Dense Cores and SF Galaxies: Multi-J & Multi-lines

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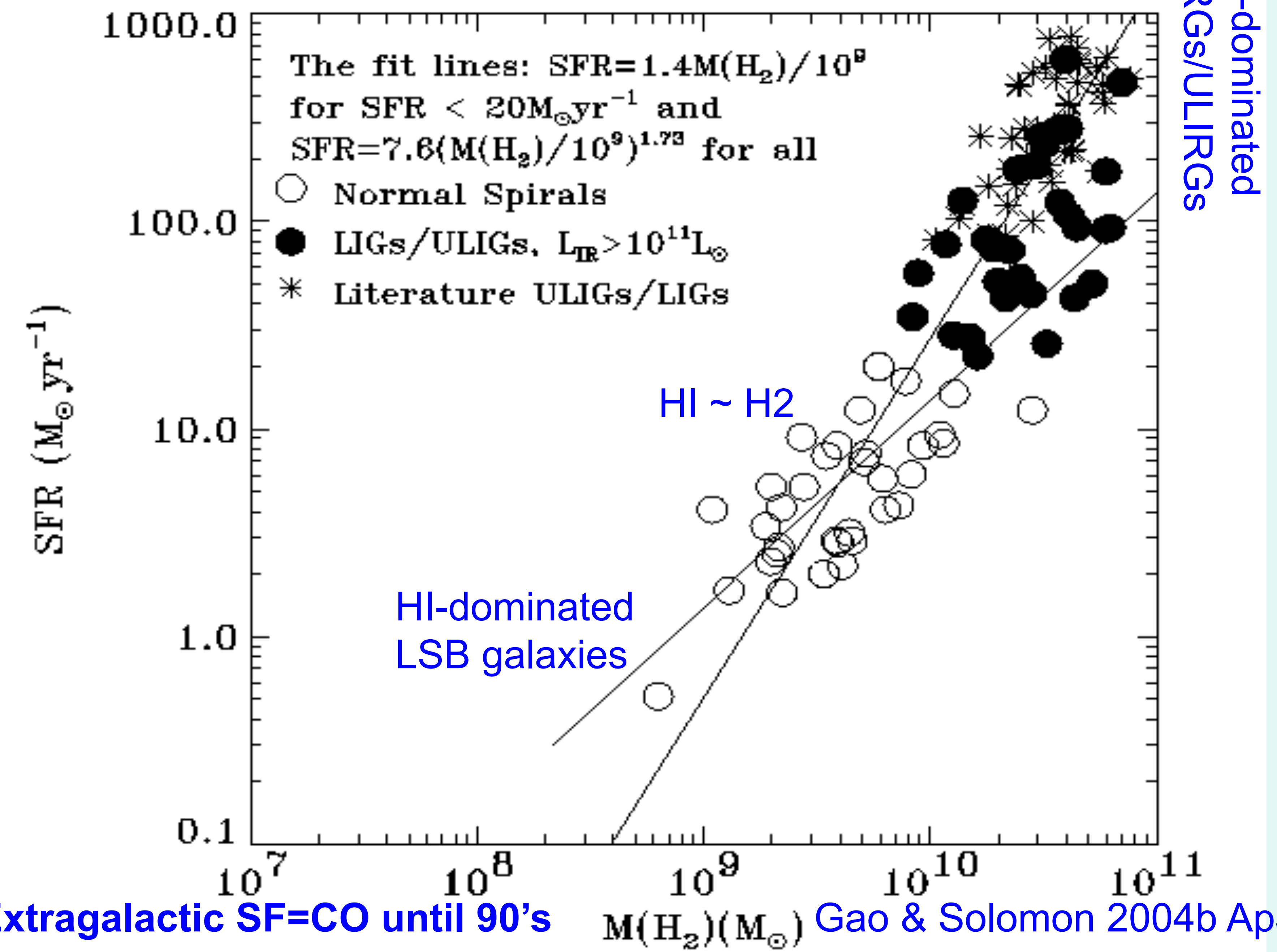
Outline of this talk

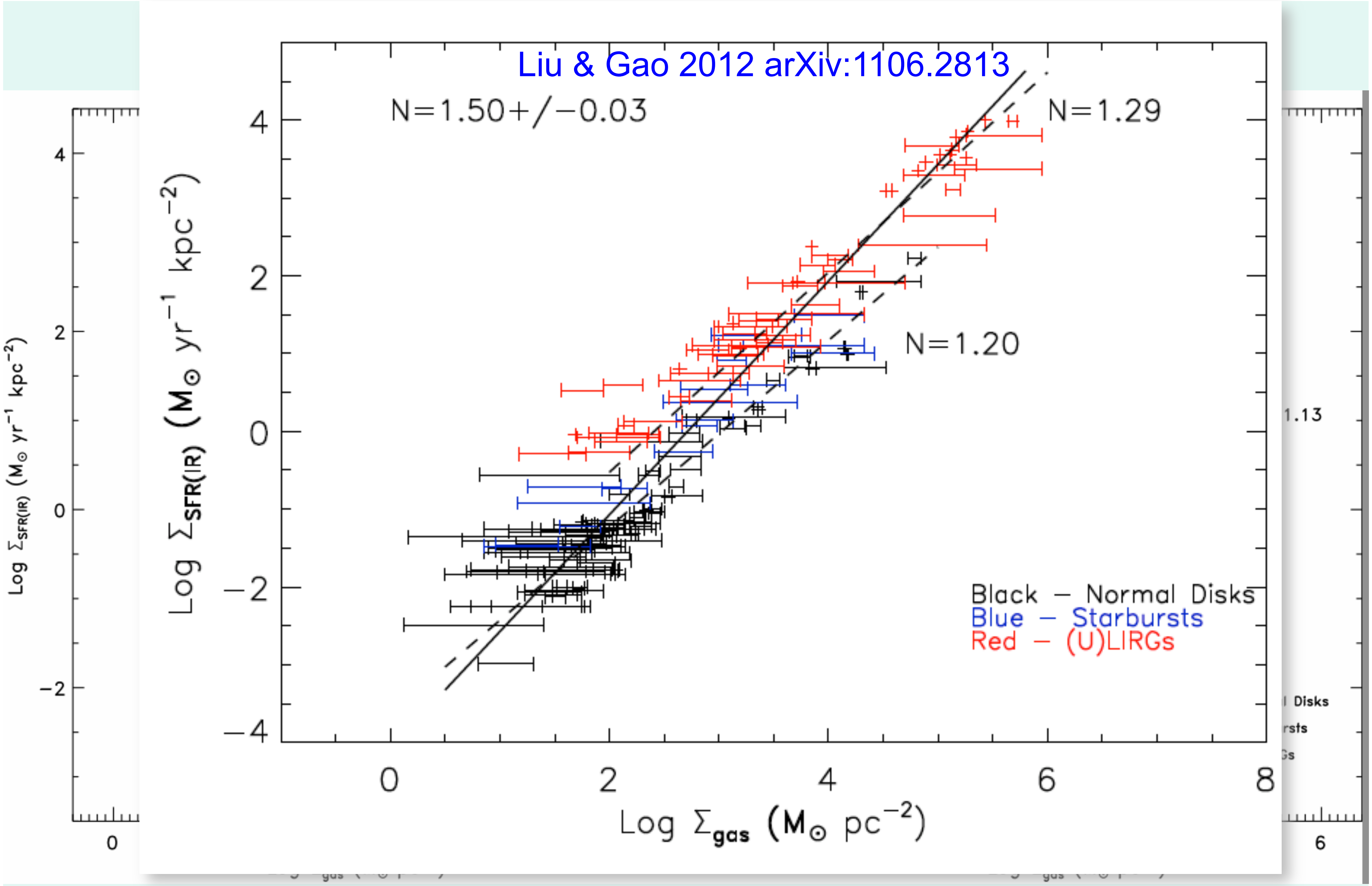
- SF rate (SFR)--gas (HI, CO) scaling laws? Dense cores & dense gas in galaxies
- A linear FIR(SFR)--HCN (dense gas tracers) relation for all star-forming systems: SF law in dense gas
- Multi-lines, hi-J CO & CS surveys
- Conclusion & future

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



Extragalactic SF=CO until 90's

Gao & Solomon 2004b ApJ



Bi-modal SF laws in high-z gals (Daddi+2010; Genzel+2010) also exist in local gals

High Density Tracers

Merging/interactions trigger gas infall to nuclear regions

Nuclei of Galaxies should possess denser gas

as GMCs have to survive to **tidal forces (must be denser, thus probably only the dense cores)**

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 **(>~5)** levels of CO (nu ~ J)

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

* & high dipole moment molecules

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

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

*

ANNUAL REVIEWS
A NONPROFIT SCIENTIFIC PUBLISHER

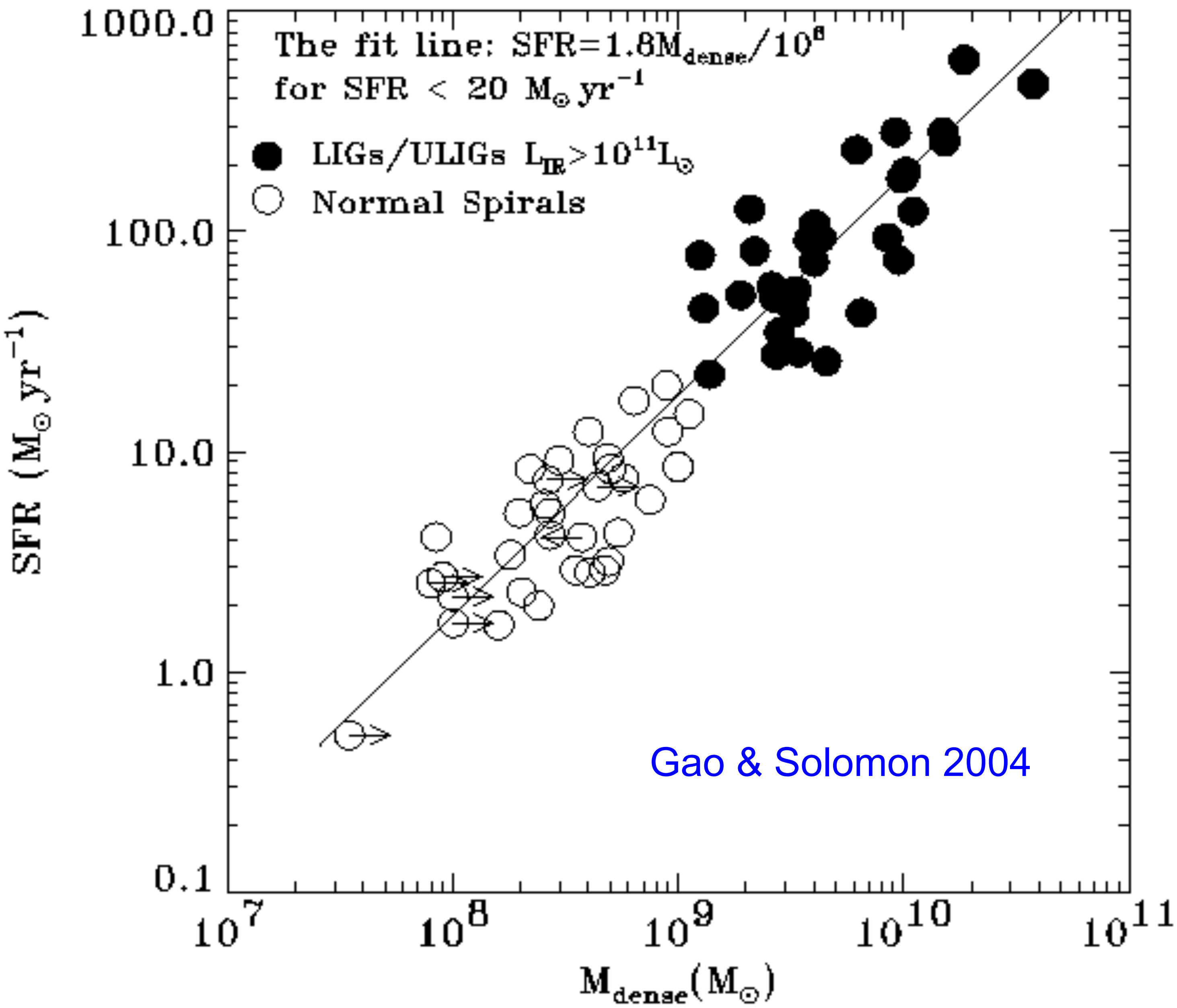
Evans 1999 ARA&A

TABLE 1 Properties of density probes

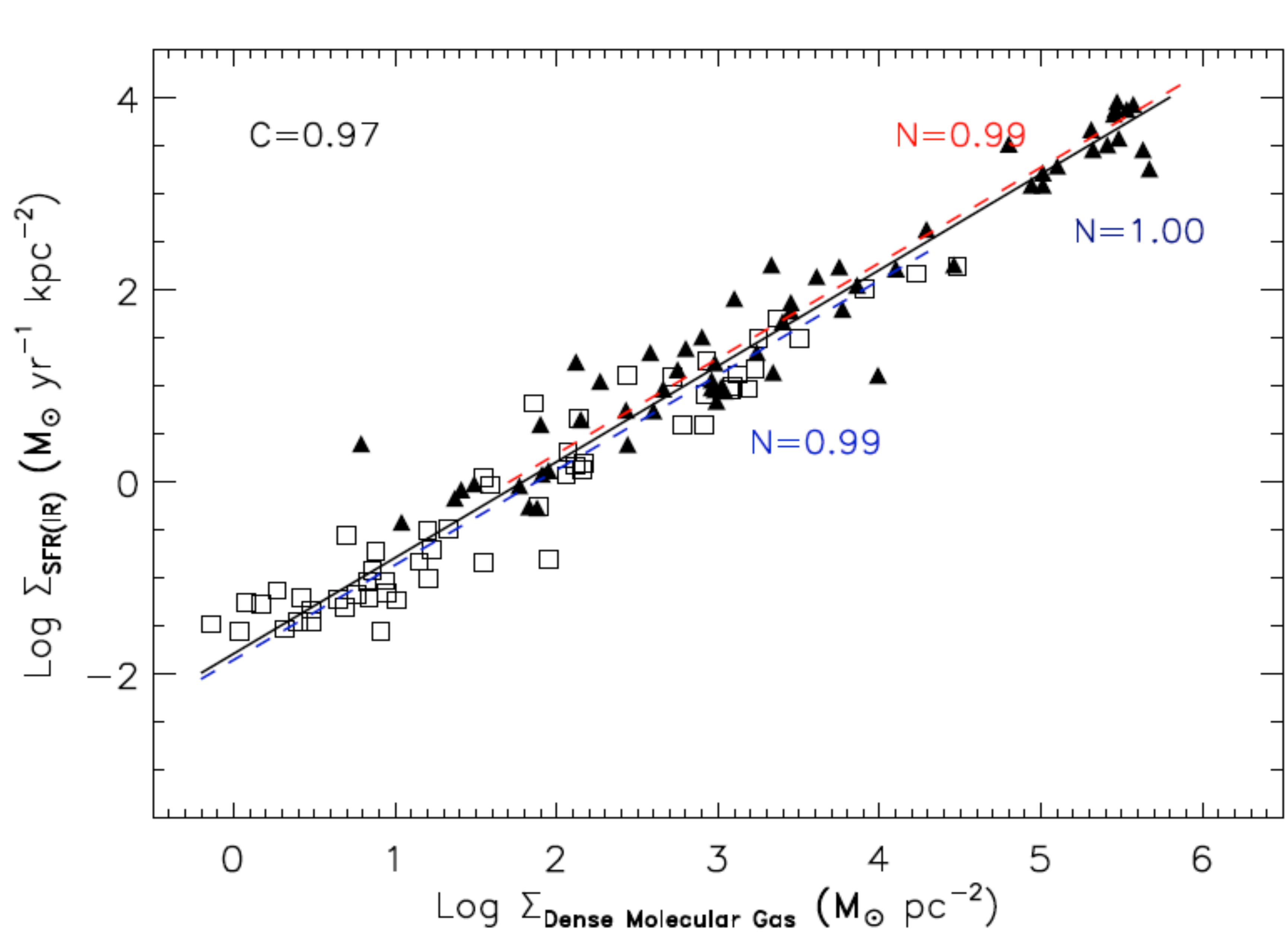
Molecule	Transition	ν (GHz)	E_{up} (K)	n_c(10 K) (cm^{-3})	n_{eff}(10 K) (cm^{-3})	n_c(100 K) (cm^{-3})	n_{eff}(100 K) (cm^{-3})
CS	$J = 1 \rightarrow 0$	49.0	2.4	4.6×10^4	7.0×10^3	6.2×10^4	2.2×10^3
CS	$J = 2 \rightarrow 1$	98.0	7.1	3.0×10^5	1.8×10^4	3.9×10^5	4.1×10^3
CS	$J = 3 \rightarrow 2$	147.0	14	1.3×10^6	7.0×10^4	1.4×10^6	1.0×10^4
CS	$J = 5 \rightarrow 4$	244.9	35	8.8×10^6	2.2×10^6	6.9×10^6	6.0×10^4
CS	$J = 7 \rightarrow 6$	342.9	66	2.8×10^7	…	2.0×10^7	2.6×10^5
CS	$J = 10 \rightarrow 9$	489.8	129	1.2×10^8	…	6.2×10^7	1.7×10^6
HCO^+	$J = 1 \rightarrow 0$	89.2	4.3	1.7×10^5	2.4×10^3	1.9×10^5	5.6×10^2
HCO^+	$J = 3 \rightarrow 2$	267.6	26	4.2×10^6	6.3×10^4	3.3×10^6	3.6×10^3
HCO^+	$J = 4 \rightarrow 3$	356.7	43	9.7×10^6	5.0×10^5	[illegible]	1.0×10^4
HCN	$J = 1 \rightarrow 0$	88.6	4.3	2.6×10^6	2.9×10^4	[illegible]	[illegible] 10^3
HCN	$J = 3 \rightarrow 2$	265.9	26	7.8×10^7	7.0 × 1[illegible]	[illegible]	[illegible]
HCN	$J = 4 \rightarrow 3$	354.5	43	1.5×10^8	6.0 × 1[illegible]	[illegible]	[illegible]
H_2CO	$2_{12} \rightarrow 1_{11}$	140.8	6.8	1.1×10^6	6.0 × 1[illegible]	[illegible]	[illegible]
H_2CO	$3_{13} \rightarrow 2_{12}$	211.2	17	5.6×10^6	3.2 × 1[illegible]	[illegible]	[illegible]
H_2CO	$4_{14} \rightarrow 3_{13}$	281.5	30	9.7×10^6	2.2 × 1[illegible]	[illegible]	[illegible]
H_2CO	$5_{15} \rightarrow 4_{14}$	351.8	47	2.6×10^7	[illegible]	[illegible]	[illegible]
NH_3	(1,1)inv	23.7	1.1	1.8×10^3	[illegible]	[illegible]	[illegible]
NH_3	(2,2)inv	23.7	42	2.1×10^3	[illegible]	[illegible]	[illegible]

…means no value; inv means inversion transition.

SFR vs. M_dense(H2): FIR-HCN linear correlation



ΣMdense vs. ΣSFR

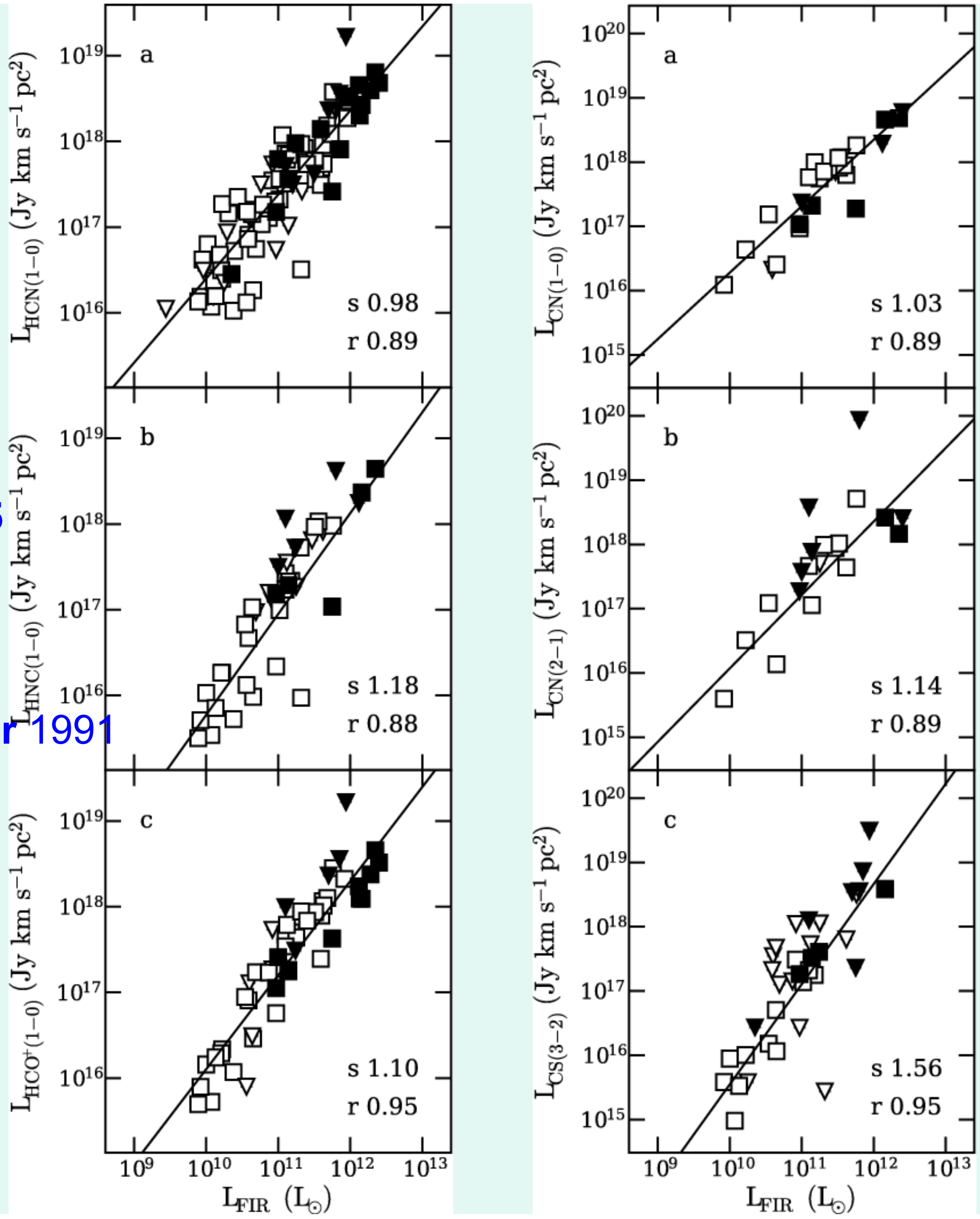


Dense H2 show the best correlation with SFR (linear Liu & Gao 2012).

Baan, Henkel, Loenen + 2008

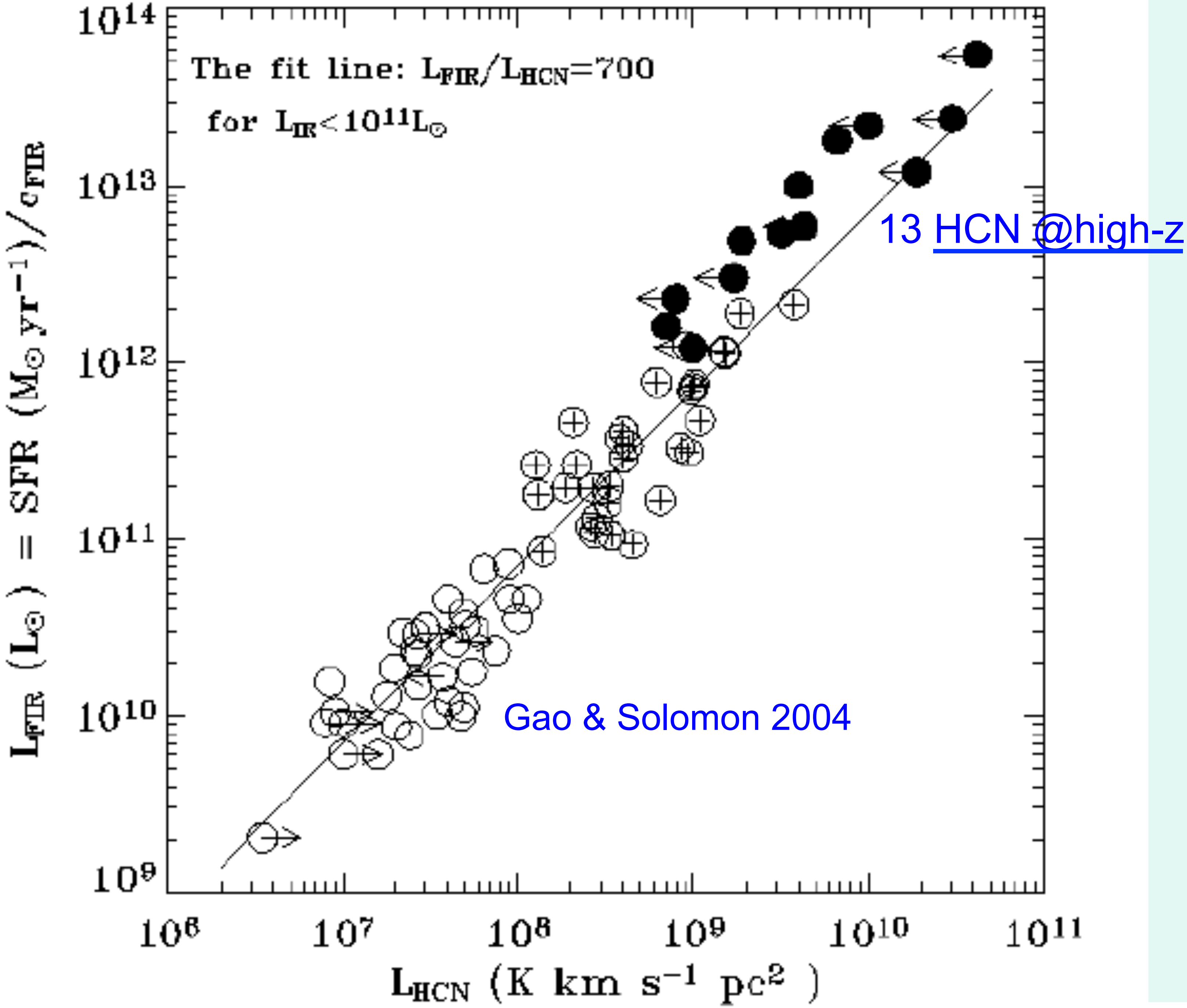
HCN,CS,HNC etc. in SF gals.

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

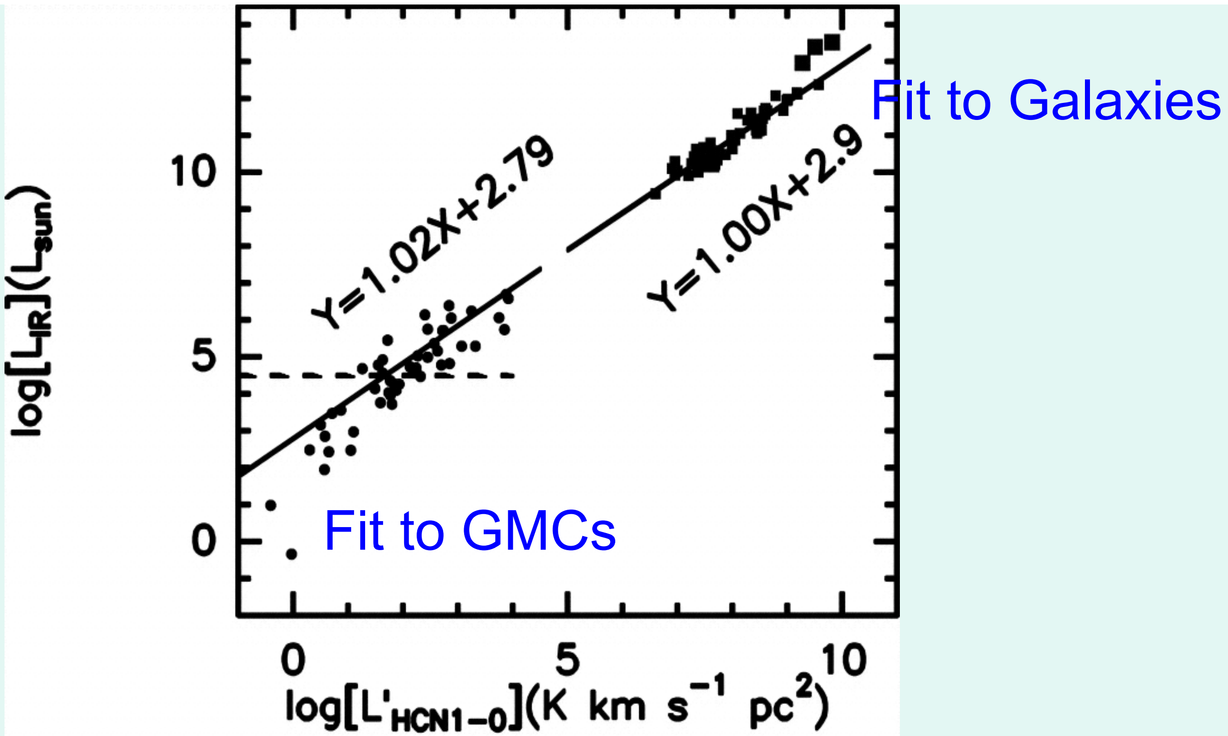


Best case studies:
Arp 220 & NGC 6240
(Greve + 2009)

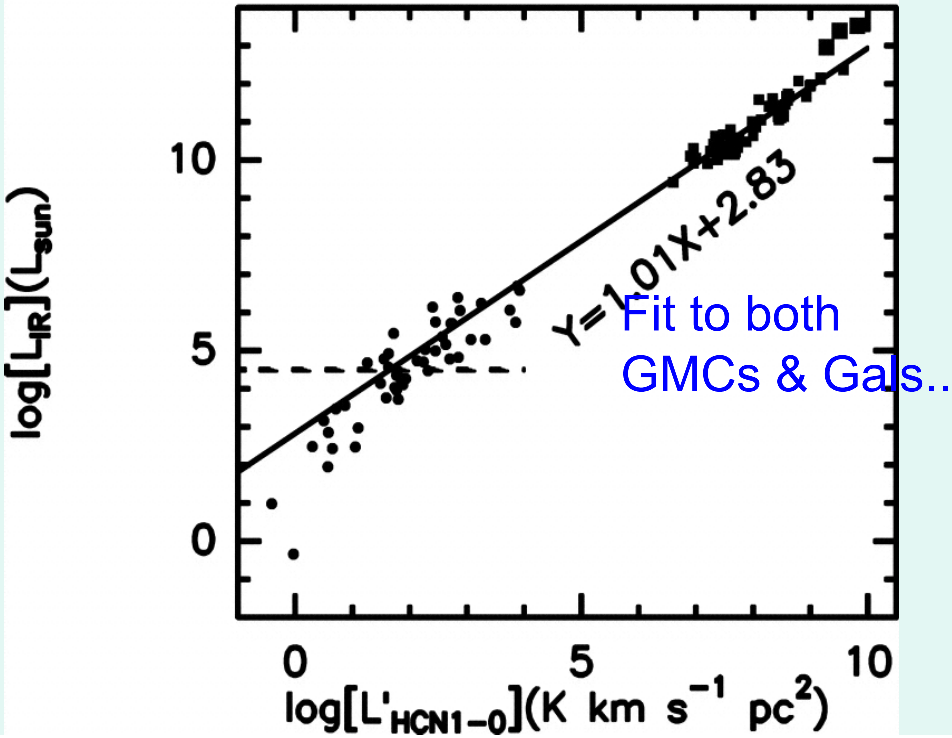
Gao, Carilli, Solomon & Vanden Bout 2007 ApJ, 660, L93



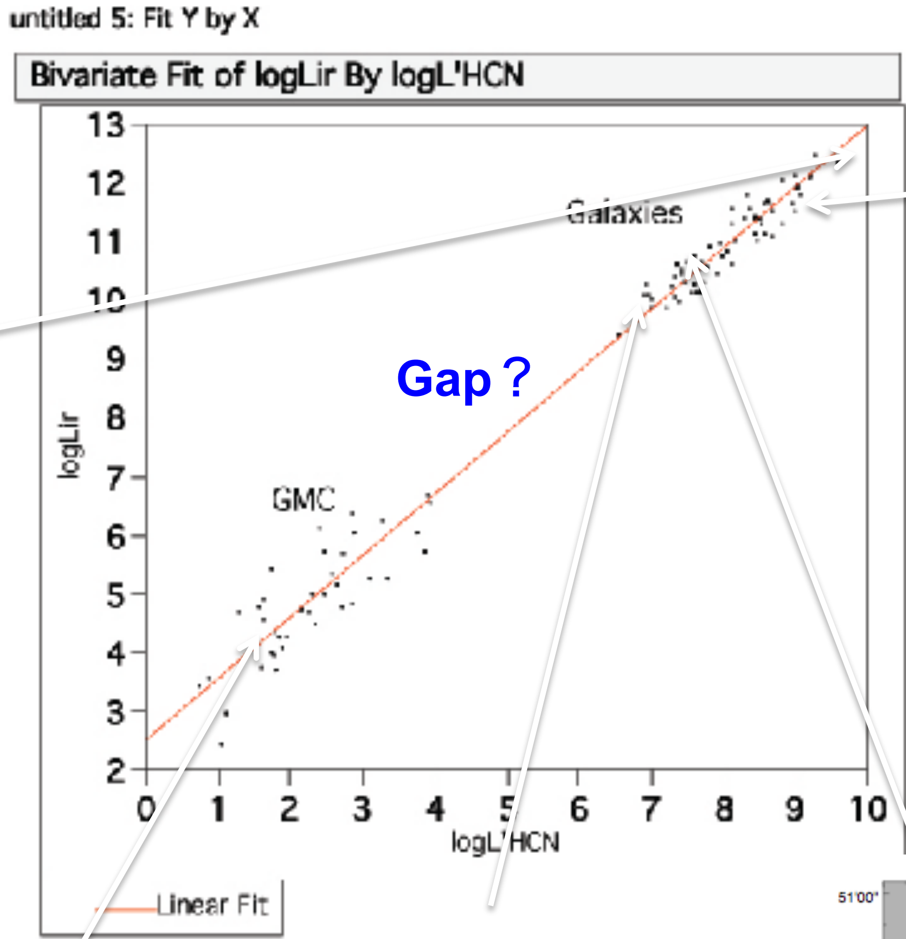
Wu, Evans, Gao et al. 2005 ApJL

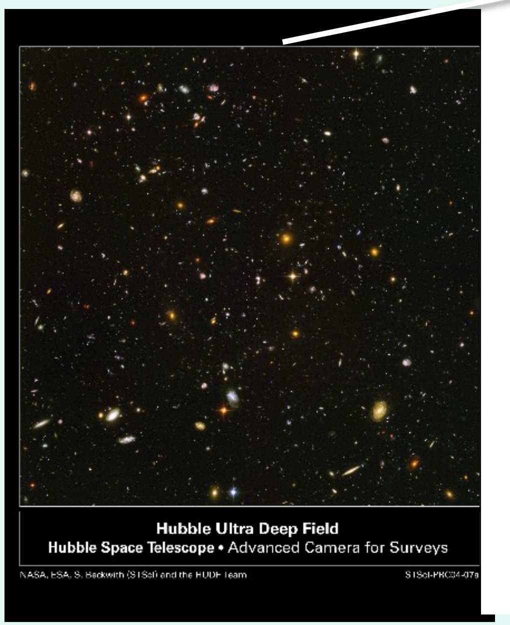


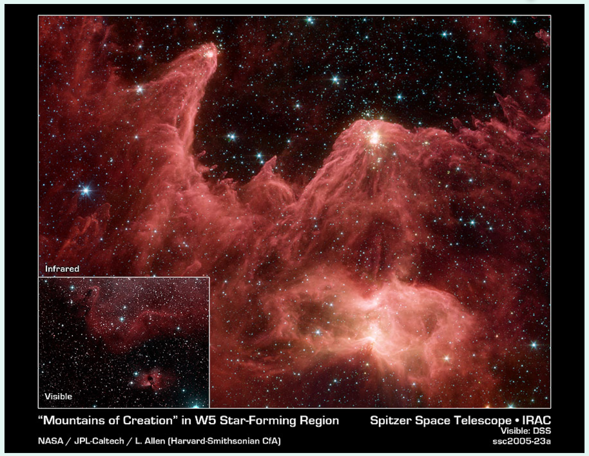
Wu+2010

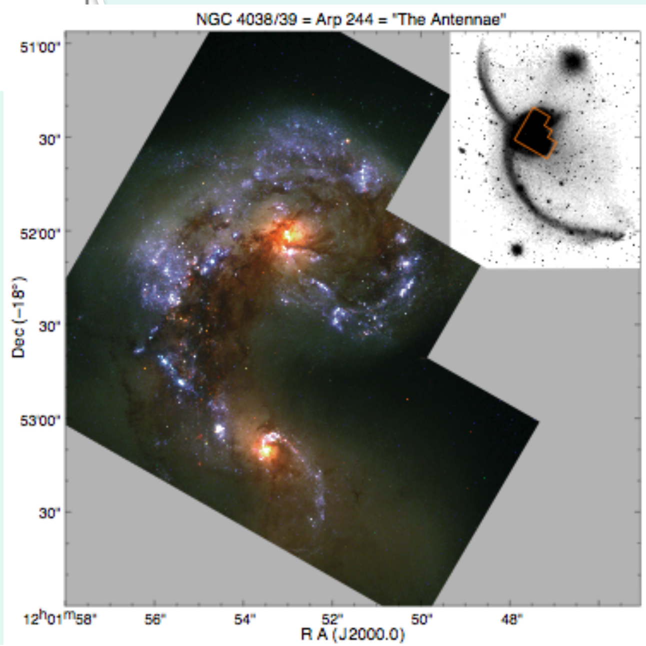


Can DCs in nearby galaxies fill in the gap in FIR-HCN corr.?

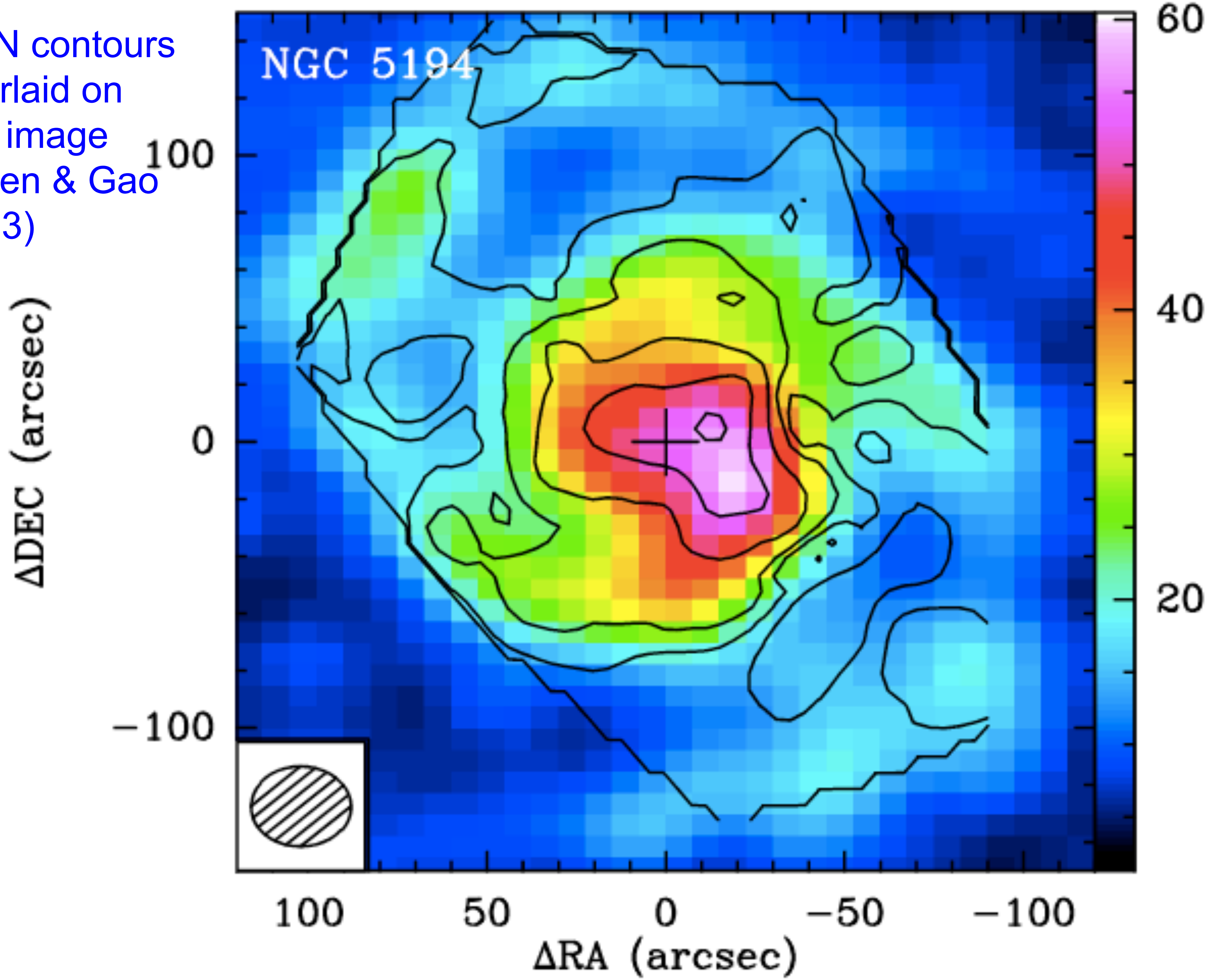


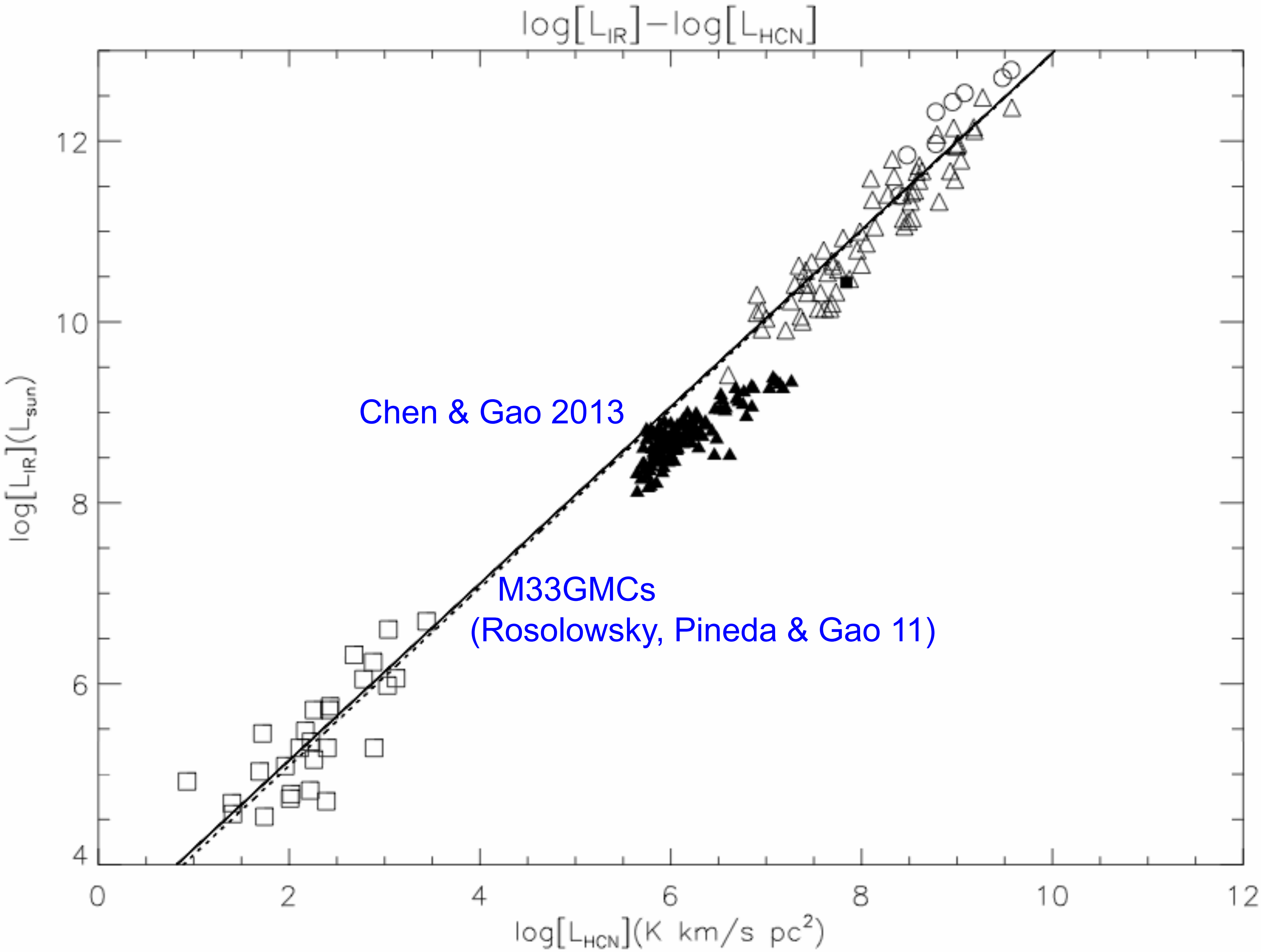






HCN contours overlaid on CO image (Chen & Gao 2013)





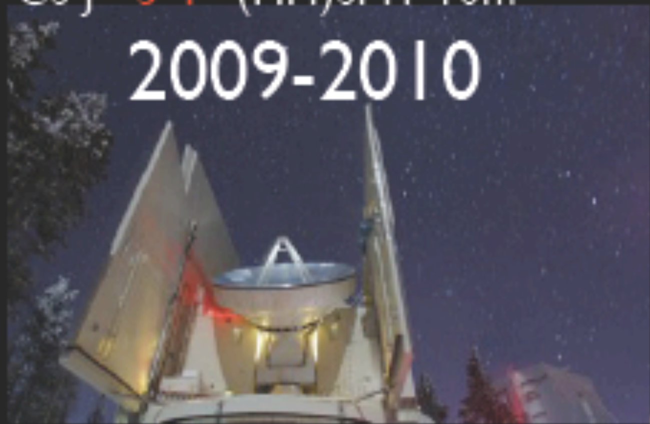
log[L_IR]−log[L_HCN]
Chen & Gao 2013
M33GMCs
(Rosolowsky, Pineda & Gao 11)
log[L_IR](L_sun)
log[L_HCN](K km/s pc^2)
0
2
4
6
8
10
12

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



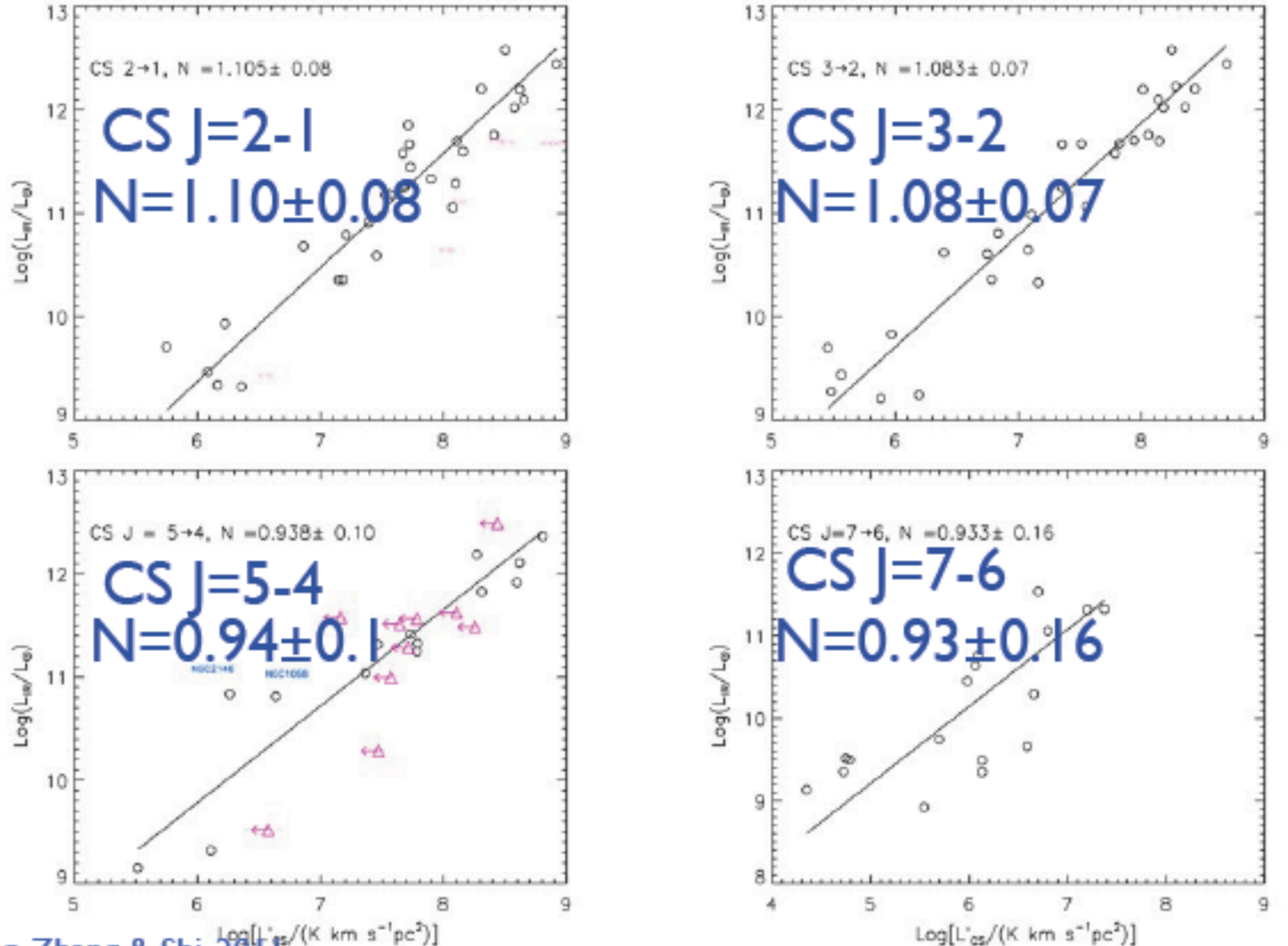
CS J= 7-6 APEX 12m

CS J= 1-0 GBT 100m

CS J= 1-0 EVLA

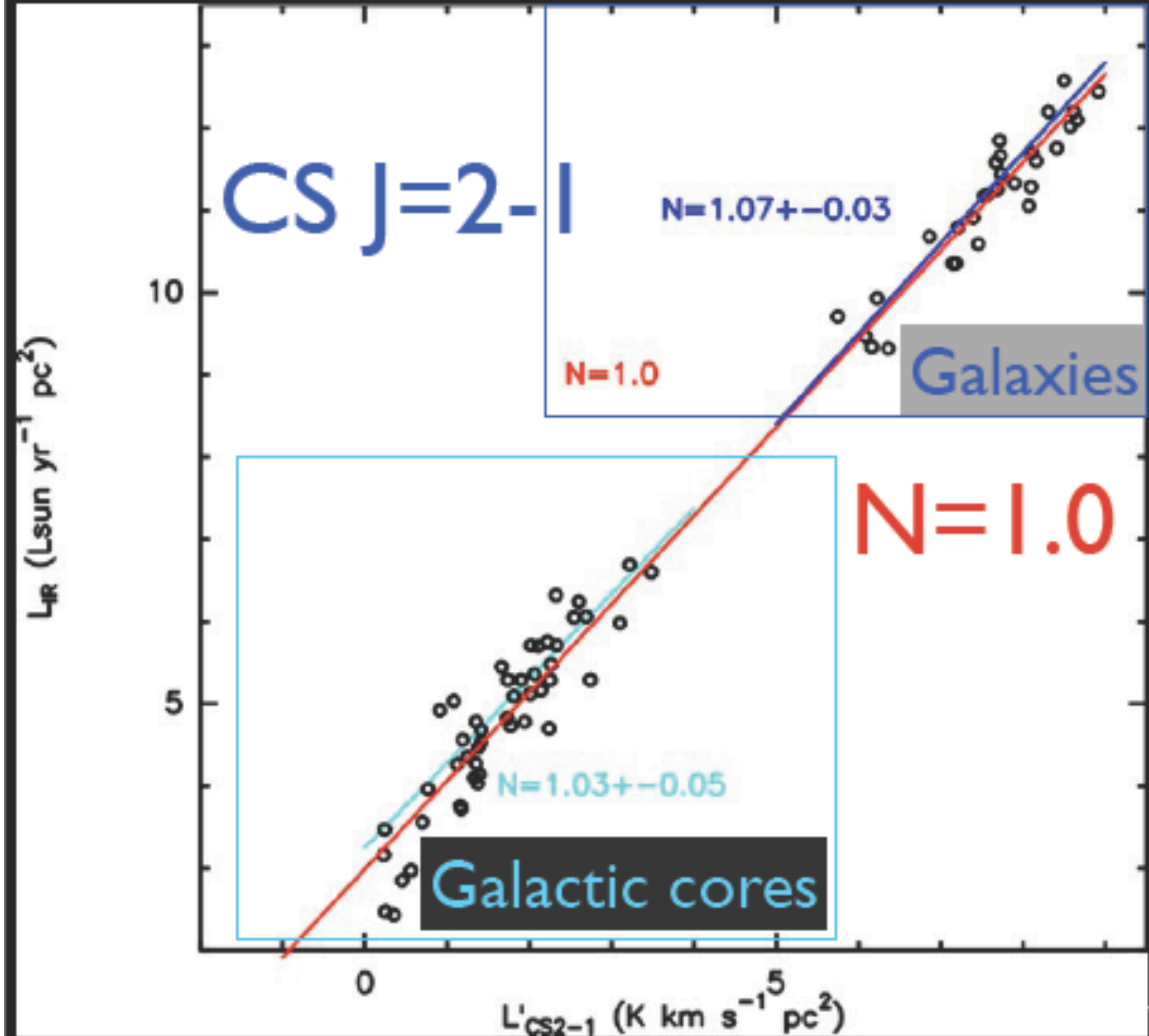
L'cs-LIR correlations

CS: better tracer of dense gas than HCN!



Wang, Zhang & Shi, 2011

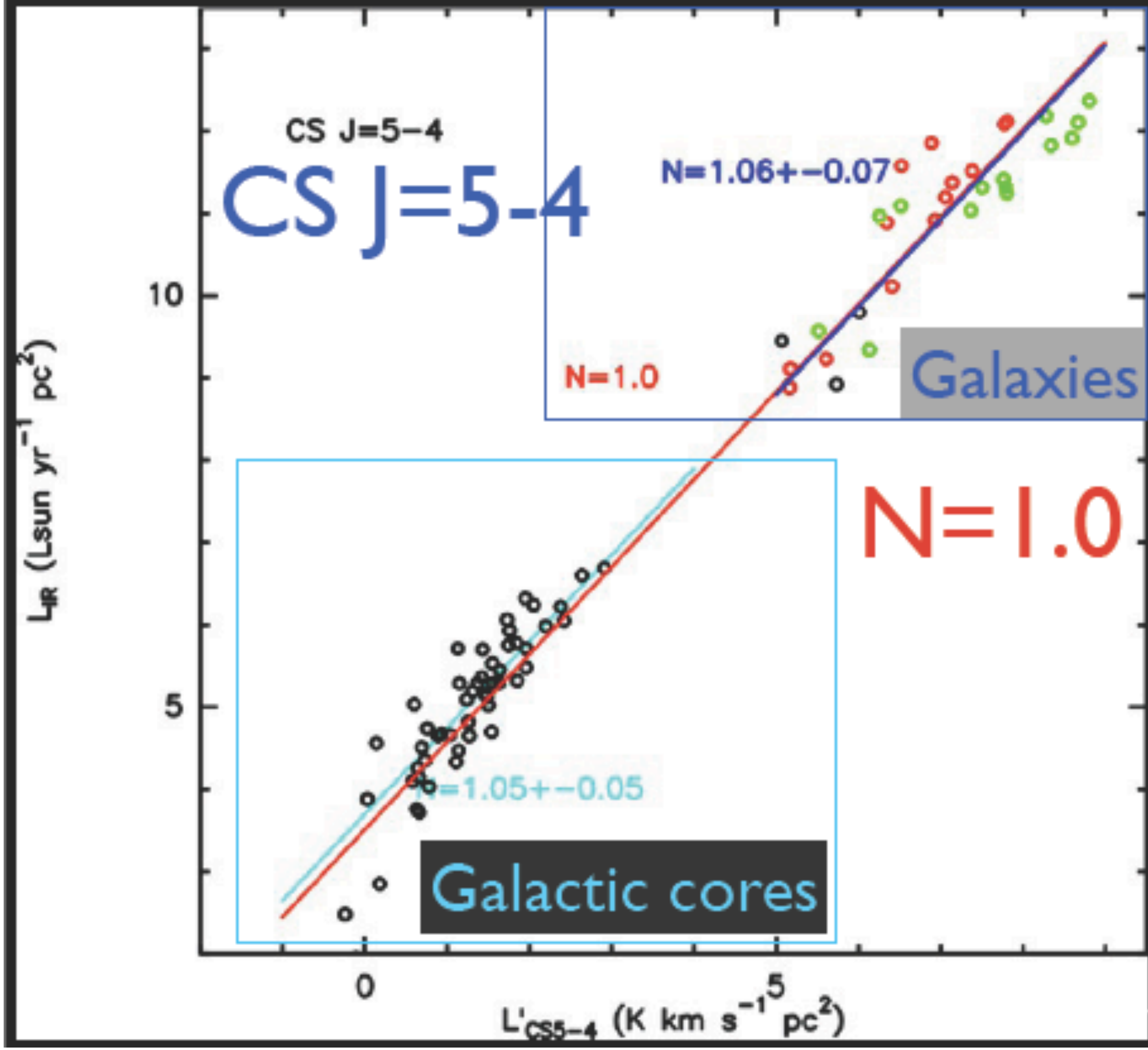
Connecting with Galactic CS study ~ 10 orders of magnitude



- IRAM 30m

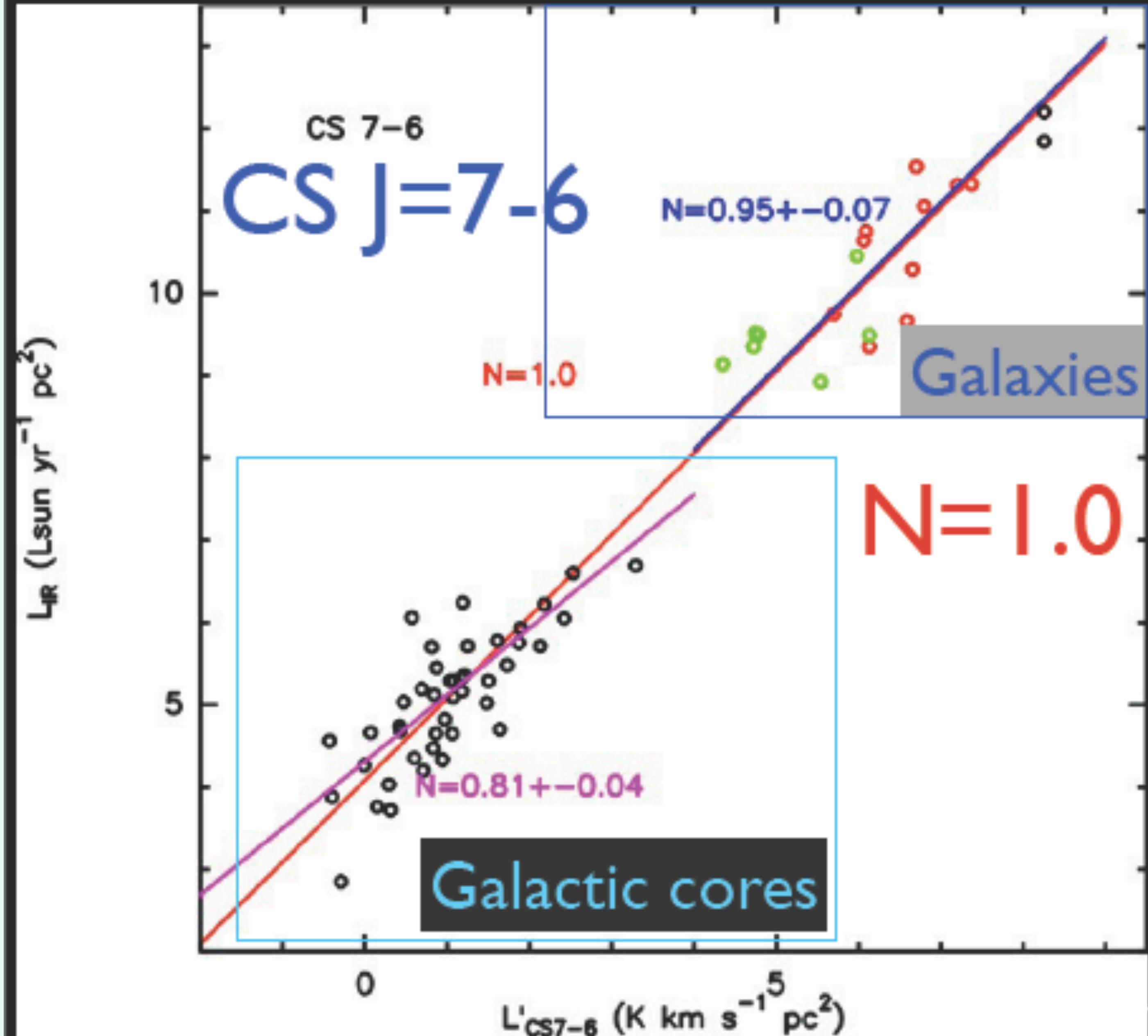
Wu+2010

Connecting with Galactic CS study ~ 10 orders of magnitude



SMT 10m
IRAM 30m
Baan + 2008

Connecting with Galactic CS study ~ 10 orders of magnitude

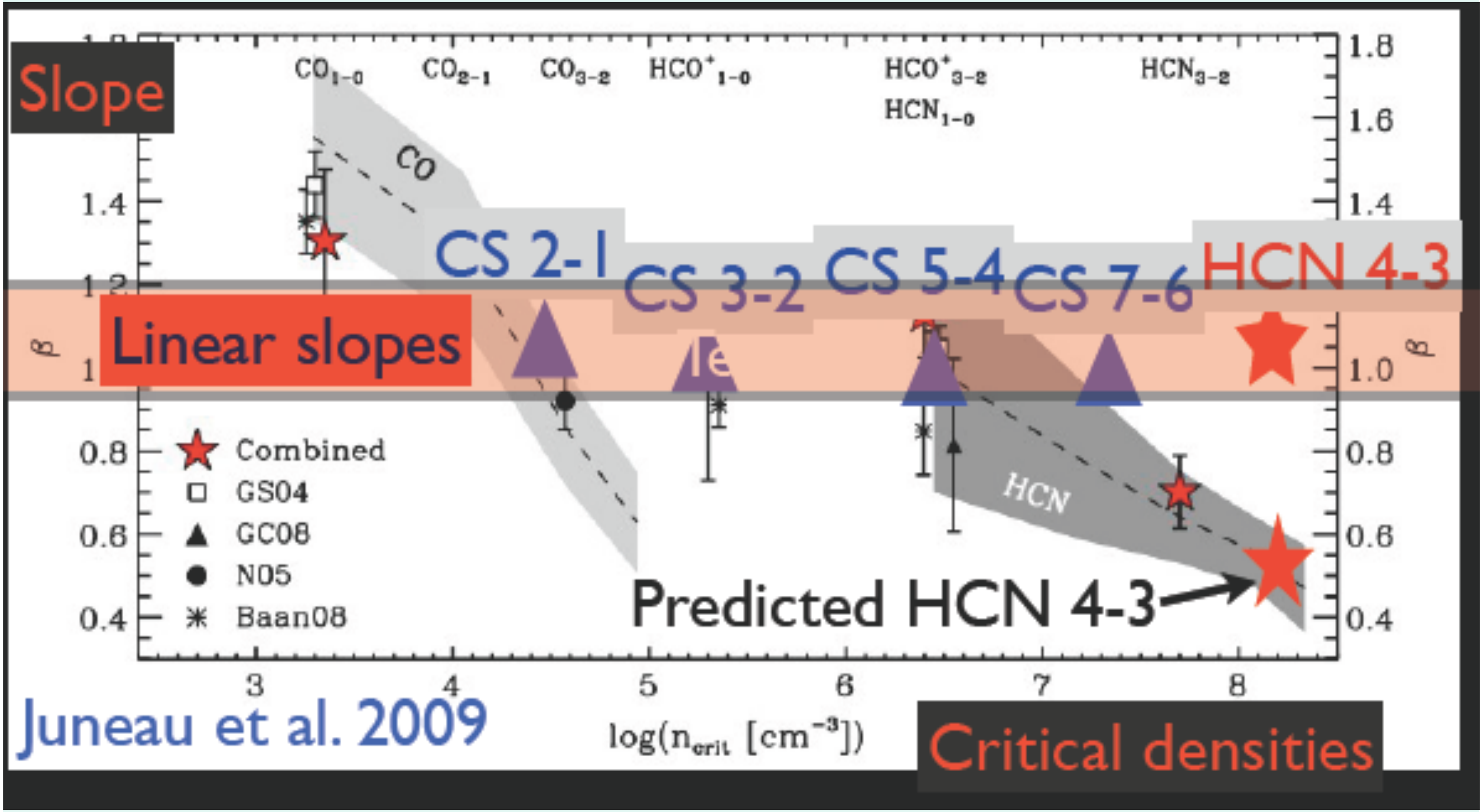


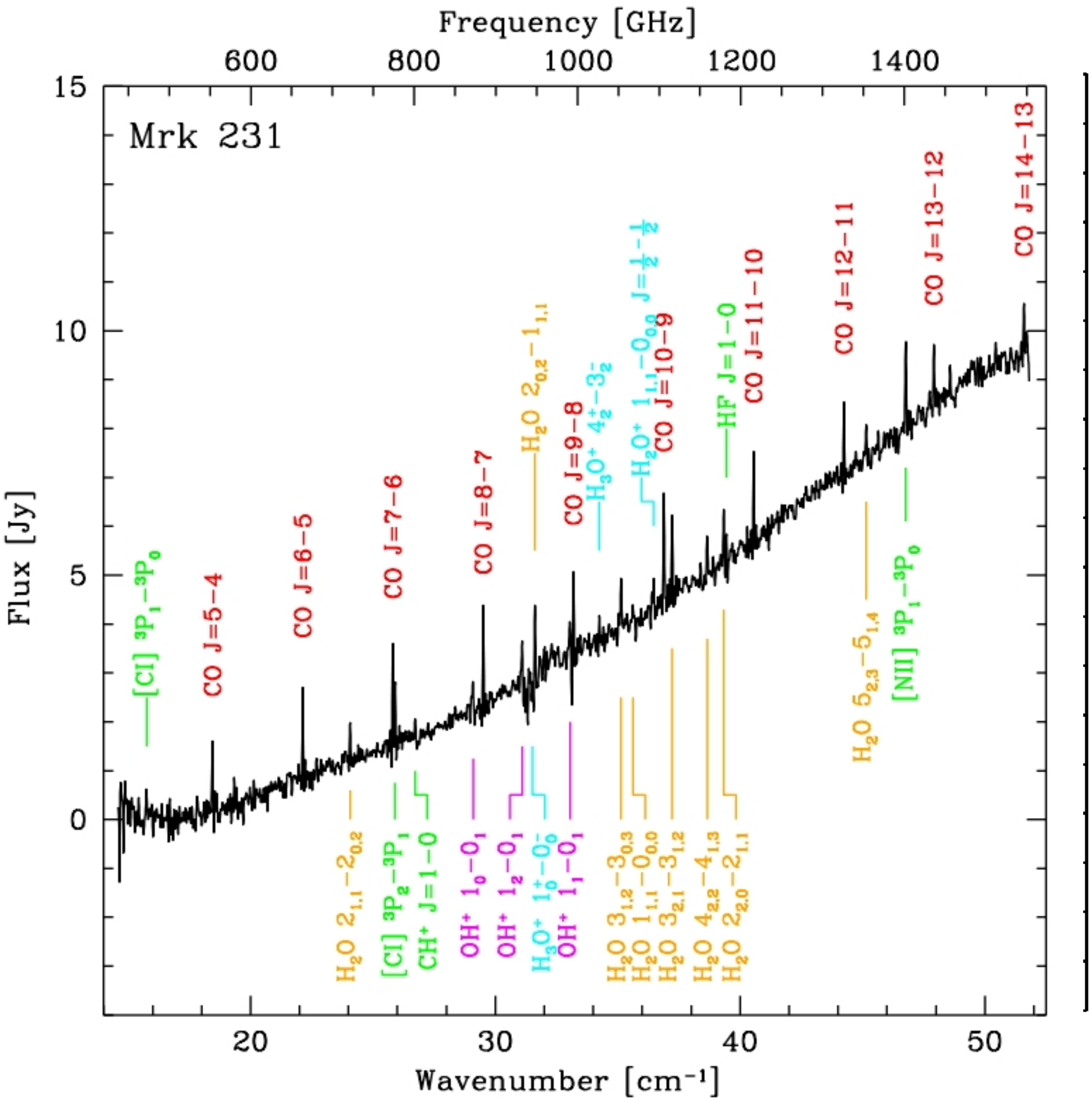
Bayet + 2009

Greve + 2009

APEX 12m

- Dense gas over a range of 10^4-8 /cm^3



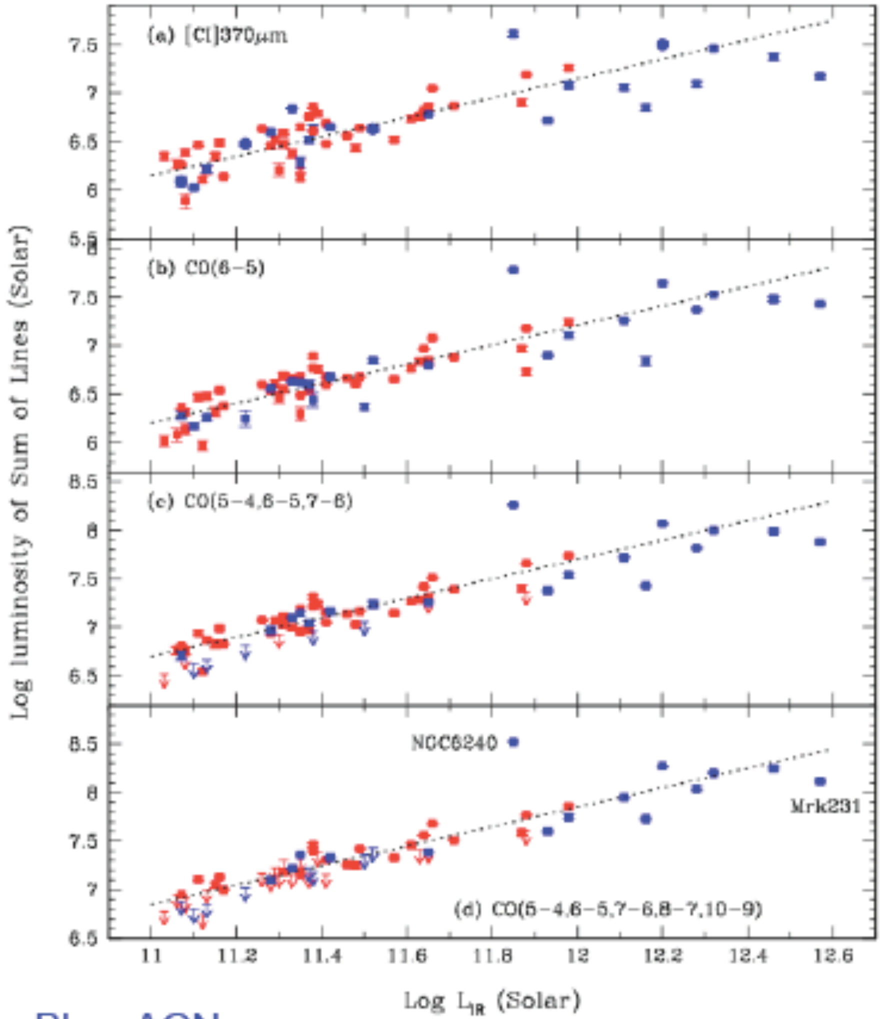


Mrk231 SPIRE FTS

Van der Werf *et al*., 2010)

Dust and Molecular Gas Heating

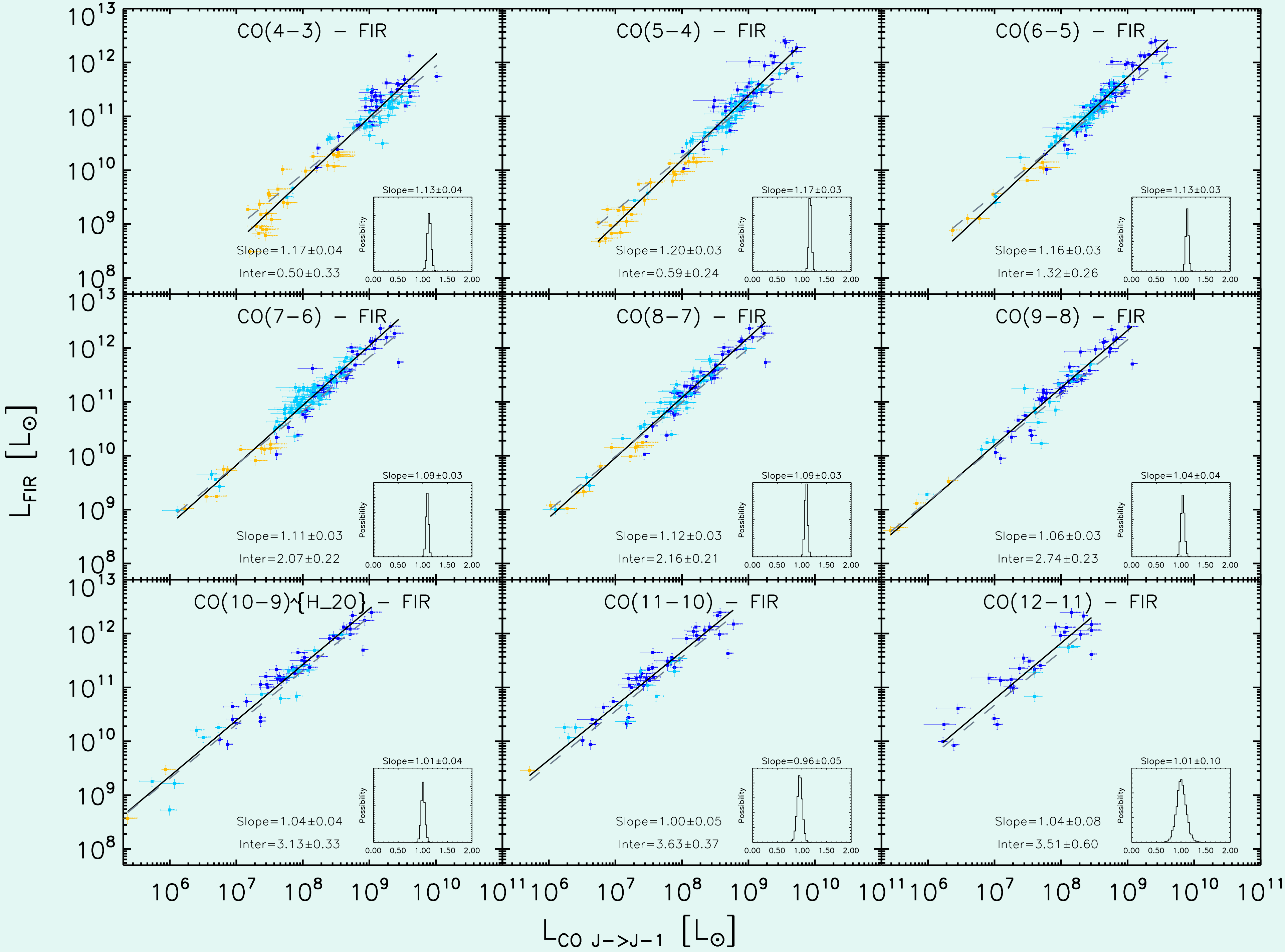
Linear fits with a fixed slope of 1

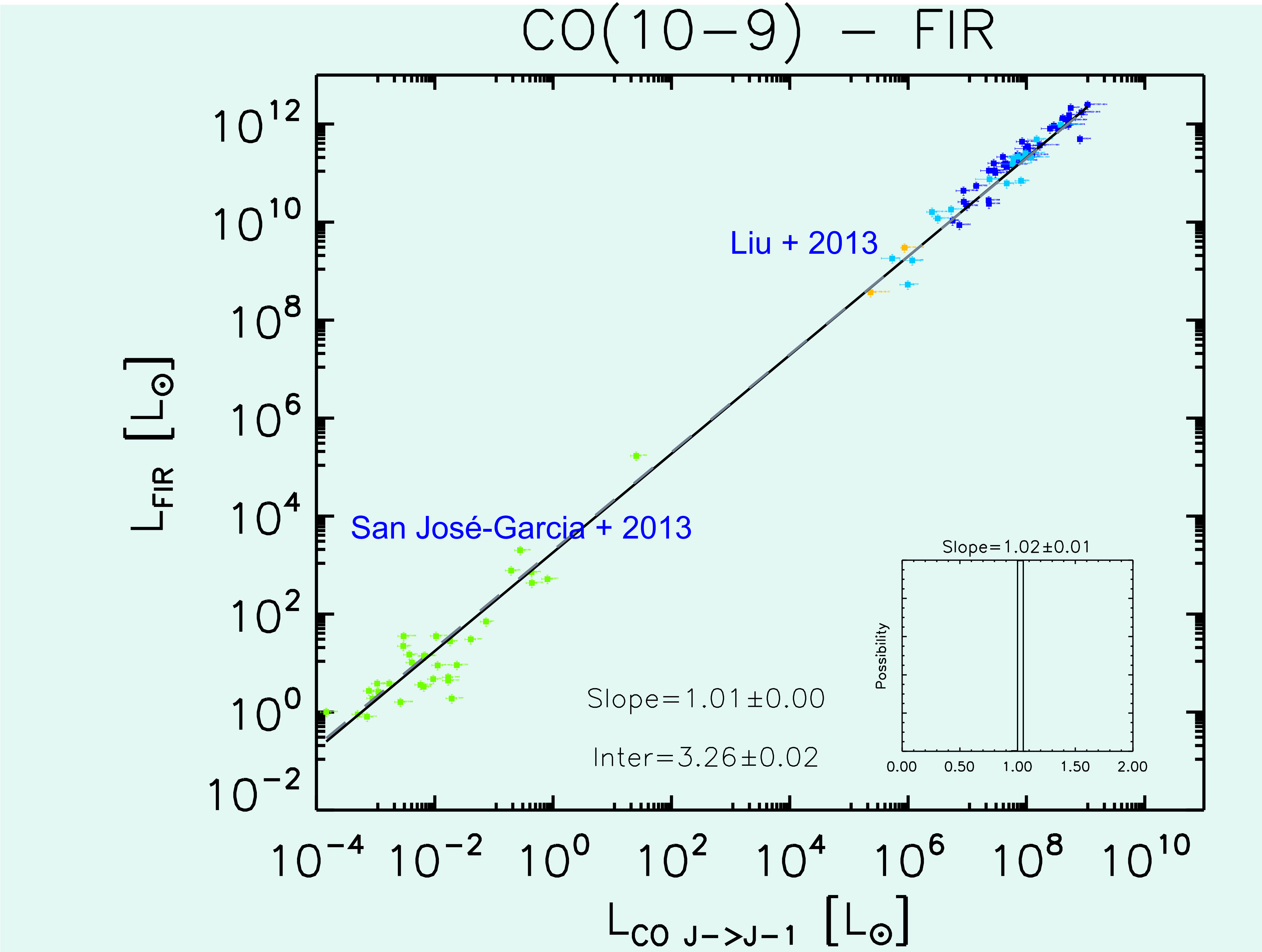


Blue: AGN;
Red: non AGN.

- 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.

Lu + 2013


CO(4−3) − FIR
Slope=1.17±0.04
Inter=0.50±0.33
Slope=1.13±0.04
CO(5−4) − FIR
Slope=1.20±0.03
Inter=0.59±0.24
Slope=1.17±0.03
CO(6−5) − FIR
Slope=1.16±0.03
Inter=1.32±0.26
Slope=1.13±0.03
CO(7−6) − FIR
Slope=1.11±0.03
Inter=2.07±0.22
Slope=1.09±0.03
CO(8−7) − FIR
Slope=1.12±0.03
Inter=2.16±0.21
Slope=1.09±0.03
CO(9−8) − FIR
Slope=1.06±0.03
Inter=2.74±0.23
Slope=1.04±0.04
CO(10−9)^{H_2O} − FIR
Slope=1.04±0.04
Inter=3.13±0.33
Slope=1.01±0.04
CO(11−10) − FIR
Slope=1.00±0.05
Inter=3.63±0.37
Slope=0.96±0.05
CO(12−11) − FIR
Slope=1.04±0.08
Inter=3.51±0.60
Slope=1.01±0.10
Possibility
L_{FIR} [$L_\odot$]
$L_{CO\ J->J-1}$ [$L_\odot$]



CO(10−9) − FIR
Liu + 2013
San José-Garcia + 2013
Slope=1.01±0.00
Inter=3.26±0.02
Slope=1.02±0.01
Possibility
0.00
0.50
1.00
1.50
2.00
L_{FIR} [$L_\odot$]
$L_{CO\ J->J-1}$ [$L_\odot$]
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}

Conclusion & future

- Dense Molecular Gas → High Mass Stars
- SFR ~ M(DENSE), **linear?!** dense gas
- Dense gas tracers (e.g. HCN, CS, COJ>4… gas density >~10^5 cc), linear with FIR
- HI → H_2 → DENSE H_2 → Stars

Schmidt law : HI(gas reservoir) → Stars X

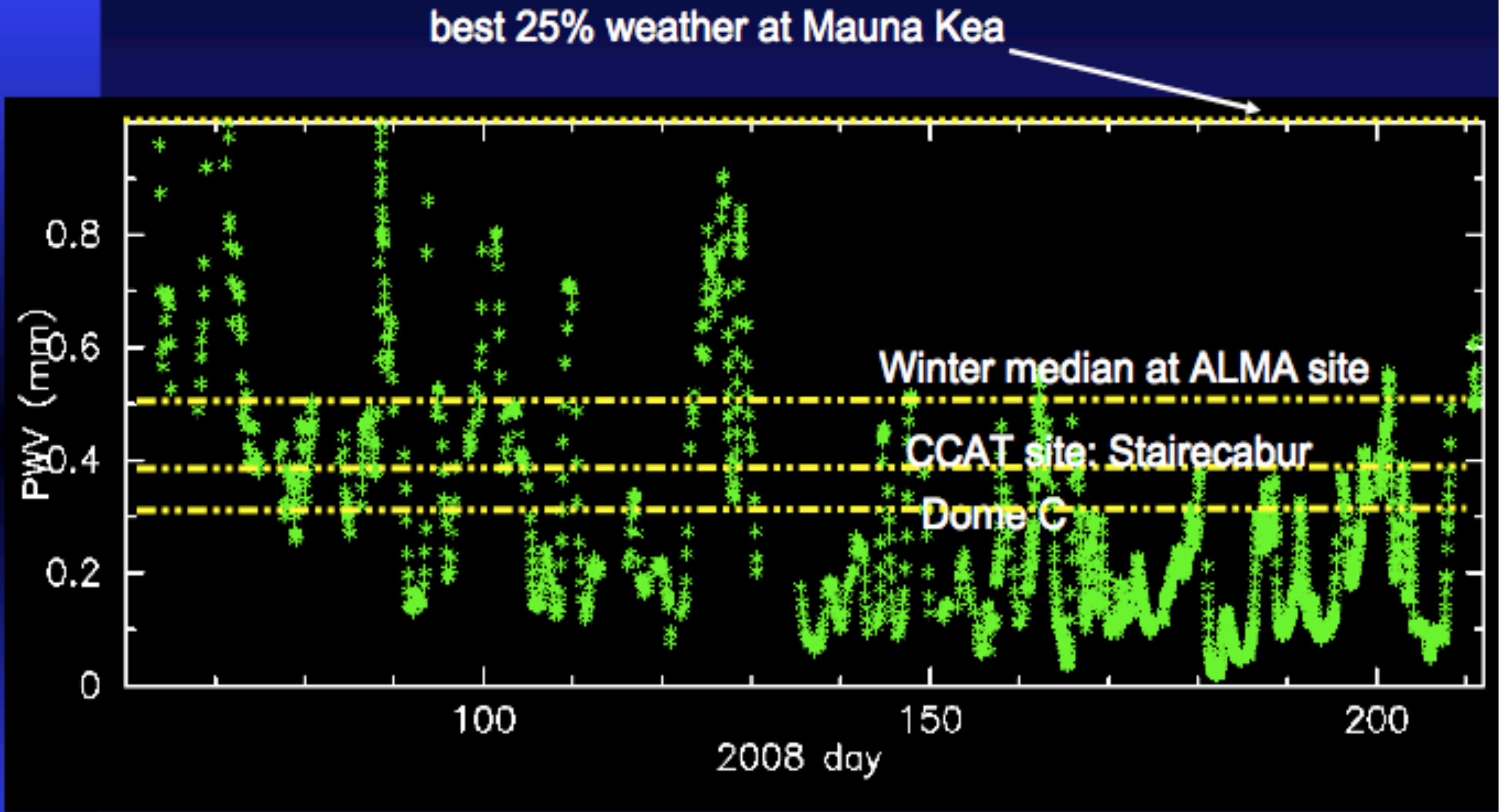
Kennicutt : HI(gas reservoir) + H_2(fuel?)→ Stars X

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

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

Multi-lines + multi-J: denseH2 best correlates with star formation!

PreHeat: Precipitable water vapor from Dome A



Walker, Kulesa et al.

Best site on Earth before going to space:
the Dome-A on Antarctica