Imaging the Galactic Center:
The Submillimeter Array

ALMA Coming
(AgrandMA)

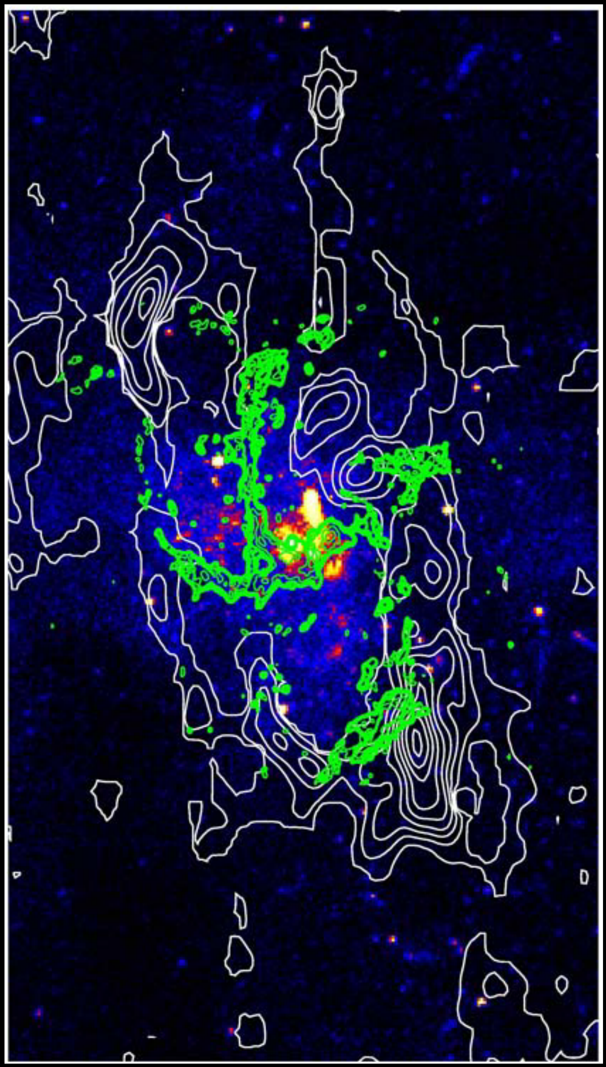
SOFIA 06.07.2010

Paul Ho, SAO/ASIAA

Outline

- Nearest Example of SMBH: SgrA*
- Circumnuclear Disk (CND)
- The Submillimeter Array
- Images of Galactic Center Region
- Future in this Field

SOFIA DRMCS: CND at Galactic Center



Morris, Erickson, Chuss, Stacey, Staguhn (2008)

Instruments: EXES, FORCAST, FIFI-LS, GREAT, CASMIR, HAWC

Region: 4pc x 2pc

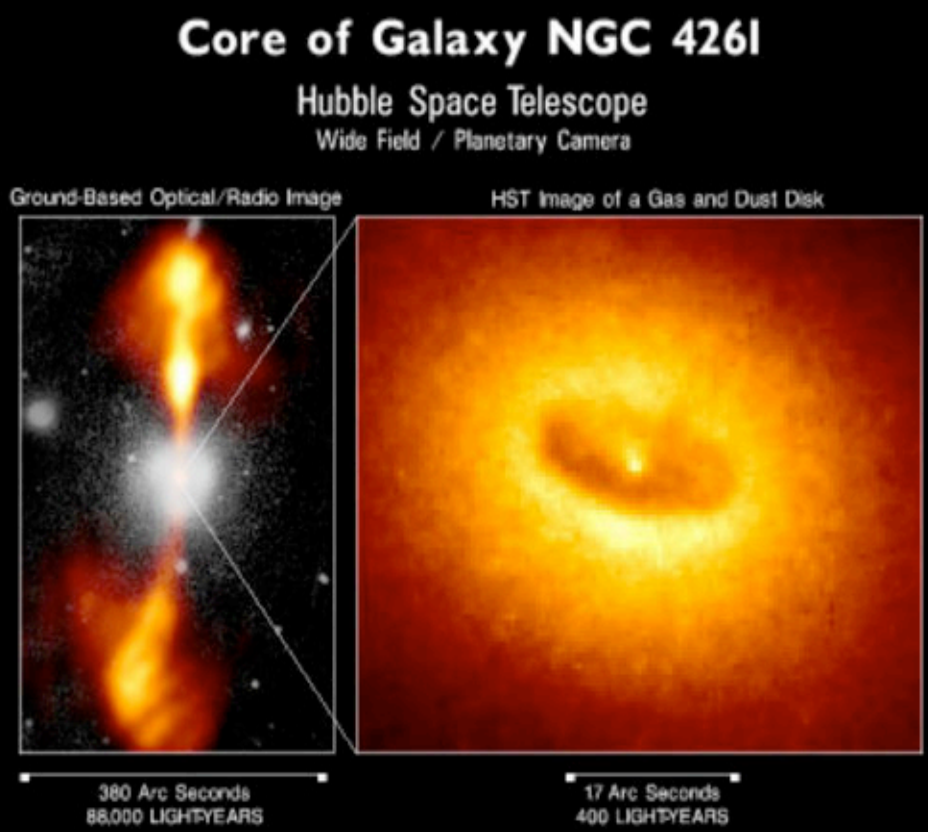
white contours: HCN (Christopher et al. 2005)

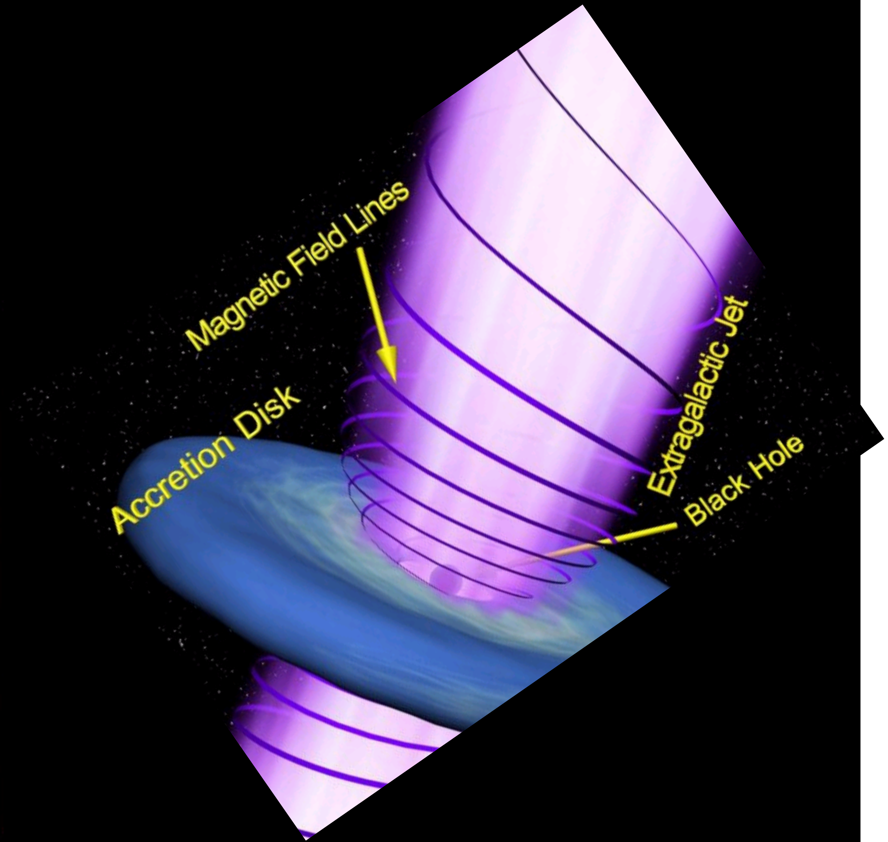
green conttours: 6cm continuum

Color: 2-8 kev X-ray

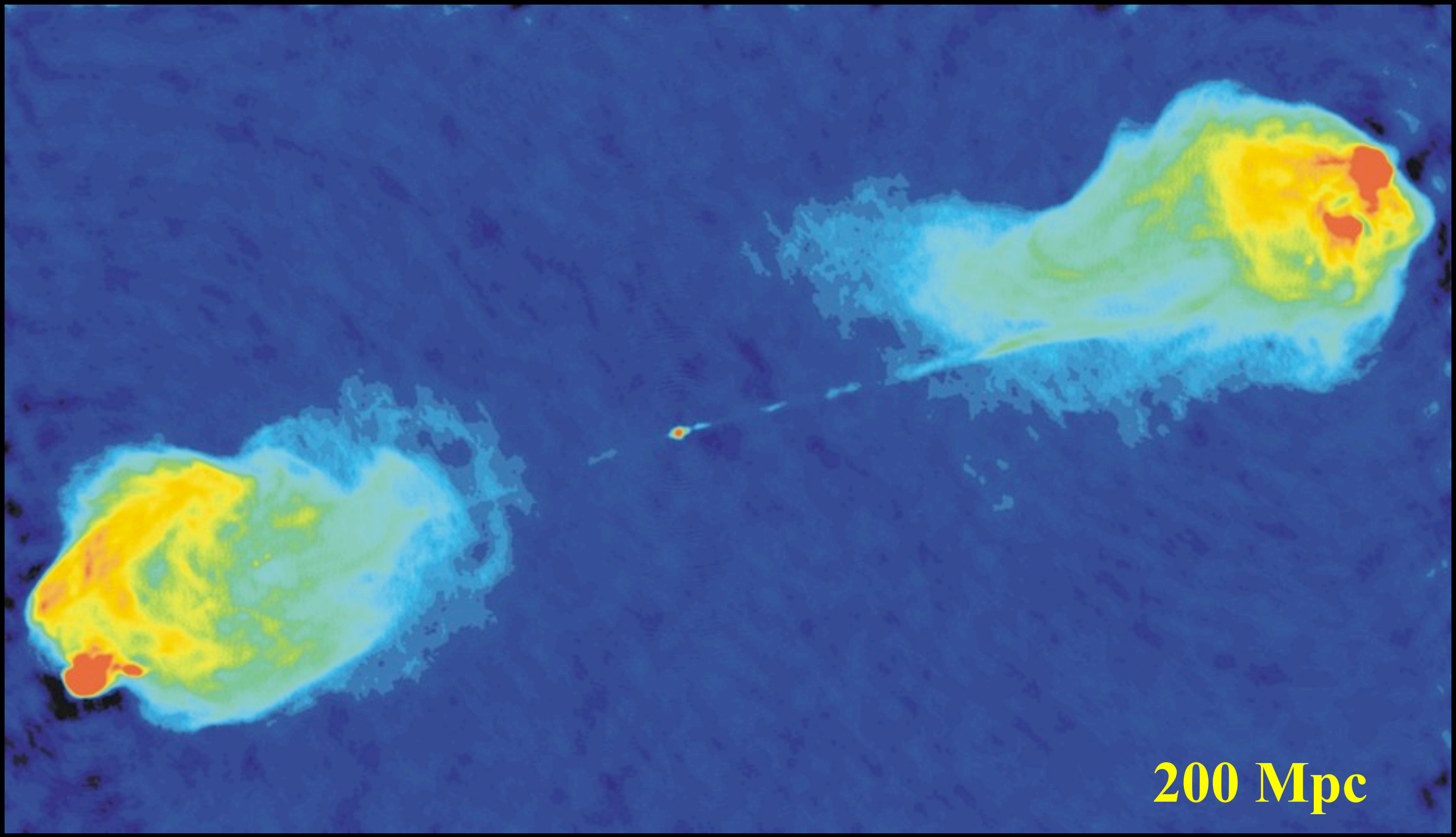
IMAGING Problem from 35 years ago!

Science Driver: Black Hole + Accretion Disk



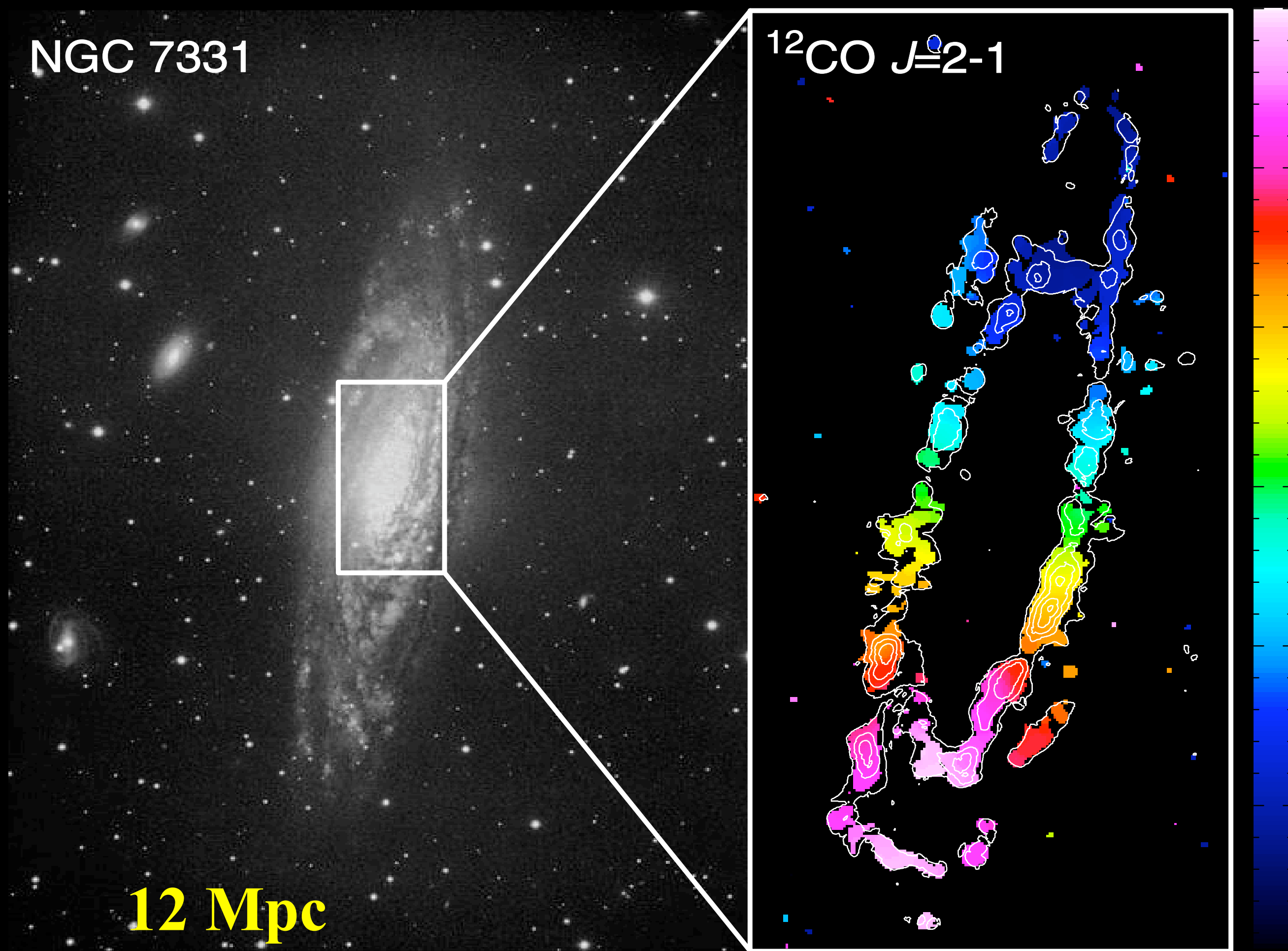


Radio Galaxy: Cygnus A



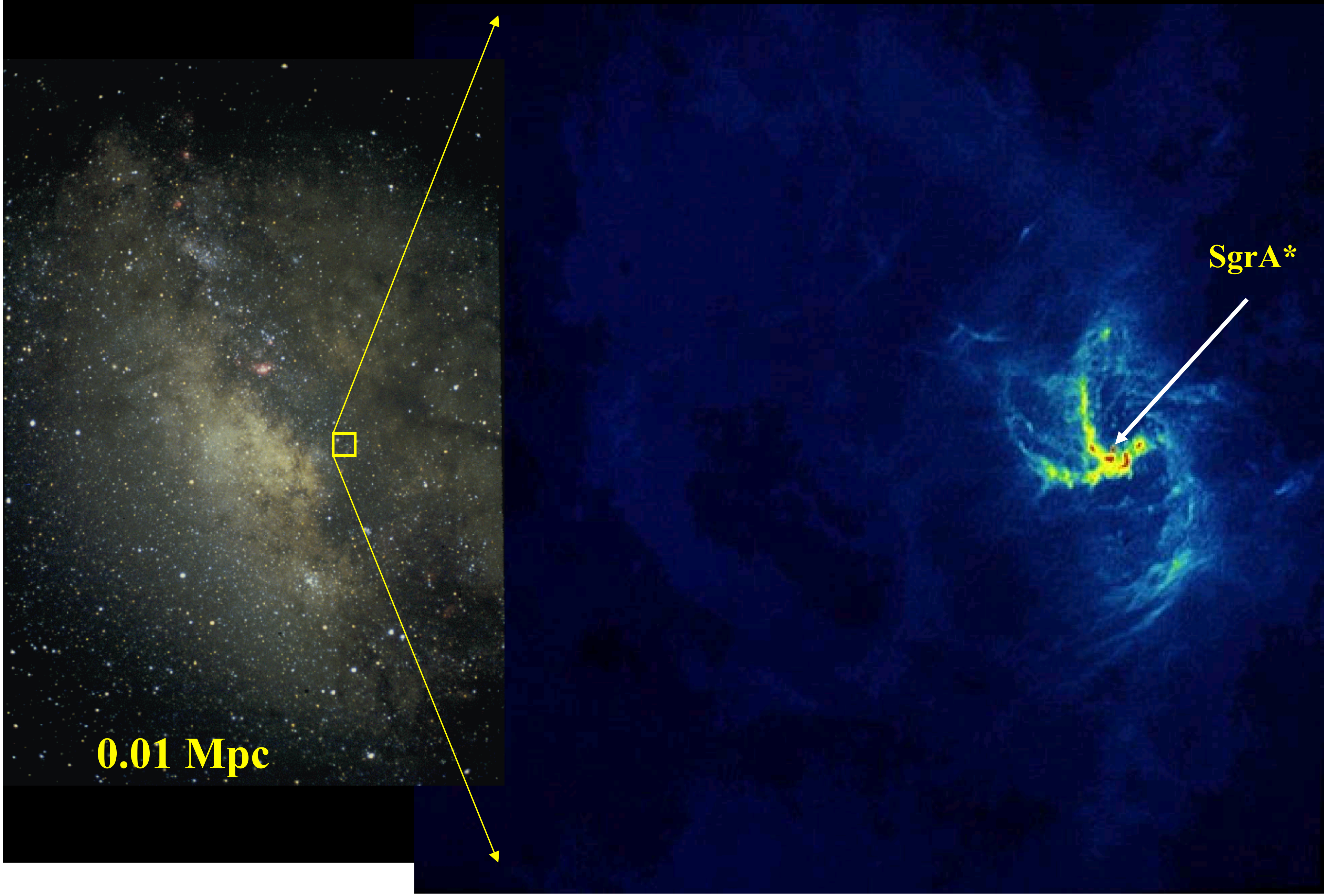
A Central Black Hole is ejecting Powerful Jets

Milky Way "Twin" NGC 7331

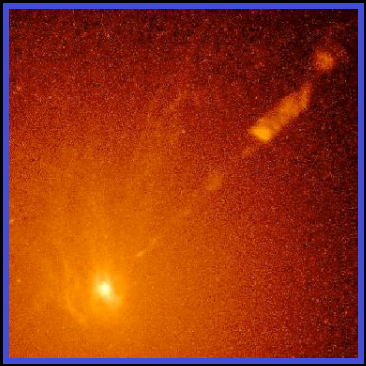


Petitpas *et al.* 2008

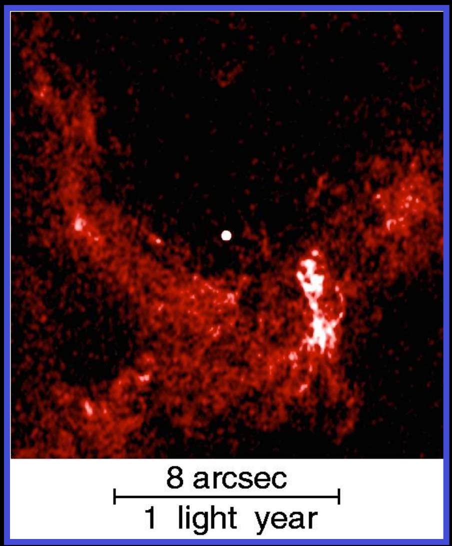
Center of the Milky Way



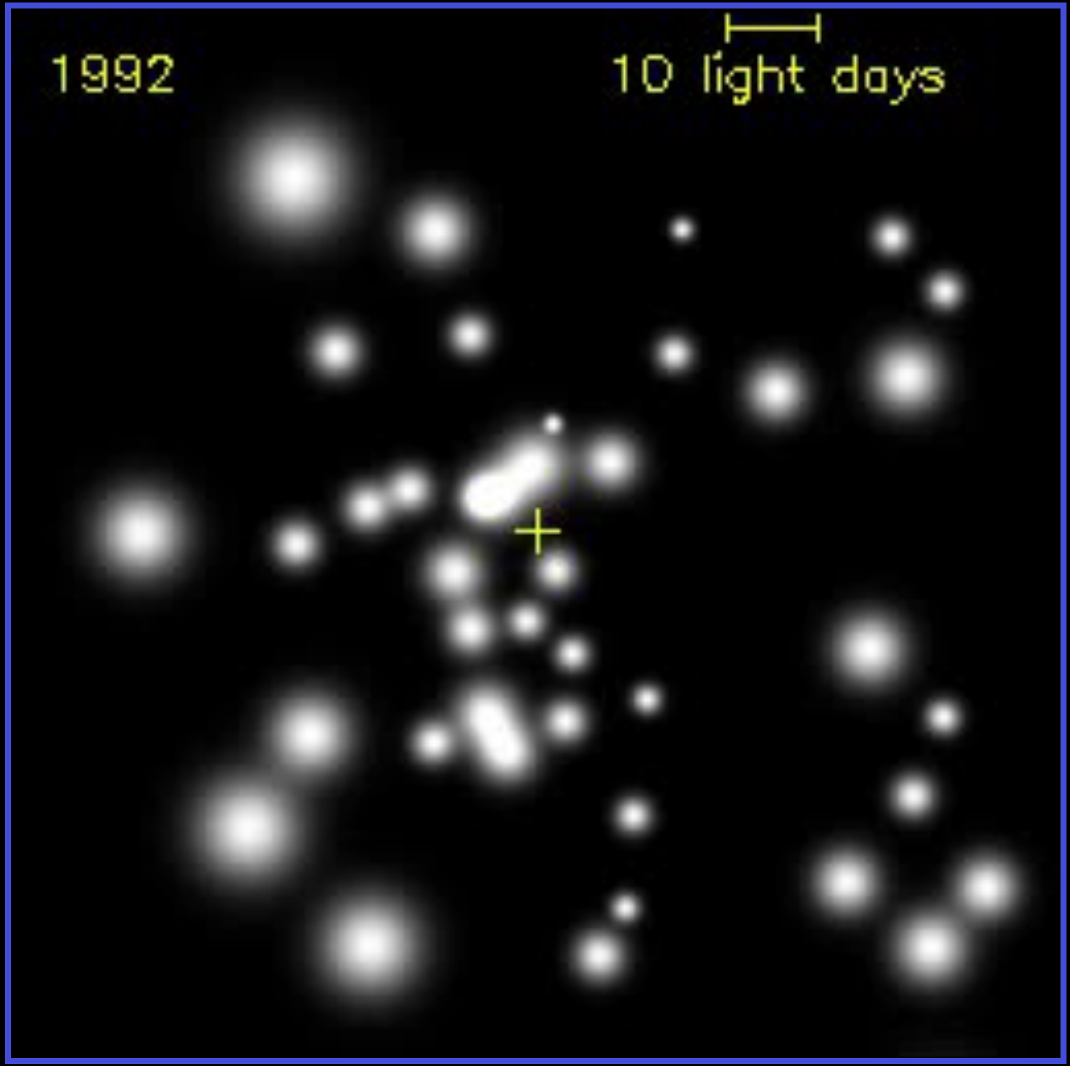
Dynamical Evidence of SMBH



M87 Jet



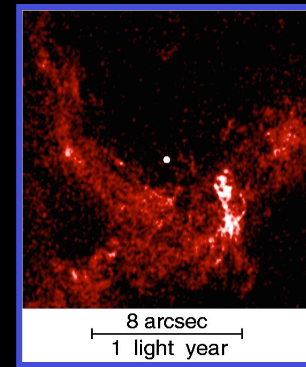
Sgr A* SMBH



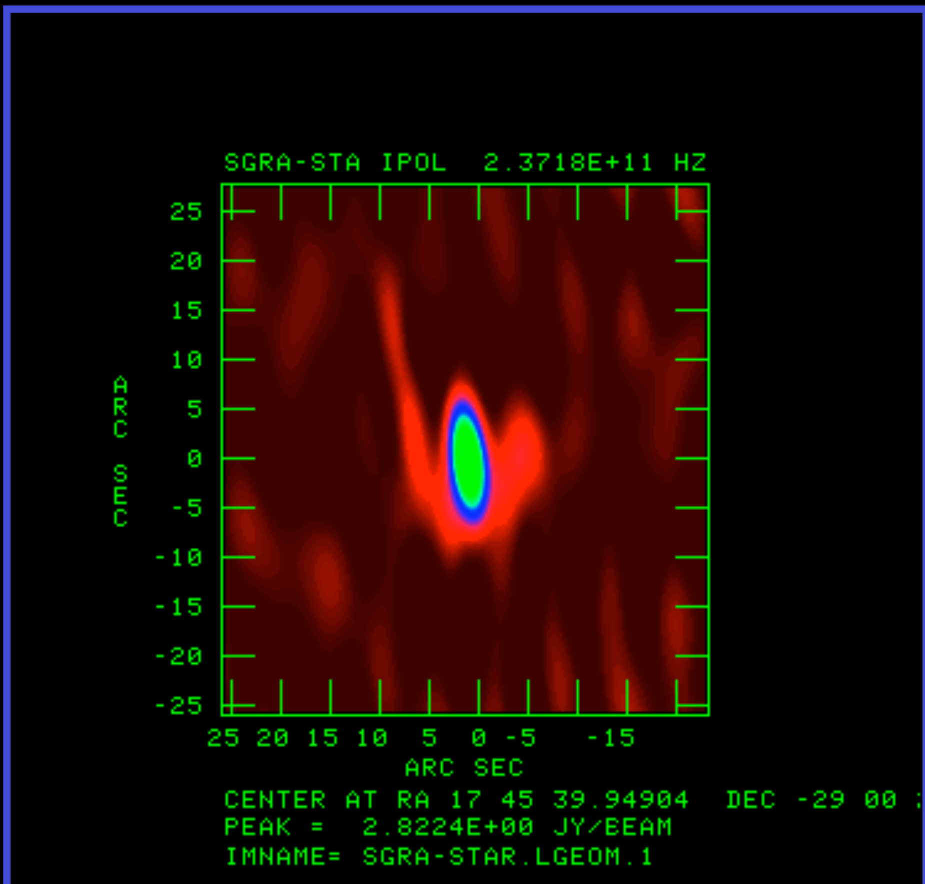
Summary Simulation from MPE Group

Galactic Center

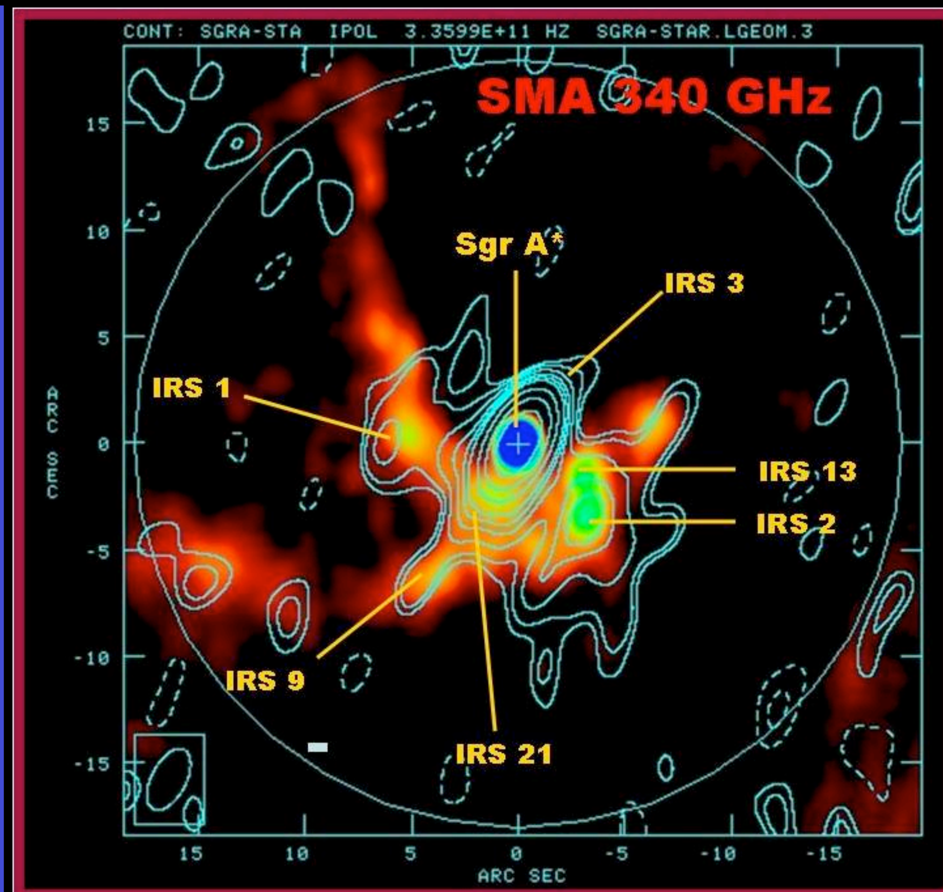
SgrA* Dominates, Dust Emission?



1mm



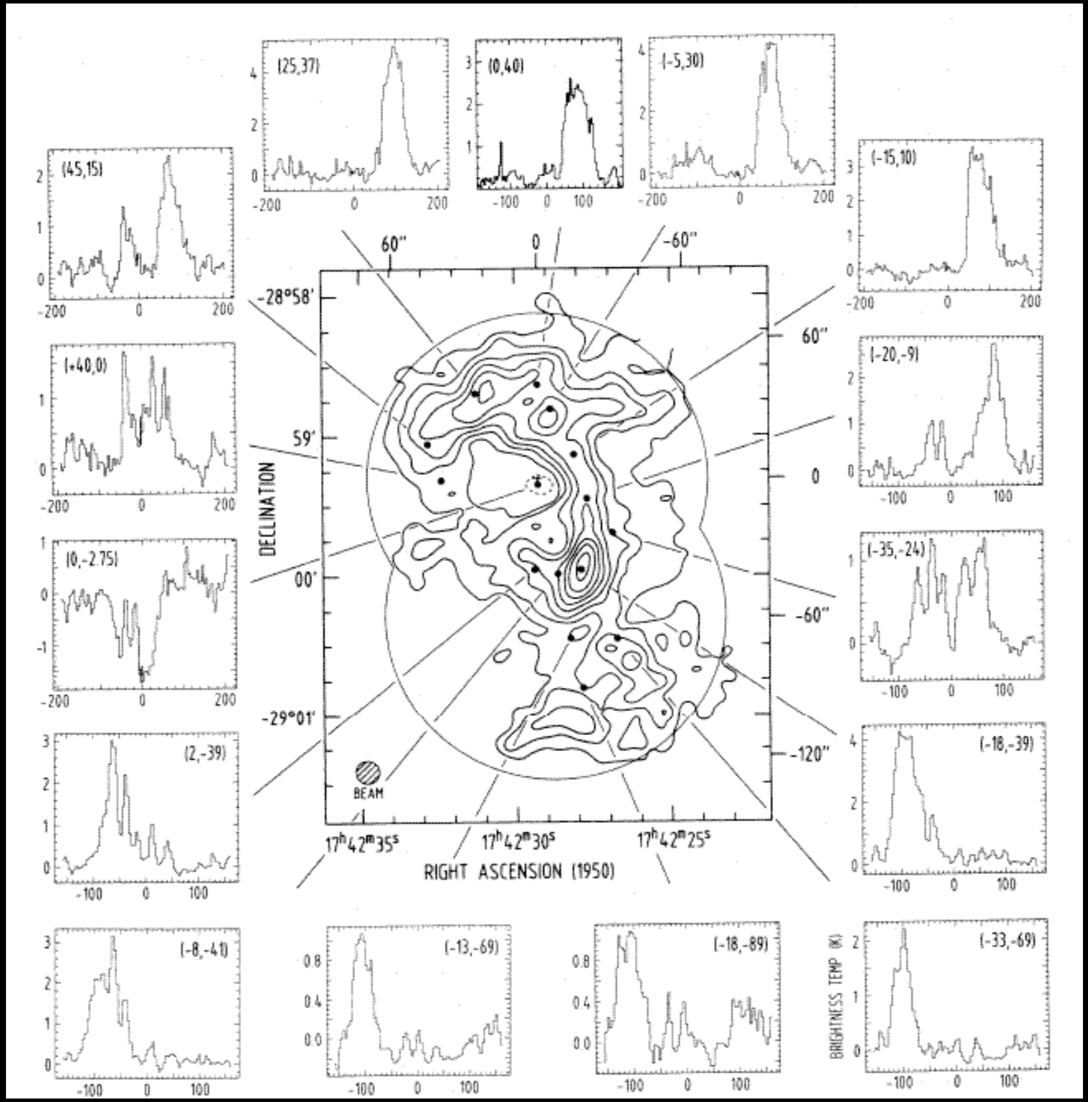
0.8mm



J-H Zhao

CND: HCN(1-0) in the Galactic Center

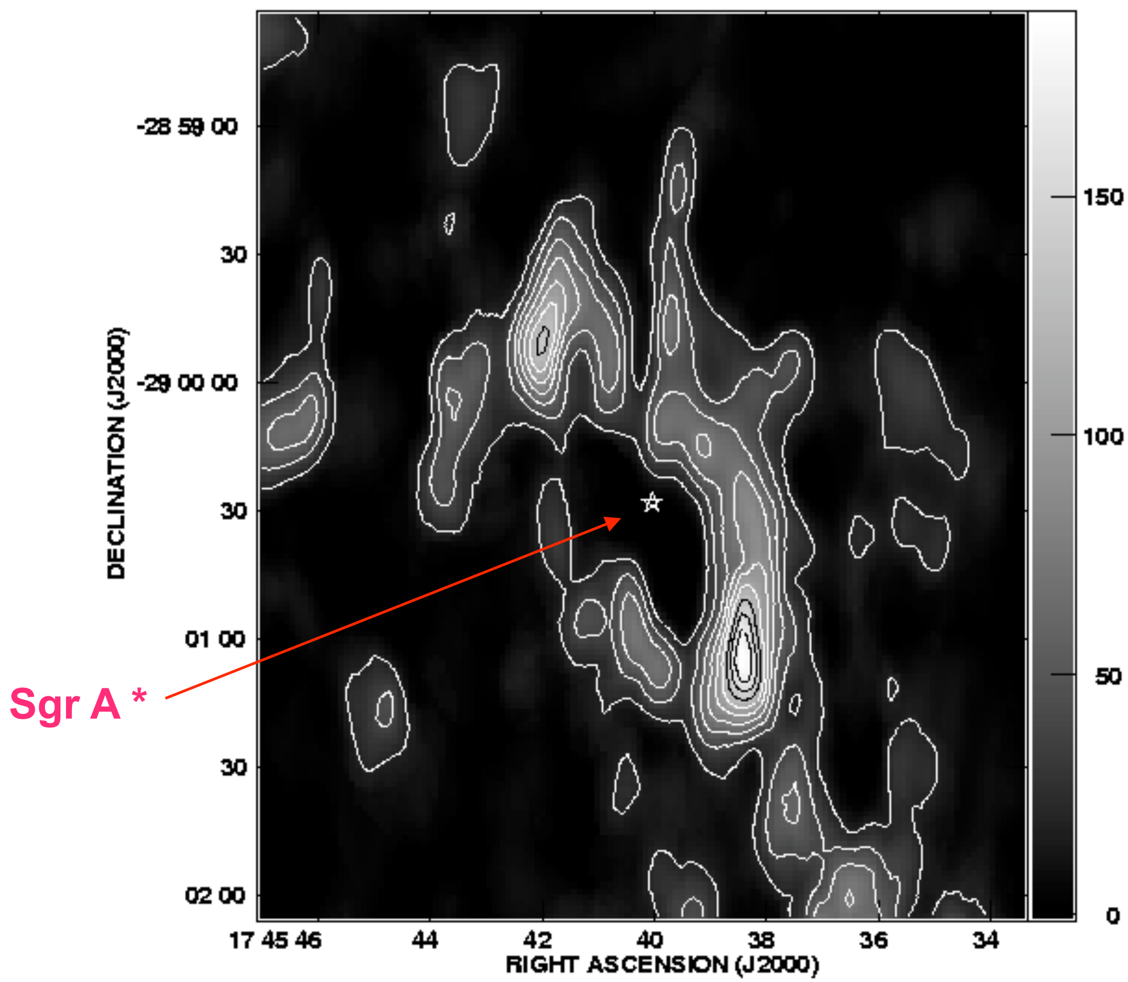
Historical Data: **Hat Creek 11" x 9"**



Güsten et al. 1987, ApJ, 318, 124

HCN(1-0) in Next BIMA Synthesis

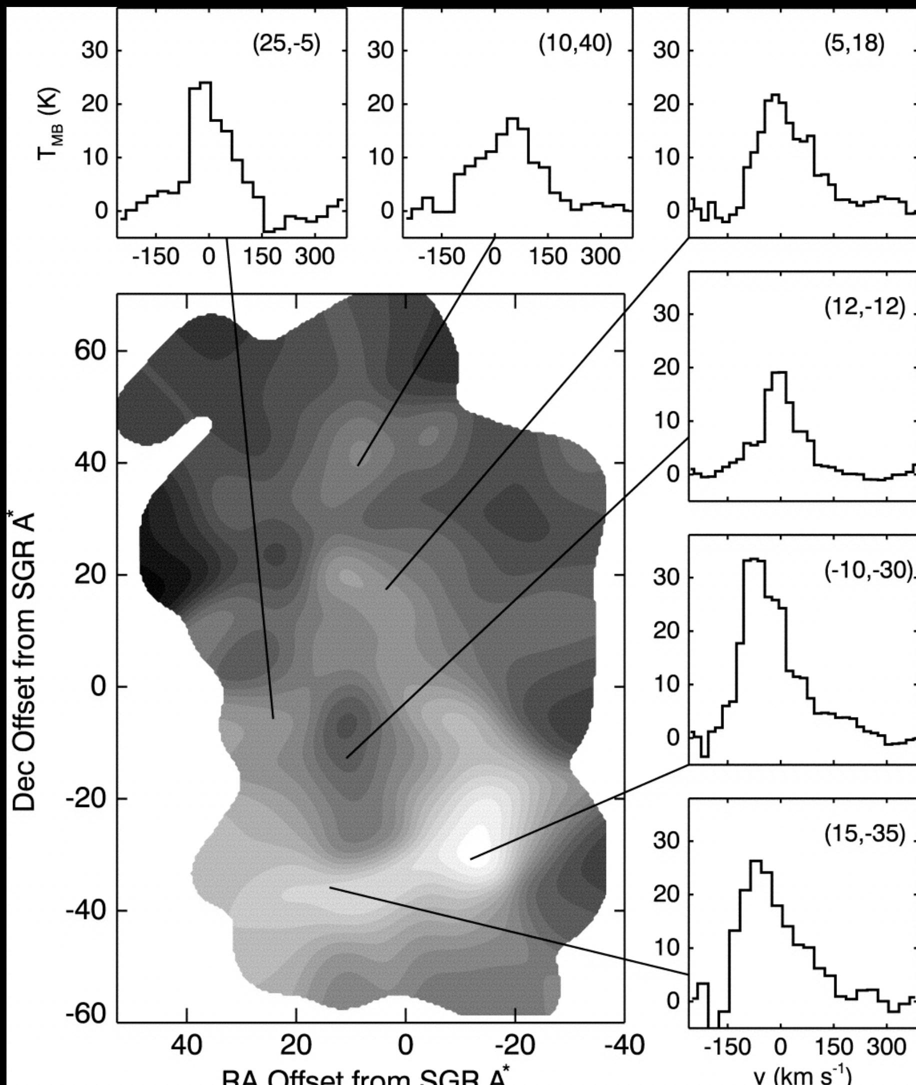
13” x 4”

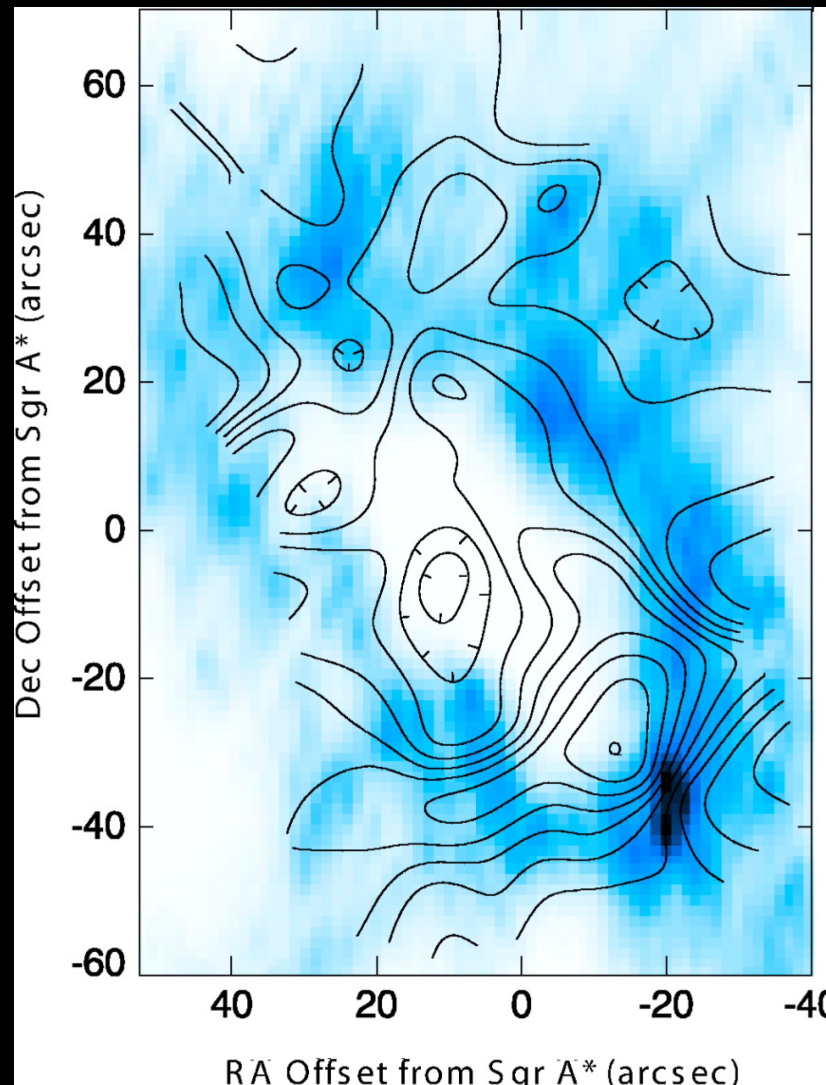


Wright et al. 2001, ApJ, 551, 254

CO (7-6) in the Galactic Center

CSO 11”

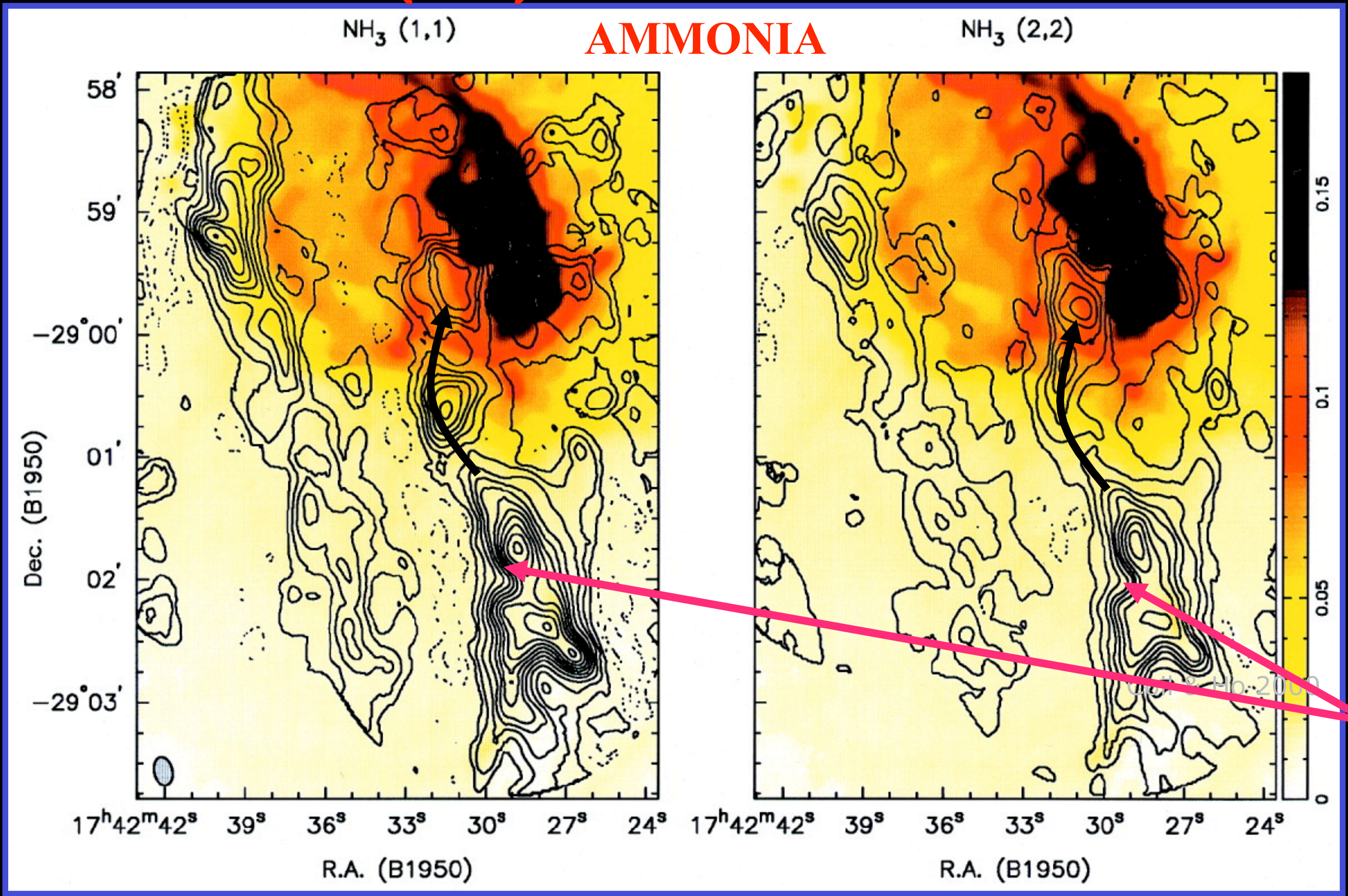




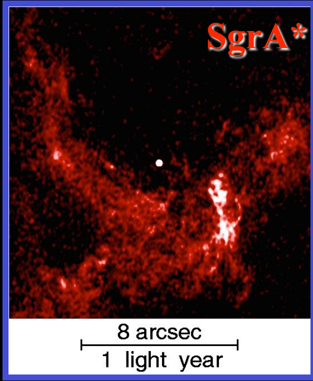
Bradford et al. 2005, ApJ. 623, 866

NH_3 Imaging of SgrA*/GC CND

Coil and Ho (1999)   VLA 14" x 9"



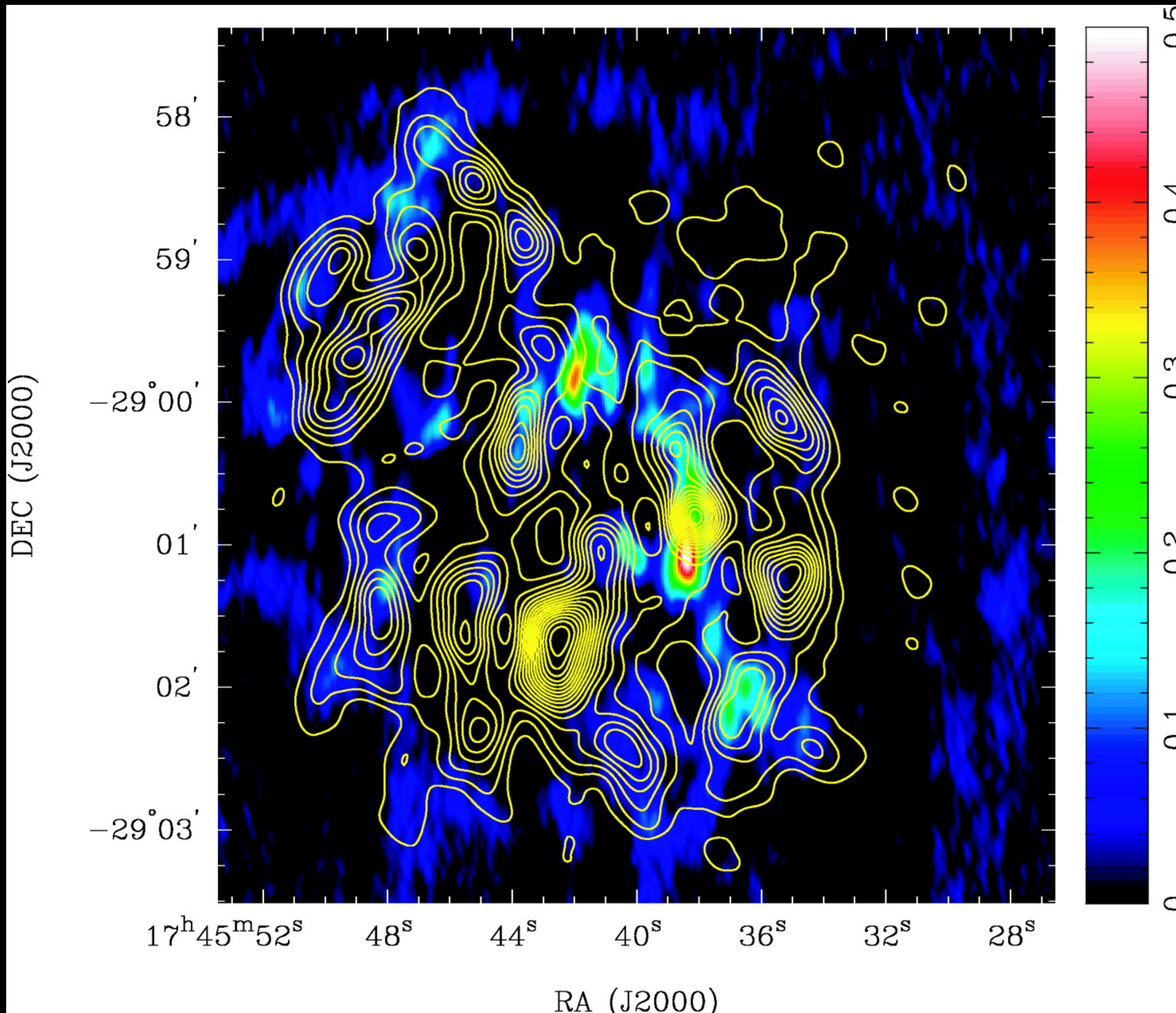
20 km/s cloud



Possible infall of gas from the 20 km/s GMC to the CND via the "southern streamer"

TRACING the DENSE ISM

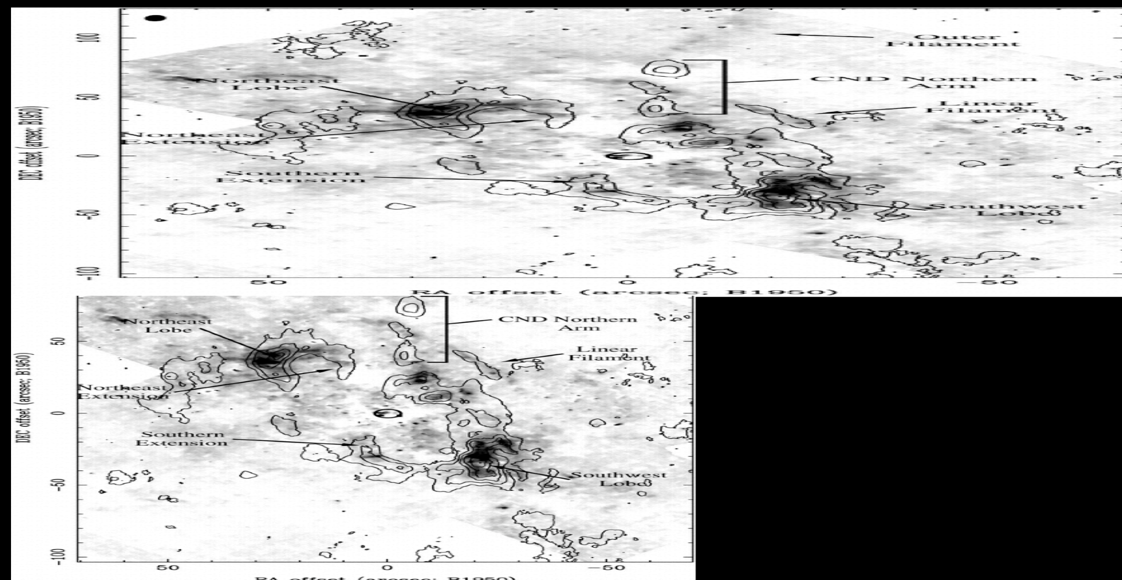
VLA NH_3 (3,3) and BIMA HCN (1-0)



McGary, Coil, and Ho, 2001, ApJ, 559, 326

More HCN(1-0) Imaging of GC CND

OVRO 5.1" x 2.7"



Is it a Disk?

Ring?

Streamers?

Sgr A*

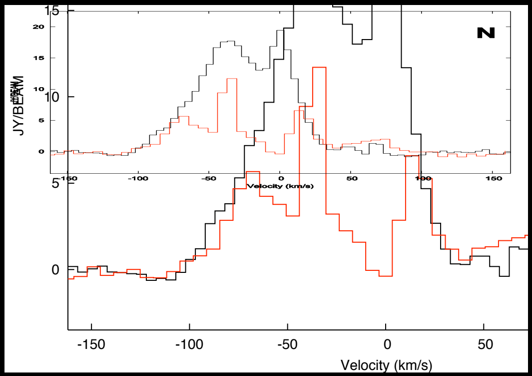
Contours: HCN(1-0) (Christopher et al., 2005, ApJ, 622, 346).

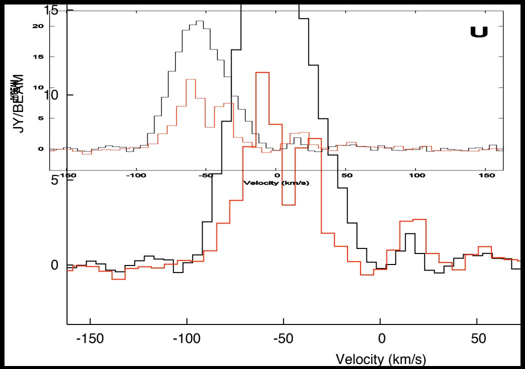
Greys: H_2(1-0) (Yusef-Zadeh et al., 2001, ApJ, 560, 749).

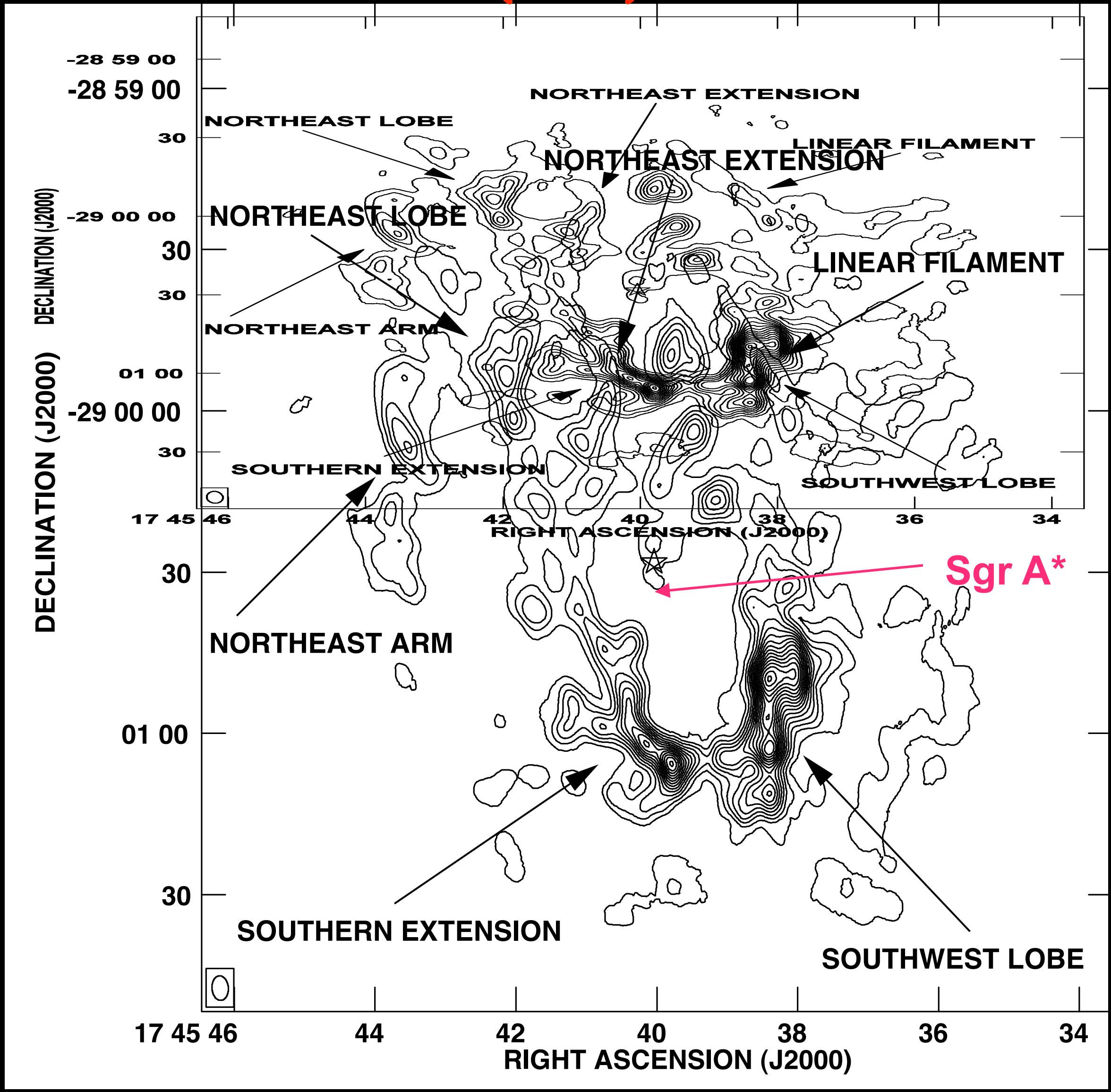
New HCN(4-3) Imaging of GC CND

Montero and Ho (2009) 4.6" x 3.1"

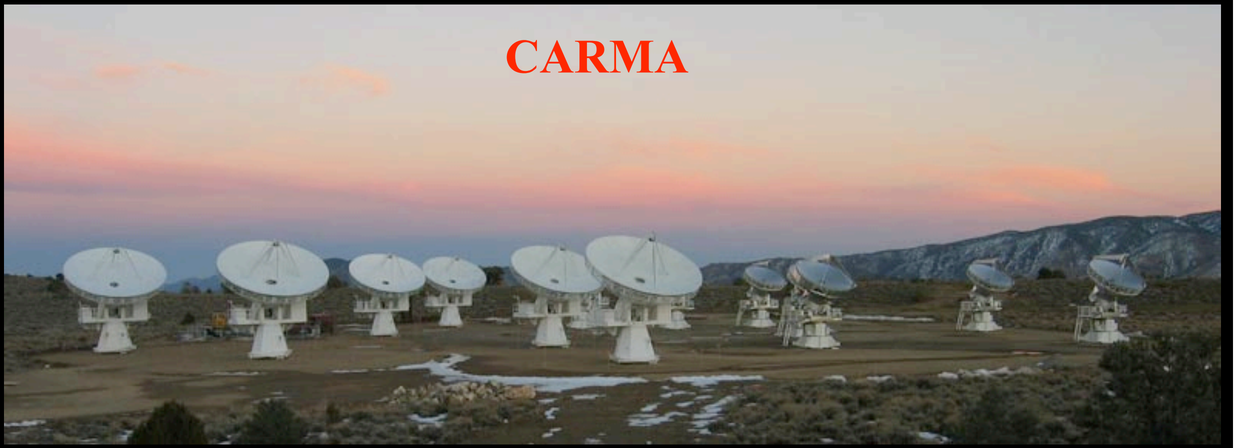
SMA: HCN(4-3)



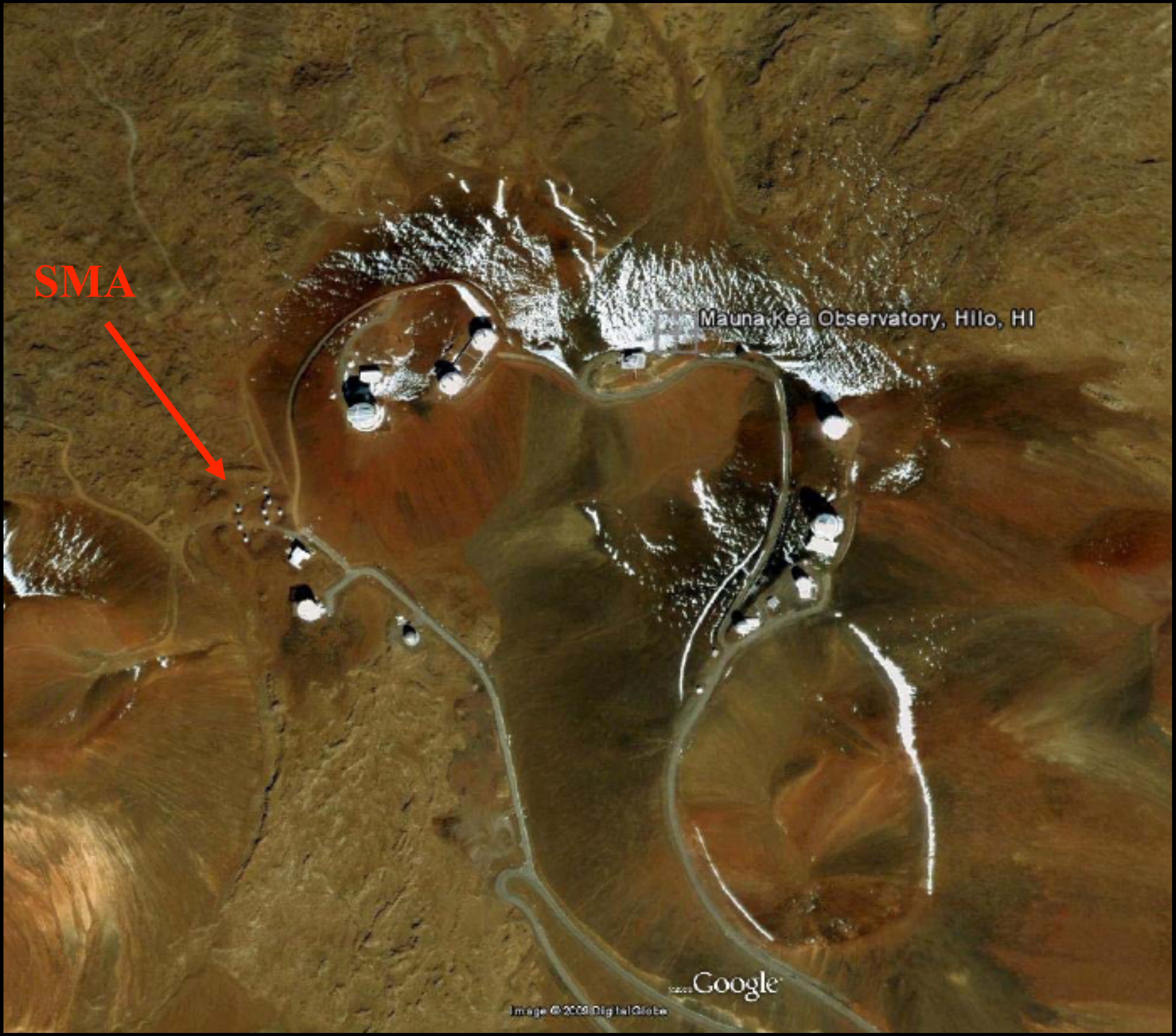




mm and submm Interferometers
>30 Years of development



Top of Mauna Kea



Submillimeter Telescopes

SubMillimeter Array

1984: Proposal to Smithsonian Institution
1987: Submillimeter Receiver Lab Funded
1989: Design Study Funded
1991: Construction Money Funding 6 Elements
1996: ASIAA Joins Project by Adding 2 Elements
1998: First Fringes at Westford with 2 Prototypes
1999: First Fringes on Mauna Kea
2003: All 8 Elements Deployed; Array Completed

Why Submillimeter?

- **Universe is Cold: CMB (3K); ISM (~10K)**
- **10 K Energy Peak @ FIR (100 μm)**
  submm (300-1000 μm) from the ground
- **ISM/dust is optically opaque**
  submm can penetrate the dust
- **Existence of Abundant Molecules**
  submm has many spectroscopic tools
- **Universe is Expanding**
  submm sees the Redshifted Distant Universe

Moving to SubMillimeter

Mauna Kea: 4000m

Dust: $S_\nu \propto \nu^4$

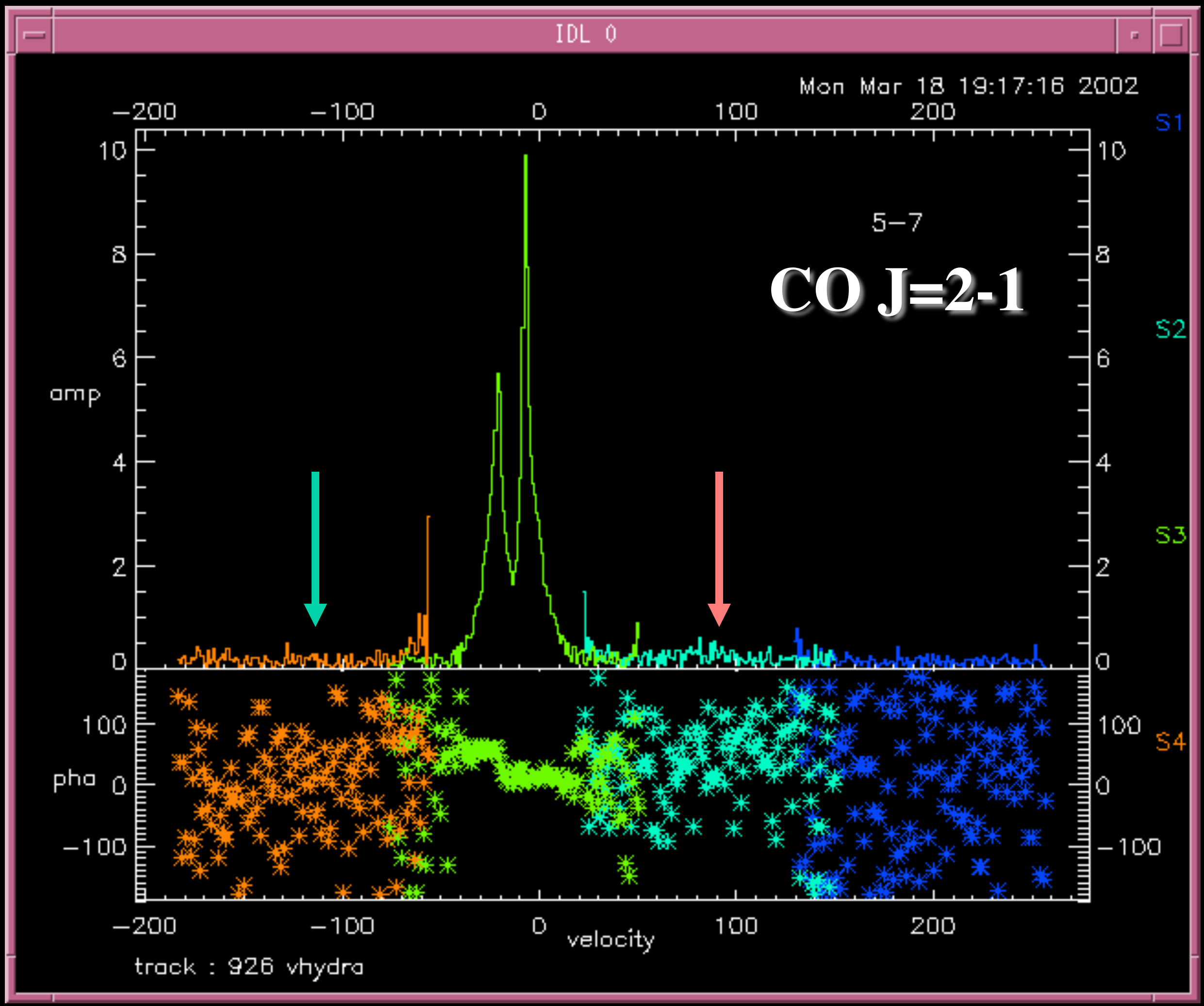
For ν^2 Dust Emissivity
Rayleigh-Jeans Limit for
Blackbody Radiation

Spectral Lines: $S \propto \nu^5$

For Optically Thin Lines
Einstein $A \propto \nu^3$
Integrated Line Intensity

Spectroscopy & Interferometry

CO J=2-1 emission from V Hya

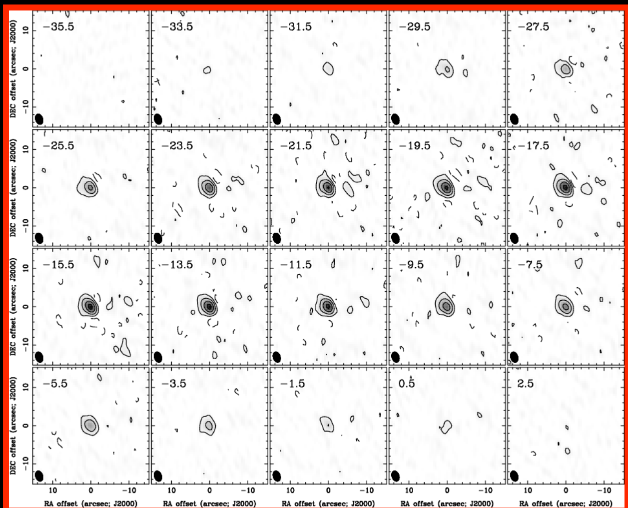


PHASE COHERENCE

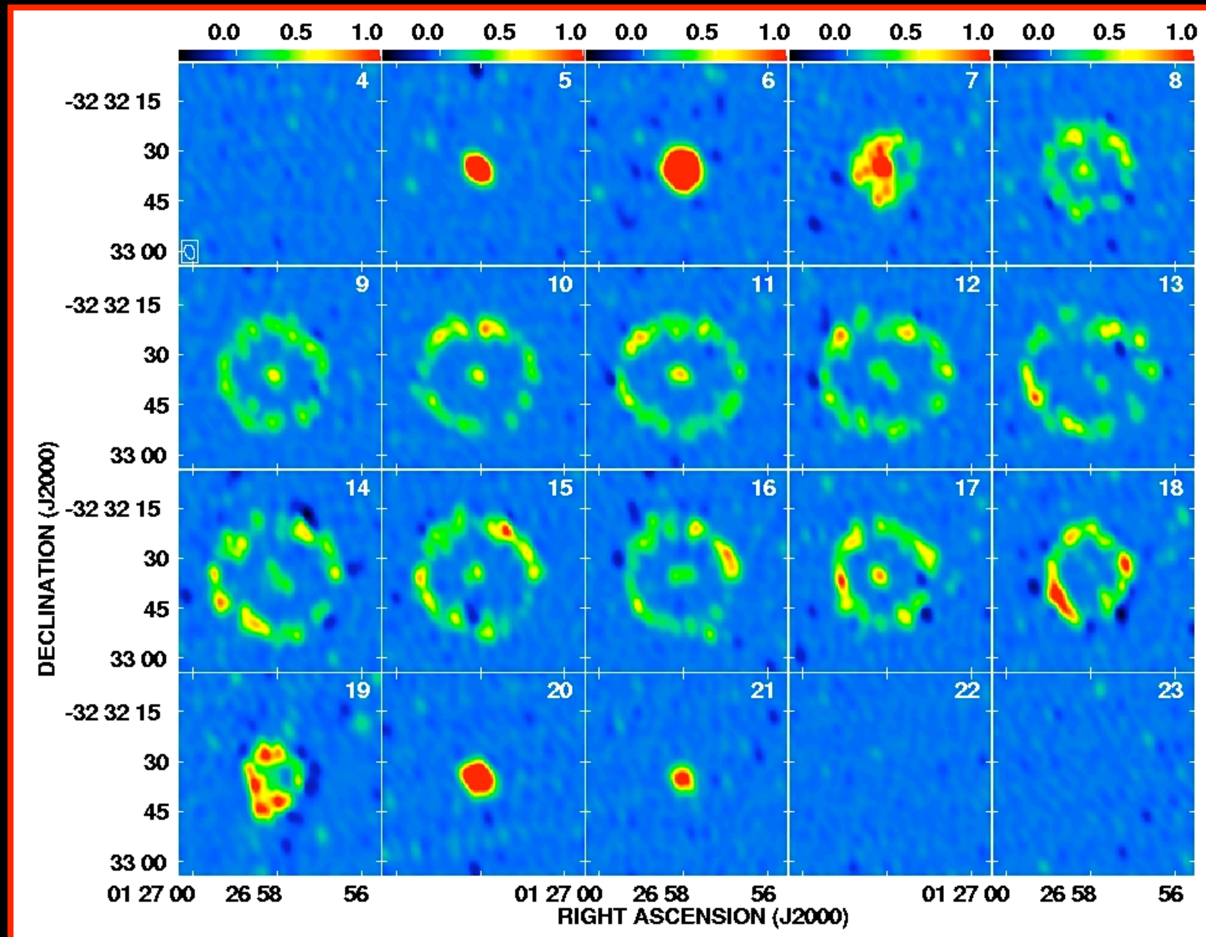
even when AMPLITUDES are WEAK

IMAGING : R Sculptoris

ATCA: HCN J=1-0



SMA: CO J=2-1

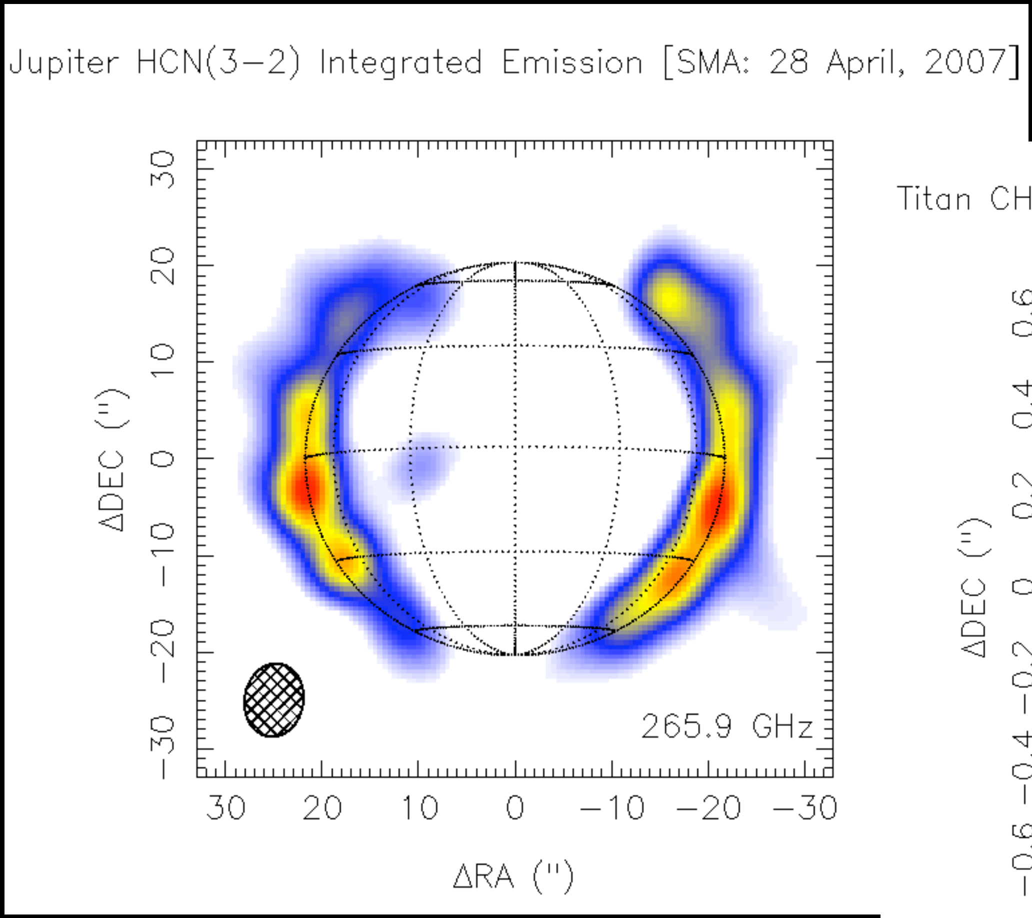


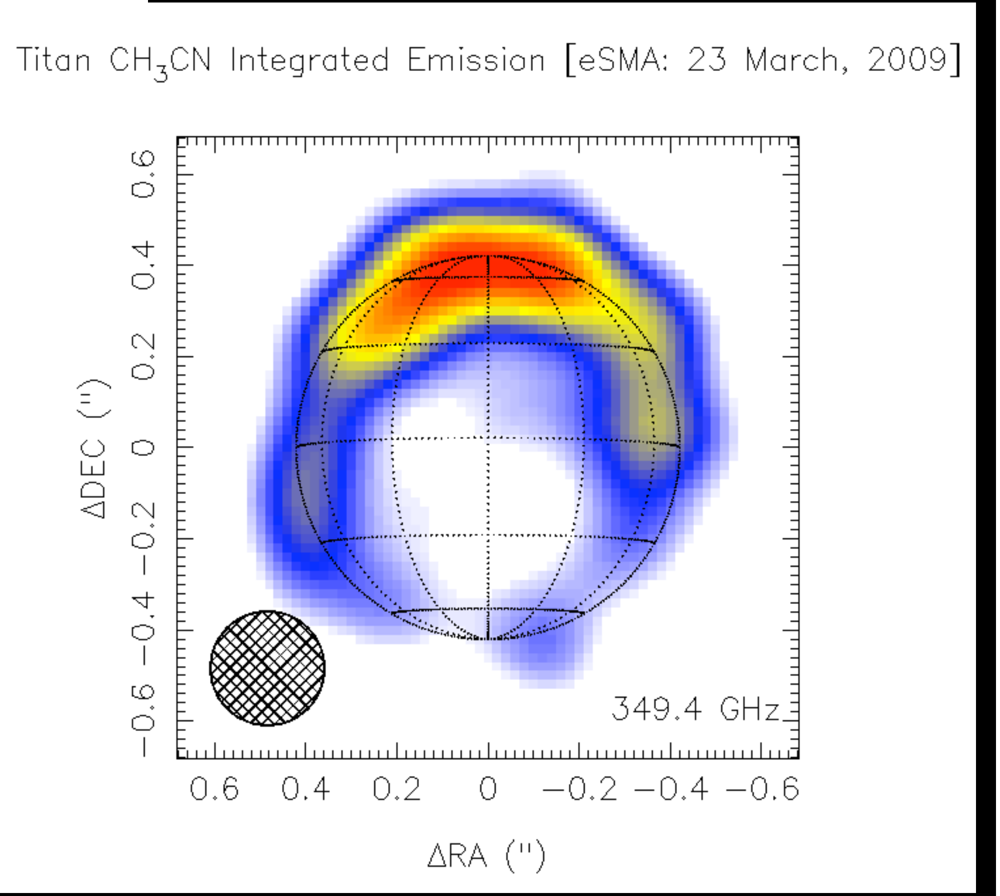
Detached Spherical CO Shell around an AGB Star + a Core

D.V. Trung

Field of View/Resolution

images courtesy Mark Gurwell





30 arcsec

0.3 arcsec

Field of View/Angular Resolution

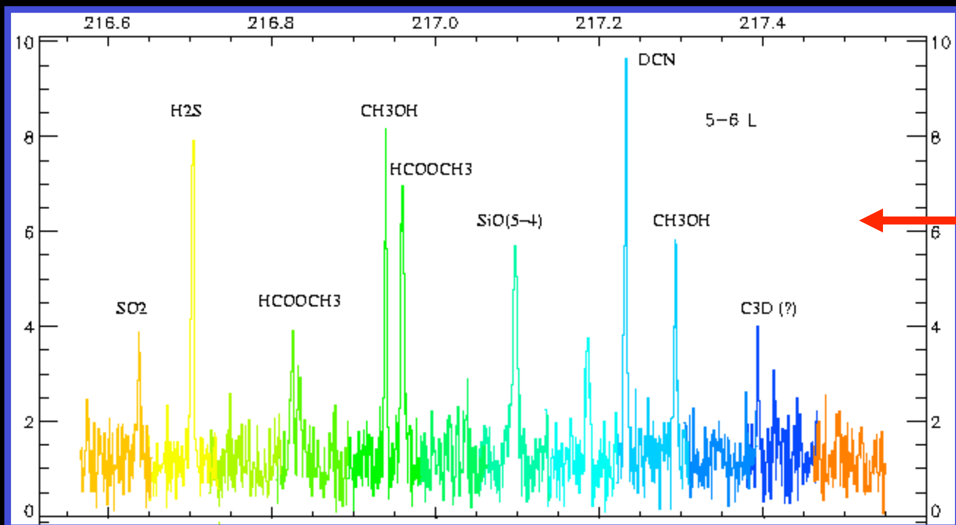
Frequency (GHz)	Primary Beam FWHM	Spatial Resolution		
		Compact Array	Extended Array	Very Ext. Array
230	~52"	~3"	~1"	~0.4"
345	~35"	~2"	~0.7"	~0.3"
690	~17"	~1"	~0.35"	~0.15"

(CSO: 3 beams; JCMT: 6 beams)

>0.1M pixels, >12000 synthesized beams per pointing

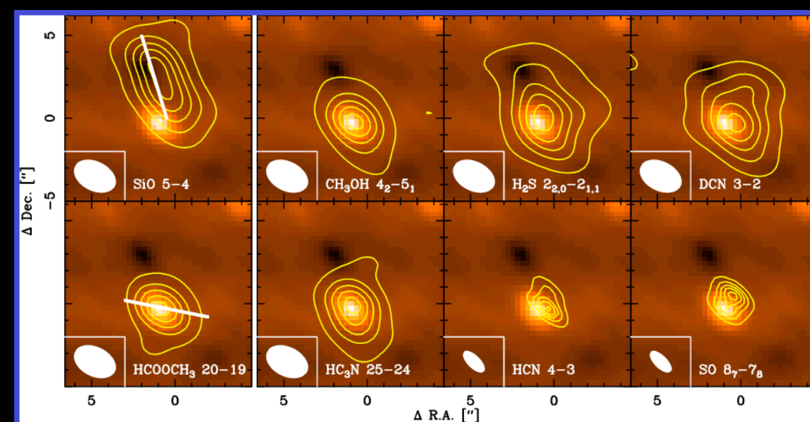
Do See Many Lines

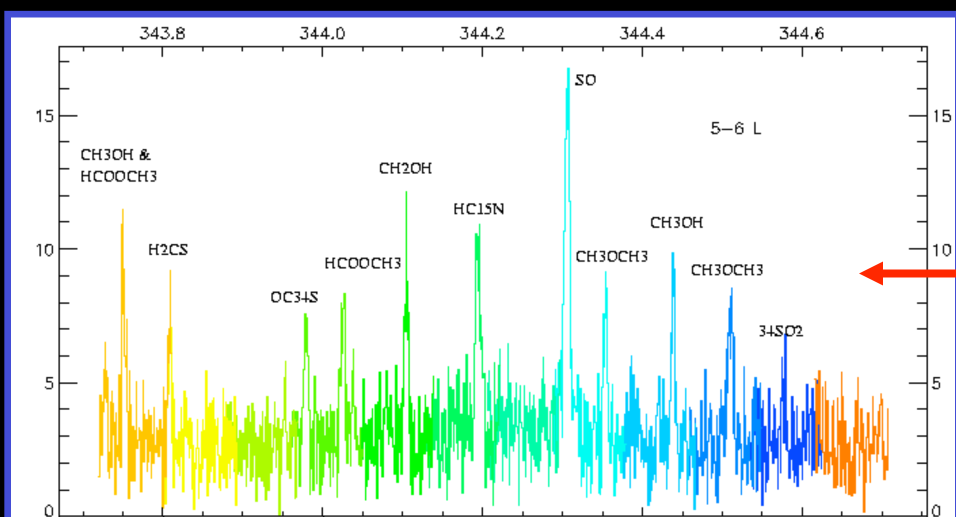
Submm Line Forest as Expected: Higher Einstein A



1 GHz bandwidth

1mm band





0.8mm band

H. Beuther

IRAS18089-1732

Spectral Coverage and Resolution

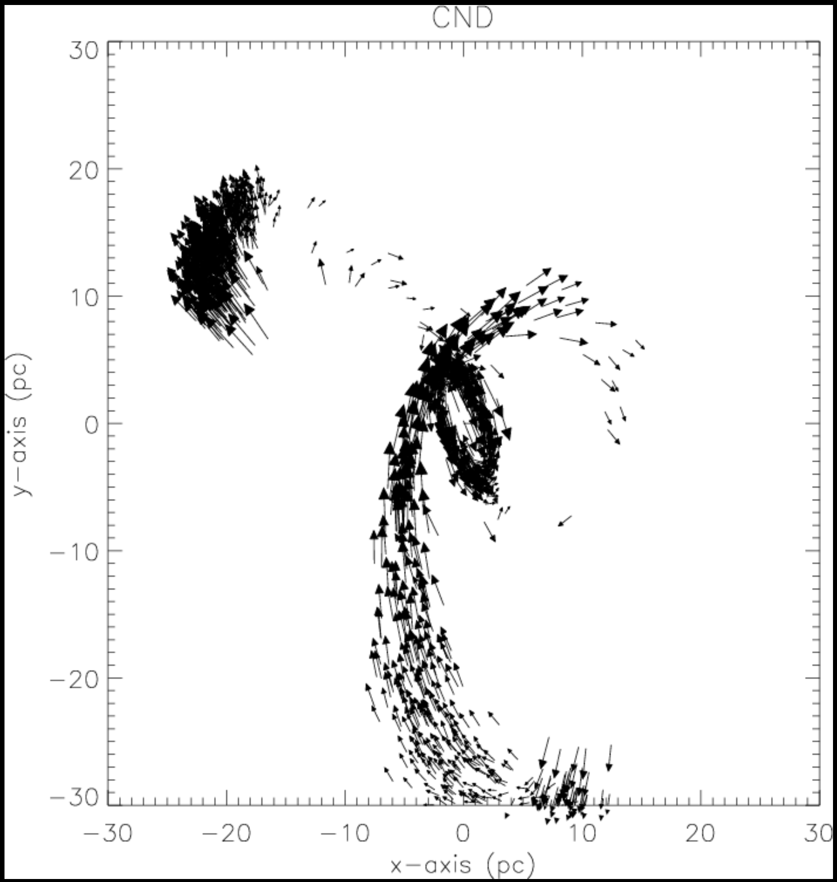
Bandwidth		Velocity Resolution (km/s)		
		230 GHz	345 GHz	690 GHz
Full Continuum	2 GHz / sideband	2600	1740	869
Standard Spectral Res.	~800 kHz	1	0.7	0.35
Maximum* Spectral Res.	~200 kHz	0.25	0.175	0.09

Maximum Resolving Power of >3,000,000

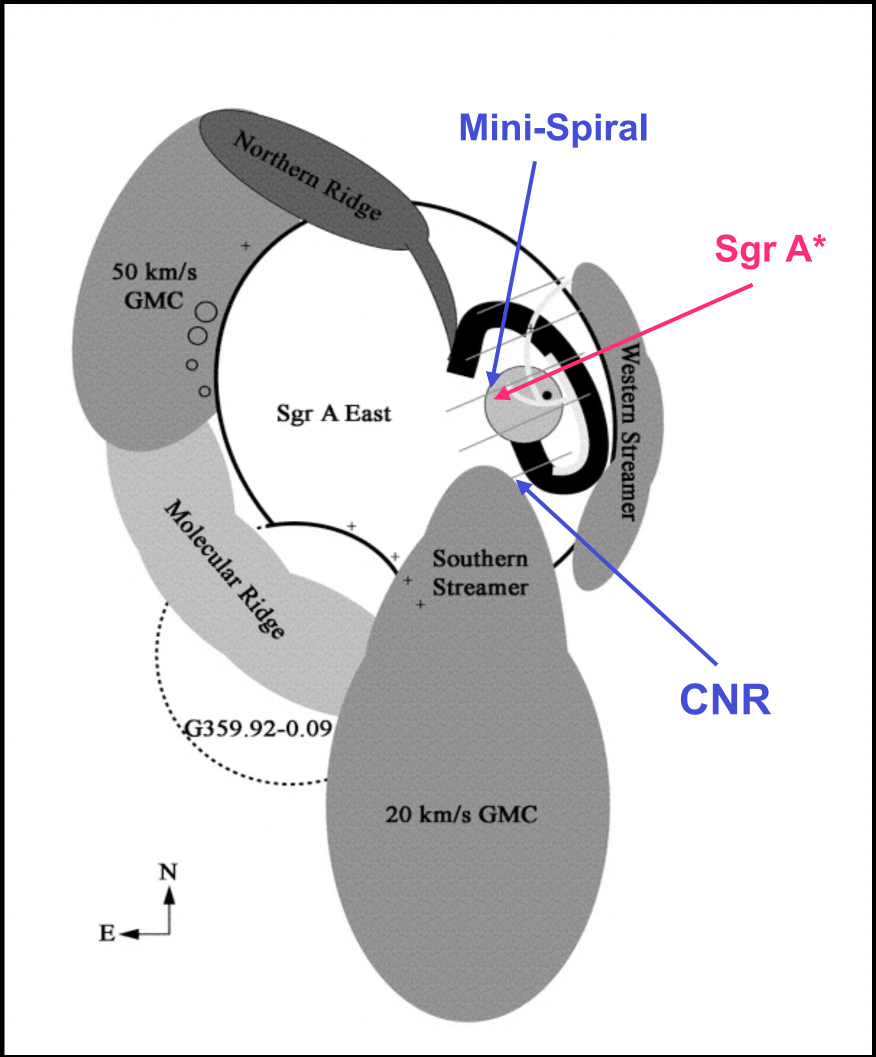
Galactic Center Circumnuclear Disk

- Origin of CND?
- Stability of CND?
- Feeding of Central Black Hole?

Central 10 pc



Vollmer & Duschl 2002, A&A 388, 128



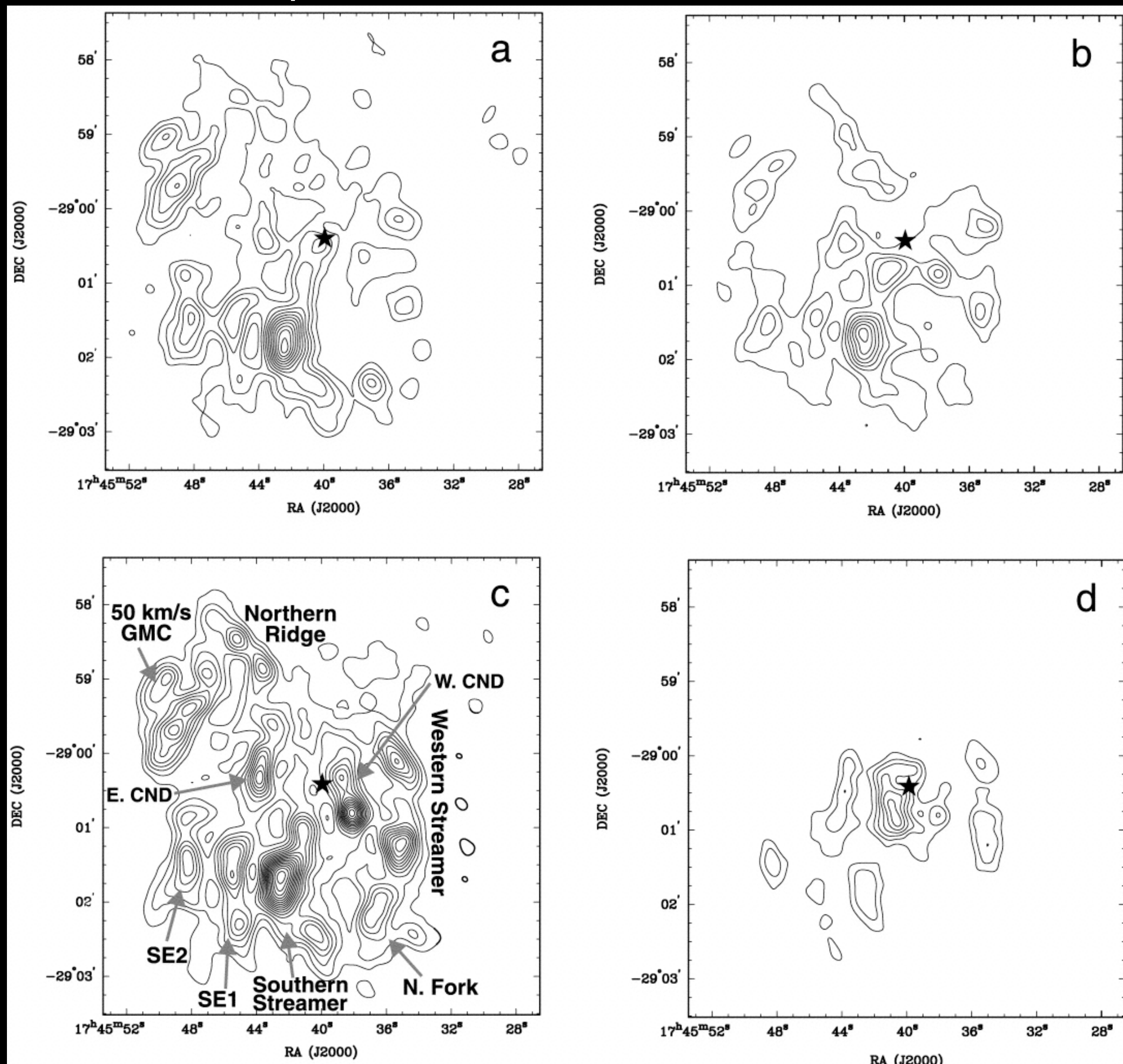
Herrnstein & Ho 2005, ApJ, 620, 287

NH_3 in the Galactic Center

Central 10 pc   Herrnstein & Ho 2005, ApJ, 620, 287

$NH_3(1,1)$ $NH_3(2,2)$

$NH_3(3,3)$ $NH_3(6,6)$

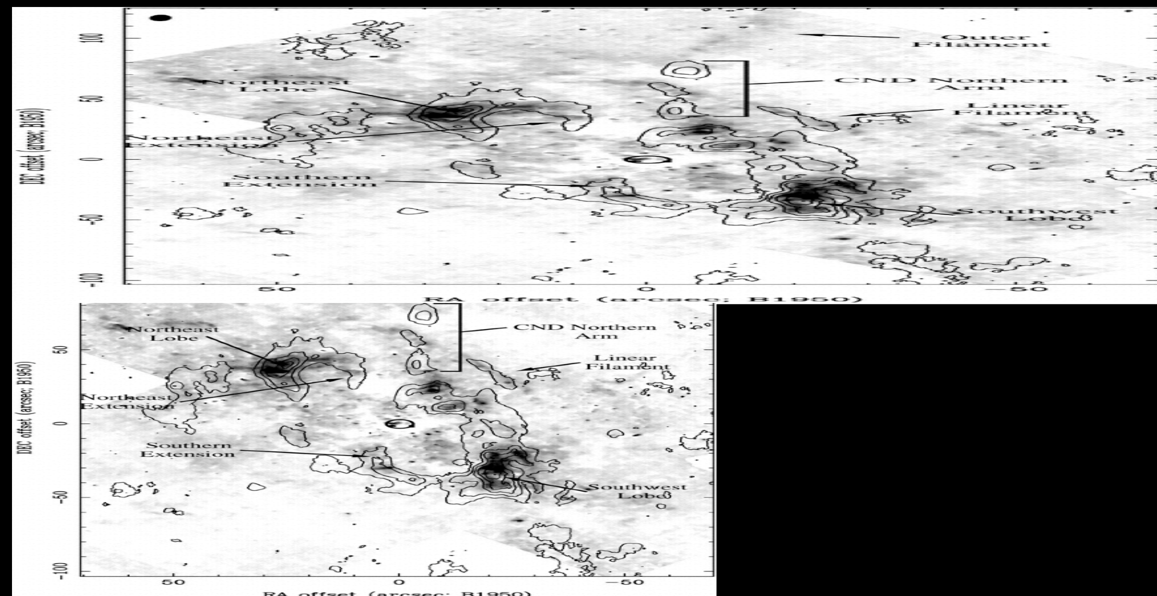


HCN(1-0) in the Galactic Center

CND Clumpy,

Incomplete.

Shocked



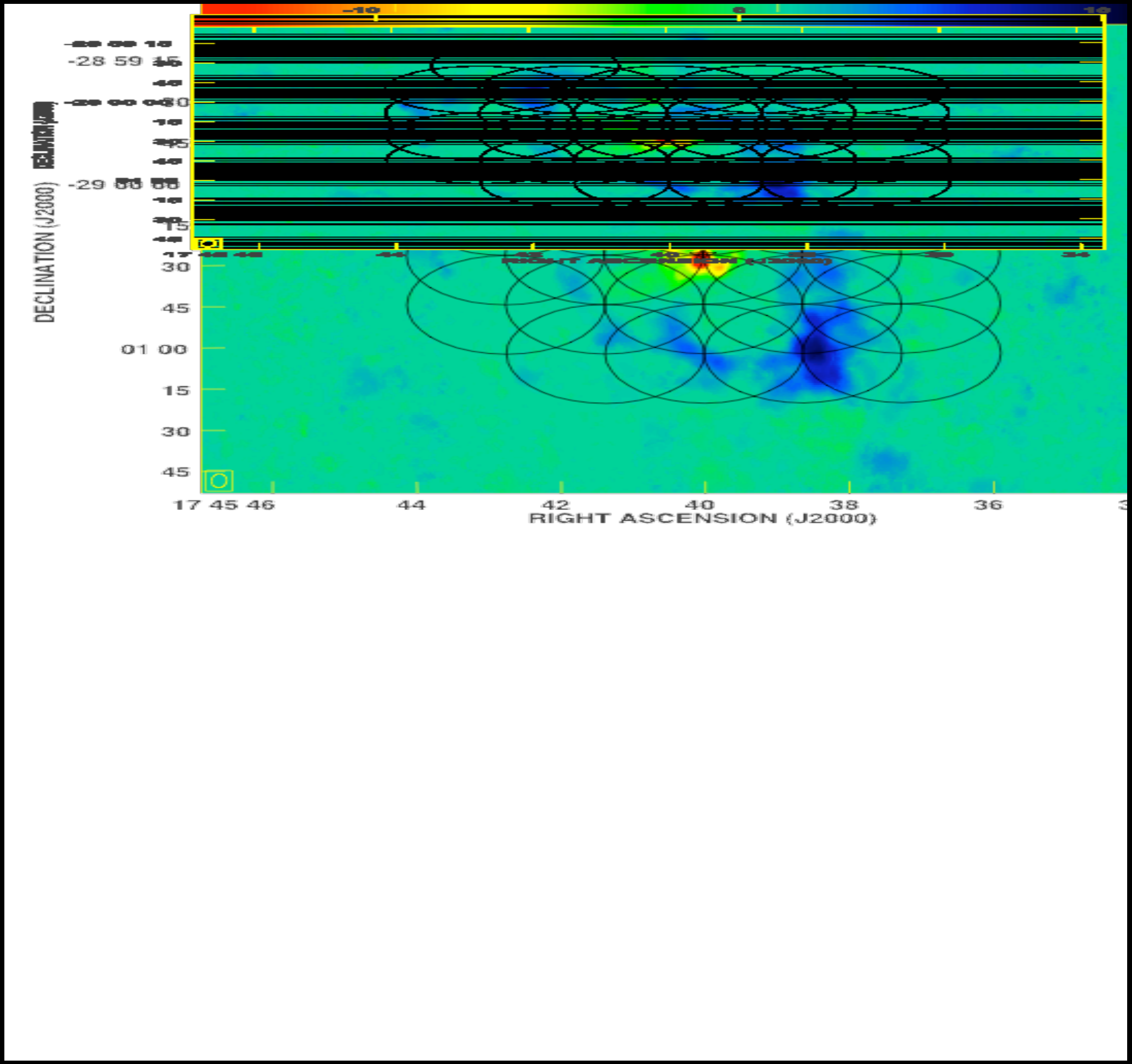
Sgr A*

HCN(1-0) in contours (Christopher et al., 2005, ApJ, 622, 346).

H_2(1-0) in grey scales (Yusef-Zadeh et al., 2001, ApJ, 560, 749).

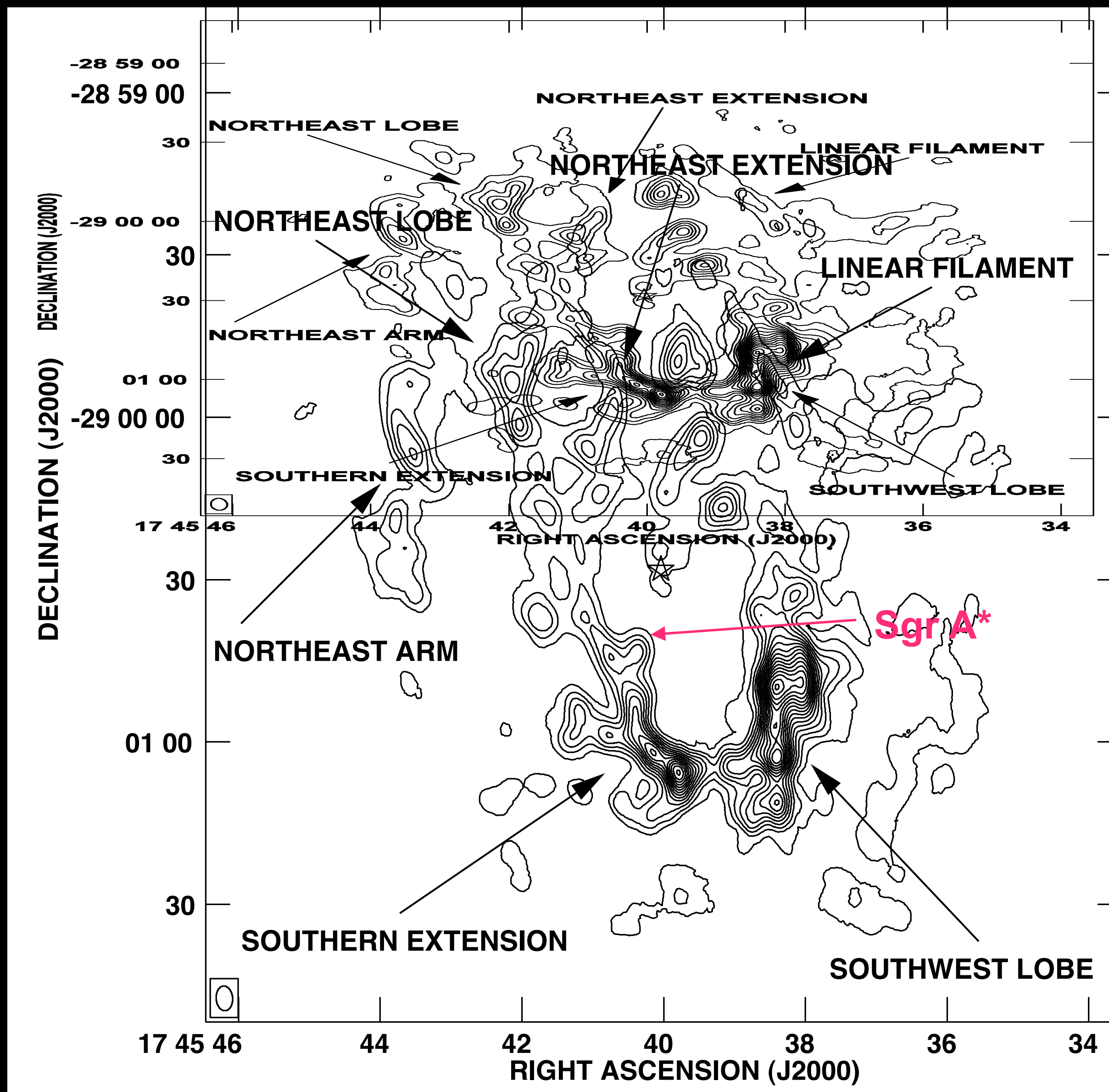
SMA Observations: HCN(4-3) and CS(7-6)

Mosaic of 25 Fields Montero, Herrnstein, and Ho (2009)



Color Background: HCN(1-0) of Christopher et al. 2005, ApJ, 622, 346

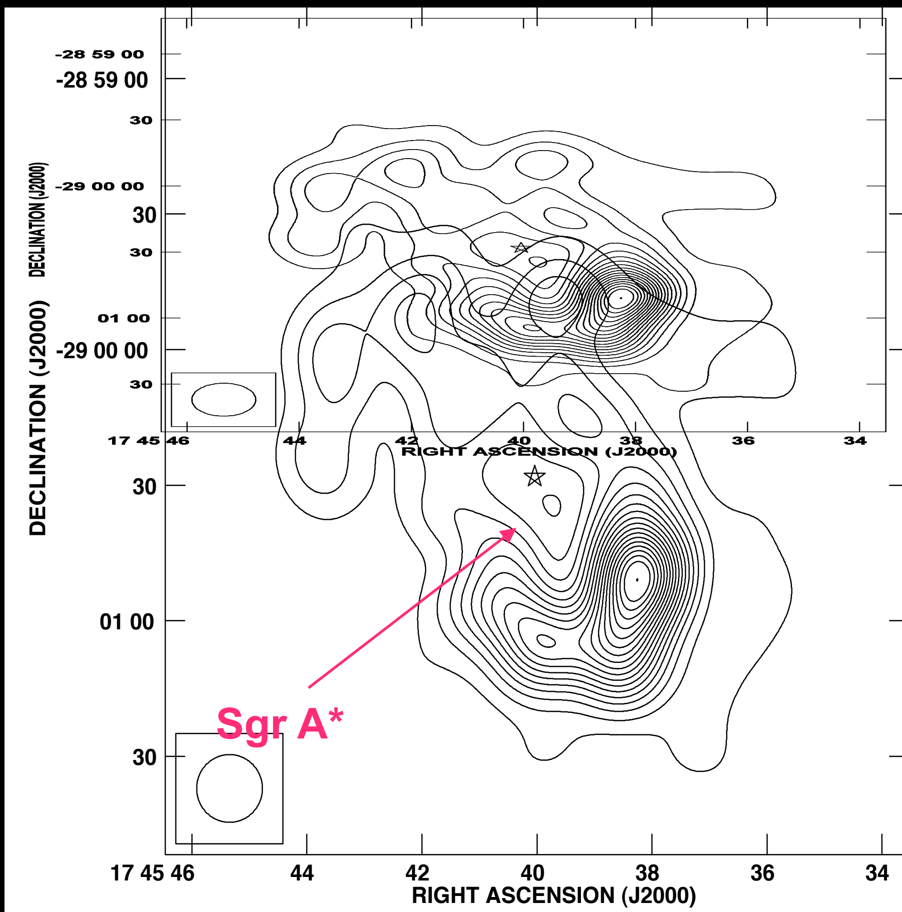
HCN(4-3) in the Galactic Center



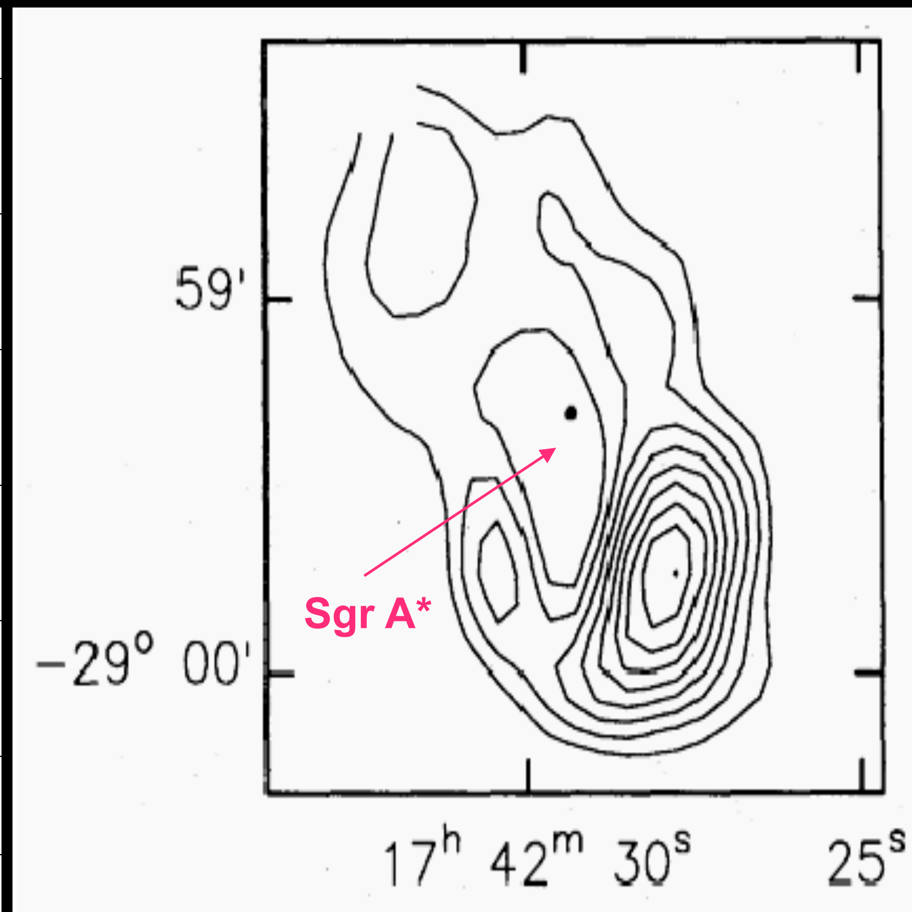
Compared to Single Dish Results

Convolving SMA map to JCMT 15” beam

HCN(4-3) SMA



HCN(4-3) JCMT



61% of JCMT flux recovered

Marshall et al. 1995, MNRAS, 277, 594

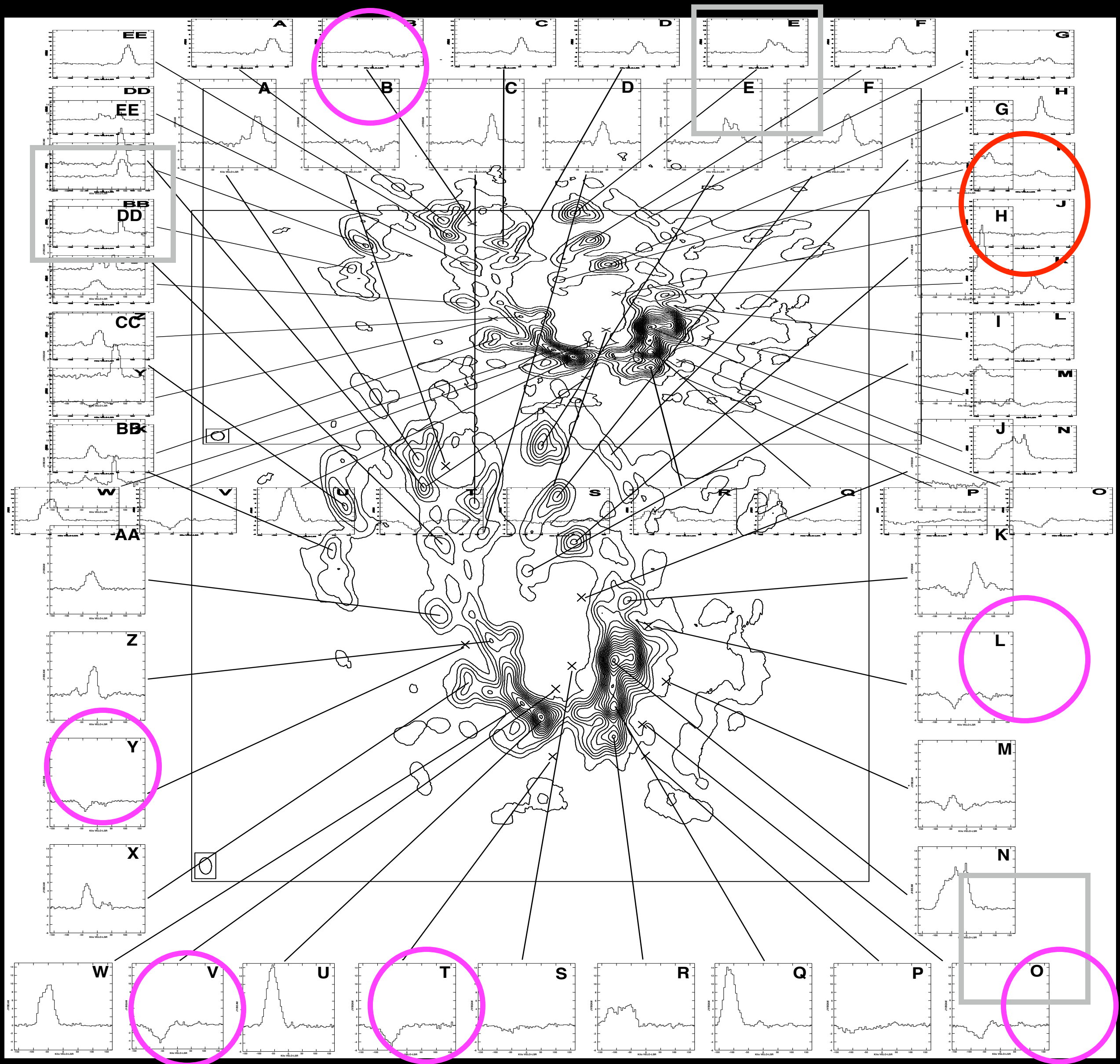
Overall Rotation of CND

Spectra show:

Missing Flux Problem

Double Peaked Lines

Asymmetric Profiles

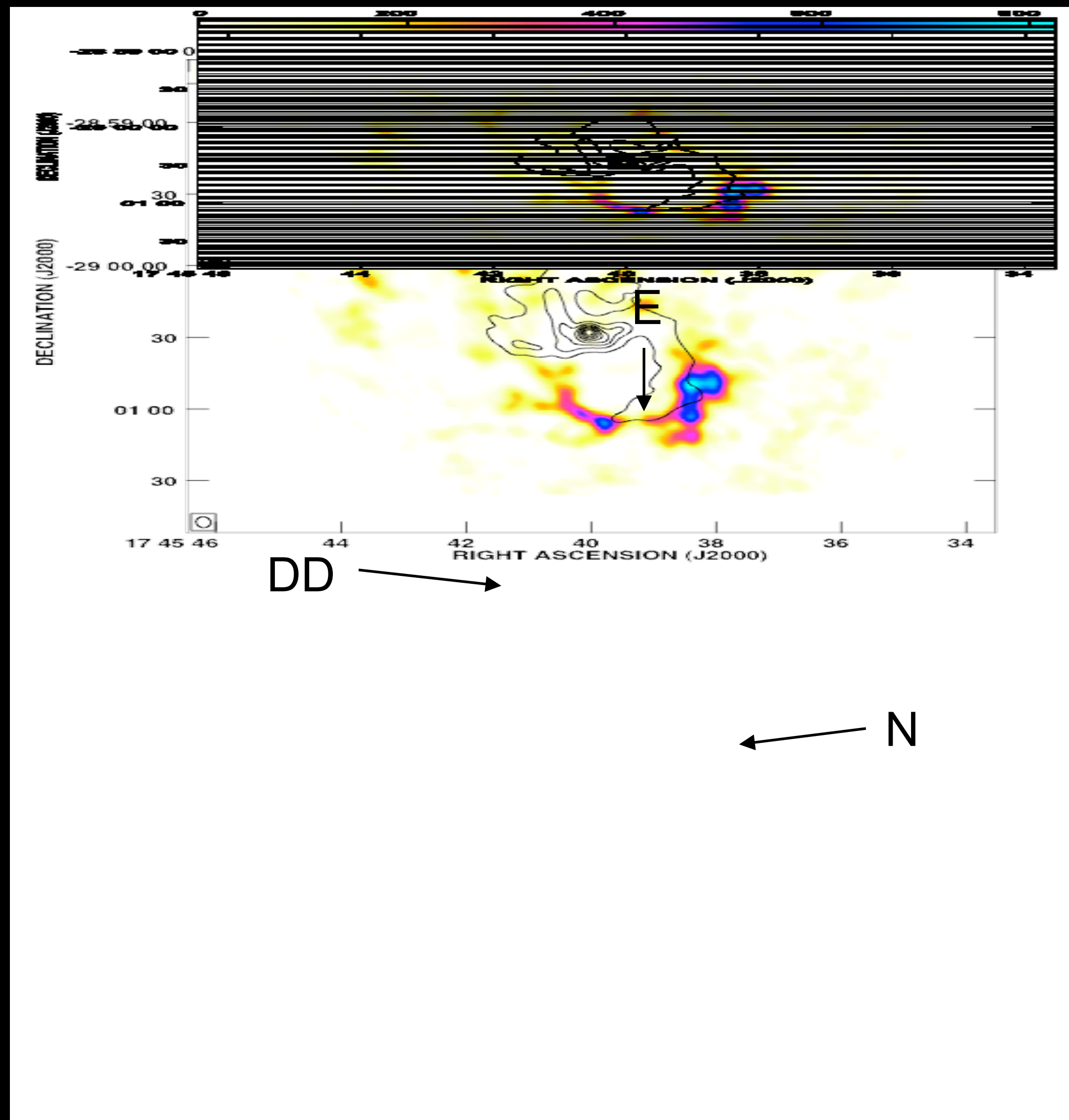


V_{rot} ~110 km/s

P_{rot} ~ 8 x 10^4 yrs

Comparison with 6cm Continuum

HCN CND fits around the MINI SPIRAL



HCN(4-3) in color.

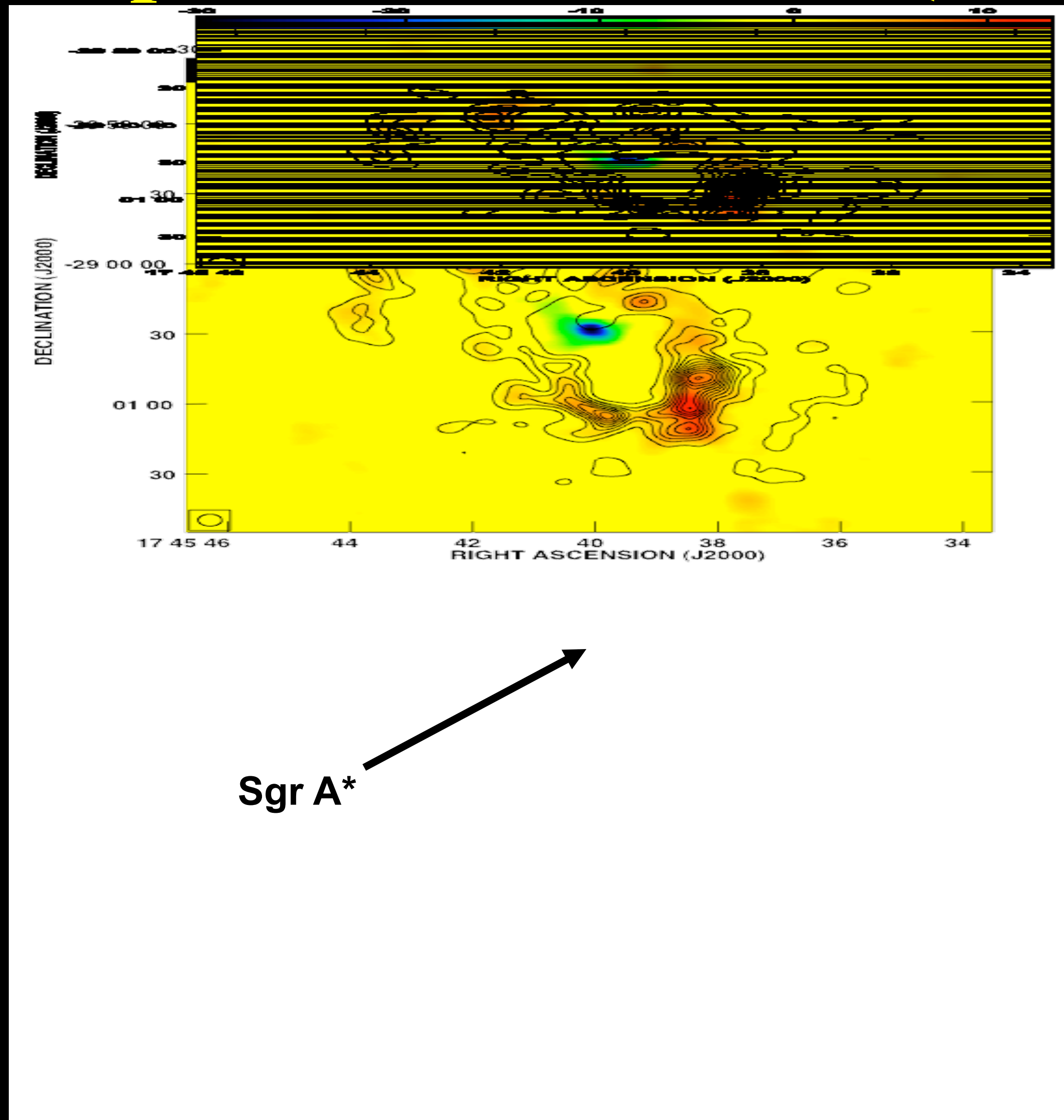
6cm Continuum in contours (Yusef-Zadeh & Morris 1987, ApJ, 320, 545).

Comparison with HCN(1-0)

Overall Agreement

HCN 4-3 shows more complete "Ring"

Relative Intensities Different

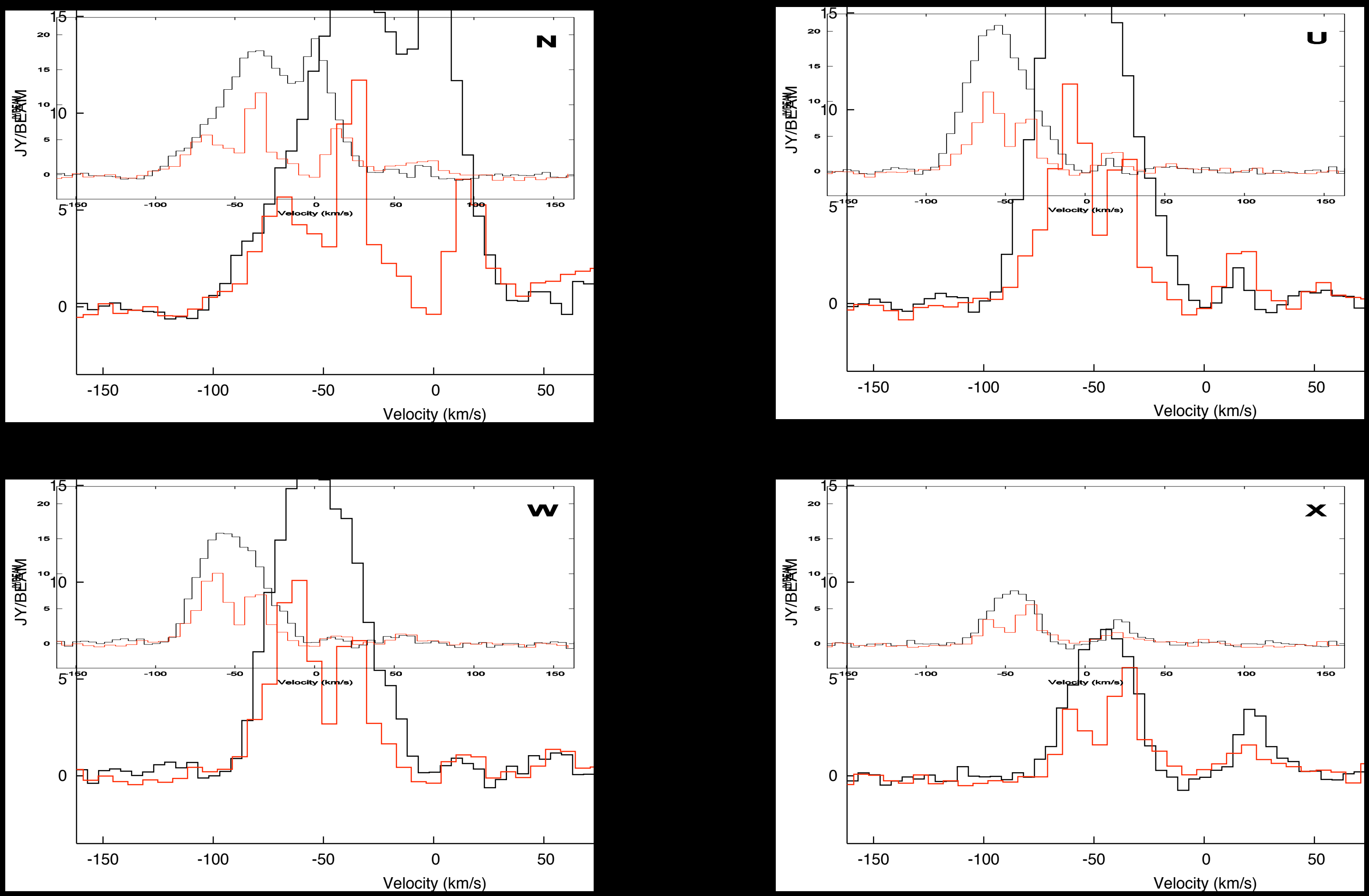


HCN(4-3) in contours.

HCN(1-0) inn color

(Christopher et al., 2005, ApJ, 622, 346).

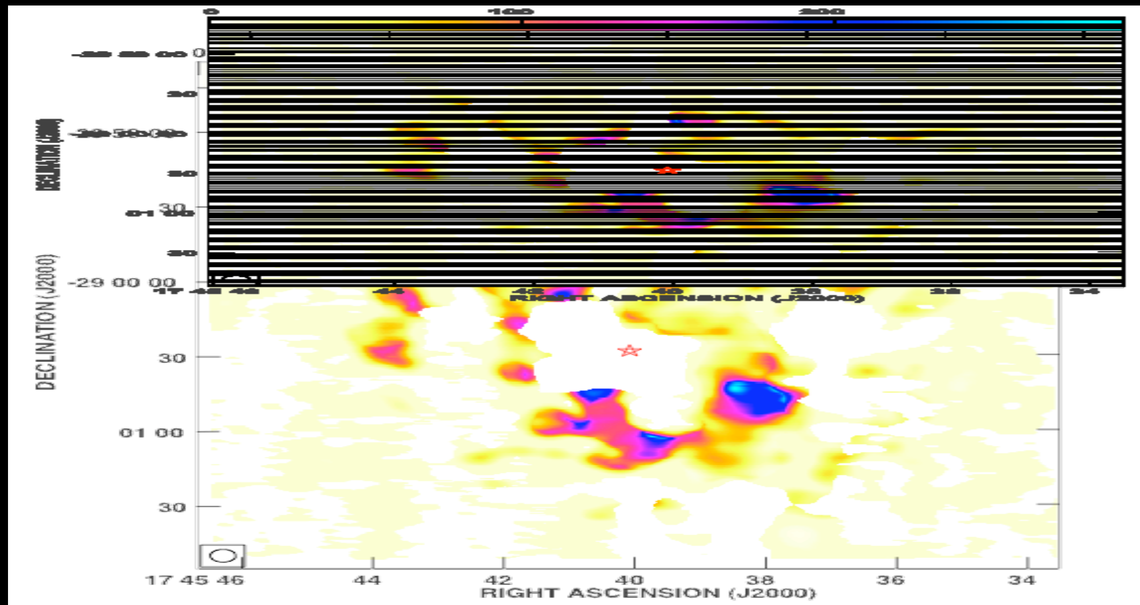
HCN 4-3 Overcomes Absorption



Black Contours: HCN(4-3)

Red Contours: HCN(1-0) (Christopher et al. 2005, ApJ, 622, 346)

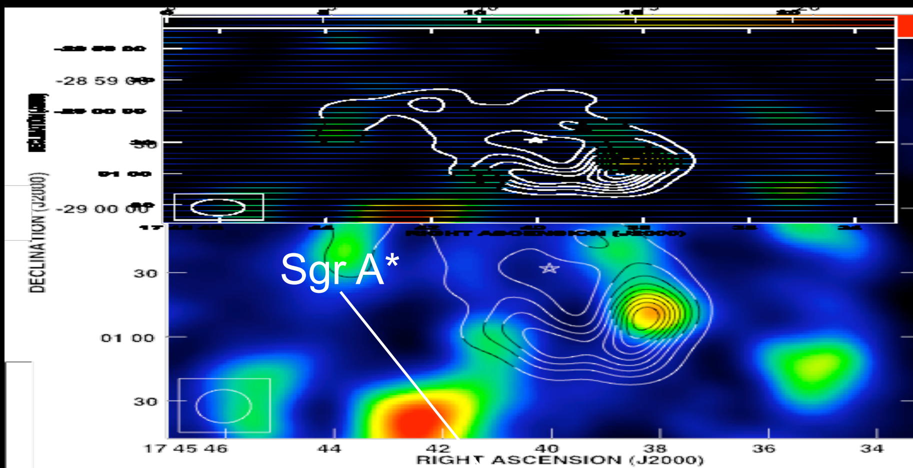
HCN(4-3)/HCN(1-0) Ratio

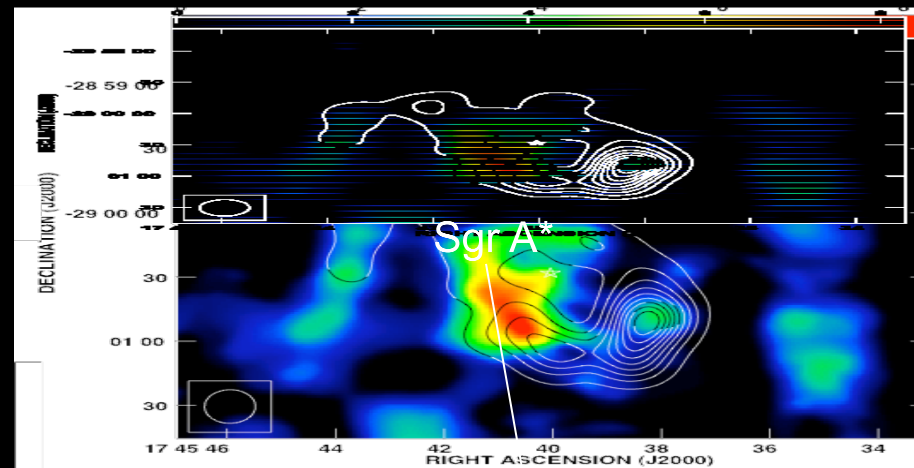


Comparison with NH_3

Connecting CND to the Outside

$NH_3(3,3)$ **HCN(4-3) in contours** $NH_3(6,6)$



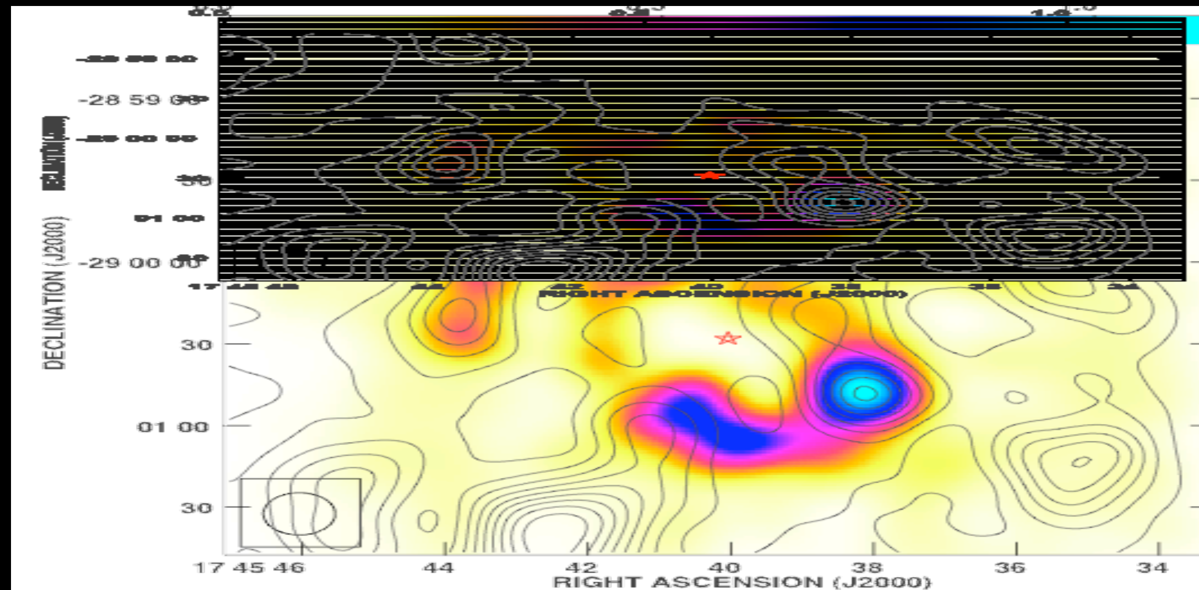


McGary, Coil & Ho 2001, ApJ, 559, 326

Herrnstein & Ho 2002, ApJ, 579, L83

HCN(4-3)/HCN(1-0) Ratio – NH_3(3,3)

Warmer HCN is Also Tracked by NH_3 (3,3)

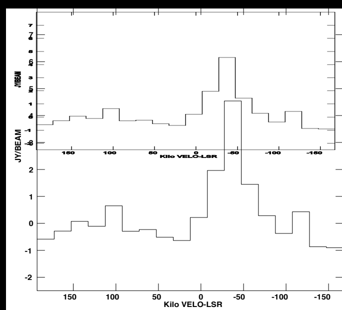


HCN(4-3)/HCN(1-0) Ratio in color.

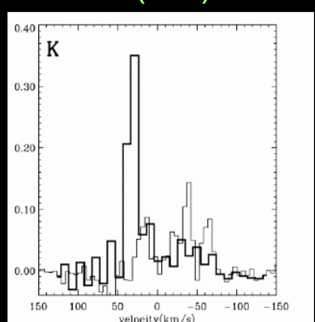
NH_3(3,3) in contours (McGary, Coil & Ho 2001, ApJ, 559, 326).

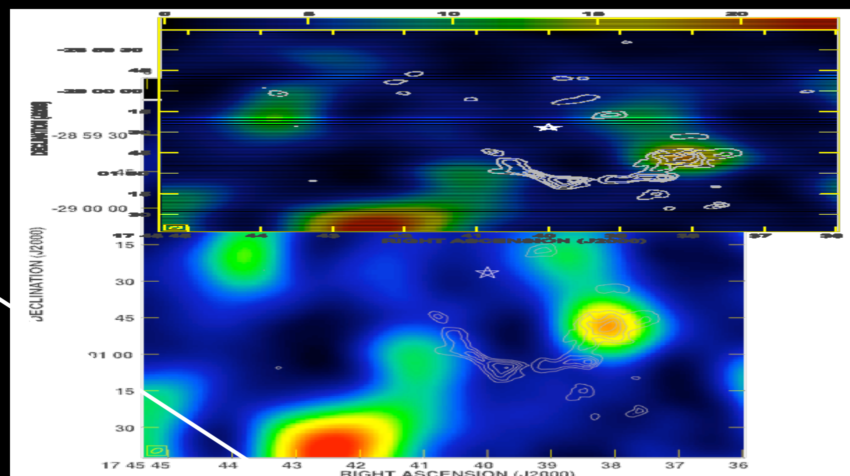
Comparison with NH_3(3,3)

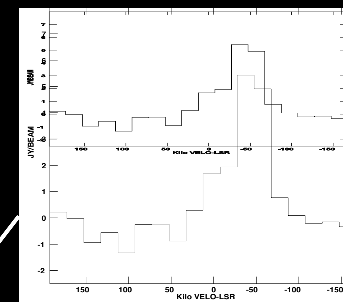
NH_3(3,3): narrower lines, HCN: broader lines



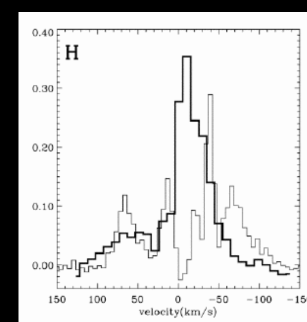
HCN(4-3)







HCN(4-3)

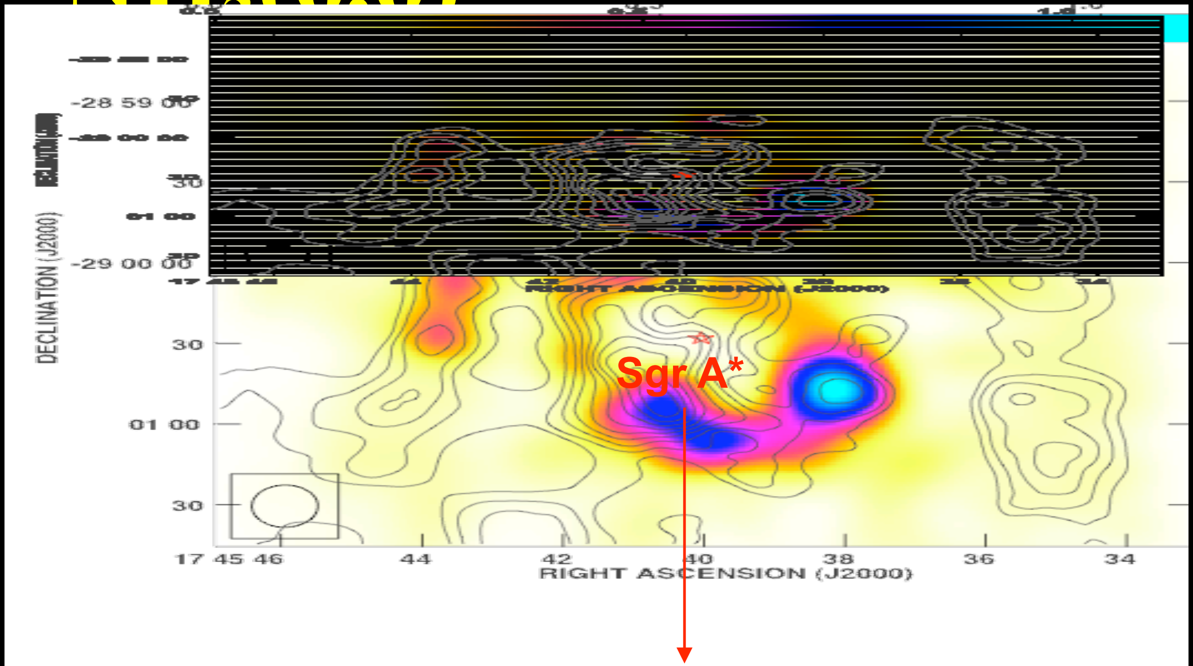


NH_3(3,3) in thick line (McGary et al. 2001)
HCN(1-0) in thin lines (Wright et al. 2001)

NH_3(3,3) in thick line (McGary et al. 2001)
HCN(1-0) in thin lines (Wright et al. 2001)

HCN(4-3)/HCN(1-0) Ratio – NH_3(6,6)

Excited Eastern Side of CND Continues toward SgrA* Vicinity



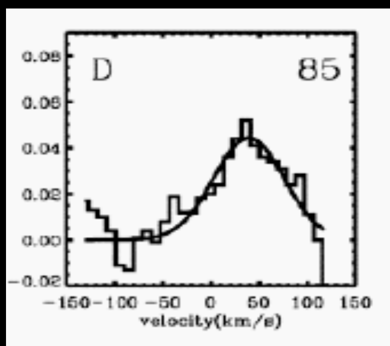
HCN(4-3)/HCN(1-0) Raio in color.

NH_3(6,6) in contours (Herrnstein & Ho 2002, ApJ, 579, L83).

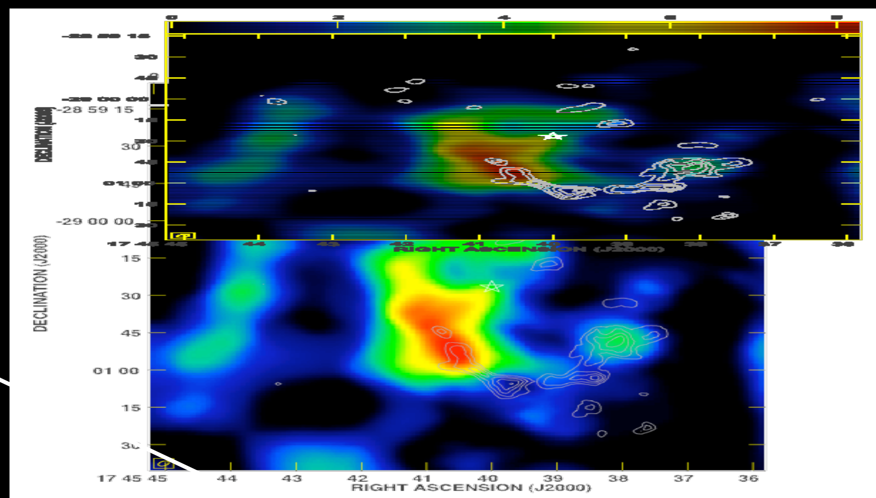
Comparison with $NH_3(6,6)$

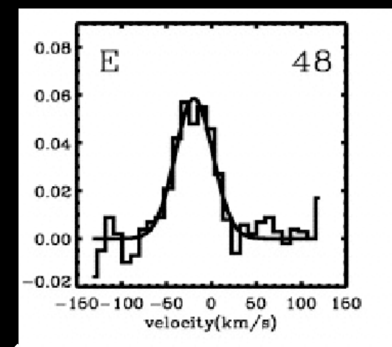
HCN: Narrower Lines

$NH_3(6,6)$: Broader Lines

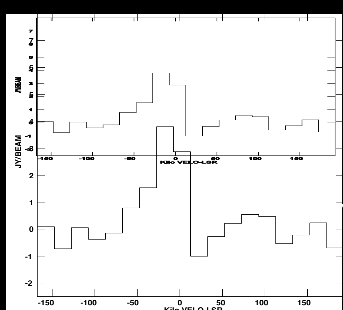


$NH_3(6,6)$ spectra
(Herrnstein & Ho 2002)

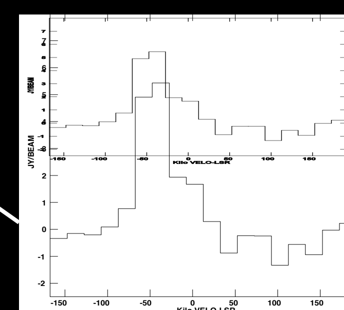




$NH_3(6,6)$ spectra
(Herrnstein & Ho 2002)

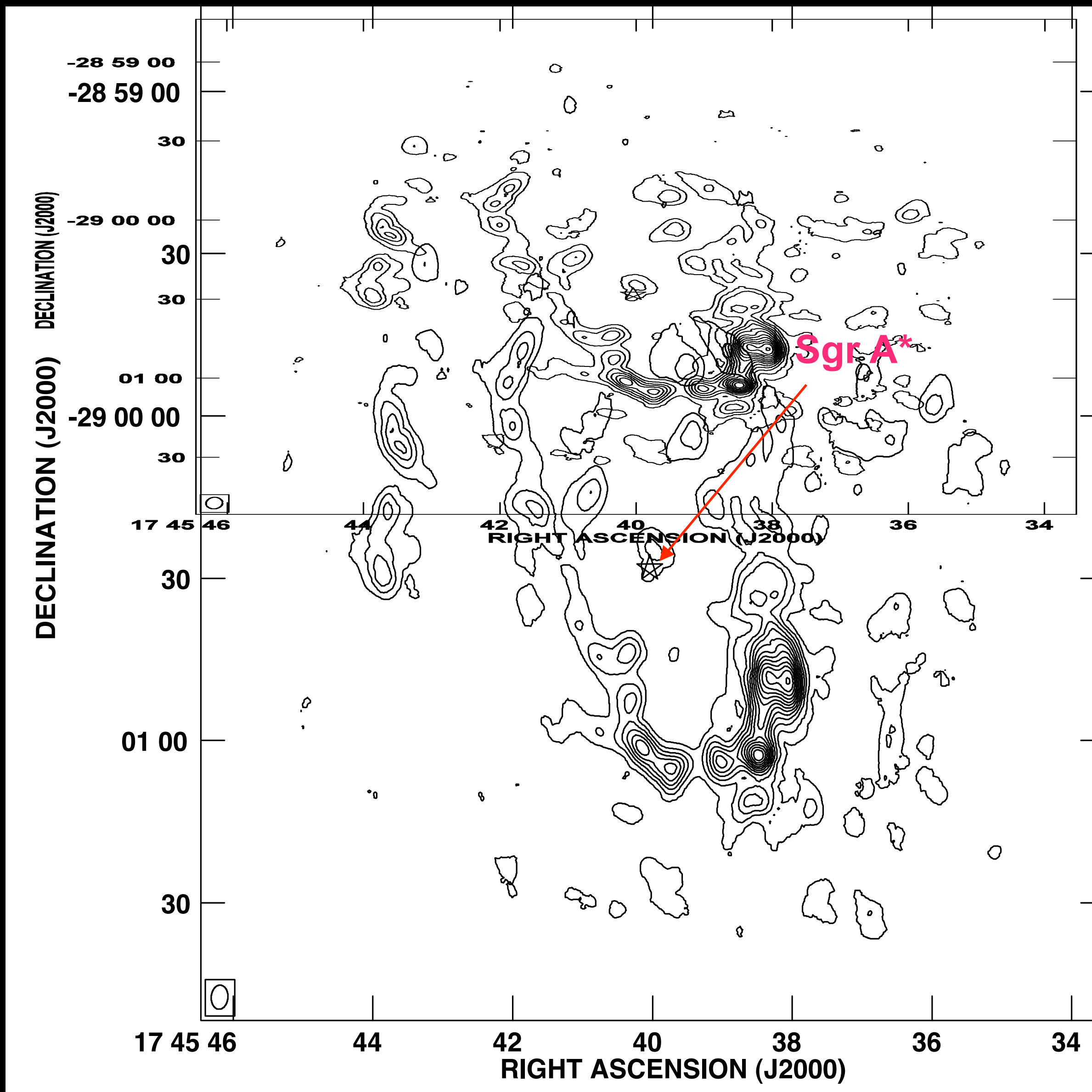


HCN(4-3)

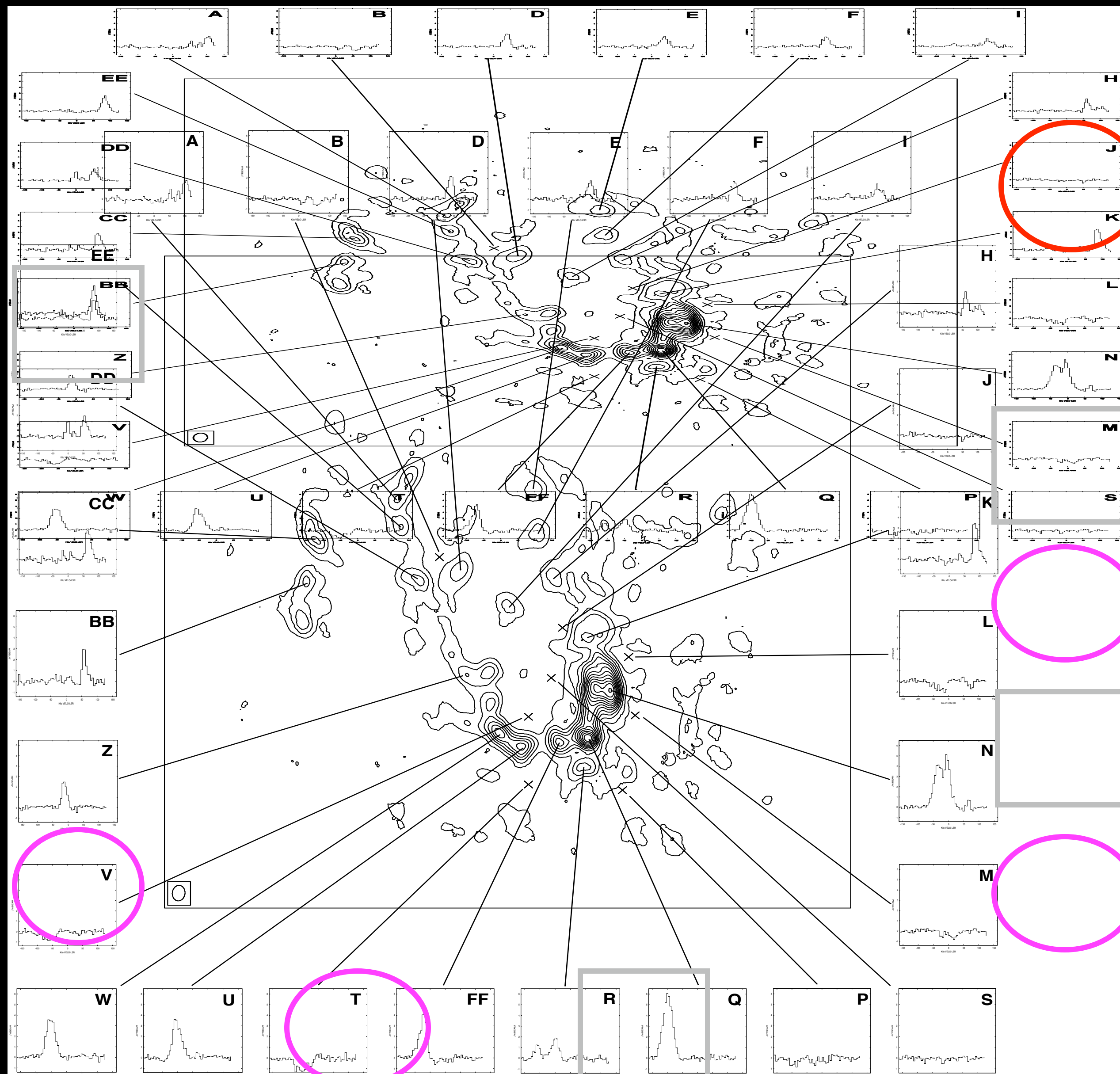


HCN(4-3)

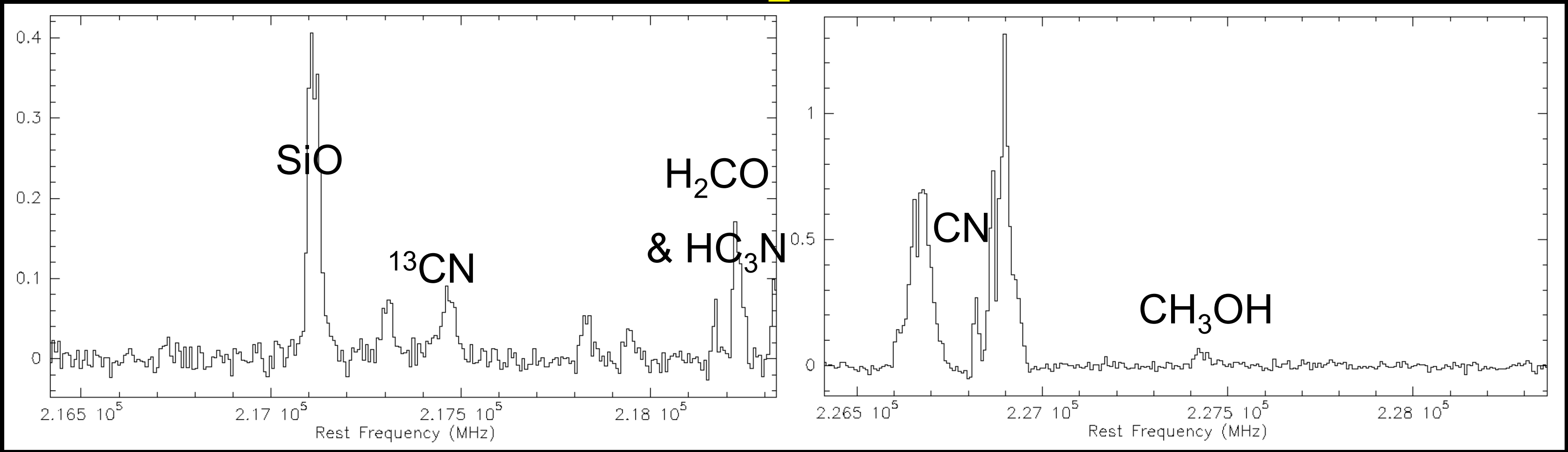
CS(7-6) in the Galactic Center

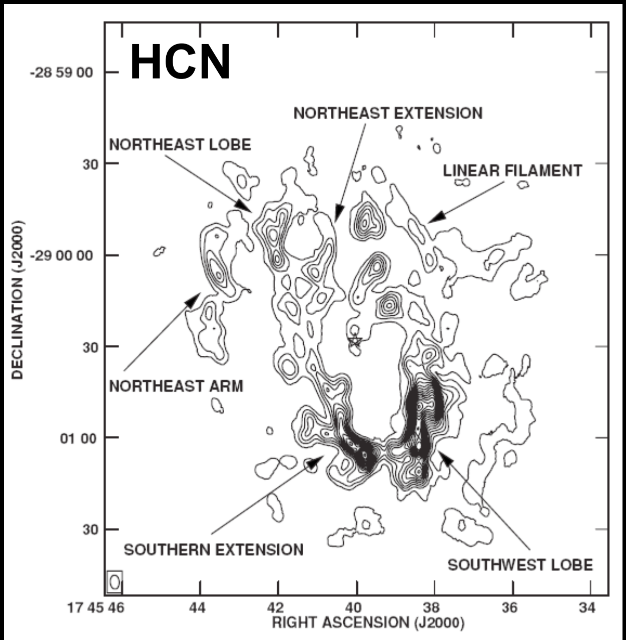


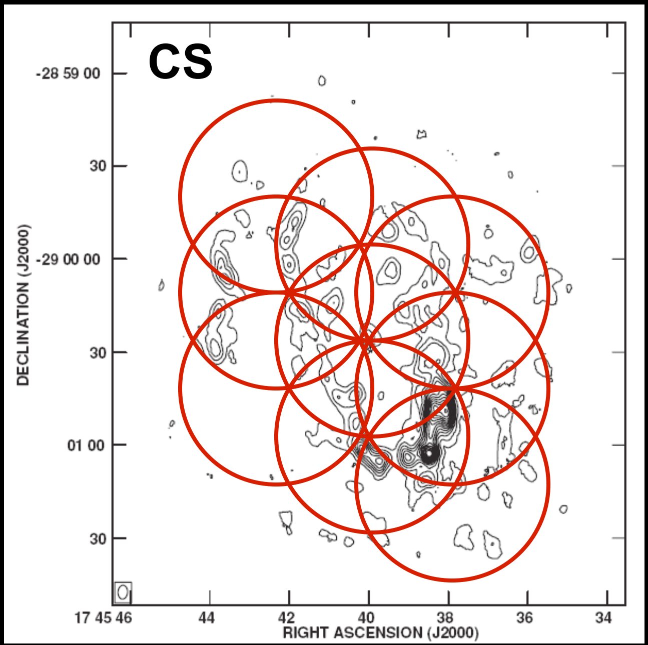
CS Kinematics



Other SMA Spectral Lines

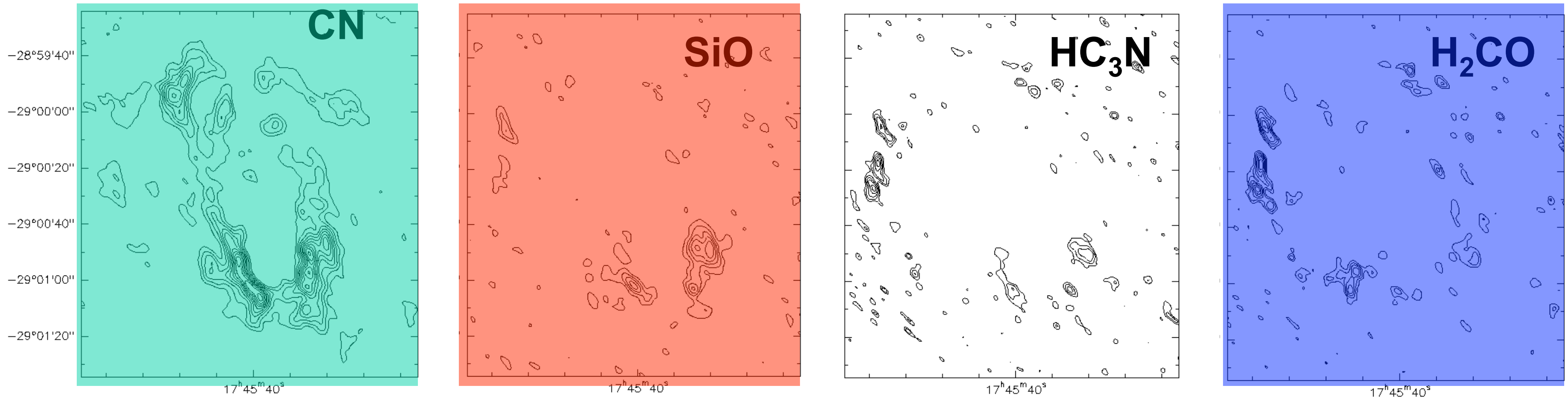


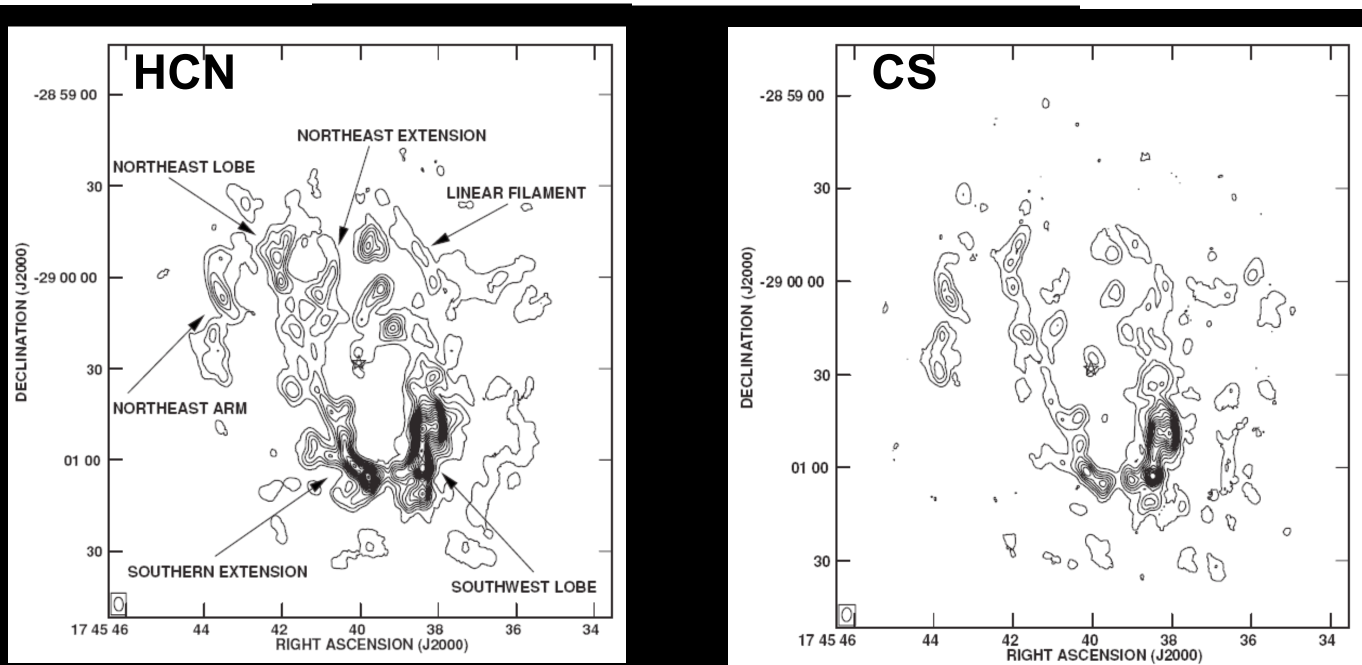




(Martin et al. 2009)

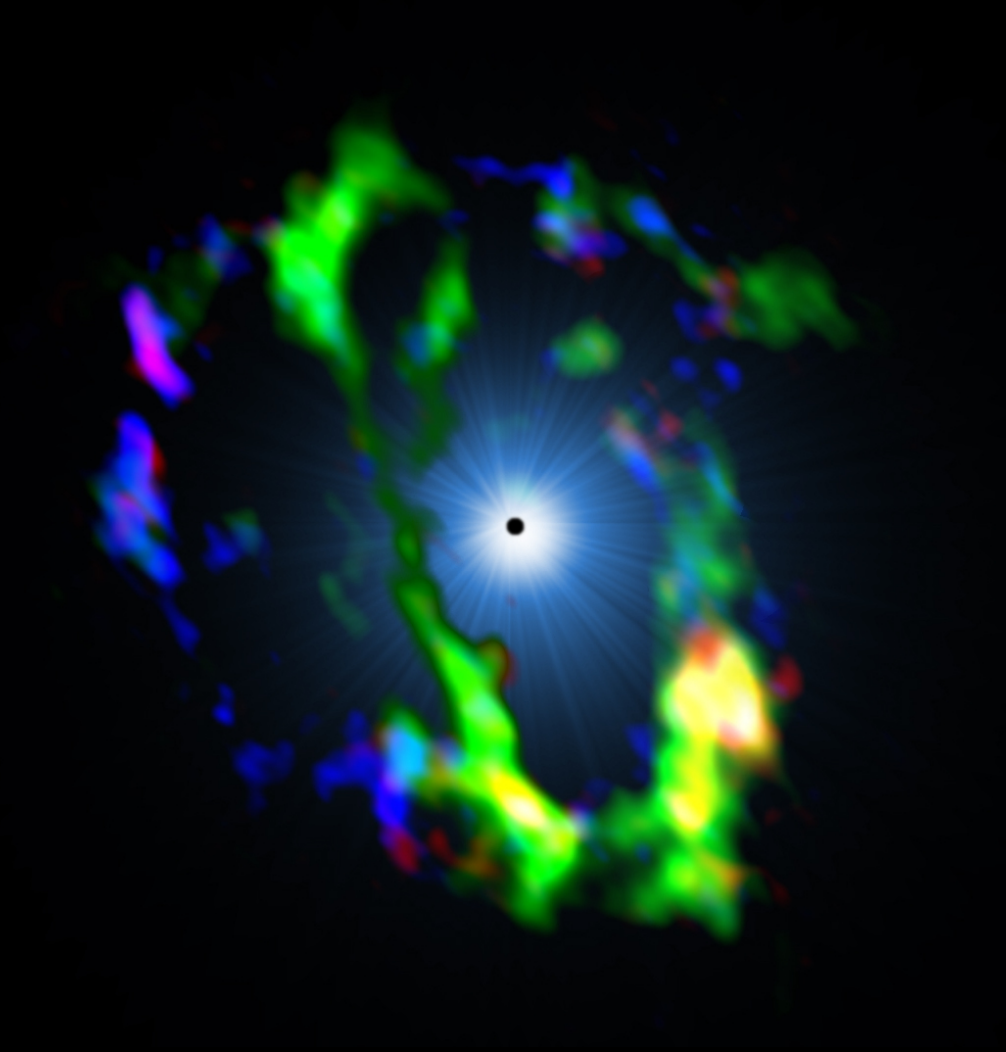
4 More SMA Molecules Mapped





(Montero-Castano et al. 2009)

Excitation in the CND



Molecules:

CN, HCN, CS: dense

H_2CO, HC_3N: diffuse

SiO: shock

Martin et al. 2009

Summary of Current Thinking on CND

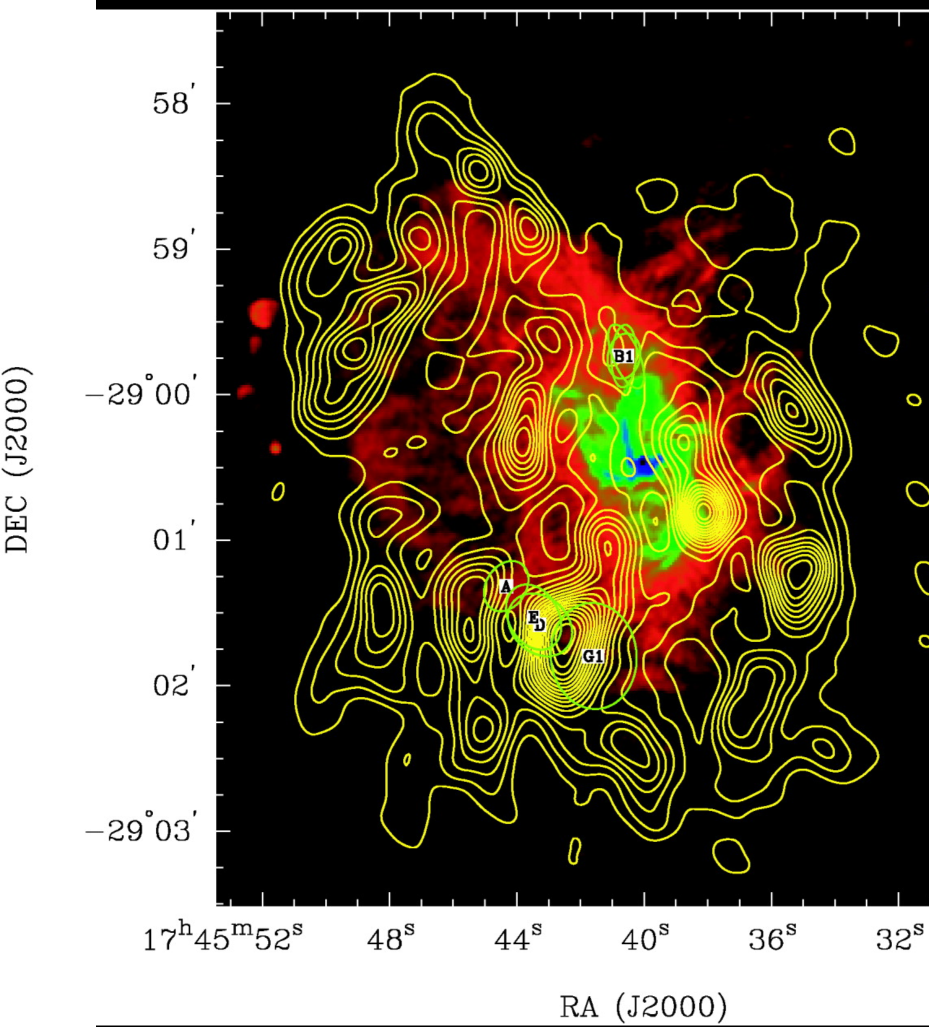
- Clumpy, Line Widths > 20 km s^{-1}, Mass > 10^3 M_O
- Virial Density > 3 x 10^7 cm^{-3} → Clumps within CND stable against Tidal Shear
- Excitation within CND non-uniform, warmer in the southern part
- Hot gas, >300K, inside CND
- Accretion time towards SgrA* >9 x 10^6 yrs, longer than CND rotation time ~ 8 x 10^4 yrs

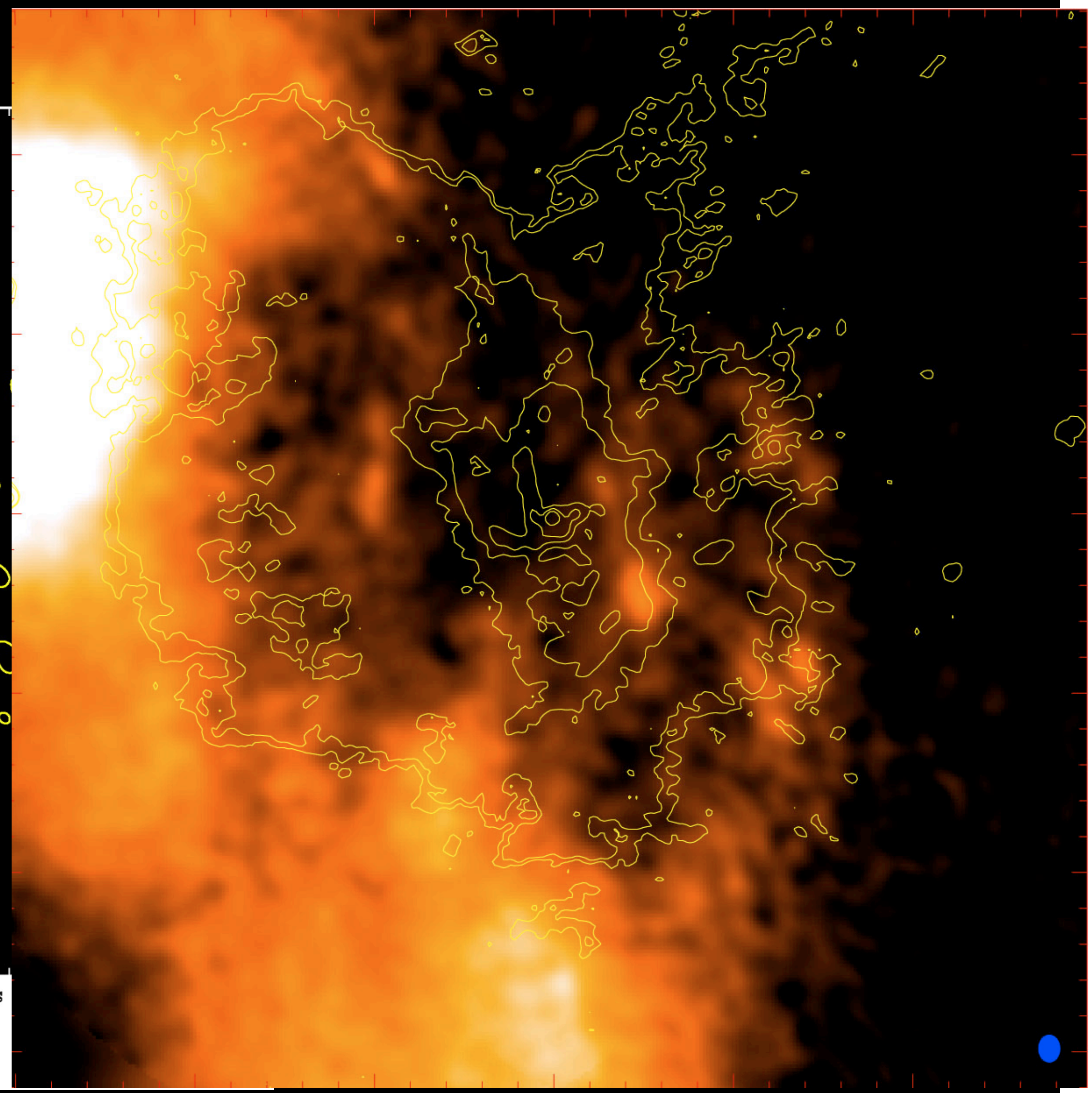
↓

CND *Not* a Transient Structure

Combine VLA and GBT in NH_3 (3,3)

Must Improve Imaging

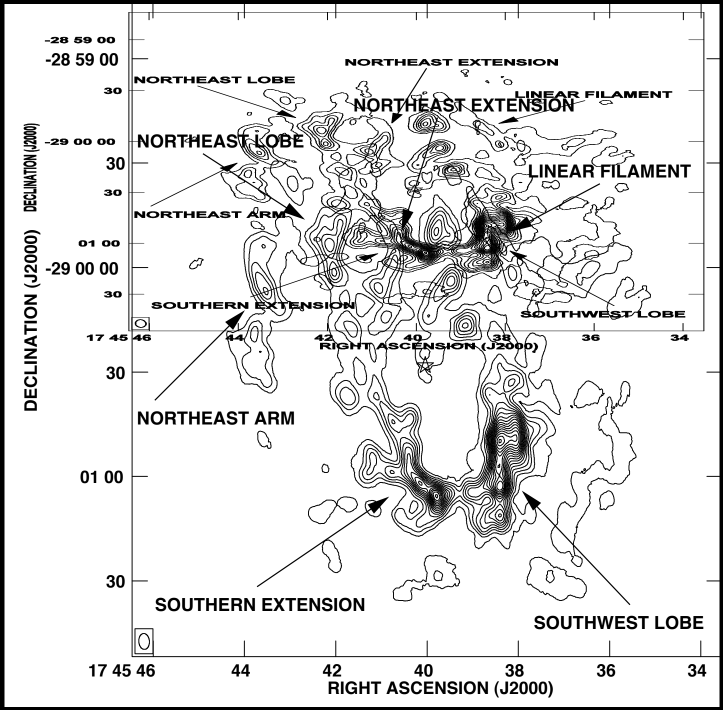


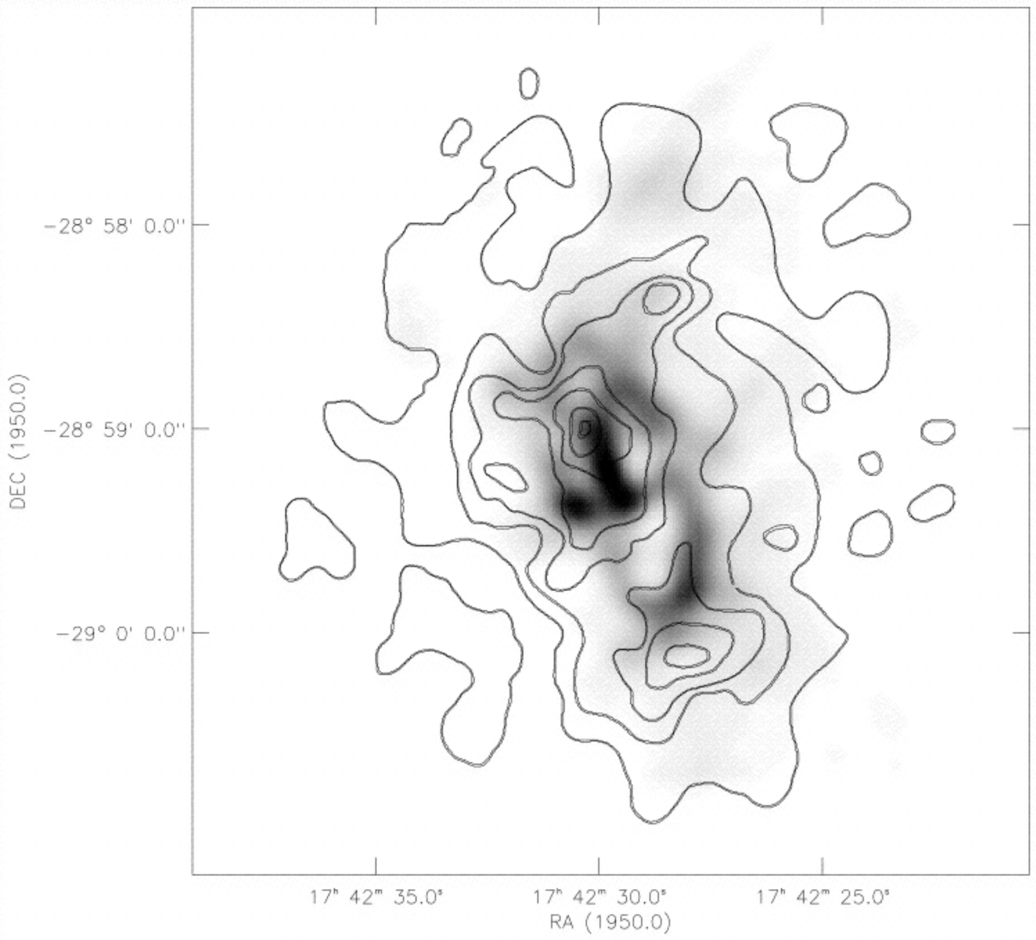


Higher Excitation with SOFIA

KAO: 37.7μm (5.7”) and OI 63μm (20”)

Must Sample Closer In





Latvakoski et al. 1999, ApJ, 511, 761

Summary

- At 3" resolution, Submillimeter Lines, sensitive to high temperature and high density, see inside the CND
- The "Submillimeter Advantage", Einstein A coefficient **($S \propto \nu^5$)** and Rayleigh-Jeans Grey-Blackbody Radiation **($S_\nu \propto \nu^4$)**, will be even more important in the FIR
- SOFIA can do a lot for Galactic Center studies, and not only in the CND