Water masers and the physics of stellar winds

Anita Richards

UK ALMA Regional Centre

thanks to K Assaf, I Bains, A Baudry, M Elitzur, S Etoka, M Gray, E Humphreys, M Masheder, K Murakawa, G Rudnitskij, H van Langevelde, J Yates and many others

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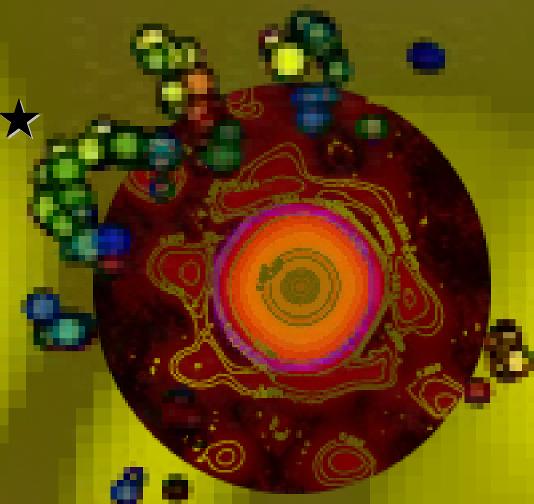
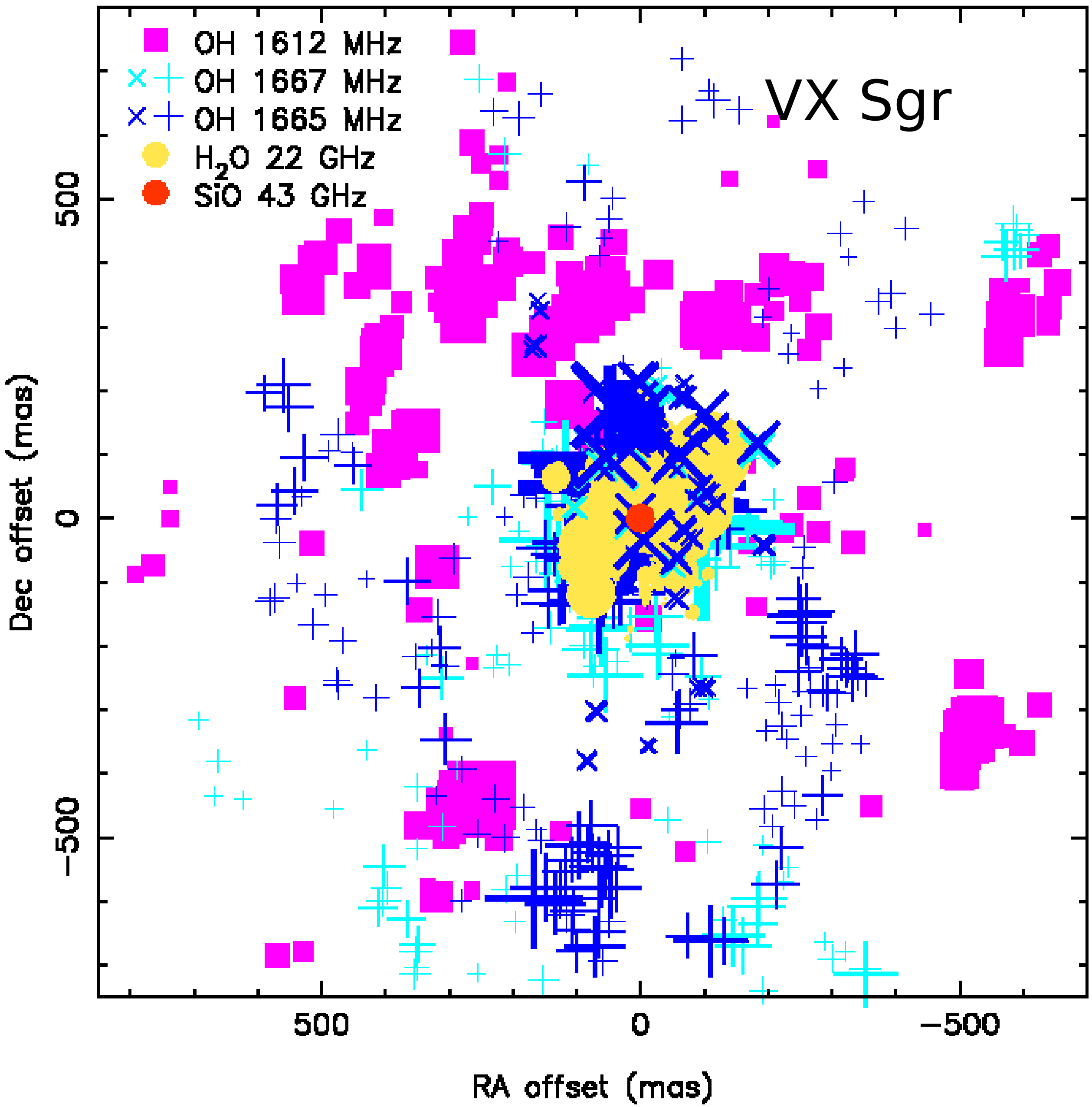
S Per 22 GHz

Masers round cool late-type stars

- RSG VX Sgr Stellar disc at 2 μm *Chiavassa+ 2010*
  - $R_\star$ 4 mas ~ 7 AU
  - SiO *Chen+06* 43 GHz 2—4 $R_\star$
  - H_2O *Murakawa03* 22 GHz
    - Overdense clumps
    - 5 – 50 $R_\star$
- Red Supergiants >~8 $M_\odot$
- Lower-mass AGB stars have $R_\star$ ~1 AU
  - Periods ~1 yr (RSG longer), T_{eff} ~2300–3300 K
  - Mass loss 10^{-7} – 10^{-5} $M_\odot$/yr



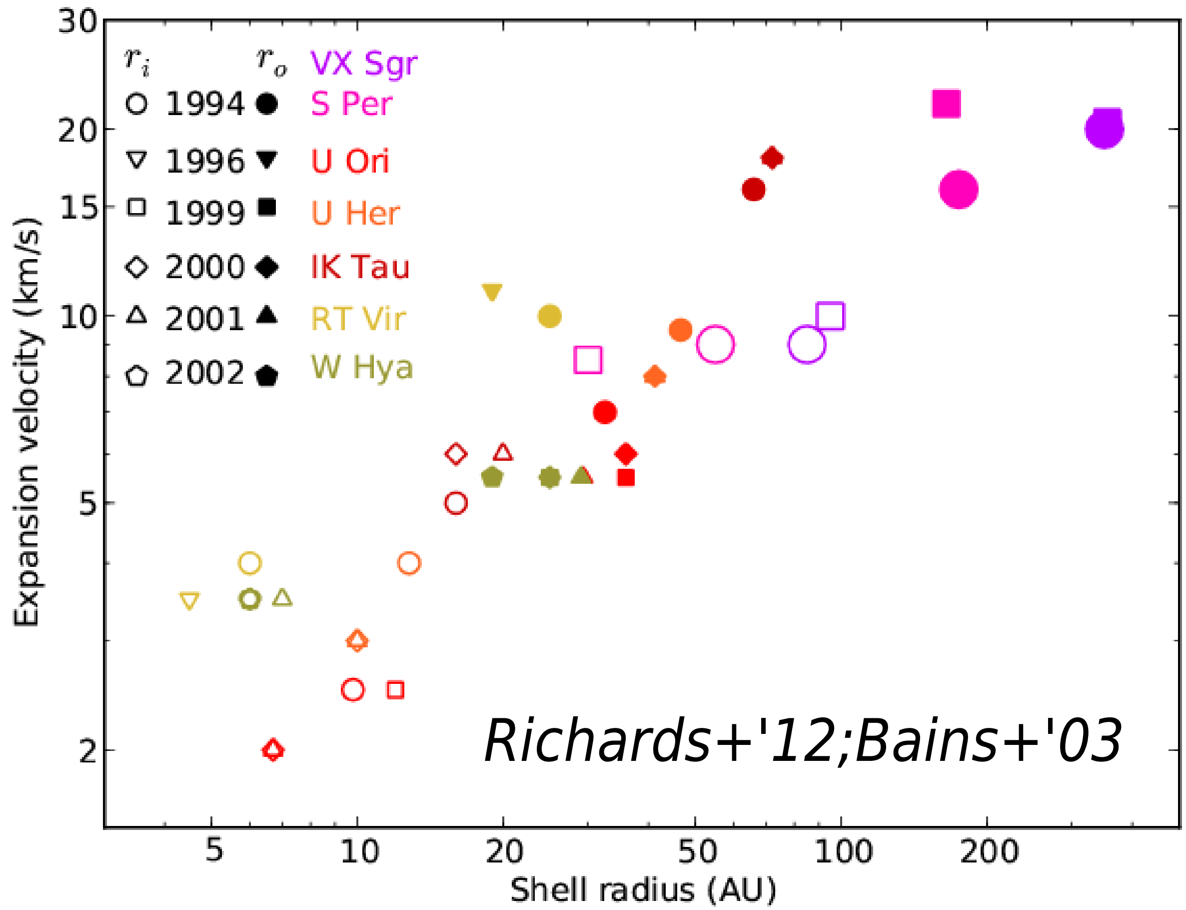
Masers resolve winds on AU scales



- SiO>42 GHz (T_E >2000 K) < 4 $R_\star$
- H_2O 22GHz (T_E ~650 K), 5-30 $R_\star$
- OH 1612 MHz (T_E few K, long column depth), at >50 $R_\star$
- OH mainlines (1665-7 MHz) can overlap H_2O and/or extend as far as 1612 MHz masers

What accelerates the wind?

- Water maser shell limits show $V_{exp} \propto r$
  - Relationship holds for $M_\star$ ~1 to >10 $M_\odot$
- τ or momentum coupling changes?
  - *Ivezic & Elitzur'10*
- Dust absorption efficiency evolves?
  - *Chapman & Cohen 86; Verhoelst+*
- Also seen in other lines incl. Hershel
  - *Decin + '10*

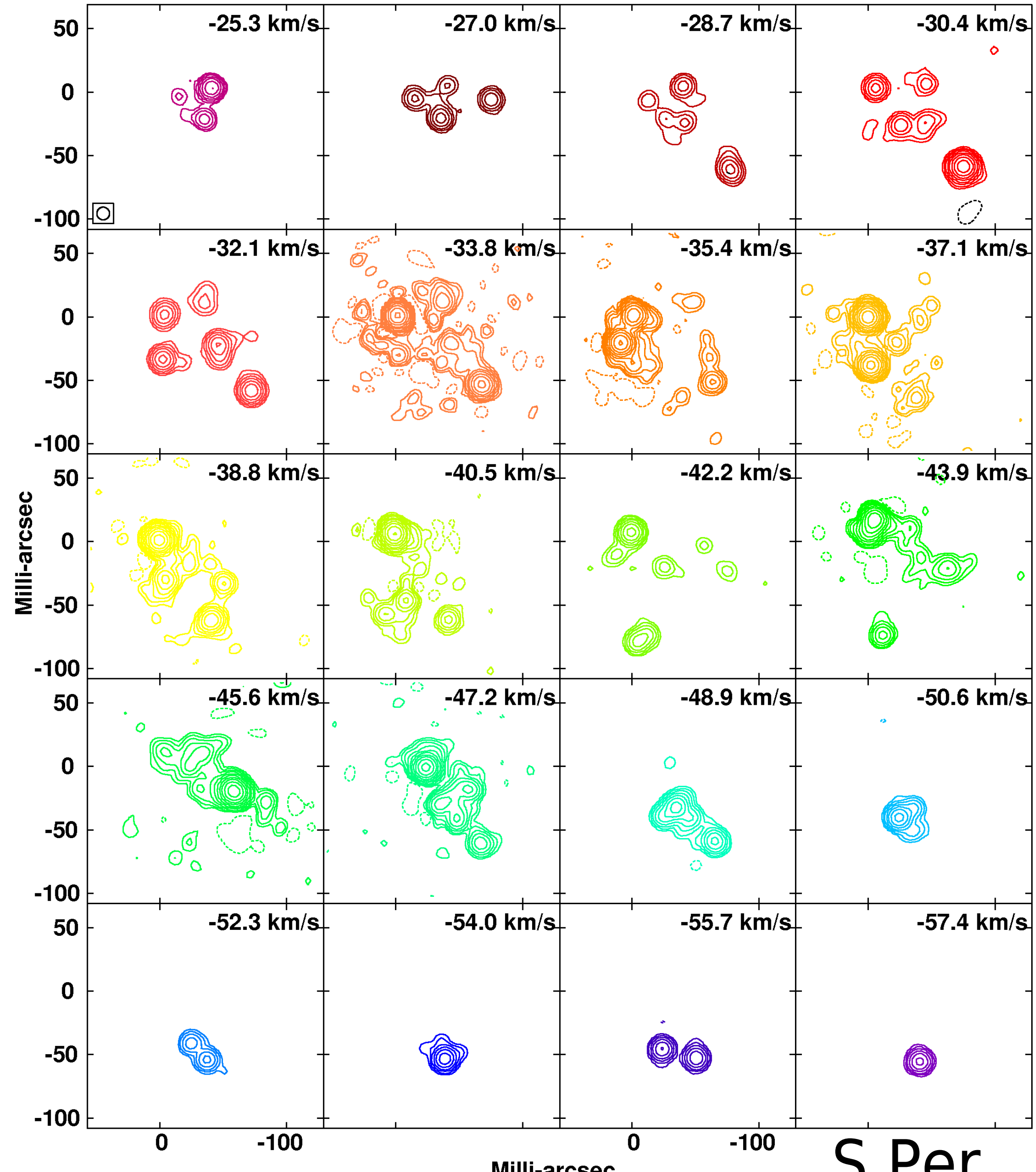


Mass loss problems

- Can pulsation drive mass loss from the star's surface?
  - Pulsation shocks $\lesssim$5 km/s ($\lesssim$10 km/s in RSG)
- Can radiation pressure on dust drive O-rich winds?
  - No: Woitke 2006
  - Yes: Alumina nucleation *Wittkowski+ 2007*
    - Large grains at 2 R_* *Barnaby+ 2012* (Nature)
  - SiO masers reach ~7 km/s but also infall
  - H_2O masers show acceleration past escape velocity
- Who made all the dust?
  - Clumping scales – can it survive into the ISM?
- Do solitary stars produce axisymmetric PNe?
  - OH (and other) masers polarized, asymmetric
    - What is role of magnetic field?

22 GHz H_2O channel maps

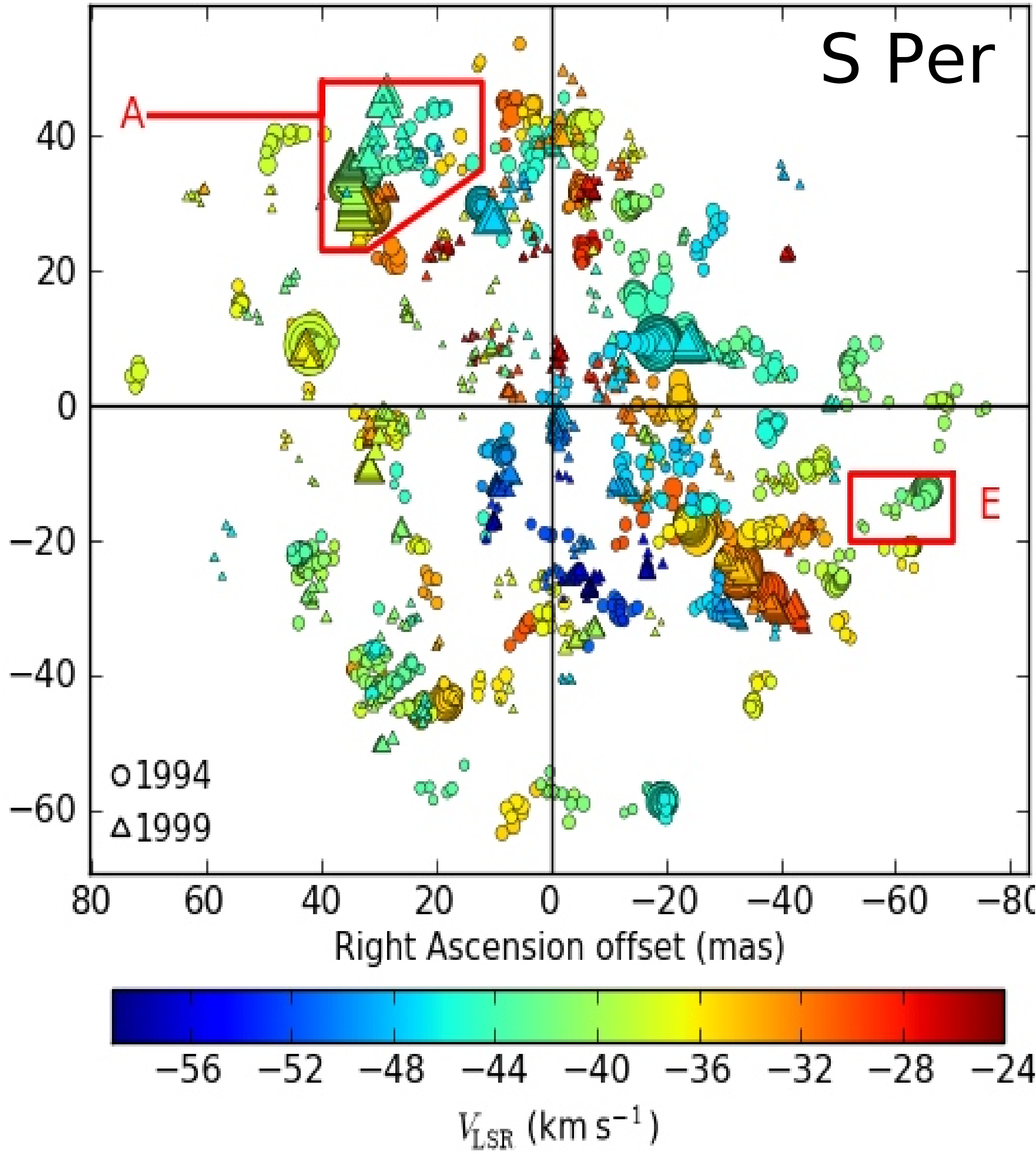
- MERLIN images
  - Compact front and back caps
  - Extended emission in plane of sky
    - Accelerating radial outflow
  - 10 mas beam θ
    - 2D Gaussian components
    - $\sigma_{pos} \sim \theta / (S/\sigma_{rms})$
      - 0.2 mas @ 10 Jy



S Per

Cloud measurements

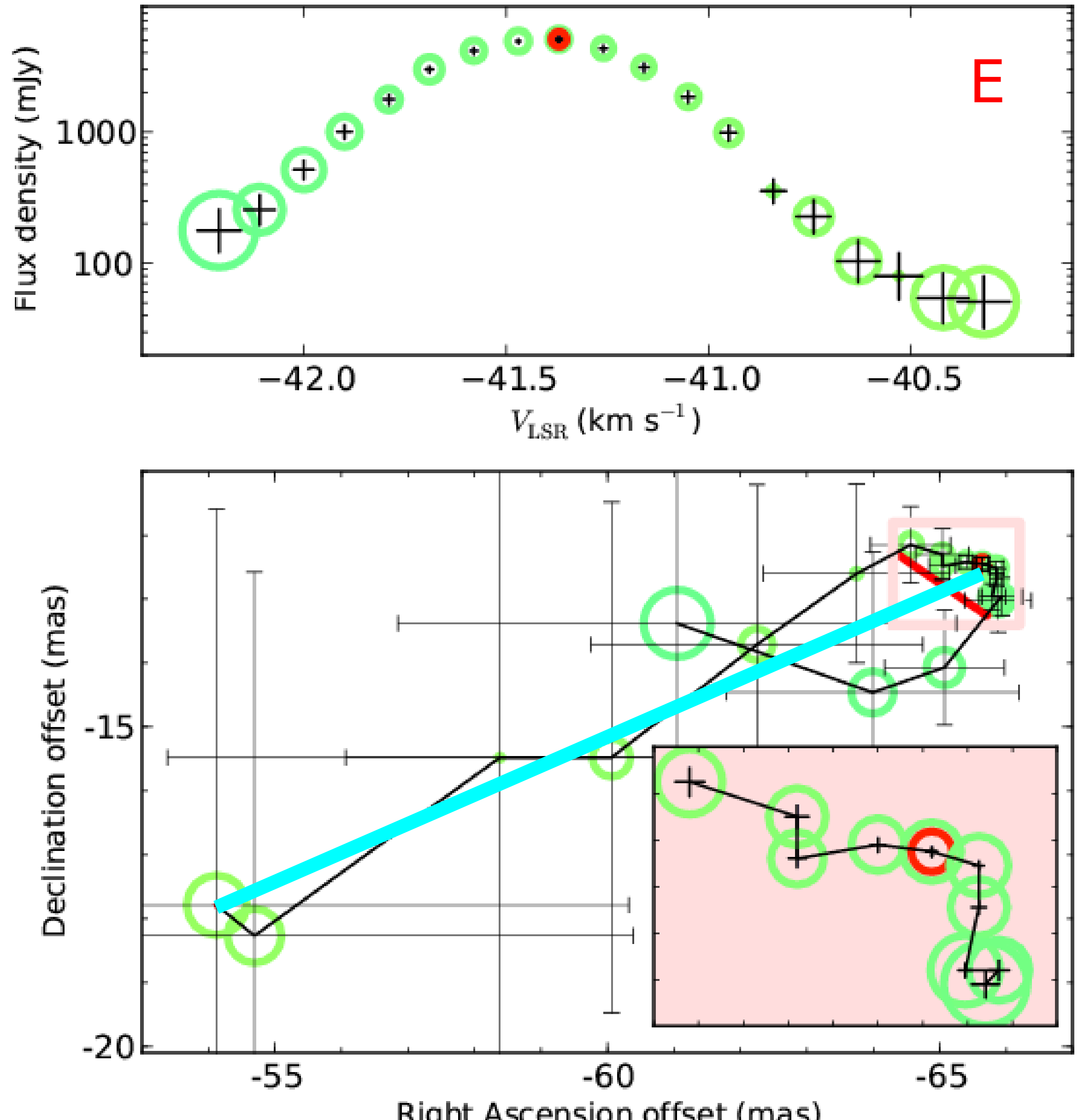
- Each component beamed size
  - 1-2 km s^{-1} series
    - Gaussian spectra
      - $\Delta V_c \gtrsim \Delta V_{th}$
- Series = discrete clouds
    - R_{cAGB} 1 - 2 AU
    - R_{cRSG} 10-15 AU
      - $2R_c \gtrsim$ gain length
  - Density/temperature/ composition determines cloud size
    - Not just velocity coherence



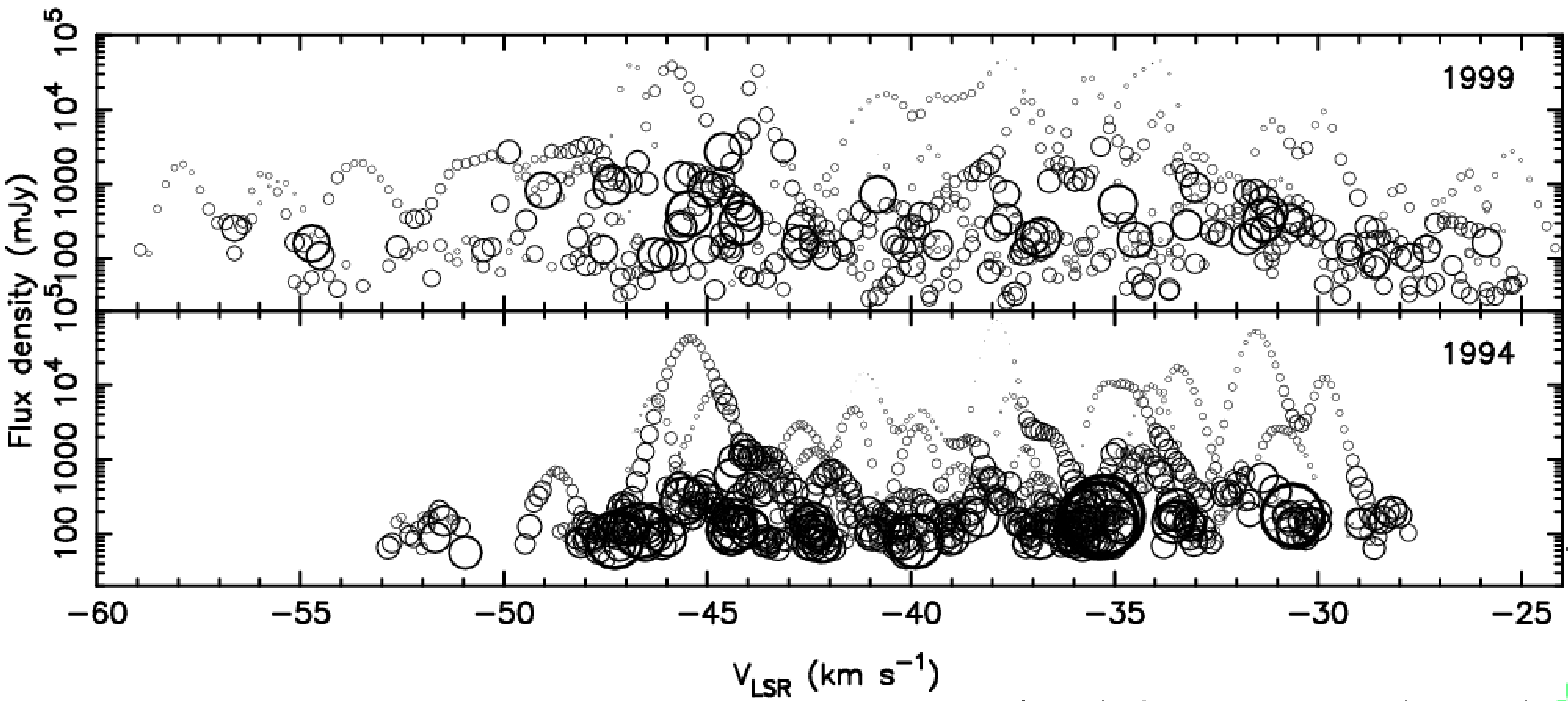
Initially assume clouds ~spherical

- Linear strings of components indicate velocity gradient
  - Not necessarily elongated maser
- Internal gradients vary at ~sound speed
- Beaming angle

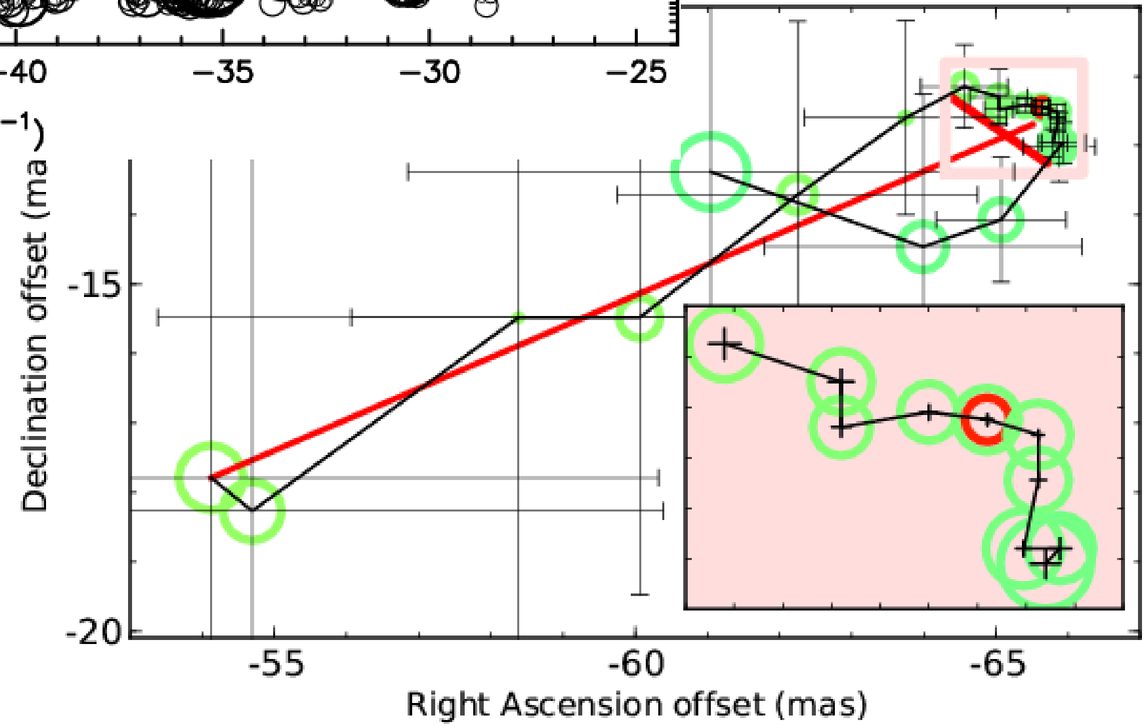
$$\Omega \sim \left(\frac{\text{feature FWHM}}{\text{feature size}}\right)^2$$



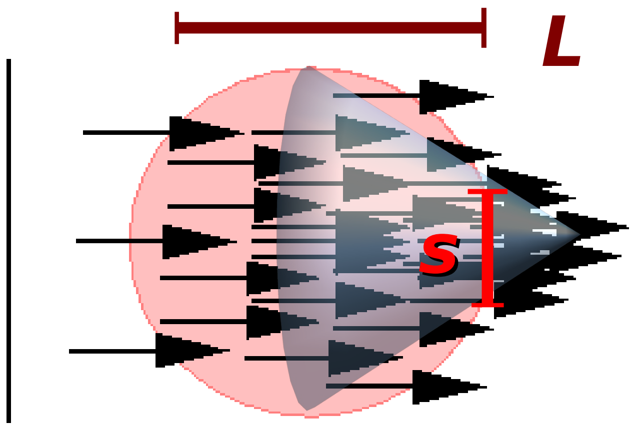
Shrinking of brighter masers



- Brighter components near line peaks are generally smaller
- Coherent, curved spatial distribution
  - S Per, some AGB ✷

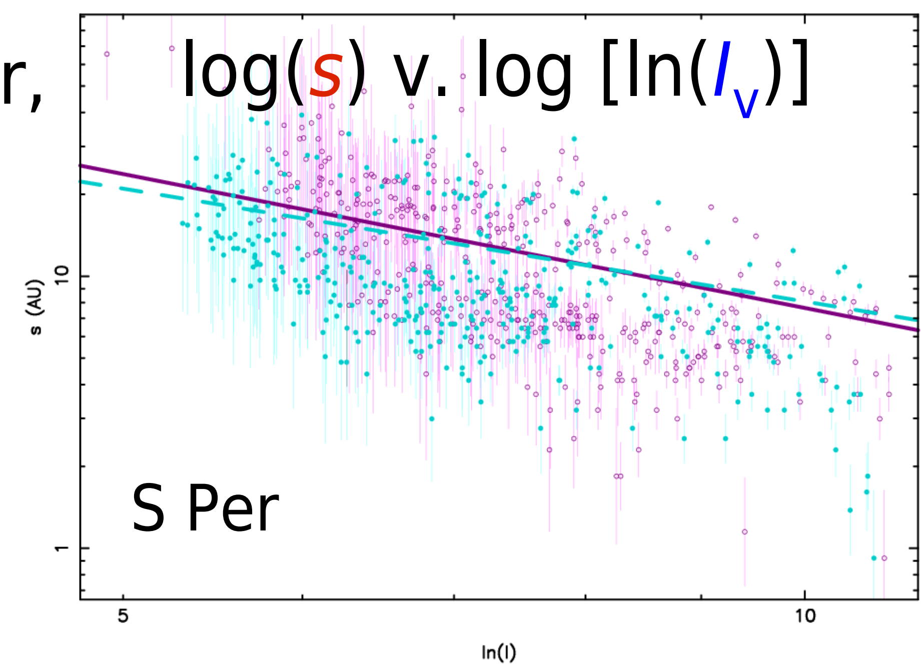


Beaming from spherical clouds



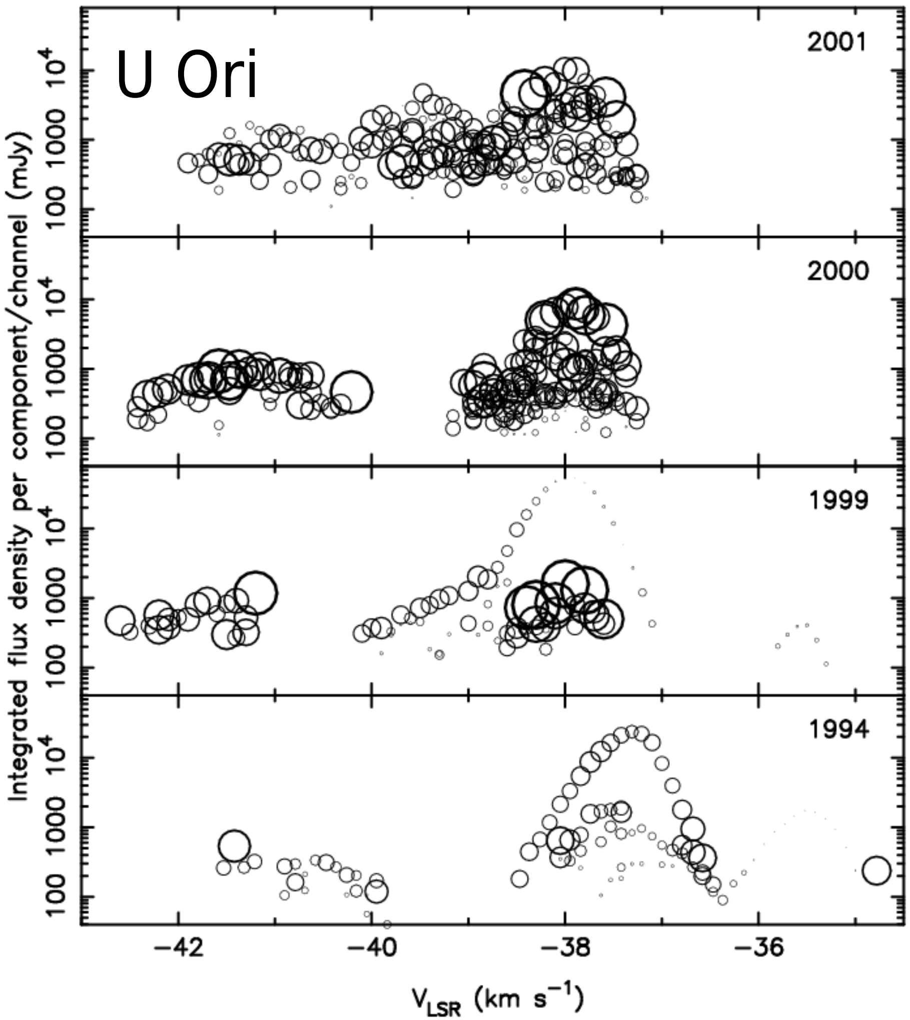
- "Amplification-bounded beaming"
  - L = Measured size of multi-chan clouds
  - Observed (beamed) size *s*
    - Measured component size per channel
  - Brighter maser (peak I_v), tighter beam
  - $s \propto 1/\mathrm{sqrt}\,[\ln(I_v)]$

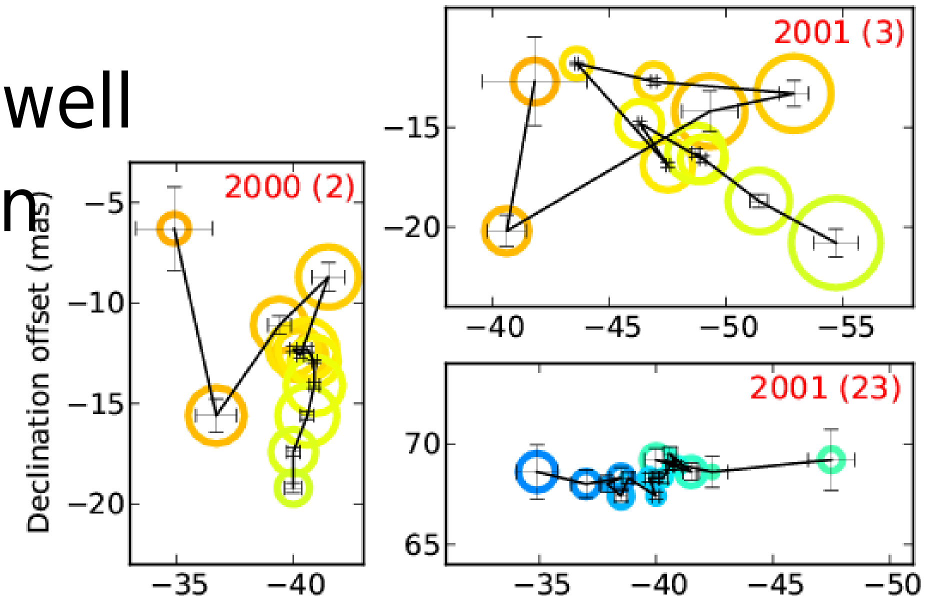
- Slope ~ -0.5 to -1.5 for S Per, RT Vir, IK Tau (mostly)
  - Bright, well-filled maser shells
  - Small-amplitude, less regular optical periods

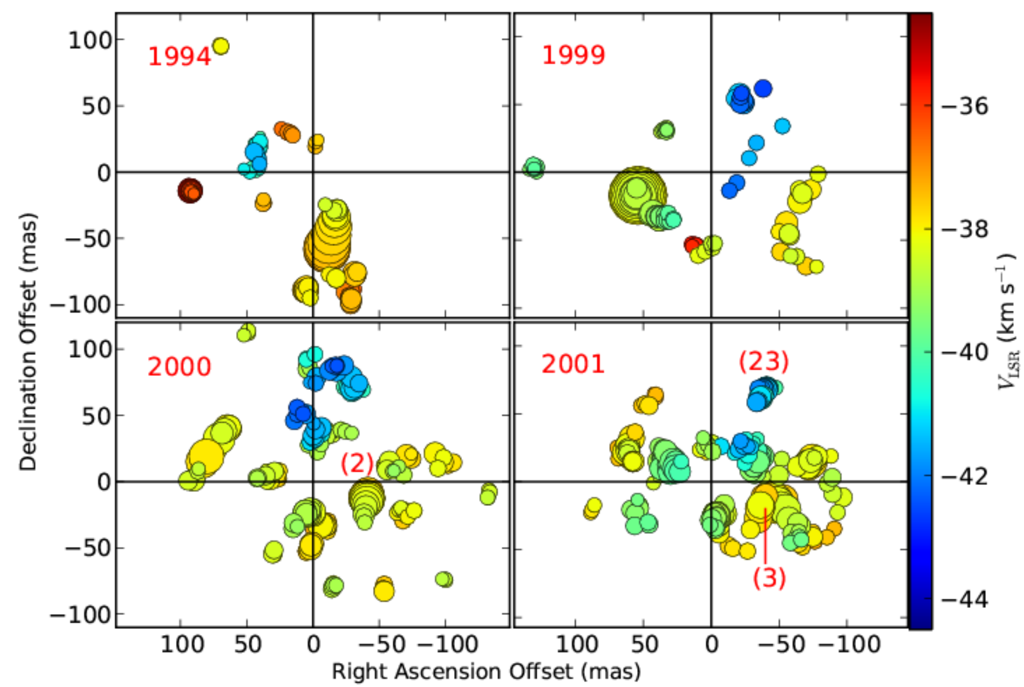


But *sometimes* brighter=bigger

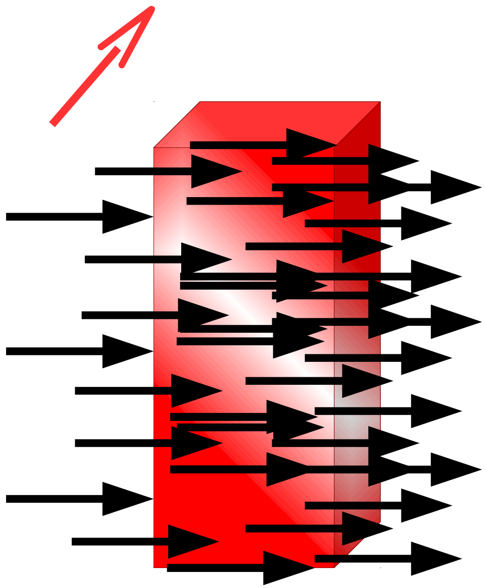
- Spectral peak components swell
- Disorderly spatial distribution







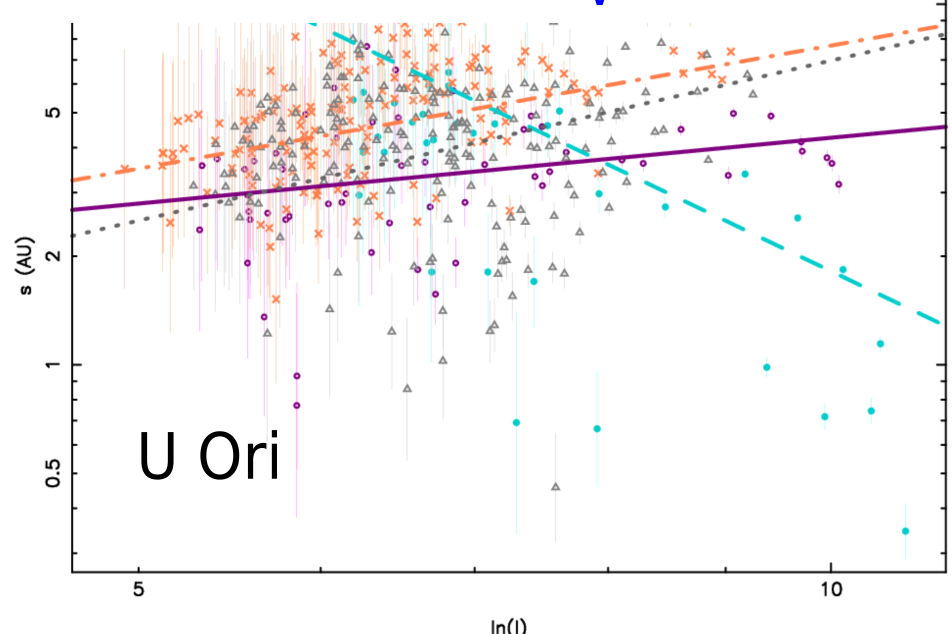
Beaming from shocked slabs



- 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)

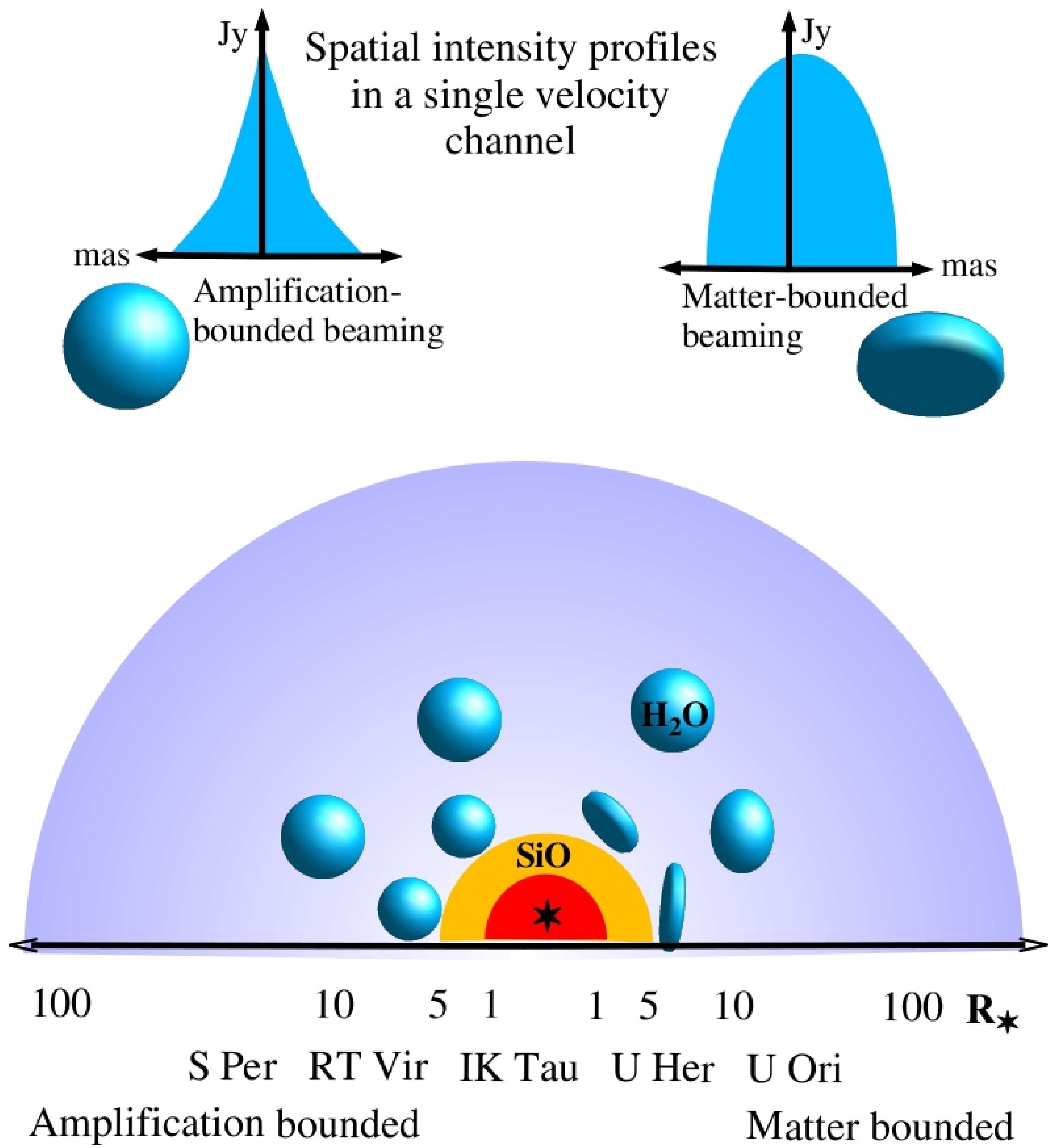
- Slope ≫ 0 or large scatter for U Ori, U Her
  - Other evidence for shocks:
    - OH 1612 MHz flares
      - *Pataki+74; Chapman+85; Etoka+97*
    - Regular, deep pulsations

log(s) v. log [ln(I_ν)]



Maser properties reveal wind disturbances

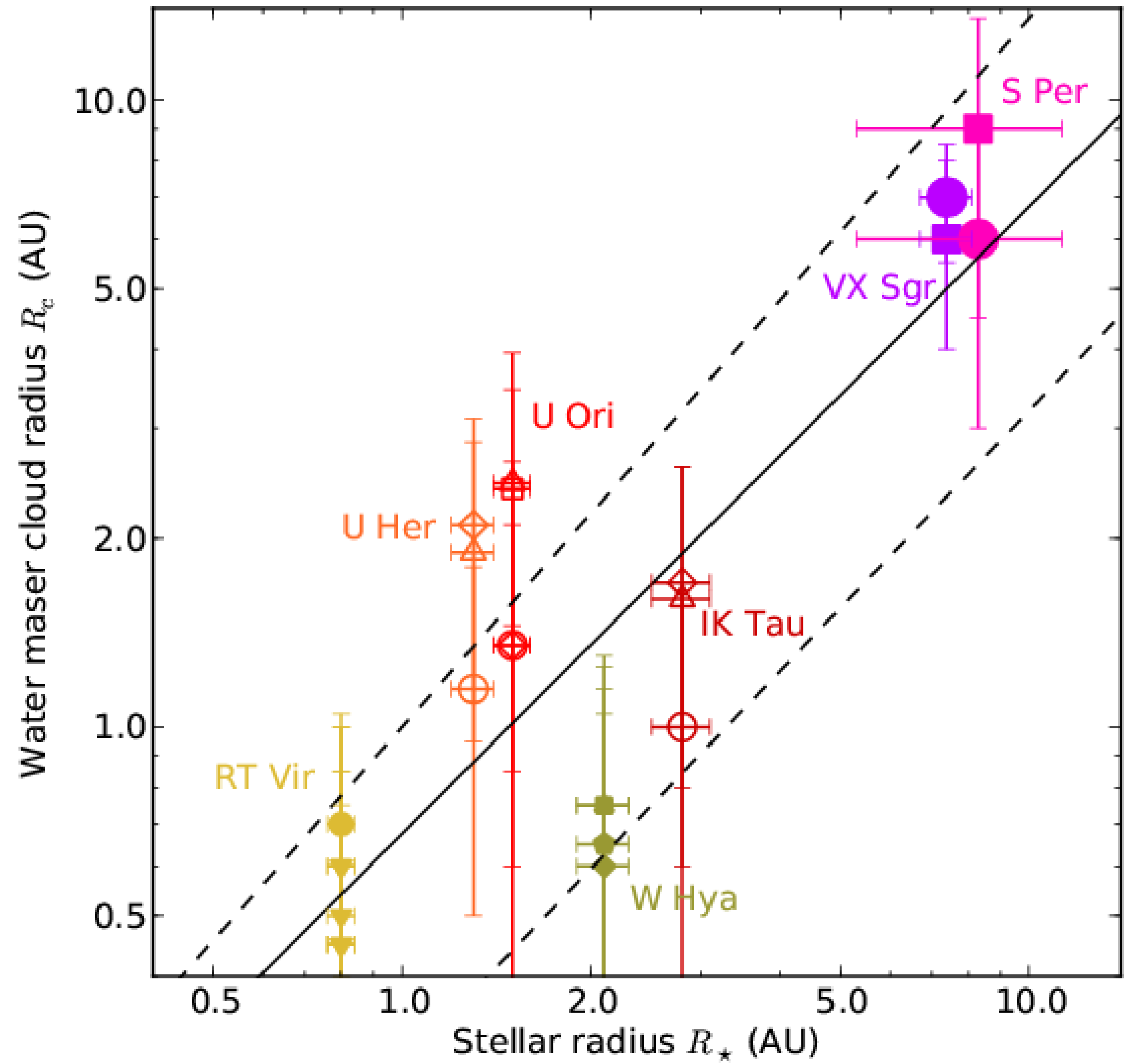
- Brighter = smaller beamed size?
  - $s \propto 1/\mathrm{sqrt}\,[\ln(I_\nu)]$
    - Smoothly expanding spheres
- Brightest emission often ~cloud size?
  - Rapid maser variability
  - Stars with deepest periods
    - Shocked slabs



Richards Elitzur & Yates 2011
Elitzur Hollenbach & McKee 1992

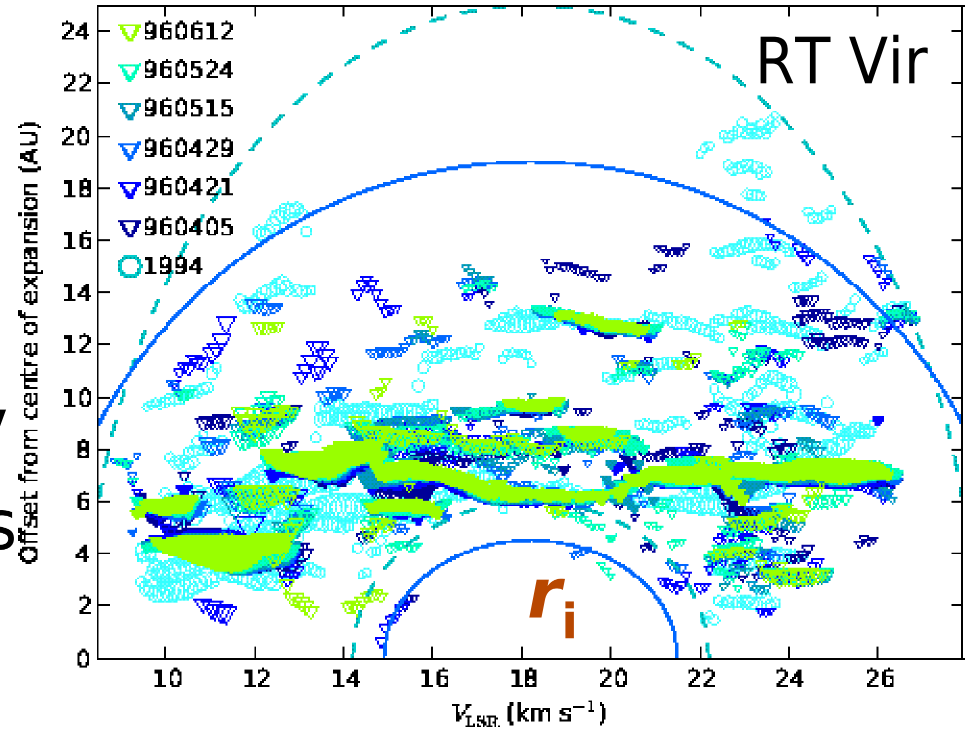
Water maser clumps scale with ✶

- 22 GHz maser thick shell
  - ~5 – 50 $R_\star$
    - Ten-fold range of $R_\star$, SRs to RSG
- Cloud radius ~ 1 $R_\star$
  - Assuming radial expansion, birth radius 5%–10% $R_\star$
- Must be determined by stellar properties
  - Not dust cooling or other microphysics
    - Would be same scale for all stars



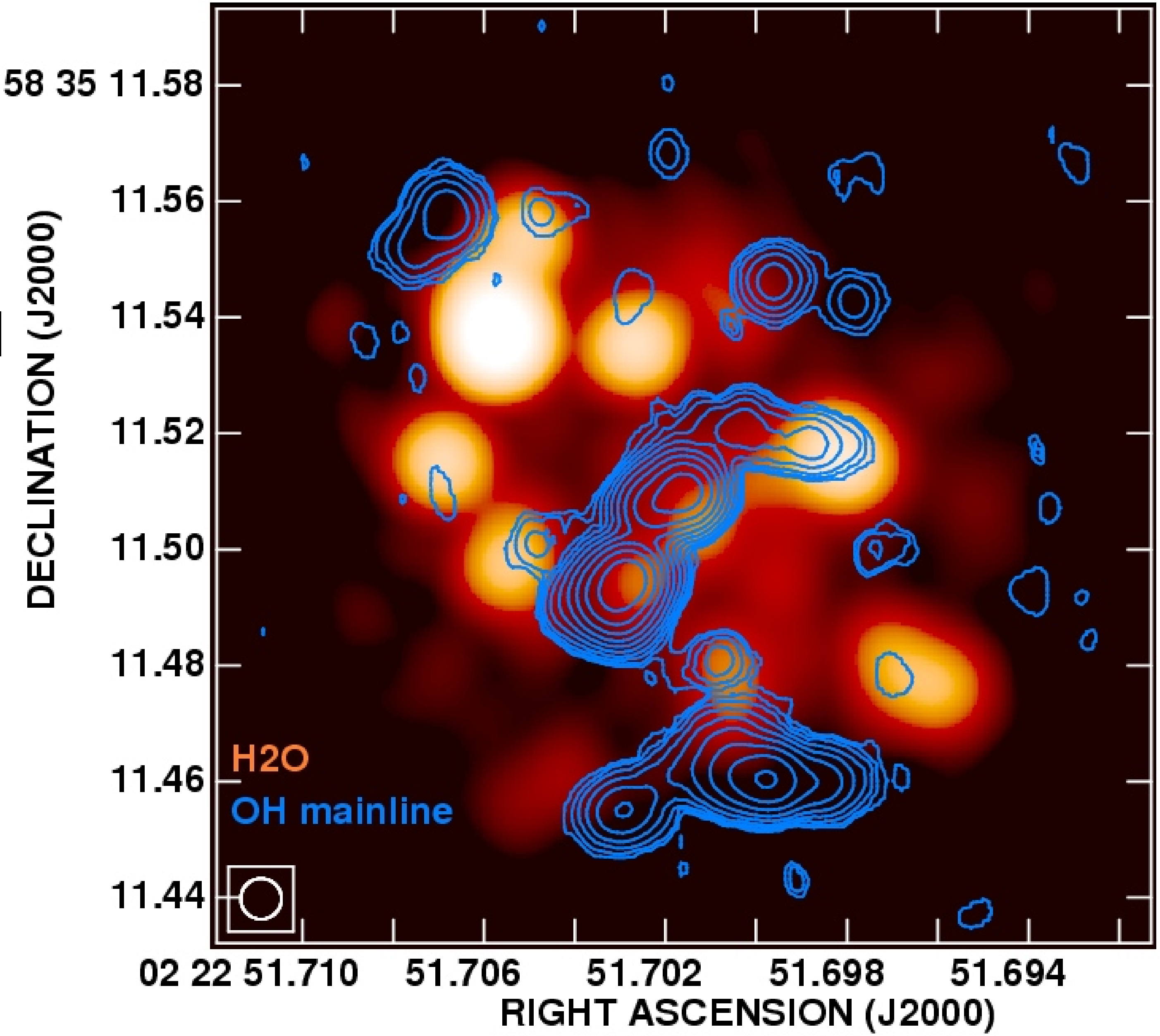
Cloud density

- **H_2O** 22 GHz maser ***r_i***
  - Collision rate < masing rate *Cooke & Elitzur '85*
  - Quenching density ~$5 \times 10^{15} m^{-3}$
- ~50x average wind density
  - Clouds 50-90% wind mass
    - Filling factor ≲1%
  - **H_2O** shell crossing times:
    - Few decades (AGB stars); ≲ century (RSG)
  - Imaged clouds last ≲2 yr (AGB), ≲10 yr (RSG)
    - Pushchino monitoring shows masers blink, clouds persist
- Overdense, probably hotter – how can clouds survive?
  - Frozen-in magnetic field?

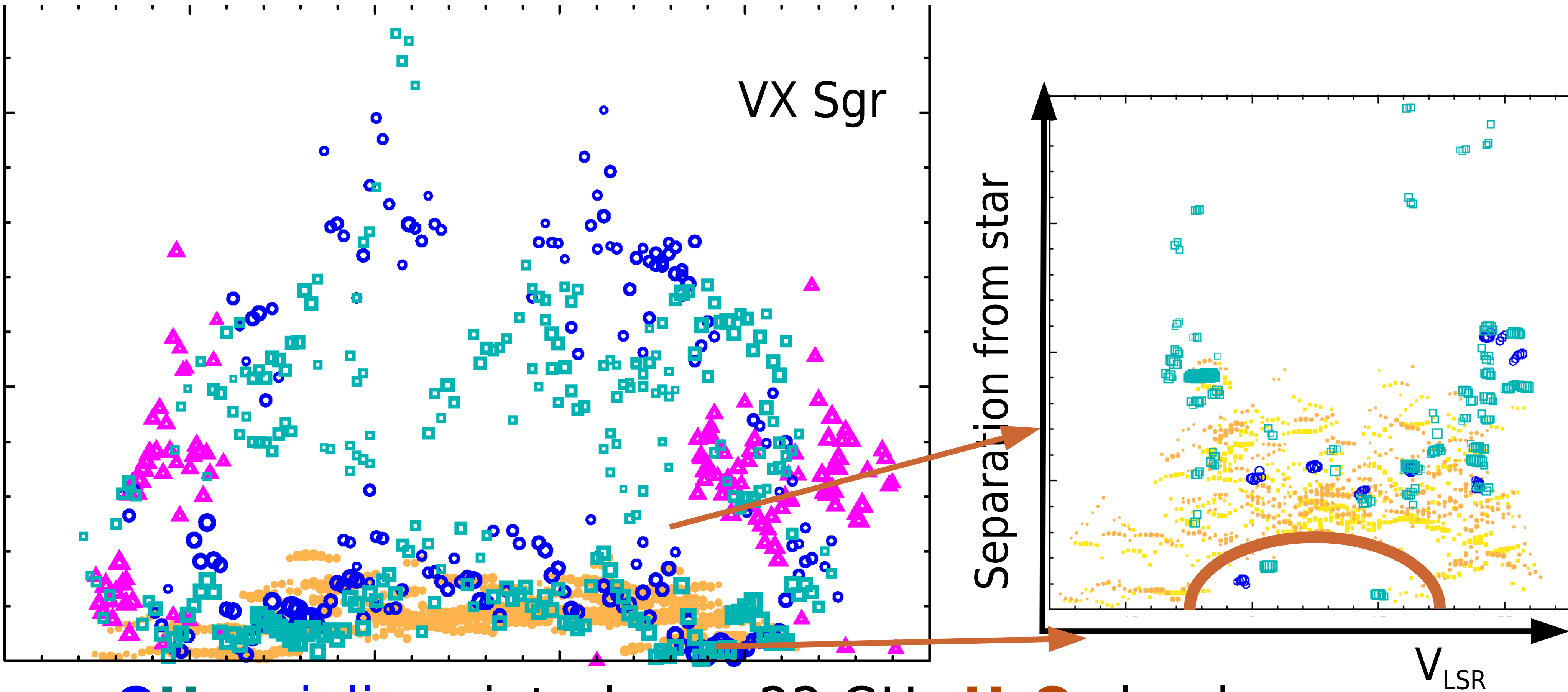


S Per maser clumps

- MERLIN **H_2O** masers 22 GHz
  - 10-mas beam
- EVN/Global VLBI 1.6 GHz **OH mainlines**
  - Same resolution
  - Interleave H_2O
  - Extended OH resolved-out



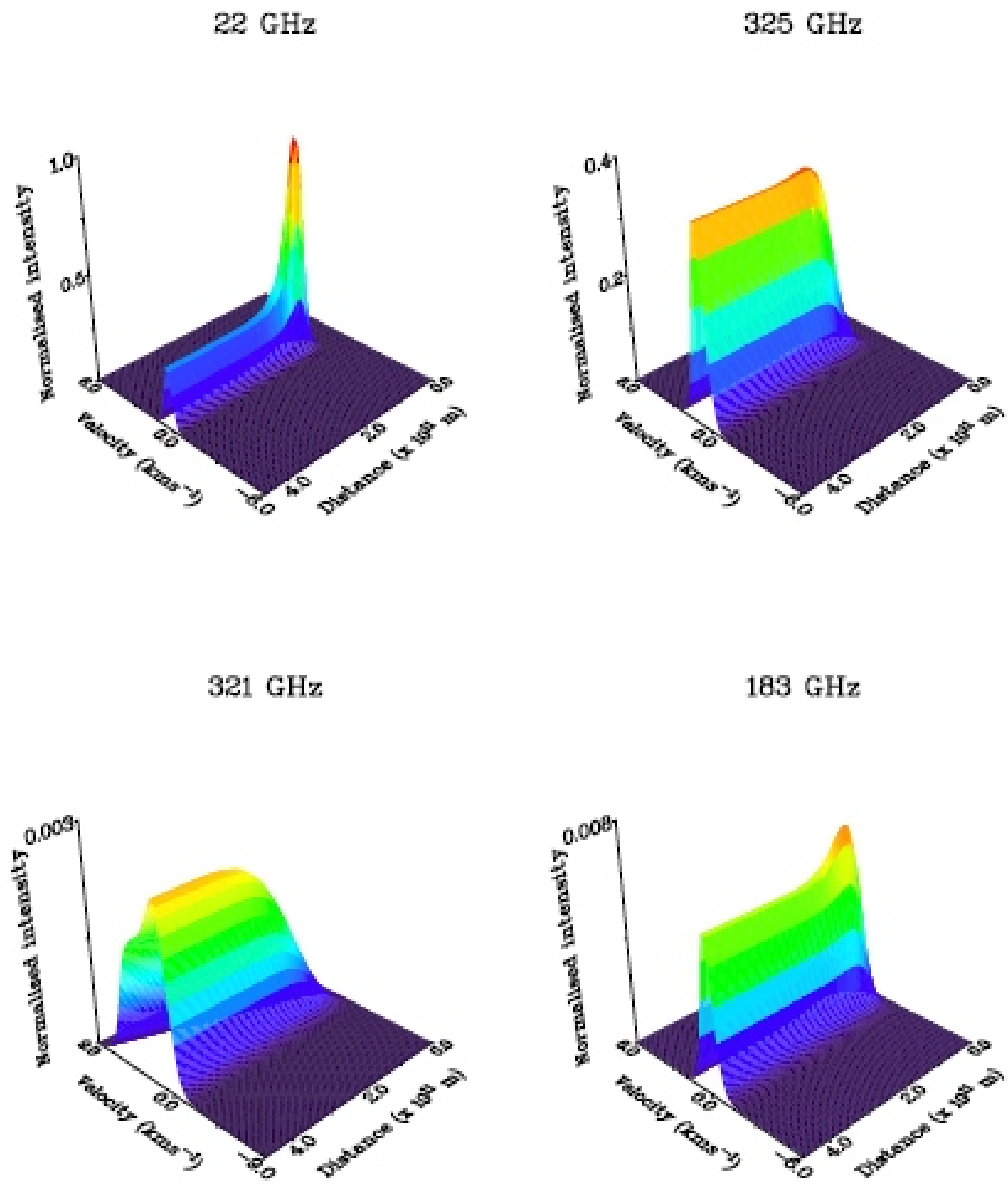
Lower density surroundings



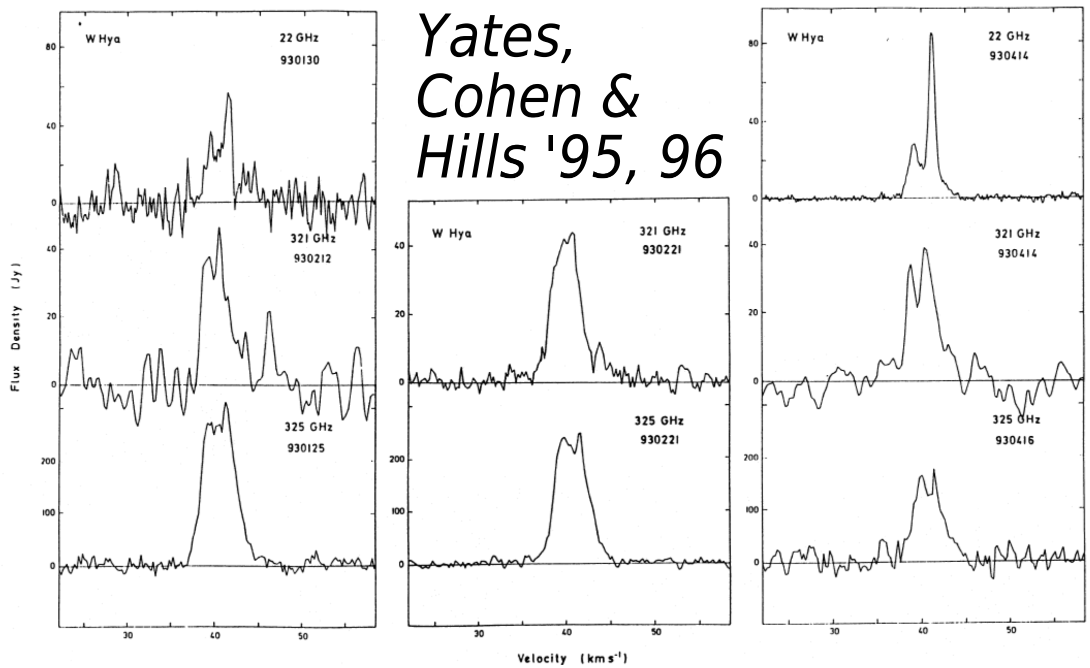
- **OH** mainlines interleave 22 GHz **H_2O** clouds
  - Need ~1/50 H_2O gas density, T<500 K
  - Seen for most RSG, about half AGB
- **OH 1612** MHz further out where they belong

Modelling (sub-)mm water

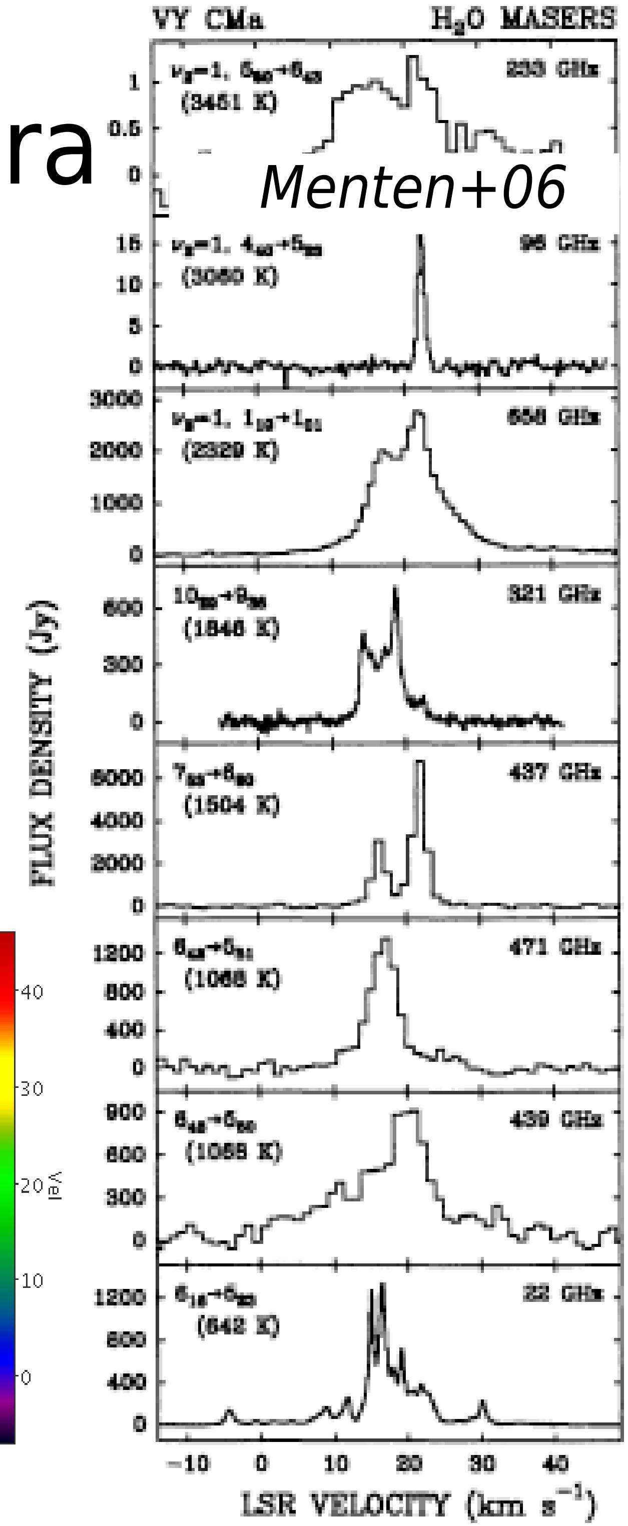
- Vibrational ground-state models (*Humphreys+'01*):
  - 325 GHz wide span
  - 321 GHz peaks close to star (inside dust formation region?)
- 183 GHz peaks resemble 22 GHz
  - Less variable *(Gonzales-Alfonso+98)*



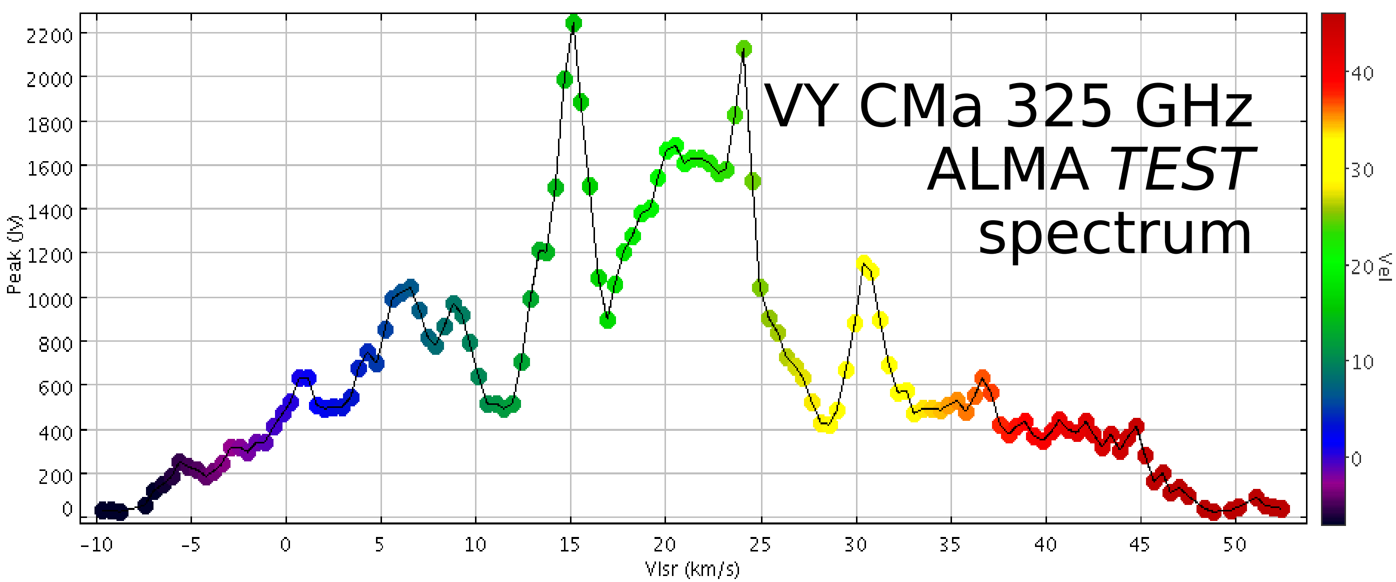
(Sub)mm water maser spectra



Yates, Cohen & Hills '95, 96



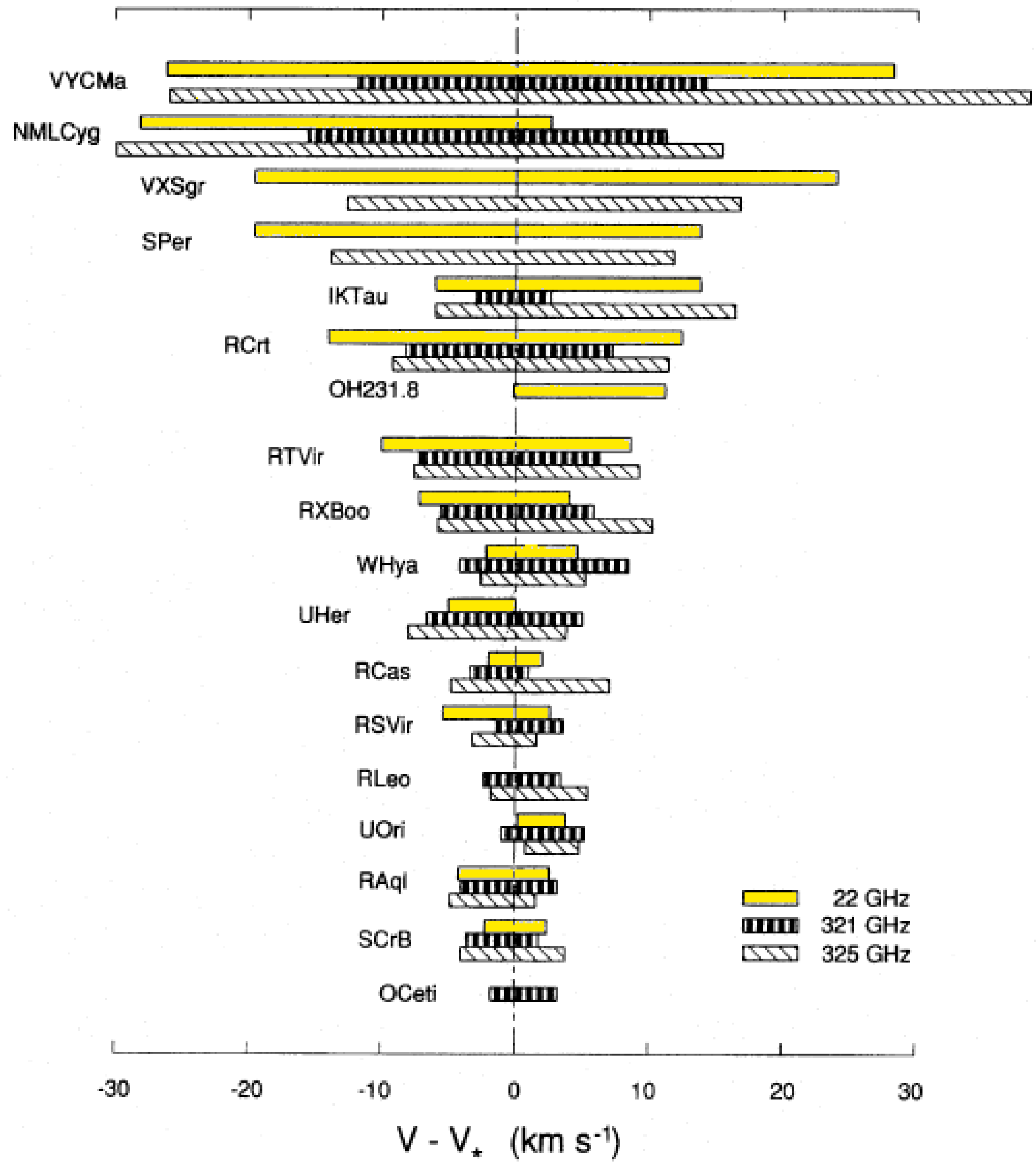
Menten+06



VY CMa 325 GHz ALMA *TEST* spectrum

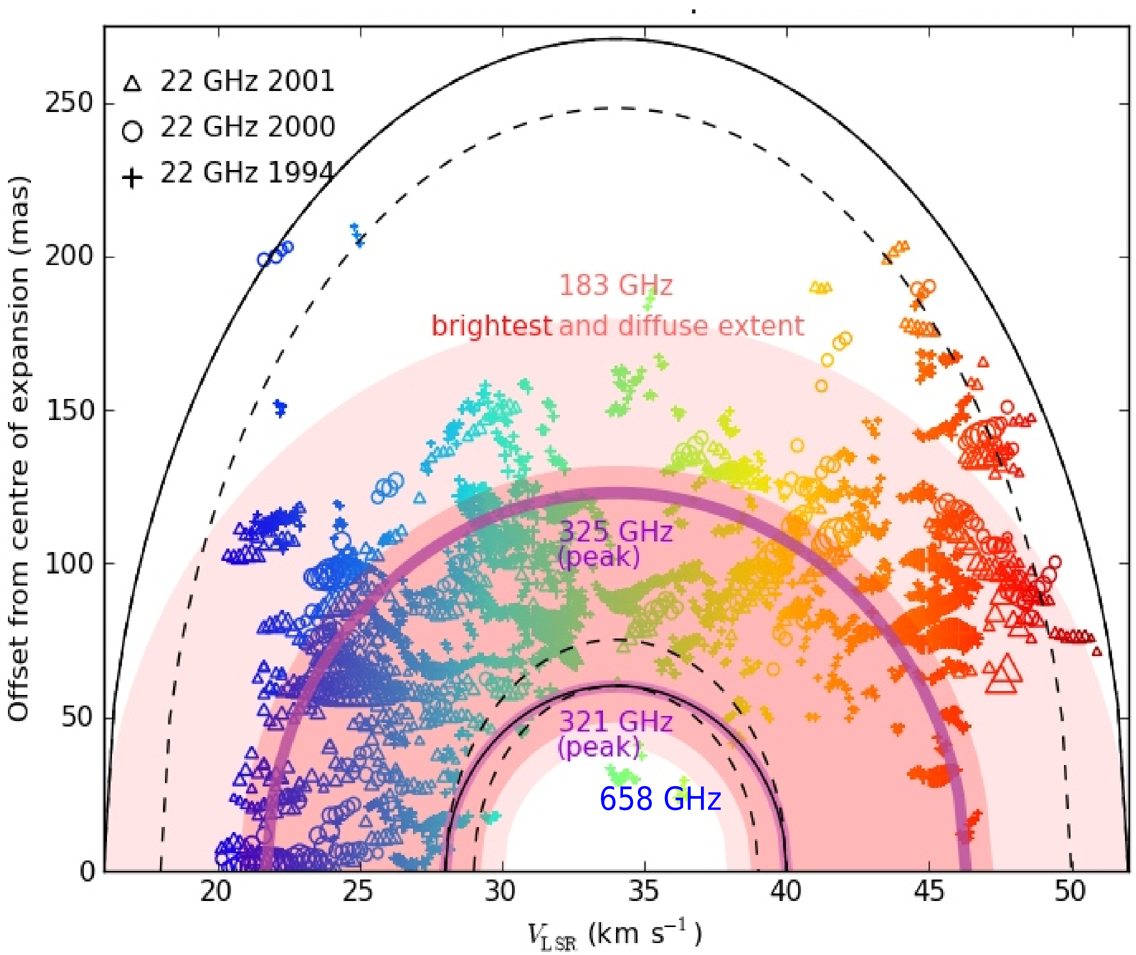
Observations of (sub-)mm water

- Compare spectral extent
  - 70% 22-GHz sources have 321, 325 GHz emission
    - *(Yates+ 96)*
- 325 GHz spectra resemble 22 GHz
- 321 GHz narrower, weaker, more variable



Tracing different conditions

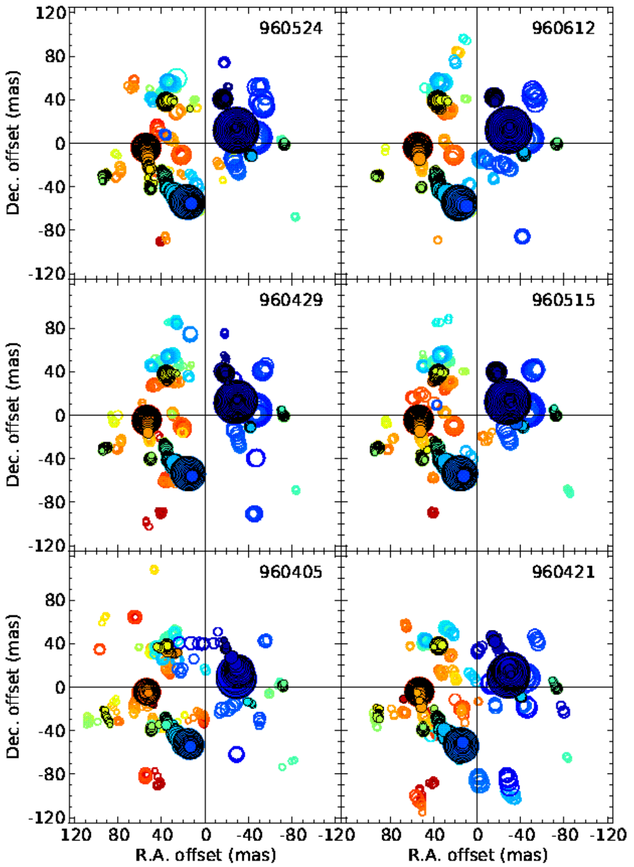
- **Toy** IK Tau model
  - 658, 321 GHz peaks inside 22-GHz r_i
  - 325 GHz outside
  - 183 GHz spans dust formation
    - *Neufeld+ 91, Humphreys+ 01*
  - 325 GHz traces 22-GHz clumps?

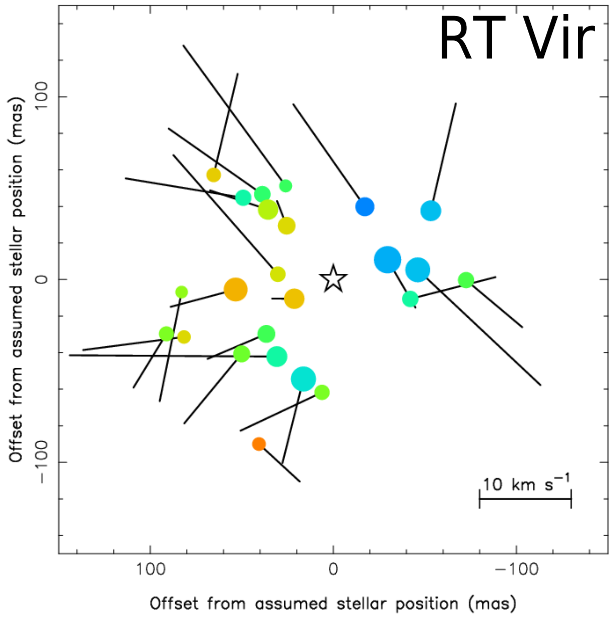


  - 321 GHz excited state maser from inter-clump gas?
    - Equatorial density enhancement? biconical outflow?
- Gray, Baudry, Yates, Humphreys developing models

Proper motions

- 22-GHz masers identifiable ~1 yr
  - 5 km/s~4 mas/yr @ 250 pc
    - Trackable with MERLIN/ ALMA
- SiO near star has shorter life
  - 0.3 mas/month – VLBA
- Need VLBI for 321 (& 325?) GHz kinematics
  - Strong acceleration?
    - Dense clumps
  - Weak radial acceleration?
    - Surrounding gas
  - Outflow and infall like SiO?
    - Possible for 321-GHz masers



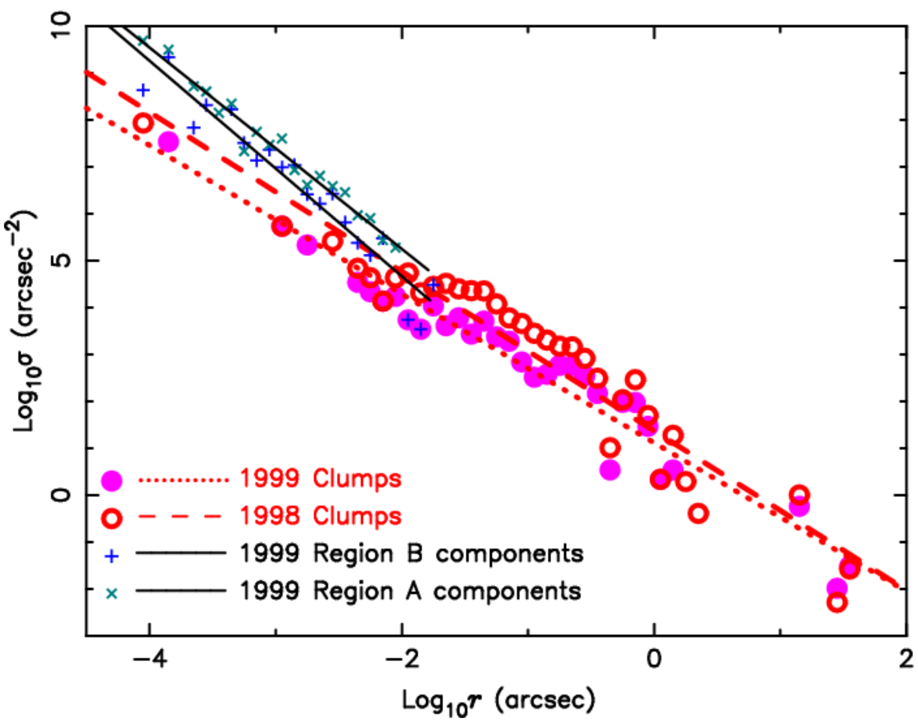


sub-mm maser physics

- Extended ALMA resolution similar to e-MERLIN
  - Resolve 325-GHz clumps if they are similar to 22 GHz
  - 321-GHz masers probably closer to star
    - Also from similar, radially expanding clouds?
      - More compact – need higher resolution
    - Or emanate from inter-cloud gas?
- R_{cloud} ~2 AU @ 15 $R_{\star}$; 0.4 AU @ 3 $R_{\star}$ (1 mas @ 250 pc)
- Need to measure sub-mas component separations
  - Are brighter sub-mm masers smaller?
    - Emission from stable clouds is tightly beamed
  - Bright emission random-sized/more extended?
    - Suggests shocked material

Shocks and Turbulence

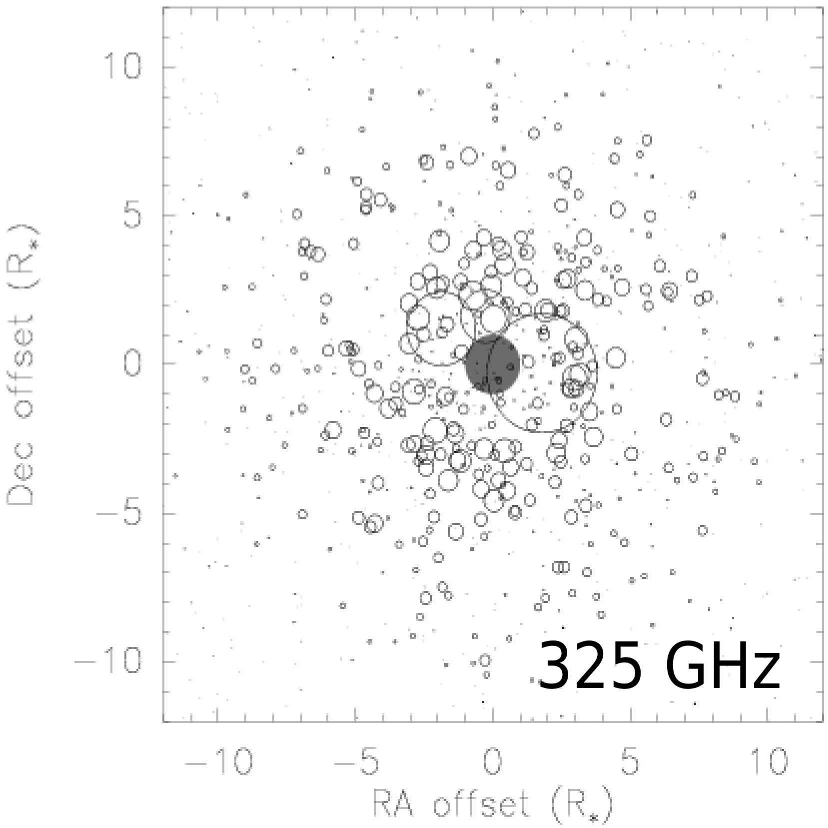
- How far does the stellar pulsational influence reach?
  - Why are SiO maser motions so disordered?
- Direct measurements of turbulence:
  - Line width fluctuations
  - Maser proper motions
- Fractal scales
  - Incompressible/ Kolmogorov within clumps
  - Shallower slope on larger scales suggests supersonic dissipation
- Need full range of scales
  - *Strelniski+'02, Silant'ev+06, Gray'12*

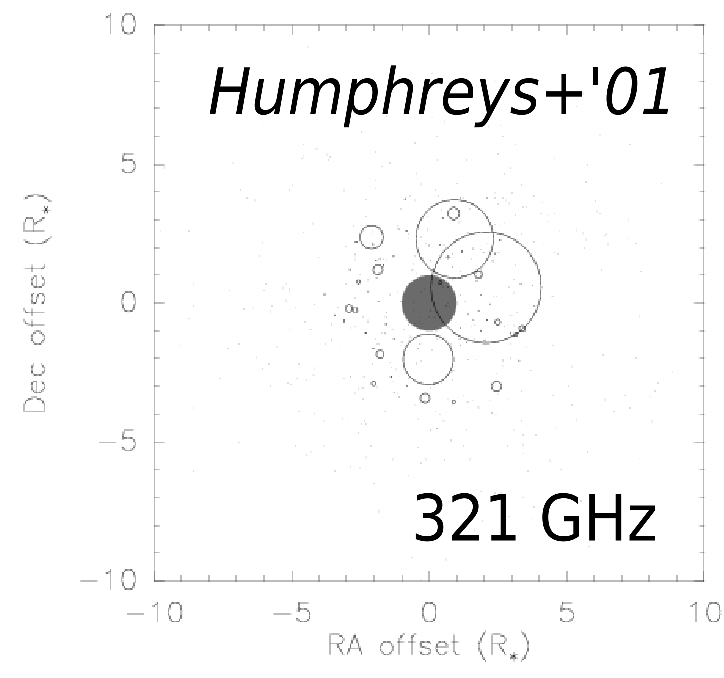


SFR S128A (22 GHz)
- *Richards, Lekht+'04*

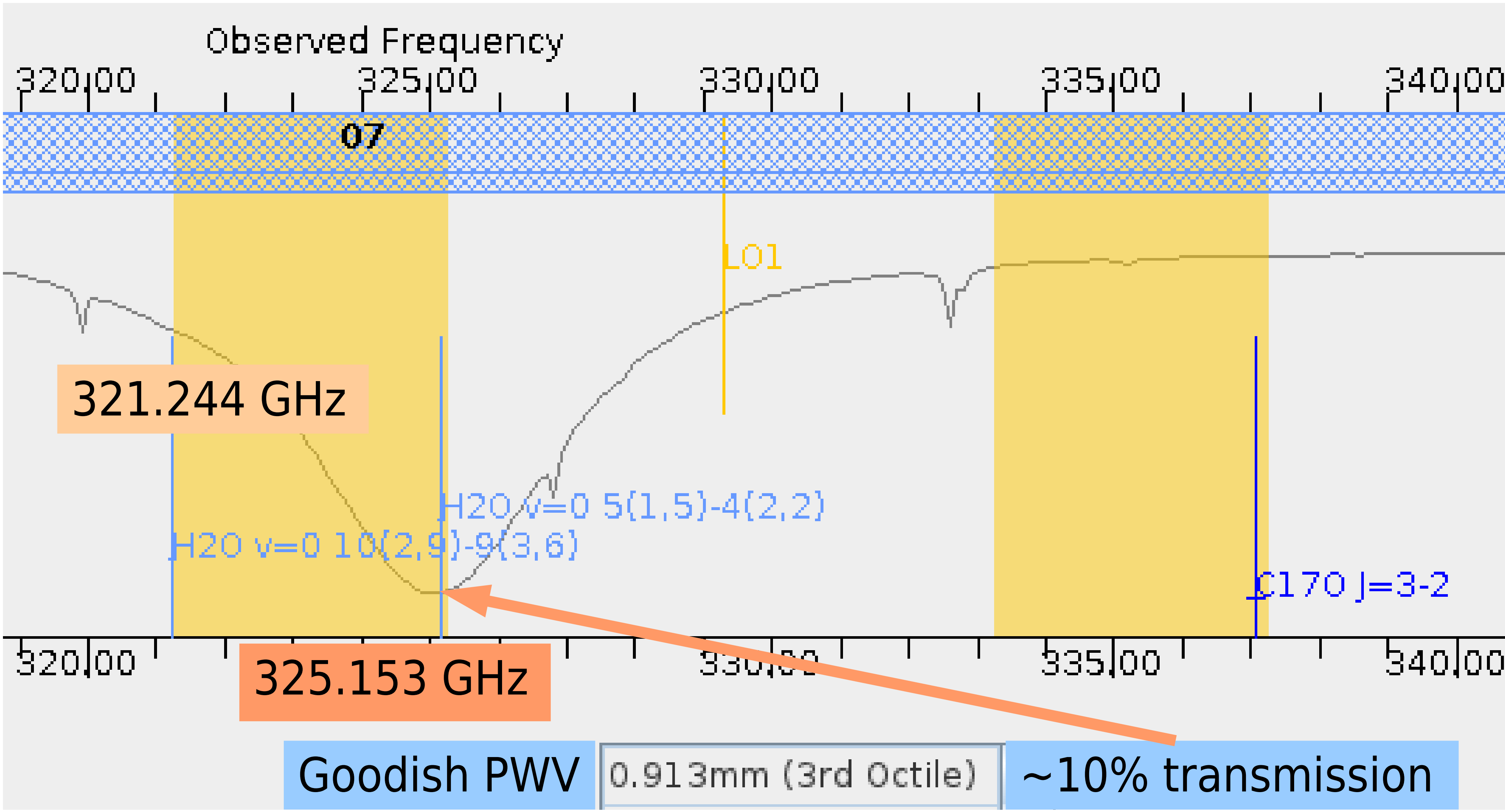
Copropagation

- Conditions for excitation of 321 and 325-GHz masers overlap
- Copropagation *or* segregatation constrains temperature, density, velocity gradient
- Need positions to <<1 mas
- Only maser VLBI can achieve this in CSE





Band 7 GHz water masers



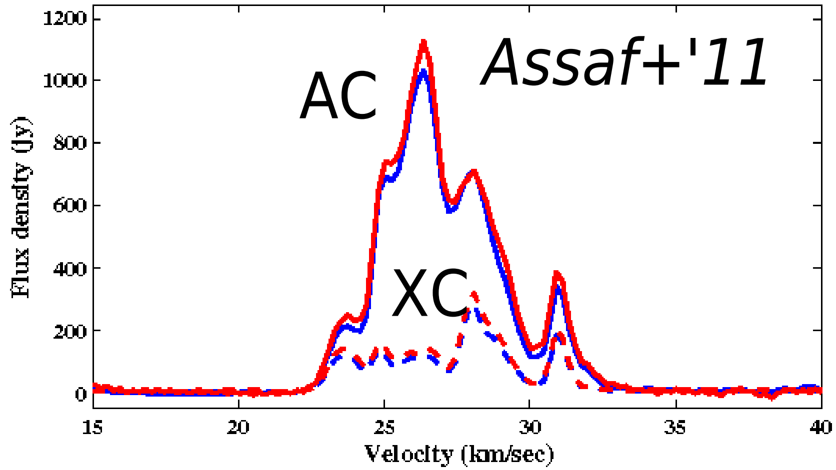
VLBI sensitivity

- λ ~ 0.9 mm, >6000 km baselines
  - <30 μas resolution
  - Say, collecting area/conditions ~ 1/2 ALMA (32 ants)
    - 1 mm PVW
  - Declination –26°
- Sensitivity at 325 GHz ~0.2 Jy in 2 hr
  - 0.2 km/s bandwidth, 30 μas beam
  - 5σ 1 Jy ~ 1.3 10^{10} K
  - 321 GHz: 5σ 0.04 Jy ~ 5 10^{8} K
- Maximum resolution ~15 μas, 0.03 km/s
  - 325 GHz needs 1.4 10^{11} K for 5σ detection in 2 hr

VLBI detectability

- Typical 22-GHz maser 0.1 – few mas
  - Resolved by MERLIN, VLBA
  - Peaks 10^{9} – 10^{14} K
- 325 GHz > 1000 Jy in VY CMa, 100 Jy in AGB stars
  - Likely to exceed 1.3 10^{10} K
- 321 GHz masers often ~1/10 strength
  - But noise limits are better than 1/10 lower
- *What about calibration?*
  - Compact QSO continuum 1 Jy?
    - Bandpass dynamic range per 0.2 km/s ~10 in 10 hr ☹
  - Can this be mitigated?
  - Accurate delay vital to align lines
    - Reasonable amplitudes, especially for physics

Missing flux



- R Cas SiO 43 GHz, 176 pc
- Over half flux missed by VLBA
  - Scales > 5 mas
    - *NB some polarization >100% - smaller-scale structure!*
- VLBI likely to resolve out 90% of sub-mm masers
  - Still measure kinematics, fractals,co-propagation...
    - Total flux densities needed for full maser modelling
      - Need within weeks? Ideally days.
- ALMA will detect all the flux, separate clouds
  - Interpolate assuming Gaussian beamed profiles?
  - Detect star, provide astrometry?
- Can ALMA alone also help bandpass calibration?
  - e.g. half array phased, half extended?

Summary

- 321/5 GHz VLBI tests CSE clumpy mass loss model
  - Location:
    - Does 325 GHz trace 22 GHz?
    - 321 GHz from sub-AU clouds close to star?
      - and/or inter-clump gas further out?
  - Masers from ~spherical clouds or shocked slabs?
    - High-resolution beaming properties differentiate
  - Are clouds internally ~incompressible, but with large-scale motions like dissipative turbulence?
    - Different fractal degrees on μas v. mas scales
- ALMA half & half VLBI, extended configuration
  - Detect all flux, star for astrometry
  - Per-phased-array bandpass calibration?