

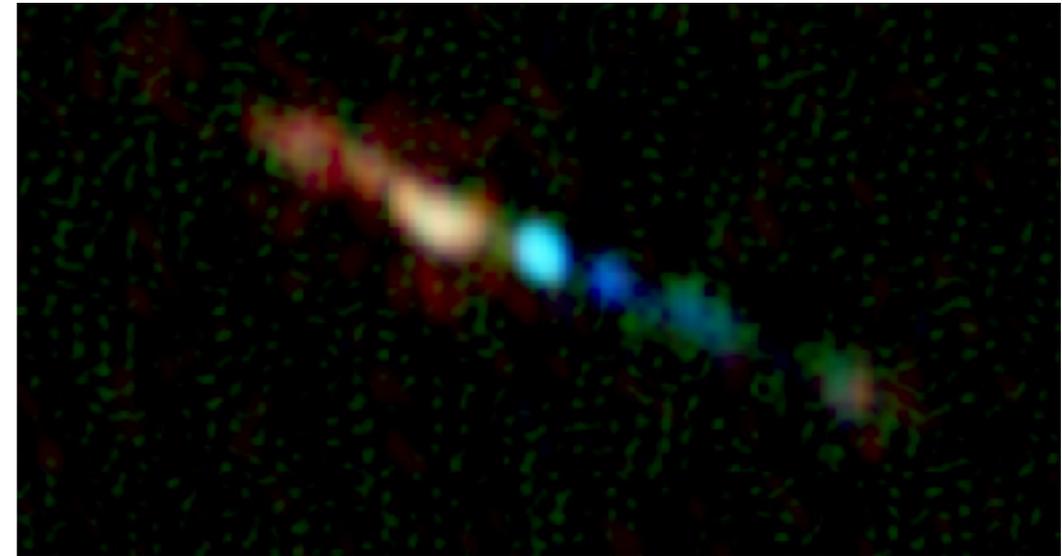
# A Radio Absorption Study of AGN Tori

Seiji Kameno (Joint ALMA Observatory / NAOJ)

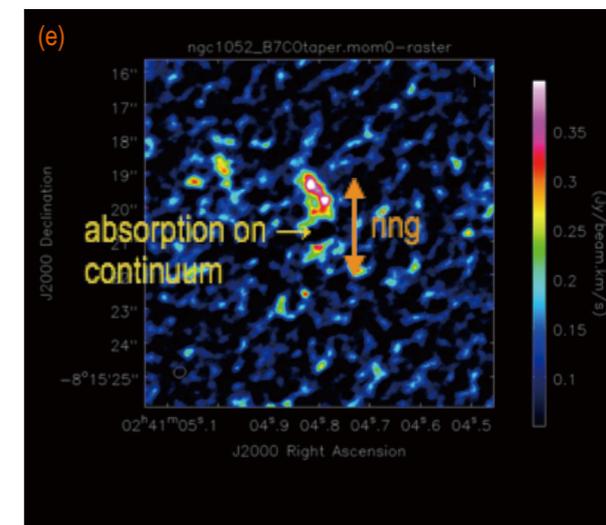
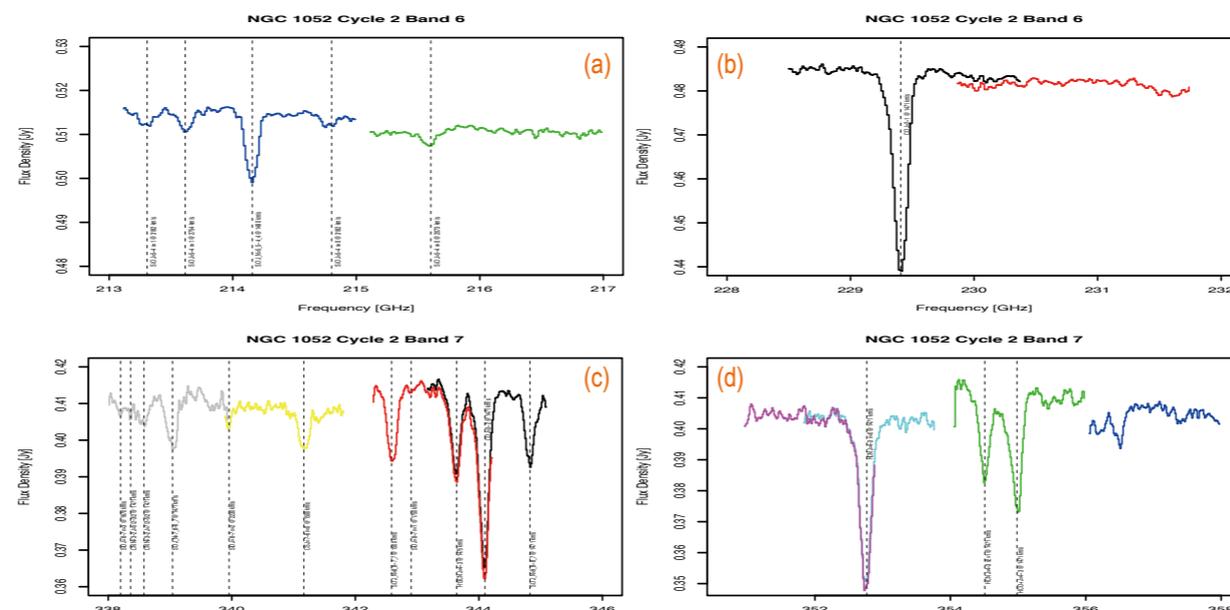
collaborated with

M. Inoue, K. Wajima, S. Sawada-Satoh, Z.-Q. Shen

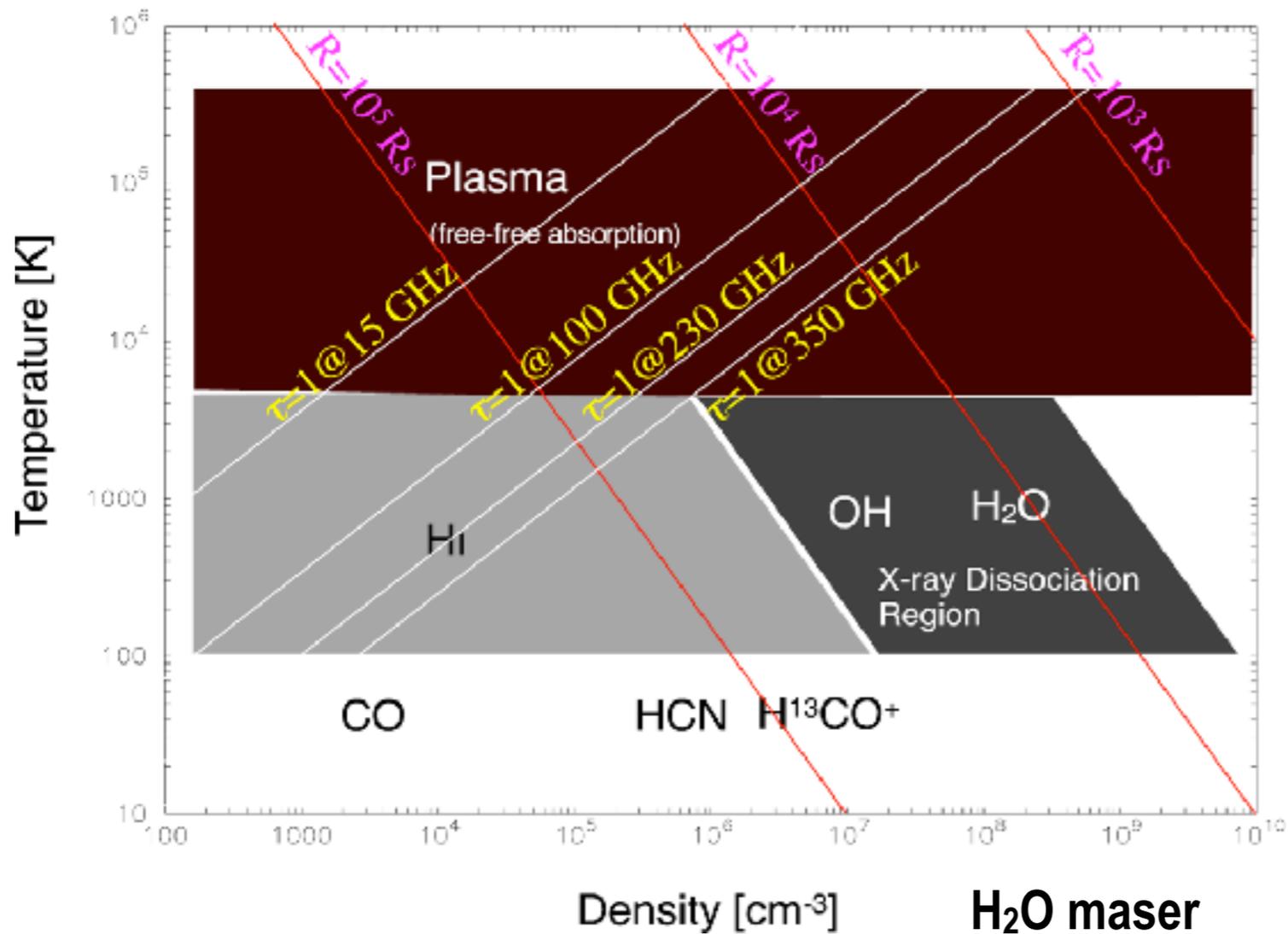
for plasma free-free absorption



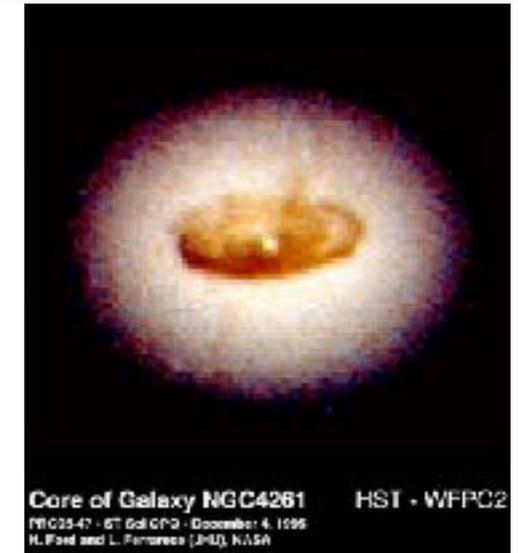
V. Impellizzeri, D. Espada, S. Martin, S. Sawada-Satoh, N. Nakai, H. Sugai, Y. Terashima, K. Kohno, L. Minju  
for molecular absorption lines



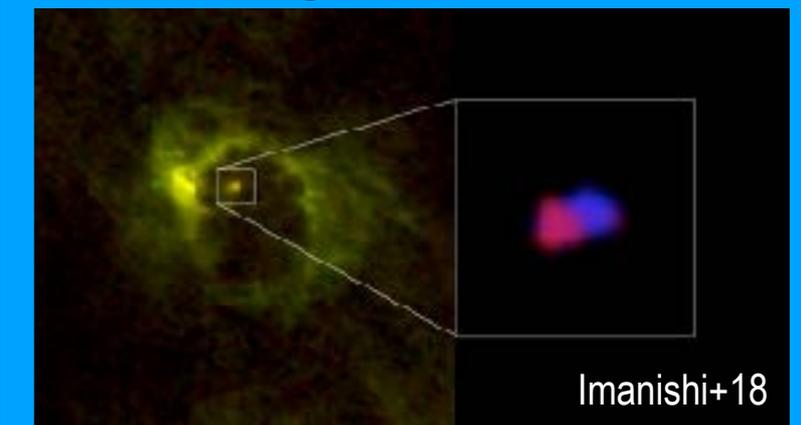
# Multiple ingredients in AGN tori



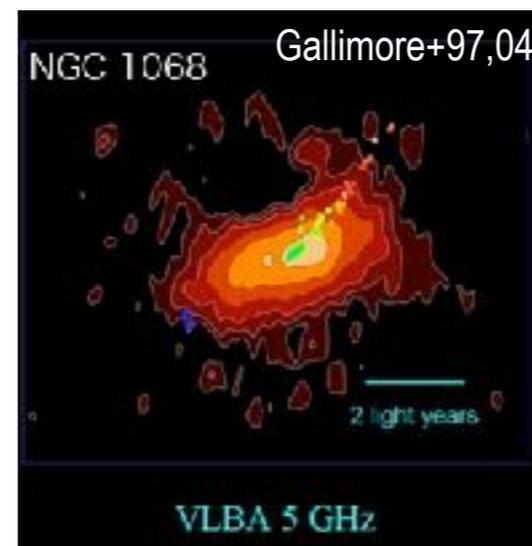
Dust



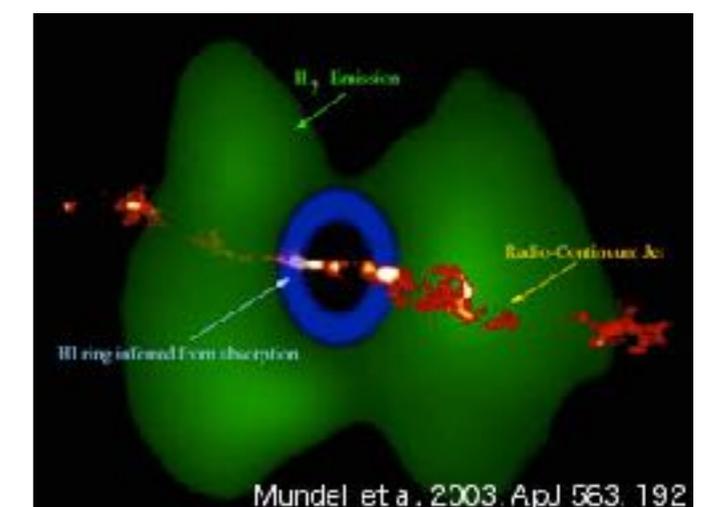
Molecular gas



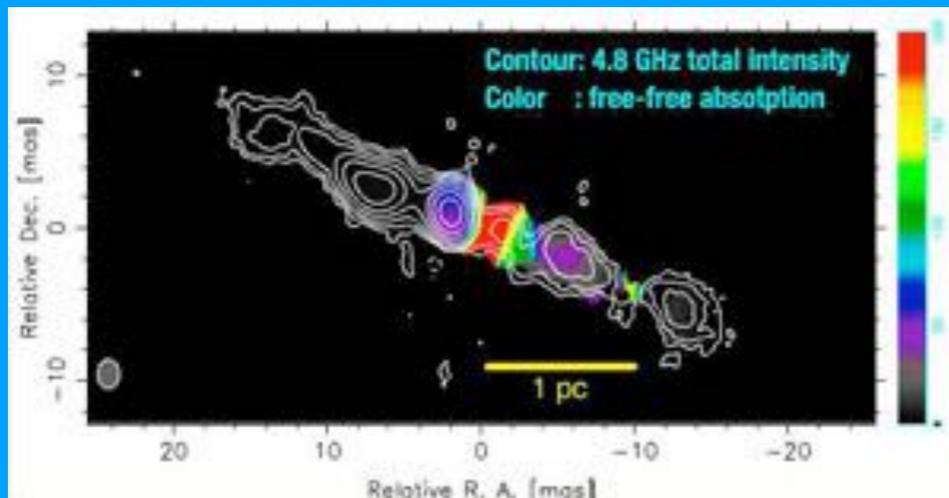
H<sub>2</sub>O maser



Neutral gas (H<sub>I</sub>)



Plasma



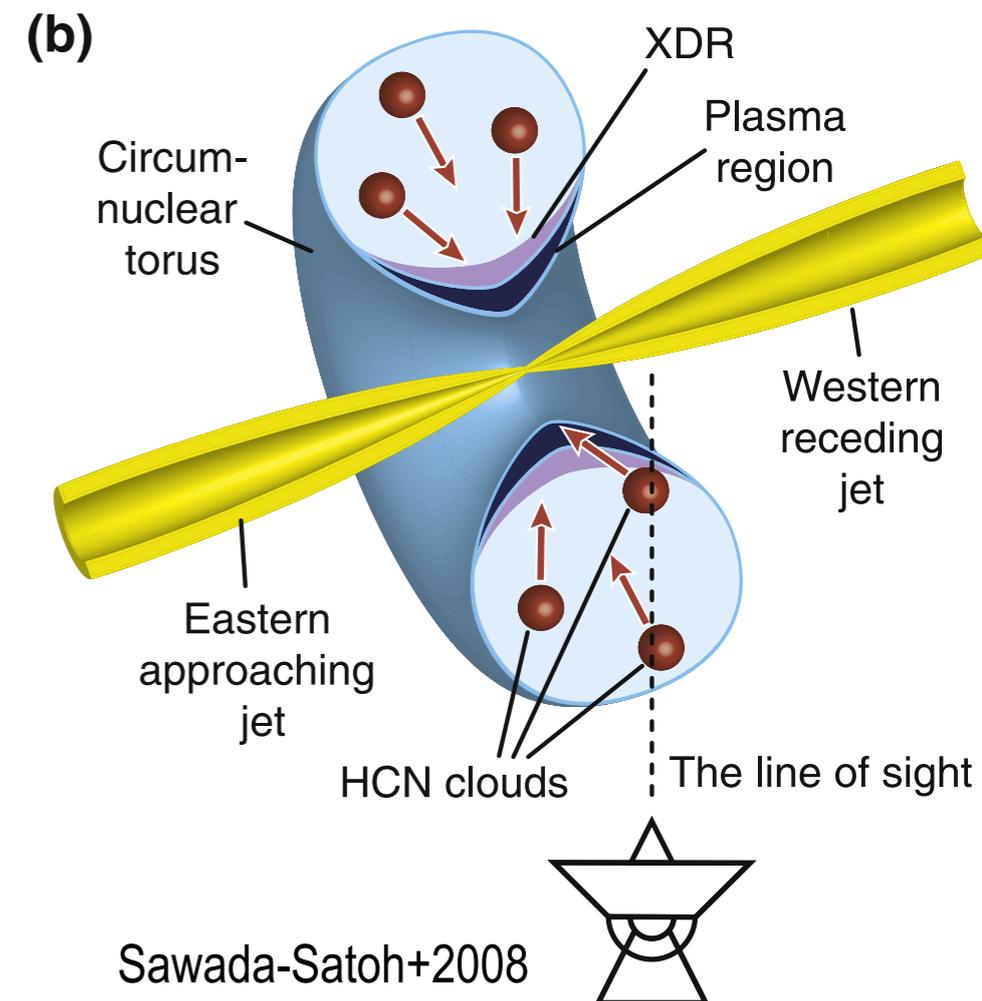
# Summary

## Radio absorption observations offer...

- Distribution of thermal plasma (w/ background synchrotron emitter)
- Velocity of molecules along the line of sight

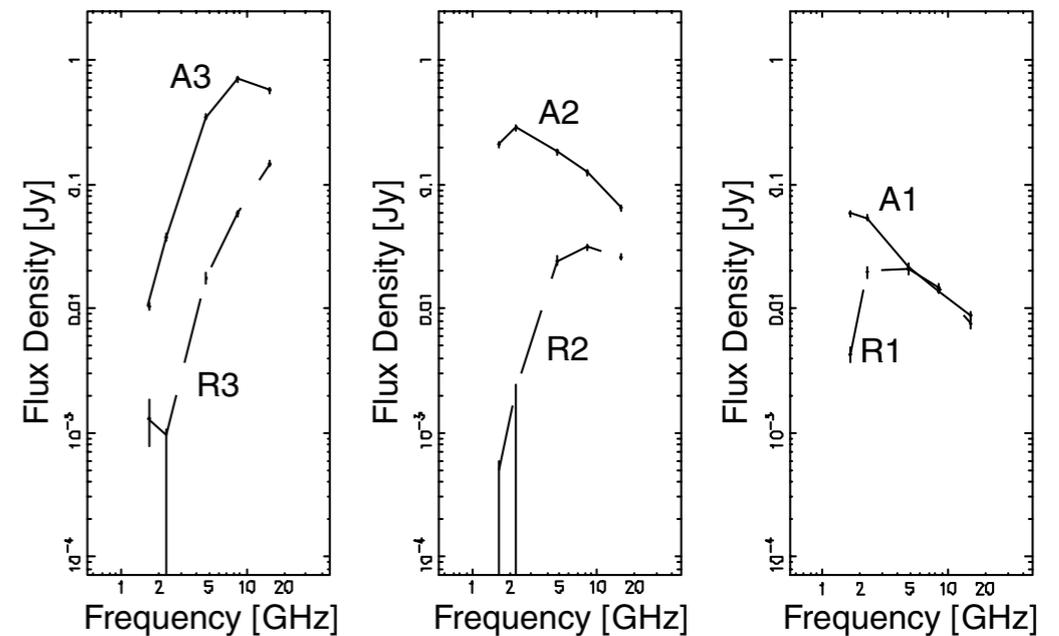
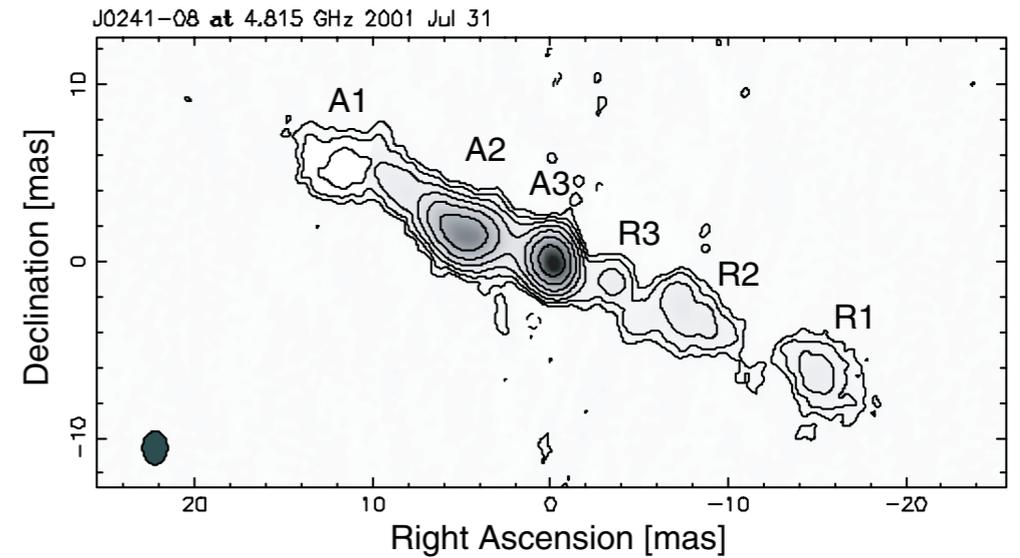
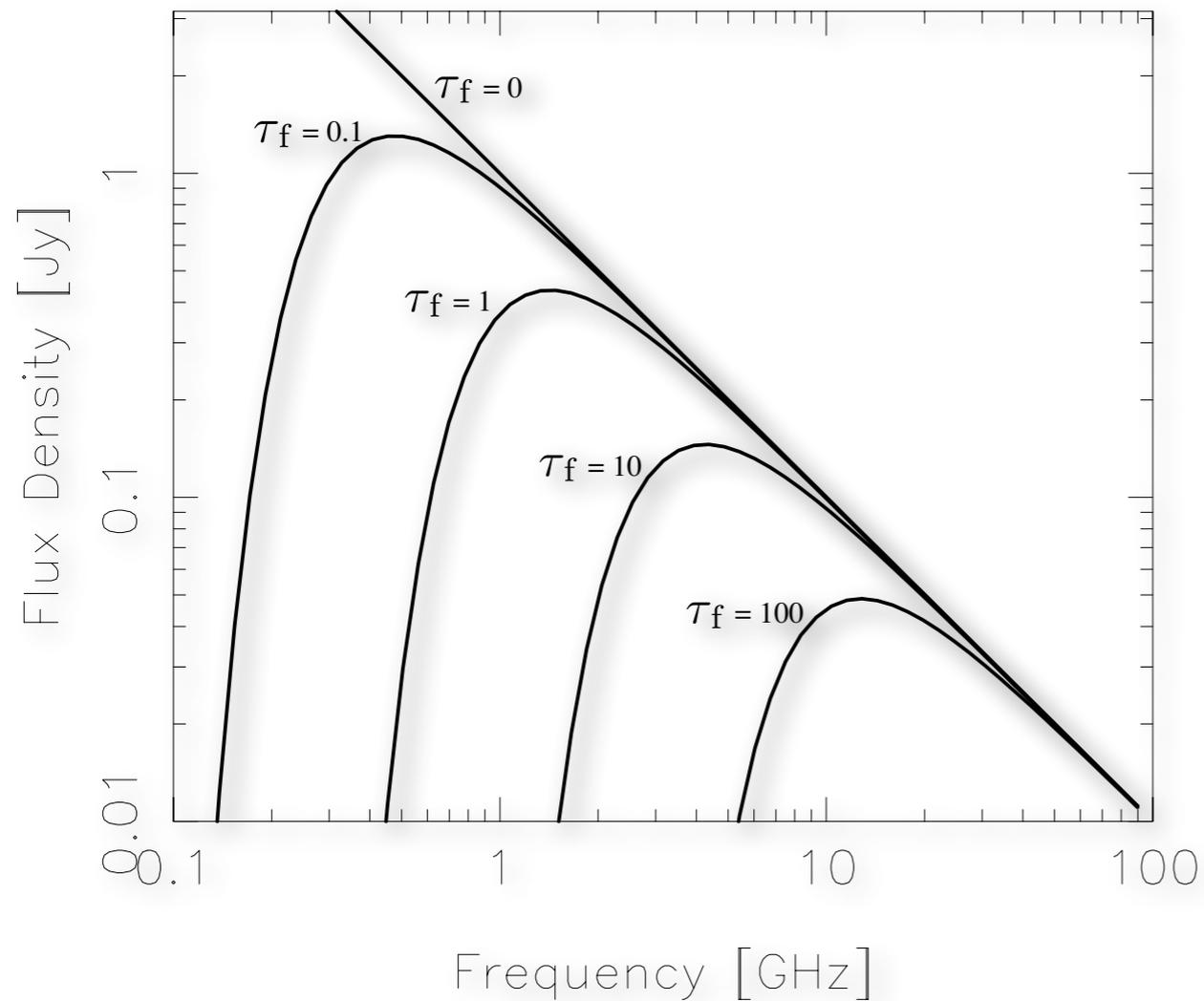
## For the torus structure and dynamics

- Temperature and density
- Chemical composition in molecular torus
  - CO, HCN, HCO<sup>+</sup>, CS, SO, and CN
  - isotopologues : H<sup>13</sup>CN, HC<sup>15</sup>N
  - vib-excited HCN, HCO<sup>+</sup>
- Vertical structure of a geometrically thick torus
  - Molecular + XDR + plasma
  - Clumpy molecular clouds



# Plasma free-free absorption

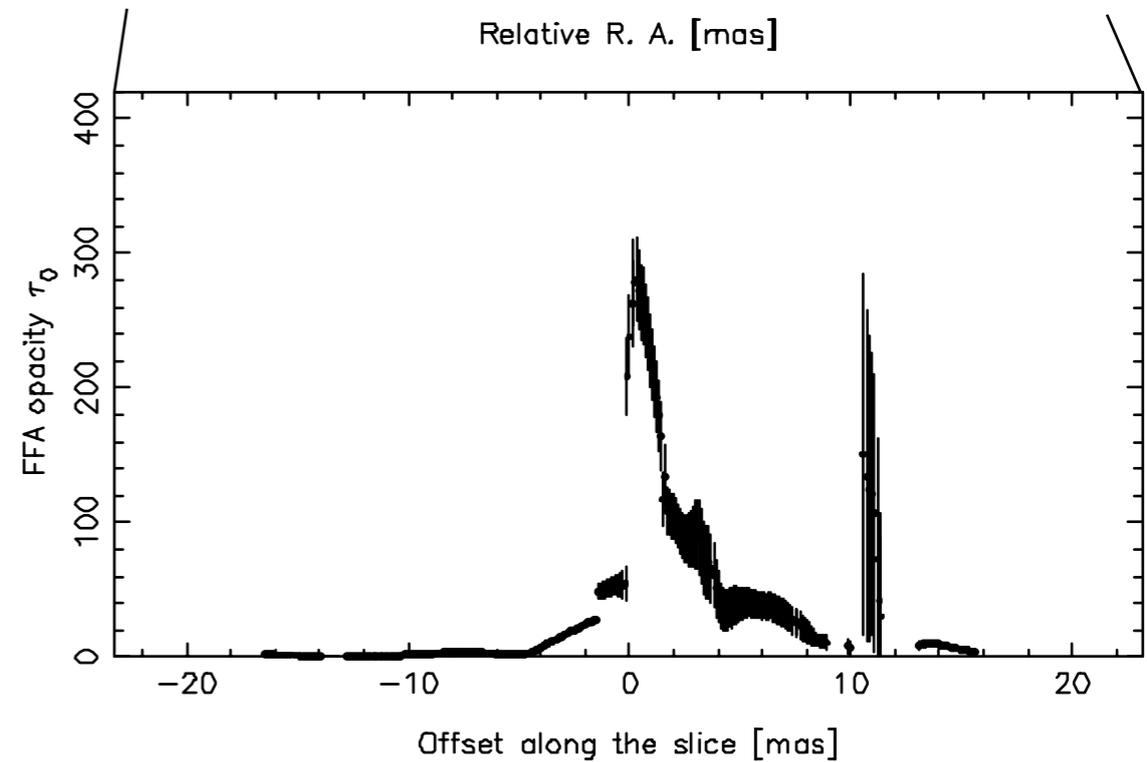
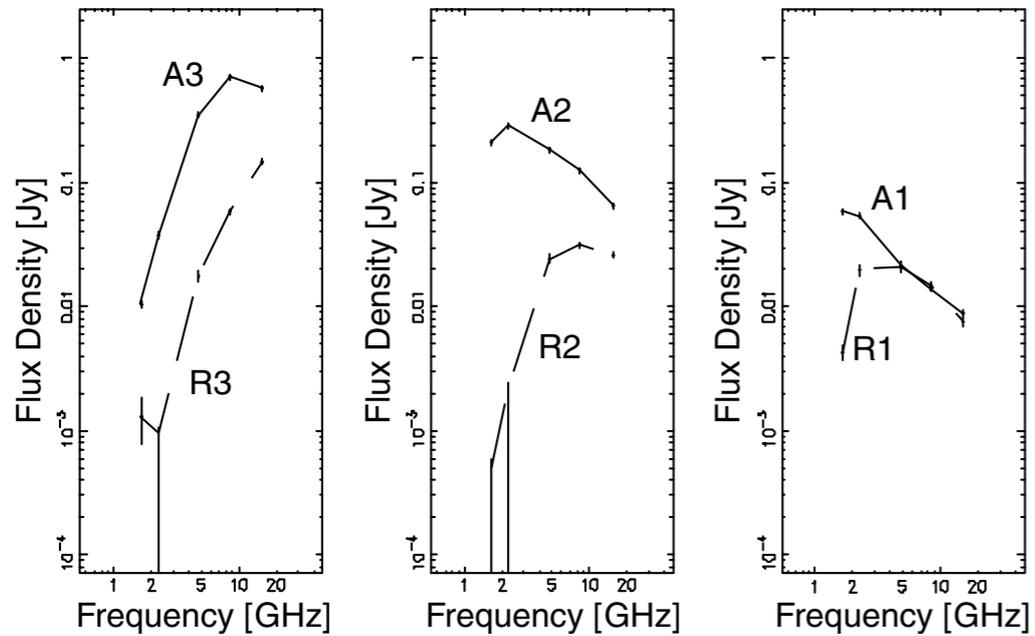
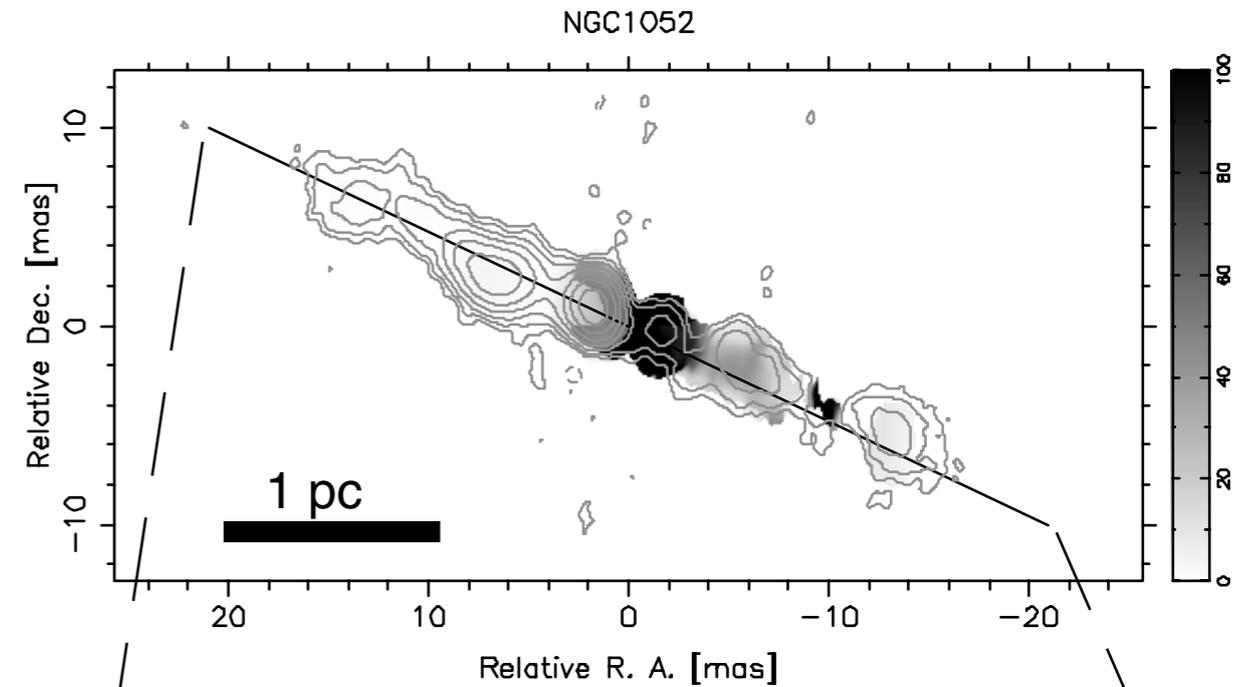
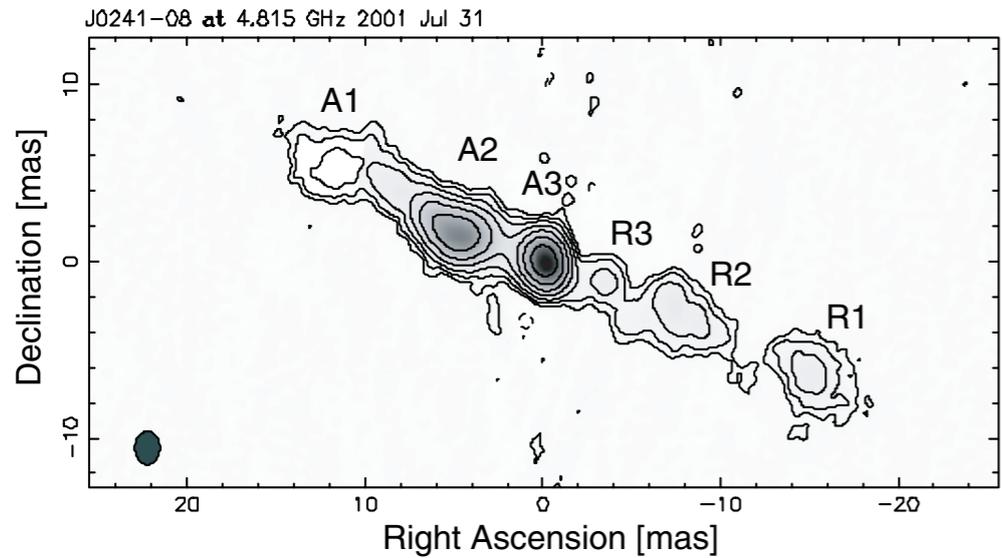
Changes of the peak frequency for various FFA opacities



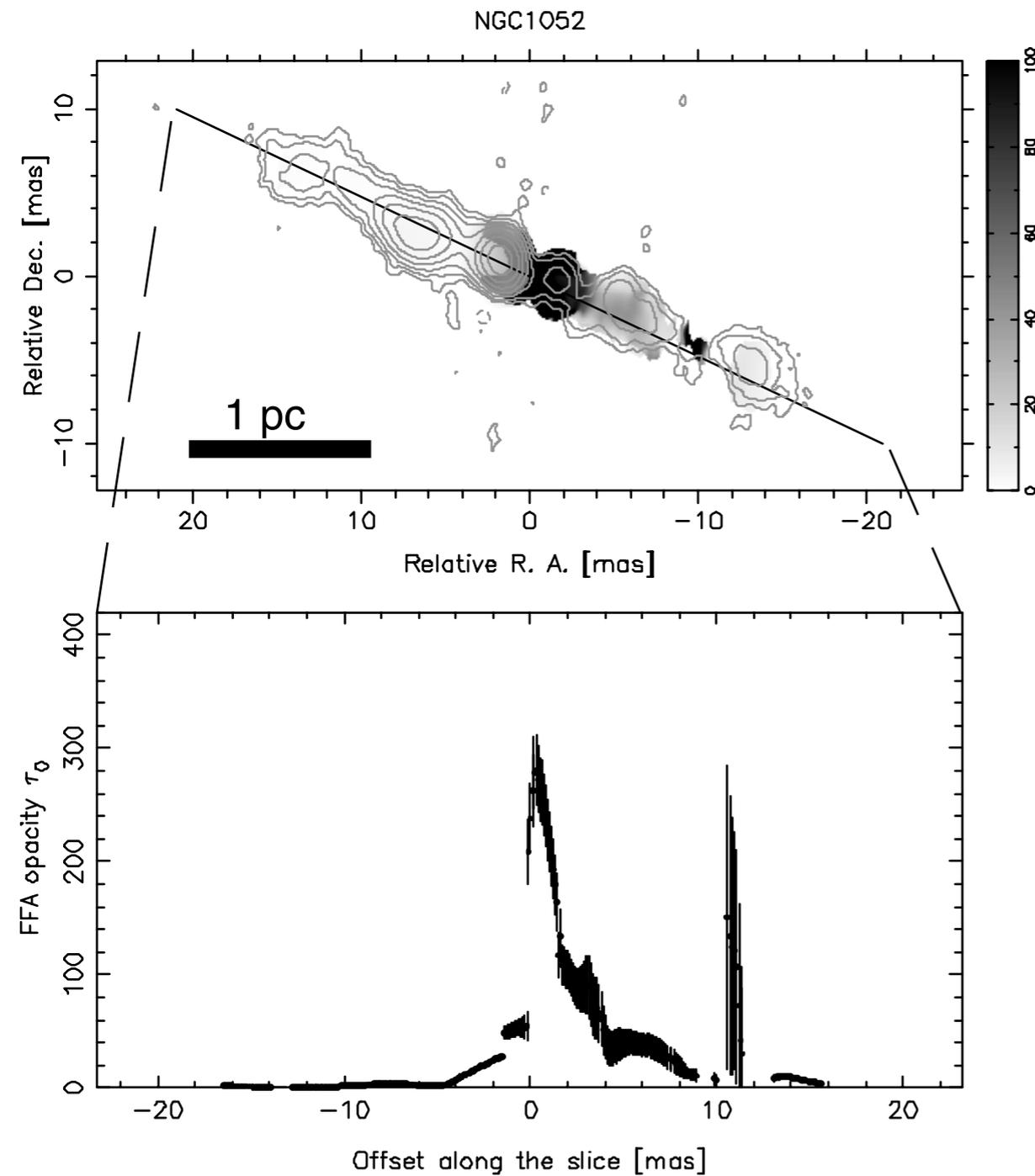
$$\tau_f = 0.46 \int_{\text{LOS}} T_e^{-\frac{3}{2}} n_e^2 dL,$$

optical depth is proportional to the emission measure

# Plasma free-free absorption



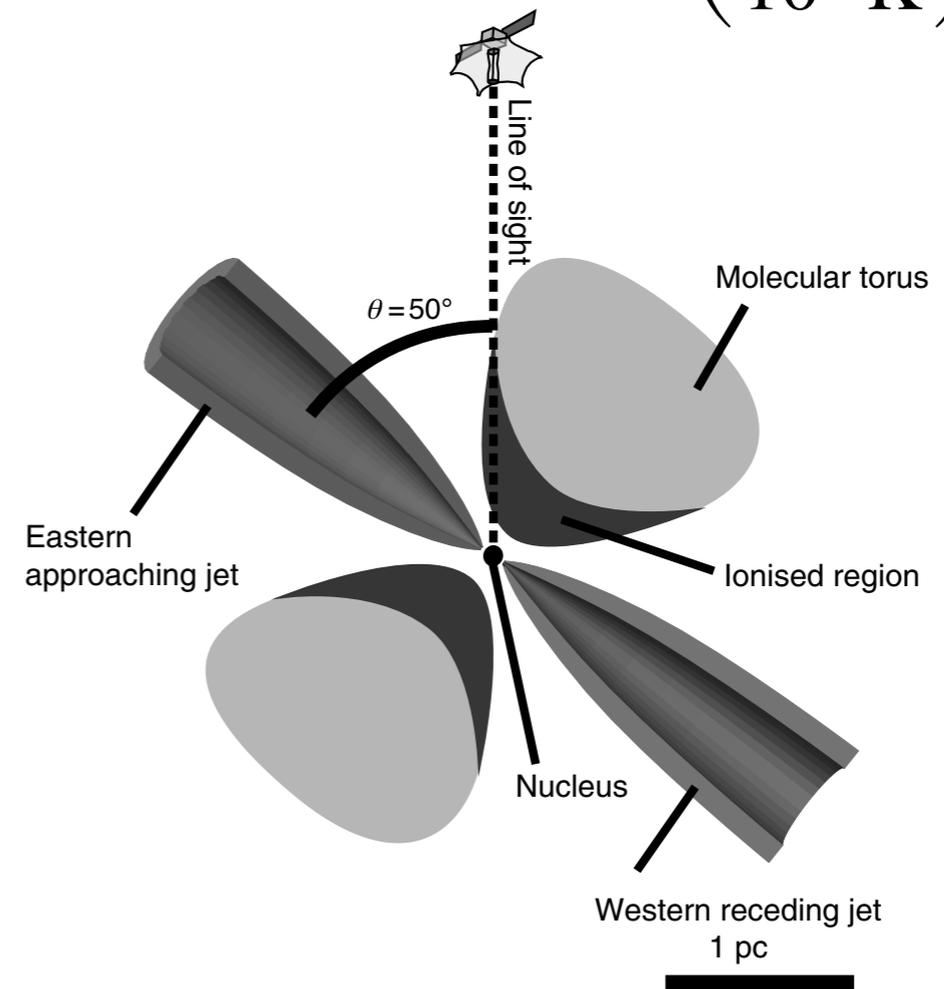
# Plasma free-free absorption



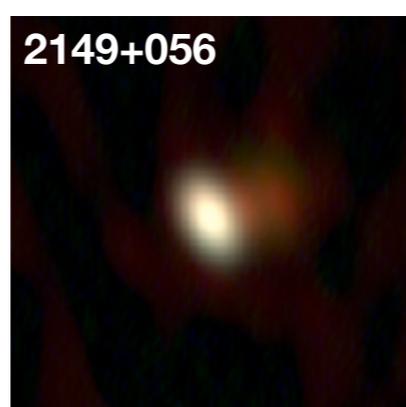
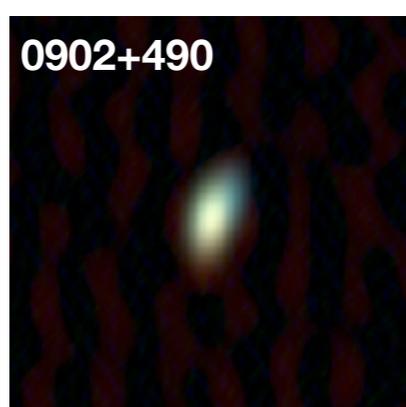
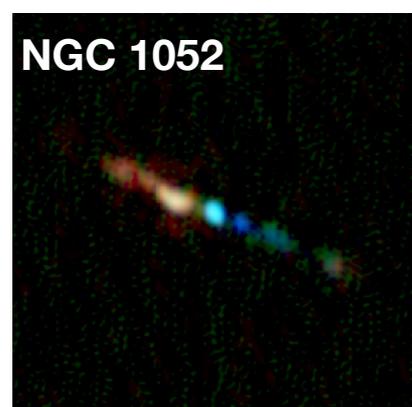
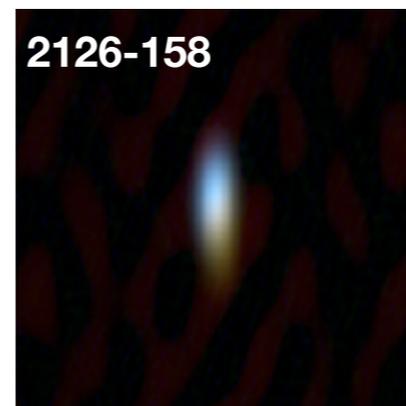
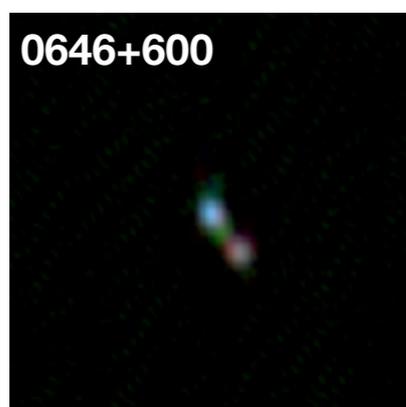
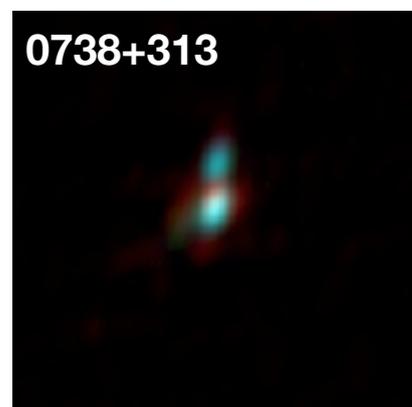
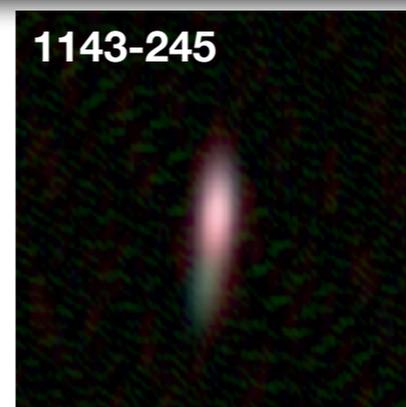
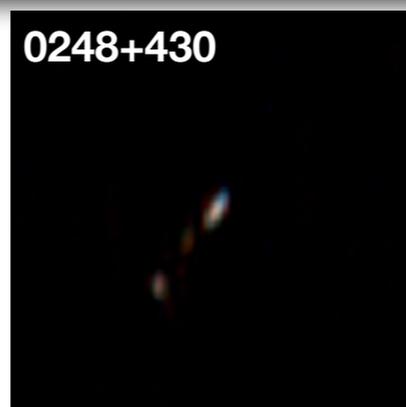
$$\tau_{\text{ff}} \simeq 300$$

$$\rightarrow n_e^2 T_e^{-3/2} = 650,$$

$$\rightarrow n_e L = 0.8 \times 10^{23} \left( \frac{T_e}{10^4 \text{ K}} \right)^{3/4} \text{ cm}^{-2}$$



# Plasma free-free absorption survey

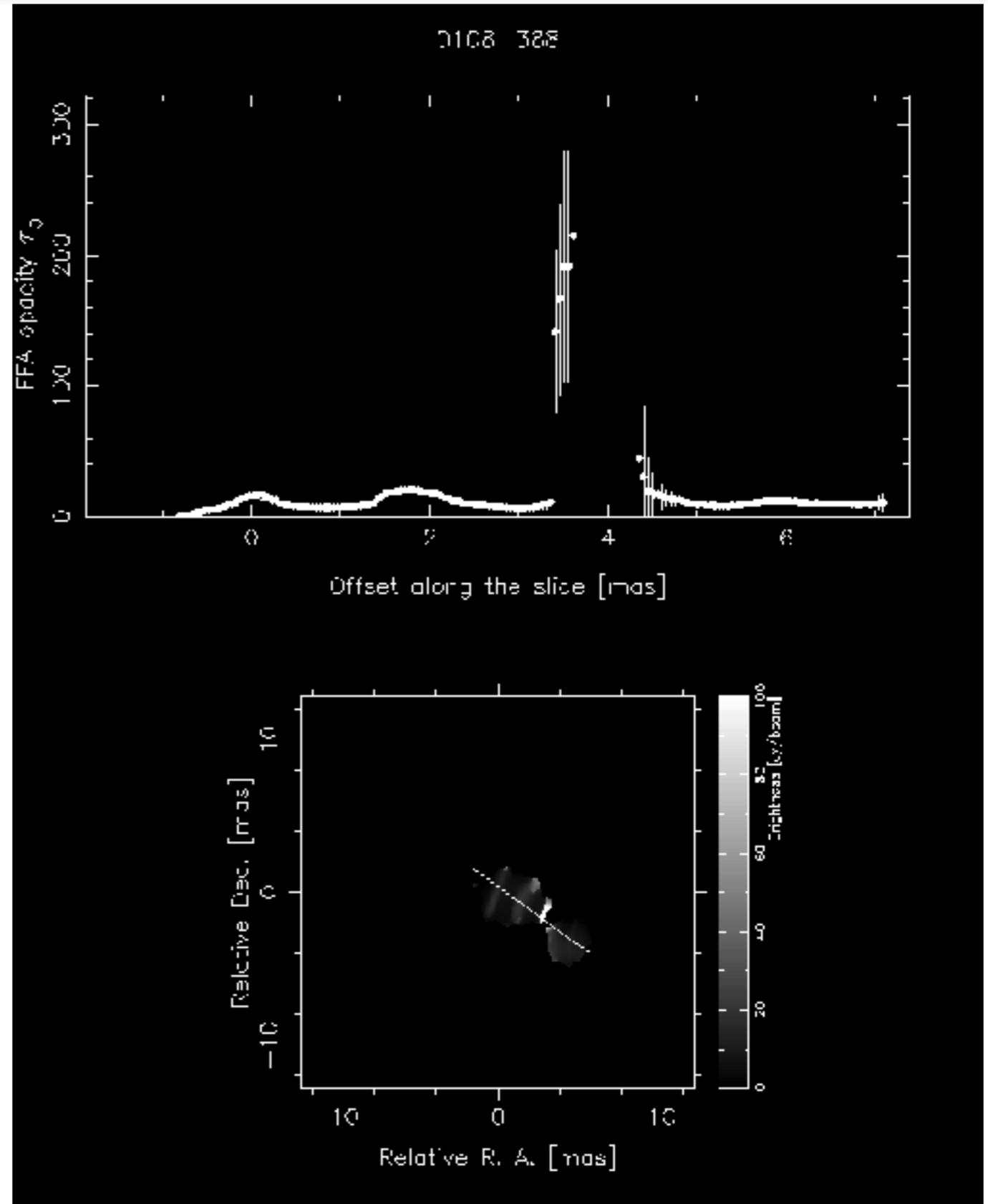
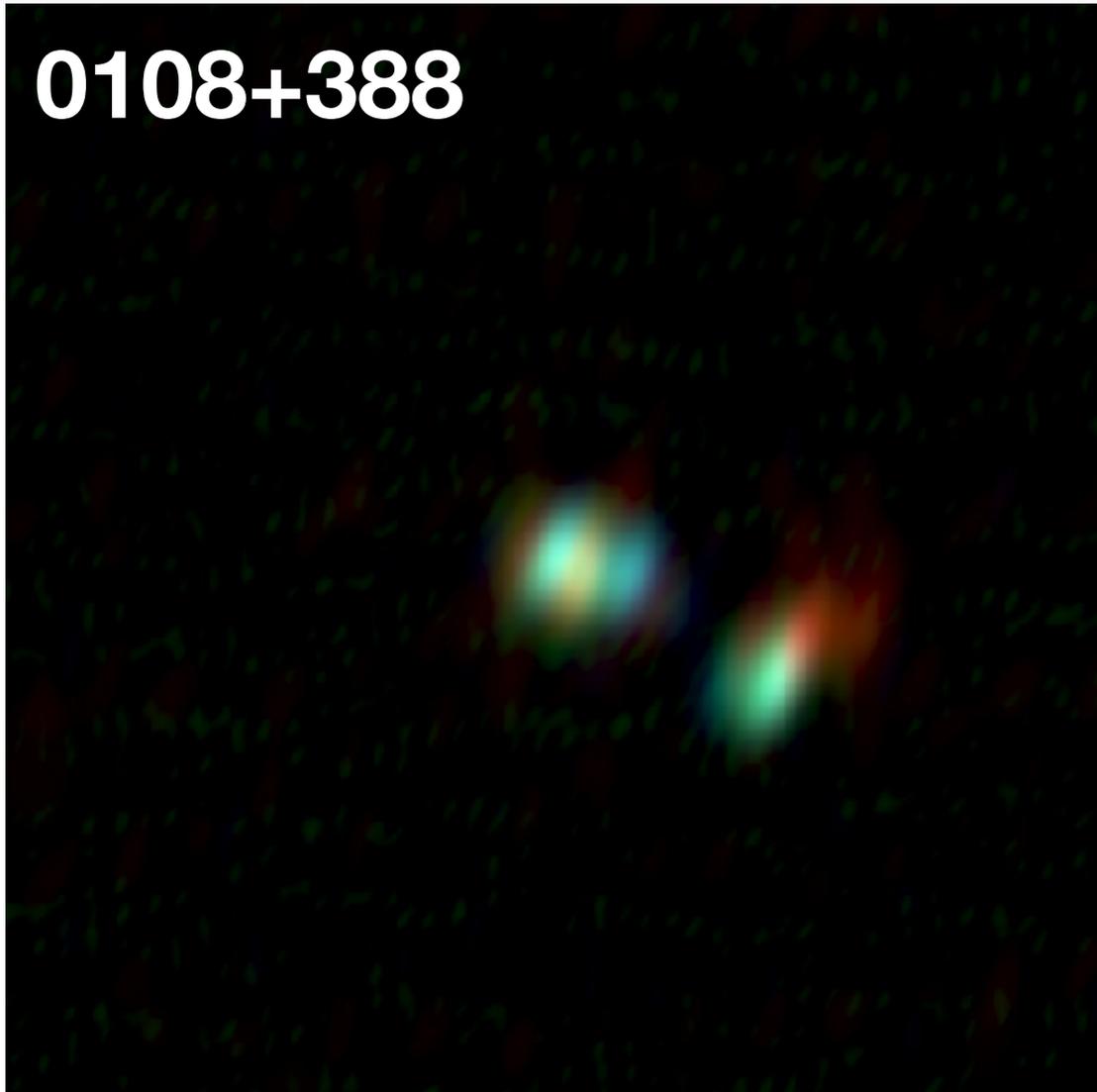


- 19 GPS sources (young radio galaxies)
- five-frequency VSOP + VLBA obs.
- 6/19 show torus-like FFA



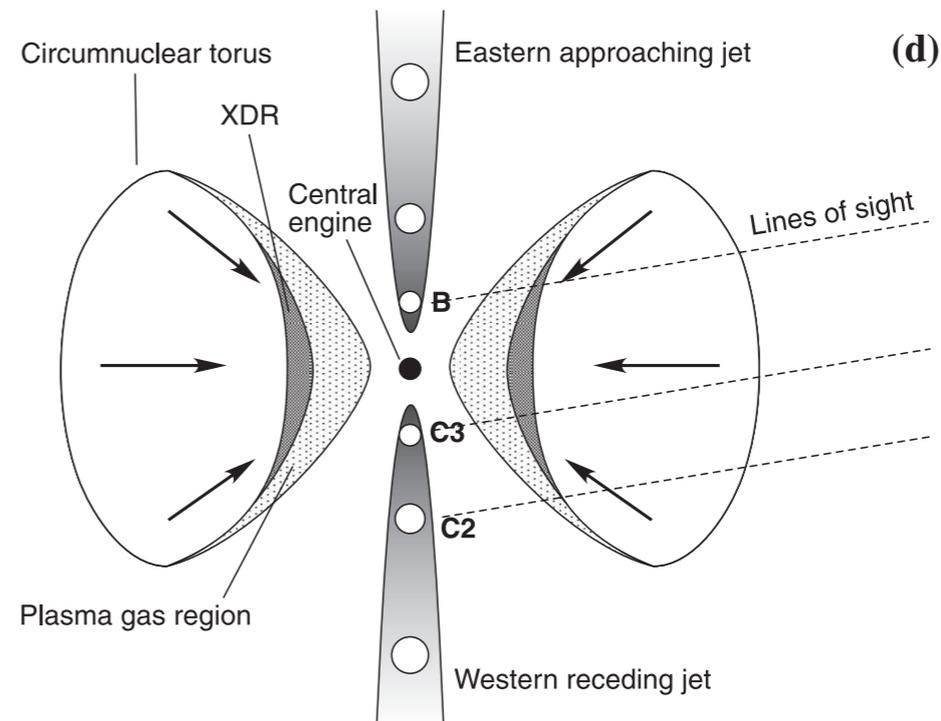
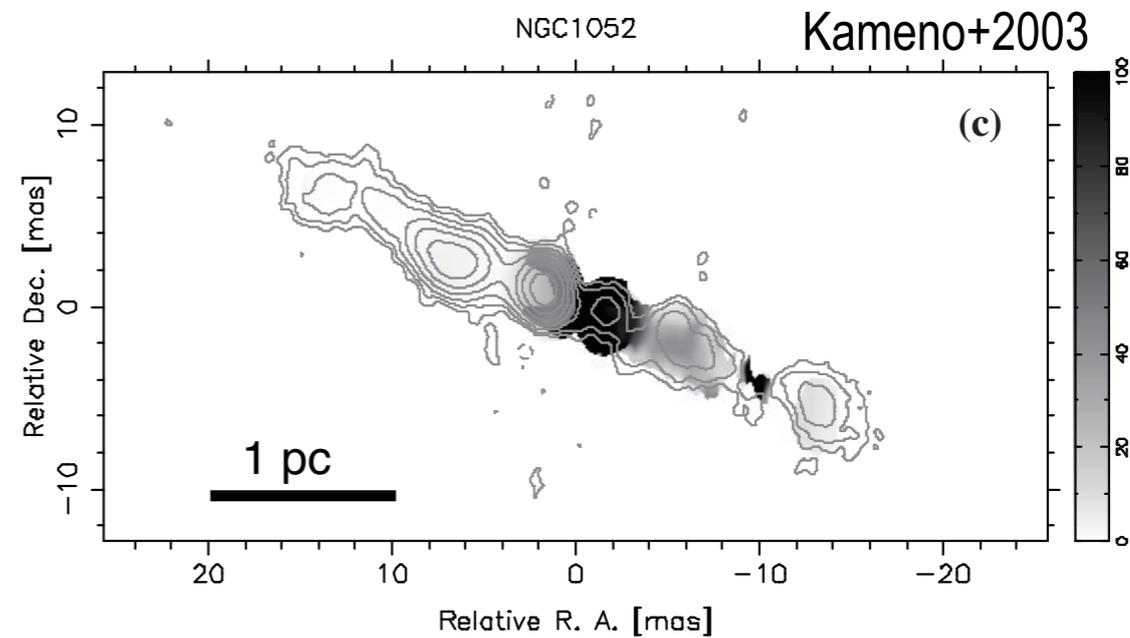
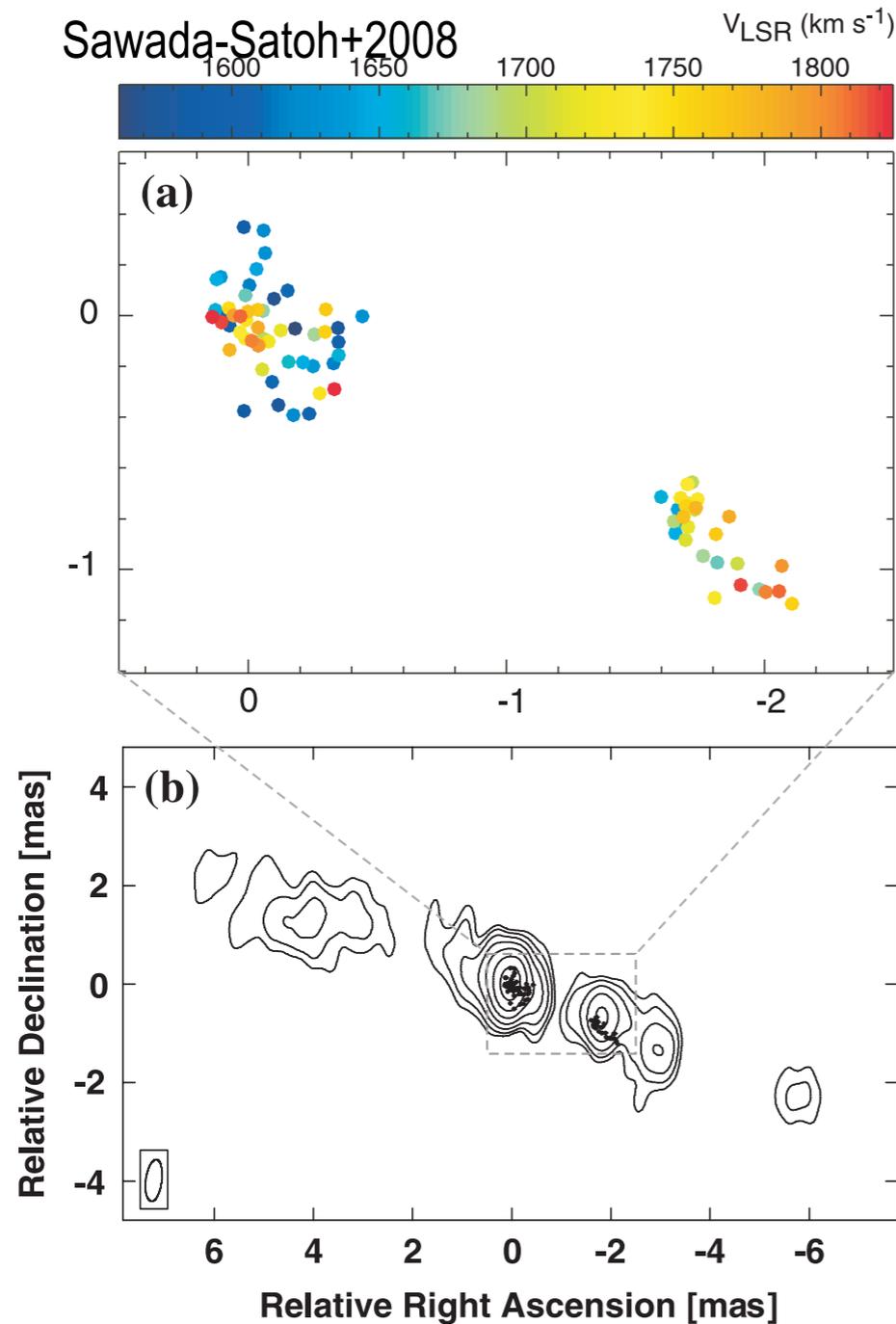
# Plasma free-free absorption survey

0108+388



# Spatial coincidence of FFA and H<sub>2</sub>O masers

Masers (XDR) locate where  $\tau_{\text{FFA}, 22 \text{ GHz}} \sim 0.2$   
 Amplification of background jet radiation



ALMA molecular absorption survey  
in  
nearby radio galaxies

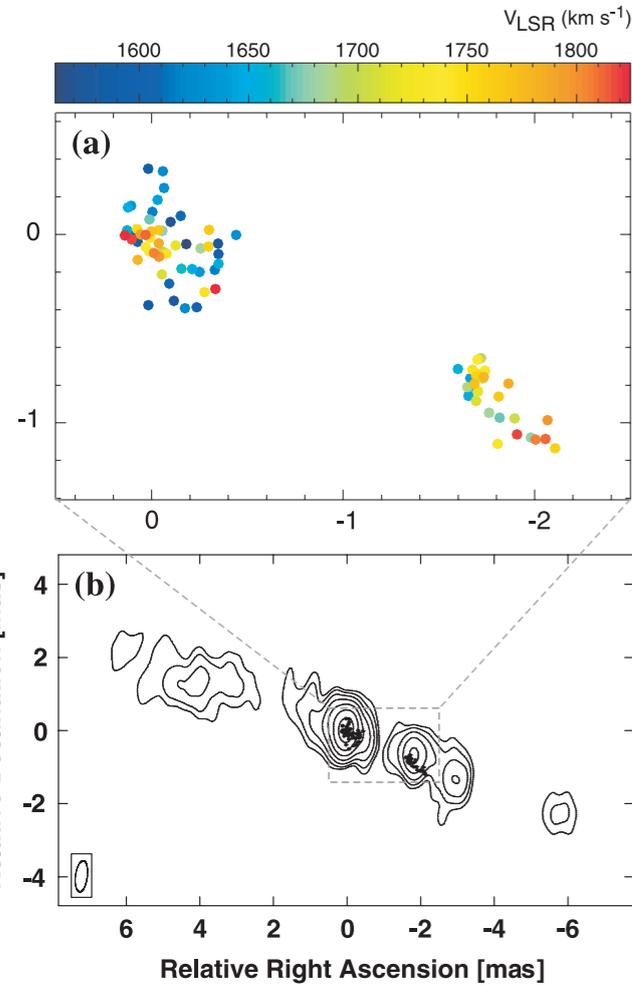
# ALMA molecular absorption survey in nearby radio galaxies

Source	Host galaxy	FFA	Dust disk	Emission	Absorption
NGC 1052	E	Y	Y	CO	CO, HCN, HCO <sup>+</sup> , SO, CS, CN, H <sub>2</sub> O, HCS <sup>+</sup>
NGC 4261	E	Y	Y	CO	CO, HCN, HCO <sup>+</sup> , CS
NGC 6328	SAB	?	Y	CO, HCO <sup>+</sup> , CS	HCO <sup>+</sup>
IC 1459	E	?	Y	-	CO, HCO <sup>+</sup> (?)
3C 75	E, binary	?	?	-	CO (?)

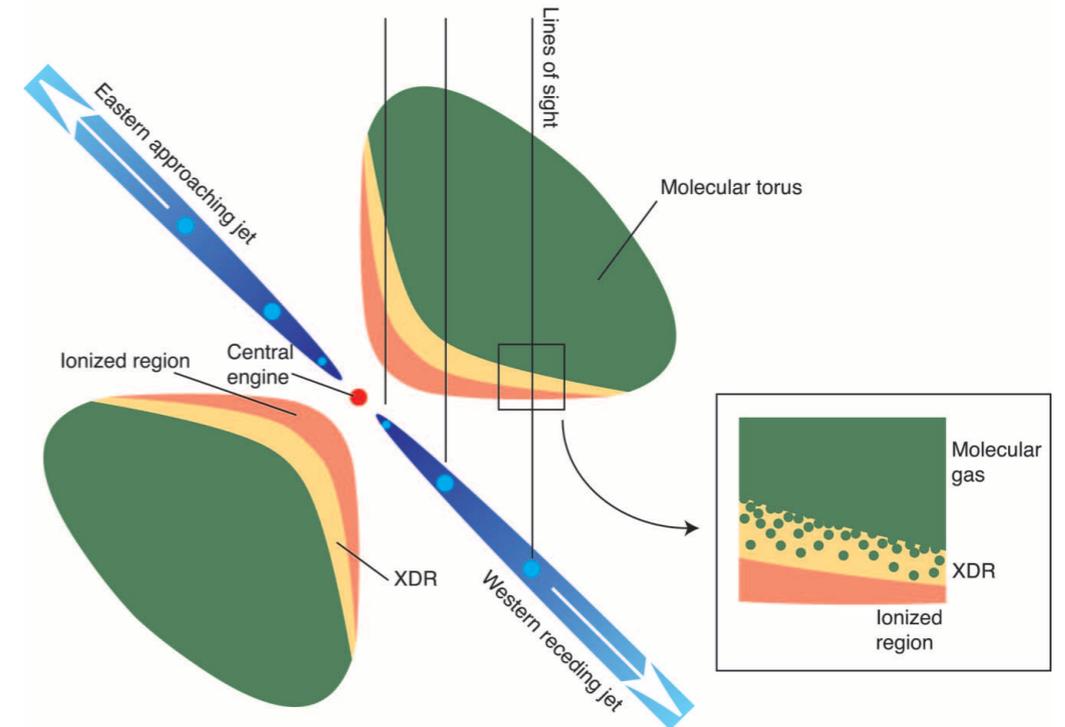
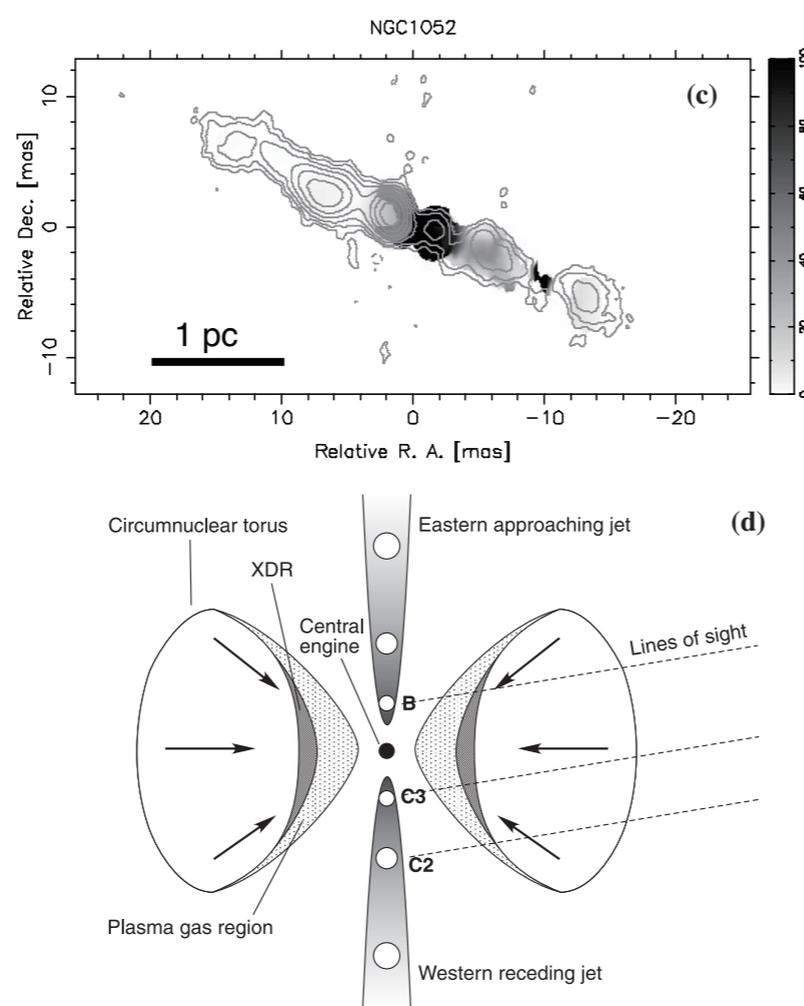
# NGC 1052

Host galaxy E4  $B_T=11.41$  mag  
 Distance 20.3 Mpc,  $1''=98$  pc  
 Velocity  $V_{\text{sys}}(\text{LSR, Radio}) = 1471$  km s $^{-1}$   
 Radio continuum 0.4 Jy@345 GHz  
 Radio Jet  $\beta = 0.25$ ,  $i=62^\circ \pm 10^\circ$   
 H $_2$ O maser velocity = 1400 - 1850 km/s  
 Line absorption HI, OH, HCO $^+$ , HCN, CO  
 Free-free absorption

Sawada-Sato+2008



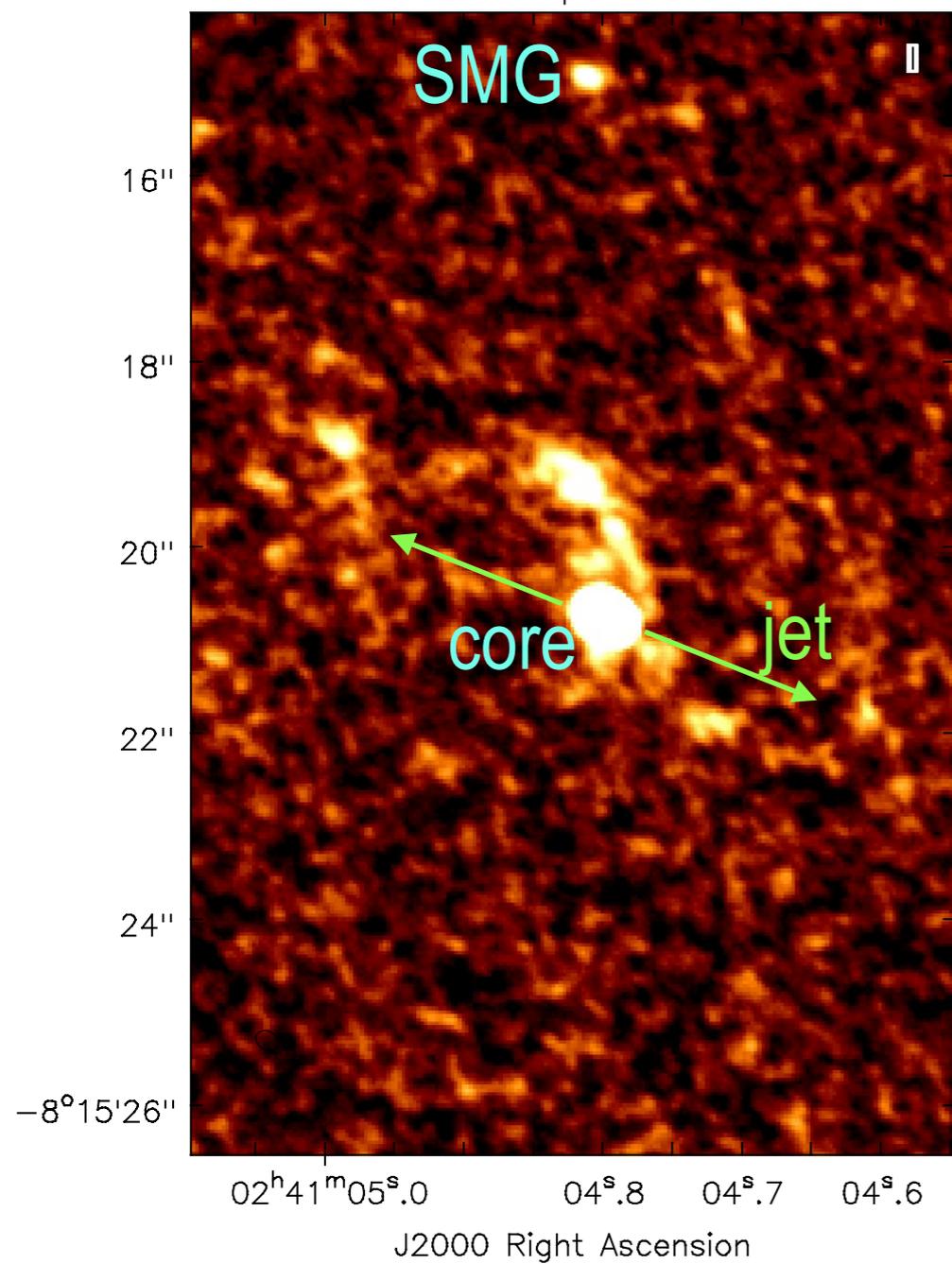
Kameno+2003



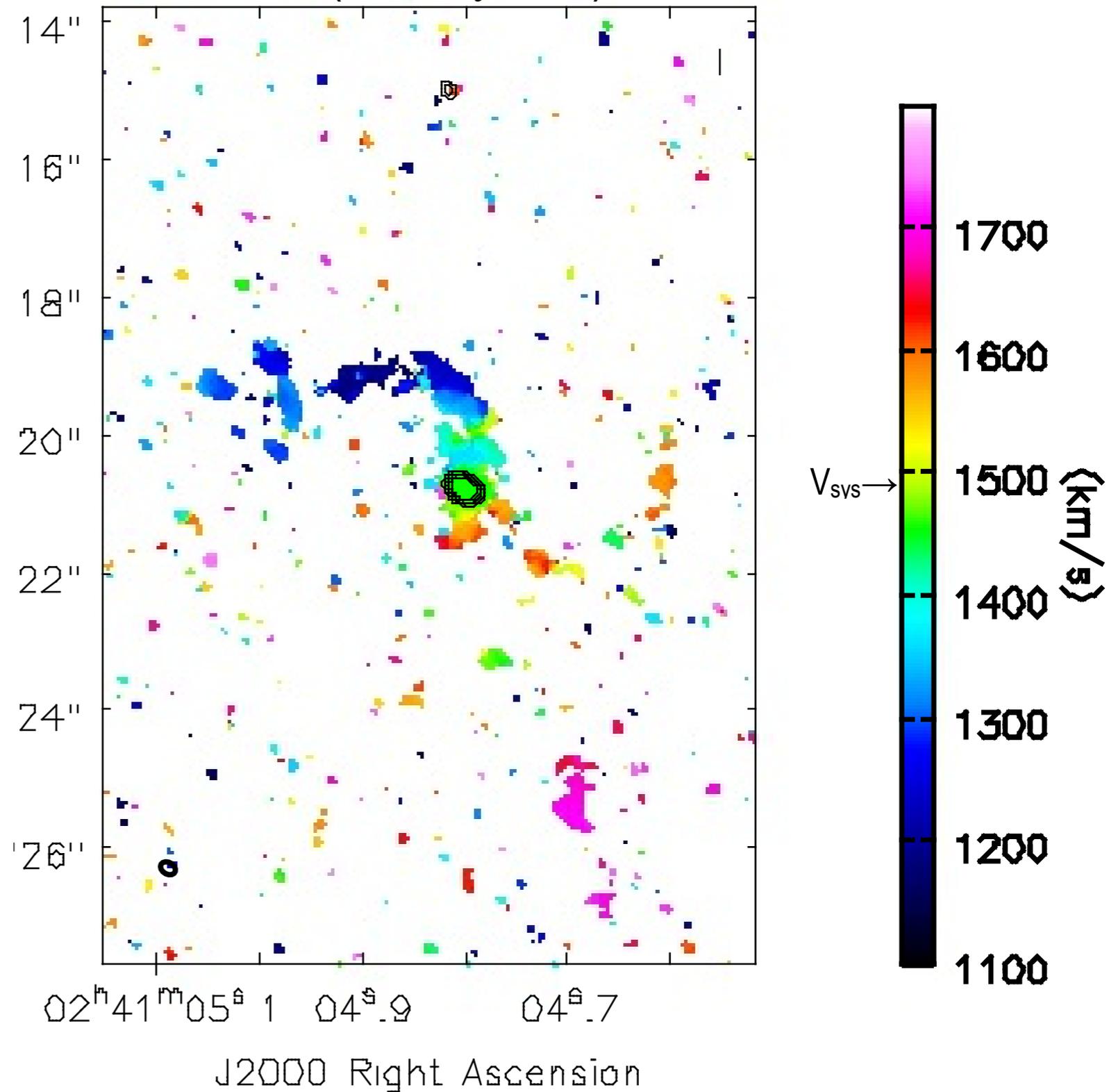
Kameno+2005

# Molecular gas distribution and velocity (CO)

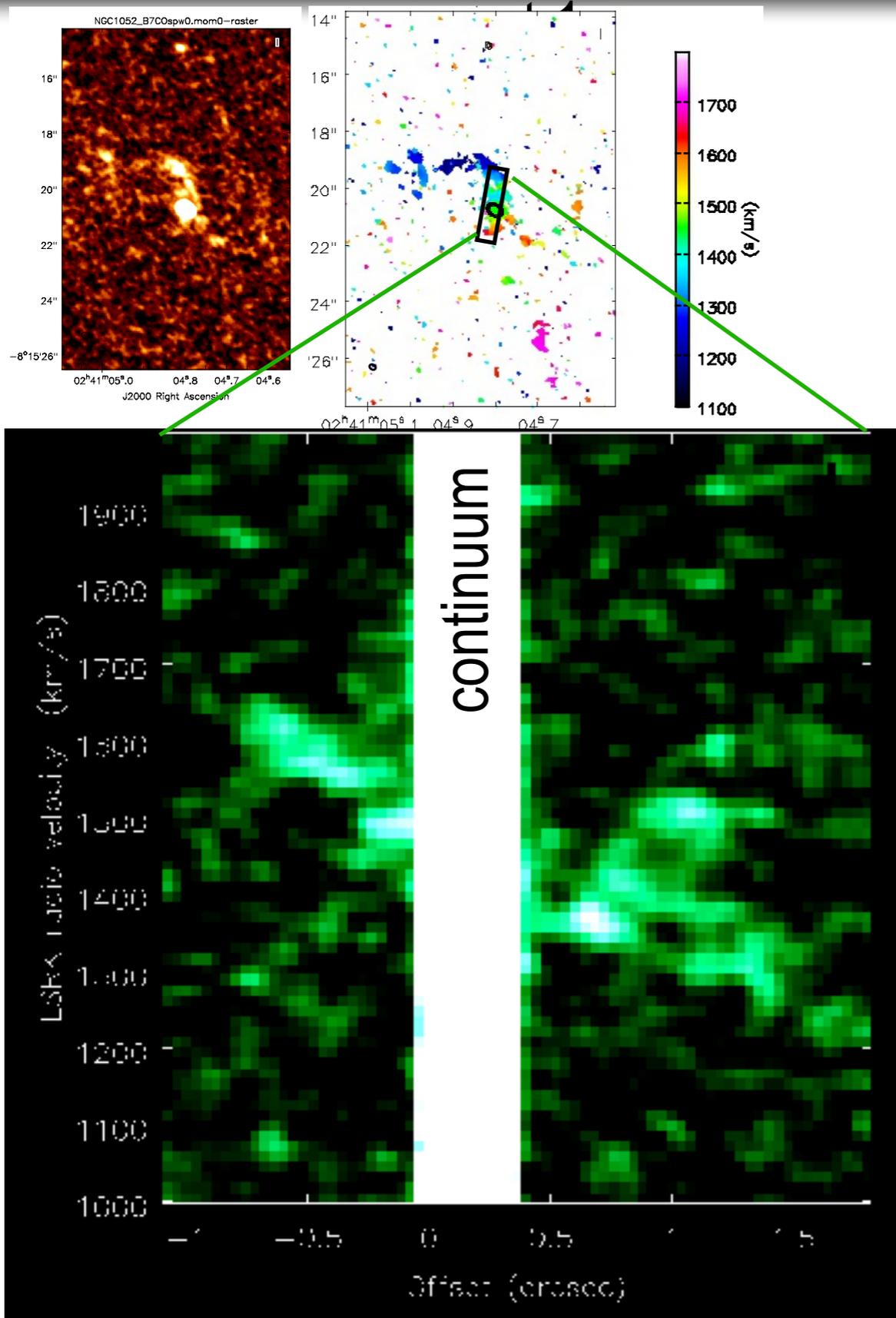
CO (3-2) total intensity map



moment-1 (velocity field)

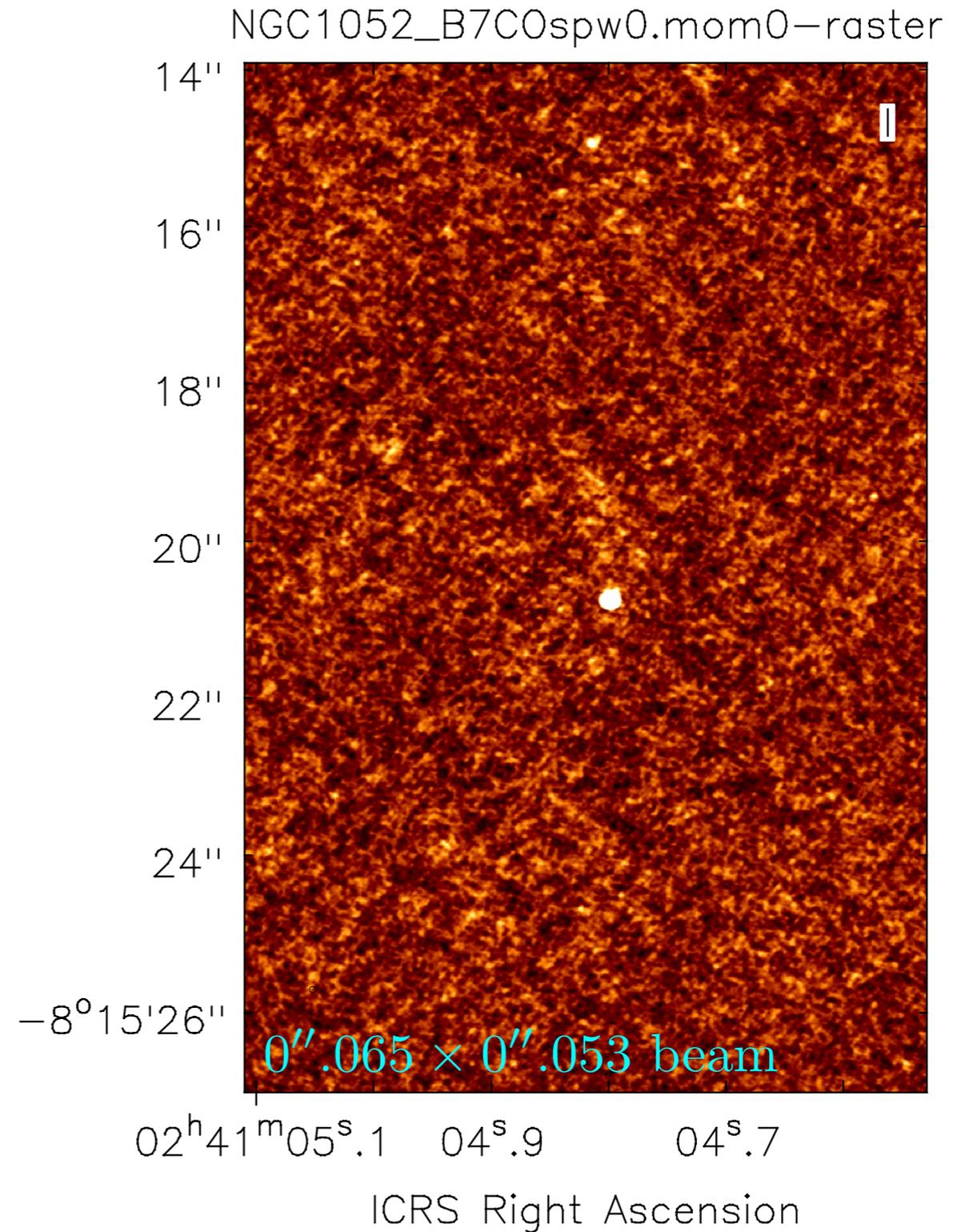
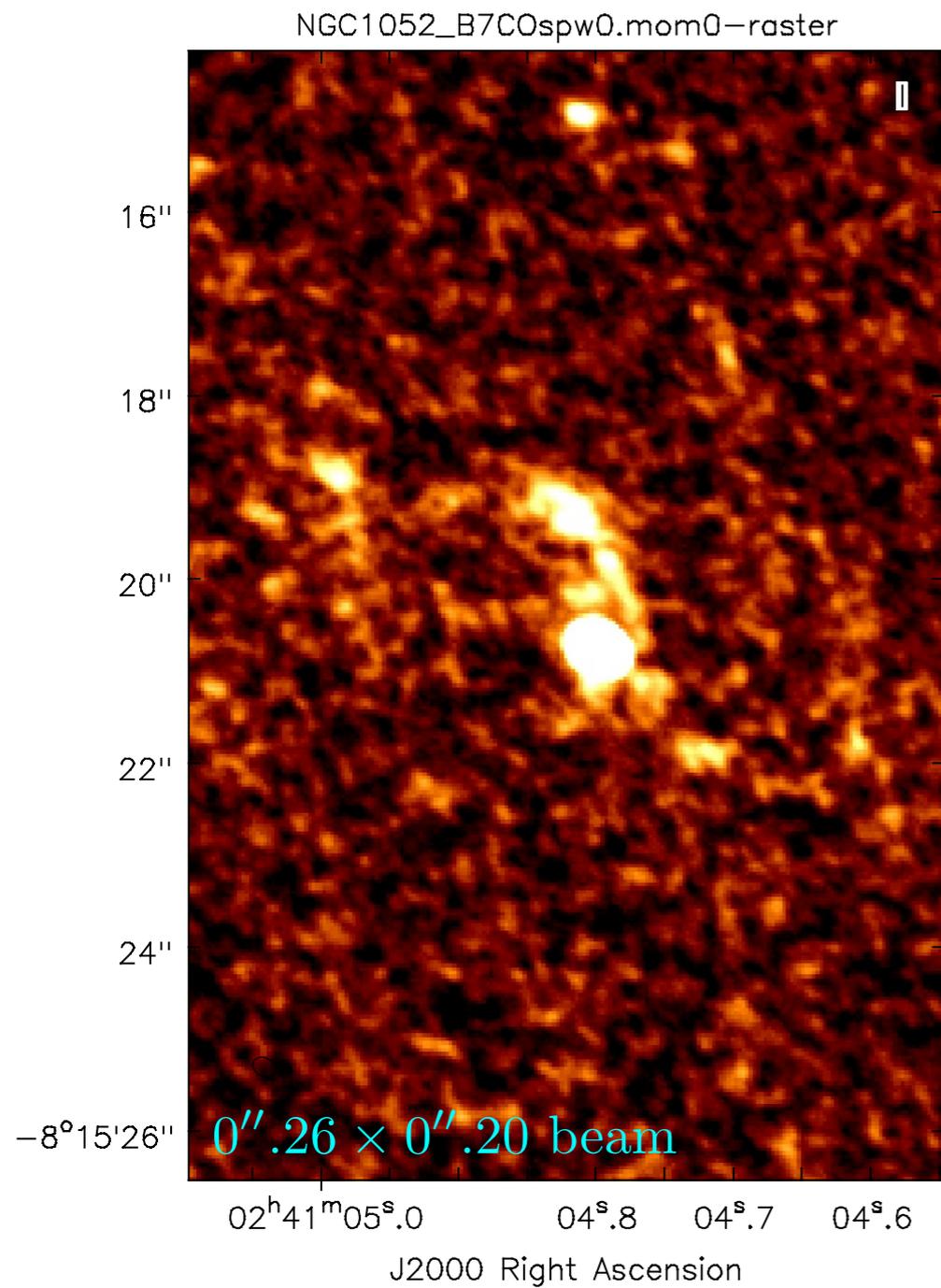


# CND (CircumNuclear disk) rotation

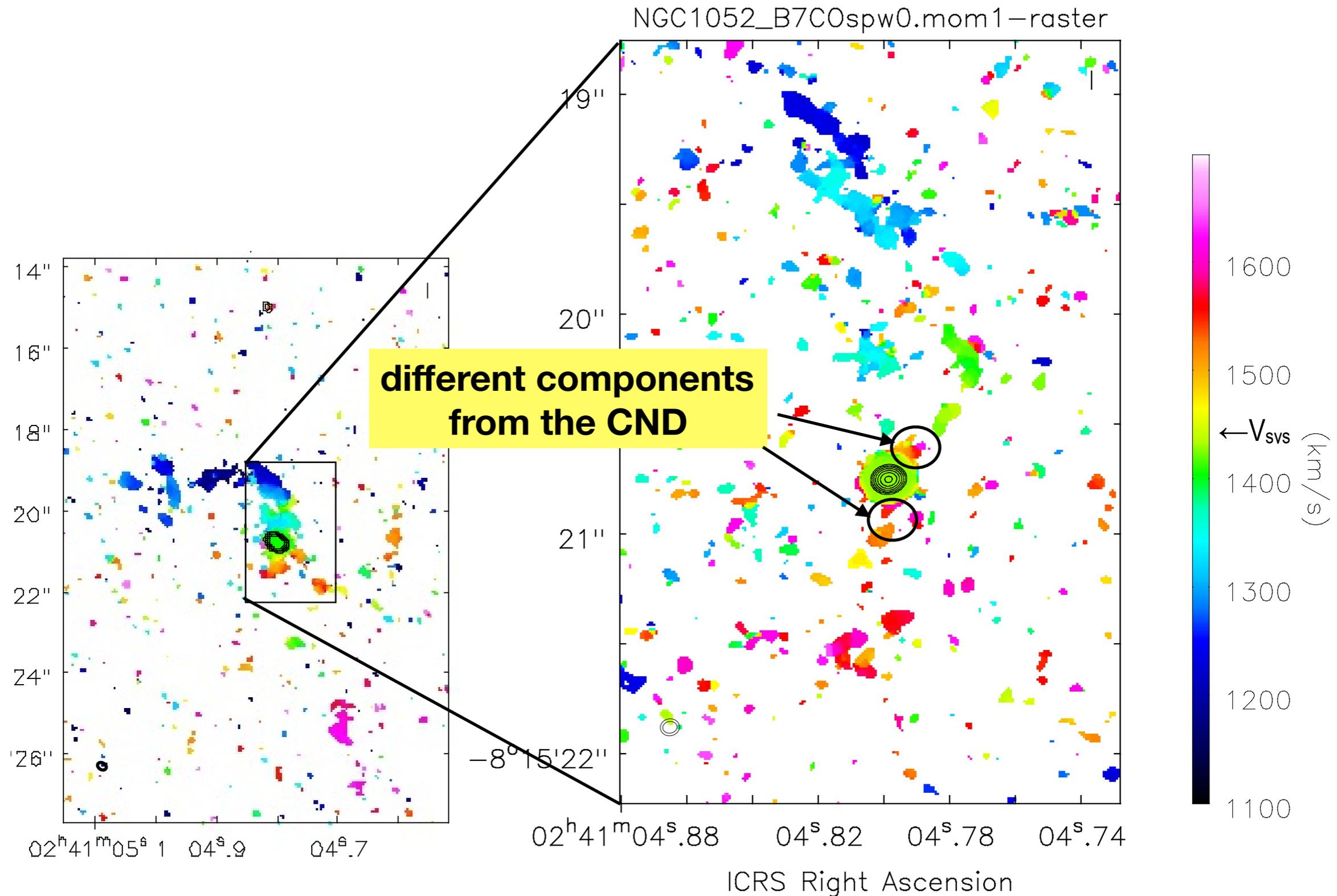


- radius  $\sim 100$  pc
- rotation speed  $\sim 150$  km s<sup>-1</sup>
- enclosed mass =  $5 \times 10^8 M_{\odot}$

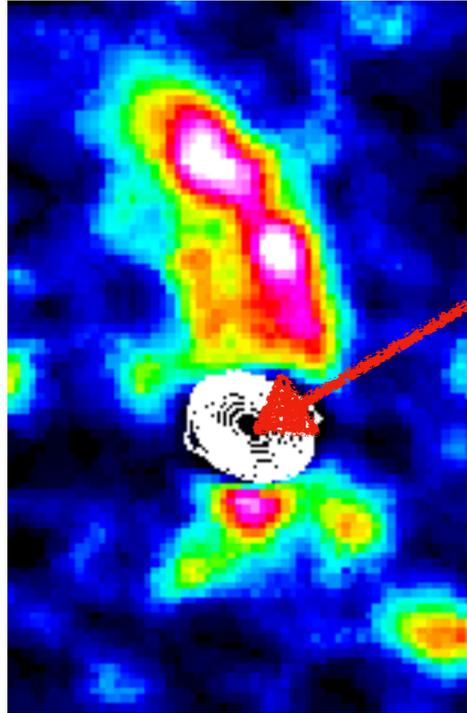
# Long-baseline view



# High-resolution velocity field



# CO line profile toward the nucleus

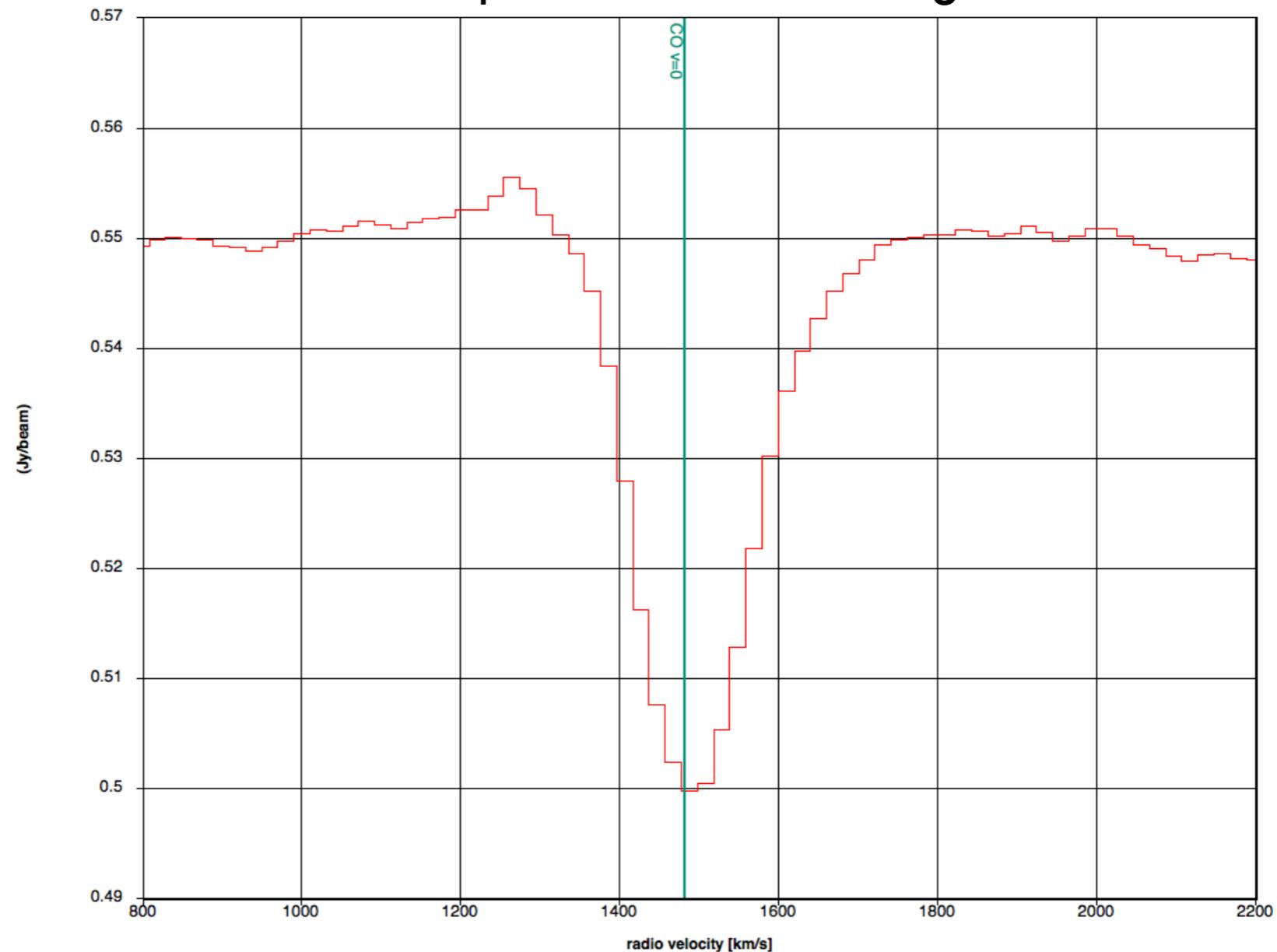


Spectra toward  
the nucleus

**CO (J=2-1) : inverse P-Cyg profile**

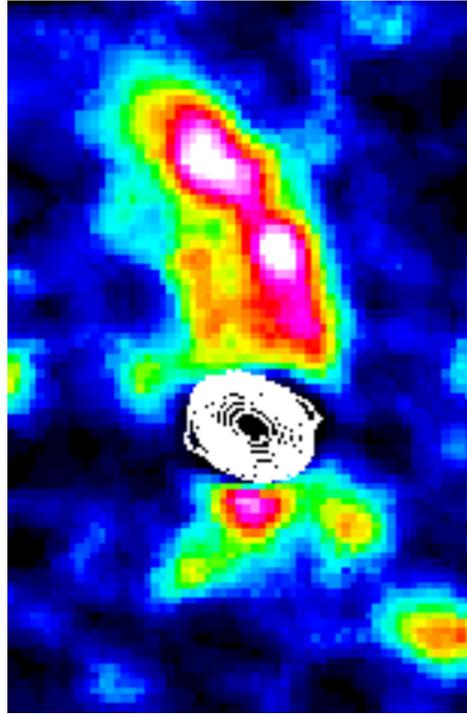
blue emission + red absorption

implication of inward gas motion



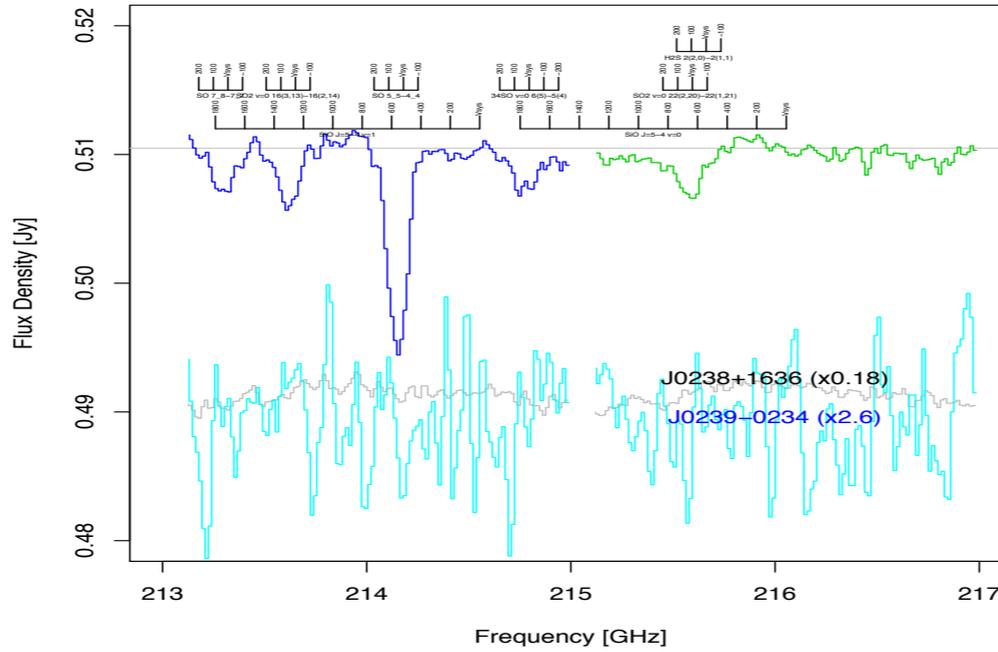
# Absorption features

- CO, HCN, HCO+, CS, SO, and CN
- isotopologues : H<sup>13</sup>CN, HC<sup>15</sup>N
- vib-excited HCN, HCO+

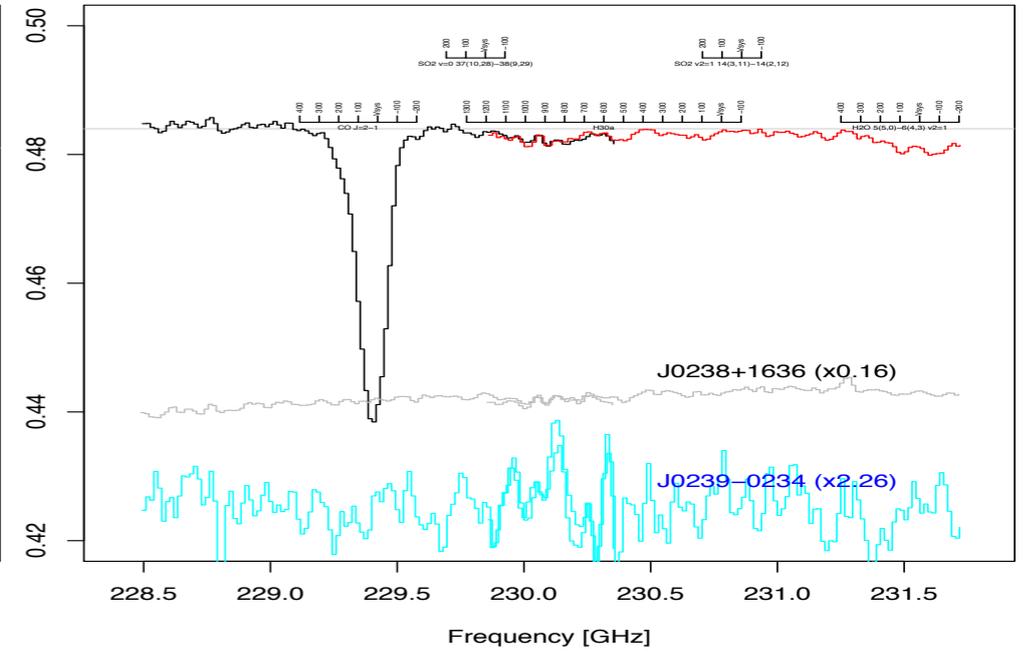


Spectra toward the nucleus

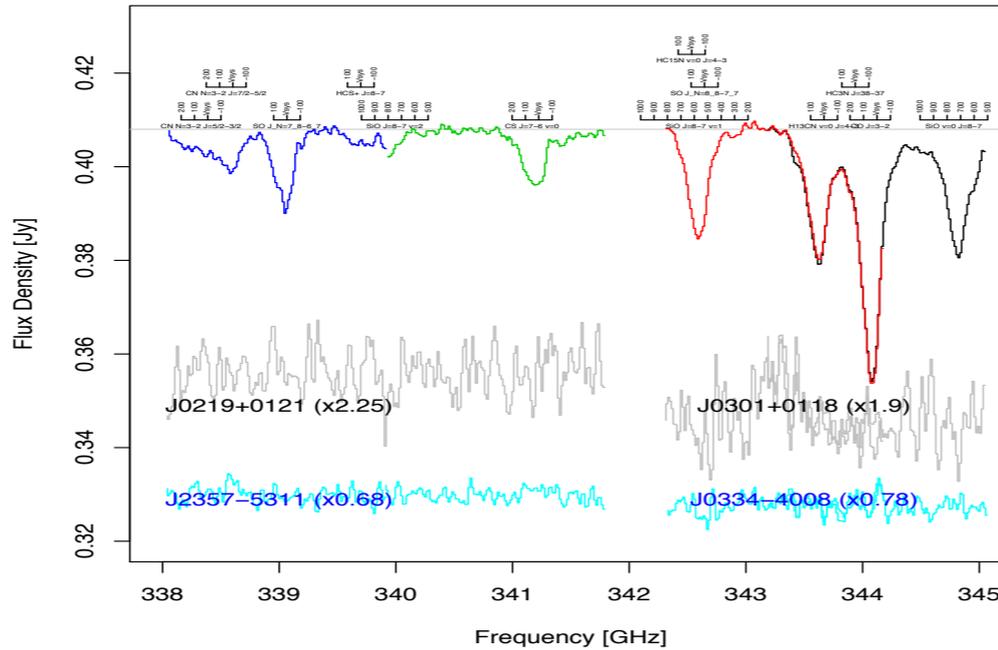
NGC 1052 Cycle 2 Band 6



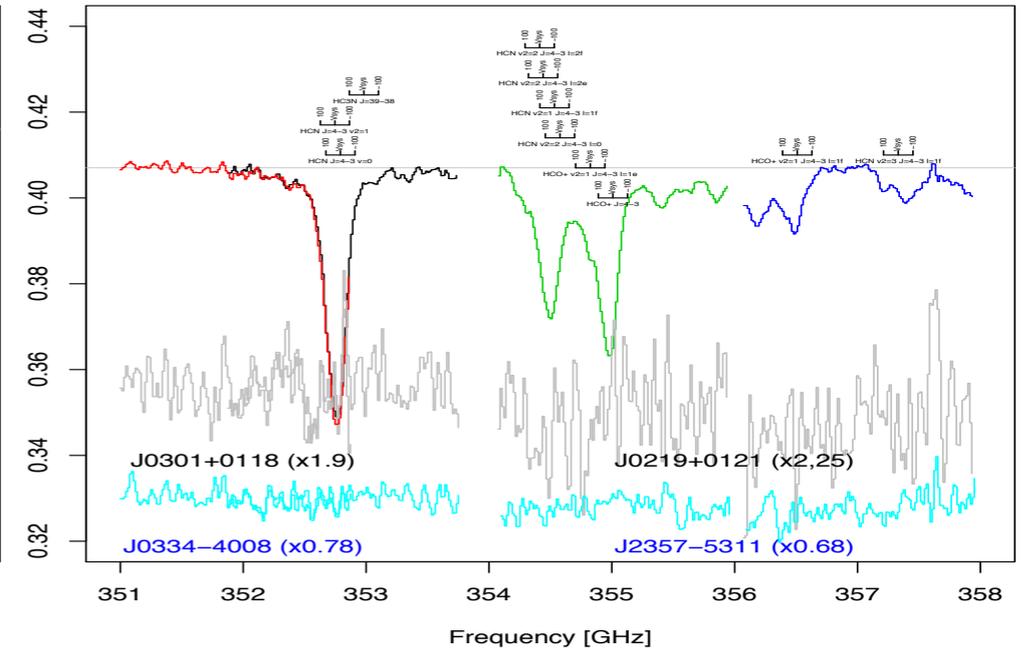
NGC 1052 Cycle 2 Band 6



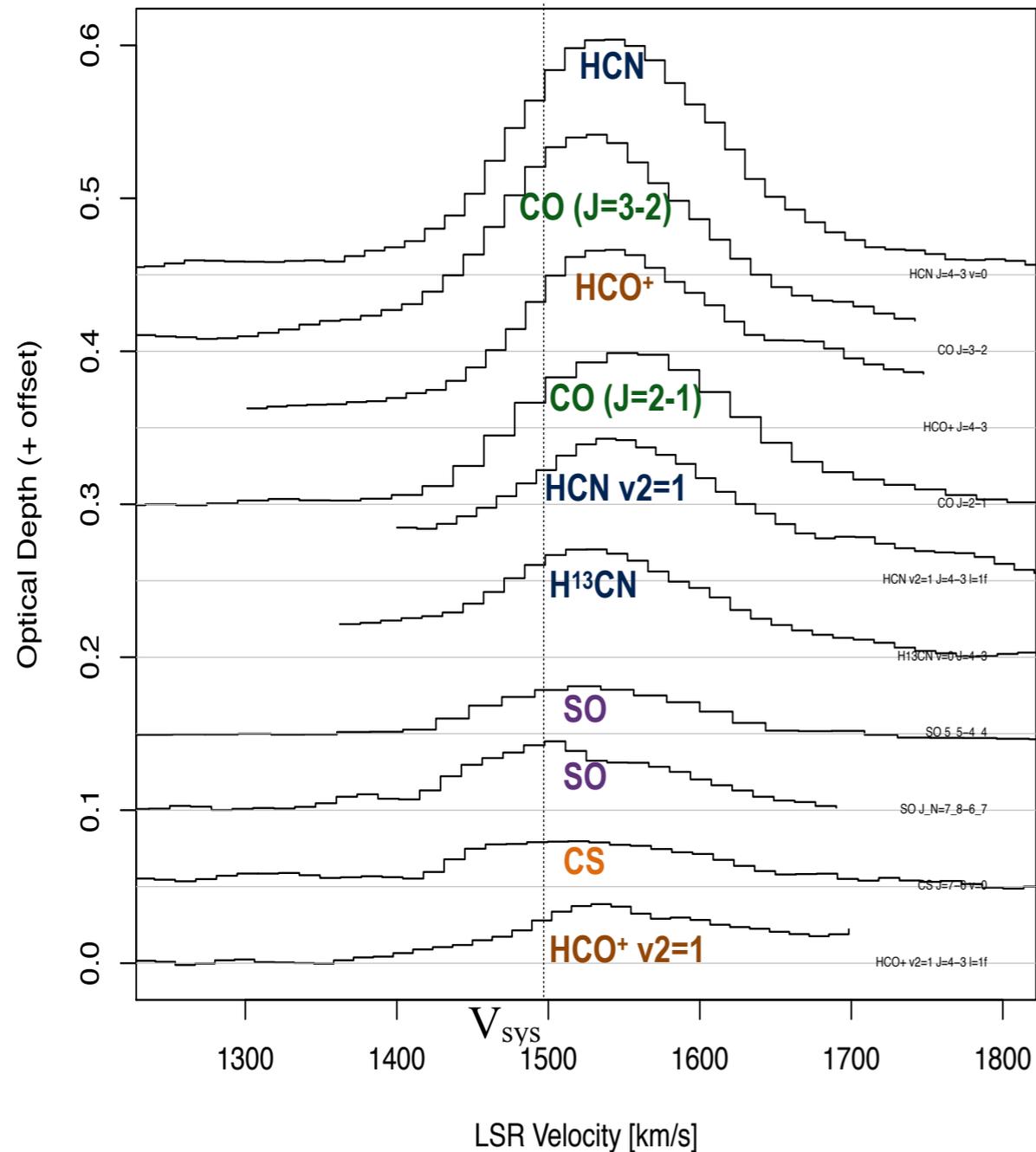
NGC 1052 Cycle 2 Band 7



NGC 1052 Cycle 2 Band 7



# Optical depths



- Mostly redshifted w.r.t.  $V_{\text{sys}}$
- Wider than CND
- HCN deeper than CO

$$V_{\text{sys}}^{+250}_{-100} \text{ km s}^{-1}$$

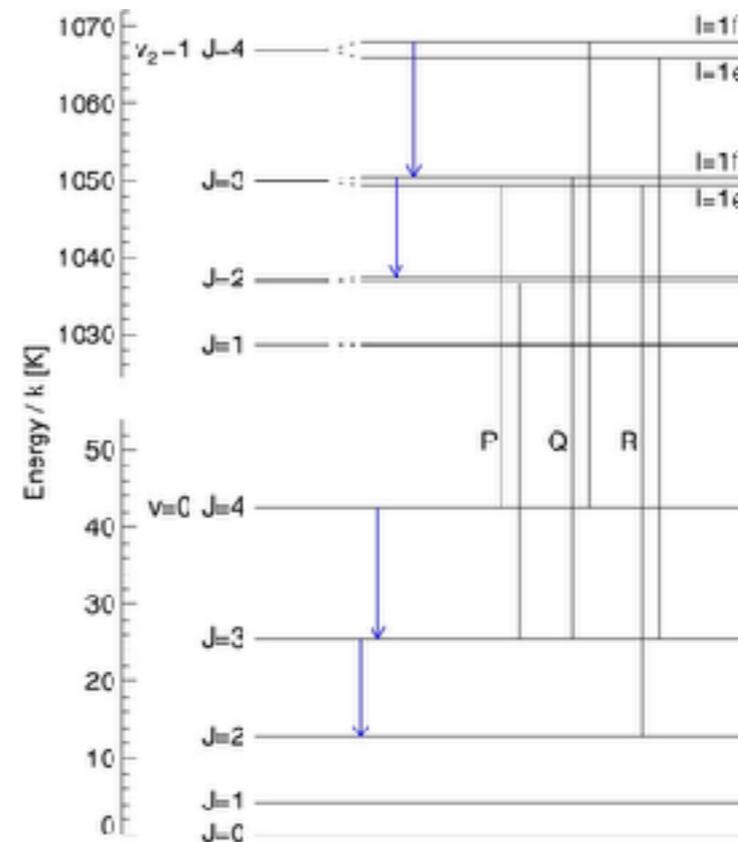
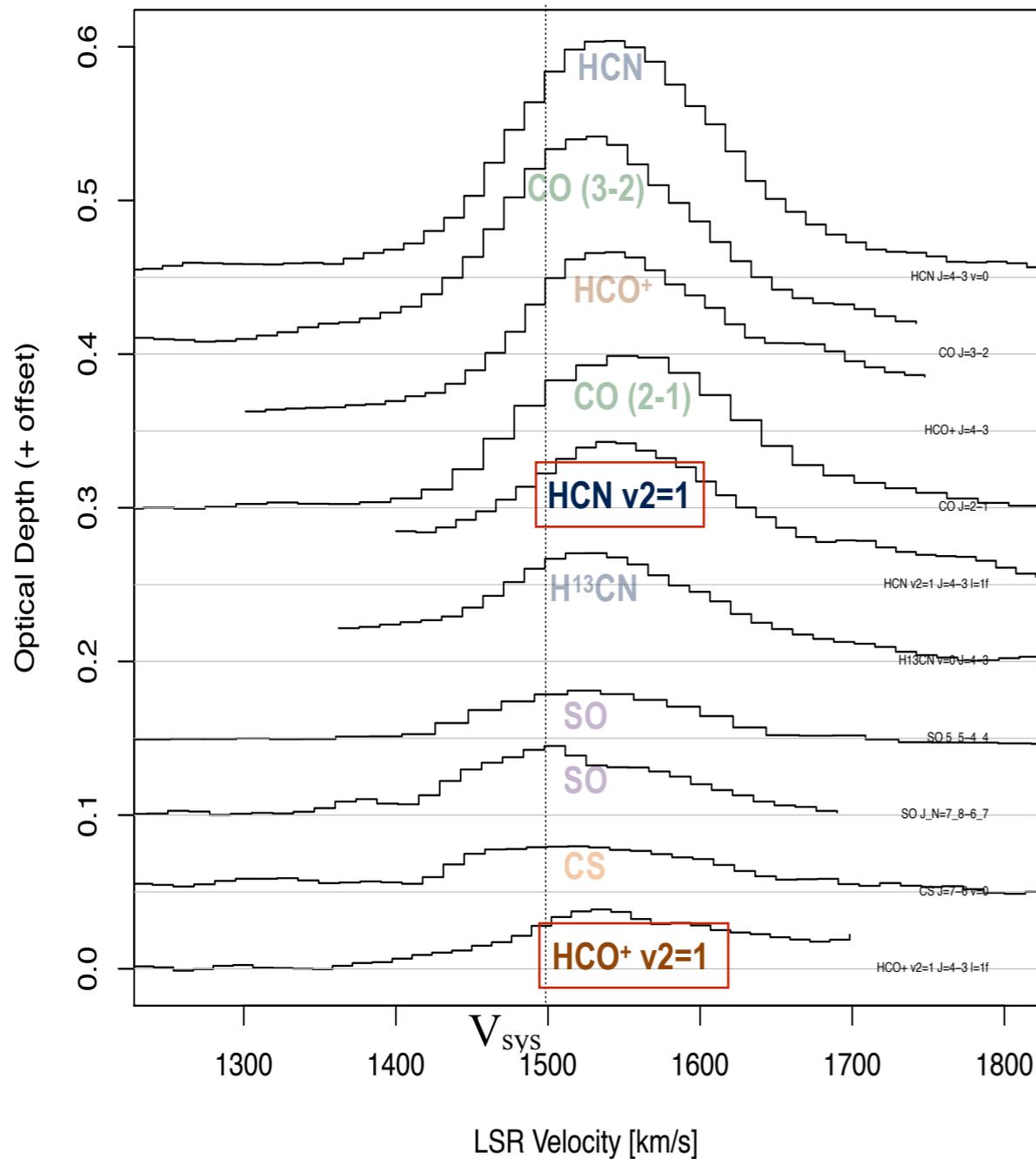
$$EW = \int \tau(v) dv = 24.4 \text{ kms}^{-1}$$

Absorption features are likely to originate in a molecular torus

# Presence of vibrationally excited lines

## HCN J=4-3 and HCO<sup>+</sup> J=4-3

- line ratio ( $v=0$  to  $v_2=1$ ) :  $R=0.6$
- if optically thin,  $T_{\text{ex}} = 520$  K
- IR ( $14 \mu\text{m}$ ) pumping from hot dust?

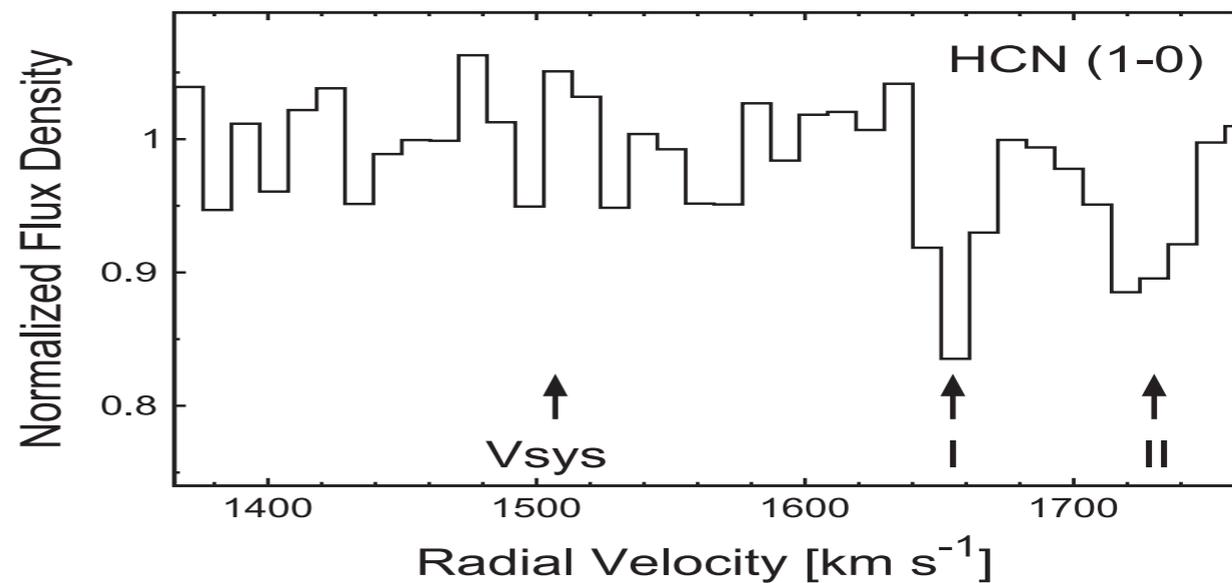
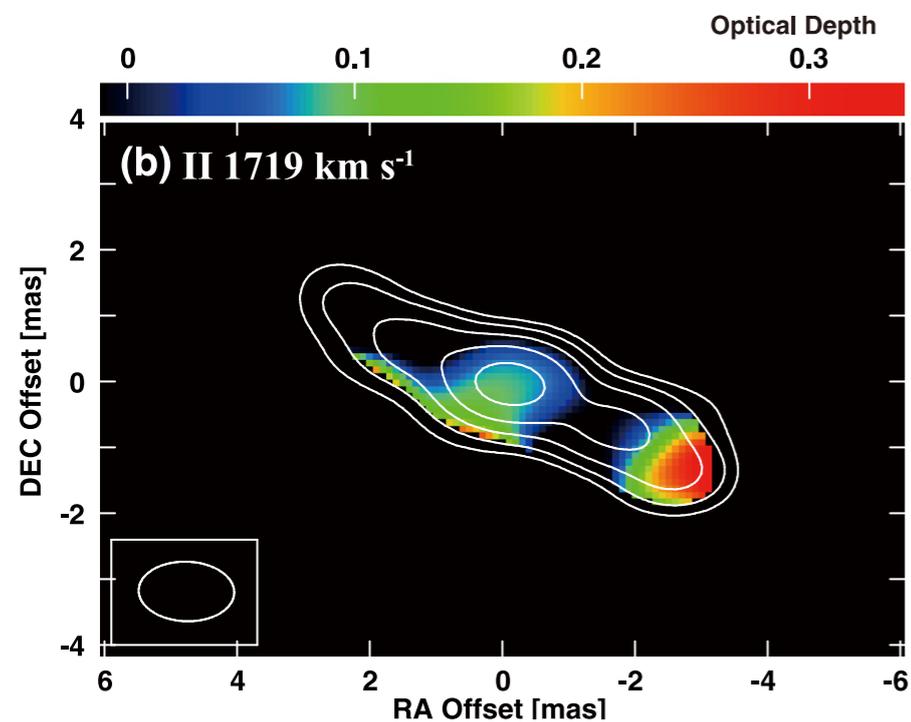
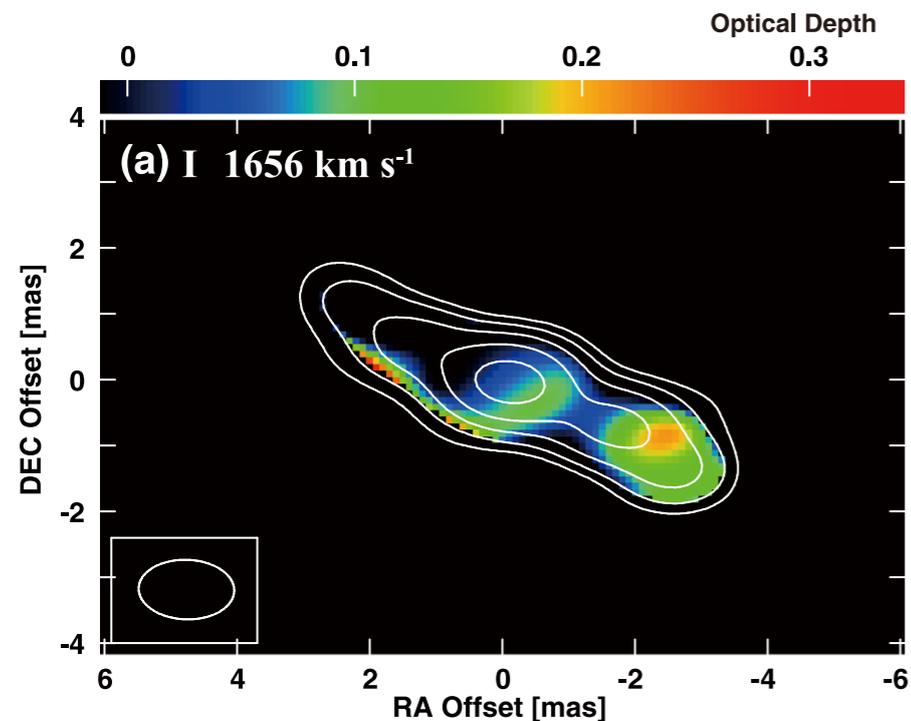


Sakamoto+2010, ApJL, 725, L228

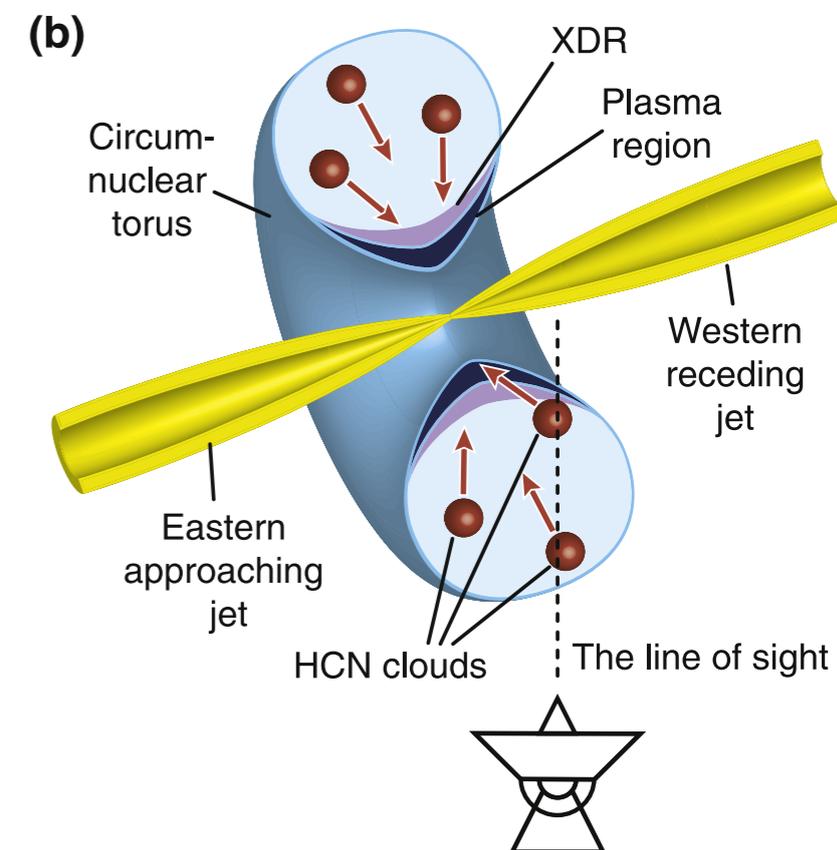
# Locating HCN absorption with KVN

Sawada-Sato+2016: HCN absorption with KVN

SAWADA-SATOH ET AL.



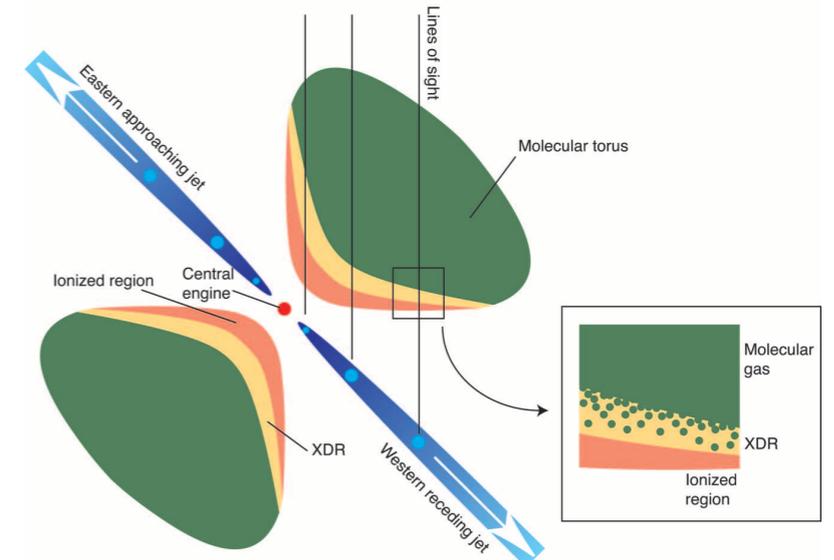
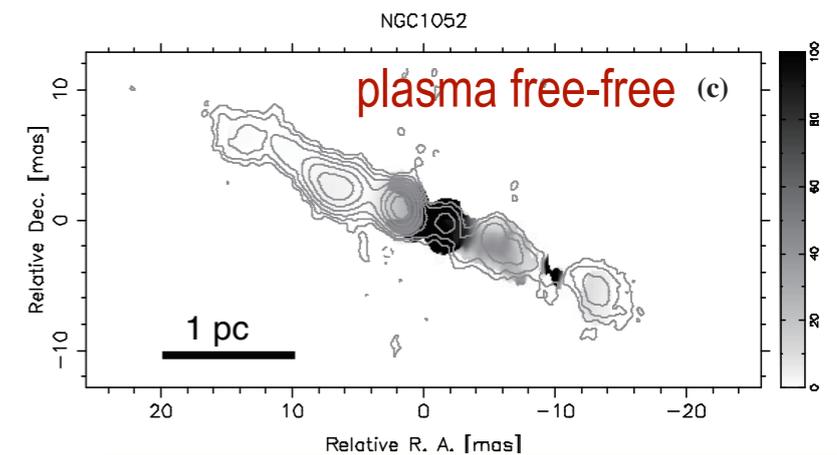
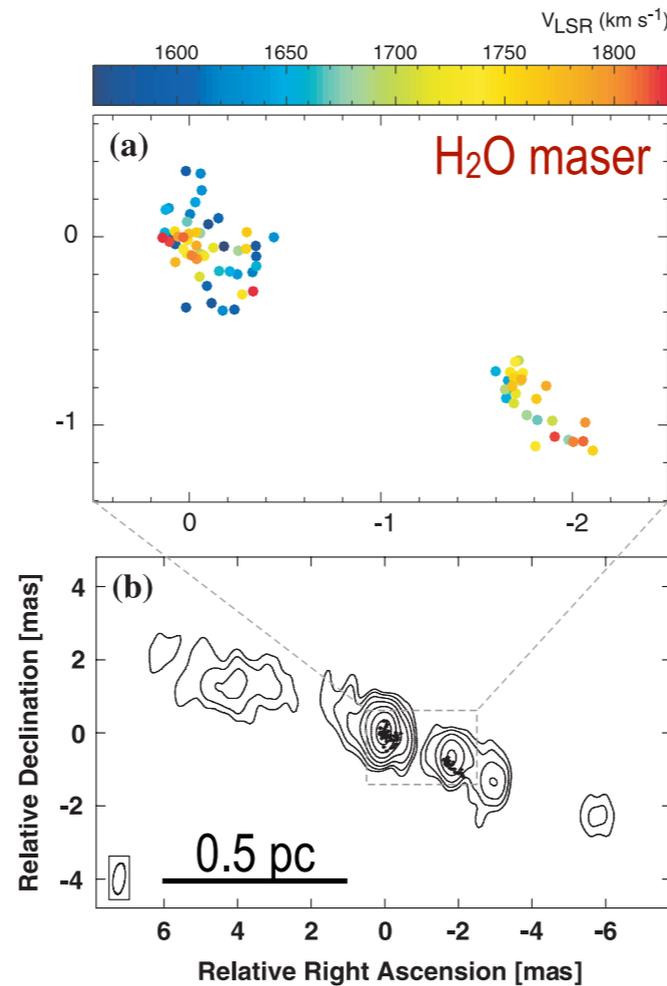
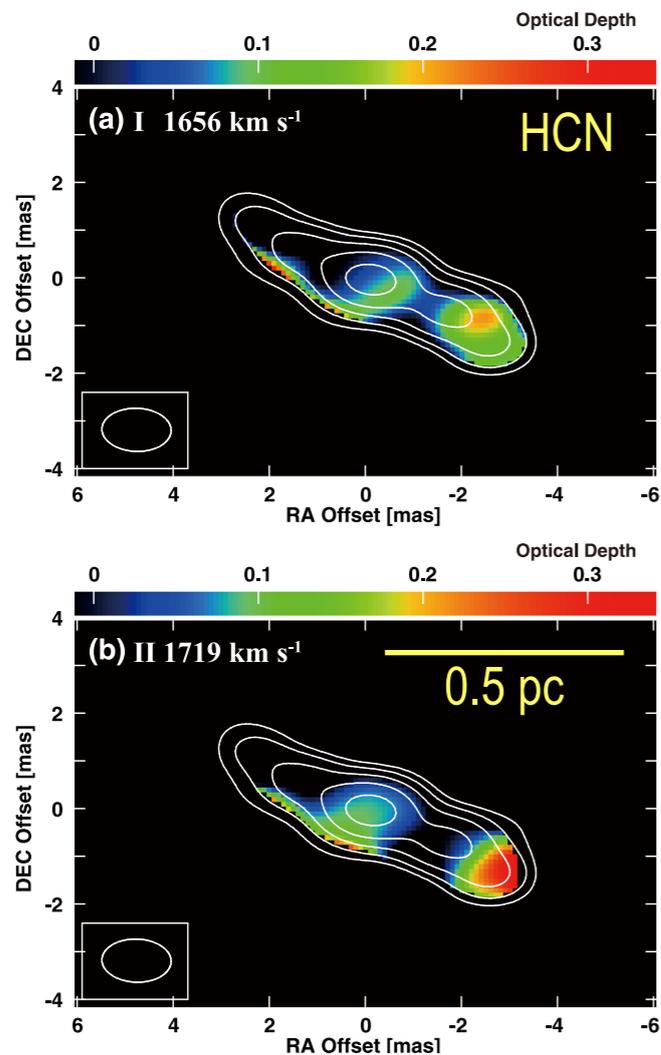
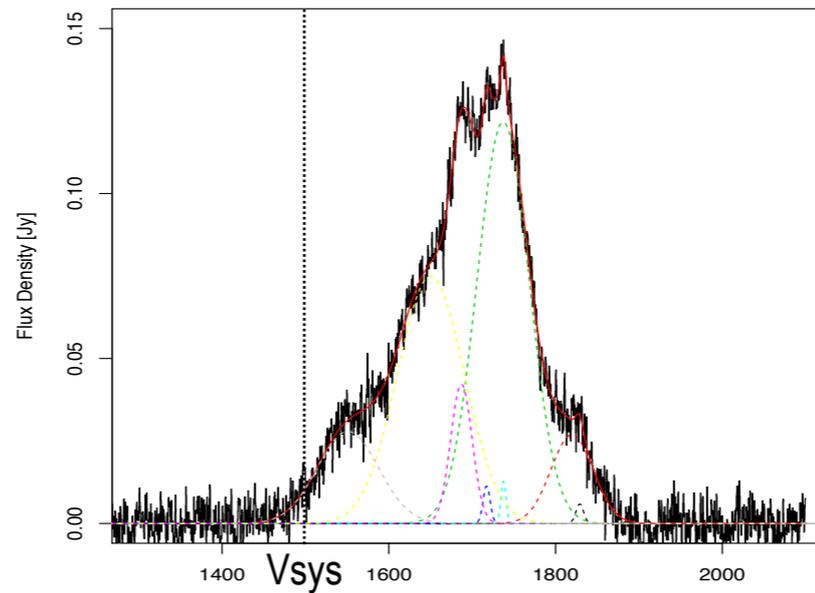
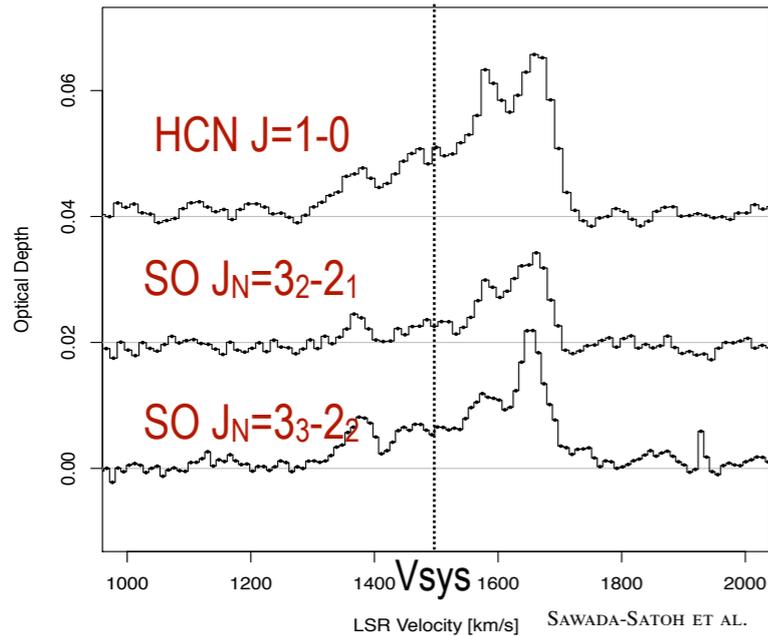
- absorption feature toward receding jet
- clumpy, with a filling factor  $\sim 0.03$



# Absorption features and H<sub>2</sub>O maser

NGC 1052 H<sub>2</sub>O maser

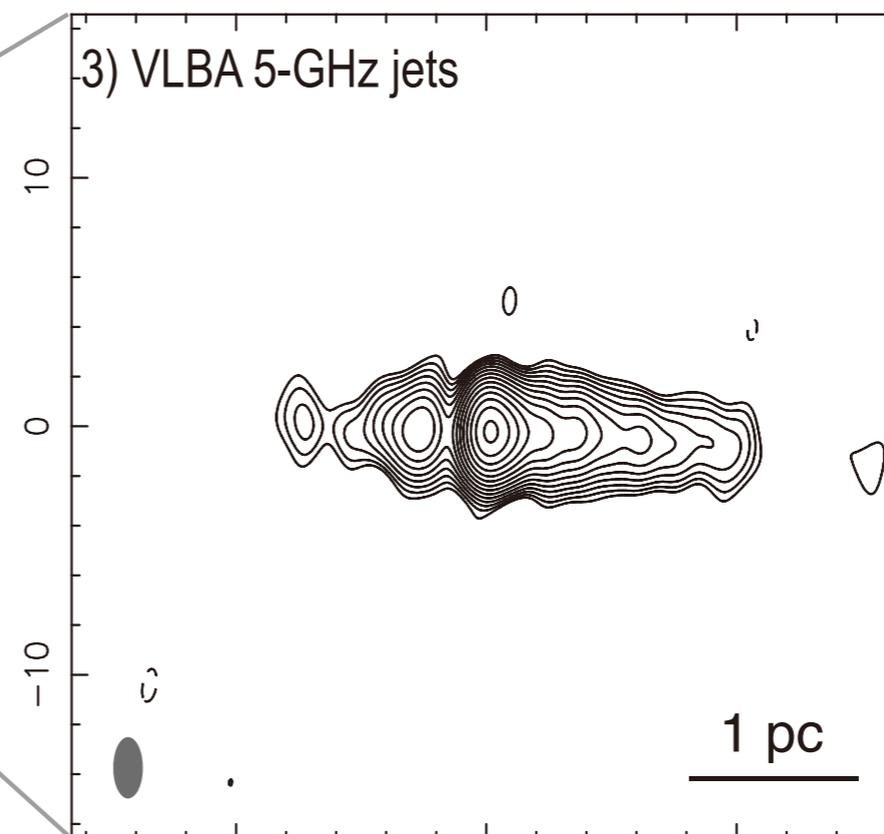
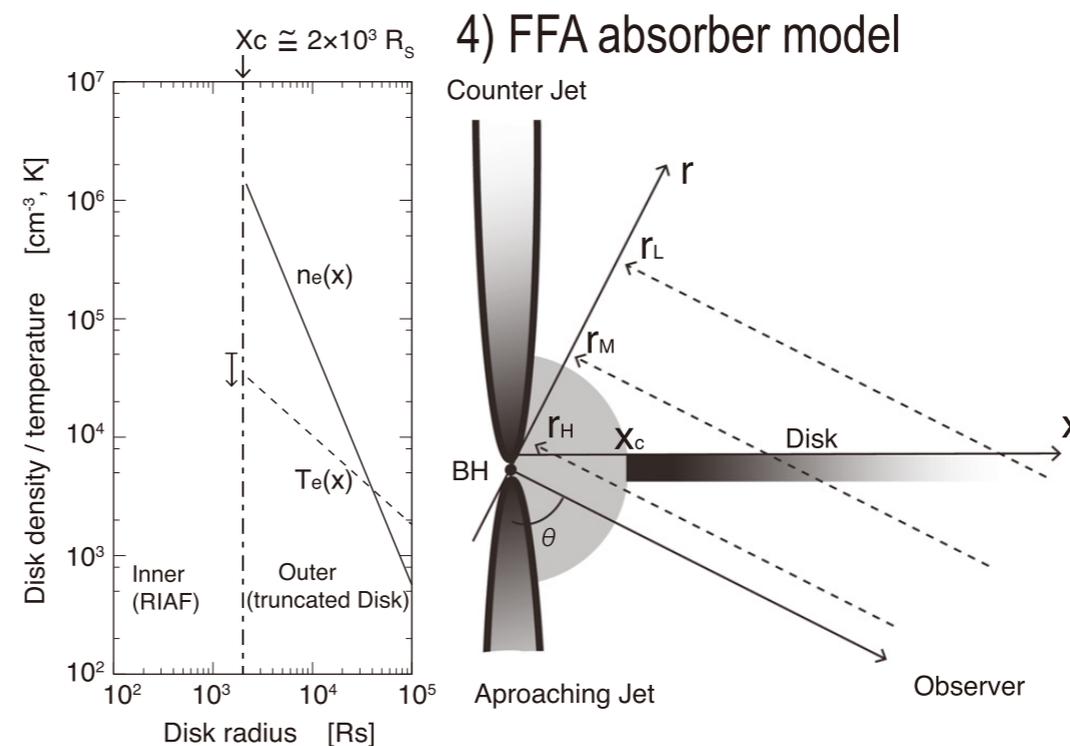
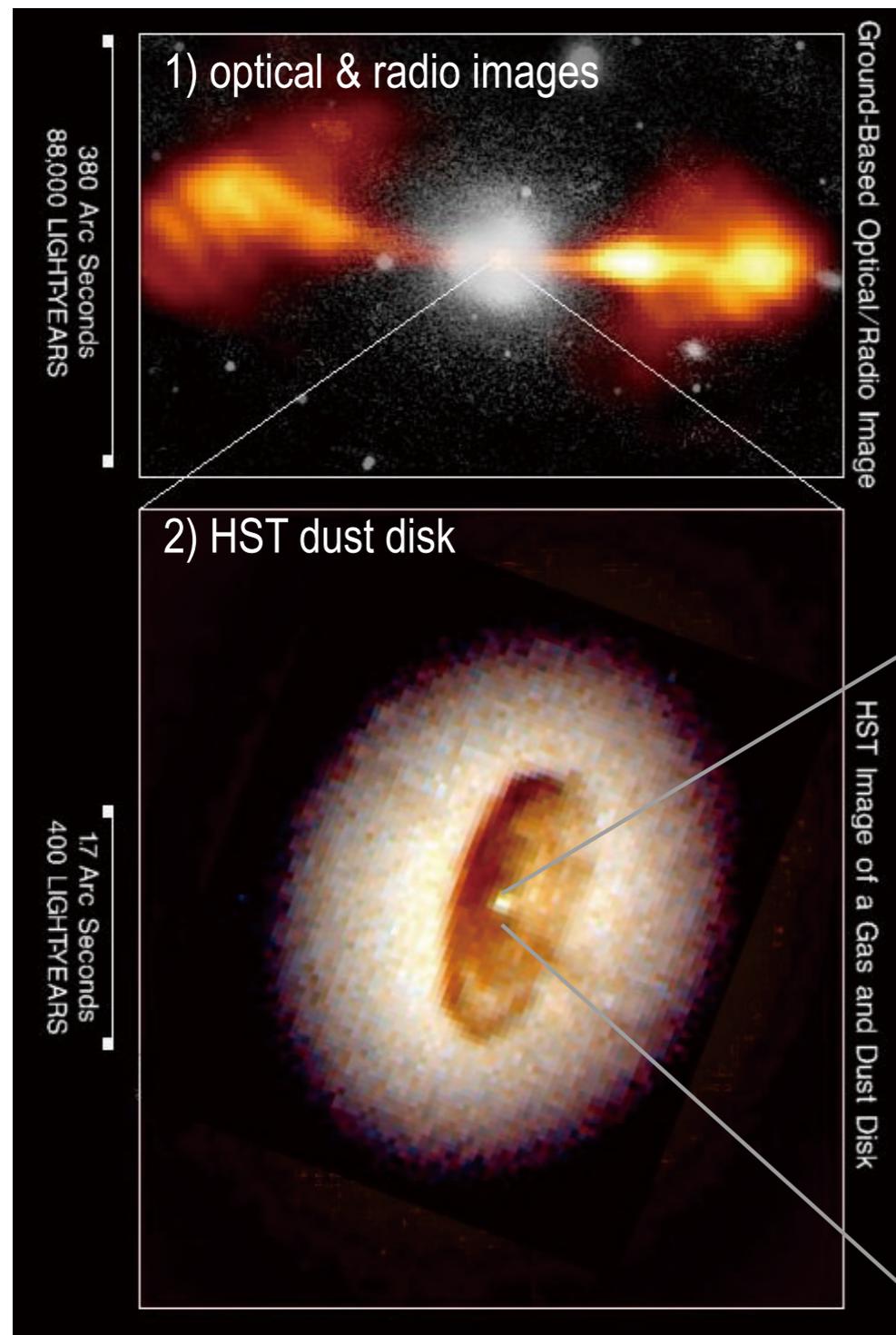
- Asymmetric profile
- sharp red edge
- Less redshifted than H<sub>2</sub>O maser
- Inside molecular torus?



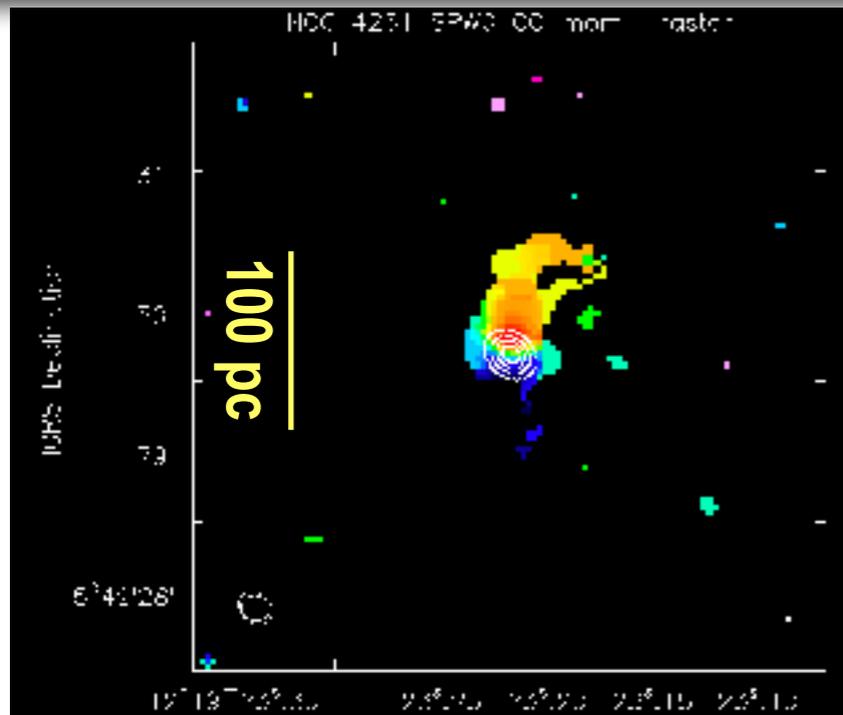
# NGC 4261

Host galaxy E2-3  
 Distance 30.56 Mpc,  $1''=181$  pc  
 Velocity  $V_{\text{sys}}(\text{LSR, Radio}) = 2214 \text{ km s}^{-1}$   
 Radio continuum  $0.21 \text{ Jy}@345 \text{ GHz}$   
 Free-free absorption (Haga+16)

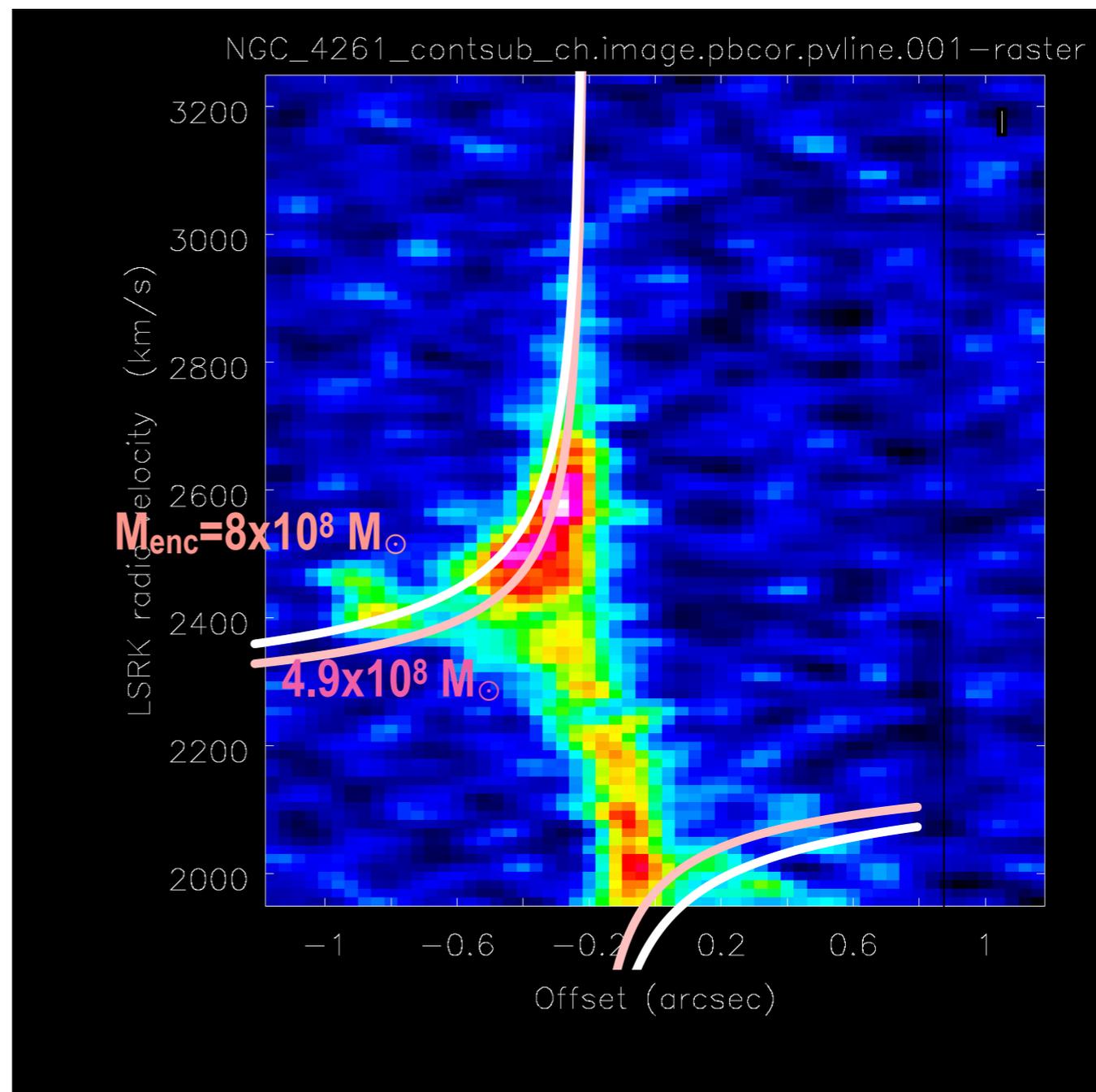
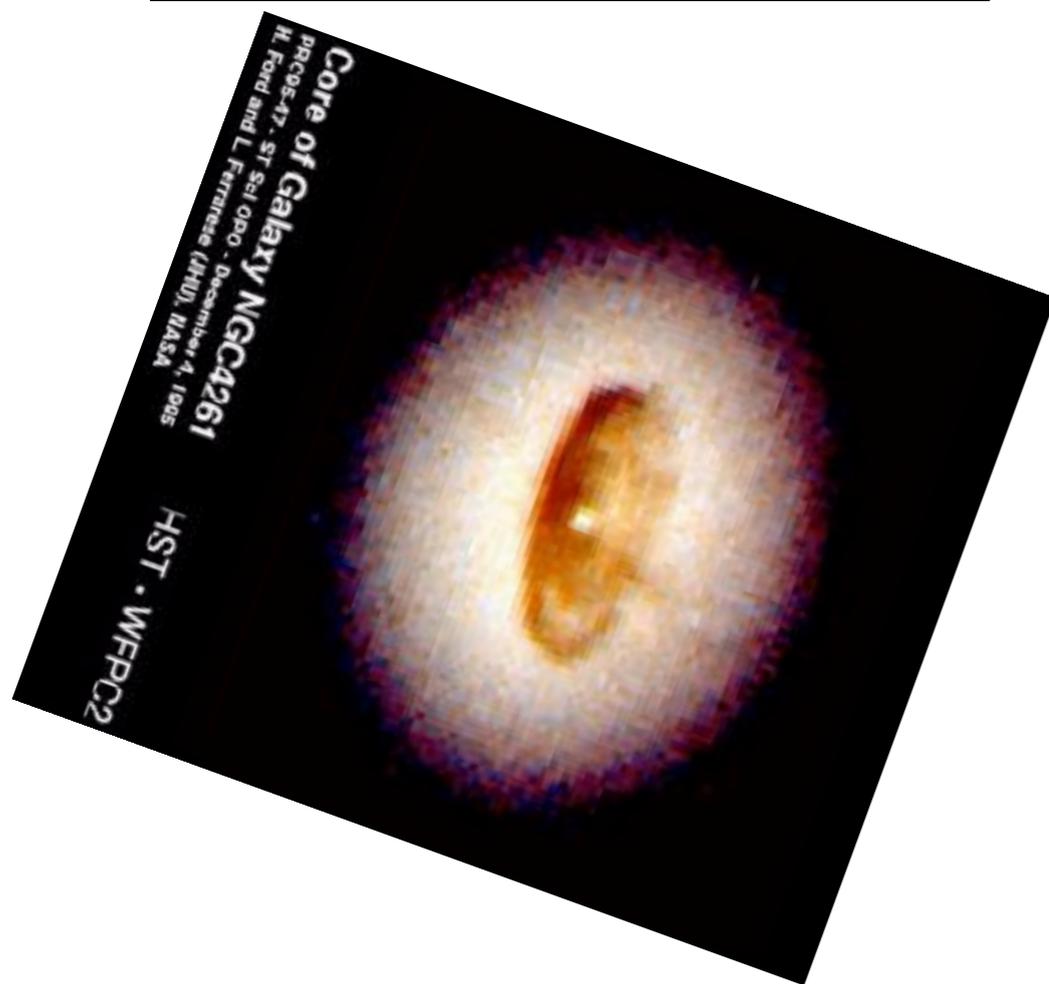
## (a) NGC 4261



# NGC 4261 : CO emission in CND

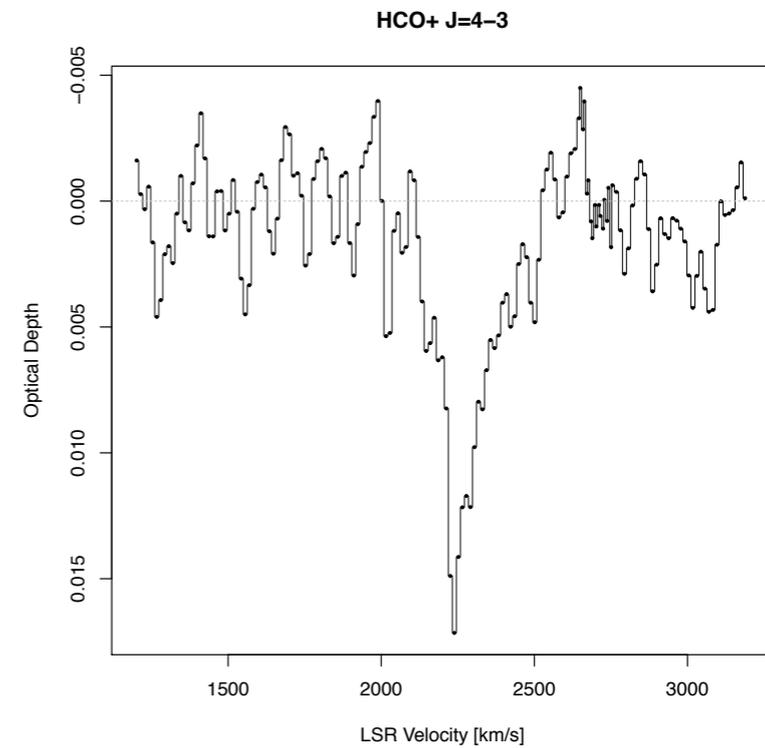
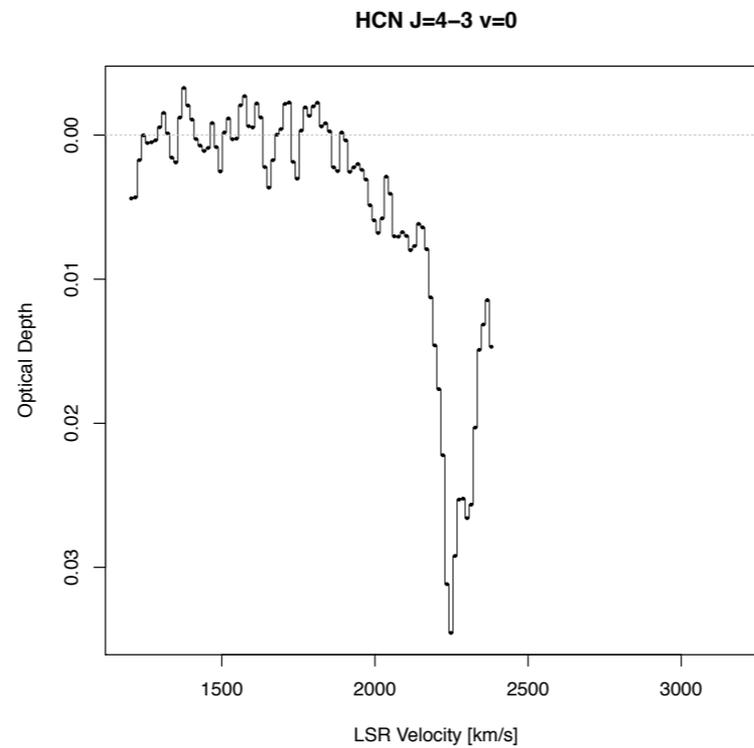
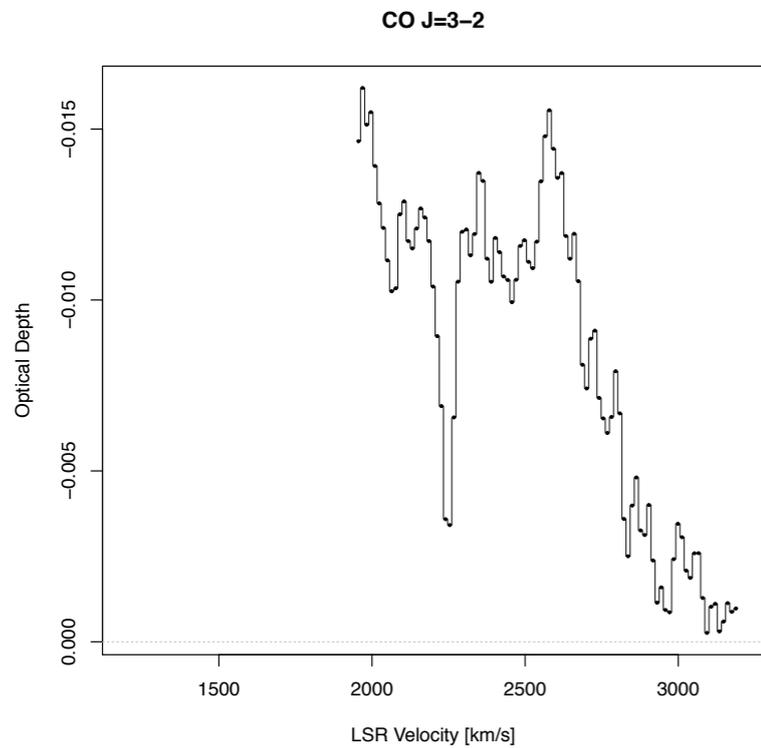
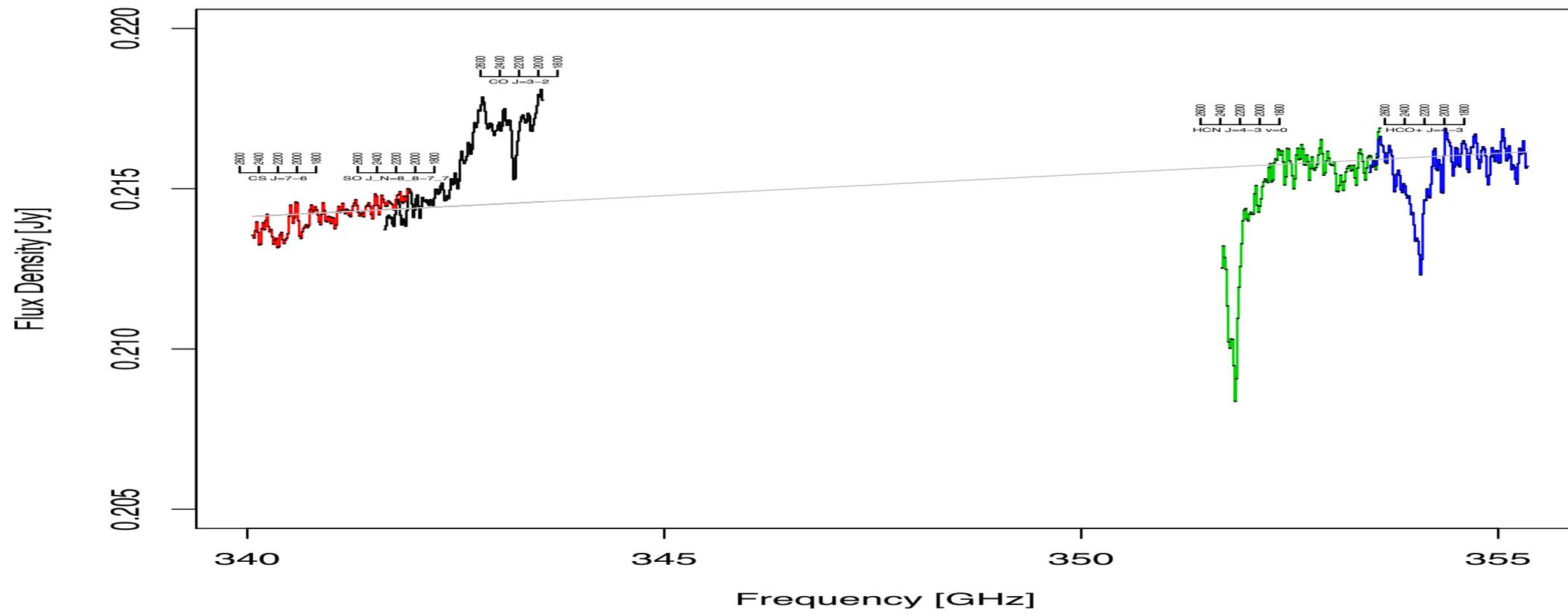


- Keplerian rotating disk
- $M_{\text{enc}} = 8 \times 10^8 M_{\odot} = 1.6 M_{\text{BH}}$
- Coincidence with the dust disk

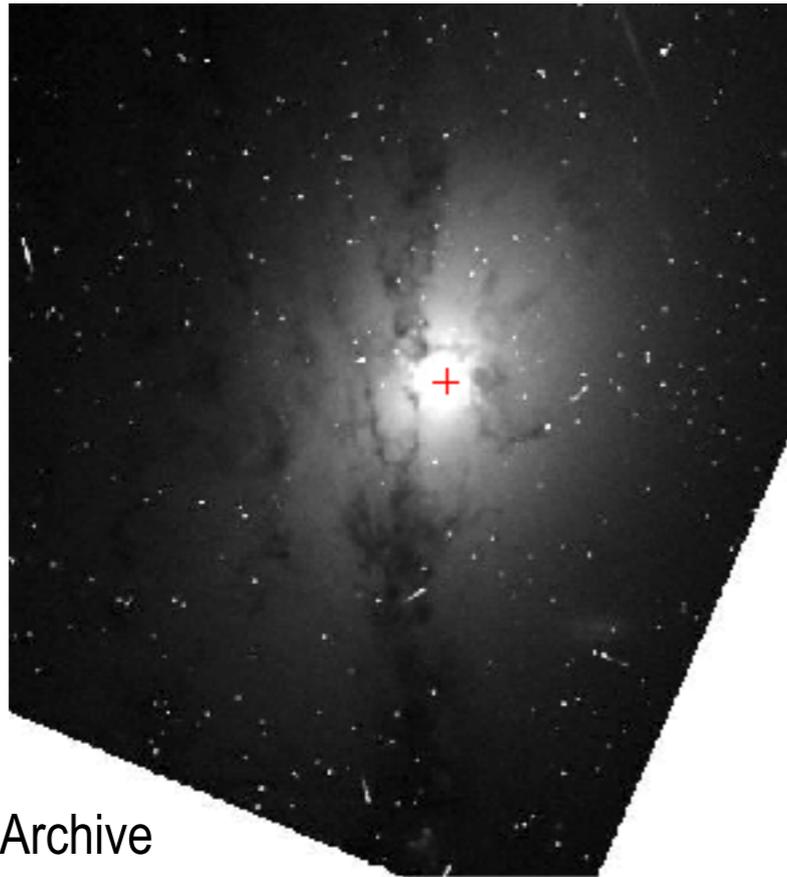


# NGC 4261 : absorption lines

NGC 4261 Band 7

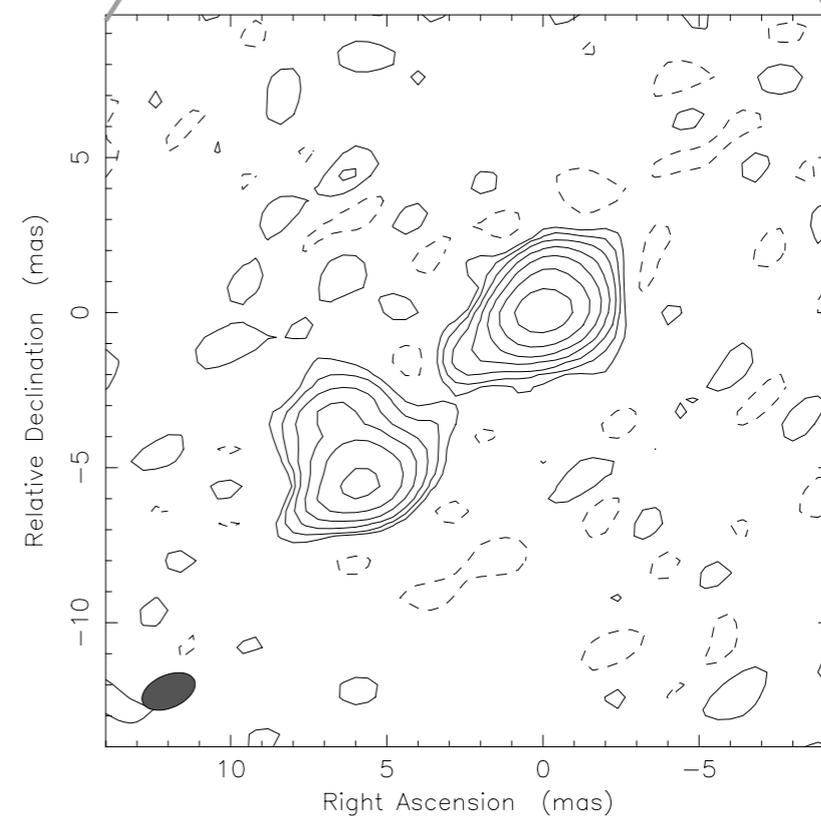
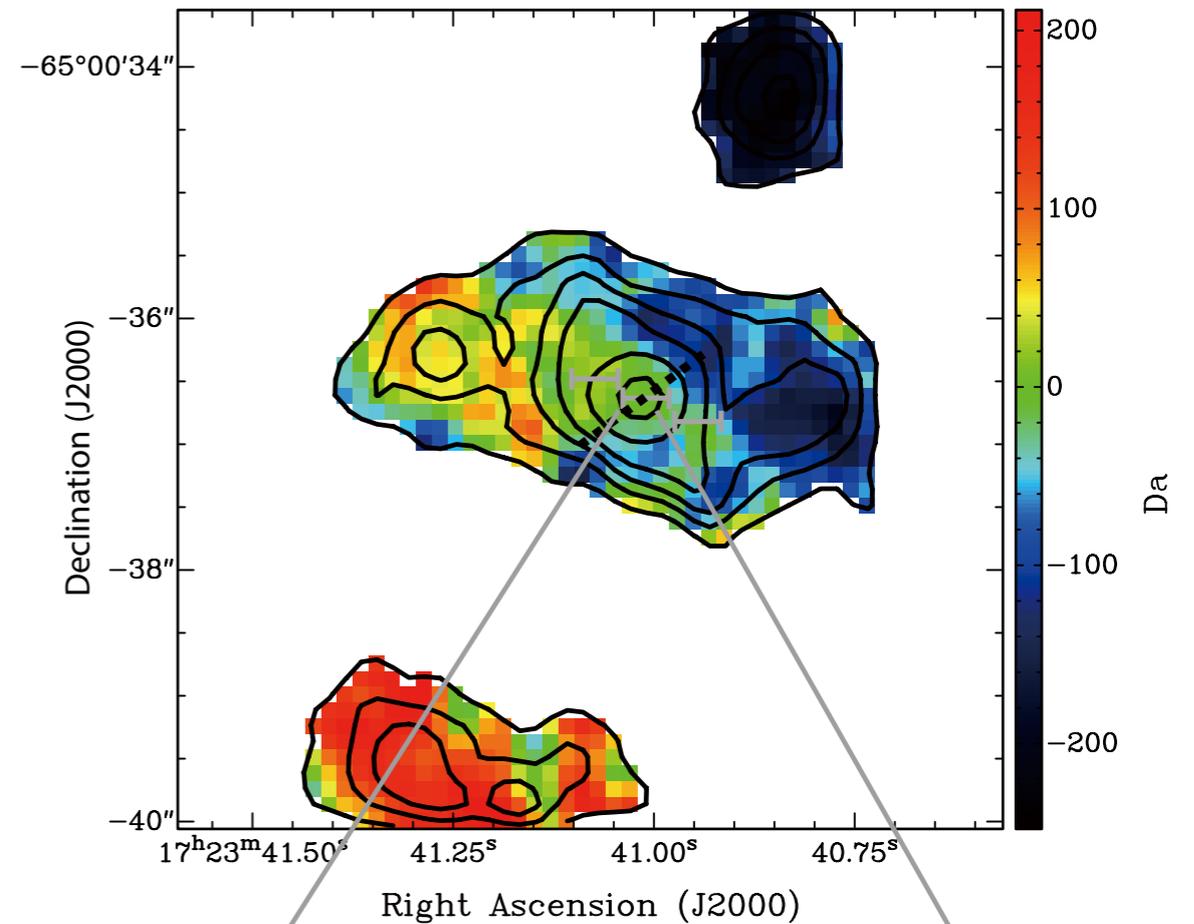


# NGC 6328

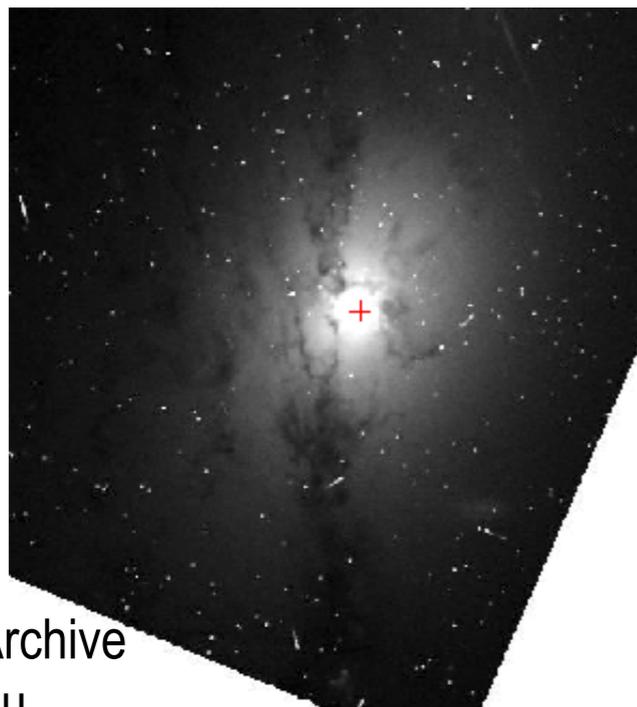


Hubble Legacy Archive  
<http://hla.stsci.edu>

Host galaxy            SAB  
Distance            61.25 Mpc, 1"=306 pc  
Velocity             $V_{\text{sys}}(\text{LSR, Radio}) = 4324 \text{ km s}^{-1}$   
Radio continuum   0.2 Jy@345 GHz  
GHz-Peaked Spectrum source (Tingay+97)  
 $\text{H}_2$  molecular absorption (Maccagni+16)

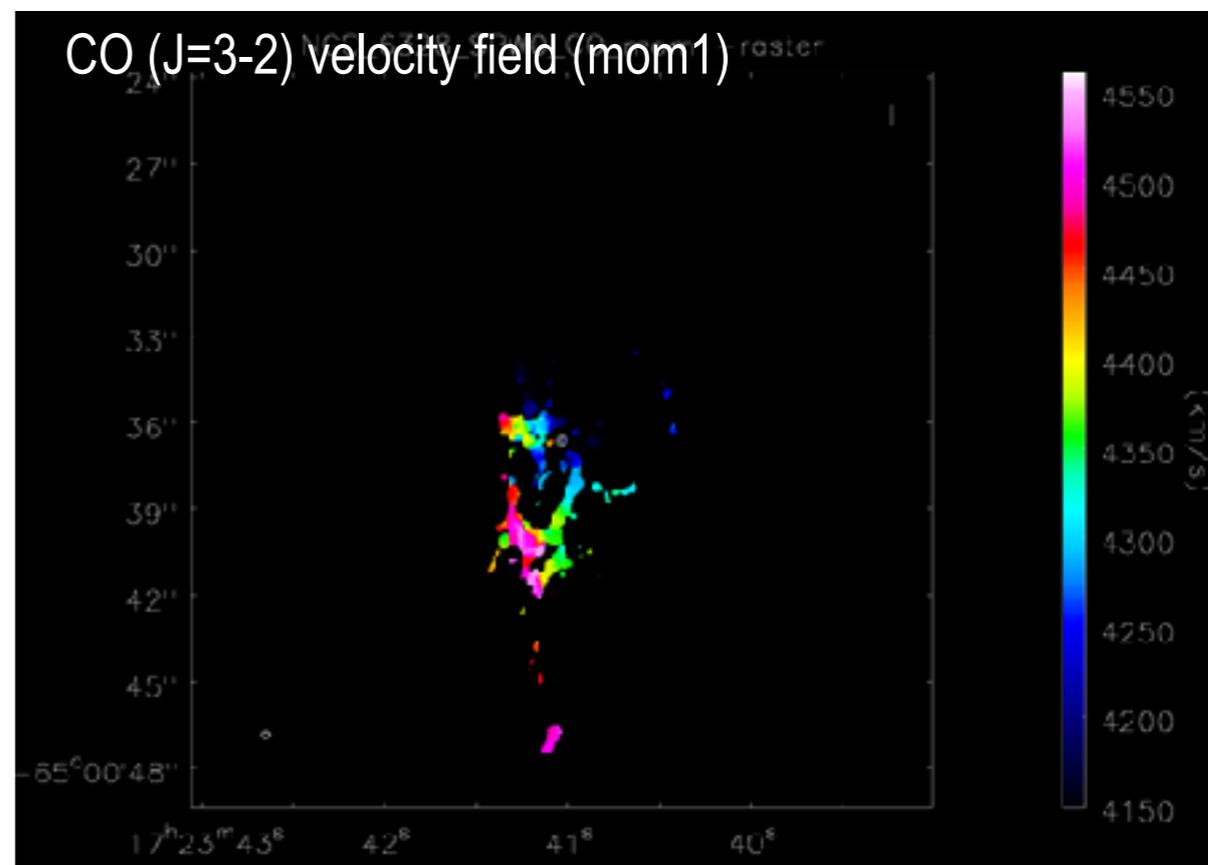
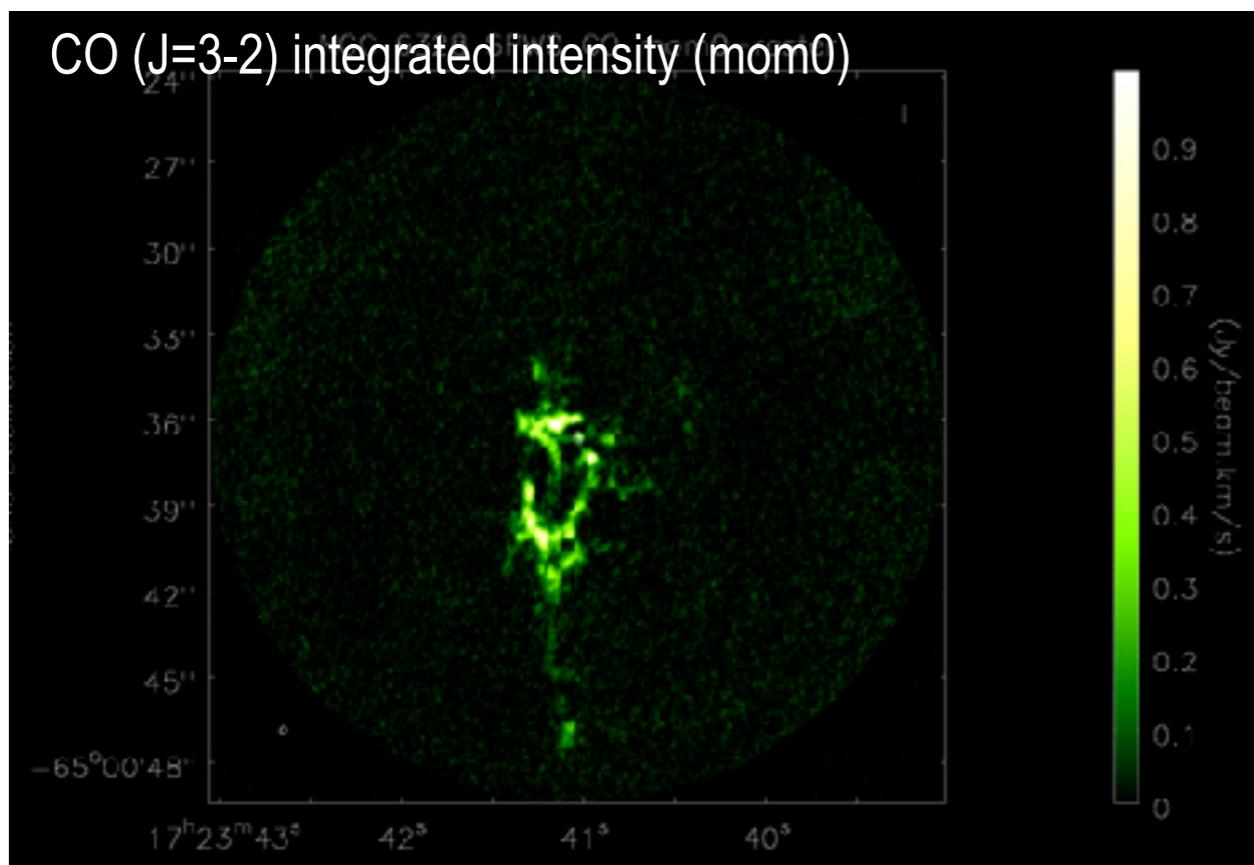


# CO (J=3-2) emission



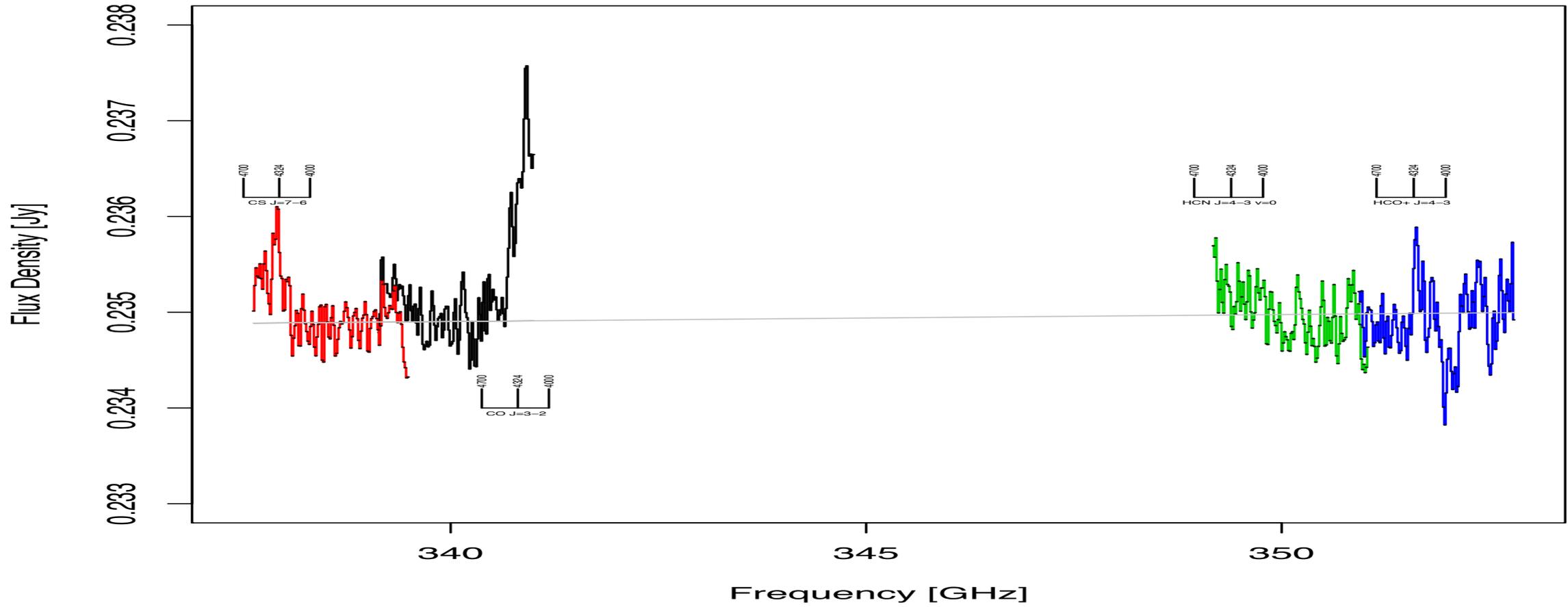
- Galactic arm structure
- Coincidence with the dust lane

Hubble Legacy Archive  
<http://hla.stsci.edu>

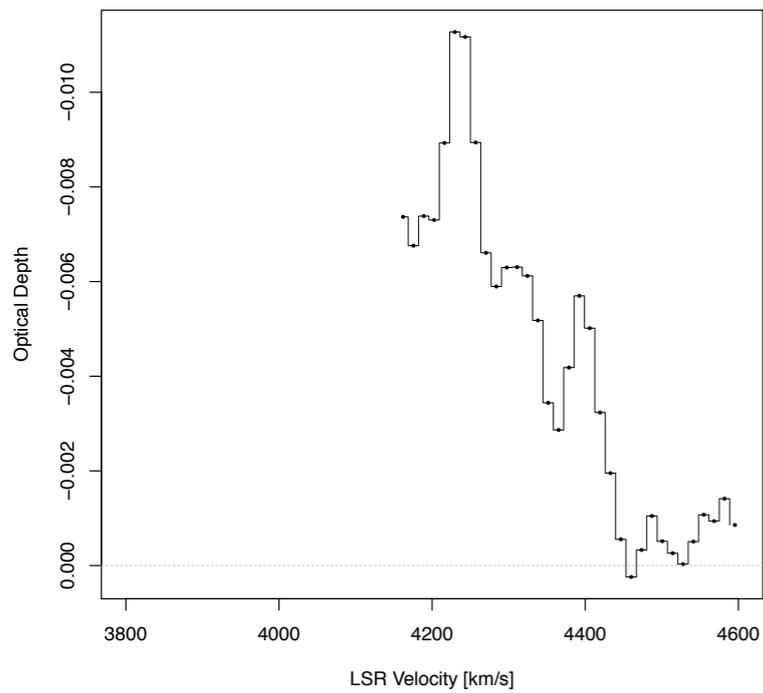


# NGC 6328 : molecular lines

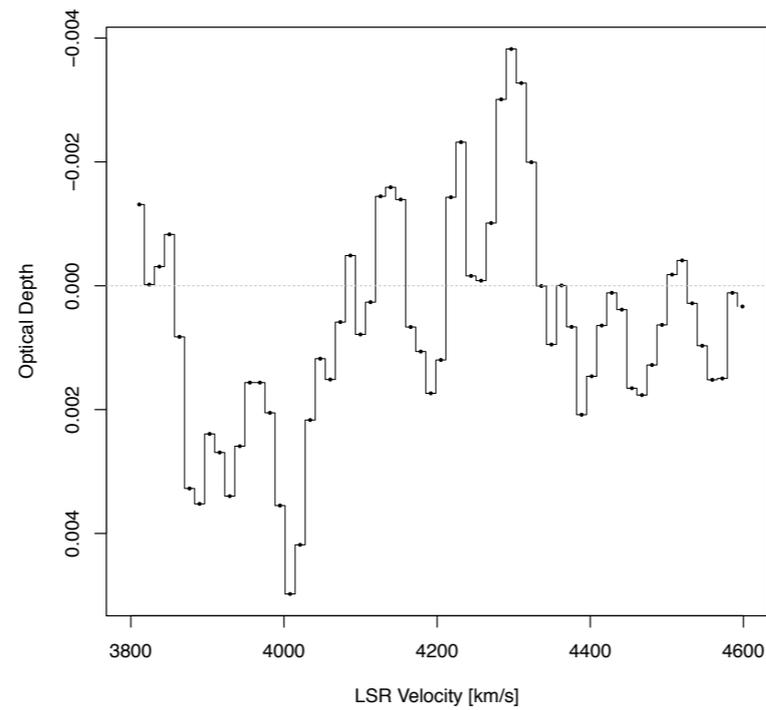
## NGC 6328 Band 7



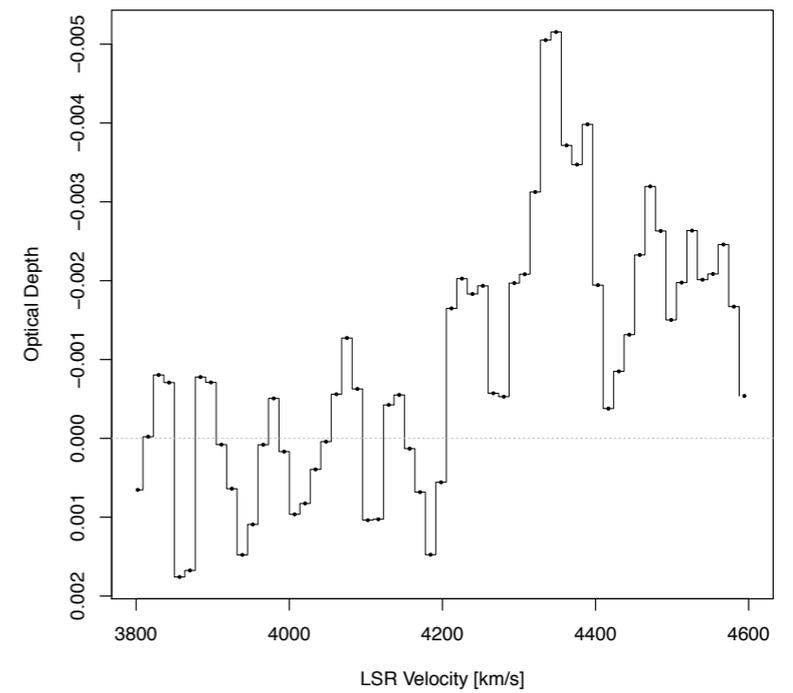
CO J=3-2



HCO+ J=4-3

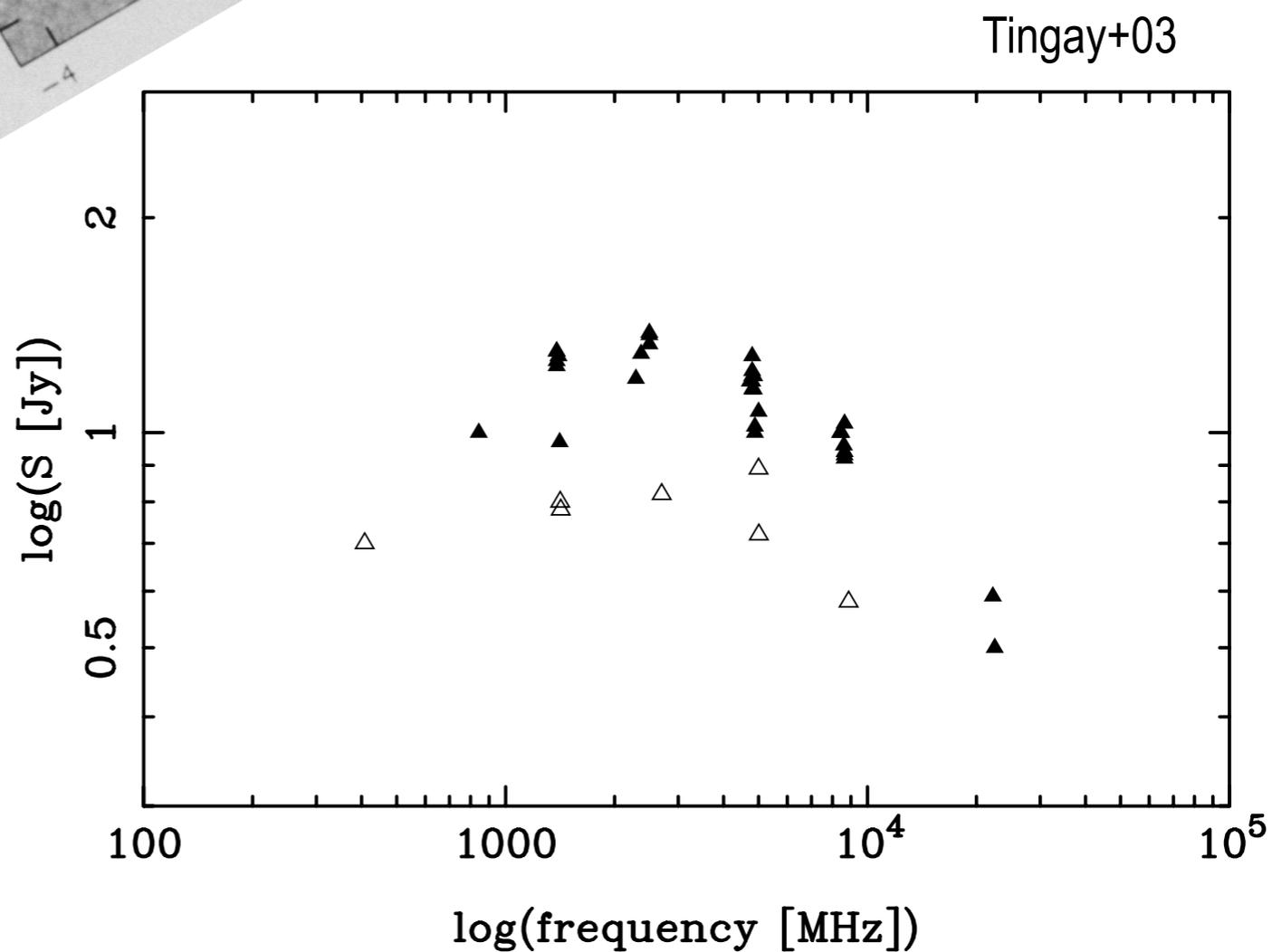
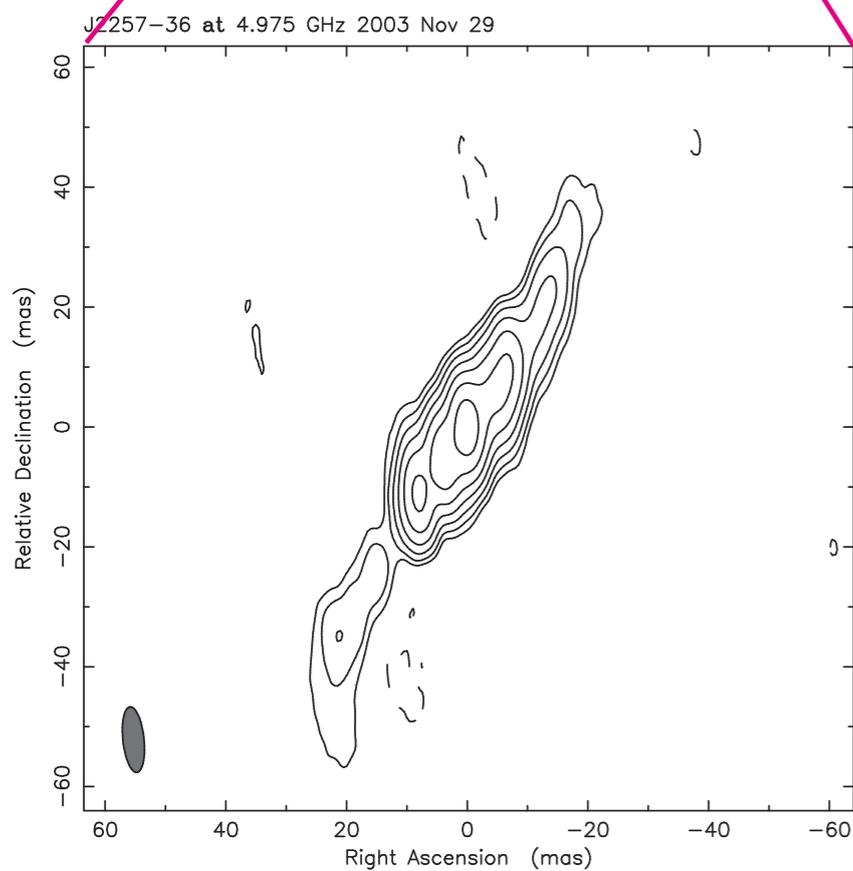
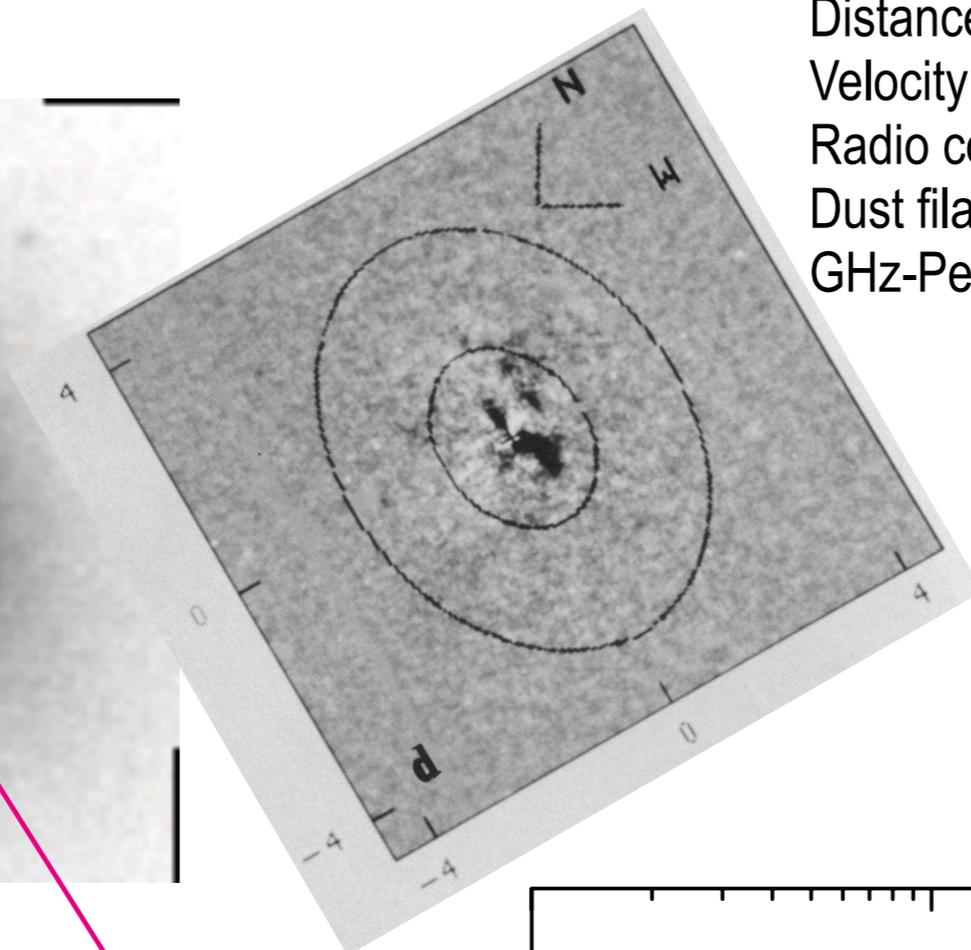
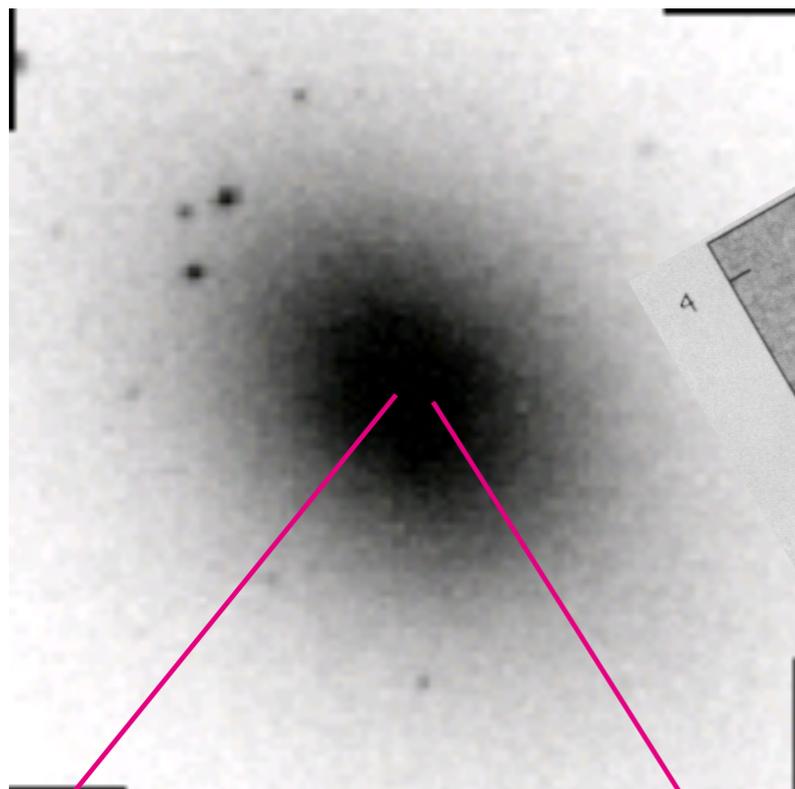


CS J=7-6



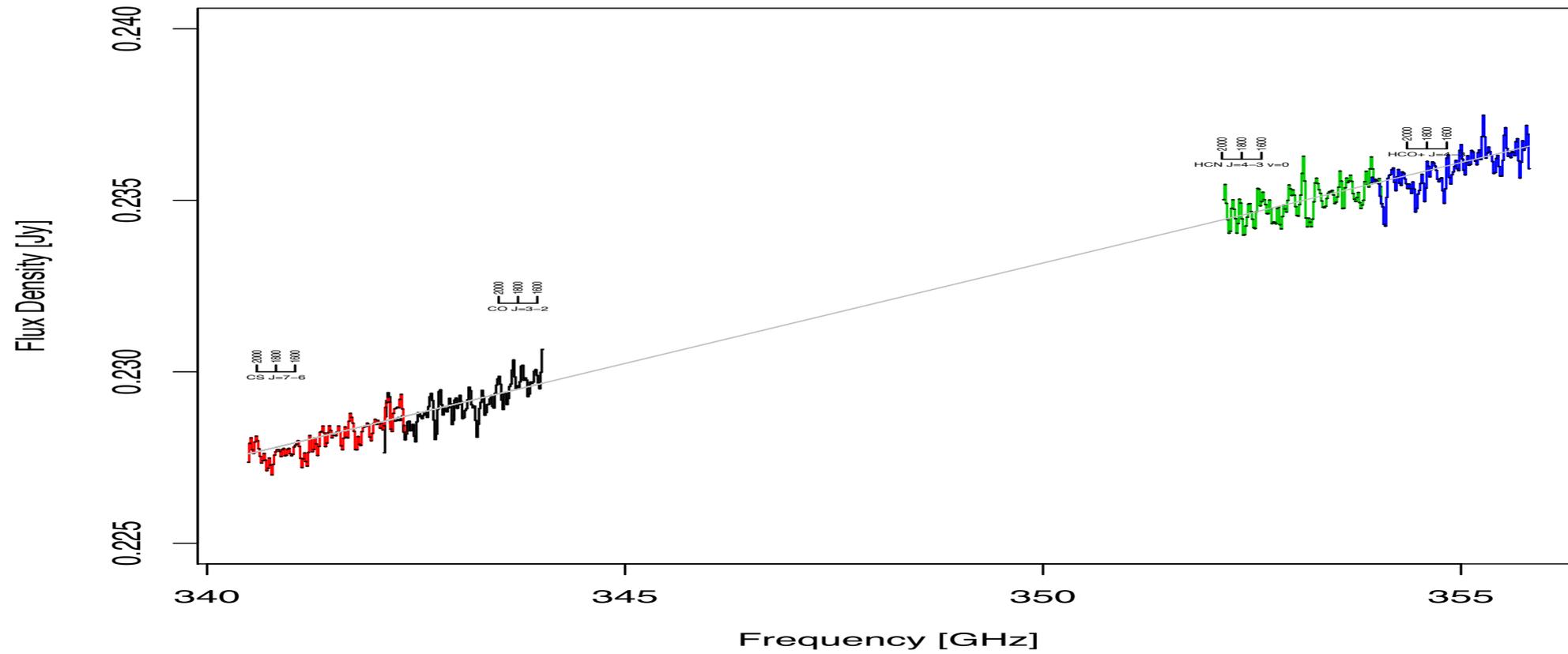
# IC 1459

Host galaxy E3-4  
Distance 26.93 Mpc,  $1''=131$  pc  
Velocity  $V_{\text{sys}}(\text{LSR, Radio}) = 1800 \text{ km s}^{-1}$   
Radio continuum 0.2 Jy@345 GHz  
Dust filaments  
GHz-Peaked spectrum source (Tingay & Edwards+15)

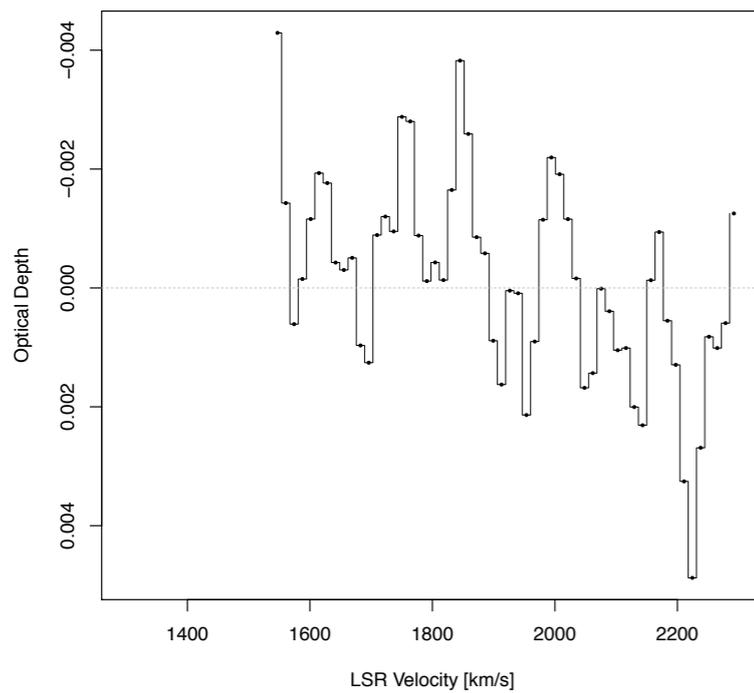


# IC 1459 : CO and HCO<sup>+</sup> absorption (?)

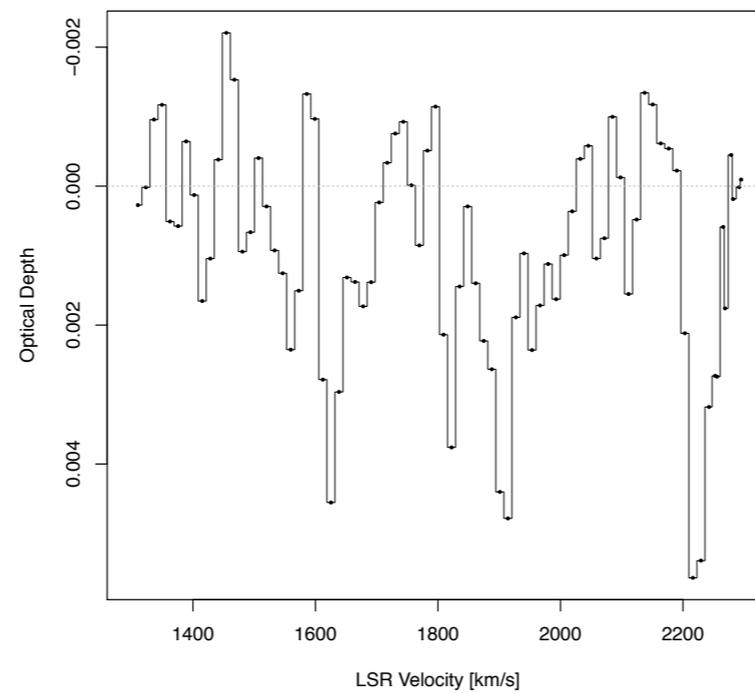
IC 1459 Band 7



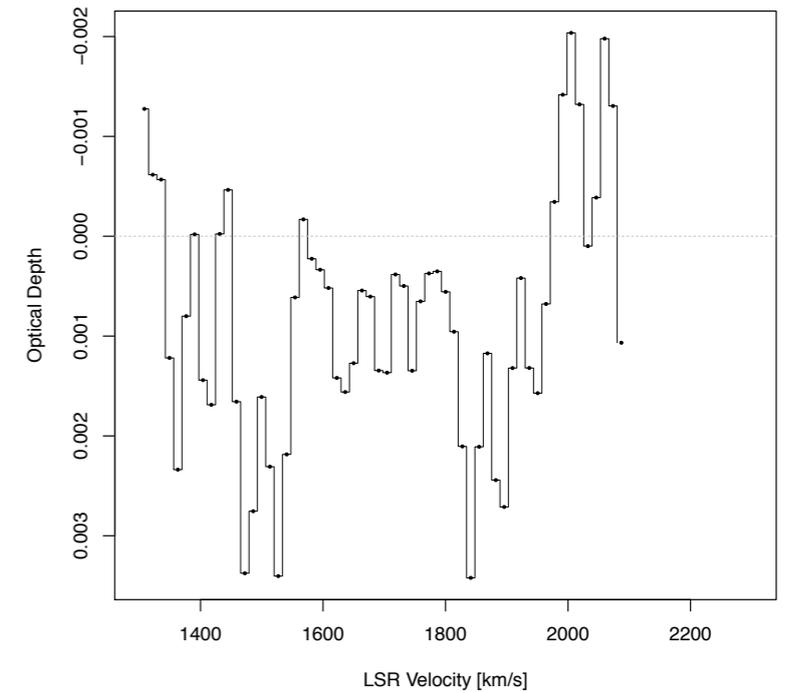
CO J=3-2



HCO<sup>+</sup> J=4-3

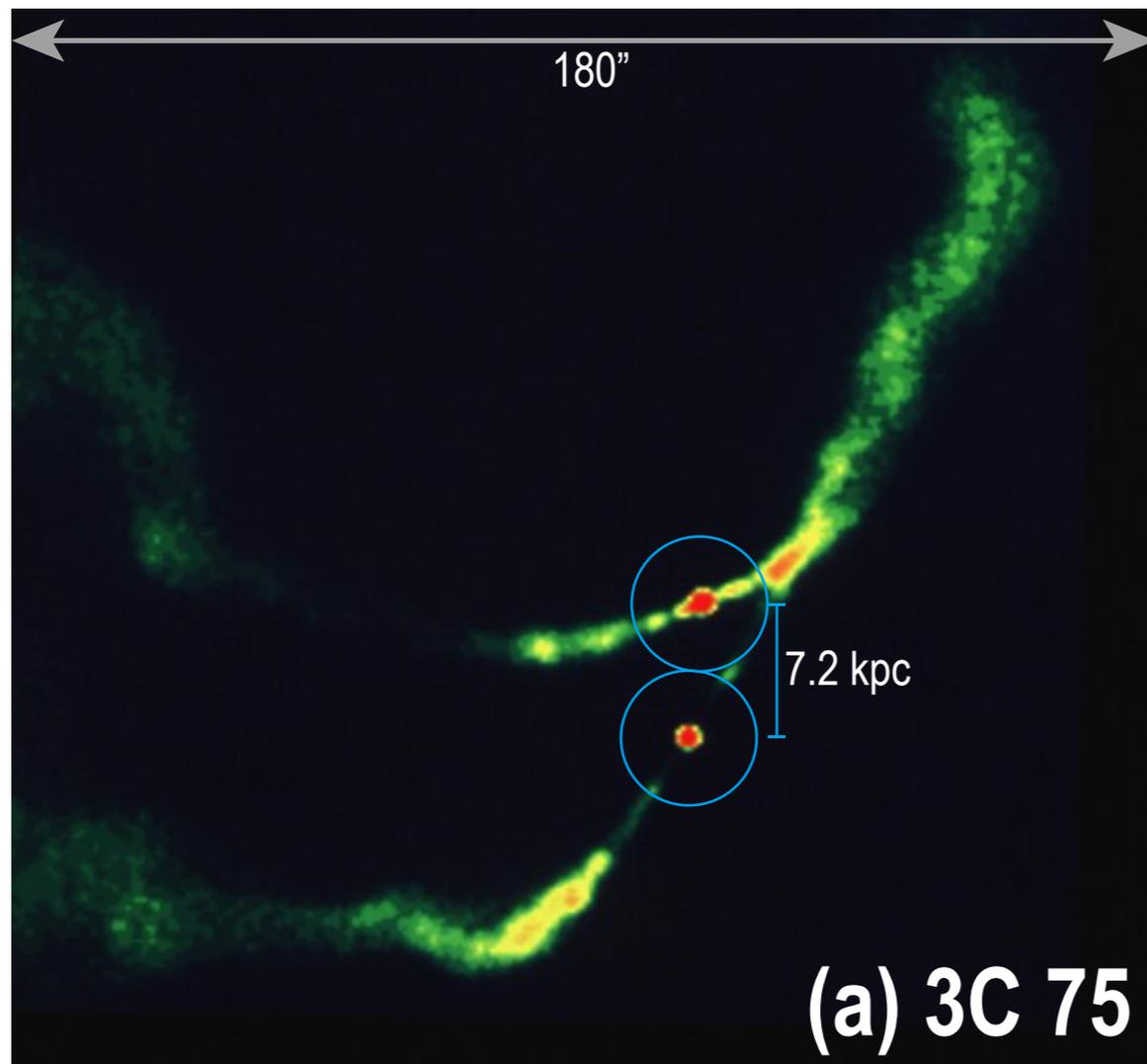


CS J=7-6

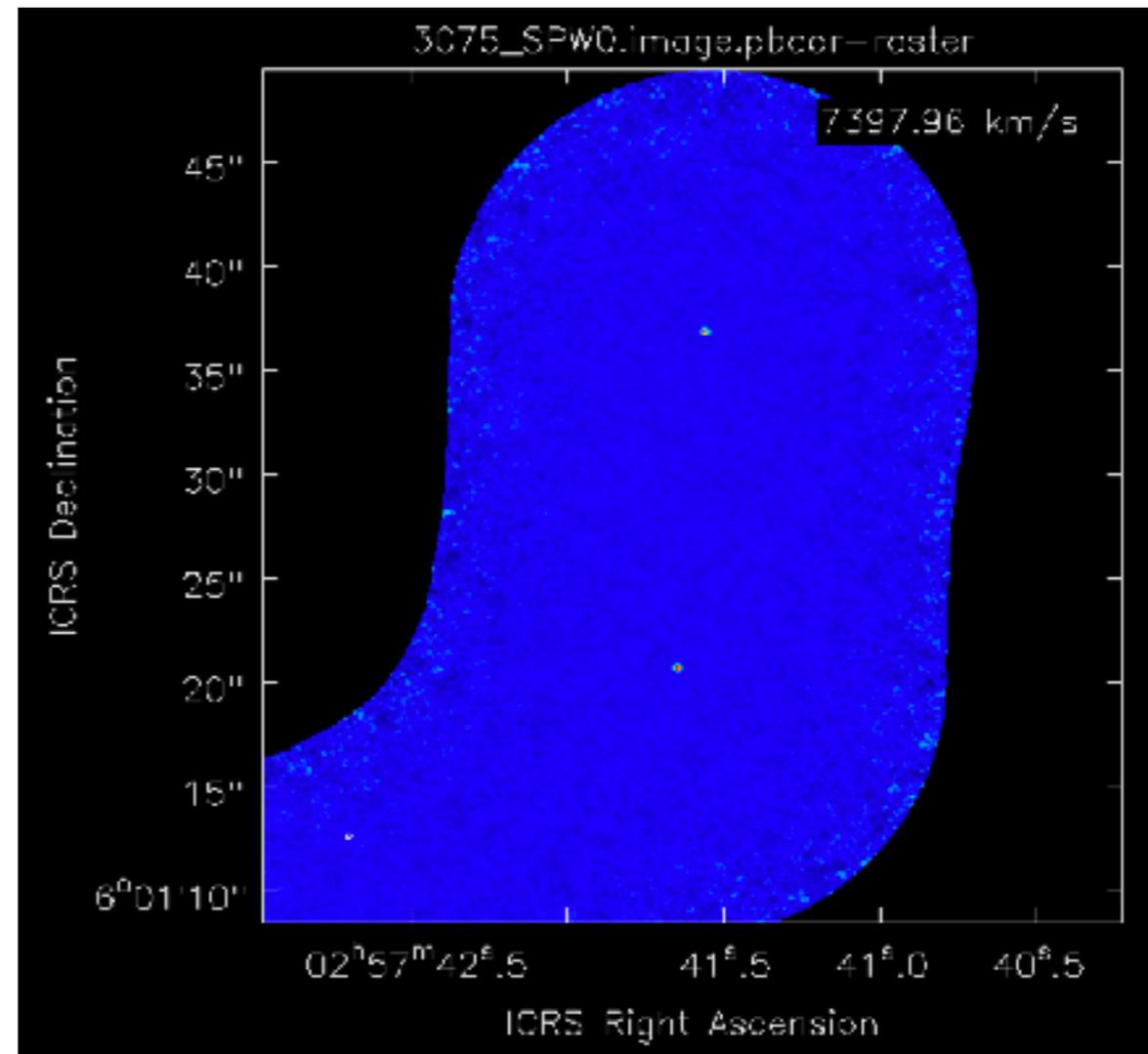


# 3C 75

Double radio galaxy (projected separation= 7.2 kpc)  
Both have extended double-sided jets

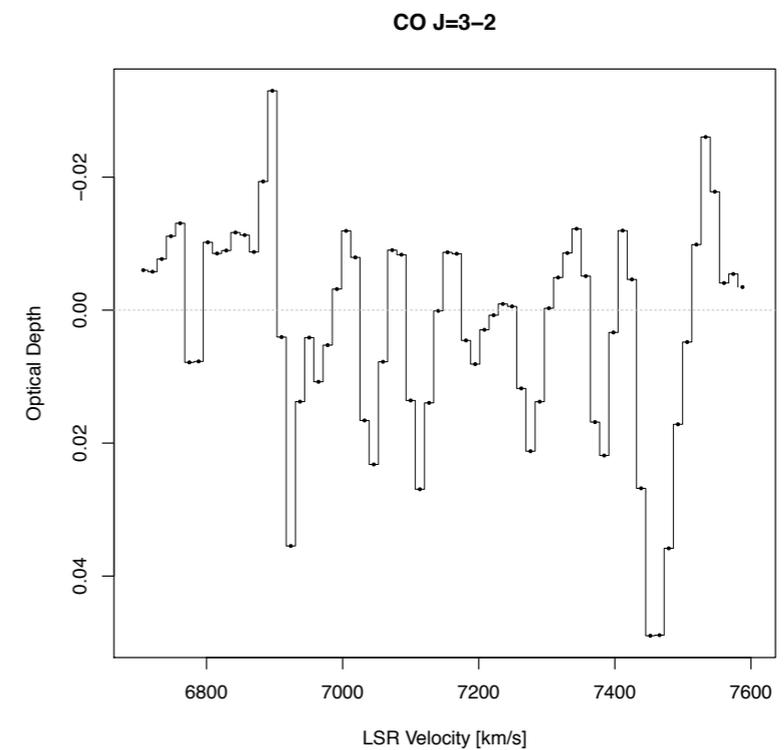
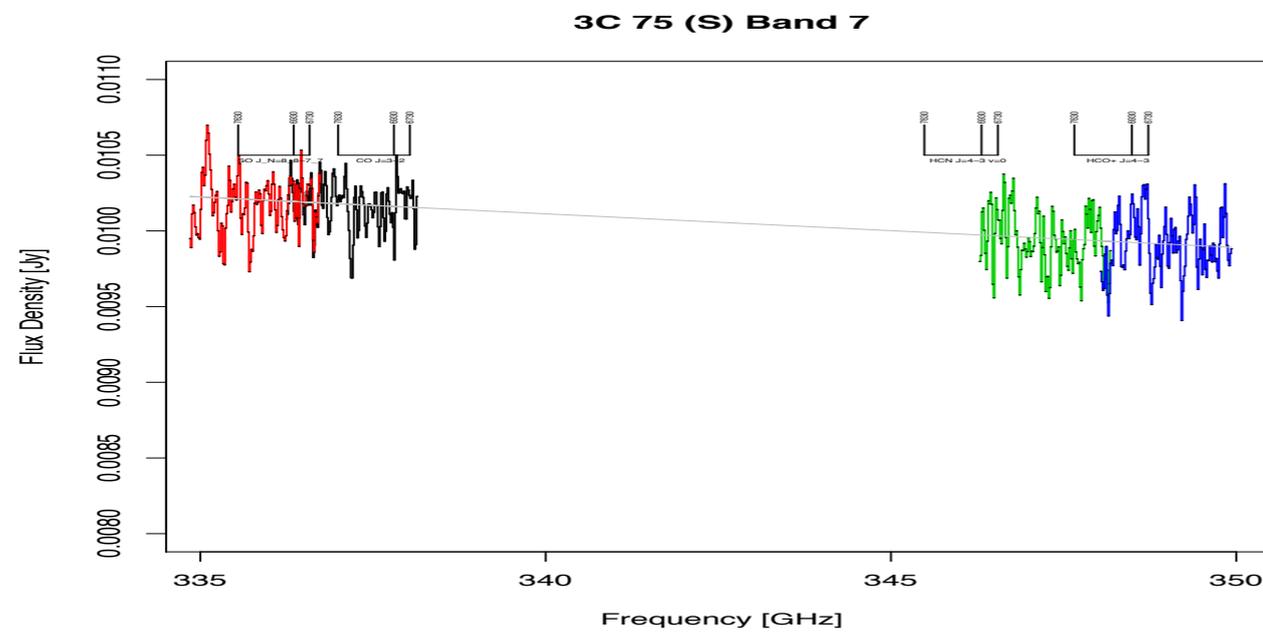
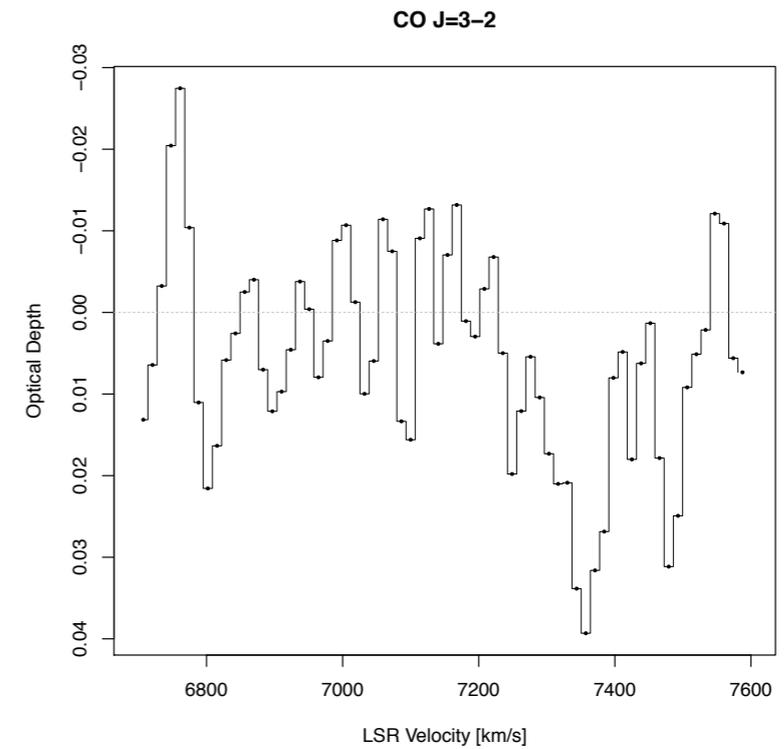
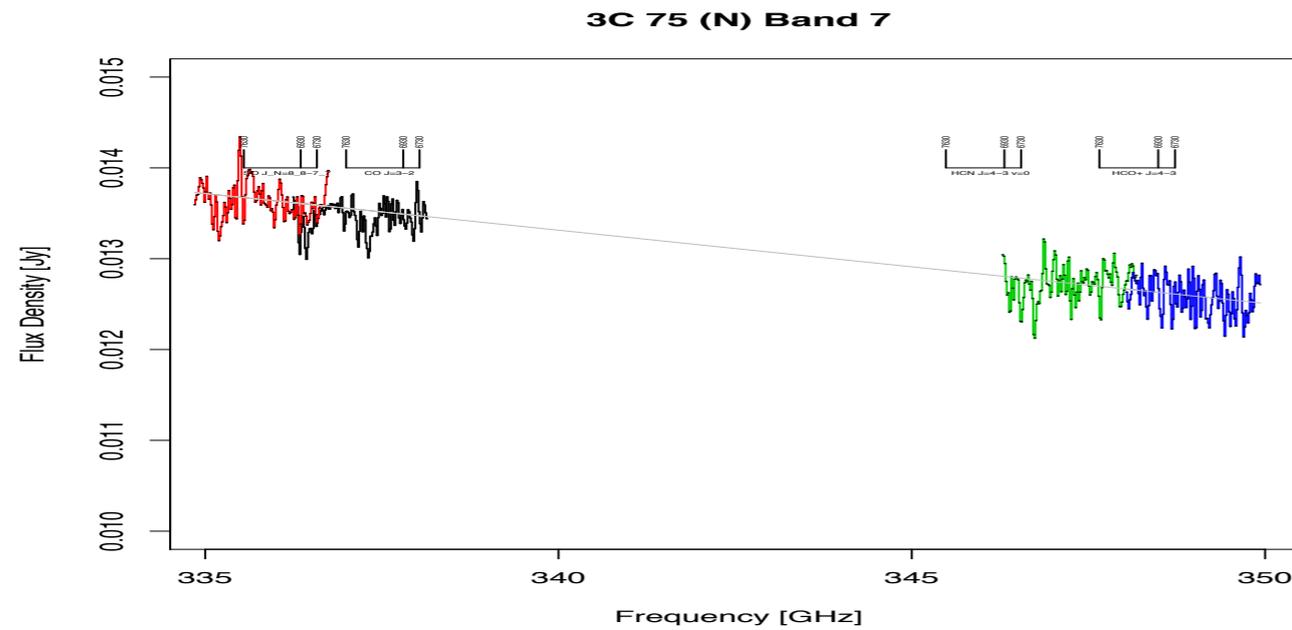


VLA 5 GHz (Owen+85)



ALMA 340 GHz (this work)

# 3C 75 : high-velocity CO absorption?



# ALMA molecular absorption survey in nearby radio galaxies

**3/5 confident + 2/5 marginal detections**

Source	Host galaxy	FFA	Dust disk	Emission	Absorption
NGC 1052	E	Y	Y	CO	CO, HCN, HCO <sup>+</sup> , SO, CS, CN, H <sub>2</sub> O, HCS <sup>+</sup>
NGC 4261	E	Y	Y	CO	CO, HCN, HCO <sup>+</sup> , CS
NGC 6328	SAB	?	Y	CO, HCO <sup>+</sup> , CS	HCO <sup>+</sup>
IC 1459	E	?	Y	-	CO, HCO <sup>+</sup> (?)
3C 75	E, binary	?	?	-	CO (?)

# Summary

## Radio absorption observations offer...

- Distribution of thermal plasma (w/ background synchrotron emitter)
- Velocity of molecules along the line of sight

## For the torus structure and dynamics

- Temperature and density
- Chemical composition in molecular torus
  - CO, HCN, HCO<sup>+</sup>, CS, SO, and CN
  - isotopologues : H<sup>13</sup>CN, HC<sup>15</sup>N
  - vib-excited HCN, HCO<sup>+</sup>
- Vertical structure of a geometrically thick torus
  - Molecular + XDR + plasma
  - Clumpy molecular clouds

