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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et al.

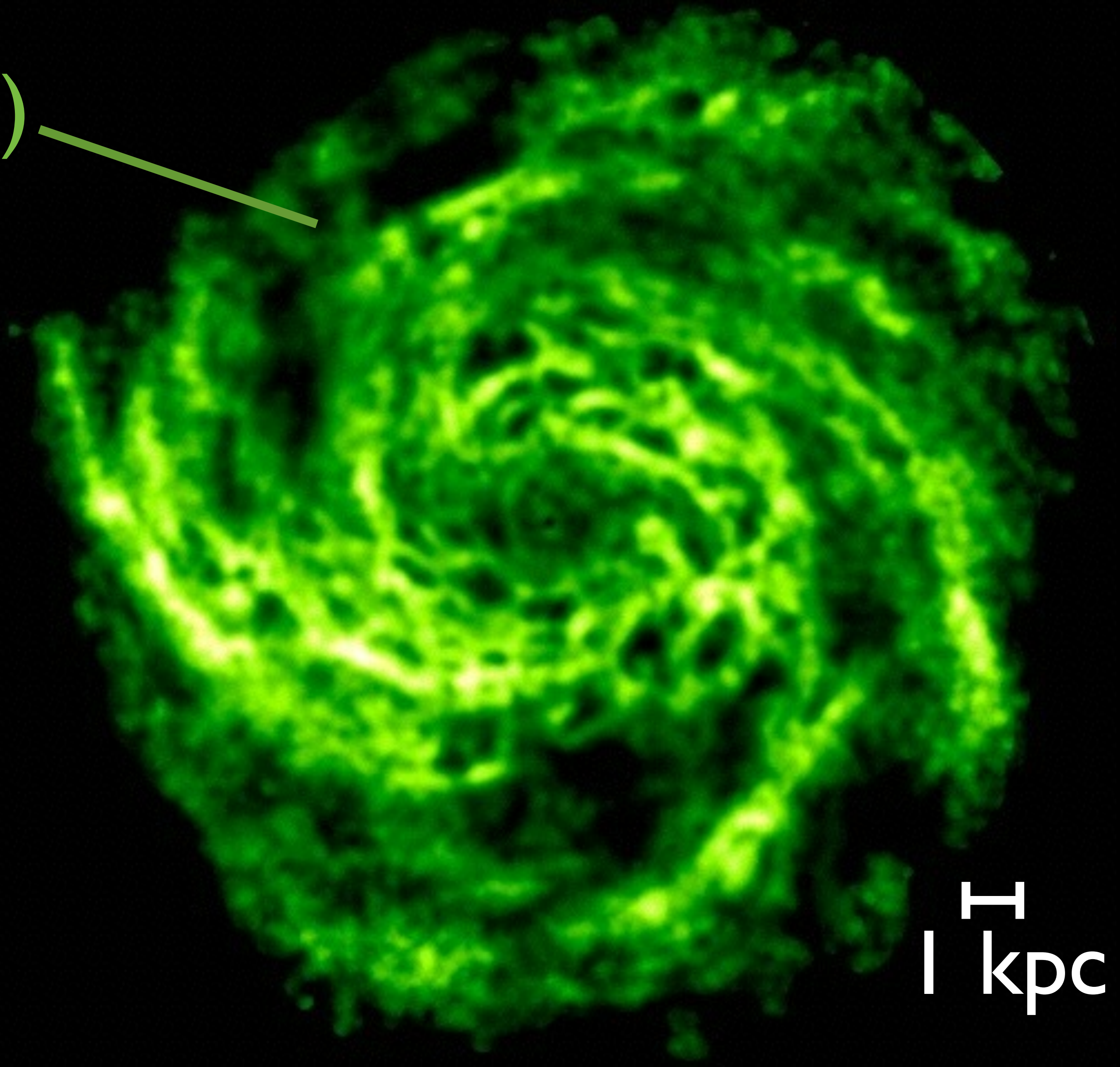
Outline

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

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

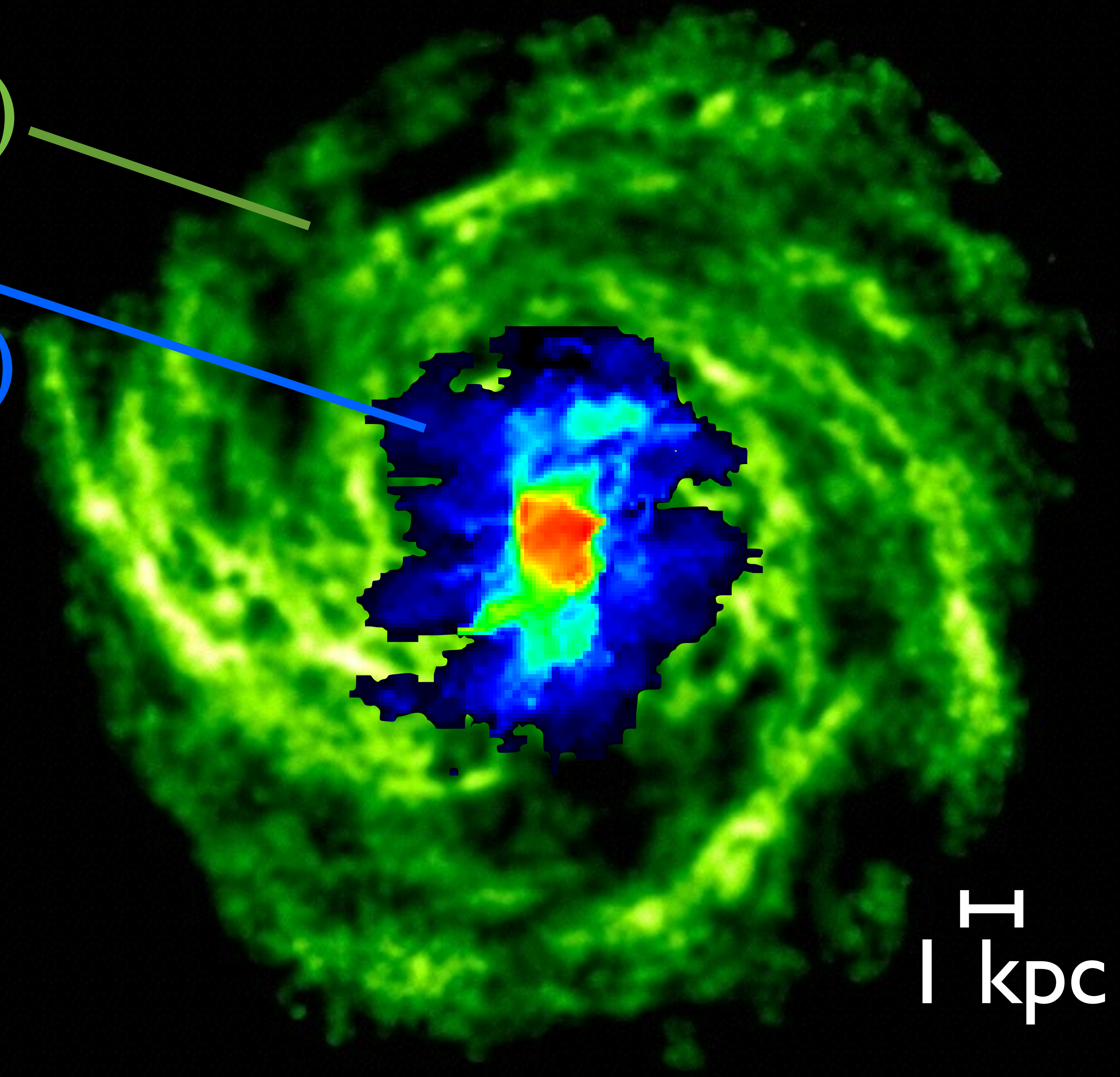
- Summary

Which gases are forming stars?



THINGS

Which gases are forming stars?



IC 342

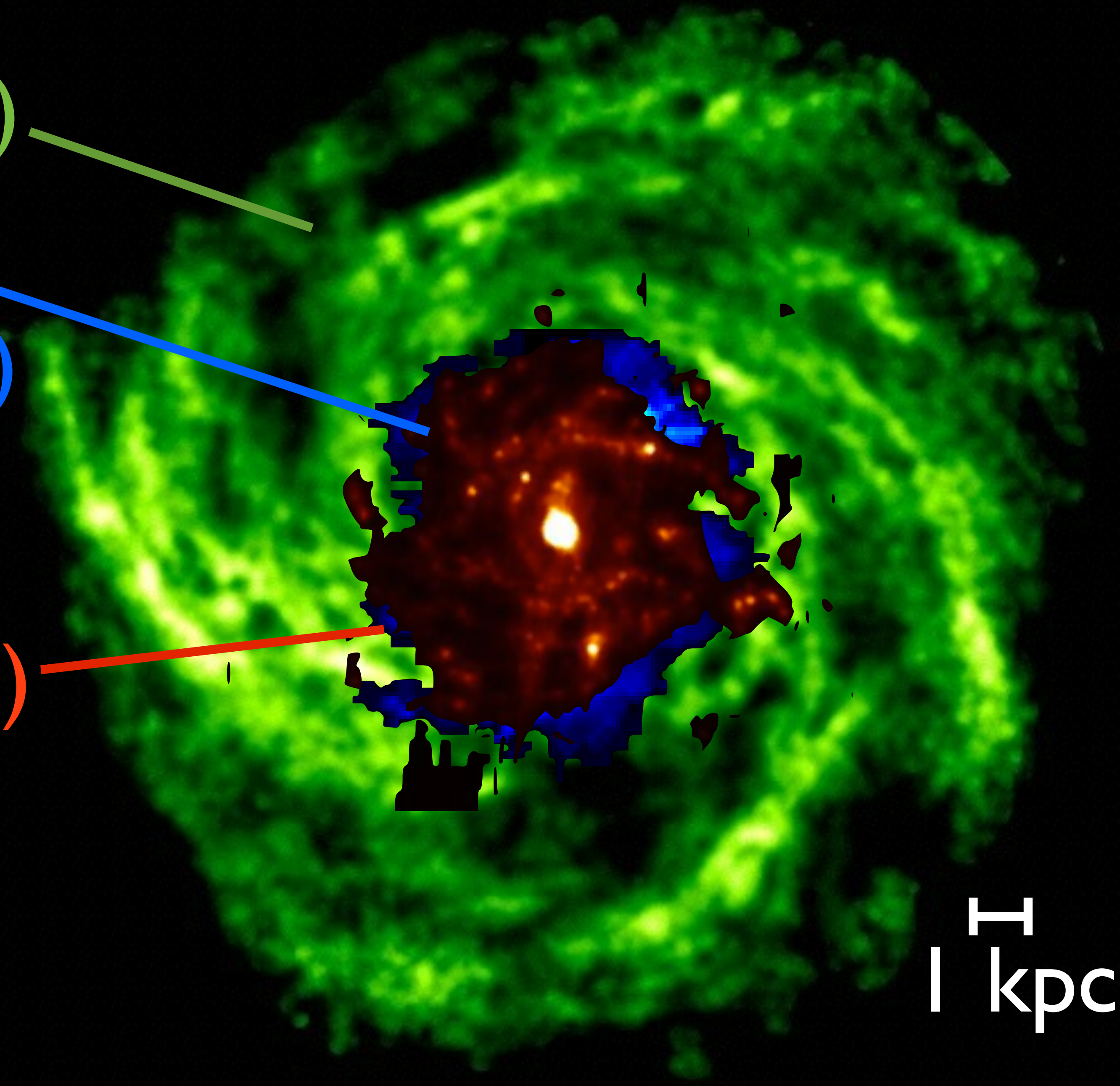
HI (atomic gas)

^{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 related to H_2 gas, rather than HI

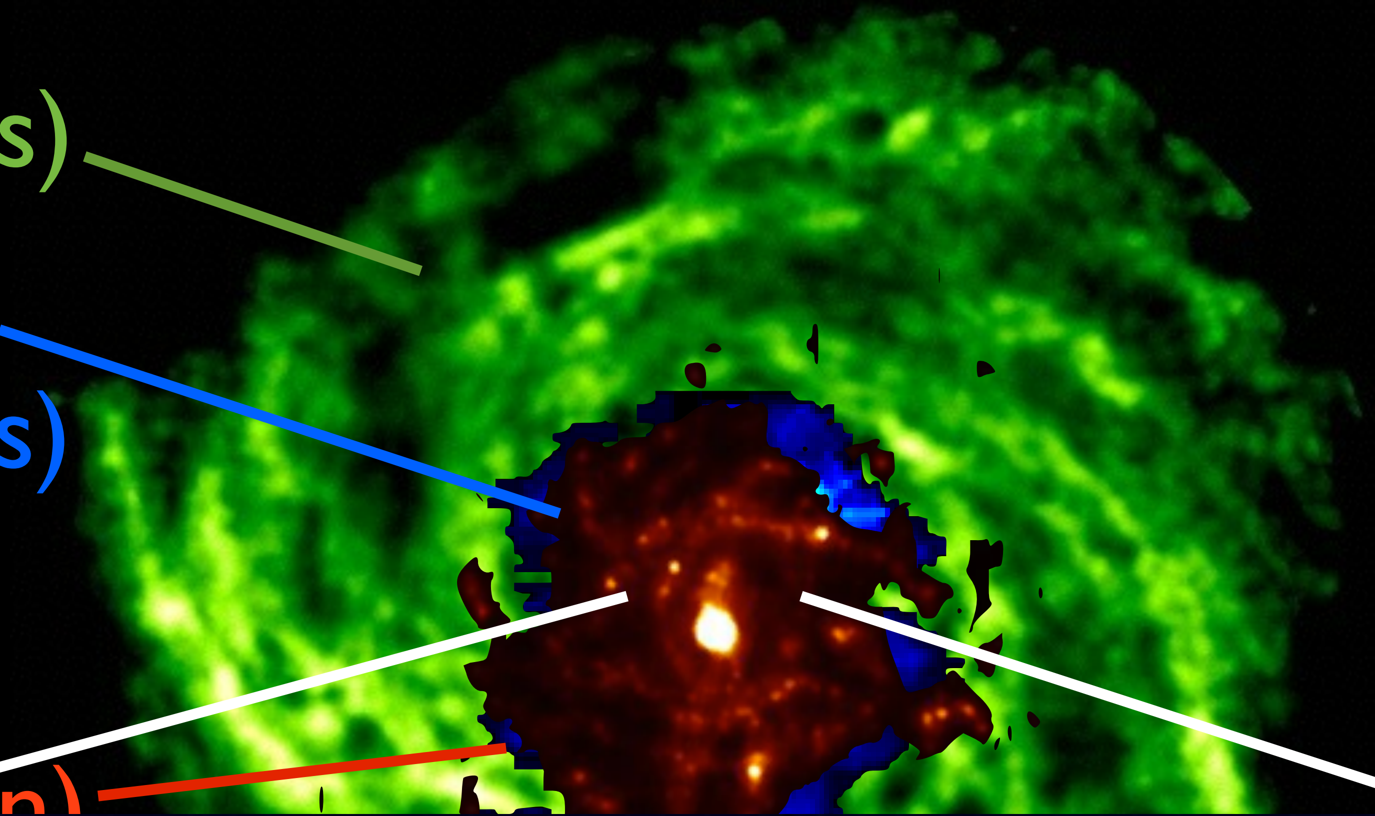
Which gases are forming stars?

IC 342

HI (atomic gas)

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

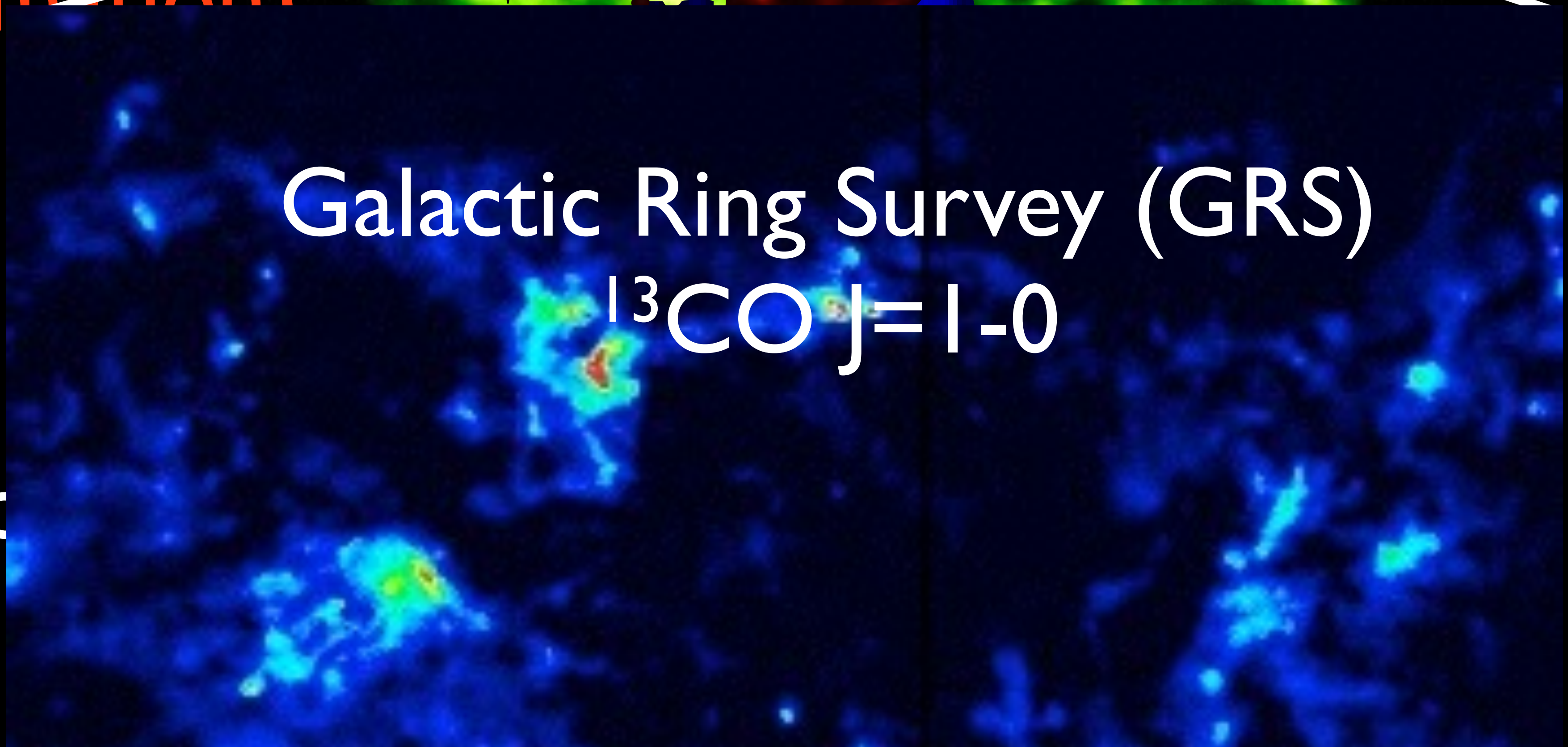
IR emission
(star formation)



THINGS

NRAO 12m

Spitzer 70um

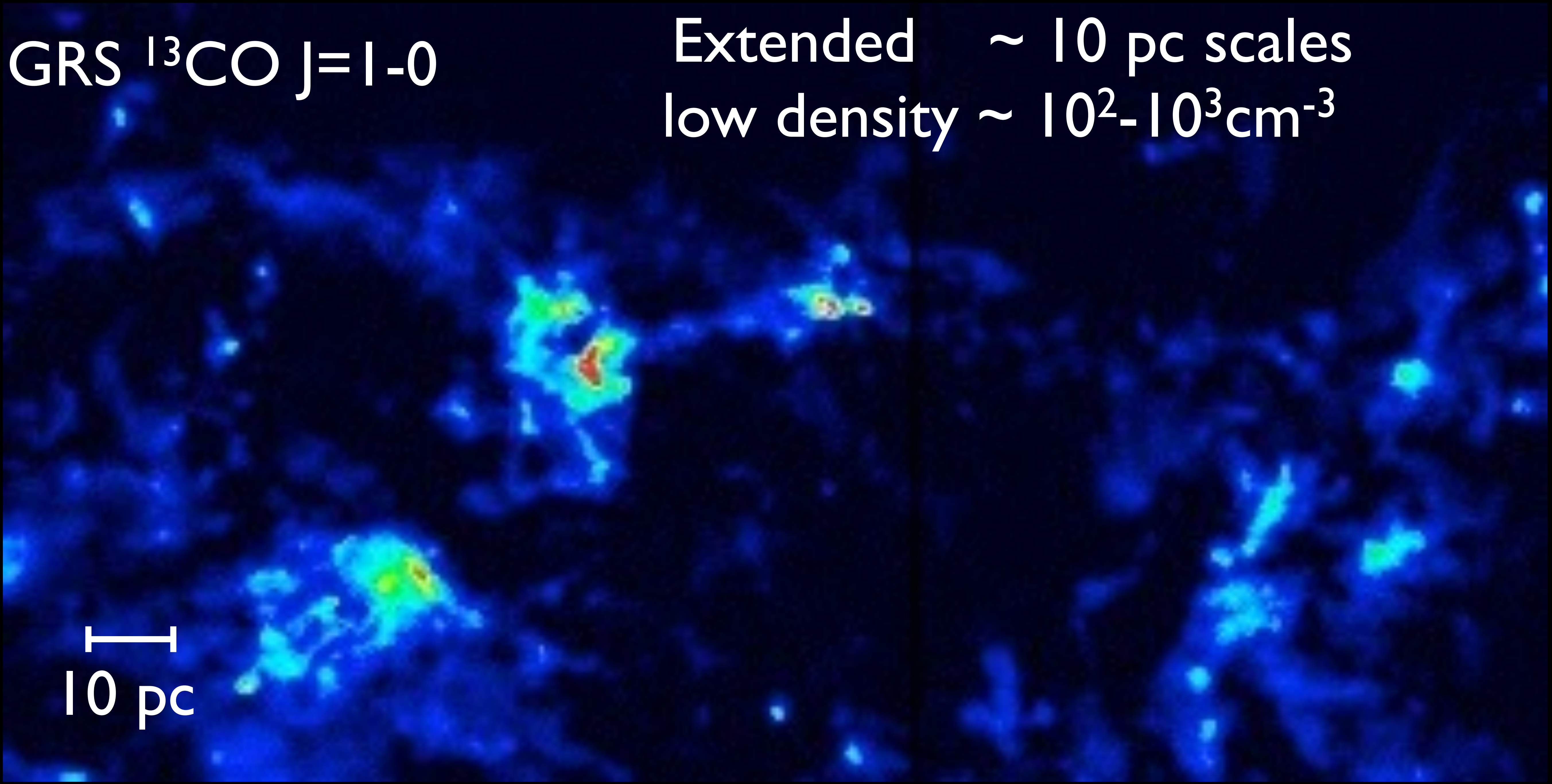


Galactic Ring Survey (GRS)
^{13}CO J=1-0

On kpc

than HI

Which gases are forming stars? - Galactic view

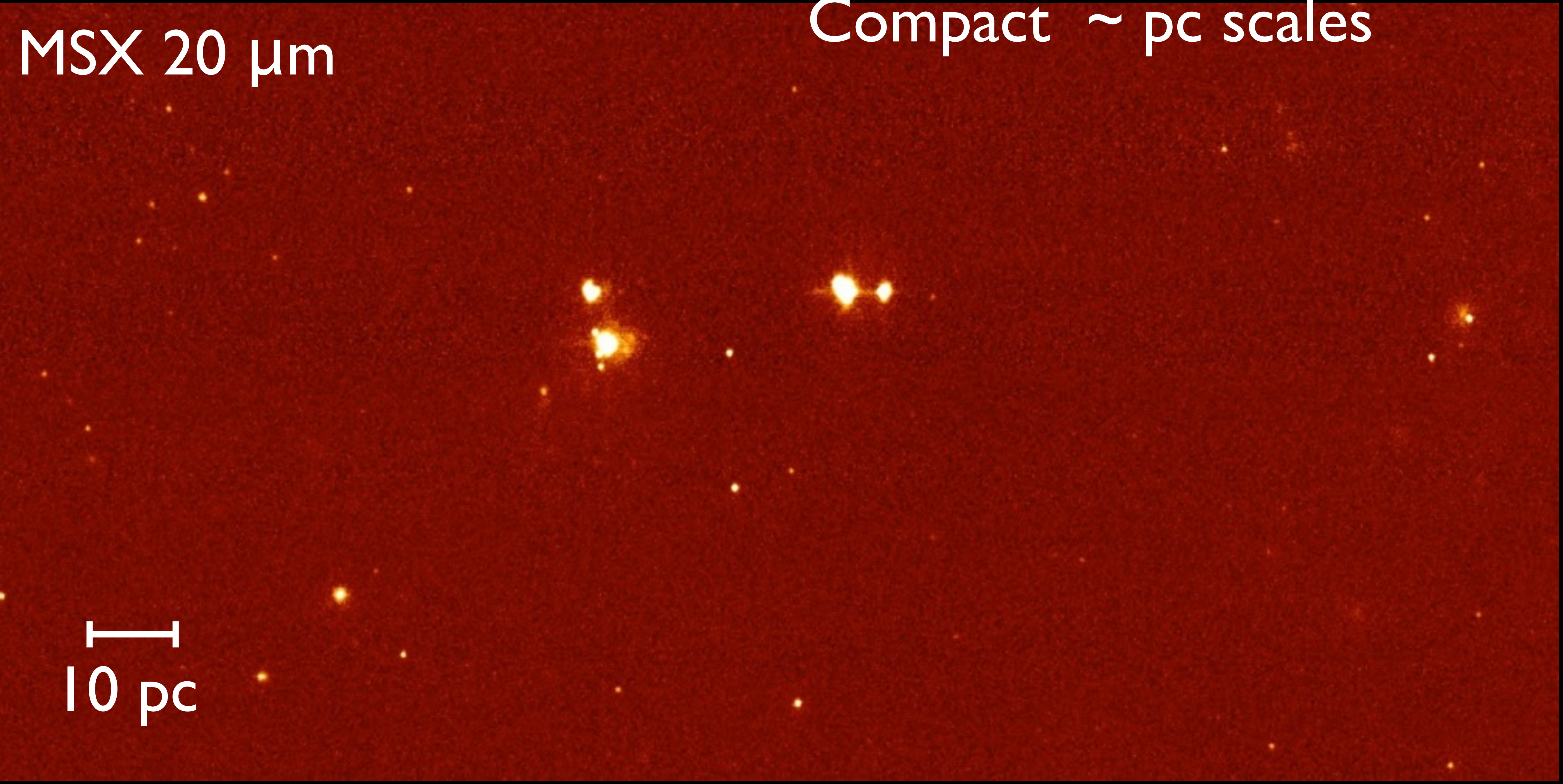


GRS ^{13}CO J=1-0

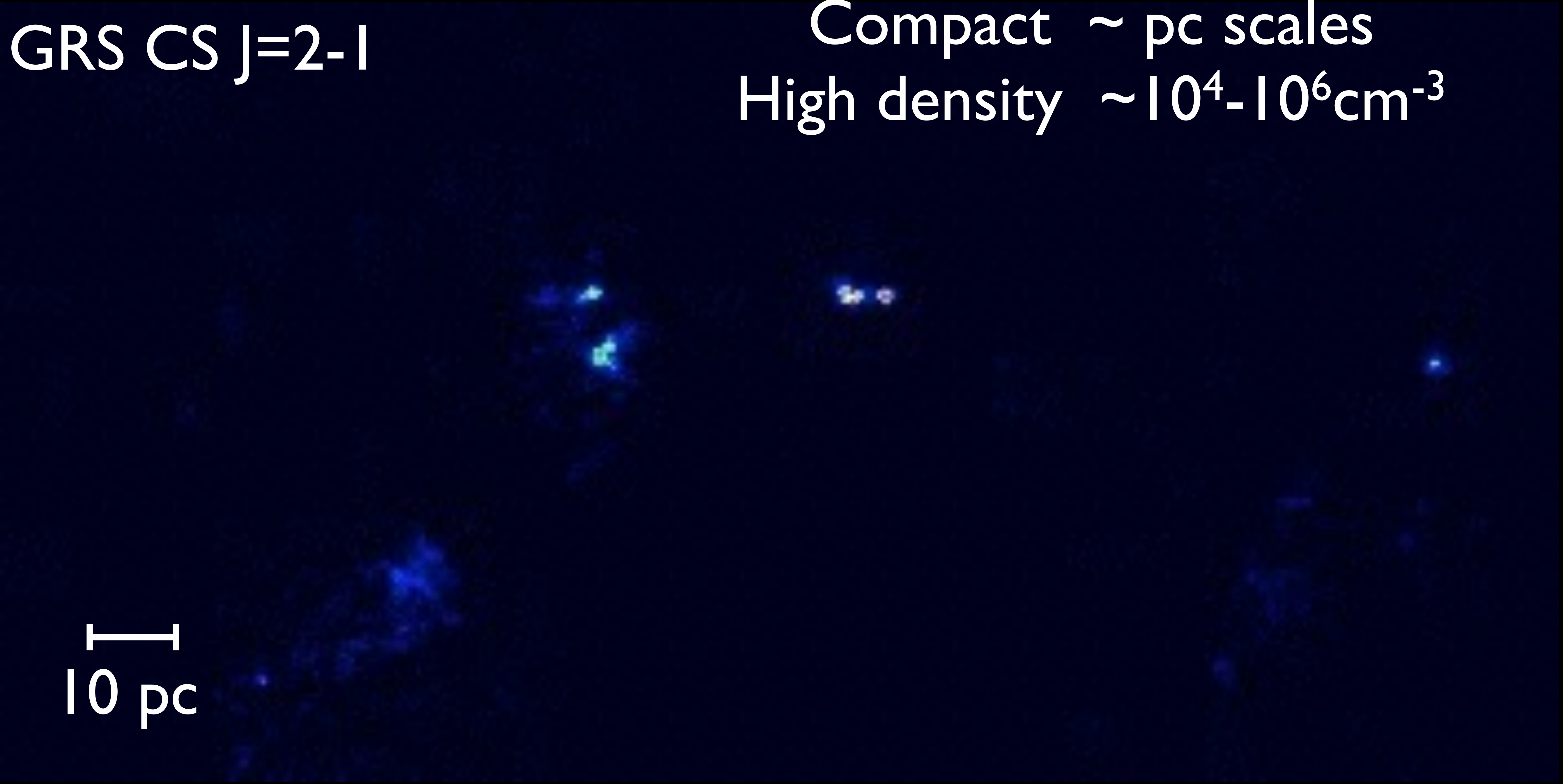
Extended ~ 10 pc scales

low density ~ 10^2-10^3cm^{-3}

Which gases are forming stars? - Galactic view



Which gases are forming stars? - Galactic view



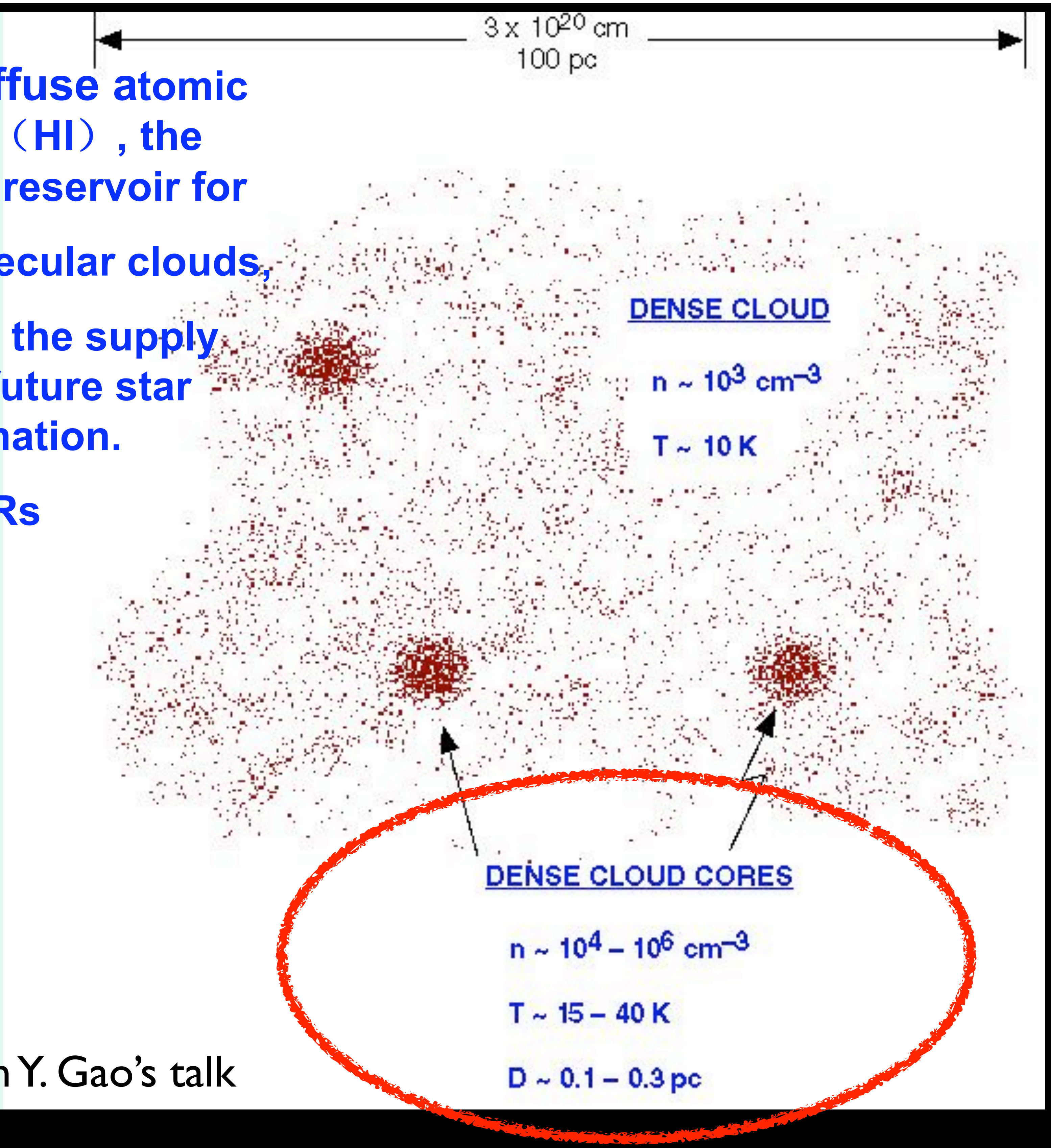
Compact ~ pc scales

High density ~10^4-10^6cm^{-3}

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



3×10^{20} cm

100 pc

DENSE CLOUD

n ~ 10^3 cm^{-3}

T ~ 10 K

DENSE CLOUD CORES

n ~ 10^4 – 10^6 cm^{-3}

T ~ 15 – 40 K

D ~ 0.1 – 0.3 pc

from Y. Gao's talk

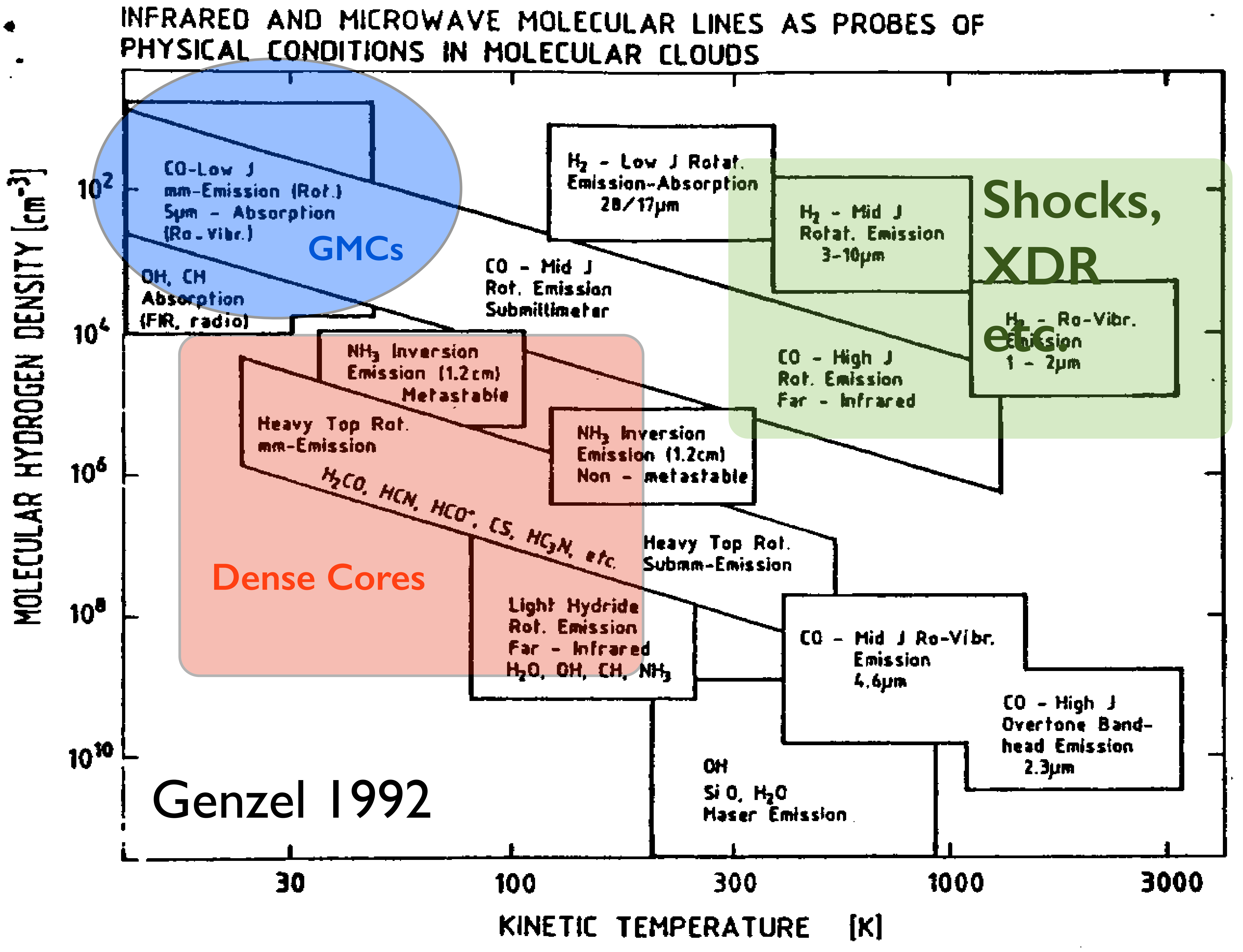
GMCs:

$n(H_2)$ ~ 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 - 40 K
D ~ 0.1- 0.3 pc
self-gravity bound

Tracers of Physical Conditions in Molecular Clouds



INFRARED AND MICROWAVE MOLECULAR LINES AS PROBES OF PHYSICAL CONDITIONS IN MOLECULAR CLOUDS

Genzel 1992

Dense gas tracers

When $n(H_2) > n_{crit}$:

Collisional excitation dominant.

Easily be thermalized.

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

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, n_e, and B-field.

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

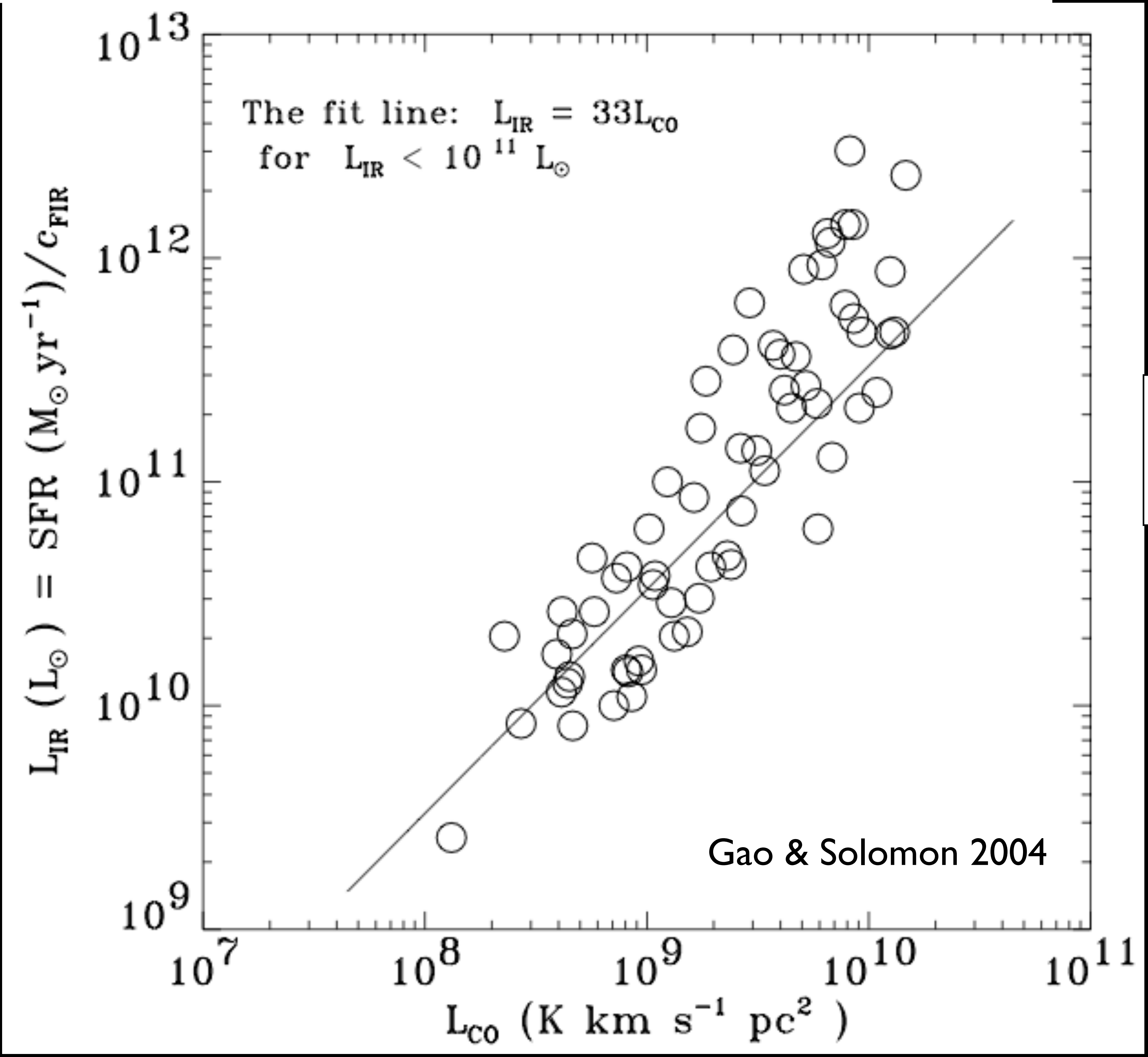
high-J CO : Do not trace cold and dense gas.

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})

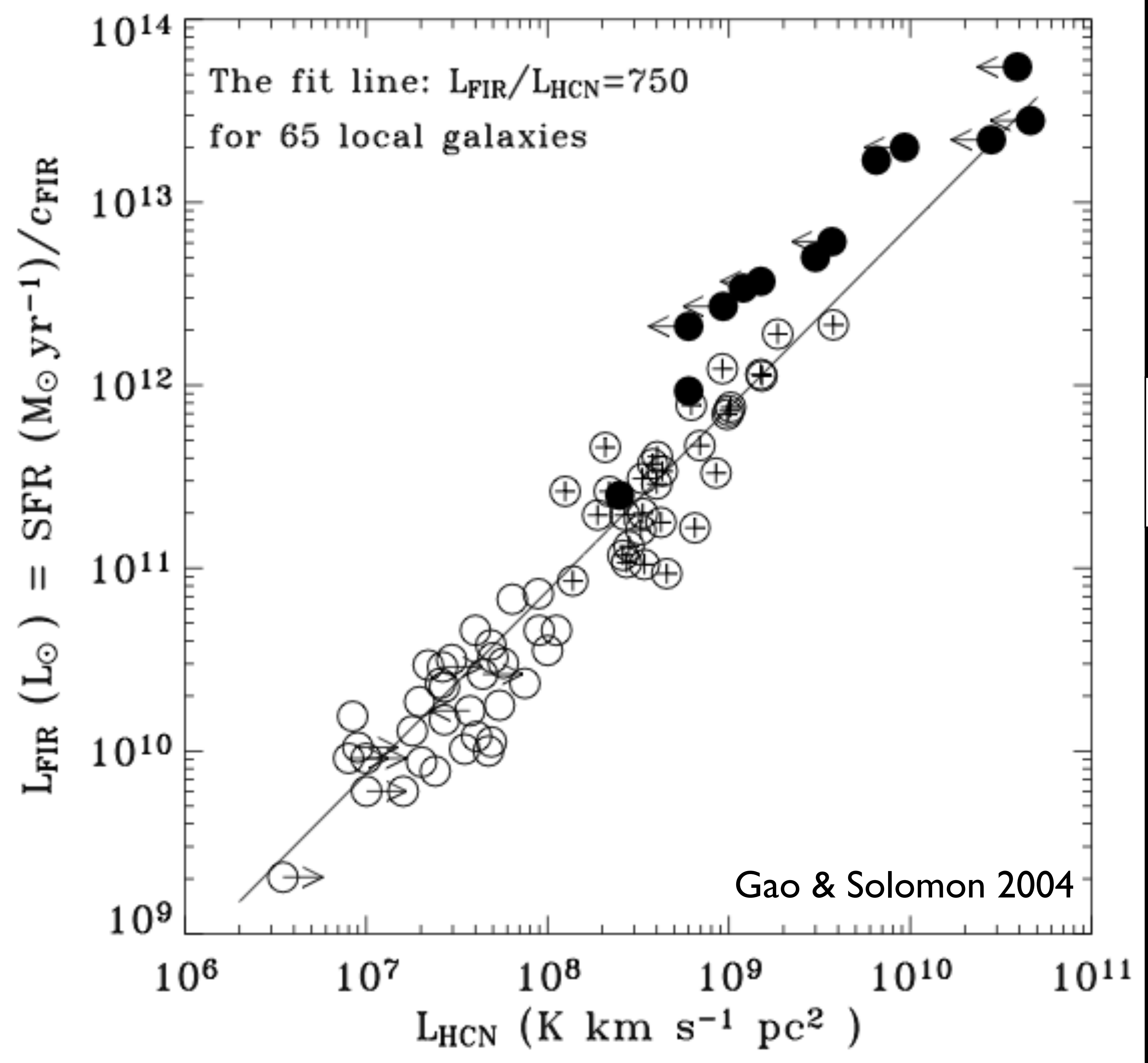


Gao & Solomon 2004

Slope~1.4

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

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

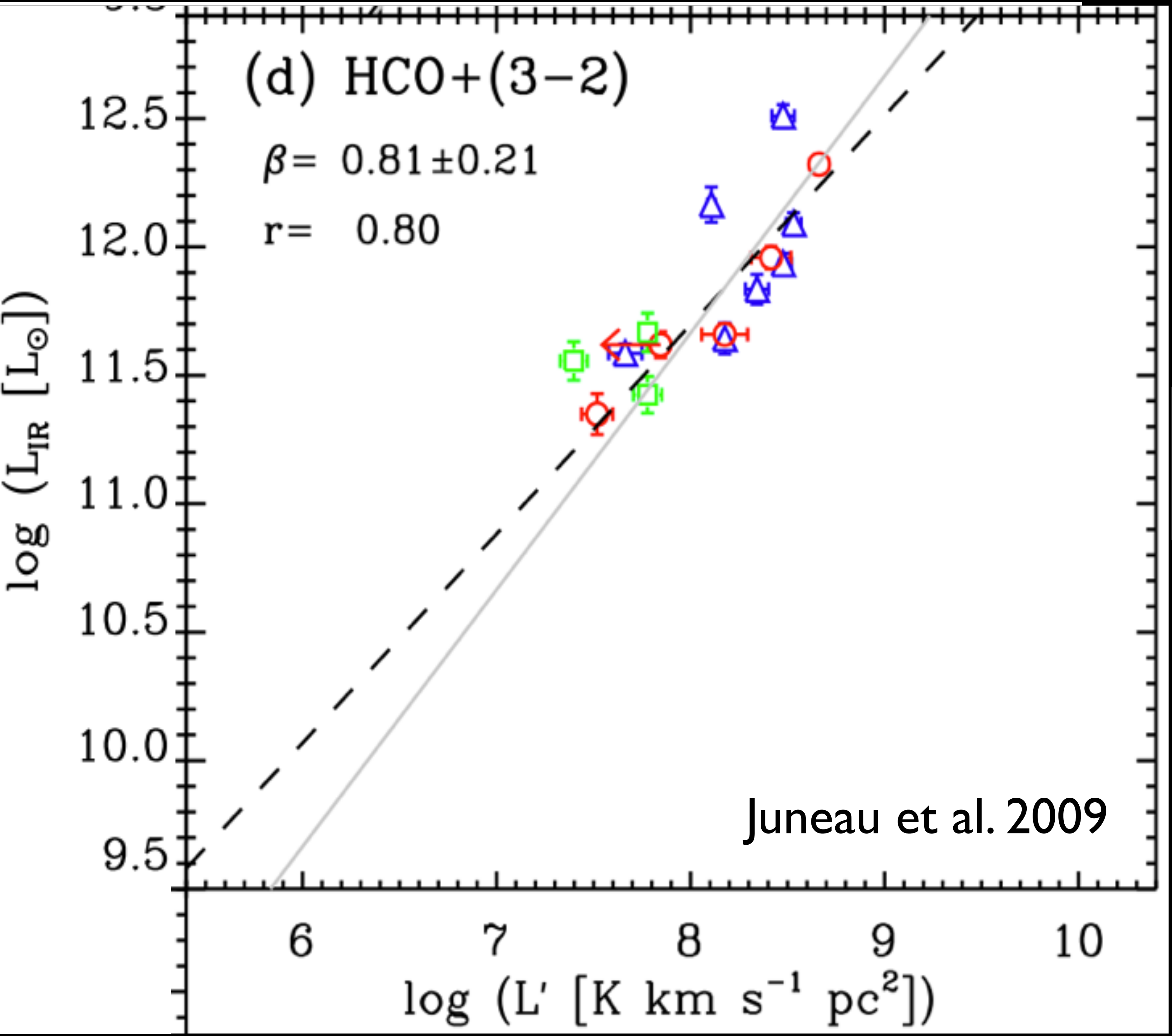


Gao & Solomon 2004

Slope=1

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

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

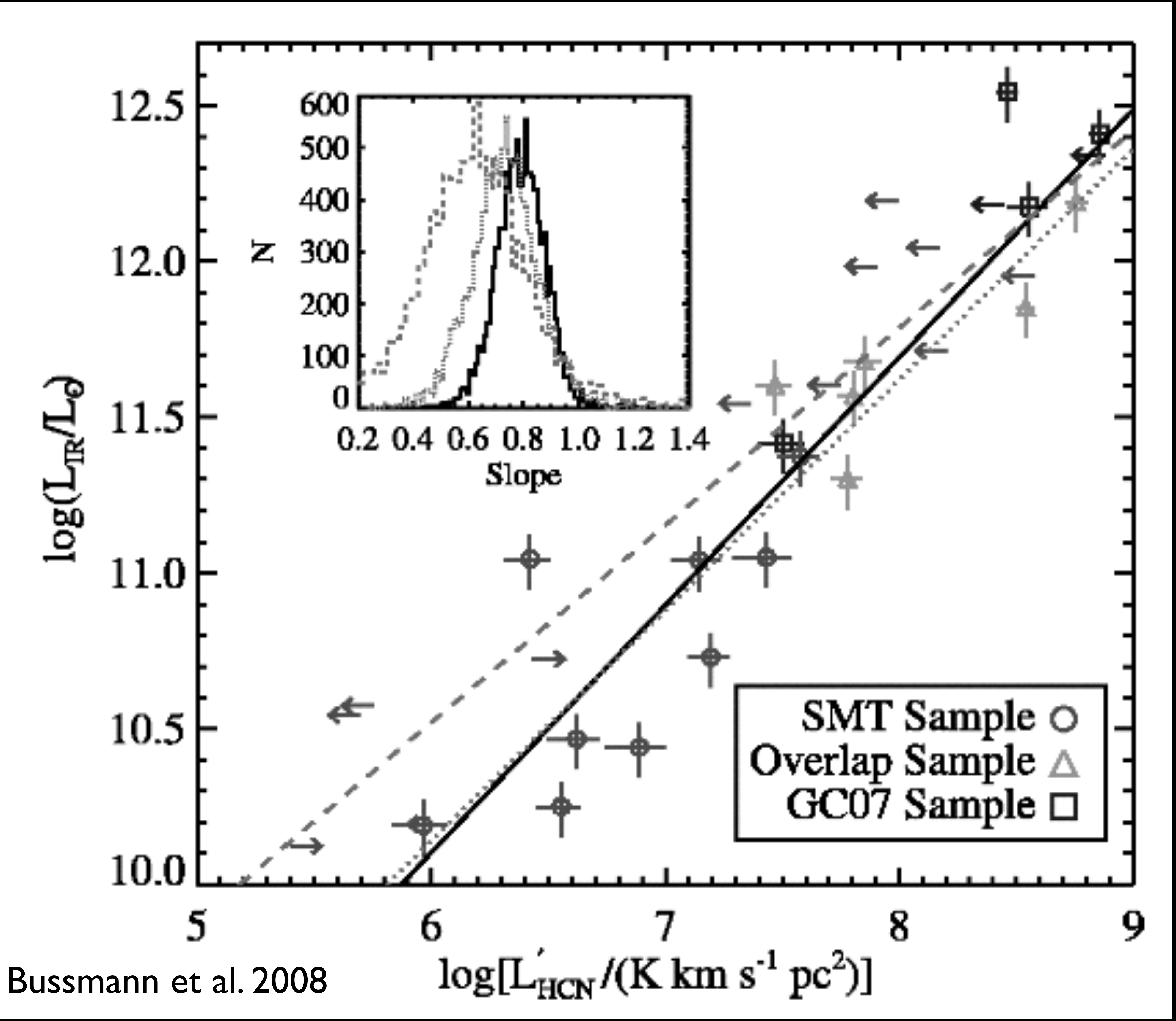


Juneau et al. 2009

Slope=0.8

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

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

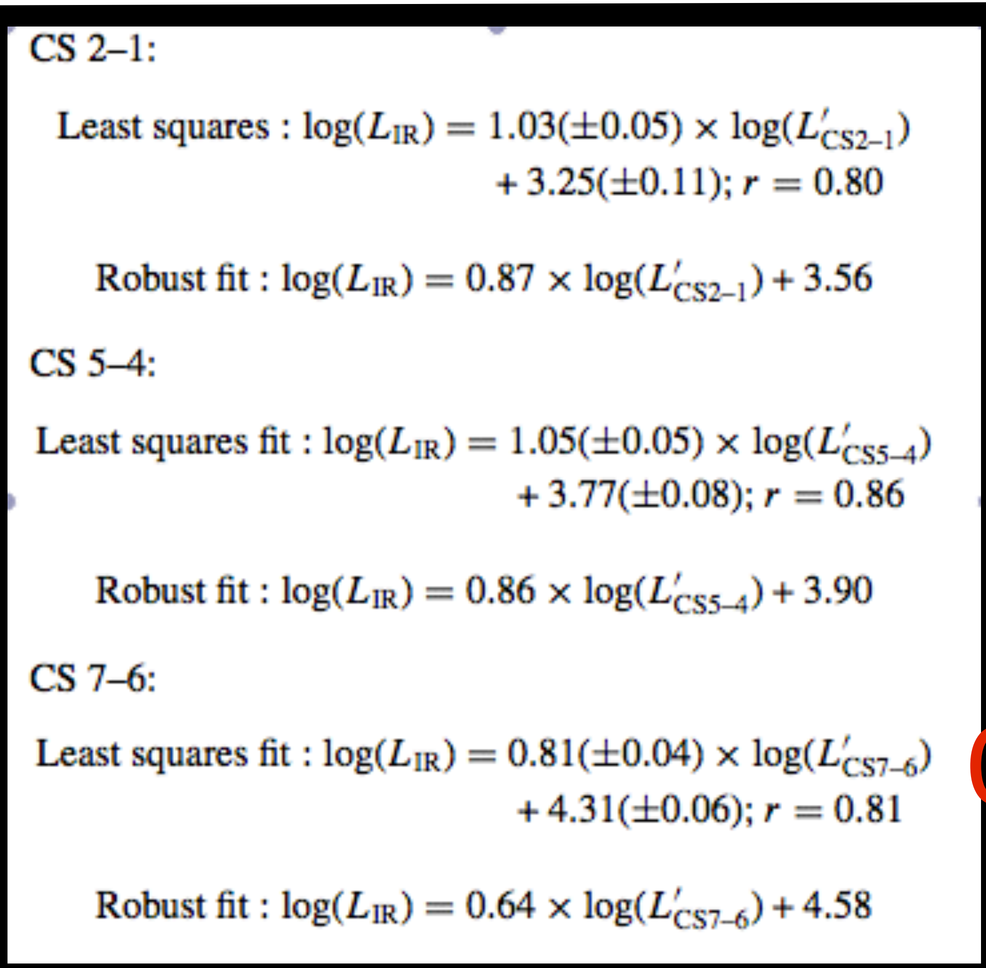


Bussmann et al. 2008

N~0.7

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

Galactic CS & HCN studies



CS 2–1:

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

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

CS 5–4:

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

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

CS 7–6:

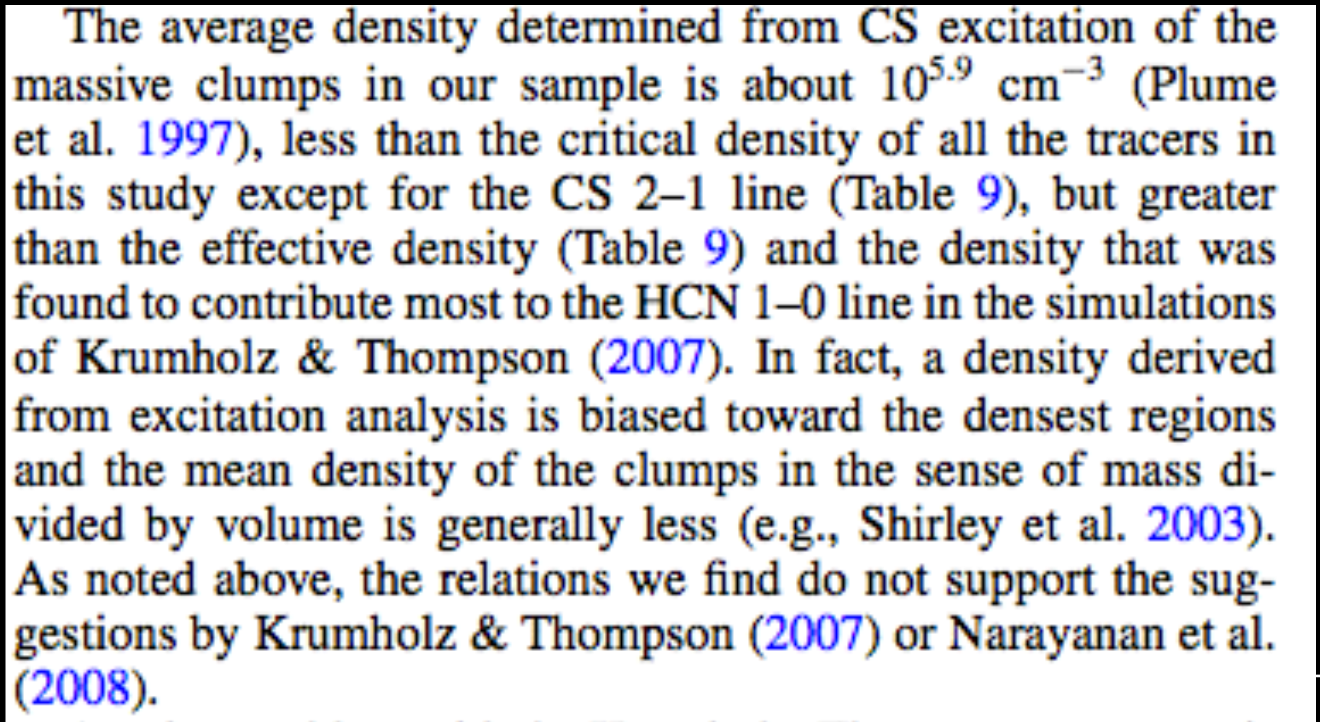
$$\text{Least squares fit}: \log(L_{\rm IR}) = 0.81(\pm 0.04) \times \log(L'_{\rm CS7\text{–}6}) + 4.31(\pm 0.06);\ r = 0.81$$

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

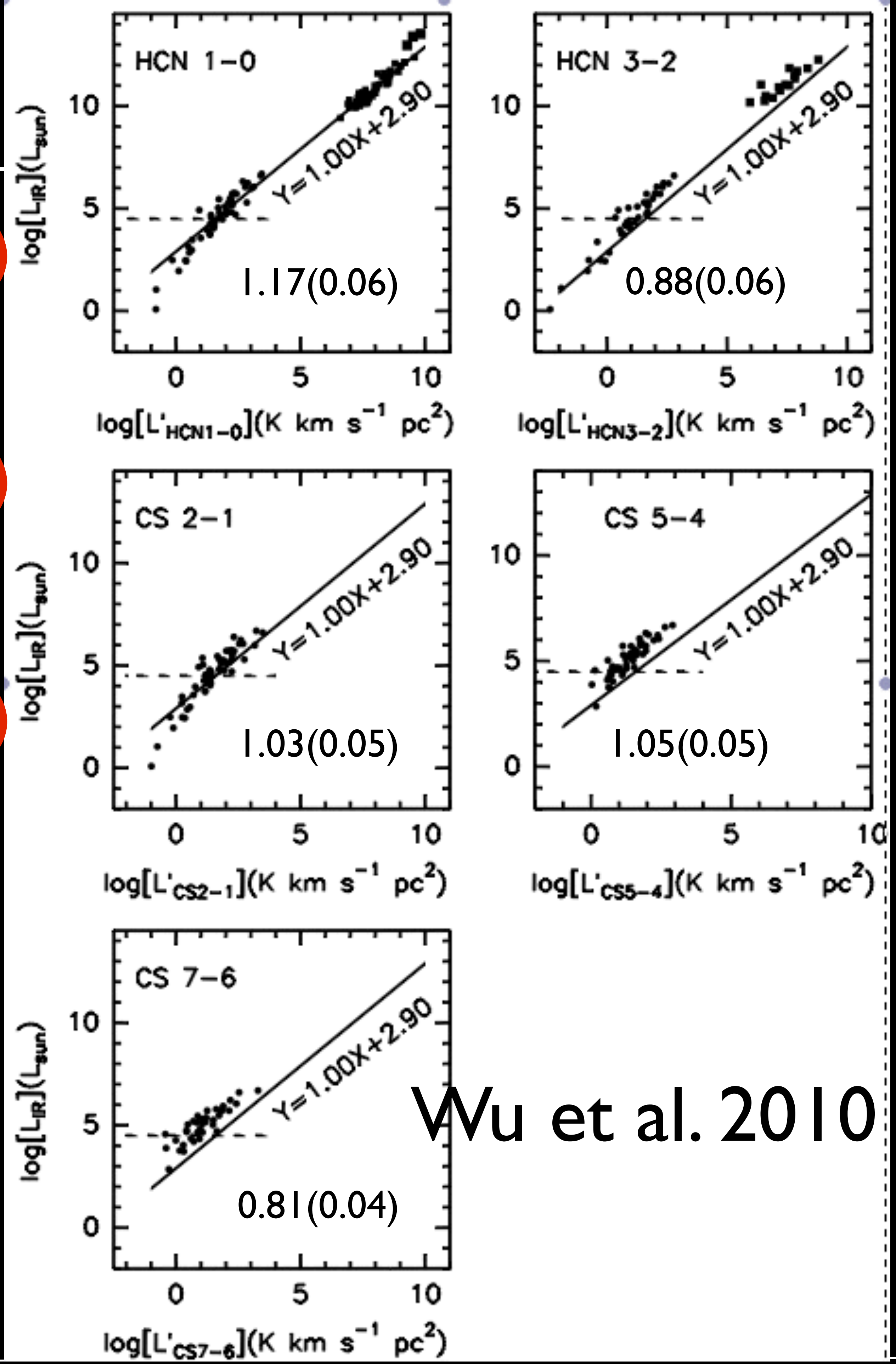
1.03(0.05)

1.05(0.05)

0.81(0.04)



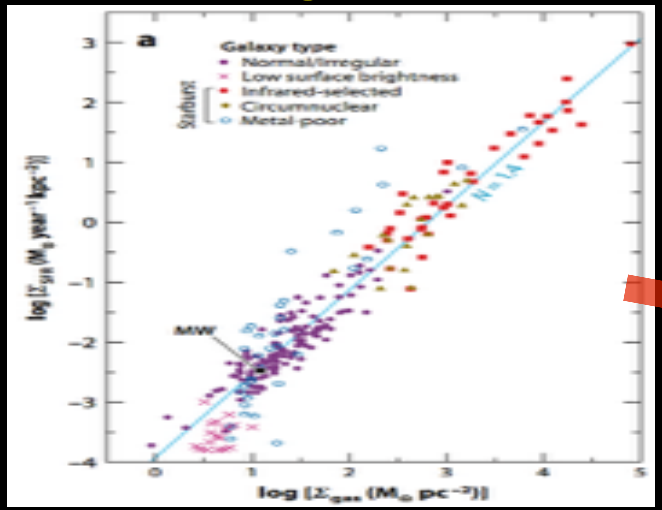
The average density determined from CS excitation of the massive clumps in our sample is about $10^{5.9}$ cm^{-3} (Plume et al. 1997), less than the critical density of all the tracers in this study except for the CS 2–1 line (Table 9), but greater than the effective density (Table 9) and the density 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).

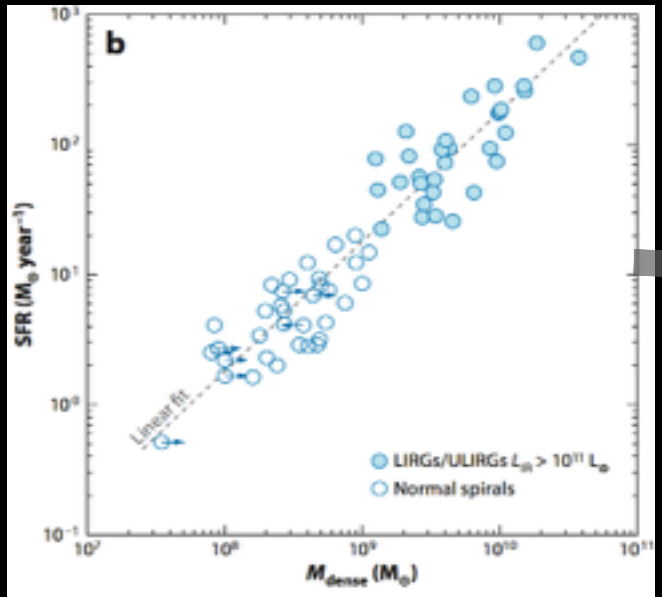


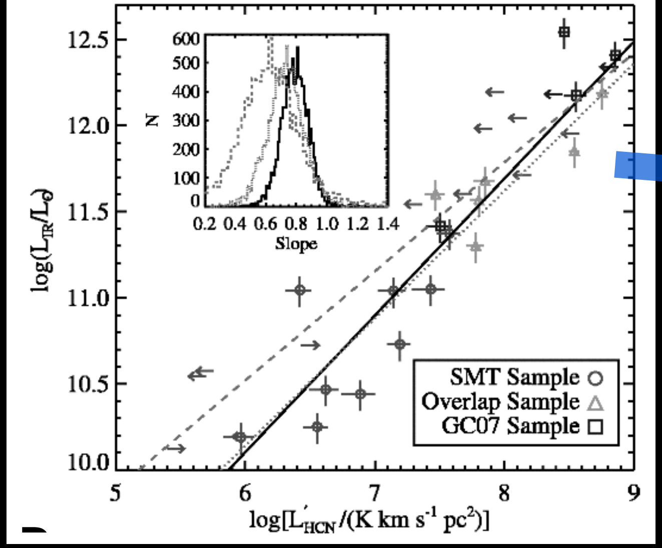
Wu et al. 2010

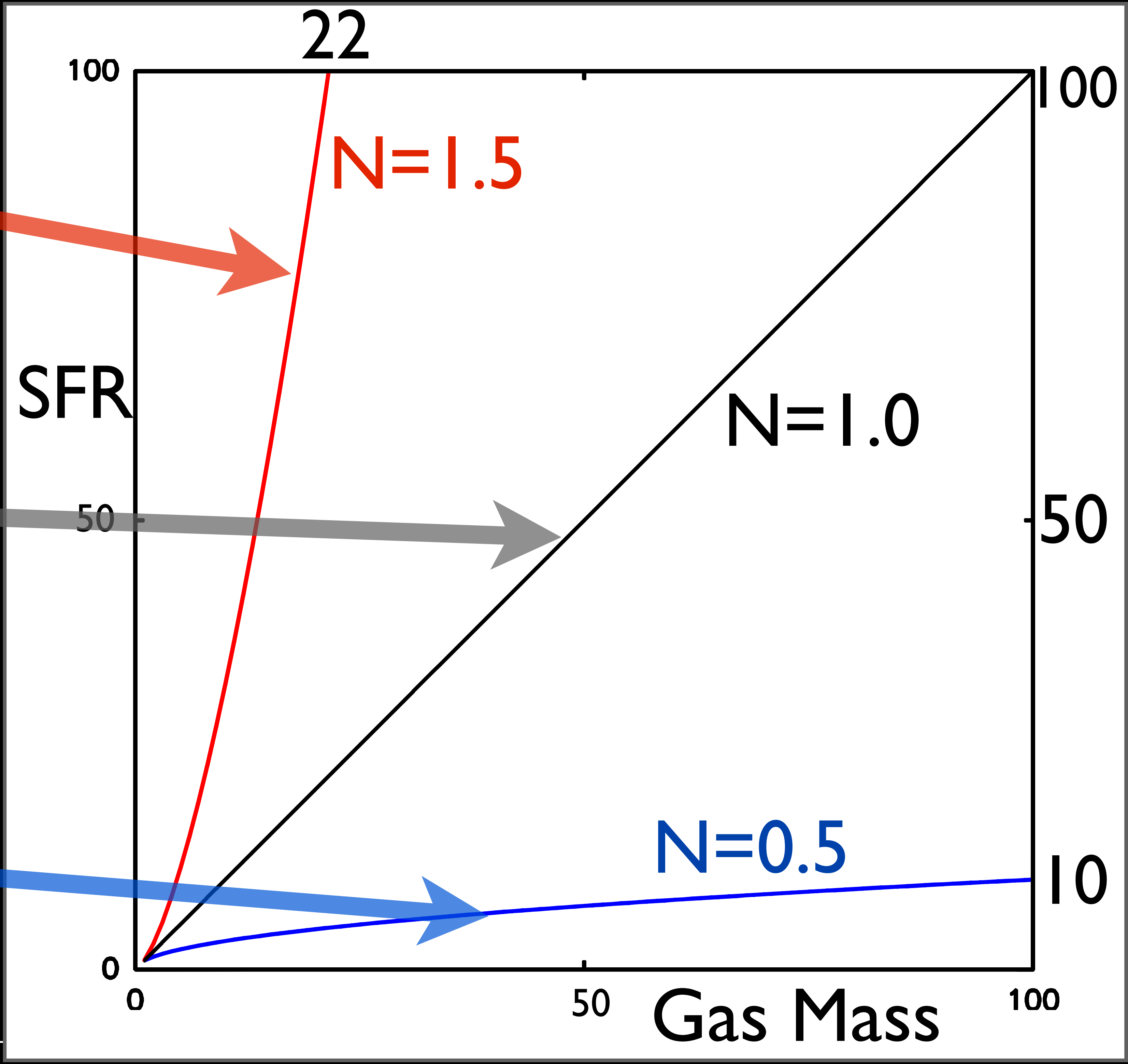
Why slopes matter? Different SFE

Which gases are forming stars?









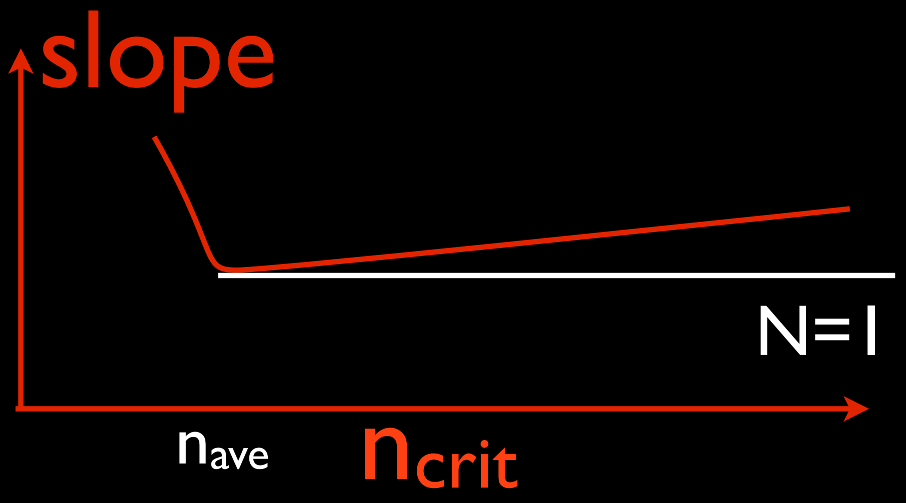
16 Jul. 2014, Sesto, Zhi-Yu Zhang

Theoretical works

1) Krumholz et al. (2007):

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

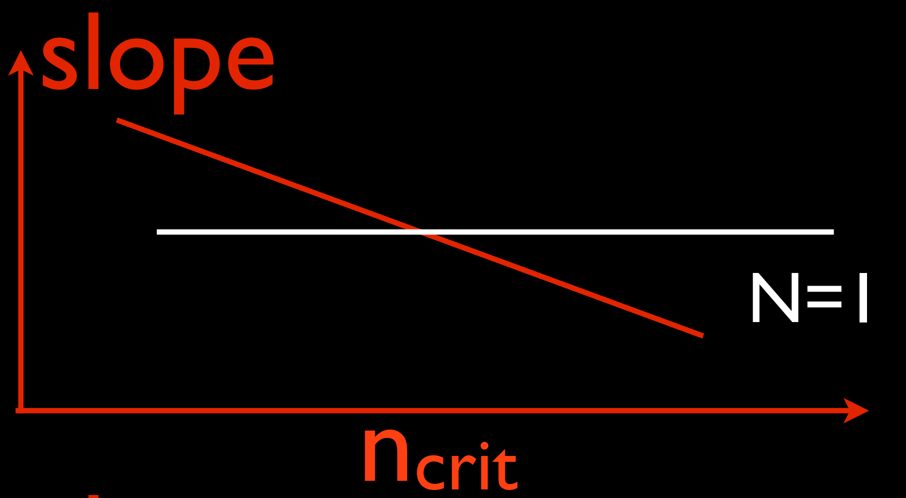
$n_{crit} > n_{ave}$: slope ~1 e.g., HCN 1-0



2) Narayanan et al. (2008):

Sub-thermal excitation.

Slope decreases with n_{crit}.

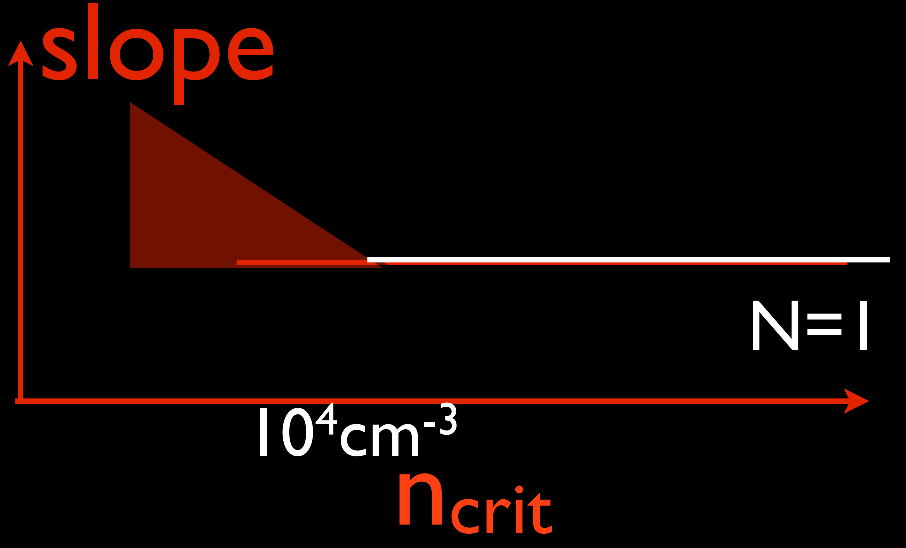


3) Lada et al. (2012):

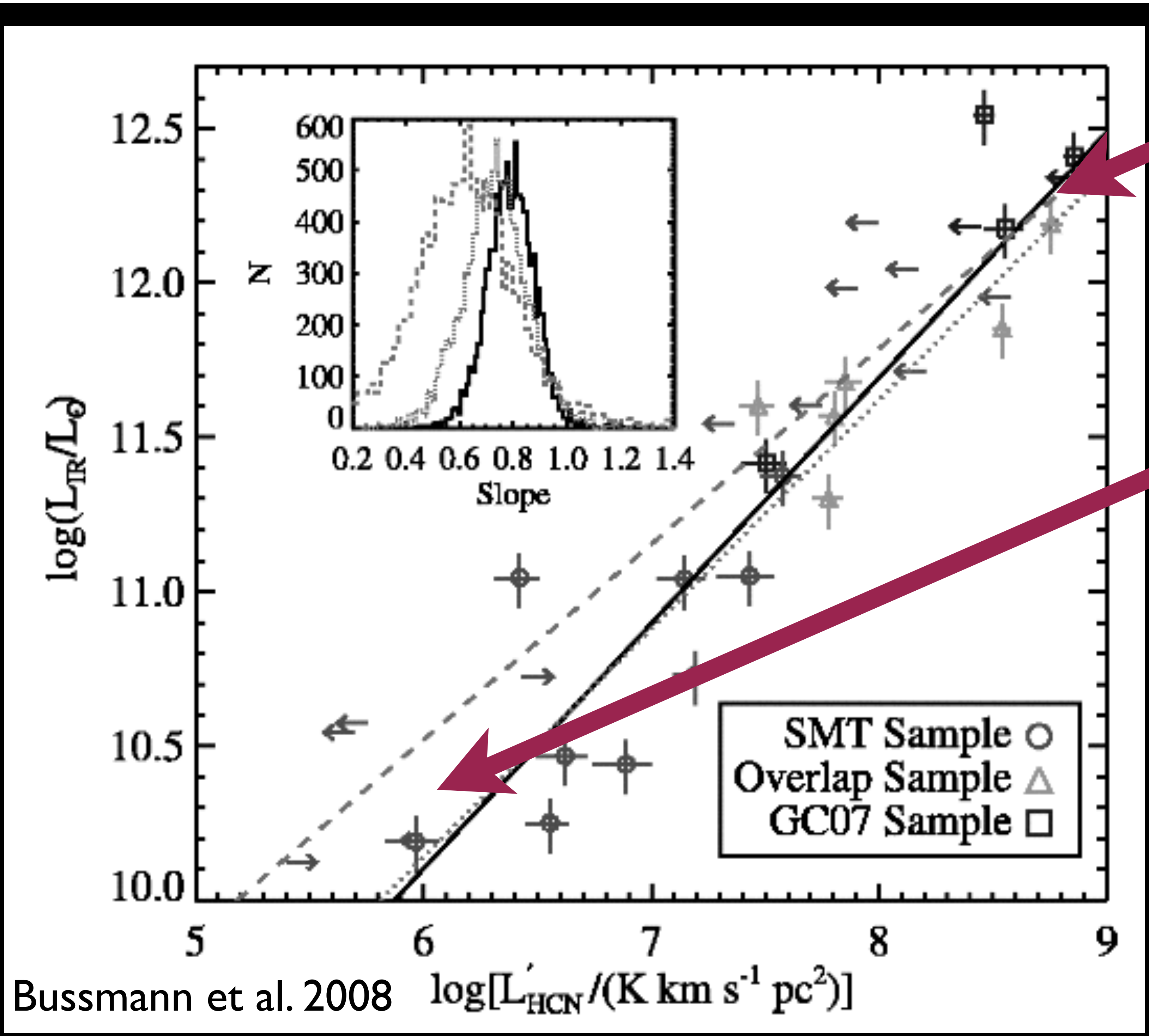
Linear slope for lines with $n_{crit} > 10^4 cm^{-3}$

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

80 hours

2009 ~ 2010

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

50 hours

2009

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

40 hours

2011

CS J= 1-0 GBT and the EVLA

60 hours

2012-2013

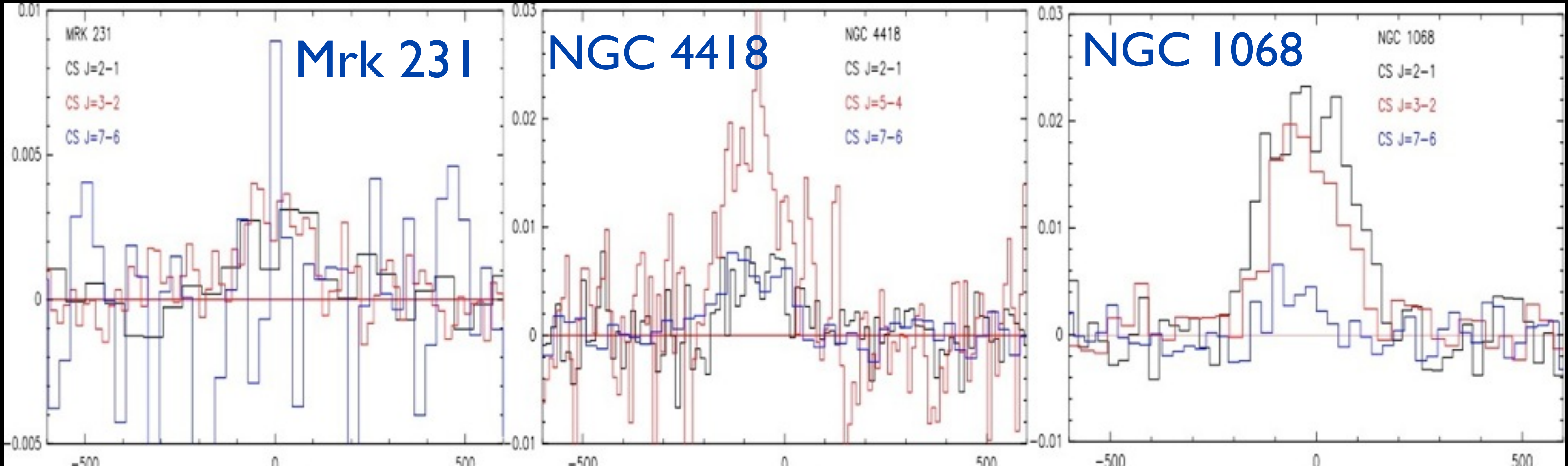
~40 hours

still ongoing

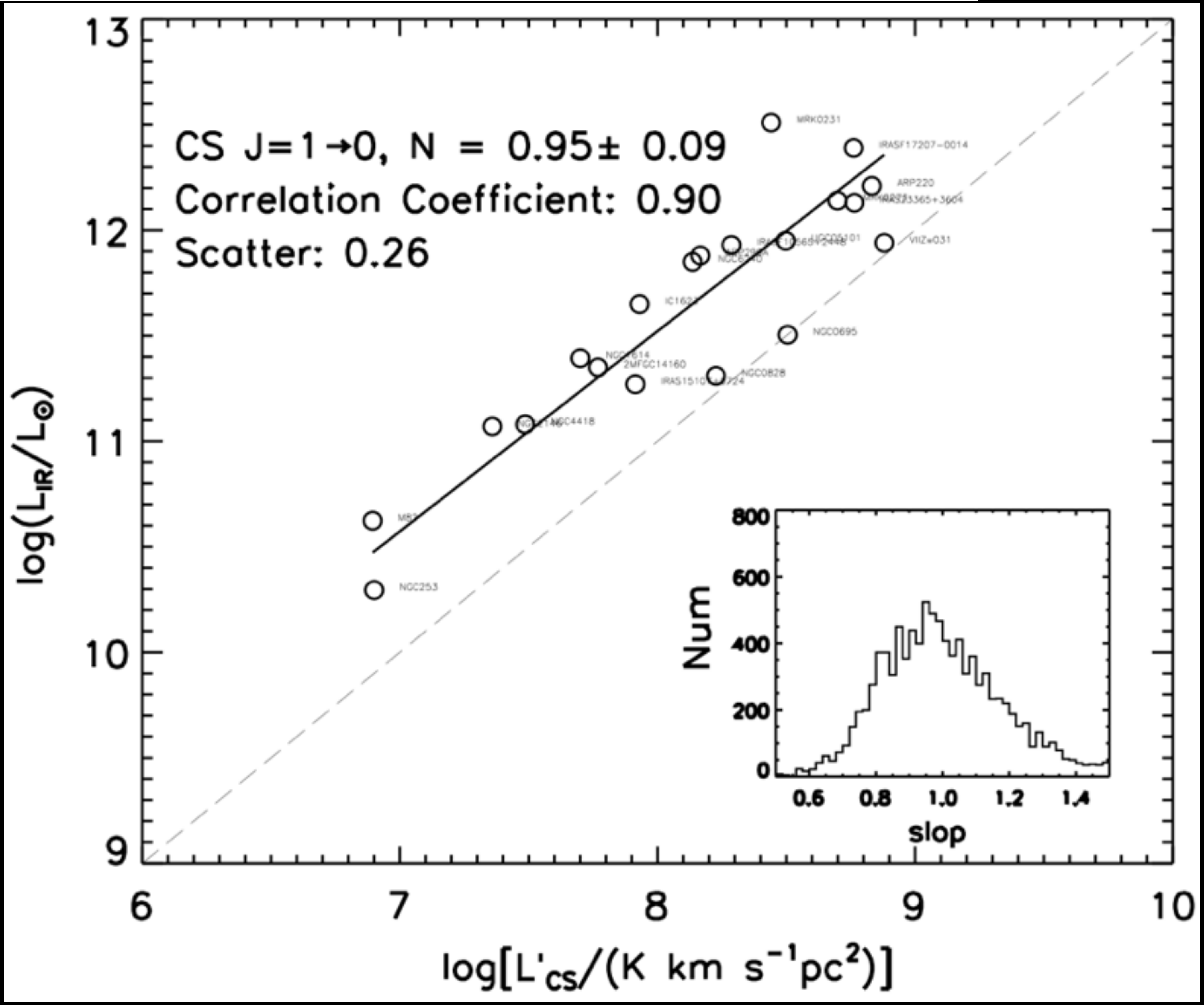
Spectra

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 HCN/HCO$^+$4-3 simultaneously
C^{34}S J=2-1: 5 detections

+ CS detections in literatures

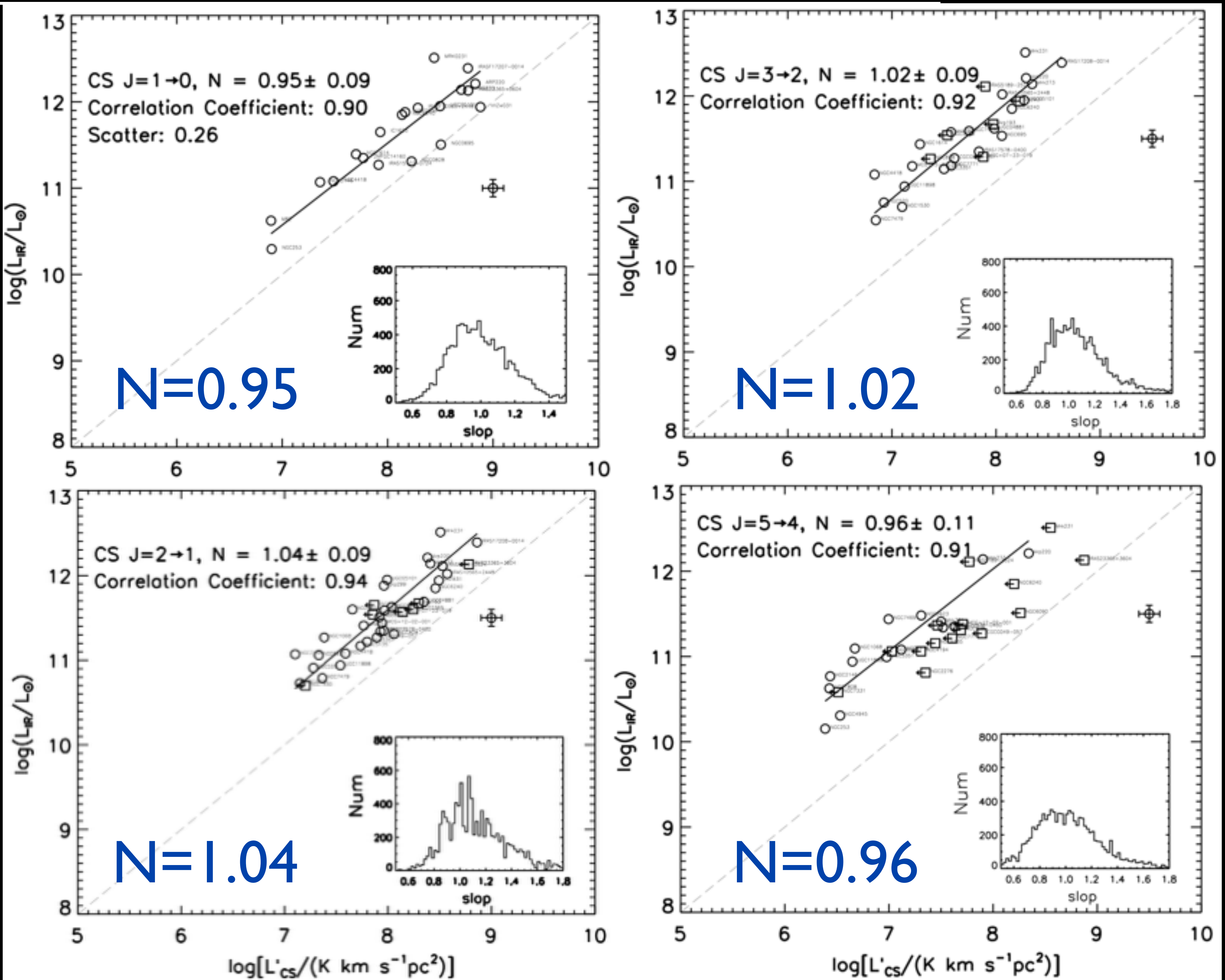


L'_{gas}-L_{IR} (point source) CS1-0 n_{crit}~ $1x10^4 cm^{-3}$



L’cs-L$_{IR}$ correlations

Point sources only



N=0.95

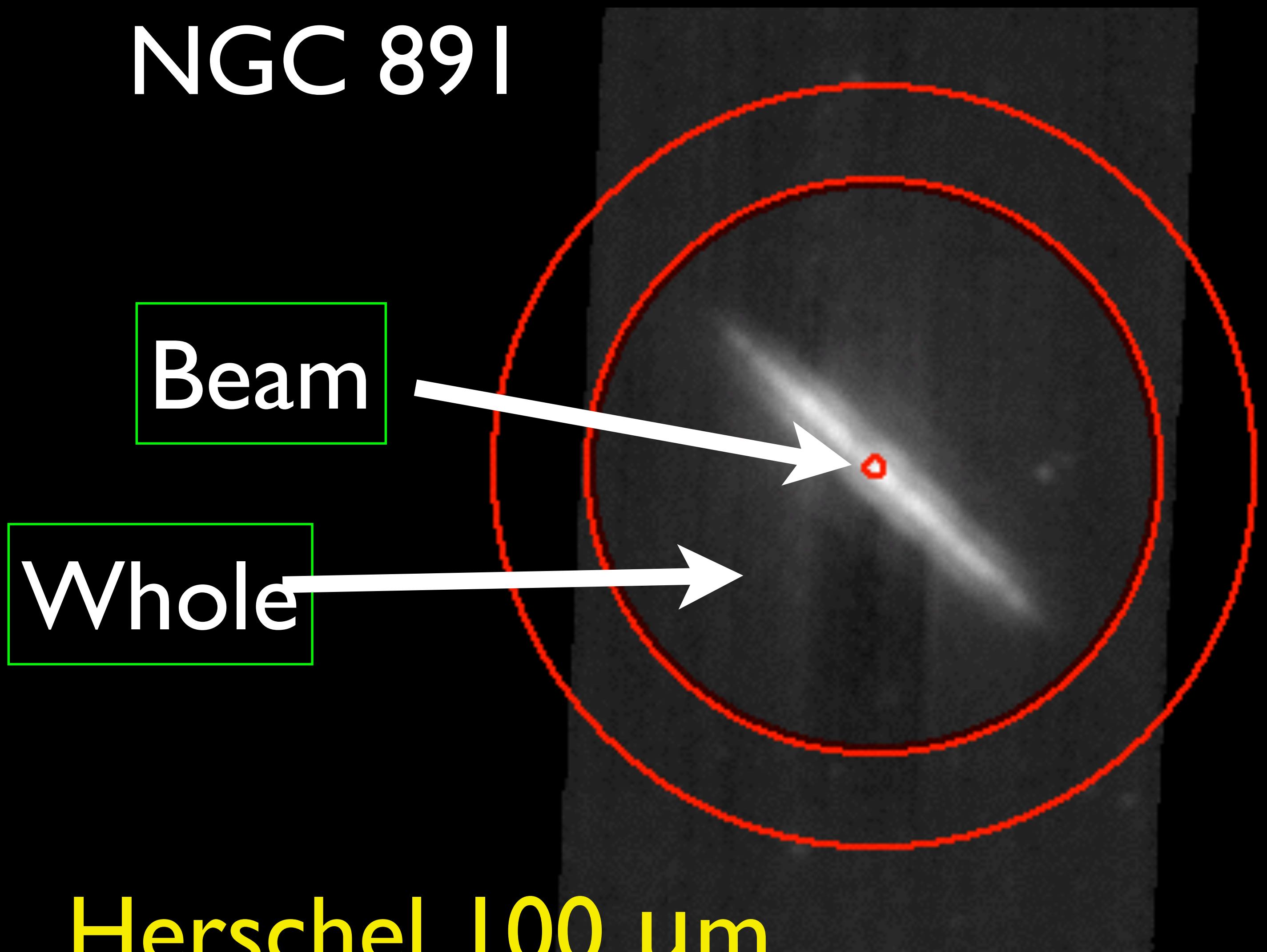
N=1.02

N=1.04

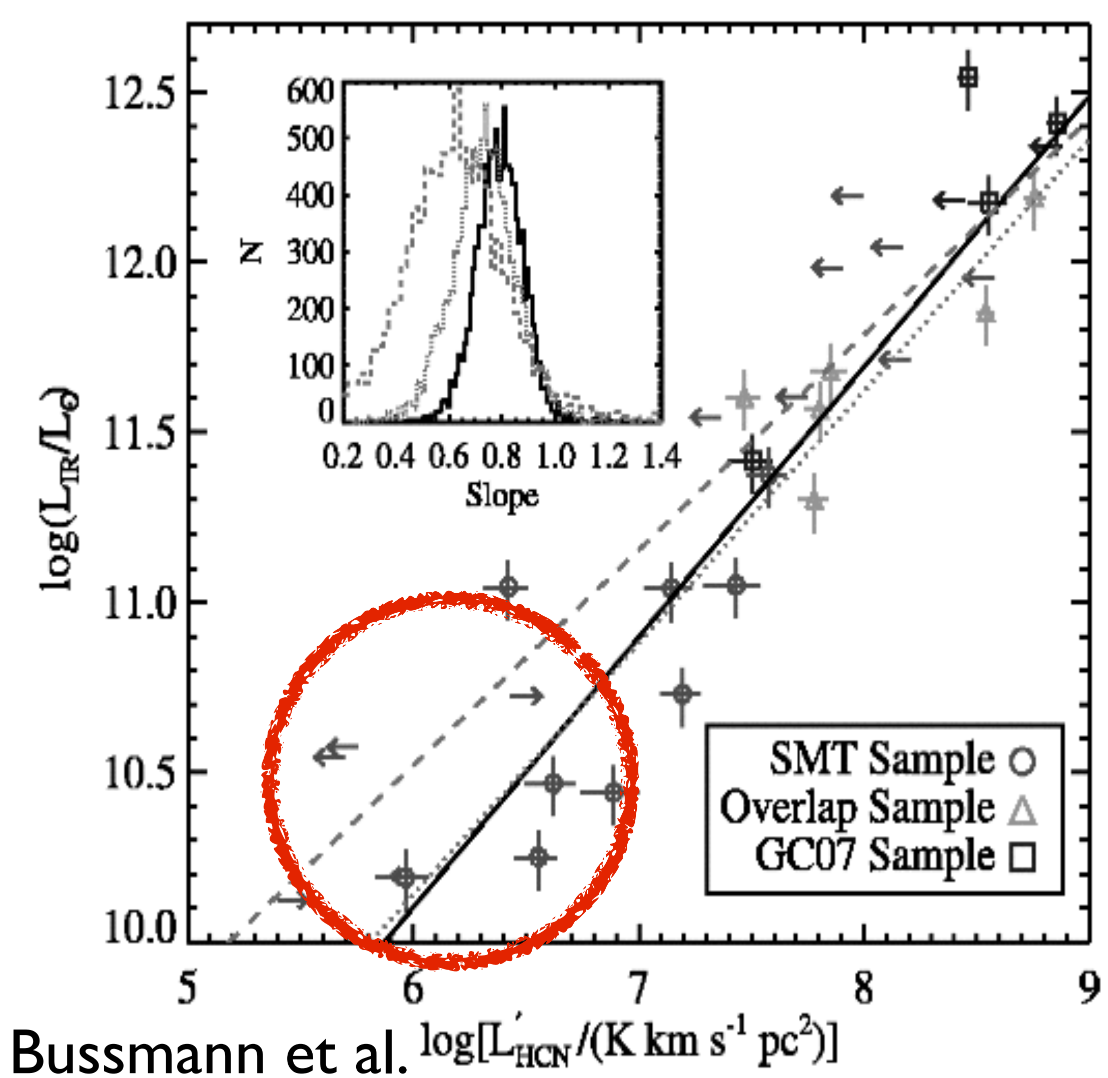
N=0.96

Beam matching photometry

NGC 891



Herschel 100 μm



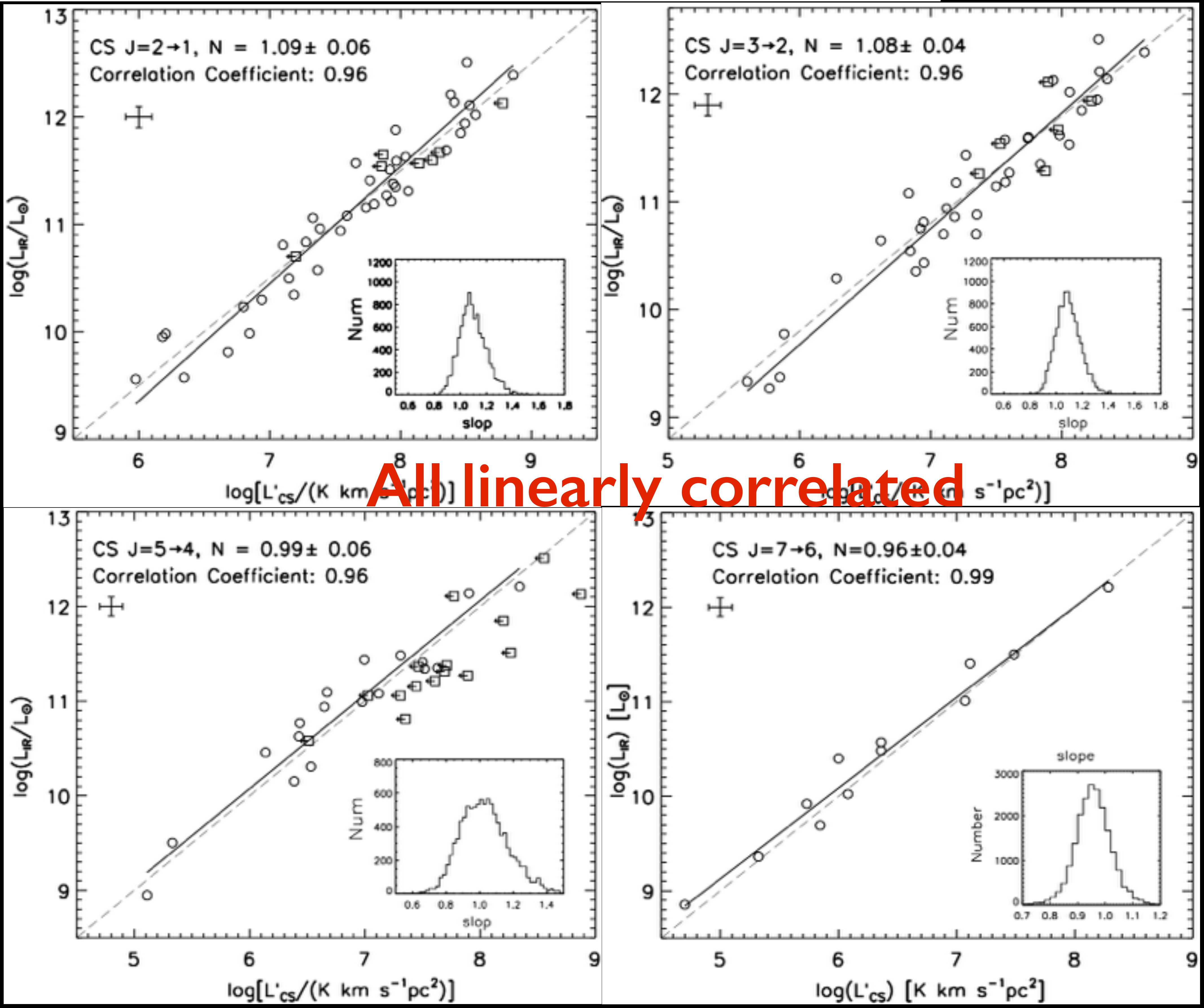
Bussmann et al.

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

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

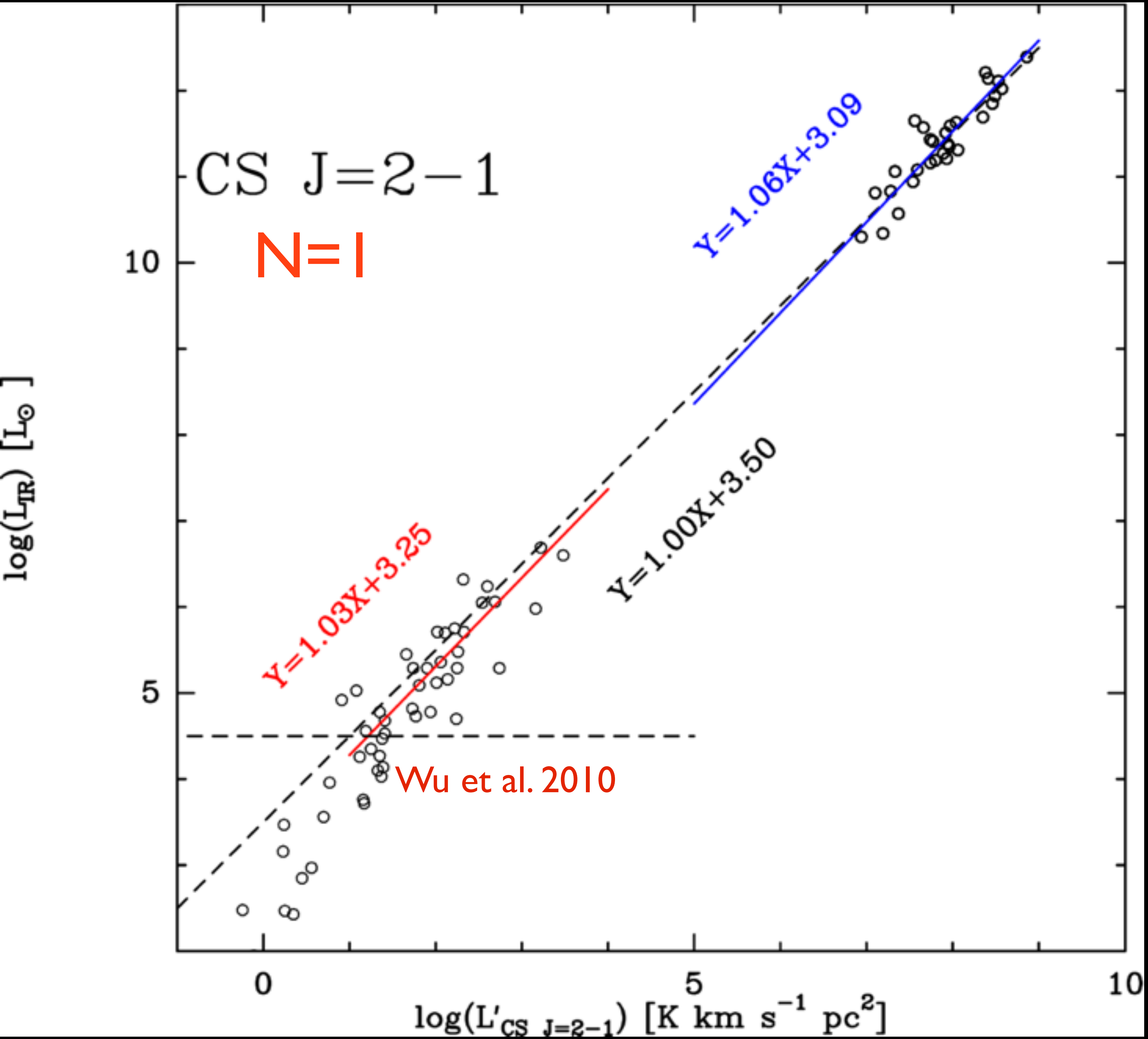
Assuming whole galaxy share one IR SED.

L'cs-L_{IR} correlations Beam matching correction



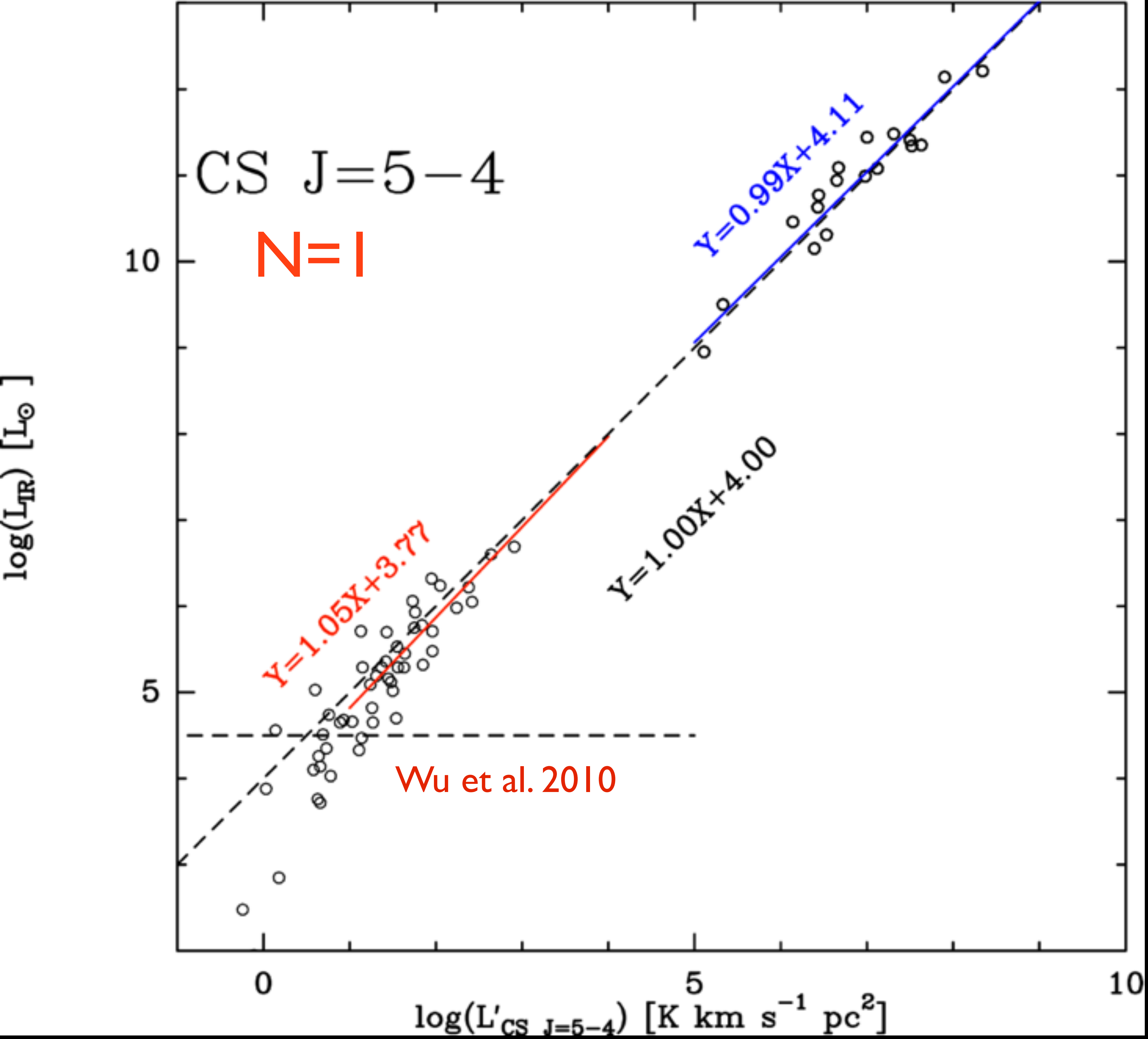
All linearly correlated

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



n_{crit}~ 1x10^{5}cm^{-3}

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

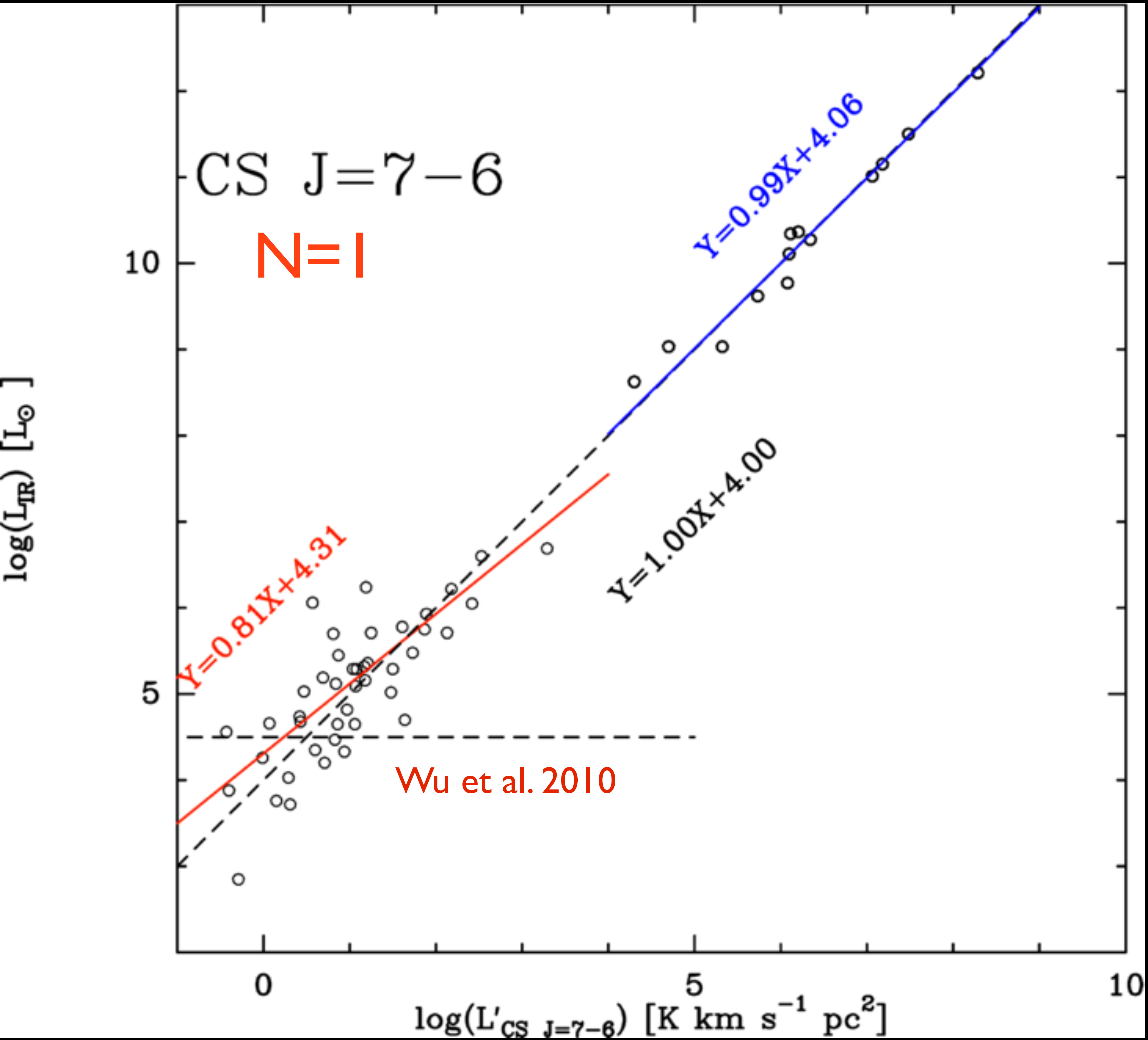


N=1

Wu et al. 2010

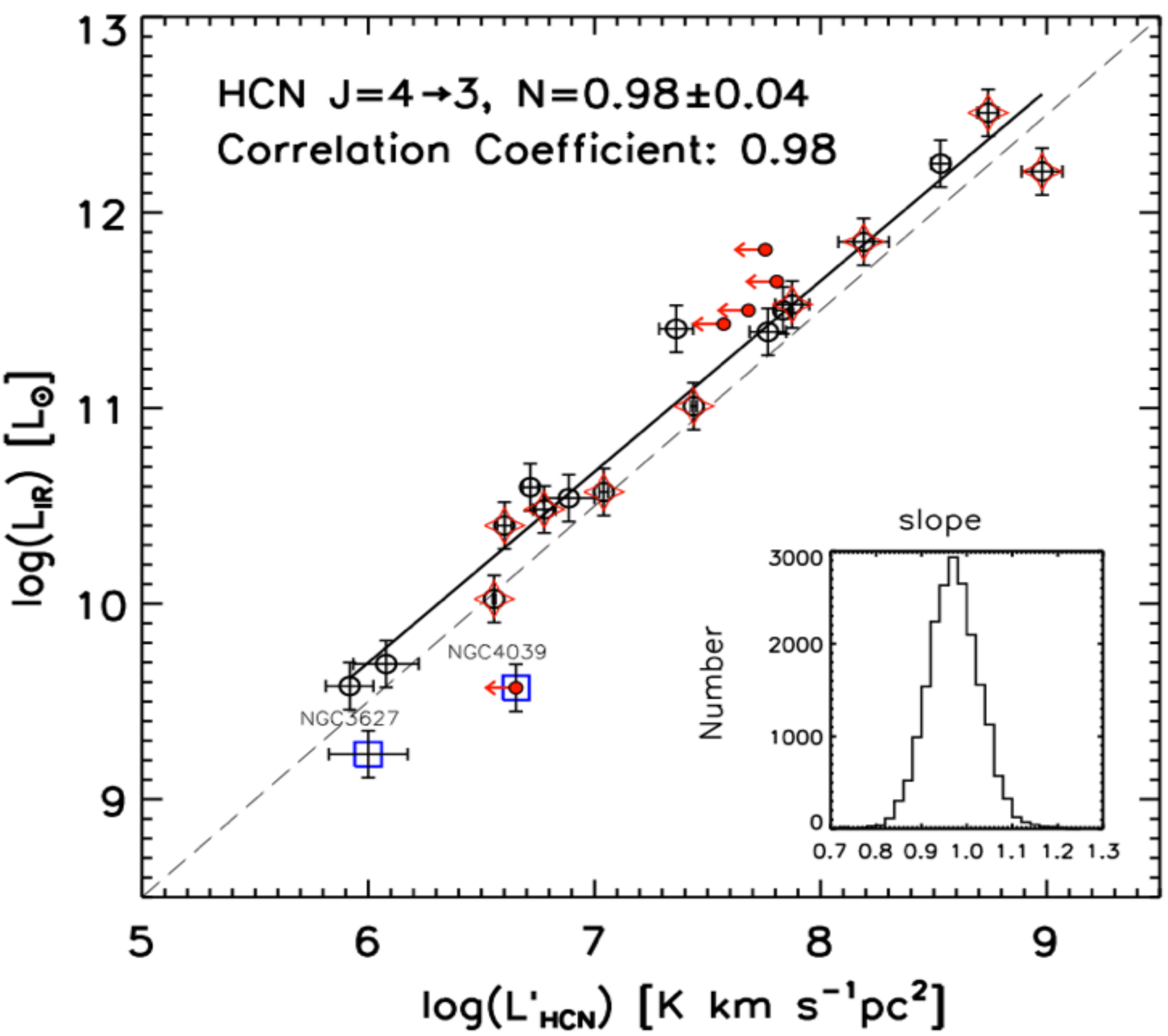
n_{crit}~ 2×10^{6}cm^{-3}

L’$_{CS}$-L$_{IR}$ correlations ~ 8 orders of magnitude



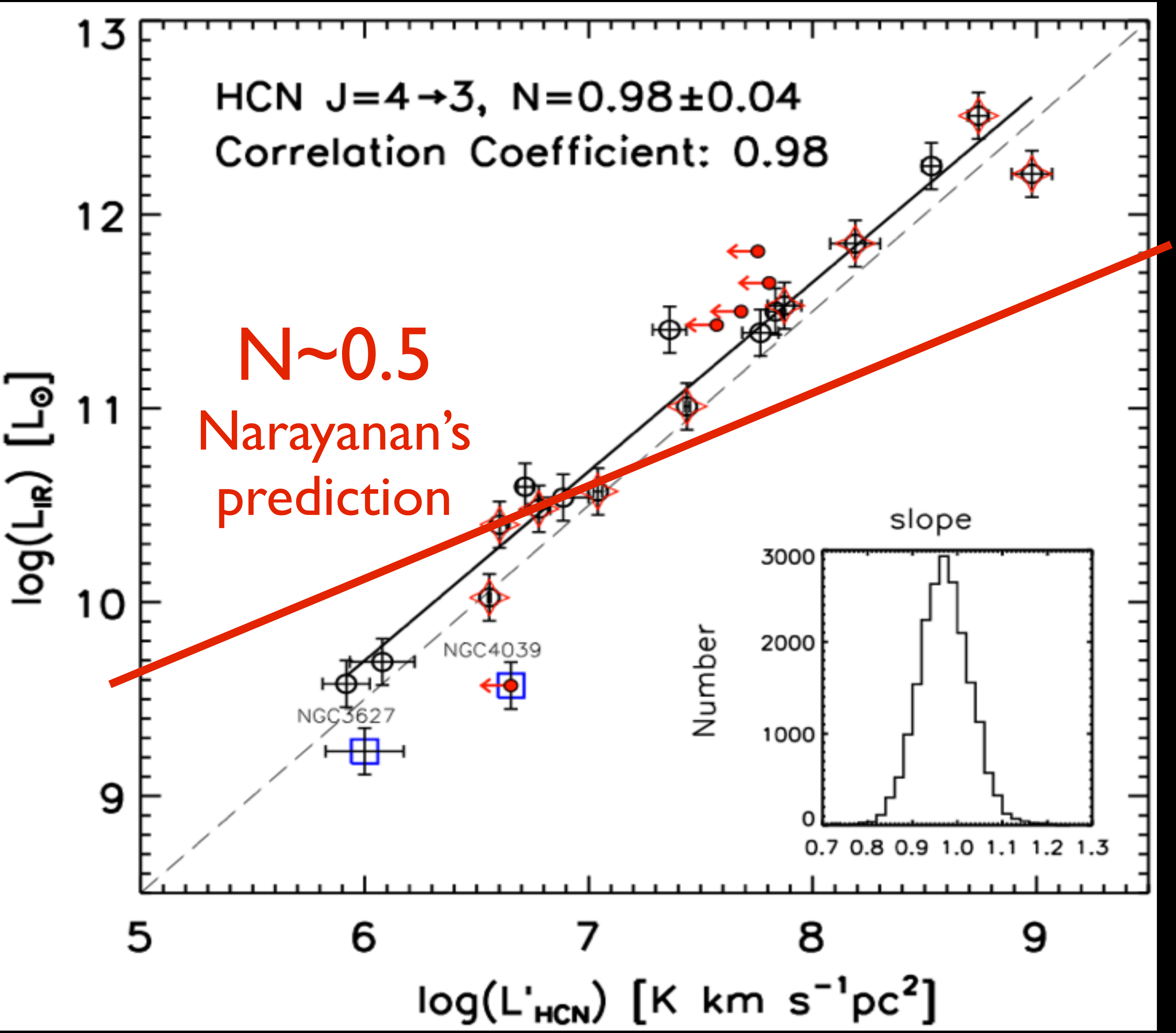
n$_{crit}$~ 5x10^{6}cm^{-3}

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



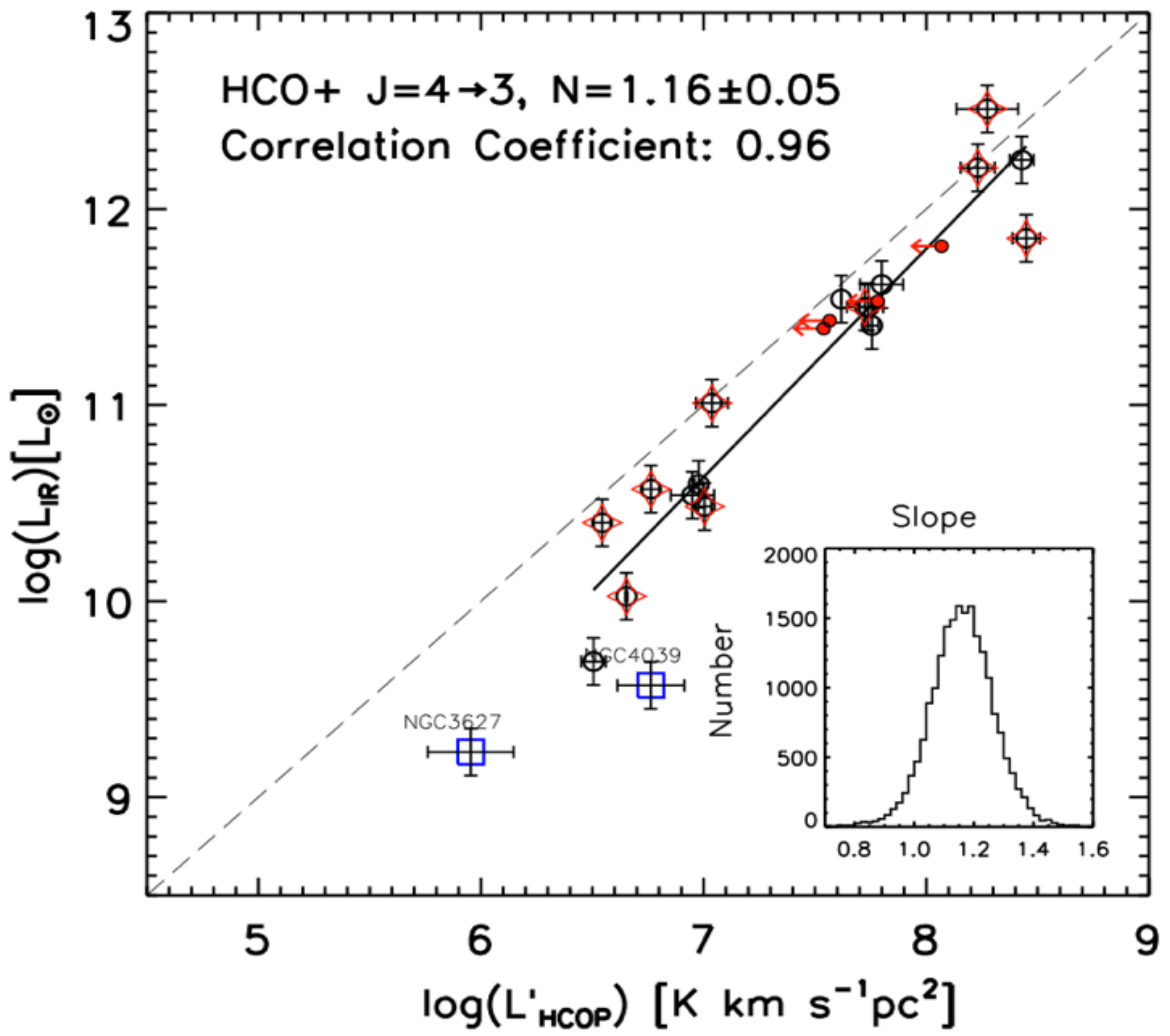
$n_{crit} \sim 1\times10^{7} cm^{-3}$

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



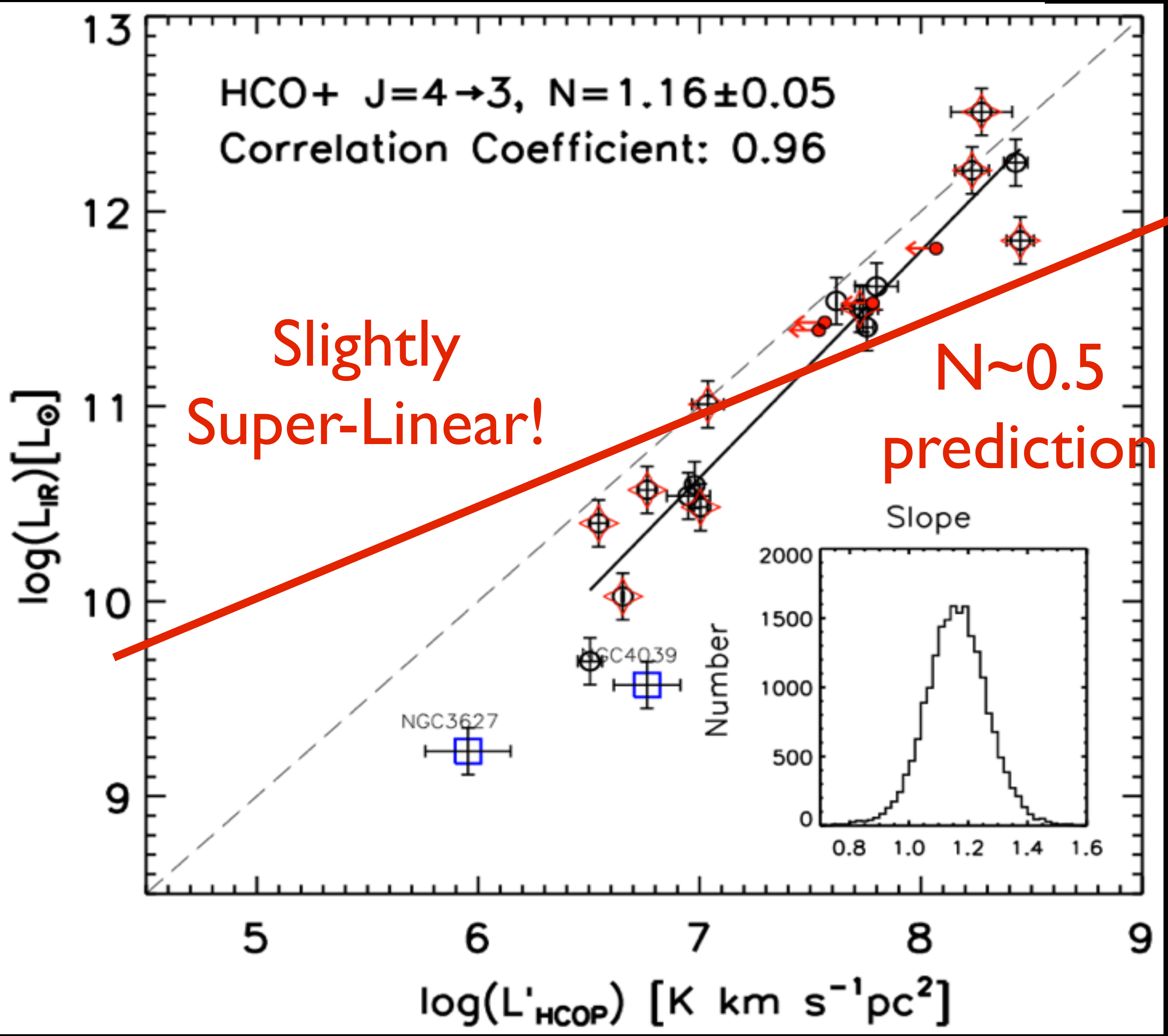
$n_{crit} \sim 1\times10^7 cm^{-3}$

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



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

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



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

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)

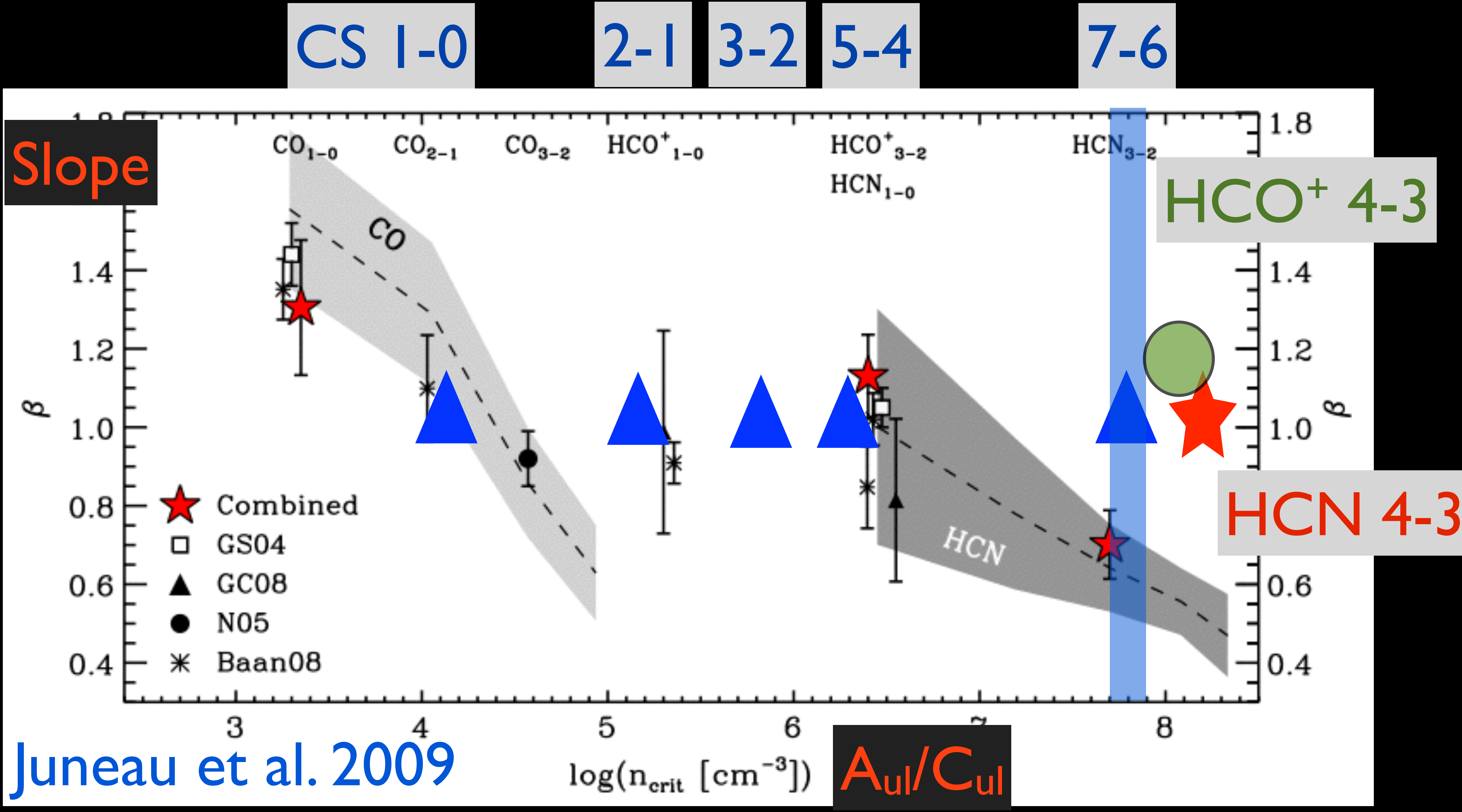
Papadopoulos et al. 2007

Shock environment

Shocks produce electron-rich outer layers

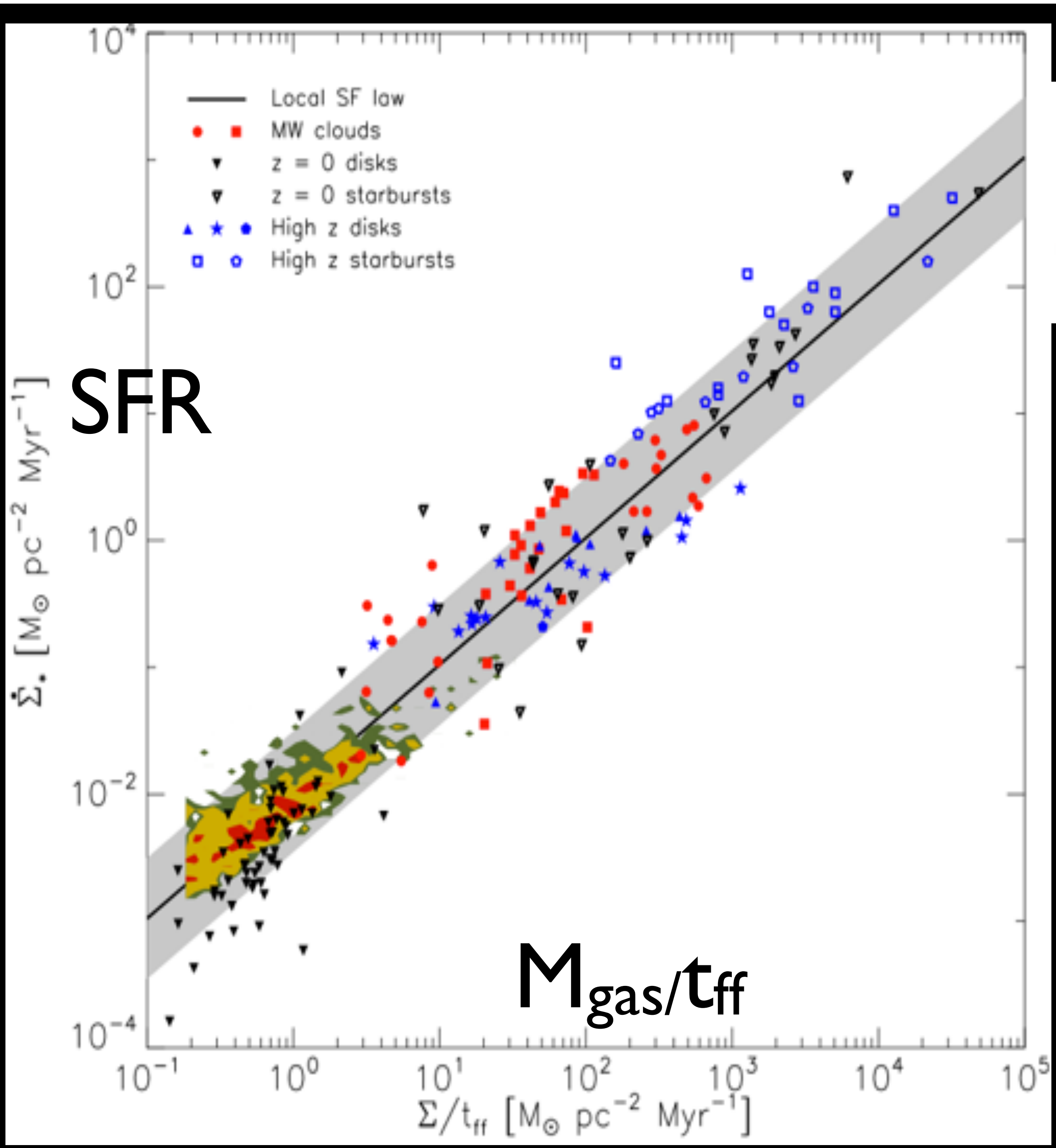
Xie et al. 1995

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 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

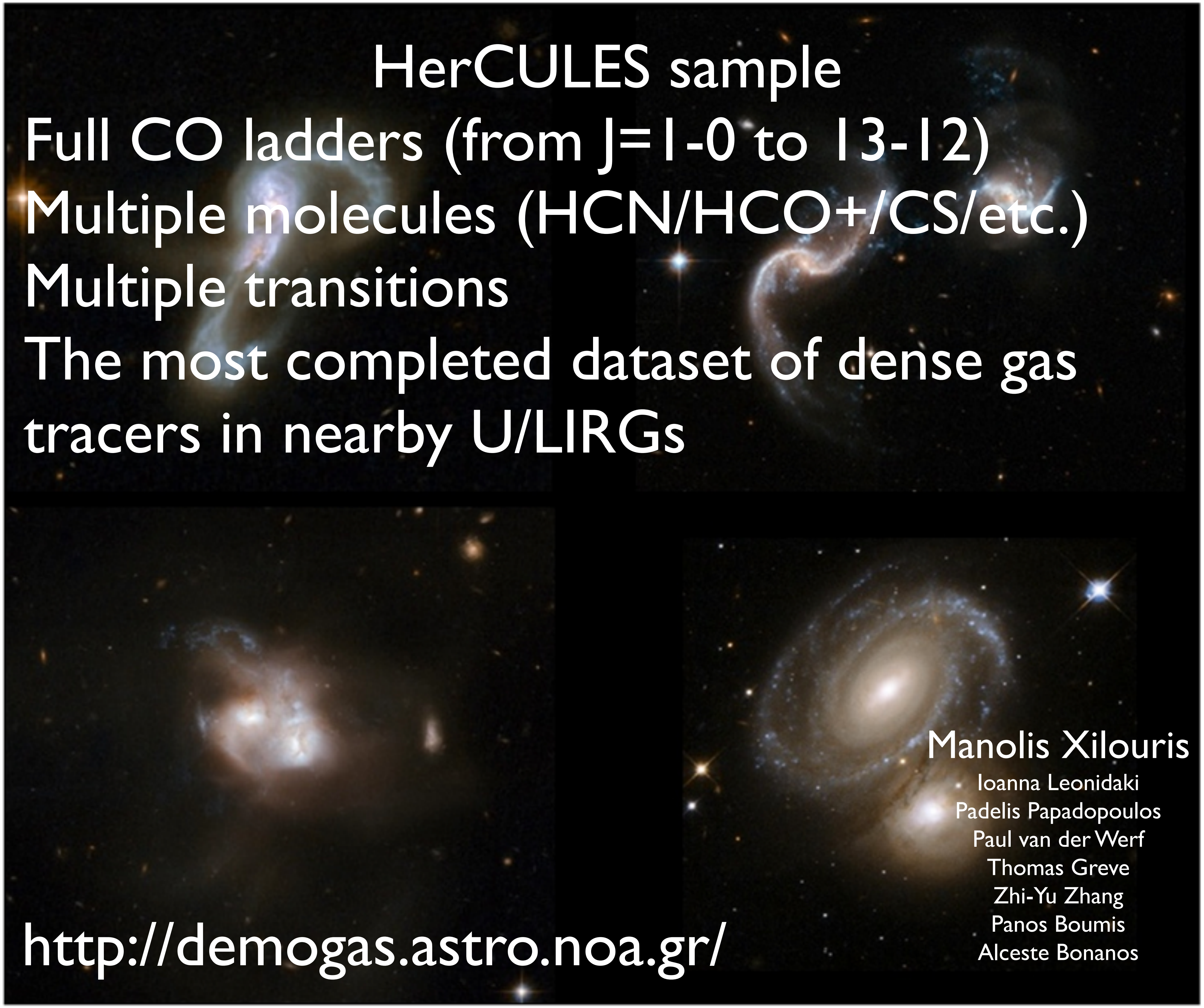
f_{H2} : H_2 fraction

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.

A Step in the Dark: The Dense Molecular Gas (DeMoGas) in Galaxies†



HerCULES sample

Full CO ladders (from J=1-0 to 13-12)

Multiple molecules (HCN/HCO+/CS/etc.)

Multiple transitions

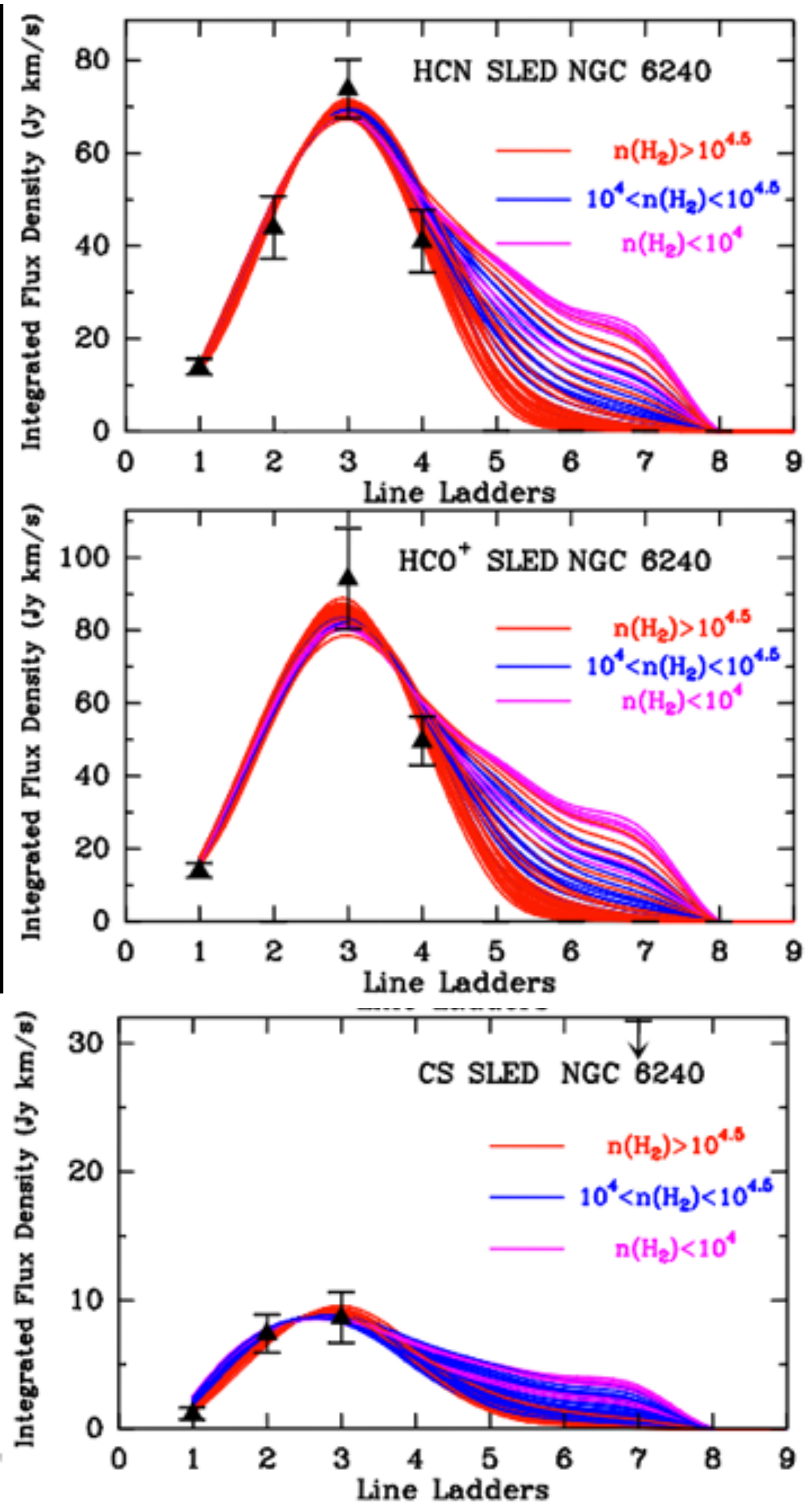
The most completed dataset of dense gas tracers in nearby U/LIRGs

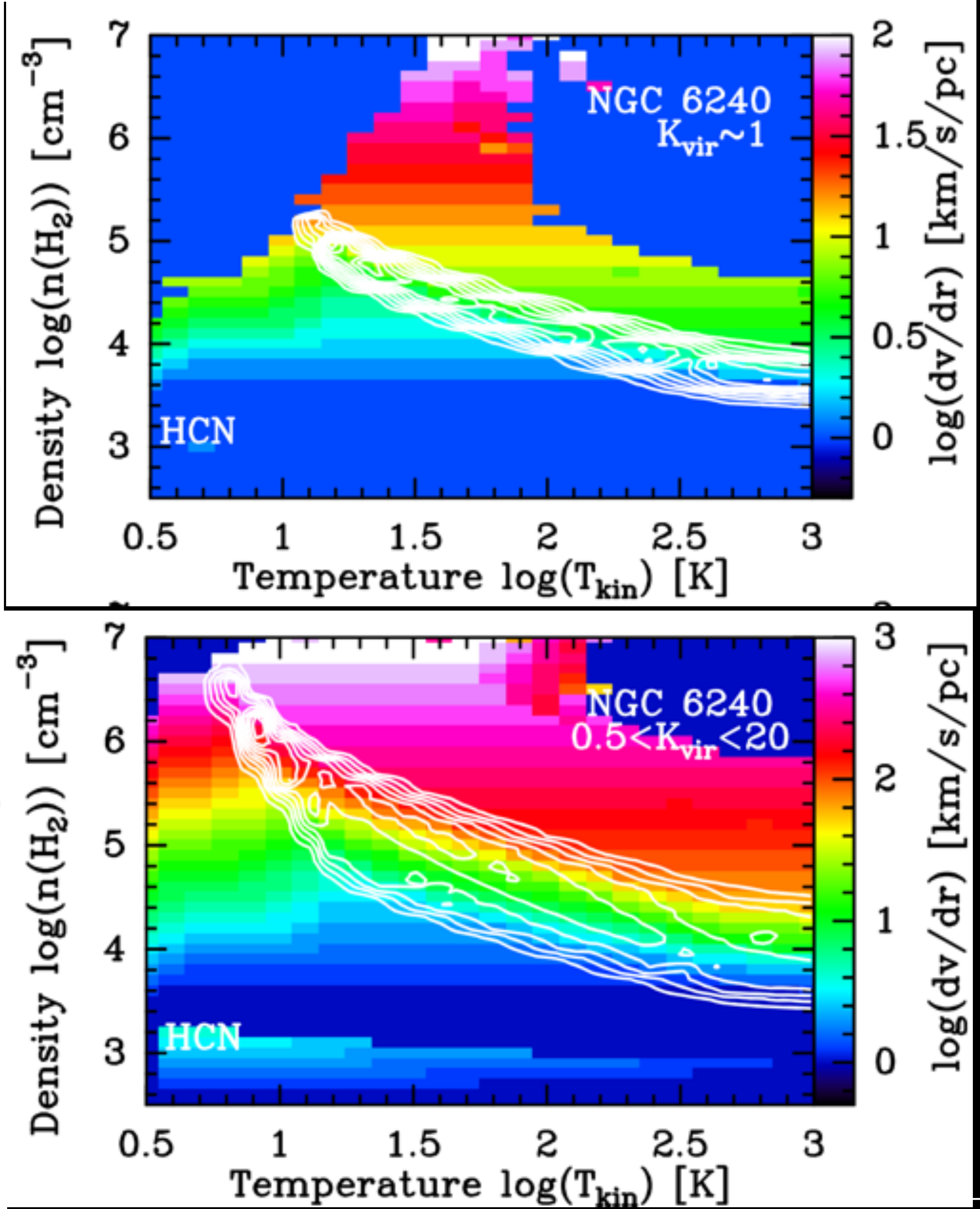
Manolis Xilouris

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

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

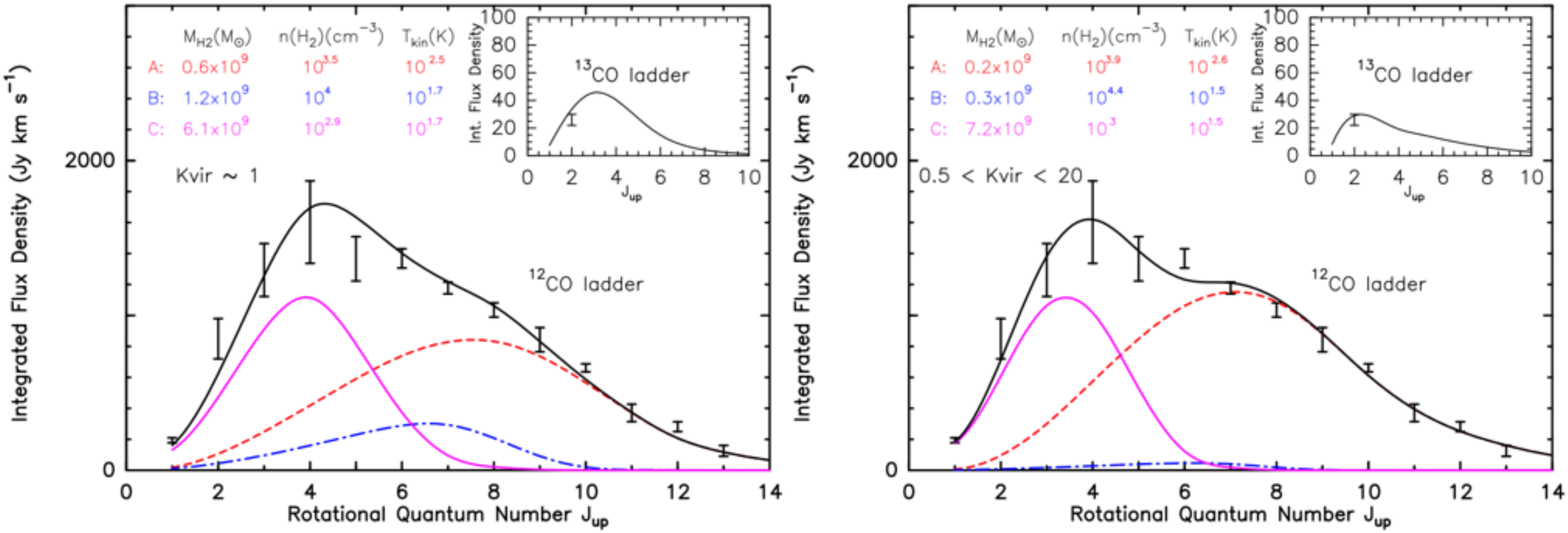
LVG Modelling with HCN, HCO$^+$, and CS





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) M_{dense}-SFR has nothing to do with the free-fall time (t_{ff}).

5) More detailed modelings are on the way.

Spatially resolved studies in external galaxies? -- ALMA

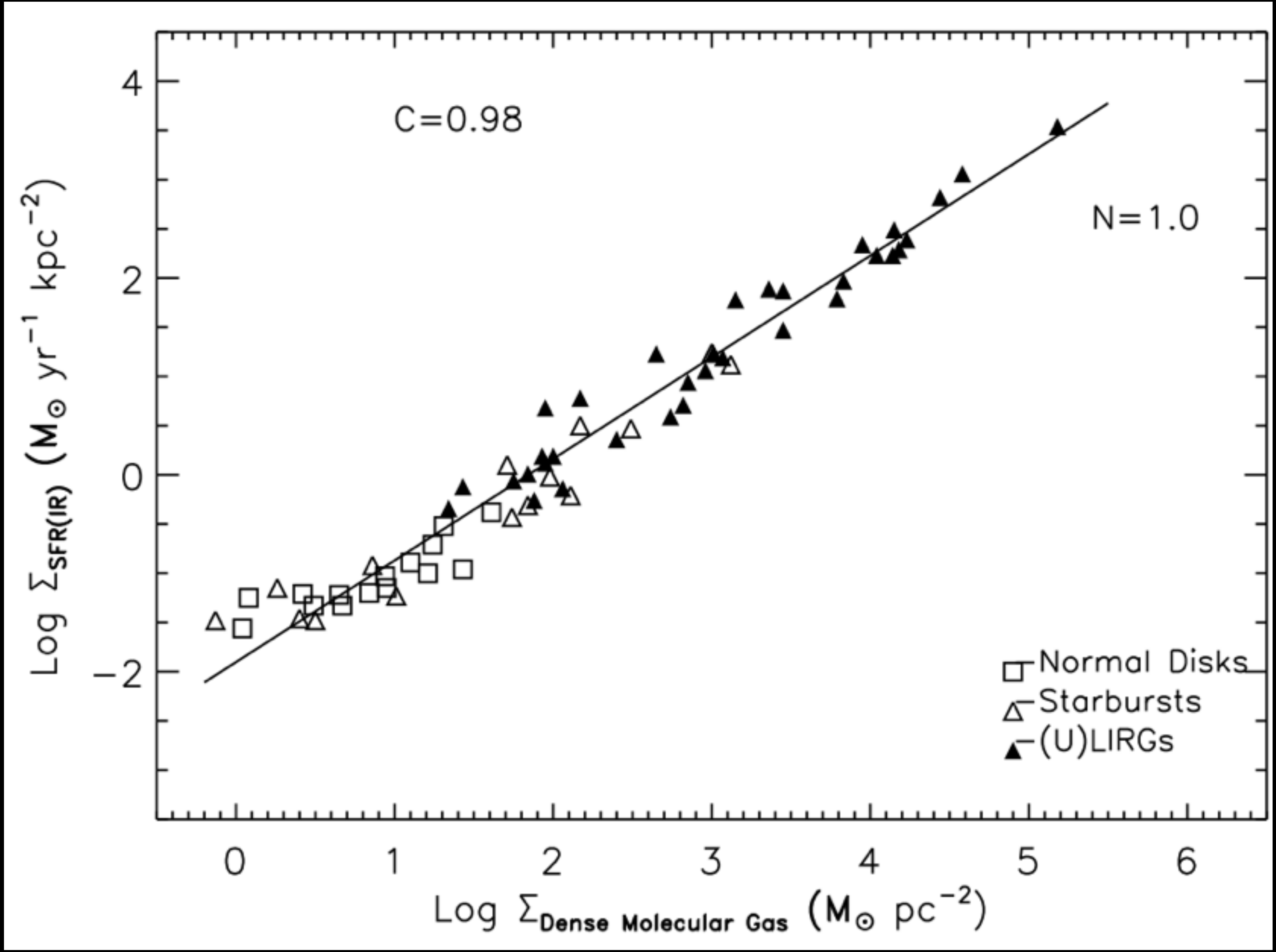
Background music: broadcasting gymnastics for Chinese schools

ALMA will be helpful!

Thank you!

Backup Slides

Surface density correlation of HCN -10



Fitting results

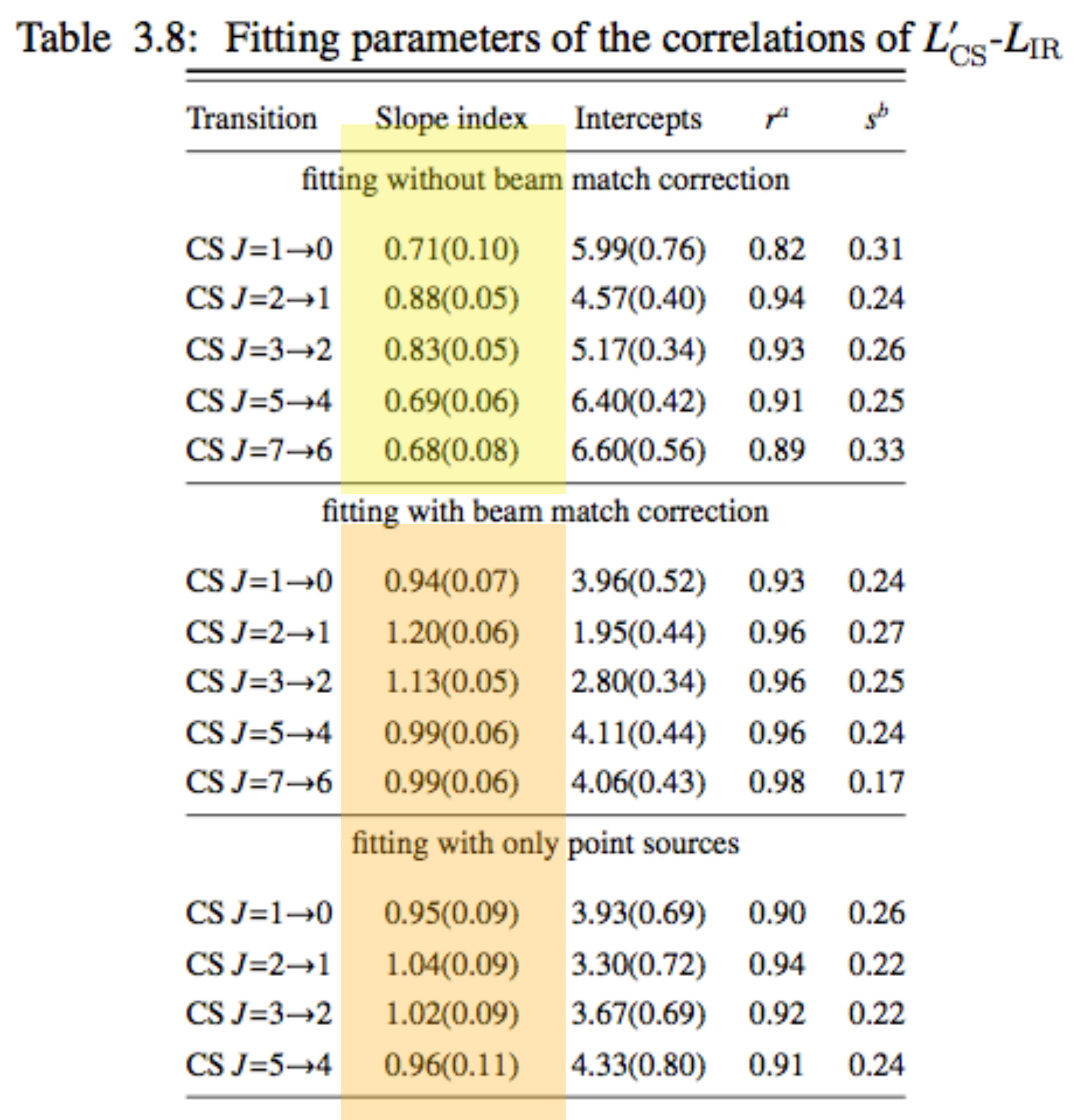
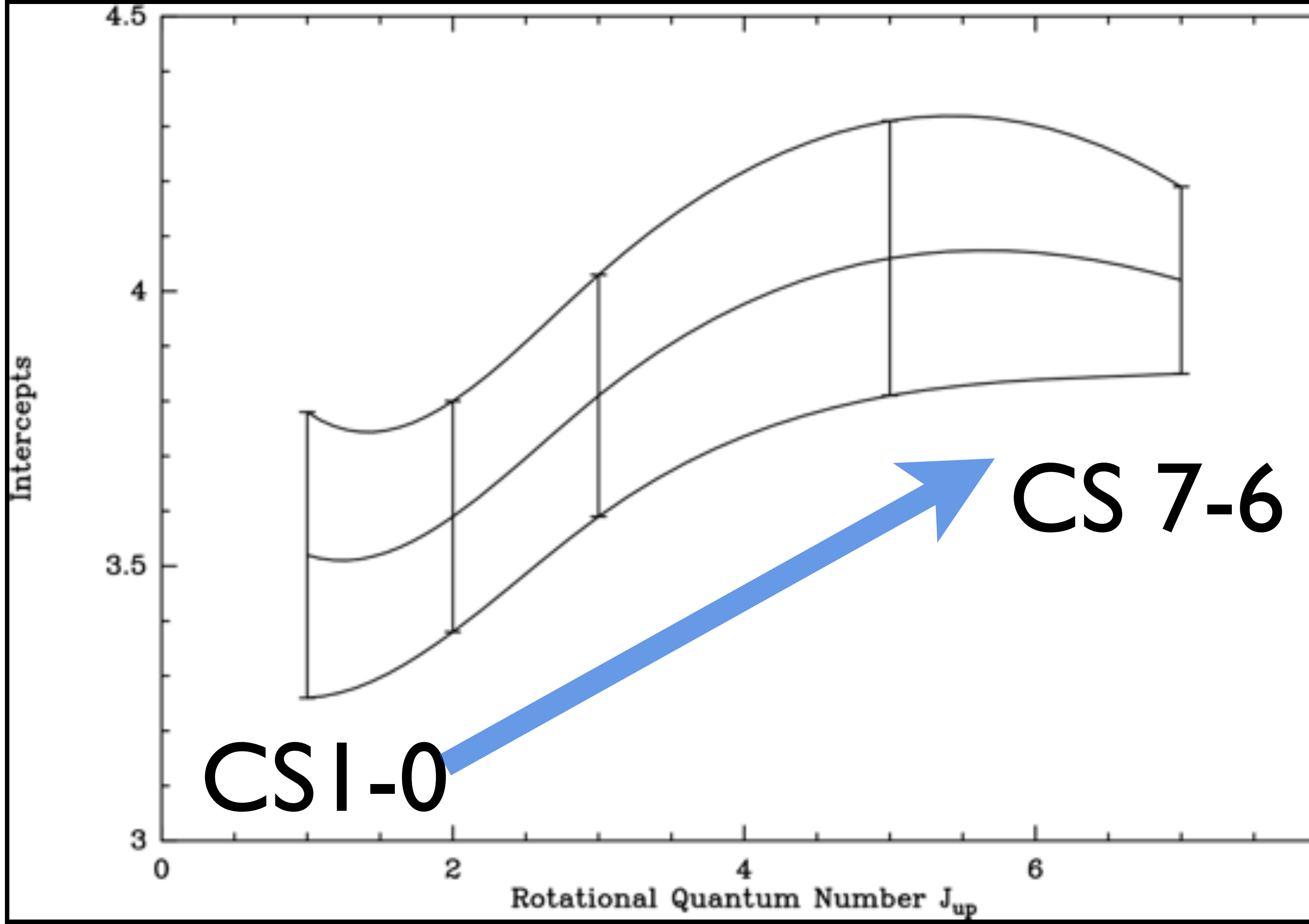


Table 3.8: Fitting parameters of the correlations of $L'_{\rm CS}$-$L_{\rm IR}$

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

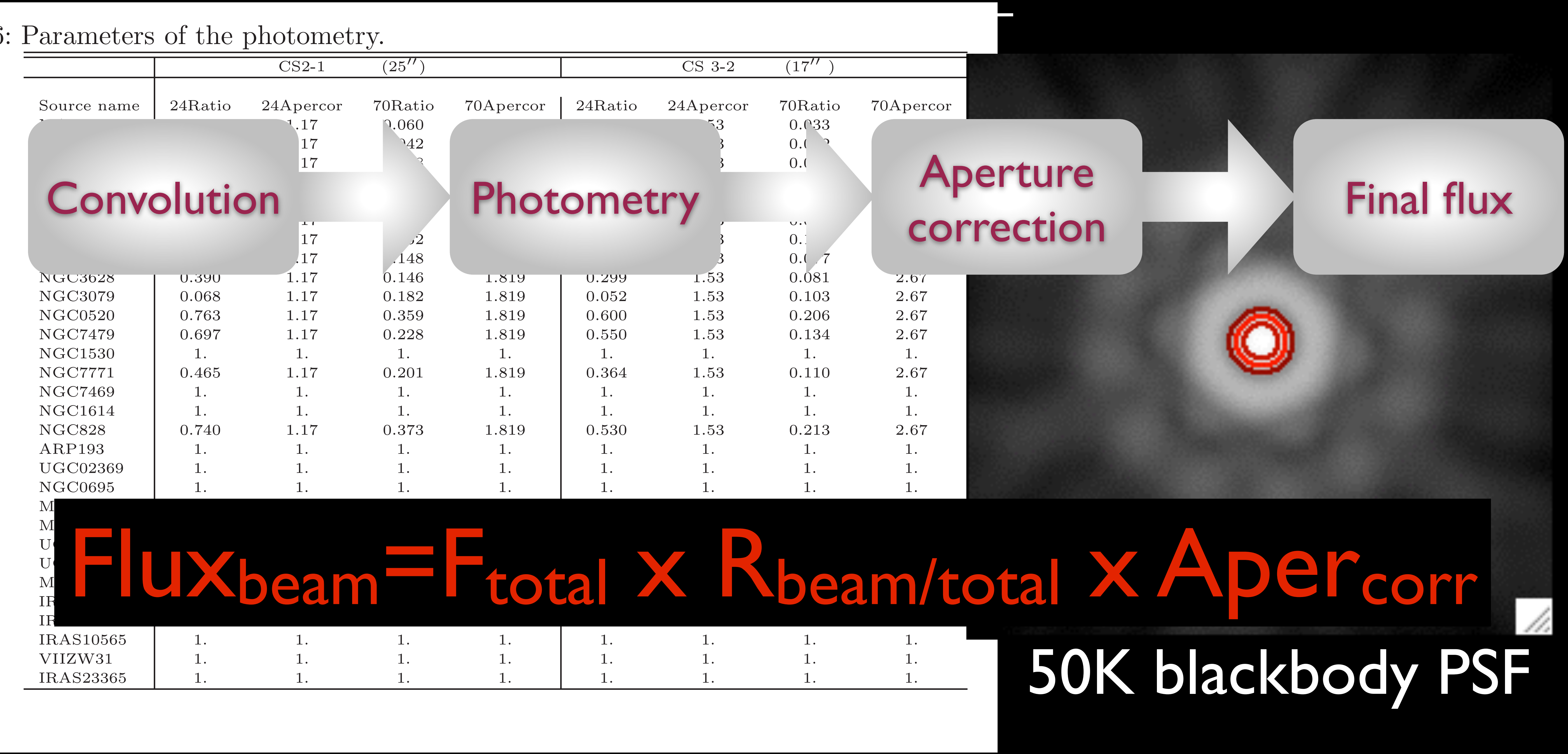
Intercept vs. J



sub-linear slope indices for uncorrected targets

linear correlations for point targets and beam matched targets

Aperture Correction -- beams are small



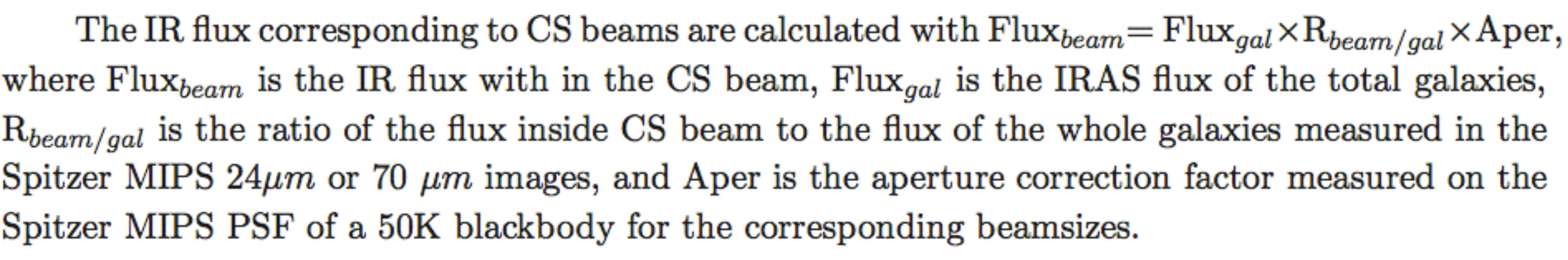
Convolution → Photometry → Aperture correction → Final flux

6: Parameters of the photometry.

	CS2-1	(25″)			CS 3-2	(17″)		
Source name	24Ratio	24Apercor	70Ratio	70Apercor	24Ratio	24Apercor	70Ratio	70Apercor
		1.17	.060			53	0.033	
		17	42			3	0.	
		17				3	0.	
		17	2			3	0.	
		.17	.148			3	0. 7	
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								
M								
U								
U								
M								
IR								
IR								
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.

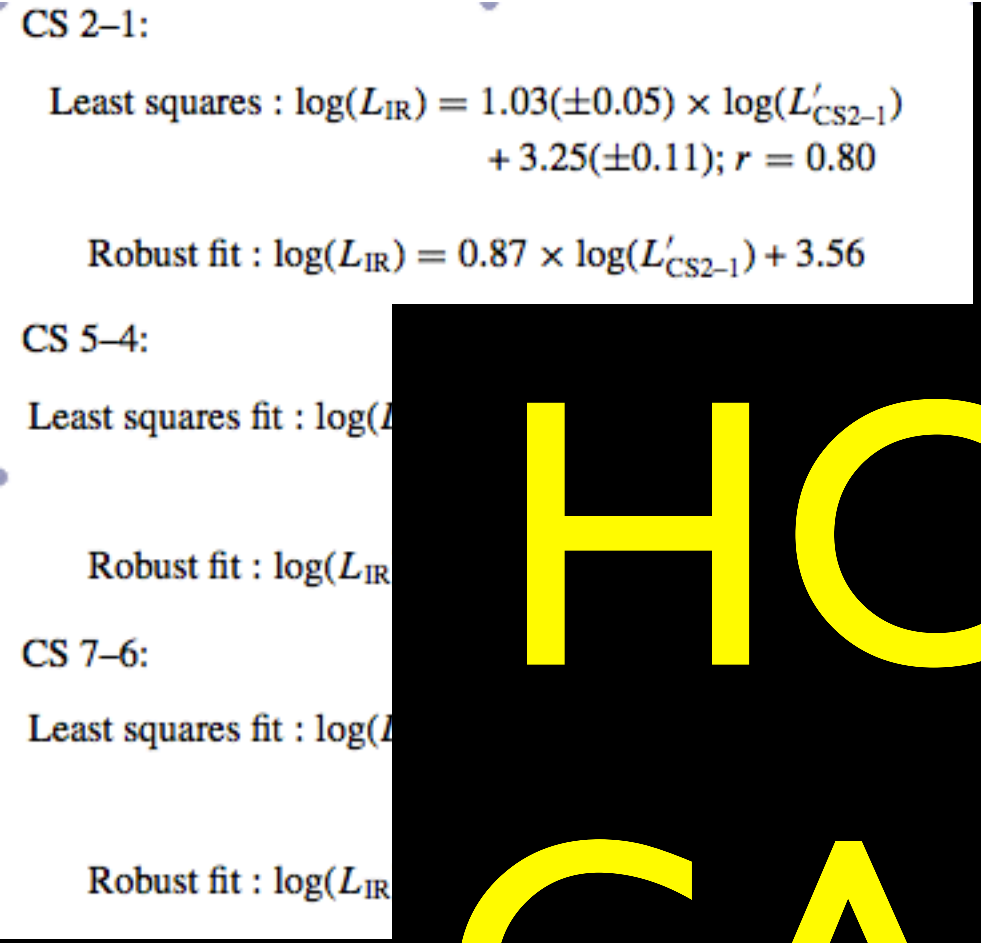
$$Flux_{beam}=F_{total} \times R_{beam/total} \times Aper_{corr}$$

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 $24\mu m$ or $70\ \mu m$ 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:

Least squares : $\log(L_{\rm IR}) = 1.03(\pm0.05) \times \log(L'_{\rm CS2-1}) + 3.25(\pm0.11);\ r = 0.80$

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

CS 5–4:

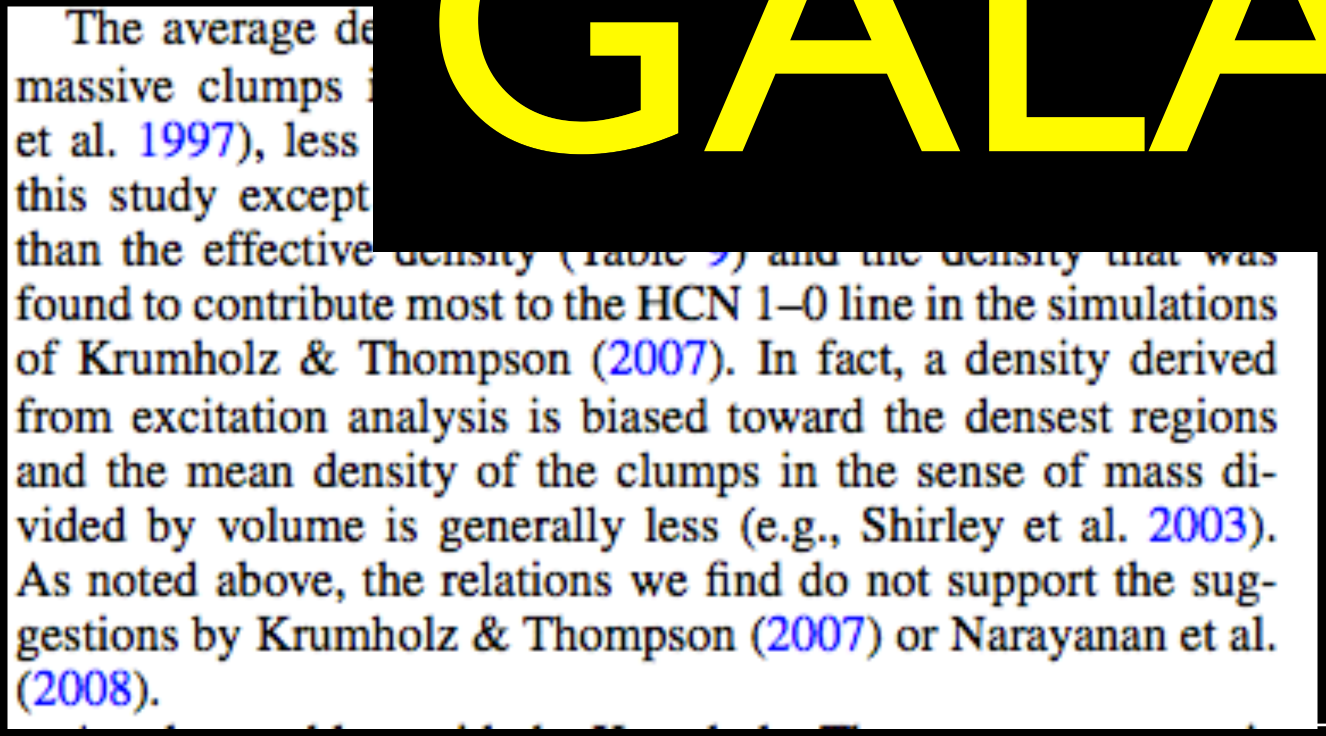
Least squares fit : log(L

Robust fit : $\log(L_{\rm IR}$

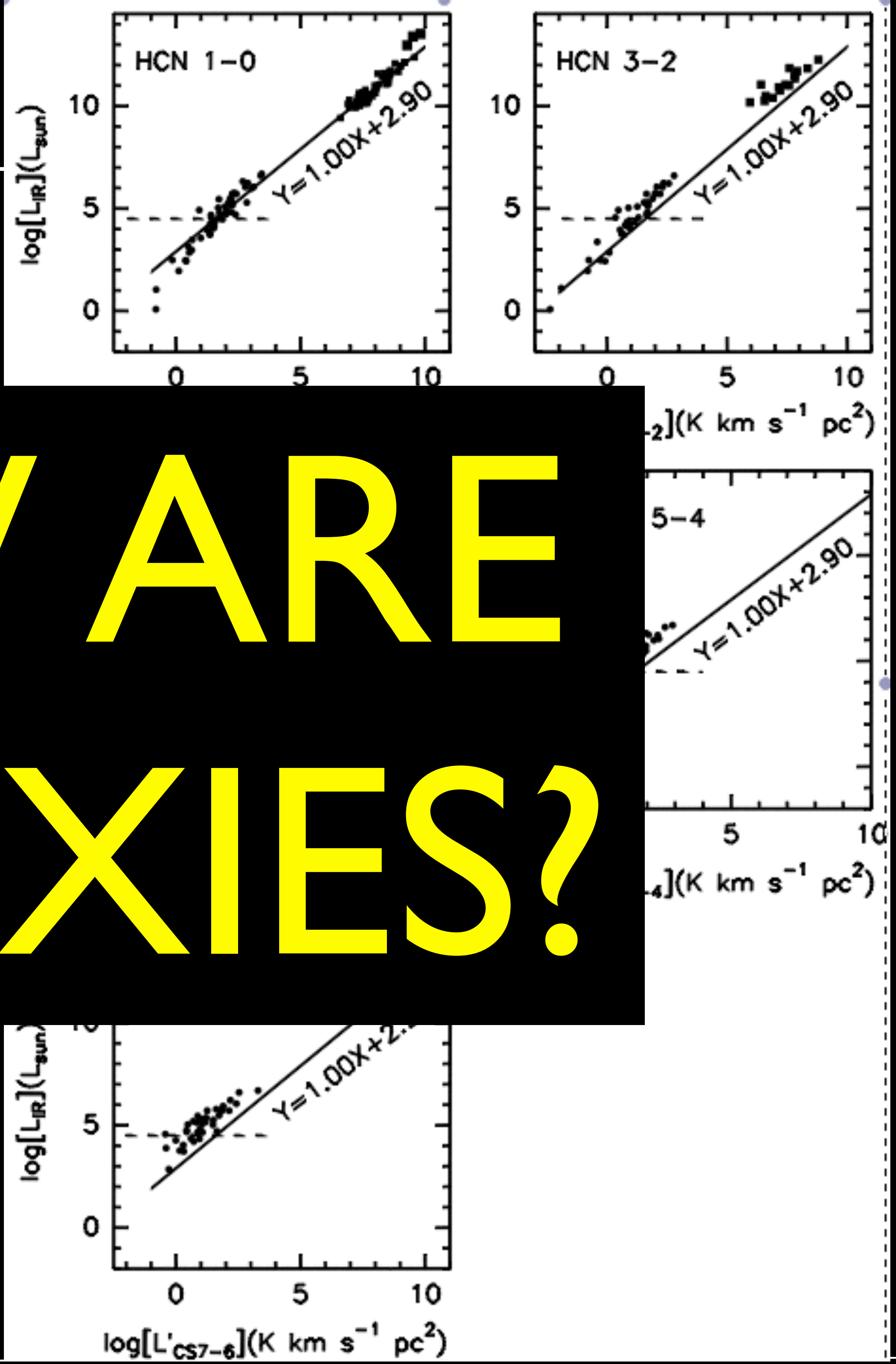
CS 7–6:

Least squares fit : log(L

Robust fit : $\log(L_{\rm IR}$



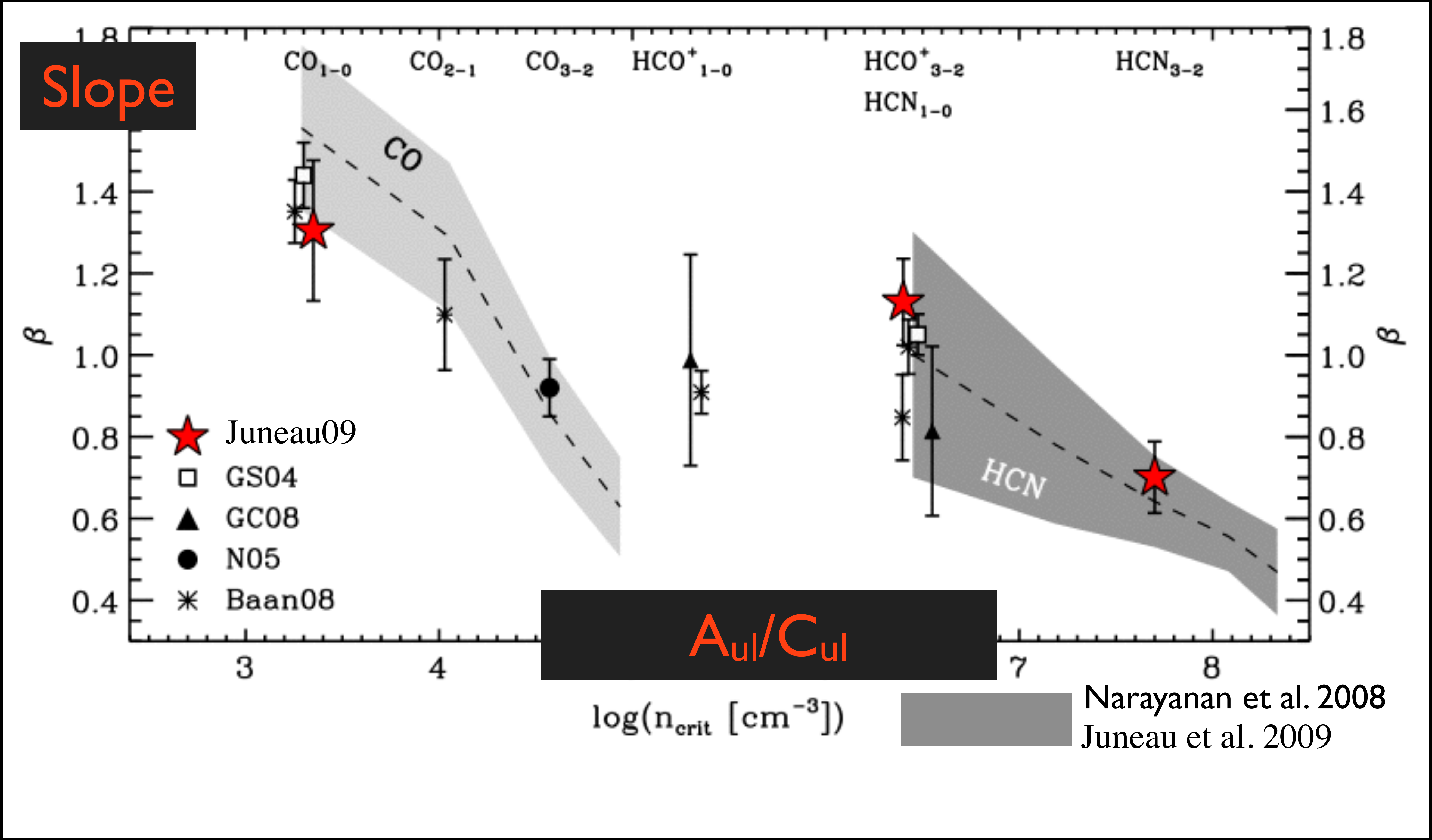
The average de
massive clumps i
et al. 1997), less
this study except
than the effective
found to contribute most to the HCN 1–0 line in the simulations of Krumholz & Thompson (2007). In fact, a density derived from excitation analysis is biased toward the densest regions and the mean density of the clumps 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).



HOW ARE GALAXIES?

Simulations vs. Observations

higher transitions/densities have lower slope indices.

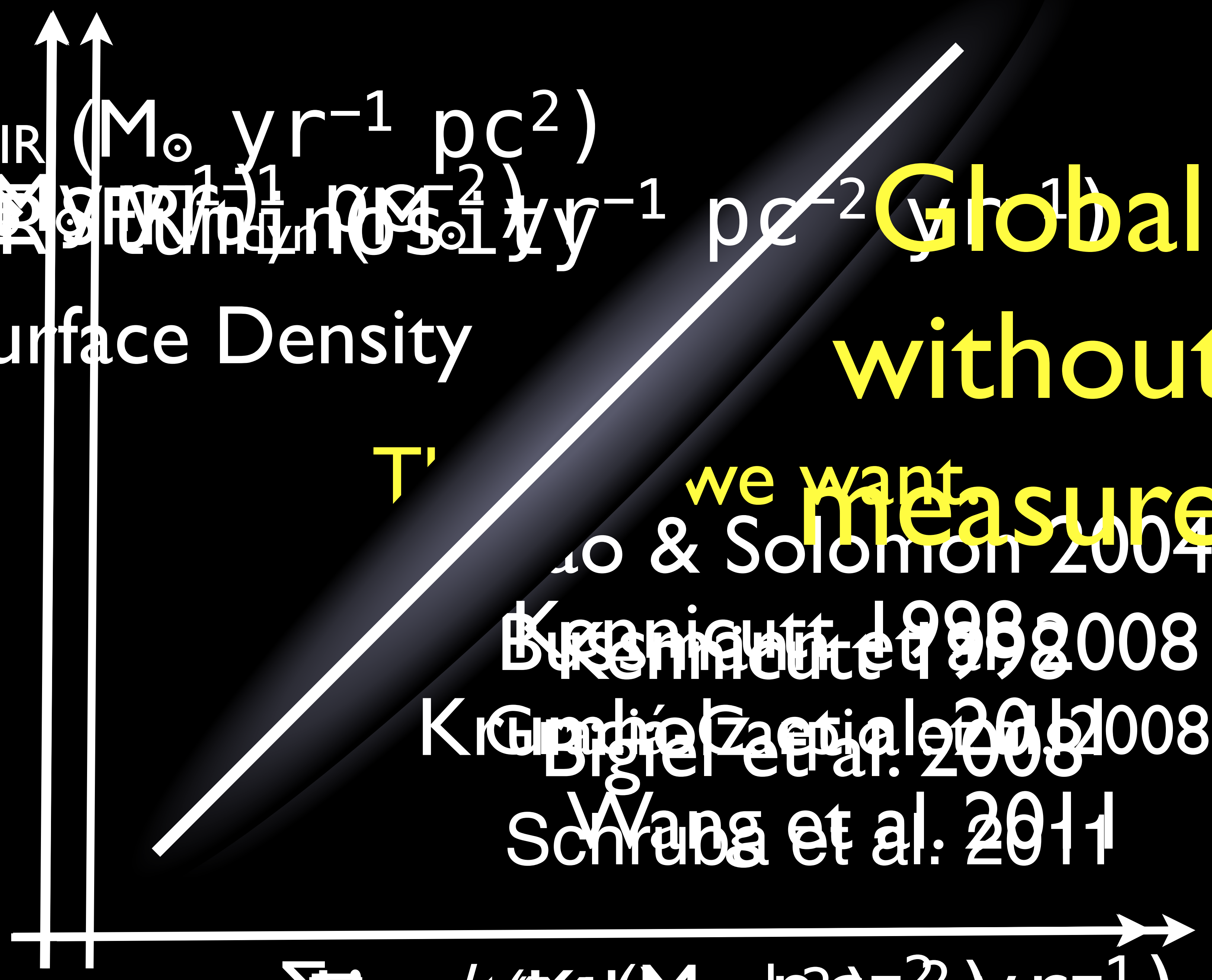


Slope

A_{ul}/C_{ul}

▨ Narayanan et al. 2008
Juneau et al. 2009

Star Formation Law (Units)



L_{IR} ($M_\odot$ yr^{-1} pc^{2})

Σ_{SFR} ($M_\odot$ yr^{-1} pc^{-2})

SFR ($M_\odot$ yr^{-1})

IR luminosity

($M_\odot$ yr^{-1} pc^{-2} yr^{-1})

SFR Surface Density

Global SFL without size measurement

T we want

ao & Solomon 2004

Kennicutt 1998

Bussmann et al. 2008

Kennicutt 1998

Krumholz et al. 2012

Gutermuth et al. 2011

Bigiel et al. 2008

Wang et al. 2011

Schruba et al. 2011

Σ_{gas}/t_{ff} ($M_\odot$ pc^{-2} yr^{-1})

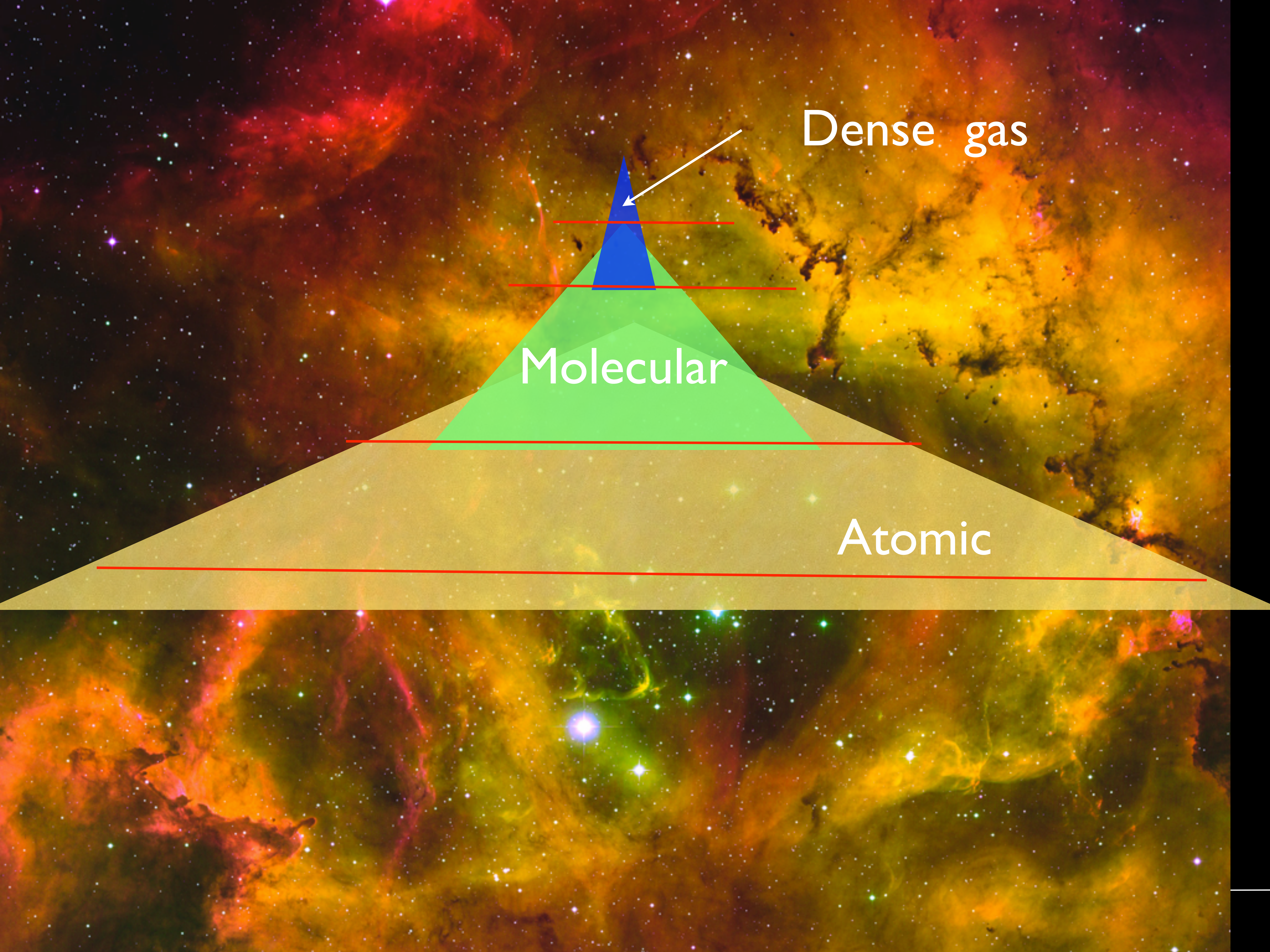
M_{gas} ($M_\odot$)

Σ_{gas} ($M_\odot$ pc^{-2})

(K km/s pc^{2})

Gas Surface Density

Gas luminosity

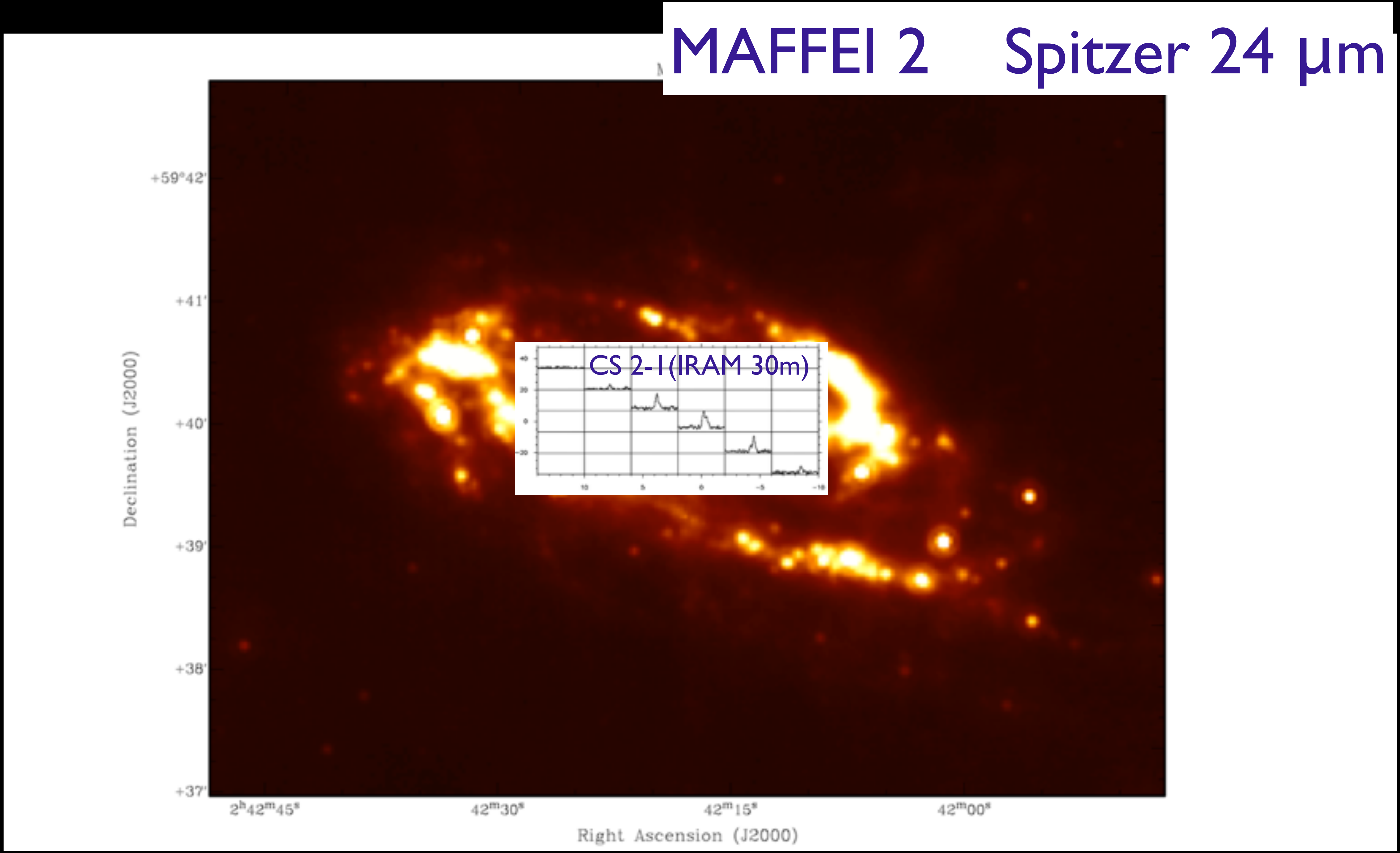


Dense gas

Molecular

Atomic

Extended CS emission on the disk



Dense gas tracers

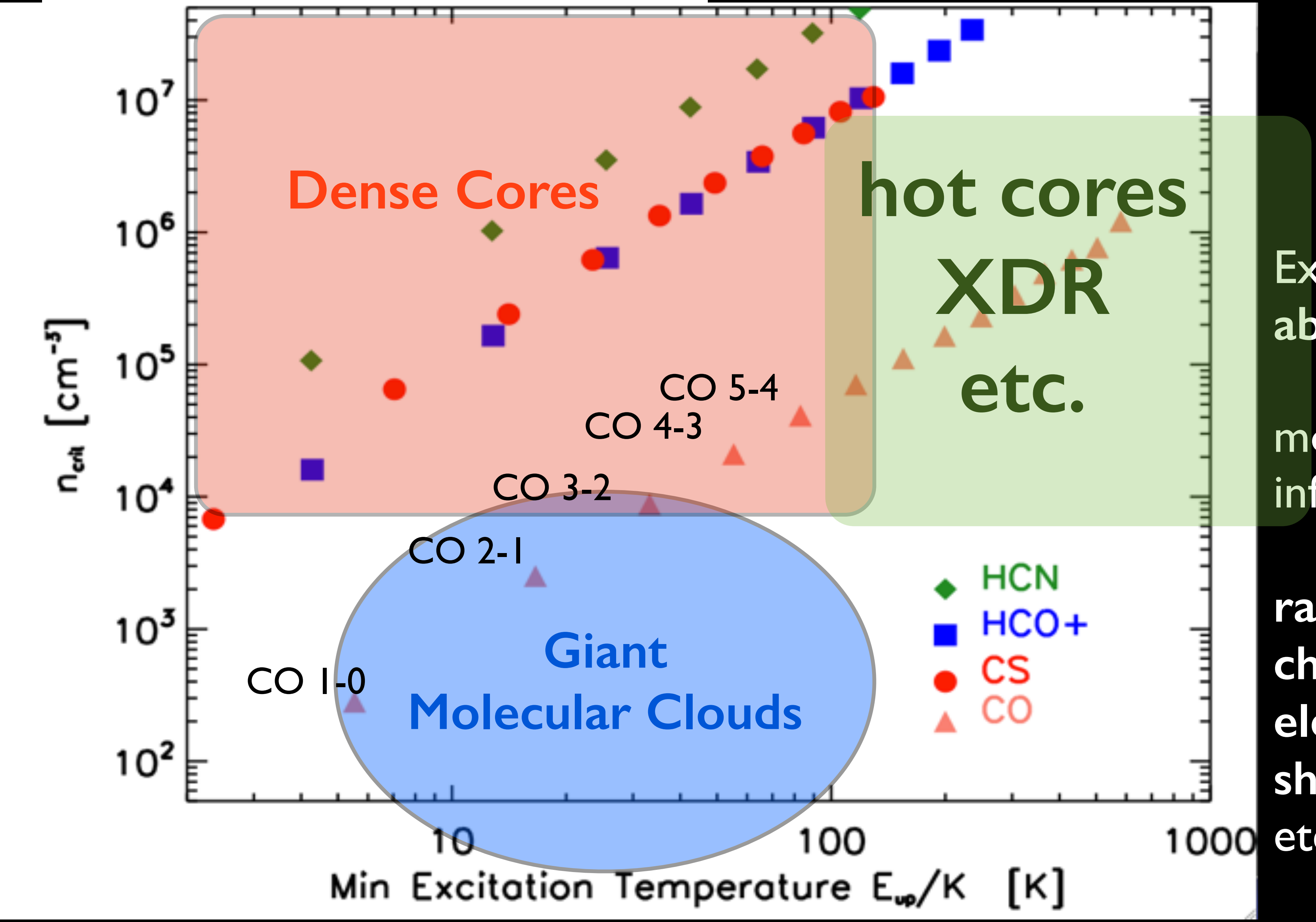
Critical Density:

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

Rotational transitions of heavy molecules

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

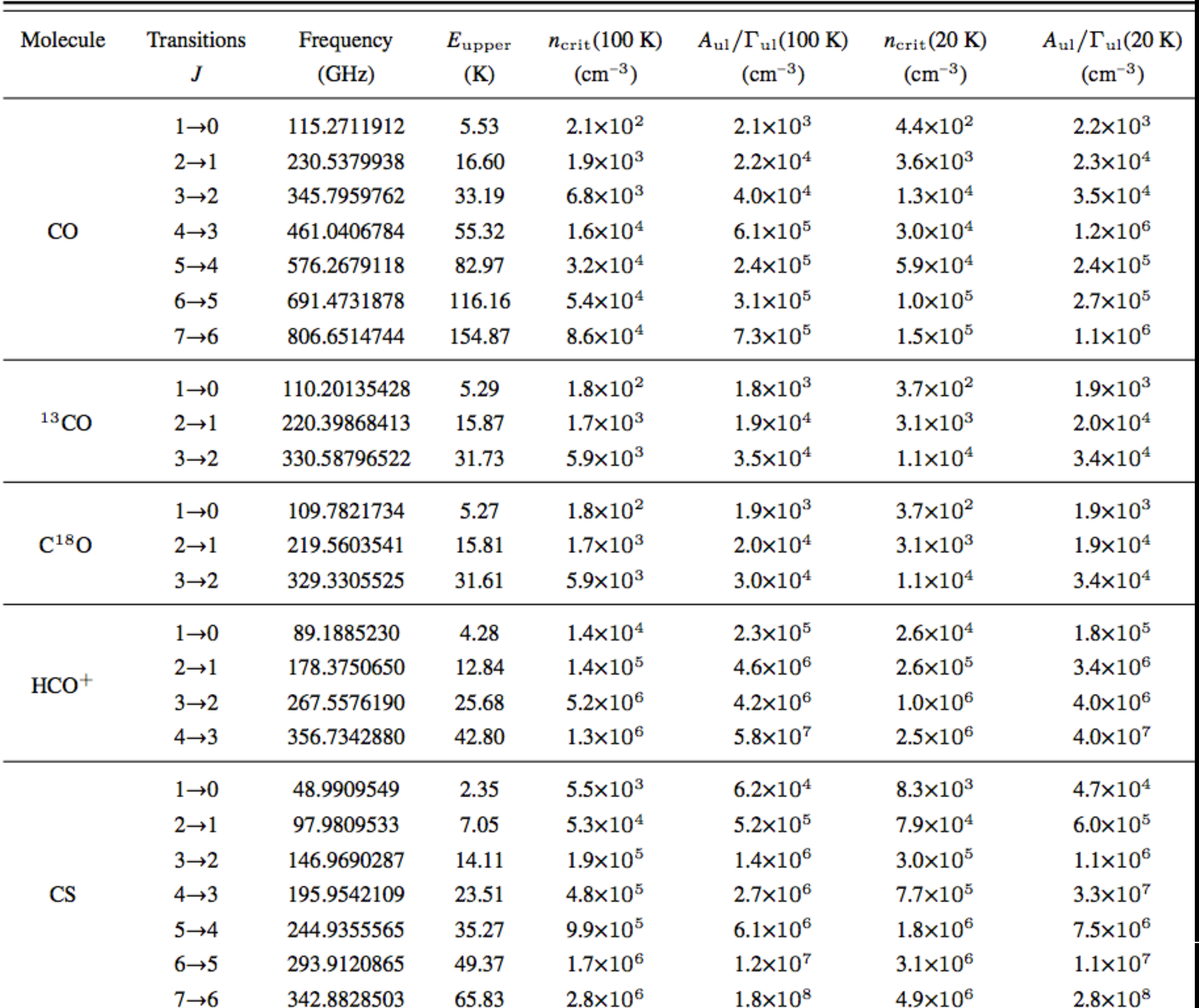
Dense gas tracer: $n_{\mathrm{crit}} > 10^4 \mathrm{cm}^{-3}$



Except for
abundance and excitation,

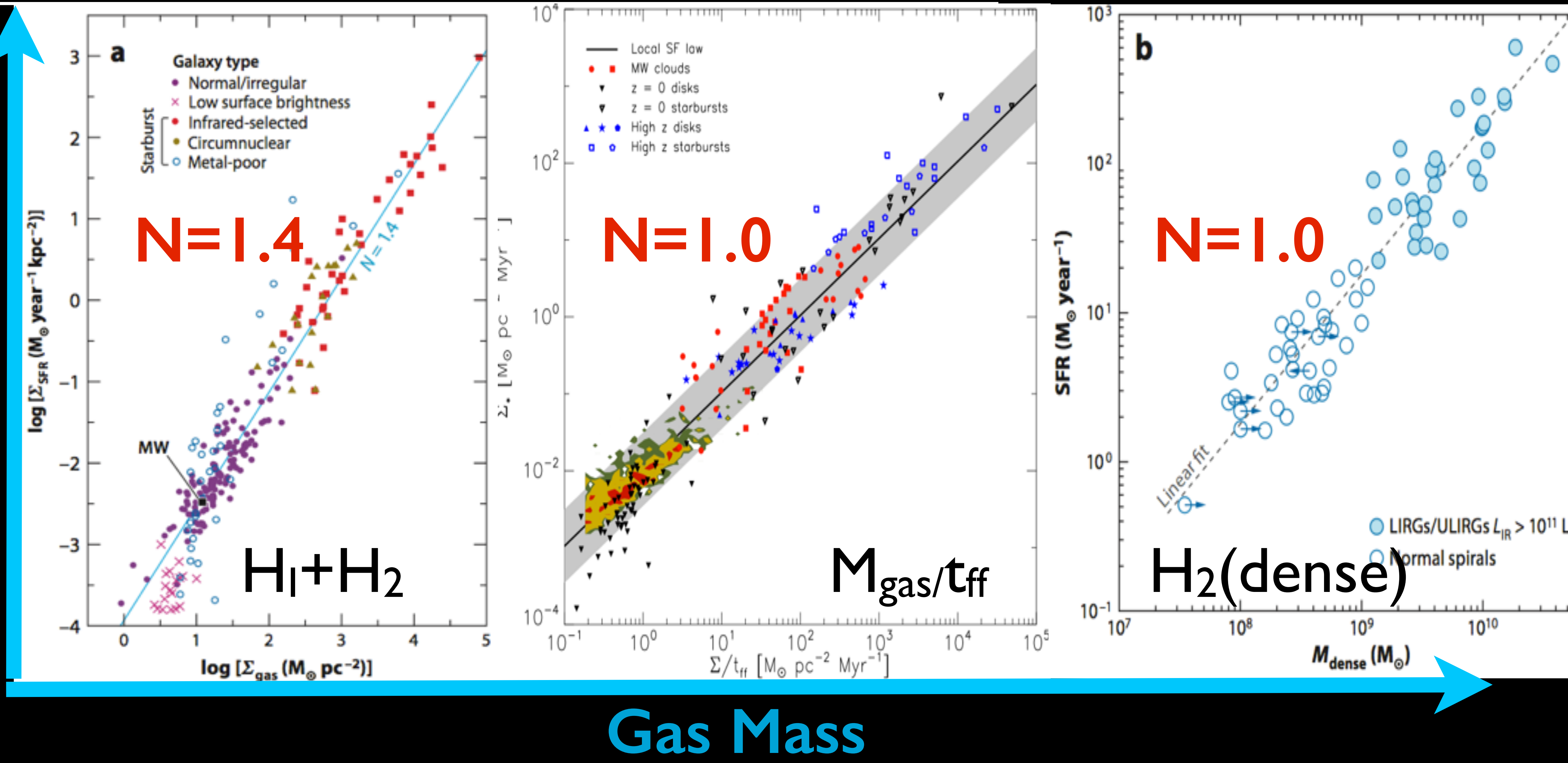
molecular emissions can be
influenced by:

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

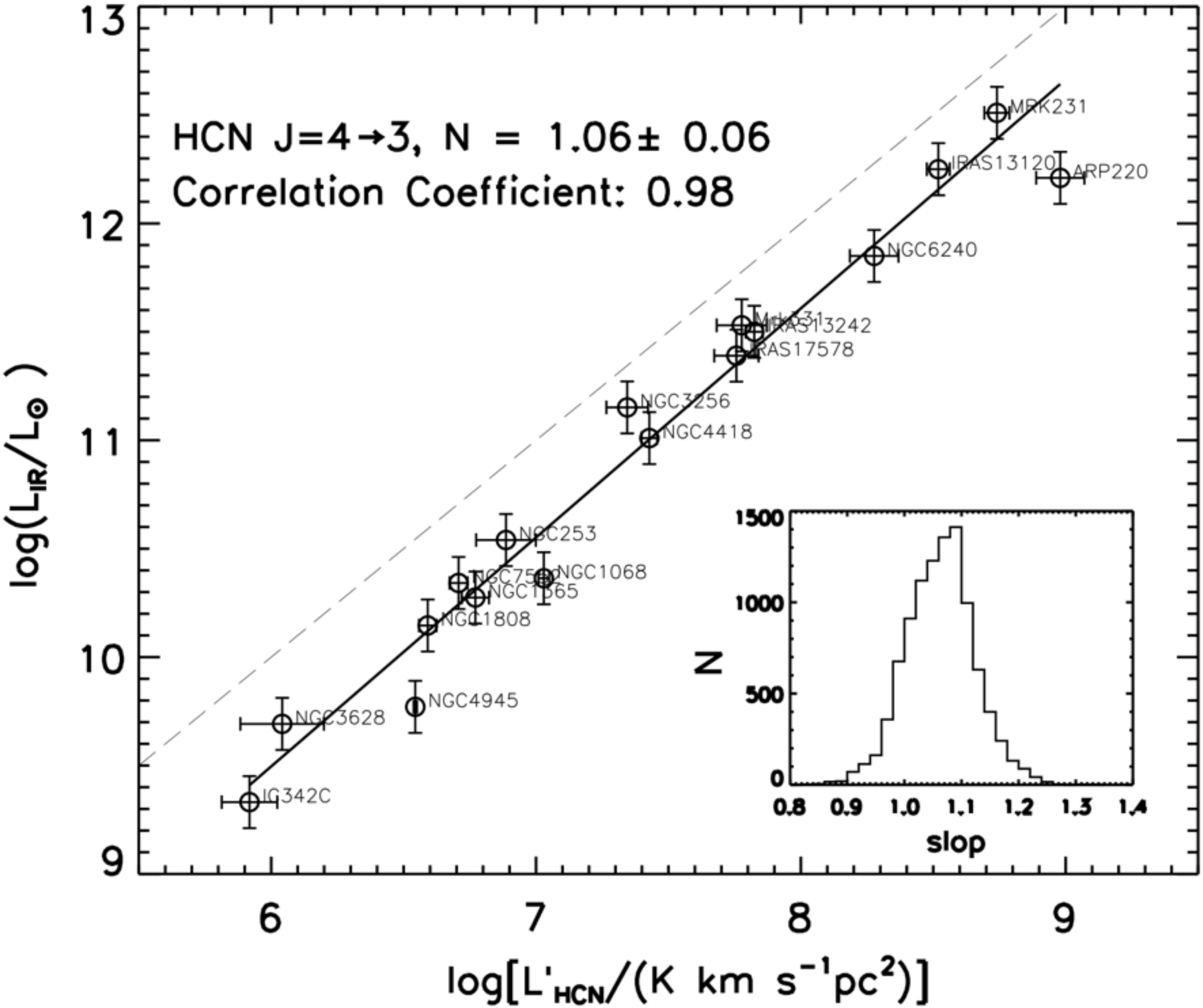
Gas - SFR relations



Kennicutt 1998

Krumholz et al. 2012

Gao & Solomon 2004


HCN J=4→3, N = 1.06± 0.06
Correlation Coefficient: 0.98
MRK231
IRAS13120
ARP220
NGC6240
Mrk331
IRAS13242
IRAS17578
NGC3256
NGC4418
NGC253
NGC7552
NGC1068
NGC1365
NGC1808
NGC4945
NGC3628
IC342C
log(L_IR/L_⊙)
13
12
11
10
9
log[L'_HCN/(K km s^-1pc^2)]
6
7
8
9
1500
1000
500
0
N
0.8
0.9
1.0
1.1
1.2
1.3
1.4
slop