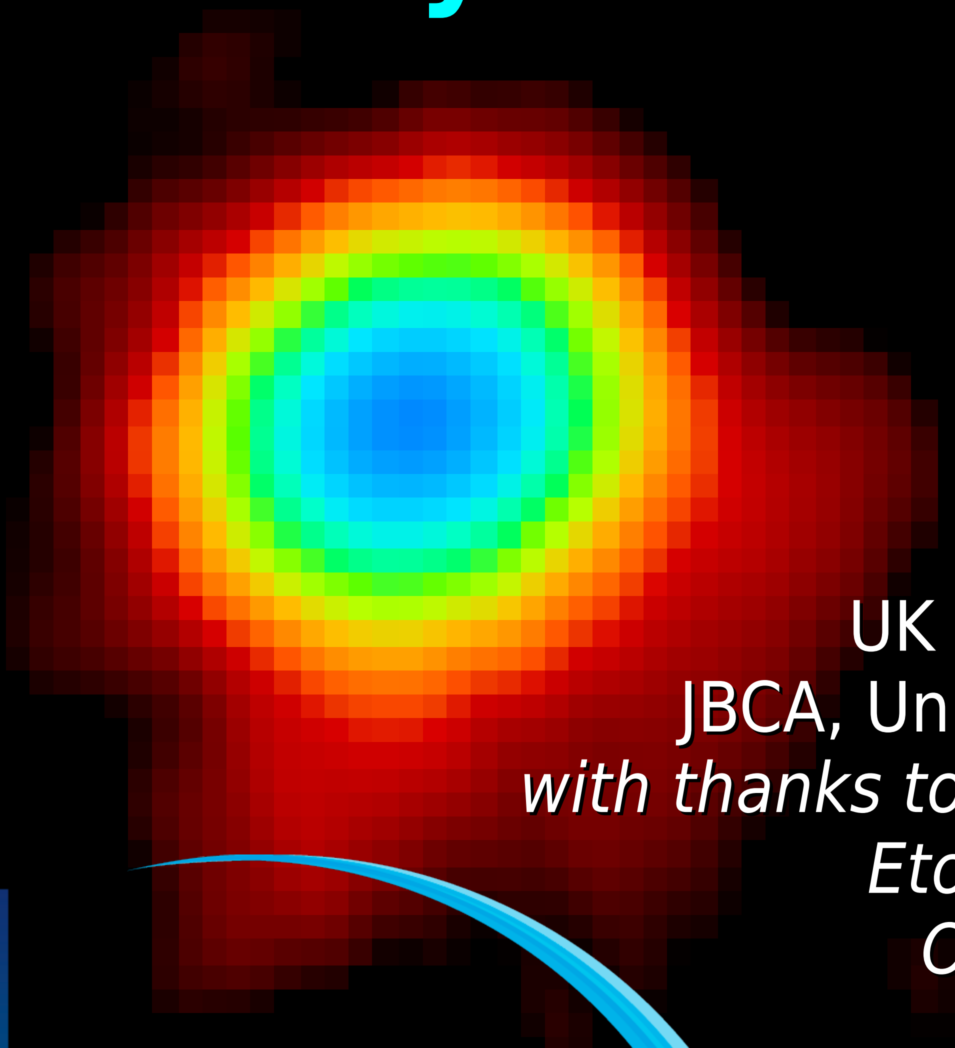
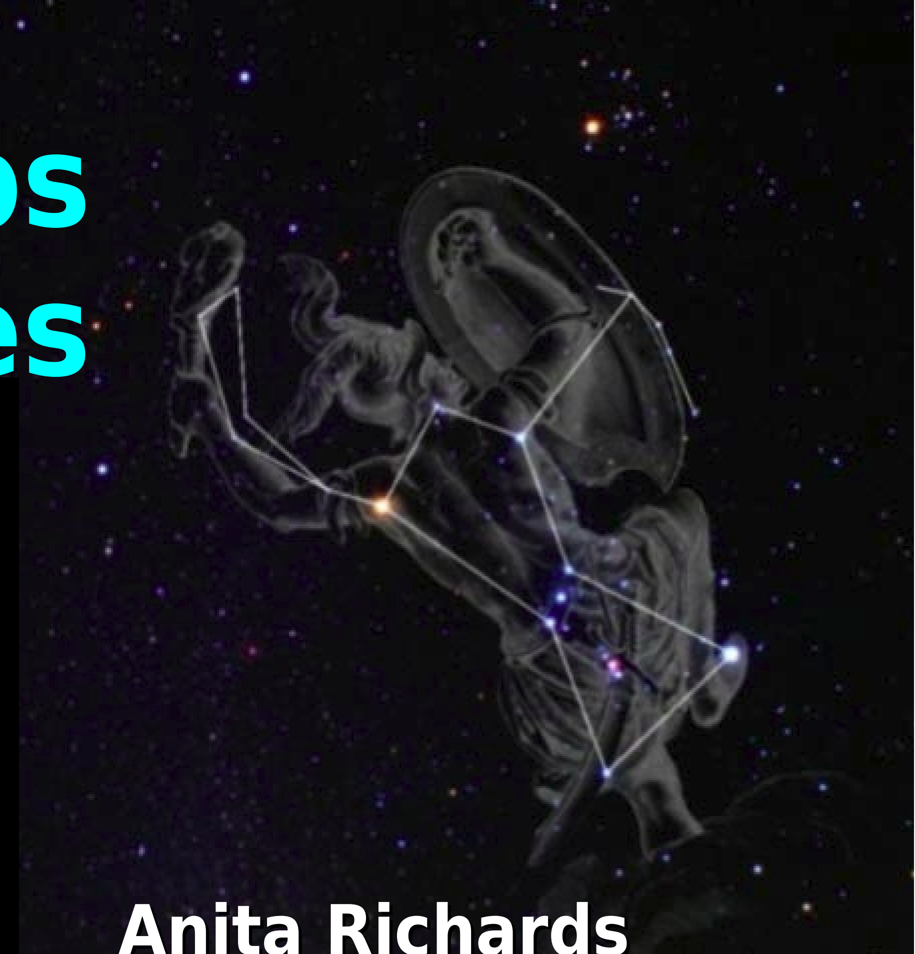
Origins of clumps & asymmetries





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with thanks to Assaf, Baudry, Decin, Etoka, Gray, Humphreys, O'Gorman, Vlemmings, Wittkowski & many others

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Origins of clumps & asymmetries

More observation than explanation
in a very restricted sub-sample...

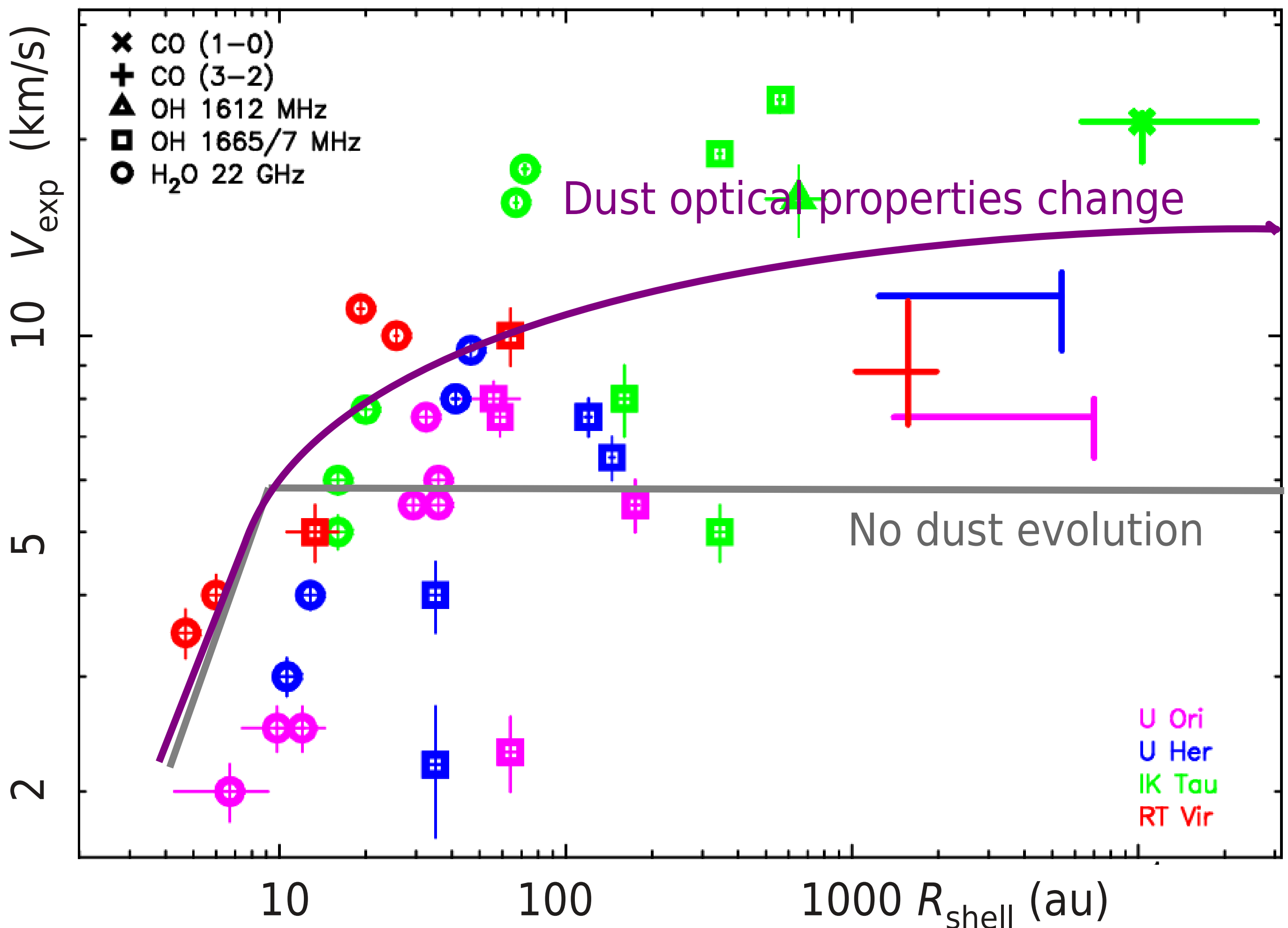
- AGB and RSG
- Solitary/mildly-interacting binary
  - Remote, or potential low-mass companion
- (mostly) radio interferometry
  - Try to understand small-scale wind properties
    - Less averaging of physical conditions
- Small contribution to big questions
  - How is mass lost from the stellar surface?
  - Do dust and molecules survive into the ISM?
- Maser and other high-resolution radio interferometry
  - Mostly O-rich stars – no room here for HCN masers

How does wind get beyond 5 $R_{\star}$?

- Ample evidence for radial, dust-driven wind once dust is fully(?) formed at >(5-20) $R_{\star}$
  - How does O-rich wind get as far as forming dust?
- Shocks propagate in sub-photospheric layers *Jorissen* (even in Miras: *Belova+'14*)
  - <5-10 km/s outside photosphere (*Reid & Menten'97*)
    - Average SiO maser max. V_{exp} 7 km/s (*Kim+'14*)
- Other forces as well as pulsations needed
  - Large grains? Scattering? (*Norris+'12*)
  - *Hoefner*, *Bladh*, *Scicluna* presentations
  - Poster *van de Sande*
- <5$R_{\star}$ pulsation dominated, SiO maser outflow & infall
- >5$R_{\star}$ H_2O 22 GHz, OH maser accelerating mass loss

Wind acceleration

- Gradual acceleration over 10's – 100's R_*
  - Maser shell limit velocities (and CO) v. distance to star
    - Four AGB stars (also in RSG), *Richards+'12*

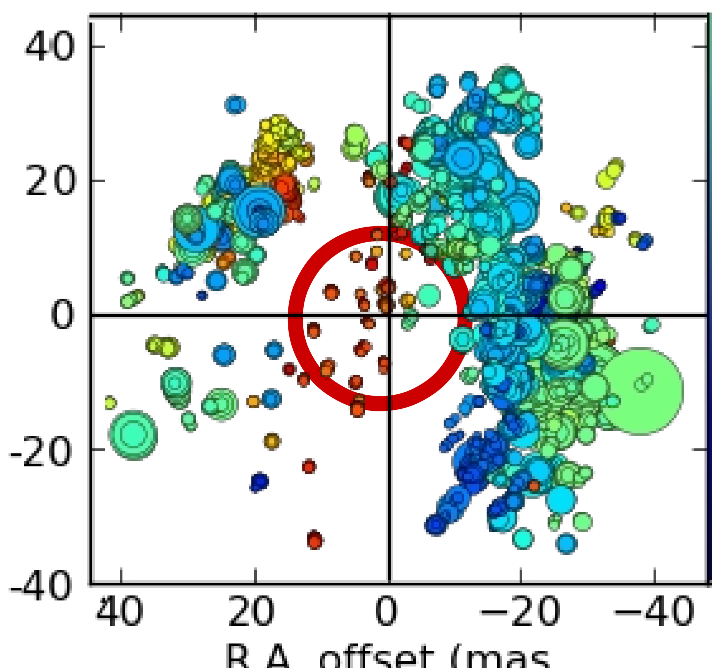


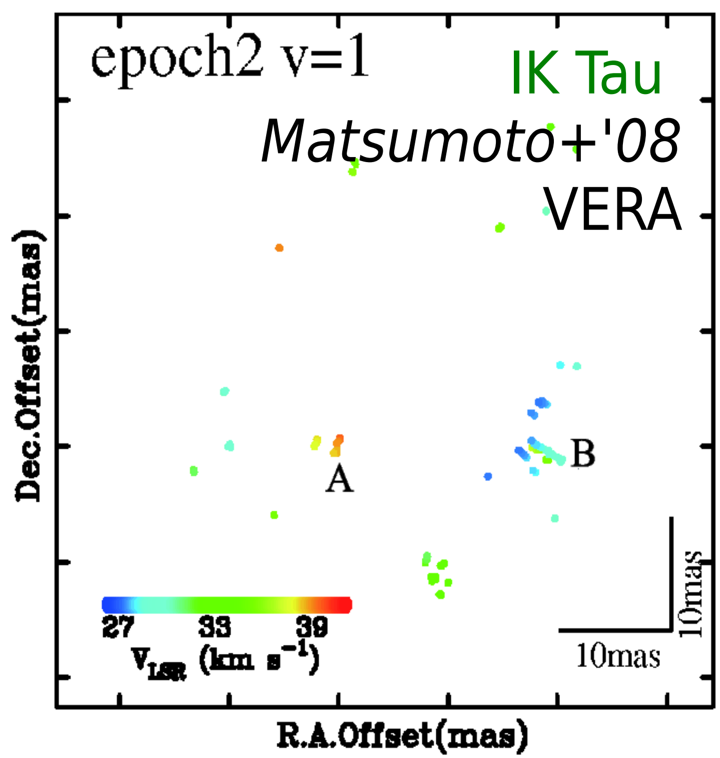
- Acceleration also seen in *Herschel* results for IK Tau
  - *Decin+'10*
- Dust annealing?
  - *Chapman & Cohen'86*
  - *Verhoelst+'09*
- Optical depth effects?
  - *Ivezic & Elitzur'10*

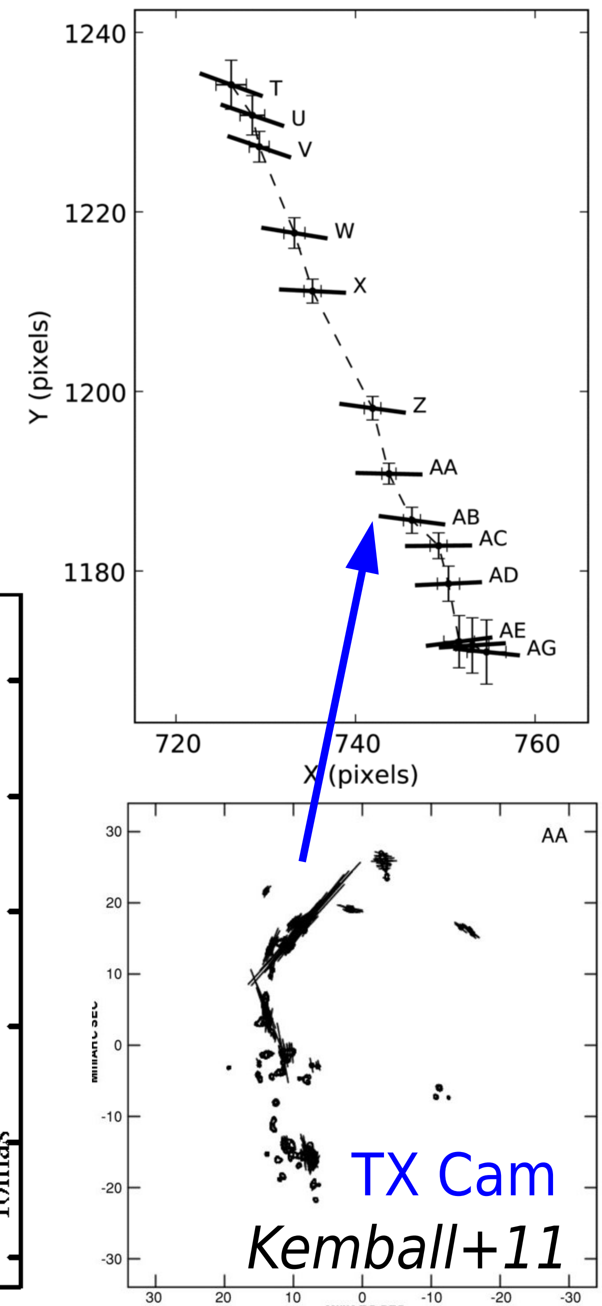
Inside r_d: SiO ballistic? Magnetic driving?

- 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

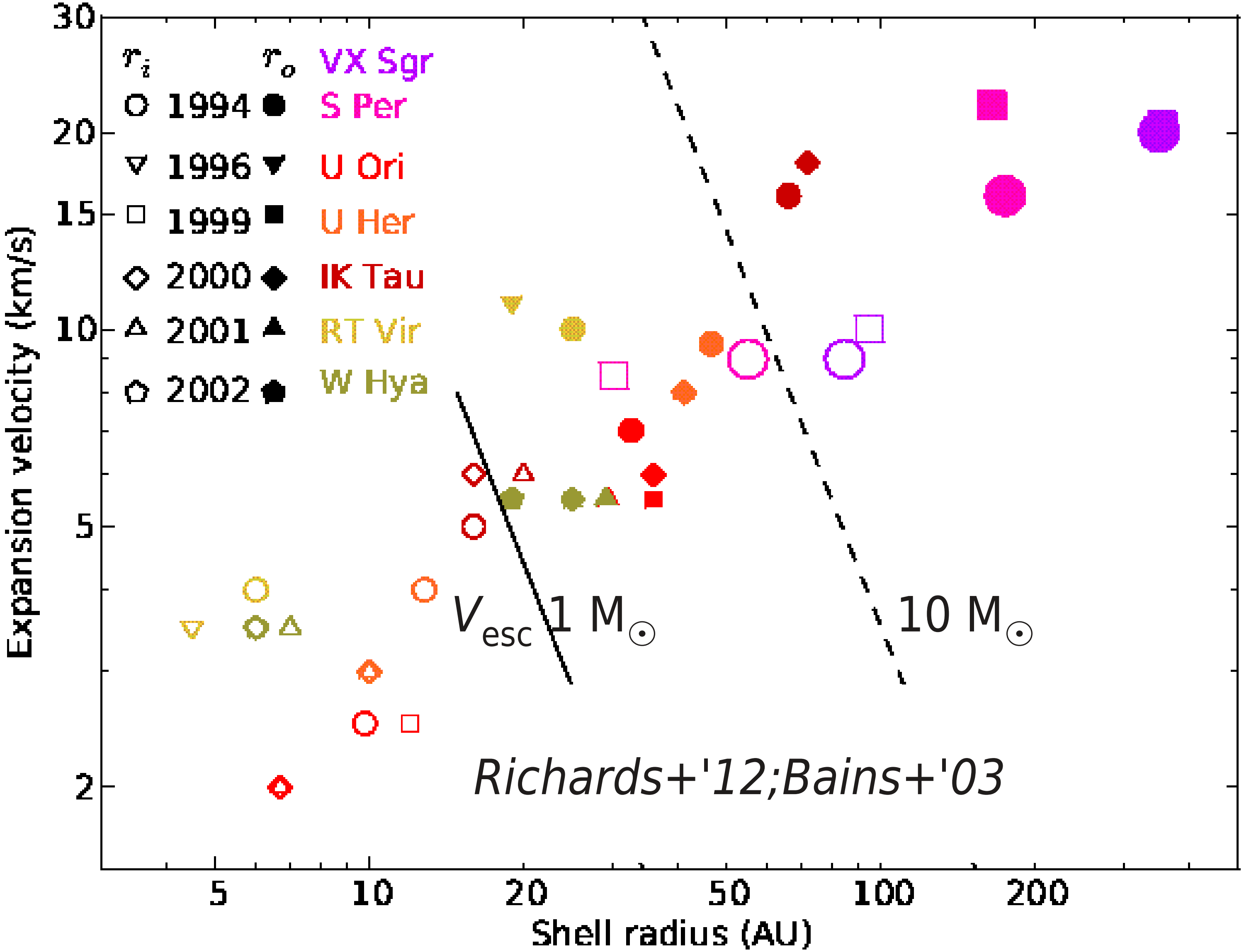
R Cas *Assaf+'10* VLBA







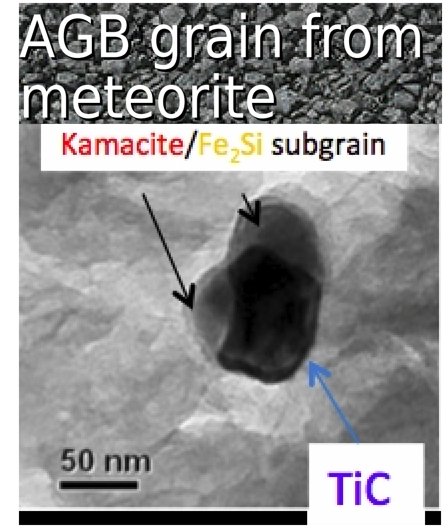
Escape velocity reached in 22 GHz shell



- 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_*

Productive cool stars

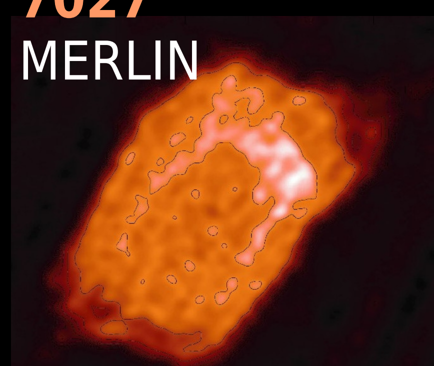
- Much C, N, F, neutron-capture elements, half of all elements heaver than Fe (*Karakas*)
  - See previous talks for latest numbers
- Up to 90% Galactic dust from AGB/RSG
  - e.g. *Gehrz'89,* Posters e.g. *Treja-Cruz*
    - Does it survive ISM sputtering, UV etc.?



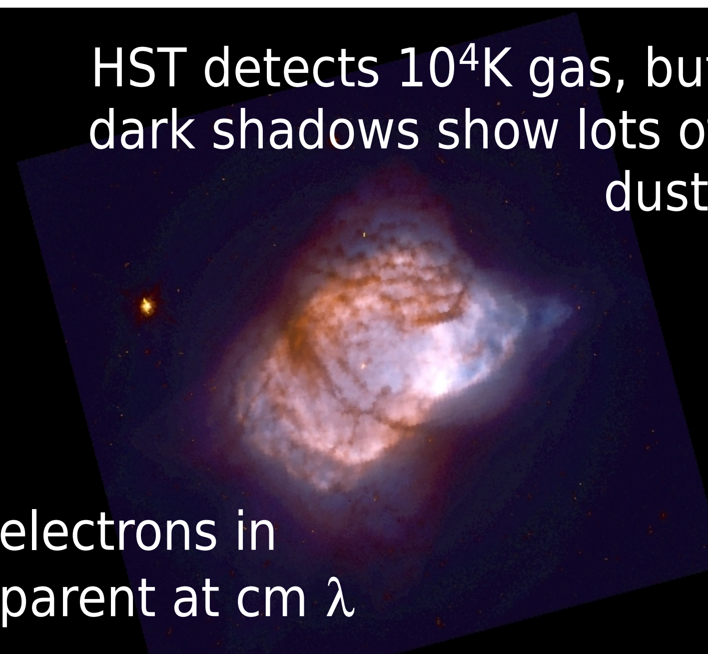
presolar.wustl.edu

  - Some – AGB inclusions in meteorites (*Zijlstra*)
  - Dust protected by clumps (and later icing)?

NGC 7027
MERLIN



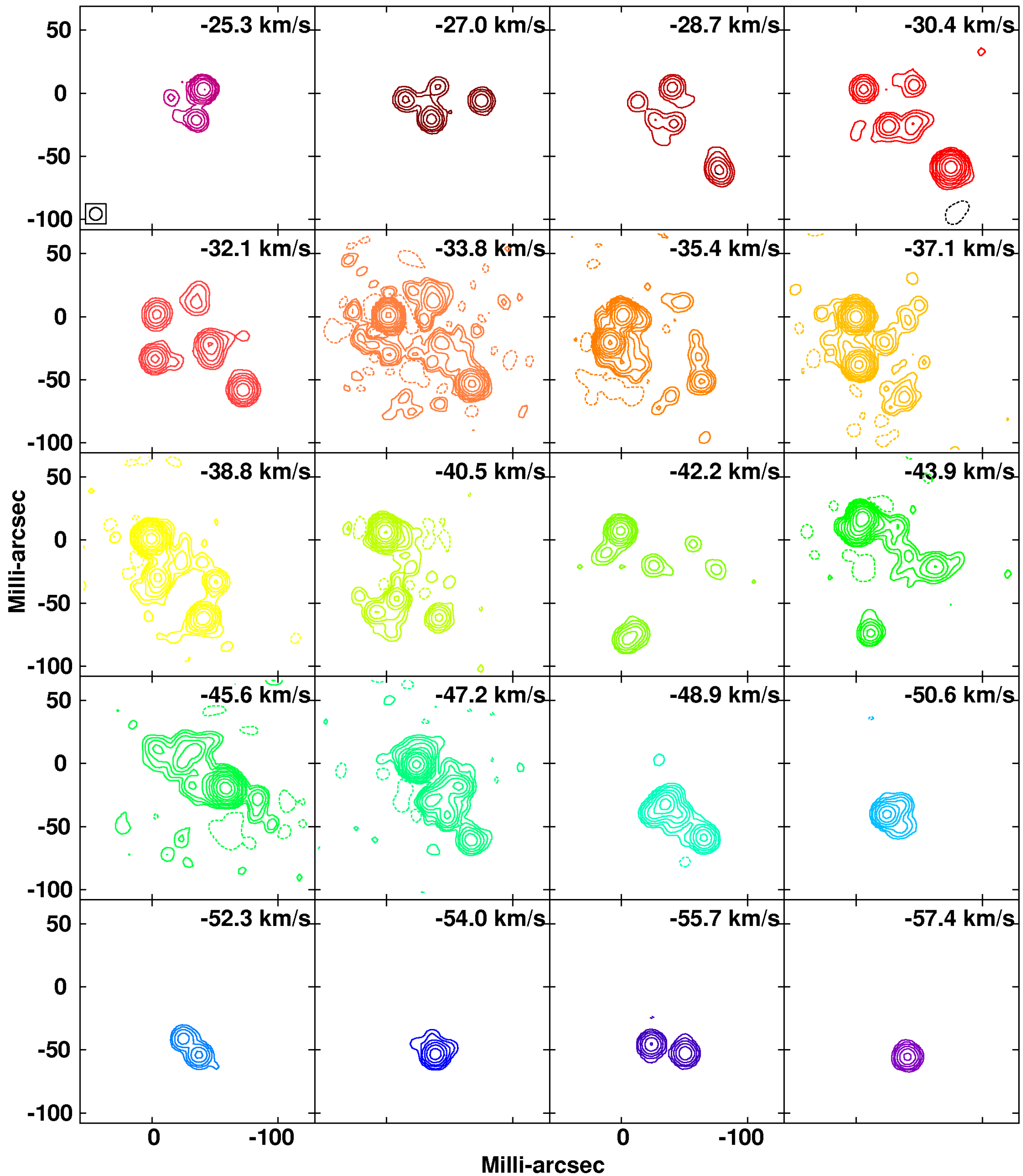
HST detects 10^4K gas, but dark shadows show lots of dust



Radio emission from hot electrons in diffuse gas. Dust is transparent at cm λ

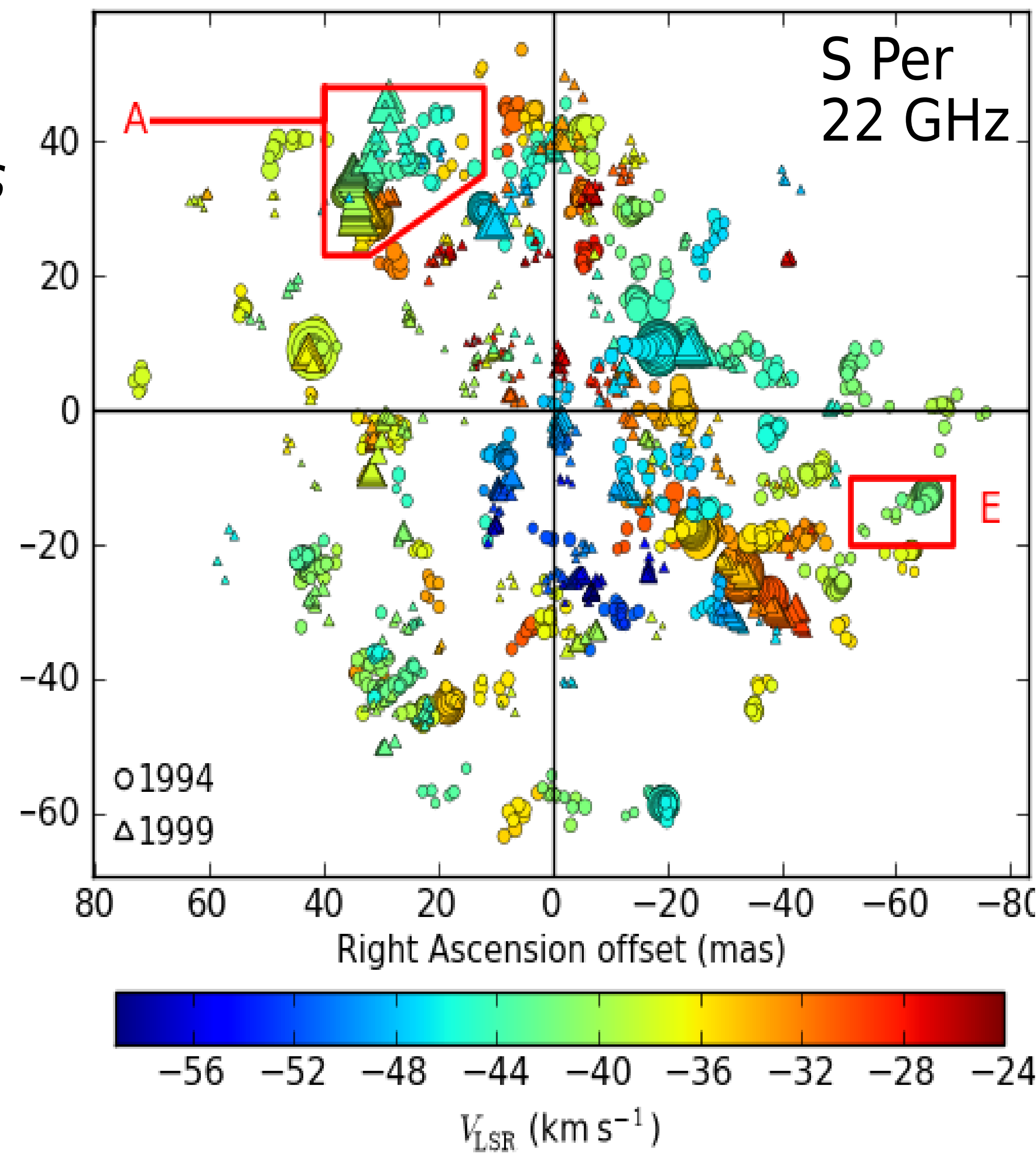
Measuring masers

- 22-GHz channel maps
  - Smoothed for display
- Fit 2-D Gaussian components
  - Multiple spots per (full resolution) channel
  - MERLIN 10 mas beam
  - Position accuracy = (beam size)/(signal to noise ratio)
    - σ_{pos} <0.1 mas for a 10 Jy maser



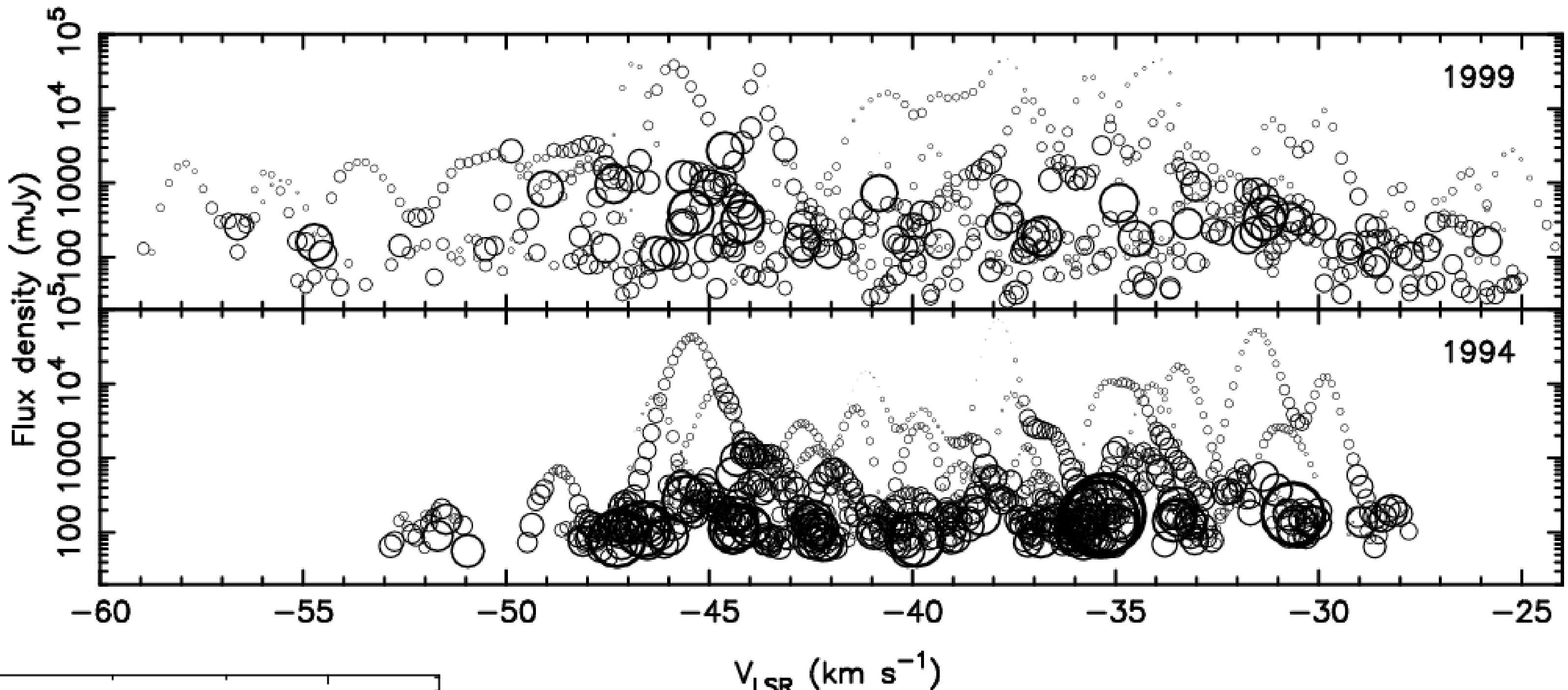
Cloud measurements

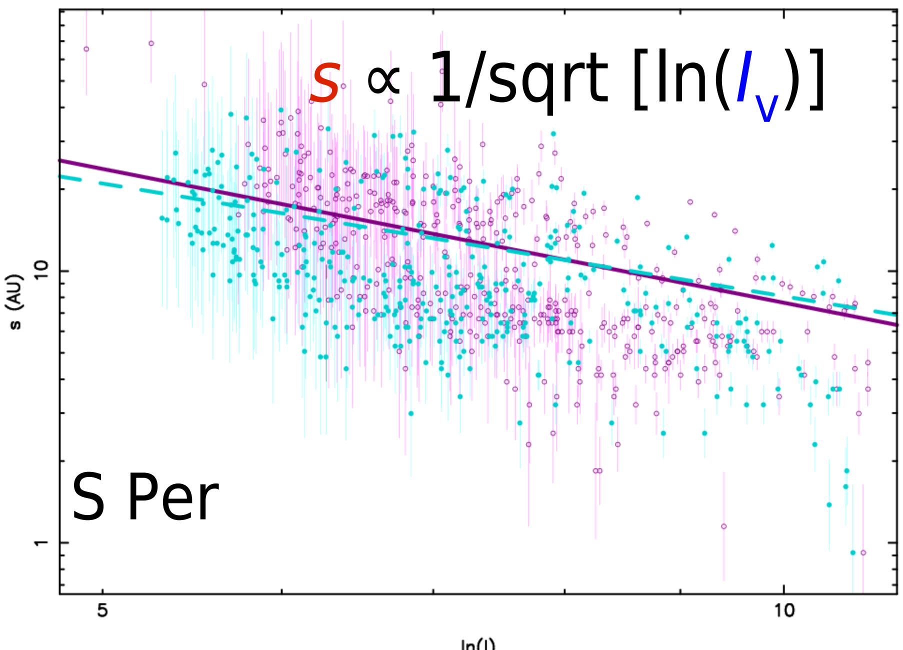
- Component beamed size *s*
  - 1-2 km s^{-1} series
    - Gaussian spectra
      - $\Delta V_c \gtrsim \Delta V_{th}$
- Series = discrete clouds
  - R_{cAGB} 1 - 2 AU
  - R_{cRSG} 10-15 AU
- Beaming angle $\sim(0.5s/R_c)^2$



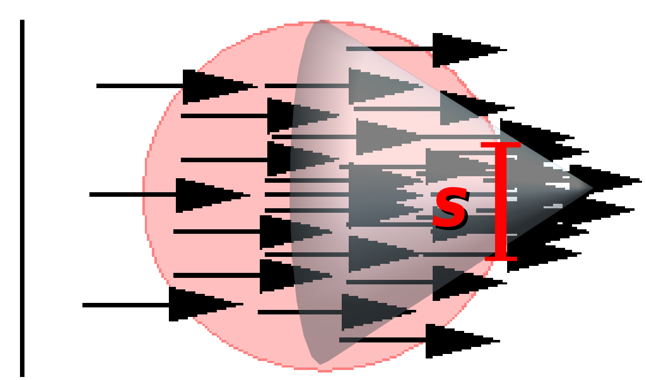
Shrinking of brighter (22 GHz) masers

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



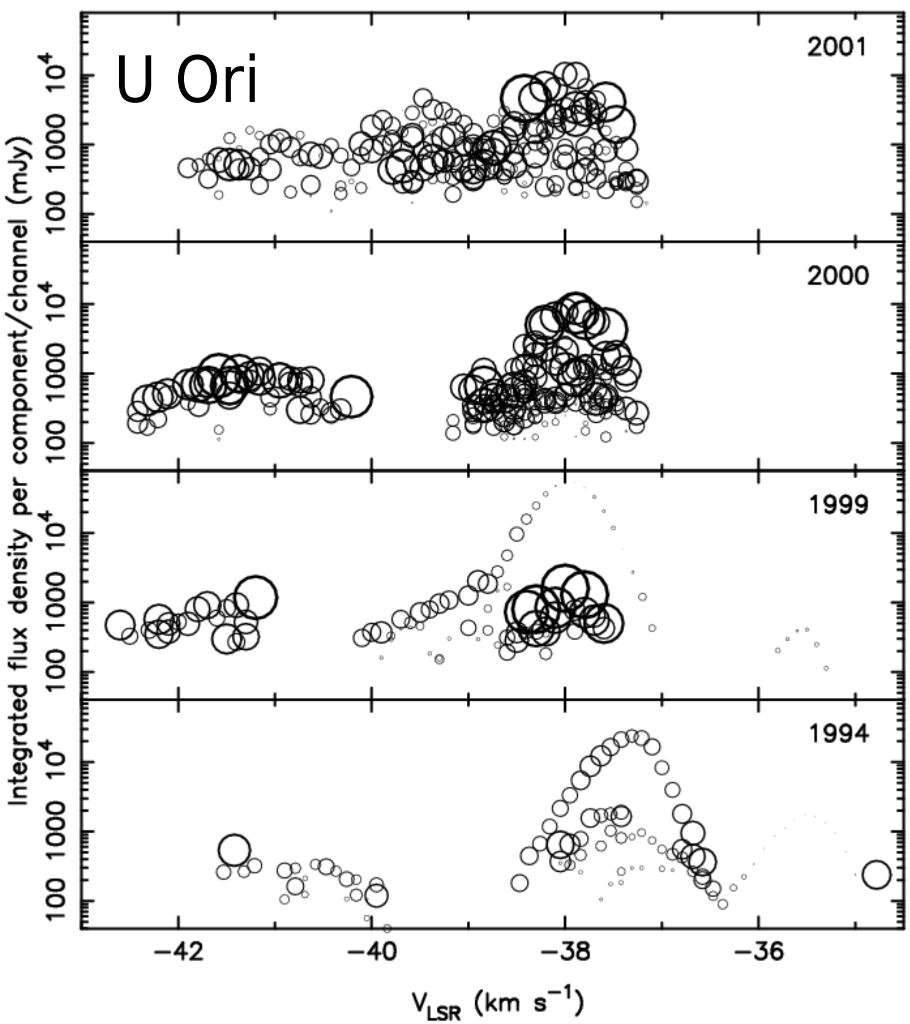


- "Amplification-bounded" beaming from ~spherical clouds

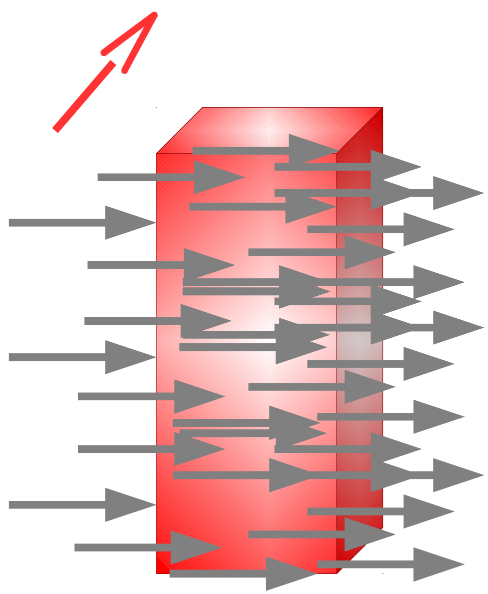


But *sometimes* brighter=bigger

- Spectral peak components swell

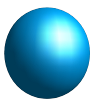


- Shock 'into page'
  - Maser propagates perpendicular to shock
  - Pump photons escape orthogonally
  - Entire surface emission is amplified
  - "Matter bounded" beaming
  - Apparent size ~ actual size



H_2O masers provide shock diagnositic

- Brighter masers have smaller beamed size?



Smoothly expanding spheres

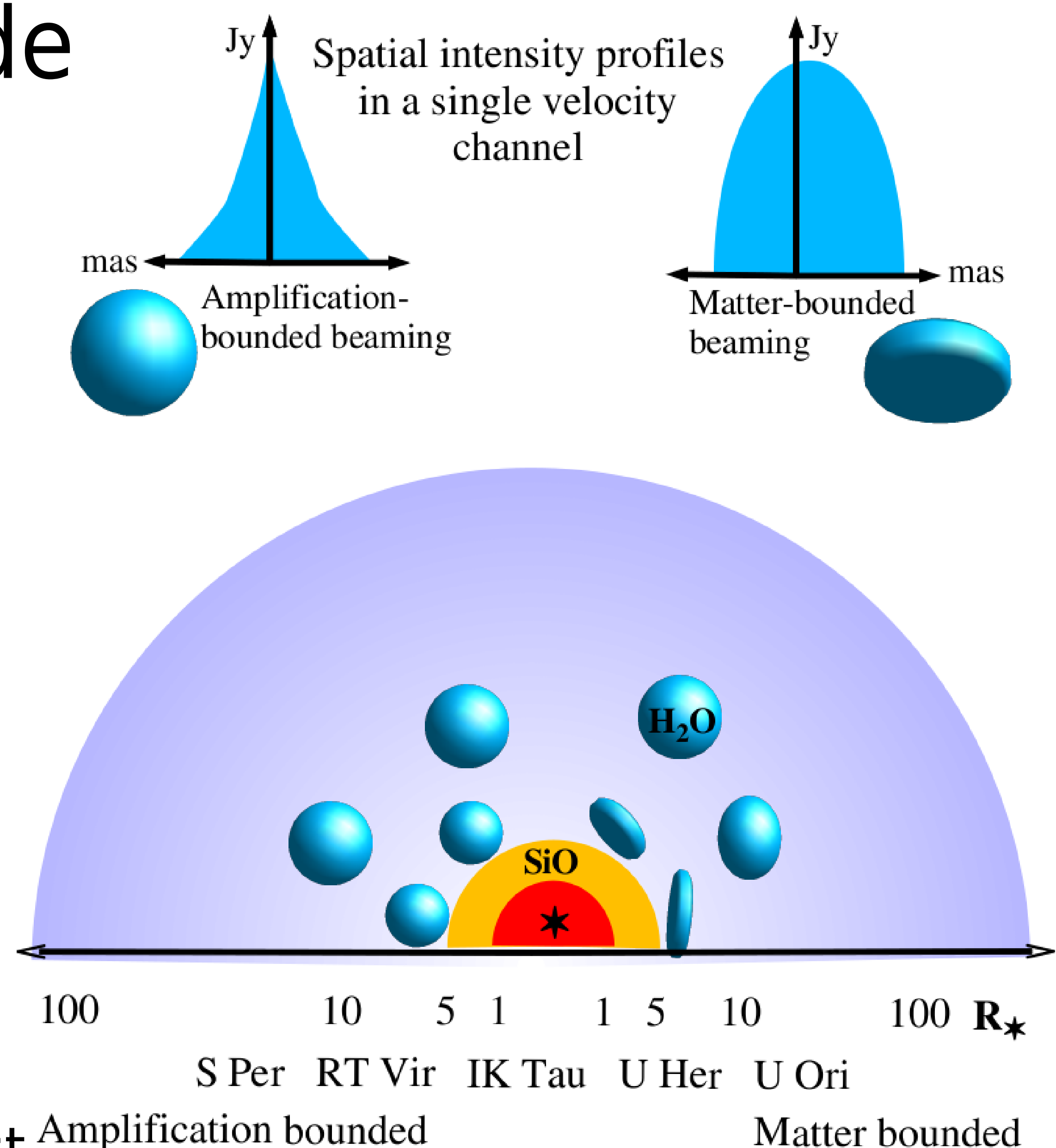
  - Thick, well-filled CSE

- Brightest emission often ~cloud size?

Shocked slabs

  - Thinner-shelled Miras
  - Extreme variability
  - Deep stellar periods
  - Some OH flares

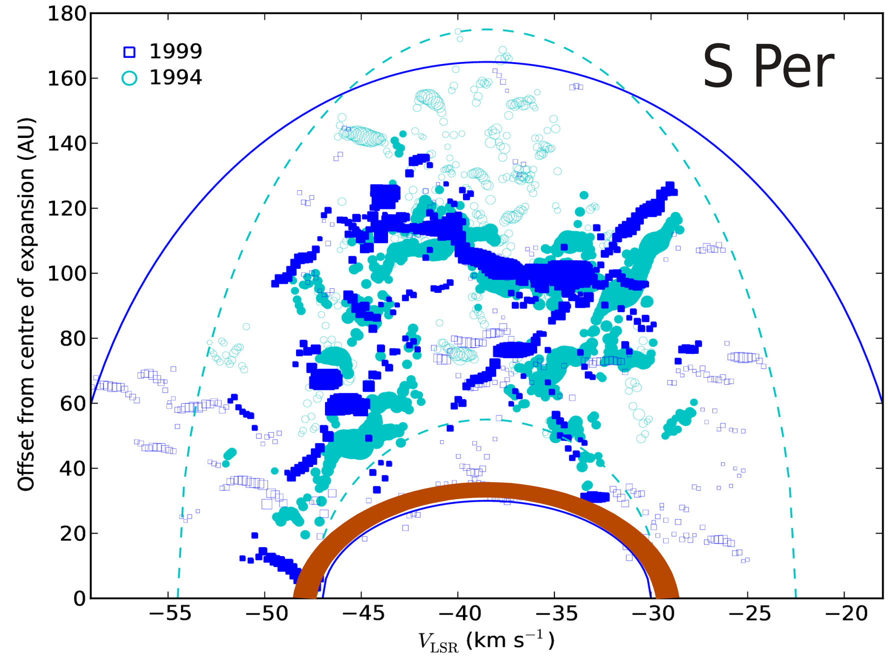
- Pulsation(?) shocks affect just some, inner 22-GHz masers?
  - But *Imai+'03* found a shock-accelerated outer 22-GHz clump

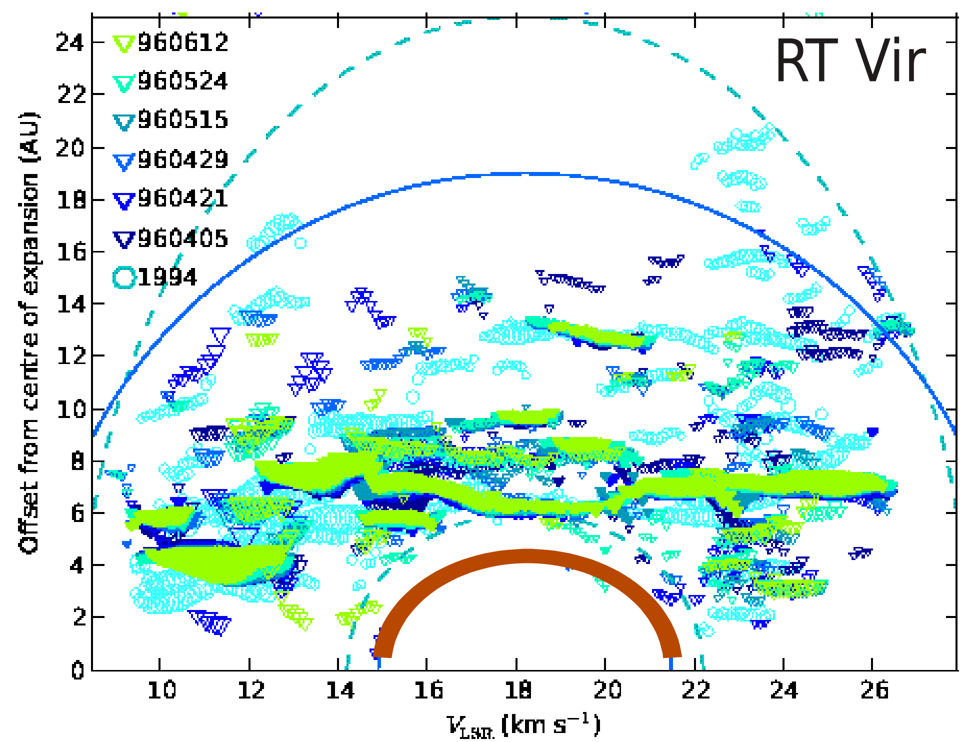


Richards Elitzur & Yates 2010
Elitzur Hollenbach & McKee 1992

Cloud density

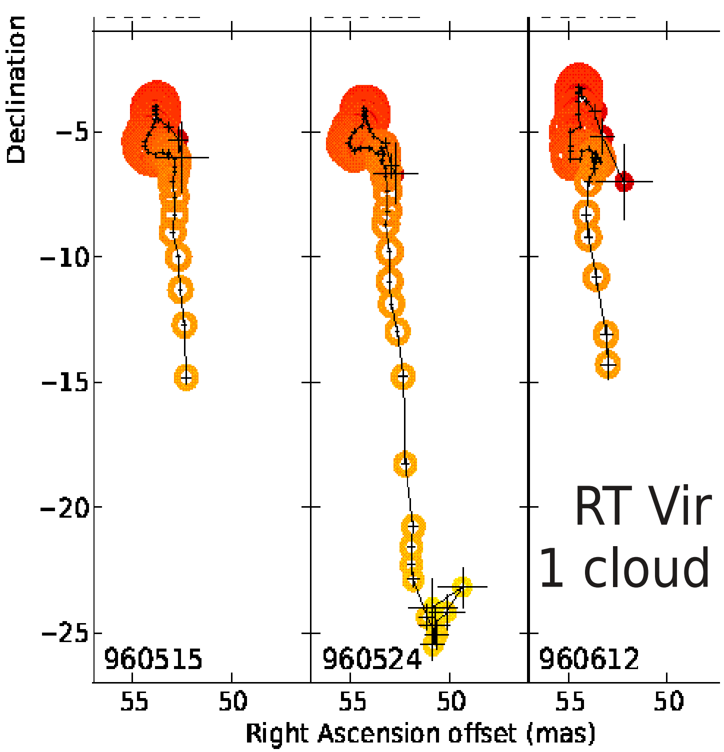
- 22 GHz **H_2O** masers start at r_i
  - 40–70 AU RSG, 5–15 AU AGB
    - – Collision rate < masing rate (*Cooke & Elitzur 85, Bowers+93, Yates & Cohen 94*)
      - Quenching density ~$5\text{x}10^{15}\text{m}^{-3}$
- Clouds ≳45x average (e.g. CO) wind density
  - – Filling factor ≲1%
  - – Up to 90% mass loss concentrated in clouds
  - – 2–6 clouds/stellar period
    - *(Richards+'13)*

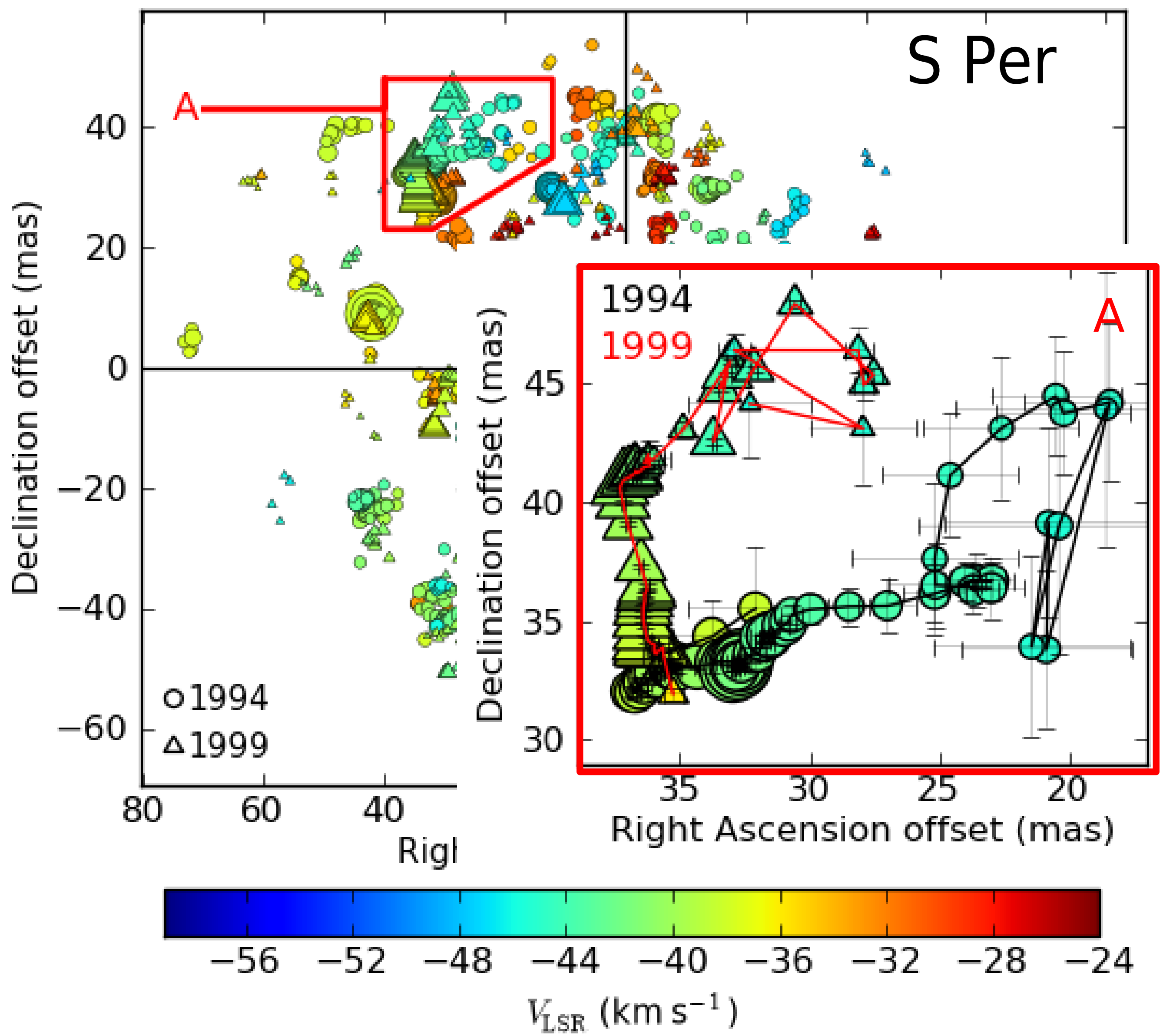




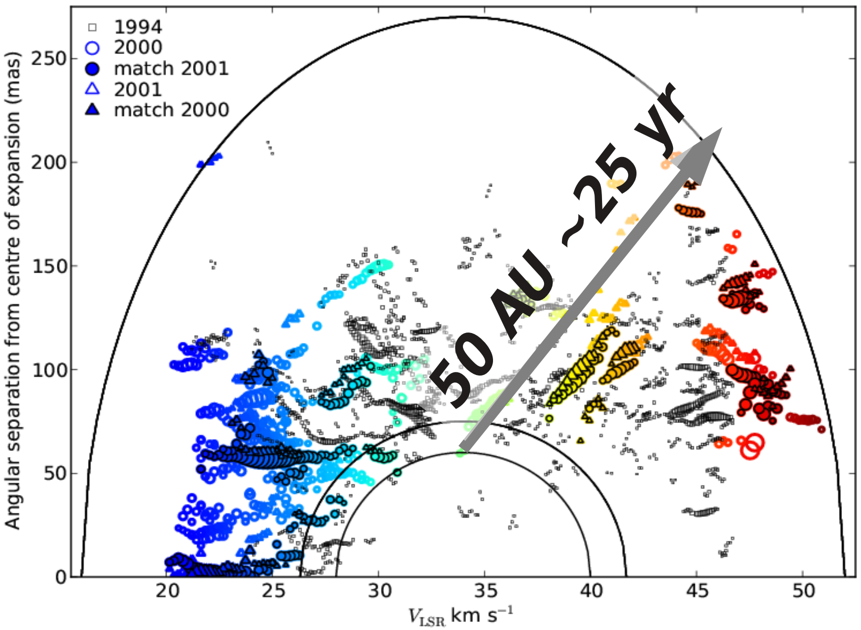
Cloud survival, maser variability

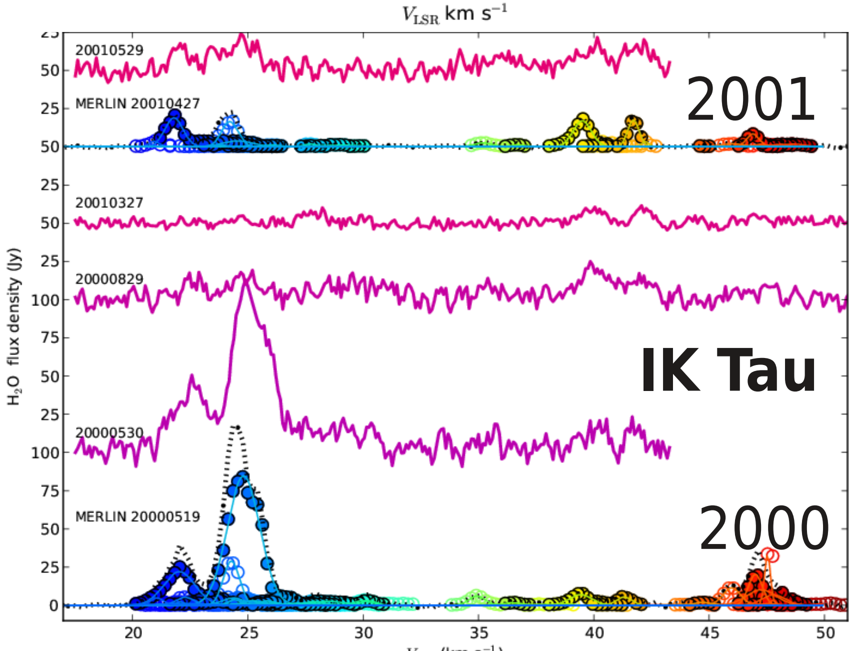
- Specific RSG masers can be tracked for ≥5 yr
- AGB masers survive ⩽2 yr
  - Similar to sound-crossing time





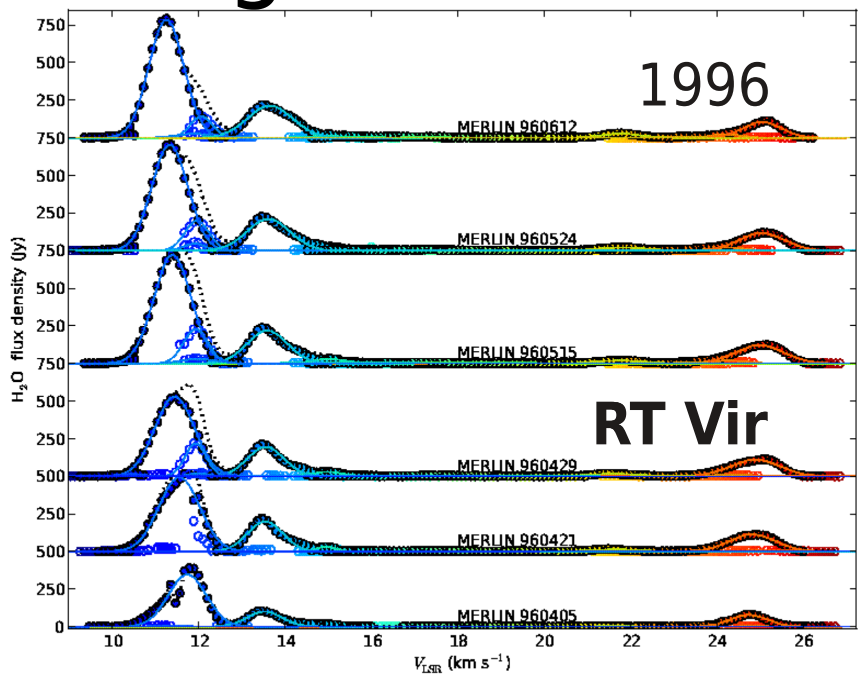
Masers blink, clouds survive

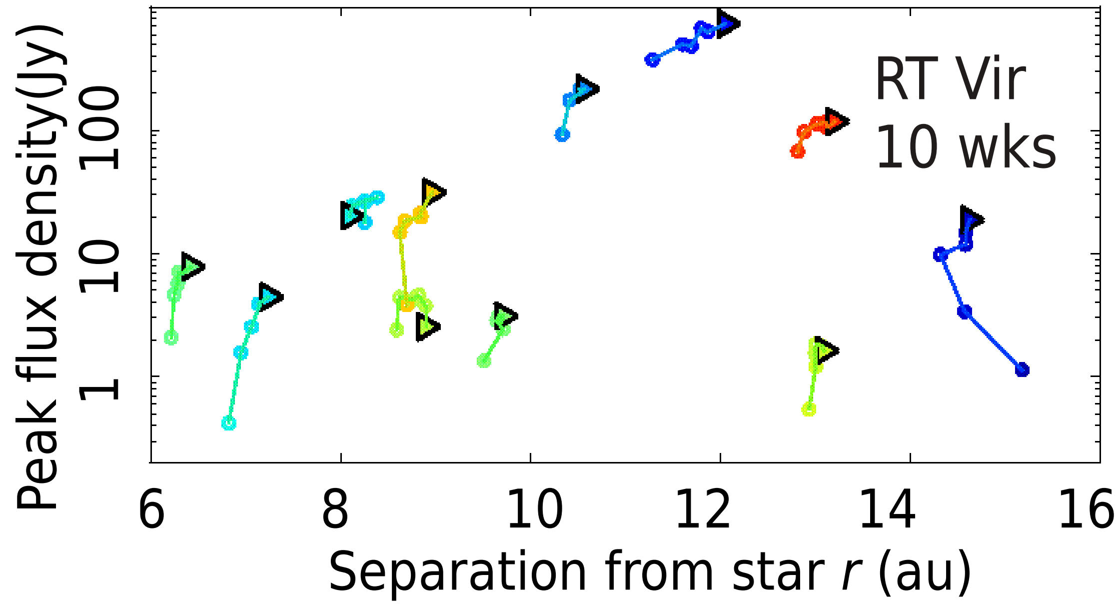




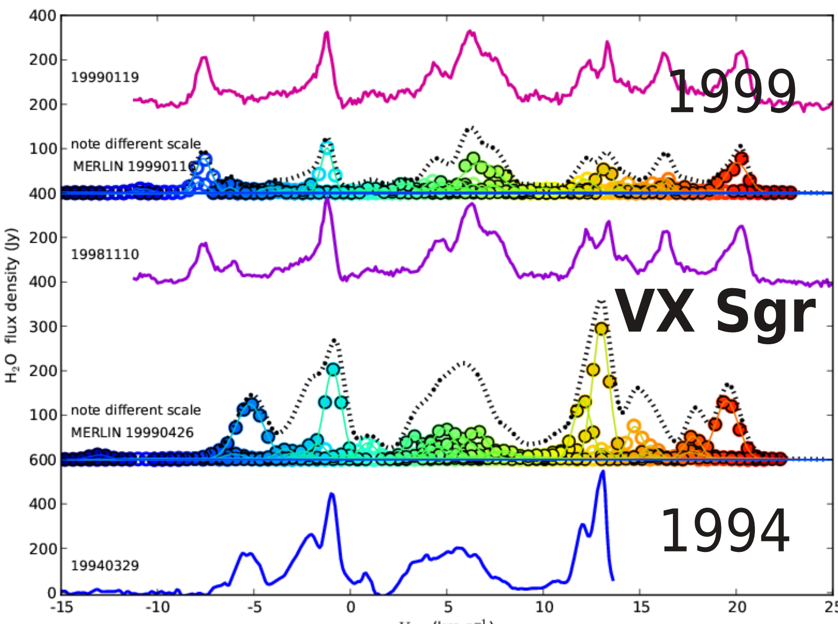
- 22-GHz shell crossing times
  - Decade(s) for AGB stars
  - Up to century for RSG
- 40 yrs of Pushchino spectra
  - Peaks vanish, some reappear between imaging epochs
  - Dispersed clouds couldn't reform
    - Clouds survive as clumps
    - Masers turn on and off
      - Turbulence/beaming?
      - Shocks/excitation?
    - Clumps – medium friction?
- CO shells at 1000's $R_\star$ suggest clumping on consistent scales
  - Bergman+'93, Olofsson+'96,'10

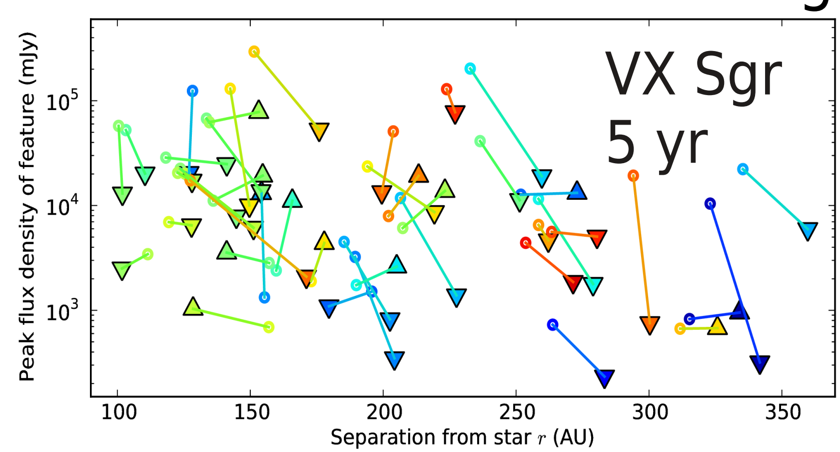
Brightness of whole shell varies





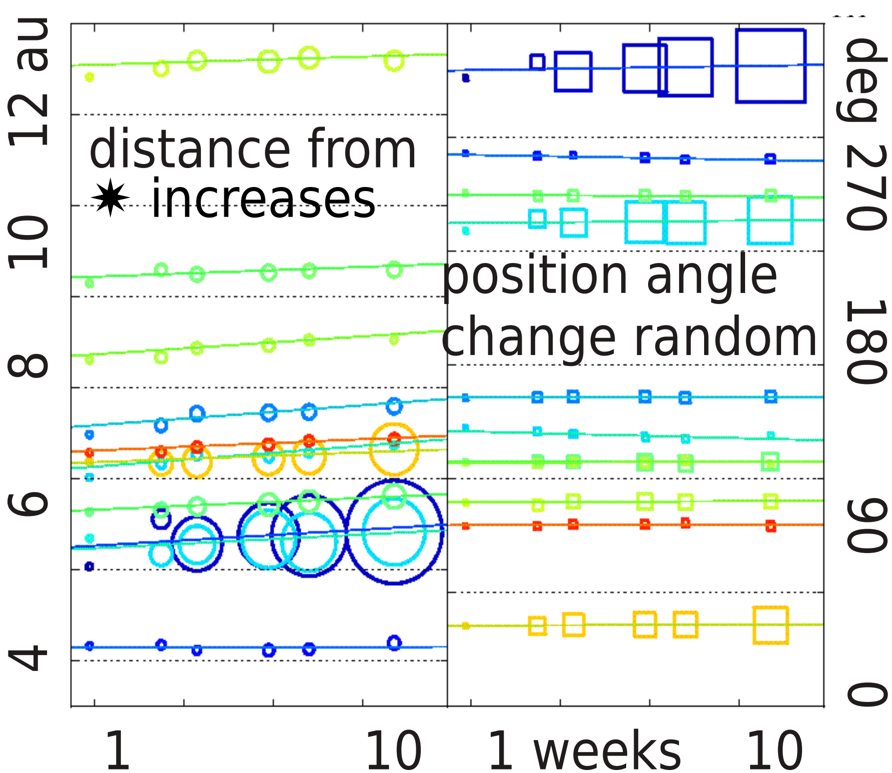
– Interferometric-match features show coordinated variability
  - At any distance from star
– Must be radiative effect e.g. heating



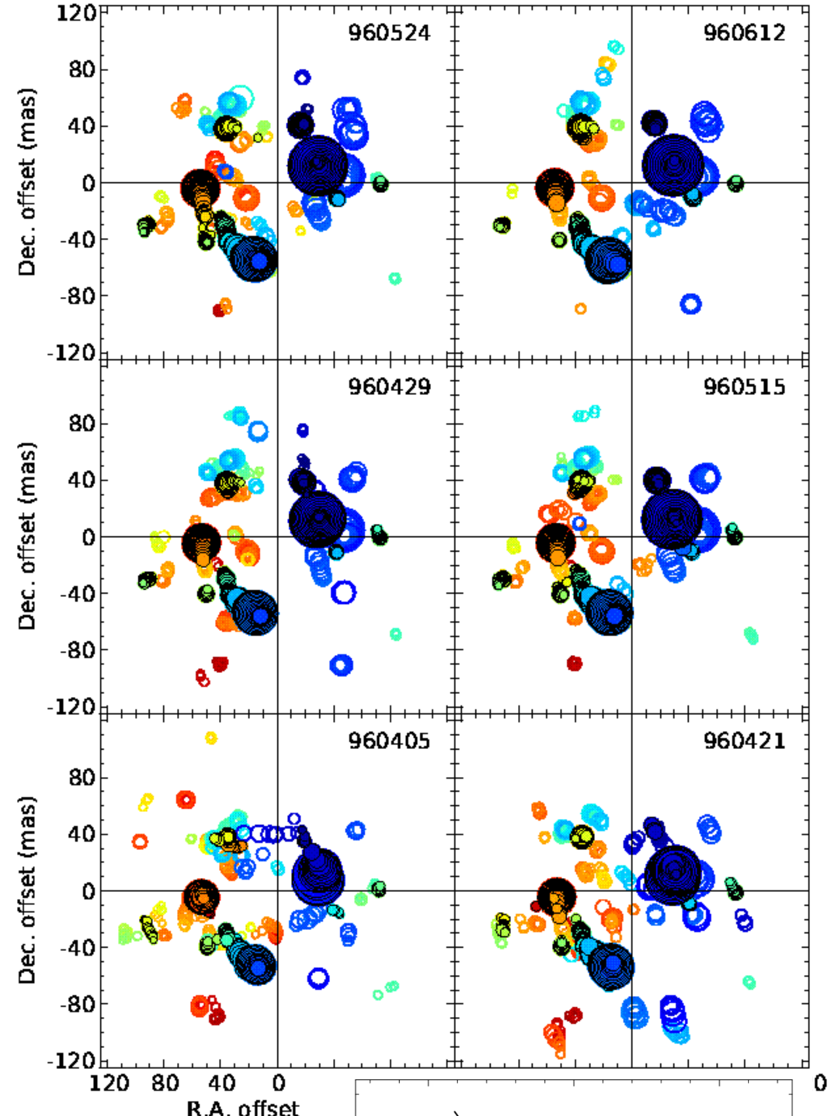


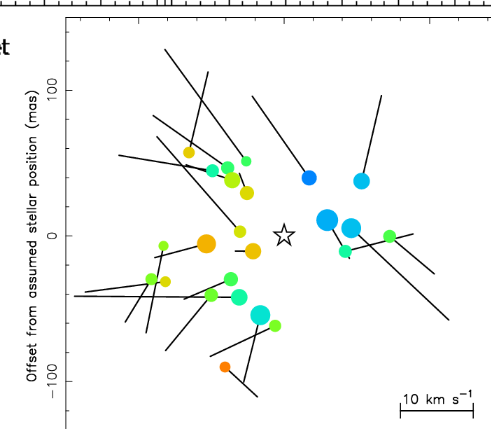
Proper motions

- RT Vir ~133 pc (*vanLeeuwen'07*)
  - Proper motions consistent with Doppler velocity
- Accelerating, radial expansion
  - No rotation (*Richards+13; Imai+03*)
- 7 AGB/RSG similar (not VY CMa)



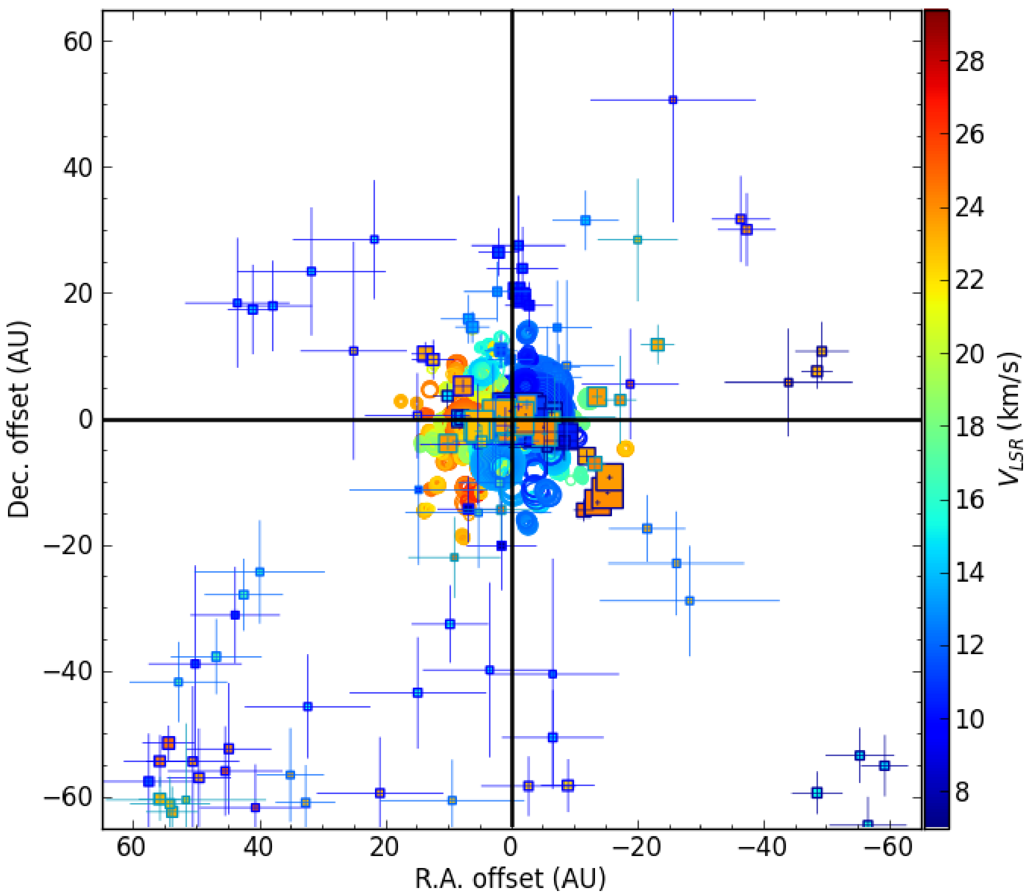
- Reddish -bluish offset >10 yr
  - Slightly flattened spheroid
    - Density contrast (like VX Sgr)?

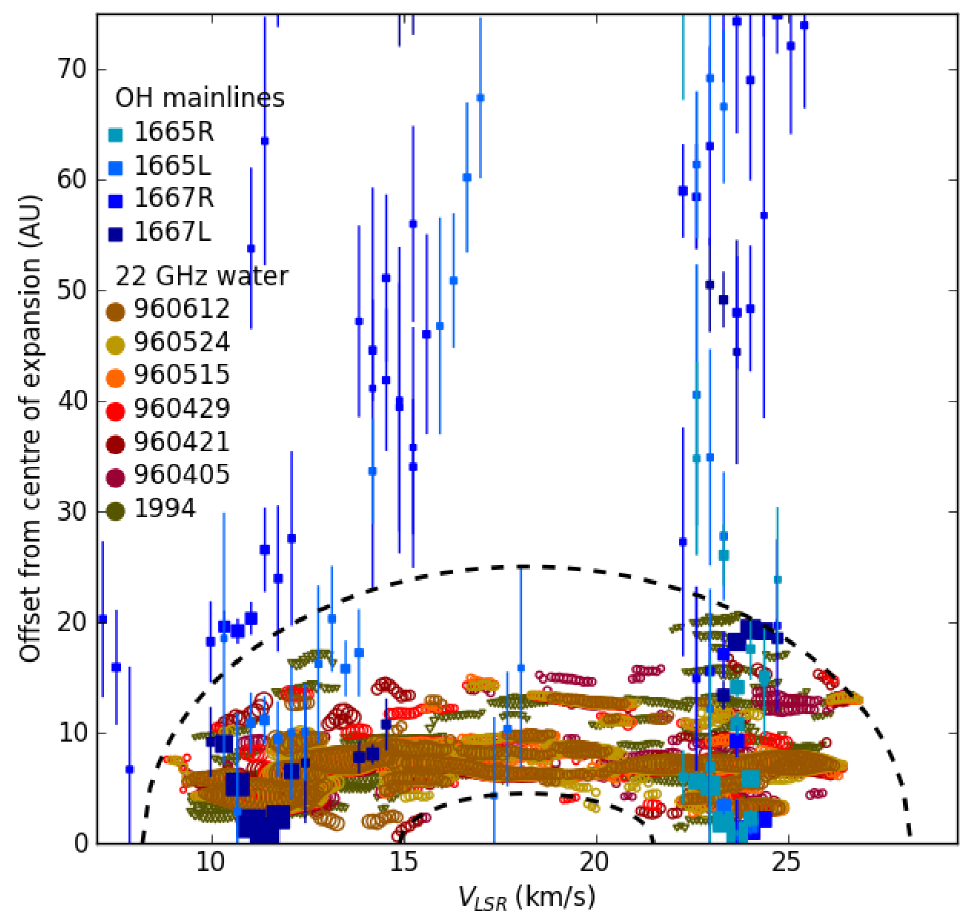




Proper motion vectors

RT Vir 22 GHz and OH masers

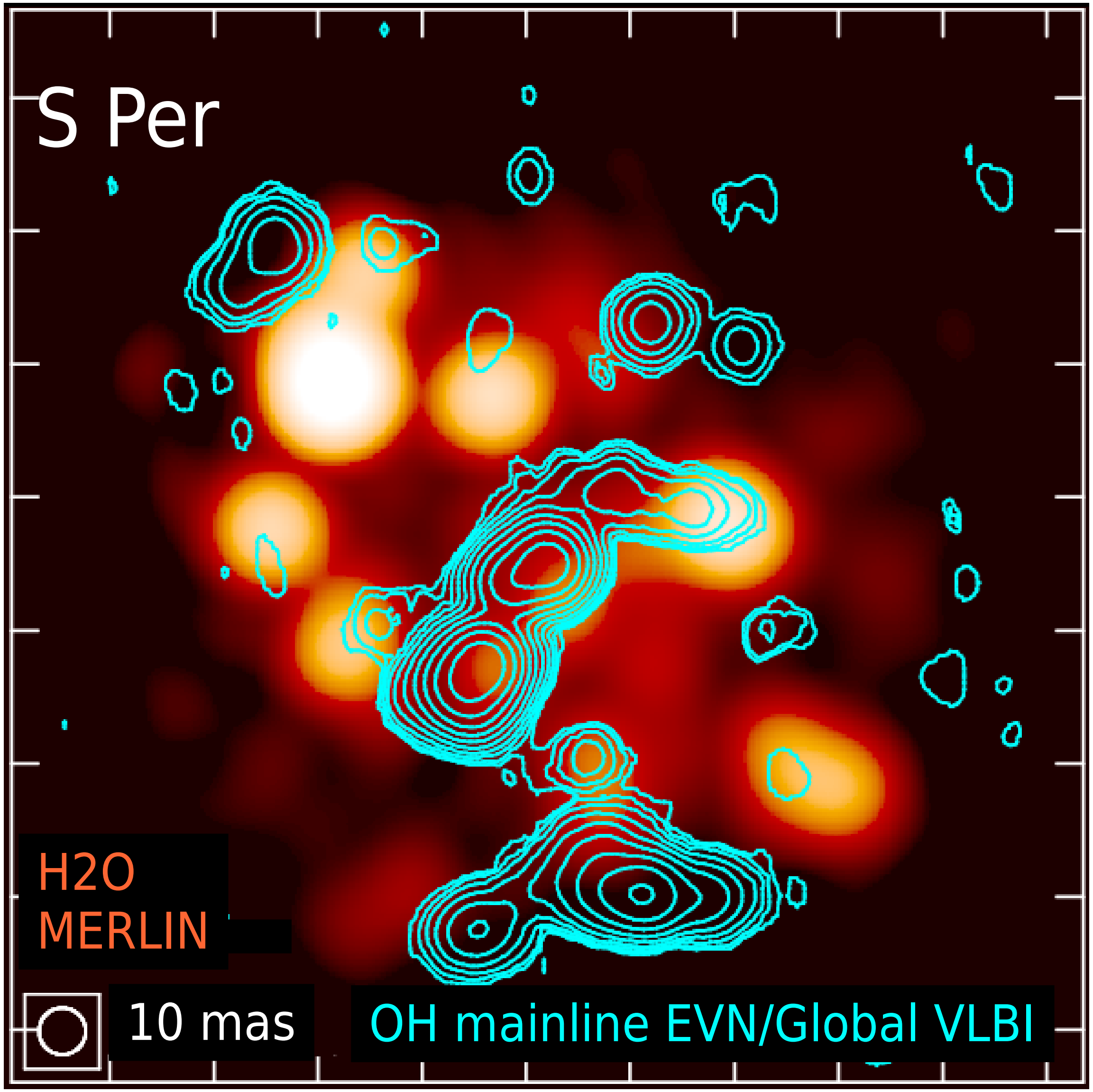




- 22-GHz H_2O circles, inner 25 AU
- OH mainlines (position error bars)
  - Elongation orthogonal to 22-GHz
  - Inner OH interleaves water masers

- OH Zeeman splitting to be analysed
- B_{H2O} 140-180 mG (*Leal-Ferreira+'13*)

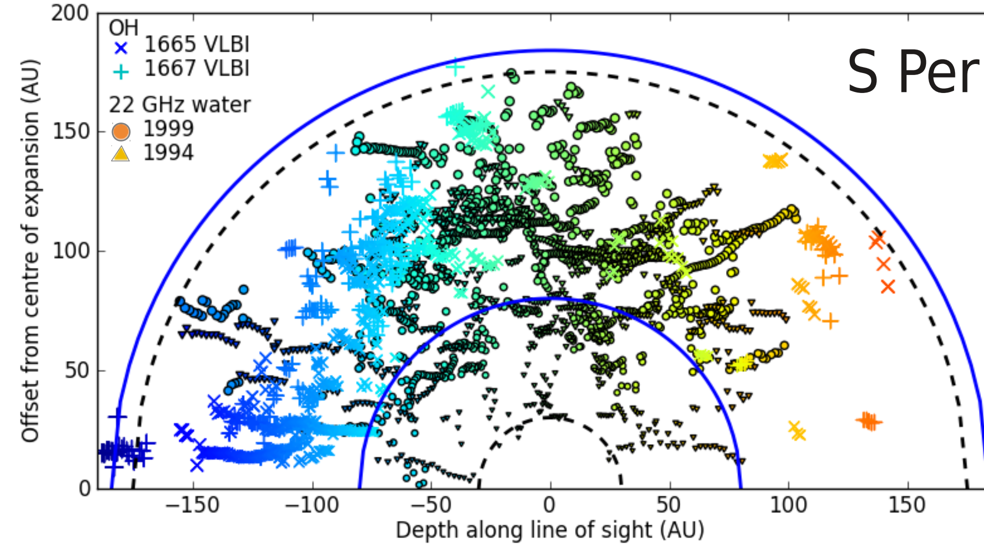
OH mainlines interleave water clumps

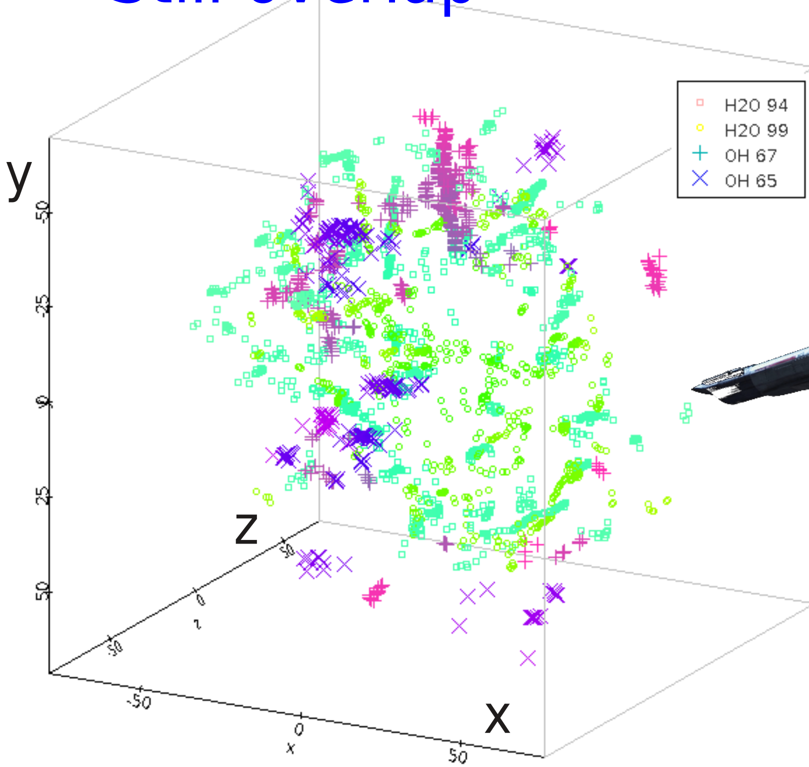


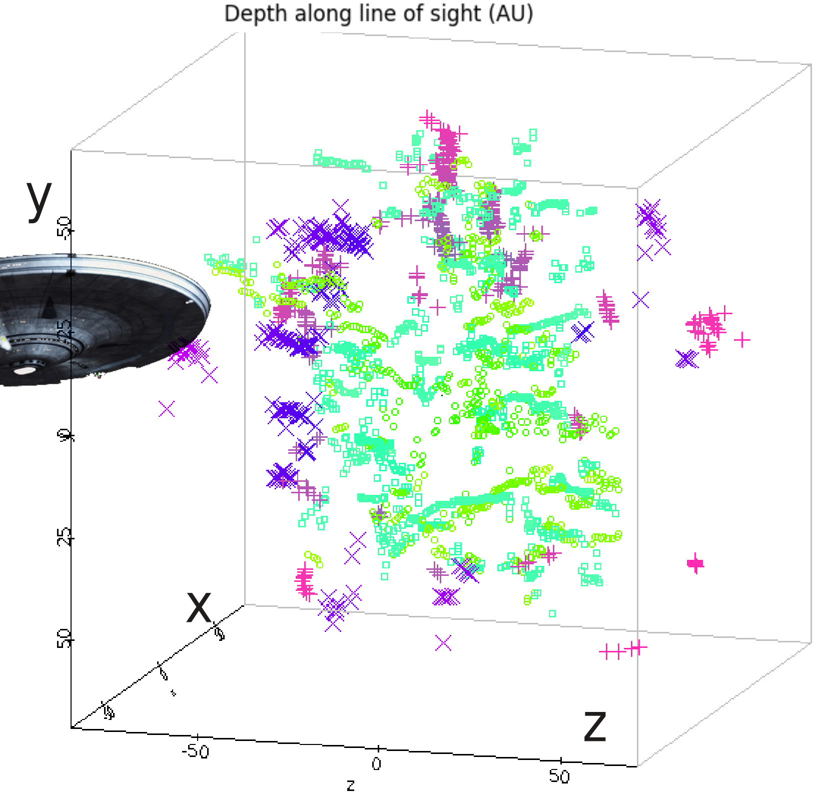
- OH 1665/1667 MHz interleaves 22 GHz H_2O
  - No excited-state OH
    - T_{OH} ≲500 K
    - T_{H2O} ≲1000 K
    - n_{OH} ≲10^{14} m^{-3}
    - n_{H2O} ≲5 10^{15} m^{-3}
- OH mainlines from lower-density inter-clump gas
  - *Richards, Etoka, Gray, Masheder, van Langevelde, Yates 2014*
- OH 1612-MHz in outer shell where it should be
  - *Richards+'99*

RSG overlapping maser shells

- Assume radial, symmetric acceleration for each of H_2O and OH
- Solve for 3D structure
  - Have a look from the side
- Still overlap

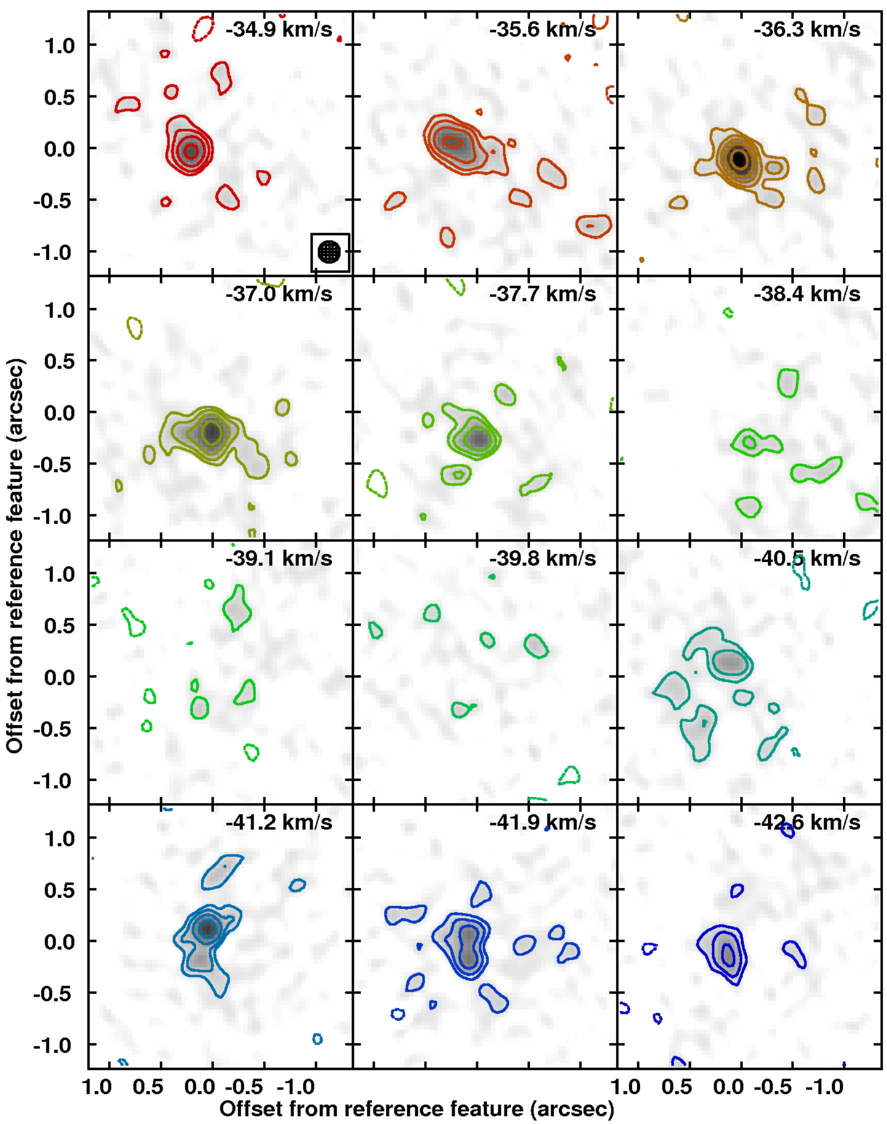


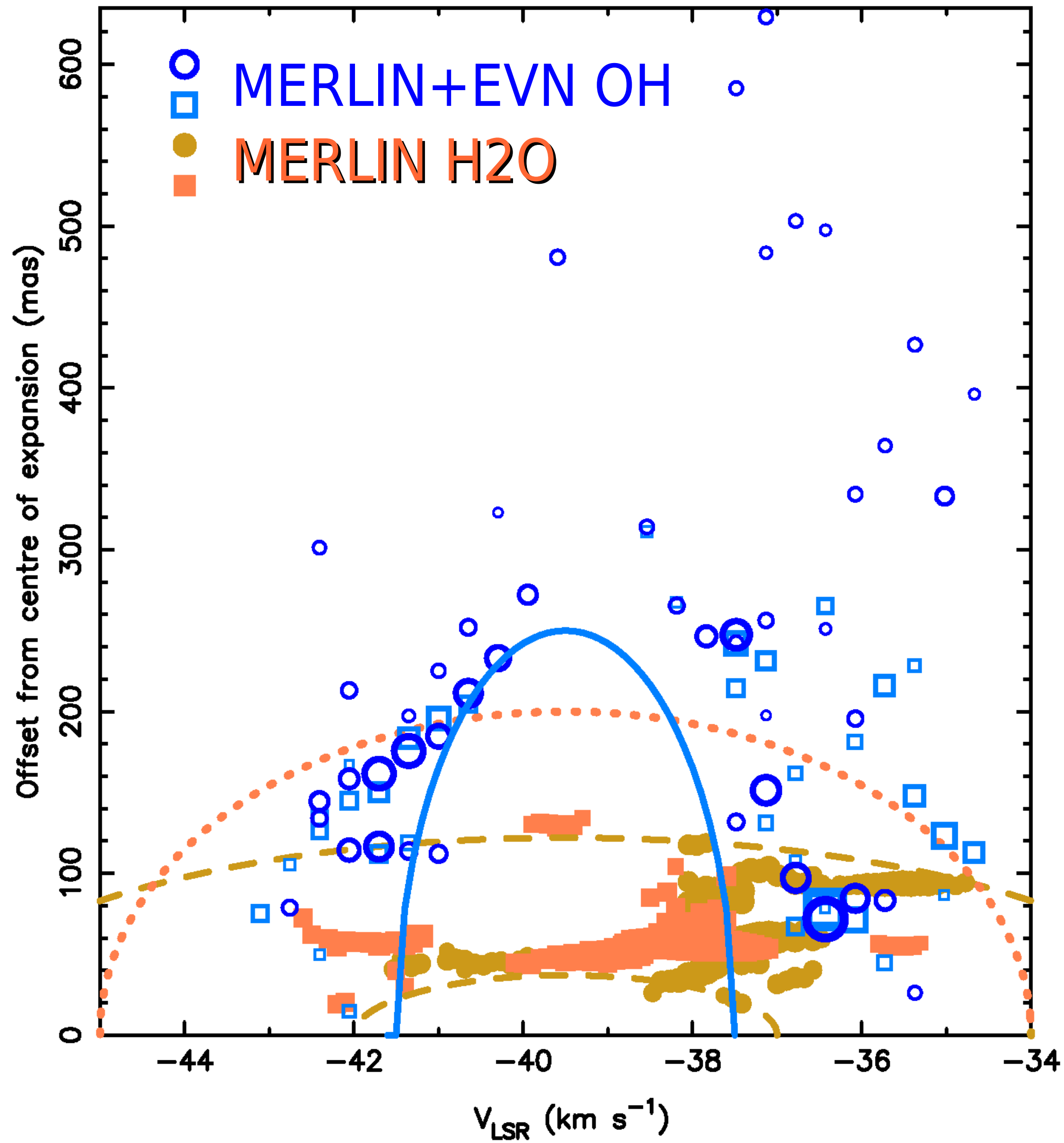




U Ori – AGB overlap

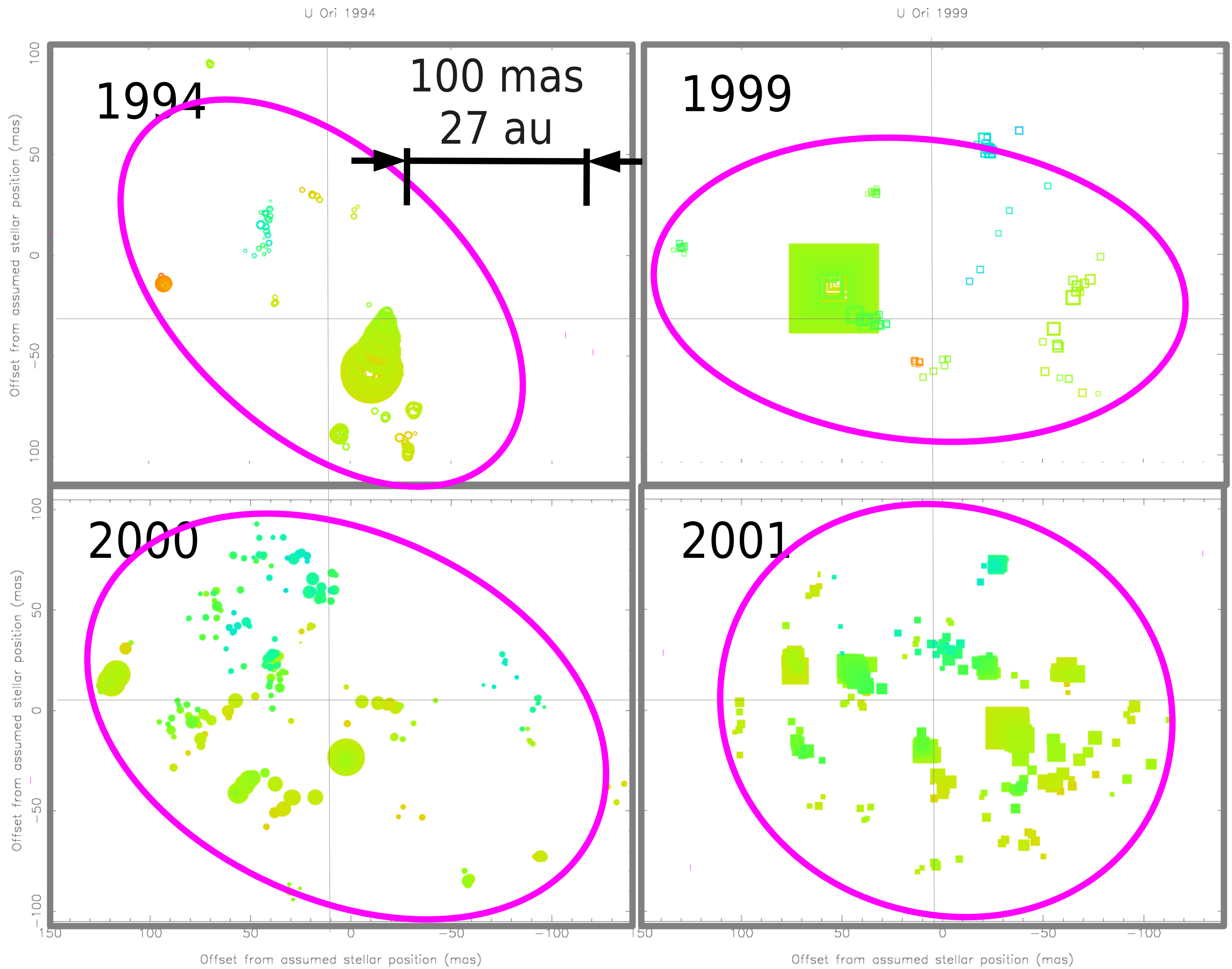
- Fairly well-filled, stable OH mainline shell
- Trace of inner OH mainline emission



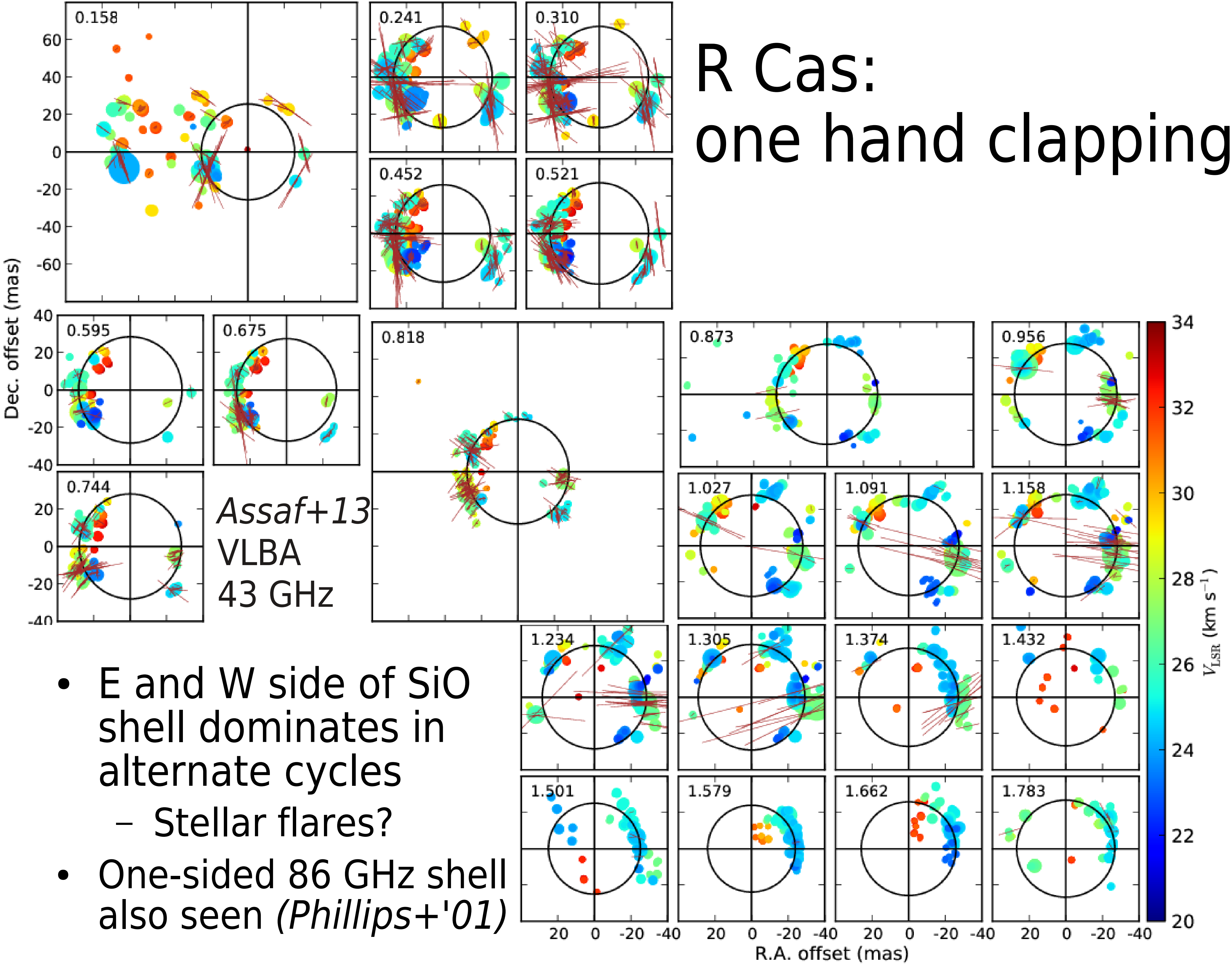


Asymmetry or poor filling?

- U Ori 22 GHz H_2O shell shape changes over 7 years
  - Masers dis/appear in different regions
  - Survive ≲1 yr
- Peaks at different position angles
  - But similar velocities and angular separations from centre of expansion



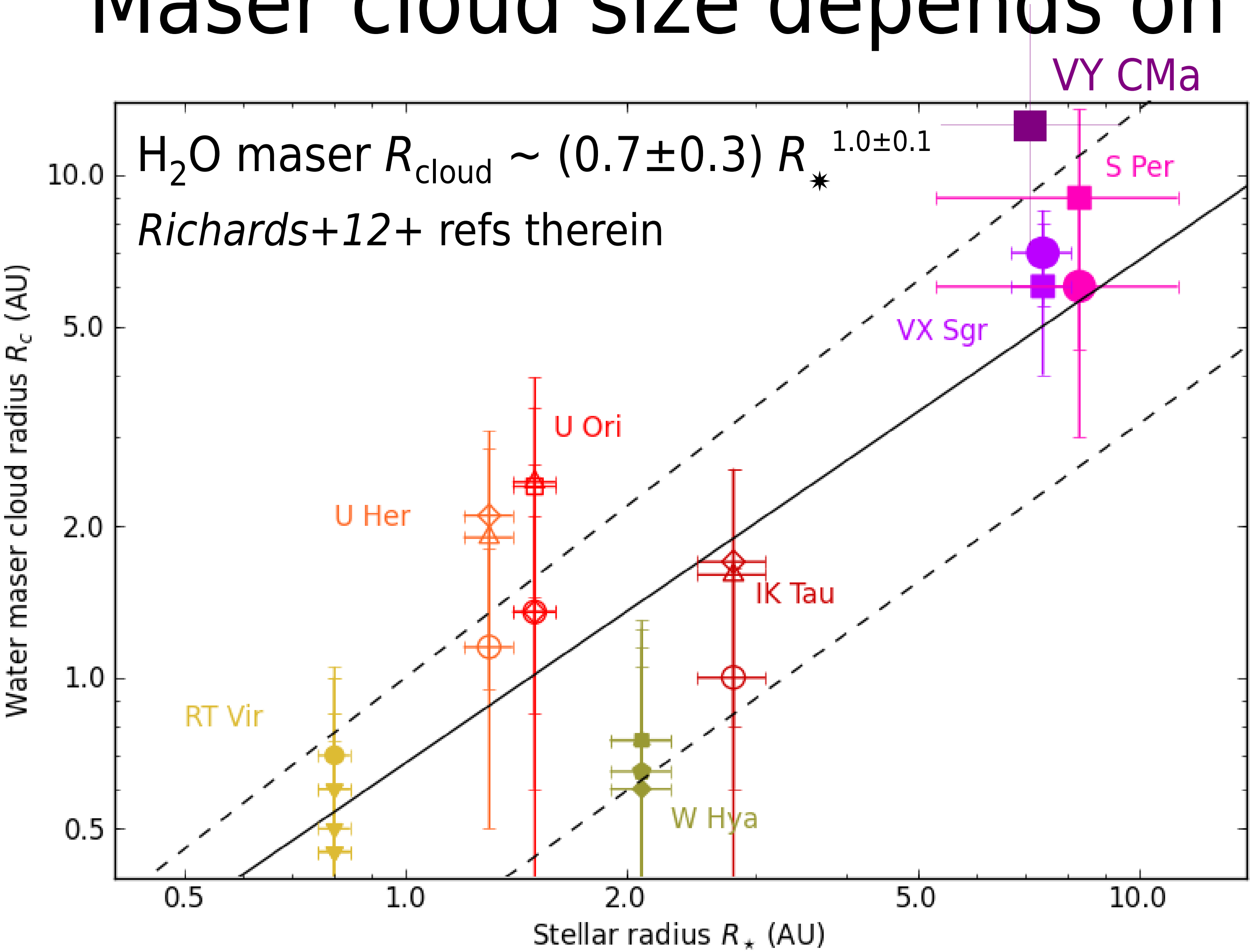
R Cas: one hand clapping



Assaf+13
VLBA
43 GHz

- E and W side of SiO shell dominates in alternate cycles
  - Stellar flares?
- One-sided 86 GHz shell also seen *(Phillips+'01)*

Maser cloud size depends on star size

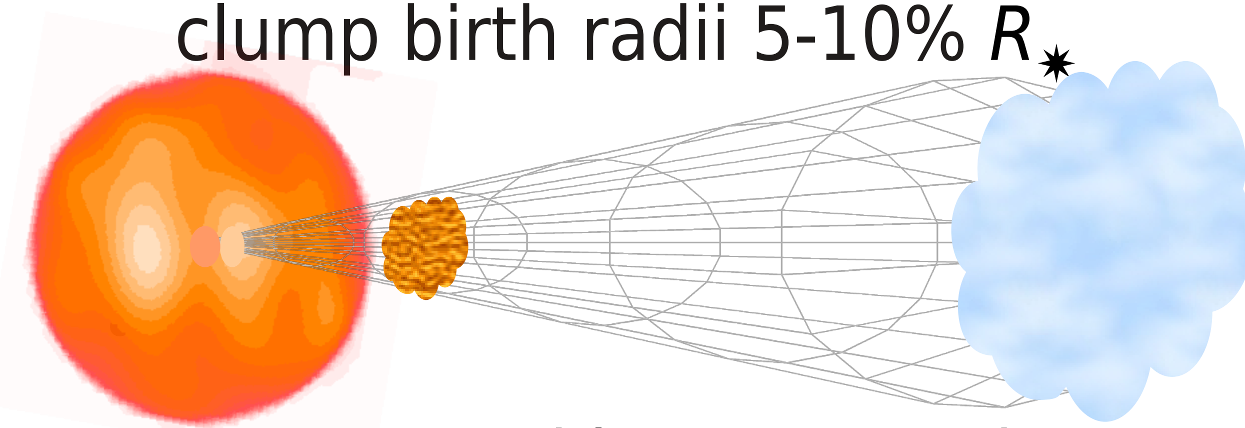


- Cloud properties determined at ejection from star *
  - Not micro-physics of dust cooling
- If outflow expands as r^{-2}, birth radius (5–10)% R_*

* *or are they?* Can wind instability scales depend on size of CSE?
  - See *Gray et al. in prep*

How is matter ejected from star?

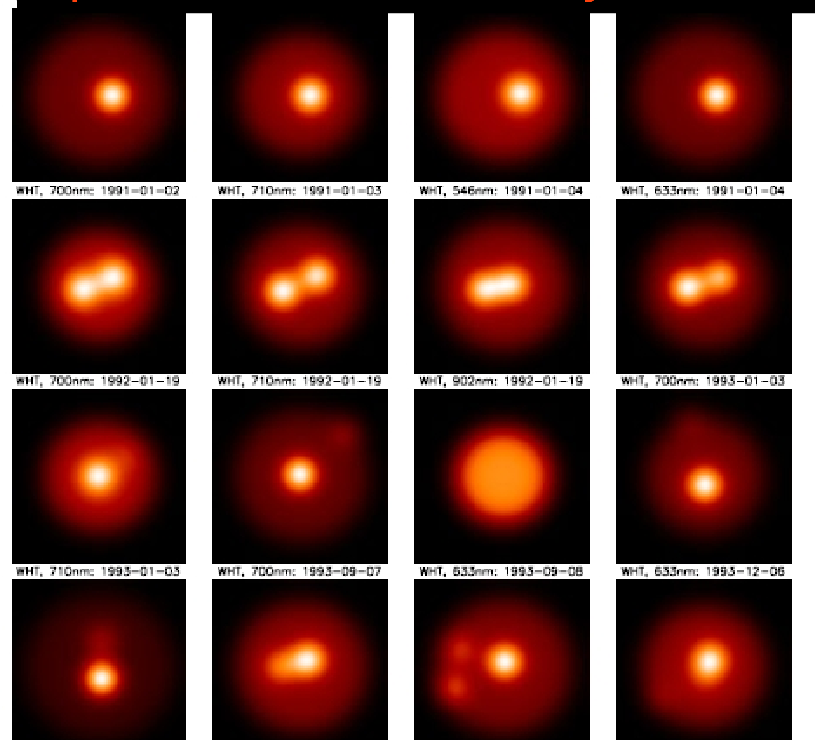
- Assuming radial expansion, H_2O clump birth radii 5-10% $R_{\star}$

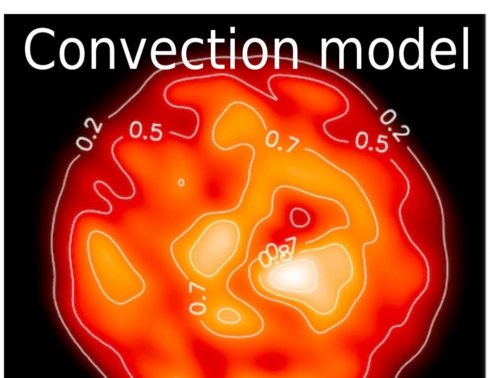


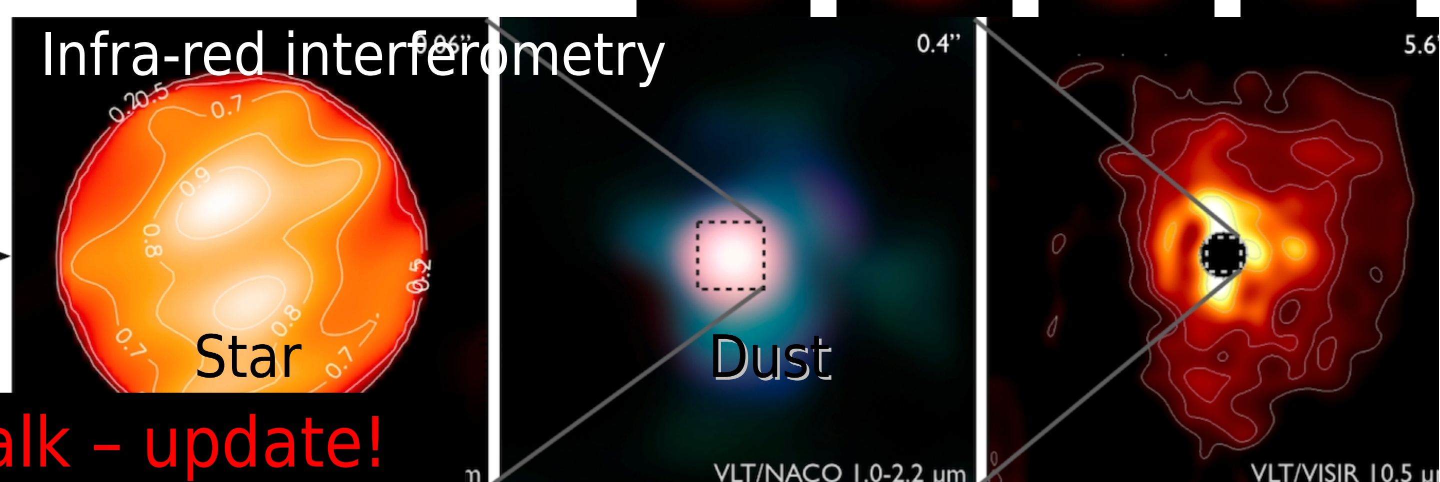
  - Comparable to convection models and observed starspots

Chiavassa+'10, *Haubois*+'09, *Kervella*+'09,'11

Tuthill+'97 Betelgeuse optical interferometry







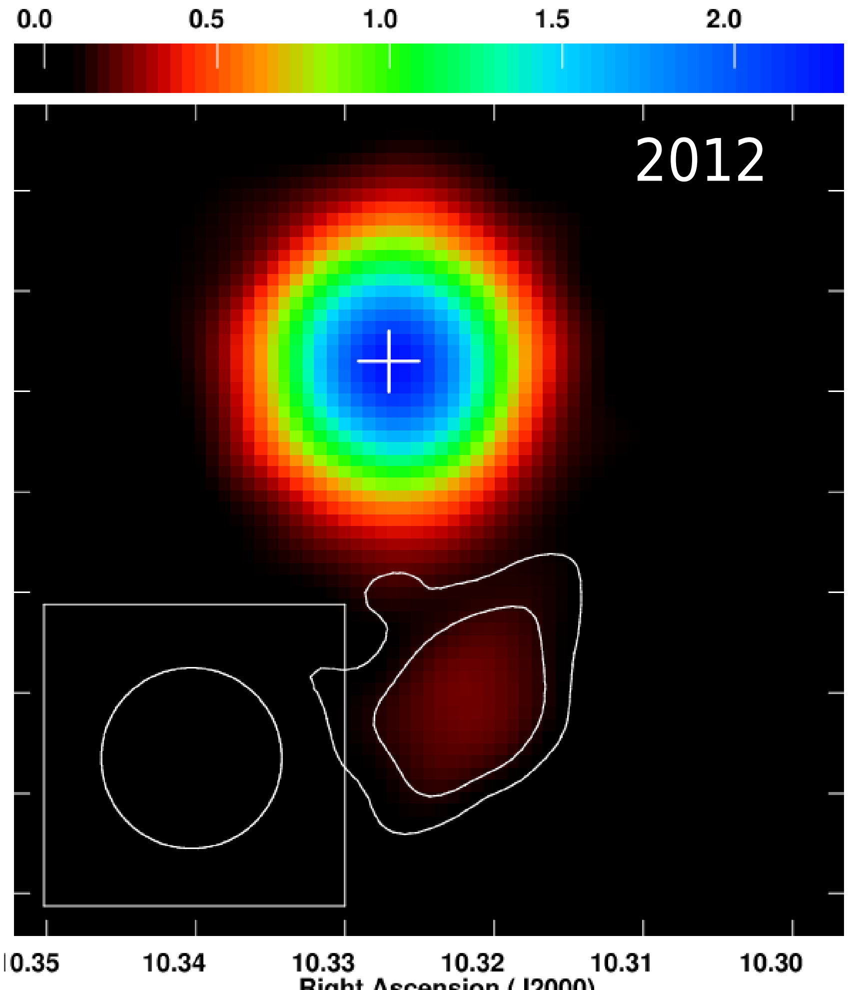
But see Kervella talk – update!

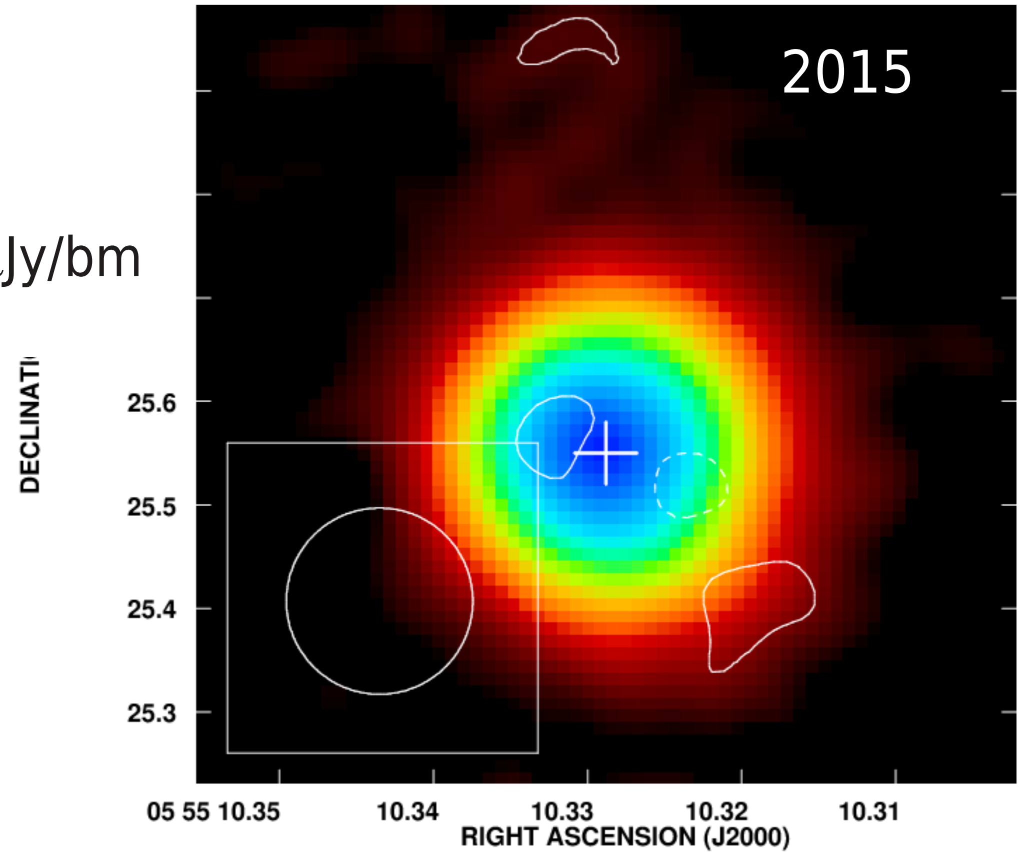
Resolving Betelgeuse

- e-MERLIN observations 2012, 2015a (2015b to come)
  - 2012 reprocessed - missing receiver axis offset, sorry!
- 2015 PI O'Gorman, see next talk
  - *Preliminary results here, need checking/refining!*
- Photosphere $R_{\star 2\mu m}$ 21 mas at 2 μm (*Ohnaka+'11*)
  - 4.3 au at 197 pc (*Harper+'08*)
    - Larger at radio wavelengths
- e-MERLIN: 0.5 GHz b/w around 5.75 GHz (λ 5.2 cm)
  - 1σ noise ~16 μJy in 78x58 mas^2 beam
    - Similar to *Kervella 2015* VLTI resolution

Resolving Betelgeuse

- Taper to 180-mas resolution
  - Fit elliptical 2D Gaussian
    - Contours residuals (-1,1,2)x63 μJy/bm

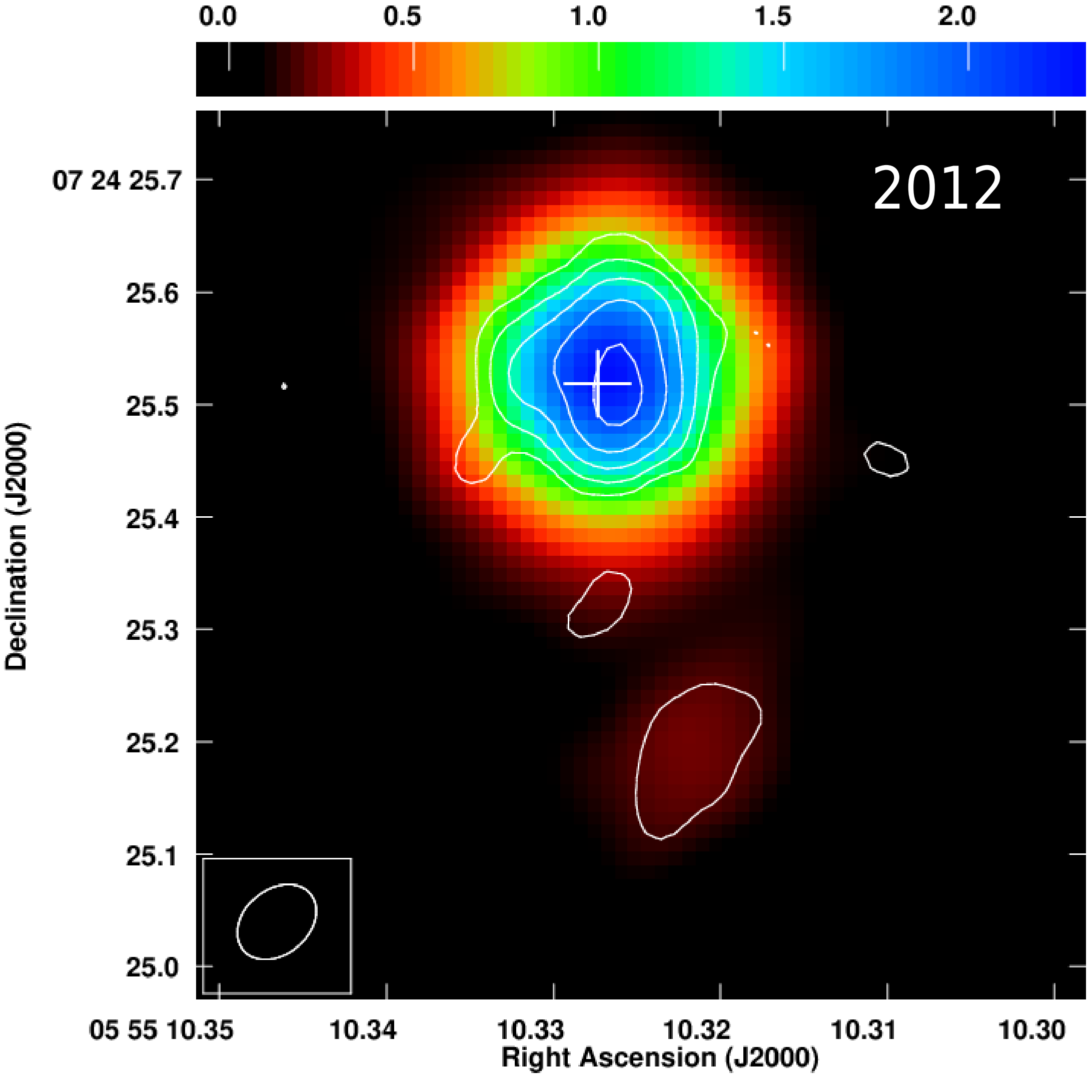


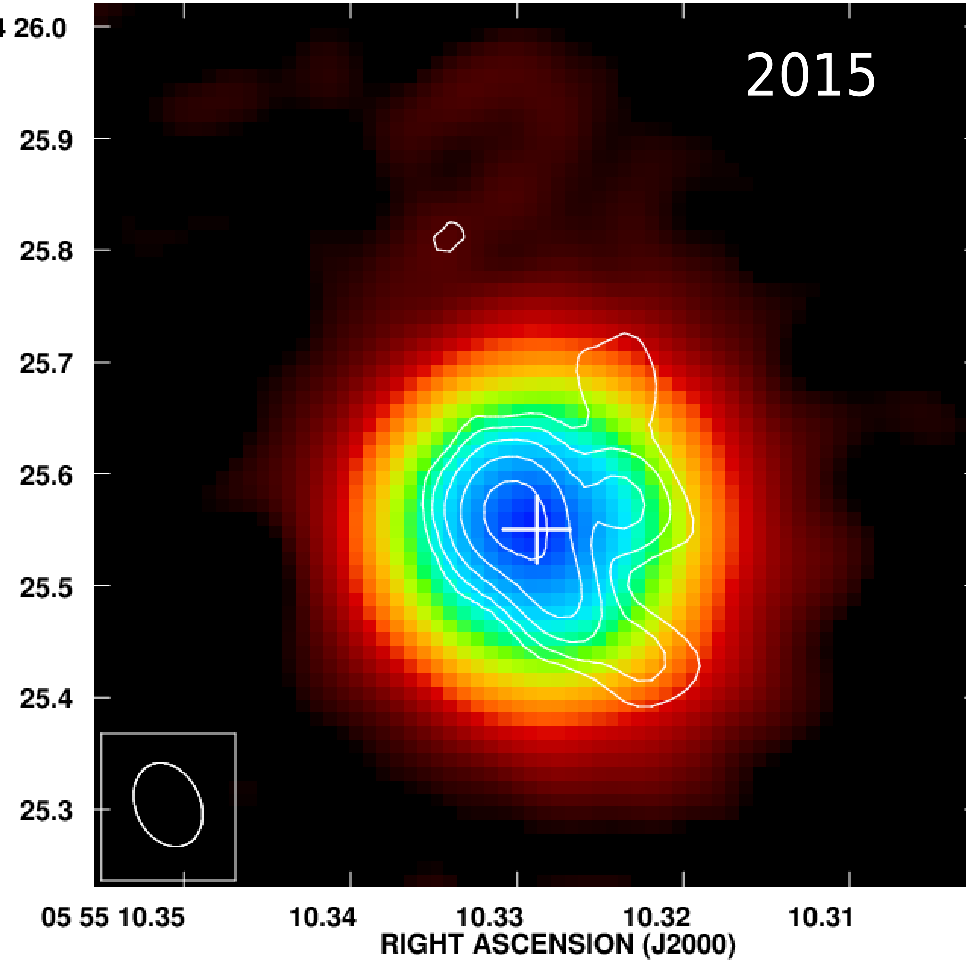


- 2012: 1.448 mJy, 204x195 mas^2
  - Tb 1925 K
- 2015: 1.604 mJy, 210x201 mas^2
  - Tb 2010 K
  - ~5% flux scale uncertainty

Resolving Betelgeuse

- Full resolution (78x58) mas^2
  - Contours (-1,1,2,4...)x63 μJy/bm

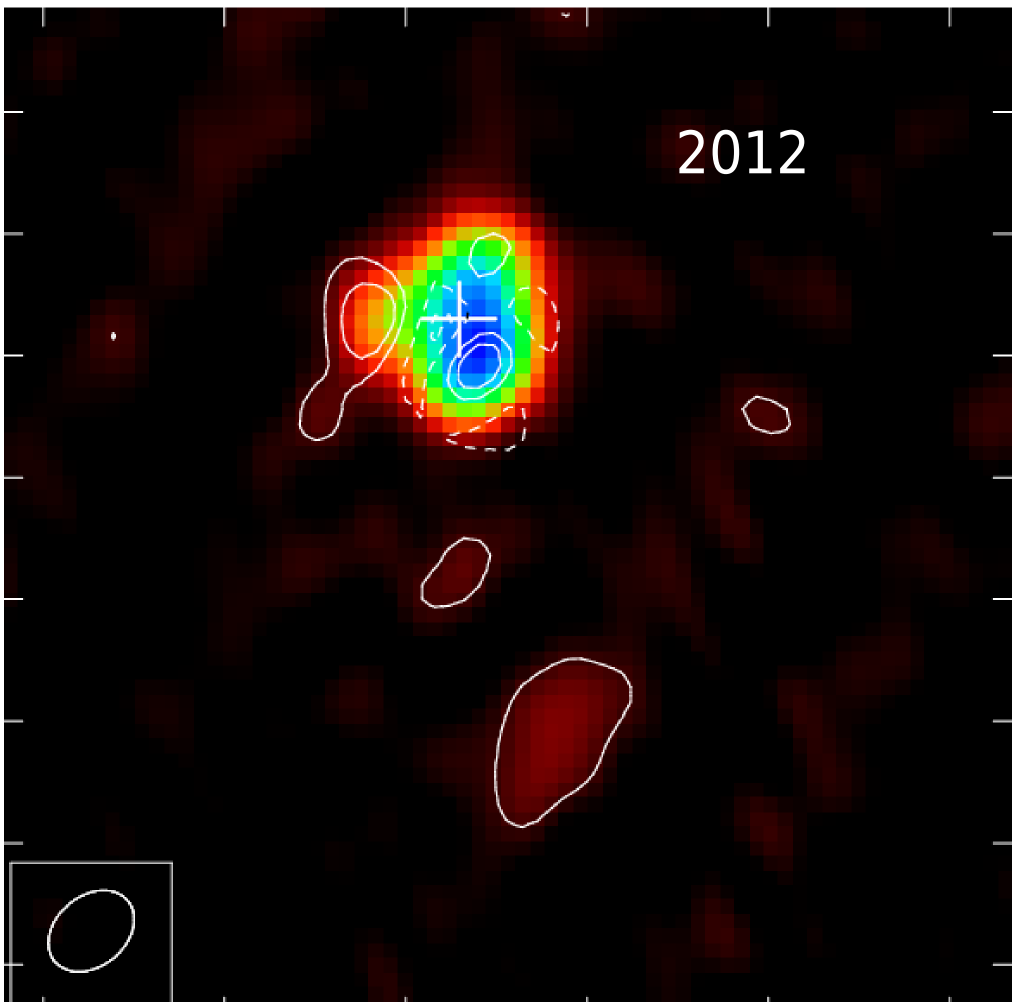


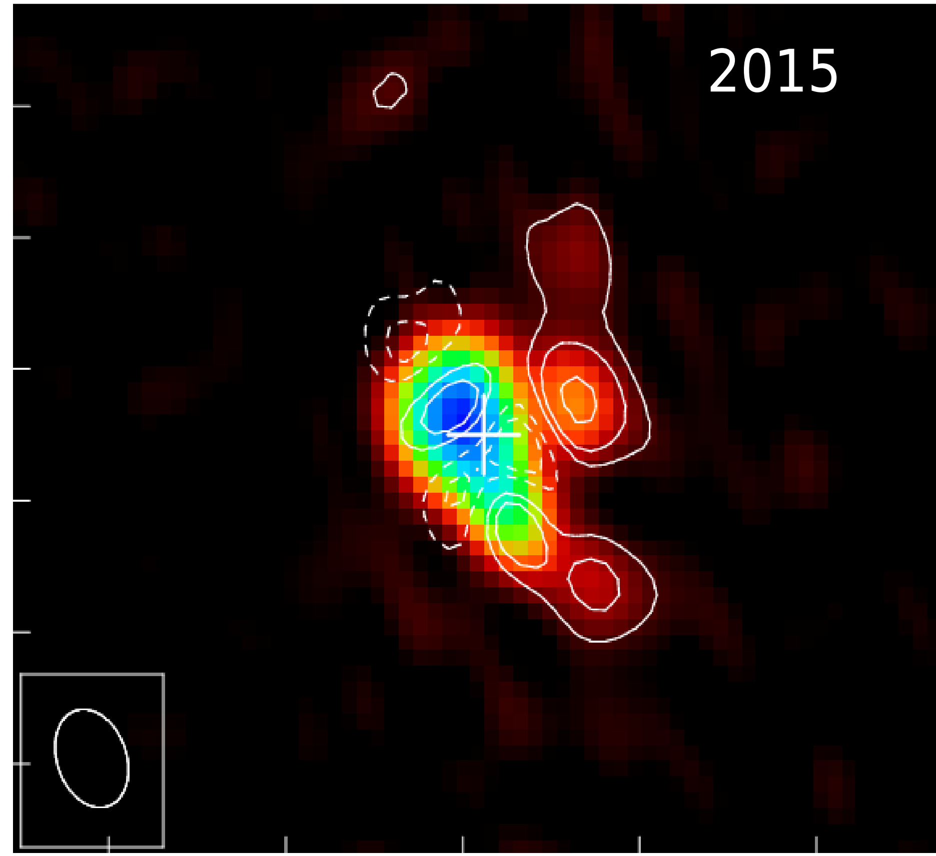


- Proper motion roughly as expected
  - ┼ marks low-res peak

Resolving Betelgeuse

- Full resolution, fit Gaussian
  - Residuals (-2,-1,1,2)x63 μJy/bm
    - ***+ive & -ive*** (*O'Gorman+'15*)





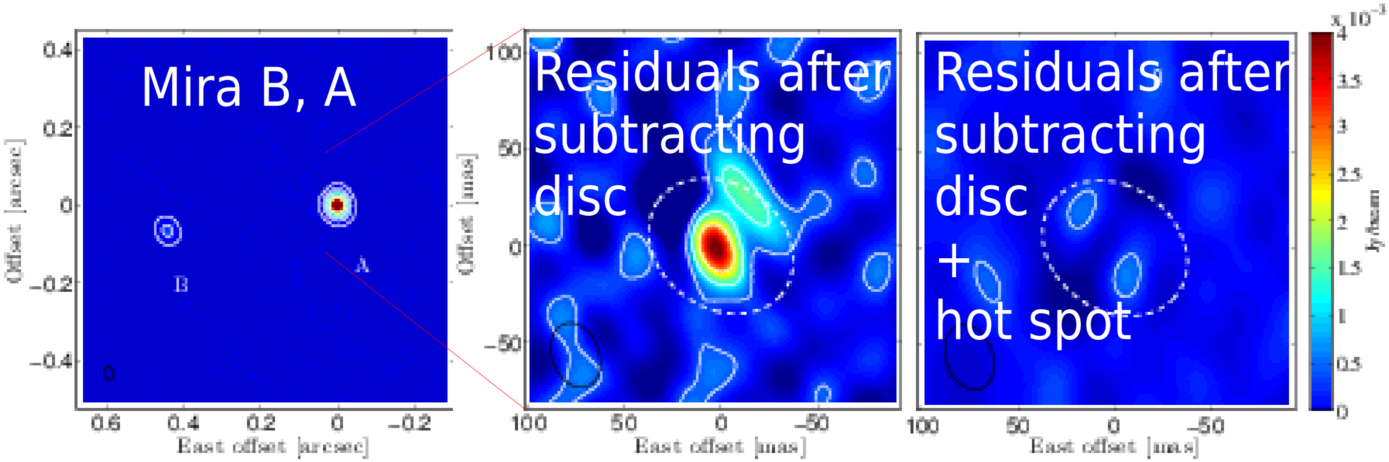
- 2012: Central residuals sum ~0
  - ≲±8% smoothed (180-mas) flux
- 2015: Residuals sum ~+40% total flux
  - ≲ ±10% smoothed flux

Betelguese spots and mass loss

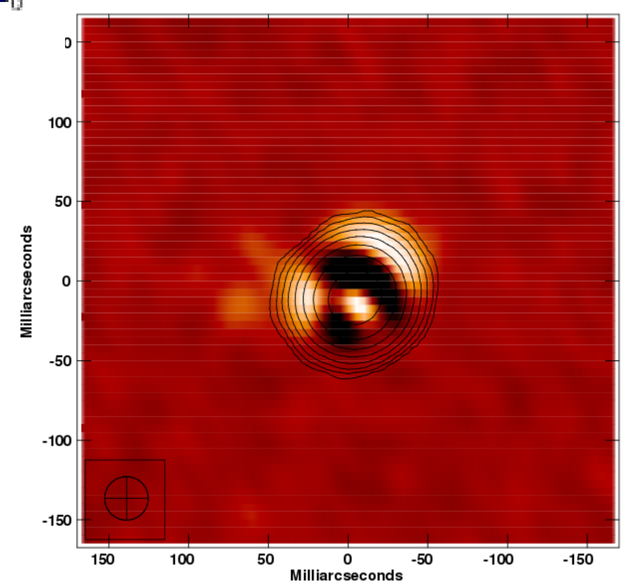
- e-MERLIN results at 180-mas resolution broadly consistent with VLA (*O'Gorman+'15*)
  - $R_{5cm} \sim 5R_{\star 2\mu m}$; $T_b \sim 2000$ K
- 6-8 hot & cool spots $\lesssim \pm 10\%$ (100-200K)
  - Unresolved by ~60 mas beam, combined flux small
    - Explains lack of 1.6 GHz excess in unresolved VLA disc?
- Betelguese $\dot{M} \sim 10^{-6} M_{\odot}$/yr (*Le Bertre+'12*)
  - Strong silicate dust *was* only seen at >20 $R_\star$
    - *Skinner+'88, Danchi+'94* etc.
  - Episodic mass loss? e.g. multiple dust & CO shells
    - *Harper; Le Bertre+'12; Decin+'12,O'Gorman+'12*
  - Possible to have an *irregular*, dust-driven wind?
  - Currently dust-forming! (*Kervella*)

Mira starspot

- ALMA 230 GHz, 30-mas resolution (*Vlemmings+'15*)
  - Mira A disc $R_\star$ ~2 au, T_b 2500 K, with 10^4 K hotspot

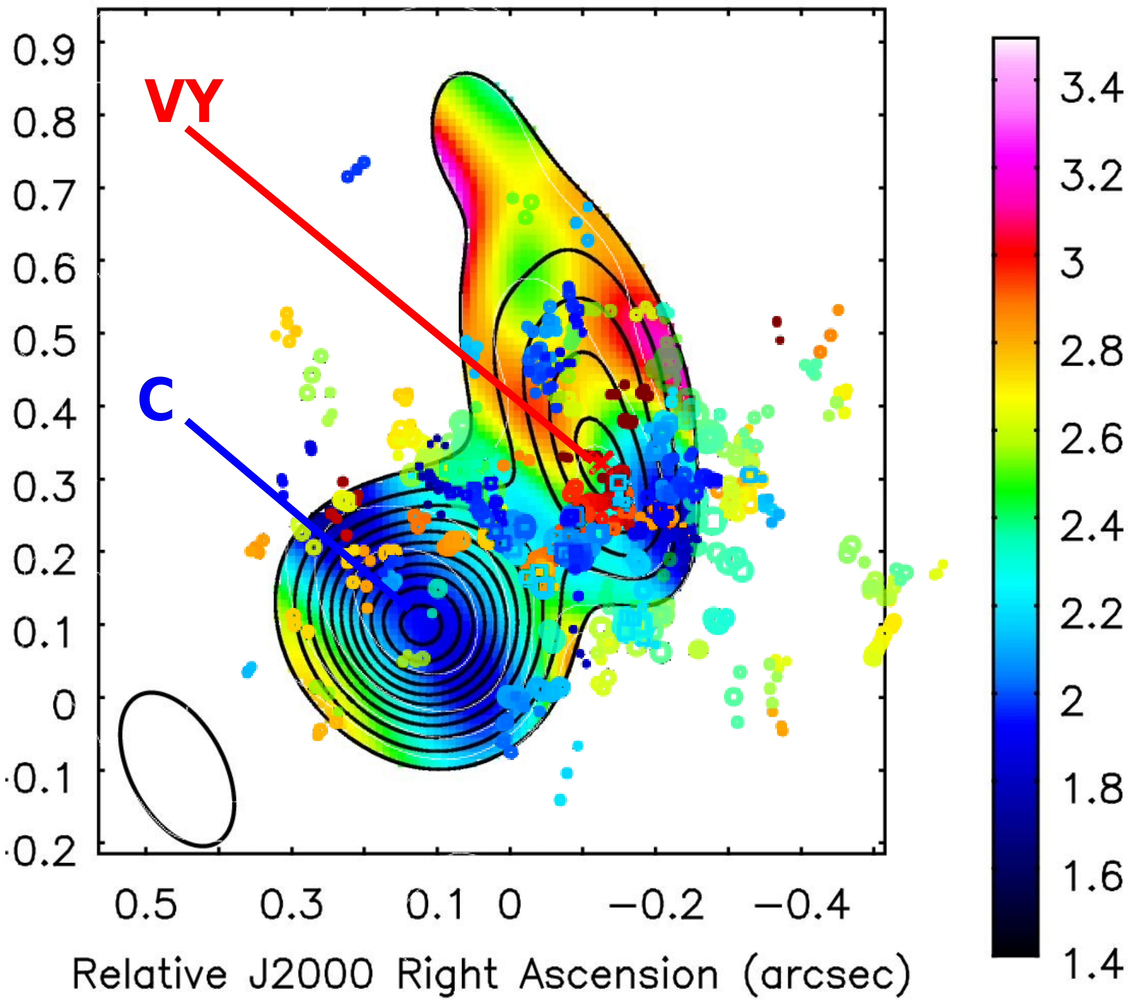


- Same ALMA SV data processed by *Matthews+'15*
  - Similar but not identical disc (contours) and residuals



ALMA Science Verification: VY CMa

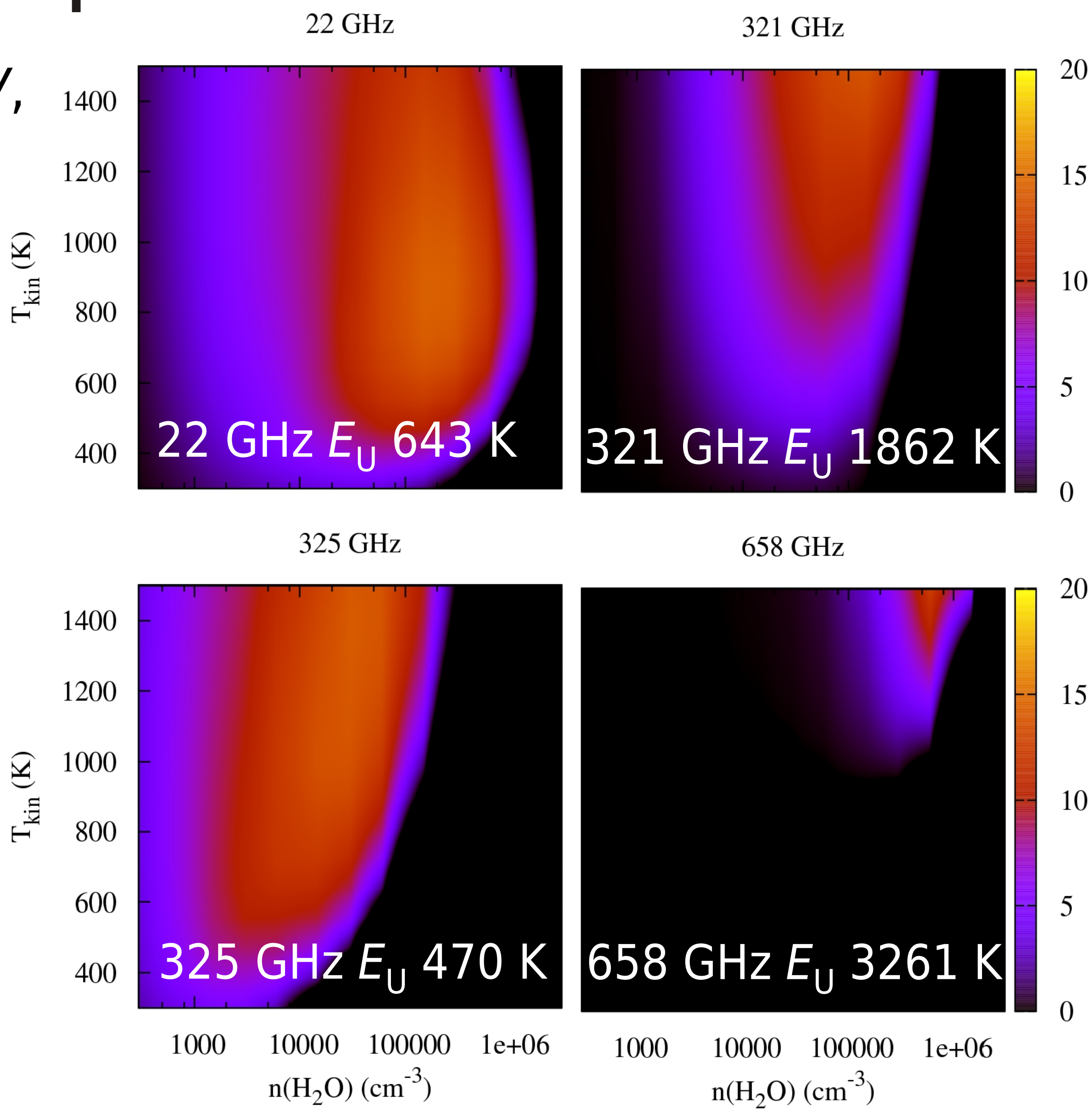
- 2nd peak VY marks maser centre of expansion
  - Dense Clump cooler
- At least 17% dust concentrated in clumps
- N, SE extensions show wind asymmetries must have persisted for decades
  - ≫convection cell life
- All species highly asymmetric incl. thermal
  - *de Beck+'15,Decin+15, Humphreys talk*



Colour: 321-658 GHz spectral index
Symbols: 321-GHz masers
O'Gorman+'14, Richards+'14

Maser predictions

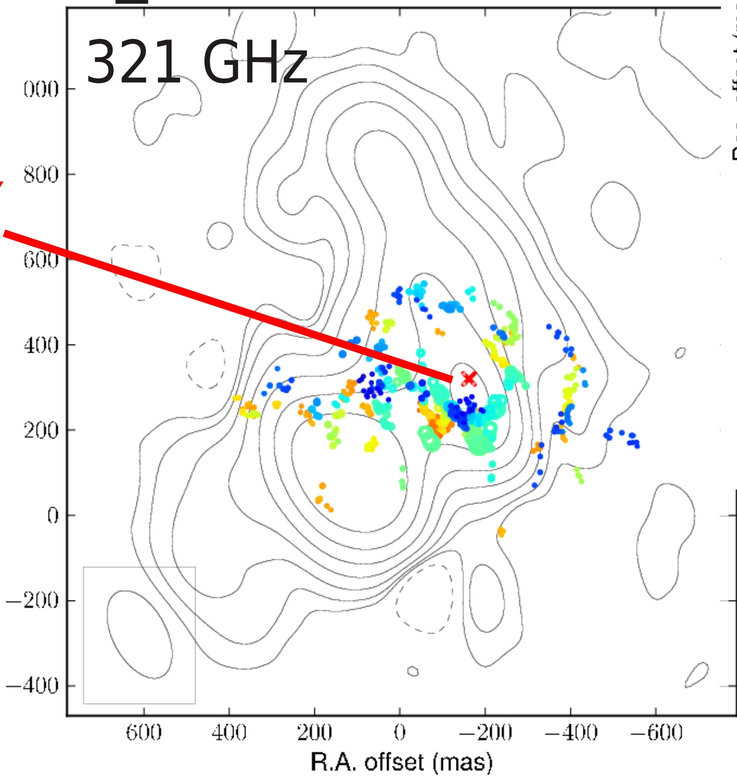
- Density, radiation field, dV, as well as E_U, determines maser excitation
- 22 GHz wide span
  - Quenched at high densities
  - Fades <~400 K
- 325 GHz boundaries at lower densities
  - Extends to cooler T
- 321 GHz narrower range
- 658 GHz hot, dense environment
  - Similar to SiO masers

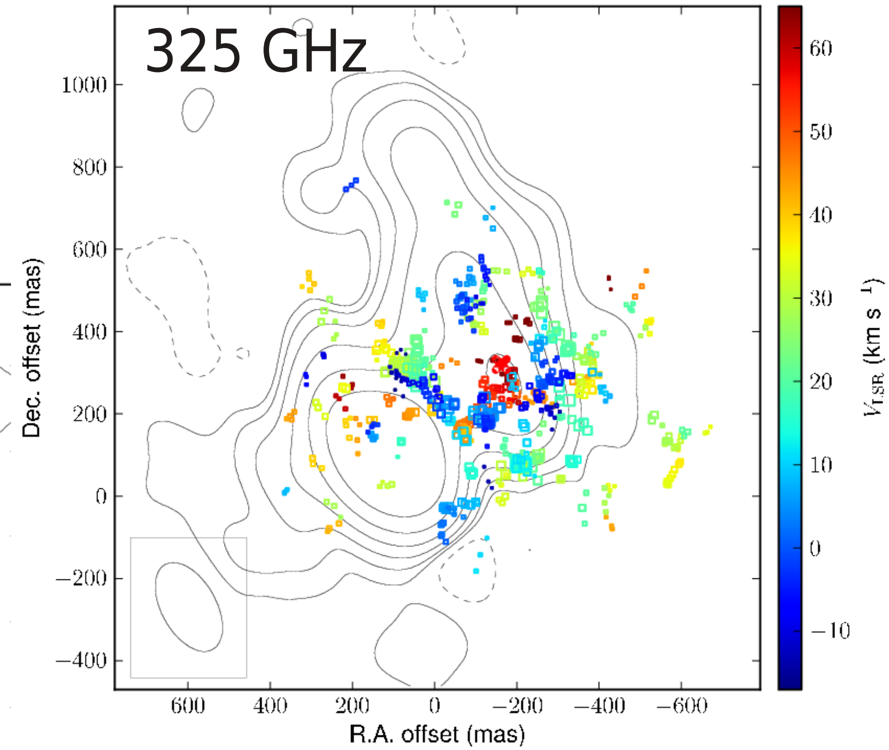


Gray et al. in prep.

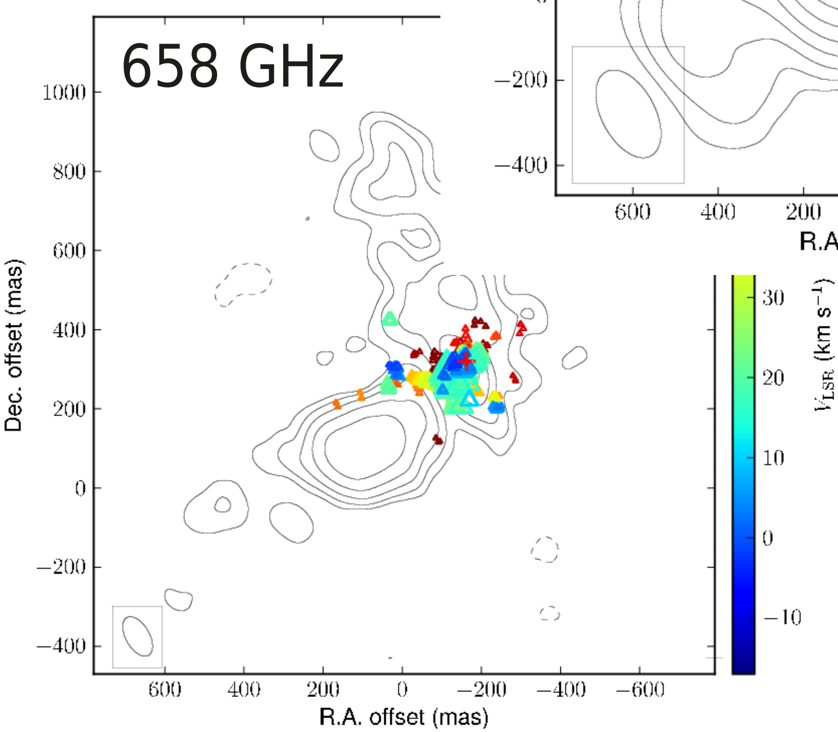
First resolved stellar sub-mm H_2O masers

- Expanding away from 2nd peak VY



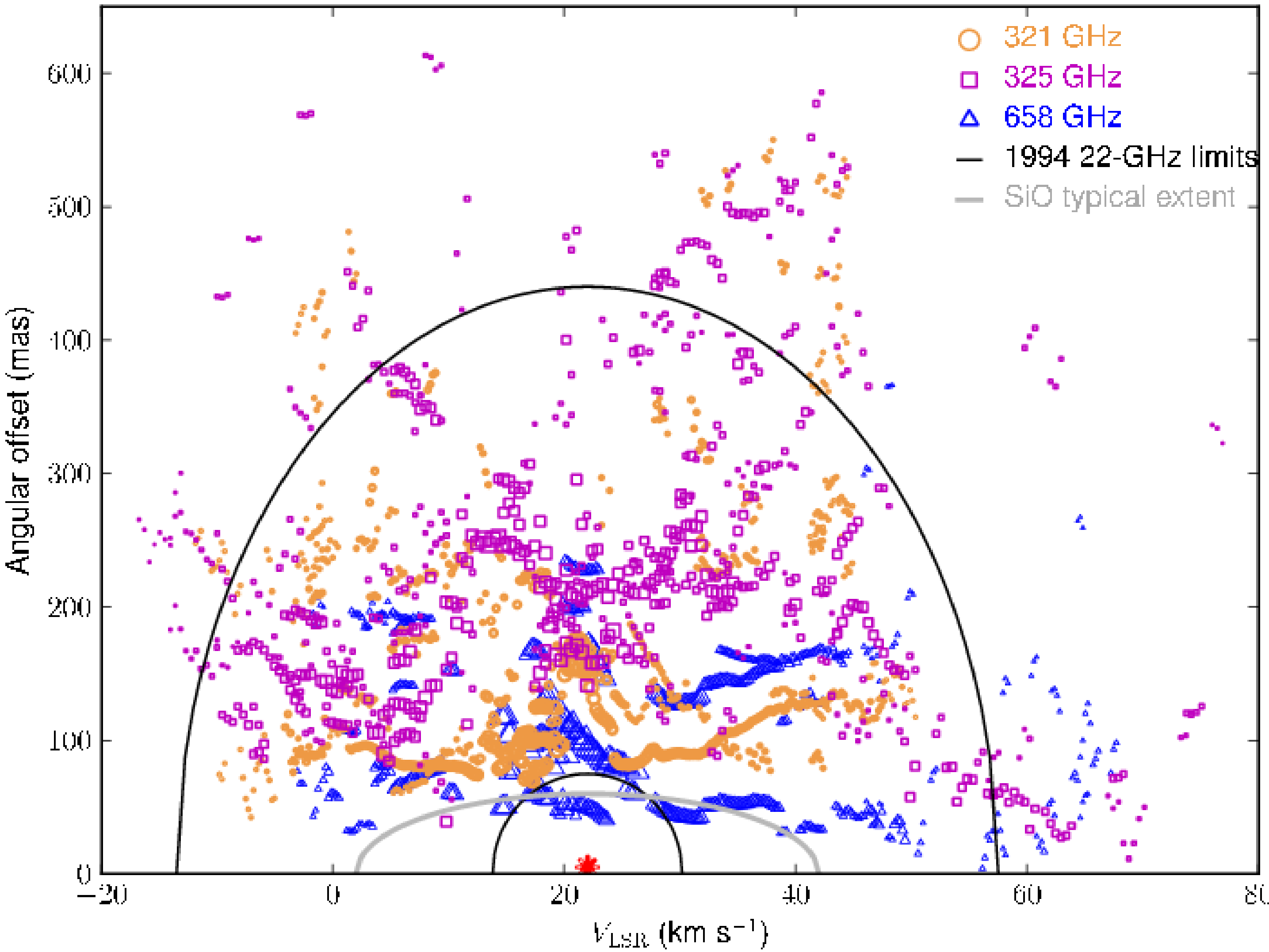


- 325-GHz most extended, as predicted
  - Moderate acceleration



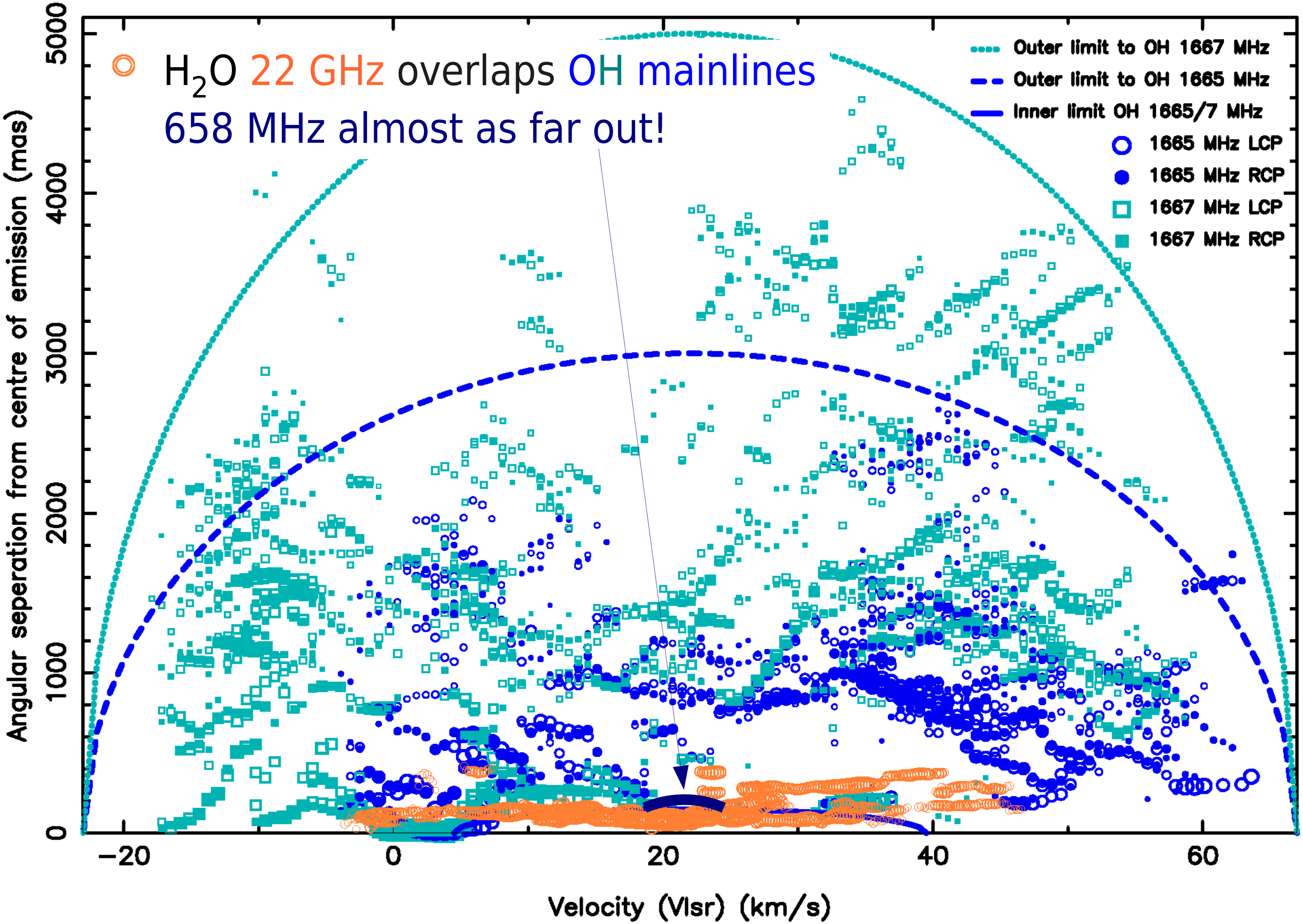
- 321-GHz similar distrib. to 22 GHz
  - Strong acceleration
- 658-GHz starts at few $R_{\star}$, inside dust formation/SiO maser radius – OK
  - Extends to tens $R_{\star}$!

Spatial distribution



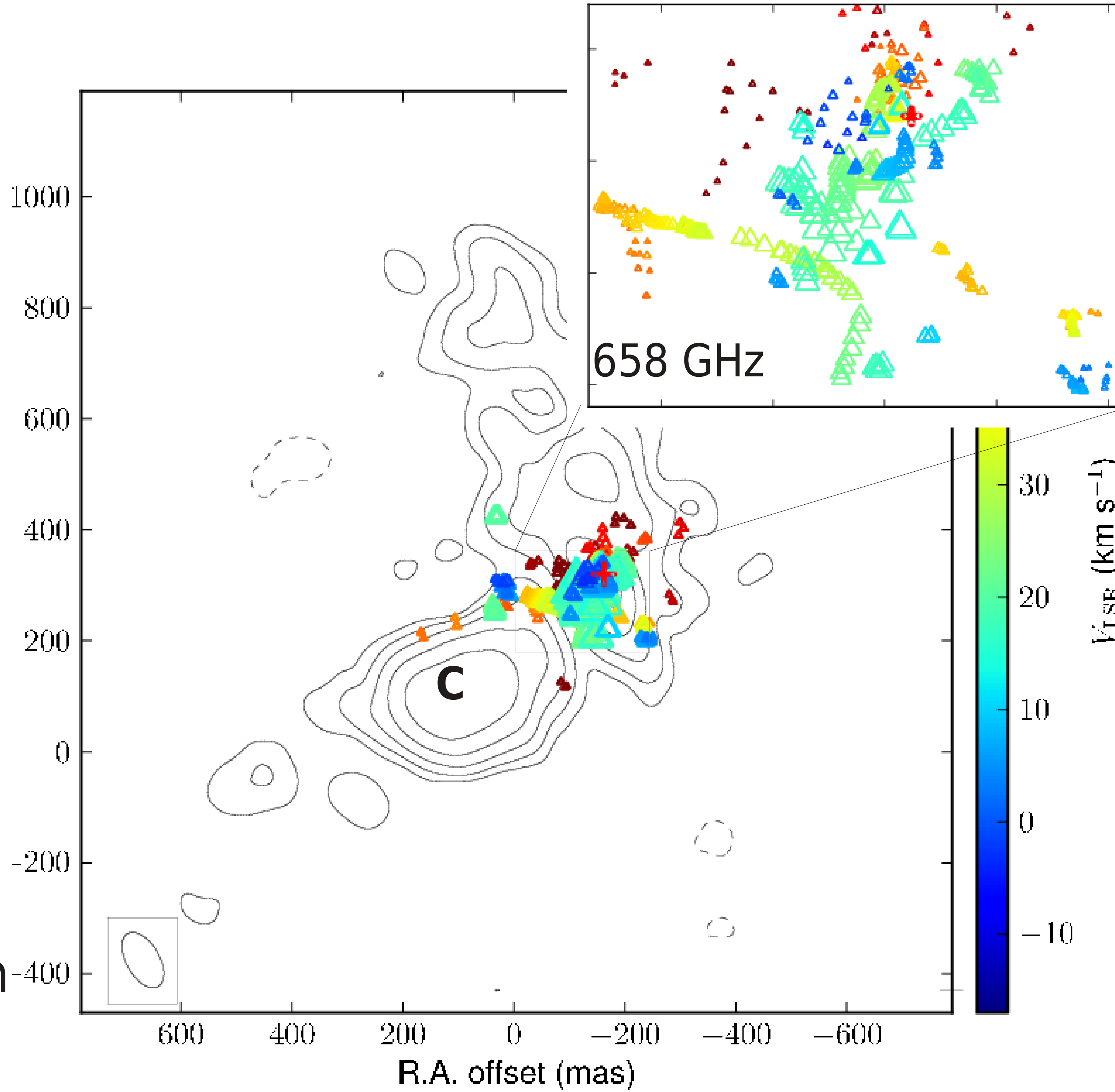
- Different maser lines separate on scales of tens au
  - Could be at similar radii in different clumps and inter-clump gas?
    - Hot/dense v. cool/diffuse
- 658 GHz starts inside dust formation zone
  - But at larger radii than SiO, extends much further

VY CMa mixed-up masers



Shocks?

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

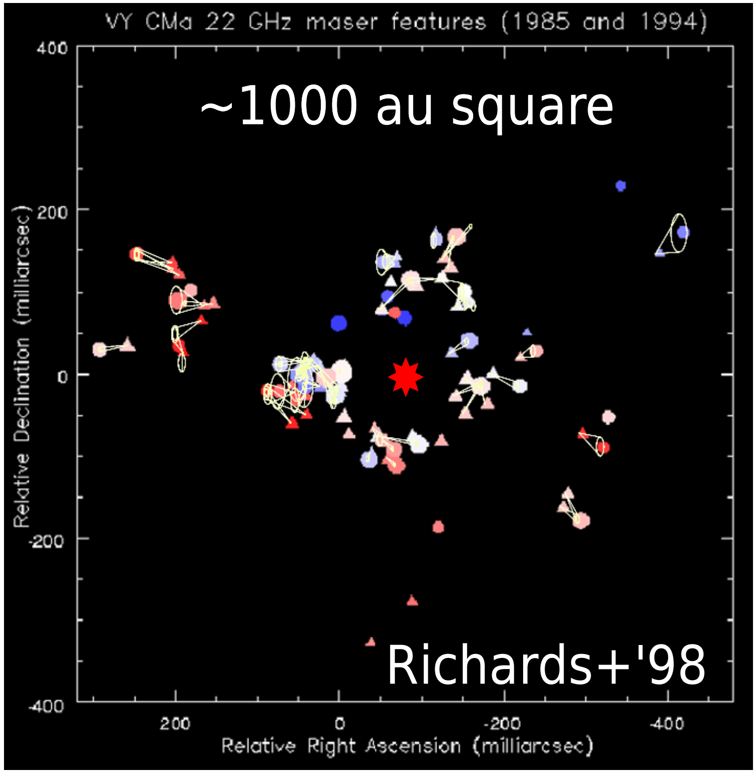


Maser lessons for VY CMa

- Dust well-established by 60-100 au (*Danchi*+'96, *Decin*+'06)
- 658-GHz masers inside and outside inner dust rim r_d
  - Could proper motions show change in velocity field at r_d?
- 321, 22, 325 GHz masers overlap but lowest E_U extends furthest
  - Clump sizes ~50% scatter but 658 GHz smallest, 325 GHz largest
    - All in clumps? Some inter-clump gas?

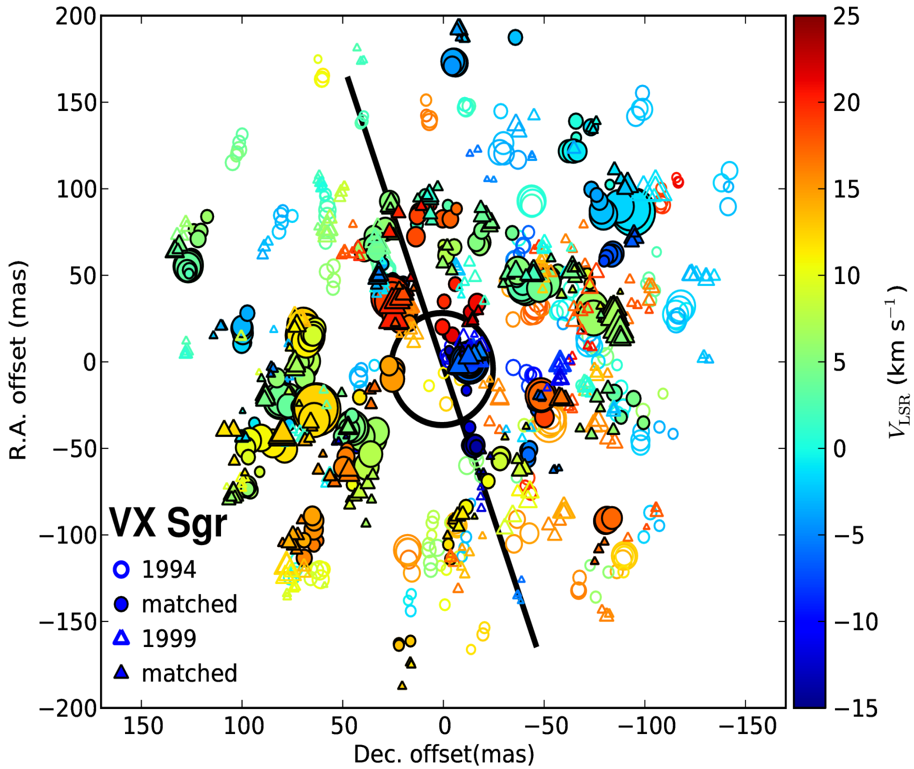
Line (GHz)	658	321	22	325
*R*clump (au)	10	18	12	24
ΔVtot (km/s)	1.9	1.8	2.8	2.7

- 22-GHz Doppler & proper motions show radial acceleration
  - 'Ears' (& thermal lines, *Decin*+'06) suggest biconical outflow+disc
    - But also very irregular kinematics

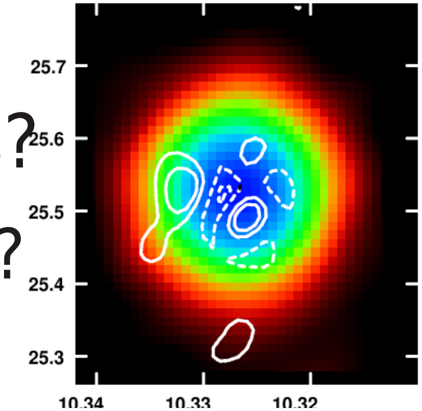


ALMA masers

- 44 H_2O maser lines accessible to ALMA (+ 4 B2, B5)
  - 19 detected (some unconfirmed), 5 mapped
    - E_U 200 – 6000 K, collisional & radiative pumping
      - Models (*Gray'12 & in prep & refs*) show they need distinct combinations of temperature, number density, H_2O fraction, velocity & radiation fields.
  - + e-MERLIN 22 GHz
- Image in better-behaved VX Sgr
  - Use V_{LSR} to deduce *z* position
  - Refine models
    - Resource for au-scale physics in any wet environment

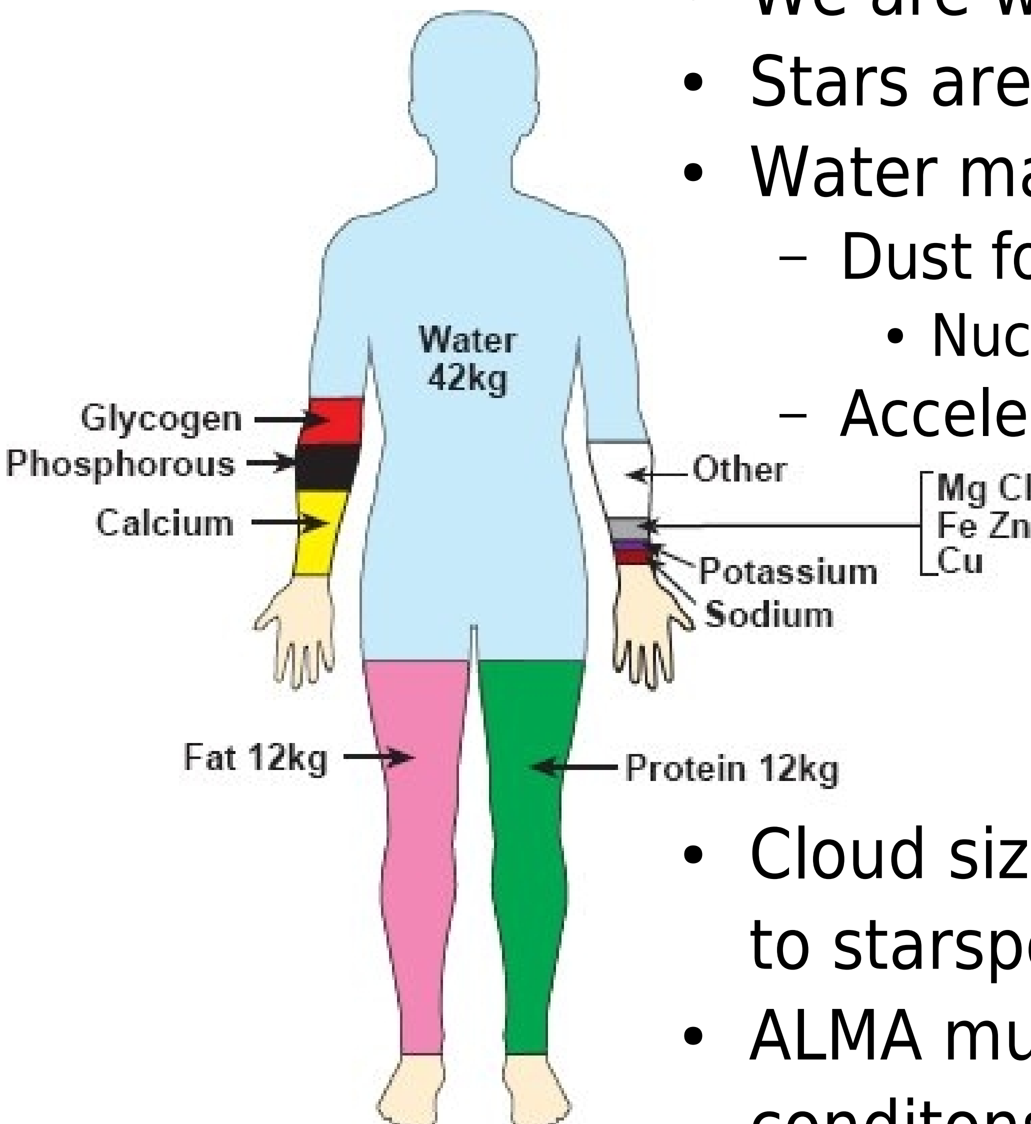


Summary I: Spotty stars, clumpy winds

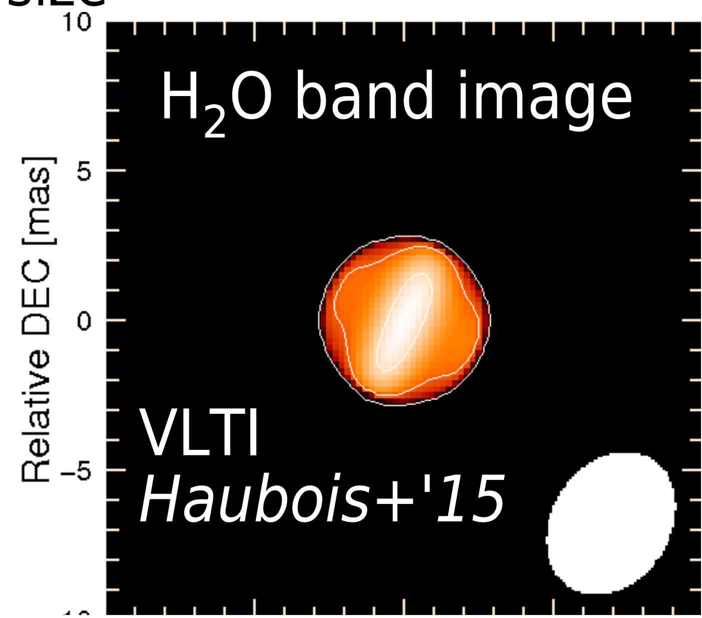


- Stellar hot/cool spots related to wind clumps?
  - Cool spots enhance molecule/dust formation?
  - Hot spots related to magnetic buoyancy?
    - Few clumps per stellar period contain 30-90% mass lost
      - Convection (*Jorissen*) – chemically distinct? Poster *Gobrecht*
  - Wind clumps overdense, overheated, must be over-pressurised
    - Yet survive >> sonic turbulence timescale
      - Magnetic confinement?
- Mild asymmetry (except extreme RSG), no rotation
- Whatever the cause, clumps/asymmetry protect dust in ISM?

II Why astronomers need water



- We are wet!
- Stars are wet!
- Water masers reveal kinematics:
  - Dust formation zone (with SiO)
    - Nucleation to full-size
  - Acceleration zone



- Cloud size related to starspot size
- ALMA multi-masers will resolve physical conditons on (sub-)au scales