Multi-maser measurements

physical conditions and astrophysical properties

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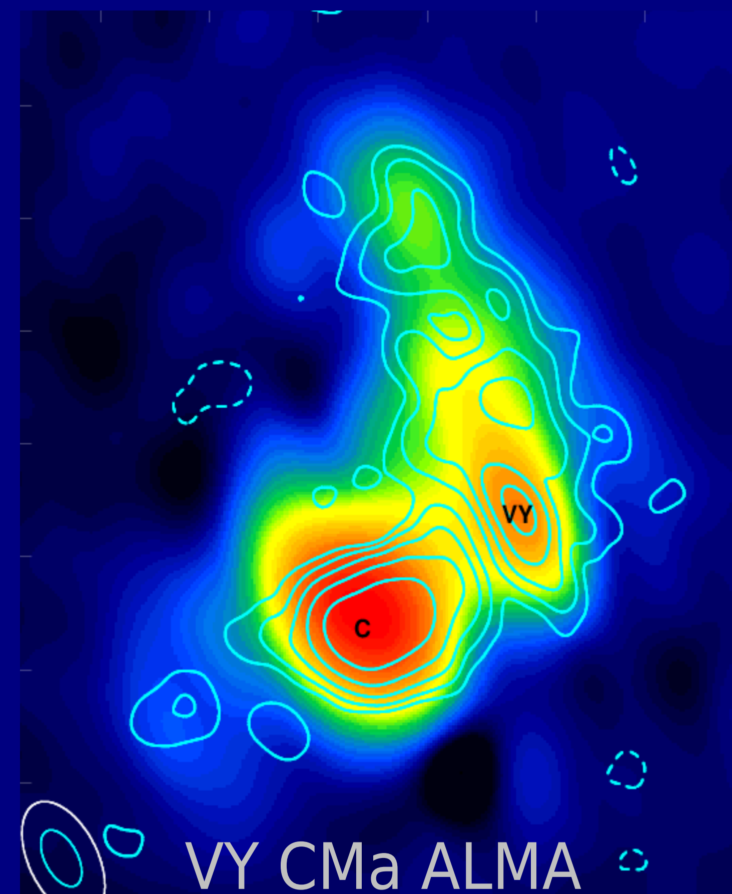
thanks to Malcolm Gray and many collaborators

- Evolved stars: mass loss
  - How; what survives
- Water around evolved stars
  - Scales from μas to tens mas
    - Morphology, kinematics
- Multiple transitions constrain physical conditions
  - High precision measurements of molecular gas properties



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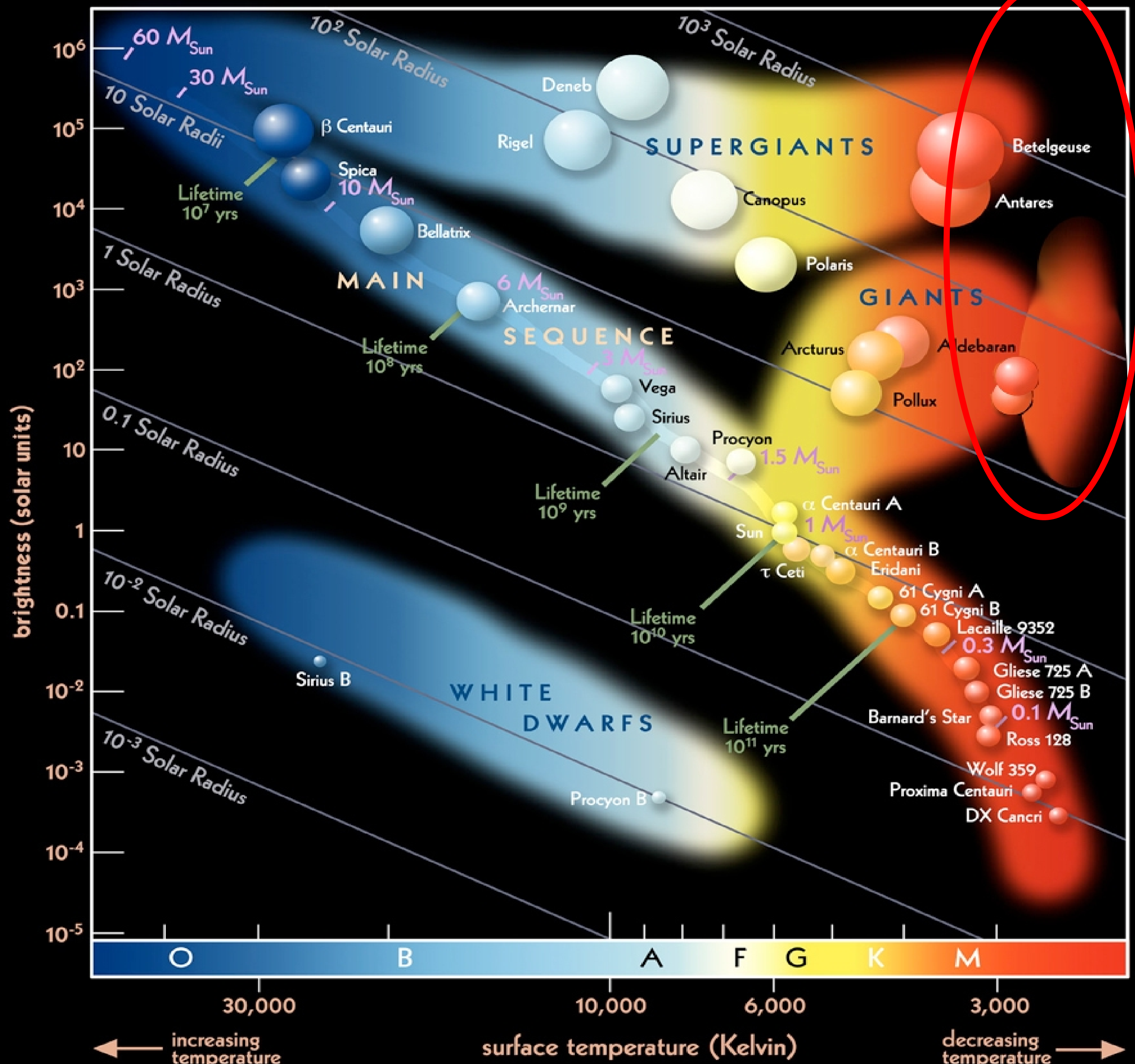
Evolved stars

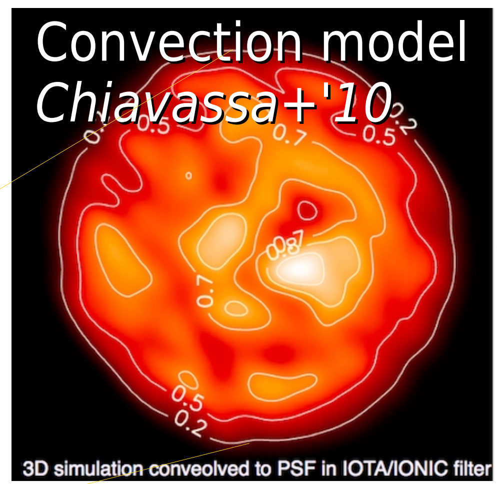


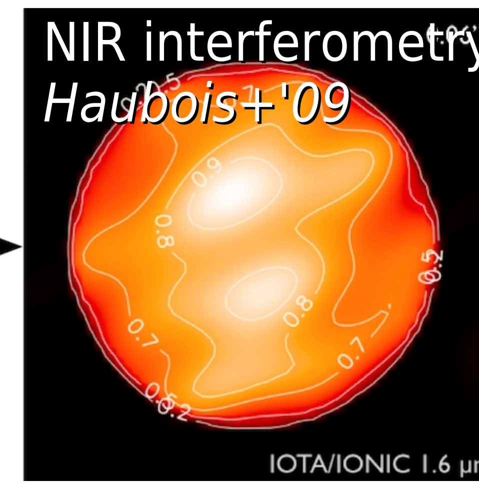
Asymptotic Giant Branch (Miras etc.) & Red Supergiant stars

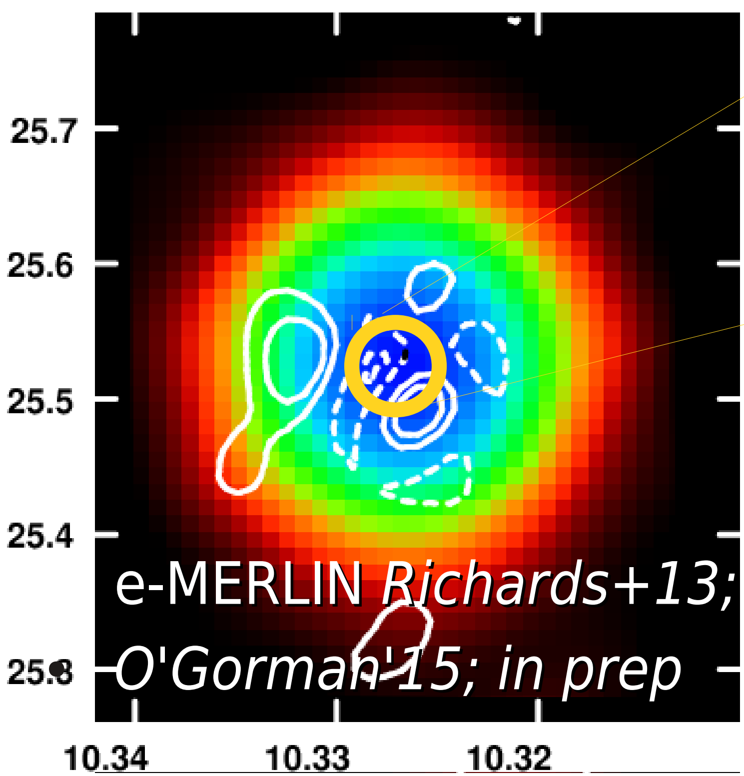
- T_{eff} 2500-3500K
- $R_{\star}$ 0.5 – 5 au
- Pulsation P ~yr
- Mass loss rate
- 10^{-8} – 10^{-4} $M_{\odot}$/yr
- Enriched in dust and molecules

What don't we know?

- How is mass lost from the stellar surface?
  - Pulsation? Convection cells?
    - Peturbations ~0.1 R_* optical and radio







- Betelgeuse; similar hot/cold spots also seen in other RSG and Mira (*Vlemmings+'15*)
  - Low-filling-factor chromosphere
    - *Harper & Brown 2006*

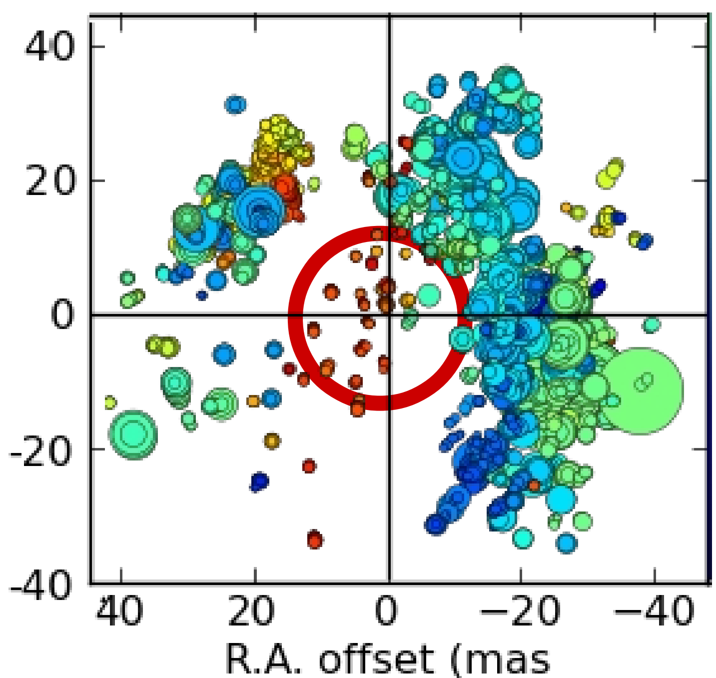
What don't we know?

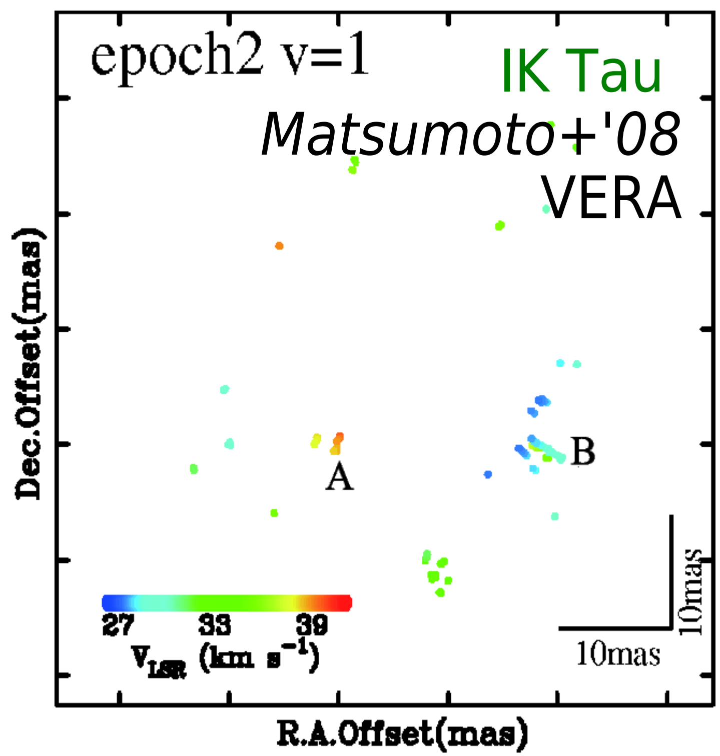
- How are winds driven?
  - Radiation pressure on dust, once it has formed
    - Simple model needs help
      - Large grains? Scattering?
      - Models: *Hoffner, Bladh;* Observations: *Norris*
- Spherical, solitary stars produce asymmetric PNe/SNR
  - Unseen companions/planetary remnants?
  - No surface rotation on AGB/RSG
    - Spinning core?
  - Magnetic field?
    - Zeeman splitting (masers, stellar lines)
      - Stellar-centred field – but Dipole? Solar-type? Toroidal?

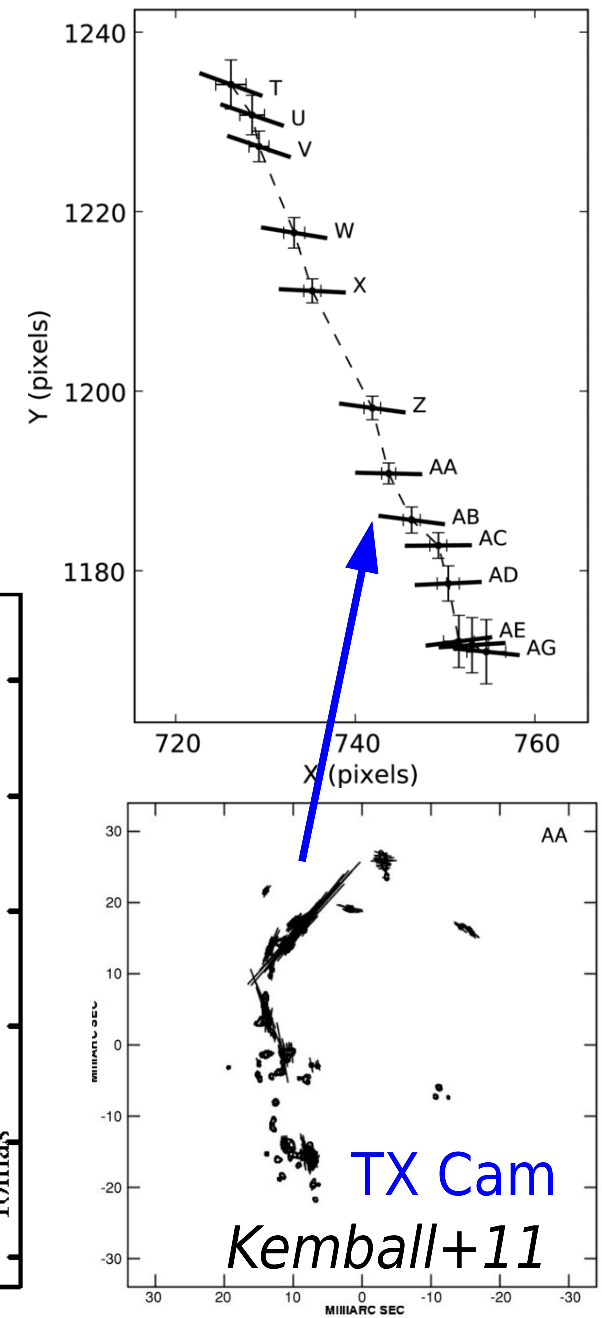
Inside $r_{\mathbf{d}}$: SiO ballistic? Magnetic driving?

- R Cas shows central redshifted emission
  - Must be near-side infall
- TX Cam maser proper motions non-radial, follow polarization vectors
  - Dragged or dragging (*Hartquist+96*)?
- But ballistic trajectories fitted for IK Tau

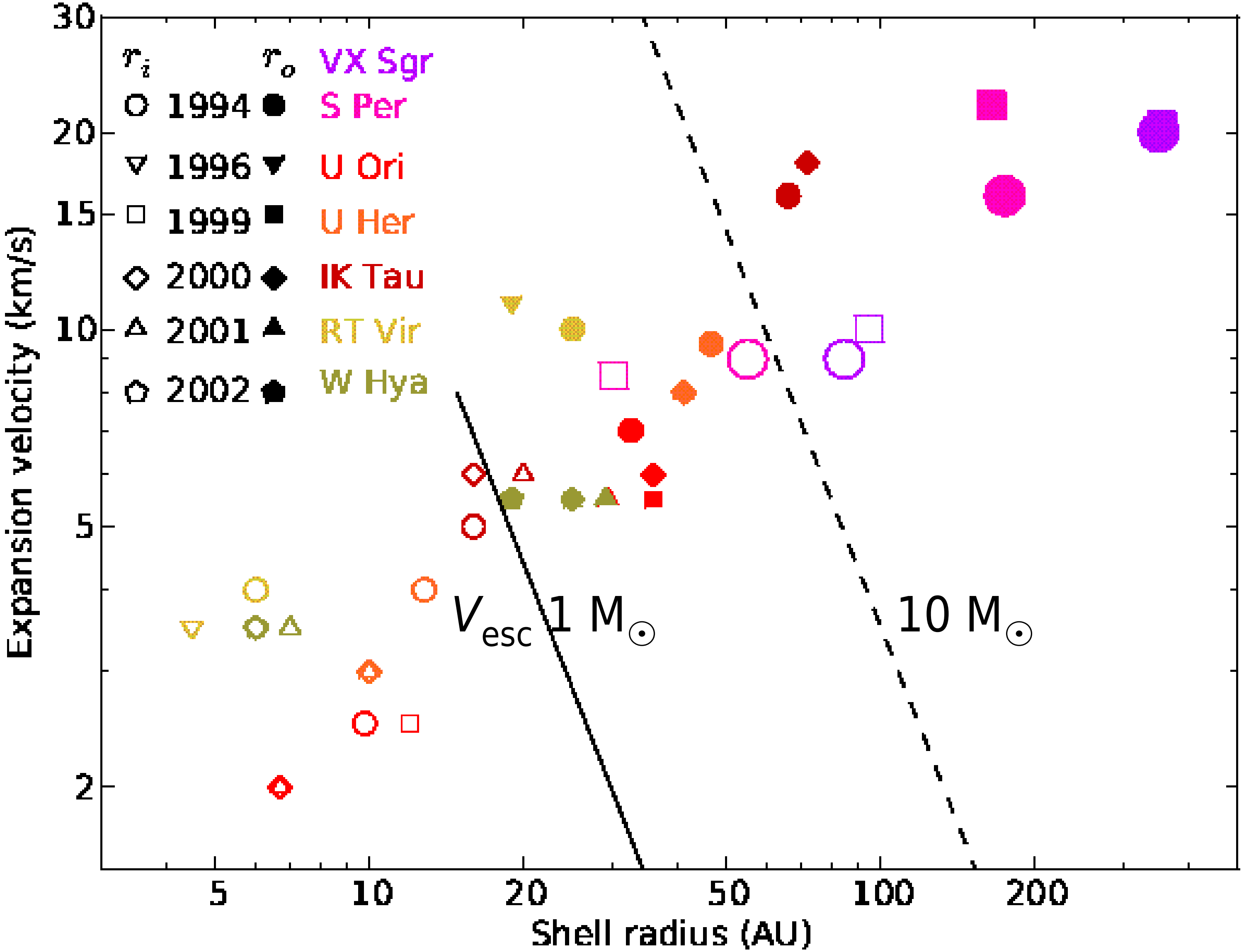
R Cas *Assaf+'10* VLBA







Escape velocity reached in 22 GHz shell

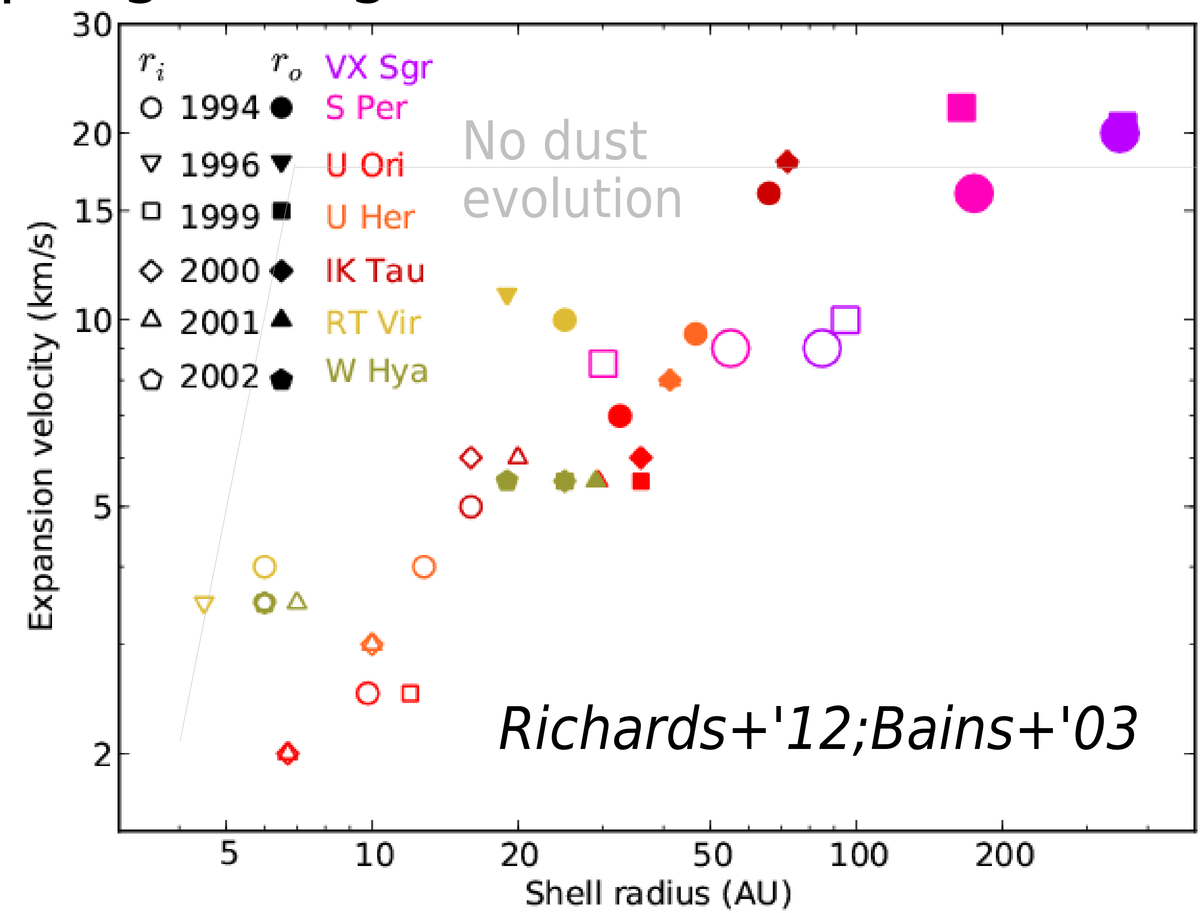


Richards+'12; Bains+'03

- First noted by Yates & Cohen 1994
  - Symbols show H_2O maser shell limits
    - Hollow inner
    - Filled outer
  - Lines show escape velocity
- Wind bound till ~10 R_*

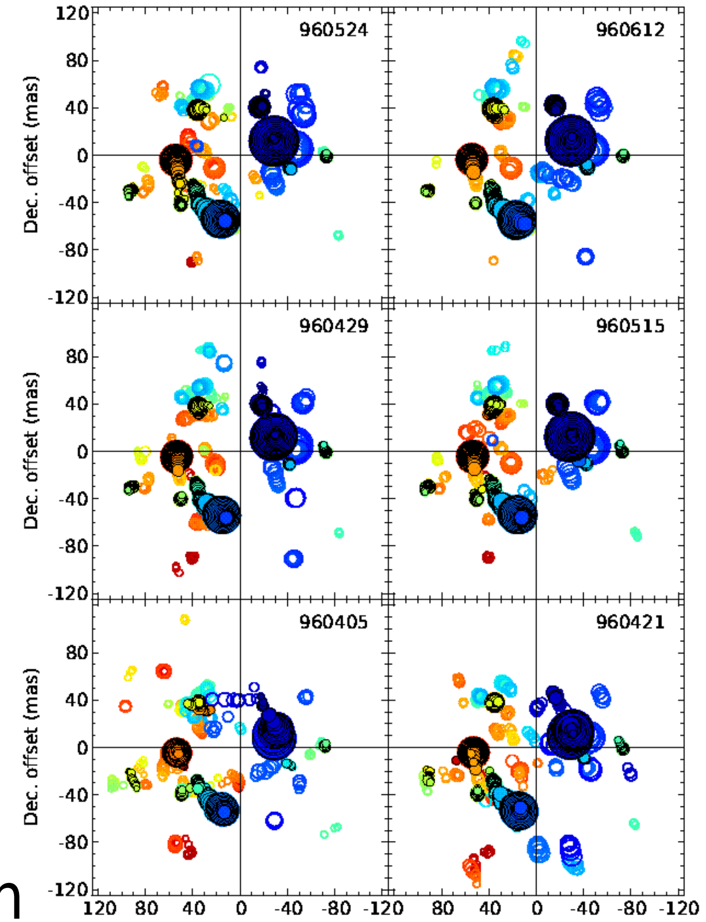
What accelerates the wind?

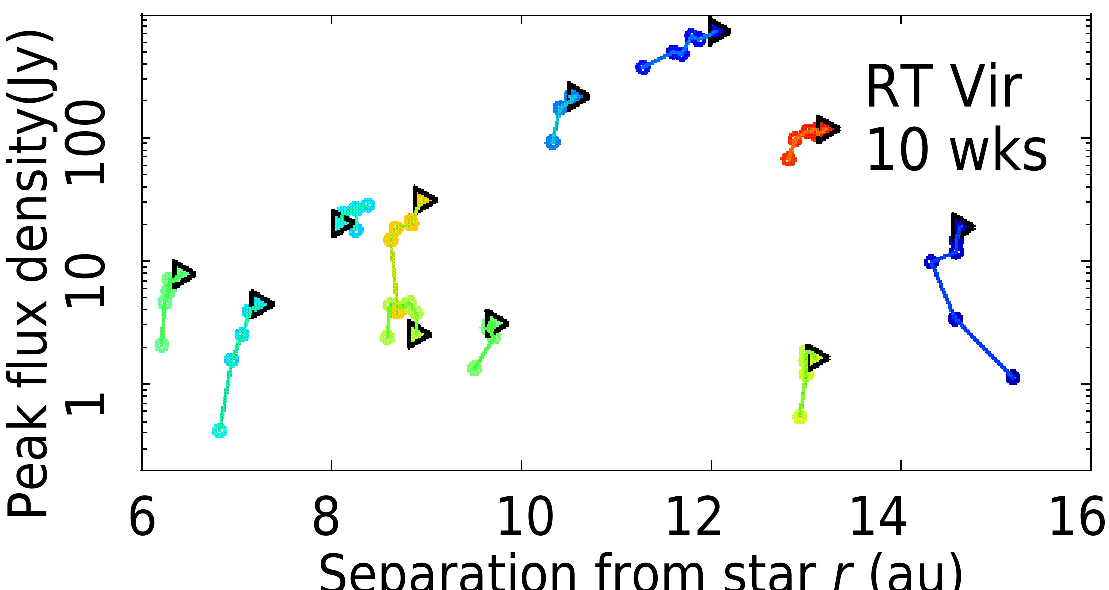
- Water maser shell limits show *gradual* $V_{exp} \propto r$
  - Relationship holds for AGB, RSG out to many 100s $R_\star$
- τ or momentum coupling changes?
  - *Ivezic & Elitzur'10*
- Dust absorption efficiency evolves?
  - *Chapman & Cohen 86; Verhoelst+*
- Also seen in other lines incl. Hershel
  - *Decin + '10*



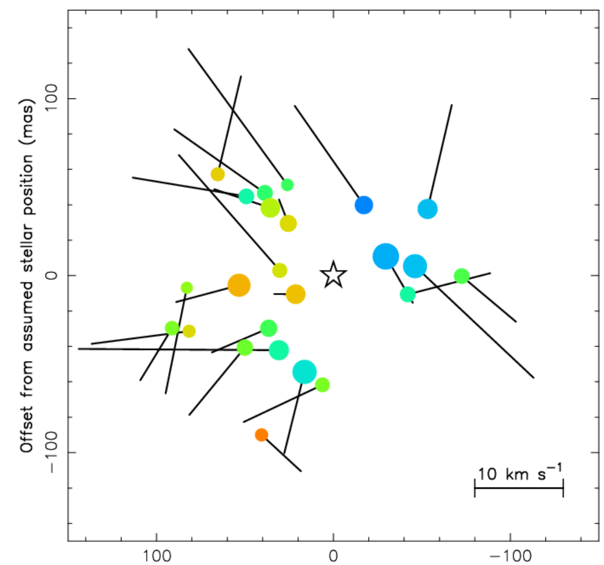
Proper motions

- RT Vir ~133 pc (*van Leeuwen'07*)
- 6 MERLIN epochs over 10 weeks
  - 22 GHz proper motions consistent with Doppler velocity
    - Accelerating, radial expansion
      - No rotation (*Richards+13; Imai+03*)
- 22 GHz 15-au thick shell
  - Clouds at all distances brighten, then dim





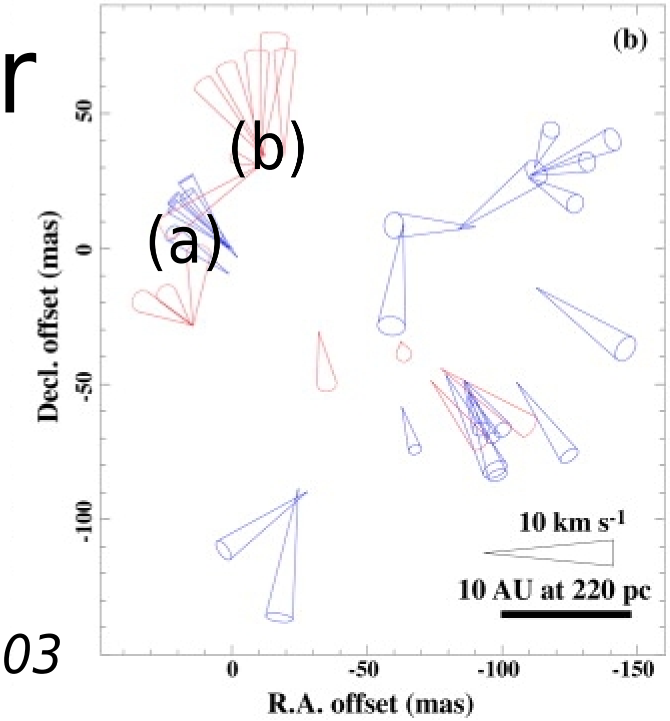
- Must be radiative effect
- Heating increases collision pump?
- Radiative pumping?



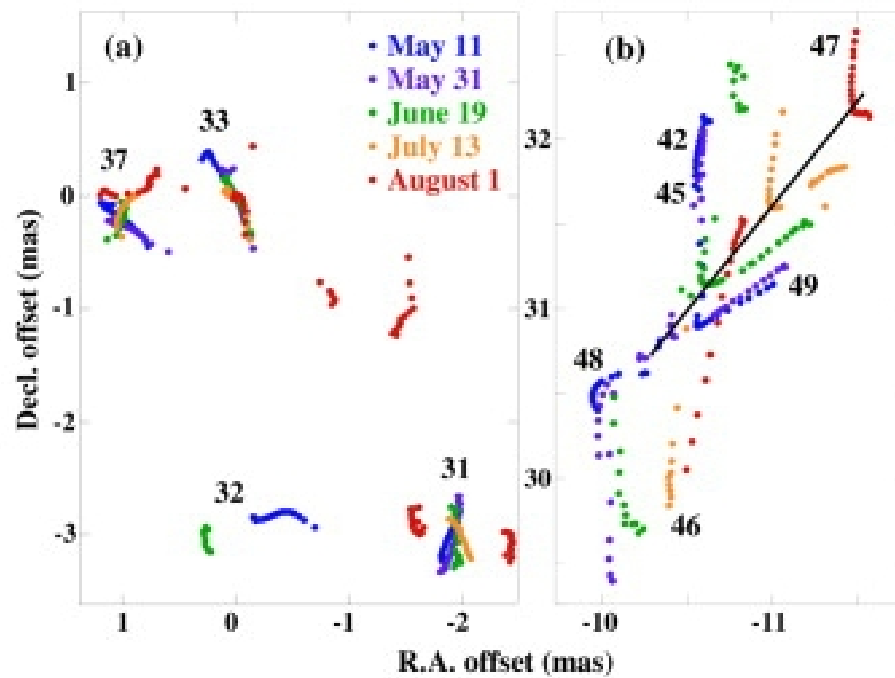
Proper motion vectors

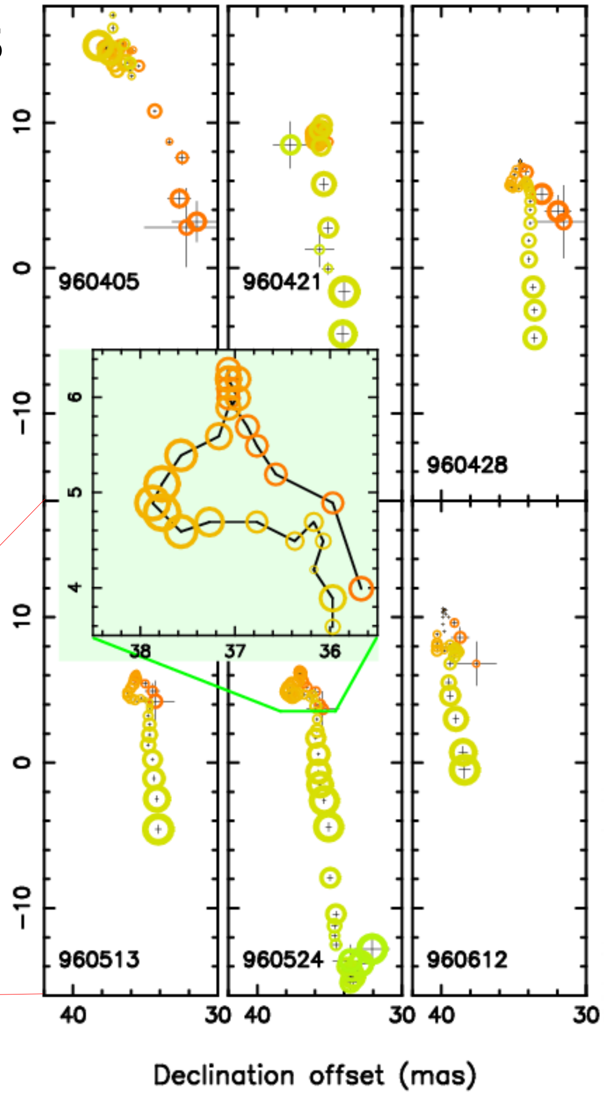
Cloud internal motions RT Vir

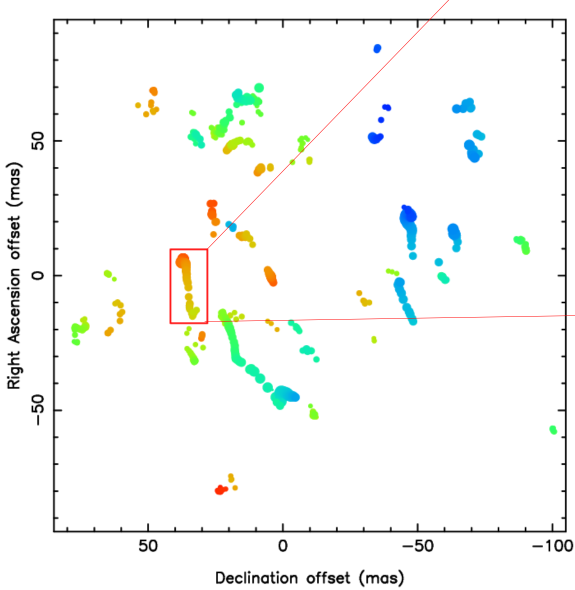
- Vel. gradient changes in 10 wks (not aligned with bulk expansion)
  - Coherence path in turbulent, ~sphere?
  - Bow shock?
  - Field lines (magnetic confinement)?



Imai+'03
VLBA
• Shock acceleration?



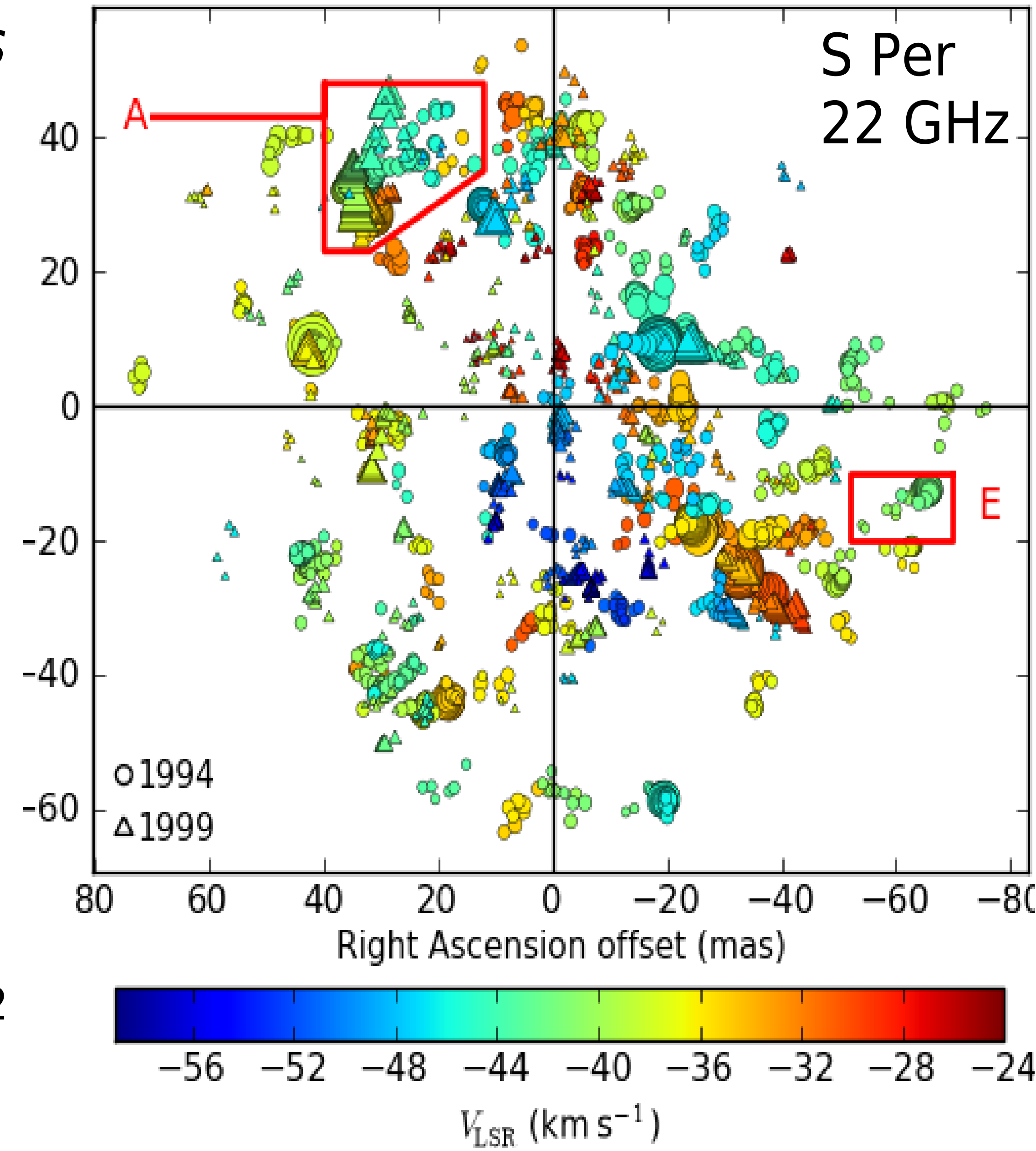




Richards+'13
MERLIN

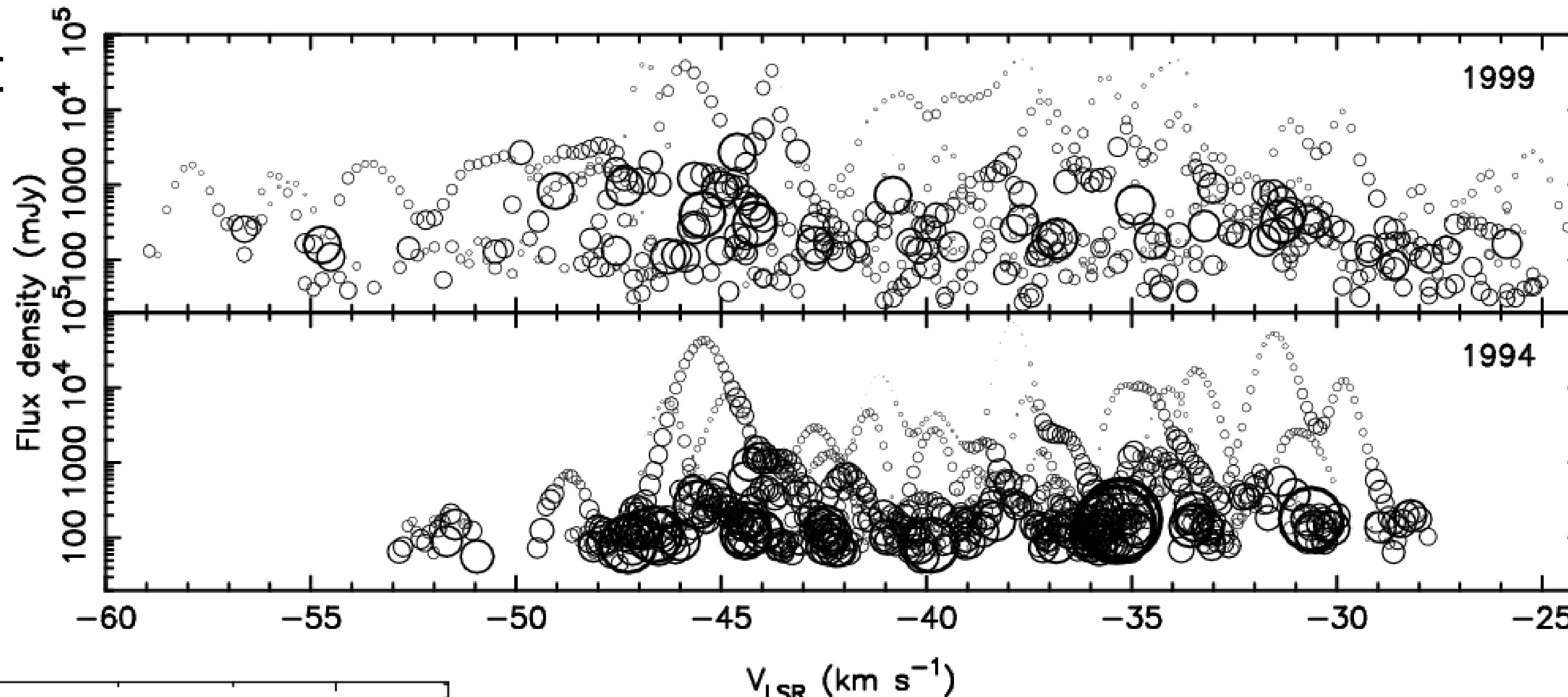
Water cloud measurements

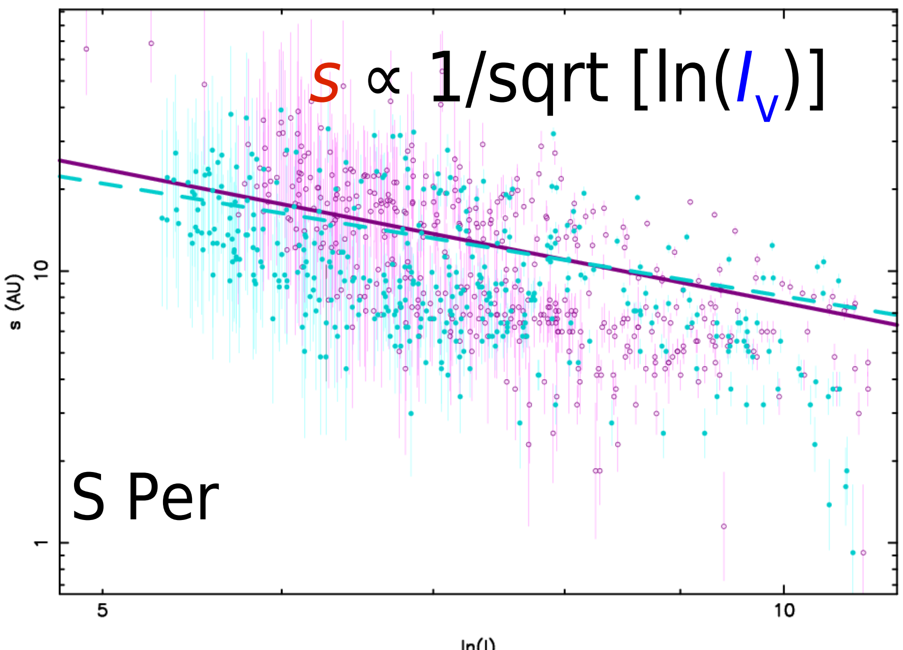
- Component beamed size *s*
  - <1 to a few tens mas
    - MERLIN data: fit & de-convolve 2D Gaussians
  - 1-2 km s^{-1} series
    - Gaussian spectra
      - $\Delta V_c \gtrsim \Delta V_{th}$
- Measure lengths of series of components
  - Unbeamed cloud size
    - R_{cAGB} 1 - 2 AU
    - R_{cRSG} 10-15 AU
- Beaming angle ~$(0.5s/R_c)^2$



Shrinking of brighter masers

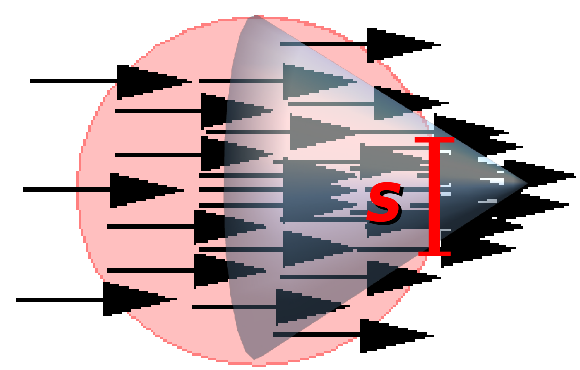
- Component size s
- Intensity I_ν
- Brighter spots are smaller





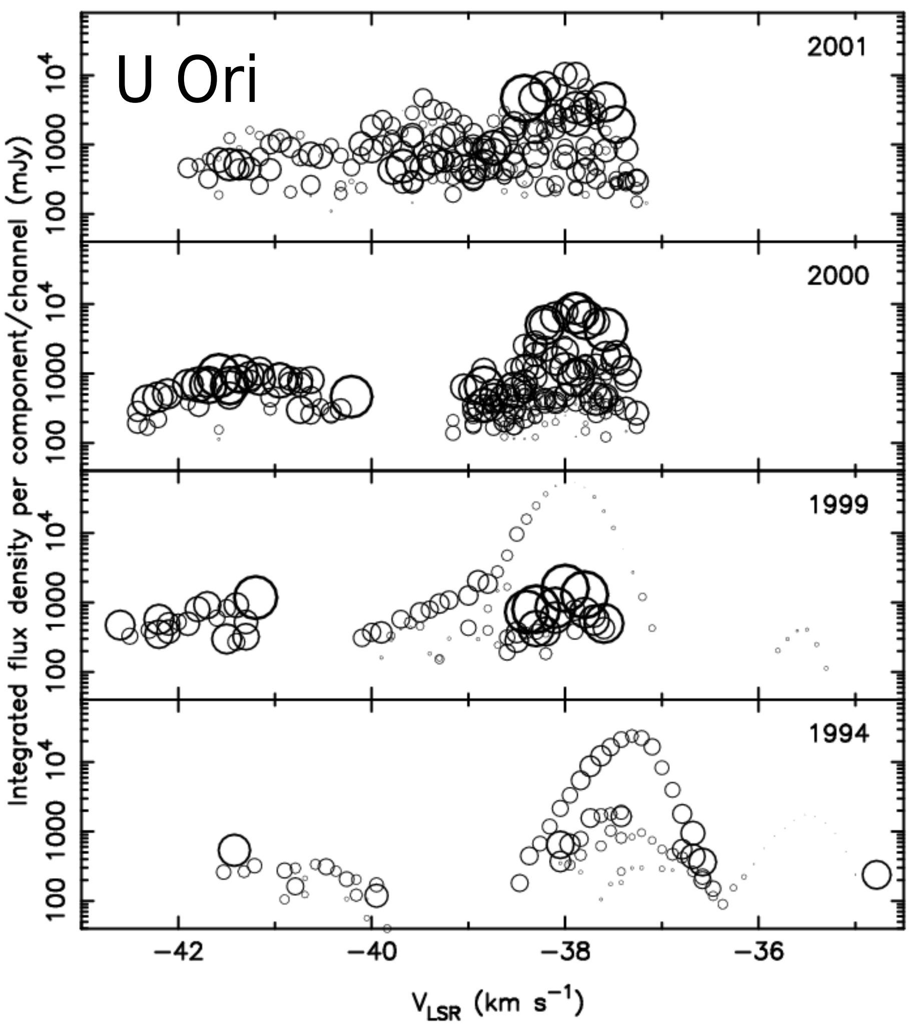
- “Amplification-bounded” beaming from ~spherical clouds

Richards+11
Elitzur+92

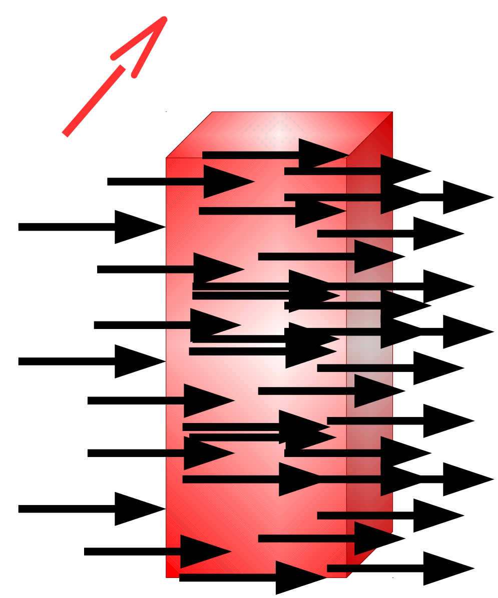


But *sometimes* brighter=bigger

- Spectral peak components swell

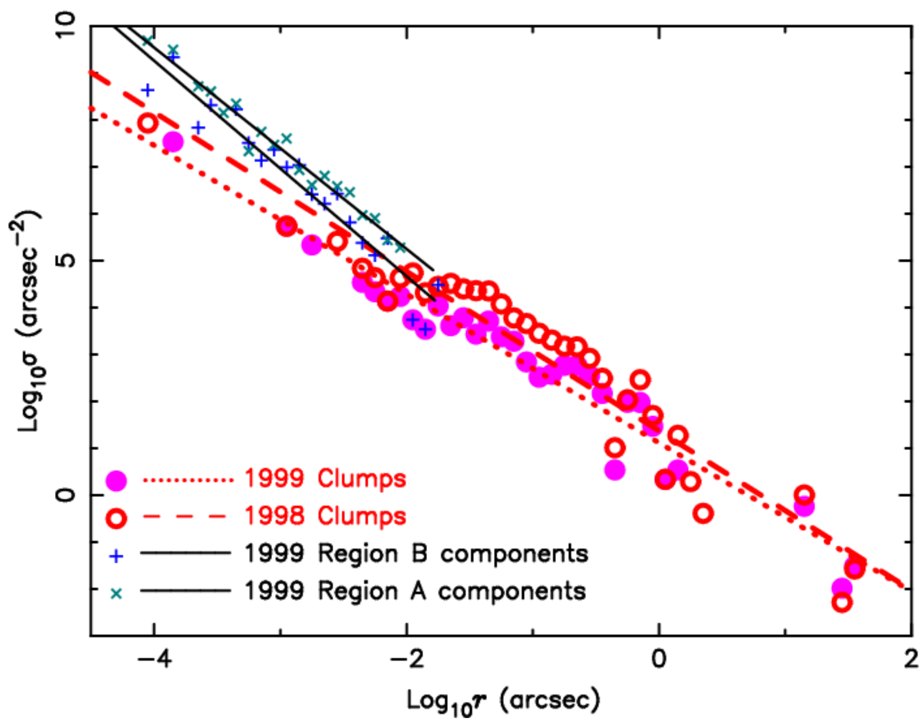


- Shock 'into page'
  - Maser propagates perpendicular to shock
    - Pump photons escape orthogonally
    - Entire surface emission is amplified
    - “Matter bounded” beaming
    - Apparent size ~ actual size



Fractal analysis

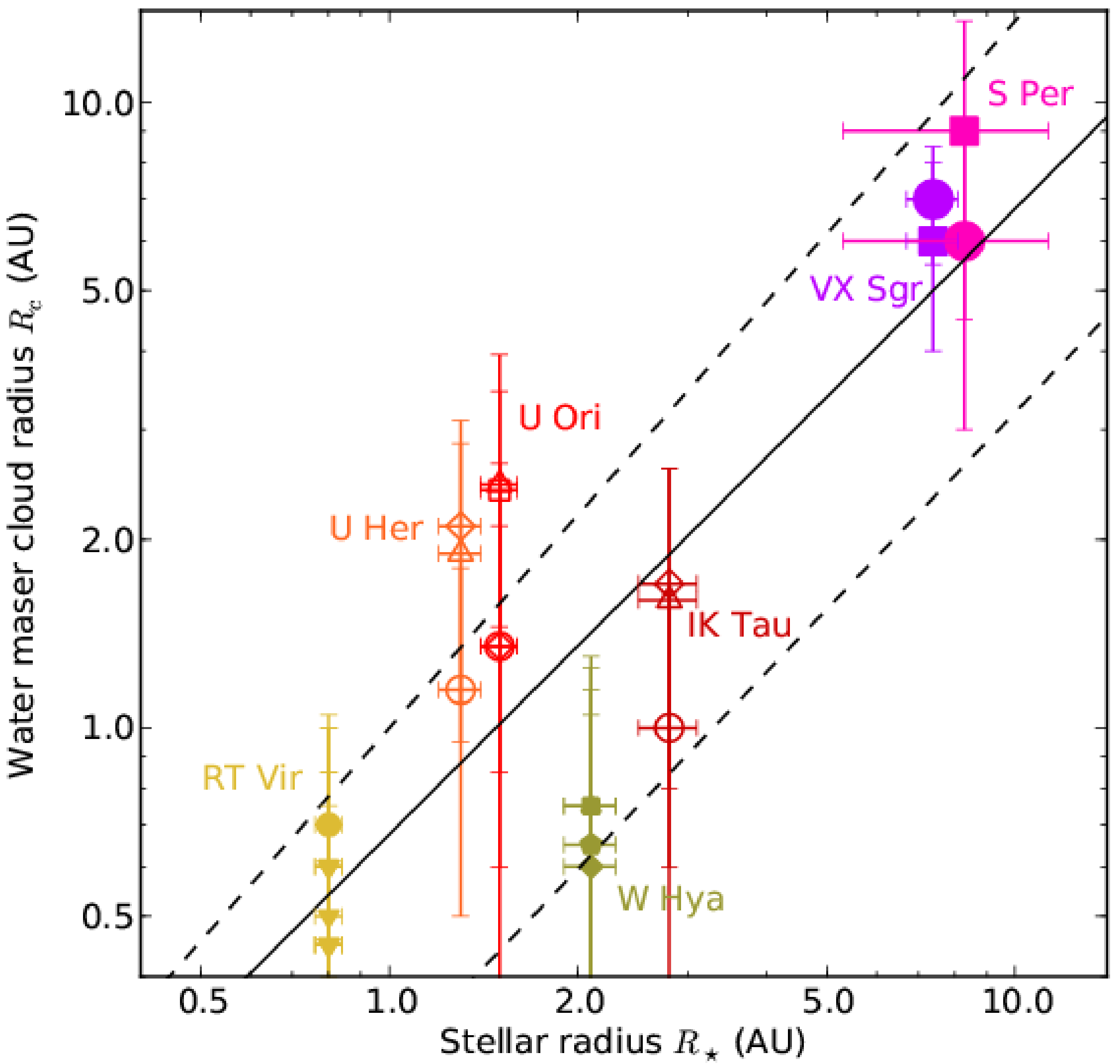
- How far does the stellar pulsational influence reach?
  - Why are SiO maser motions so disordered?
- Direct measurements of turbulence:
  - Line width fluctuations
  - Maser proper motions
- Fractal scales
  - Incompressible/ Kolmogorov within clumps
  - Shallower slope on larger scales suggests supersonic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



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

Water maser clumps scale with ✶size

- 22 GHz maser thick shell
  - $r_i \sim 5\ R_\star$; $r_o \sim 50\ R_\star$
- $R_{cloud} \sim 1\ R_\star$ at $r \sim 10 R_\star$
  - Assuming radial expansion, birth radius 5%–10% $R_\star$
- Determined by stellar properties?
  - Dust cooling or other microphysics same scale for all stars
- Or scale set by instabilities in spherical geometry (*Gray in prep.*)



AGB RSG

Richards et al. 2013

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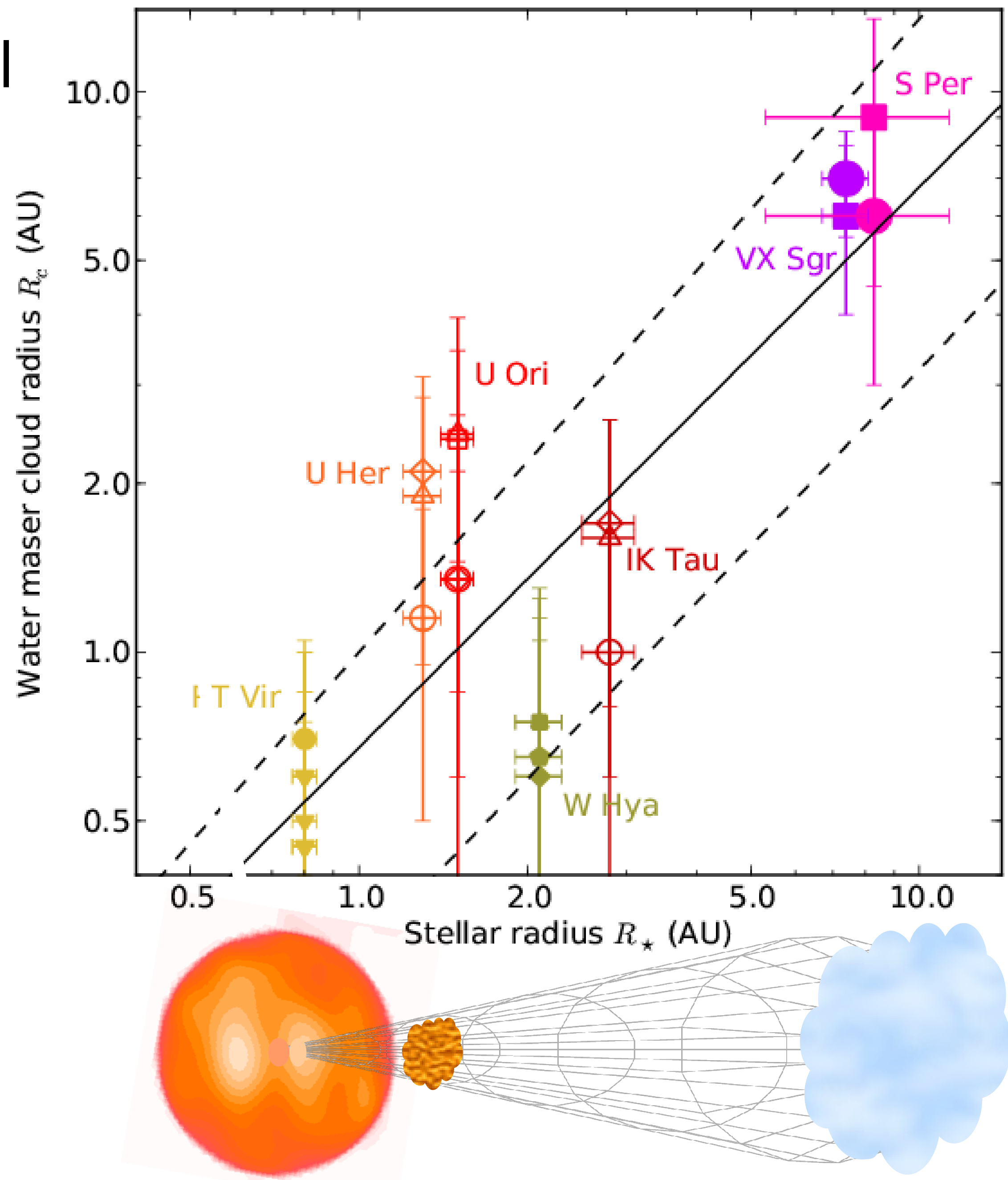
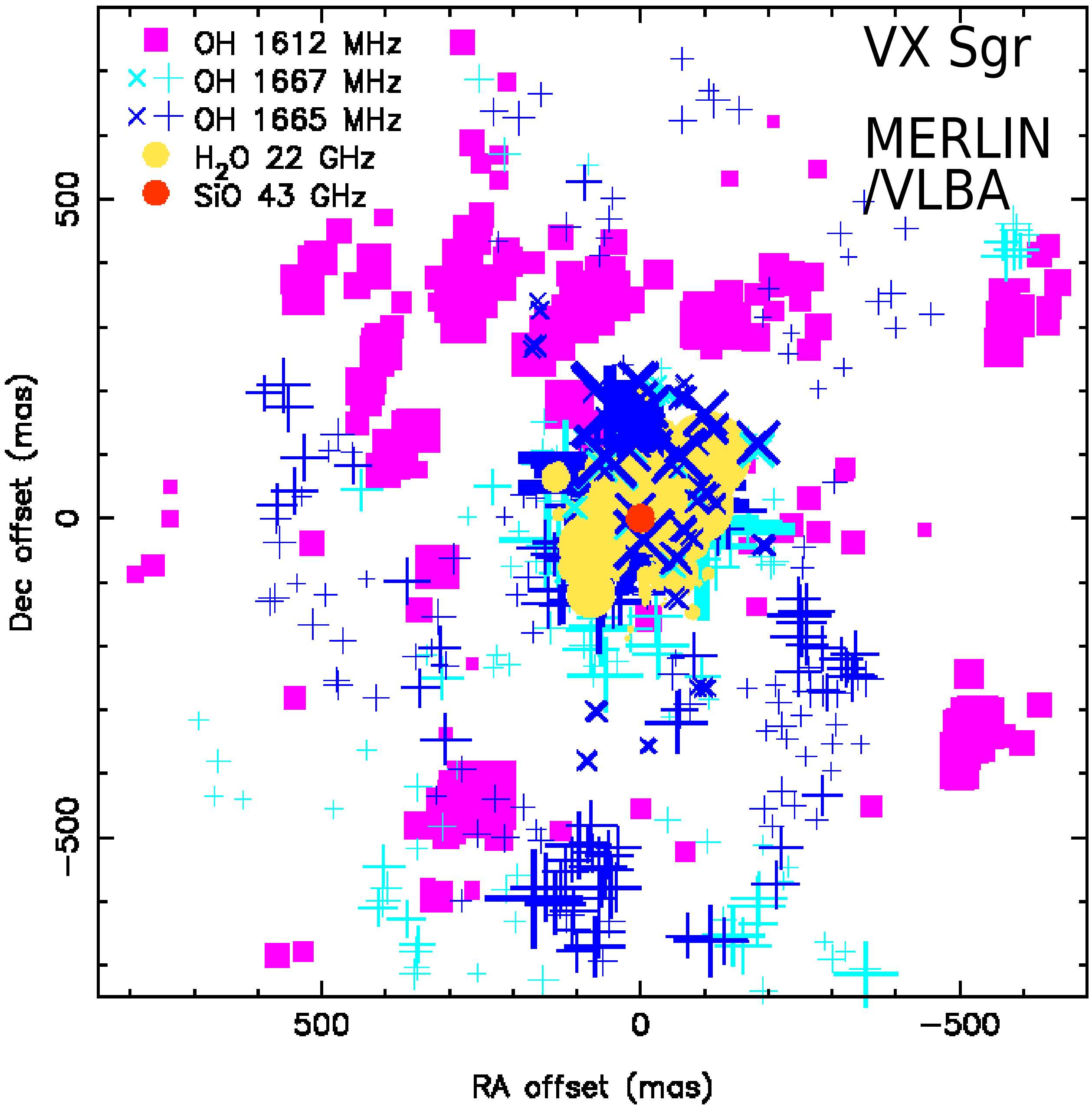
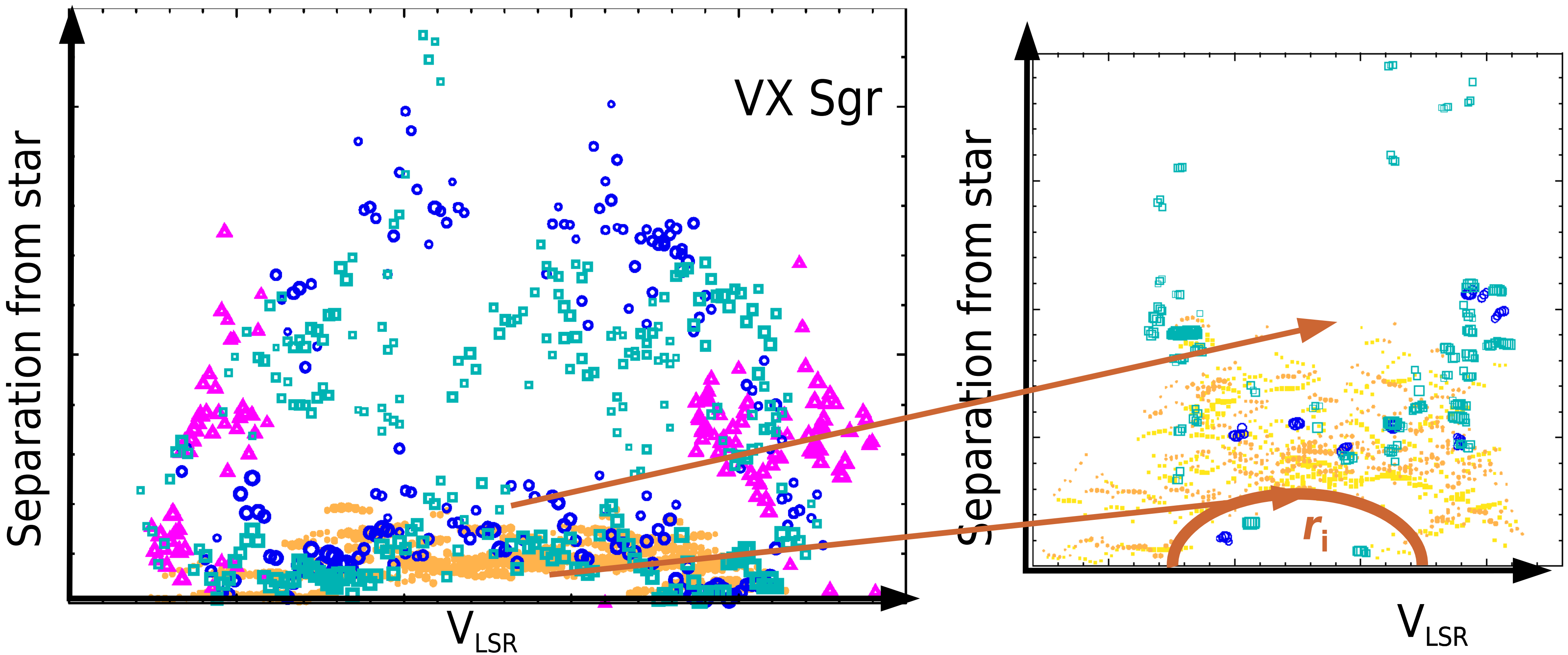


Maser location consistent with E_U ?



- SiO 43, 86 GHz
  - E_U >1800 K
  - < 4 $R_\star$
- H_2O 22GHz
  - E_U ~650 K
  - 5-30 $R_\star$
- OH 1612 MHz
  - E_U tens K
  - >50 $R_\star$
- OH mainlines (1665-1667 MHz)
  - E_U < 500 K
  - Intermediate locations

22 GHz H_2O and OH masers



- 22 GHz r_i set by quenching density ~5 10^{15} m^{-3} at 1000 K
- OH mainlines (global VLBI) 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

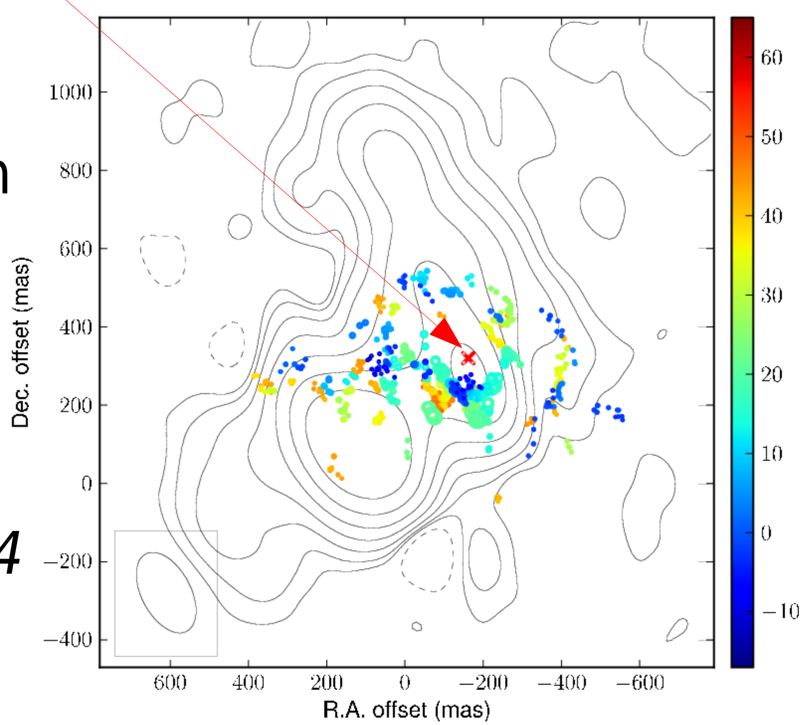
ALMA: first detailed sub-mm maser maps VY CMa

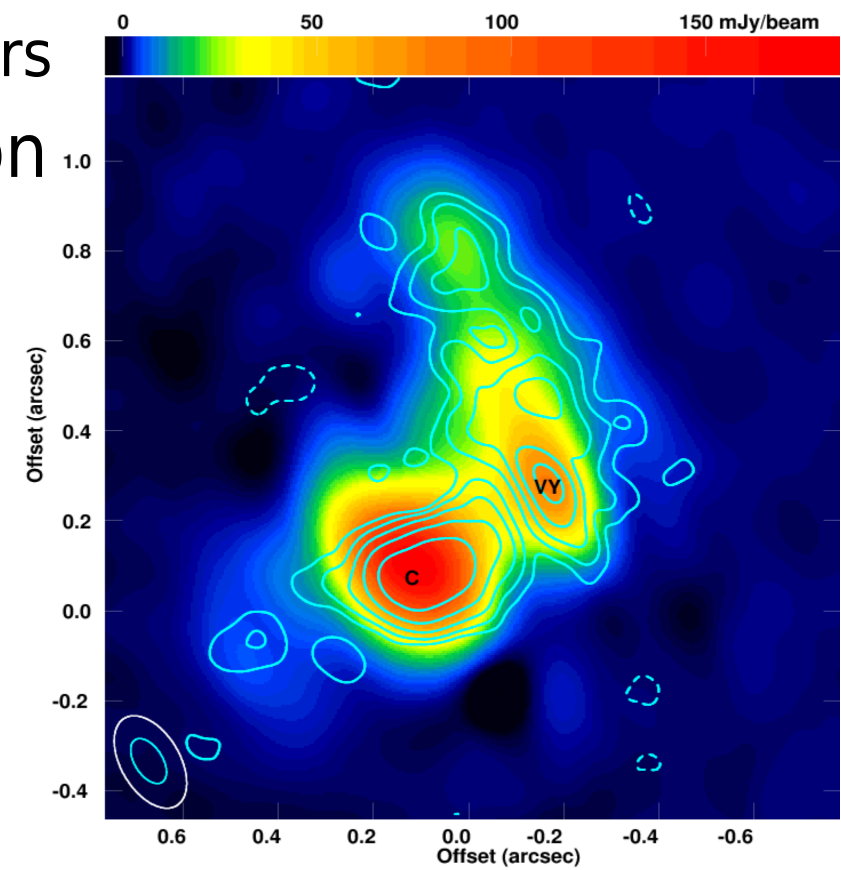
- ~20 antennas, ≤2.7 km baselines
  - Resolution ~0".05 Band 9, ~0".1 Band 7
    - Covers 658, 325, 321 GHz masers
- Star at centre of maser expansion
    - '**VY**' – fainter than '**C**'!

Contours:
B7 continuum

Symbols:
321 GHz
masers

OGorman+'14
Richards+'14

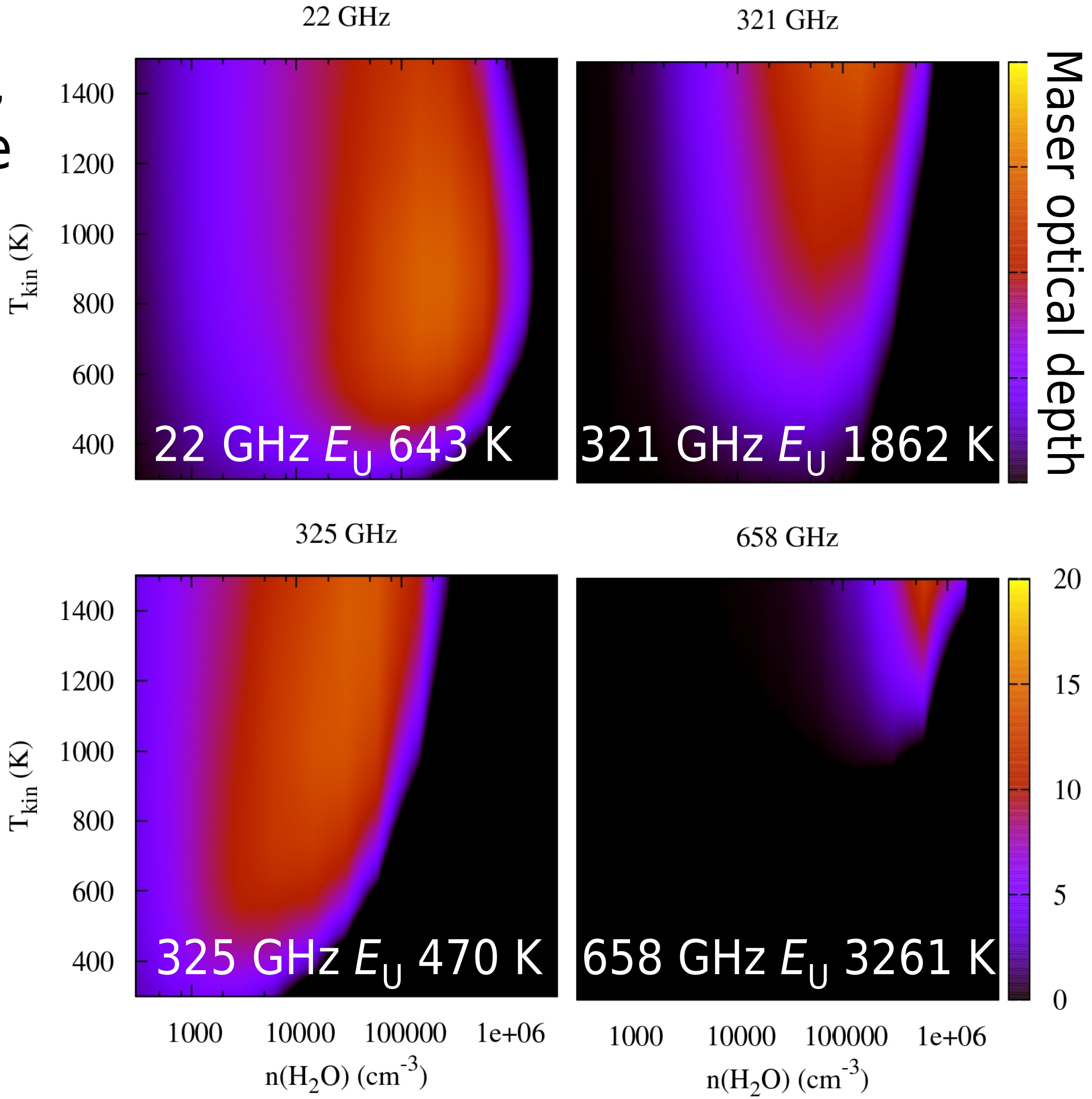




Continuum:
colour B7, contours B9

Sub-mm maser predictions

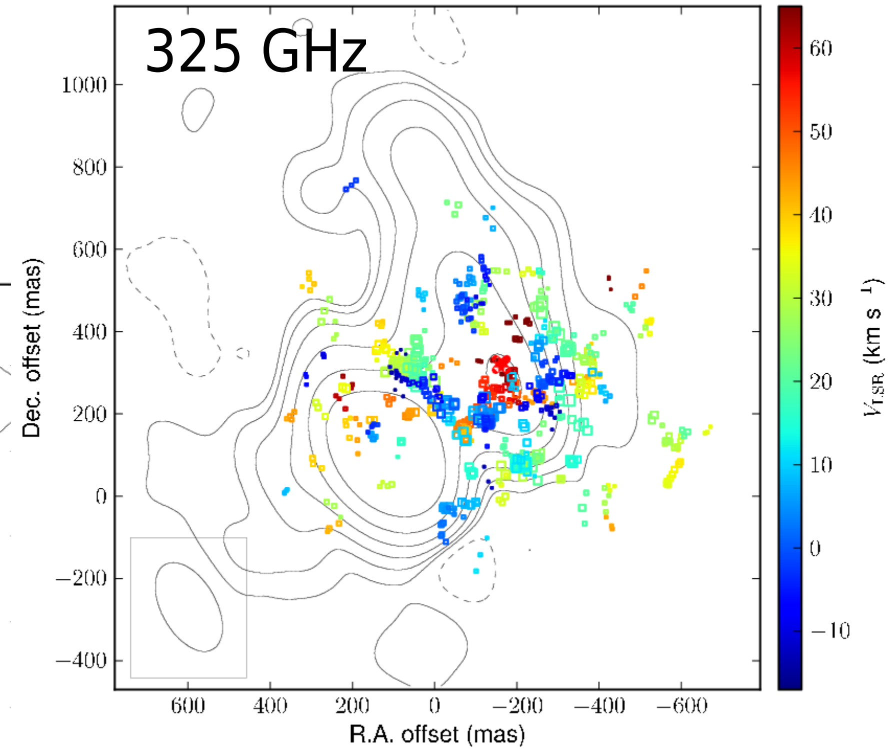
- Density n, radiation field, T, dV, E_U, N_{H2O} determine maser excitation
- 22 GHz wide span
  - Quenched at high n
  - Fades <~400 K
- 325 GHz boundaries at lower densities
  - Extends to cooler T
- 321 GHz narrower range
- 658 GHz hot, dense environment

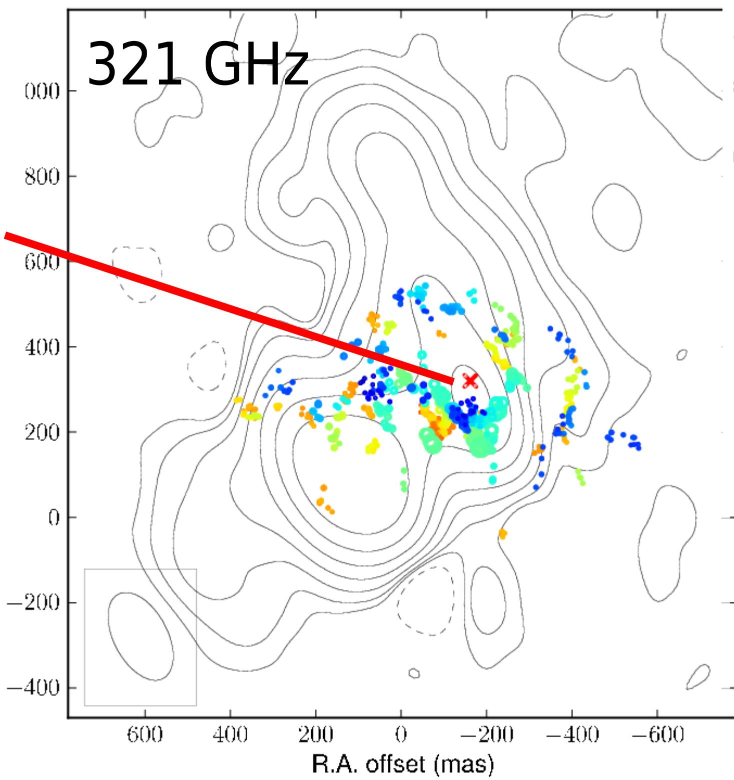


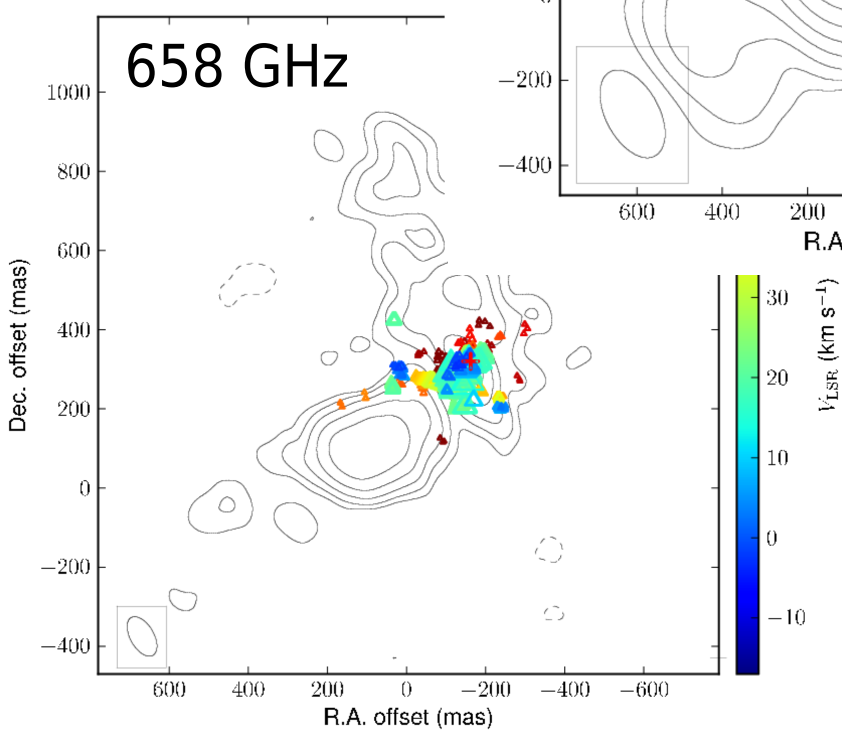
Gray et al. 2015

First resolved stellar sub-mm H_2O masers

- Expanding away from 2nd peak VY



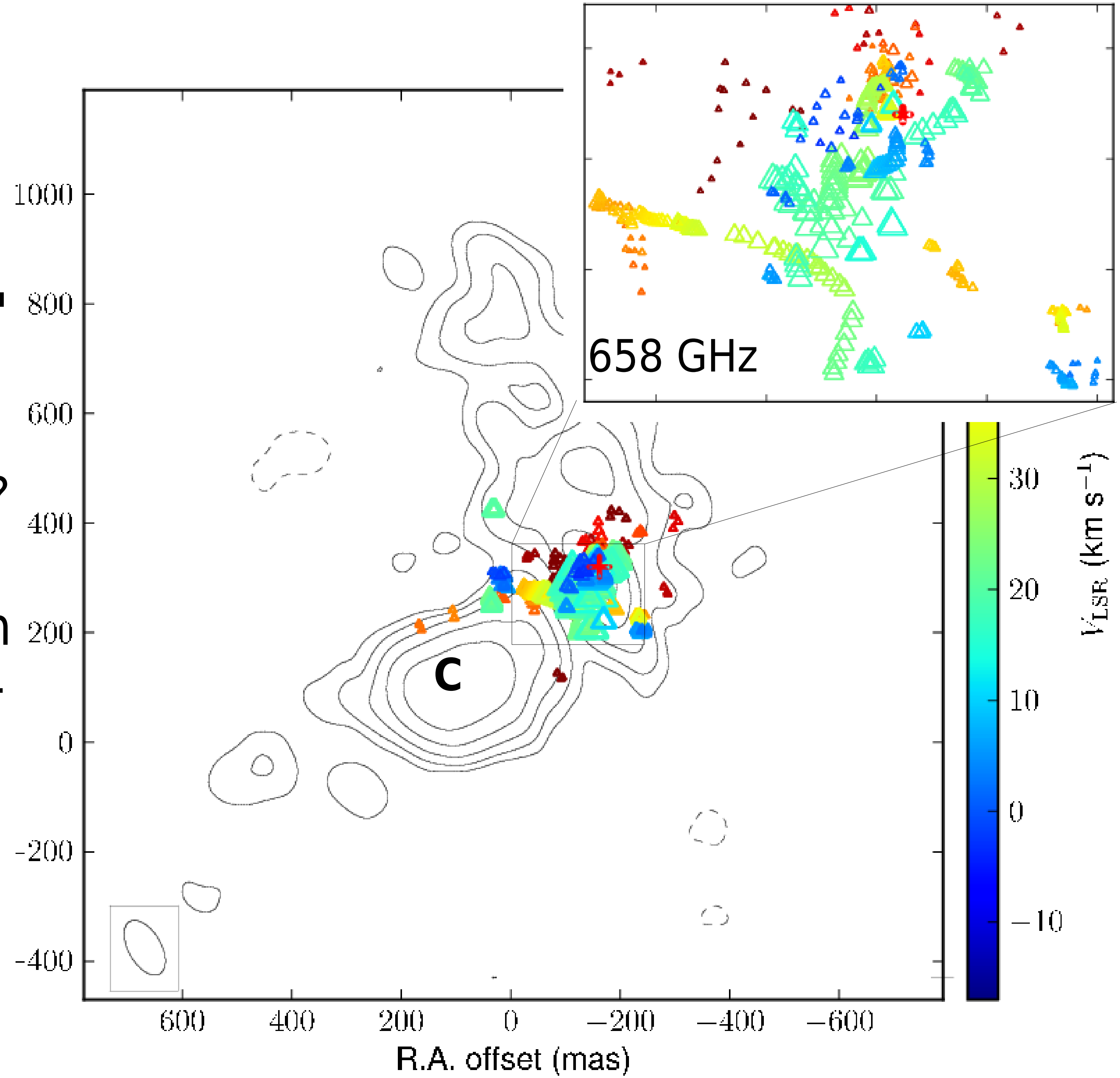




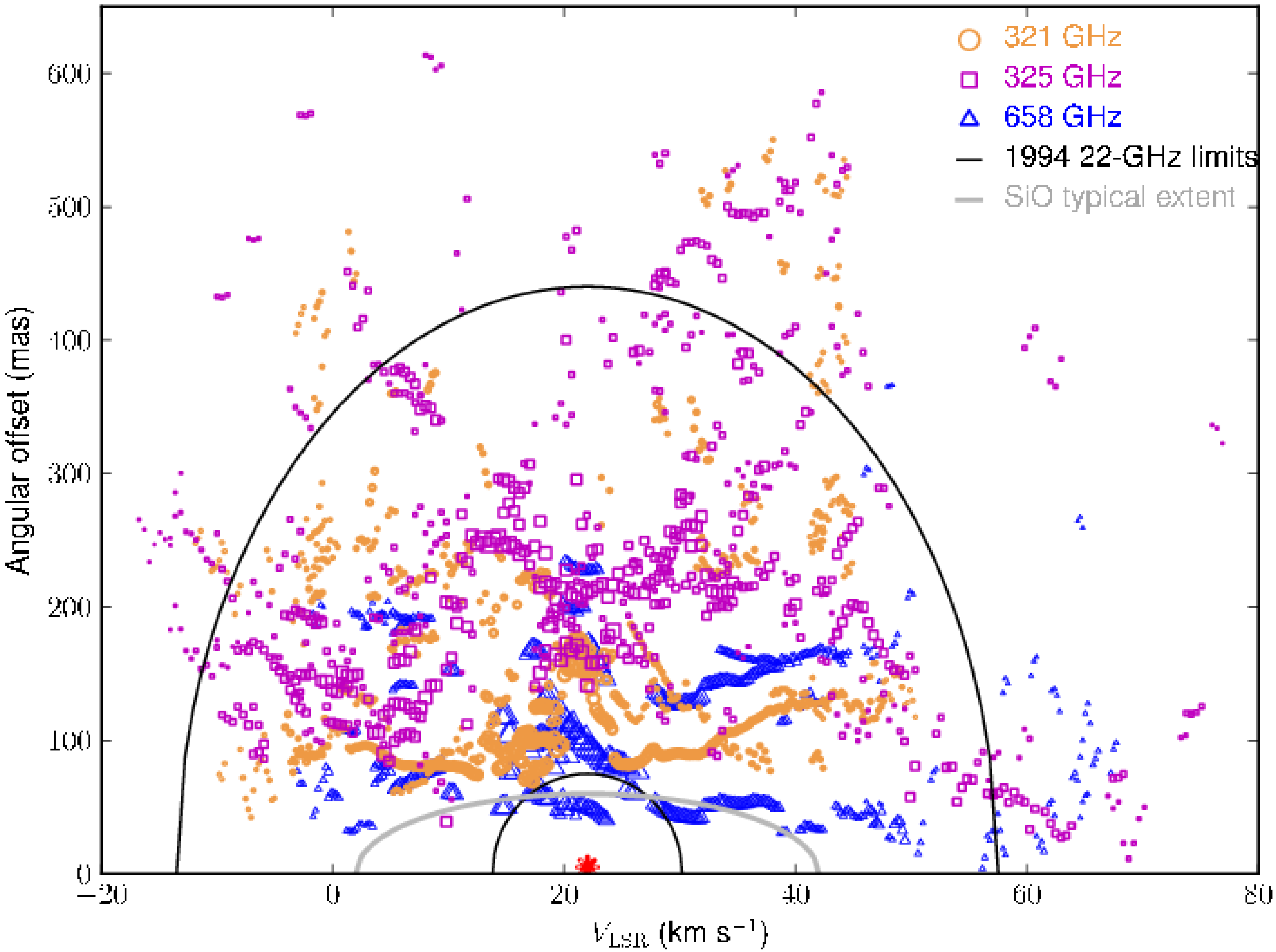
- 325-GHz most extended, as predicted
  - Moderate acceleration
- 321-GHz similar distrib. to 22 GHz
  - Strong acceleration
- 658-GHz starts at few R_*, inside dust formation/SiO maser radius
  - But extends to tens R_*!

Shocks?

- 658- and 321-GHz masers appear to curve round '**C**'
  - Wind colliding with dense clump?
- Can shock heating explain extended high-excitation lines?



VY CMa sub-mm spatial distribution



- Average cloud properties

ν GHz	R_c au	ΔV km/s
658	8	1.6
321	19	1.6
325	24	2.2
22	9*	2.2

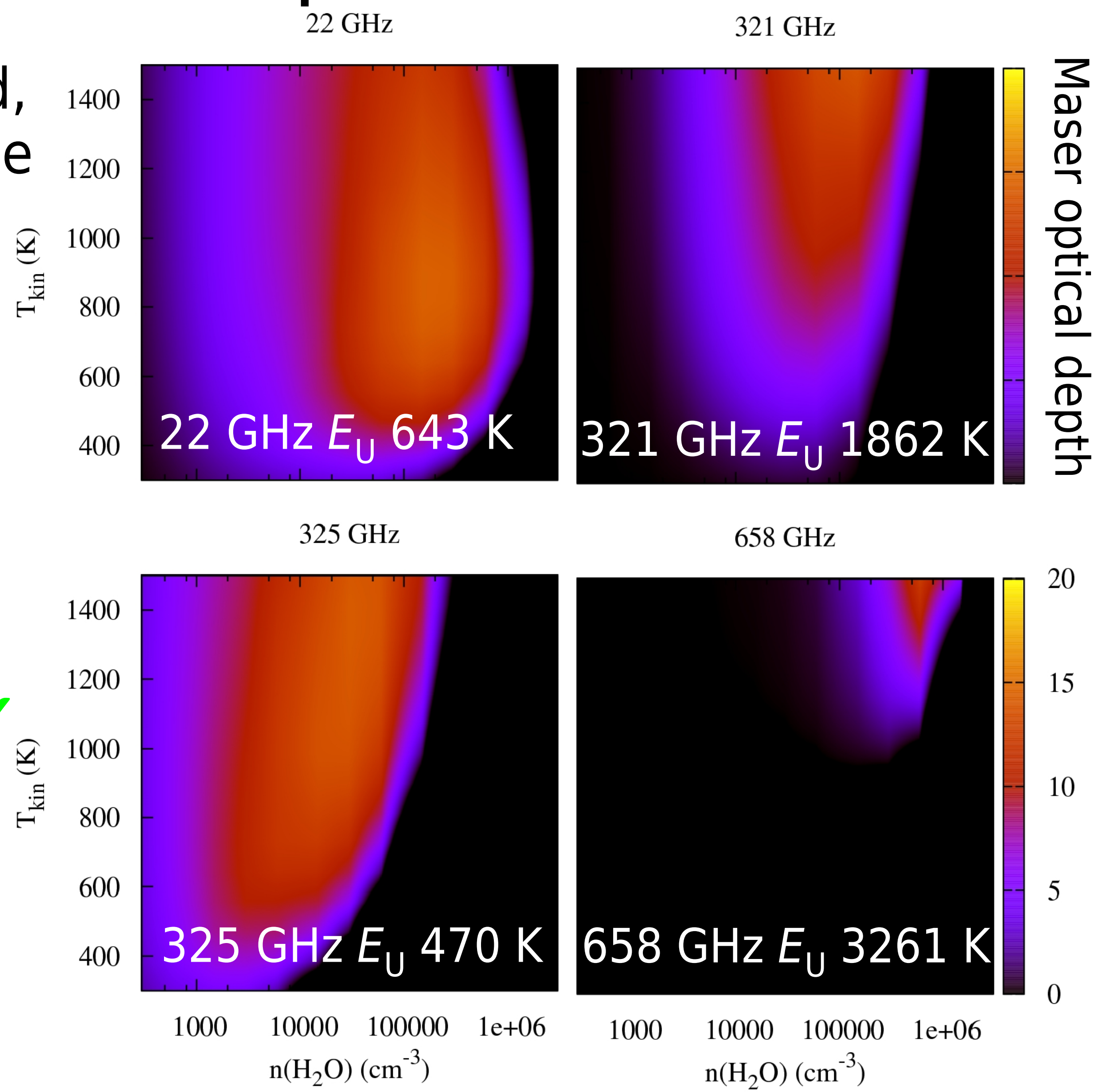
*sensitivity limited

  – Roughly consistent with expansion in outflow

- Different lines not found within ~10 au at similar velocities
  – Clump v. interclump different *T*, *n*, velocity gradient, N_{H2O}?

Sub-mm maser predictions

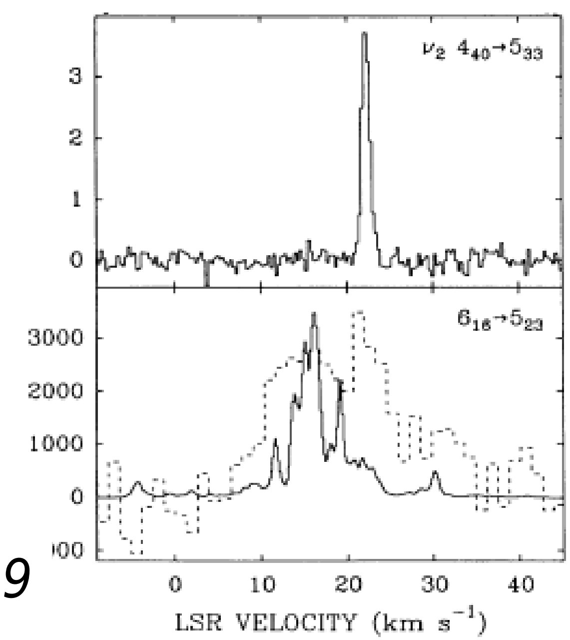
- Density *n*, radiation field, *T*, d*V*, E_U, N_{H2O} determine maser excitation
- 22 GHz wide span
  - Quenched at high *n*
  - Fades <~400 K ✔
- 325 GHz boundaries at lower densities
  - Extends to cooler T ✔
- 321 GHz narrower range ✔
- 658 GHz hot, dense environment ✔?
  - Shocks or ? needed



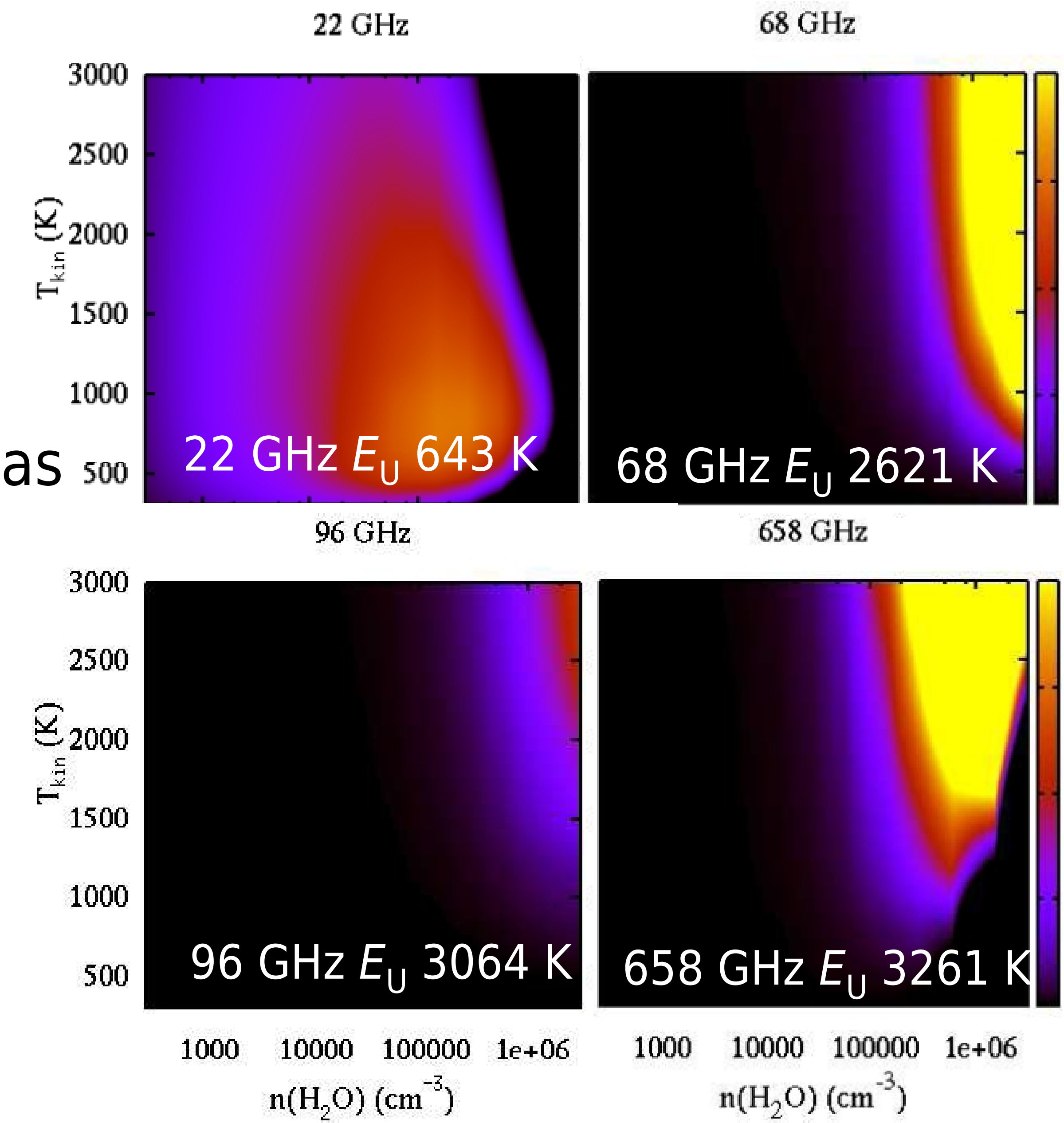
Gray et al. 2015

mm (<100 GHz) maser predictions

- 68 GHz needs higher densities than 658 GHz
  - Similarly bright
    - Maser τ >3x22GHz
  - extends to cooler gas
- 96 GHz v. hot, dense gas
  - Narrow line in VY CMa



Menten & Melnick '89

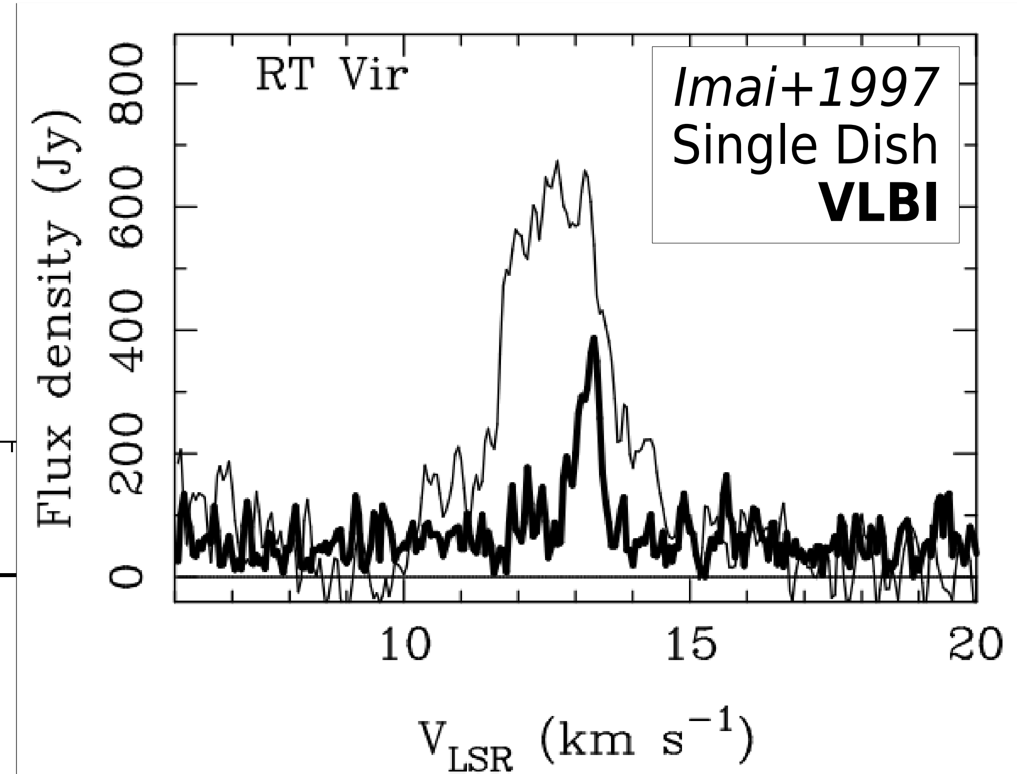


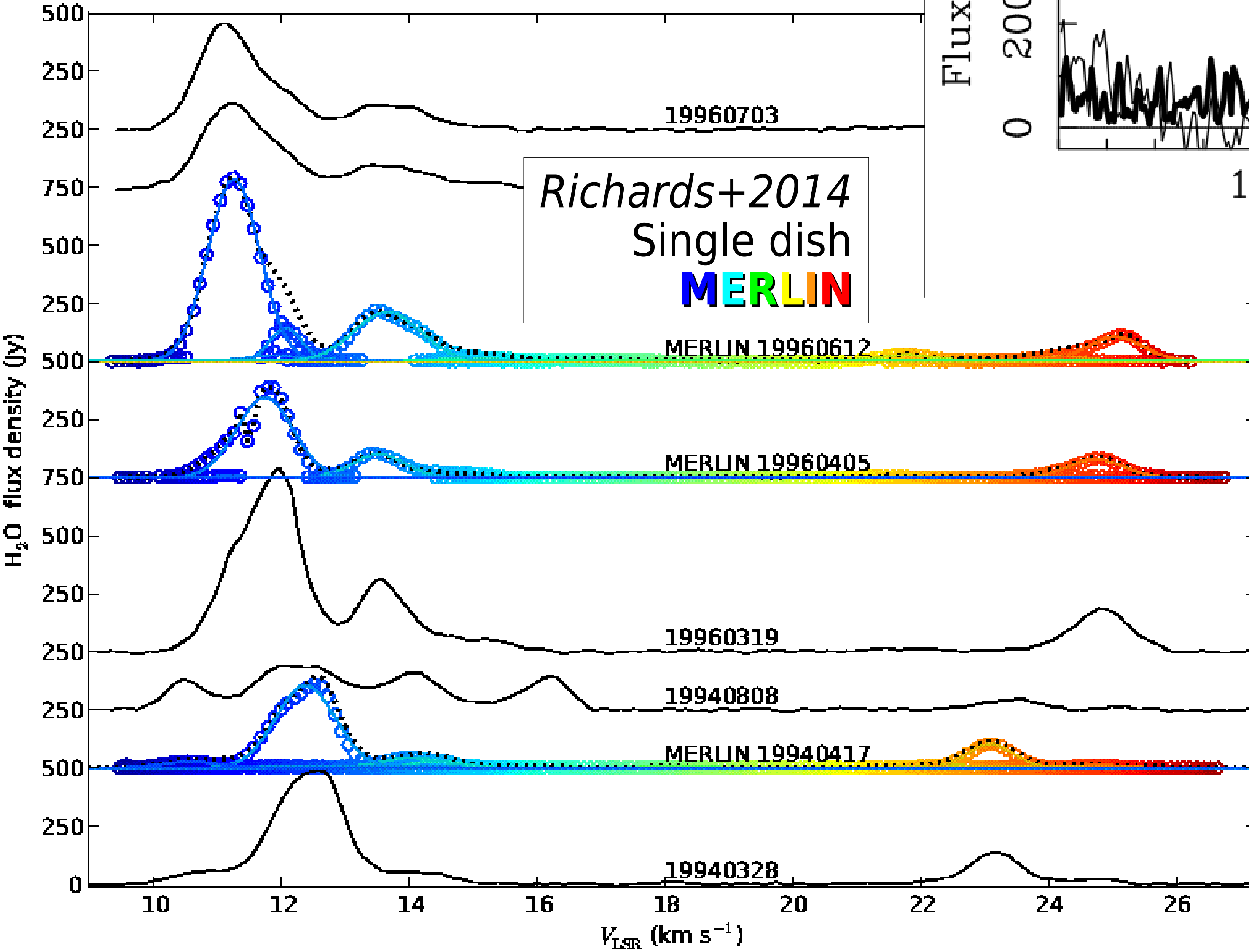
3 – 13 mm water (& other) masers

- 68 and 96 GHz lines sample dense conditions
  - 96 GHz confined to hot regions but is favoured by steeper velocity gradient (*Gray+15*)
    - Maybe reveal stellar ejection process? Pulsations?
  - 68 GHz could trace cooler shock-compressed gas
    - Similar to anomalously distant 658 GHz VY CMa maser?
- + 22 GHz, trace kinematics across dust formation zone
- Multi-species observations allow precise models of temperature, density, water abundance
- Likely to occur mainly <5 $R_{\star}$
  - Zone radius 20 mas for AGB star at 250 pc
  - ALMA resolution ~100 mas in lowest bands

Flux detection scales

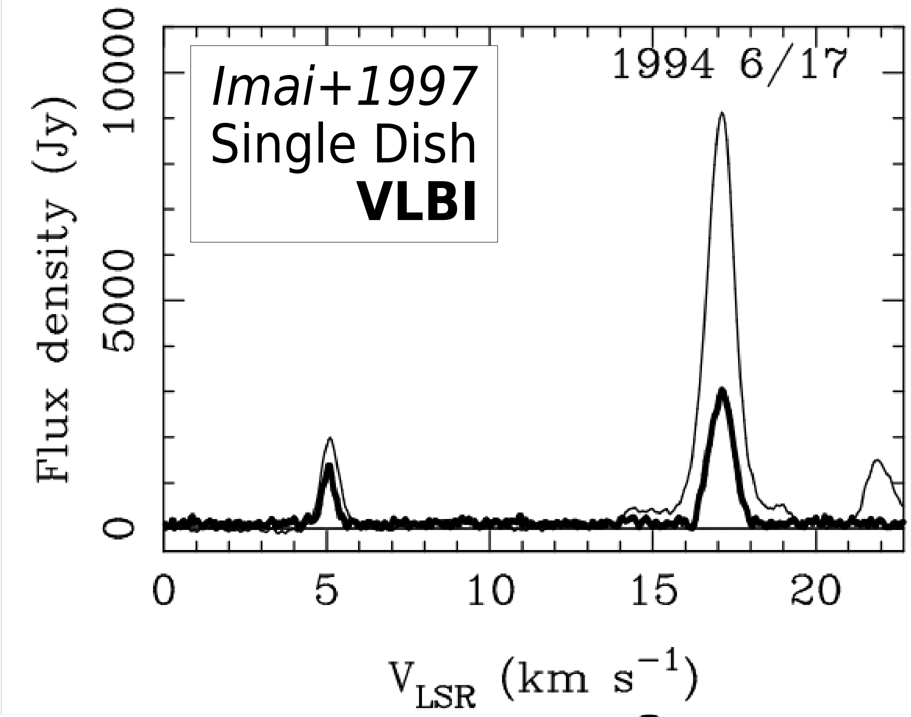
AGB star RT Vir (133 pc)
22 GHz water maser





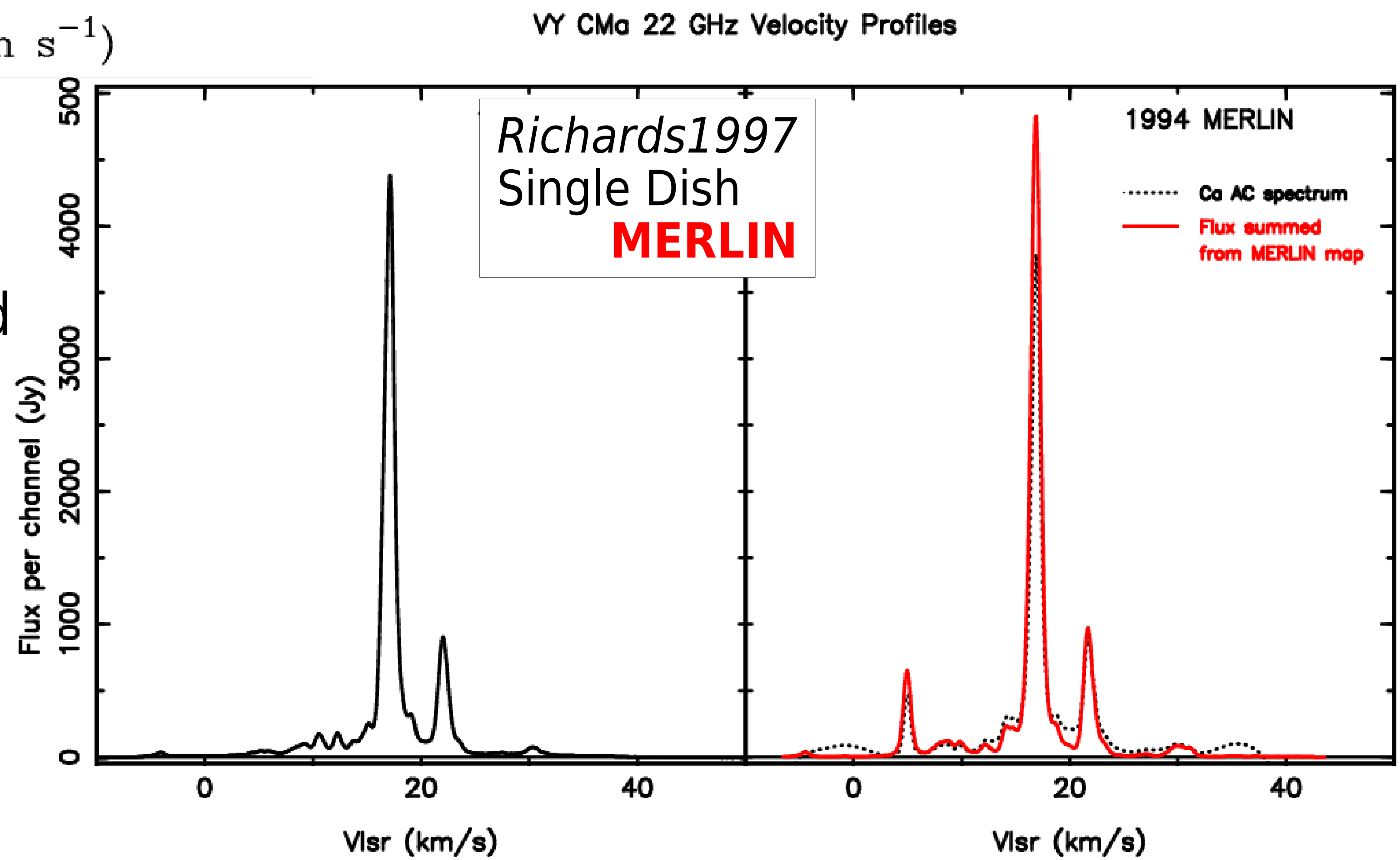
- J-Net VLBI (1300 km baselines)
  - Resolves out 10-50% of single dish flux
- MERLIN (200 km)
  - Detects ~all Pushino single dish flux

Flux detection scales

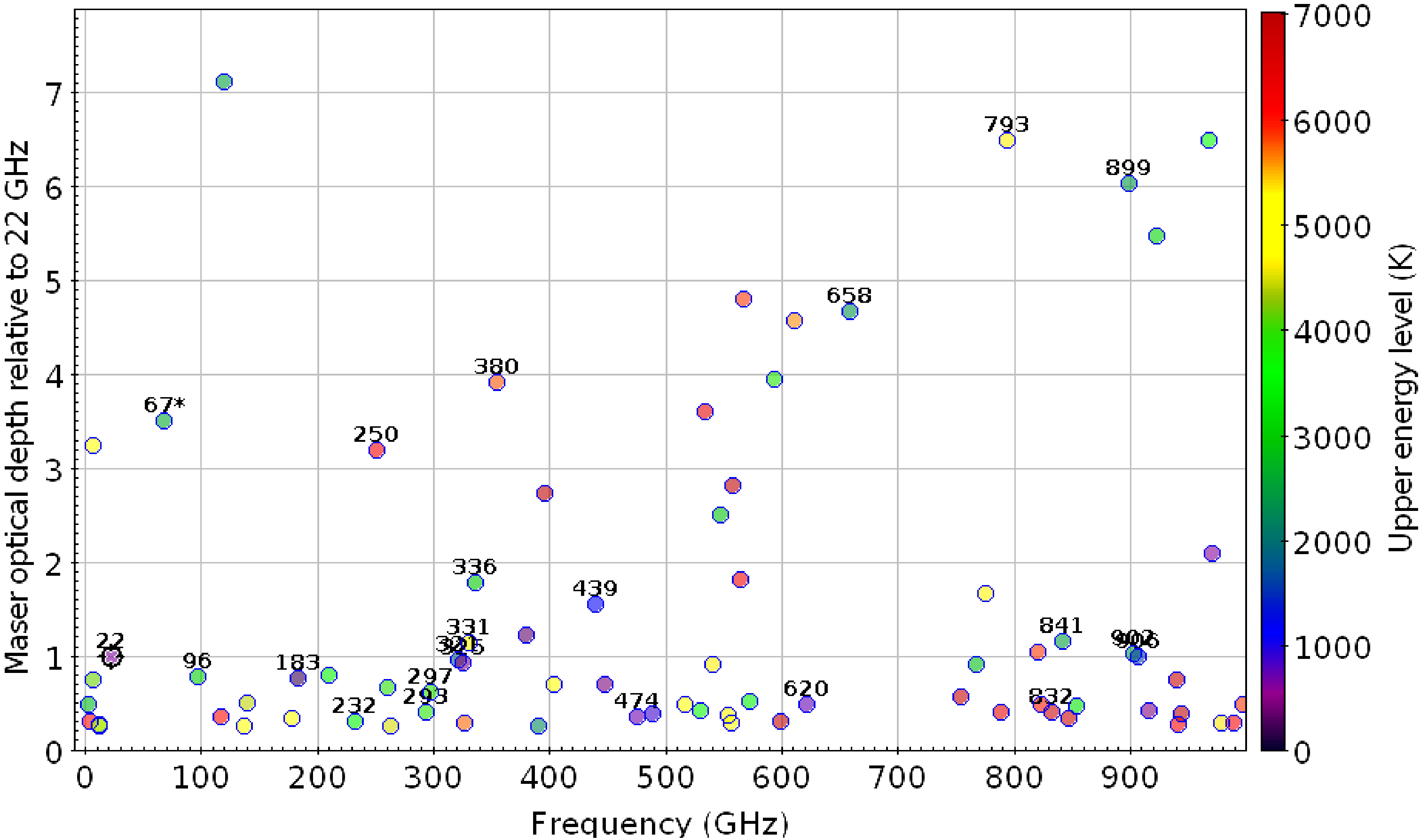


RSG VY CMa (1115 pc)

- Much resolved out by VLBI
- All flux detected by MERLIN

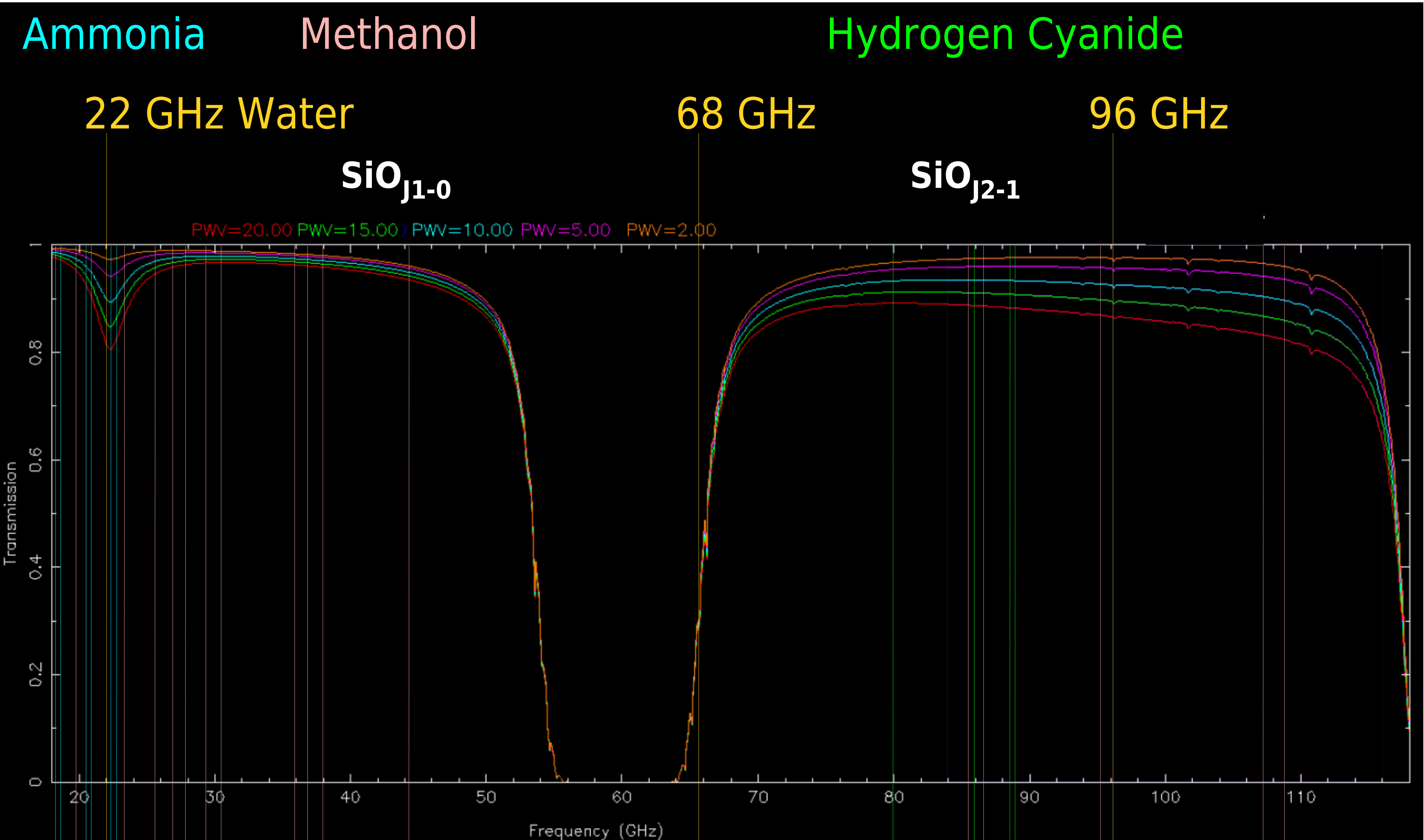


H_2O known/predicted masers <1 THz



Gray et al. 2015 MNRAS in press

18 – 118 GHz masers



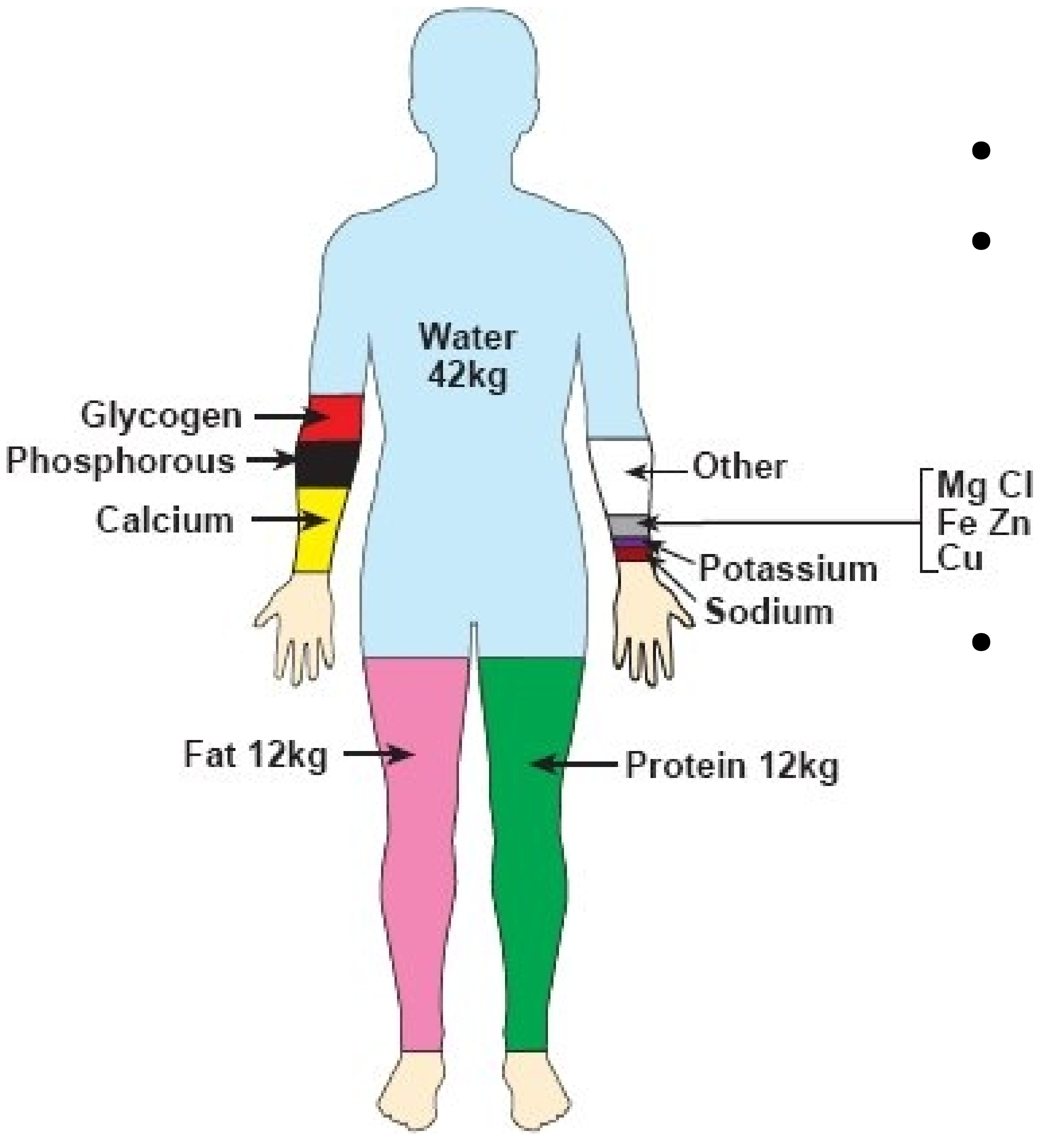
VLBI on tens to thousand km scales

- Milli-arcsec resolution measures kinematics
  - Track motions and fluctuations on ~week timescales
  - Compare 22, 68, 96 GHz (+ other lines and SiO)
- Need tens-mas resolution to detect all the flux
  - Combine with mas resolution to resolve maser location in clumps, or interclump gas, or shocks..
    - Maser beaming characterises shocks
  - Fractal analysis
    - Are clouds internally ~incompressible, but with large-scale motions like dissipative turbulence?
- Dust formation episodic – how are masers affected?
  - ALMA will image dust and star
  - ALMA (& in VLBI) for higher ν masers
- Complement with single-dish variability monitoring

Multi-frequency, ***multi-scale*** VLBI

- Simultaneous/within ~1 min multi-ν?
  - Chose sources with bright 22 GHz &/or SiO masers
  - Transfer calibration to less well-known lines
  - **V. good bandpass calibration essential**
    - 0.1 km/s resolution (smear flux too much at >0.5km/s)
  - Use fringe finder/amp cal source, phase ref if pos.
- Single-frequency (within hours) capability?
  - Combine with ν-flexible array
    - &/or v. sensitive 'antenna' e.g. IRAM/phased ALMA
      - Allows use of faint but close phase-ref sources
  - Calibrate baselines to well-calibrated antennas
- Will be advantageous to calibrate shorter b'lines 1st
  - Help model bandpass calibrator (probably resolved)
  - **Plus use short (100s-km) baselines for science!**

Why astronomers need water



- We are wet (& mostly made in stars)!
- Stars are wet!
- Water masers reveal kinematics:
  - Dust formation zone (with SiO)
    - Nucleation to full-size
  - Acceleration zone
- Evolved star winds have simpler kinematics than YSO's!
  - Best laboratories to test 1st comprehensive water maser models
    - *Gray, Sobolev, Nesternoek, Neufeld*
  - Apply to SFR, active galaxies ....