Detailed SiO proper motion analysis
slow net expansion, small correlation with mag. field

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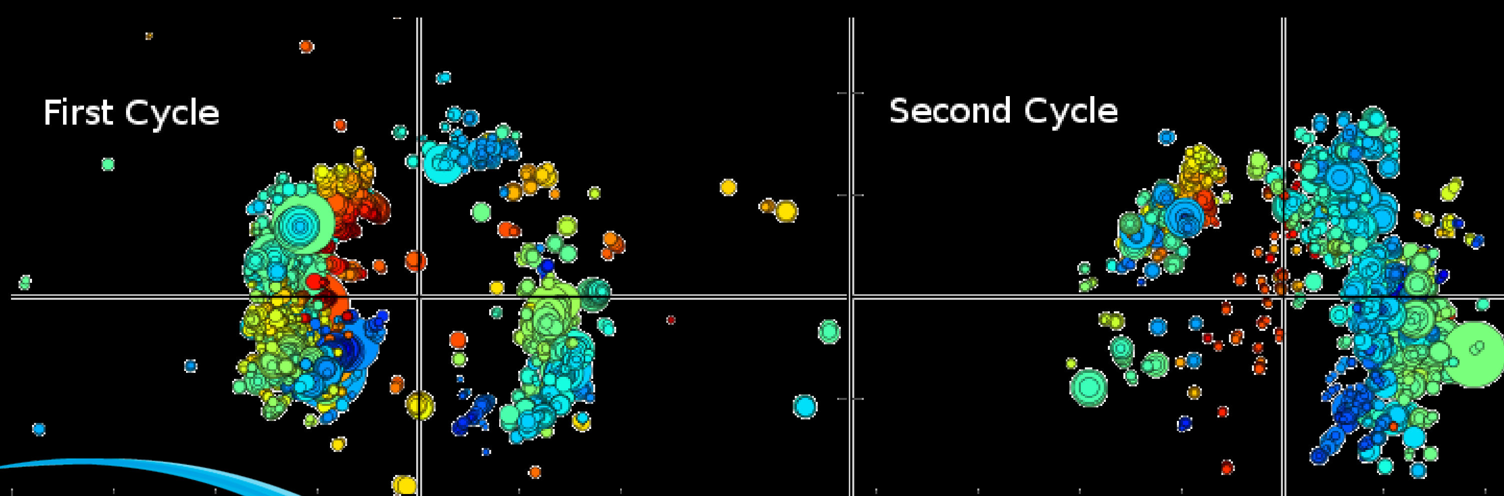
Presented on behalf of Khudhair Assaf, University of Wasit, Iraq;
see *Assaf, K. 2018 ApJ (submitted), Assaf et al. 2011, 2013*



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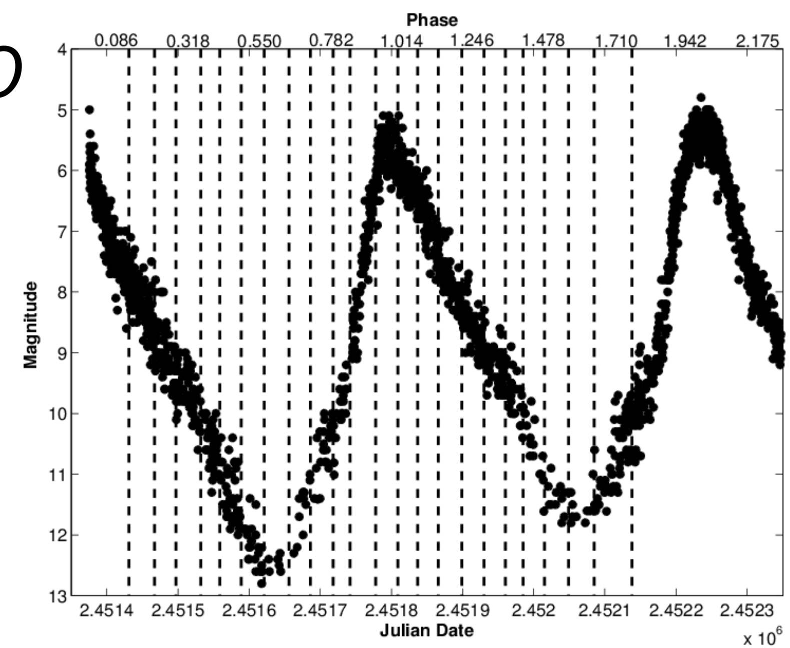
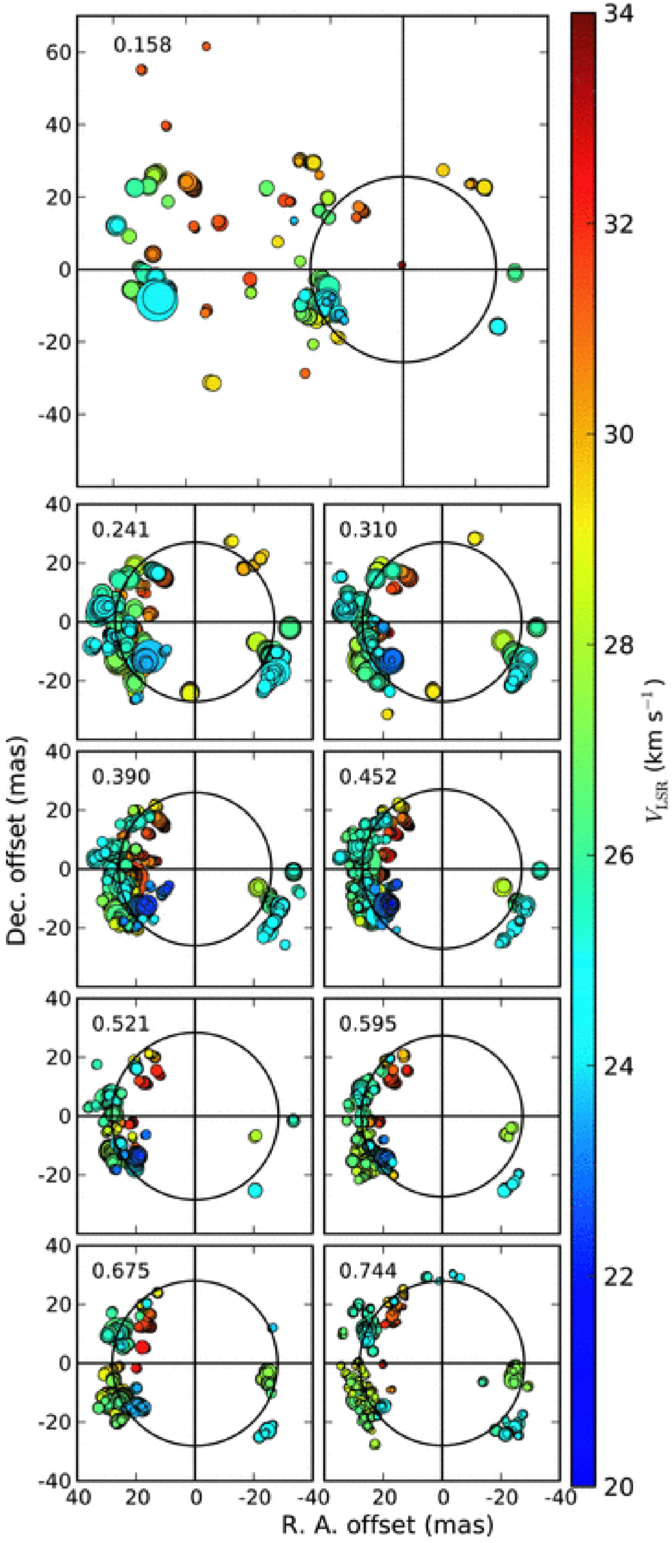
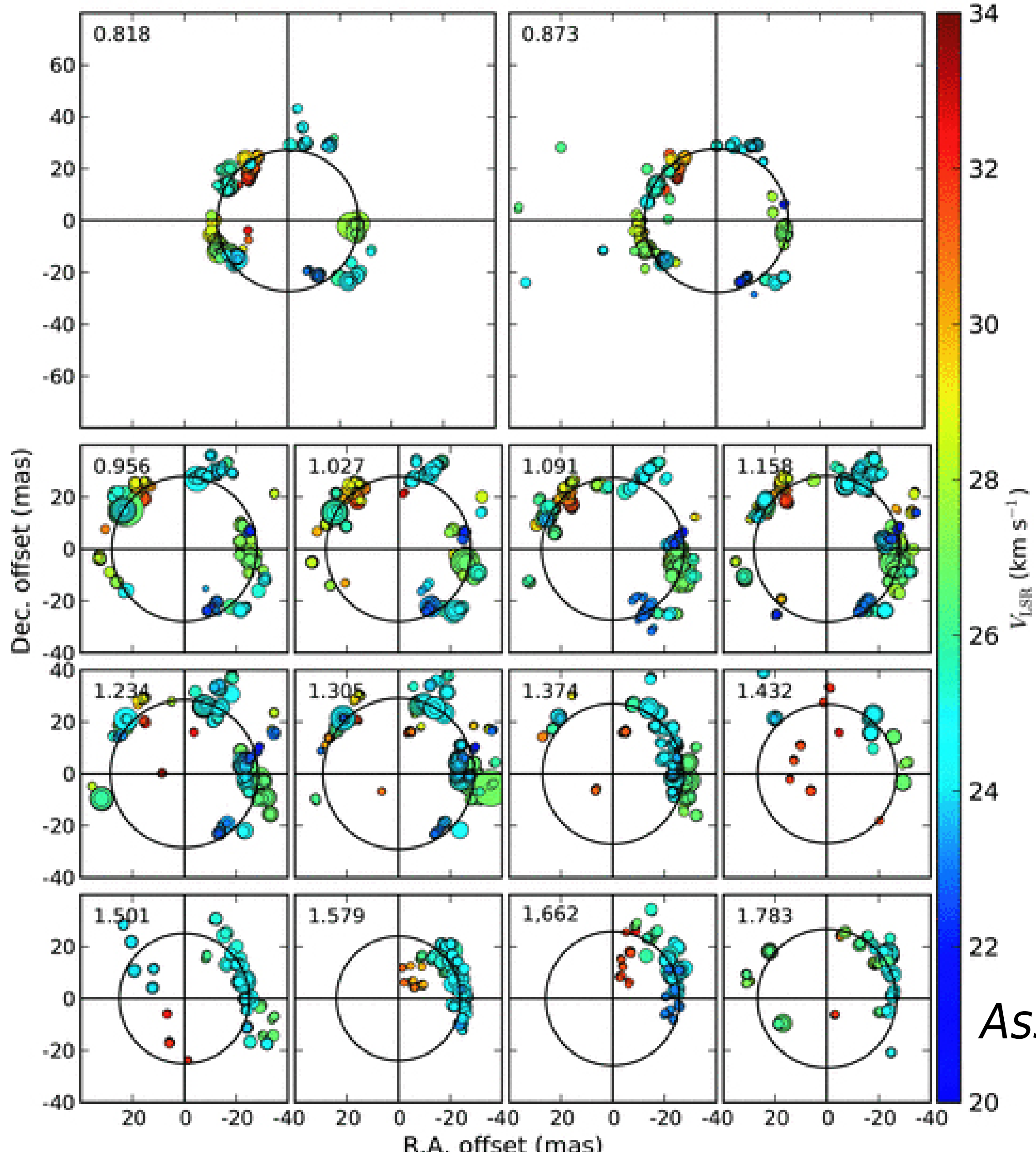
AGB star R Cas: vital statistics

- Distance ~176 pc — *Vlemmings+'02*
- $V_{\star}$ ~24 km/s — *Assaf+'11 & refs*
- $M_{\star}$ ~1.2 $M_{\odot}$ — *Truong-Bach+'99*
- $R_{\star}$ ~ 12.6 mas (2.22 au) — *Weigelt+'00*
- $\dot{M}$ ~ 6–10x10^{-7} $M_{\odot}$ /yr — *Weigelt+'01; Truong-Bach+'98*
- P ~ 430 d — *AAVSO*
- Observed for 23 epochs over 2 stellar periods using VLBA
- Polarization angle calibration accurate to ~10^{o}
- Fractional linear pol. accuracy ~5%



R Cas SiO ϕ 0.1 - 1.8





v=1
J=1-0

43 GHz

Assaf+ 2010

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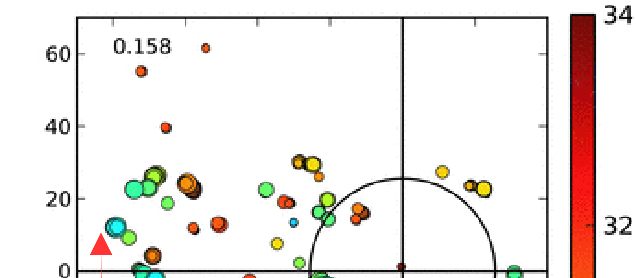
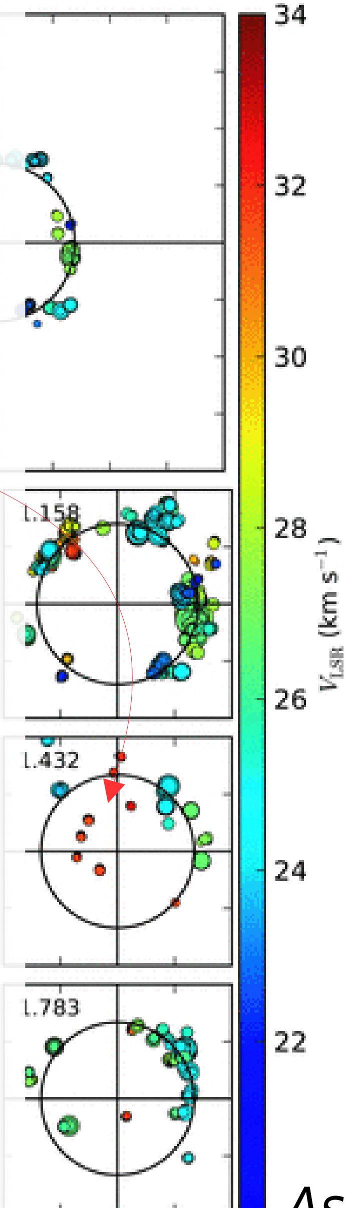


- Ring shown is average maser radius
  - Except for a few epochs where an outer remnant double shell is still detectable
- Some faint emission in front of star
  - Mostly red-shifted, infall
- Max. Doppler (line of sight) V_{exp} 10 km/s
- Adopt 'main ring' between R_* and max. radius of single-shelled epochs
  - 12.6 – 44 mas (2.22 – 7.7 au)
  - Assume that ring-like appearance is due to tangential beaming
    - Greatest component of motion is in plane of sky



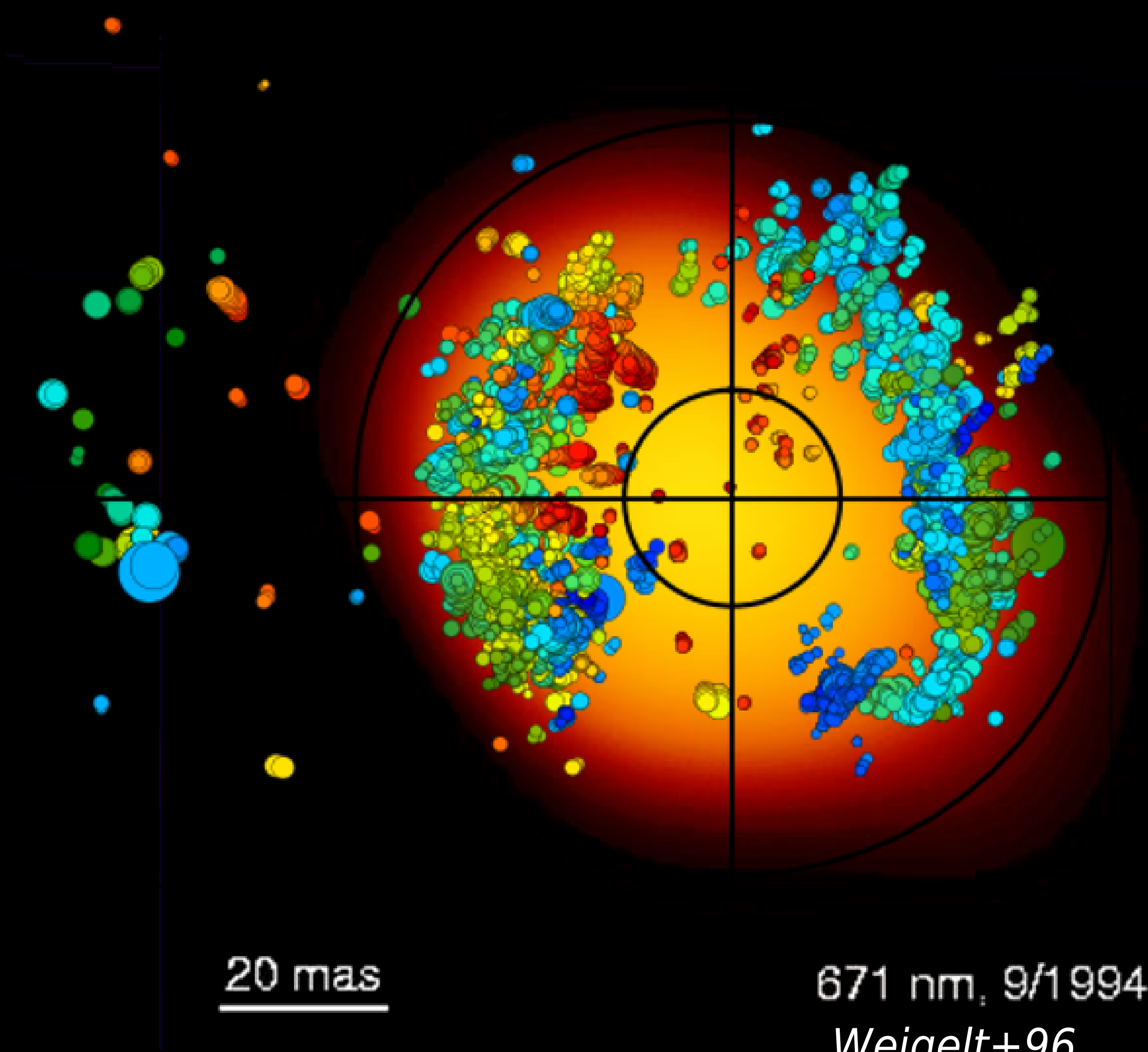
Assaf+ 2011

Masers and the star

Inner circle:
deconvolved
stellar disc
$R_{\ast}$ =2.22 au

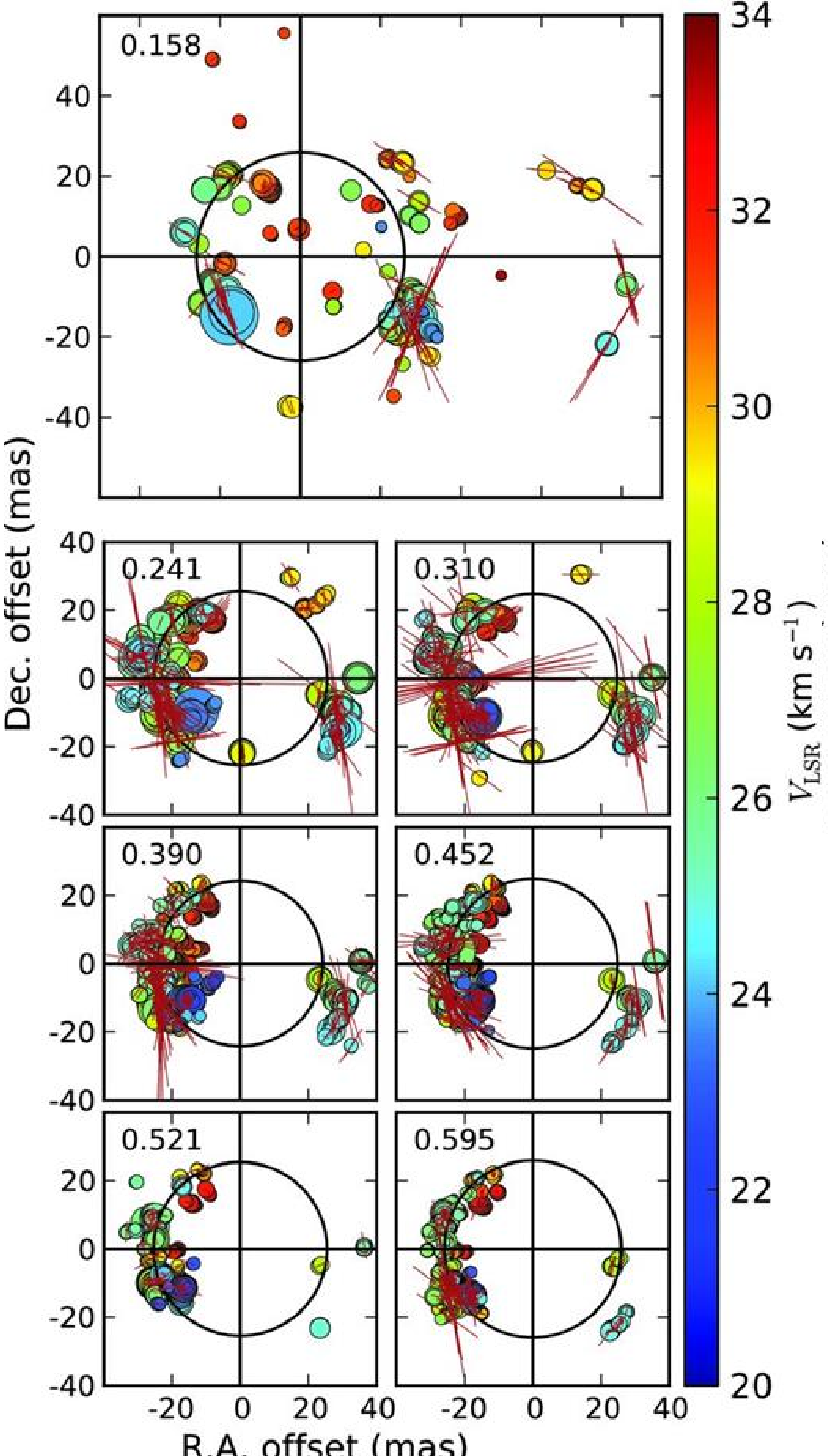
Outer circle:
limit of 'main'
SiO maser ring
$R \sim 3.5\ R_{\ast}$
(outermost 8 $R_{\ast}$)

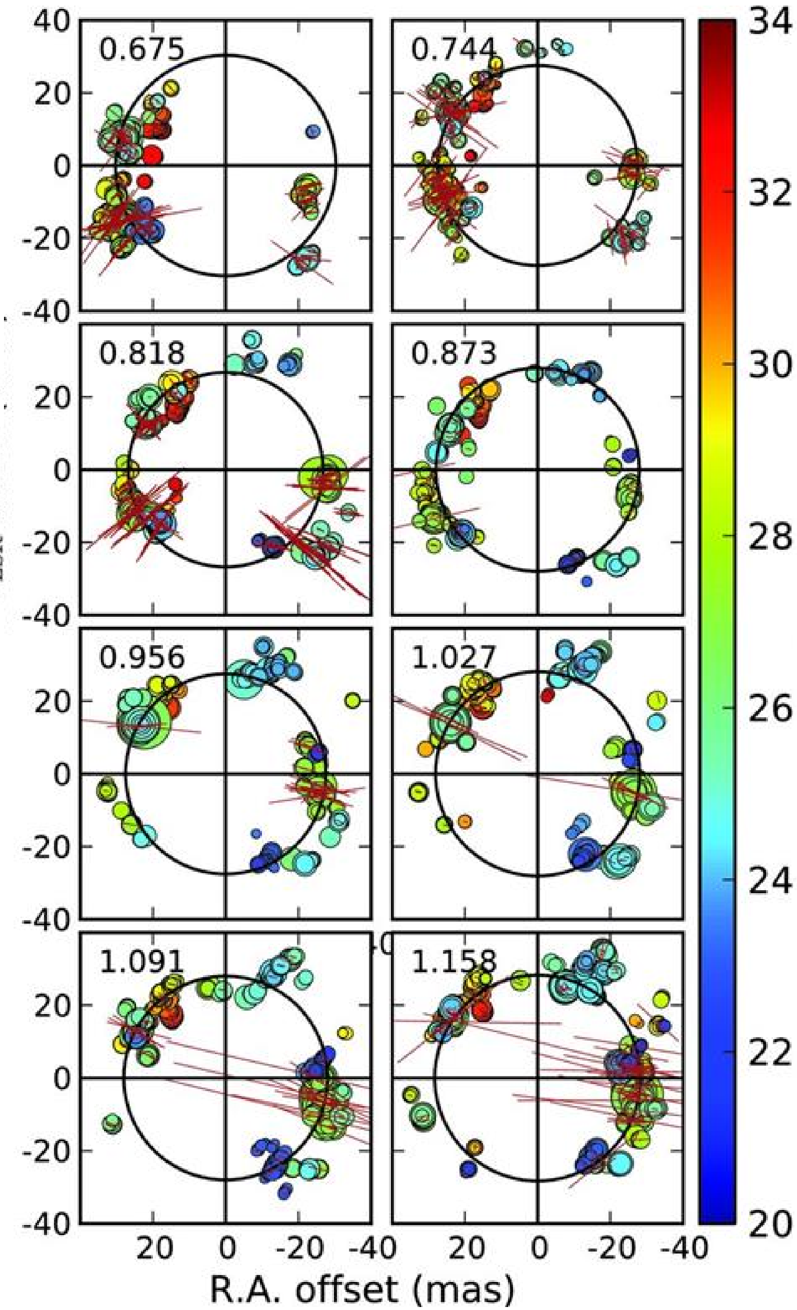
Obs. other stars
suggests radio
photosphere at:
22 GHz~ $2R_{\ast}$
5 GHz~ $6R_{\ast}$



Weigelt+96

R Cas polarization





brown:EVPA

- Mean linear polarization per epoch 10% – 60%
- Possible overestimate as total intensity is smoother and more resolved-out than Q & U

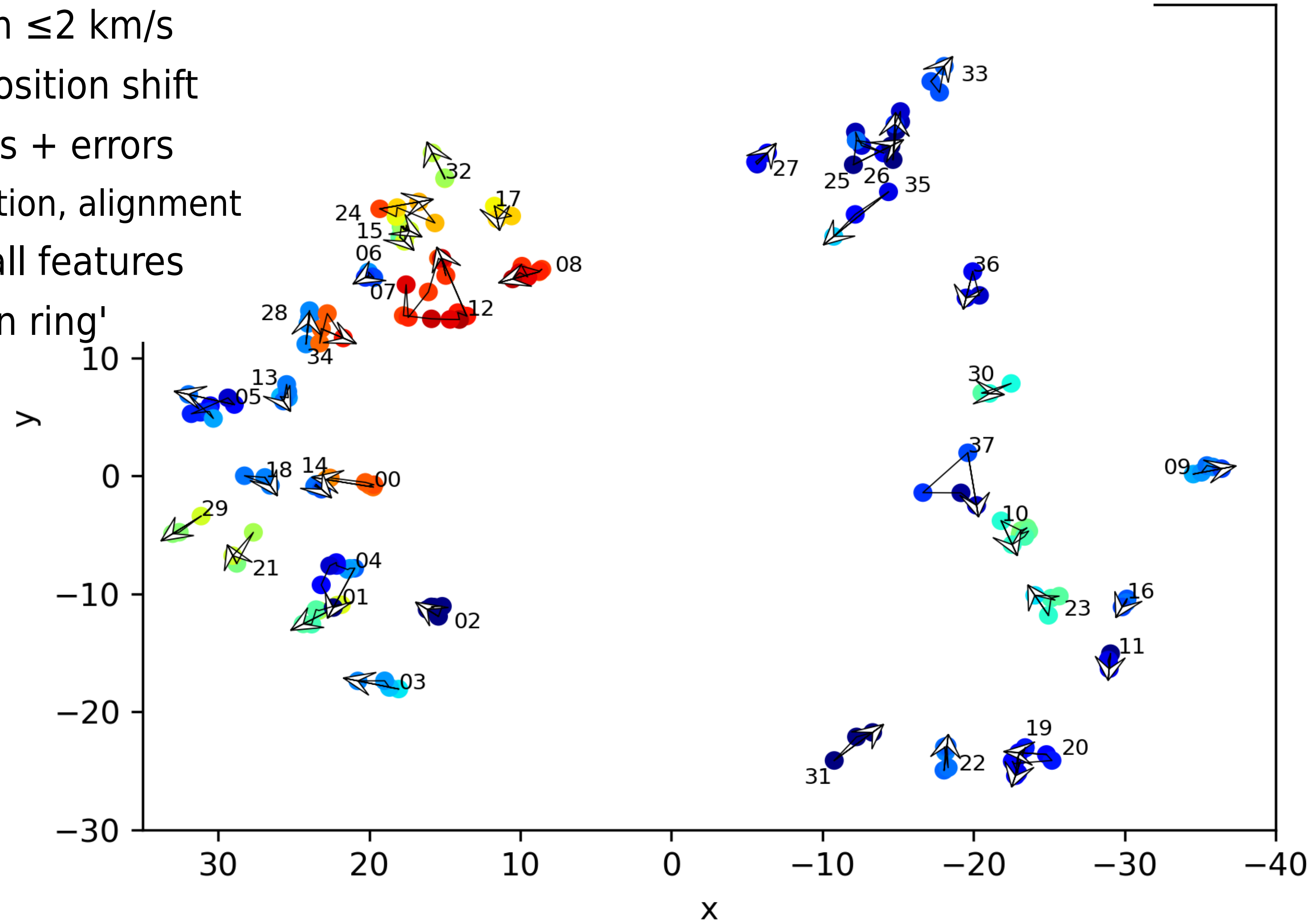
Assaf+ 2013

R Cas polarization

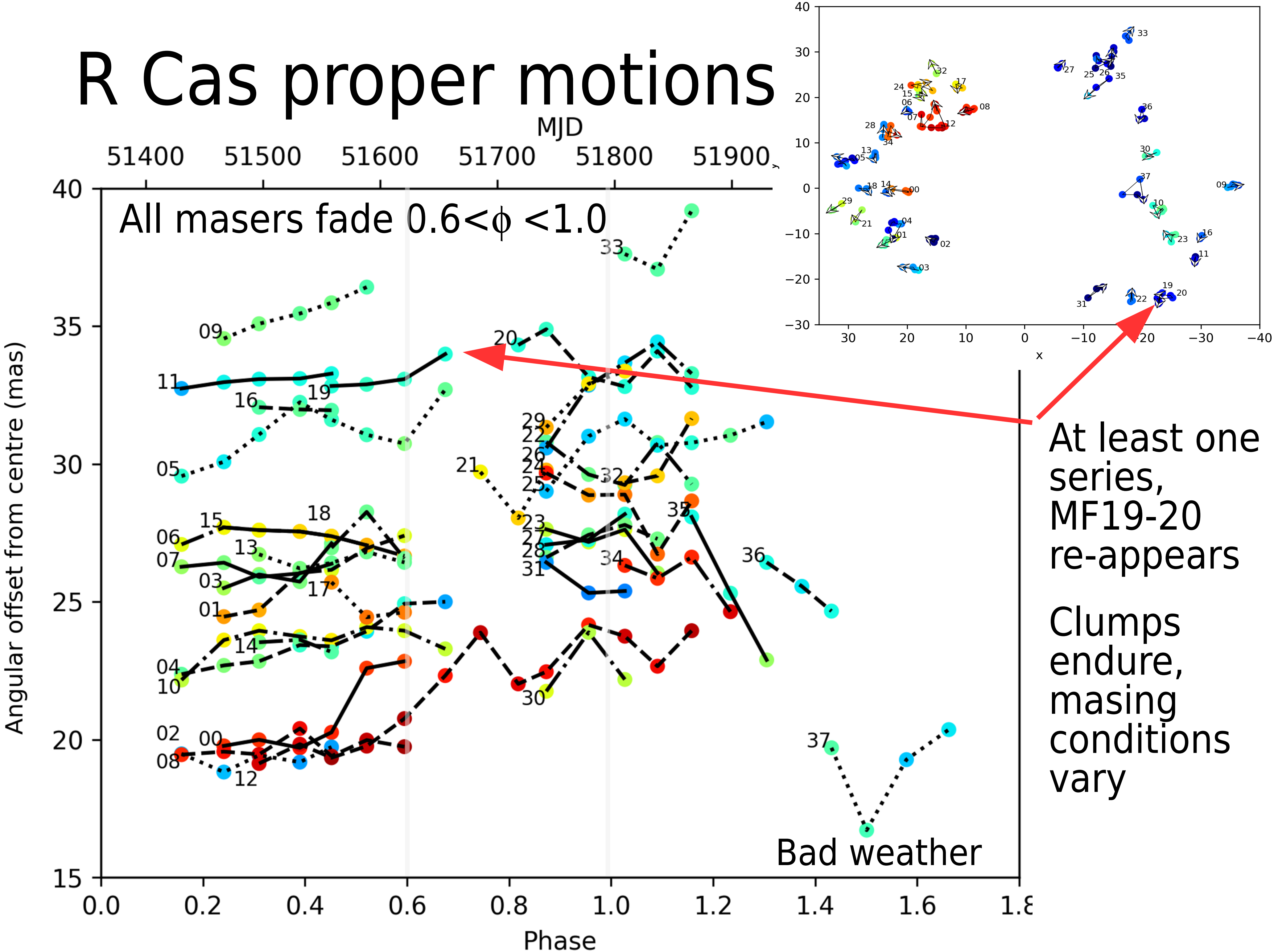
- For this transition radiative decay rate $\Gamma < 1\ s^{-1}$
- Stimulated emission rate for saturation (*Kemball+09*) $R = 23\ (T_b/2\times10^{10}\ K) \times (d\Omega/0.01\ sr) \sim 15\ s^{-1}$ using:
  - Estimated mean T_b $2.8\text{x}10^9$ K (suggests saturation)
  - Beaming angle $d\Omega$ 0.047 sr
- Zeeman splitting of 86 GHz SiO (single dish)
  - Magnetic field 0.9 – 2.8 G (*Herpin+06*)
  - SiO Zeeman splitting rate $g\Omega \sim 900\ s^{-1}$ (*Plambeck+'03*)
- $g\Omega \gg R \gg \Gamma$
- All supporting **Zeeman (magnetic) polarization origin** (*Goldreich+'73*)

R Cas proper motions

- 38 series of features matched for ≥3 epochs (max. 13)
  - Separation ≤2 km/s
  - ≤3 mas position shift
    - 20 km/s + errors
      - Position, alignment
  - ~20% of all features
  - All in 'main ring'



R Cas proper motions

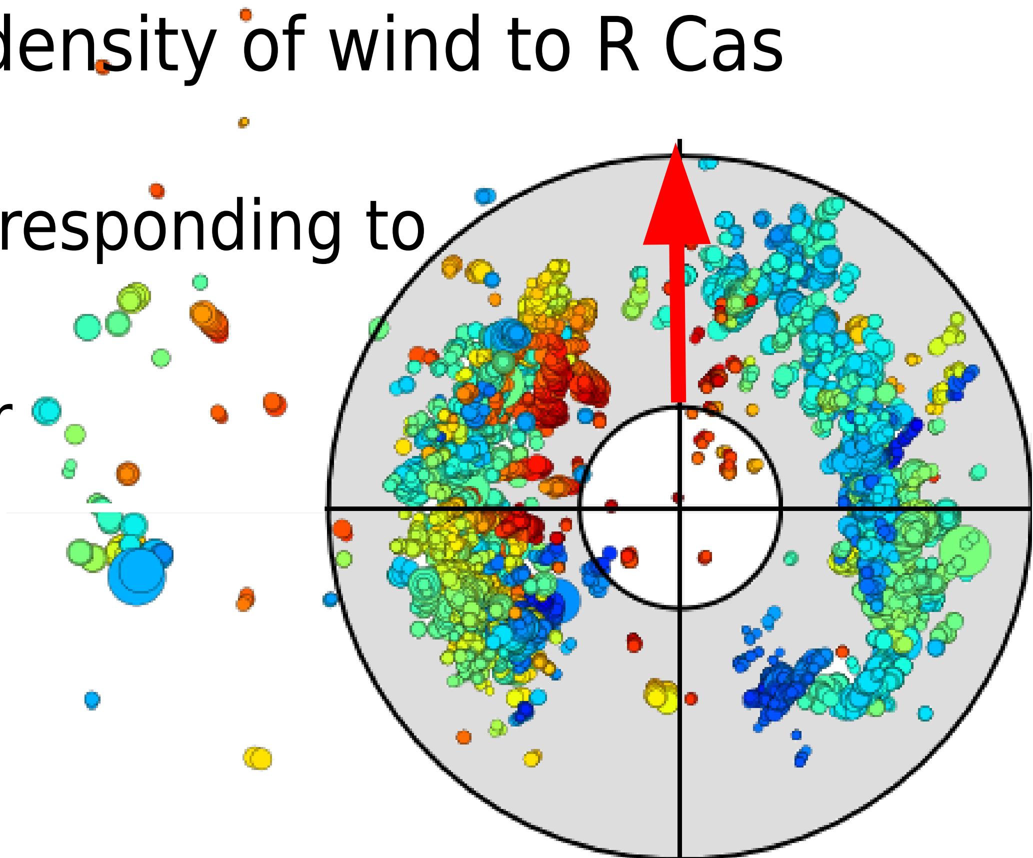


At least one series, MF19-20 re-appears

Clumps endure, masing conditions vary

Transport of mass from star

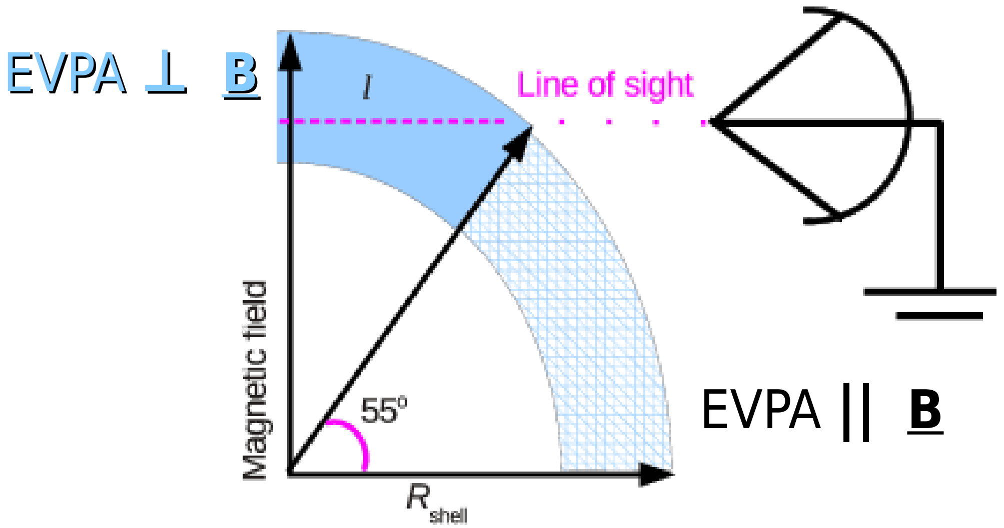
- Average radial proper motion over 2 yr +0.4±0.1 km/s
  - Lower limit to V_{exp} (if entirely in plane of sky)
    - Upper 3D limit ~0.4 x √2 km/s
  - Wind takes ~67–47 yr to cross main ring
- Scale *Ireland+'11* model density of wind to R Cas stellar properties
  - Mass in spherical shell corresponding to main ring is 2.4×10^{-5} $M_\odot$
    - Implies $\dot{M}$ $4\text{-}6 \times 10^{-7}$ $M_\odot$/yr
      - Upper limit agrees with *Weigelt+'01* dust $\dot{M}$
- No systematic rotation



Mass in SiO clumps

- Estimate volume in clouds from epochs with most maser clumps
  - Assume clumps are typical of all epochs even if not masing
  - Average clump extent 0.3 au
    - Matched clumps tend to be larger ~0.44 au
  - Filling factor ≲1%, average mass per clump ~2.6×10^{-9} $M_\odot$
    - Total mass in clumps per epoch ~1.4×10^{-7} $M_\odot$

- Angle between EVPA and magnetic field vector **B** depends on angle θ between **B** and line of sight (*Goldreich+'73*)
  - θ <55^o (van Vleck angle) gives EVPA perpendicular to **B**



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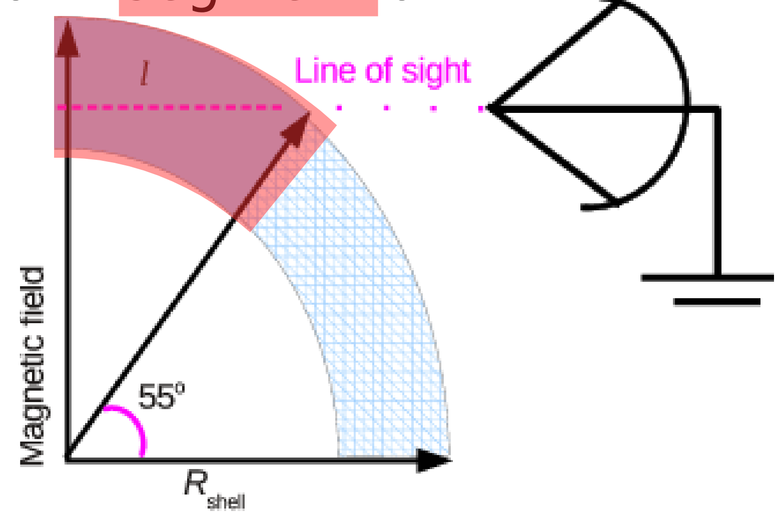
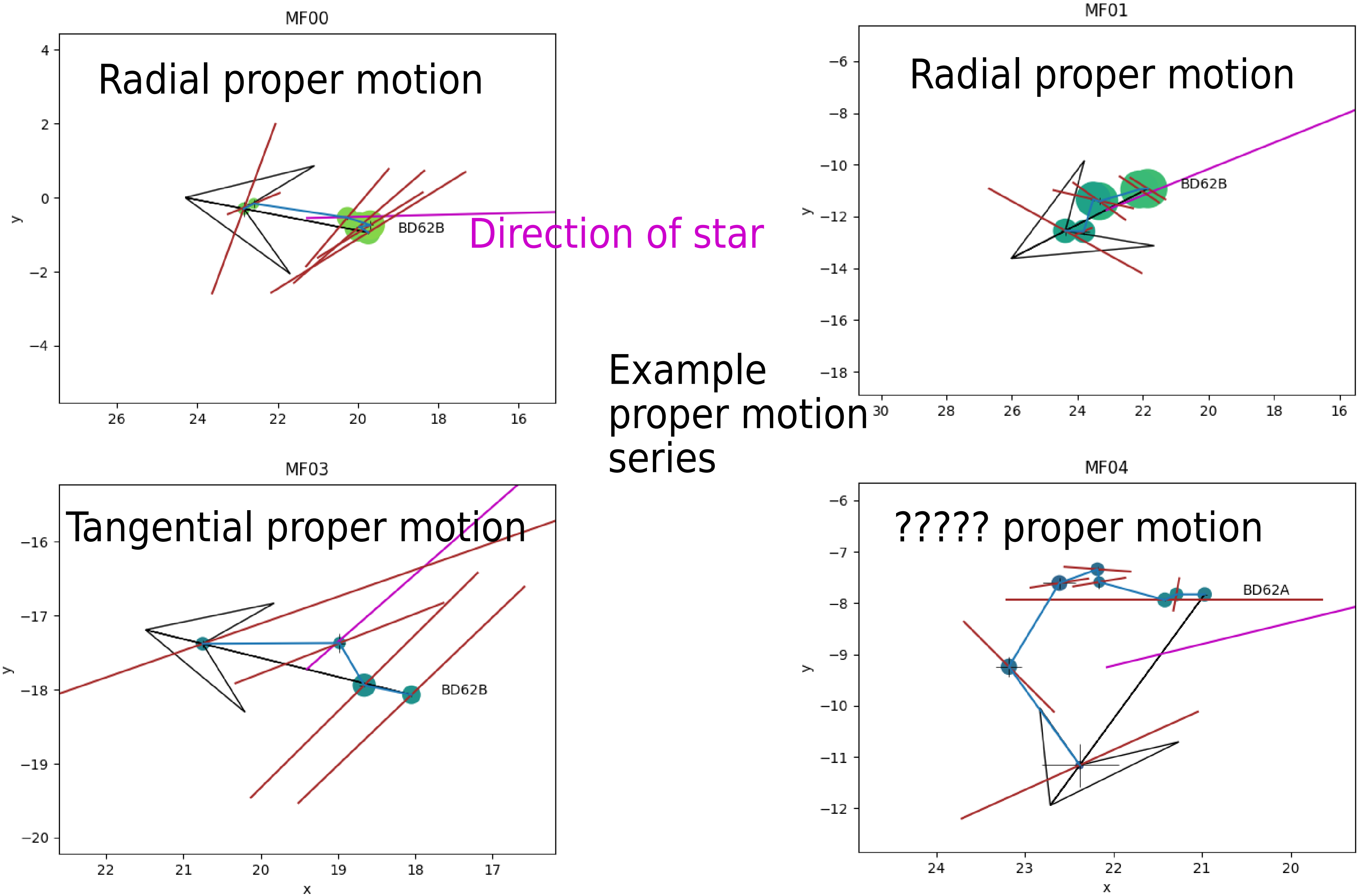
  - EVPA 90^o flips suggest SiO detected from segment of sphere excluding ~50^o face-on cones
    - Assume clumps evenly distributed
      - Total mass in clumps ~2.2×10^{-7} $M_\odot$
        - Assuming wind density homogenous
          - Probably wrong



Magnetic force

- Estimate mean bulk energy density of each cloud:
  - E_{bulk} (bulk motion) ~ 0.0134 J/m^3 (from proper motions)
  - E_{th} (thermal) ~ 0.0029 J/m^3 (*Ireland/Gray* model)
    - Assume angular separation from star is total distance R
- The equivalent magnetic energy density E_B requires magnetic field strength $B = [(E_{bulk} + E_{th})/4\text{x}10^{-3}]^{0.5}$ G (*Kemball+09*)
  - B in range 0.2 – 4.5 G, mean 2 G
    - +one 19 G; prob. R underestimate, T and E_{th} overestimate
- Measured B range 0.9 – 2.8 G (*Herpin+'06*)
  - Magnetic field is comparable in energy to kinetic energy

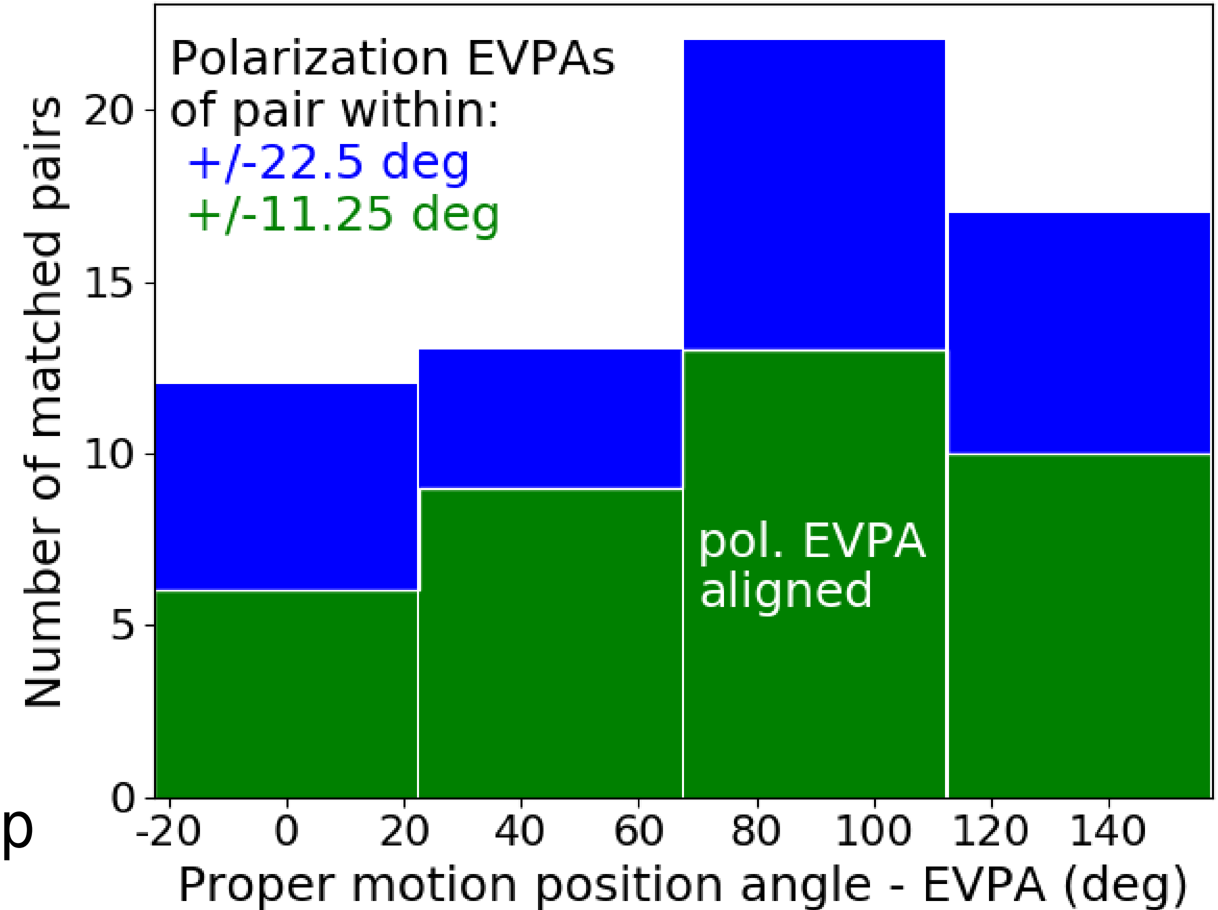
Polarization alignment?



Example proper motion series

Polarization alignment?

- Select pairs of clumps where the EVPA is significant and differs by less than 11.25° or 22.5°
  - 13 or 22 pairs of features have EVPA within 22.5° orthogonal to proper motions
  - Most popular orientation at 2σ significance for either cut-off
    - Only ~half with radial motion
    - Only 4 in series consistently in expansion
  - Ignoring van Vleck flip

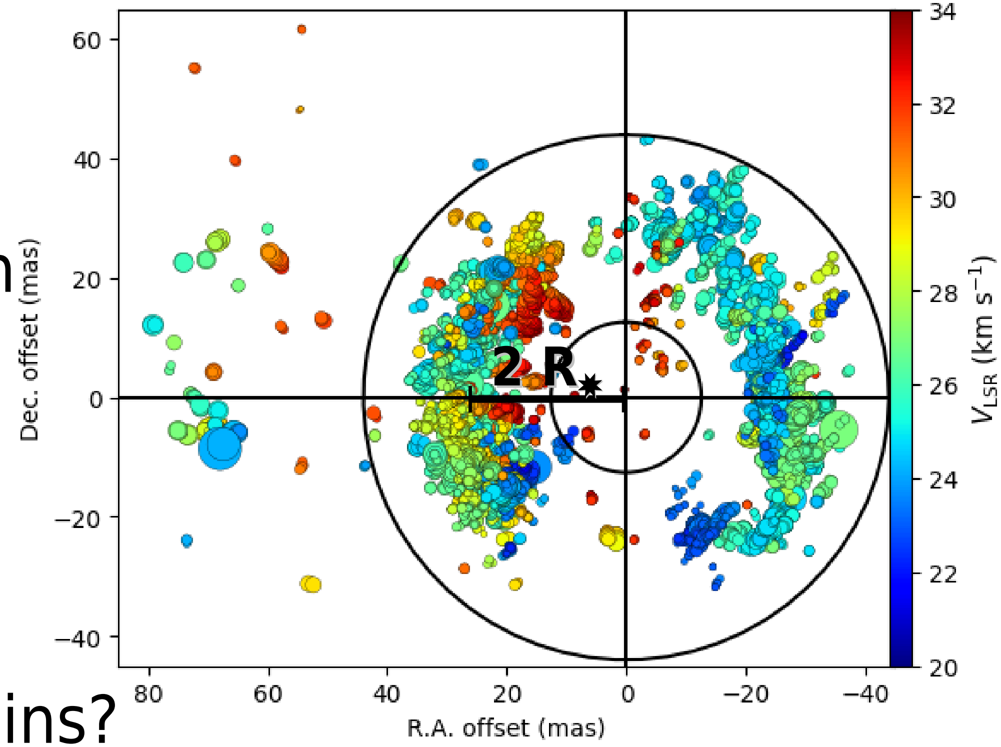


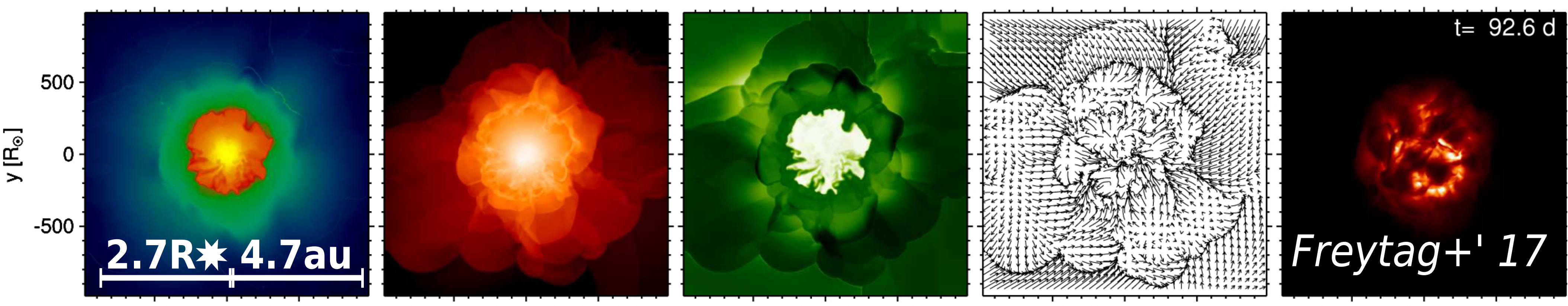
R Cas SiO: Conclusions

- ~20% of features identified for ≥3 epochs out of 23
    - Clumps probably survive, masers vary
- Wind takes 50–70 years to cross SiO maser shell
    - Thickness ~2.5 R_* at net speed ~0.4 km/s
    - Long SiO shell crossing time could help dust formation
- $\dot{M}$ SiO proper motions & *Ireland/Gray* model ~ $\dot{M}$ dust obs.
- Slight preference for mag. field – proper motion alignment
    - But small minority of features/large uncertainties
        - Complicated directions of field and motions
- Need VLBI+short spacings to detect all masers & resolve star
    - Model mass specifically in clumps
    - Better polarization calibration

What forces act on SiO at 2-5 $R_\star$?

- Heating⇨expansion⇨convection
  - Fails once τ_{NIR} <1 (inside 2 $R_\star$)
    - But + pulsation = waves
- Flow mostly not along B lines?
  - (or data too messy...)
- Scattering by heat-resistant grains?
- Magnetic buoyancy?
  - Obs. evidence for small-scale field complexity; *Lopez Ariste* model

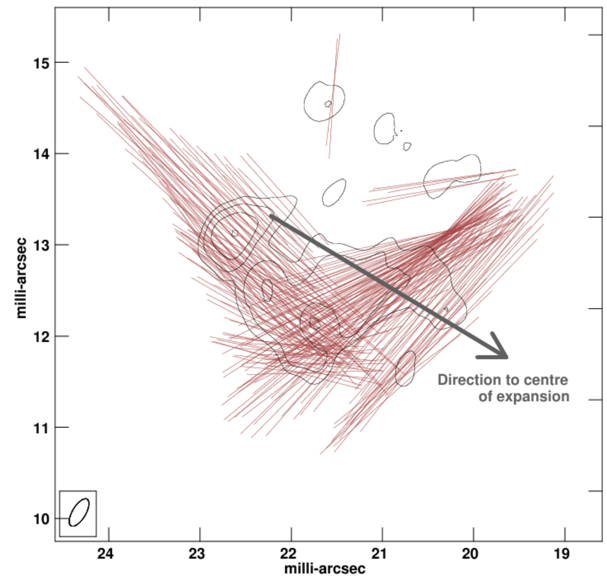


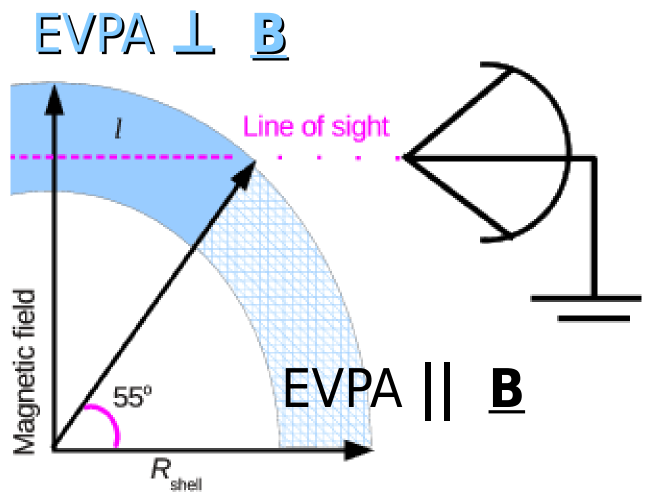


Temperature Density Entropy ~streamlines opt. intensity

Polarization angle EVPA

- Tendency for EVPA to be closer to radial or tangential than intermediate, for all features with significant polarization
- Angle between EVPA and magnetic field vector **B** depends on angle θ between **B** and line of sight (*Goldreich*+'73)
  - $\theta < 55^o$ (van Vleck angle) gives EVPA perpendicular to **B**
  - Otherwise parallel
- R Cas SiO consistent with radial magnetic field + peturbations
  - Masers beamed from a region extending a bit more than 55^o out of the plane of the sky with the star





R Cas feature crossing the van Vleck angle (also seen in TX Cam, *Kemball*+'09)