Maser studies in evolved stars

SiO in AGB CSEs

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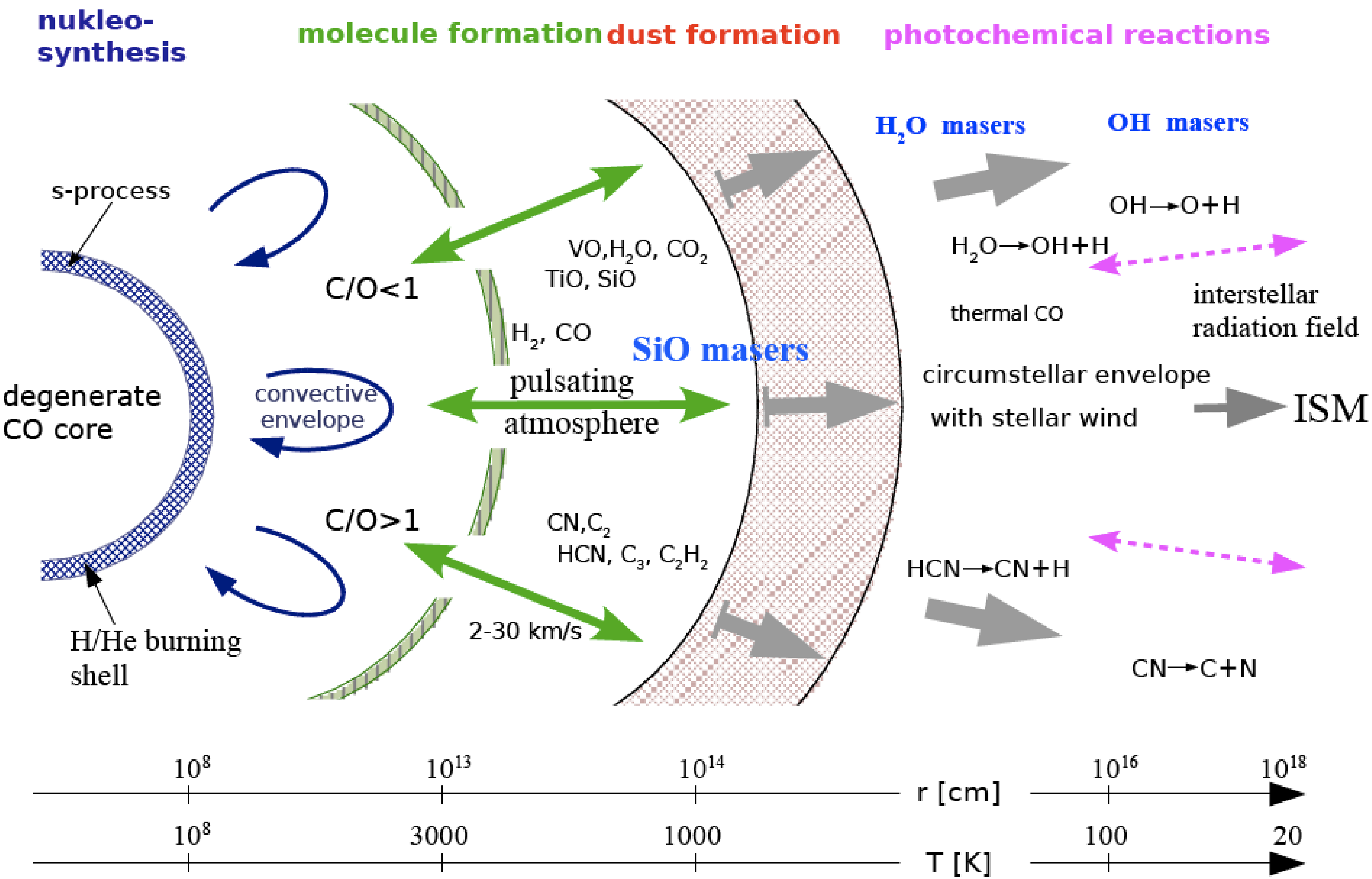
Please visit…

- Poster #2 by **Amini et al.** on OH masers in the PN W43A.
- Poster #9 by **Fujisawa et al.** on a water maser outflow in NML Cyg, studied with the Japan VLBI Network.
- Poster #11 by **Honma et al.** on the galaxy's rotation by water masers using VERA.
- Poster #15 by **Lindquist et al.** on OH masers in OH/IR stars as studied by MERLIN.
- Poster #18 by **Matsumoto et al.** on 9 epochs of SiO v=1 and v=2 J=1-0 masers in IK Tau observed with VERA.
- Poster #21 by **Rioja et al.** on SiO masers in R LMi studied by VERA.

- Next talk by **Anita Richards**
- Talk by **Yoon Kyung Choi** to measure distance to VY CMa with VERA using water masers (on Friday).
- Talk by **Hiroshi Imai** on OH masers on water fountain sources
- Talk by **Sandra Etoka** on PPN OH231.8+4.2

Schematic view of an AGB star



Basics of maser emission

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

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

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

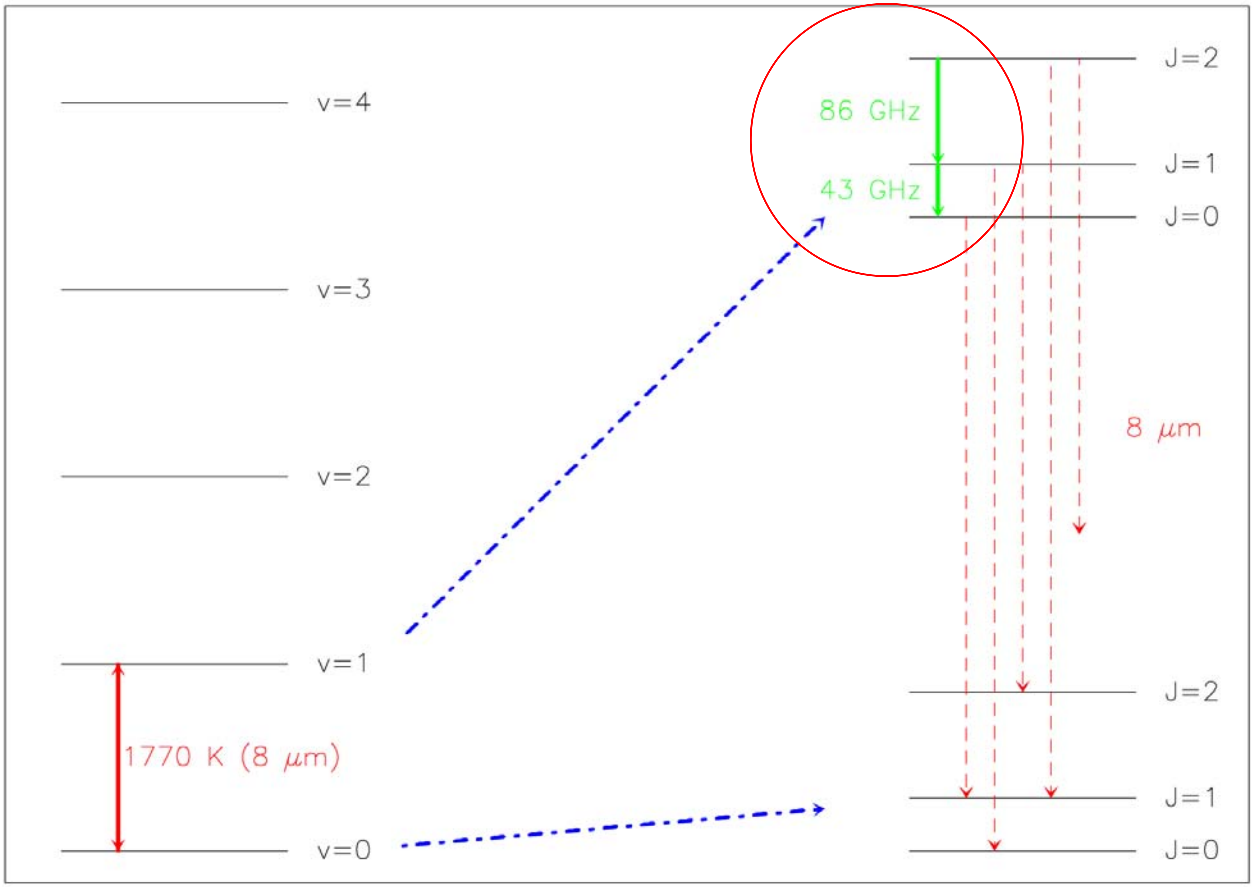
$$j_\nu = \phi(\nu)\, \frac{h\nu}{4\pi}\, g_u\, A_{ul}\, x_u$$

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

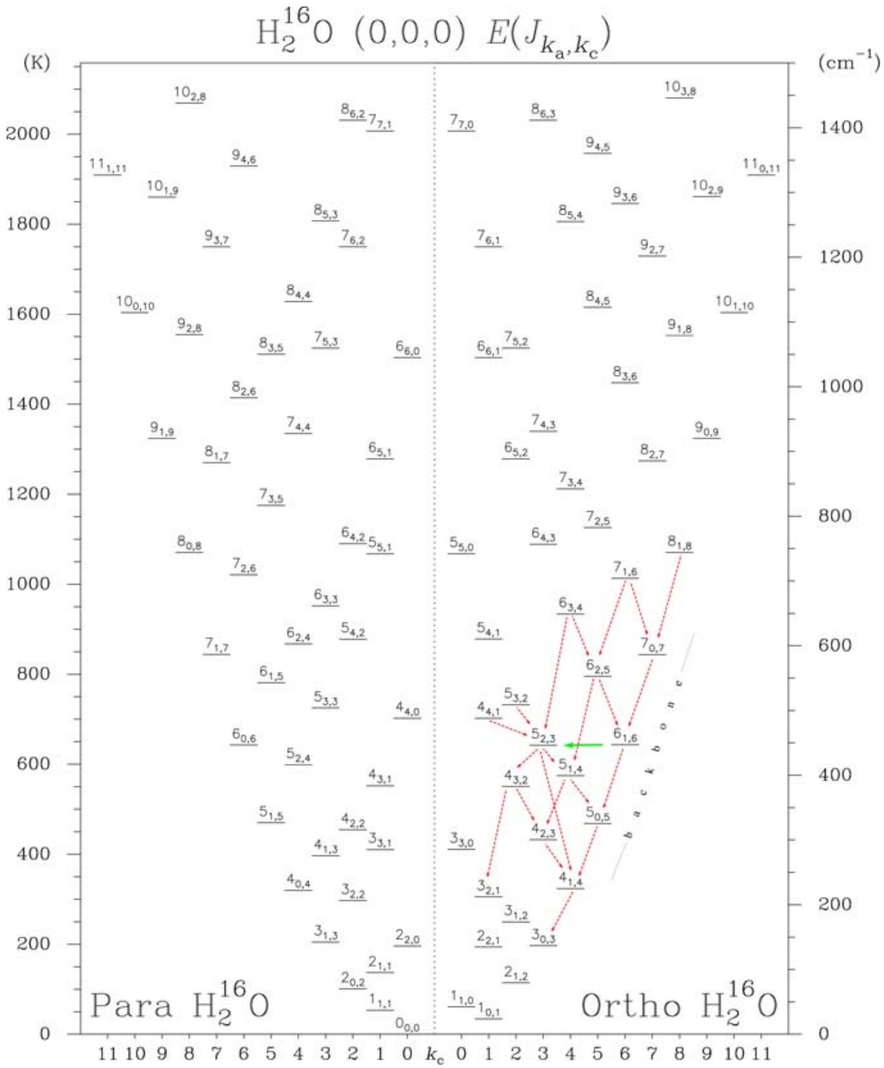
$$T_b(\nu) = T_c\, e^{-\tau_\nu}$$

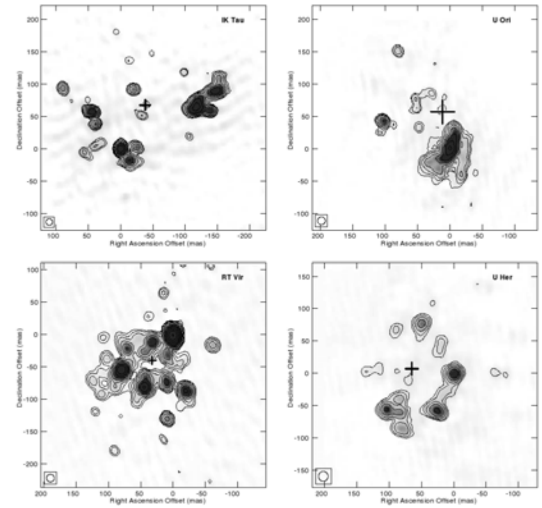
$$\Delta\nu \approx \frac{\Delta\nu_\phi}{\sqrt{|\tau_{\nu_o}|}}$$

SiO masers

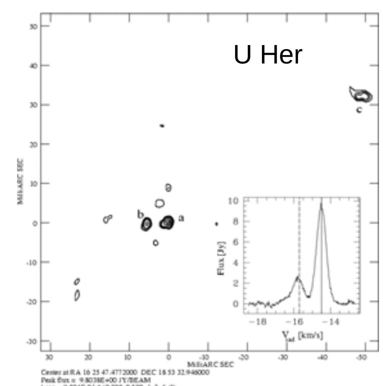


Water masers





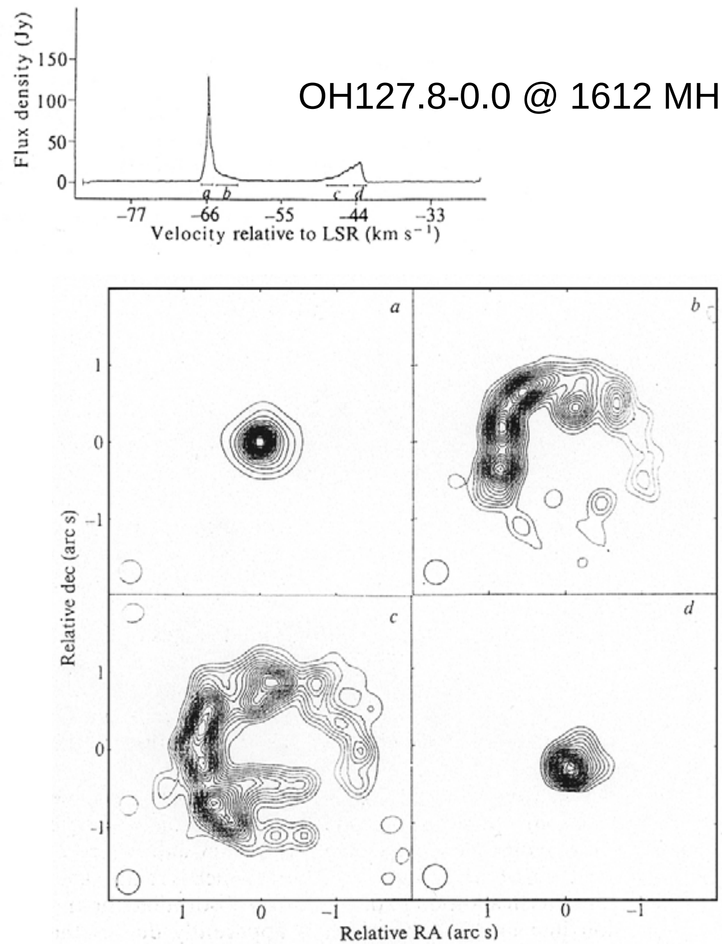
Bains et al. (2003) MNRAS 342, 8



Vlemmings et al. 2005, A&A 434, 1029)

OH masers

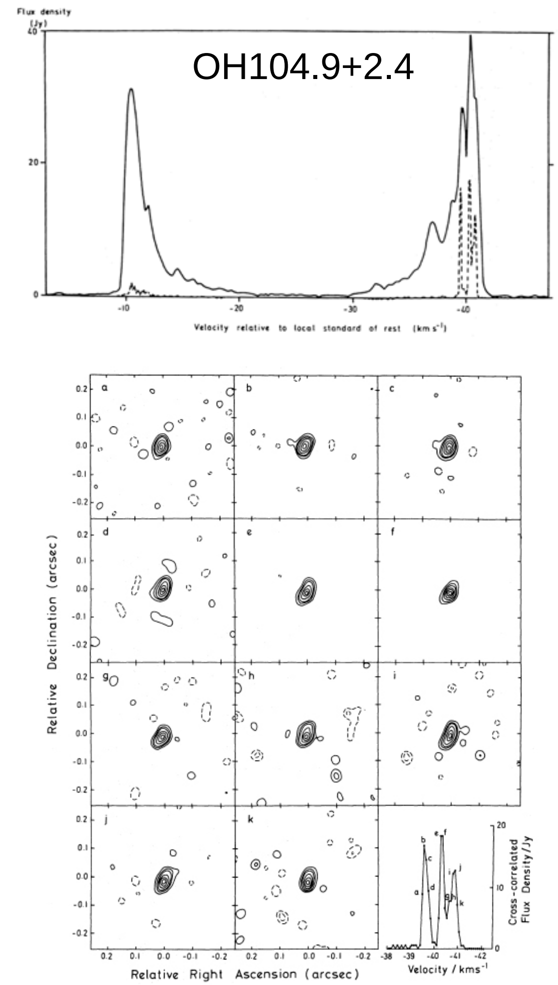
OH127.8-0.0 @ 1612 MHz



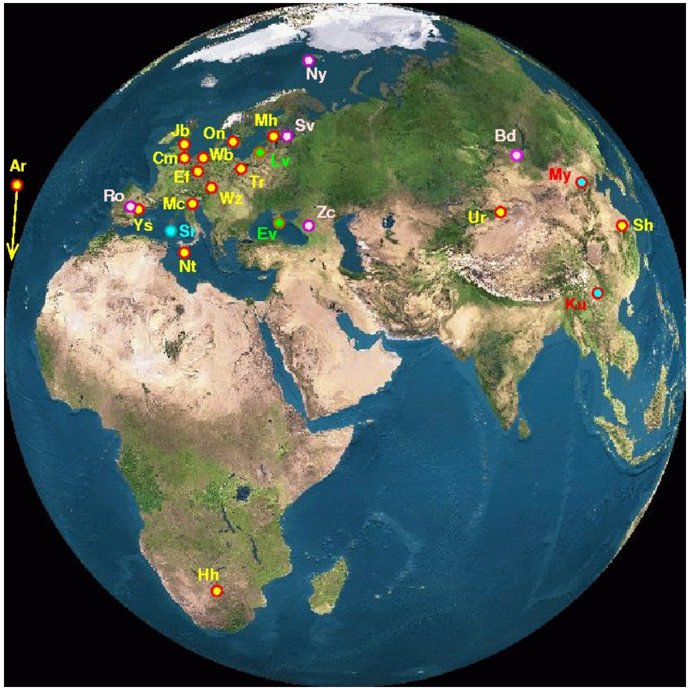
Booth et al. (1981) Nature 290, 382

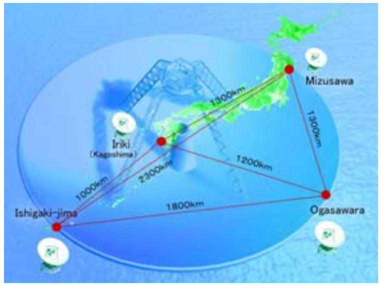
Norris et al. (1983) MNRAS 208, 435

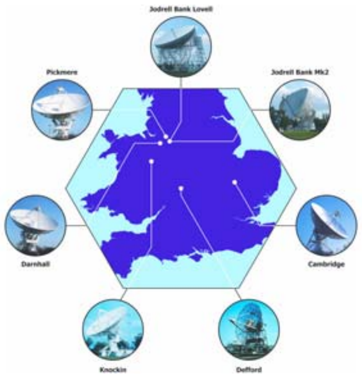
OH104.9+2.4



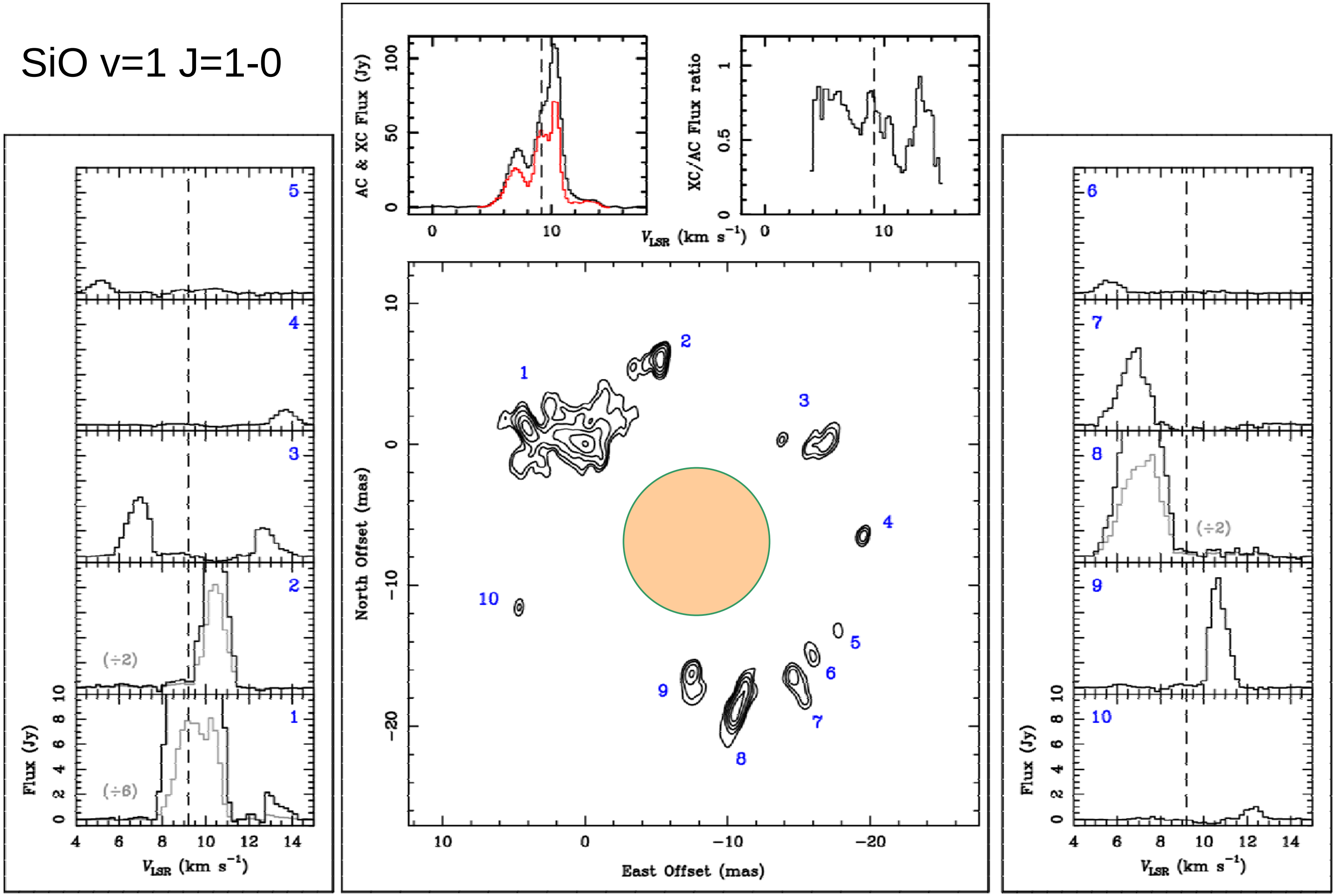
The instruments







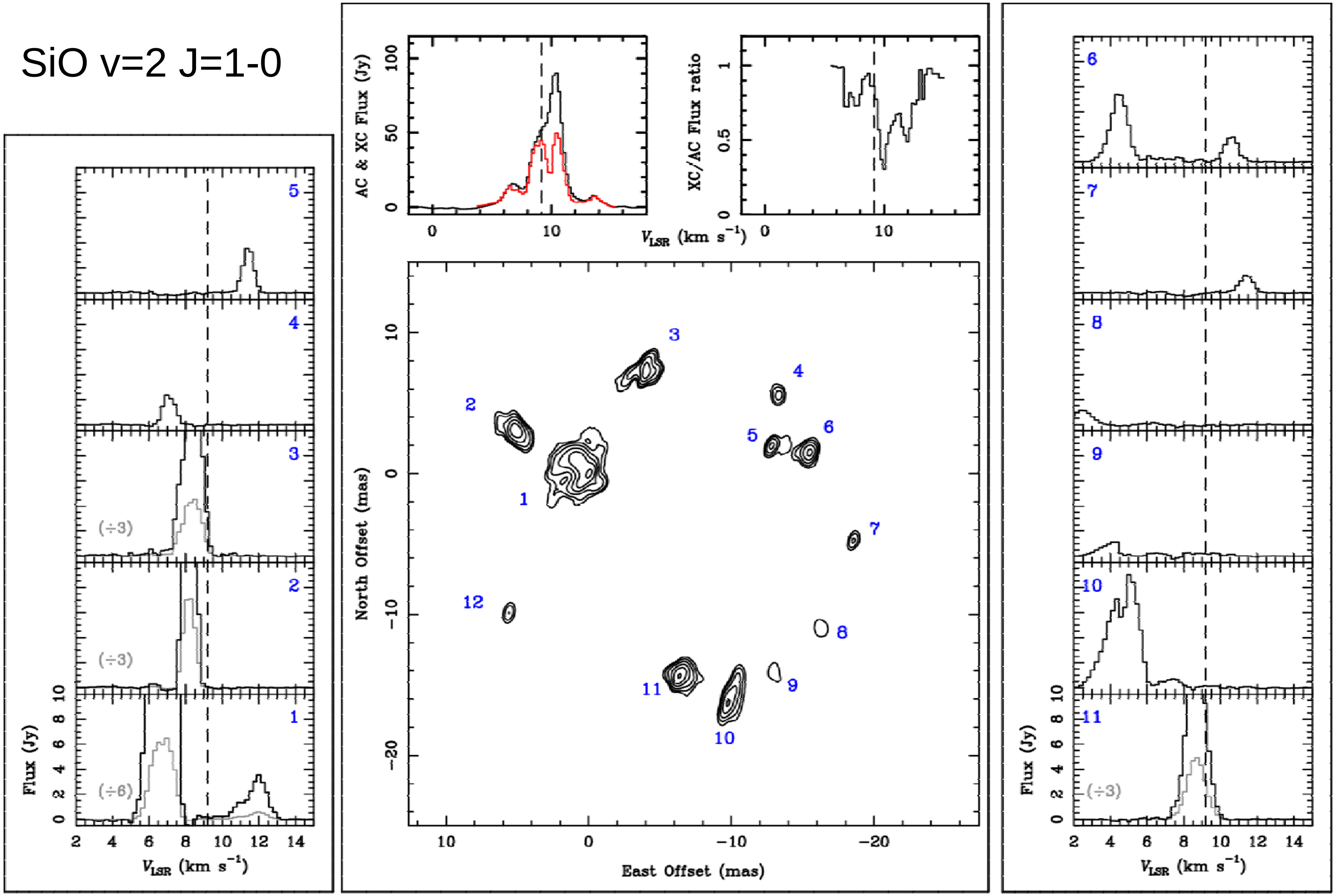
AGB stars: IRC+10011



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

IRC+10011

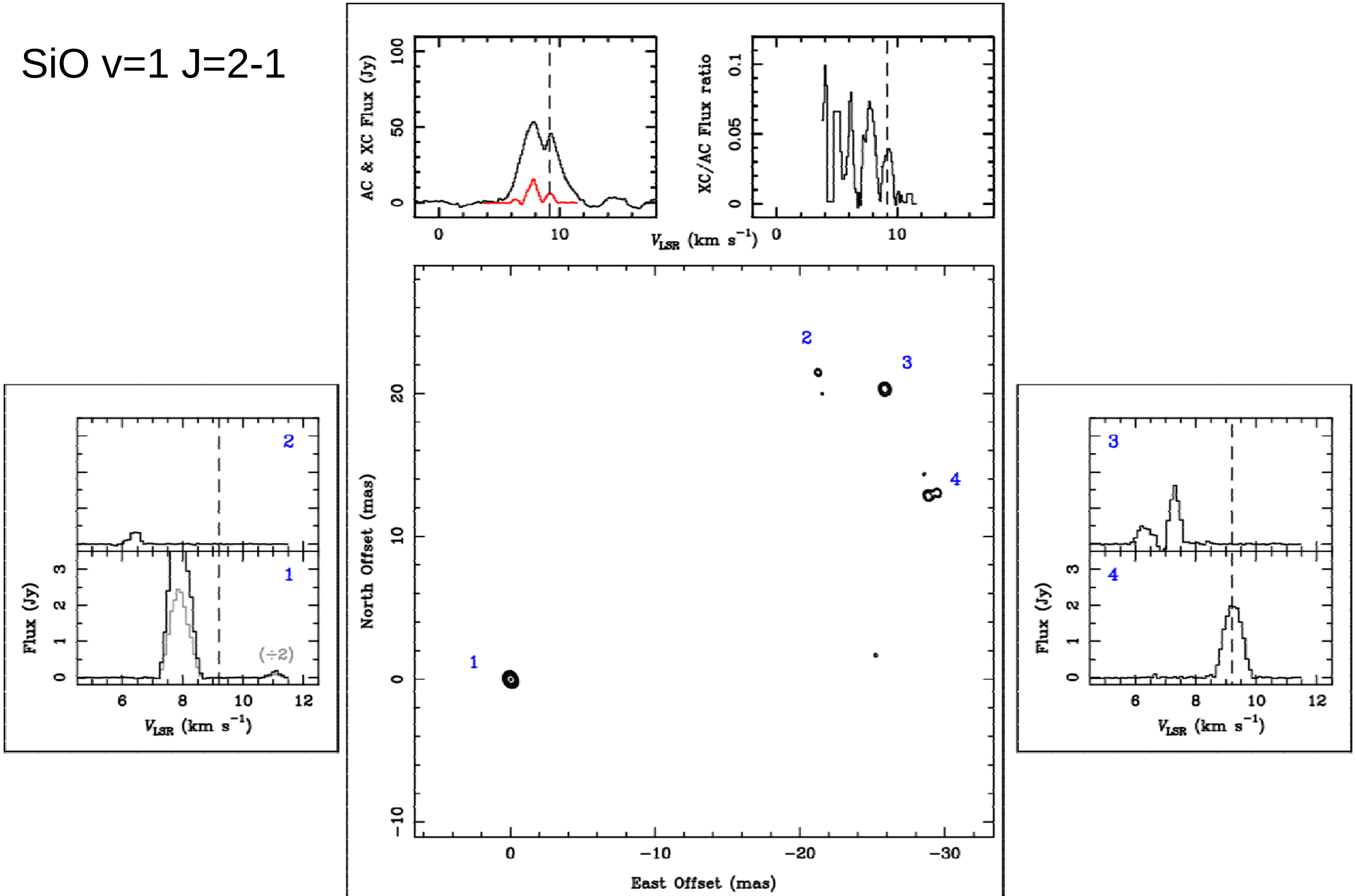
SiO v=2 J=1-0



Soria-Ruiz et al. (2004)

IRC+10011

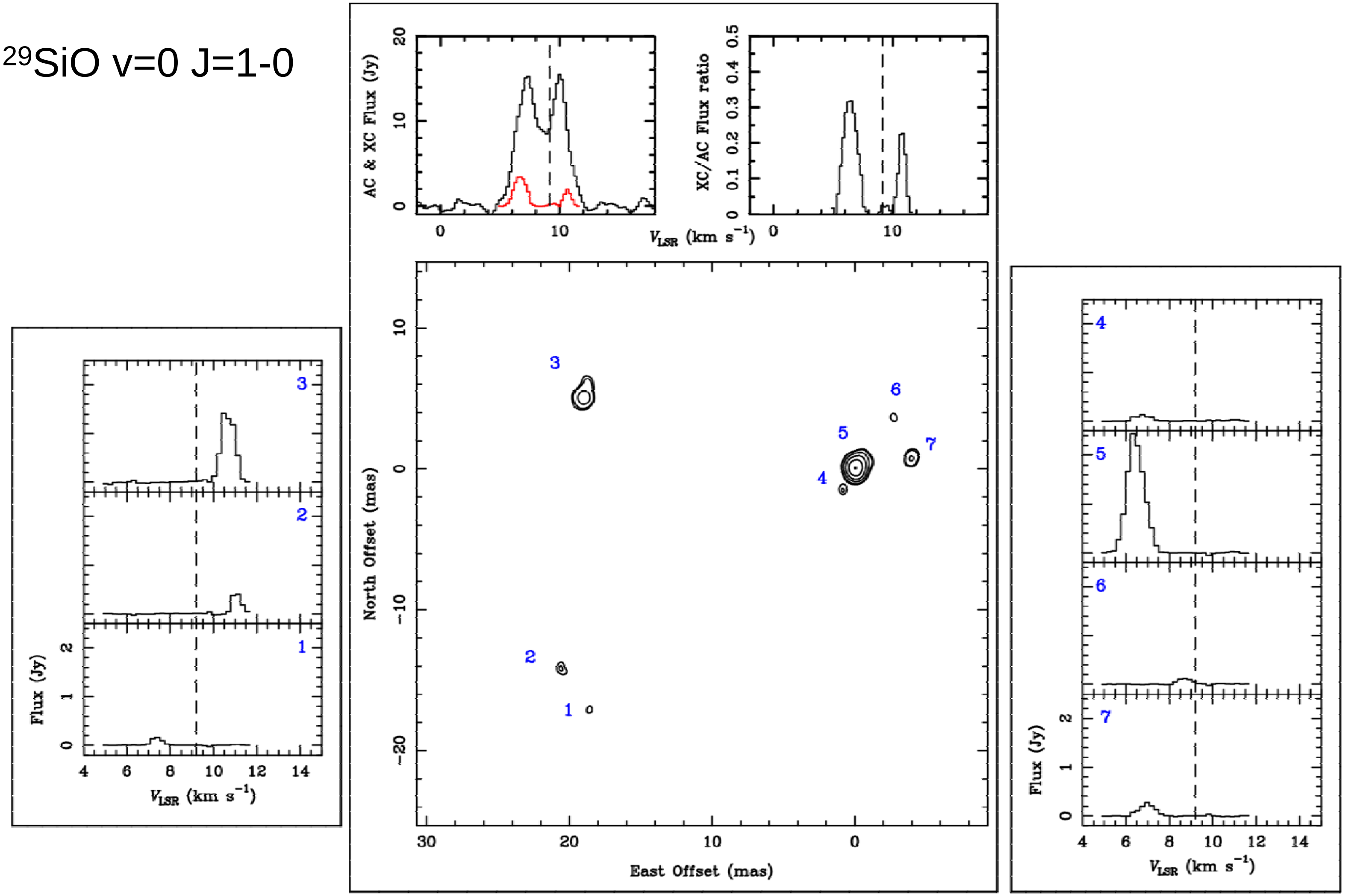
SiO v=1 J=2-1



Soria-Ruiz et al. (2004)

IRC+10011

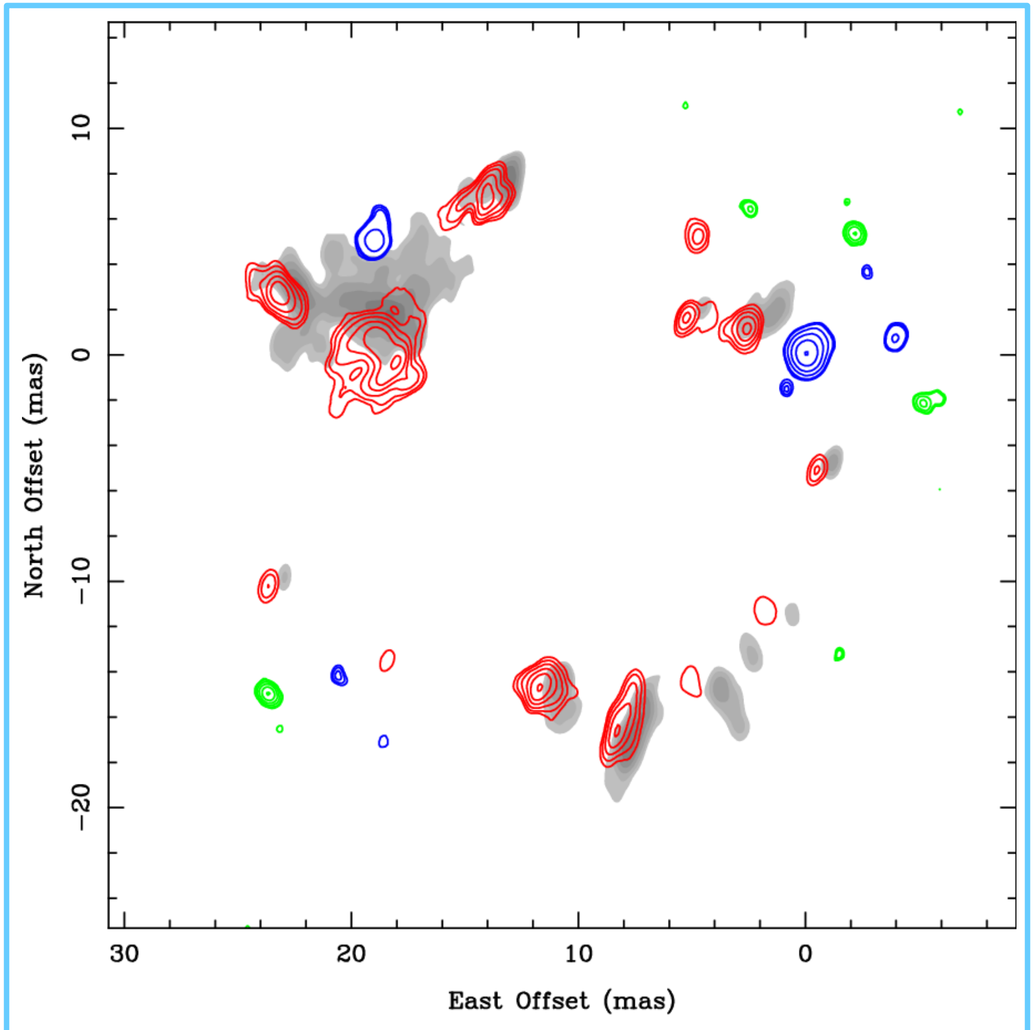
^{29}SiO v=0 J=1-0



Soria-Ruiz et al. (2004)

IRC+10011

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

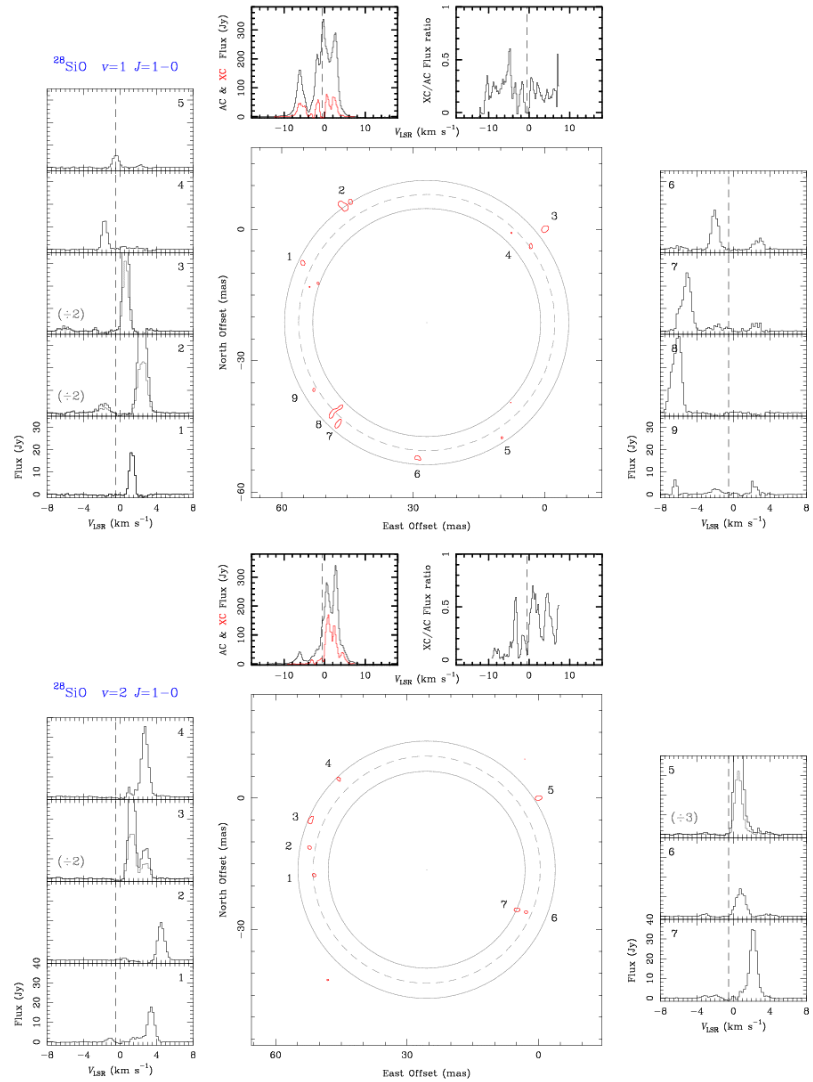


^{29}SiO $v = 0$ $J = 1–0$ ^{28}SiO $v = 1$ $J = 2–1$
^{28}SiO $v = 1$ $J = 1–0$ ^{28}SiO $v = 2$ $J = 1–0$

Soria-Ruiz et al. (2004)

Other AGB stars

AGB star	*J* = 1–0 (43 GHz)		*J* = 2–1 (86 GHz)	
	v =1	*v* =2	*v* =1	*v* =2
IRC +10011	**X**	**X**	**X**	non det
	X	**X**	**X**	—
R Leo	**X**	**X**	**X**	non det
TX Cam	**X**	**X**	—	non det
	X	**X**	**X**	**X**
chi Cyg	**X**	**X**	**X**	**X**



Models of SiO maser emission

Need to describe:

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

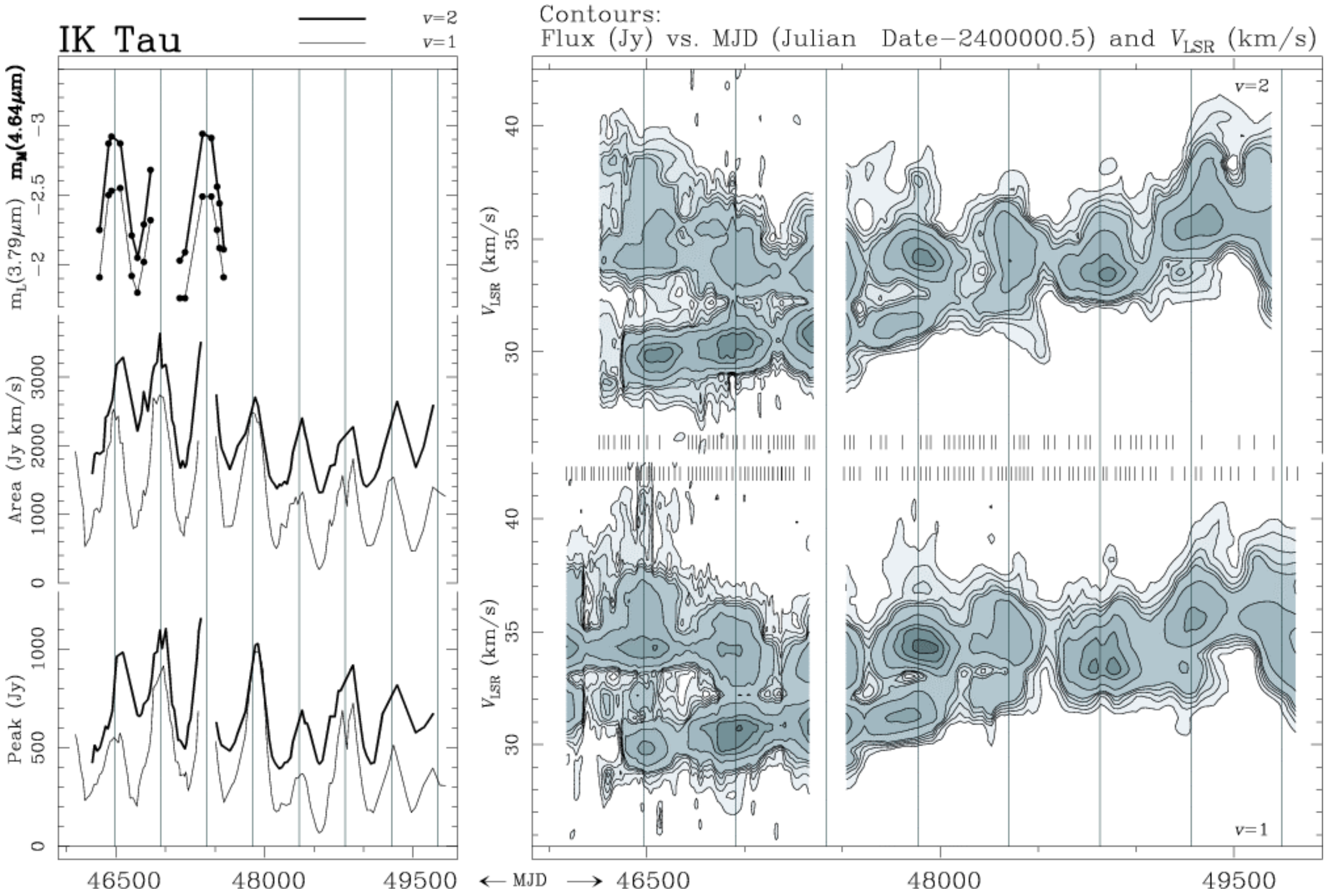
Spatial distribution

- Ring structure:
  - Explained by tangential amplification (eg. Bujarrabal & Nguyen-Q-Rieu 1981)

- Time variability:
  - Correlation with IR pumping from the central star (eg. Pardo et al. 2004)

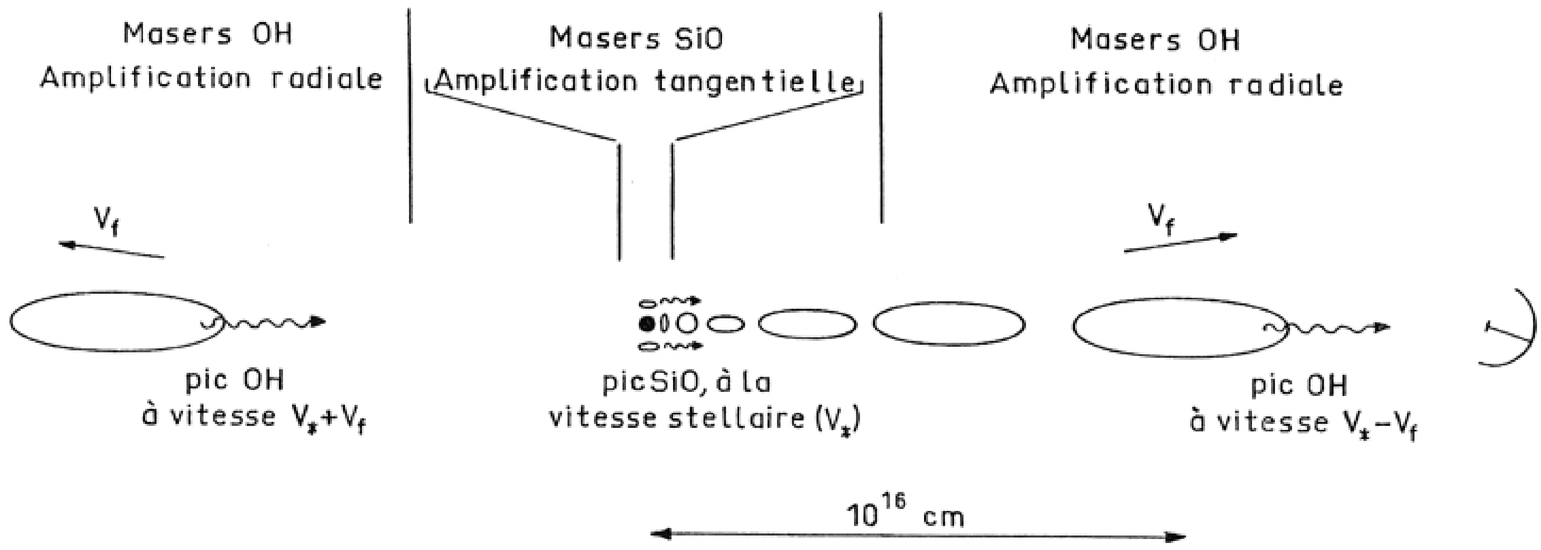
- Clumpiness:
  - Humphreys et al. (1996) MNRAS 282, 1359
  - Doel et al. (1995) A&A 302, 797

Time variability



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

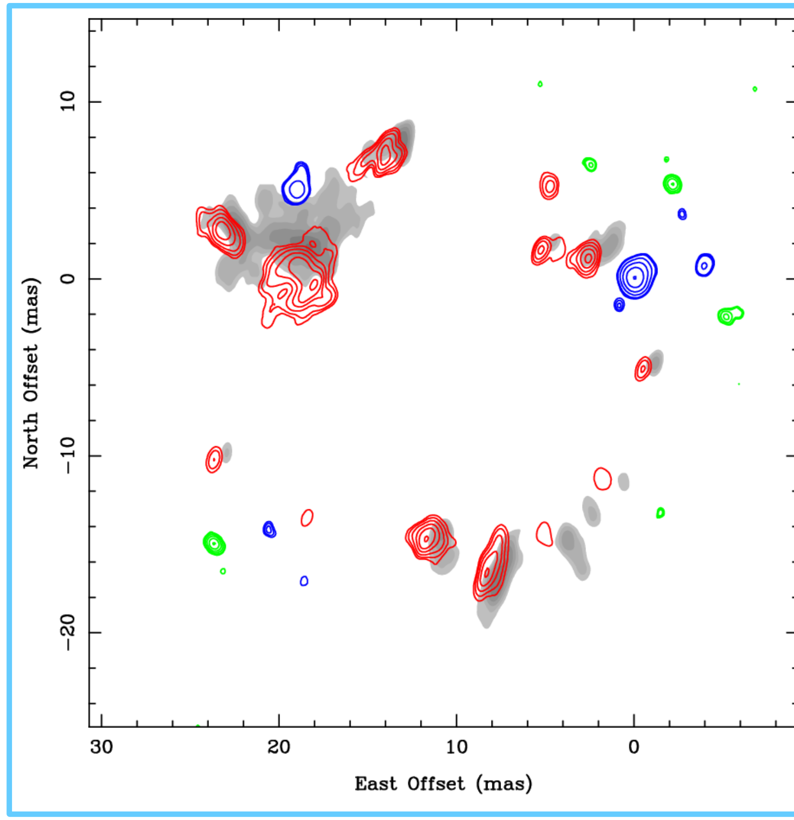
Tangential amplification = Rings



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

Multitransition studies

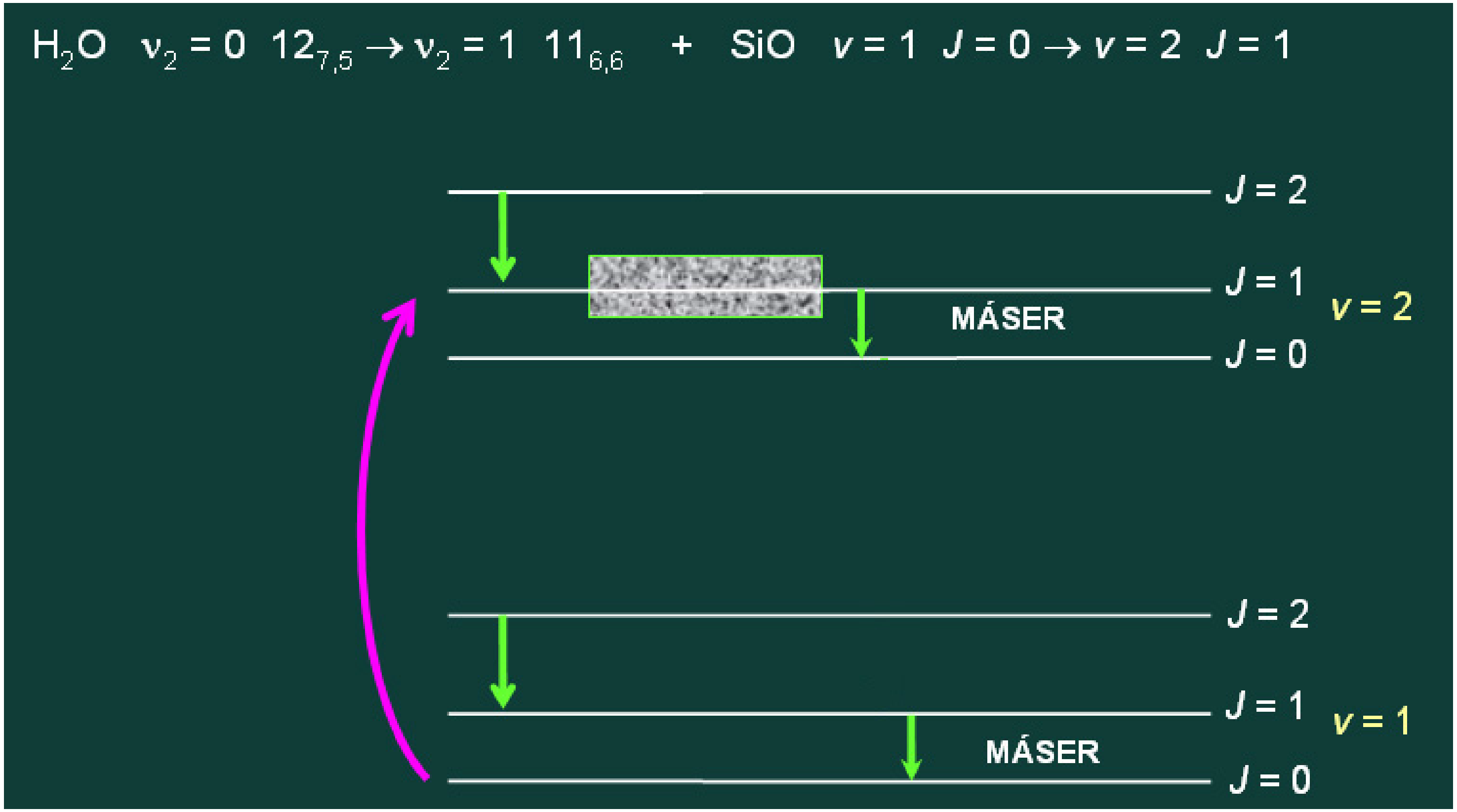
AGB star	$J = 1–0$ (43 GHz)		$J = 2–1$ (86 GHz)	
	$v = 1$	$v = 2$	$v = 1$	$v = 2$
IRC +10011	X	X	X	non det
	X	X	X	—
R Leo	X	X	X	non det
TX Cam	X	X	—	non det
	X	X	X	X
chi Cyg	X	X	X	X



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

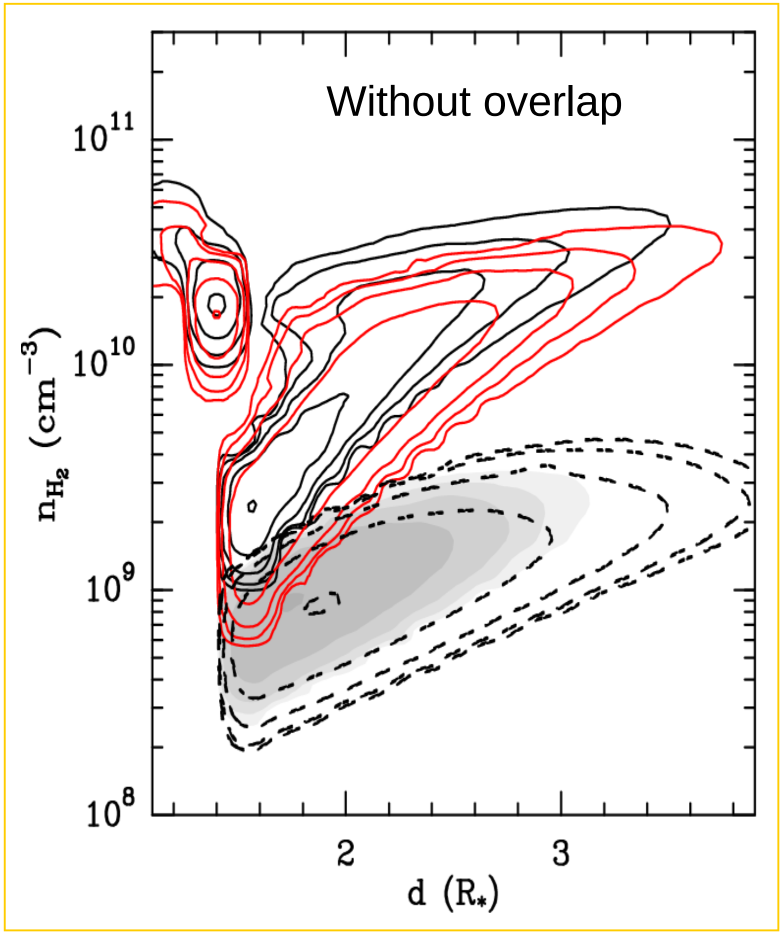
^{28}SiO $v = 1$ $J = 1–0$ ^{28}SiO $v = 2$ $J = 1–0$

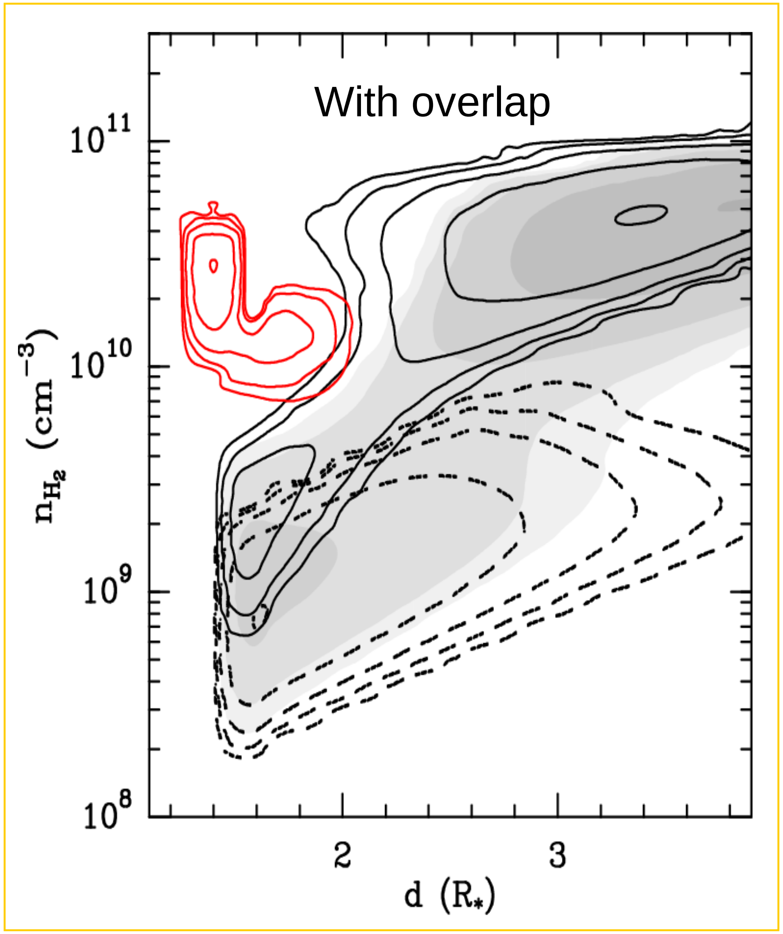
The case of SiO v=2 J=2-1



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

Line overlap effects





Greys	$v = 1$ $J = 1–0$	———	$v = 2$ $J = 1–0$
- - - - - - - -	$v = 1$ $J = 2–1$	——— (red)	$v = 2$ $J = 2–1$

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.

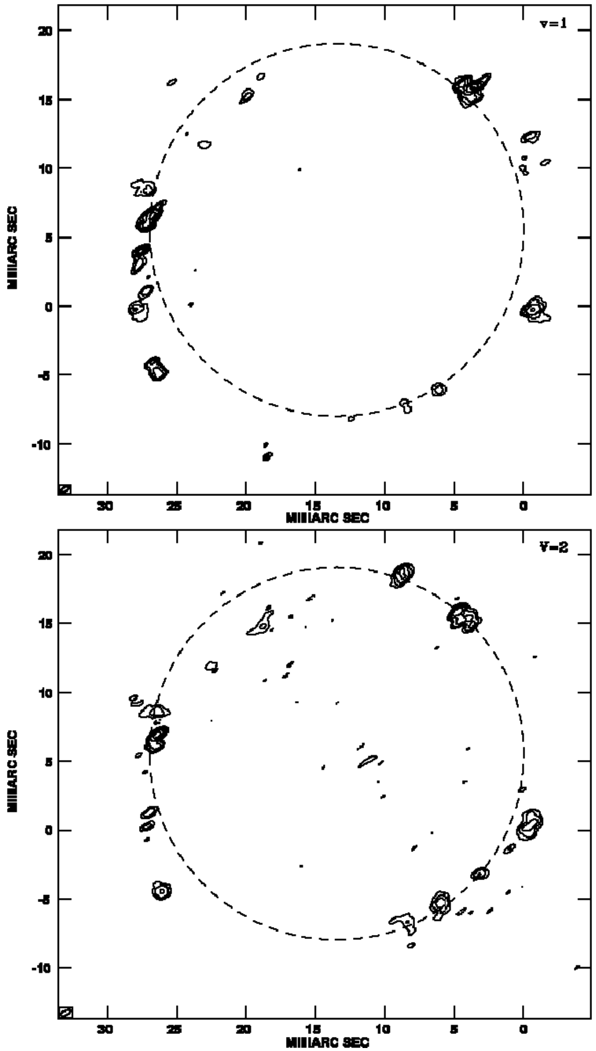
3. Frequency-phase transfer.

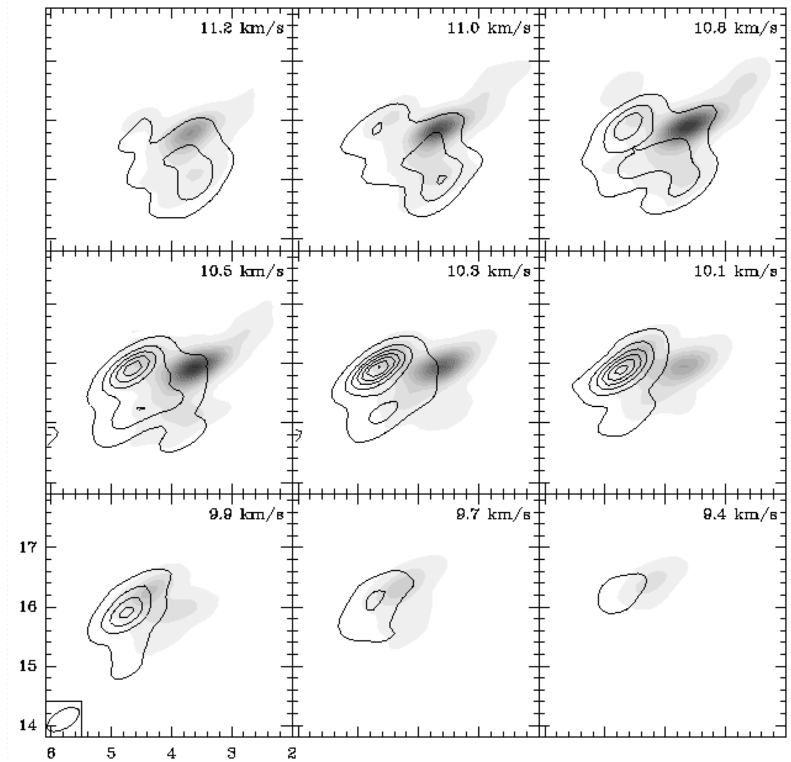
4. Absolute astrometry by phase referencing to quasars.

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

1. Alignment by centroid

TX Cam

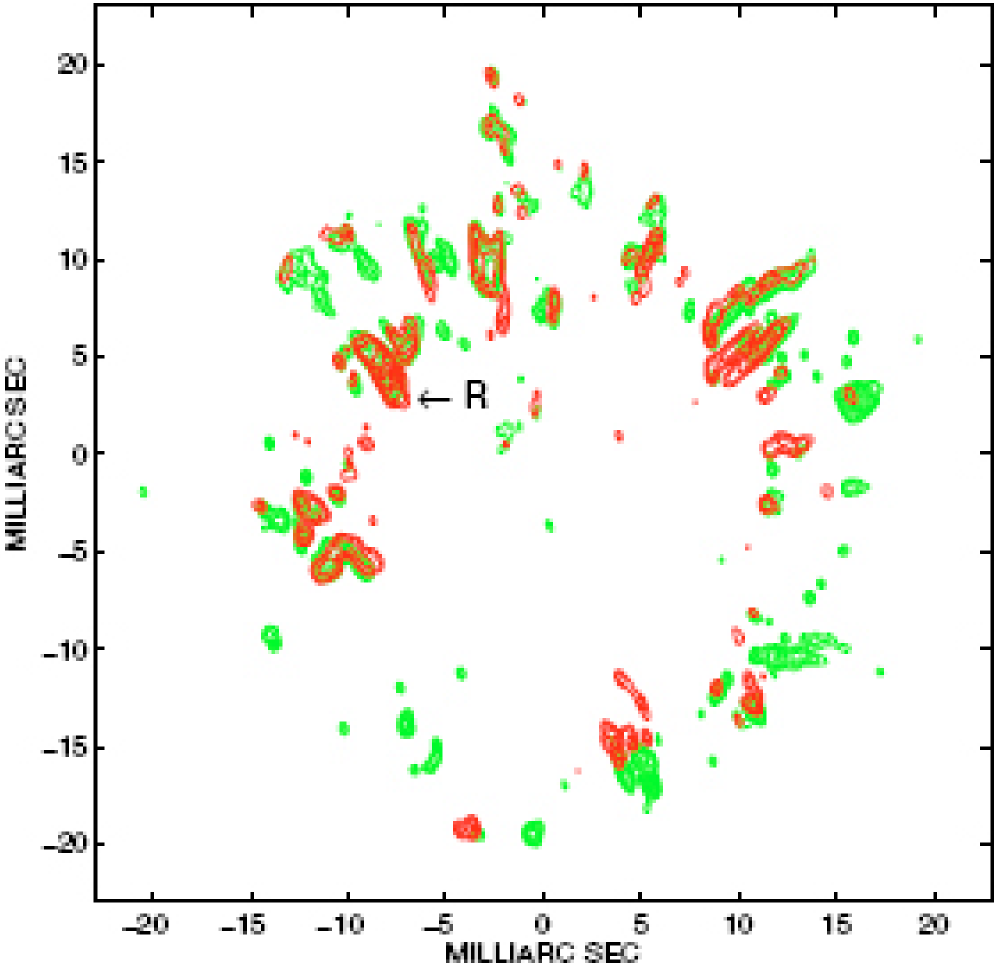




Desmurs et al. (2000) A&A 360, 189

2. Alignment by phase tracking

TX Cam

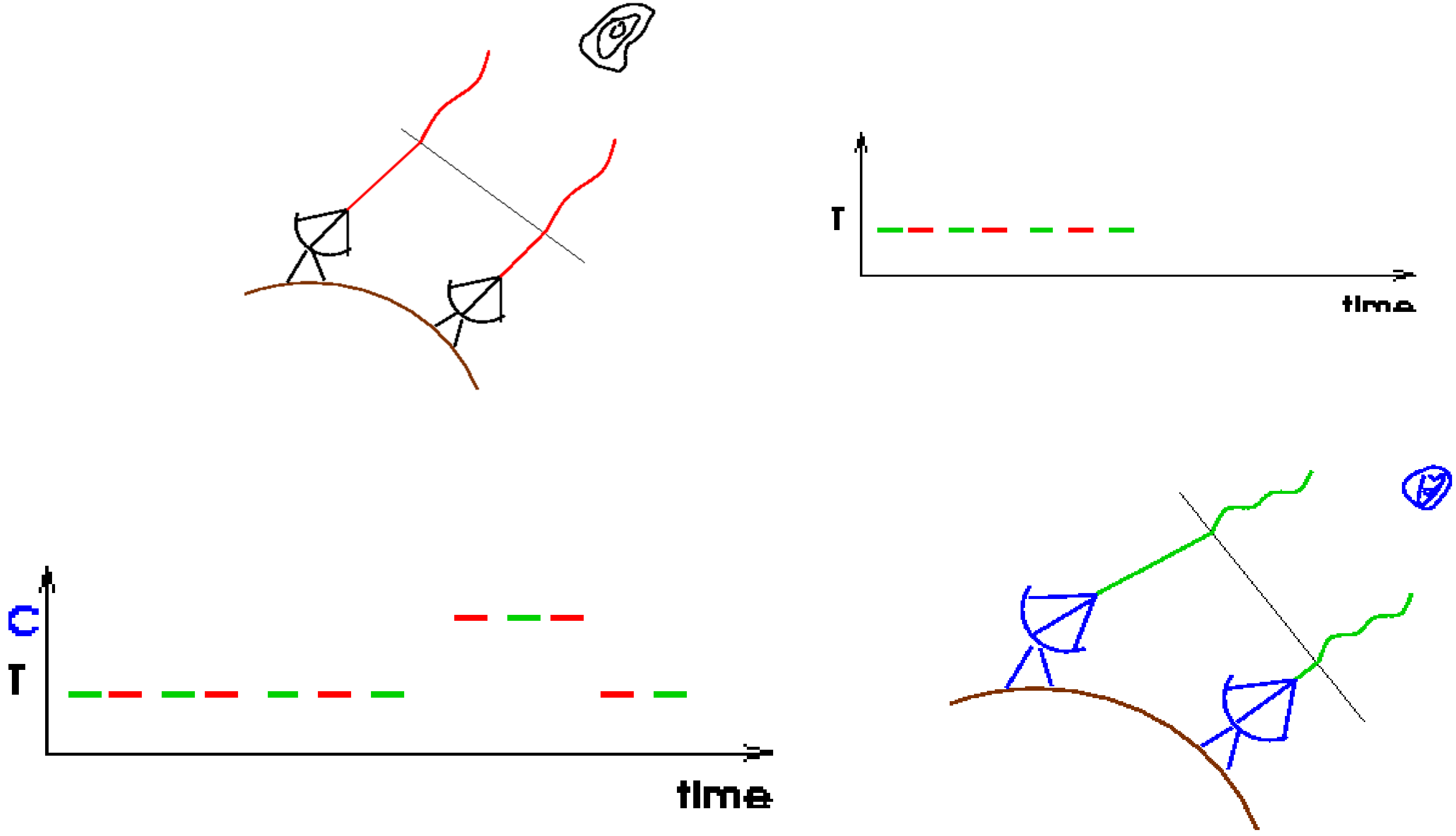


SiO v=1 J=1-0

SiO v=2 J=1-0

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

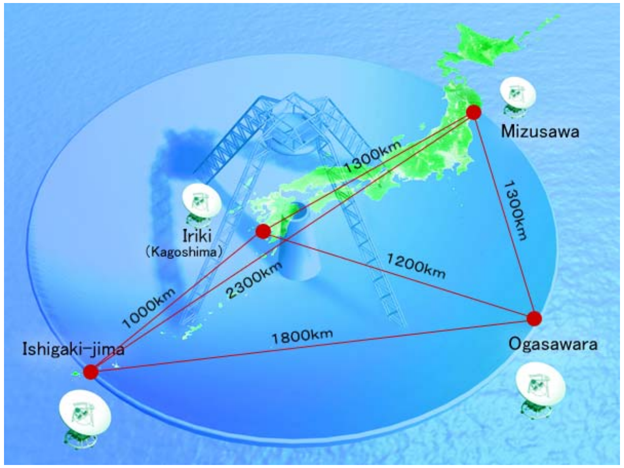
3. Frequency-phase transfer



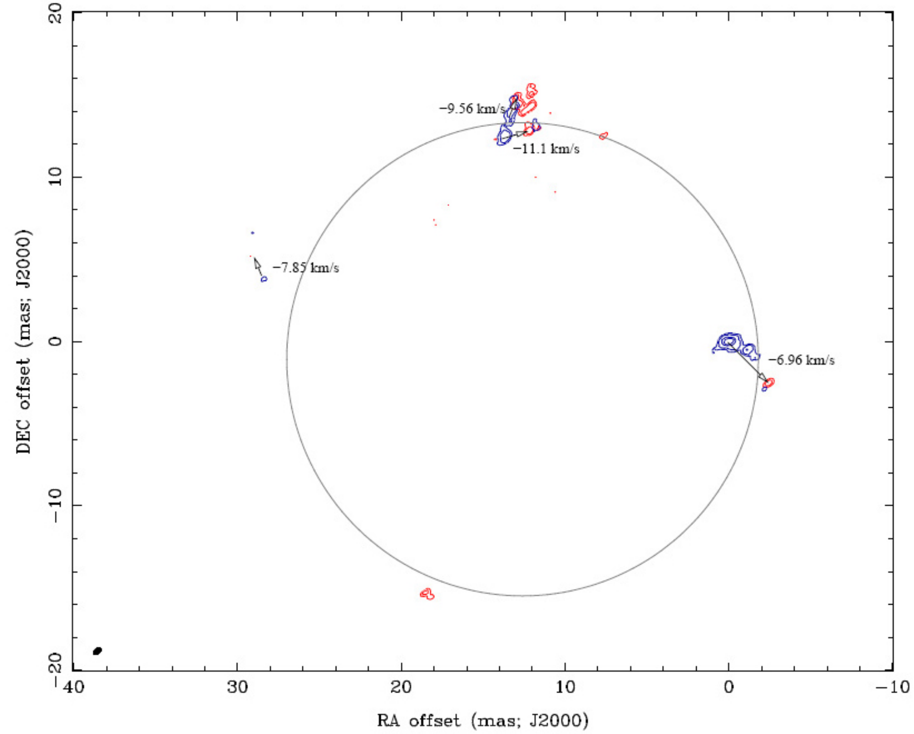
Rioja et al. (2008) PASJ

see talk by Taehyun Jung & poster by Rioja et al. (#21)

4. Absolute astrometry: VERA

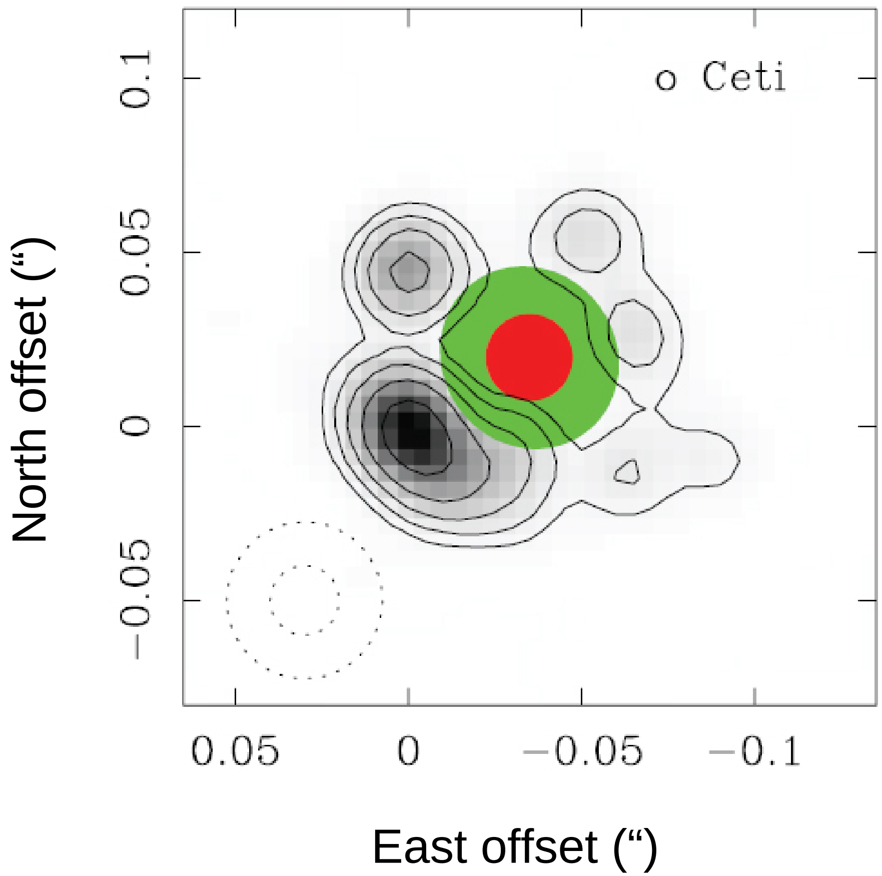


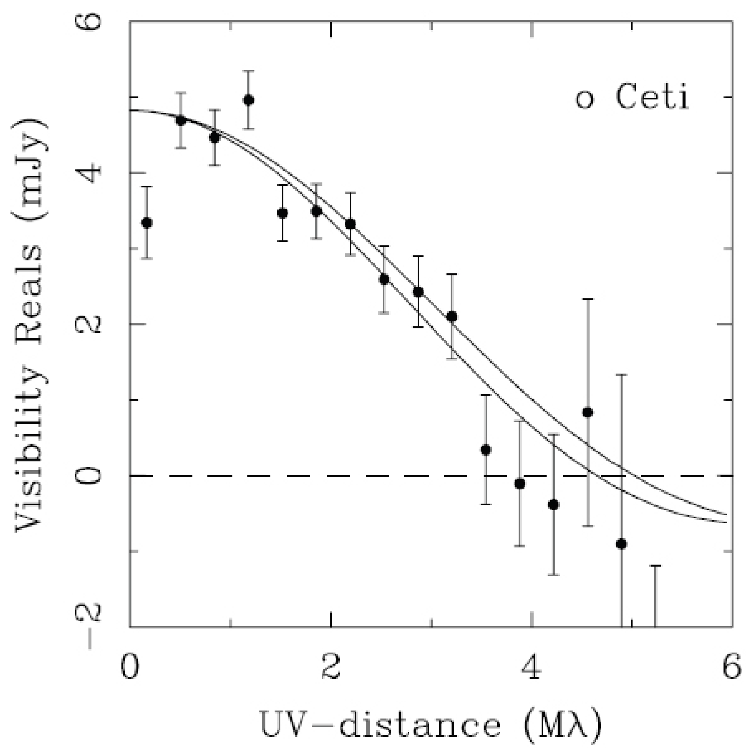
R LMi



Rioja et al. (2008) PASJ
see also Posters #18, # 21

Imaging the photosphere!



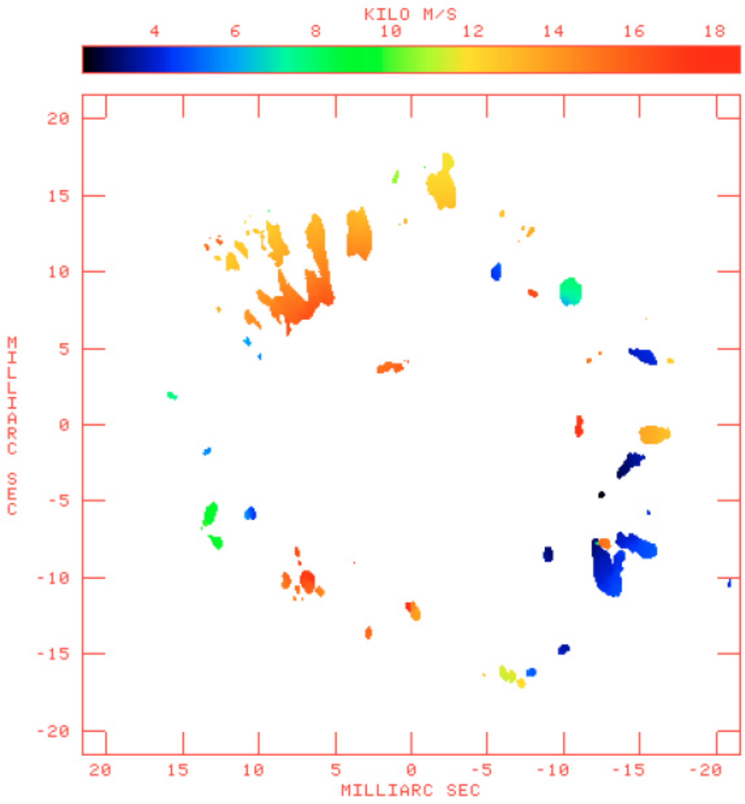


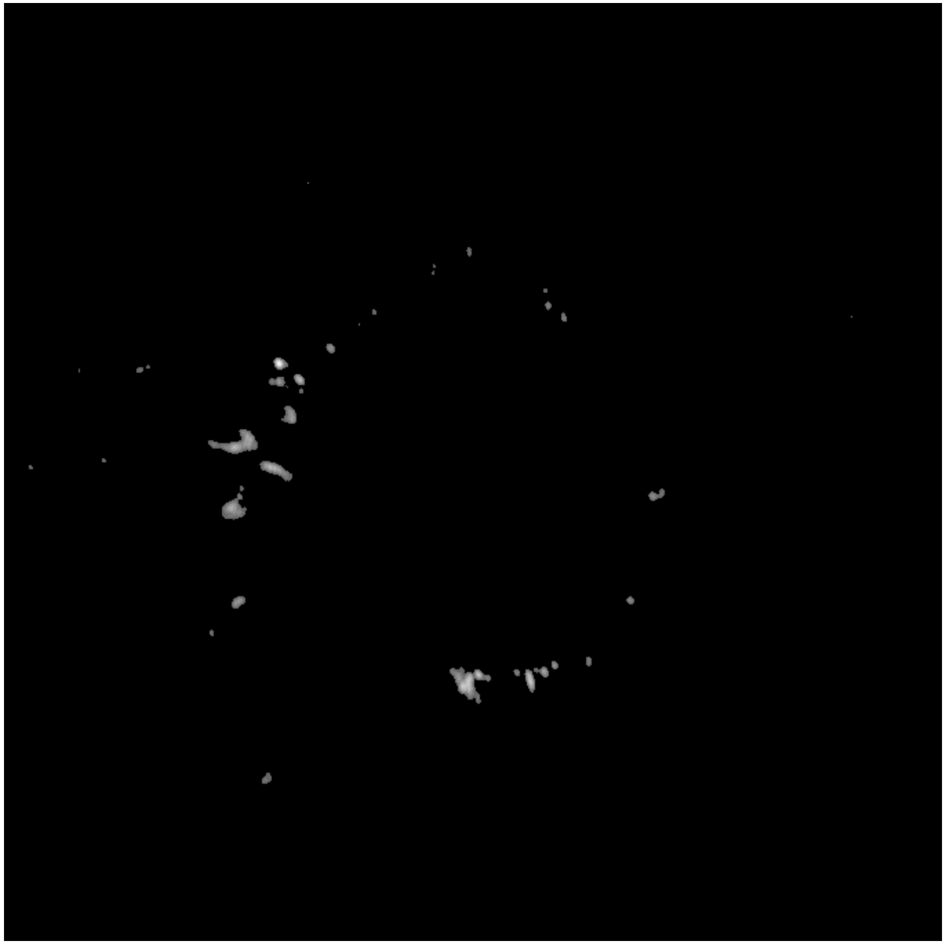
$R_* = 5.6$ AU
$R_{SiO} = 8$ AU

Reid & Menten (2007) ApJ 671, 2068

Kinematics

TX Cam

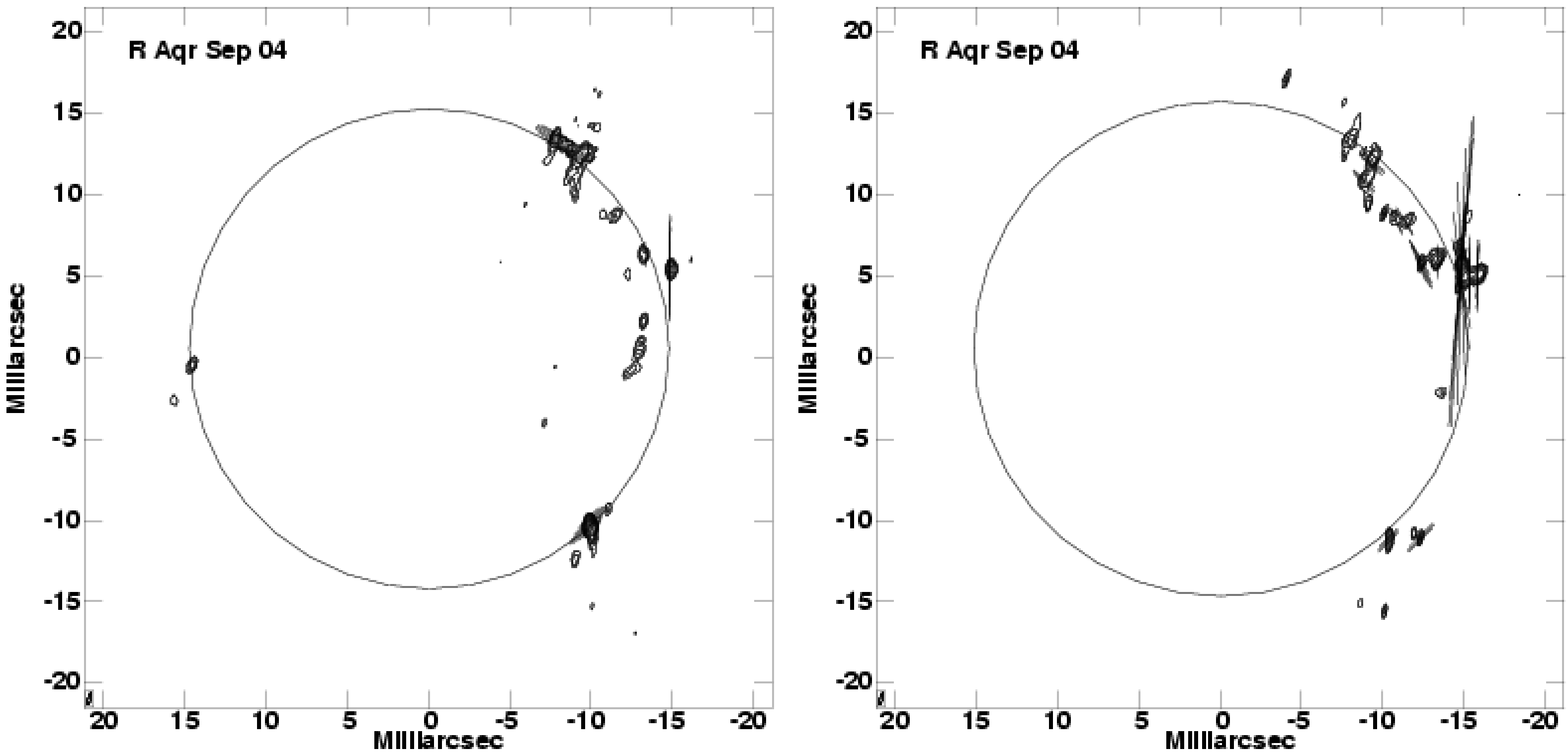




Yi et al. (2005)

Gonidakis, Diamond & Kemball (2008)

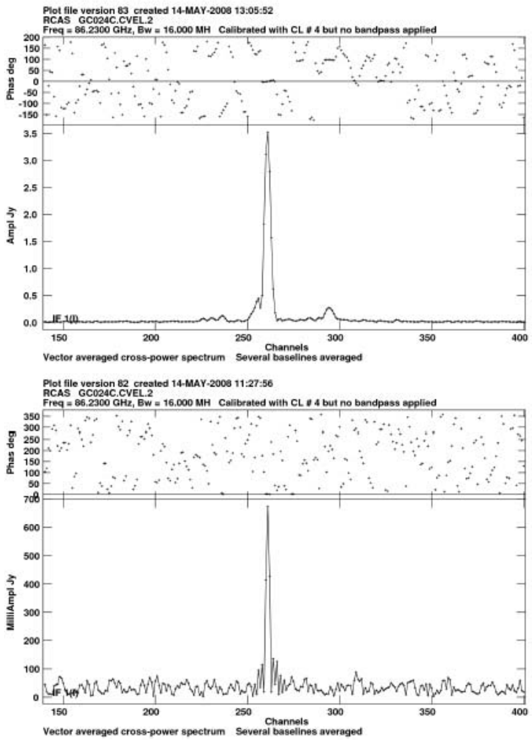
Polarization

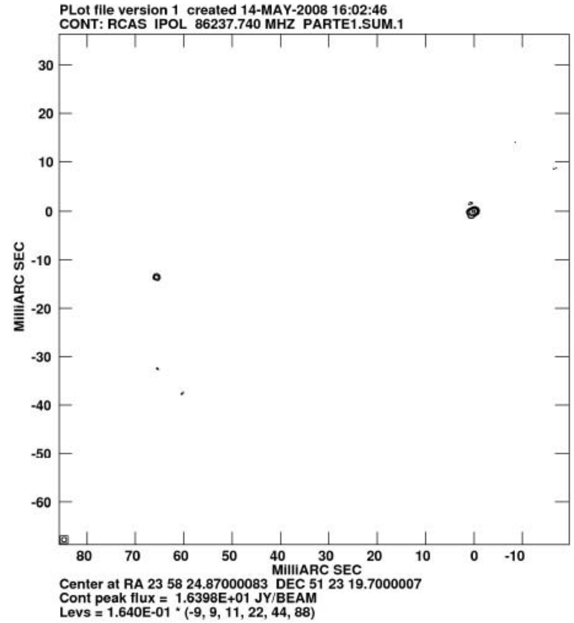


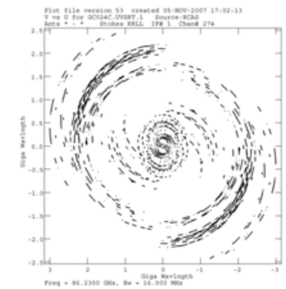
Cotton et al. (2006) A&A 456, 339; Cotton et al. (2004) A&A 414, 275

SiO masers at GMVA

R Cas

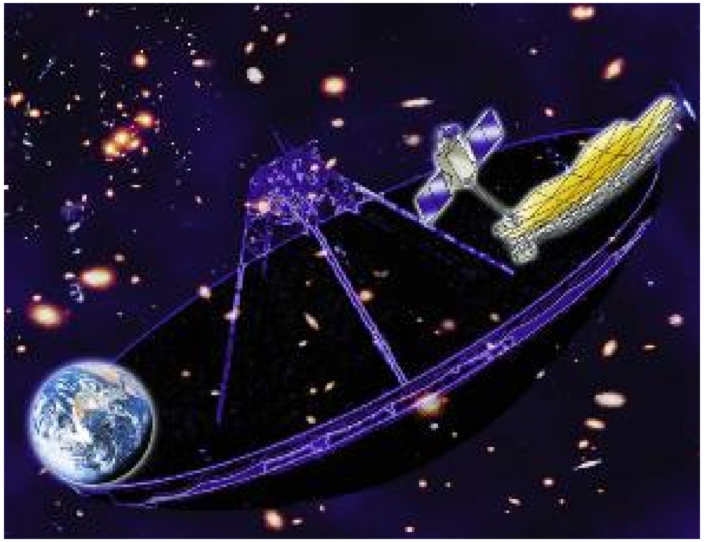


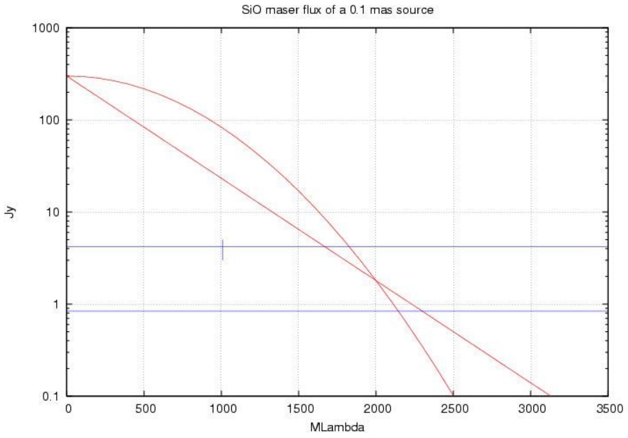




Colomer et al. (2008) PASJ

VSOP-2

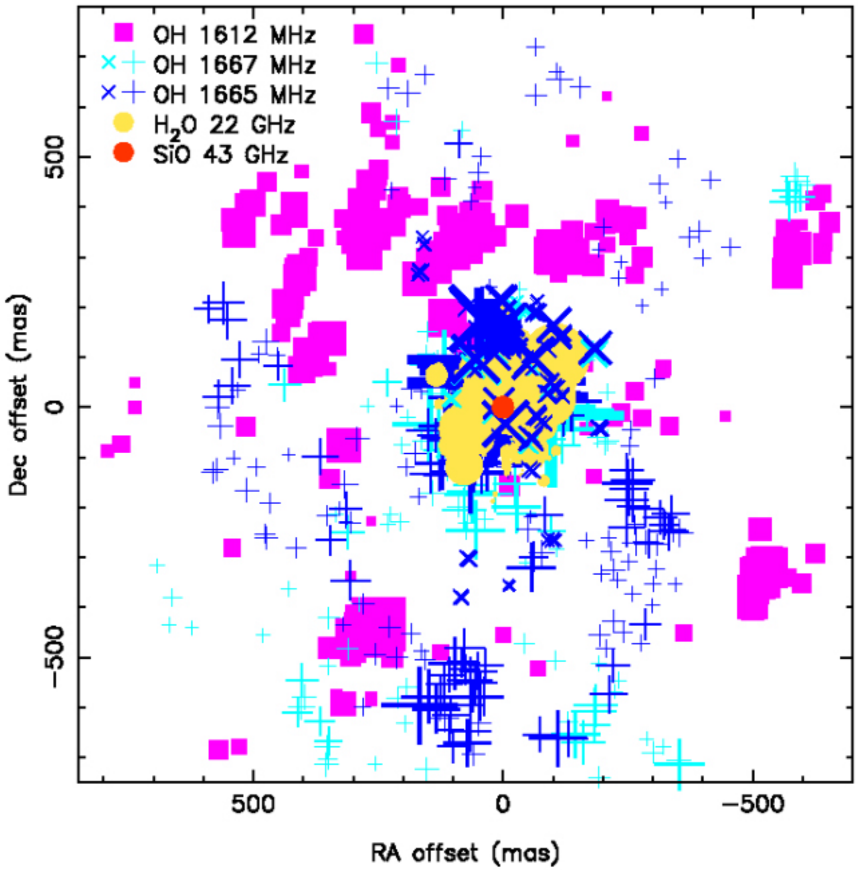




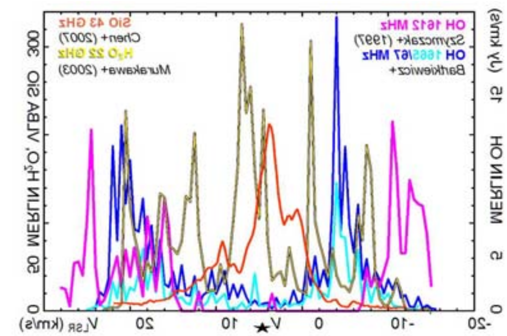
- It will operate at the 22 and 43 GHz bands (H_2O and SiO masers).

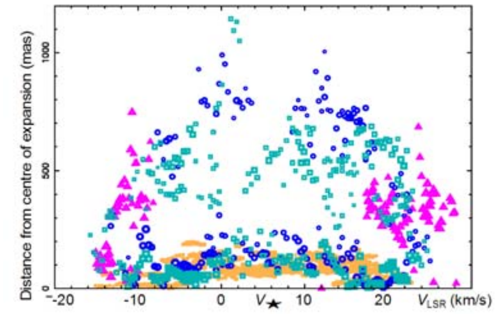
- VSOP-2 to ground baselines at 43 GHz will have the same spatial resolution as the GMVA at 86 GHz.

VX Sgr at mas resolution



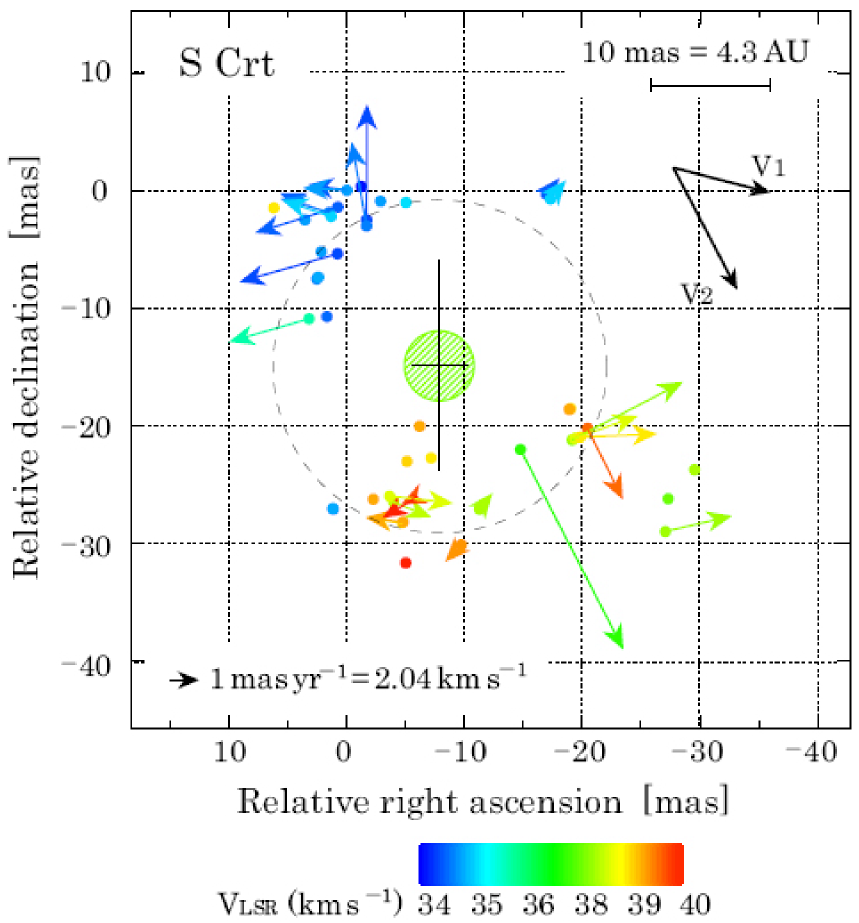
- OH 1612 MHz masers at 800-2000 au (65-170 $R_\star$)
- H_2O masers at 95-325 au (8-27 $R_\star$)
- SiO masers within 3 $R_\star$
- OH mainlines overlap H_2O and 1612 MHz



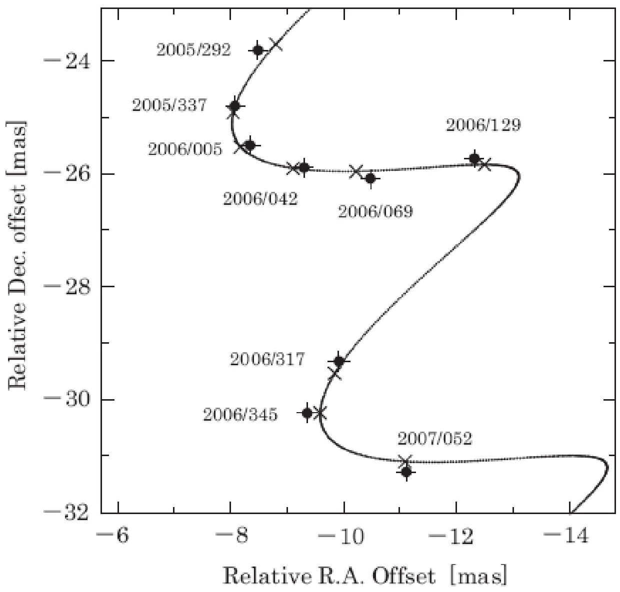


Richards et al. (2007) IAU242, 261

VERA parallaxes

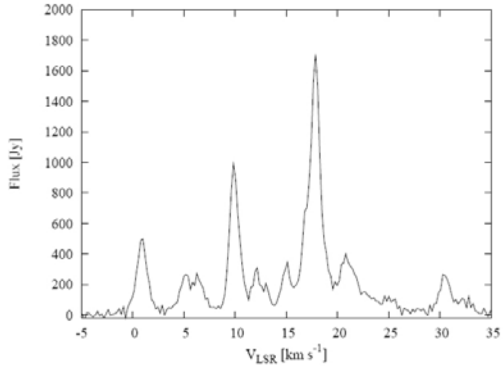


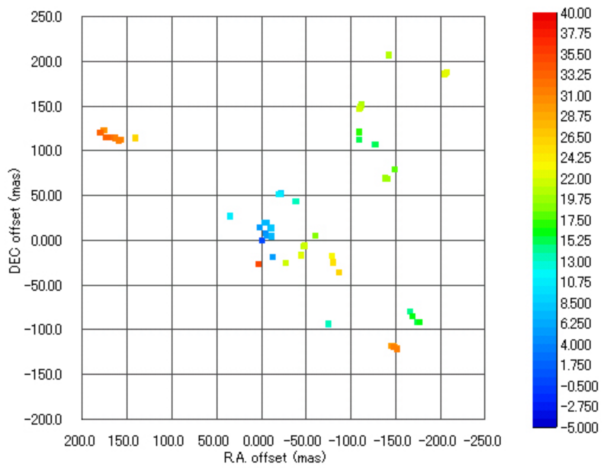
- Water masers @ 22 GHz
- D = 430 pc



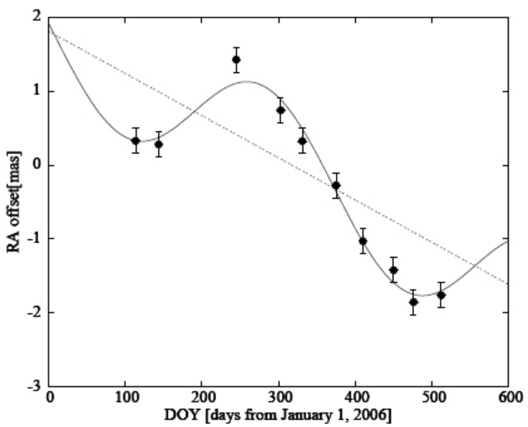
Nakagawa et al. (2008) PASJ

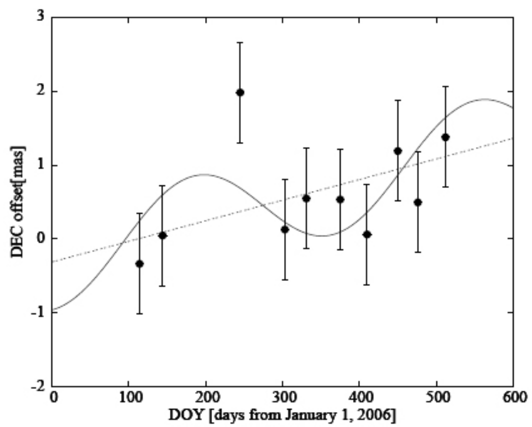
VY CMa





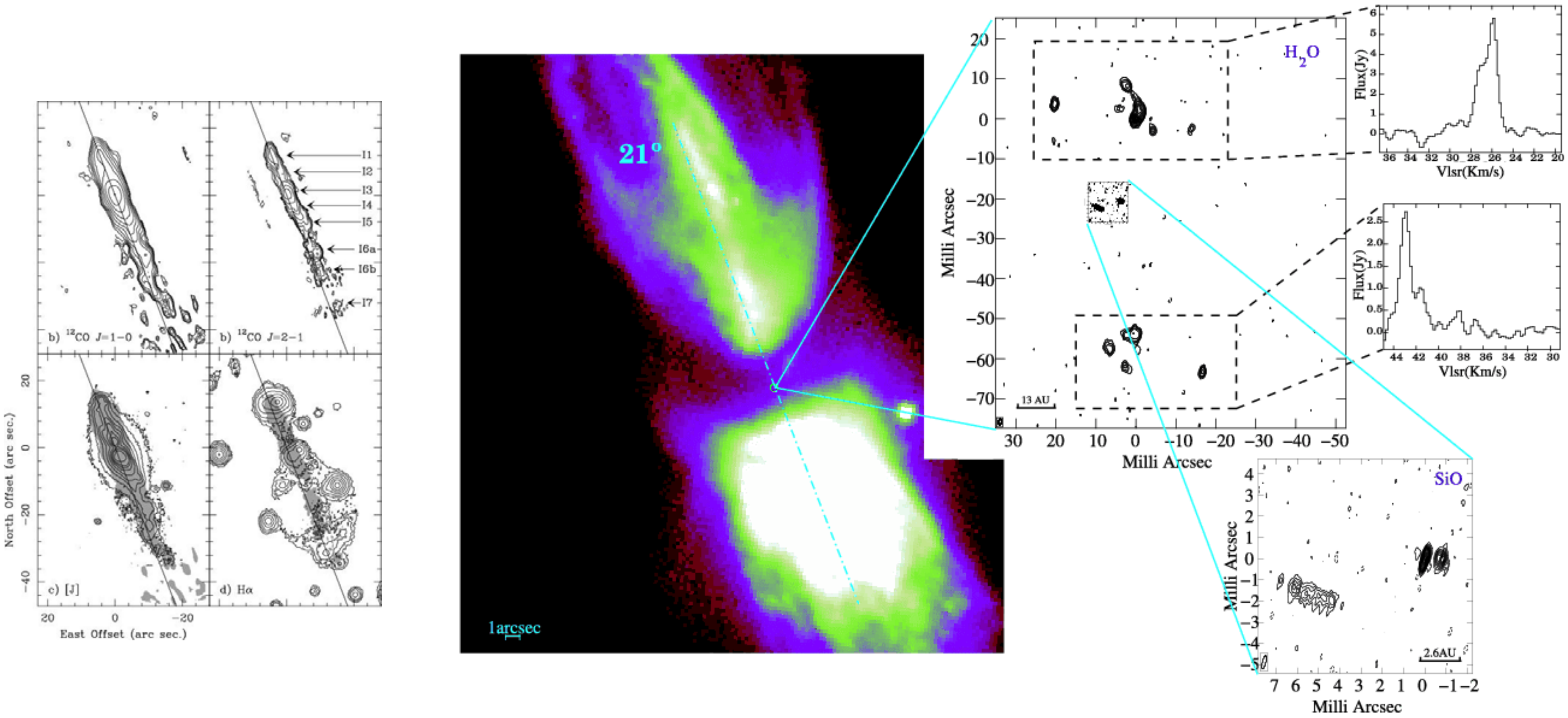
- D = 1.14 kpc
- L = 3 10^5 Lsun





Choi et al. (2008) PASJ
see also talk (on Friday)

PPNs: OH231.8+0.4



Desmurs et al. (2007) A&A 468, 189

see also talk by Sandra Etoka (on Friday)

Conclusions

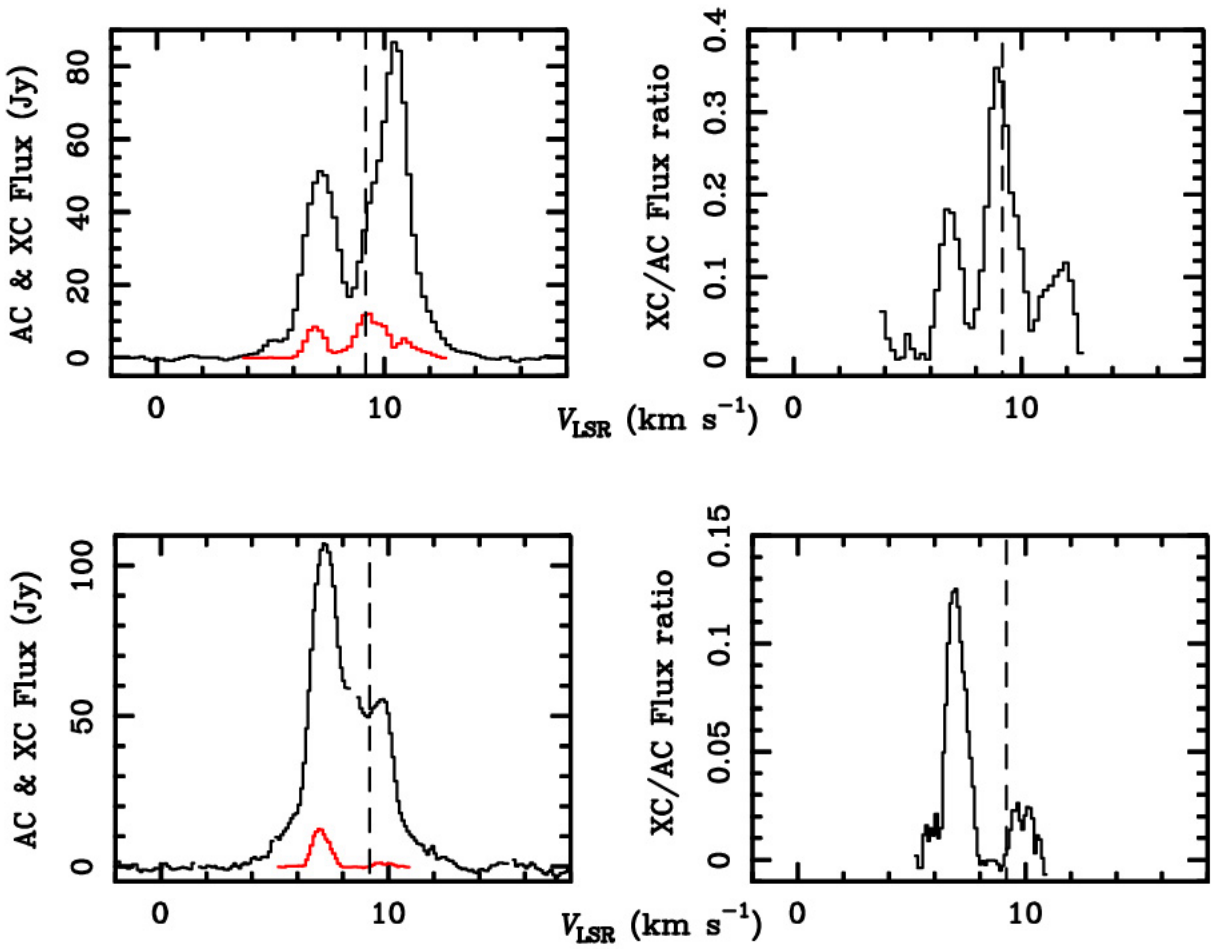
- High resolution maps of maser emission provide detailed information on processes occurring in circumstellar envelopes of AGB stars.
- A particularly detailed picture of the inner layers is provided by SiO masers.
- Multi-transition simultaneous observations of these masers are needed to better constrain the models.
- Maps of different maser transitions must be spatially aligned.
- Models are still unable to explain all their characteristics together (distribution, variability, etc). Much more work is needed!
- New generation instruments (VERA, VSOP-2), new observational techniques (frequency-phase transfer), and models will help solving the puzzle.

Thank you!

The missing flux problem

SiO v=1 J=1-0

SiO v=1 J=2-1



Soria-Ruiz et al. (2004)