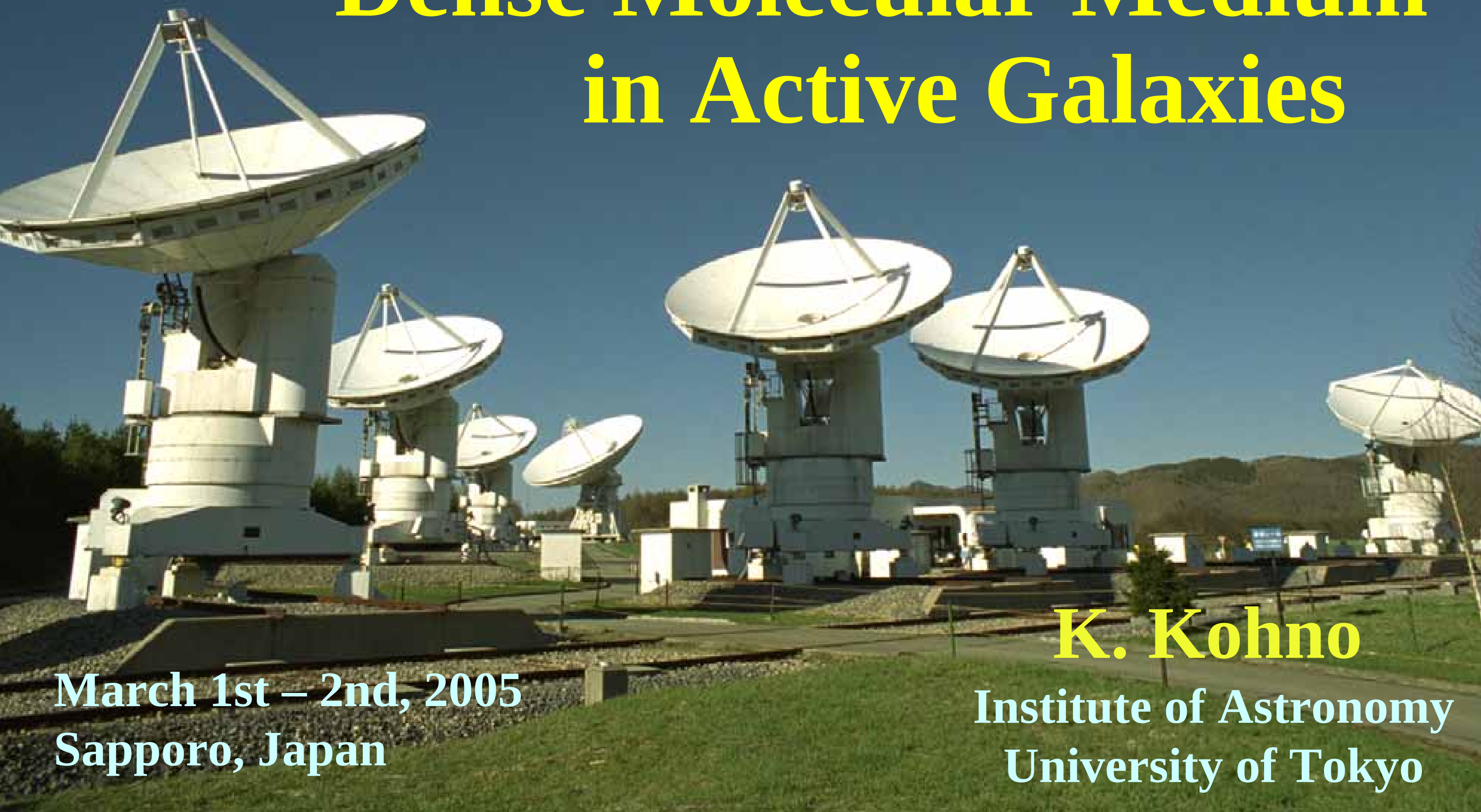
4th International Symposium on New Trends of Physics:
Recent Advances in Astrophysics and Planetary Science
- from the early universe to the Solar system -

Dense Molecular Medium in Active Galaxies



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Outline

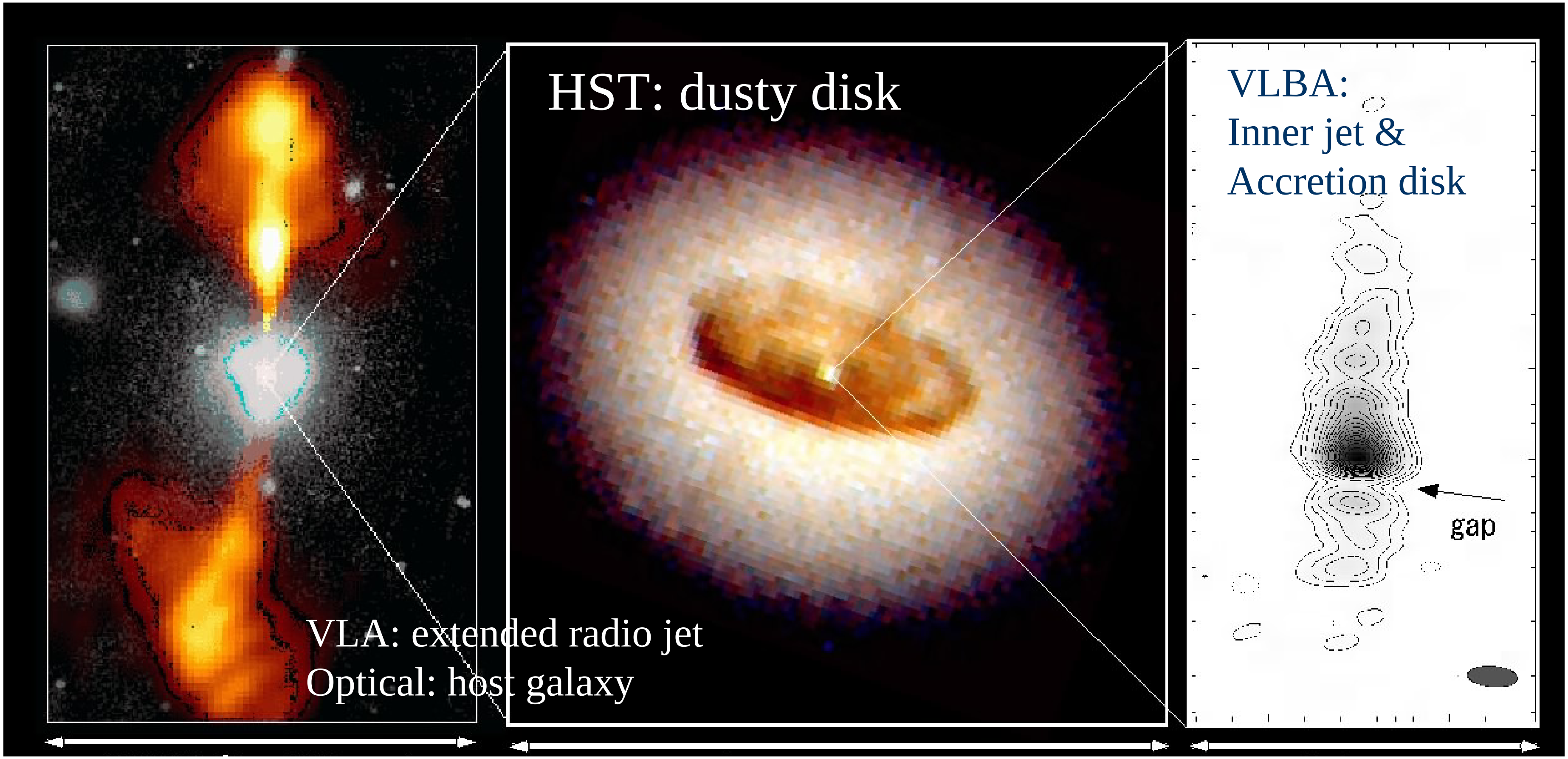
- Introduction: role of dense molecular medium
  - AGN – nuclear starburst connection
- NMA/RAINBOW survey of local active galaxies
  - A HCN(1-0), HCO^+(1-0), & CO(1-0) high resolution imaging survey of Seyfert and starburst galaxies using Nobeyama Millimeter Array & RAINBOW interferometer
- Results & Discussion
  - HCN/HCO+ & HCN/CO ratios diagram as a new diagnostics of power source in active galaxies: applicable to very dusty galaxies (free from dust extinction)
  - Comparison with diagnostics at other wavelengths
- Toward ALMA
  - Application of our diagnostics to LIRGs/ULIRGs
  - Observing dense molecular gas using Atacama submillimeter Telescope Experiment (ASTE): a precursor to ALMA

Introduction

Active galaxies

- Active galactic nucleus (AGN)
  - A galaxy that has a high luminosity, radiating large amounts of non-stellar radiation
  - Release of energy through accretion of matter onto super massive black holes (SMBHs)
  - Quasars/Seyfert galaxies/low luminosity AGNs depending on its luminosity ($L_x \sim 10^{39-41}$ erg/s or less for LL-AGN, $L_x > 10^{44-46}$ erg/s for quasars)
  - Two types based on optical spectroscopy
    - with broad line: type 1, without broad line: type 2

Active galaxy NGC 4261 (3C270) - from 100 kpc to 1 pc -



320 arcsec (62 kpc) 4 arcsec (780 pc) 0.02 arcsec (4 pc)

Jaffe et al. 1993, Nature, 364, 213

Jones et al. 2000, ApJ, 534, 165

Relationship between AGN & SB

- One of unresolved issues in AGNs: relationship between AGN and star formation/starburst
- Starburst
  - means successive burst of massive star formation
  - Also show high luminosity, but they originate from <u>stellar</u> radiation.

AGN – nuclear starburst connection

- Starbursting dense obscuring torus
  - Cid Fernandes & Terlevich 1995, MNRAS, 272, 423
- Obscuration due to compact (r < 100 pc) starburst
  - Fabian et al. 1998, MNRAS, 297, L11
- SNe due to starburst support the geometry of dense obscuring torus
  - Wada & Norman 2002, ApJ, 566, L21
- Radiation pressure support the geometry of dense obscuring torus
  - Pier & Krolik 1992, ApJ, 399, L23
  - Osuga & Umemura 2001, A&A, 371, 890
- starburst → intermediate mass BHs→ SMBHs
  - Matsumoto et al 2000; Matsushita et al. 2000; Ebisuzaki et al. 2001

Structure of obscuring material around Sy nuclei with associated nuclear SB

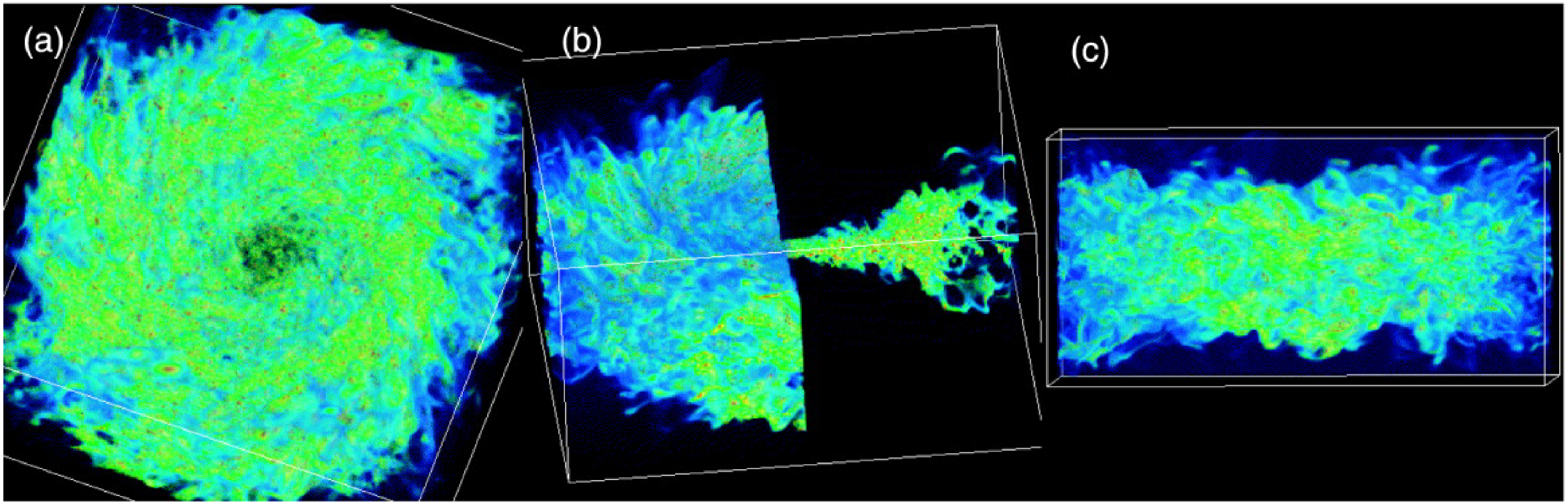


FIG. 1.—Three-dimensional density distribution represented by a volume-rendering technique. Colors represent the relative opacities based on the line-of-sight column density, but they do not represent the absolute opacity or any physical value. Regions colored red or yellow are more optically thick than blue regions. The right side of panel *b* is a surface section.

- Successive SNe produce large velocity dispersion
  ➔ supporting a geometrically thick structure

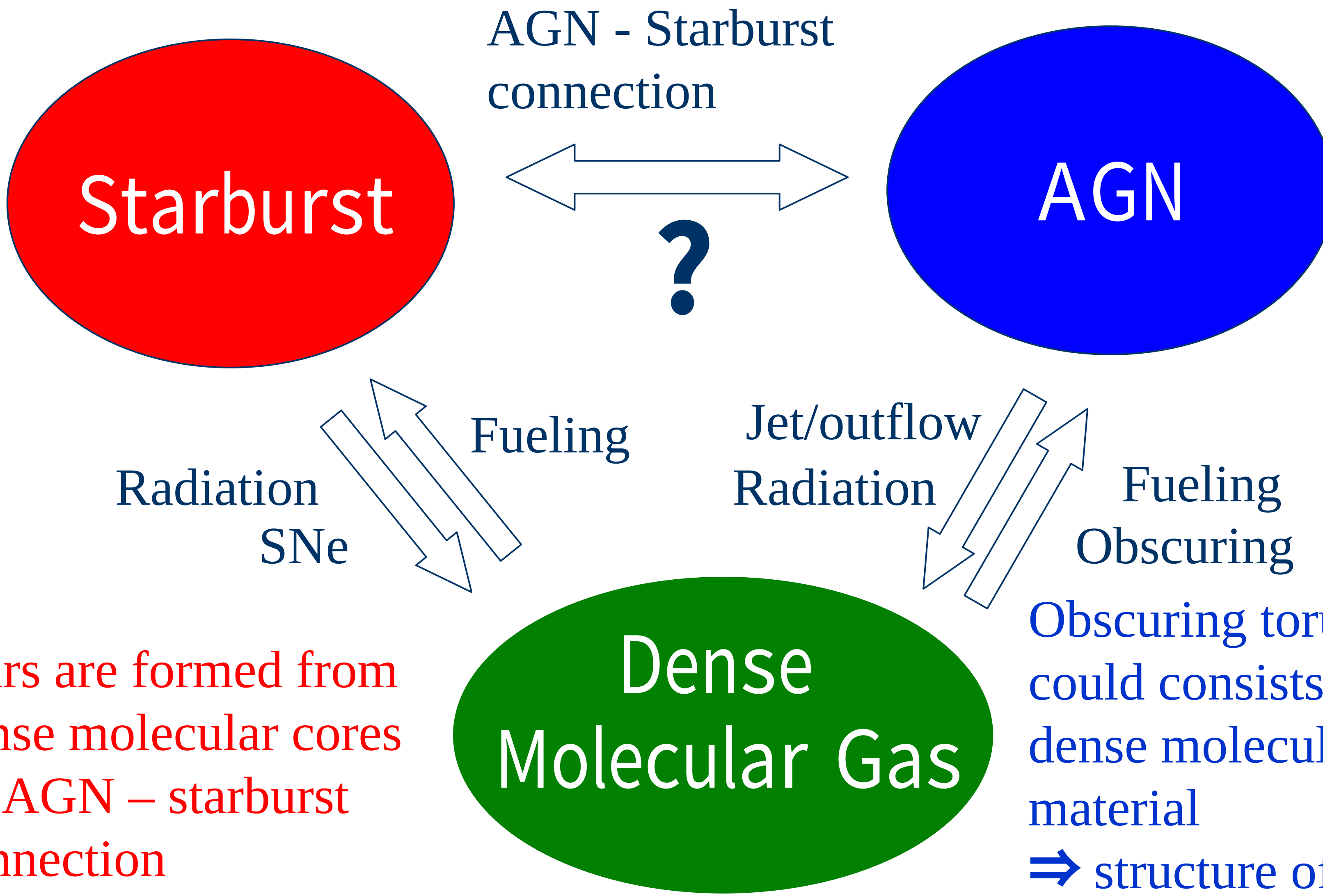
Wada & Norman 2002, ApJ, 566, L21

AGN – nuclear starburst connection

- Connection of AGN and nuclear starburst: essential issue to understand the nature of AGNs
- Many diagnostics have been proposed:
  - UV/optical spectroscopy
  - NIR/MIR spectroscopy (PAH feature)
  - Hard X-ray spectroscopy

  But, it is *not easy* for heavily obscured galaxies.
- ➔ it is important to establish new diagnostic that is applicable to very dusty galaxies.

Roles of Dense molecular gas in the centers of active galaxies



Stars are formed from dense molecular cores
⇒ AGN – starburst connection

Obscuring torus could consists of dense molecular material
⇒ structure of AGN/fueling

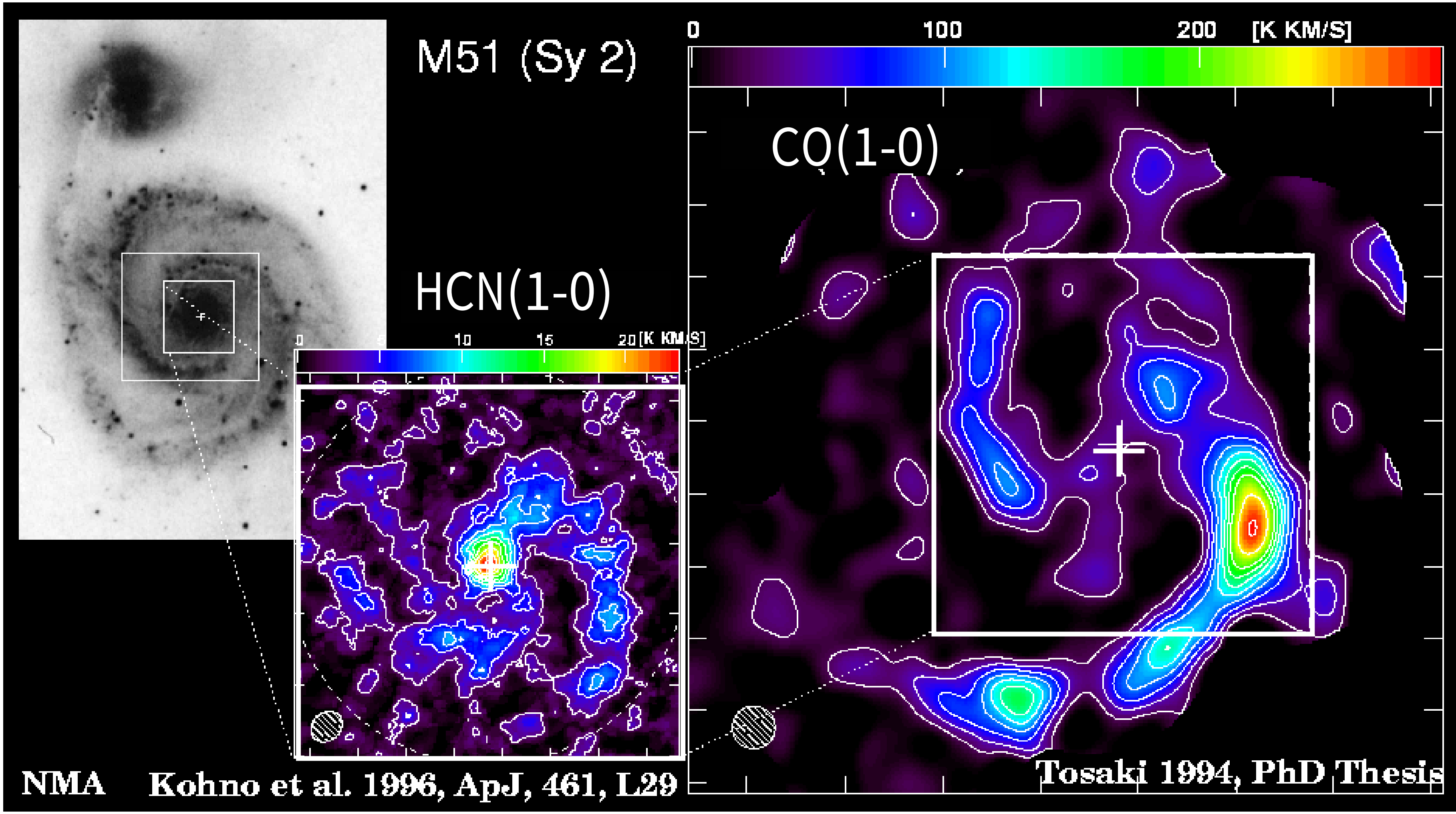
How to trace dense molecular gas

- High-J CO lines
  - Large *A*-coeff., large statistical weight g_J
    ➔ tracer of dense (and warm) molecular gas
  - using submillimeter single dishes:
    JCMT, CSO, HHT, ASTE, APEX
  - SMA: an ideal tool before ALMA
- High dipole moment molecules
  - such as HCN, HCO+, CS., NH_3, etc.
  - ⇒ using millimeter interferometers
    NMA+RAINBOW/PdBI/OVRO/BIMA/ATCA
  - cm-to-mm wave telescopes
    including Hokkaido Univ. 11m telescope

“HCN enhanced Seyfert nuclei”

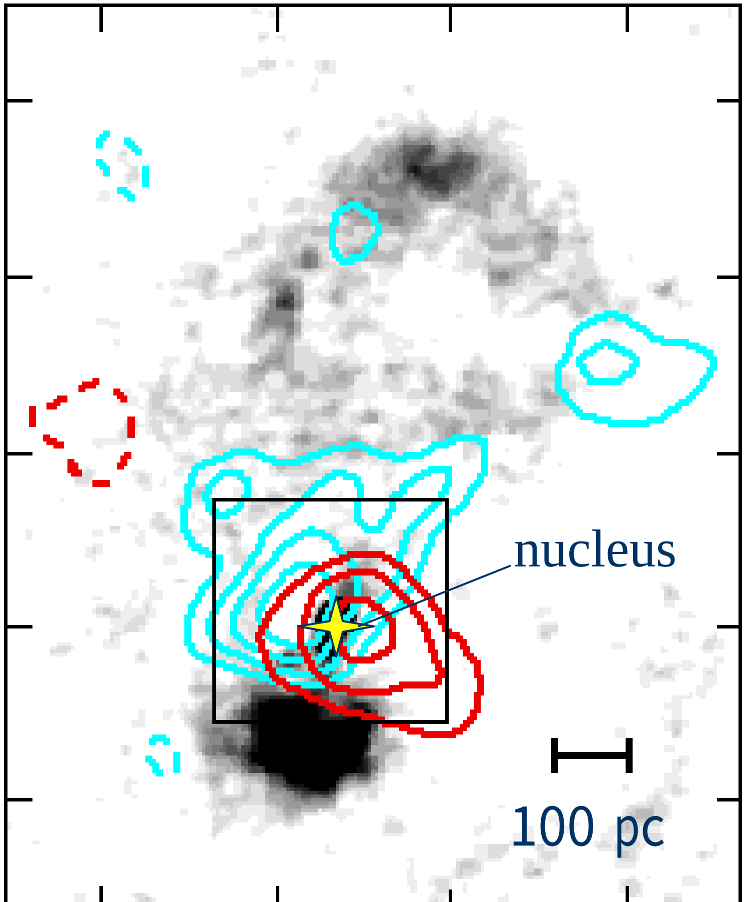
- Prototype: NGC 1068
  - I(HCN)/I(CO) intensity ratio up to ~ 0.6
  - Never observed in nuclear starbursts
  - Presence of rotating dense molecular gas disk; perpendicular to large scale jet
    - Jackson et al. 1993, ApJ, 418, L13
    - Tacconi et al. 1994, ApJ, 426, L77
    - Helfert & Blitz 1995, ApJ, 450, 90
- Subsequent observations reveals:
  - NGC 5194
    - Kohno et al. 1996, ApJ, 461, L29)
  - NGC 1097
    - Kohno et al. 2003, PASJ, 55, L1)

Enhanced HCN in NGC 5194 (Sy2)



- I(HCN)/I(CO) are enhanced up to 0.5
- (cf. Milky Way ~ 0.08 with similar spatial extent)

Dense gas disk around Sy2 nucleus of NGC 5194



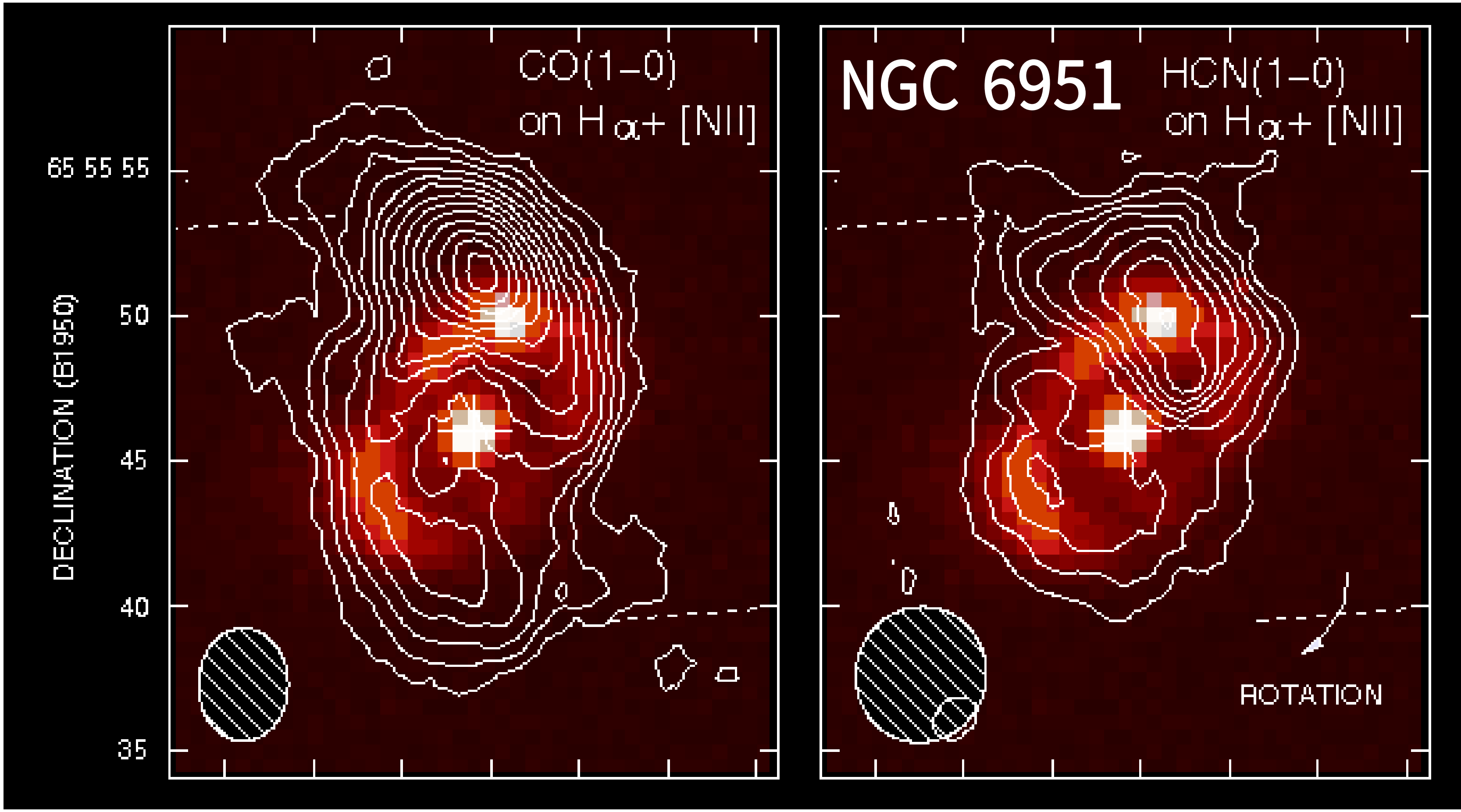
Contour: HCN blue & red shifted components (NMA)
Grey scale: radio jet @ 6 cm (VLA)

- Dense ($n_{H_2}>10^4 cm^{-3}$) rotating gaseous disk with a radius of ～ 70 pc
- Rotation axis is aligned to the radio jet, not aligned to the galactic rotation
- Column density from HCN observations (N_H～10^{24} cm^{-2}) is consistent with that from X-ray observations (Terashima et al. 2000 etc.)

⇒ outer envelope of dense obscuring material ?

Kohno et al. 1996, ApJ, 461, L29

Seyfert nucleus w/o HCN enhancement



- Spatial correlation between dense molecular gas (traced with HCN) and massive star forming regions (grey scale, Halpha)

Kohno et al. 1999, ApJ, 511, 157

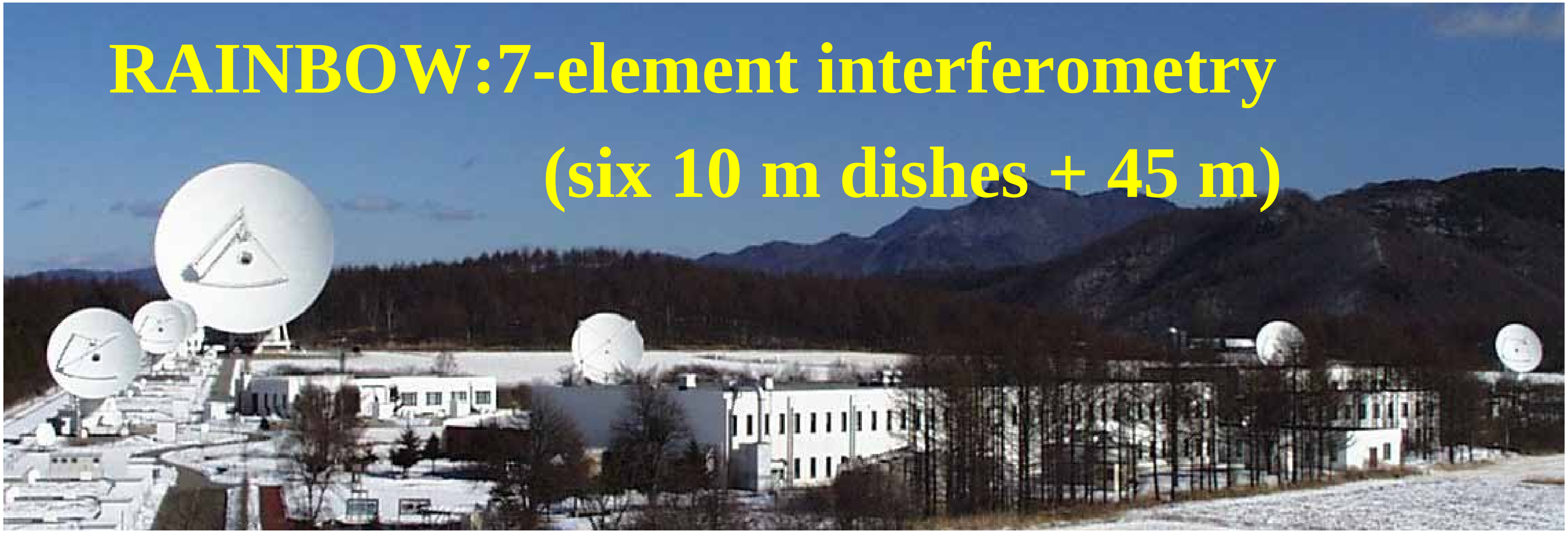
Questions

- HCN enhancement：what is this ?
  - Related to star formation, as seen in starburst galaxies ?
  - or .. ?
- How common ?
  - Occurrence as a function of
    - Seyfert types （type 1 vs type 2）
    - AGN luminosity (LL-AGN, Seyfert, Quasar, …)

Survey

NMA/RAINBOW survey

- High resolution (a few arcseconds) imaging
  ⇒ a few 100 pc scales at D ～ a few 10 Mpc
- CO(1-0): whole molecular medium (n_{H2}>10^2 H_2 cm^{-3})
- HCN(1-0) & HCO+(1-0): dense molecular gas (n_{H2}>10^4 H_2 cm^{-3})



The Sample

- Mainly from 「Palomar Seyfert Sample」
  - Ho et al. 1997
  - Based on systematic search for Seyfert galaxies (cf. CfA sample etc.)
  - Nearby (D < 70 Mpc)
  - 52 Seyferts (11 Sy1s, 41 Sy2s)
- NMA/RAINBOW survey sample
  - 17 Seyferts in CO (33% of the whole sample)
  - Sy1 sample: completed; Sy2 sample in progress..
- some additional Southern Seyferts
  - NGC 1097, NGC 5135, NGC7465, 7469, etc.

Survey status

Sy1s	CO	HCN	HCO+
N1097	○	○	○
N3227	○	○	○
N4051	○	○	○
N5033	○	○	○
N7469	○	○	○

Sy2s	CO	HCN	HCO+
N1068	(○)	○	○
N1667	○	▽	▽
N3079	○	○	○
N3982	○	▽	▽
N4258	○	▽	▽
N4501	○	▽	▽
N4579	○		
N5135	○	▽	▽
N5194	○	○	○
N6764	○	○	○
N6951	○	○	▽
N7465	○	▽	▽
N7479	○	○	○

- Spirals (including S0)
- previous CO detection

⇒ biased to CO-luminous Seyfert galaxies

○ : completed ▽ : in progress

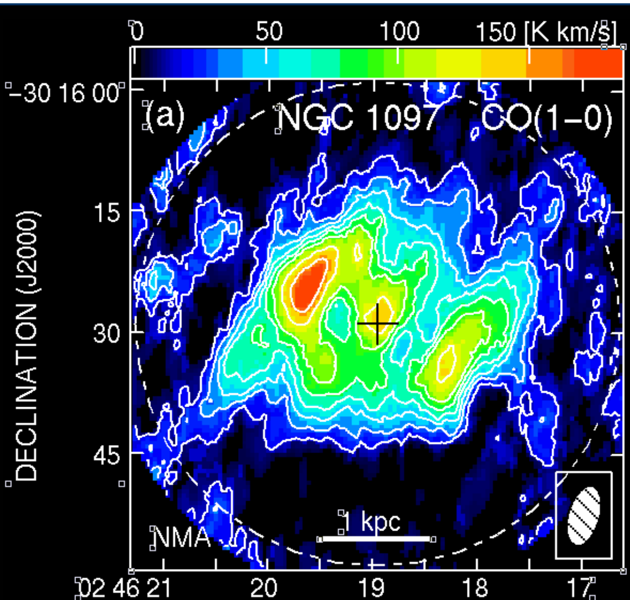
Starburst sample

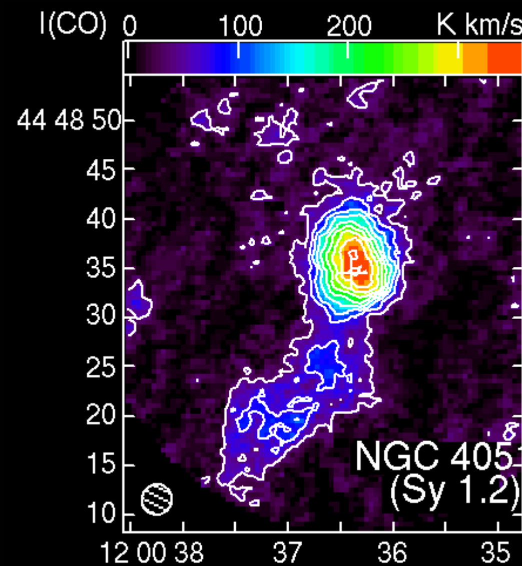
Non-Sys	CO	HCN	HCO+
Maffei2	○	○	○
IC 342	○	○	○
M82	○	○	○
N3504	○	○	▽
N3627	○	○	○
N3628	○	○	○
N4527	○	○	○
N4736	○	○	
M83	○	○	▽
N5195	○	○	○
N6946	○	○	○

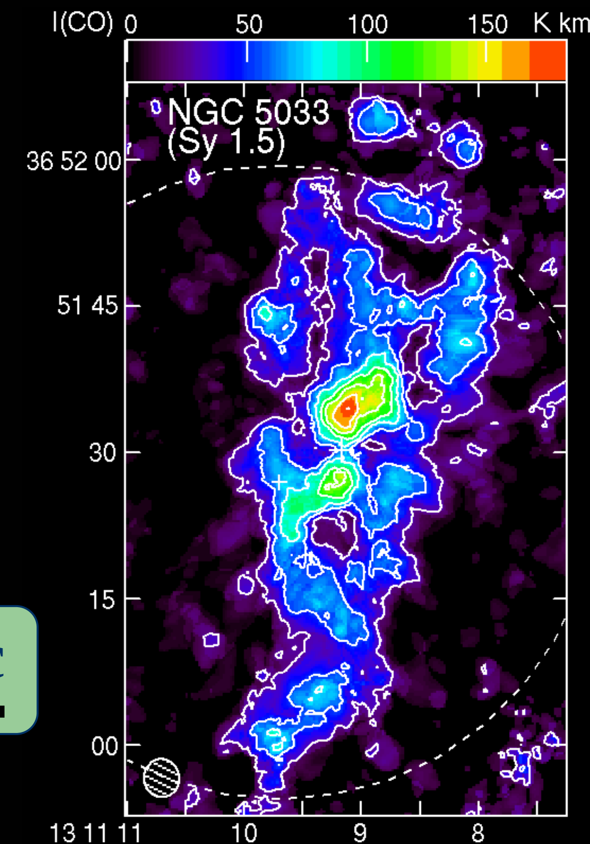
- nearby galaxies (D < 20 Mpc)
- nuclear starburst and evolved starburst galaxies
- to compare with molecular properties in Seyferts

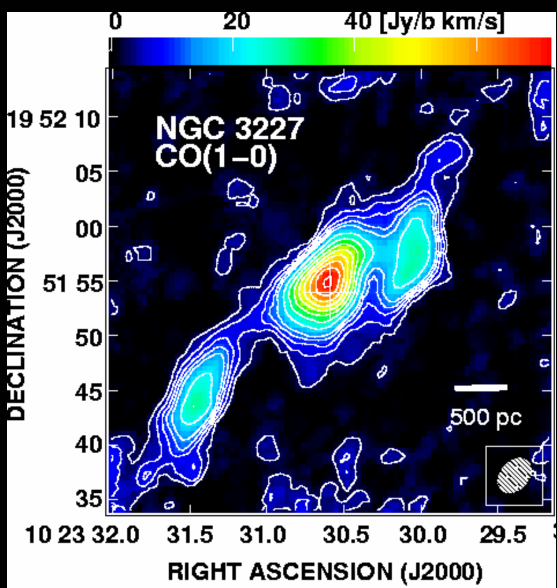
Results

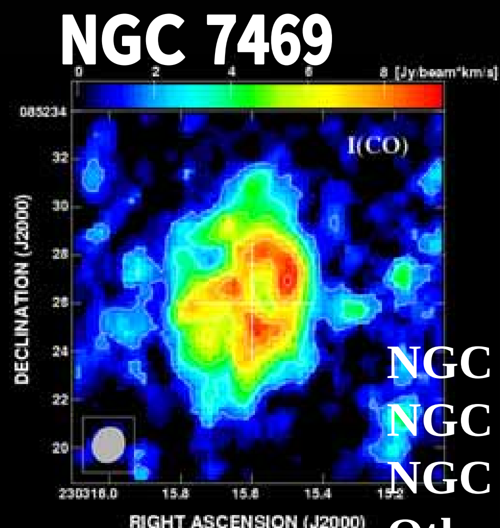
CO(1-0) images of type-1 Seyferts





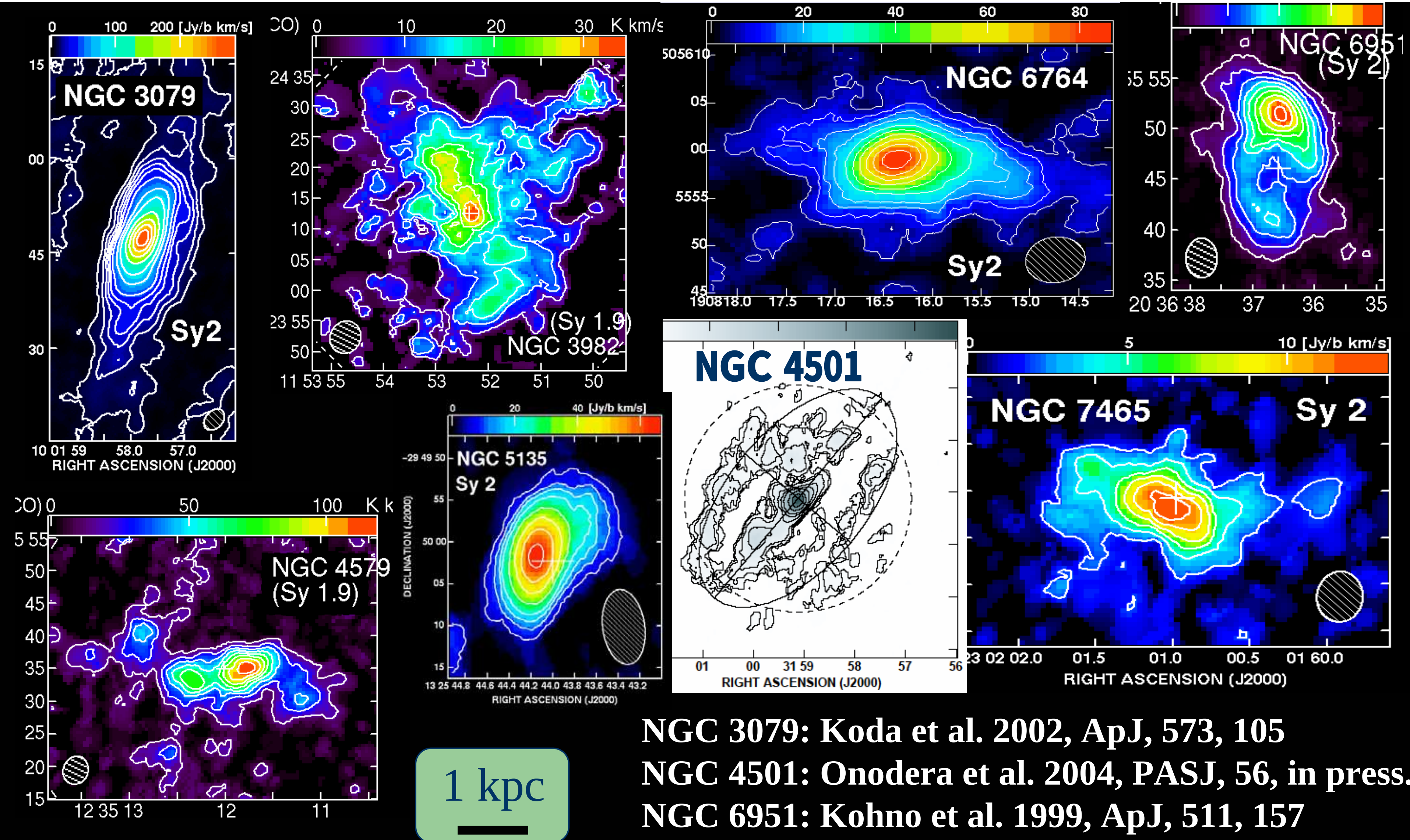






NGC 1097: Kohno et al. 2003, PASJ, 55, L1
NGC 5033: Kohno et al. 2003, PASJ, 55, 103
NGC 7469: Okiura et al. 2004, PASJ, in prep.
Other galaxies: Kohno et al. 2004, in prep.

CO(1-0) images of type-2 Seyferts



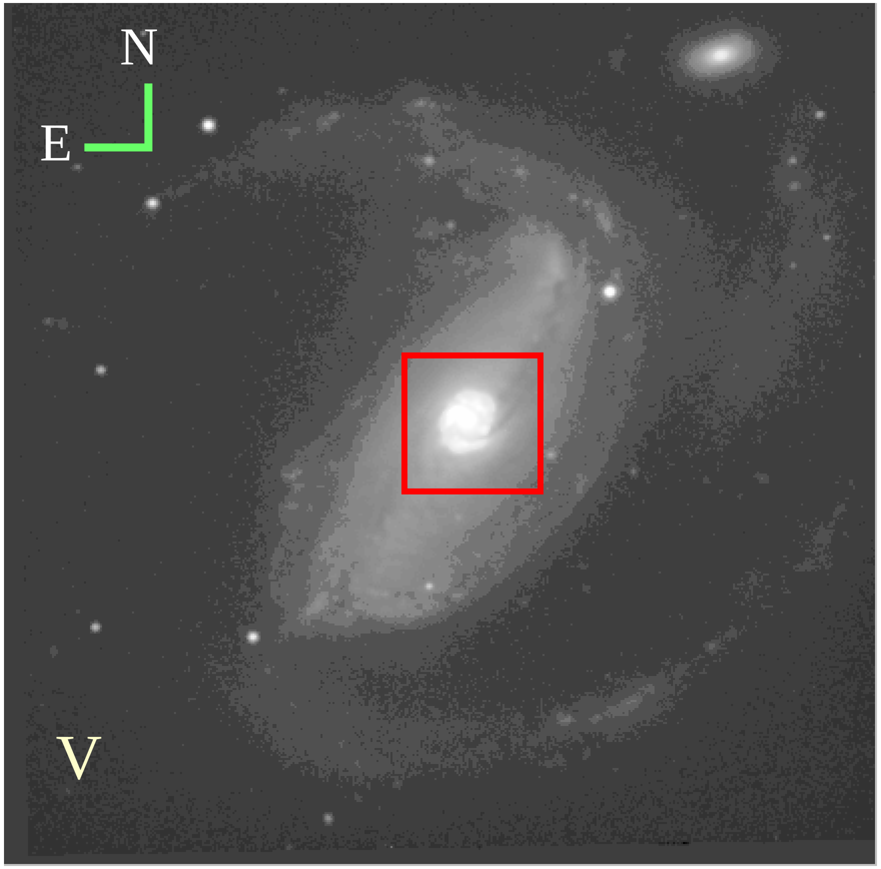
NGC 3079: Koda et al. 2002, ApJ, 573, 105

NGC 4501: Onodera et al. 2004, PASJ, 56, in press.

NGC 6951: Kohno et al. 1999, ApJ, 511, 157

Other galaxies: Kohno et al. 2004, in prep.

NGC 1097: Sy1 + Circumnuclear SB

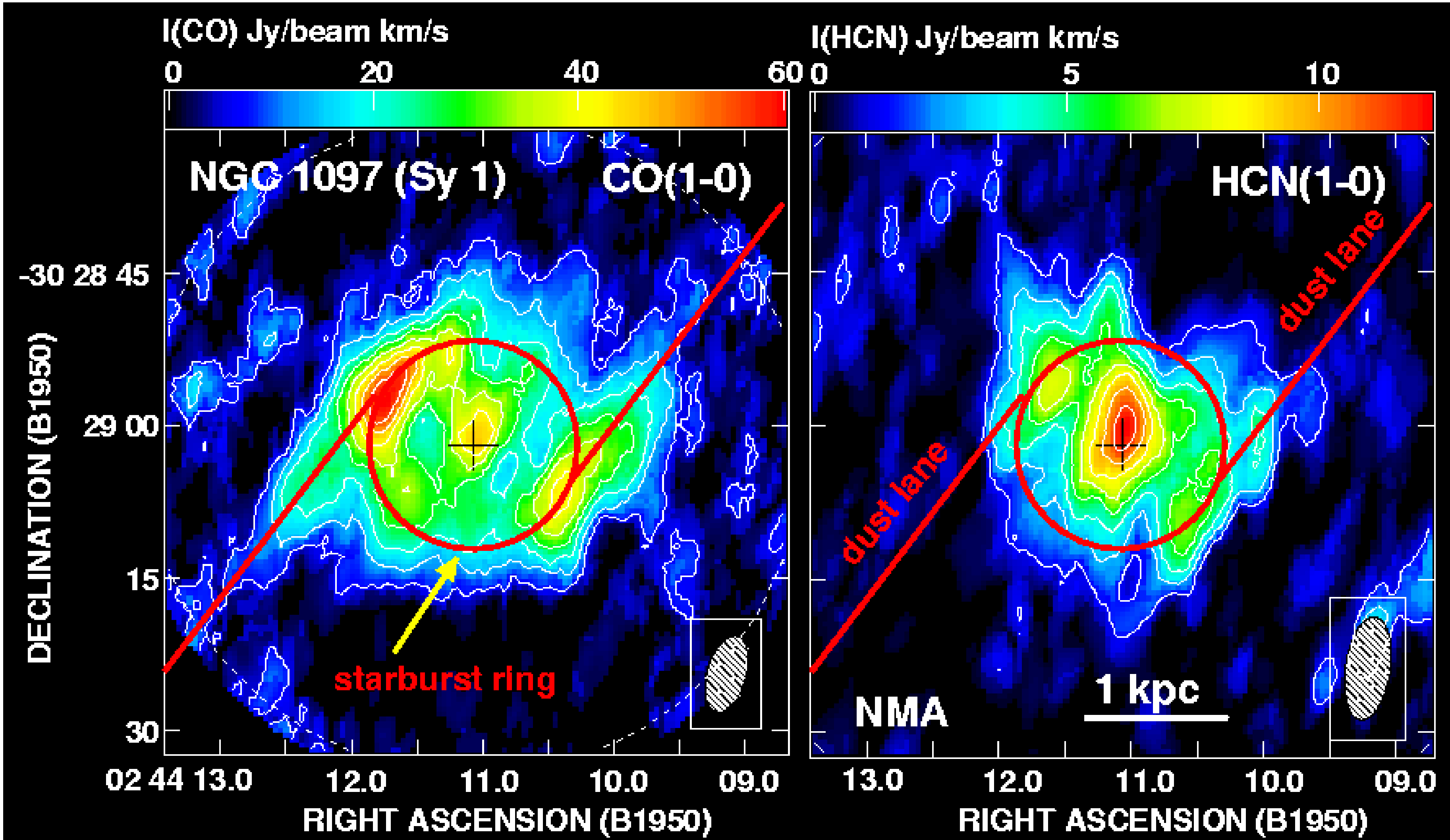


- Low luminosity Sy1 + luminous SB ring

Quillen et al. 1995, AJ, 110, 156

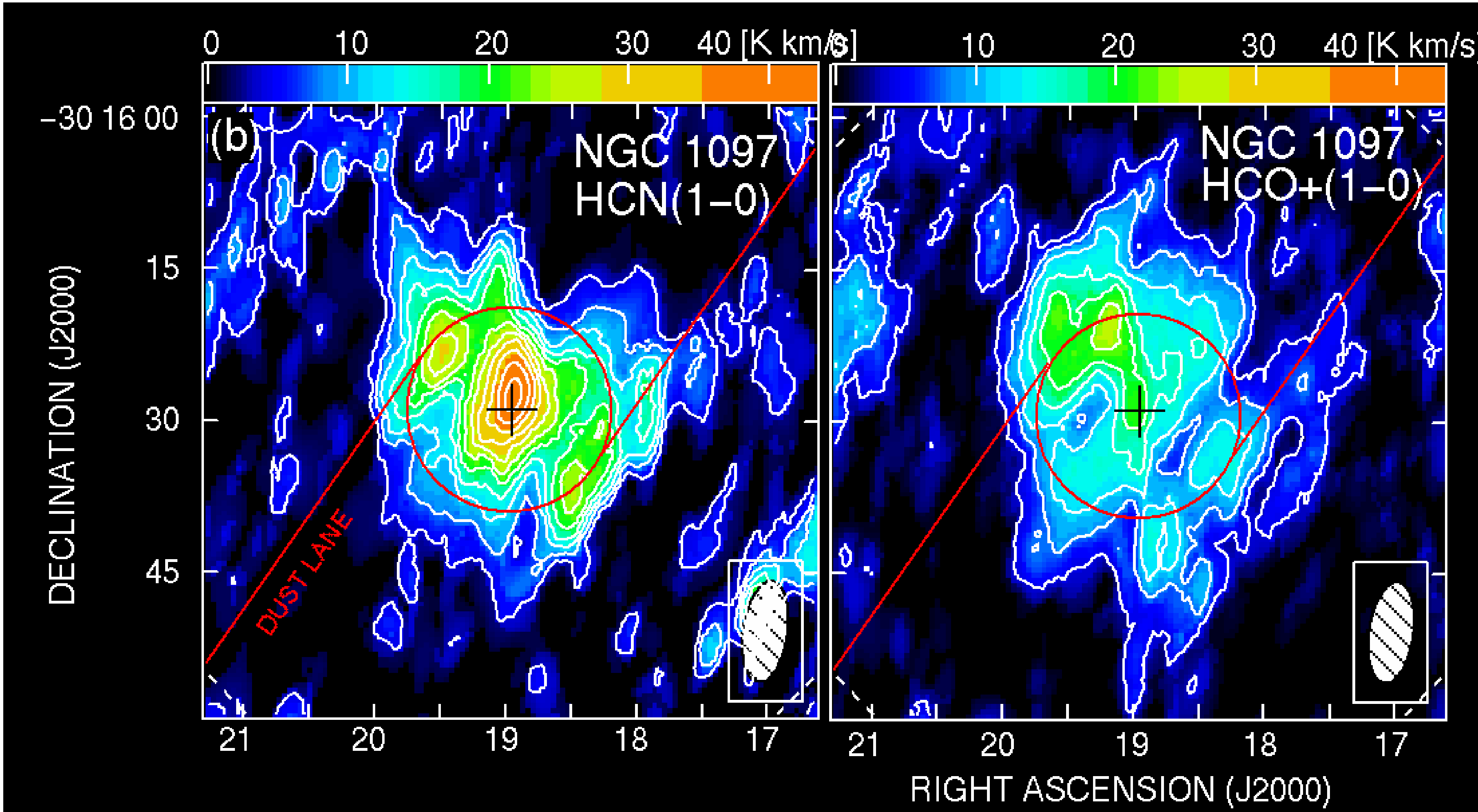
Enhanced HCN in NGC 1097

Kohno et al. 2003, PASJ, 55, L1



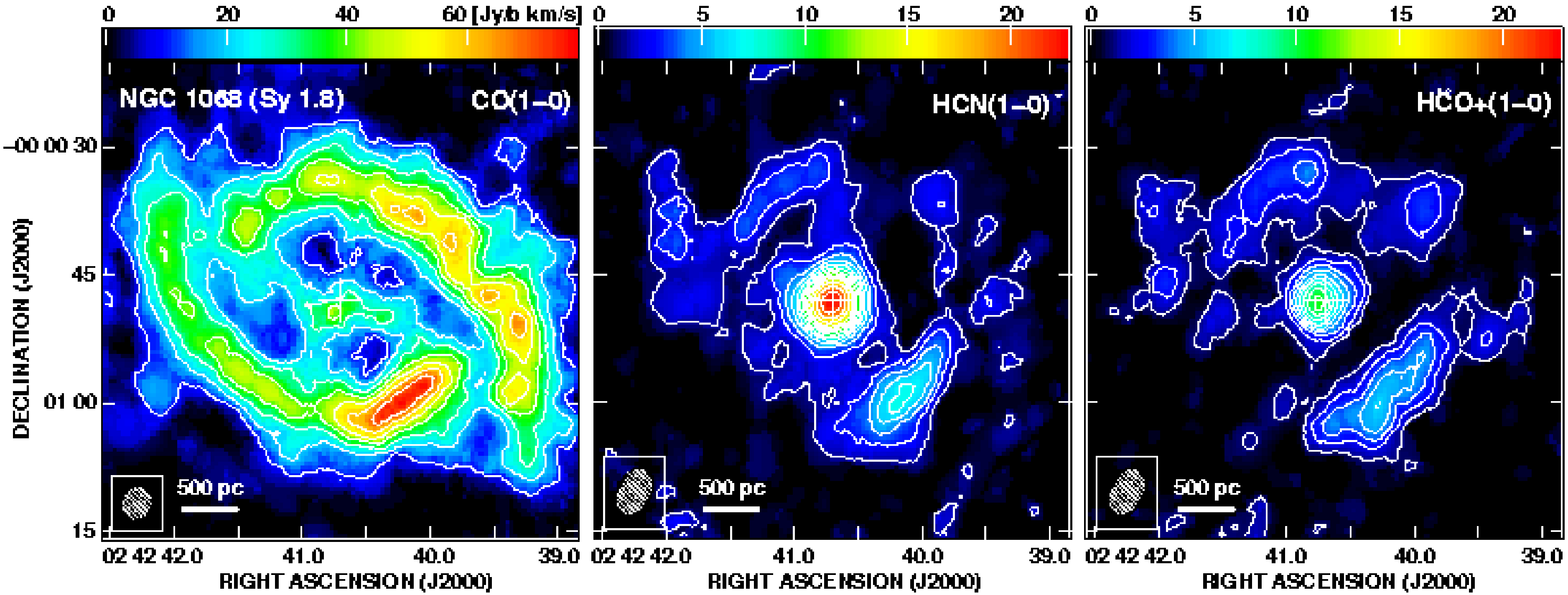
- I(HCN)/I(CO) in Tb scale is ～ 0.36

Enhanced HCN, but not enhanced HCO+ line



- I(HCN)/I(HCO+) ratio = 2.1 at the nucleus
- ⇒ *any causes other than elevated gas density ?*

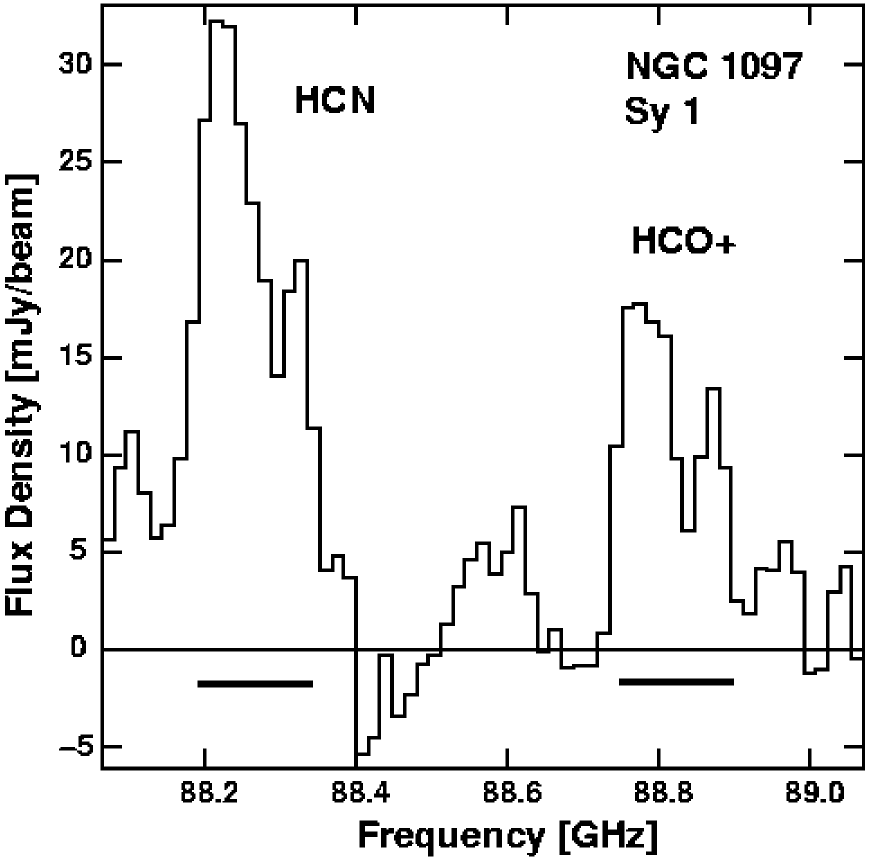
New HCN/HCO+ images of NGC 1068

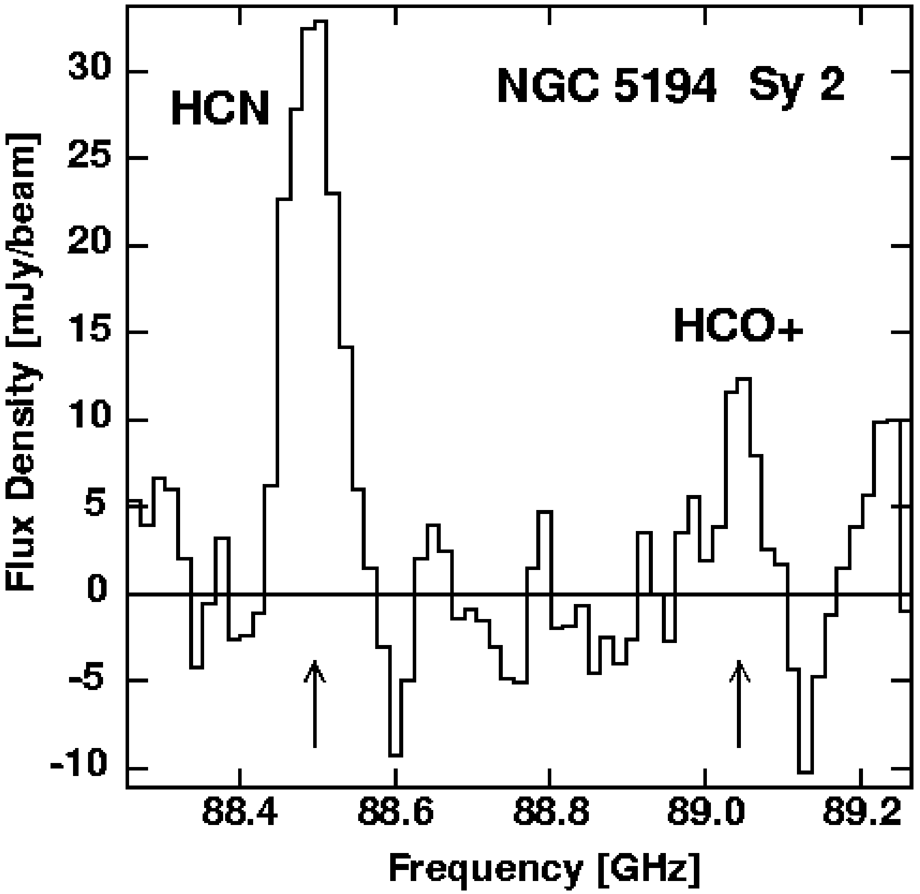


Helfer & Blitz 1995 Kohno et al. 2005, in prep.

- Nucleus： I(HCN)/I(CO)=0.54, I(HCN)/I(HCO+)=2.1
  ➔ significant enhancement of HCN
- Disk：I(HCN)/I(CO)=0.10, I(HCN)/I(HCO+)=1.3
  ➔ typical values for starburst regions

Spectra of HCN enhanced Seyferts

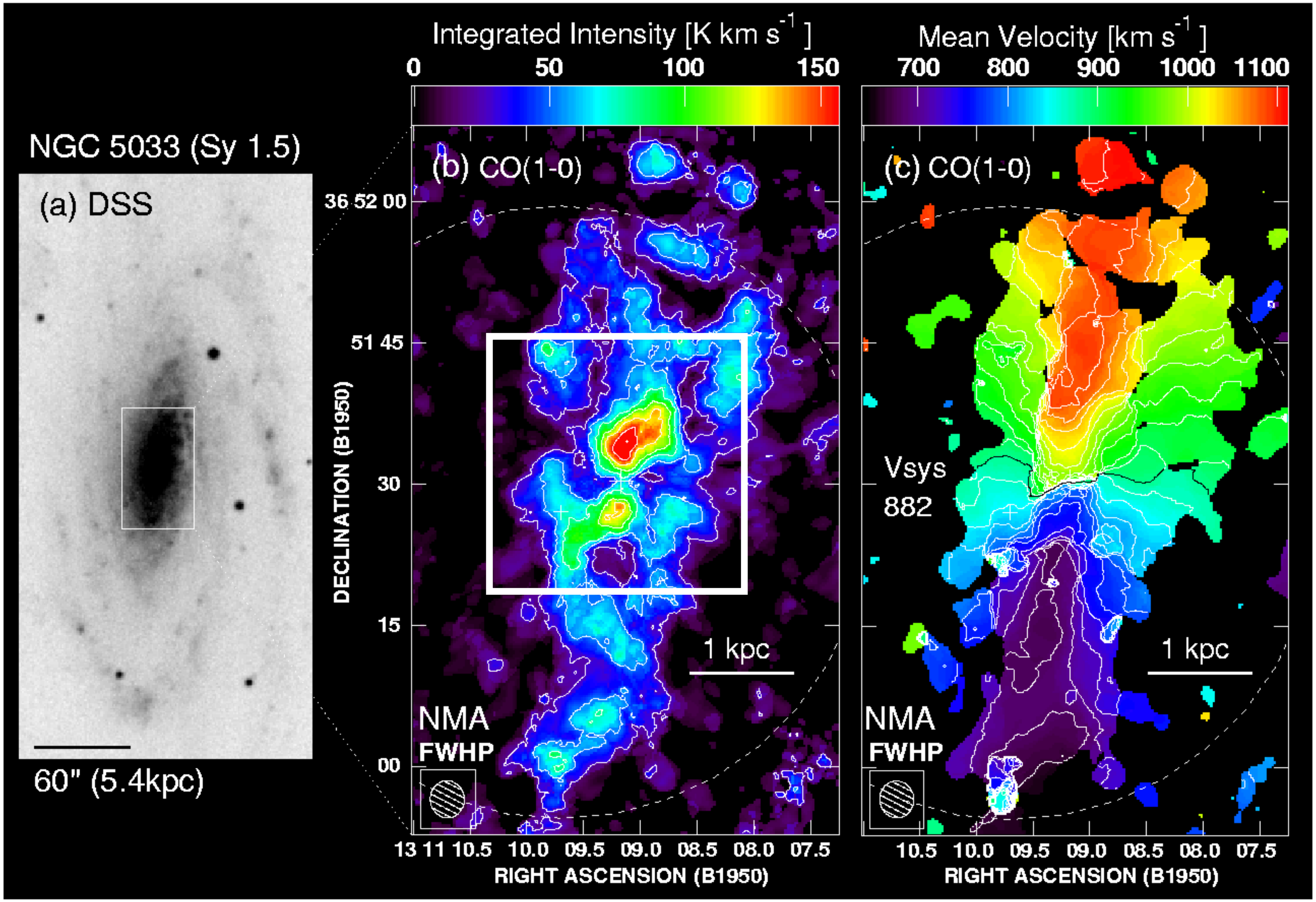




Kohno et al. 2005, in prep.

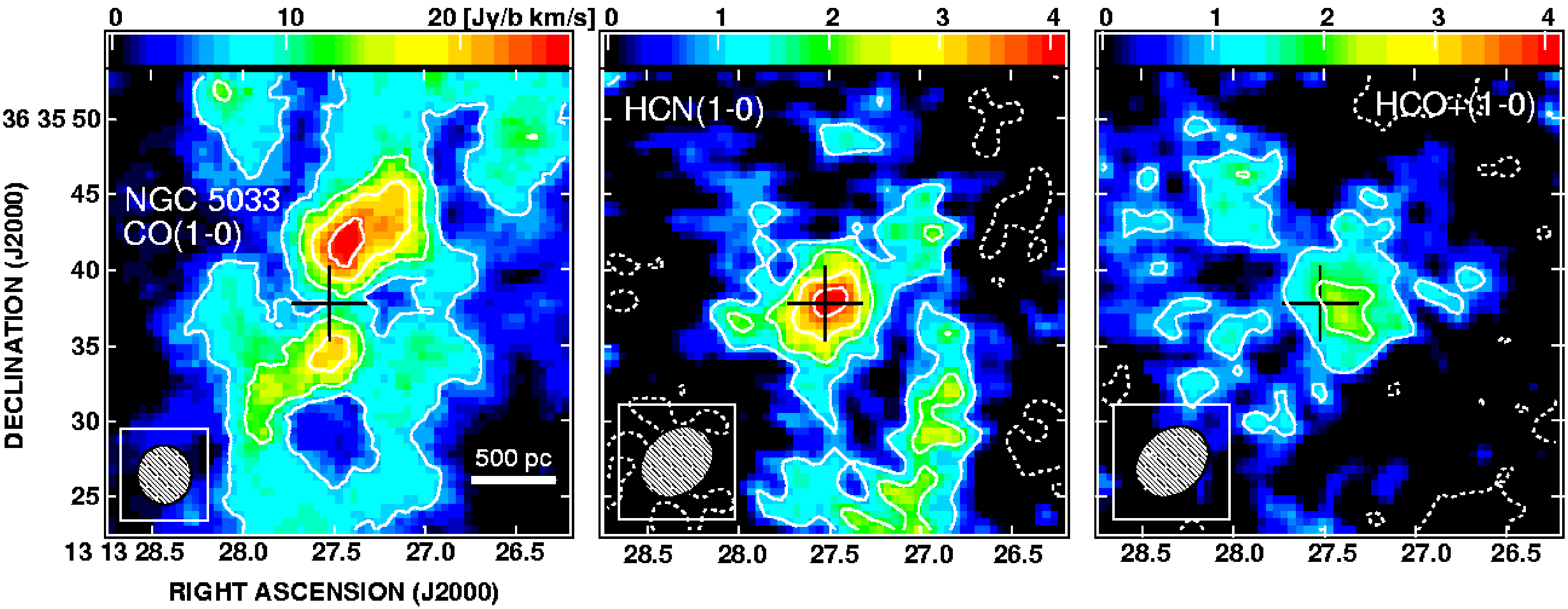
Significant enhancement of HCN can also be seen in spectra.

CO intensity and velocity field in the “non-barred” Seyfert galaxy NGC 5033



- Kohno et al. 2003, PASJ, 55, 103

New HCN enhanced Seyfert: NGC 5033



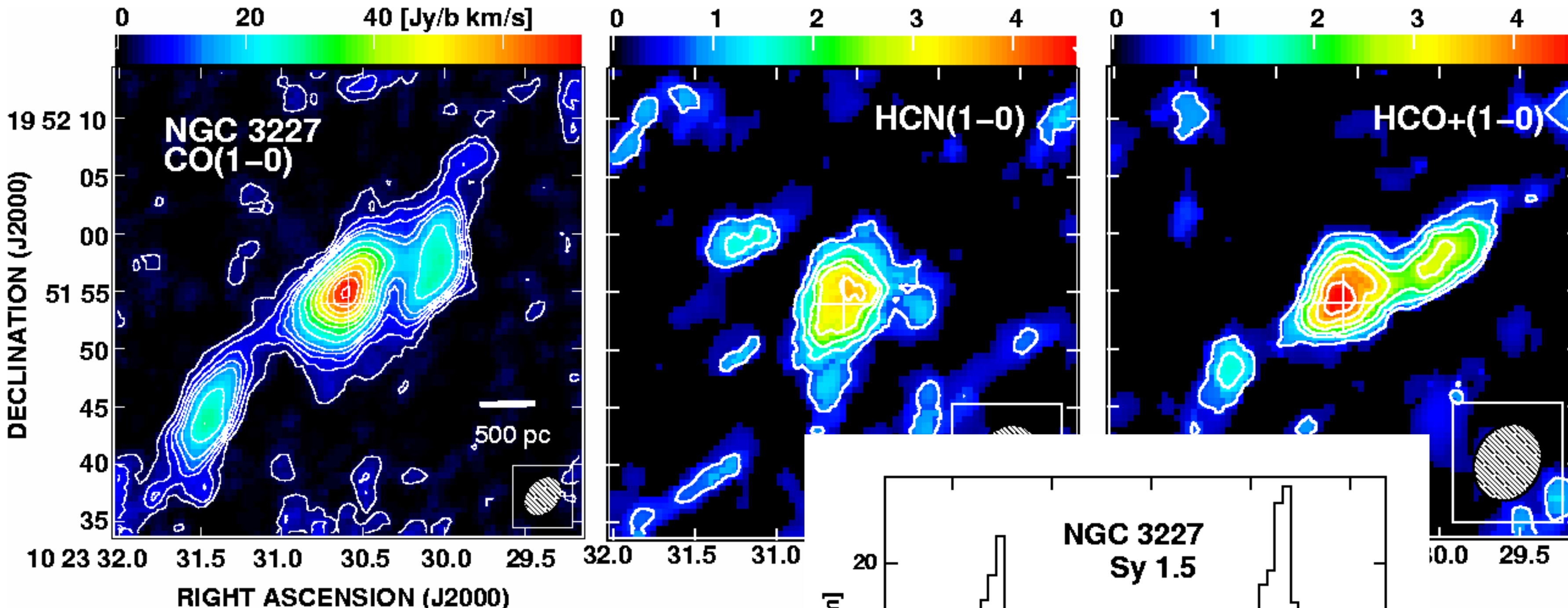
Flux at the nucleus: 31±2 Jy/b km/s   4.3±0.63 Jy/b km/s   2.3±0.63 Jy/b km/s

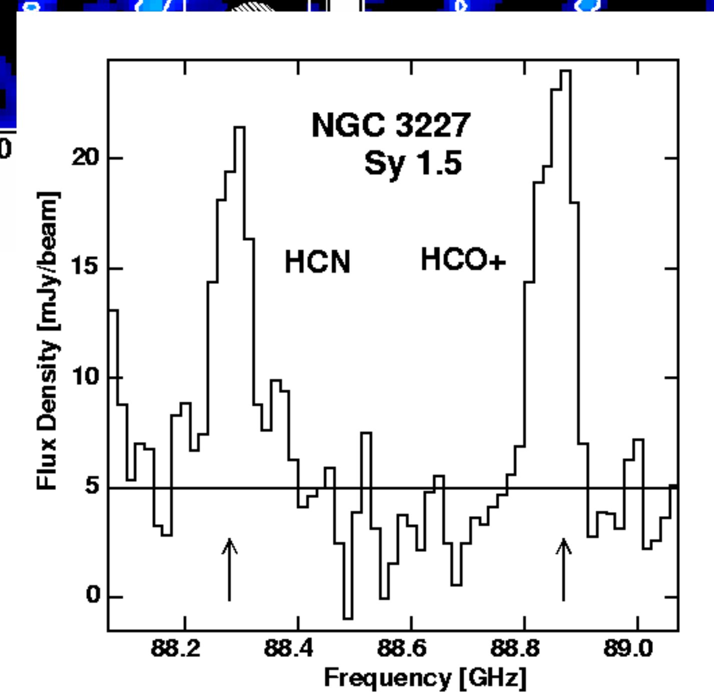
- HCN and HCO+: central concentration; no clear counterpart to CO twin peaks
- I(HCN)/I(CO)~0.23 in Tb, I(HCN)/I(HCO+)~1.9

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

Kohno et al. in prep.

NGC 3227: no HCN enhancement

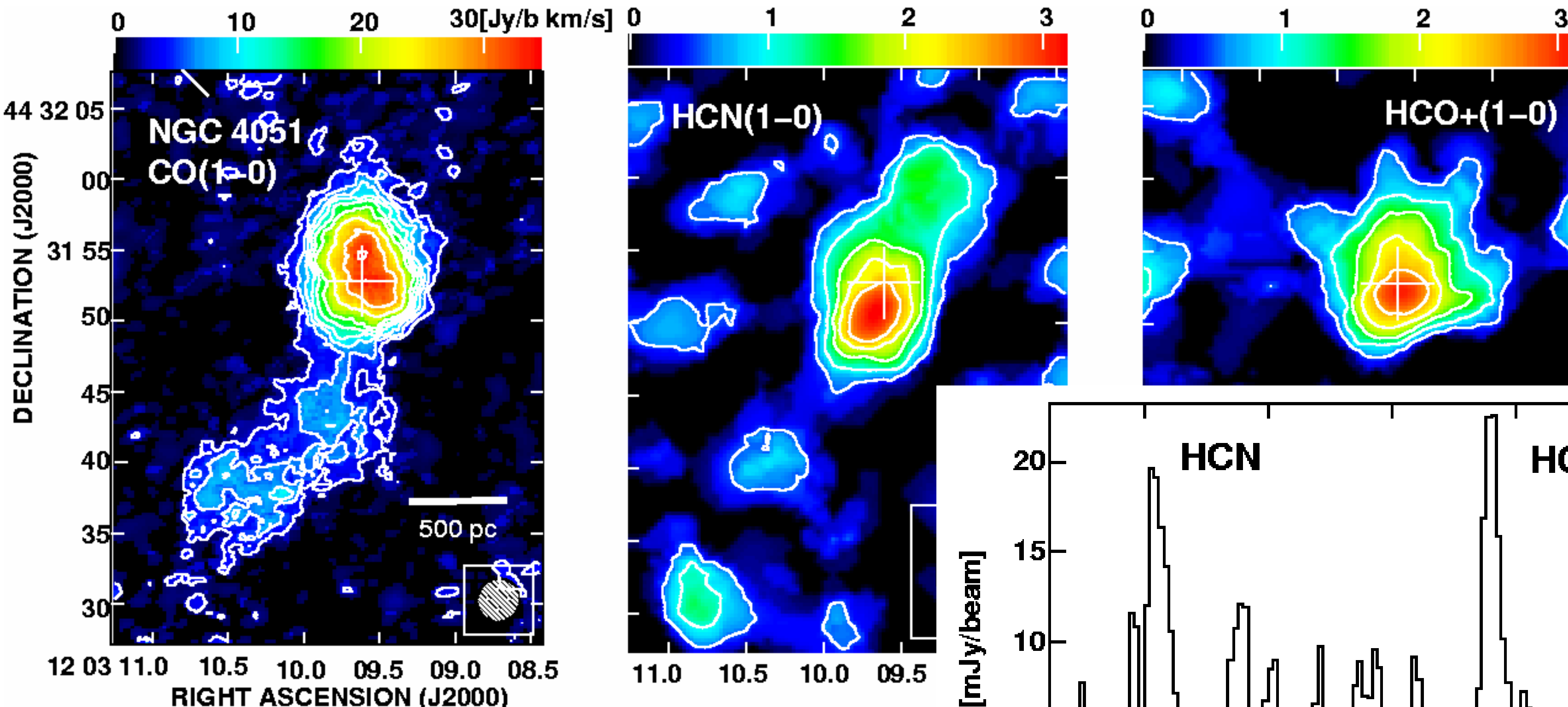


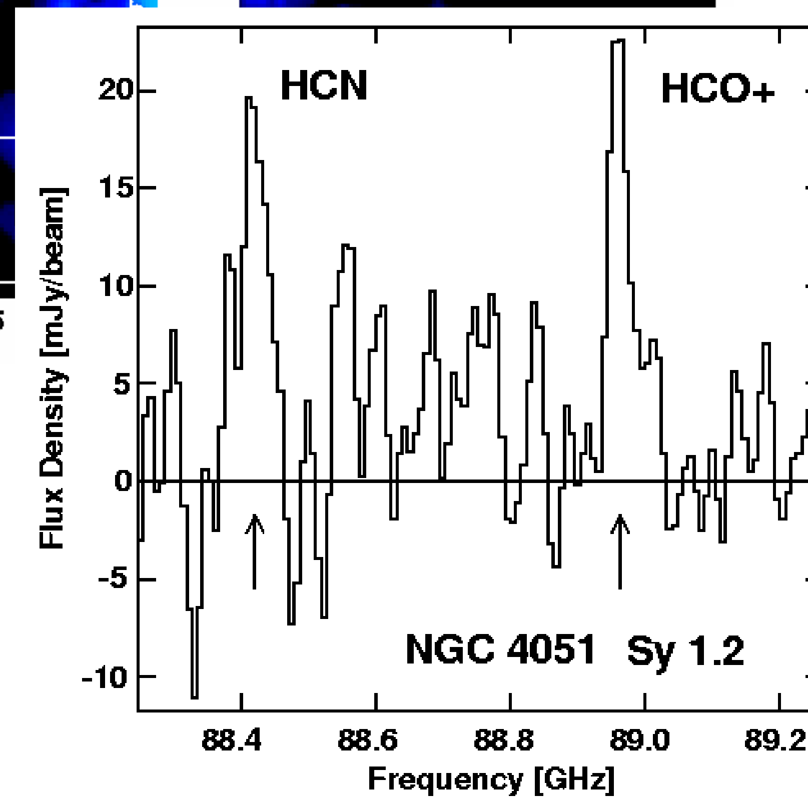


- I(HCN)/I(CO)～0.043
- I(HCN)/I(HCN+)～0.79

Kohno et al. 2005
in prep.

NGC 4051: no HCN enhancement



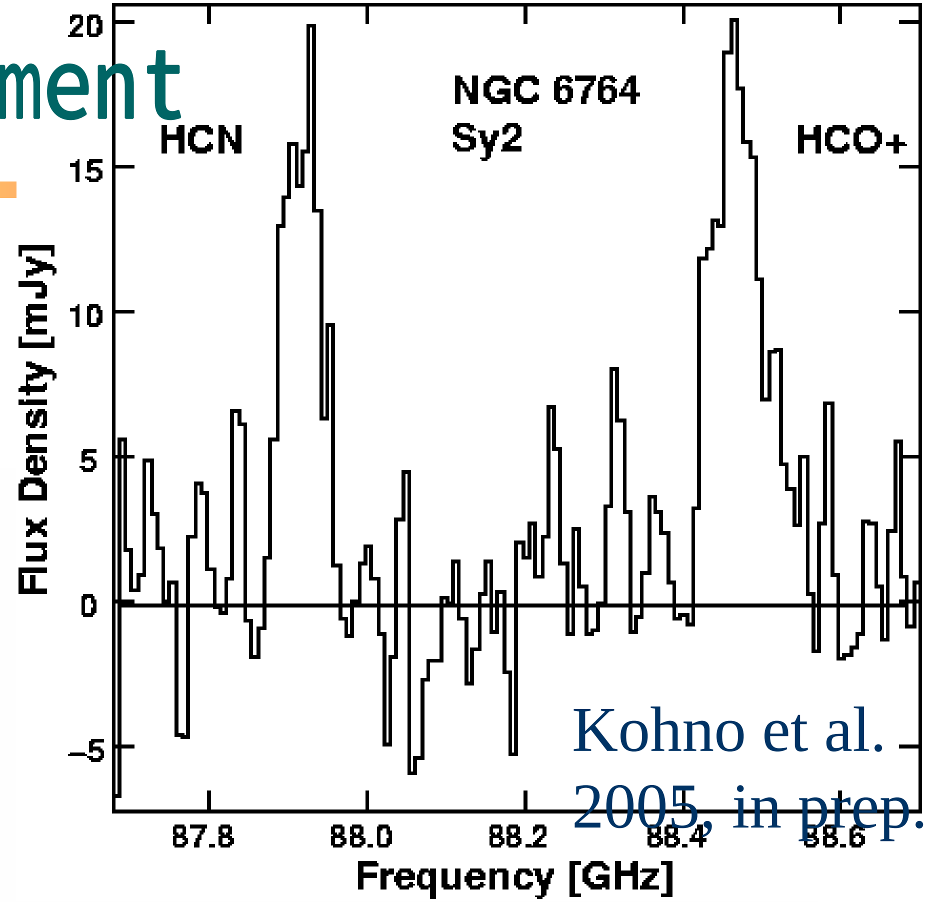


- I(HCN)/I(CO) = 0.043
- I(HCN)/I(HCO+) = 0.83

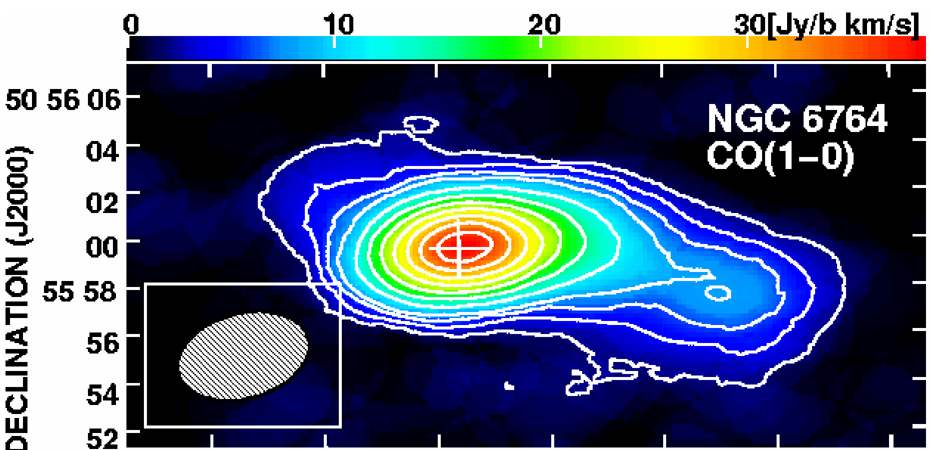
Kohno et al. 2005, in prep.

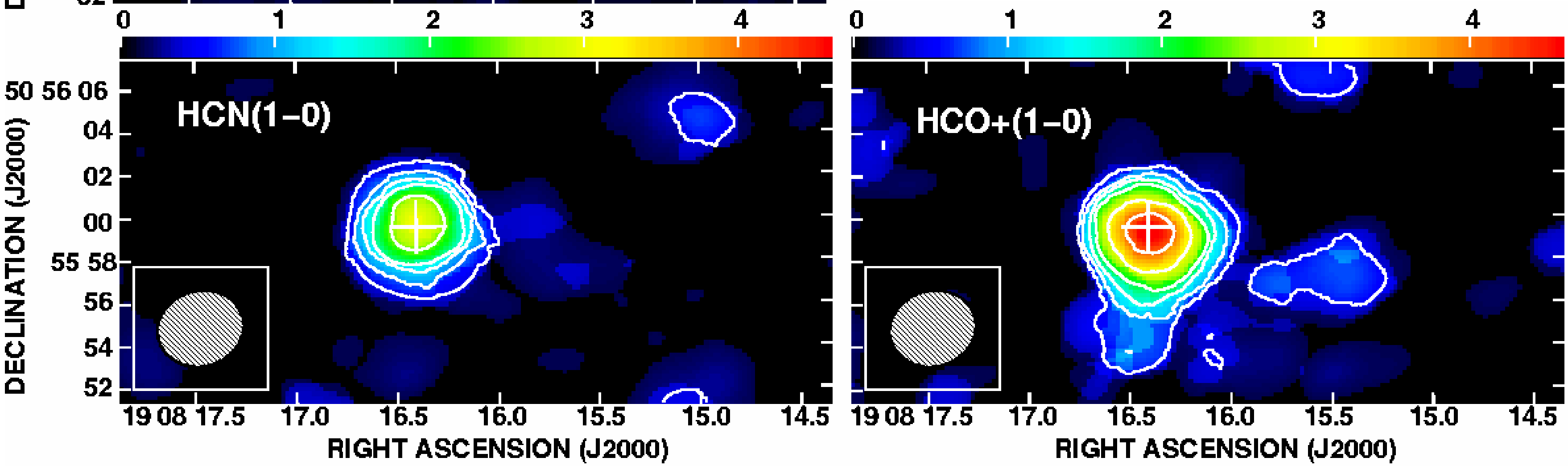
NGC6764: no enhancement

- I(HCN)/I(CO) = 0.14
- I(HCN)/I(HCO+)= 0.63



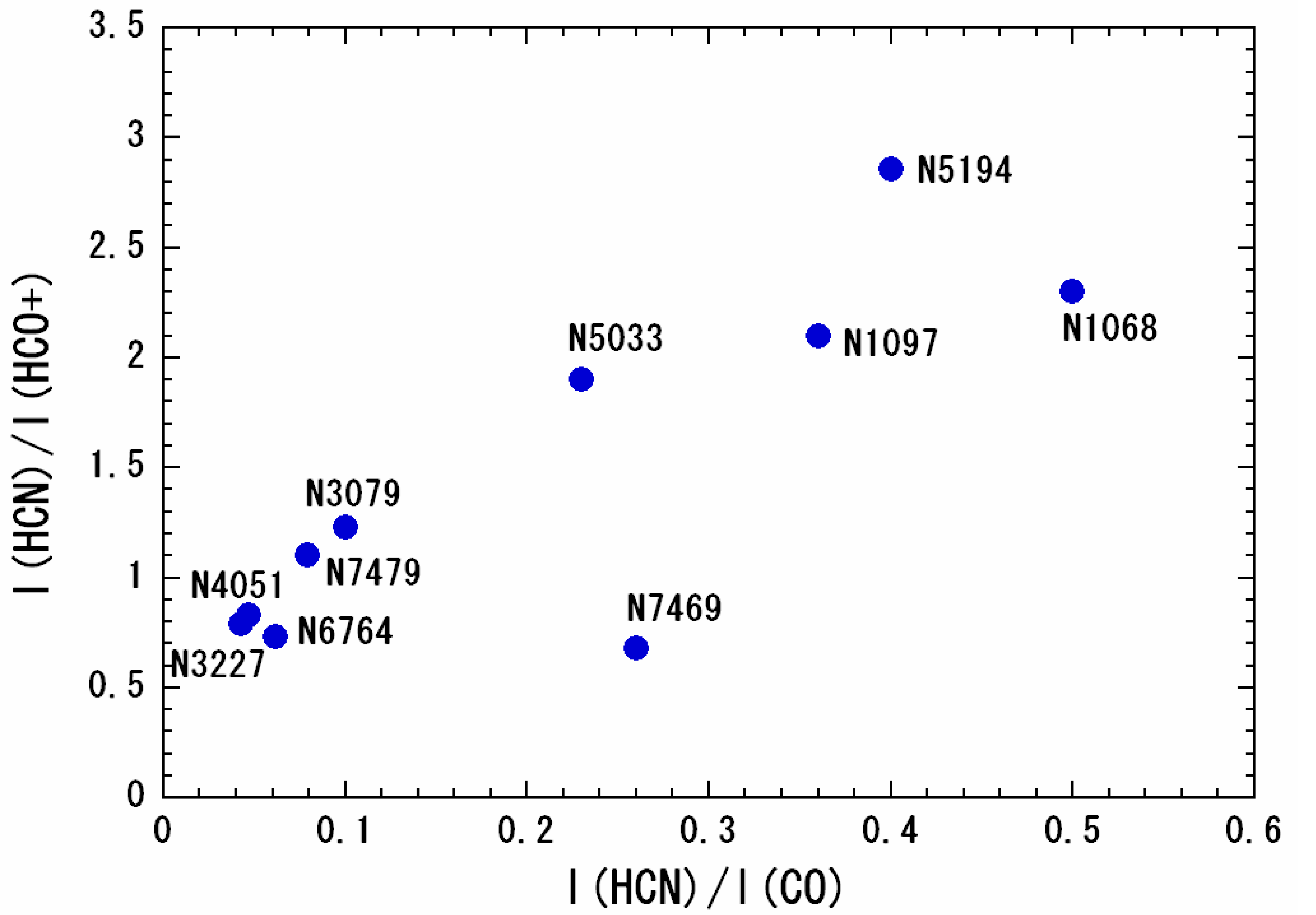
Kohno et al. 2005, in prep.



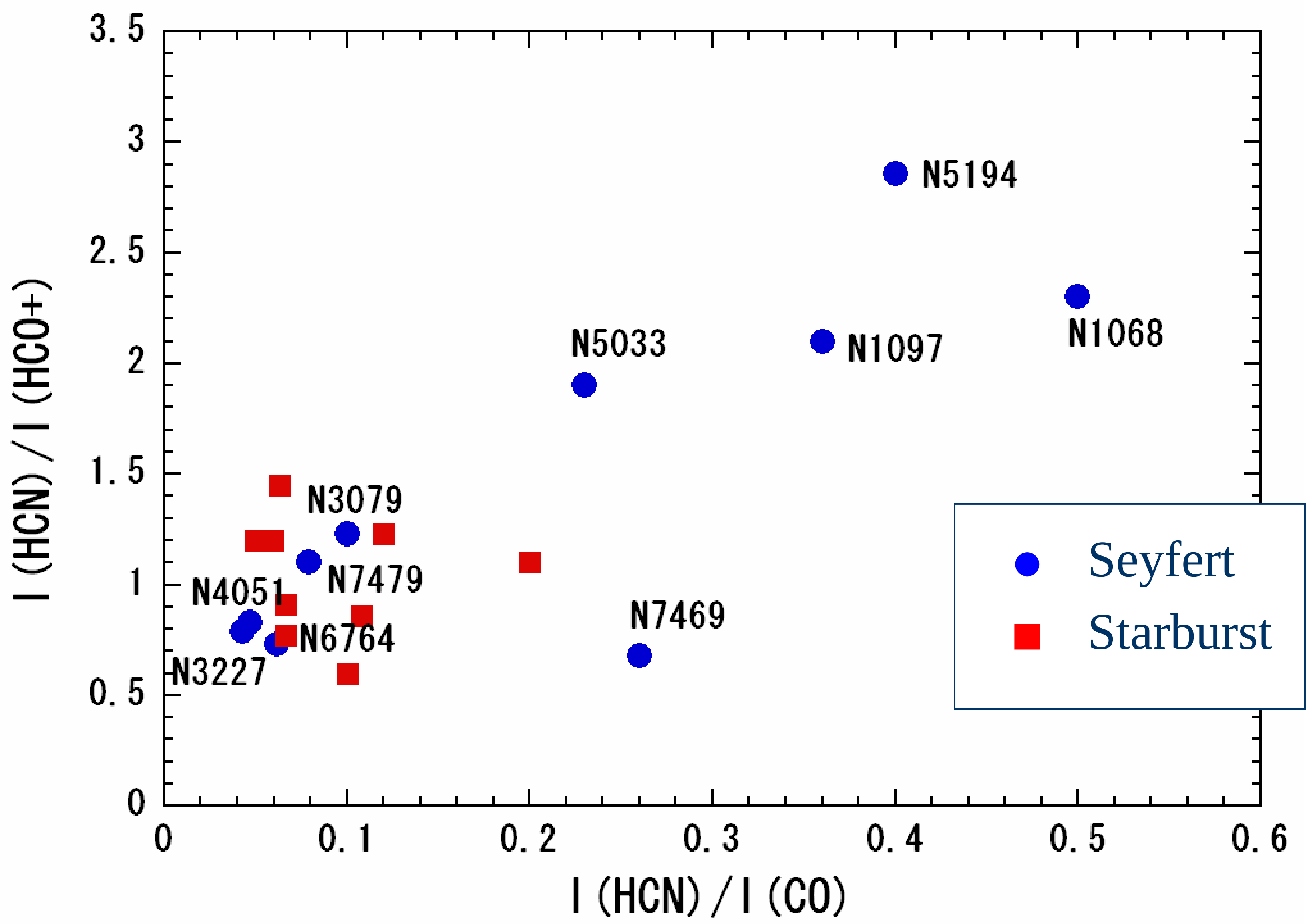


Summary of results: Line ratios

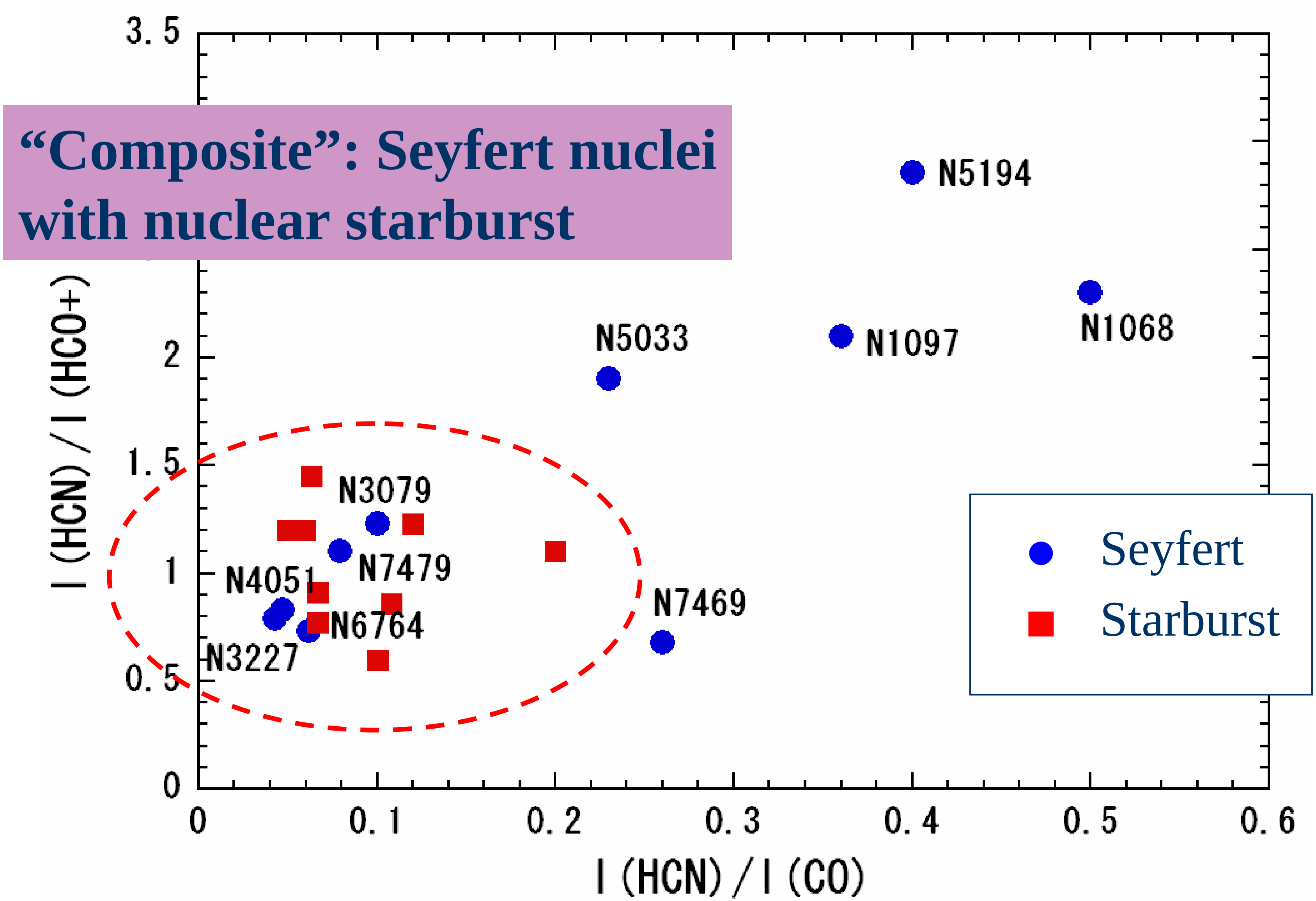
HCN/HCO+/CO diagram: 10 Seyferts



Seyfert vs Starburst galaxies

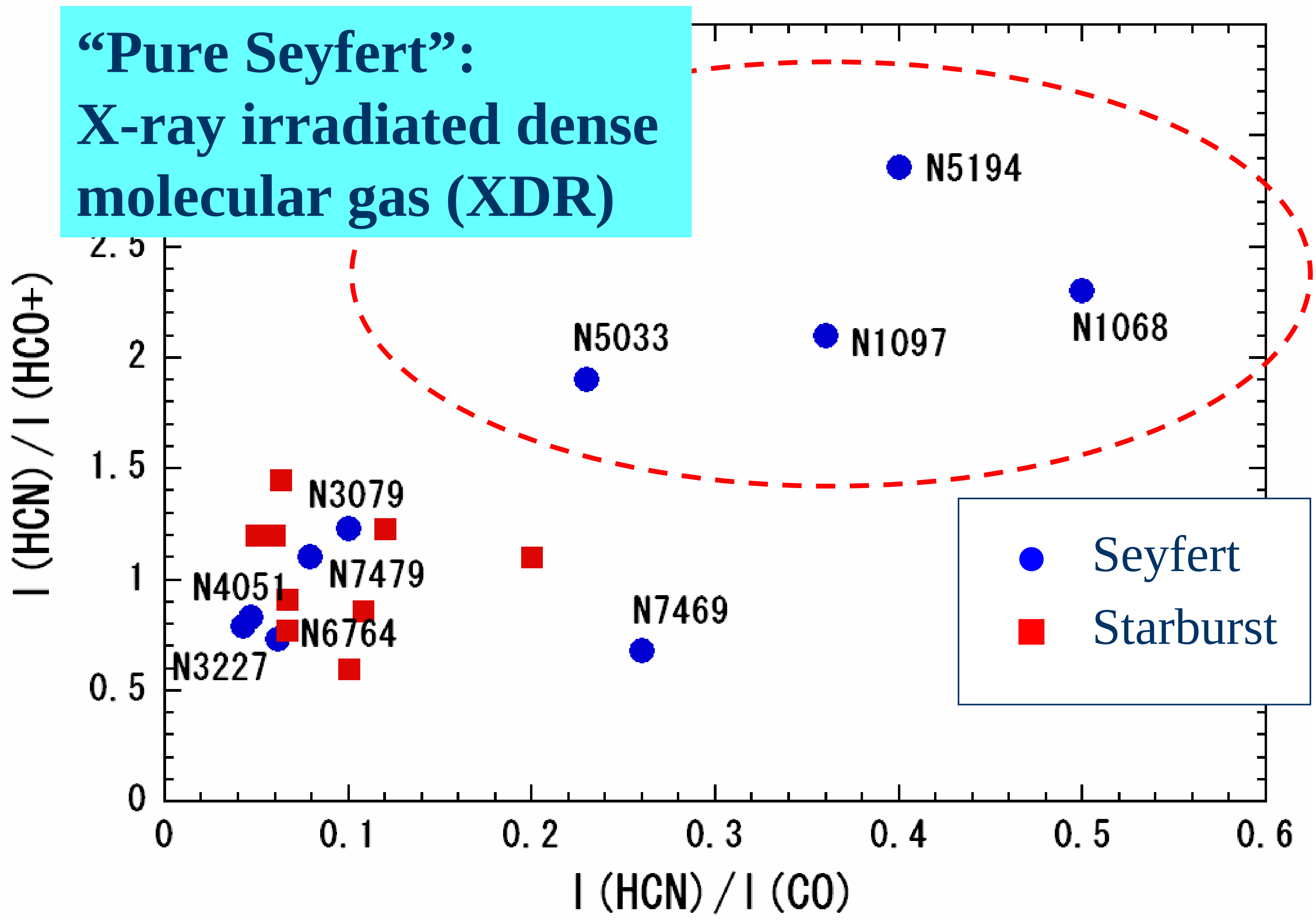


Seyfert vs Starburst galaxies



Seyfert vs Starburst galaxies

"Pure Seyfert":
X-ray irradiated dense molecular gas (XDR)

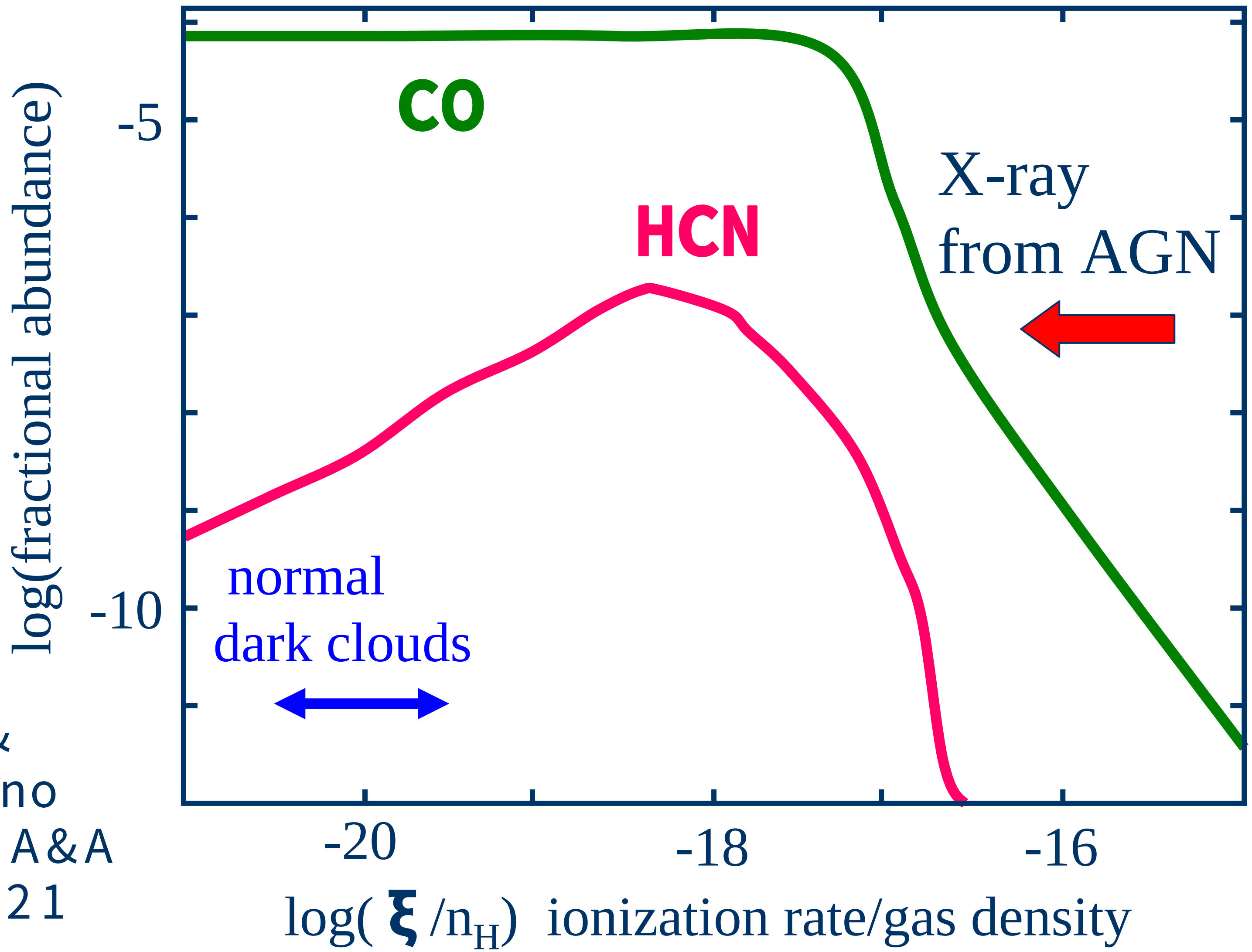


Discussion

Validity of the interpretation

- Is it reasonable to expect enhanced HCN emission toward “pure” AGNs?
- Is this interpretation supported by observations at other wavelengths?

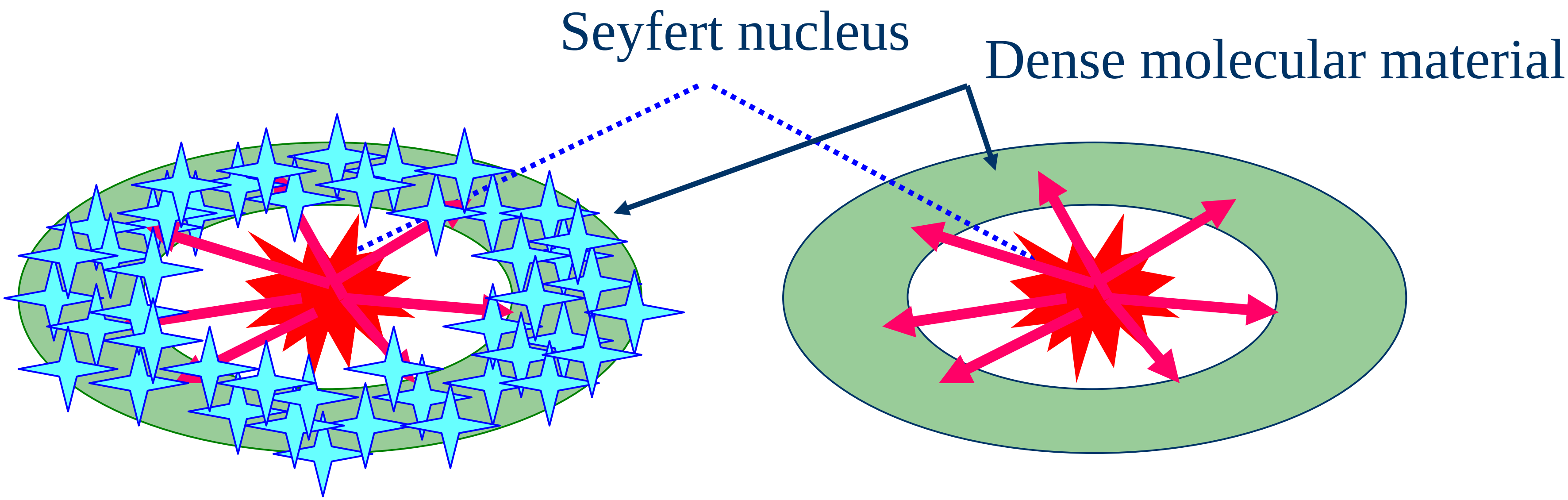
Increase of HCN abundance in X-ray dominated region (XDR)



Lepp & Dalgarno 1996, A&A 306, L21

- HCN abundance is enhanced within XDR (Maloney et al. 1996)

“pure” vs “composite” Seyferts



- Starbursting dense obscuring torus

= 「nuclear SB- AGN connection」

e.g. NGC 3227, 4051, 6764

HCO+ is also enhanced due to shocks from SNe

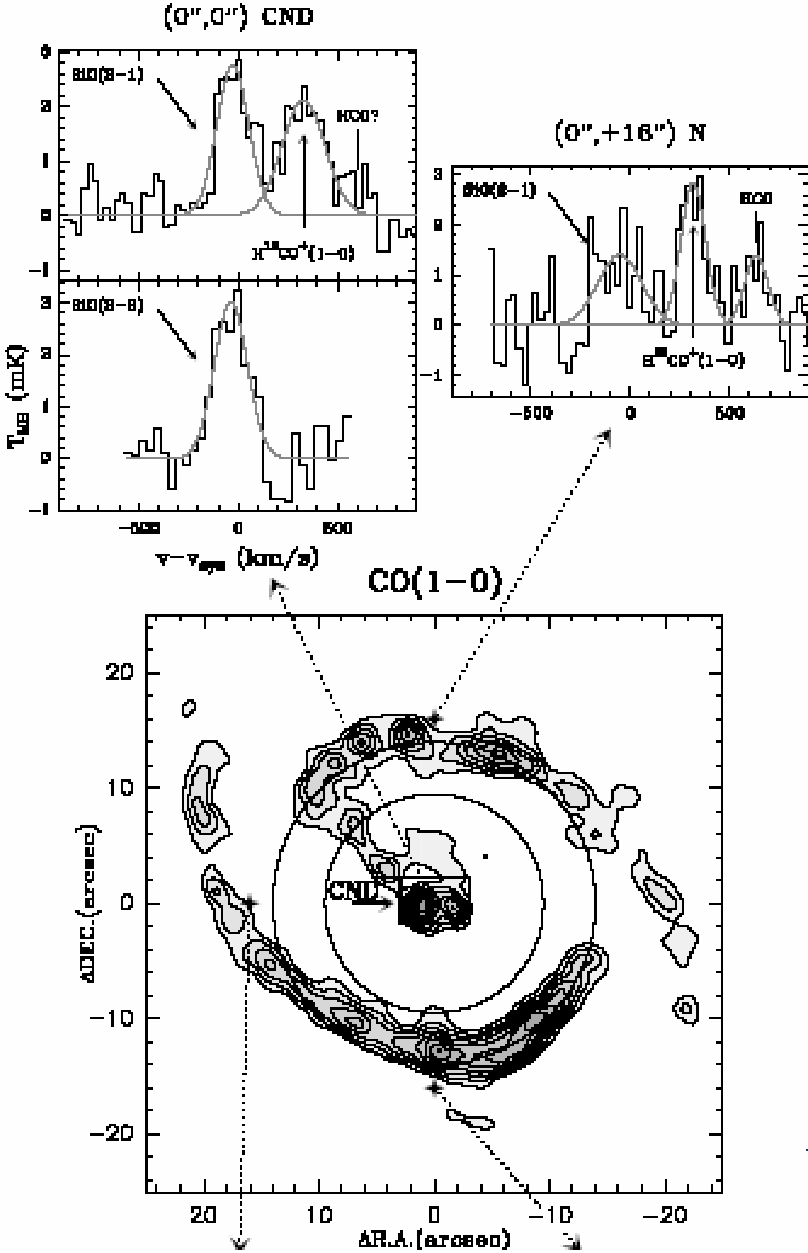
- X-ray irradiated dense obscuring torus

= 「pure Seyferts」

e.g. NGC 1068, 1097, 5194, 5033

HCN is enhanced due to enhanced X-ray flux

XDR chemistry in NGC 1068



- Multi-line observations using IRAM 30 m
  - SiO, CN, HCO+, HOC+, $H^{13}CO^+$ and HCO and also HCN, CS, CO
- The CND of NGC 1068 (~100 pc scale) is a giant X-ray Dominated Region (XDR).

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

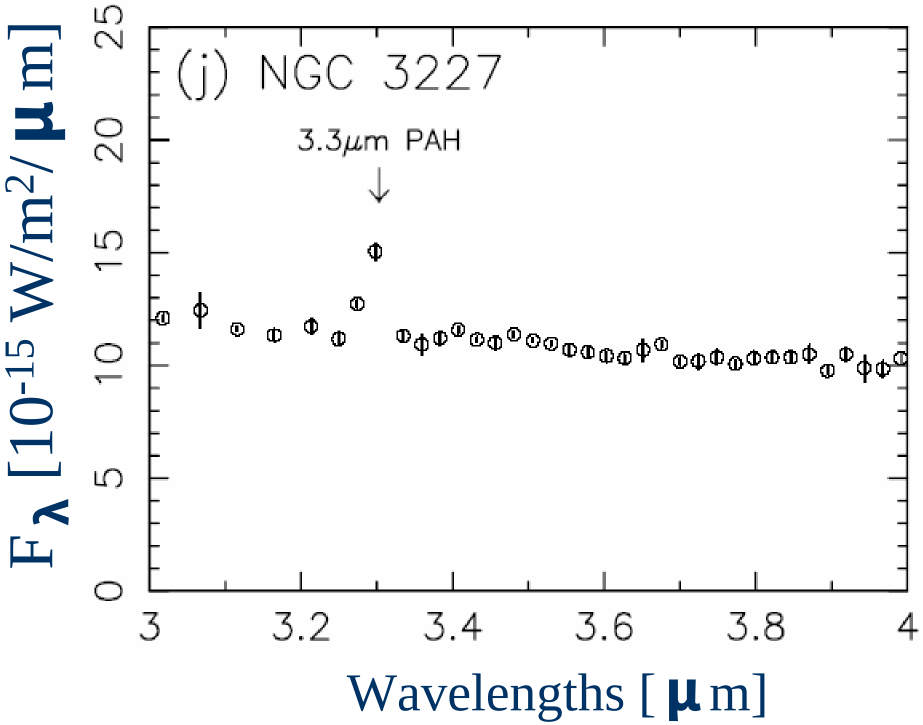
Validity of the interpretation

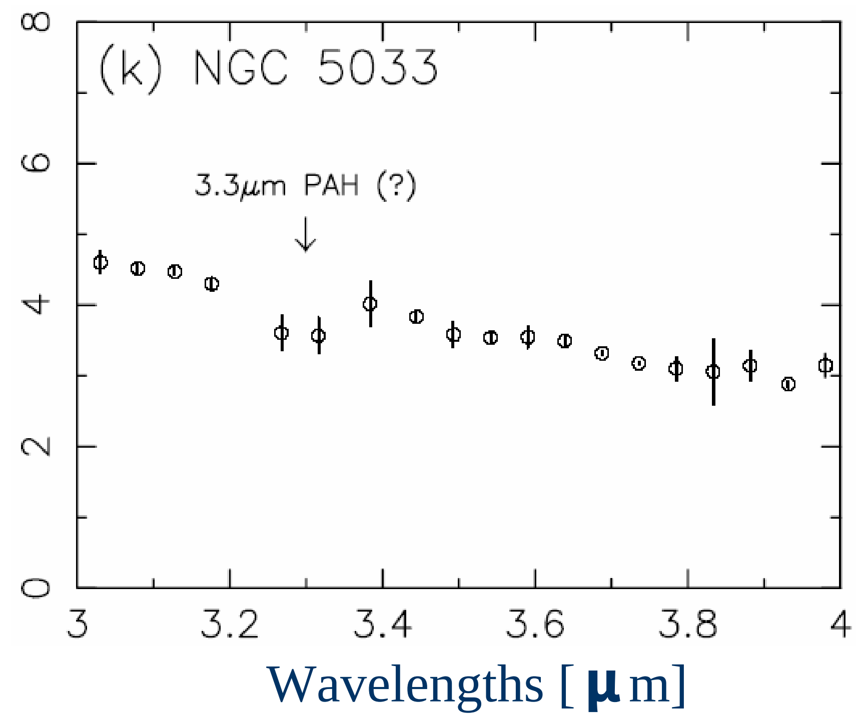
- Is it reasonable to expect enhanced HCN emission toward "pure" AGNs?
- Is this interpretation supported by observations at other wavelengths?

Comparison with other diagnostics

- Polycyclic aromatic hydrocarbon (PAH) emission feature at 3.3 μm
  - Commonly observed in starburst regions, but it is destroyed in AGN irradiated region.
  - L-band → lower extinction effect
    - e.g, Imanishi & Dudley 2000, ApJ, 545, 701
  - Sample: NGC 1068, 3227, 4051, 5033, 7469
- Ultra-high resolution radio continuum observations
  - Patch clumps → radio SNe
  - Core-jet structure → AGN
    - e.g., Arp 220 , Smith et al. 1998
  - Sample: NGC 7469

Comparison with 3.3μm PAH diagnostic





Imanishi 2002, ApJ, 569, 44

- NGC 3227 : with nuclear starburst
- NGC 1068, 5033 : without nuclear starburst

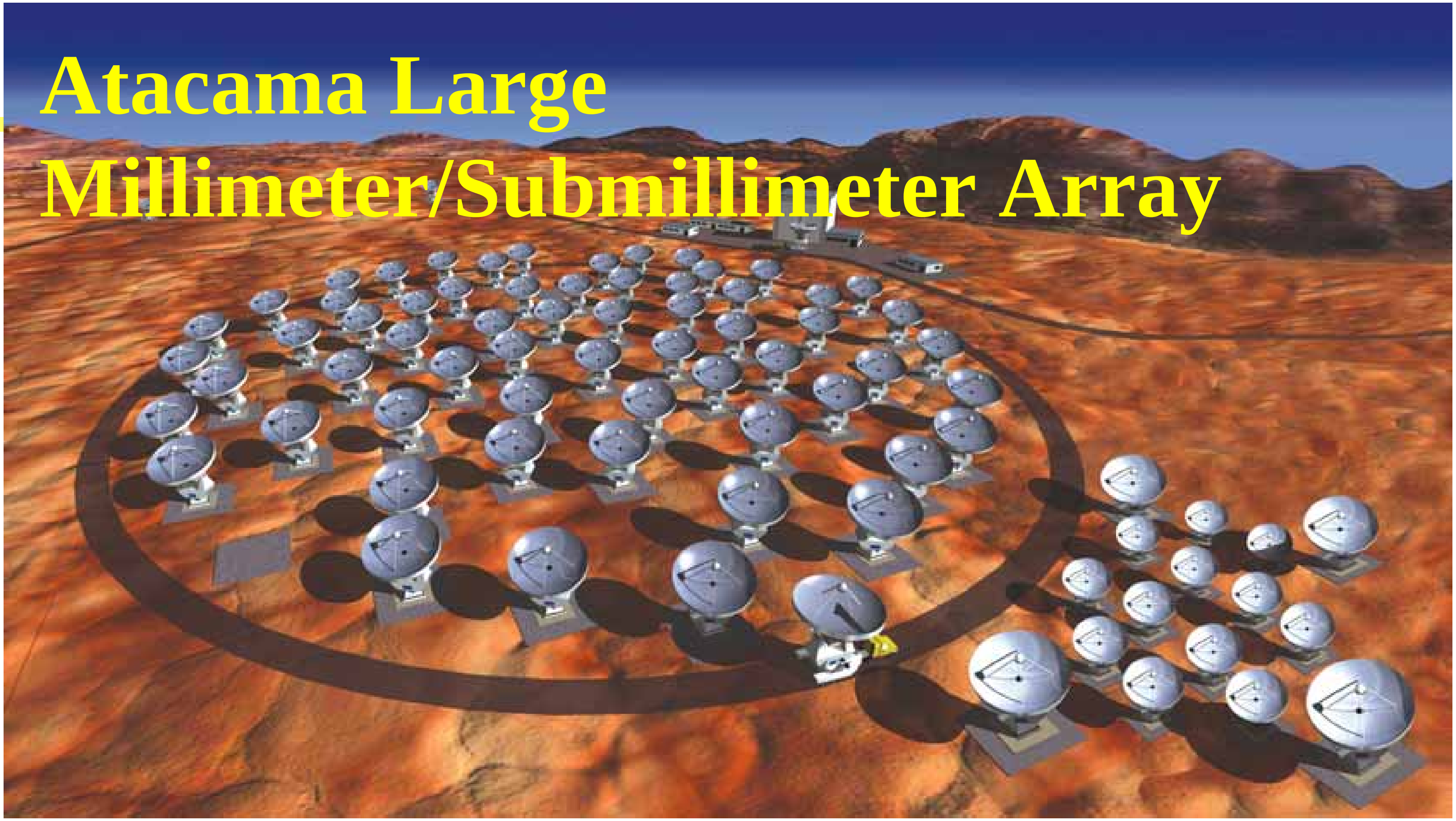
⇒ consistent with HCN/HCO+ & HCN/CO diagram

Our survey suggests:

- HCN/HCO+ & HCN/CO ratio diagram
  ⇒ a new diagnostic of power source in dusty active galaxies ("pure" vs "composite")
  - must be powerful for extremely dusty nuclei such as ULIRGs and high-z submm galaxies, because mm/submm lines are free from dust extinction
    ⇔ UV/optical/IR spectroscopy
- Prevalence of compact (<a few 100 pc) nuclear starbursts in Seyfert galaxies
  - 6 seyferts out of 10 shows a signature of composite nuclei
    ⇒ expand the sample for a statistical study

Toward ALMA

Atacama Large Millimeter/Submillimeter Array



- 64 12-meter diameter antennas
- ALMA compact array (ACA): 4 12-m + 12 7-m
- Frequency bands covering 90 GHz to 900 GHz
- Wide band (4 GHz) spectro-correlator system
- Full operation：2012～

Toward ALMA

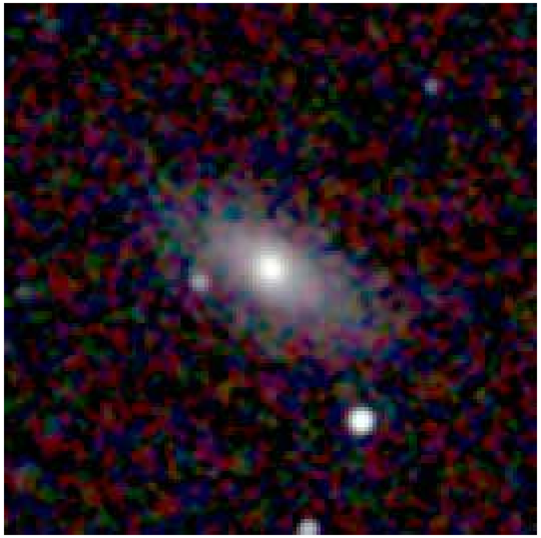
- Establishment of new power diagnostic technique that is free from dust extinction based on HCN/HCO+ line ratios.

- Application of this diagnostic to LIRGs/ULIRGs
  - NMA/RAINBOW observations of NGC 4418 by Imanishi, Nakanishi, Kuno, and Kohno 2004
- High-z dusty galaxies (such as submm galaxies)
  - To apply this method to high-z objects, high-J lines such as HCN(4-3) etc. should be observed. ➔ survey of submm lines w/ASTE

Application to Luminous IR galaxies: a case for NGC 4418

- $L(IR)=9\times10^{10}$ Lo or $10^{44.5}$ erg/s
- Abundant molecular gas
  - Kawara et al. 1991
- no clear Seyfert signatures in its optical spectrum
  - Armus, Heckman, & Miley 1989
  - Lehnert & Heckman 1995
- Evidence for buried AGN ?
  - The 5–23 μm mid-infrared spectrum of NGC 4418 has the typical shape of an obscured AGN (Roche et al. 1991; Spoon et al. 2001)
  - But still not conclusive yet (Evans et al. 2003)

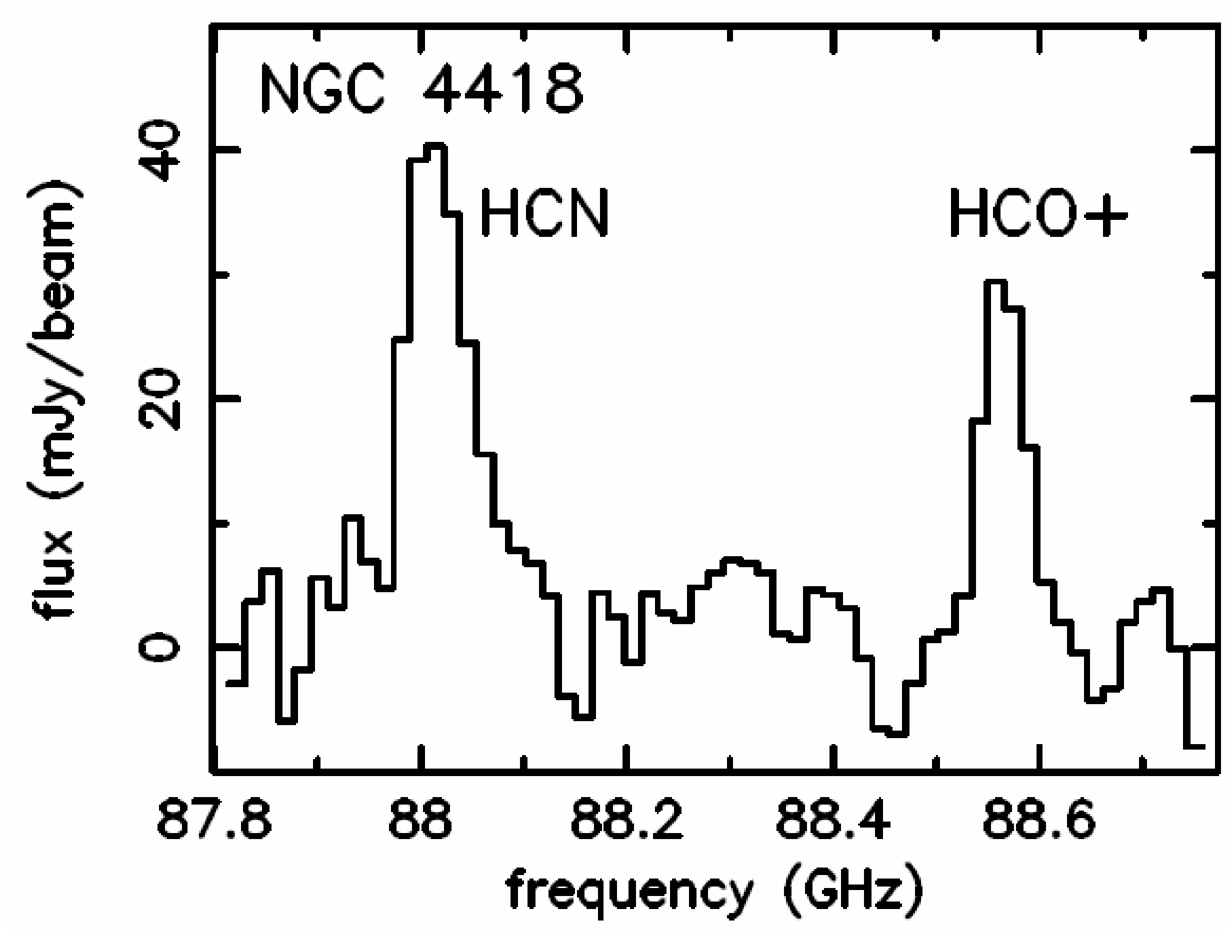
NGC 4418
2MASS JHK



1 arcmin
or 8 kpc

at D = 28 Mpc

HCN enhancement in NGC 4418

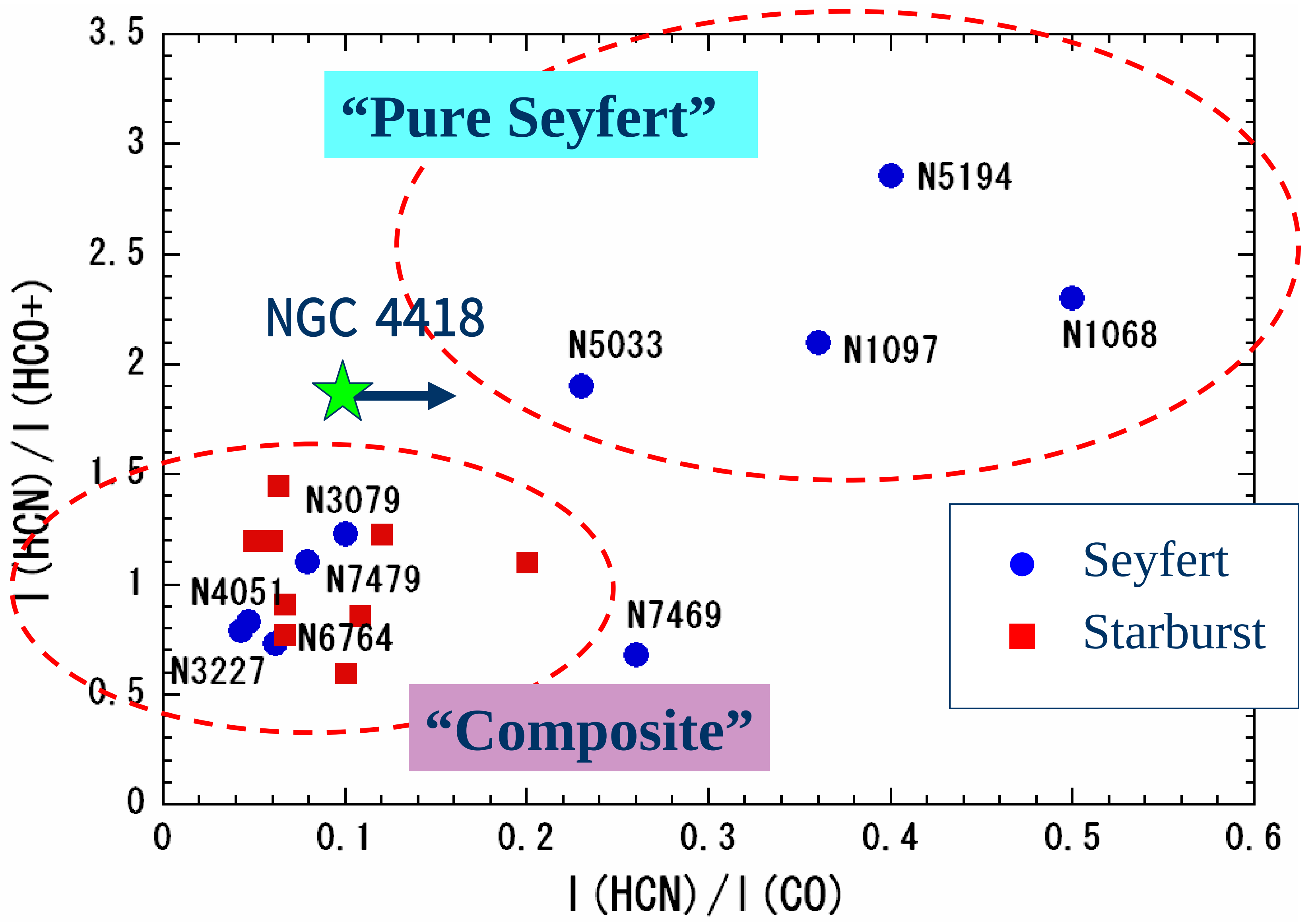


- S(HCN)=10.3 Jy km/s
- S(HCO+)=5.6 Jy km/s

RAINBOW interferometer

Imanishi et al. 2004, AJ, 128, 2037

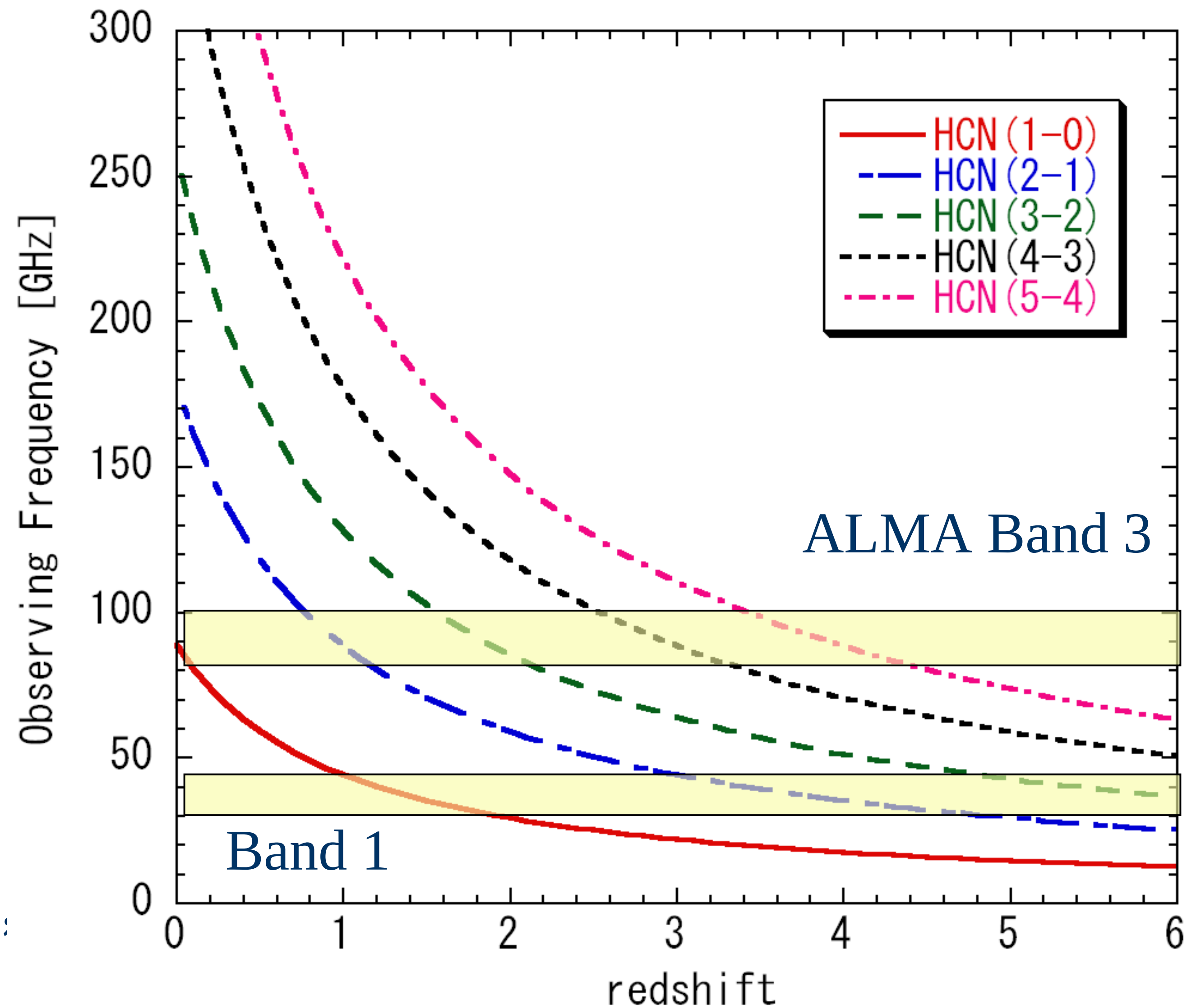
Buried AGN in NGC 4418 ?



Diagnostic of high-z dusty galaxies

- XDR/PDR diagnostic using HCN/HCO+/CO line ratios
  - seems to be very useful among nearby AGNs
  - ➔ application to dusty, high-z galaxies
  - ➔ observations of high-J HCN/HCO+ lines
- Multi-J CO line ratios
  - Implication from CO(2-1)/CO(1-0) ratios
    - NGC 5033 from OVRO (Baker et al. 1999)
    - NGC 7469 from PdBI + NMA
  - Power of SMA !!
    - CO(3-2) of NGC 5194 (Matsushita et al. 2004)
- CO/CI ratios （??）

Redshifted HCN transitions



- ALMA band 1 is essential, but …

Existing extragalactic HCN(4-3) / HCO+(4-3) observations

HCN ($J = 4 \rightarrow 3$) Line Parameters in Galaxies

Galaxy[a]	$\int T_{mb} bv$ (K km s^{-1})	Peak T_{mb} (K)	T_{rms} (K)	ΔV (km s^{-1})	HCN $\frac{(J = 4 \rightarrow 3)}{(J = 1 \rightarrow 0)}$ [b]	$\frac{CO(J = 3 \rightarrow 2)}{HCN(J = 4 \rightarrow 3)}$
NGC 253:						
15″ NE	38.5	0.23	0.03	120	0.6–0.8	
Center	71.4	0.36	0.07	125	0.8–1.1	20
15″ SW	21.5	0.19	0.05	110	0.3–0.4	
M82:						
10″ NE	<3.3	<0.07	0.04	150[c]	<0.1	
Center	<3.3	<0.05	0.03	180[c]	<0.1	>300
10″ SW	<4.2	<0.09	0.04	150[c]	<0.1	
IC 342	5.9	0.09	0.02	30	0.2–0.3	30
NGC 4945[d]	50.9	0.20	0.03	>300[e]	0.5–2.1[e]	>15
NGC 1068	<4.5	<0.10	0.05	70	<0.2	
Maffei 2	<5.3	<0.09	0.04	125[f]	<0.2	

Jackson et al. 1995, ApJ, 438, 695

- Limited numbers of observations, but ASTE can:
  - Simultaneous CO(3-2) and HCO+(4-3) observations
  - Simultaneous HCN(4-3) and HCO+(4-3) observations (near future)

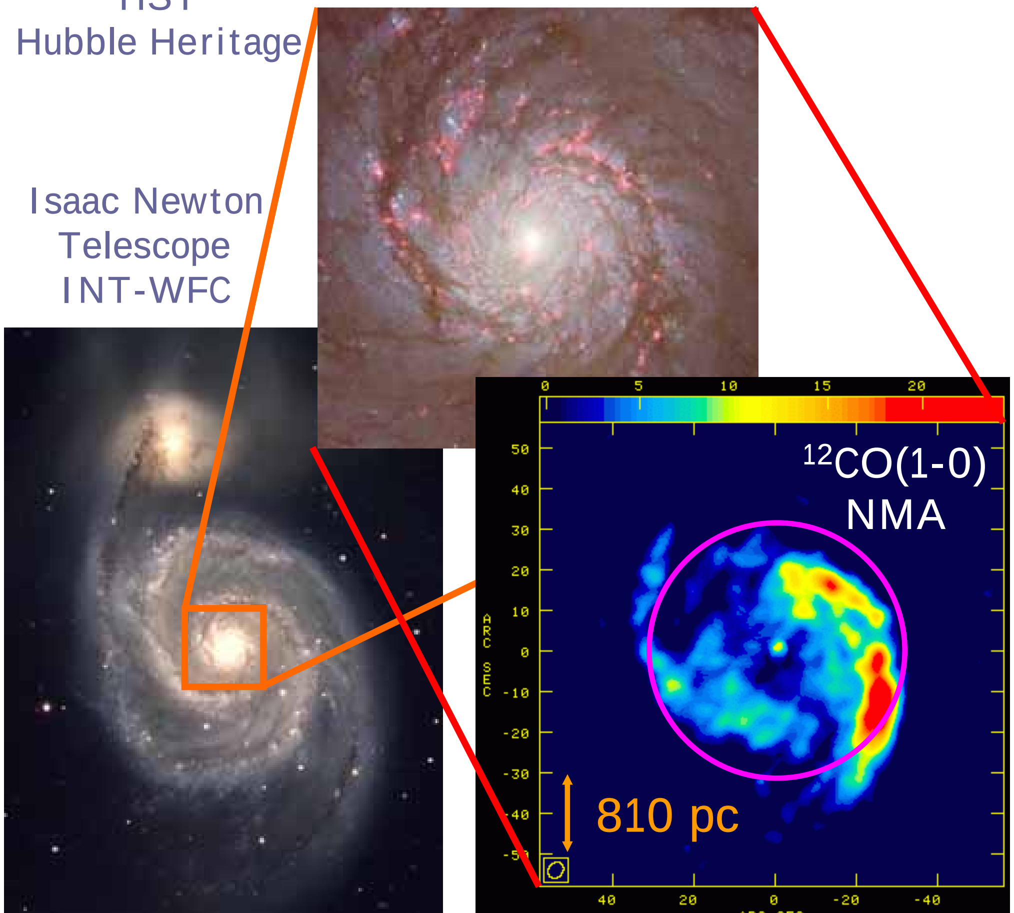
Multi-J CO observations

- High-J CO transitions
  - High A-coeff., high statistical weight
  - ➔ tracing dense and warm molecular gas
- Some of high-J CO observations show significant enhancement of high-J CO intensities at the centers of active galaxies
  - NGC 7469 (Davies et al. 2004, ApJ, 602, 148 vs Okiura et al. 2004, in prep.)
  - M51 (Matsushita et al. 2004, 616, L55)

Multi-J CO Line observations of the Seyfert 2 Galaxy M51

HST
Hubble Heritage

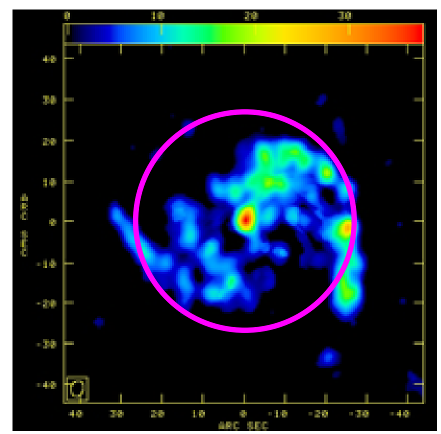
Isaac Newton
Telescope
INT-WFC



Sakamoto et al.
(1999, ApJS, 124, 403)

^{12}CO(2-1) SMA

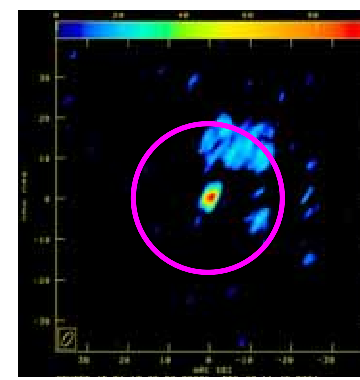
5 Antenna Observation



Sawada-Satoh et al.

^{12}CO(3-2) SMA

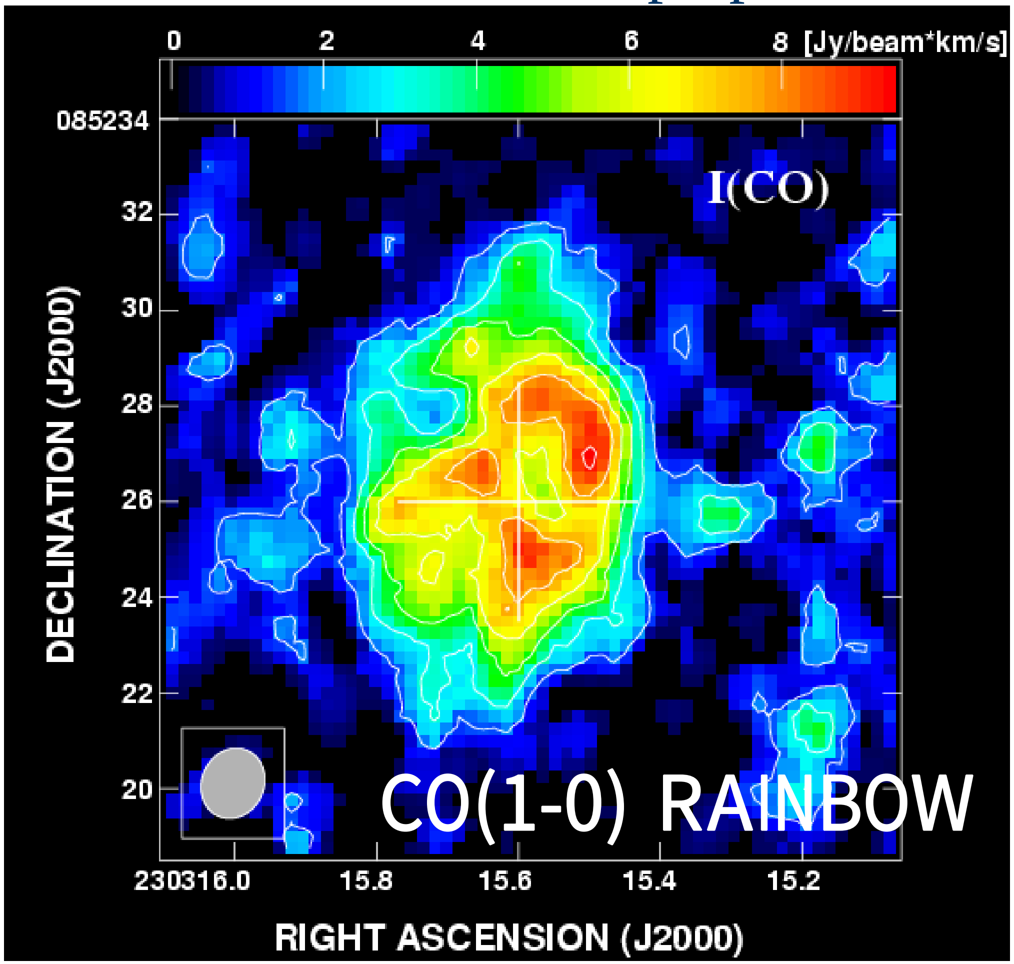
4 Antenna Observation



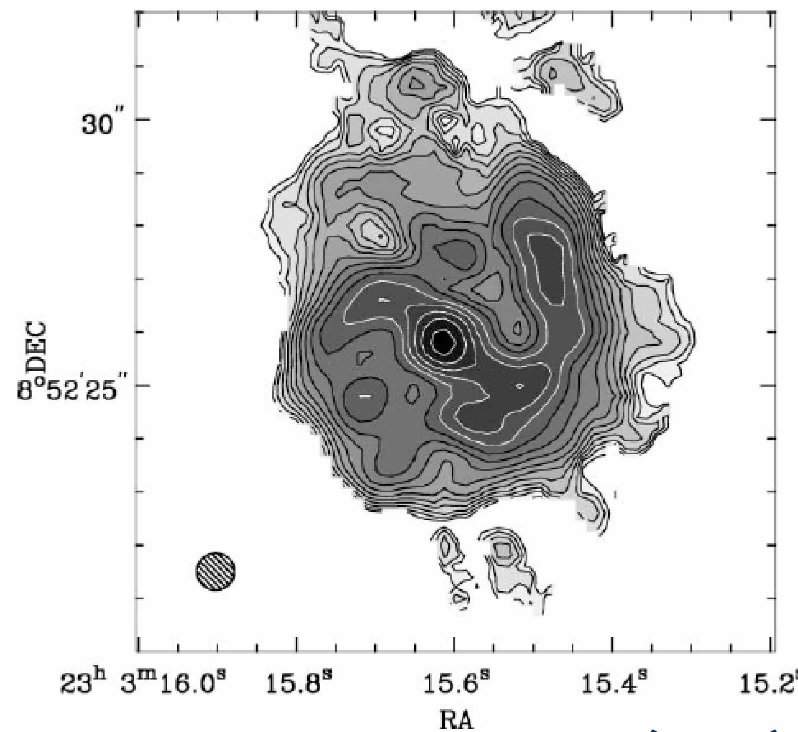
Matsushita et al.
(2004, ApJL, 616, L55)

NGC 7469: CO(1-0) vs CO(2-1)

Okiura et al. 2005, in prep.



Davies et al. 2004, ApJ, 602, 148

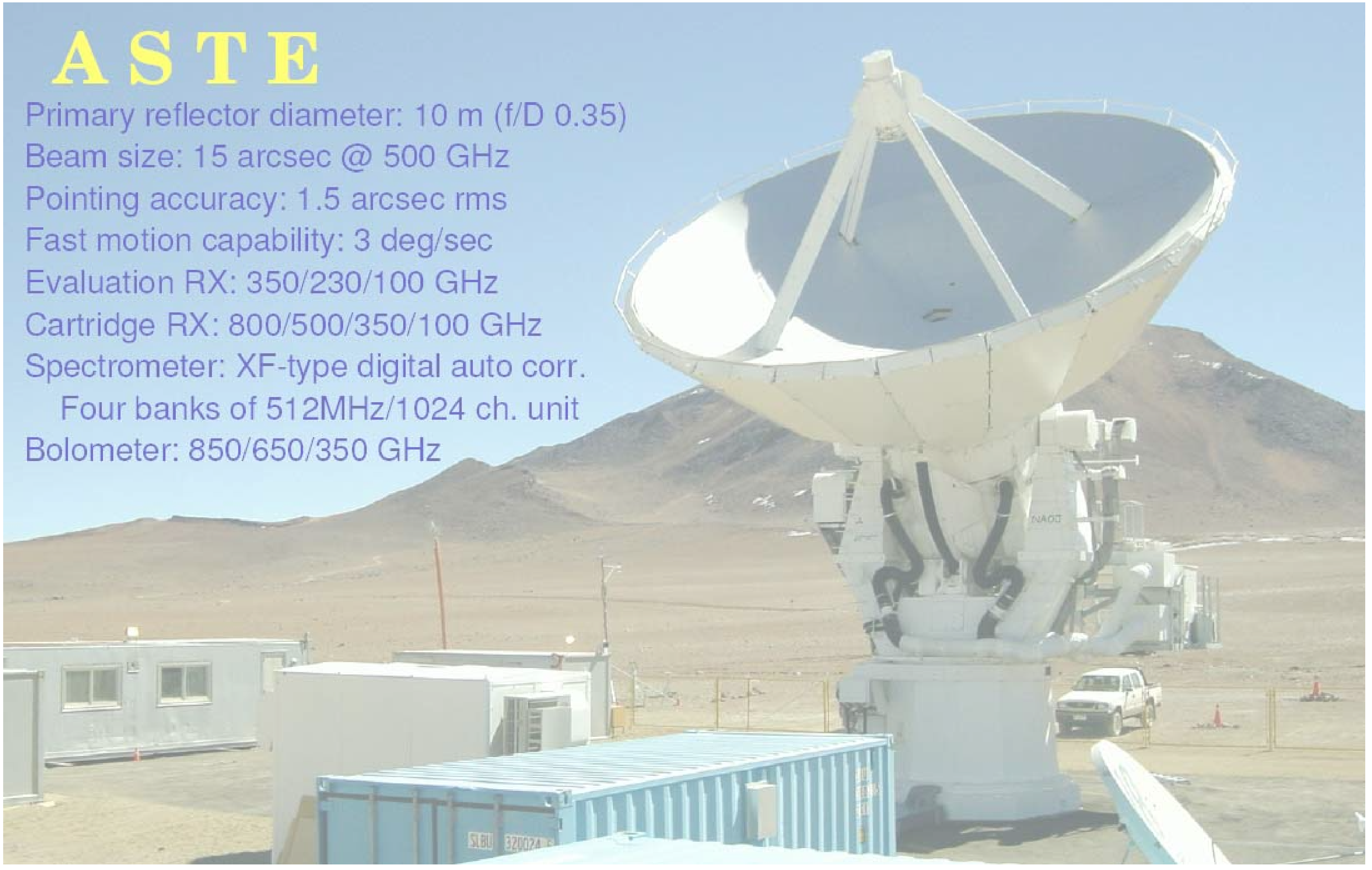


CO(2-1) PdBI

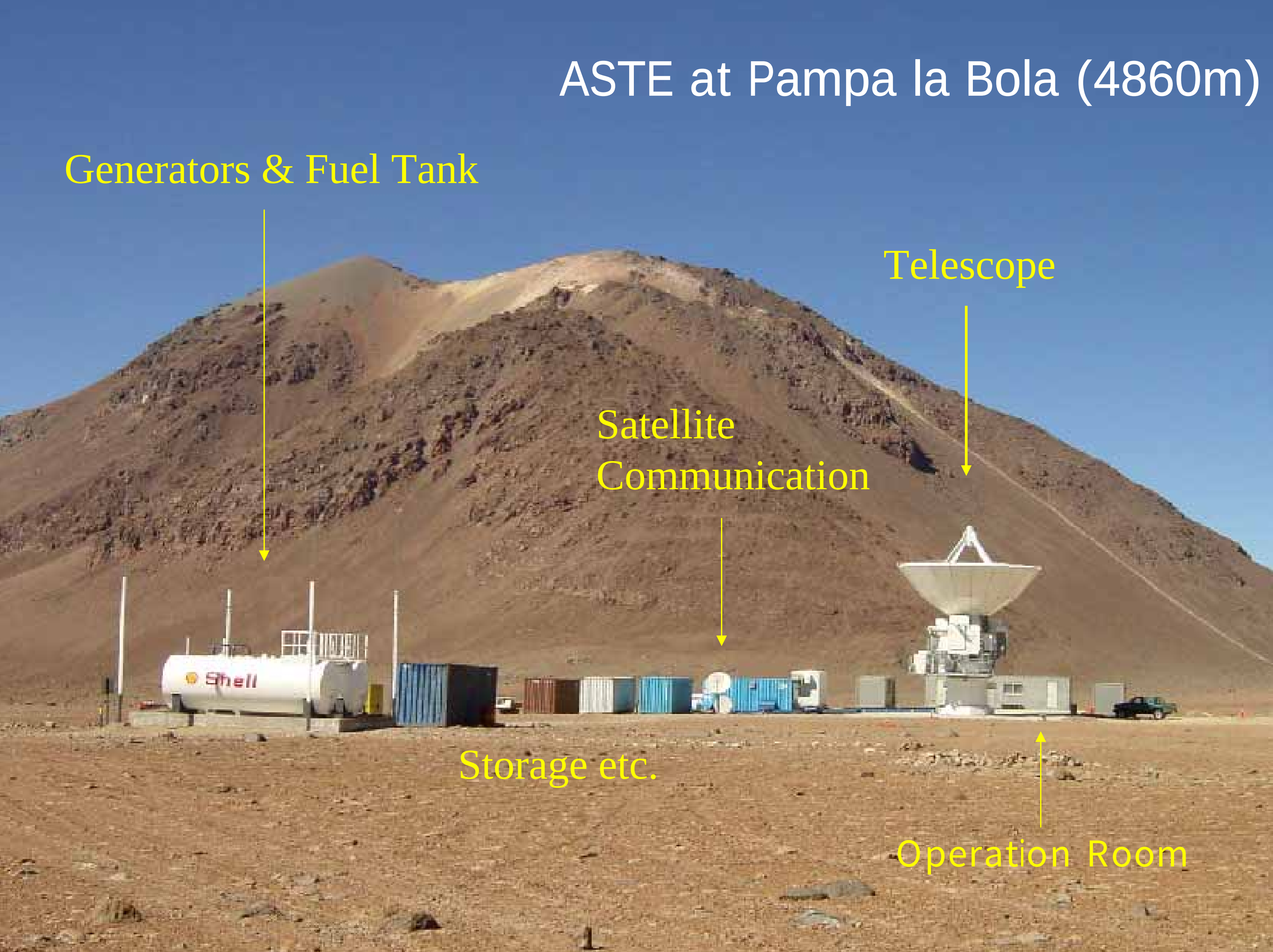
- Significant enhancement of CO(2-1) at the nucleus !!
- Overall structure agrees well each other.

ASTE:
a precursor to ALMA

Atacama Submillimeter Telescope Experiment



Joint project among NAOJ, Univ. Tokyo, Nagoya, Osaka Pref. & U. Chile


ASTE at Pampa la Bola (4860m)
Generators & Fuel Tank
Telescope
Satellite
Communication
Shell
Storage etc.
Operation Room

Inside view of observing room

Dining room

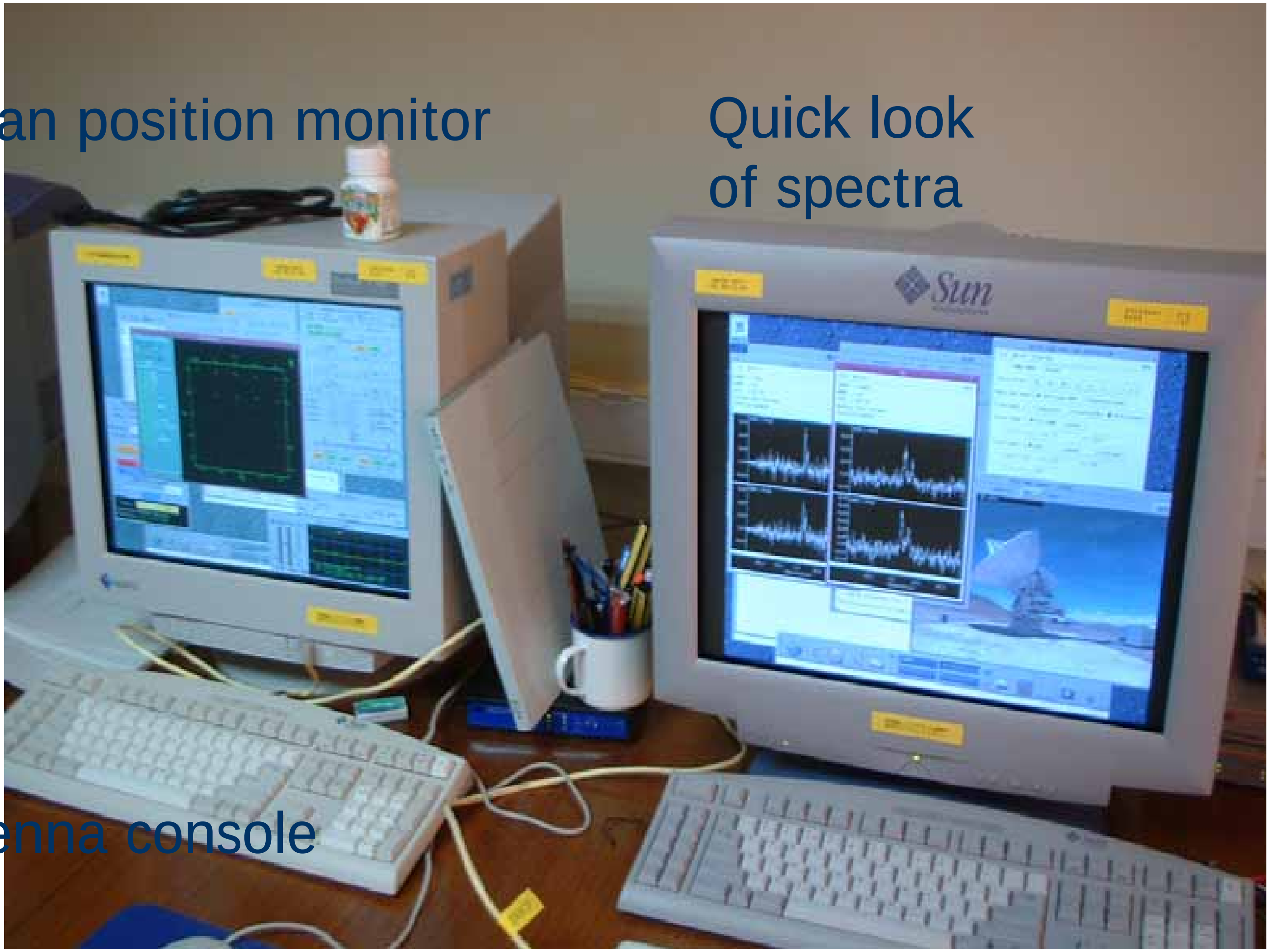
- Air conditioner
- O_2 enrichment system
- With *tatami* mats

Feel at home !

Power generators & fuel tanks

200 kW,15000 litters×2

Remote observations from San Pedro de Atacama



Scan position monitor

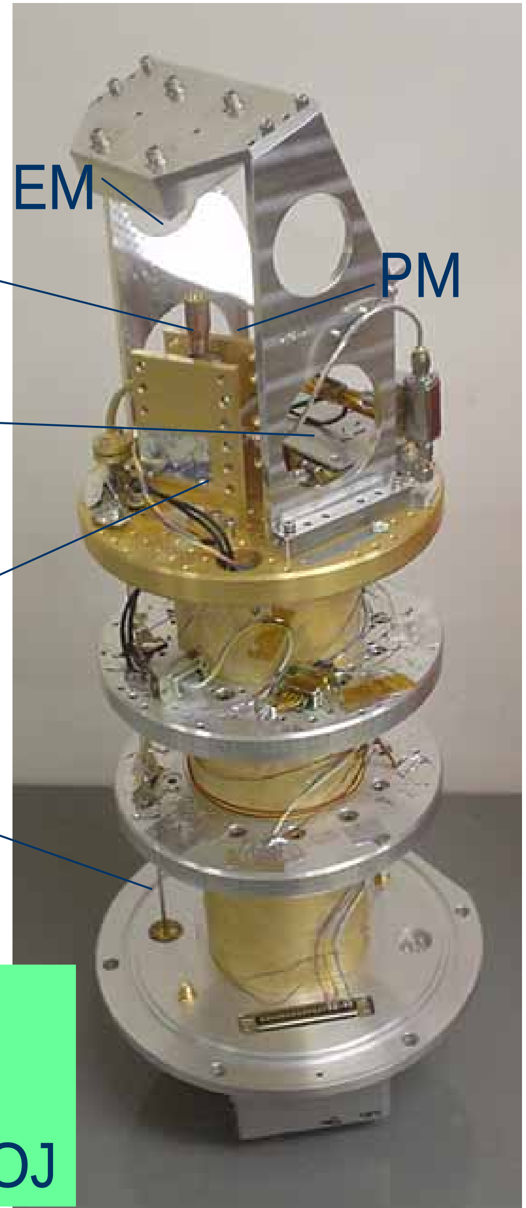
Quick look of spectra

Remote camera

Antenna console

Installation of dewar

New 345 GHz RX (Since Sep.2004)

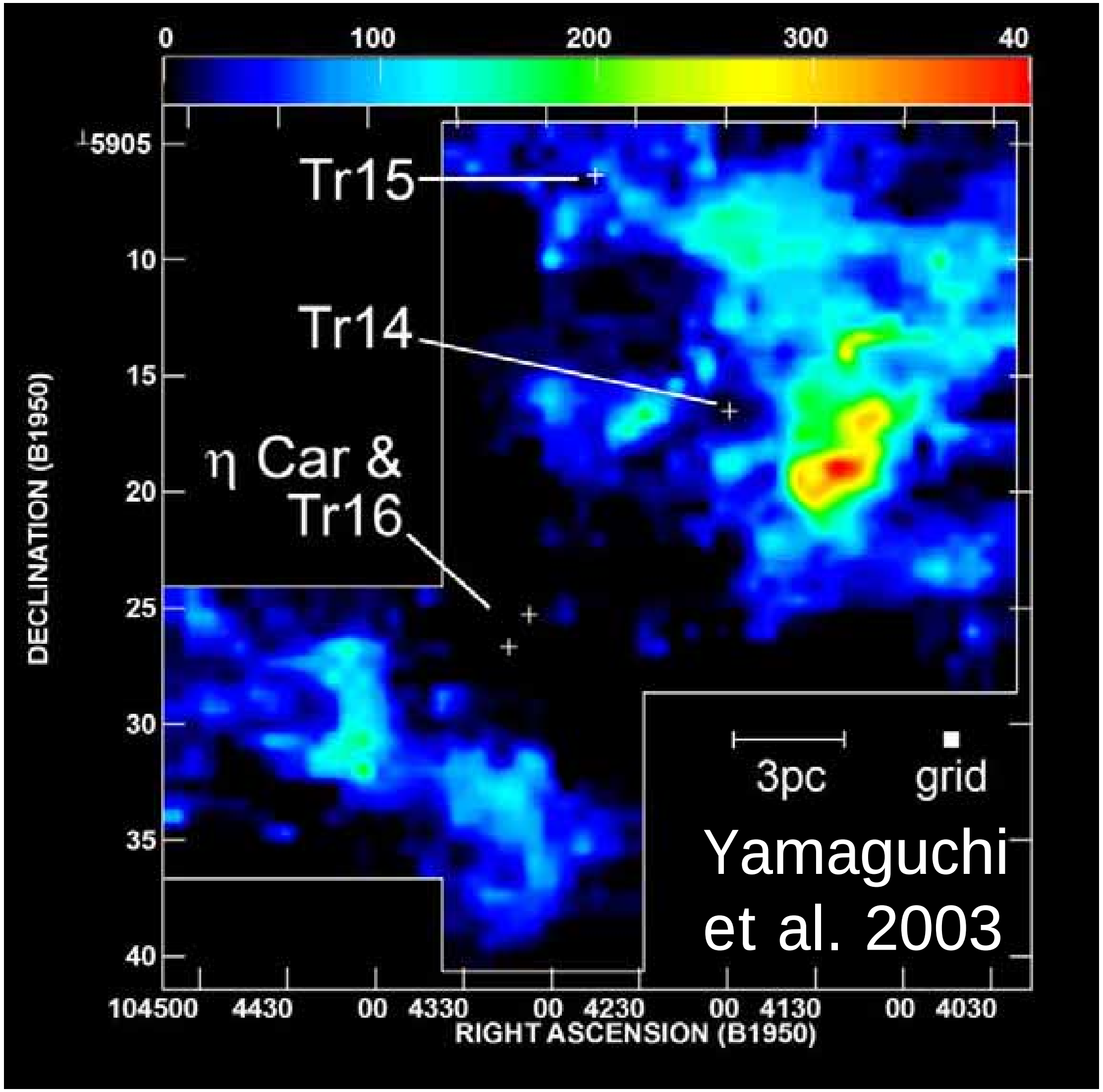


Univ. of Tokyo
Osaka Pref. Univ
Nagoya Univ. & NAOJ

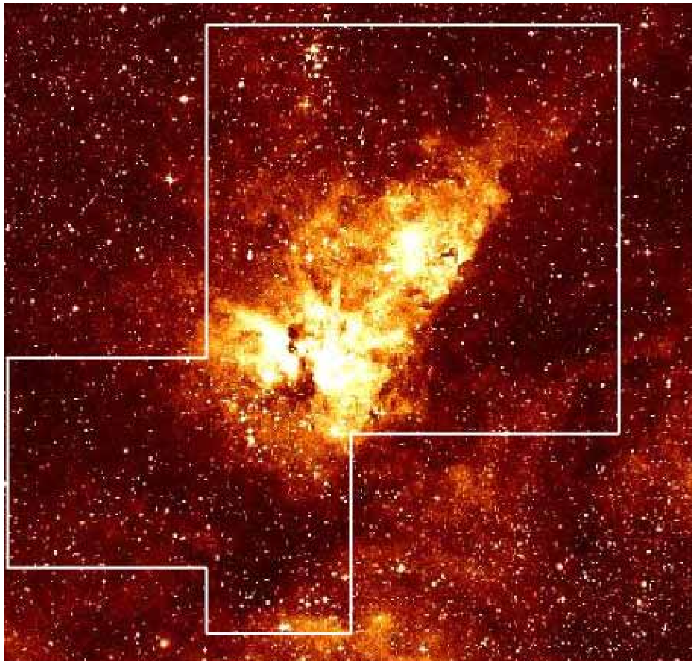
- Cartridge type
- Cool optics
- IF frequency: 4 – 8 GHz, DSB
- T(RX) ~ 100 K or 6 times quantum noise limit ($h\nu/k_B$)
- T(sys) < 200 K !!! in DSB, when $\tau_{220} \sim 0.03$

Muraoka 2005
Master thesis

Carina nebula CO(J=3-2)



- (left) More than 3000 spectra were obtained. (bottom) Optical image of Carina nebula. Mapped area with ASTE is indicated.



Summary

- NMA/RAINBOW 3D imaging survey of CO(1-0), HCN(1-0), and HCO+(1-0) in nearby Seyfert & starburst galaxies.
- HCN/HCO+ & HCN/CO ratios could be a new diagnostic of power source in dusty active galaxies.
  - HCN is enhanced in X-ray dominated region (XDR)
  - HCO+ is enhanced due to shocks of SNe
  - Mostly consistent with other diagnostic (3.3 μm PAH)
- Application of this method (w/ high-J HCN/HCO+ lines) to high-z dusty galaxies (ULIRGs, submm galaxies, etc.) using ALMA is promising
- A dense molecular gas survey plan using Atacama Submillimeter Telescope Experiment (ASTE)