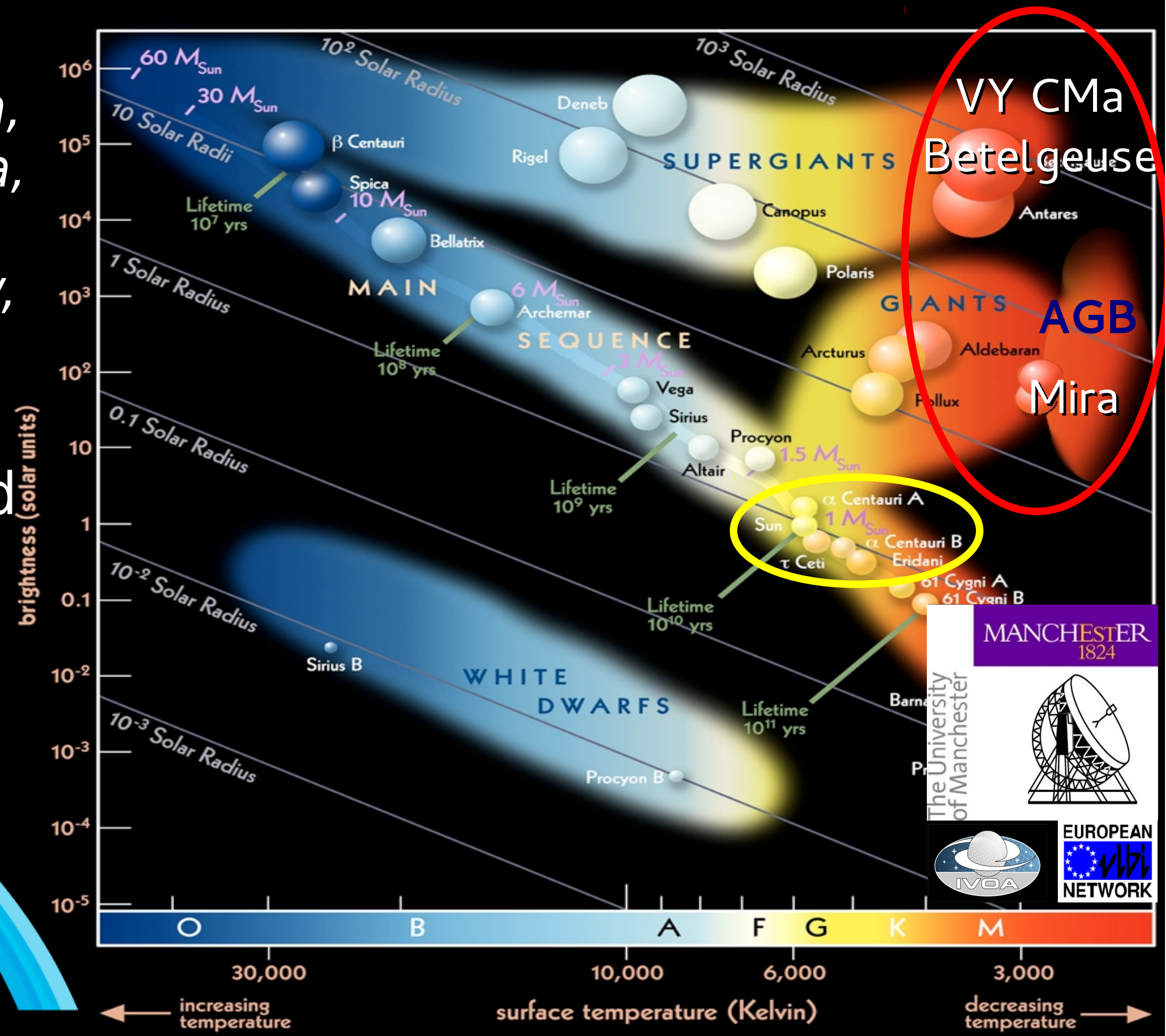
How do stellar winds break free from the star's gravity?

Anita Richards, UK ARC, Manchester

Impellizzeri, Humphreys, Vlahakis, Vlemmings, Baudry, De Beck, Decin, Etoka, Gray, Harper, Hunter, Kervella, Kerschbaum, McDonald, Melnick, Muller, Neufeld, O'Gorman, Parfenov, Peck, Shinnaga, Sobolev, Testi, Uscanga, Wootten, Yates, Zijlstra

VY CMa ALMA A&A letter submitted



EUROPEAN ARC

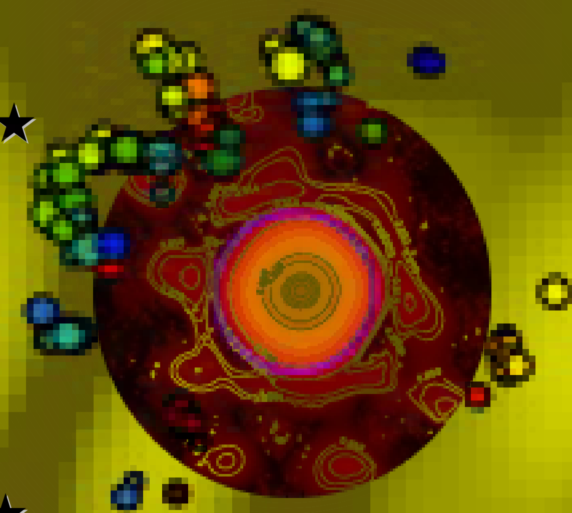
ALMA Regional Centre || UK

How do RSG and AGB stars lose mass?

- General model cool M-type ($\lesssim$3200 K, cool RSG, AGB)
  - Pulsations levitate photosphere *Bowen*'*88*
    - Copious dust forms at ~$5R_\star$
- But how is mass lost from the stellar surface?
  - Convection cells? Star spots? Magnetic forces?
- Can dust formation alone explain the transition from complex infall/outflow inside ~$5R_\star$, to a steady wind?
    - Very small grain nuclei are ~transparent
      - Larger grains seen close to low-mass stars *Norris+12*
- *Most* solitary AGB/RSG have ~spherical CSE
  - Modest equatorial density enhancement/fainter bicones
    - Maybe related to stellar magnetic field

Masers round cool late-type stars

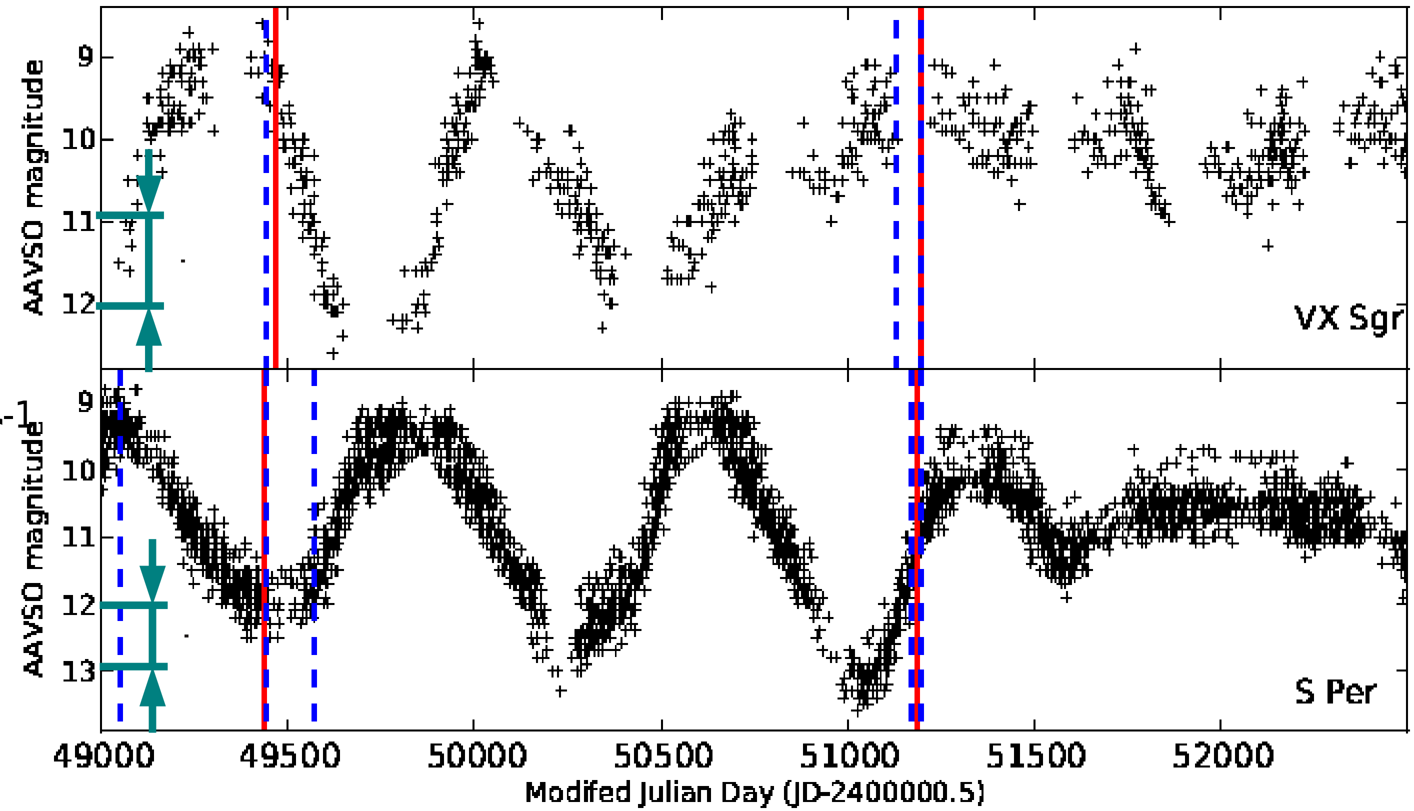
- RSG VX Sgr Stellar disc VLTI 2 μm *Chiavassa+ 2010*
  - $R_\star$ 4 mas ~ 7 AU
  - SiO *Chen+06* 43 GHz 2—4 $R_\star$
    - VLBA
  - H_2O *Murakawa03* 22 GHz
    - MERLIN
    - Overdense clumps 5 – 50 $R_\star$
- Red Supergiants >~8 $M_\odot$
- Lower-mass AGB stars have $R_\star$ ~1 AU
  - Periods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

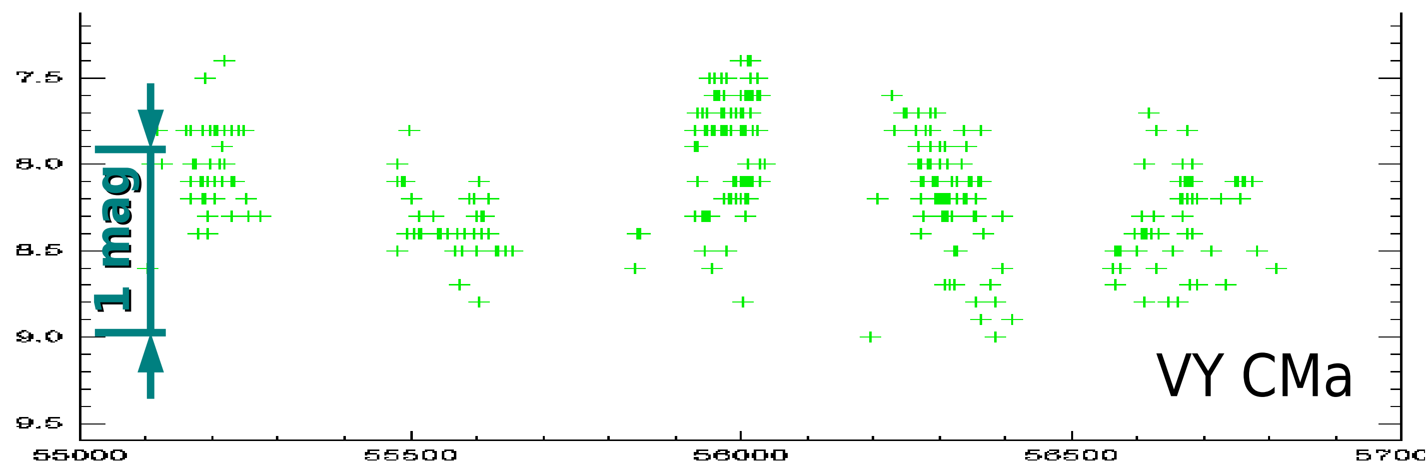


Pulsation amplitude isn't everything

- Other cool RSG: S Per, VX Sgr
  - Δ_{mag} 3~4
  - $\dot{M}$ 3-7 x10^{-5} $M_\odot yr^{-1}$
- VY CMa
  - Δ_{mag} 1~2
  - P ~870d? ~1600d?
  - Recently ~400d
  - $\dot{M}$ ~10^{-4} $M_\odot$ yr^{-1}

Thanks to AAVSO, AFOEV

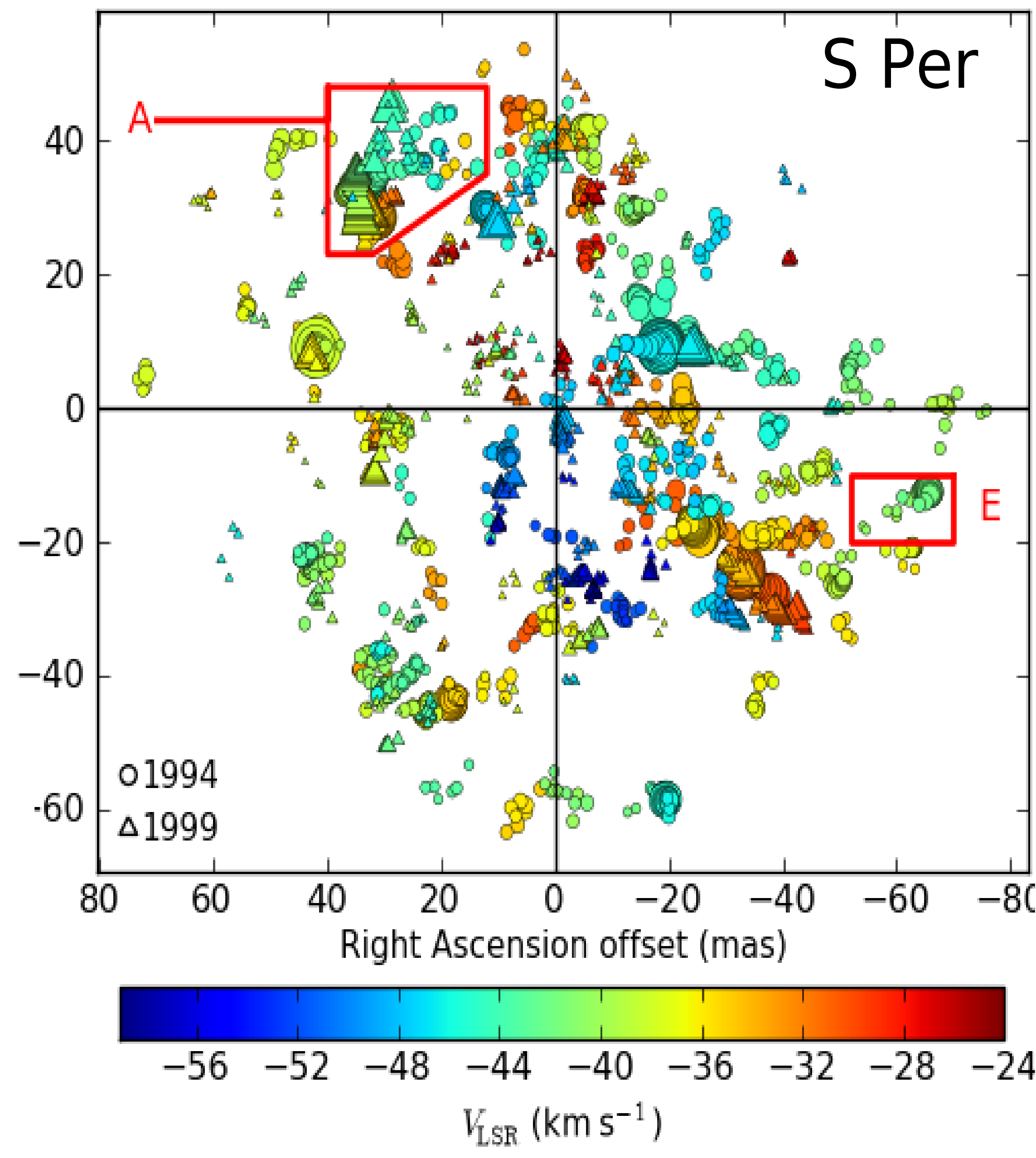




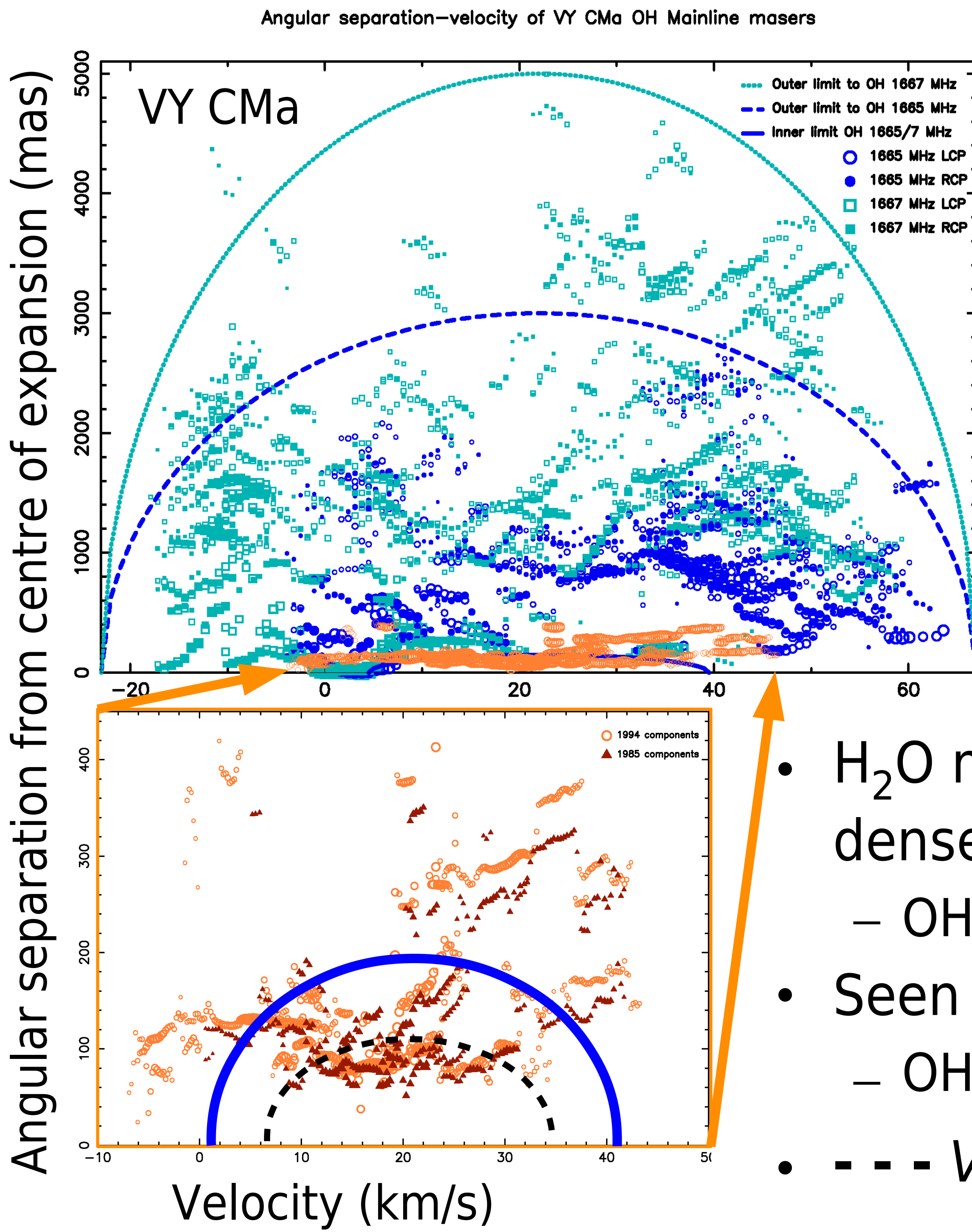
Cloud measurements

- 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
- Beaming angle

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



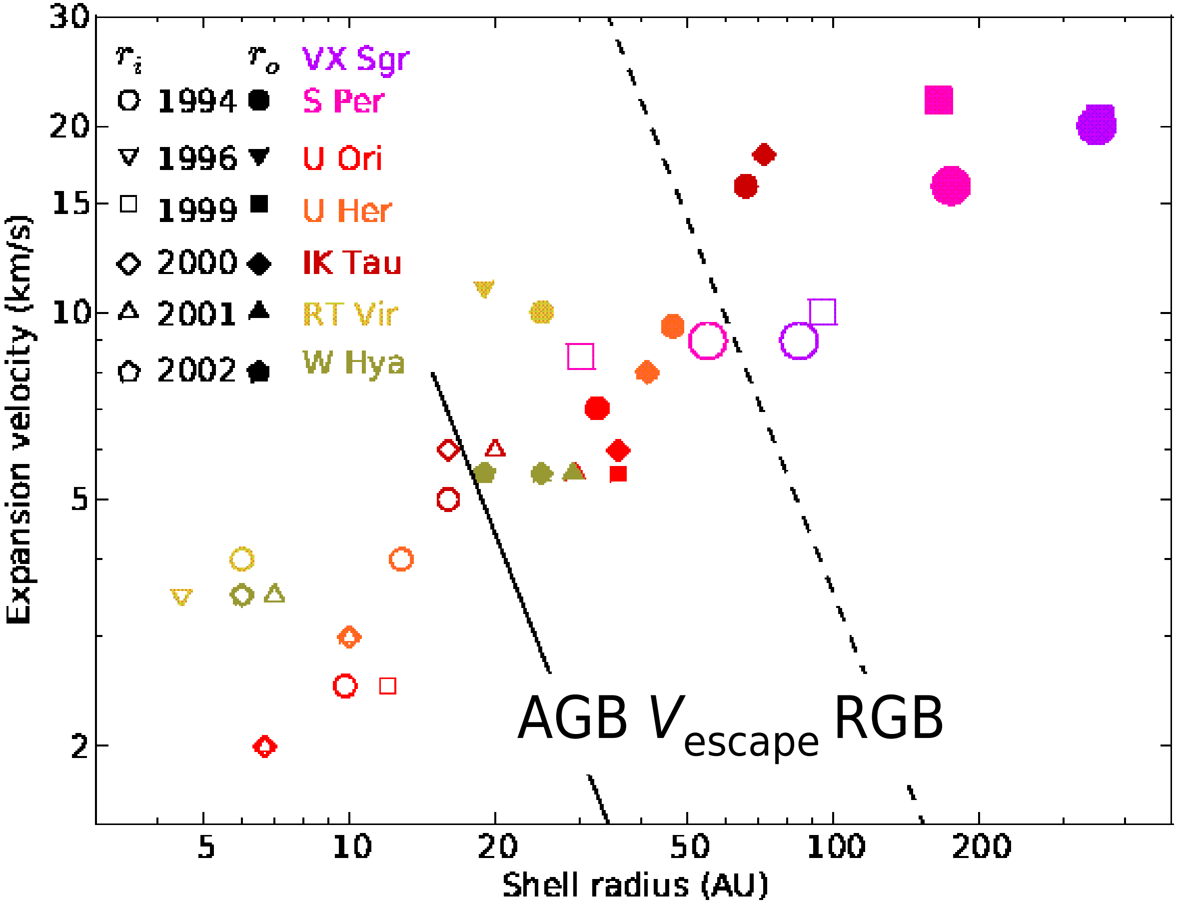
OH masers interleave H_2O



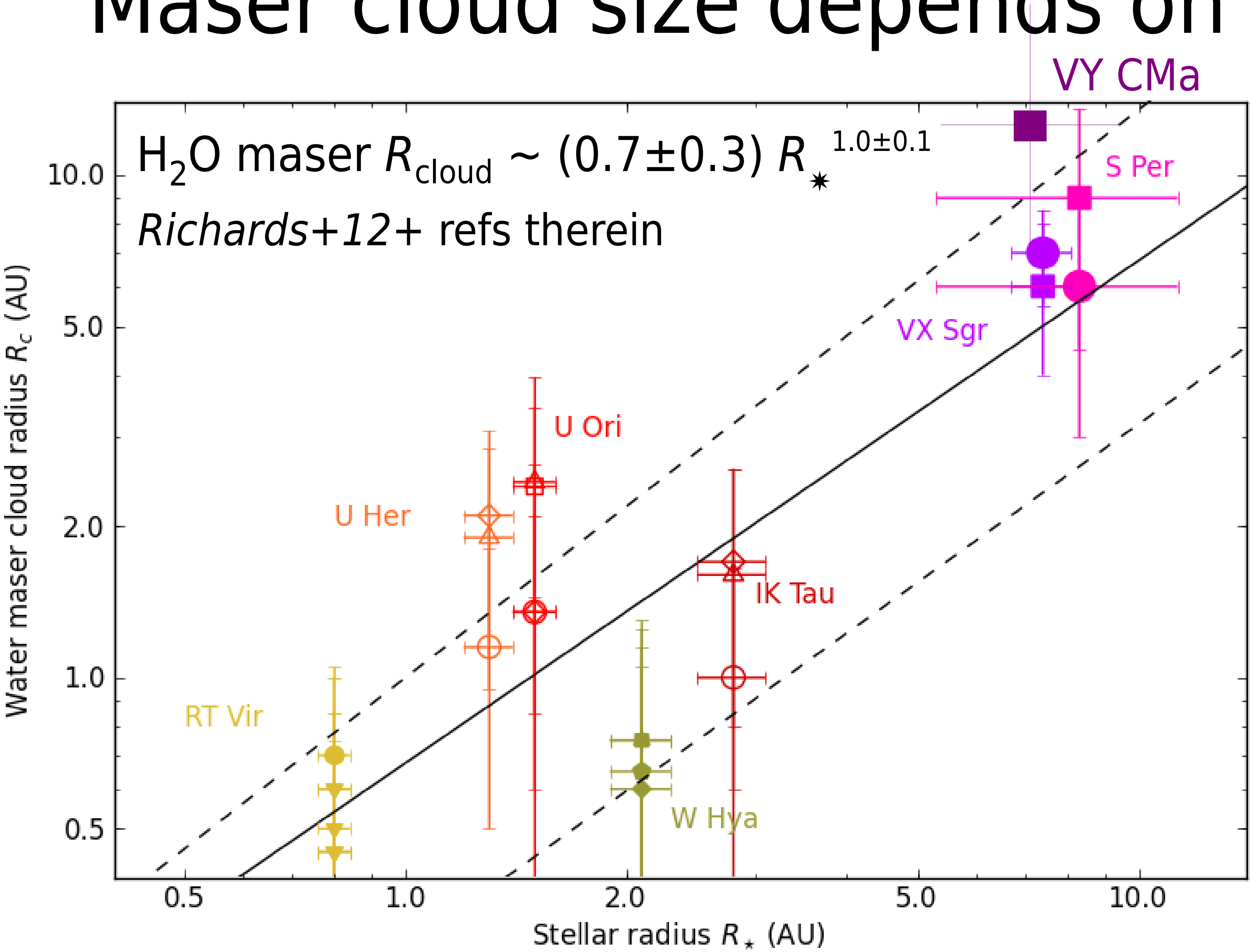
- Mainline OH inner rim in 22-GHz H_2O shell
  - 22 GHz 400-1200K, $n \leqq 5\times10^{15}$ m^{-3} (quenching density)
  - OH needs <500K, lower density gas
- H_2O masers concentrated in dense clumps
  - OH from gas in between
- Seen for other evolved stars
  - OH 1612 always outside H_2O
- - - - V_{esc}

What accelerates the wind?

- Water maser shell limits show $V_{exp} \propto r$ (*Richards+'12*)
  - 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+11*
- Also seen in other lines incl. Hershel
  - *Decin + '10*
- Wind accelerated through V_{esc} while crossing 22-GHz shell



Maser cloud size depends on star size

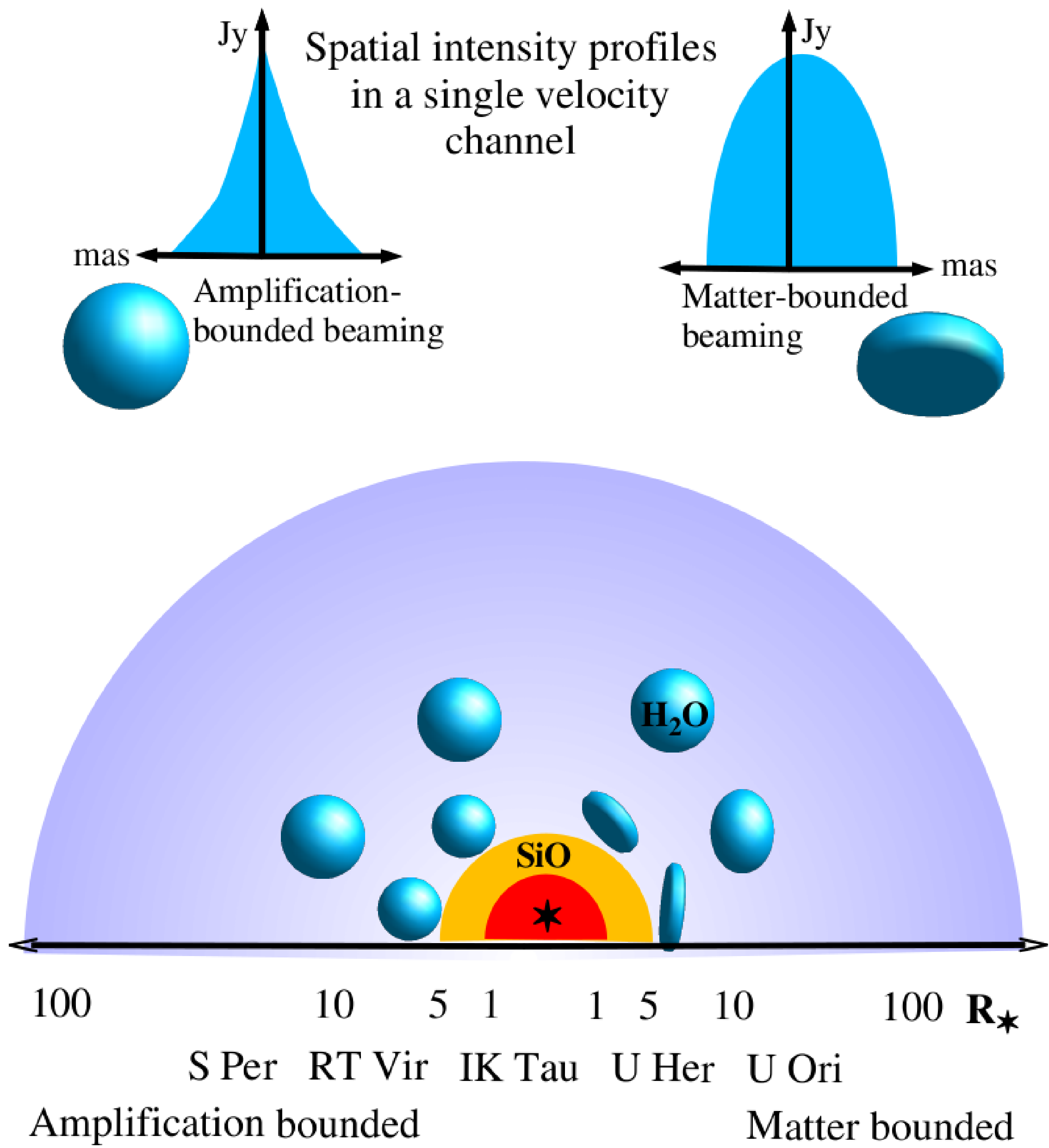


- Cloud properties determined at ejection from star
  - Not micro-physics of dust cooling
- Clouds 30–100 x overdense
- If outflow expands as r^{-2}, birth radius (5–10)% R_*

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

Maser properties reveal wind disturbances

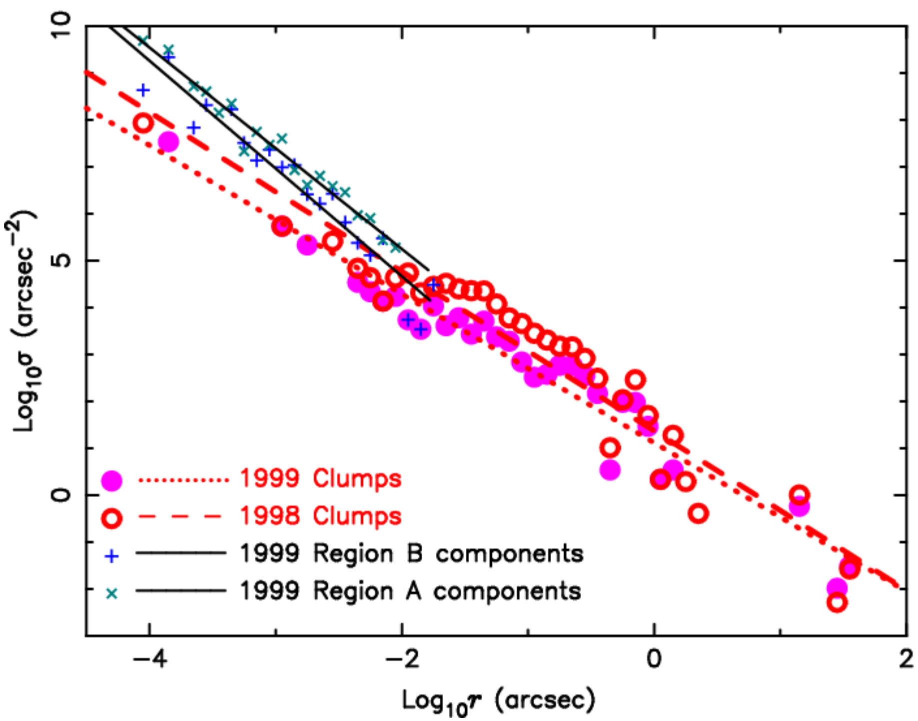
- Brighter = smaller beamed size?
  - $s \propto 1/\mathrm{sqrt}\,[\ln(I_v)]$
    - Smoothly expanding spheres
- Brightest emission often ~cloud size?
  - Rapid maser variability
  - Stars with deepest periods
    - Shocked slabs



Richards Elitzur & Yates 2011
Elitzur Hollenbach & McKee 1992

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)

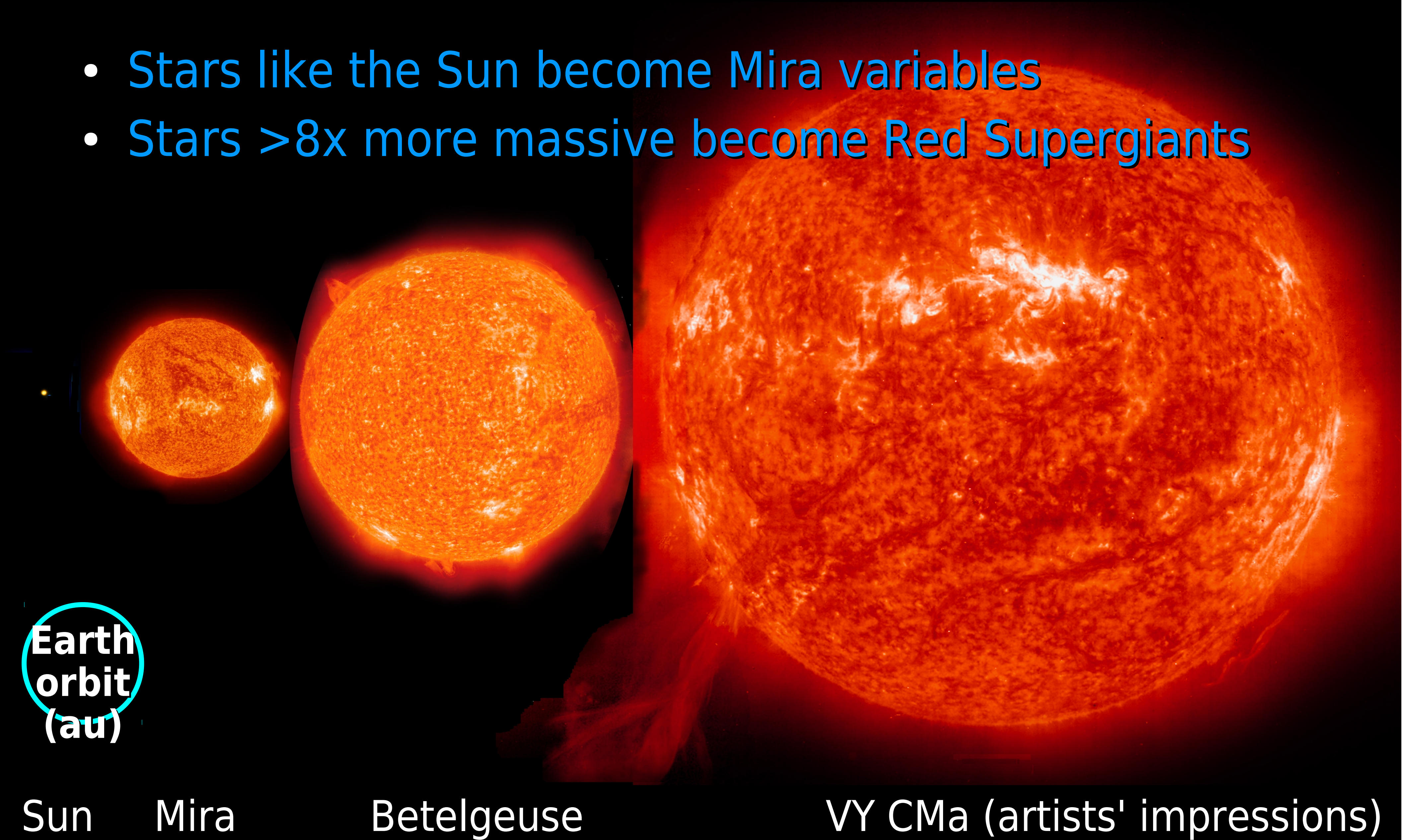
- *Richards, Lekht+'04*

Almost-VLBI with ALMA

- SV observations to test up to 2.7-km baselines
  - sub-mm masers bright enough to self-cal
- 16-20 antennas, bands 7 and 9
  - 321, 325 GHz masers in 3.5 GHz each B7
  - 658 GHz maser in 1.75 GHz B9
    - Standard observing & data reduction
      - Cycle time 7 – 9 mins (now know shorter better?)
        - » PWV 0.3 – 0.7 mm
    - ~1.5 hr on target per frequency
- Spatial/spectral resolution 50 – 200 mas / ~0.5 km/s
  - Depending on frequency & weighting
- Data public via ALMA science portal

VY CMa – the largest Red Supergiant

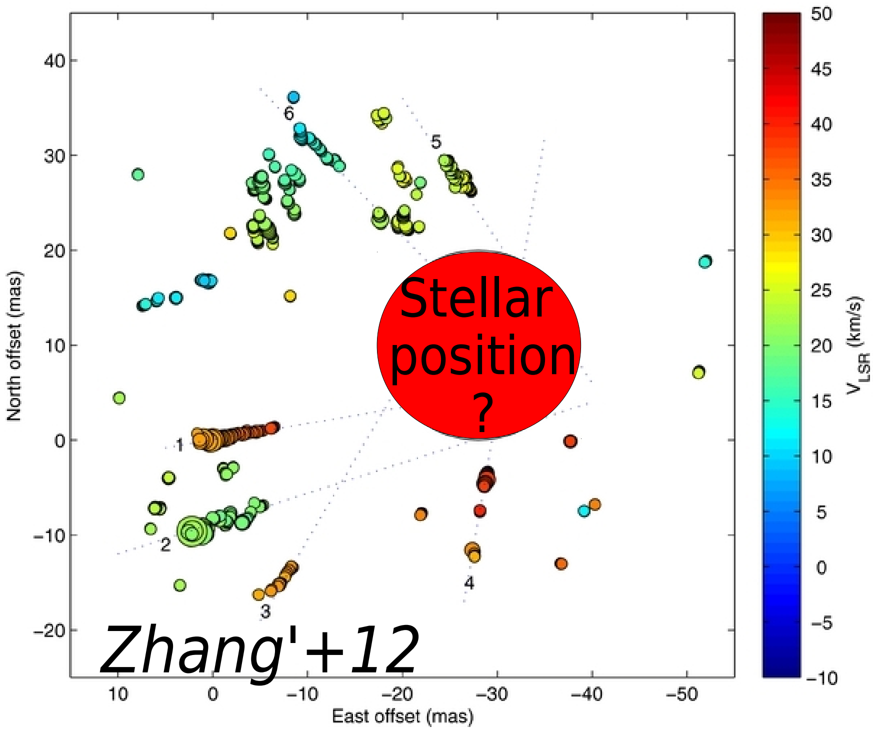
- Stars like the Sun become Mira variables
- Stars >8x more massive become Red Supergiants



The largest red supergiant

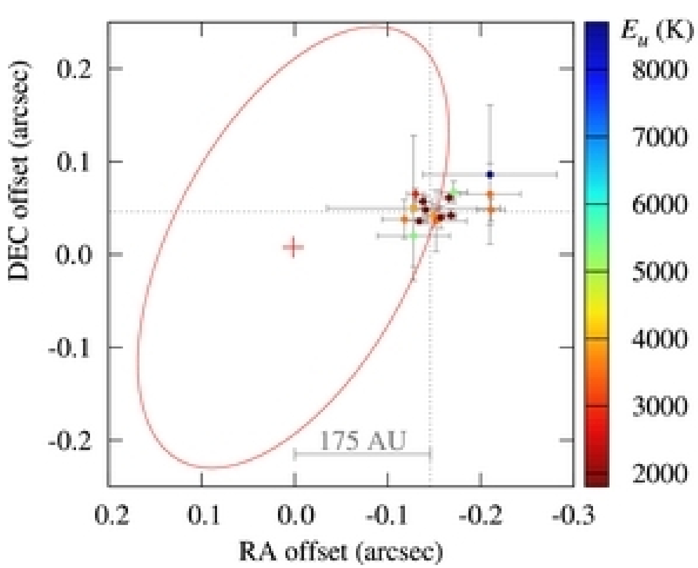
- VY CMa has the largest diameter known for a cool red supergiant
- Distance ~1.2 kpc
  - VLBI maser parallax *Choi+ '08, Zhang+ '12*
- 2 μm angular size 11.4 mas ~13 au *Wittkowski+'12*
  - Progenitor mass ~25 $M_\odot$, currently ~15 $M_\odot$
  - T_{eff} 3490 K (but 2800 K, *Decin+'06*)
- Luminosity 3x10^5 $L_\odot$ *Smith+01*
- Spectral type M2.5 – M5e1a *Wallerstein'58*

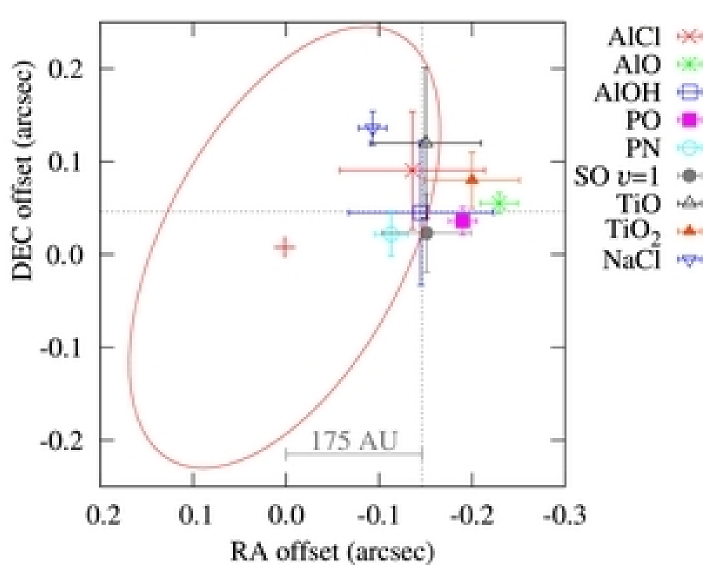
But where's VY CMa itself?



- SiO masers within 2-4 $R_\star$
  - VLBI, star not detcted
    - Assume it's at centre of expansion
- Continuum barely resolved even if detected (SMA, IRAM..)
  - But intriguing offset...

    Kaminski+'13; Muller+07





- Oval shows SMA continuum
- Left: masers
- Right: compact thermal lines

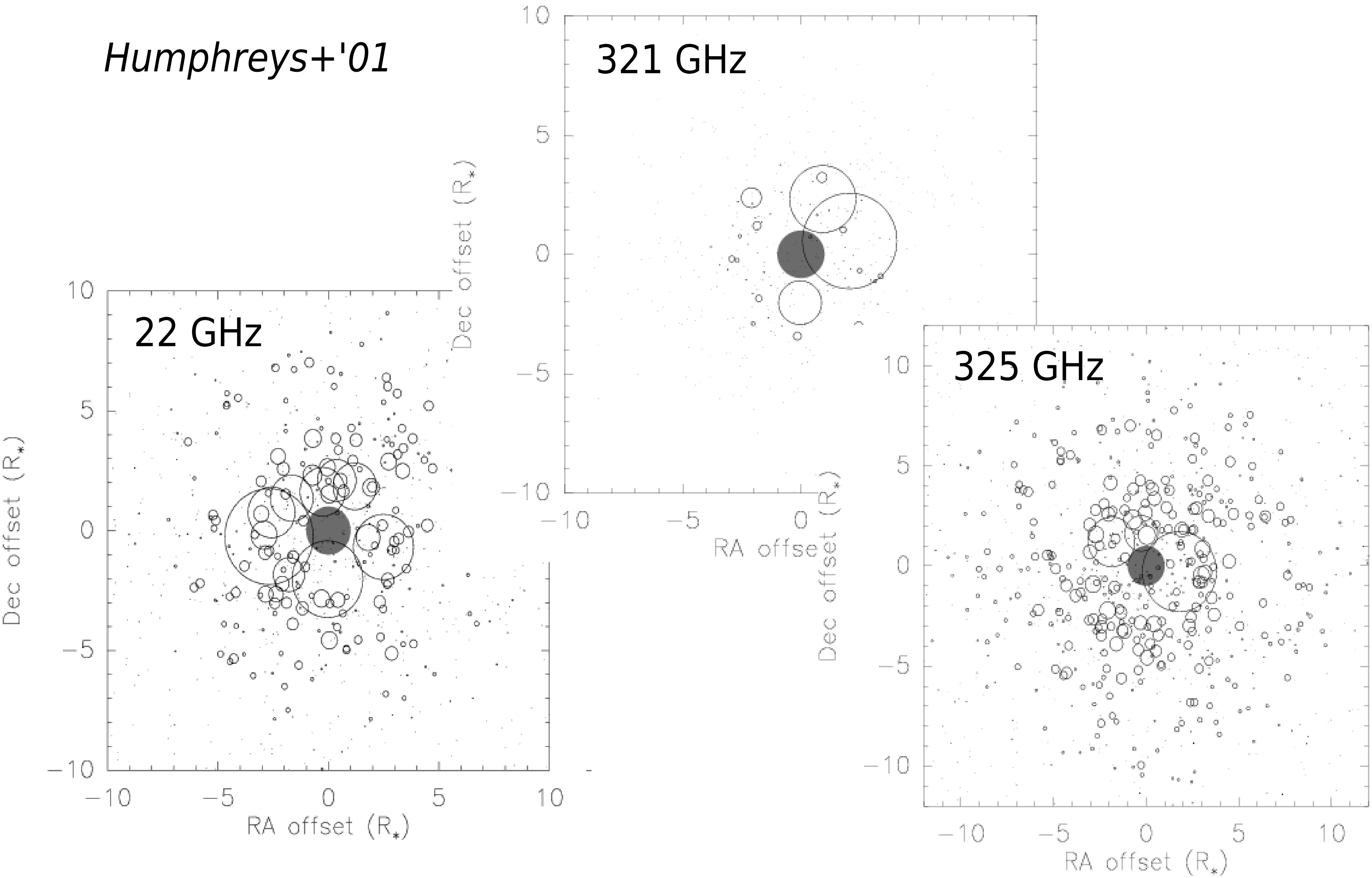
Water masing lines (few of many!)

Frequency (GHz)	Transition ($J_{Ka,Kc}$)	ν_2	E_U (K)	Spin (level)	Discovery (reference)
22.23508	$6_{1,6}$–$5_{2,3}$	0	643	*o*	C69
321.22564	$10_{2,9}$–$9_{3,6}$	0	1862	*o*	M90
325.15292	$5_{1,5}$–$4_{2,2}$	0	470	*p*	M91
658.00655	$1_{1,0}$–$1_{0,1}$	1	2361	*o*	M95

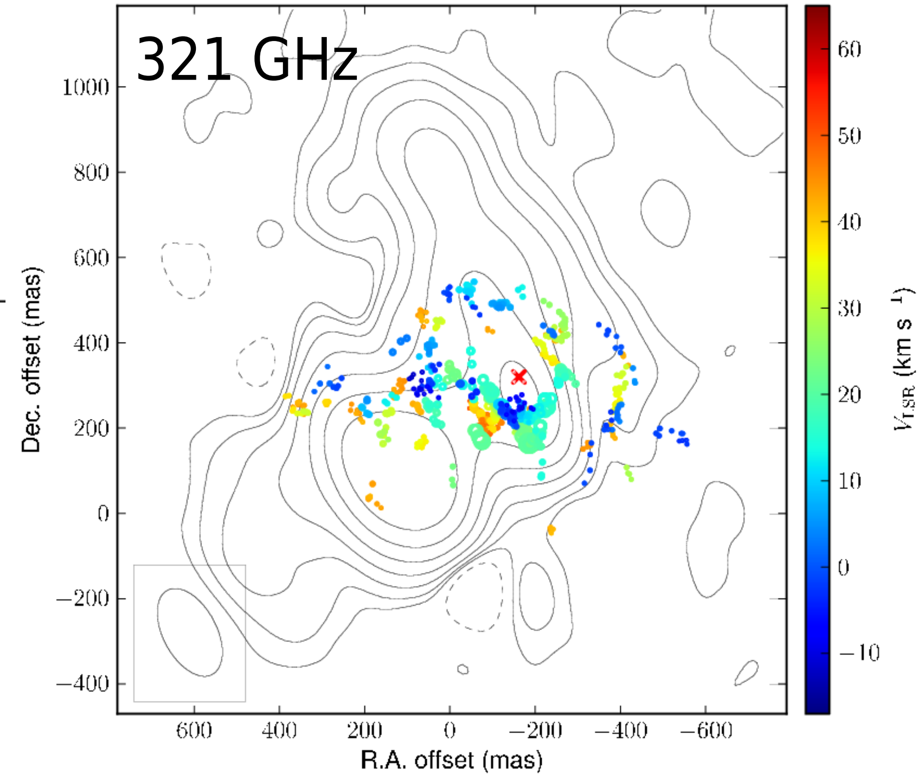
- Expect 658 GHz H_2O inside $5R_*$, with SiO masers
  - SiO E_U 1800 K
- Predict ground vibrational state lines at increasing radii as excitation temperatures increase
  - e.g. Neufeld & Melnick '91, Yates+'97...

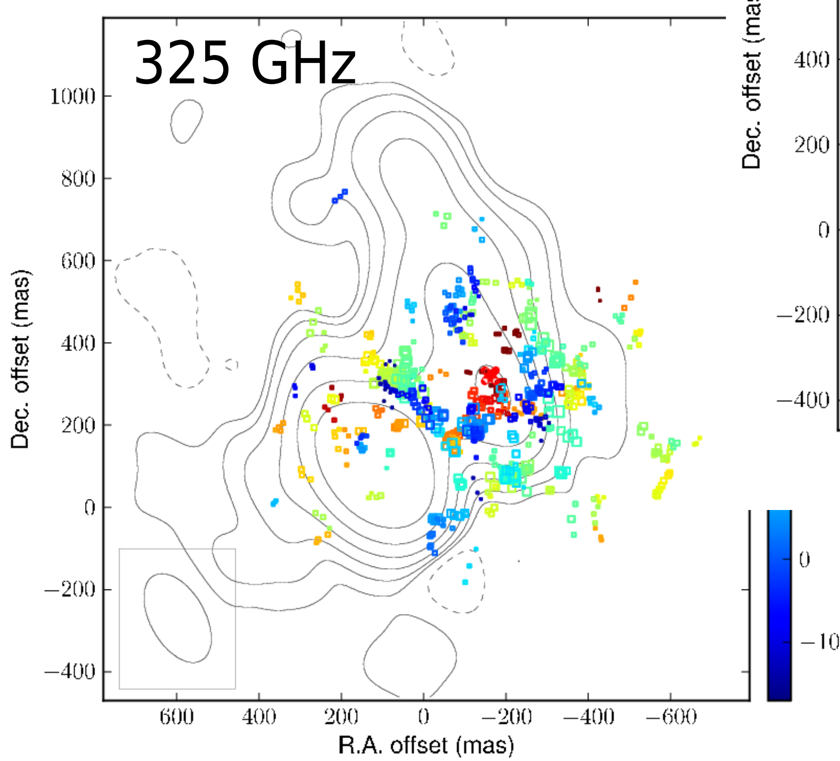
Maser predictions

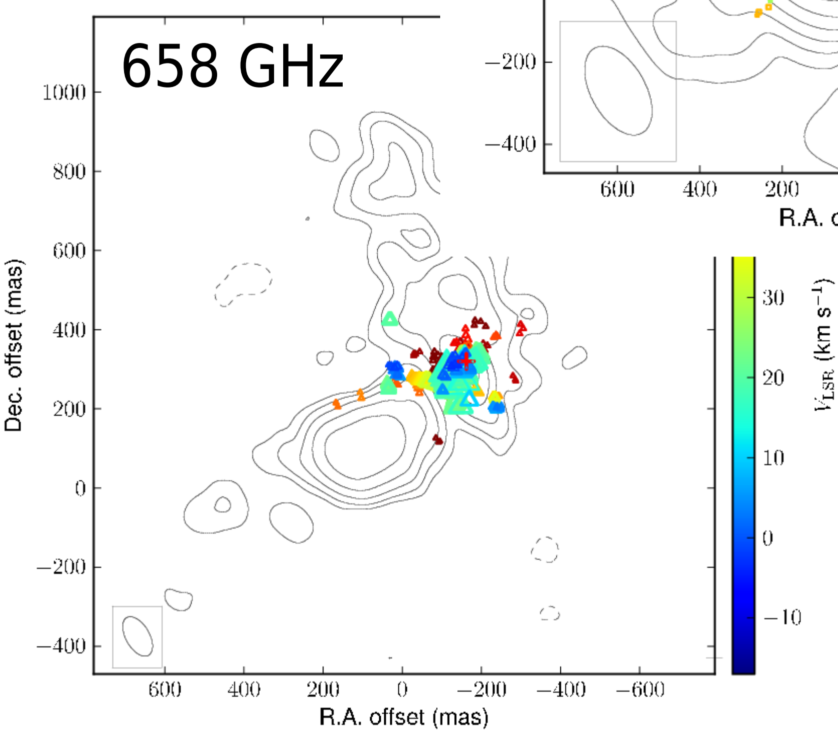
Humphreys+'01



ALMA finds the star x



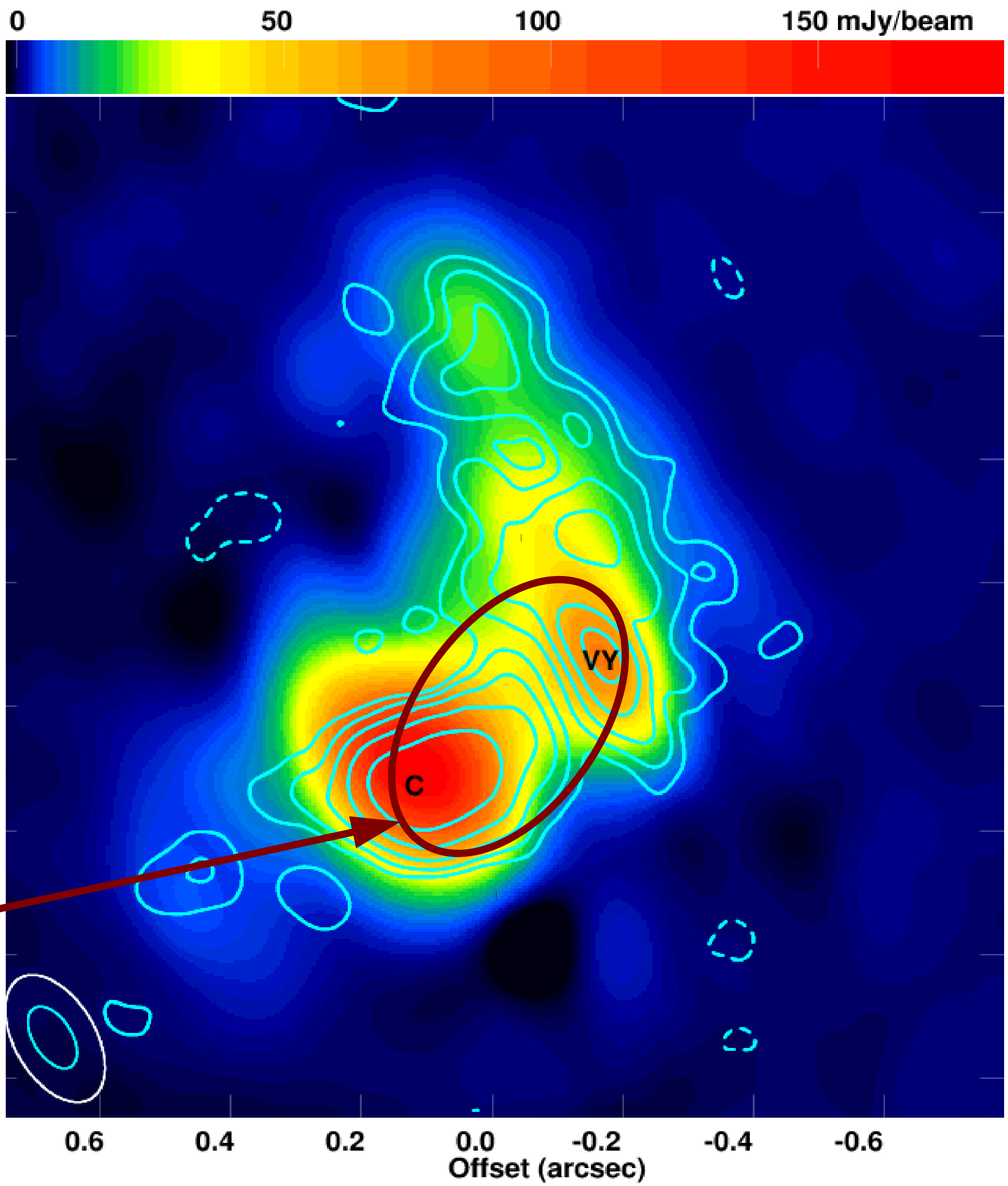




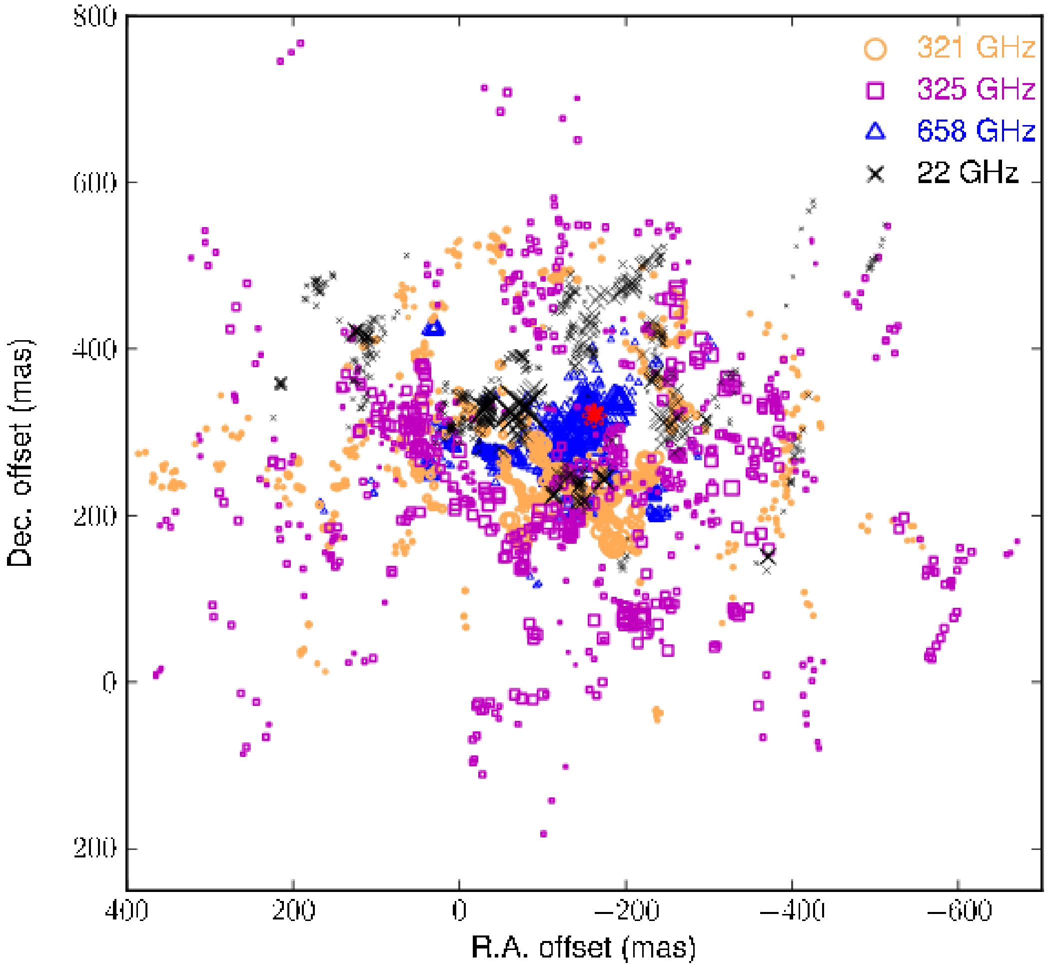
- Centre of expansion found by maximising separation from emission close to $V_\star$
- All three masers centred on 2nd peak

VY CMa continuum

- Self-cal on maser peak
  - Apply to all channels
  - Map continuum
- B9 contours, B7 colour
  - Resolution 50-150 mas
- '**C**' 134 mJy/bm B7
  474 mJy/bm B9
- '**VY**' 72 mJy/bm B7
  296 mJy/bm B9
- Unseparated by SMA
- *O'Gorman+A&A*, submitted



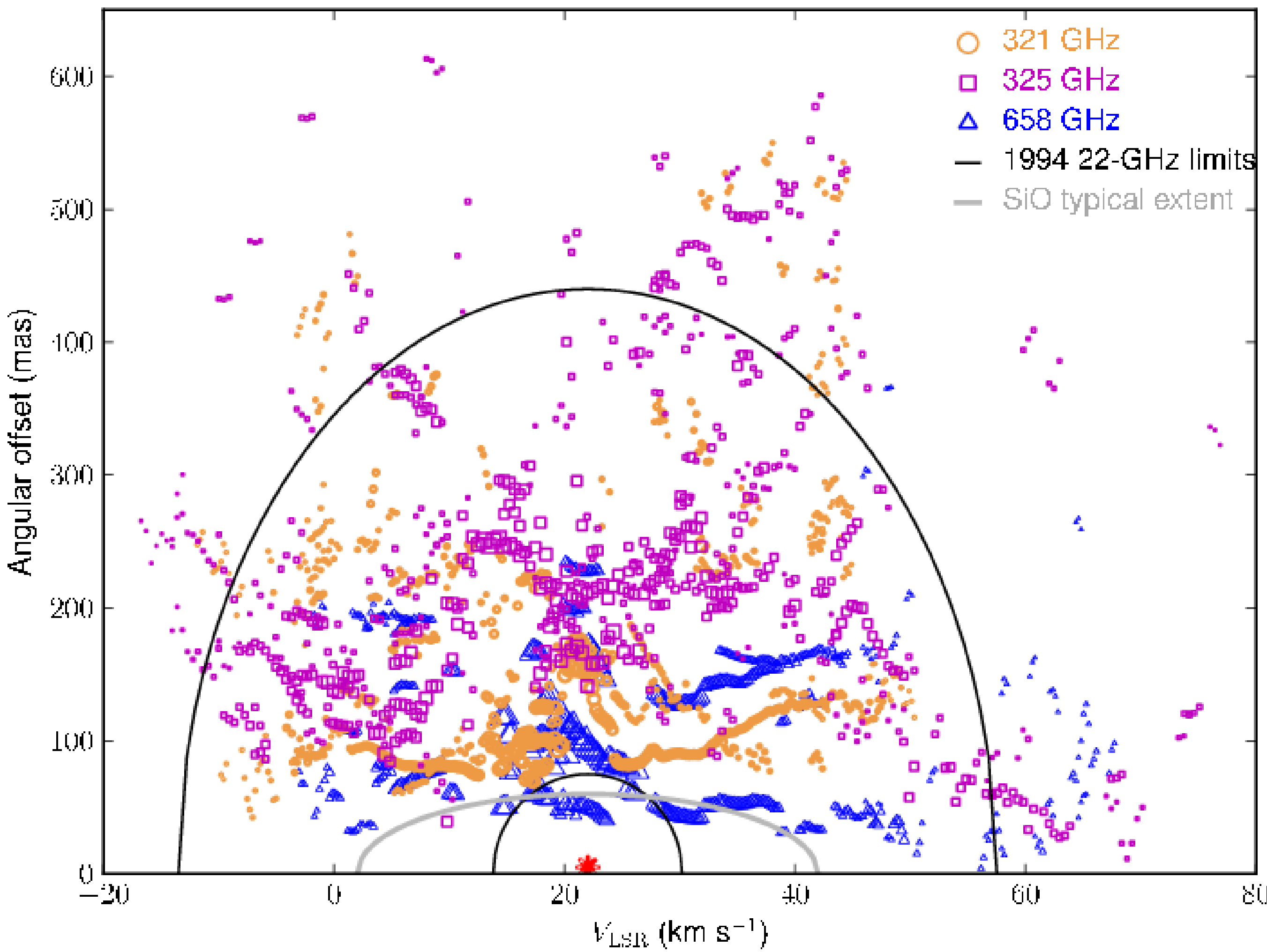
Spatial distribution



- 658-GHz may have infall or outflow close to the star
  - But it is so extended!!!

- 321 similar to 22 GHz
  - Ring-like appearance suggests ~spherical shell strongly accelerated
  - Longest velocity-coherent line of sight around limb
    - Tangential beaming
  - How can wind be hot enough at 100s au?
    - Shocks?

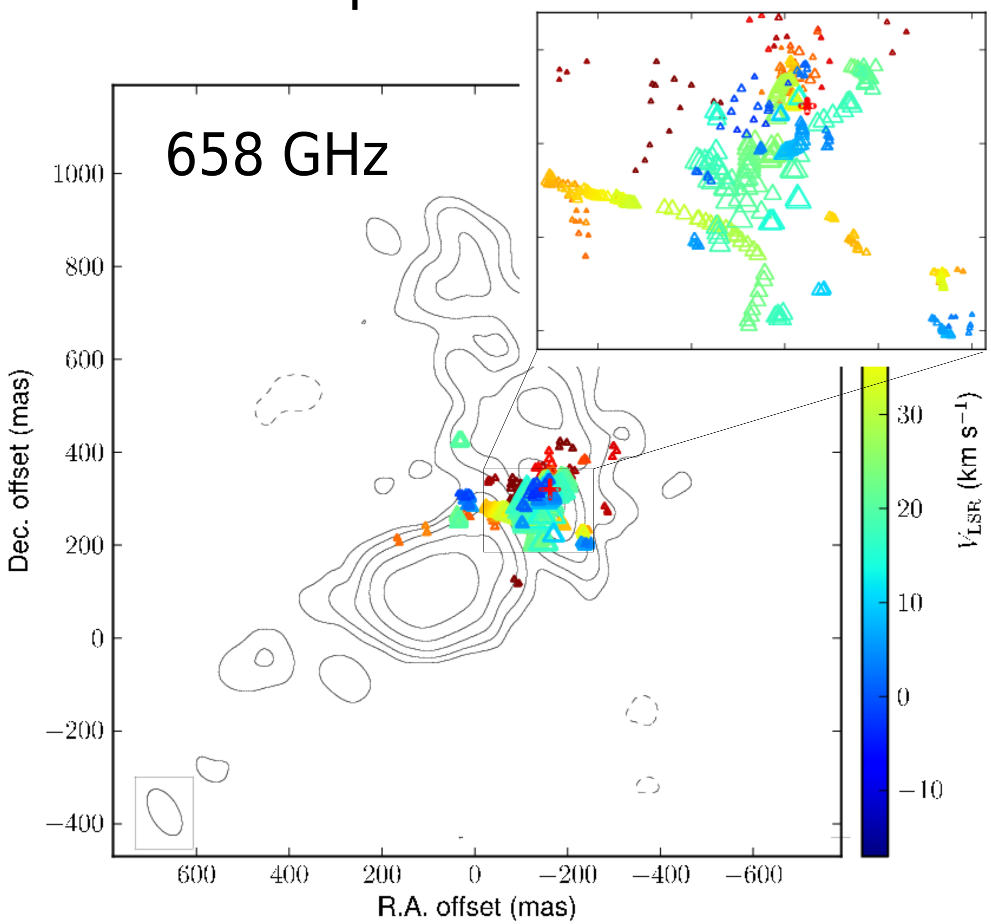
Spatial distribution

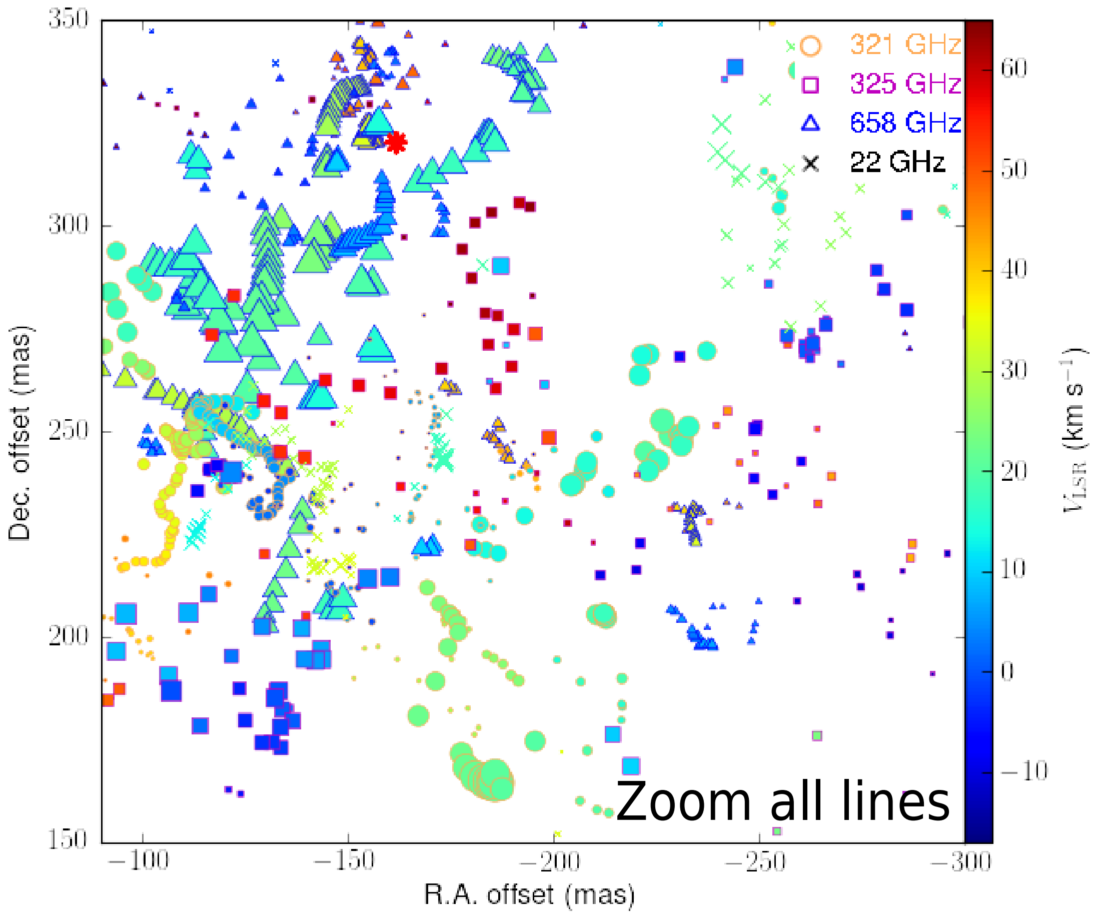


- 658 GHz starts inside dust formation zone
  - But at larger radii than SiO
  - Extend almost to where OH begins!!!
- At least 325-GHz is as predicted
  - Low excitation temperature, large inner radius
- 325-GHz some faint extreme-velocity emission
  - Close to line of sight to star
    - Moderate acceleration

Environment?

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

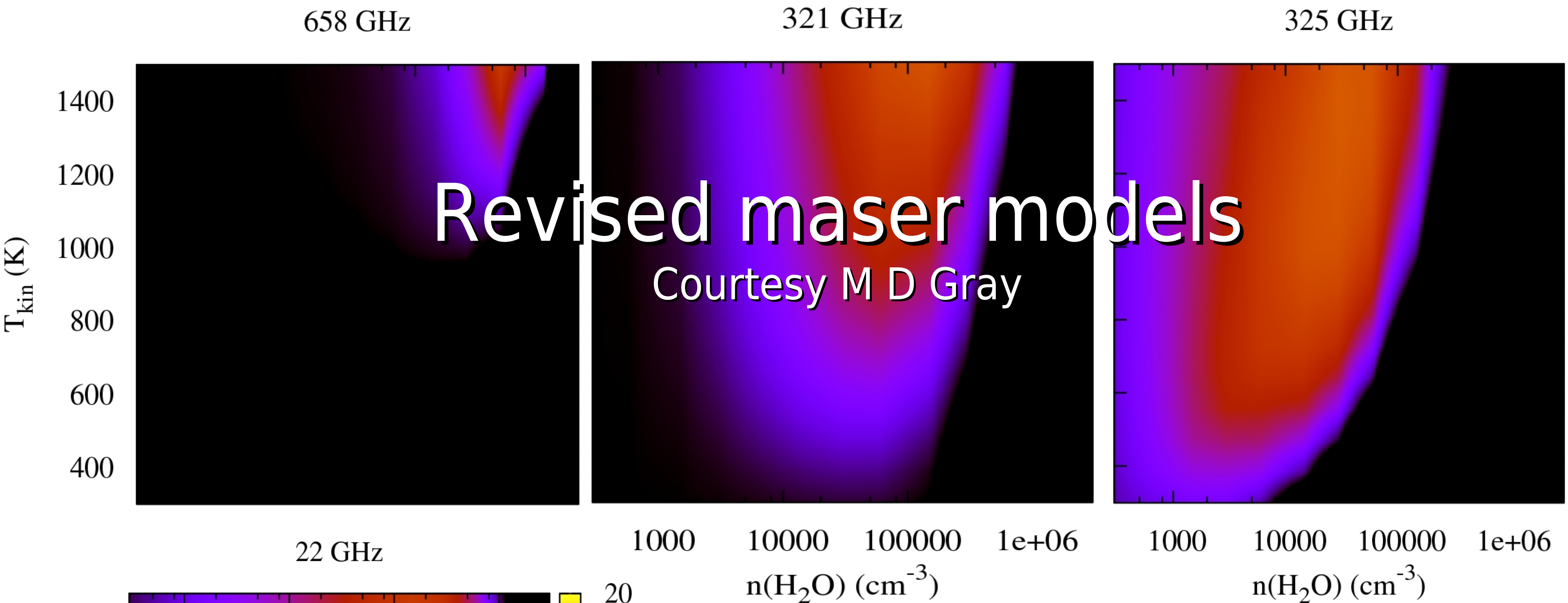


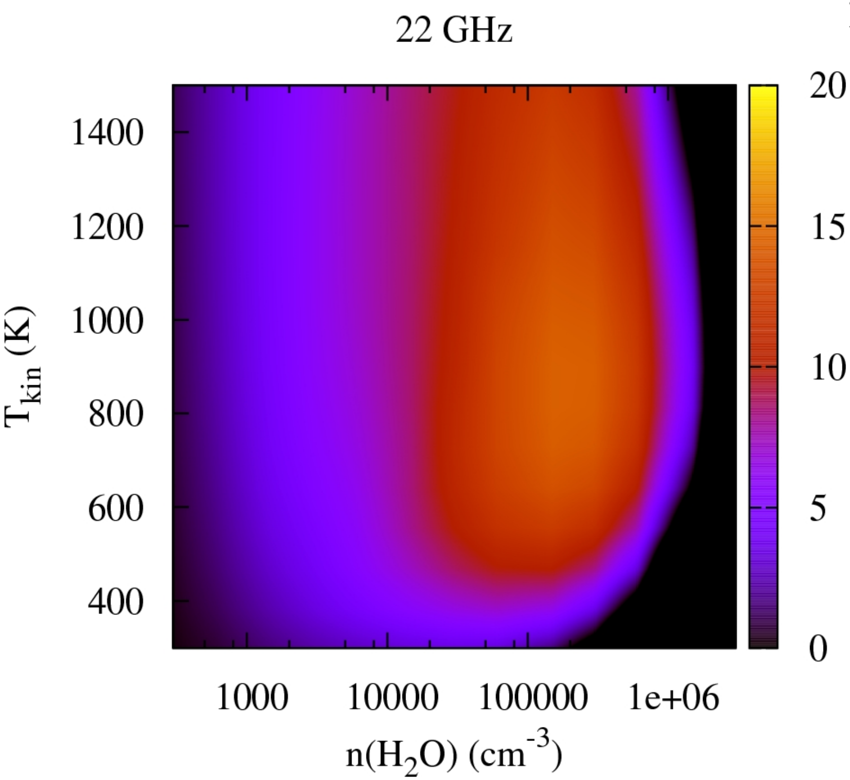


- Asymmetric distributions
- Disc? (*Decin+06*)
  - + random ejecta (*Humpheys+07*)?
- Species separate 10-au scales
  - At similar radii in different-density environment/clumps?
    - Not co-propagation

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
  - But how are 658, 321 so extended?

ALMA's VY CMa

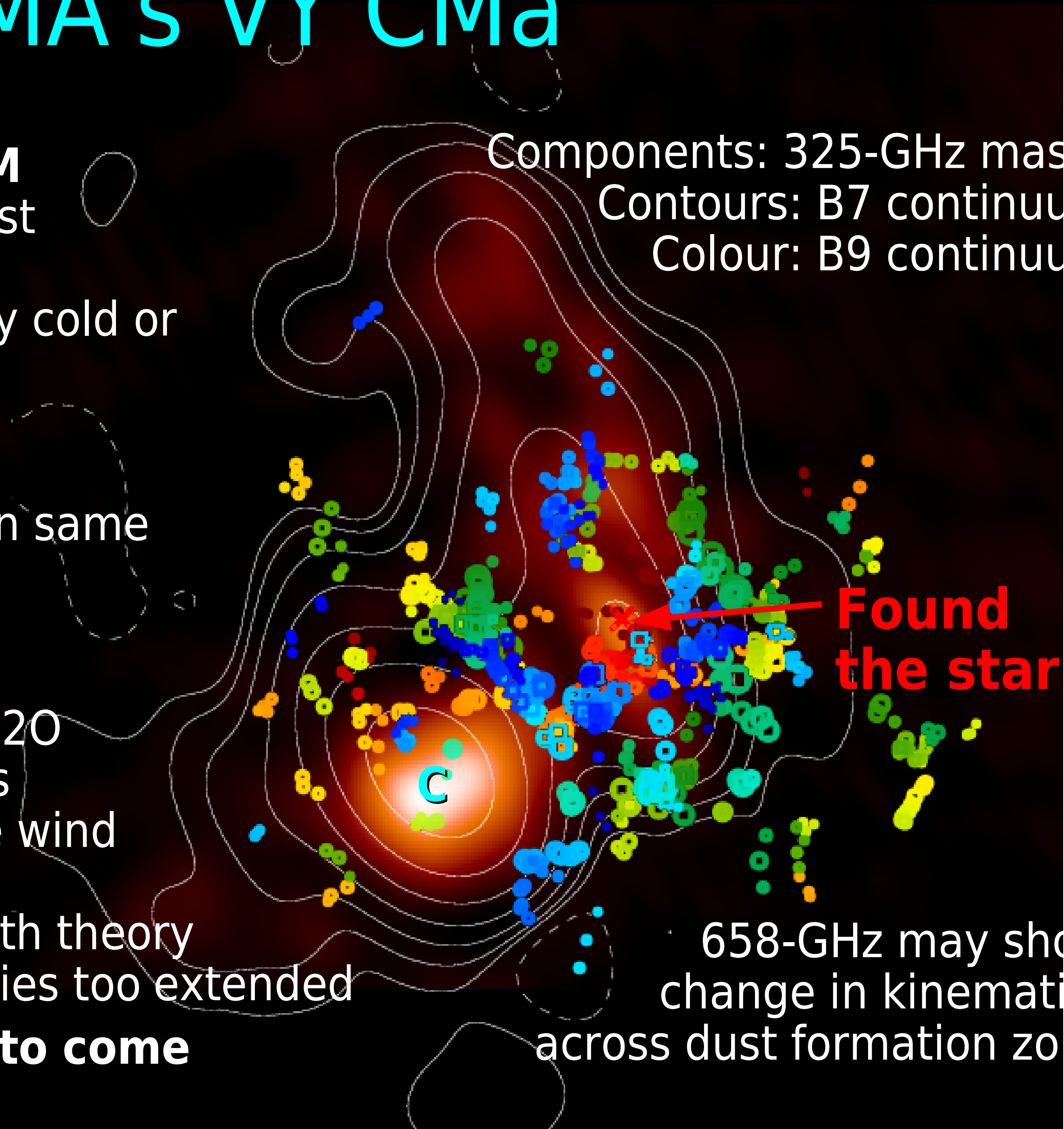
CONTINUUM

- Resolved the inner dust
  - Must be clumpy
- '**C**' may be surprisingly cold or amazingly dense
- Shape is wierd
  - Random ejecta?
  - But taken 100s yrs in same directions....

MASERS

- First-ever sub-mm H2O circumstellar images
- Acceleration, maybe wind collisions
- Broad agreement with theory High excitation species too extended

Lots of papers to come



VLBI + ALMA for sub-mm masers

- Sub-mm VLBI needed to resolve proper motions, spots
  - Kinematics, fractals, co-propagation...
    - Shock diagnostics on sub-au scales
- Typical 22-GHz maser 0.1 – few mas
  - Resolved by MERLIN, VLBA, peaks 10^9 – 10^{14} k
  - VLBI resolves ~90% - still leaves 10s- >100s Jy
    - Total flux densities needed for full maser modelling
- ALMA subarray e.g. 0.5 -15 km to detect all the flux
  - Detect star, provide astrometry
  - Help calibration
  - LAMA? (~400 km South American baselines)
- Global sub-mm resolution ~ RadioAstron at 22 GHz

ALMA long baseline progress

- All 66 antennas delivered, all but a few at AOS
  - Bands 3,6,7,9 working (84-700GHz)
  - Polarization science verification
  - Bands 4,8,10 science verification & commissioning
- Long baseline campaign (up to ~10-km baselines)
  - Fast switching, band-to-band phase transfer...
  - Weak calibrator survey (QSO, stars, asteroids...)
    - Bologna ARC prepared VLBI, VLA, ATCA lists to seach
    - Predict *S*(90GHz) ~ *S*(20GHz)/4 – confirmed!
      - Almost all VLBI S-band calibrators detected
        - 80% > 40 mJy at Band 3 (96 GHz)
      - ~1% resolved at 0”.5 resolution
      - Strategy for imaging at higher resolution if needed

and VLBI progress

- Plans to use ALMA in (sub-)mm VLBI
  - Not just for the Event Horizon Telescope!
- Hydrogen maser successfully installed and tested at AOS (high site)
- Eight Phasing Interface Cards (PICs) installed in correlator (see also *Baudry 2013*)
  - Two per quadrant
- Successful phasing-up test (previous talk)
  - 3 antennas as a single dish
- Two recorders shipped to OSF

Remote ALMA antenna with ASTE and Nanten2 in the background