# Masers around evolved stars
## from kinematics to physics


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with thanks to

Al-Muntafki, Bains, Bartkiewicz, Diamond, Elitzur, Etoka, Gray, Humphreys, Murakawa, Rosa-Gonzalez, Szymczak, van Langevelde, Yates et al.

photos: Diah Gunawan

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The University of Manchester
Jodrell Bank Observatory

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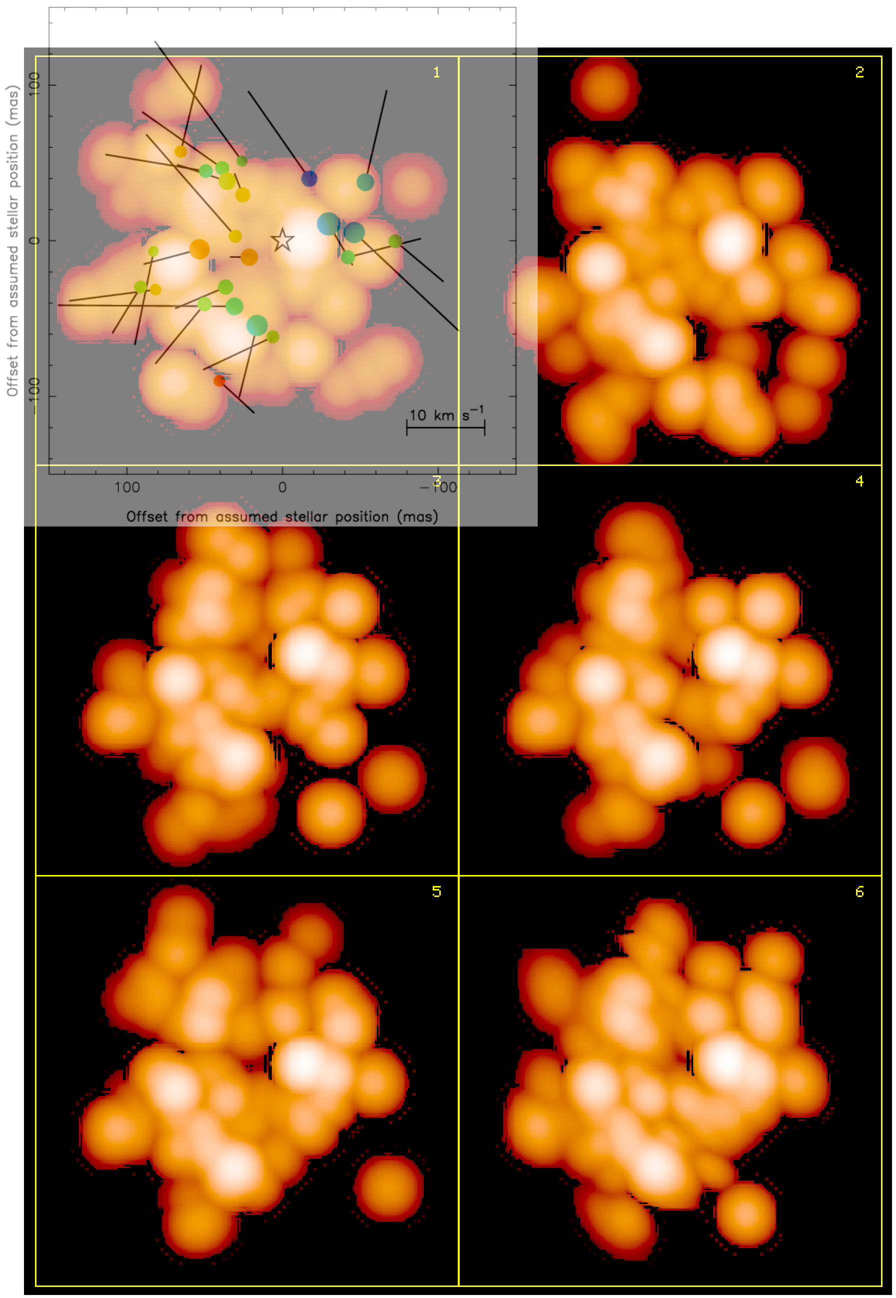
# Overview

- Water maser 3-D kinematics
  - Radial acceleration
- AU-scale resolution
  - Water maser clumps in OH gas
  - Implies density, temperature contrast
  - Need e-MERLIN plus VLBI for full picture
- Test models of maser beaming
  - Spherical clouds or shocked slabs?
- How does star lose mass?
- ALMA+e-MERLIN+EVN submm to cm at mas resl'n
  - Star/masers/thermal lines/dust
  - Reconstruct detailed physical conditions
  - Suitable targets for early science/mm VLBI

# Proper motions –expansion, acceleration

- MERLIN well-resolves 22-GHz water masers, detects all emission
  - Proper motion velocities consistent with Doppler acceleration
  - No significant rotation
- RT Vir clouds 1-2 AU
  - Shell inner radius determined by quenching density
  - Clouds ~50x over dense



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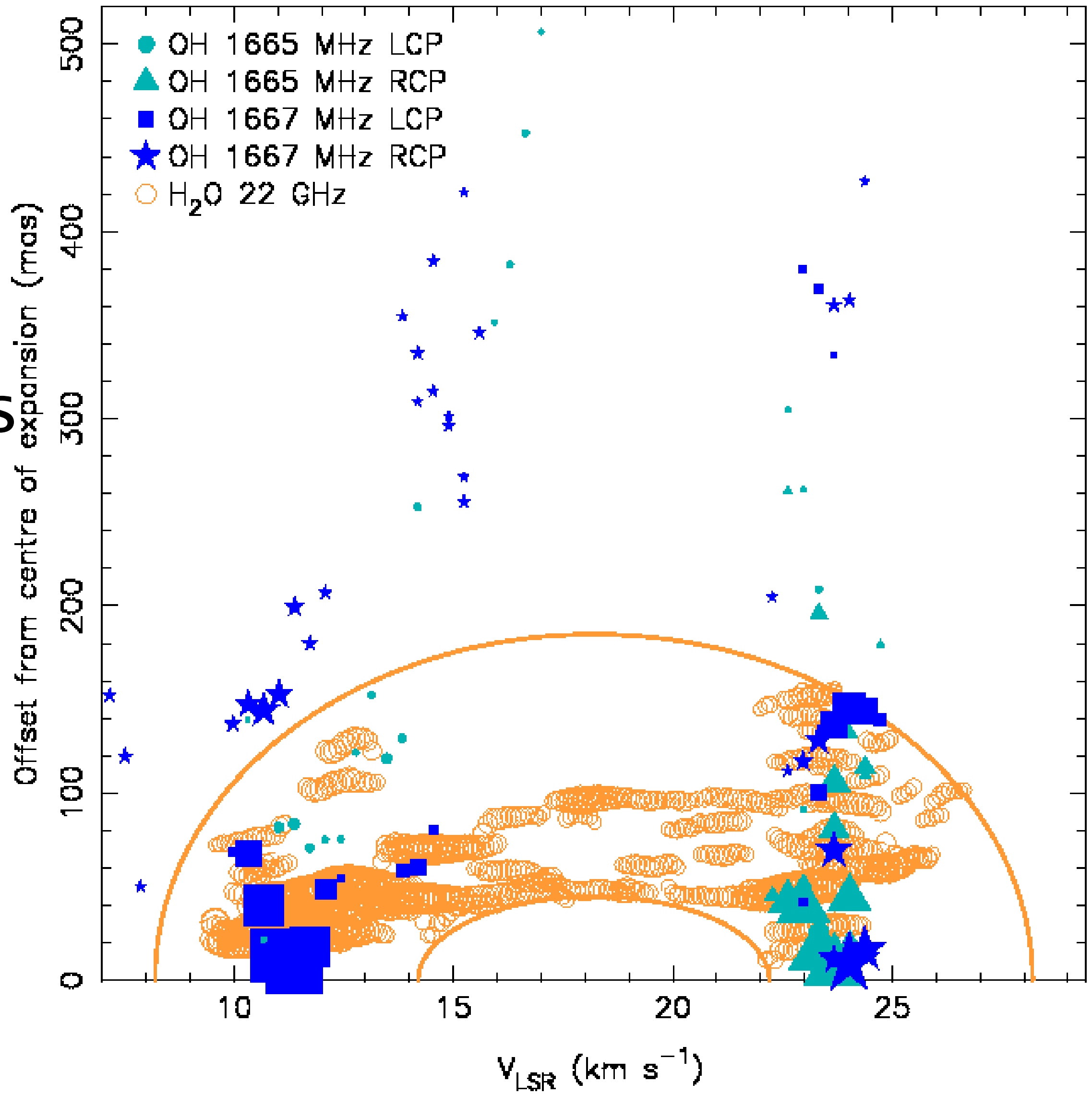
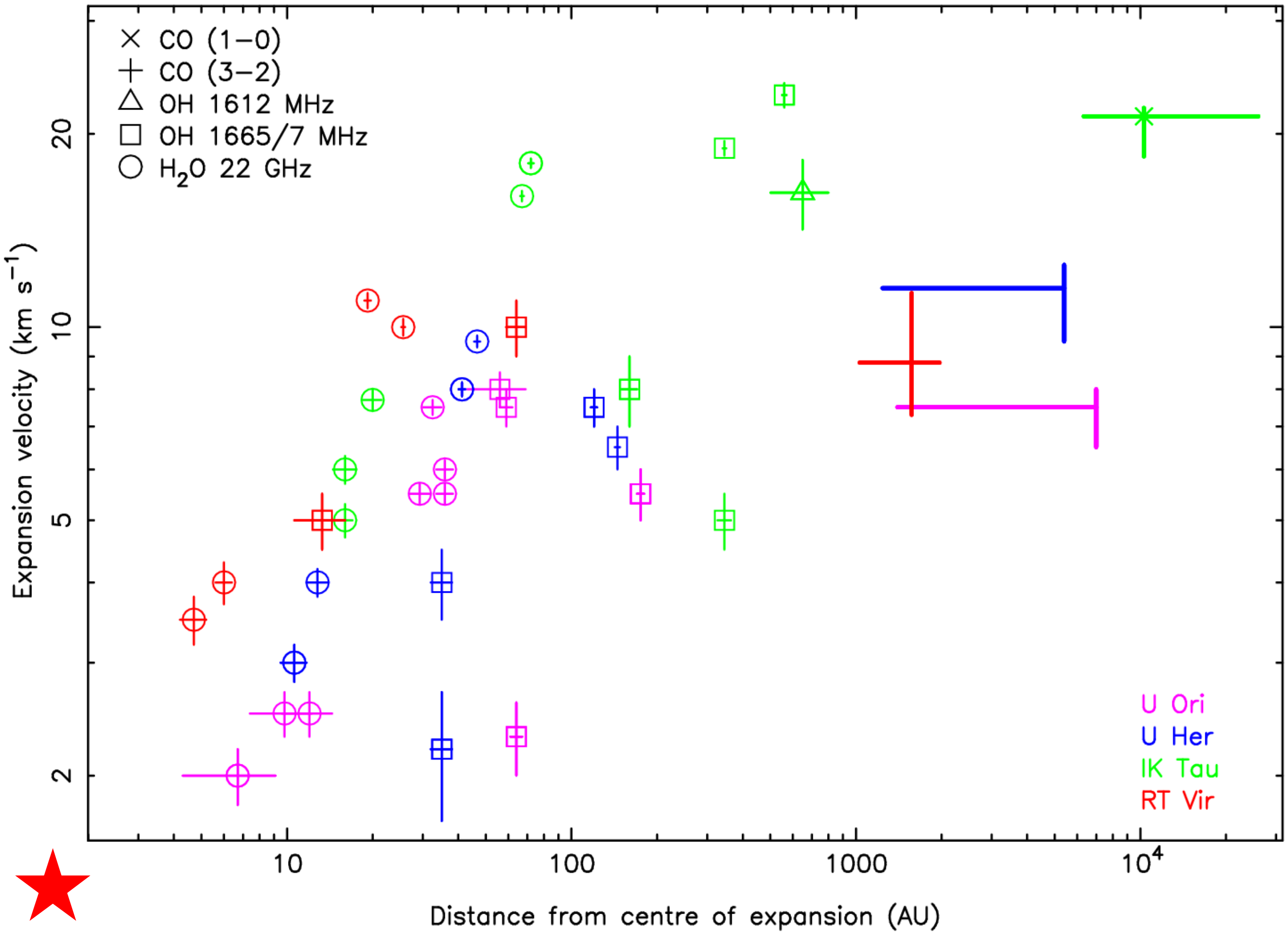


# Dust-driven wind acceleration

- Bounds of resolved maser shells
  - CO outer limits
- Wind accelerates to 100s AU
  - Dust absorption coefficient increases
  - $\kappa_D \propto r$ *(Chapman & Cohen 86)*
  - Why do OH mainlines have bigger scatter?
  - IR shows dust properties evolve
    - *Verhoelst et al.*

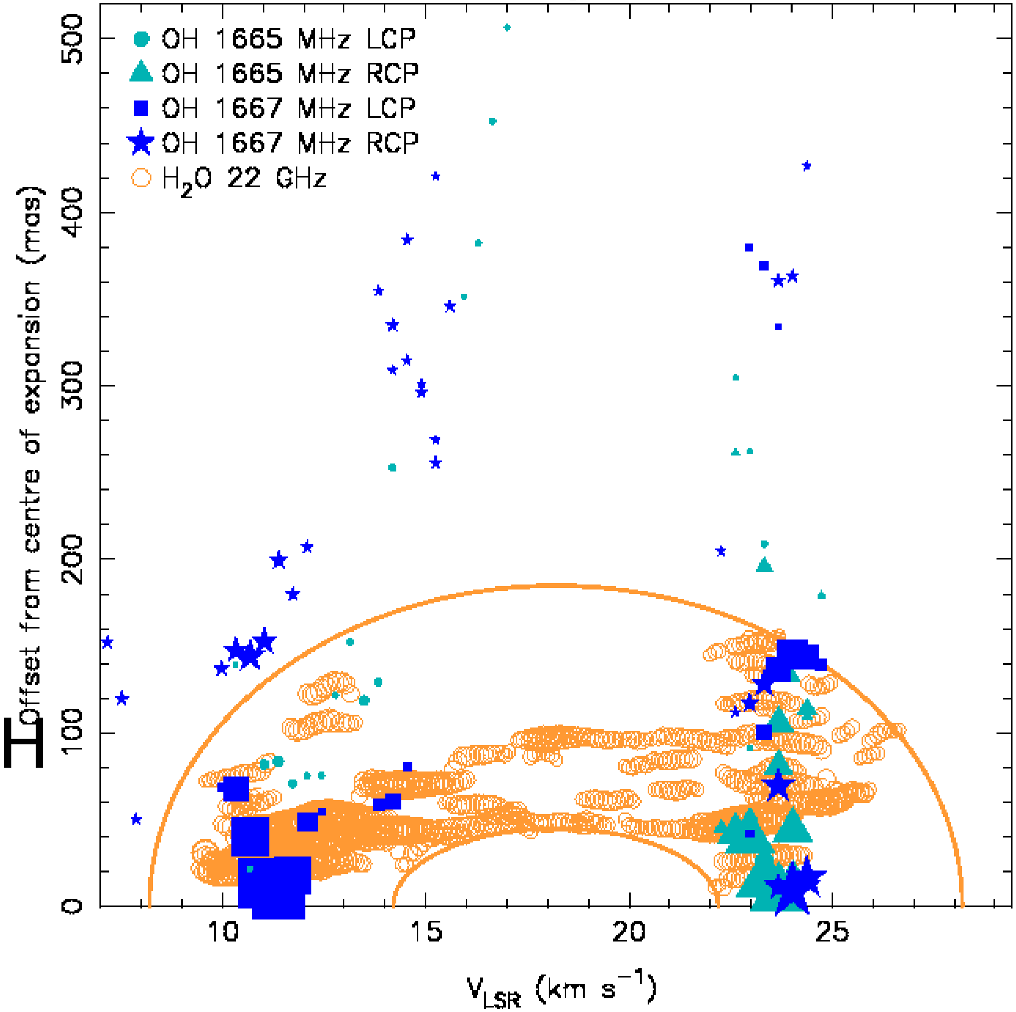



Data: *Bains+ 2003* (incl. CO refs), MERLIN $H_2O$, MERLIN+EVN OH

# OH in unexpected places

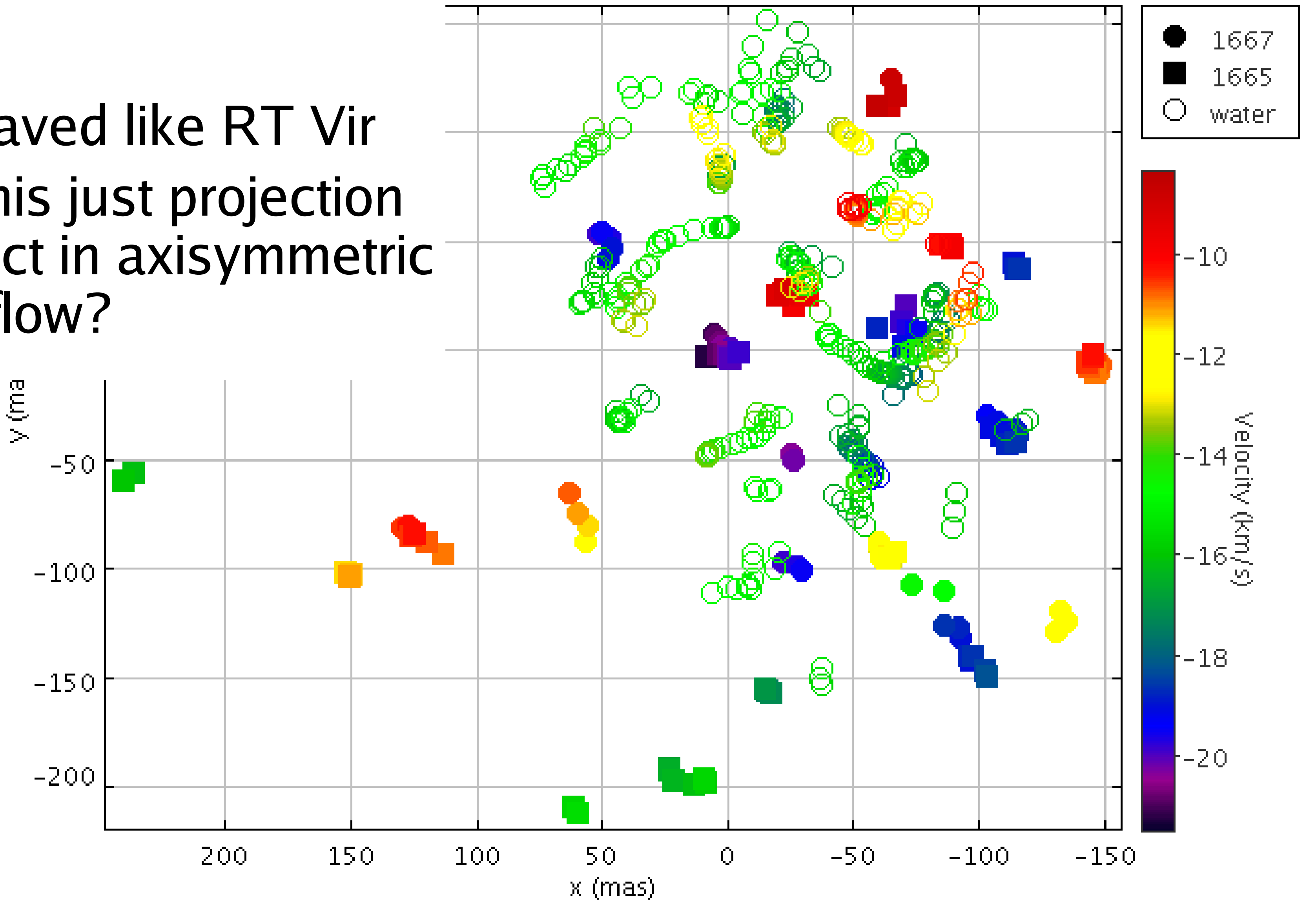
- OH mainlines interleave outer $H_2O$ shell
  - Greater spatial extent but less acceleration
  - More evidence for lower density (less efficient coupling to dust-driven acceleration).
- No 4-6 GHz OH detection is problematic constraint
  - Temperature required for OH excitation << $H_2O$
  - Need VLBI to probe more distant sources

– MERLIN resolves RT Vir at 133 pc



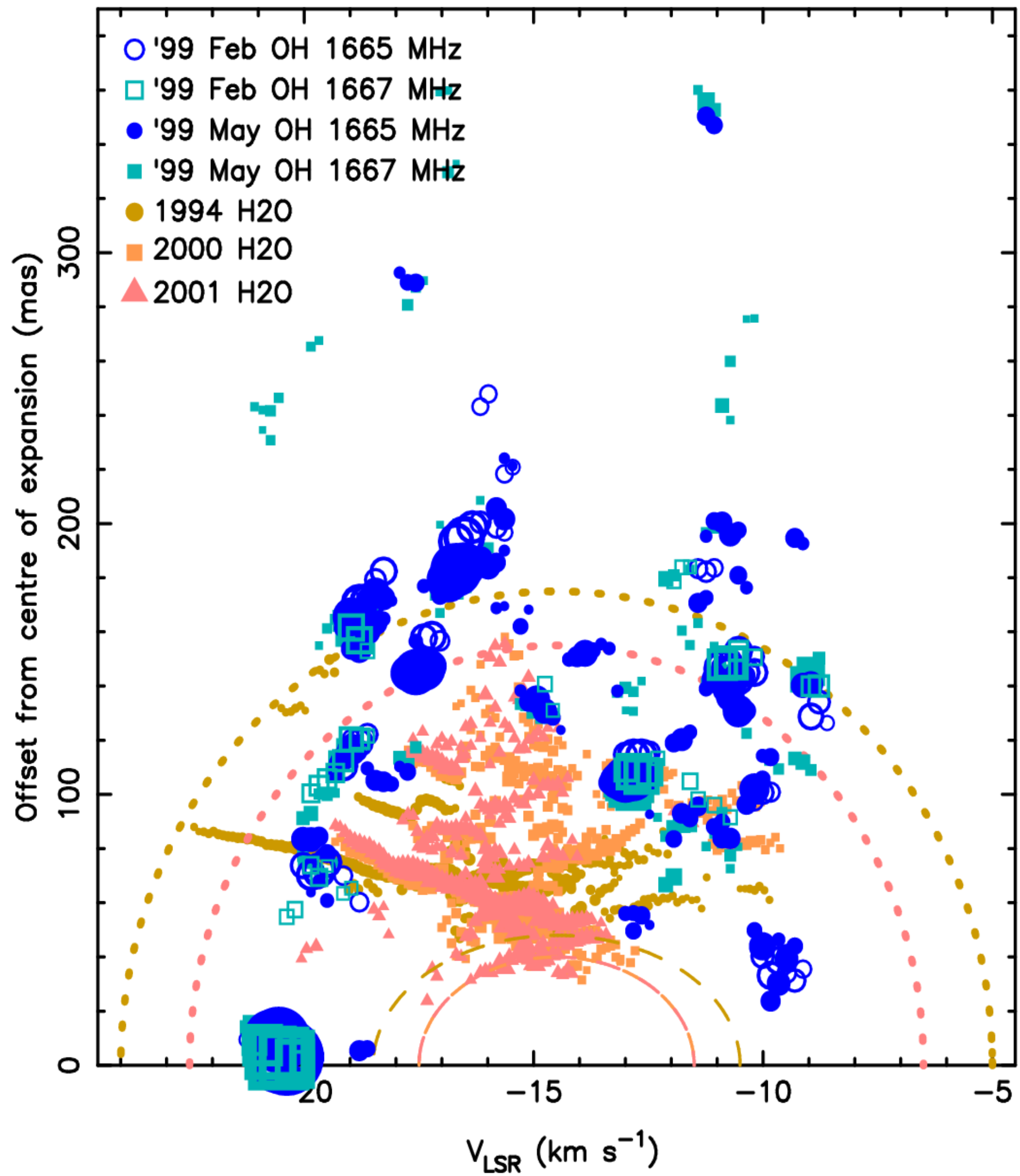
# Projection effect?

- U Her
  - Interleaved like RT Vir
    - Is this just projection effect in axisymmetric outflow?



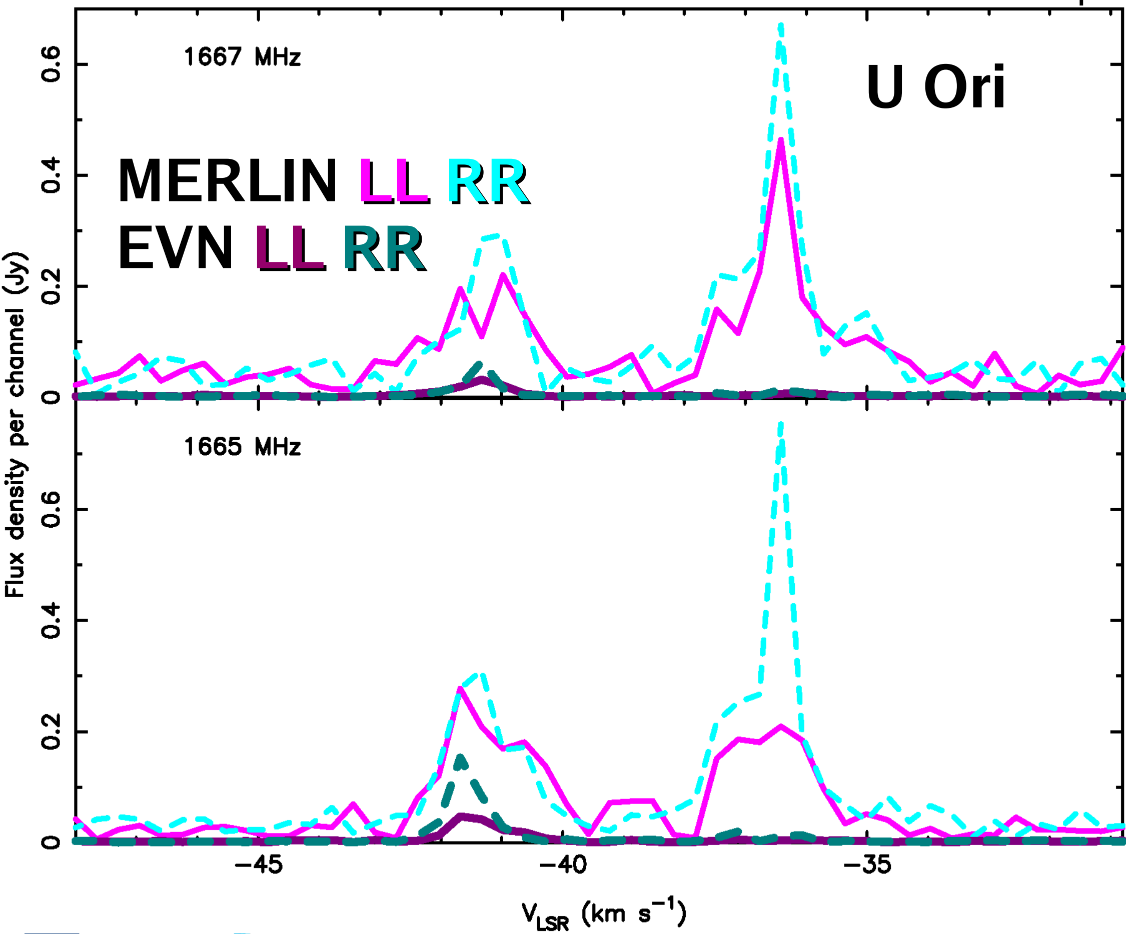
# Maser survival

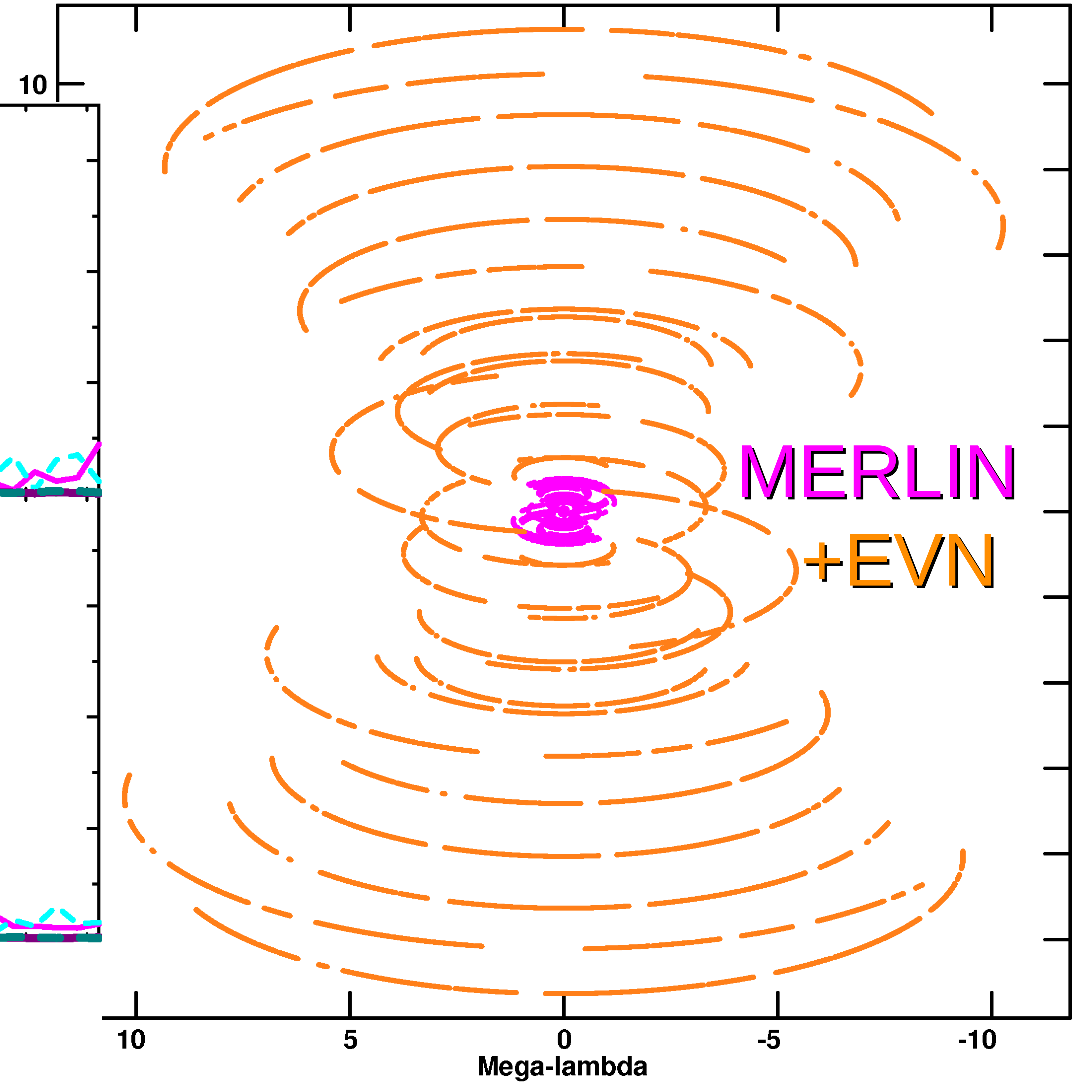
- U Her $H_2O$ 2000-2001
  - 14 clouds matched
  - Expansion 2.7(0.1) km/s
  - Rotation 0.3(0.1) km/s
- 4 epochs EVN OH
  - 3 reduced
  - Hope to measure proper motions
  - Deduce 3D structure and hence location
    - Is the OH really as close to the star as it looks?



# OH mainlines need e-MERLIN+EVN

- EVN resolves out 30%-95% of emission
  - MERLIN-only barely resolves



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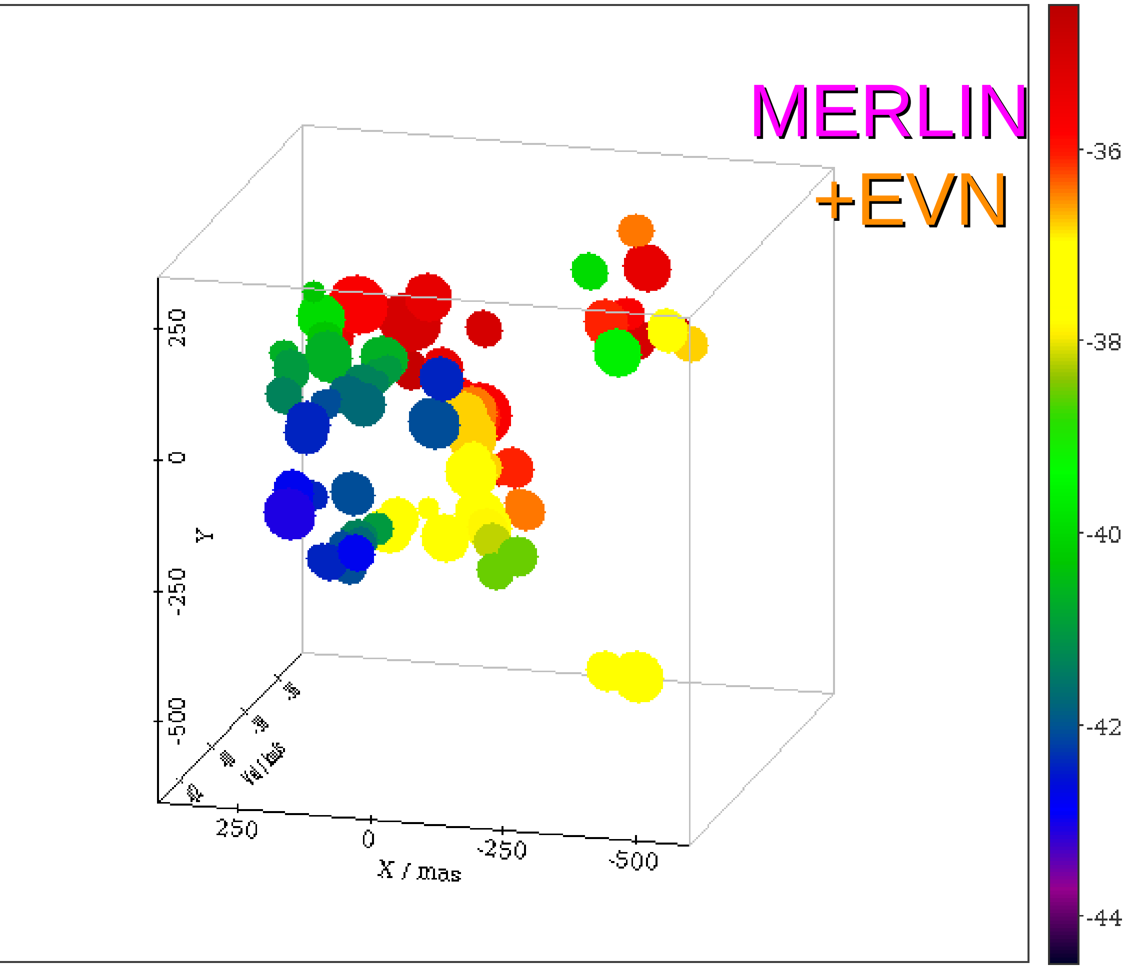
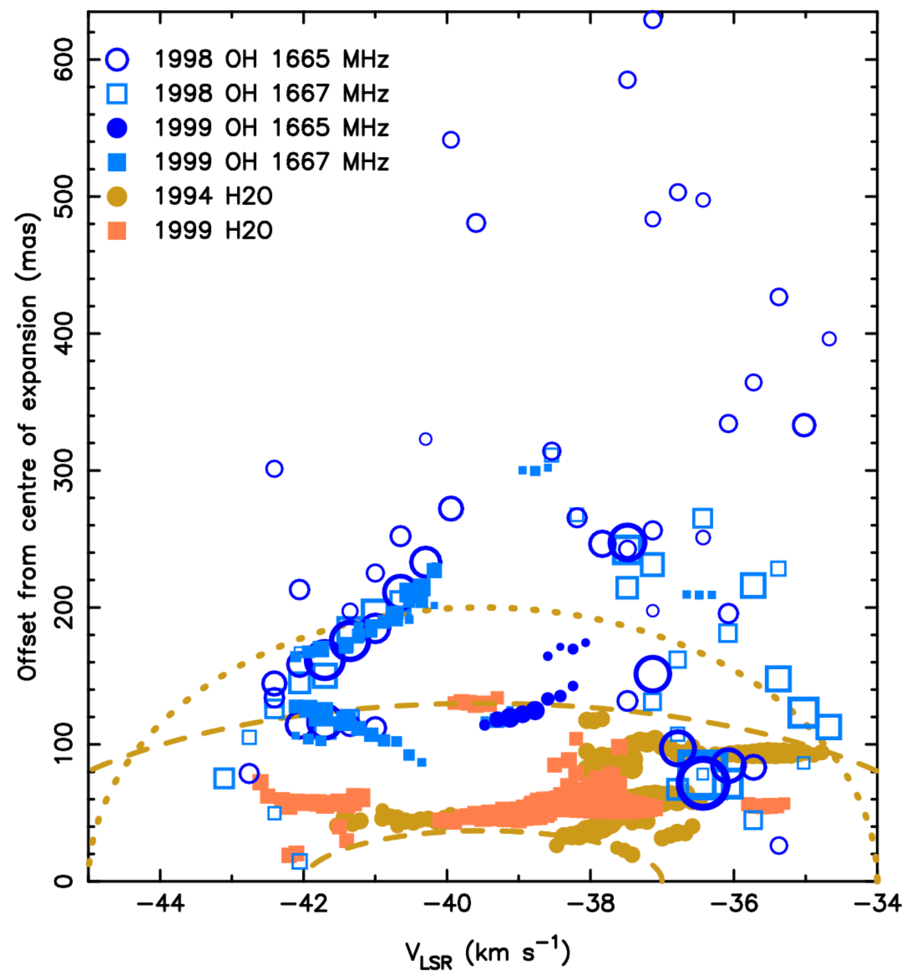
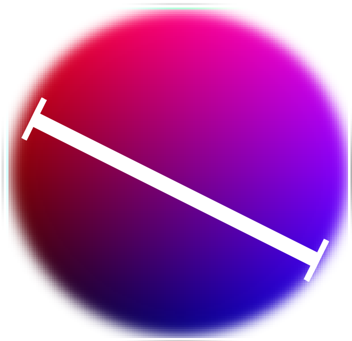
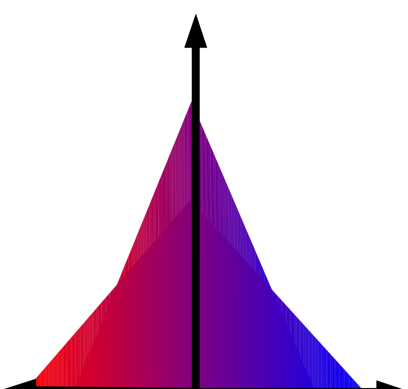


# Maser components and cloud sizes

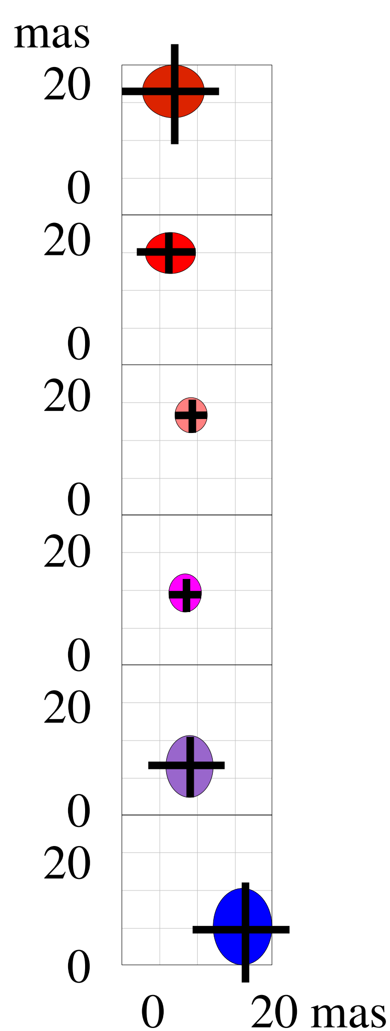
Spherical
$D$=18 AU @1 kpc



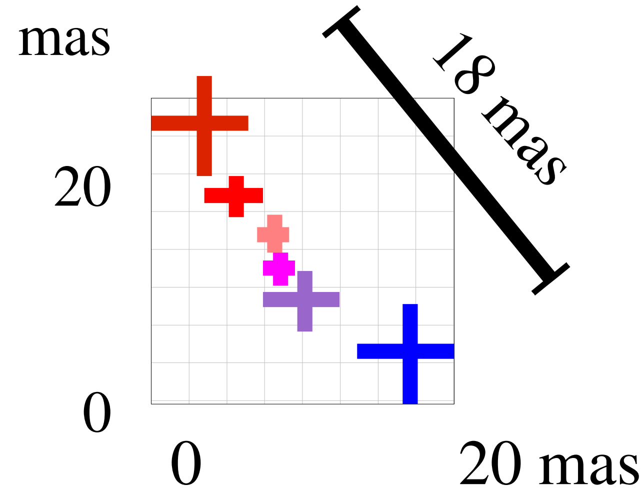


1.2 km/s total line width

## Channel maps every 0.2 km s$^{-1}$



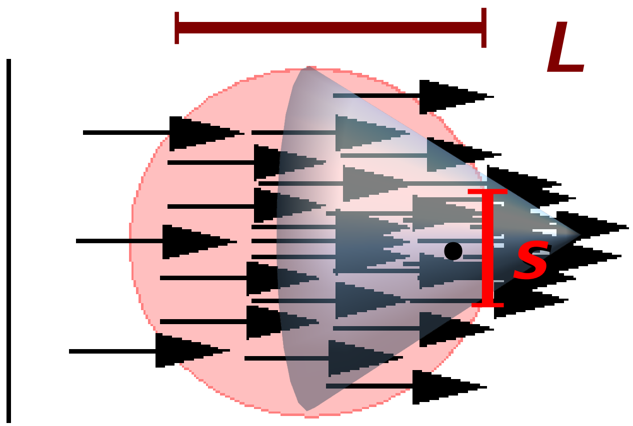

## Component measurements




*Individual* component has *beamed* size

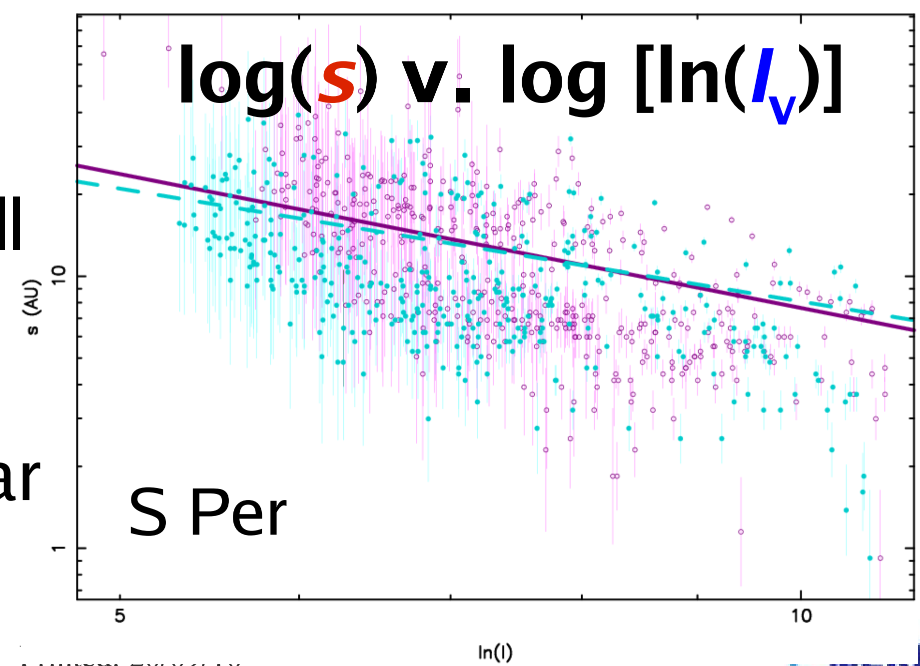
Largest angular separation *across all channels* is *actual* cloud size (18±5 mas)

# Beaming from spherical clouds



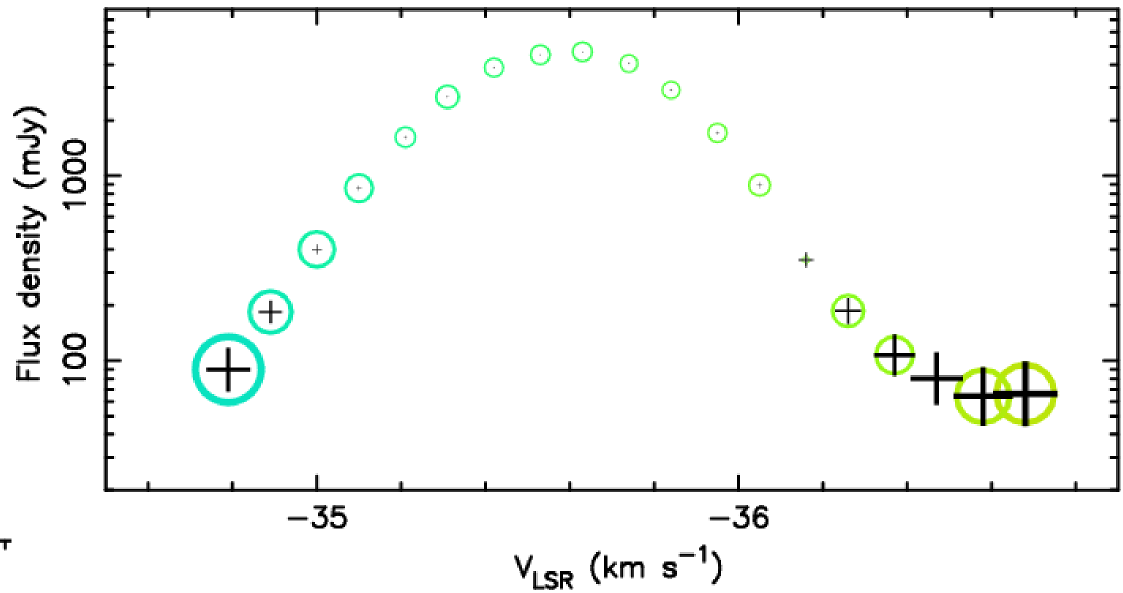

- "Amplification-bounded beaming"
  - L = Measured size of multi-chan clouds
  - Observed (beamed) size *s*
    - Measured component size per channel
  - Brighter maser (peak $I_\mathrm{v}$), tighter beam
  - $s \propto 1/\mathrm{sqrt}\,[\ln(I_\mathrm{v})]$

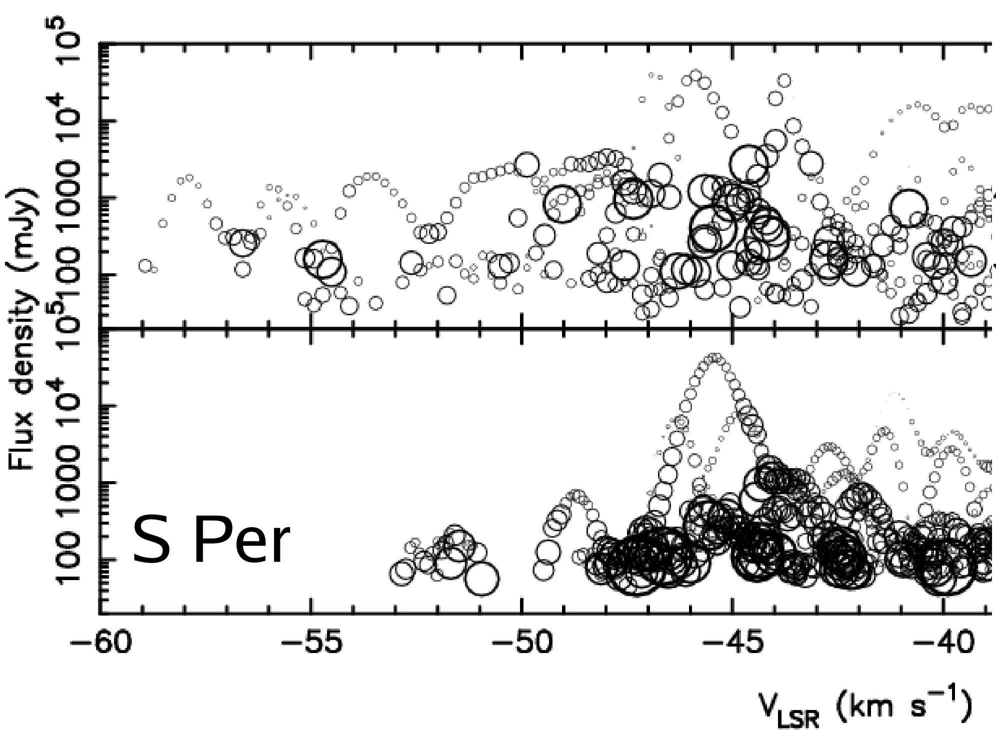
- Slope ~ -0.5-1.5 for S Per, RT Vir, IK Tau (mostly)
  - Bright, well-filled maser shell
    - Steeper may be due to saturation
  - Small-amplitude, less regular optical periods

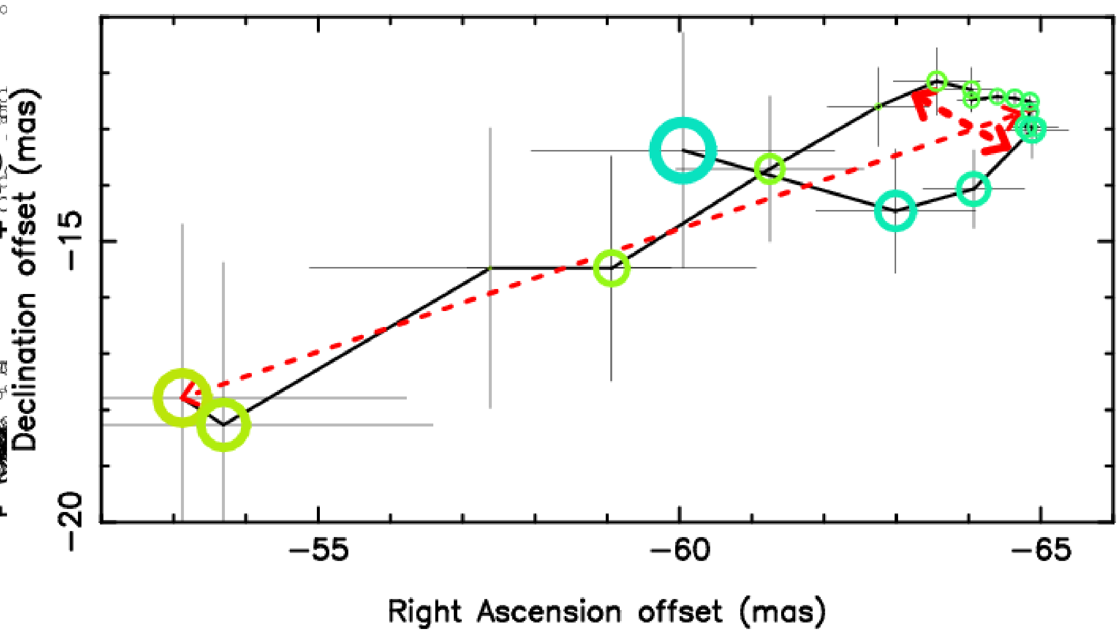


# Amplification bounded spheres

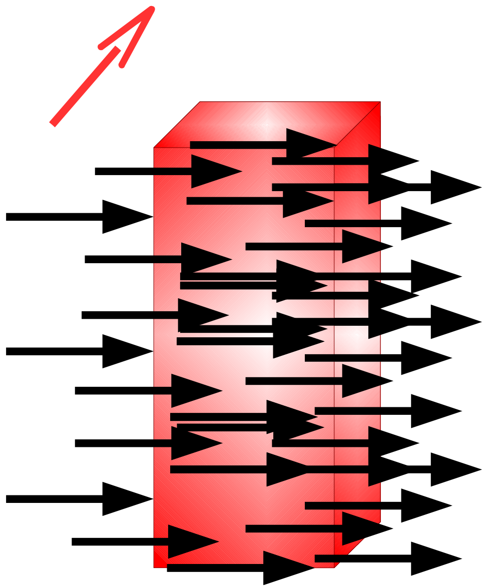
- Brighter components near line peaks are smaller
- Coherent, curved spatial distribution



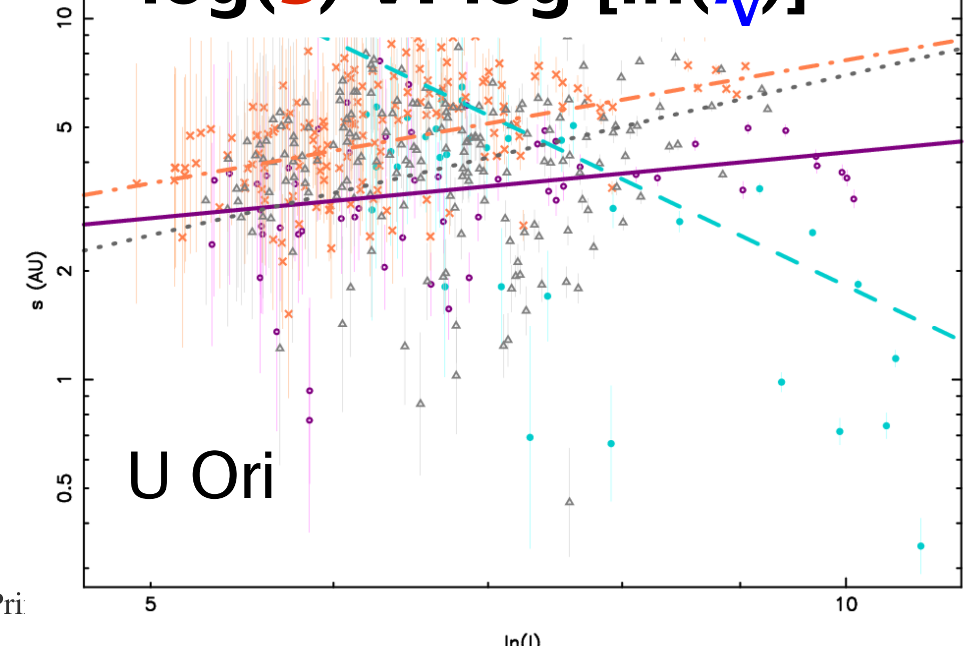



# Beaming from shocked slabs

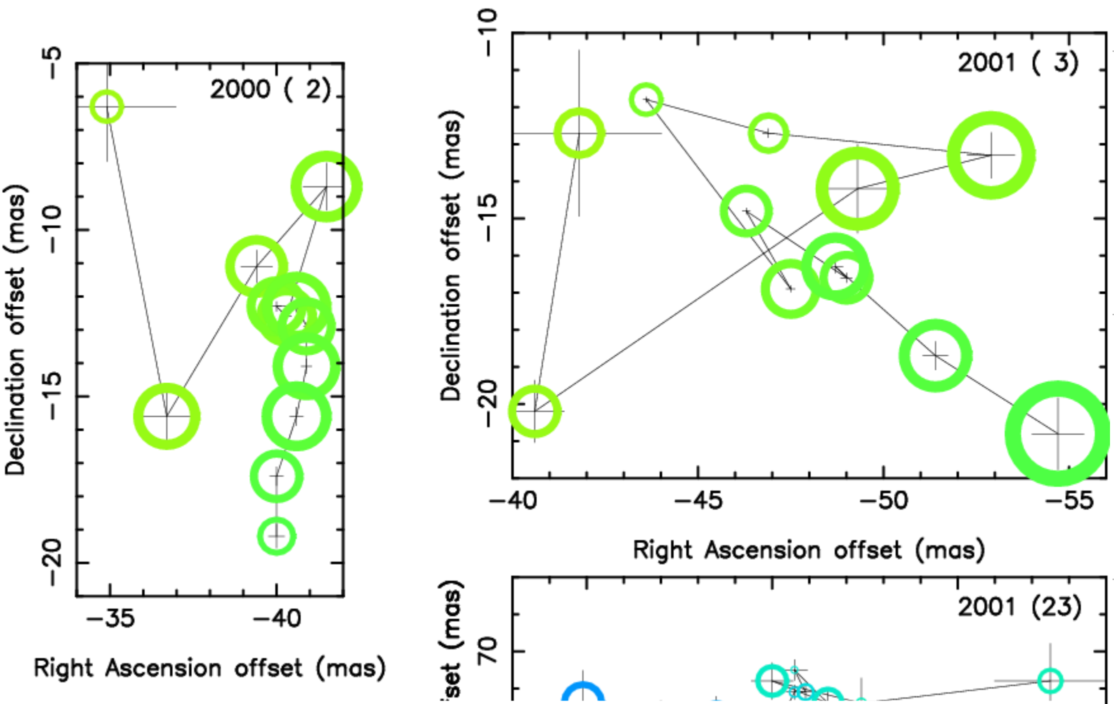


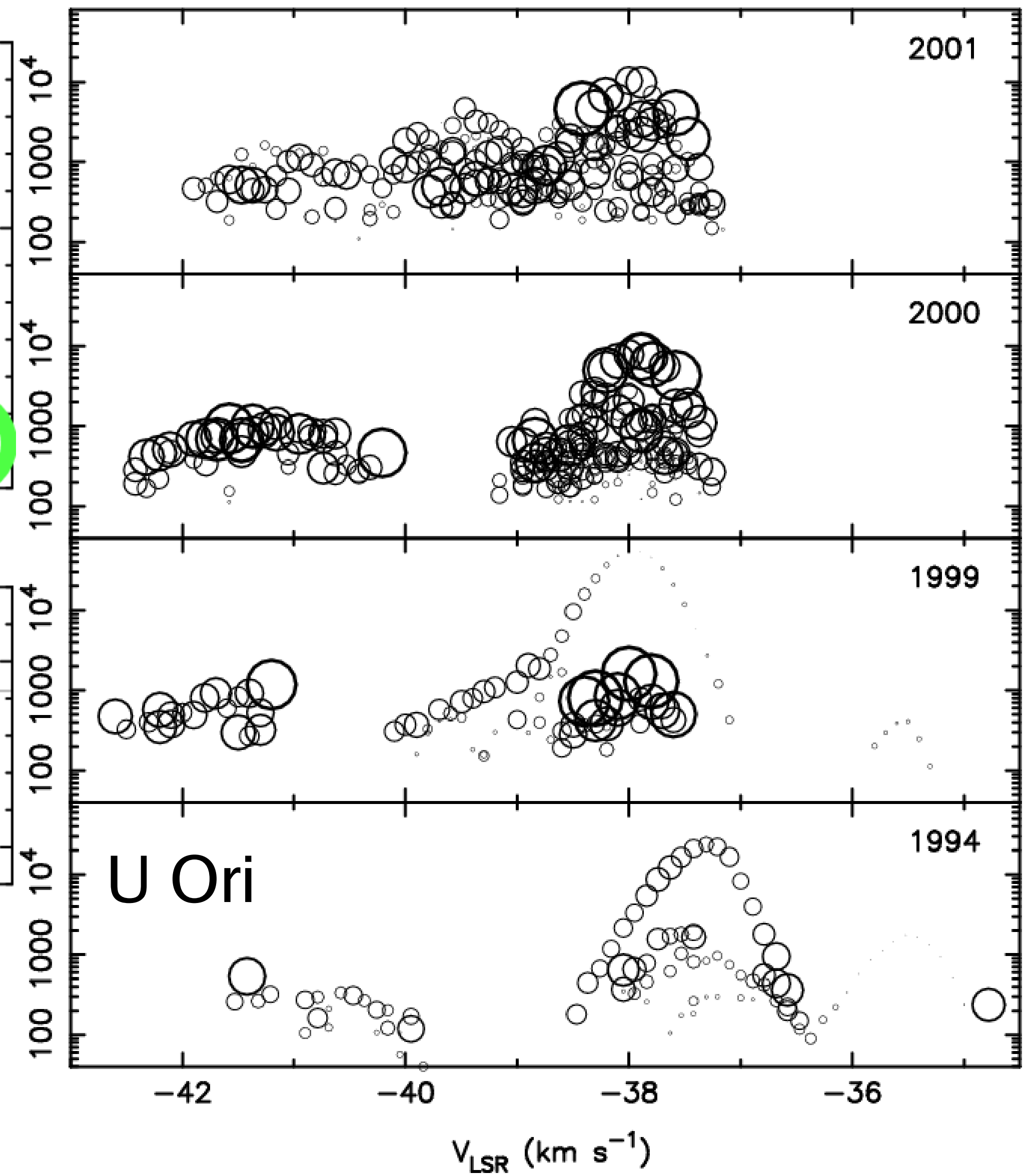
- Shock 'into page'
  - Maser propagates perpendicular to shock
  - Pump photons escape orthogonally
  - Entire surface emission is amplified
  - "Matter bounded"beaming
  - apparent size ~ actual size ($s$ ~ $L$)
- Slope >> 0 or large scatter for U Ori, U Her
  - Other evidence for shocks:
    - Regular, deep pulsations (*AAVSO*)
    - OH and H$\alpha$ flares (*Etoka, Rudnitskj etc.*)

**log($s$) v. log [ln($I_v$)]**



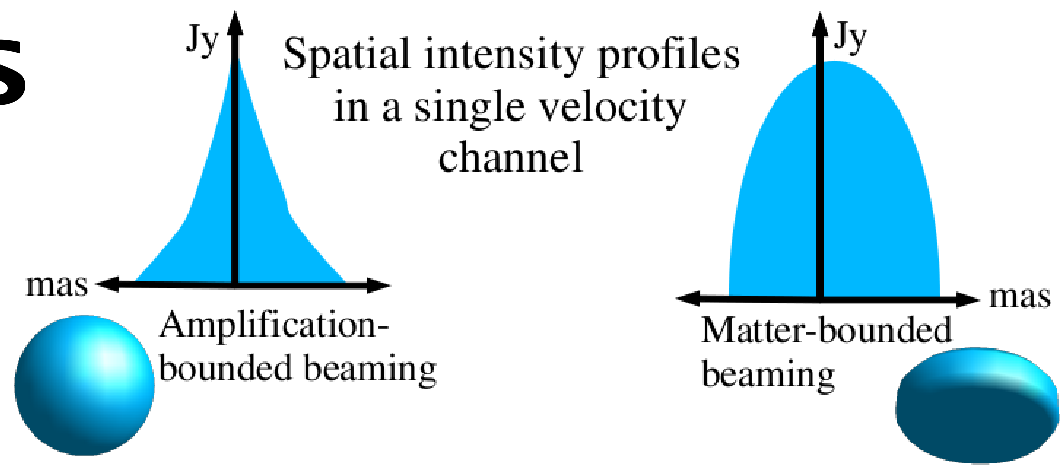
# Matter-bounded shocked masers



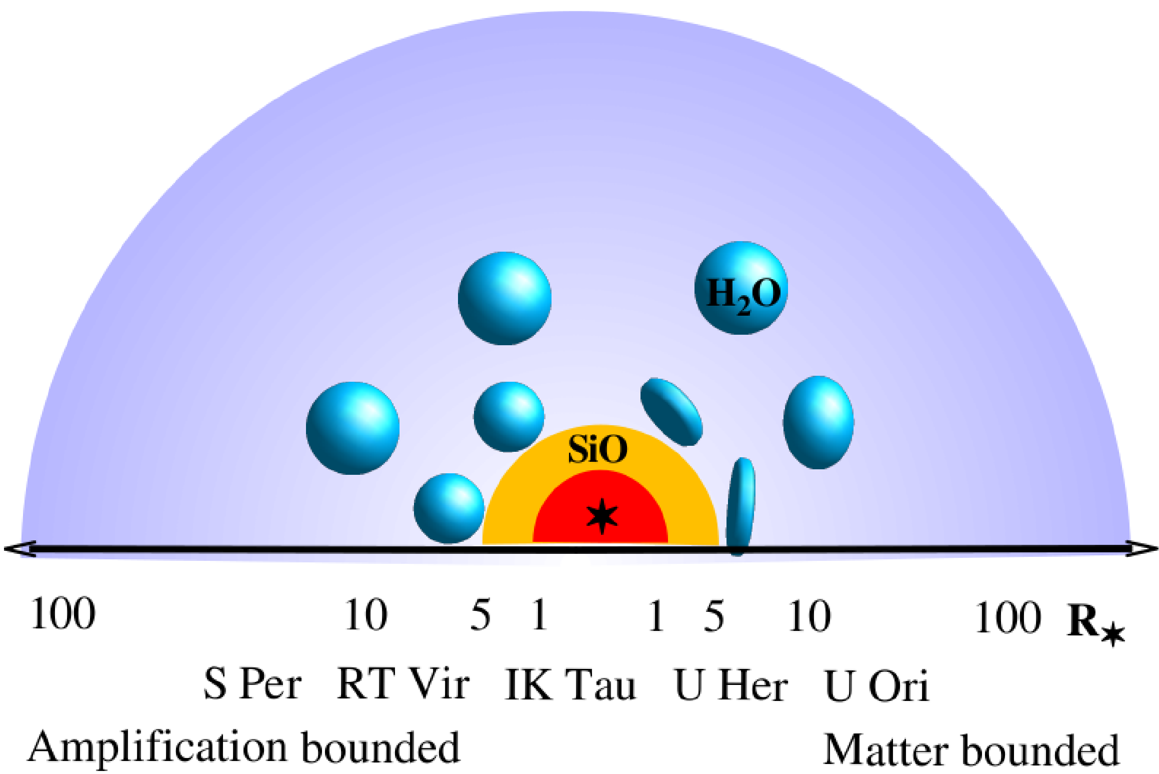




- Peak components often as large as in wings
- Tangled spatial distribution
- Fainter, poorly filled maser shells

# Maser properties reveal wind disturbances



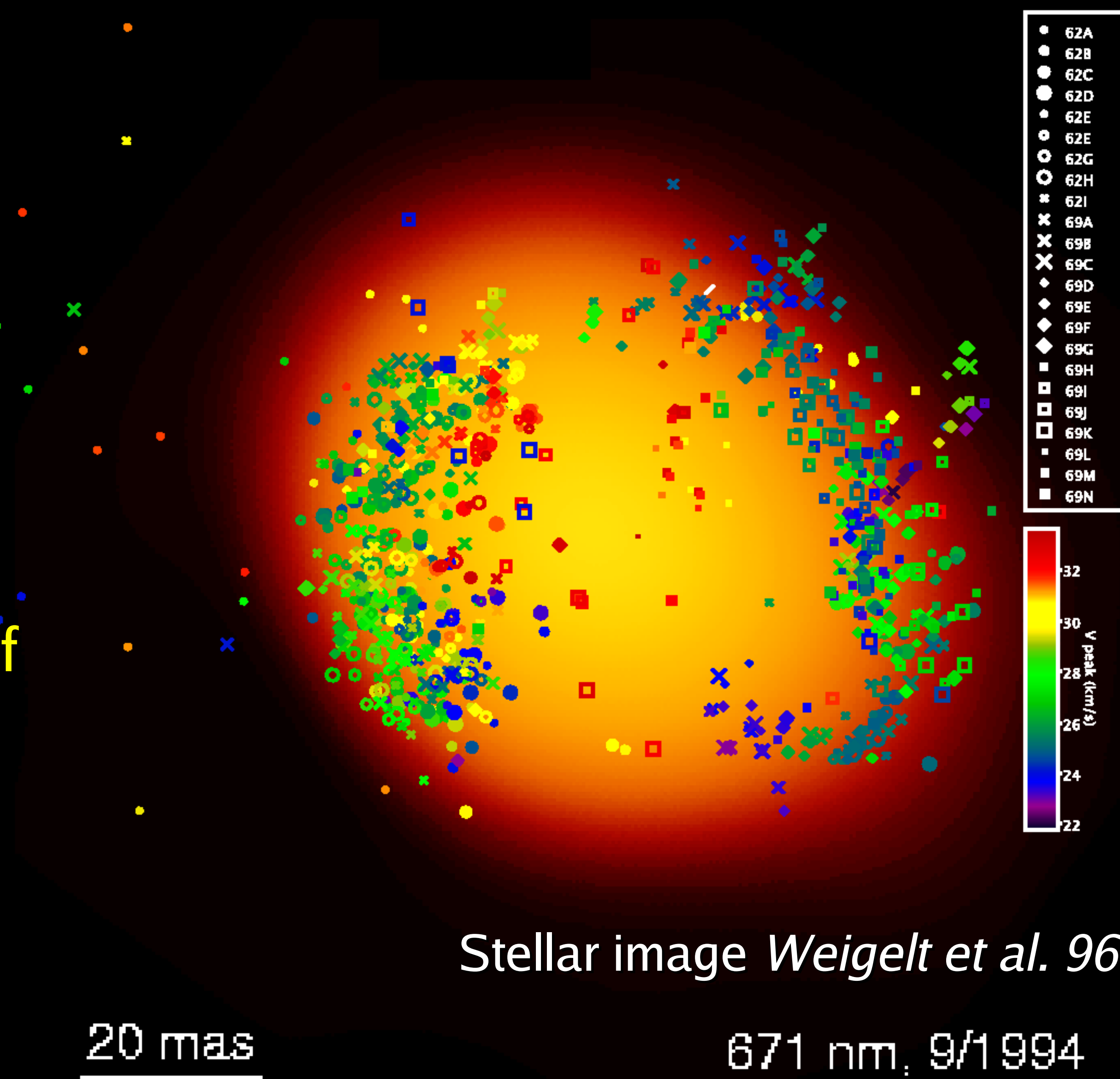

- Distinguish between smoothly expanding regions and those affected by pulsations
  - Need to detect ~all the emission
- e-MERLIN+EVN for OH




Based on
*Richards Elitzur & Yates 2010*
*Elitzur Hollenbach & McKee 1992,*

# R Cas SiO

- 21 epochs (2 stellar cycles)
  - See poster by *Al-Muntafki*
- Infall/outflow?
- Or new shells emerging/ old shell fading?
  - Seems to come from half the star in turn
- ALMA+ e-MERLIN + VLBI trace mass loss from star to ISM




Stellar image *Weigelt et al. 96*

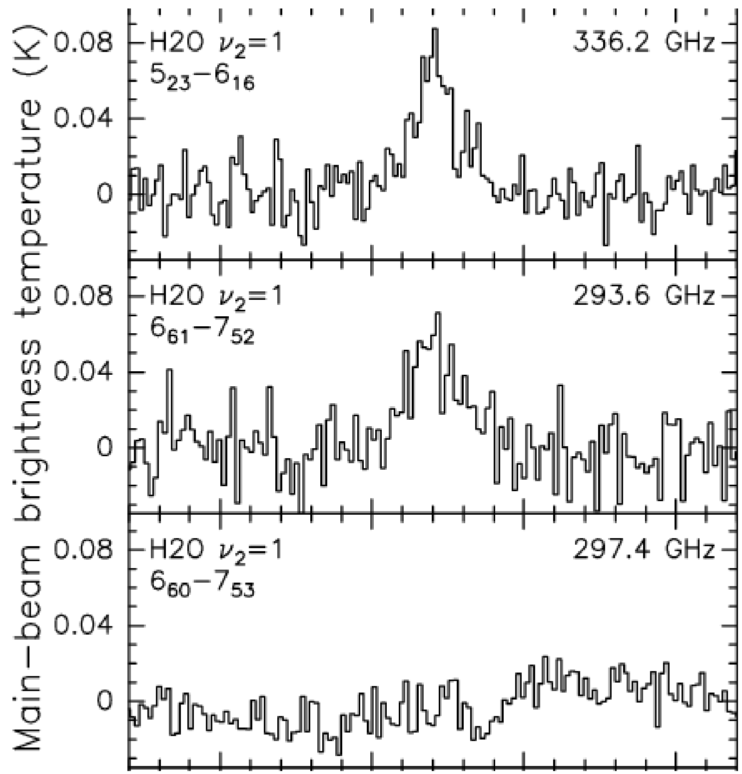
# ALMA evolved star masers

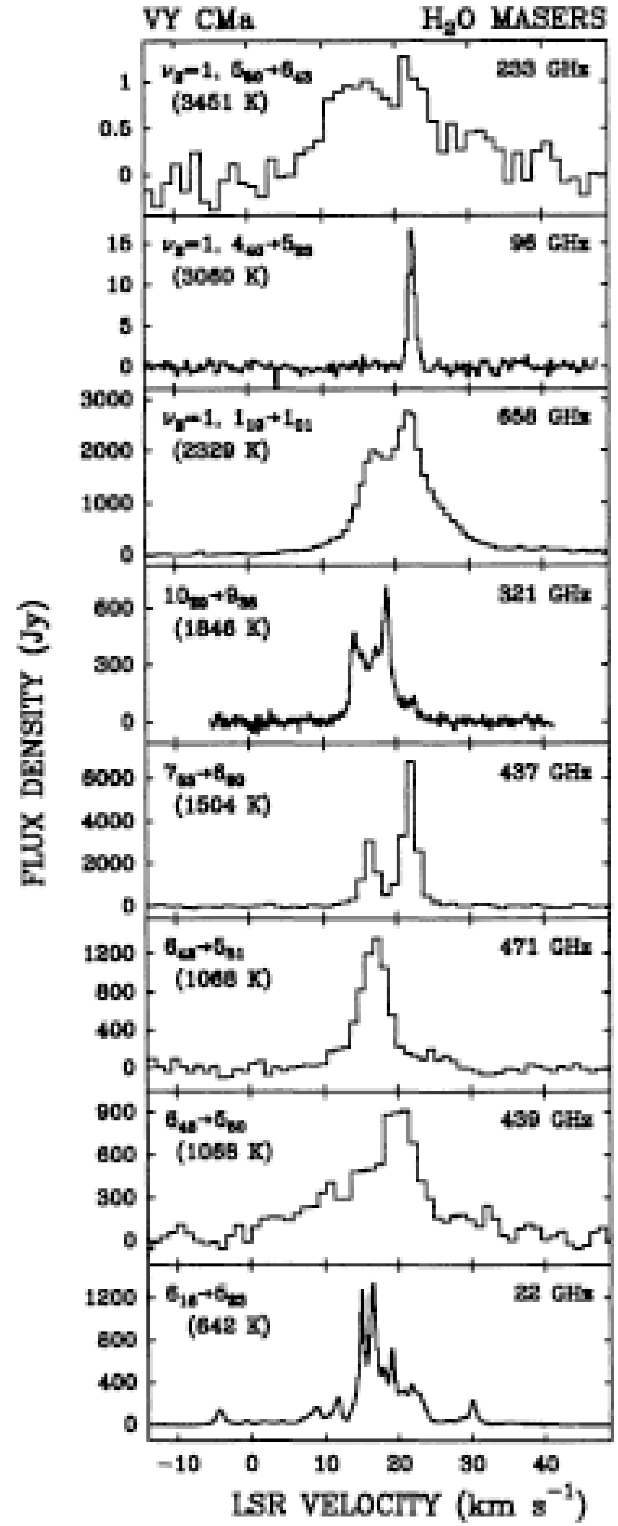
| Band | $\theta_{B(16km/1km)}$ (mas) | $H_2O$ (GHz) | SiO (GHz) | HCN (GHz) |
|---|---|---|---|---|
| 3 | 40 / 650 | 96 | | |
| 5 | 20 / 320 | 183 | | 177 |
| 6 | 16 / 250 | 232 | 214, 216, 257, 259 | |
| 7 | 10-15 / 160-240 | 293, 321, 325, 336, 354 | 300, 302, 336*, 343, 345 | |
| 8 | 9 / 145 | 437, 439, 471 | | |
| 9 | 6 / 100 | 658 | | |
| 10 | 5 / 80 | | *isopotomer | 805, 891 |

- Multiple lines constrain physics much better
  - *e.g. Humphreys 2007 and refs*
- Early science - VLA-like resolution
  - Full ops - cm-wave-VLBI-like resolution

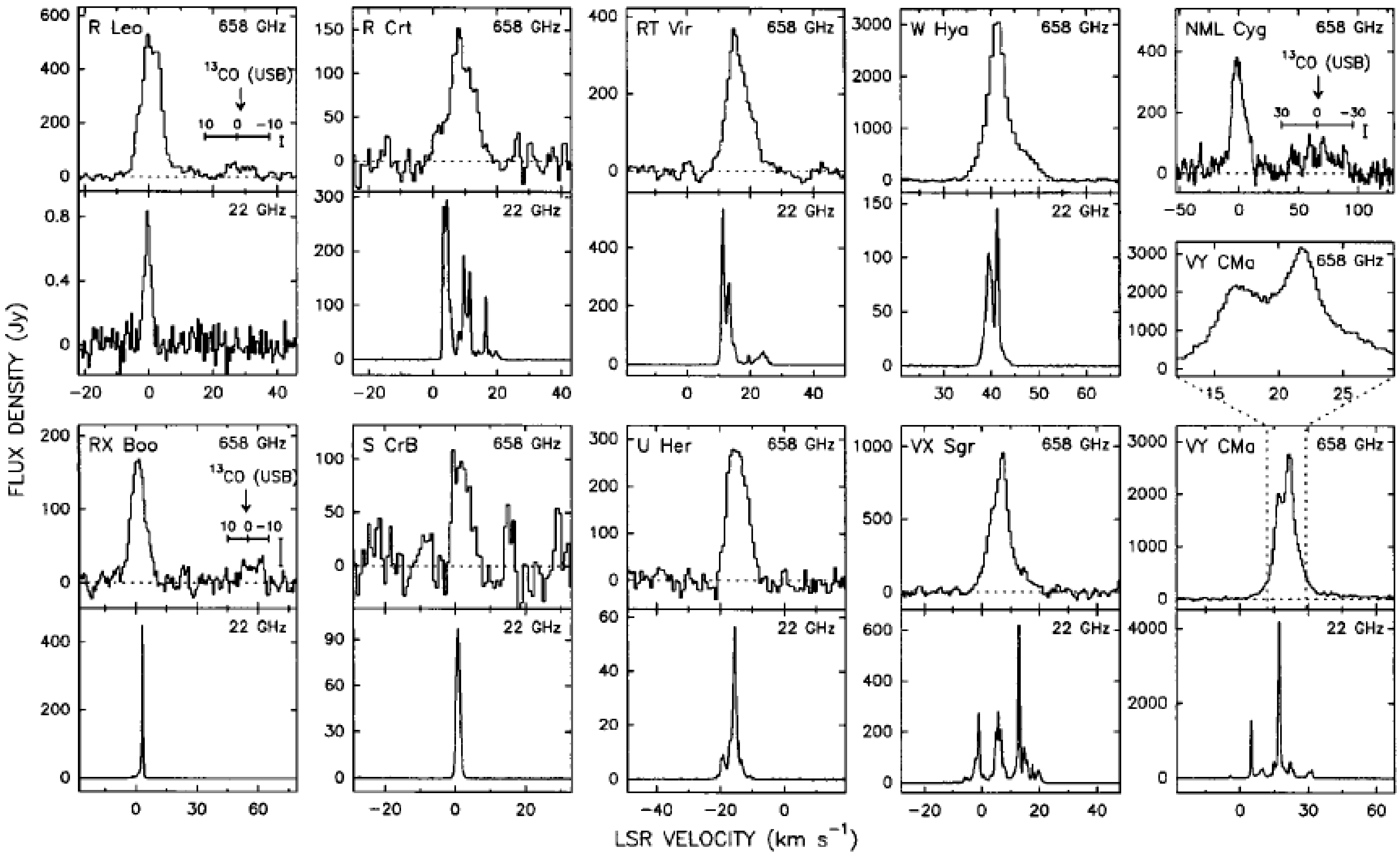
# (Sub)mm water

- Multiple transitions detected in circumstellar envelopes
  - *Menten 96; Menten+ 06*
- Guess locations from line widths/ variability/ correlation with cm transitions



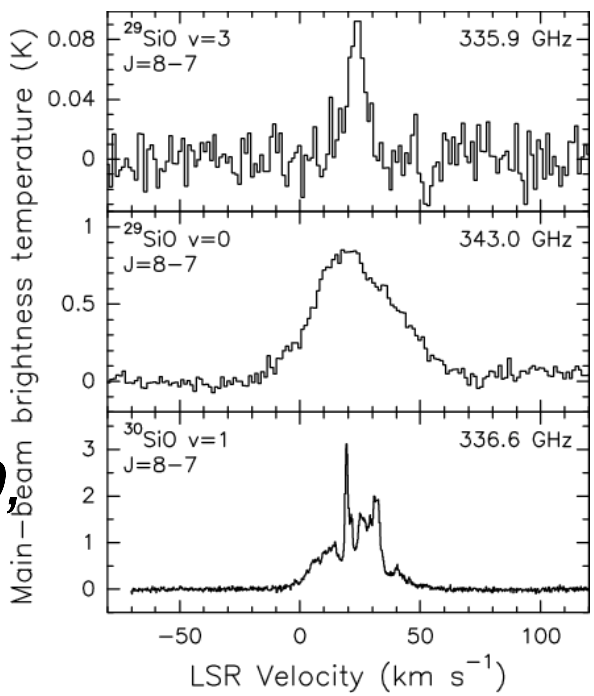
# Vibrationally excited water



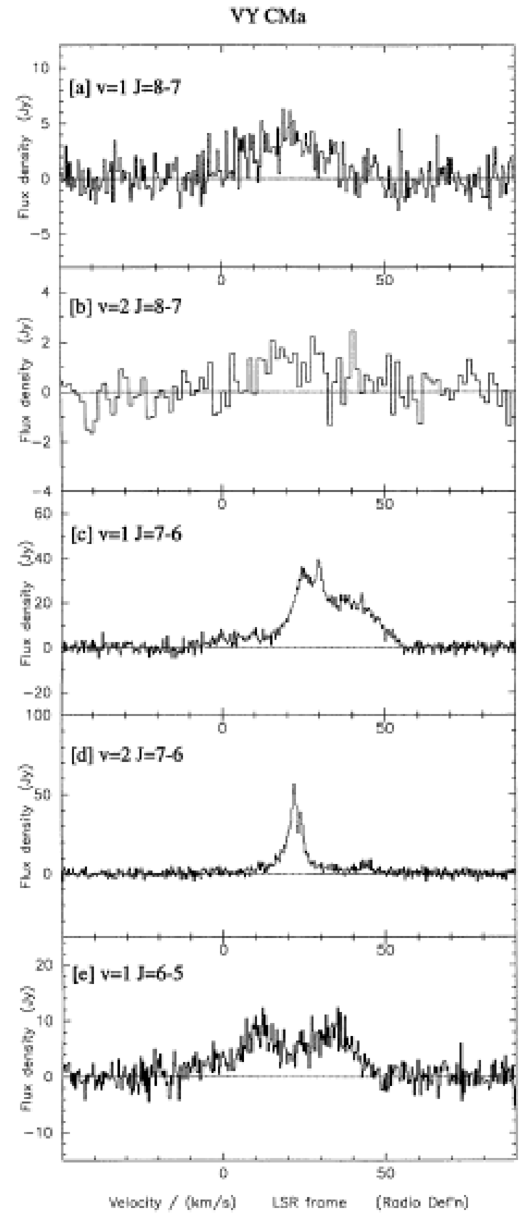

- Widespread, wide velocity 658 GHz emission

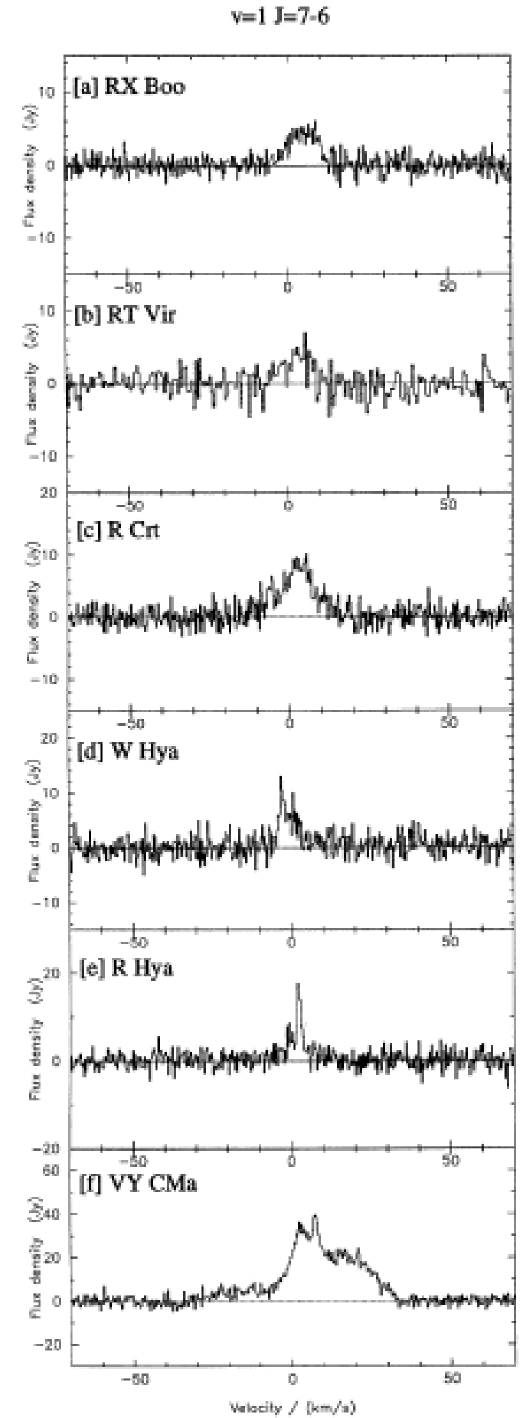
# SiO masers

- Many lines detected
  - $v$ = 0 to 4, $J$=1-0 … $J$=8-7
- Higher rotational transitions weaker, more time variable
  - Faintest at $\phi$ 0.4 - 0.7



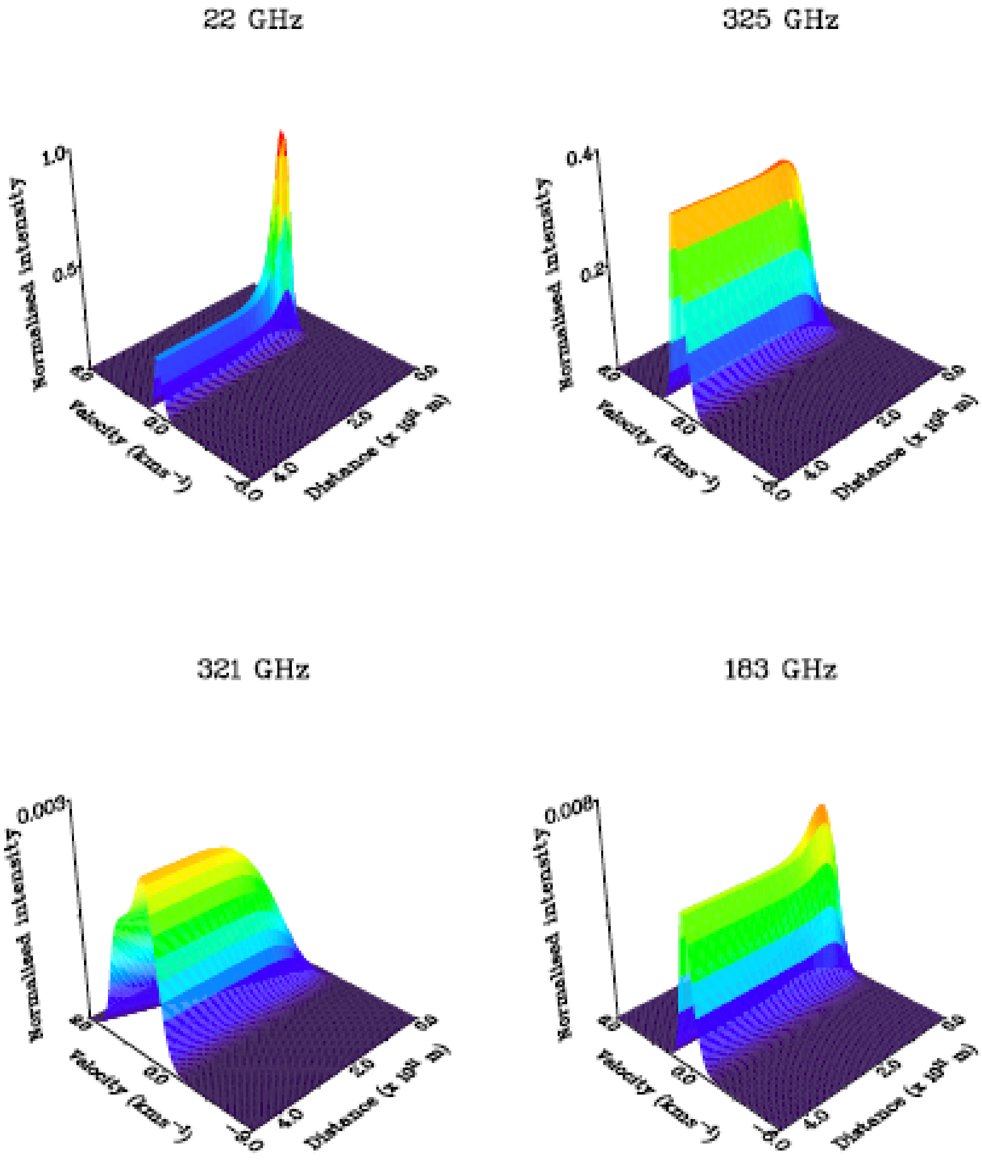

*Menten+06, Humphreys+ 96, 97, Grey+ 98, 99, Pardo+ 98*



# Sub-mmaser model predictions

- Vibrational ground-state:
  - 321 GHz peaks close to star (inside dust formation region?)
    - Anomalously wide in symbiotic R Aql (*Ivison+98*)
  - 183 GHz peaks resemble 22 GHz
  - 325 GHz wide span
  - *Humphreys+ 01*



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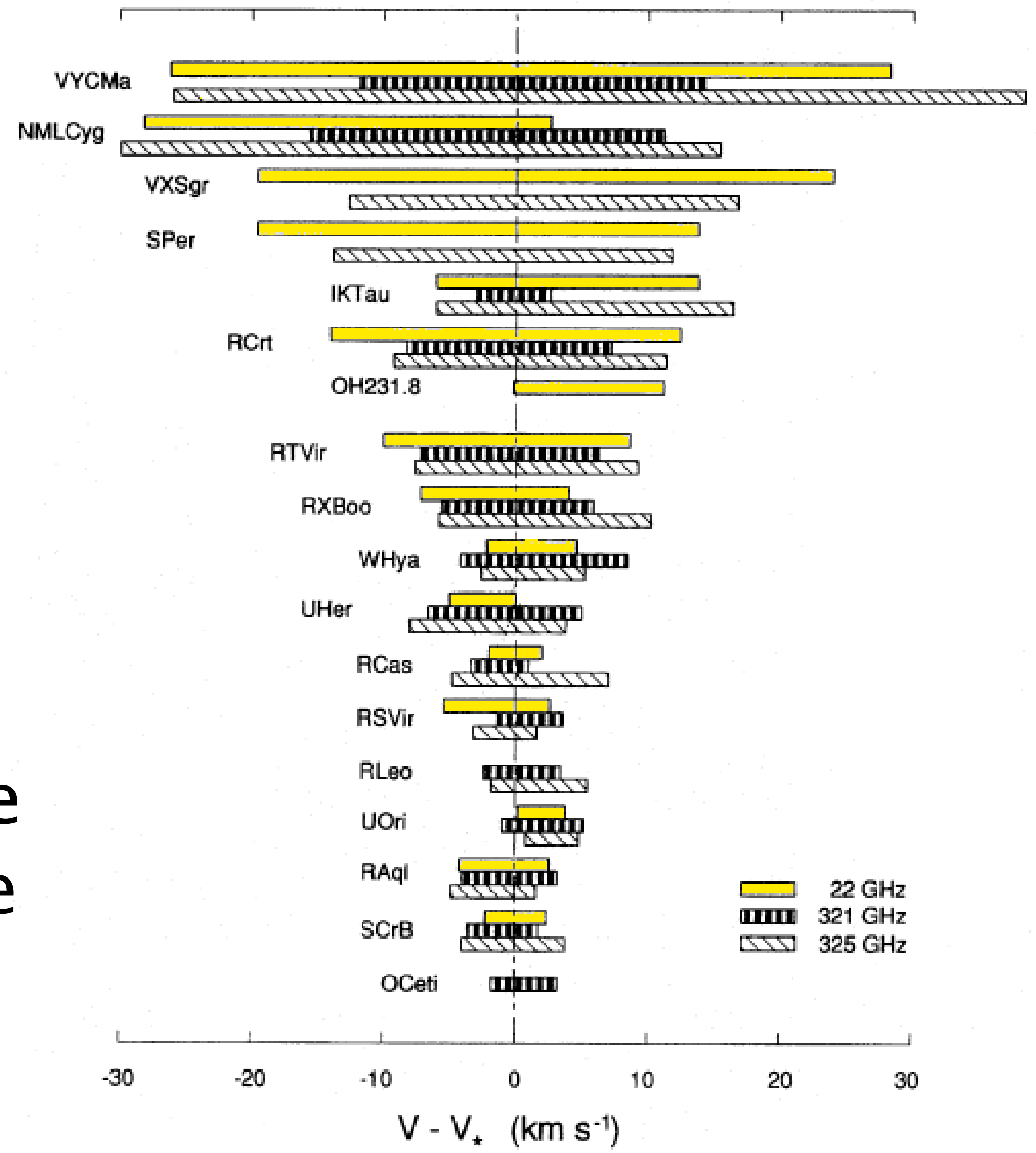
# Properties of (sub-)mm water

- Compare with cm-wave images
  - 70% 22-GHz sources have 321, 325 GHz emission *(Yates+ 96)*
- 325 GHz spectra resemble 22 GHz
- 321 GHz narrower, weaker, more variable
- 183 GHz less variable
  - *(Gonzales-Alfonso+98)*



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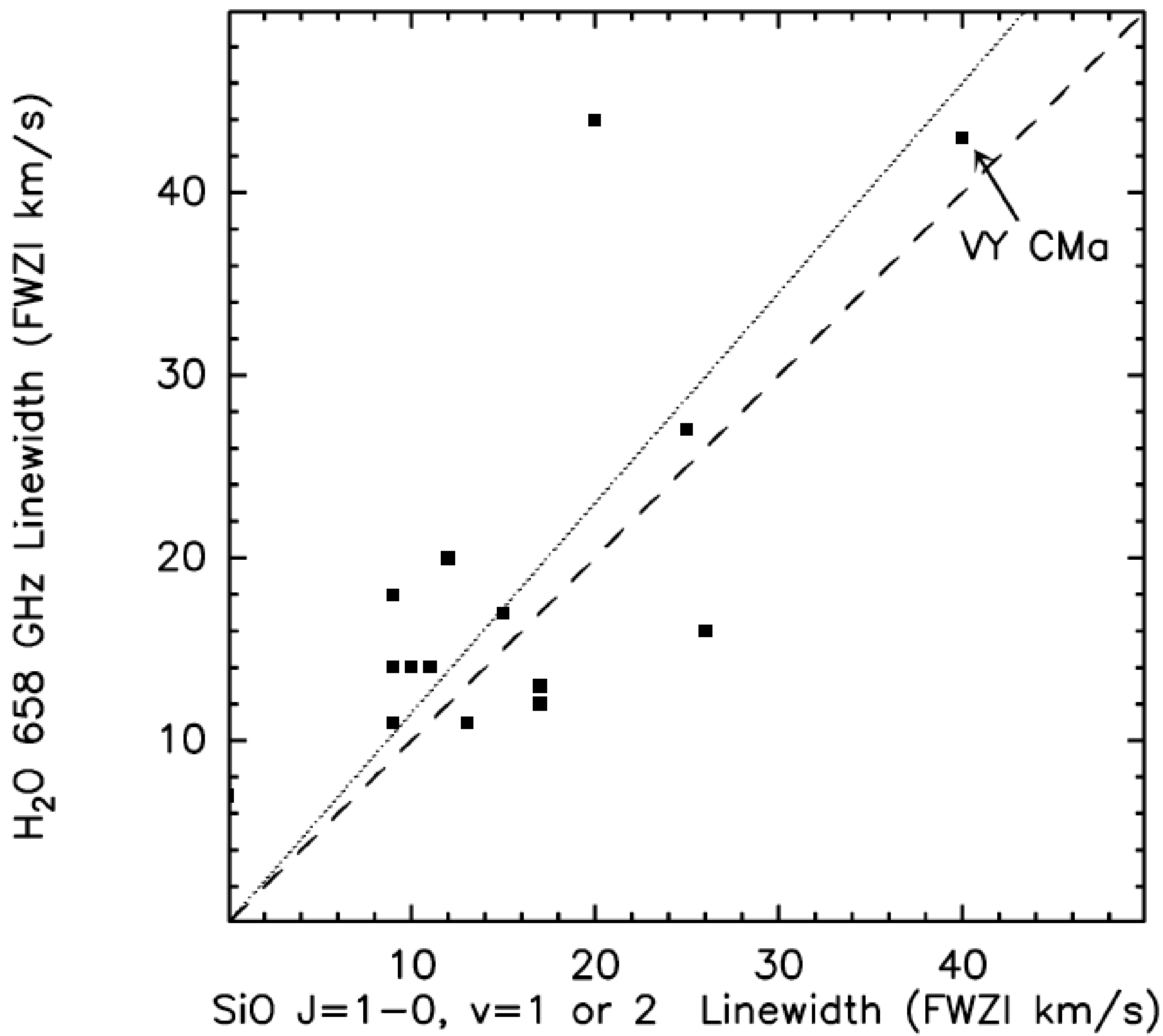
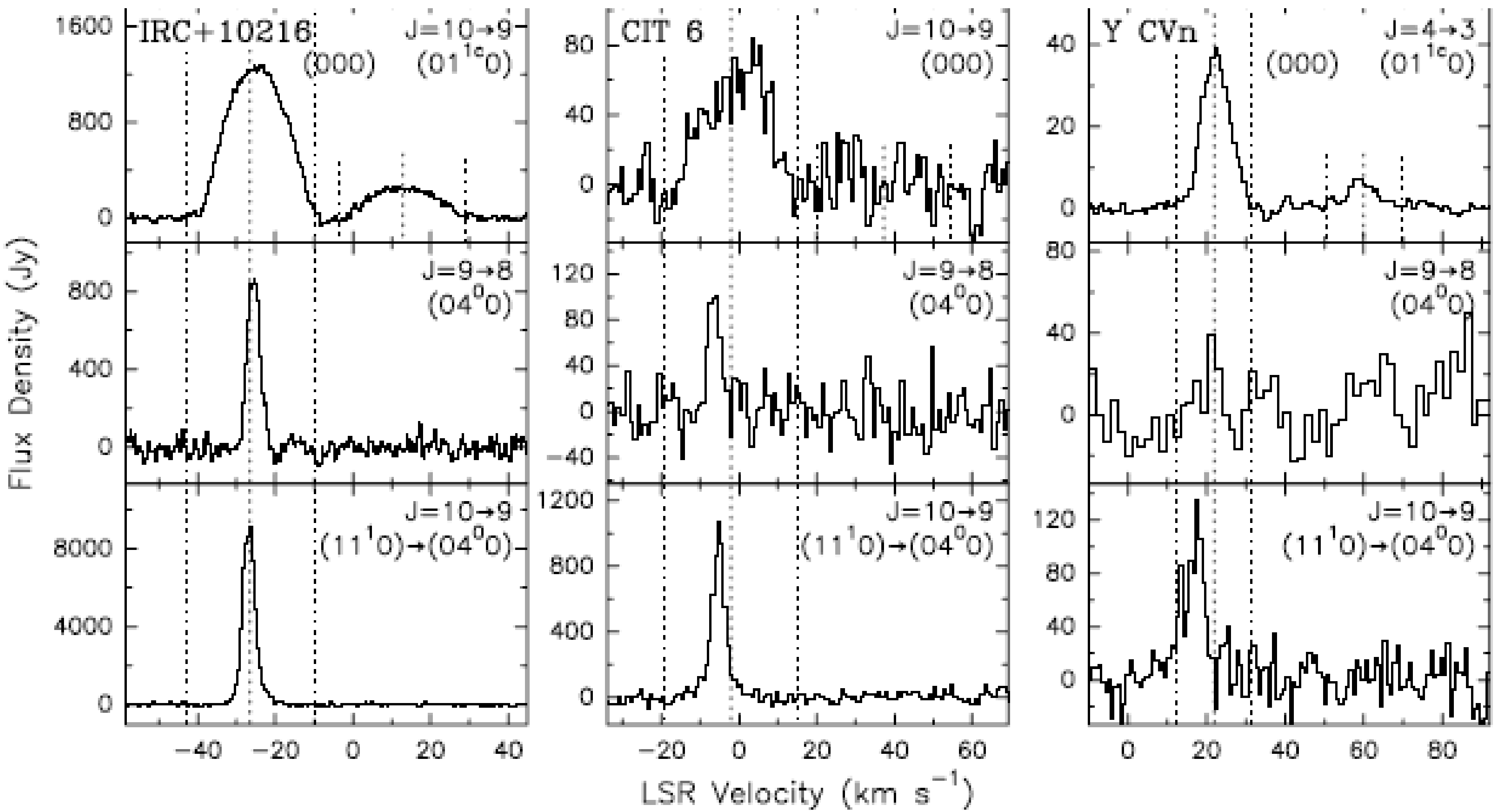
# Where is vibrationally extd water?

- Excited state $v_2$=1:
  - Probably within a few $R_\star$
  - 658 GHz commonly strong
  - Correlation with SiO maser zone
  - *Hunter+ 07*

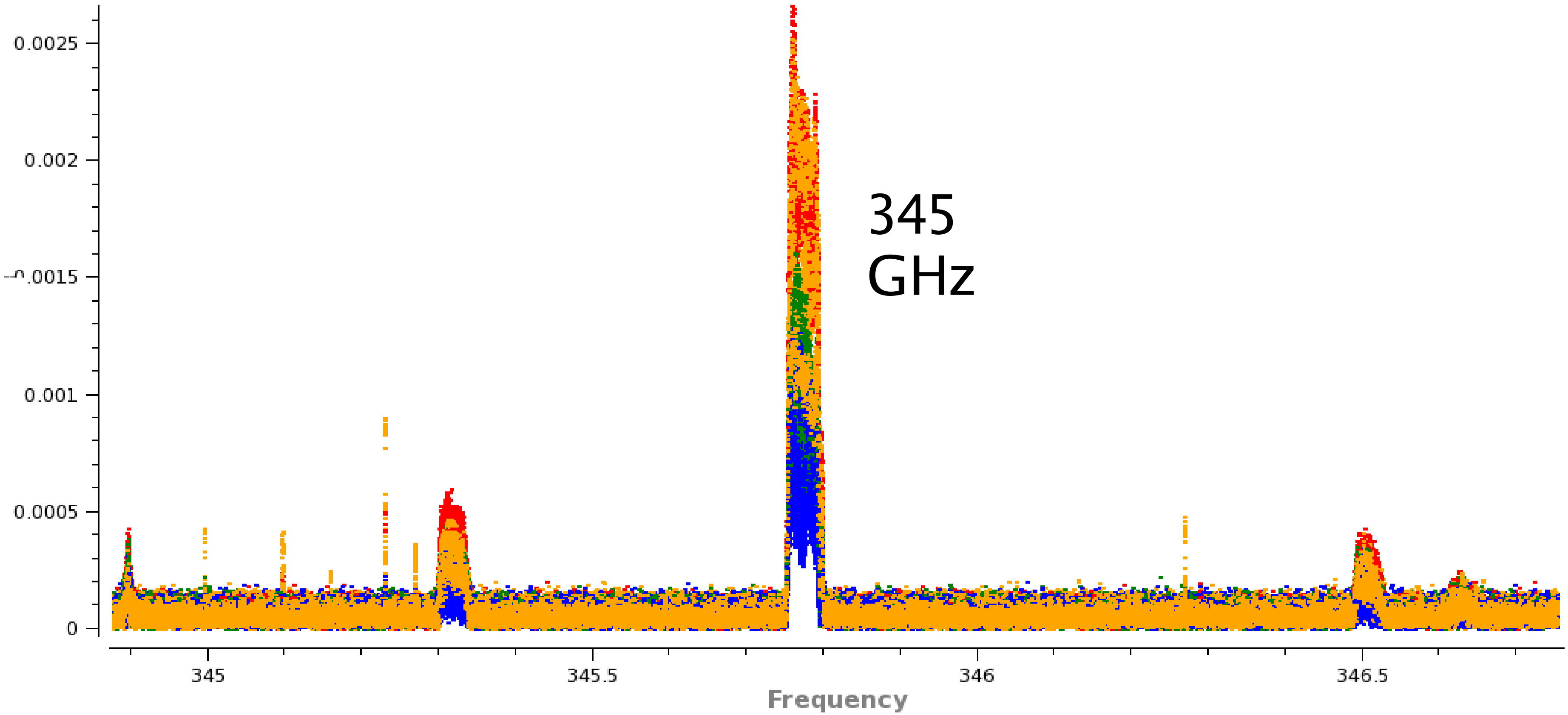


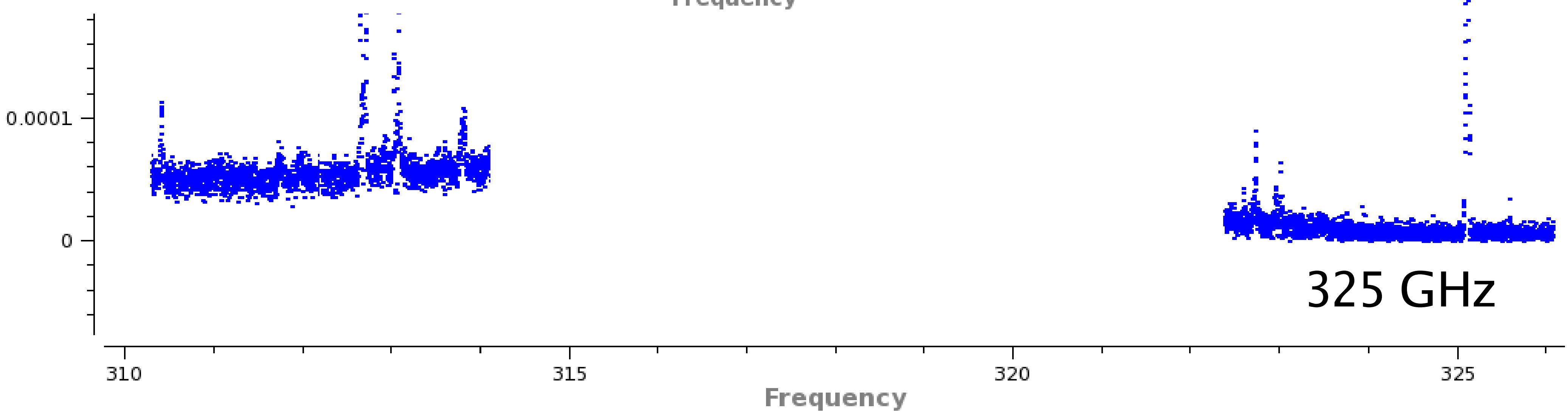
# Masers around C-stars




- HCN 805, 891 GHz
  - *Schilke+ 00, 03*
- SiS
  - More lines from SOFIA

# Thermal lines and dust



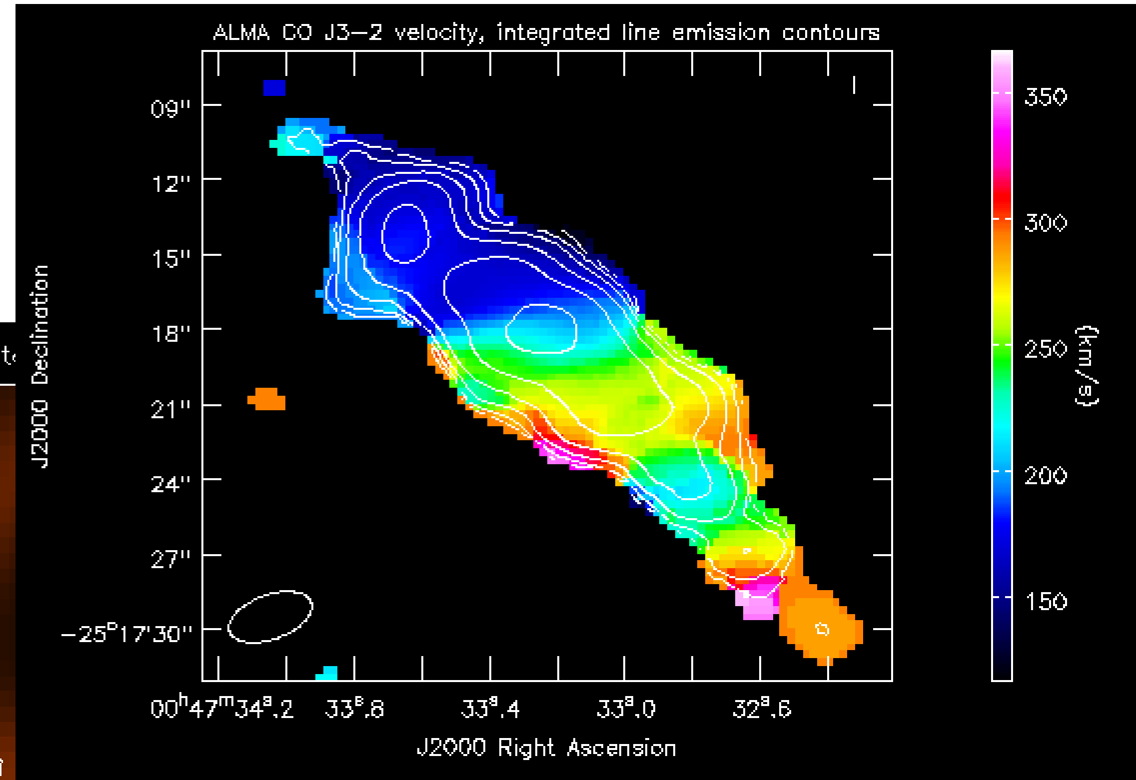



# Thermal lines and dust

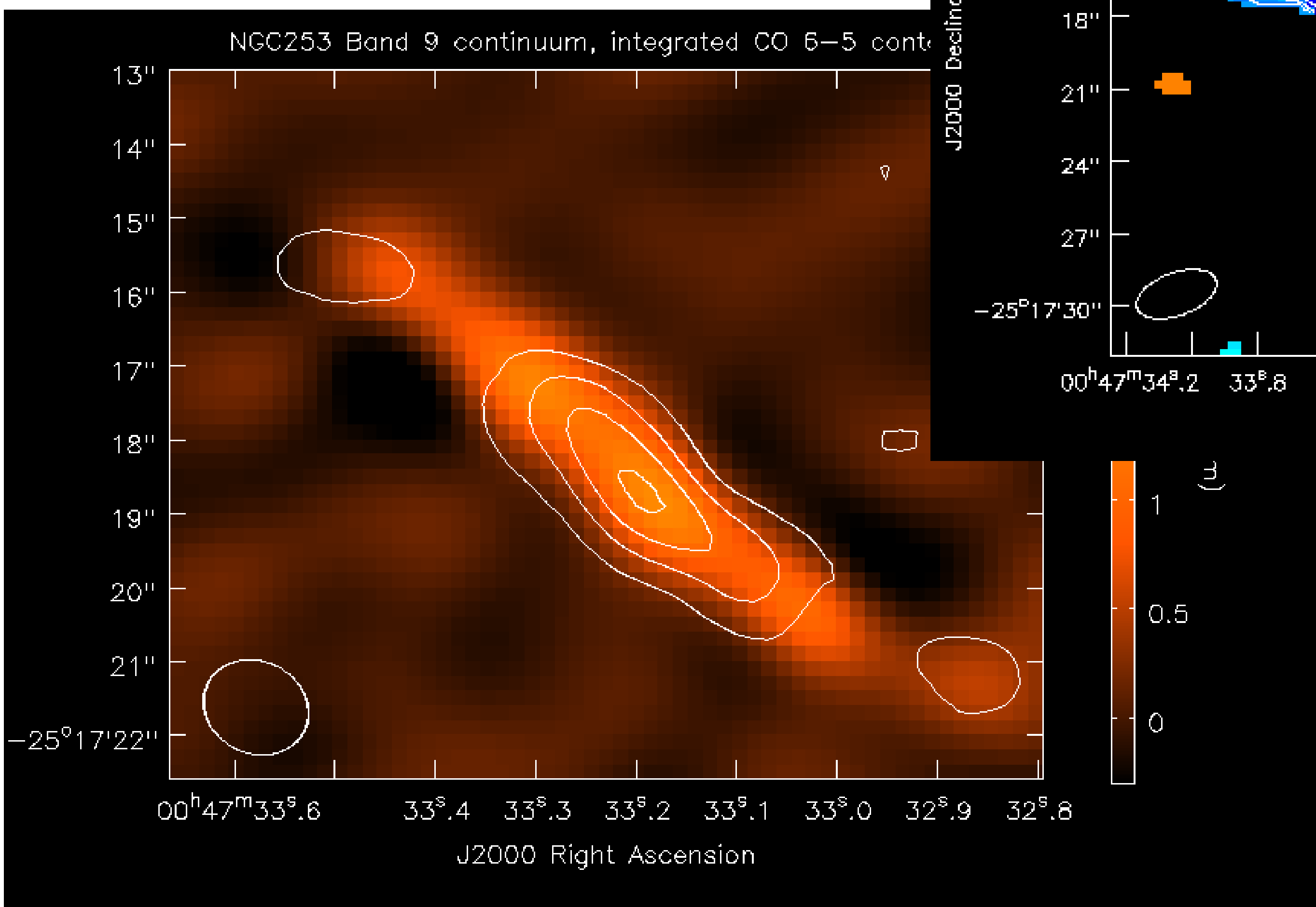
- 3-6 antennas already MANY lines
  - Resolve outer CSE in early science
- Dust &/or star continuum seen
- ALMA early science: 1-km baselines
  - 100-mas resolution at 650 GHz
  - ~5 $R_\star$ for AGB stars at 100-200 pc, RSG at 1-2 kpc
    - Dust formation complete?
  - Longer wavelengths - dust composition/grain size
- Full ALMA: 7 to 10-mas resolution
  - Size of water maser clumps
    - Mass ~0.1 - 0.5 $M_\oplus$ (AGB), 1 -- 10+ $M_\oplus$ (RSG)
    - Dust fraction ~ 0.1 -- 5 $M_☾$
    - Detectable in a day / few hr

# ALMA *TEST* results NGC 253

- Observations made to test performance and observing strategies
  - Not science!
    - 1-2 hr, 4-6 antennas
  - Not "1 st ALMA images"




- Band 7/345 GHz CO J=3-2
- Band 9/690 GHz C0 J=6-5
  - 0.12 mm PWV



# ALMA *"fringe meeting"* Thu lunch

- ALMA early science
  - Band 3, 6, 7 and 9; 4 and 8 where possible
  - 16 antennas, 0.25 –1 km baselines