Star Formation Law in Dense (Molecular) Gas: from Dense Cores to Extreme Starbursts

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Talk Outline

- 1) Introduction: Historic Perspectives

  Physics of Star Formation, Ingredients, Recipes

- 2) Challenges: Massive Star Formation (SF), Overlap Starbursts, & Dense Gas in Galaxies

  Dense Cores, Schmidt-Kennicutt SF Law

  Importance of Dense Gas from Normal Spirals to

  Ultraluminous Gals.(ULIRGs) & Numerical Simulations

- 3) Linear Far-IR—H CN Correlation

  SF Rate vs. Dense Molecular Gas in Galaxies

- 4) Global SF Law: from Dense Cores (@z=0) to

  Extreme Starbursts (Hyper/ULIRGs @High-z)

1. Introduction: Historic Perspectives

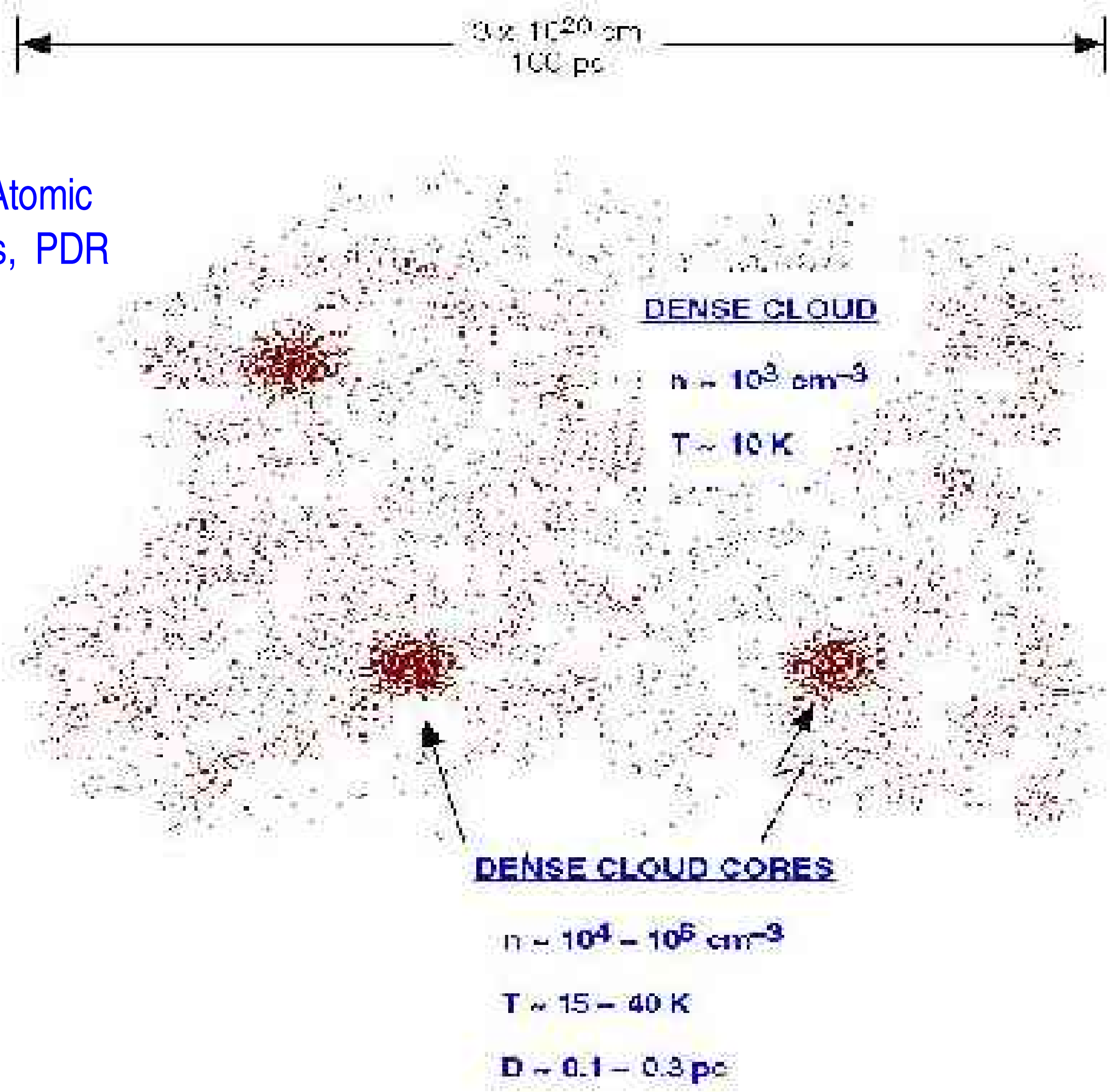
- I. Kant: Stars are born from gas clouds (philosophy, not physics! >200yrs)
- Schmidt Law of Star Formation (<50yrs)
- CO J=1-0 rotation line @2.6mm (H_2)
- Millimeter Astronomy! (~35yrs)

  GMCs (Giant Molecular Clouds)
- CO in Ext. Gals (<30yrs), Kennicutt (<20yrs)
- CO in Hyper/Ultraluminous Gals (~10yrs)
- CO at the Edge of Universe! (~3yrs, 13Gyr)

SF Drives Galaxy Evolution!

STRUCTURE OF DENSE MOLECULAR CLOUDS

HI Atomic
Gas, PDR



1. Introduction (cont.)

- Physics of SF

  Shu et al. low-mass *, well established
- Massive SF?

  Many recent IAU Symposia, ‘hot’ topics
- Ingredients: SFR, Gas

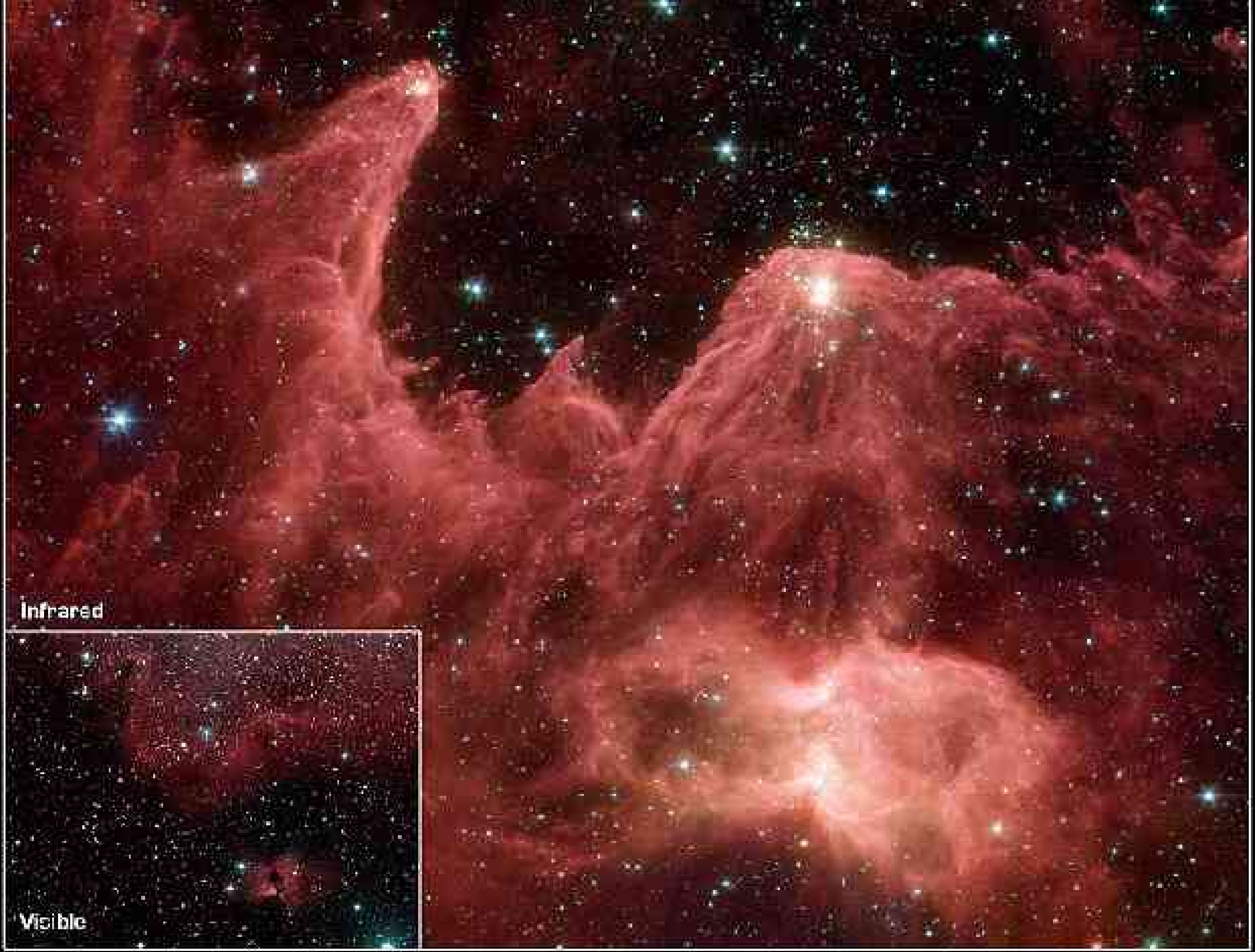
  SFR (UV, Far-IR etc.); Gas (HI, H2, dense H2, hot gas etc.); SF+feedback
- Recipes: SFR~Gas

  From Schmidt law Kennicutt law ?

2. Challenges:

Massive Star Formation?
Details of the Dense cores
Gas Phases, Dense Gas in Gals.
Overlap Starbursts in Mergers

Merging/interaction is norm during the formation and evolution of galaxies



"Mountains of Creation" in W5 Star-Forming Region

Spitzer Space Telescope • IRAC

Visible: DSS

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

ssc2005-23a

Wolk et al. 2006 (**astro-ph/0604384**)

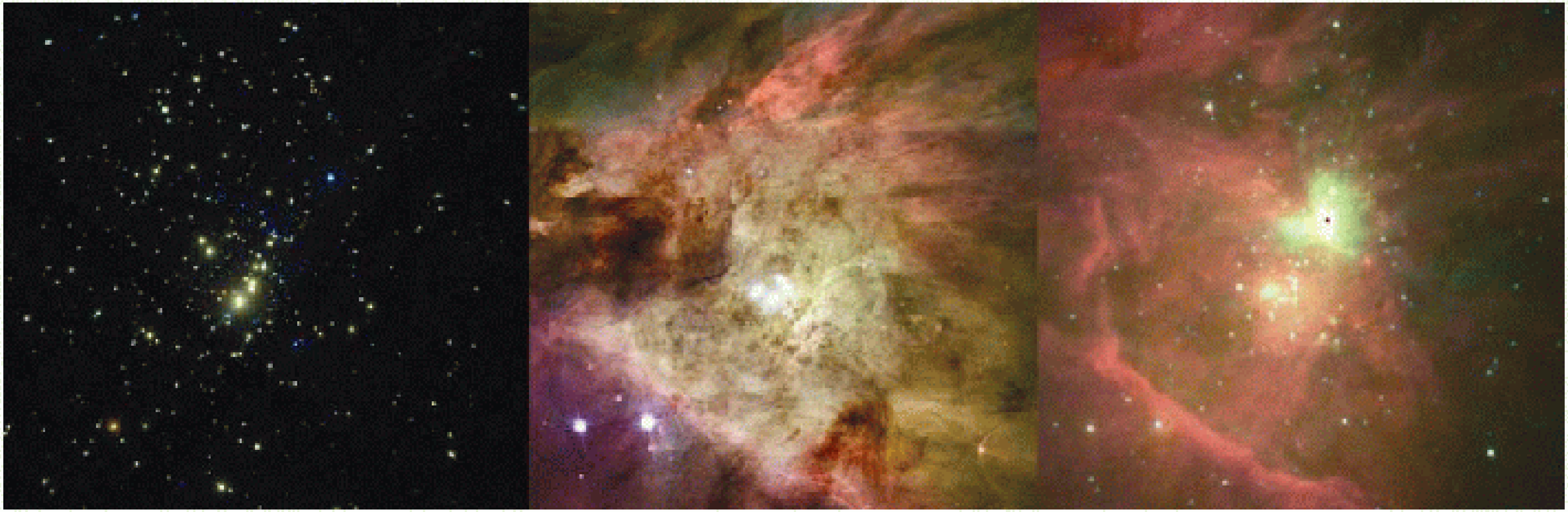
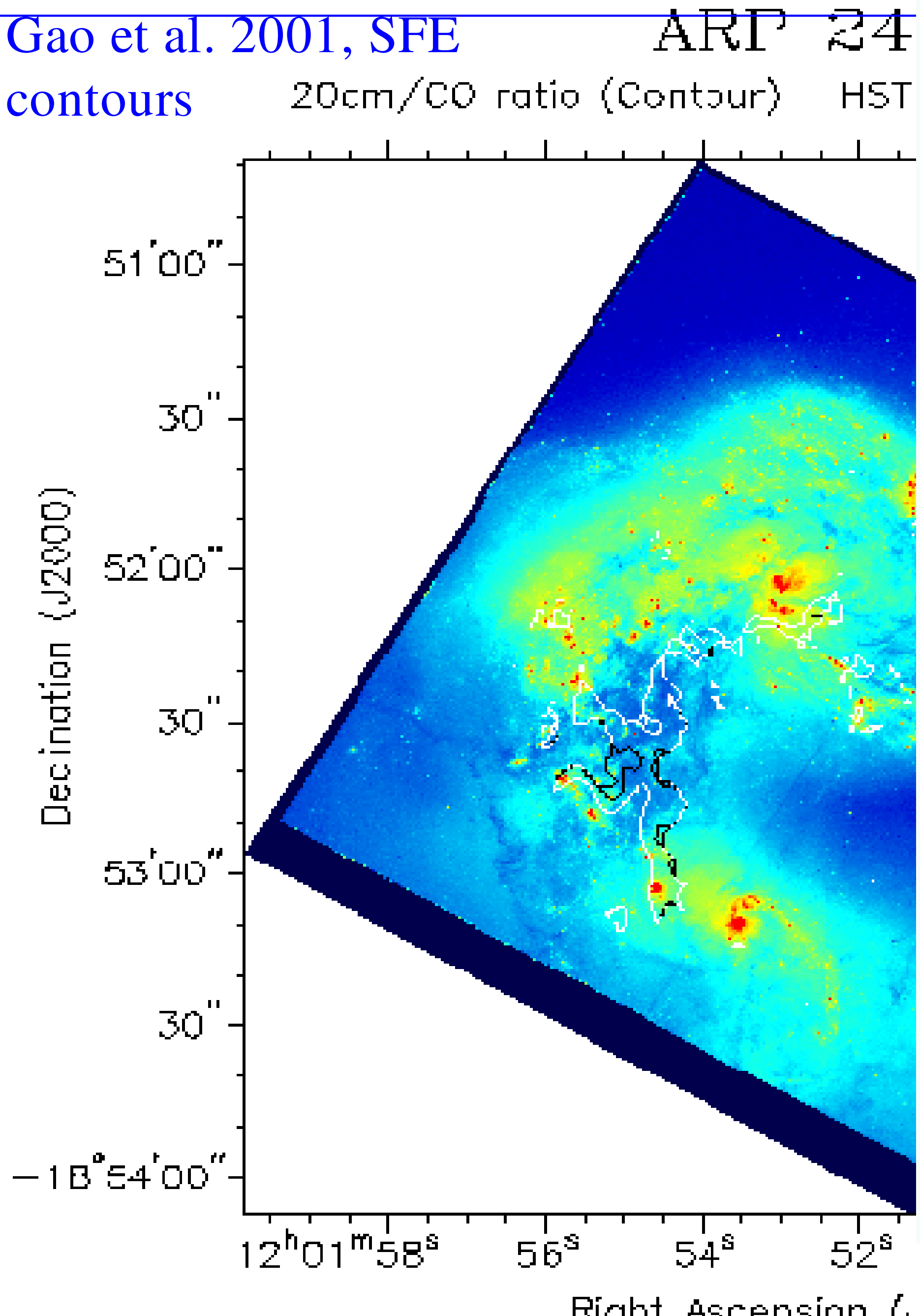
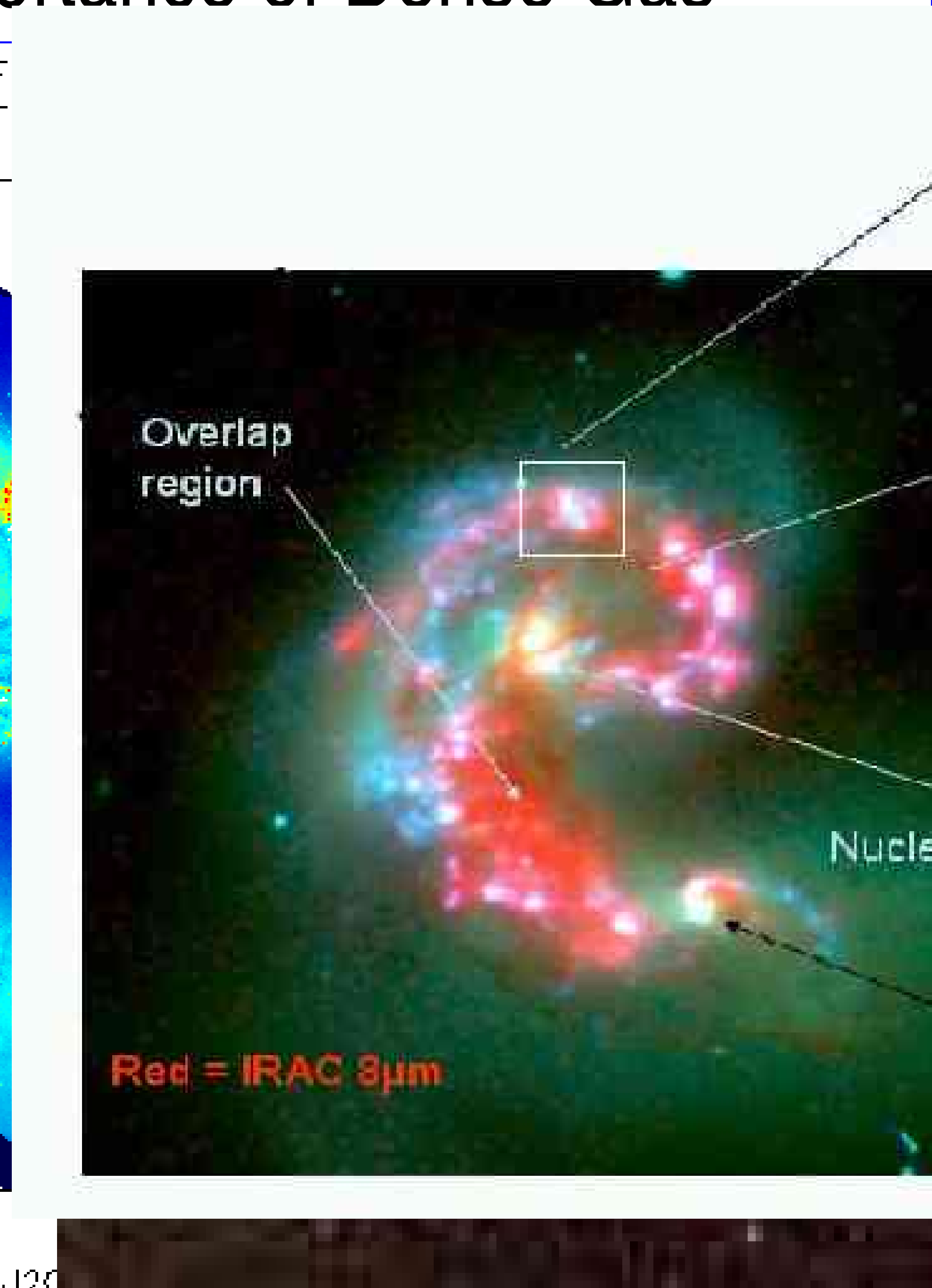


Figure 2: Orion as an example: The images above show X-ray (*Chandra*), optical (*HST*) and mid-IR(*Spitzer*) views of the central 7' of the ONC. The near-IR and X-ray images trace the stellar population equally well. The IR-luminosity traces the bolometric luminosity; the X-ray luminosity traces the magnetic fields or winds. This optical/HST image is dominated by the gas. The Spitzer image shows strong diffuse PAH emission the Kleinman-Low Nebula is overexposed.

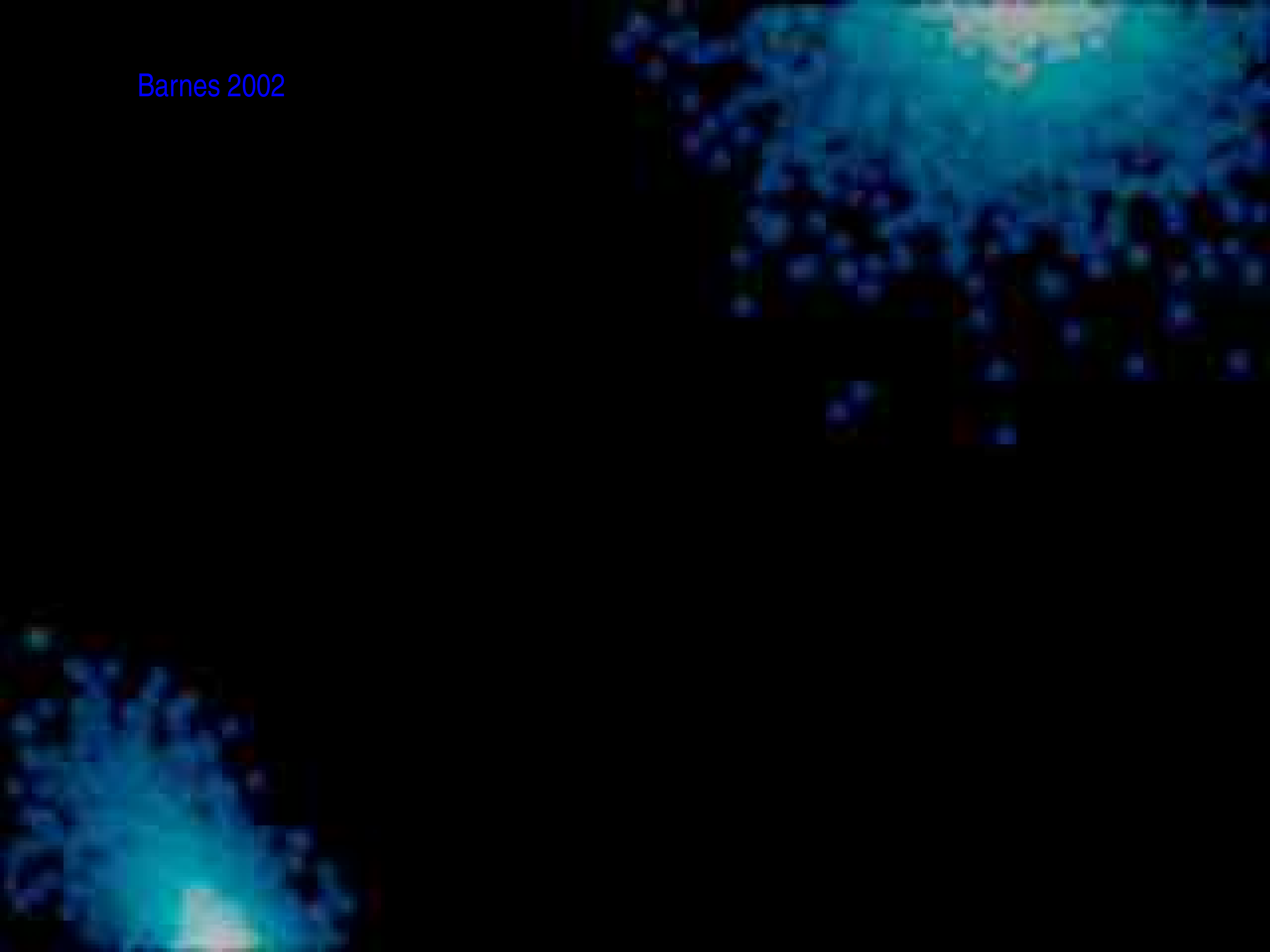
SF in Galaxies: Importance of Dense Gas

Gao et al. 2001, SFE contours

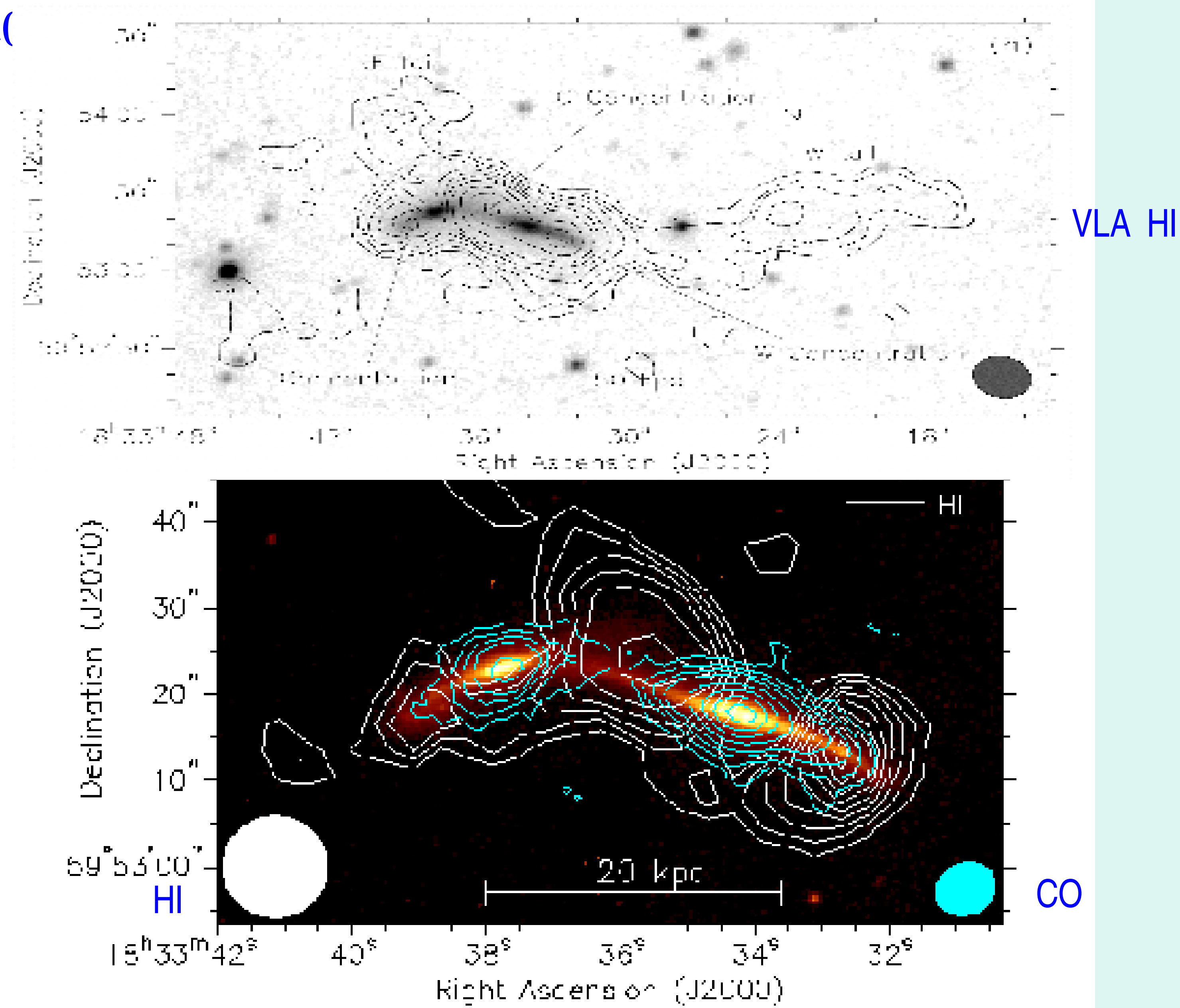


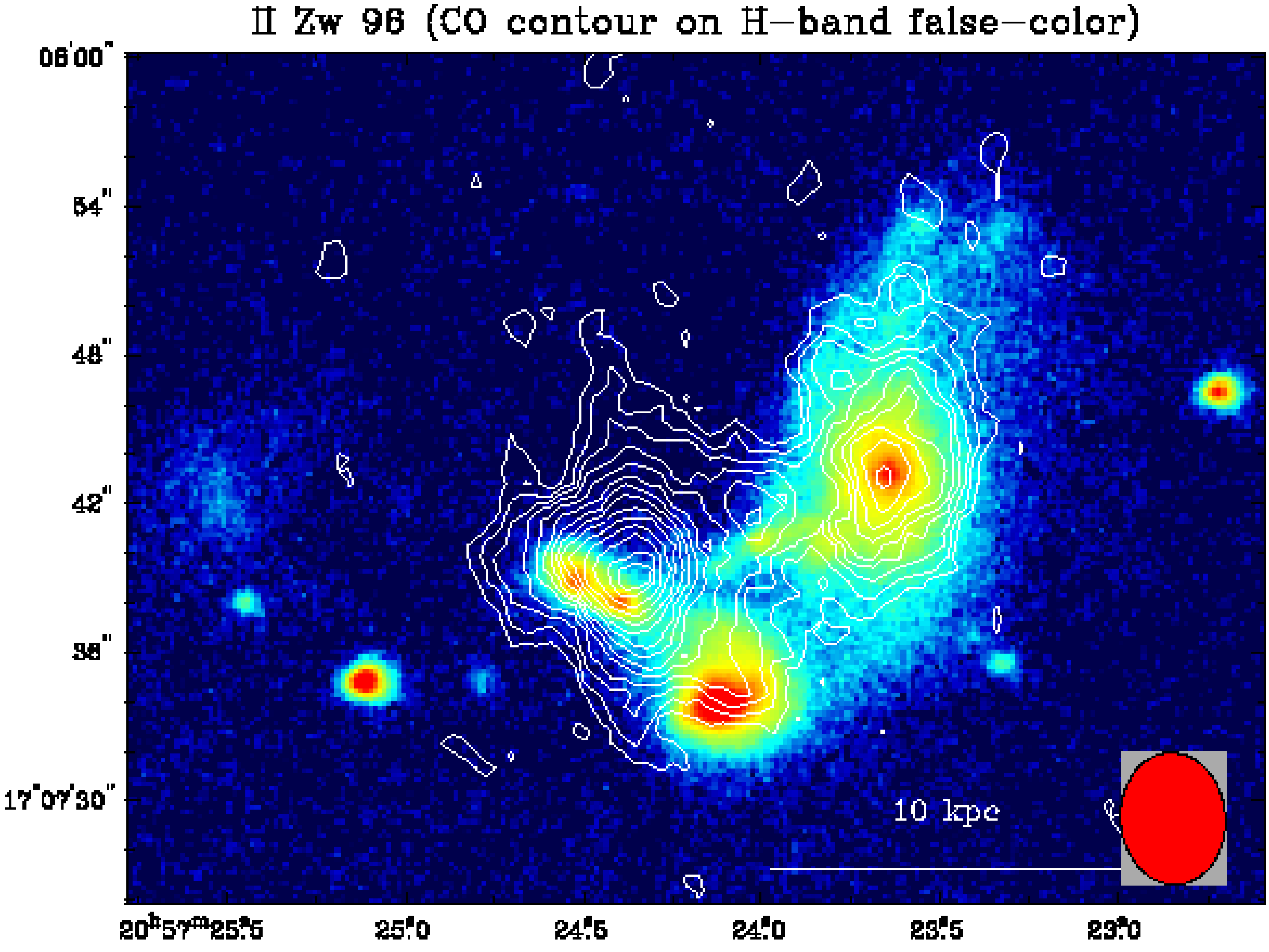


Barnes 2002

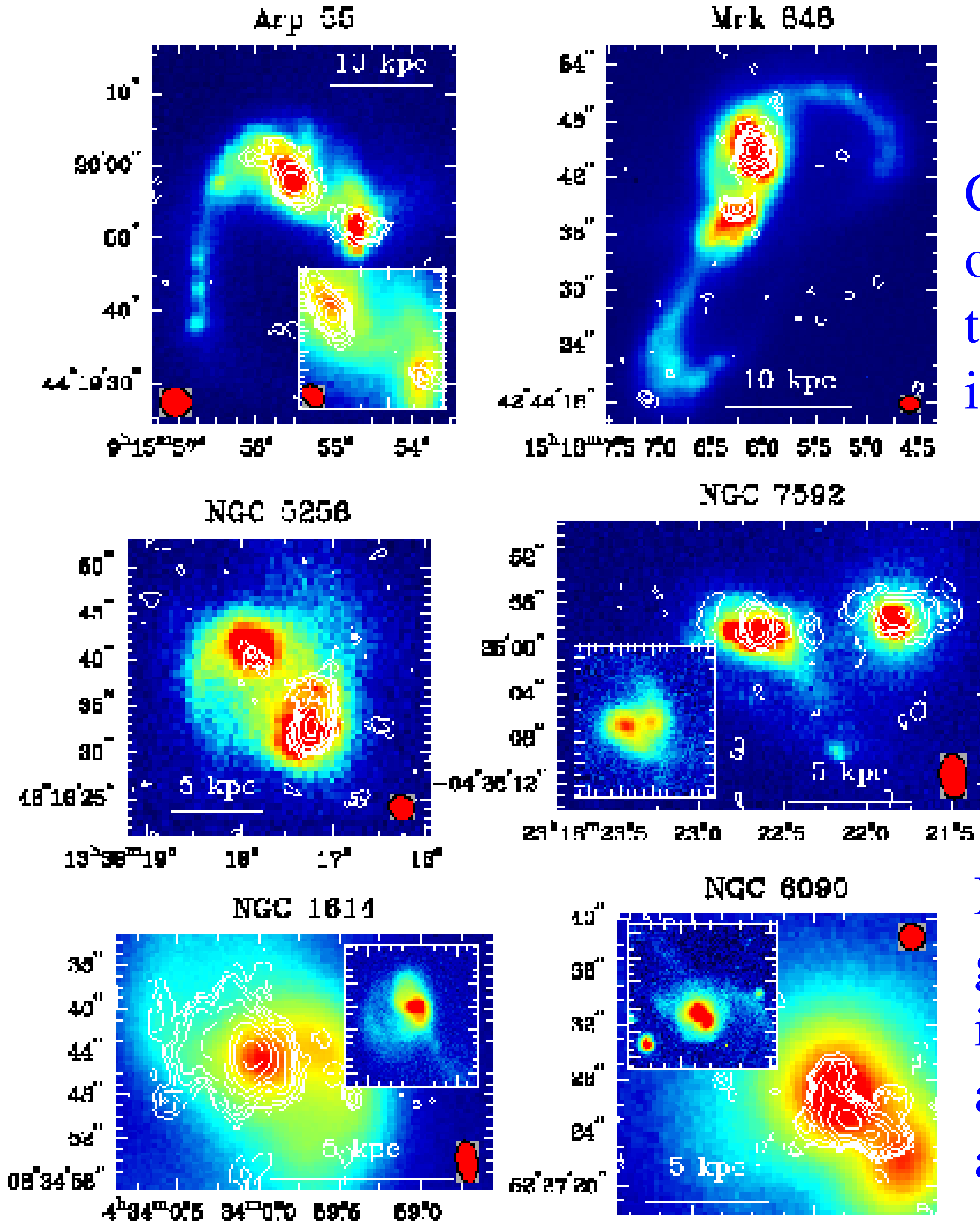


Early Merger N6670 (Wang, Lo, Gao & Gruendl 2(





II Zw 96 (CO contour on H−band false−color)
06'00"
54"
48"
42"
36"
17°07'30"
20h57m25s.5
25s.0
24s.5
24s.0
23s.5
23s.0
10 kpc



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

Gao et al. 1999

Molecular gas density increases as merging advances

Overlap Starbursts: Questions

- **How did the molecular gas get there?**
- **Does this happen quite often in gas-rich mergers? Mergers at high-z?**
- **In the context of galaxy evolution: a disk-disk merger sequence?**
- **“Overlap” starbursts? Some nearby examples of the ongoing mergers**
- **Connections: Bulge—Starburst—AGN?**

Dense Gas & SF in Galaxies

- 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

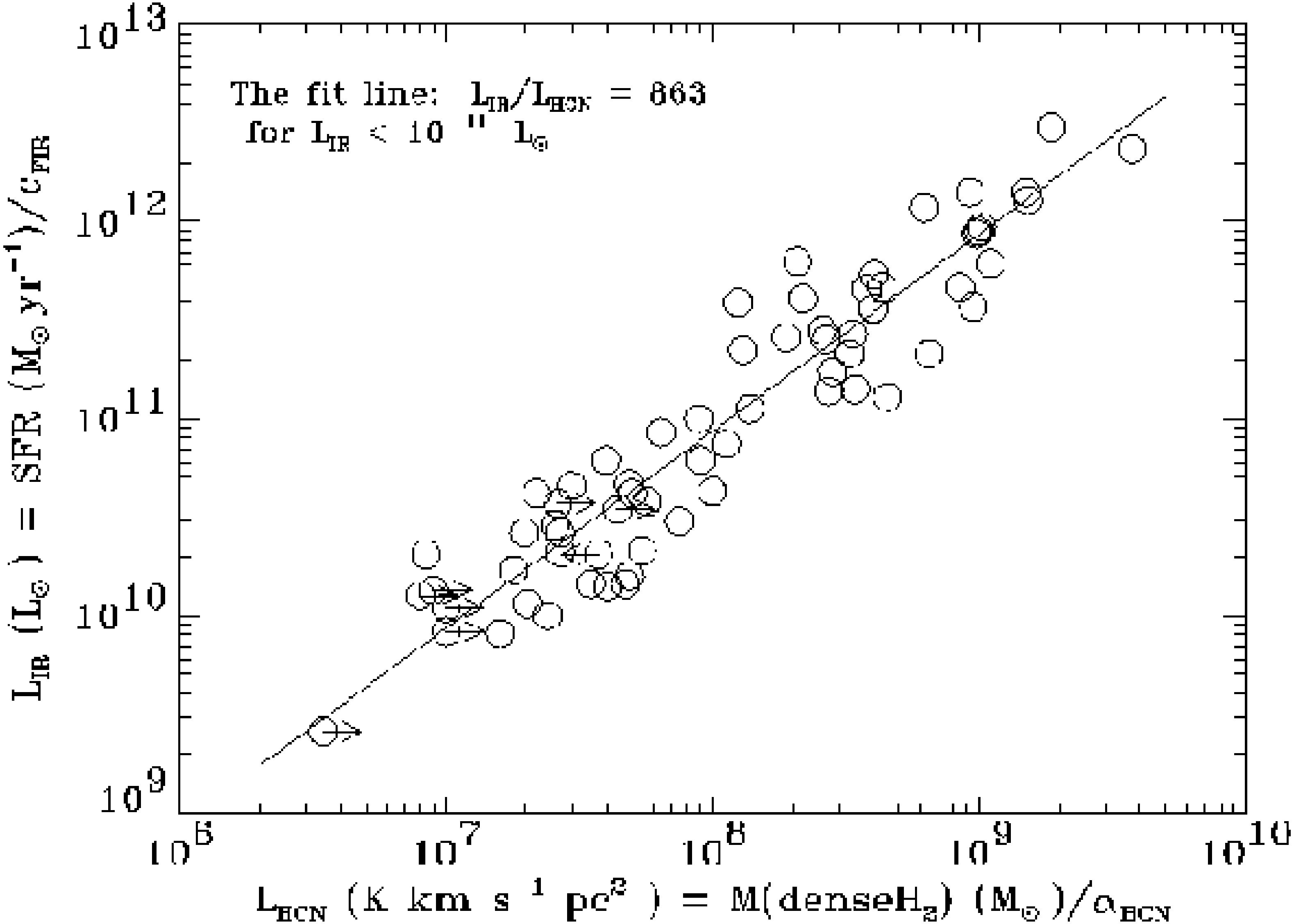
3. FIR—HCN Correlation: Dense gas is the essential fuel for high mass SF

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, $\delta \gtrsim -35^{\circ}$.
- Relatively Distant ($cz \gtrsim 10,000 km/s$) Ultraluminous Infrared Galaxies (ULIGs)

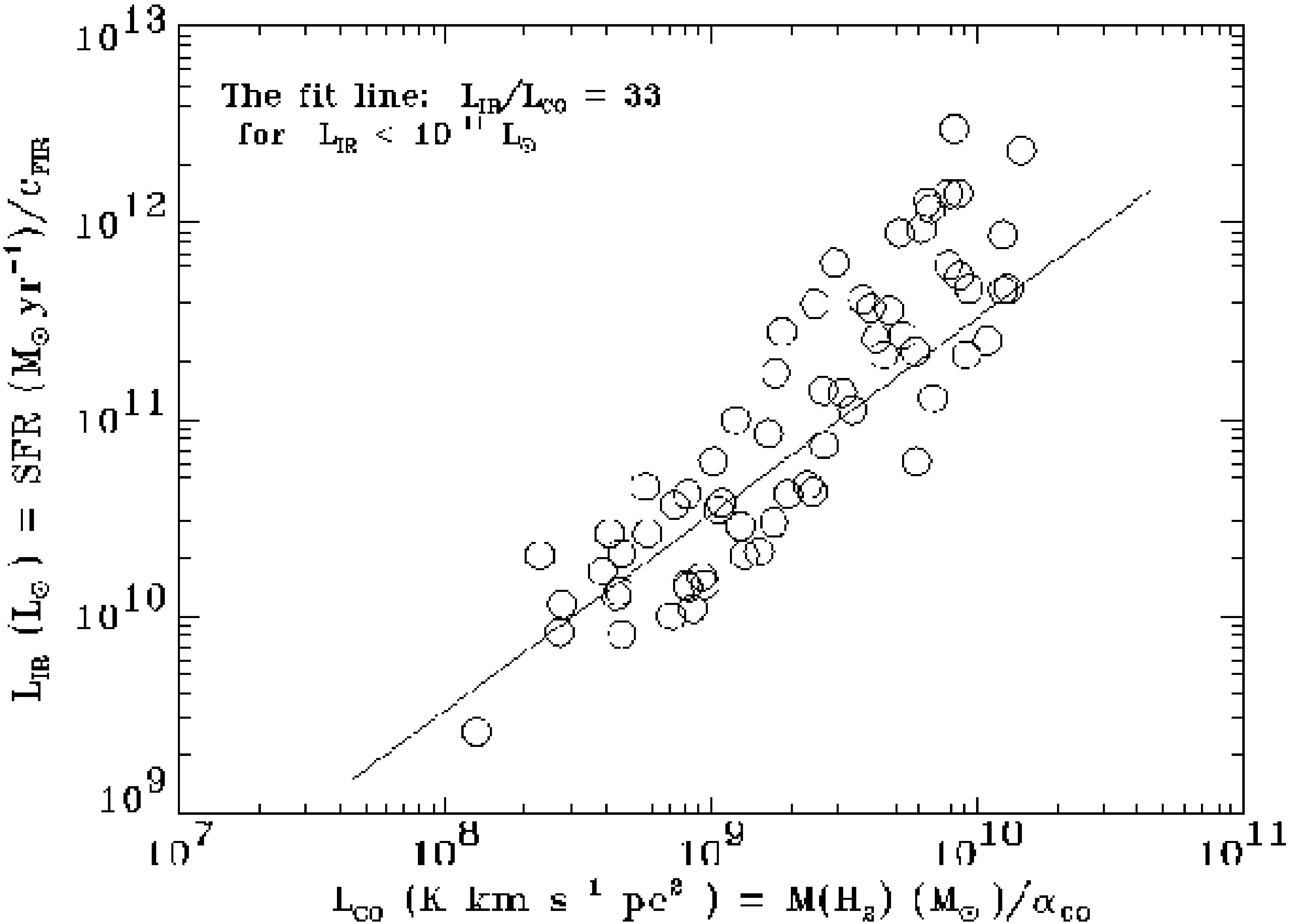
Gao & Solomon 2004a ApJS

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

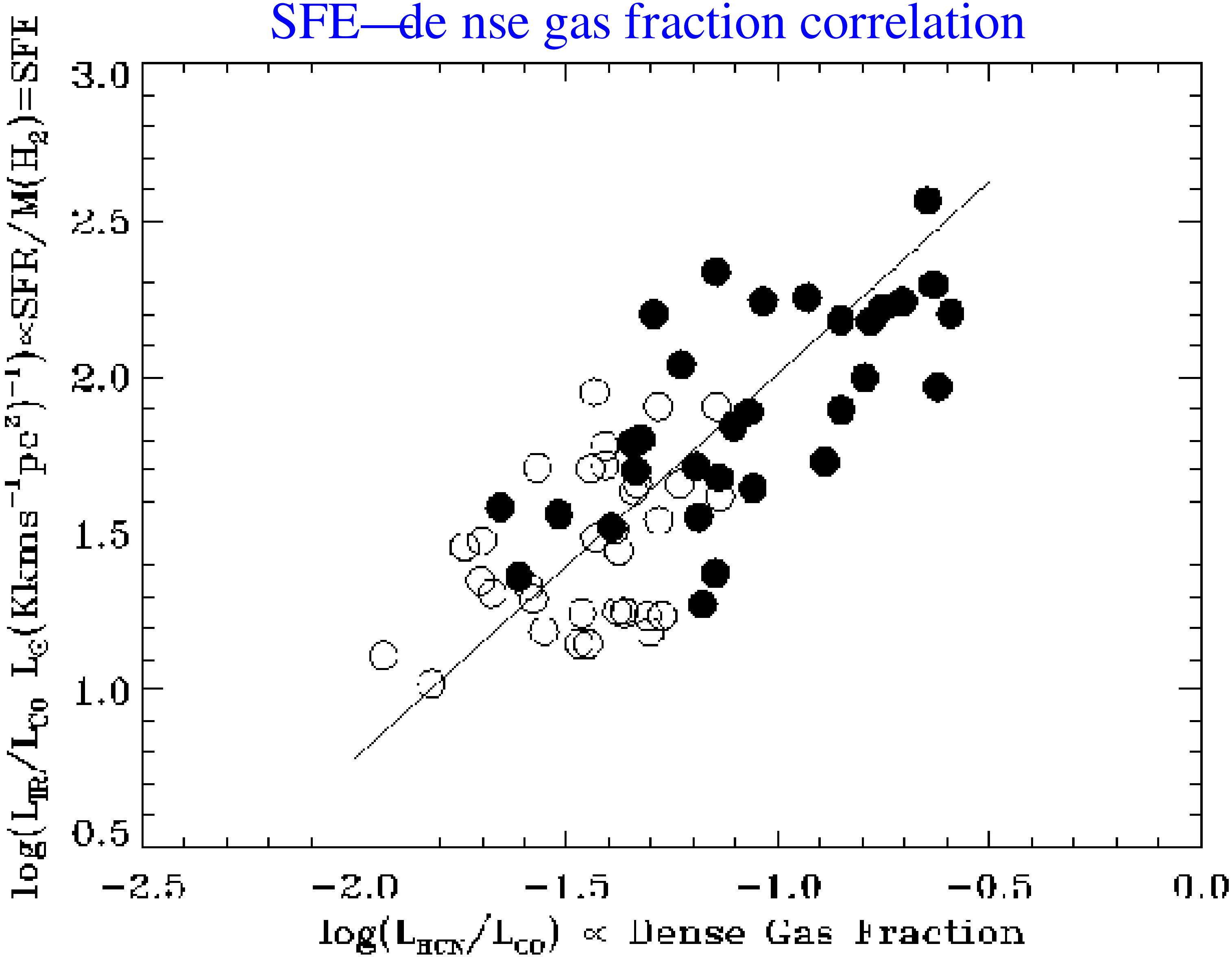


The fit line: L_IR/L_HCN = 863
for L_IR < 10^11 L_⊙
L_IR (L_⊙) = SFR (M_⊙ yr^-1)/c_FIR
L_HCN (K km s^-1 pc^2) = M(denseH_2) (M_⊙)/α_HCN
10^9
10^10
10^11
10^12
10^13
10^6
10^7
10^8
10^9
10^10

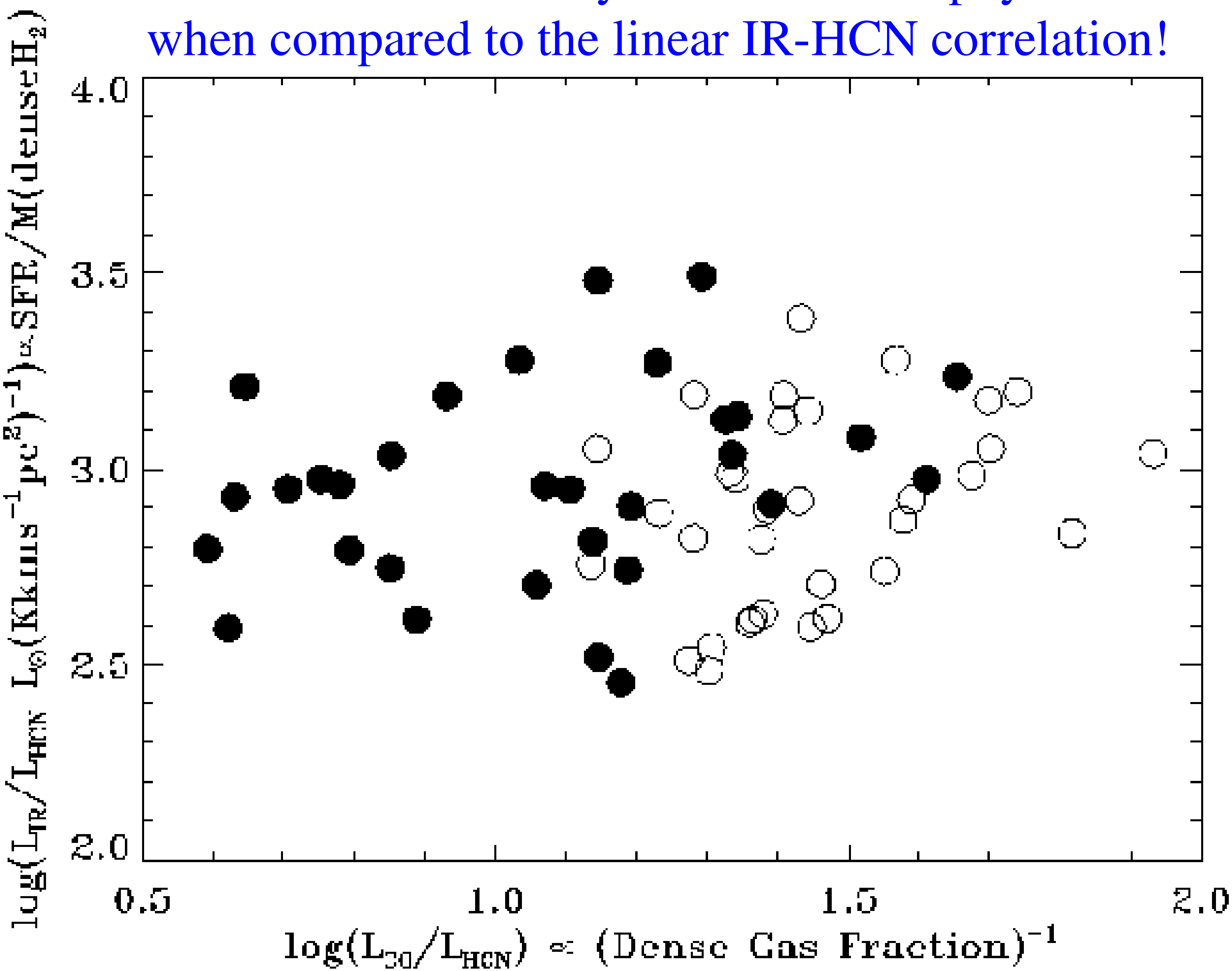
More CO data of ULIGs (Solomon et al. 1997) that Lco > ~ 10^10 K km/s pc^2



Normalized IR—H CN correlation=
SFE—de nse gas fraction correlation



IR-CO correlation may not have much physical basis when compared to the linear IR-HCN correlation!



SUMMARY

- L_{HCN} (DENSE gas) is strongly correlated with L_{IR} (SFR) over 4 orders of mag. (65 galaxies) up to and including ULIGs.

- The HCN–IR correlation is linear, substantially stronger than CO–IR (more scatters, breaks down $> 10^{11} L_\odot$). The results demonstrate that SFR depends linearly on the mass of dense molecular gas, not on the total gas mass.

- There is still a strong correlation between L_{IR}/L_{CO} (SFE) and L_{HCN}/L_{CO} (fraction of dense molecular gas), but no correlation between L_{IR}/L_{HCN} and L_{CO}/L_{HCN}.

- ULIGs are powered by star formation (if $L_{HCN}/L_{CO} \gtrsim 0.1$) and have the same rate of star formation per solar mass of dense molecular gas as ordinary spiral galaxies. The Schmidt law: SFR$\sim n(dense\ H_2)^N$, $N \gtrsim 1$.

4. The Star Formation Law: from GMC Dense cores to Extreme Starbursts/ULIRGs at 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)

  vs. Dense molecular gas ?

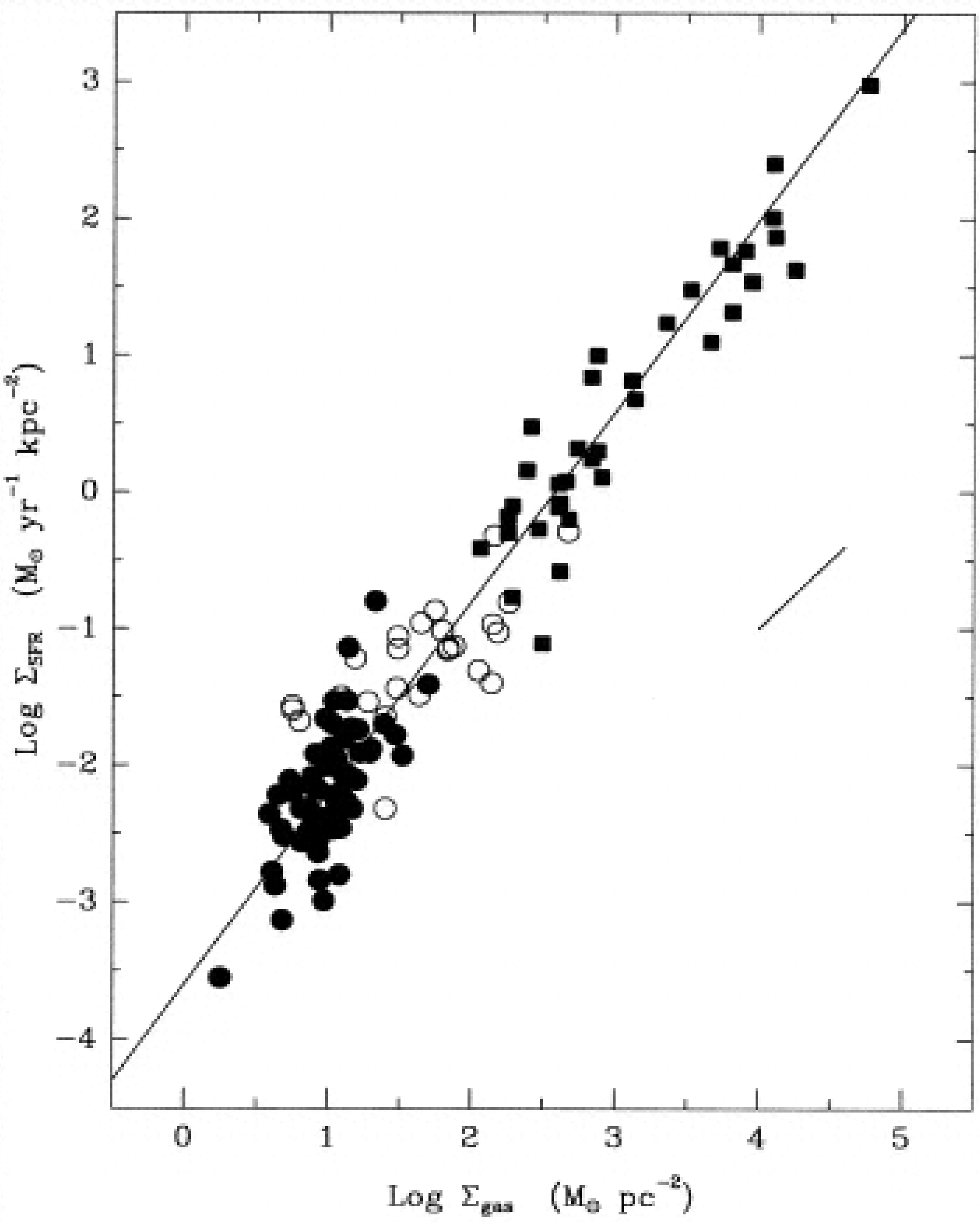
- **Better SF law in dense gas?**

  Gao & Solomon (2004)

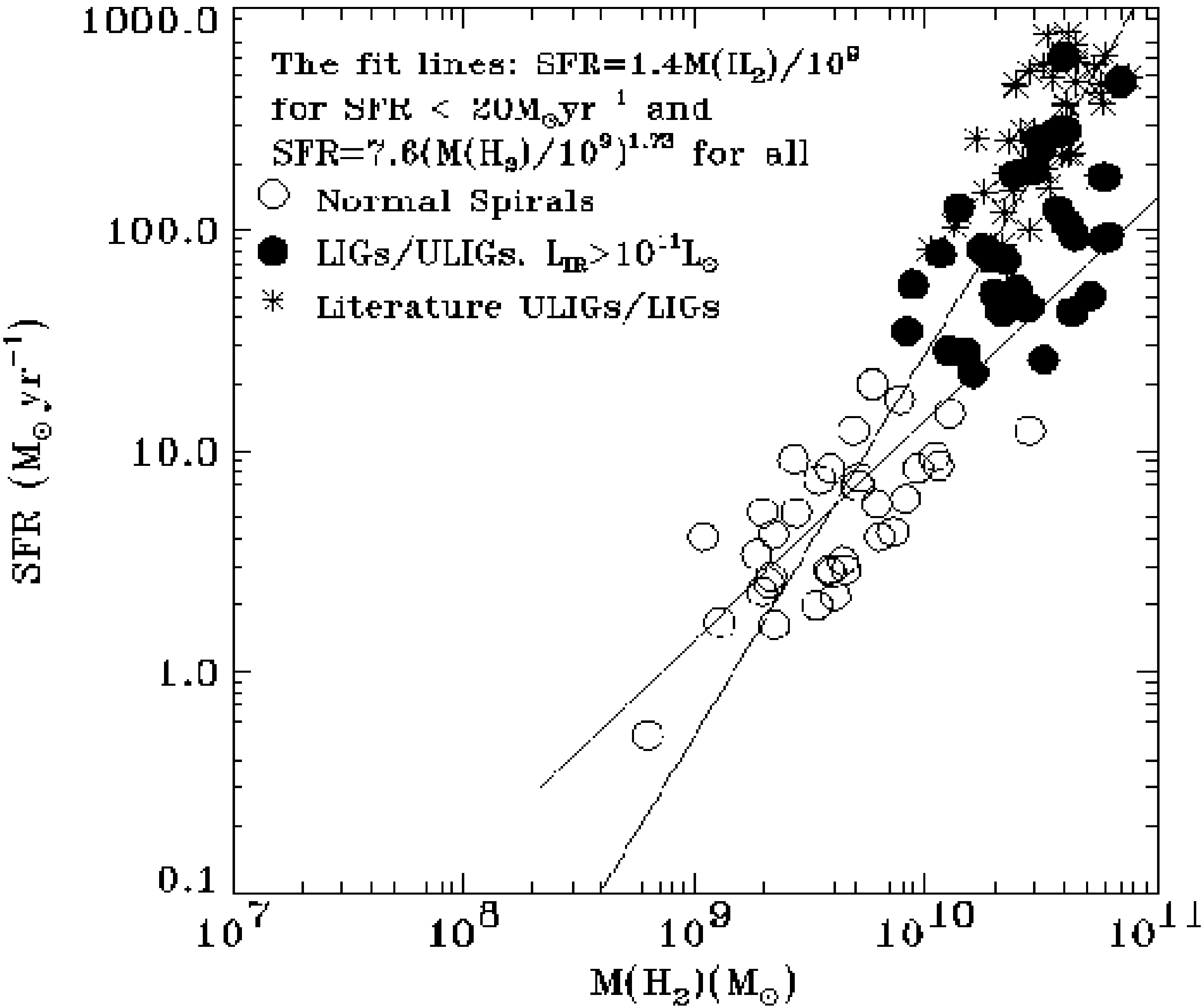
  Dense gas linearly correlates with SFR

  (Hubble law, H_0 analogy)

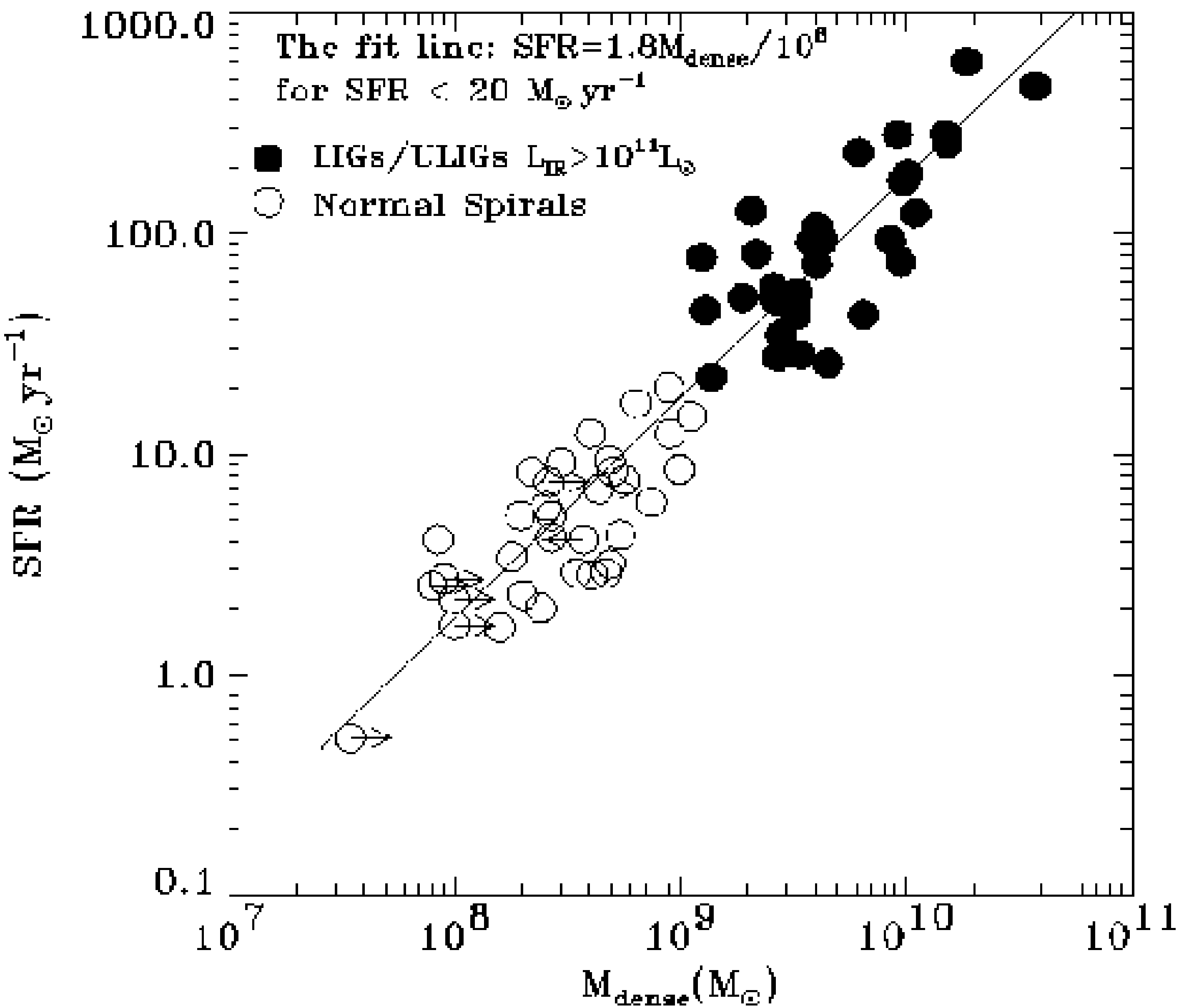
Kennicutt 1998



SFR vs. M(H2): No Unique Slope (1—2)



SFR vs. M_dense(H2): linear correlation



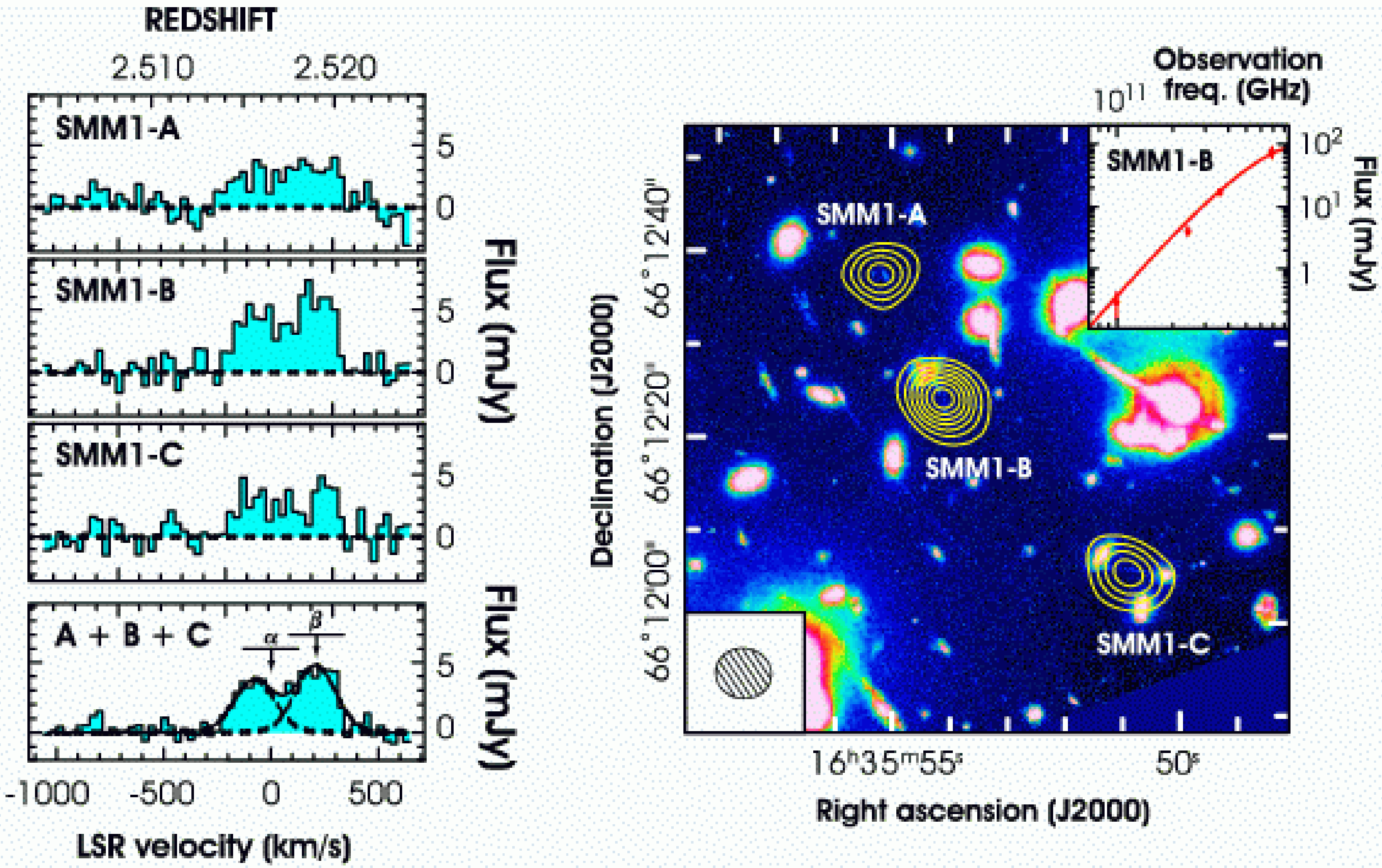
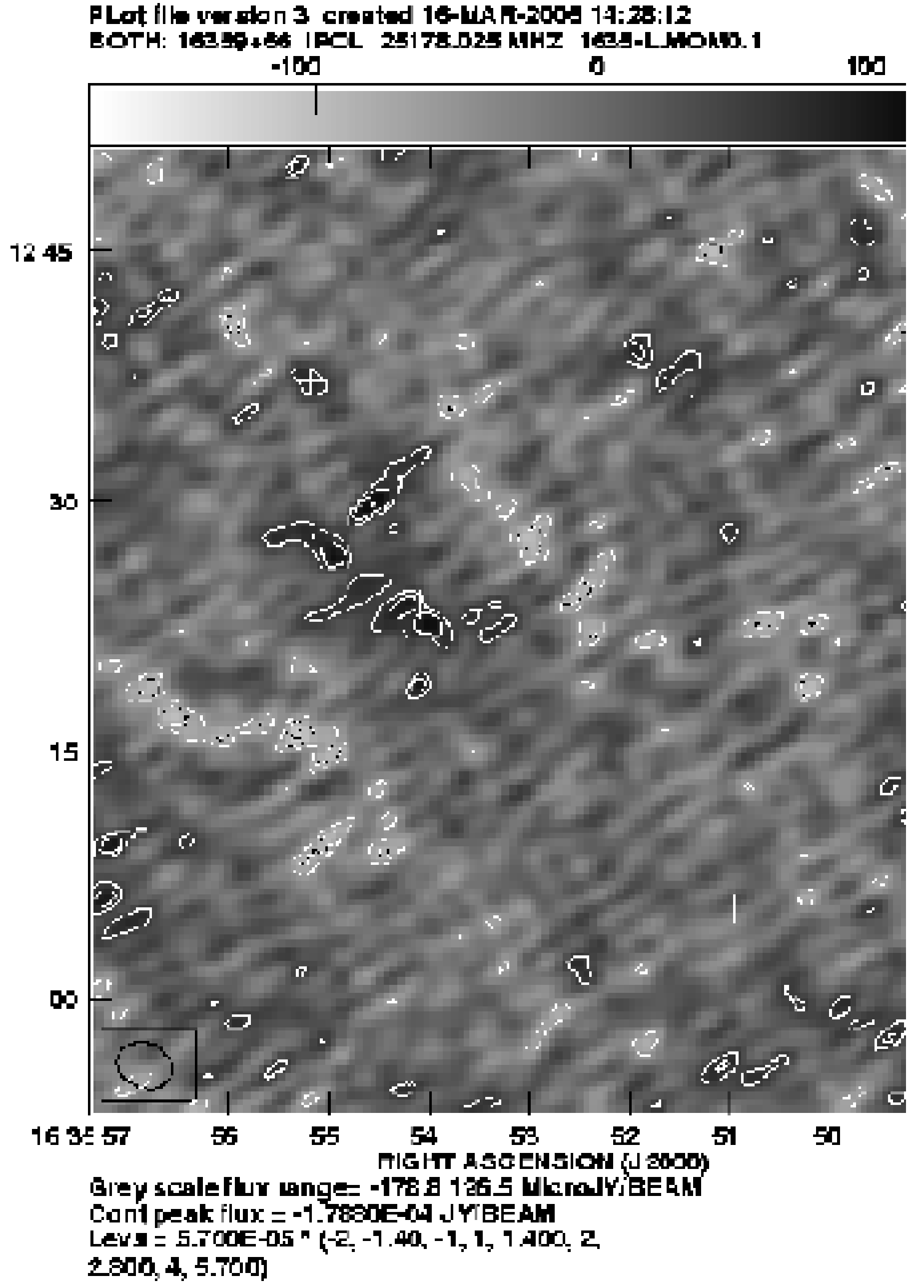
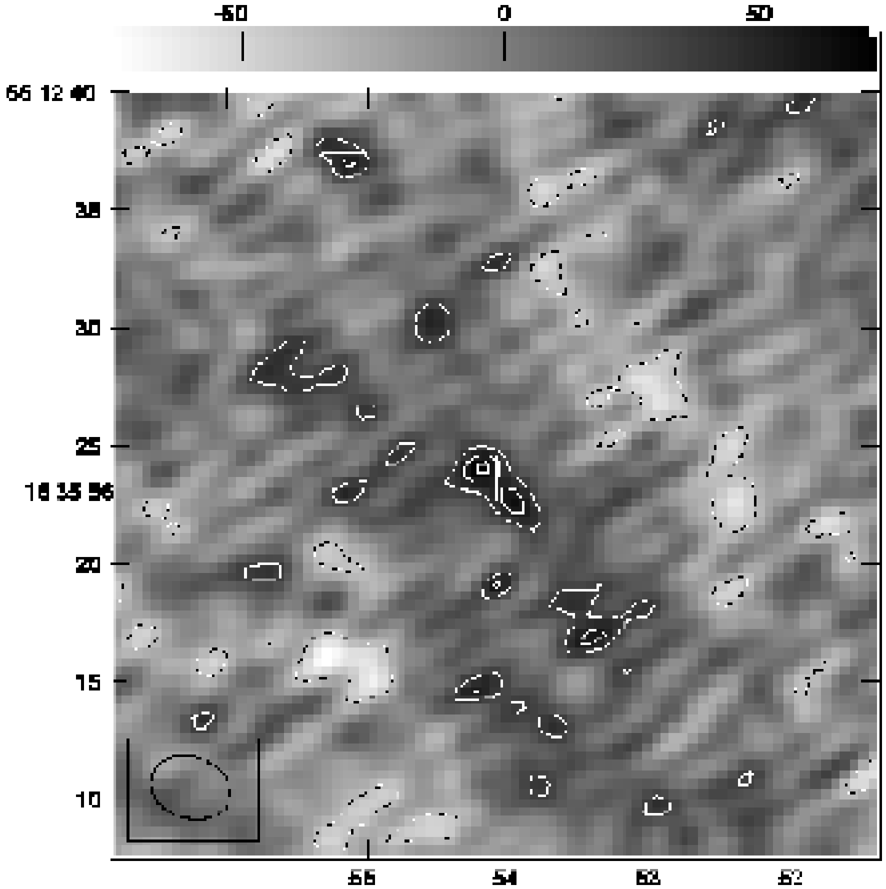
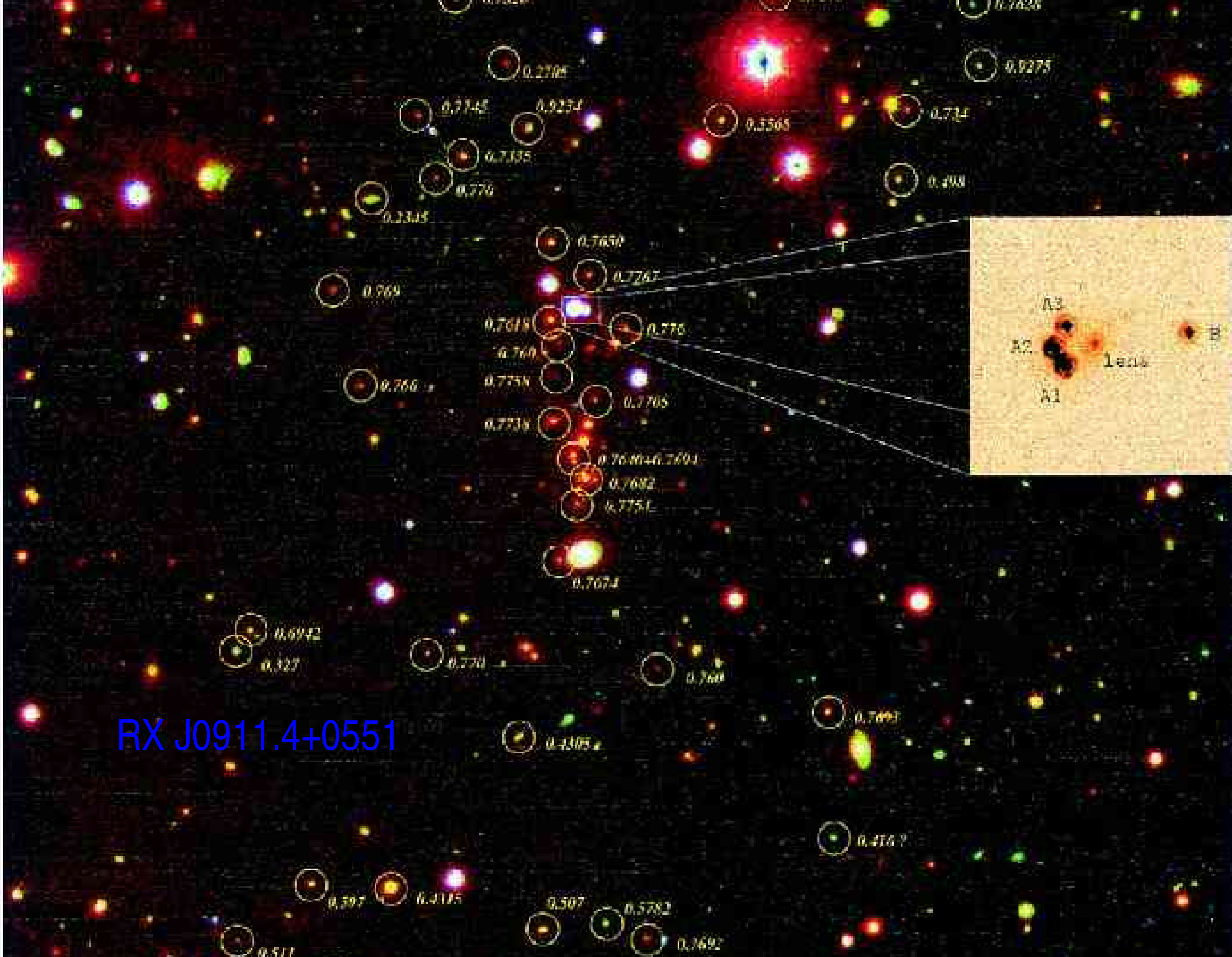


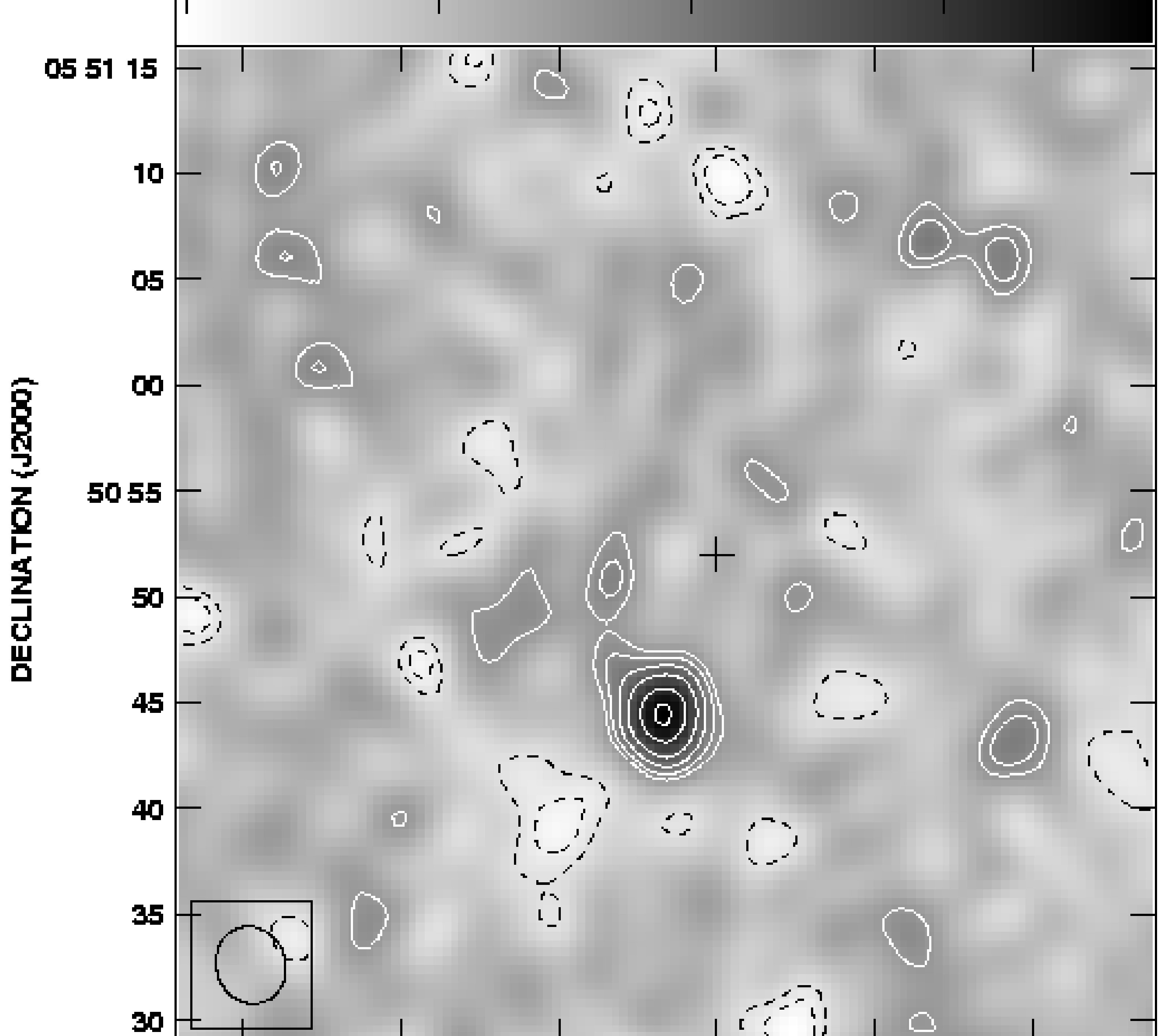
Figure 5: The lower panel shows SMM J16399 in CO(3–2) emission that has been triply imaged by a gravitational lens (Kneib et al. 2004a). The total

Gao, Carilli, Solomon & Vanden Bout 2006 ApJL, submitted






RX J0911.4+0551



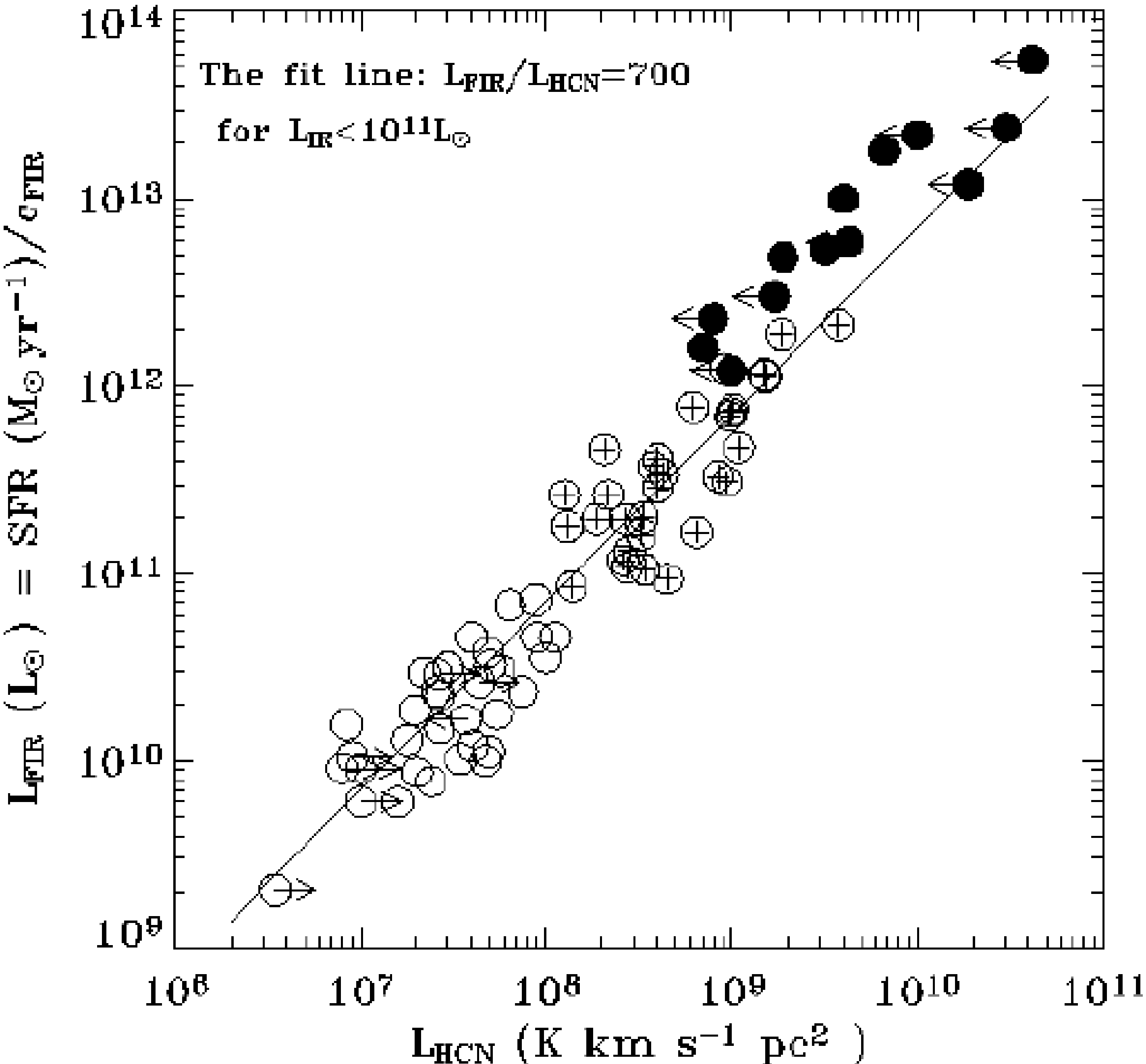
DECLINATION (J2000)
05 51 15
10
05
00
50 55
50
45
40
35
30

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

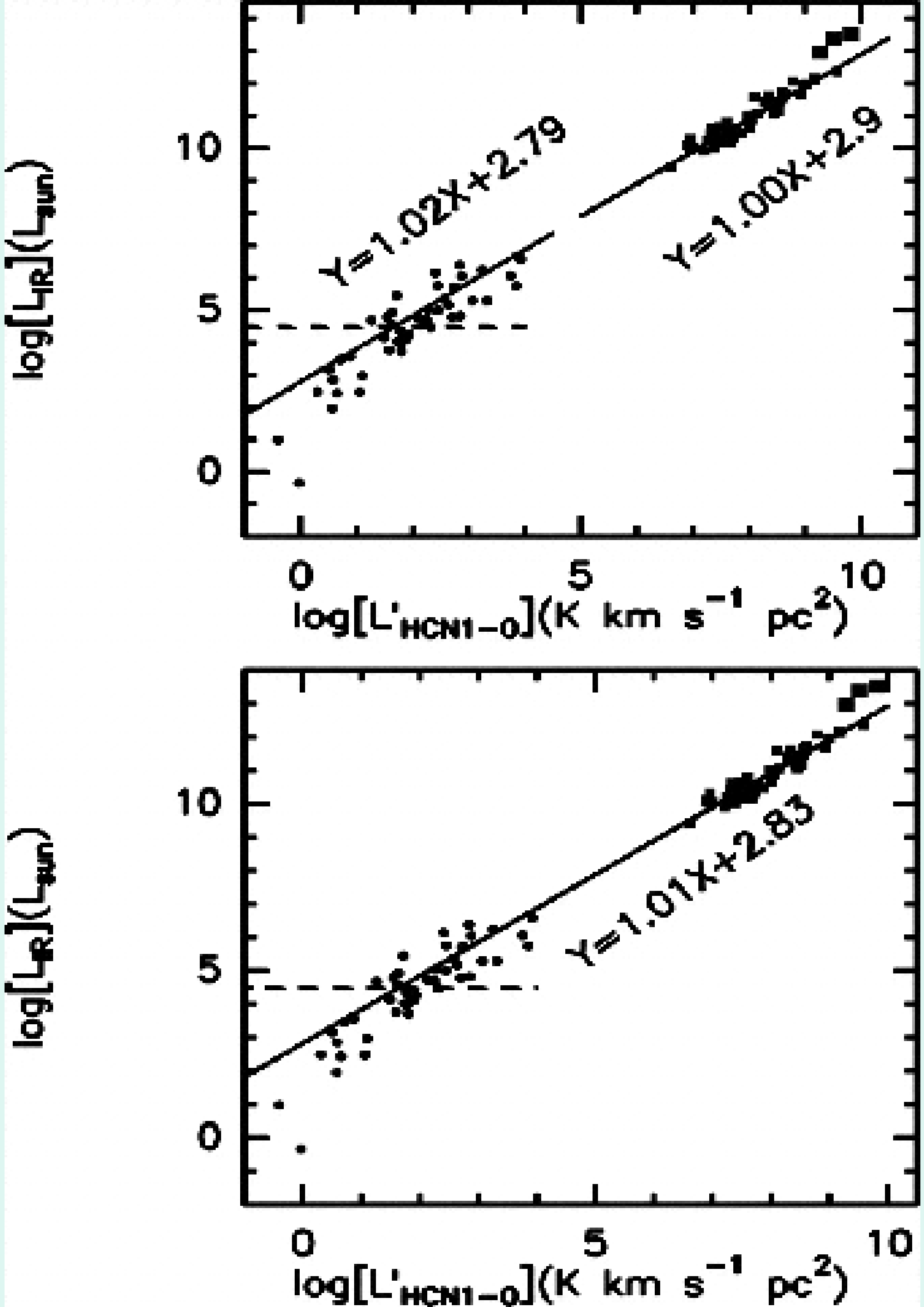
Complications: lens, L_IR, SFR vs AGN, CO(1-0)

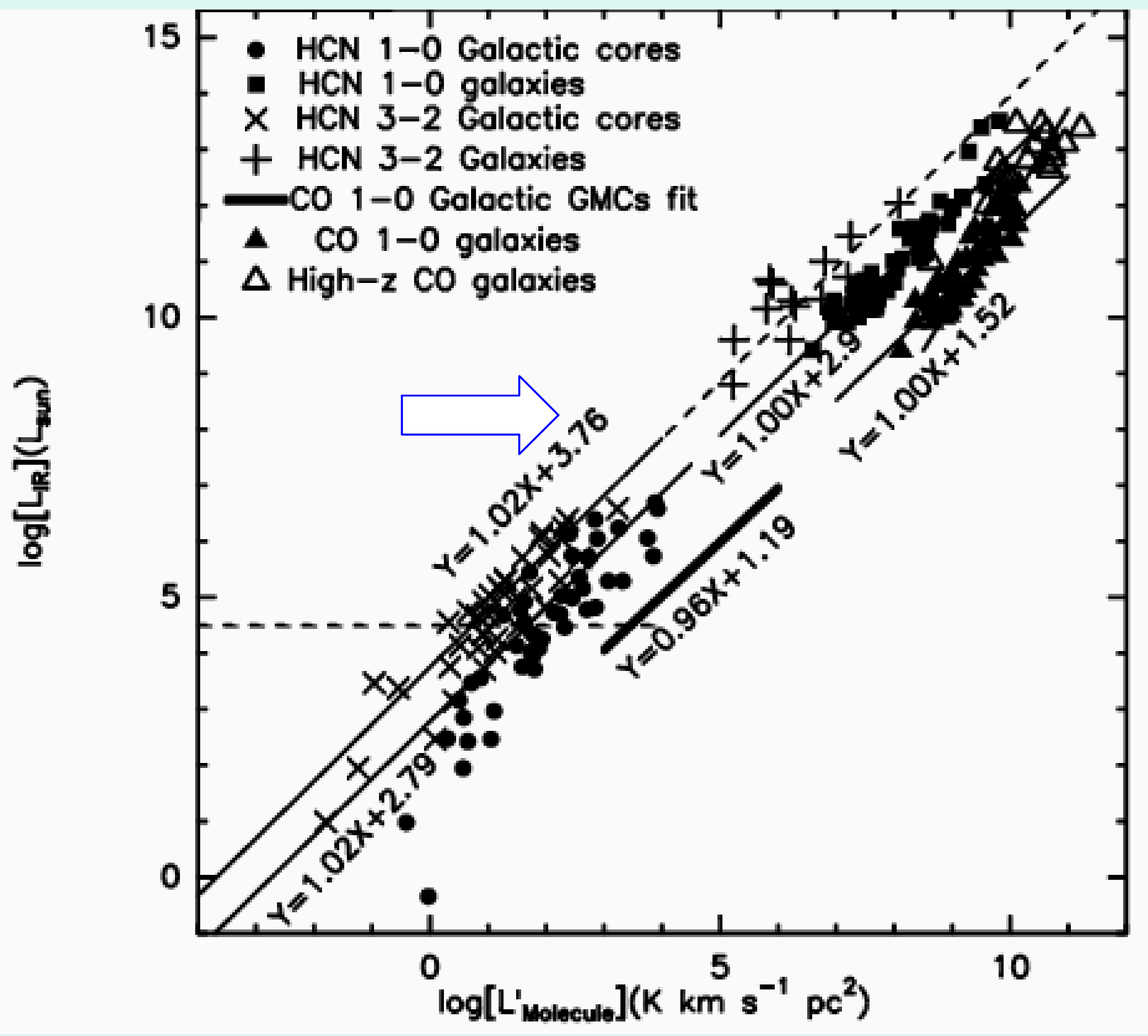
	Source	Lfir	Lhcn	Lco	hcn/co	mag.f
a	H1413+117	5.4	3.2	40.0	0.08	11
	F1021+472	4.9	1.9	9.1	0.20	12
	J1409+562	18.	6.7	82.	0.08	1
	A0827+525	10.	4.0	14.	0.28	10
B	J02399-0134	5.9	<4.3	21.	<0.20	2.5
	J0413+102	24.	<30.3	170.	<0.18	1.3
	J0911+055	2.3	<0.8	5.2	<0.17	21.8
	J1635+661	1.6	0.7	3.7	0.19	22
c	B1202-072	55.	<42.	105.	<0.40	1
	J1148+525	22.	<10.	27.	<0.36	1
	J1401+025	3.0	<1.7	19.	<0.09	5
	M0751+271	1.2	<1.0	9.7	<0.11	17
	J02396-0136	12.	<19.	48.	<0.39	2.5

New Results (13 HCN@high-z)



Wu, Evans, Gao et al. 2005
ApJL

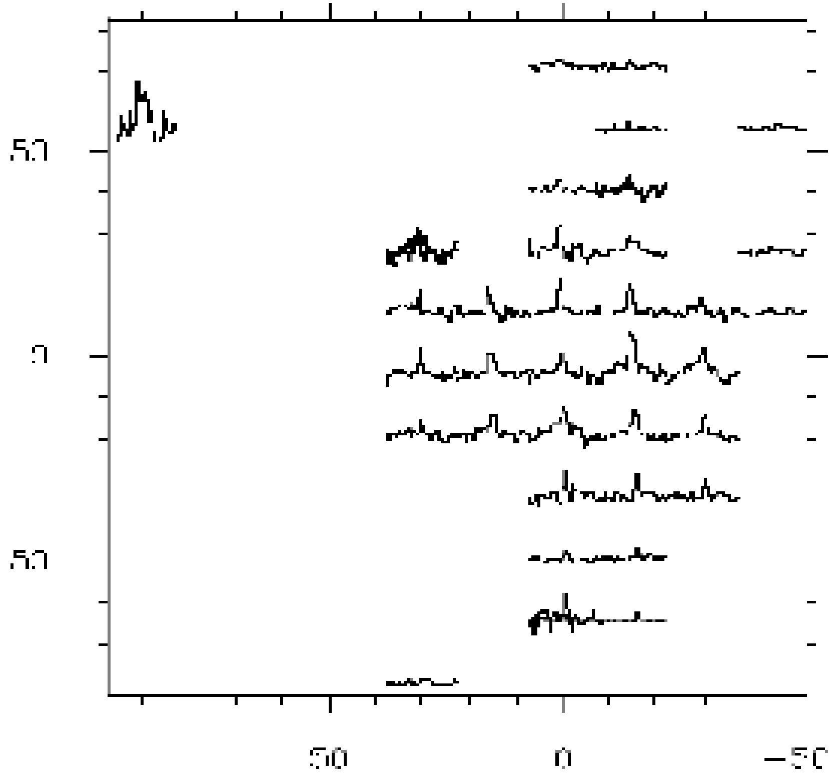




HCN 1−0 Galactic cores
HCN 1−0 galaxies
HCN 3−2 Galactic cores
HCN 3−2 Galaxies
CO 1−0 Galactic GMCs fit
CO 1−0 galaxies
High−z CO galaxies
Y=1.02X+3.76
Y=1.02X+2.79
Y=1.00X+2.9
Y=1.00X+1.52
Y=0.96X+1.19
log[L_IR](L_sun)
log[L'_Molecule](K km s^-1 pc^2)
15
10
5
0
0
5
10

Resovled Local SF Law ?

In Dense Gas (M51 & N6946)



New Star Formation Law

- Dense Molecular Gas   High Mass Stars
- SFR ~ M(DENSE) or density of dense gas

  (e.g. gas density >~10^5 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

SFR (Mo/yr) ~ 2 M_dense/10^8 Mo