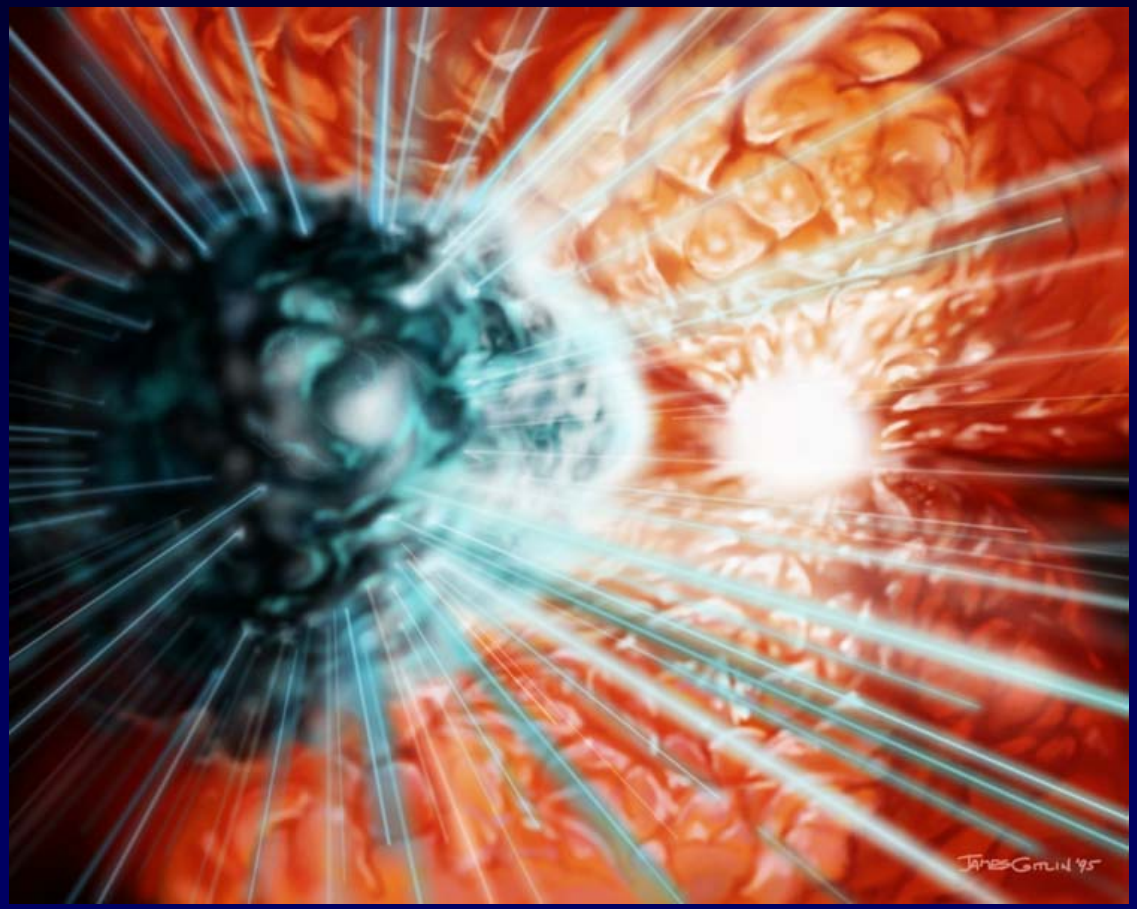
USNO

VLBI Studies of Circumstellar Masers

Dave Boboltz (USNO)



- Maser Basics
- Recent Results
- Future Directions

UV lasers from APOD
credit: J. Gitlin, STScI

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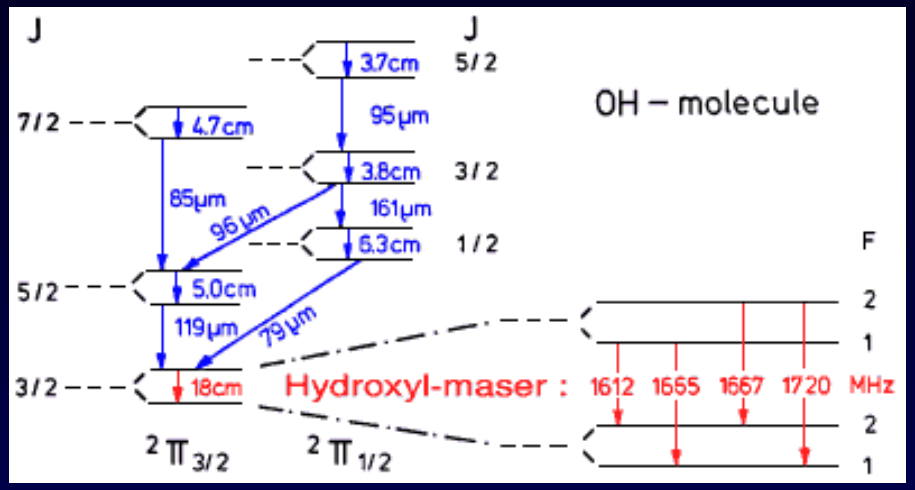
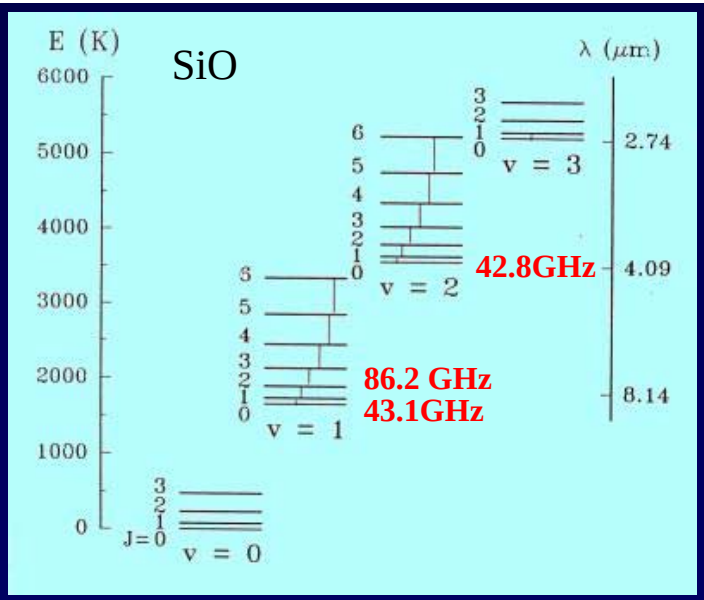
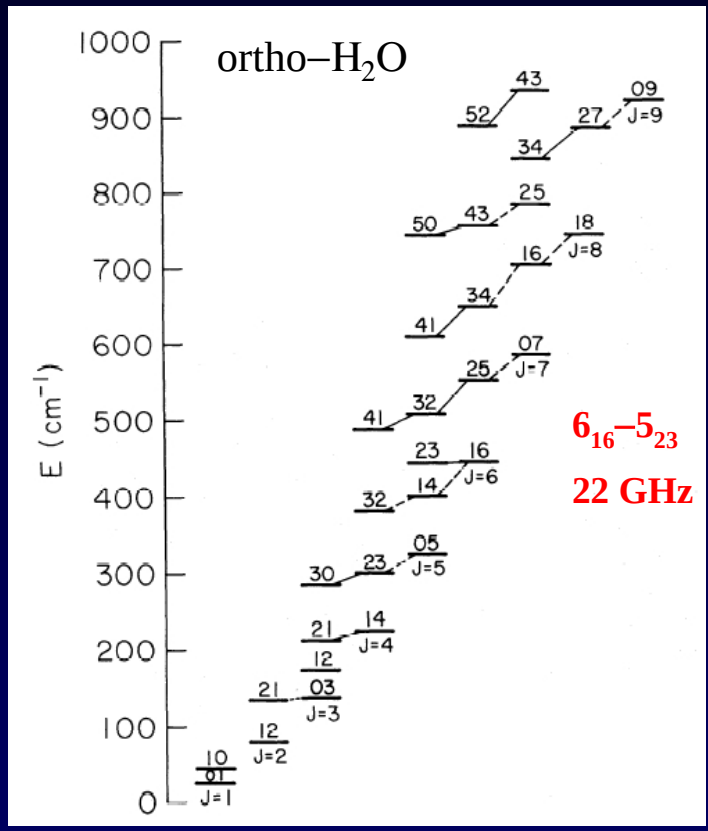
Maser Transitions: OH, H_2O & SiO

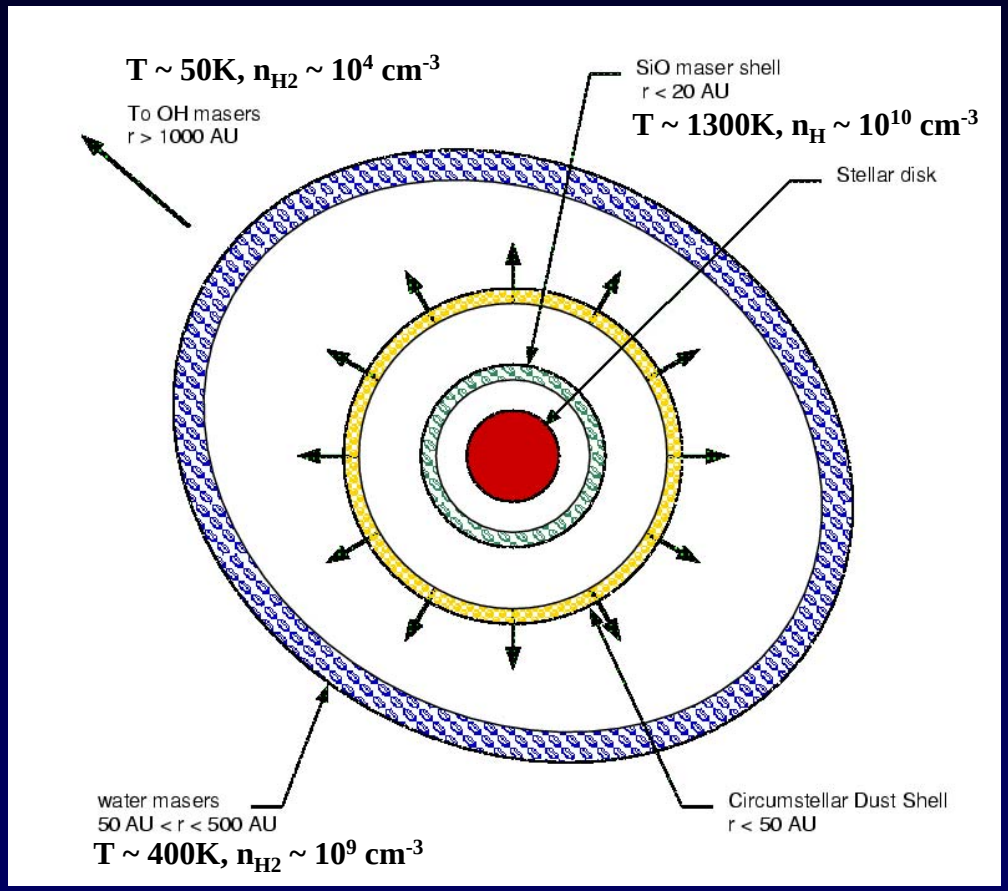






Where are the Circumstellar Masers Located?

- Circumstellar Envelopes (CSE) of Asymptotic Giant Branch (AGB) Stars.
  - Miras, Semi-regular Variables, Supergiants, OH/IR Stars, Proto-planetary Nebulae (PPN).
- Various maser species typically found at increasing distances from the stellar surface SiO, H_2O, OH.

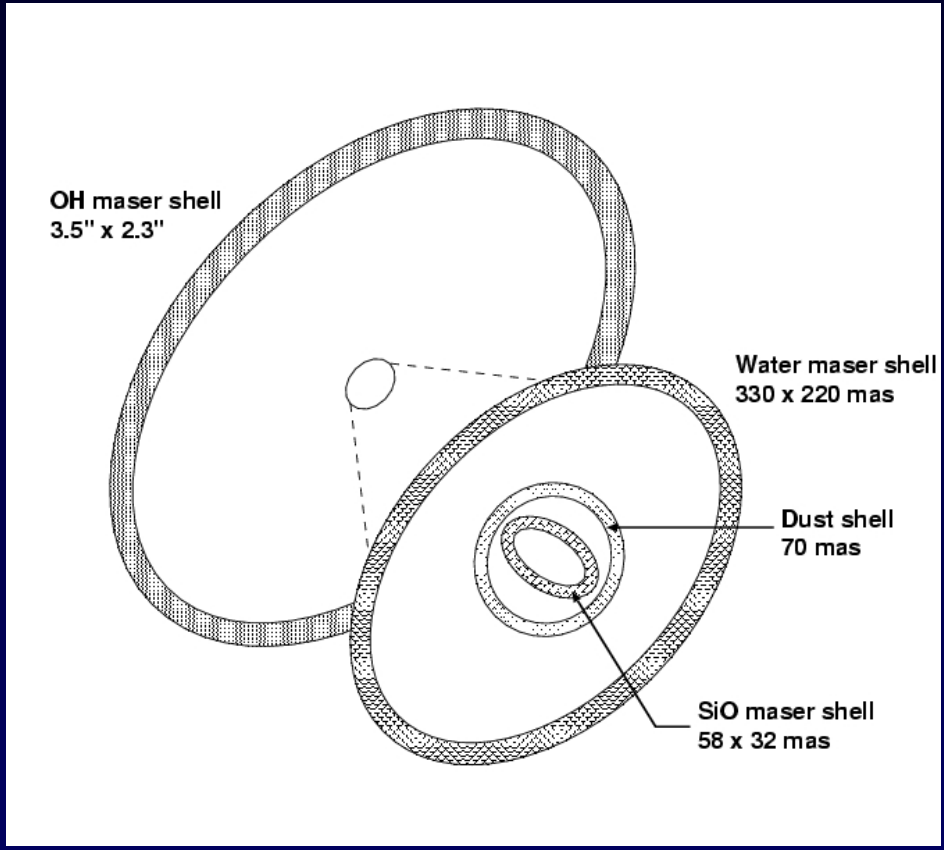


Why Study Circumstellar Masers?

- Learn something about the host objects (AGB stars).
  - Structure of the CSE at various distances.
  - Kinematics of the CSE.
  - Polarization and magnetic fields.
- Learn something about the masers themselves.
  - Correlate observations with maser theory & simulations.
  - Pumping mechanisms.
  - Maser polarization.
- Use the masers for astrometry.
  - Parallaxes yield distances.
  - Proper motions yield motions in region.

Circumstellar Envelope Structures

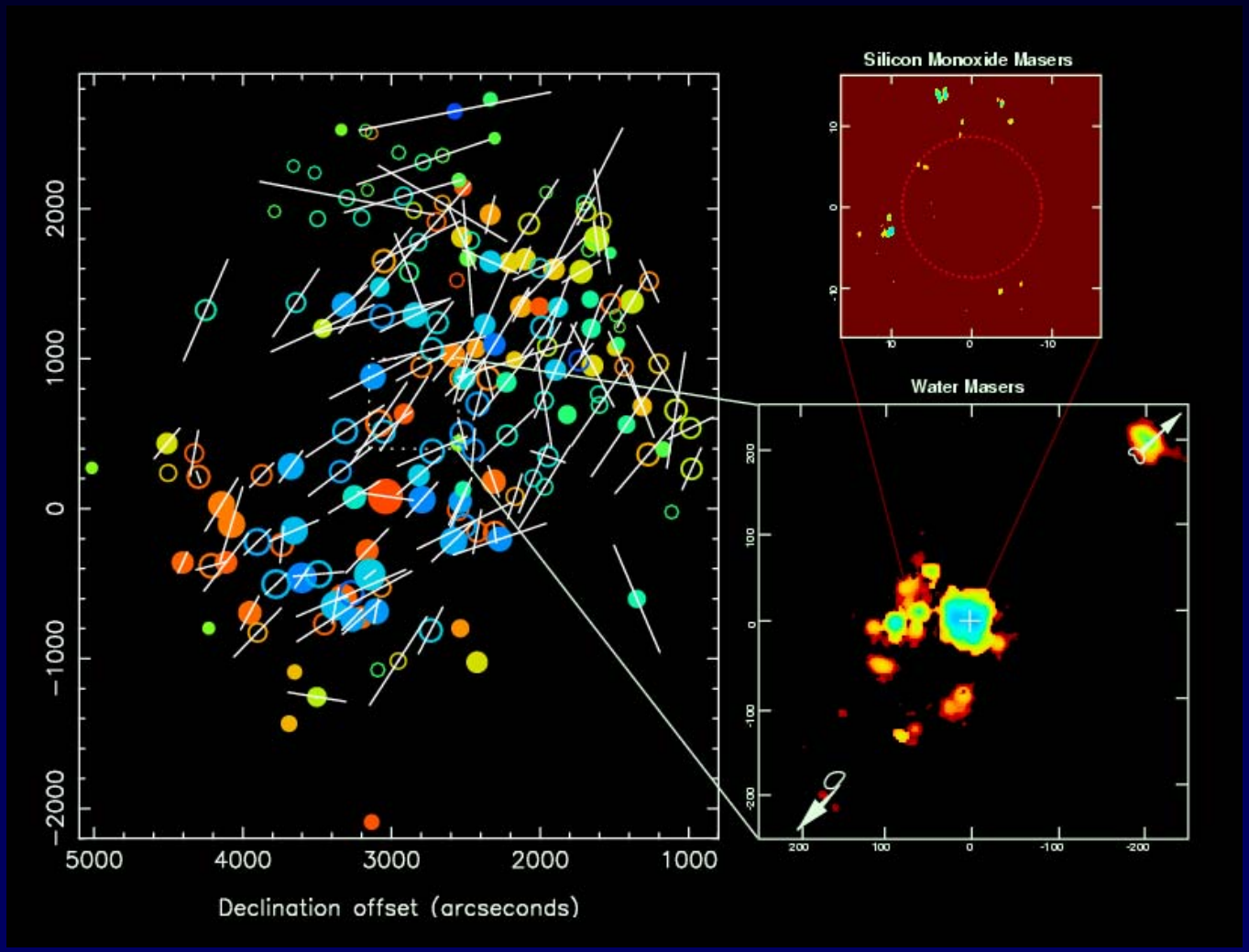
- Masers trace the structure of the CSE at various distances from the star.
- Symmetric vs. asymmetric structures.
- Signatures.
  - Bipolar outflows.
  - Non-radial stellar pulsations.
  - Binarity.



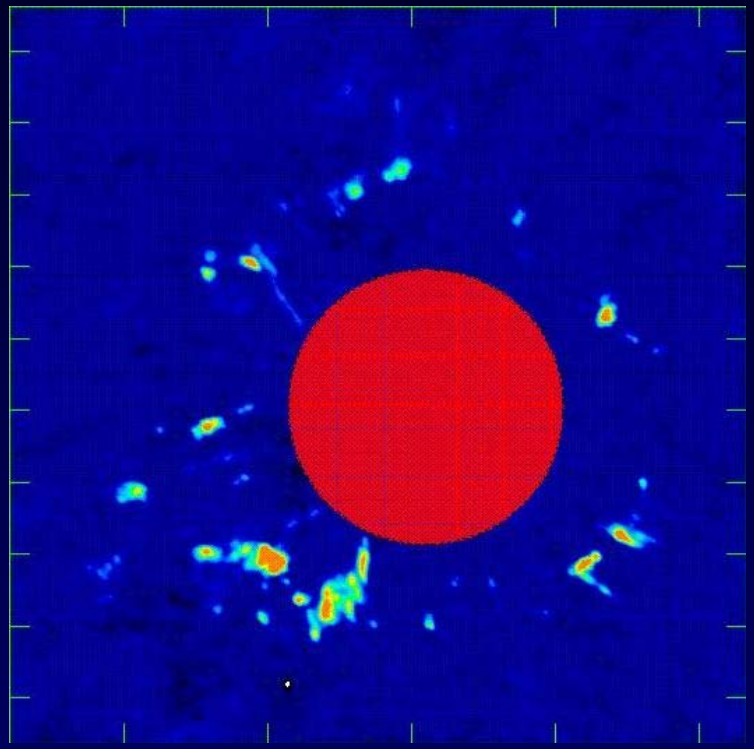
Schematic of IK Tau

Composite of NML Cyg

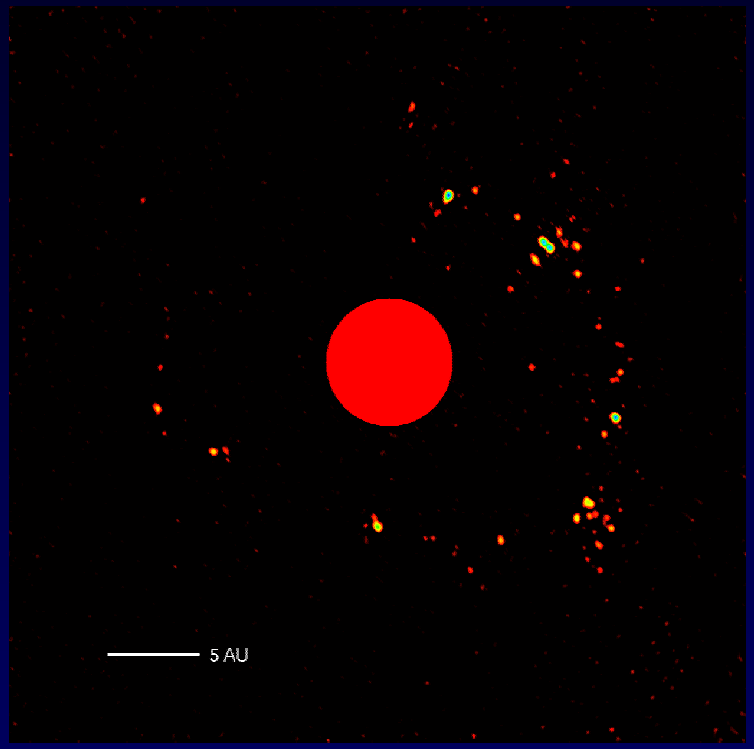
- Diamond, Richards, Boboltz & Marvel
- OH, H_2O, SiO axially symmetric.
- H_2O bipolar outflow.



Not All SiO Rings Are Created Equal



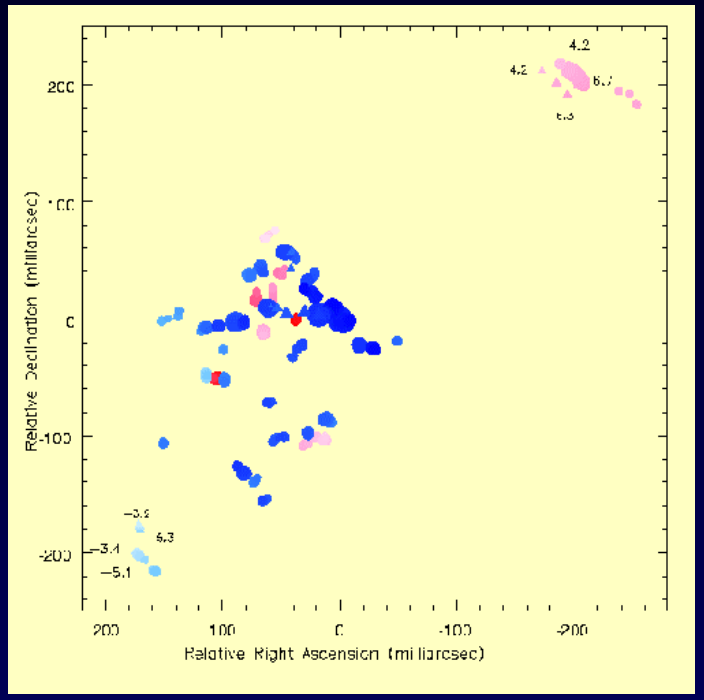
TX Cam: circular ring
Diamond & Kemball, 1997

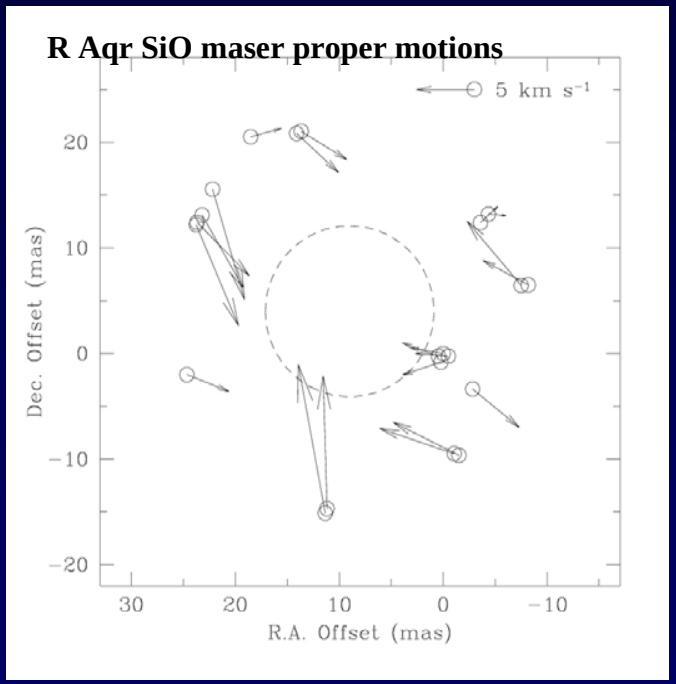


IK Tau: elliptical distribution
Boboltz & Diamond, 2000

Kinematics of the CSE

- Single-epoch studies yield maser radial velocity vs. maser position.
  - NML Cyg H_2O masers
    Richards, Yates & Cohen, 1996

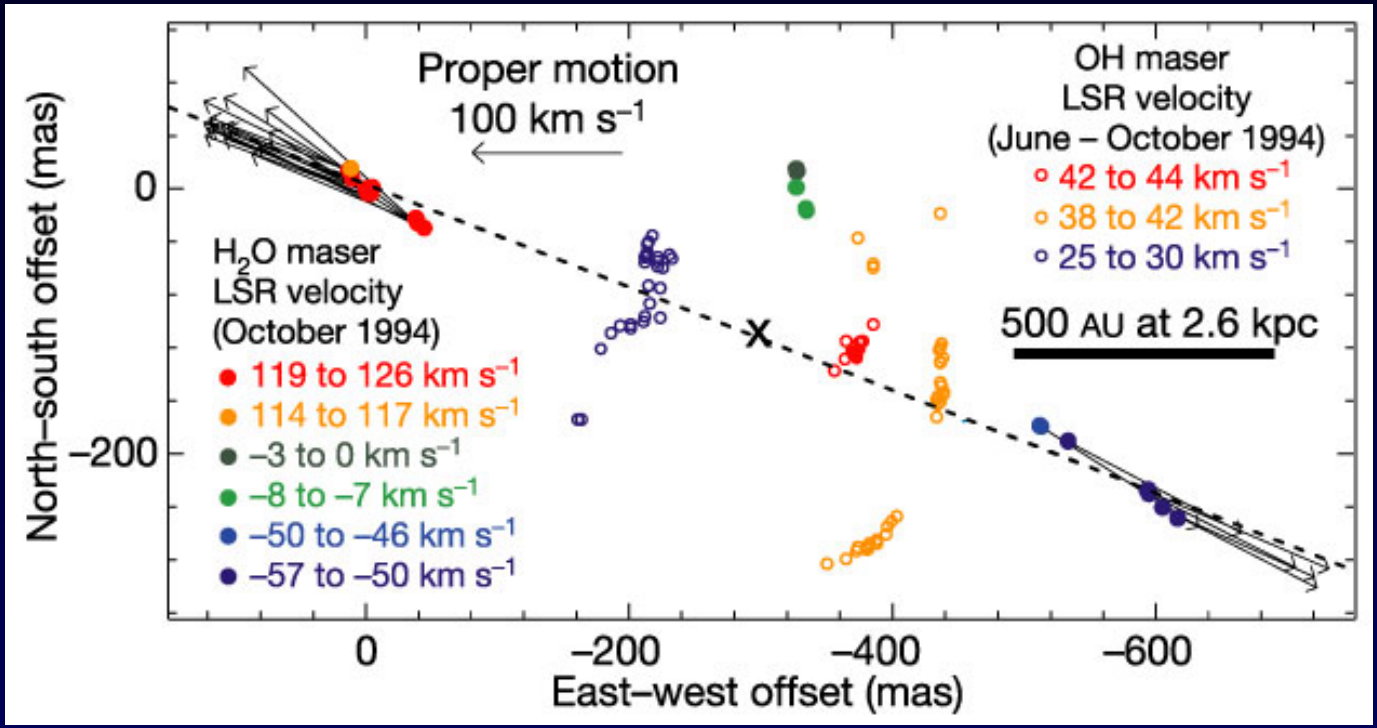




- Multi-epoch studies yield proper motions of the masers.
- Nice movies (TX Cam, S Per)

W43A OH/H_2O Masers

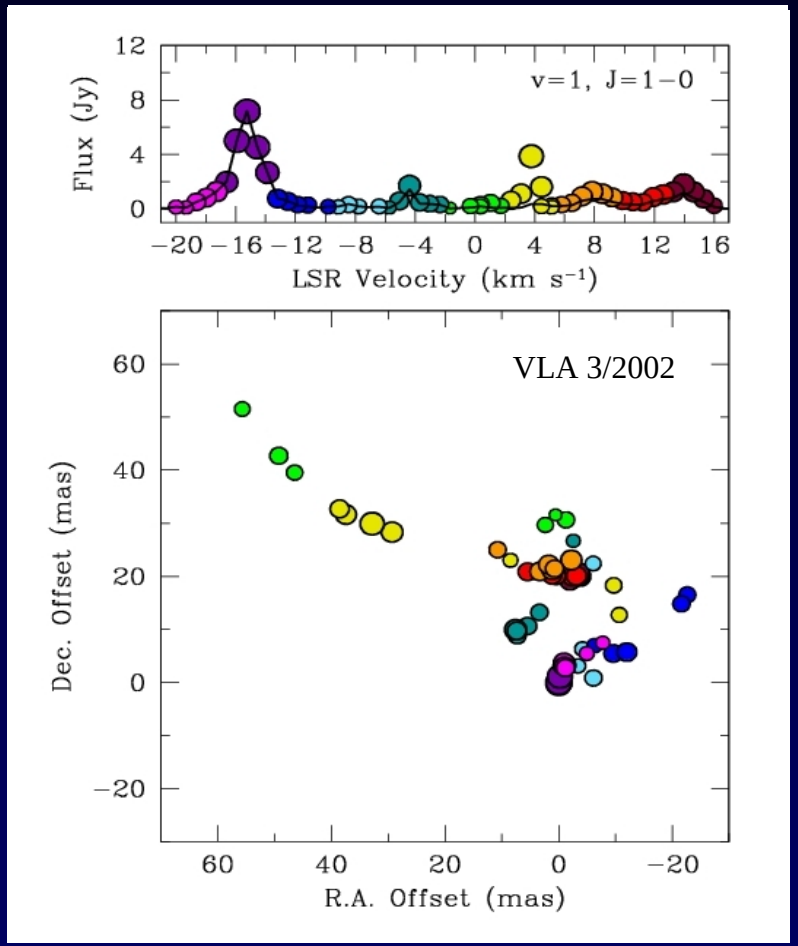
Imai et al., 2002, Nature



- H_2O masers twice the separation of the OH masers.
- Form a collimated, precessing jet.
- Imai talk this session.

Rotation in the SiO Maser Region?

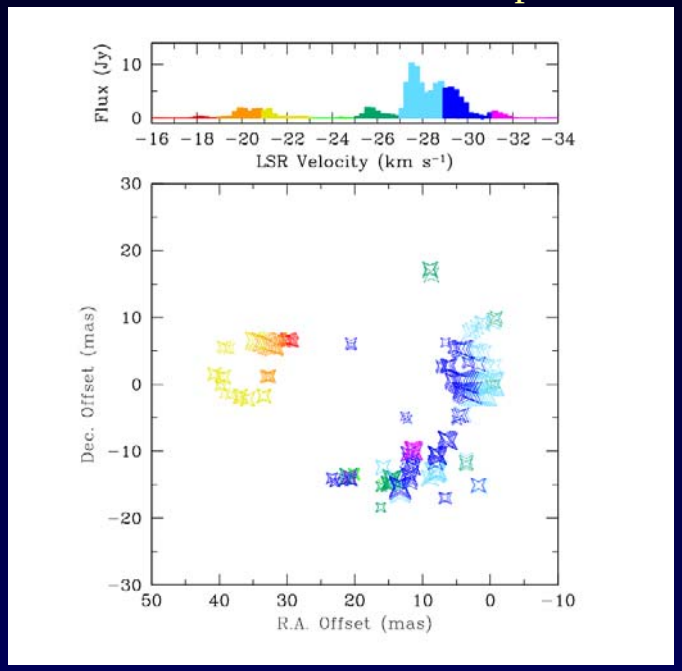
- Rotation signatures in the SiO shells.
  - VX Sgr (Doeleman et al., 1998)
  - NML Cyg (Boboltz & Marvel, 2000)
  - R Aqr (Hollis et al., 2000; 2001)
  - IK Tau (Boboltz & Diamond, 2000; 2003)
  - OH 231.8+4.2 (Sanchez Contreras et al., 2002)



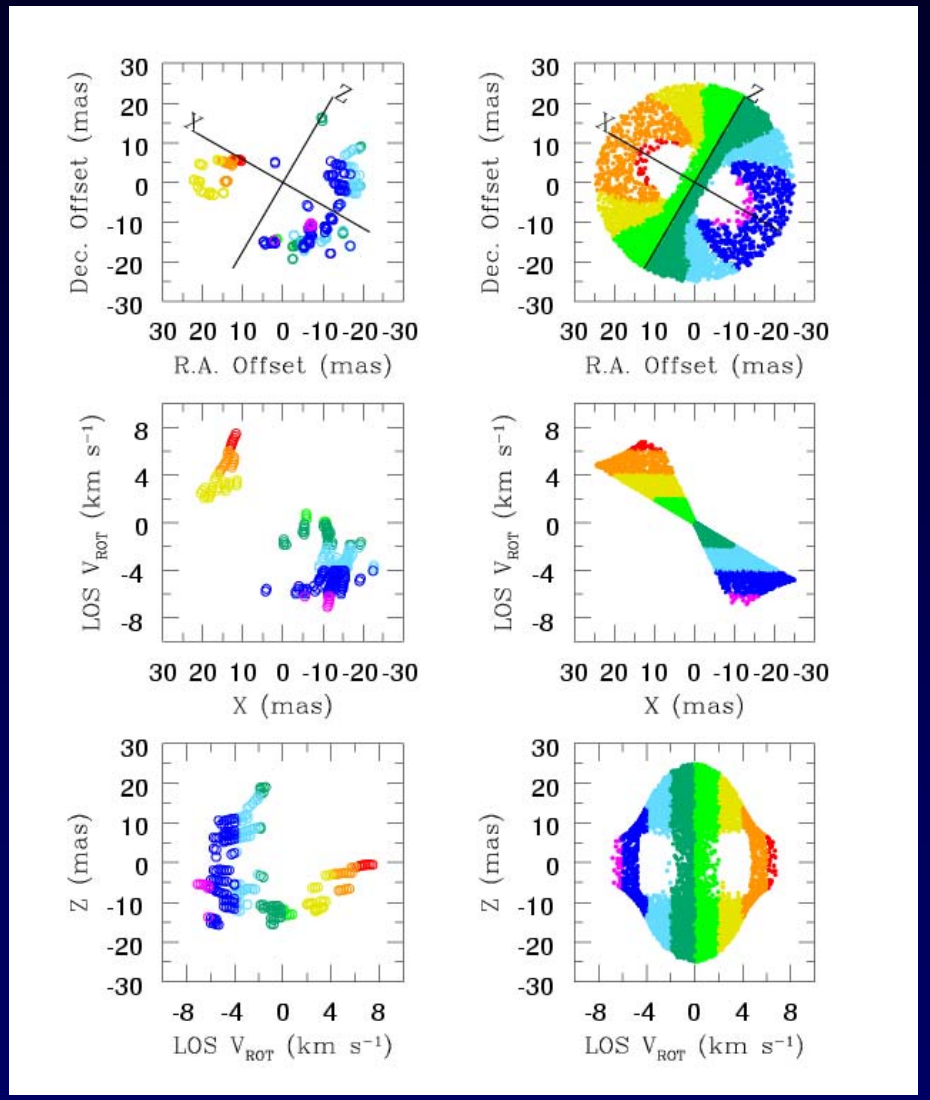
NML Cyg velocity structure

R Aqr: More Rotation

Hollis et al., 2001, ApJ

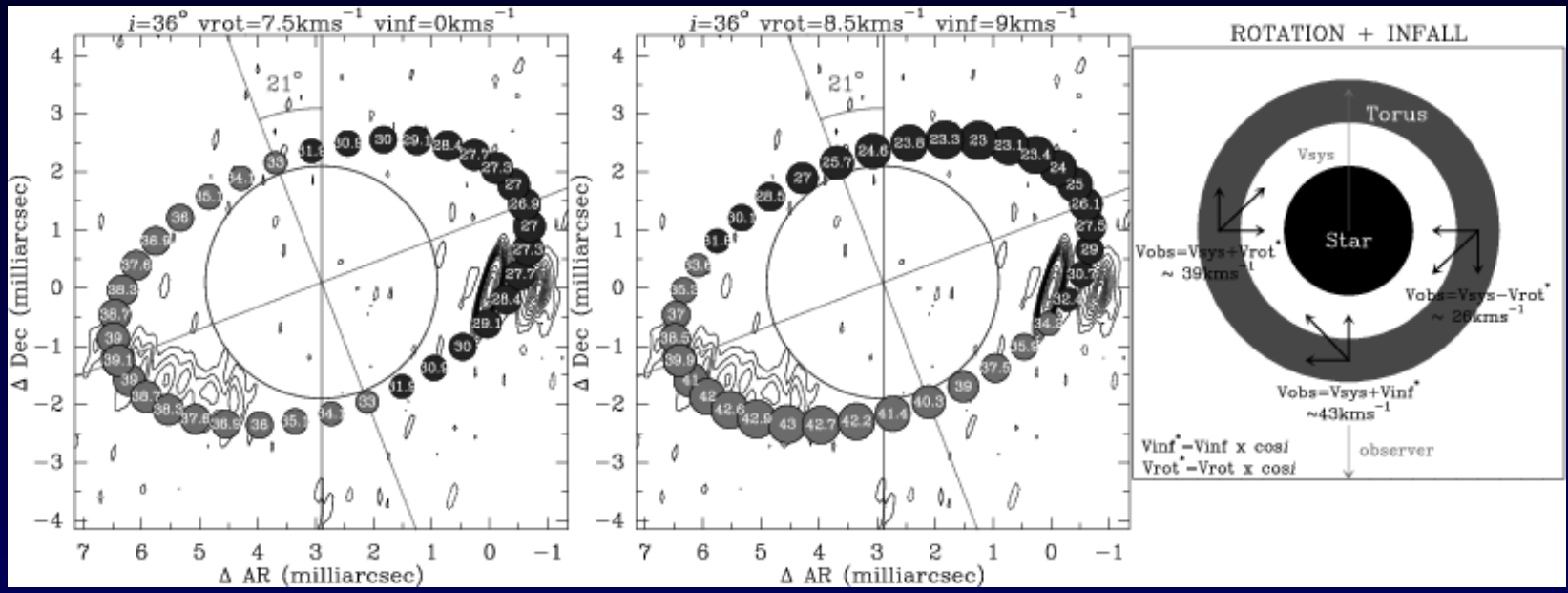


- Have to resolve tangential amplification with apparent rotation.
- $V_{LOS} \propto \sqrt{GM / r^q}$
  - q ≈ 1.09 quasi-Keplerian



OH 231.8+4.2: Rotation + Infall

Sanchez Contreras et al., 2002, A&A



- Proto-planetary Nebula.
- Distribution suggests tangentially amplified torus.
- Rotation and infall velocities of order 7 – 10 km/s.

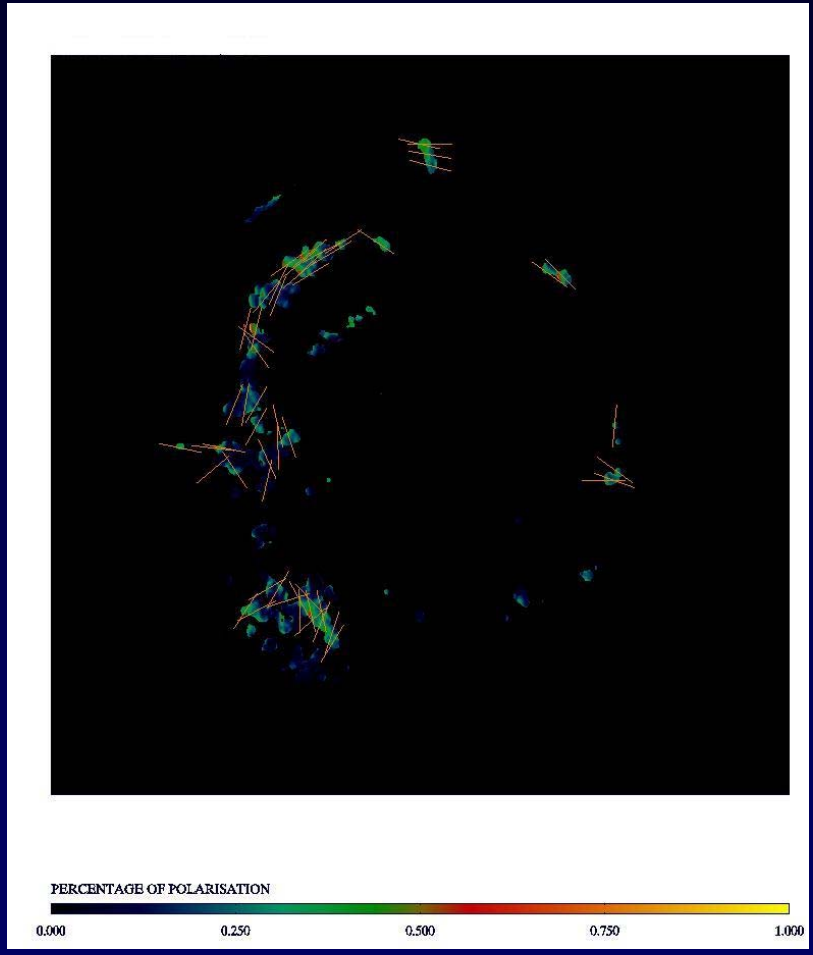
Circumstellar Maser Polarization

- OH
  - Open shell molecule, paramagnetic.
  - To get Zeeman splitting – B ~ 10^{-7} G.
  - Resolve Zeeman pattern ($g\omega_B > \Delta\nu_D$) B ~ 10^{-3} G (relatively easy).
  - Expect both circular & linear polarization.
- H_2O and SiO
  - Closed shell, non-paramagnetic.
  - To get Zeeman splitting – B ~ 10^{-5}, 10^{-4} G respectively.
  - Resolve Zeeman pattern – B ~ 10 G (relatively difficult).
  - Expect linear polarization, not much circular polarization.
- Maser polarization observations
  - Very calibration intensive.
  - Provide feedback to maser polarization theories.

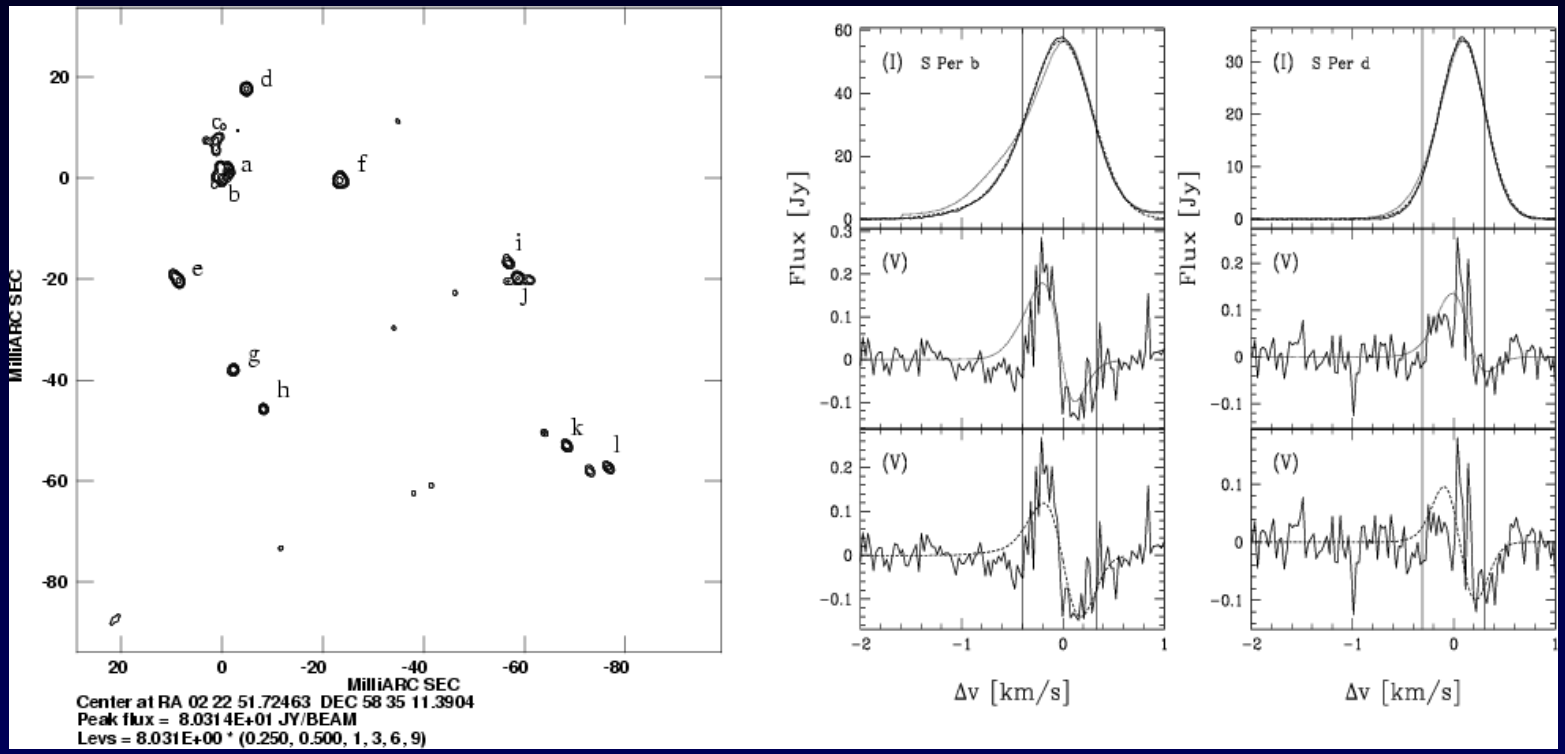
SiO Maser Polarization

- Linear polarization
  - 20-30% on average
  - Components as high as 80-90%
  - Linear pol. vectors tangent or perpendicular to maser shell.
- Circular polarization
  - Less than 10%
- Magnetic field strength depends on polarization interpretation
  - Zeeman – tens of G
  - Non-Zeeman – tens of mG
- Kemball, Diamond & Gonidakis talk this session.

TX Cam linear pol. Gonidakis



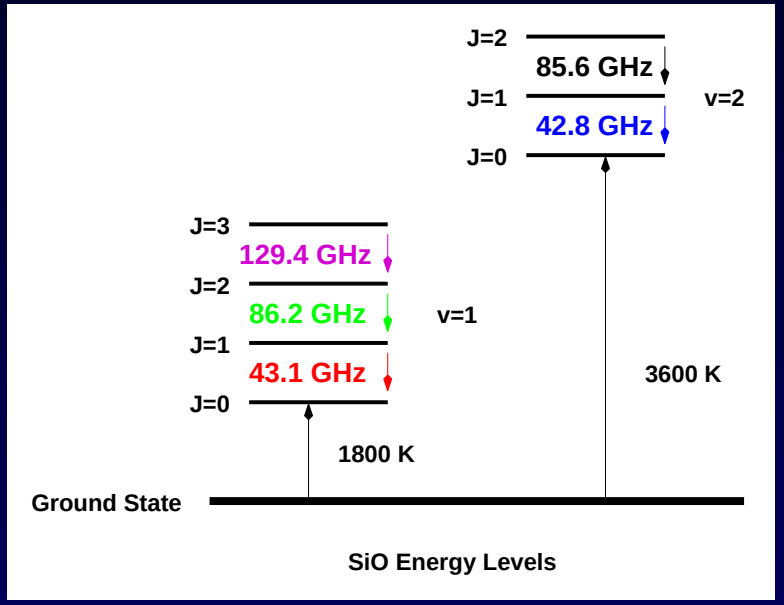
H_2O Maser Polarization



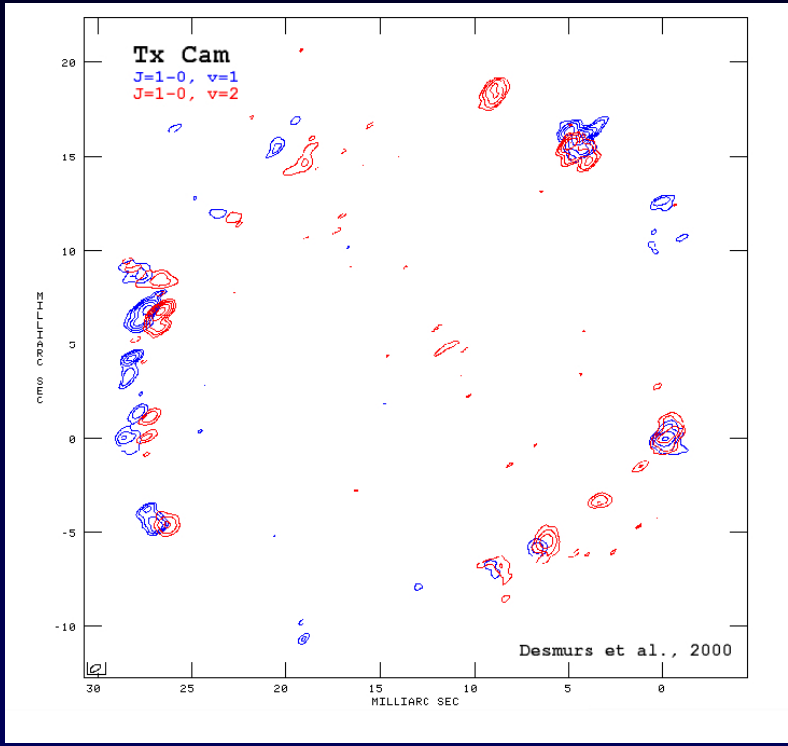
- Vlemmings, Diamond & van Langevelde, 2001,2002 A&A.
- High spectral resolution – detect the Zeeman pattern.
- Magnetic field strengths 150 mG – 1.5 G
- Vlemmings talk this session.

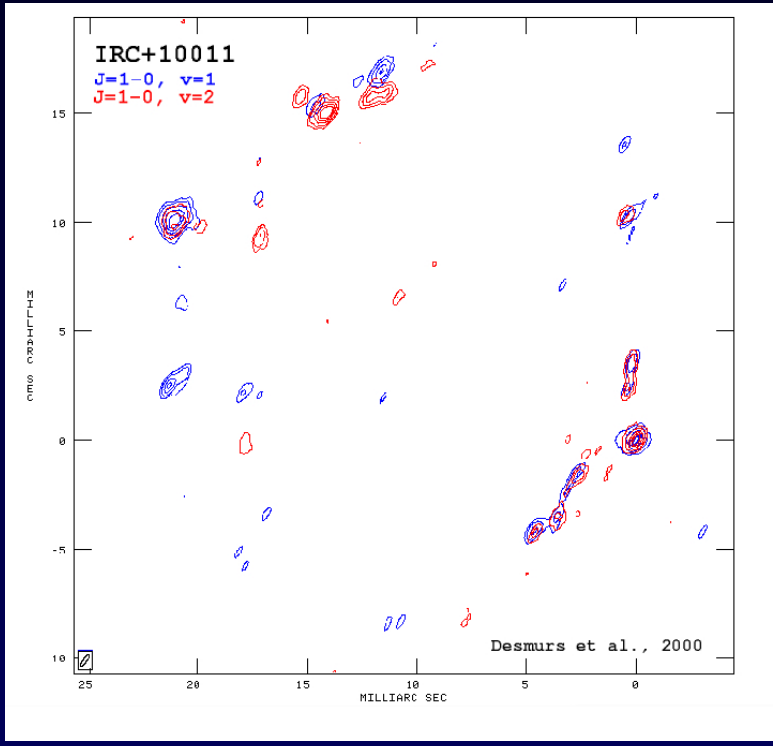
SiO Maser Pumping Mechanisms

- Radiative, collisional, or combination pumping?
- Models predict ring radii for the transitions as a function of stellar phase.
  - i.e. Gray & Humphreys, 2000; Humphreys et al. 2002
- Simultaneous multi-transition VLBI mapping.
  - v=1, J=1-0
  - v=2, J=1-0
  - v=1, J=2-1
- Are the transitions co-spatial?



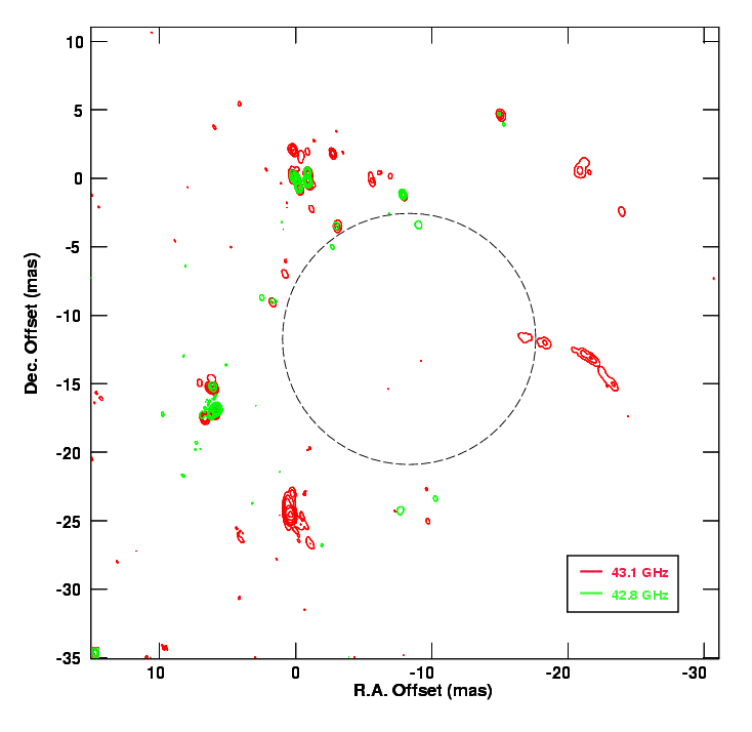
In Favor of Radiative Pumping

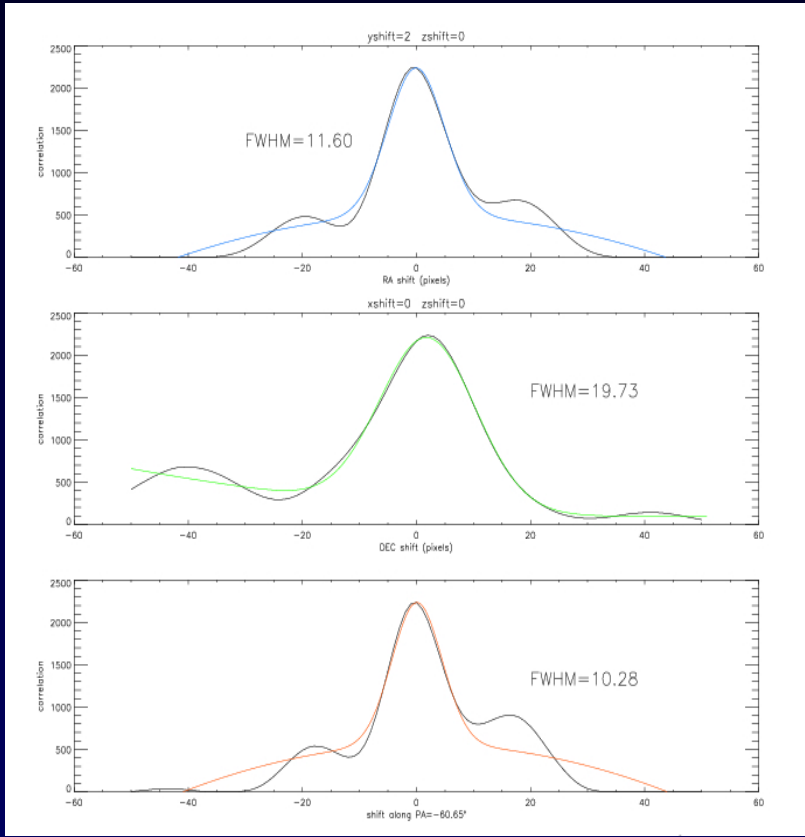




- Desmurs et al., 2000, A&A
- 1–2 mas offsets argue in favor of radiative pumping.

Collisional or Combination Pumping?





- NML Cyg 2-D correlation (by Doeleman).
- < 0.1 mas (<0.05 AU) shift.

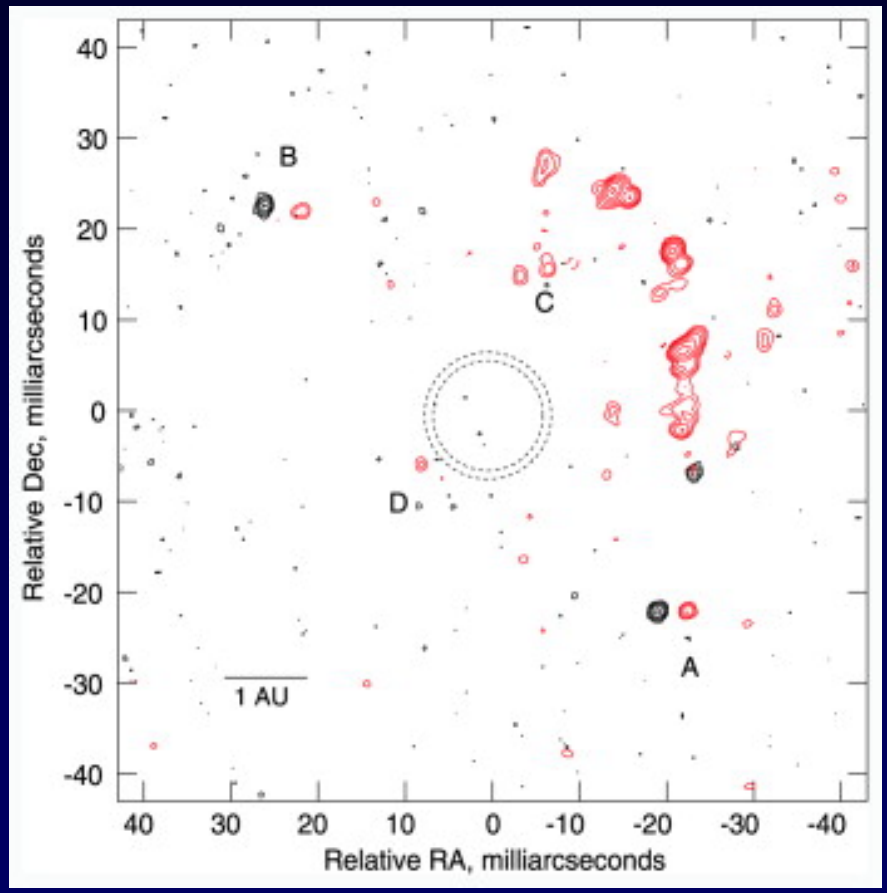
Future Directions

- 3 Millimeter wavelengths and beyond.
  - Relevant with new mm/sub-mm arrays in the works.
  - SiO: 86 GHz – 336 GHz.
  - H_2O masers: 96 GHz, 183 GHz, 321 GHz, 325 GHz.
- Stellar astrometry using masers.
  - Relevant considering astrometric satellite missions are in vogue (i.e. SIM and GAIA).
- Multi-wavelength studies of AGB stars.
  - Relevant with new optical/IR interferometers coming online.
  - Combine Long Baseline Interferometry (LBI) with VLBI to get a better picture of the star and its CSE.

3mm SiO VLBI Becoming Routine

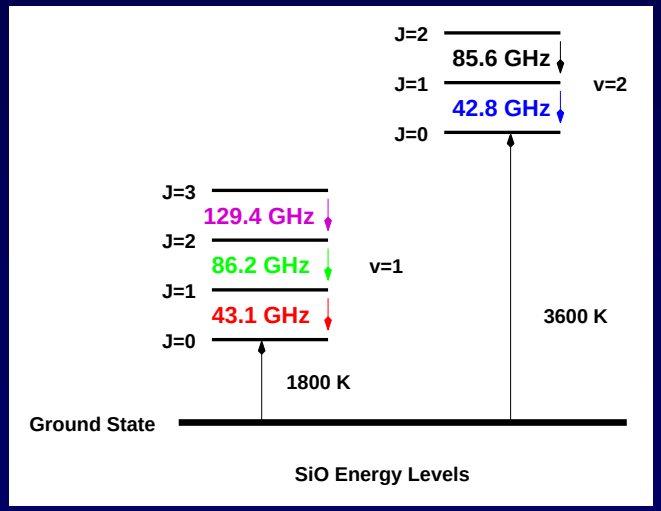
- Previously performed by an ad hoc array of millimeter observatories coordinated by the CMVA.
- Taken over by VLBA as 3mm receivers came on line.
  - 7 VLBA antennas equipped with 3-mm receivers.
- Allows simultaneous comparison of 7mm and 3mm transitions.
  - i.e. Soria-Ruiz et al. talk this session.

R Cas 3mm (black) 7mm (red)
Phillips et al., 2003

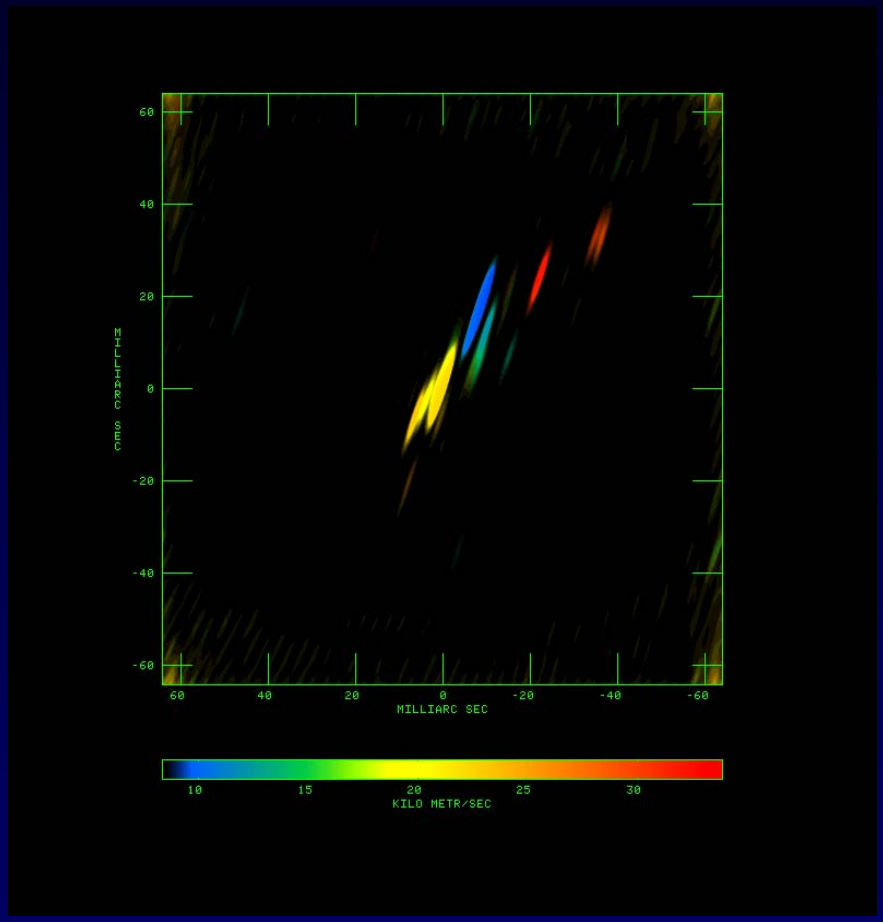


2mm VLBI of SiO Toward VY CMa

- Observed v=1, J=3-2 (129 GHz) transition.
- Single baseline HHT to Kitt Peak.
- Also planned J=4-3 (172 GHz), J=5-4 (215 GHz).



Doeleman et al., 2002



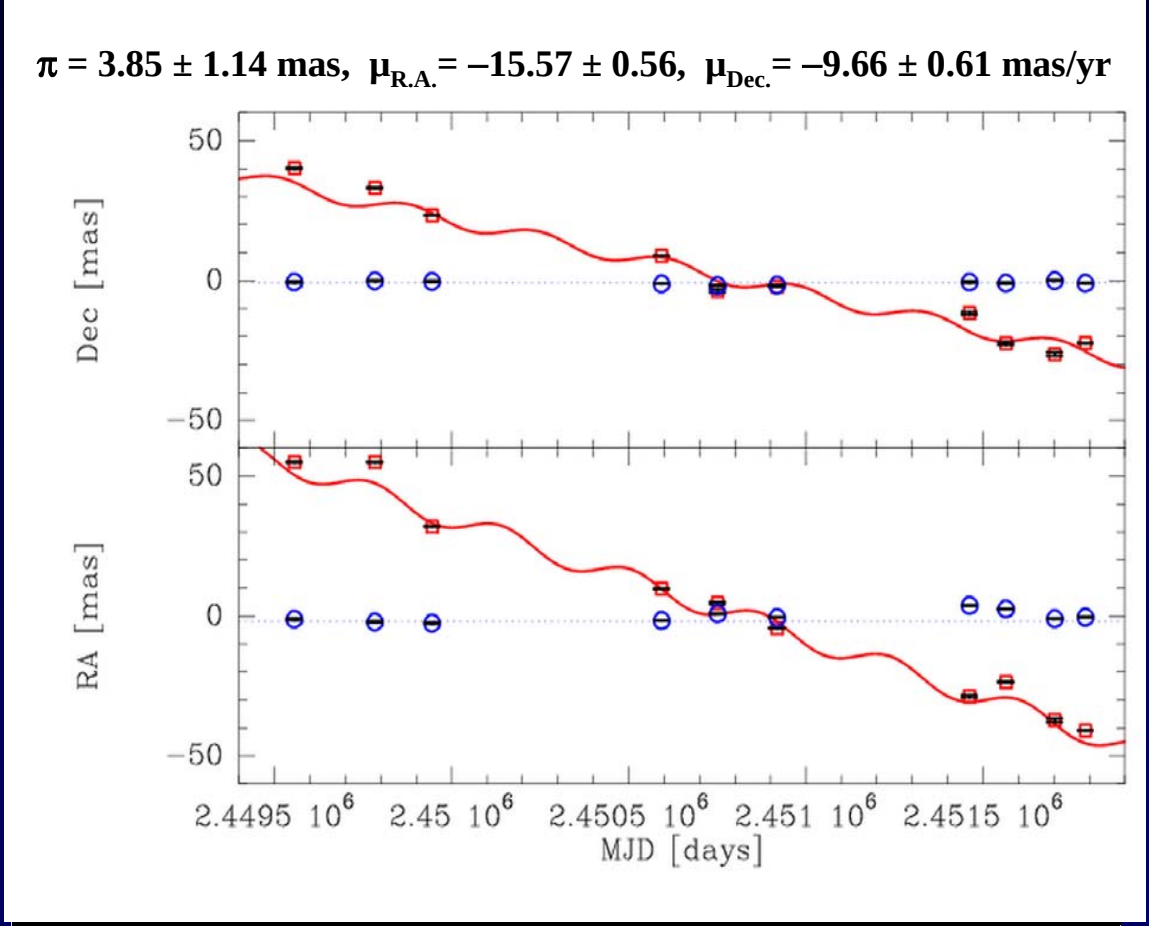
AIPS User 7 VYCMA V=1 J=3-2

Stellar Astrometry

- Masers can be used to determine stellar parameters (parallax, π and proper motion, μ) of AGB stars.
  - Galactic center – 8 kpc π = 0.250 mas
  - Distances to LMC & SMC – 50 kpc π = 0.04 mas.
  - Align radio reference frame to optical/infrared frames.
- Which masers to use?
  - OH: ~20 mas resolution, radial amplification
  - H_2O: ~0.05 mas resolution, radial amplification, variable
  - SiO: ~0.01 mas resolution, tangential amplification, variable
  - All require phase-referencing to nearby quasar.
- VERA (VLBI Exploration or Radio Astrometry)
  - Dedicated dual-beam, phase-referencing, VLBI array.
  - H_2O and SiO maser astrometry.
  - Kobayashi talk this meeting.

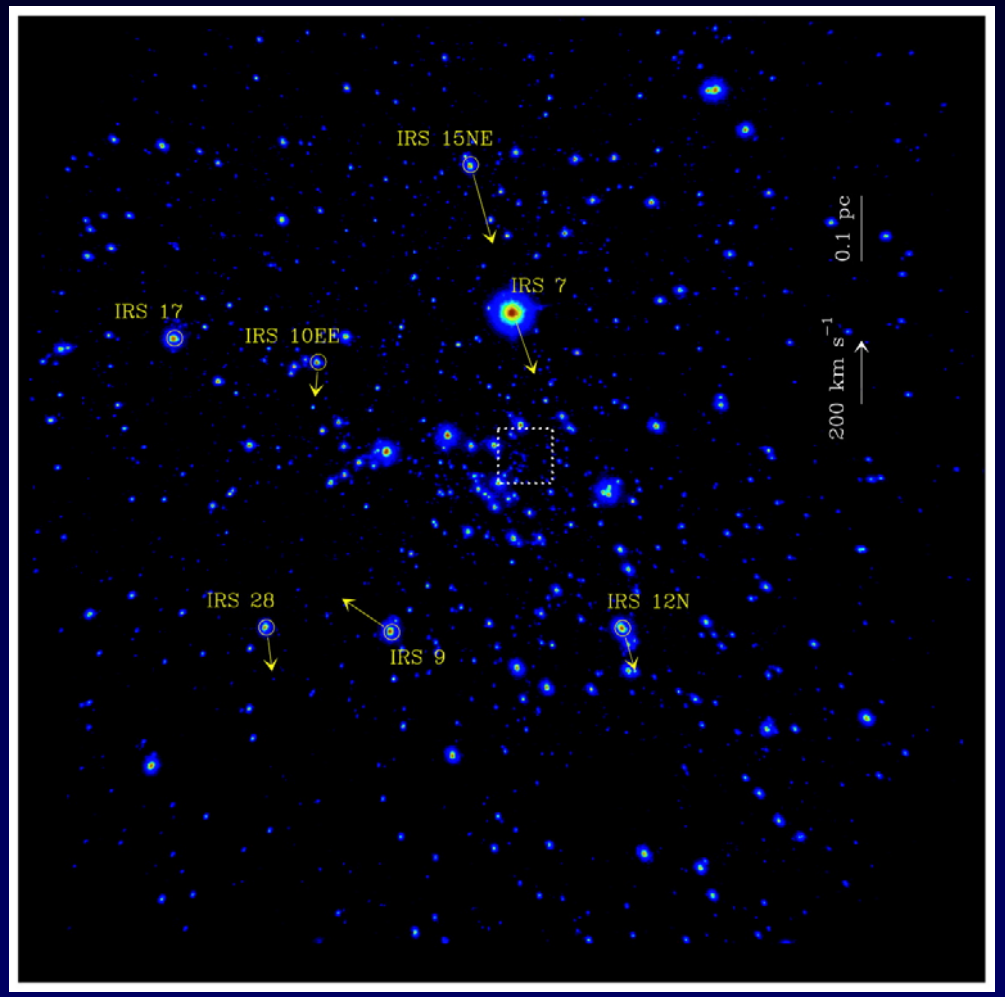
OH/H_2O Maser Astrometry

- U Her 1667-MHz OH
  - van Langevelde et al., 2000.
- 3 additional stars.
  - W Hya, R Cas, S CrB.
  - Errors comparable to Hipparcos.
  - van Langevelde, Vlemmings & Diamond poster this meeting.
- U Her H_2O maser astrometry.
  - With MERLIN.
  - Vlemmings, van Langevelde & Diamond, 2002, 2003.

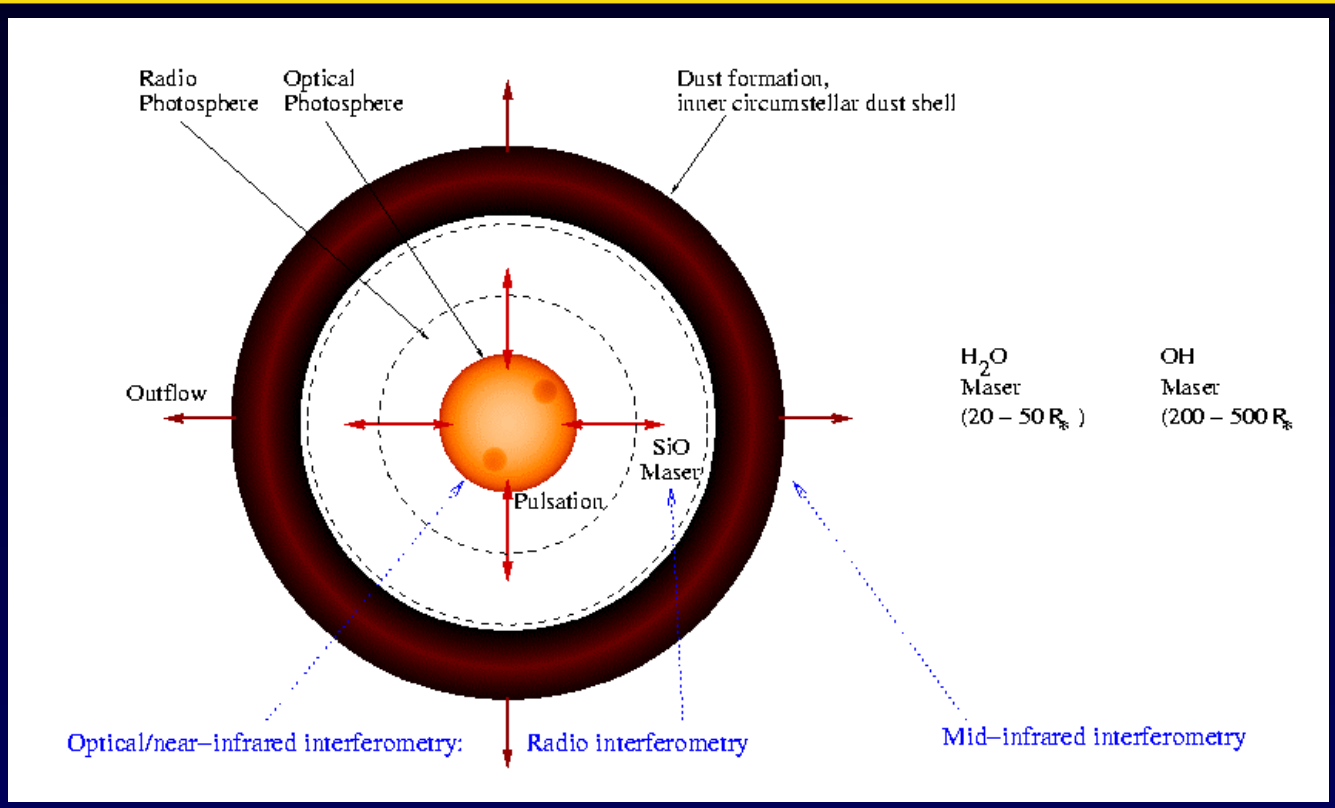


SiO Maser Astrometry Near Sgr A*

- Reid et al., 2003, ApJ
- Used Sgr A* as a phase reference.
  - Strong interstellar scattering.
  - Limited to baselines <1500 km.
- At 8 kpc, the SiO rings are < 1-2 mas.
- For 7 stars
  - positions ~1 mas
  - proper motions ~1 mas/yr.

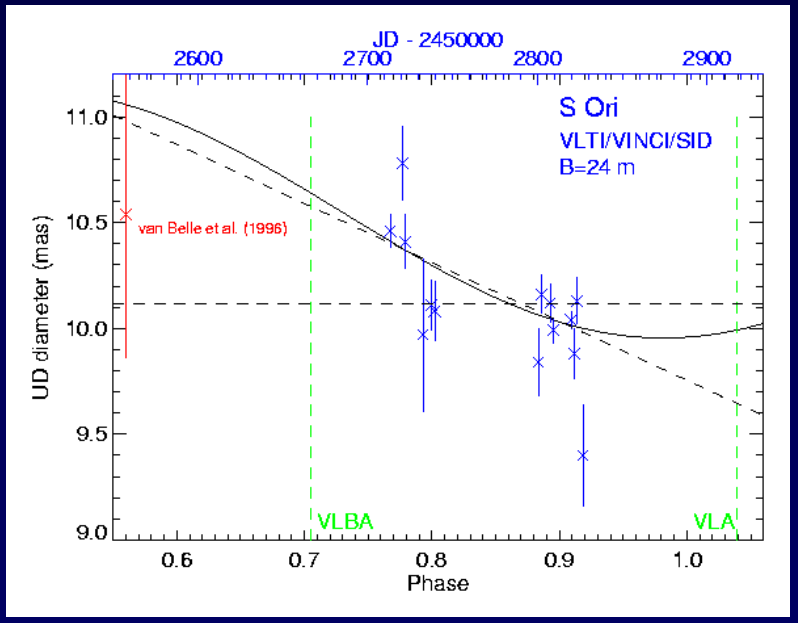


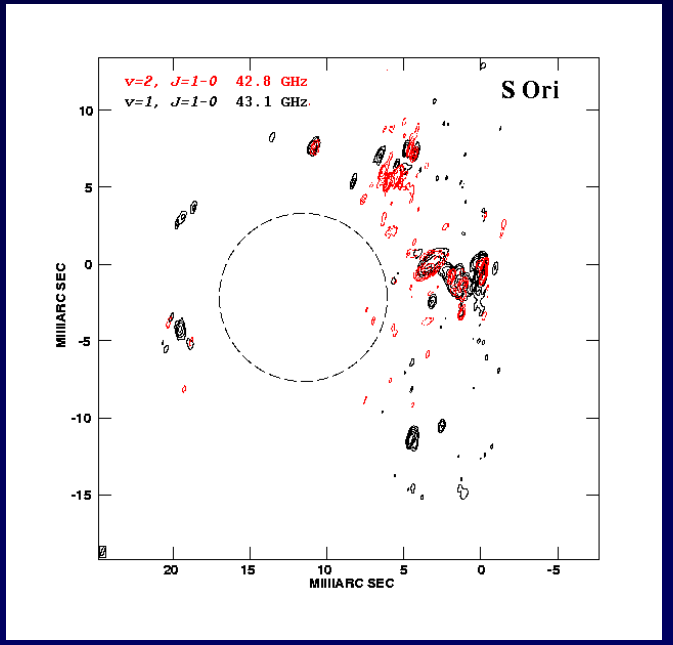
Multi-Wavelength Studies of AGB Stars



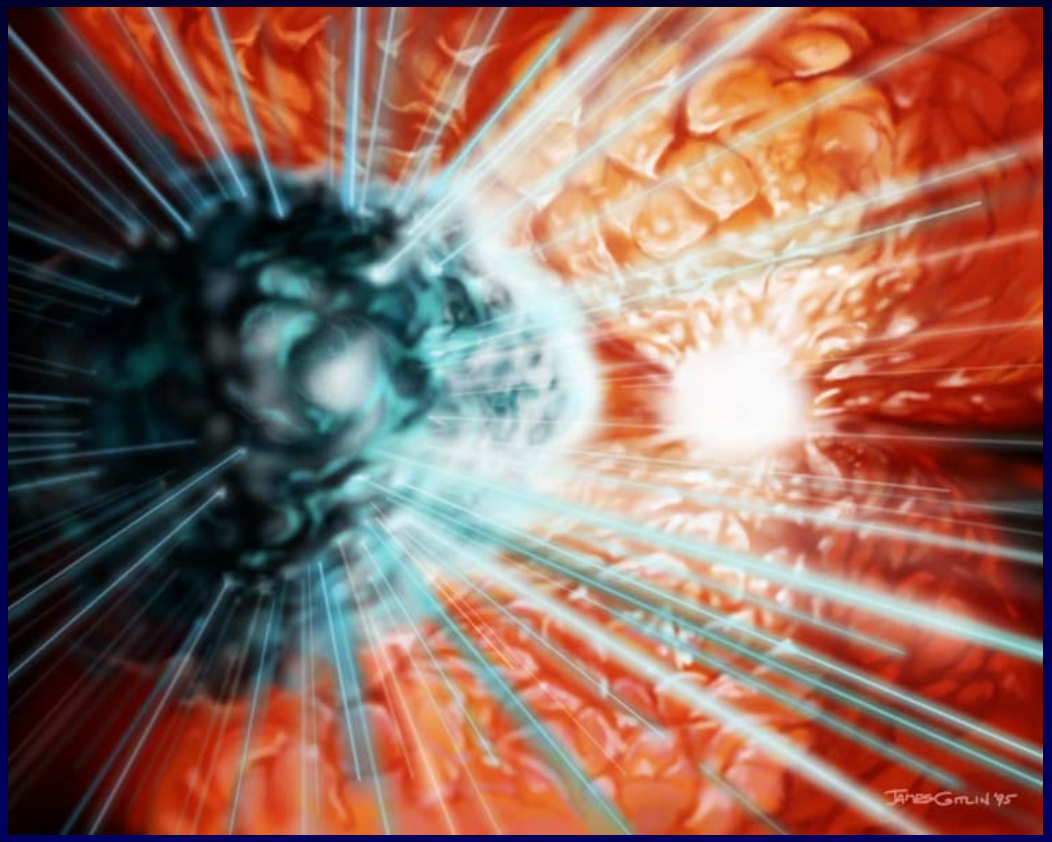
- We'd like to know stellar and dust shell parameters at the time of our maser observations.
- Optical/IR can fill in the missing pieces.
- Cotton et al.; Wittkowski & Boboltz talks this session.

VLBA/VLTI Observations of S Ori



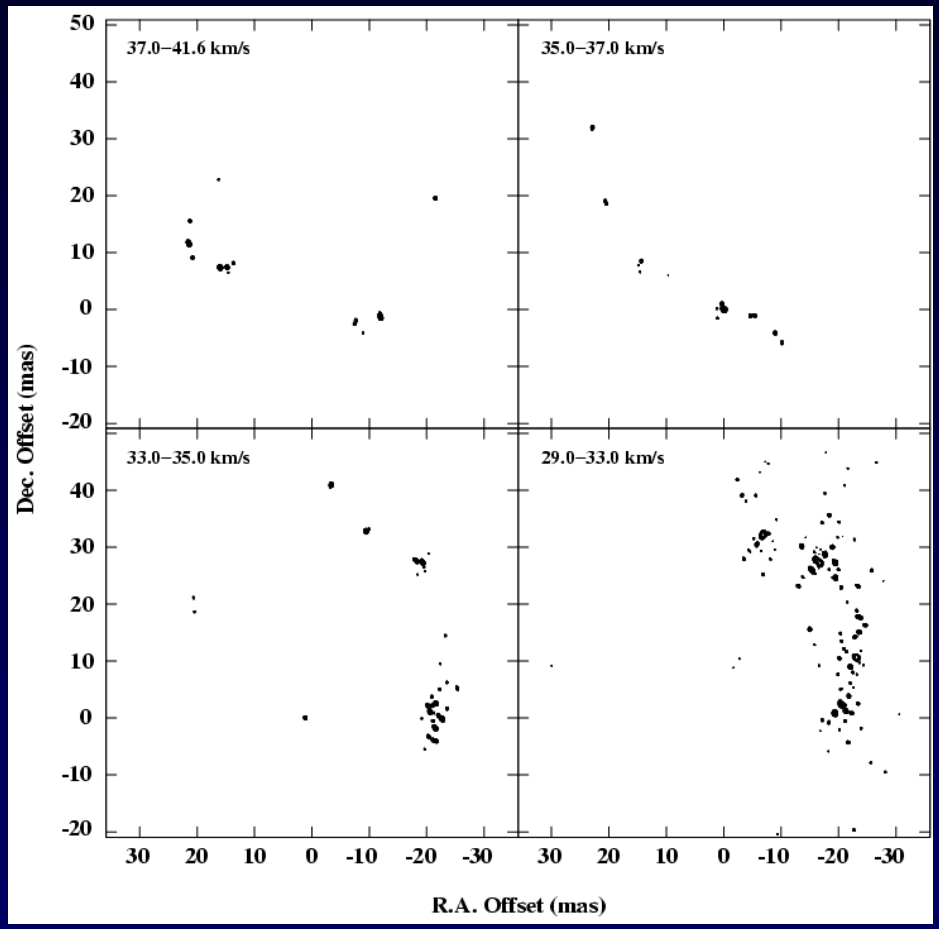


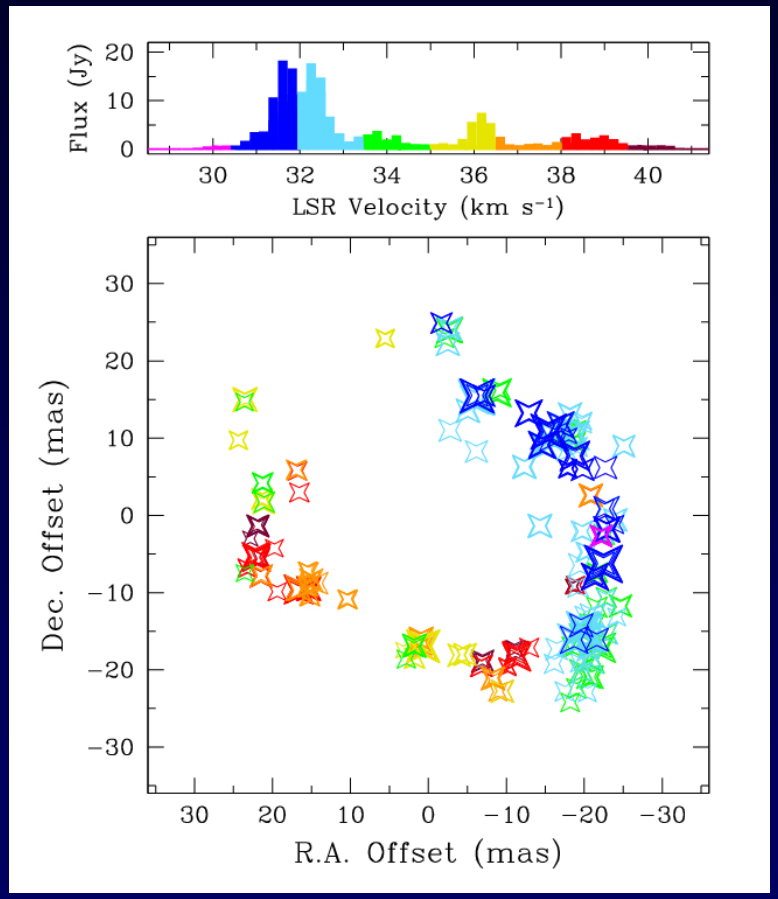
Summary



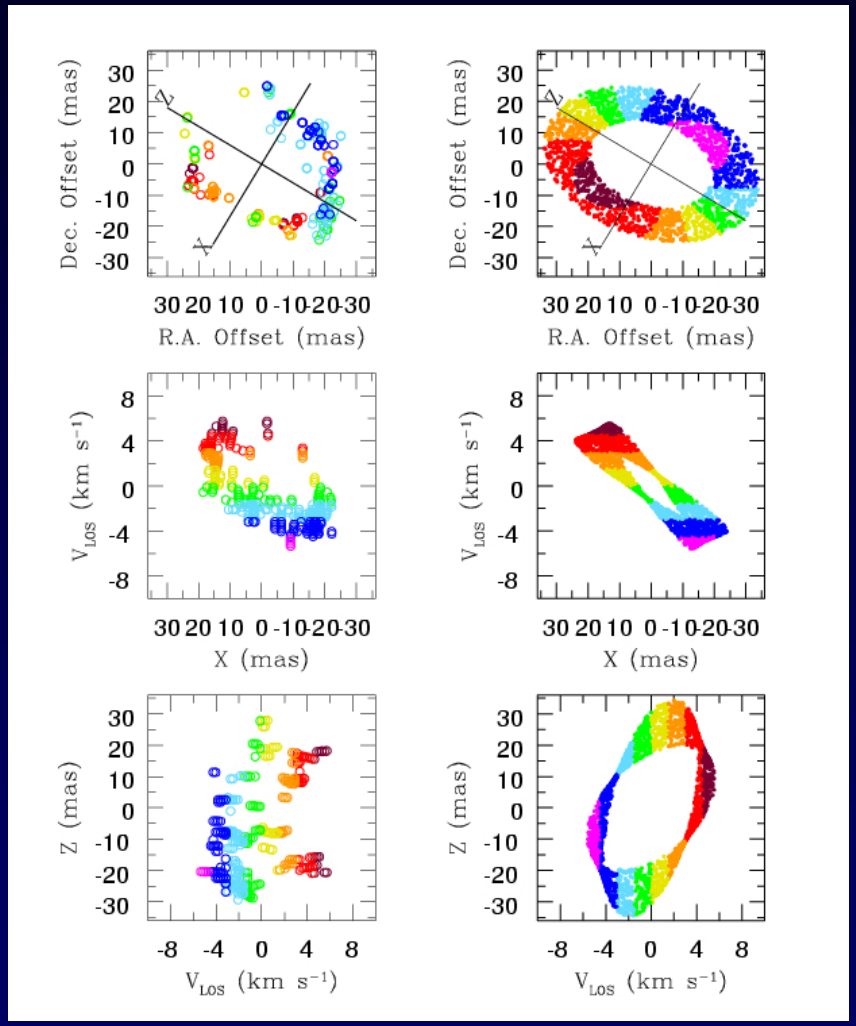
- So many stars so little time.
- Maser observations are reduction intensive.
  - Worth the effort.
  - Reduction pipelines can help.
- Interaction with other communities a good fit.
  - LBI, astrometric satellite.
  - Attract new users to VLBI.

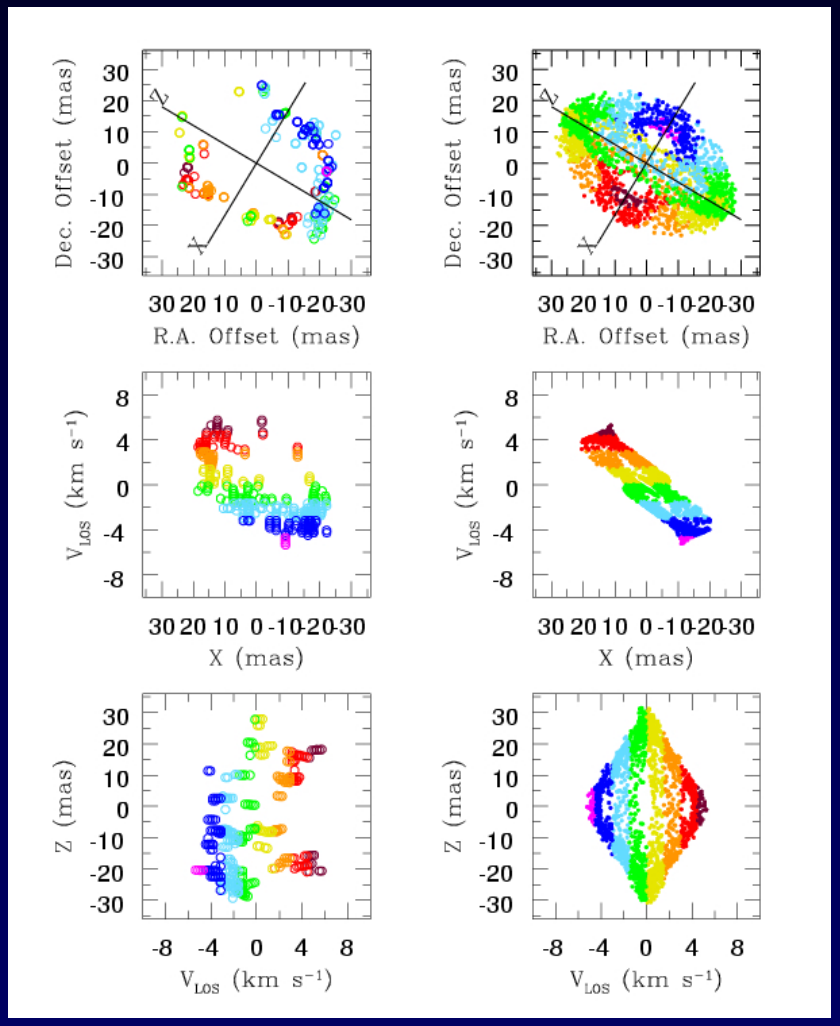
IK Tau: Rotation



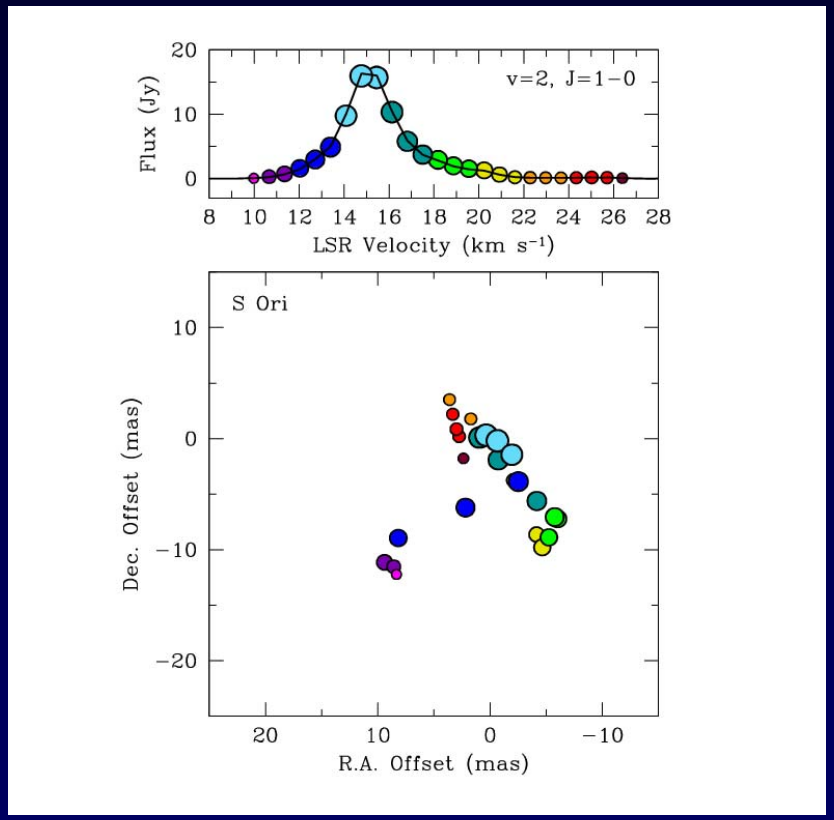


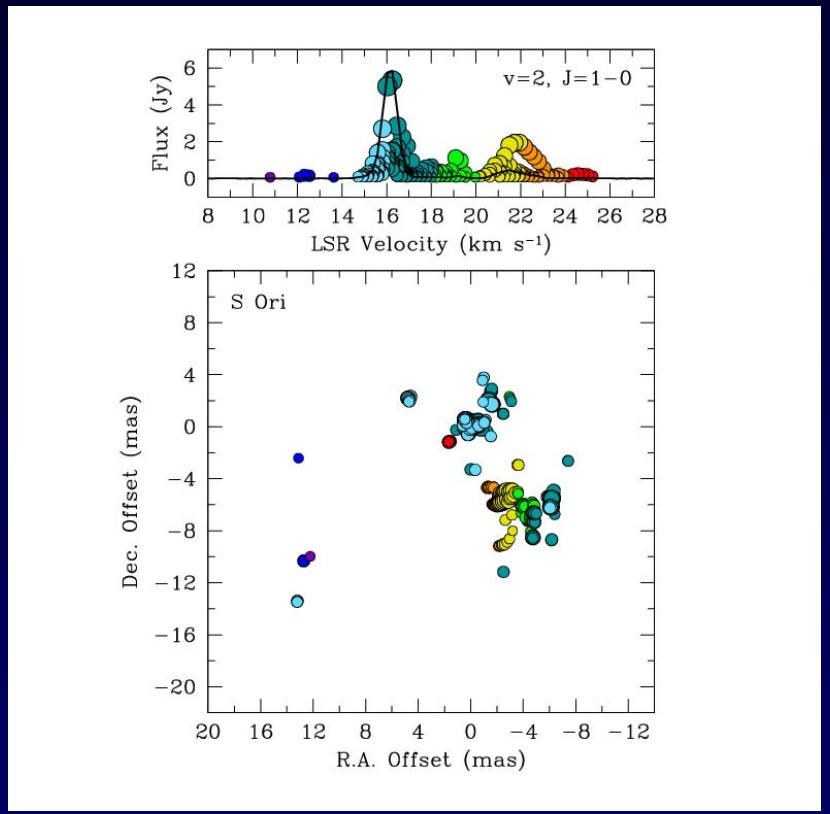
IK Tau: Disk or Shell





VLA vs. VLBA: S Ori





VLA vs VLBA: NML Cyg