SiO masers in evolved stars

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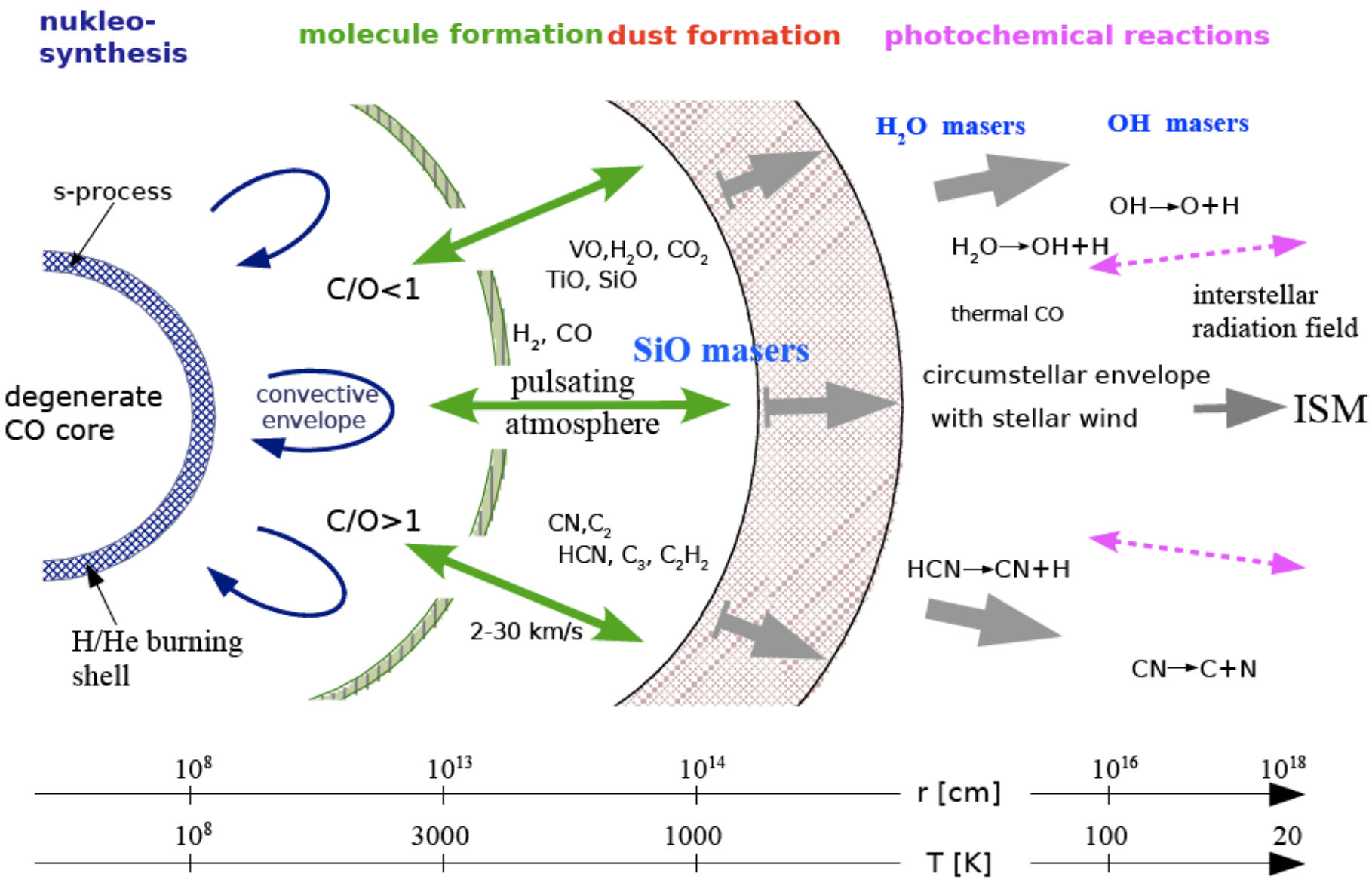
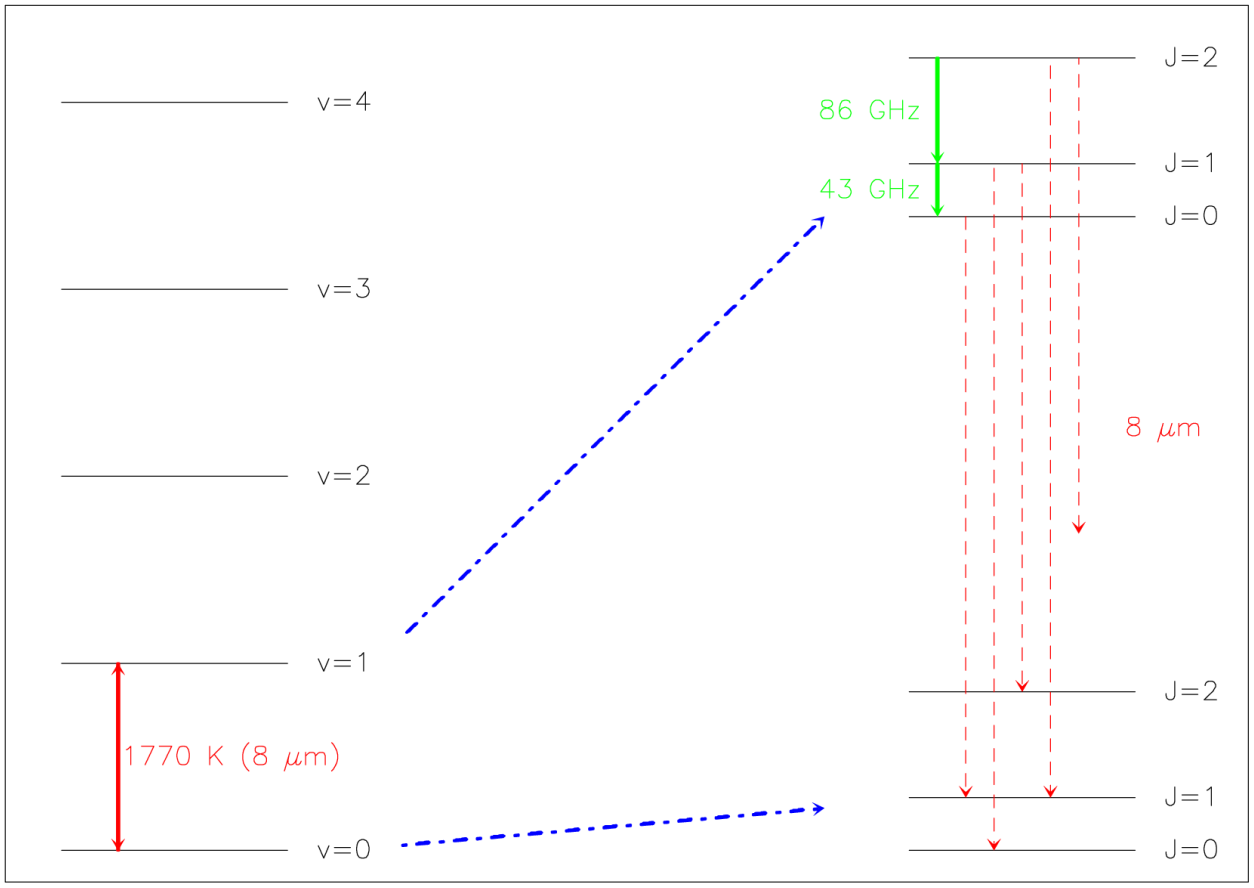
Schematic view of an AGB star

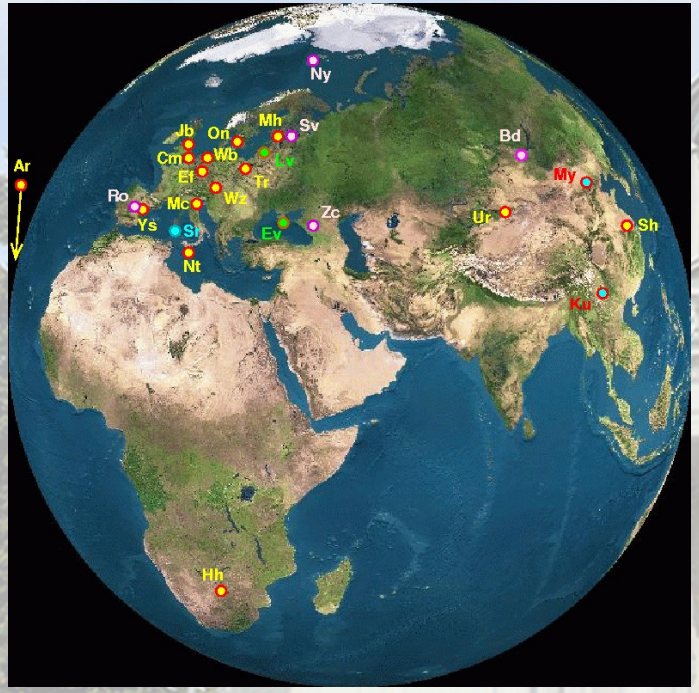



SiO : LEVELS AND TRANSITIONS
v=4
v=3
v=2
v=1
v=0
1770 K (8 μm)
86 GHz
43 GHz
J=2
J=1
J=0
8 μm
J=2
J=1
J=0

Observations of SiO maser emission

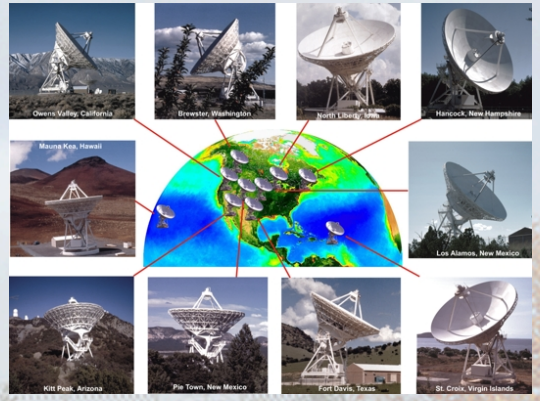
- Spatial distribution
- Kinematics
- Region / spot sizes
- Clumpiness
- Time variability
- Polarization

The instruments for SiO



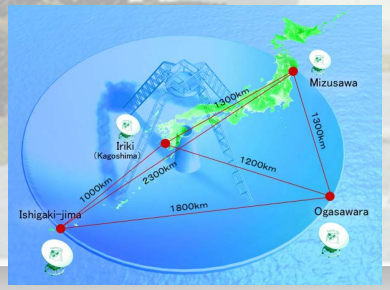
EVN

VLBA

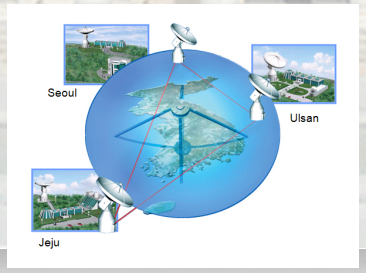


VLA

GMVA



VERA

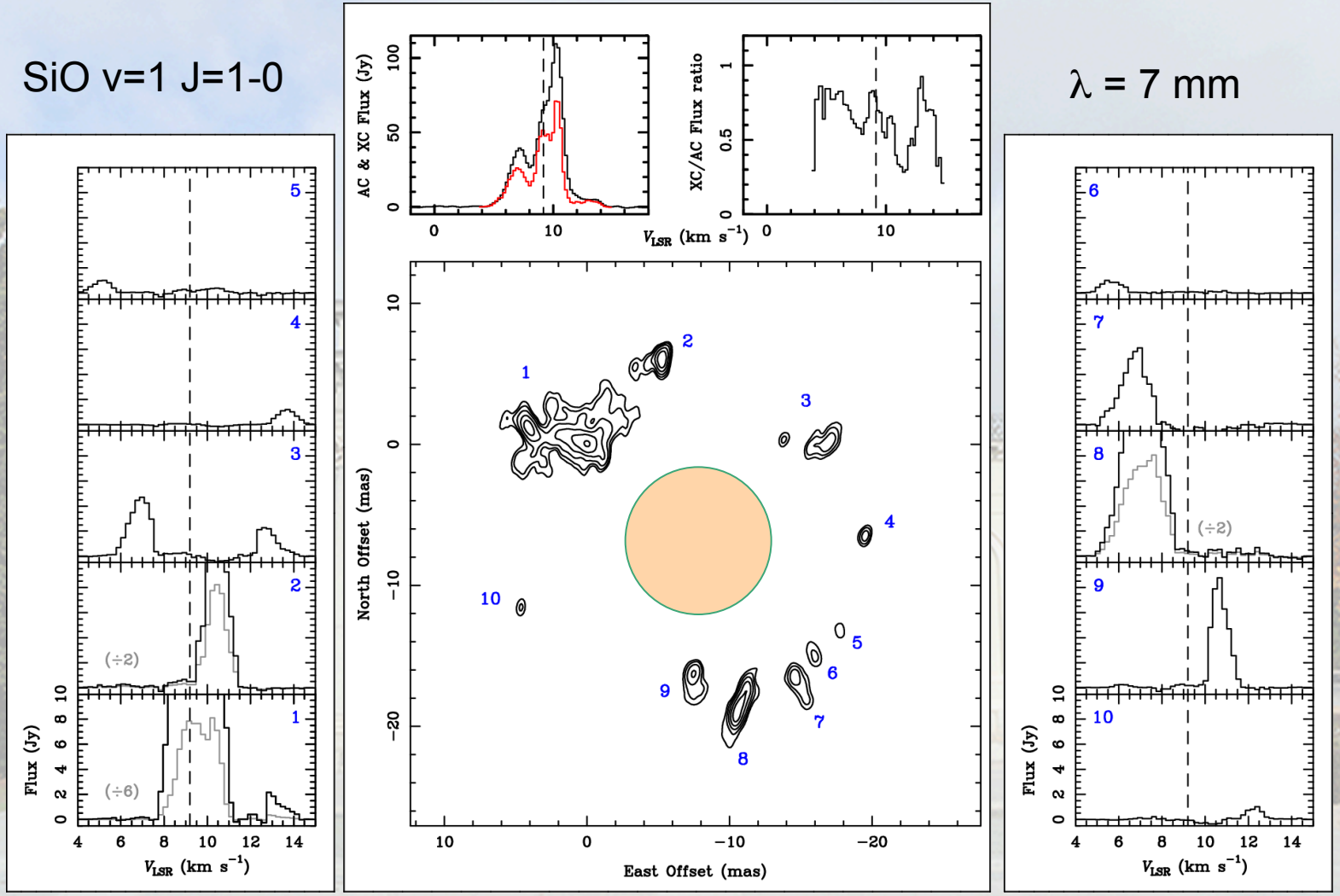


KVN

ALMA

IRC+10011 by VLBA

SiO v=1 J=1-0

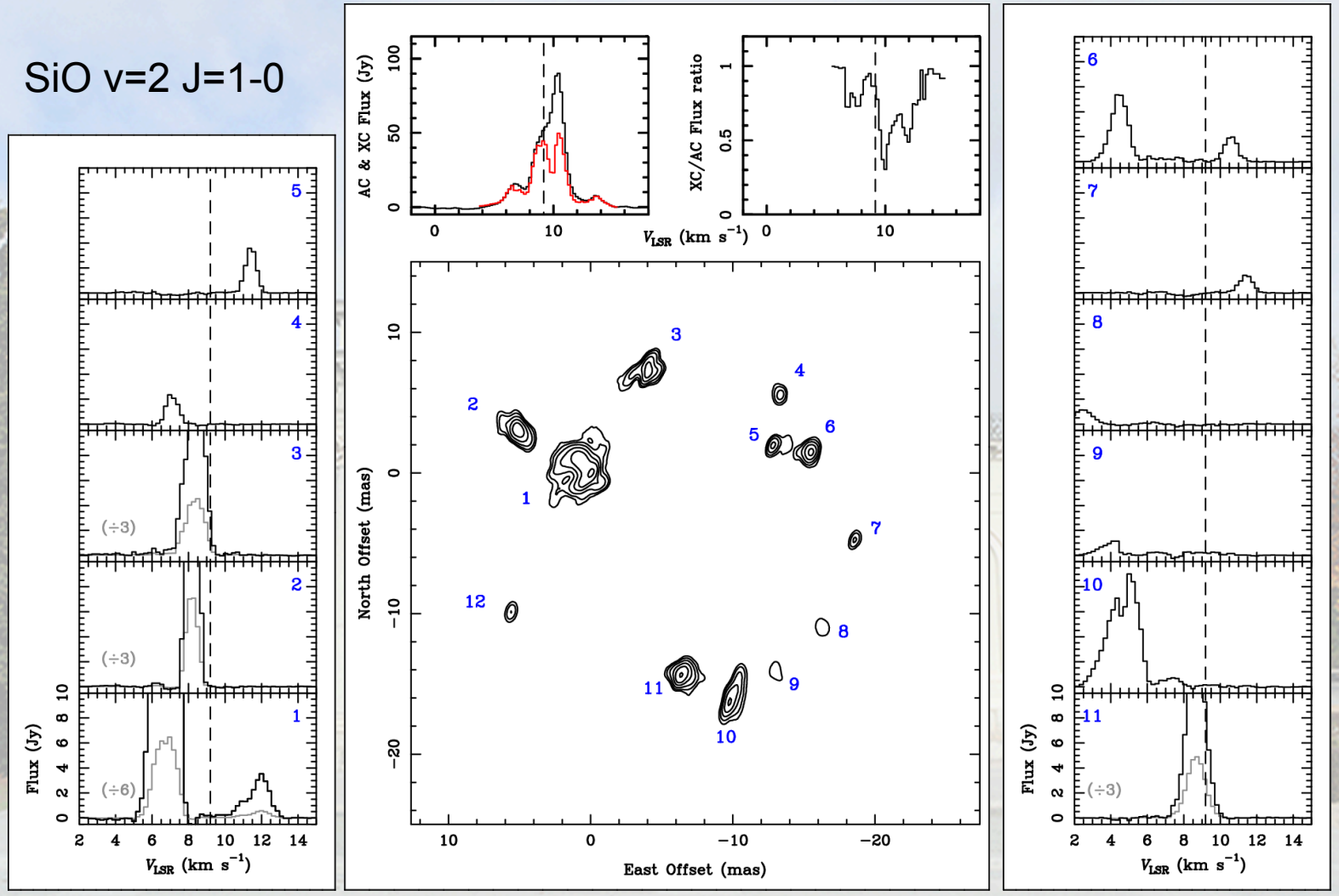


λ = 7 mm

Soria-Ruiz et al. (2004) A&A 426, 131

SiO masers in evolved stars

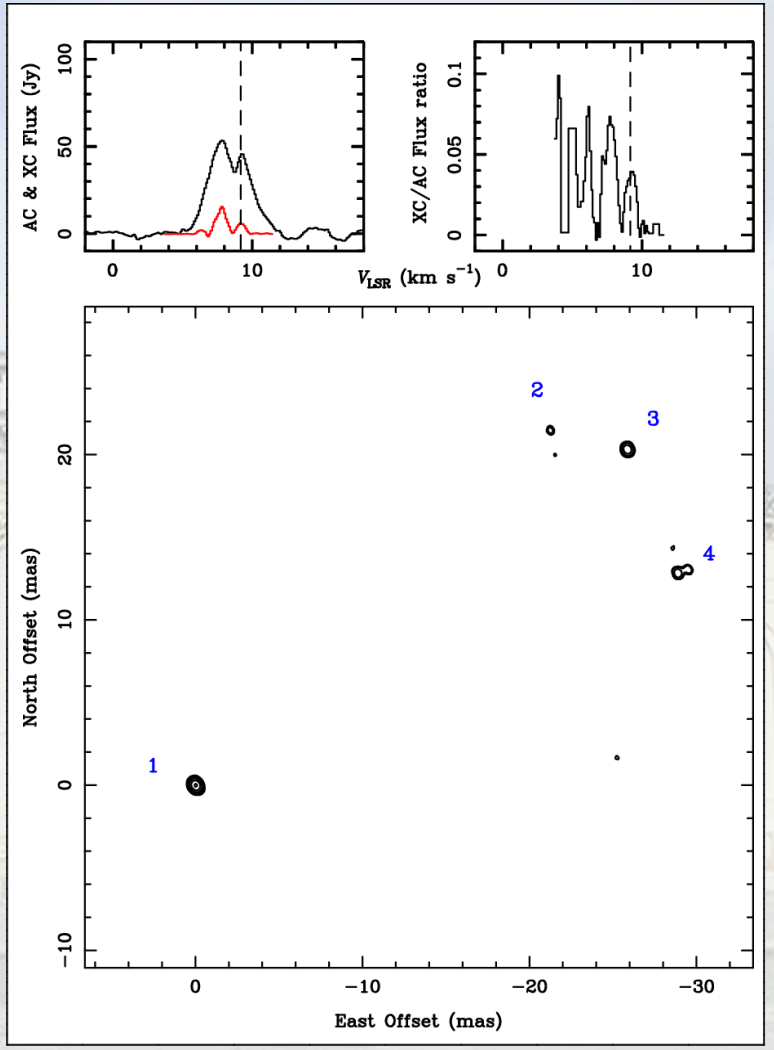
SiO v=2 J=1-0

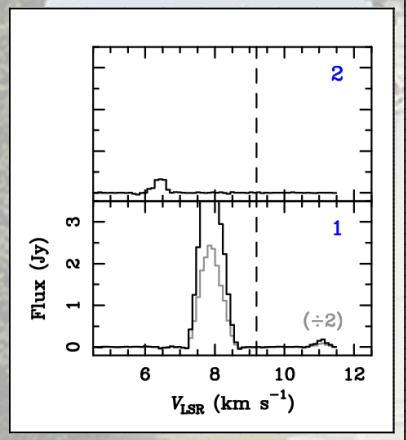


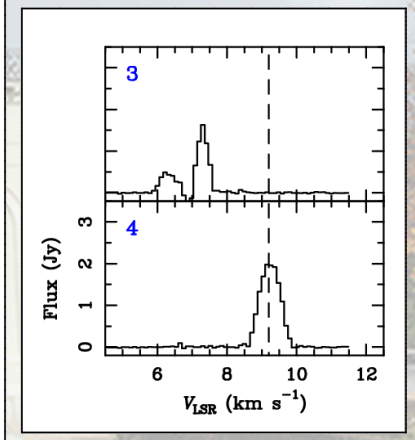
SiO masers in evolved stars

SiO v=1 J=2-1

λ = 3 mm



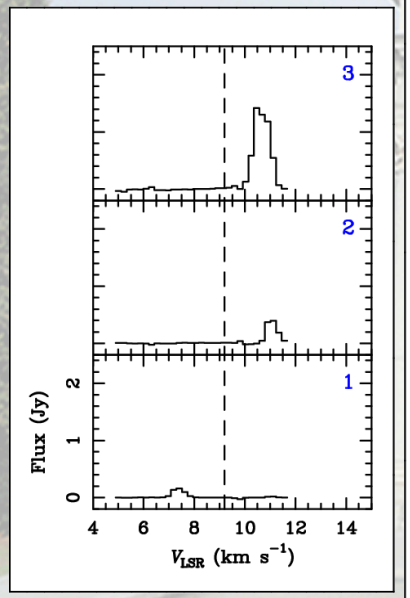


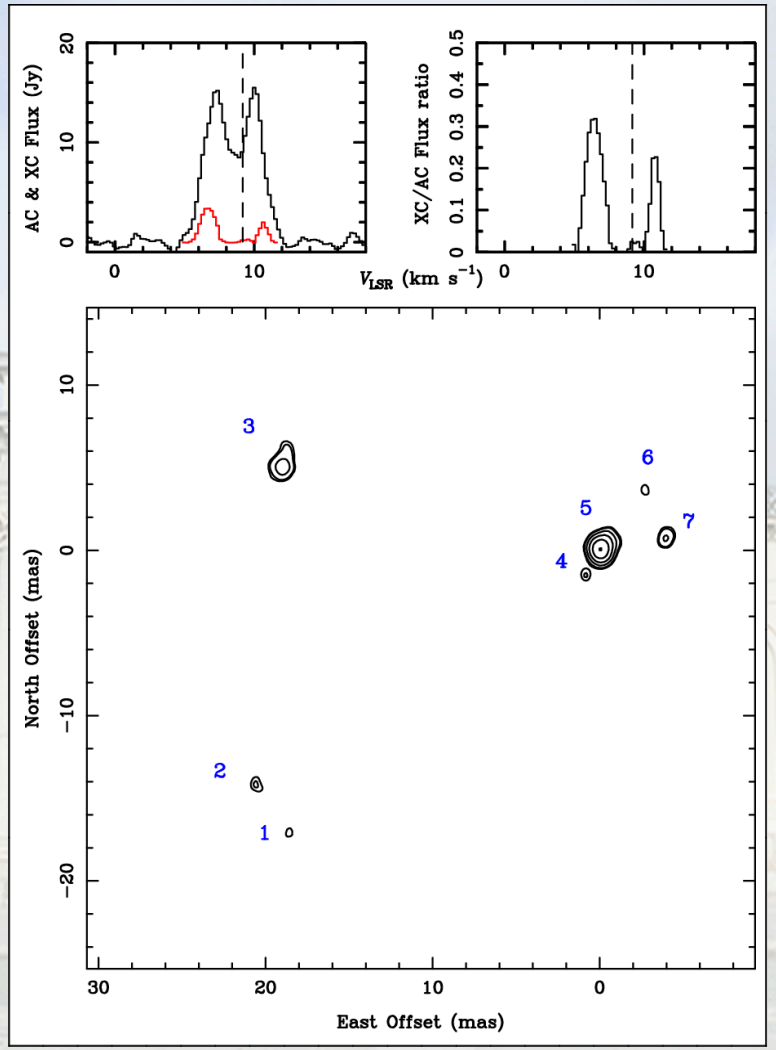


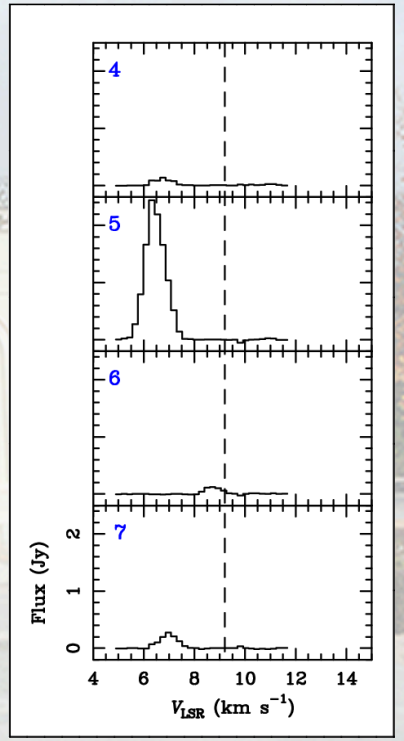
SiO masers in evolved stars

^{29}SiO v=0 J=1-0

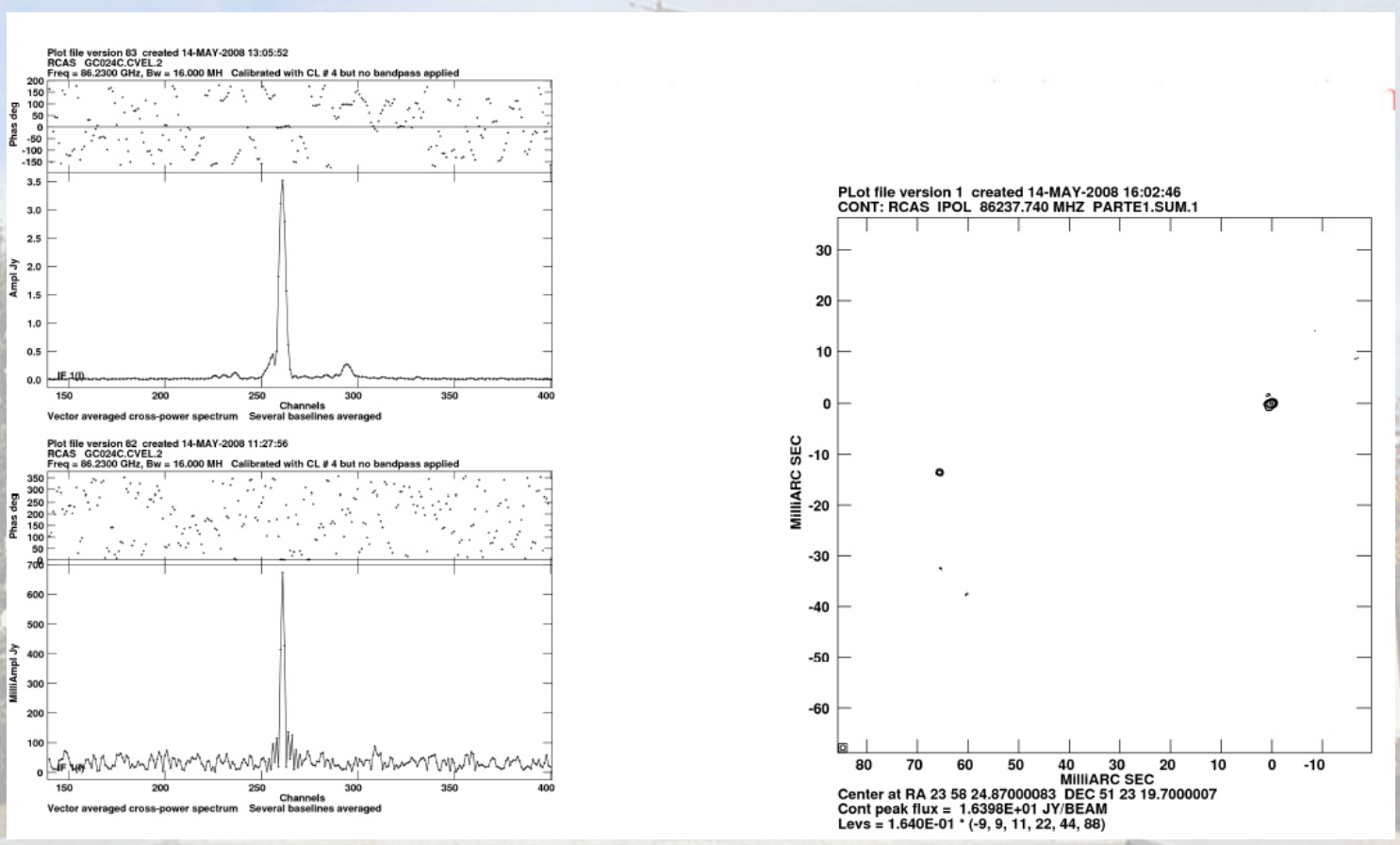
λ = 7 mm







R Cas by GMVA (λ = 3 mm)



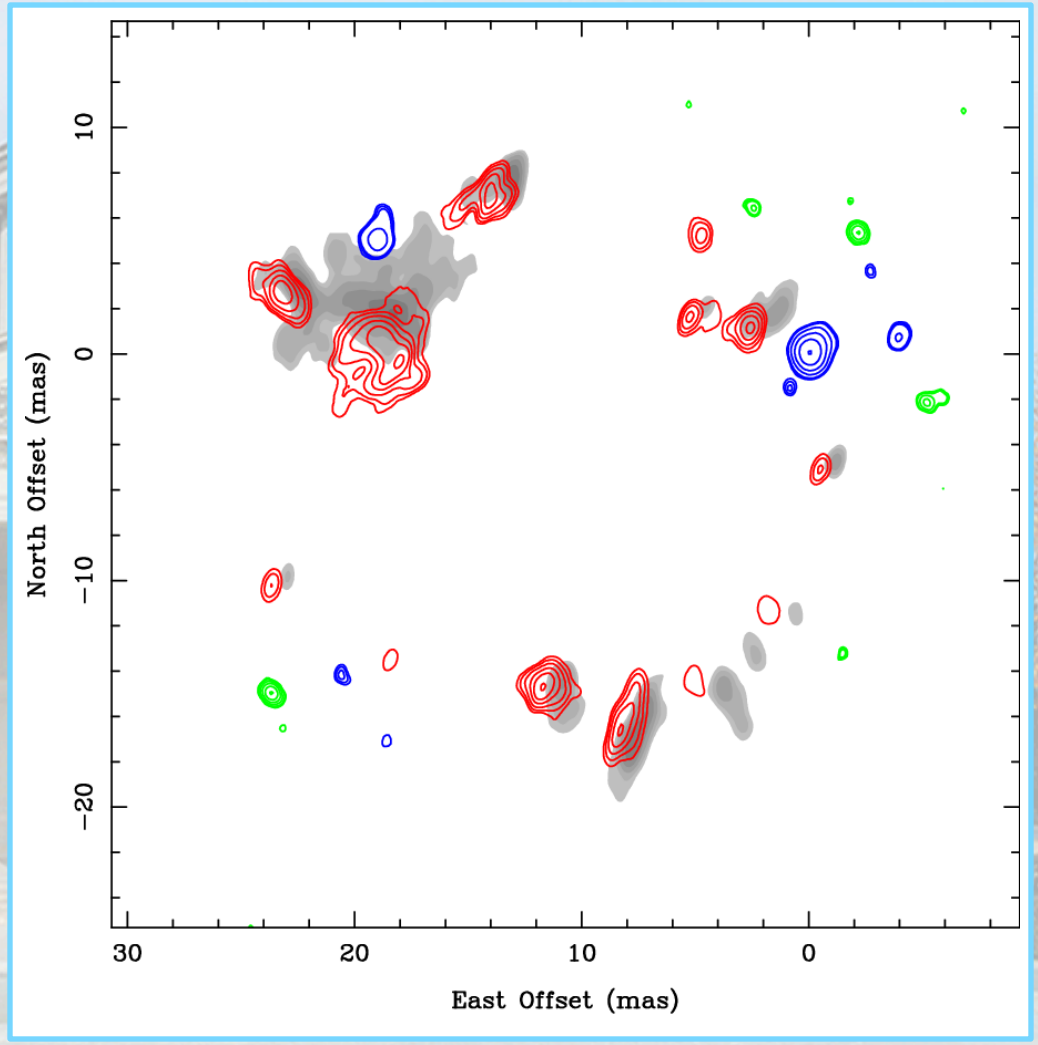
Colomer et al. (2009) ASPC 402, 404

IRC+10011

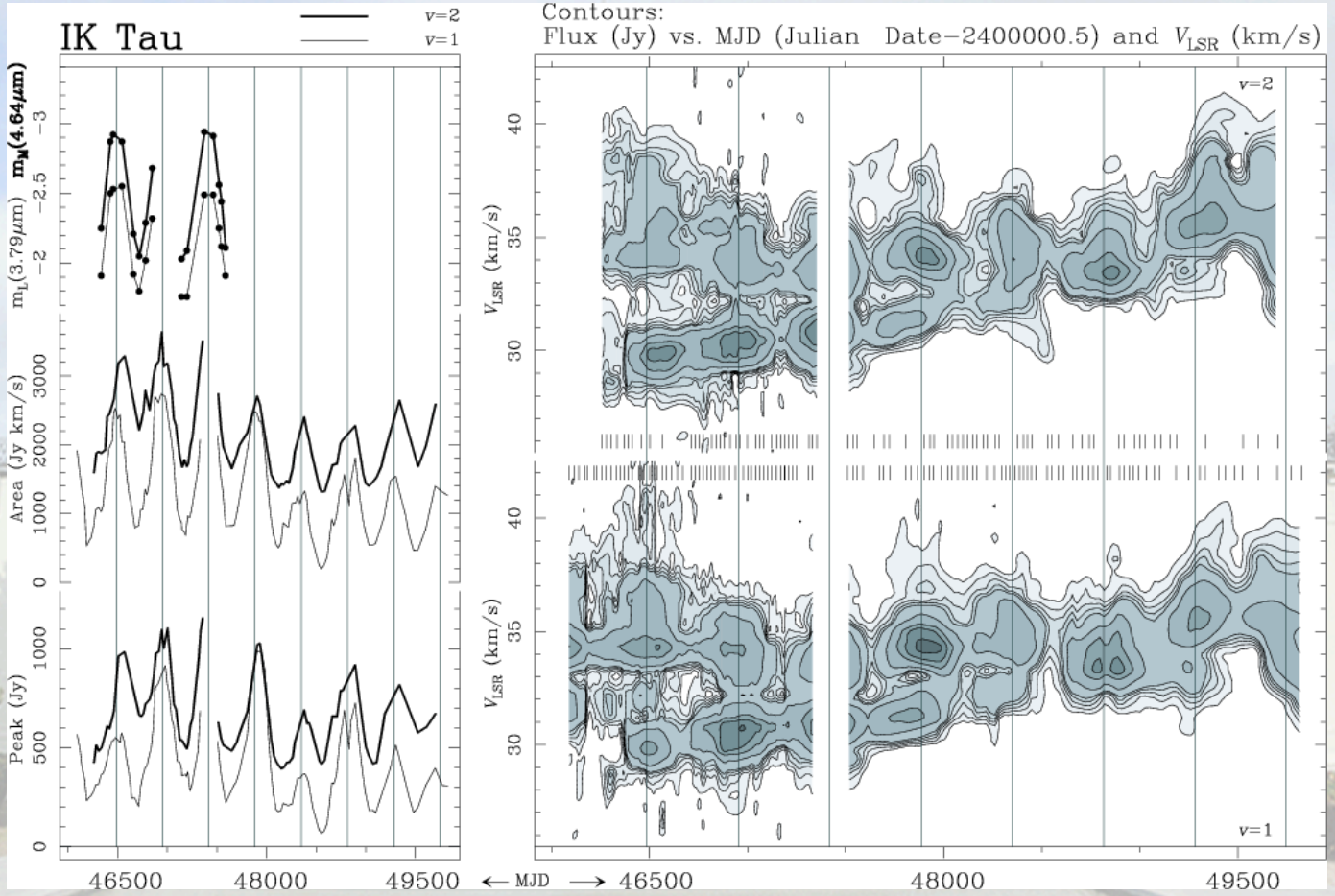
- Ring-like structure
- Clumpy distribution
- v=2 and v=1 J=1-0 are similar, with v=2 slightly smaller
- v=1 J=2-1 is larger

^{29}SiO v = 0 J = 1-0 ^{28}SiO v = 1 J = 2–1
^{28}SiO v = 1 J = 1–0 ^{28}SiO v = 2 J = 1–0

Soria-Ruiz et al. (2004)



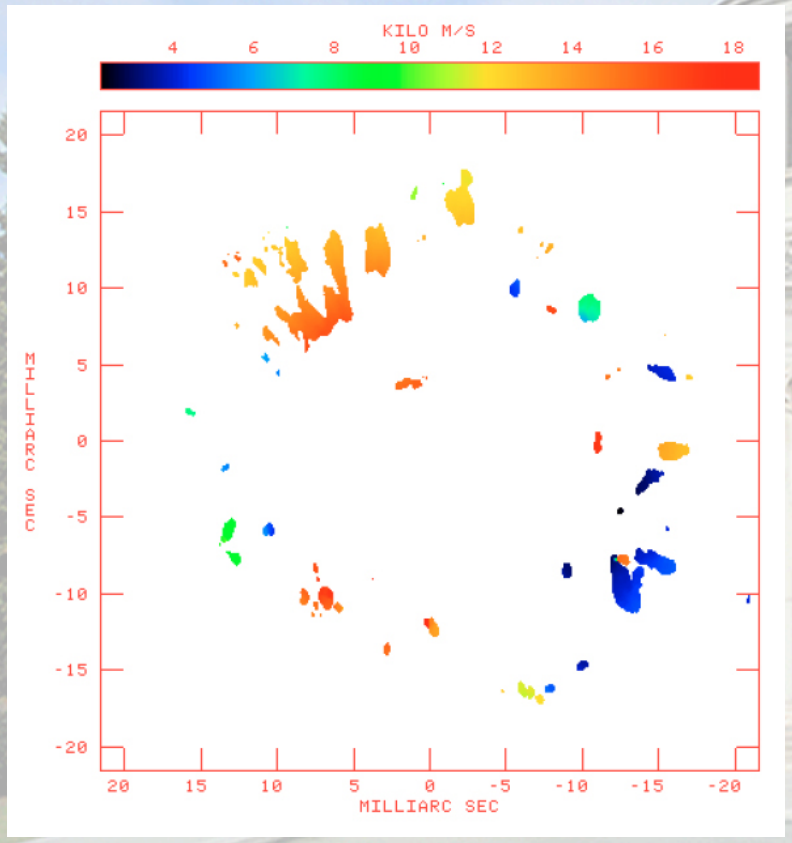
Time variability



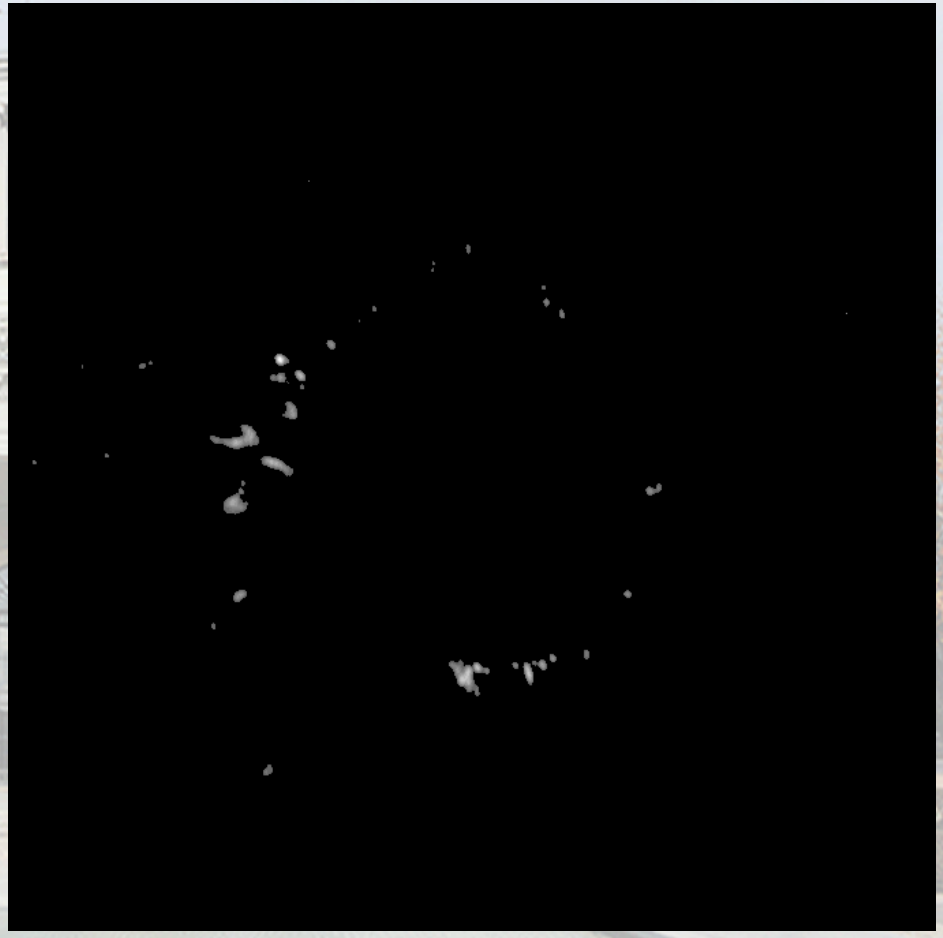
Pardo et al. (2004) A&A 424, 145

Kinematics

TX Cam

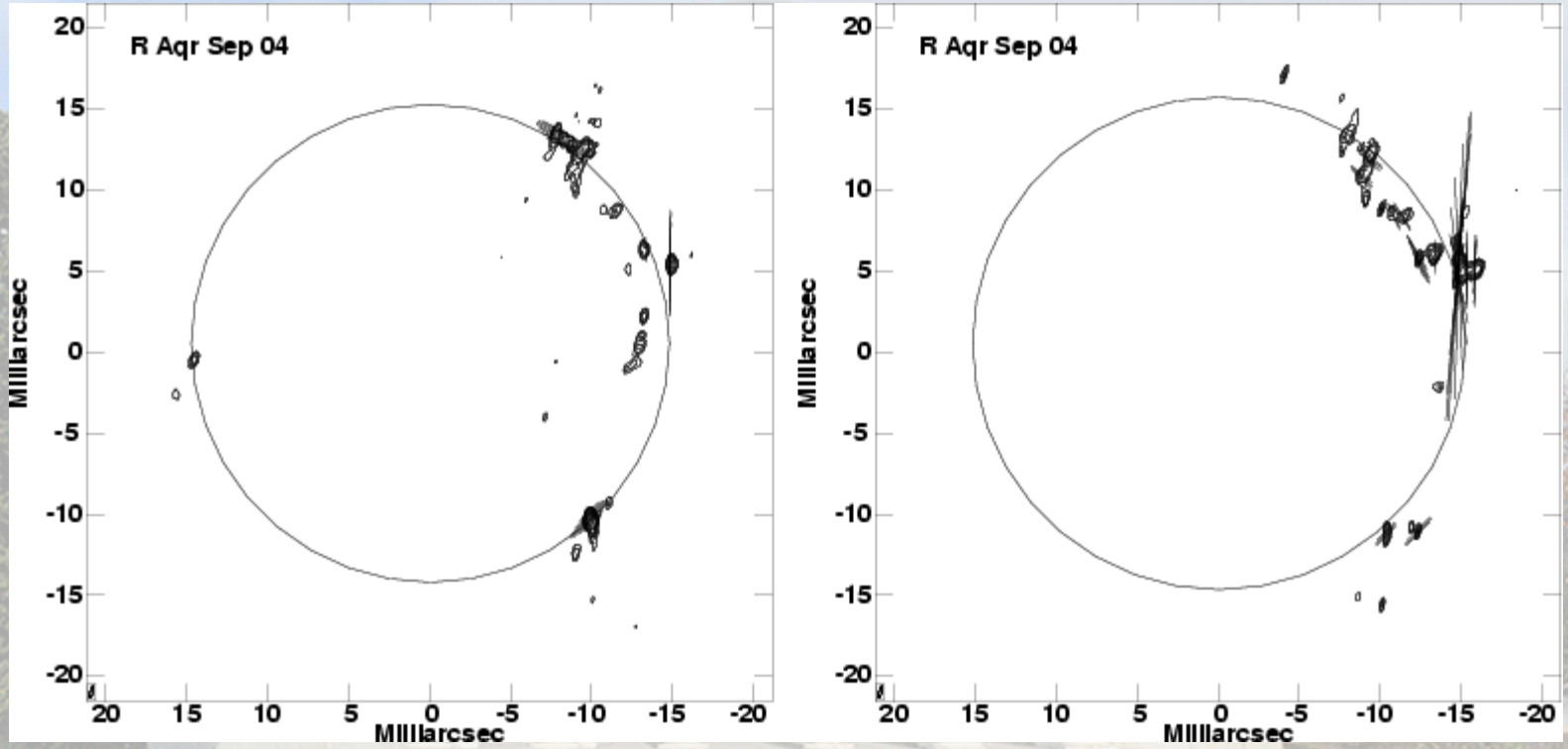


Yi et al. (2005)



Gonidakis, Diamond & Kemball (2008)

Polarization

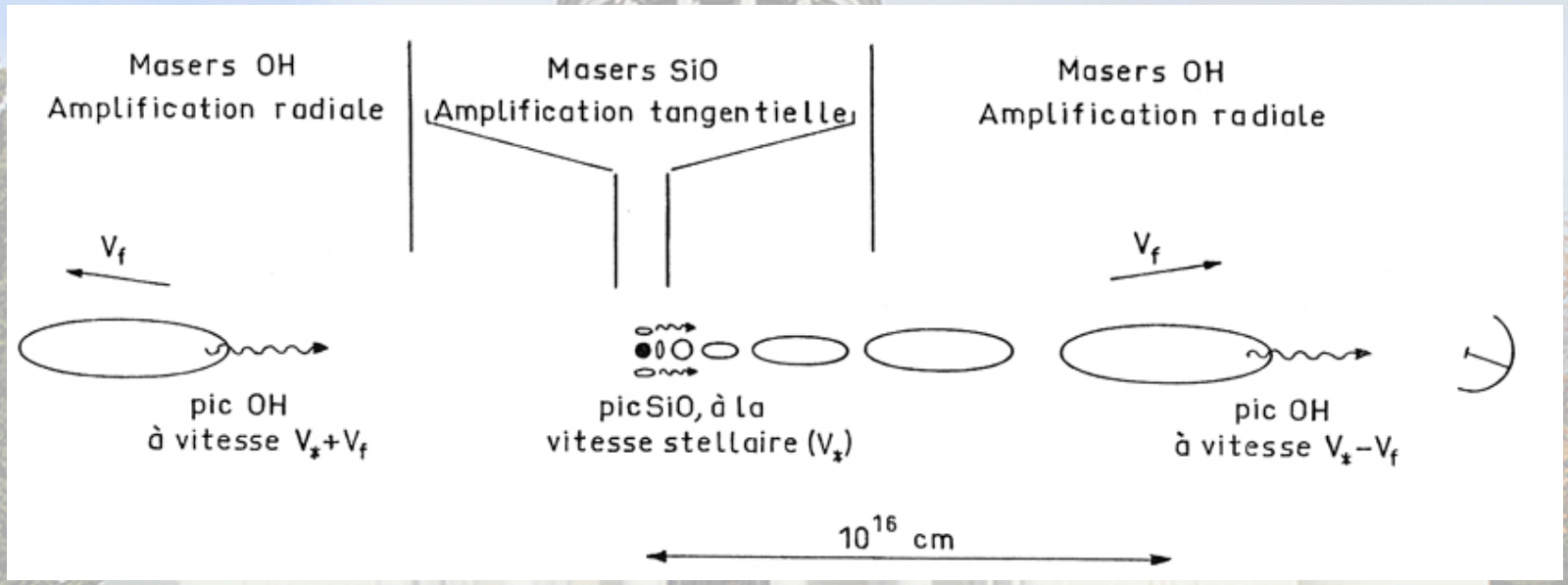


Cotton et al. (2006) A&A 456, 339; Cotton et al. (2004) A&A 414, 275

Models of SiO maser emission

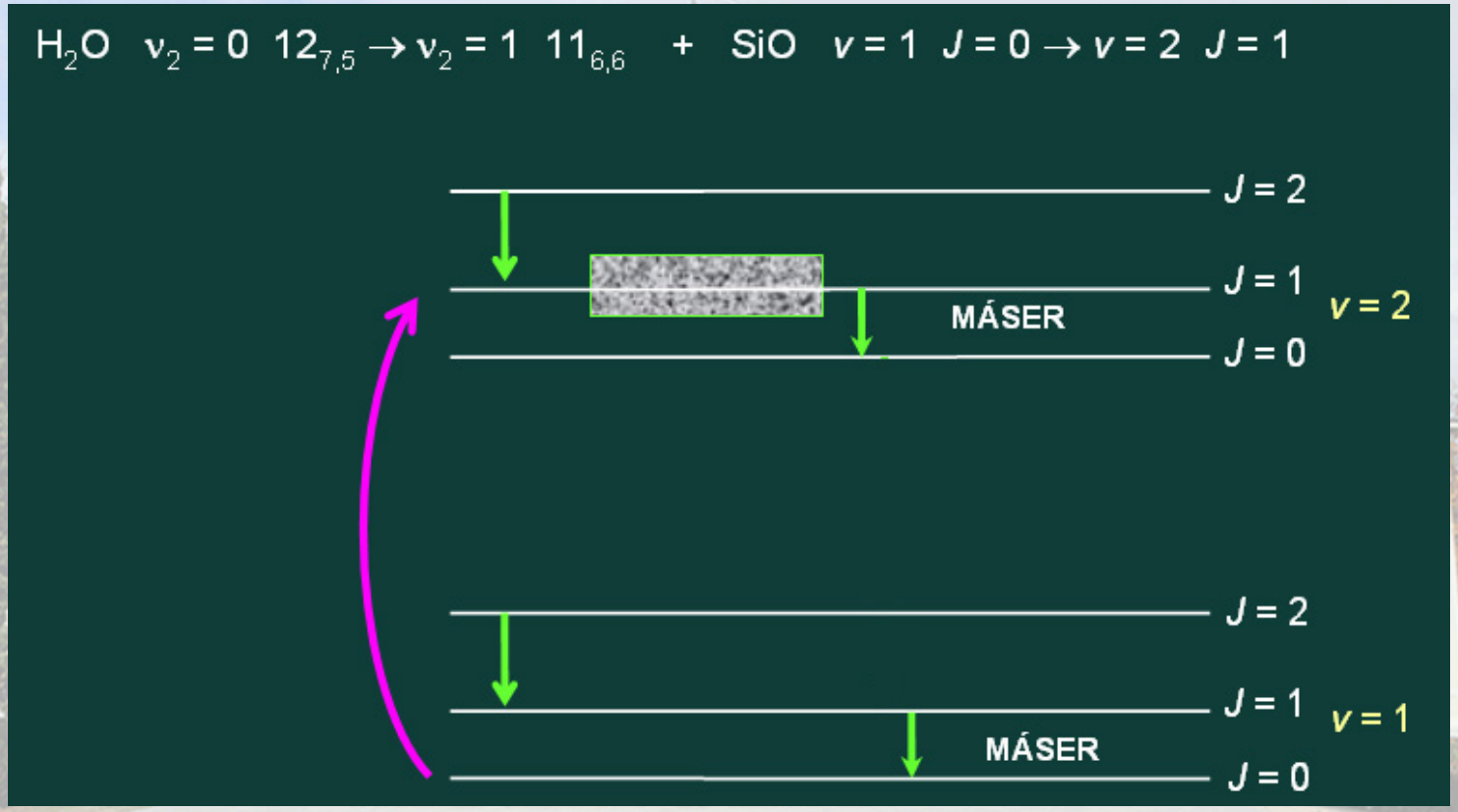
- Ring structure:
  - Explained by tangential amplification (eg. Bujarrabal & Nguyen-Q-Rieu 1981)
  - Peculiar v=2 J=2-1 SiO behaviour
- Time variability:
  - Correlation with IR pumping from the central star (eg. Pardo et al. 2004)
- Clumpiness:
  - Humphreys et al. (1996) MNRAS 282, 1359
  - Doel et al. (1995) A&A 302, 797

Tangential amplification = Rings



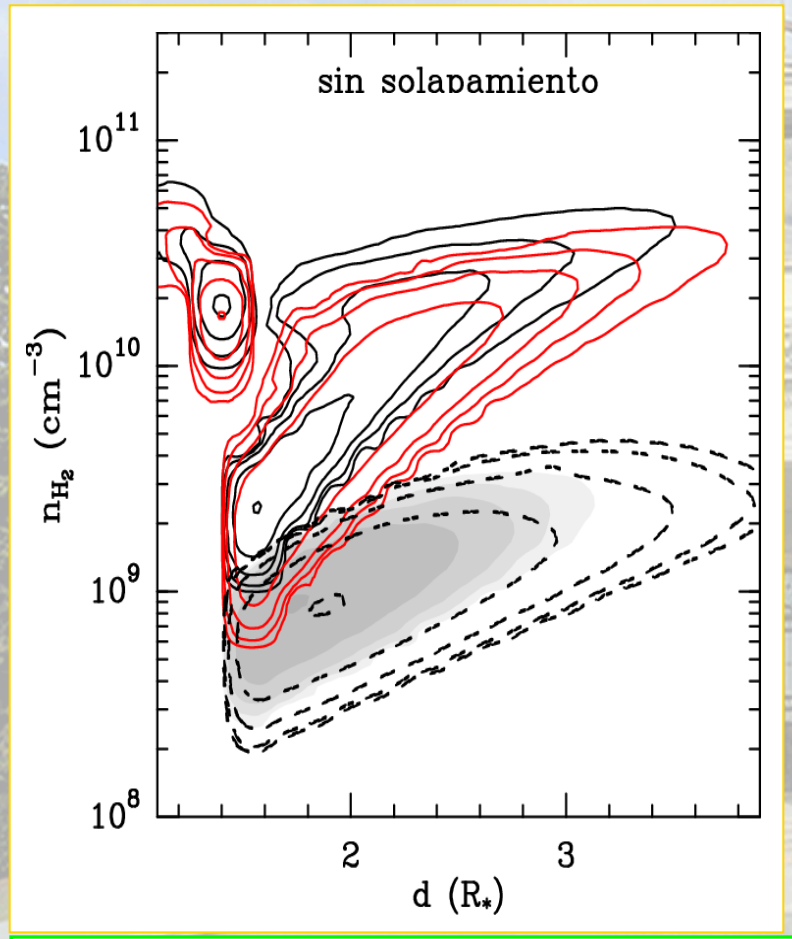
Bujarrabal (1981) PhD Thesis
See also Bujarrabal & Nguyen-Q-Rieu (1981) A&A 102, 65

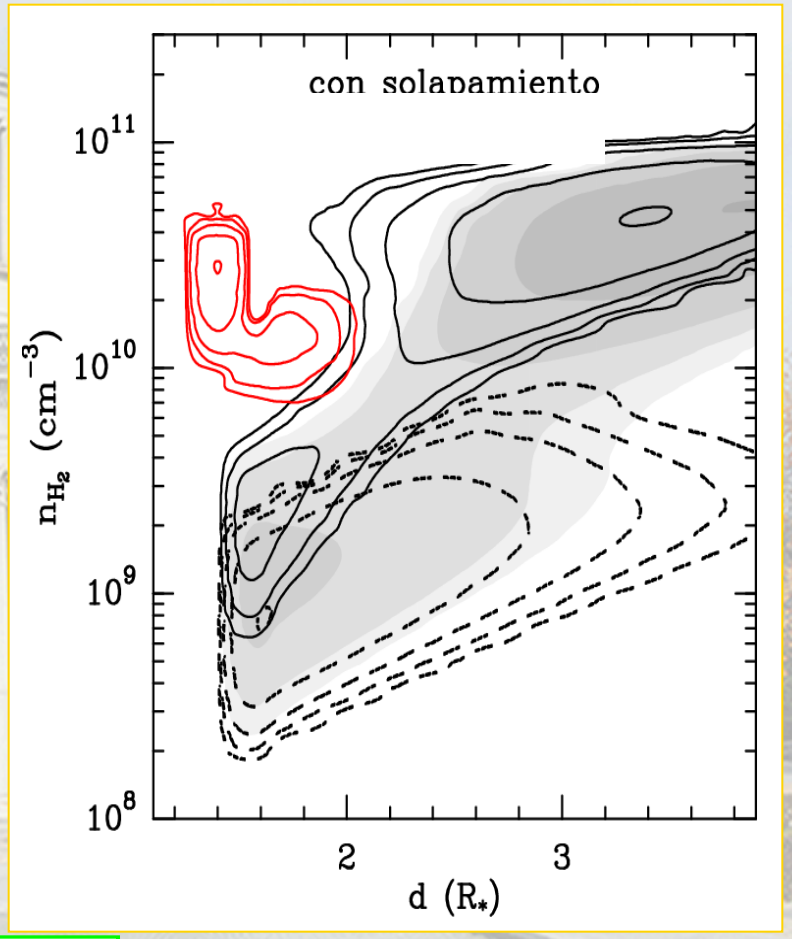
The case of the weak SiO v=2 J=2-1



First proposed by Olofsson et al. (1981, 1985)

Line overlap effects





Greys $v = 1$ $J = 1$-0 ——— $v = 2$ $J = 1$-0

- - - - - - - - $v = 1$ $J = 2$-1 ——— $v = 2$ $J = 2$-1

Soria-Ruiz et al. (2004)

The alignment problem

It is essential to properly align the images of different maser transitions.
Methods:

1. Calculate centroid of emission; align clumps of same velocity.
2. Follow the interferometric phase from one maser line to the other.
3. Frequency-phase transfer.
4. Absolute astrometry by phase referencing to quasars.

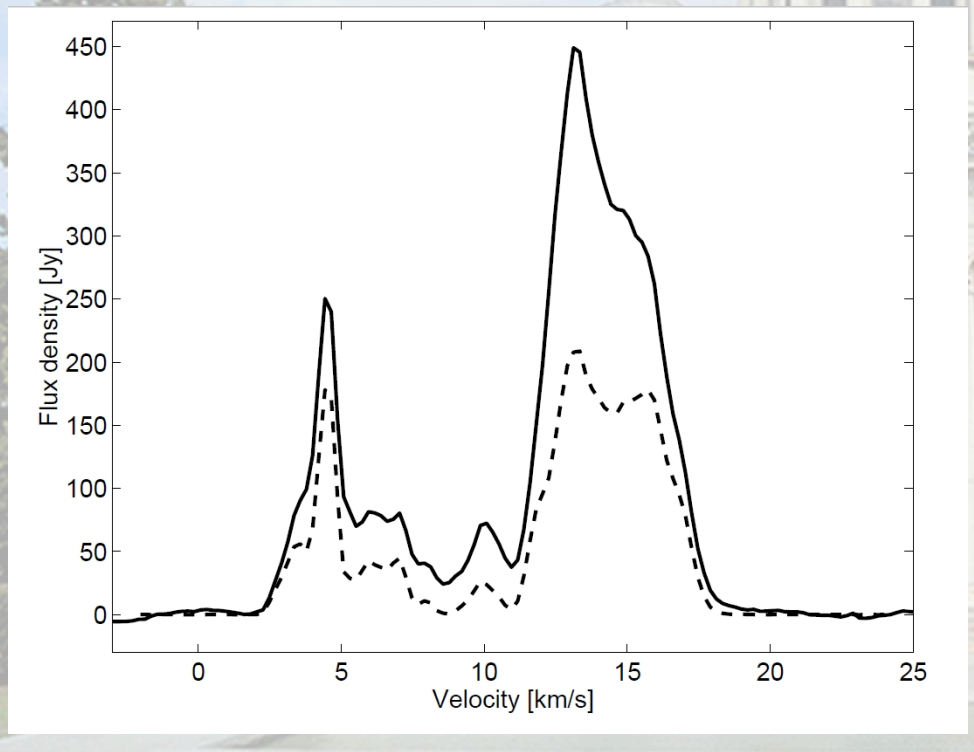
And it is important to relate these positions to the actual position of the central star!

ALMA in a mm-VLBI array

- Missing flux problem
- Detection of stellar photosphere, and alignment of SiO masers positions.
- Better uv coverage, and access to the Southern hemisphere.

The missing flux problem

Yi et al. (2005)



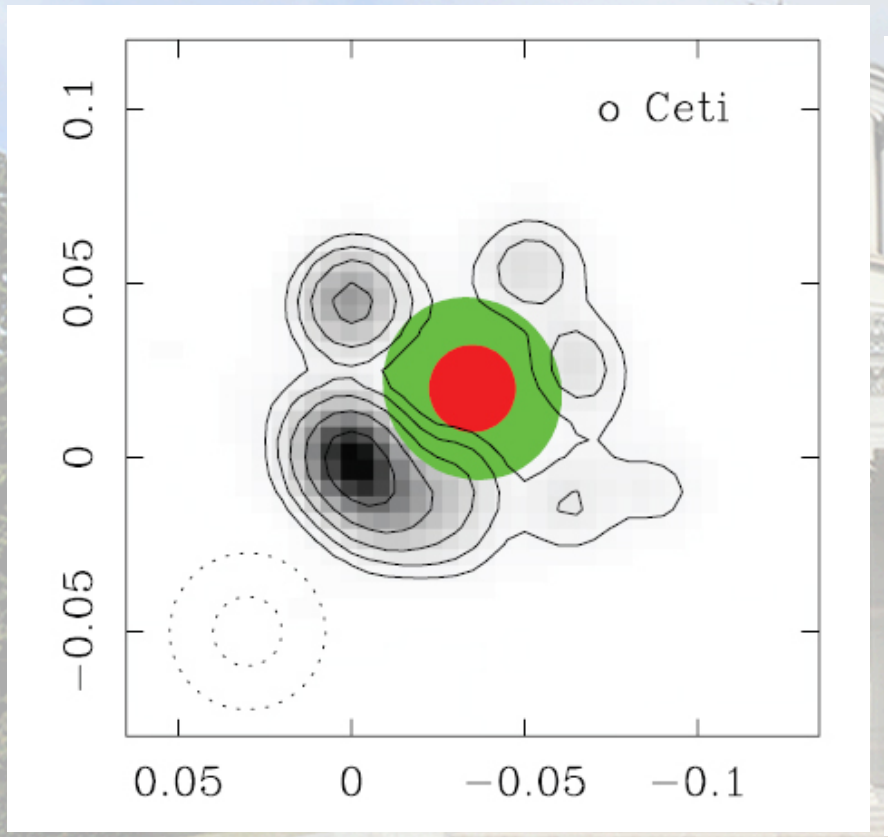
Large difference between SiO masers total flux (solid line) and crosscorrelated flux (dashed line).

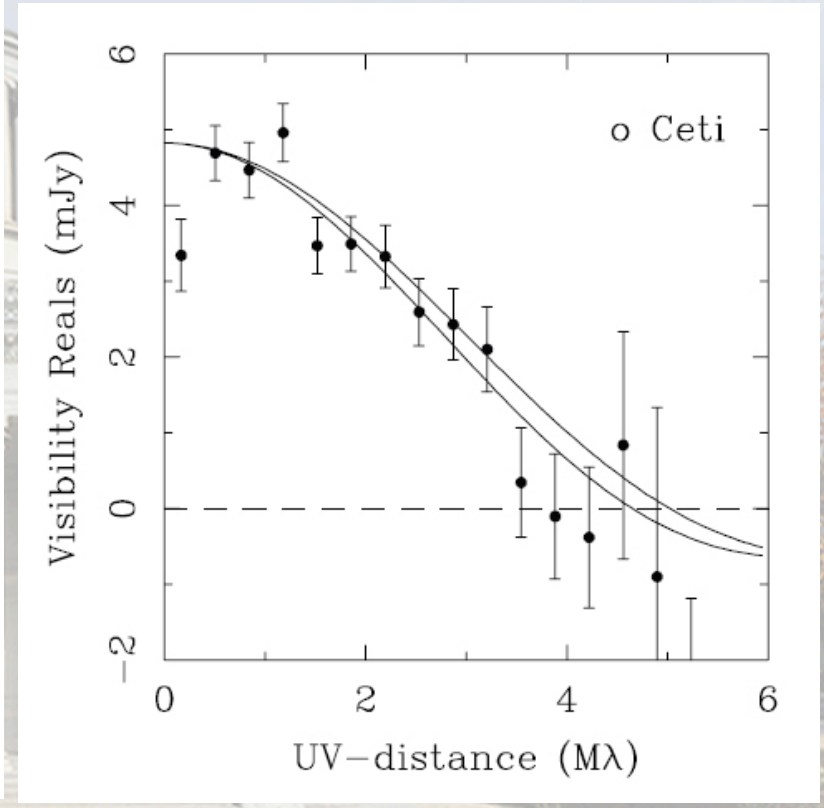
Is there an extended emission which is resolved by VLBI?

- Many small and weak spots?
- Extended weak emission?

ALMA may give the answer !

Imaging the photosphere!





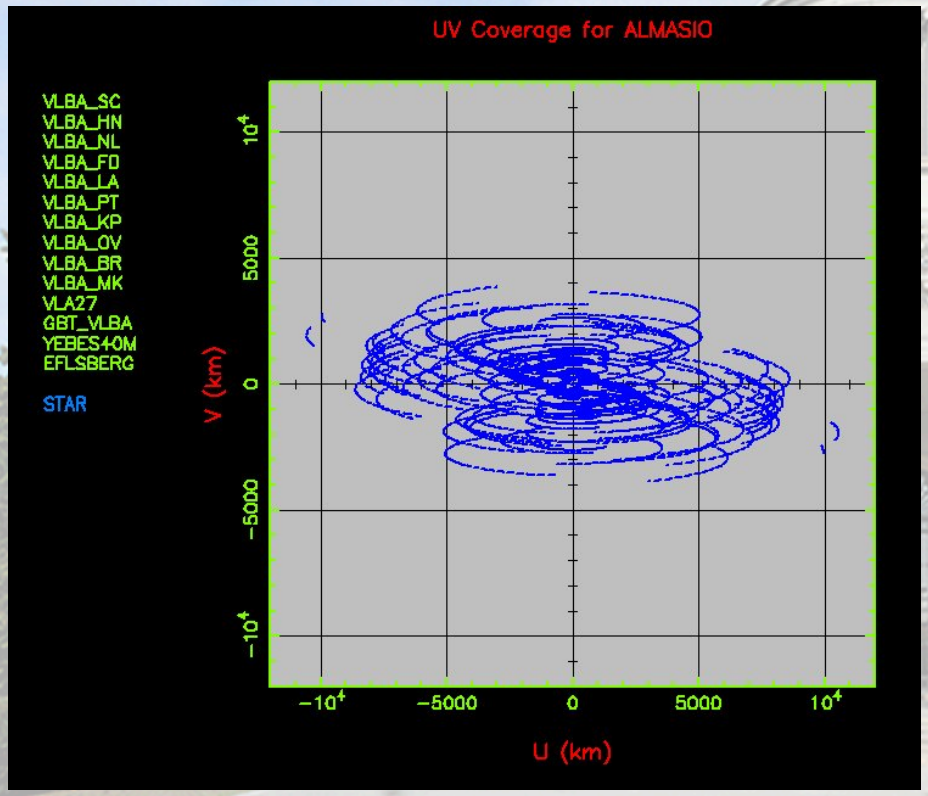
$R_* = 5.6$ AU

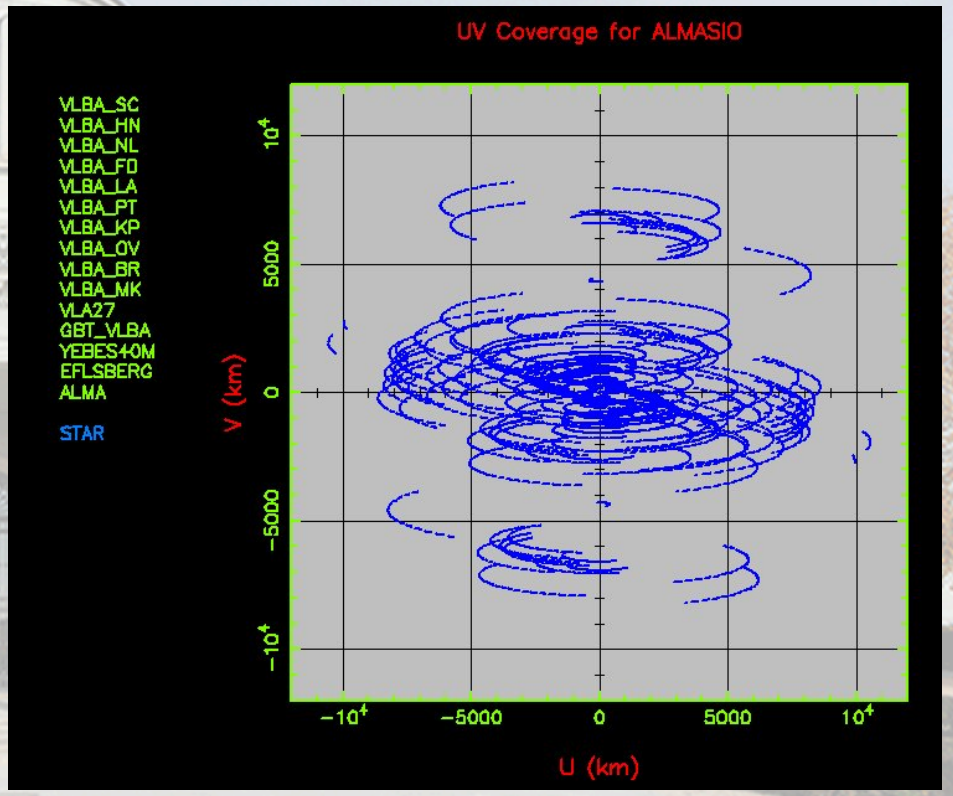
$R_{SiO} = 8$ AU

Reid & Menten (2007) ApJ 671, 2068

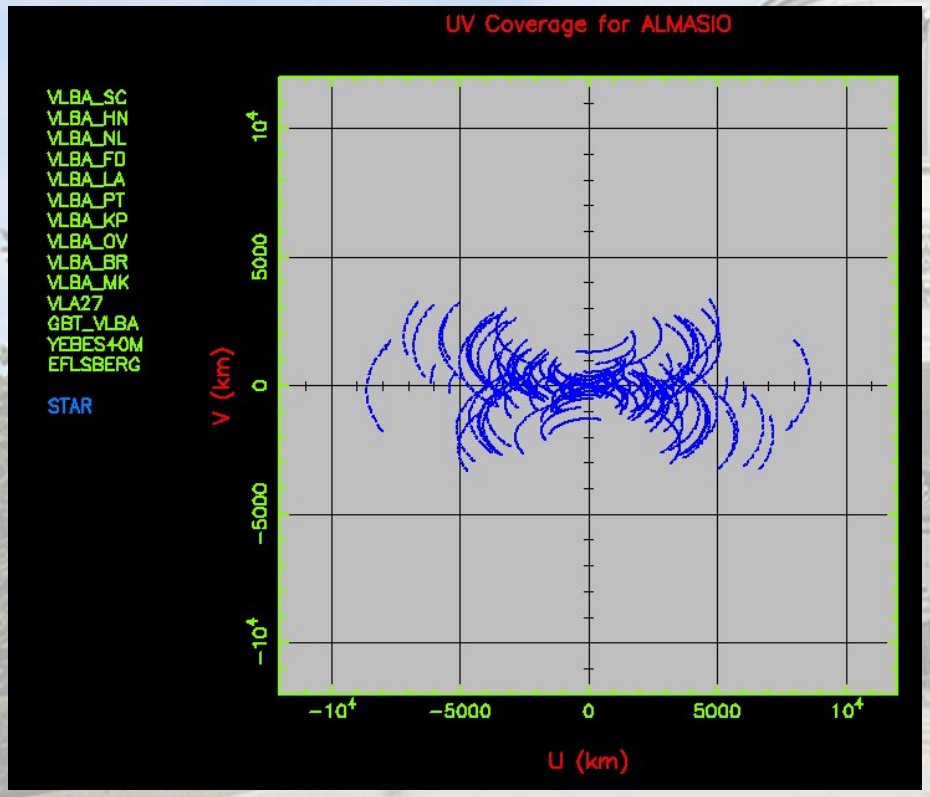
ALMA in a mm-VLBI array

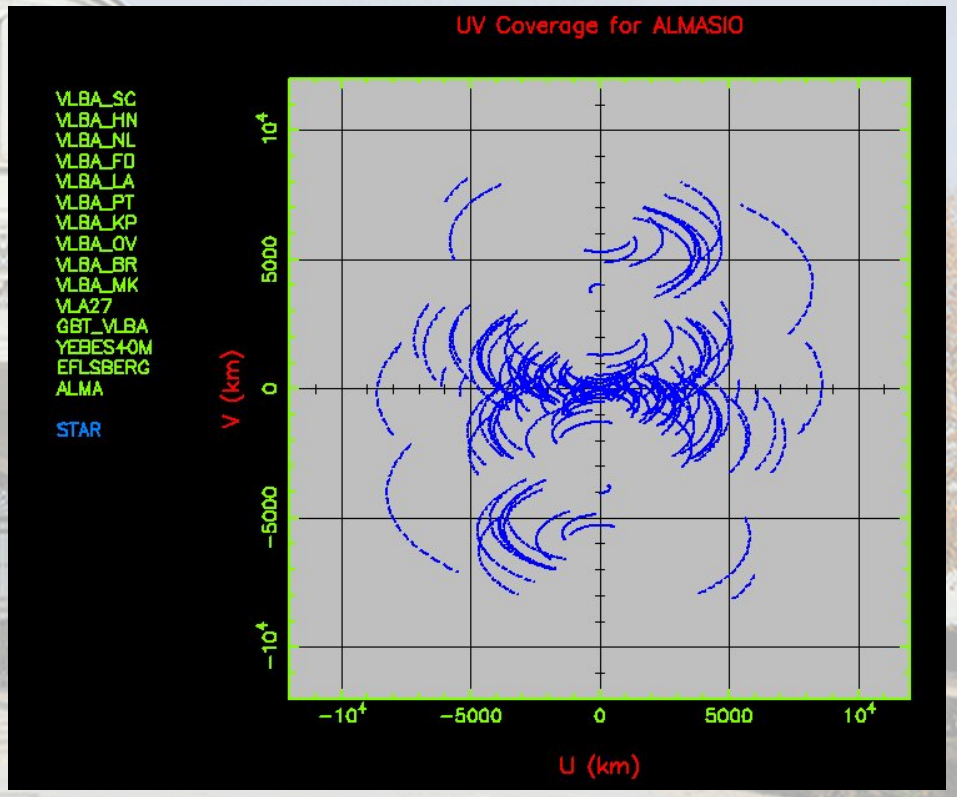
uv coverage (δ=10º)





uv coverage (δ=-30º)





ALMA in a VLBI array

- High resolution maps of maser emission provide detailed information on processes occurring in circumstellar envelopes of AGB stars.
- A particularly detailed picture of the inner layers is provided by SiO masers, which appear as very compact features (spots).
- Multi-transition simultaneous and aligned observations of these masers are needed to better constrain the models.
- VLBI maps show typically 20 – 60% (up to 90%) of total flux.
- Missing flux may come from many small weak spots, or extended haloes around or in between strong spots; ALMA baselines may detect and distinguish both scenarios: a new class of maser sources.
- ALMA provides baselines to south hemisphere sources (e.g. Magellan Clouds).
- ALMA+VLBI array will detect features in the photosphere of stars.

Thank you !

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Extra slides

Basics of maser emission

$$\frac{dI_\nu}{ds} = -I_\nu k_\nu + j_\nu$$

$$j_\nu = k_\nu B_\nu(T) = k_\nu \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1}$$

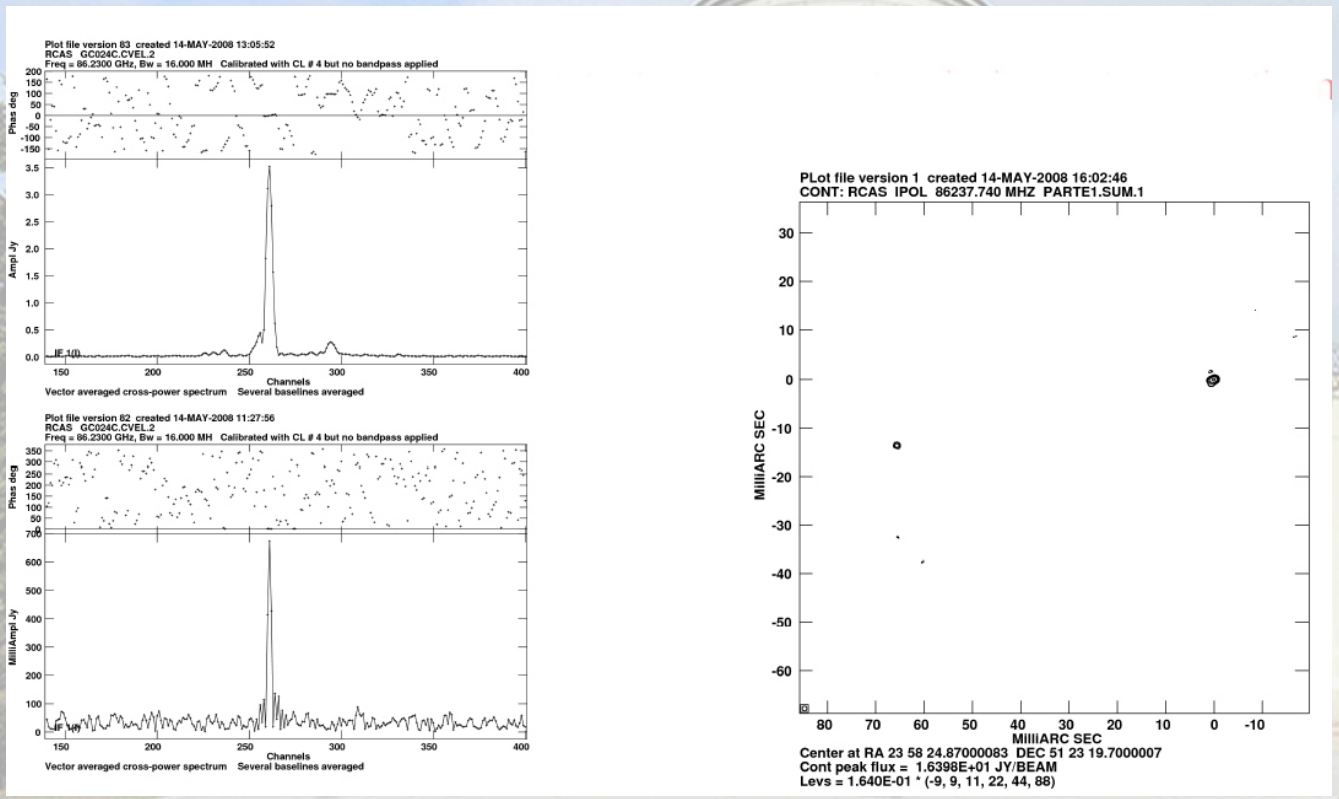
$$I_\nu(x) = I_\nu(0)\, e^{-k_\nu\, x} + B_\nu(T)\,(1 - e^{-k_\nu\, x})$$

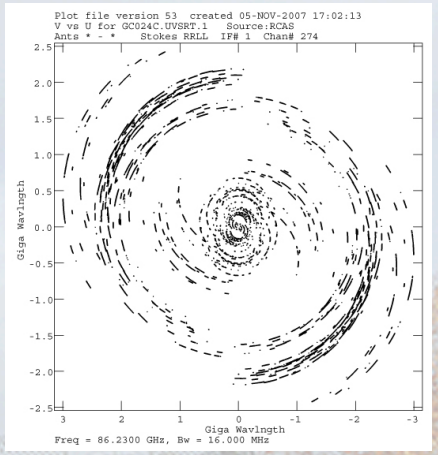
$$j_\nu = \phi(\nu)\, \frac{h\nu}{4\pi}\, g_u\, A_{ul}\, x_u \qquad k_\nu = \phi(\nu)\, \frac{c^2}{8\pi\nu^2}\, g_u\, A_{ul}\,(x_l - x_u)$$

$$T_b(\nu) = T_c\, e^{-\tau_\nu}$$

$$\Delta\nu \approx \frac{\Delta\nu_\phi}{\sqrt{|\tau_{\nu_o}|}}$$

R Cas by GMVA





Colomer et al. (2009) ASPC 402, 404

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It is essential to properly align the images of different maser transitions. Methods:

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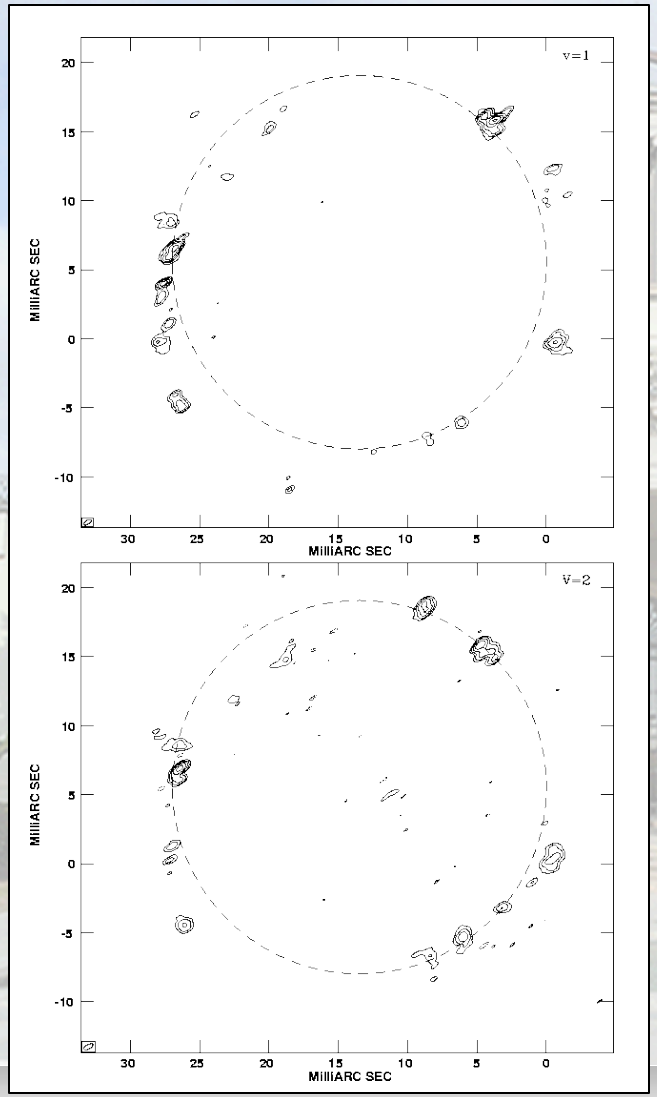
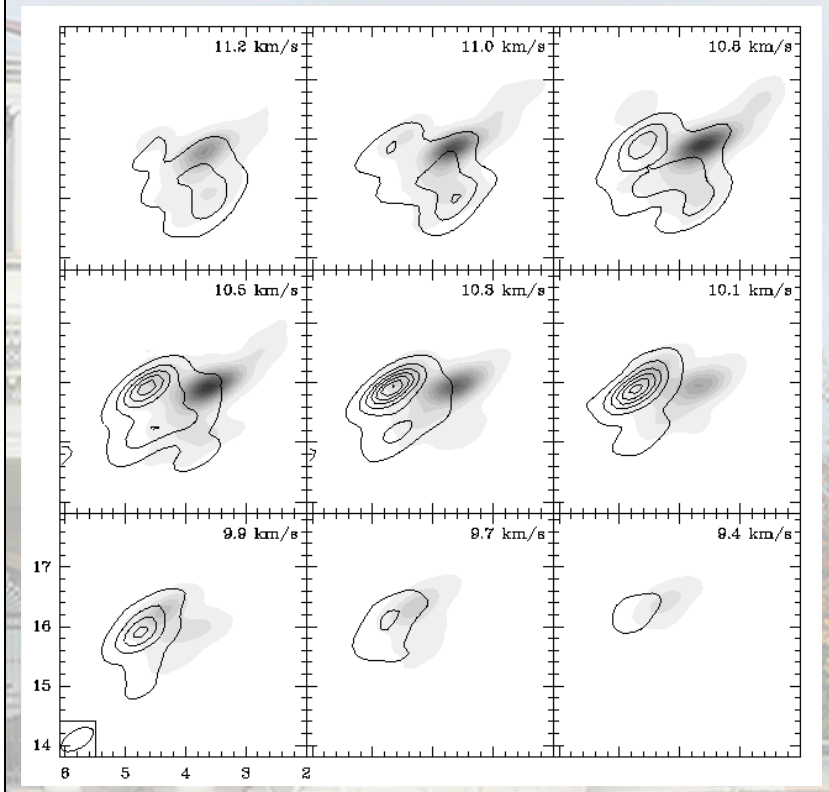
And it is important to relate these positions to the actual position of the central star!

1. Alignment by centroid

TX Cam





Desmurs et al. (2000) A&A 360, 189

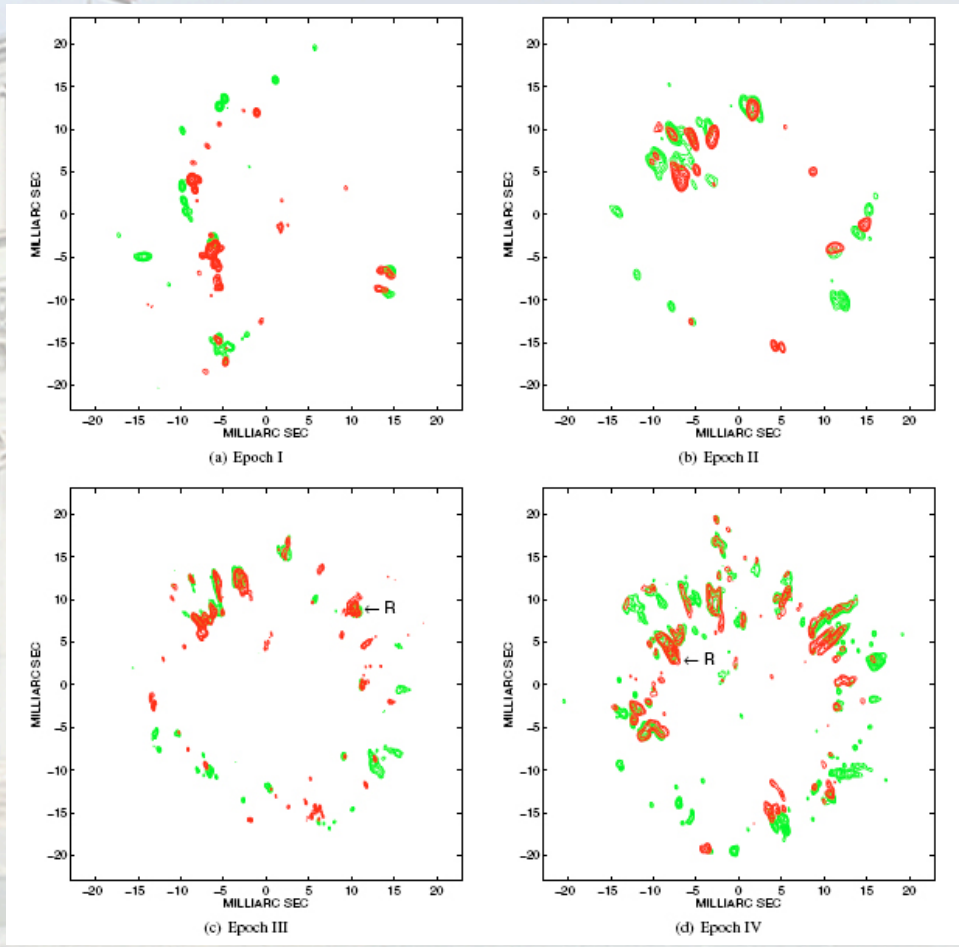
2. Alignment by phase tracking

TX Cam

SiO v=1 J=1-0

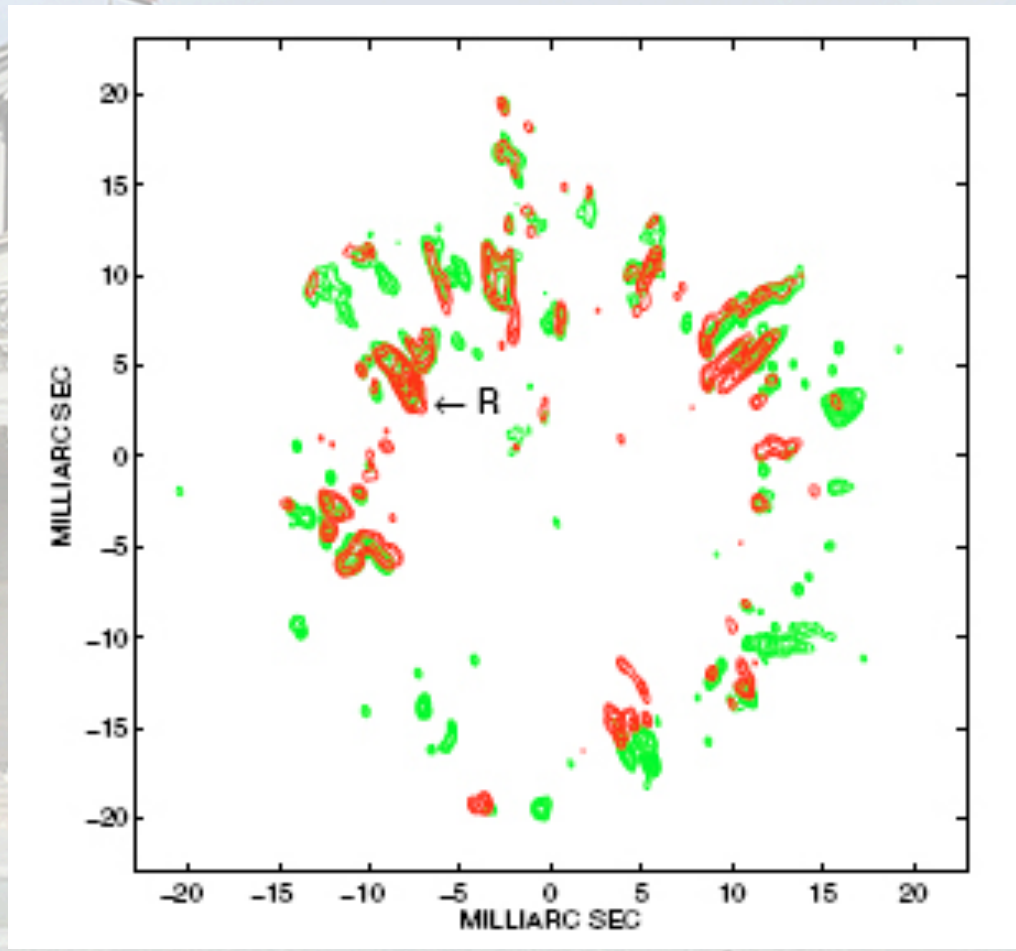
SiO v=2 J=1-0

Yi et al. (2005) A&A 432, 531



2. Alignment by phase tracking

TX Cam

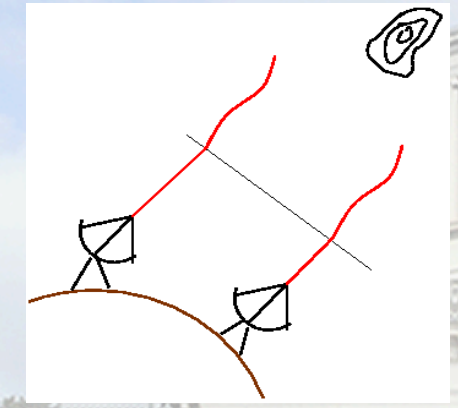


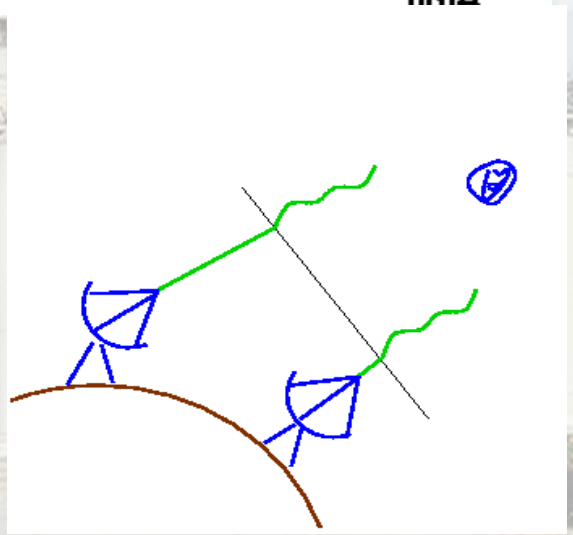
SiO v=1 J=1-0

SiO v=2 J=1-0

Yi et al. (2005) A&A 432, 531

3. Frequency-phase transfer

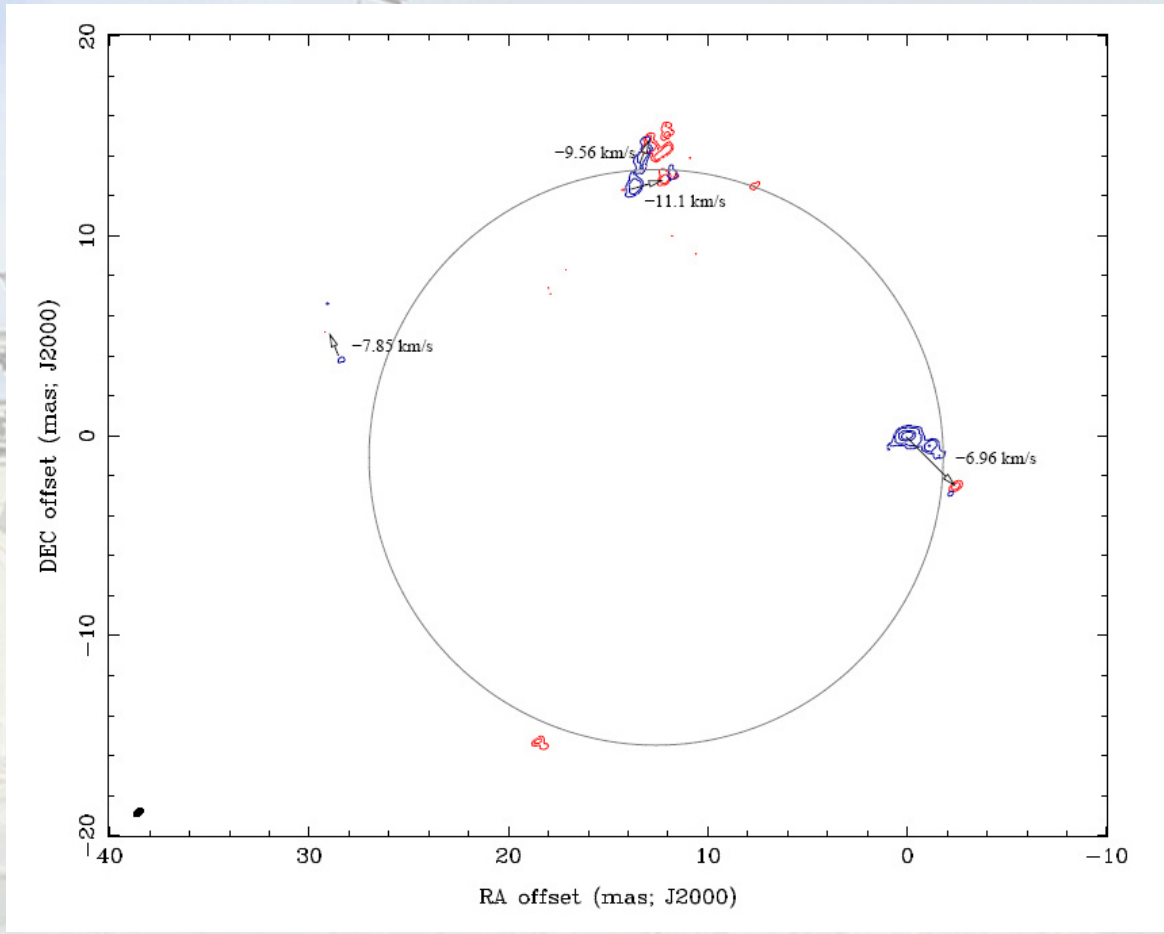




Rioja et al. (2008) PASJ Vol. 60 (5), p. 1031

4. Absolute astrometry: VERA

R LMi



Rioja et al. (2008)

ALMA in a mm-VLBI array