Mass loss from Betelgeuse

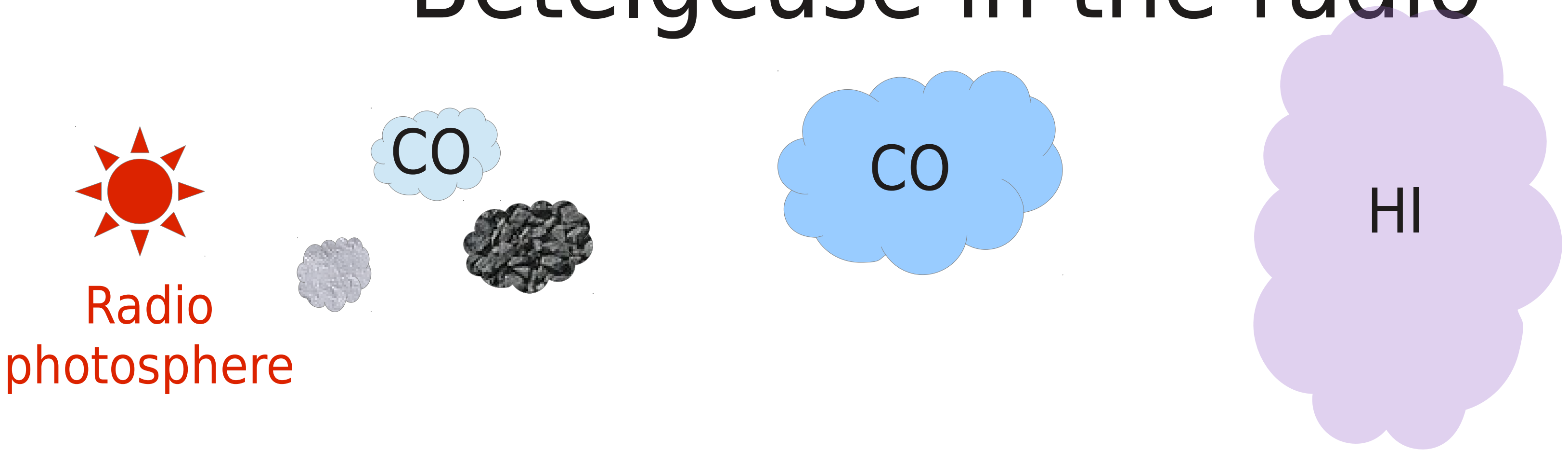
where is it going?

Anita Richards, JBCA, Manchester

The radio view of Betelgeuse
How do red (super)giants lose mass?
How is it returned to the ISM
What lies ahead for Betelgeuse?
Lessons from more evolved RSG and masers
Future radio observations and modelling needs

EUROPEAN ARC
ALMA Regional Centre || UK

Betelgeuse in the radio



VLA, e-MERLIN, CARMA, IRAM, Bell Labs 7-m, NRT, VLA

$\nu > 1.4$ GHz 230, 115 GHz 1.42 GHz

Lim, Richards, Harper, O'Gorman, Kaminski, Le Bertre, Matthews ....

- Future:
  - ALMA: Star, more CO transitions, other molecules, dust
  - Combine with single dish for lower-excitation transitions
- Molecular bands, dust also mapped in IR
  - *Decin, Ohnaka, Smith, Wittkowski, Perrin and many others*

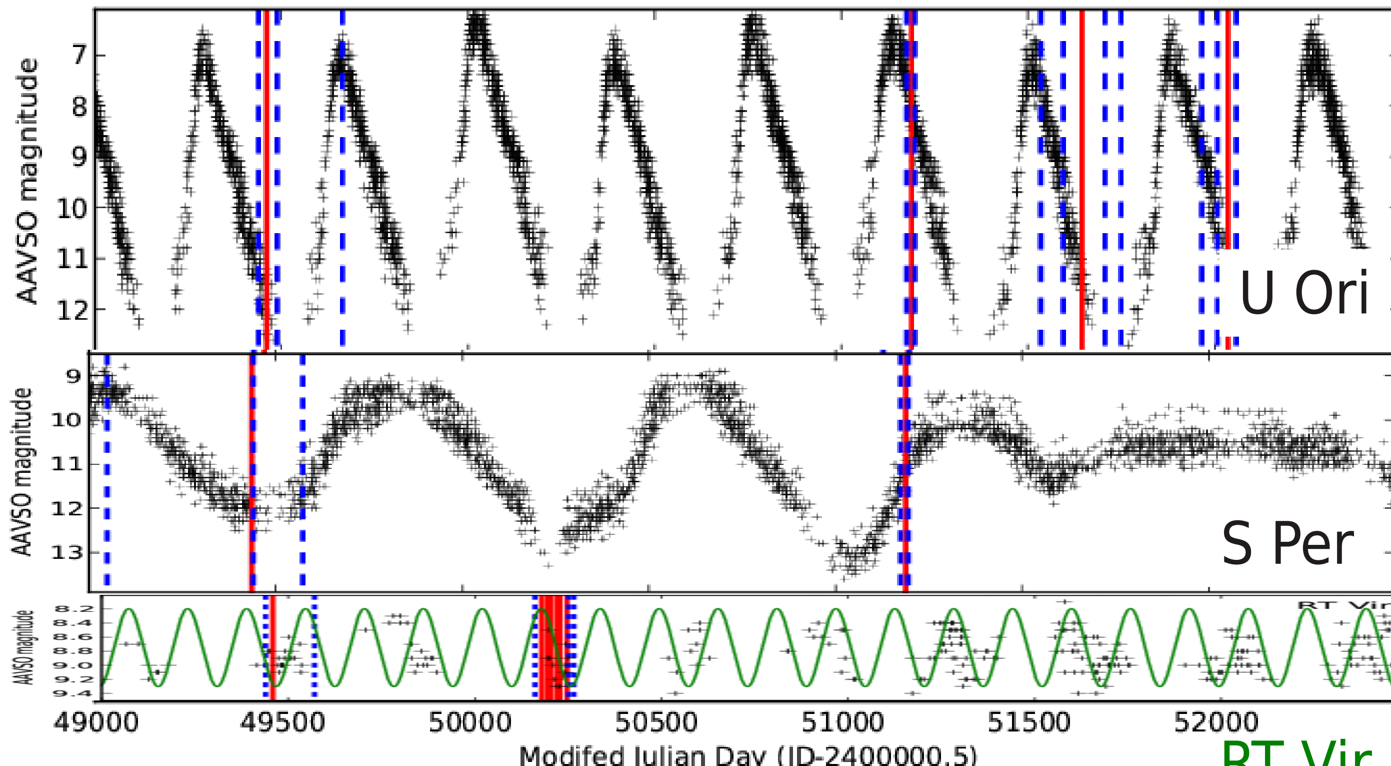
How do RSG lose mass?

- General model for *late* M-types (e.g. S Per, VX Sgr, AGB✸s)
  - Pulsations levitate photosphere *Bowen'88*
    - Copious dust forms at ~5$R_{\star}$
      - Dust-driven winds
        - AGB stars $\dot{M}$ $10^{-7\,-\,-6}$ $M_{\odot}$ yr^{-1}; RSG ~10^{-5} $M_{\odot}$ yr^{-1}
- Betelgeuse M21ab
  - Alumina nucleates inside 2$R_{\star}$ **(***Perrin+07*)
    - but very small, transparent, grains (e.g. *Woitke06*)
  - Silicate dust r_i 0.5 – 1 arcsec, >30 $R_{\star}$ (*Danchi+94, Skinner+97*)
    - How does the wind get that far?
- What do high-resolution studies of more evolved RSG/AGB stars winds tell us about its mass loss process?

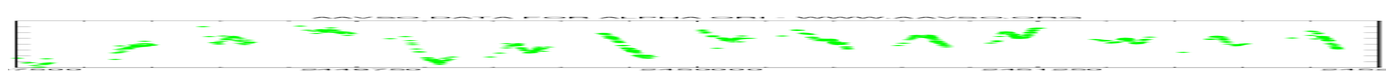
Pulsation size doesn't matter?

- Mira: U Ori
  - Δ_{mag} 5–6
  - $\dot{M}$ 2.3 10^{-7} $M_{\odot} yr^{-1}$
- Late-M RSG:

  S Per
  - Δ_{mag} <4
  - $\dot{M}$ 3.8 10^{-5} $M_{\odot} yr^{-1}$
- AGB SRb: RT Vir
  - Δ_{mag} <2
  - $\dot{M}$ 1.3 10^{-7} $M_{\odot} yr^{-1}$
- Betelgeuse
  - Δ_{mag} <2
  - $\dot{M}$ 3 10^{-6} $M_{\odot}$ yr^{-1}



RT Vir



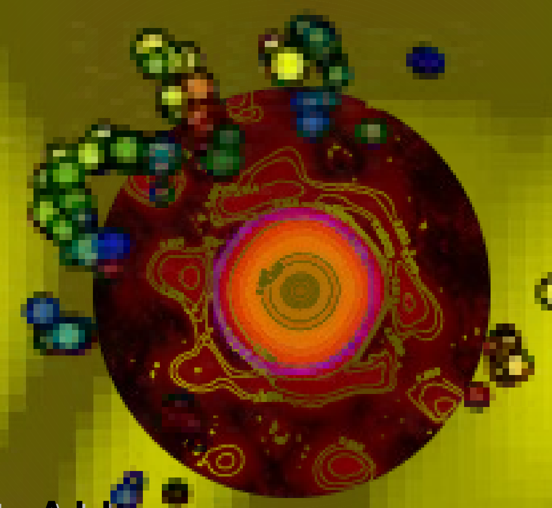
α Ori

All plots:
3 mag

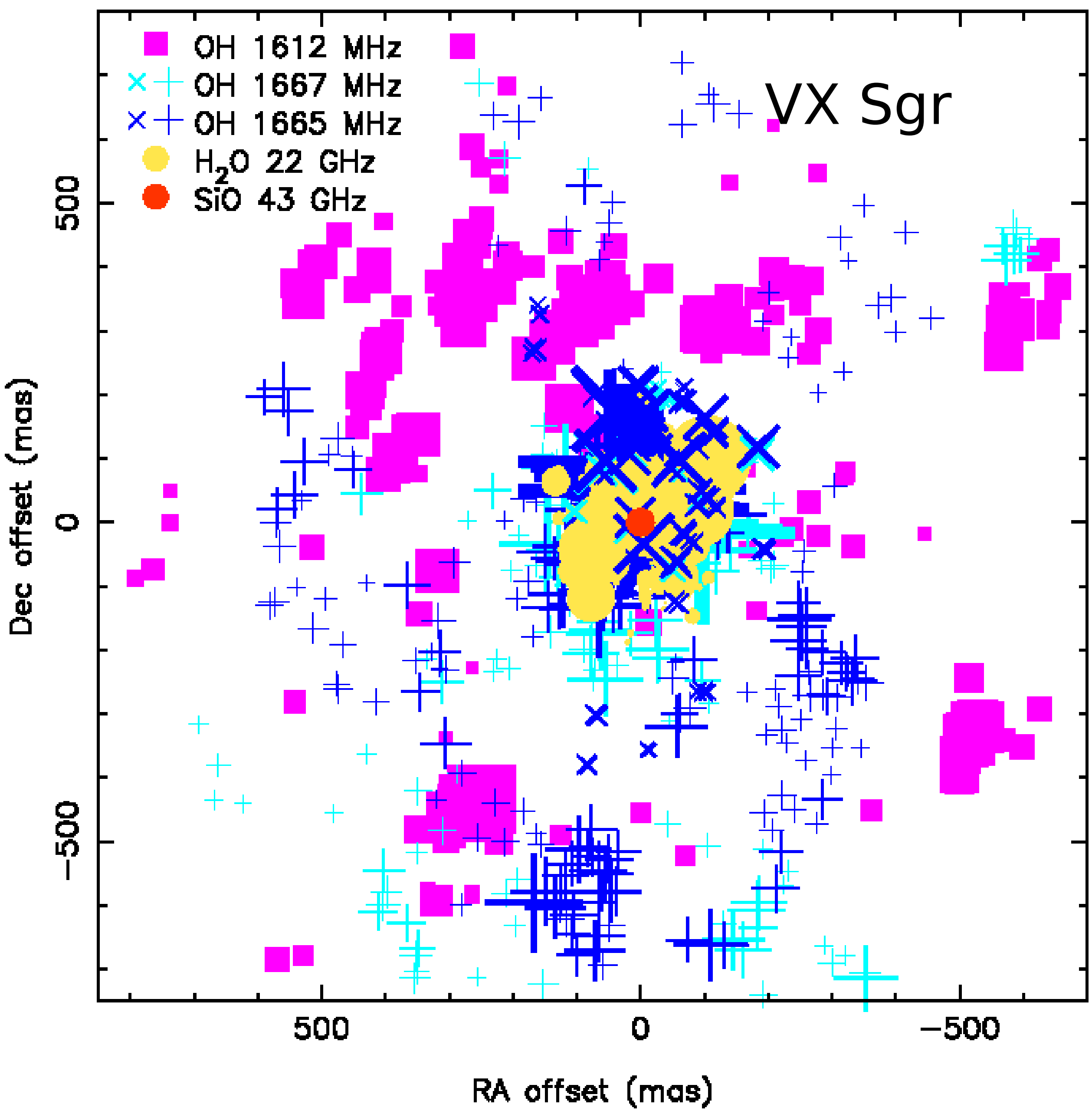
Thanks to AAVSO

Masers round cool late-type stars

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

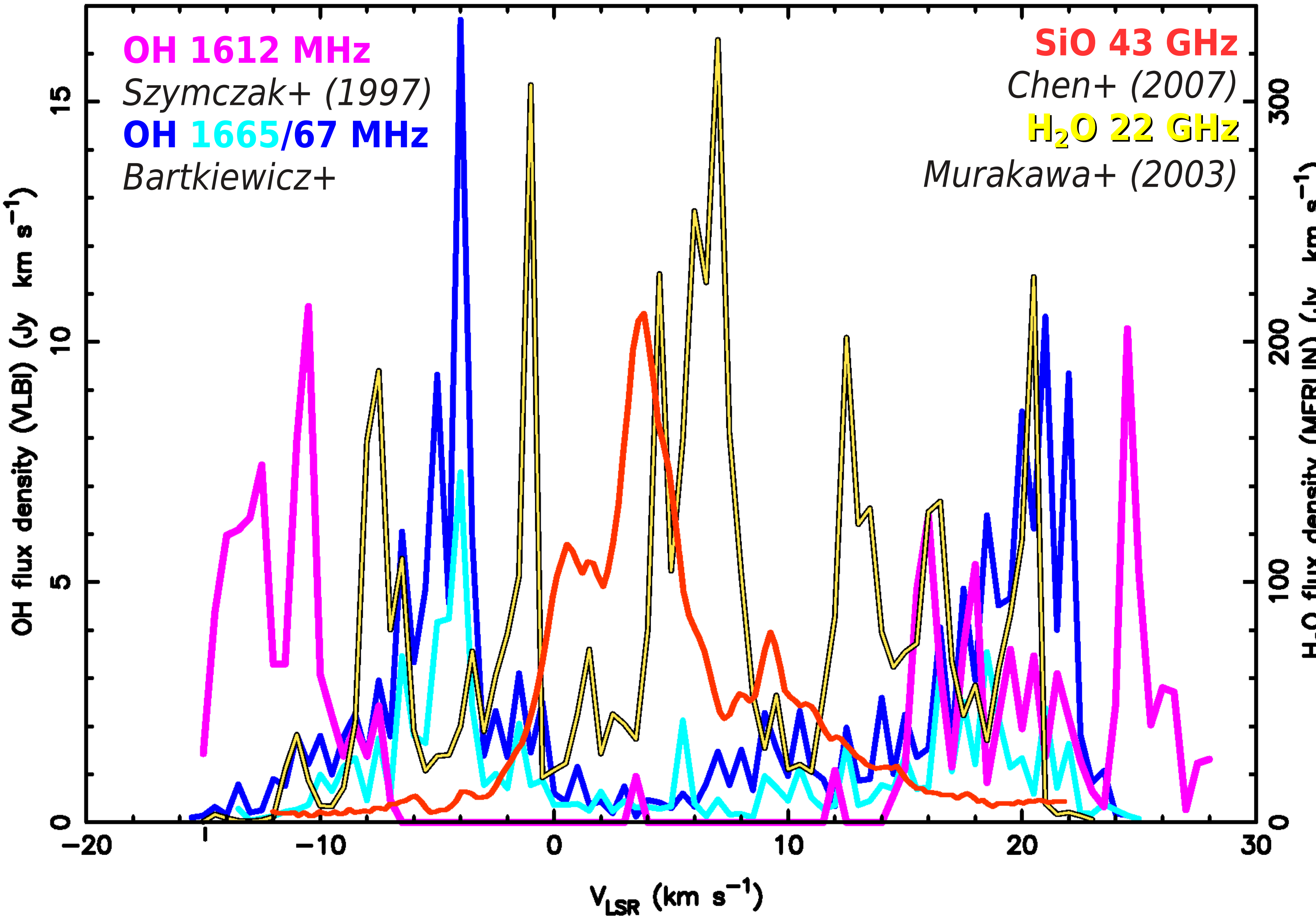


Masers resolve winds on AU scales

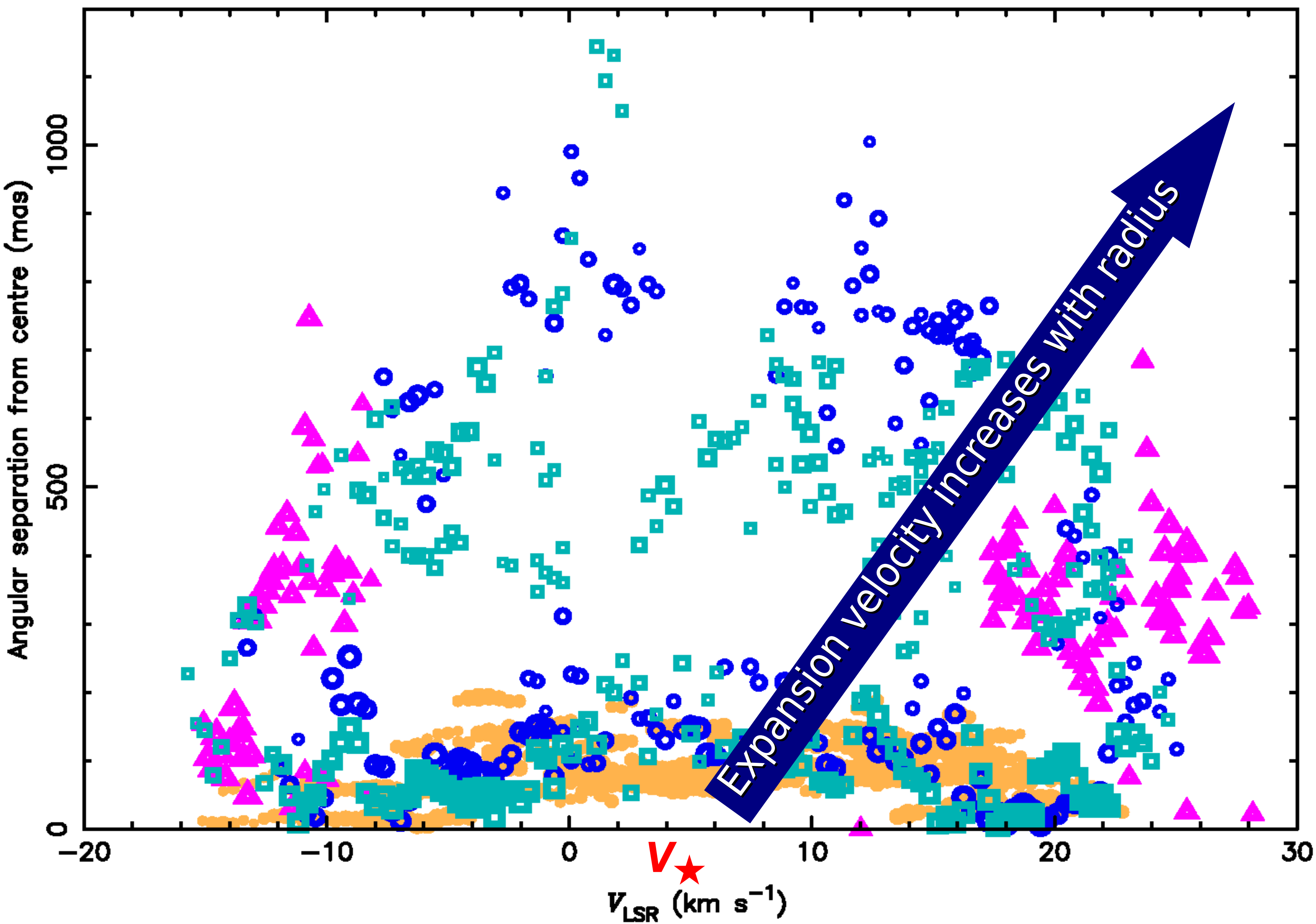


- OH 1612 MHz
  - T_E tens K, long column depth)
  - >50 $R_\star$
- H_2O 22GHz
  - T_E ~650 K)
  - 5-30 $R_\star$
- SiO>42 GHz
  - T_E >2000 K
  - < 4 $R_\star$
- OH mainlines (1665-7 MHz)
  - Can overlap H_2O and/or extend as far as 1612 MHz masers

Velocity profiles: expansion

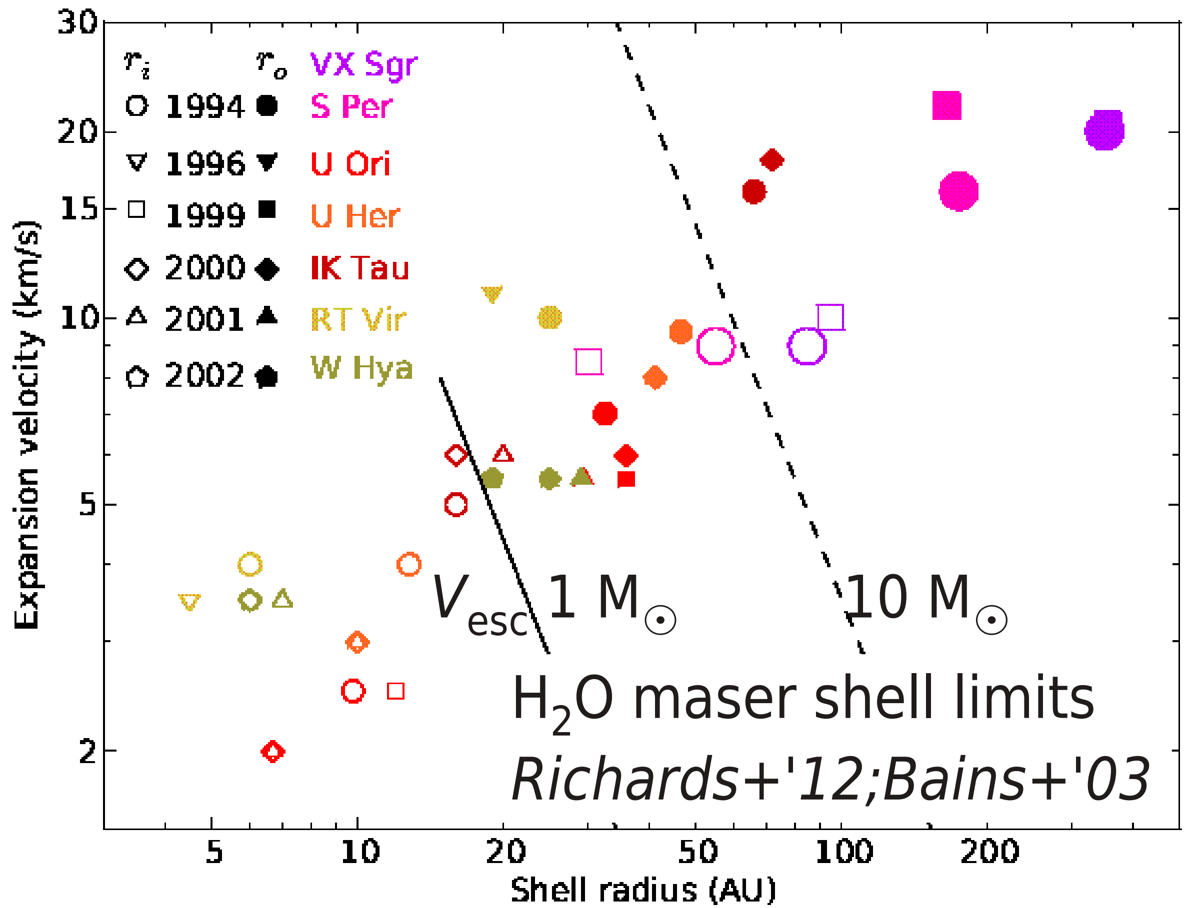


Radial acceleration



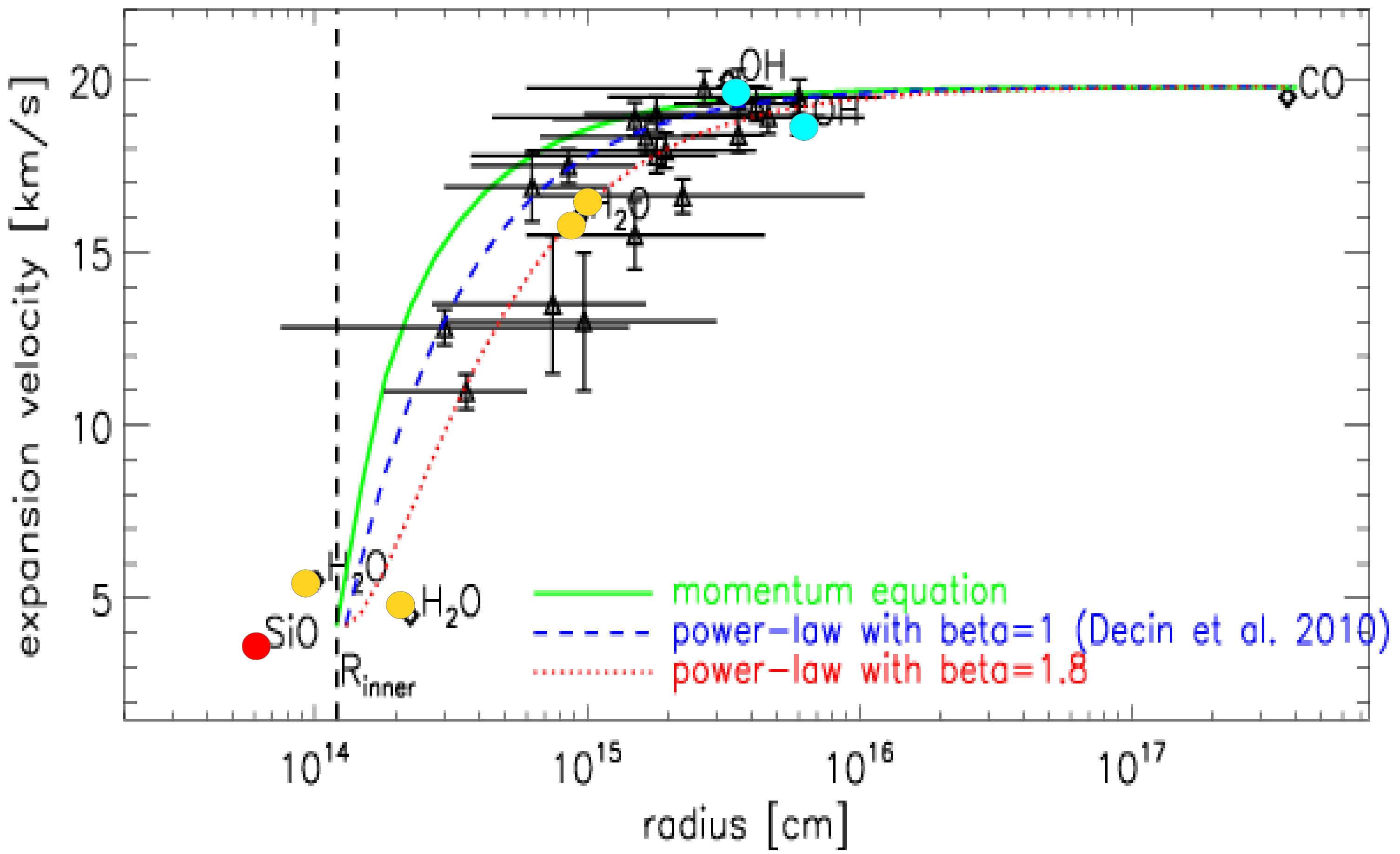
What accelerates the wind?

- Water maser shell limits show $V_{exp} \propto r$ out to 100s $R_\star$
  - Relationship holds for $M_\star$ ~1 to >10 $M_\odot$
    - Wind exceeds escape velocity V_{esc} during passage through H_2O shell
- First noticed for VX Sgr SiO, H_2O, OH
  - *Chapman & Cohen 1986*
  - Collision rate too low for aggregation at $r \gg r_i$
  - Dust absorption efficiency evolves?
    - *Verhoelst+09*
  - Changing momentum coupling or τ?
    - *Ivezic&Elitzur'10*



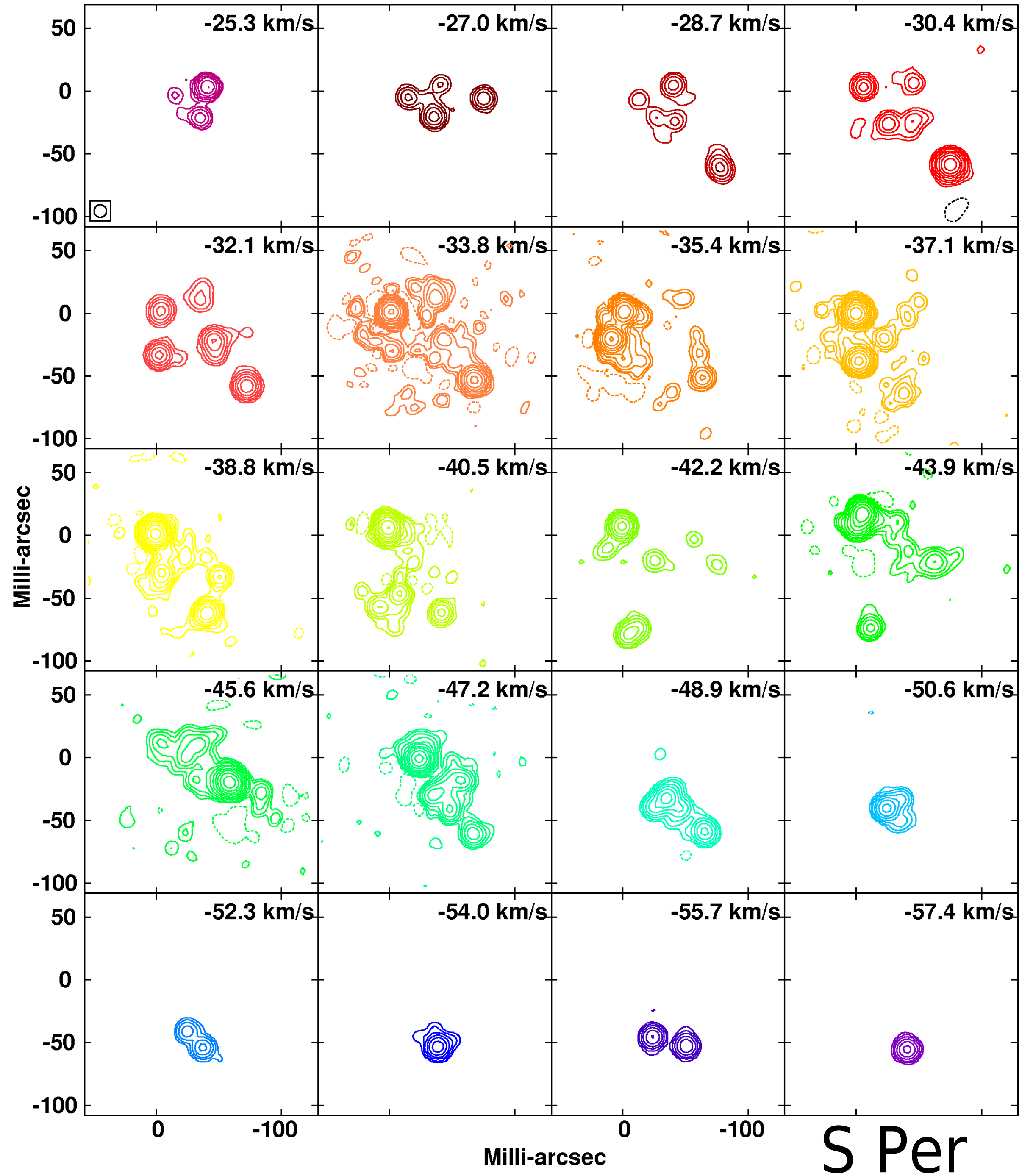
Herschel gradual acceleration

- IK Tau HIFI survey 480-1150 & 1410-1910 GHz
  - $v(r) \sim v_i + (v_\infty - v_i)(1 - R_\star / r)^\beta$
- *Decin+'10*
- Line width relates to excitational state
- Higher *T* lines at lower V_{exp}



Water maser channel maps

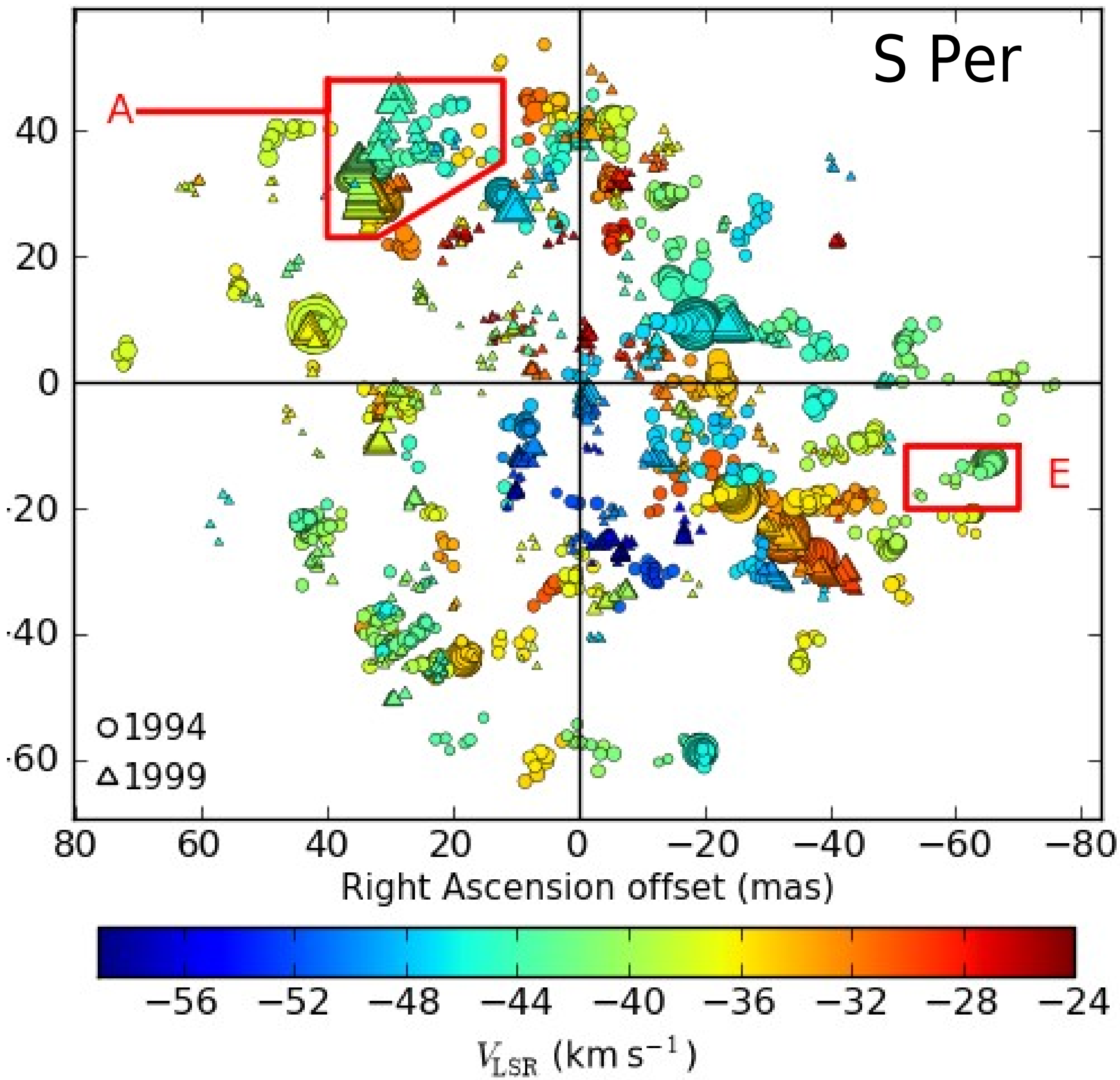
- MERLIN radio interferometry images
  - 22 GHz (λ 1.3 cm)
  - 10 milliarcsec beam
- Compact front and back caps
- Bright extended emission in plane of sky with star
- Spherical, radially accelerating outflow



S Per

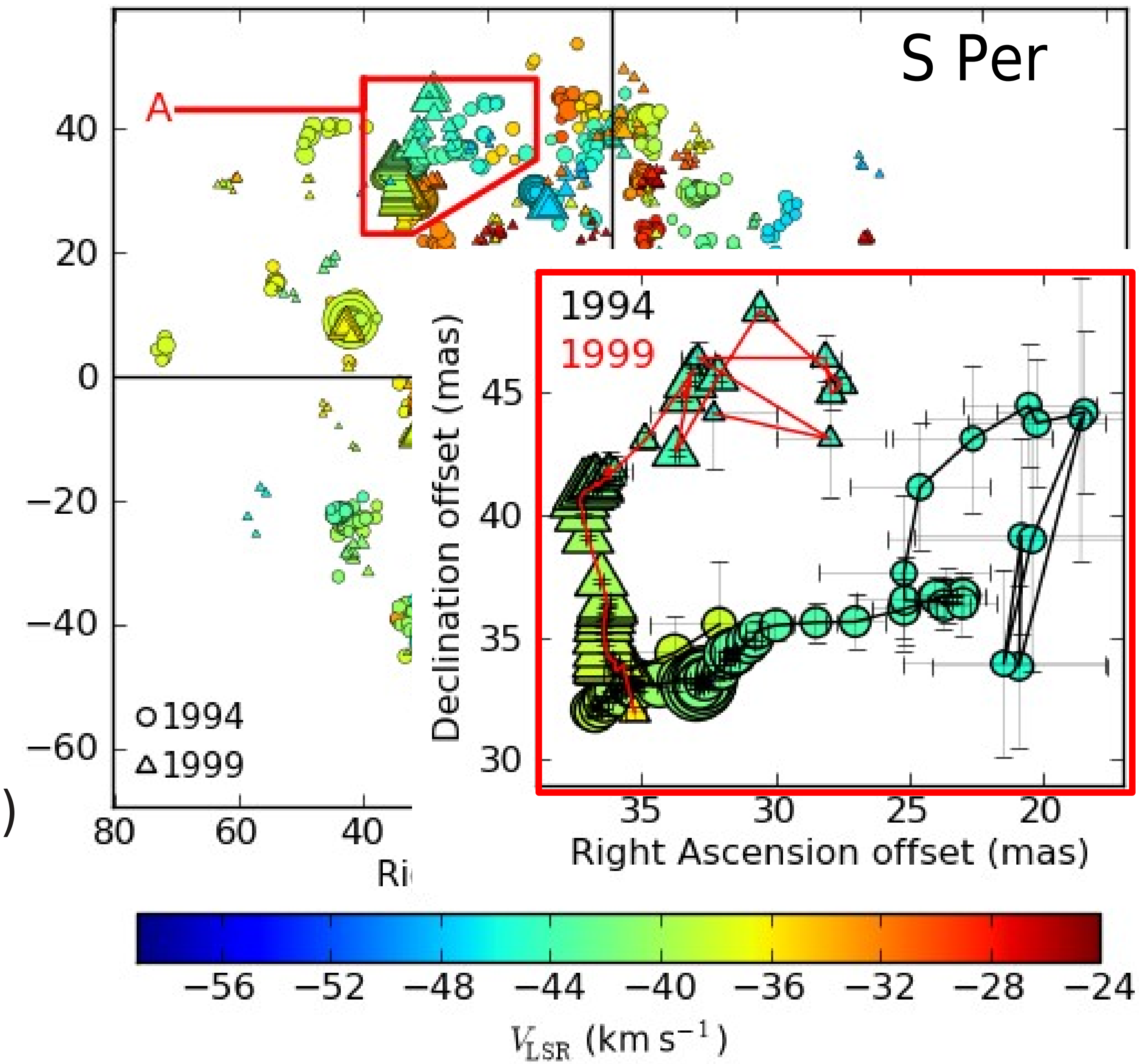
Cloud measurements

- Measure channel emission by fitting 2-D Gaussian components
  - Individual component beamed size
    - 1-2 km s^{-1} groups
- Series provide 'true' size of discrete clouds
  - RSG 10-20 AU
  - AGB 1-few AU

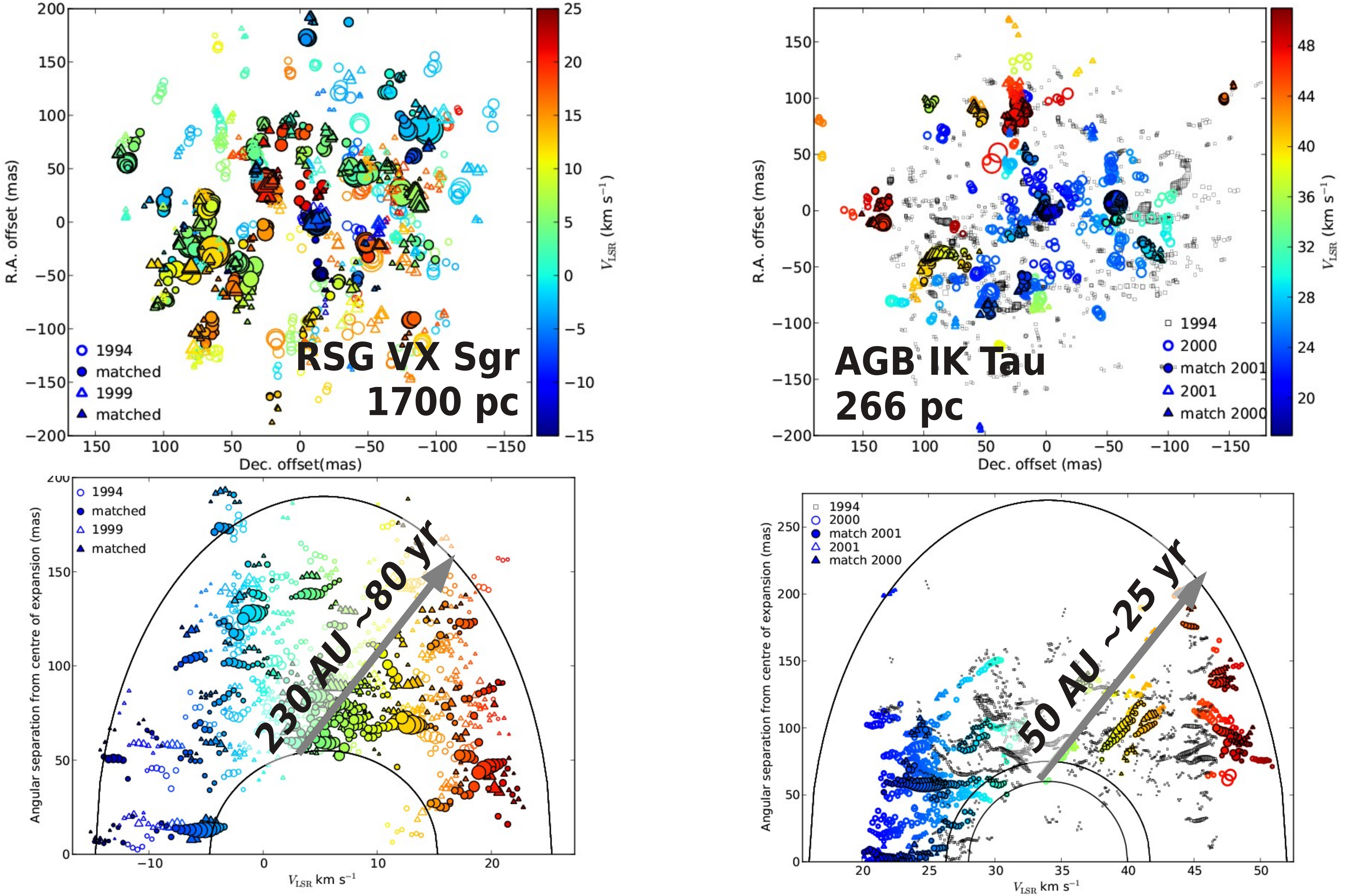


Cloud survival, maser variability

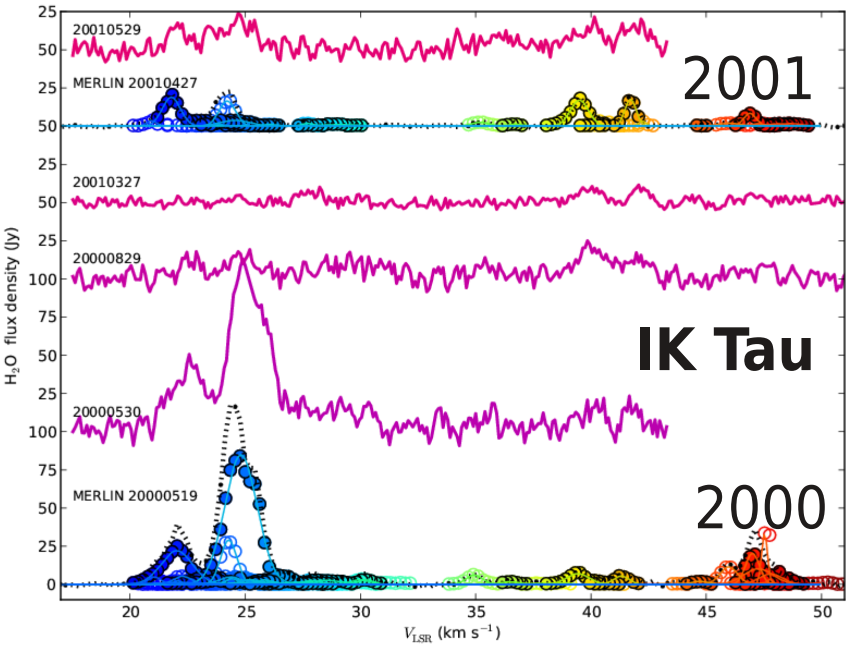
- Specific RSG masers can be tracked for ≥5 yr
- AGB masers survive ⩽2 yr
  - Similar to sound-crossing time
- Much less than shell crossing time
  - Decade(s) (AGB)
  - Up to a century (RSG)

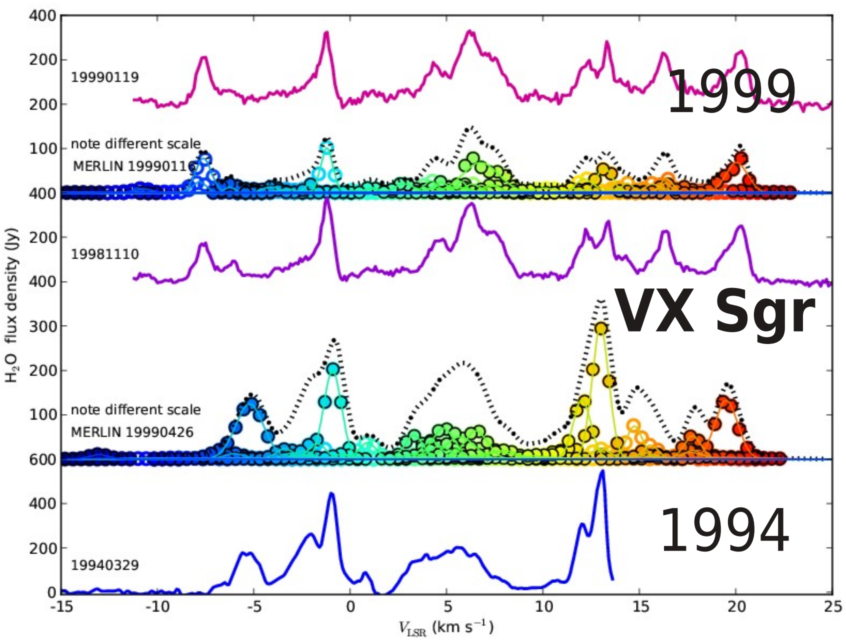


Shell-crossing times



Masers blink, clouds survive

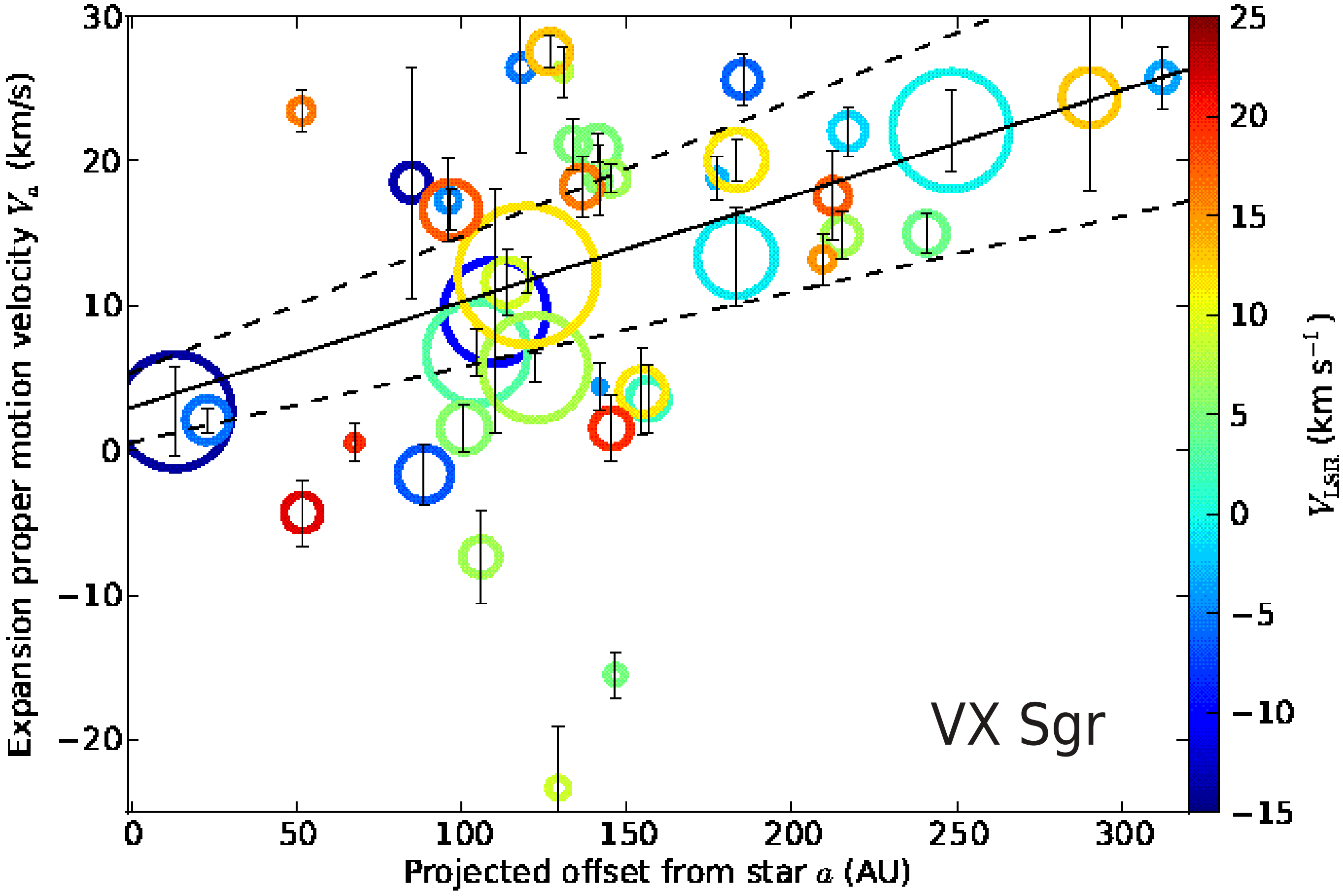




- Pushchino ~bimonthly spectral monitoring
- MERLIN imaging every few years (colour)
  - Matched features: black outlines
- Spectral variability between images
  - Peaks vanish, some reappear
- Clouds unlikely to reform if dispersed
  - Clouds survive as clumps
  - Masers turn on and off
    - Turbulence/beaming?
    - Shocks/excitation?

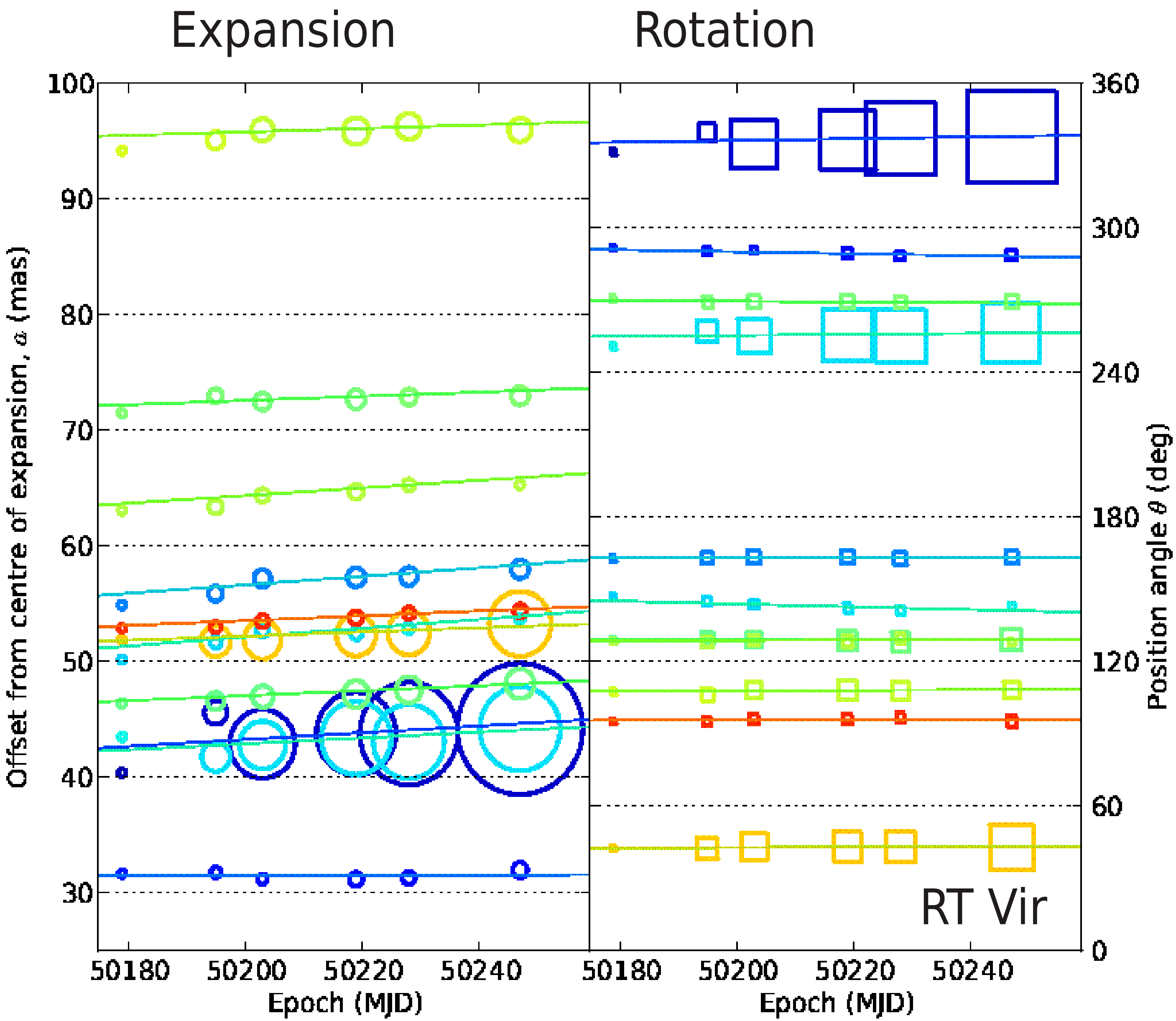
Expansion proper motions

- Proper motion velocities consistent with Doppler velocities
  - Similar radial acceleration



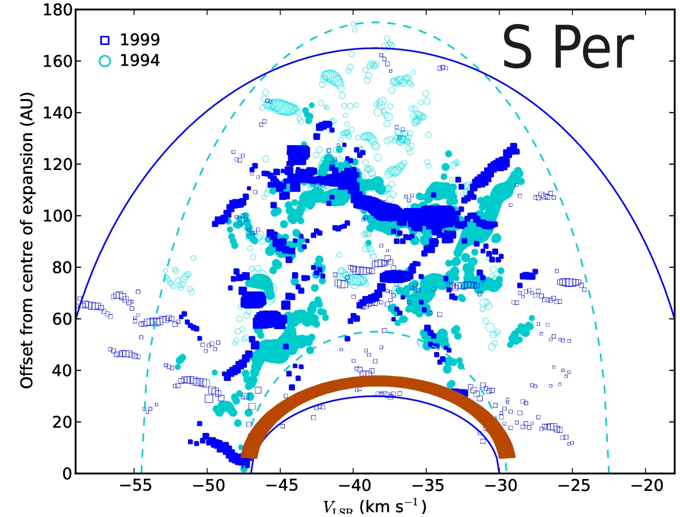
Expansion proper motions

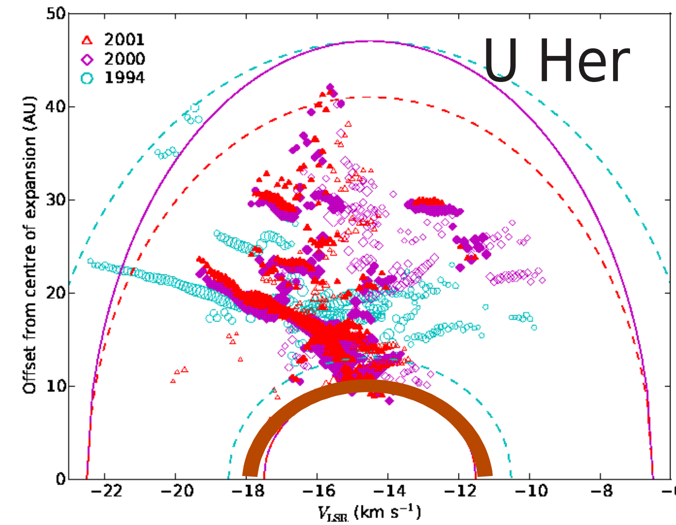
- Proper motion velocities consistent with Doppler velocities
  - Similar radial acceleration
- ~No rotation
  - Upper limits:
  - VX Sgr 0.8∓0.8
  - S Per 0∓1
  - RT Vir 0.1∓0.1 km/s
- Tight SiO limits from VERA

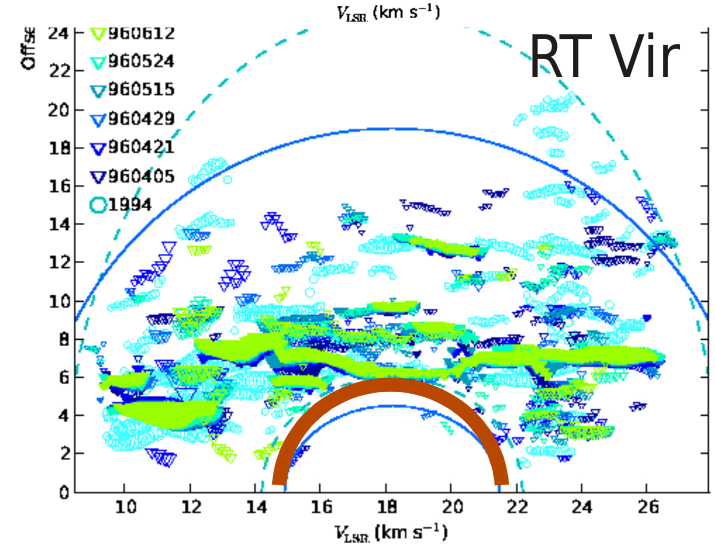


Cloud density

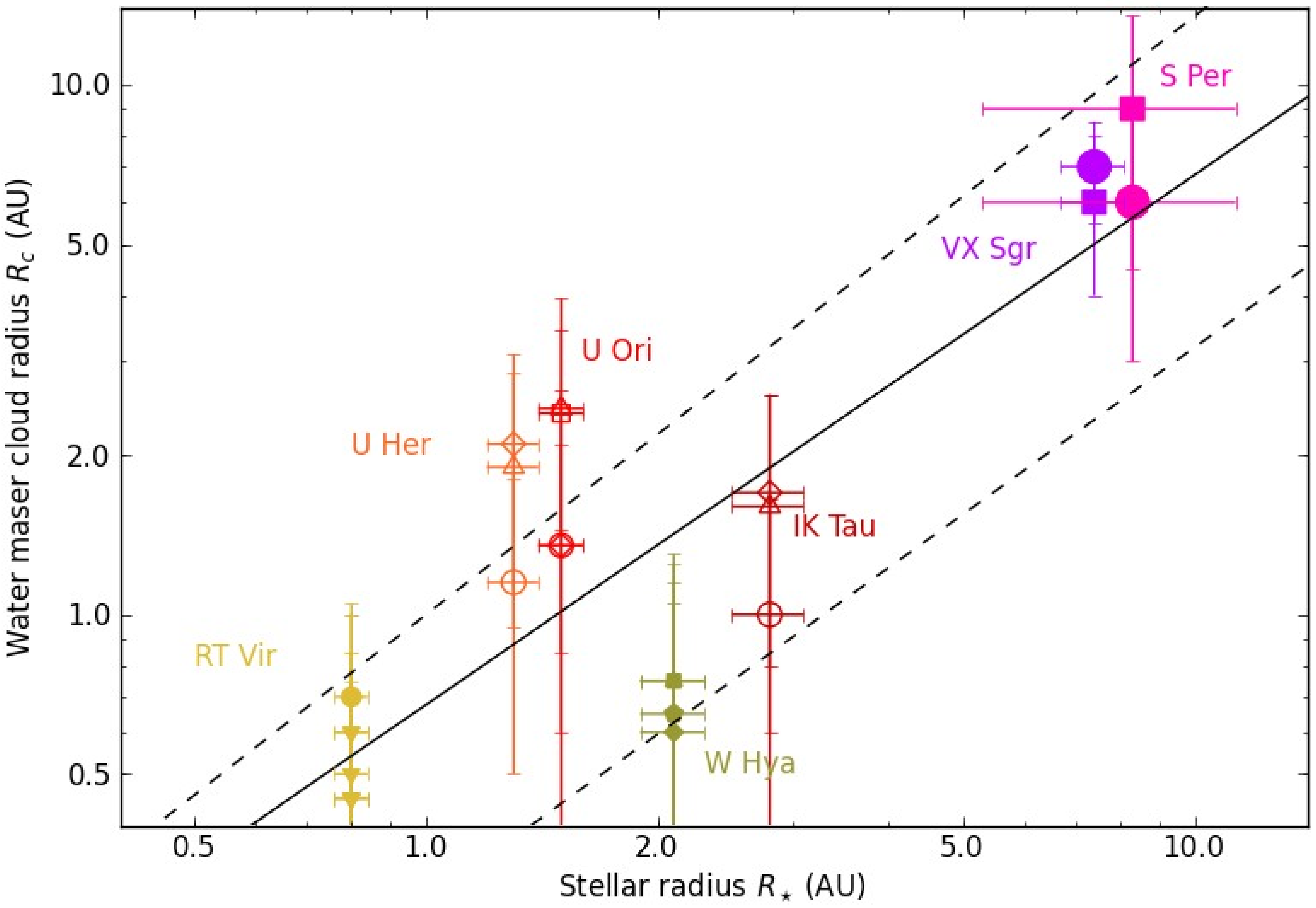
- **H_2O** masers start at r_i
  - 40–70 AU RSG, 5–15 AU AGB
  - – Where collision rate < masing rate (*Cooke & Elitzur 85*)
    - Quenching density ~$5 \times 10^{15} m^{-3}$
  - – Clouds ≳45x average (e.g. CO) wind density
    - Upper limit: surrounding gas density > 0
  - – Filling factor ≲1%
  - – >90% mass loss in clouds
  - – 2–6 clouds/stellar period







Cloud size depends on star size

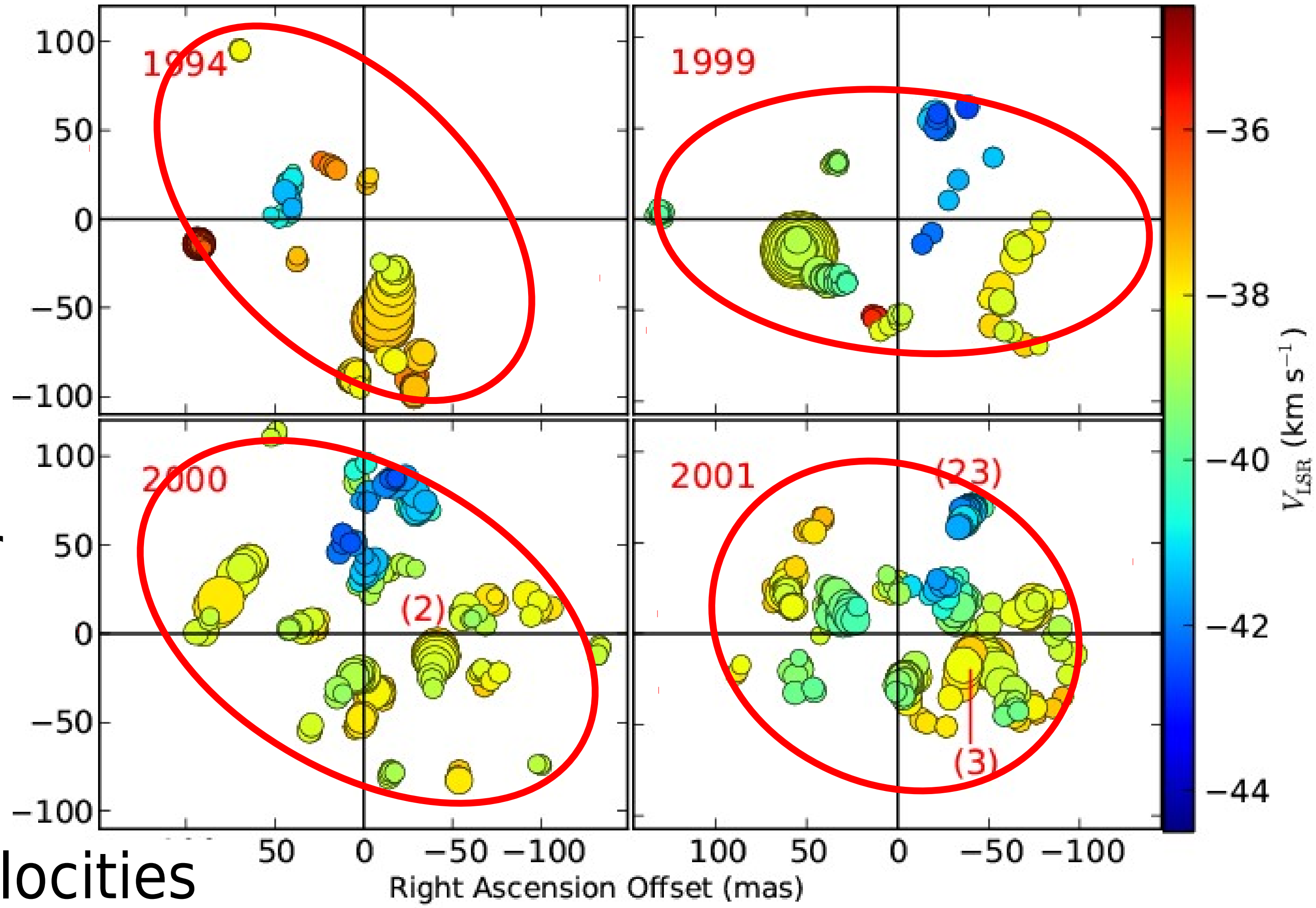


R_{cloud} set by star properties?

- Measure stellar radius $R_\star$ from opt/IR interferometry
  - *Skinner+88, Mennesson+02, Monnier+04, Ragland+06*
- **Cloud radius is a function of stellar radius**
  - In H_2O maser shell $\boldsymbol{R_c \sim (0.7 \pm 0.3)\, R_\star^{1.0\pm0.1}}$
  - Mass per cloud consistent with CO clump models
    - *Bergman+93, Olofsson+96*
- ***Suggests that cloud properties are determined when mass is ejected from star***
  - Not e.g. due to cooling scales during dust formation
    - Such microphysics should not care about $M_\star$
  - Birth radius (5–10)% $R_\star$ if outflow expands as r^{-2}
  - VLTI etc. observations suggest stellar surface inhomogeneities on ~10% scale e.g. *Wittkowski+11*

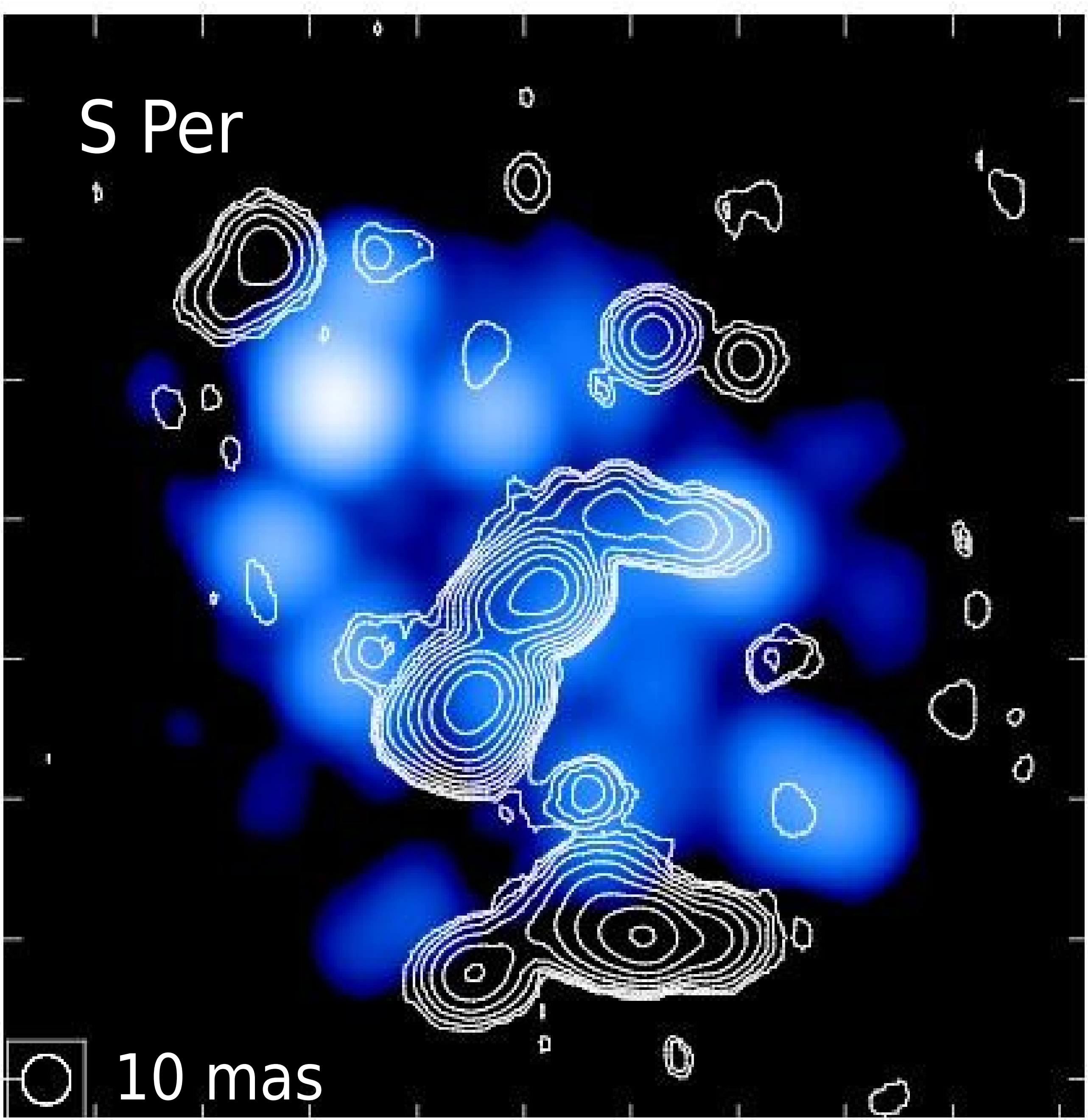
Asymmetry or poor filling?

- U Ori 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



- *Asymmetries within ≥100 R_* transient compared with shell crossing time*

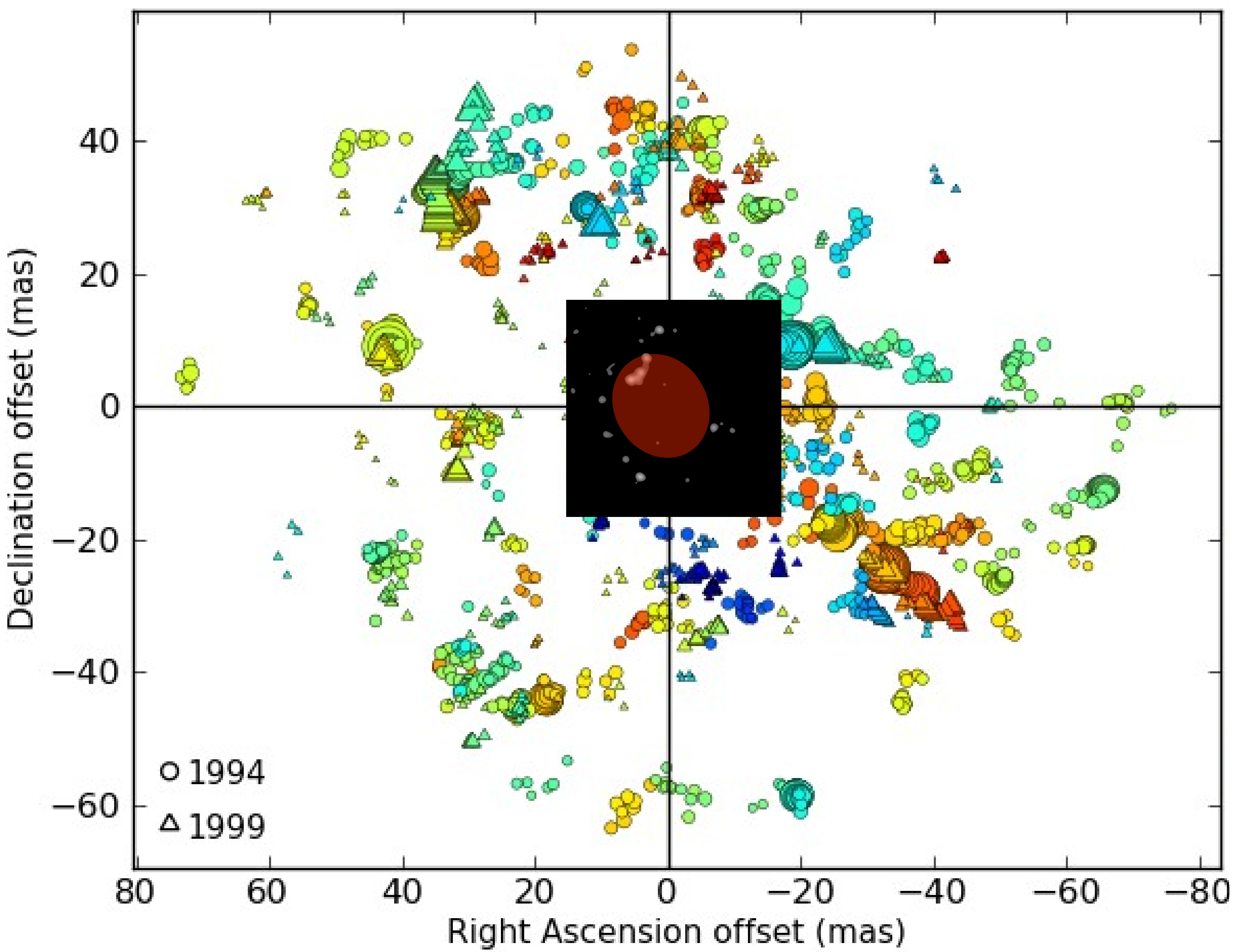
OH mainlines interleave H_2O



- MERLIN H_2O (blue)
- EVN/global mainline OH (contours)
- OH mainlines interleave H_2O
  - Excited-state OH not detected
    - T_{OH} ≲500 K
    - T_{H2O} ≲1000 K
    - n_{OH} ≲10^{14} m^{-3}
    - n_{H2O} ≲5 10^{15} m^{-3}
- OH from lower-density inter-clump gas

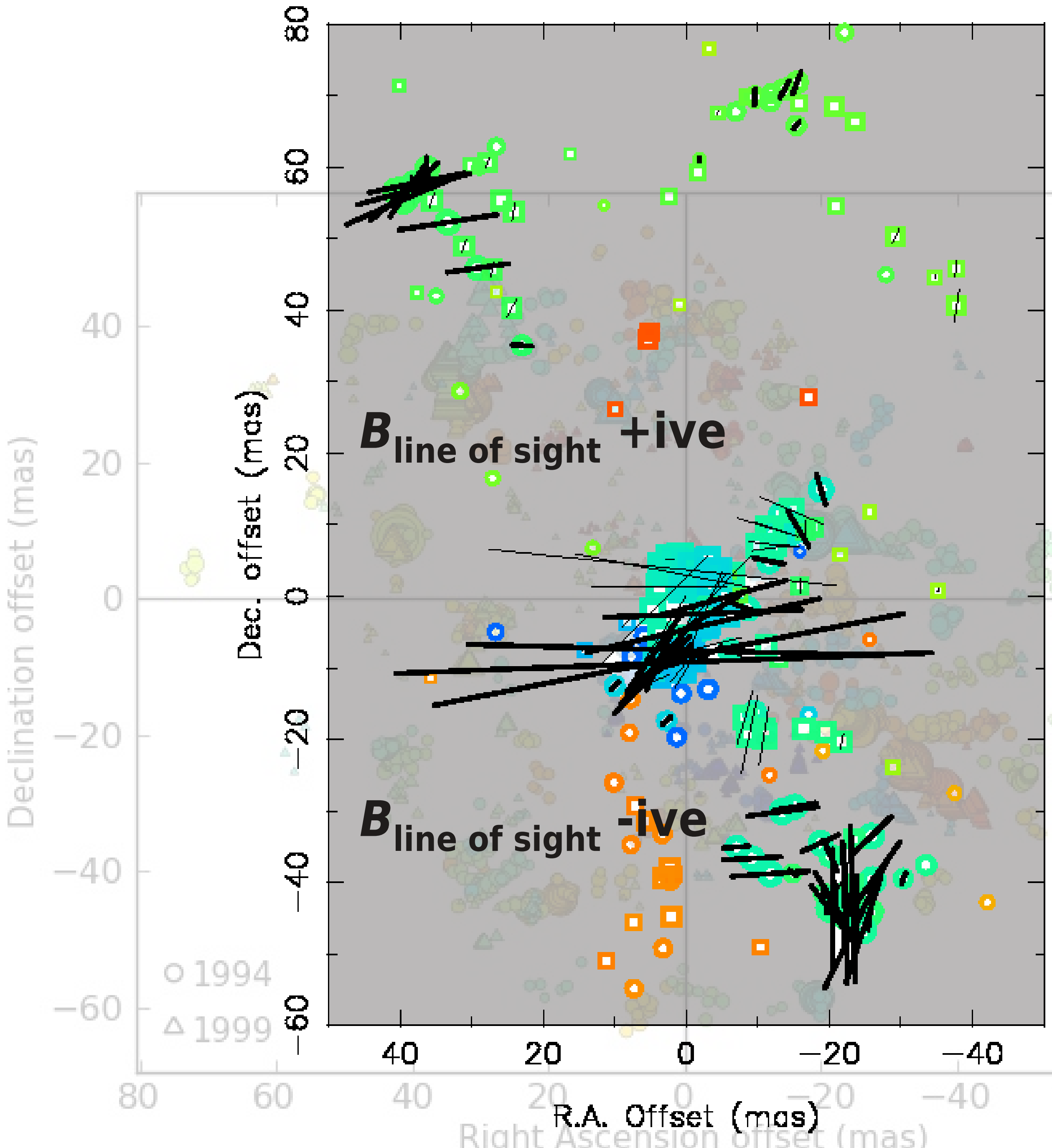
Richards, Masheder, van Langevelde, Yates 2013?

S Per H_2O masers almost spherical



- Slight E-W elongation
  - Declining 1980's > 2000's
- SiO (*Ostrowski-Fukuda*) very variable
- $R_\star$ ~12 AU (*Thompson+03*)
  - Direction of elongation might be variable

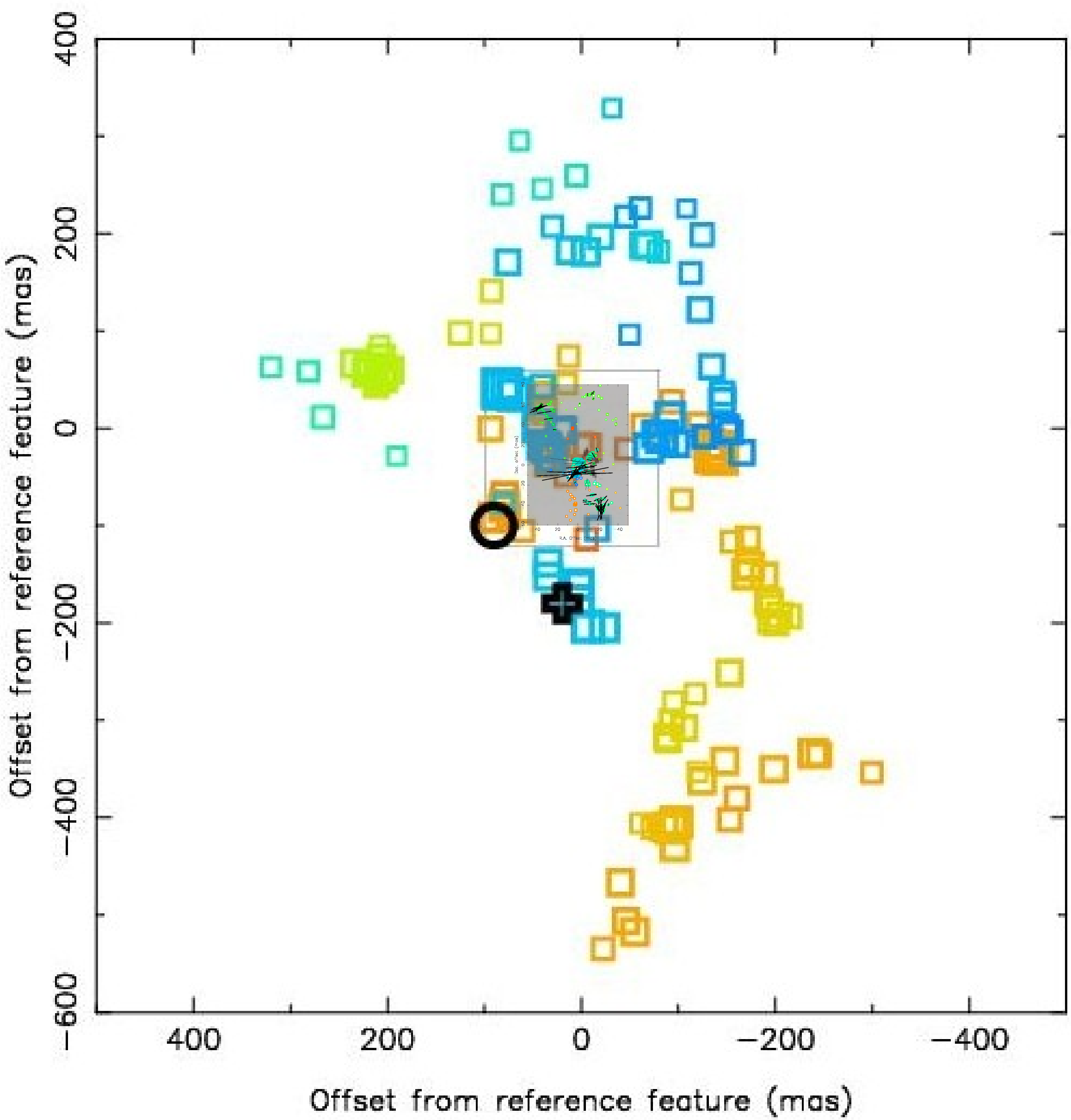
Incipient asymmetry



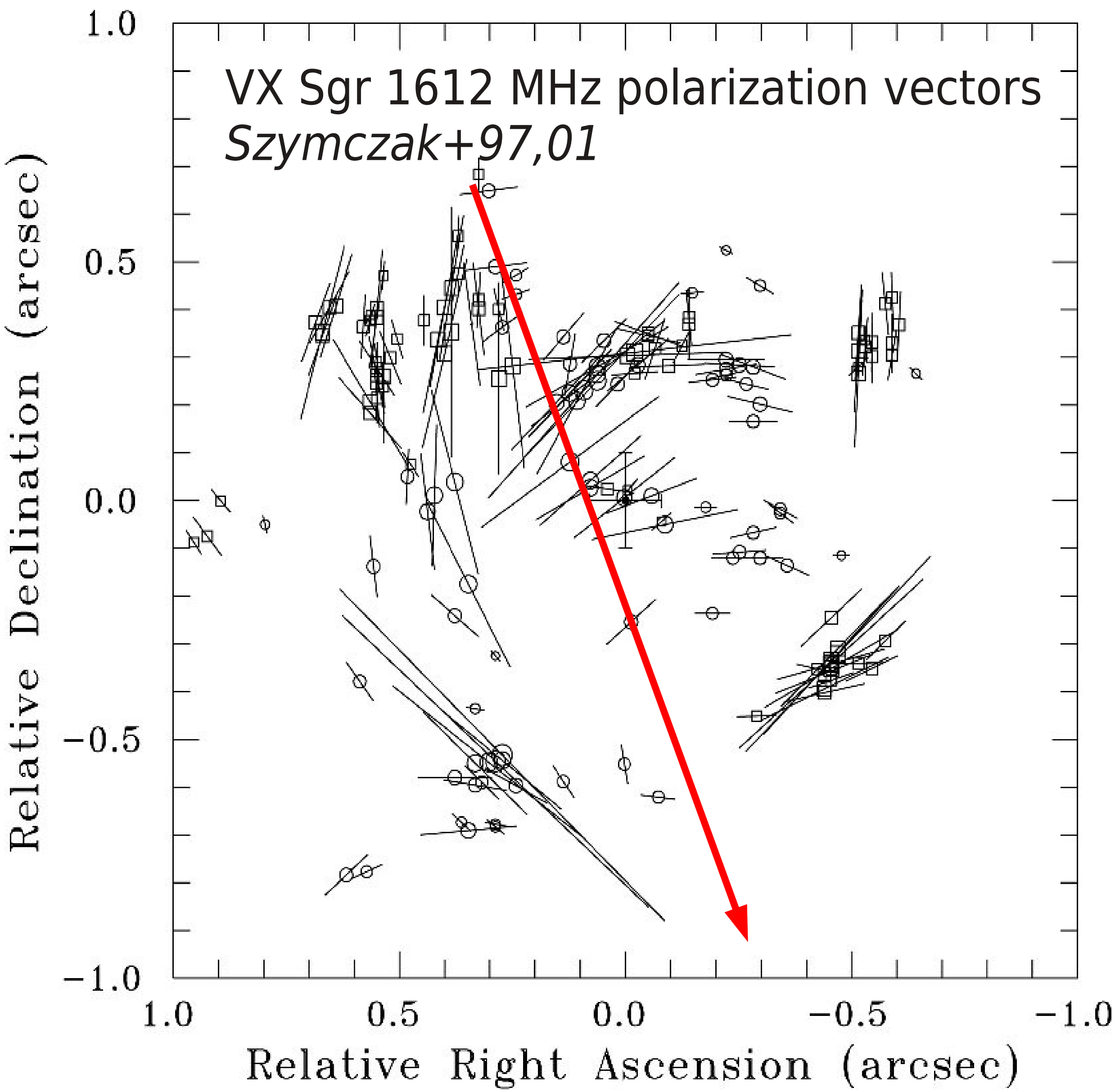
- OH mainlines elongated NNE-SSW
- Possibly trace surface of bicone
- Polarization consistent with magnetic field along axis
- Tilted so some masers sample field at ~55° to line of sight
  - No red-shifted linear polarization
- Circular pol. (Zeeman) shows |*B*| 0.1–1.1 mG

Persistent axisymmetry

- OH 1612 MHz > 2000 AU
  - ~5x H_2O shell
  - OH axisymmetric for several centuries
- Possible magnetic axis aligment?
  - NB No discernable rotation



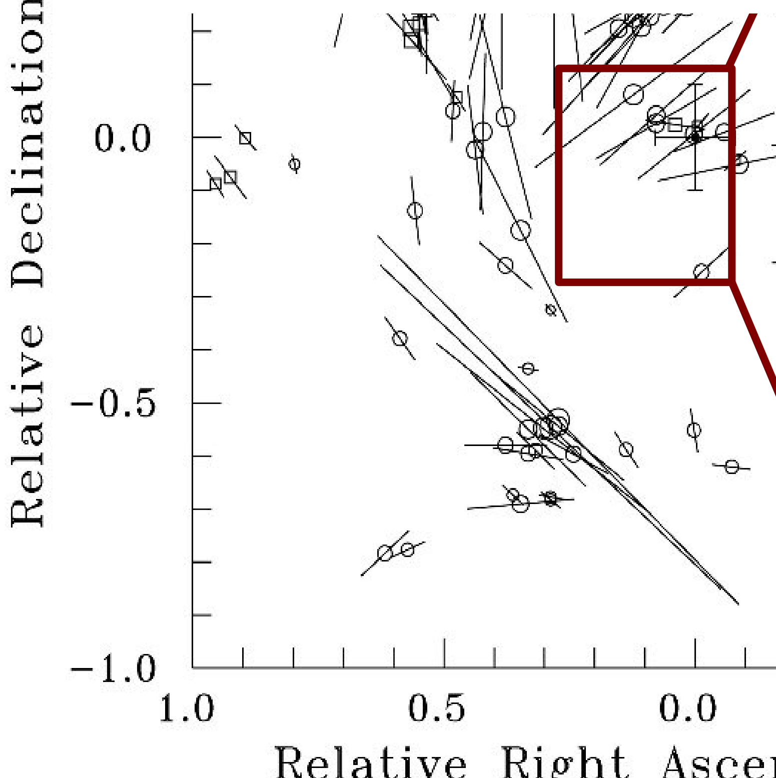
VX Sgr magnetic field

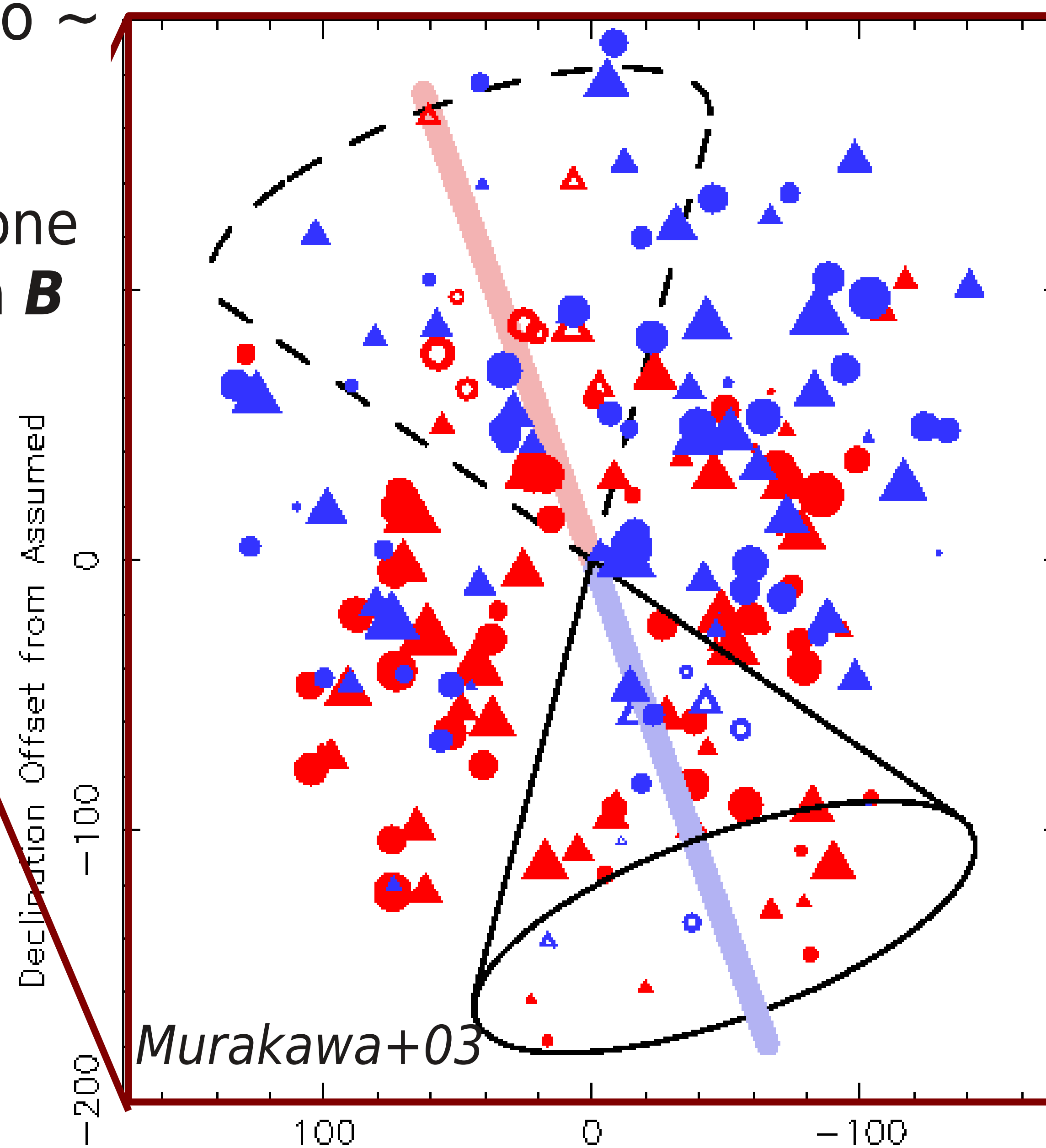


- OH 1612-MHz ~spherical
  - Strong Zeeman splitting
    - Stellar-centred dipole
    - Axis PA 20°, S approaching
    - *B*~1 mG at ~1".4 (~190 R_*)
- (OH mainline polarization a mess - as in VY CMa…)

VX Sgr asymmetry

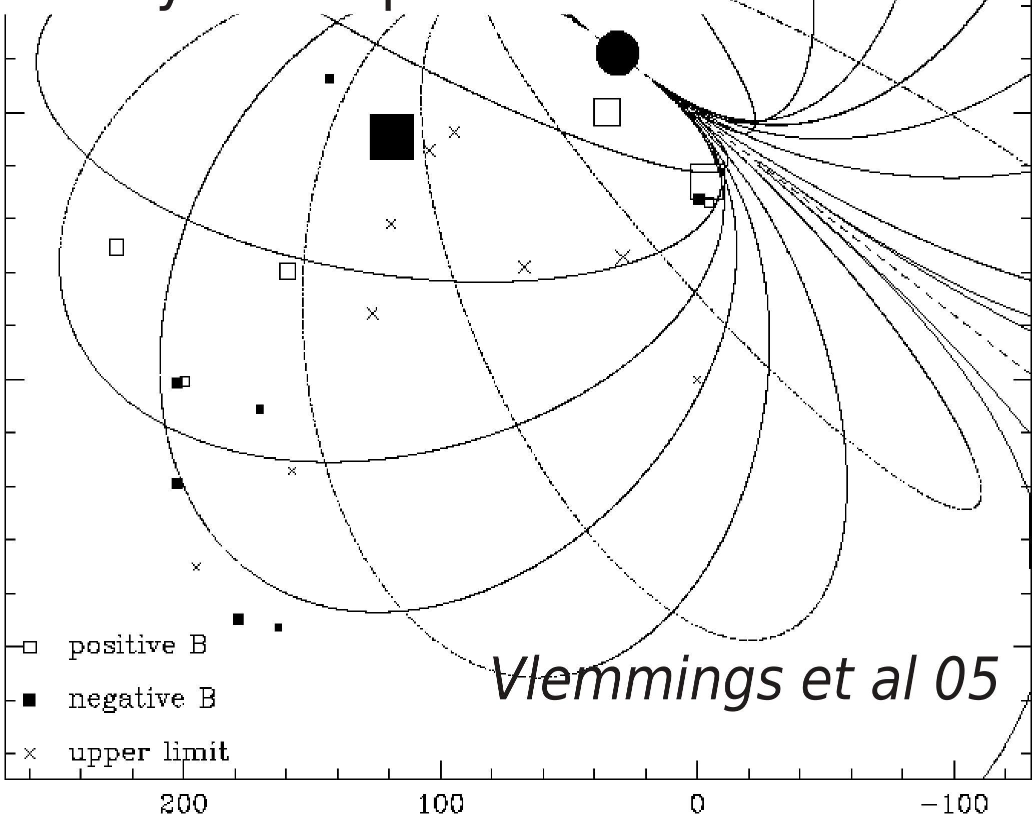
- H_2O maser shell also ~ spherical, 11-42 $R_\star$
  - Lower-density bicone △ ○ aligned with ***B*** axis

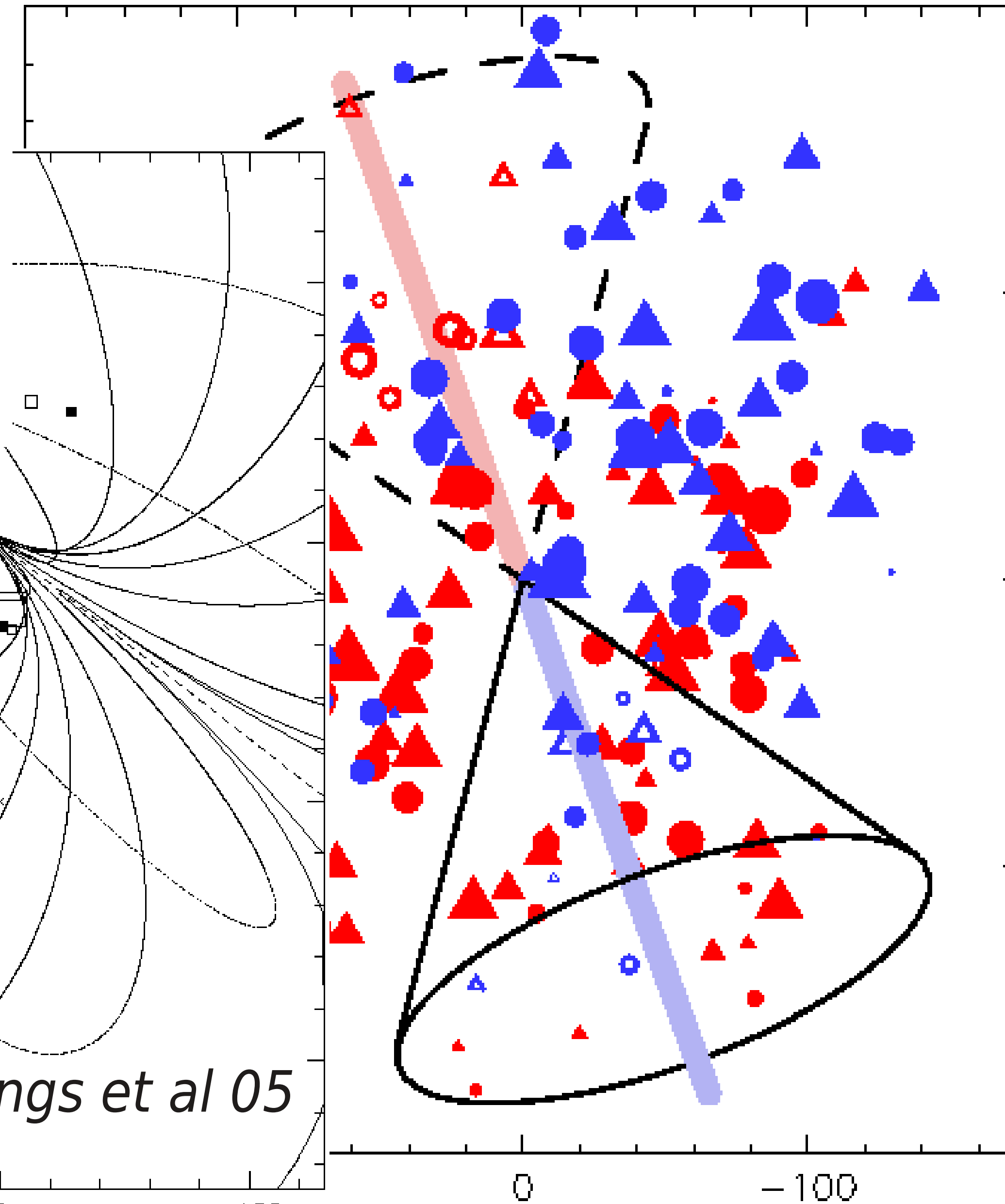




H_2O magnetic field

- H_2O ***B*** axis also aligned
  - ~0.1 to few G
- Magnetic energy density ≥ kinetic energy density
  - Likely to shape wind

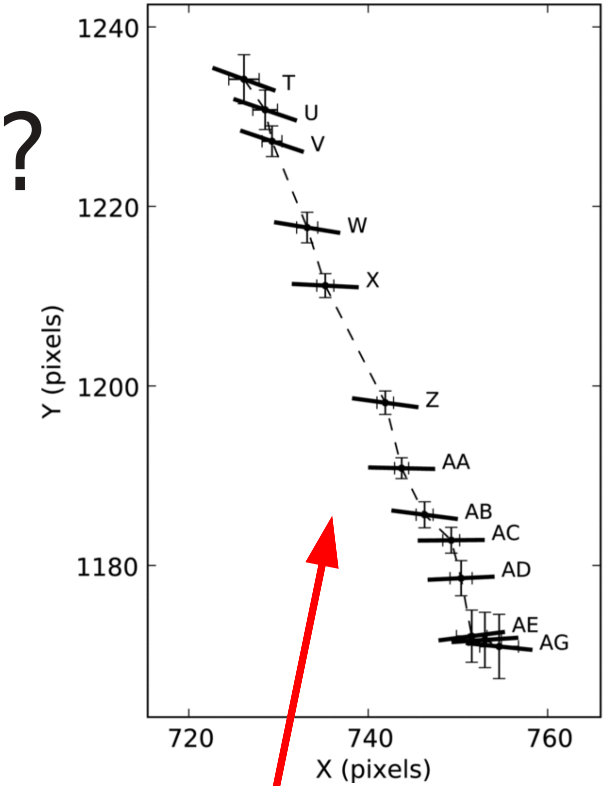


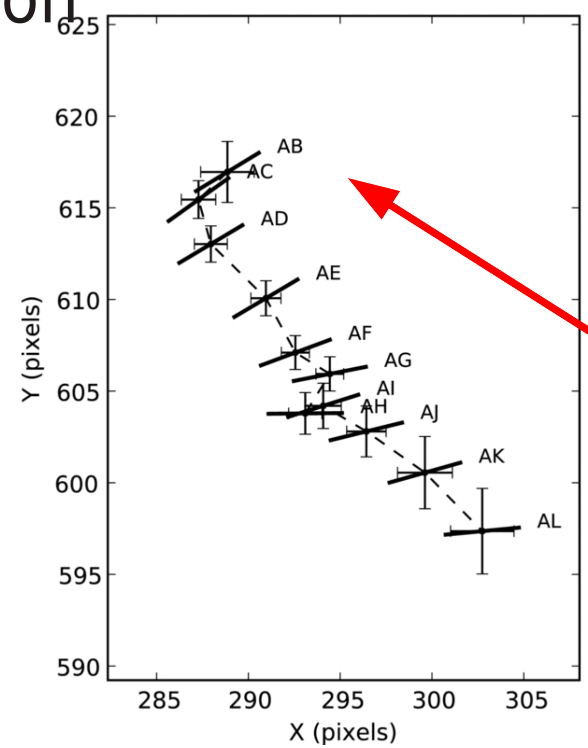


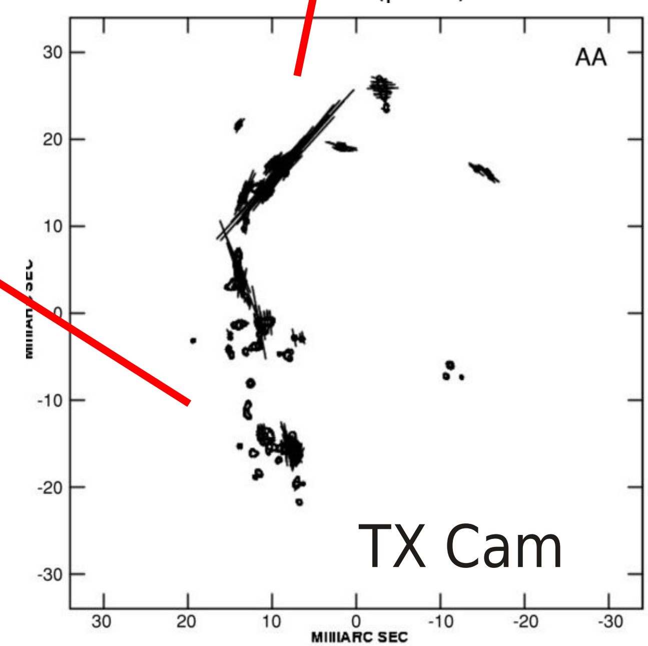
Vlemmings et al 05

SiO clumps follow field lines?

- TX Cam proper motions not consistently radial (*Kemball+11*)
  - Non-ballistic?
  - Polarization vectors <u>*B*</u> follow direction of motion
  - Are masers tracing matter accelerated along field lines?
    - Or dragging the field in masing clumps? (*Hartquist+96*)

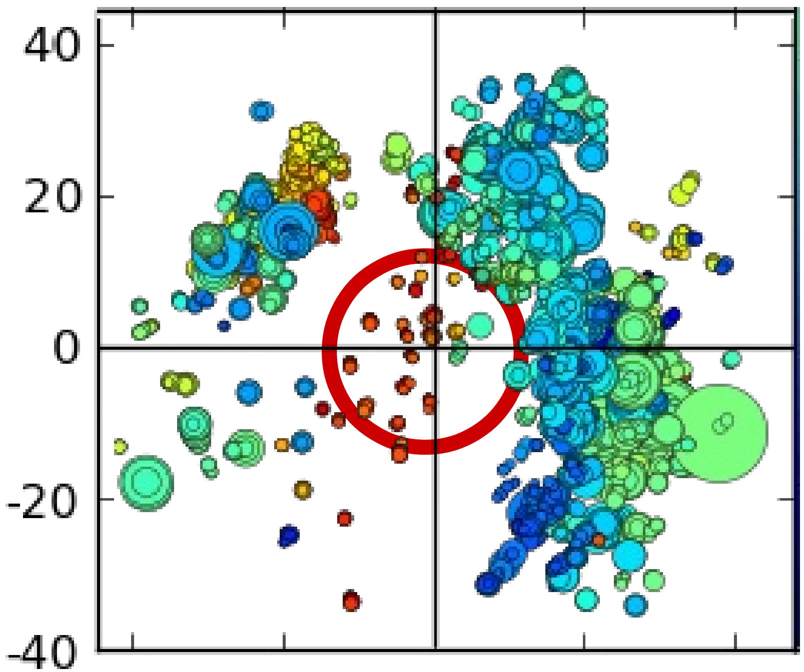




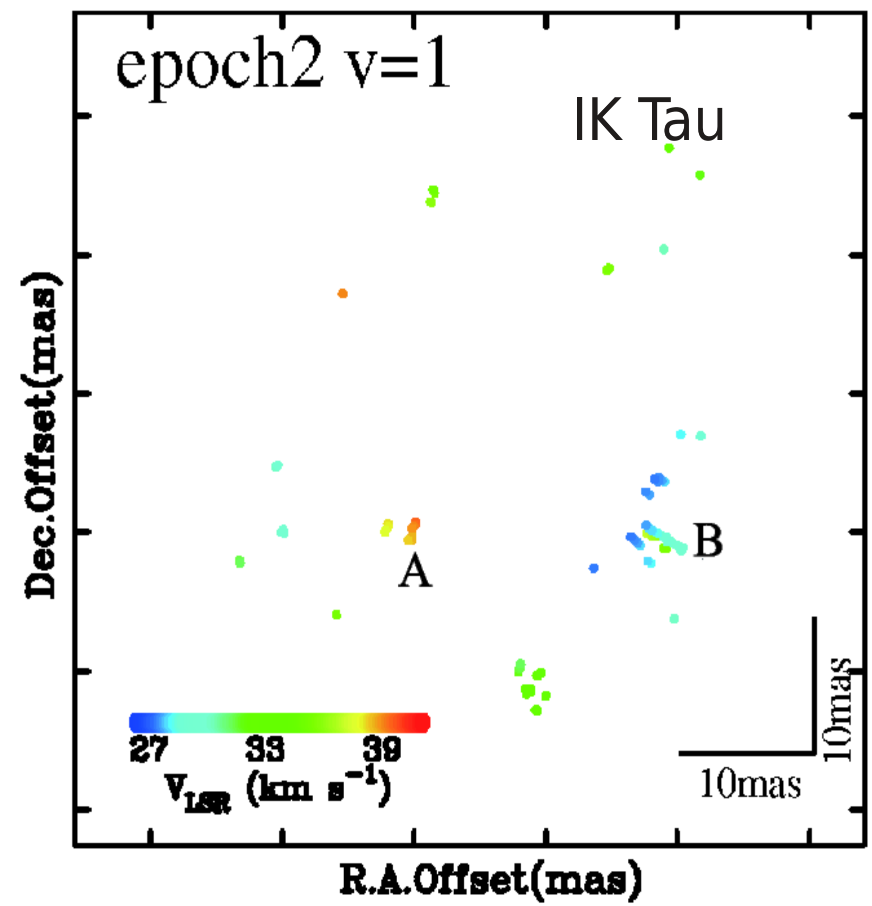


Or ballistic proper motions?

- Ballistic trajectories fitted to IK Tau (*Matsumoto+08*)
  - Including deceleration due to star's gravity
- R Cas shows some central redshifted emission (*Assaf+10*)
  - Must be near-side infall
    - $R_\star$ ~13 mas (*Weigelt '00*)

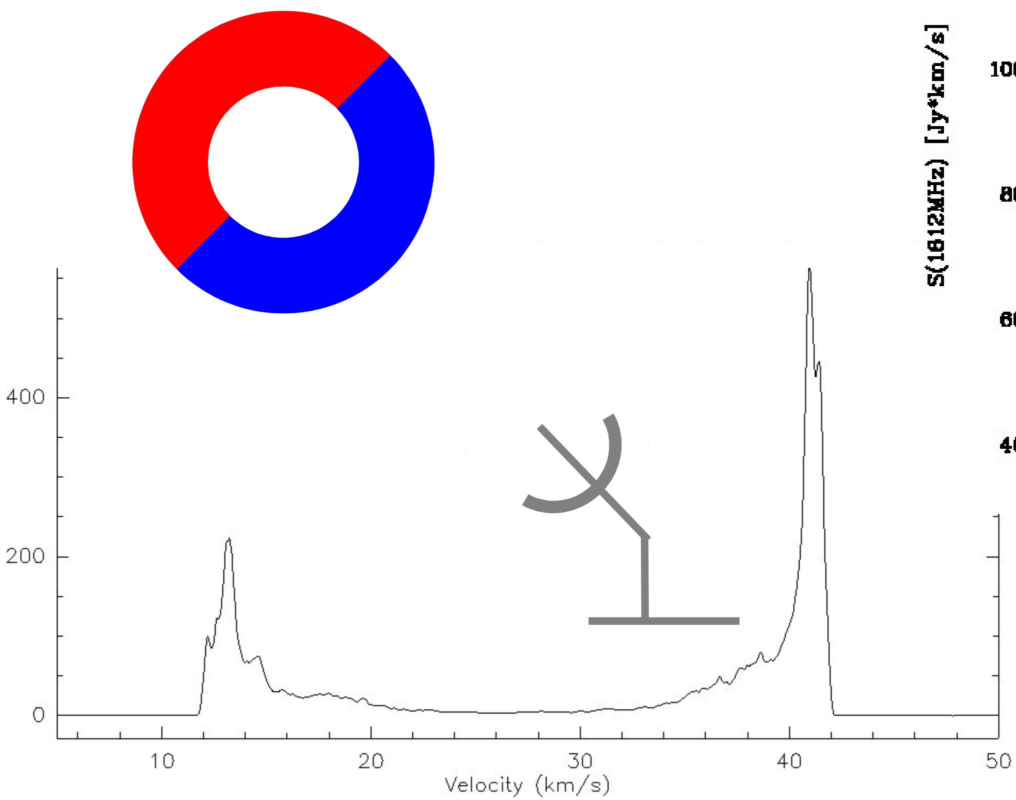


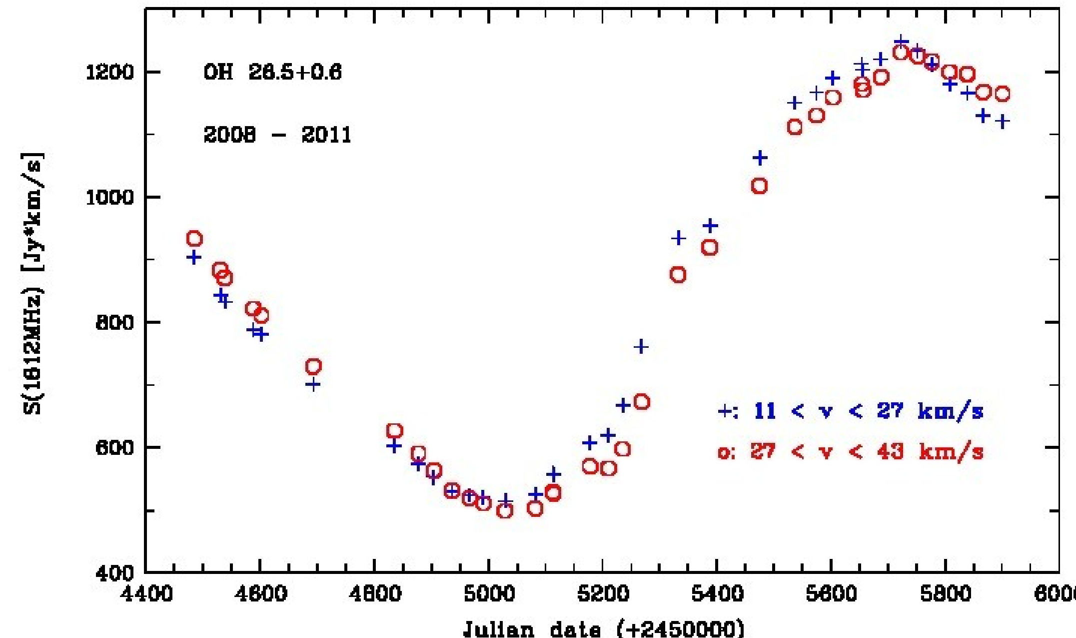
R Cas *Assaf+12*



OH 1612-MHz Phase Lag

- OH 1612-MHz masers pumped by warm dust
  - Most strongly heated close to stellar maximum (*P* several yr)
    - Light travel time from near (blue) side of shell weeks less than from far (red) side
      - "Phase lag"



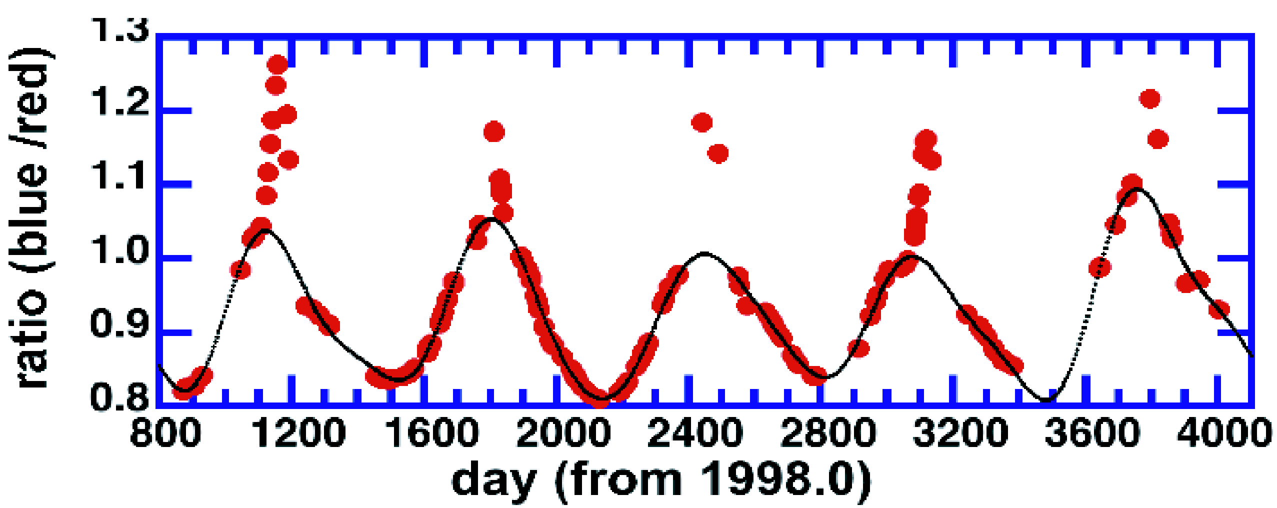


- OH 26.5+0.6
  - 35-day phase lag
- *Engels'12*

Episodic dust formation in WX Psc

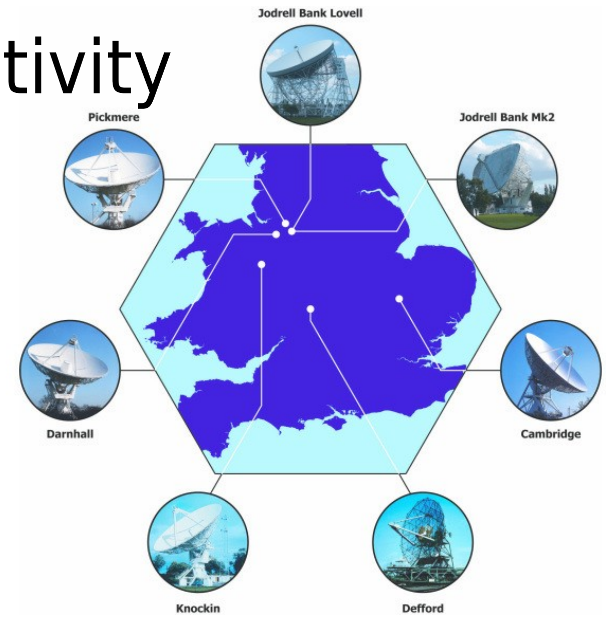
- OH 1612-MHz masers pumped by warm dust
  - More effectively heated close to stellar maximum
    - Light travel time from near (blue) side of shell days less than from far (red) side
      - “Phase lag”
- WX Psc shows unexpected cusps in blue:red peak flux ratio
- Light passes through discrete, thick dust layer
  - Surge in 53 μm pump photons
  - We see effect on near (blue) side first
    - Dust layer produces additional delayed effects on both sides

Lewis'*11*
Nancay &
Aricebo

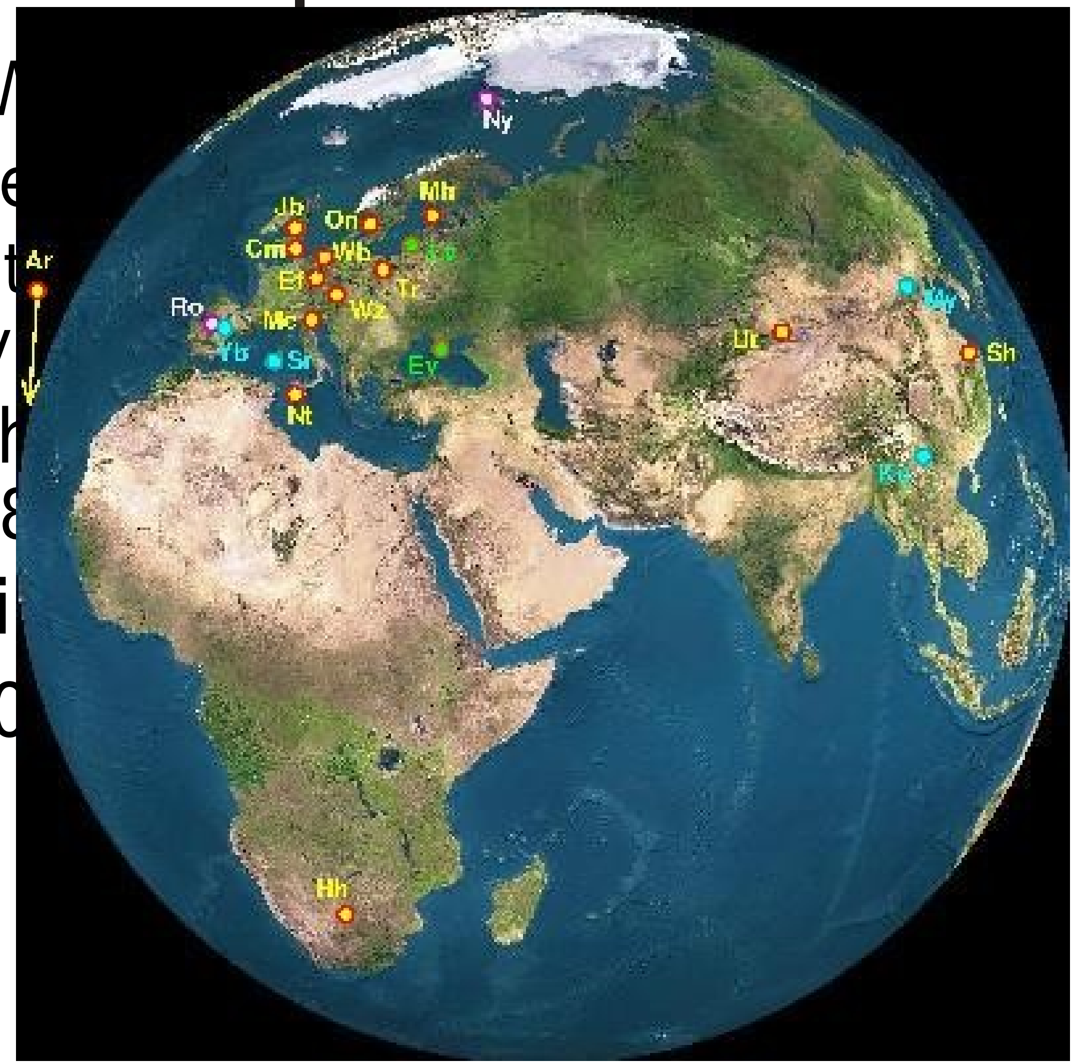


eMERLIN capabilities

- Resolution matches HST/JWST/ALMA
- 1.3-1.7, 4-8, 21-26 GHz wavebands ($\leq$2-GHz bw)
- 200 - 10 mas angular resolution
  - Sub-mas ICRF astrometry, in-beam calibration
- 6 μJy 3-σ sensitivity in 12 hr at 4-8 GHz
  - 40-mas resolution, up to 8-arcmin field of view
- Other bands ~15 μJy continuum sensitivity
- Spectral line: 7-20 mJy in 0.1 km/s
- Full polarization
- Dec $\gtrsim$ -30^{o} ~ 20^{o}
- Cycle 1 later this year
- Joint observations with EVN/Global VLBI
- http://www.e-merlin.ac.uk



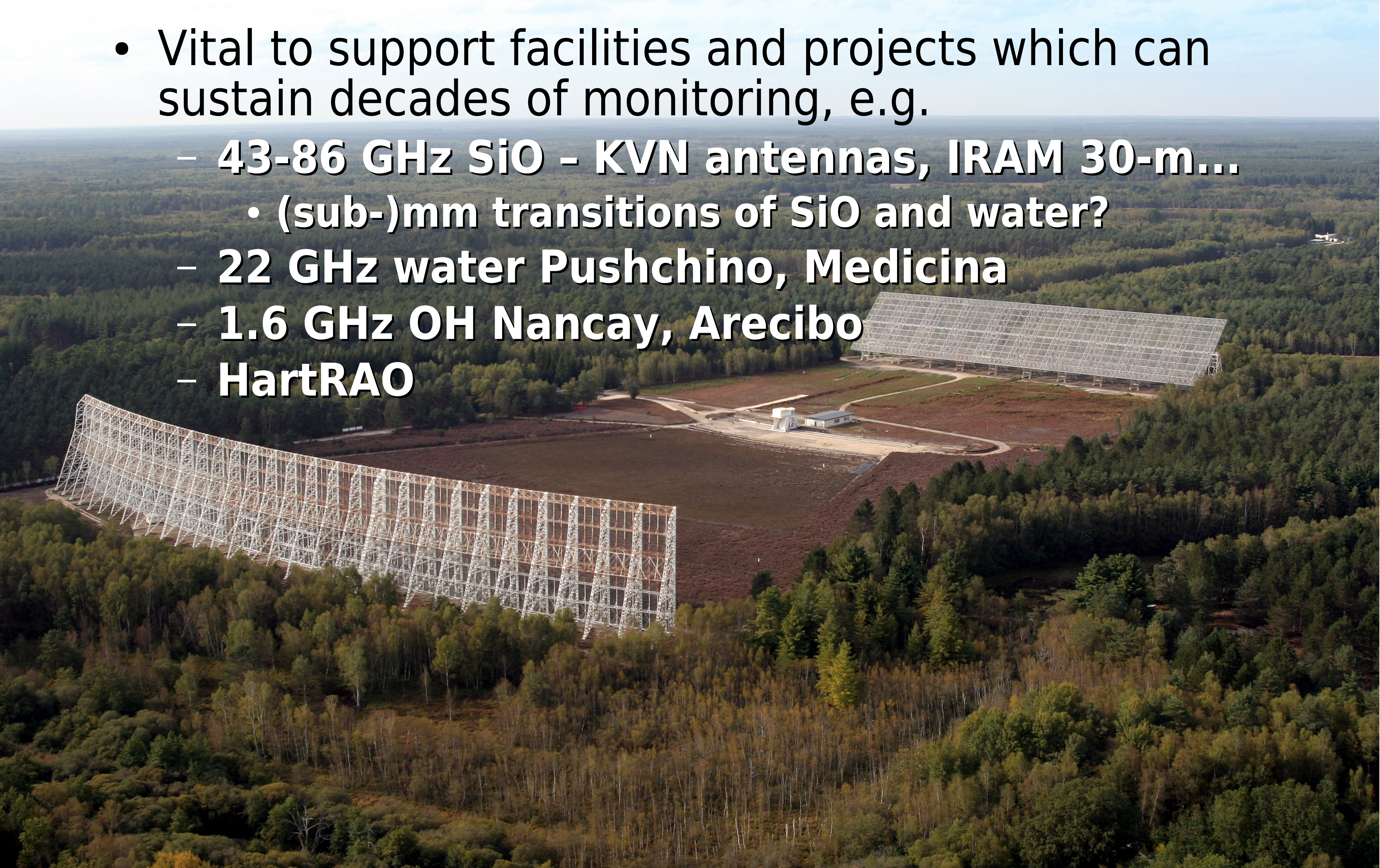
eMERLIN + VLBI capabilities



- Resolution matches HST/JW
  - 1.3-1.7, 4-8, 21-26 GHz wave
  - 200 - 10 mas angular resolut
    - Sub-mas ICRF astrometry
- 6 μJy 3-σ sensitivity in 12 h
  - 40-mas resolution, up to 8
- Other bands ~15 μJy conti
- Spectral line: 7-20 mJy in 0
- Full polarization
- Dec ≳ -30º ~ 20º
- Cycle 1 later this year
- Joint observations with EVN/Global VLBI: mas resolution
  - http://www.evlbi.org

Long-term single dish monitoring

- Vital to support facilities and projects which can sustain decades of monitoring, e.g.
  - **43-86 GHz SiO – KVN antennas, IRAM 30-m…**
    - **(sub-)mm transitions of SiO and water?**
  - **22 GHz water Pushchino, Medicina**
  - **1.6 GHz OH Nancay, Arecibo**
  - **HartRAO**



Summary of wind properties from H_2O masers

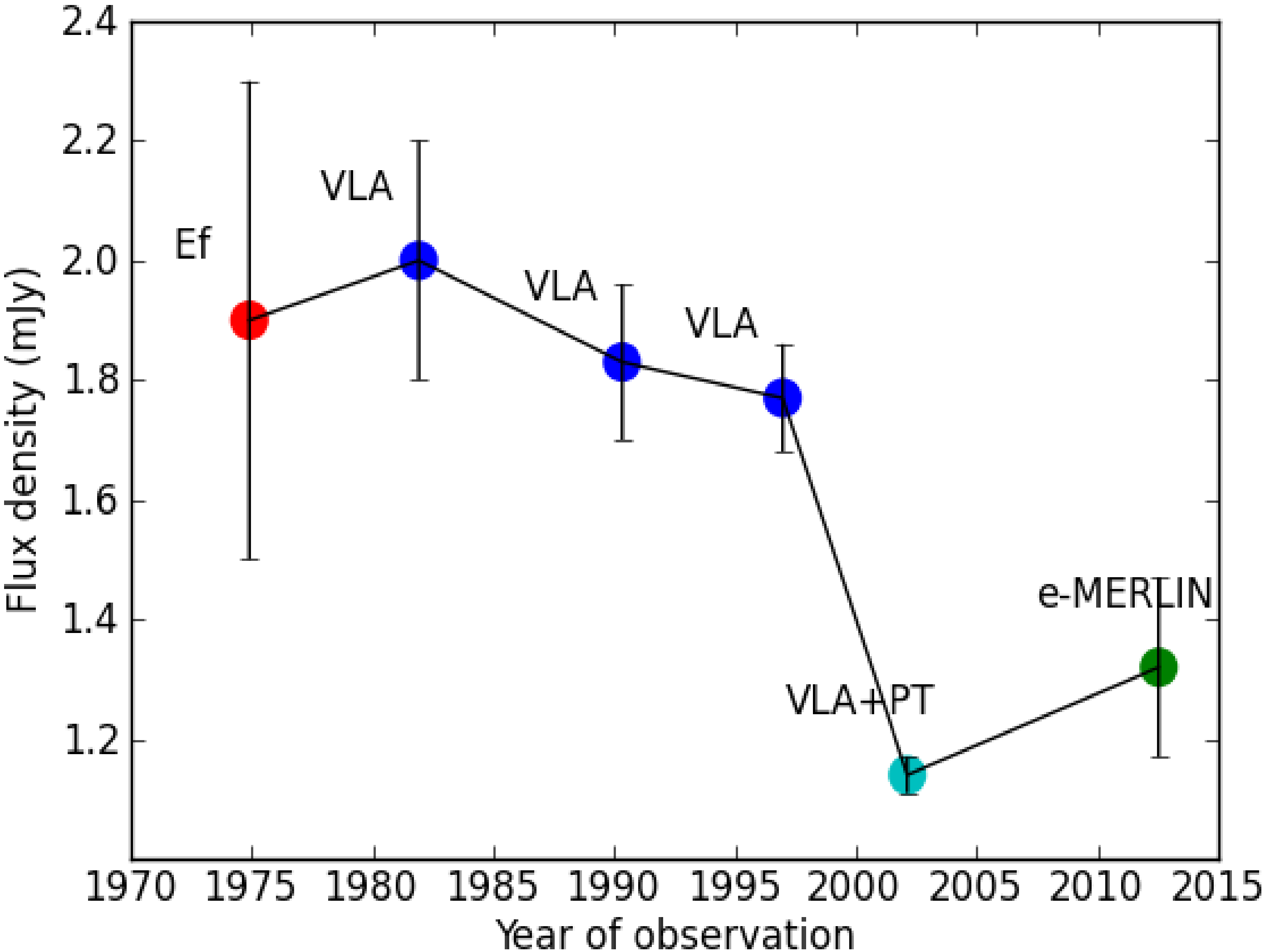
Star	$R_{\odot}$	R_{cloud} (average)	$\dot{M}_{total}$	n_{cloud} / $n_{average}$	M_{cloud} (single)	$\dot{M}_{clouds}$ / $\dot{M}_{total}$	Filling factor
	AU	AU	10^{-6} $M_{\odot}$/yr		10^{-6} $M_{\odot}$		
VX Sgr	7.4	6.5	72	107	17	0.2	0.09%
S Per	8	7.5	38	43	14	1.3	0.95%
U Ori	1.5	1.9	0.23	72	0.24	1.8	0.95%
U Her	1.3	1.7	0.37	88	0.29	1.8	0.79%
IK Tau	2.8	1.4	2.6	75	0.16	0.2	0.10%
RT Vir	0.8	0.5	0.13	55	0.004	0.4	0.26%
W Hya	2.1	0.7	0.23	55	0.015	0.2	0.19%

- Properties of clouds derived from 22-GHz maser measurements
  - 7 stars, MERLIN & Pushchino monitoring *Richards+2011,12*
    - Uncertainties, references therein for $R_{\star}$ & $\dot{M}$

What lies in store for Betelgeuse?

- Later RSG mass loss concentrated in ~50x overdense clumps
  - Size consistent with ~0.05-0.1 R_* convection cells
  - 3-6 clumps ejected per few-year stellar period
    - Episodic mass loss could form concentric, clumpy shells
  - Clump distribution ~spherical, negligible rotation
    - Inter-clump lower-density gas can have biconical concentration
  - Large scale (within astropause) always ~axisymmetric except VY CMa!
- Stellar-centred *B* fields
  - ≳10s G at photosphere, $\propto r^{-2 - -3}$, ≲G at ~5 – 10R_*, 1-0.1mG at ~20-100R_*
  - May depend on local density, strong enough to influence (not drive) wind
- Acceleration continues to many 100s R_*
- SiO masers appear first
  - Keep watching at 43, 86, 211-6, 256-9, 300-3, 344-6 ... GHz
  - Maybe excited H_2O e.g. 658 GHz...

Variability at λ 6cm (4.8 GHz)

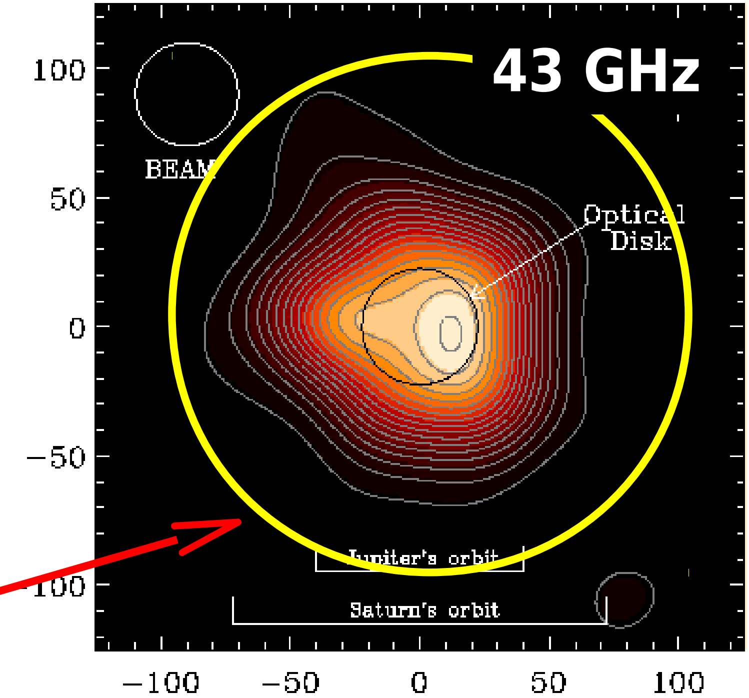


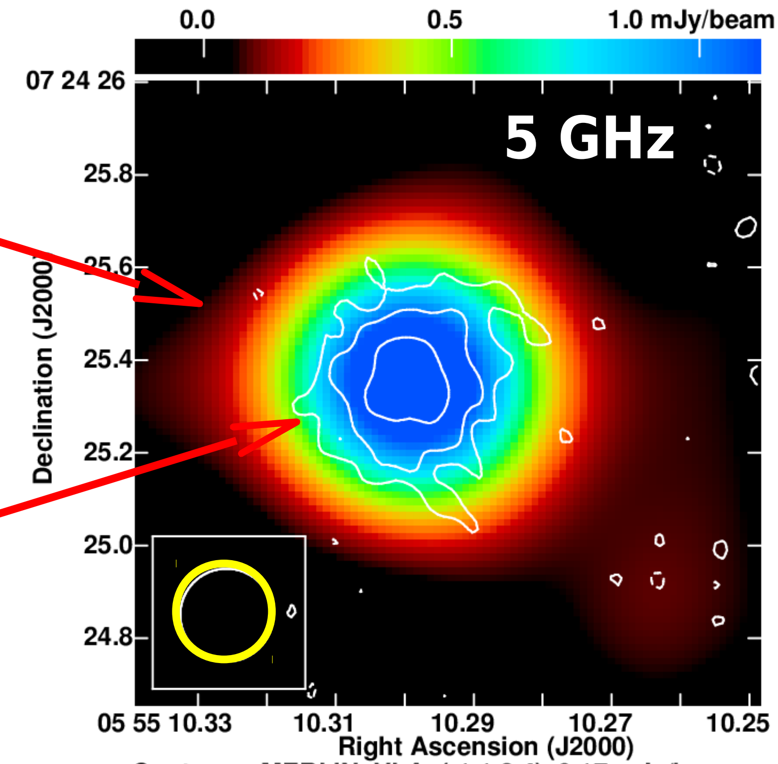
Altenhoff+79, *Newell+82*, *Skinner+97*, *Lim+98*, *Harper+03*, *Richards+12*

- Radio variability 20-30% in weeks/months
  - *Bookbinder+87, Drake+92*
- Fading since 80s
  - 2012 e-MERLIN extrapolated from 5.75 GHz assuming 1.32 spectral index
- Shrinking 11.15 μm diameter *Townes+'09*
  - ~56⇒48 mas in 1993⇒2009

Radio photosphere

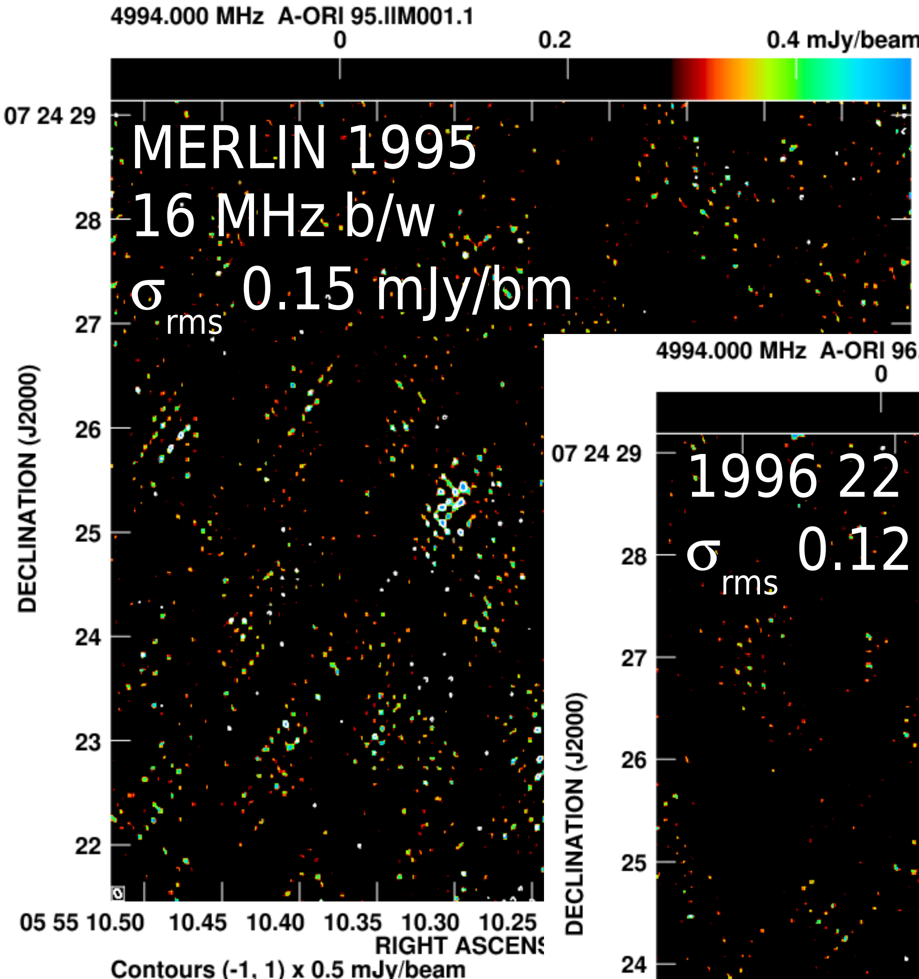
- Barely resolved by VLA alone
  - *Lim+98, Harper+06*
  - 43-GHz (λ 7 mm) irregularities
    - 50-mas beam, sensitivity-limited
  - Measure ellipticity at lower ν
    - 5-GHz (λ 6 cm) 400-mas beam (colour scale)
- Combine with old MERLIN 1996
  - **200-mas resolution** contours
    - Still sensitivity limited

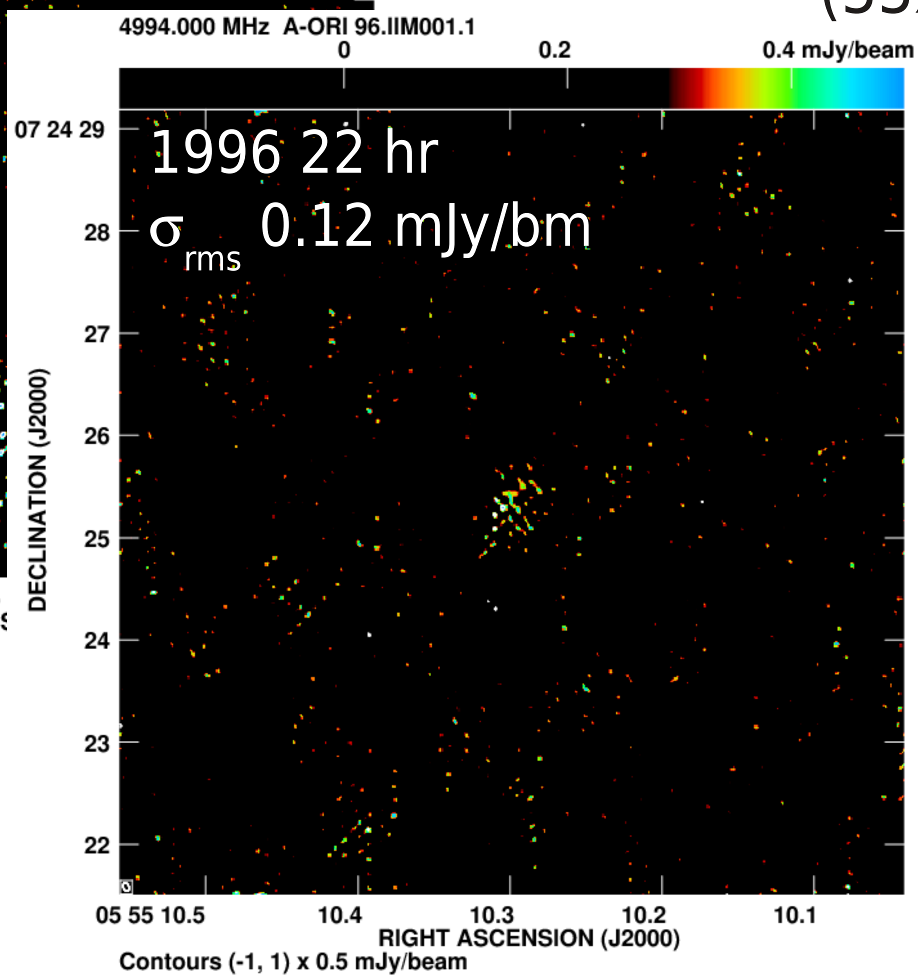




Contours: MERLIN+VLA, (-1,1,2,4)x0.17 mJy/beam
Colour: VLA image at 0.4 arcsec resolution

'Old' MERLIN: 5 GHz hot spots



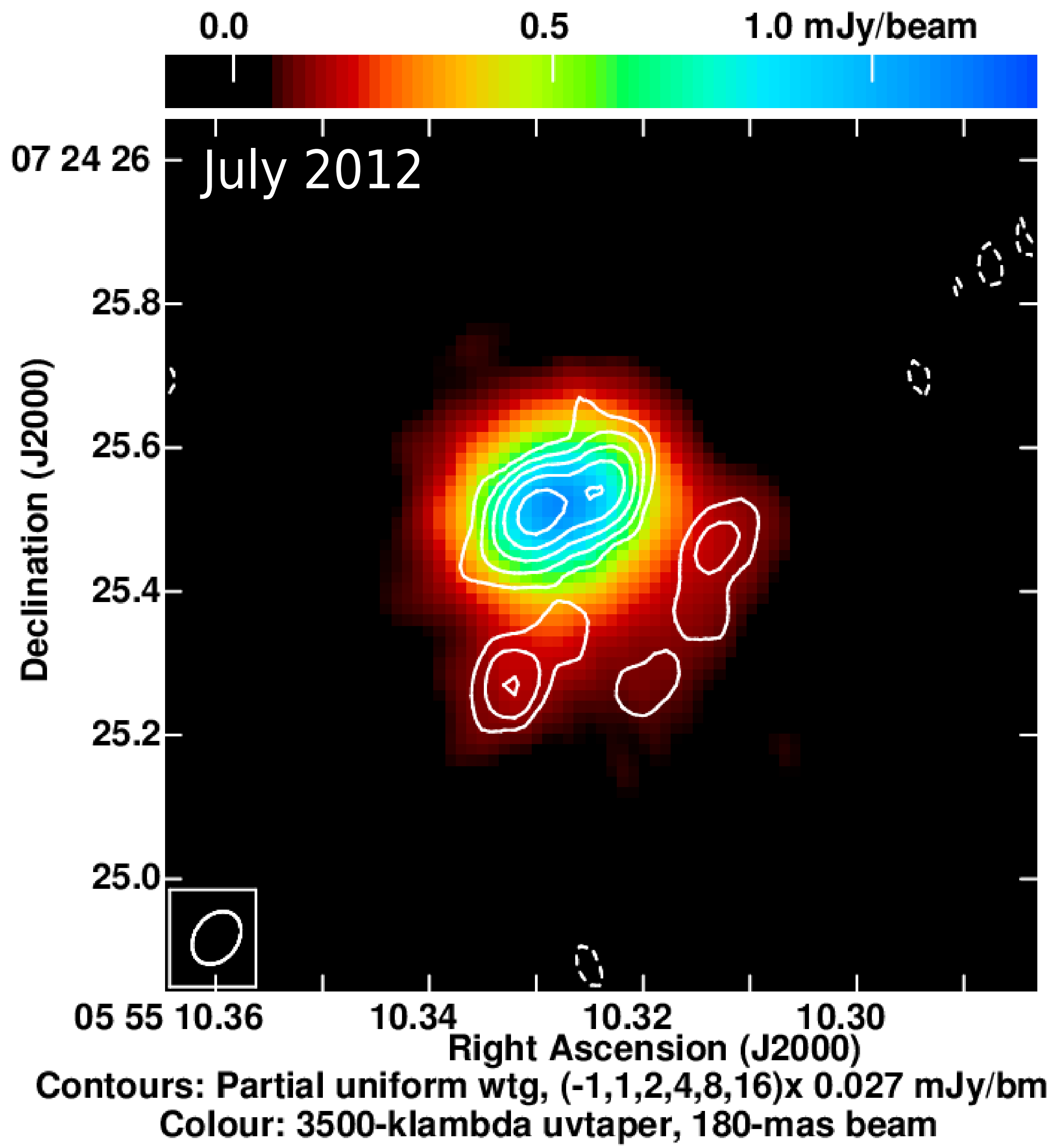


- 4 – 5 spots > $4\sigma_{rms}$
  - 0.48 – 0.78 mJy/bm
    - (55x85) mas beam
- Shortest spacing ≡ >0".5
  - Sensitivity limited
- Brightness temp T_b 6000-8000 K
- σ_{Tb} 2000 K
  - >3600 K photosphere to have been detected at all

Davis, Skinner, Morris, Richards

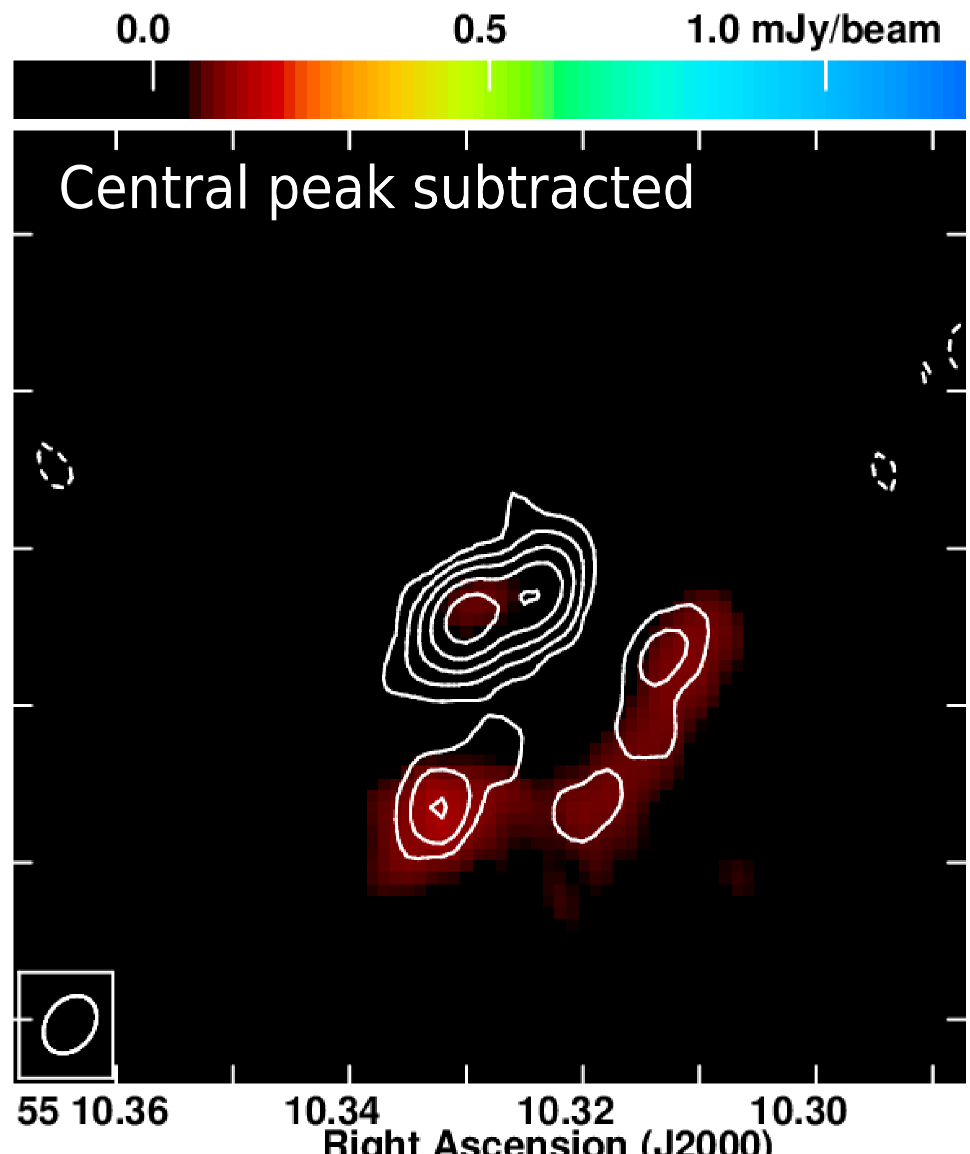
α Ori e-MERLIN 5.75 GHz

- *Richards, Davis, Decin, Lim, Etoka, Garrington, McDonald, Wittkowski*
- 6-8 hr, 400 MHz b/w
  - Colour: 180-mas beam
    - σ_{rms} 0.027 mJy/bm
    - Fit elliptical Gaussian 1.619 mJy
      - 235x218 mas^2
    - Small central 0.082 mJy residual
  - Main disc T_B 1250∓135K



SW Arc

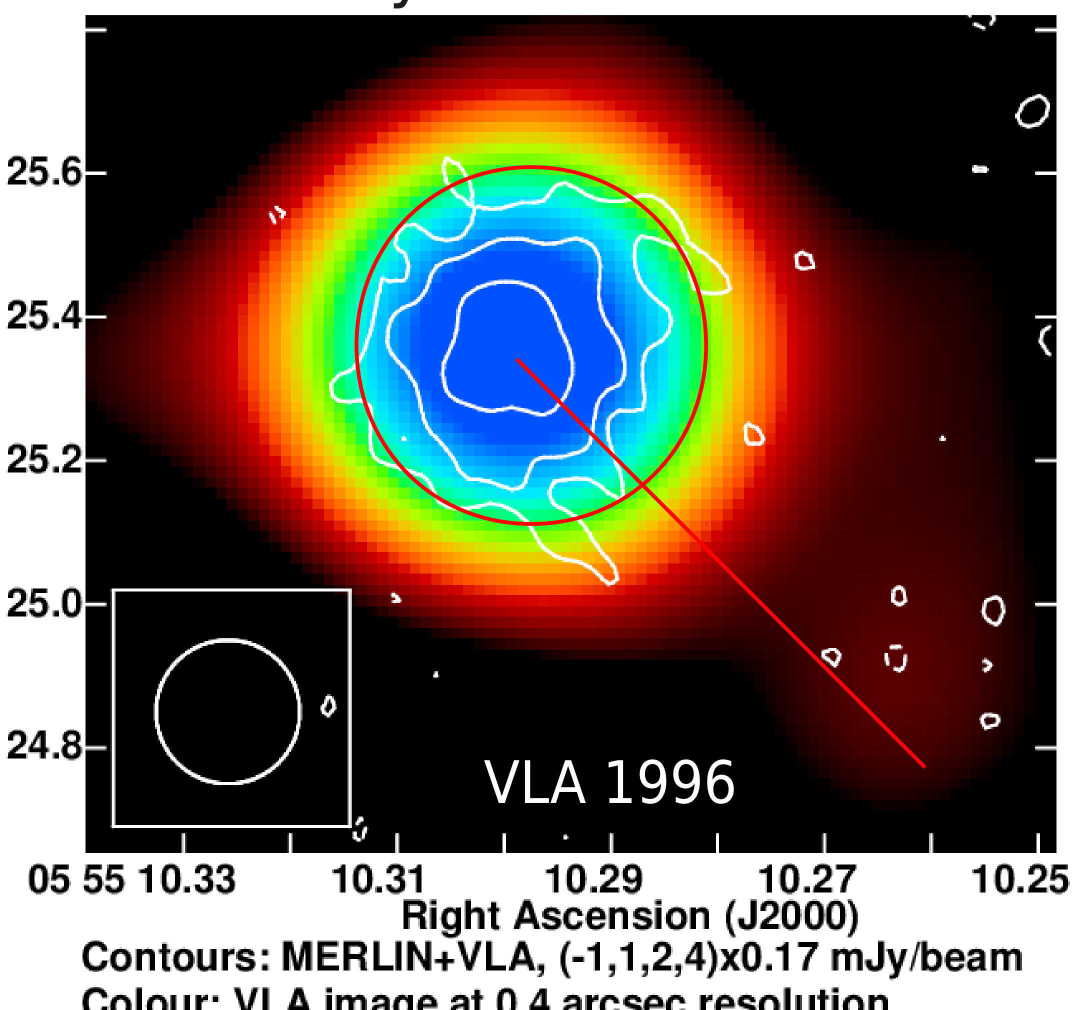
- SW residual after subtracting Gaussian
  - 0.175-0.275 asec radius arc
    - Total flux density 0.088 mJy in 0.0249 asec^2
    - Arc T_B 150∓40K

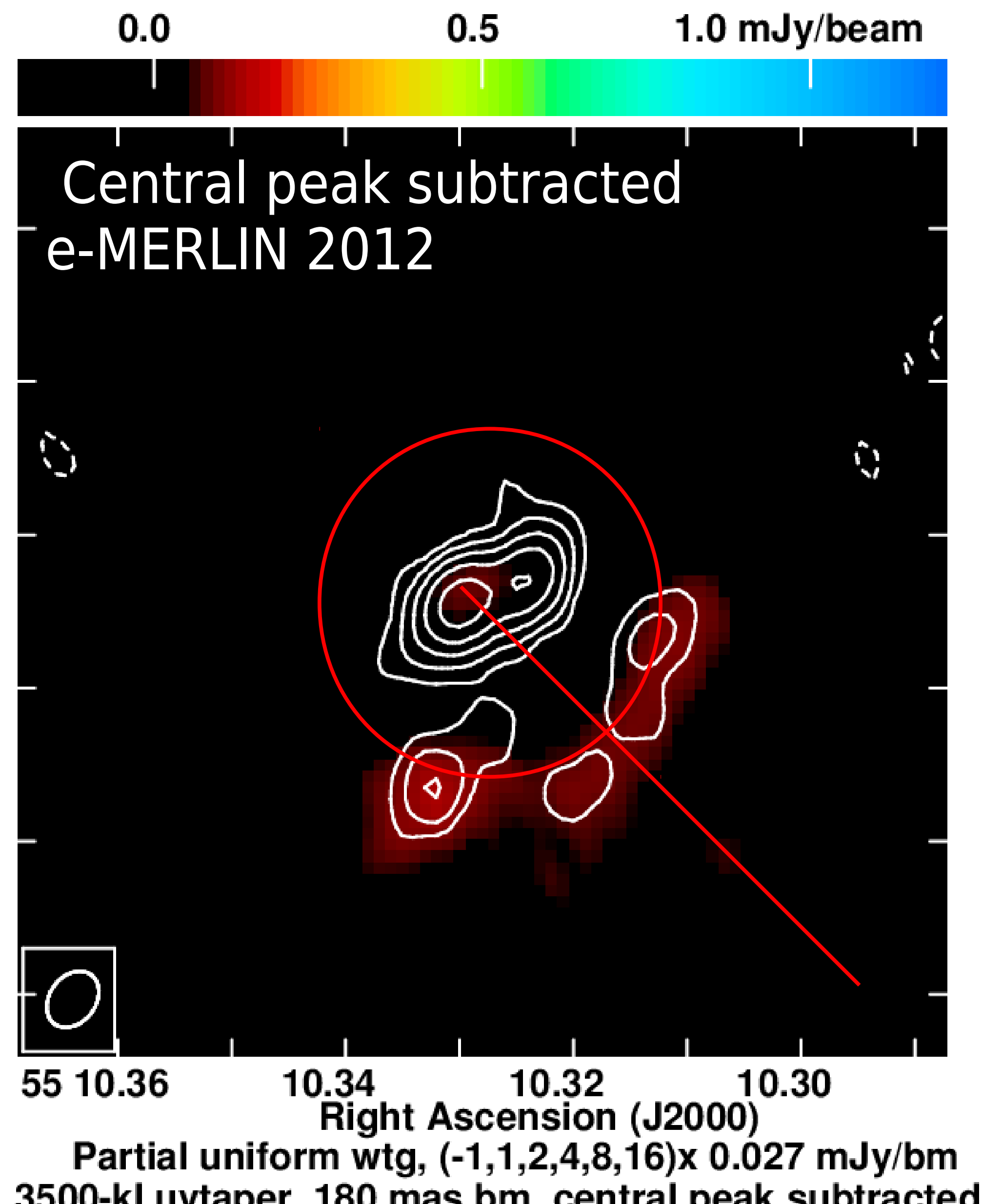


Contours: Partial uniform wtg, (-1,1,2,4,8,16)x 0.027 mJy/bm
Colour:3500-kl uvtaper, 180 mas bm, central peak subtracted

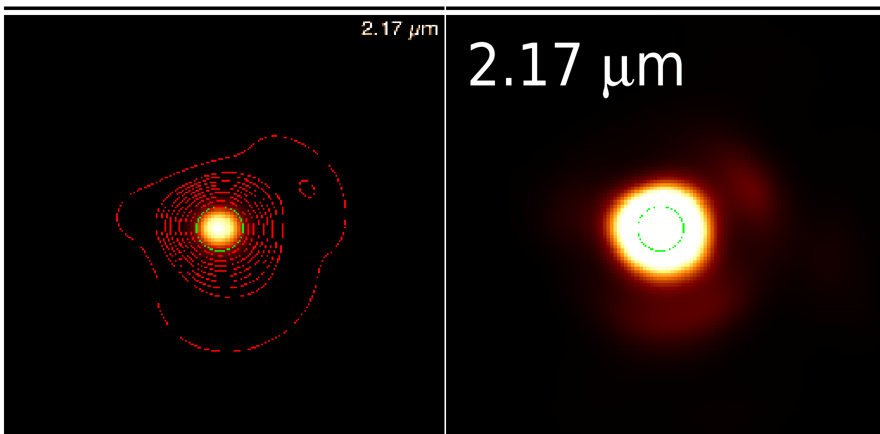
SW Arc

- Similar direction extension at ~0.6 asec in 1996 VLA data
  - Barely 3σ

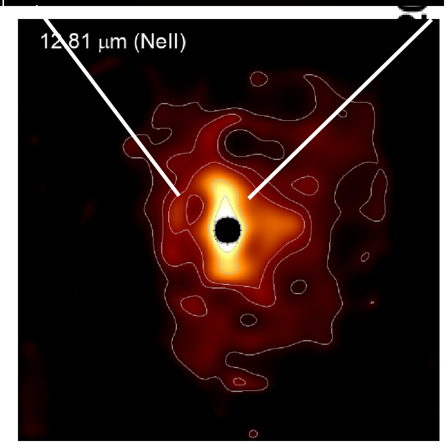




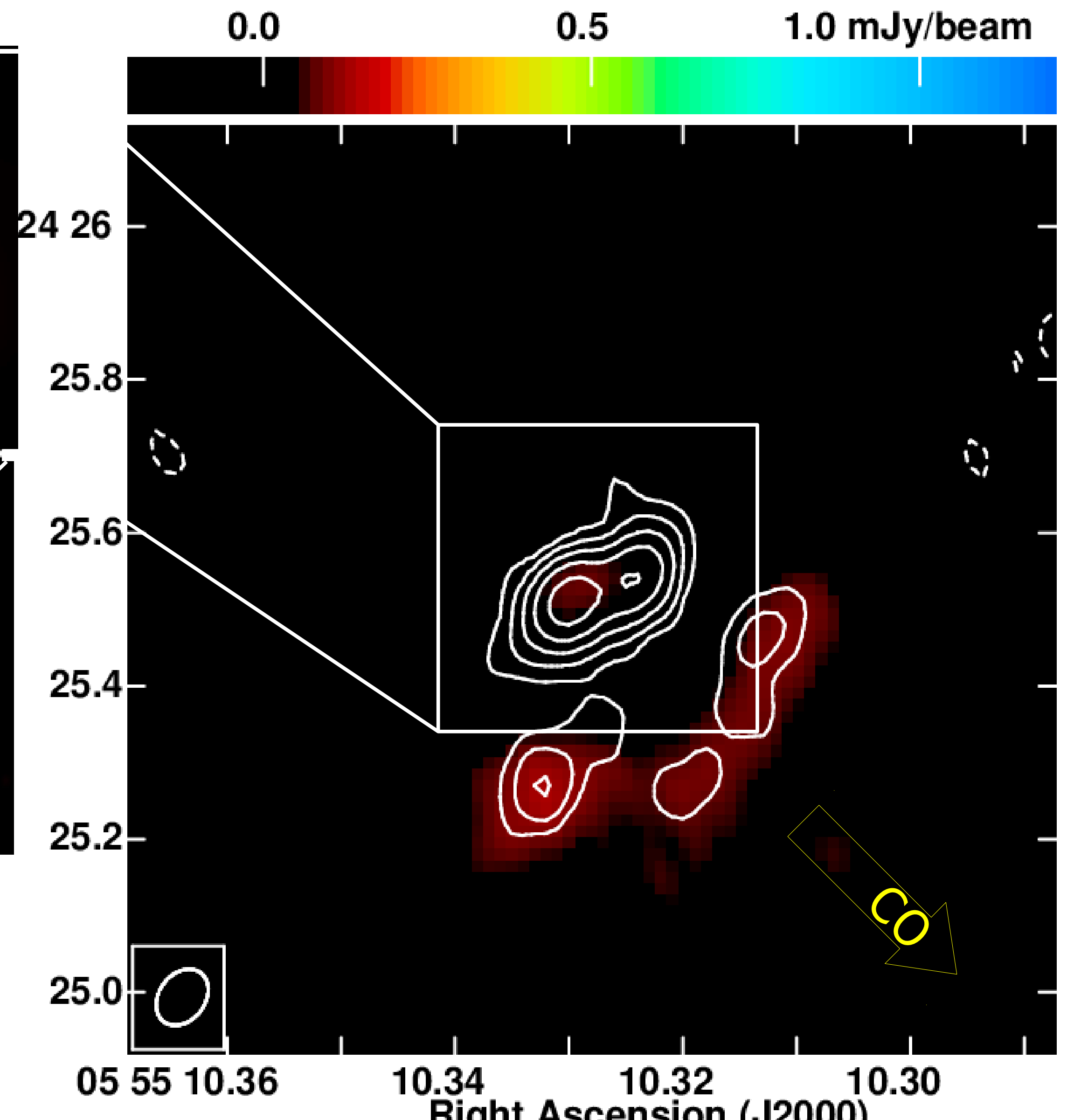
SW emission on other scales



- SW extension similar direction to IR plume
  - *Kervella+09, Kervella+11*

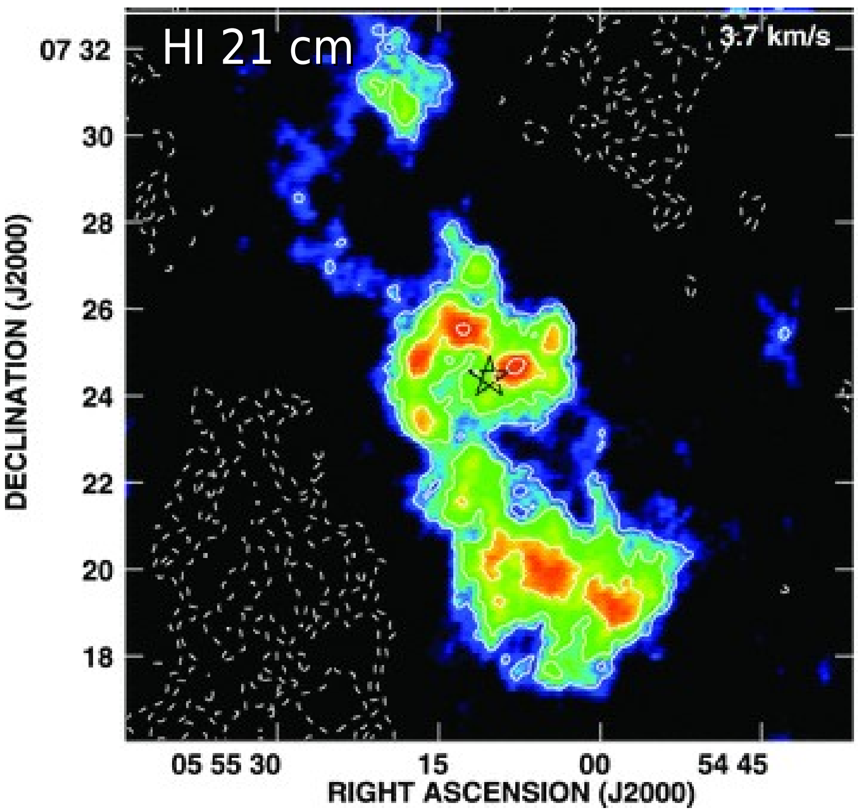


- Detatched CO source 5” SW
  - *O'Gorman+12*

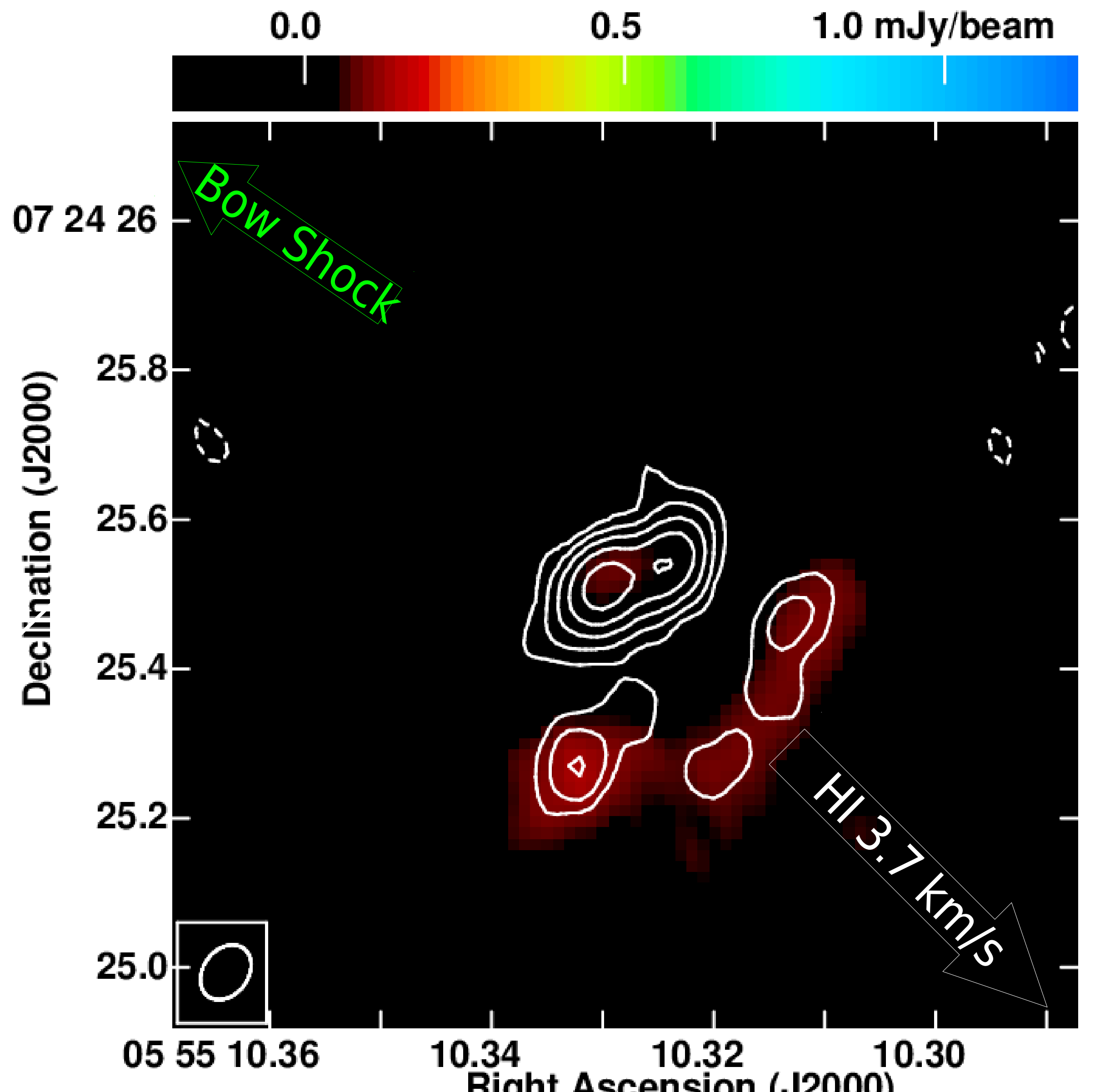


Contours: Partial uniform wtg, (-1,1,2,4,8,16)x 0.027 mJy/bm
Colour:3500-kl uvtaper, 180 mas bm, central peak subtracted

SW arc on arcmin scales



- Elongation of HI close to $V_{\star}$ (*Le Bertre+12*)
- NE bow-shock IRAS, Galex *(Noriega-Crespo'97), Herschel (Decin'12)*
  - Arcmin scales



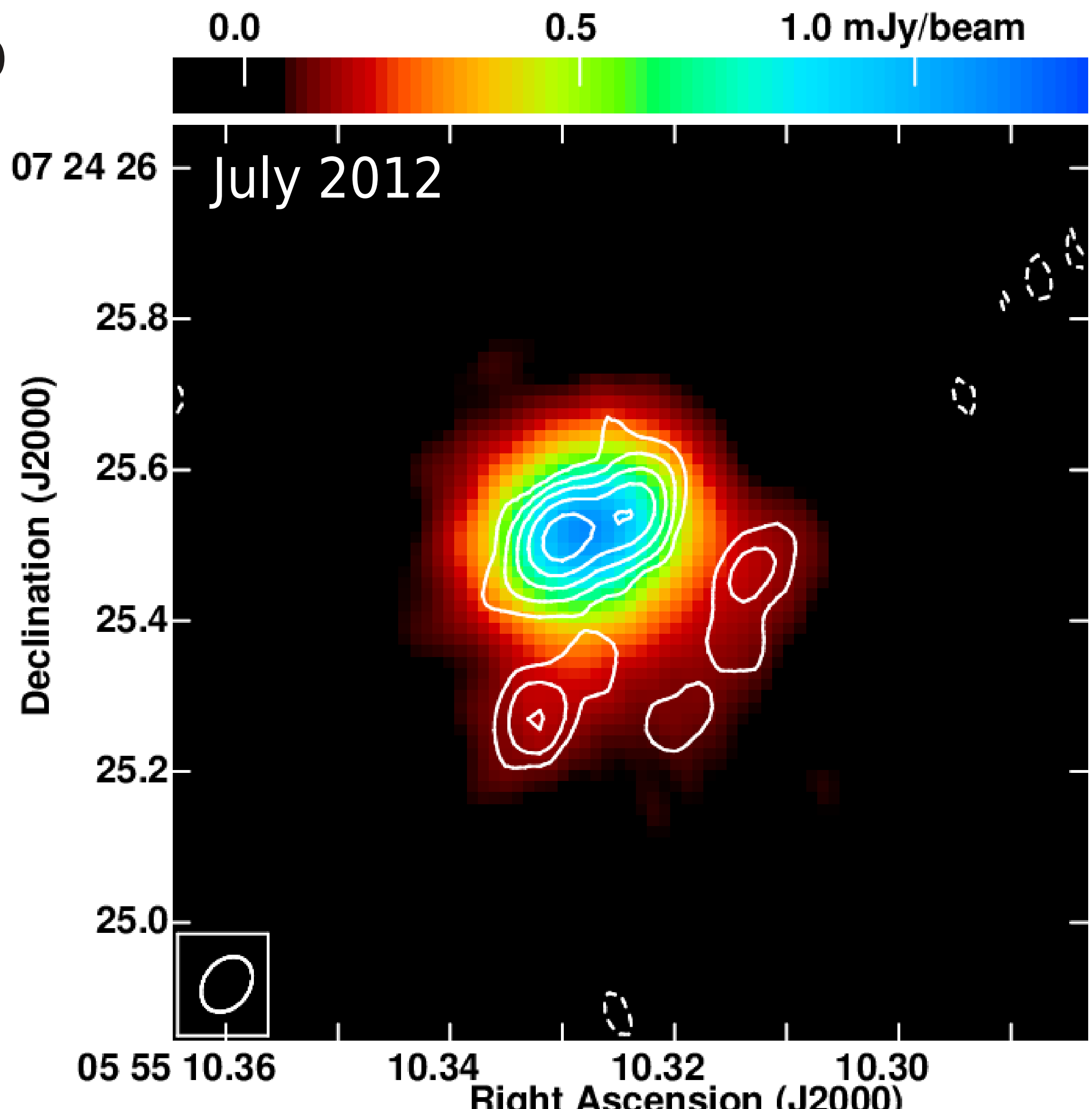
Contours: Partial uniform wtg, (-1,1,2,4,8,16)x 0.027 mJy/bm
Colour:3500-kl uvtaper, 180 mas bm, central peak subtracte

Preferred direction? Chance?

- IR and radio arcs within ~1” ejected at many PA
  - SW preferred at several epochs at least since 1996
  - 225-mas 'beard' – 20-40 yr from $R_{\star}$ @ 5-10 km/s
  - CO at 5” equivalent to >500 yr @ 9 km/s
- Material within astropause shares star's bulk motion
  - Bow shock cannot cause (sub-)arcsec SW ejecta(?)
- Direction similar to magnetic axis *Dupree*
  - But why not equivalent NE arcs/plumes
    - Combination of episodic ejection/preferred direction?
- ~Thousands-yr HI, CO shells spherical
  - Preference transient?

5.75 GHz high resolution

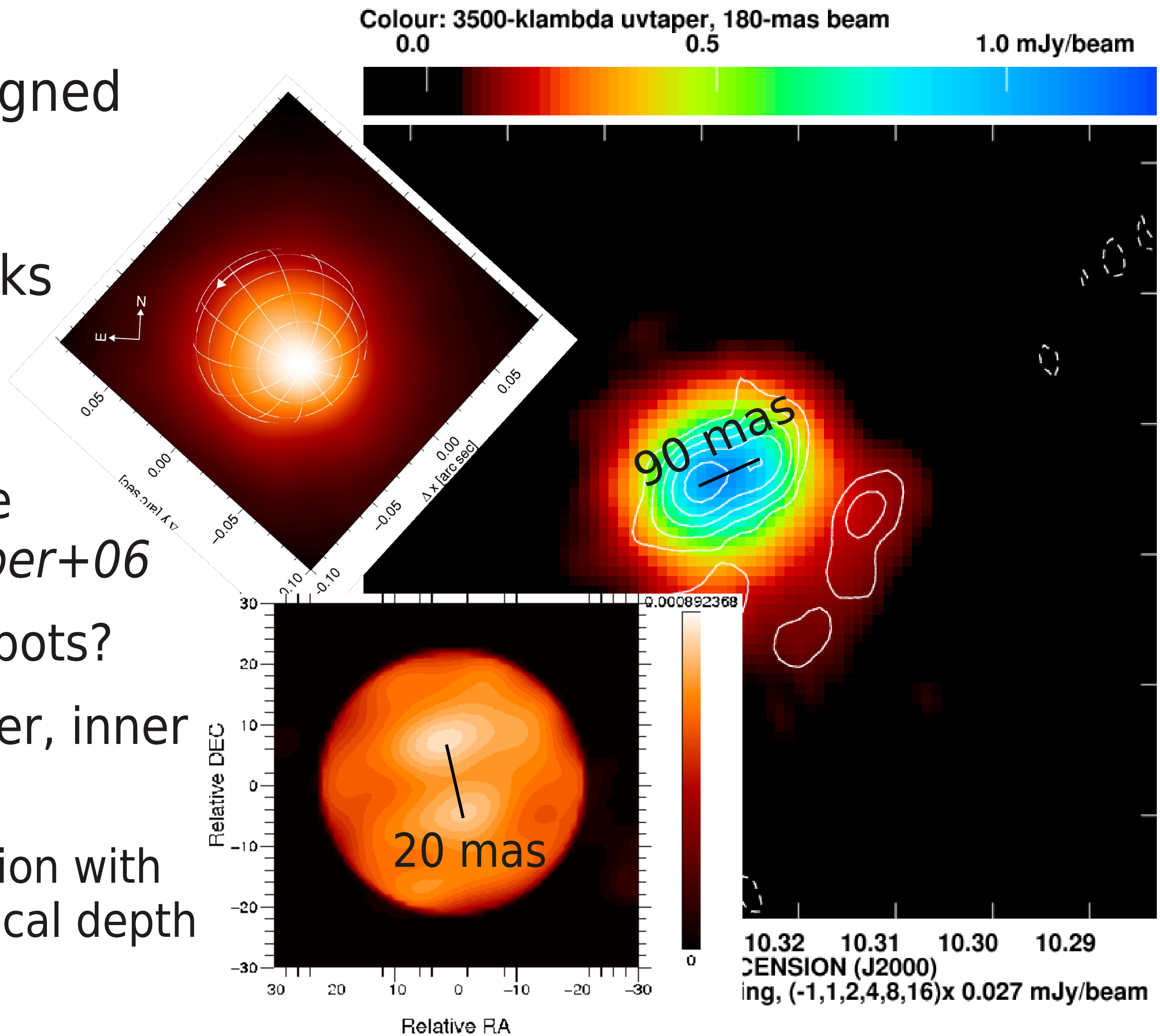
- Contours: weighting to (80x60) mas beam
  - Reduced sensitivity to low surface brightness emission
    - σ_{rms} 0.09 mJy/bm
    - Peaks 0.706, 0.489 mJy/beam
    - T_B 5400∓600K, 3800∓500K
    - Separation 90∓10 mas, PA 110°∓10°



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

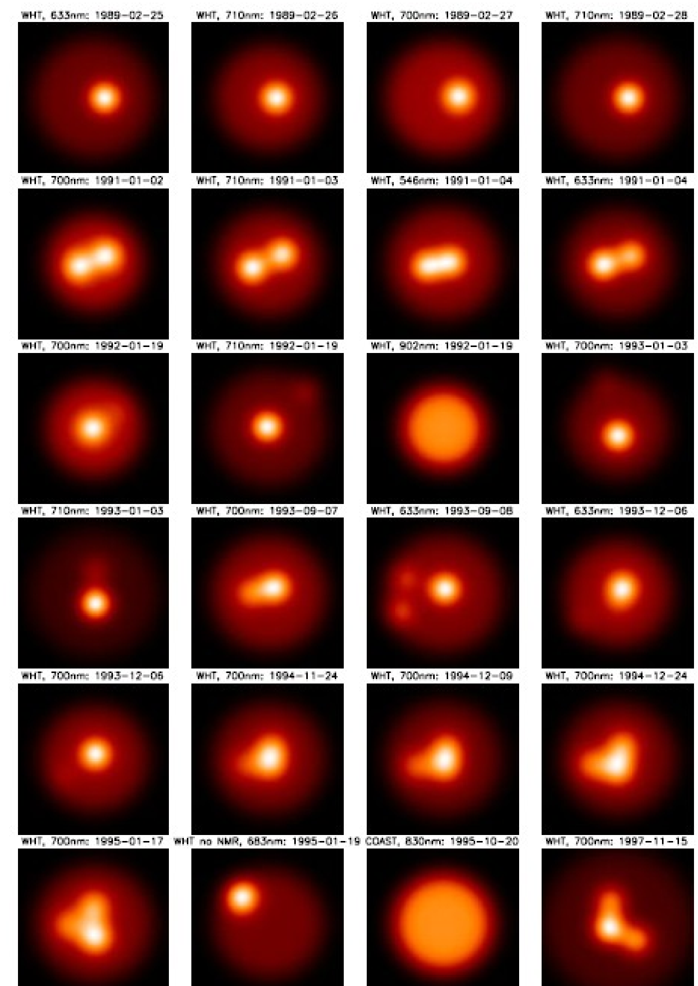
Relationship with optical hot spots

- Hotspots not aligned with 'pole' *Uitenbroek+98*
- Nor H-band peaks *Haubois+09*
- Tb>4000K:
  - Chromosphere patches? *Harper+06*
  - Elevated hotspots?
  - View into hotter, inner surface?
    - through region with steeper optical depth gradient



Optical hotspots

- Locations of optical hot-spots varies
  - 2-3 hotspots, 3-9 months survival *Tuthill+97*
  - *Freytag+02* compiled 9 yrs data
    - Visible/NIR WHT and COAST
      - NB entire optical disc similar in size to 5-GHz radio beam
- Radio might see same hotspots if they subtend a similar solid angle at 5-6 R_{*}
  - If not, a single blob would be seen *if* upper layers transparent
  - Or, do radio hotspots have a different origin?



Possible origins of radio hotspots

1 Chromospheric patches

- Hα to 4.5 R_* *Hebden+87*
  - Heating needed *Harper06*

2 Cooler higher layers expose photosphere

- Unrealistically cool?
- Only in central ~50 mas

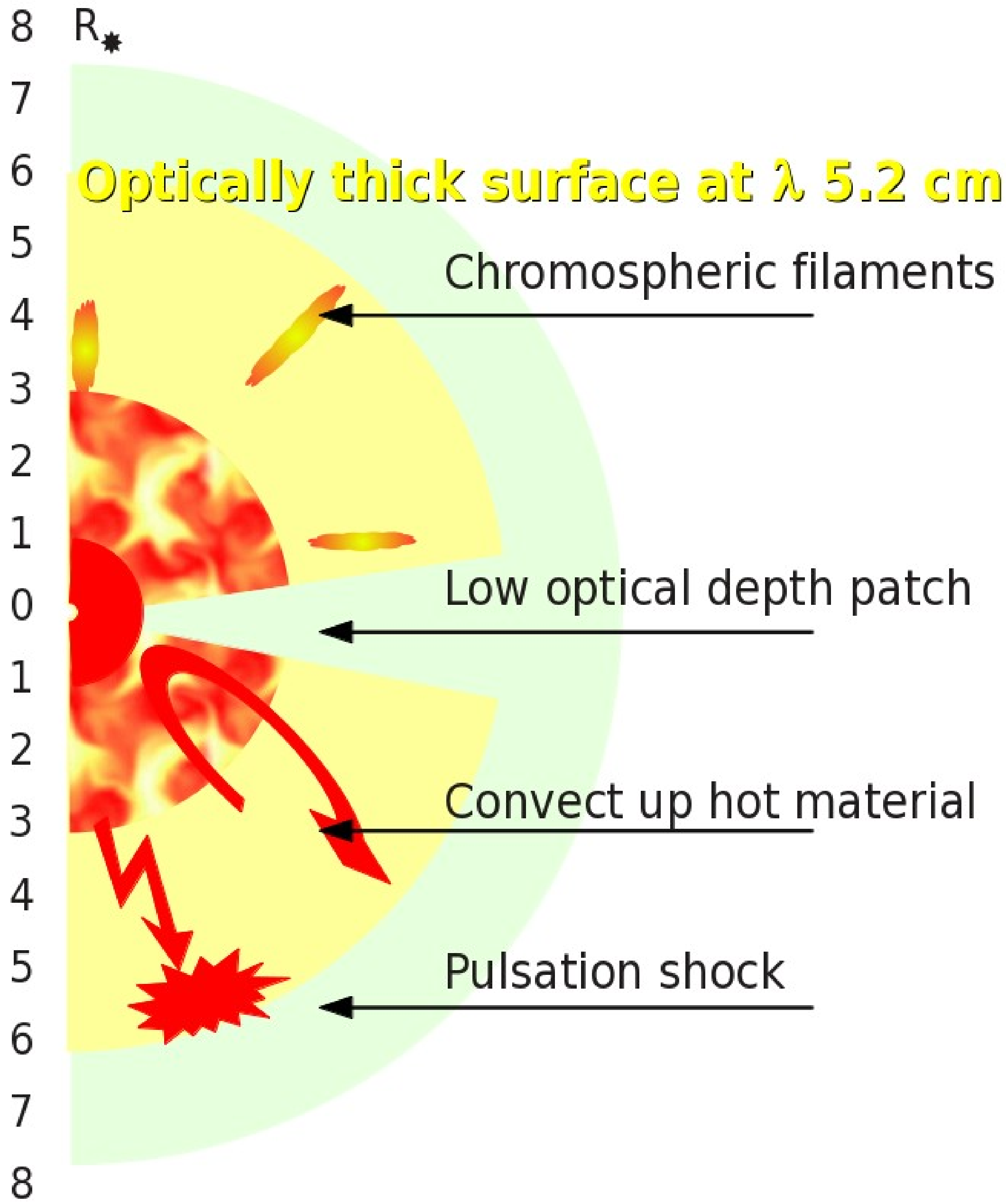
3 Convection

- How is gas kept hot?

4 Pulsation

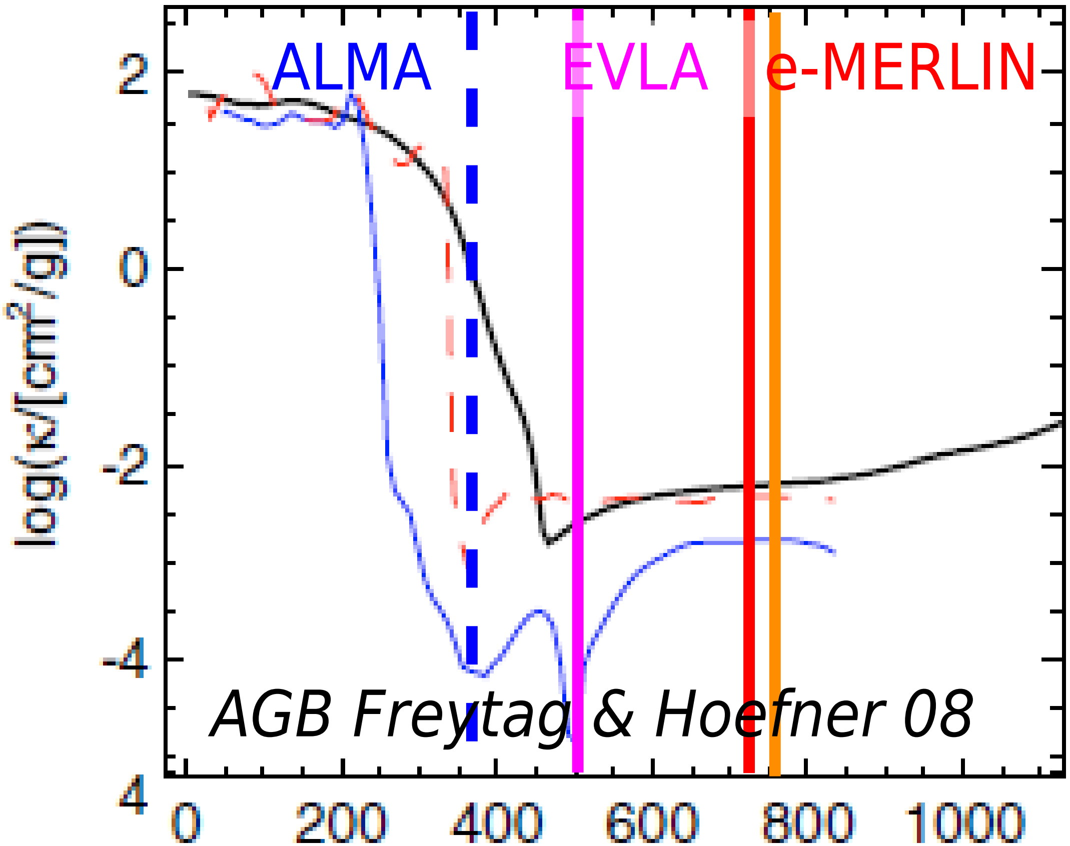
- *Ireland+11* models to 5R_*
  - What velocity needed?

Only 1 and 4 might explain Tb $\gtrsim$ 3600 K



Different ν's trace different layers

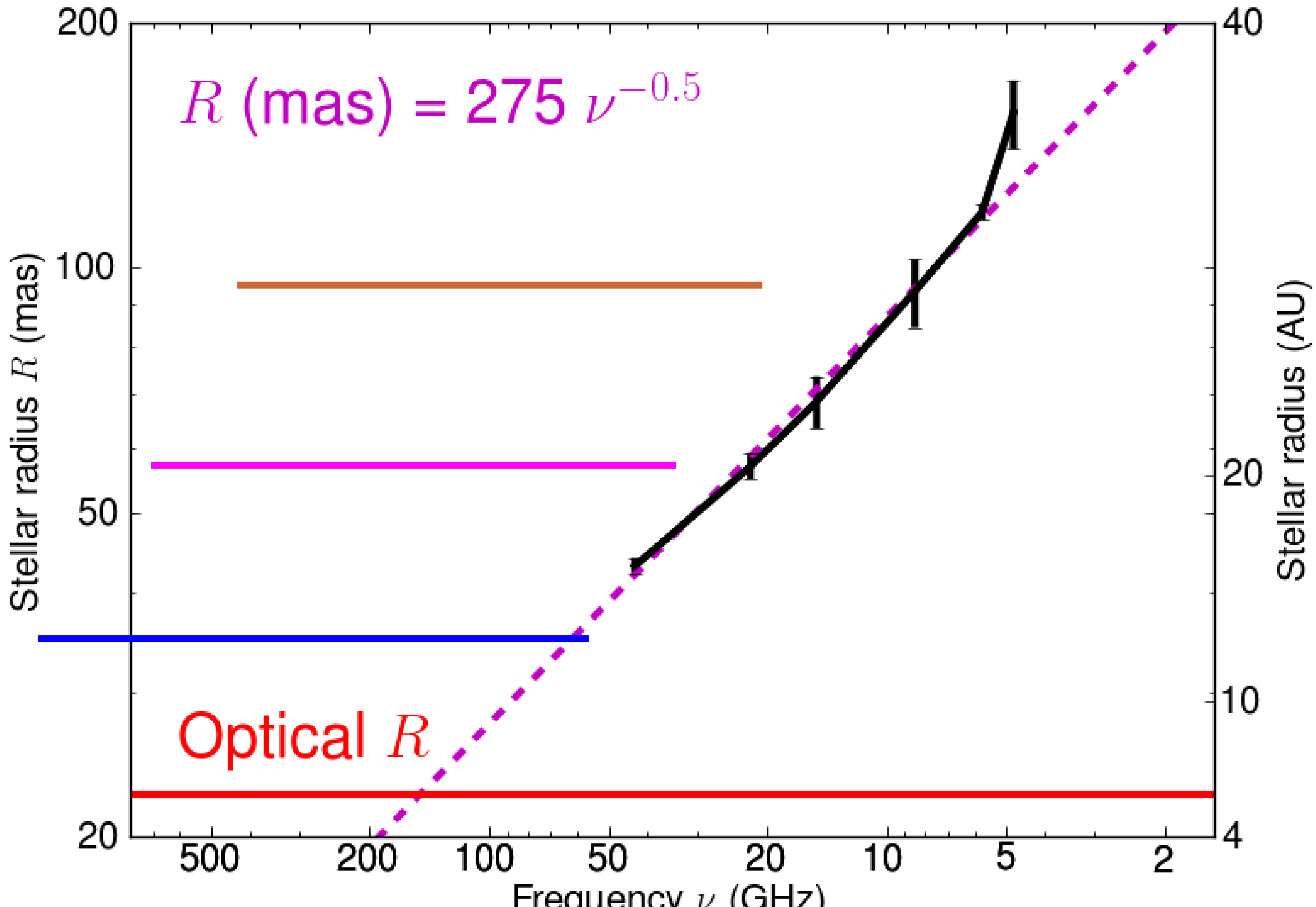
- $r_{22\ \mathrm{GHz}} \sim 2r_{\mathrm{photosphere}}$
- $r(\nu) \sim 55 \times \nu^{-0.5}$ (AU)
- $r\ (\tau \rightarrow 1) \uparrow$ as $\nu \downarrow$
  - Radiosphere *V* 10 km/s?
    - $r_{43} \rightarrow r_{22}$ ~2 AU, ~1 yr
    - $r_{25} \rightarrow r_{22}$ ~4.5 months
- Monitor at decreasing ν
  - See same layer as it expands?
    - Correlated changes: pulsation?
    - Variegated changes: convection?
    - Persistent axis: magnetic field?



- 20~50 mas resolution

What is (sub-)mm radius of Betelgeuse?

- 4-40 GHz radio radius roughly follows ν^{-2}
  - but must flatten off at higher frequencies
  - Beware variability
  - e-MERLIN
  - VLA
  - ALMA



Is mass loss initiated in the radio photosphere?

- Need models of radio photosphere from 800 - 1 GHz
  - λ 0.3 mm to 30 cm; 1~10 $R_{\star}$
  - What is depth of surfaces ALMA will see?
    - How far out can convection work?
    - How far can chromospheric patches survive?
    - Heating by pulsation shocks
  - Chemistry of mass loss
    - Is the stellar surface chemically inhomogenous?
      - Clumps could be intrinsically, chemically distinct
- ALMA will resolve deep stellar layers, thermal lines, dust
- e-MERLIN/VLA will resolve 2 - ~10 $R_{\star}$
  - Maybe detect the first SiO masers!