Innermost Envelope of the Peculiar Red Supergiant VY Canis Majoris

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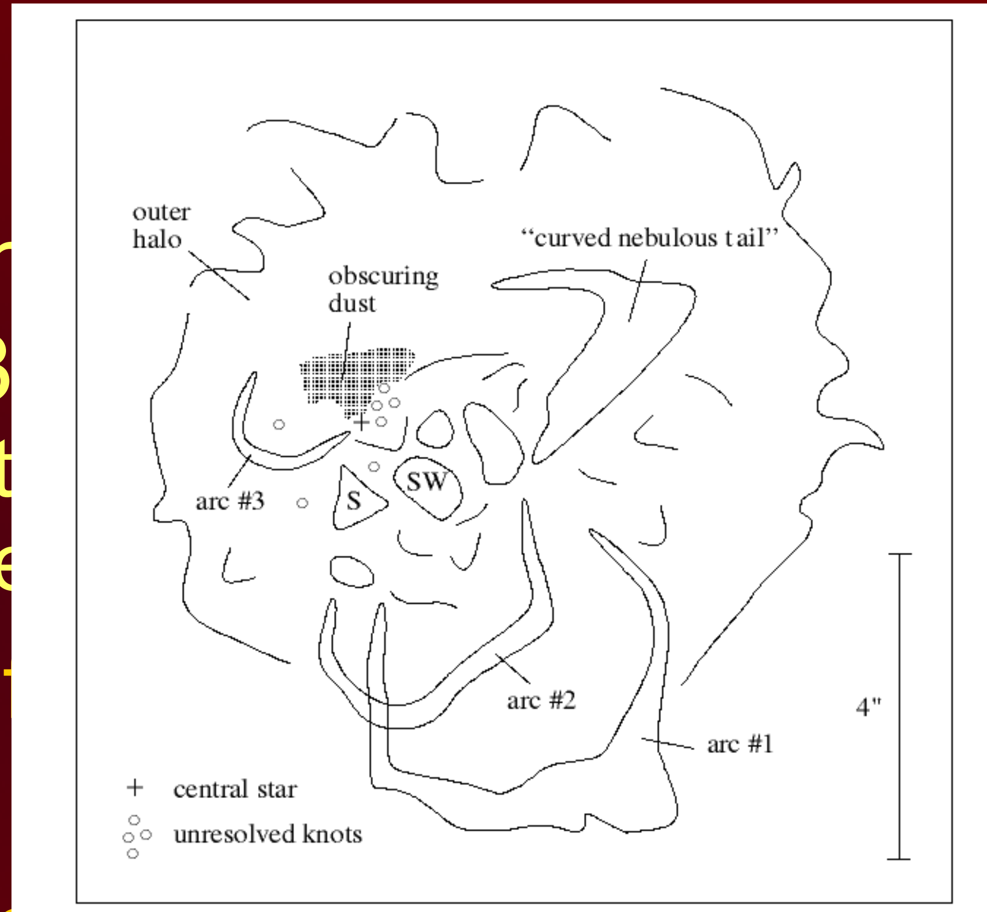
VY Canis Majoris

- M-type red supergiant (M5Ib)
- distance 1.17 kpc
  - $M_* \sim 25\ M_{sun}$,
  - $L_* \sim 5\times10^5\ L_{sun}$
  - $T_* \sim 3490 \pm 90$ K (Wittkowski '12),
  - Extremely high mass loss rate $\sim 3 \times 10^{-4}\ M_{sun}$ /yr
  - Complicated dust structures surrounding the star
    - (e.g., Monnier et al. 1999, Smith et al. 2001)

HST composite image
(Smith et al. 2001)

The Environment

- Edge of huge (5 deg in
  HII region Sharpless 3
  - Evolved so quickly that
    located at the rim of the
- Asymmetric nebula is
  optical and infrared.
- Complicated dust structure surrounding the source.



Sketch of dust features
(Smith et al. 2001)

The Envir

- Edge of hug
  HII region S
  - Evolved sc
    located at t
- Asymmetric
  optical and
- Complicated
  surrounding

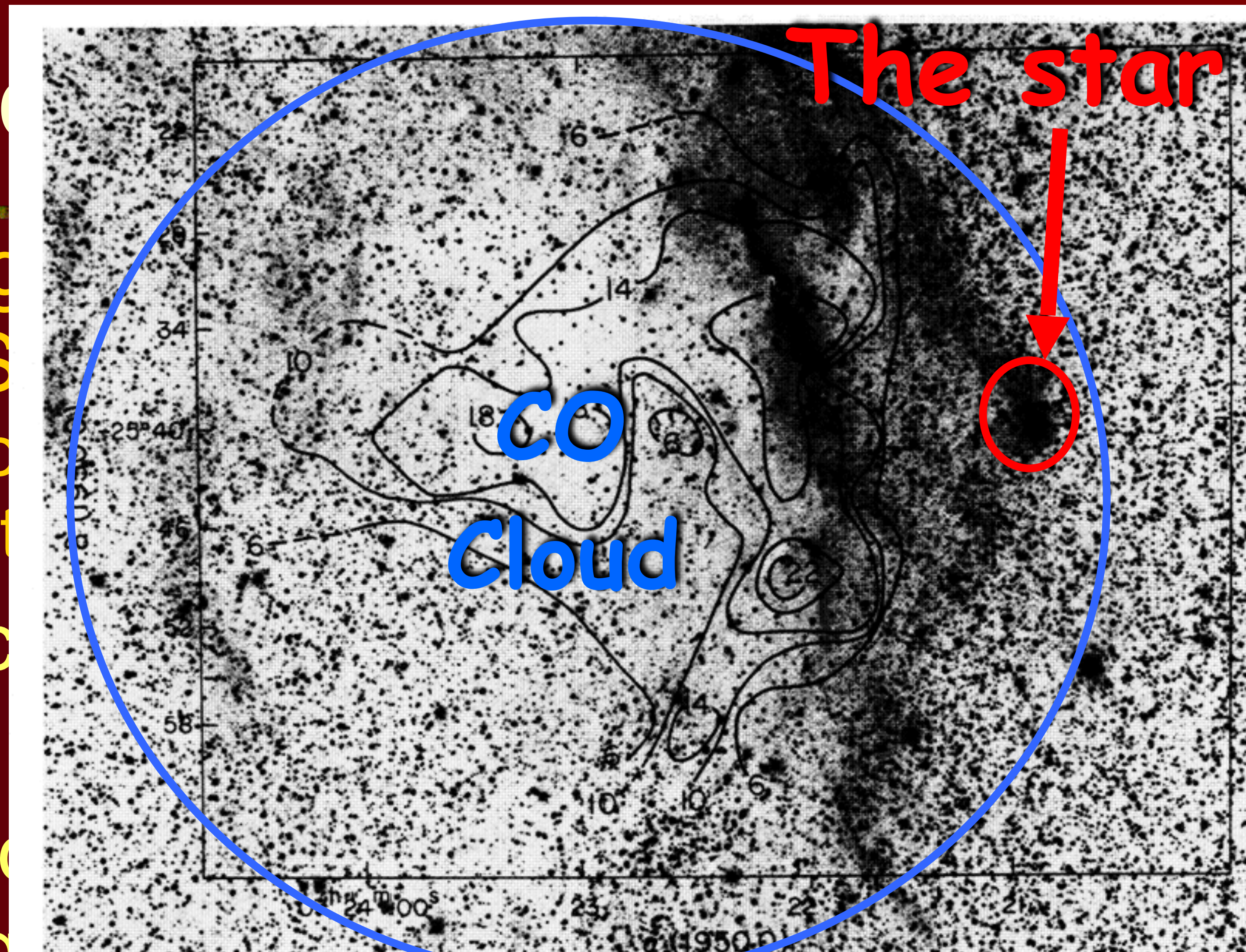


FIG. 1.—Contour map of peak ^{12}CO apparent brig temperature, in un K, superposed on a deep red photograph of the region of sky near VY CMa. The photograph is a composite of five negatives taken with the 20 inch (51 cm) Uppsala Schmidt telescope at Mount Stromlo Observatory by C. Roslund and B. Karlsson. The composite was assembled and printed by R. Wilson at Lick Observatory. The position of VY CMa (α_{1950} = 07^{h}20^{m}54^s.6, δ_{1950} = −25°40′11″.9) is indicated. The overlaid coordinate scales are accurate to about 10″.

Contour: CO; Grey scale:K band (Lada&Reid1973)

The Uniqueness of the Source

- A lot of strong maser lines observed in many transitions of multiple molecules (H_2O, OH, SiO)
- Highly polarized SiO *v*=0 maser

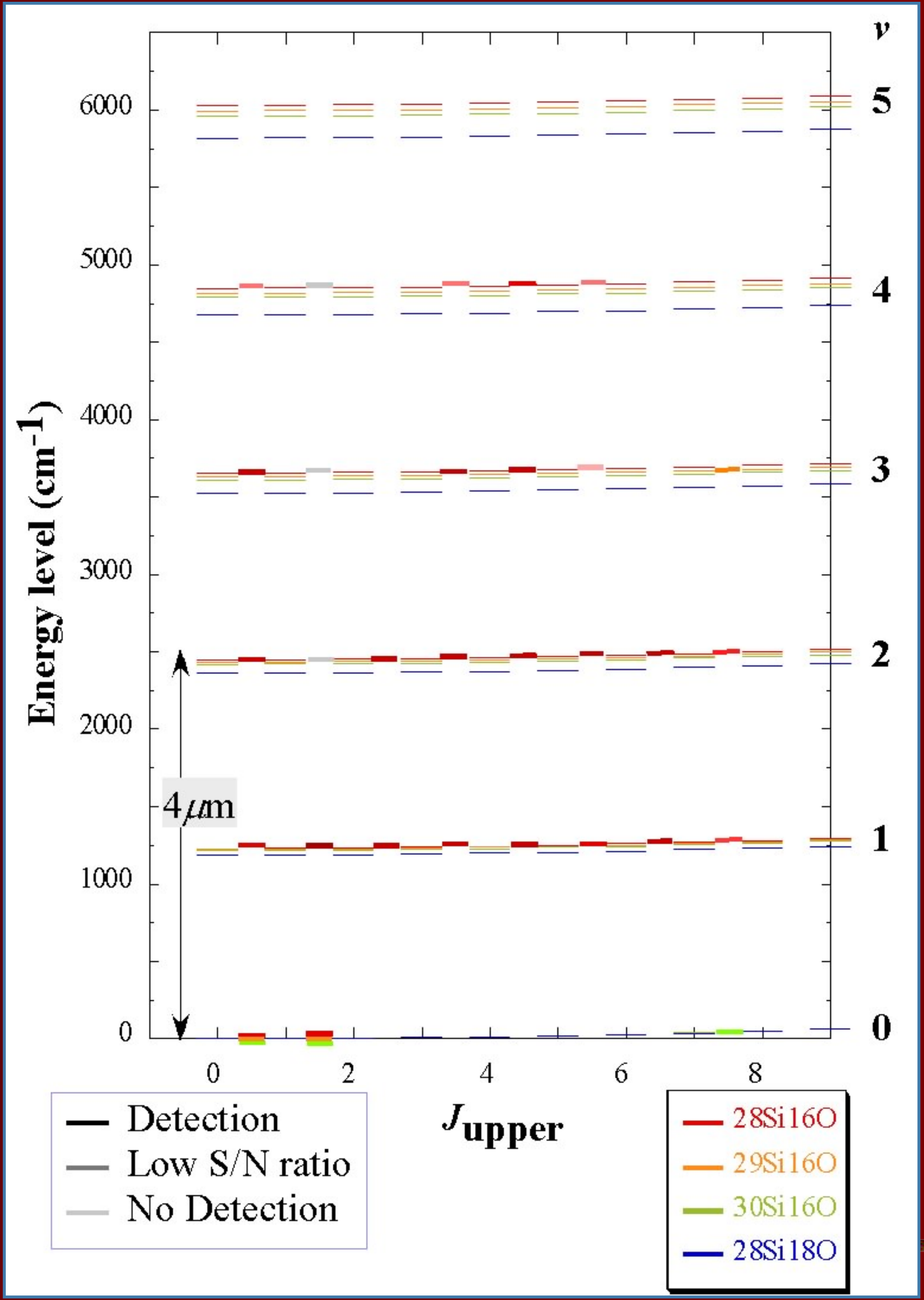
  (Shinnaga et al. 1999).
- A lot of transitions at various vibrational excitation states (up to v=5) are observed
  - (Cernicharo et al. 1993).
- Polarized in optical/IR continuum, too.
  - With time variation.

Motivation

- How is mass loss of evolved massive stars taking place in the innermost circumstellar region?
- High degree of polarization in SiO emission in multiple transitions, even at v=0, are observed.
  - They are likely maser origin.
  - Pumping mechanism?
  - Is it related to circumstellar magnetic field?
- Is magnetic field driving the mass loss?

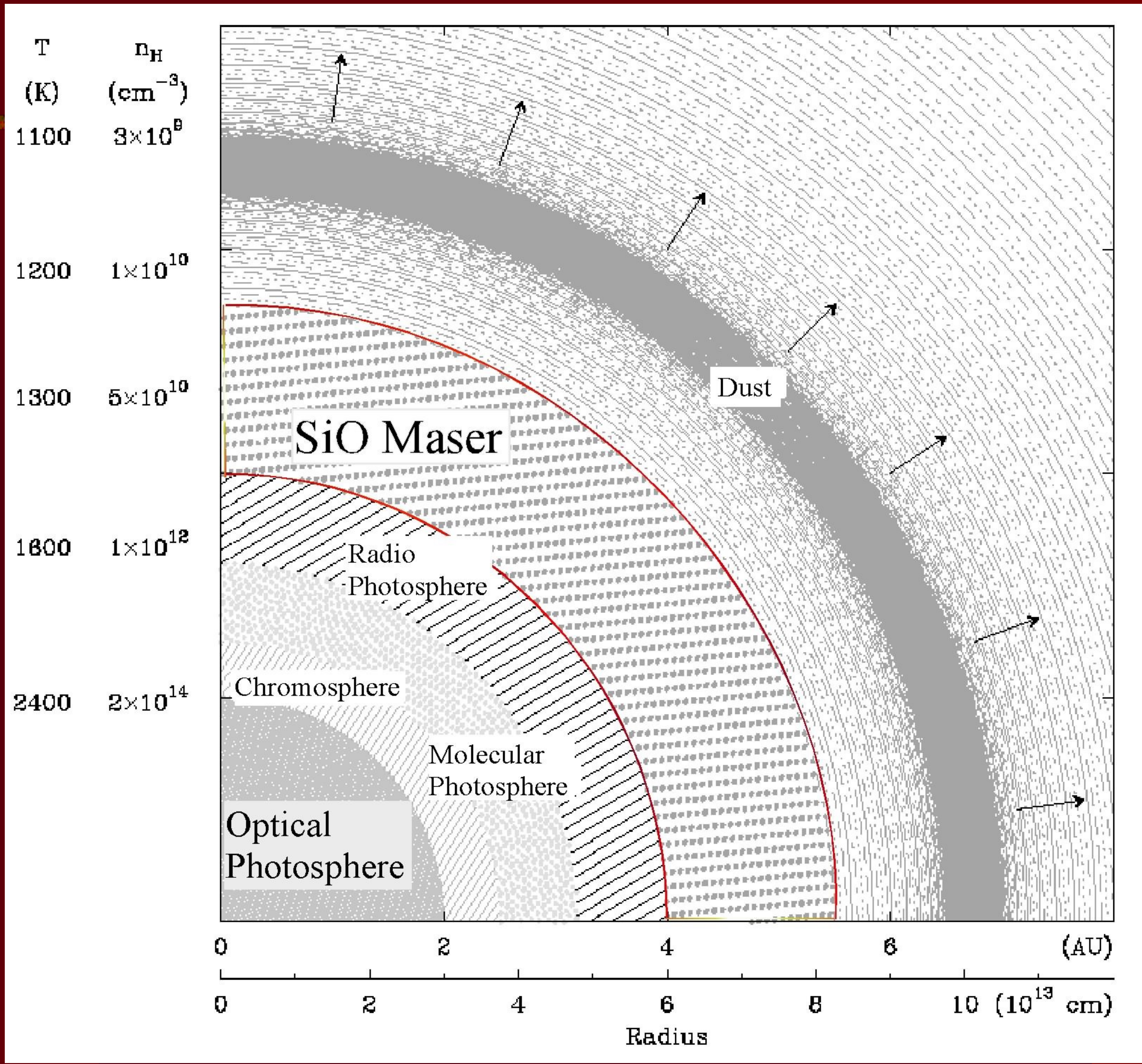
Highly Excited SiO Transitions

- SiO rotational transitions at different vibrational states have been observed towards the source
- Many of SiO transitions are highly linearly polarised.



SiO v≧1 Maser: Great Tool for Inner Envelope

- Trace inner circumstellar region
  - Just above the photosphere
- The pumping mechanism still remains unclear.



Schematic picture of stellar atmosphere (Reid & Menten '97)

SiO v>0 M
Envelope

- Trace inner
  circumstella
  - Just ab
    photos
- The pump
  mechanism
  remains u

J.F. Desmurs et al.: VLBA observations of SiO masers 191

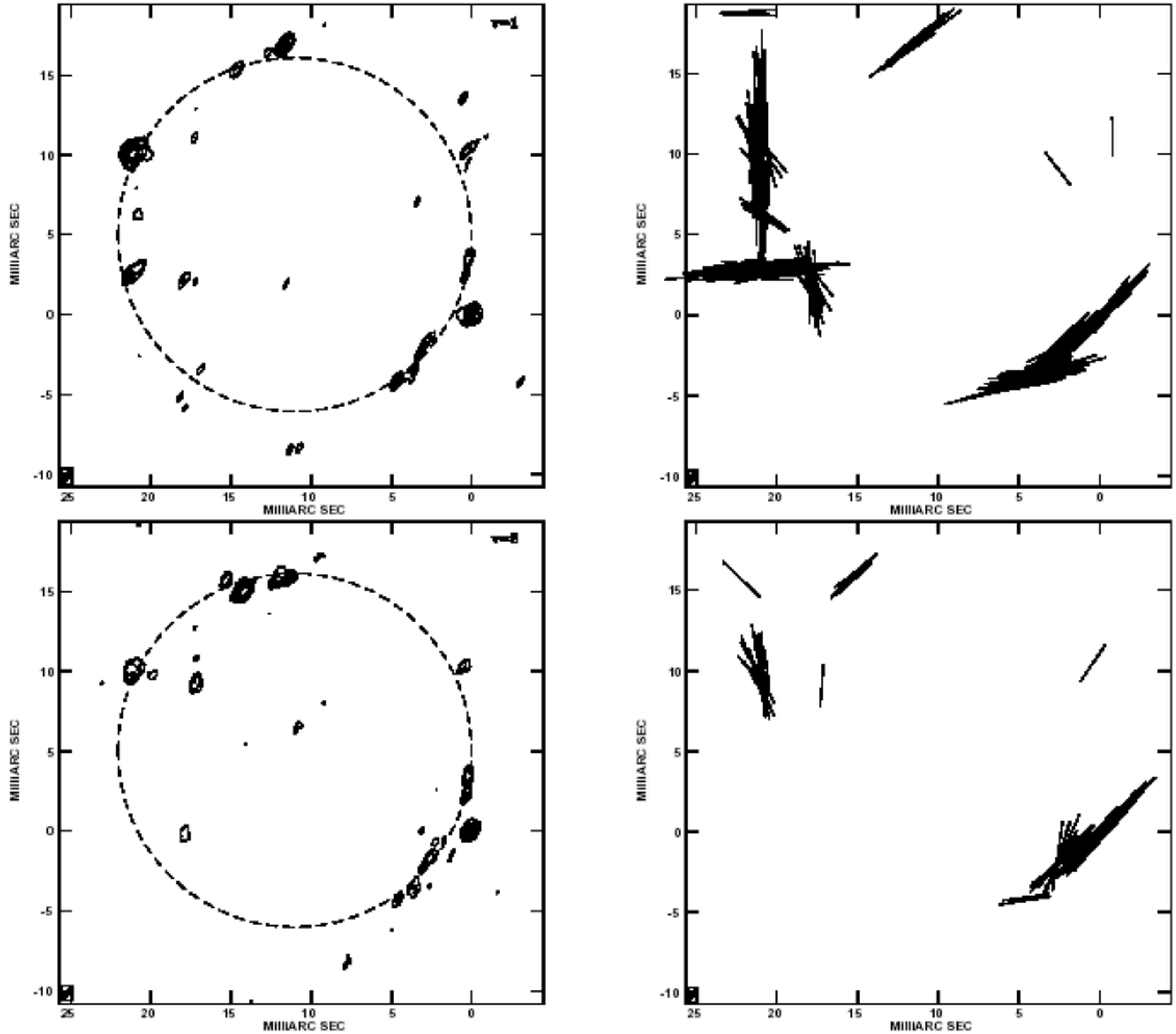
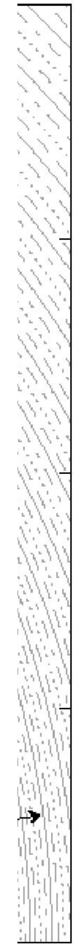


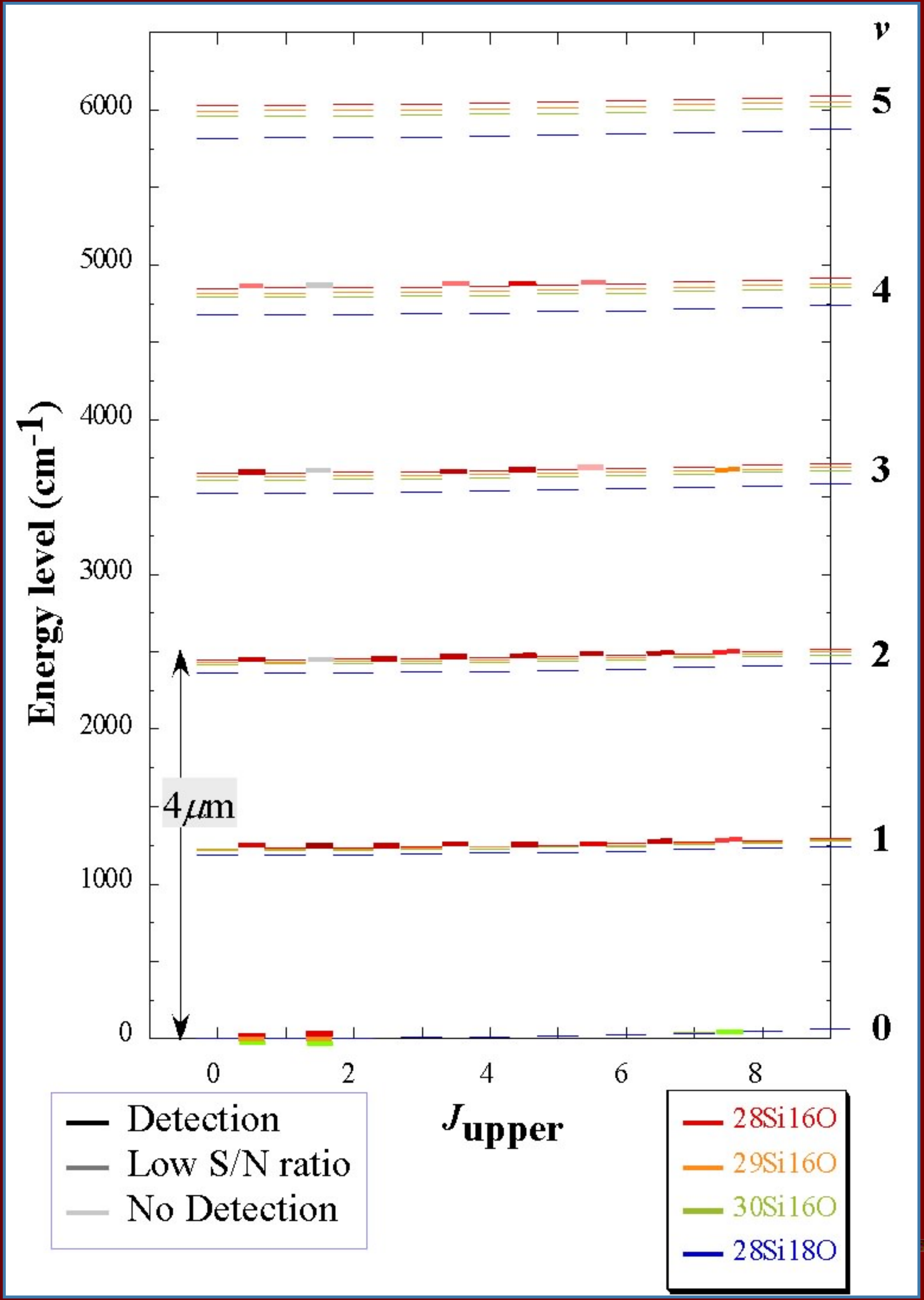
Fig. 2. Integrated intensity (left) and polarization maps (right) of the v=1 (top) and v=2 (bottom) J=1–0 lines of SiO towards IRC +10011. Contours are multiples by 10% of the peak flux in each transition (68 Jy and 67 Jy, respectively). The vectors in the linear polarization maps indicate the plane of the electric field vector and their length are scaled as 1 mas ≡ 0.5 Jy beam^{-1}. The dashed circles are identical and are drawn to ease the comparison of both images



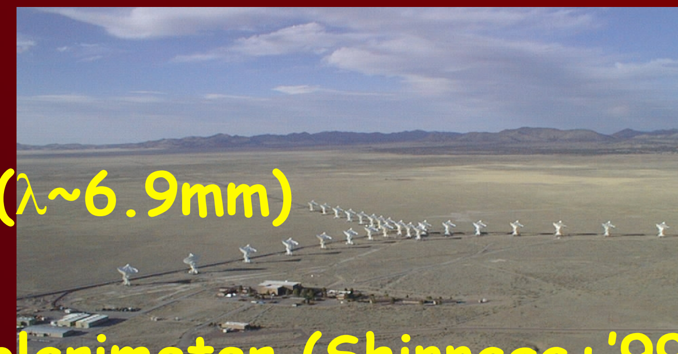
(Desmures et al. '00)

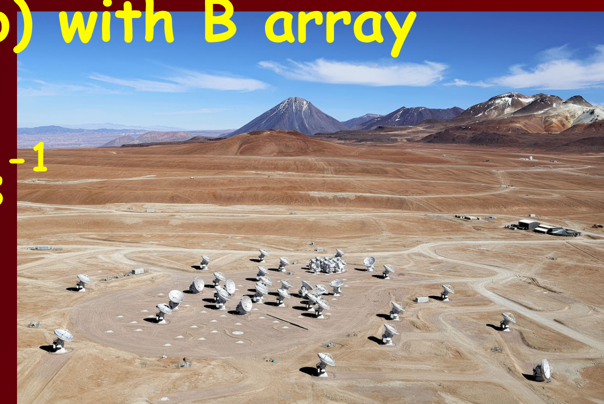
Highly Excited SiO Transitions

- Pumping mechanism of SiO v=0 rotational maser emission must be quite different from those of SiO v≧1 transitions



Observations





Transition: SiO v=0 J=1-0 ν=43.423858 GHz (λ~6.9mm)

Single-dish Observations

Nobeyama 45m telescope +Millimeter Polarimeter (Shinnaga+'99)

Interferometric Observations

- VLA(Very Large Array at NRAO Socorro) with B array

Covered ΔV~ 87 kms^{-1} ($\Delta\nu$=12.5 MHz)

Velocity resolution: 2.7 kms^{-1} and 5.4 kms^{-1}

Polarization calib. using 3C138(5021+166)

- SMA Observation

SiO high J maser transition (5-4, v=1) at 215.596 GHz (λ~1.39mm)

- ALMA Observations

321/325/658 GHz Bands; H2O Maser Transitions

SiO v=0 Maser Observations

- Nobeyam 45m
  Polarimeter rev
  polarization (Sh
- VLA imaging at
  made (Shinnag
- SiO v=0 maser
  outflow emanat
  - SiO v=0 polariz
    outflow.
  - Indicate well-o
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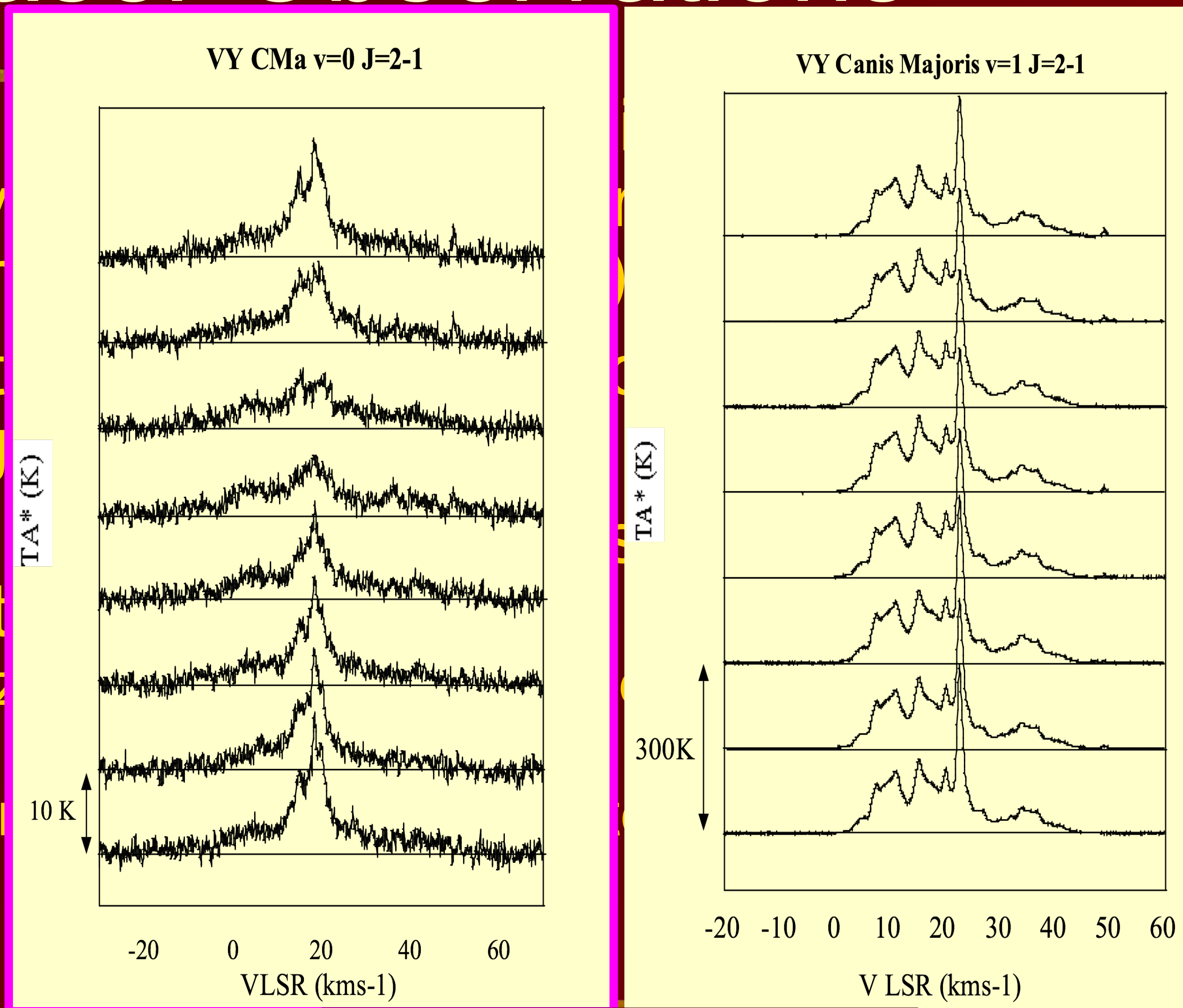
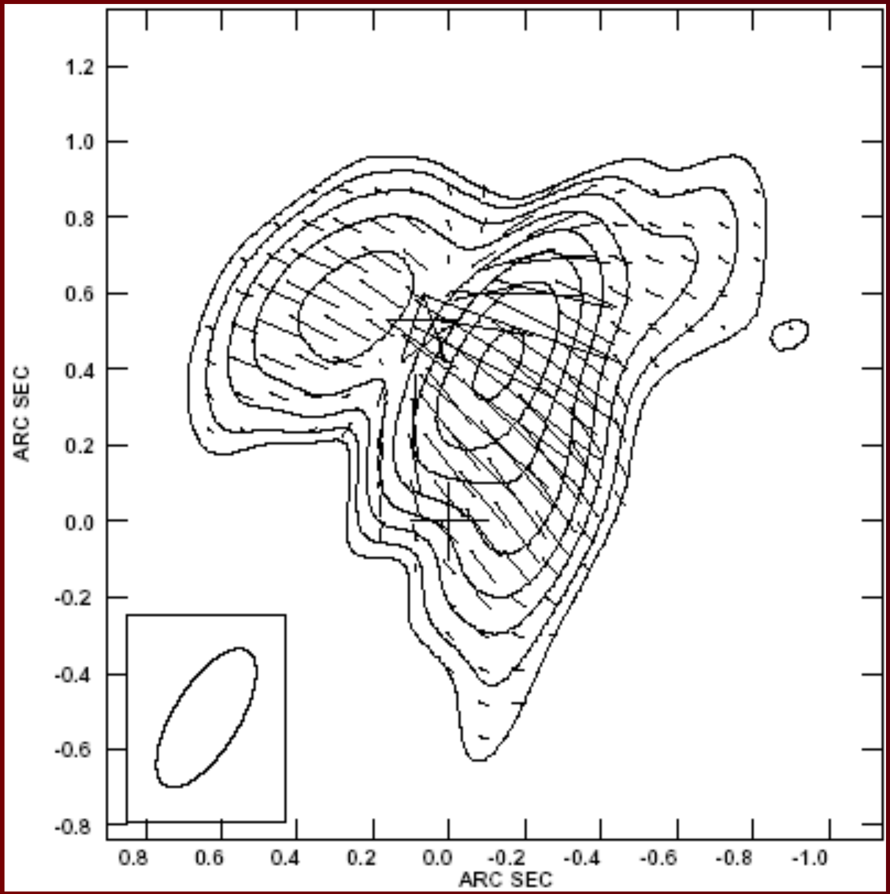
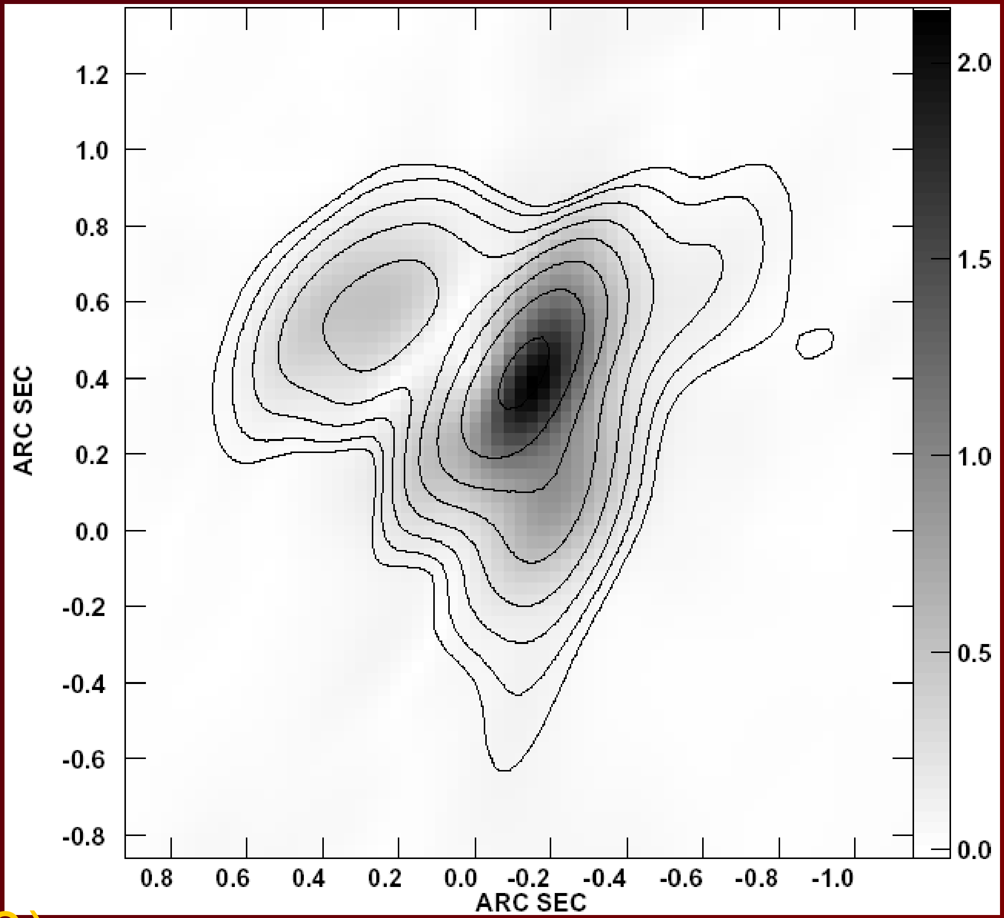


Shinnaga et al. 1999

SiO *v*=0 Maser Observations

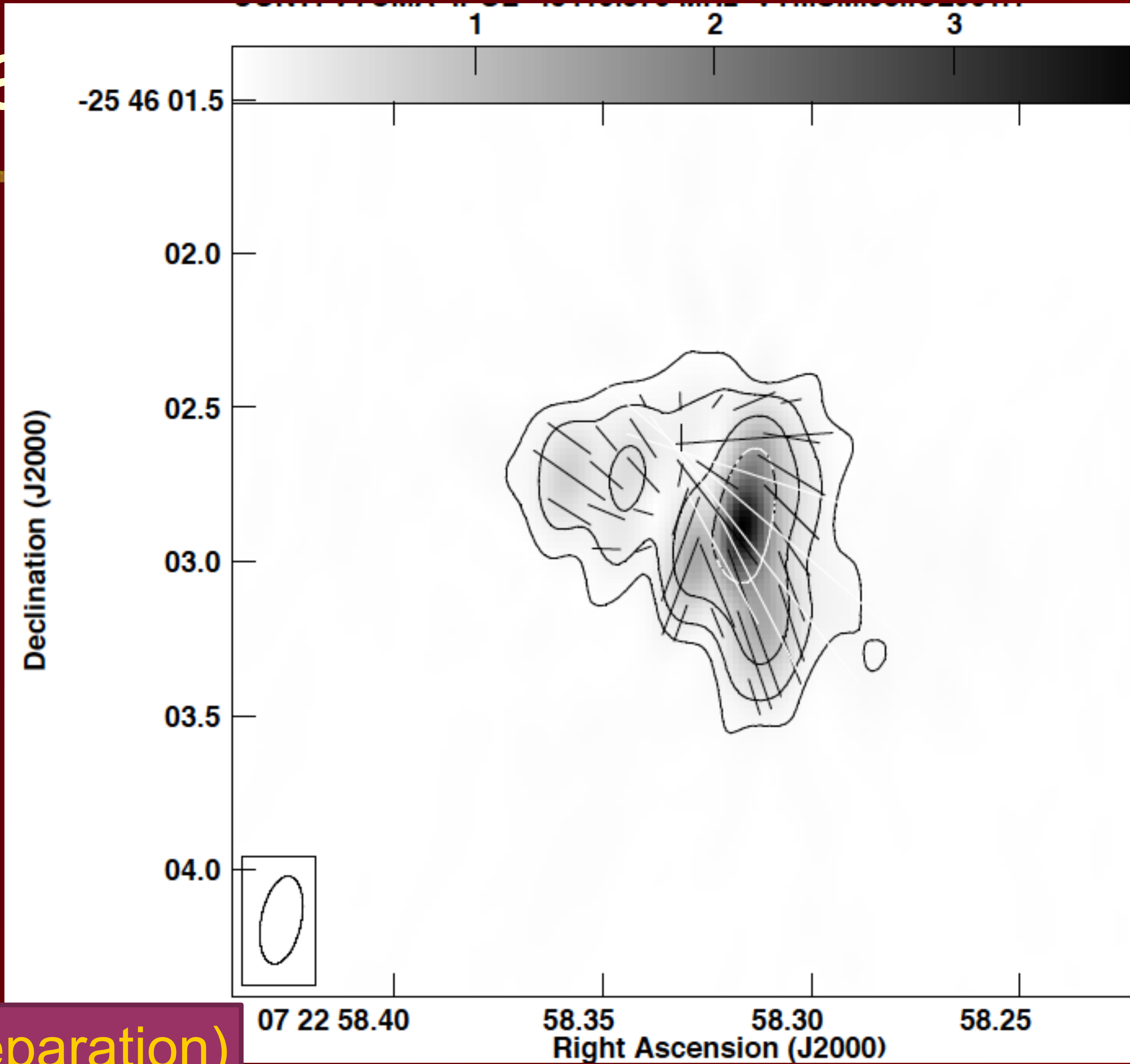




(Shinnaga, Claussen et al. '03)

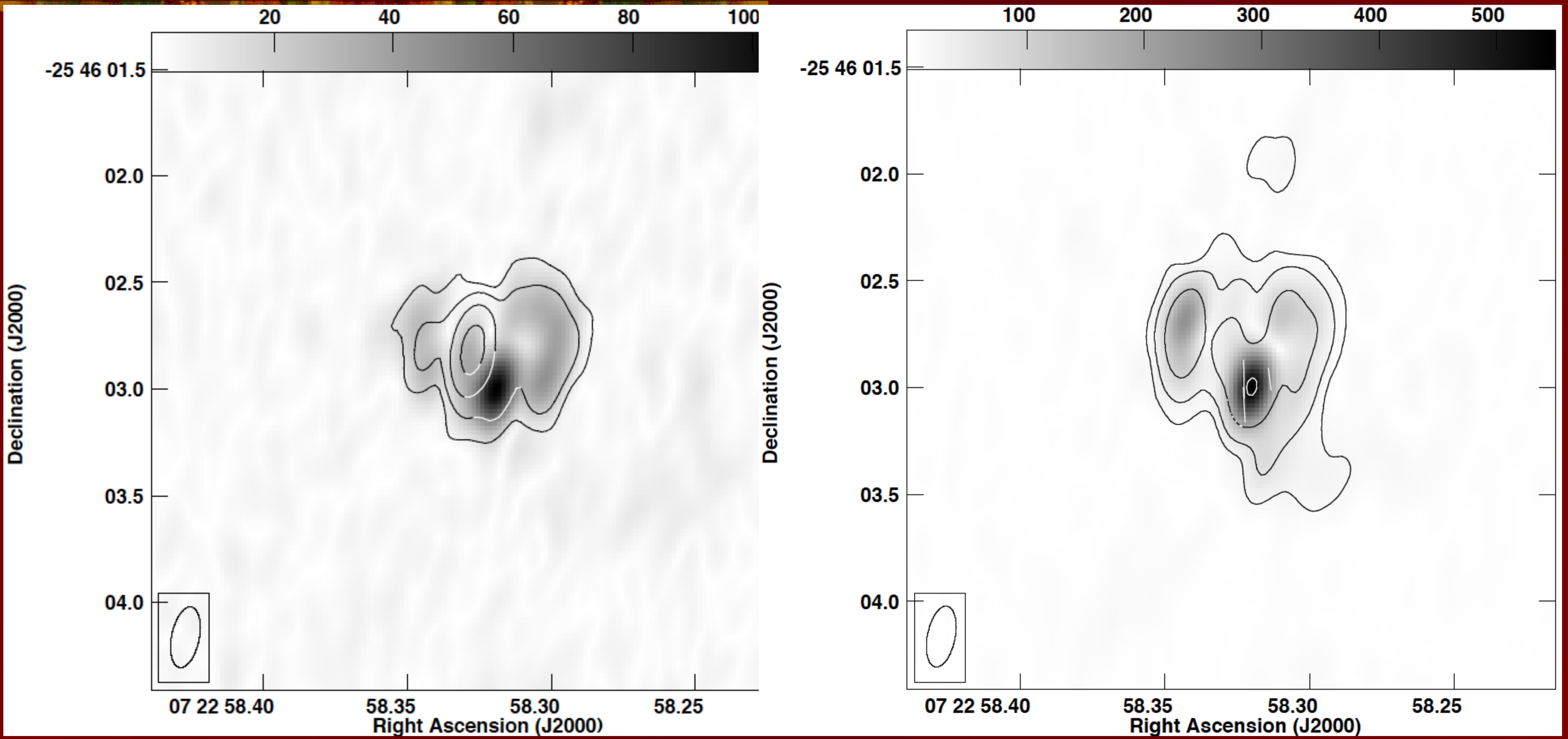
SiO *v*=0 Ma

- Without tapering/ UVFTFN, we start seeing more components inside the bipolar feature.



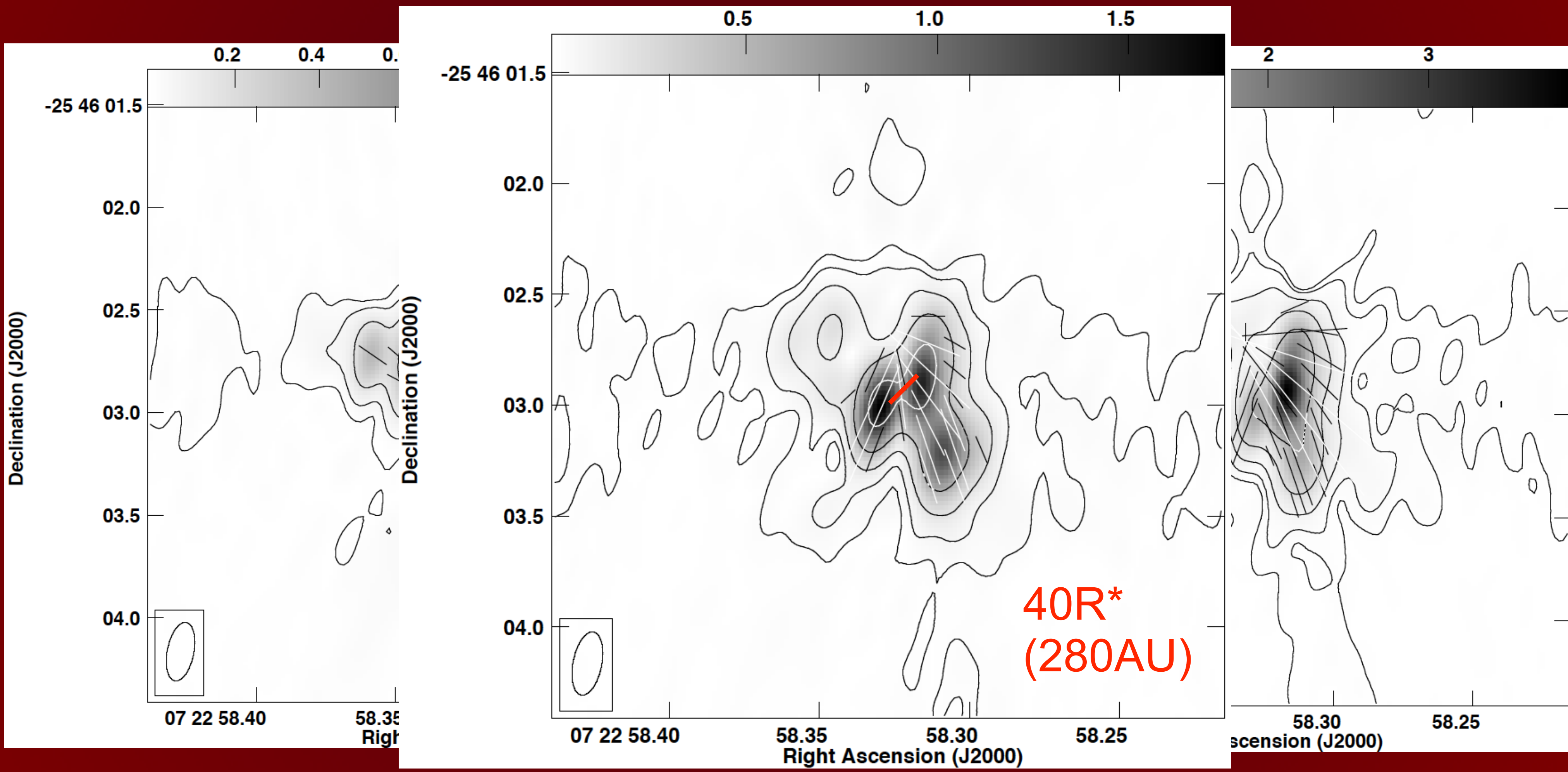
(Shinnaga+ in preparation)

SiO *v*=0 Maser Observations



(Shinnaga+ in preparation)

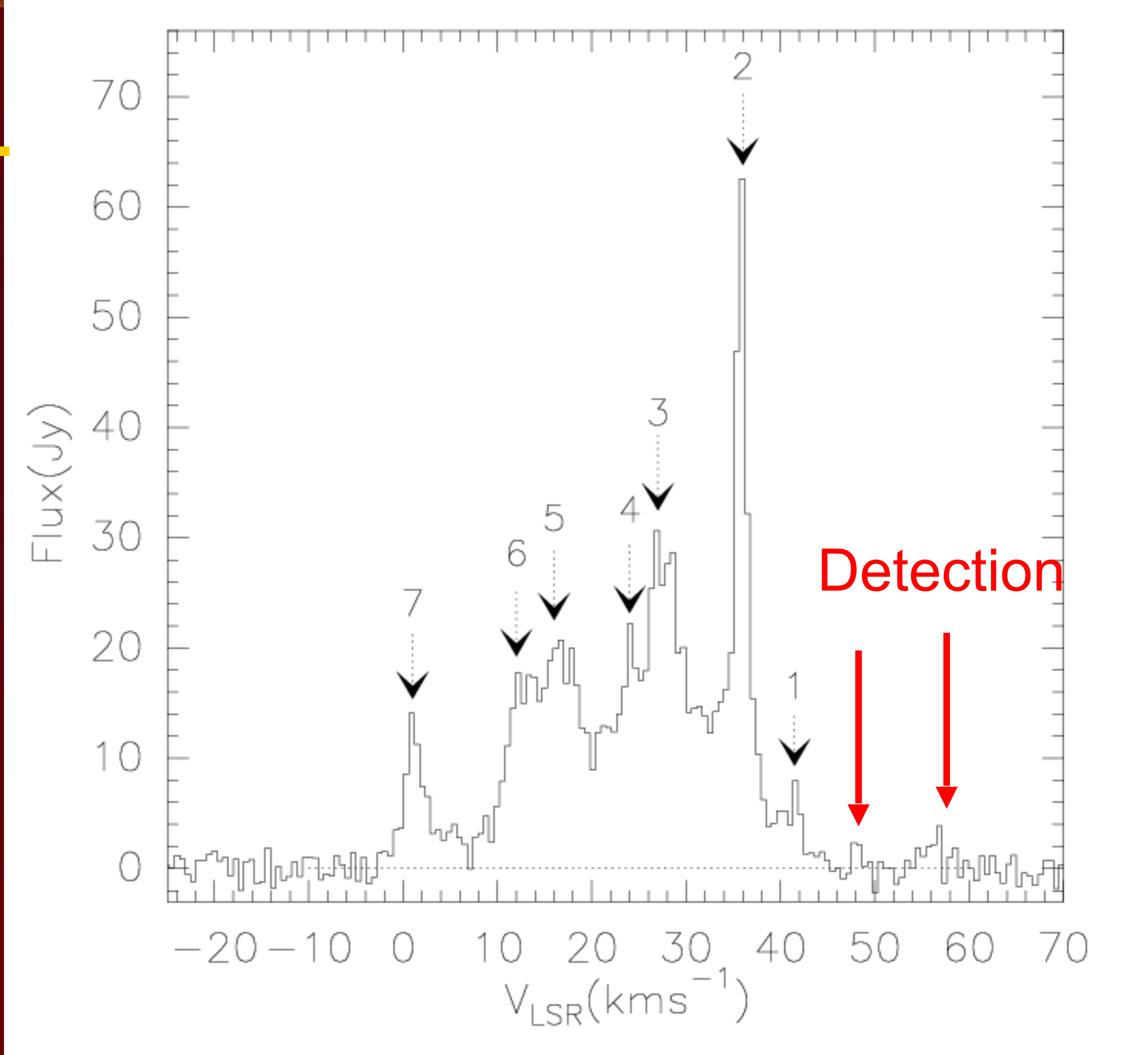
SiO *v*=0 Maser Observations



(Shinnaga+ in preparation)

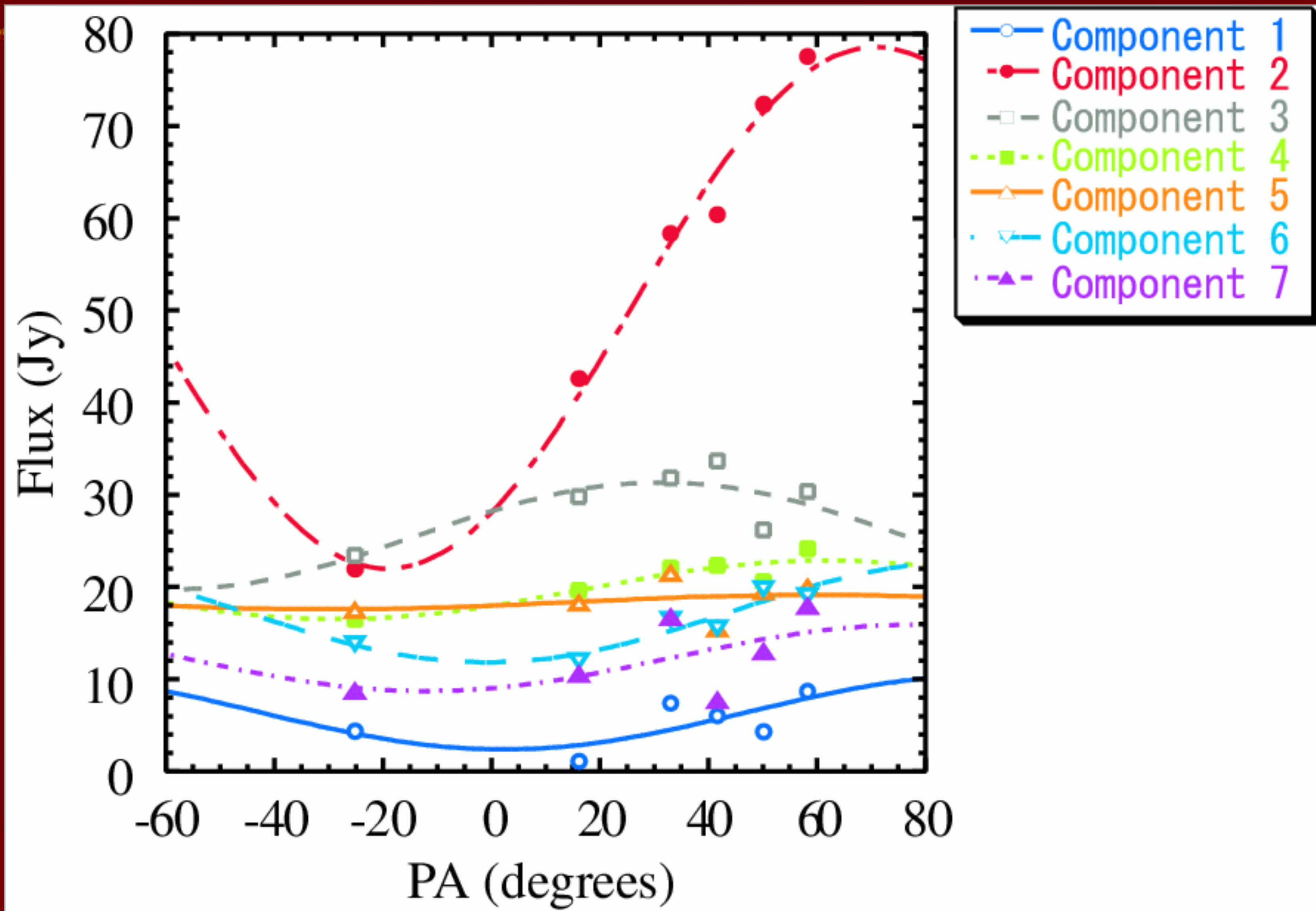
Line Profile of SiO *J*=5-4 *v*=1

- Broad velocity range.
  - over > ~60km/s.
- Main 7 components.
  - Spiky line profile.
- Comp. 2 → Most prominent.
  - Must be closest to. the central star.



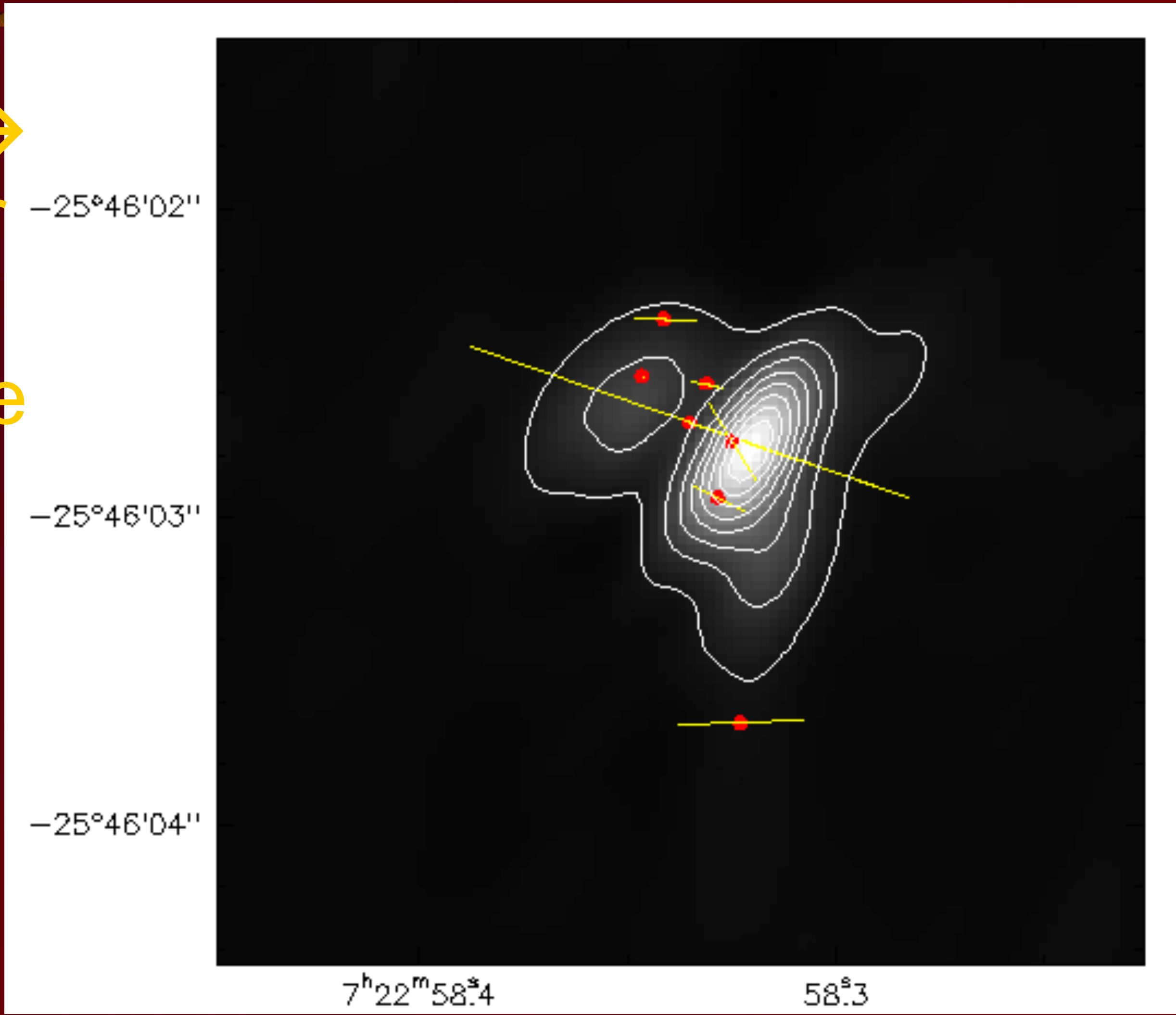
(Shinnaga et al. ’04)

Linear Polarization of The Maser Components



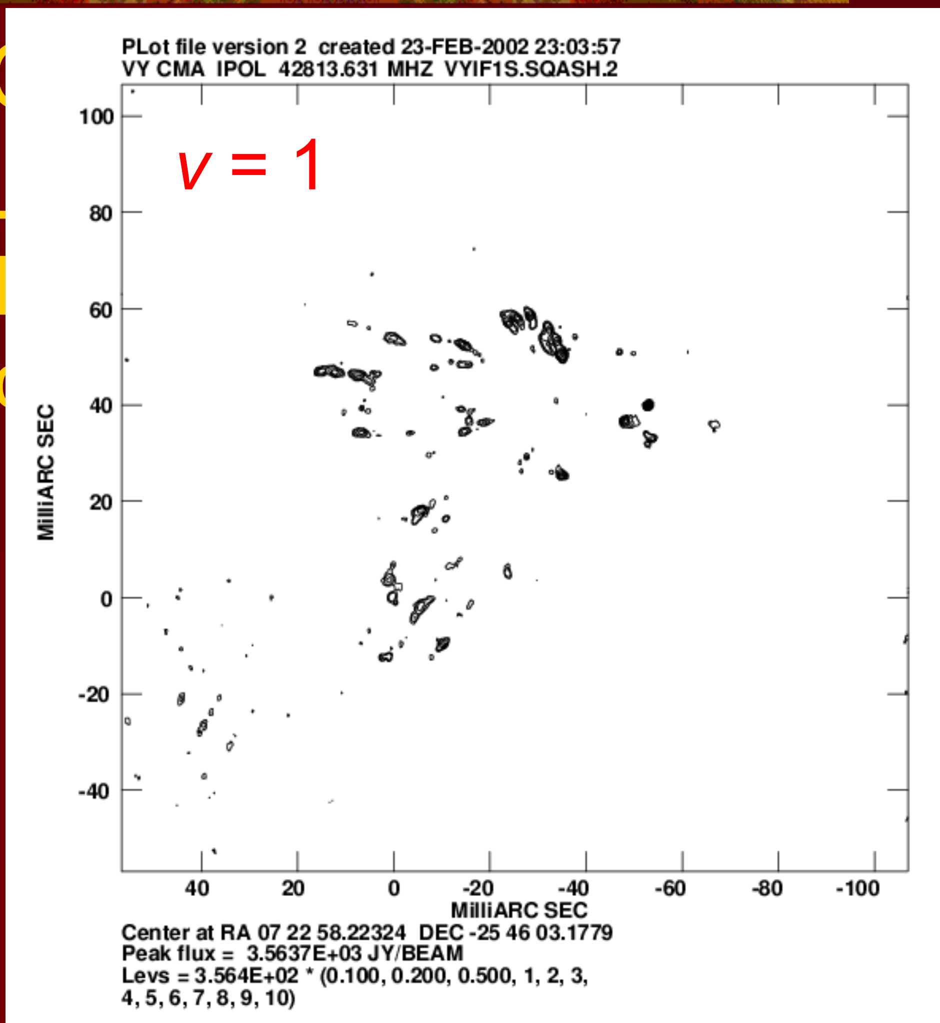
Polarization of Major Maser Spots

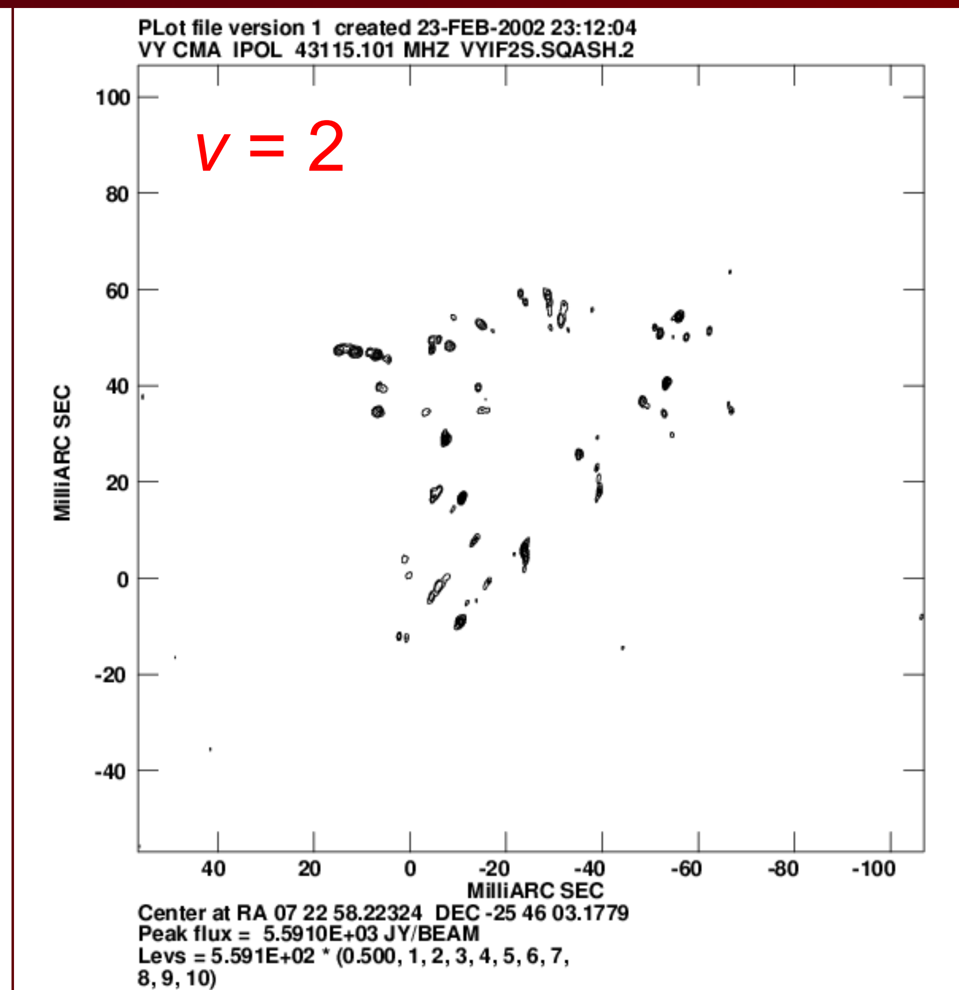
- Polarization angles → Parallel to the bipolar outflow axis.
- Except for one, all the other showed significant polarization (>15%).
- Most of them are parallel or perpendicular to the radial direction.



Comparison with SiO v≧1 Masers

- Si
  VL



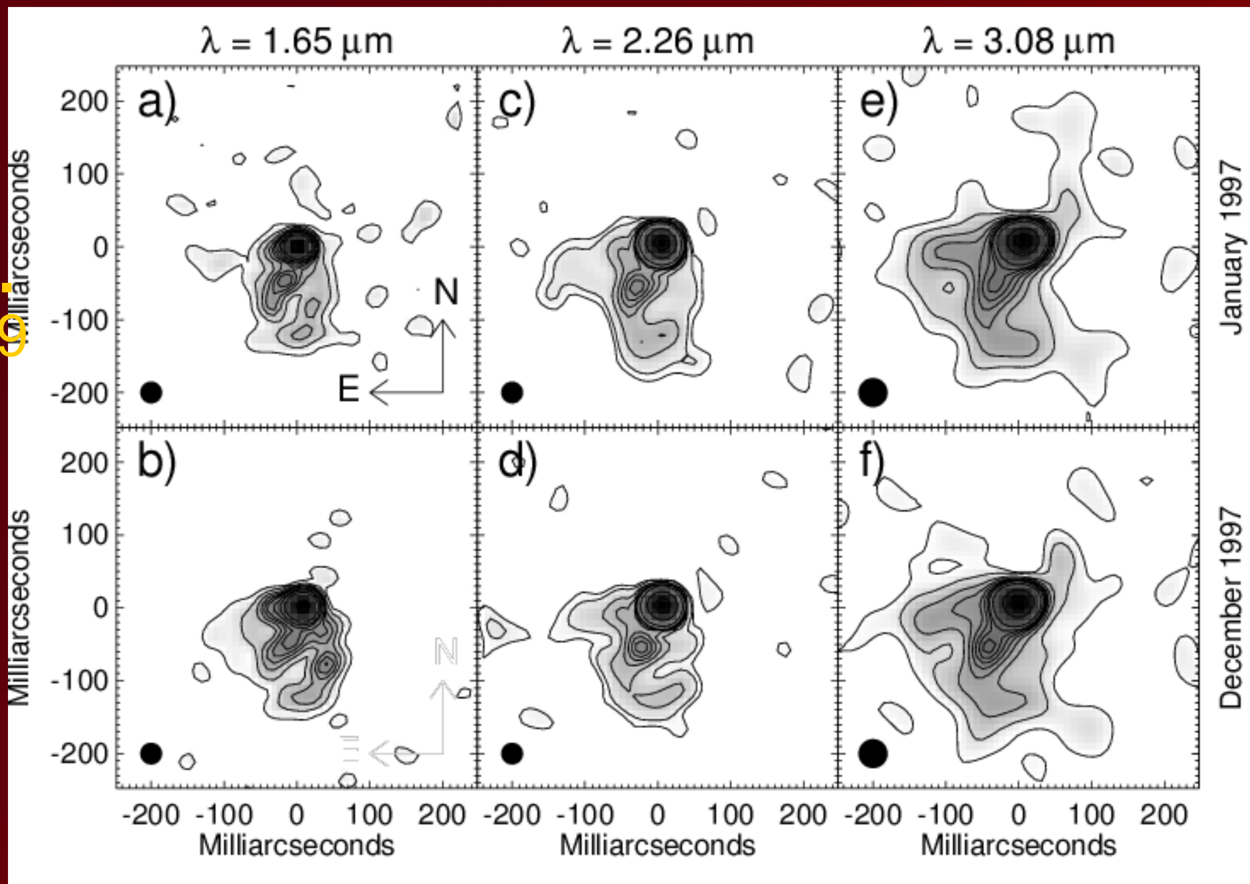


Comparison with Optical, IR Images

- Correlation with the southeast extended feature.

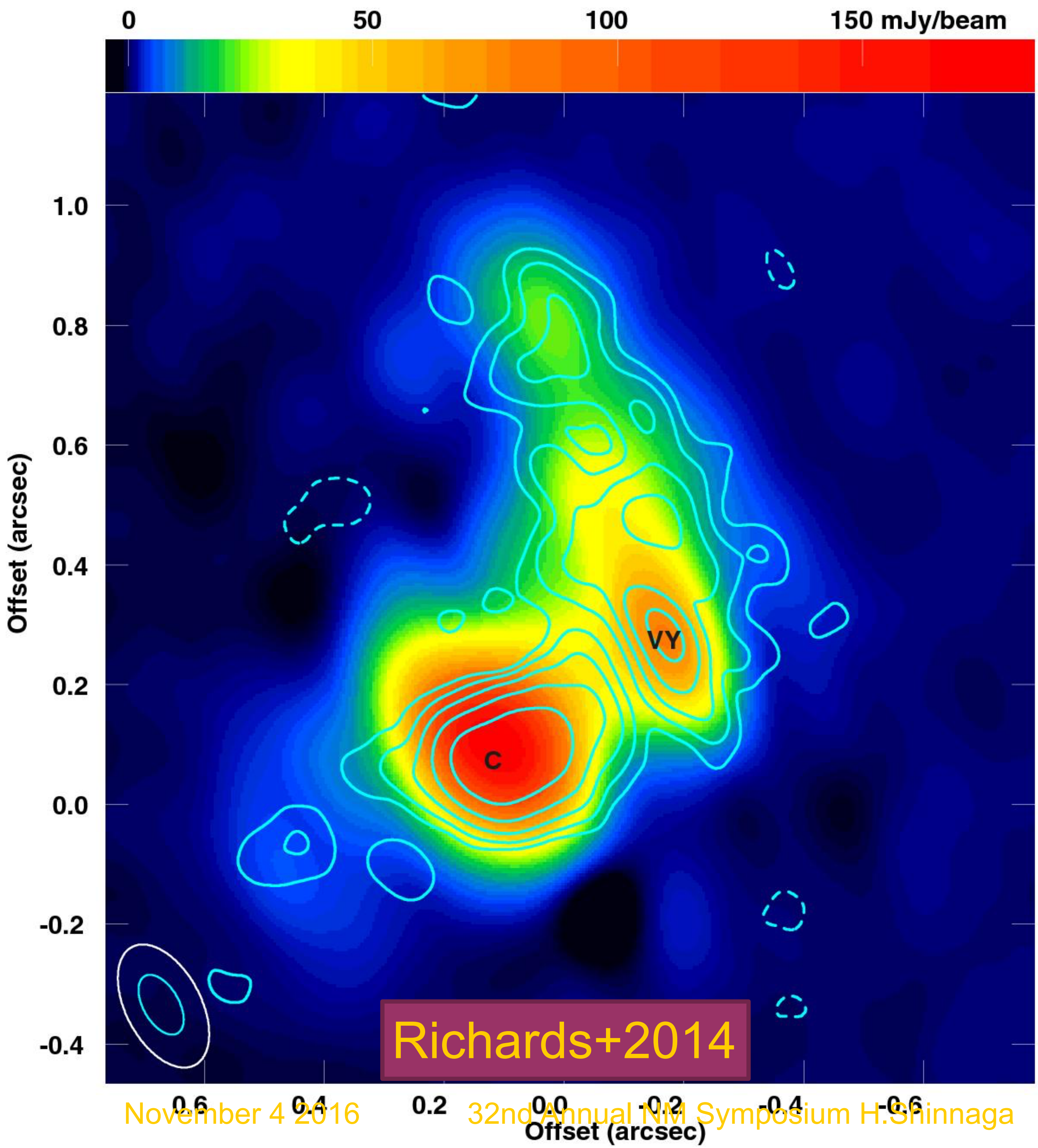
  Monnier et al. 1999

  - This structure is also observed in SiO v=1,2, J=1-0 VLBA images.

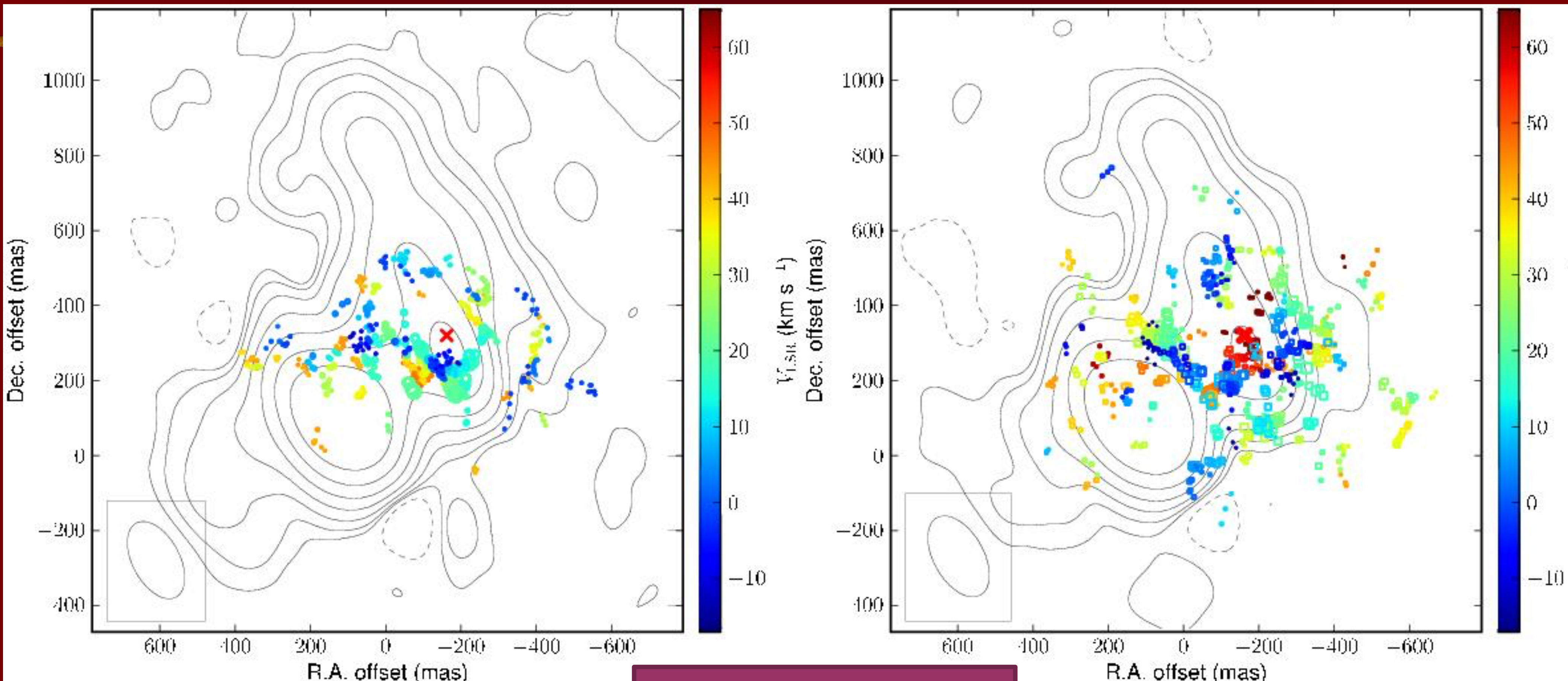


ALMA Obs

- Color scale: 321GHz continuum
- Contours: 658GHz continuum



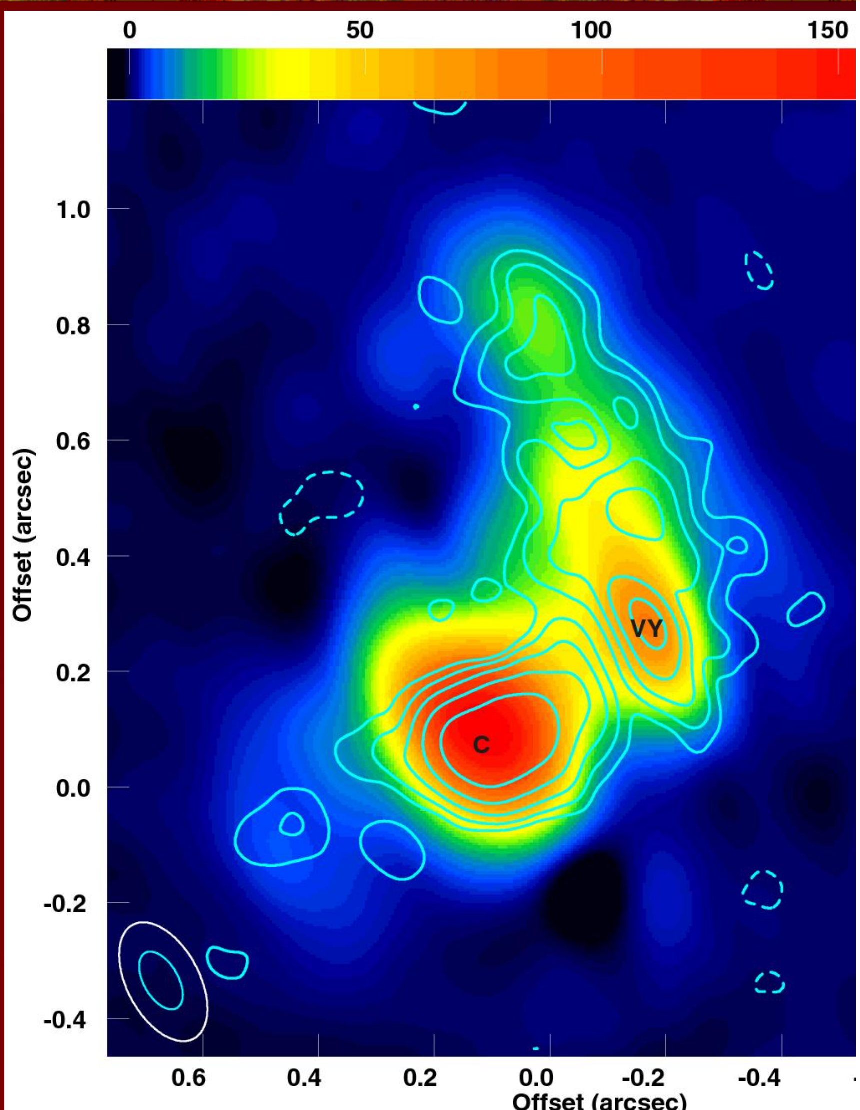
ALMA Observations

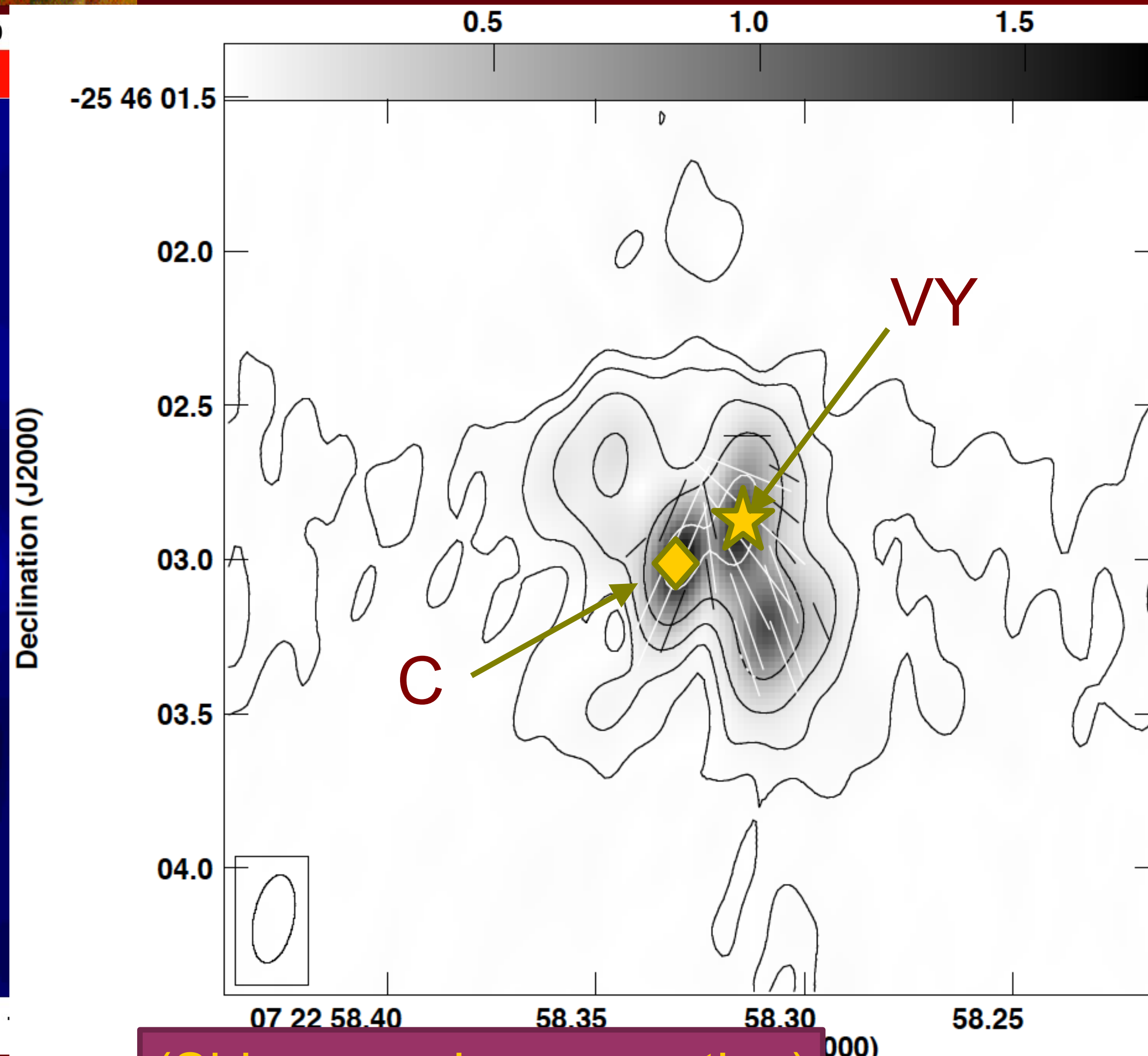


Richards+2014

321 GHz (left) and 325 GHz (right) maser positions over continuum contours. The red cross marks VY (the star).

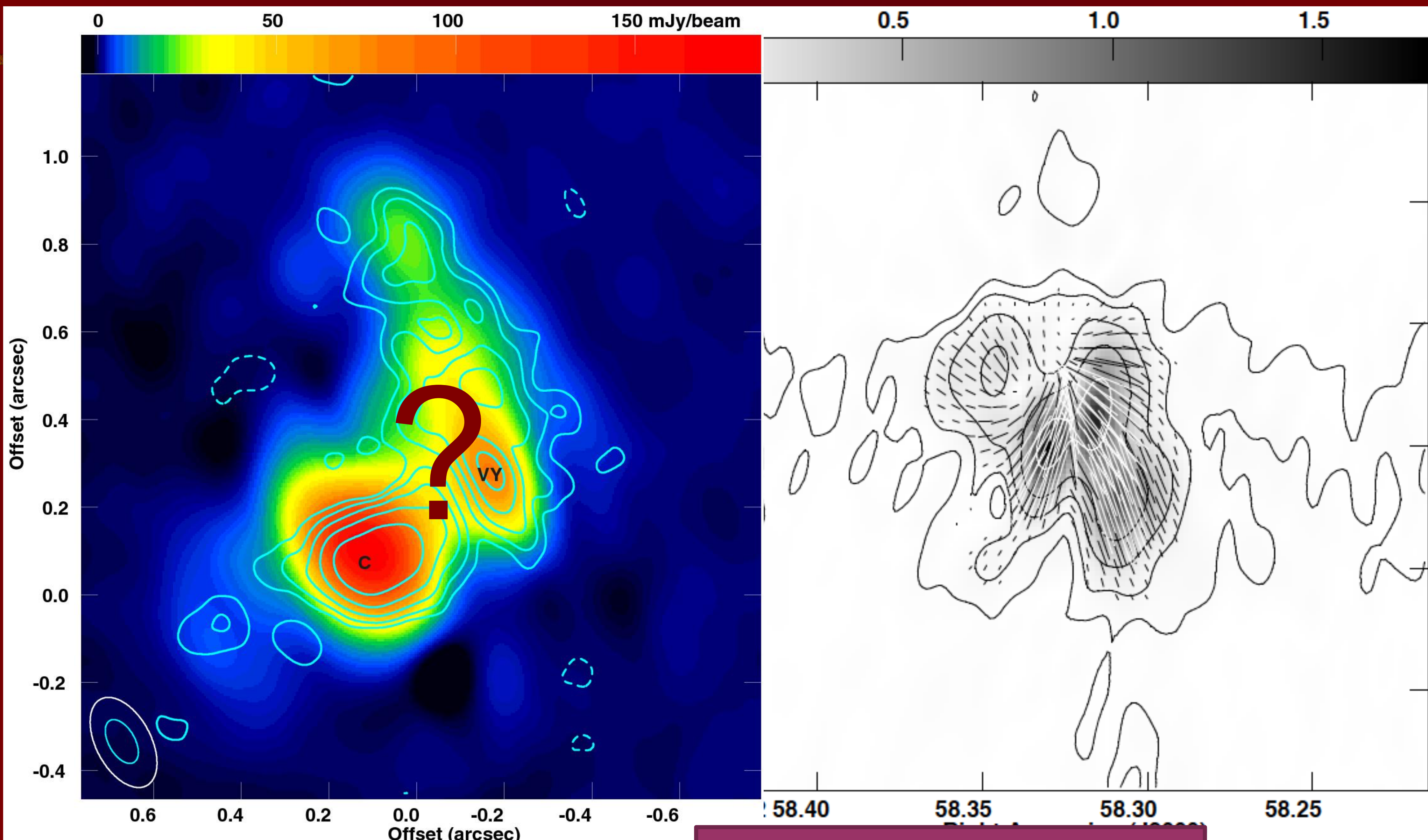
Submm Continuum vs SiO v=0





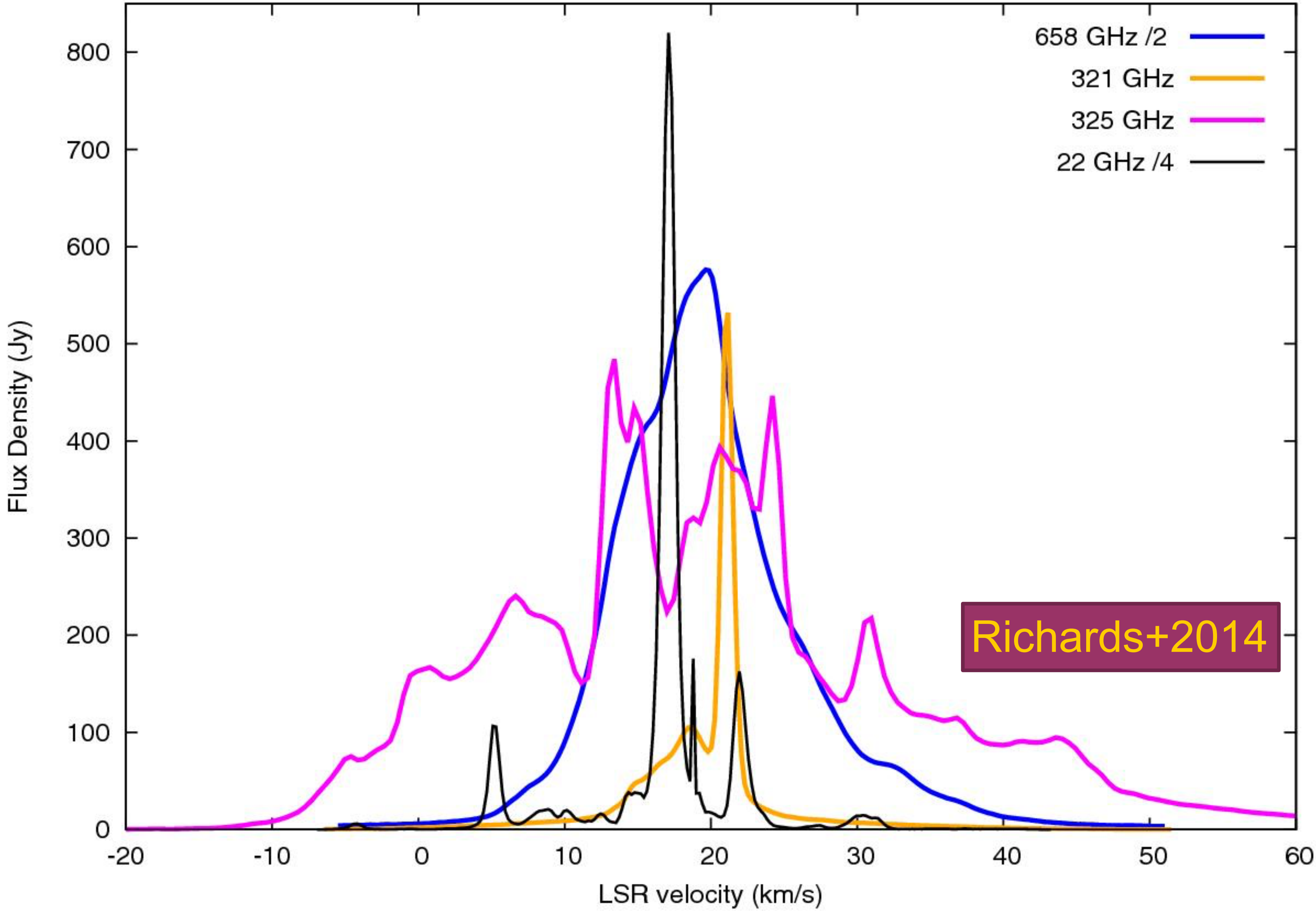
(Shinnaga+ in preparation)

Waiting for ALMA Cycle 4 Data



(Shinnaga+ in preparation)

Thank you!


658 GHz /2
321 GHz
325 GHz
22 GHz /4
Richards+2014
Flux Density (Jy)
LSR velocity (km/s)
0
100
200
300
400
500
600
700
800
-20
-10
0
10
20
30
40
50
60

ALMA Observations to come

- Cycle 4 Observing time was awarded for this project.
- We are waiting for the data to be taken and delivered.

Comparison with Masers of Other Molecules

- H_2O maser VLBA imaging
  - Marvel et al. '98
- SiO (low *J*) maser VLBA imaging
  - Miyoshi private communication