Turbulent and Steamy Supergiants

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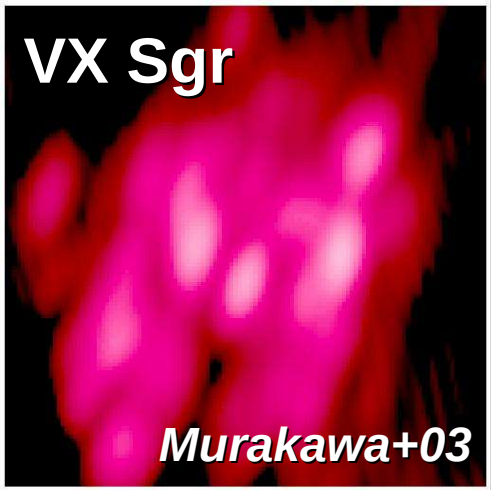
- **High-mass AGB analogues: M_{*} 10 - 50 $M_{\odot}$**
  - **Return >>50% enriched mass to ISM**
- **Water masers from wet, dusty clouds**
  - **Over-dense, over-magnetised, accelerated**
  - **Birthplace, birth rate, survival**
- **Hydroxyl masers from diffuse gas**
  - **Mainlines overlap water masers**
  - **Irregular polarization near star**
- **Massive stellar evolution**

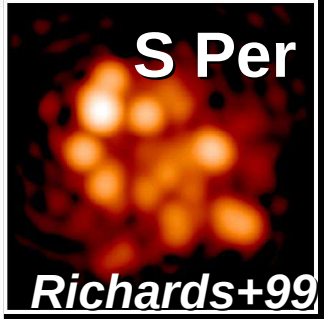
The Cast

ordered by increasing post-MS evolutionary stage

Red Super Giant Star	M_{*} ($M_{\odot}$)	Distance (kpc)	T_{*} (K)	IRAS colour region[1]	Silicate feature, dust[2]	OH 1612 MHz shape, peak log(Jy)
S Per	20	2.2	2400	IIIa	Emission, compact	Biconical, 0
VX Sgr	10	1.7	2900	VII	Emission, compact	~Spherical, 1
VY CMa	50	1.5	2700	VII	Declining, complex	~❤, 2
NML Cyg	50	2.0	3650	VIb	Absorption, multi-shell	Elongated, detatched, 2

[1]van der Veen & Habing (1988) [2]Monnier et al 1998, 1999, 2000, 2004



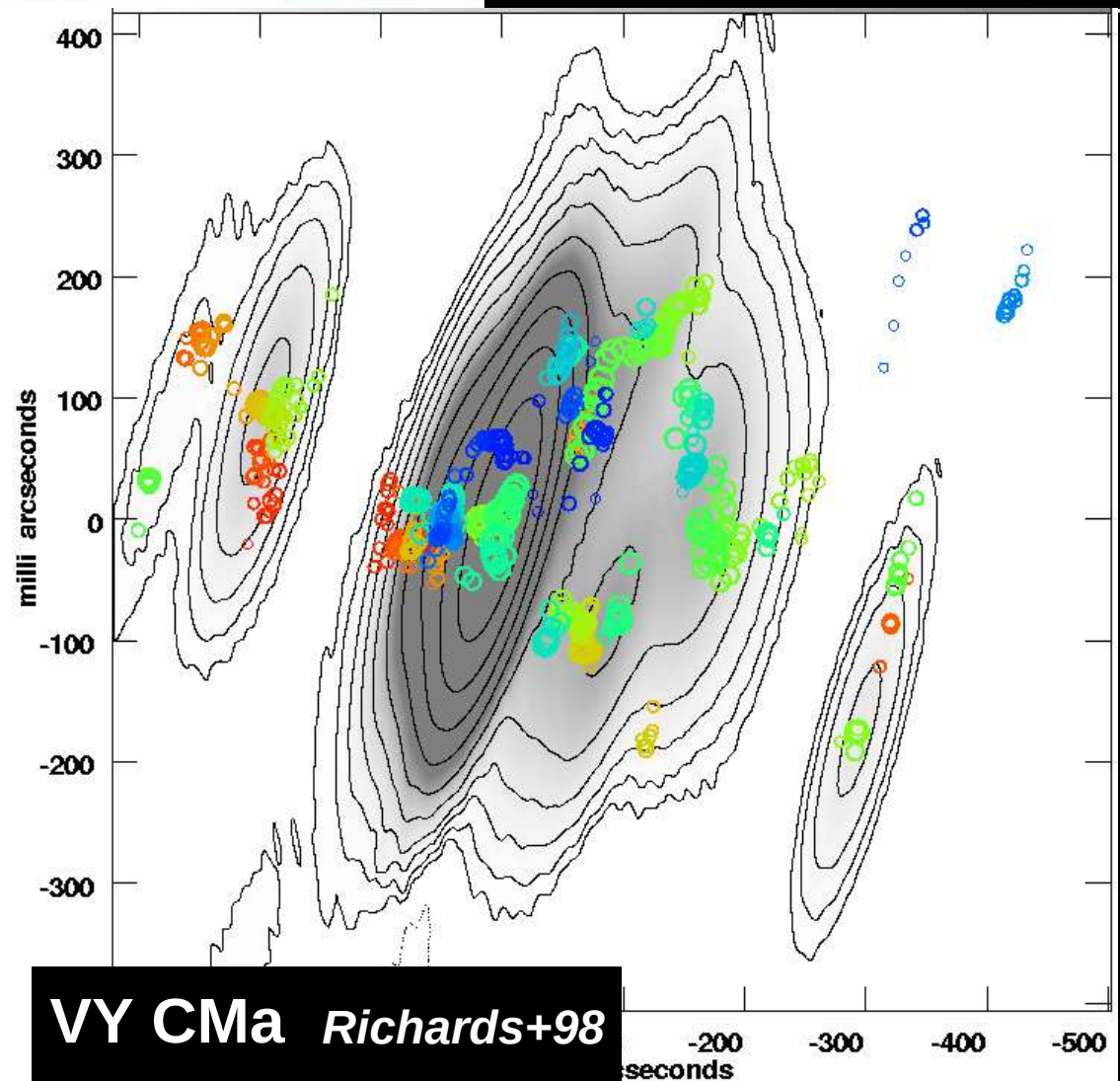


400 AU

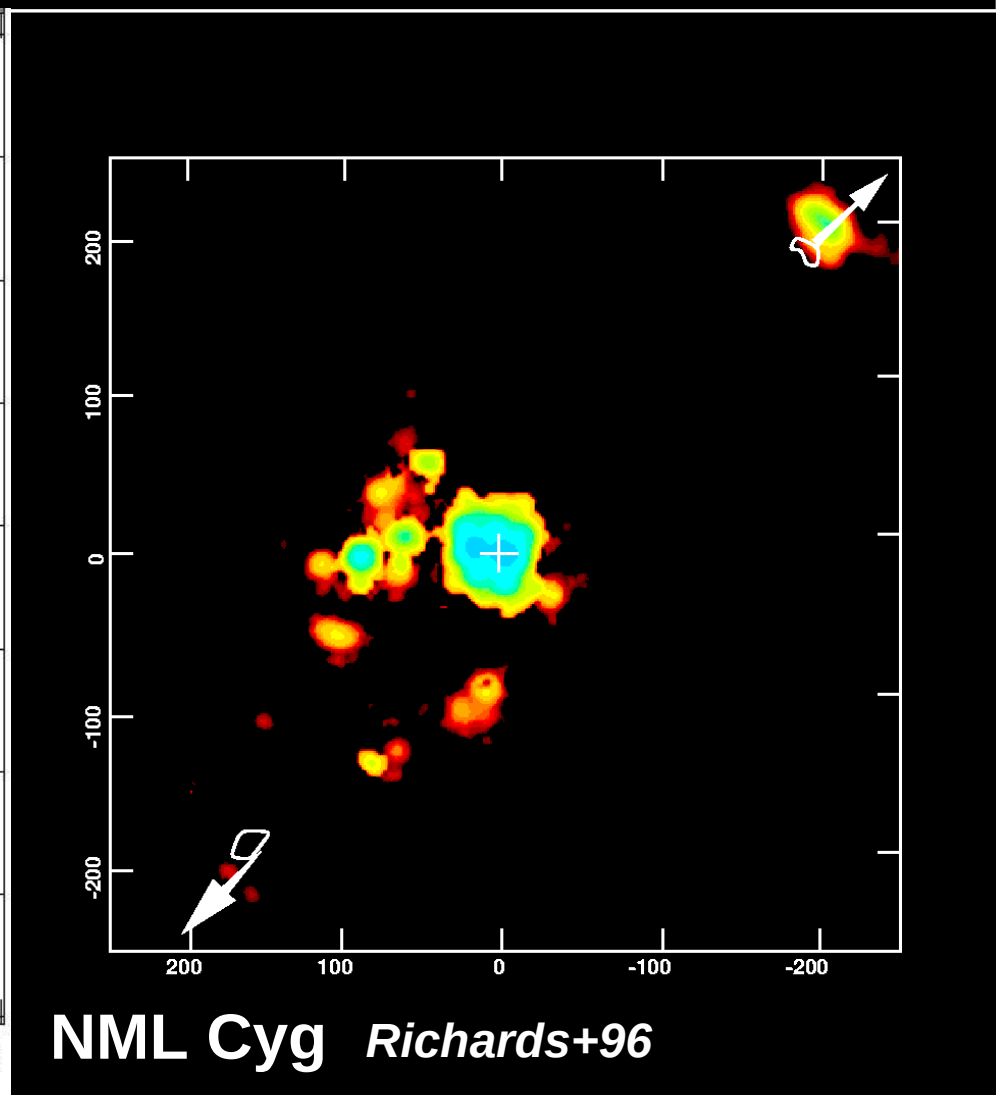
Water maser shells

adjusted to common distance

MERLIN proper motion/acceleration



VY CMa *Richards+98*

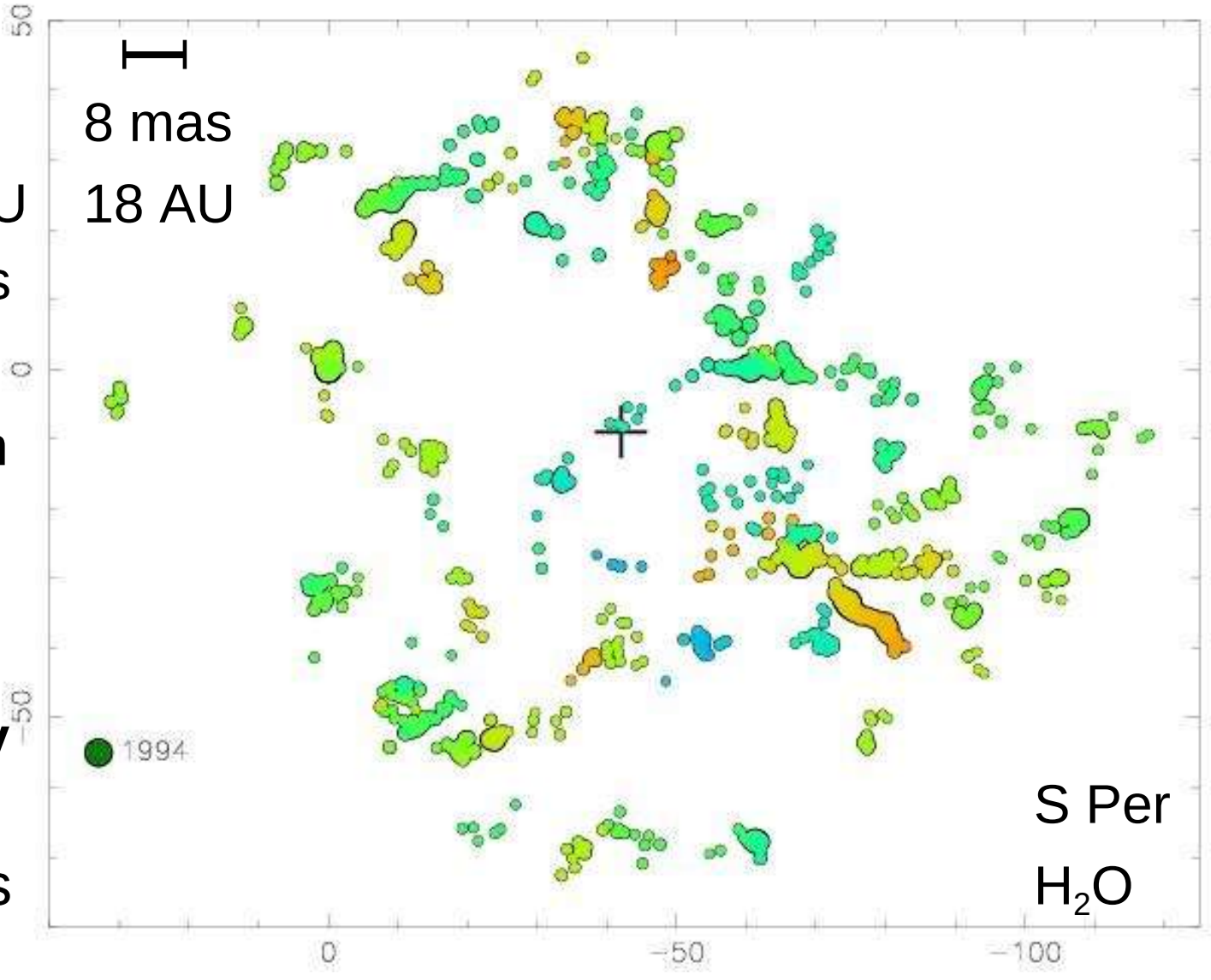


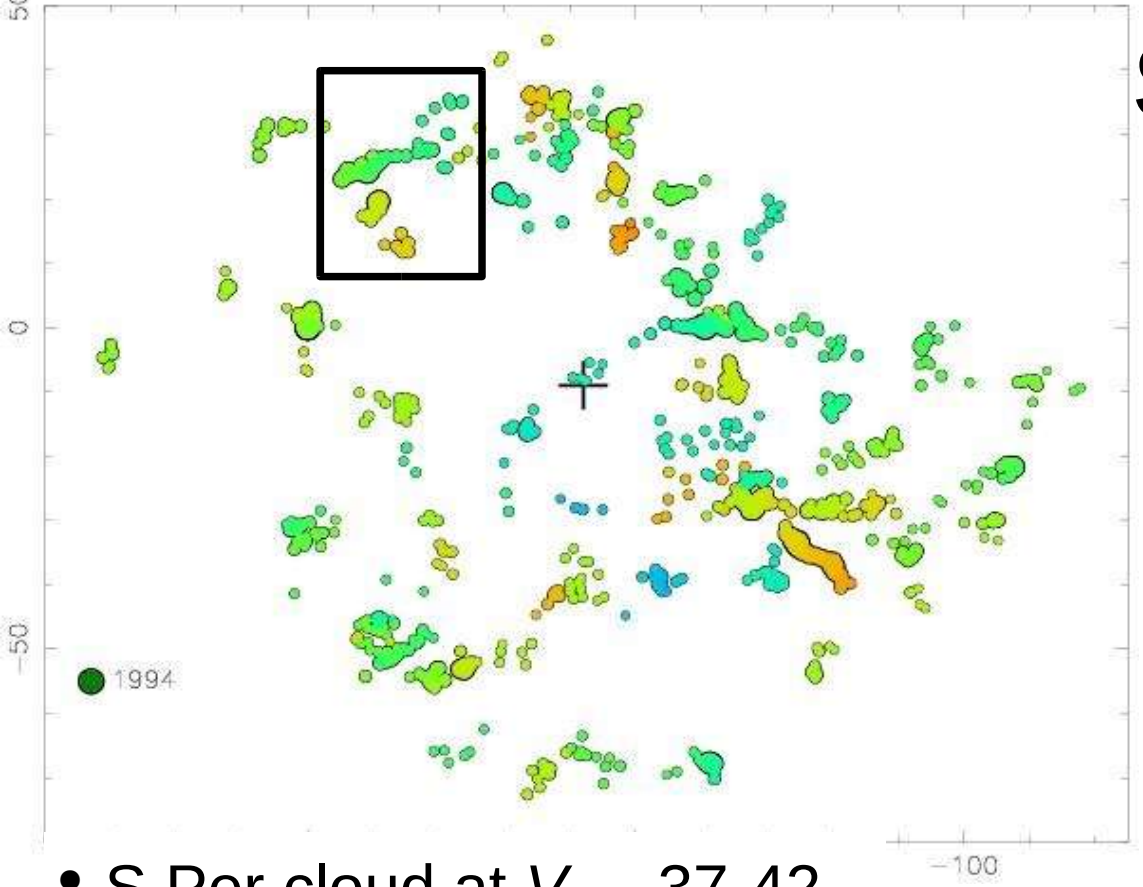
NML Cyg *Richards+96*

Measuring maser cloud size

S Per, VX Sgr

- Colour ∝ velocity
- H_2O - MERLIN detects ~all flux
  - Typical size L 18 AU
  - ΔV_{cloud} 0.5 - >2 km/s
- For many clouds:
  - Diameter $L > l$ (gain length)
  - $\Delta V_{cloud} > \Delta V_{th}$
  - **Clouds must be defined by density &/or composition**
- VLBI over-resolves OH, L ≥ 15 AU





Some RSG clouds last 5 yr+

but half or more vanish

Yet **total shell crossing time** is 50 - 80 yr

- S Per cloud at V_{LSR} 37-42 km s^{-1} imaged 1994, 1999
- Vanishes in Puschino data 1995-7 (*Lekht+05*)
- Accident of excitation or beaming?
- Images show gas clump survives
- Pattern speed ~sonic

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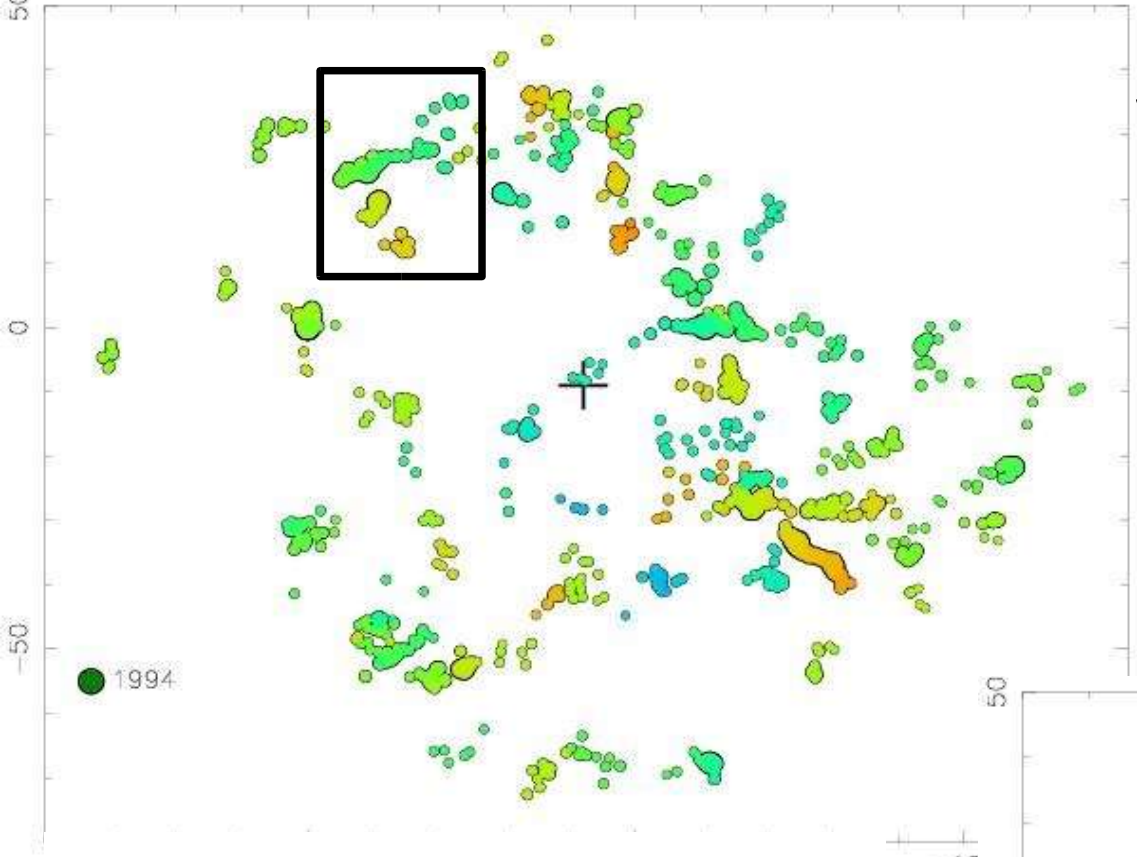

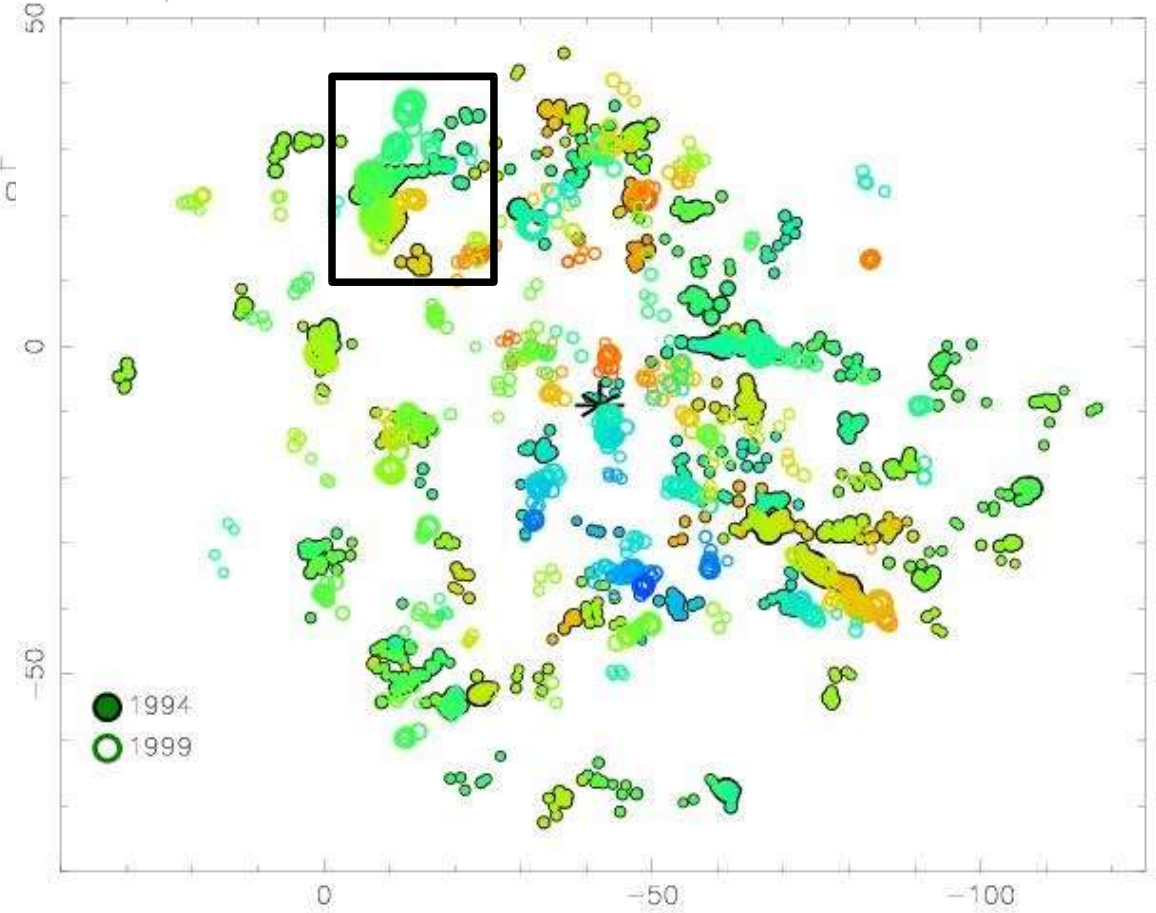

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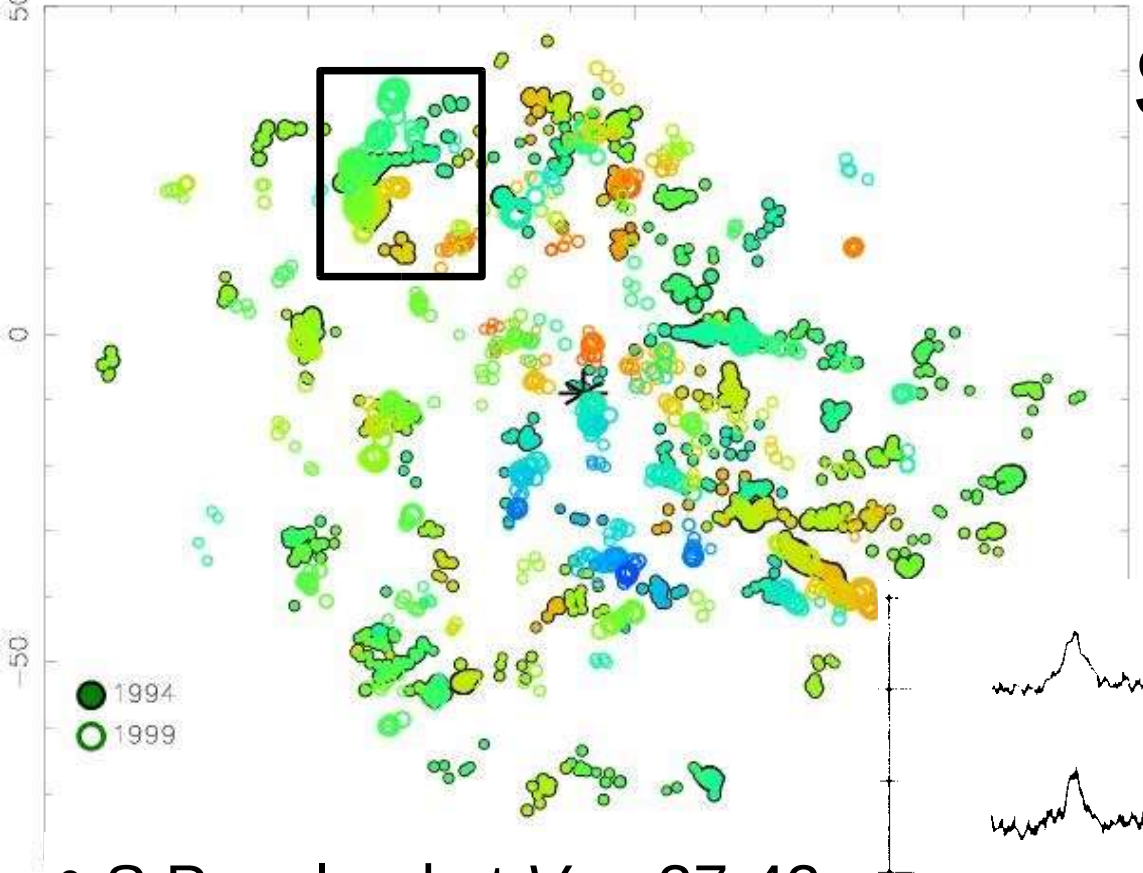

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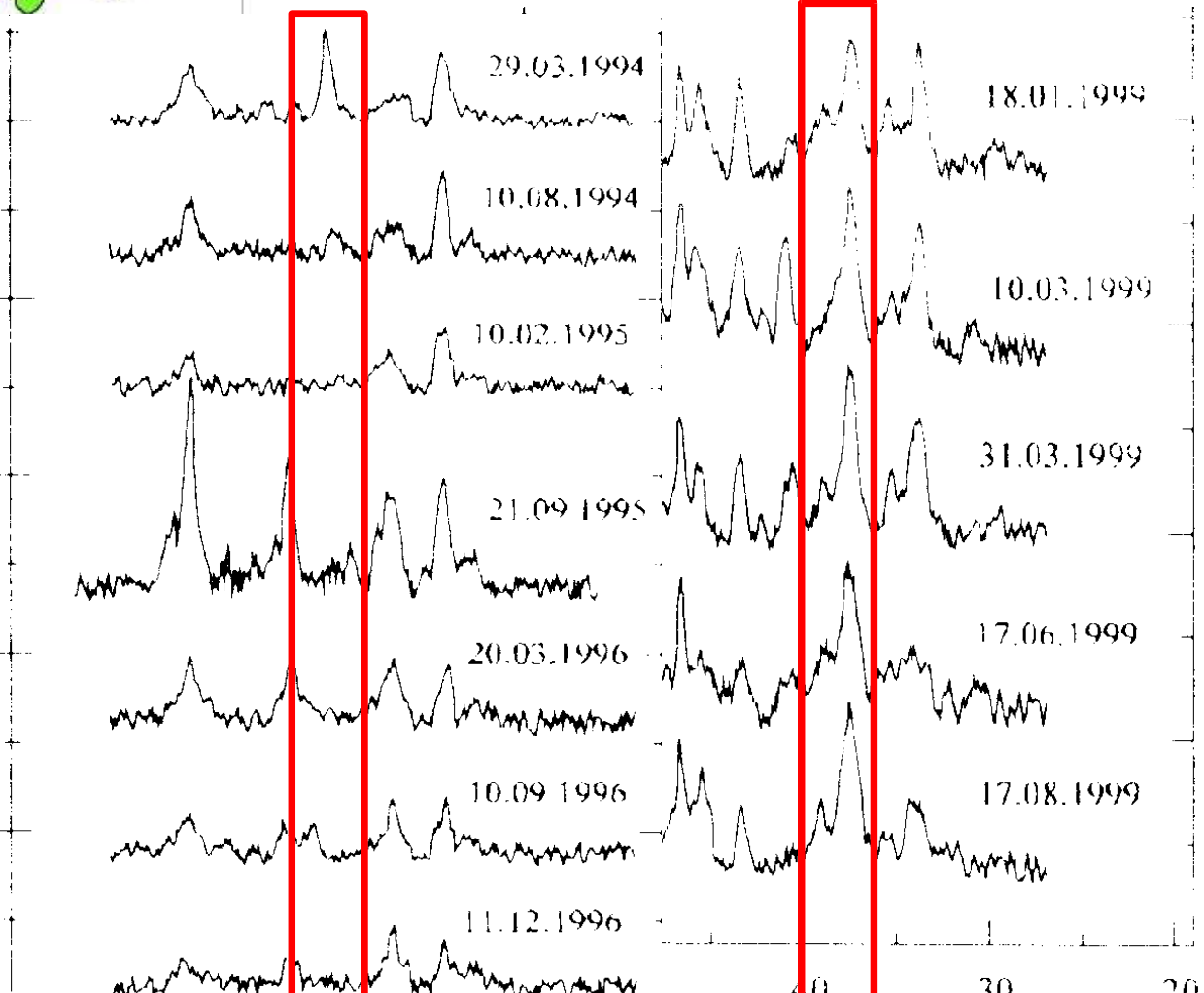
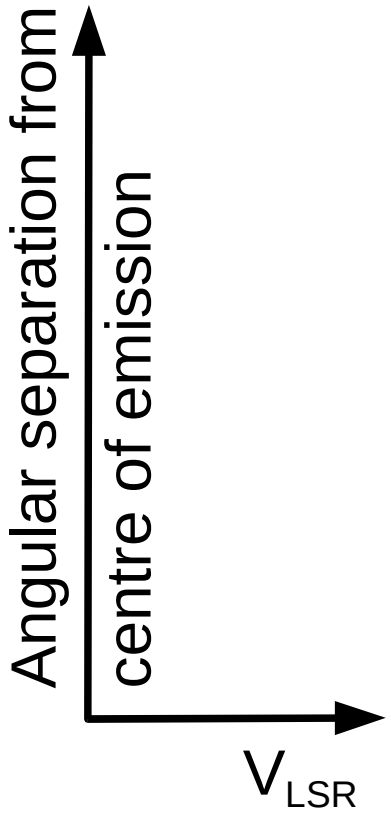
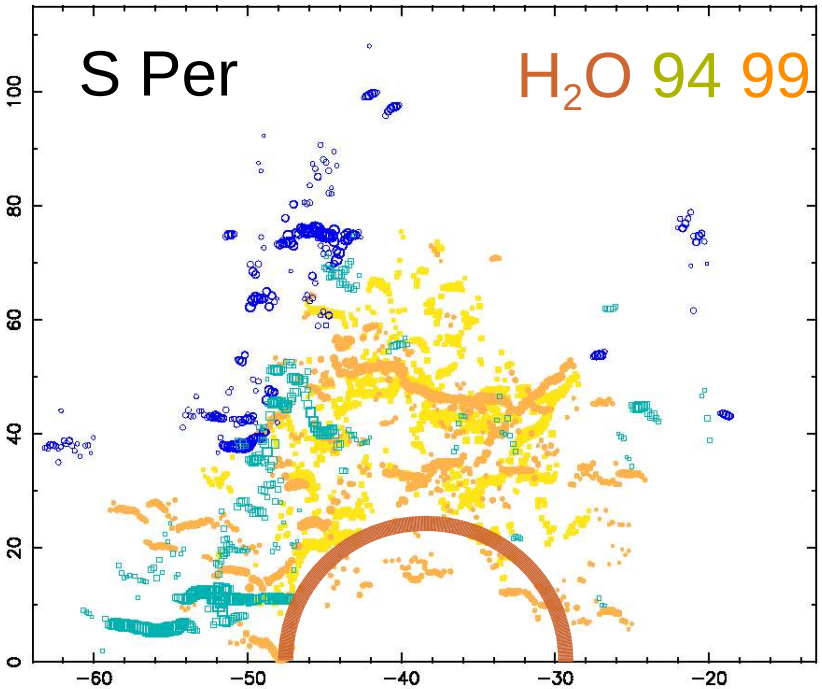
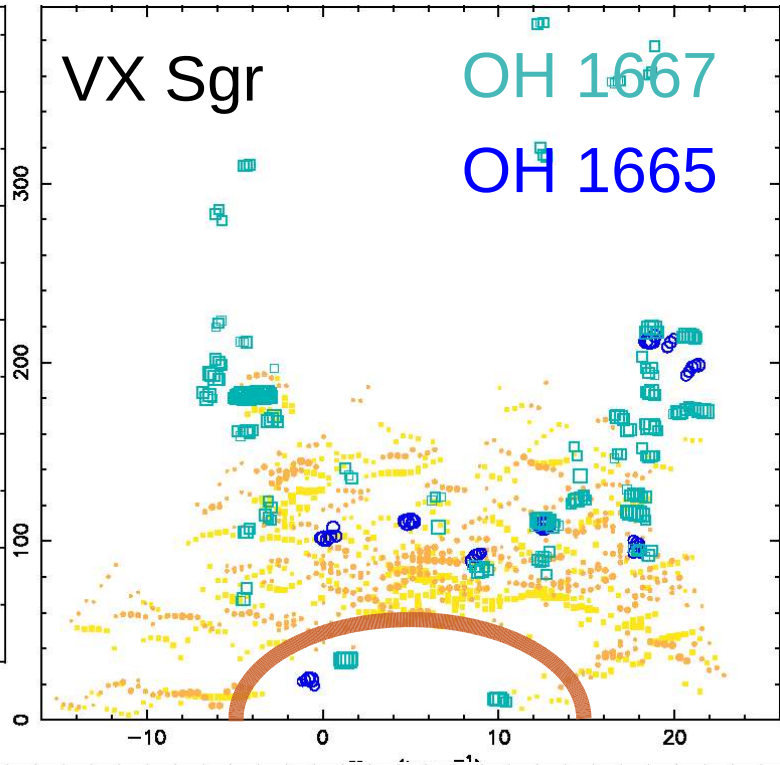
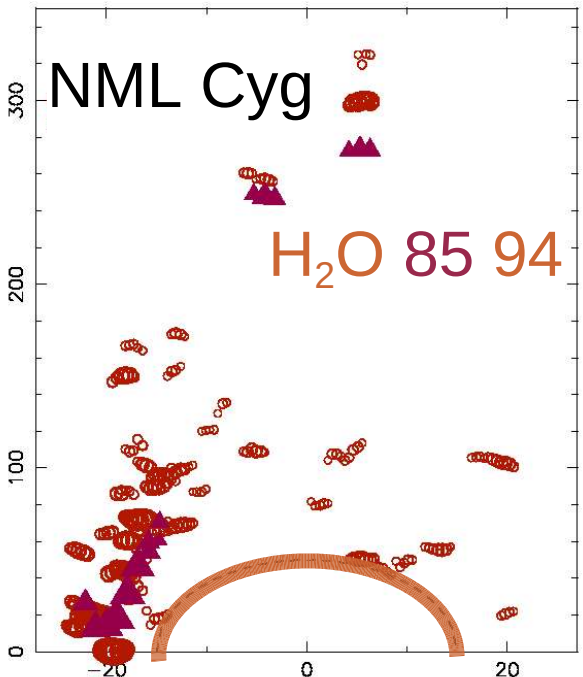


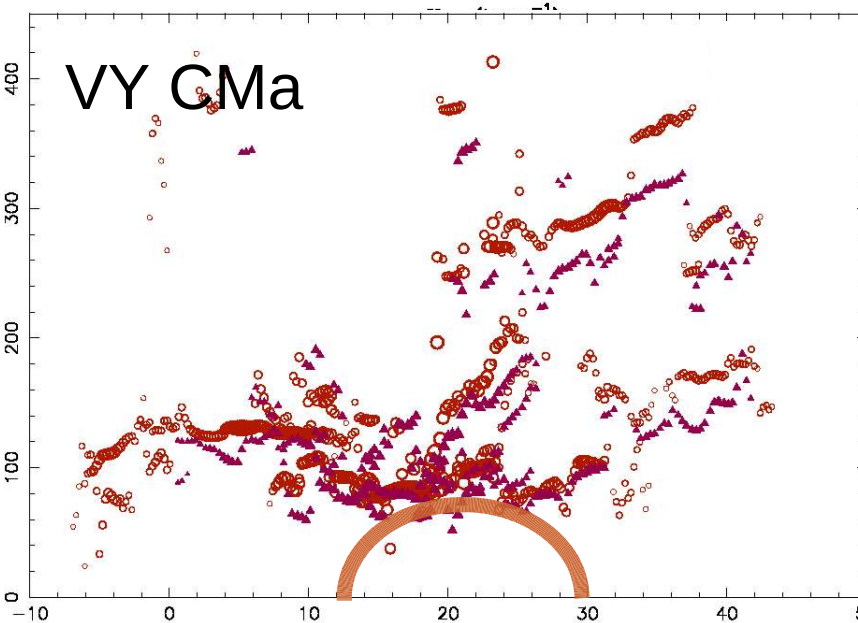
Water maser cloud density











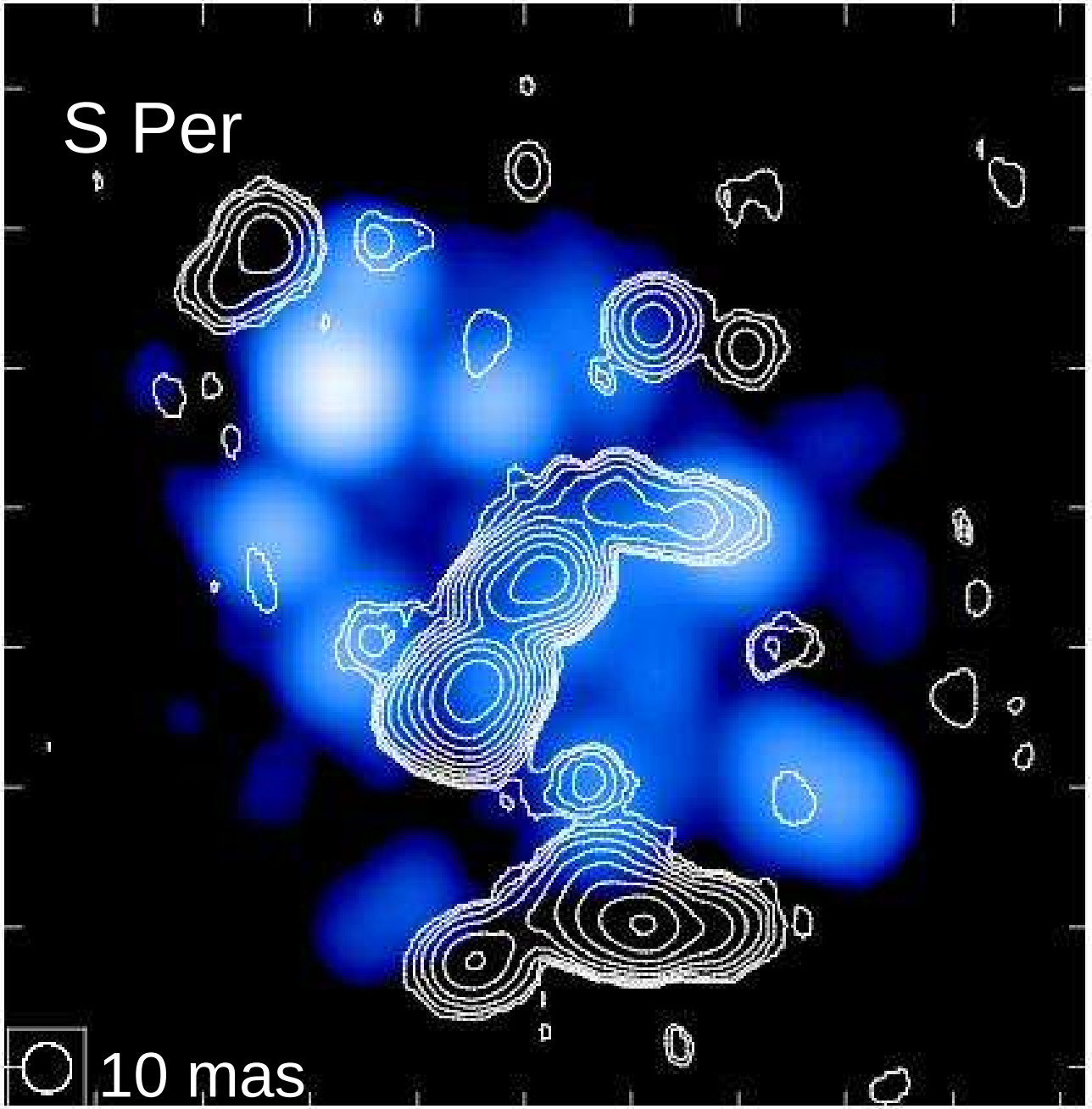
- **Quenching radius**
- **Collision rate > masing rate**
  - **Quenching density $n_q \sim 5\times10^{15}$ m^{-3}**
  - **$dM/dt_q = 4\pi r_i^2 v_i \rho q$**

Water (and OH) maser cloud properties

RSG	d*M*/d*t* CO/IR ($M_\oplus$ yr^{-1})	H_2O shell r_i (AU)	d*M*/d*t* H_2O n_q ($M_\oplus$ yr^{-1})	Number of H_2O clouds	H_2O cloud size <L> (AU)	H_2O cloud mass yr^{-1} ($M_\oplus$ yr^{-1})	H_2O shell r_o (AU)	OH cloud size <L> (AU)
S Per	3–60	55	(930)	100	18 (44)	15–20	165	>13 (66)
VX Sgr	5–80	95	(1900)	100	21	10–15	320	>13 (42)
VY CMa	65–115	115	(3150)	55			540	
NML Cyg	35–60	100	(5150)	40			480	

- H_2O maser cloud filling factor <few %
- Solves mass loss rate discrepancy
- Few clouds formed per stellar period
- *Clouds much denser than surroundings:* $n_{H2Ocloud}$ (15–70)× n_{OHgas}
- Some clouds have multiple peaks up to larger size estimate
  - OH mainlines <*L*> lower limit as sensitivity-limited

OH mainline masers interleave H_2O



- MERLIN H_2O (blue)
- EVN/global mainline OH (contours)
- OH mainlines inter-leave H_2O
  - Some OH at close to V_* - not just projection of front/back caps
- Clump radii
  - r_{OH}~9 au r_{H2O} ~9 au
- OH masers so close to star!
  - T_{OH}~500 K max?
  - T_{H2O} ~1000 K

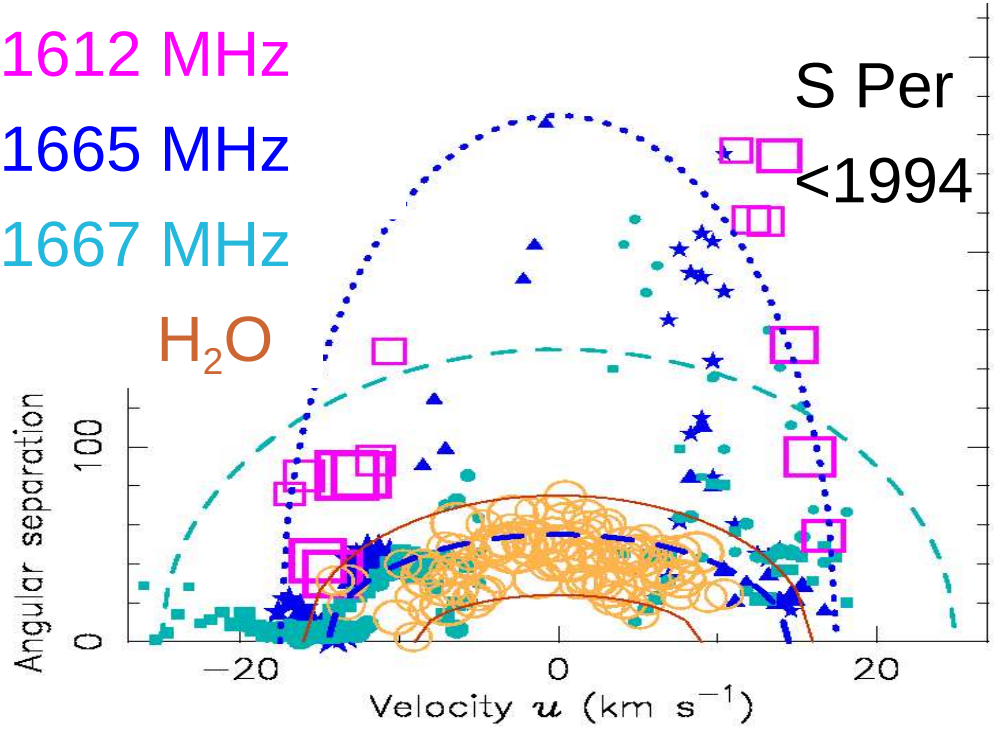
Angular radius-velocity all OH

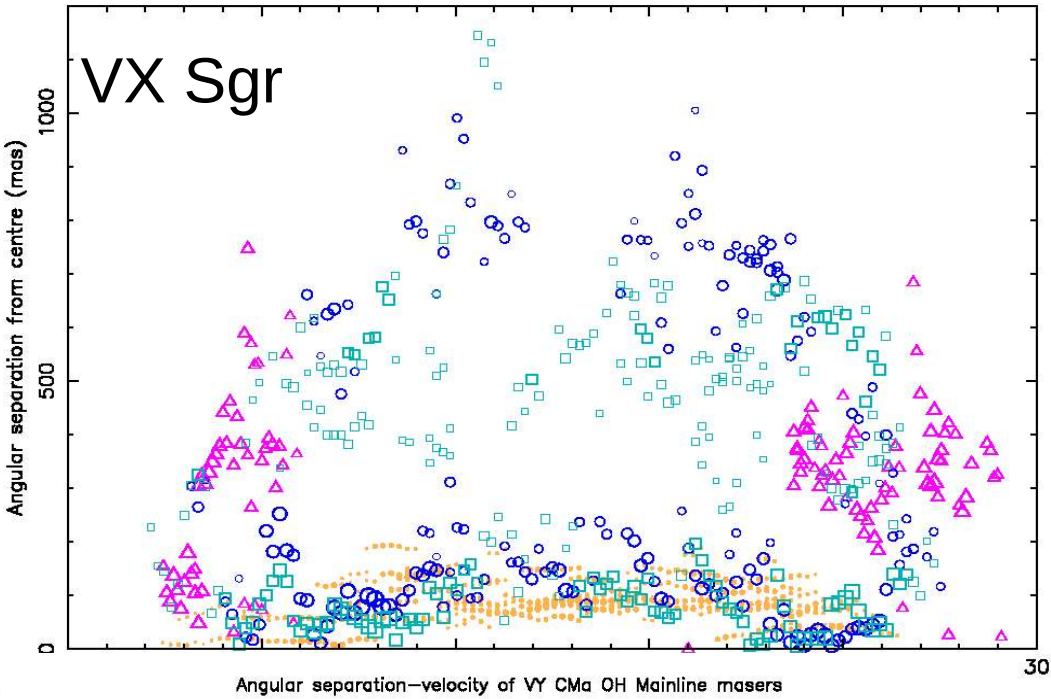
1612 MHz

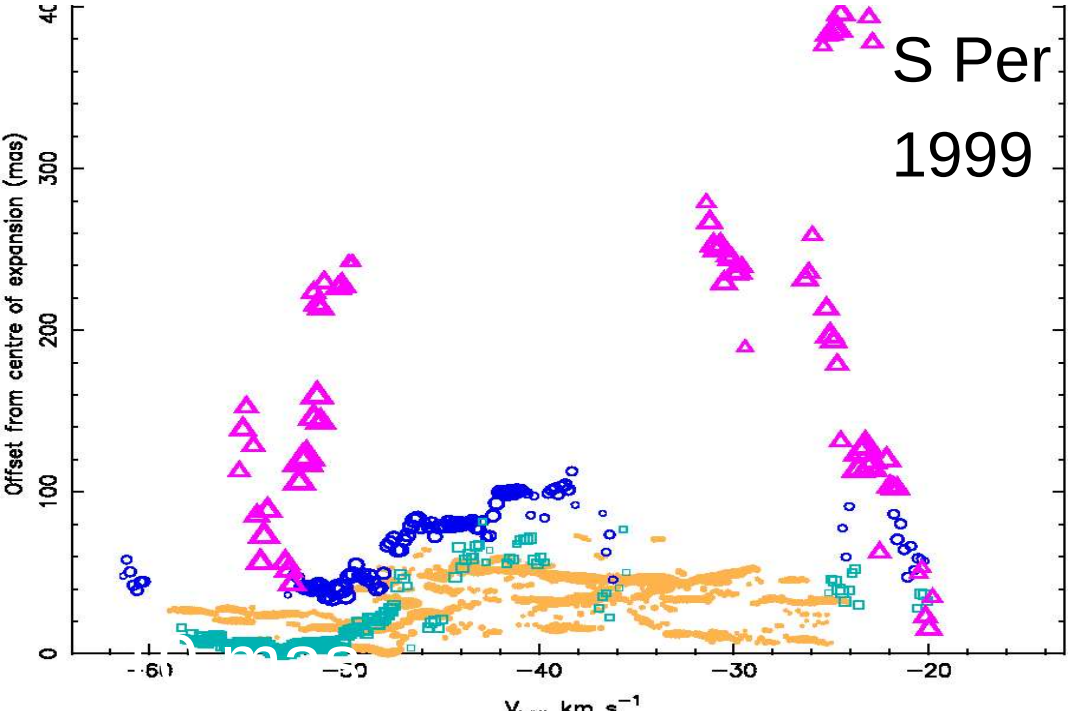
1665 MHz

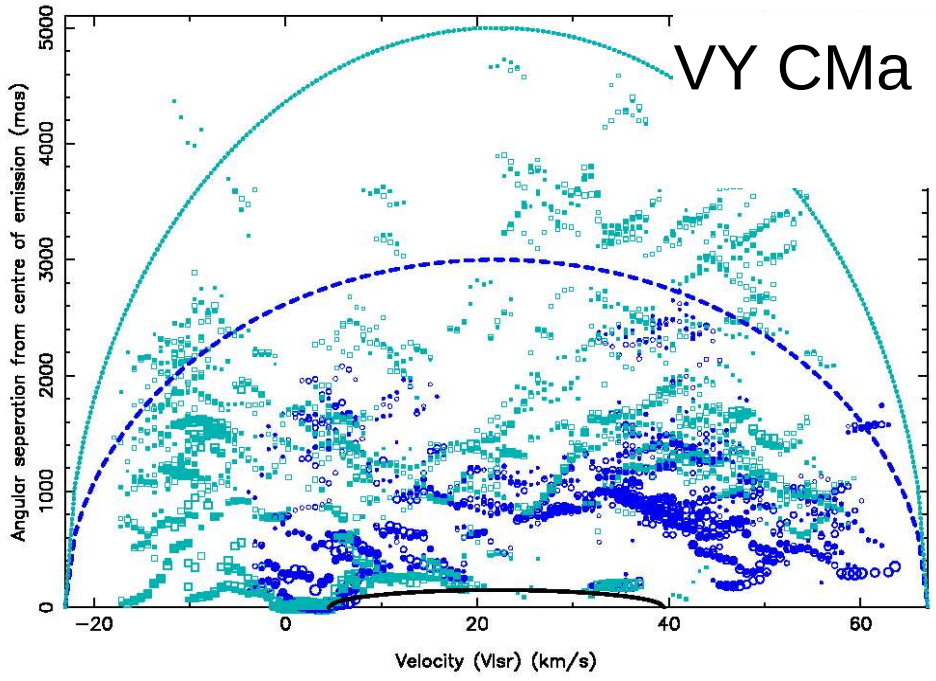
1667 MHz

H_2O







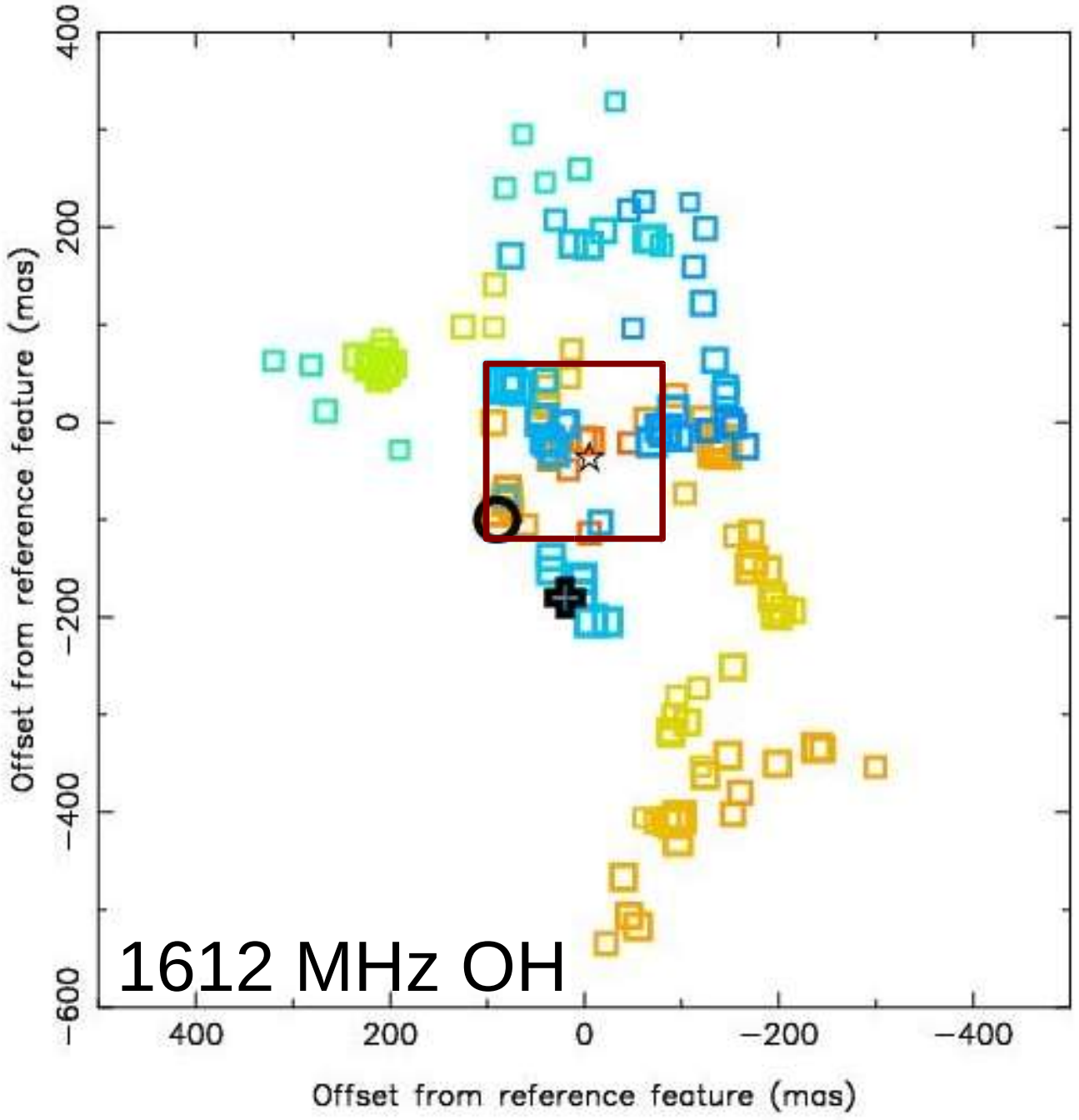


Water and OH mainline shells

RSG	H_2O shell r_i (AU)	H_2O shell r_o (AU)	OH mainline shell r_i (AU)	OH 1665-MHz shell r_o (AU)	OH 1667-MHz shell r_o (AU)
S Per	55	165	80	570/175[3]	570/245[3]
VX Sgr	95	320	130	540/1950[4]	540/1950[4]
VY CMa	115	540	225	4500	10000
NML Cyg	100	480	2400[1]/3000[2]	3200[1]	5000[2]

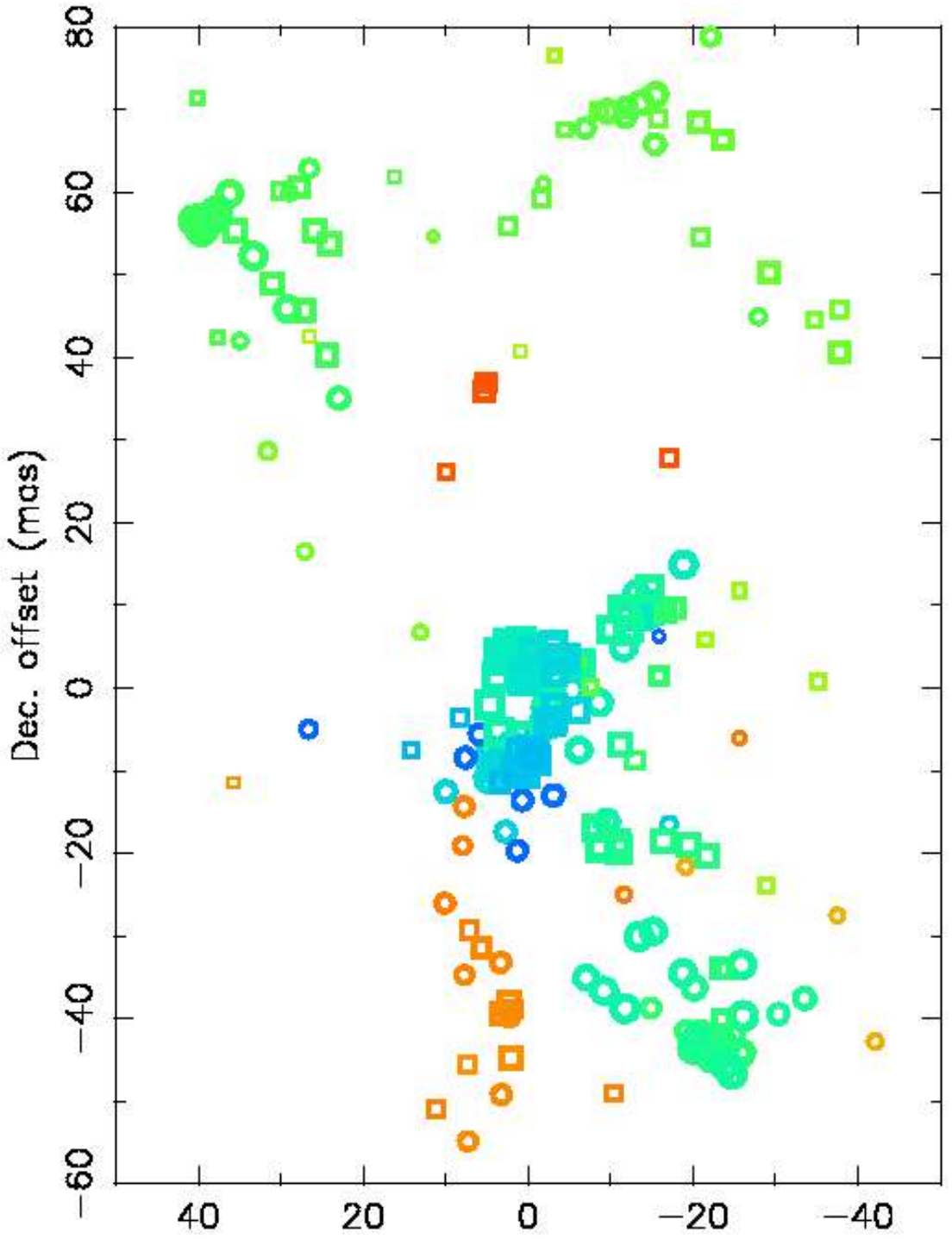
1. 1665 MHz *Etoka & Diamond 2004*
2. 1667 MHz *Diamond*
3. Larger outer radius in 1994 - could be sensitivity or variability
4. Double shell structure

S Per OH Asymmetry



- 1999 MERLIN
- OH 1612 MHz
  - Axisymmetry for several centuries
- Box shows H_2O/ mainline OH region

OH Asymmetry

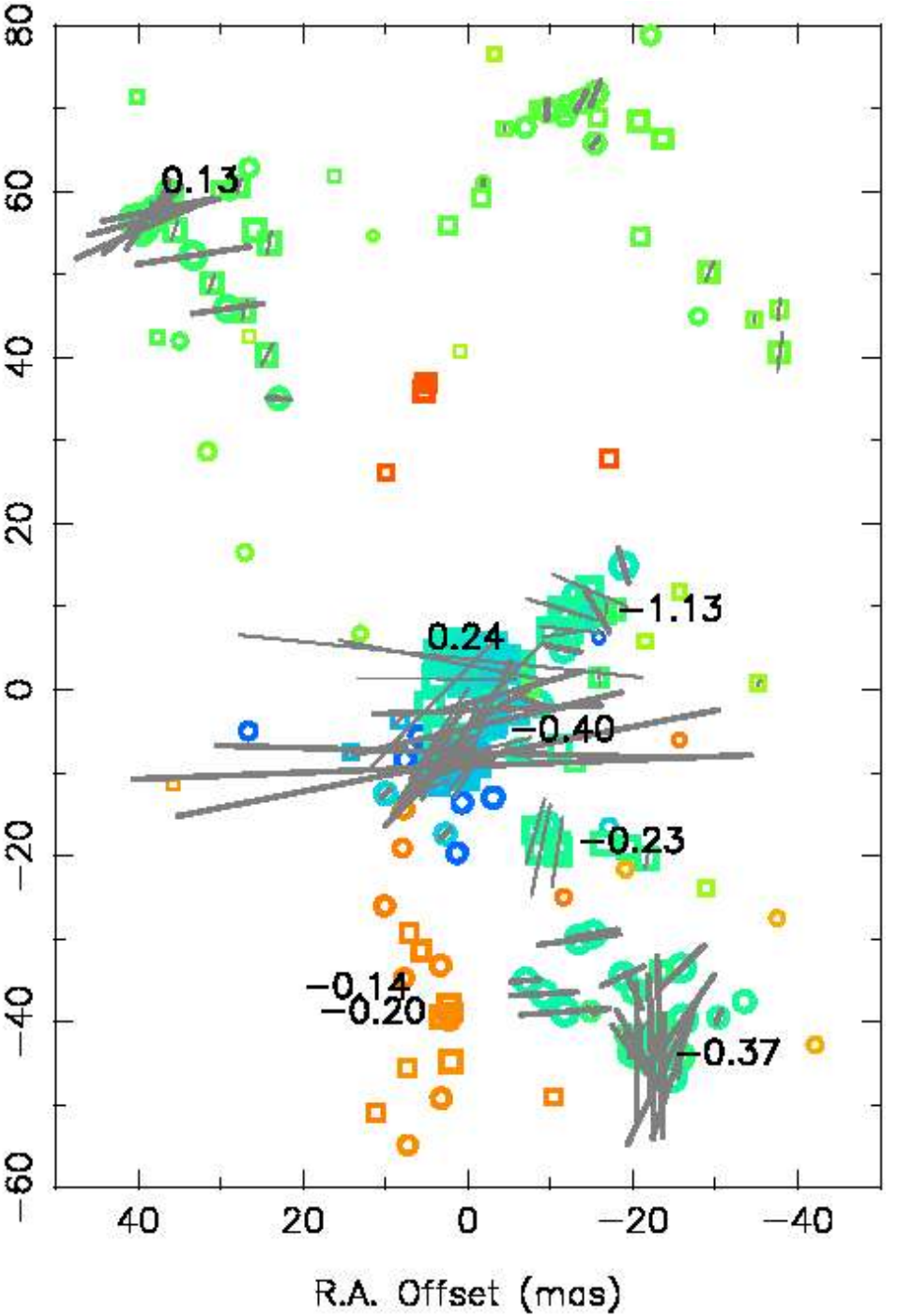


- 1999 MERLIN
- OH 1612 MHz
  - Axisymmetry for several centuries
- Box shows H_2O/ mainline OH region

- O/□ 1665/7 MHz
  - Similar shape
  - Different velocities along limbs

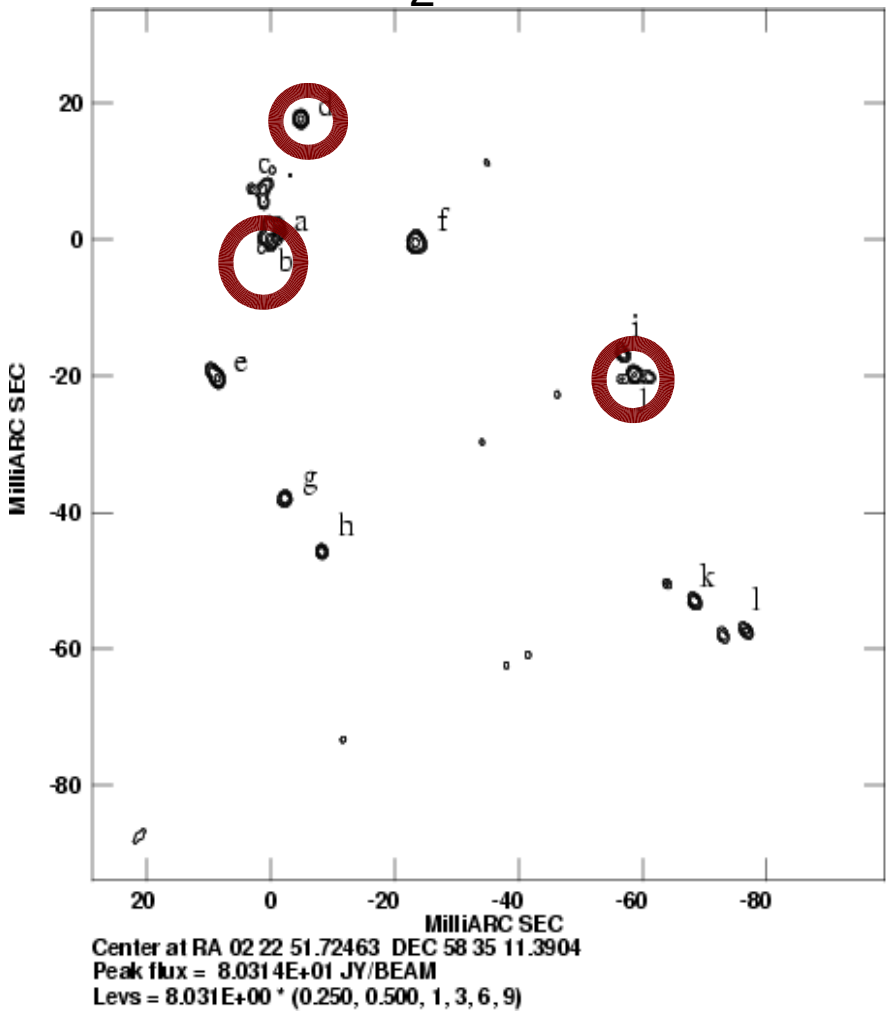
S Per OH Mainline polarization

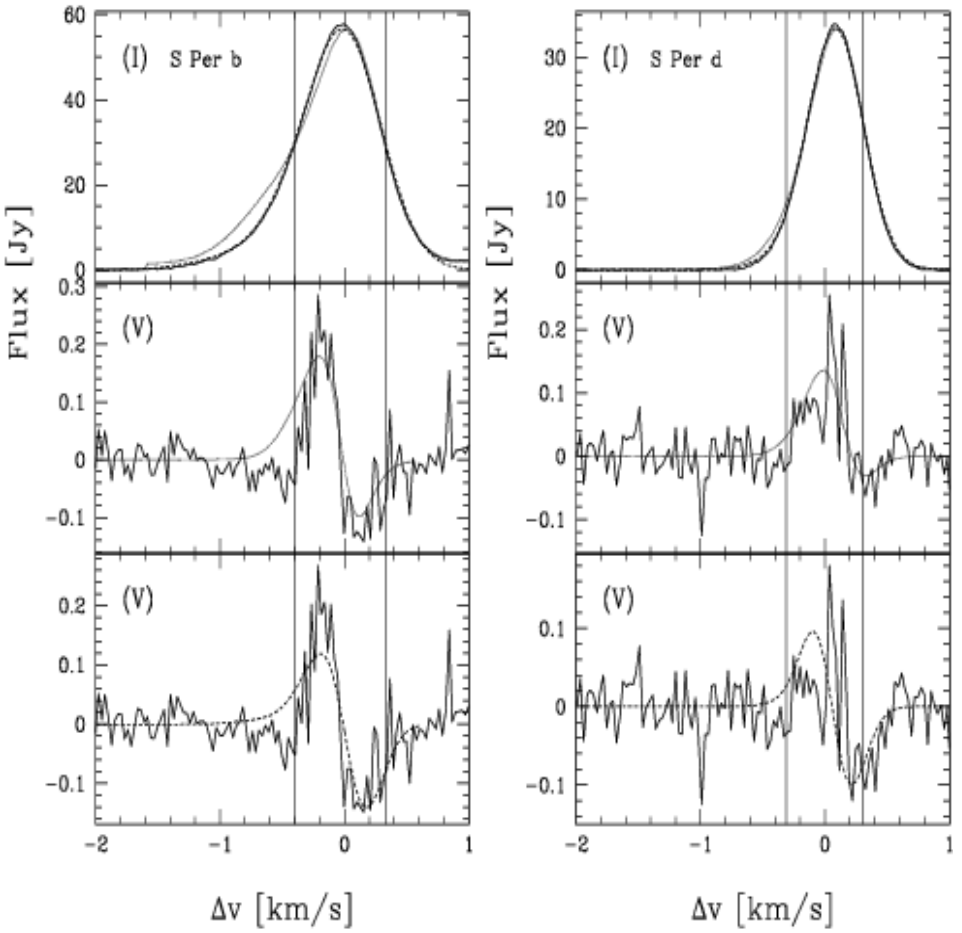
- Circular polarization ⇒ $\underline{B}_{\parallel}$
  - Strength in μT
    - mean 0.3 μT
  - Consistent with NNE - SSW dipole, S approaching
- Linear polarization vector at PolA
  - If θ > 55°, PolA ∥ $\underline{B}_{\perp}$
  - else PolA ⊥ $\underline{B}_{\perp}$
  - Δ_{PolA} typically 16° per clump
    - Faraday rotation?
    - Fractional ionisaton $\leq \sim 10^{-6}$
  - Linear pol seen from near side only
    - Pol. from far side scrambled?
- But conflicting theories
  - Inferred $\underline{B}_{\parallel}$ strength
  - PolA varies with path length
  - ISM Faraday rotation



H_2O Zeeman splitting

- S Per VLBA (*Vlemming, Diamond & van Langevelde 02*)
- $B_{||}$ 7 - 20 μT (70- 200 mG) (model-dependent)
- Brightest H_2O masers @ *R*~90 au (2.3 kpc) - take *B* ~15 μT

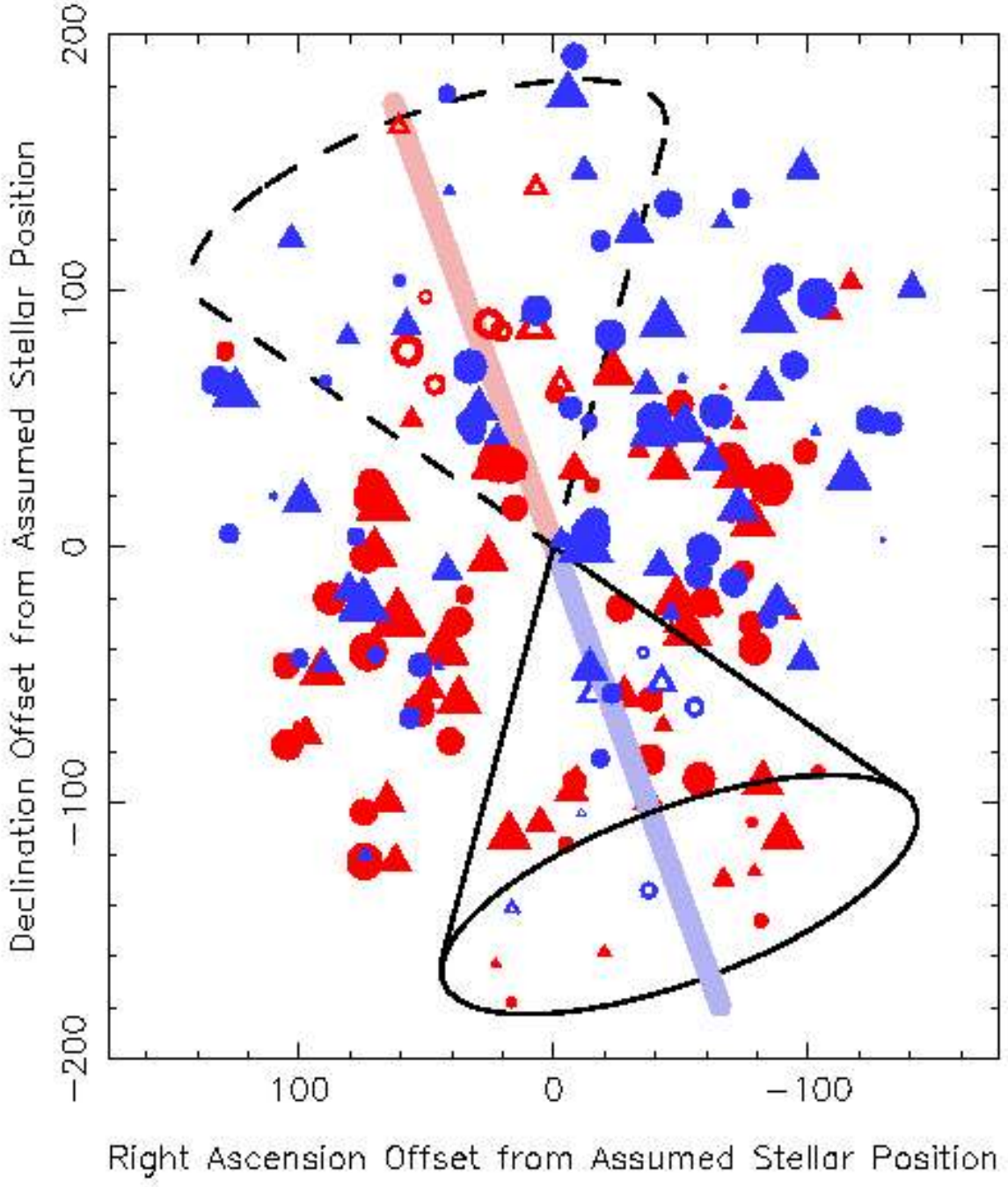




S Per magnetic field $B_{H2O} >> B_{OH}$

- OH mainlines *B* ~0.3 μT at up to 140 au
- H_2O *B* ~ 15 μT at ~90 au (brightest masers)
- Stretched dipole? $B \propto R^{-2}$, expect 6 μT @ 140 au
  - 6 μT would split OH by~18-30 km/s; aligments ambiguous
- Selection effect?
  - Only strongest/weakest splitting detectable in H_2O/OH?
- H_2O clumps ~50x denser than OH gas (*Richards+ 99*)
  - Frozen-in $B \propto n^{\sim 0.3 - 0.5}$ (*Mouschouvias 87*)
    - $n \propto R^{-2 - -3}$ (no/strong acceleration) so frozen-in $B \propto R^{-1 - -1.5}$
    - $B(H_2O)$ @ R_i ~30μT where *B*(OH) would be ~4μT
- Extrapolate to 140 au (stretched dipole) *B*(OH) ~0.6 μT
  - This implies clump *B* >> inter-clump *B* after dust forms
  - Precursors of water maser clumps already denser?

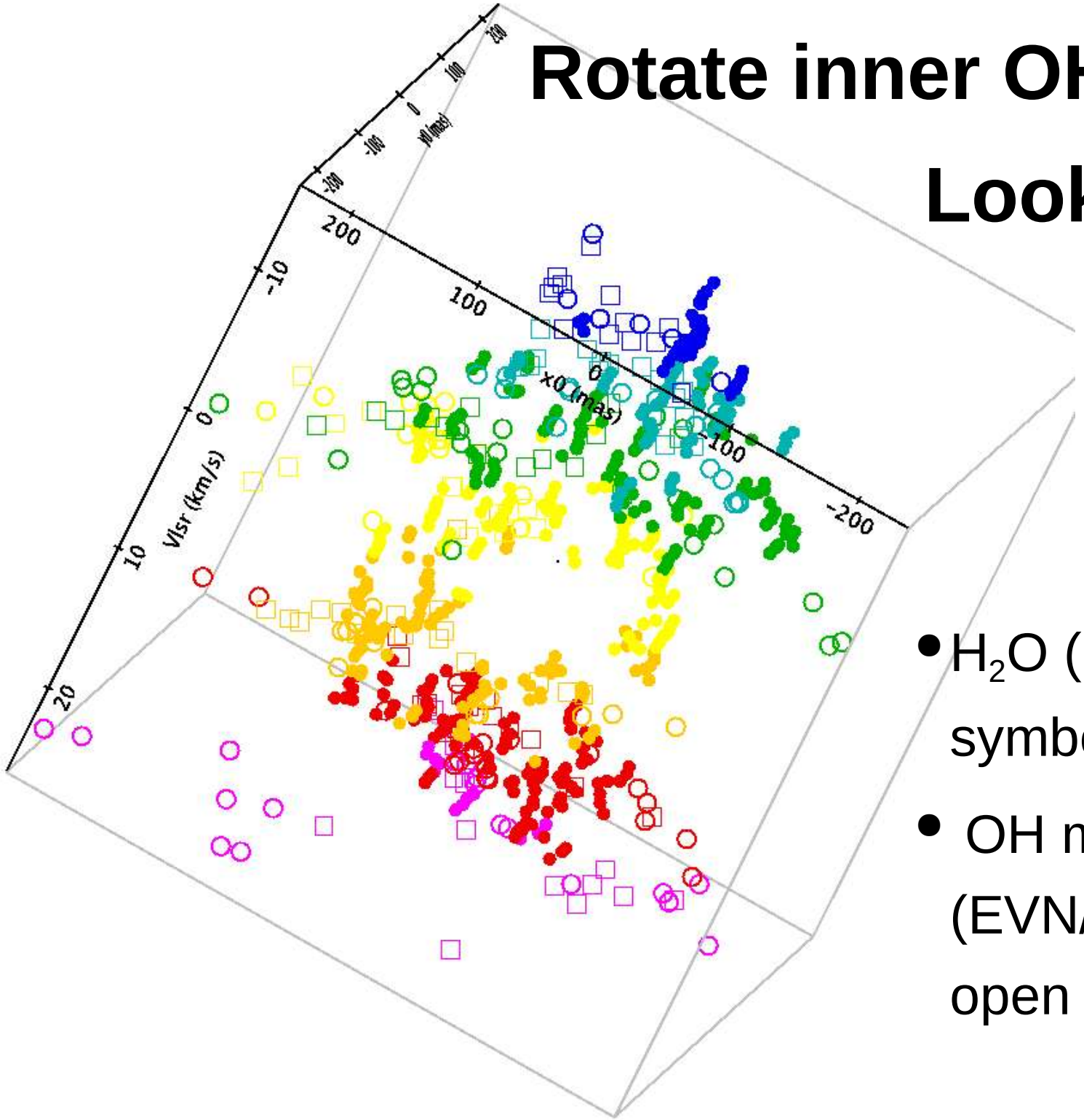
VX Sgr OH/H_2O axisymmetry



- H_2O kinematic axis *(Murakawa et al.)*
- OH 1612 dipole *(Szymczak et al.)*
- H_2O magnetic axis *(Vlemmings et al.)*

Rotate inner OH/H_2O cube

Look down axis

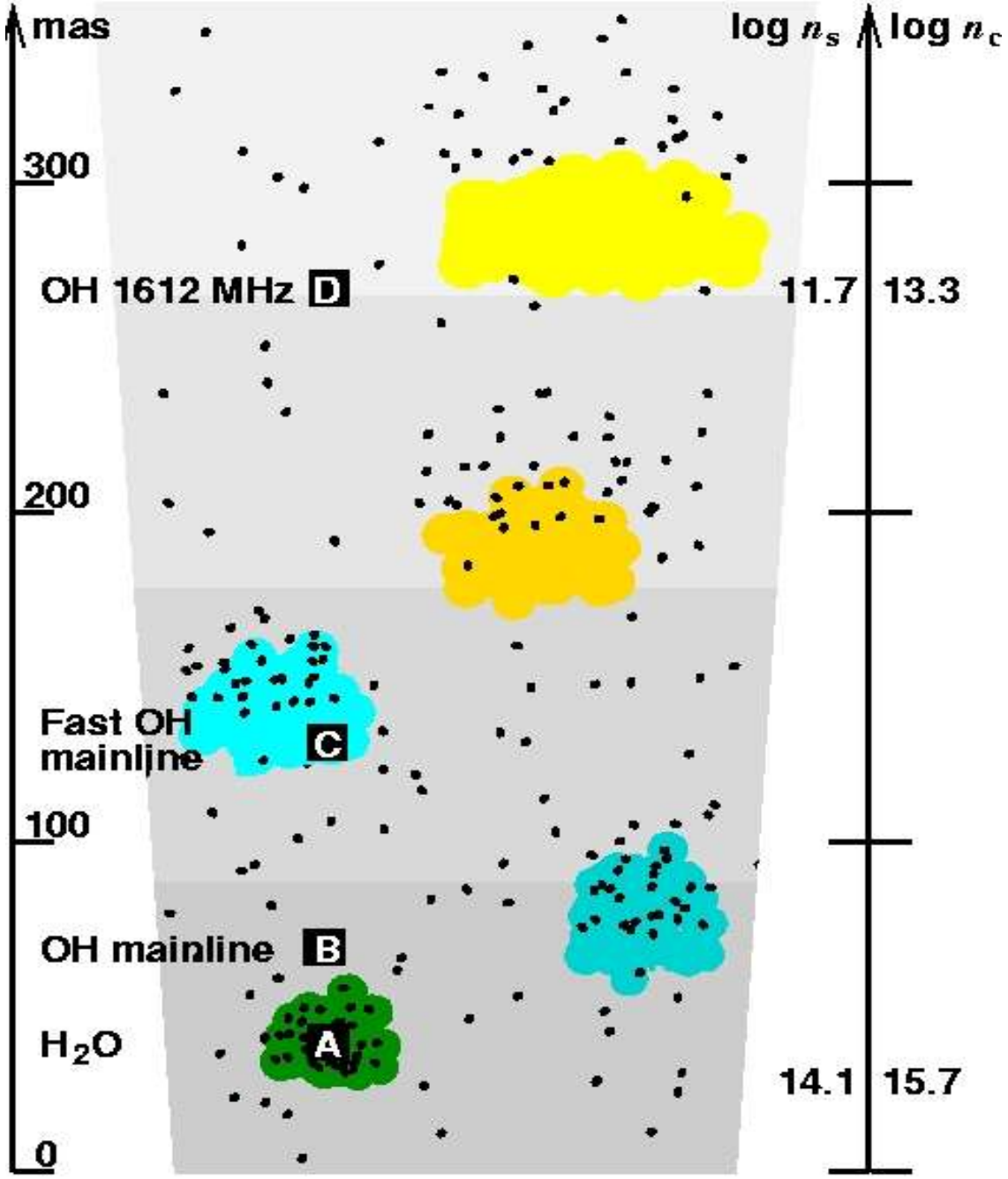


- H_2O (MERLIN) solid symbols
- OH mainlines (EVN/Global VLBI) open symbols

Evidence for density-bounded clumps

- Water maser clouds dusty, rapidly accelerated
  - Cloud diameters can exceed several ΔV_{th}, maser gain lengths
  - Water maser clouds over-dense: $n_{(H2O\ cloud)}$ ~50x $n_{(OH\ gas)}$
    - Also required for OH maser pumping schemes
  - Direct measurement of spot size and beaming angle
    - Most H_2O maser clouds ~spherical, a few shocks
- Masing lifetimes < cloud lifetimes (shell crossing time)
- $B_{OH} \sim 0.05 B_{H2O}$ at same distance from star
  - Frozen-in $B \propto n^{\sim 0.3 - 0.5}$ (*Mouschouvias 87*)
- 'True' sizes measured across multiple spectral channels
- $\langle R_{(H2O\ clouds)} \rangle$ & shell size $\propto R_\star$ ($R_{RSG} \geq 10x\ R_{AGB}$)
  - Contrast e.g. P, V_{exp} only vary by factors of a few
- **Cloud size determined by $M_\star$ not micro-physics**

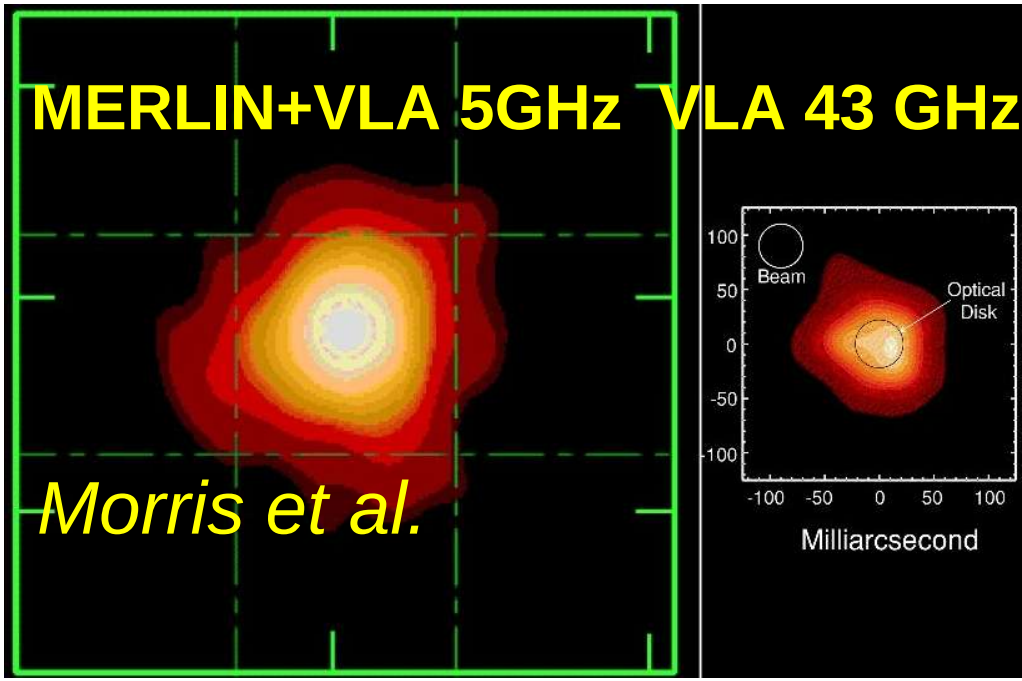
Summary



- H_2O clumps dustier, better accelerated, frozen fields?
  - Tends to tangential beaming
  - 30 - 300 x mean wind *n*
- Interleaving gas supports OH mainlines near star
  - Mixed, mainly radial beaming
- OH 1612 further out
  - Needs ~steady velocity
  - Radial beaming
- Some H_2O & OH mainlines reach high velocities
- Can overshoot OH 1612
  - At different latitudes?

Mass loss from the stellar surface

- α Ori lumpy, aspherical
- RSG clouds 5-10% $R_{\star}$ at birth
  - Star spots?
  - Chemical inhomogeneity?
  - Convection cells?
- *e*-MERLIN, eVLBI
  - Up to 2 GHz b/w
  - μJy continuum - stars, cals
  - 100's km/s b/w
  - <0.1 km/s chans (Zeeman)



- Resolve even cooler RSG/AGB - convection cells?
  - *e*-MERLIN, eVLBI, EVLA
- SiO masers @ 2-4 $R_{\star}$ with VERA/VLBA (CMA?)
- Track the dust as it forms with ALMA
- Water masers @ 5-50 $R_{\star}$, OH masers @ 10-500+ $R_{\star}$
  - *e*-MERLIN for all the flux, VLBI for rapid proper motions