The Star Formation Rate in Galaxies: Far-IR vs. HCN

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Before the talk…

- Personal perspectives: 1) No observing facilities in research uiniversities capable of doing research; 2) No world-class observing facilities even at major observatories of CAS; 3) Need to establish more observationally oriented research groups in CAS
- NAOC/CAS research groups: only 6-8 groups in 1)Galaxies/cosmology 2) Stars 3) Sun

Talk Outline

- 1) Massive Star Formation (SF) & HCN

  GMC Dense Cores, Importance of Dense Molecular Gas in Galaxies (cf. FIR—20cm)

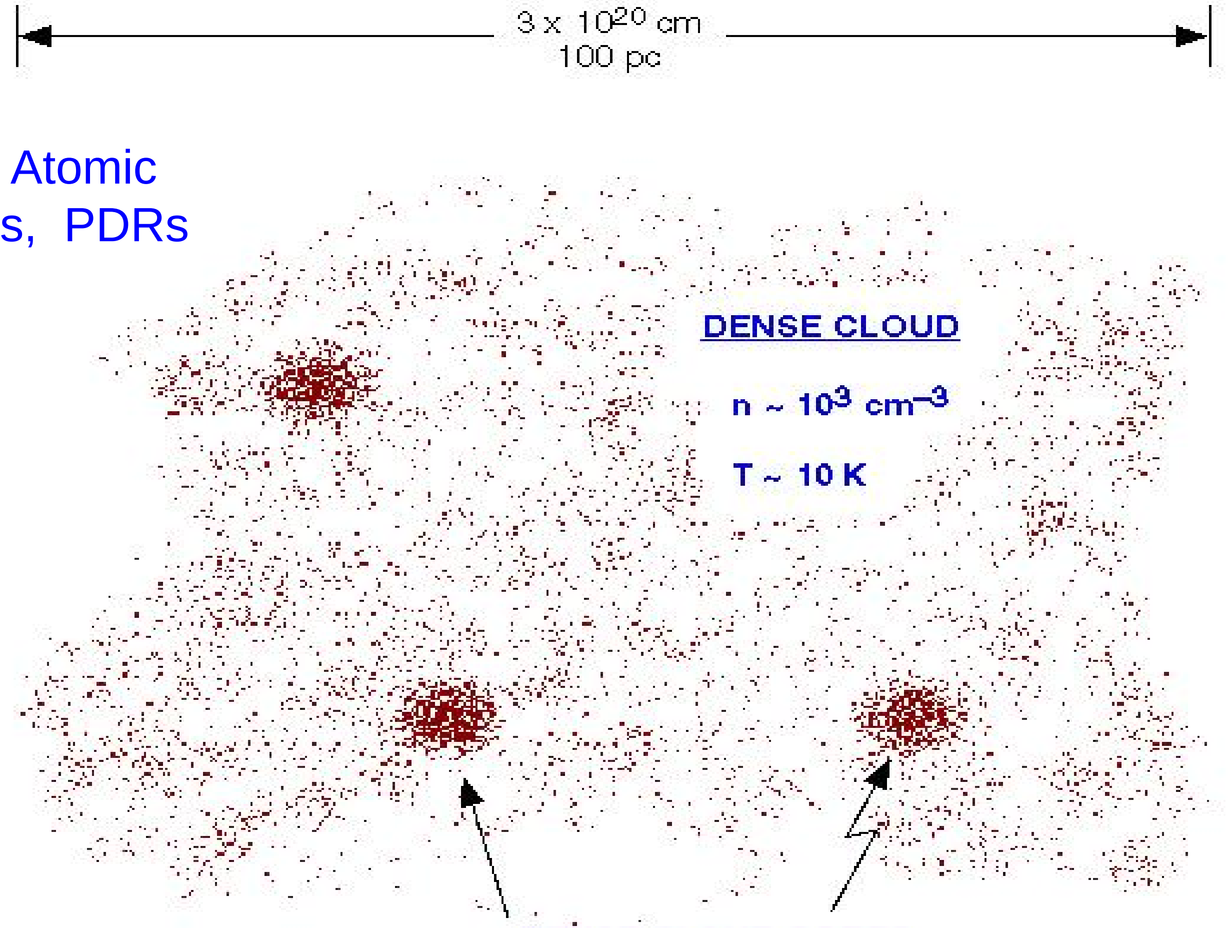
- 2) HCN Observations in Local Galaxies

  a) Observations of HCN in 65 Galaxies
  b) FIR--HCN Correlation

- 3) New HCN Obs. @ High-z (FIR—HCN)

- 4) FIR-HCN (Global SF Law) Dense Cores to Hyper/Ultraluminous Galaxies (@High-z)

STRUCTURE OF DENSE MOLECULAR CLOUDS



3×10^{20} cm
100 pc

HI, Atomic
Gas, PDRs

DENSE CLOUD

$n \sim 10^3$ cm^{-3}

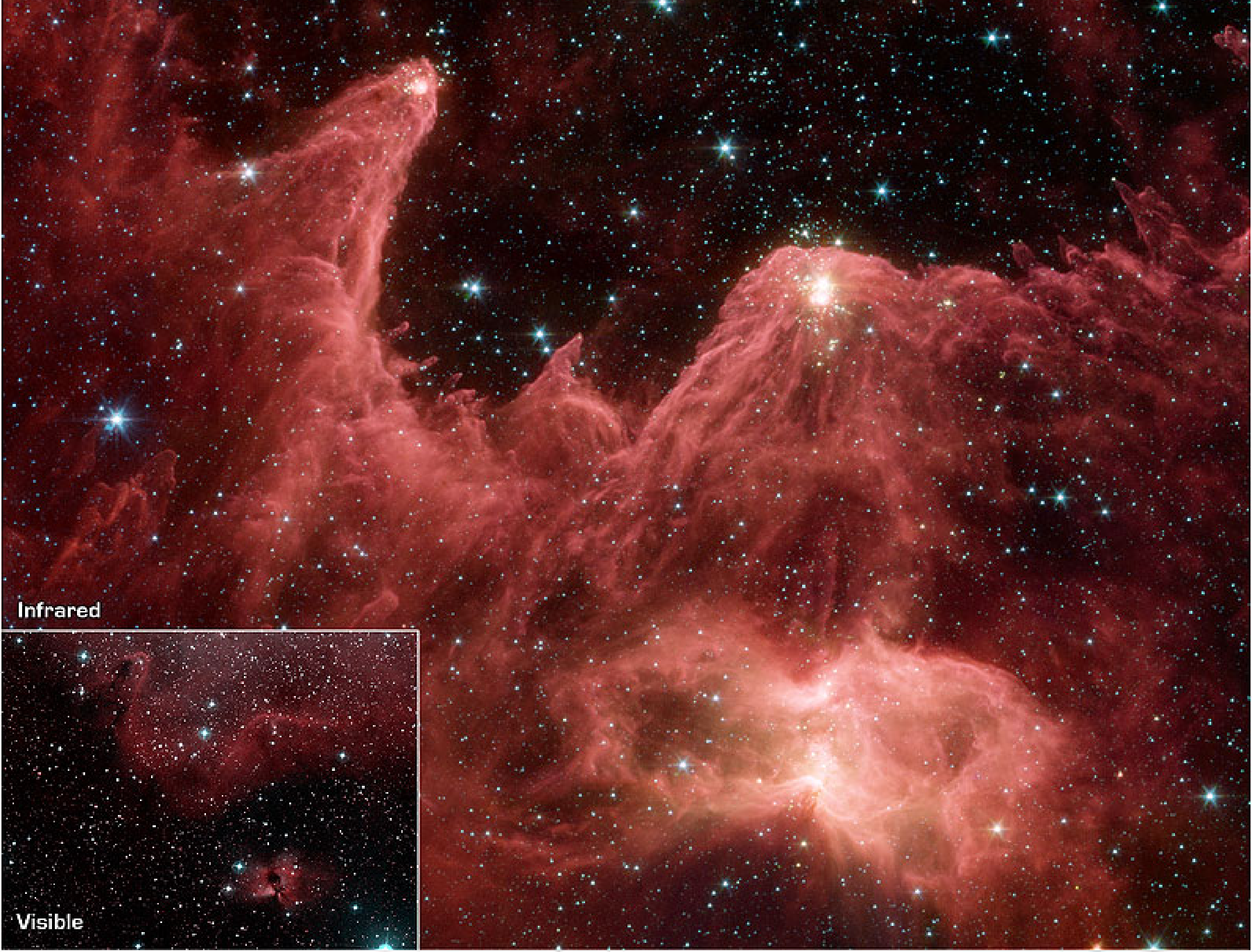
T ~ 10 K

DENSE CLOUD CORES

$n \sim 10^4 - 10^6$ cm^{-3}

T ~ 15 – 40 K

D ~ 0.1 – 0.3 pc



"Mountains of Creation" in W5 Star-Forming Region

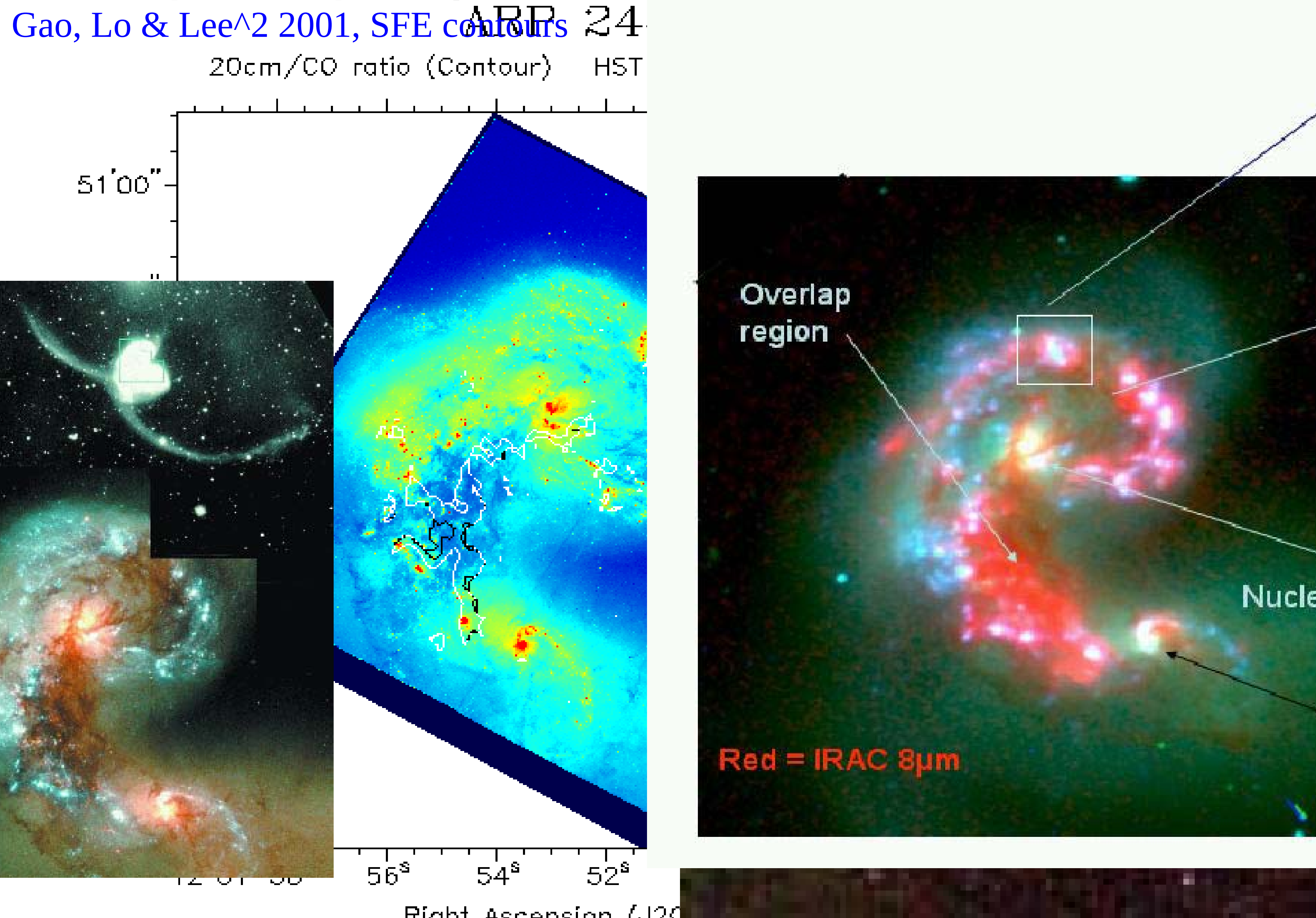
Spitzer Space Telescope • IRAC
Visible: DSS

NASA / JPL-Caltech / L. Allen (Harvard-Smithsonian CfA)

ssc2005-23a

1.(Cont.) Importance of Dense Gas

Gao, Lo & Lee^2 2001, SFE contours



Gao 2008

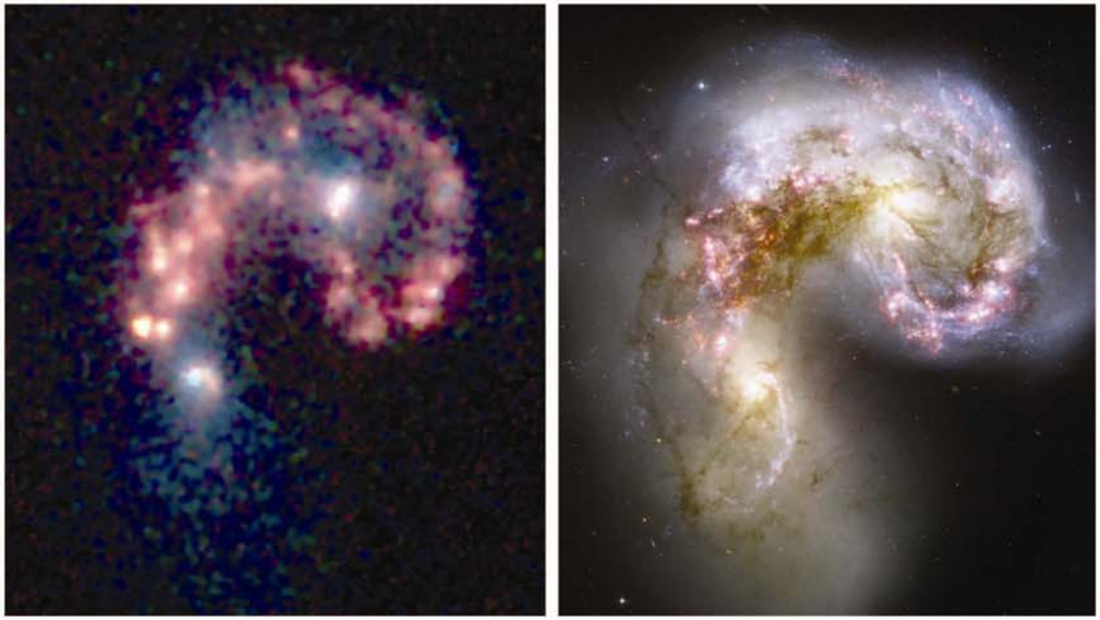


Figure 1 | Buried in dust. These two images of the spectacular merger of the nearby Antennae galaxies — on the left from NASA's Spitzer Space Telescope, on the right from the Hubble Space Telescope — show the train wreck of two gas-rich spirals. The proximity of the galaxies allows detailed imaging of newborn star clusters and the infrared hotspots that mark starburst sites. The dusty regions between the two galaxies, heavily obscured in the Hubble optical image, are in fact the dominant sites of active star formation as traced by the Spitzer Infrared Array Camera at an infrared wavelength of 8 micrometre emission (red). Indeed, the brightest infrared hotspot (bottom left of the Spitzer image) is almost entirely unseen. Extreme starbursts near and far are more than several tens of times brighter than the Antennae galaxies, and the most intense examples are usually hidden in dust, making comparisons between observations at different redshifts particularly tricky.

Bank Telescope in West Virginia to investigate 19 close galaxies that emit strongly in the infrared ***[OK?]***. They surveyed radio waves emitted by the galaxies at centimetre wavelengths corresponding to two '*K*-doublet' transitions of the organic molecule formaldehyde (H_2CO) — a reliable density and temperature probe in the star-forming molecular clouds in our own Galaxy.

Mangum and colleagues' sample of nearby galaxies has a redshift of almost zero.

Newborn stars emit light mostly at ultraviolet wavelengths. This light heats the surrounding interstellar dust, which then radiates at infrared wavelengths. Because of the redshift effect, Hathi *et al.*[2] used two cameras aboard the Hubble Space Telescope that were sensitive at optical and near-infrared wavelengths, miss the dominant infrared radiation reradiated by the dust. That supposition is supported by recent surveys of the deep Universe, such as COSMOS[7], GOODS[8] and SWIRE[9], which are finding more and more high-redshift dust-obscured galaxies with large infrared-to-ultraviolet luminosity ratios that had been missed in traditional optical surveys.

That would seem to lead to one of two conclusions. First, that Hathi and colleagues' high-redshift galaxies are powered by even brighter extreme starbursts, largely hidden in dust, than those found in the local Universe — with concomitantly much higher densities of molecular gas than could possibly be extrapolated from Mangum and colleagues' H_2CO results. Recent efforts to detect HCN at high redshifts have offered some evidence for a higher ratio of star-formation rate to dense gas at early cosmic times[10–12]. An alternative explanation for the anomaly is that the earlier starbursts might simply be very much larger in extent, with intensities comparable to those of the nearby starburst galaxies.

If the earlier starbursts are indeed in general much more intense, we might suppose that they have a different physical origin. The extreme starburst activity of nearby ULIRGs is thought to have been triggered by the strong interaction or merger of gas-rich spiral galaxies (Fig. 1). A possibility for the high-redshift starbursts is that a fraction of the luminosity is caused by at least one dust-obscured 'active galactic nucleus' (AGN) — a black hole at the centre of the merging galaxies. If that is so, are there any evolutionary connections between extreme starbursts, the build-up of massive AGNs, and how galaxies assemble? A link

Taffy: CO contours on Near-IR, Mid-IR 20cm cont., & HI images (Gao, Zhu & Seaquist 2003)

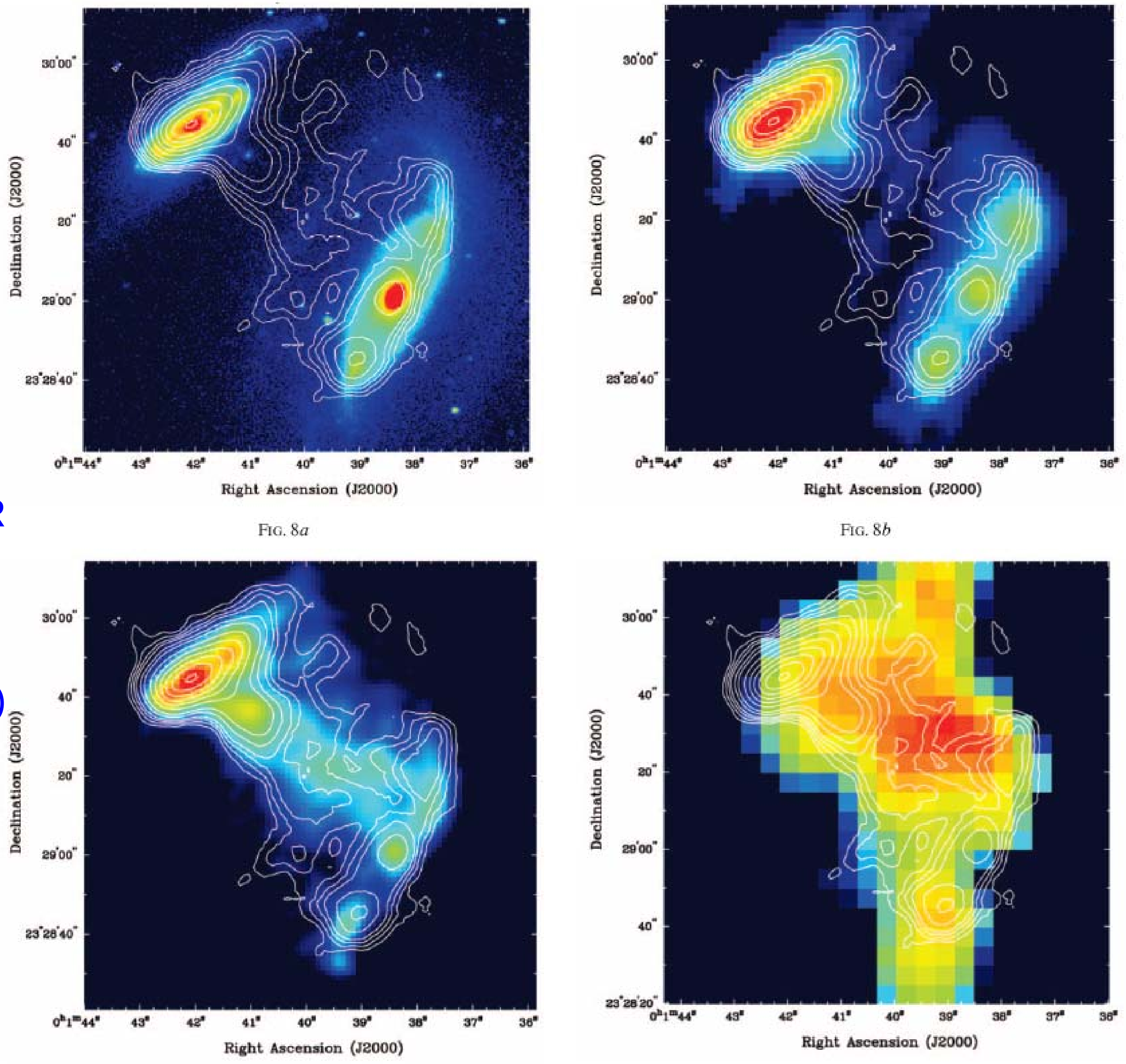


FIG. 8*a*

FIG. 8*b*

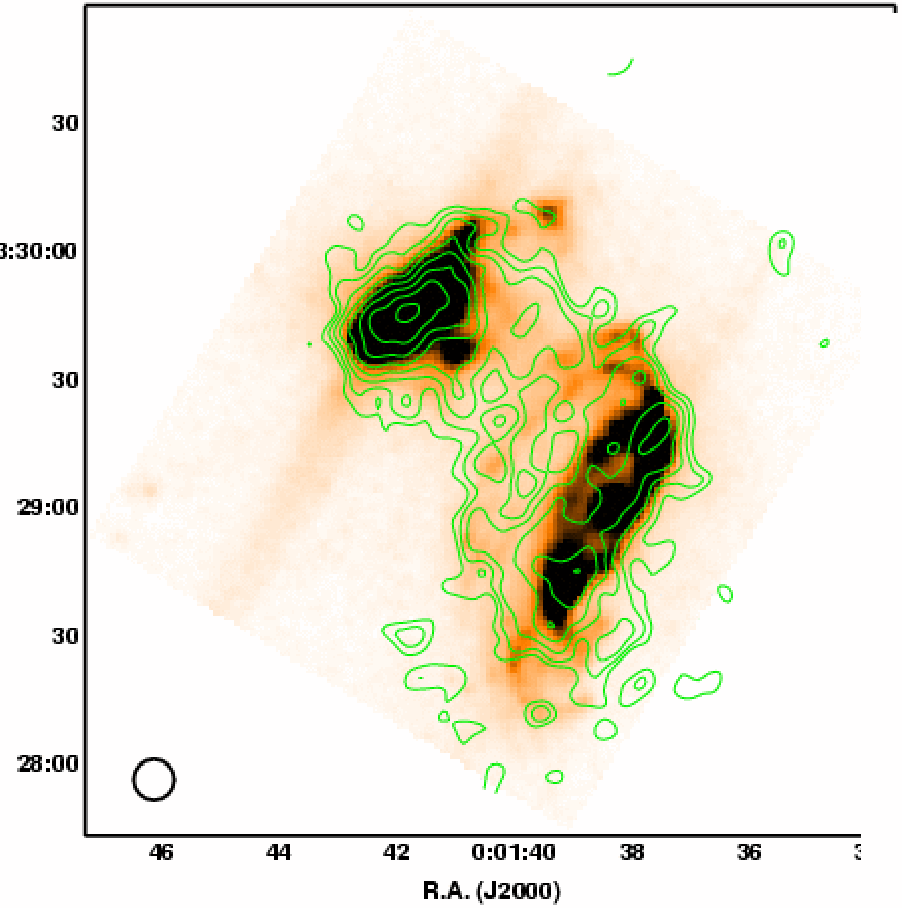
FIG. 8*c*

FIG. 8*d*

FIG. 8.—CO contours compared with the multiwavelength images of (*a*) the near-IR *H* band, (*b*) *ISO* mid-IR 15 μm, (*c*) VLA 20 cm radio continuum, and (*d*) 21 cm H I line . The CO contours of 22.5, 25, 27.5, 30, 35, 40, 50, 60, 70, 80, 90, and 99 percent of the peak emission are plotted in all panels.

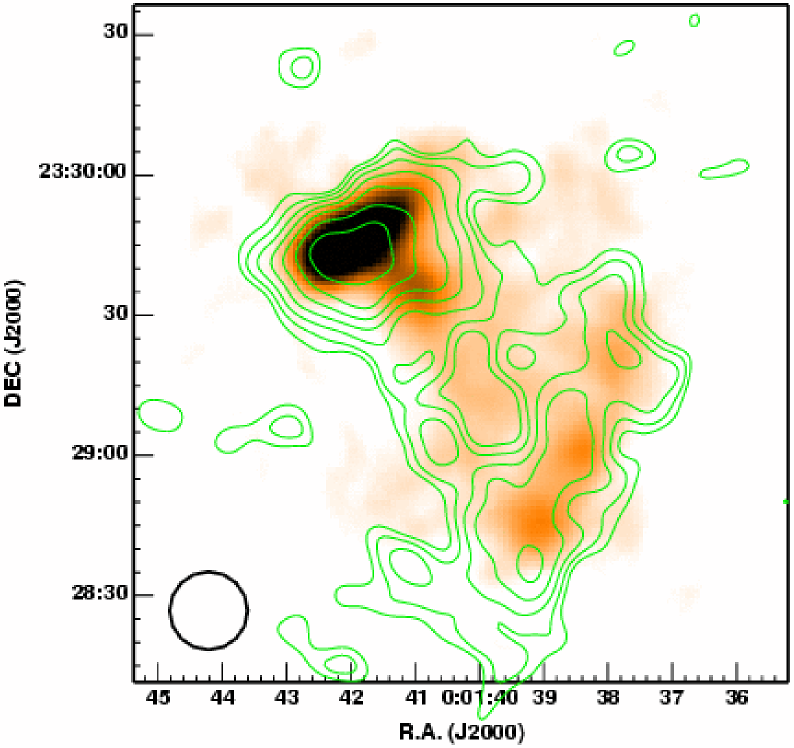
SCUBA: Zhu, Gao, Seaquist & Dunne 2007

450um contours on 8um image

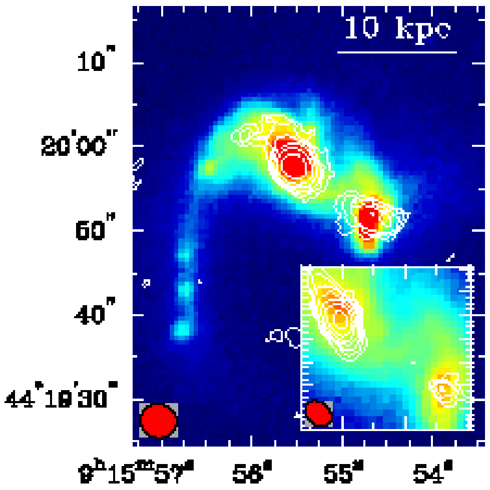


CO: Gao, Zhu, Seaquist 2003

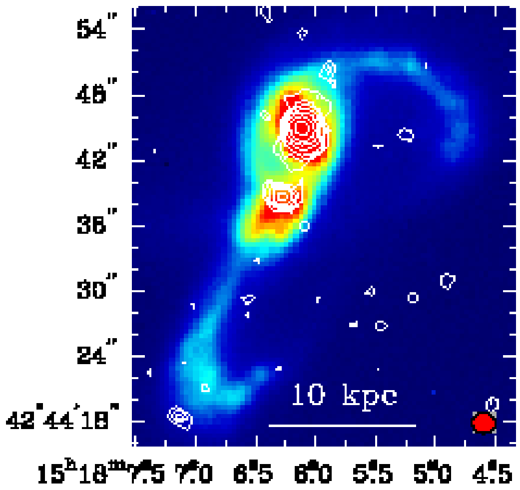
850um contours on CO image



Arp 55

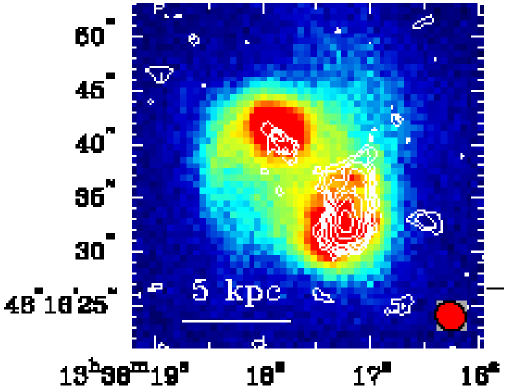


Mrk 848

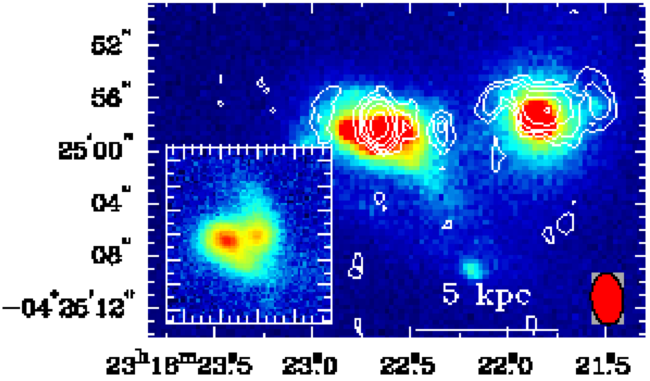


CO Contours overlaid on the optical images (false-color)

NGC 5256

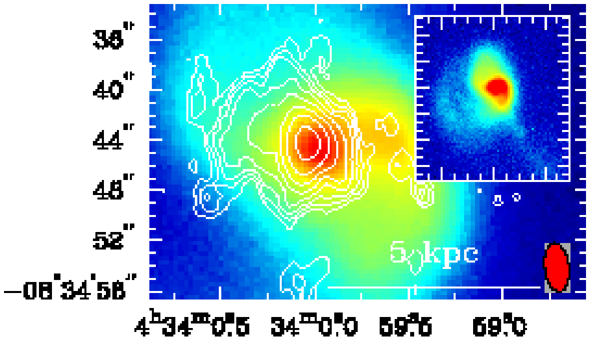


NGC 7592

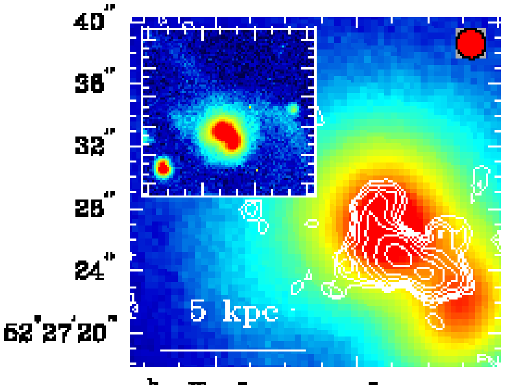


Gao, Gruendl, Hwang, Lo 1999

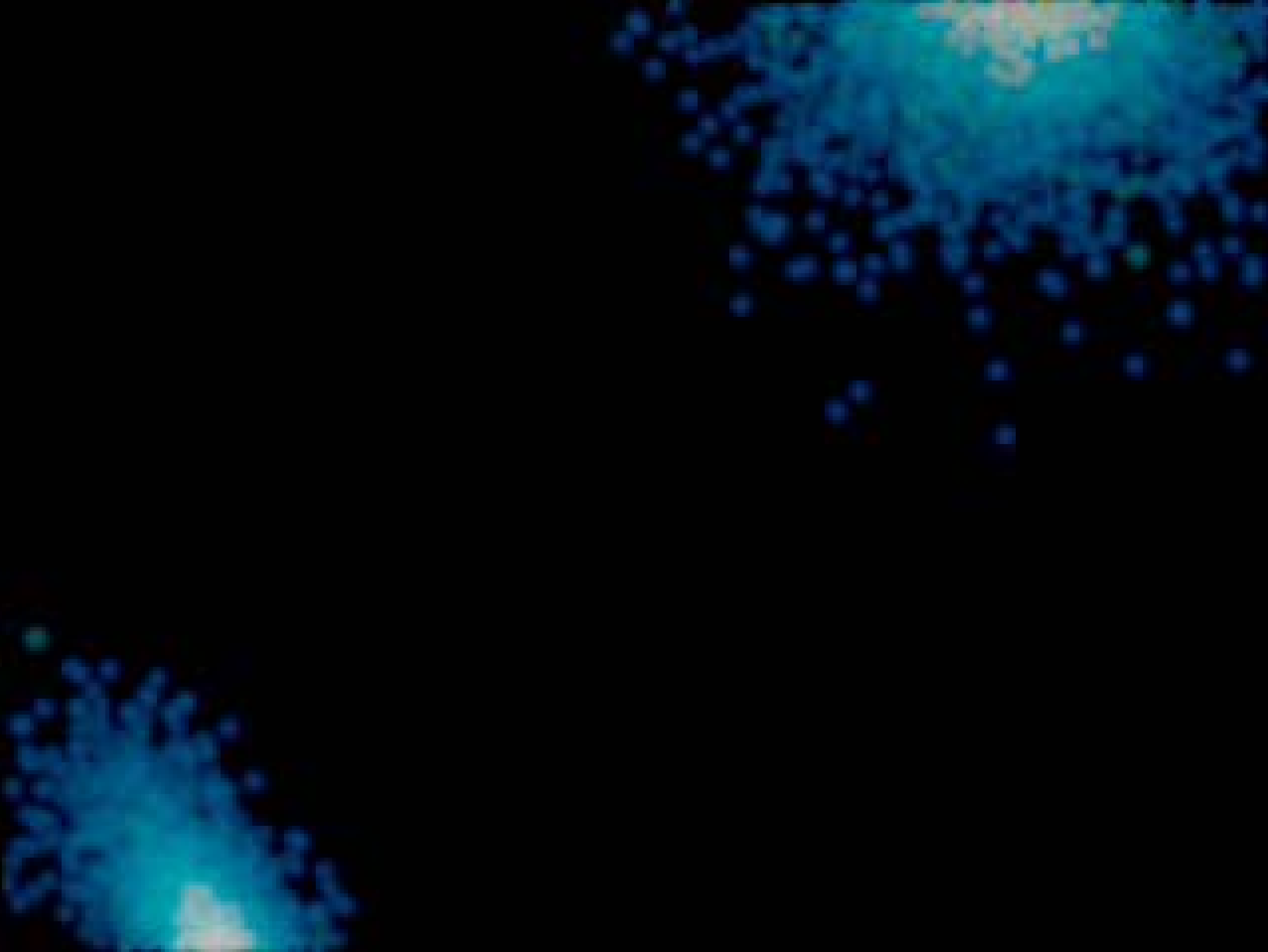
NGC 1614



NGC 6090



Molecular gas density increases as merging advances



Intro: Summary of Dense Gas

- Dense molecular gas is the ultimate material to make stars in star-forming regions (dense cores to ultraluminous galaxies) in galaxies
- Simulations & observations reveal how interaction drives gas into inner disks, overlap starburst regions, and nuclear regions (& becomes much denser) so that ultraluminous starbursts can be initiated
- Dense gas (traced by HCN, CS etc.), not the total gas (H2+HI), is the key to star formation

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2. Dense gas is the essential fuel for high mass SF in Galaxies

The HCN Survey of ~60 Galaxies:

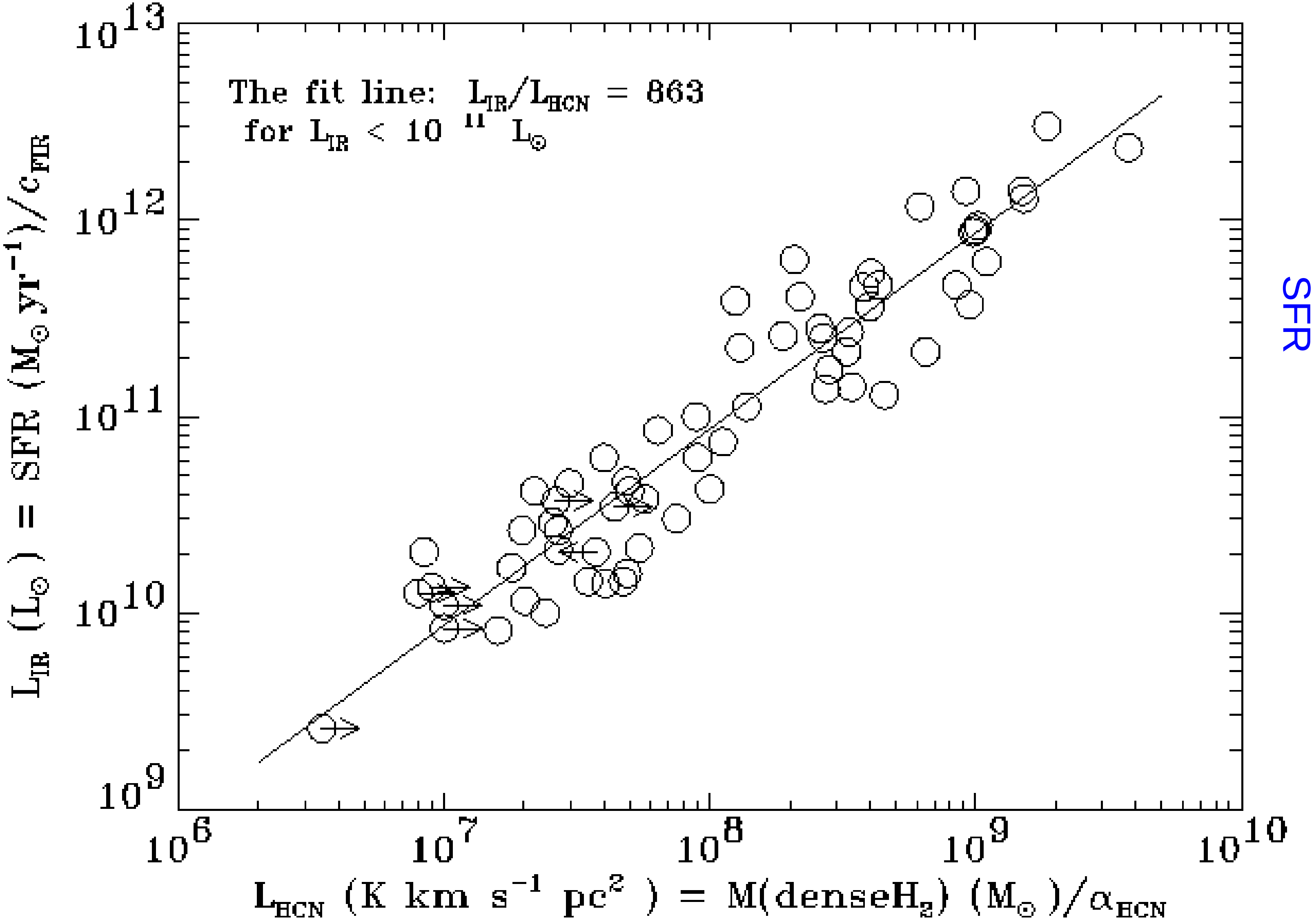
- **Nearest CO-bright Galaxies, e.g., NGC 891, NGC 253**
- **Normal Spiral Galaxies and Luminous Infrared Galaxies (LIGs)**
- **An Almost Complete Sample of Galaxies with** $f_{100\mu\mathrm{m}} \gtrsim 100$**Jy** $\delta \gtrsim -35^\circ$.
- **Relatively Distant** $(cz \gtrsim 10,000 km/s)$ **Ultraluminous Infrared Galaxies (ULIGs)**

HCN Surveys in 53 Galaxies: Gao & Solomon 2004a ApJS

Far-IR, HCN, CO Correlations: Gao & Solomon 2004b ApJ

2. (Cont.) HCN Obs. in Local Gals.

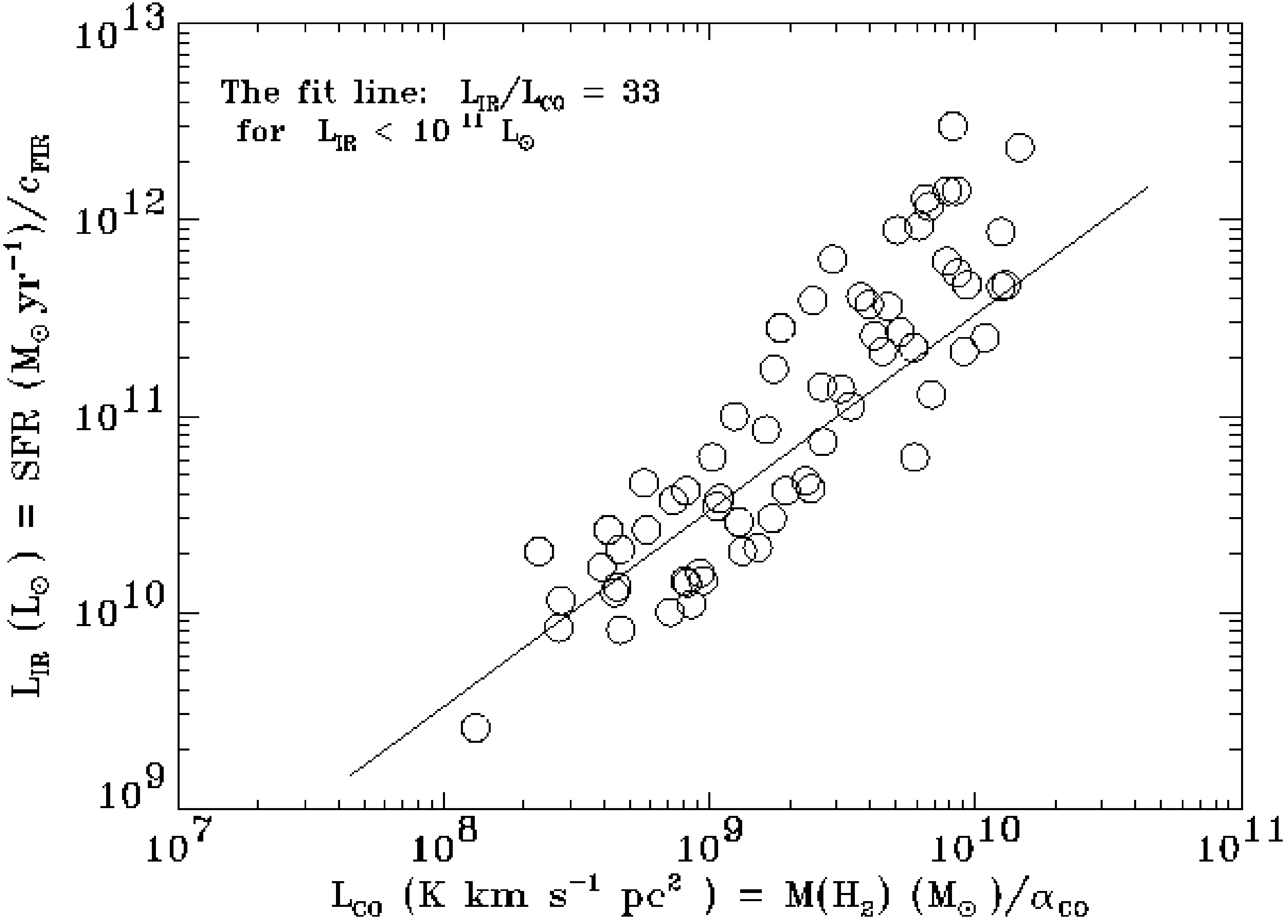
- **Baan et al. (2007) arXiv:0710.0141**
- **Kohno 2007, et al. (2003)**
- **Imanishi**
- **Aalto et al. 1995**
- **Solomon et al. 1992**
- **Nguyen** et al. 1992
- **Henkel et al. 1990** (NGC4945)
- **Henkel, Baan, Mauersberger** 1991



SFR

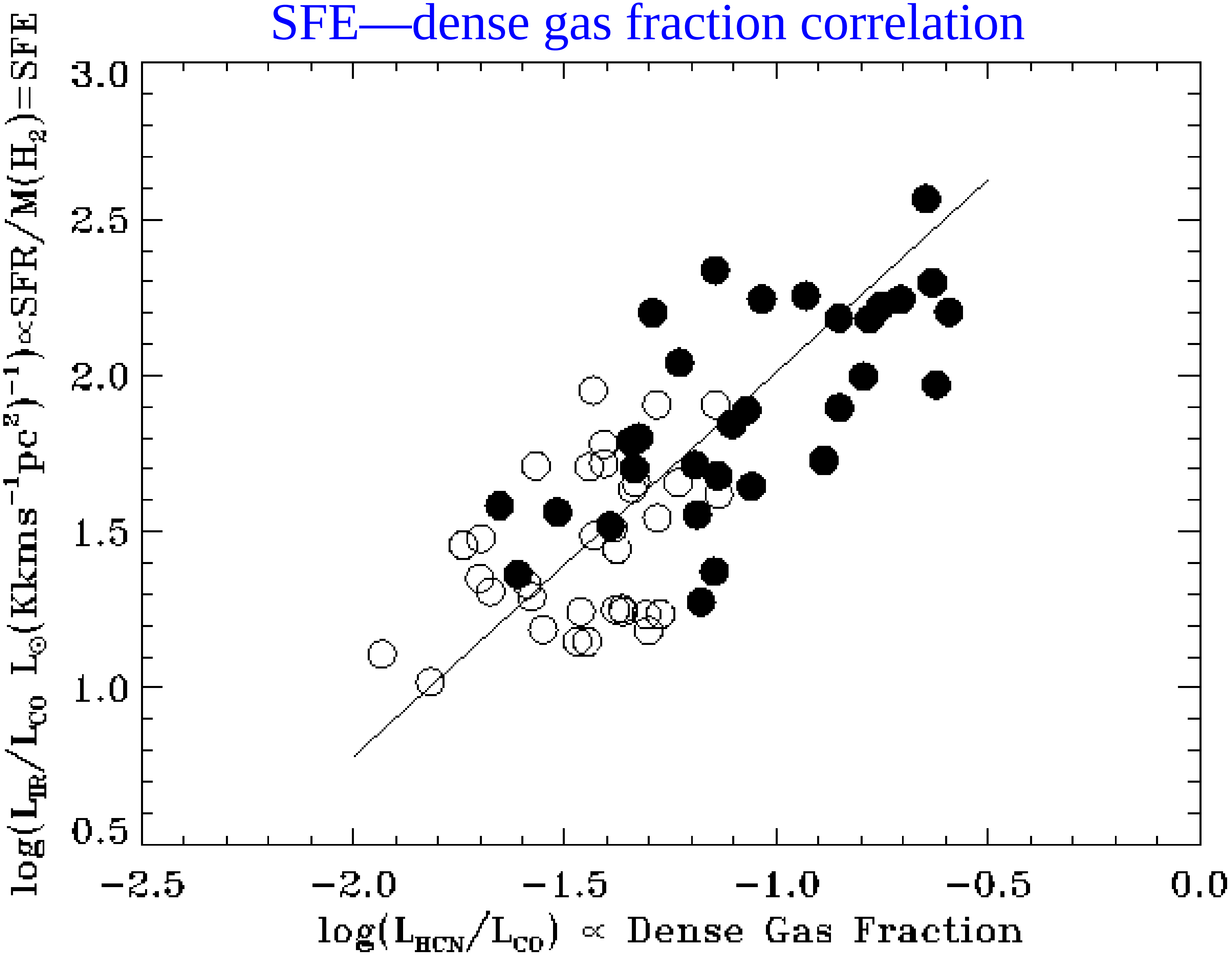
Dense Molecular Gas

More CO data of ULIGs (Solomon et al. 1997) that Lco > ~ 10^10 K km/s pc^2

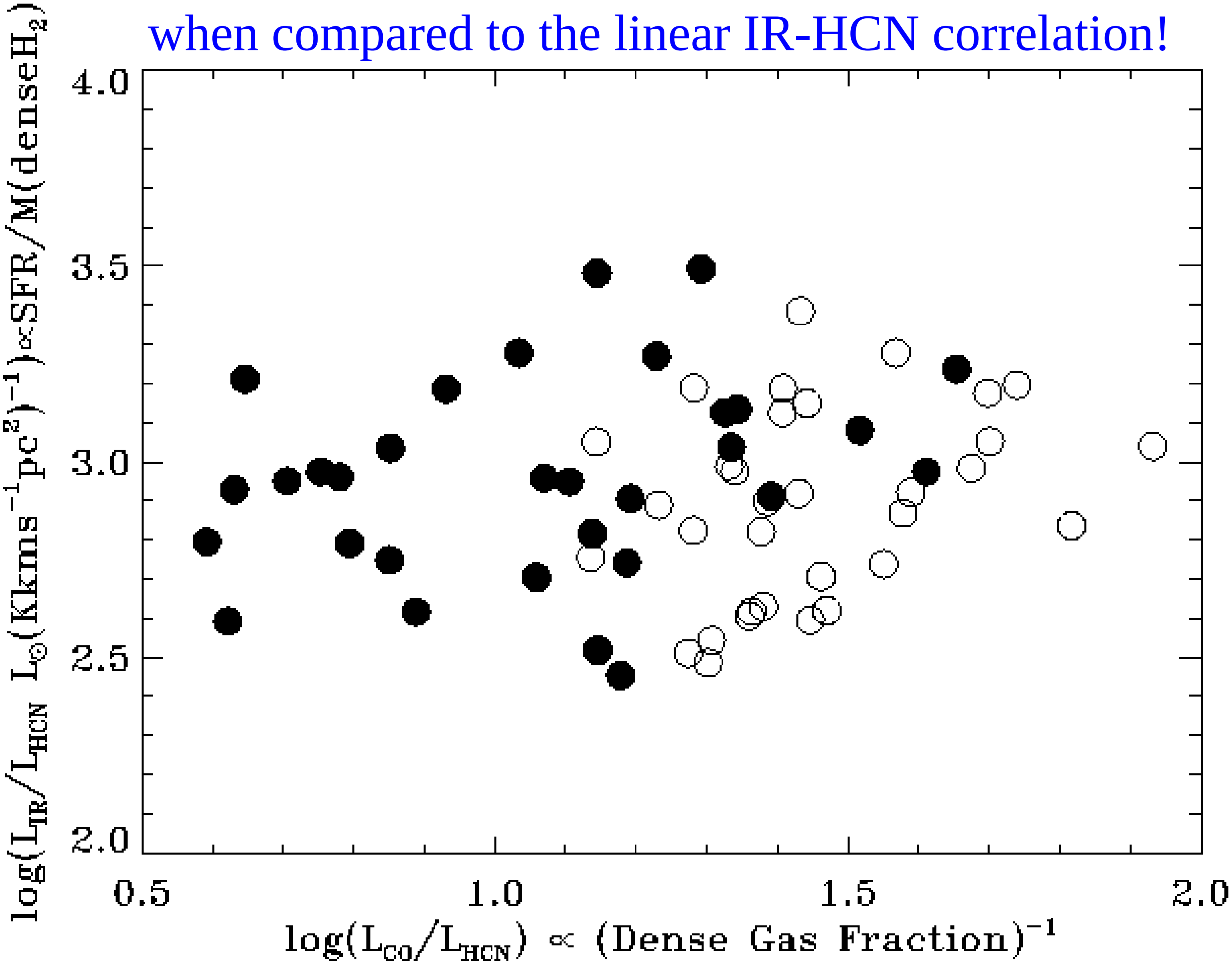


Total Molecular Gas Mass

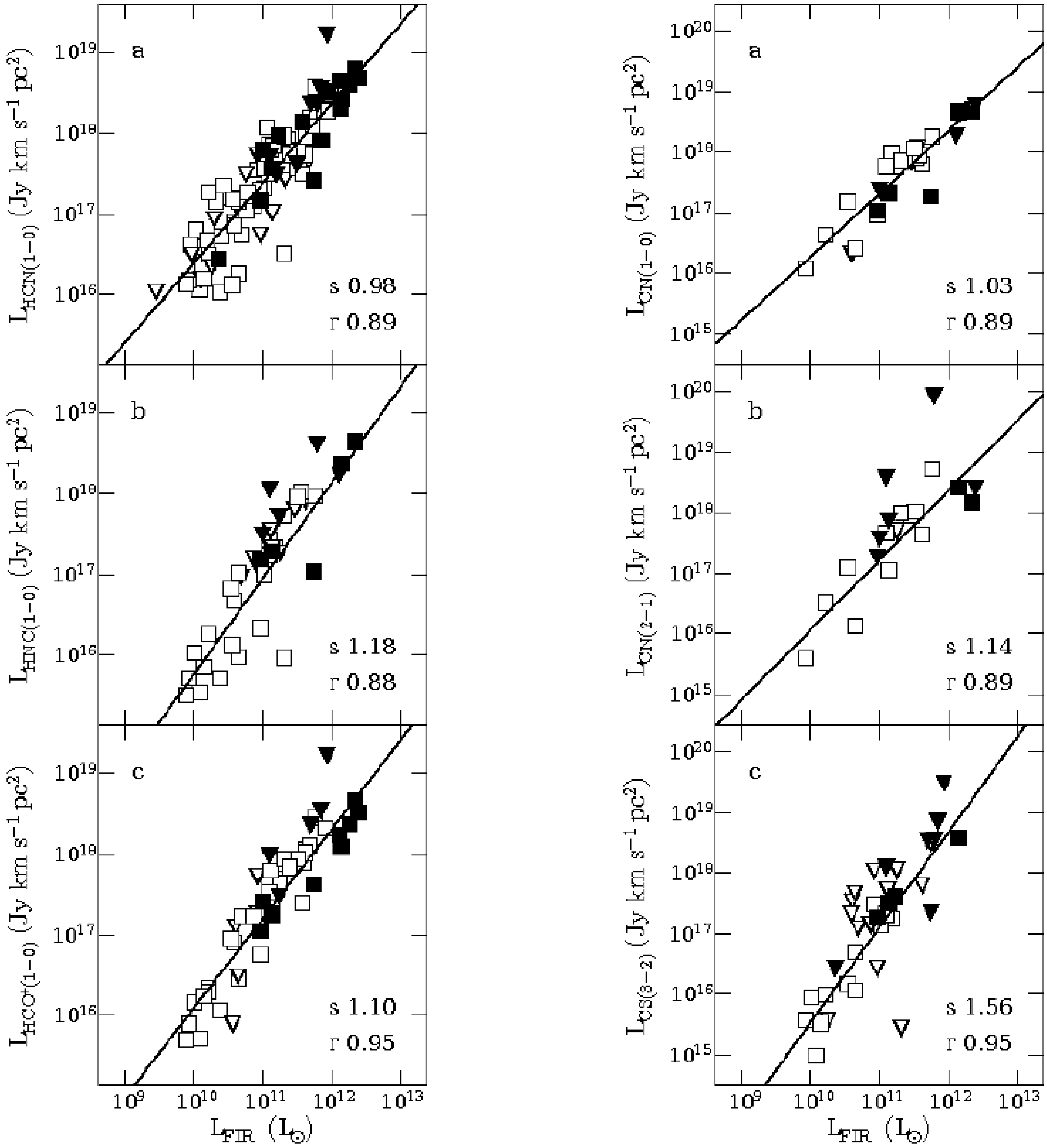
Normalized IR—HCN correlation= SFE—dense gas fraction correlation



IR-CO correlation may lack strong physical basis when compared to the linear IR-HCN correlation!



Baan, Henkel, Loenen et al. (2008, arXiv: 0710.0141)



Liu & Gao 2008 ApJ submitted

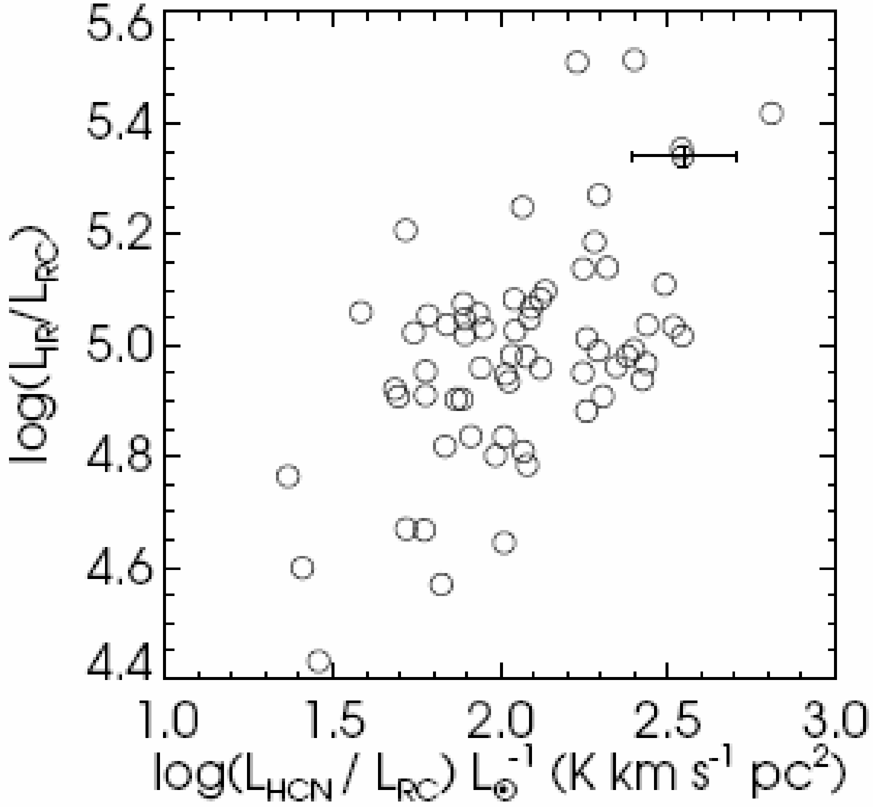


Fig. 4c.— The correlation between IR and HCN is still prominent even after normalization by L_{RC} (R = 0.57, R^2 = 0.33), which suggests a true physical relation between IR and HCN luminosities. The uncertainties for the various ratios are $\sigma_{L_{IR}/L_{HCN}}$ ~ 30% and $\sigma_{L_{RC}/L_{IR}}$ ~ 4% (duplicated uncertainties can be found in captions of previous figures.)

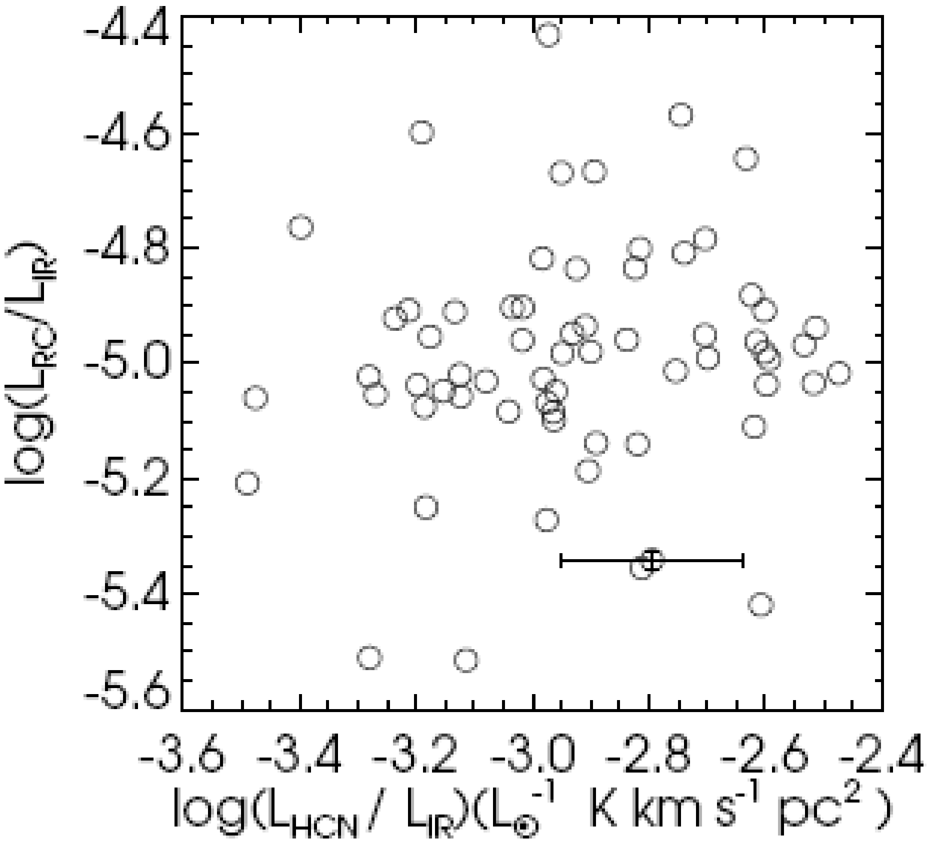


Fig. 4b.— Normalized by L_{IR}, the correlation between RC and HCN completely disappeared (R = 0.14, R^2 = 0.02).

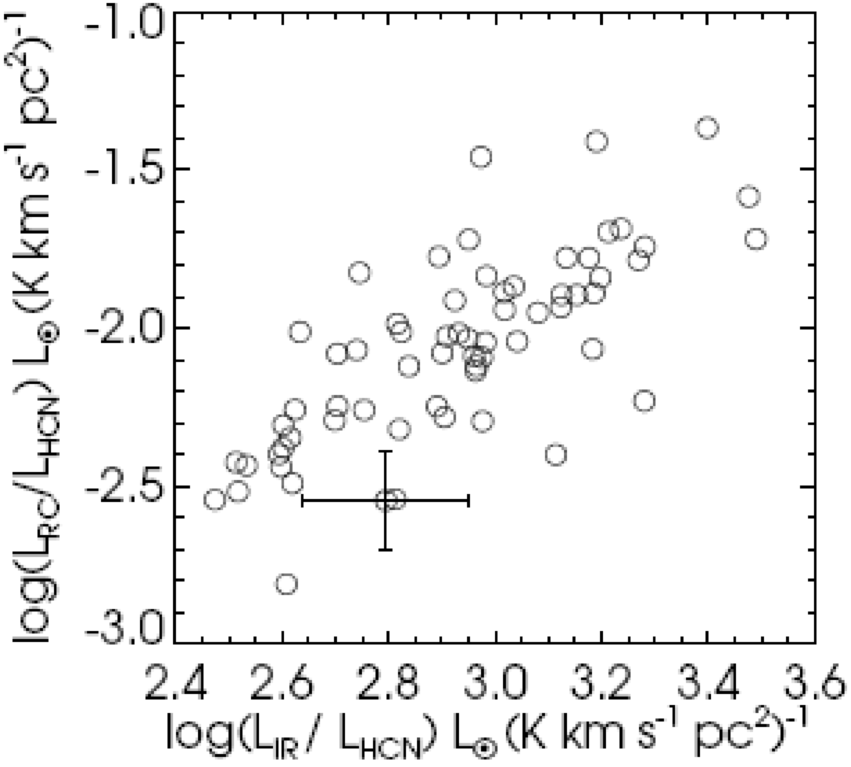


Fig. 4a.— The correlation between RC and IR is very prominent even after normalization by L_{HCN} (R = 0.74, $R^2 = 0.55$), which implys a true physical relation between RC and IR luminosities.

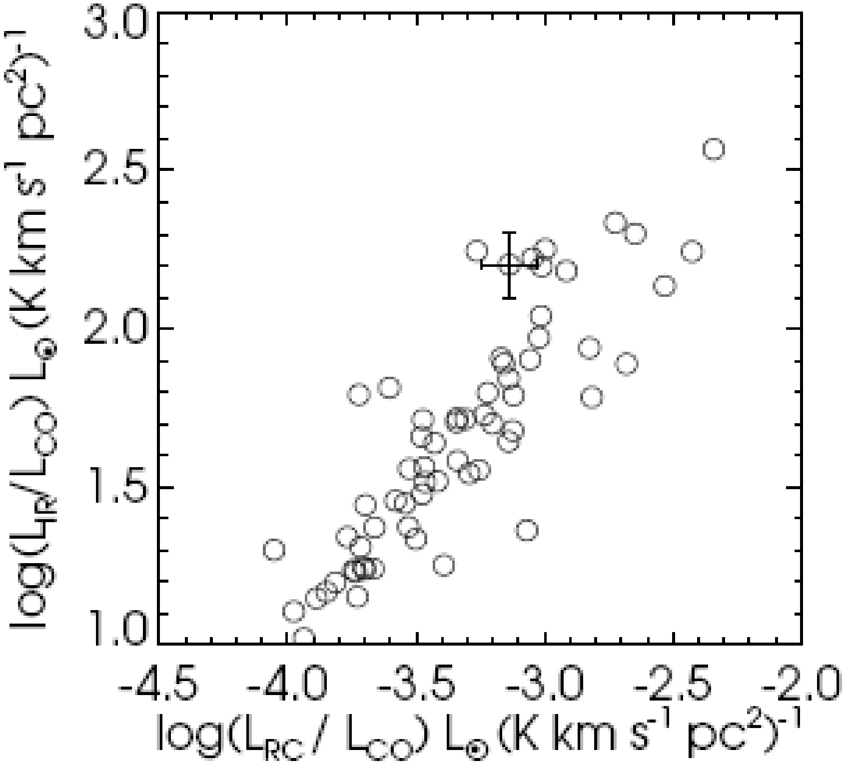


Fig. 5b.— The correlation between IR and RC is very tight even after normalization by L_{CO} (R = 0.92, $R^2 = 0.85$). The uncertainty of L_{CO}/L_{RC} is $\sigma_{L_{CO}/L_{RC}} \sim 21\%$ (duplicated uncertainties can be found in captions of previous figures.)

FIR-radio vs. FIR-HCN correlations

Differ both spatially and temporally

- FIR, radio continuum (RC), HCN & CO
- FIR-RC > FIR/RC-HCN > FIR/RC-CO
- Star Form. → SN/SNRs → RC
- Star Form. → UV/dust → FIR
- CO → HCN → SF → FIR → RC
- FIR-RC & FIR-HCN corr. the strongest!

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3.New HCN@hi-z Obs.(+Literature)

Complications: lens, LIR (SFR vs AGN), CO(1-0)

	Source	**Lfir**	**Lhcn**	**Lco**	**hcn/co**	**mag.f**
a	**H1413+117**	**5.0**	**3.0**	**37.**	**0.08**	**11**
	F1021+472	**3.4**	**1.2**	**6.5**	**0.18**	**17**
	J1409+562	**17.**	**6.5**	**74.**	**0.09**	**1**
	A0827+525	**0.25**	**0.25**	**.92**	**0.27**	**80**
B	***J02396-0134***	***6.1***	***<3.7***	***19.***	***<0.20***	***2.5***
	J0413+102	***22.***	***<28***	***159.***	***<0.18***	***1.3***
	J0911+055	***2.1***	***<0.6***	***4.8***	***<0.13***	***22***
	J1635+661	***0.93***	***0.6***	***3.7***	***0.18***	***22***
c	B1202-072	55.	<39.	93.	<0.42	1
	J1148+525	20.	<9.3	25.	<0.36	1
	J1401+025	0.7-3.7	<0.3-1.5	4-18	<0.08	25-5
	M0751+271	2.7	<0.9	9.3	<0.10	17
	J02399-0136	28.	<46.	112.	<0.41	2.5

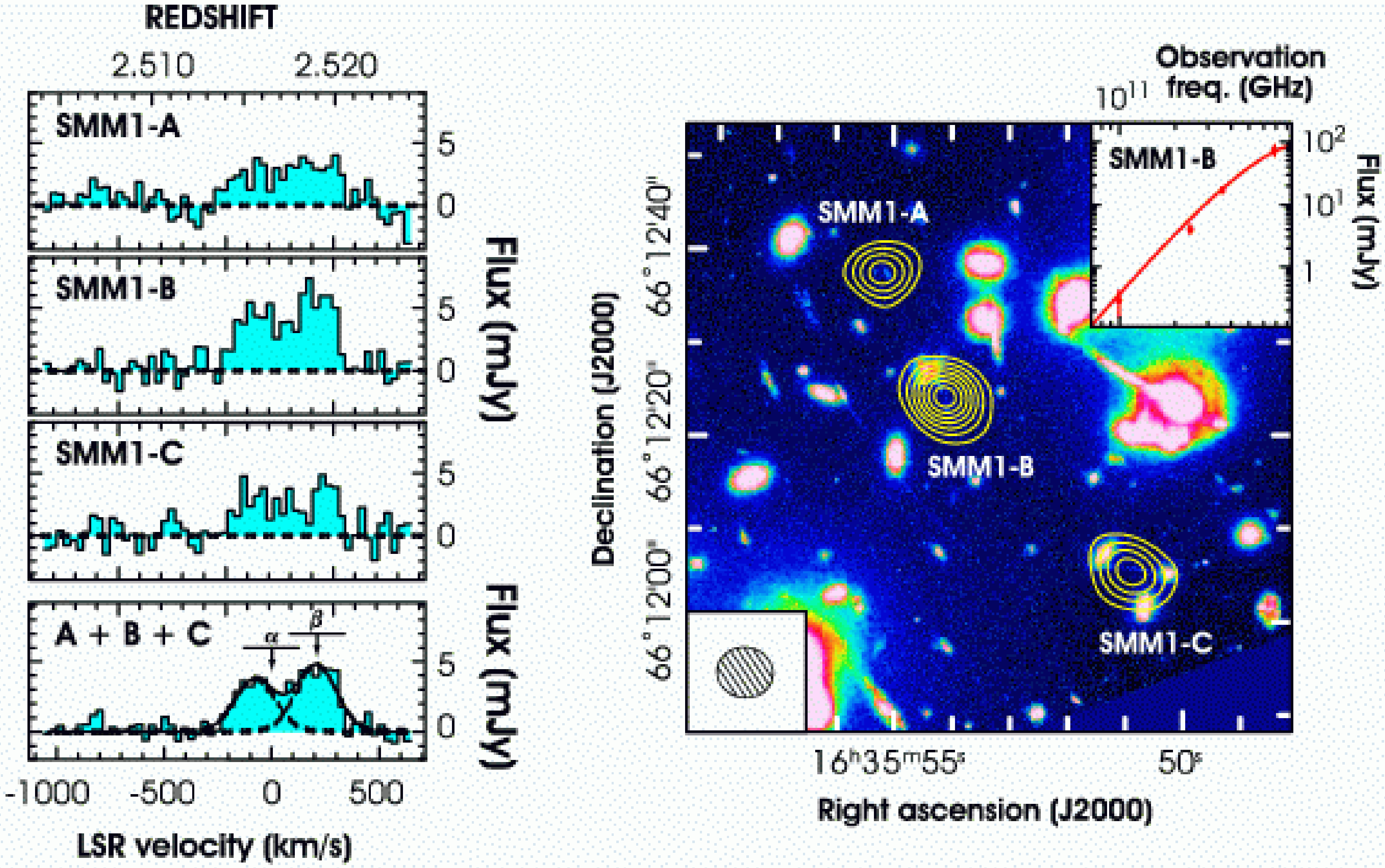
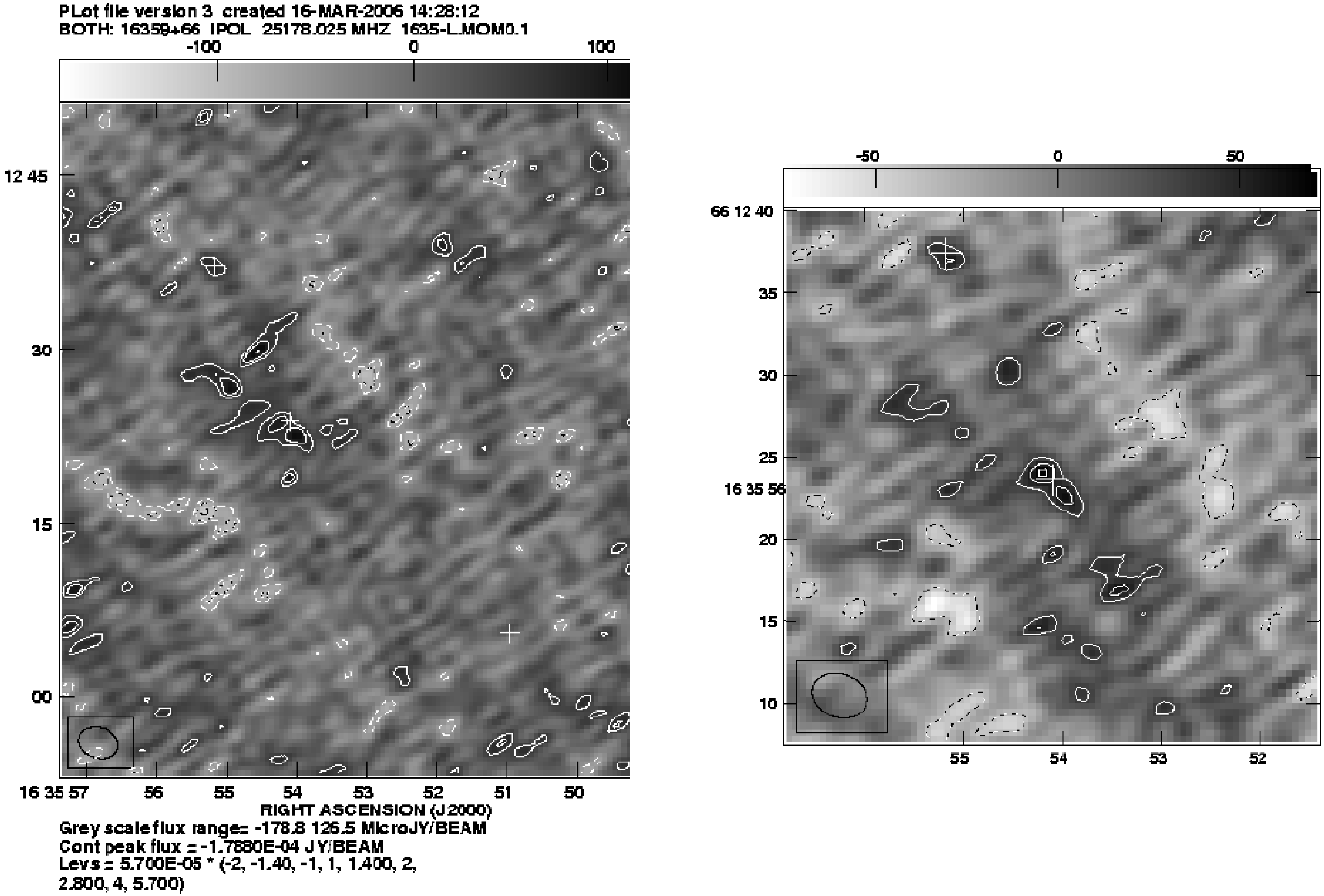
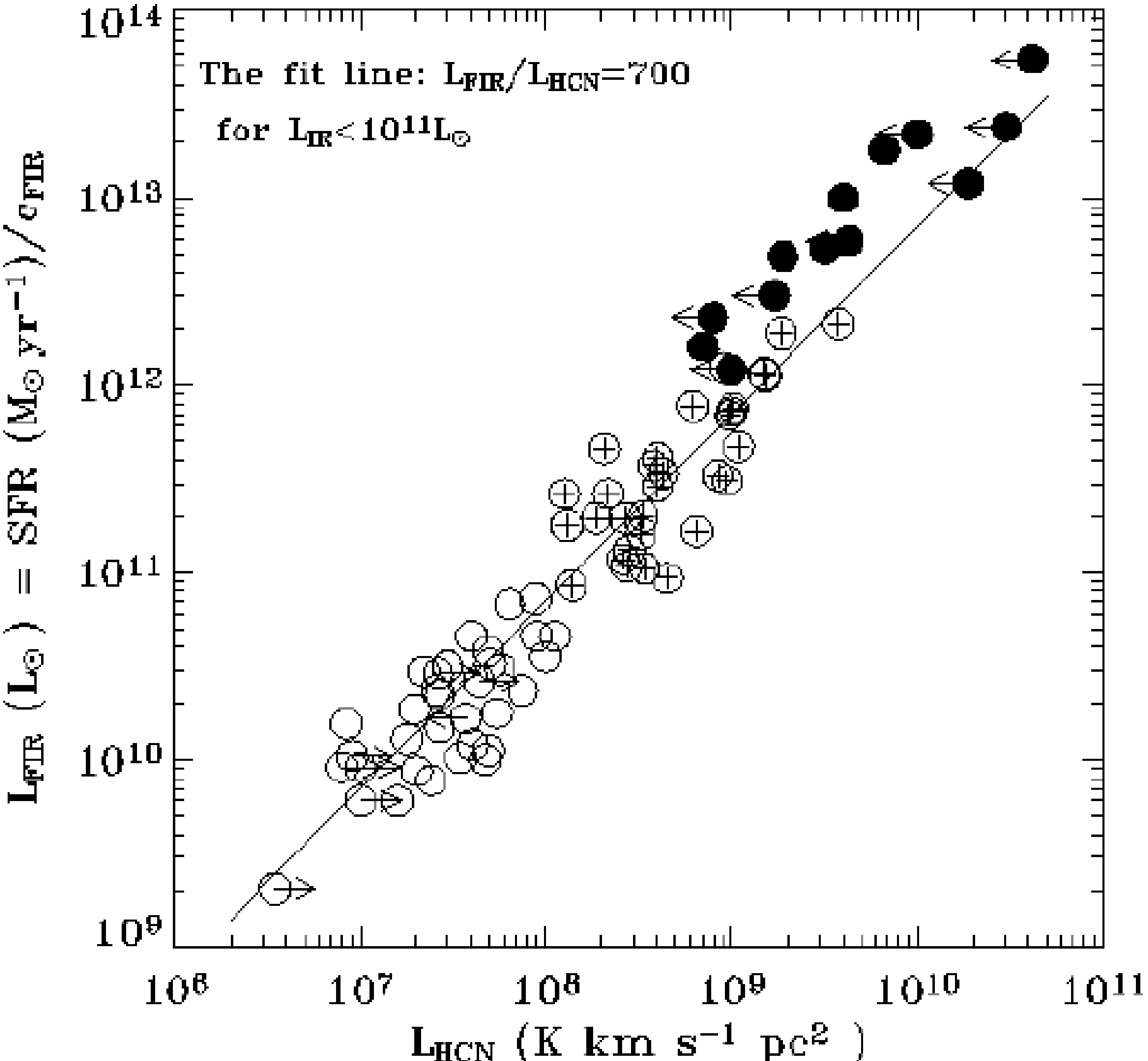


Figure 5: The lower panel shows SMM J16399 in CO(3–2) emission that has been triply imaged by a gravitational lens (Kneib et al. 2004a). The total

Gao, Carilli, Solomon & Vanden Bout 2007 ApJ, 660, L93 (astro-ph/0703548)



New Results (13 HCN@high-z)



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- **Kennicutt (1998): n=1.4 ?**

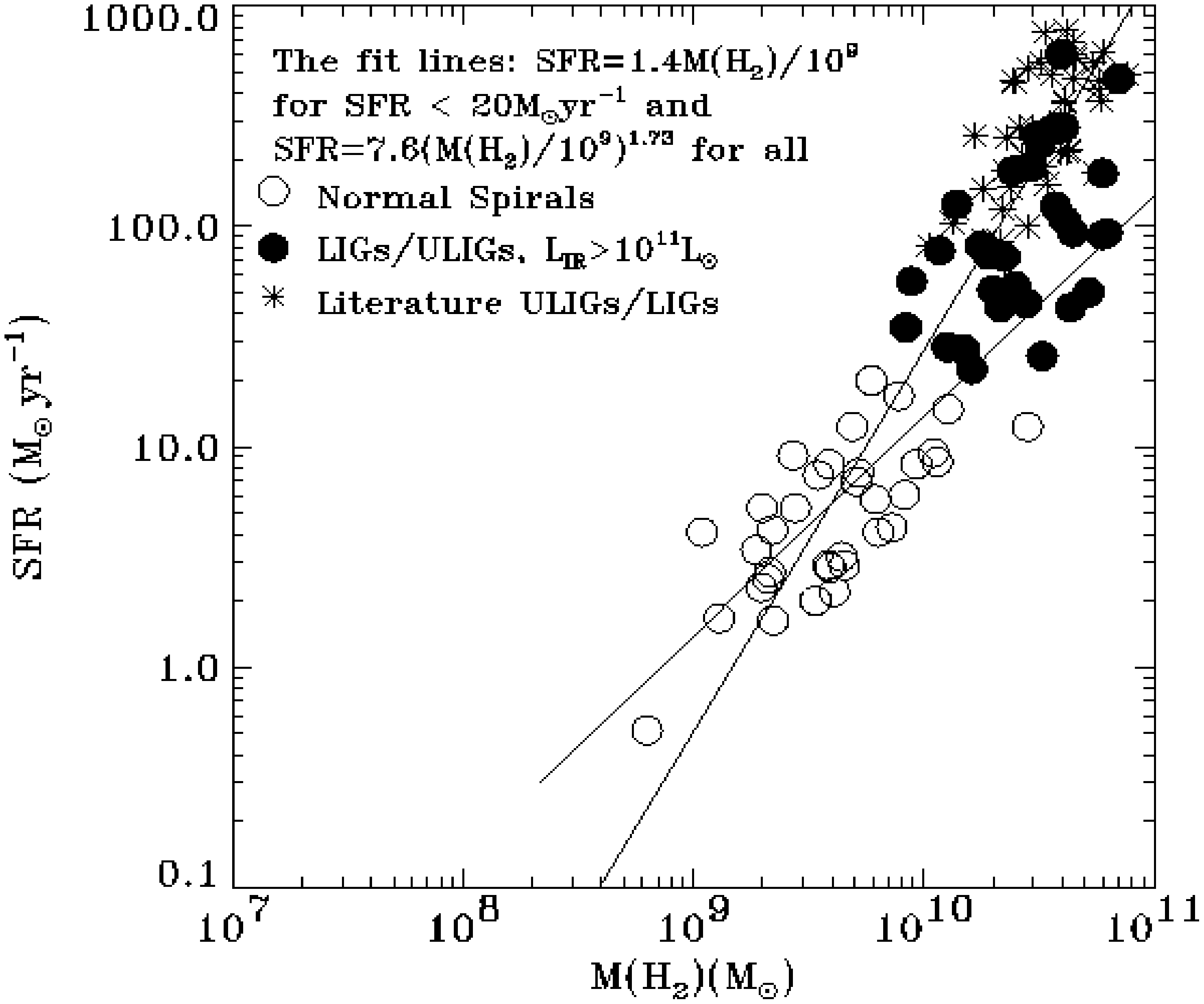
  Total gas (HI + H2) vs. Molecular gas

  Sample dependent !! (e.g., Wong & Blitz 2002; Heyer et al. 2004; etc.)

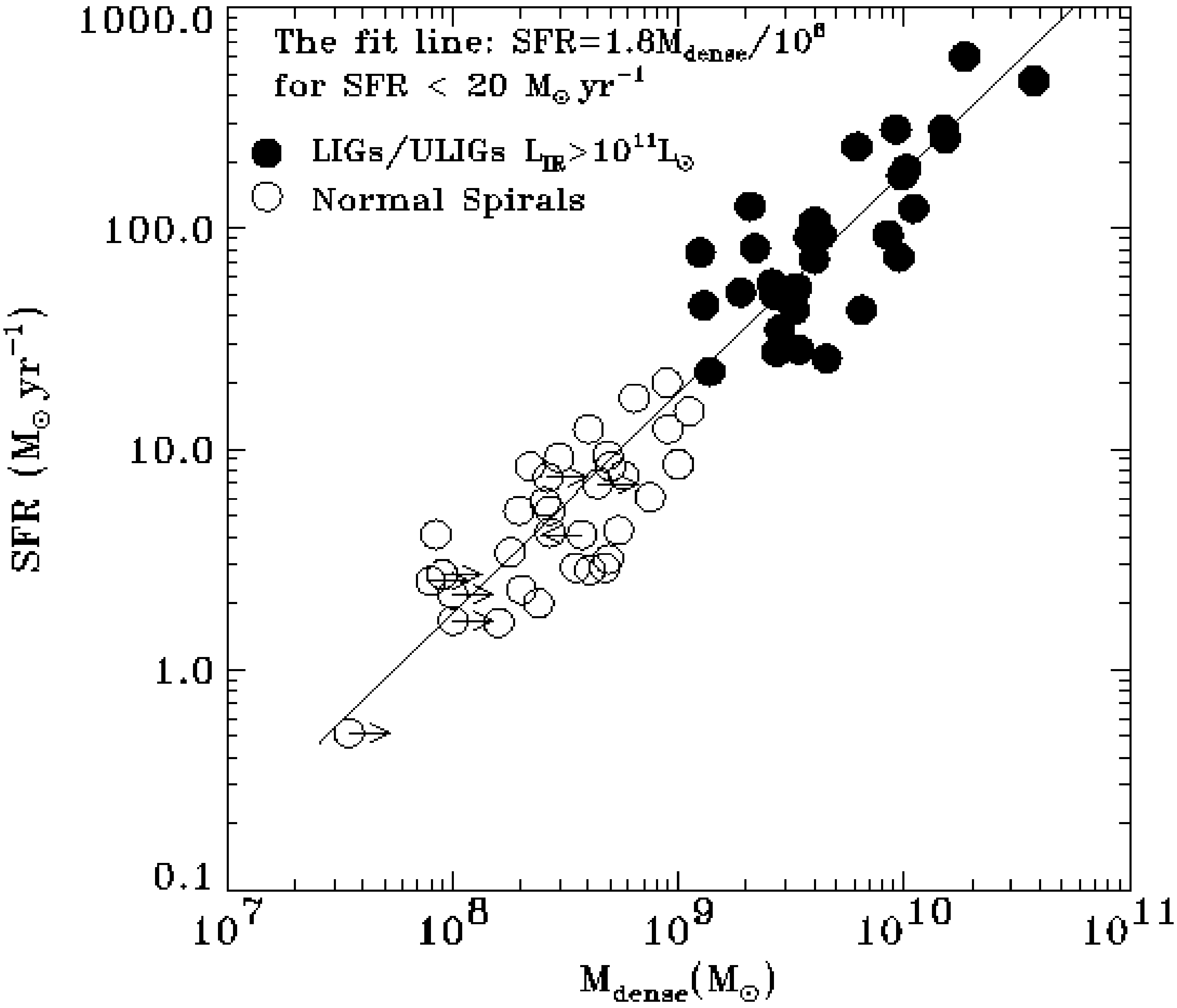
  vs. Dense molecular gas !?

- **Better SF law in dense molecular gas!**

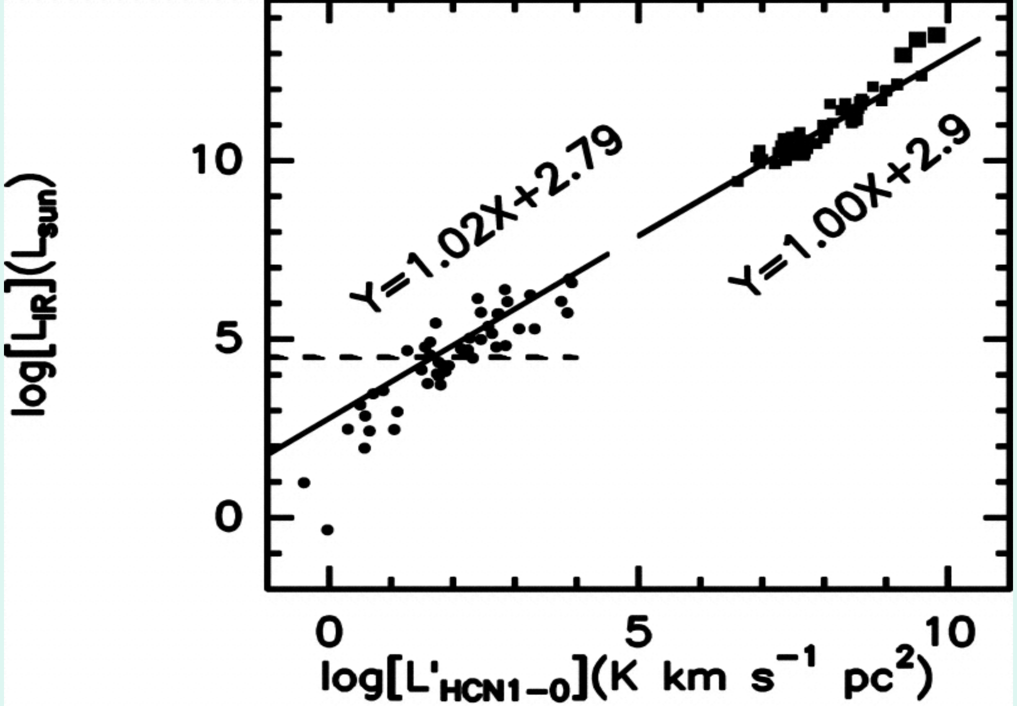
SFR vs. M(H2): No Unique Slope:1, 1.4, 1.7?



SFR vs. M_dense(H2): linear correlation

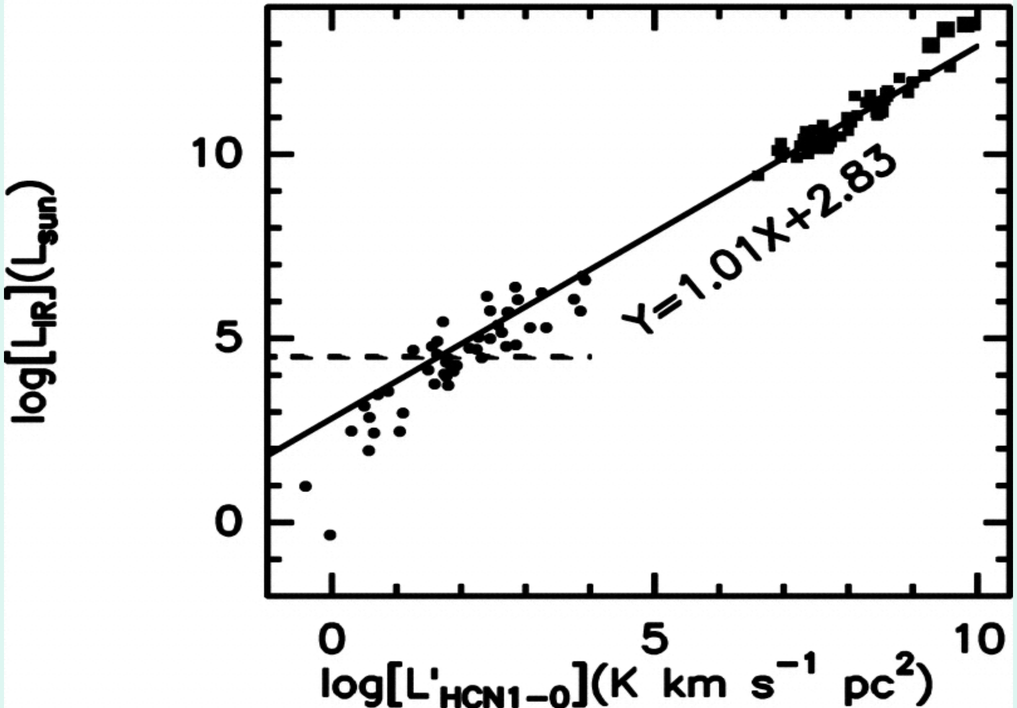


Wu, Evans, Gao et al.
2005 ApJL

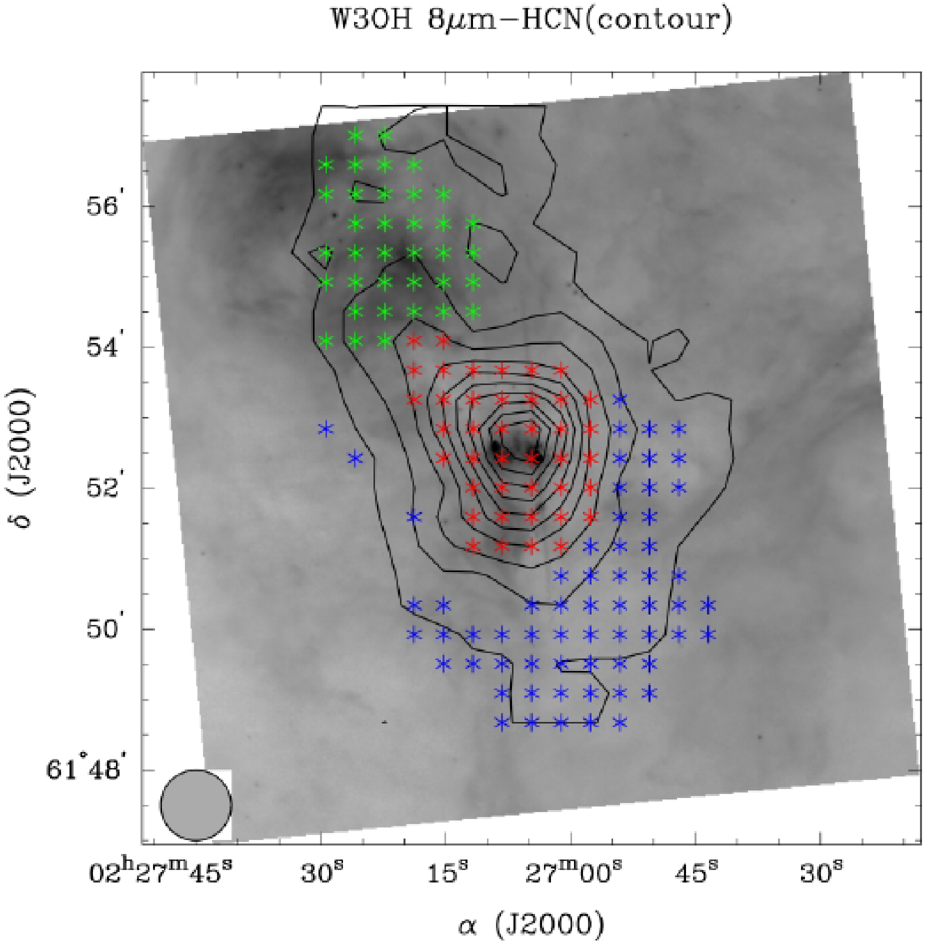


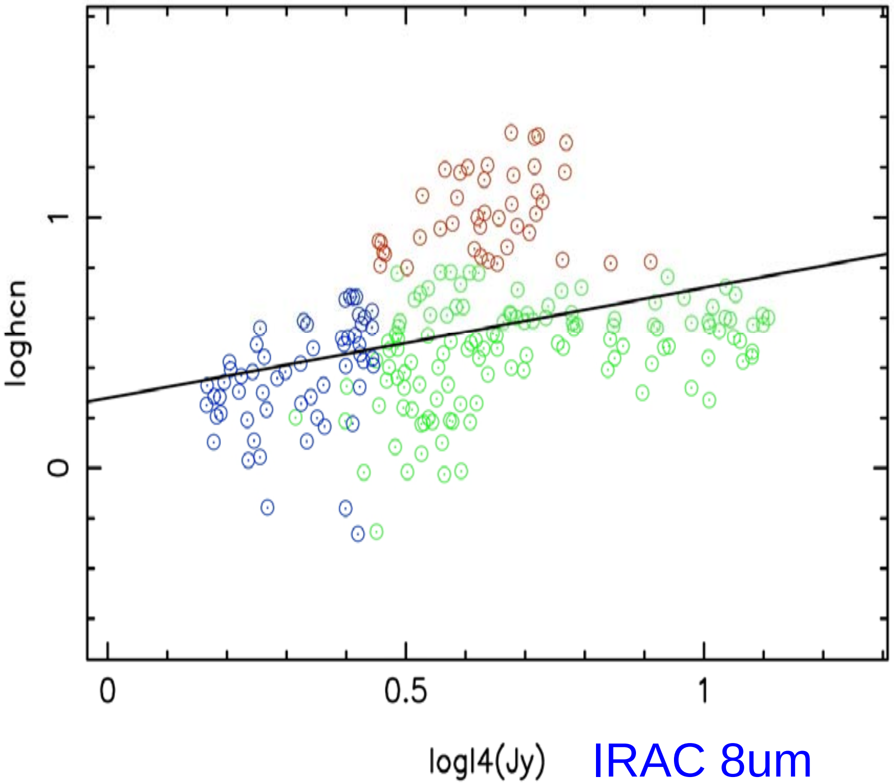
Krumholz & Thompson
arXiv:0704.0792 !!!

Papadopoulos et al.



Ma, Gao & Wu 2008 in prep.

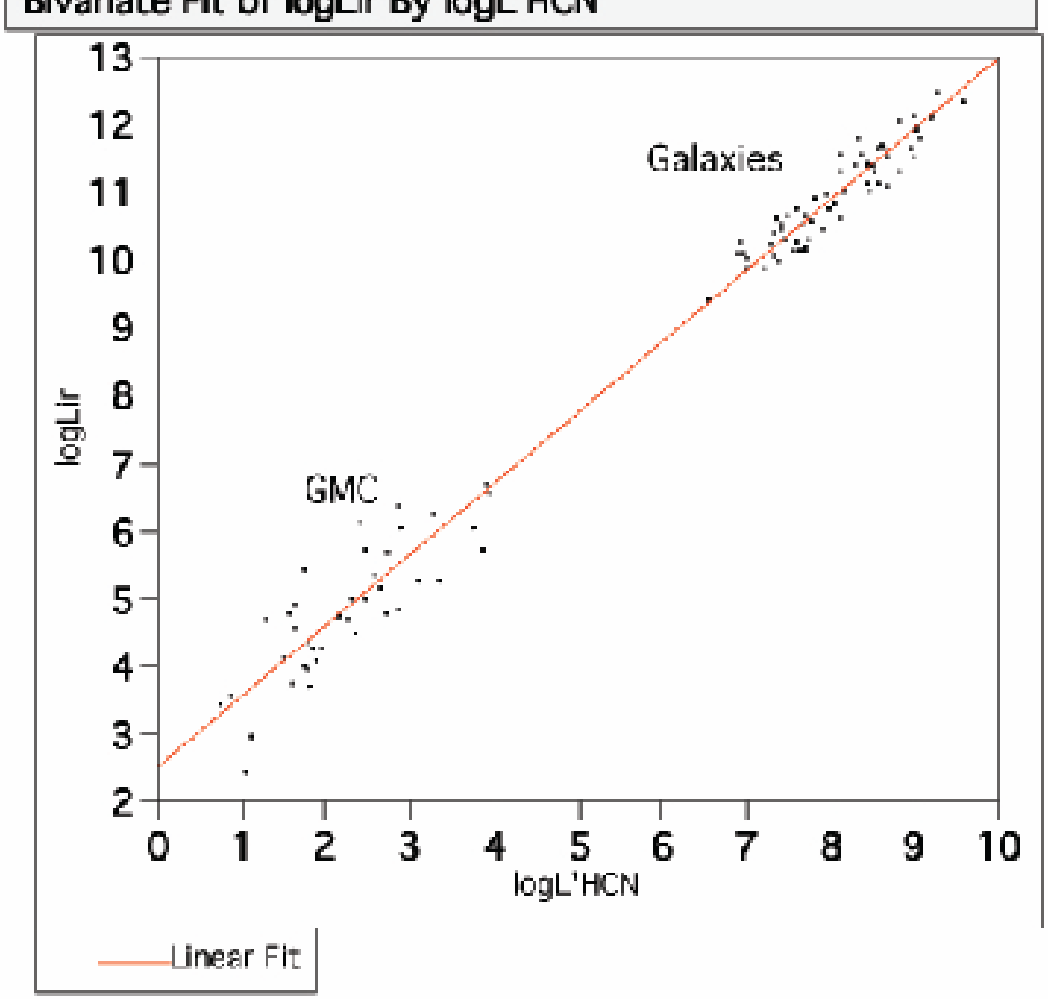




IRAC 8um

GBT

VLA → EVLA!


Bivariate Fit of logLir By logL'HCN
13
12
11
10
9
8
7
6
5
4
3
2
logLir
0
1
2
3
4
5
6
7
8
9
10
logL'HCN
Galaxies
GMC
Linear Fit

New Star Formation Law

- Dense Molecular Gas → High Mass Stars
- SFR ~ M(DENSE) ~ density of dense gas (e.g. gas density >~100,000 cc), linear
- HI → H_2 → DENSE H_2 → Stars

Schmidt law : HI → Stars

Kennicutt : HI + H_2 → Stars

Gao & Solomon: Dense H_2 → Stars

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