The Star Formation Law in Dense Molecular Gas: the Far-IR and HCN Correlation

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Talk Outline

- 1) Massive Star Formation (SF): Dense Gas

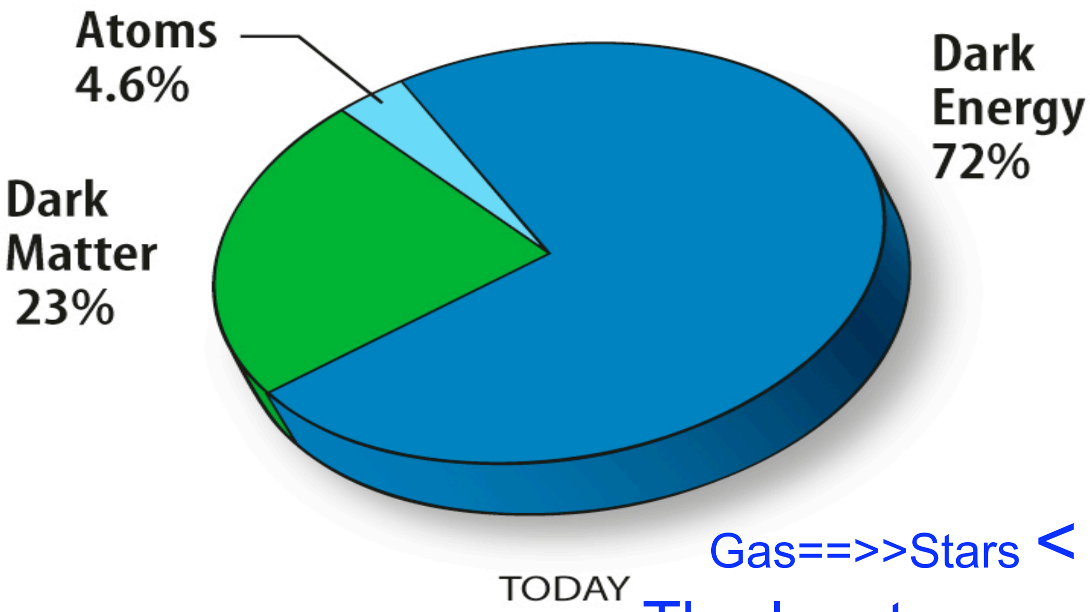
  GMC Dense Cores, Importance of Dense Molecular Gas in Galaxies, SFR & Dense Gas Tracers
- 2) FIR--HCN in Local Galaxies

  SF Rate vs. Dense Molecular Gas in 65 Galaxies (the FIR--HCN Correlation, linear!)
- 3) FIR--HCN in High-z & GMC cores

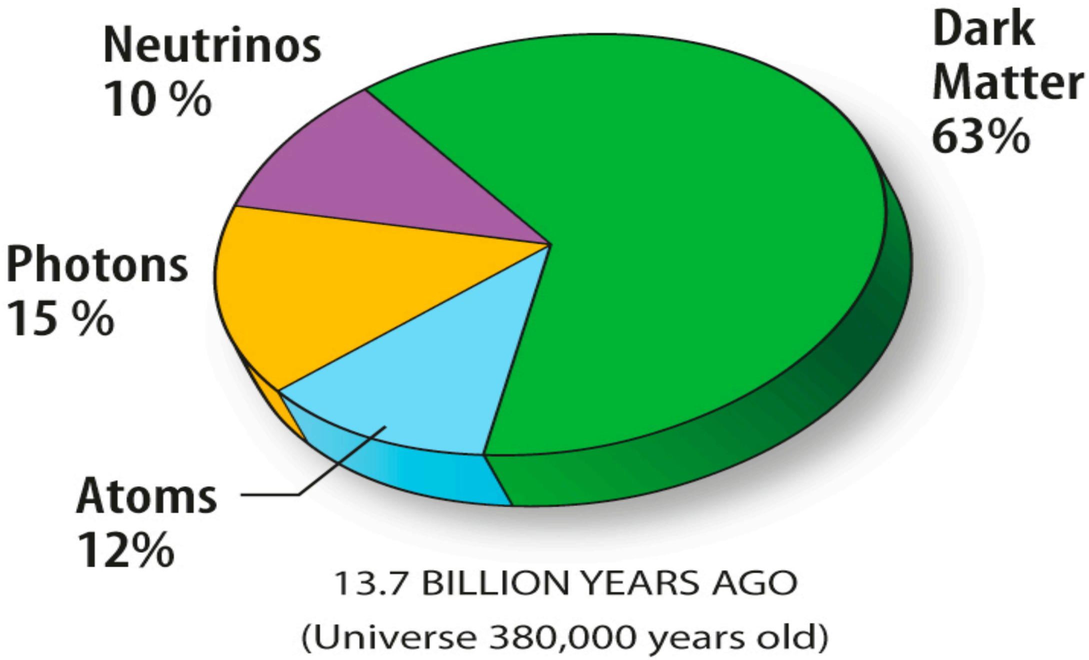
  (FIR—HCN correlation over 10 orders of mag. + work in progress: resolved disks M51, N6946 & GMC cores)
- 4) Global SF Law: from dense GMC Cores to Hyper/Ultraluminous Galaxies at High-z
- 5) Conclusion

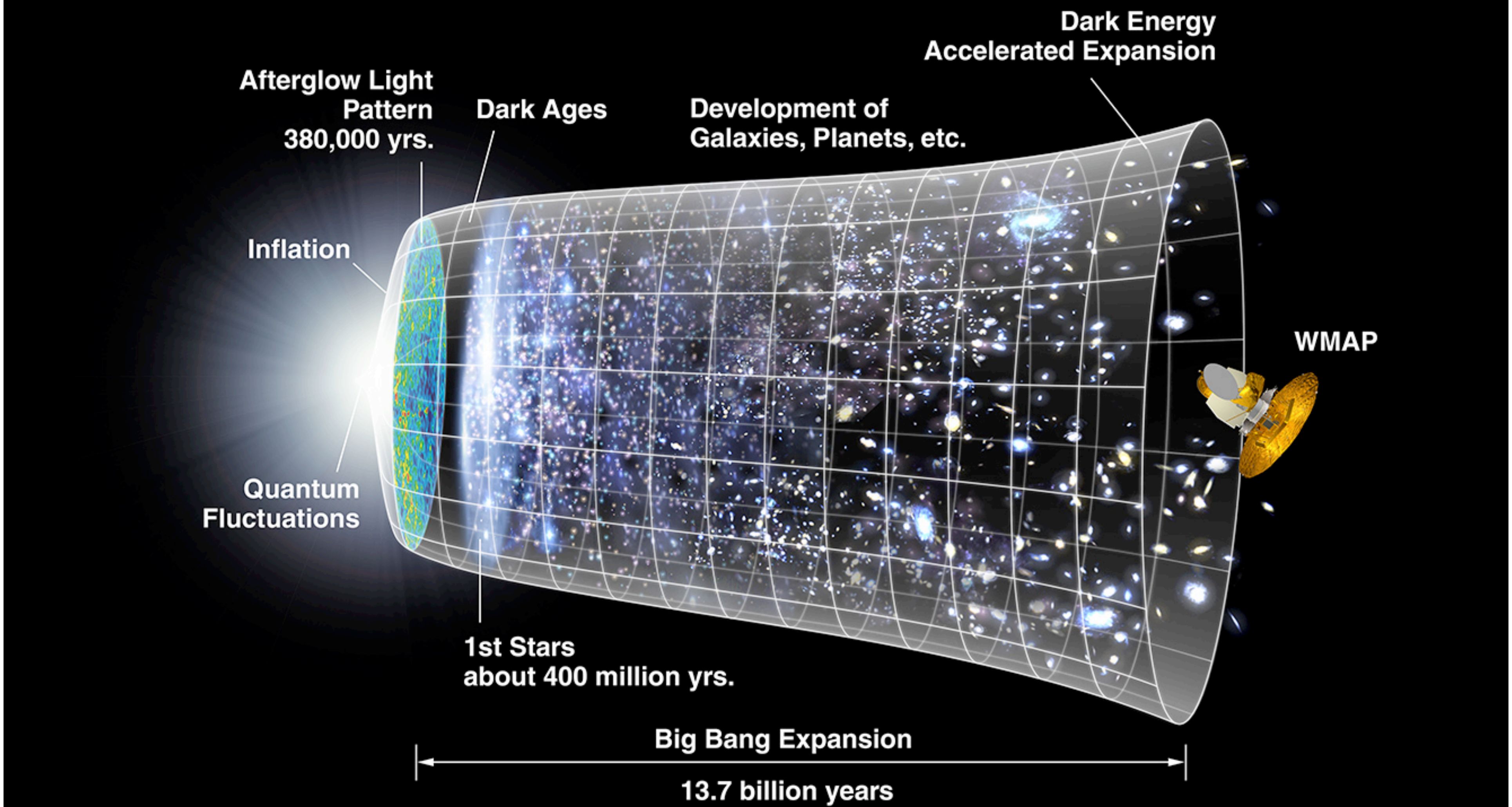
  Non-linear CO-->H2, HCN-->DenseH2 conversions

Content of the Universe



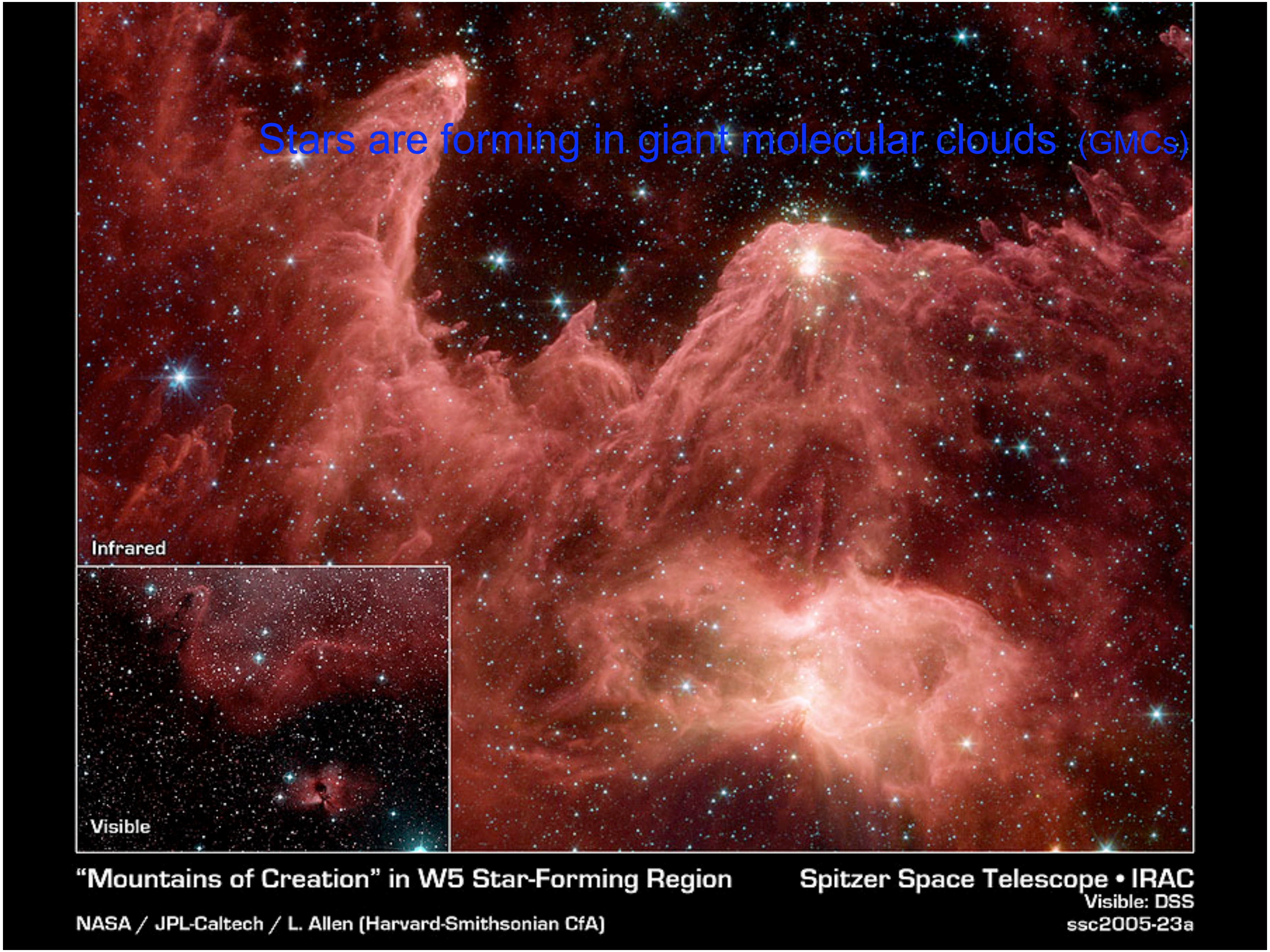
Gas==>>Stars < 1%
The least component





Gas: most important in shaping up the Cosmic SF history

Stars are forming in giant molecular clouds (GMCs)

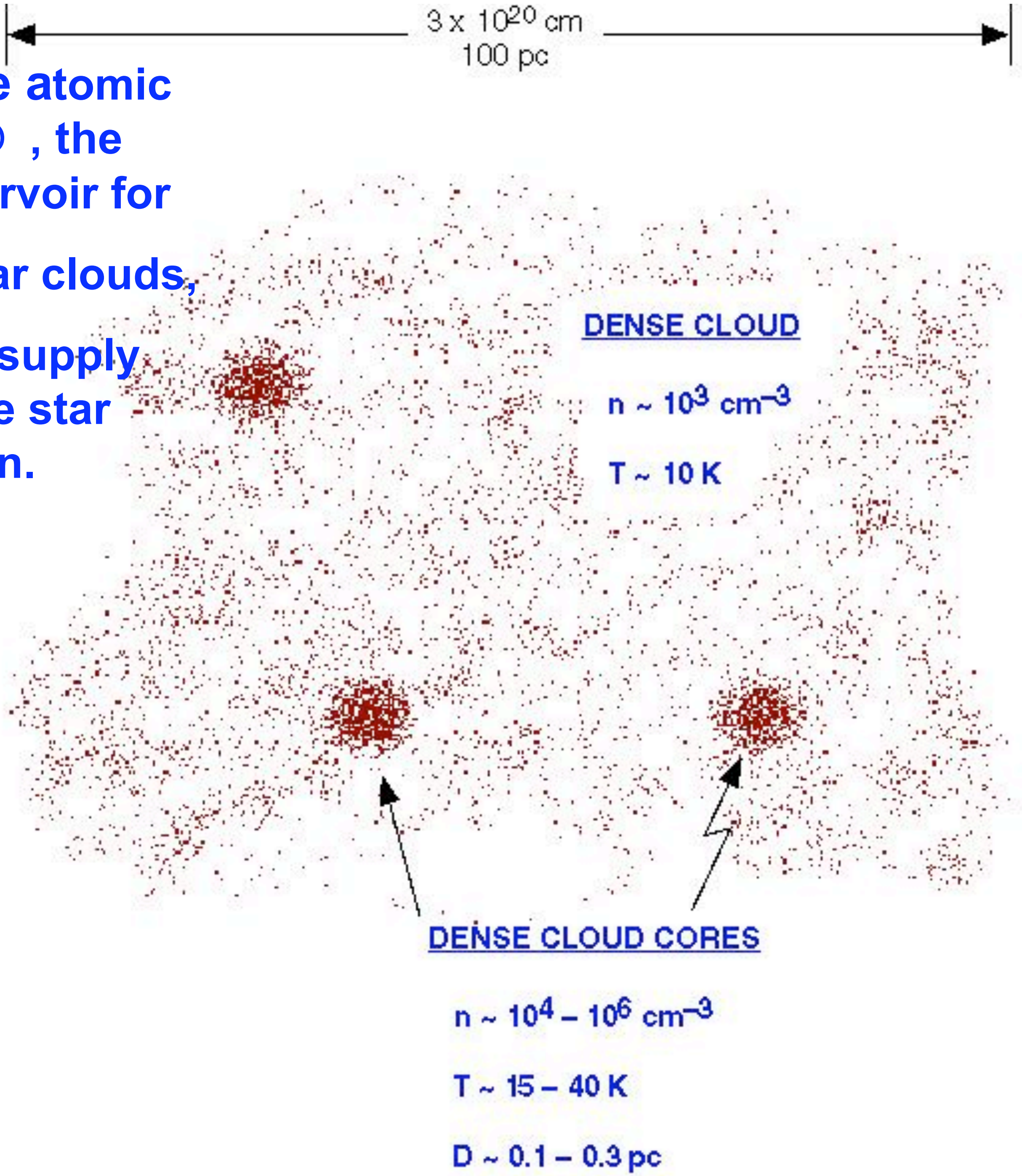


Diffuse atomic gas（HI）, the gas reservoir for

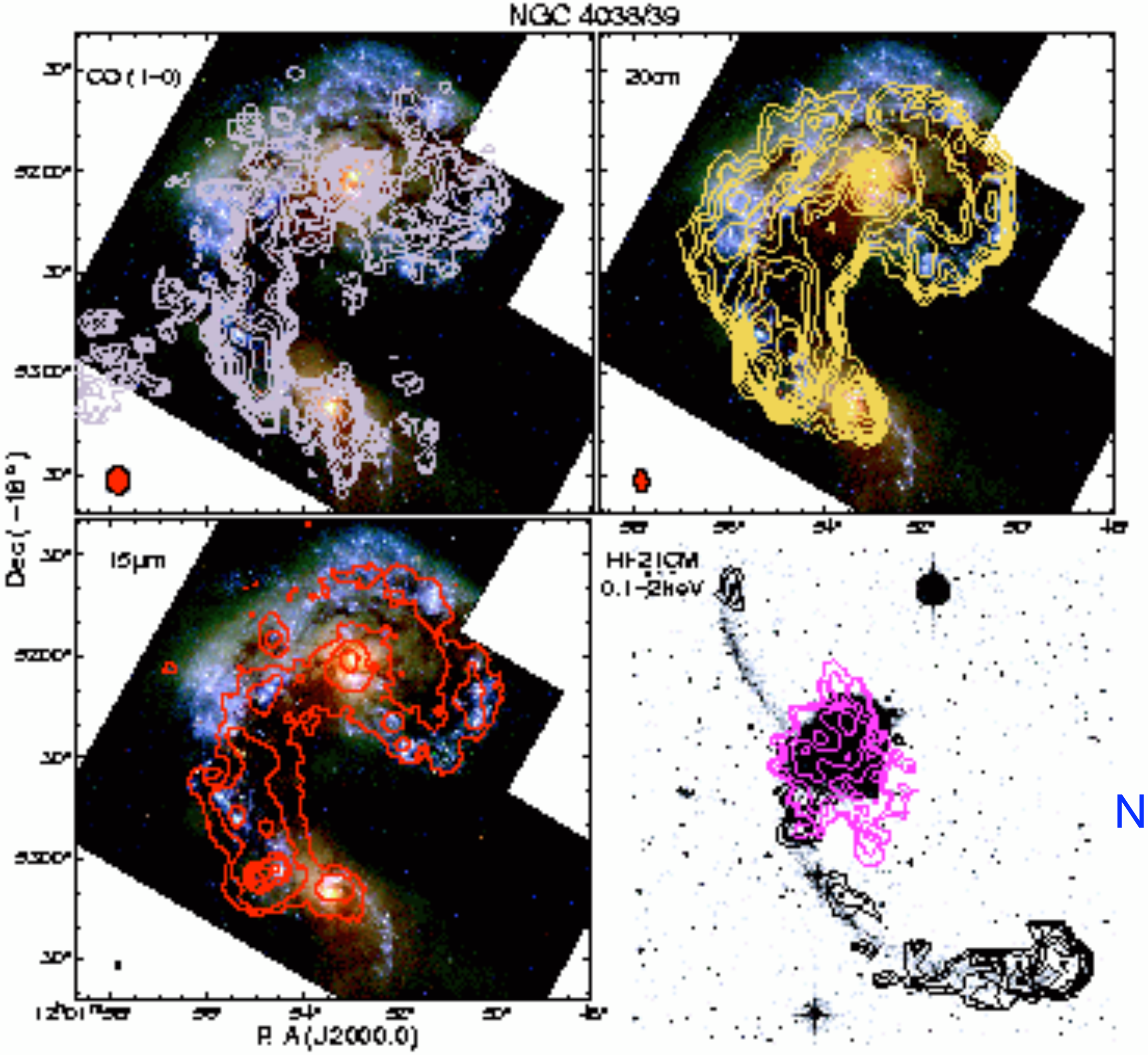
molecular clouds,

And the supply for future star formation.

PDRs



The nearest example of huge gas concentrations between two merging galaxies: the Antennae



N4039: LINER

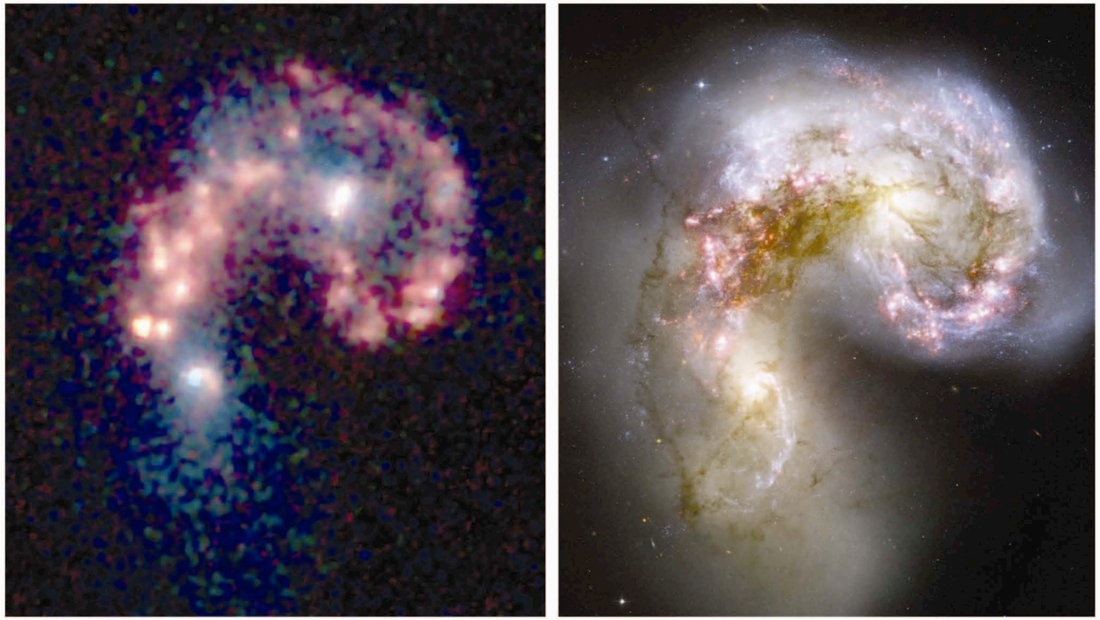


Figure 1 | Buried in dust. These two images of the spectacular merger of the nearby Antennae galaxies — on the left from NASA's Spitzer Space Telescope, on the right from the Hubble Space Telescope — show the train wreck of two gas-rich spirals. The proximity of the galaxies allows detailed imaging of 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.

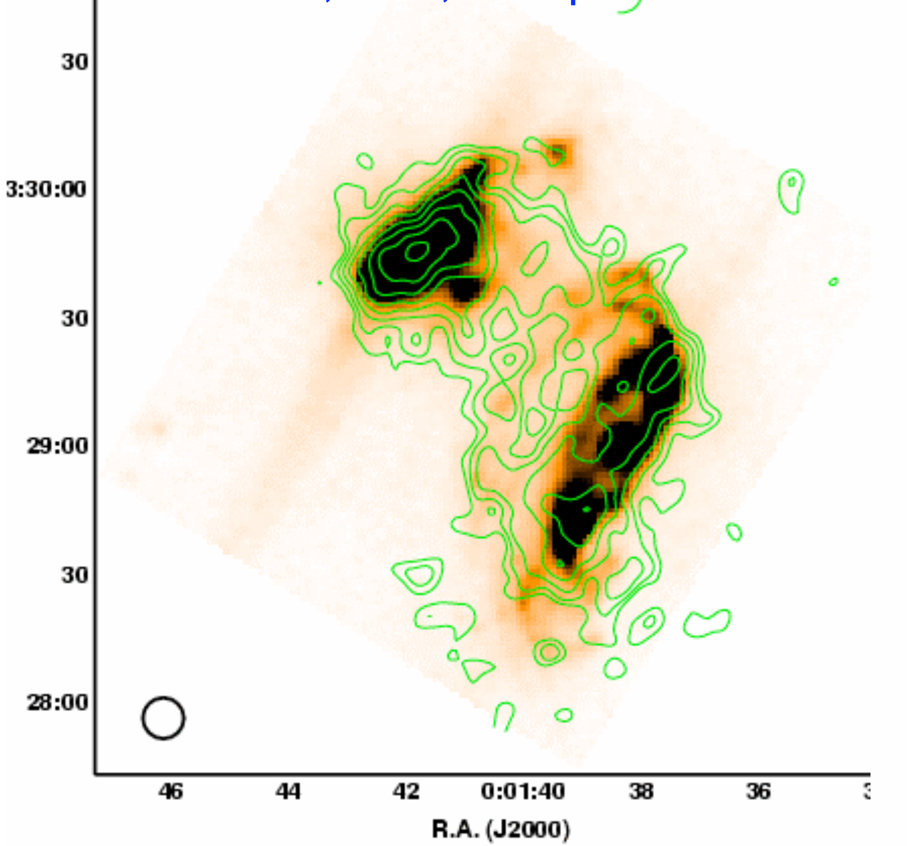
Newborn stars emit light mostly at ultraviolet wavelengths. This light heats the surrounding interstellar dust, which then radiates at infrared wavelengths. Because of the redshift effect, Hathi *et al.*[2] used two cameras aboard the Hubble Space Telescope that were sensitive at optical and near-infrared 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

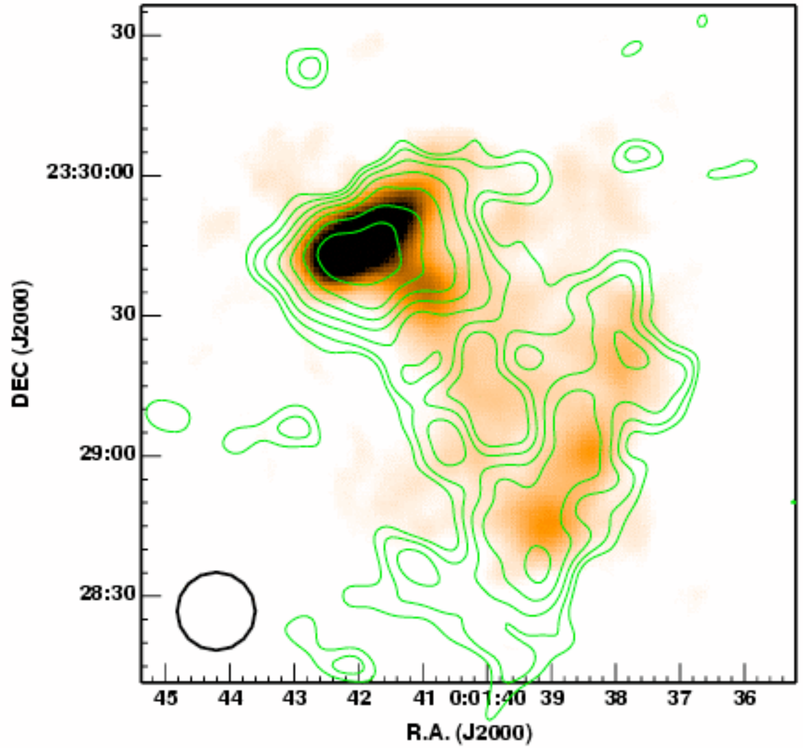
450um contours on 8um image

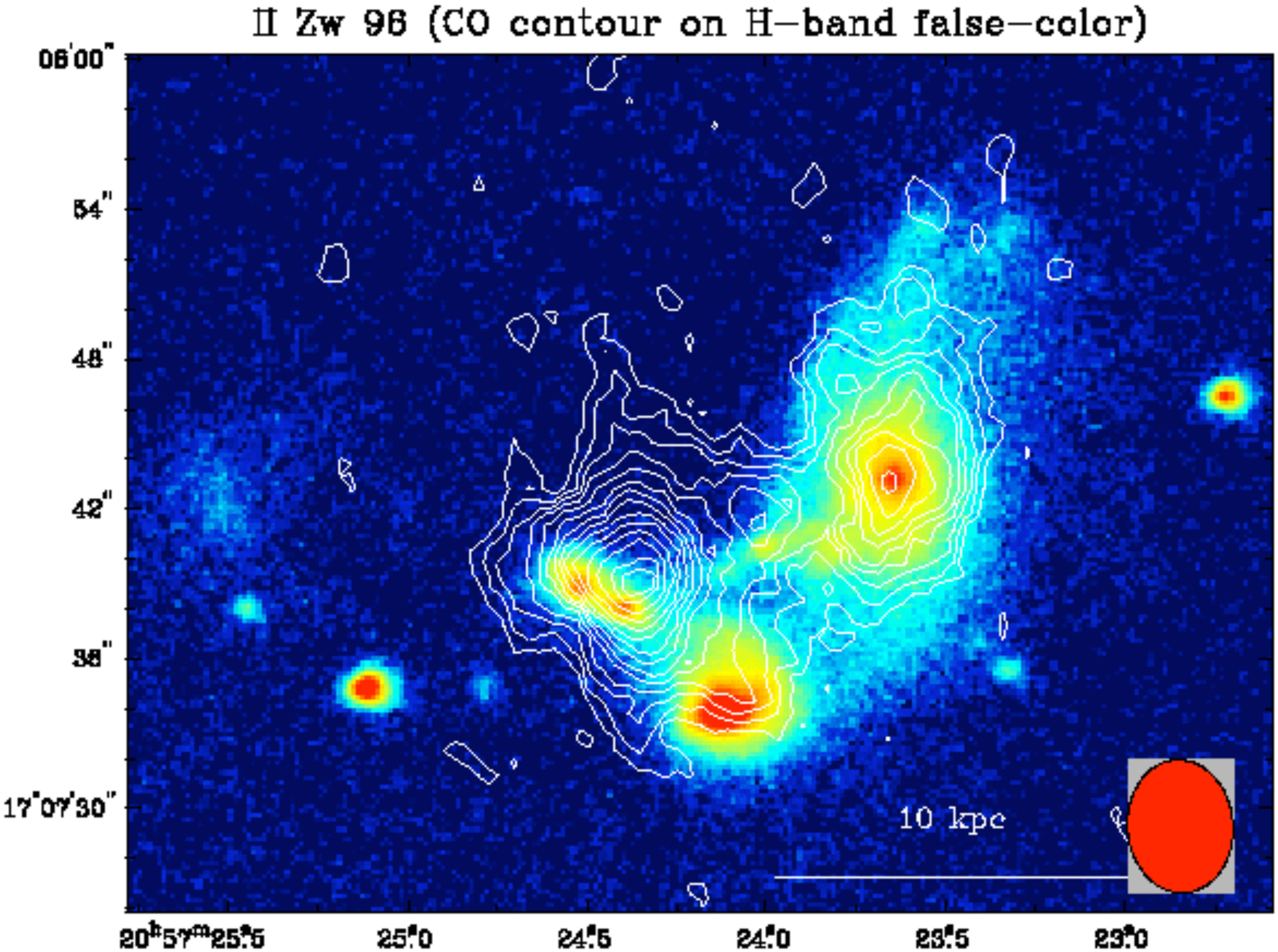
SCUBA: Zhu, Gao, Seaquist & Dunne 2007



850um contours on CO image

CO: Gao, Zhu, Seaquist 2003




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

The most distant CO images: **extended ‘dense’ gas**

VLA ---> EVLA

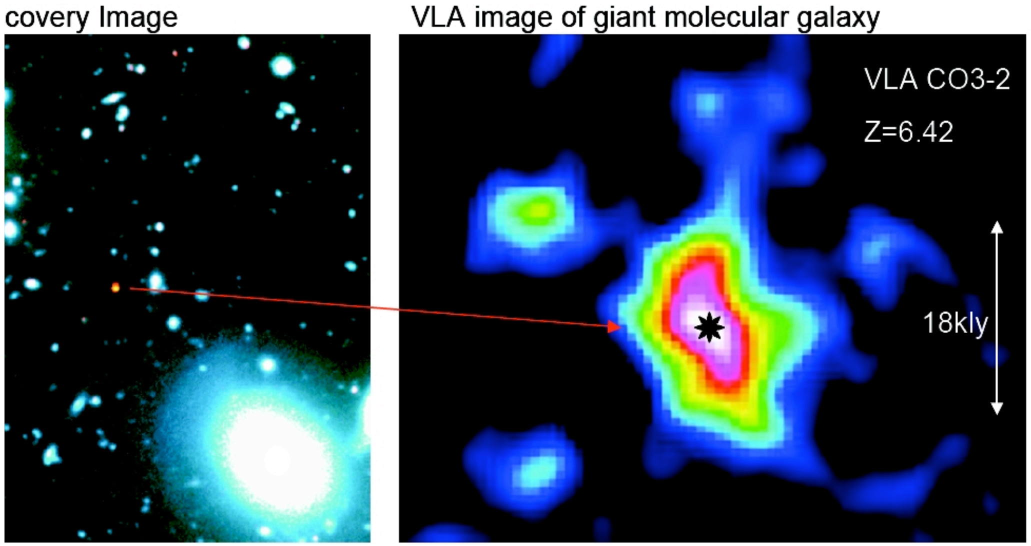
- $M_{gas} = 2 \times 10^{10} M_{sun}$
- $M_{dyn} \sim 6 \times 10^{10} M_{sun}$
- $M_{BH} = 3 \times 10^{9} M_{sun}$

$M_{dyn} \sim M_{gas}$

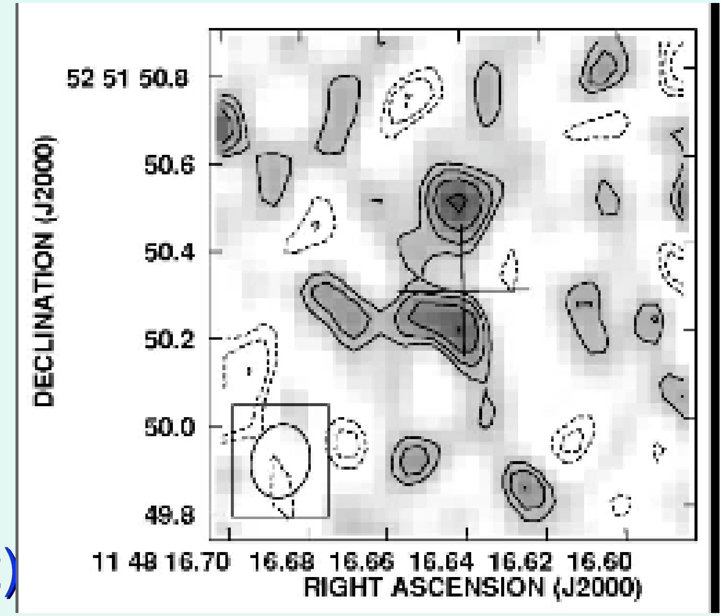
$M_{dyn} = 20\ M_{BH}$

breakdown of relation seen at z=0?

extra-nuclear overlap?



8+5251: Coeval formation of a super massive black and giant elliptical galaxy within 870Myr of the Big Bang

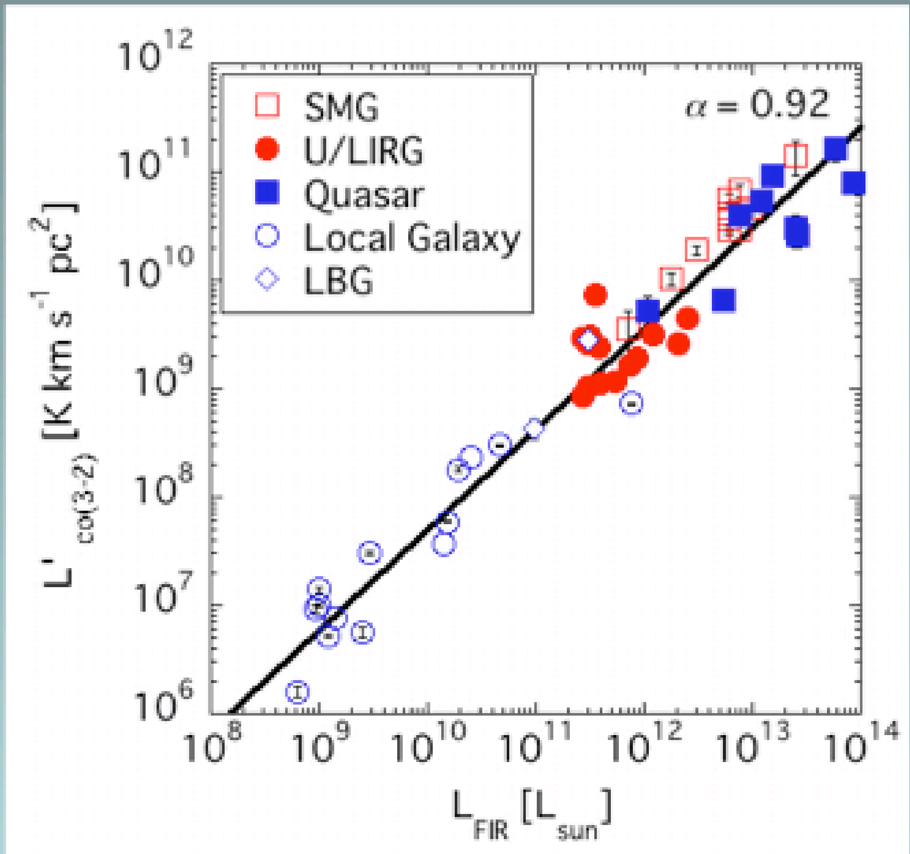


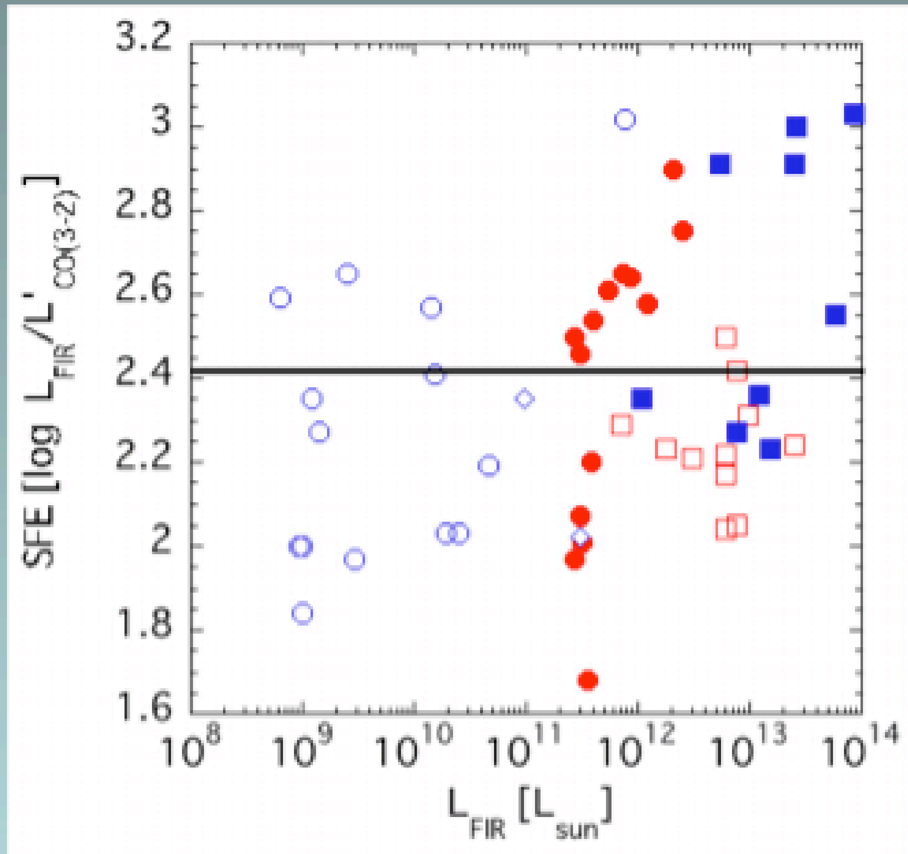
Walter et al. (2004)

5 kpc reservoir

Perhaps most ‘famous’ QSO:J1148+5251(z=6.42)

CO(3-2) traces dense star forming gas

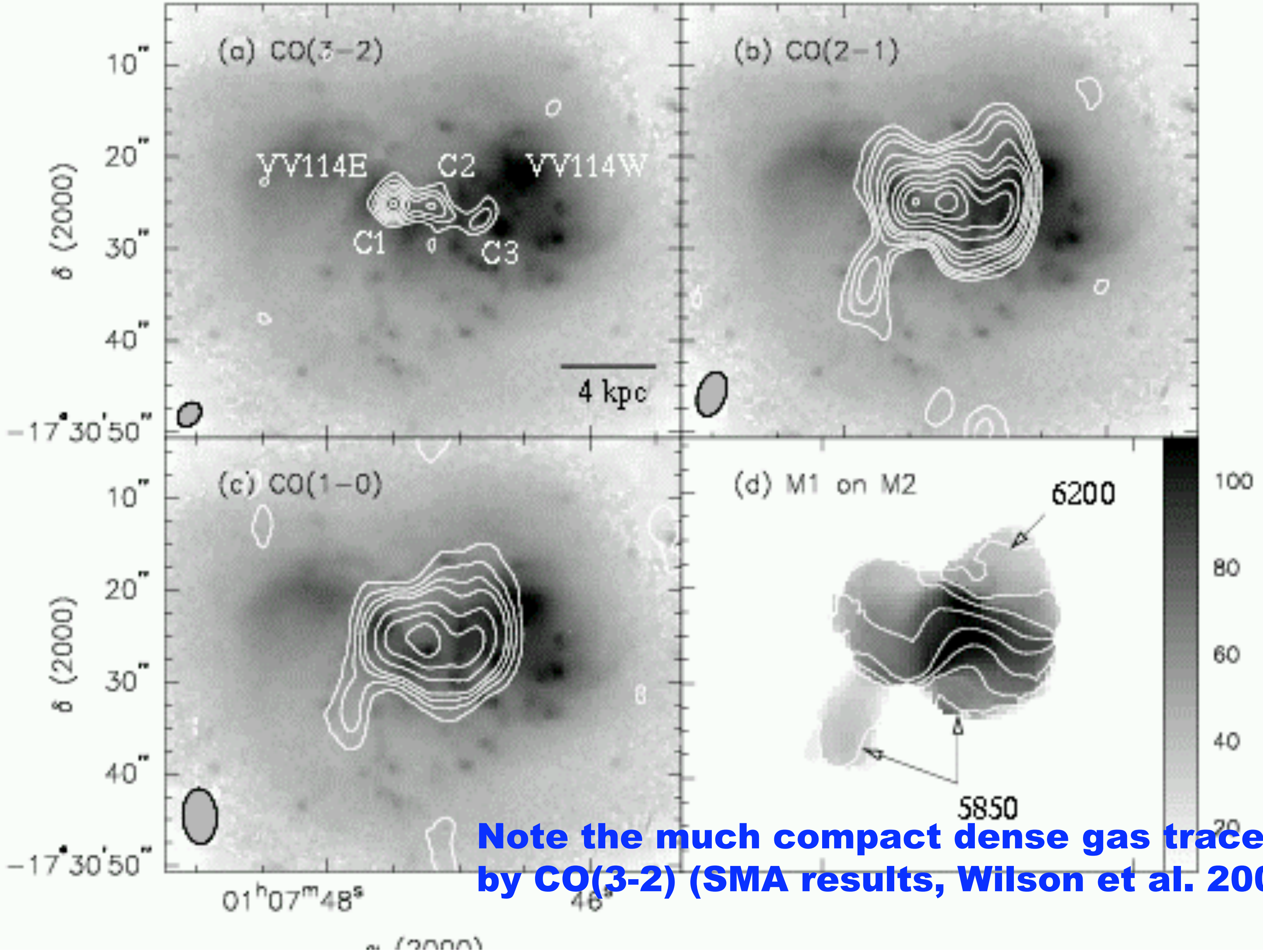




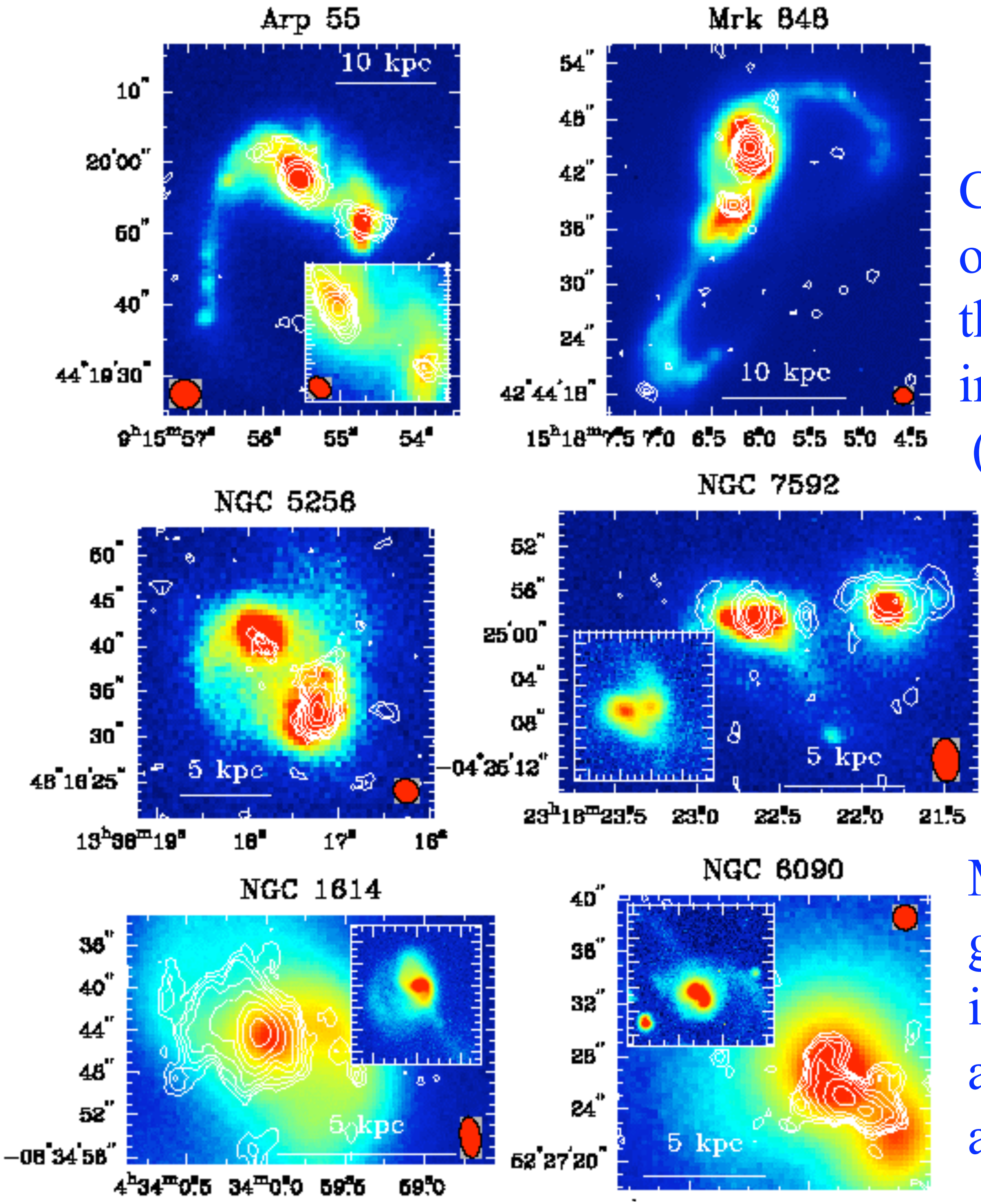
Slope (0.92+/-0.03) is similar to HCN (Gao & Solomon 2004)

Wilson et al. 2008; Iono et al. 2009

CO in VV 114 (Iono et al. 2004, Yun et al. 1994)



Note the much compact dense gas traced by CO(3-2) (SMA results, Wilson et al. 2008)



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

Gao et al. 1999

Molecular gas density increases as merging advances

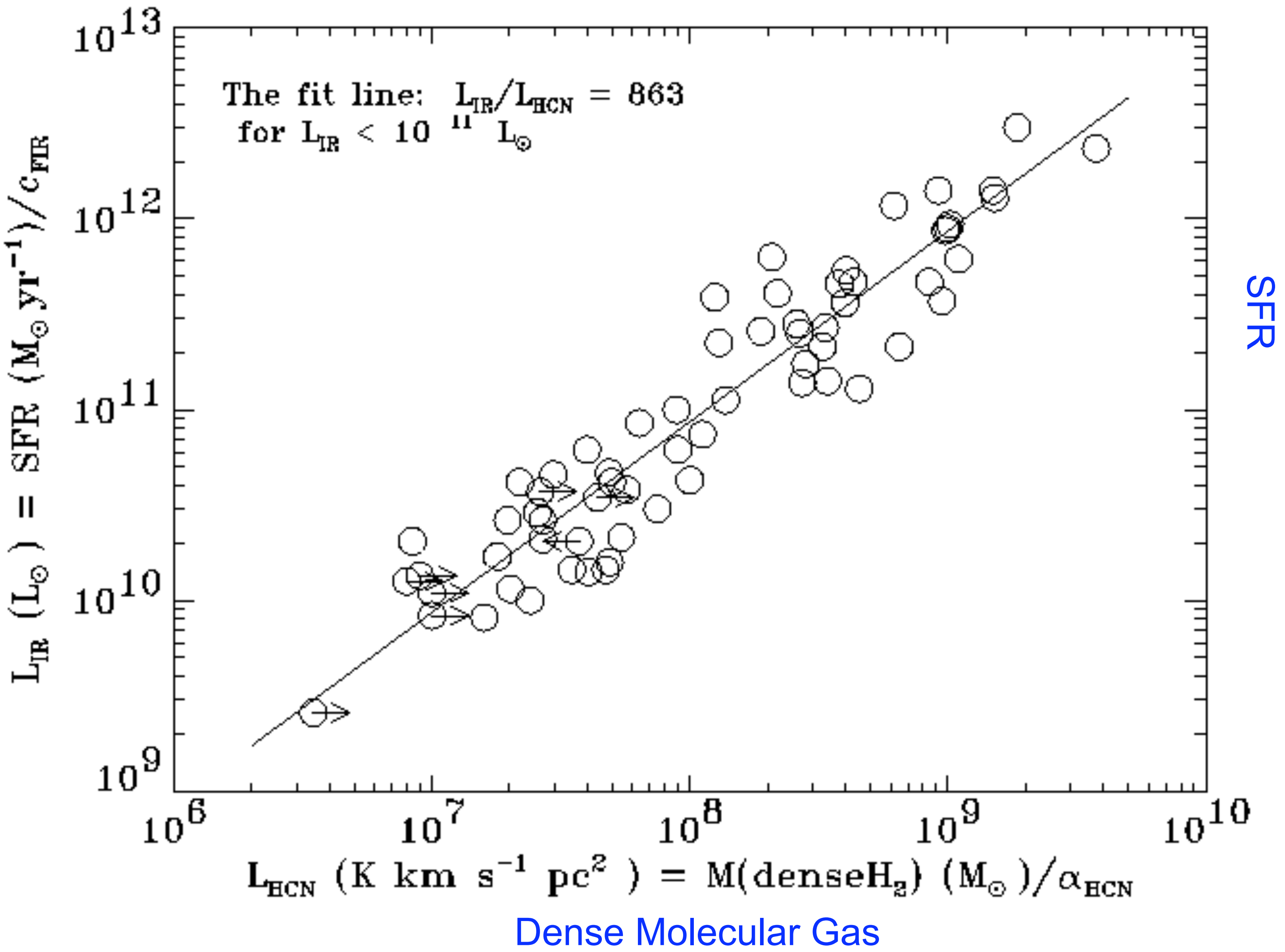
2. Dense gas is the essential fuel for high mass star formation in Galaxies

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)

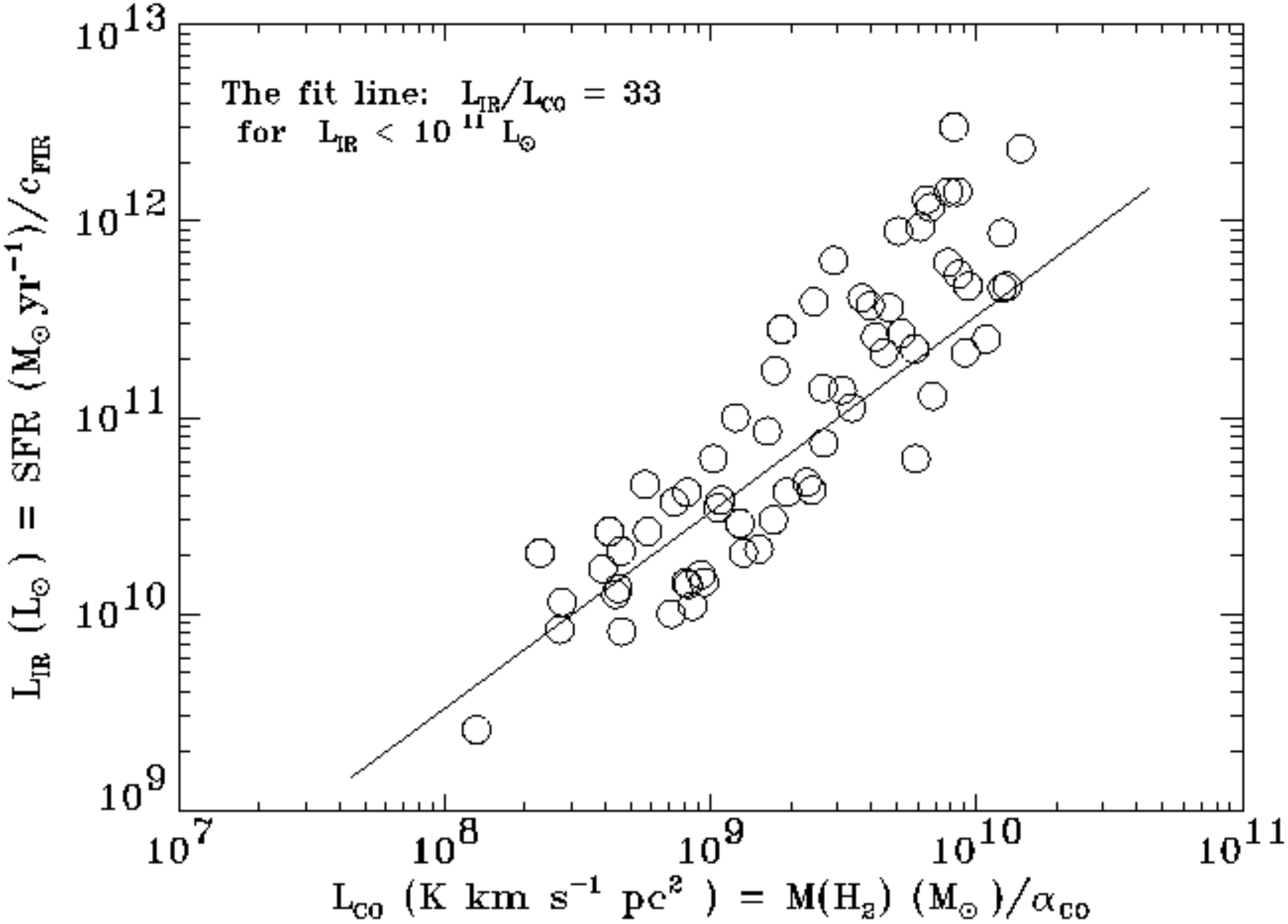
HCN Surveys in 53 Galaxies: Gao & Solomon 2004a ApJS

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



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
SFR
Dense Molecular Gas

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

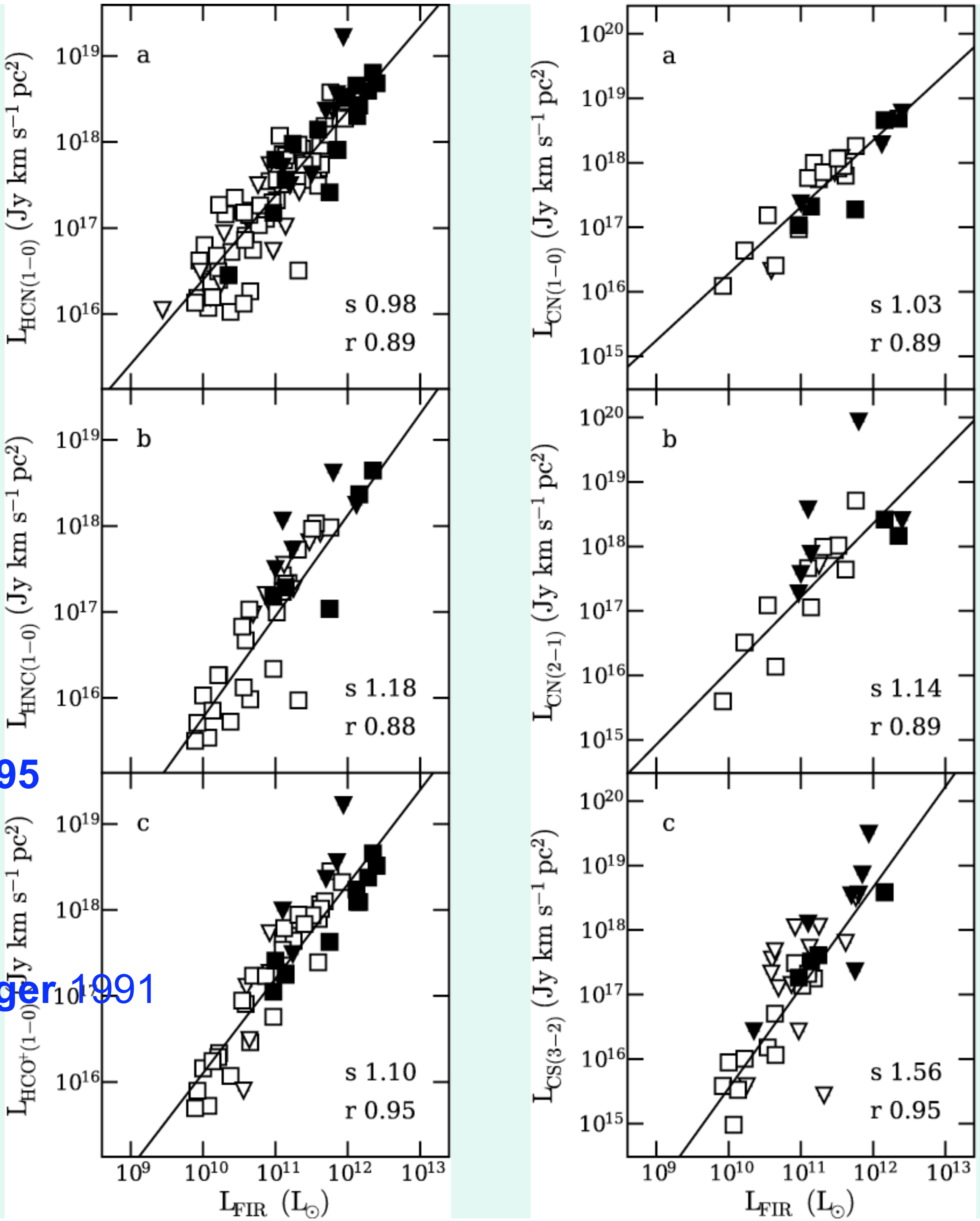


Total Molecular Gas Mass

Baan, Henkel, Loenen et al. 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**



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	(Solomon+03)
	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	

- 5 detections,1@GBT,3@VLA,1@PdBI (HCN5-4)+4VLA ^limits (Carilli+05).
- 4 new searches with VLA (Gao+07), a couple sub-mm galaxies, >50hrs)

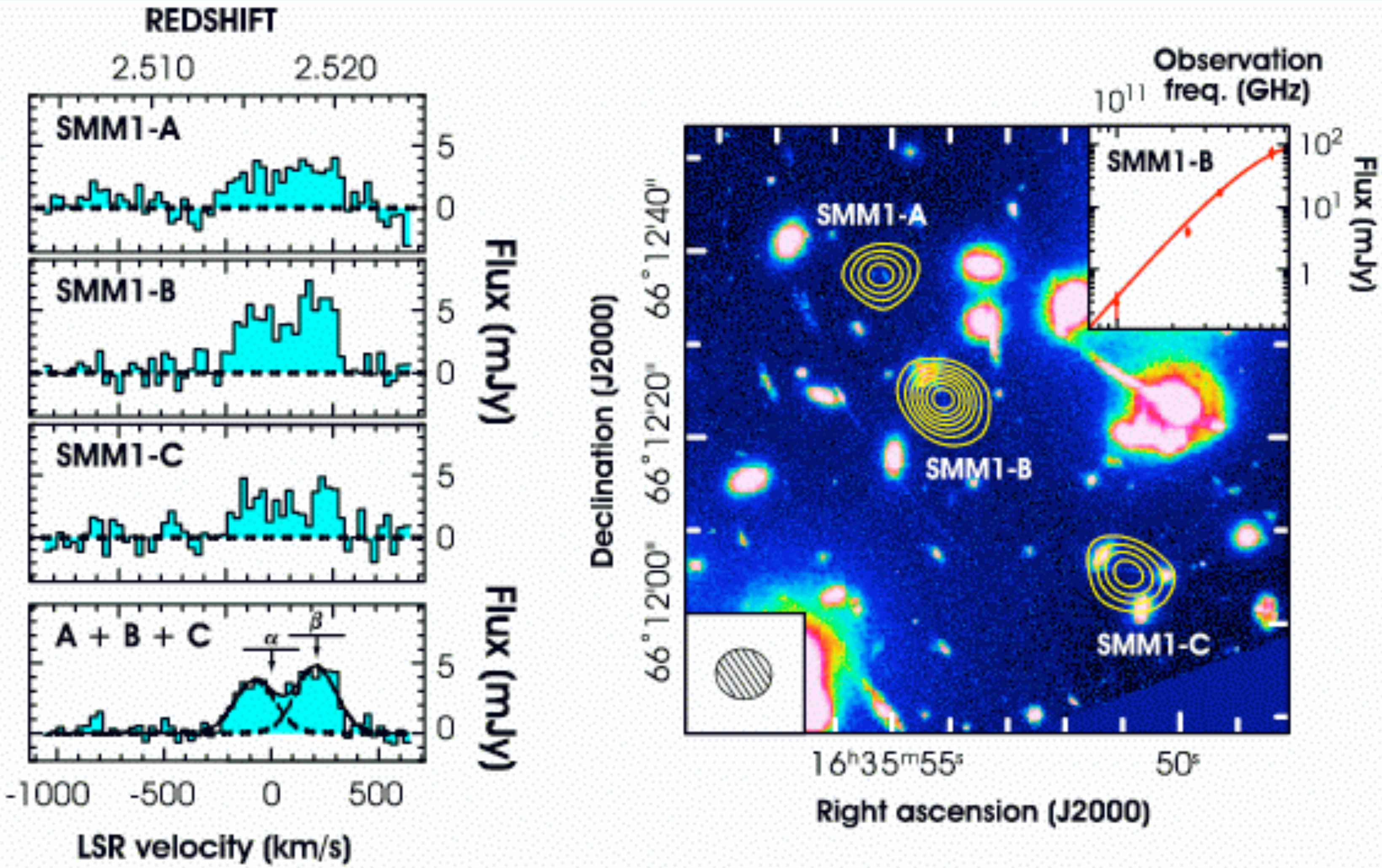
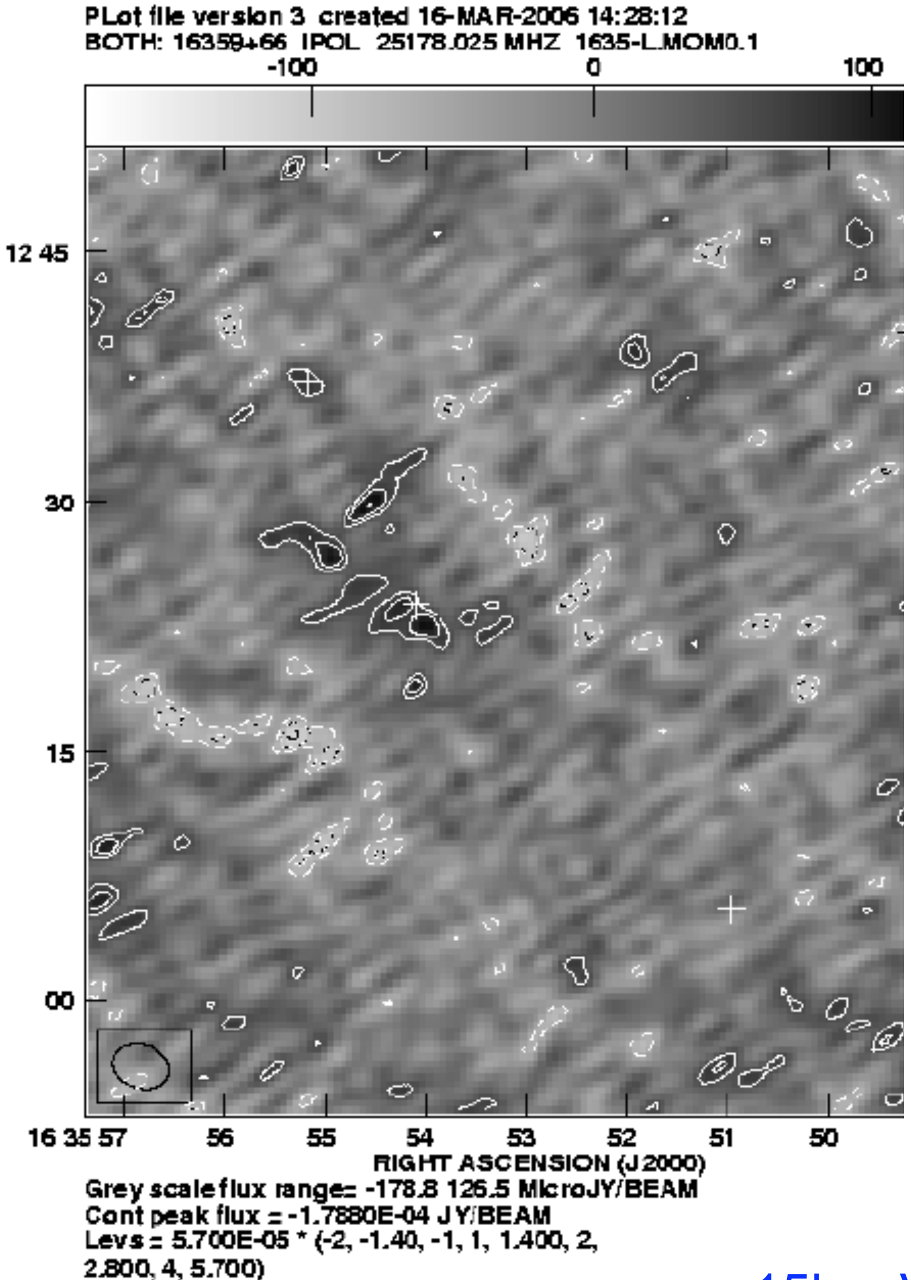
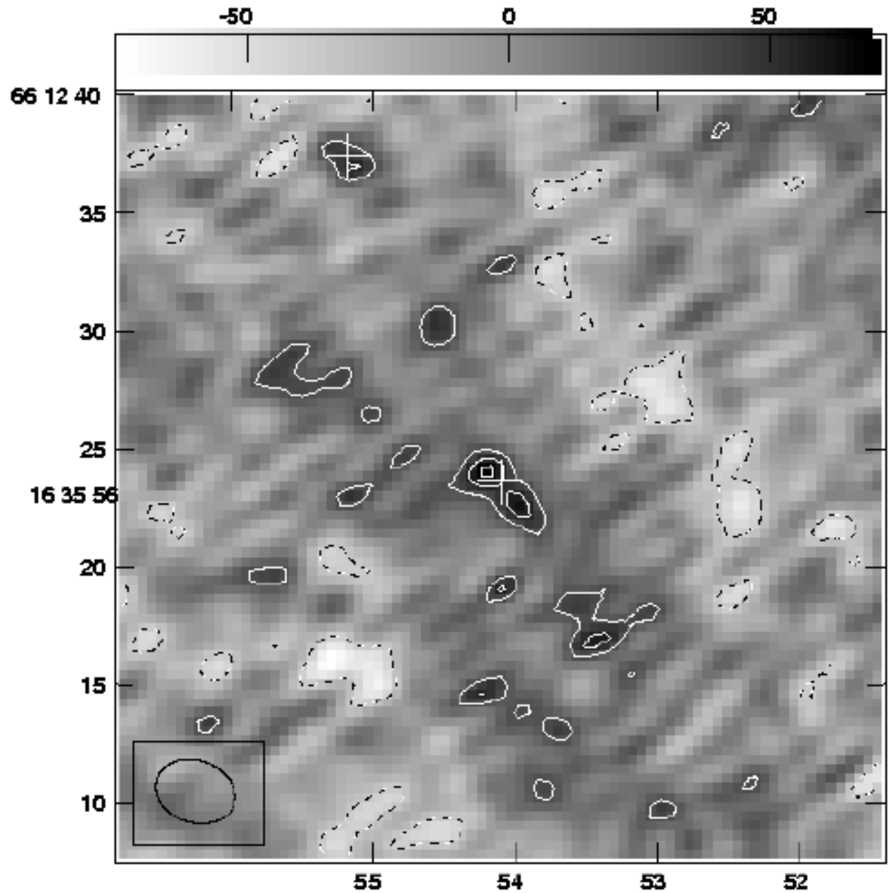


Figure 5: The lower panel shows SMM J16399 in CO(3–2) emission that has been triply imaged by a gravitational lens (Kneib et al. 2004a). The total

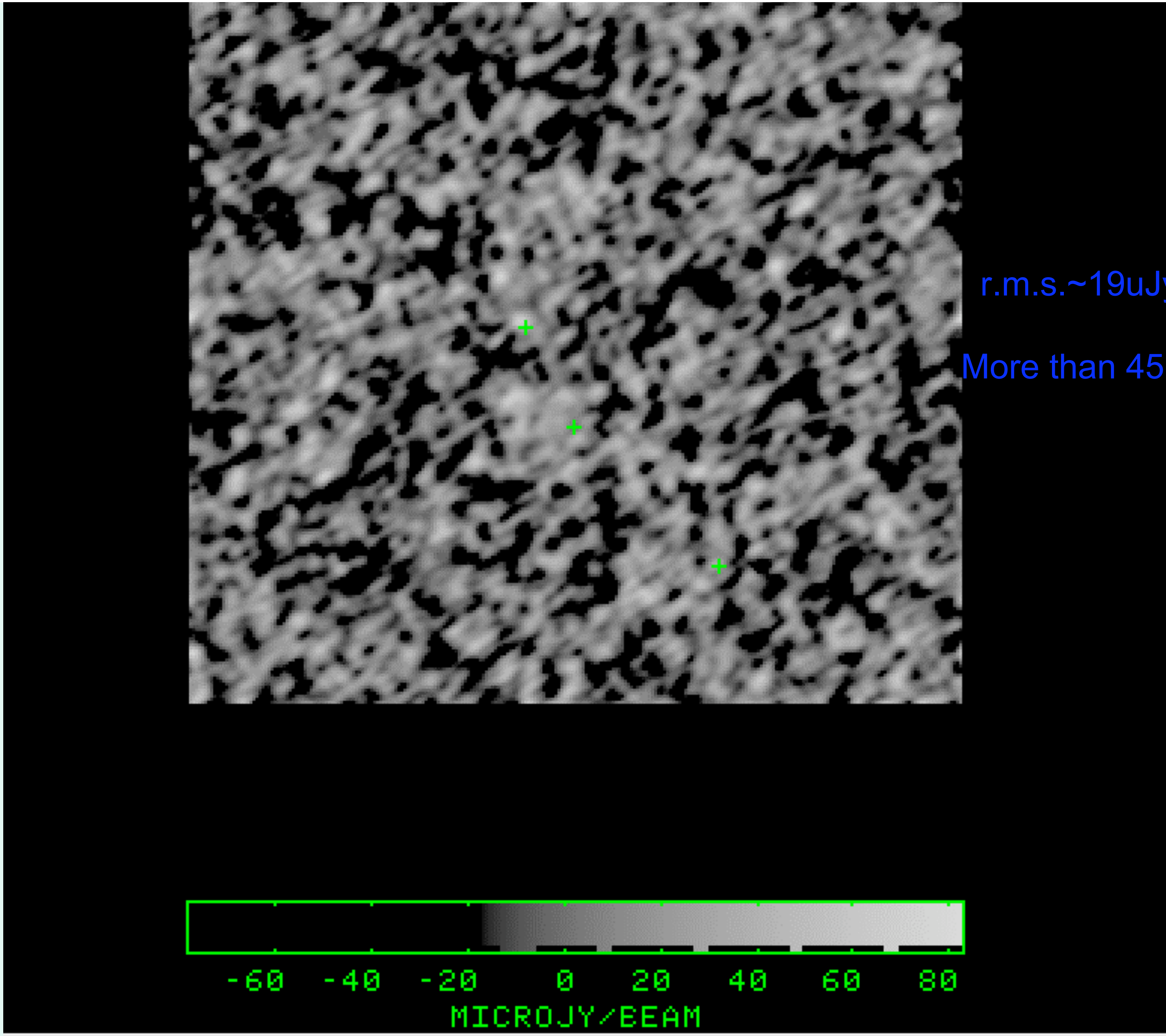
Gao, Carilli, Solomon & Vanden Bout 2007 ApJ, 660, L93





~15hrs VLA,

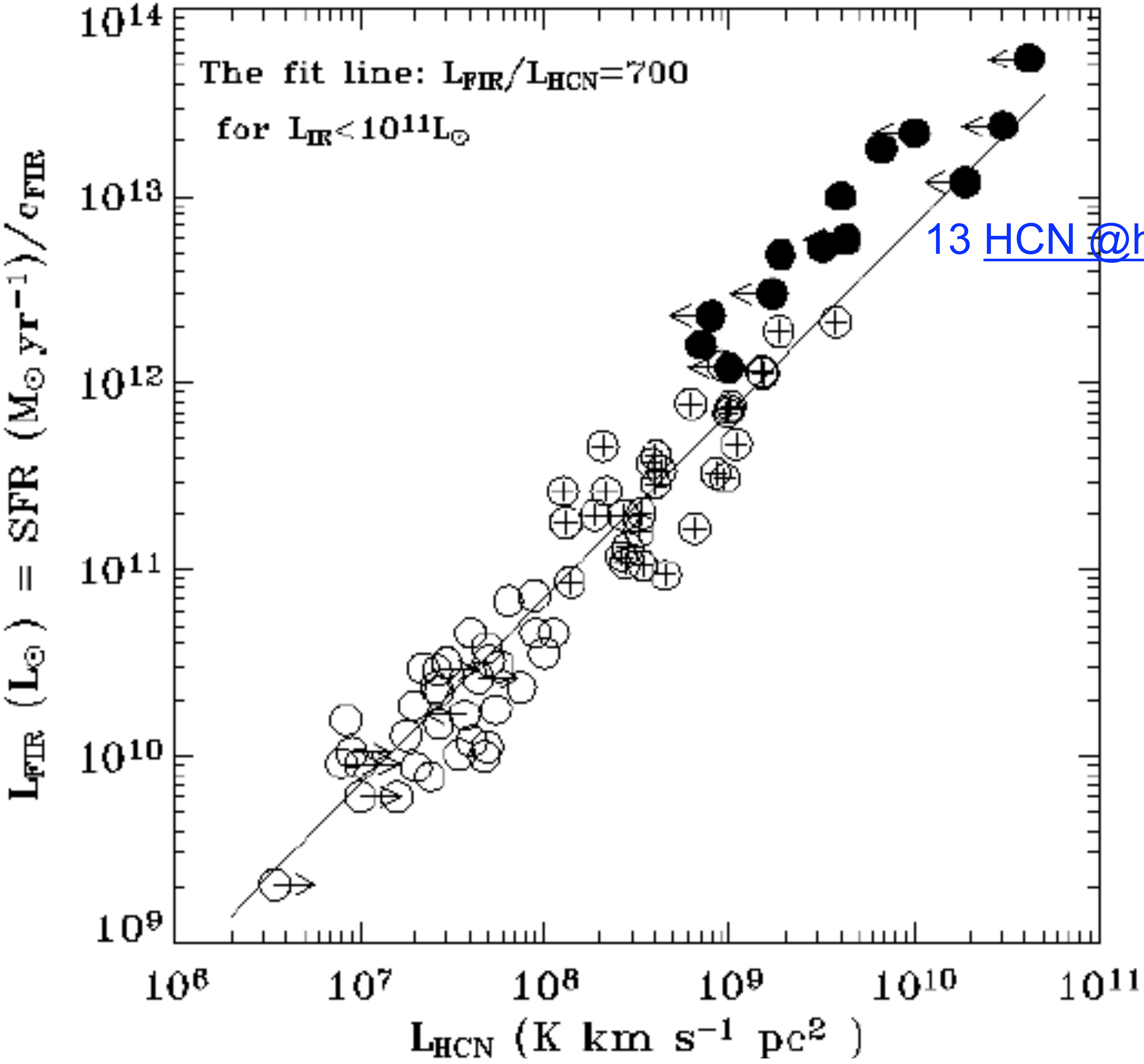
^^^
||
stacking 3 lens components



r.m.s.~19uJy/beam

More than 45hrs VLA

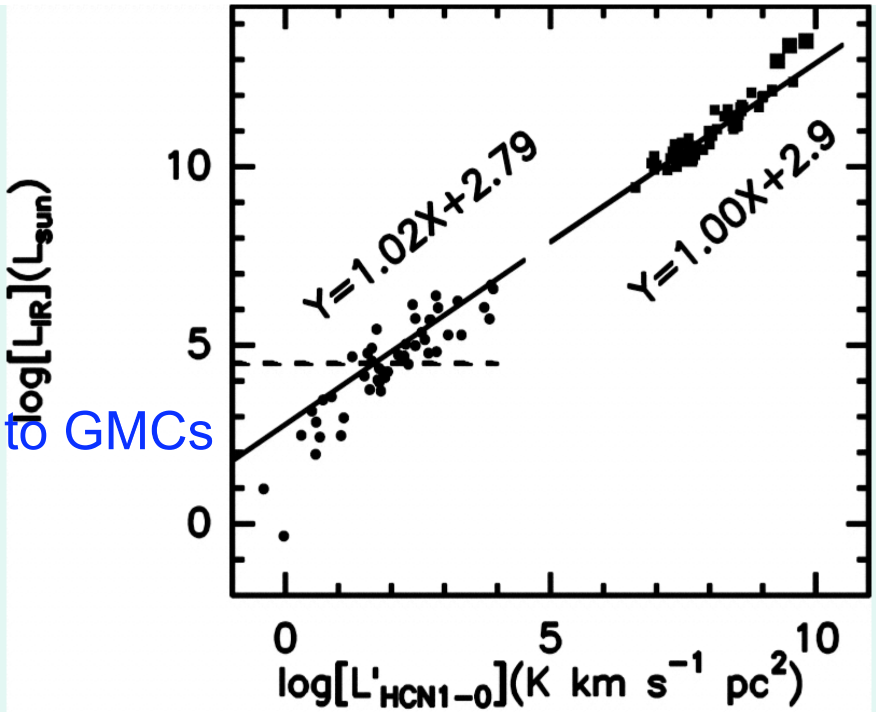
Gao, Carilli, Solomon & Vanden Bout 2007 ApJ, 660, L93



13 HCN @high-z

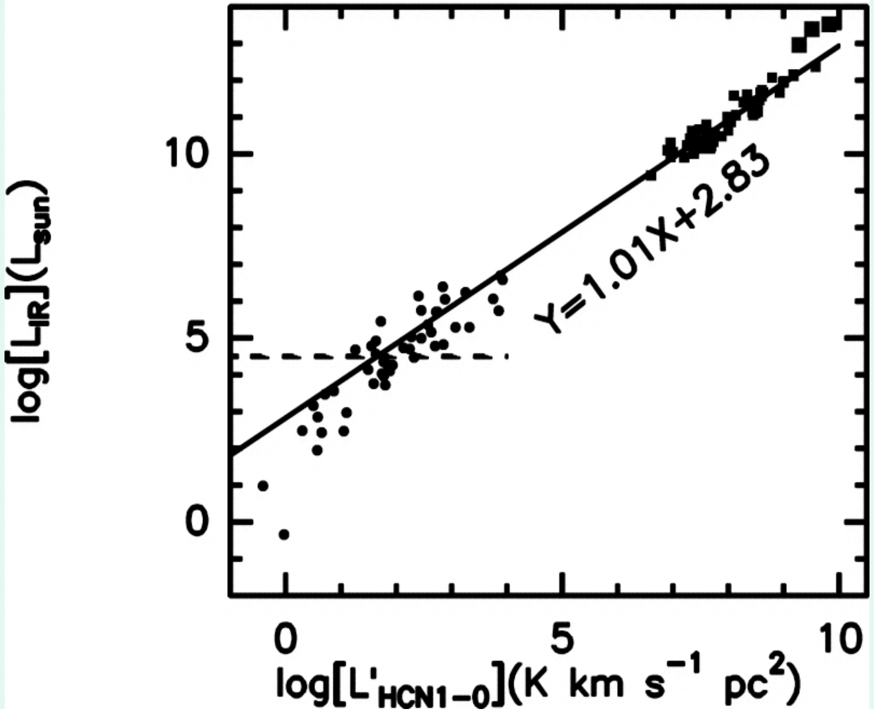
Wu, Evans, Gao
et al. 2005 ApJL

Fit to Galaxies

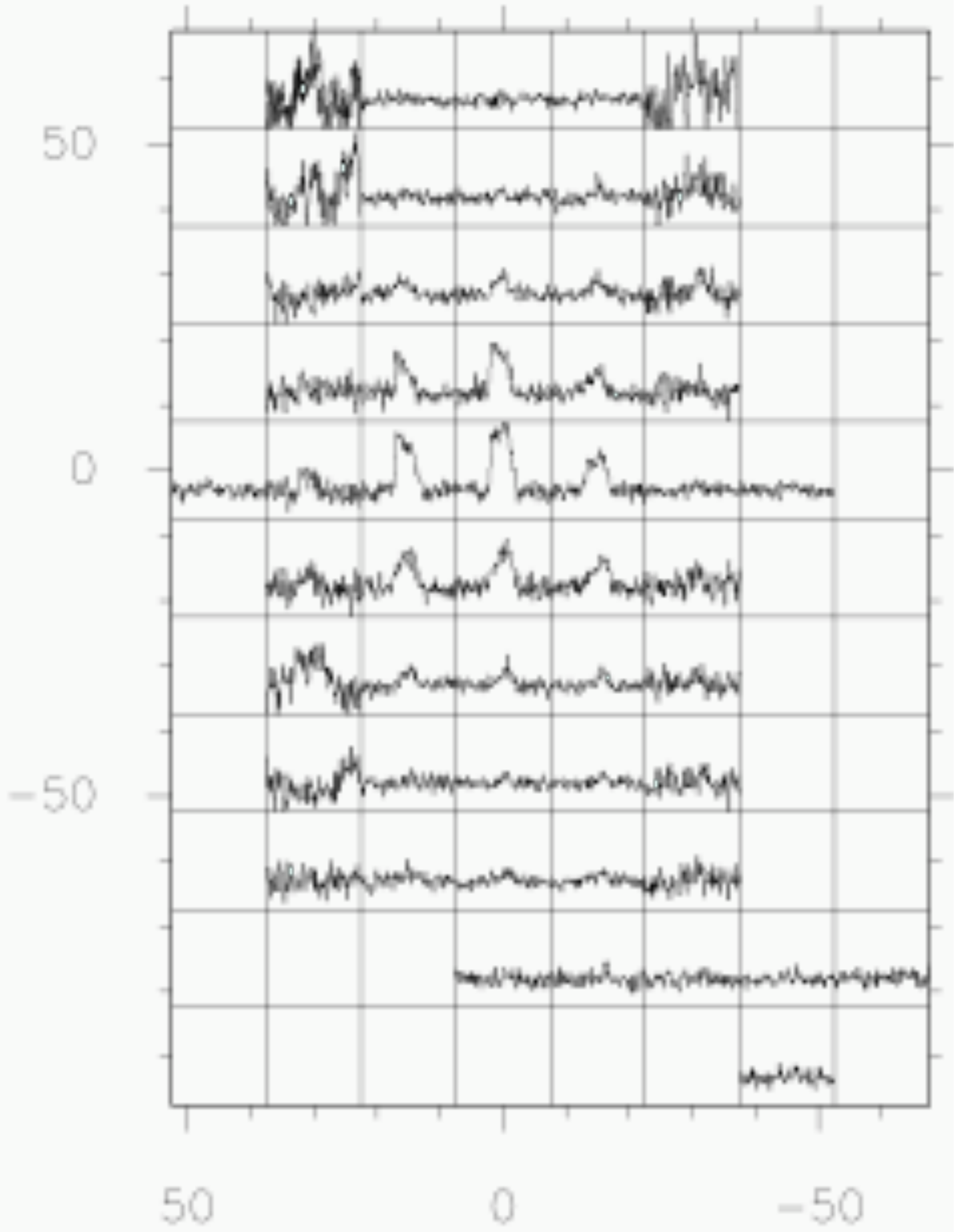


Fit to GMCs

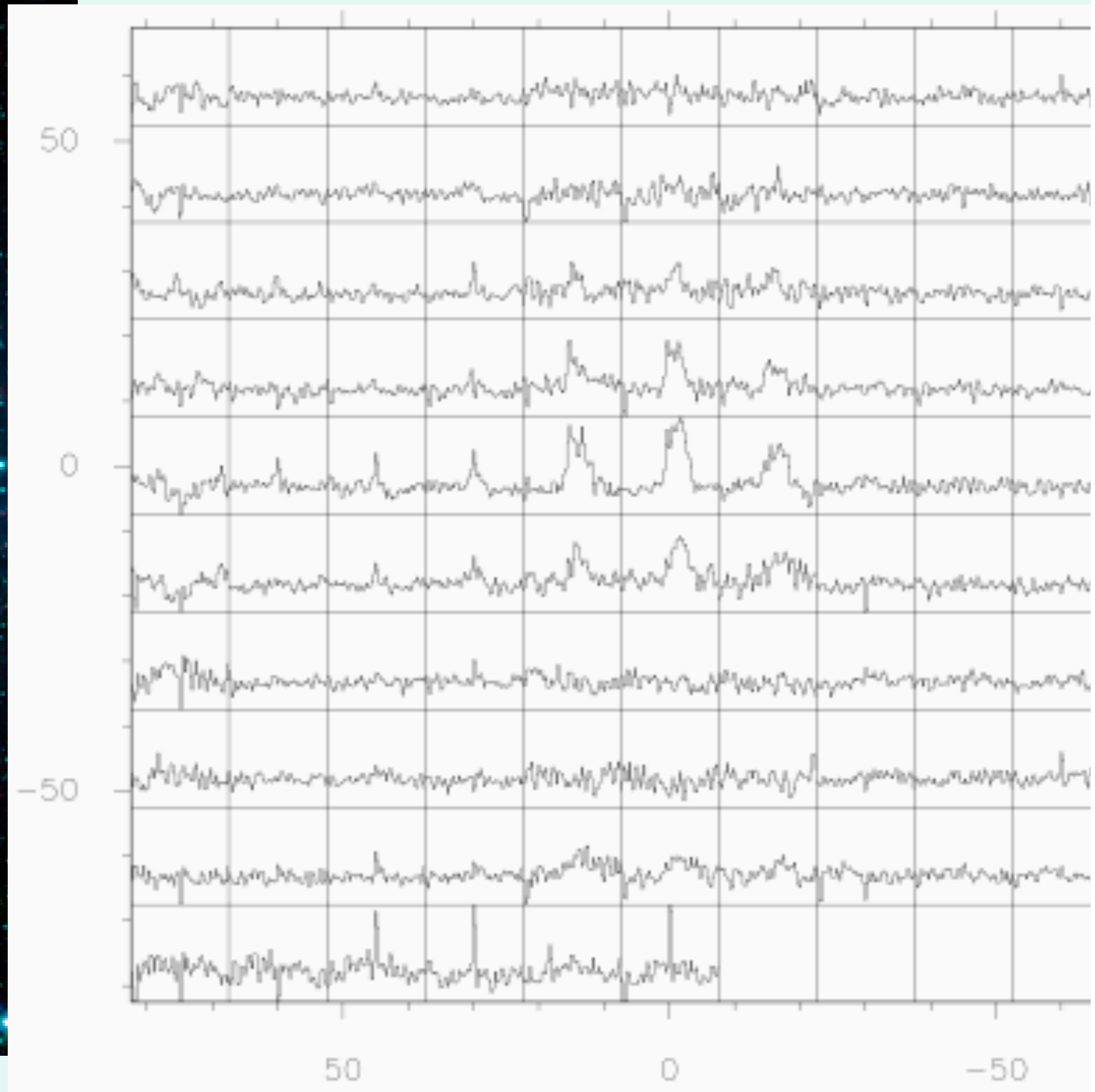
Krumholz & Thompson
2007



Fit to both
GMCs & Gals..



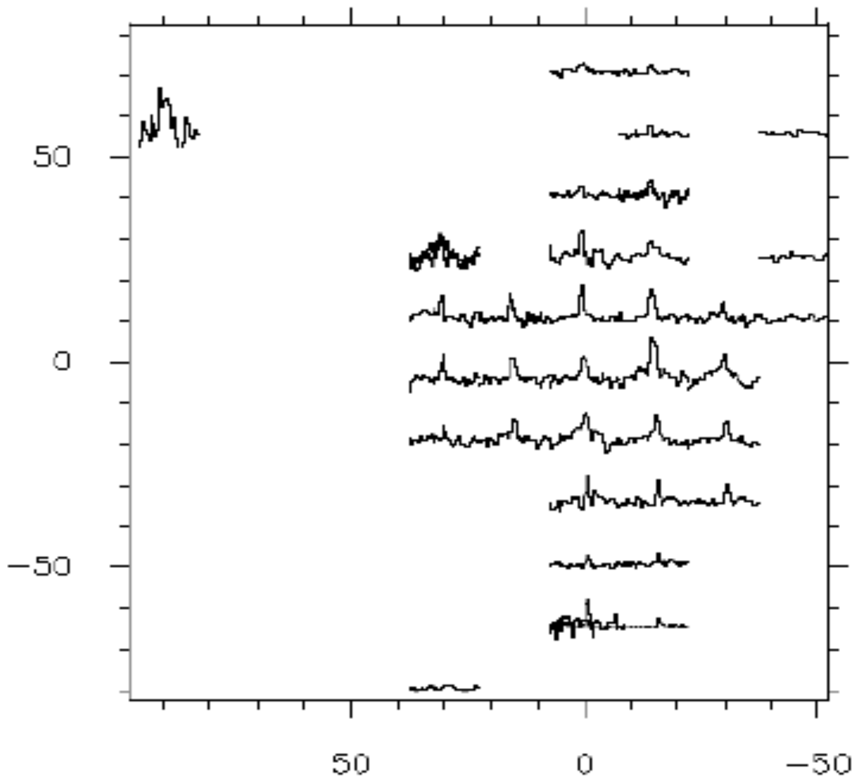
50
0
−50
50
0
−50

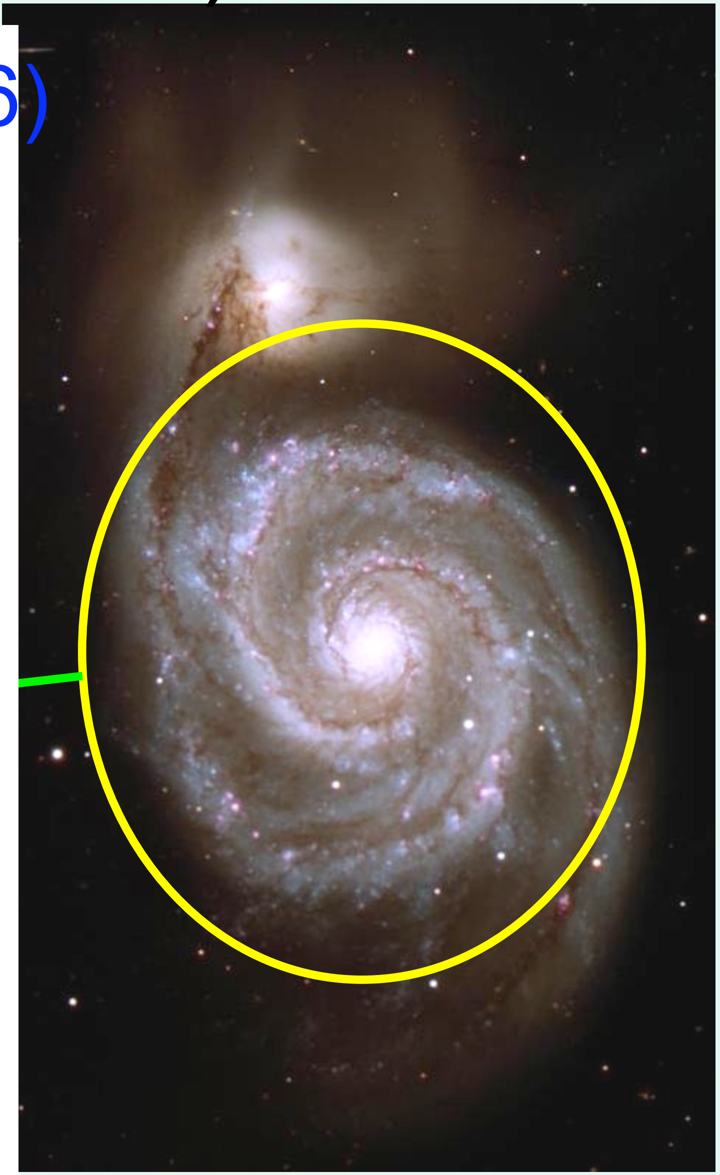


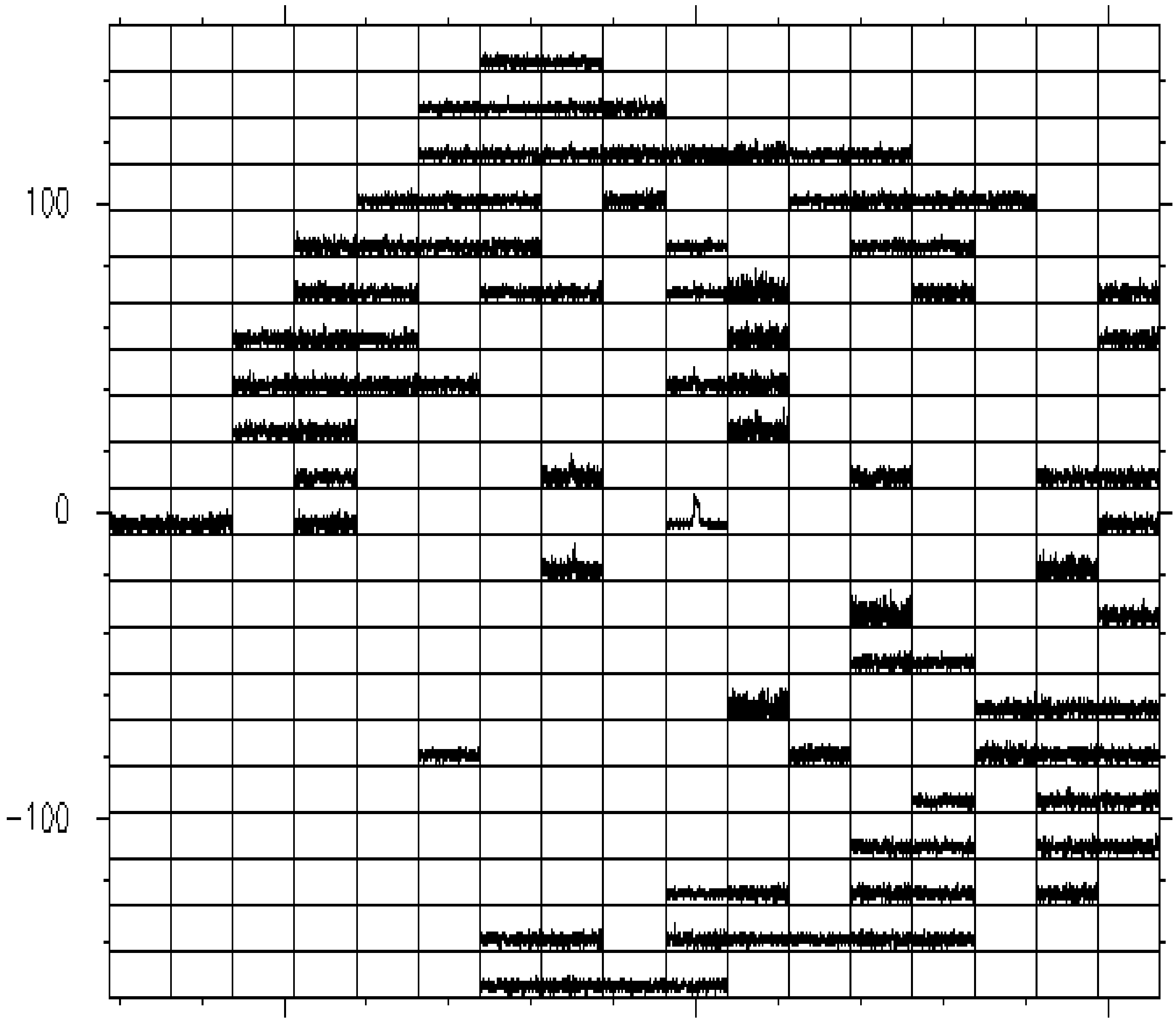
50
0
−50
50
0
−50

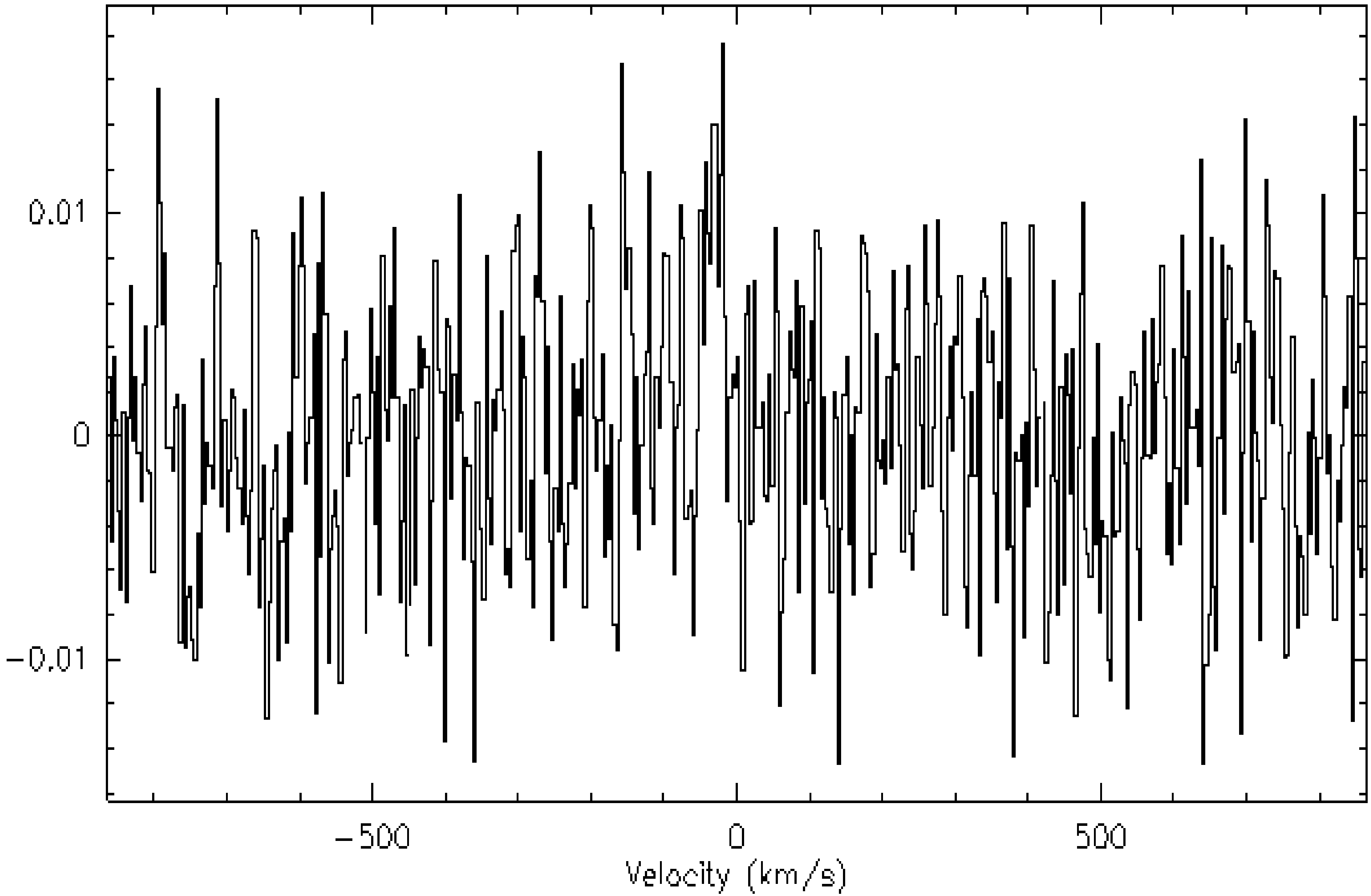
Resovled Local (FIR-HCN) SF Law ?

In Dense Gas (M51 & N6946)

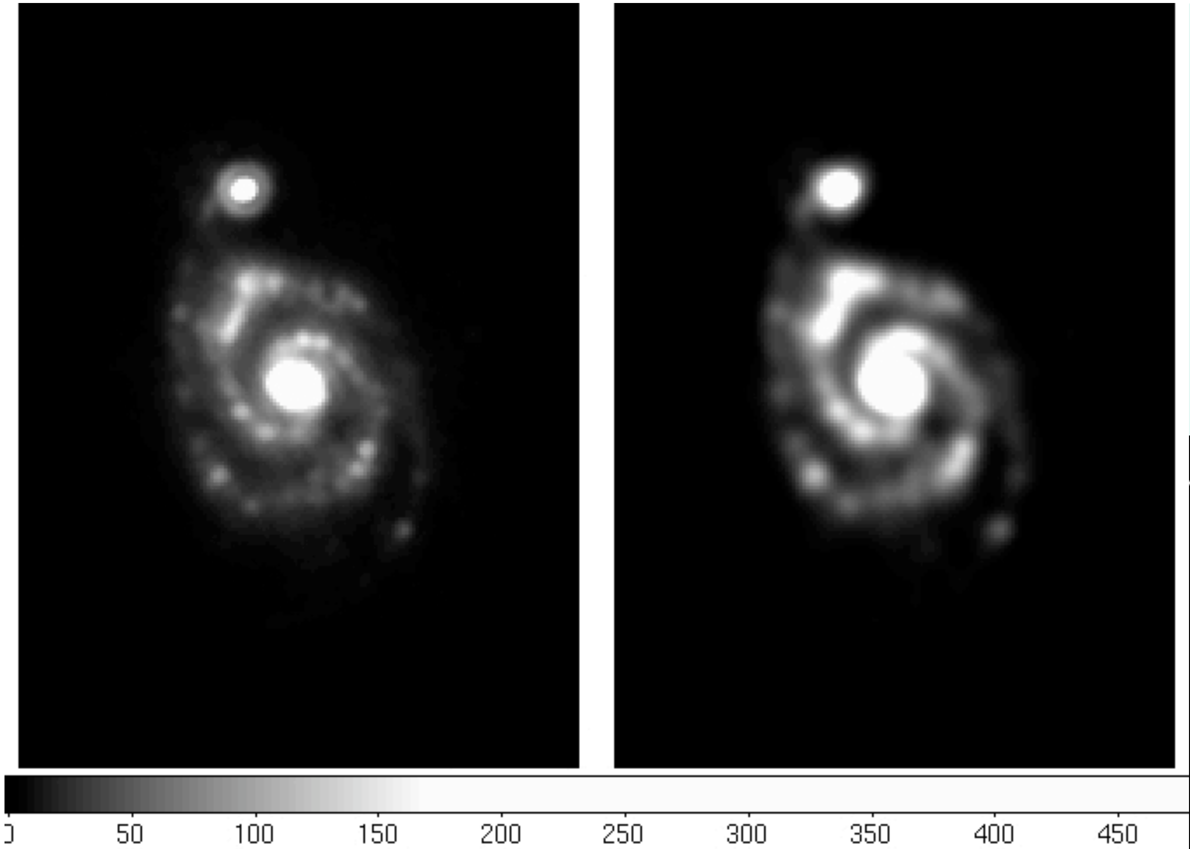




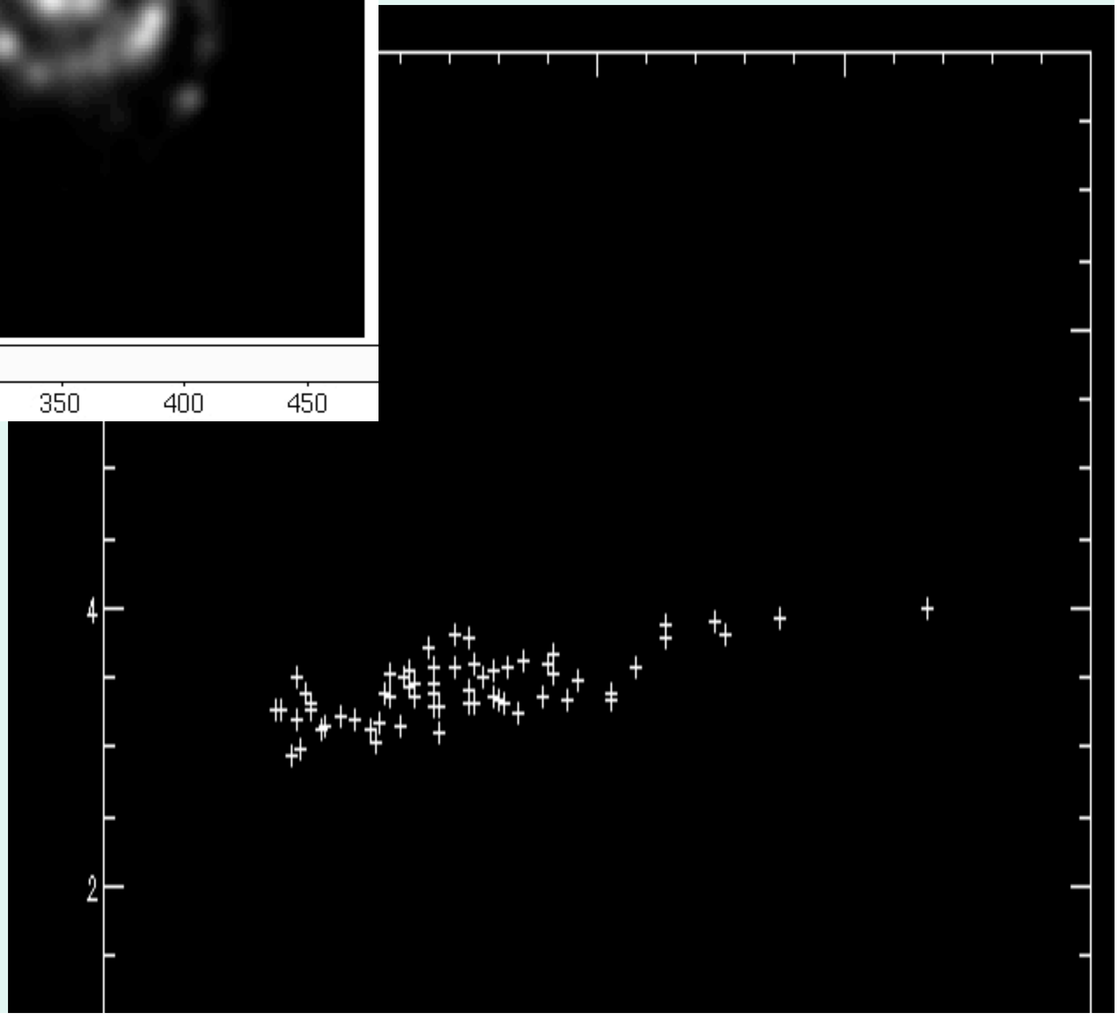

100
0
−100



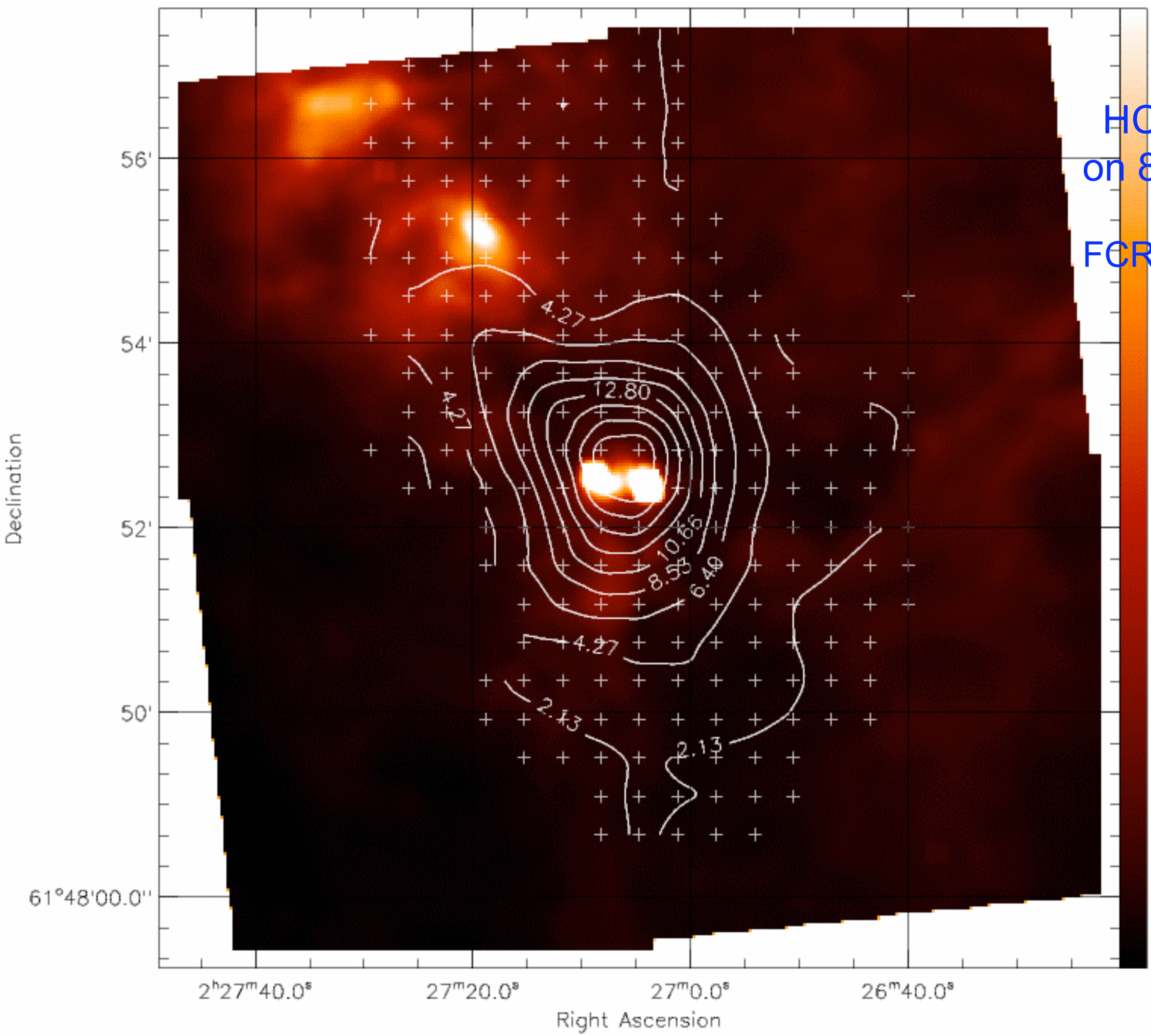
0.01
0
−0.01
−500
0
500
Velocity (km/s)



70um maps & compared to HCN measurements



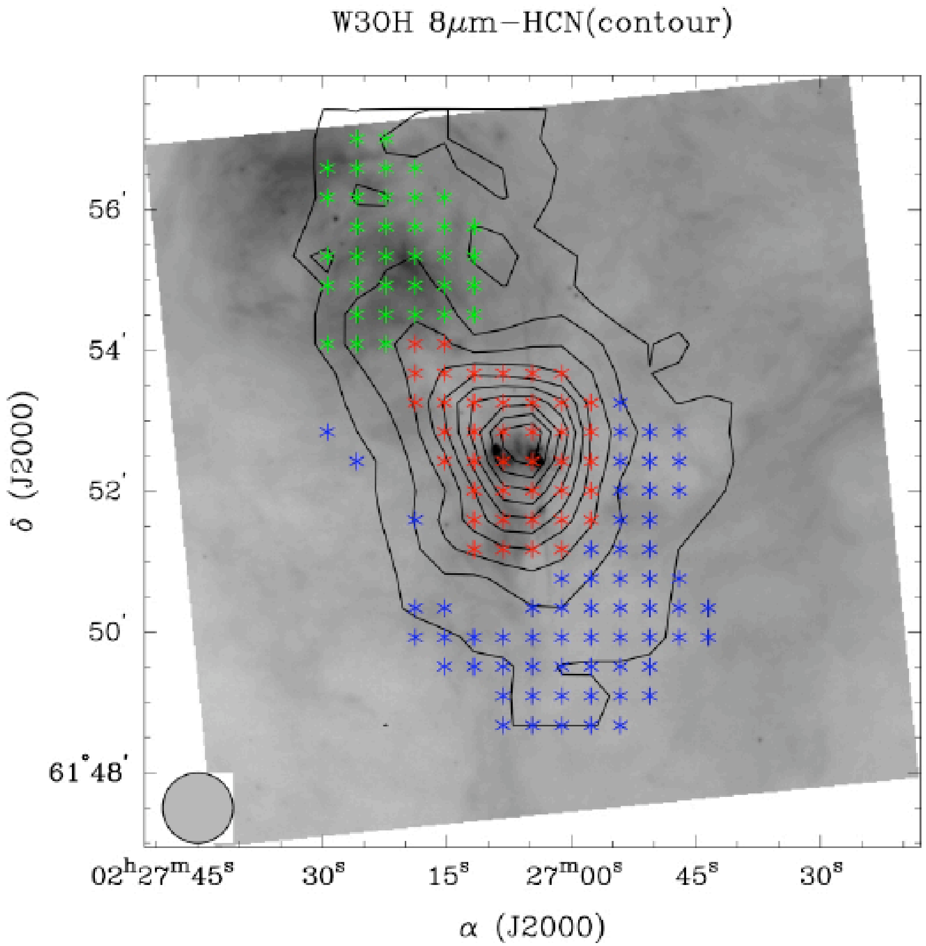
Work in progress

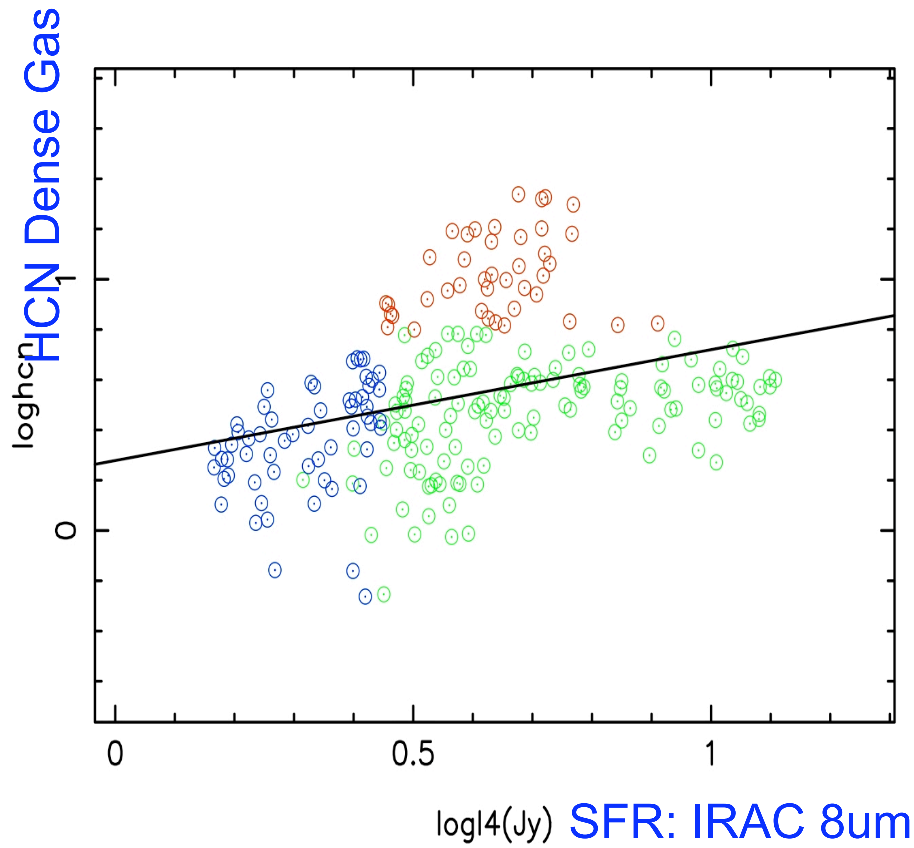


HCN contours on 8um in W3OH

FCRAO SEQUOIA

Ma, Gao & Wu 2009 in prep.

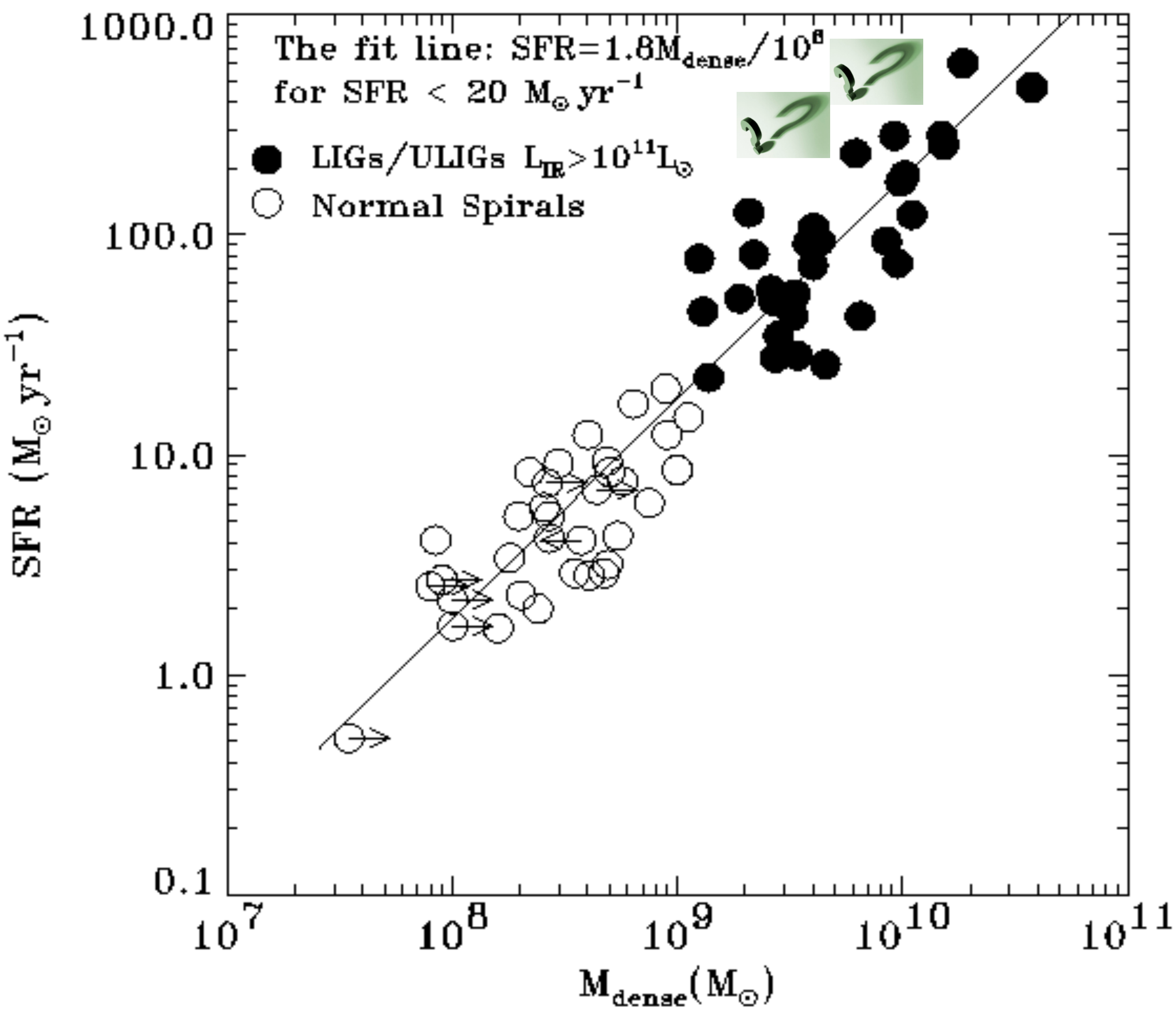




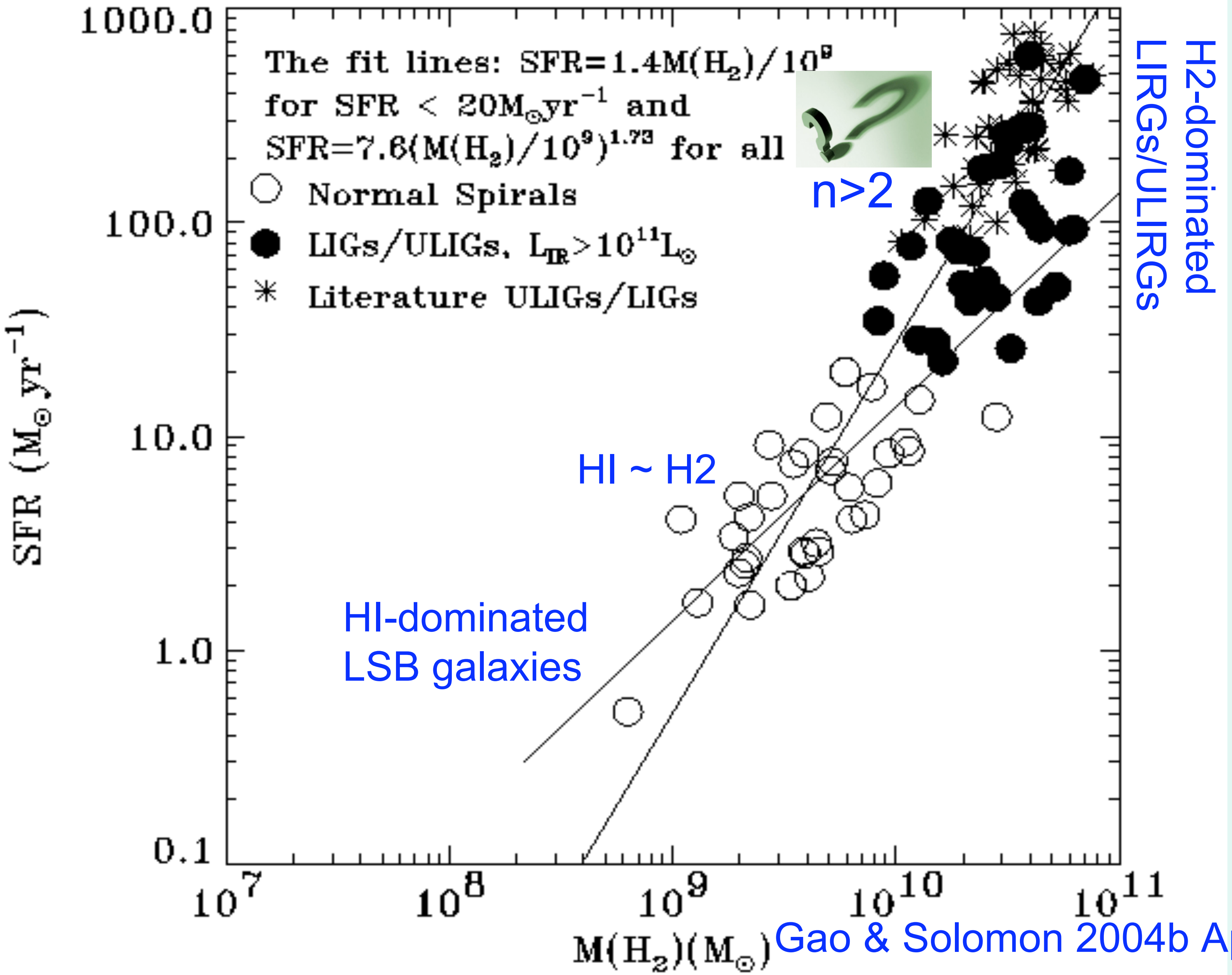
4. Star Formation Schmidt Law: from GMC cores to ULIRGs (& high-z)

- Schmidt (1959): SFR~density(HI)^n,
  n=1-3, mostly 2-3 in ISM of our Galaxy.
- Kennicutt (1989):
  Disk-average [SFR~ density(HI+H2)^n]
  n is not well constrained. ~1-3, wide spread.
- Kennicutt (1998): n=1.4 ?
  Total gas (HI + H2) vs. Dense gas
- Better SF law in dense gas?

SFR vs. M_dense(H2): linear correlation



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



Gao & Solomon 2004b ApJ

5. Concluding Remarks

- Dense Cores Dense Molecular Gas → High Mass Stars
- (FIR-HCN Correlation) SFR ~ M(DenseH2): the total mass of dense molecular gas in galaxies

  (e.g. gas density >~10^5 cc), linear?
- FIR-HCN Correlation in all star-forming systems?
- HI → H2 → DENSE H2 → Stars

  Schmidt law : HI → Stars

  Kennicutt law : HI + H_2 → Stars

  Gao & Solomon: Dense H_2 → Stars

From GMC Cores to High-z: Dense Gas → Massive SF
FIR-HCN linear! -->? SF law linear? n~1.5? In dense gas!