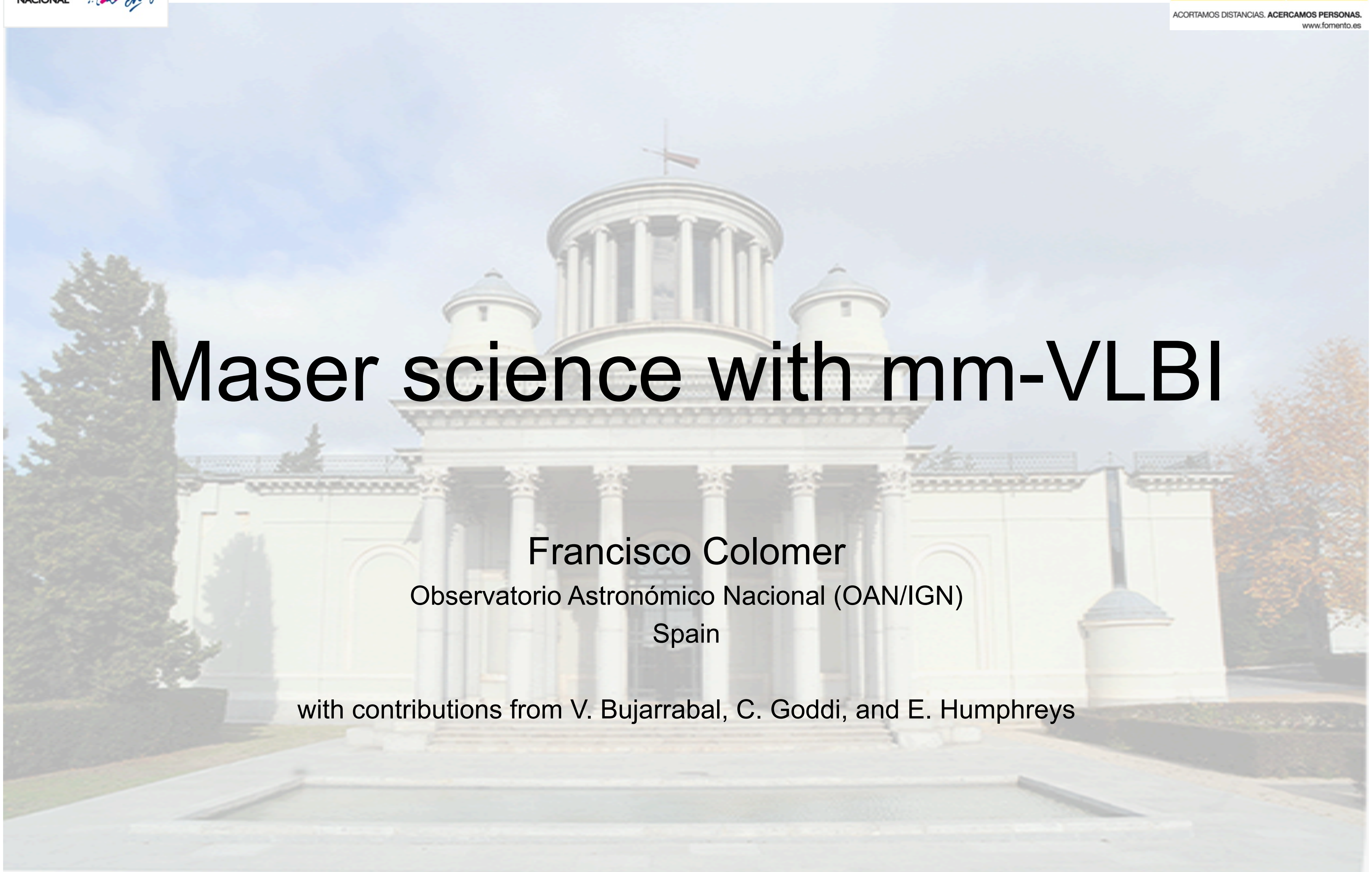

Maser science with mm-VLBI

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with contributions from V. Bujarrabal, C. Goddi, and E. Humphreys

Contents

- Introduction
- Masers in stars and star forming regions
- Masers in galaxies
- Masers as tools
- Summary

References:

-*"Future mmVLBI Research with ALMA: A European vision"*, by Tilanus et al. (2014, see http://arxiv.org/abs/1406.4650)

-*"High-angular-resolution and high-sensitivity science enabled by beamformed ALMA"*, by Fish et al. (2013, see http://arxiv.org/abs/1309.3519)

Masers at ALMA frequencies

- SiO (43, 86, 129, 210 GHz)
- H_2O (183, 321, 325, 439, 471 GHz)
- HCN (89 GHz)
- CH_3OH (> 44 GHz)

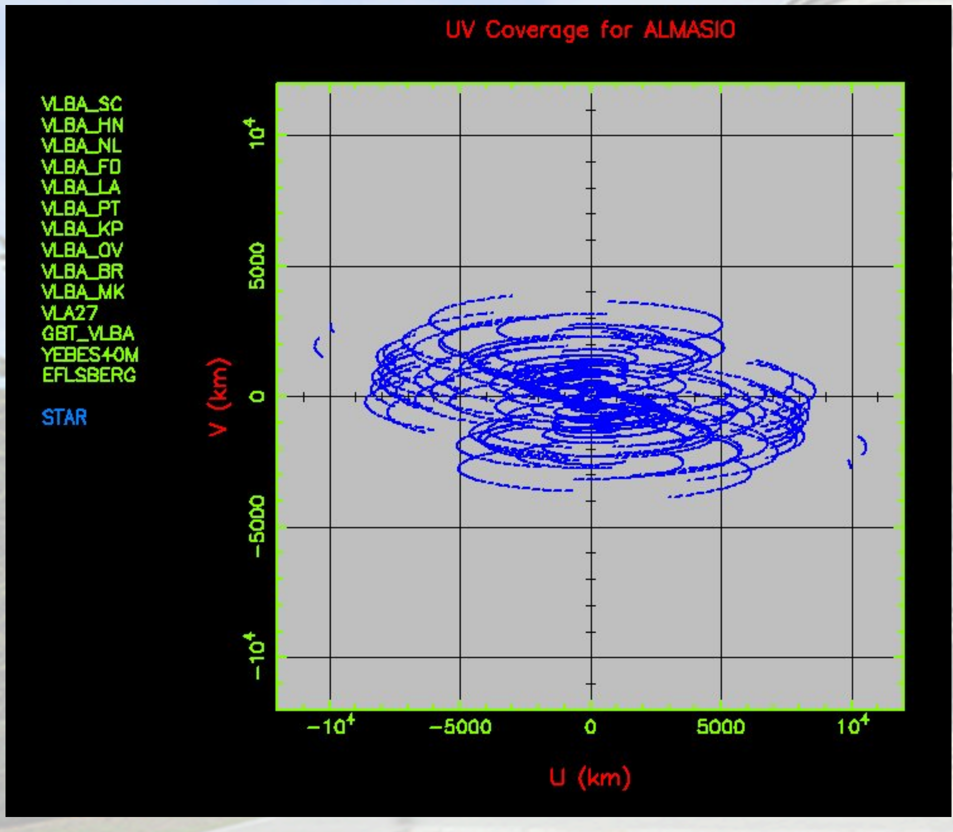
ALMA in a mm-VLBI array

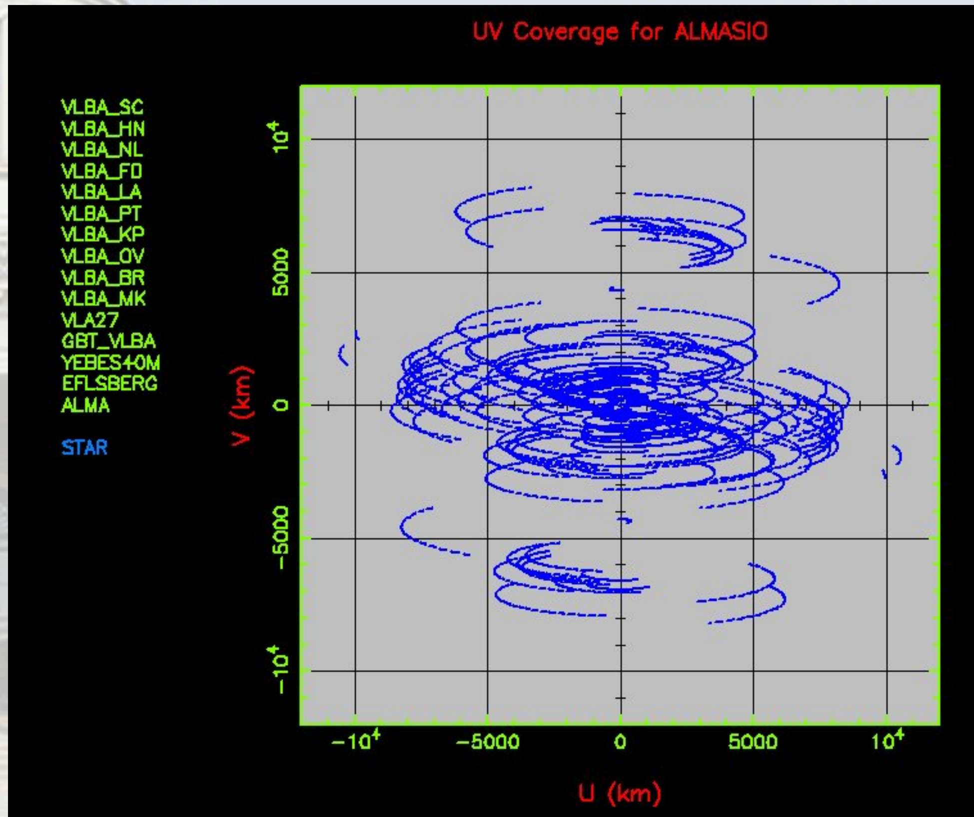
Instruments for masers at ALMA frequencies

- SiO (43, 86, 129, 210 GHz)
- H_2O (183, 321, 325, 439, 471 GHz)
- HCN (89 GHz)

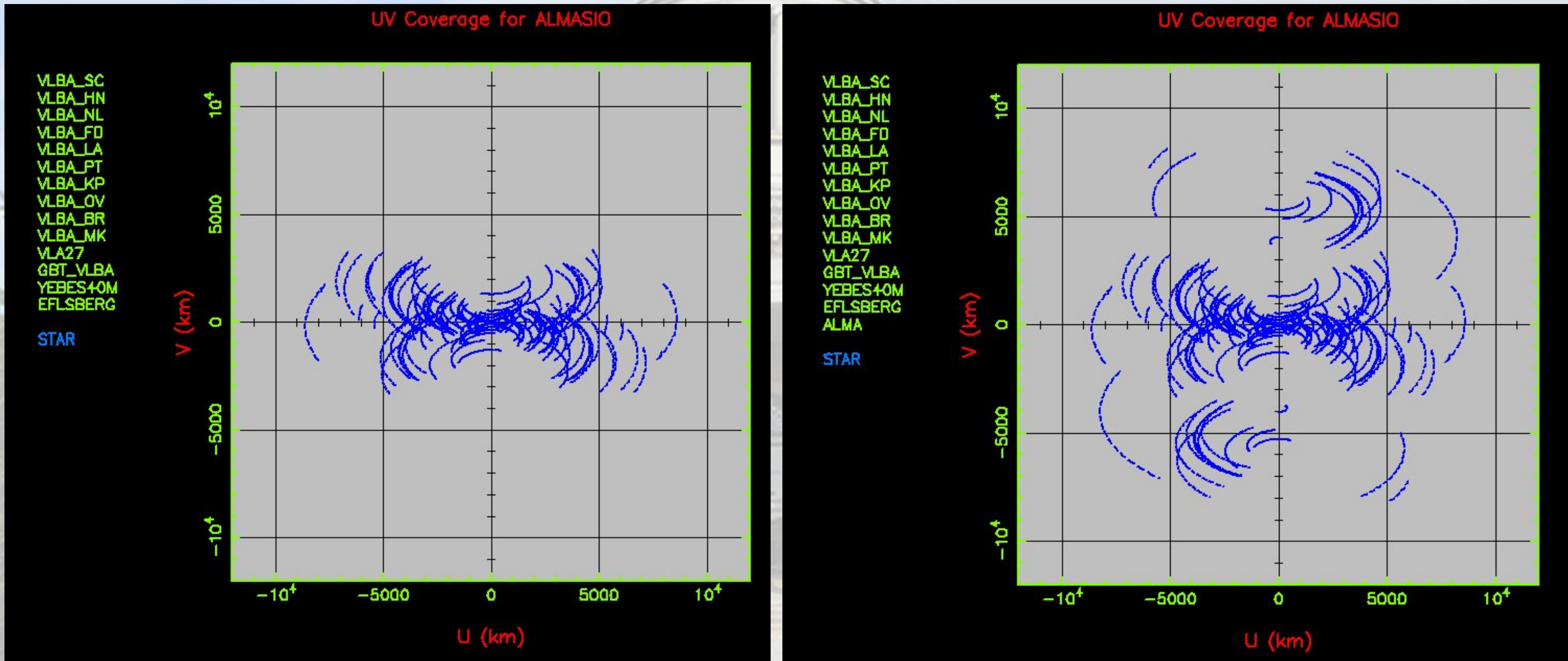
- 43/86 GHz: EVN, VLBA, VERA, GMVA, KVN
- 129 GHz: KVN, IRAM
- 215 GHz: IRAM, CARMA, SPT
- 183, 321, 325 GHz: IRAM, CSO, SMA
- 439, 471 GHz: CSO, SMA

uv coverage (δ=10º)

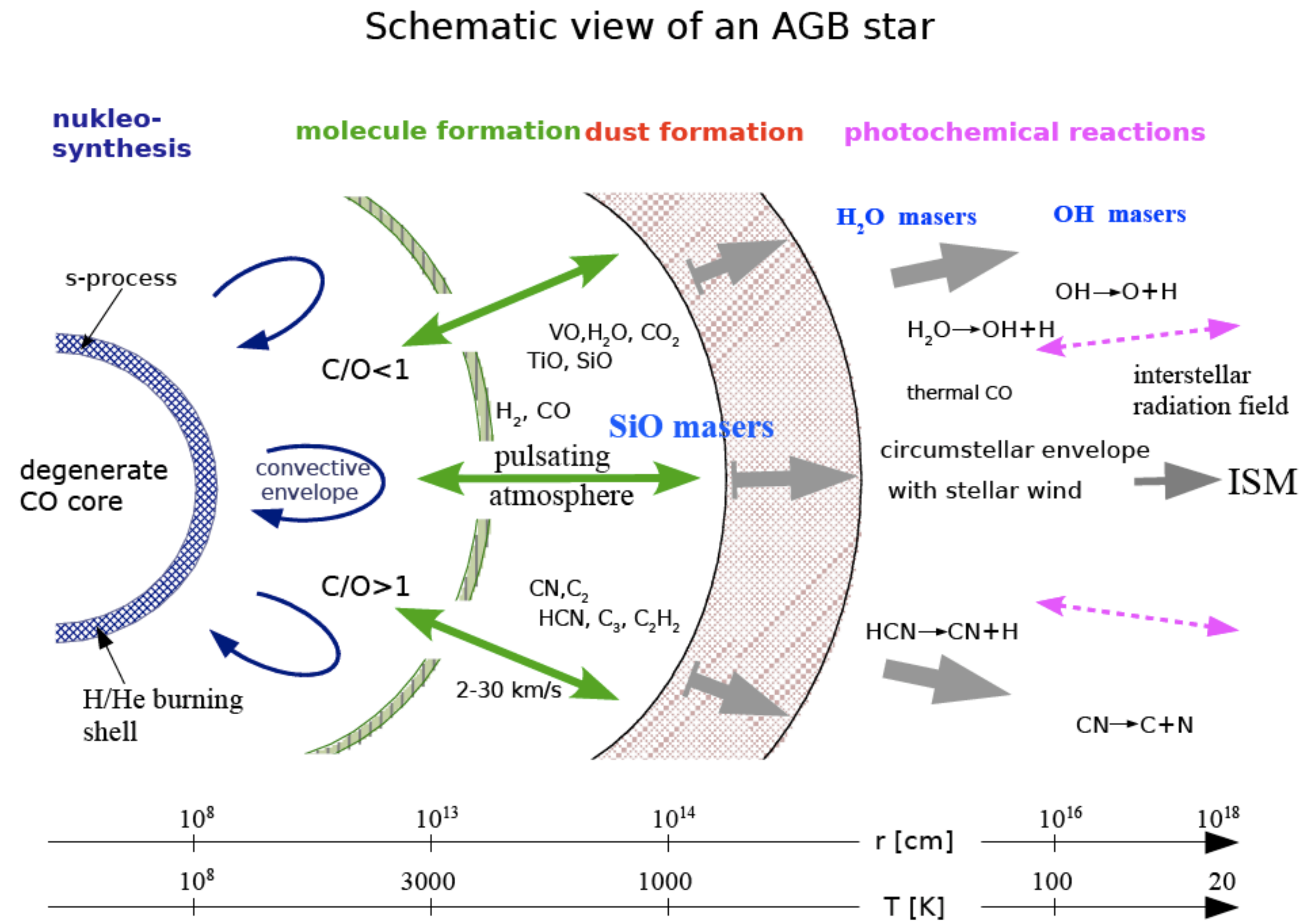


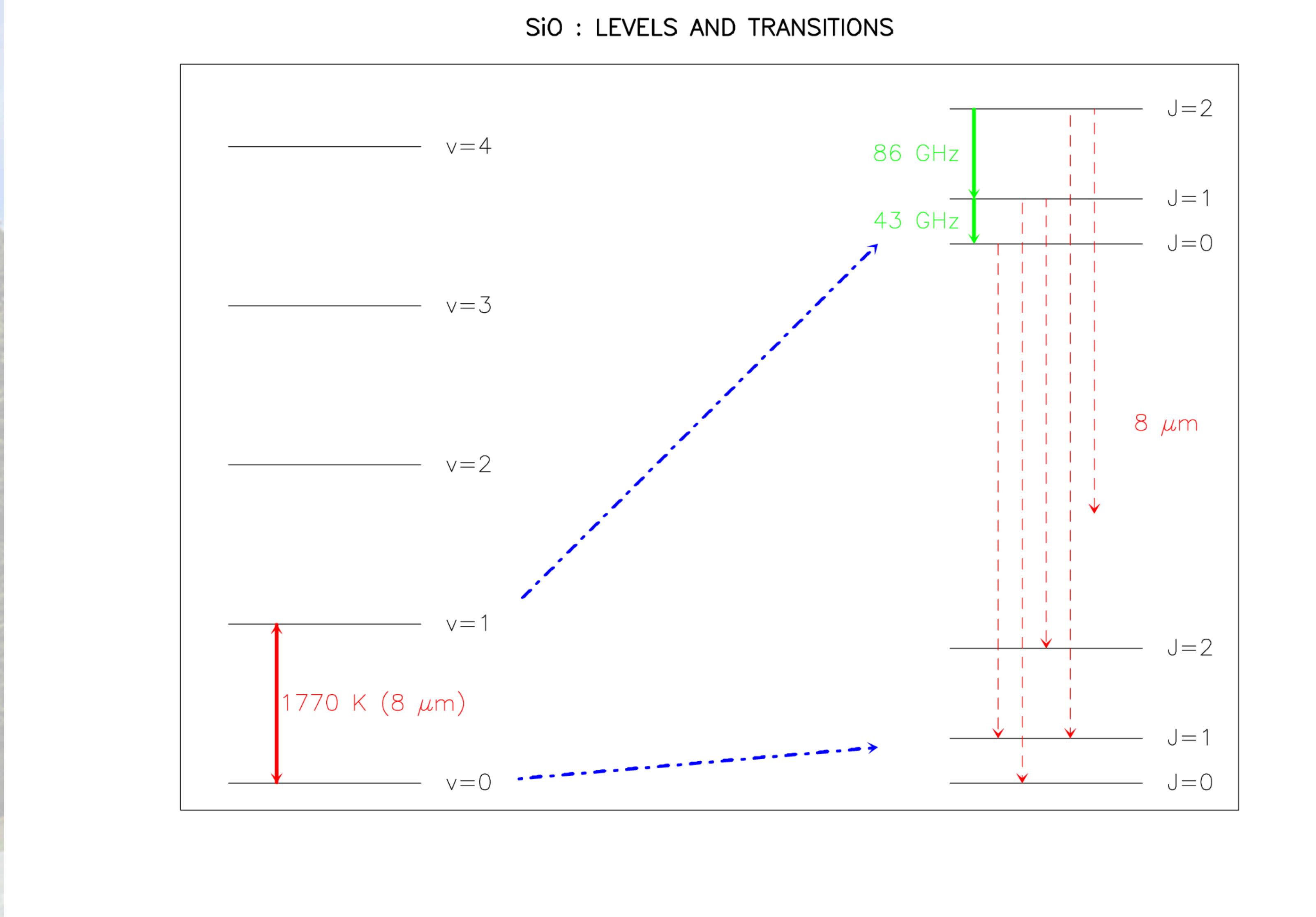


uv coverage (δ=-30º)



Masers in stars: evolved stars




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

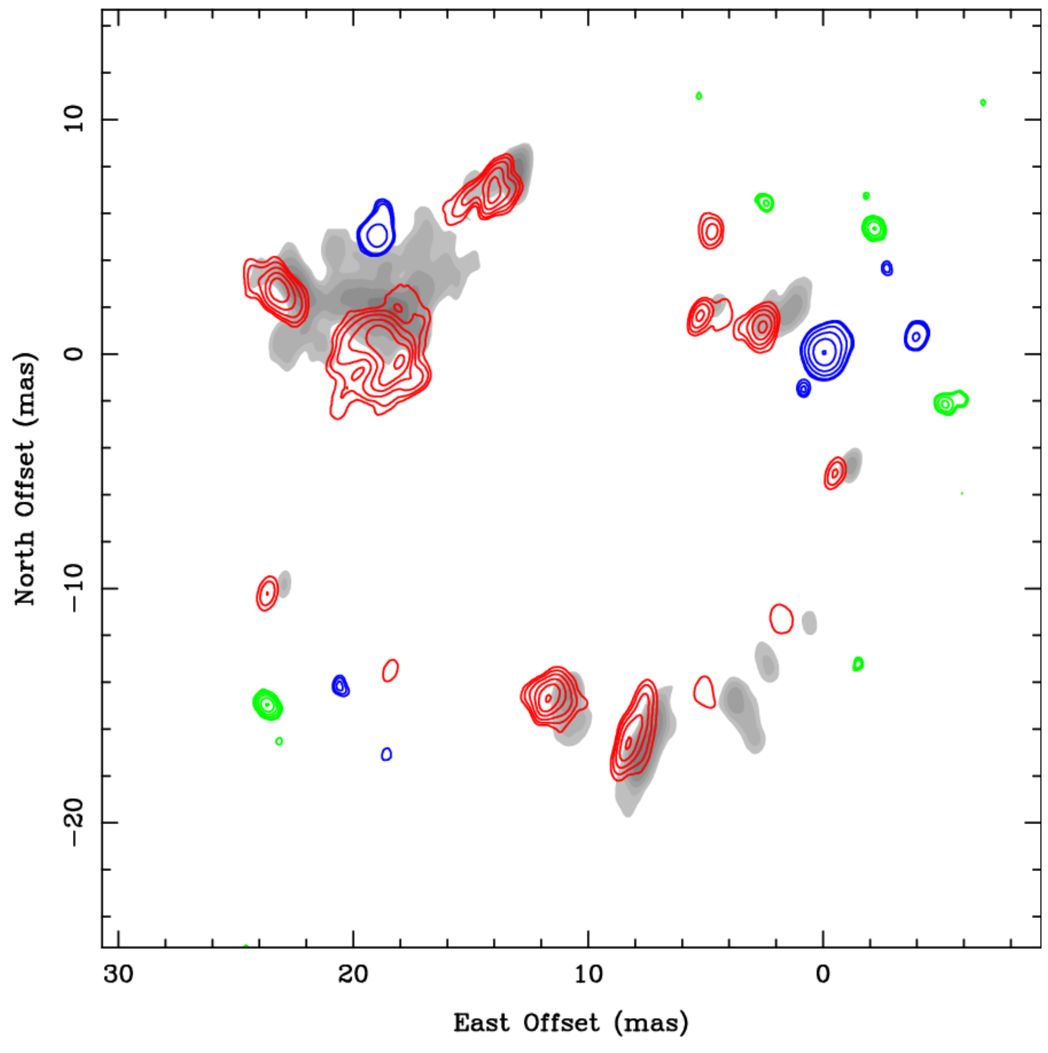
Observations of SiO maser emission

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

IRC+10011

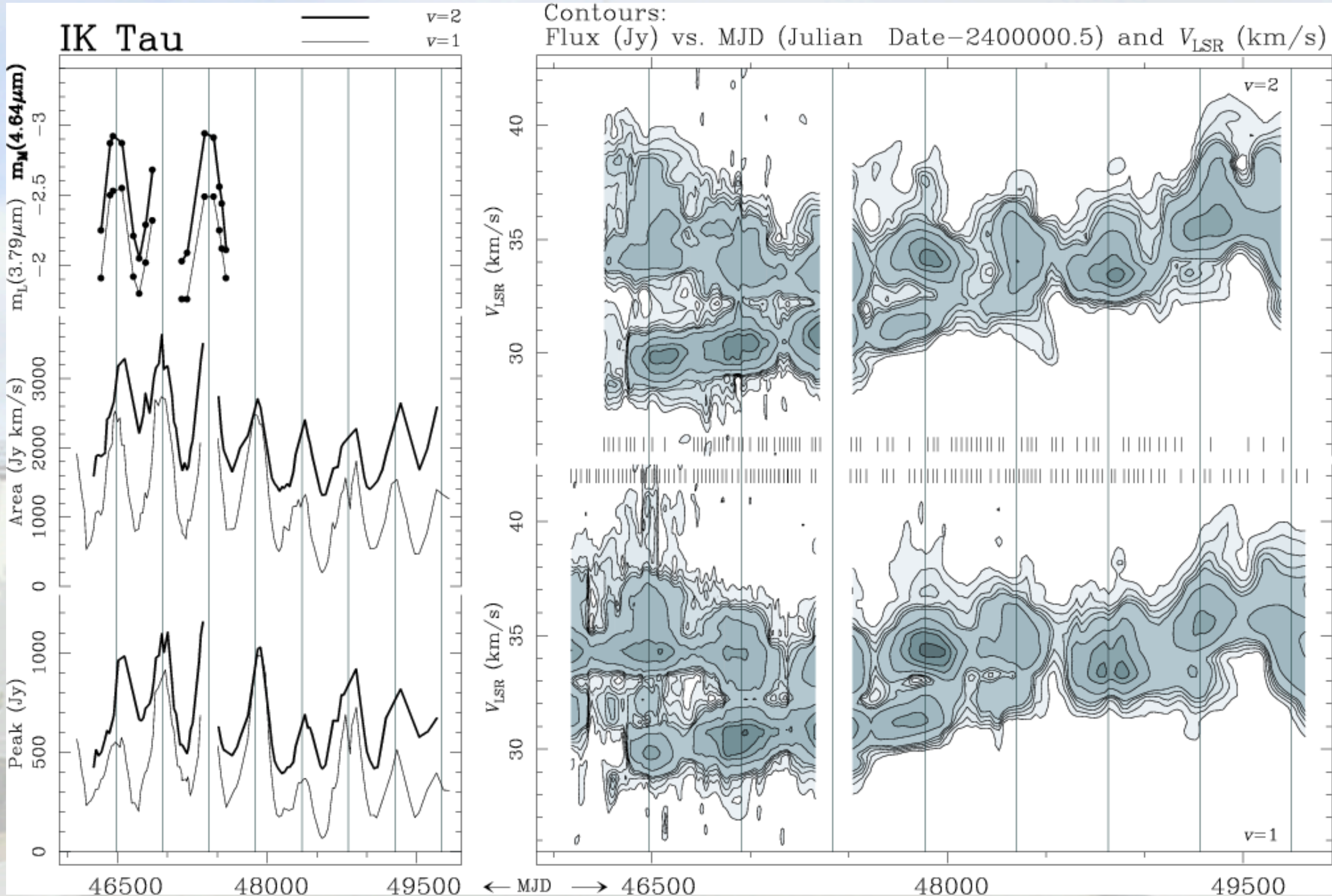
- Ring-like structure
- Clumpy distribution
- v=2 and v=1 J=1-0 are similar, with v=2 slightly smaller
- v=1 J=2-1 is larger

^{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)

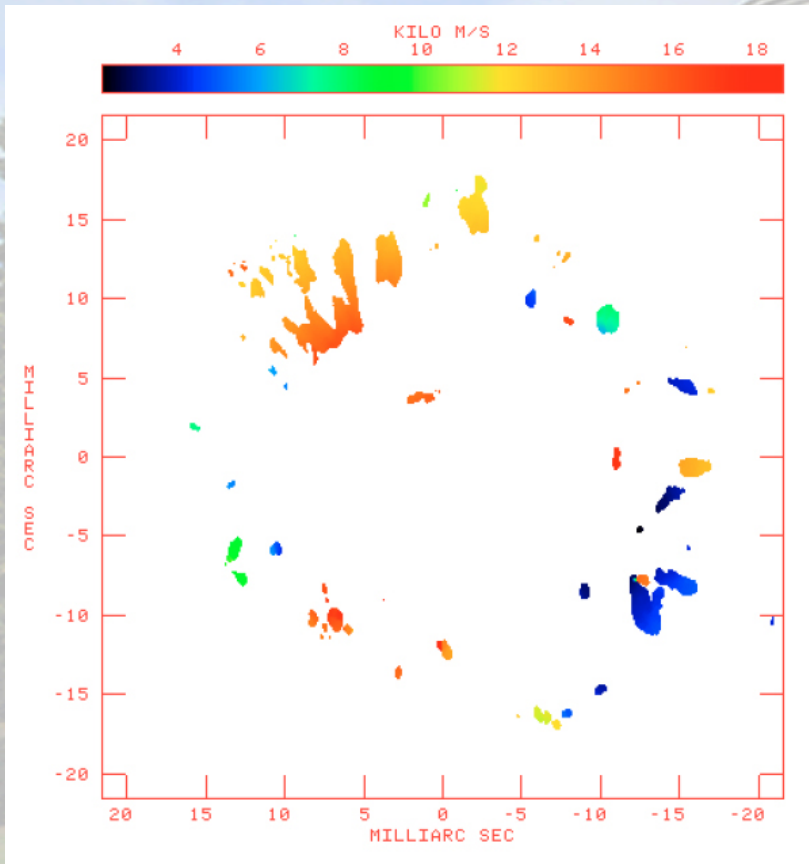
Time variability

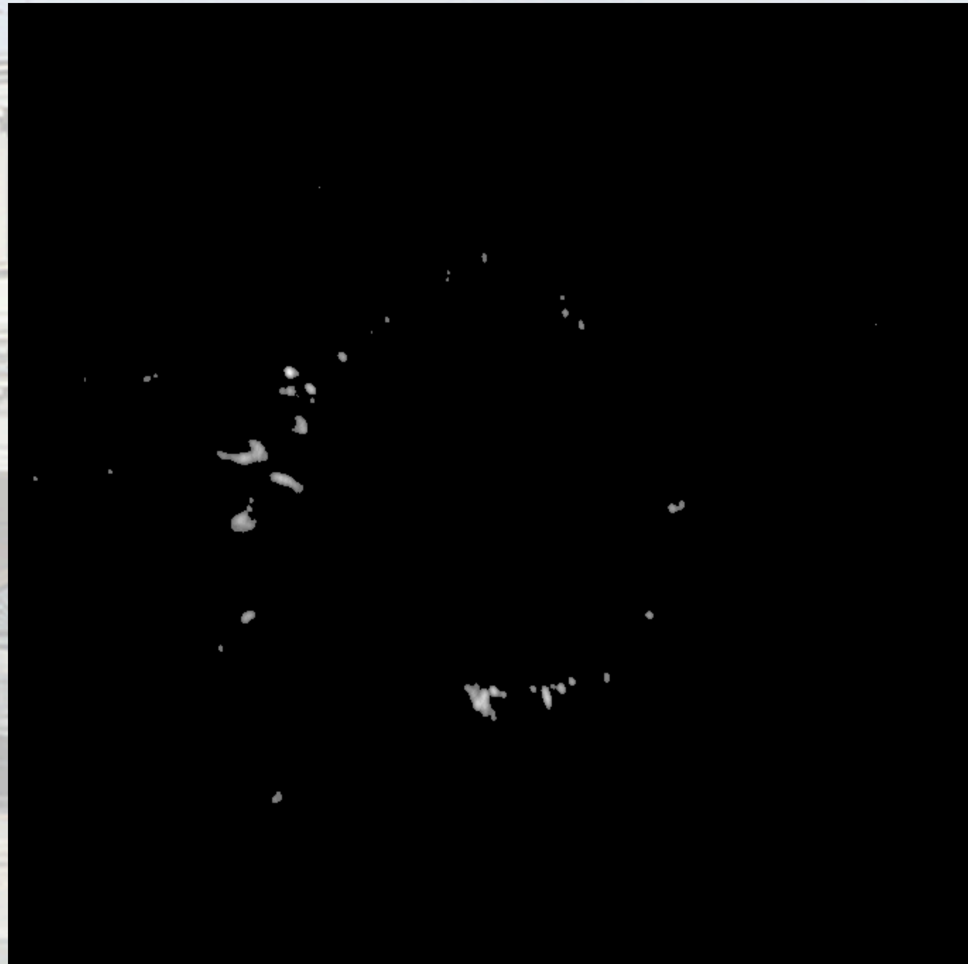


Pardo et al. (2004) A&A 424, 145

Kinematics

TX Cam

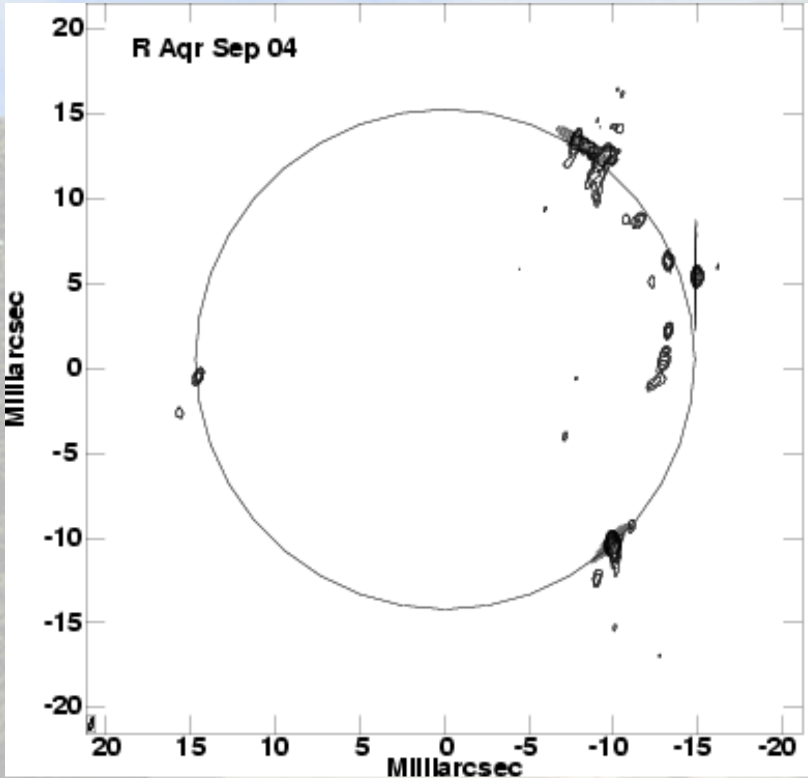


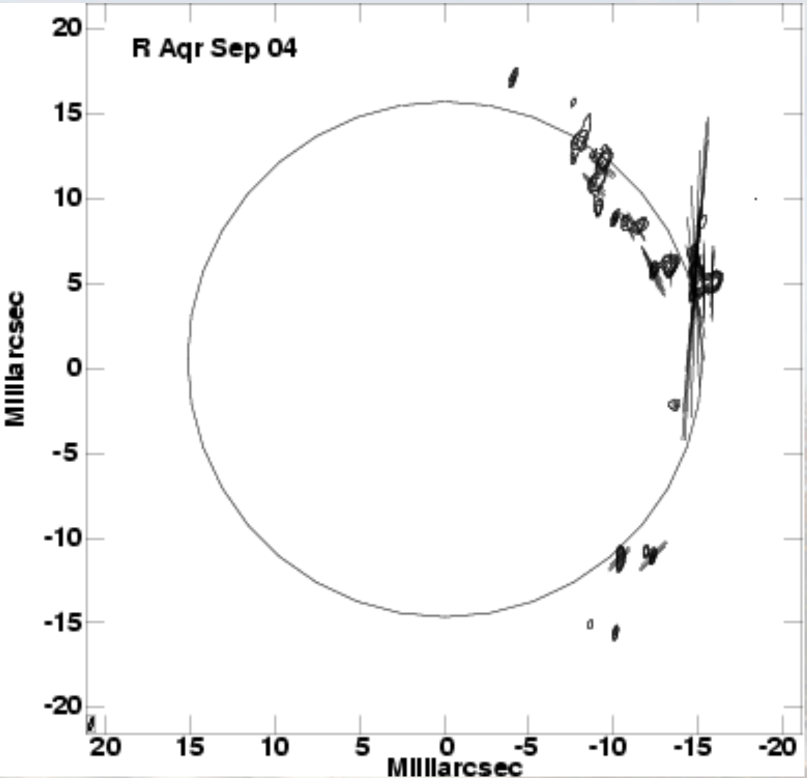


Yi et al. (2005)

Gonidakis, Diamond & Kemball (2008)

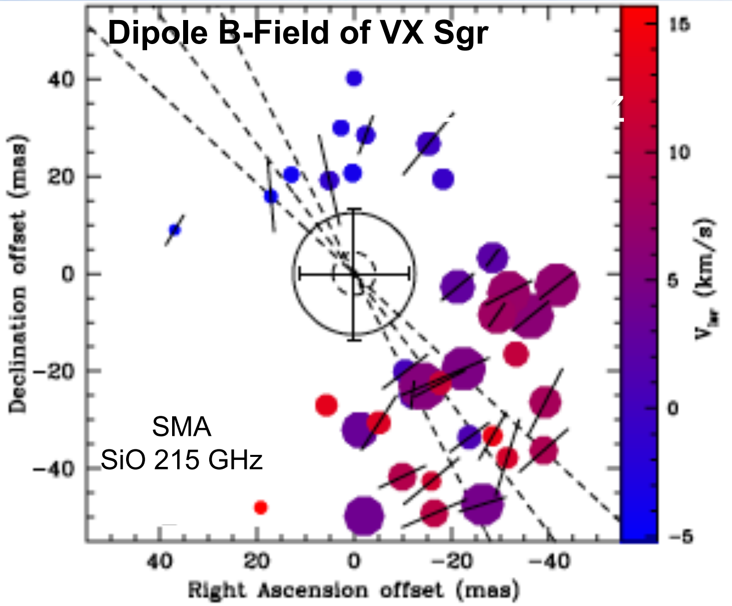
Polarization

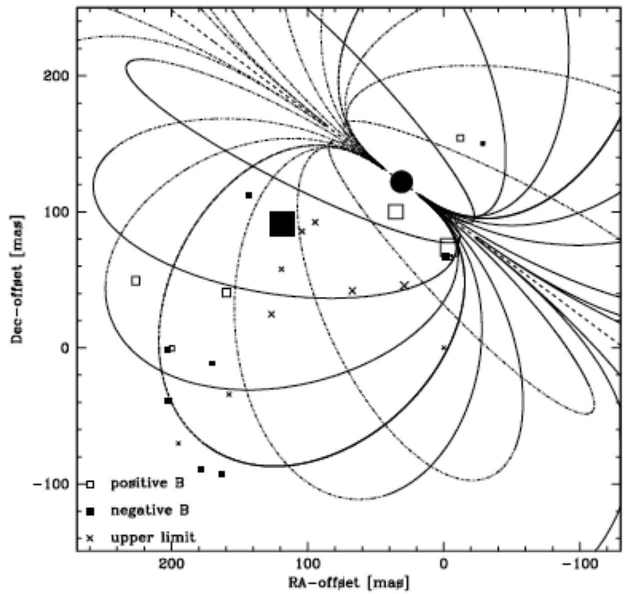




Cotton et al. (2006) A&A 456, 339; Cotton et al. (2004) A&A 414, 275

Magnetic Mapping of the Near Stellar Environment





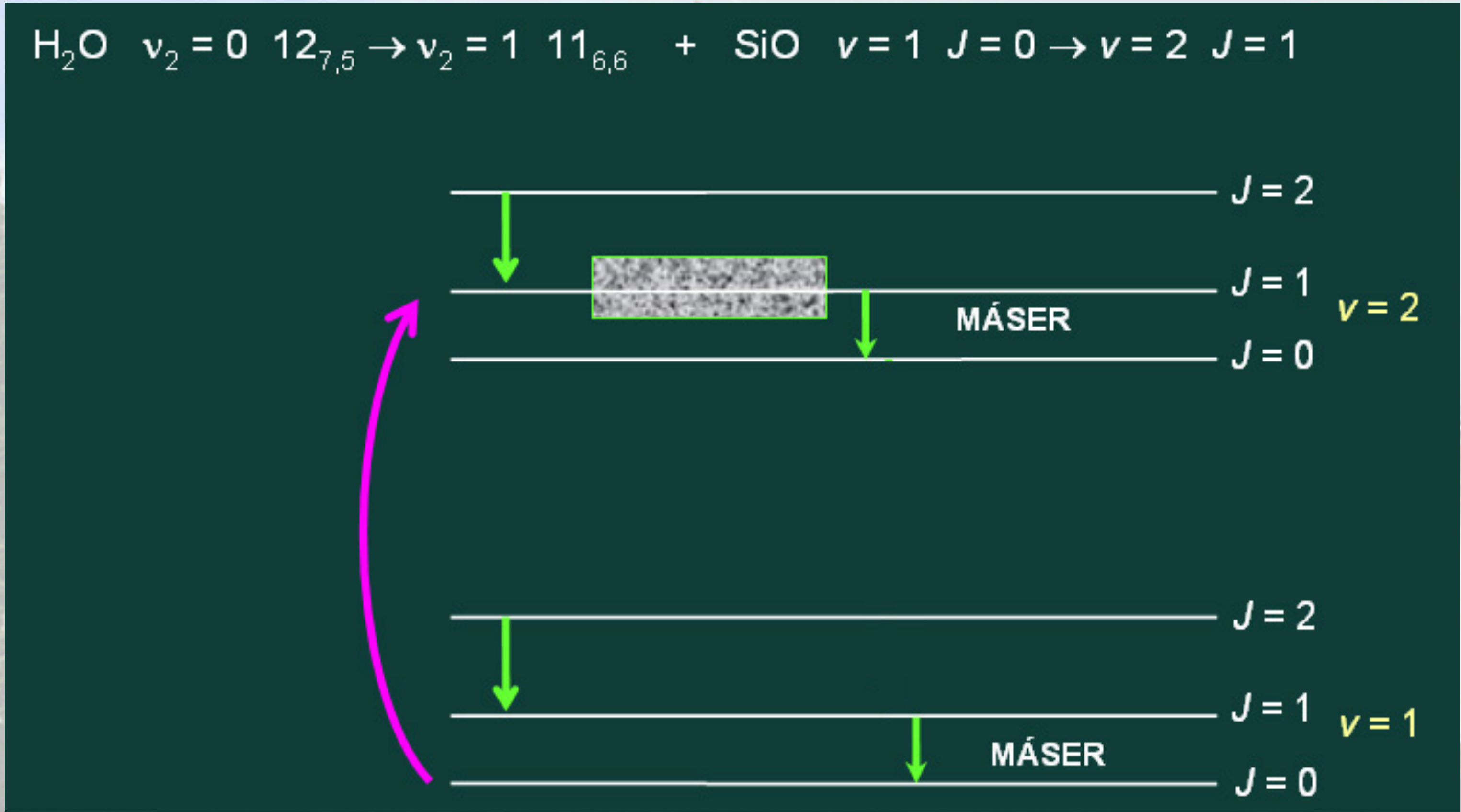
- Highly polarized (>20%) high-frequency SiO masers are good probes of B-field morphology within a few stellar radii
- With mmVLBI including phased ALMA it will be possible to map in detail the B-field on the smallest scales
- Via monitoring, it could be possible to trace magnetic ejections from evolved stars and determine their magnetic activity
- For C-rich stars, the 89 GHz HCN maser could be used

Vlemmings, van Langevelde & Diamond (2005)

Models of SiO maser emission

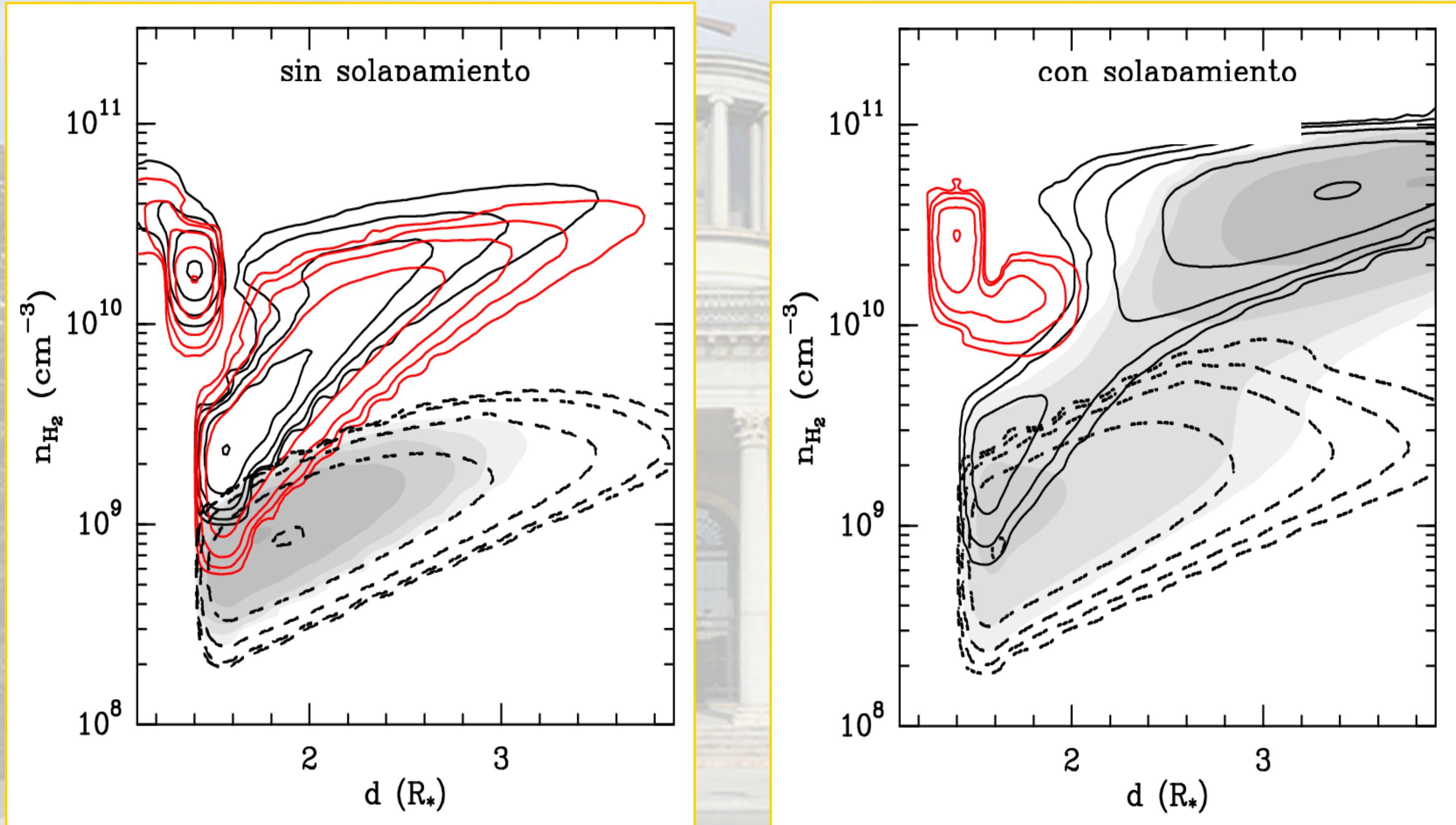
- Ring structure:
  - Explained by tangential amplification (eg. Bujarrabal & Nguyen-Q-Rieu 1981)
  - Peculiar v=2 J=2-1 SiO behaviour
- Time variability:
  - Correlation with IR pumping from the central star (eg. Pardo et al. 2004)
- Clumpiness:
  - Humphreys et al. (1996) MNRAS 282, 1359
  - Doel et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

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	———— (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.

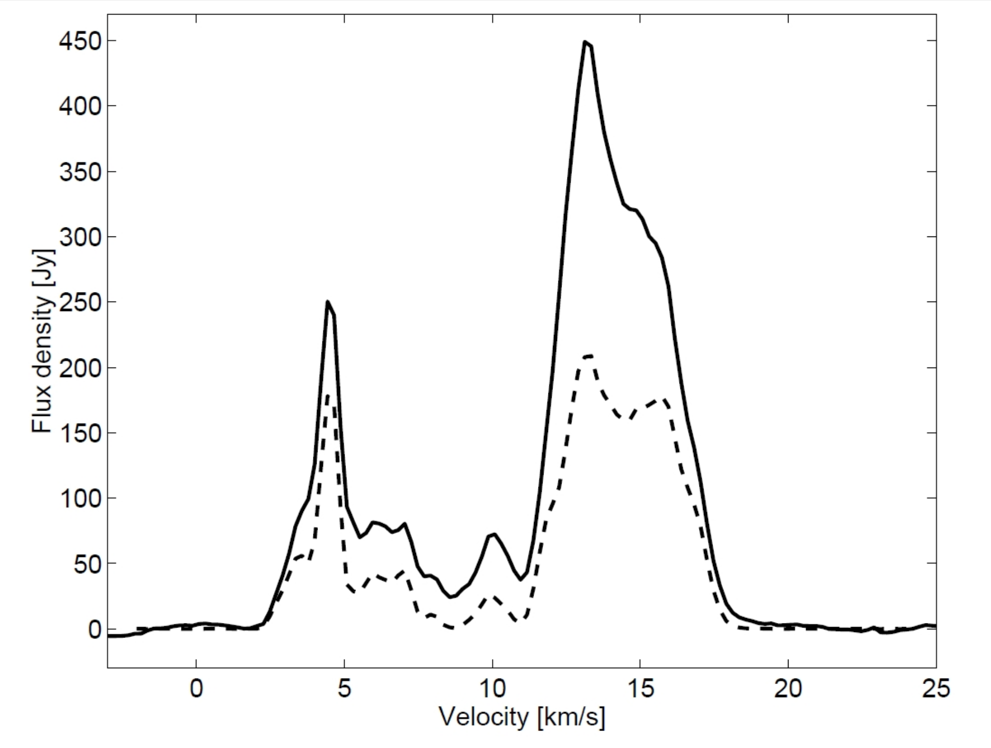
And it is important to relate these positions to the actual position of the central star!

ALMA in a mm-VLBI array for SiO masers in stars

- Study of several spectral lines simultaneously
- Alignment of SiO masers positions (by ALMA subarraying)
- Missing flux problem (ALMA sensitivity)
- Detection of stellar photosphere.
- Better uv coverage, and access to the Southern hemisphere.

The missing flux problem

Yi et al. (2005)



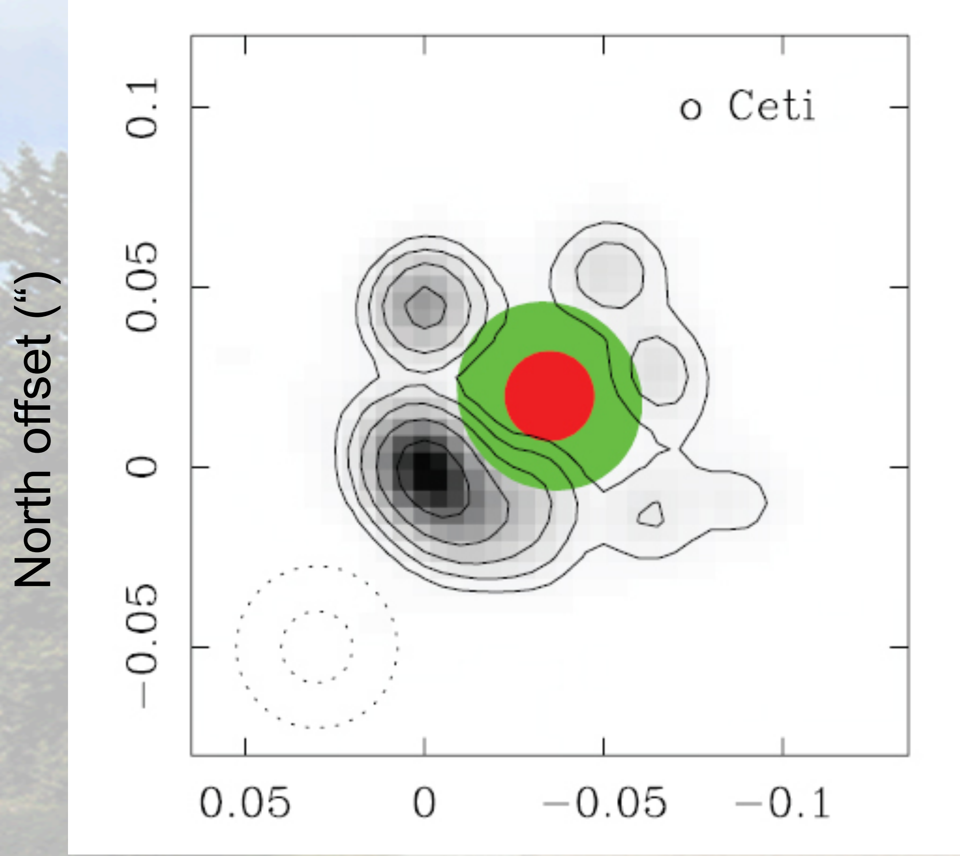
Large difference between SiO masers total flux (solid line) and crosscorrelated flux (dashed line).

Is there an extended emission which is resolved by VLBI?

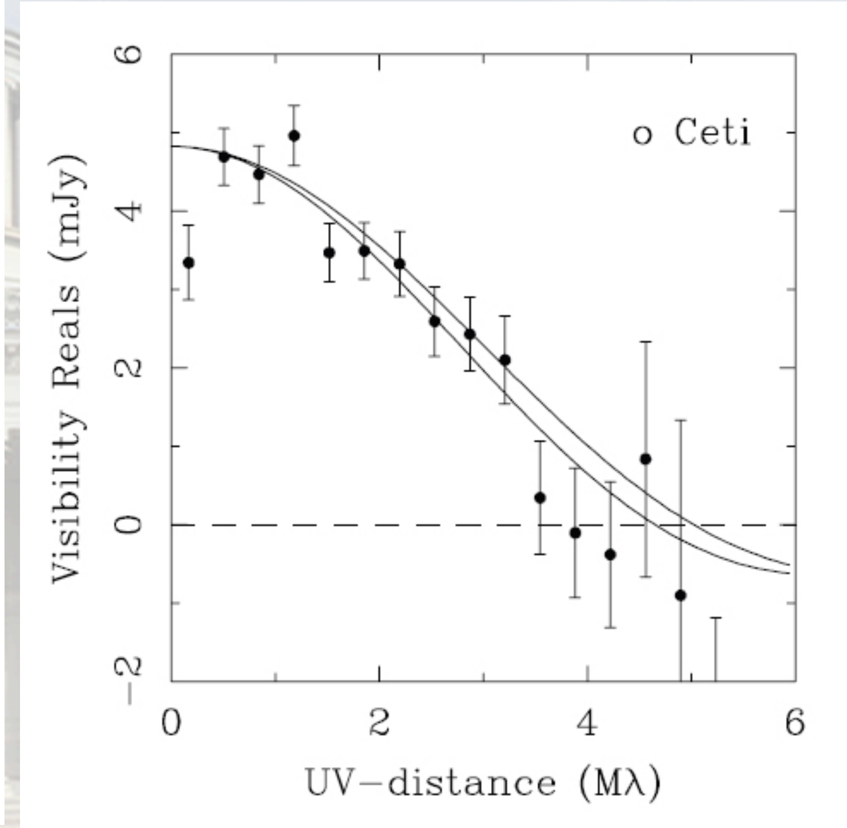
- Many small and weak spots?
- Extended weak emission?

ALMA-VLBI may give the answer !

Imaging the photosphere!



East offset (")



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

Reid & Menten (2007) ApJ 671, 2068

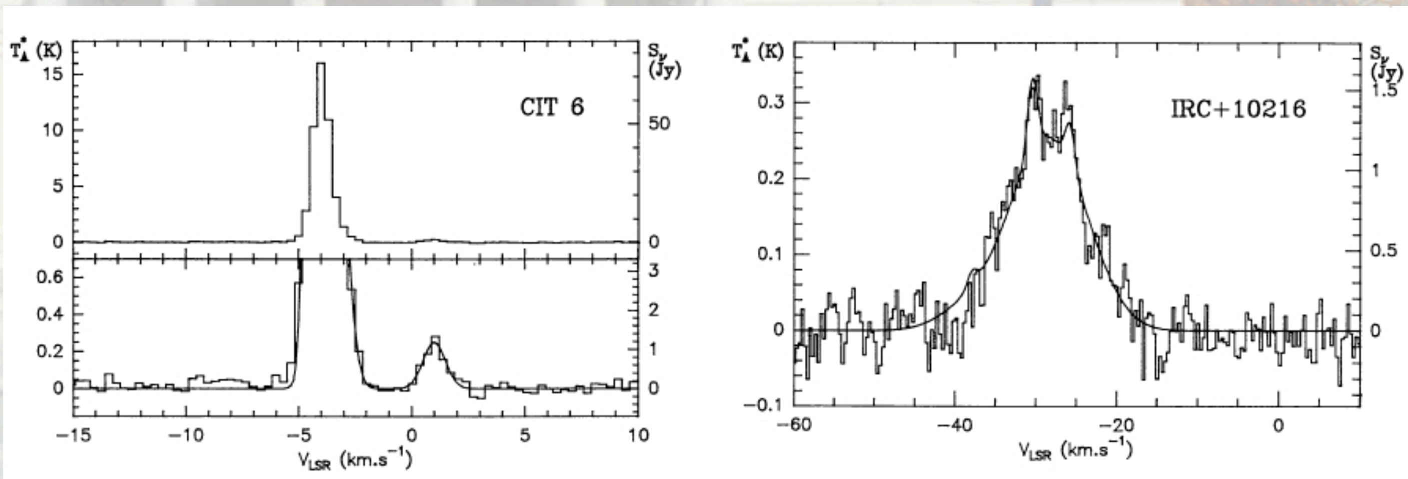
Observations of water maser emission in late-type stars

(see next talk by Anita Richards)

Other masers: HCN (in C-rich stars)

- Detected in just a few sources (< 10)
- **Ground state (000) J=1–0 (@ 89 GHz)** masers of HCN & $H^{13}CN$
- Vibrationally excited masers of HCN:
  $(02^{0}0)$ J=1–0 **(@ 89 GHz)**
  $(01^{1c}0)$ J=2–1 **(@ 178 GHz)**
  $(04^{0}0)$ J=9–8 (@ 805 GHz)
- No VLBI maps yet.

Refs: Izumiura et al. (1985), Guilloteau et al. (1987), Lucas & Cernicharo (1989), Schilke & Menten (2003), Smith et al (2014), and references therein.



Why submm molecular masers in **SFRs**?

- Where different maser transitions trace the same gas, we can place **new constraints on radiative transfer models** to determine temperature and density maps of the circumstellar gas with high spatial resolution

  => e.g. the cm/mm H_2O line ratios can be valuable diagnostics for shocked material in protostellar outflows.

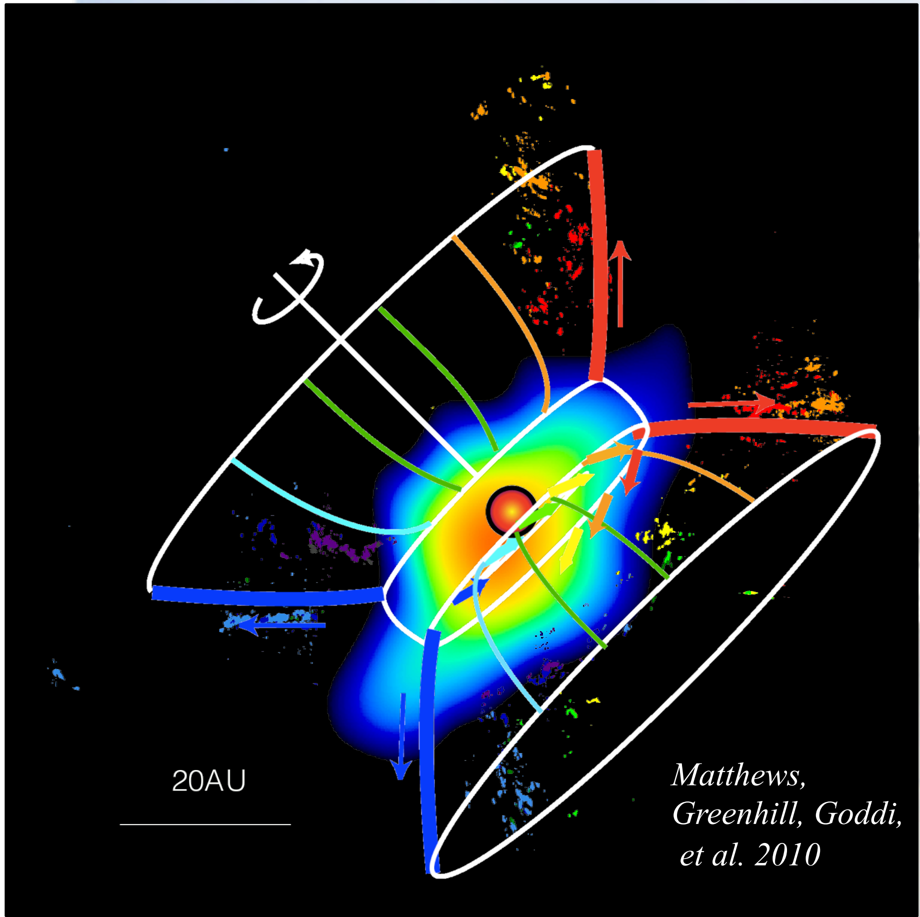
- Where **maser lines probe different portions of circumstellar gas** and/or different scales, we can map out more of source structures, dynamics, and physical conditions than just with cm lines.

- Submm masers could be particularly important probes of regions in which longer λ maser emission is **subject to obscuration** (e.g., free-free or synchrotron opacity).

- To understand the **physics** of the excitation of submm water maser transitions.

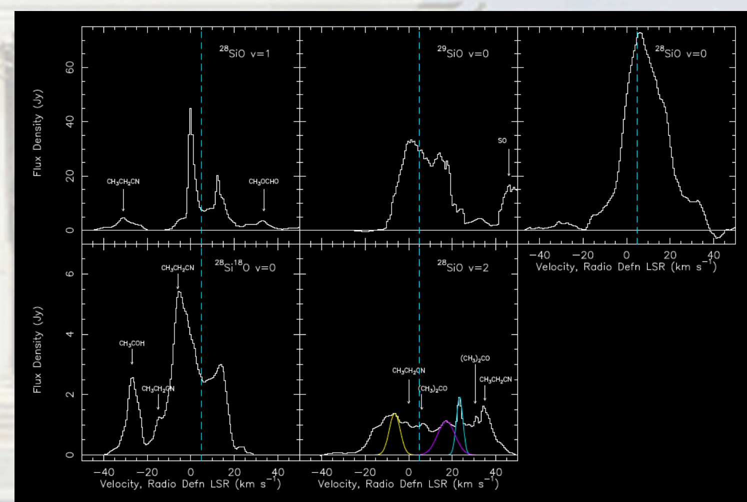
- For **calibration** and commissioning purposes of new submm arrays, as the maser sources with bright narrowband point emission provide excellent targets for assessment of the delays, pointing, baselines as well as strong phase calibrators

Unveiling the powering source of Orion BN/KL



mm-VLBI can :

- Establish maser nature of high-J lines
- Constrain radiative transfer models to make T/dens. maps
- Probe closer gas to YSO, i.e. R<15 AU



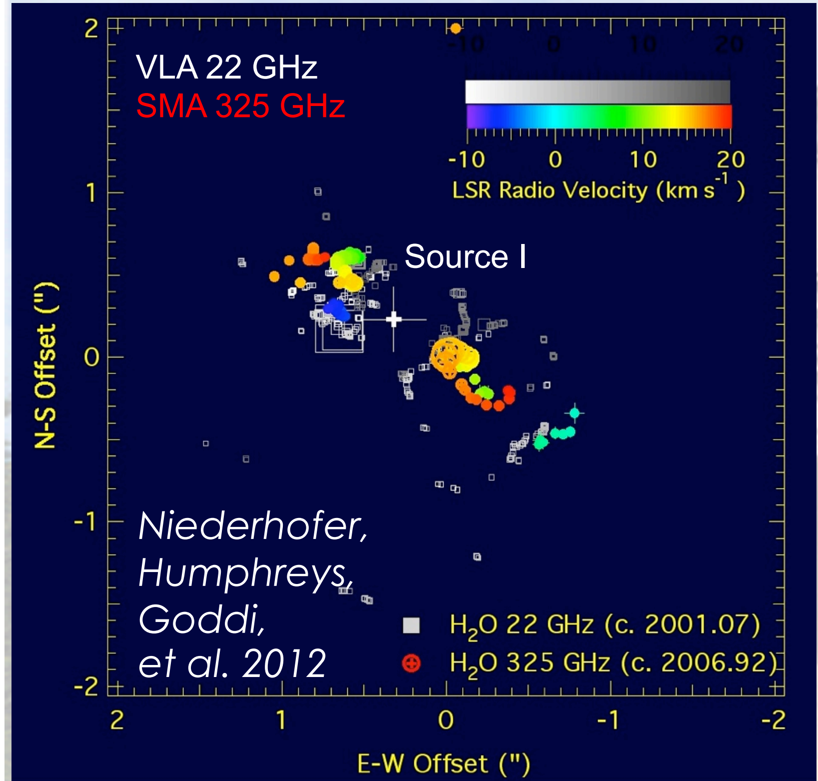
ALMA Cycle 0 Band 6
J=5-4 **SiO** lines
(~220 GHz)

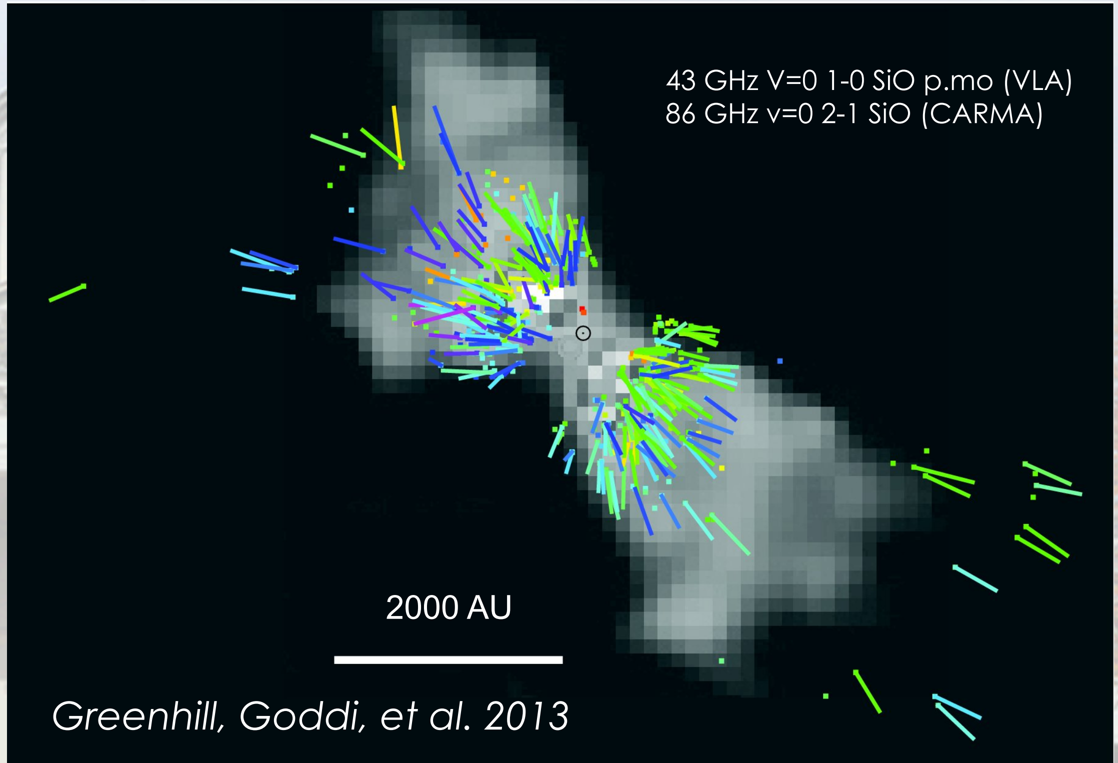
Niederhofer, Humphreys, Goddi 2012

- SiO emission at R=15-70 AU
- No SiO emission *in* the disk midplane

Our best chance to resolve the root of a disk/jet system in a YSO !!

Gas dynamics and physical conditions in massive protostellar outflows (183, 321, 325, 690 GHz H_2O masers)



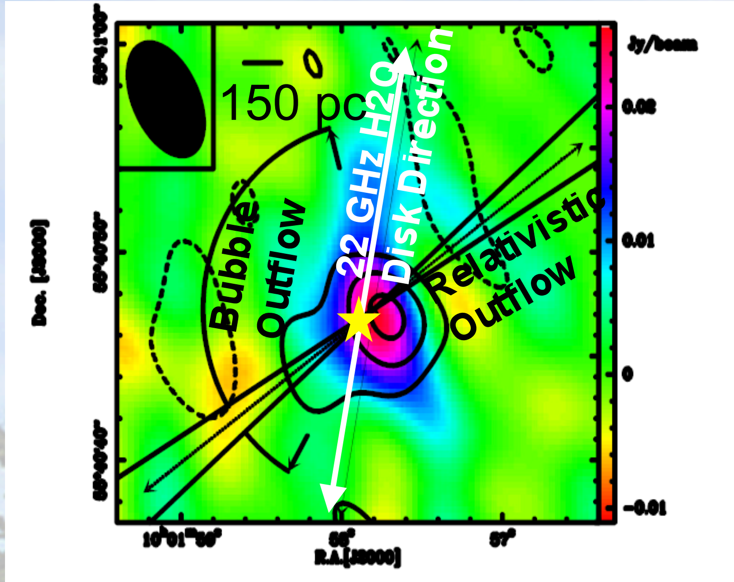


- The 325 GHz H_2O masers trace same bipolar outflow as the 22 GHz but a more collimated flow
- Strong correspondence of 22 and 325 GHz emission along the outflow
- *Can mmVLBI probe the "primary wind" along jet axis rather than entrained material ?*

mmVLBI can measure proper motions of masers < 0.1 mas/yr (< 2 km/s at d > 5 kpc) over 1 month

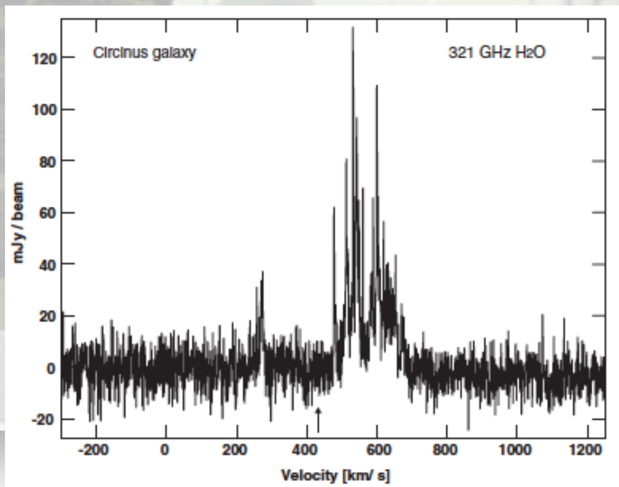
Megamasers for testing the Unified Model in AGN

NGC 3079: 183 GHz Maser



0.5 Jy; Humphreys et al. (2005)

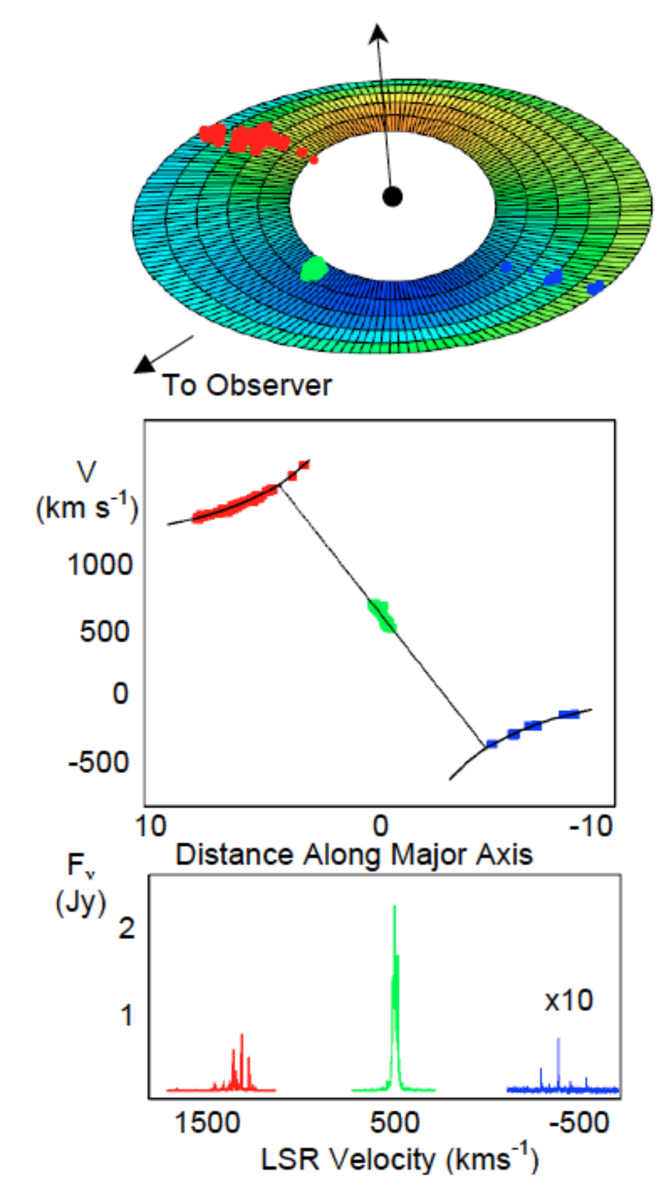
Circinus: 321 GHz Maser



Hagiwara et al. (2013)

- Extragalactic 22 GHz water masers are found in a number of environments including AGN and starburst galaxies
- Masers currently provide **the only way to map** the structure of circumnuclear accretion disks within a parsec of AGN supermassive black holes
- In local AGN (D < 30 pc), mmVLBI maser observations can be used to test the AGN unified model (e.g. is there a need for a torus) and AGN central engine physics

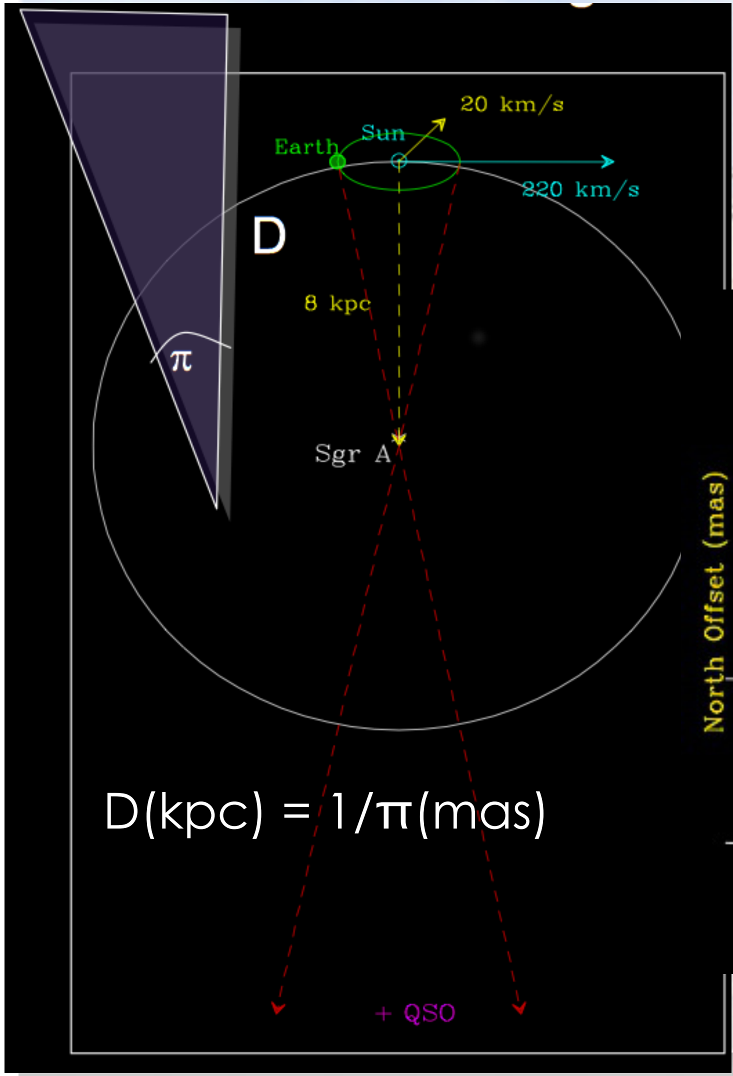
Maser cosmology and determination of H_0



Humphreys et al. (2013)

- For distant AGN (> 50 Mpc), water maser geometric distances can yield a high accuracy H_0 and constrain Dark Energy
- Outstanding issues remain using 22 GHz water masers. Portions of the maser disks may be obscured by ionized material at 22 GHz
- **Need stronger/unobscured masers** for cosmology using more distant galaxies
- With some redshift, arguably more promising masers can become shifted to lines at 183, 321 GHz and 325 GHz bands

Masers as tools: measuring distances

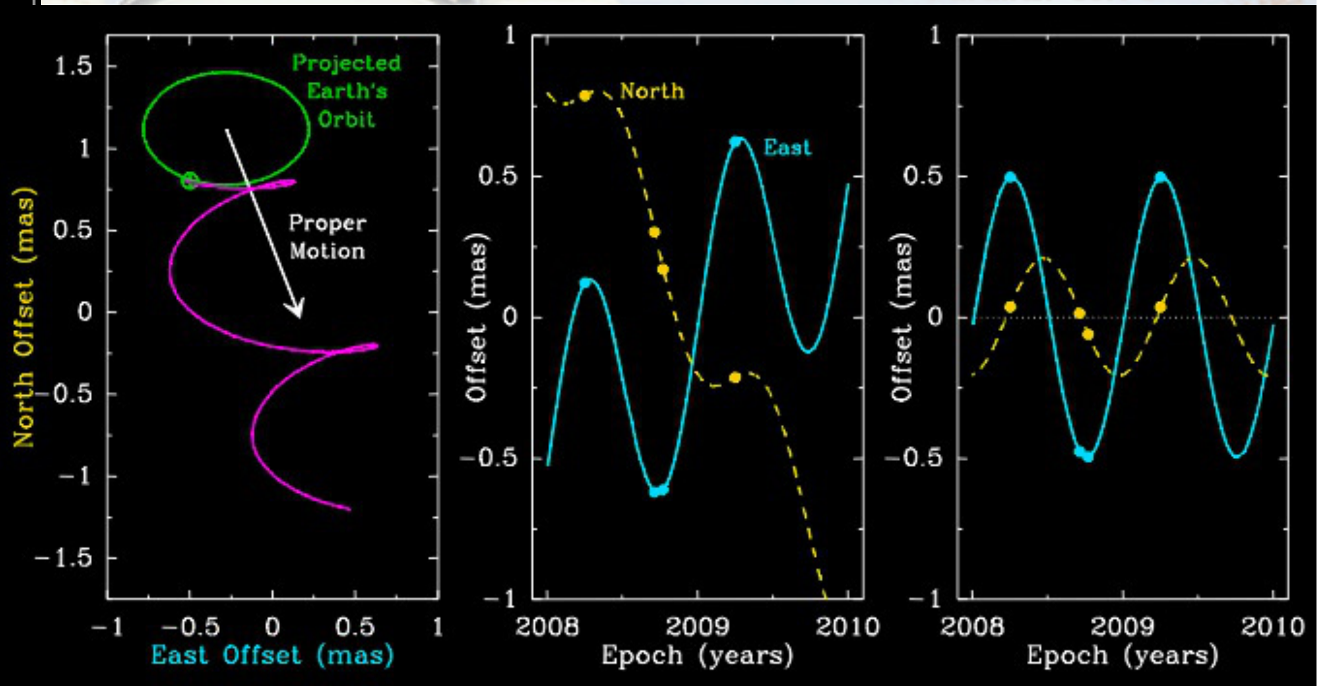


Trigonometric parallax : triangulation using Earth's orbit as one side of the triangle

Sky projected motion
- Curlicues on sky -

Position offsets vs. **time**
- North & East directions -

Position offsets vs. **time**
(with removed Galactic proper motion)
- Parallax curve -



ALMA in a VLBI array (I)

- High resolution maps of maser emission provide detailed information on processes occurring in SFRs and circumstellar envelopes of AGB stars.
- Multi-transition simultaneous and aligned observations of these masers are needed to better constrain the models.
- VLBI maps show typically 10 – 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.

ALMA in a VLBI array (II)

Advantages of participation of phased-ALMA in a mm-VLBI array for masers:

- Much enhanced sensitivity (missing flux)
- Sub-arraying (for map alignment, multifrequency)
- Access to southern hemisphere sources

Thank you !

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