Dense gas in nearby active and normal galaxies

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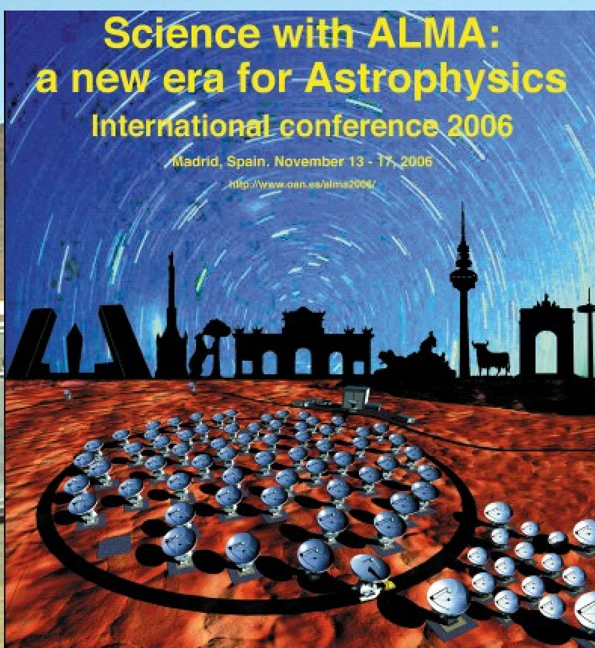
Univ. of Tokyo

Nov. 16, 2006



Outline

- Introduction: Dense molecular gas in galaxies

- ASTE observations of dense molecular gas in galaxies and the Galaxy
  - ✓ CO(3-2) mapping of galaxies (M83 etc.) ➔ correlation between CO(3-2)/CO(1-0) ratio and star formation efficiency?
  - ✓ CO(3-2) mapping of Sgr arm regions, the Galactic Center, etc.
- NMA observations of dense molecular gas in the central regions of Seyfert and starburst galaxies
  - ✓ "HCN enhanced Seyfert galaxies": a signature of X-ray dominated regions (XDRs)

Collaborators

- ASTE observations
  - ✓ K. Muraoka, B. Hatsukade, T. Tosaki, N. Kuno, R. Miura, S. Sakamoto, J. Cortes, L. Bronfman, H. Ezawa, K. Kamegai, K. Tanaka, R. Kawabe, T. Oka, T. Sawada, T. Kamazaki, N. Yamaguchi, S. Yamamoto, S. Komugi, S. Onodera, F. Egusa, A. Hirota & ASTE team
- NMA survey
  - ✓ T. Shibatsuka, K. Nakanishi, M. Imanishi, T. Tosaki, S. Ishizuki, S. Matsushita, M. Okiura, K. Sorai, S. Onodera, A. Doi, H. Nakanishi, Y. Sofue, S. K. Okumura, B. Vila-Vilaro, T. Okuda, K. Muraoka, A. Endo, B. Hatsukade, R. Kawabe
- ATCA observations
  - ✓ T. Wong, S. Ryder, R. Buta

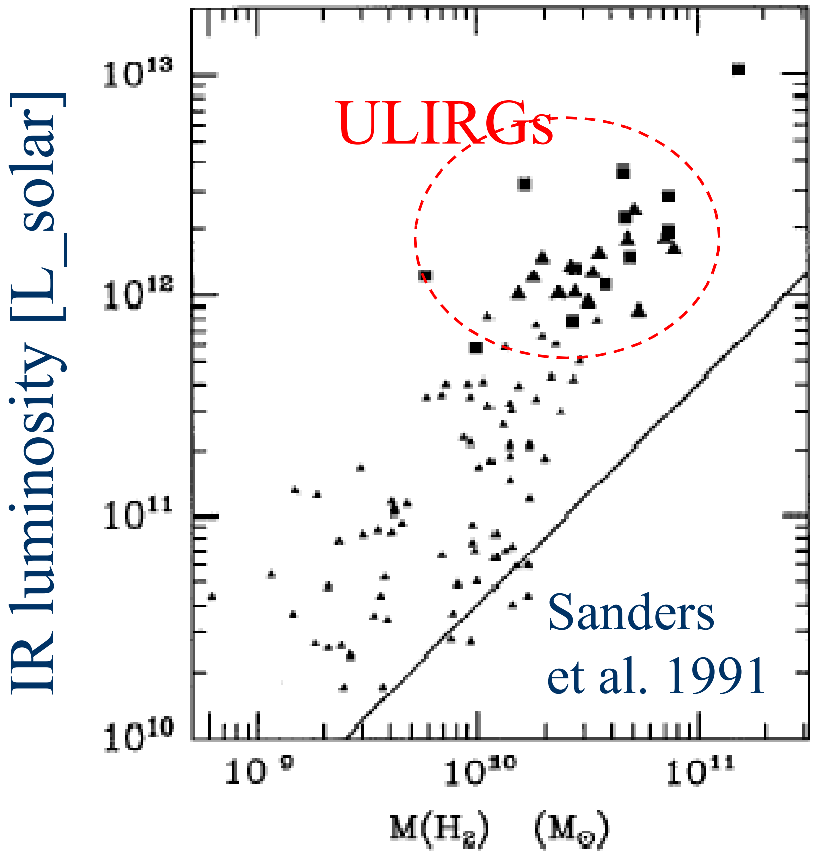
Introduction

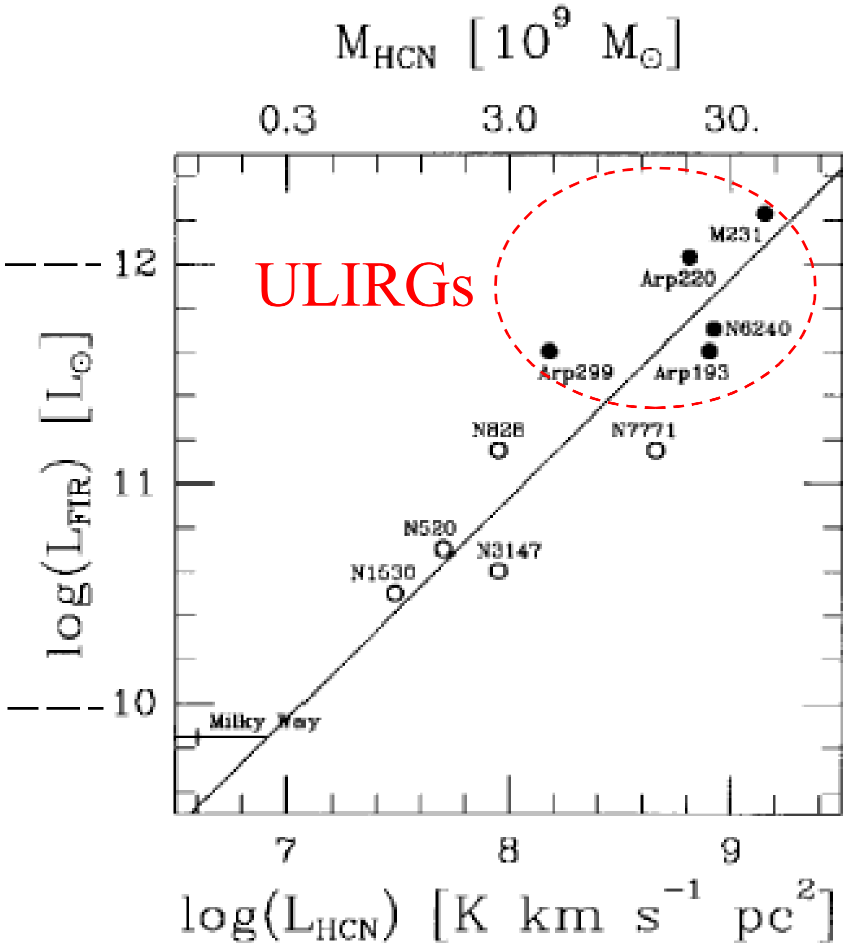
Dense molecular gas in galaxies

- Tight connection to massive star formation
  - ✓ Stars are formed from densest parts of GMCs (i.e., dense cores), not from diffuse envelopes of GMCs
  - ➔ Observational study of dense molecular medium is essential for the understanding of star formation law in galaxies, from nearby to high-z galaxies!
- An example: HCN(1-0) as a tracer of dense gas
  - ✓ quantitative correlation between HCN(1-0) and FIR luminosities (Solomon et al. 1992, ApJ, **387**, L55; Gao & Solomon 2004, ApJ, 606, 271)
  - ✓ Spatial correlation between HCN(1-0) and Halpha/radio continuum distributions (Kohno et al. 1999, ApJ, 511, 157)

! Note that I concentrate just a few dense gas tracers in this talk

Early study on HCN-FIR correlation in galaxies





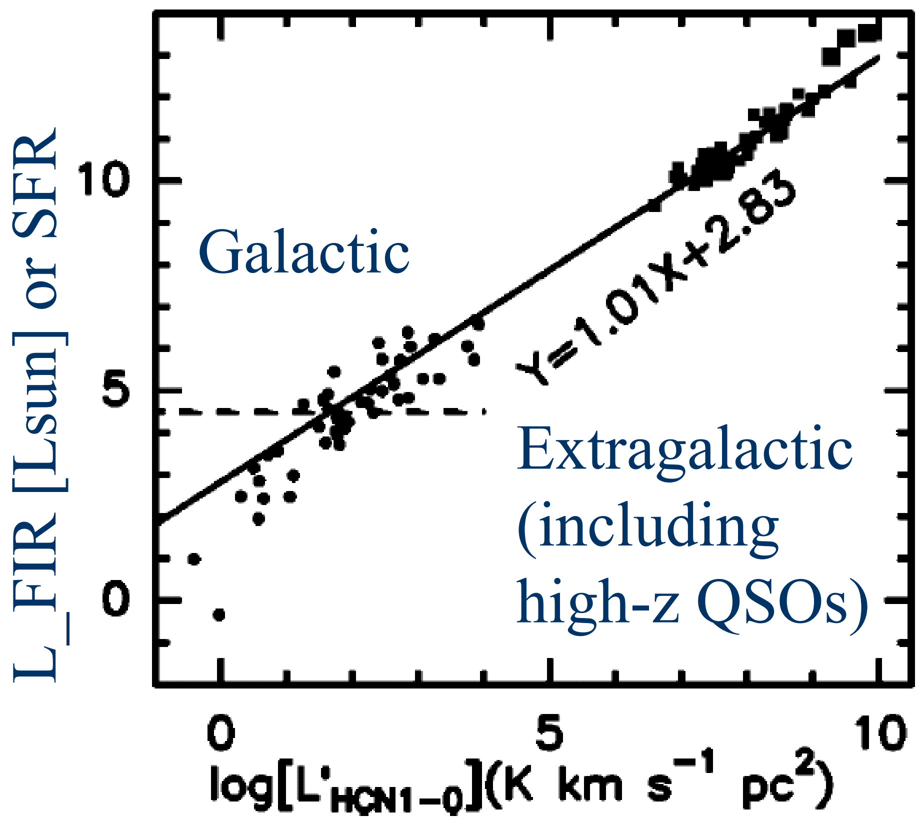
- Non-linear correlation between L_CO and L_FIR
- Linear and tight correlation between L_HCN and L_FIR

Solomon et al. 1992
ApJ, **387**, L55

Now situation becomes much clear

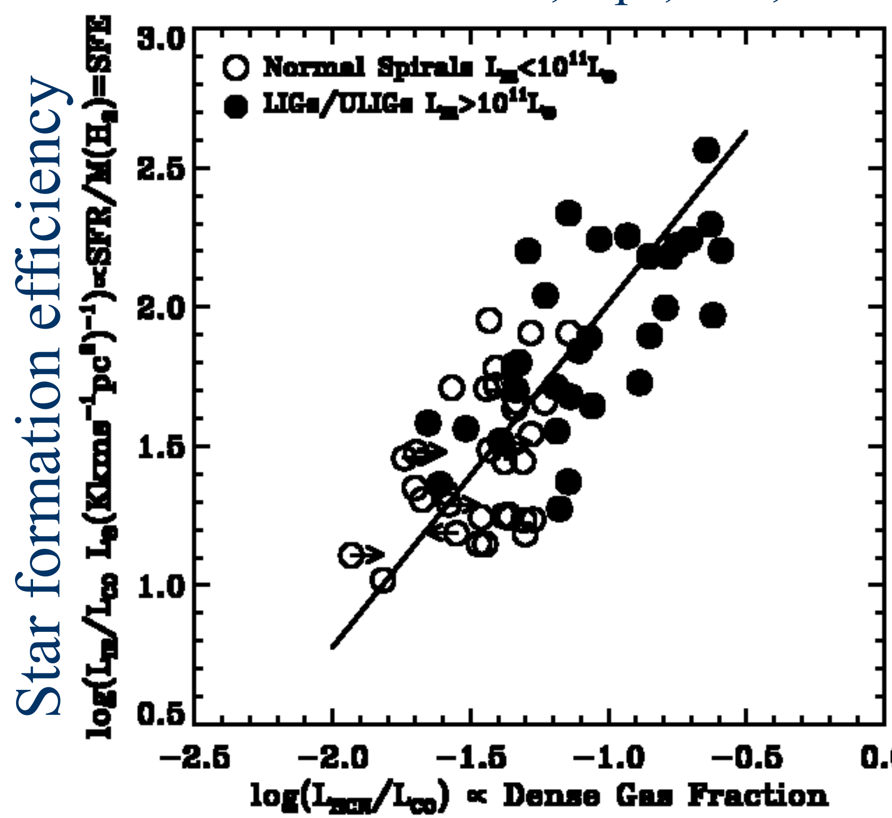
- Linear and tight correlation between L_HCN & L_FIR over 8orders
- Correlation between dense gas fraction & star formation efficiency

Wu et al. 2005, ApJ, 635, L173



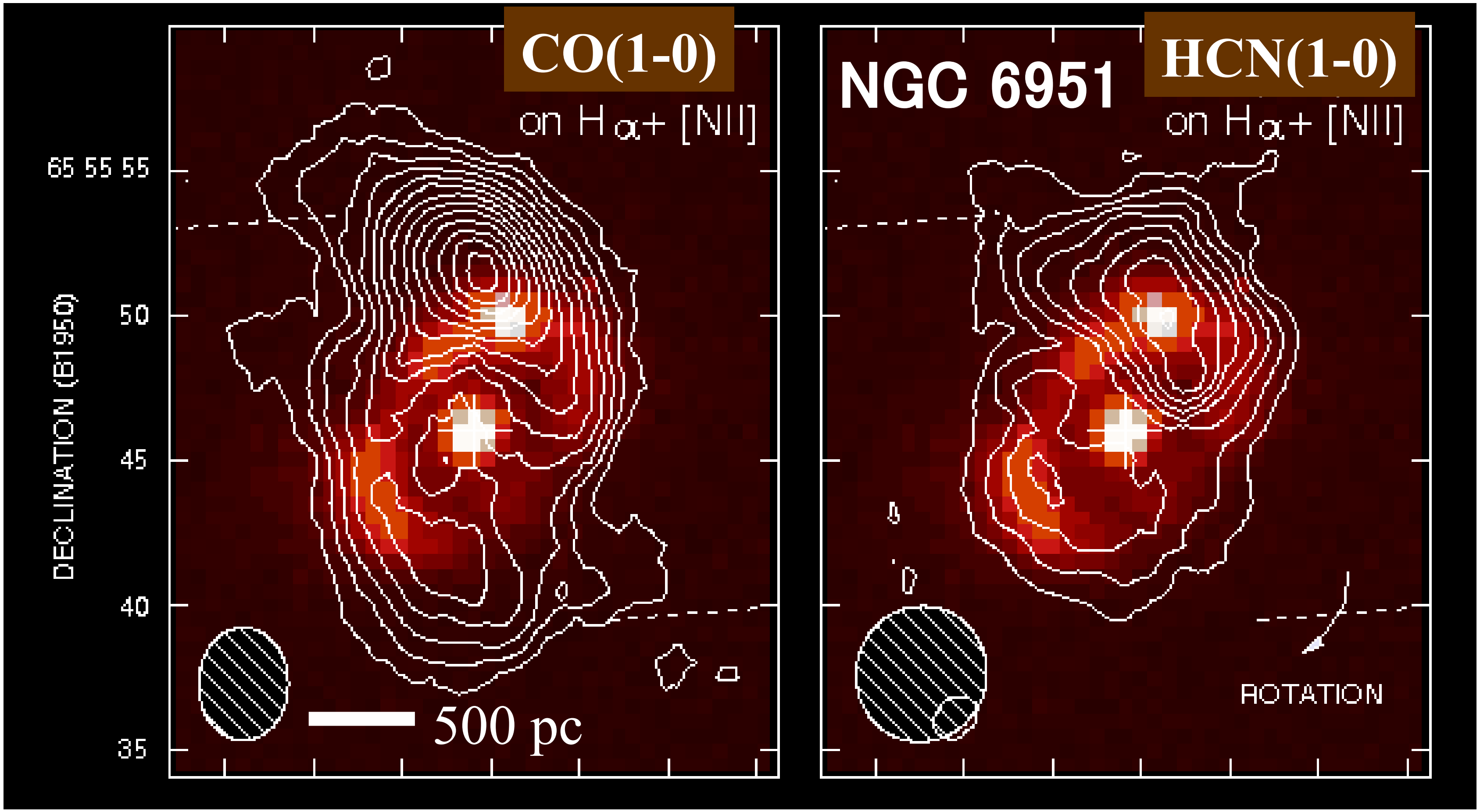
L_HCN or dense gas mass

Gao & Solomon 2004, ApJ, 606, 271



HCN/CO ratio or dense gas fraction

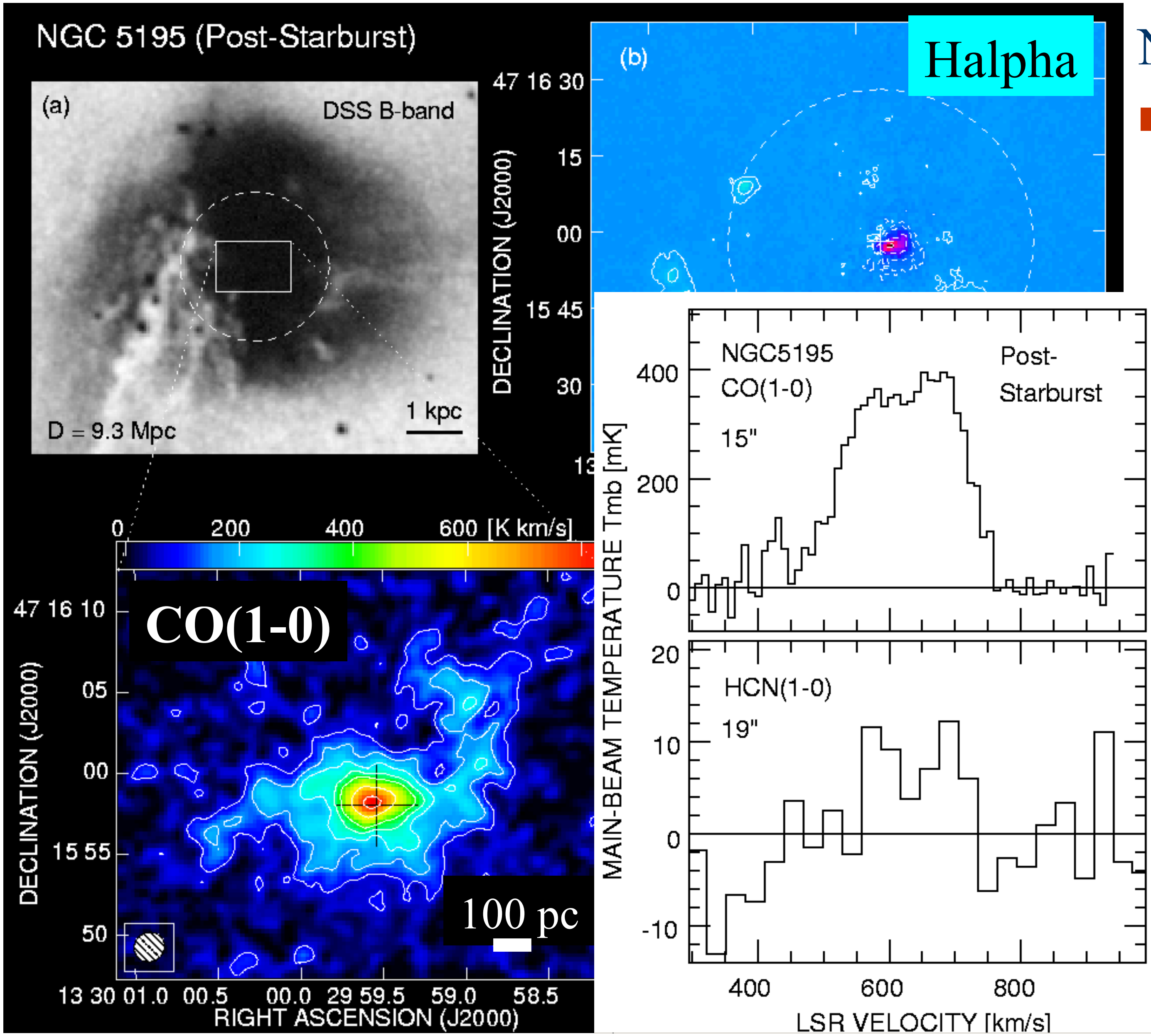
Spatial correlation between HCN & Ha



- HCN map shows better spatial correlation between dense molecular gas (traced with HCN) and massive star forming regions (grey scale, Halpha) than that of CO

Kohno et al. 1999, ApJ, **511**, 157

CO luminous, but no massive star formation



NGC 5195

- High concentration of molecular gas at the center; Σgas ~ 3000 Mo/pc^2
- Yet no current massive star formation. Why?

The answer is:
no dense gas!
(HCN/CO ~ 0.02)

Kohno et al. 2002, PASJ, 54, 541

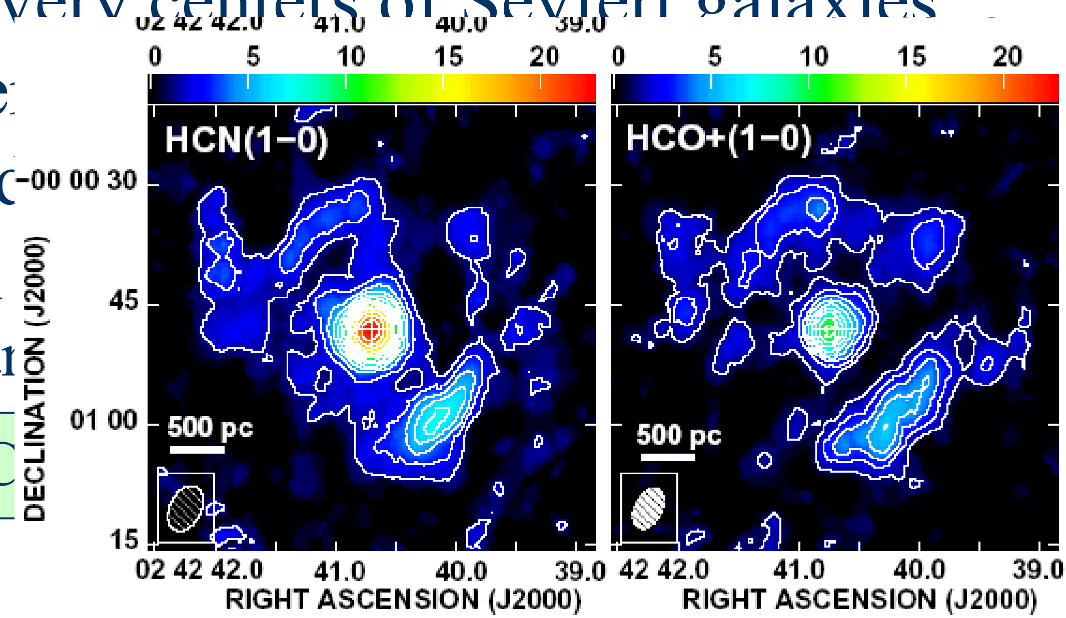
Questions

- How about other dense gas tracers, such as high-J CO?
  - ✓ HCN is very weak in the disk regions of galaxies; if high-J CO lines such as CO(3-2) is usable as a tracer is dense gas, it is very helpful for understanding of disk star formation
  - ✓ ➔ examine correlation between star formation and CO(3-2)

ASTE CO(3-2) observations of the Galaxy and galaxies

- What is happening at the very centers of Seyfert galaxies (such as NGC 1068), whe
emission is often observed
  - ✓ Given the tight connection
means that massive nuclear

NMA survey of HC



ASTE observations of dense gas in galaxies

ASTE **D**ense gas **I**maging **o**f **S**piral galaxies

ADIoS project

- **Goals of the project: (1) SFE variation**
  - ✓ Wide area **CO(3-2)** imaging survey of nearby spiral galaxies
  - ✓ **CO(1-0)** data from 45m+BEARS, Mopra, etc.
  - ✓ + **Halpha, radio/MIR continuum** etc.
  - ➔ understand spatial variation of star formation efficiency in terms of "dense gas fraction"
- **Goals of the project: (2) ISM phase variation**
  - ✓ **CI** (490 & 800 GHz RX in ASTE, in progress)
  - ✓ **CII** (from AKARI satellite 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

ASTE Dense gas Imaging of Spiral galaxies
ADIoS project

- **Sample 1: a coordinated CO(3-2) & CO(1-0) imaging survey w/ ASTE 10m + NRO 45m/25BEARS**
  - ✓ **M83 5'x5'** completed (Muraoka et al. 2006, submitted to PASJ)
  - ✓ **M31 2'x2'** completed (Tosaki et al. 2006, submitted to PASJ)
  - ✓ **NGC 604/M33 5'x5' OTF** completed (Miura et al., see poster #272)
  - ✓ **NGC 253 8'x2' OTF** completed (Nakanishi et al., in prep.)
  - ✓ **NGC 2903 3'x5' OTF** in progress (Hirota et al. in prep.)
- **Sample 2: southern galaxies (not accessible from Nobeyama etc., but Coordination w/ ATCA and/or Mopra telescope)**
  - ✓ **NGC 1672, NGC 7552, NGC 7310** in progress (Kohno et al. in prep.)
  - ✓ **ESO 184-G82** (Hatsukade et al. 2006, submitted to PASJ)
  - ✓ **NGC 986 3'x3' OTF** completed (Kohno et al., in prep.)
  - ✓ **NGC 1365 bar/arm 3'x3' OTF** in progress (Tosaki et al. in prep.)

Atacama Submillimeter Telescope Experiment:

Project director: K. Kohno (U. Tokyo)
Project manager: H. Ezawa (NAOJ)
Project scientist: S. Yamamoto (U. Tokyo)
under a collaboration w/ L. Bronfman (U. Chile)

http://www.das.uchile.cl/astechile/ASTEinicio.html
http://www.nro.nao.ac.jp/~aste/prop06/

東京大学 THE UNIVERSITY OF TOKYO
大阪府立大学 OSAKA PREFECTURE UNIVERSITY
茨城大学 Ibaraki University
国立天文台 NAOJ National Astronomical Observatory of Japan

Current status of ASTE 10 m dish

Accuracy	Main-beam efficiecy	Beam	Radio (abs) pointing
19um (rms)	0.6 – 0.7 @350GHz during winter night	22”	~ 2” rms.

- Receiver: 350 GHz band (320 – 370 GHz), DSB
  - ✓ Tsys ~ 200 K @ tau_220GHz ~ 0.06 ➔ 2SB RX (in 2007)
- Spectrometer: 4 banks of 512 MHz/1024ch or 128 MHz/1024ch ➔ 4 GHz/2048ch (in 2007; by Okuda, Iguchi et al.)
  - ✓ Widest velocity coverage ~ 450 km/s; highest dV ~ 0.1 km/s
- On-The-Fly capability
- Remote operation from San Pedro/Tokyo/Nobeyama

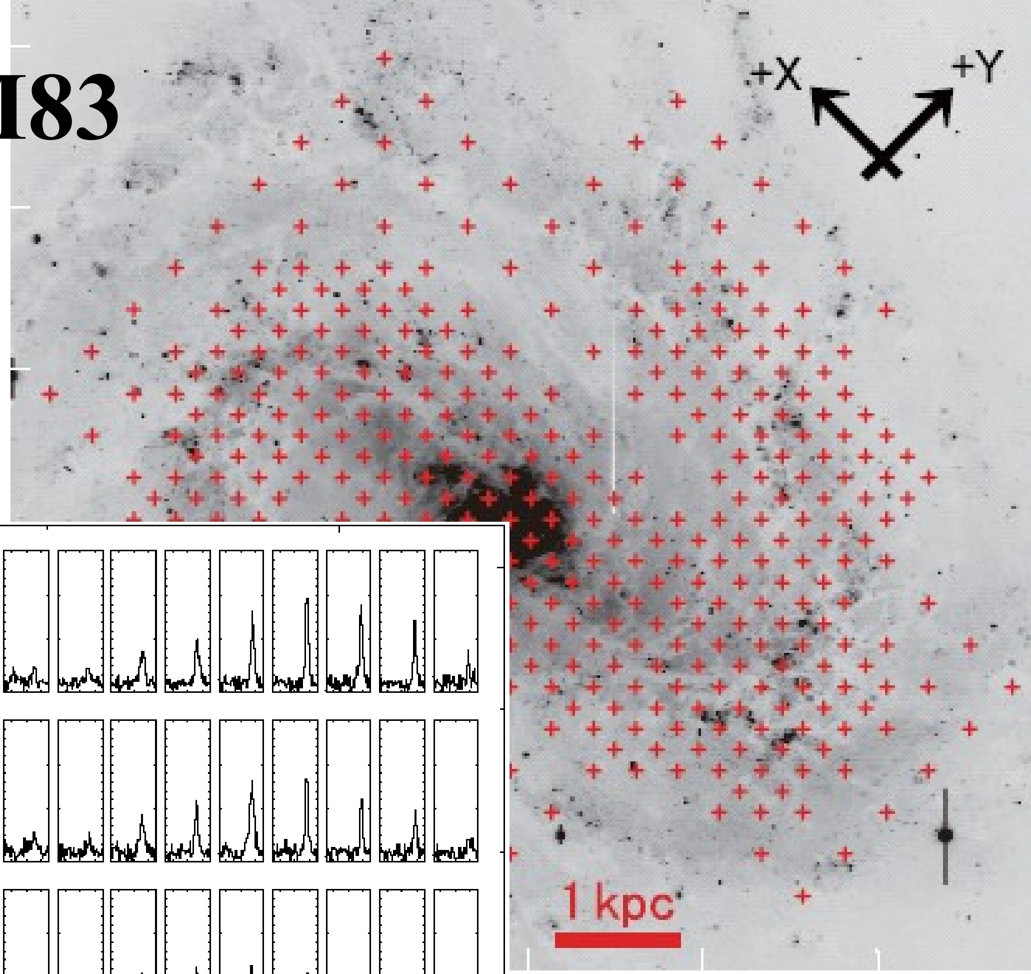
ASTE publications

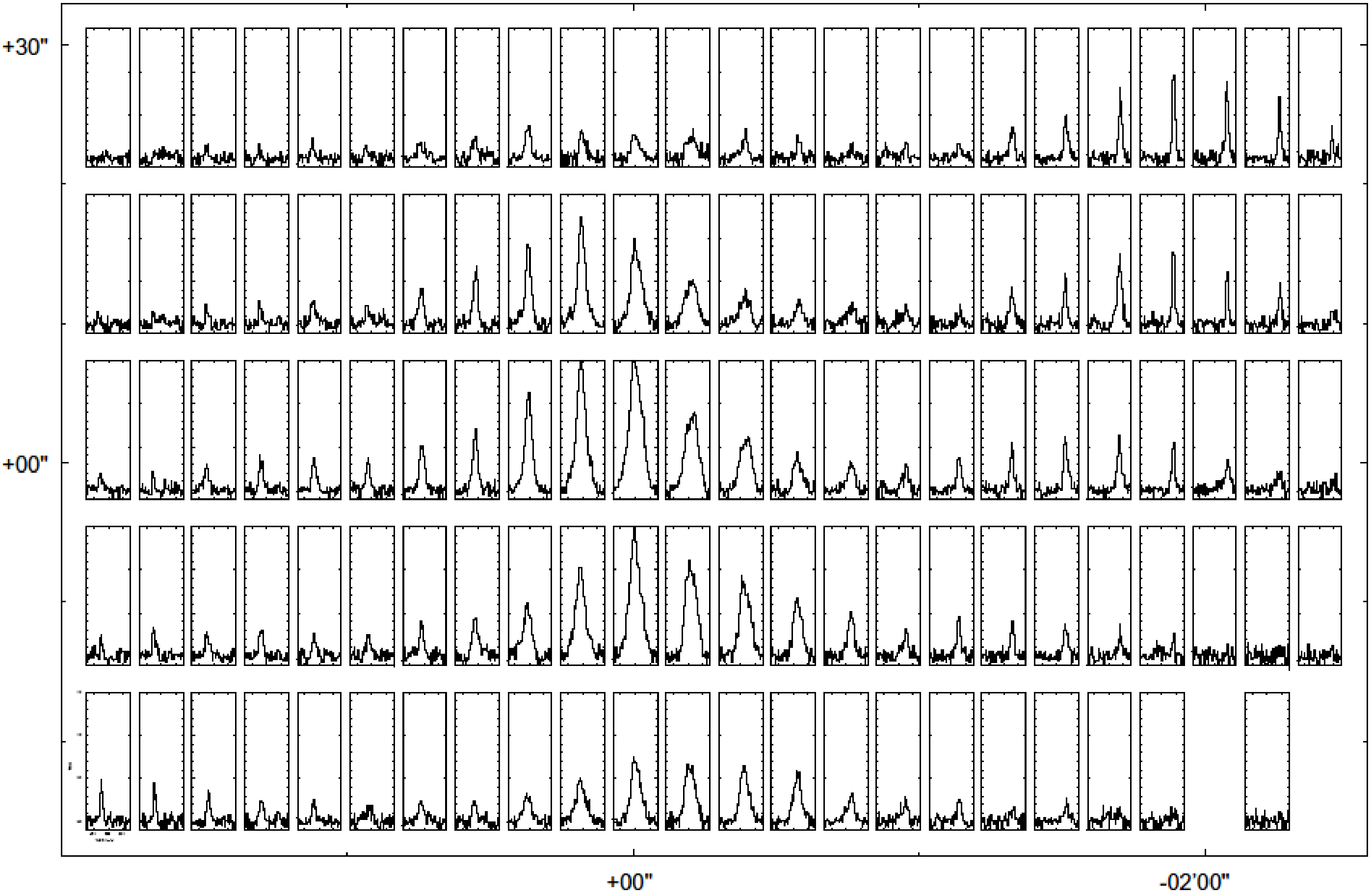
- Moriguchi et al. 2005, ApJ, 631, 947 [TeV-Gamma source]
- Yonekura et al. 2005, ApJ, 634, 476 [new outflow in CO(2-1)]
- Takami et al. 2006, PASJ, 58, 563 [YSO outflow in SiO]
- Takahashi et al. 2006, ApJ, in press [OMC 2/3 outflow]
- Takakuwa et al. 2006, PASJ, in press [low mass protostars]
- Oka et al. 2006, PASJ, in press [GC. CO(3-2) wide survey]
- Komugi et al. 2006, PASJ, in press [CO(3-2) Schmidt law]
- Tosaki et al. 2006, PASJ, submitted [M31, see poster]
- Nagai et al. 2006, PASJ, submitted [GC., multi-line & model]
- Tanaka et al. 2006, PASJ, submitted [GC., multi-line & model]
- Muraoka et al. 2006, PASJ, submitted [CO(3-2) wide map of M83]
- Hatsukade et al. 2006, PASJ, submitted [CO(3-2) in GRB host]
- Nakanishi et al. 2006, PASJ, submitted [CO(3-2) in E galaxies]

etc.. **PASJ 2007 special issue on ASTE early science programs**

ASTE CO(3-2) of M83

- CO(3-2), 5’ x 5’ wide
- 419 high quality spectra

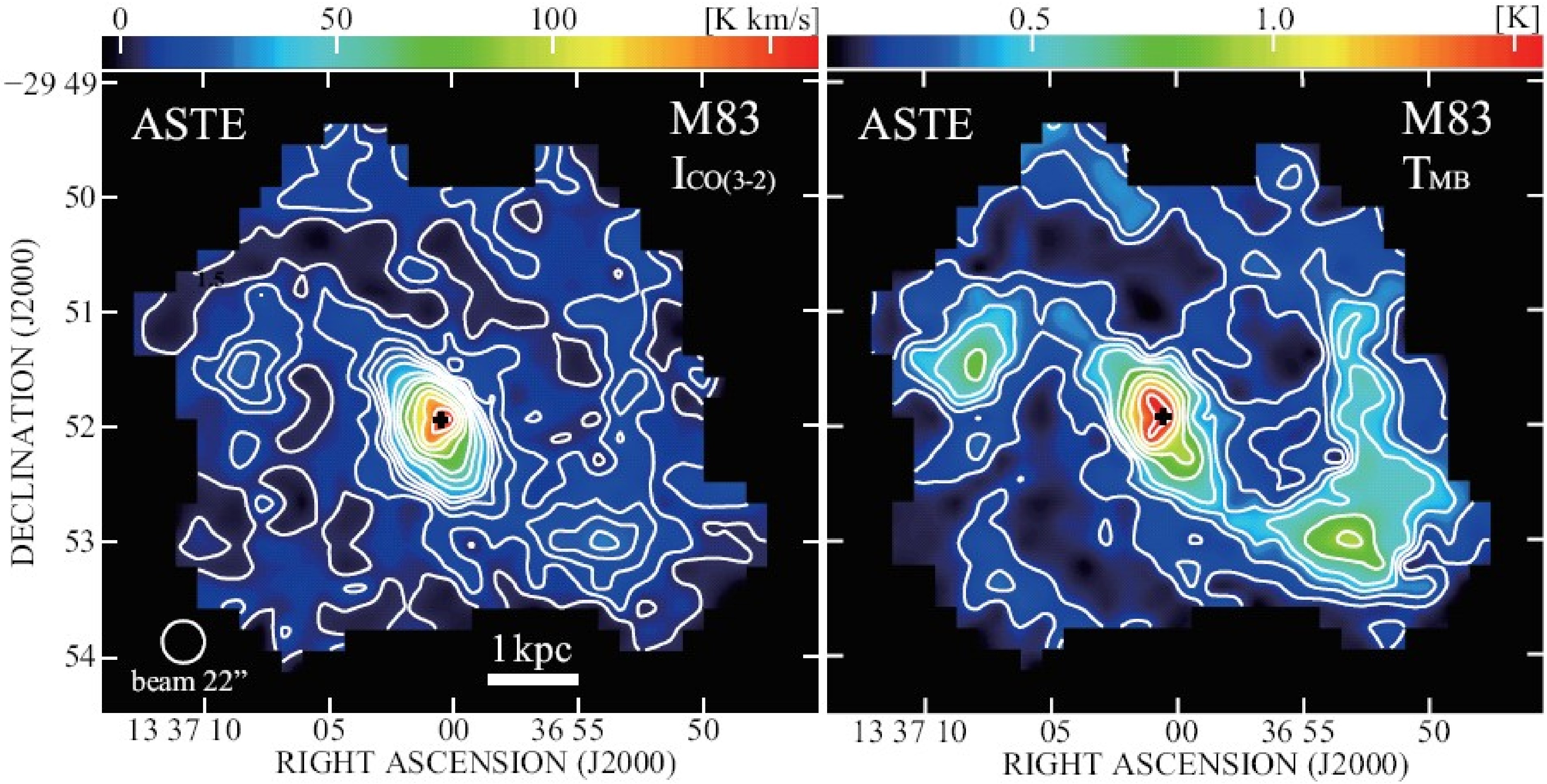




Muraoka et al. 2006, submitted

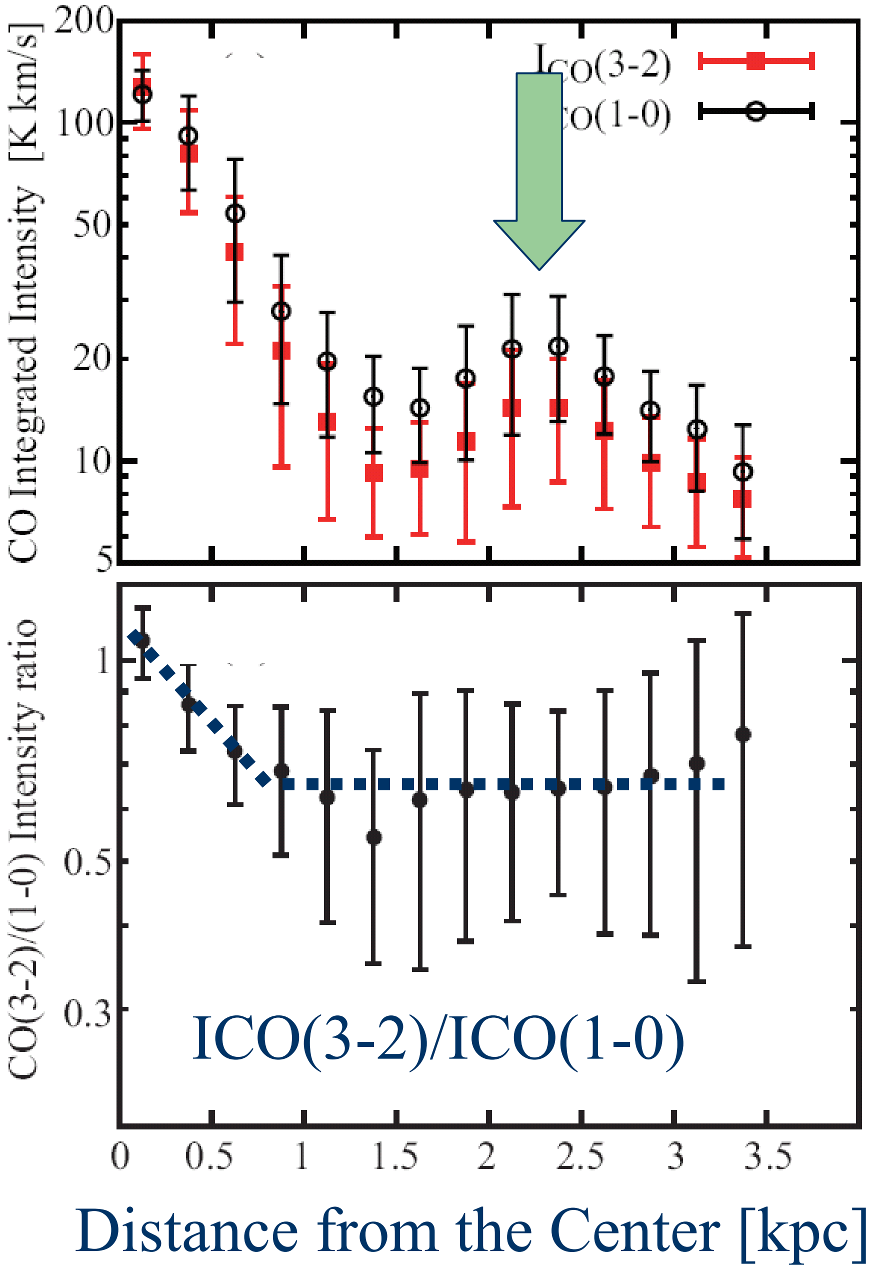
ASTE CO(3-2) 5'x5' map of M83

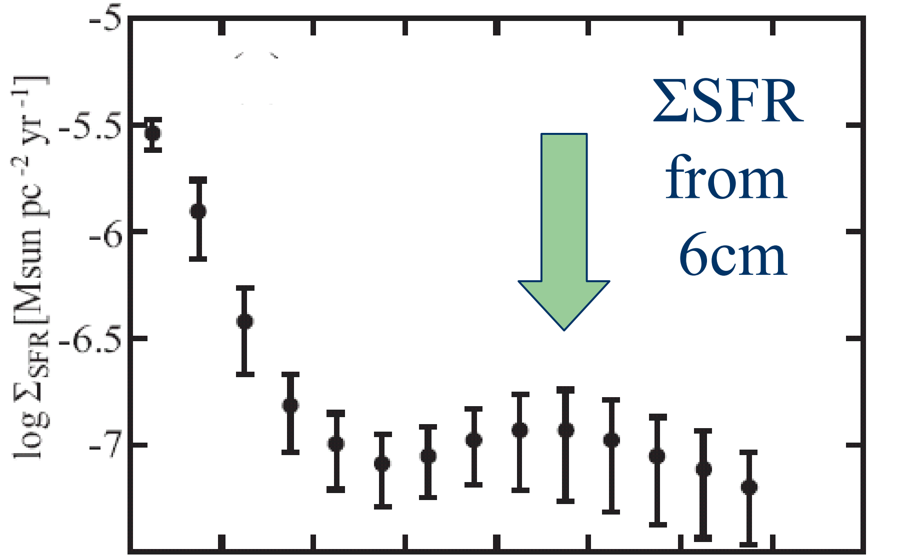
Muraoka et al. 2006, submitted



- Extended CO(3-2) emission over the disk/spiral regions
- Comparison with CO(1-0) by NRO 45m (Kuno et al. 2006, submitted)

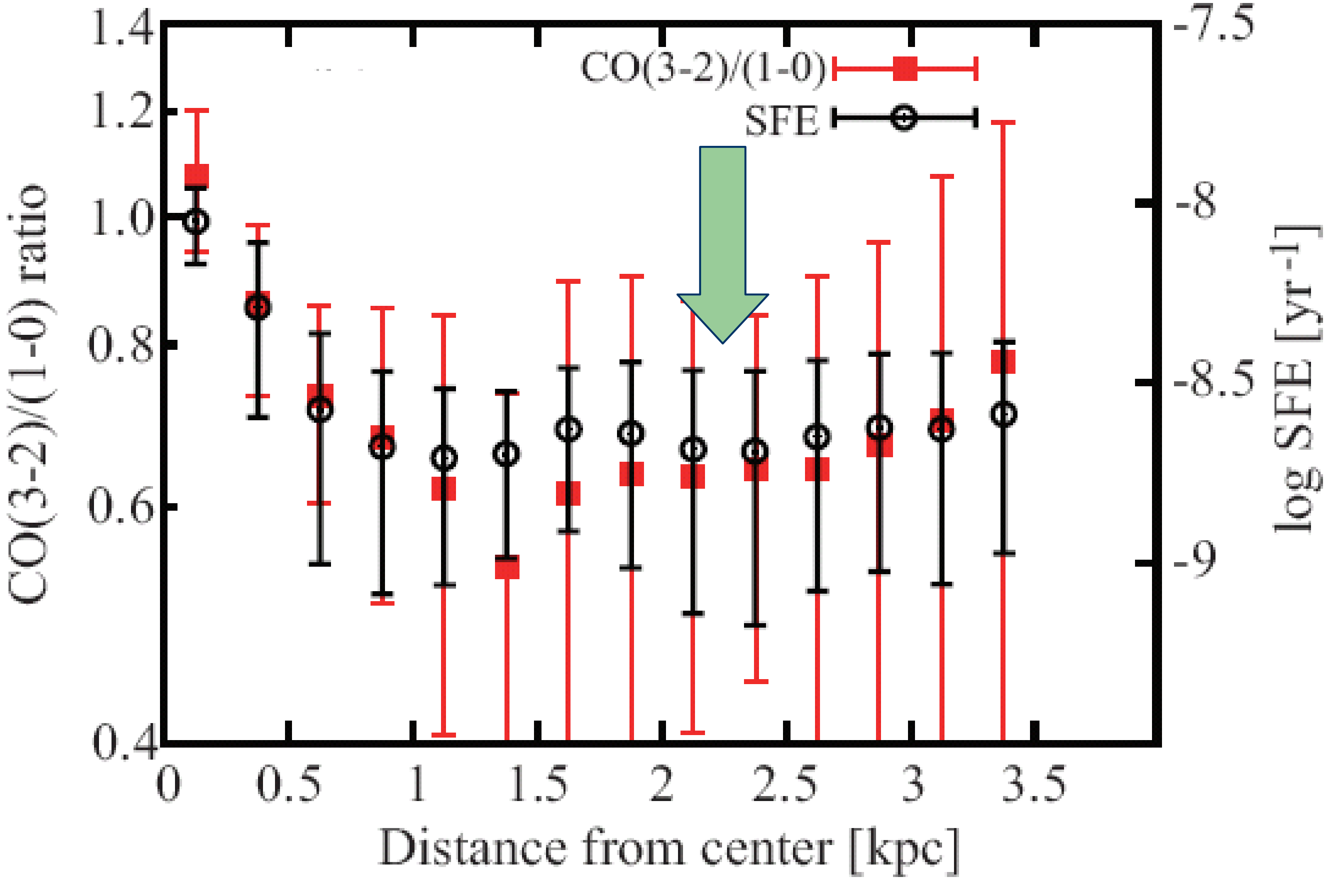
Radial distributions of CO(3-2), CO(1-0), & SFR





- ICO(3-2), ICO(1-0), and SFR: nuclear peak
  + 2nd peak at the bar-end
- CO(3-2)/CO(1-0): only nuclear peak (no 2nd peak)

SFE vs CO(3-2)/CO(1-0) ratio in M83



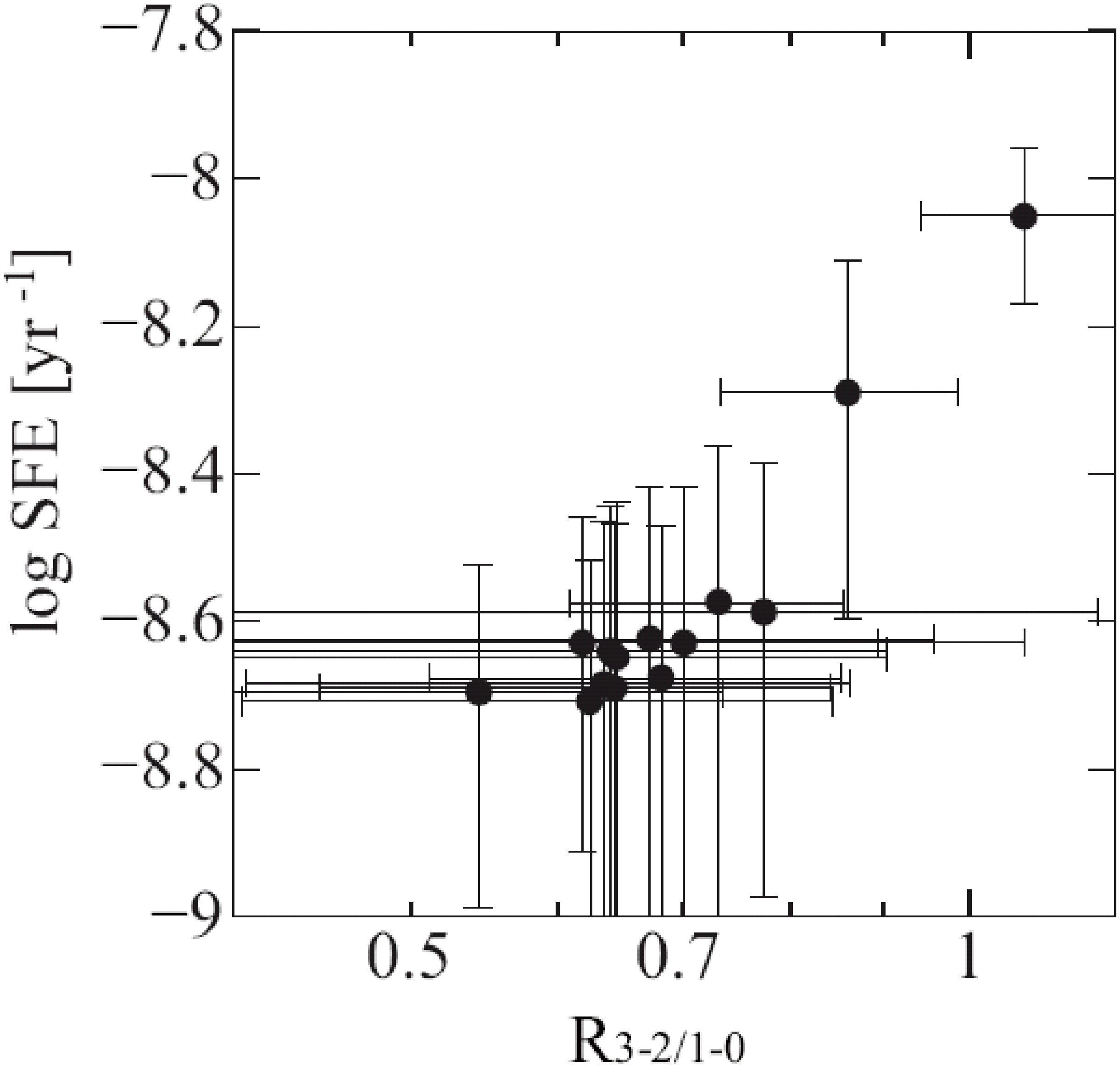
Spatial variation of SFE within M 83

caused by !?

Spatial variation of dense gas fraction traced by CO(3-2)/CO(1-0)

- No 2nd peak of SFE at the bar end
- A simple summation of star forming molecular gas at the bar end can not reproduce nuclear starbursting molecular gas

SFE vs CO(3-2)/CO(1-0) in M83



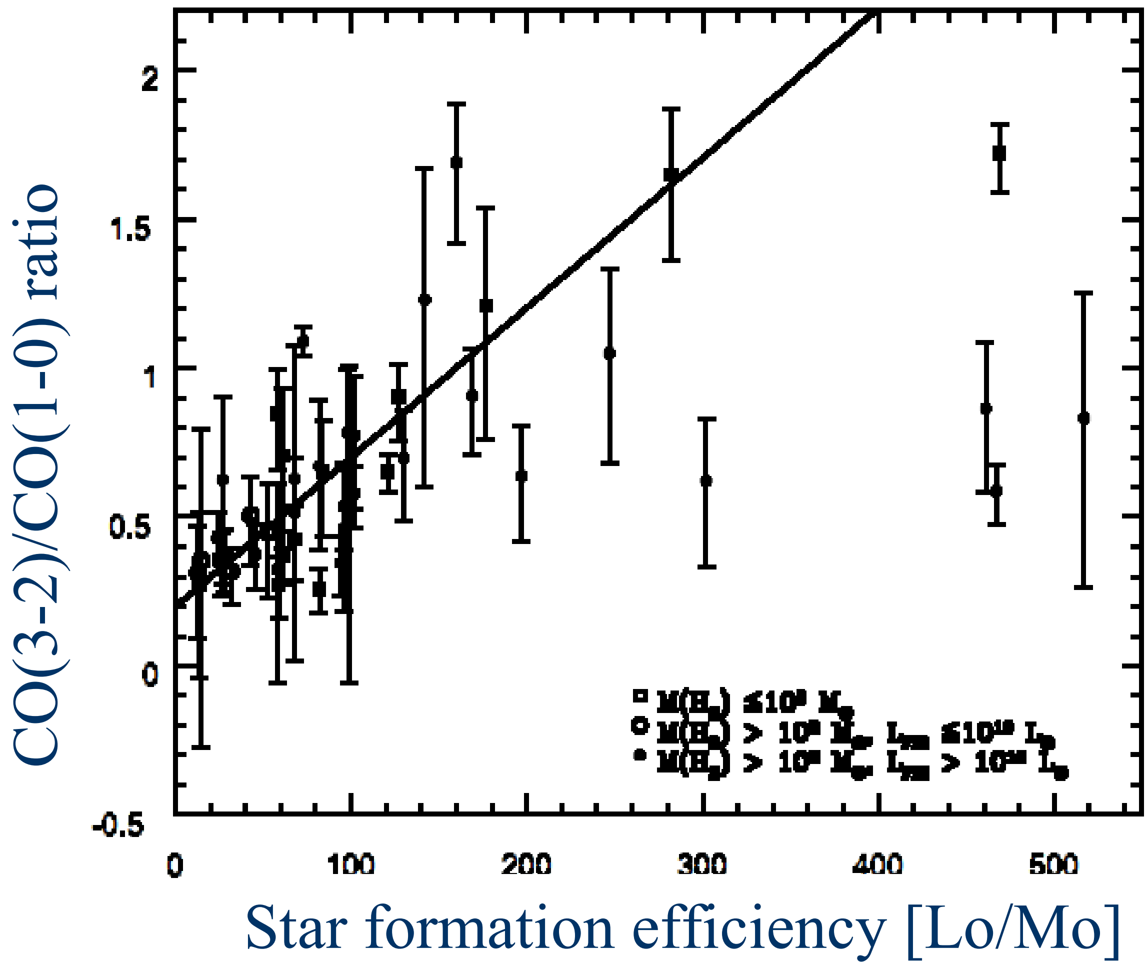
- Similar to "SFE – HCN/CO correlation"
- variation within a galaxy

  (cf. previous studies: global scales of galaxies)

- Further analysis (point – to – point comparison) is in progress.

Muraoka et al. 2006, submitted

Correlation between dense gas fraction and star formation efficiency? – a case of CO(3-2)/CO(1-0)



correlation
seen in large scale
among IR luminous
galaxies.

Yao et al. 2003
ApJ, 588, 771

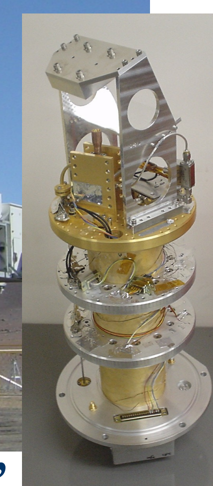
- A Survey of CO(3-2) w/ JCMT + CO(1-0) w/ NRO 45m of rather distant galaxies (i.e., observing beams cover almost entire galaxies)

High resolution & wide field mapping w/ NRO 45m & ASTE 10m + OTF

- 16” @ CO(1-0)
- 25 beams! + OTF

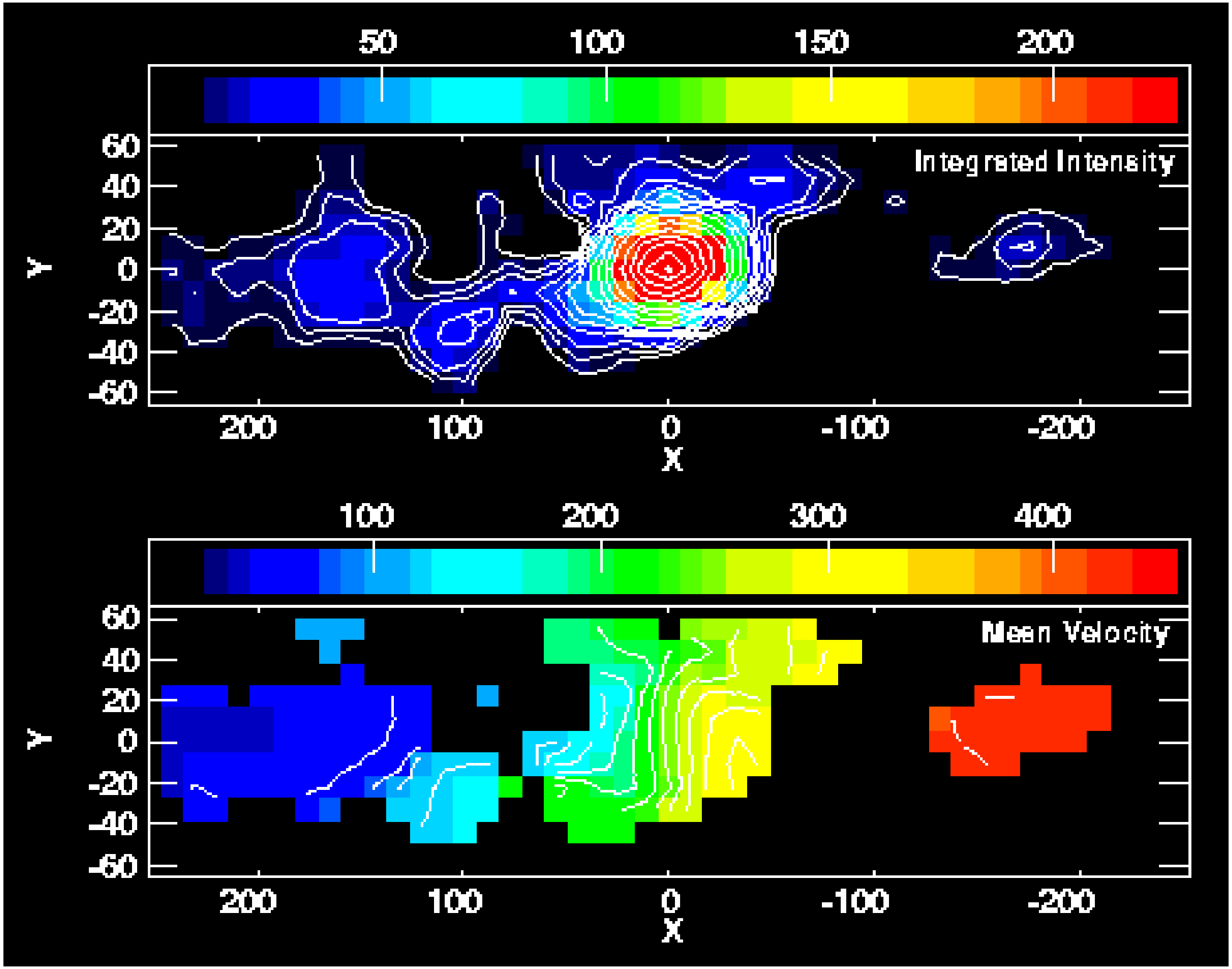
- 22” @ CO(3-2)
- Tsys~150K! + OTF

Array receivers
“25BEARS”



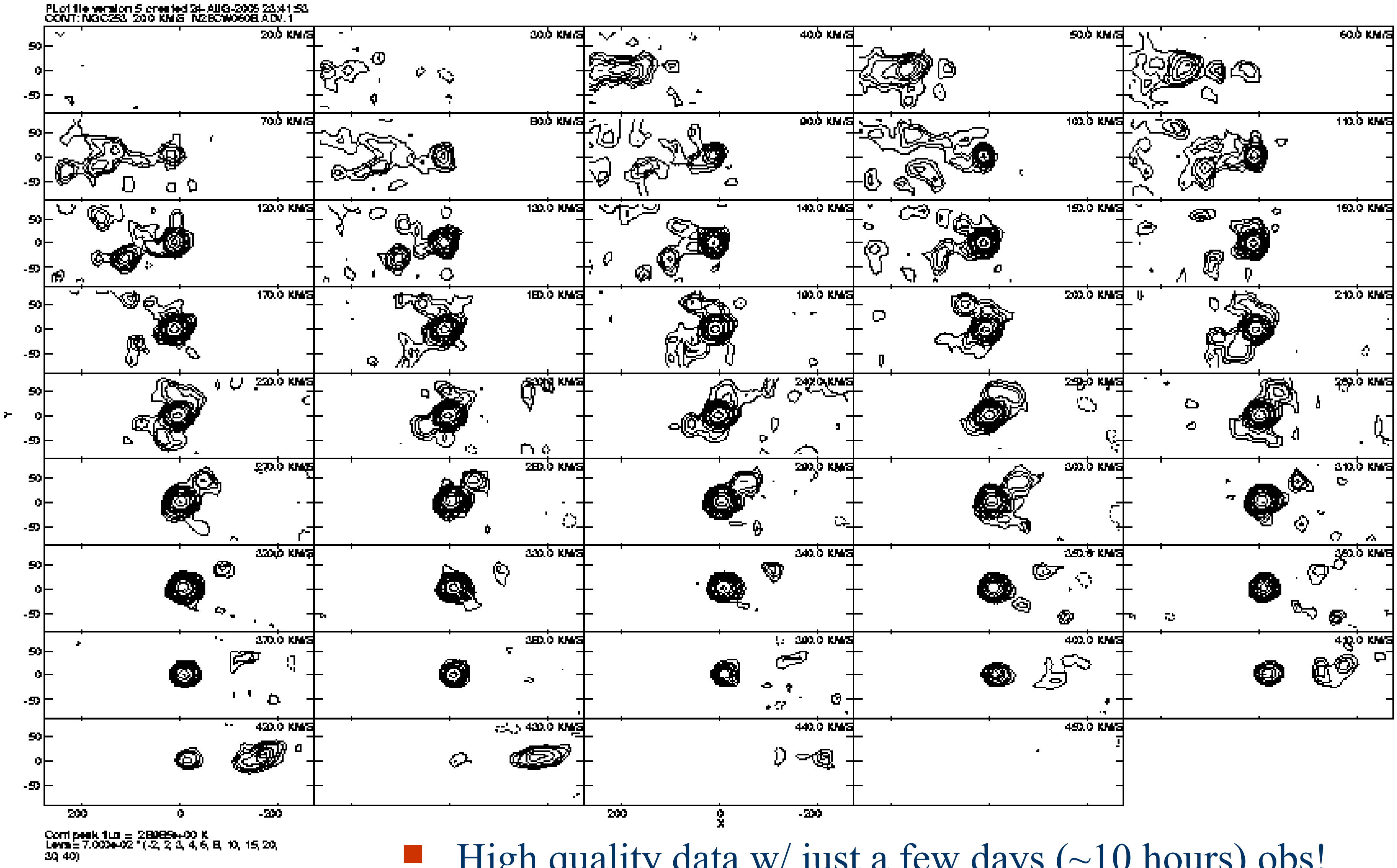
“SC345”

ASTE CO(3-2) 8’x2’ OTF map of NGC 253



- Just a few days observations! K. Nakanishi et al. in prep.

ASTE CO(3-2) channel maps of NGC 253



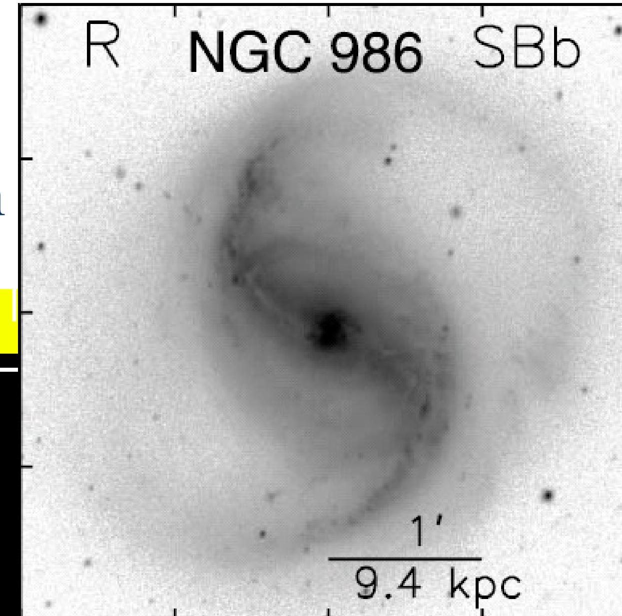
- High quality data w/ just a few days (~10 hours) obs!

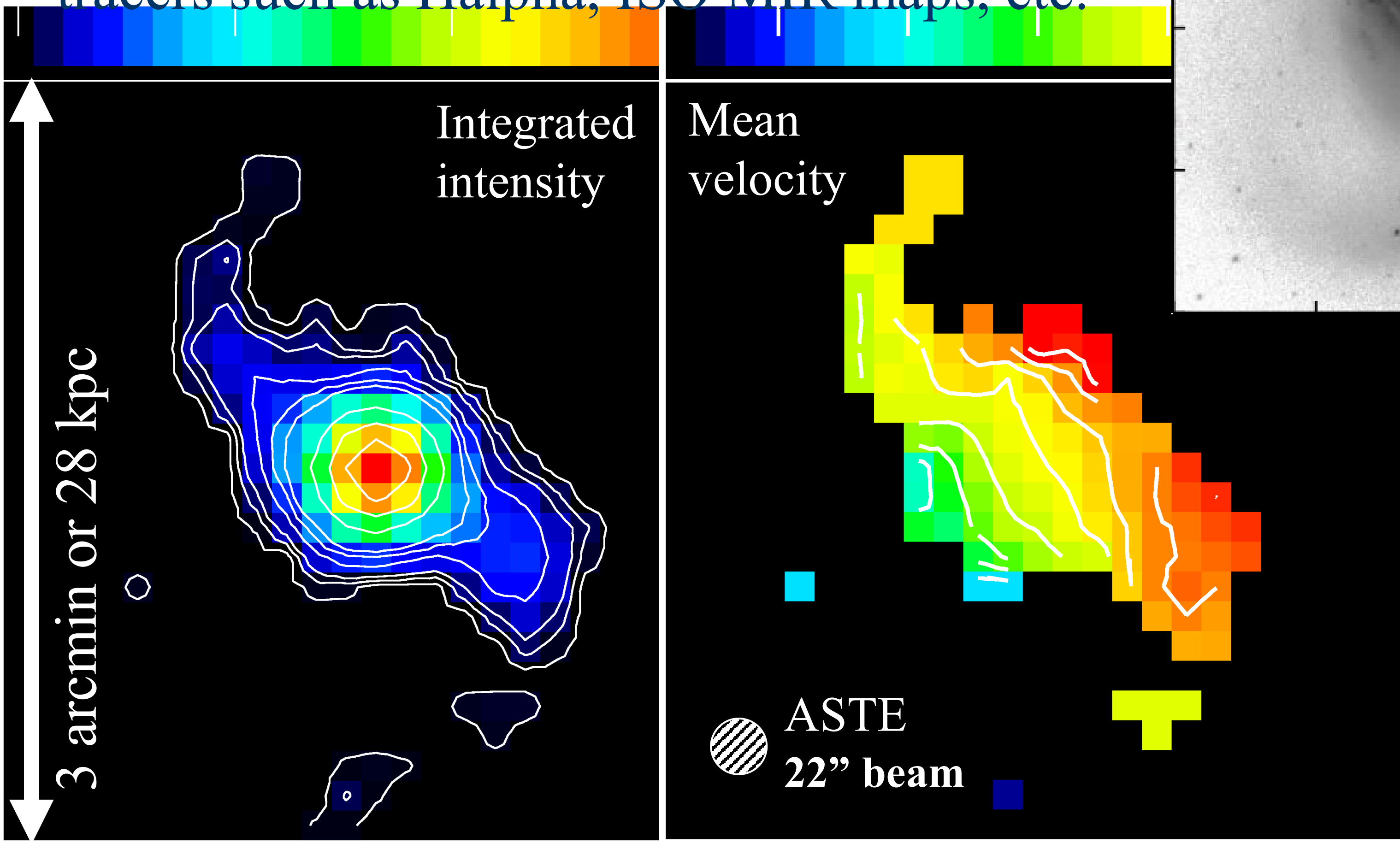
ASTE 3'x3' CO(3-2) OTF map of NGC 986

- **Discovery of "dense gas rich bar"_**

  (young bar? cf. Sakamoto's talk)

  comparison w/ existing massive star formation tracers such as Halpha, ISO MIR maps, etc.

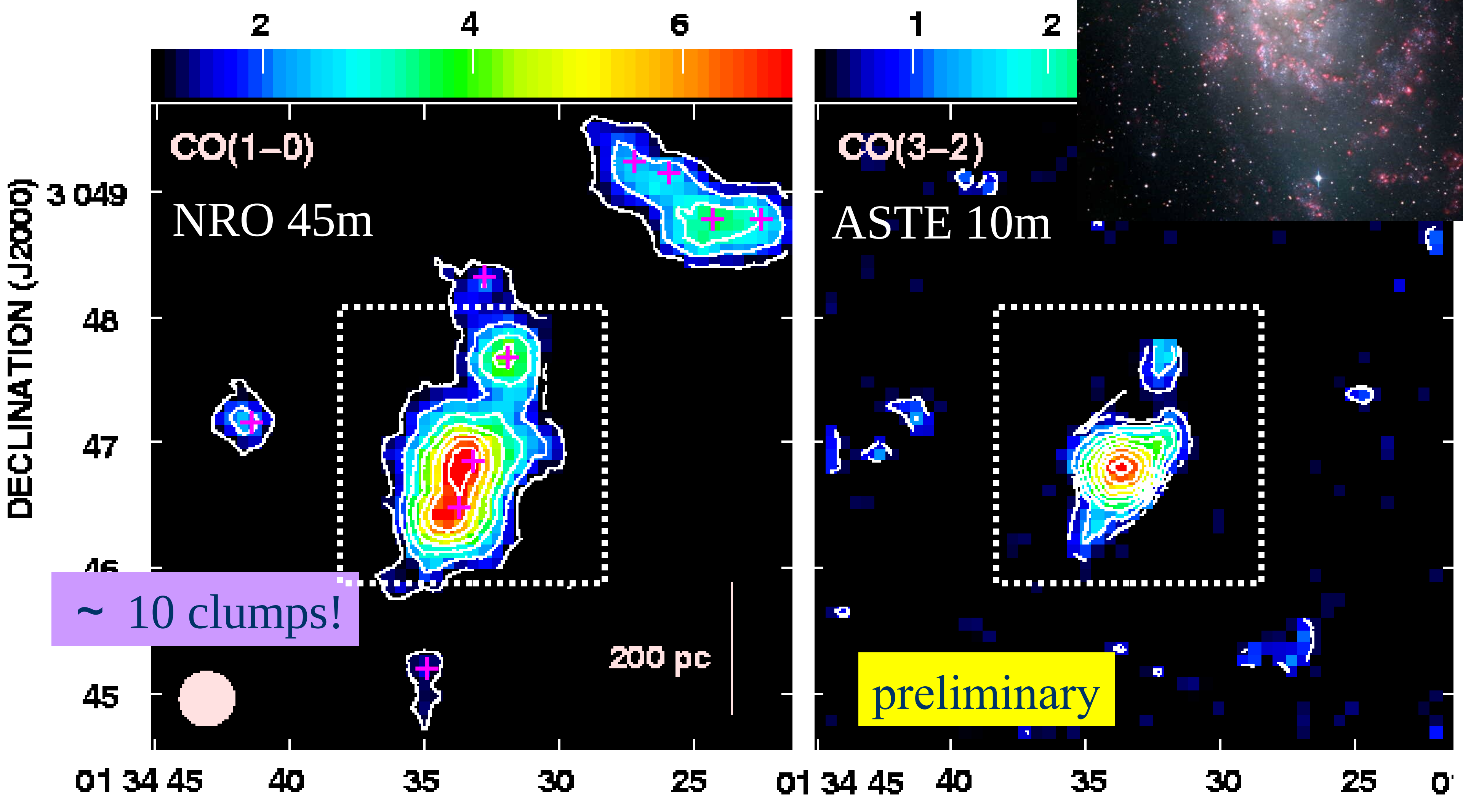




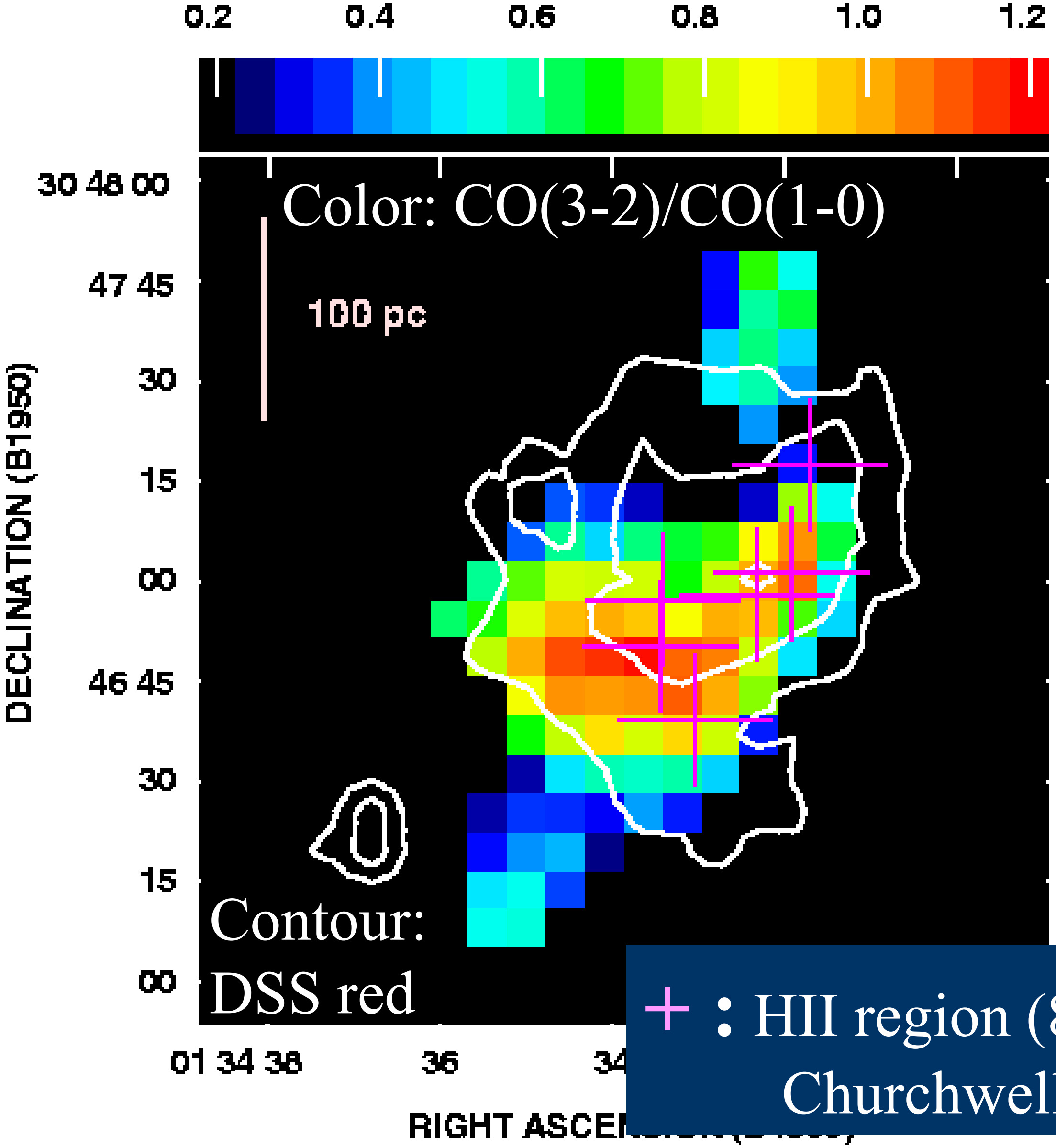
Kohno, Tosaki, Miura, Sawada et al. 2006, in prep.

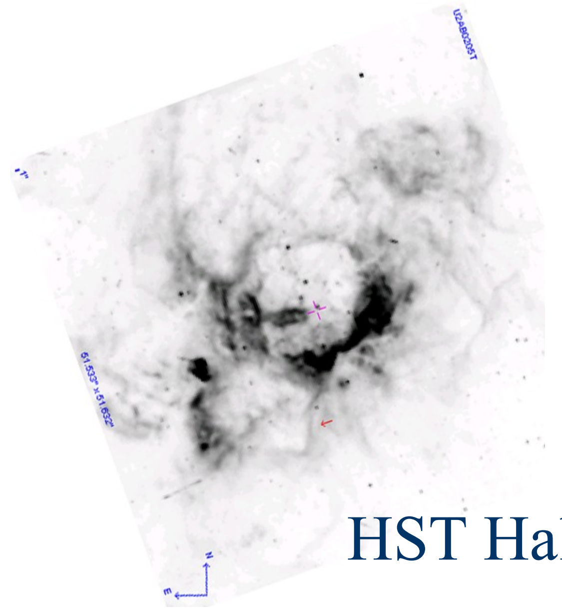
OTF CO(1-0) & CO(3-2) 5’x5’ maps of NGC604 (giant HII region in M33)

Miura, Tosaki, et al. in prep.



Arc-like distribution of CO(3-2)/CO(1-0) (partly) associated with Halpha shell structure



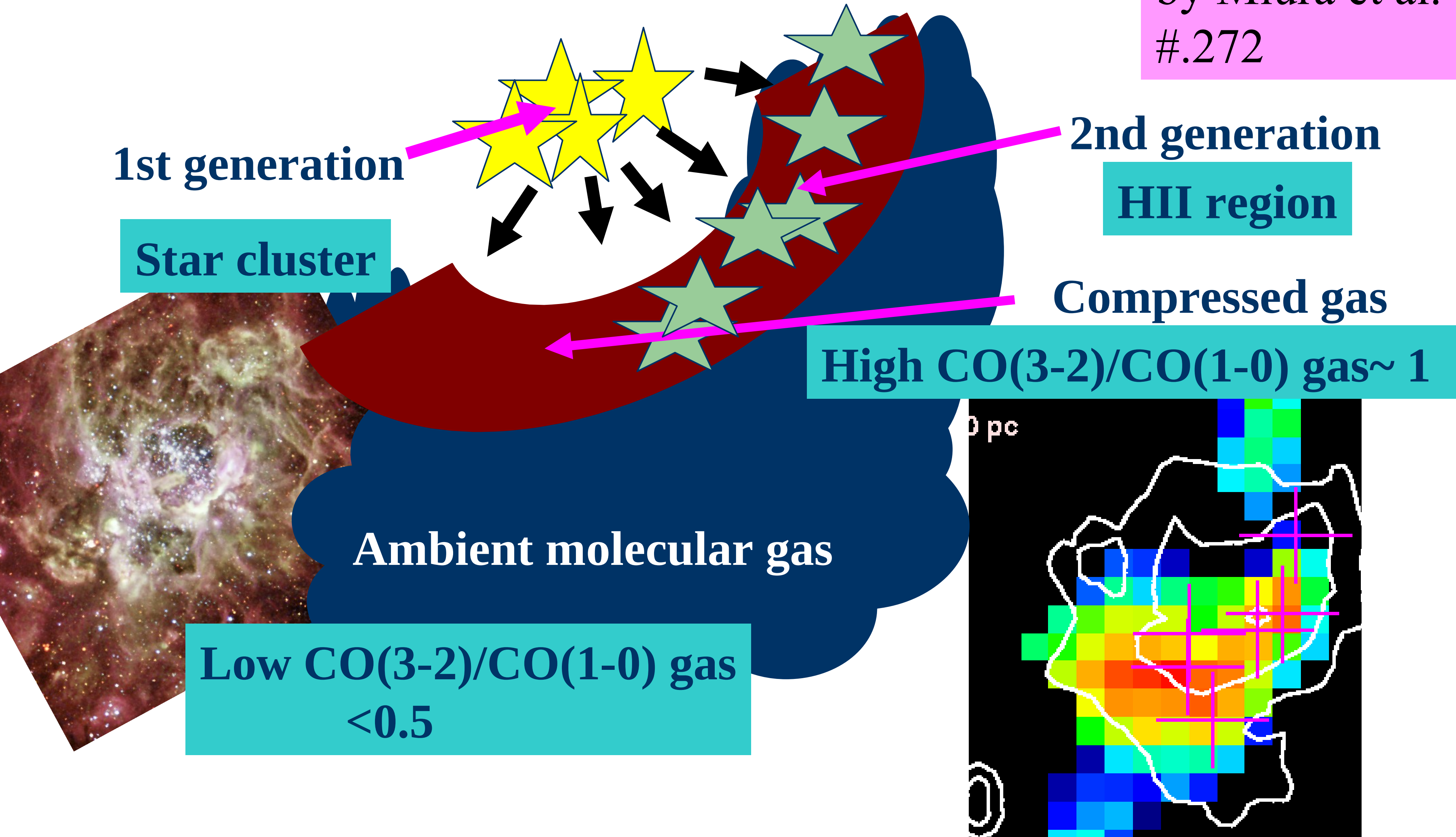


HST Halpha

+ : HII region (8GHz cont.)
Churchwell & Goss 1999, ApJ, 514, 188

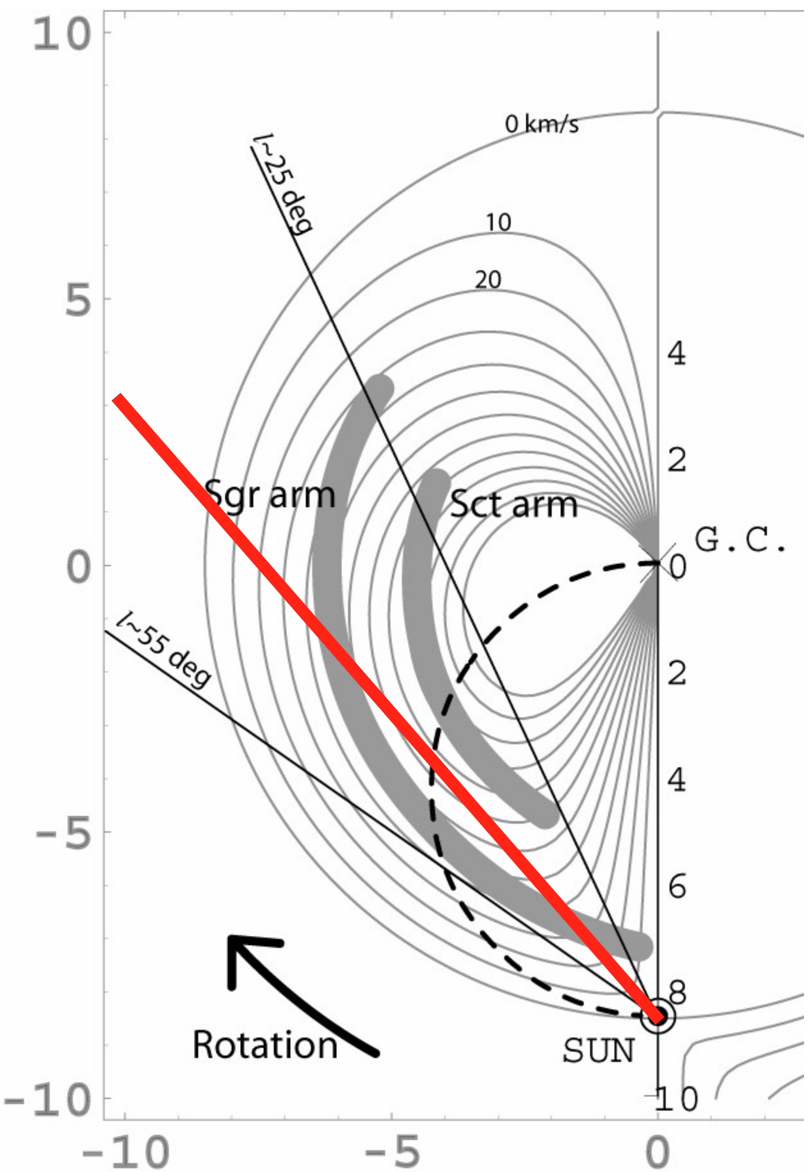
Dense gas & secondary star formation triggered by 1st generation star in NGC 604?

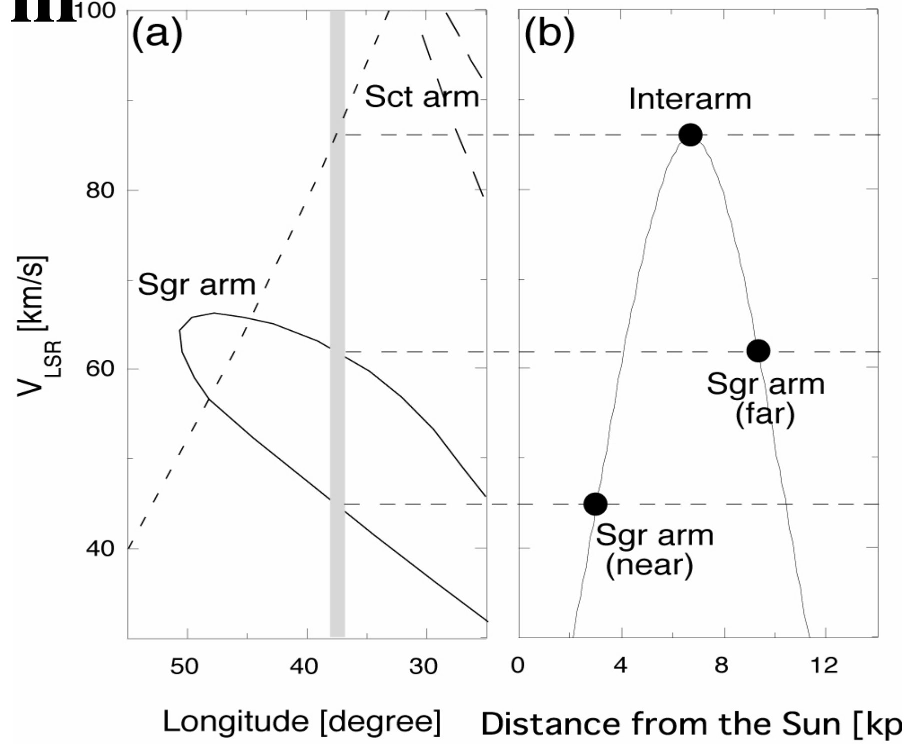
See poster
by Miura et al.
#.272



ASTE observations of Dense gas in arm/inter-arm regions of the Galaxy

Tracing arm & inter-arm regions in the Galaxy



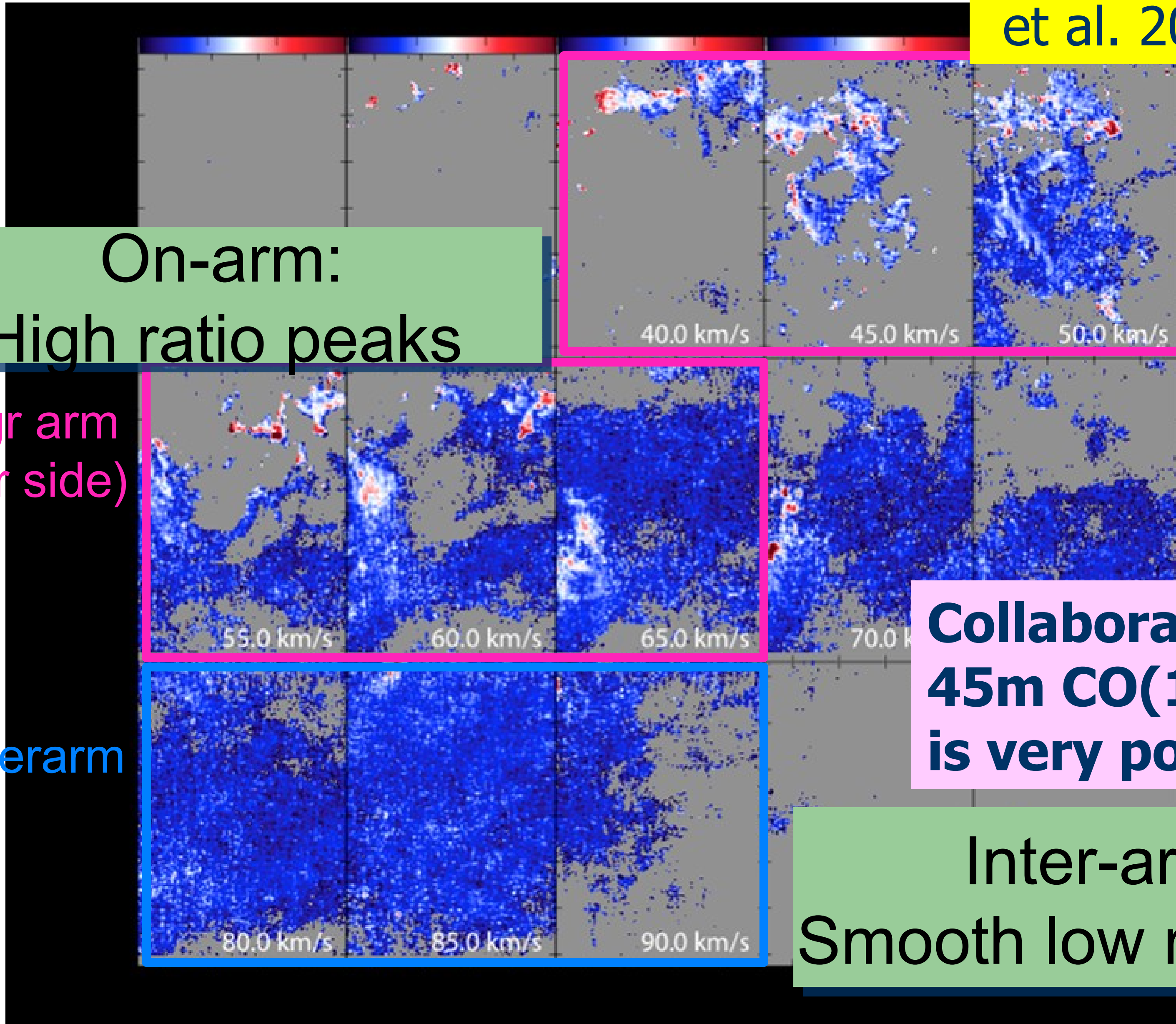


Arm and inter-arm regions are just separated by velocity!

Sawada, Koda, et al. 2006 in prep.

CO(3–2)/CO(1–0) Ratios

Sawada (NRO)、& Koda (Caltech) et al. 2006



Sgr arm (near side)

On-arm: High ratio peaks

Sgr arm (far side)

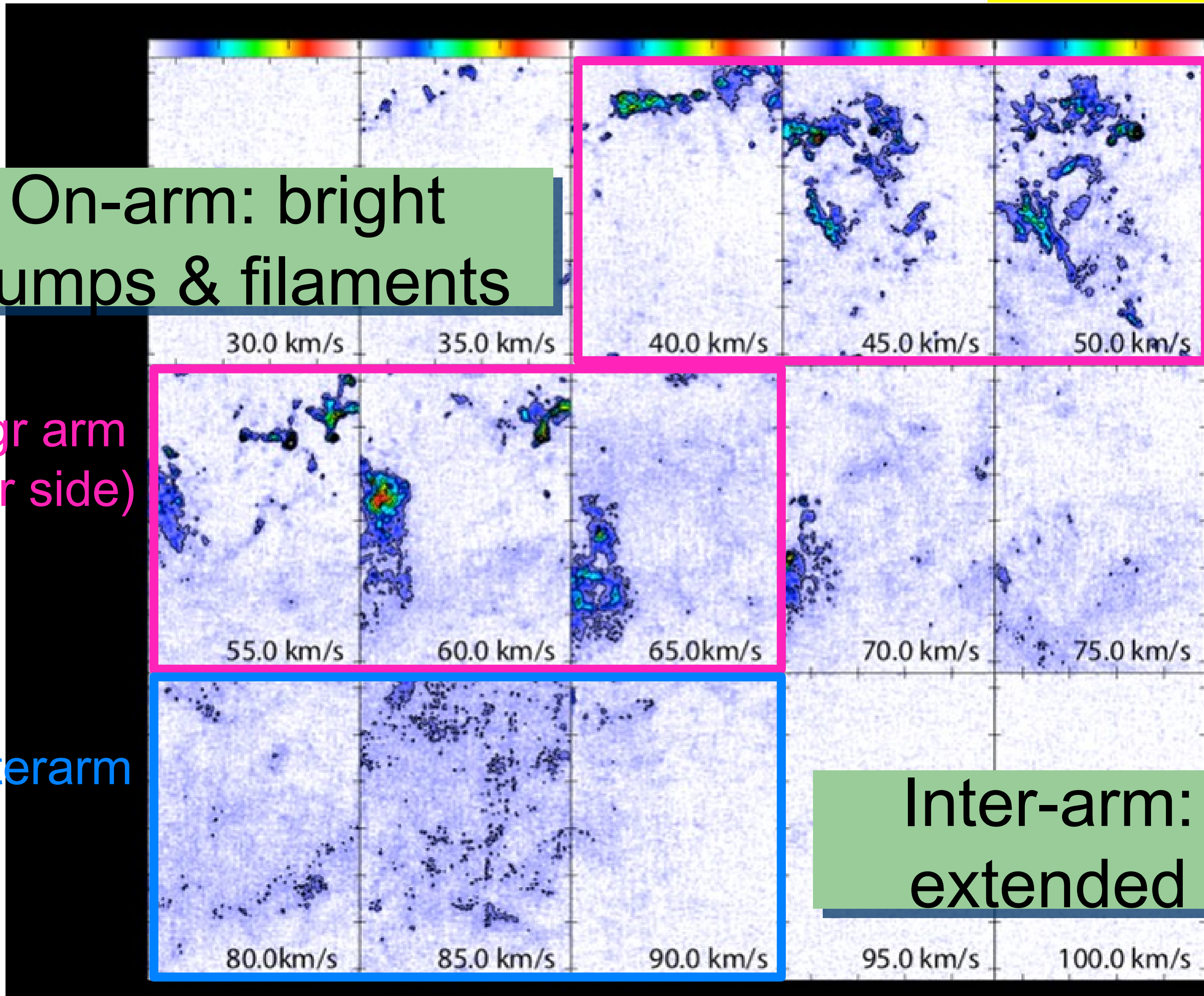
Interarm

Collaboration w/ 45m CO(1-0) is very powerful !

Inter-arm: Smooth low ratio gas

CO(3–2) channel maps of Sgr arm/interarm regions

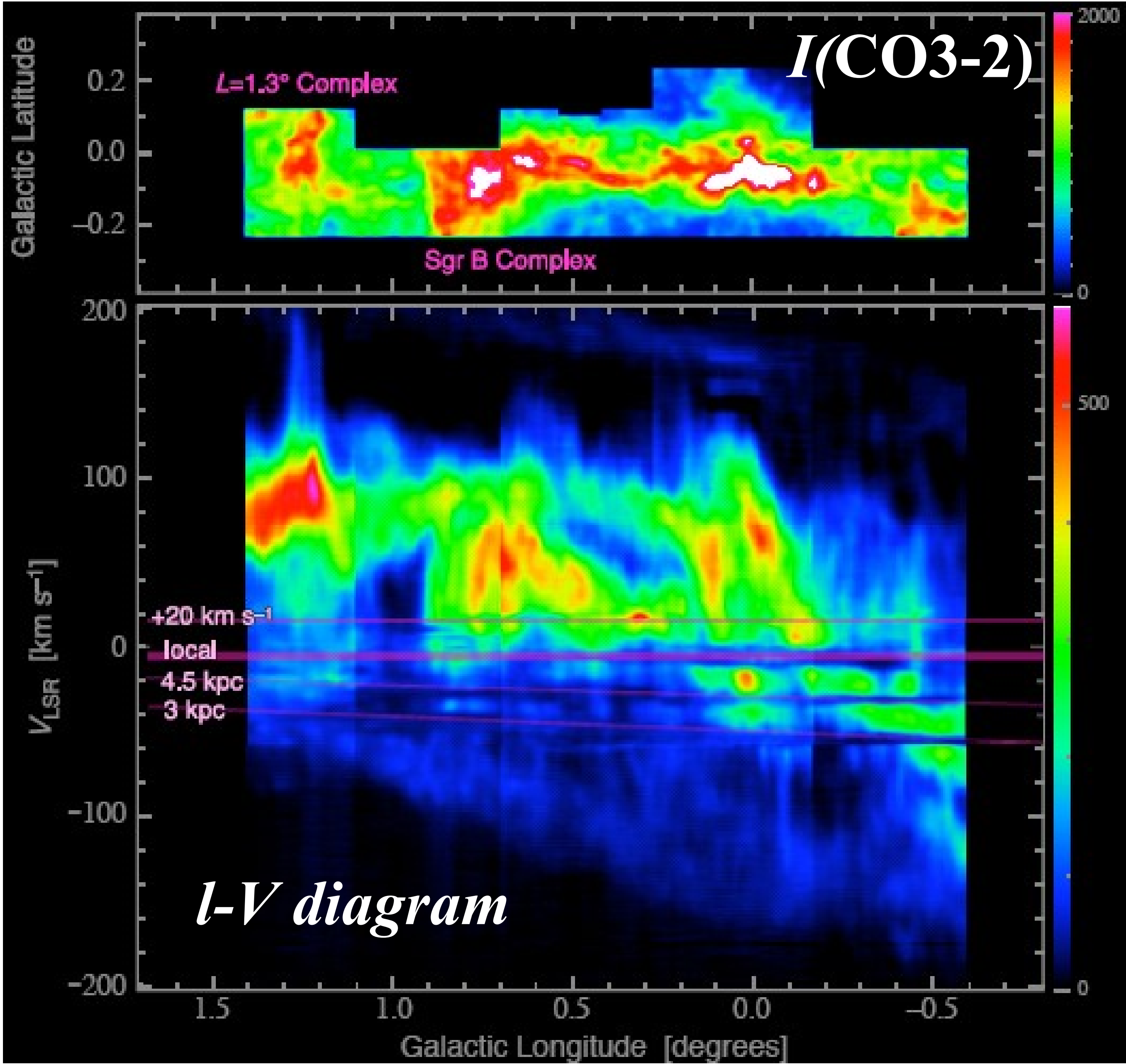
Sawada (NRO)、& Koda (Caltech) et al. 2006



ASTE observations of Dense gas in the Galactic Center

ASTE CO(3-2) map of the G.C.

2 deg x 0.4 deg

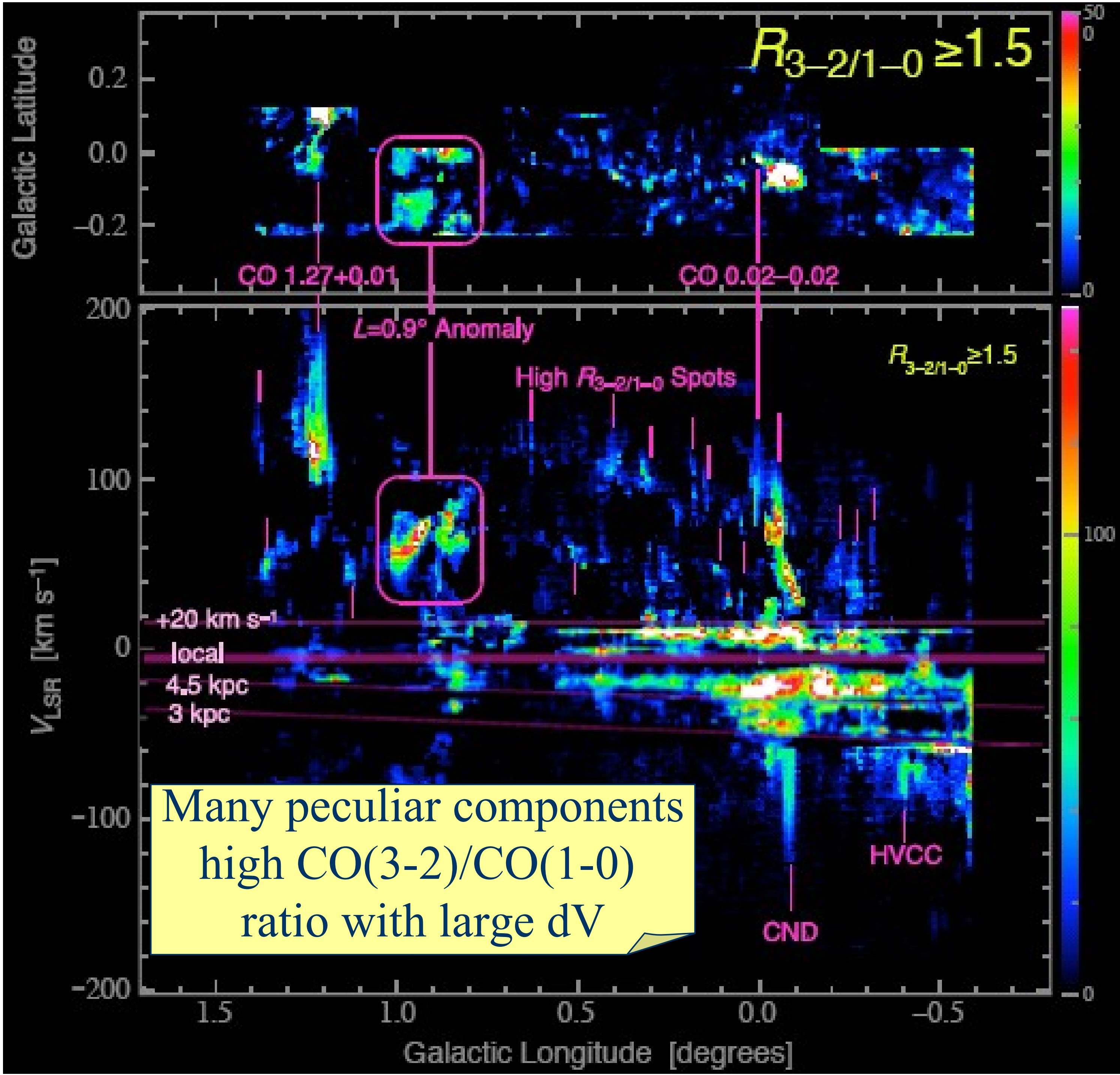


Oka et al. 2006, in press

Nagai et al.

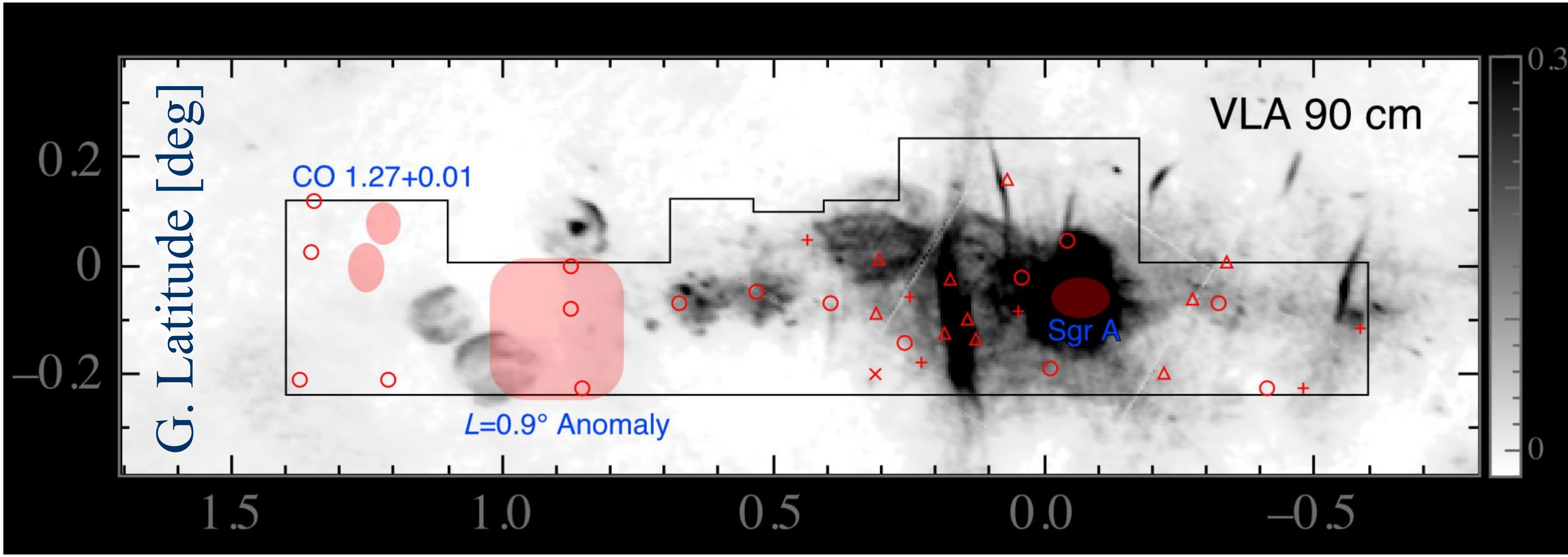
Tanaka et al. submitted

map of high CO(3-2) /CO(1-0) ratio gas



Oka et al. 2006, in press
Nagai et al.
Tanaka et al. submitted

high R(3-2/1-0) gas: associated with shock?



Galactic Longitude [deg]

- Possible coincidence of very high ratio gas with SNRs?

Oka et al. 2006, PASJ, in press

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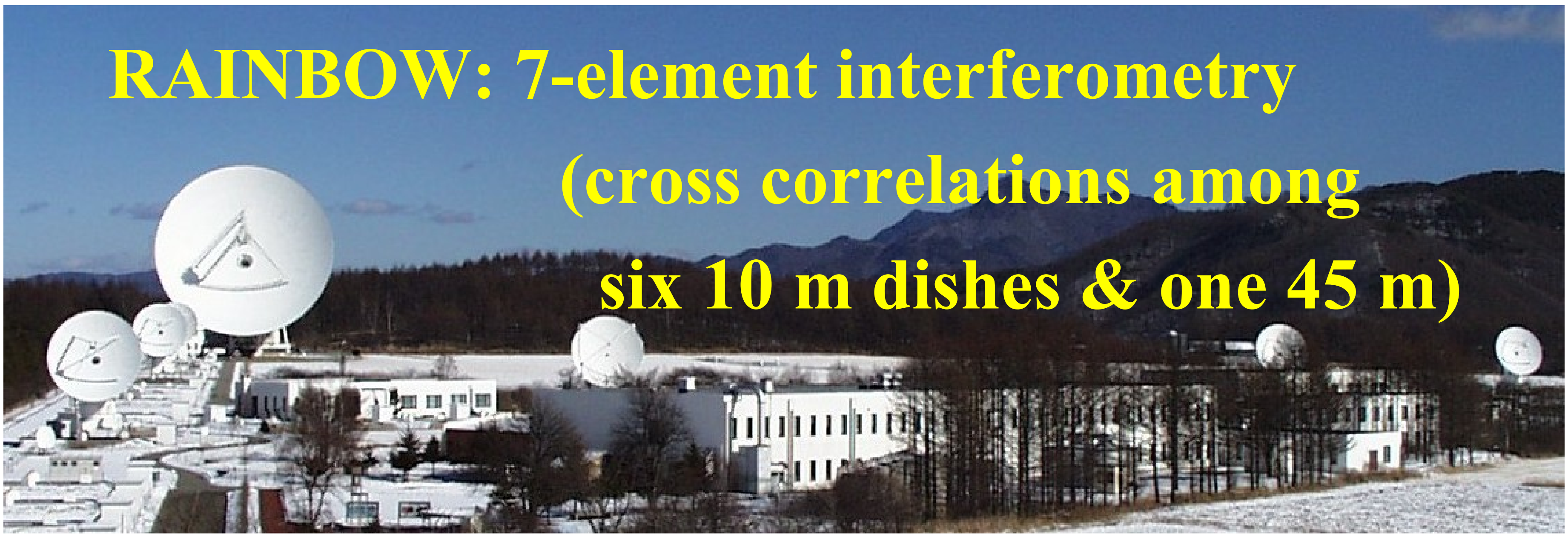
- Introduction: Dense molecular gas in galaxies
- ASTE observations of dense molecular gas in galaxies and the Galaxy
  - ✓ CO(3-2) mapping of galaxies (M83 etc.) ➔ correlation between CO(3-2)/CO(1-0) ratio and star formation efficiency?
  - ✓ CO(3-2) mapping of Sgr arm regions, the Galactic Center, etc.
- NMA observations of dense molecular gas in the central regions of Seyfert and starburst galaxies
  - ✓ "HCN enhanced Seyfert galaxies": a signature of X-ray dominated regions (XDRs)

NMA observations of Dense gas in Seyfert and starburst galaxies

NMA/RAINBOW survey of Sys & starbursts

- The mission completed! 20 Seyferts (6 Sy1s and 14 Sy2s) in total
- 12 nearby starburst galaxies for a control sample
  - ✓ Mainly from Palomar Seyfert sample (Ho et al. 1997)
- High resolution (1.6 – 8.6 arcsec) imaging of HCN(1-0), HCO^+(1-0), and CO(1-0) emission lines (+ 3 mm continuum)
- **Preliminary reports: Kohno et al. 2001, 2002, 2005**



NGC 1068

- Nucleus ：

  $R_{HCN/CO} = 0.54$

  $R_{HCN/HCO+} = 2.1$

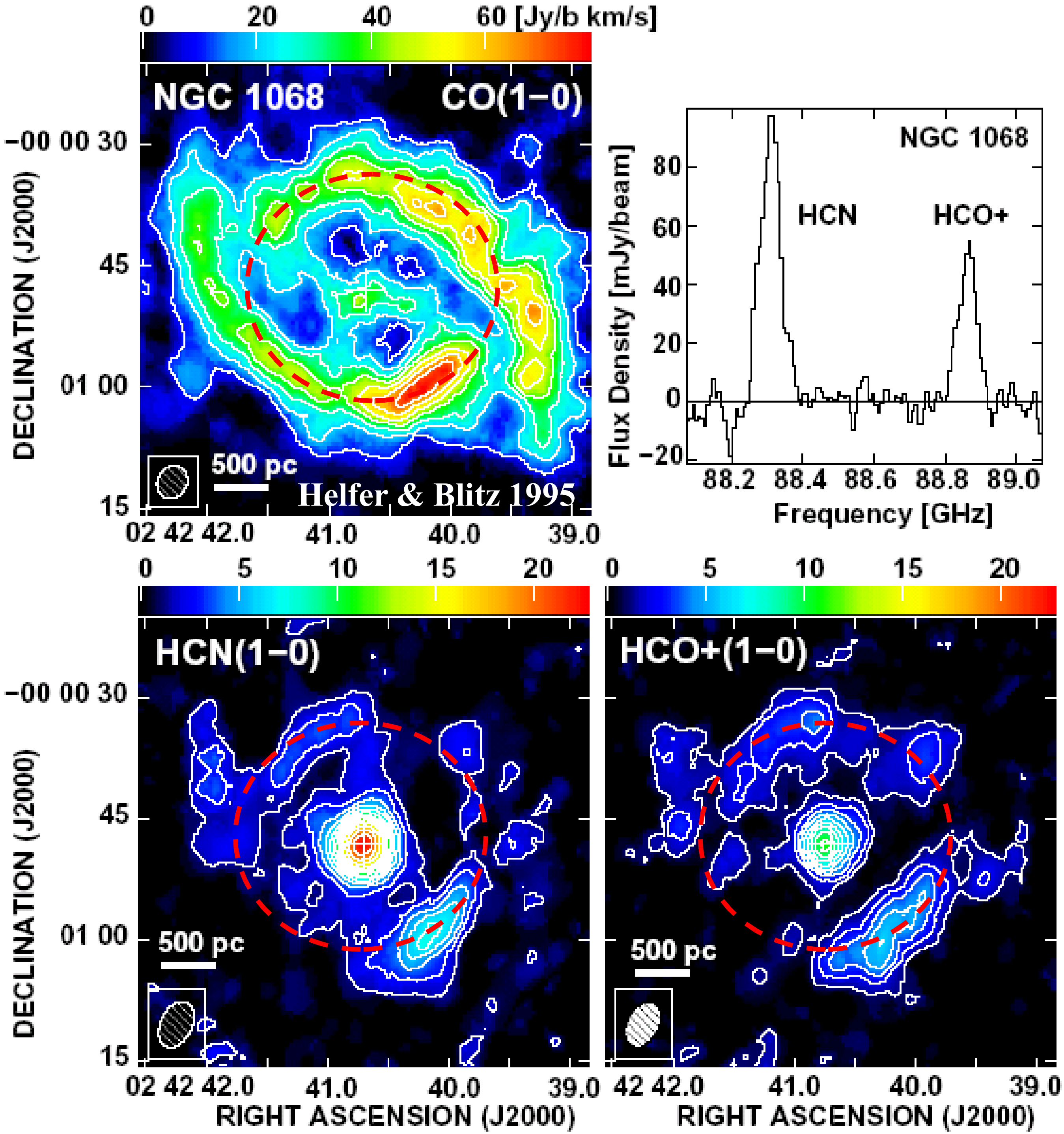
  ➔ significant enhancement of HCN

- Disk ：

  $R_{HCN/CO} = 0.10$

  $R_{HCN/HCO+} = 1.3$

  ➔ typical values for starburst regions



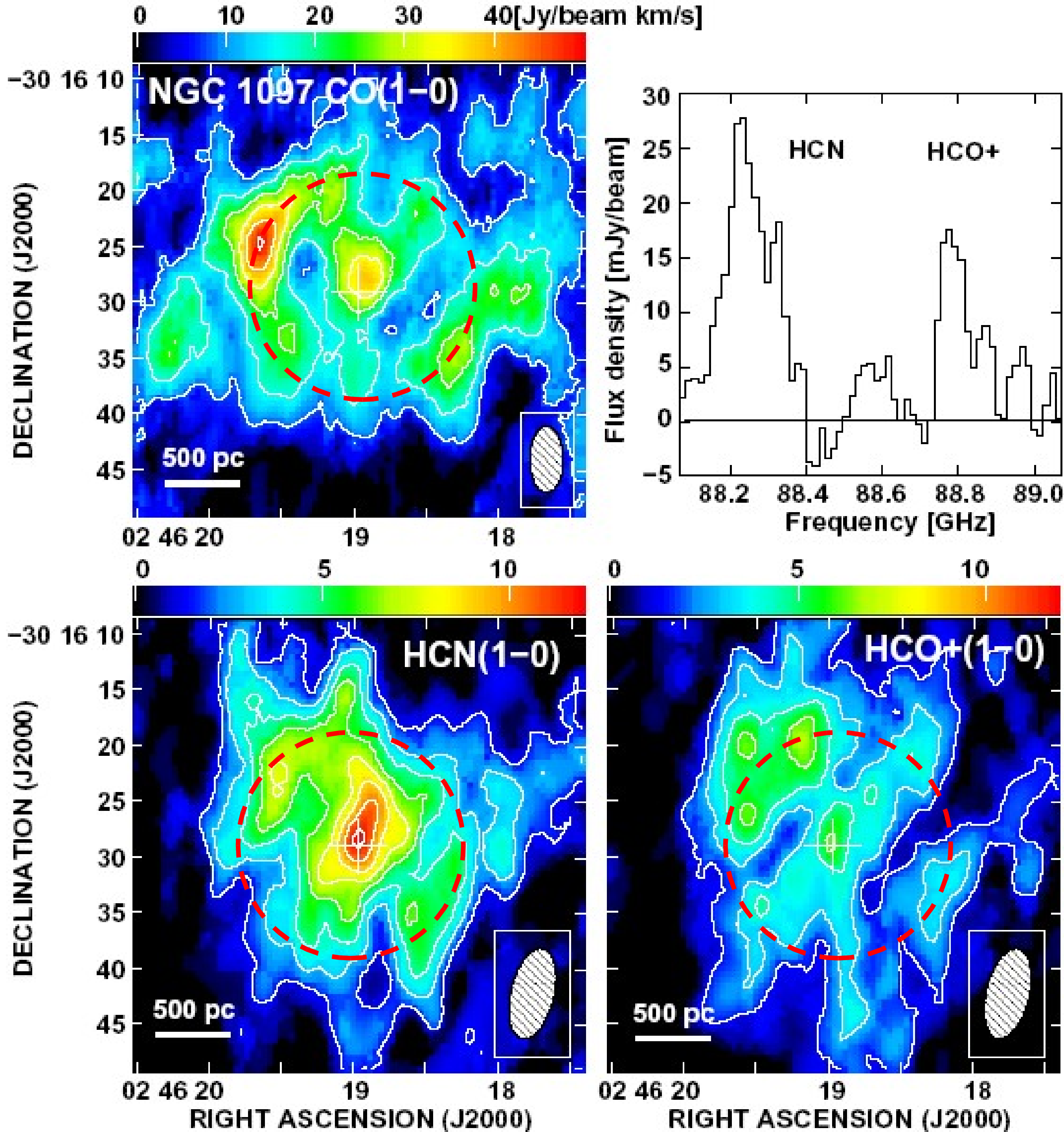
NGC 1097

- Nucleus ：

$R_{HCN/CO} = 0.39$

$R_{HCN/HCO+} = 1.9$

➔ significant enhancement of HCN, any other causes *other than* high gas density ?



NGC 5194

- Nucleus ：

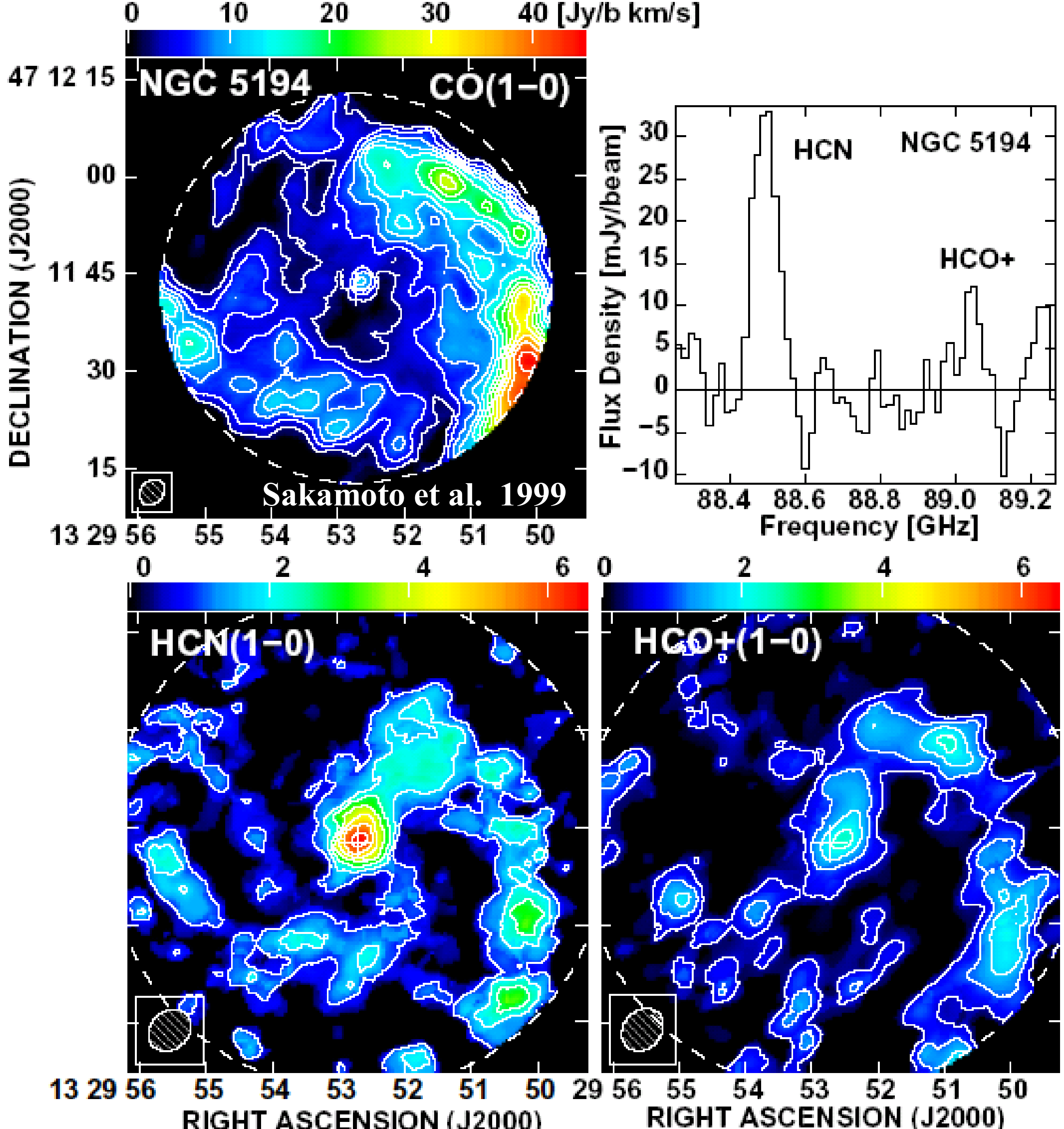
$R_{HCN/CO} = 0.56$

$R_{HCN/HCO+} = 2.5$

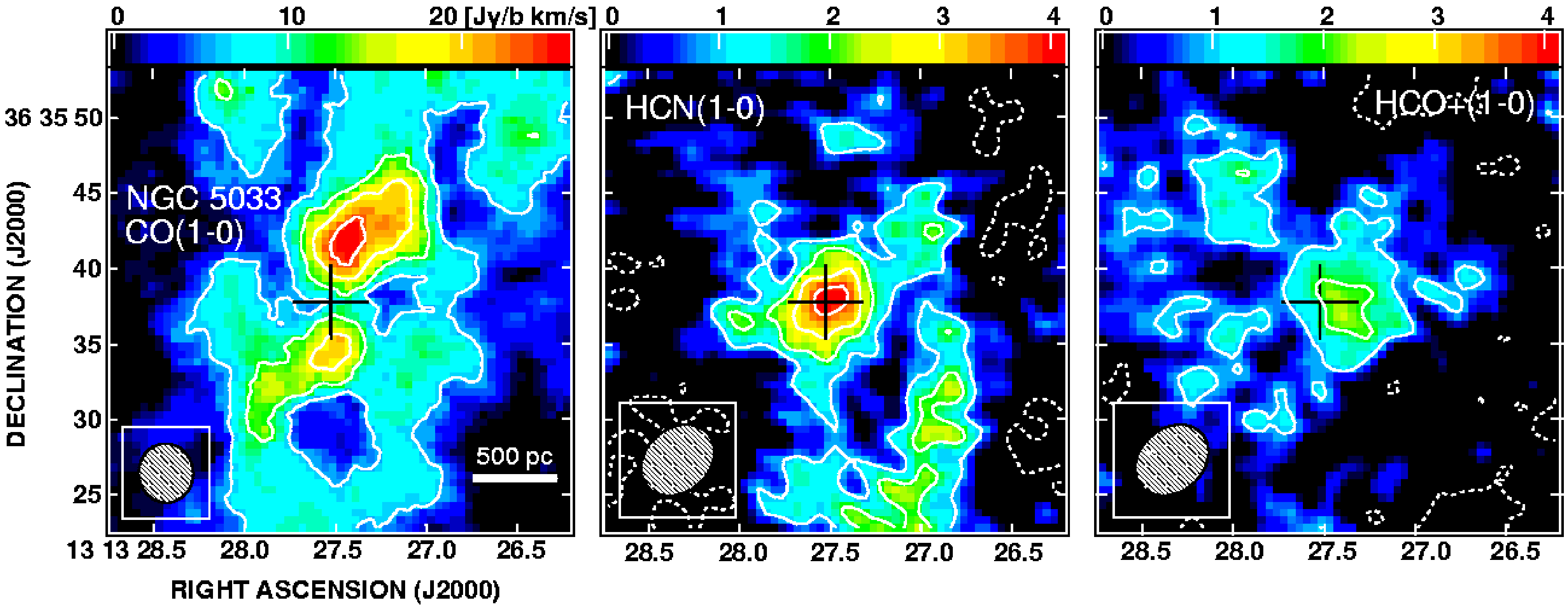
- Similar critical density (n_{H2}>10^4 H_2/cm^{-3})
- Similar optical depth (tau>>1)

⇒ difference of abundance

(filling factor)



The 4th HCN enhanced Seyfert: NGC 5033



Flux at the nucleus: 31±2 Jy/b km/s | 4.3±0.63 Jy/b km/s | 2.3±0.63 Jy/b km/s

- HCN and HCO+: central concentration, contrary to CO

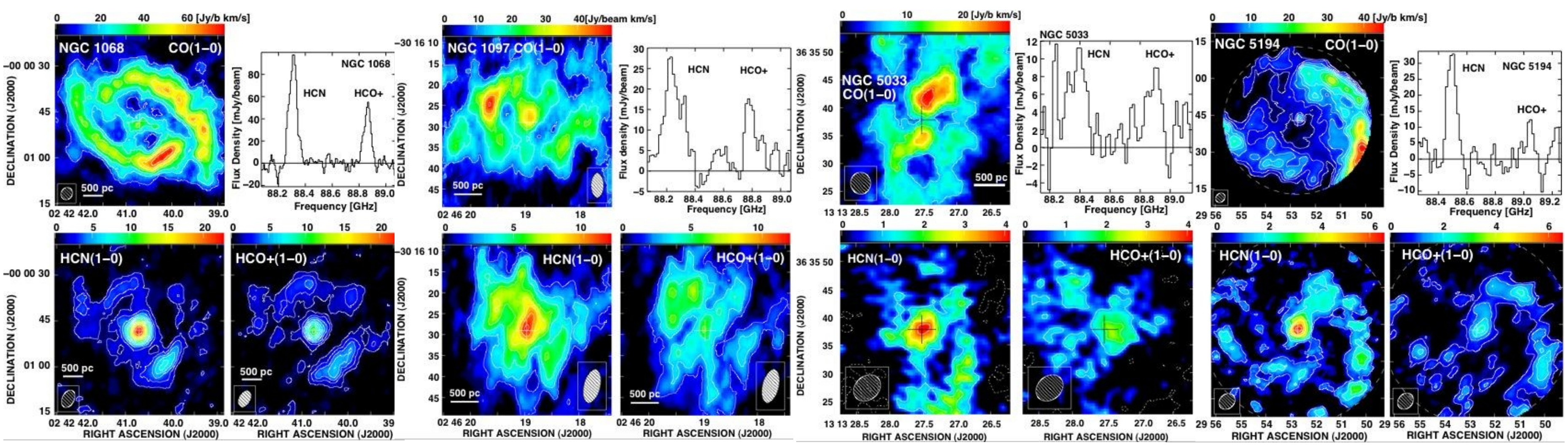
$R_{HCN/CO} = 0.23$, $R_{HCN/HCO+} = 1.9$

➔ This is the 4th "NGC 1068", i.e., HCN enhanced Seyfert nuclei.

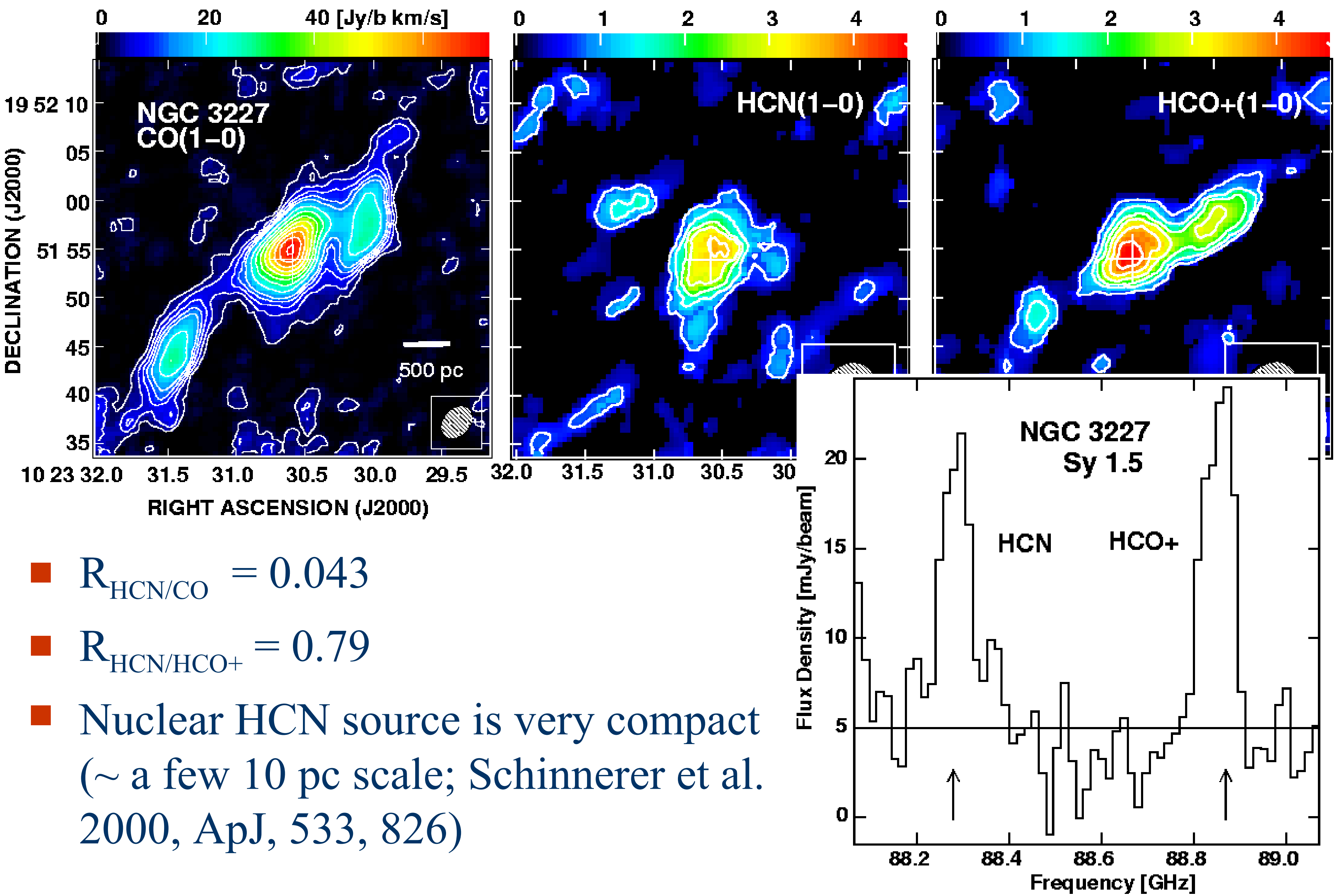
Discovery of “HCN enhanced Seyfert nuclei”

- NGC 1068 (Sy 1.8) ：
  Jackson et al. 1993 (NMA), Tacconi et al. 1994 (PdBI), Helfer & Blitz 1995 (BIMA)
- NGC 5194 (Sy 2) ：
  Kohno et al. 1996, ApJ, 461, L29 (NMA)
- NGC 1097 (Sy 1) ：
  Kohno et al. 2003, PASJ, 55, L1 (NMA)
- NGC 5033 (Sy 1.5) ：
  Kohno et al. 2005, astro-ph/0508420 (NMA)

How about other Seyferts then?



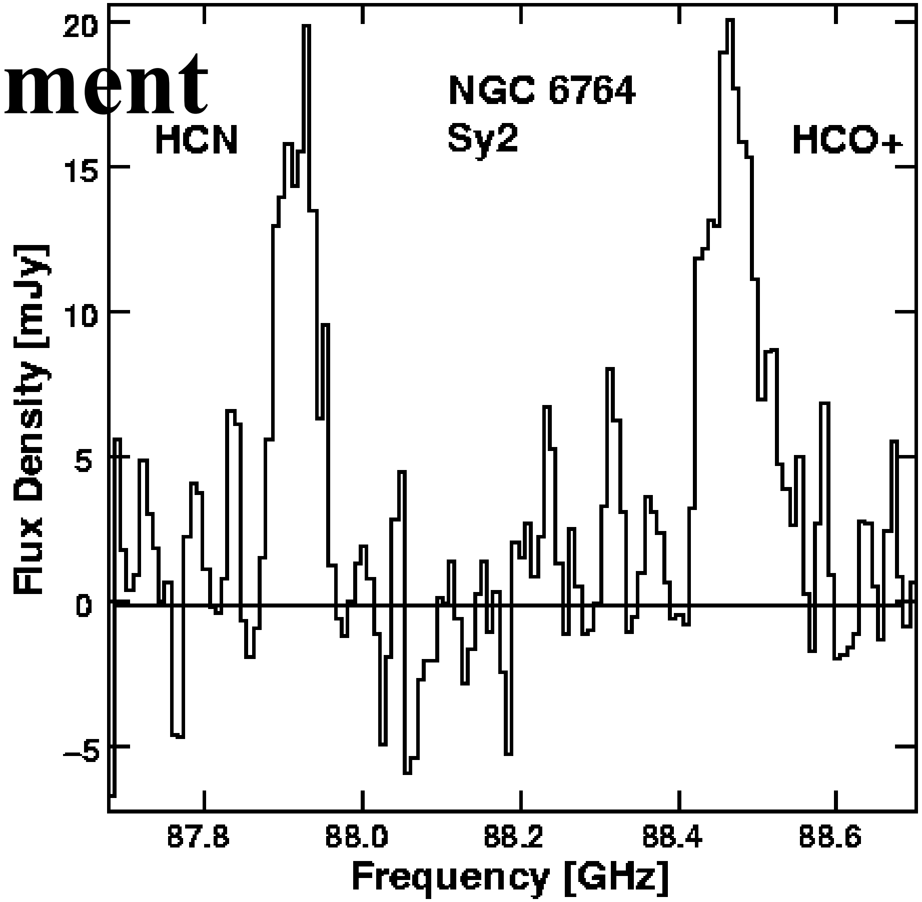
NGC 3227: no HCN enhancement

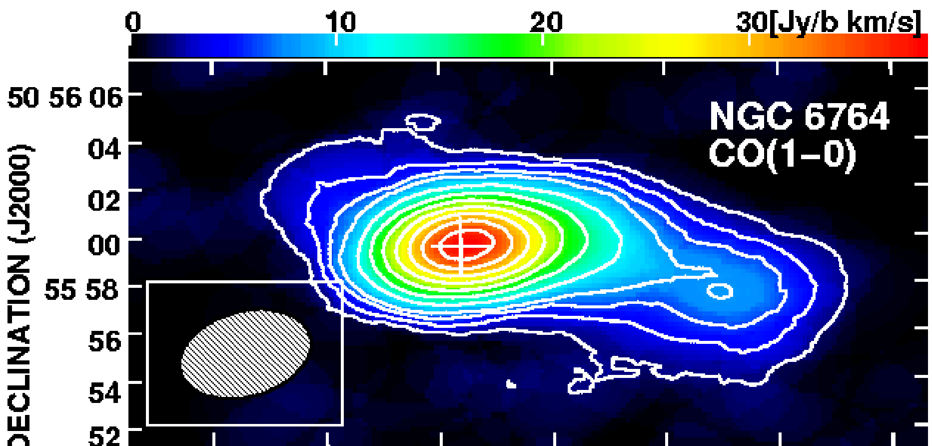


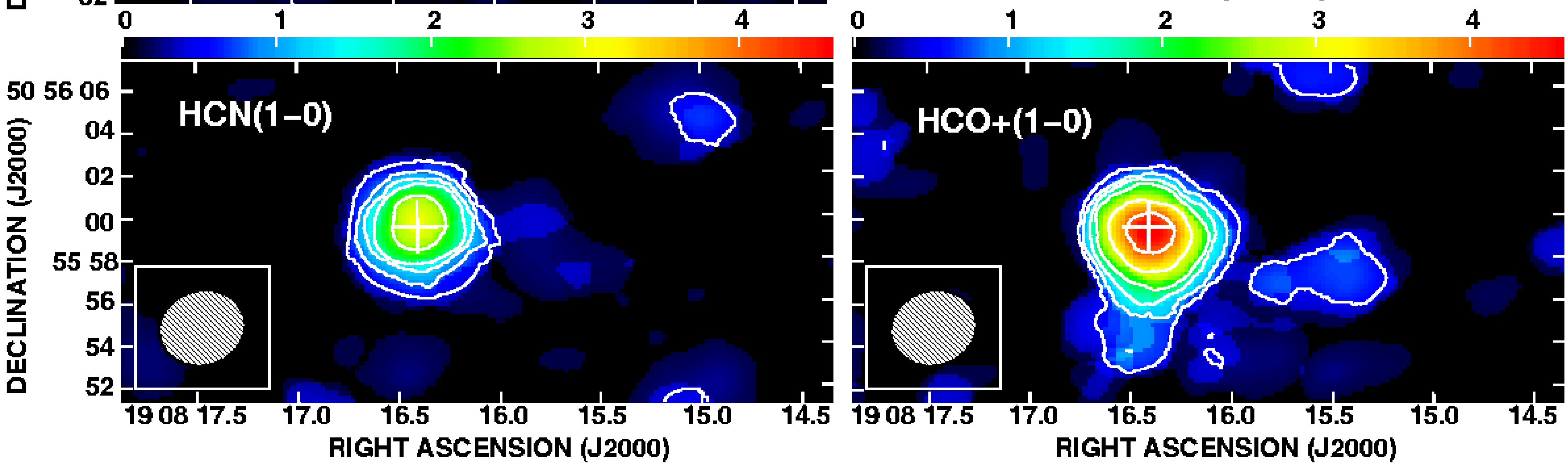
- $R_{HCN/CO}$ = 0.043
- $R_{HCN/HCO+}$ = 0.79
- Nuclear HCN source is very compact (~ a few 10 pc scale; Schinnerer et al. 2000, ApJ, 533, 826)

NGC6764: no enhancement

- $R_{HCN/CO} = 0.14$; $R_{HCN/HCO+} = 0.63$
- AGN w/ compact WR starburst (Schinnerer et al. 2000)

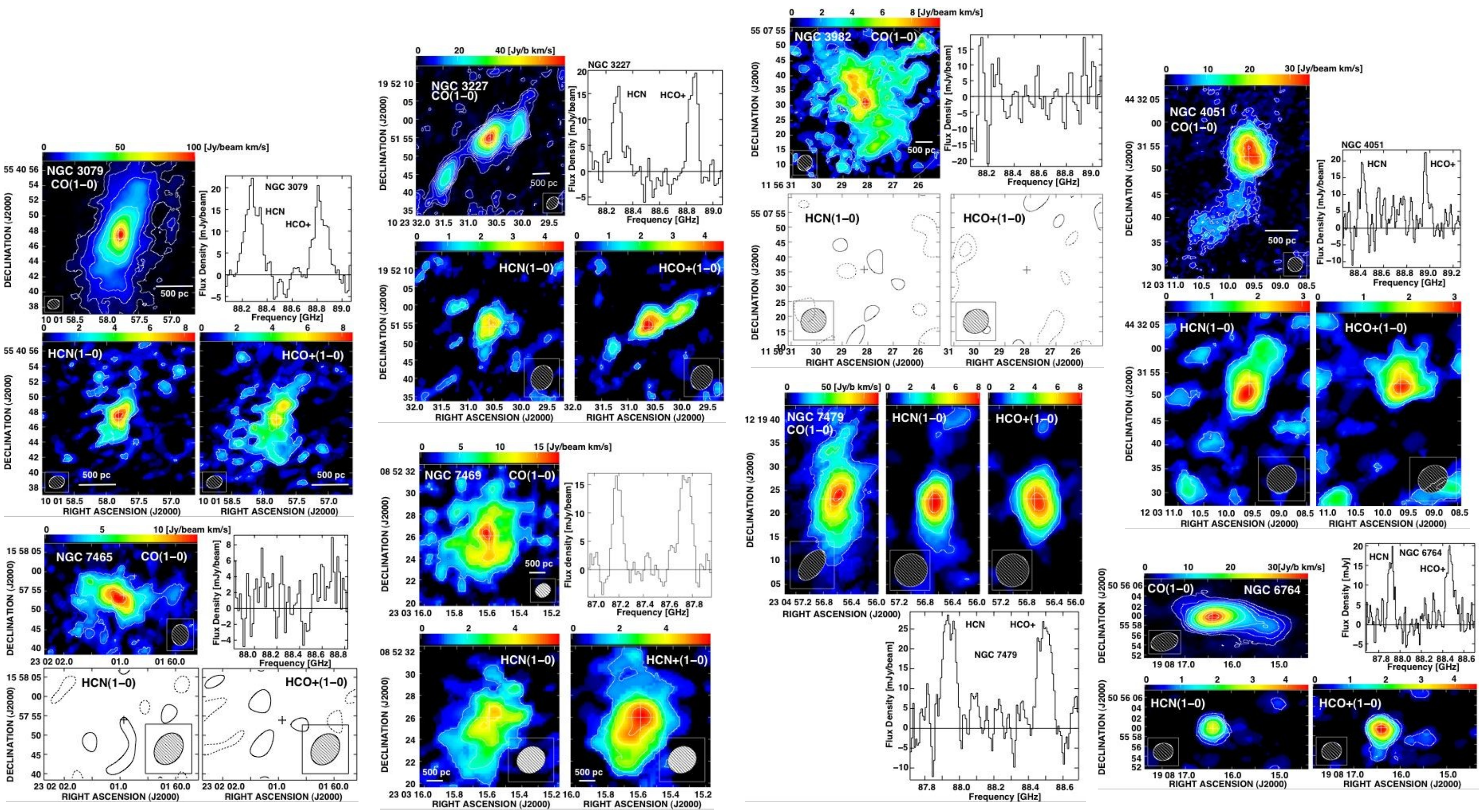




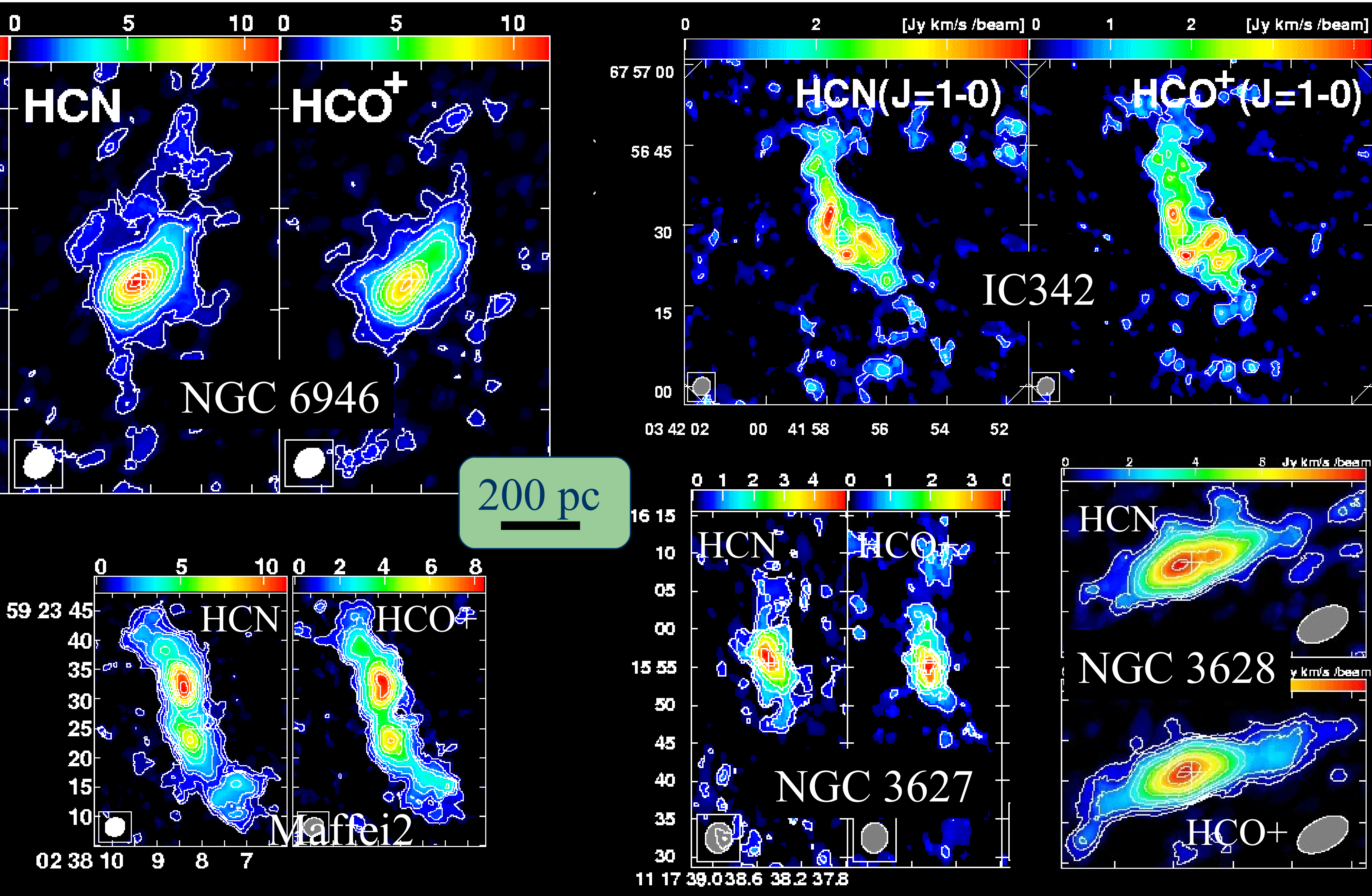


Seyfert galaxies w/ no HCN enhancement

- Currently, majority of the sample show no significant HCN enhancement.

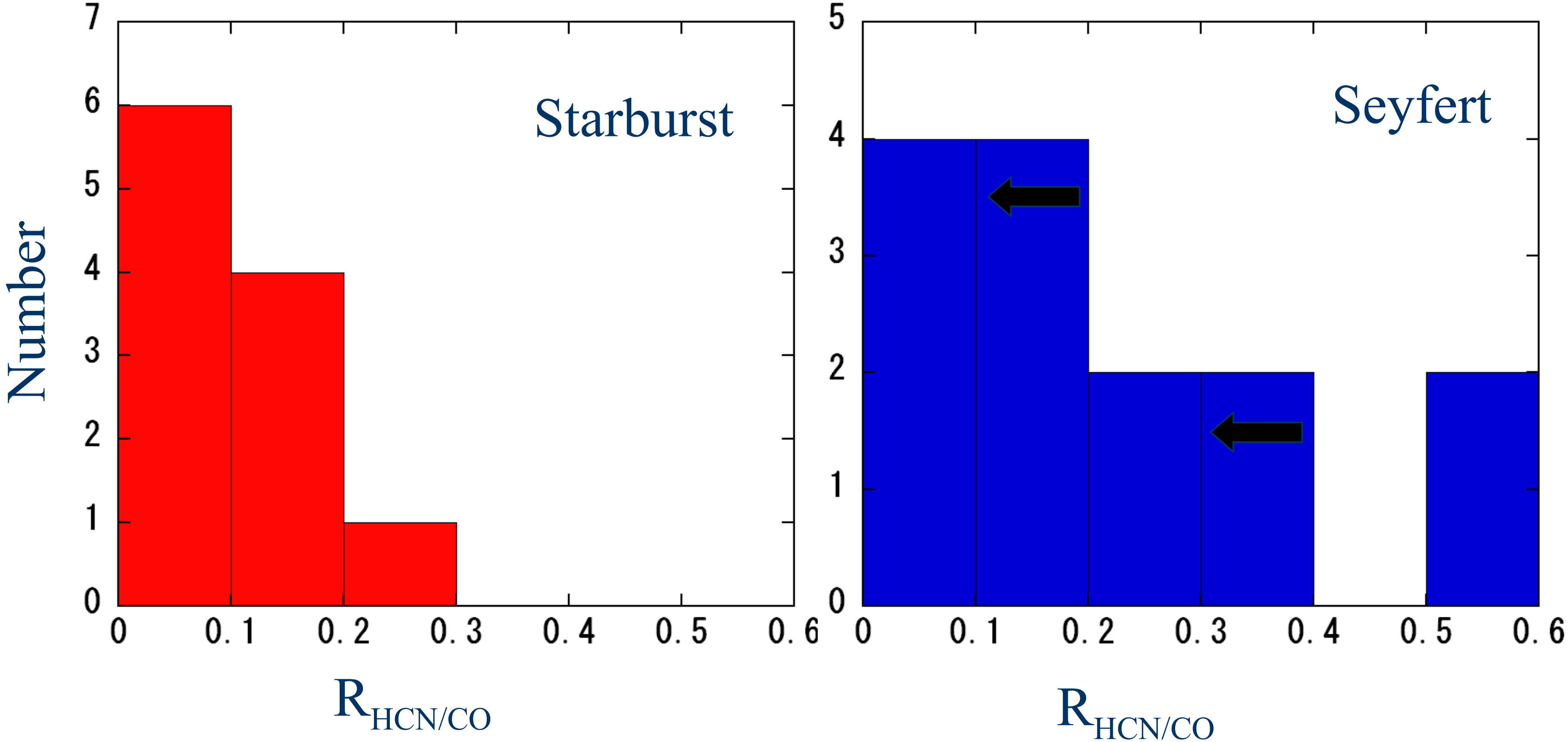


HCN & HCO^+ Images of Starburst Galaxies



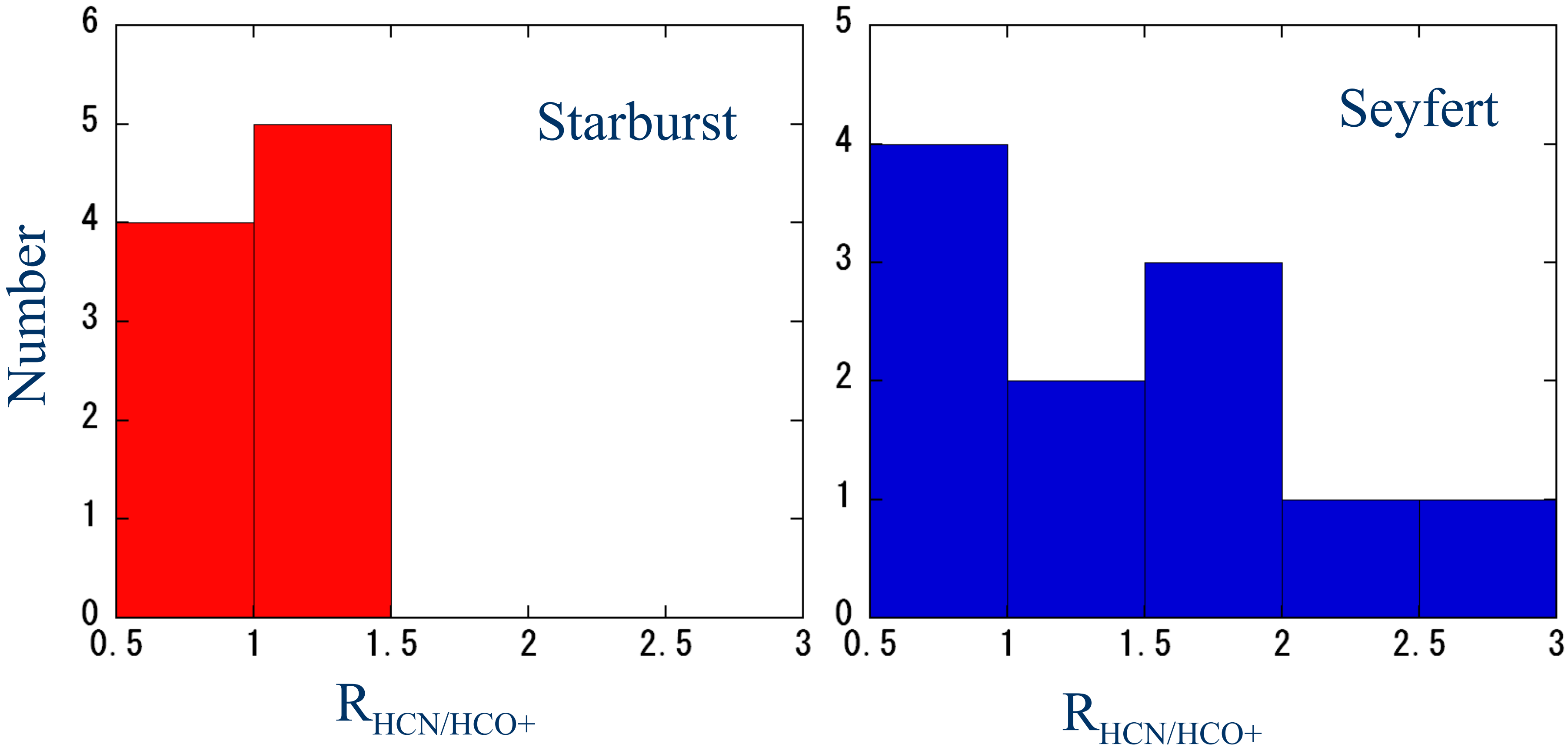
Summary of results: Line ratios

Seyfert vs Starburst: histogram of $R_{HCN/CO}$



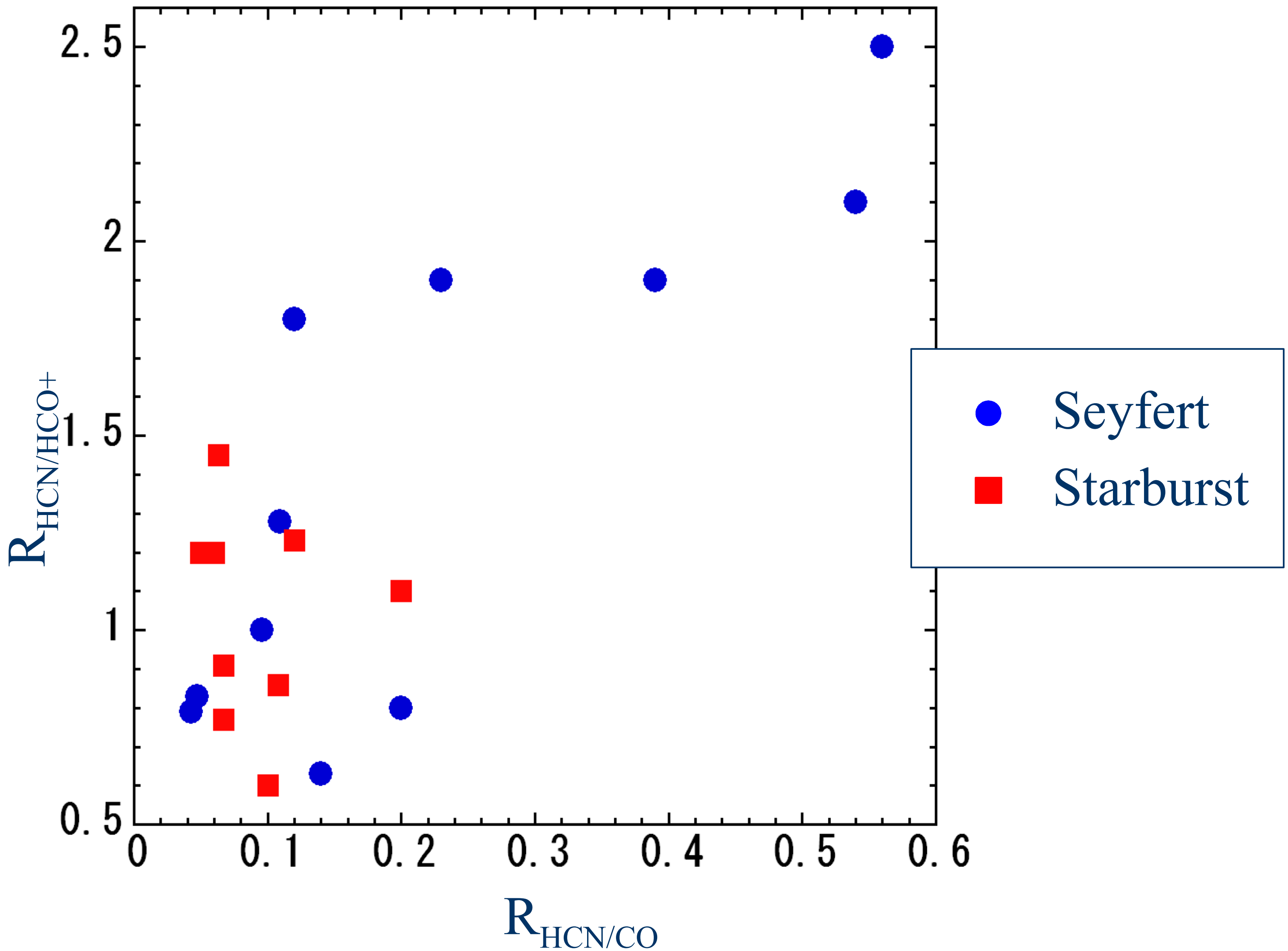
- Starburst: $R_{HCN/CO} < 0.3$
- Seyfert: enhanced $R_{HCN/CO}$(>0.3), which are never observed in SBs
- Note: $R_{HCN/CO}$ depend on spatial resolution (CO distribution)

Seyfert vs Starburst: histogram of $R_{HCN/HCO+}$



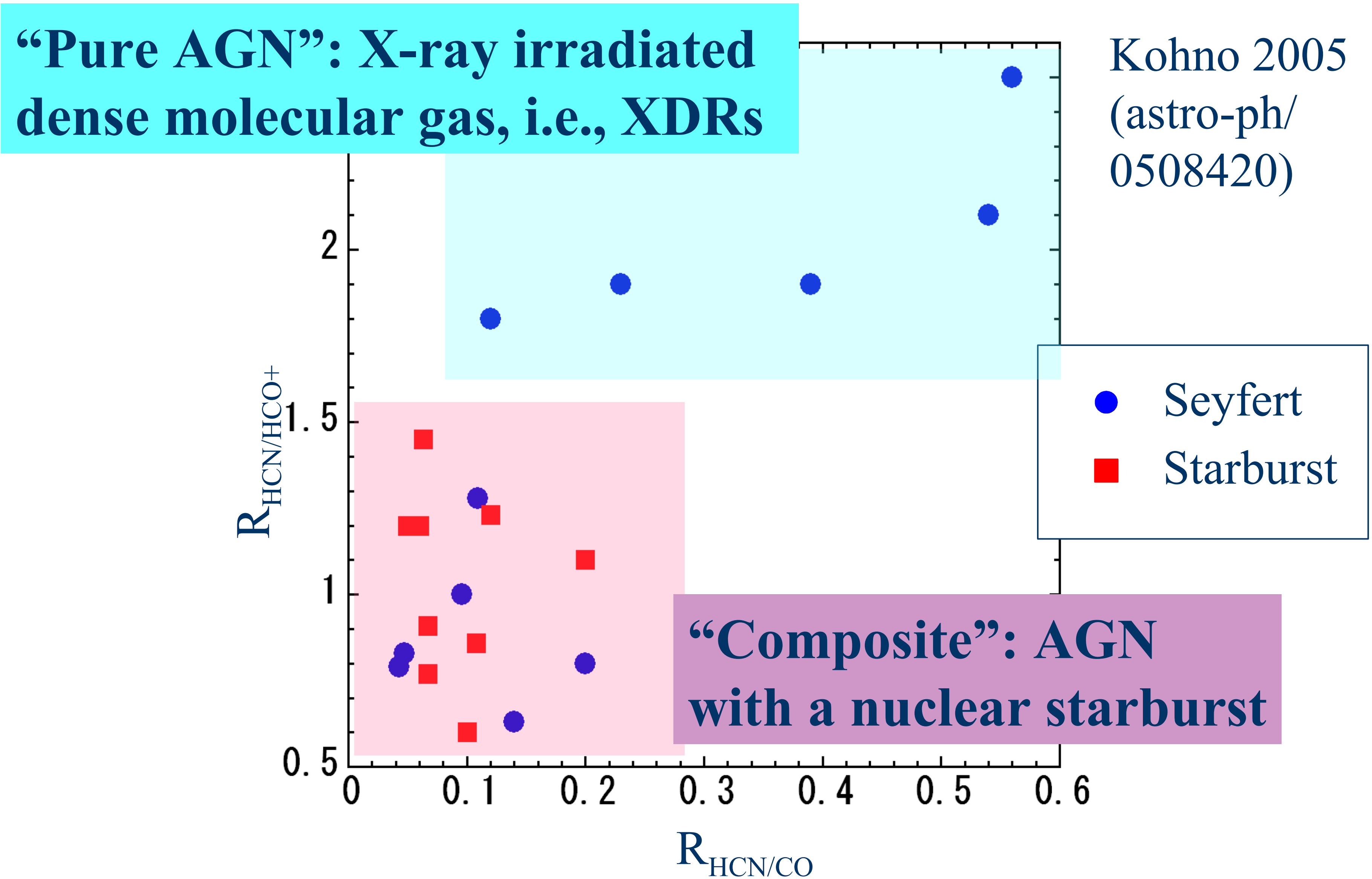
- Starburst: $R_{HCN/HCO+} < 1.5$
- Seyfert: enhanced $R_{HCN/HCO+}$ (>1.5), never observed in SBs
- Tracing dense part of gas ➔ less sensitive to extended diffuse gas

HCN/HCO+ & HCN/CO ratios: Seyfert galaxies vs starburst galaxies



Dominant power source within observing beam

Kohno et al. 2001 (astro-ph/0206398)



XDR vs PDR

- XDR ： filled w/ high energy photon ➔ penetrate into deep inside GMCs

⇔ in PDR, UV photon are blocked at the surface of GMCs

- Efficient heating due to photo ionisation

  ⇔ photo electric heating @ PDR (inefficient by an order of magnitude)

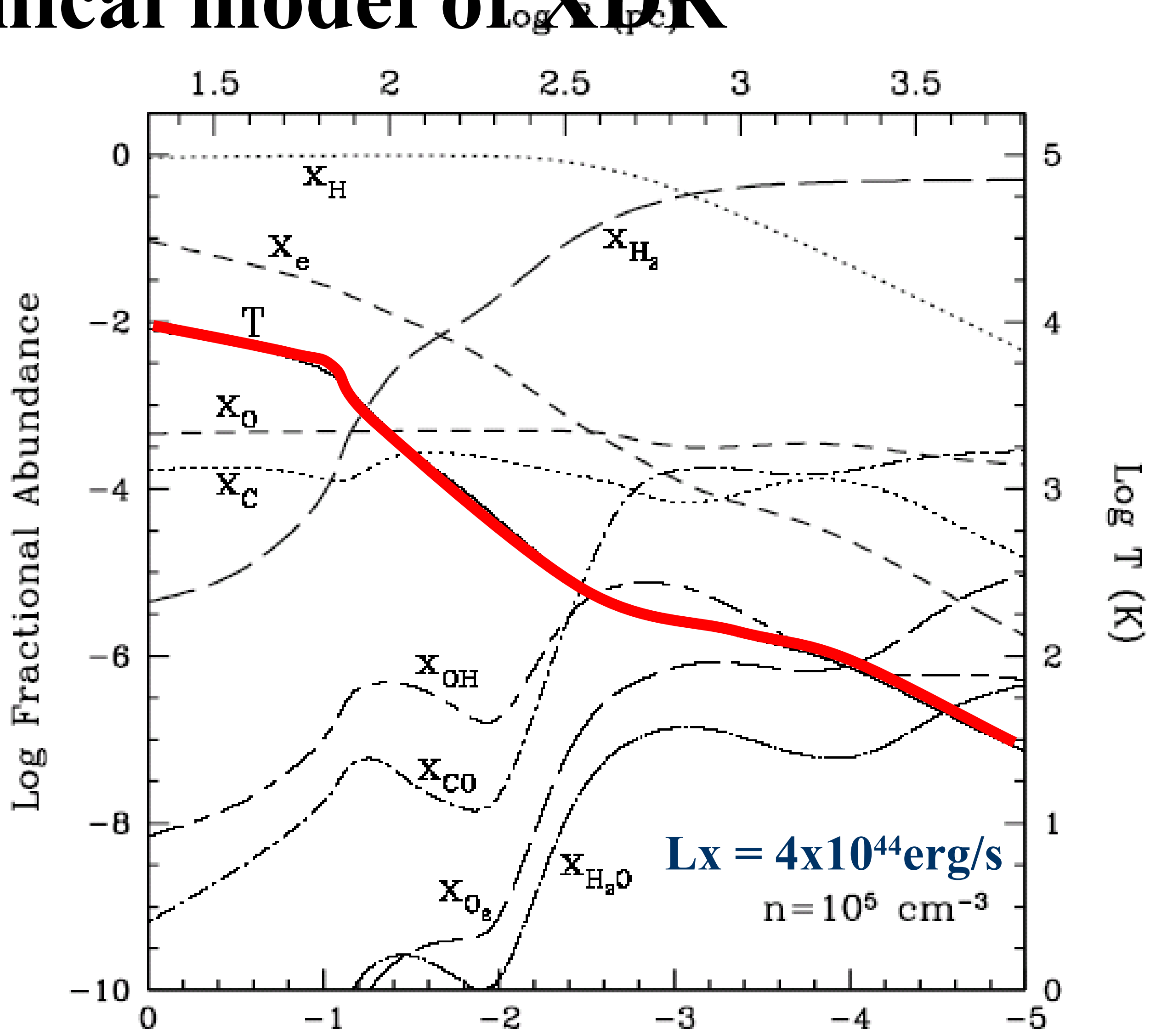
➔ Molecular clouds could be heated deep into GMCs (i.e., much wider region compared with PDR case

High Temperature deep into GMCs in XDR

Physical-chemical model of XDR

- Hx ： X-ray energy deposition rate per one H atom
- Heating rate & molecule destruction rate ∝ n・ Hx
- Cooling rate & molecule formation rate ：∝ n^2

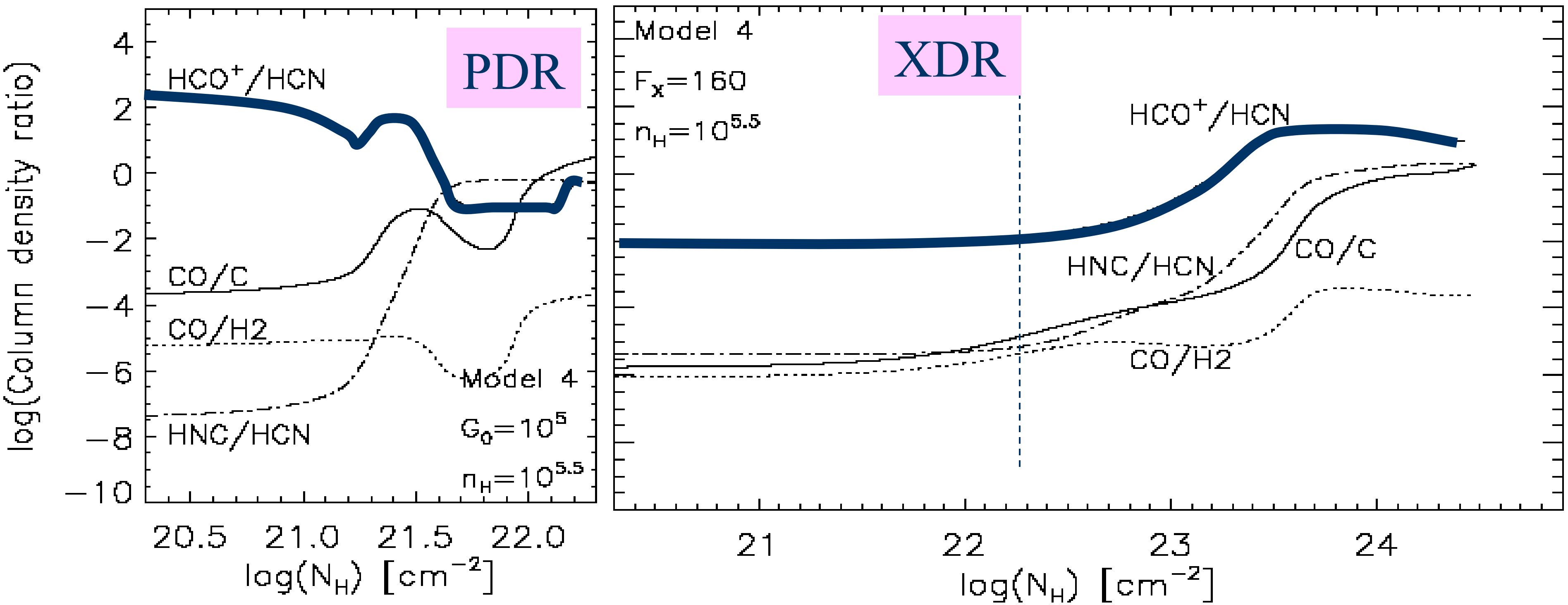
⇒ Hx/n is a key



Maloney 1999, Ap&SS, 266, 207

Ionization parameter $\xi = \frac{L_x}{nR^2} = \frac{4\pi F_x}{n}$

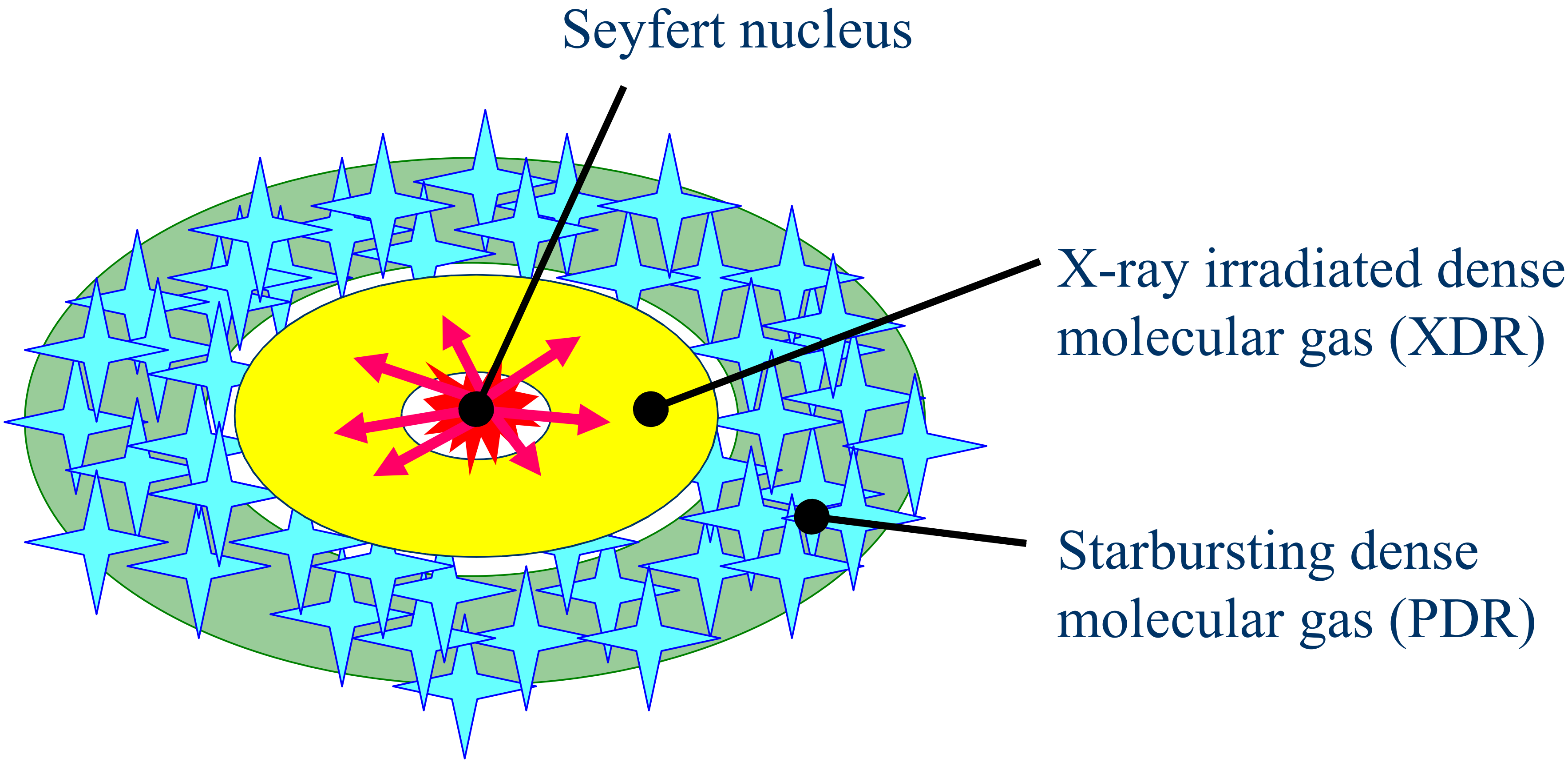
HCN/HCO+ abundance: PDR vs XDR



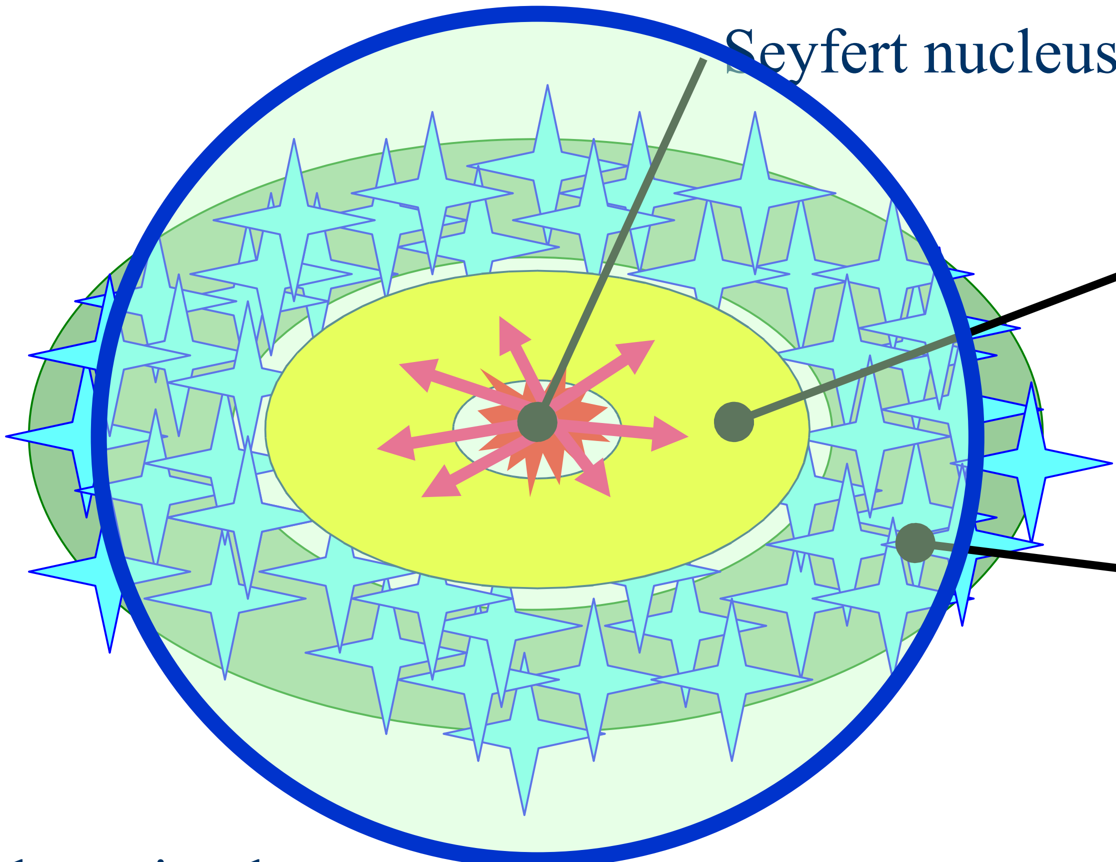
- HCN is overabundance relative to HCO^+ in XDRs
- Opposite sense in PDRs

Meijerink & Spaans 2005, A&A, 436, 397; see also Maloney et al. 1996, ApJ, 466, 561; Lepp & Dalgarno, 1996, A&A, 306, L21

“pure” vs “composite” Seyferts

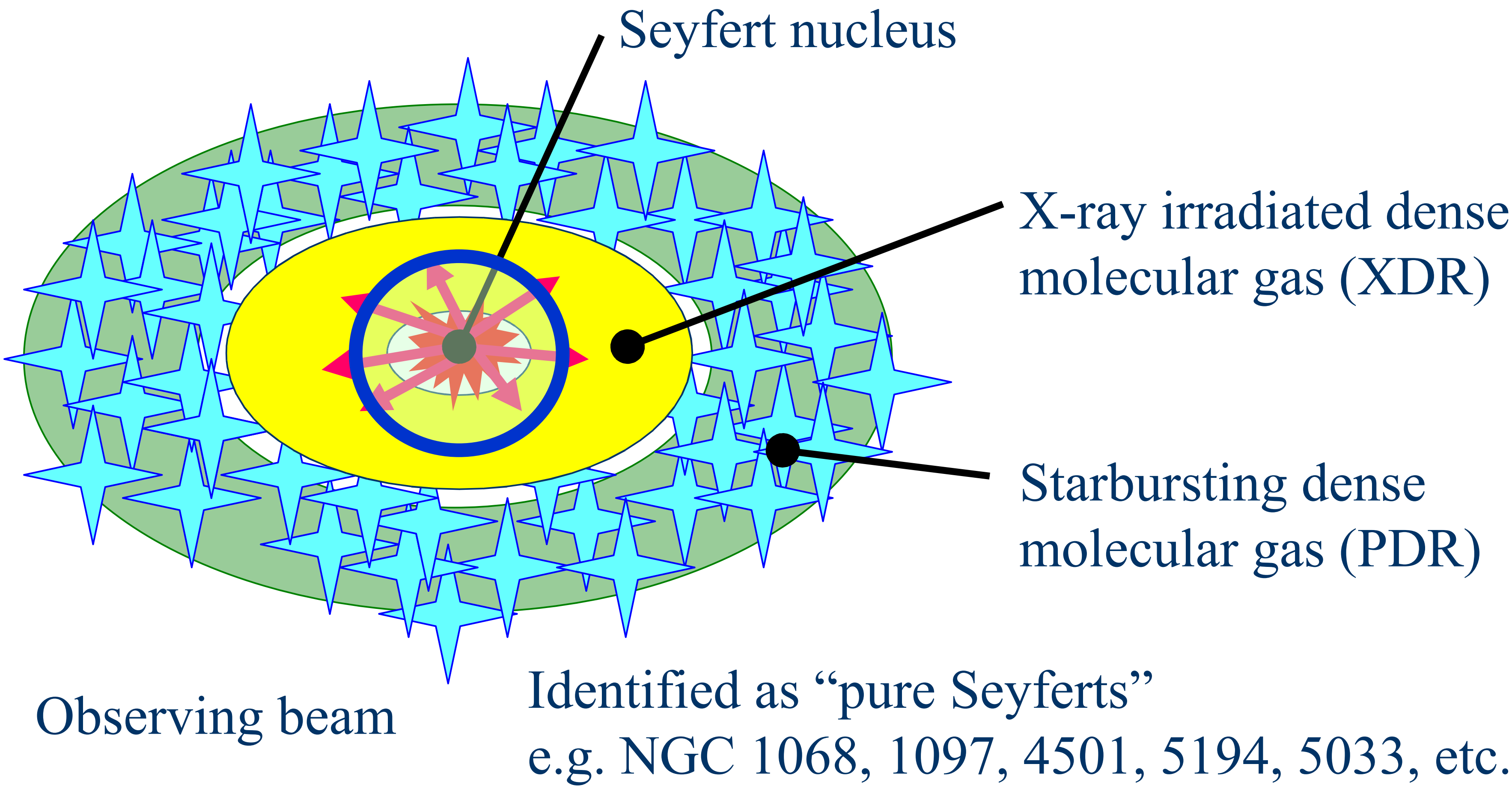


"pure" vs "composite" Seyferts: effect of aperture size (observing beam)



Identified as 「 composite Seyferts 」
e.g. NGC 3079, 3227, 4051, 6764 etc

“pure” vs “composite” Seyferts: effect of aperture size (observing beam)



- High angular resolution observations (using ALMA) is essential for the application of this method at distant sources

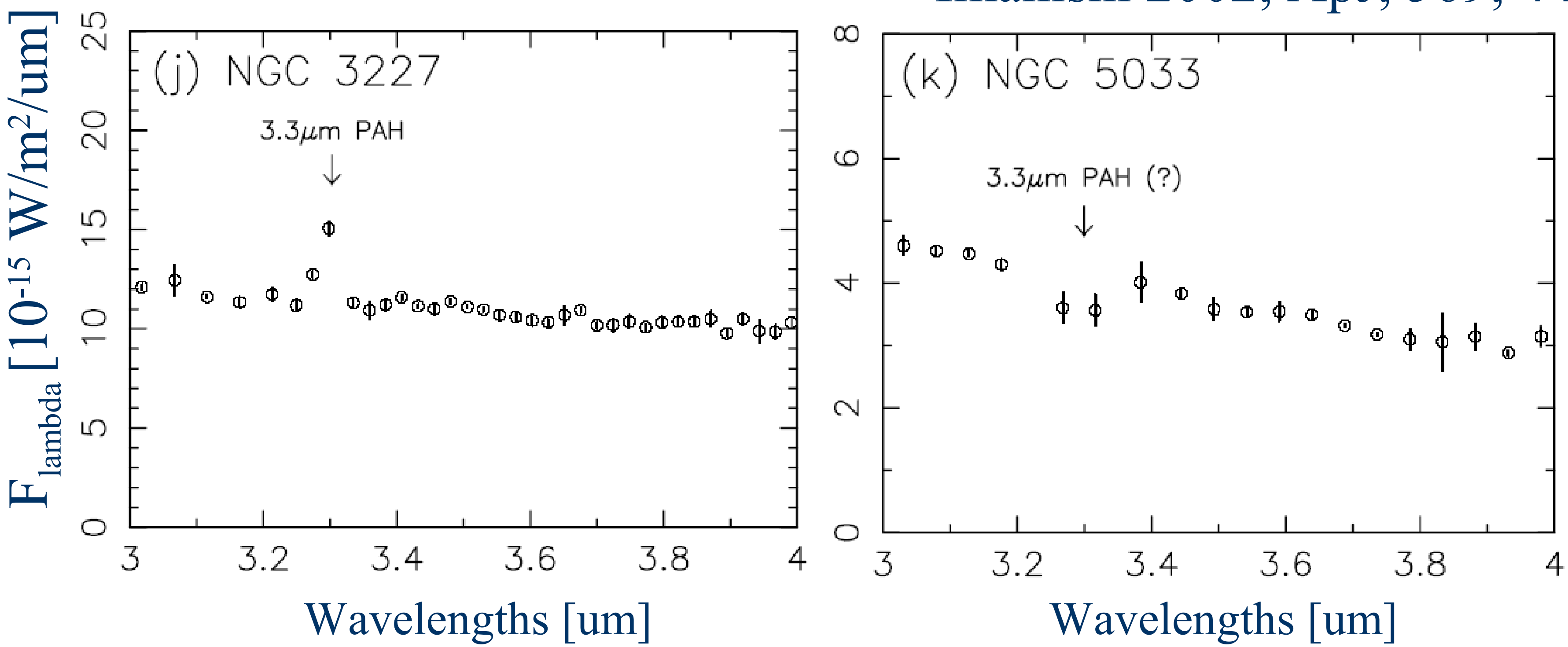
Validity of our proposed diagnostic: Comparison with PAH results

Comparison with other diagnostics

- Polycyclic aromatic hydrocarbon (PAH) emission feature at 3.3 um
  - ✓ Commonly observed in starburst regions, but destroyed due to a strong radiation field from AGN
  - ✓ L-band ➔ lower extinction effect
    - e.g, Imanishi & Dudley 2000, ApJ, 545, 701
  - ✓ Sample of comparison:
    NGC 1068, 1097, 3227, 4051, 4388,
    4501, 5033, 7469

Comparison with 3.3um PAH diagnostic

Imanishi 2002, ApJ, 569, 44



(Aperture sizes are similar to NMA obs.)

- NGC 3227 ： <u>with</u> nuclear starburst
- NGC 5033 ： <u>without</u> nuclear starburst

⇒ consistent with our HCN/HCO+ & HCN/CO diagnostic

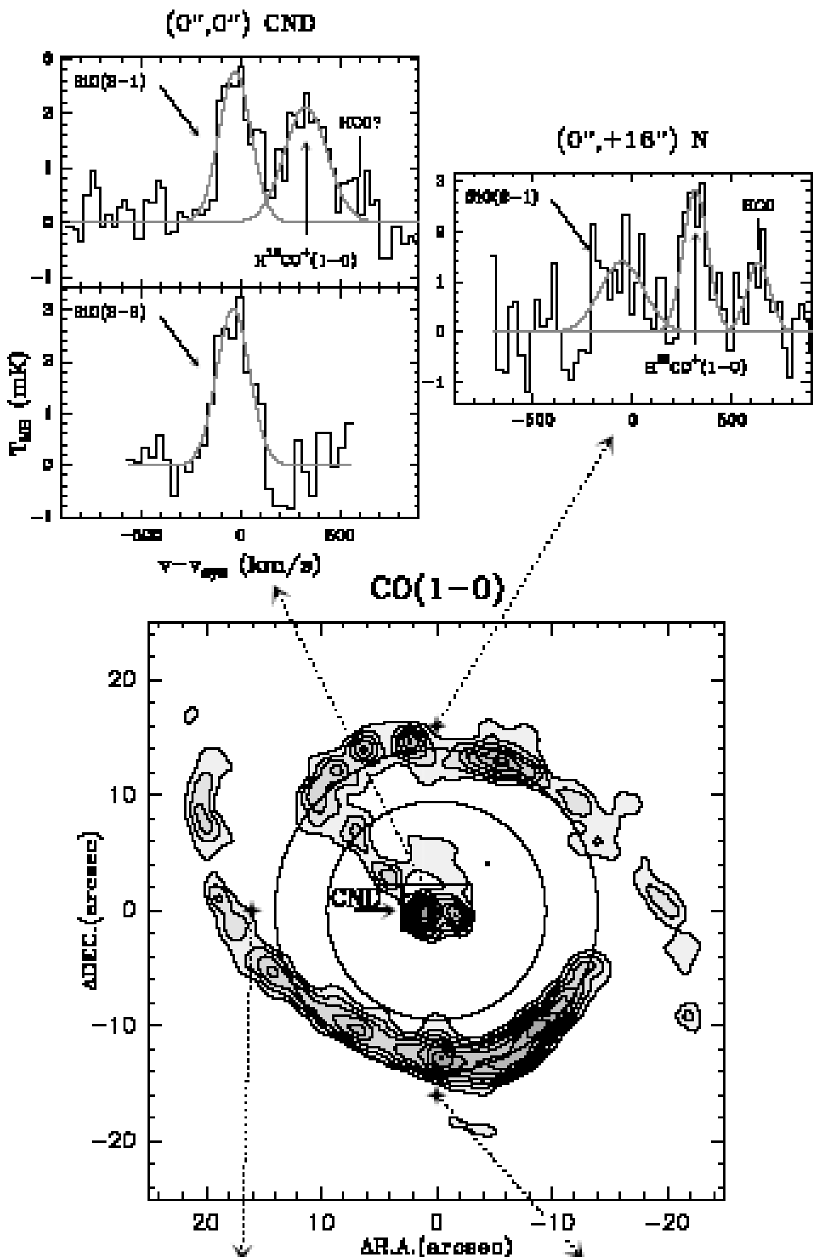
HCN/HCO$^+$ vs 3.3 um PAH diagnostics

- Currently, good agreement (7 of 8)
  - ✓ except for NGC 7469
- We may need further investigation on the nuclear power source of NGC 7469...
  - ✓ NIR photometry (Genzel et al. 1995, ApJ 444, 129)
  - ✓ Patchy radio sources at a few pc scales (Lonsdale et al. 2003, ApJ, 592, 804)
- Comparison in other Seyfert galaxies are also in progress

NGC	Nuclear starburst ?	
	HCN/HCO+	PAH
1068	No	No
1097	No	No
3227	Yes	Yes
4051	Yes	Yes(?)
4388	No	No
4501	No	No
5033	No	No
7469	Yes	No

(5548?)

XDR chemistry in NGC 1068



- The CND of NGC 1068 (~ 100 pc scale) is a giant X-ray Dominated Region (XDR).
  - ✓ Based on SiO, CN, HCO+, HOC+, H^{13}CO+ and HCO lines

➔ Also support our view

Usero et al., 2004,
A&A, 419, 897

Our survey suggests:

- HCN/HCO+ intensity ratios will be a new diagnostic of a dominant power source within the observing beam toward dusty active galaxies ("pure" vs "composite" or XDRs vs PDRs)
  - ✓ High angular resolution observations w/ ALMA will depict spatial distributions of nuclear SB regions and XDRs.
  - ✓ A caution to a use of HCN intensity as a star-forming dense gas tracer in the circumnuclear regions of AGNs
- This must be powerful even for extremely dusty nuclei (even in Compton-thick AGNs), because these mm/submm lines are **free from dust extinction**

➔ Application to LIRGs/ULIRGs (and possibly high-z submm galaxies w/ ALMA) will be very promising

- ✓ Imanishi et al. 2004, AJ, 128, 2037
- ✓ Imanishi et al. 2006, AJ, 131, 2888 [see also poster Kohno et al. #263]
- ✓ Garcia-Burillo et al. 2006, in press, etc. [see also many related posters]

Summary

- ADIoS project: ASTE CO(3-2) imaging survey of galaxies
  - ✓ A good probe of dense molecular gas even in disk regions
  - ✓ Spatial variation of star formation efficiencies caused by variation of CO(3-2)/CO(1-0) ratio (= dense gas fraction) in M83?
  - ✓ Shell-like high CO(3-2)/CO(1-0) ratio gas surrounding the central star cluster of NGC 604 in M33 ➔ site of dense gas formation?
- HCN(1-0) & HCO^+(1-0) observations of active galaxies using Nobeyama Millimeter Array (NMA)/RAINBOW
  - ✓ Discovery of "HCN enhanced Seyferts": a signature of XDR
  - ✓ A caution to a use of HCN intensity as a star-forming dense gas tracer in the vicinity of AGN
  - ✓ A new diagnostic of energy source in galaxies, applicable to dusty galaxies (high-z ULIRGs, SMGs) in the ALMA era