.3×10^{4}
	3→2	345.7959762	33.19	6.8×10^{3}	4.0×10^{4}	1.3×10^{4}	3.5×10^{4}
	4→3	461.0406784	55.32	1.6×10^{4}	6.1×10^{5}	3.0×10^{4}	1.2×10^{6}
	5→4	576.2679118	82.97	3.2×10^{4}	2.4×10^{5}	5.9×10^{4}	2.4×10^{5}
	6→5	691.4731878	116.16	5.4×10^{4}	3.1×10^{5}	1.0×10^{5}	2.7×10^{5}
	7→6	806.6514744	154.87	8.6×10^{4}	7.3×10^{5}	1.5×10^{5}	1.1×10^{6}
^{13}CO	1→0	110.20135428	5.29	1.8×10^{2}	1.8×10^{3}	3.7×10^{2}	1.9×10^{3}
	2→1	220.39868413	15.87	1.7×10^{3}	1.9×10^{4}	3.1×10^{3}	2.0×10^{4}
	3→2	330.58796522	31.73	5.9×10^{3}	3.5×10^{4}	1.1×10^{4}	3.4×10^{4}
$C^{18}O$	1→0	109.7821734	5.27	1.8×10^{2}	1.9×10^{3}	3.7×10^{2}	1.9×10^{3}
	2→1	219.5603541	15.81	1.7×10^{3}	2.0×10^{4}	3.1×10^{3}	1.9×10^{4}
	3→2	329.3305525	31.61	5.9×10^{3}	3.0×10^{4}	1.1×10^{4}	3.4×10^{4}
HCO^{+}	1→0	89.1885230	4.28	1.4×10^{4}	2.3×10^{5}	2.6×10^{4}	1.8×10^{5}
	2→1	178.3750650	12.84	1.4×10^{5}	4.6×10^{6}	2.6×10^{5}	3.4×10^{6}
	3→2	267.5576190	25.68	5.2×10^{6}	4.2×10^{6}	1.0×10^{6}	4.0×10^{6}
	4→3	356.7342880	42.80	1.3×10^{6}	5.8×10^{7}	2.5×10^{6}	4.0×10^{7}
CS	1→0	48.9909549	2.35	5.5×10^{3}	6.2×10^{4}	8.3×10^{3}	4.7×10^{4}
	2→1	97.9809533	7.05	5.3×10^{4}	5.2×10^{5}	7.9×10^{4}	6.0×10^{5}
	3→2	146.9690287	14.11	1.9×10^{5}	1.4×10^{6}	3.0×10^{5}	1.1×10^{6}
	4→3	195.9542109	23.51	4.8×10^{5}	2.7×10^{6}	7.7×10^{5}	3.3×10^{7}
	5→4	244.9355565	35.27	9.9×10^{5}	6.1×10^{6}	1.8×10^{6}	7.5×10^{6}
	6→5	293.9120865	49.37	1.7×10^{6}	1.2×10^{7}	3.1×10^{6}	1.1×10^{7}
	7→6	342.8828503	65.83	2.8×10^{6}	1.8×10^{8}	4.9×10^{6}	2.8×10^{8}



HCN J=4→3, N = 1.06± 0.06
Correlation Coefficient: 0.98
MRK231
IRAS13120
ARP220
NGC6240
IRAS13242
IRAS17578
NGC3256
NGC4418
NGC253
NGC1068
NGC1365
NGC1808
NGC4945
NGC3628
IC342C
log(L_IR/L_⊙)
log[L'_HCN/(K km s^-1pc^2)]
13
12
11
10
9
6
7
8
9
1500
1000
500
0
0.8
0.9
1.0
1.1
1.2
1.3
1.4
N
slop

HCO^+ deficient in extreme conditions??

Higher slopes for HCO^+ (only) in galaxies.

Gracia´- Carpio et al. 2006, 2008; Imanishi et al. 2007

Linear in Galactic cores, e.g., Ma et al. 2013

HCO^+ is an ionic molecule.

$$\mathbf{HCO^+ + e \rightarrow CO + H}$$

High radiation fields in ULIRGs

X-ray / Cosmic Rays => high n(e)

Papadopoulos et al. 2007

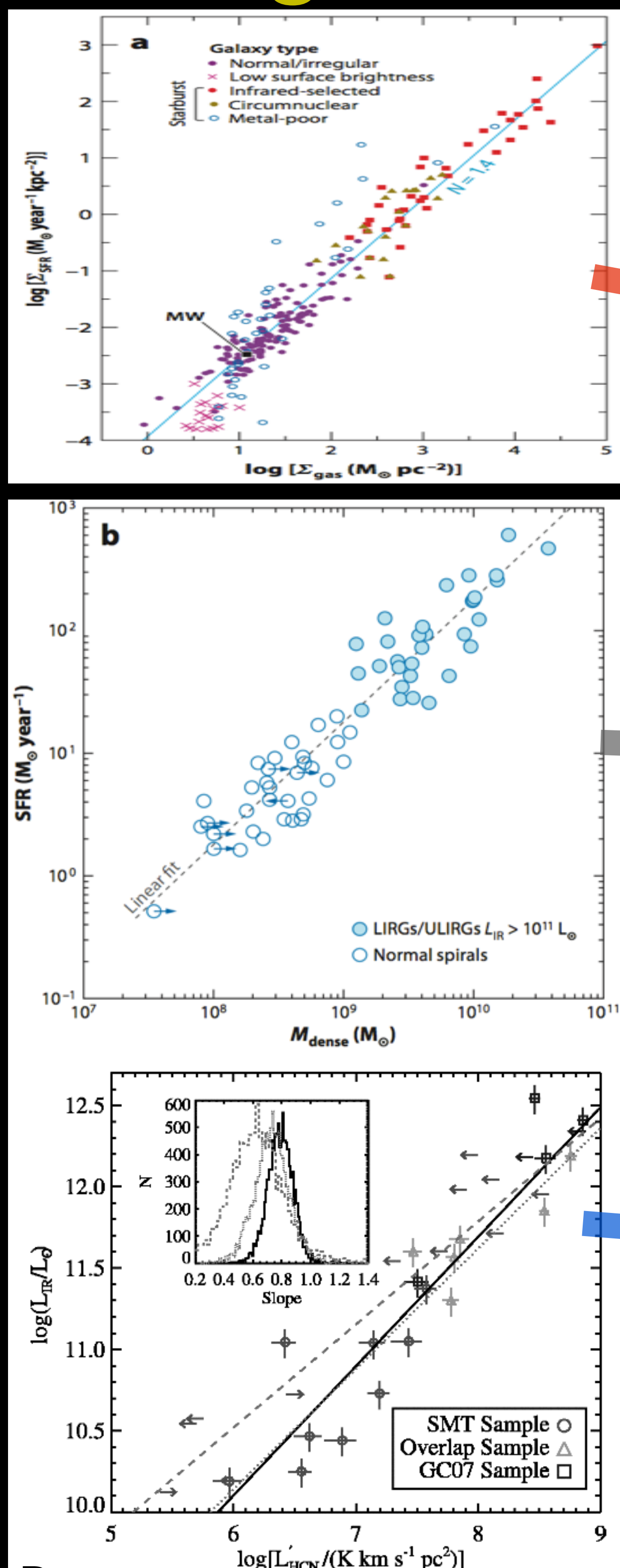
Shock environment

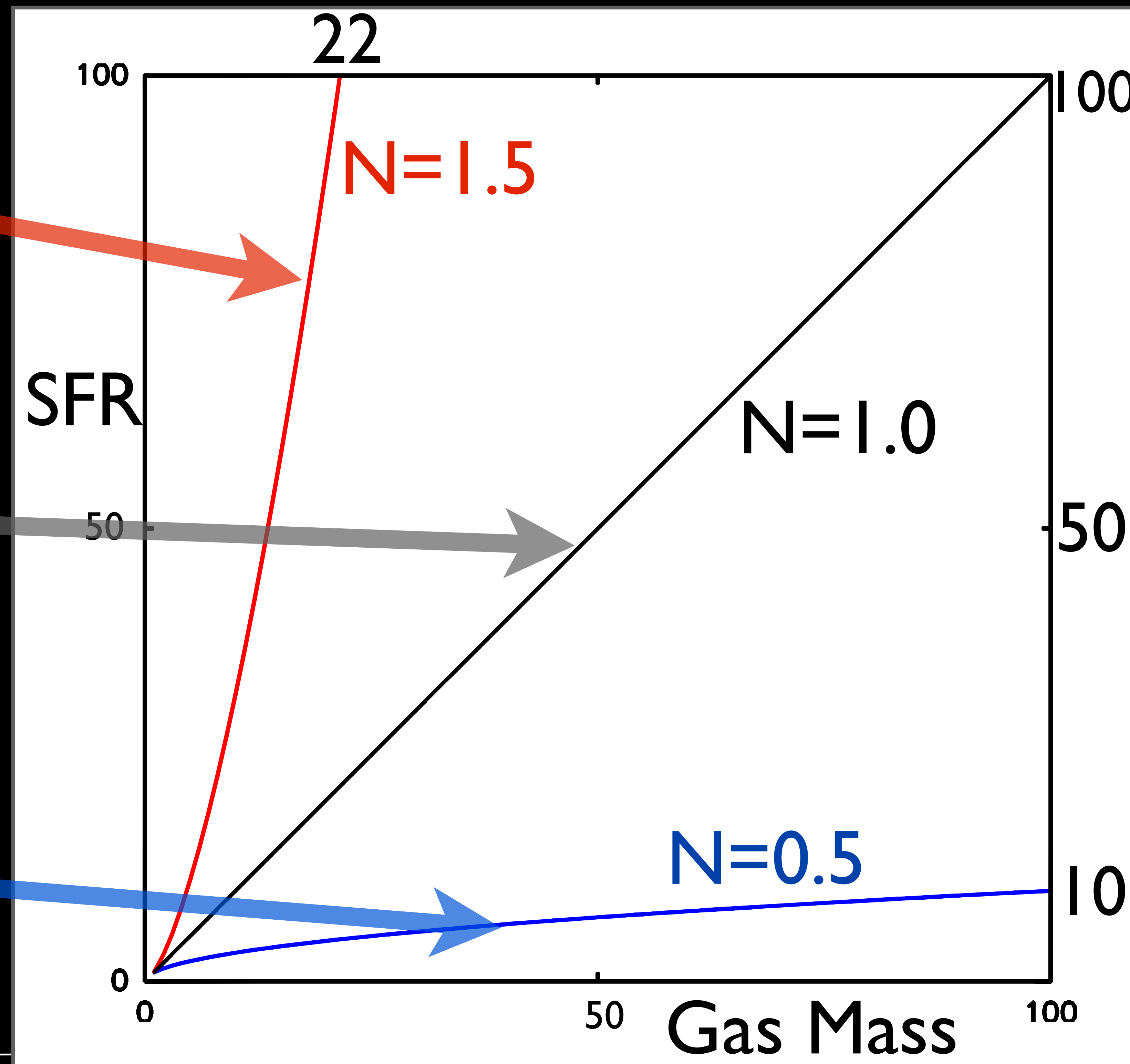
Shocks produce electron-rich outer layers

Xie et al. 1995

Why slopes matter? Different SFE

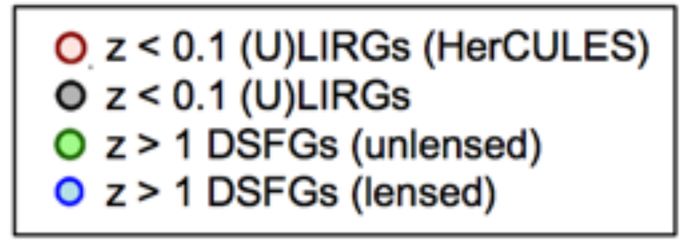
Which gases are forming stars?

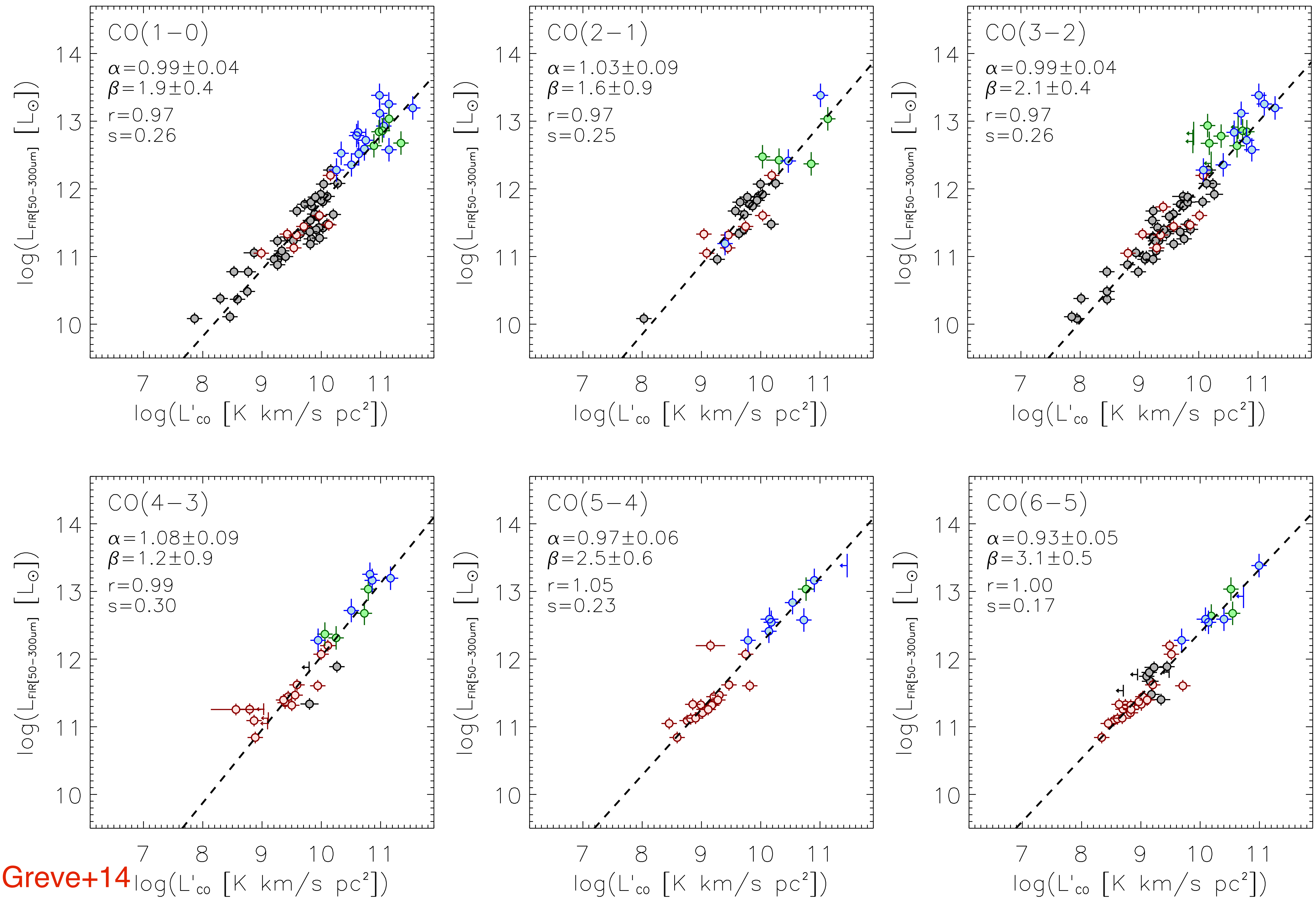




LIR-LCO relations

ULIRGs low/high-z

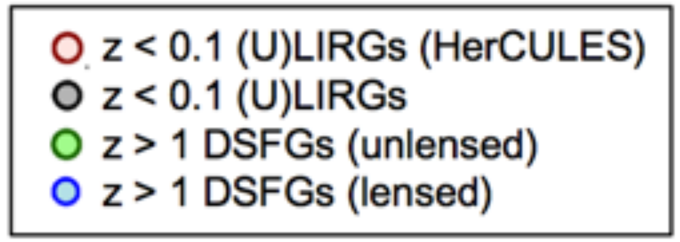


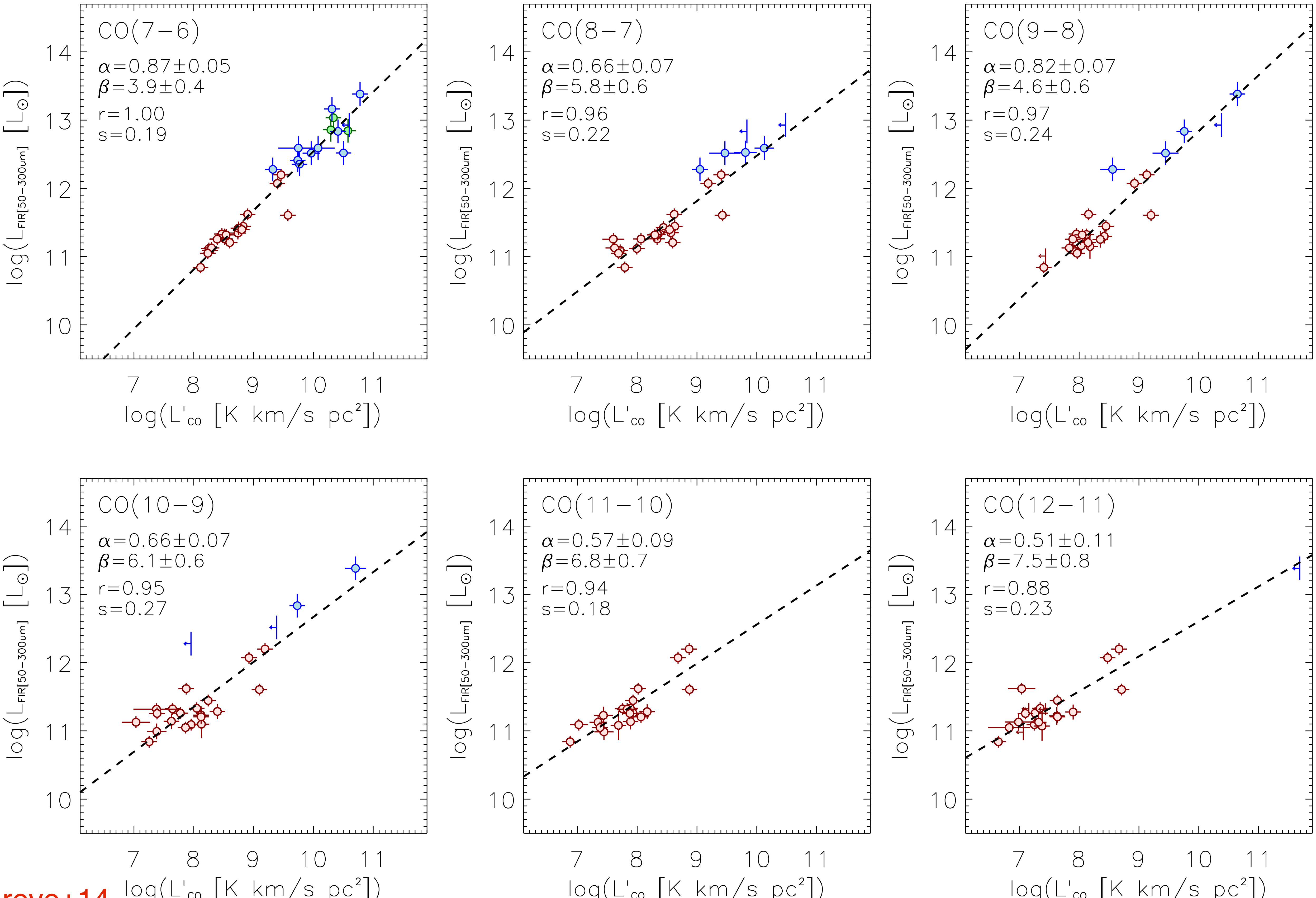


Greve+14

L_{IR}-L_{CO} relations

ULIRGs low/high-z





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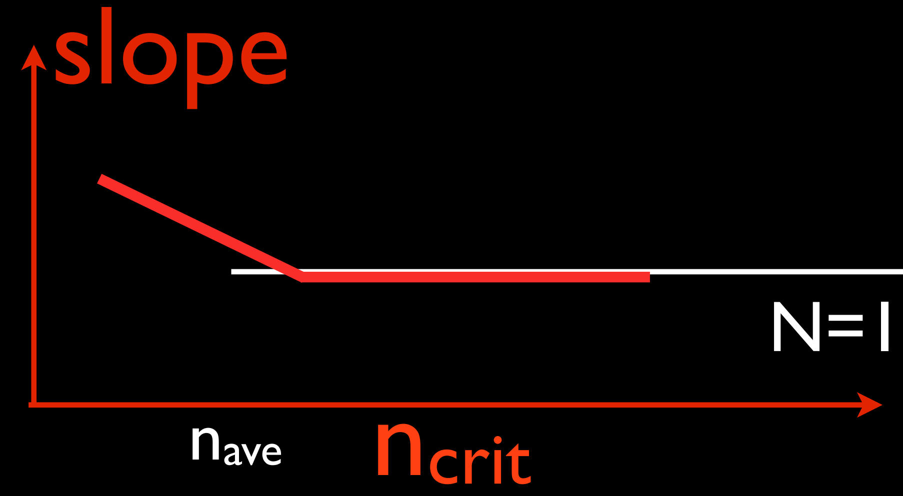
Theoretical works

1) Krumholz et al. (2007):

n_{crit} < n_{ave}: slope ~ 1.5 e.g., CO 1-0

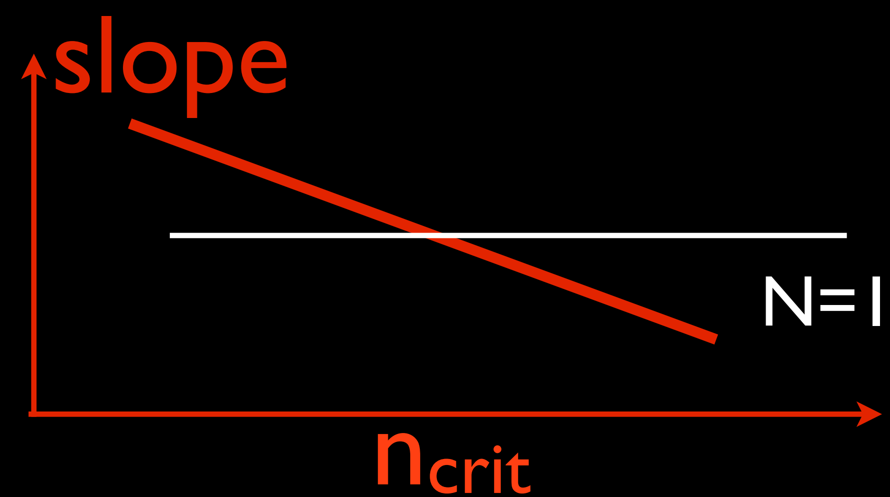
n_{crit} > n_{ave}: slope ~ 1 e.g., HCN 1-0



2) Narayanan et al. (2008):

Sub-thermal excitation.

Slope decreases with n_{crit}.

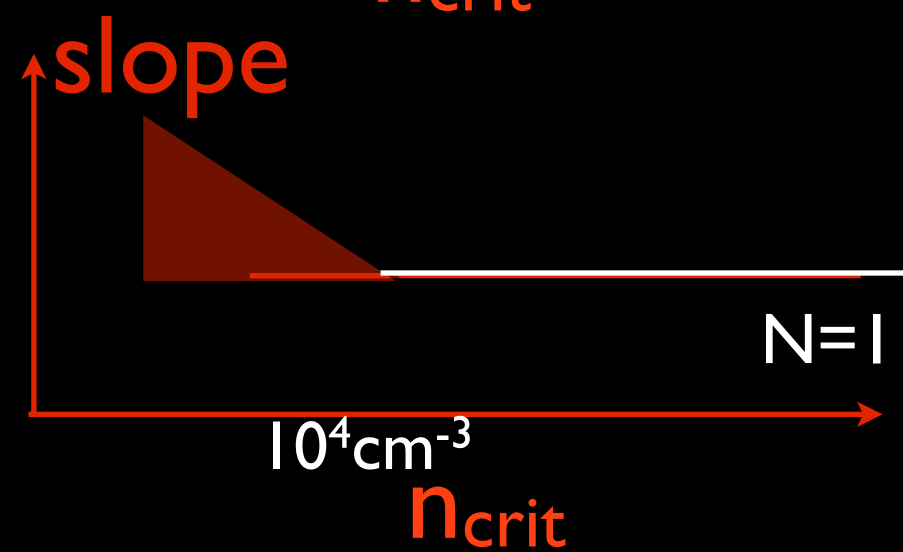


3) Lada et al. (2012):

Linear slope for lines with n_{crit} > $10^4 cm^{-3}$

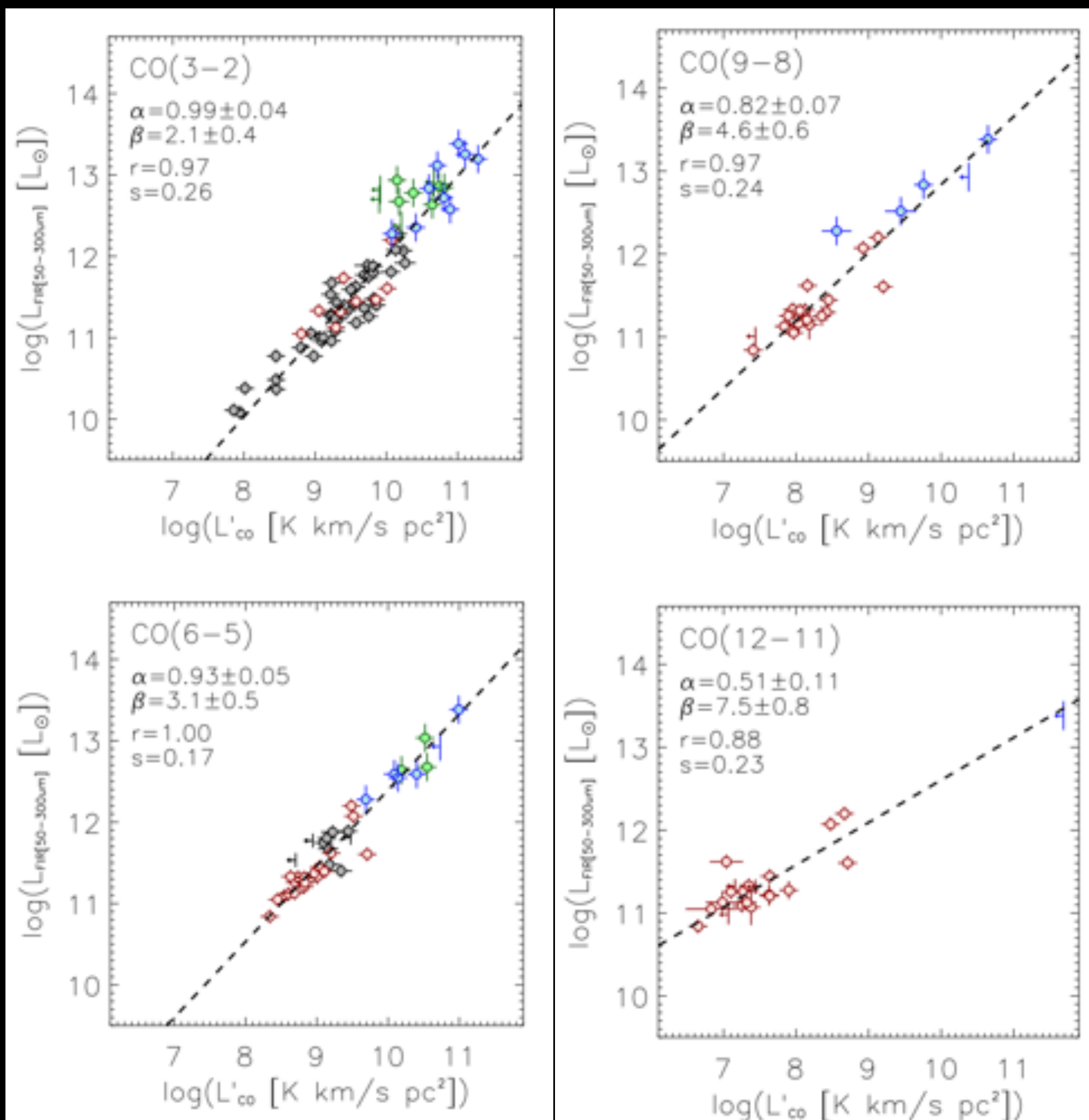
SFR is only related to M_{dense}.

K-S law slope is related to M_{dense} fraction.

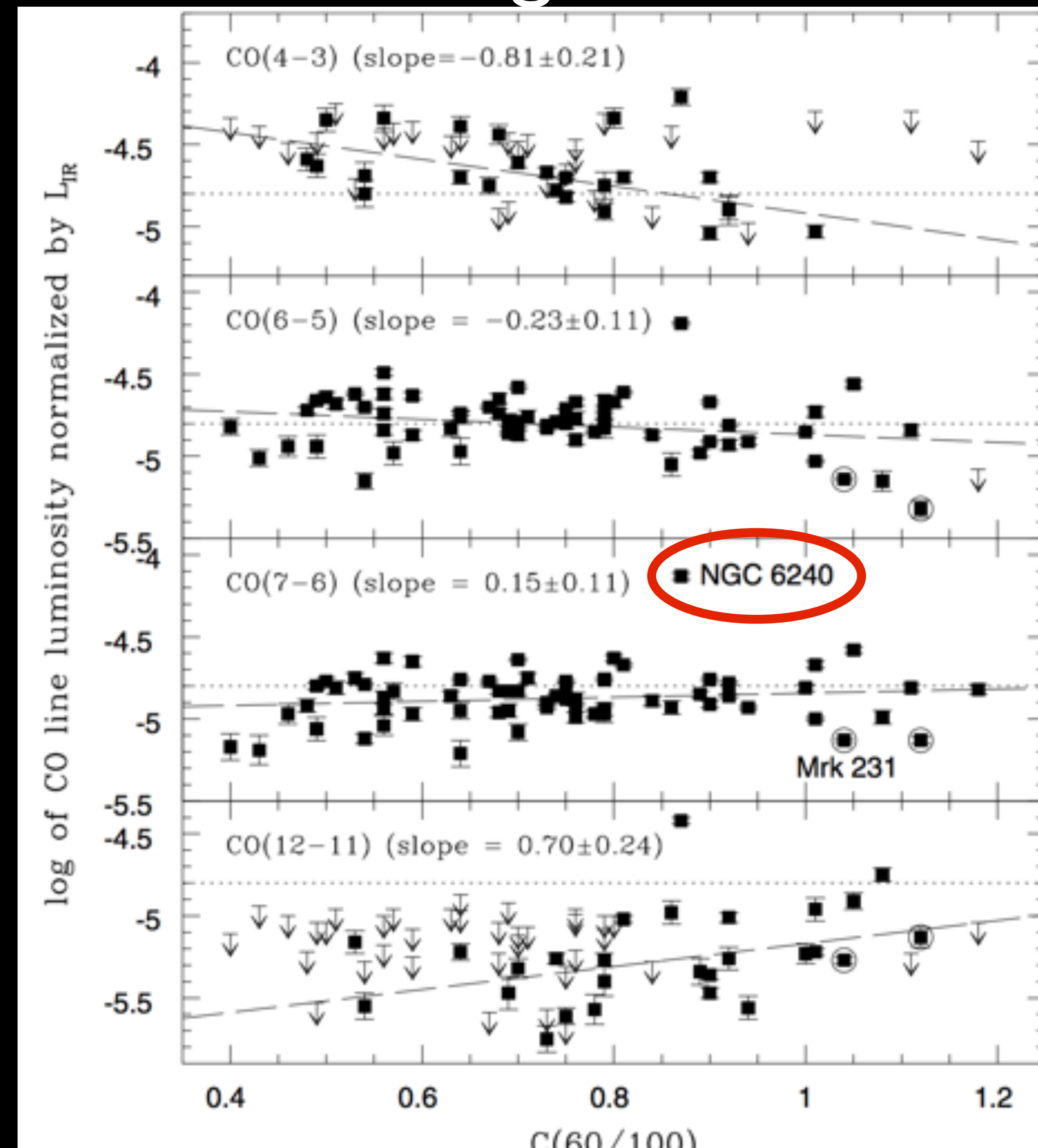


mid-&high-J CO:

Low-J CO: gas not all forming stars.
Mid-J CO: star forming gas.
High-J CO: extra heating mechanism.

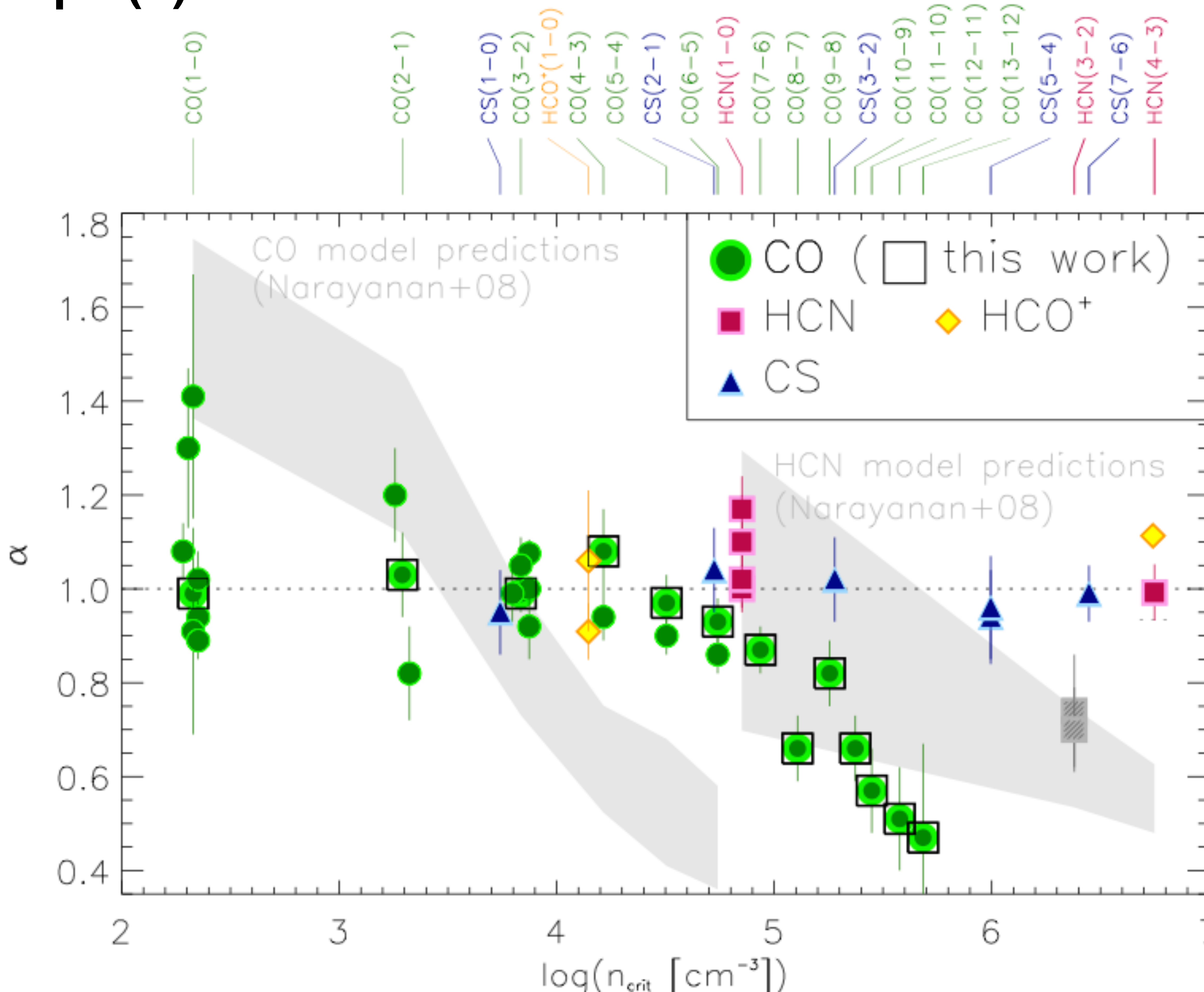


Greve et al. 2014



Lu et al. 2014

Slope (α) vs. J



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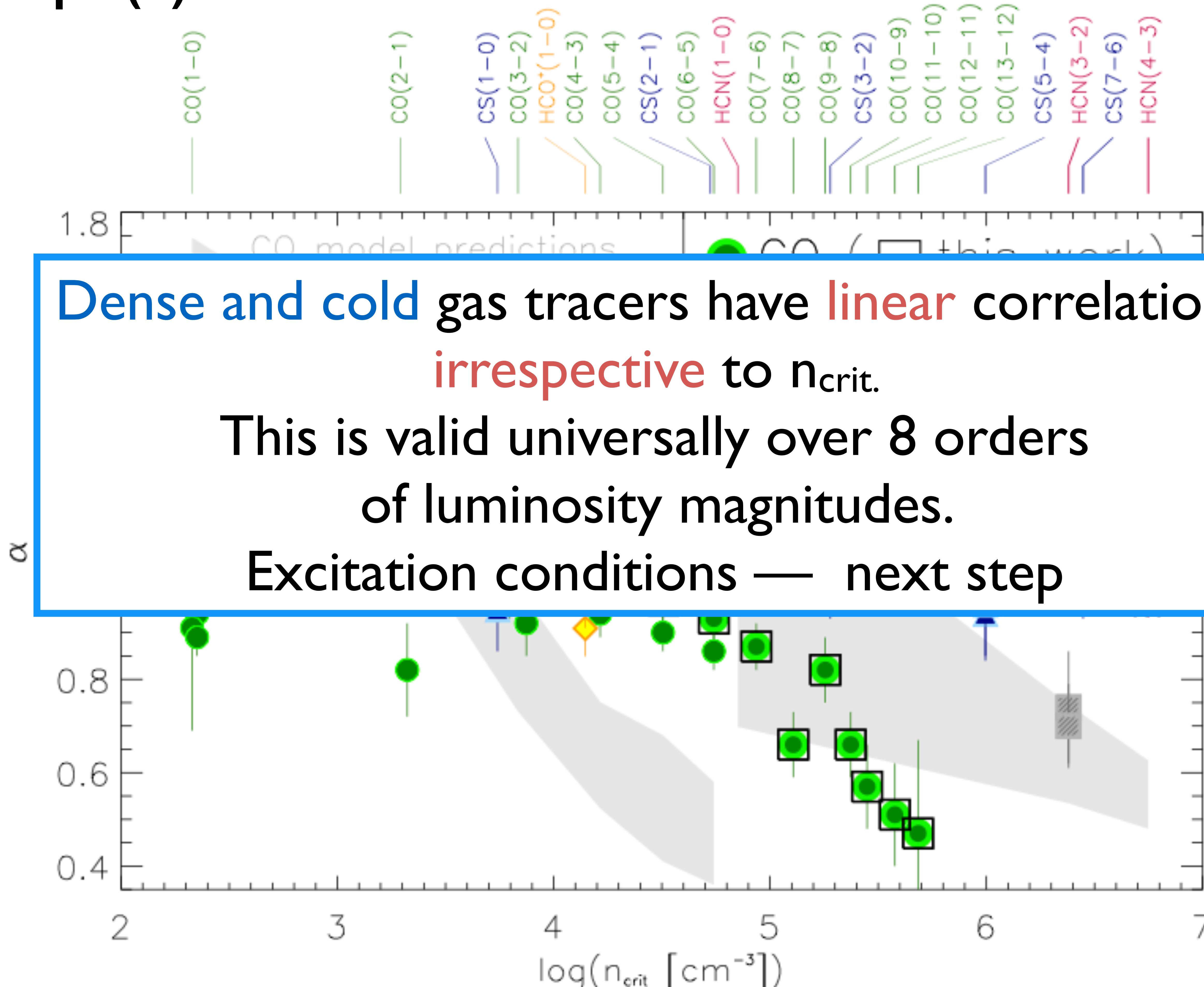
Slope (α) vs. J



Dense and cold gas tracers have linear correlations irrespective to $n_{crit.}$

This is valid universally over 8 orders of luminosity magnitudes.

Excitation conditions — next step

Greve+14

DeMoGas

http://demogas.astro.noa.gr/

- HerCULES sample
- Full CO ladders (from J=1-0 to 13-12)
- ^{13}CO ladders
- Multiple molecules (HCN/HCO+/CS/etc.)
- Multiple transitions

The most complete dataset of dense gas tracers in nearby U/LIRGs.

Manolis Xilouris
Ioanna Leonidaki
Padelis Papadopoulos
Paul van der Werf
Thomas Greve
Zhi-Yu Zhang
Panos Boumis
Alceste Bonanos