

# CO(J=3-2) observations toward the dust lane in Centaurus A

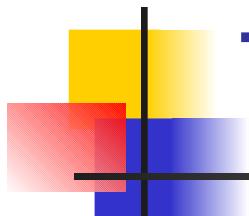


*"The Many Faces of Centaurus A "*

28<sup>th</sup> June - 4<sup>th</sup> July 2009

Sydney, Australia

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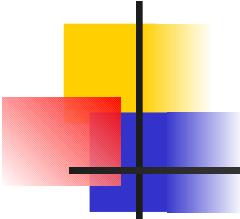


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# ASTE Dense gas Imaging of Star-forming galaxies

## *ADlos Project*



### **Goals of the project: (1) SFE variation**

- Wide area CO(3-2) imaging survey of nearby galaxies
  - CO(1-0) data from 45m+BEARS, Mopra, etc
  - + Ha, radio/Mir continuum etc
- understand spatial variation of star formation efficiency in terms of “dense gas fraction CO(J=3-2/1-0)”

### **Goals of the project: (2) ISM phase variation**

- CI(490 & 800 GHz RX in ASTE, in progress)
  - CII(from AKARI etc.)
- understand global “phase” variation of ISM, from atomic gas to dense gas (and eventually ionized gas)
- Templates for redshifted CO(3-2) & CI observations of high-z galaxies in the ALMA era

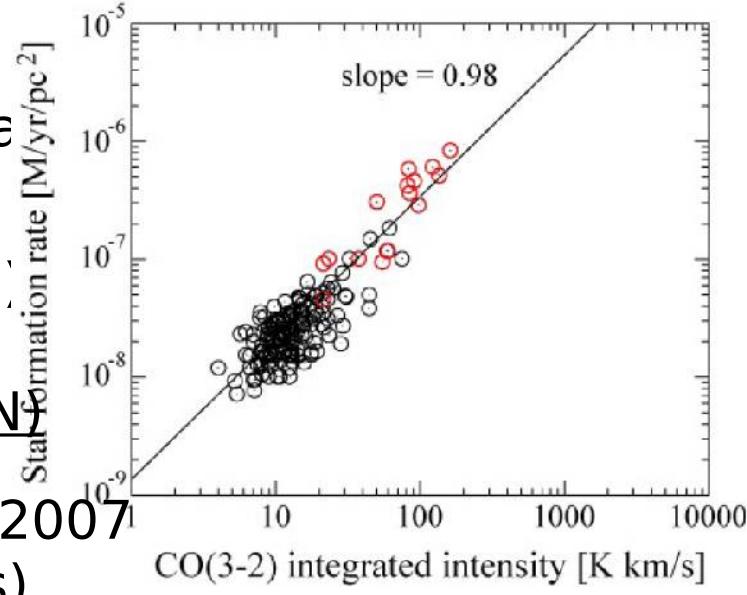


# Science goals: CO(J=3-2) mapping toward Centaurs

A

- **To Reveal a relation between star formation and dense gas in Cen A**
  - Molecular gas distribution
  - Physical property of dense molecular gas
    - Gas temperature & number density
  - Kinematics property
  - Star formation in the dust lane
  - SFR/SFE in the dust lane
    - “Schmidt law” in CO(3-2)

**linear** correlation ! (Similar to HCN)



M83: Muraoka 2007  
(PhD thesis)

# Early study: CO in CenA

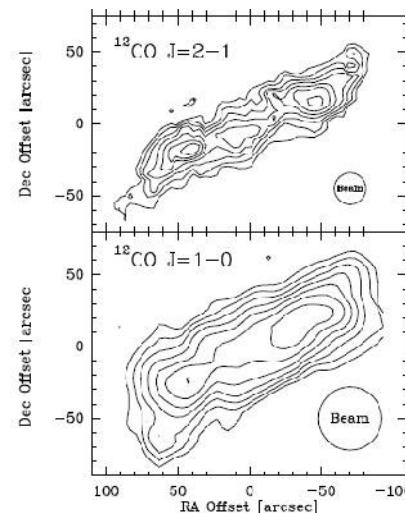
- **Single-dish (SEST/CSO/JCMT)**

- Phillips et al. (1987), Eckart et al. (1990), Israel et al (1990, 1991), Quillen et al (1992), Israel (1992), Rydebeck et al. (1993), Liszt (2001), etc
- $M(H_2) = 2 \times 10^8 M_{\text{sun}}$  (Eckart et al. 1990)
- $T_{\text{kin}} = 10-30 \text{ K}$
- $n(H_2) \sim 10^4 \text{ cm}^{-3}$

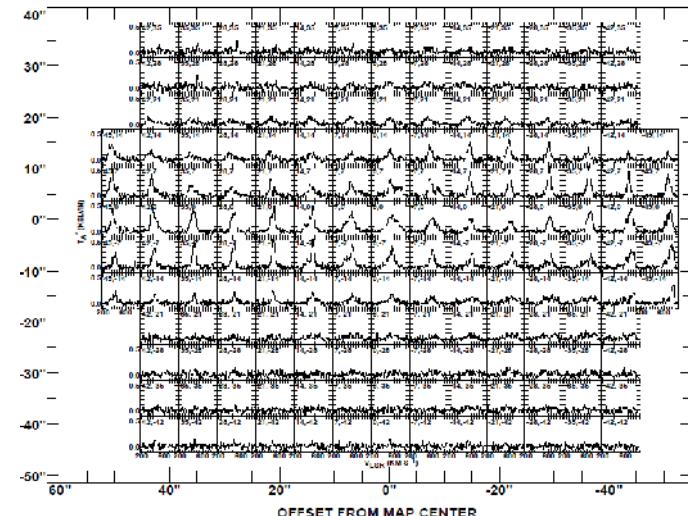
(Wild et al. 1997)

- **Interferometer (SMA)**

- Espada et al. (2009)



CO(1-0/2-1) maps  
Wiklind et al. (1997)



CO(3-2) profile map(100''x100'')  
Liszt (2001)

# CO(J=3-2) Observations w/ASTE

**Antennas:** ASTE 10m telescope

**Receiver:** CATS345 ( $T_{\text{sys}} \sim 300$  K in SSB)  
(IoA, Univ. of Tokyo)

**Spectrometer:** WHSF 2048MHz mode

**On-the-Fly mapping:** 7' x 3.5'

**CO cube**

Spatial resolution: 22 arcsec

Velocity resolution: 10 km/s

Sensitivity:  $dT_{\text{mb}} = 60$  mK  
:  $\text{rms}(M(H_2))/B = 1.5 \times 10^6 M_{\text{sun}}$

cf. Liszt 2001

$dv = 3.26$  km/s,  $dT = 55$  mK

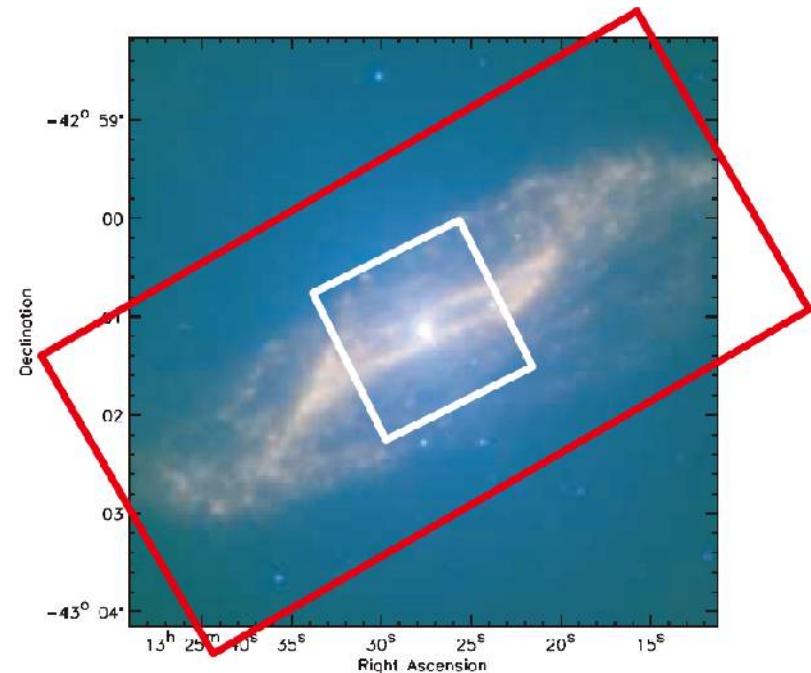
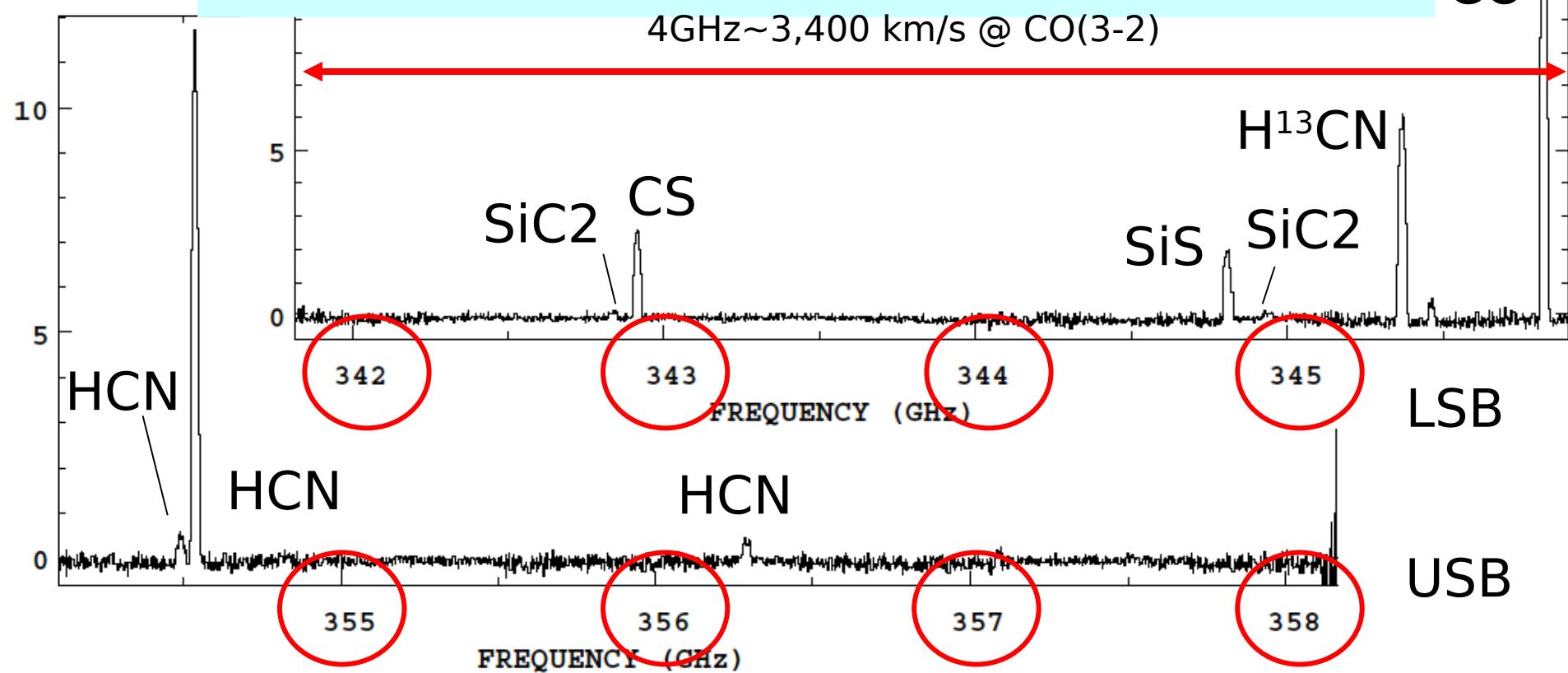


Fig. Spitzer IRAC image  
(Quillen et al. 2006)  
White Box: Liszt 2001(100''x100'')  
Red Box: This work

# CATS345(2SB RX)+WHSF: 4096MHz(USB/LSB) x 2 = 8192MHz

- IRC+10216 w/ the **WHSF + CATS345** on ASTE



Okuda & Iguchi (2007), Iguchi & Okuda (2008), Okuda et al. (in prep.)

# CO(J=3-2) Observations w/ASTE

**Antennas:** ASTE 10m telescope

**Receiver:** CATS345 (345GHz 2SB RX)  
(IoA, Univ. of Tokyo)

**Spectrometer:** WHSF 2048MHz mode

**On-the-Fly mapping:** 7' x 3.5'

**CO cube**

Spatial resolution: 22 arcsec

Velocity resolution: 10 km/s

Sensitivity:  $dT_{mb} = 60 \text{ mK}$

$$: \text{rms}(M(H_2))/B = 1.5 \times 10^6 M_{\text{sun}}$$

cf. Liszt 2001

$$dv = 3.26 \text{ km/s}, dT = 55 \text{ mK}$$

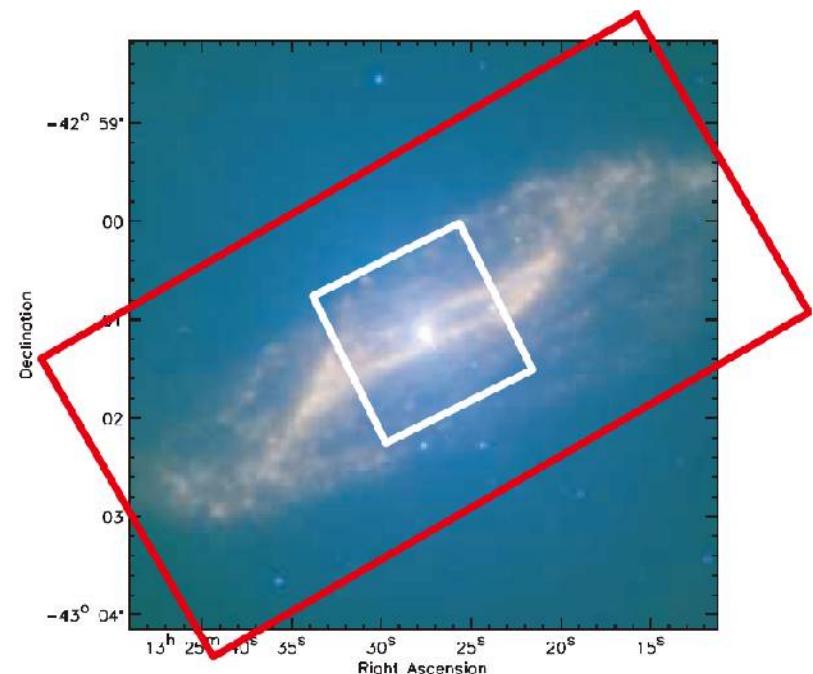
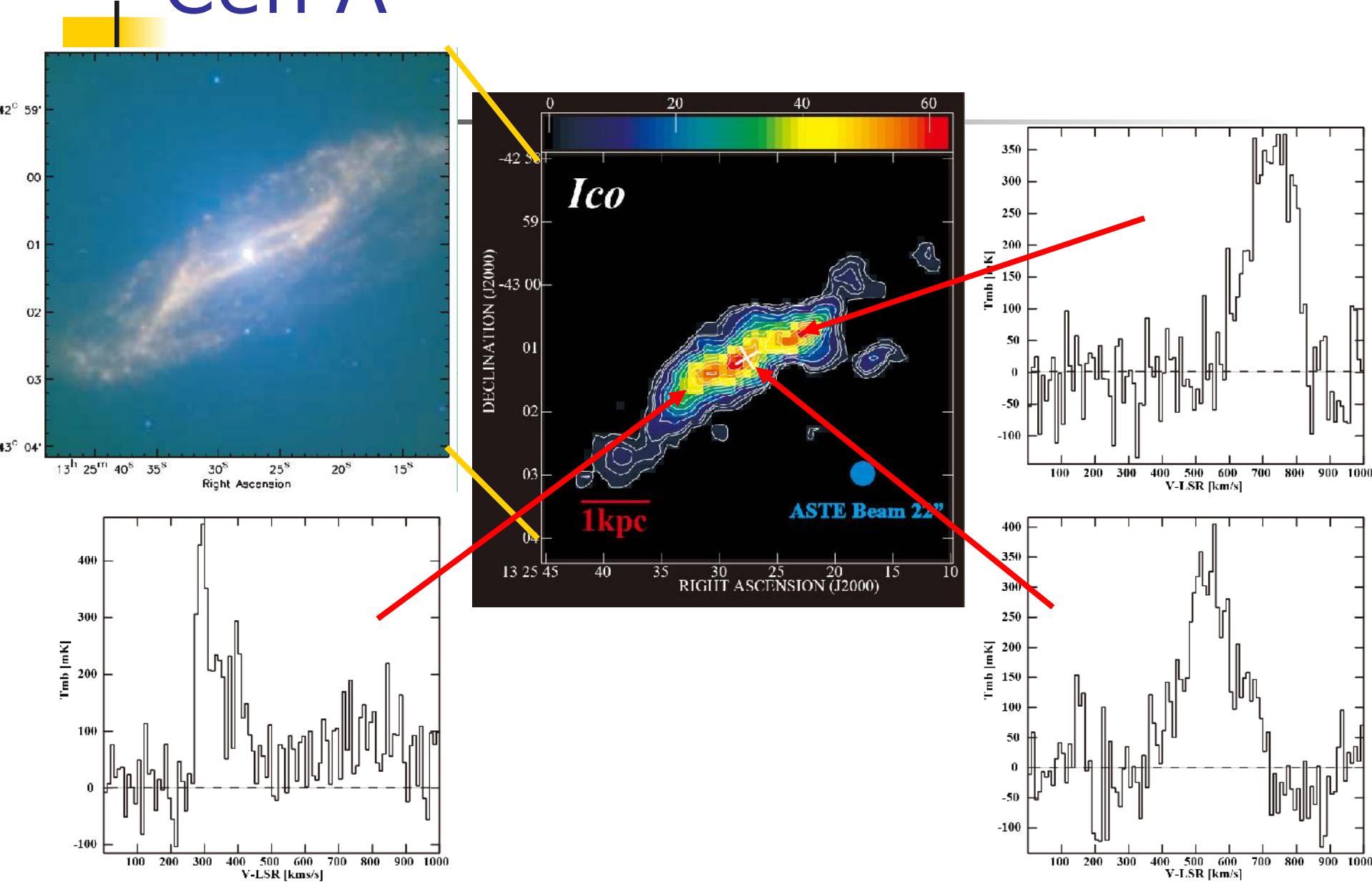
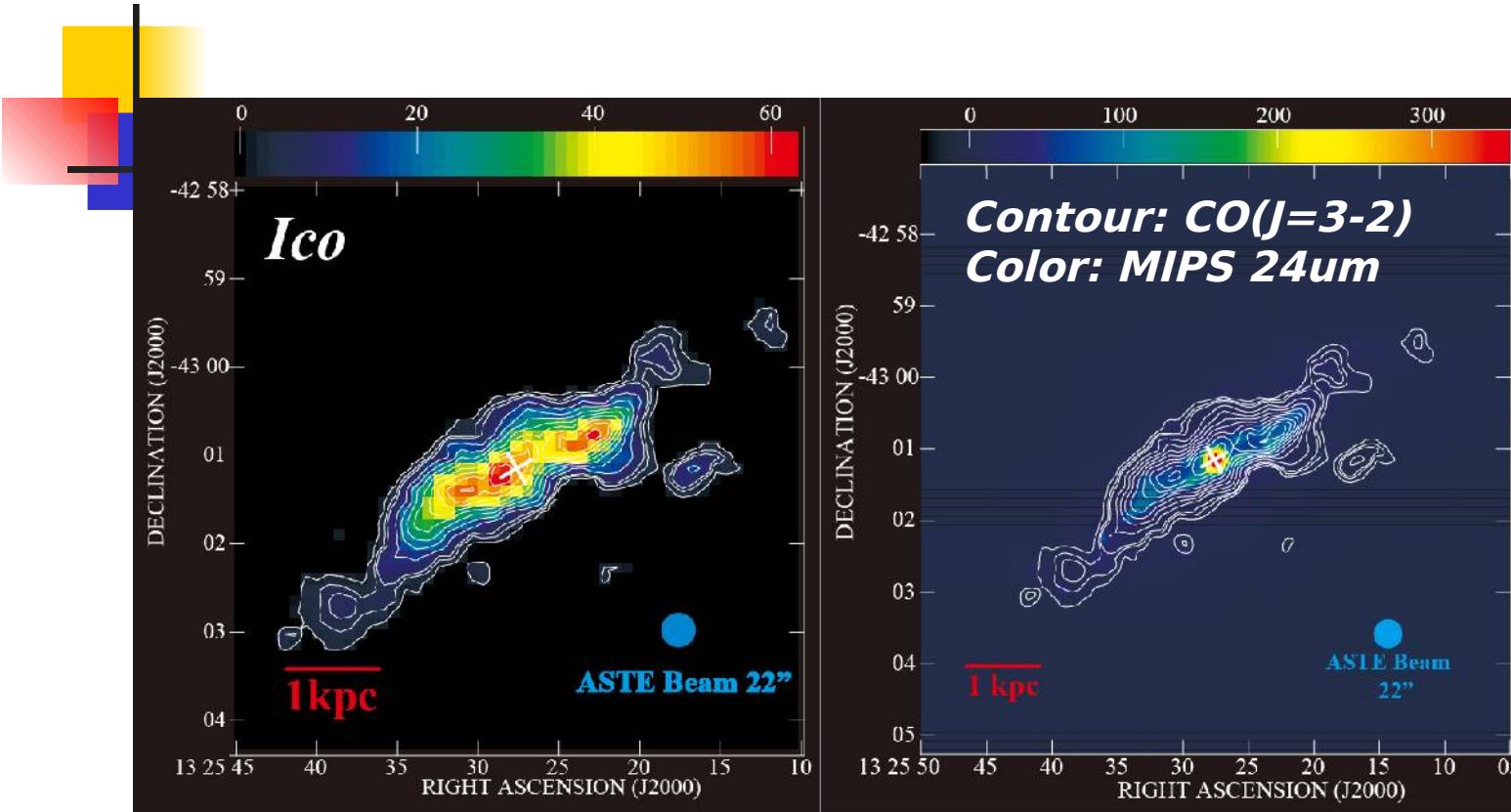


Fig. Spitzer IRAC image  
(Quillen et al. 2006)  
White Box: Liszt 2001(100''x100'')  
Red Box: This work

# CO(3-2) maps and spectra in Cen A

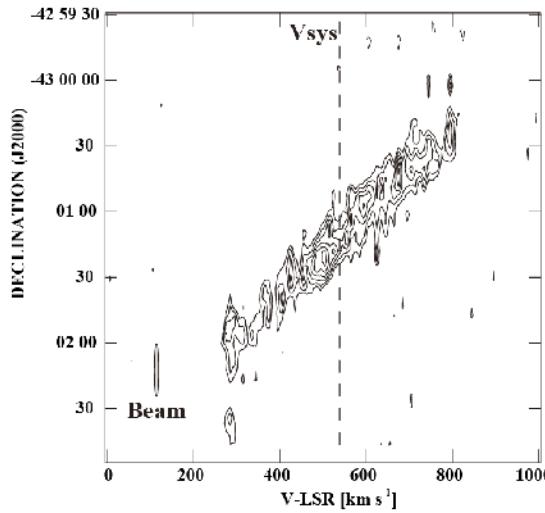
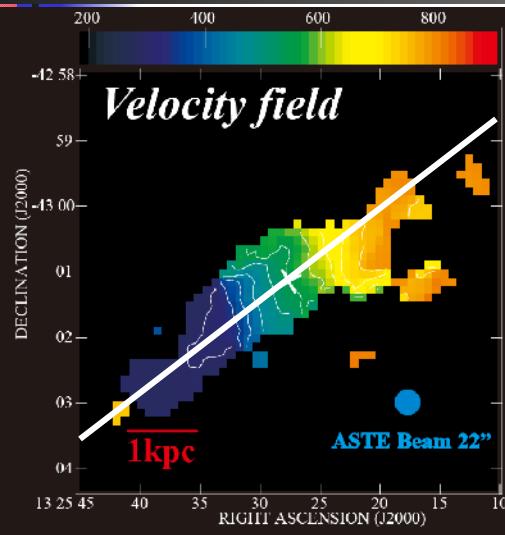


# CO(3-2) maps of Cen A w/ ASTE



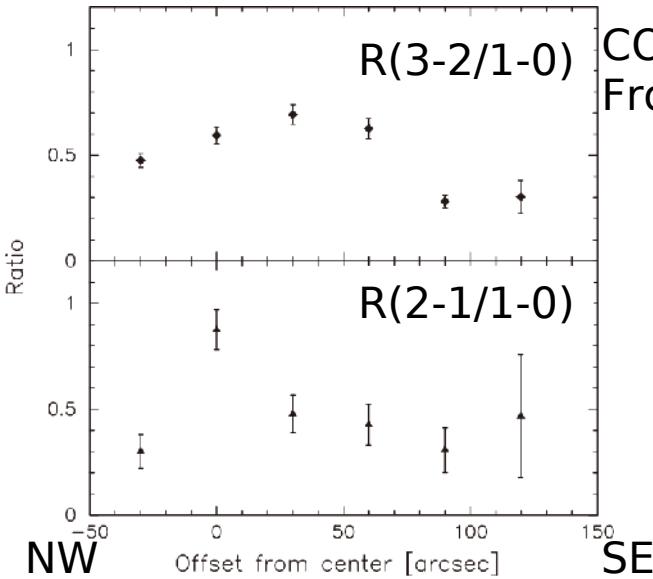
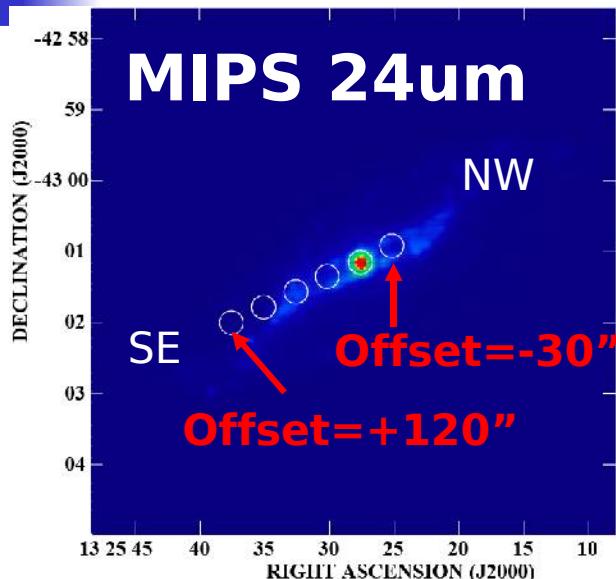
- CO( $J=3-2$ ) emission nicely coincides with the dust lane.
- $L'_{CO(3-2)} = 9.8 \times 10^7 [K \text{ km/s pc}^2]$   
Assuming  $X(CO) = 1.8 \times 10^{20} [\text{cm}^{-2}/(\text{K km s}^{-1})]$  and  
 $CO(3-2)/(1-0)$  ratio of 0.5,  $M(H_2) = 1.6 \times 10^9 M_{\text{sun}}$   
(CO(1-0) data taken from Eckart et al 1990 )

# Kinematics parameters: P-V diagram & Dynamical Mass



- Kinematic parameters derived from CO(3-2) velocity field
  - Dynamical center  
RA(J2000) : 13h25m27.23s  
Dec(J2000): -43d01'18.2"
  - I=77deg, PA=-56deg
  - Vmax = 310 km/s
- P-V diagram along PA=-56deg
  - $M_{\text{dyn}} = 5 \times 10^{10} \text{ Msun}$  ( $r < 2 \text{ kpc}$ )
  - $M(H_2) = 1.4 \times 10^9 \text{ Msun}$  ( $r < 2 \text{kpc}$ )
  - $M(H_2) / M_{\text{dyn}} = 0.03$

# CO line ratio along the dust lane



CO(1-0) &(2-1)  
From Eckart et al. (1990)

- $R(3-2/1-0)$  ( $\text{offset} < 60''$ )  $>$   $R(3-2/1-0)$  ( $\text{offset} > 90''$ )  
 $T_{\text{dust}}(r < 90'') \sim 40\text{K}$ ,  $T_{\text{dust}}(r > 90'') \sim 30\text{K}$  (Leeuw et al. 2002)  
The variation of CO(3-2)/(1-0) ratios along caused by temperature effect (?)

# Comparison between Centaurus A and FR-I type RG 3C 31

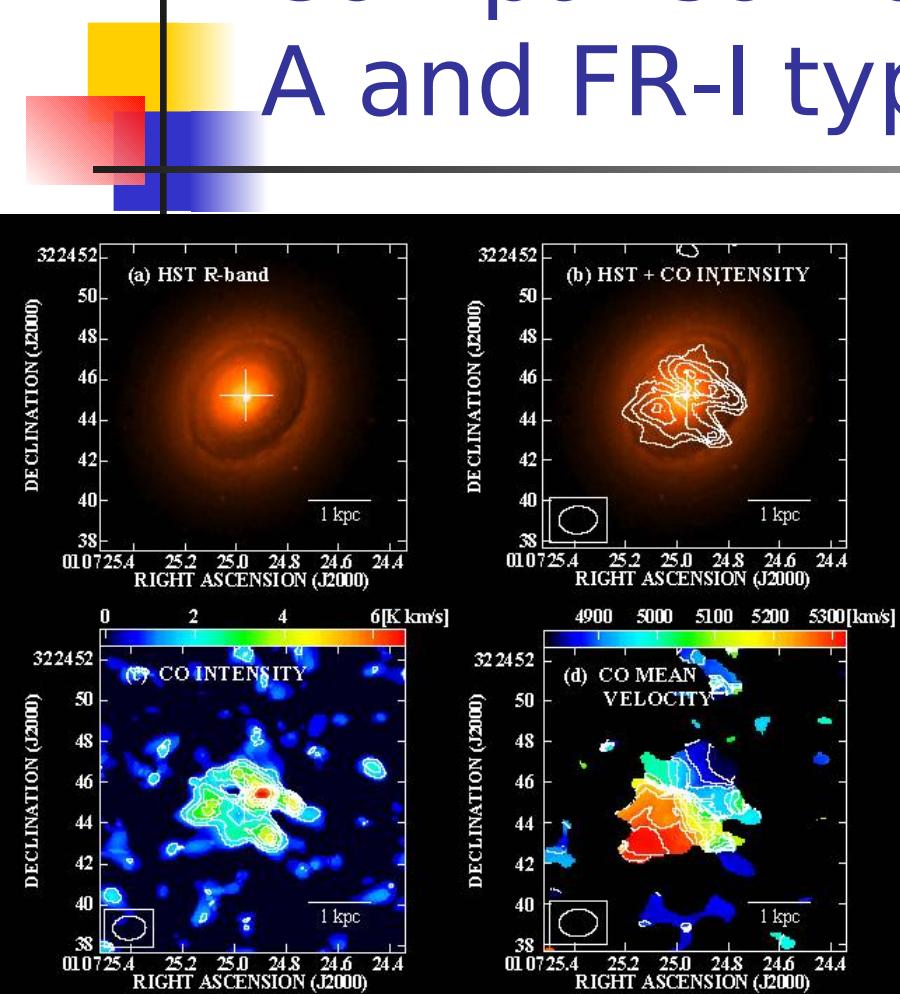


Fig. (a) HST R-band image; (b) NMA/RAINBOW CO(1-0) image superposed on HST image; (c) NMA/RAINBOW CO(1-0) image. beam size =  $1''.6 \times 1''.2$ ; (d) NMA/RAINBOW CO(1-0) mean velocity map +: nucleus (8GHz peak) (Okuda et al. 2005)

- Centaurus A

$M_{\text{dust}} \sim 10^6 M_{\text{sun}}$ ,  $T_{\text{dust}} = 30\text{-}40 \text{ K}$   
 (Leeuw & Eckart 2002)  
 $R(2\text{-}1)/(1\text{-}0) \sim 0.85\text{-}1.1$  (Wild et al. 1997)

$M(H_2) \sim 1 \times 10^9 M_{\text{sun}}$ ,  $M_{\text{gas}}/M_{\text{dyn}} = 0.03$

- 3C 31 (D=70Mpc)

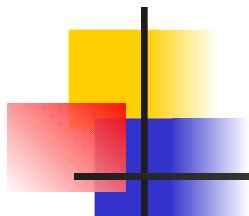
$M_{\text{dust}} = 10^7 M_{\text{sun}}$ ,  $T_{\text{dust}} = 24 \text{ K}$   
 (Muller et al. 2004)  
 $R(2\text{-}1)/(1\text{-}0) \sim 1$  (Lim et al. 2000)  
 $M(H_2) \sim 1 \times 10^9 M_{\text{sun}}$ ,  $M_{\text{gas}}/M_{\text{dyn}} = 0.02$

***No evidence of massive star formation***  
 (Owen et al. 1990)

What is a trigger of star formation RGs ?

Gravitationally instability?

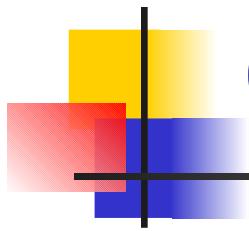
Cloud-cloud collision as a result of mergers?



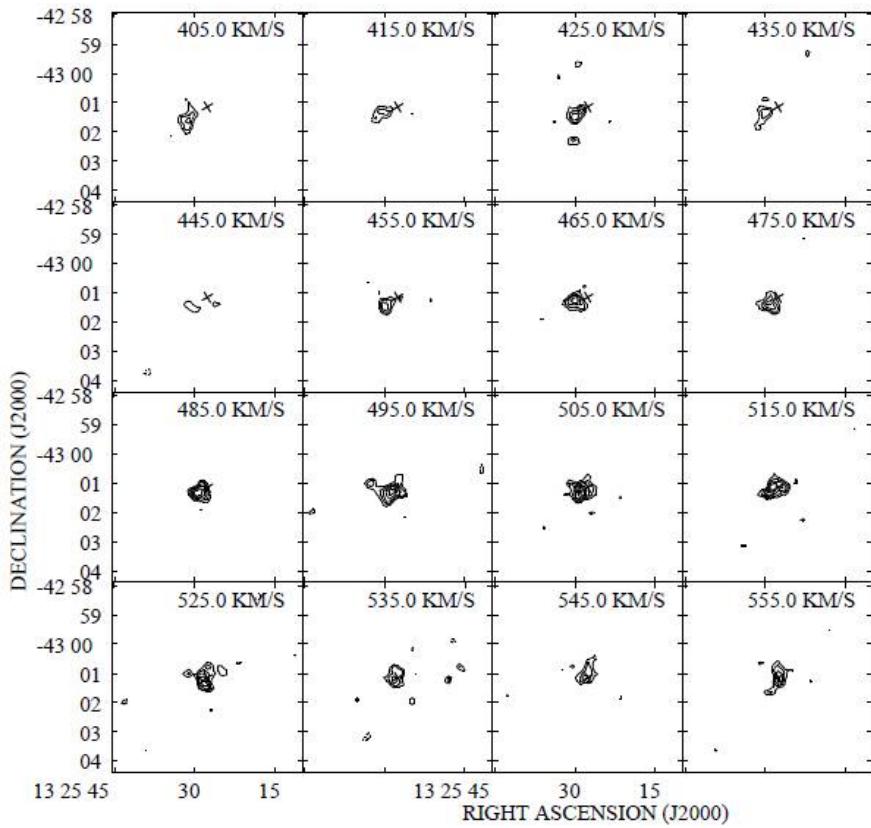
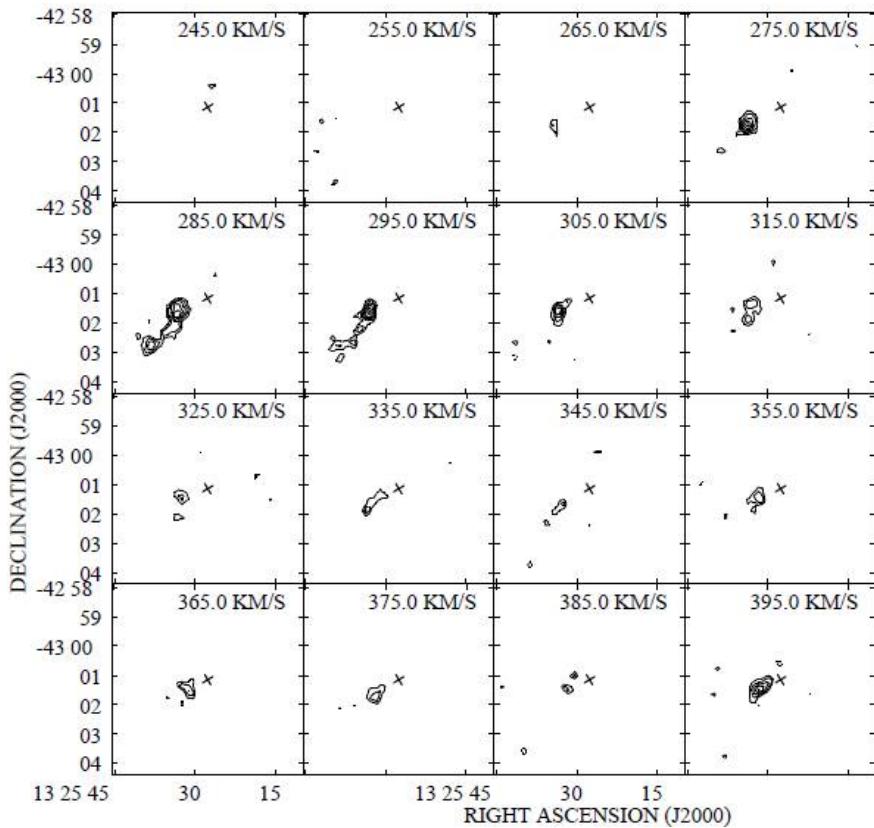
# Summary

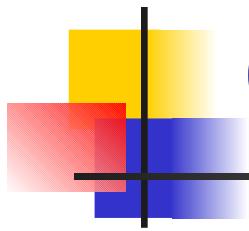
- CO( $J=3-2$ ) observations of Centaurs A have been made using ASTE and newly developed spectrometer WHSF.
- Our image shows CO(3-2) emission closely coincides with the dust lane.
- It is suggested that CO(3-2)/(1-0) ratios along the dust lane are influenced by temperature of ISM.
- ***Future***
  - CO(4-3) & CI OTF mapping w/ ASTE
  - LVG analysis to determine physical properties



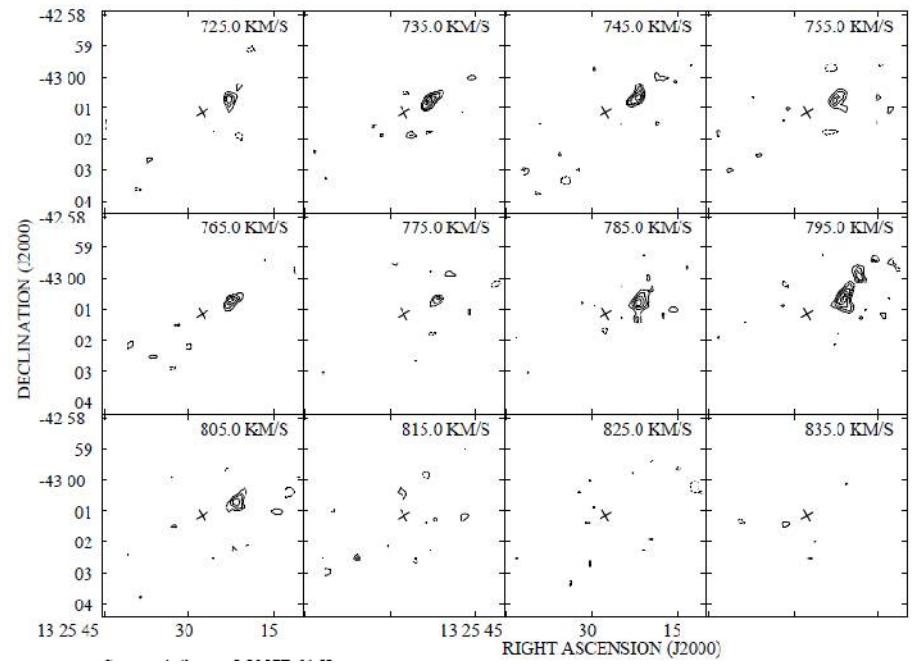
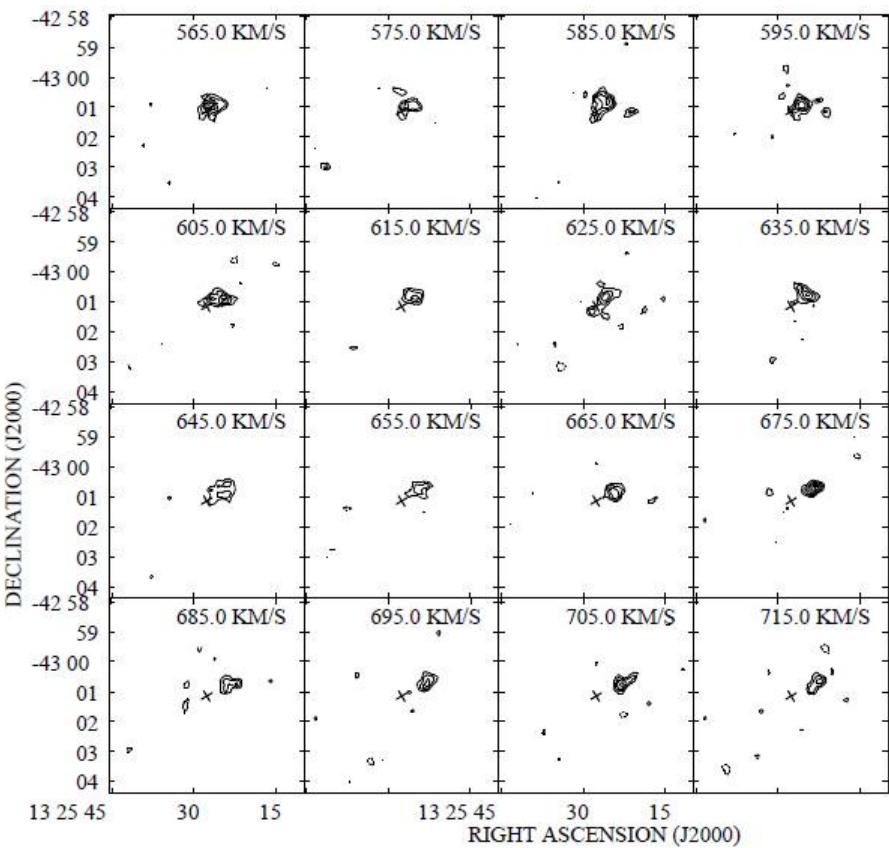


# Channel map (1)





# Channel map (2)



# New 345 GHz RX

# CATS345

- 2SB technologies implemented by Asayama et al. (NAOJ)
- IF band : 4.0 – 8.0 GHz
- Side band rejection ratio >10 dB



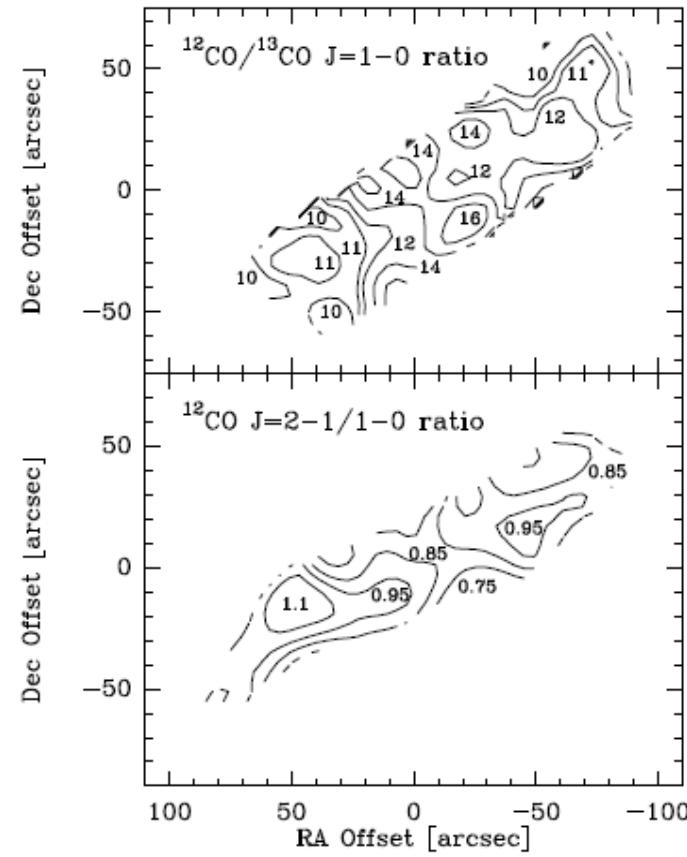
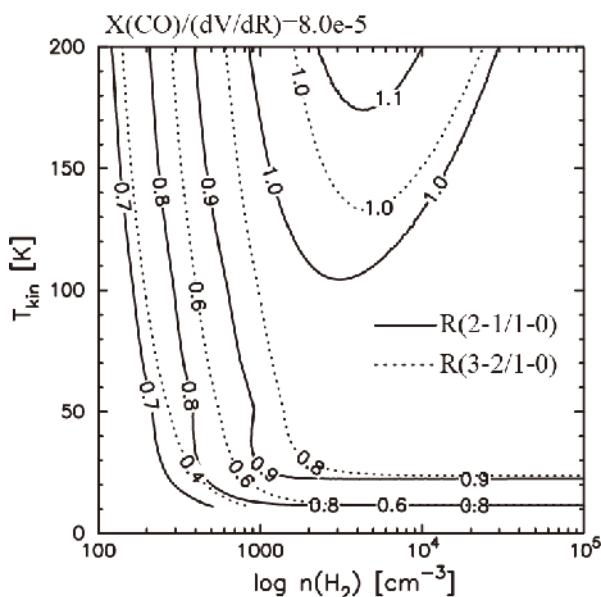
CATS345 installed in the RX cabin



Inoue Hirofumi, Sakai Takeshi (Univ. of Tokyo) et al.

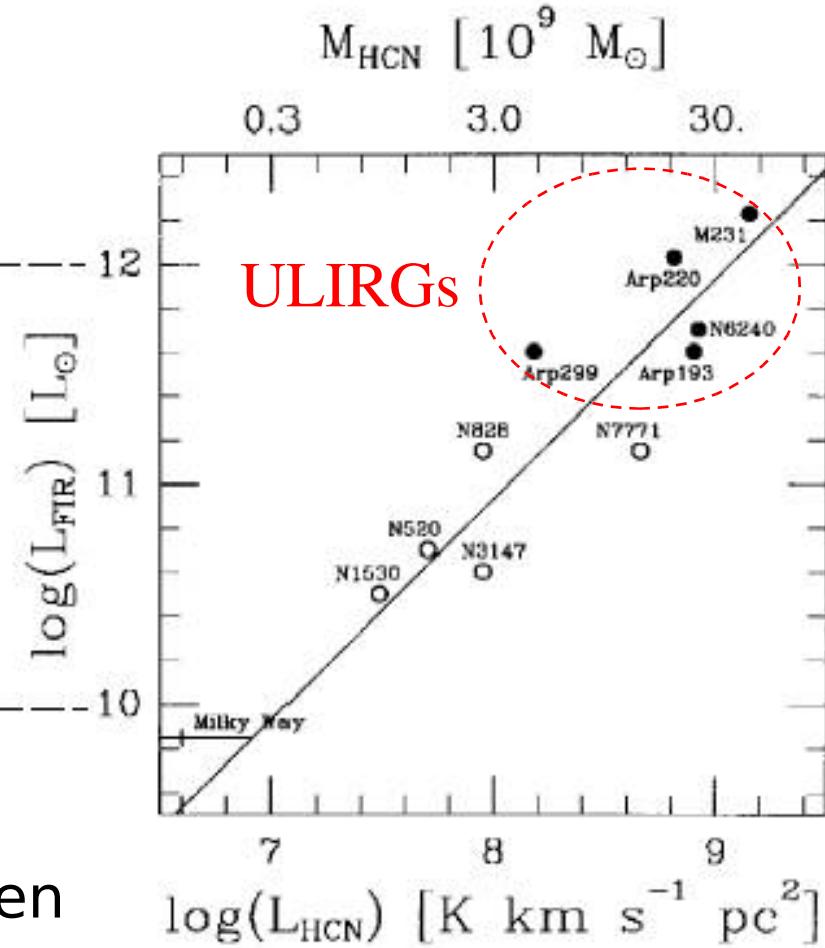
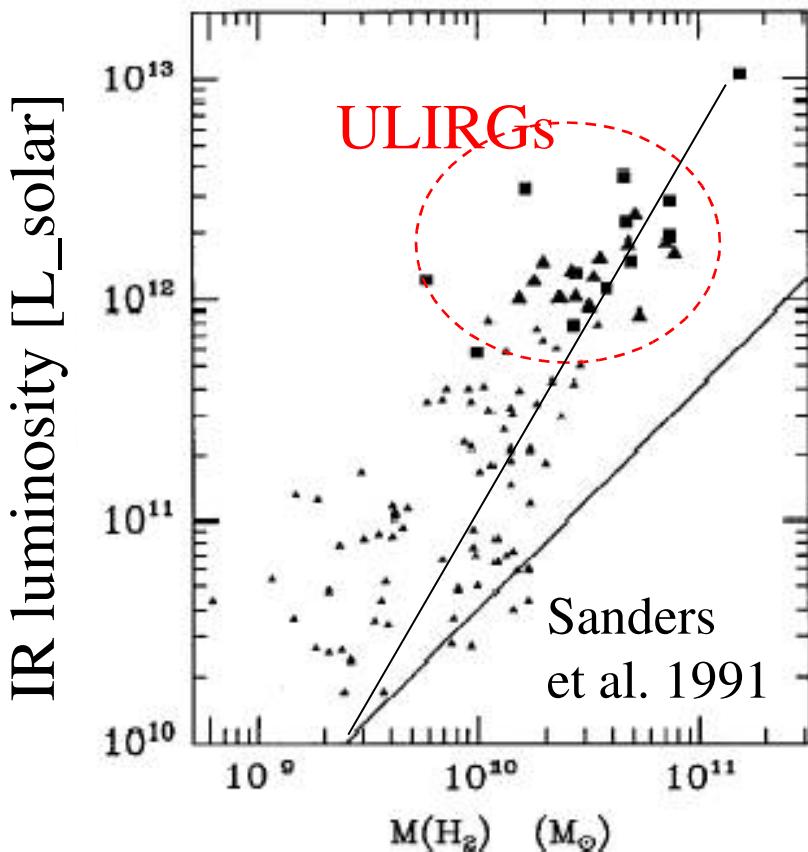
# LVG analysis in Cen A

Offset	R(2-1/1-0) (45'')	R(3-2/1-0) (45'')	R(3-2/2-1) (45'')
-30''	0.3±0.08	0.47±0.03	1.6±0.4
0''	0.9±0.09	0.59±0.04	0.68±0.07
+30''	0.5±0.09	0.69±0.05	1.4±0.3
+60''	0.4±0.09	0.63±0.05	1.5±0.3
+90''	0.3±0.1	0.28±0.03	0.92±0.32
+120''	0.5±0.3	0.30±0.08	0.65±0.4



Wild et al. (1997)

# Early study on HCN-FIR correlation in galaxies



- Non-linear correlation between  $L_{\text{CO}}$  and  $L_{\text{FIR}}$
- Linear and tight correlation between  $L_{\text{HCN}}$  and  $L_{\text{FIR}}$

Solomon et al. 1992  
ApJ, 387, L55

# Star formation in M83: (1) Schmidt law in CO(3-2)

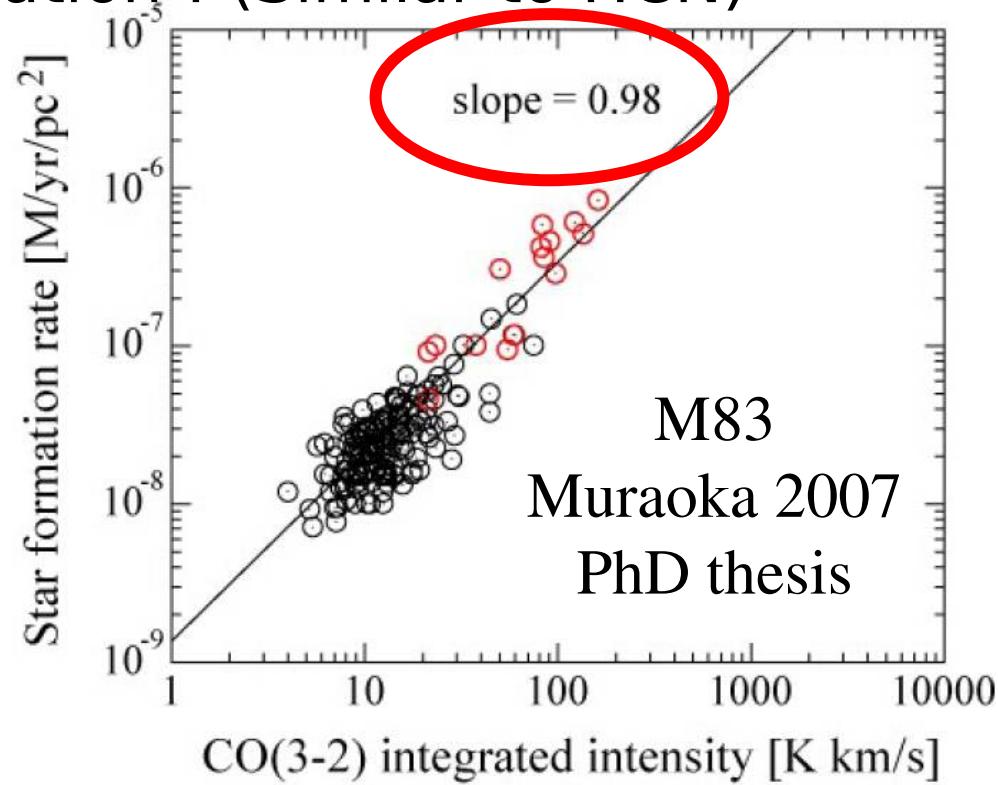
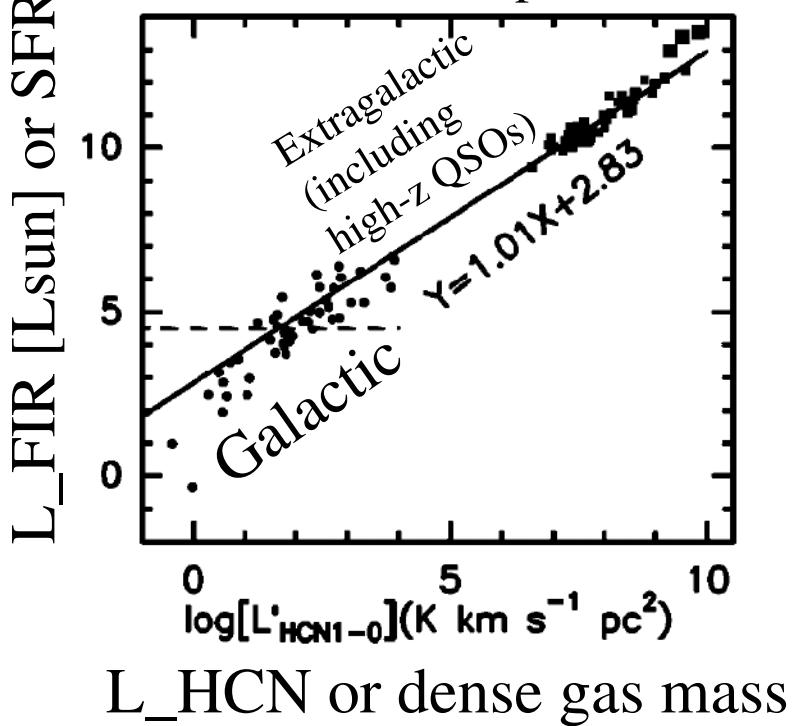
- “Schmidt law” in CO(3-2)

- SFR: extinction corrected by MIPS 24 um data:

- $L(\text{H}\alpha)\text{true} = L(\text{H}\alpha)\text{obs} + 0.031 \cdot L(24\text{um})$  (Calzetti et al. 2007)

- Results: linear correlation ! (Similar to HCN)

Wu et al. 2005, ApJ, 635, L173



# Star formation in M83: (2) SFE vs dense gas fraction traced by CO(3-2)/CO(1-0) ratio

- SFE vs “dense gas fraction” traced by CO(3-2)/CO(1-0)? → roughly correlated ! Scatters caused by temperature effect?

