Wind properties and clumping

Red Supergiants and Asymptotic Giant Branch stars
(with no obvious companions)
How are clouds formed?
What affects their journey to the ISM?

Anita Richards, Manchester
Assaf, Baudry, Decin, Elitzur,
Etoka, Gray, Lekht, Lim,
Mendoza, Murakawa, Rudniskij,
van Langevelde, Yates

S Per water maser clouds
Total extent 350 AU ~ 43 $R_\star$

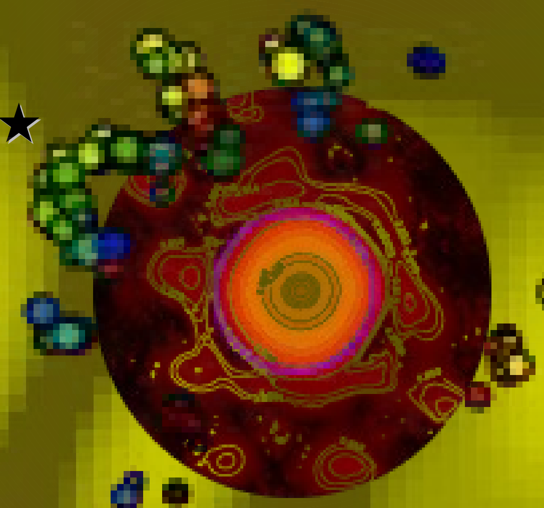
EUROPEAN ARC
ALMA Regional Centre || UK

Thanks for organising the meeting

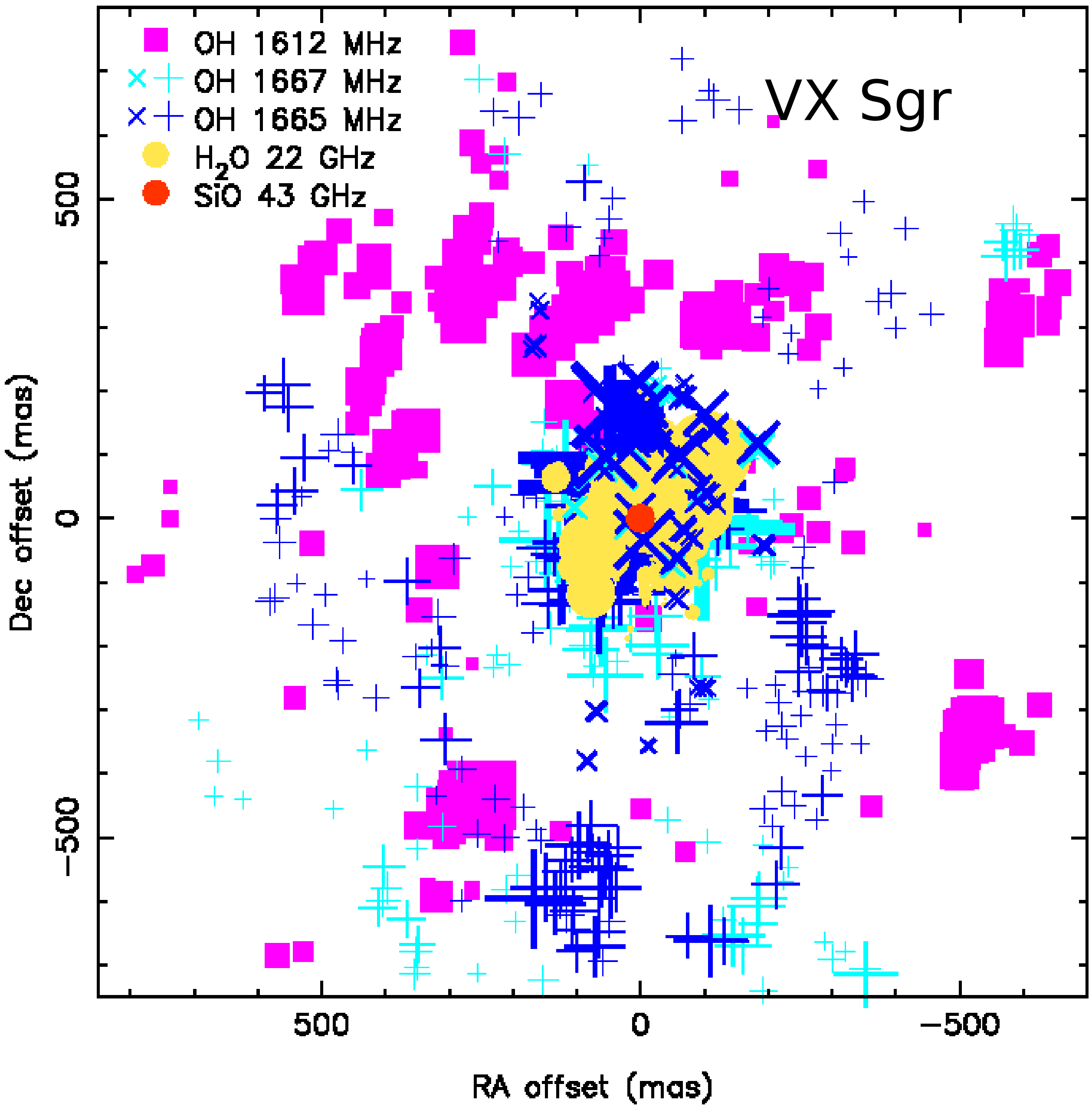
nice of you to lay on the rain to make me feel at home...

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
    - 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^{-5} $M_\odot$/yr



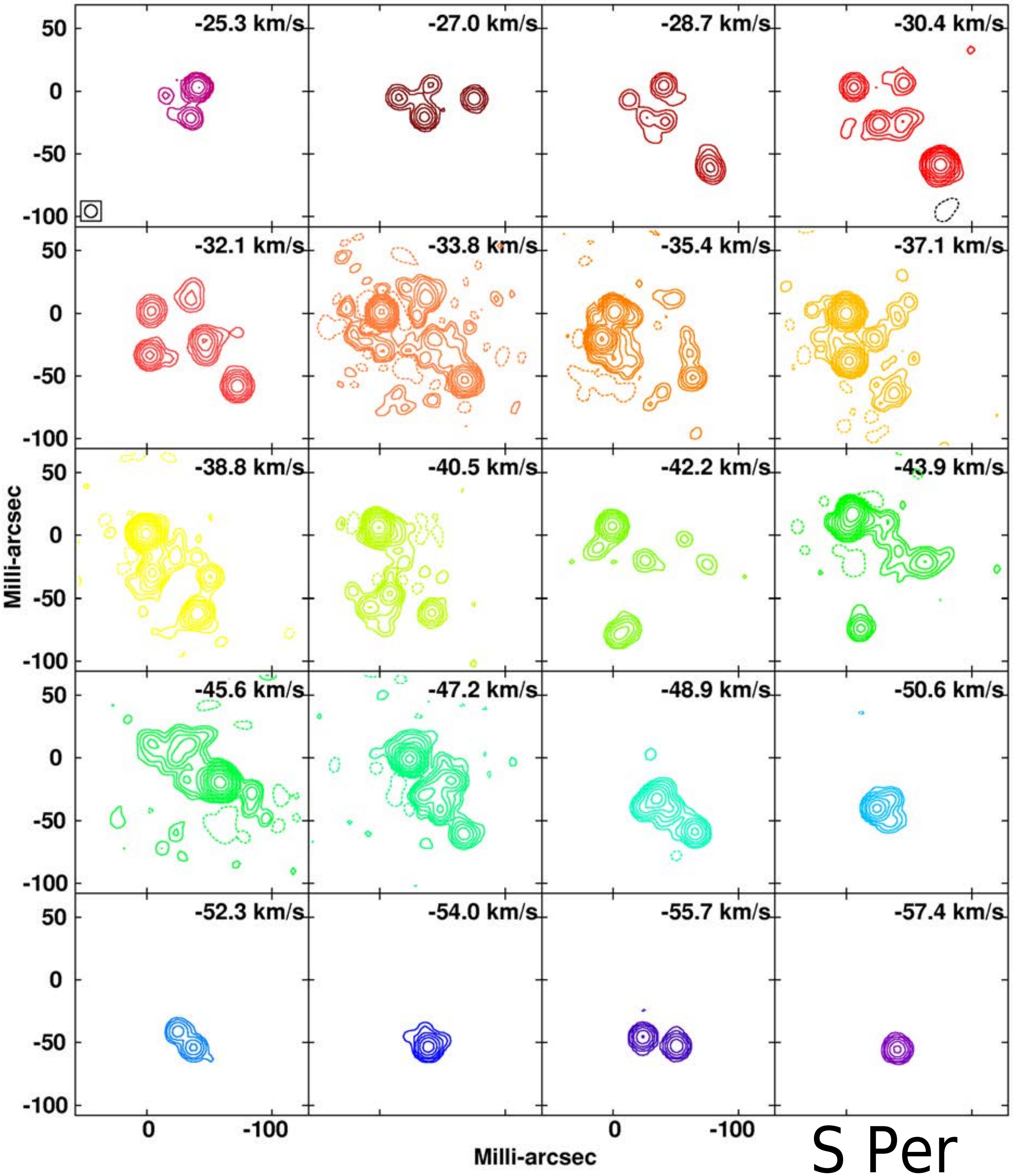
Masers resolve winds on AU scales



- OH 1612 MHz (T_E few K, long column depth), at >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

Water maser channel maps

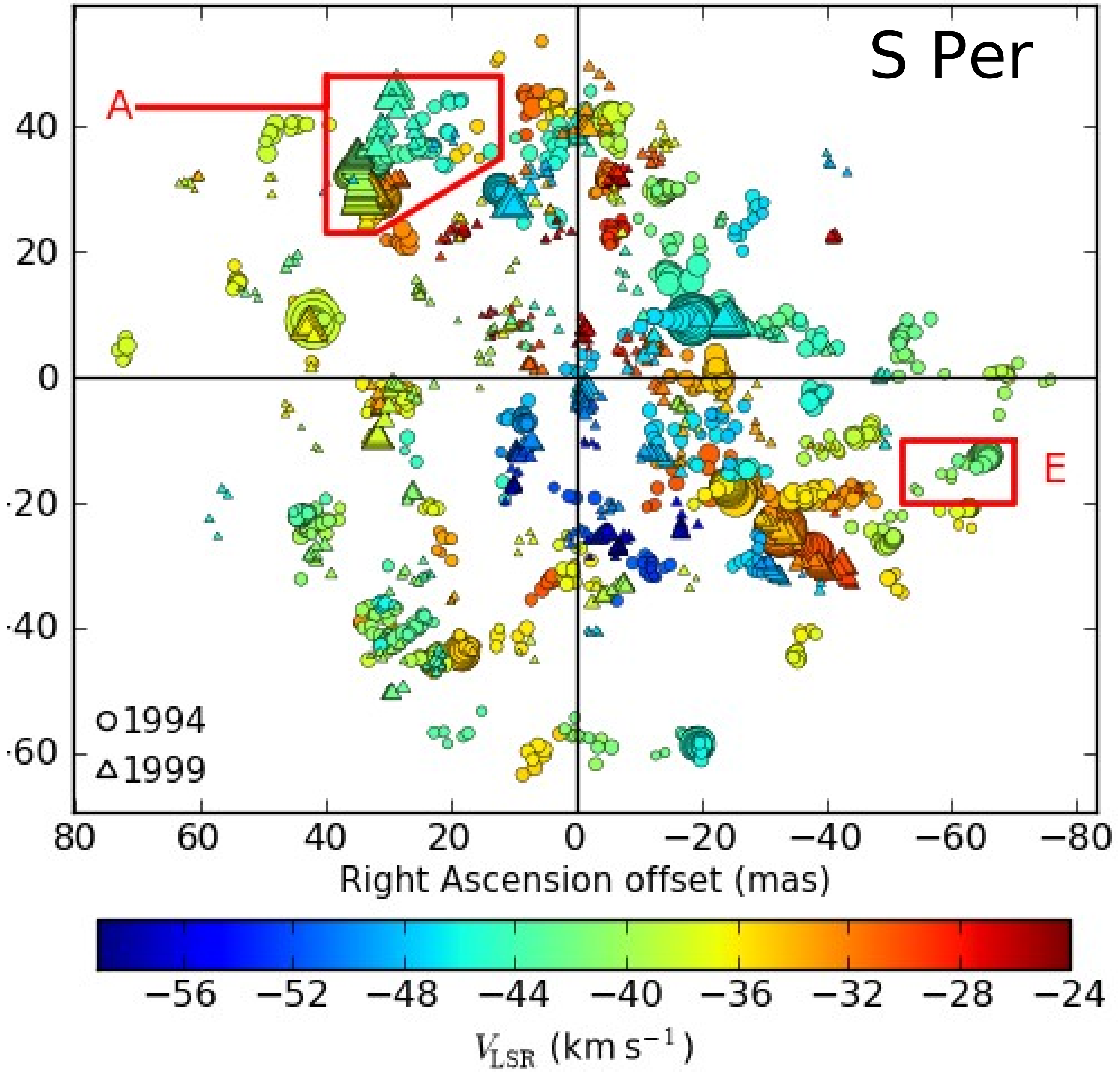
- MERLIN radio interferometry images
  - 22 GHz (λ 1.3 cm)
  - 10 milliarcsec beam
- Compact front and back caps
- Bright extended emission in plane of sky with star
- Spherical, radially accelerating outflow



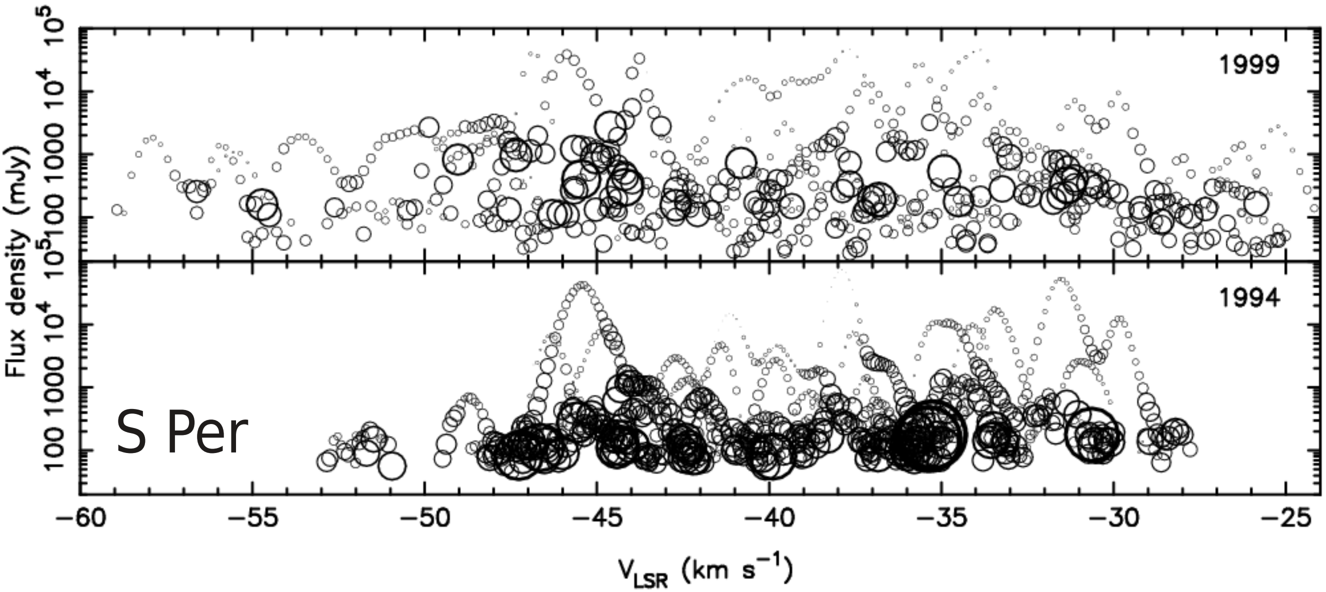
S Per

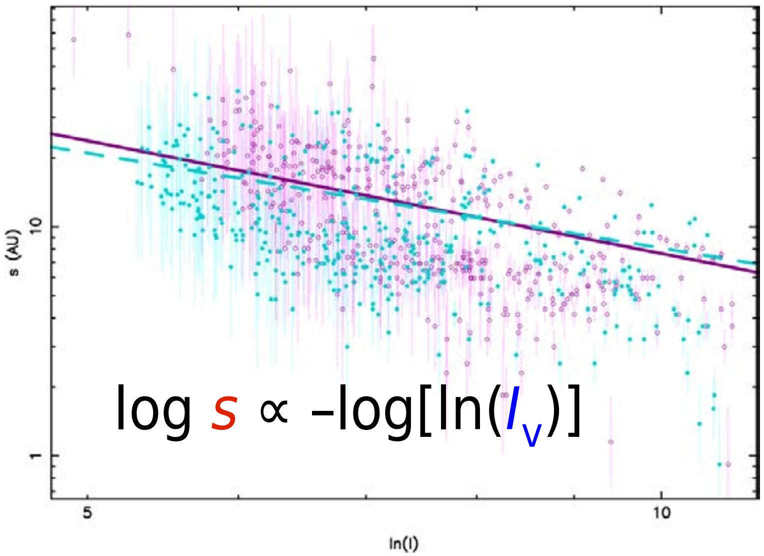
Cloud measurements

- 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

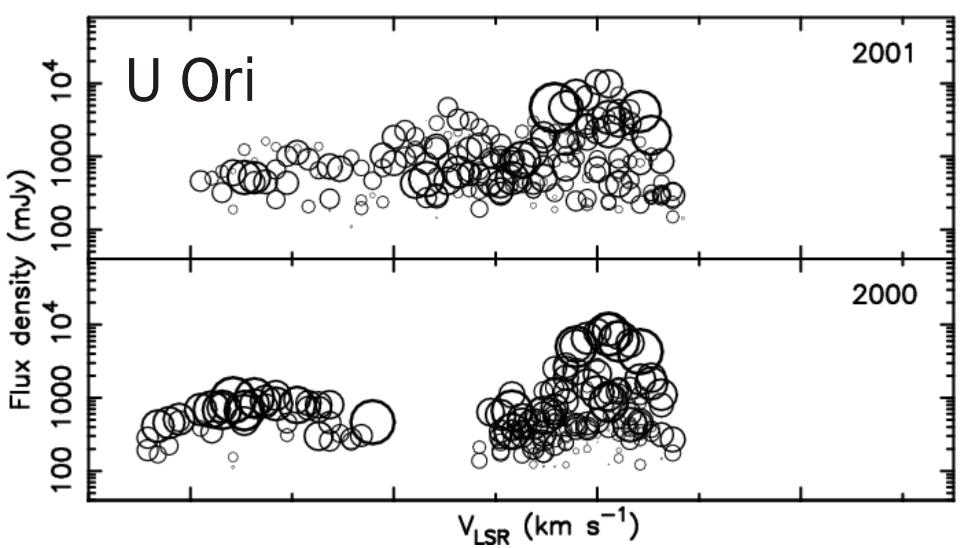


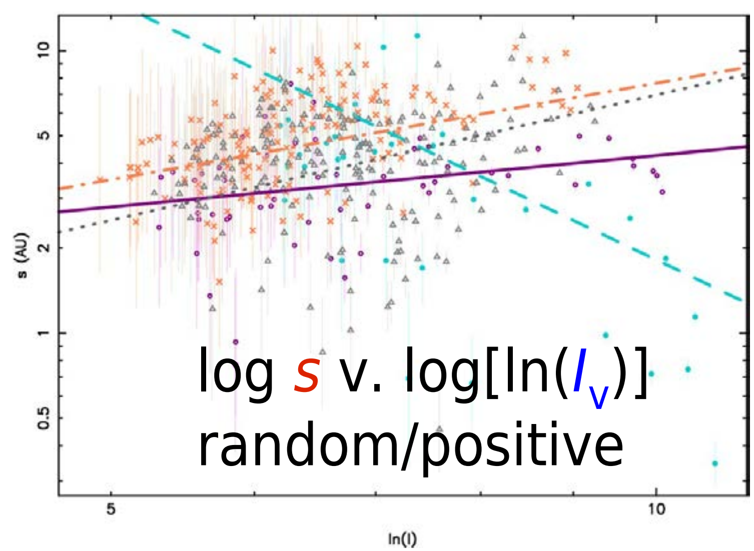
Beamed size – maser brightness





- S Per: component size s smaller in line peaks than wings
- U Ori: many brighter spots are larger





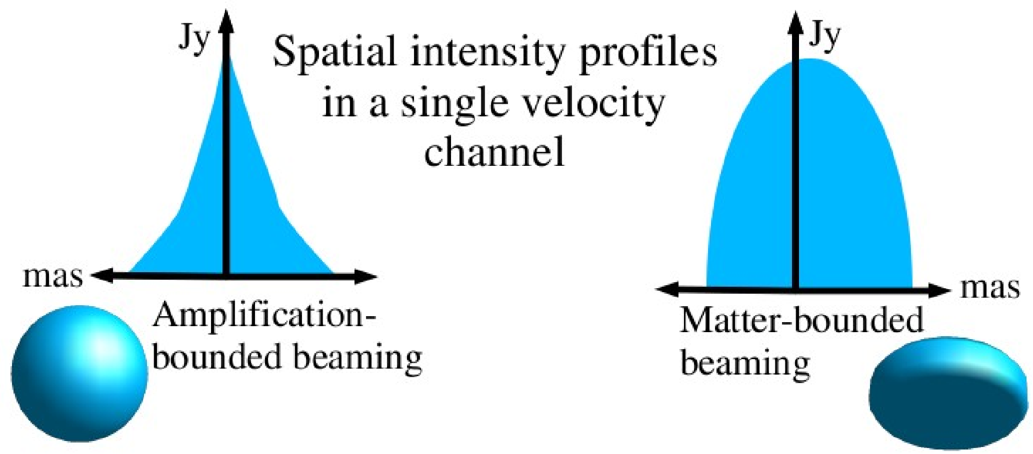
Maser properties reveal wind disturbances

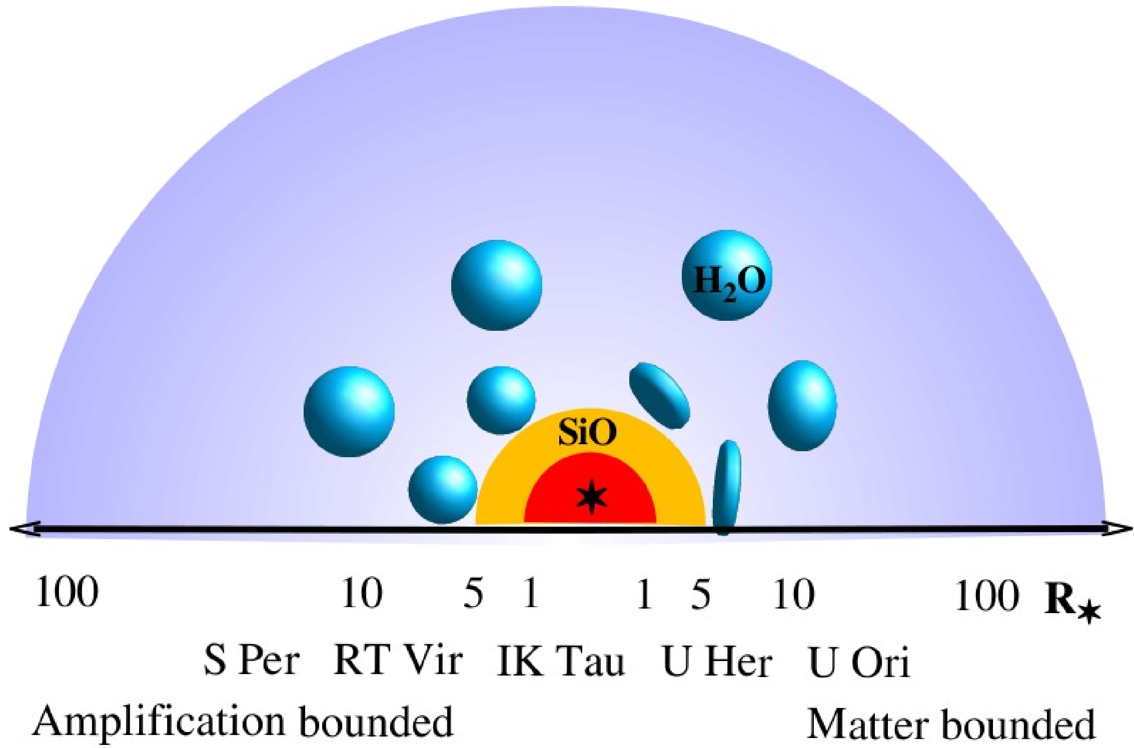
- Brighter = smaller beamed size?
  - $s \propto 1/\mathrm{sqrt}\,[\ln(I_\nu)]$

Smoothly expanding spheres

- Brightest emission often ~cloud size?
  - Extreme variability
  - Deep stellar periods
  - Some OH flares

Shocked slabs

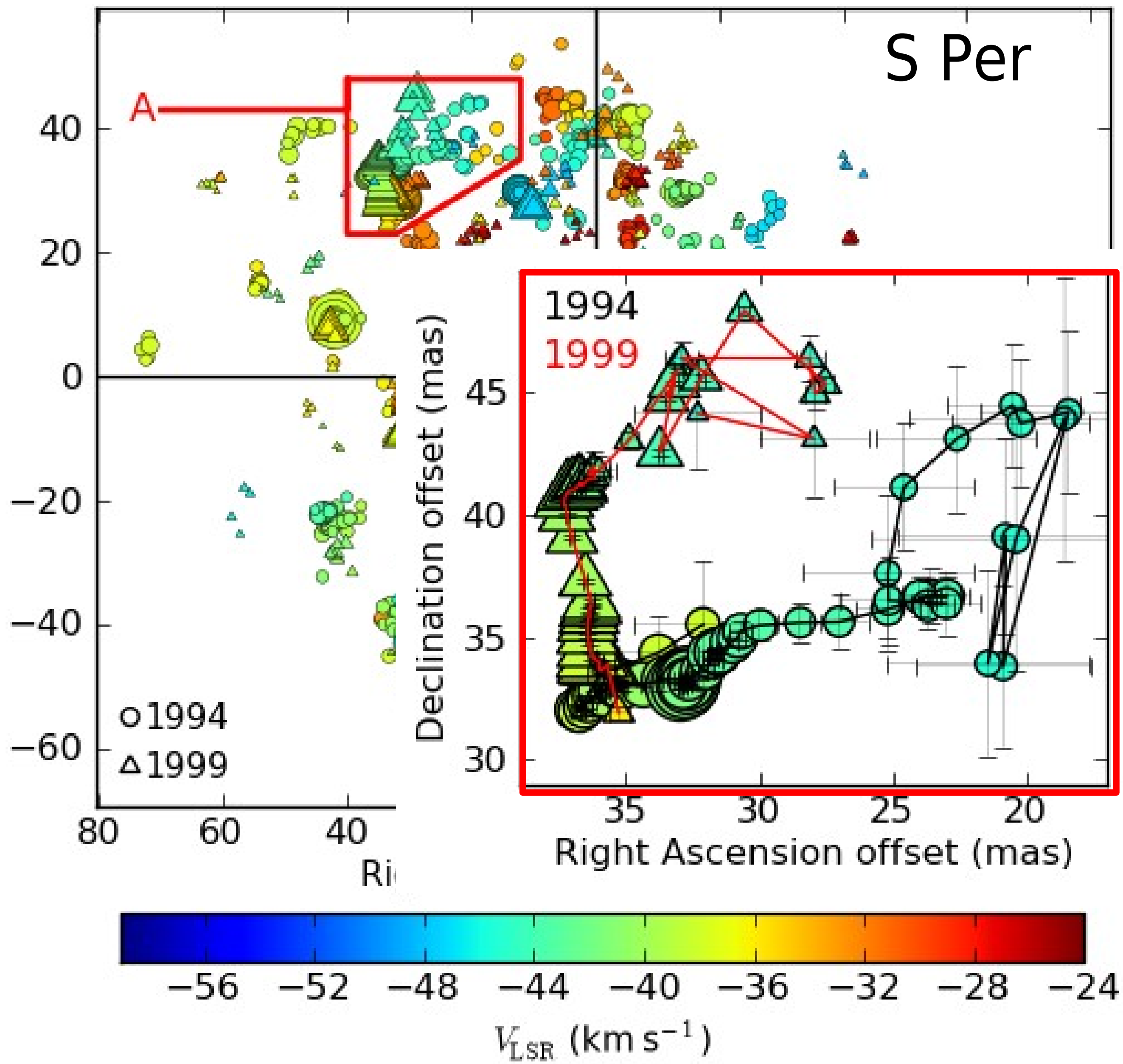




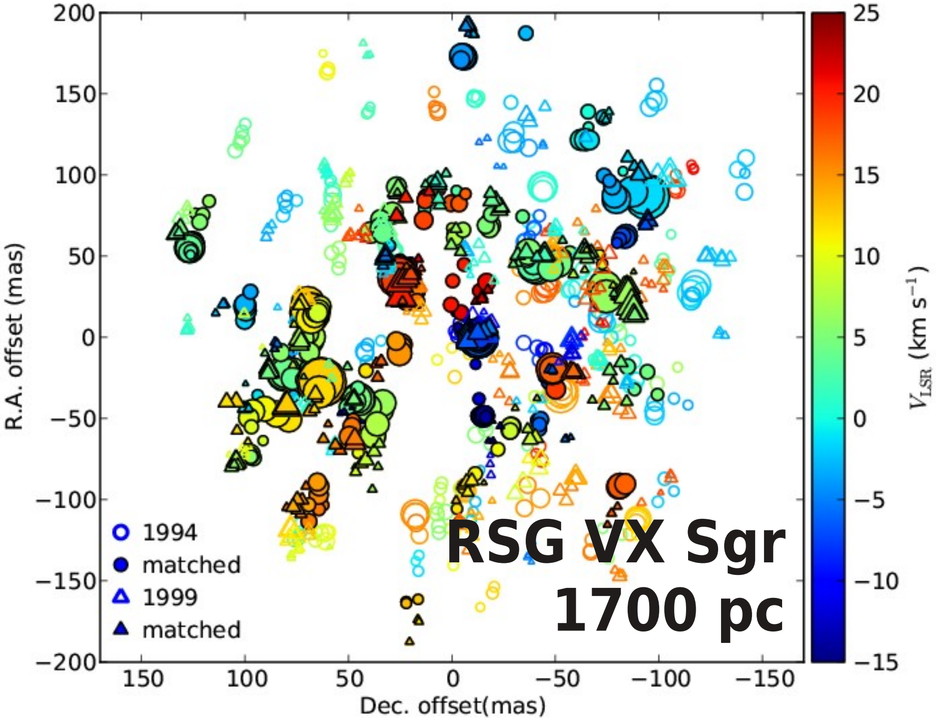
Richards Elitzur & Yates 2010
Elitzur Hollenbach & McKee 1992

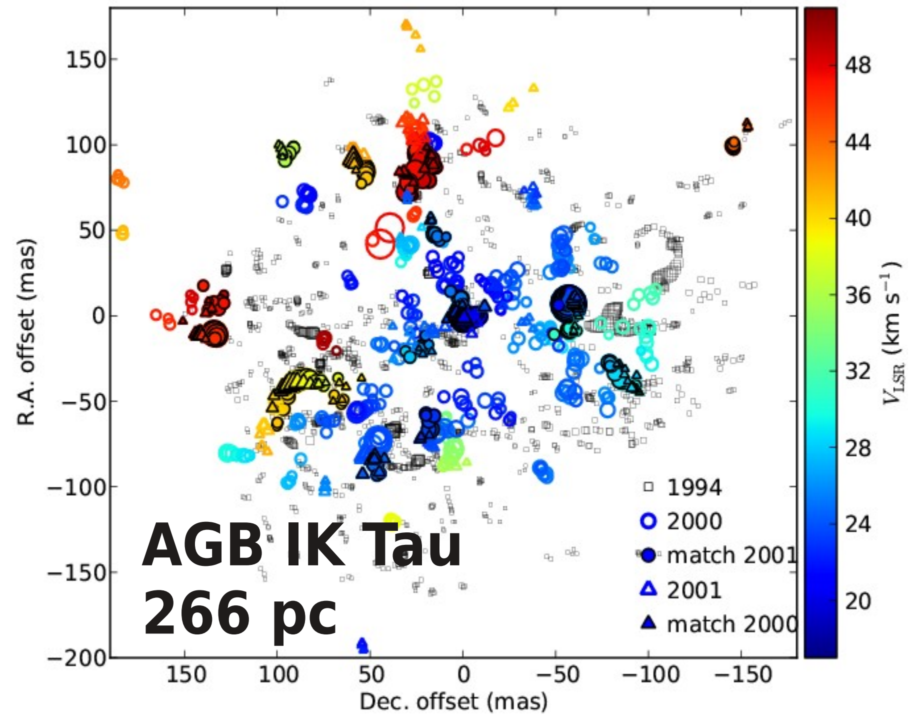
Cloud survival, maser variability

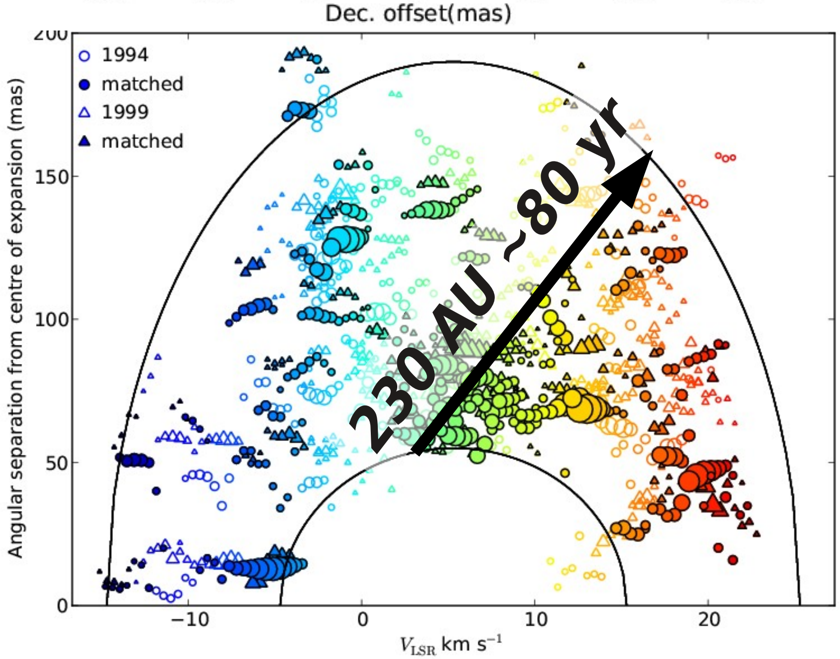
- Specific RSG masers can be tracked for ≥5 yr
- AGB masers survive ⩽2 yr
  - Similar to sound-crossing time
- Much less than shell crossing time
  - Decade(s) (AGB)
  - Up to a century (RSG)

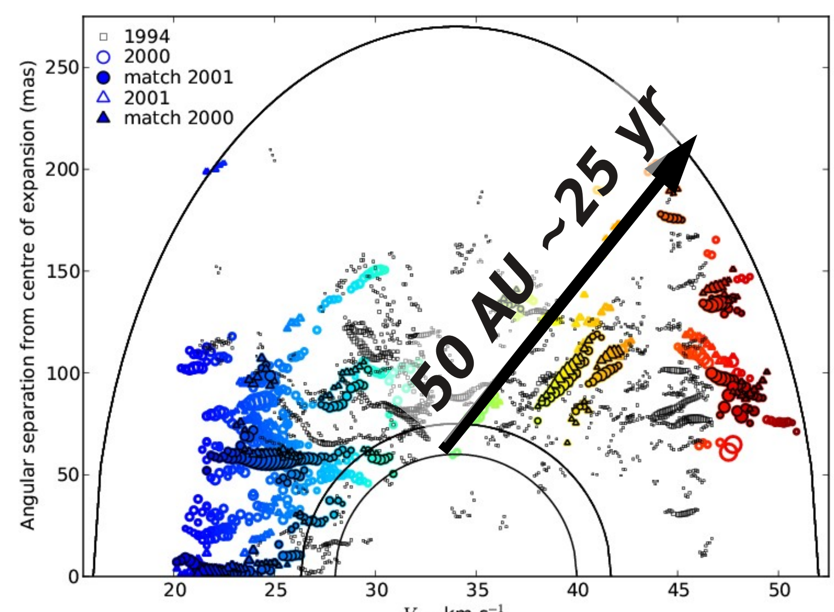


Shell-crossing times

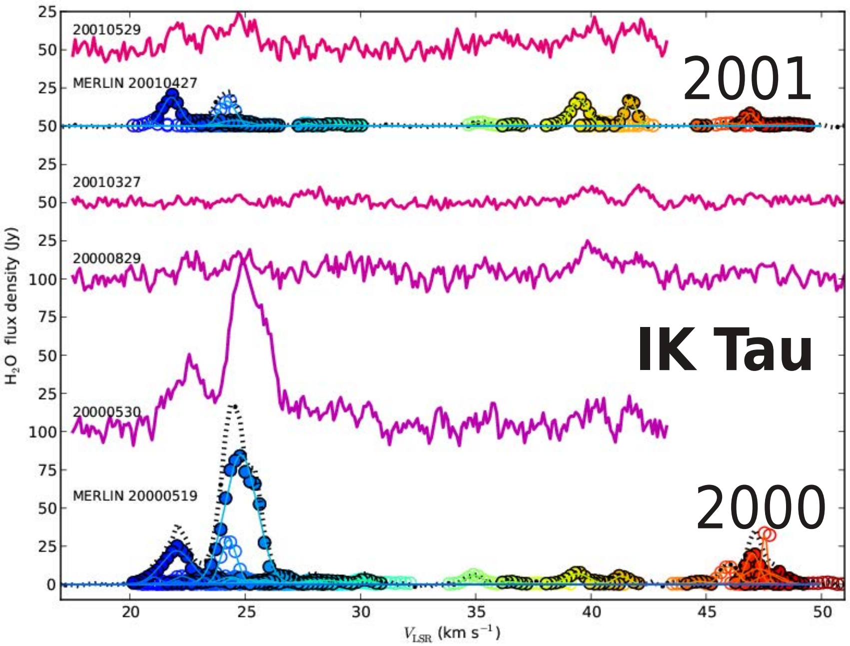


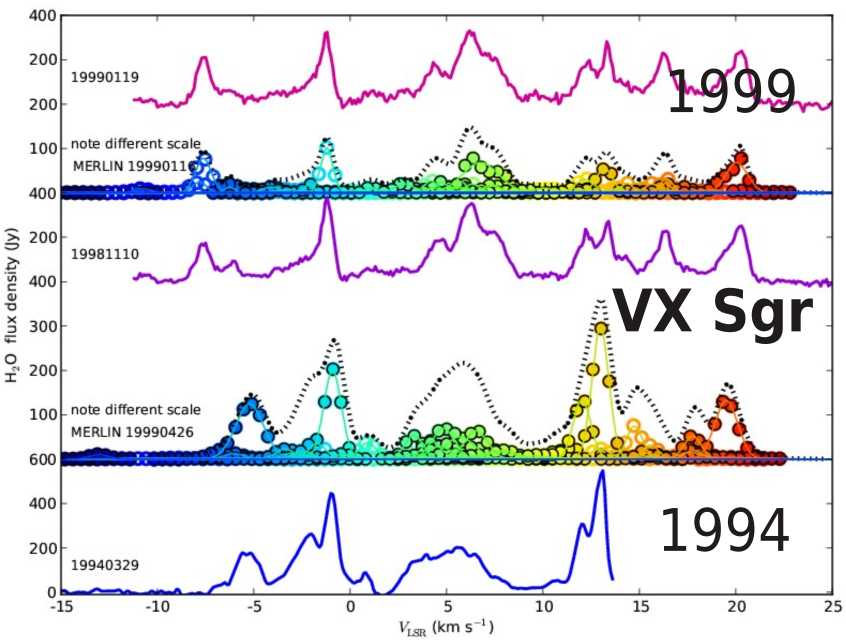






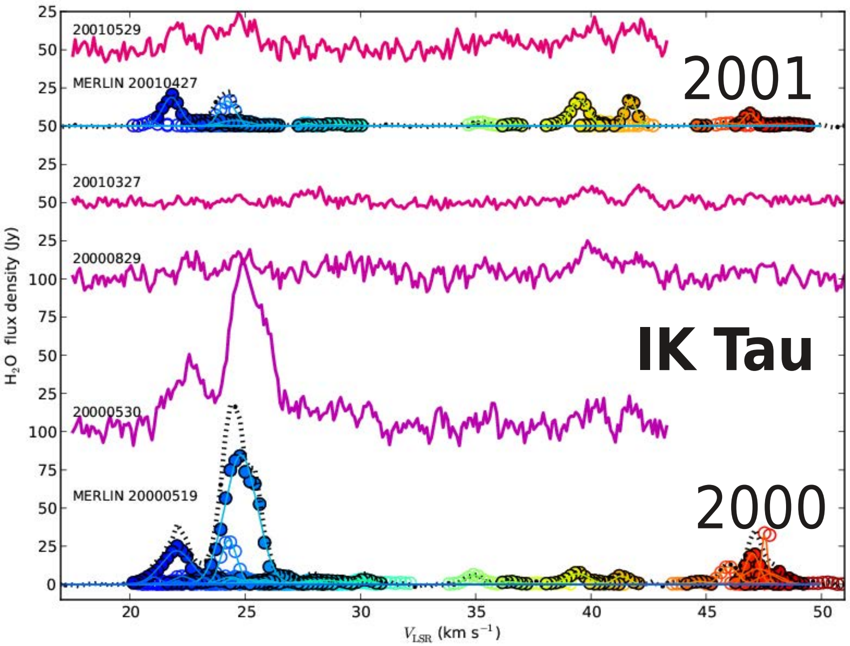
Masers blink, clouds survive

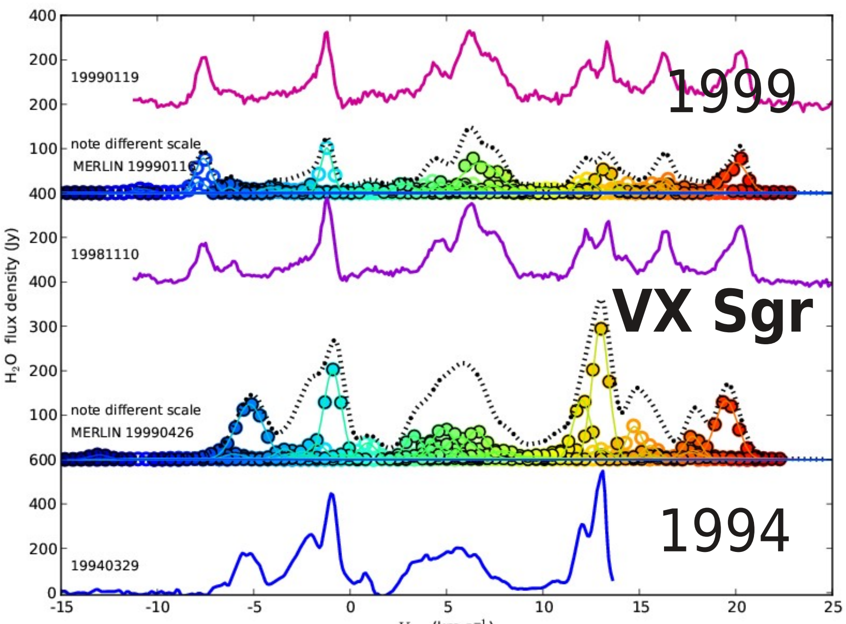


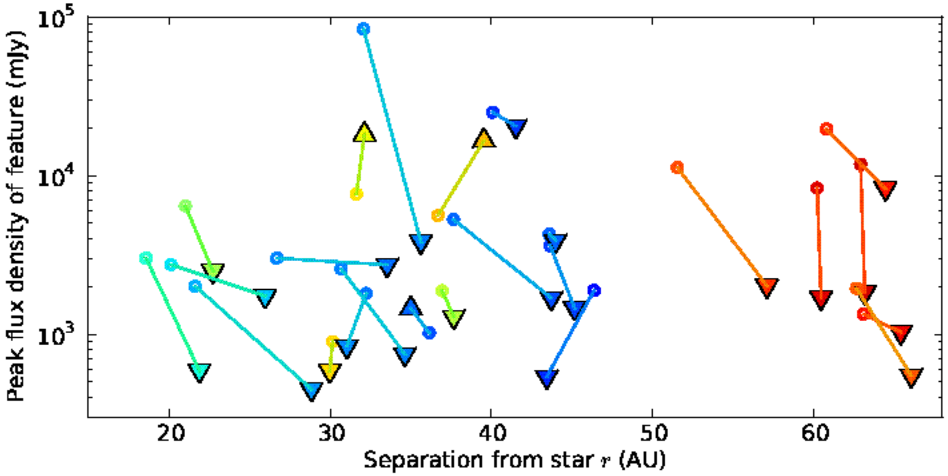


- Pushchino ~bimonthly spectral monitoring
- MERLIN imaging every few years (colour)
  - Matched features: black outlines
- Spectral variability between images
  - Peaks vanish, some reappear
- Clouds unlikely to reform if dispersed
  - Clouds survive as clumps
  - Masers turn on and off
    - Turbulence/beaming?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

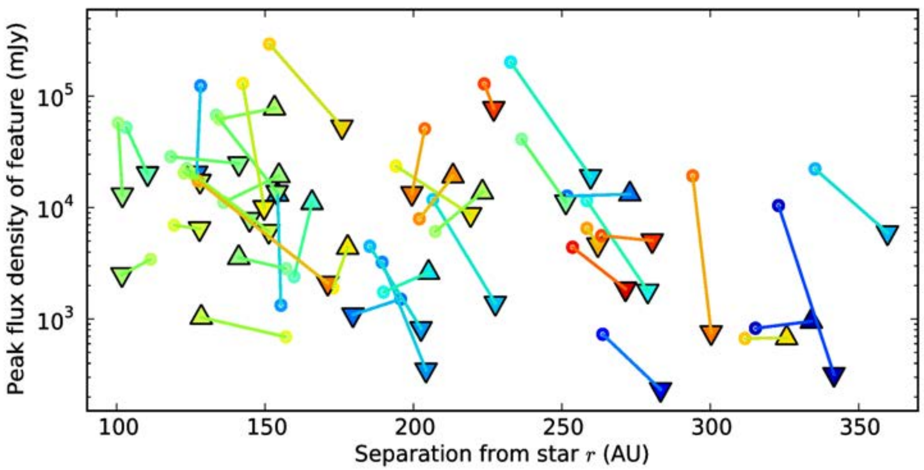
Whole shell tends to vary





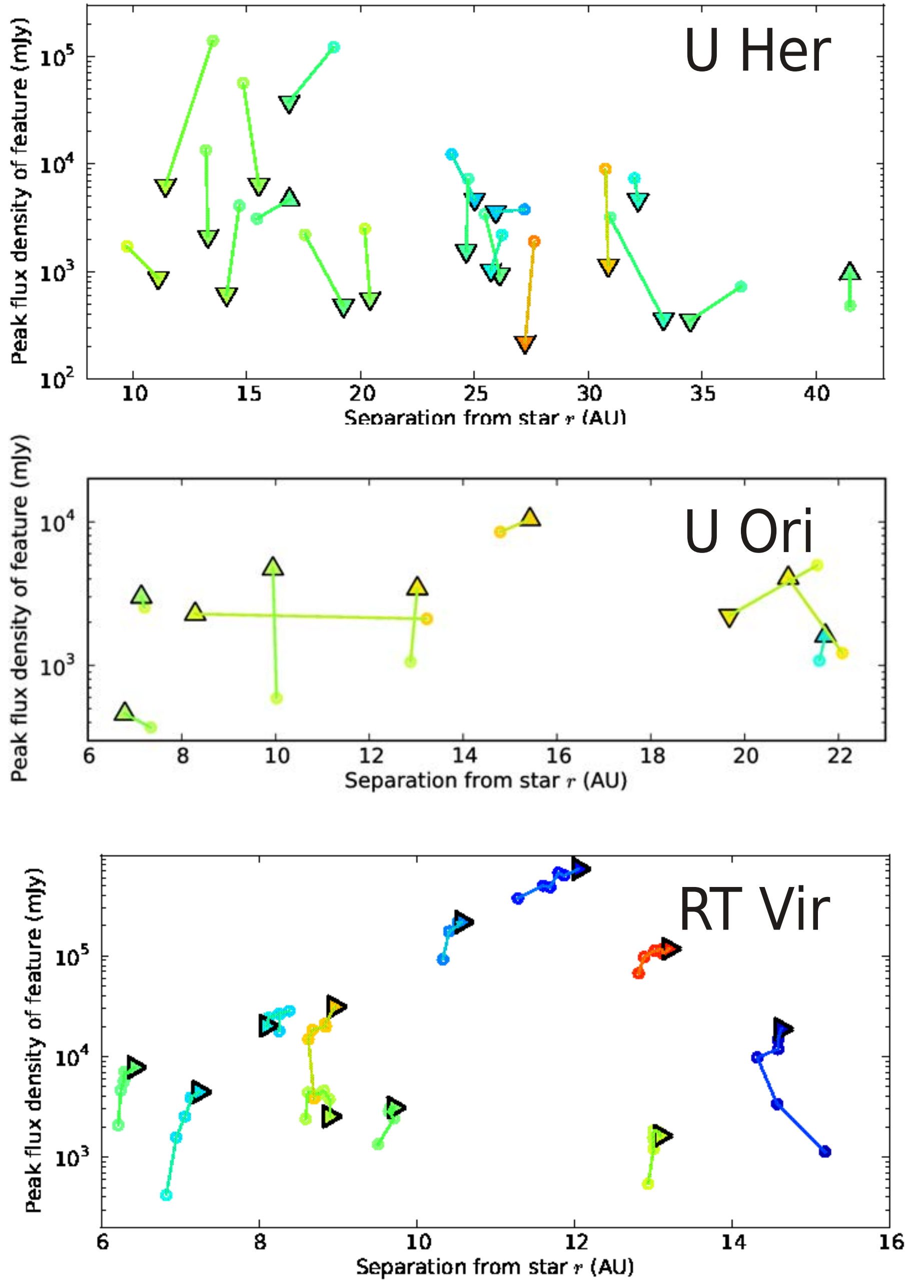


- Change in flux density v. r
  - IK Tau, VX Sgr most matched features get fainter
    - At any distance from star



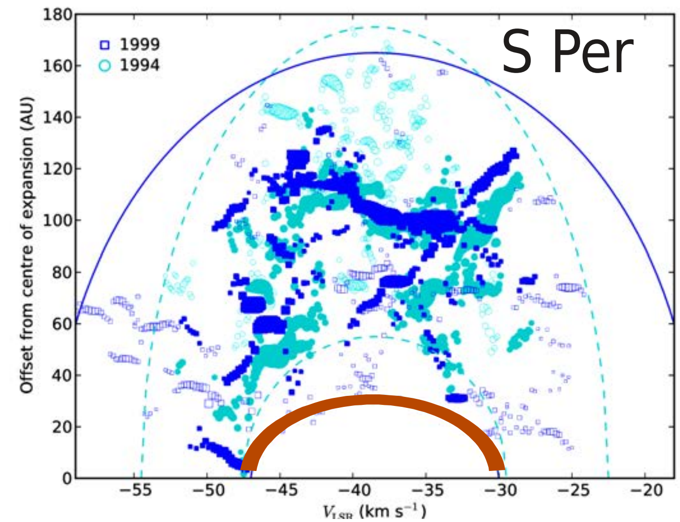
Variability faster than shocks

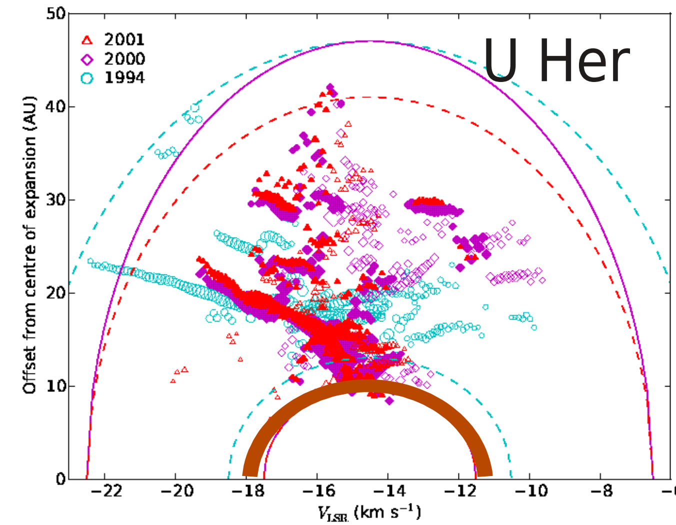
- U Her: most matched features dim in 1 yr
- U Ori: most brighten
- RT Vir: most brighten then fade over 10 weeks
- Propagation of pulsation shocks? (e.g. *Shintani+'08*)
  - *V* 100–300 km/s? **not feasible**
- Must be radiative mechanism
  - No obvious relationship with optical phase
  - Heating via IR? Lags optical by 0.1–0.2 *P* (*Smith+'06*)

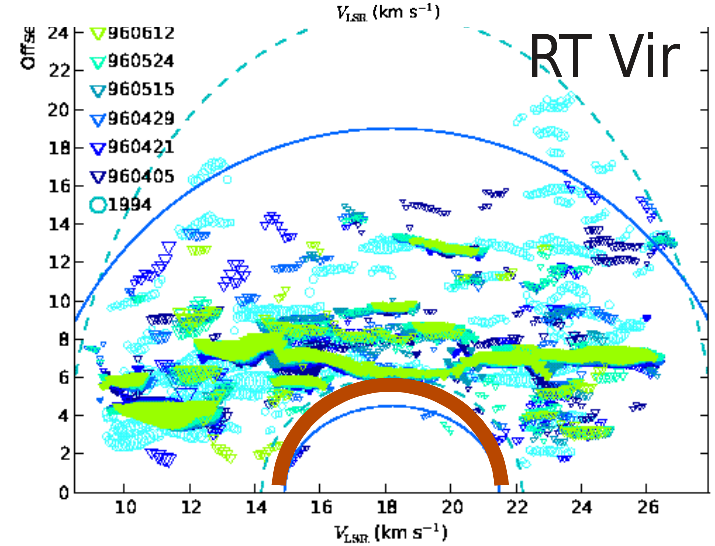


Cloud density

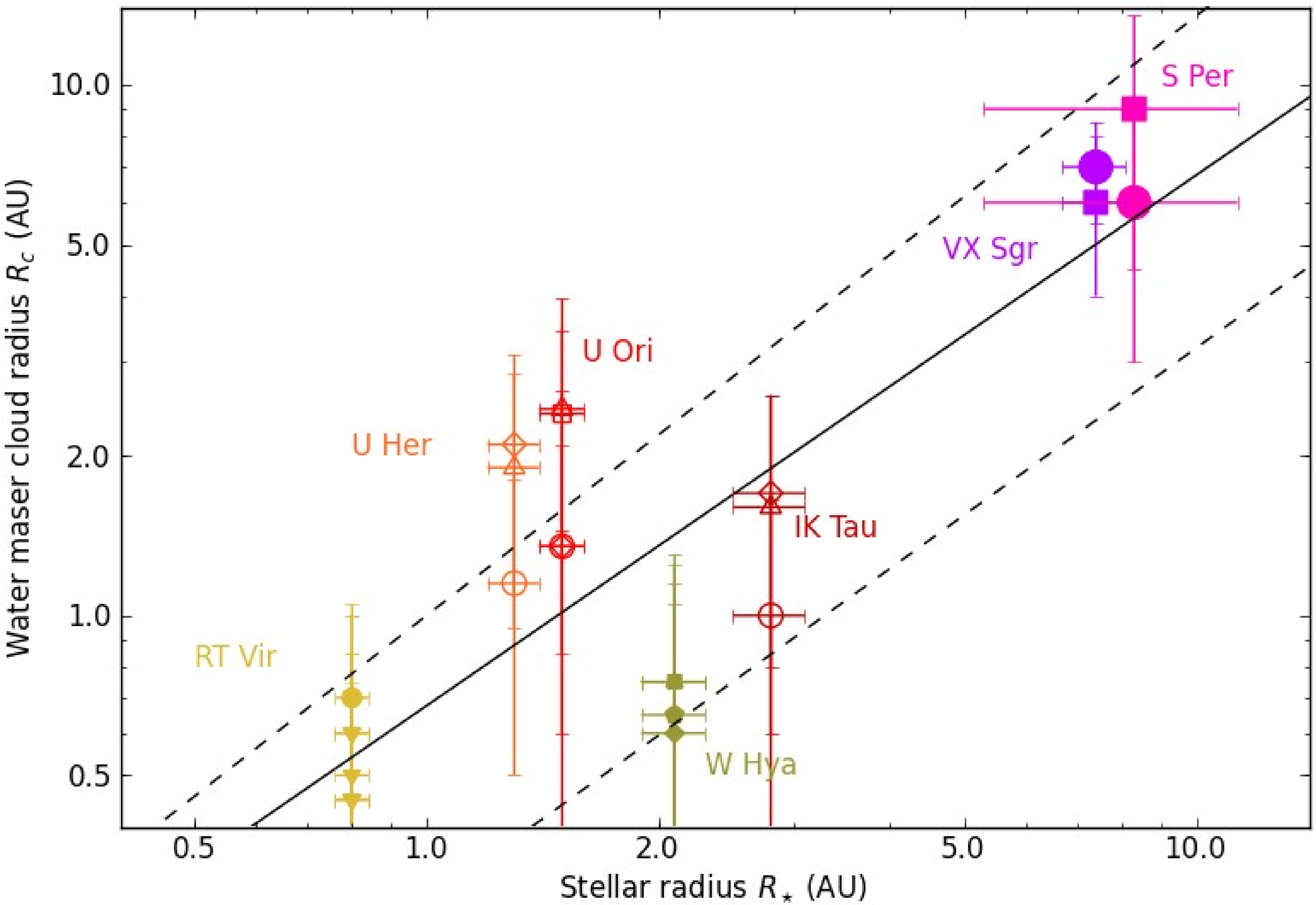
- H_2O masers start at r_i
  - 40–70 AU RSG, 5–15 AU AGB
  - Where collision rate < masing rate (*Cooke&Elitzur 85*)
    - Quenching density ~$5 \times 10^{15} m^{-3}$
  - Clouds ≳45x average (e.g. CO) wind density
    - Upper limit: surrounding gas density > 0
    - OH mainline masers interleave
  - Filling factor ≲1%
  - >90% mass loss in clouds
  - 2–6 clouds/stellar period
    - NB not all beaming towards us







Cloud size depends on star size



R_{cloud} set by star properties?

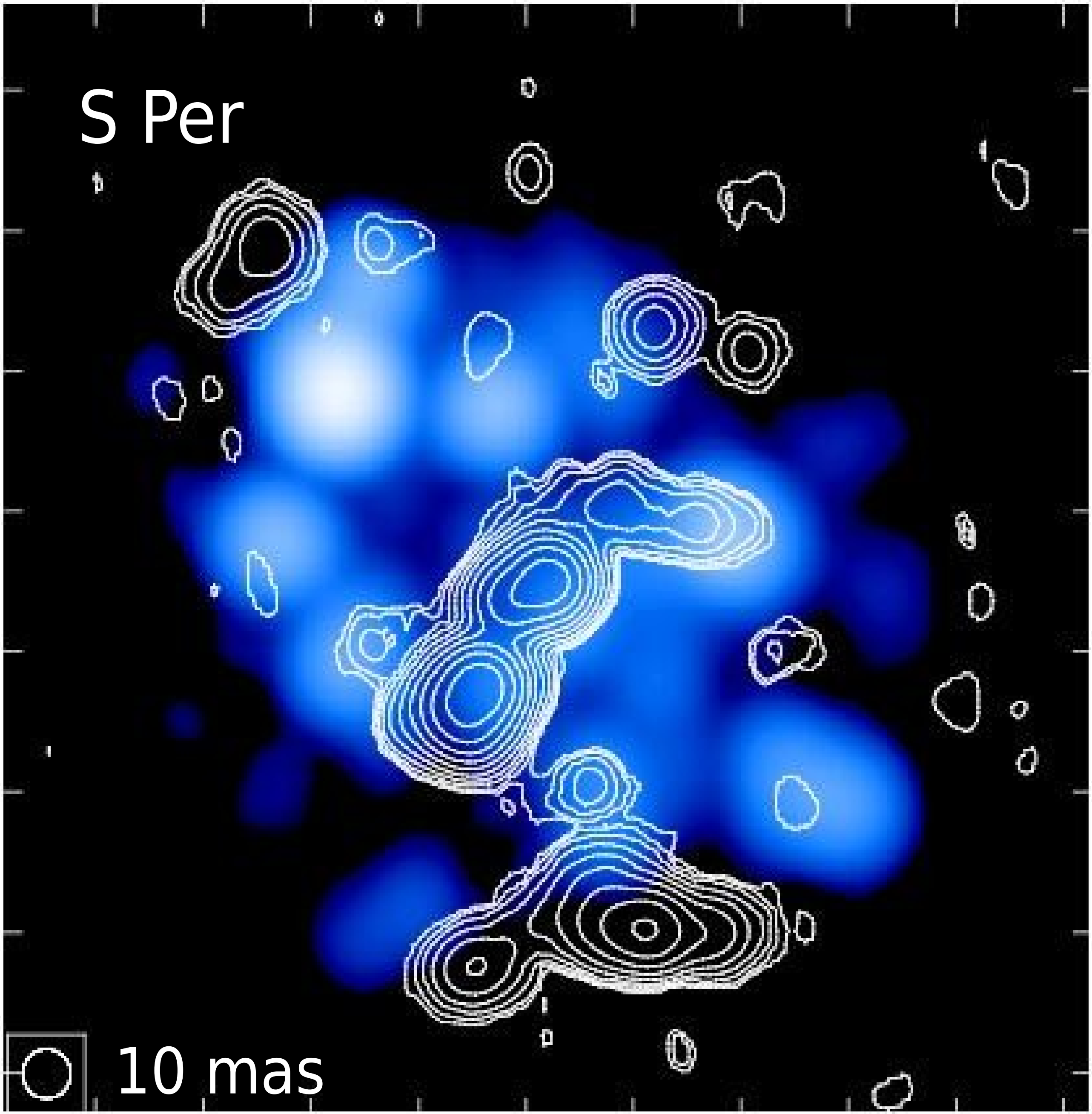
- Measure stellar radius $R_{\star}$ from opt/IR interferometry
  - *Skinner+88, Mennesson+02, Monnier+04, Ragland+06*
- **Cloud radius is a function of stellar radius**
  - In H_2O maser shell $\boldsymbol{R_c \sim (0.7 \pm 0.3)\, R_{\star}^{1.0 \pm 0.1}}$
  - Mass per cloud consistent with CO clump 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*

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%

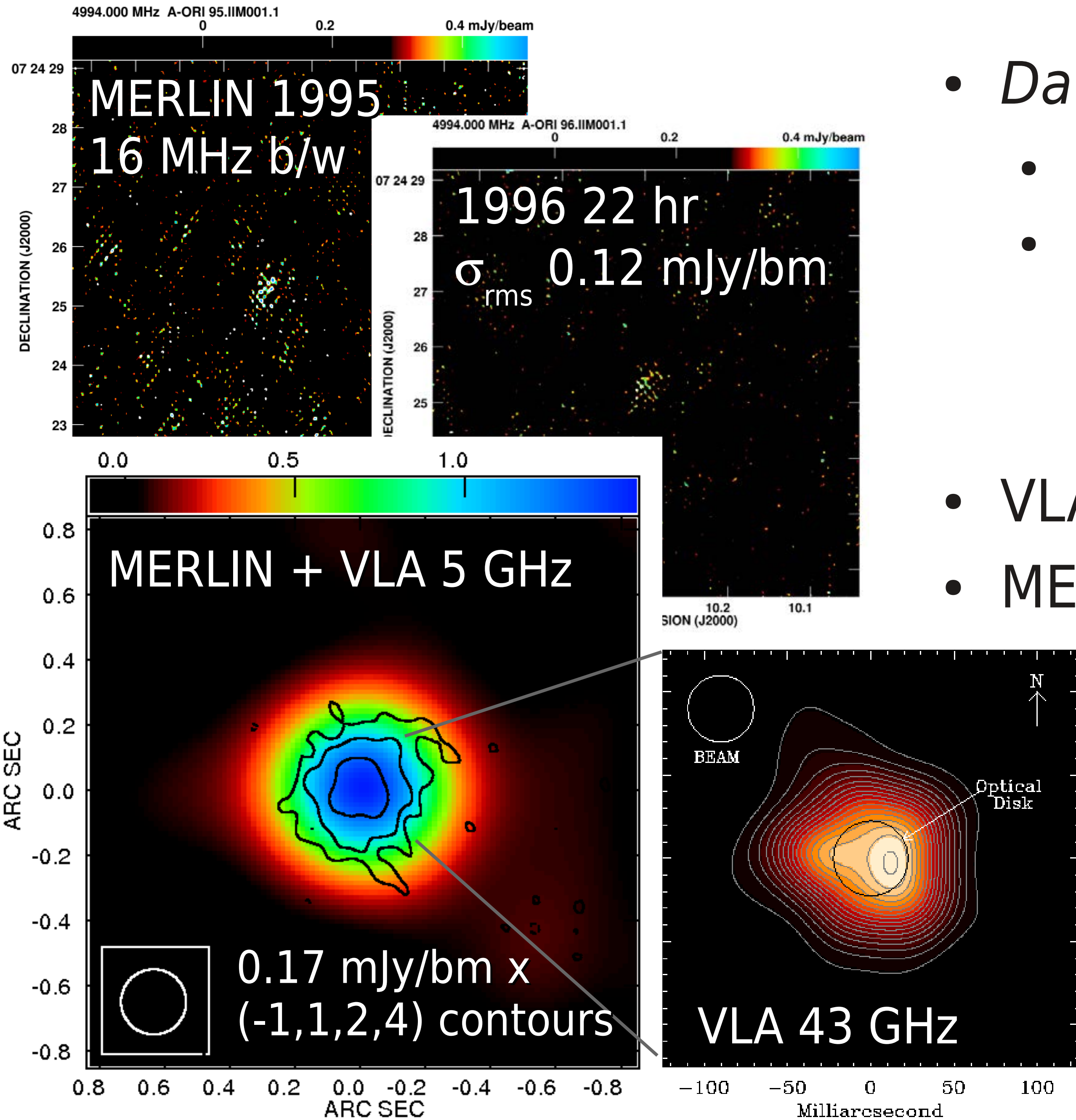
- Properties of clouds derived from 22-GHz maser measurements
  - 7 stars, MERLIN & Pushchino monitoring *Richards+2011,12*
    - Uncertainties, references therein for $R_\odot$ & $\dot{M}$

OH mainlines interleave H_2O



- MERLIN H_2O (blue)
- EVN/global mainline OH (contours)
- OH mainlines inter-leave H_2O
  - Evidence for clumps
- Only ground-state OH detected
  - T_{OH}~500 K max?
  - T_{H2O} ~1000 K ?
- 7 stars, multi-epoch EVN/MERLIN
  - *Richards, Masheder, van Langevelde, Yates 2013??*

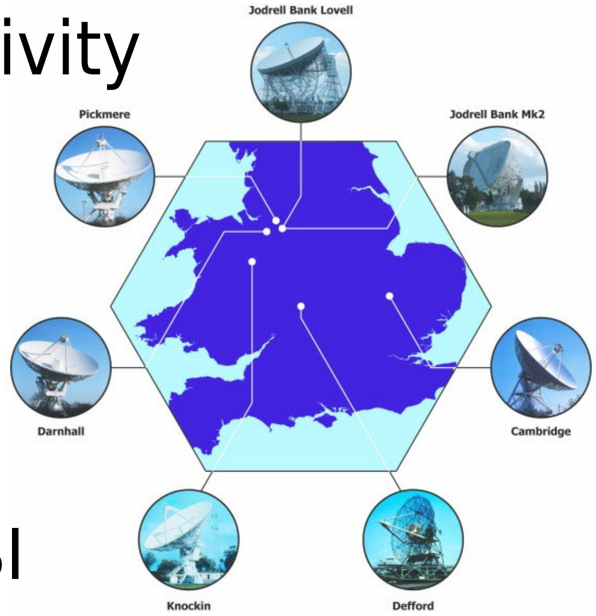
'Old' MERLIN/VLA: α Ori at 5 GHz



- *Davis, Morris, Skinner*
  - MERLIN: 7-9 spots
  - 0.40 – 0.79 mJy/bm
    - (55x85) mas resolution
      - Sensitivity limited
    - Shortest spacing ≡ >0”.5
- VLA 5 GHz barely resolved
- MERLIN+VLA
  - σ_{rms} 0.055 mJy/bm
  - 200 mas beam
  - *Lim+98*
    - VLA image
  - JVLA projects *Brown, Harper, O Gorman*

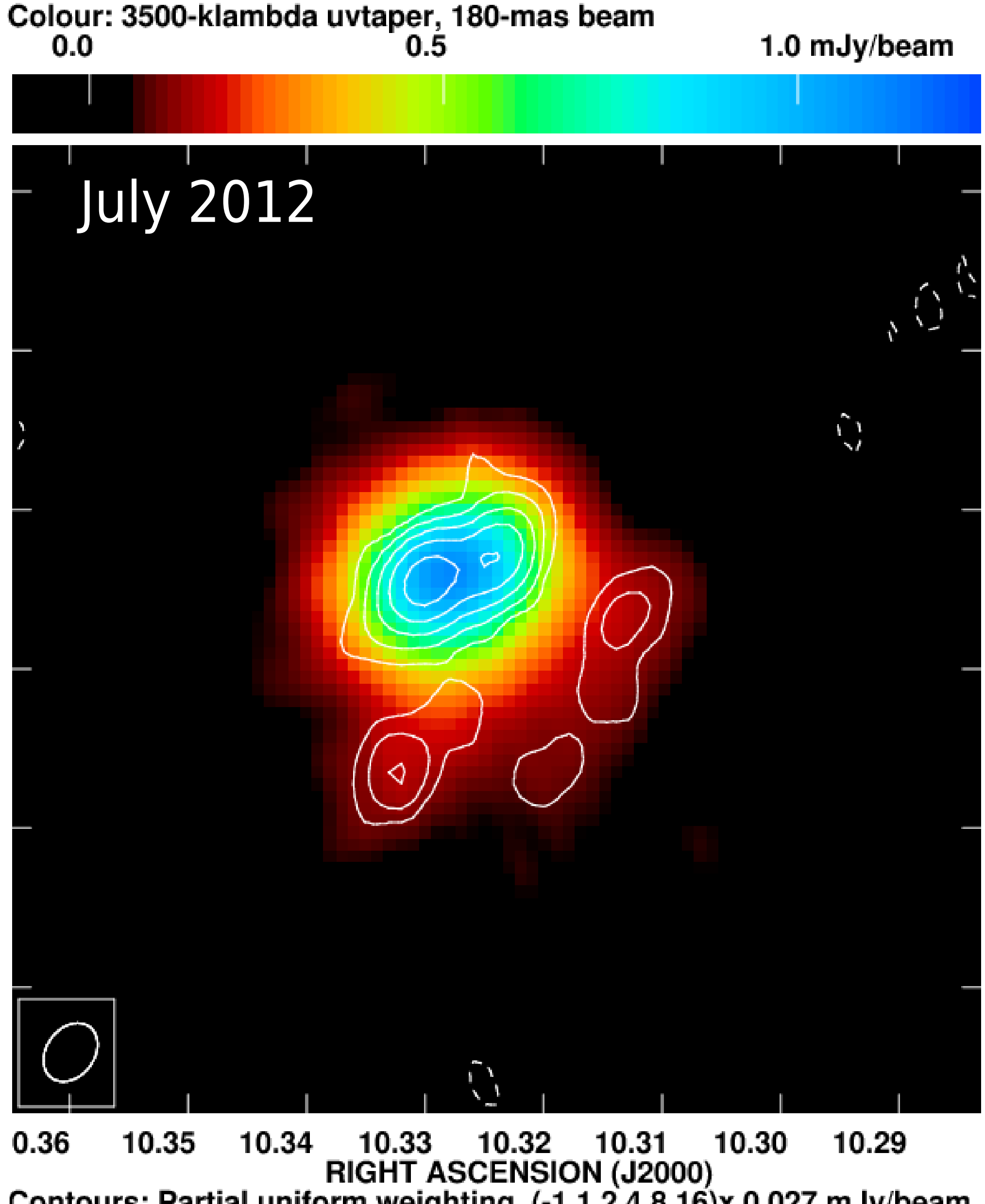
eMERLIN capabilities

- Resolution matches HST/JWST/ALMA
  - 1.3-1.7, 4-8, 21-26 GHz wavebands (≤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 ≳ -30^{o} ~ 20^{o}
- Open skies, 2nd proposal call imminent
  - Joint observations with EVN/Global VLBI
- http://www.e-merlin.ac.uk



α Ori e-MERLIN 5.75 GHz

- *Richards, Davis, Decin, Lim, Etoka, Garrington, McDonald, Wittkowski*
- 6-8 hr, 400 MHz b/w
  - Colour tapered to 180 mas resolution
    - σ_{rms} 0.02 mJy/bm
    - 1.826 mJy/0.092 asec^2
    - T_B 1220 (100) K
  - Contours (80x60) mas resolution
    - σ_{rms} 0.009 mJy/bm
    - Peaks 0.789, 0.533 mJy/bm
    - T_B ≳4000 K?
      - (similar in 1992,5,6)
    - Total disc T_B 1240 (100) K



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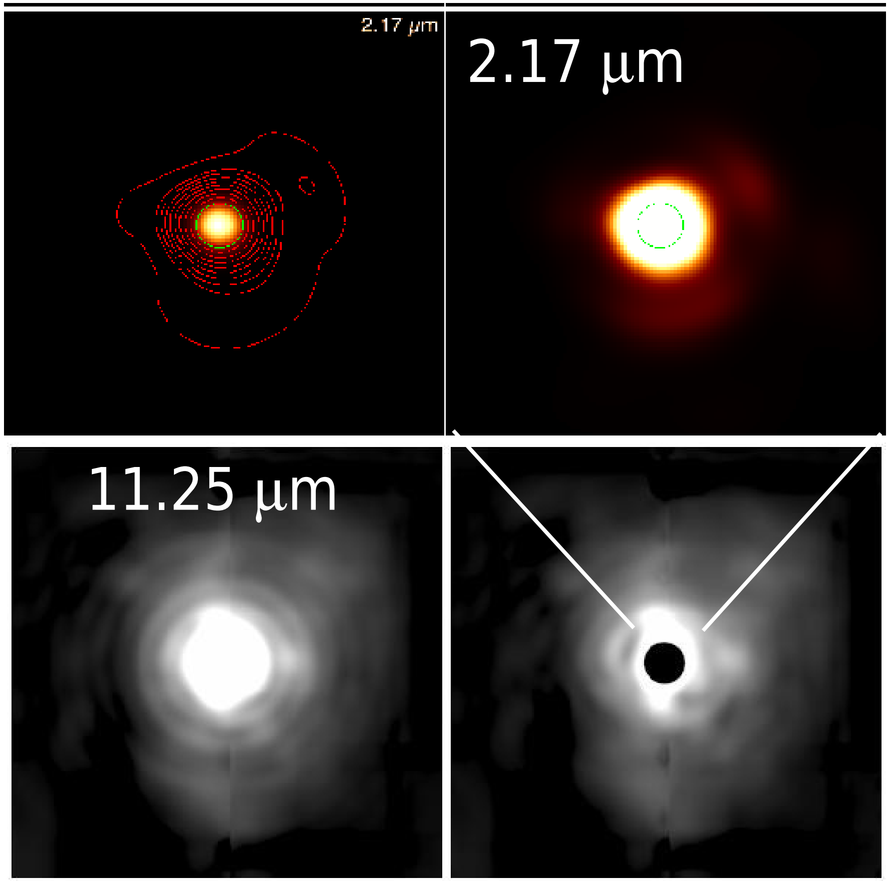
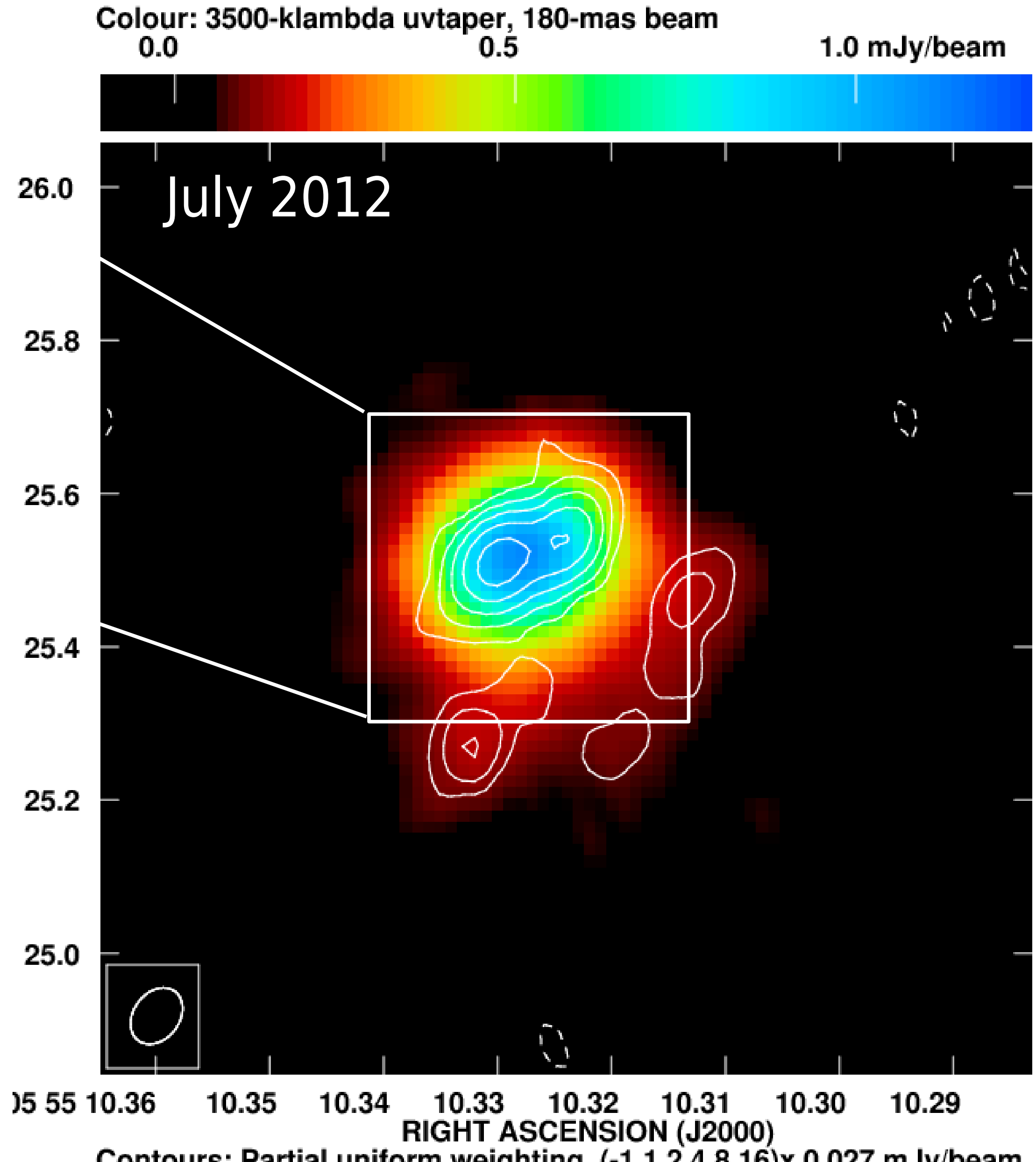
WARNING! PRELIMINARY RESULTS!
Cols have not yet checked these images

α Ori e-MERLIN 5.75 GHz

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



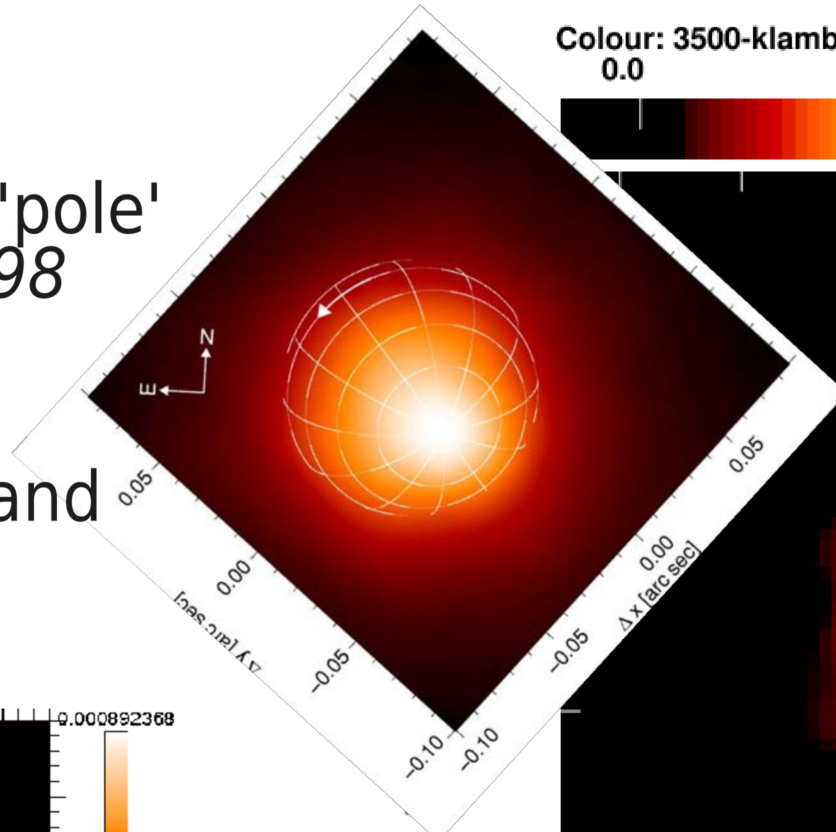
- Also CO source 5” SW (*O'Gorman+12*)

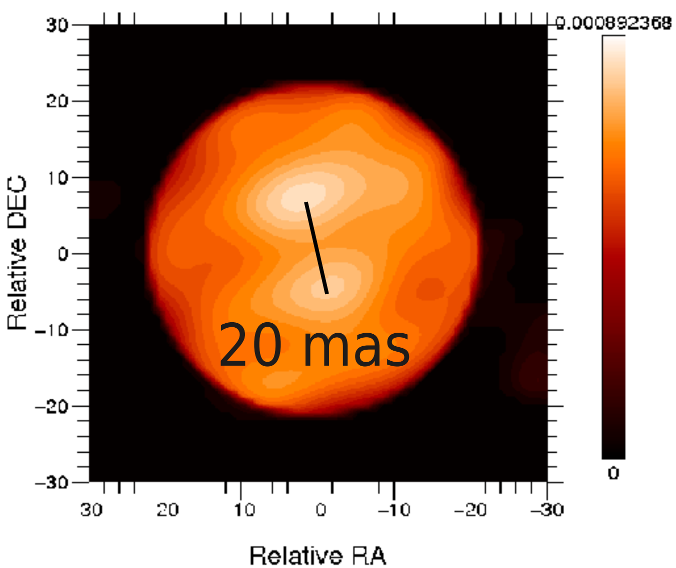


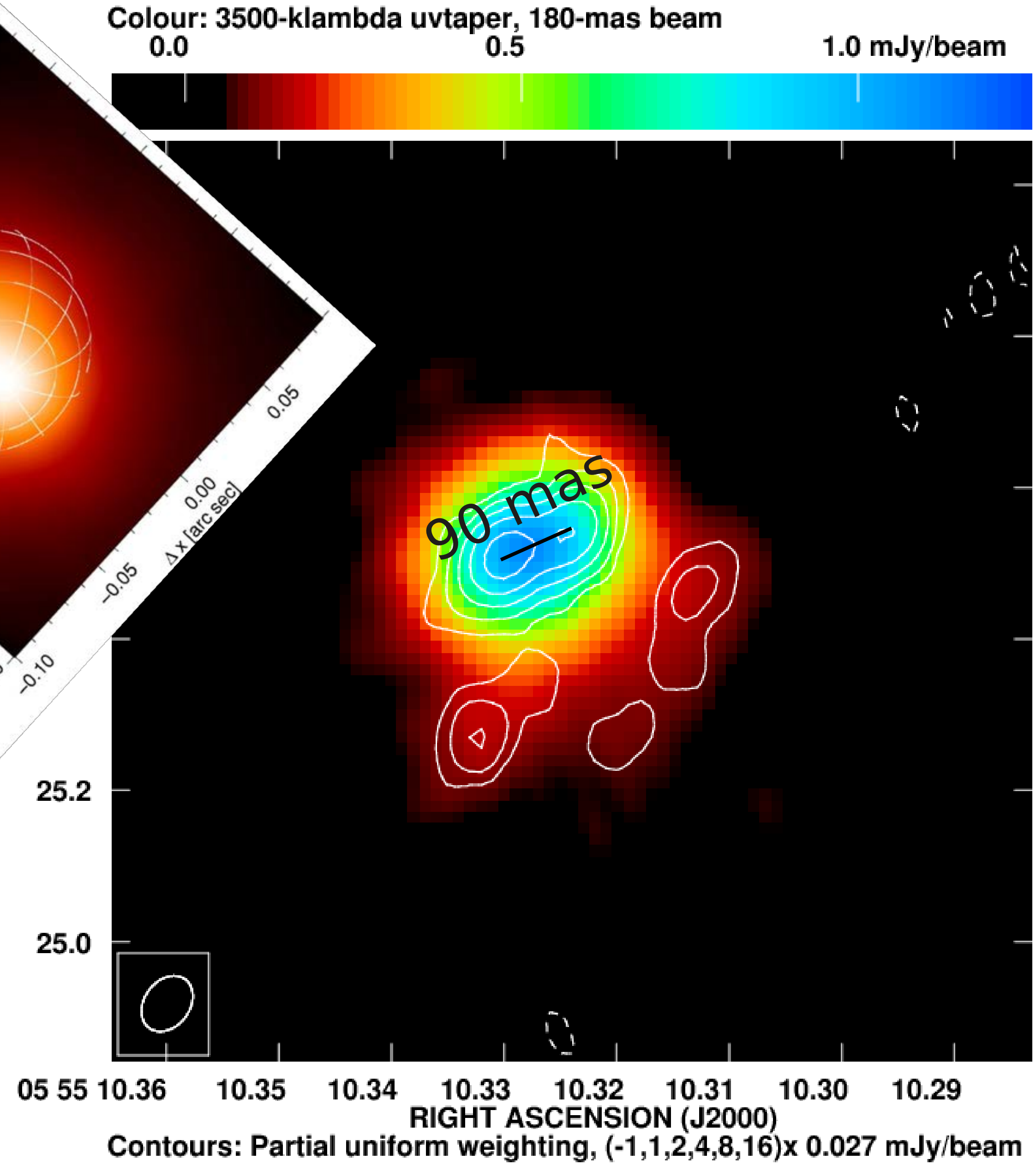
α Ori e-MERLIN 5.75 GHz

- Hotspots not aligned with 'pole' *Uitenbroek+98*

- Nor with H-band peaks *Haubois+09*

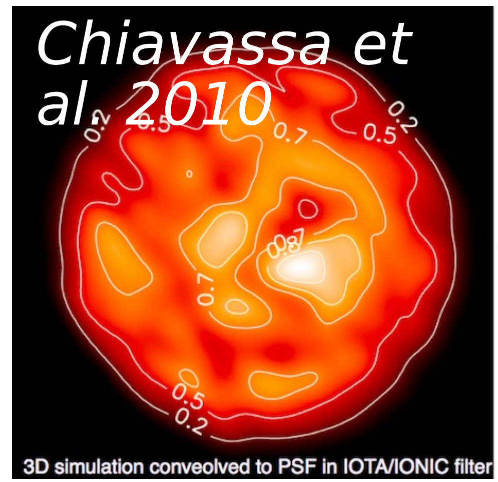




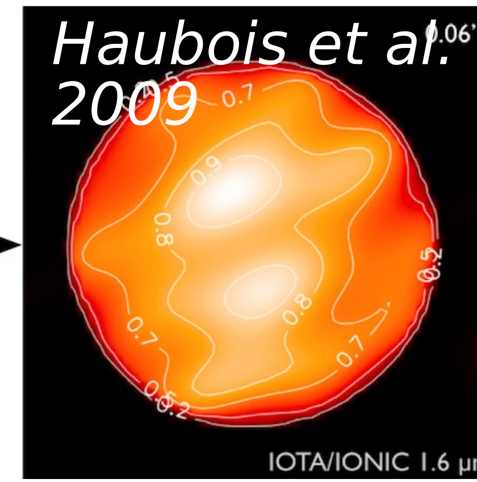


What initiates the wind?
Does this determine clump size?

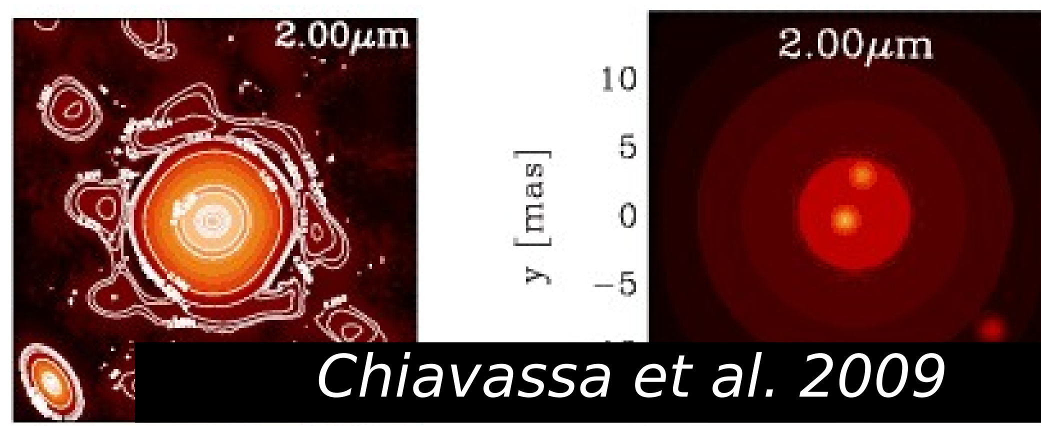
- Outer layers of AGB stars 2000 – 2500K
  - RSG up to ~3500 K
- α Ori convection model
  - Fits H-band VLTI
- VX Sgr also 'spotty'
  - Convection provides local cooling &/or lower gravity
  - Chemical or magnetic inhomogeneity?



Chiavassa et al. 2010



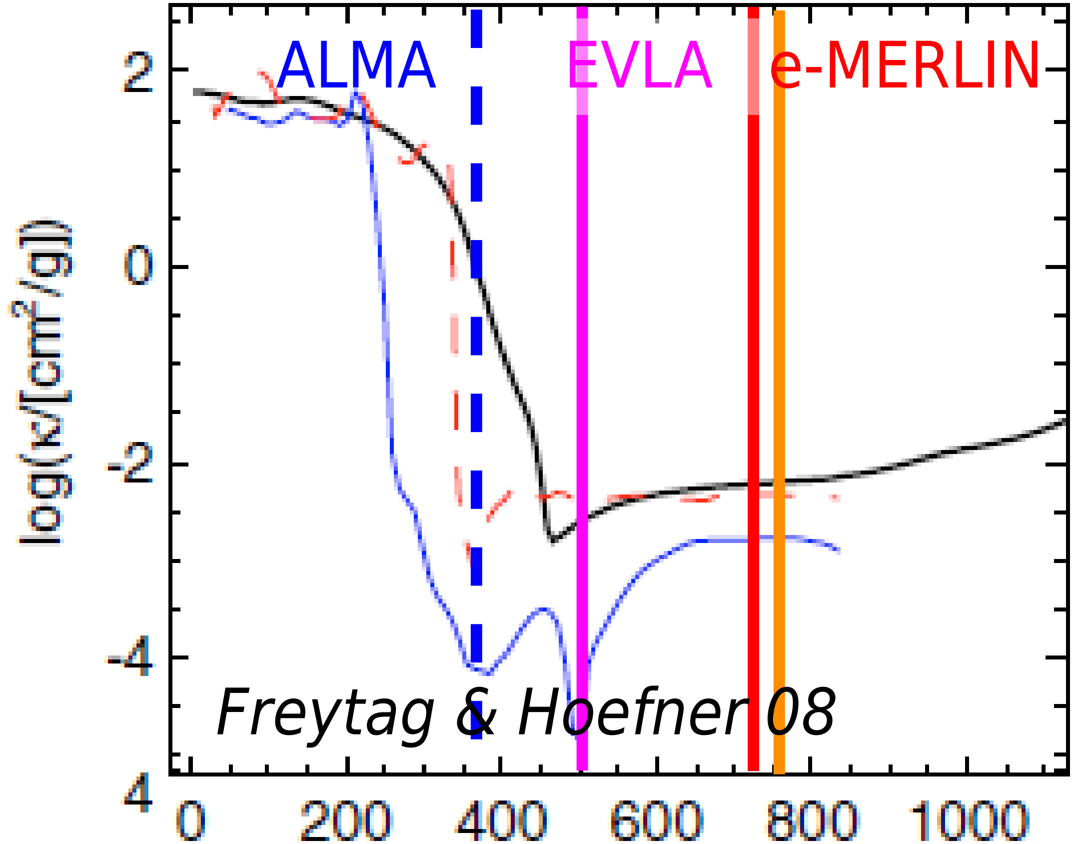
Haubois et al. 2009



Chiavassa et al. 2009

Different ν's trace different layers

- $r_{22\ \mathrm{GHz}} \sim 2r_{\mathrm{photosphere}}$
- Cool free-free gas
  - Low chromospheric filling factor
- Betelgeuse (*Harper, Lim, Chiavassa, Freytag*...)
  - 2-3 main cells
    - Lifetime years
    - Scale height 5-10% $R_\star$
    - Correlated changes: pulsation?
    - Variegated changes: convection?

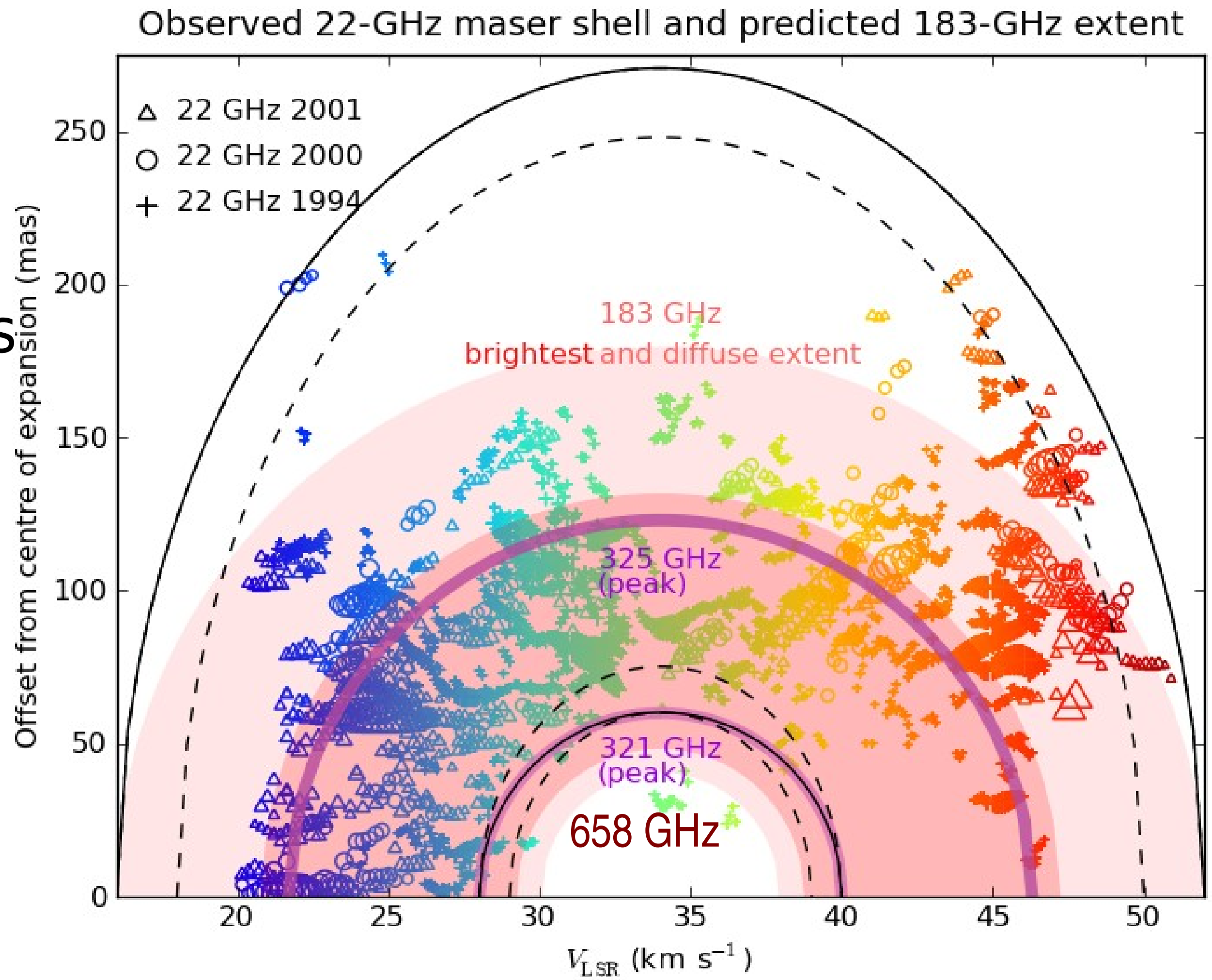


- $r\ (\tau \rightarrow 1) \uparrow$ as $\nu \downarrow$
  - Radiosphere V<5 km/s
    - $r_{43} \rightarrow r_{24}$ ~1 AU, ~1 yr
    - $r_{24} \rightarrow r_{21}$ ~2 months

Masers (and the rest) with ALMA

- Multiple transitions trace different conditions
  - Models: *Neufeld&Melnick'91, Humphreys+'01, Gray*

- 183, 325 GHz ground states
  - Trace 22-GHz clumps
  - or inter-clump gas nearer star?
- 321, excited state
  - Straddles dust formation zone?
- 658 GHz close to ✷
- Eventually resolve dust clumps, star



Track wind from photosphere to ISM

- **CO ALMA**
- **1612 MHz masers**
  - ***e-MERLIN, EVN***
- **OH 1665/7 MHz masers**
  - ***e-MERLIN, EVN***
- **H_2O masers**
  - ***e-MERLIN, ALMA***
- **Dust, chemistry**
  - ***ALMA, VLTI***
- **SiO masers**
  - ***VLBA, ALMA***
- **Star** photo/ **radiosphere**
  - ***e-MERLIN/ EVLA, ALMA,VLTI, MROI***
  - Different λ ≡ different depths