How do stellar winds break free from the star's gravity?

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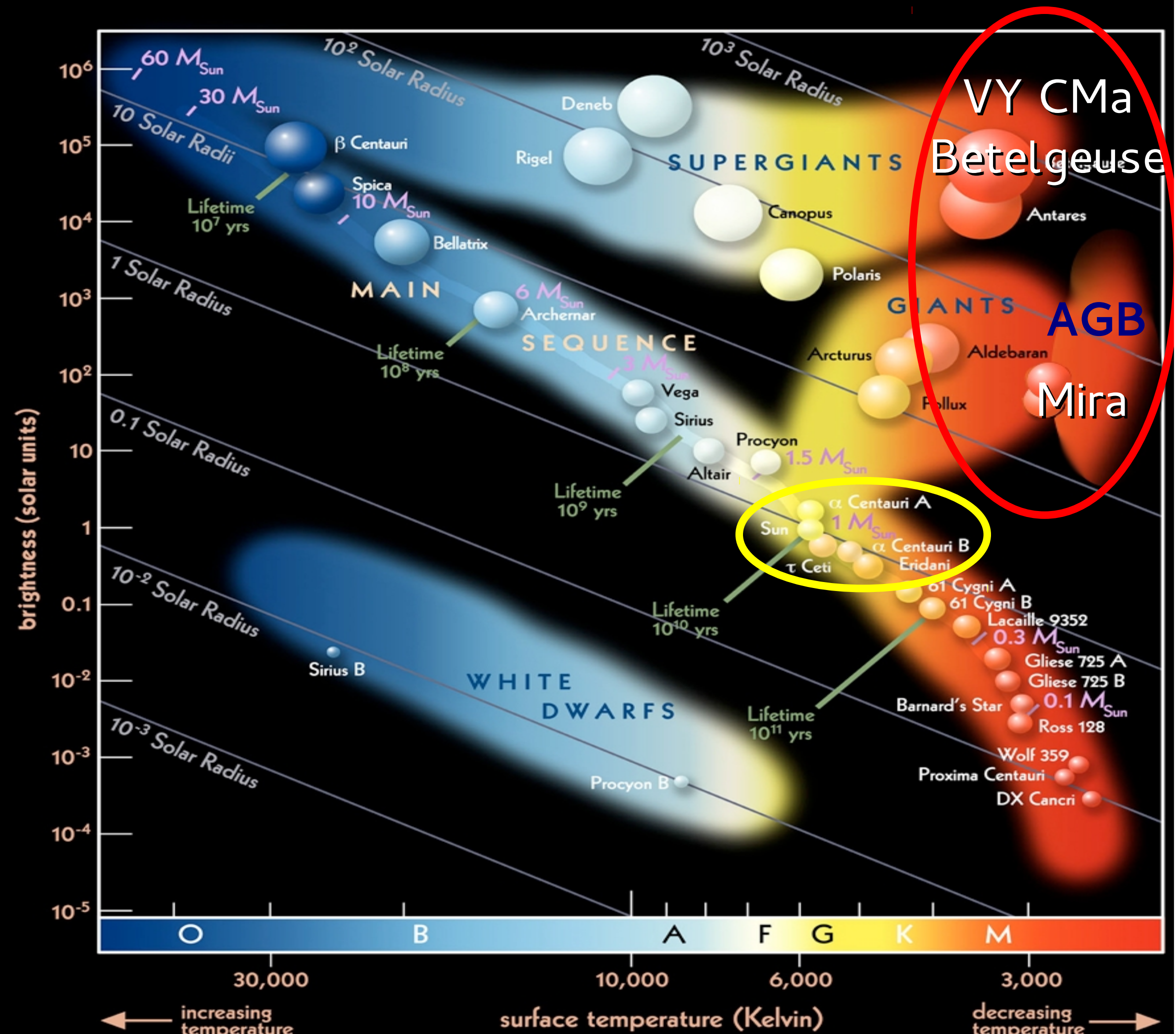
with thanks to ALMA and

e-MERLIN/EVN colleagues

Acceleration of clouds

Inhomogenous mass loss

Shocks and turbulence

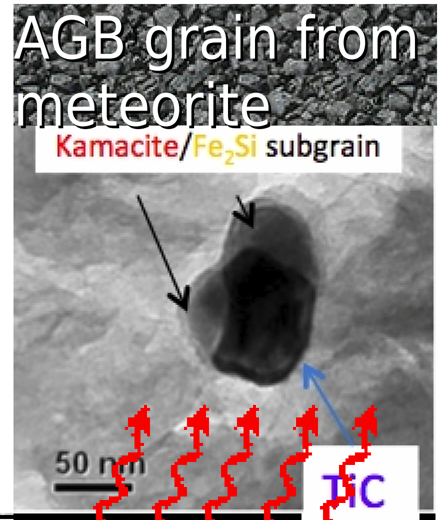


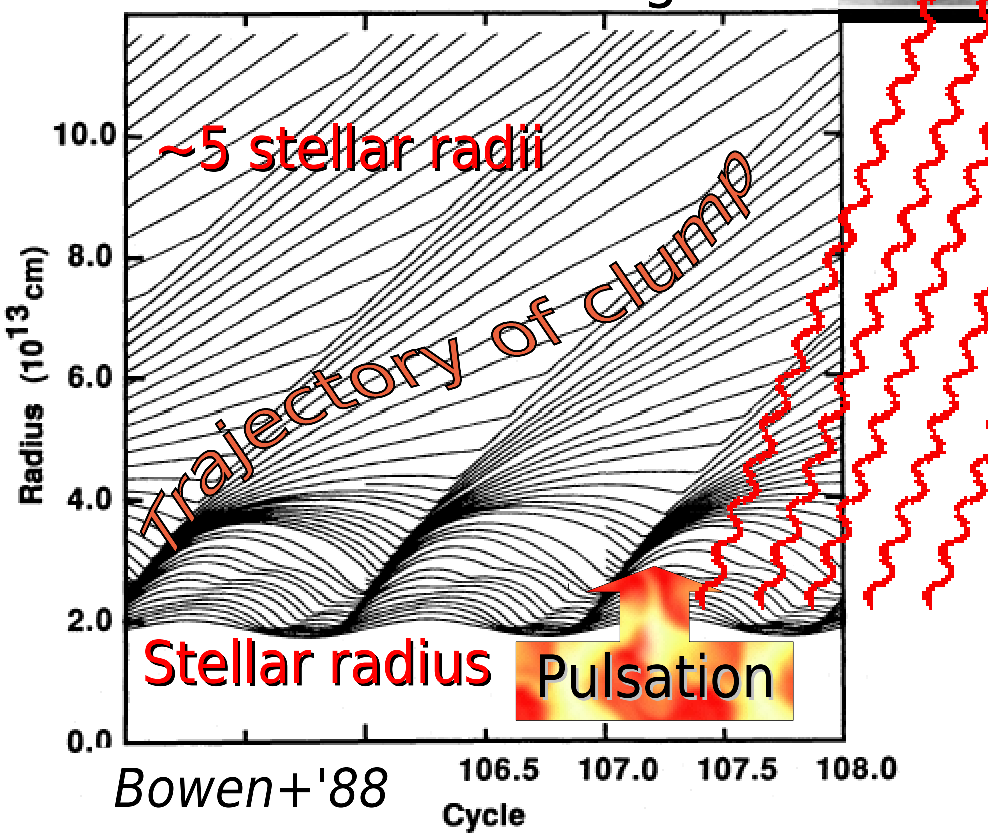
EUROPEAN ARC

ALMA Regional Centre || UK

Mass loss from AGB/RSG stars

- Stellar pulsations lift photosphere
  - 5-7 km/s (*Reid*+'97)
    - Dissipated at >5$R_{\star}$
- Wind cools, dust forms
  - Radiation drives grains



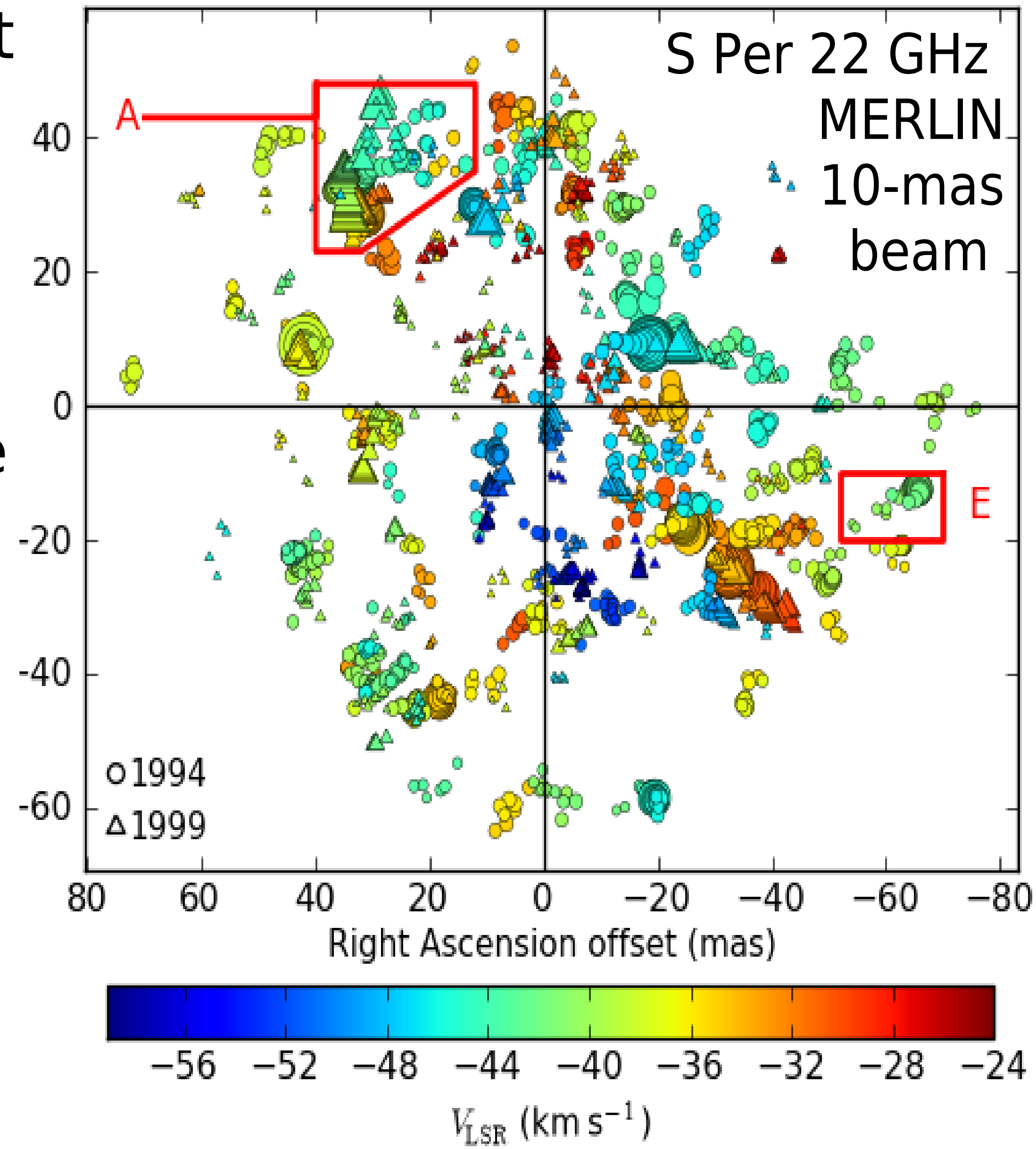


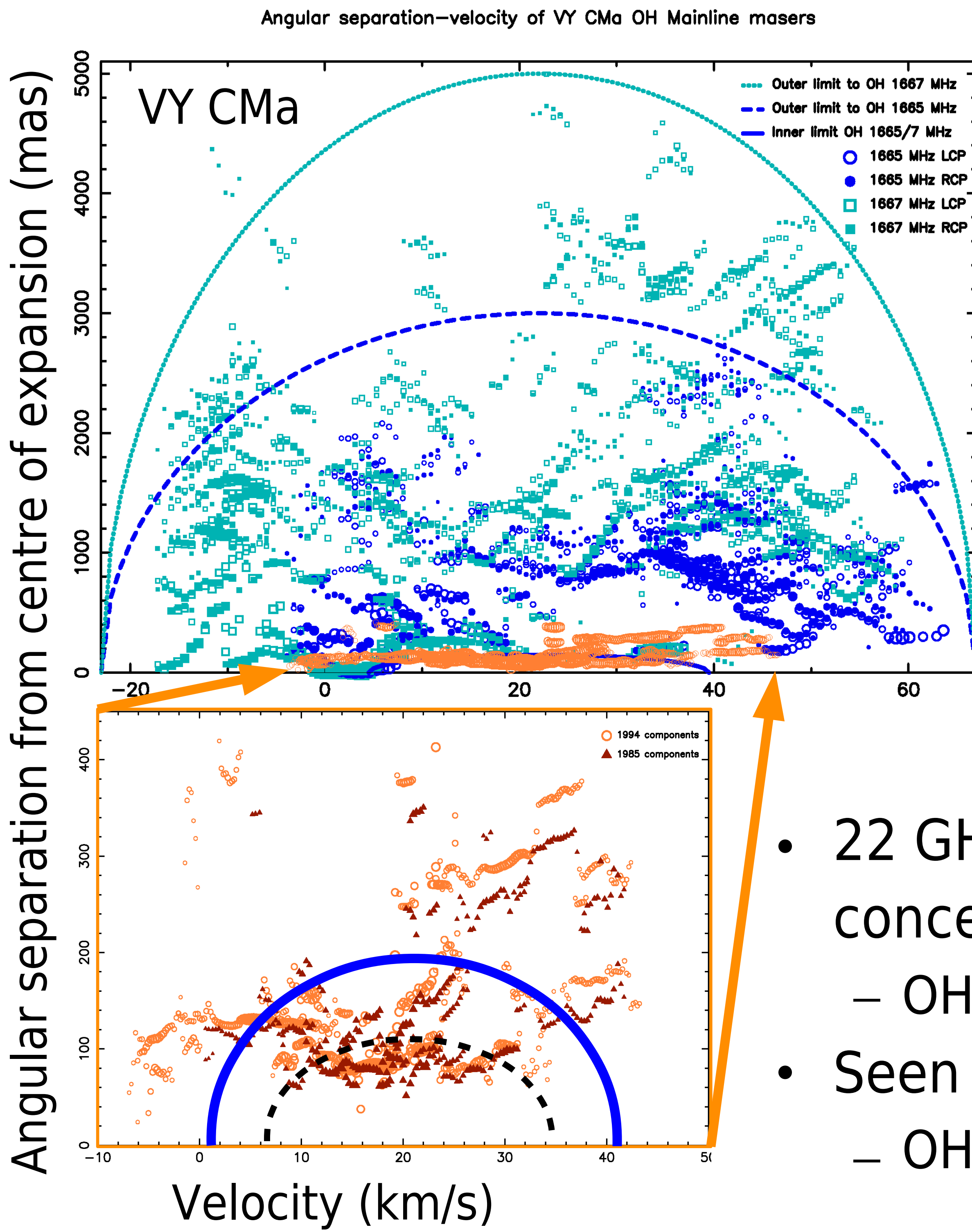
- SiO masers show infall/outflow at <5$R_{\star}$
  - How can this lead to steady expansion?
  - Pressure on small O-rich grains not efficient *Woitke06*
    - Scattering on larger grains (low-mass stars, *Norris+12*)?
    - Radiation pressure on lines?
- How is matter ejected from the stellar surface?
  - Pulsation?
  - Convection/star spots?
  - Magnetic forces?

Water maser cloud measurements

- Fit 2D Gaussian component to each spot:
  - Measure beamed size
  - Spots in 1-2 km s^{-1} series
- Series = discrete clouds
  - Clouds 30–100 x overdense
    - Filling factor <1%
    - Contain 30-90% mass
  - Few formed per stellar P
- Beaming angle

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



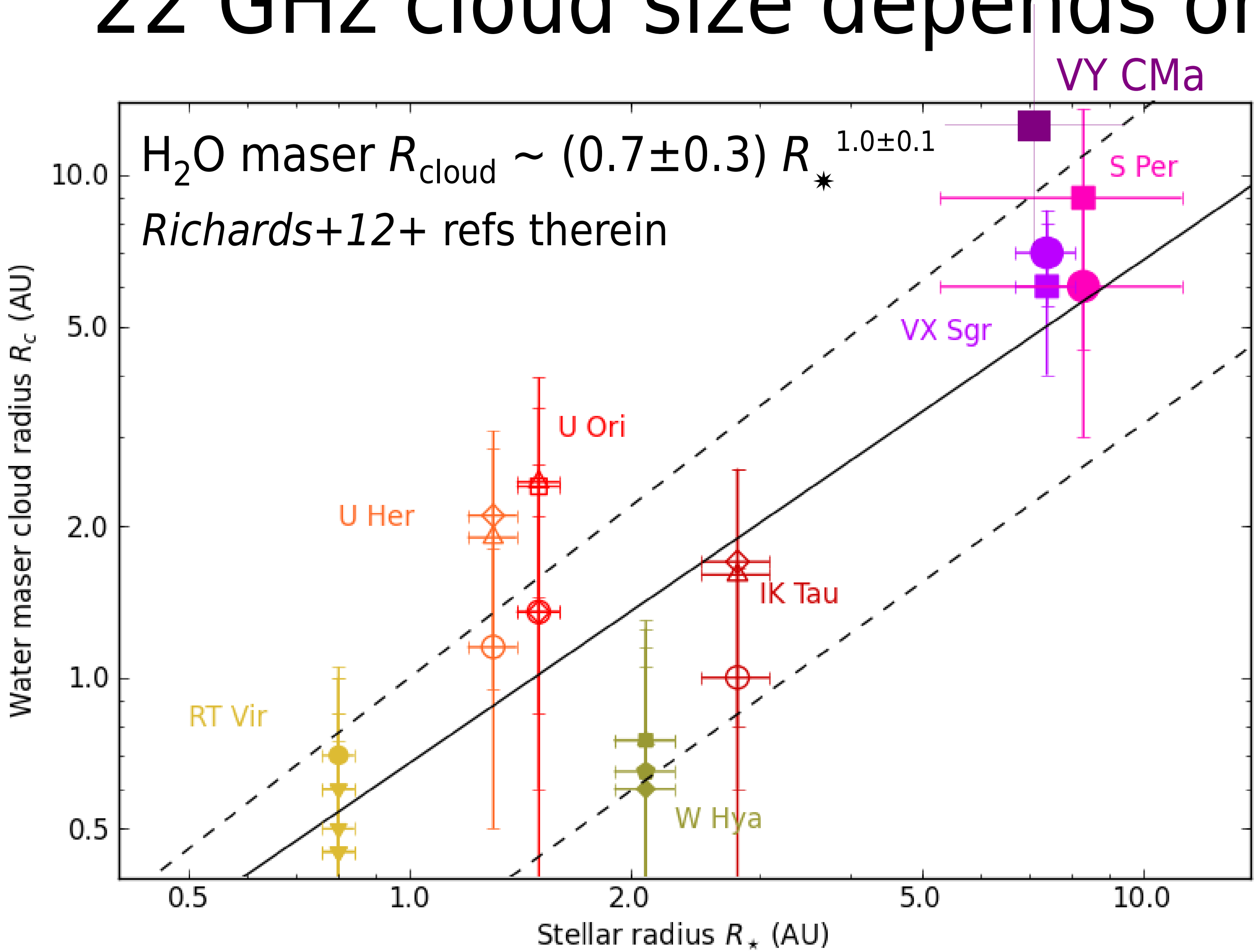


OH masers interleave H_2O

- Mainline OH inner rim in 22-GHz H_2O shell
  - 22 GHz 400-1200K, $n \leqq 5\text{x}10^{15}$ m^{-3} (quenching density)
  - OH needs <500K, lower density gas
- Abundance differences?

- 22 GHz H_2O masers concentrated in dense clumps
  - OH from gas in between
- Seen for other evolved stars
  - OH 1612 always outside H_2O

22 GHz cloud size depends on star size

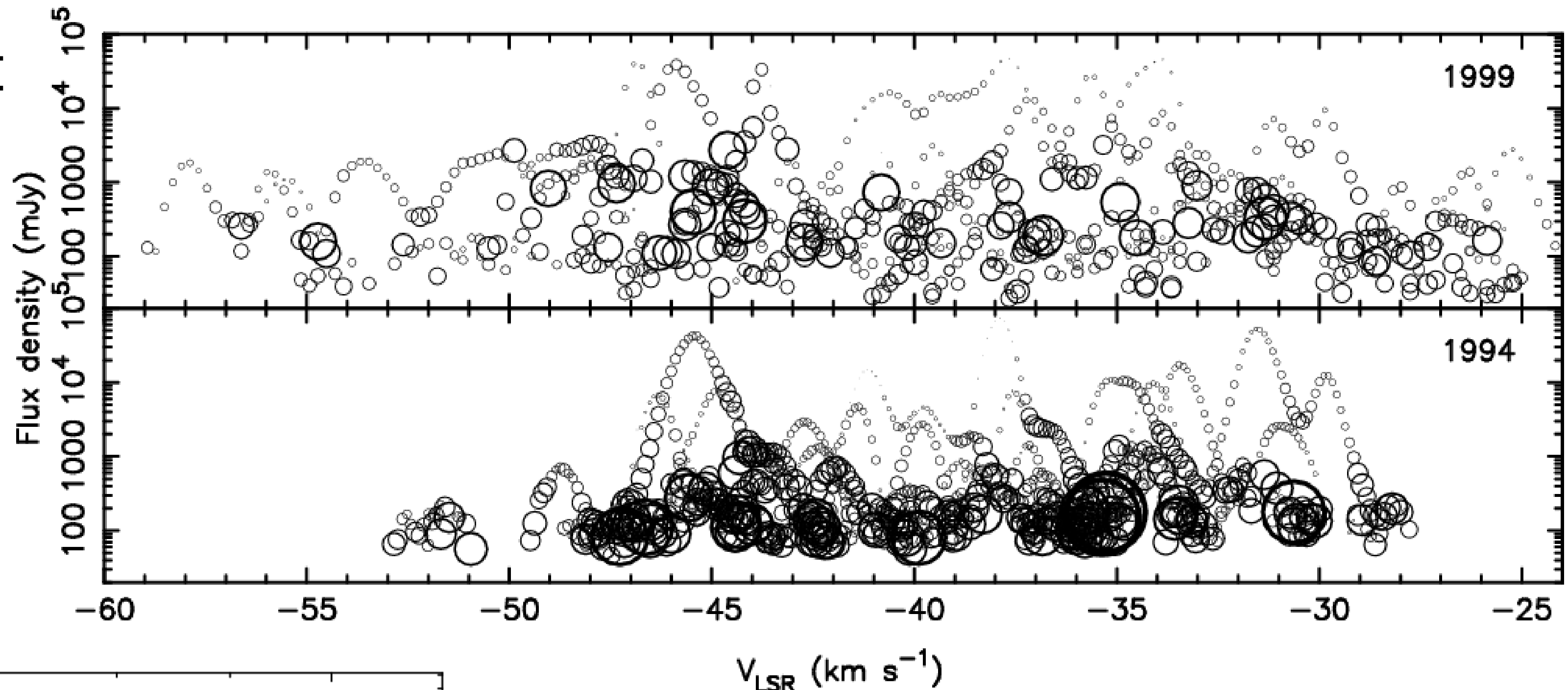


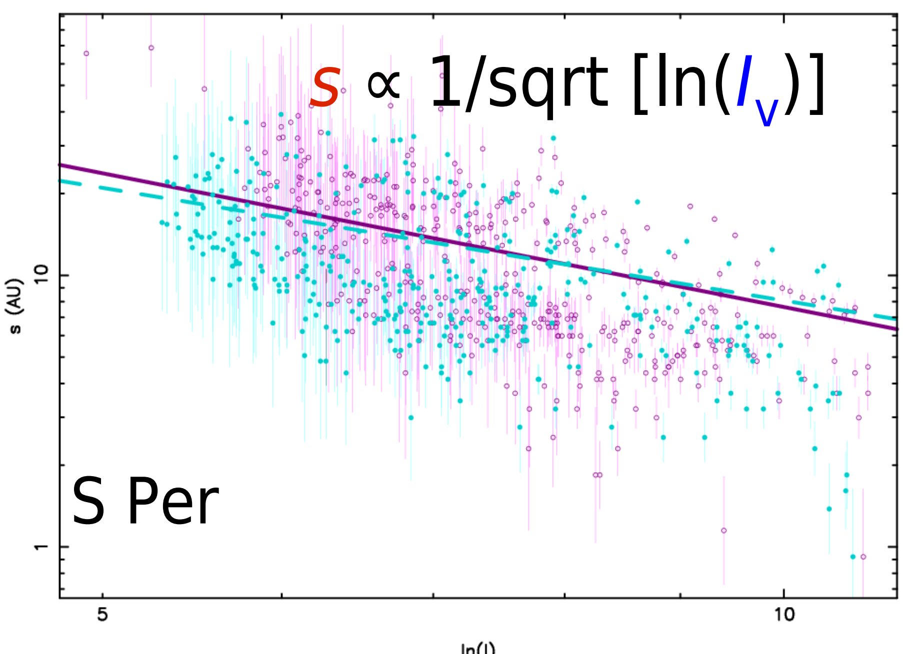
- Cloud properties determined at ejection from star
  - Not micro-physics of dust cooling
- If outflow expands as r^{-2}, birth radius (5–10)% $R_\star$

- VLTI etc. observations & convection cell models suggest stellar surface inhomogeneities on ~10% scale
  - *Wittkowski+11 ; Chiavassa+*

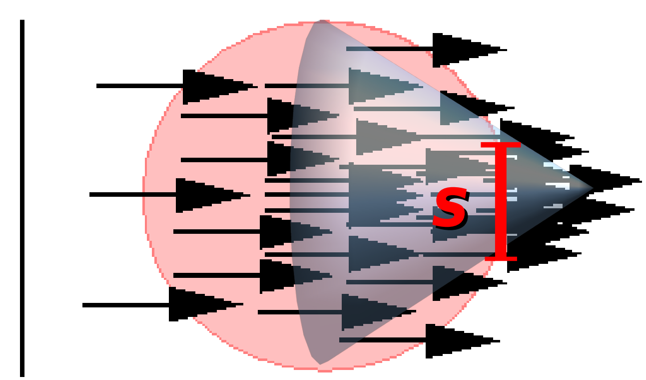
Shrinking of brighter masers

- Component size s
- Intensity I_ν
- Brighter spots are smaller



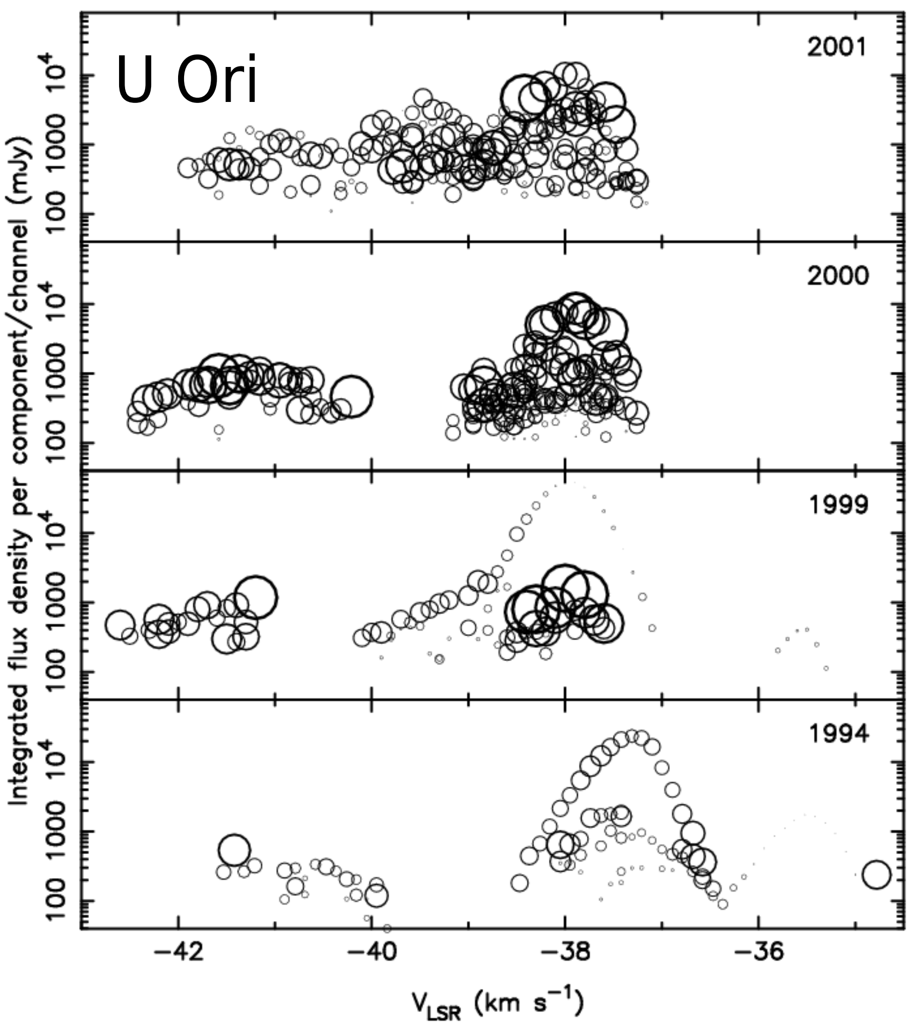


- “Amplification-bounded” beaming from ~spherical clouds

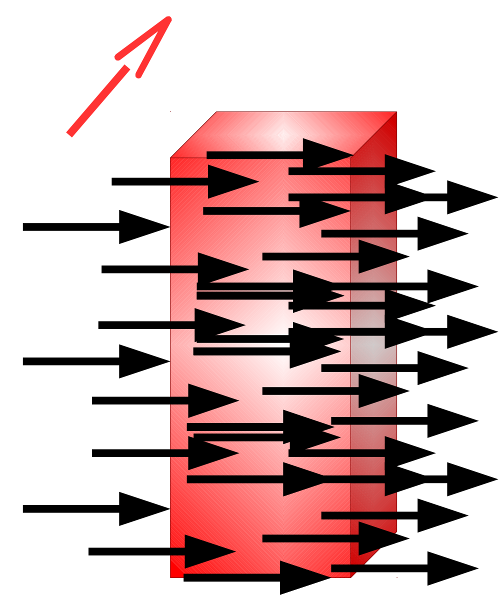


But *sometimes* brighter=bigger

- Spectral peak components swell

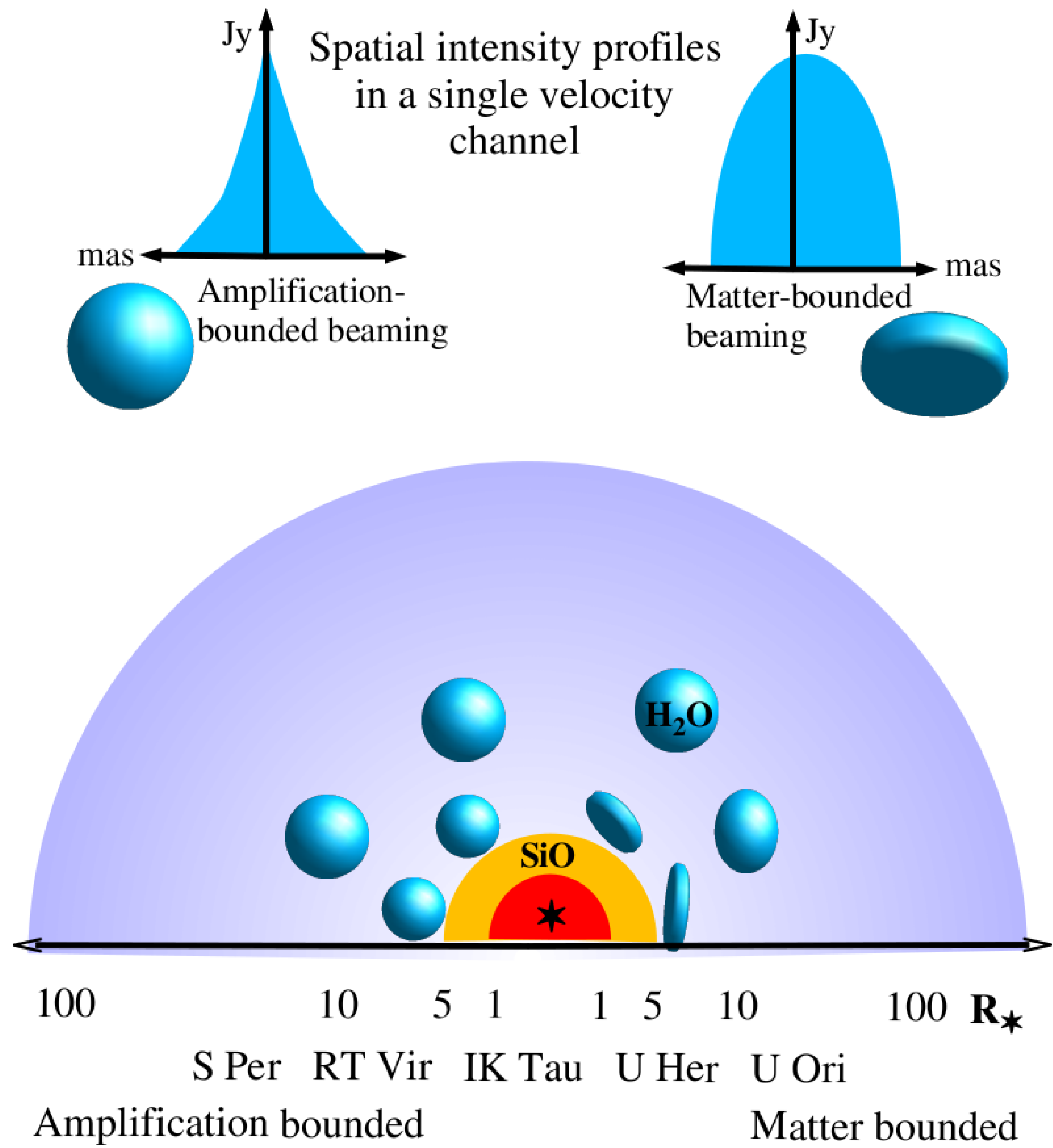


- Shock 'into page'
  - Maser propagates perpendicular to shock
    - Pump photons escape orthogonally
    - Entire surface emission is amplified
    - “Matter bounded” beaming
    - Apparent size ~ actual size



Maser properties reveal wind disturbances

- Brighter = smaller beamed size?
  - Smoothly expanding spheres
- Brightest emission often ~cloud size?
  - Rapid maser variability
  - Stars with deepest pulsation amplitudes
  - Unusual OH flares
    - Shocked slabs

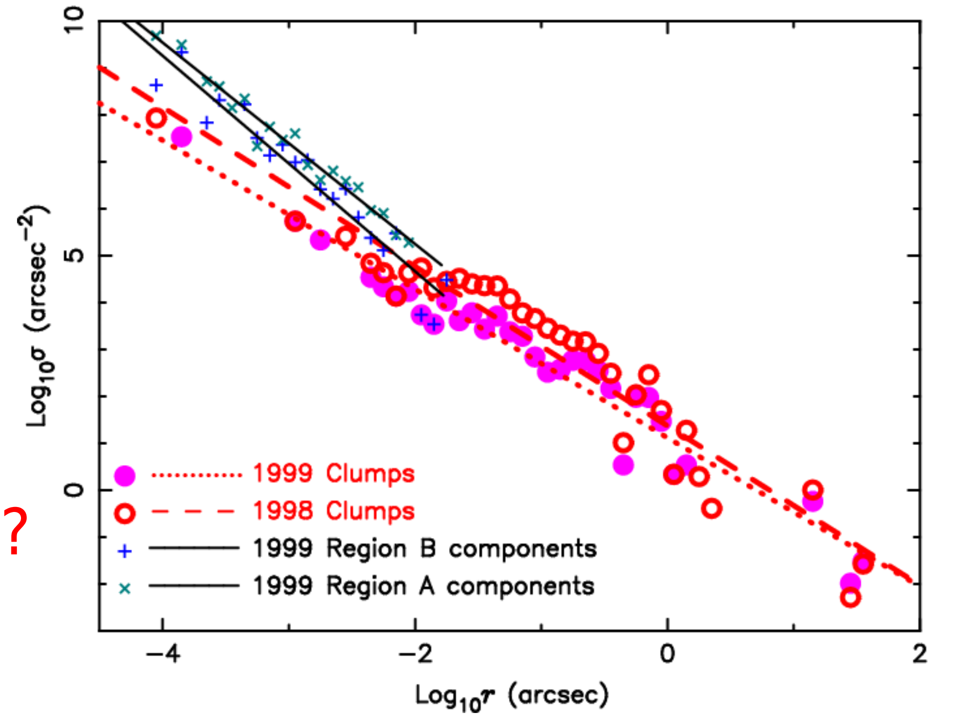


Richards Elitzur & Yates 2011
Elitzur Hollenbach & McKee 1992

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: supersonic dissipation?

    Strelniski+'02, Silant'ev+06, Gray'12, Uscanga
- Need full range of scales
  - Inside and between clouds



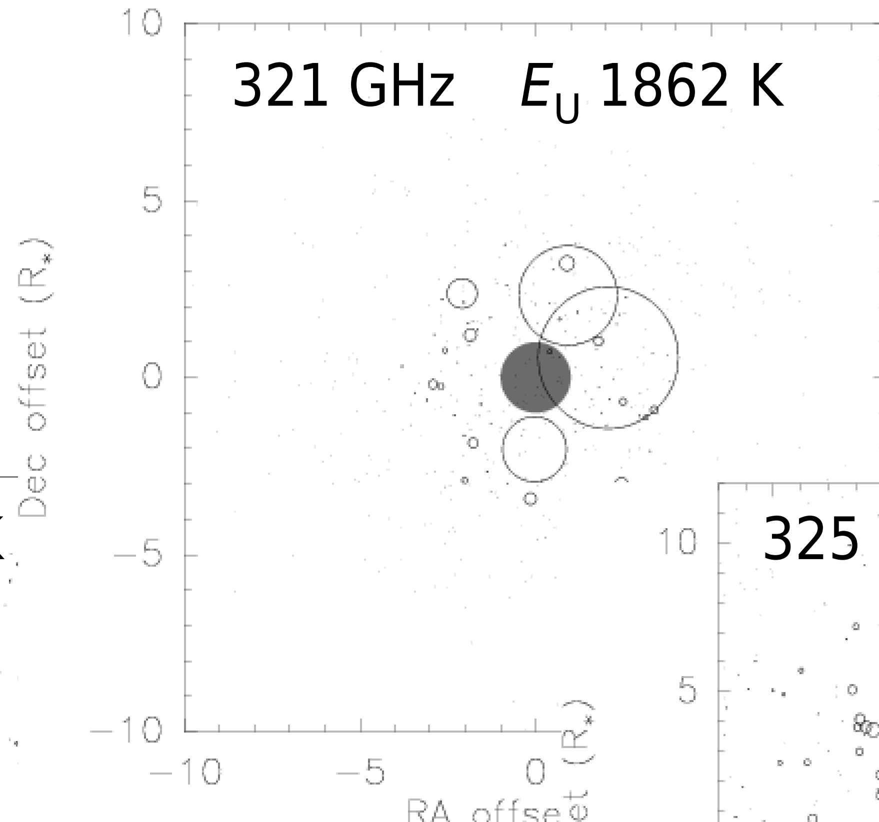
SFR S128A (22 GHz)

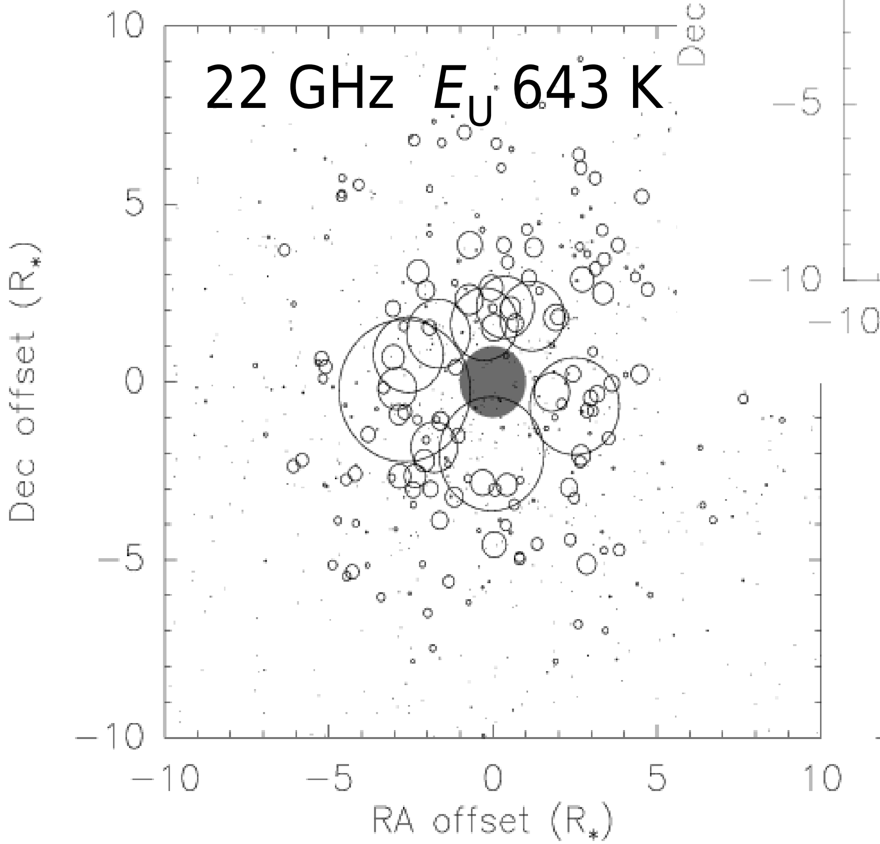
- *Richards, Lekht+'04*

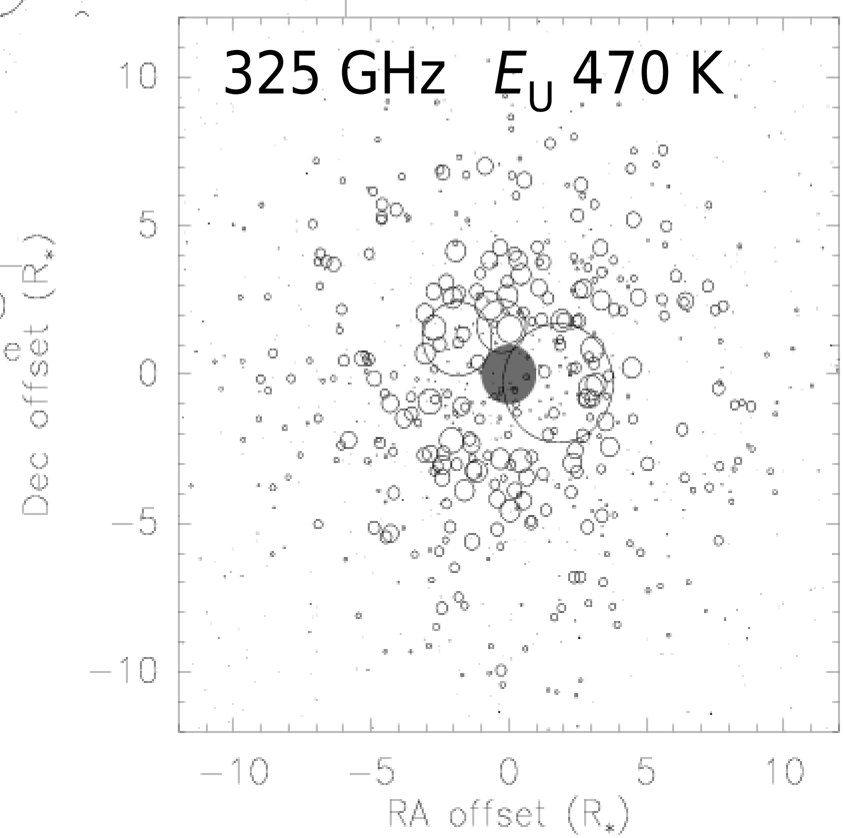
Sub-mm water maser predictions

Humphreys+'01
Neufeld+'91,'10

658 GHz E_U 2361 K
Expect to be even more compact (in SiO zone)

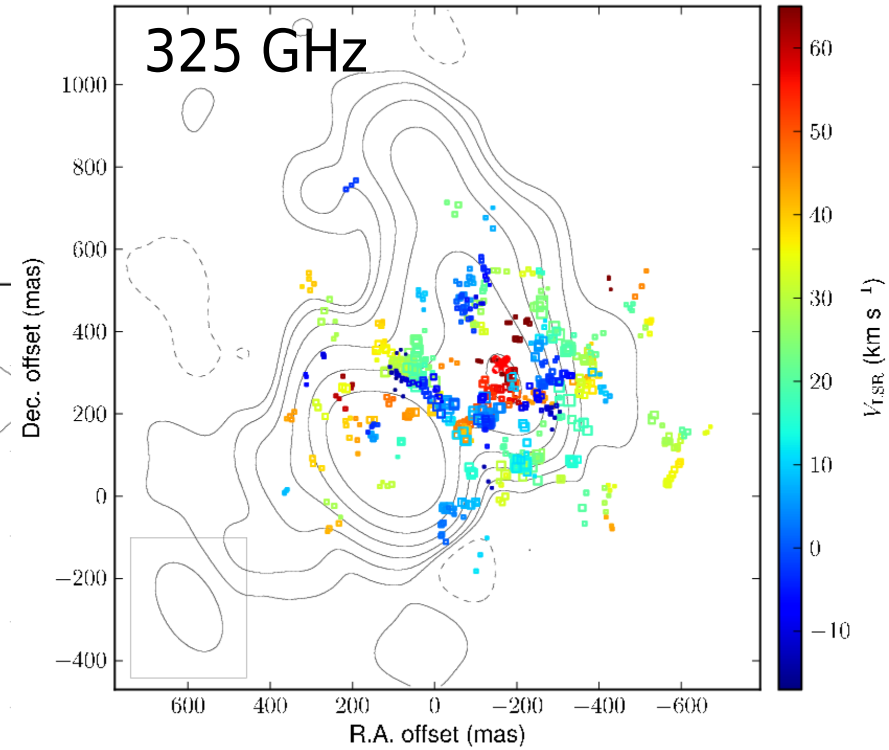


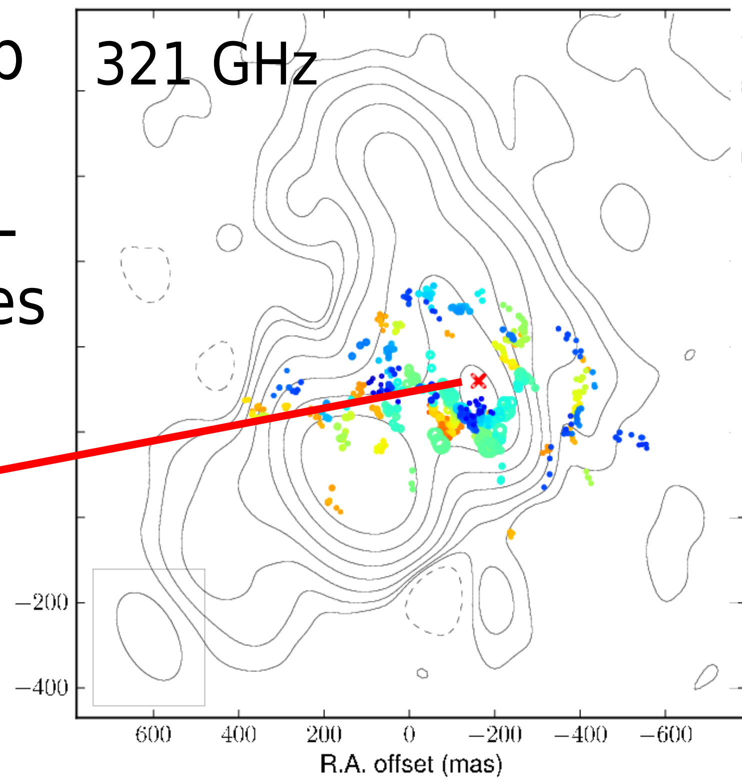


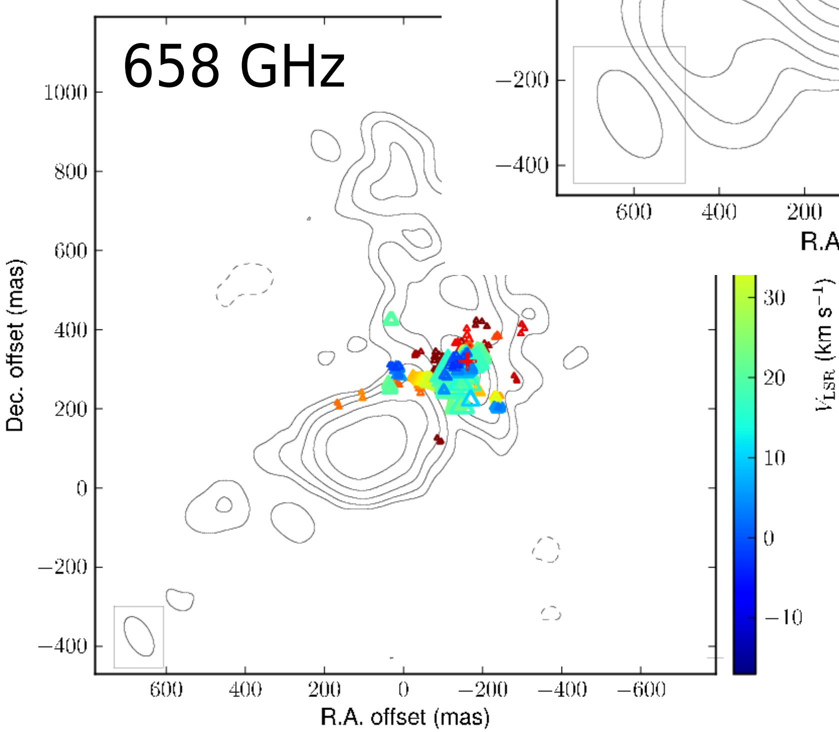


ALMA SV observations of sub-mm masers

- Baselines up to 2.7 km
  - First resolved images
  - Locate VY CMa star

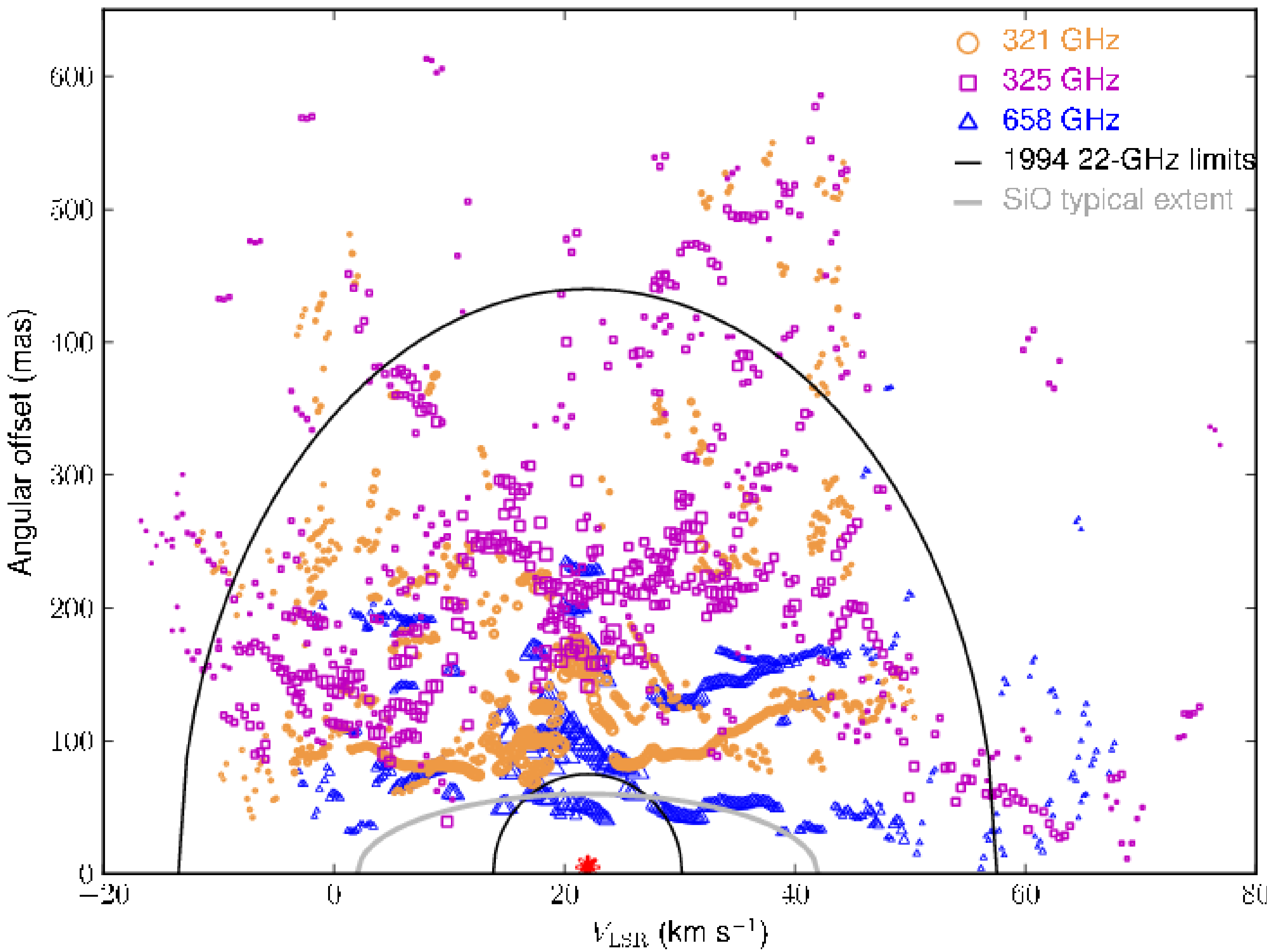






- 325-GHz most extended, as predicted
  - Moderate acceleration
- 321-GHz similar distrib. to 22 GHz
  - Strong acceleration
- 658-GHz starts at few R_*, inside dust formation radius – OK
  - Extends to tens R_*!

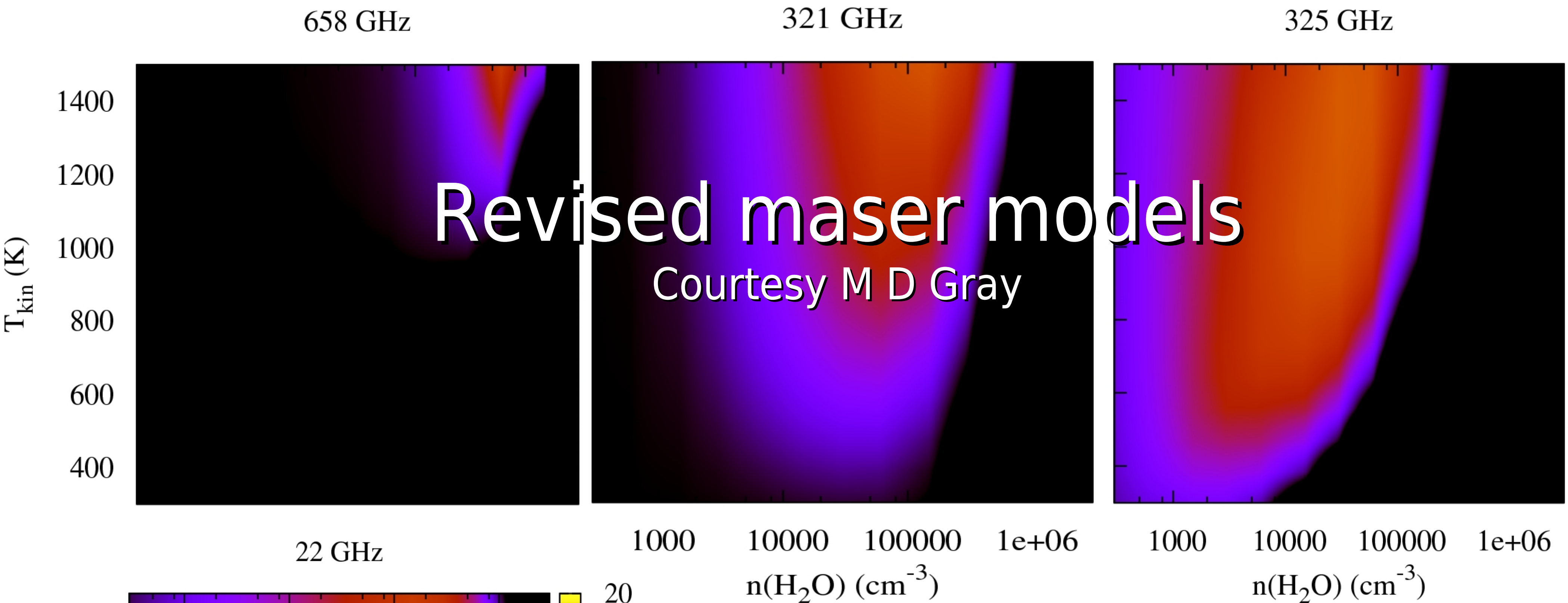
Spatial distribution

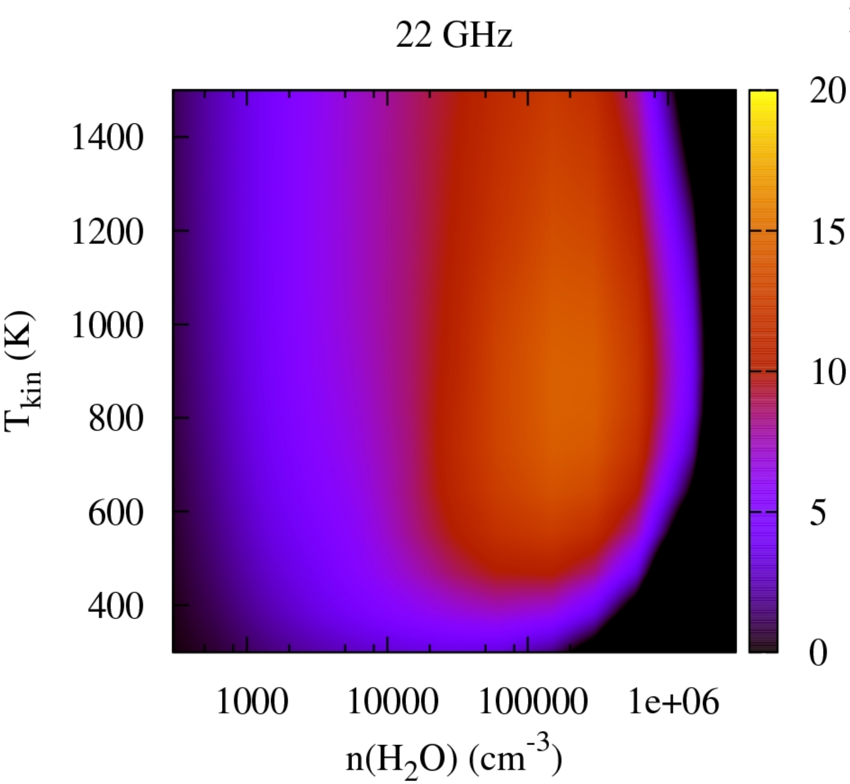


- 658 GHz starts inside dust formation zone
  - But at larger radii than SiO
  - Extend almost to where OH begins!!!
- At least 325-GHz is as predicted
  - Low excitation temperature, large inner radius
- 325-GHz some faint extreme-velocity emission
  - Close to line of sight to star
    - Moderate acceleration

Revised maser models

Courtesy M D Gray

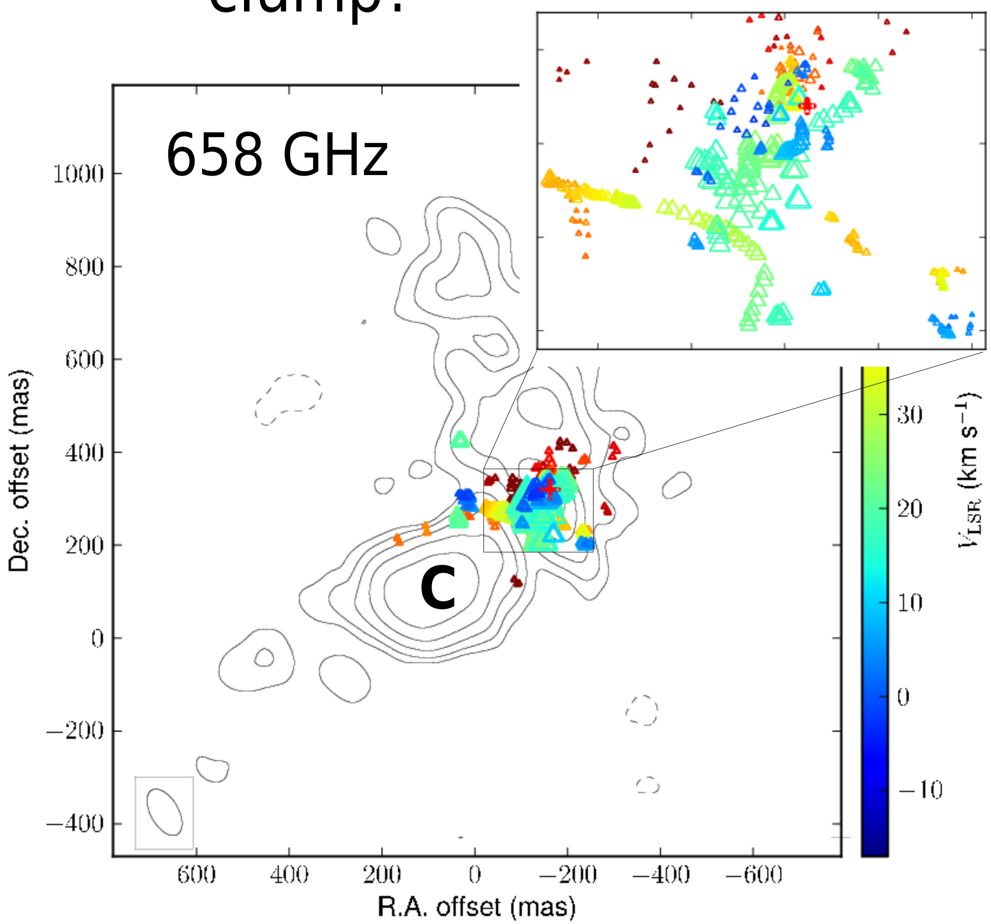


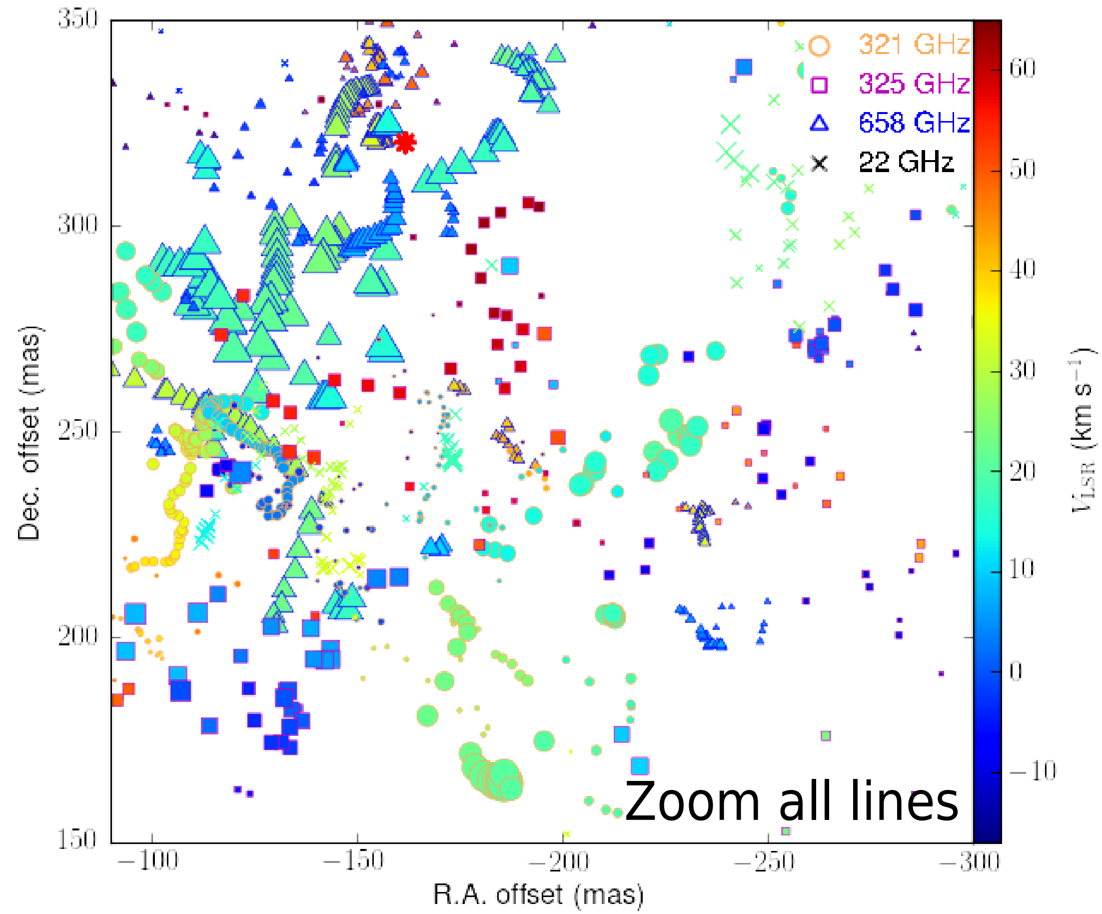


- 325-GHz extends to lower wind densities than 22 GHz
  - But more easily quenched
- 321- inner overlap with 22-GHz
- First 658-GHz model
  - Hard to explain observed extension
- Different lines – different beaming?

Shocks and inhomogeneities

- 658- and 325-GHz masers appear to curve round '**C**'
  - Wind colliding with dense clump?





- Can shock heating explain extended high-excitation lines?
  - Rel'nship shocks/dust (*Hoffner*)
- Species separate 10-au scales
  - At similar radii but in different-density environment/clumps?
    - Not co-propagation

VLBI + ALMA for sub-mm masers

- Sub-mm VLBI needed to resolve proper motions, spots
  - Multiple species: constrain temperature, density, *V* field
    - Maser physics, fundamental physics (non-Gaussianity)
  - Kinematics, fractals, (non)co-propagation…
    - Shock/turbulence diagnostics on sub-au scales
  - *Similar sub-mm water maser science possible in SFR*
- AGB/RSG spot at few 100s/1000s pc: ≤0.1 – few mas
  - Whole clouds up to few tens mas
    - Total flux densities needed for full maser modelling
  - Need 0.5 km/s spectral resolution, if possible finer
    - But also continuum for calibration sources?
- ALMA subarray e.g. 0.5 -15 km to detect all the flux
  - Detect star, provide astrometry, help calibration
  - LLAMA? (~100s km South American baselines)

Spectral line VLBI at 321/325 GHz???

- Most telescopes with 230 GHz have 345 GHz band
- Masers few Jy per 40 μmas beam per 0.5 km/s
  - 1-hr sensitivity ten(s) mJy
  - RadioAstron (similar bm) detects 22 GHz masers
- Biggest challenge bandpass calibration?
- Next… 658 GHz VLBI?
  - Polarization?
    - Avoid Faraday rotation/ beam depolarization !