The Star Formation Rate and Dense Molecular Gas: the FIR-HCN Correlation

Yu GAO

Purple Mountain Observatory, Nanjing
Chinese Academy of Sciences

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

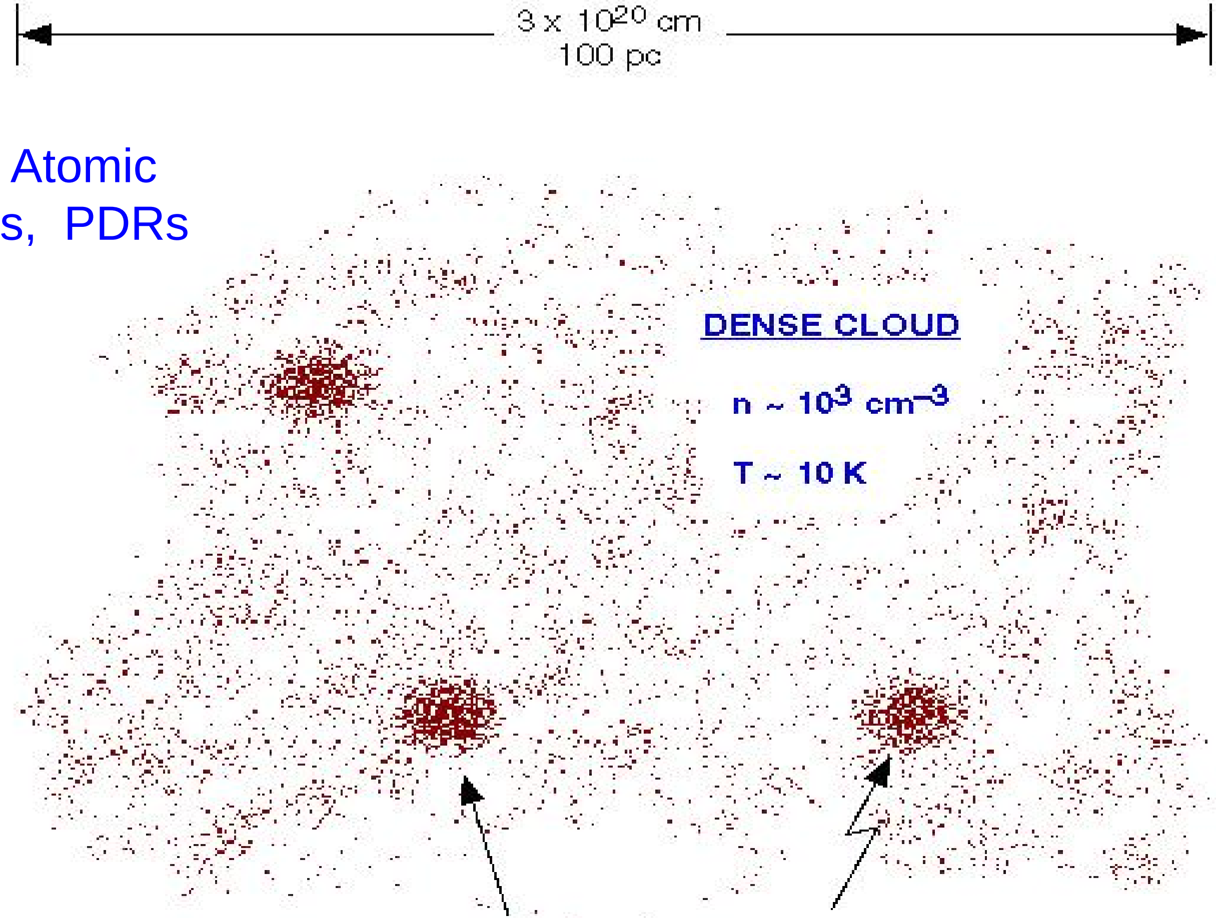
  b) FIR--HCN Correlation

- 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

HI, Atomic
Gas, PDRs



DENSE CLOUD

n ~ 10^3 cm^{-3}

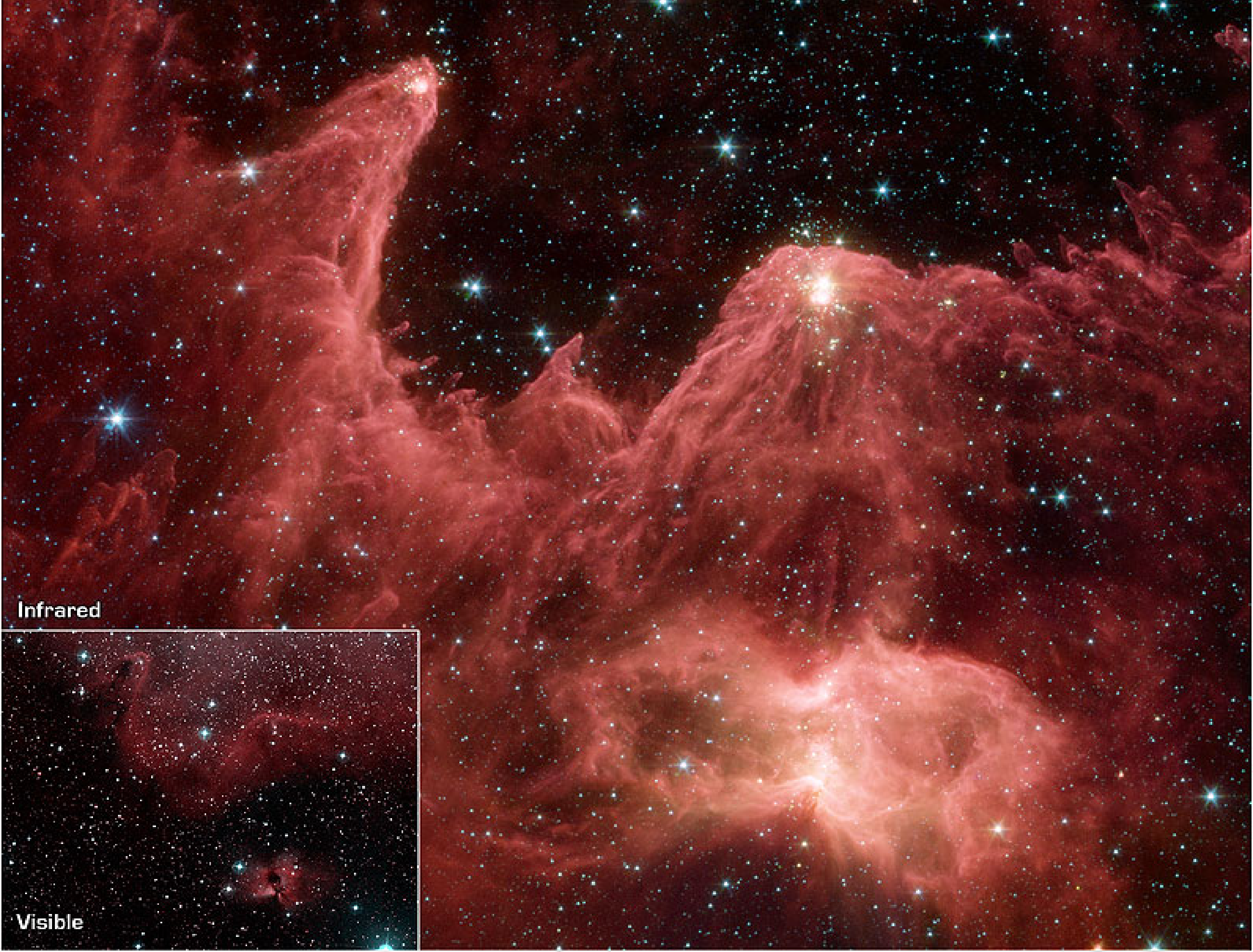
T ~ 10 K

DENSE CLOUD CORES

n ~ 10^4 – 10^6 cm^{-3}

T ~ 15 – 40 K

D ~ 0.1 – 0.3 pc



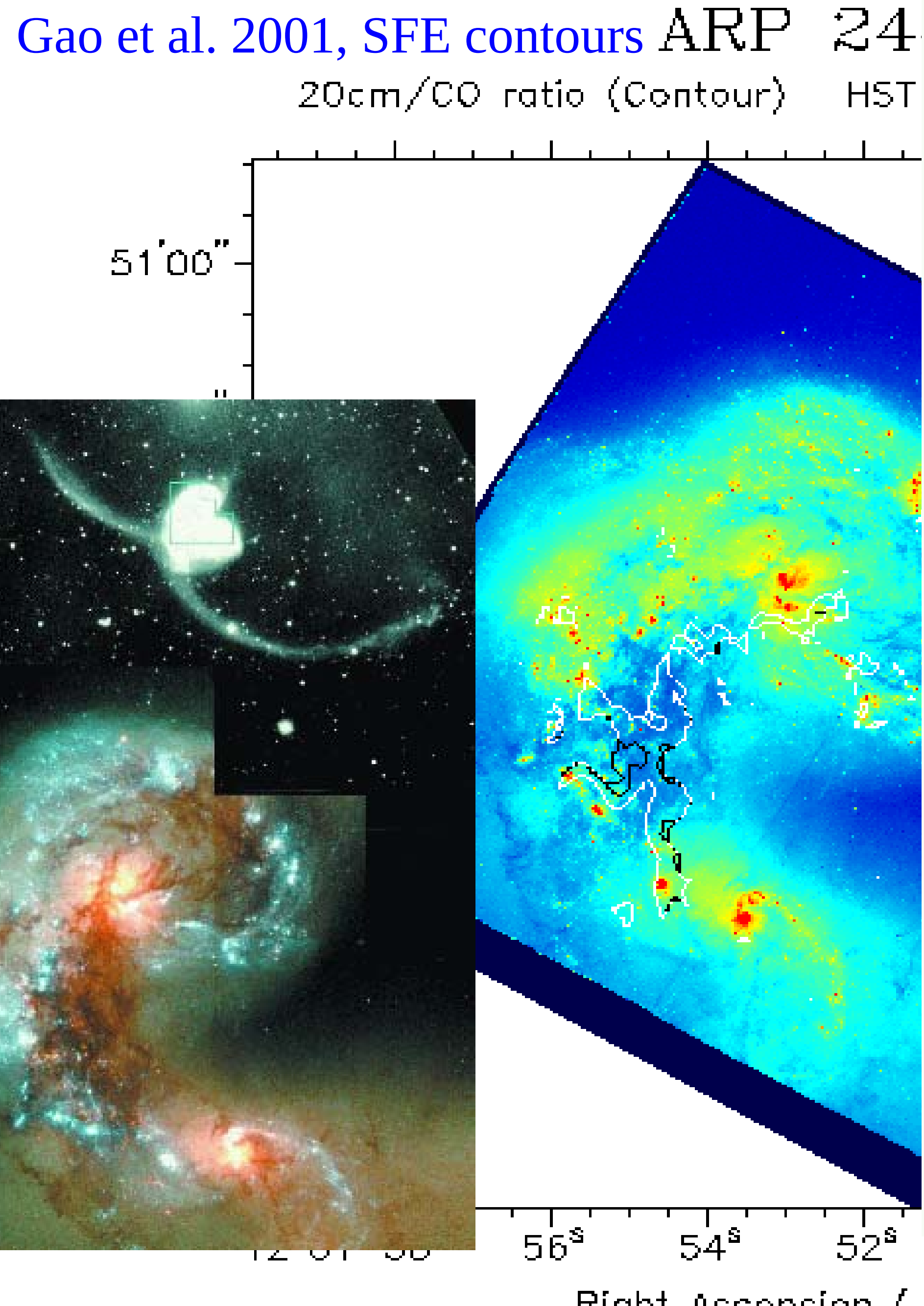
“Mountains of Creation” in W5 Star-Forming Region

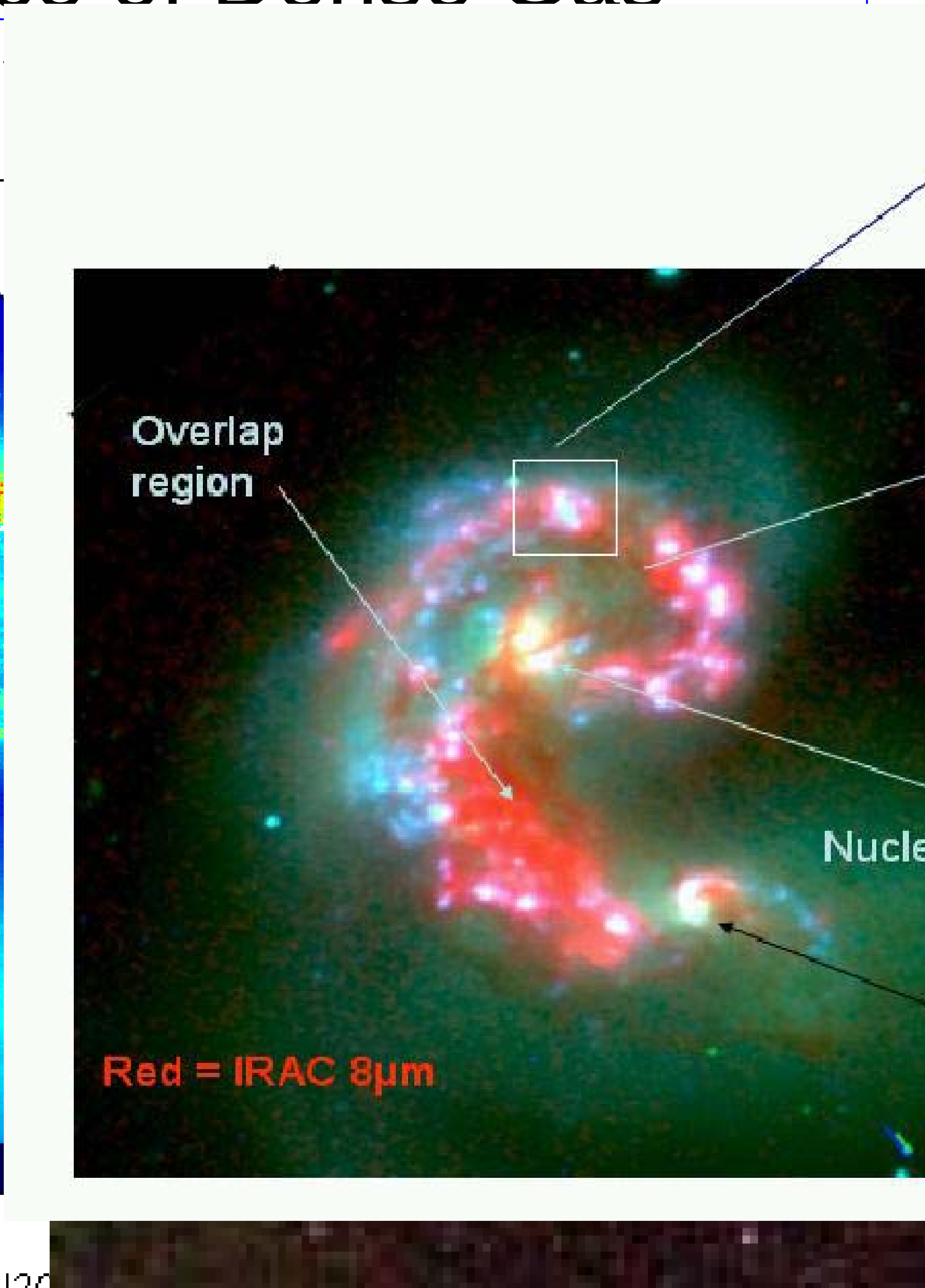
Spitzer Space Telescope • IRAC
Visible: DSS

NASA / JPL-Caltech / L. Allen (Harvard-Smithsonian CfA)
ssc2005-23a

1.(Cont.) Importance of Dense Gas

Gao et al. 2001, SFE contours





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

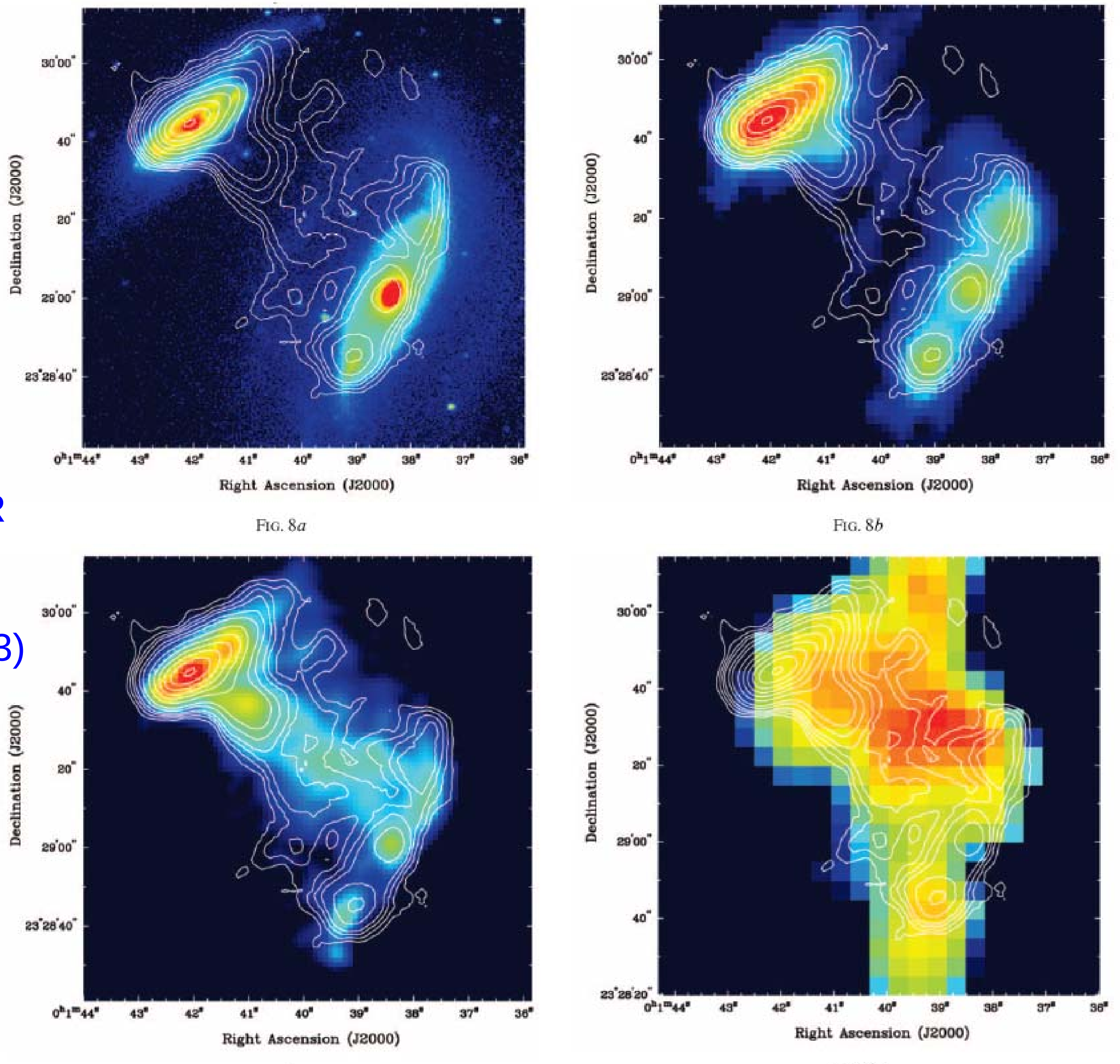


FIG. 8*a*

FIG. 8*b*

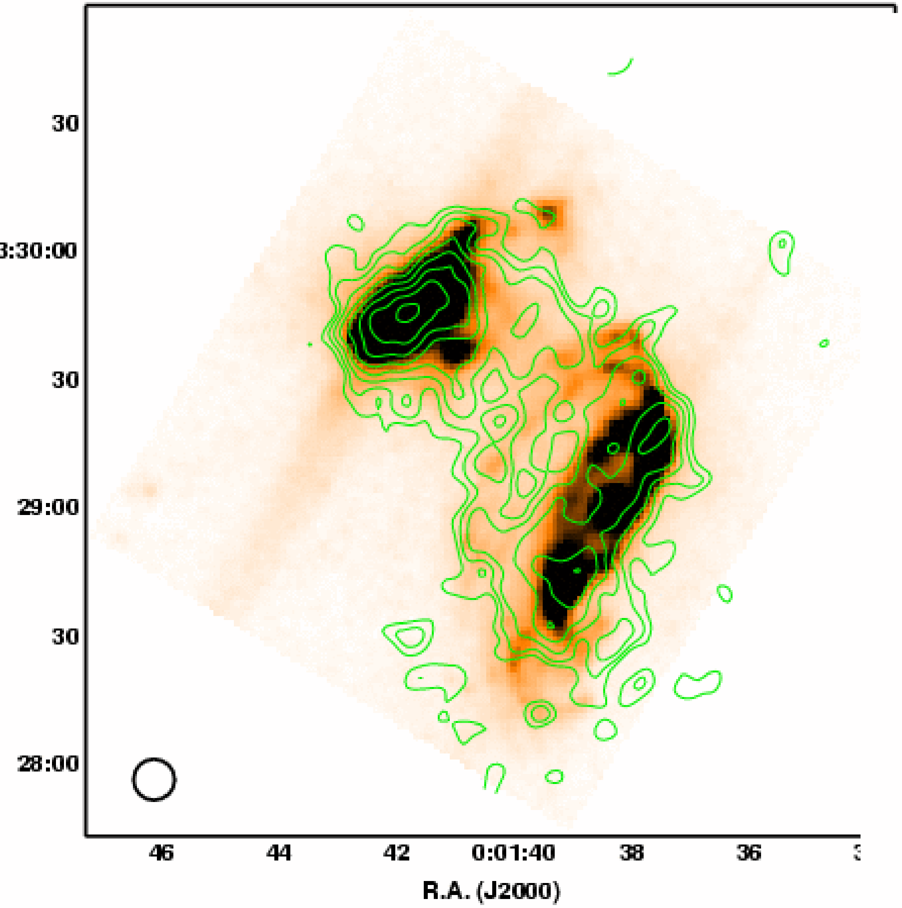
FIG. 8*c*

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.

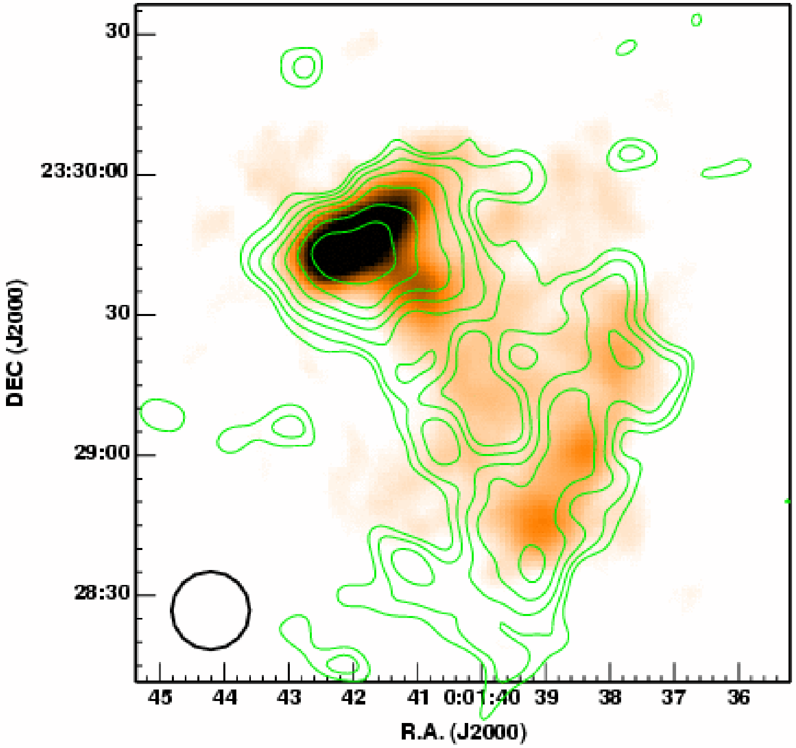
SCUBA: Zhu, Gao, Seaquist & Dunne 2007

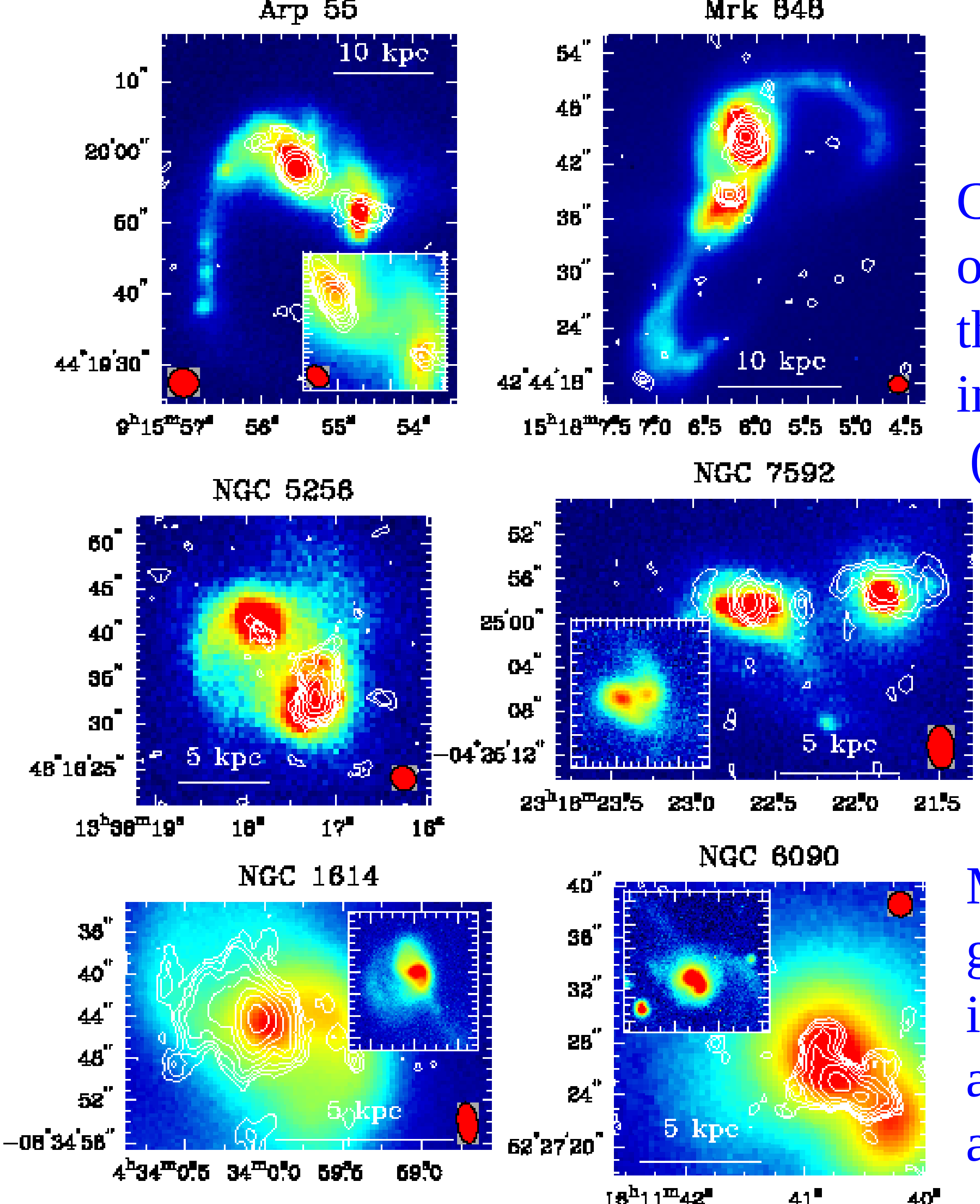
450um contours on 8um image



CO: Gao, Zhu, Seaquist 2003

850um contours on CO image

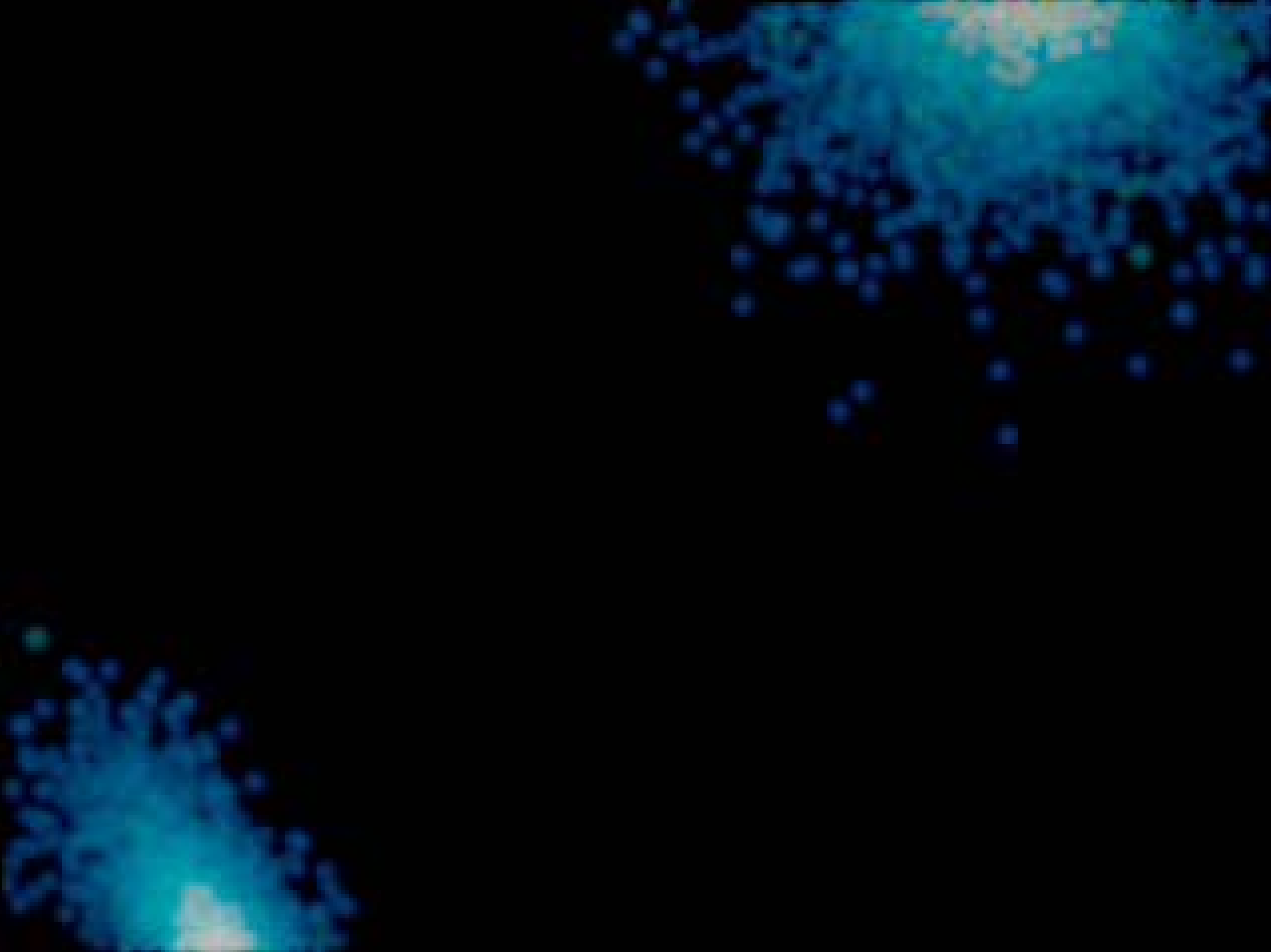




CO Contours overlaid on the optical images (false-color)

Gao et al. 1999

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

FIR-radio vs. FIR-HCN correlations

- 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!

Talk Outline

- 1) Massive Star Formation (SF) & HCN

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

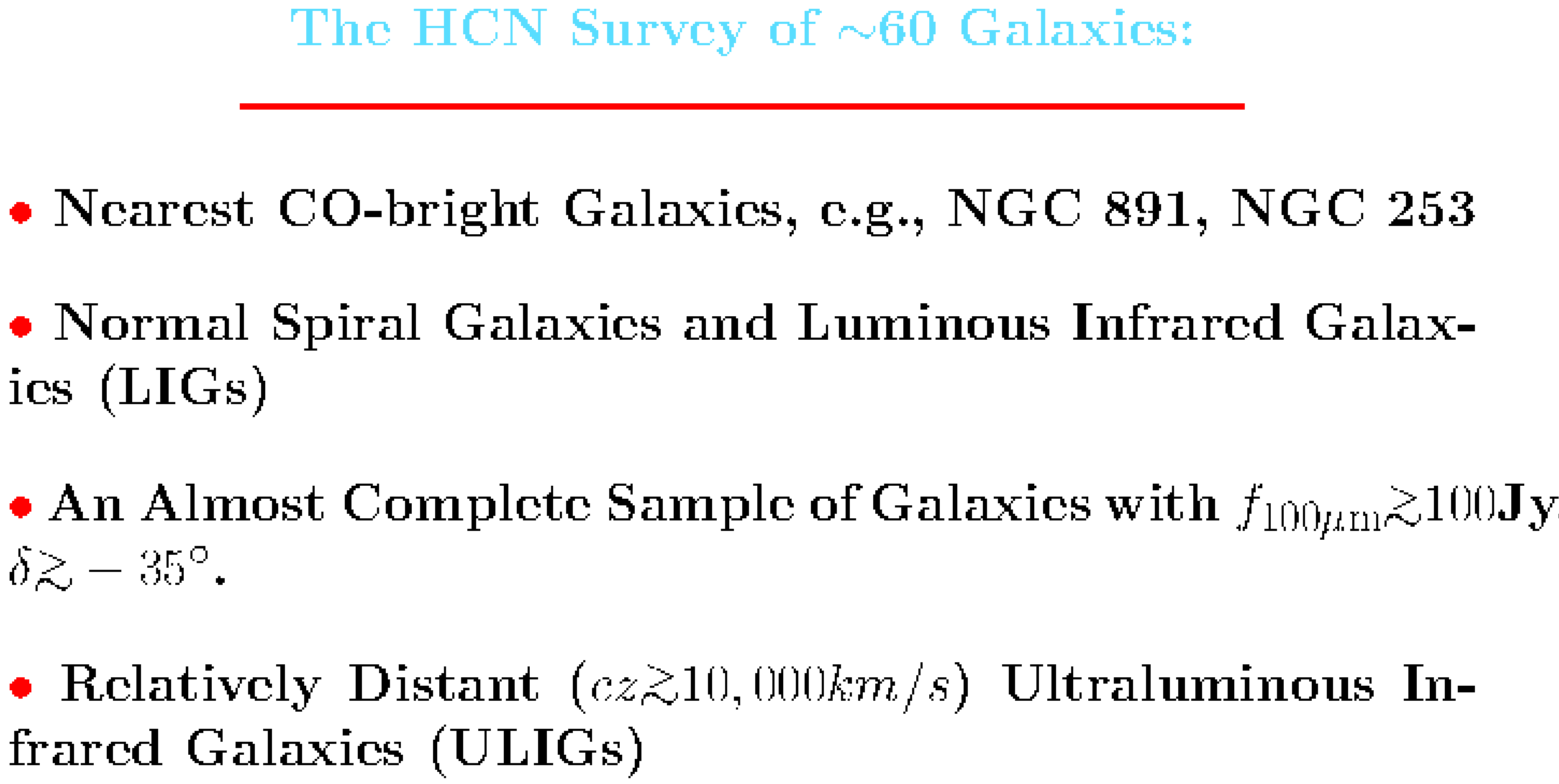
- 2) HCN Observations in Local Galaxies

  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)

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



The HCN Survey of ~60 Galaxies:

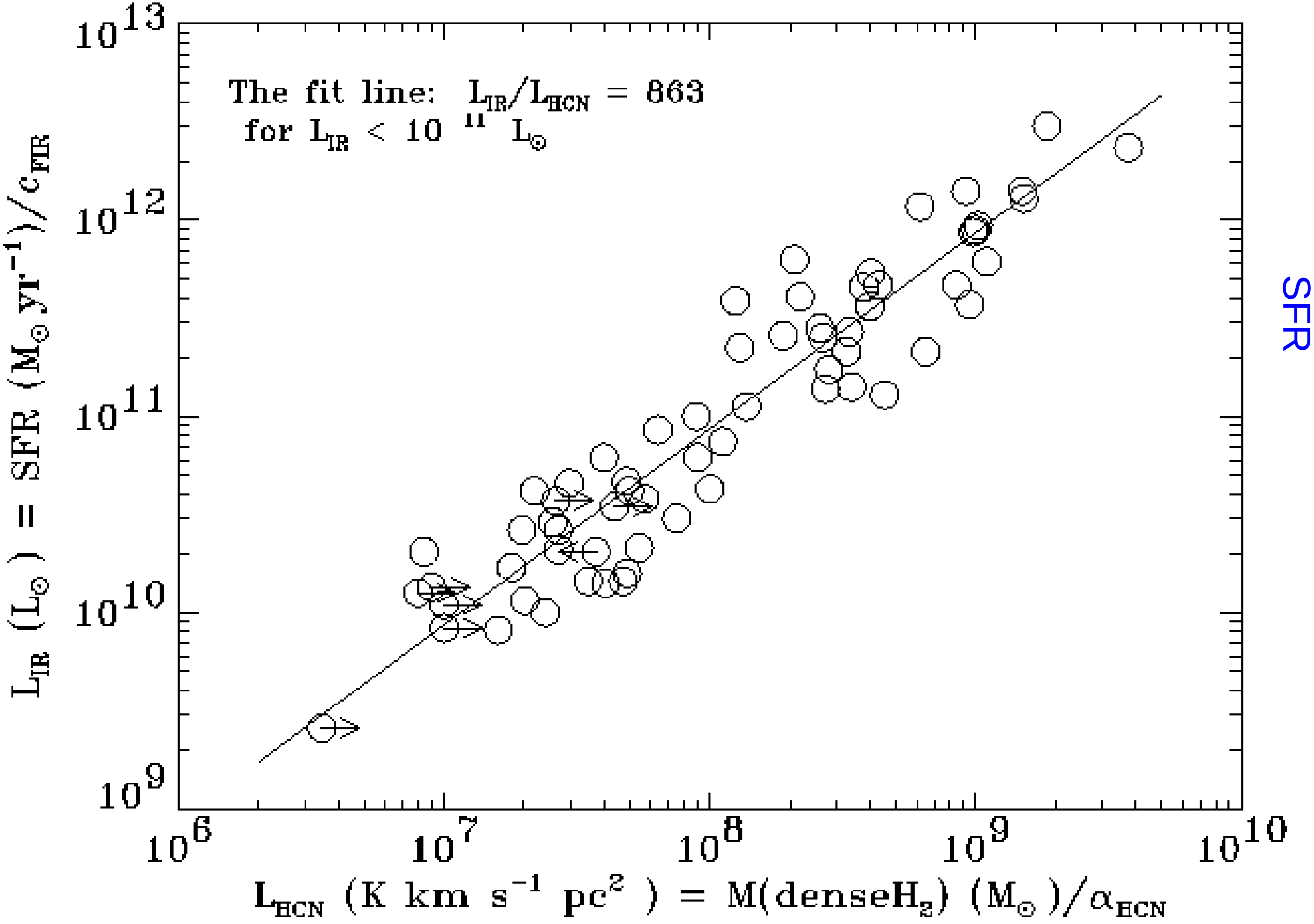
- **Nearest CO-bright Galaxies, e.g., NGC 891, NGC 253**
- **Normal Spiral Galaxies and Luminous Infrared Galaxies (LIGs)**
- **An Almost Complete Sample of Galaxies with** $f_{100\mu m} \gtrsim 100$**Jy** $\delta \gtrsim -35°$.
- **Relatively Distant** ($cz \gtrsim 10,000 km/s$) **Ultraluminous Infrared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

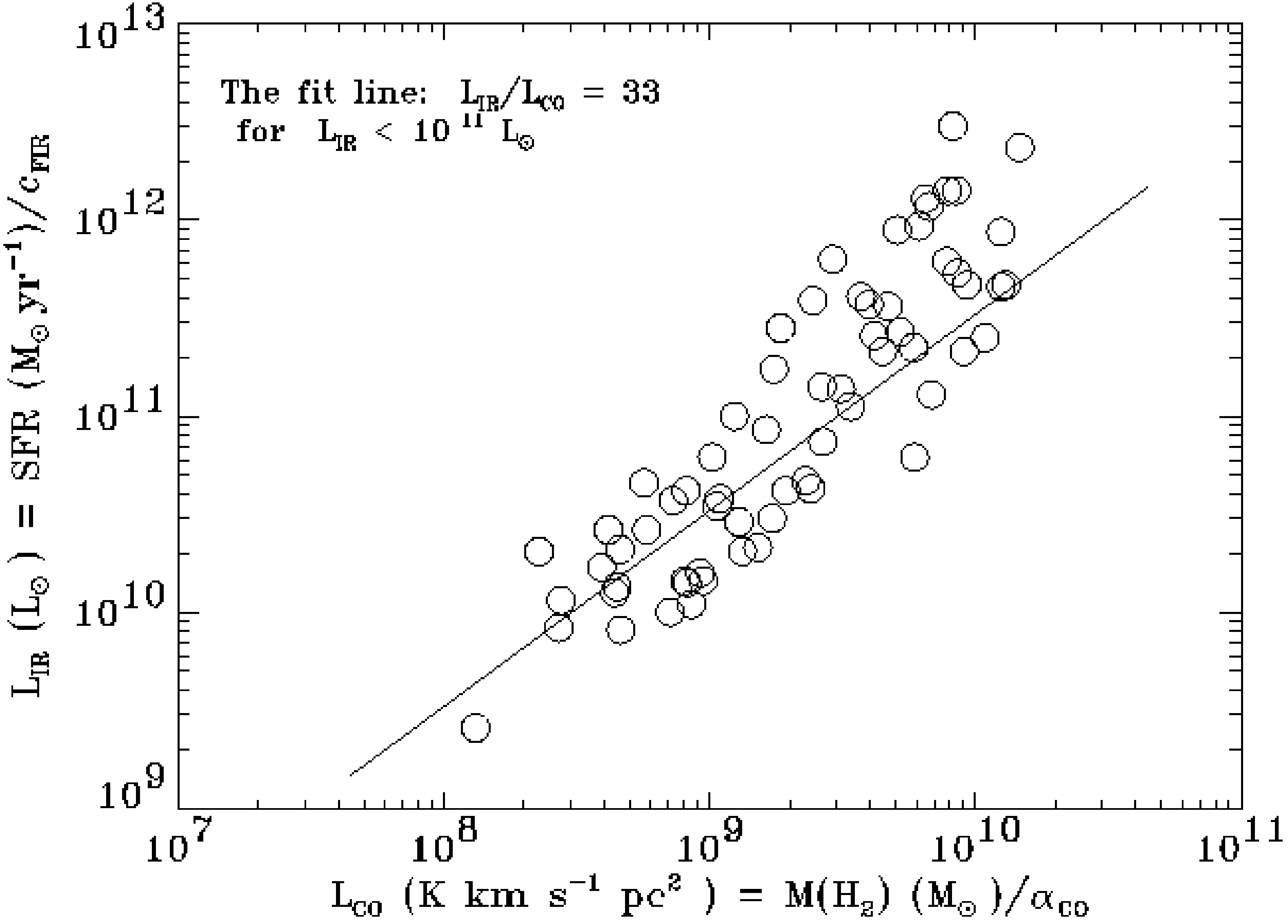
- **Baan et al. (2007) arXiv:0710.0141**
- **Kohno 2007, et al. (2003)**
- **Imanishi**
- **Aalto et al. 1995**
- **Solomon et al. 1992**
- **Nguyen** et al. 1992
- **Henkel et al. 1990** (NGC4945)
- **Henkel, Baan, Mauersberger** 1991



SFR

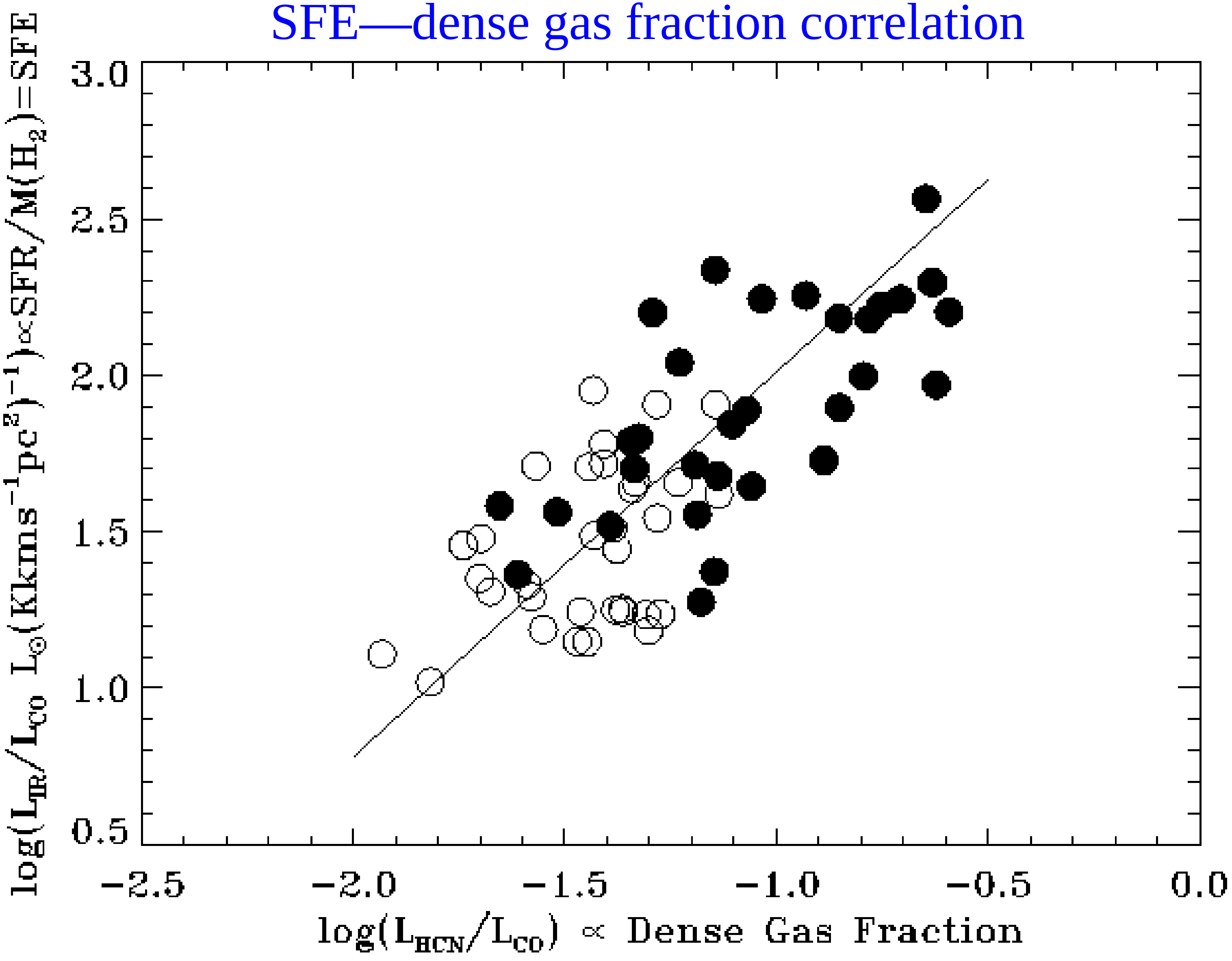
Dense Molecular Gas

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

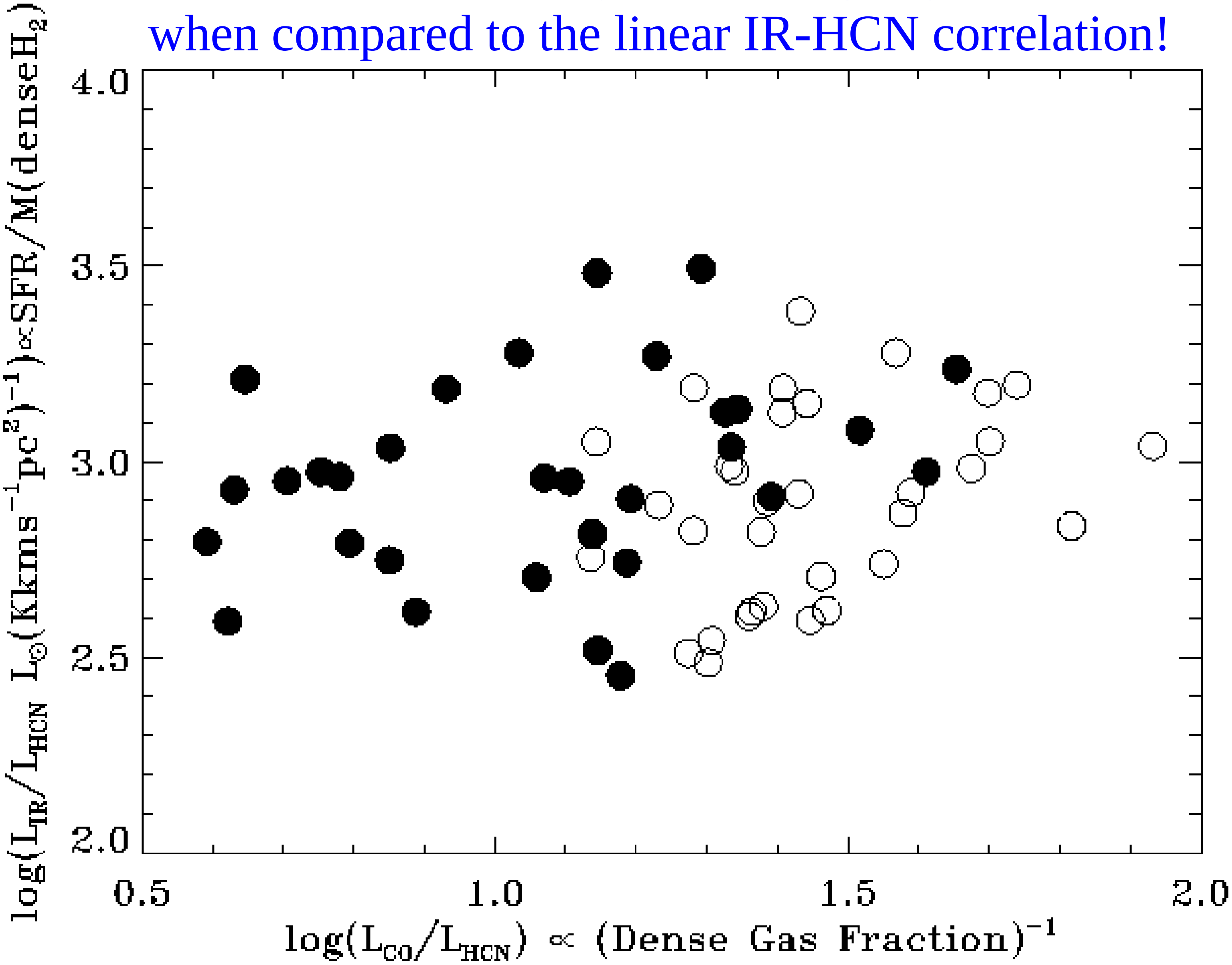


Total Molecular Gas Mass

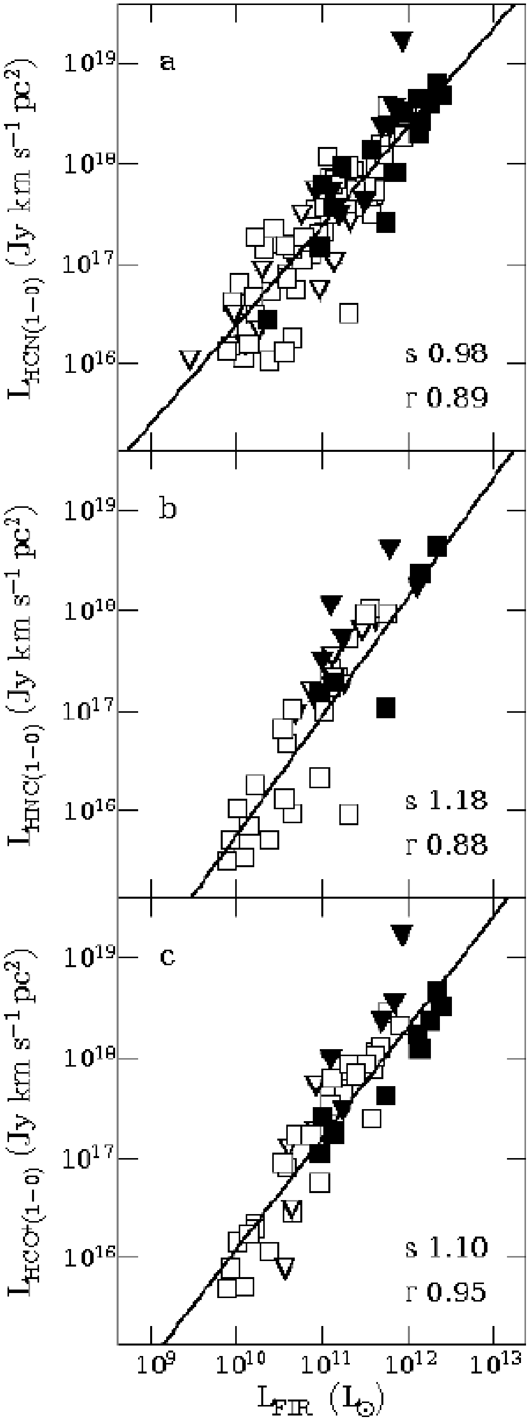
Normalized IR—HCN correlation= SFE—dense gas fraction correlation

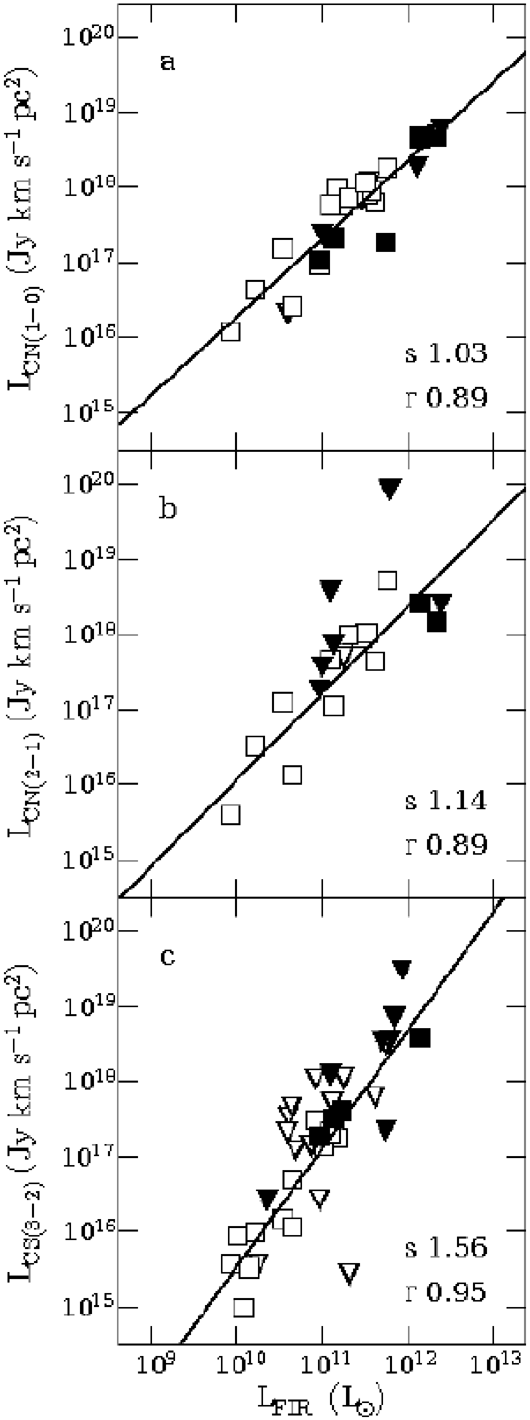


IR-CO correlation may lack strong physical basis when compared to the linear IR-HCN correlation!



Baan, Henkel, Loenen et al. arXiv: 0710.0141





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)

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

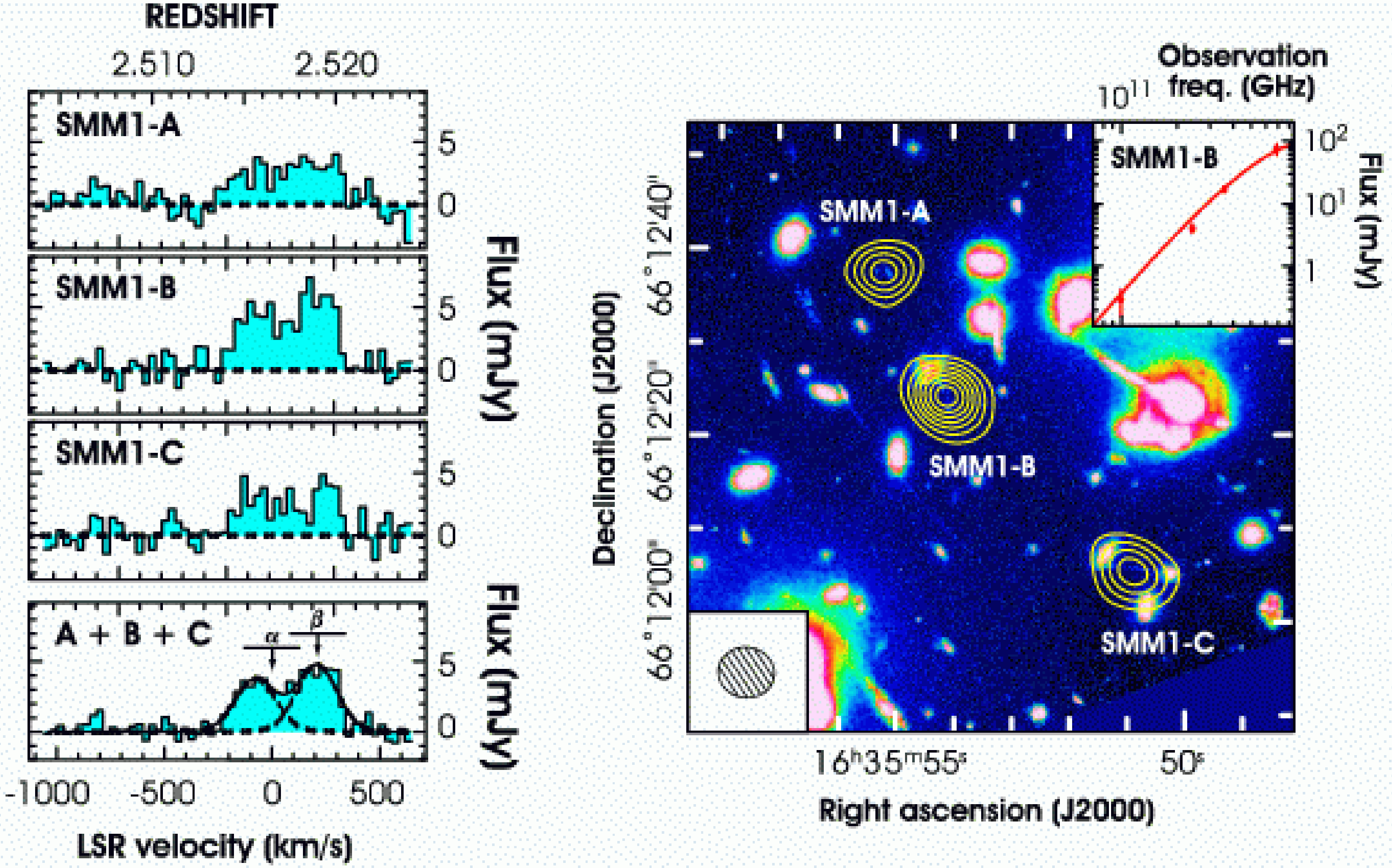
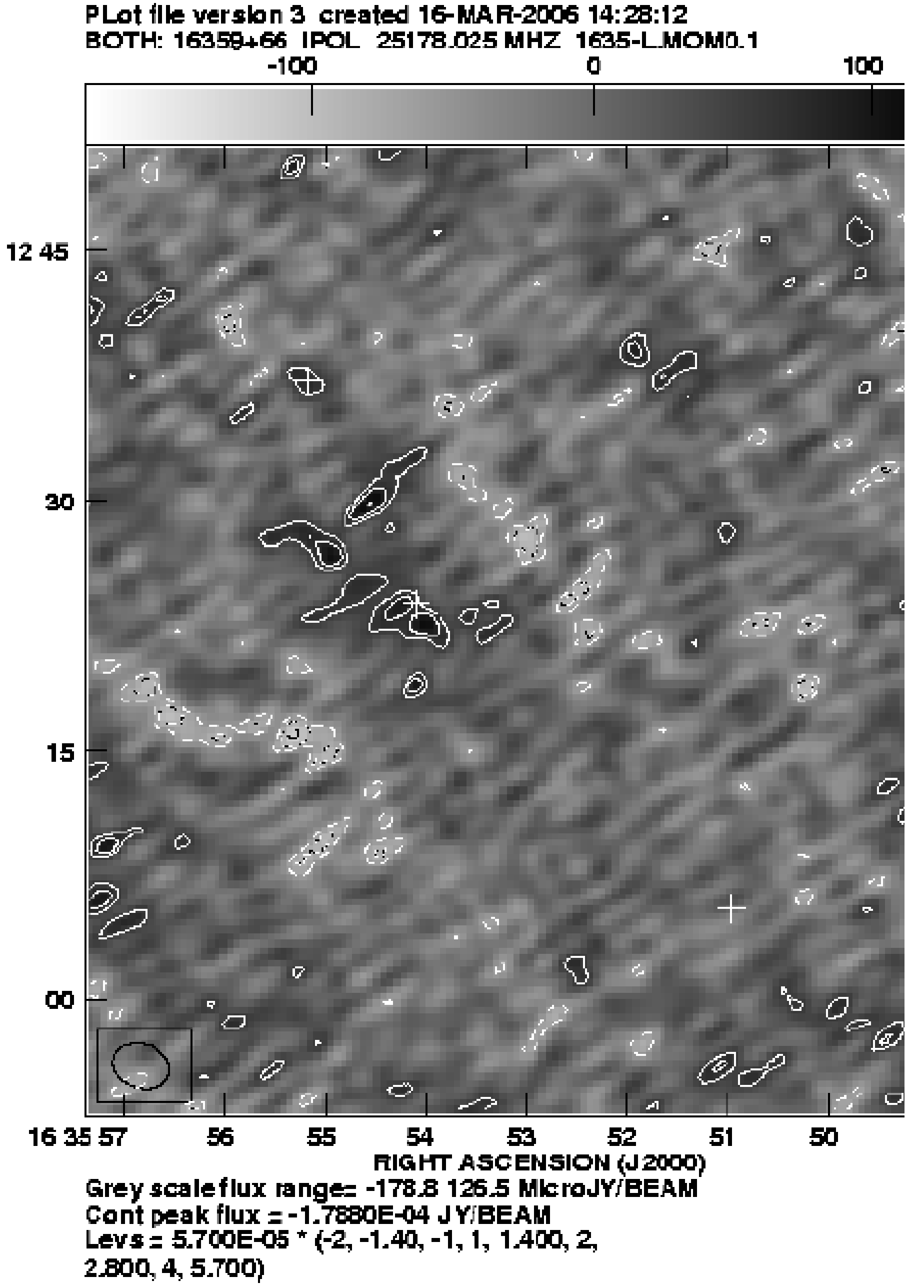
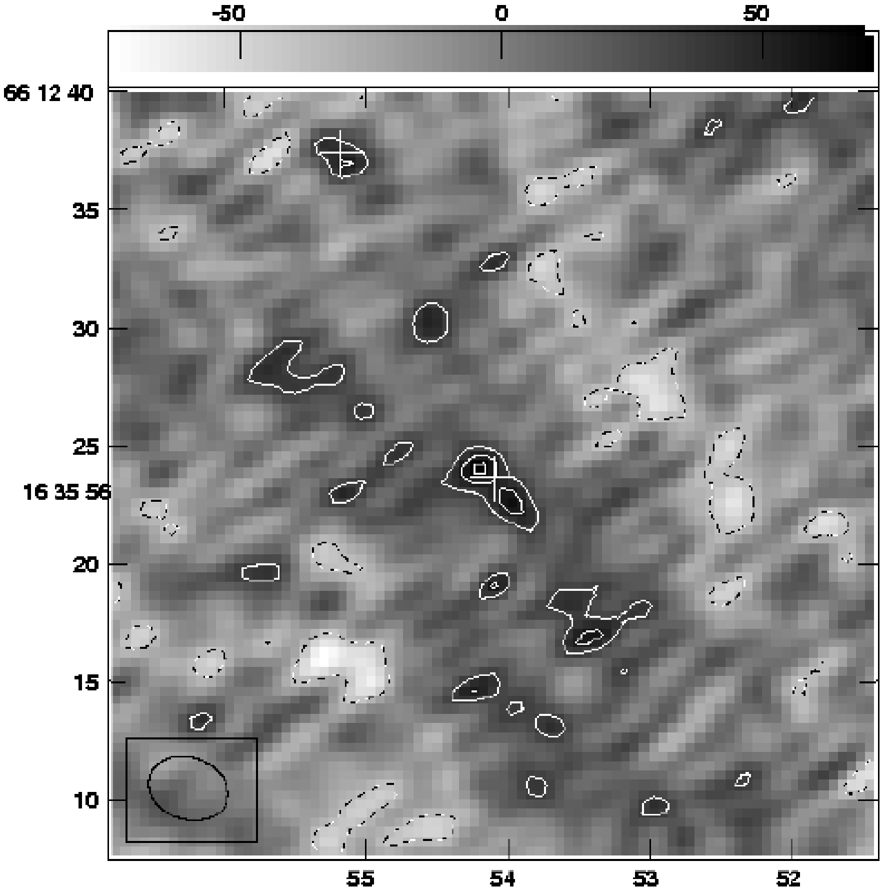


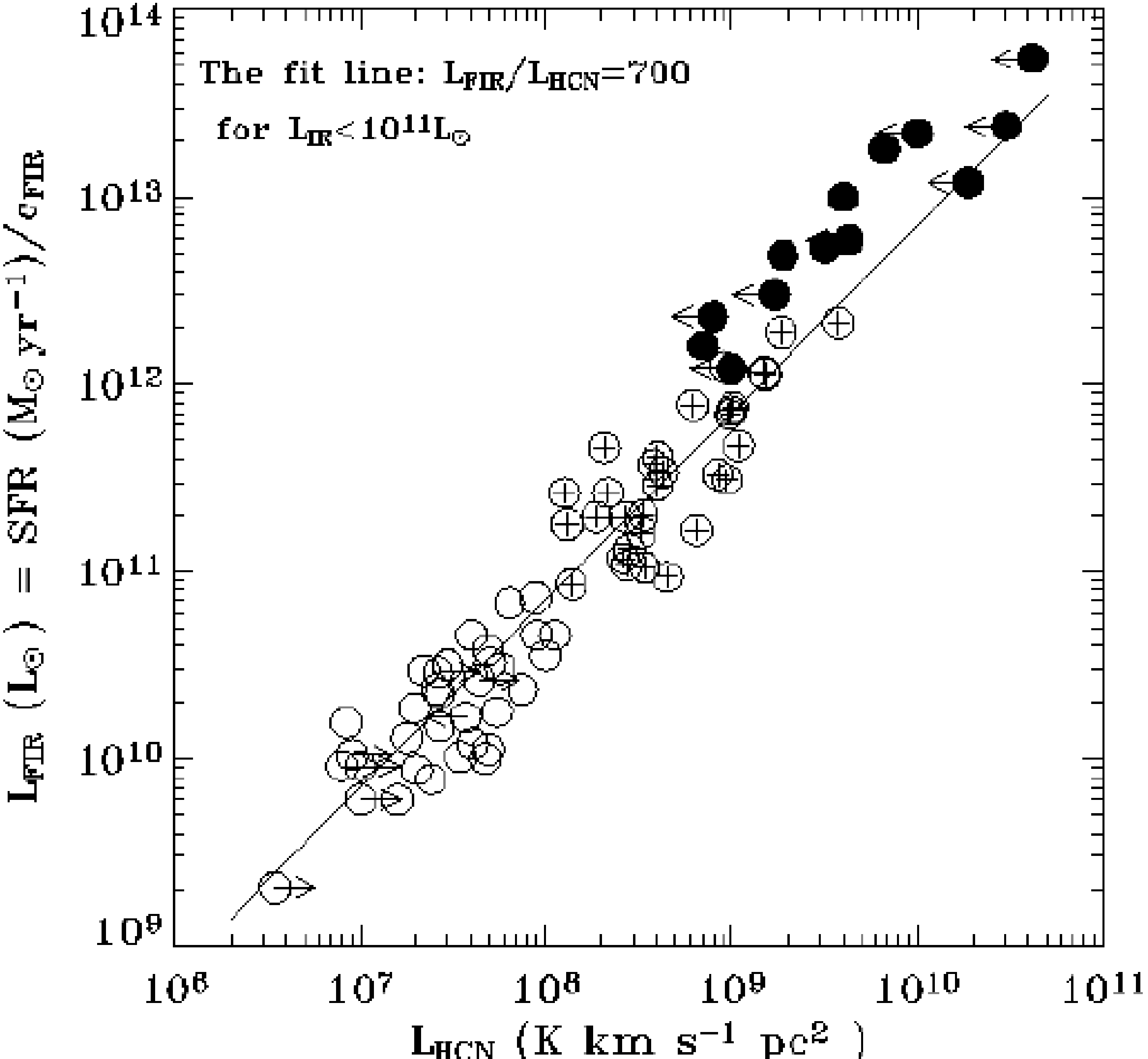
Figure 5: The lower panel shows SMM J16399 in CO(3–2) emission that has been triply imaged by a gravitational lens (Kneib et al. 2004a). The total

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





New Results (13 HCN@high-z)



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)

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

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

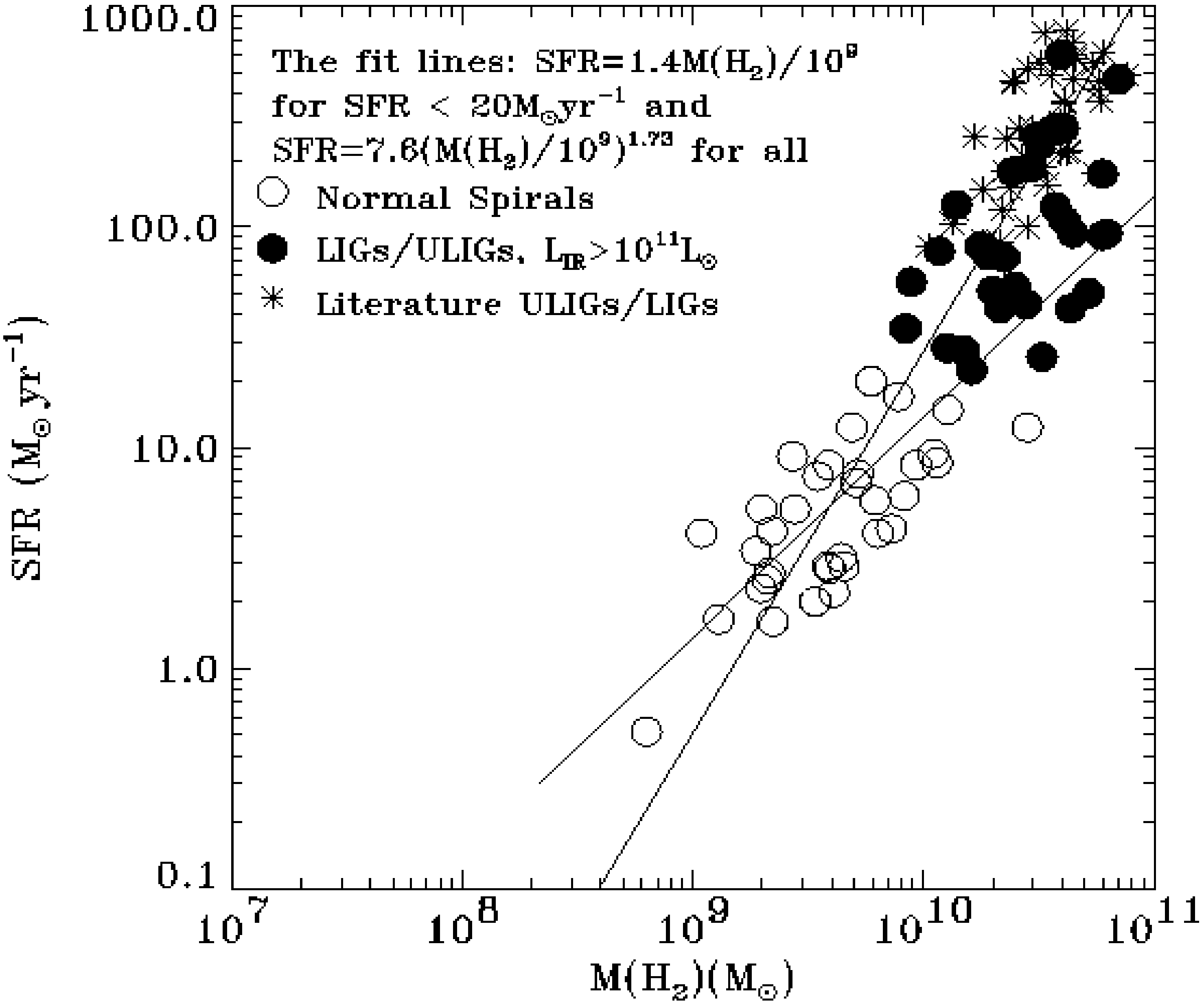
  Total gas (HI + H2) vs. Molecular gas

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

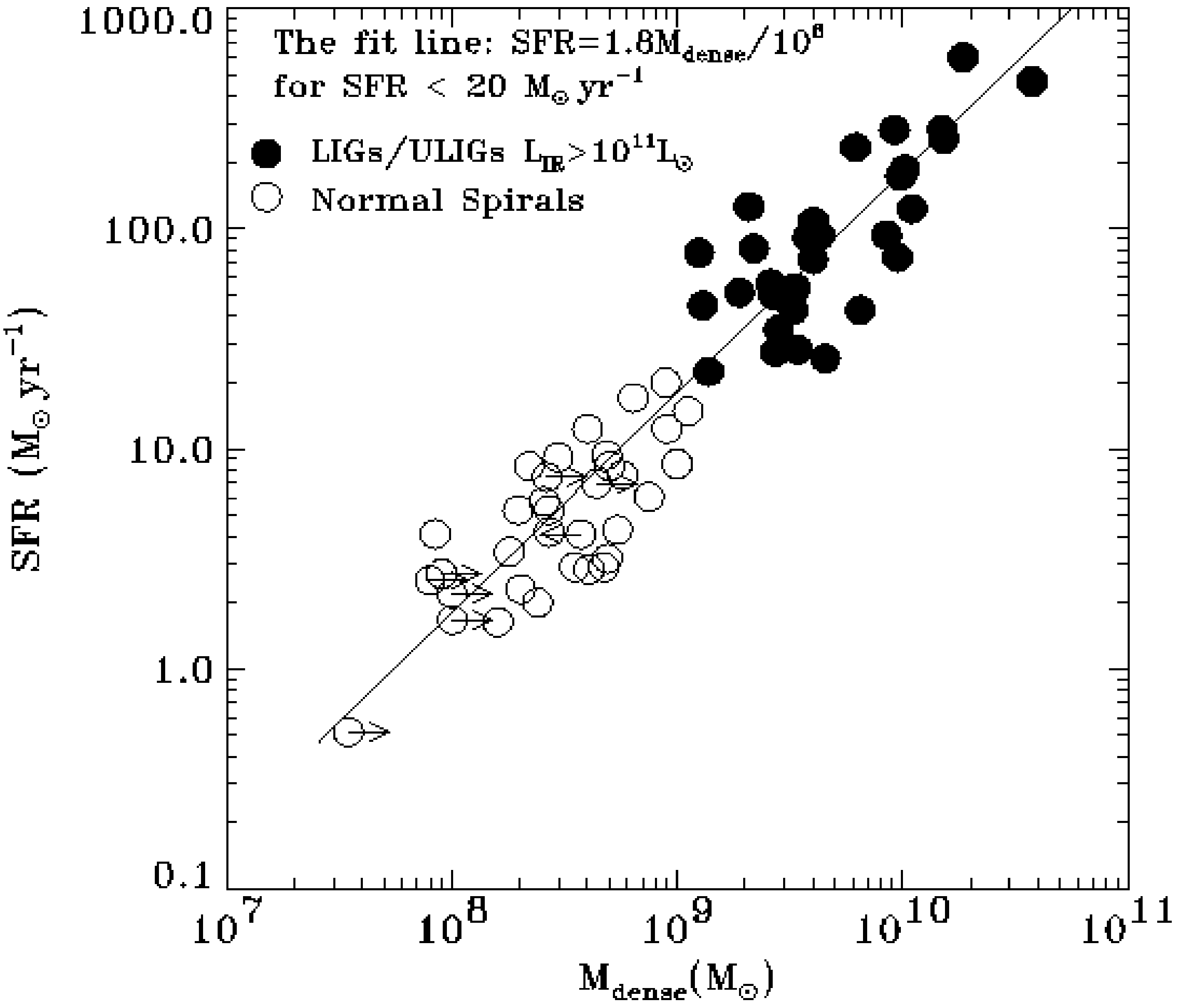
  vs. Dense molecular gas !?

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

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



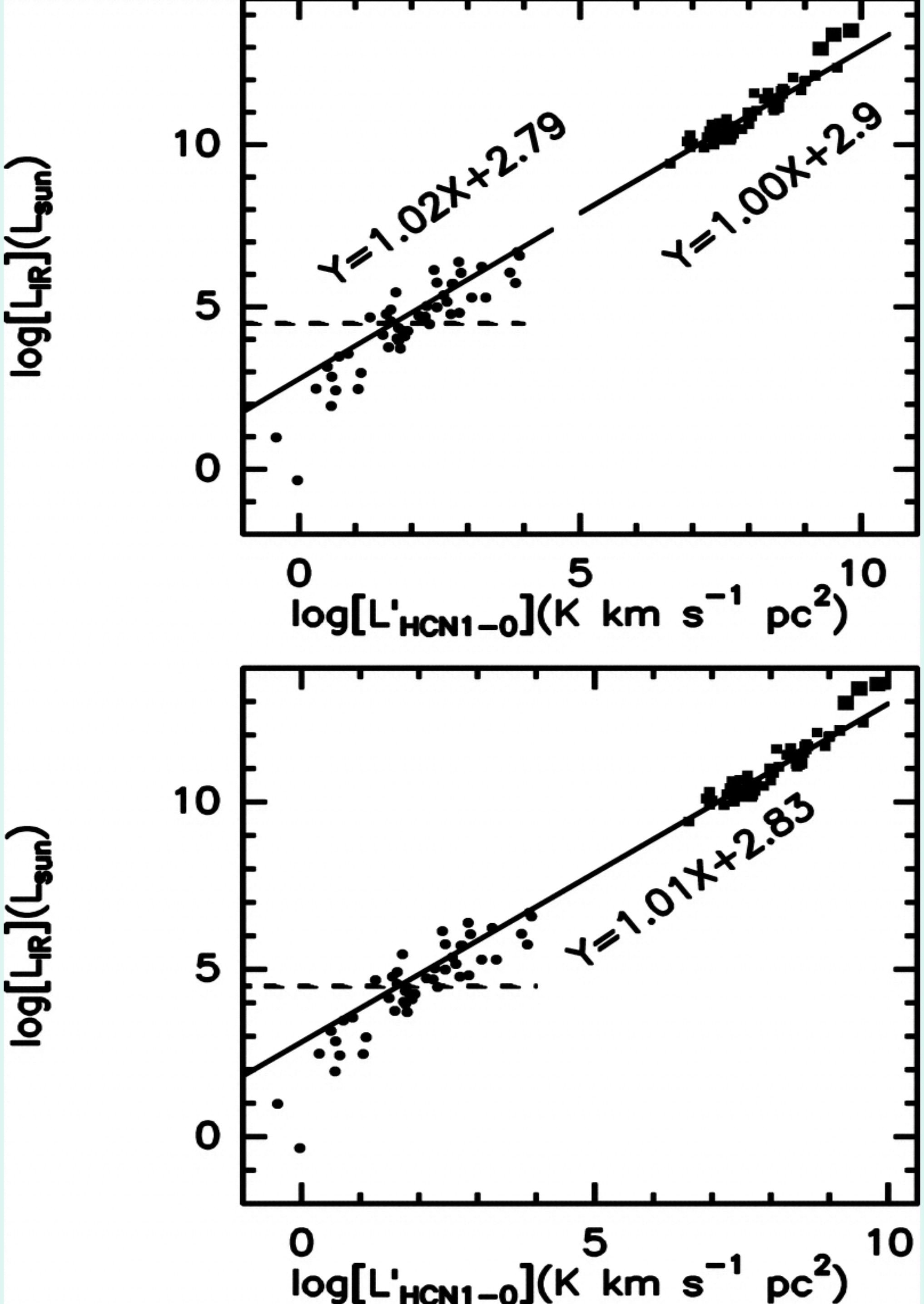
SFR vs. M_dense(H2): linear correlation



Wu, Evans, Gao et al.
2005 ApJL

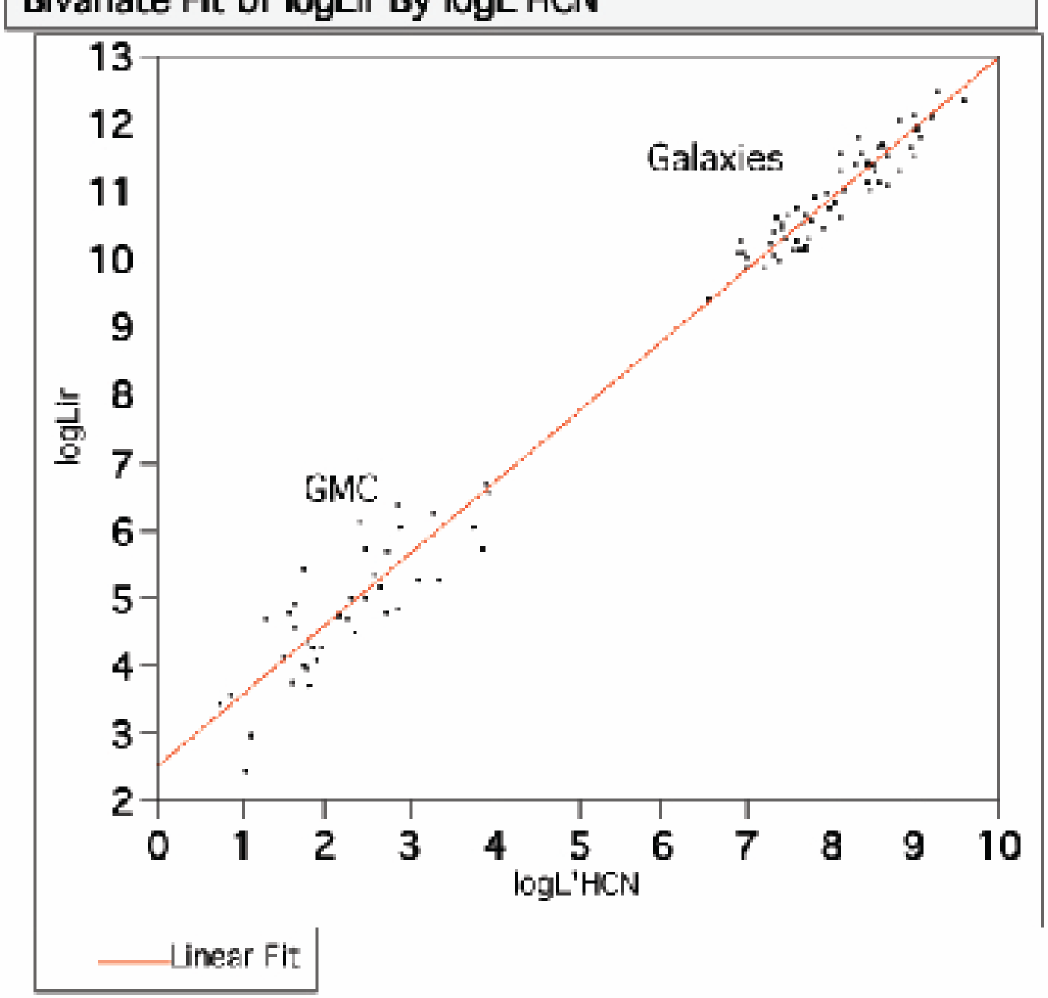
Krumholz & Thompson
arXiv:0704.0792 !!!

Papadopoulos et al.



GBT

VLA → EVLA!


Bivariate Fit of logLir By logL'HCN
logLir
logL'HCN
13
12
11
10
9
8
7
6
5
4
3
2
0
1
2
3
4
5
6
7
8
9
10
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
- $HI \rightarrow H_2 \rightarrow$ DENSE $H_2 \rightarrow$ Stars

Schmidt law : HI → Stars

Kennicutt : $HI + H_2 \rightarrow$ Stars

Gao & Solomon: Dense $H_2 \rightarrow$ Stars

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