Dense gas tracers and star formation laws:

Multiple transition CS lines in nearby active star-forming galaxies

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Which gases are forming stars?

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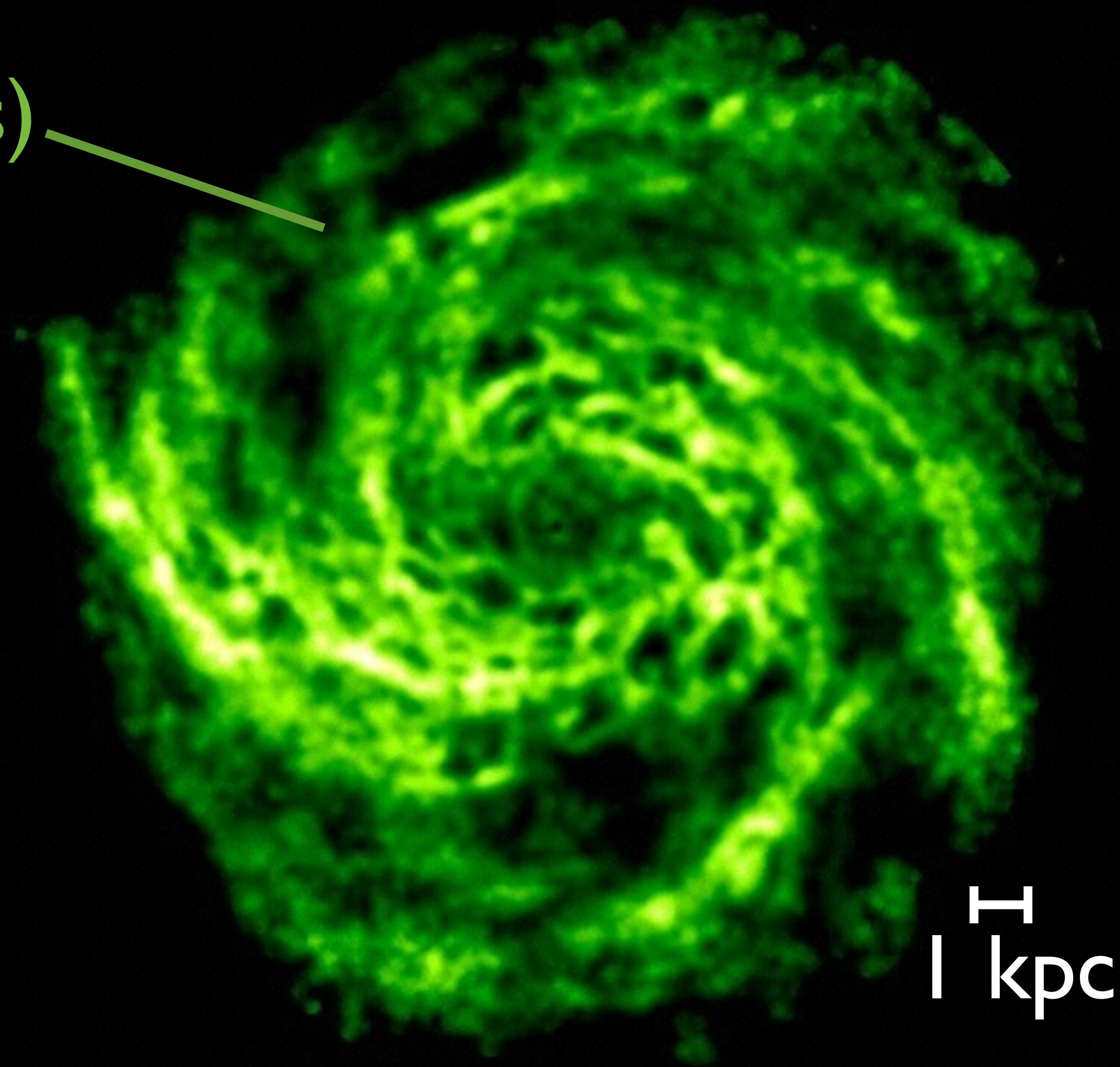
Outline

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

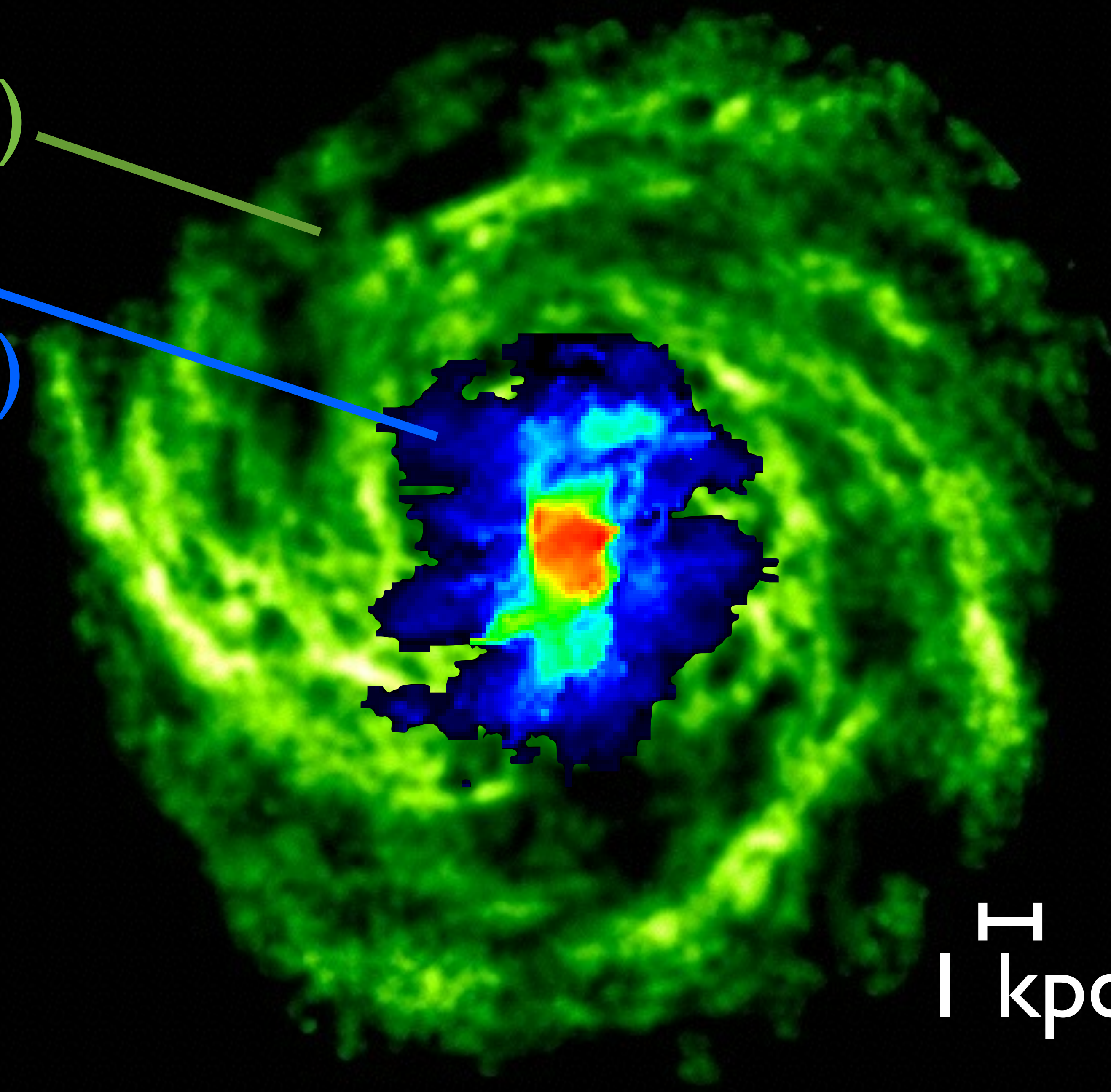
- Surveys and Results
- Multiple-J CS surveys in galaxies
- Star formation vs. dense gas emission
- DeMoGas and Excitation analysis.

- Summary

Which gases are forming stars?



Which gases are forming stars?



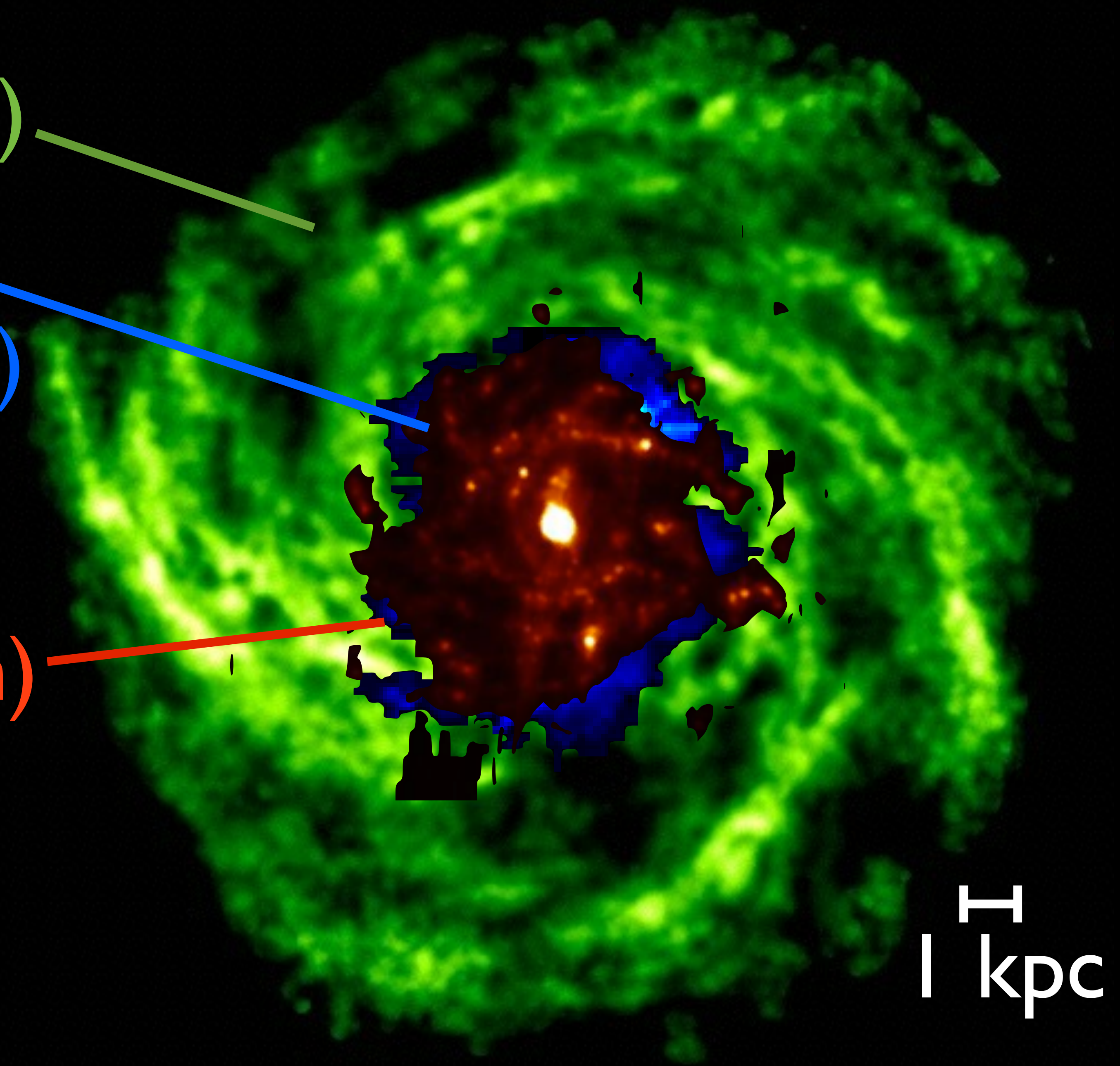
Which gases are forming stars?

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 related to H_2 gas, rather than HI

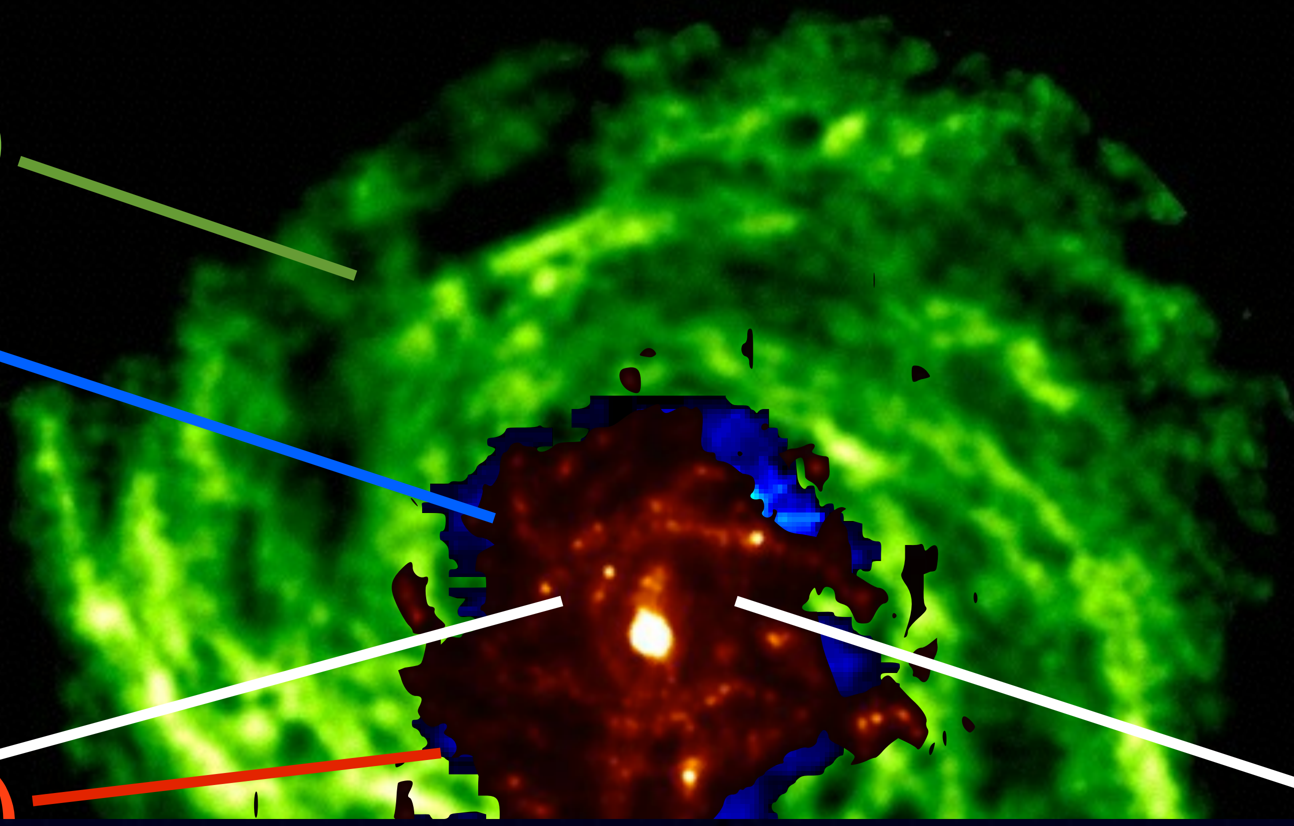
Which gases are forming stars?

IC 342

HI (atomic gas)

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

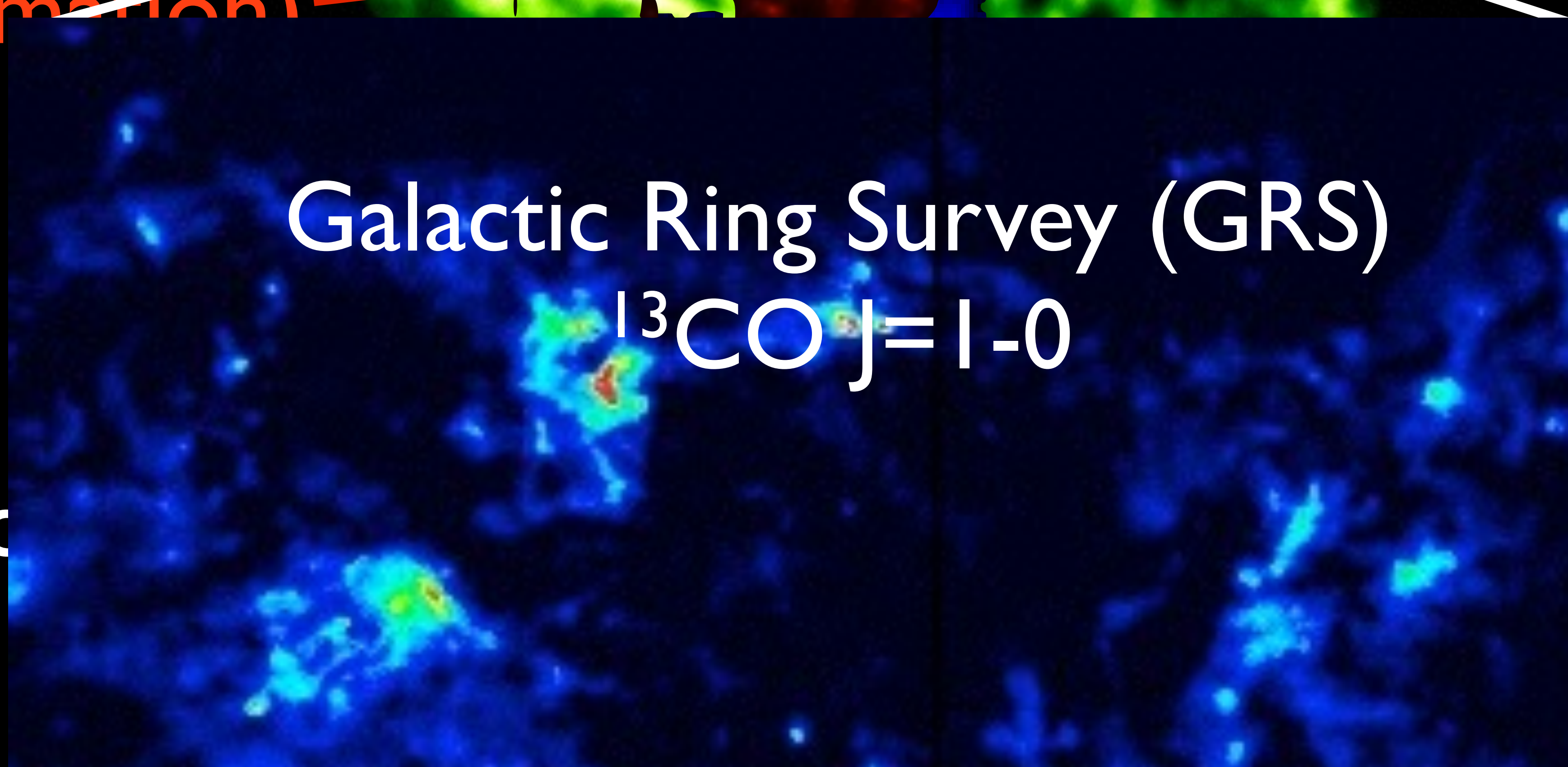
IR emission (star formation)



THINGS

NRAO 12m

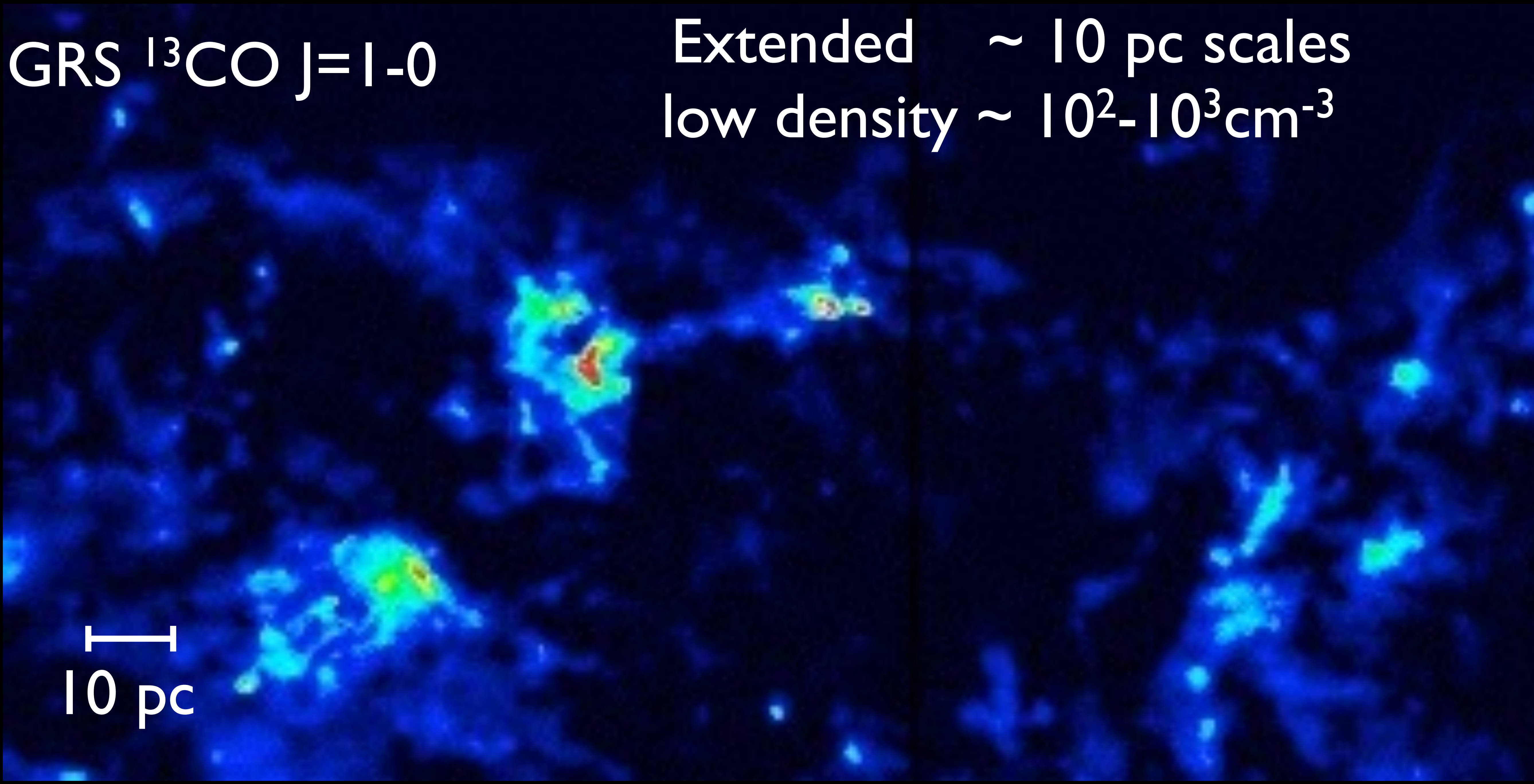
Spitzer 70um



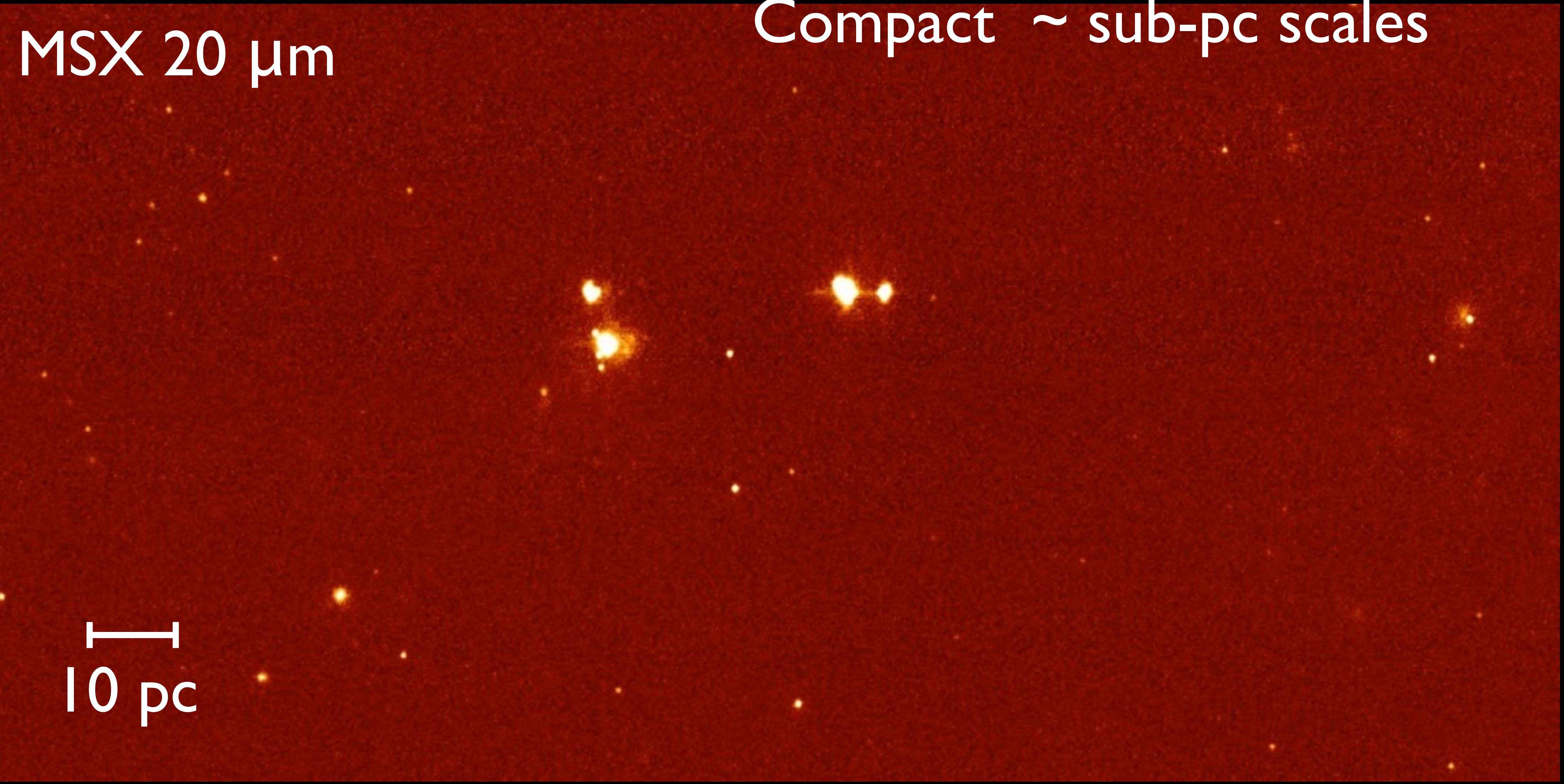
On kpc

than HI

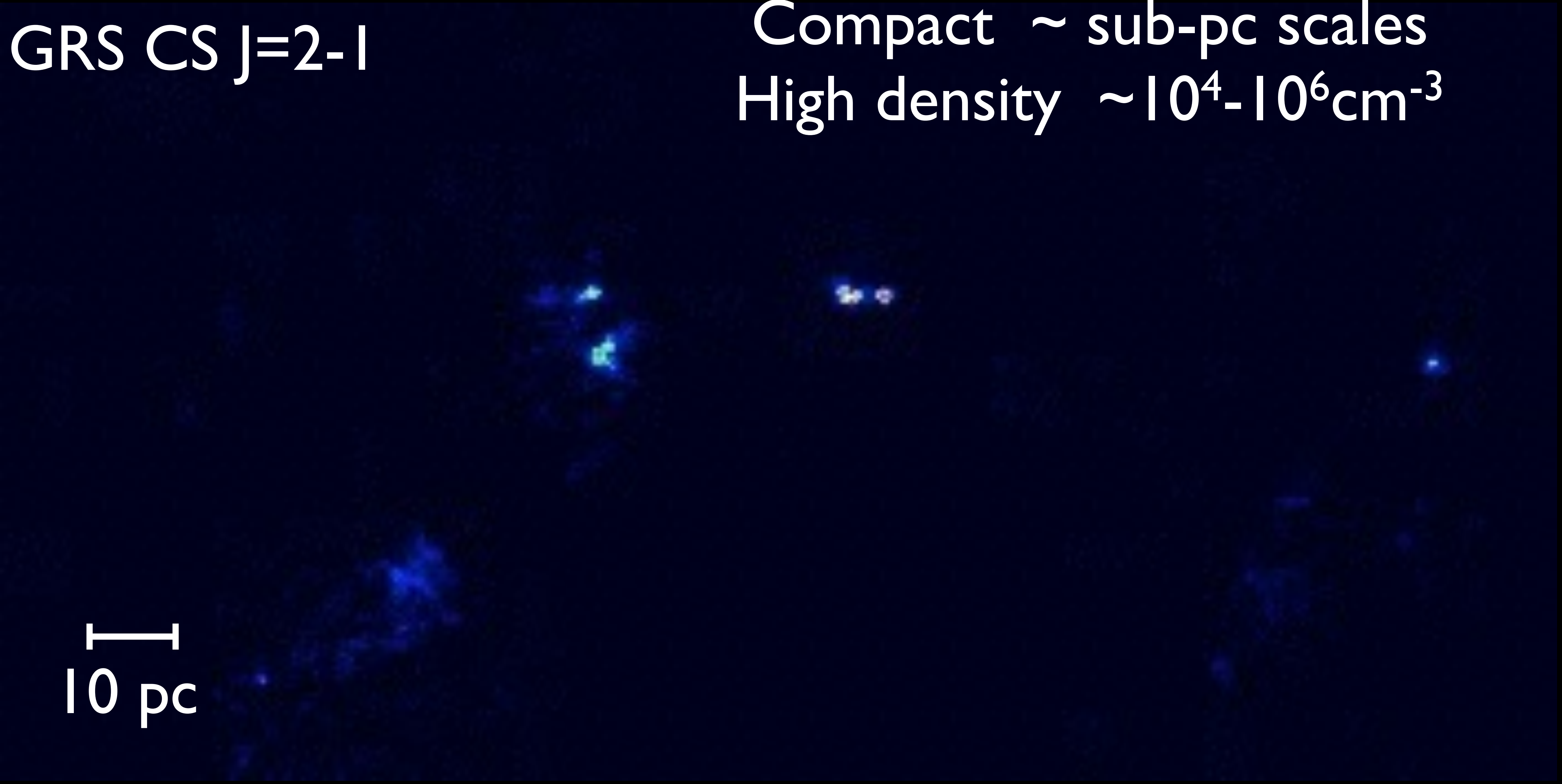
Which gases are forming stars? - Galactic view



Which gases are forming stars? - Galactic view



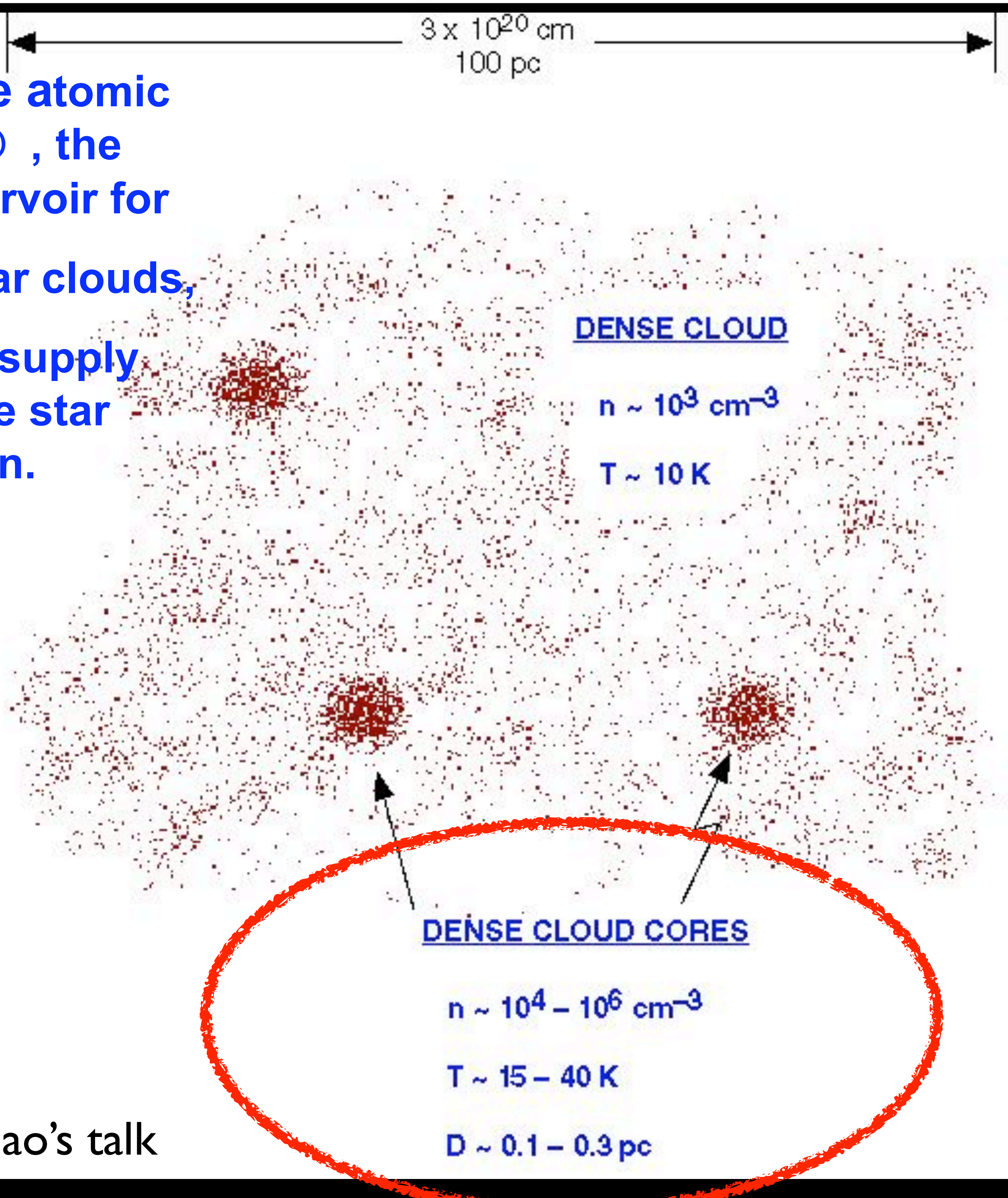
Which gases are forming stars? - Galactic view



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

Dense gas tracers

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

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

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

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

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

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

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

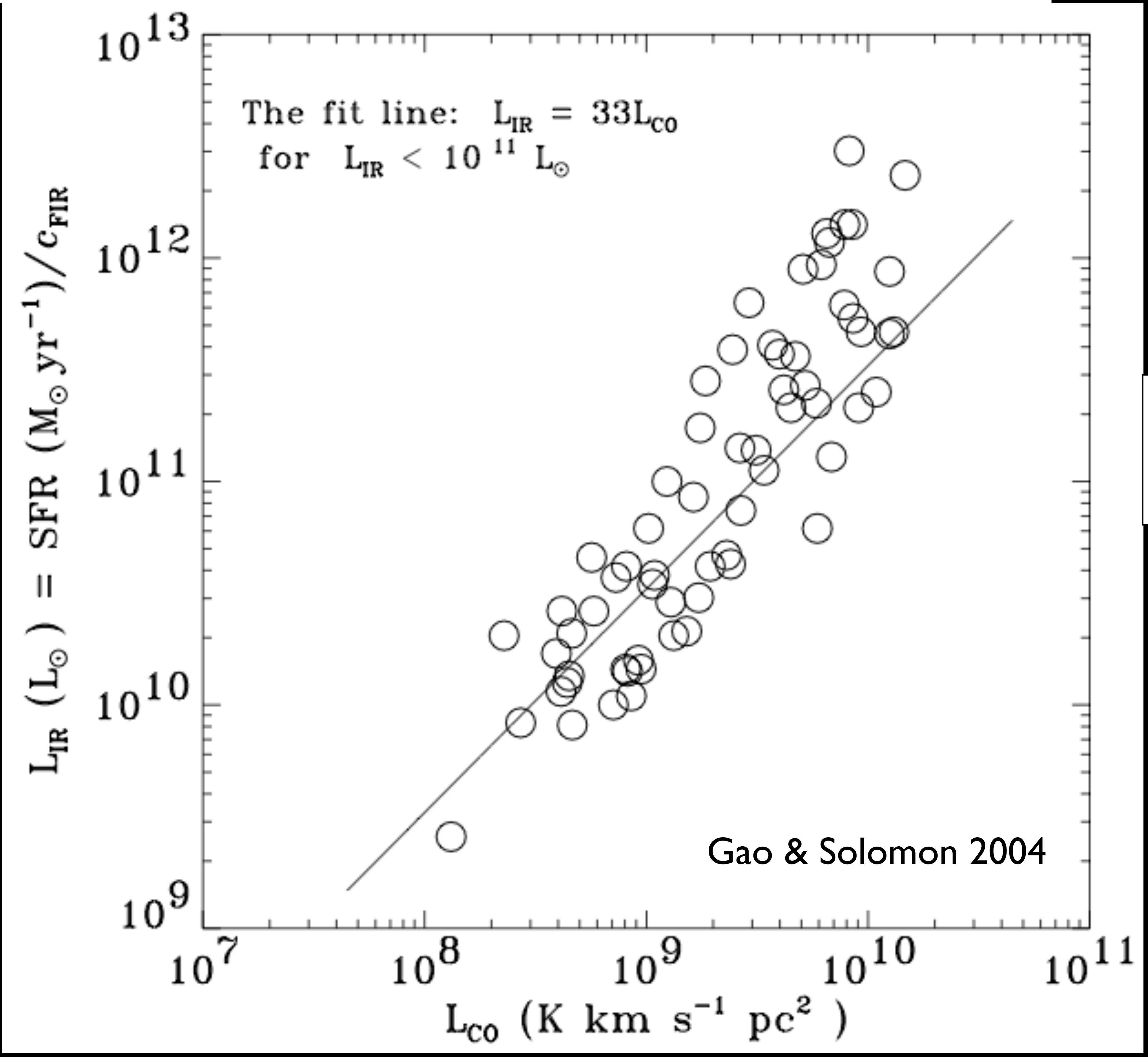
High-J CO : Do not trace cold and dense gas.

CS : Weaker emission (1/3-1/4 of HCN intensity)

The best? Less contaminated. Stable abundance.

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

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

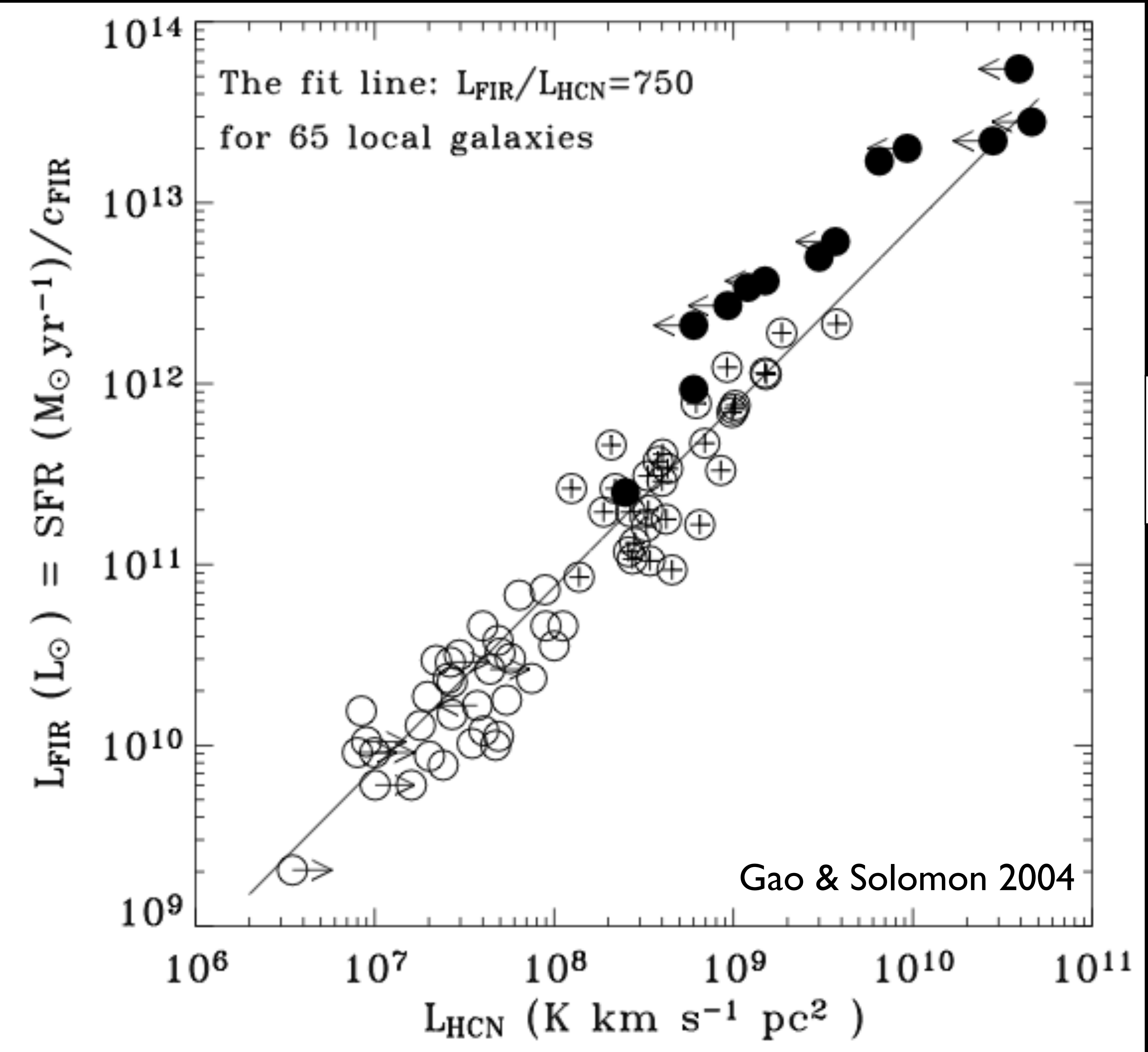


Slope~1.4

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

L_{IR} -- SFR

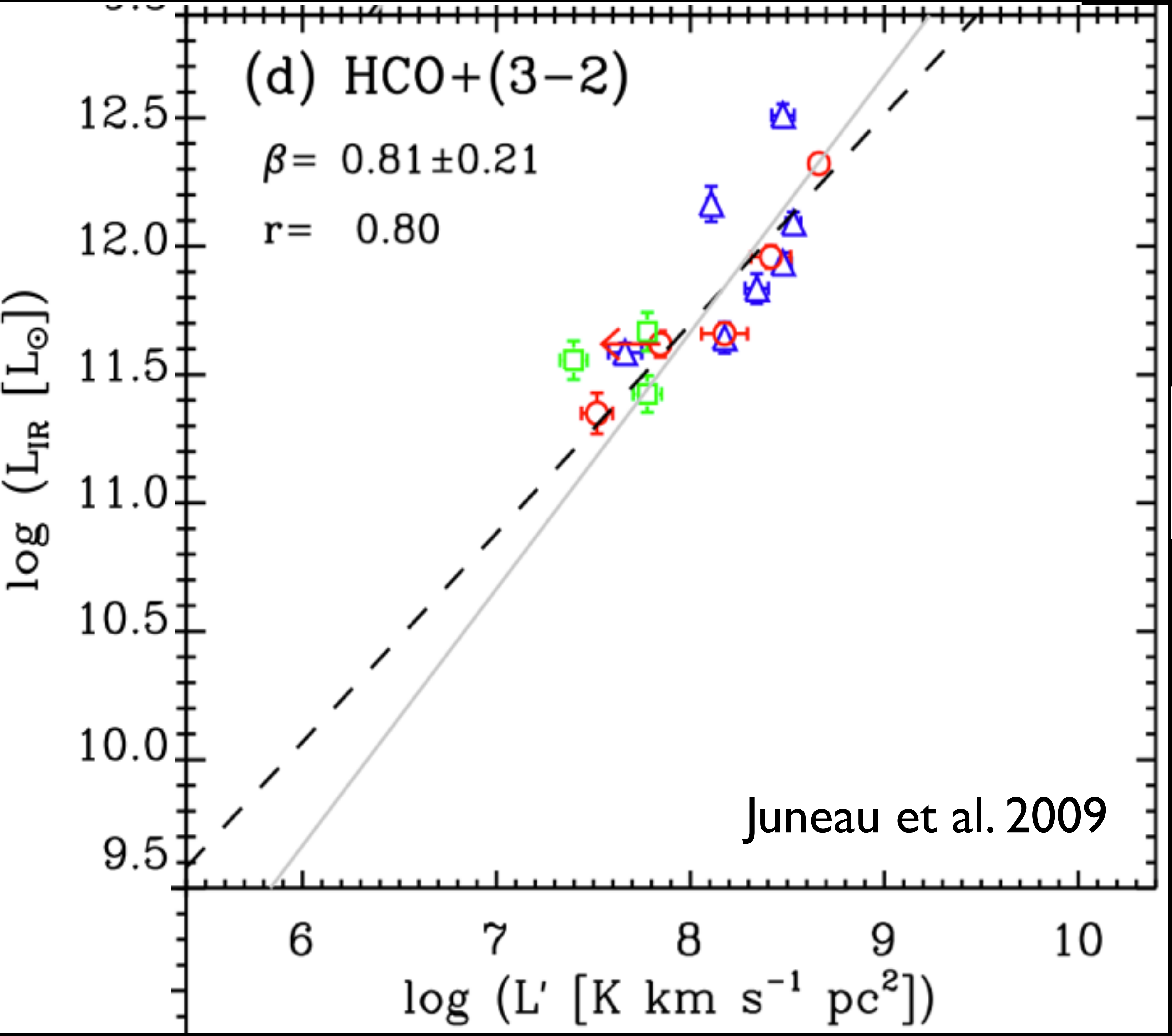
L'_{gas}-L_{IR} correlations -- HCN 1-0 (n_{crit}~ 2 x10^5cm^{-3})



Slope=1

L'_{gas} -- M_{gas}
L_{IR} -- SFR

L'_{gas}-L_{IR} correlations -- HCO^+ 3-2 (n_{crit}~ 1 x$10^6 cm^{-3}$)

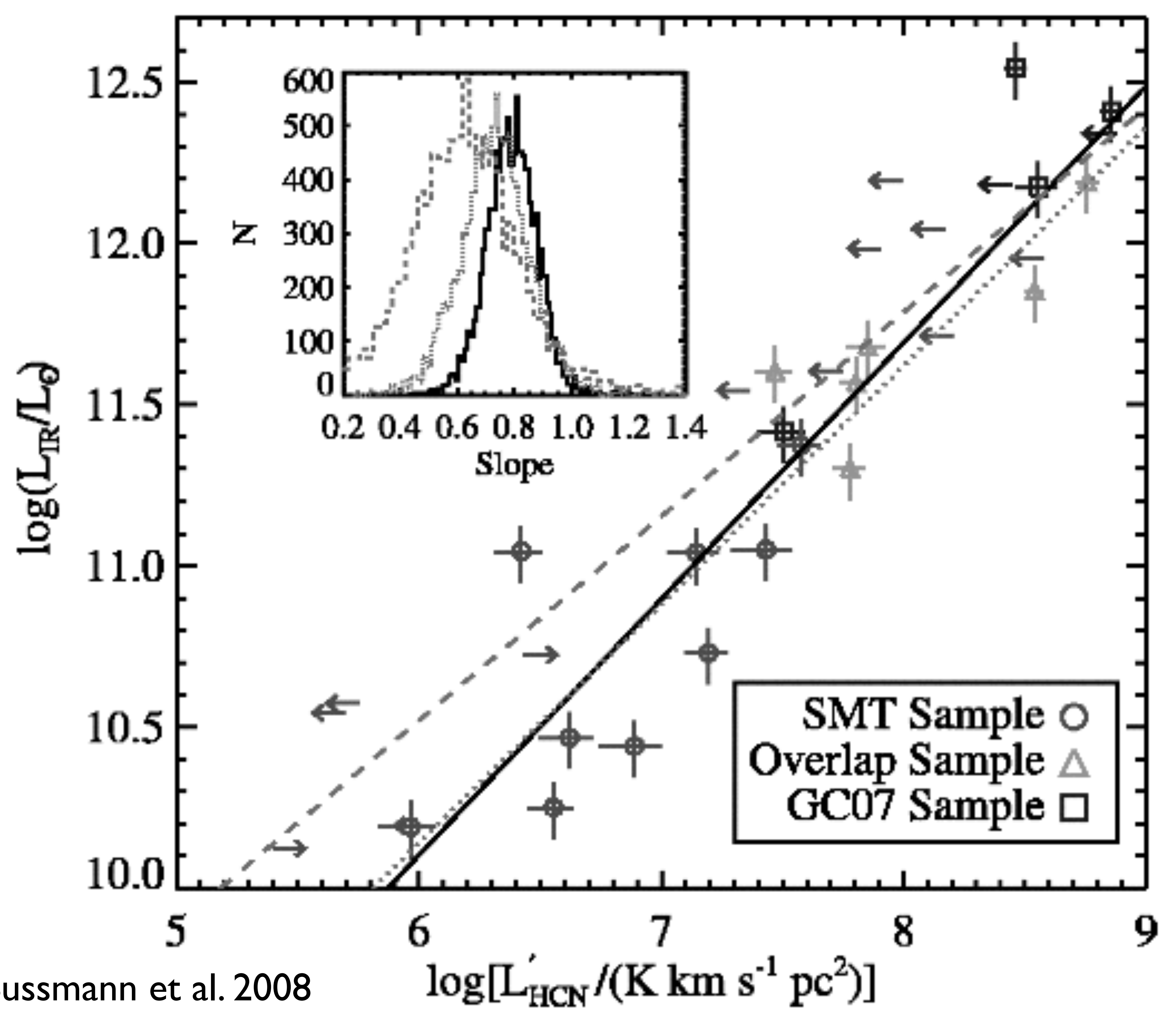


Slope=0.8

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:

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

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

CS 5–4:

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

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

CS 7–6:

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

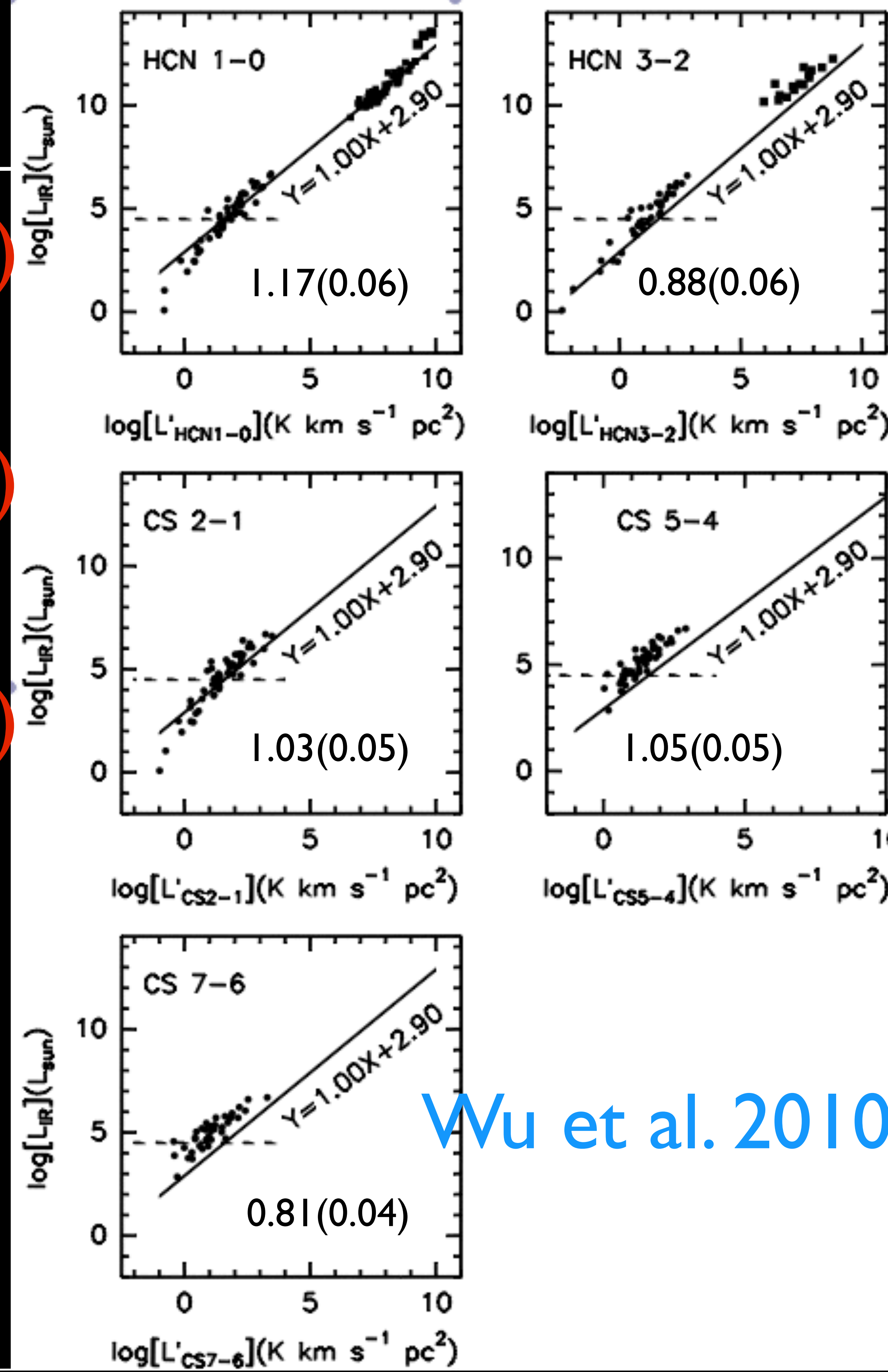
$$\text{Robust fit}: \log(L_{\rm IR}) = 0.64 \times \log(L'_{\rm CS7-6}) + 4.58$$

1.03(0.05)

1.05(0.05)

0.81(0.04)

The average density determined from CS excitation of the massive clumps in our sample is about $10^{5.9}$ $\rm cm^{-3}$ (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).



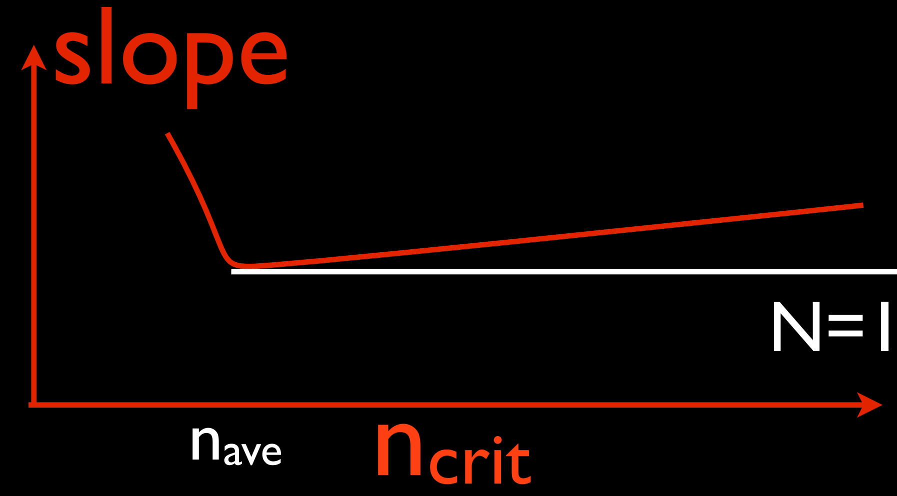
Wu et al. 2010

Theoretical works

1) Krumholz et al. (2007):

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

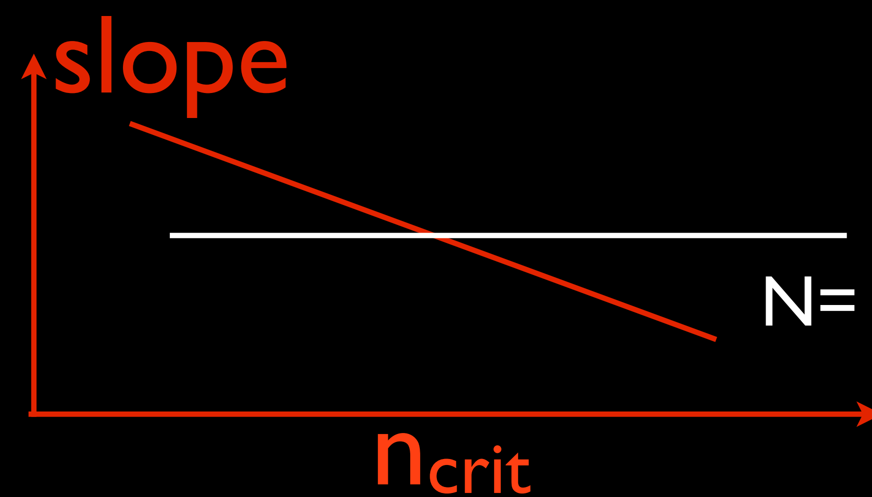
n_{crit} > n_{ave}: slope ~ 1 e.g., HCN 1-0



2) Narayanan et al. (2008):

Sub-thermal excitation.

Slope decreases with n_{crit}.

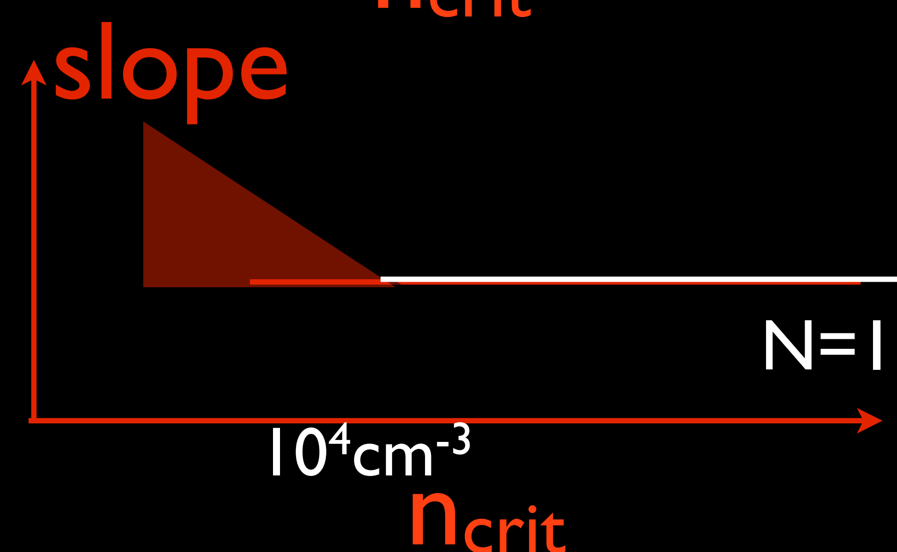


3) Lada et al. (2012):

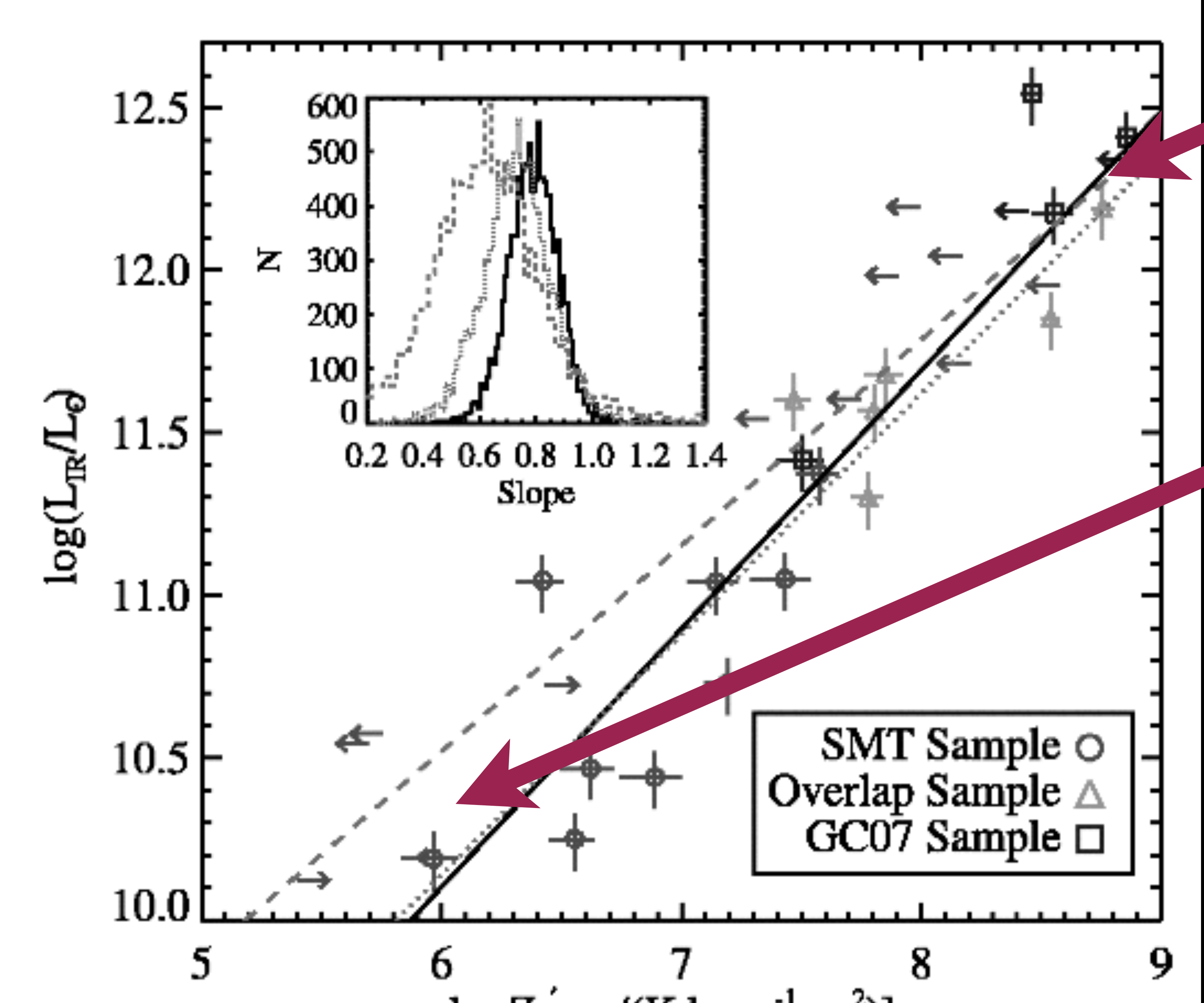
Linear slope for lines with n_{crit} > $10^4 cm^{-3}$

SFR is only related to M_{dense}.

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



Potential Issues



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, a multiple transition survey of clean dense tracers is needed, e.g. CS lines

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}, measured with IRAS.
   Nearby normal galaxies, starburst, and (U)LIRGs.

~ 40 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

~40 hours

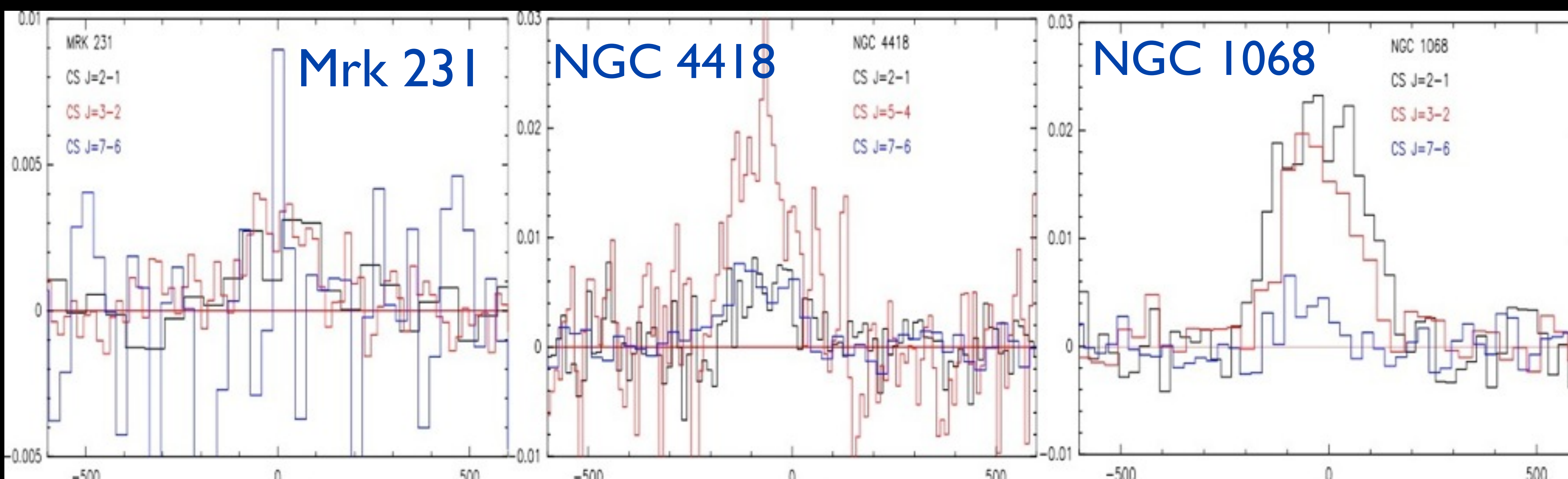
still ongoing

Spectra

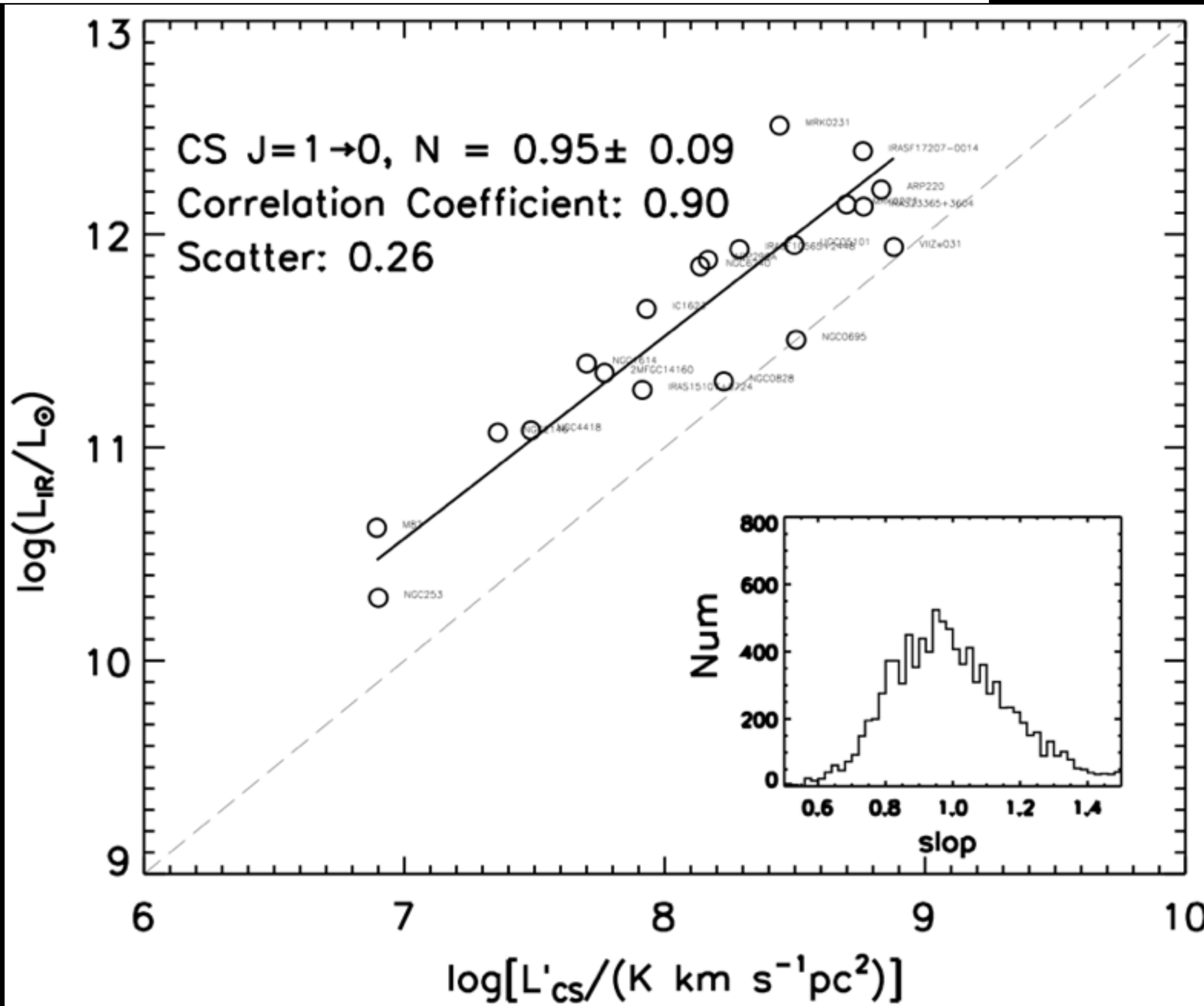
CS J=1-0 : 20/24 galaxies
CS J=2-1 : 41/47 galaxies
CS J=3-2 : 30/41 galaxies
CS J=5-4 : 21/40 galaxies
CS J=7-6 : 11/20 galaxies
$C^{34}S$ J=2-1: 5 detections

+ CS detections in literatures

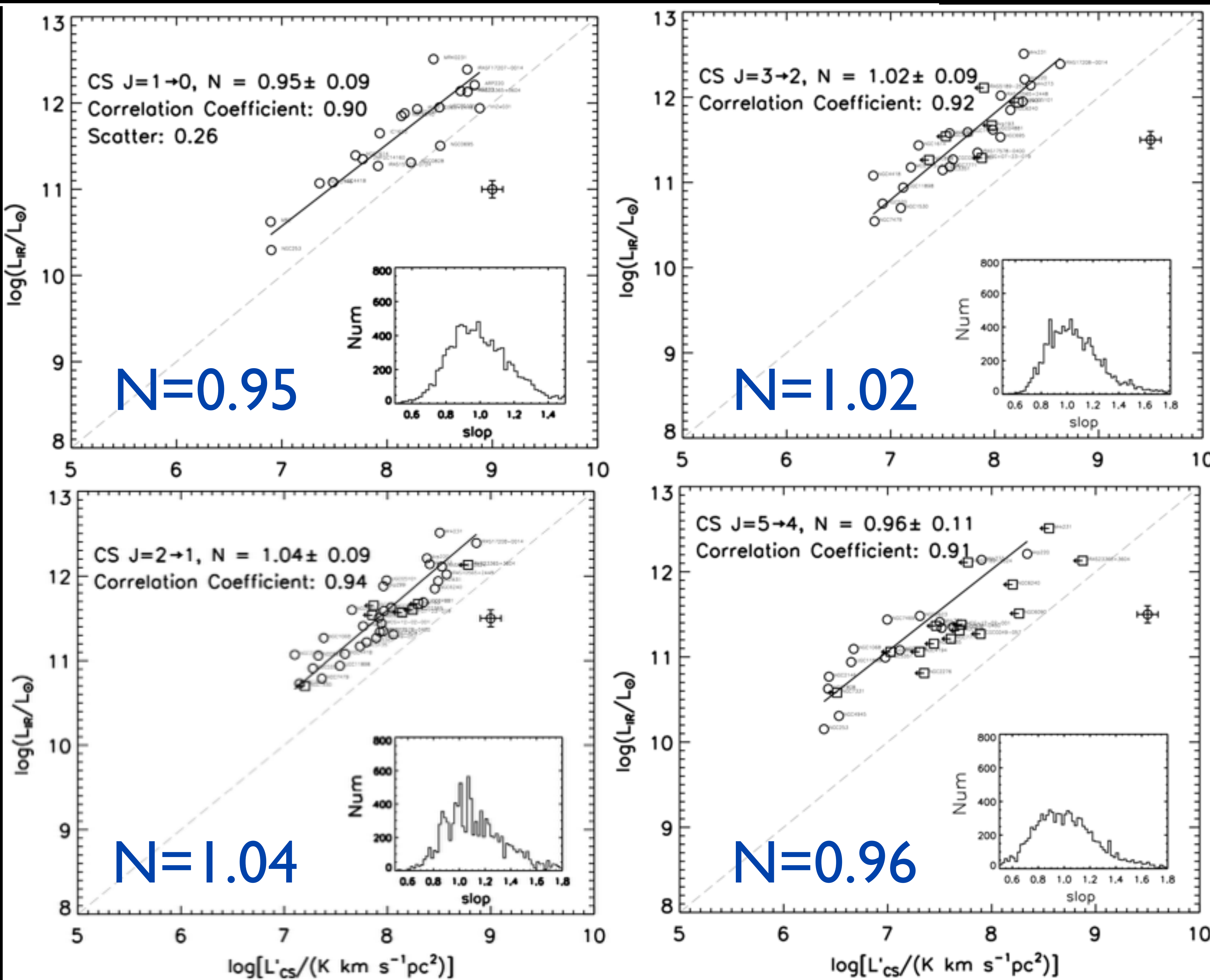
HCN/HCO^{+}4-3 simultaneously



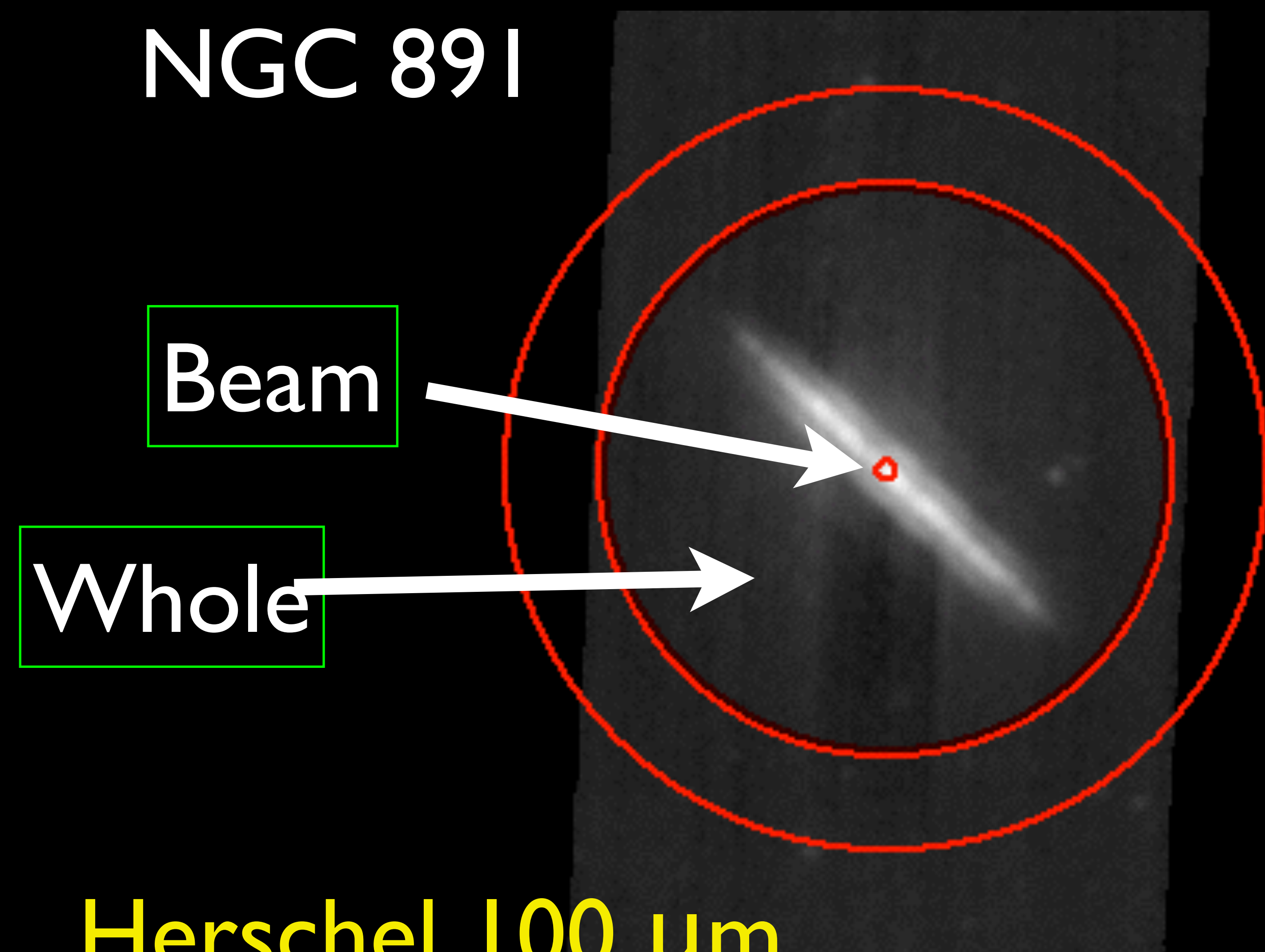
L'$_{gas}$-L$_{IR}$ (point source) CS J=1-0 n_{crit}~ 1x10^{4}cm^{-3}

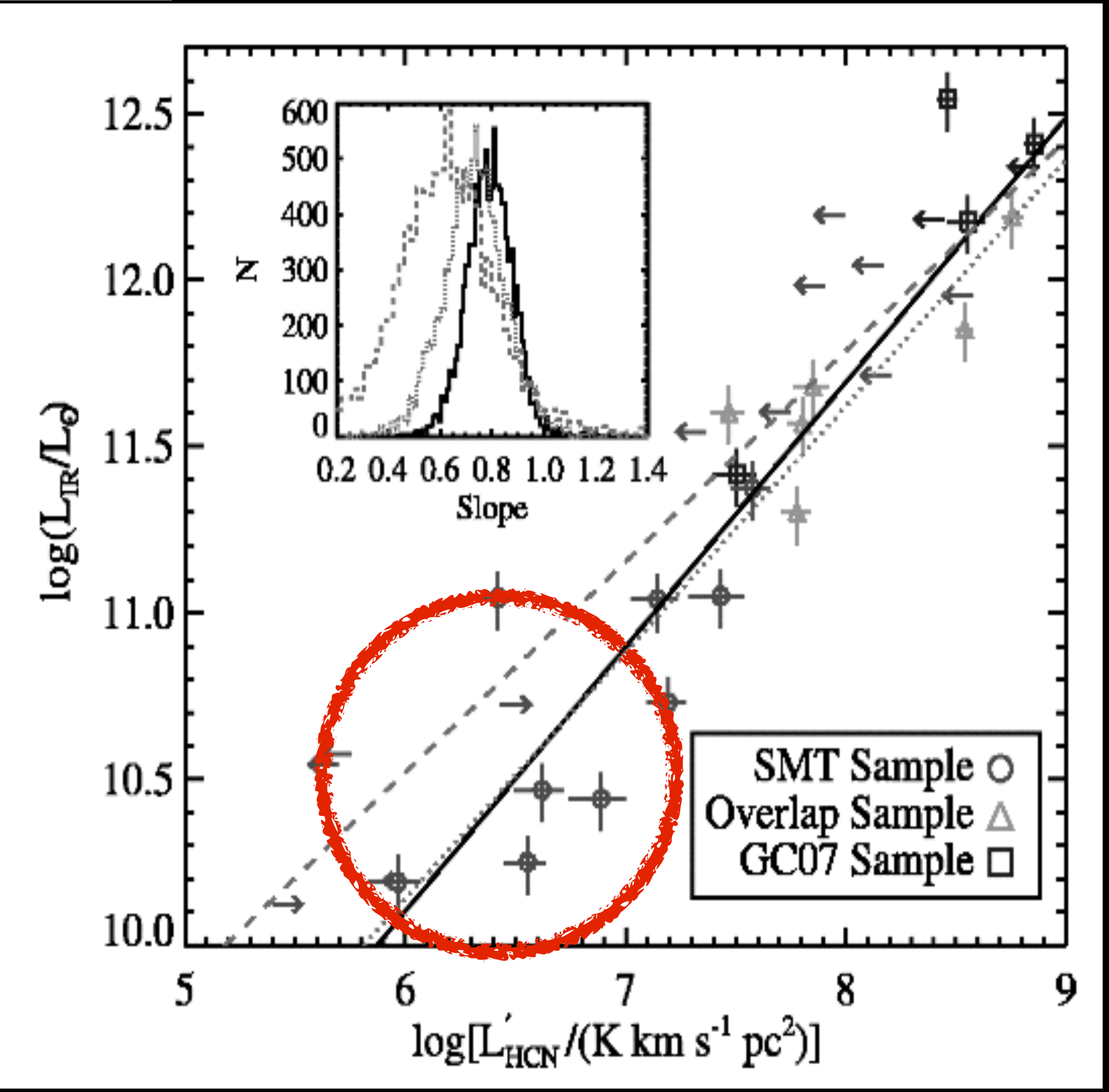


L'cs-L$_{IR}$ correlations   Point sources only



Beam matching photometry





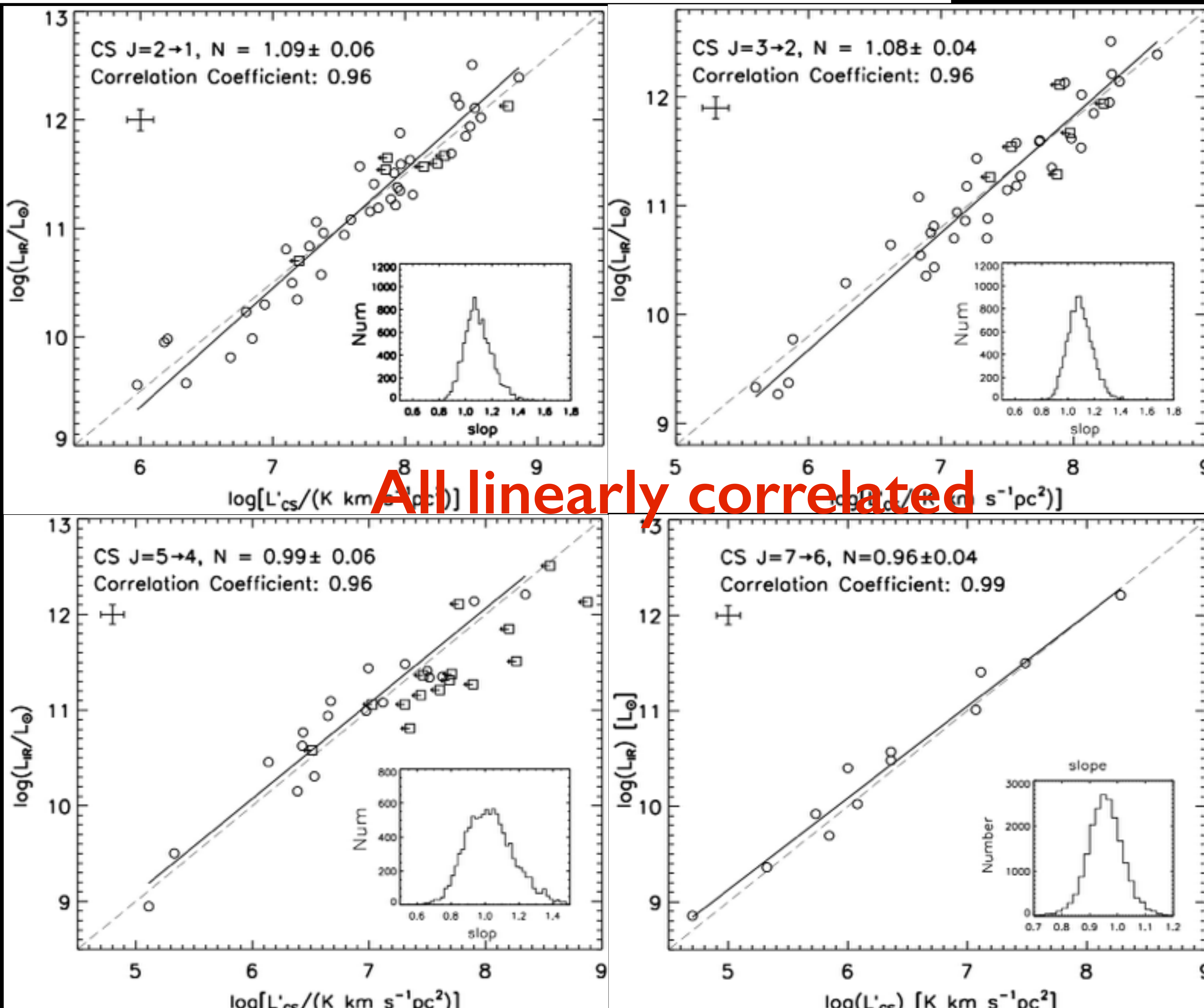
Bussmann et al. 2008

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

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

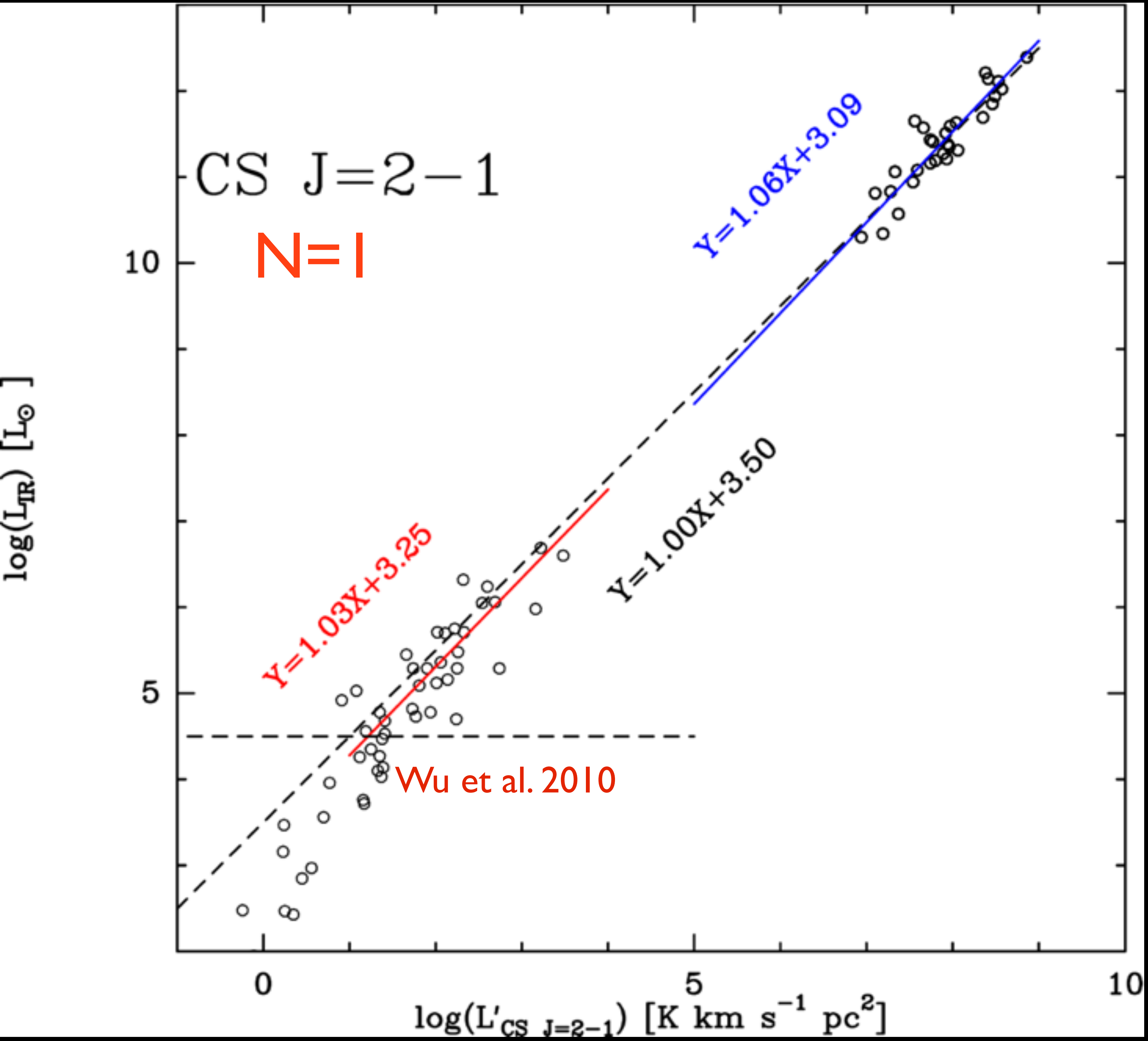
Assuming whole galaxy share one IR SED.

L'cs-LIR correlations Beam matching correction



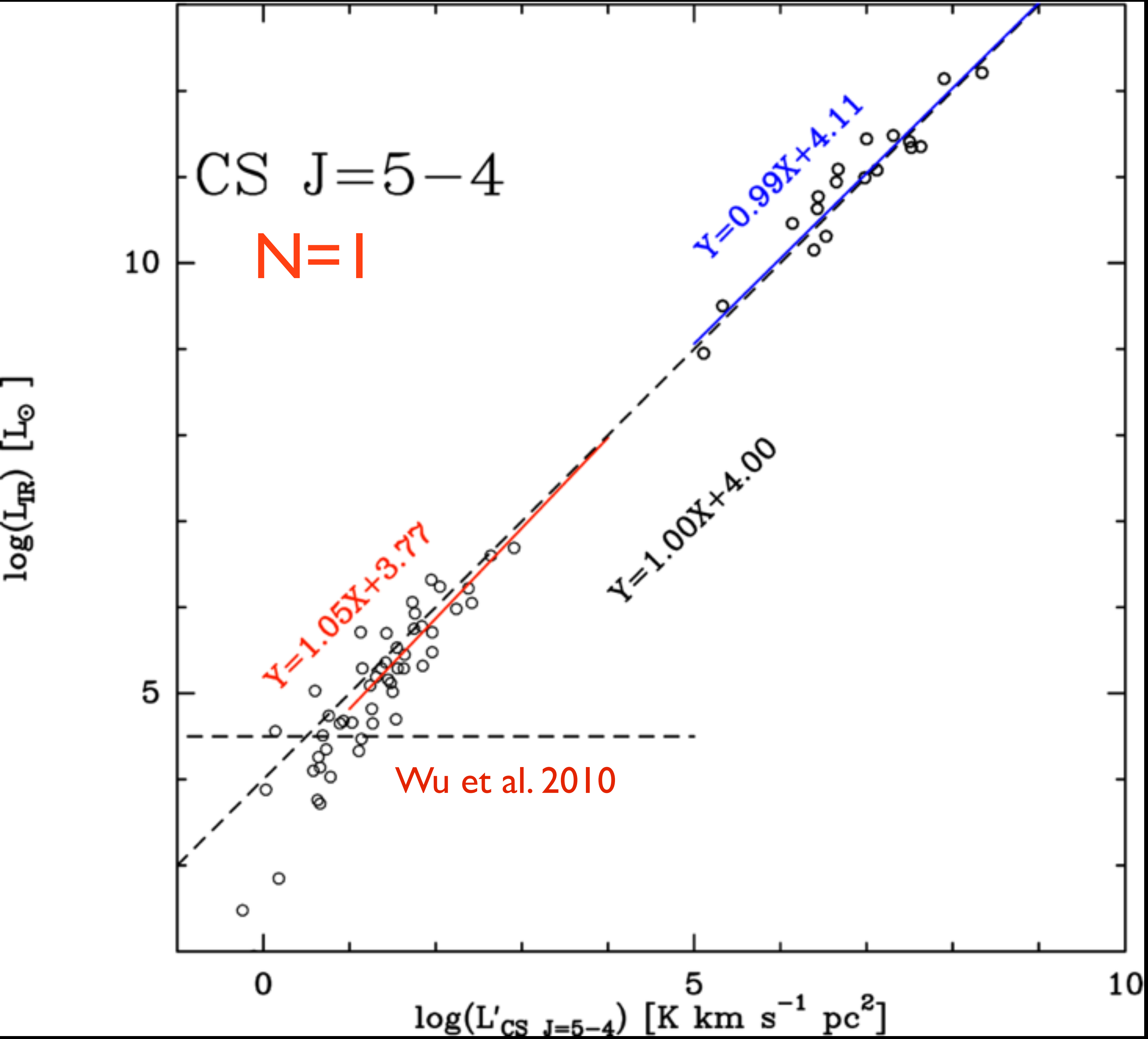
All linearly correlated

L'cs-LIR correlations ~ 8 orders of magnitude



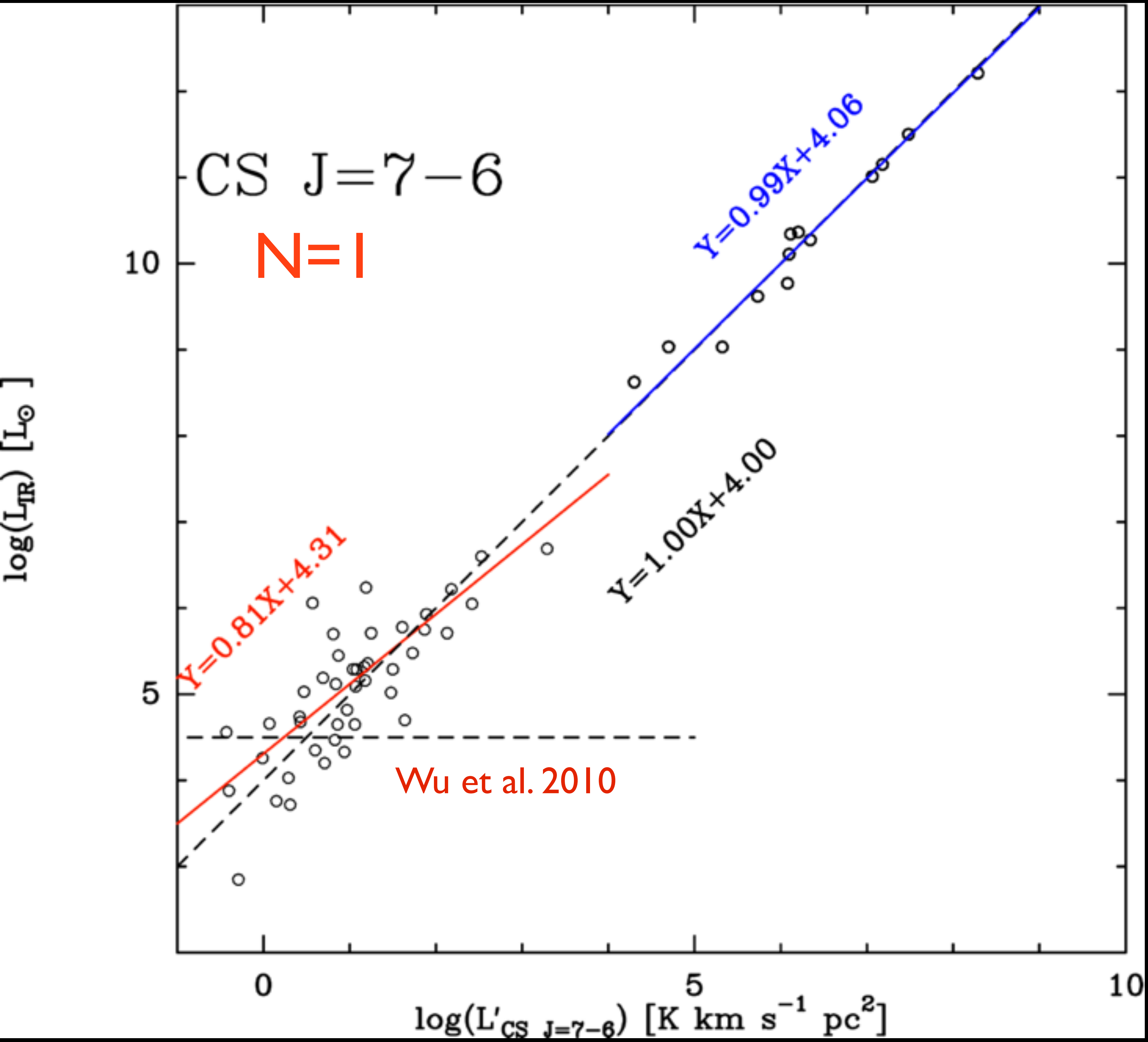
n_{crit}~ $1\times10^5 cm^{-3}$

L'cs-LIR correlations ~ 8 orders of magnitude



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

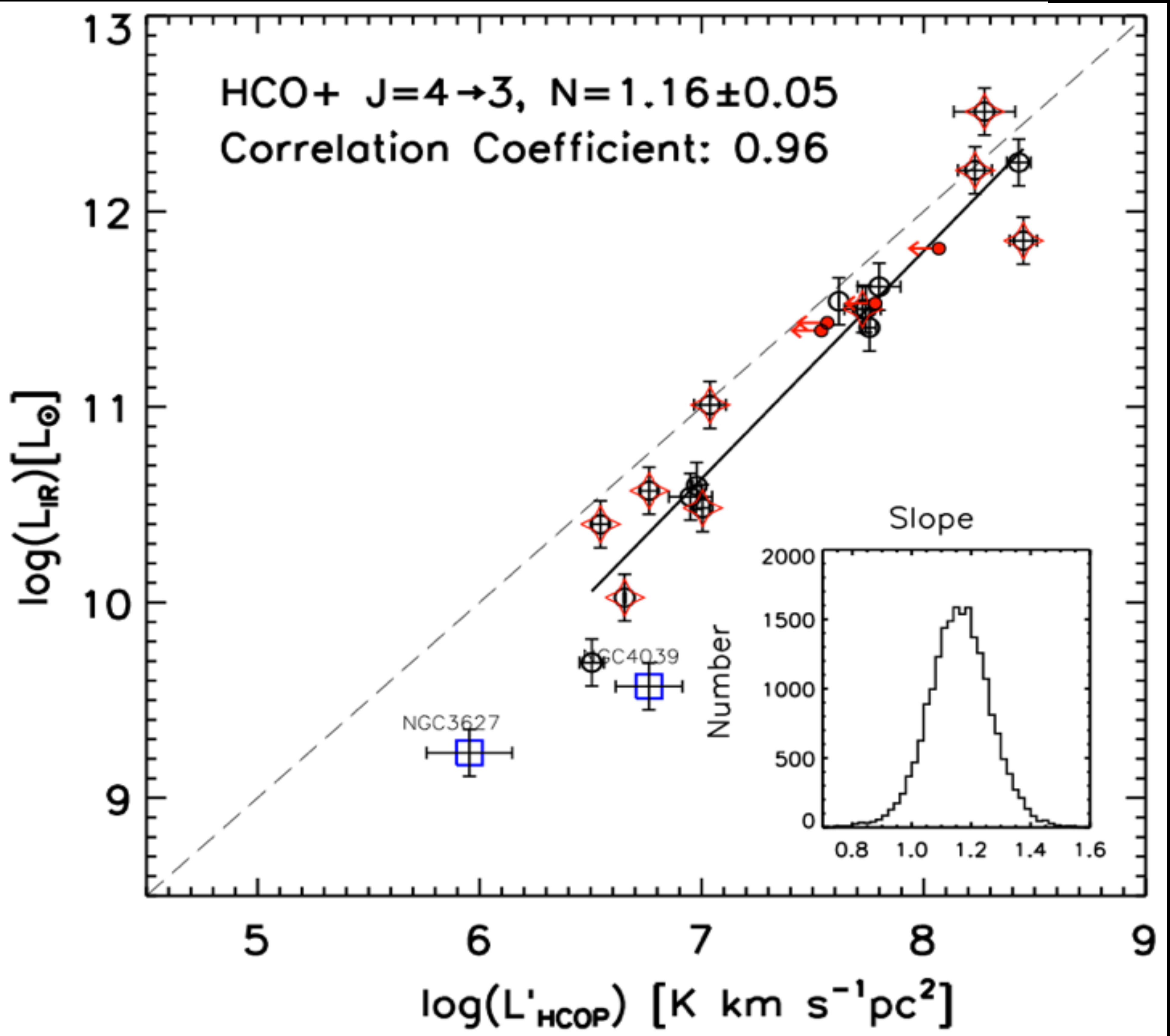
L'cs-L$_{IR}$ correlations ~ 8 orders of magnitude



n_{crit}~ $5x10^6 cm^{-3}$

Zhang et al. 2014

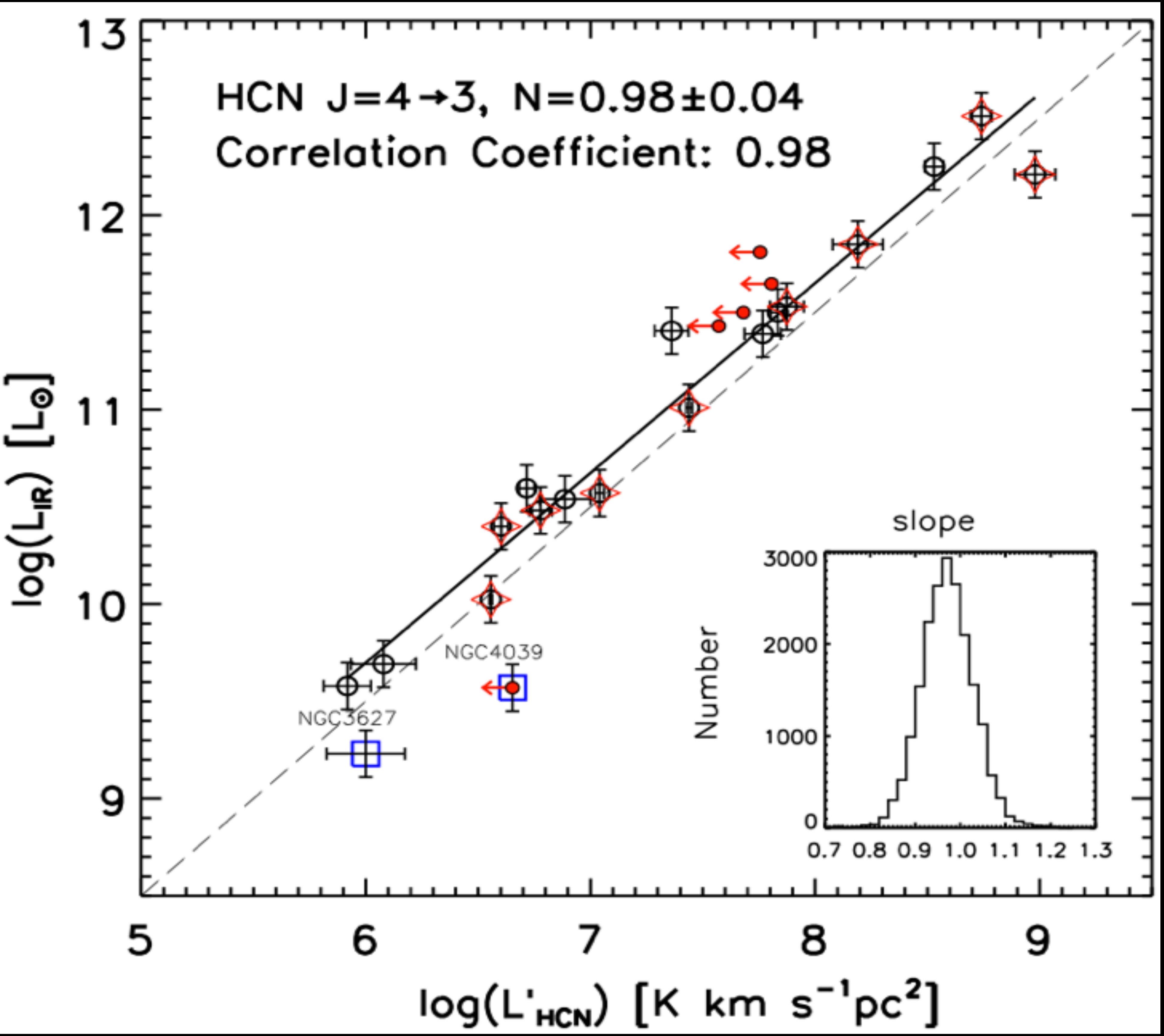
HCO^+ J=4-3 -- observed simultaneously with CS J=7-6



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

Zhang et al. 2014

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



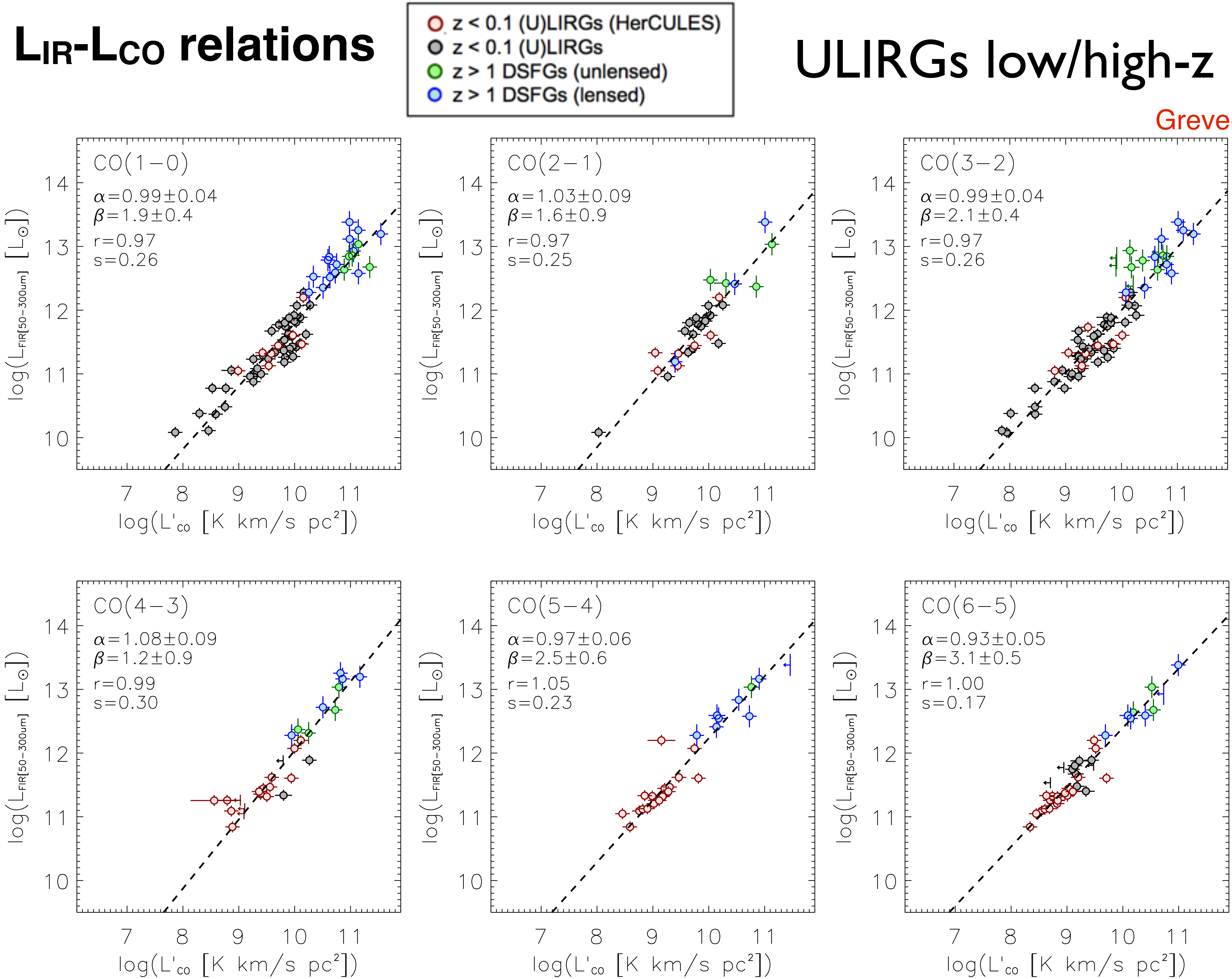
$n_{crit} \sim 1\times10^{7} cm^{-3}$

Zhang et al. 2014

L_{IR}-L_{CO} relations

ULIRGs low/high-z

Greve+14

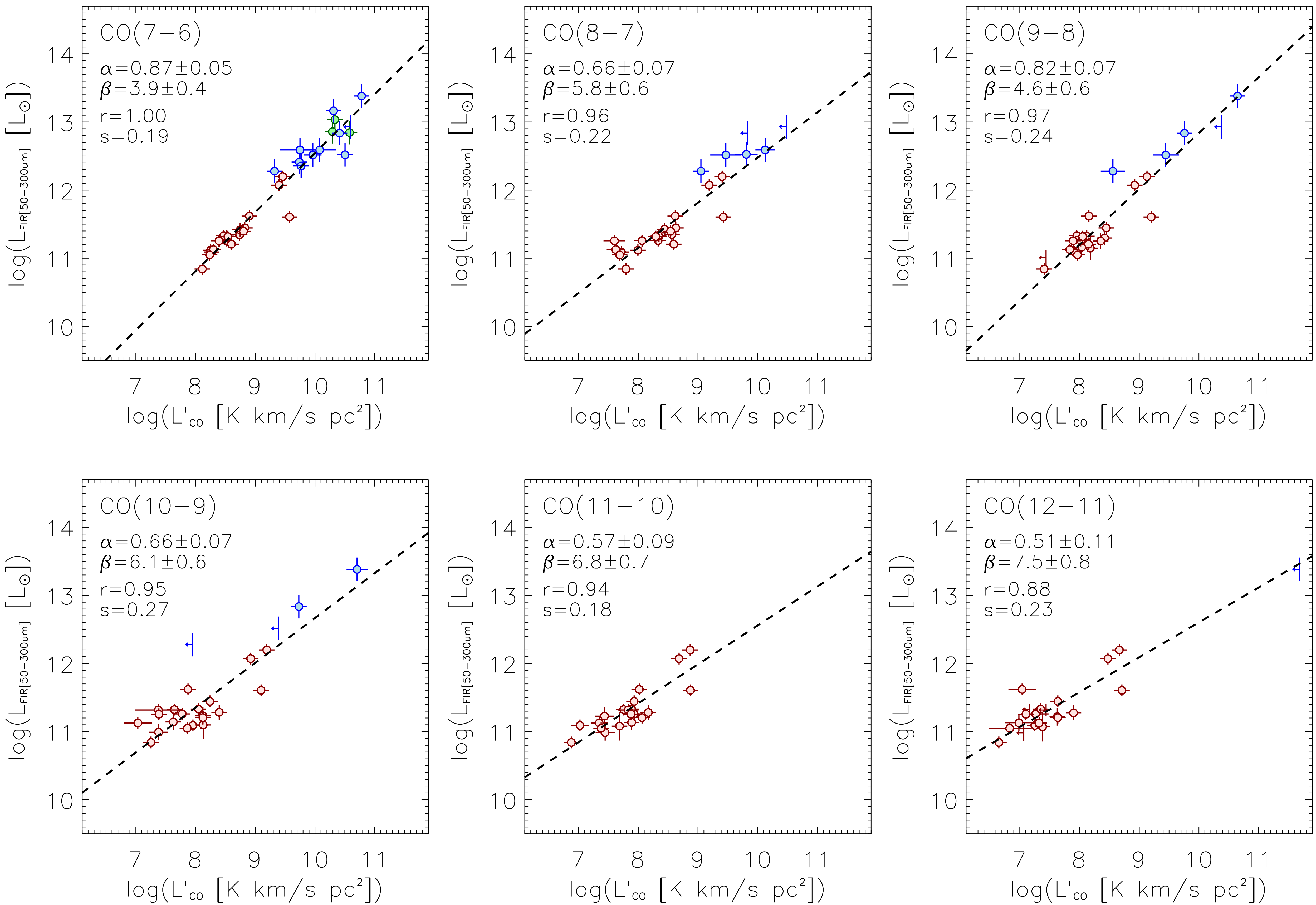


L_{IR}-L_{CO} relations

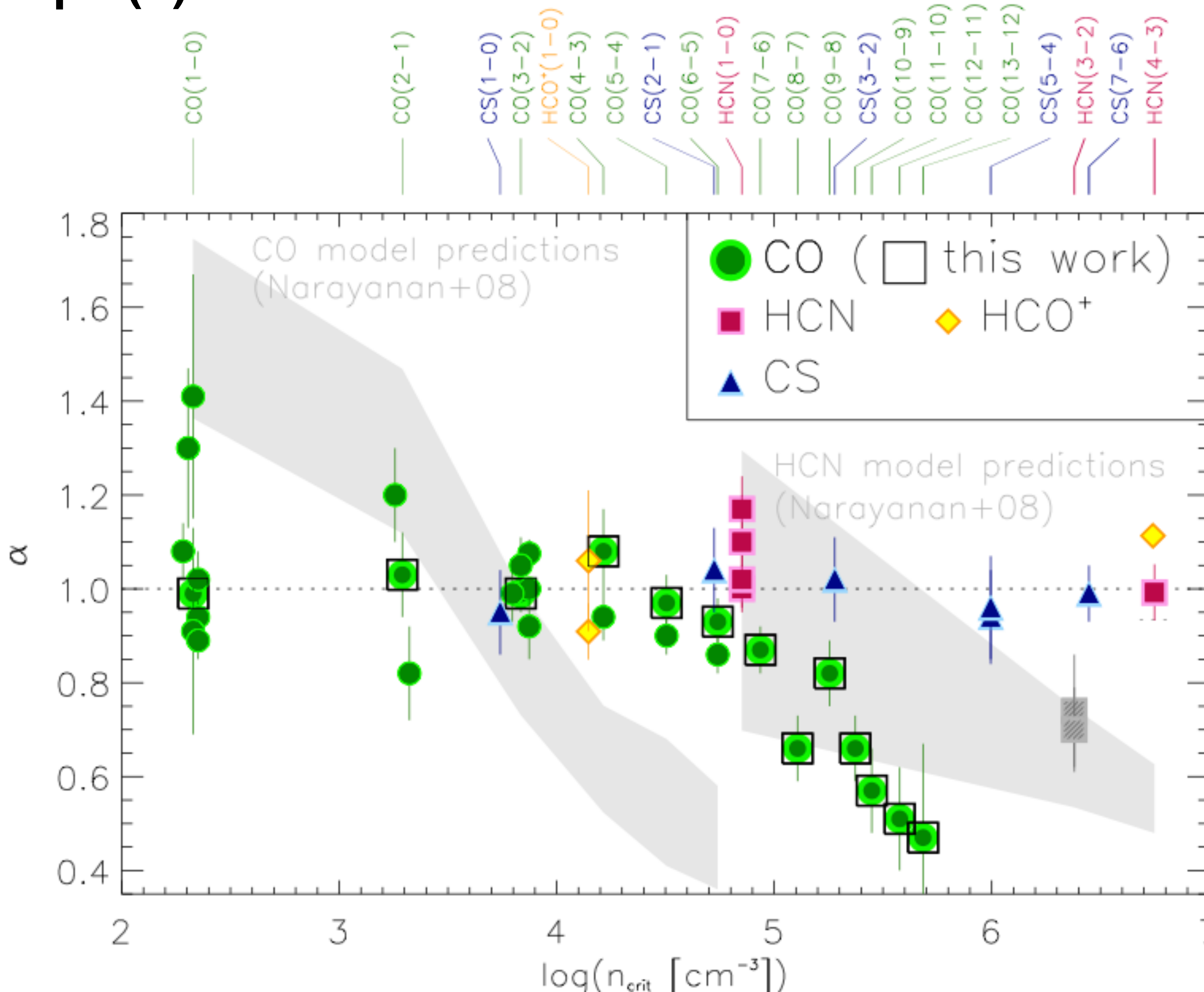
ULIRGs low/high-z

z < 0.1 (U)LIRGs (HerCULES)
z < 0.1 (U)LIRGs
z > 1 DSFGs (unlensed)
z > 1 DSFGs (lensed)

Greve+14

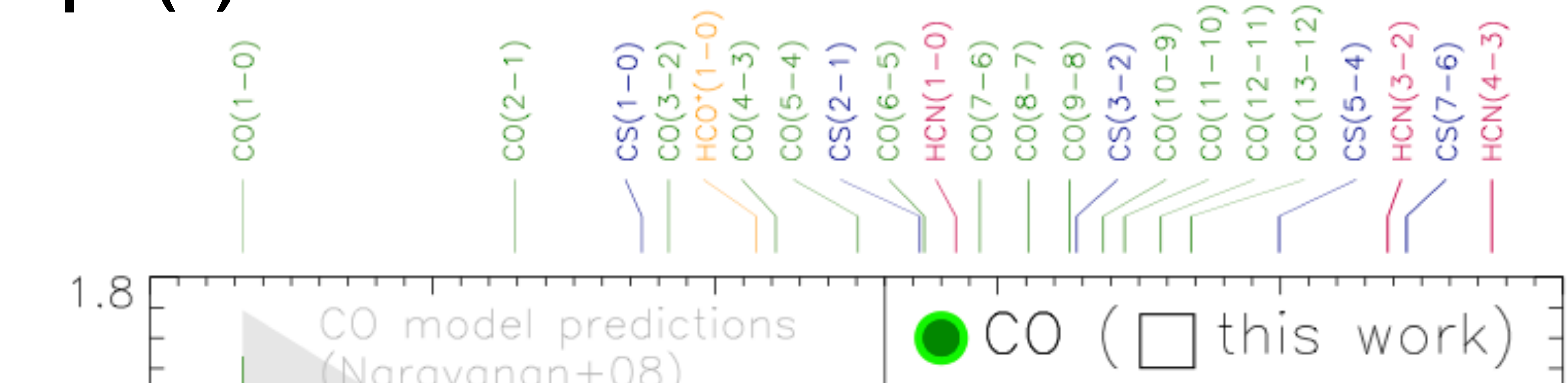


Slope (α) vs. J



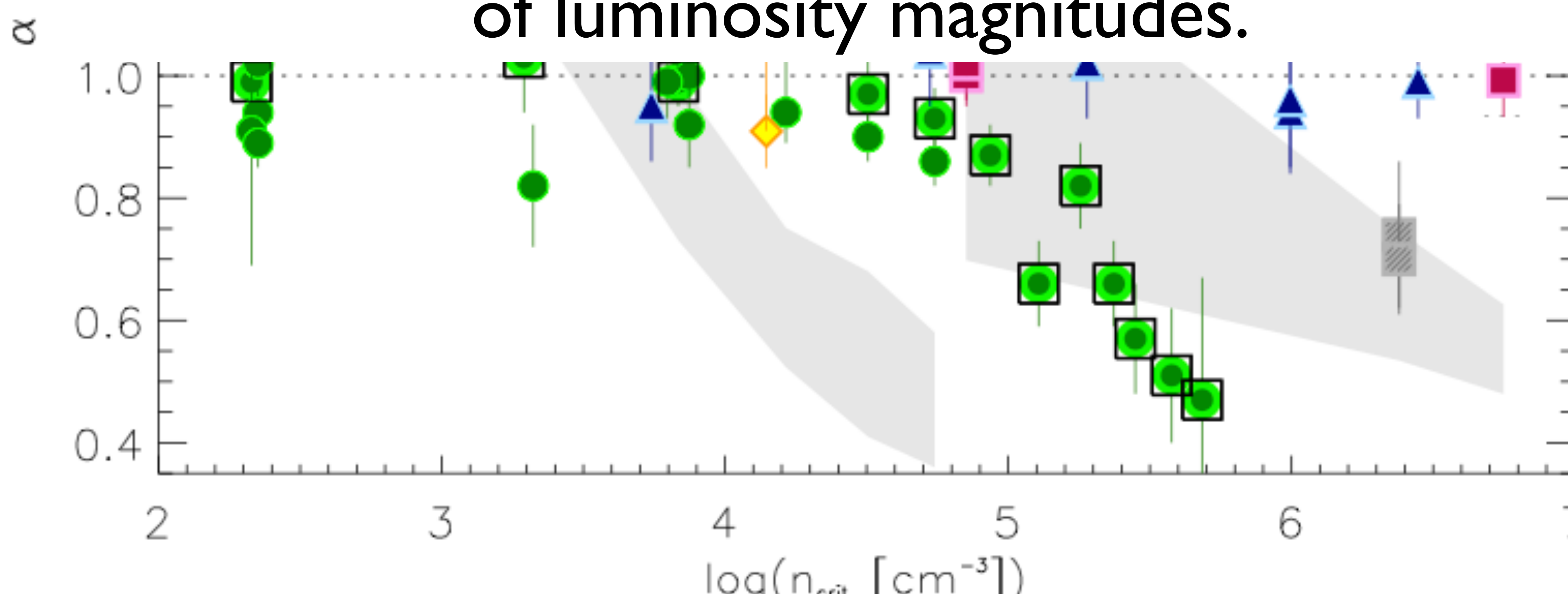
Greve+14

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.



Greve+14

Caveats

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

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

Analysis on excitation conditions are needed.

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 (1-0,2-1,….,7-6)

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

Manolis Xilouris

Ioanna Leonidaki

Padelis Papadopoulos

Paul van der Werf

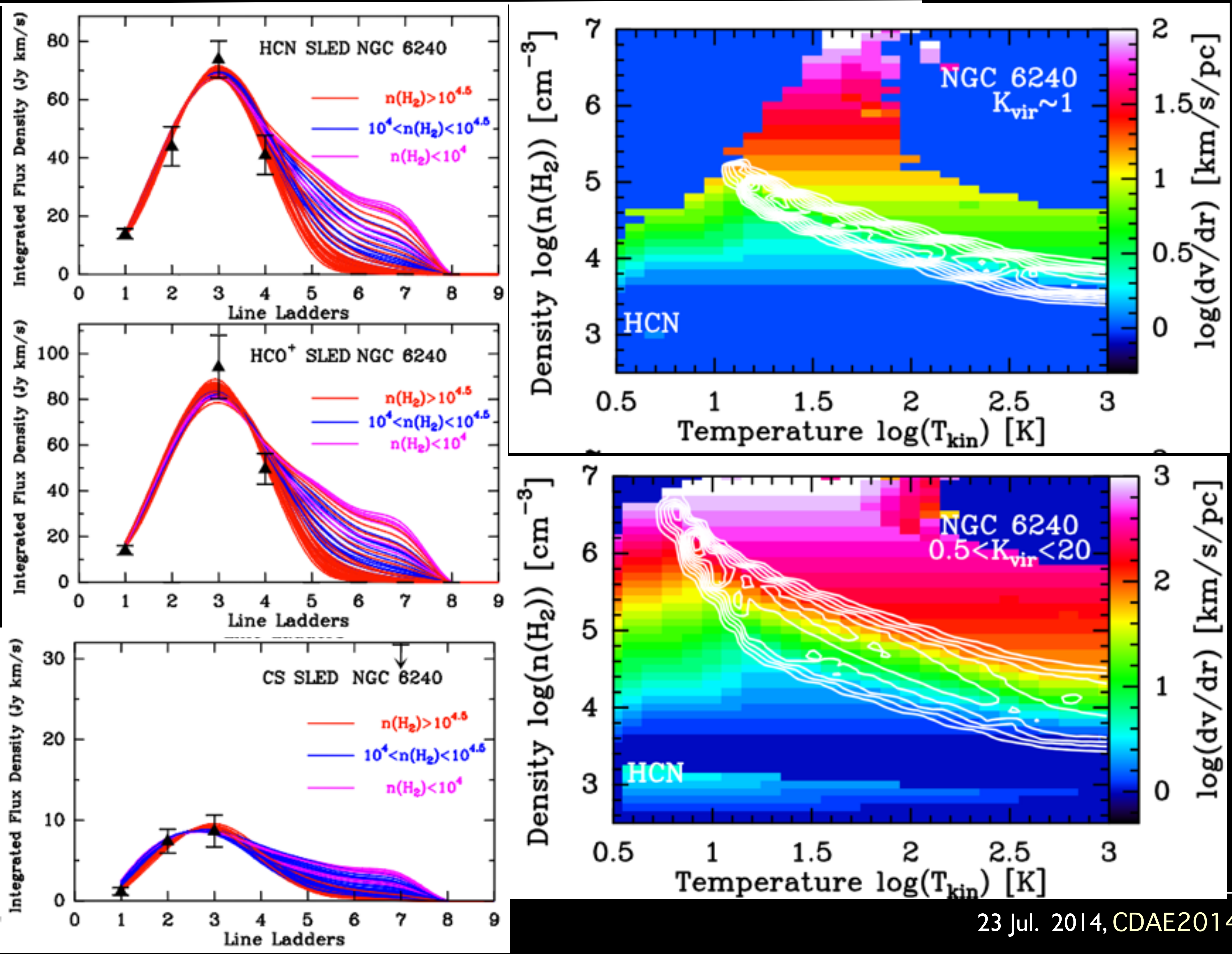
Thomas Greve

Zhi-Yu Zhang

Panos Boumis

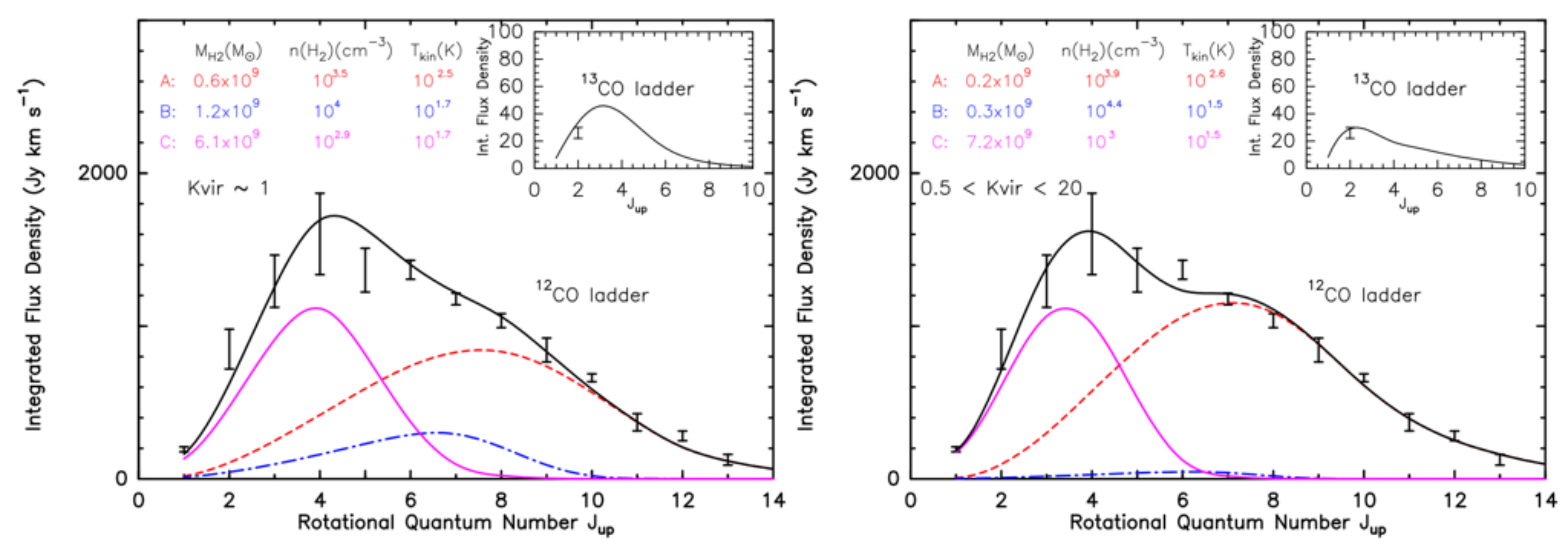
Alceste Bonanos

LVG Modelling with HCN, HCO$^+$, and CS



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.

Take Home Messages

1) Dense molecular gases ($n(H_2)$~> 10^4 cm^{-3}) are forming stars.

2) M_{dense}-SFR linearly correlates.

3) M_{dense}-SFR stays universally linear from Galactic cores to galaxies.

4) More detailed modelings are on the way.

There are dense gas without SFR, and SFR without dense gas.
Spatially resolved studies in external galaxies!
-- NOEMA/ALMA

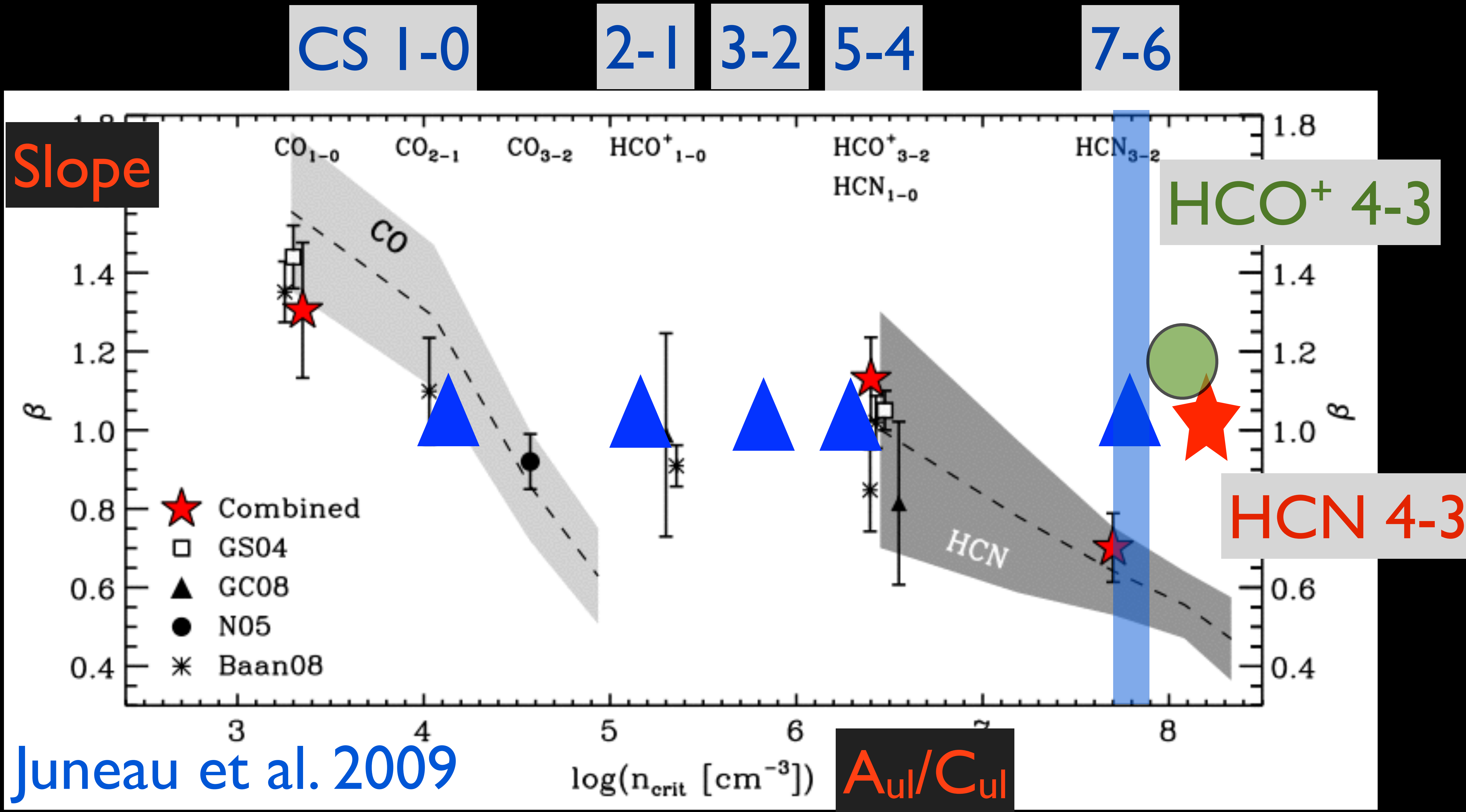
Background music: broadcasting gymnastics for Chinese schools

ALMA/NOEMA will be helpful!


Thank you!

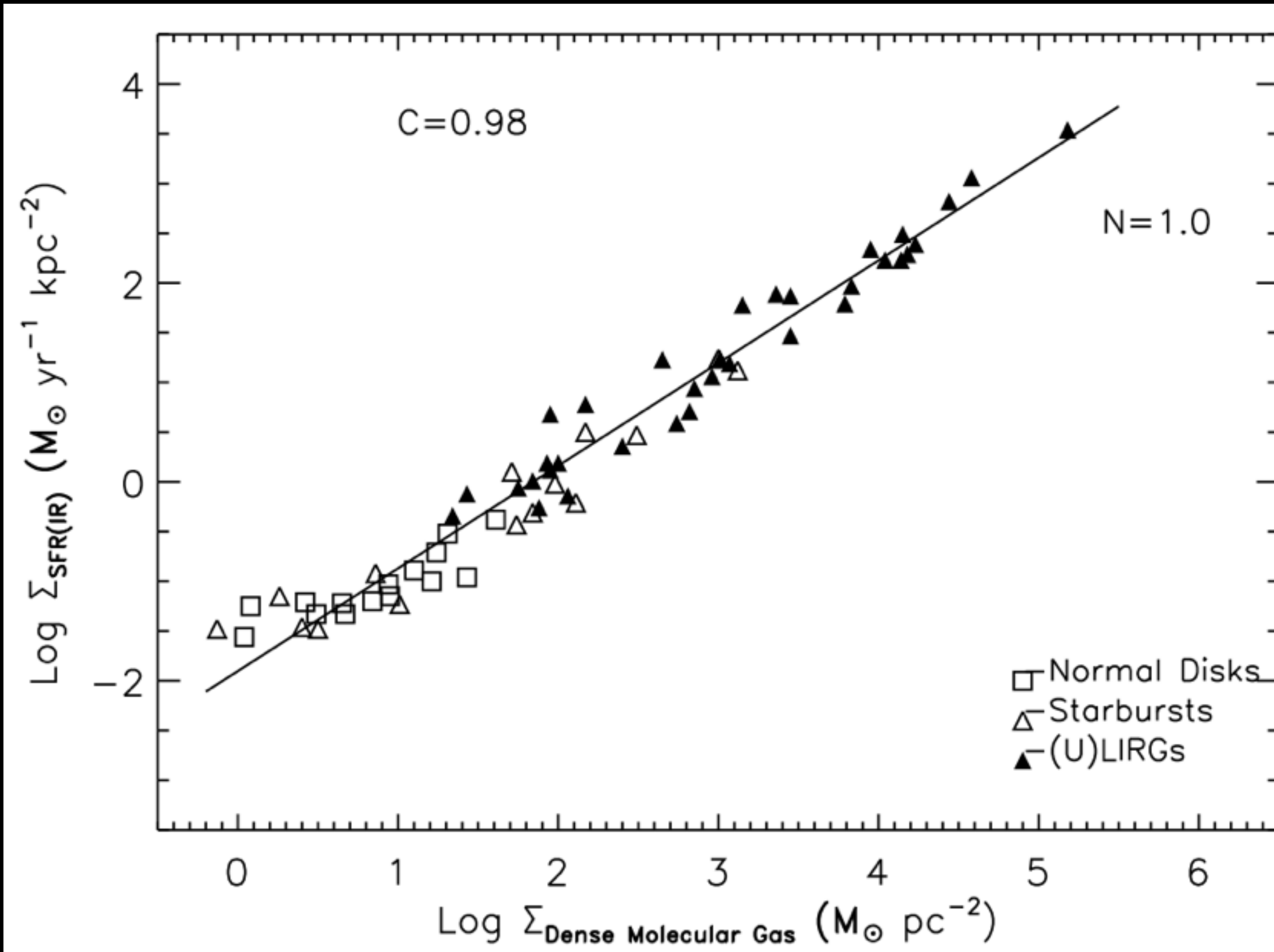
Backup Slides

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

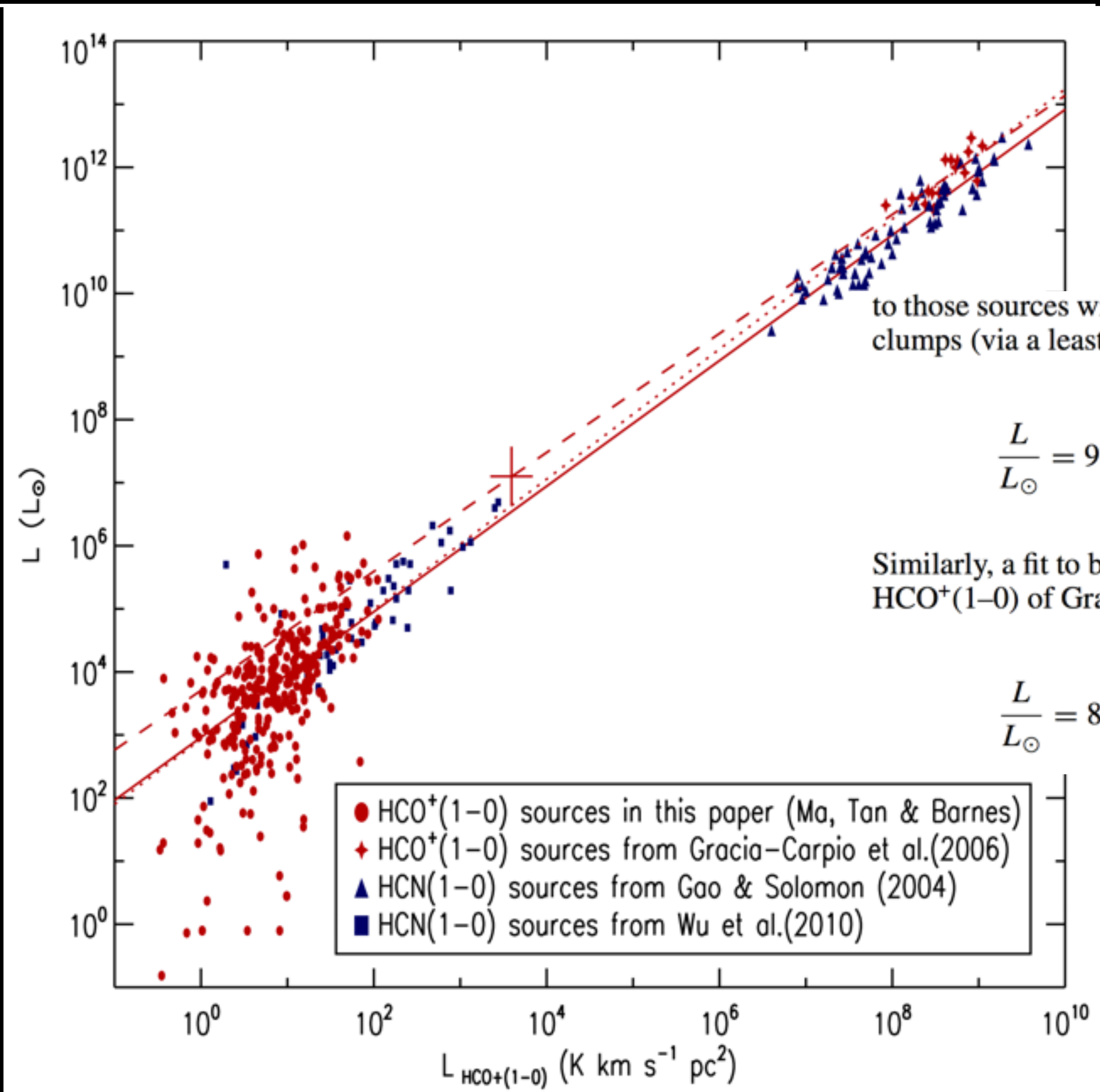


Dense gas tracers have linear correlations irrespective to n_{crit}, universally over 8 orders of luminosity magnitudes.

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

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

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

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

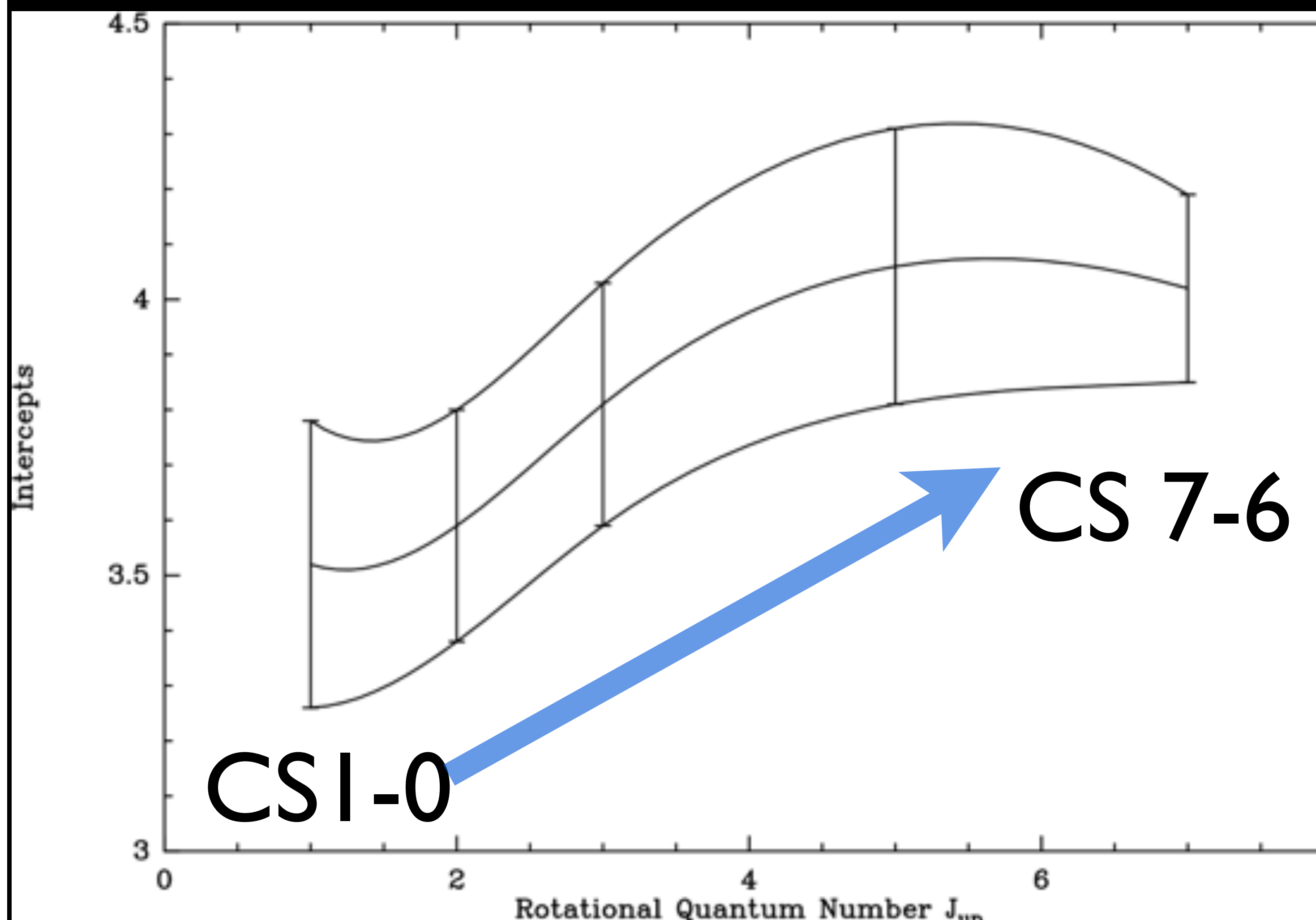
Ma et al. 2013

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

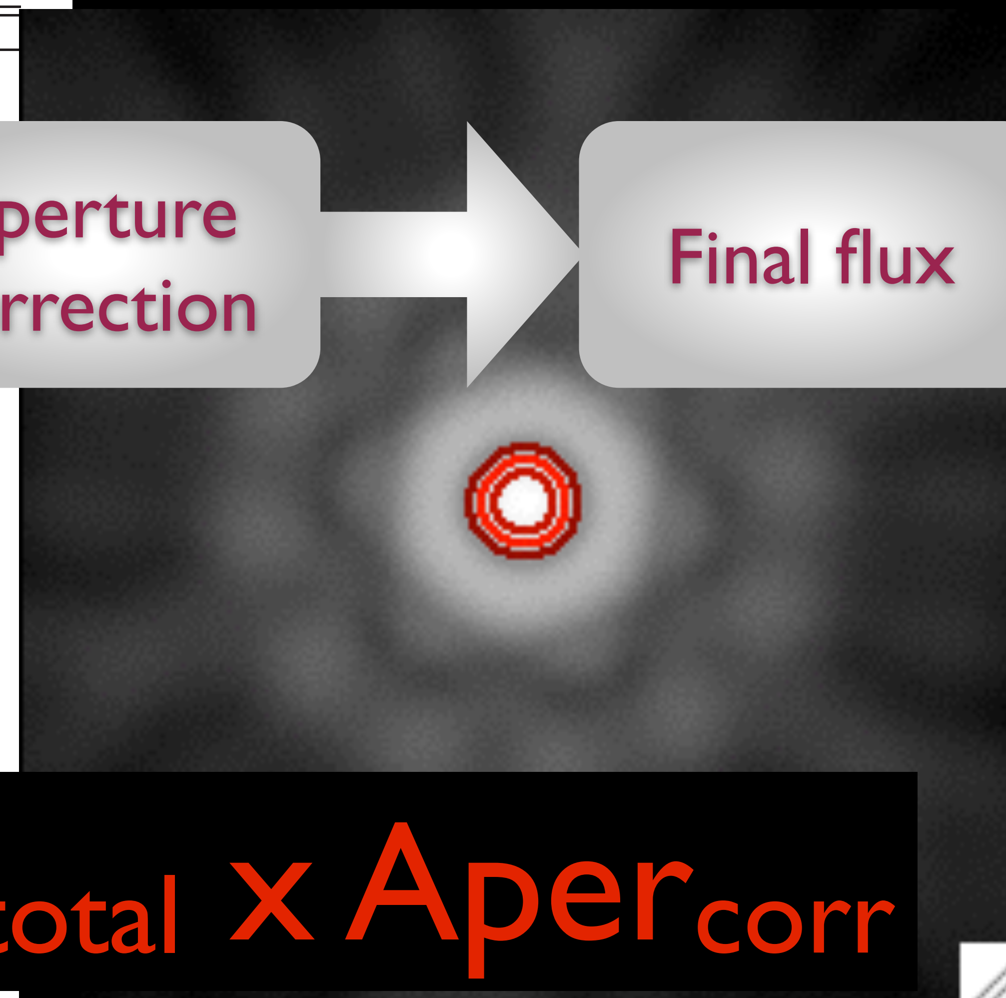
linear correlations for point targets and beam matched targets

Aperture Correction -- beams are small

:: Parameters of the photometry.

	CS2-1 (25″)				CS 3-2 (17″)			
Source name	24Ratio	24Apercor	70Ratio	70Apercor	24Ratio	24Apercor	70Ratio	70Apercor
[illegible]	[illegible]	1.17	[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]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[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



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

50K blackbody PSF

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.

Wu et al. 2010 Galactic CS

CS 2–1:

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

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

CS 5–4:

Least squares fit : log(L

Robust fit : log(L_{IR}

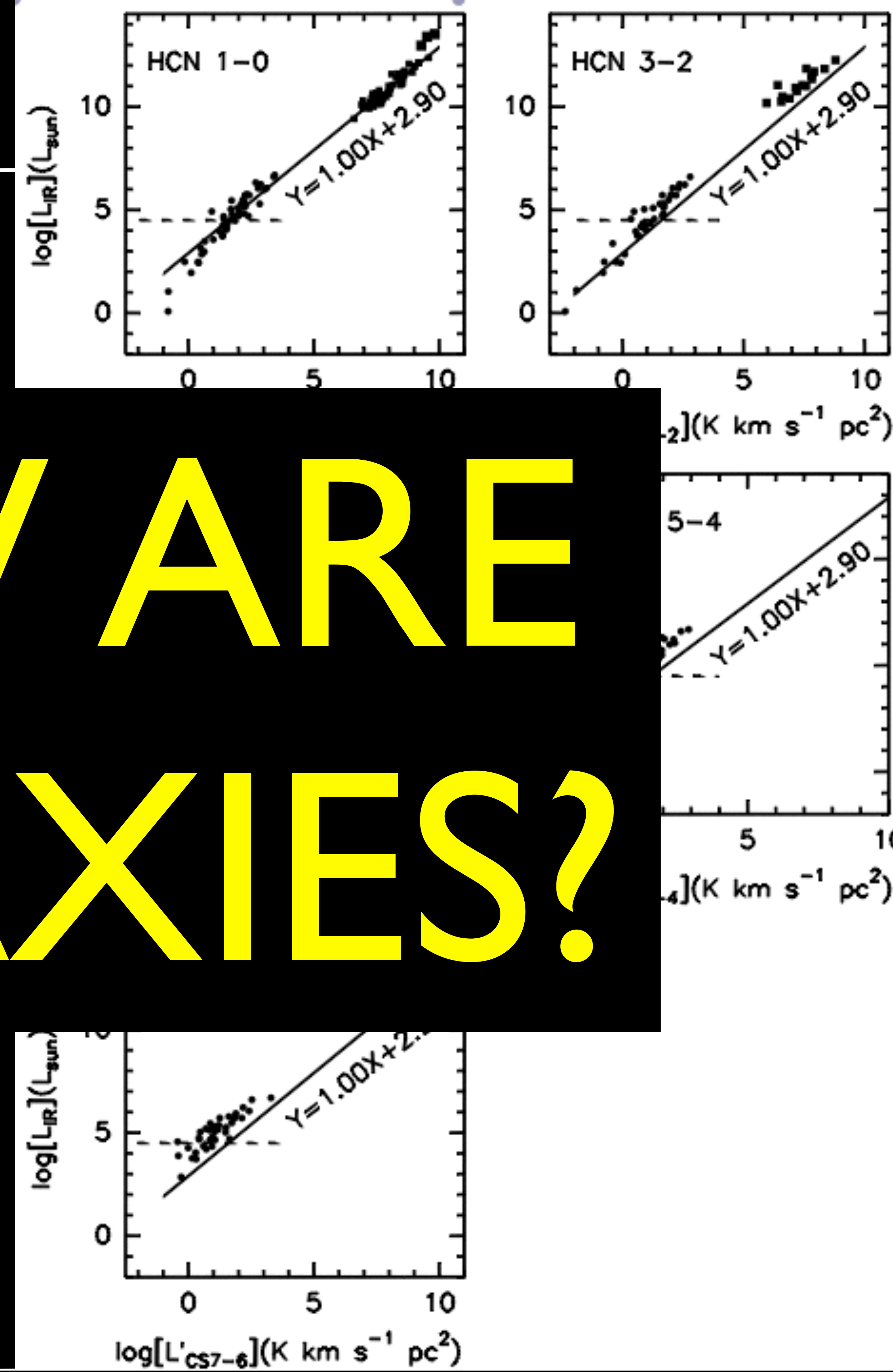
CS 7–6:

Least squares fit : log(L

Robust fit : log(L_{IR}

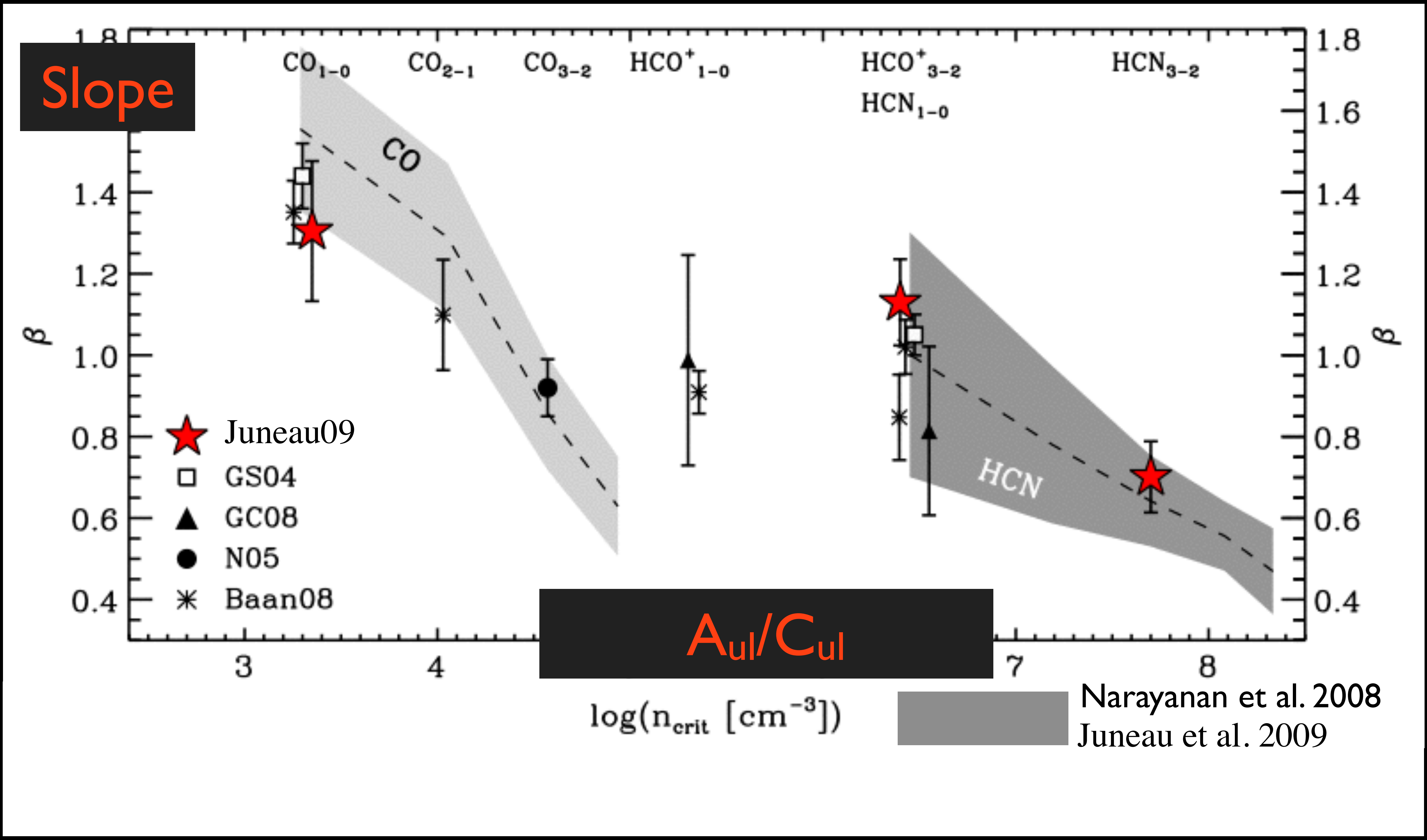
HOW ARE GALAXIES?

The average de... massive clumps i... et al. 1997), less ... this study except... 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).

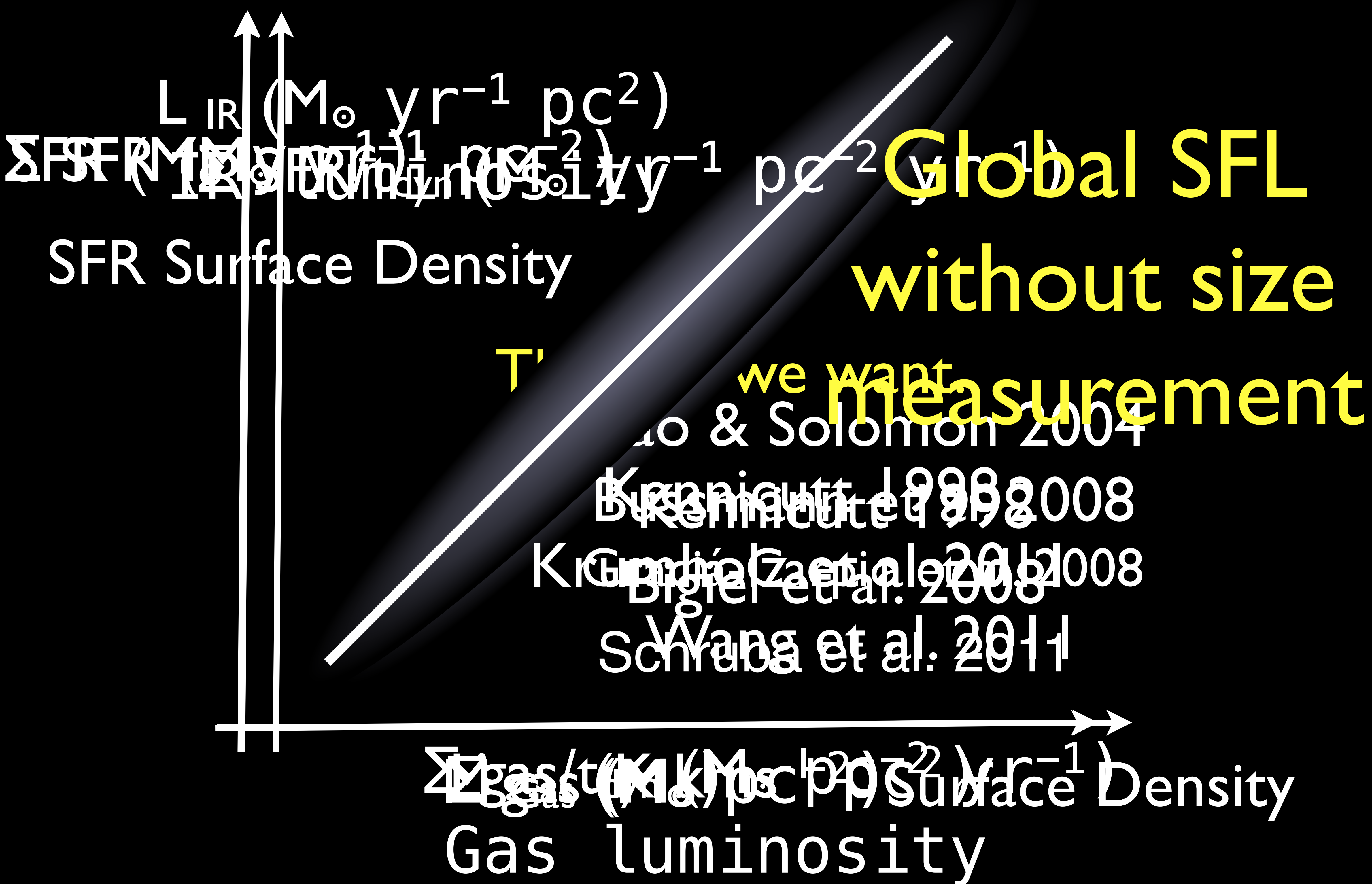


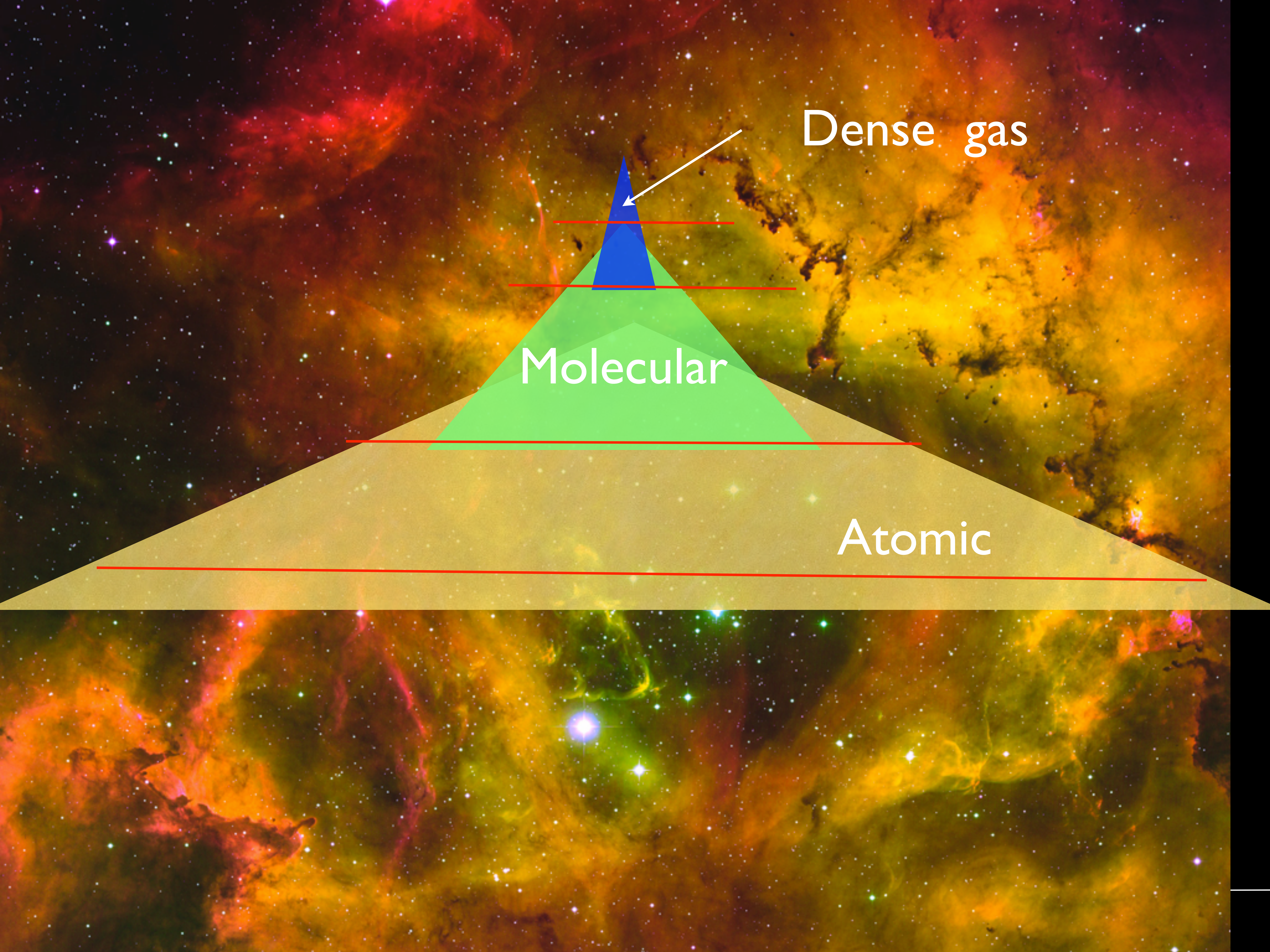
Simulations vs. Observations

higher transitions/densities have lower slope indices.

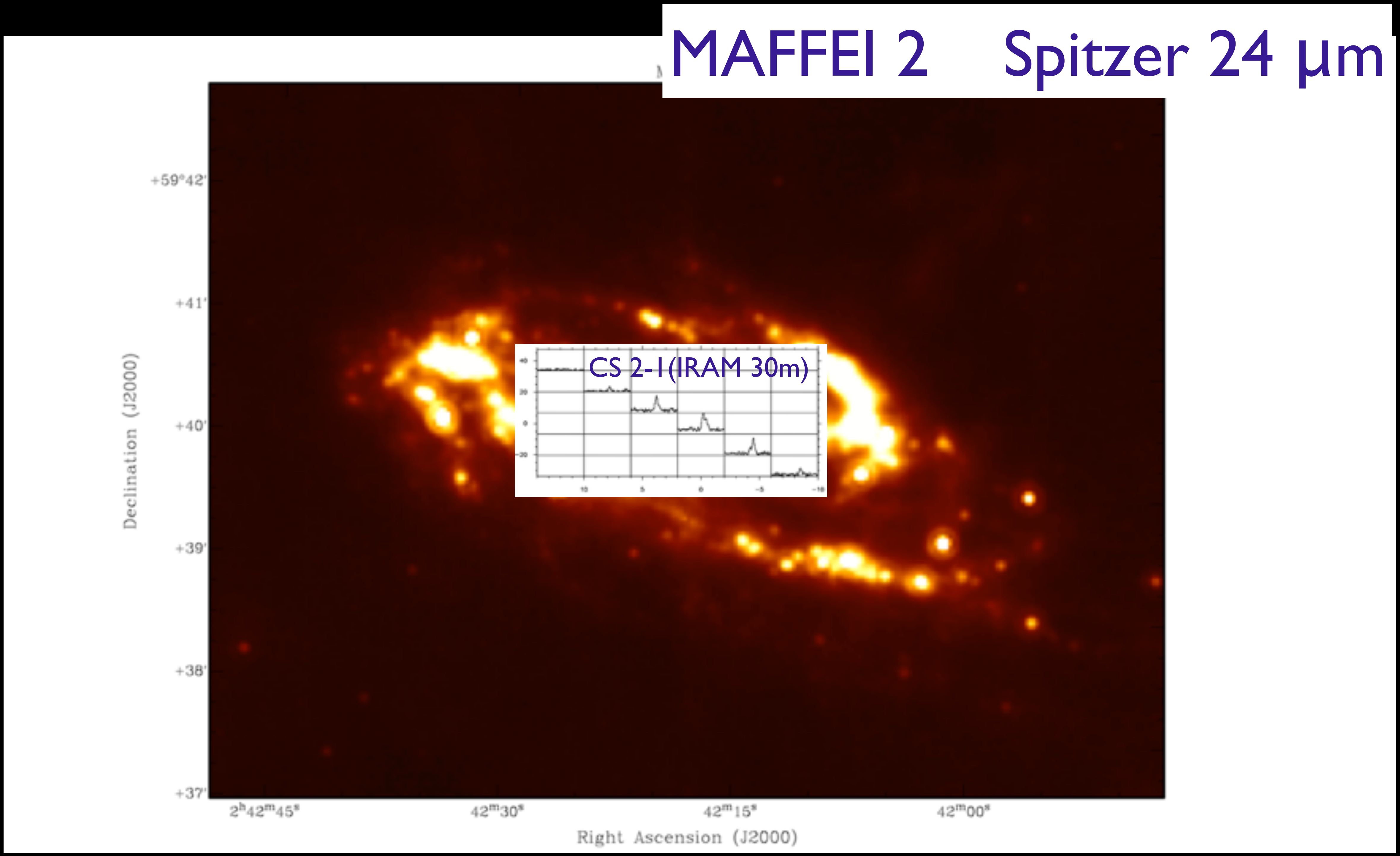


Star Formation Law (Units)




Dense gas
Molecular
Atomic

Extended CS emission on the disk



Dense gas tracers

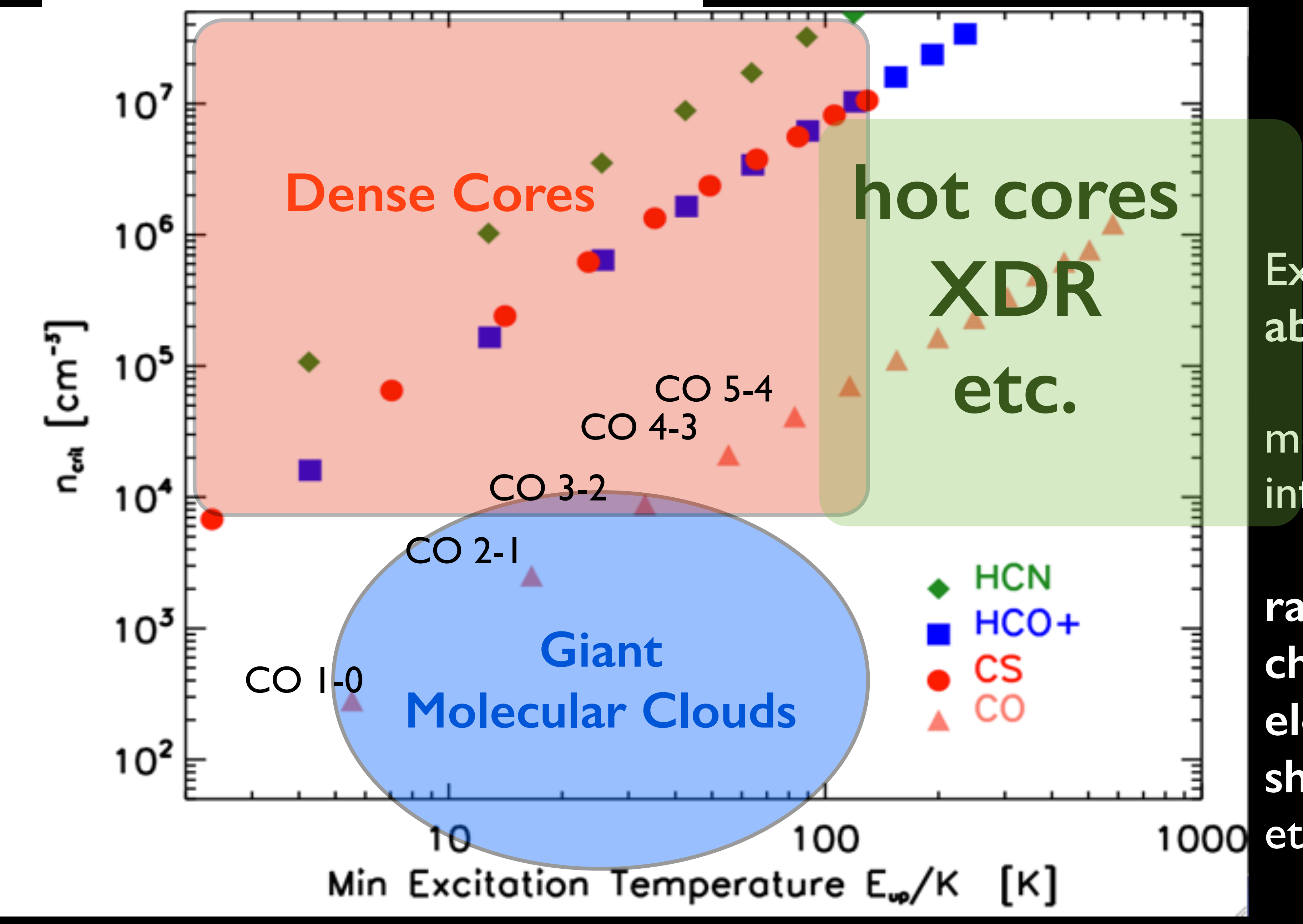
Critical Density:

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

Rotational transitions of heavy molecules

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

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



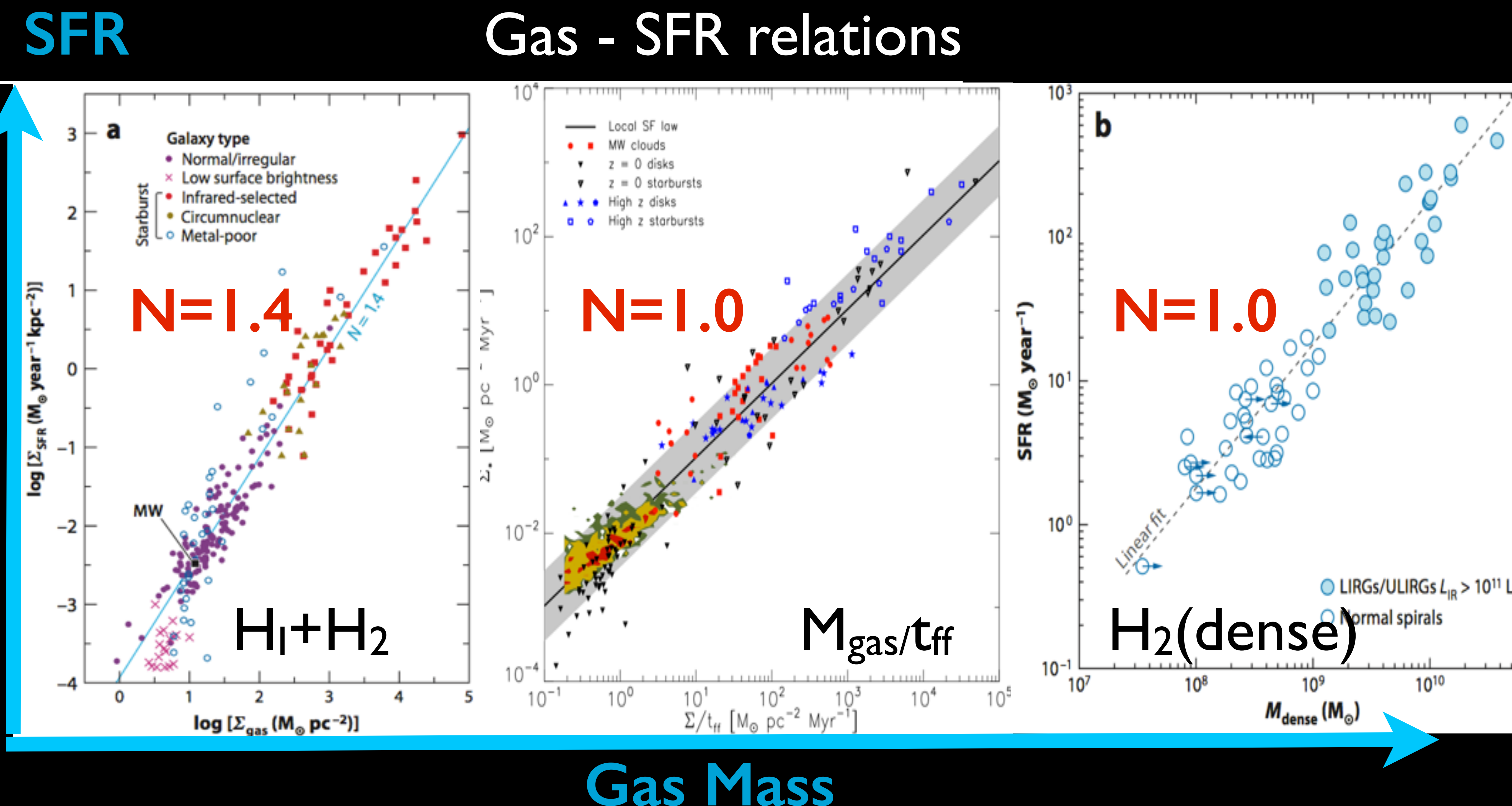
Except for abundance and excitation,

molecular emissions can be influenced by:

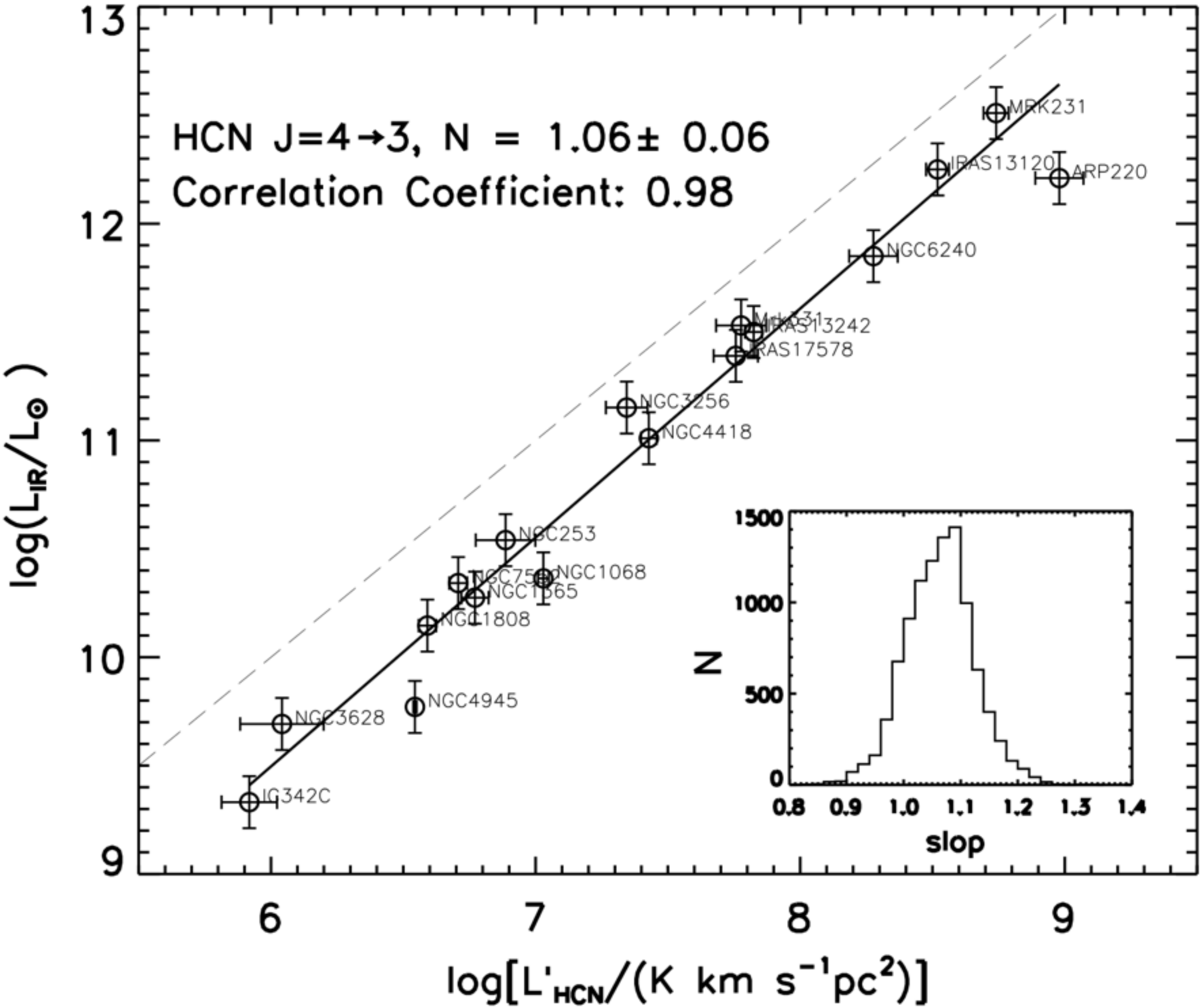
radiative pumping,
chemistry,
electron density,
shock dissociation,
etc.

Molecule	Transitions J	Frequency (GHz)	$E_{\rm upper}$ (K)	$n_{\rm crit}$(100 K) (cm^{-3})	$A_{\rm ul}/\Gamma_{\rm ul}$(100 K) (cm^{-3})	$n_{\rm crit}$(20 K) (cm^{-3})	$A_{\rm ul}/\Gamma_{\rm ul}$(20 K) (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

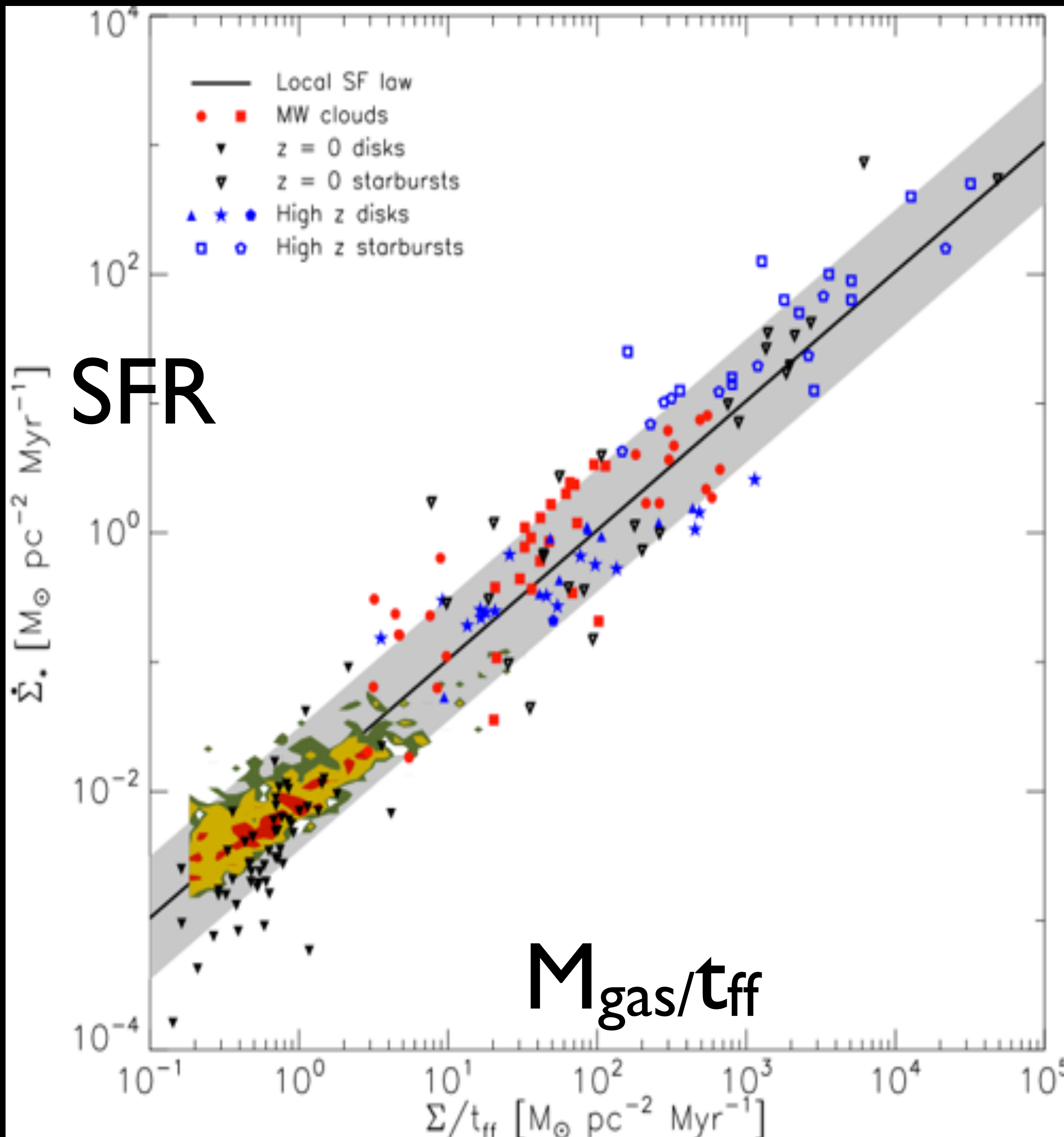
Gas - SFR relations



Kennicutt 1998 | Krumholz et al. 2012 | Gao & Solomon 2004


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

Does time scales matter? -- For Dense gas: No.



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

Krumholz et al. 2012

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.

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.

$$HCO^+ + e \rightarrow CO + H$$

High radiation fields in ULIRGs

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

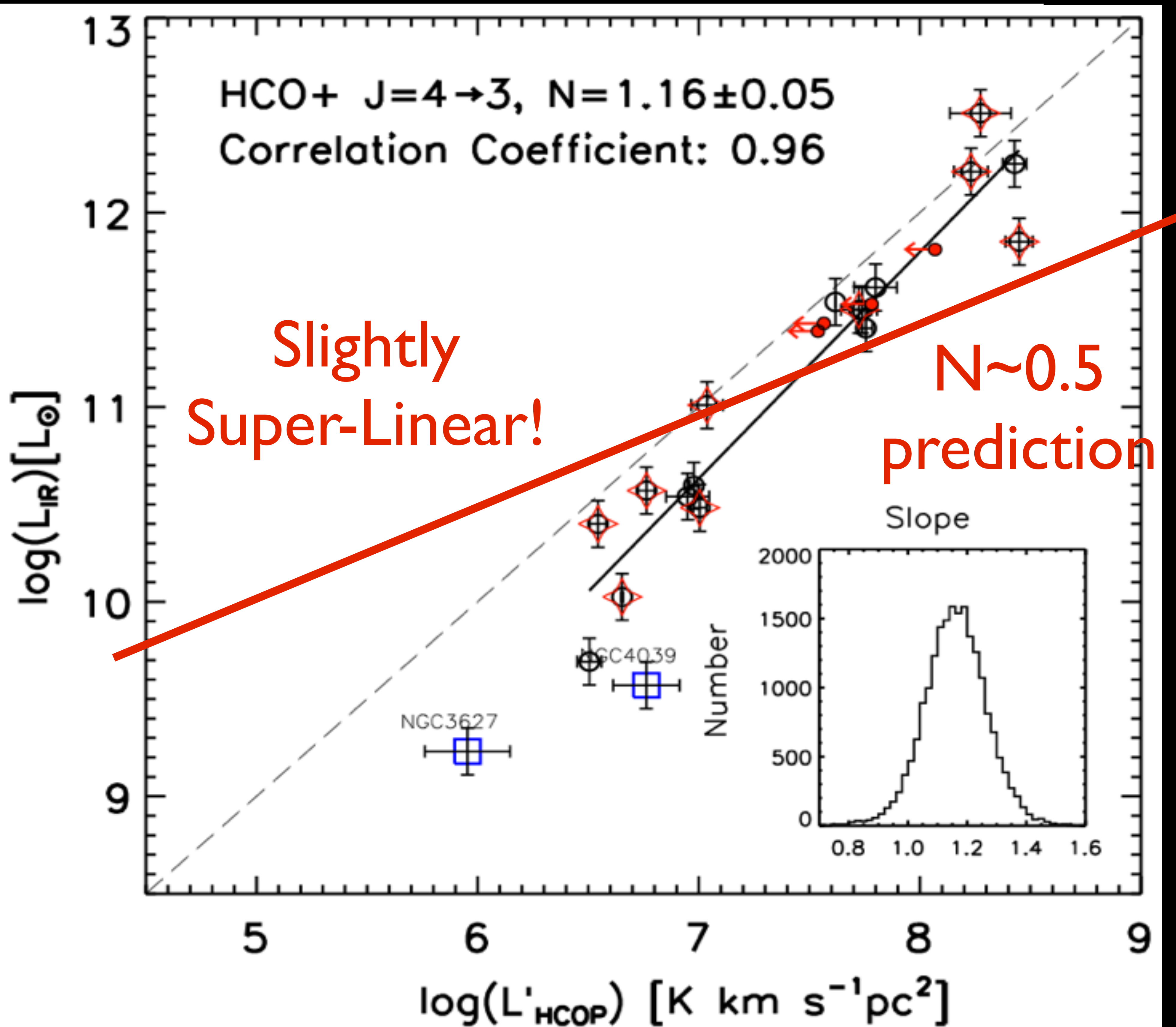
Papadopoulos et al. 2007

Shock environment

Shocks produce electron-rich outer layers

Xie et al. 1995

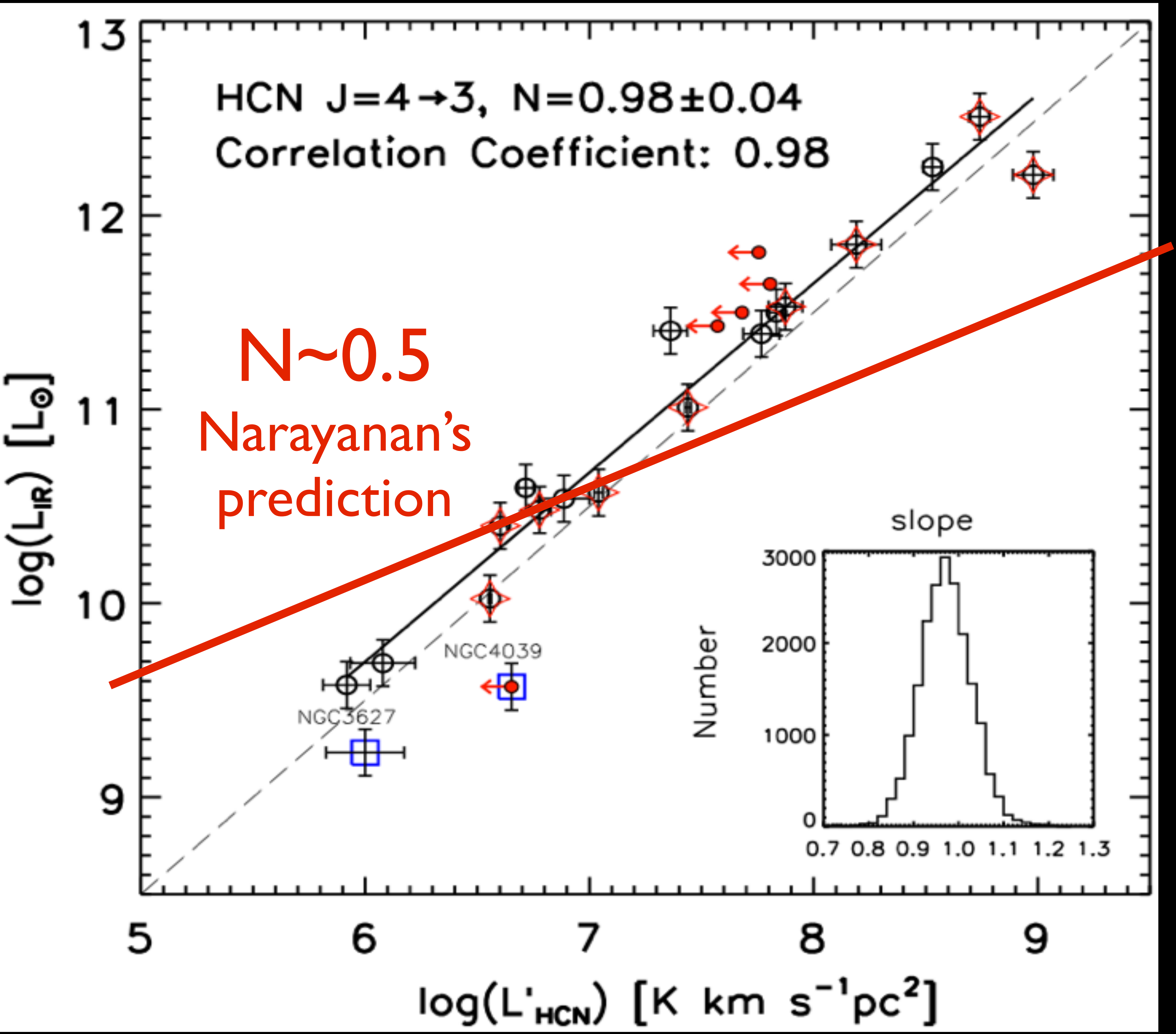
HCO^+ J=4-3 -- observed simultaneously with CS J=7-6



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

Zhang et al. 2014

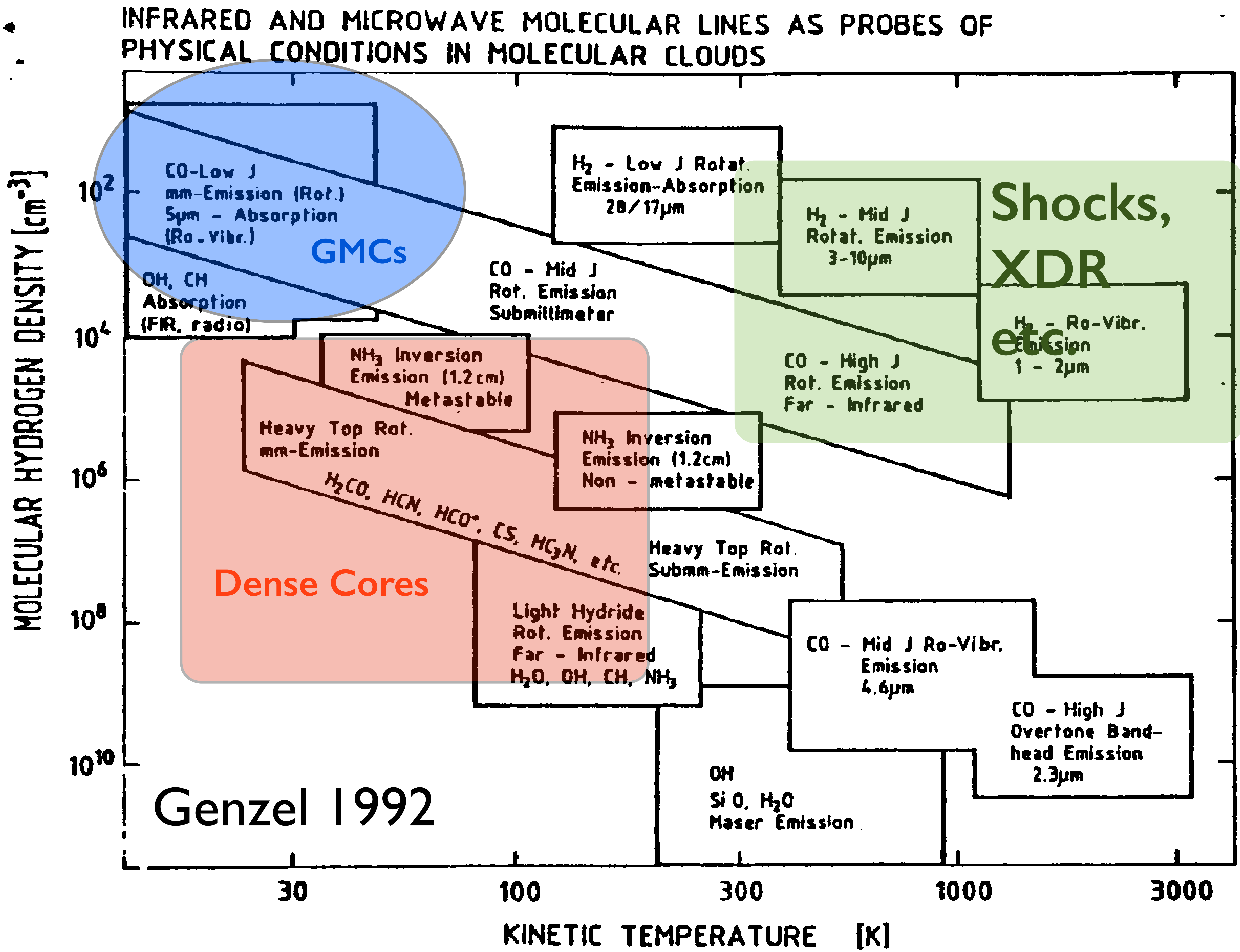
HCN J=4-3 -- the highest n_{crit} tracer



n_{crit}~ 1x10^{7}cm^{-3}

Zhang et al. 2014

Tracers of Physical Conditions in Molecular Clouds



Why slopes matter? Different SFE

Which gases are forming stars?