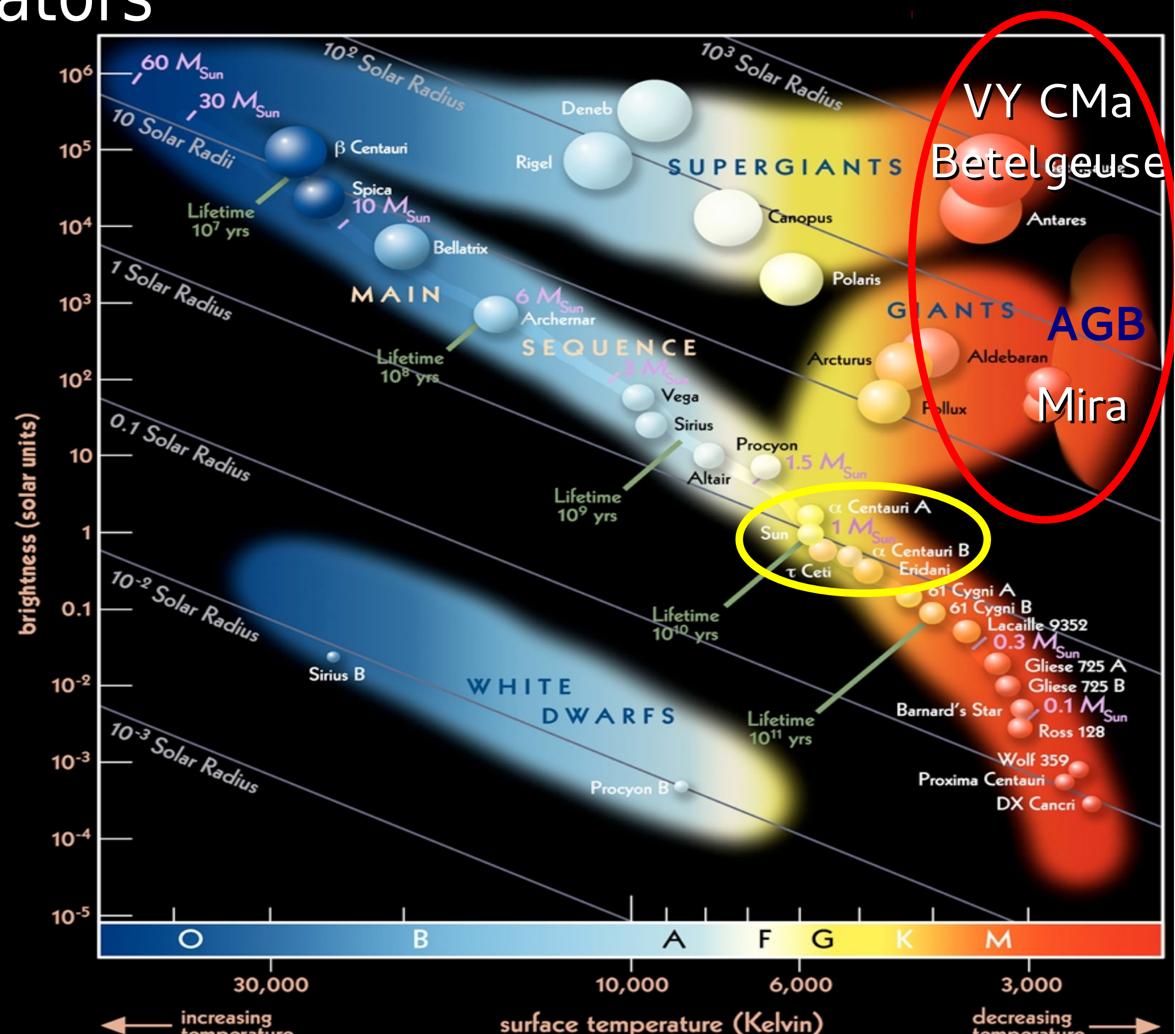
# Seeing into stars and their clouds

Anita Richards, UK ARC node, JBCA, Manchester
with thanks to many collaborators

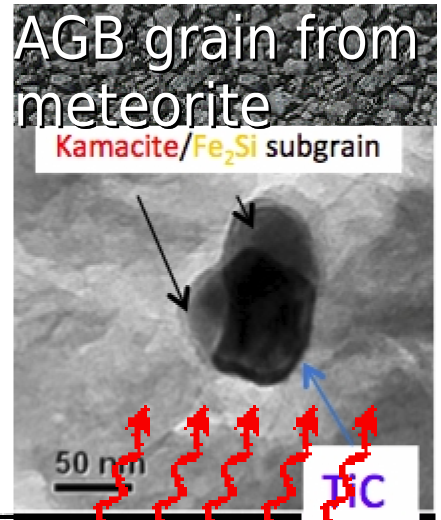
- How is matter ejected from old, cool stars?
- How is it accelerated?
- Relationships between molecules and dust

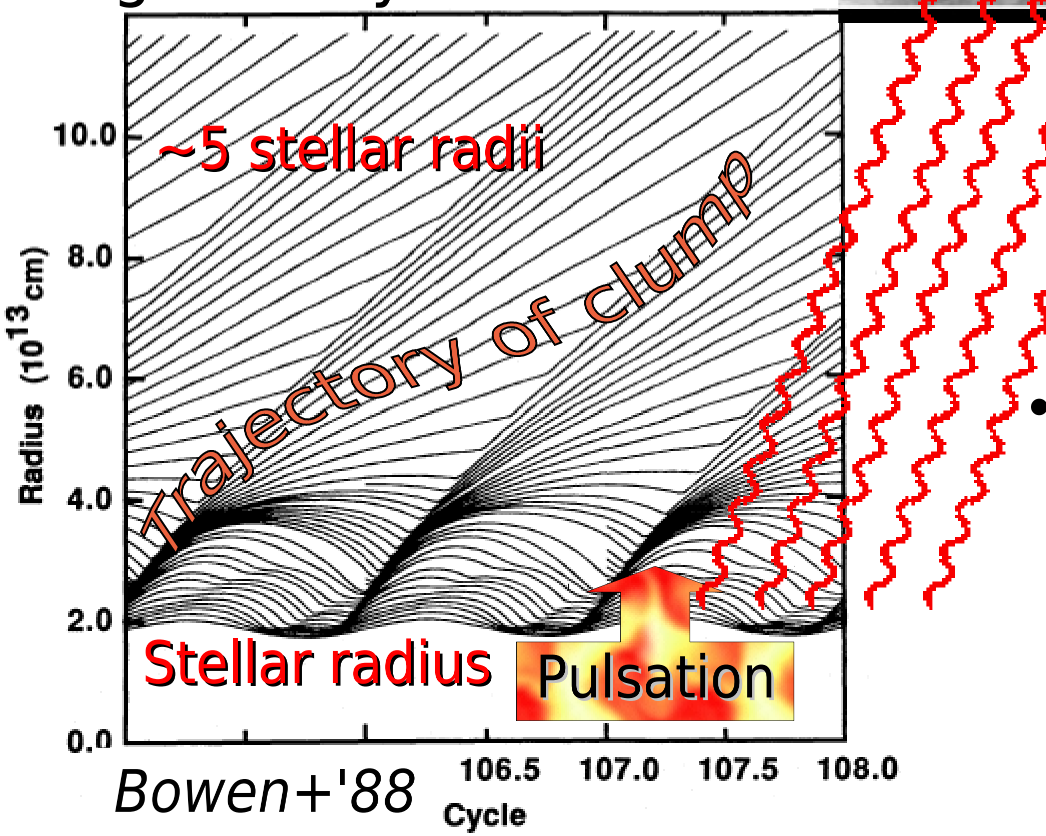



MANCHESTER 1824
The University of Manchester
EUROPEAN VLBI NETWORK
MERLIN
ALMA
EUROPEAN ARC
ALMA Regional Centre || UK

# Mass loss from AGB/RSG stars

- Stellar pulsations lift photosphere
- Wind cools, dust forms
- Radiation pressure drives grains & thus gas away from star



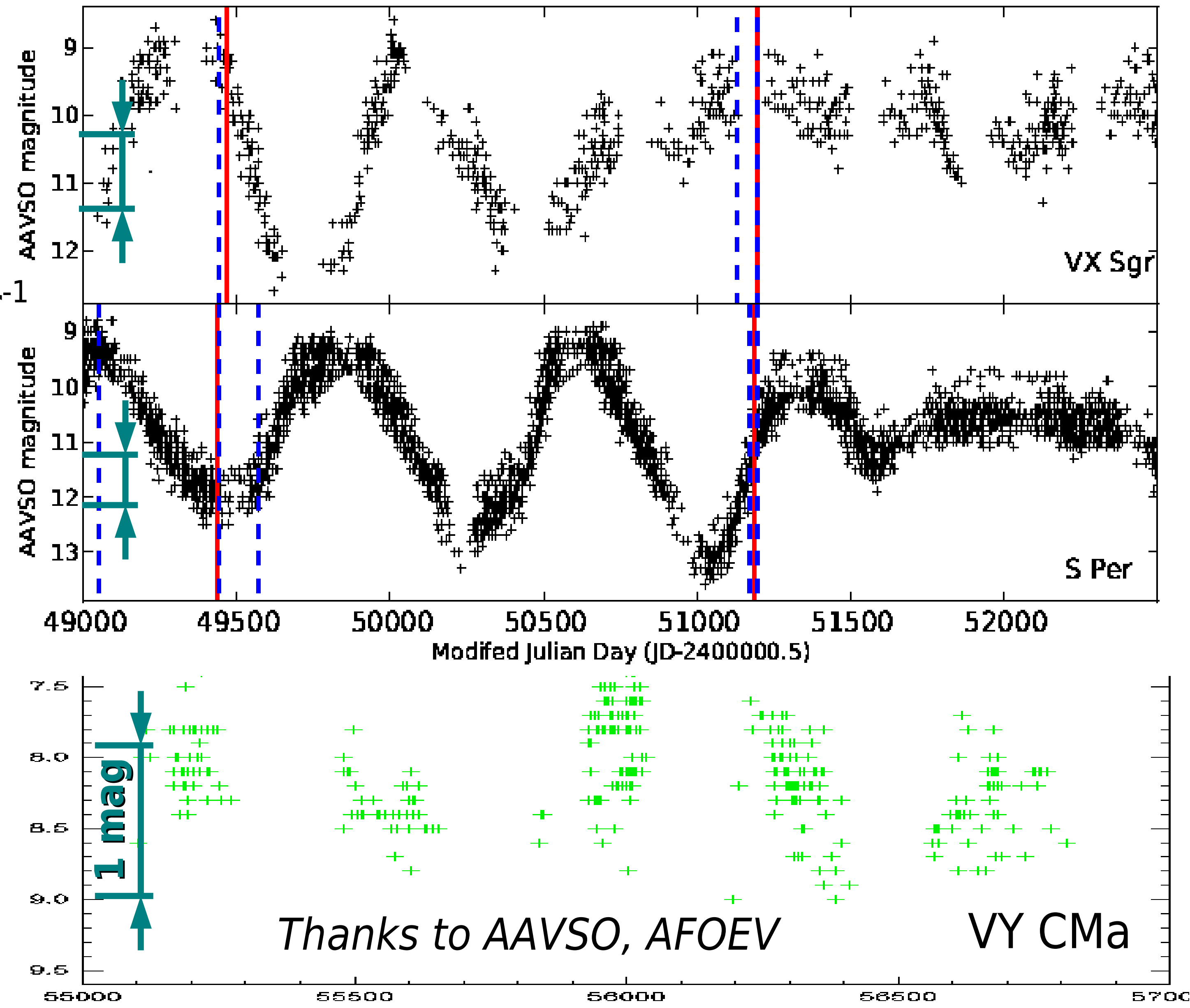




*Bowen+'88*

- SiO masers show infall/outflow at $<5R_*$
  - How can this lead to steady wind?
    - $10^{-7}$–$10^{-4}$ $M_\odot$ $yr^{-1}$
  - Pressure on small O-rich grains not efficient *Woitke06*
    - Larger grains (seen close to low-mass stars, *Norris+12*)?
    - Radiation pressure on lines?
- How is matter ejected from the stellar surface?
  - Pulsation?
  - Convection/star spots?
  - Magnetic forces?

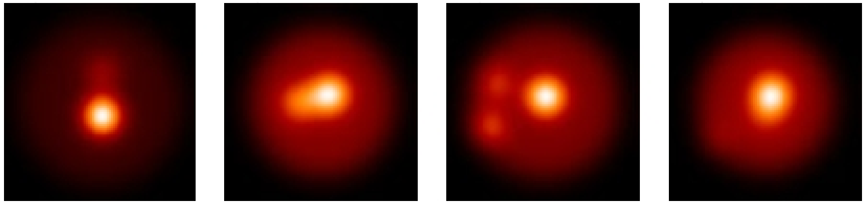
# No direct link between mass loss rate & pulsation amplitude

- Cool RSG:
  S Per, VX Sgr
  - $\Delta_{mag}$ 3~4
  - $\dot{M}$ 3-7 x$10^{-5}$ $M_{\odot}yr^{-1}$
- VY CMa
  - $\Delta_{mag}$ 1~2
  - *P* ~870d?
    ~1600d?
  - Recently ~400d
  - $\dot{M}$ ~$10^{-4}$ $M_{\odot}$ $yr^{-1}$
  - Smaller $\Delta_{mag}$ ,
    higher $\dot{M}$

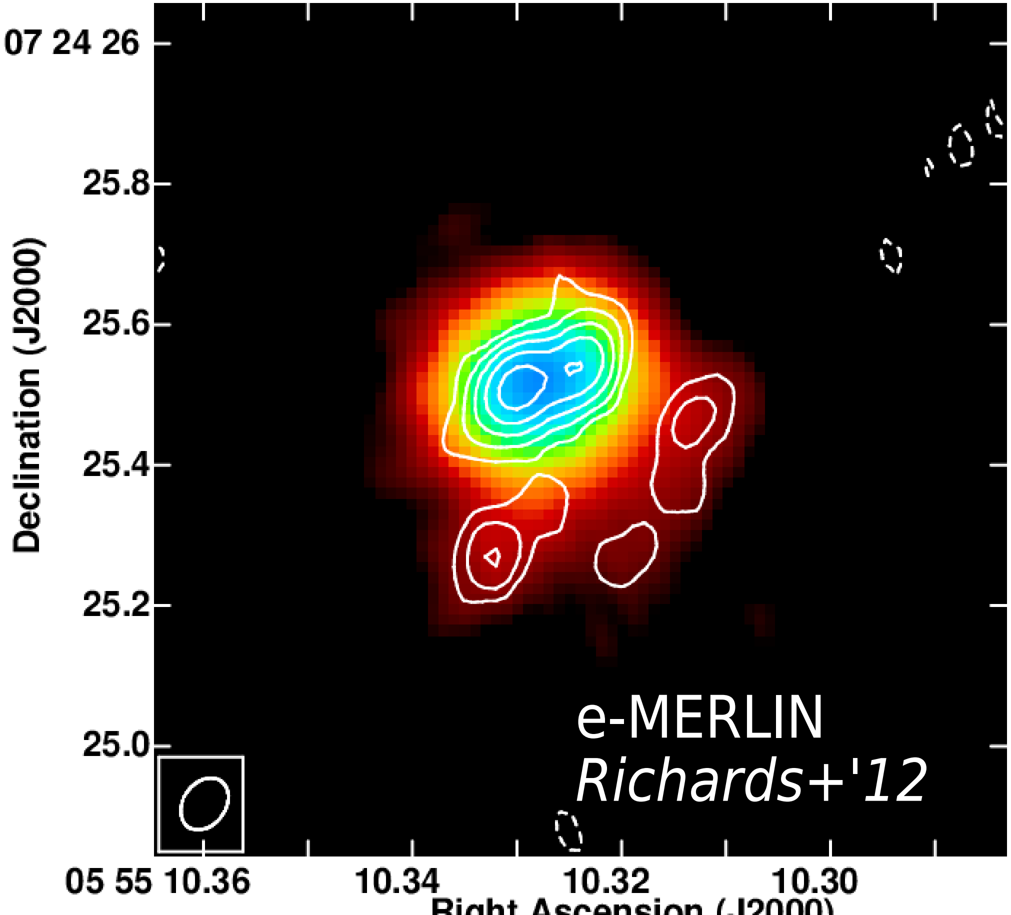


# Imaging the stellar surface

- $\alpha$ Ori 2.2 $\mu$m $R_\star$ 22.5 mas, $T_{eff}$ ~ 3600 K *Perrin+'06*
  - Optical hotspots vary
    - Timescales 3-9 months
- $\lambda$ 5 cm radio photosphere
  - $T_B$ within 5$R_\star$ 1170±150K
- Hotspots 0.71, 0.49 mJy/bm
  - $T_B$ 5400±600, 3800±500 K
    - Separation ~2x 2$R_\star$
  - Old MERLIN saw several *Skinner+97*
    - $T_B$ 6000 – 8000 K
- **$T_b$ hotspot ≫ $T_{eff}$**

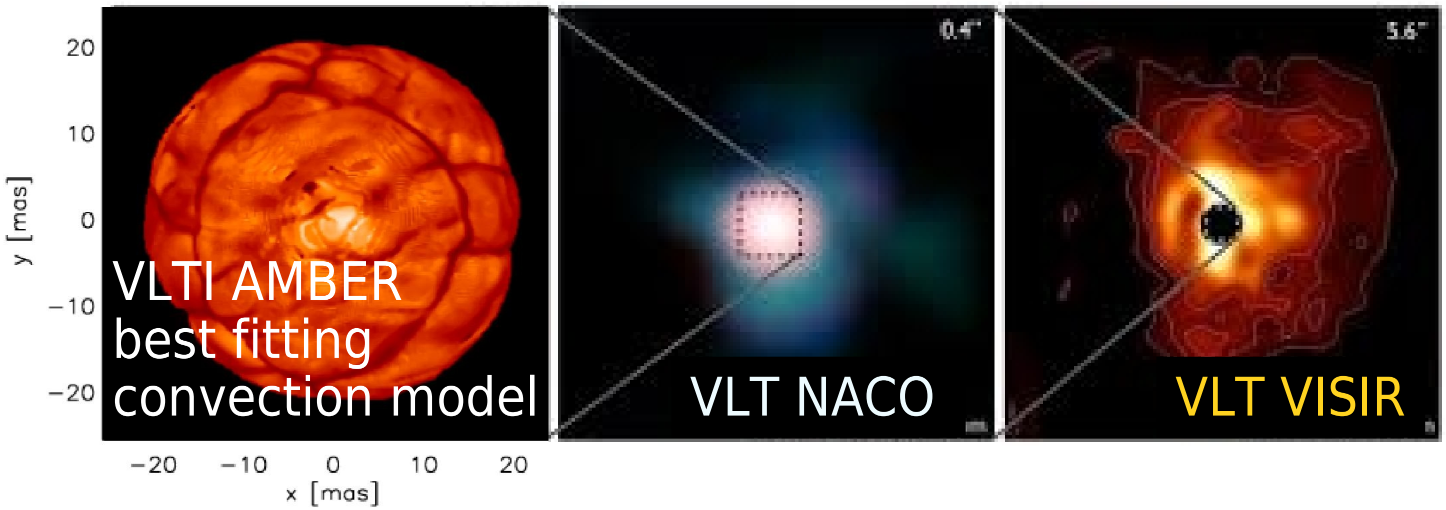


Masked WHT 710nm (*Tuthill+'97*)




Contours: Partial uniform wtg, (-1,1,2,4,8,16)x 0.027 mJy/bm
Colour: 3500-klambda uvtaper, 180-mas beam

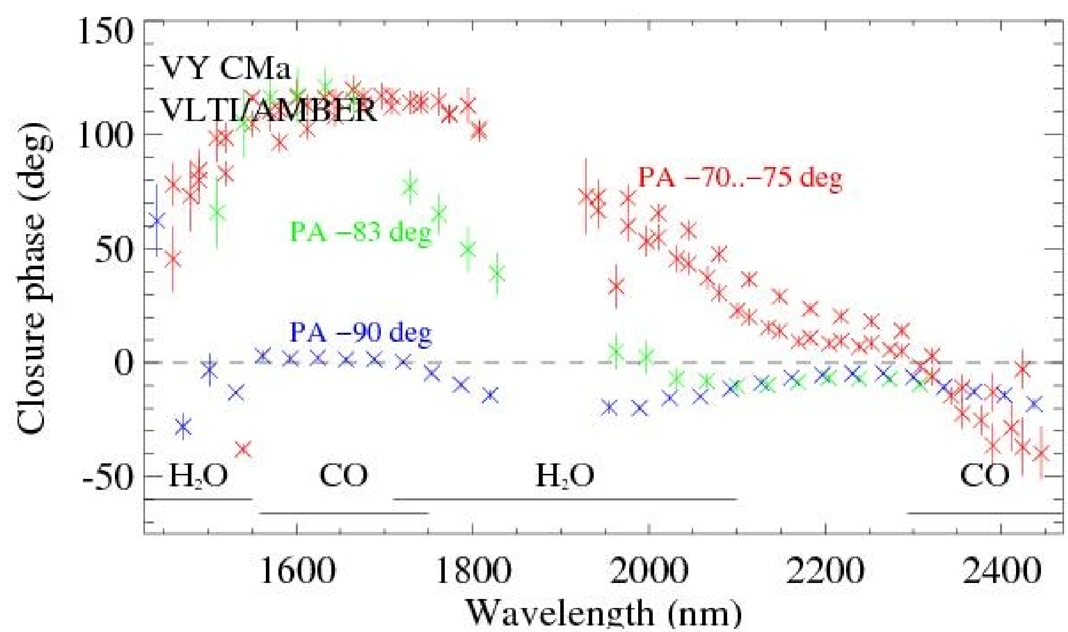
# Optical/IR high resolution




Betelgeuse

*Kervella+'14,'11,'09*

- Irregular ejection of plumes from Betelgeuse
  – Dust + molecules – CN?
- VY CMa *Wittkowski+'12*
  – $R_\ast$~ 6.5 au
  – Asymmetric, non-cospatial CO, $H_2O$ absorption layers
    - Radii ~$R_\ast$, 1~1.5 $R_\ast$



# Possible origins of radio hotspots

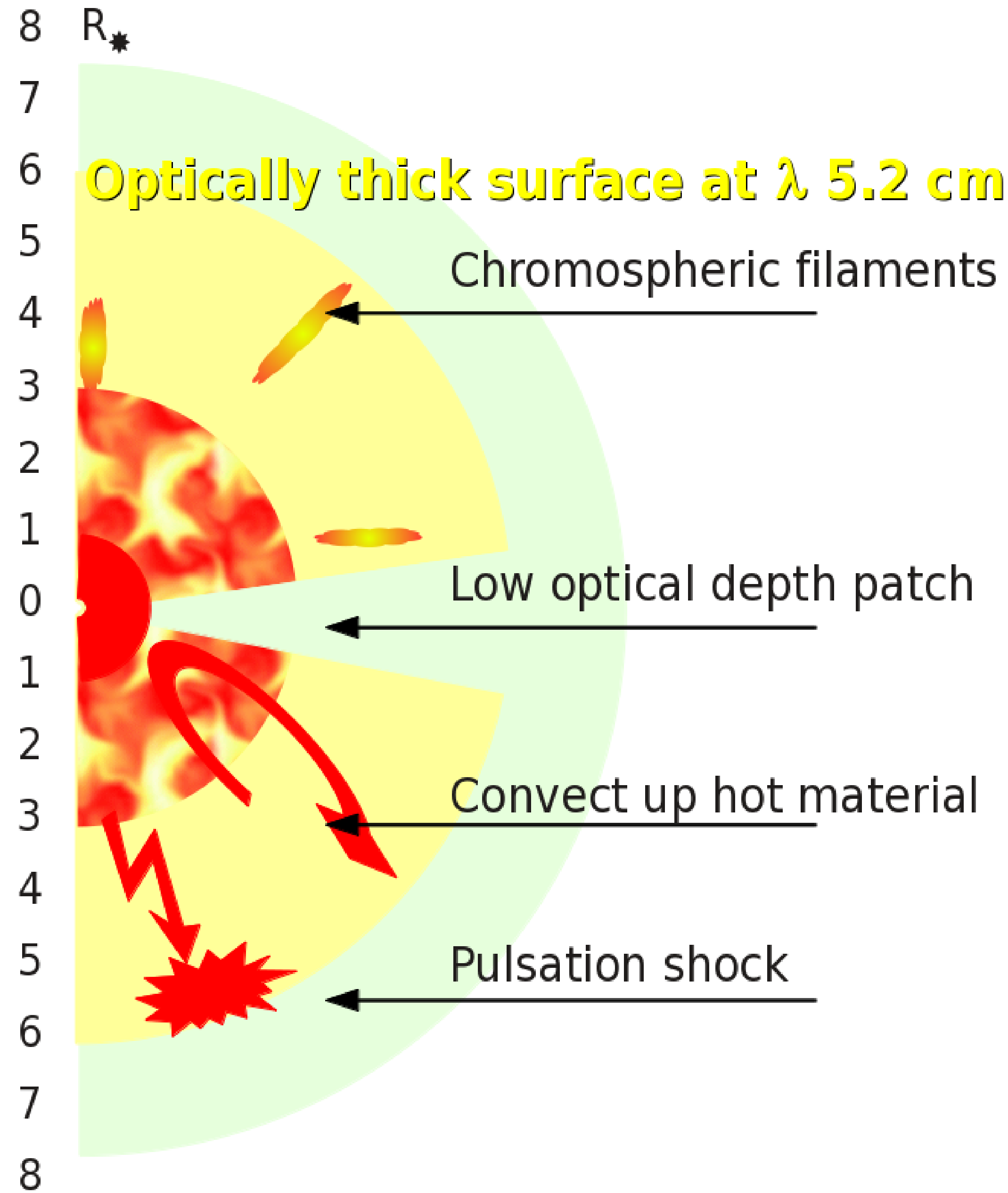
1 Cooler higher layers expose photosphere
- But whence spots $>T_{\text{eff}}$?
- Only in central ~50 mas?

2 Chromospheric patches?
- Hα to 4.5 $R_*$ *Hebden+87*
- Low filling factor *Harper+'06*

3 Convection
- Needs extra heating

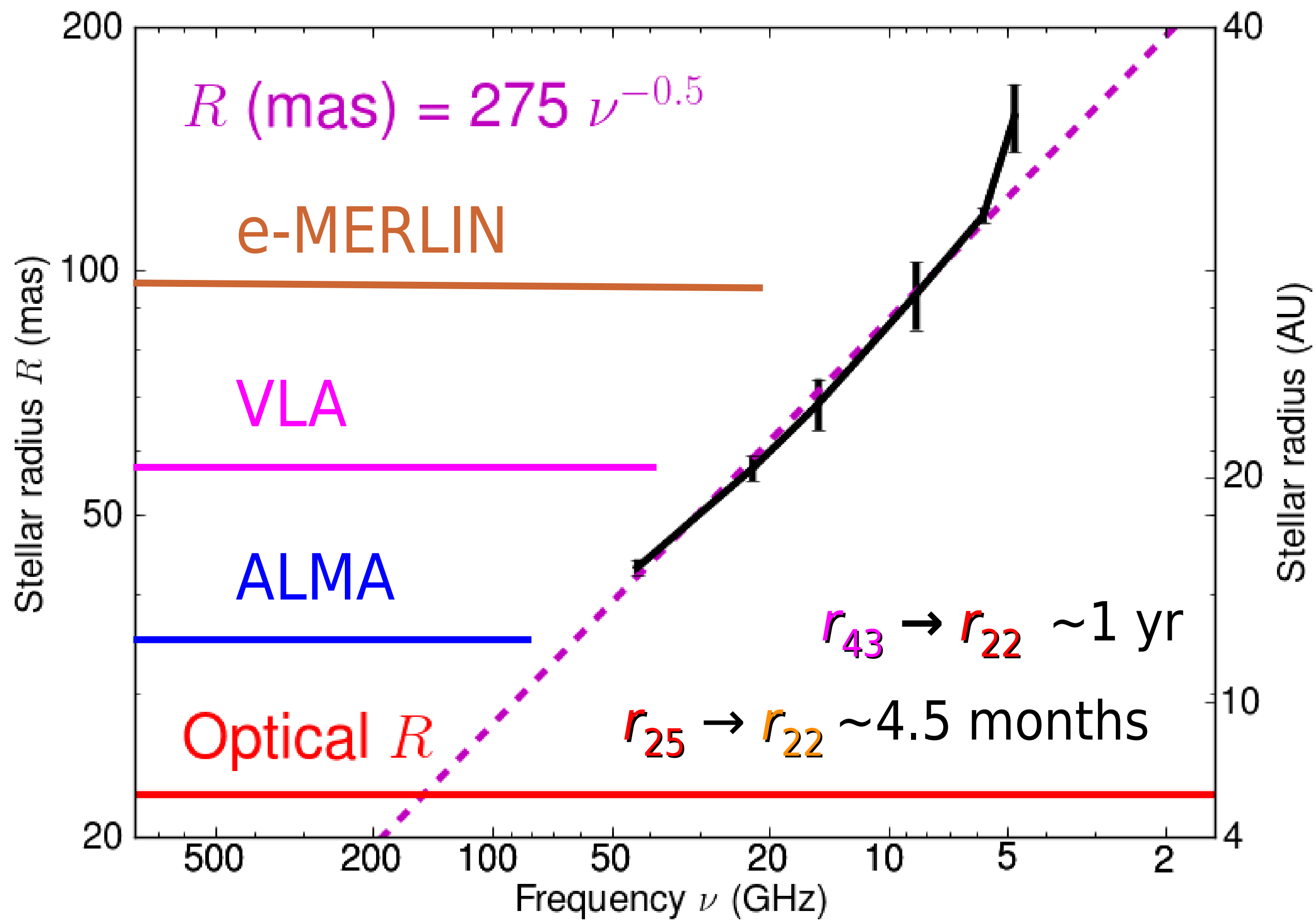
4 Pulsation
- *Ireland+11* models to 5$R_*$
  - What velocity needed?

Shock heating needed for $T_b$ > 3600 K *Harper+'06*



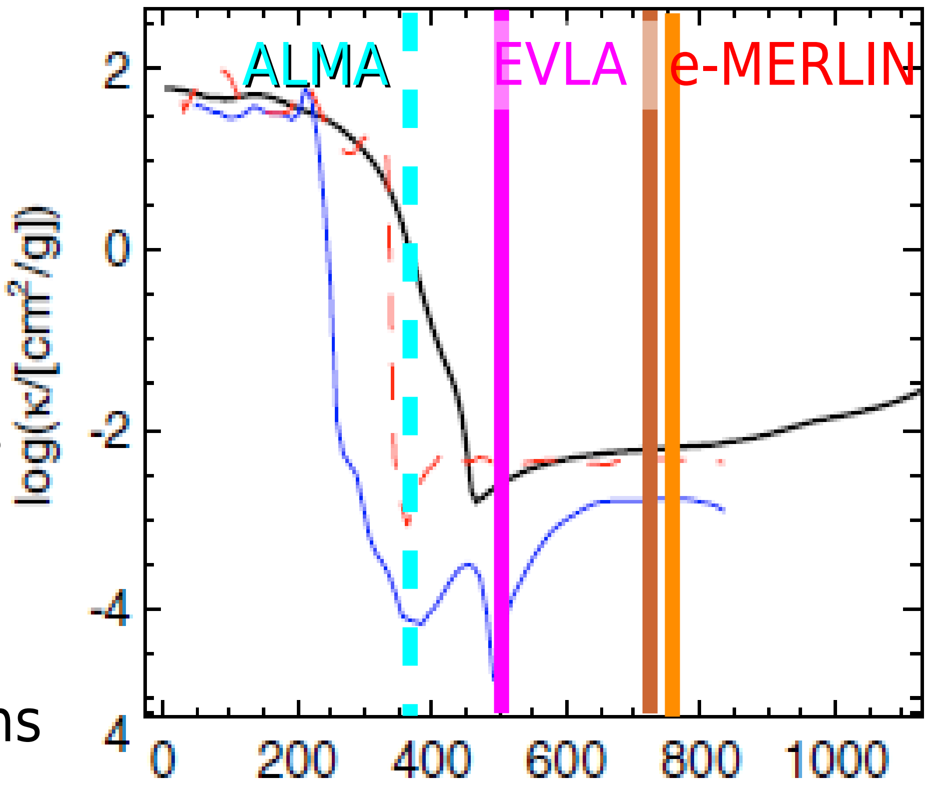
# Higher ν see deeper into photosphere

- Observations at a given frequency see τ~3 surface
  - Star looks bigger at lower ν / longer λ
- e.g. α Ori
  - *Lim+98*
- Highest radio ν see deepest layers
- Observe over months/yrs at decreasing ν
  - Trace gas ascending in photosphere



# Distinguishing kinematics

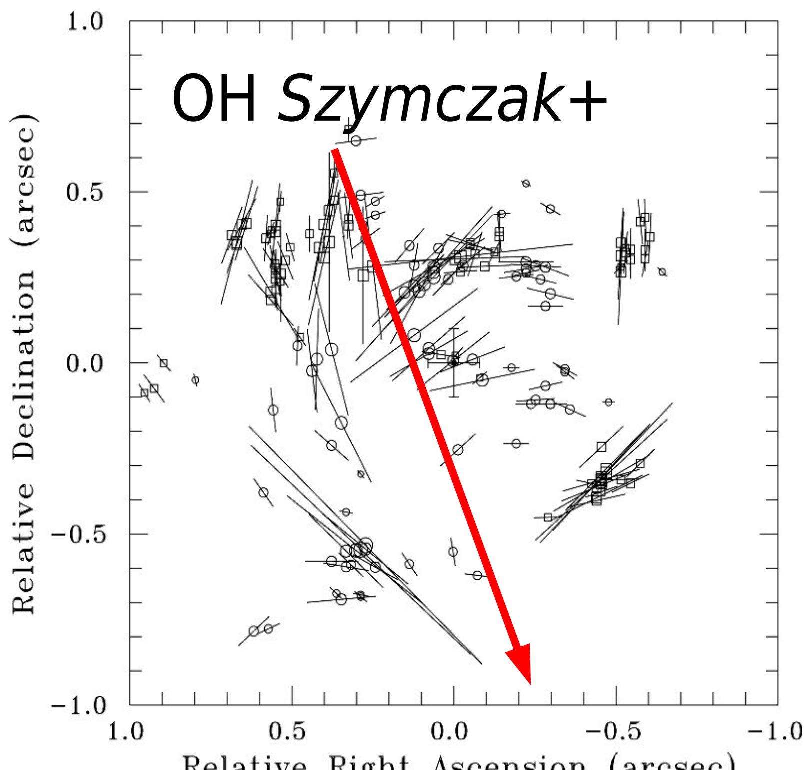
- Monitor radio
  - ~monthy at decreasing ν
  - Trace same layer expanding
    - Correlated changes: pulsation?
    - Patchy changes: convection?
    - Persistent axis: magnetic field?
- Variability timescales (*Harper'13*)
  - Betelgeuse $P_{\star\mathrm{rot}}$ ~25 yr
    - Hotspot proper motion 4 months
  - CII → CI recombination or chemical changes in months
  - Granulation 3 – 6 months
  - *P* (pulsation) ~(few) yr
  - Giant convective cells ~6 yr turnover in RSG

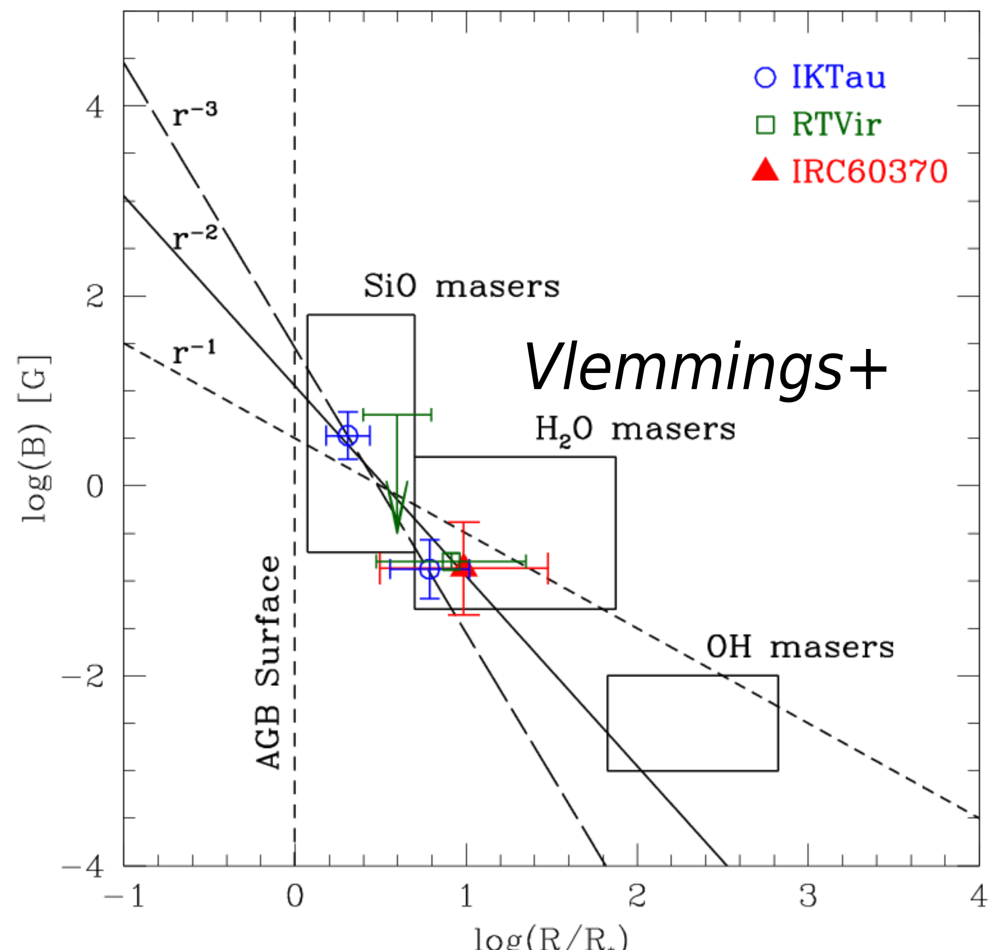



- Up/down draughts opacity model
  - *Freytag & Hoefner 08*
- ~yr to detect in AGBs
  - *Wittkowski+2011*

# Magnetic force?

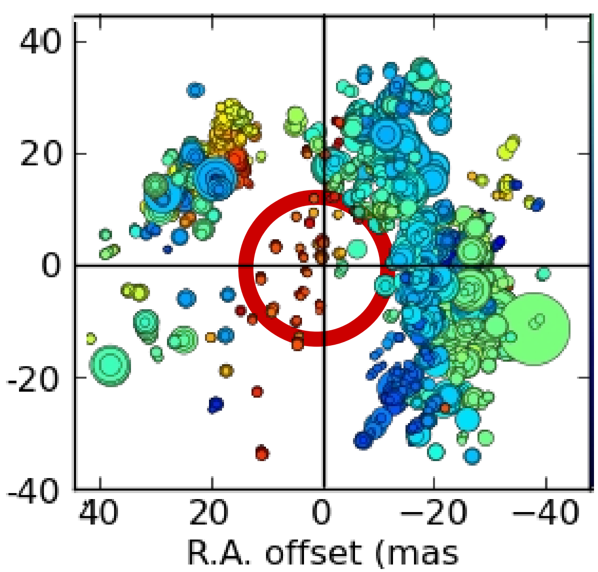
- Maser Zeeman splitting, circular & linear polarization
  - Axisymmetric (dipole?) field
  - Magnetic field enough to deflect and shape wind
    - Not main initiator of AGB/RSG mass loss?



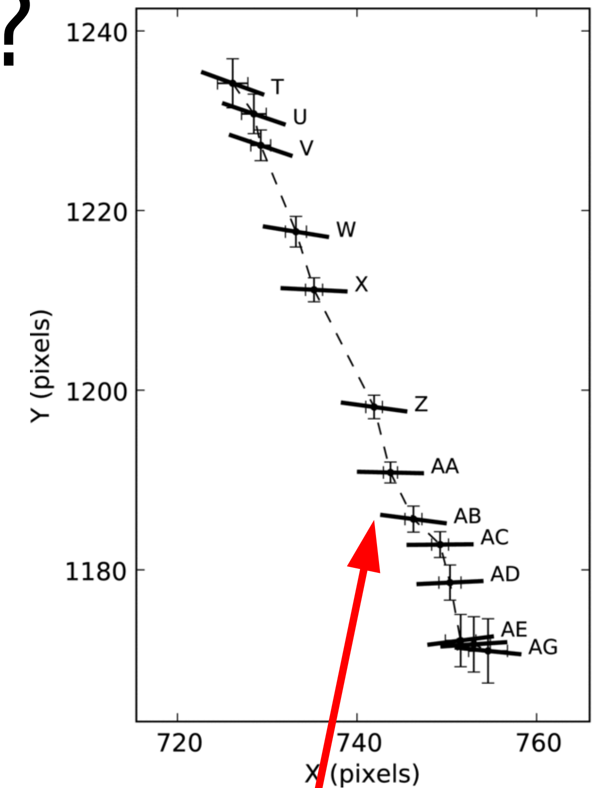



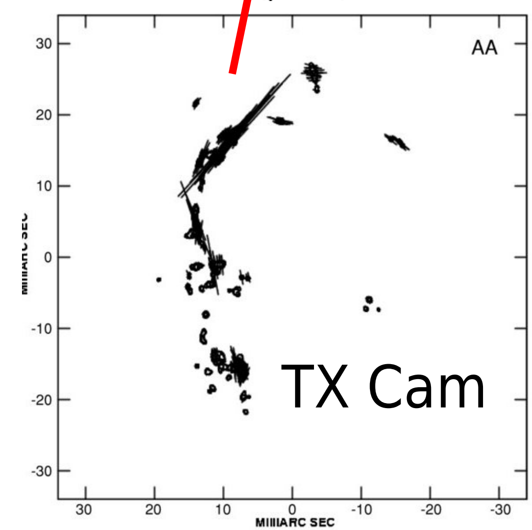
# SiO clumps follow field lines?

- TX Cam proper motions non-radial, non-ballistic (*Kemball+11*)
  - Polarization vectors follow direction of motion
    - Dragged or dragging?
- But ballistic trajectories fitted to IK Tau SiO masers (*Matsumoto+08*)

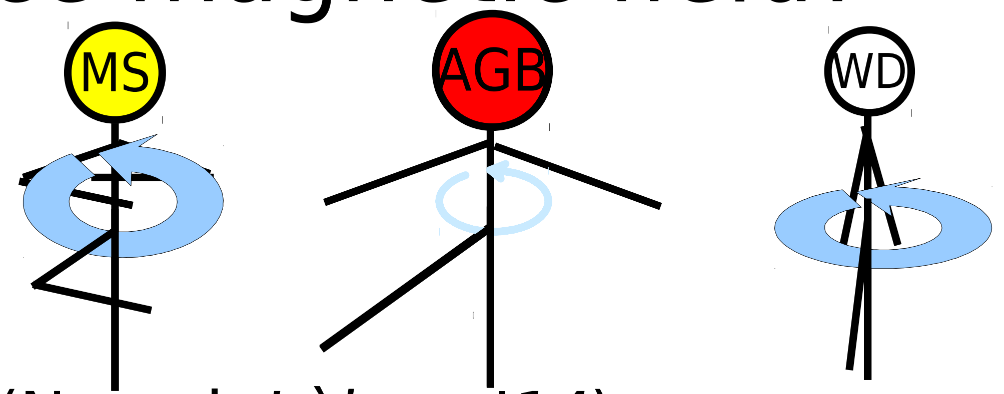



- R Cas shows central redshifted emission (*Assaf+10*)
  - Must be near-side infall



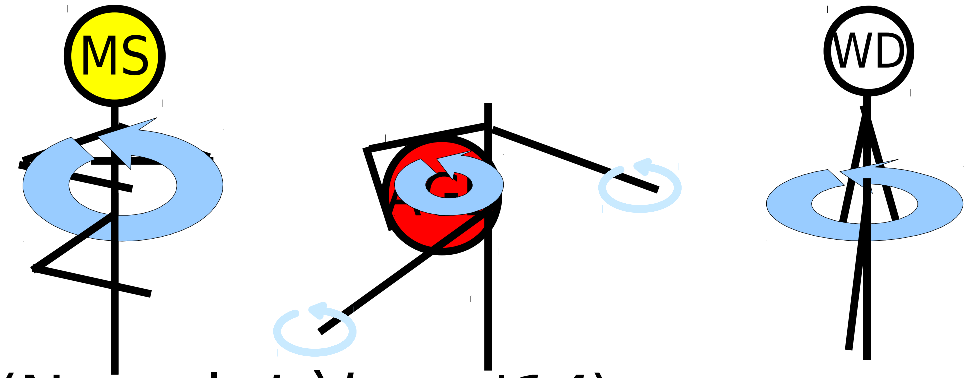



# What is stellar surface magnetic field?




- Solar field 1-1000s G
- Optical spectropolarimetry
  - $\chi$ Cyg (S-type Mira) 2-3 G (Narval, *Lèbre+'14*)
  - Central stars of PNe ≲100 G (VLT, *Steffen et al. 2014*)
- Betelgeuse variable longitudinal field (–3 to +3) G
    - *Aurière+'10; Bedecarrax+13*, Narval/ESPaDOnS
  - Young RSG, surface rotation *P* 25 yr (*Uitenbrock+'98*)
      - No detectable surface rotation in older, solitary AGB/RSG
    - Differential rotation &/or turbulent dynamo?
      - *Blackman+'01, Vogler+'07*
        - » Internal rotation sufficient to align local surface fields?
- ELT/VLTI – resolve distribution/orientation?

# Stellar surface magnetic fields




- Solar field 1-1000s G
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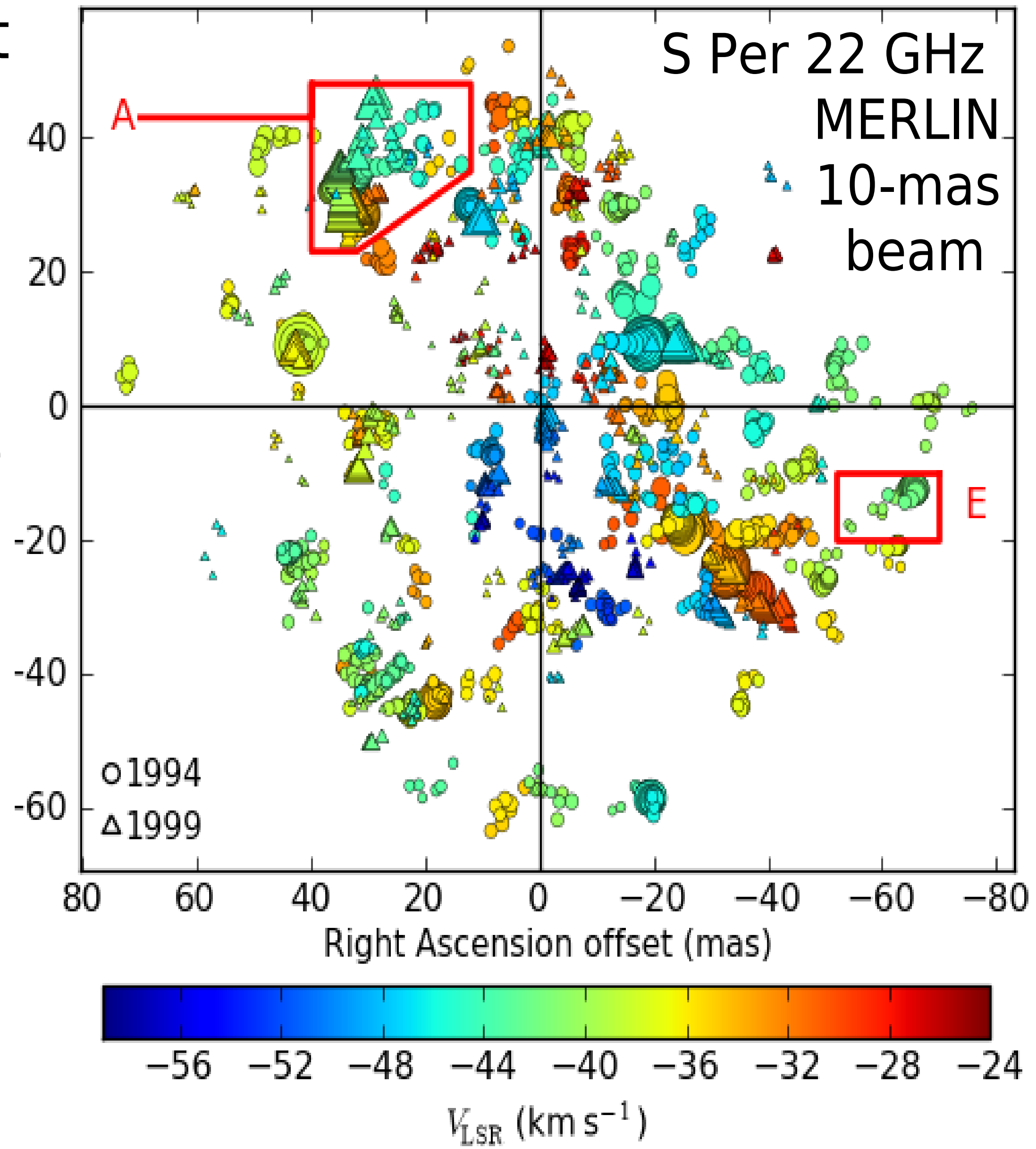
# Water maser cloud measurements

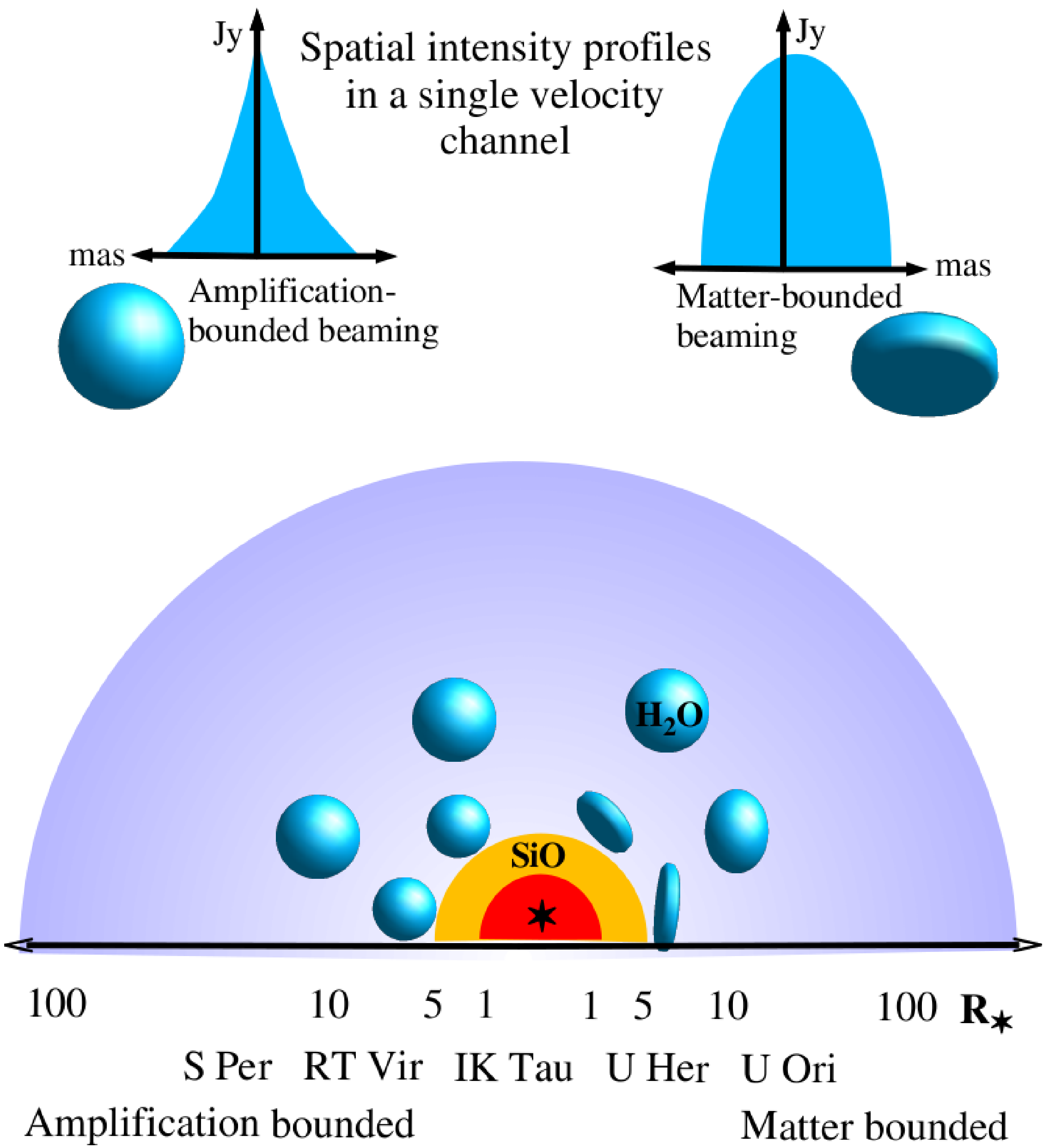
- Fit 2D Gaussian component to each spot:
  - Measure beamed size
  - Spots in 1-2 km s$^{-1}$ series
- Series = discrete clouds
  - Clouds 30–100 x overdense
    - Filling factor <1%
    - Contain 30-90% mass
  - Few formed per stellar P
- Beaming angle

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



# Maser properties reveal wind disturbances

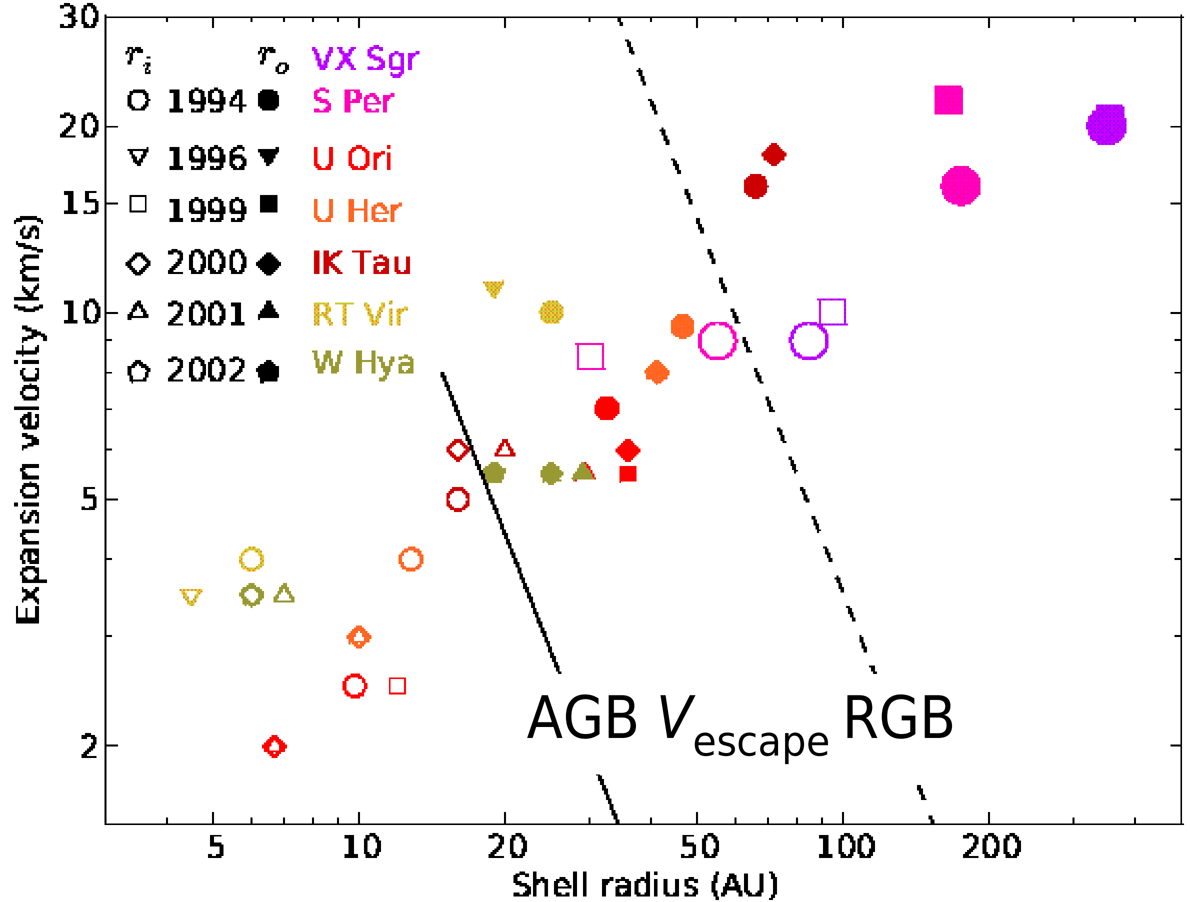
- Brighter spots smaller beamed size?
  - $s \propto 1/\mathrm{sqrt}\,[\ln(I_\nu)]$
    - Smoothly expanding spheres
- Brightest emission ~true cloud size?
  - Rapid maser variability
  - Stars with deepest periods
    - **Shocked slabs**



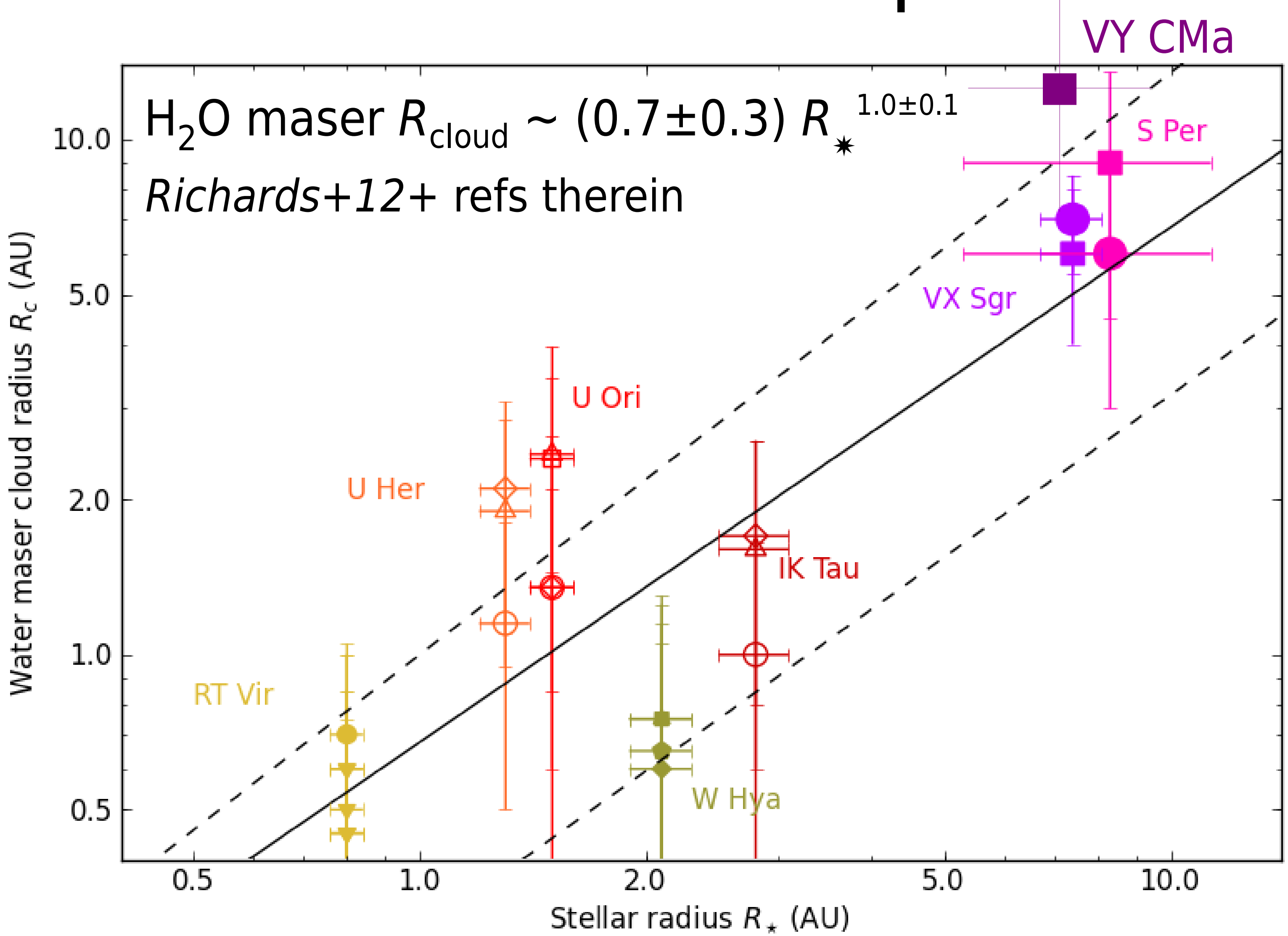

*Richards Elitzur & Yates 2011*
*Elitzur Hollenbach & McKee 1992*

# What accelerates the wind?

- Water maser shell limits show $V_{exp} \propto r$ (*Richards+'12*)
  - Neither pulsations nor grain growth operate at ≫ 5 $R_*$
- $\tau$ or momentum coupling changes? (*Ivezic & Elitzur'10)*
- Dust absorption efficiency evolves?
  - *Chapman+'86; Verhoelst+11*
- Also seen in Herschel lines (*Decin + '10*)
- Wind accelerated through $V_{esc}$ while crossing 22-GHz shell



# Maser cloud size depends on star size

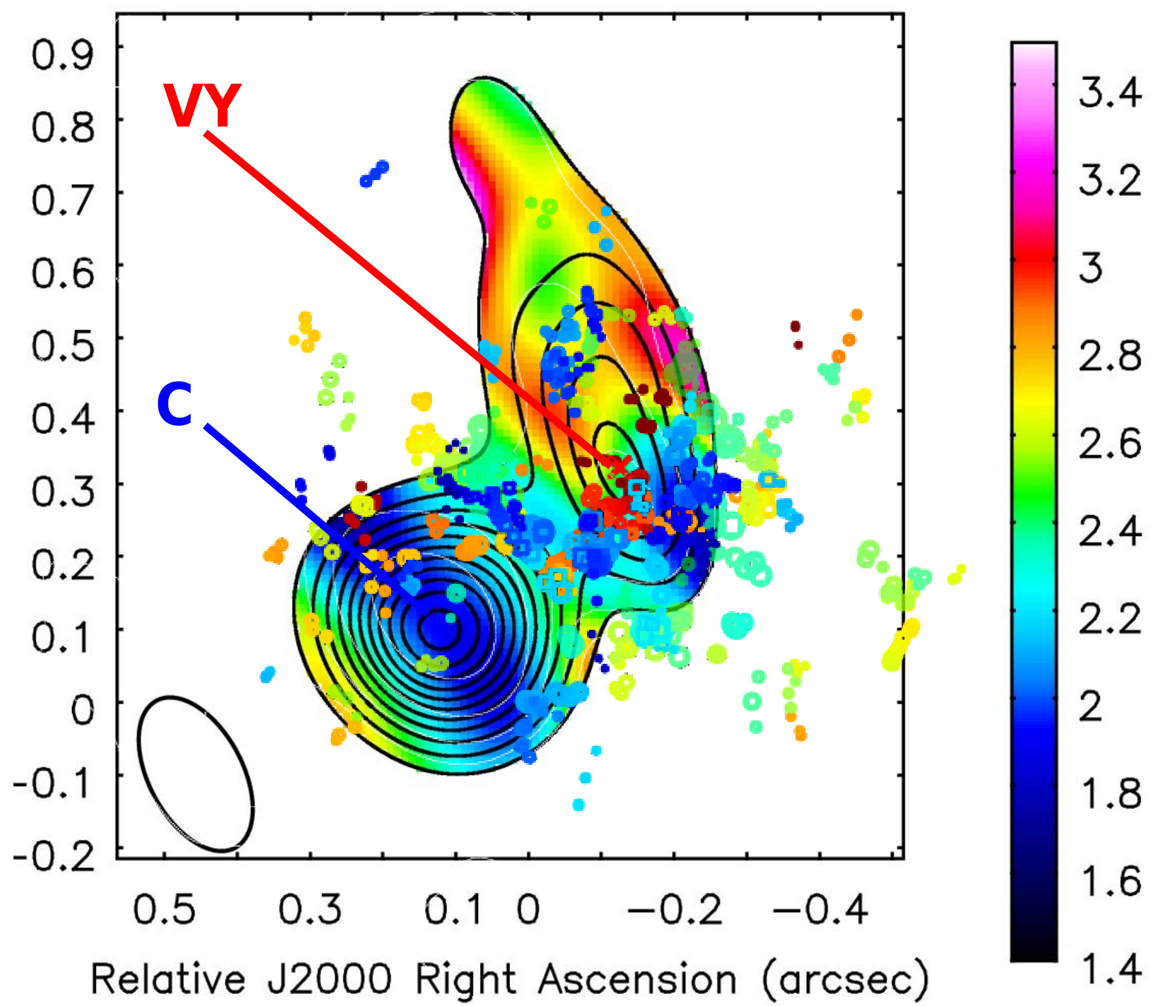



- Cloud properties determined at ejection from star
  - Not micro-physics of dust cooling
- If outflow expands as $r^{-2}$, birth radius (5–10)% $R_\star$

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

# ALMA Science Verification: VY CMa

- Spectral index shows dust warmer round 2nd peak VY
  - Dense Clump coolest
- At least 17% dust concentrated in clumps
- N, SE extensions show wind asymmetries must have persisted for decades
  - ≫convection cell lifetime



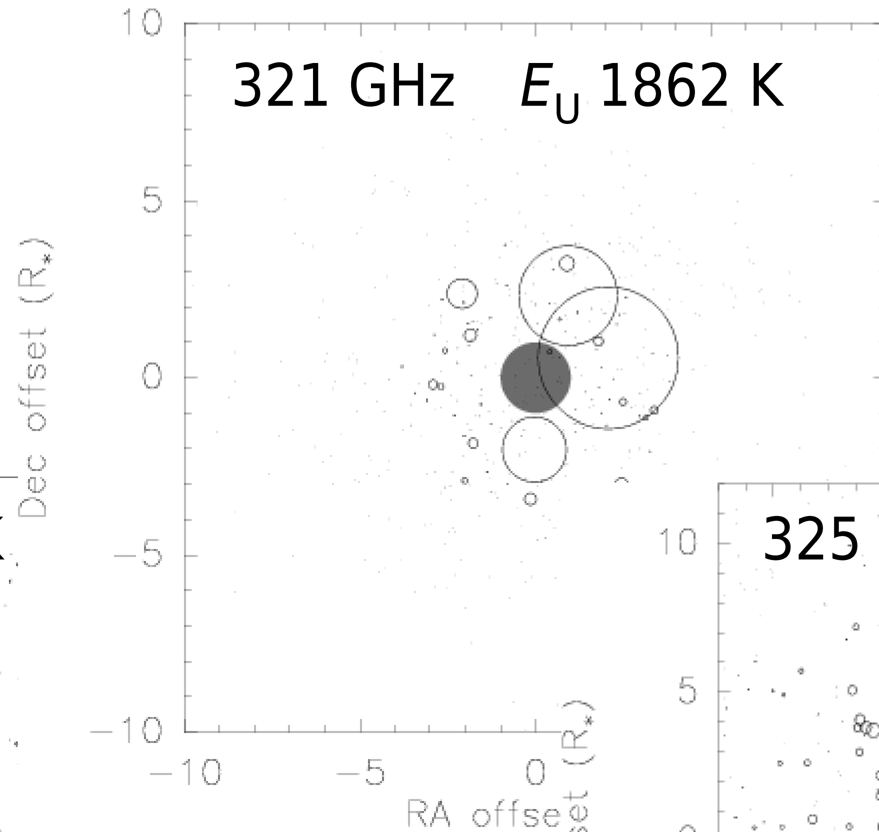

Colour: 321-658 GHz spectral index

Symbols: 321-GHz masers

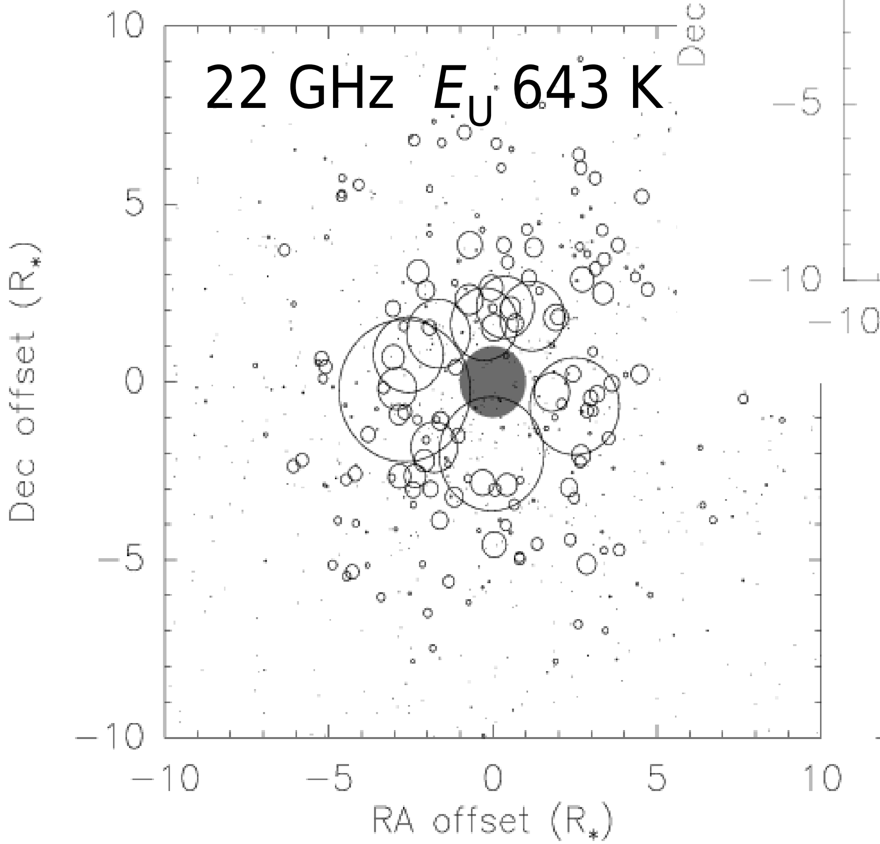
*O'Gorman+'14, Richards+'14*

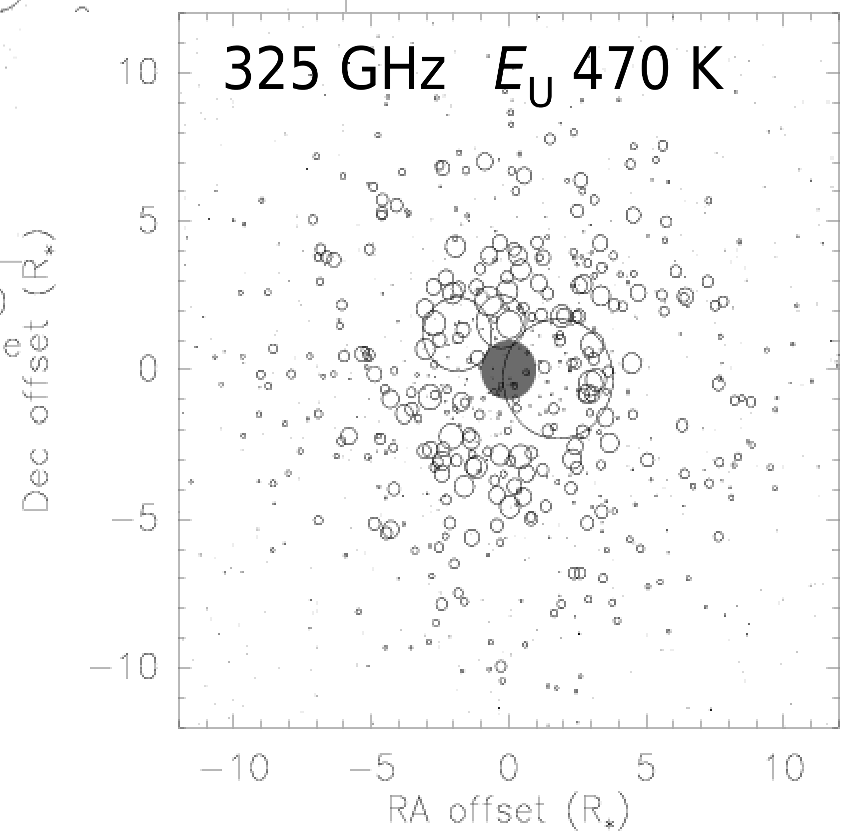
# Sub-mm water maser predictions

*Humphreys+'01*
*Neufeld+'91,'10*



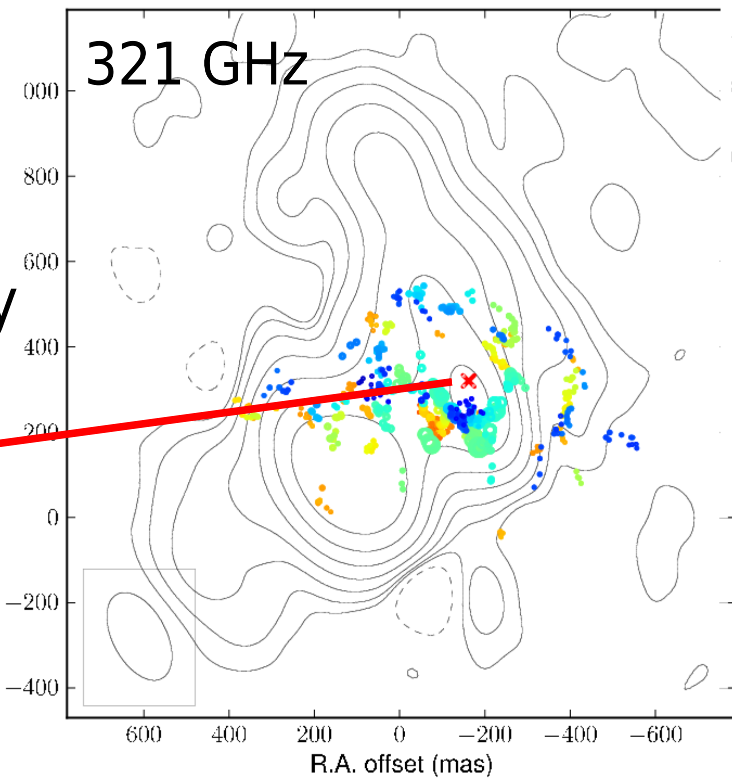

658 GHz $E_U$ 2361 K
Expect to be even more compact (in SiO zone)

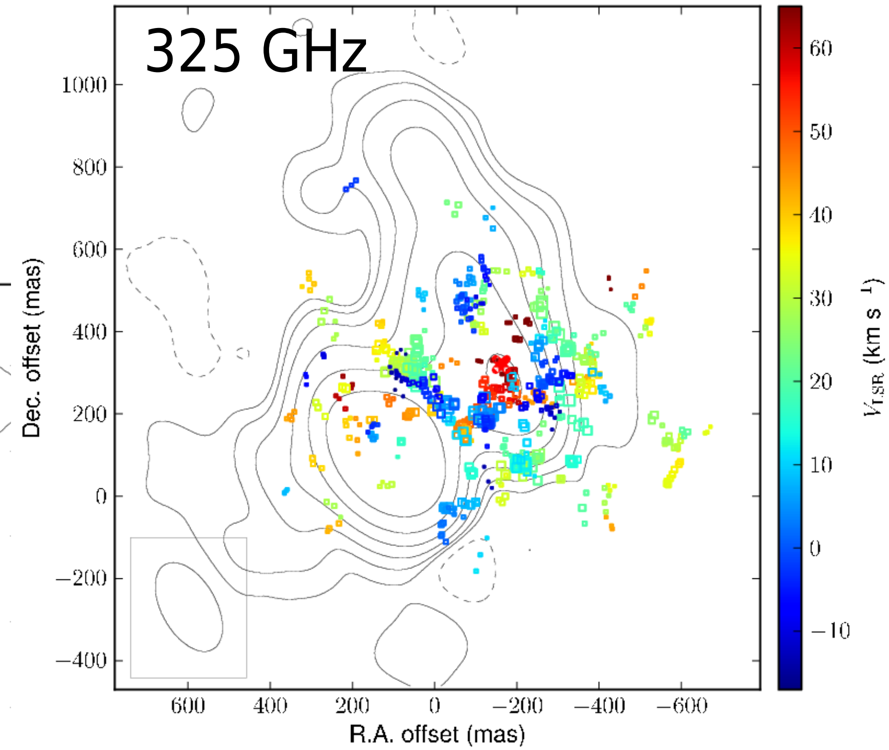


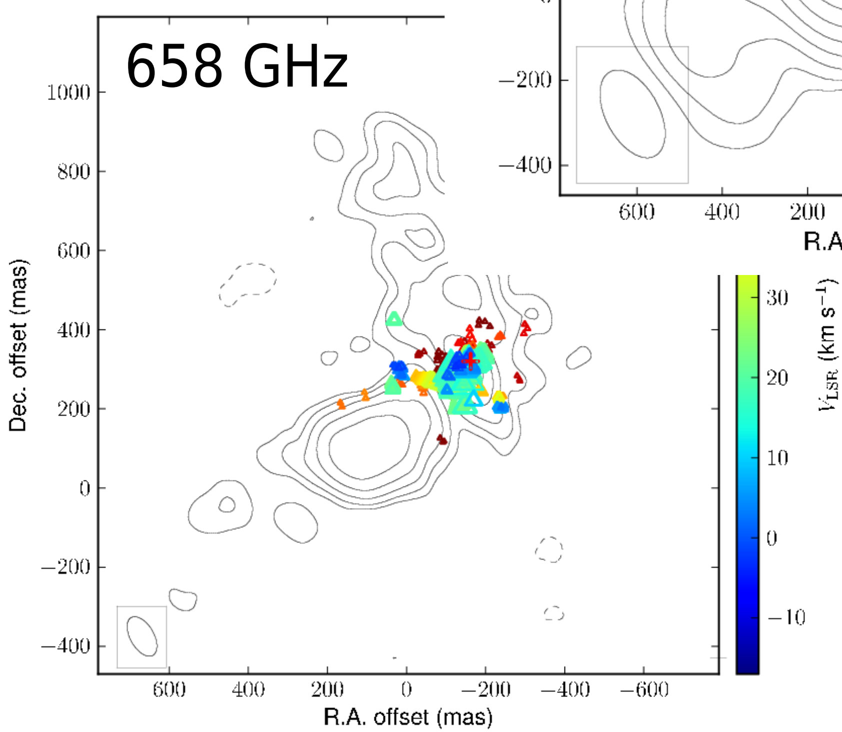



# First resolved stellar sub-mm $H_2O$ masers

- Expanding away from 2nd peak
  - Astrometry of VY CMa star! **VY**



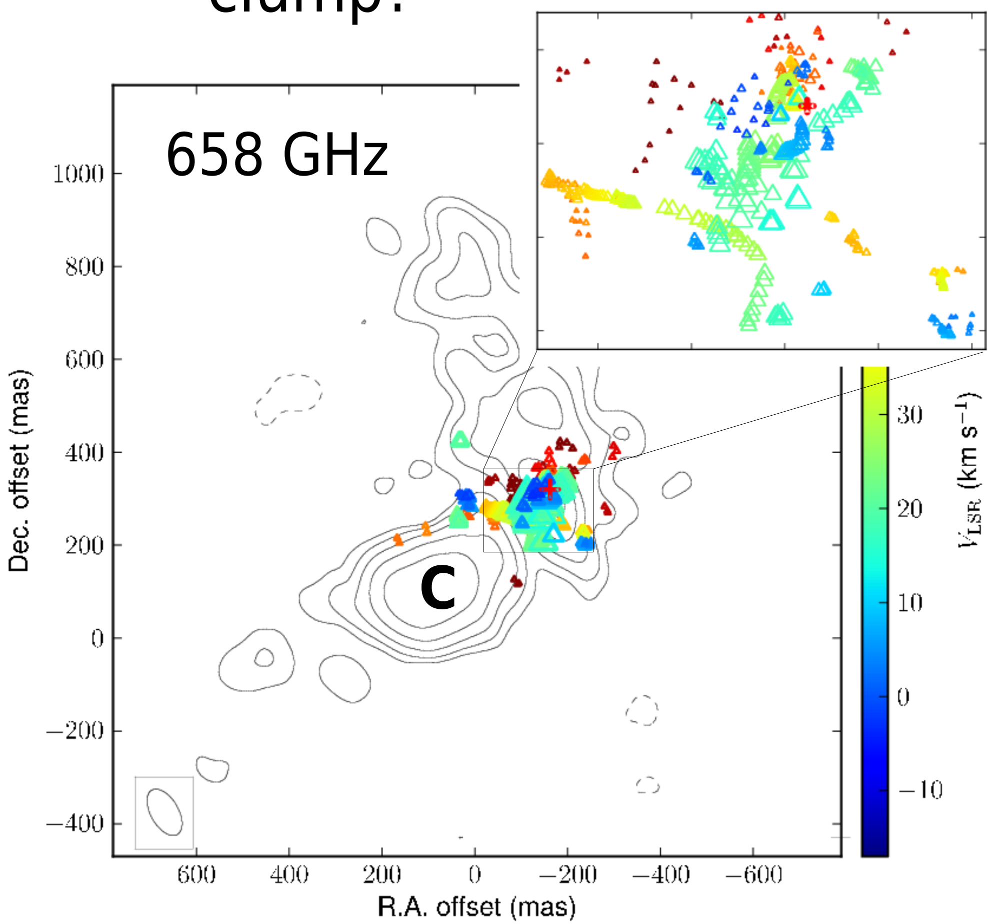



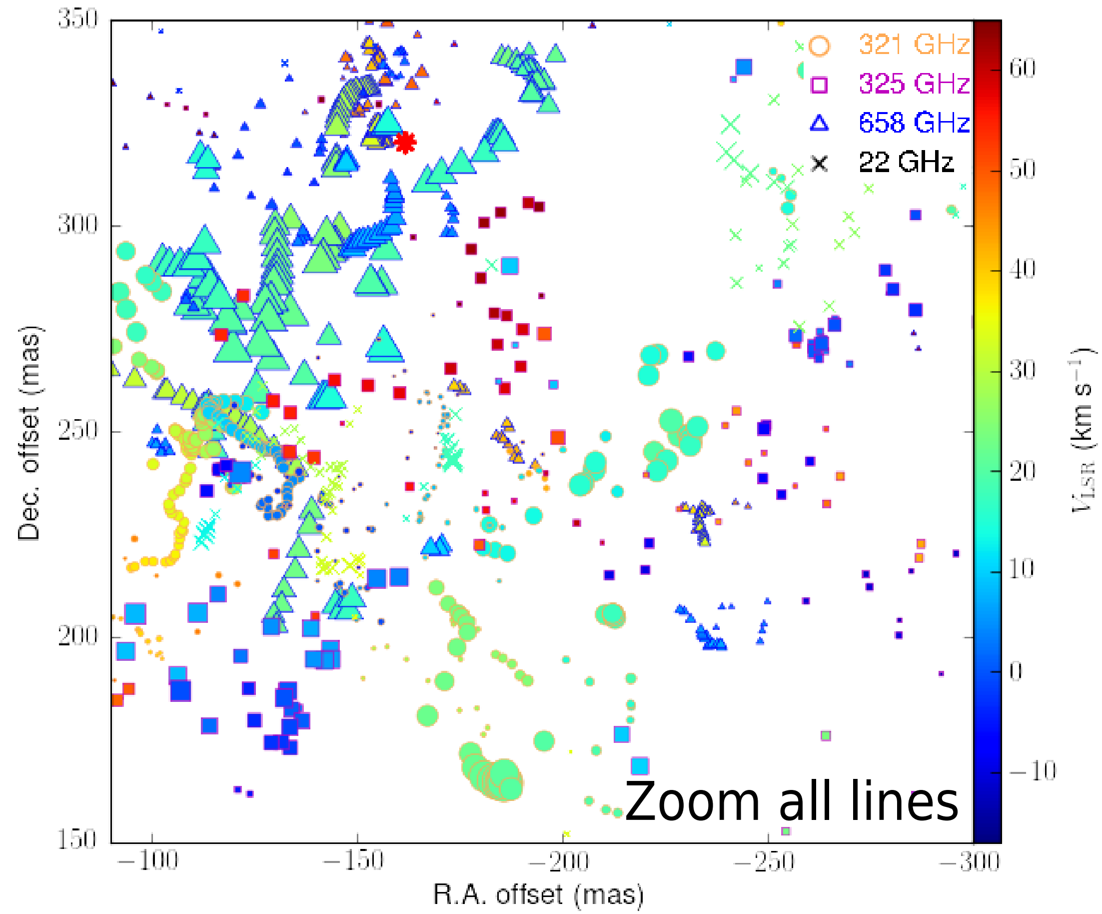




- 325-GHz most extended, as predicted
  - Moderate acceleration
- 321-GHz similar distrib. to 22 GHz
  - Strong acceleration
- 658-GHz starts at few $R_{\star}$, inside dust formation radius – OK
  - Extends to tens $R_{\star}$!

# Shocks and inhomogeneities

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

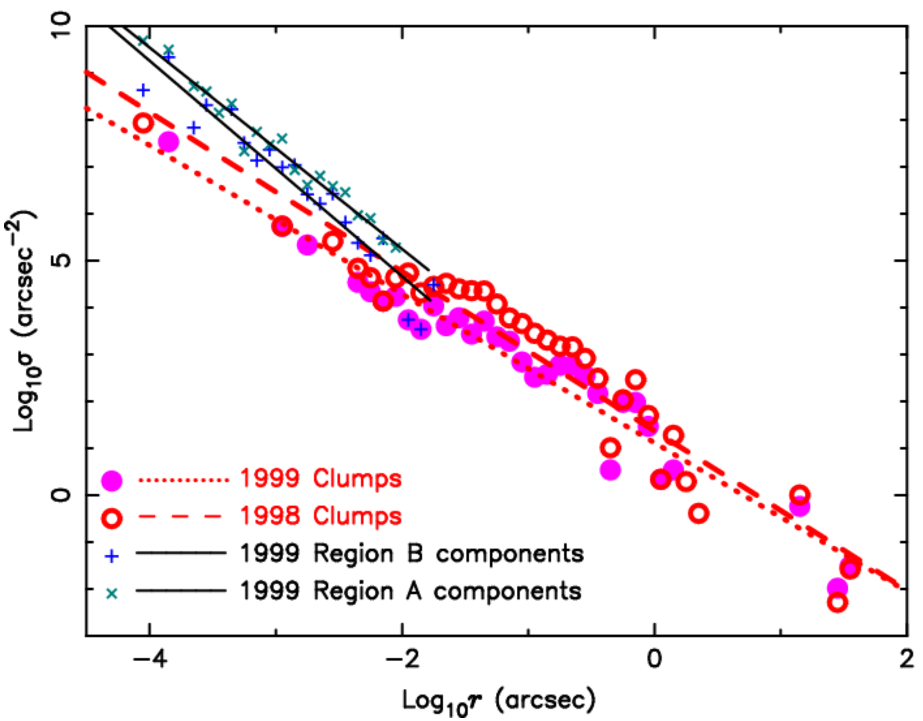



- Can shock heating explain extended high-excitation lines?
- Species separate 10-au scales
  - At similar radii but in different-density environment/clumps?
    - Not co-propagation

# 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*

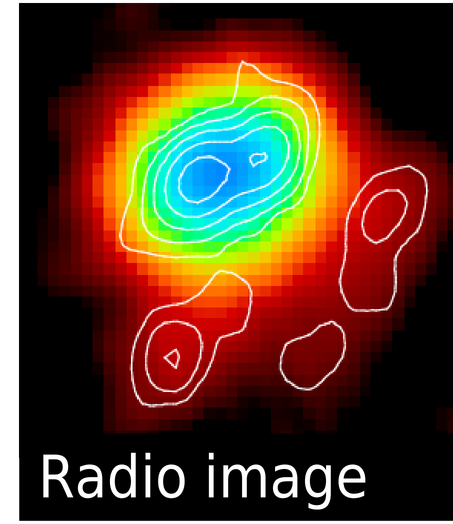


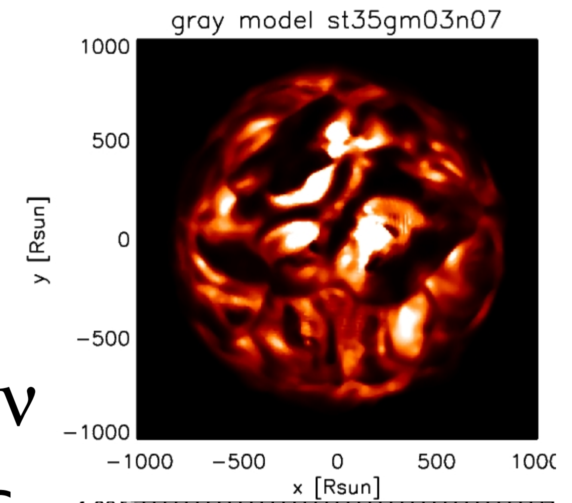

SFR S128A (22 GHz)

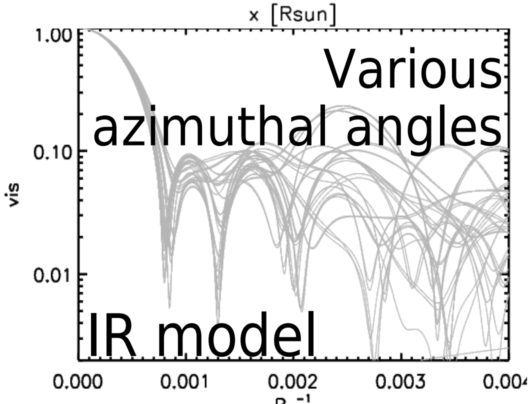
- *Richards, Lekht+'04*

# Summary I: trace stellar ejecta

- VLT(I)/ELT: deepest &/or hottest layers
  - Polarimetry- magnetic/convection link?
  - Chemical tracers?
- VLTI difficult to constrain unique model
  - Need enough time/UTs for good image!
    - ELT speckle?
- Radio interferometry successive epochs/ν
  - ALMA, VLA, e-MERLIN 10 – 50 mas beams
    - Coordinate, resolve nearby AGB/RSG stars
      - How are clumps ejected from surface?
    - Is there a link with convection cells
    - Does this lead to segregated chemistry?

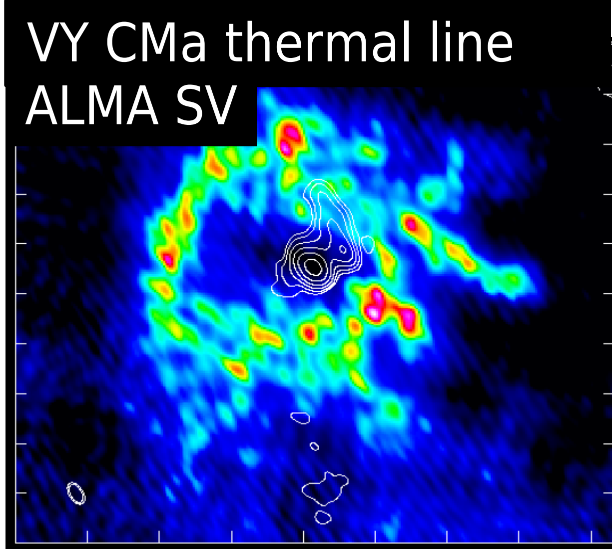



*Chiavassa+'11*

# Summary II: stellar winds




- Full resolution ALMA: resolve maser & thermal molecular/dust clumps
  - Is maser acceleration coupled to dust properties?
    - Can we see $V_{\mathrm{drift}}$ increasing as density drops?
- ALMA + high-res optical/IR
  - Dust formation, composition (spec. index, bands)
- VLBI to resolve maser proper motions, spots
  - Kinematics, fractals, co-propagation/maser physics…
    - Shock diagnostics on sub-au scales
  - ALMA in VLBI (+ subarrays/VLBA/LAMA for 10s-100s km)
- Complement cm masers with e-MERLIN/ VLBI /RadioAstron