Maser Misto

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with thanks to

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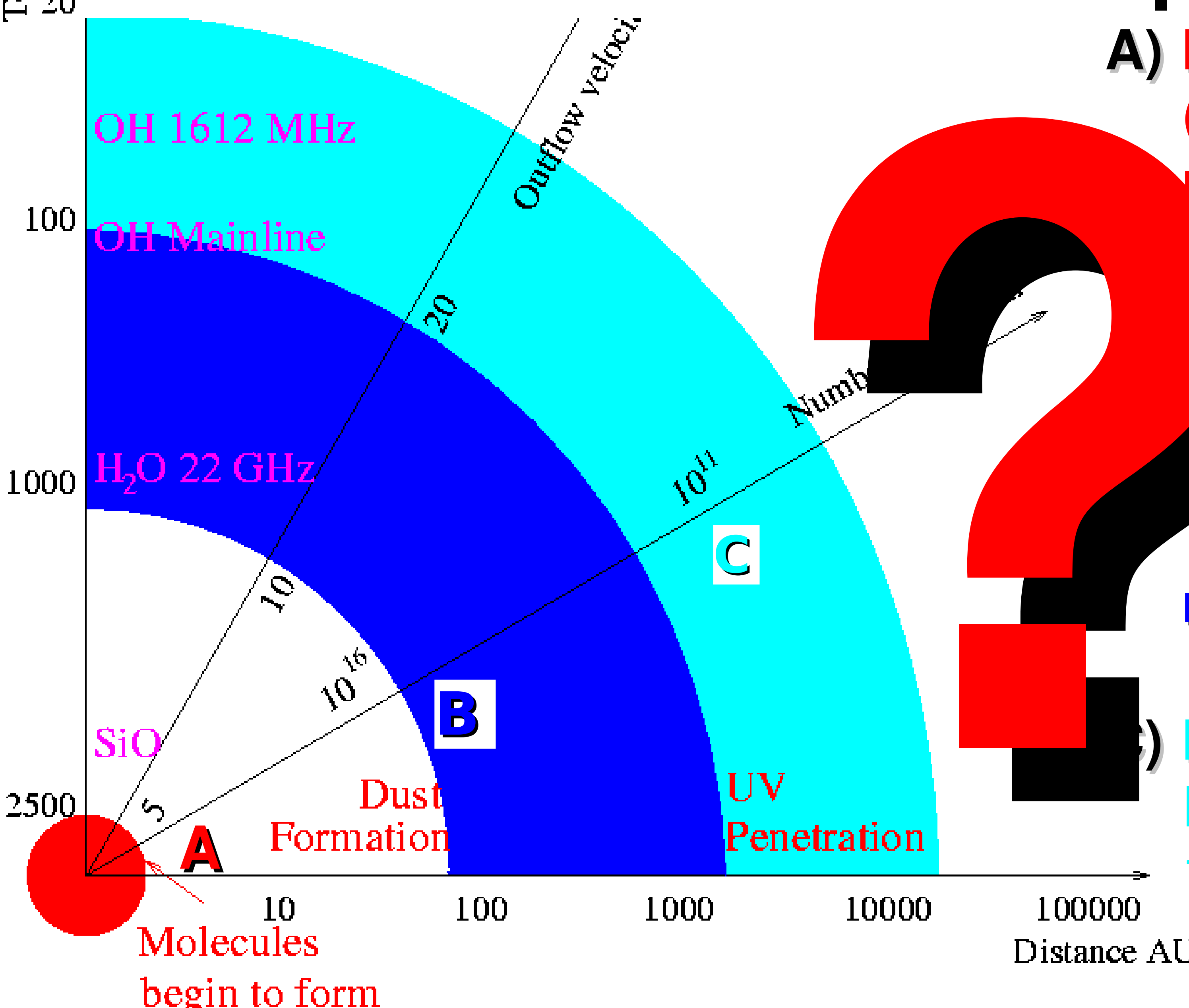
- **Traditional circumstellar envelope model**
  - **Maser segregation in shells**
- **Red Supergiant deviants**
  - **Maser segregation in clumps**
  - **Role of star v. local microphysics**
- **What about AGB stars?**
  - **New EVN+MERLIN results**
- **Why don't all OH1665-7/H_2O masers overlap?**
  - **Beware transience, asphericity ...**
- **Unsolved problems - *e*-MERLIN legacy, EVN**

'Onion shell' model for O-rich Circumstellar Envelopes

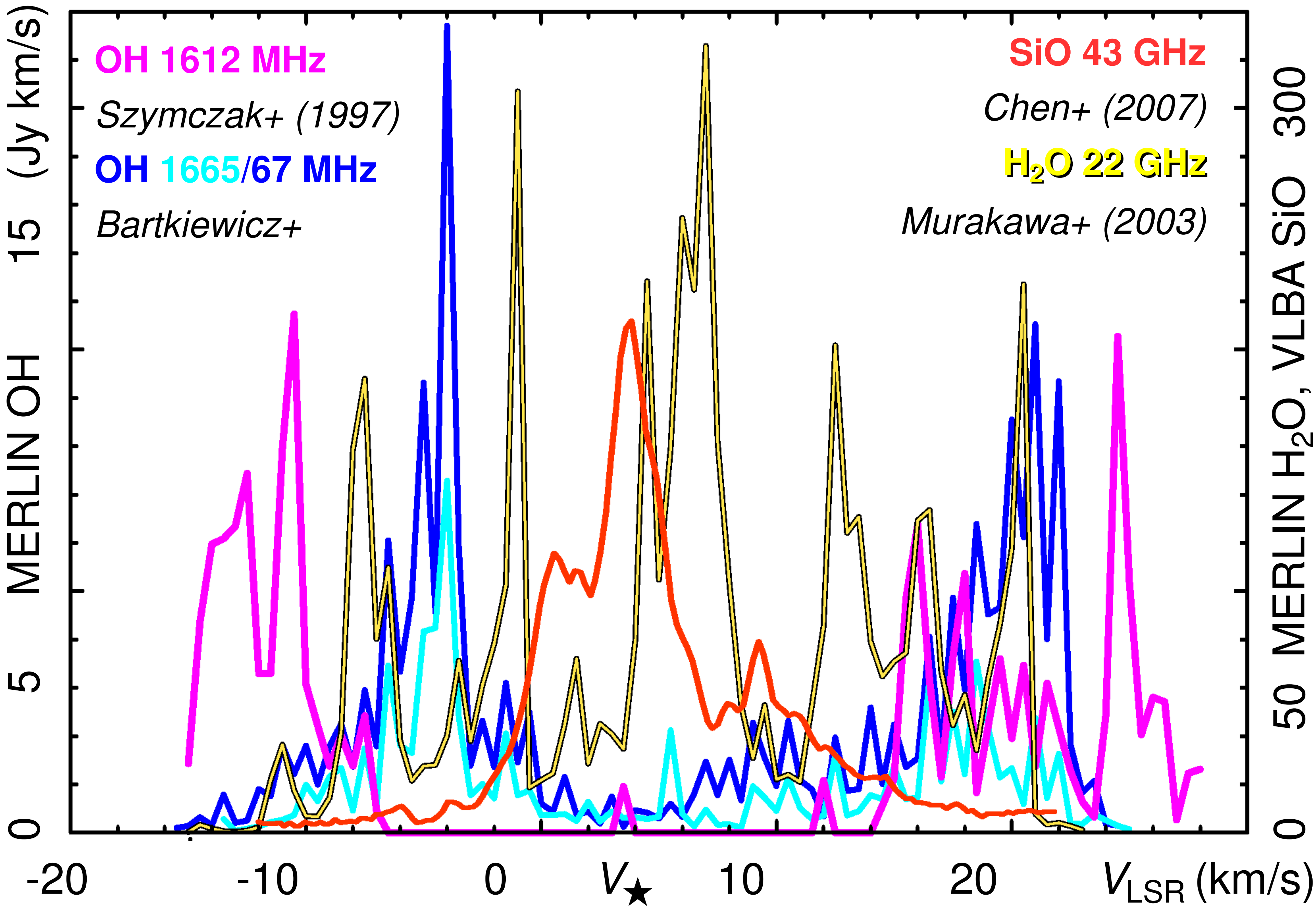


A) Form molecules (SiO, H_2O etc.) at high-n close to otosphere

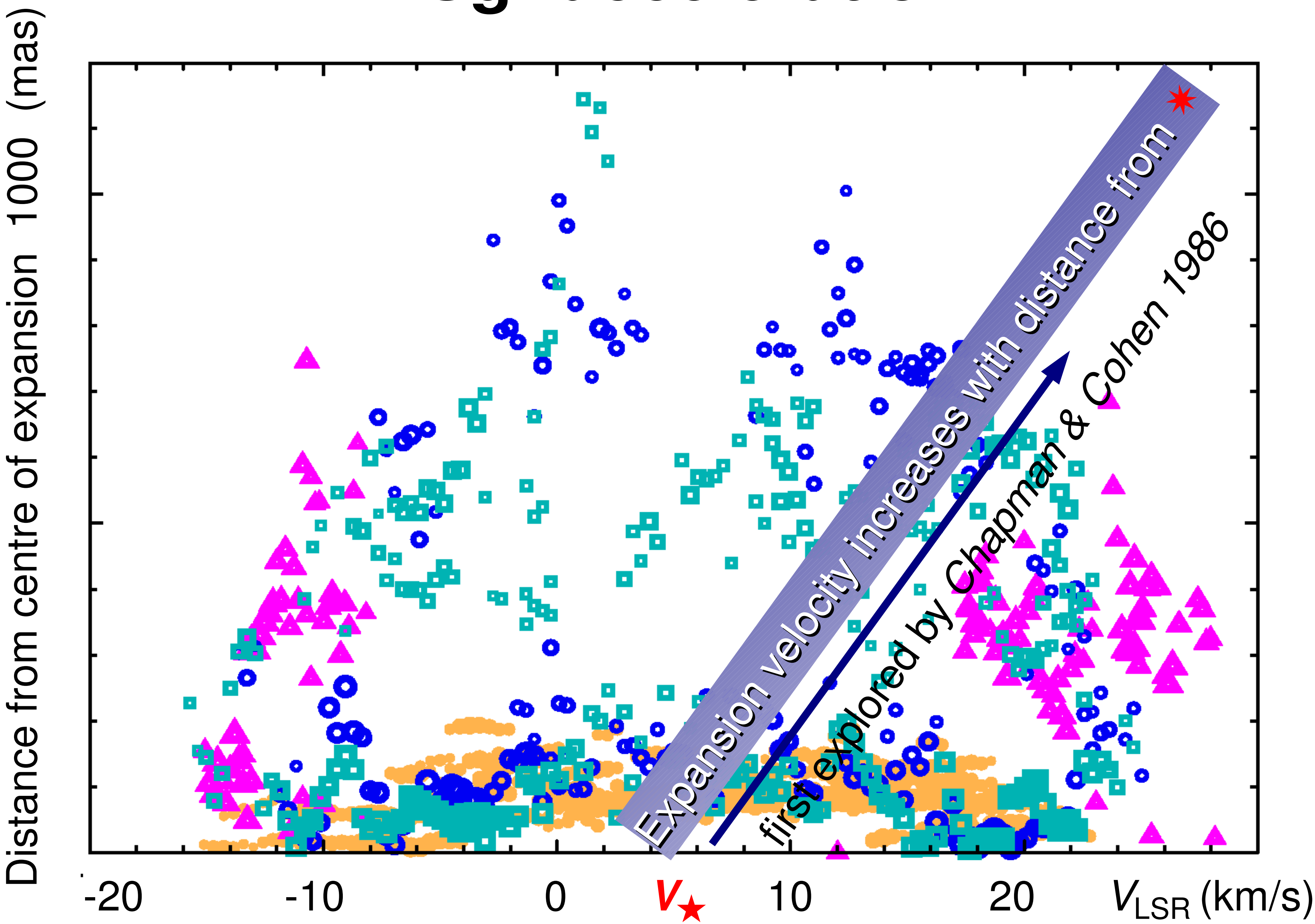
ins reach al size at ~5 $R_\star$ just inside H_2O maser shell

) Dissociation by IS UV at a few 100 $R_\star$ forms OH

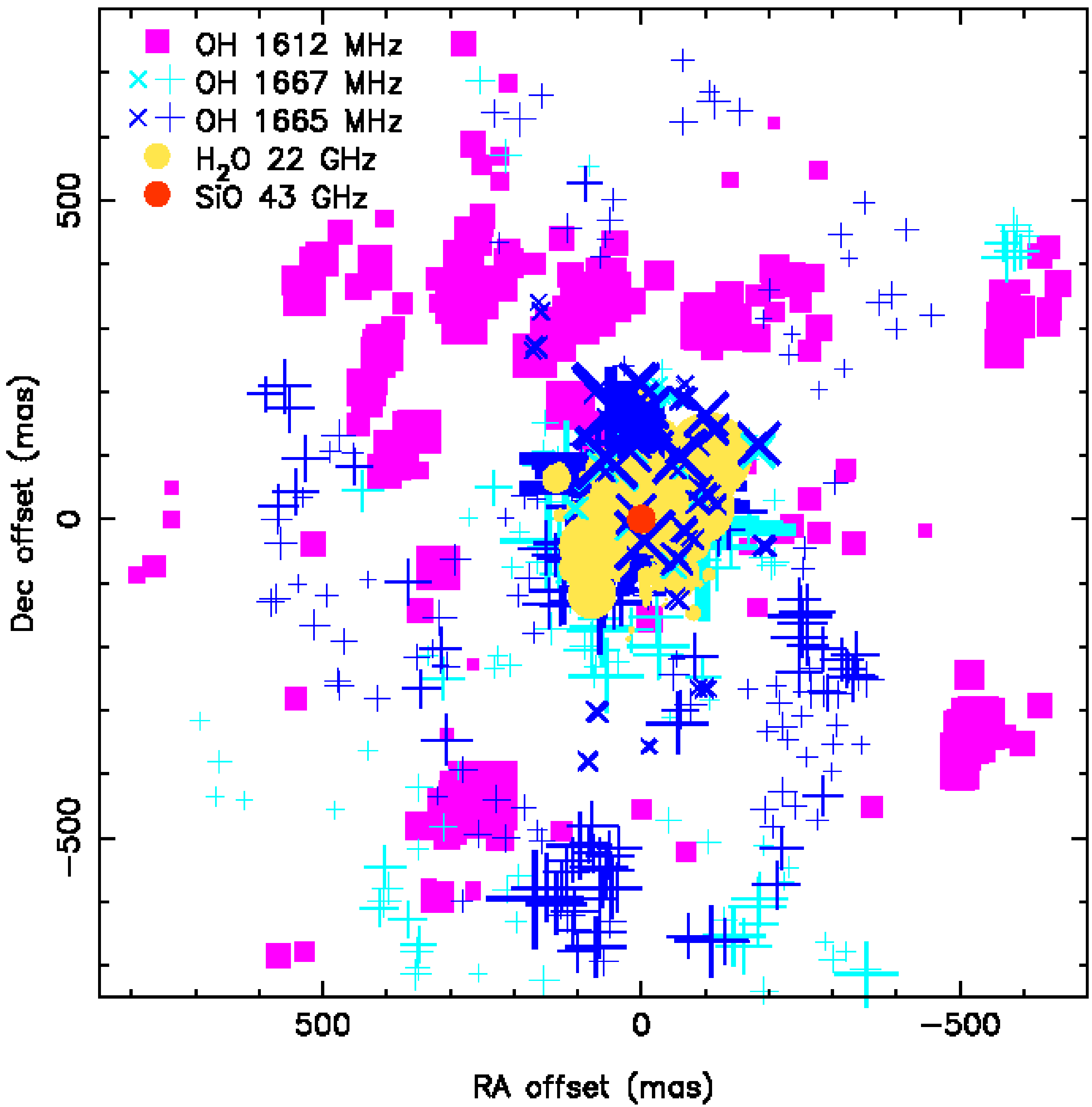
VX Sgr velocity profiles



VX Sgr acceleration

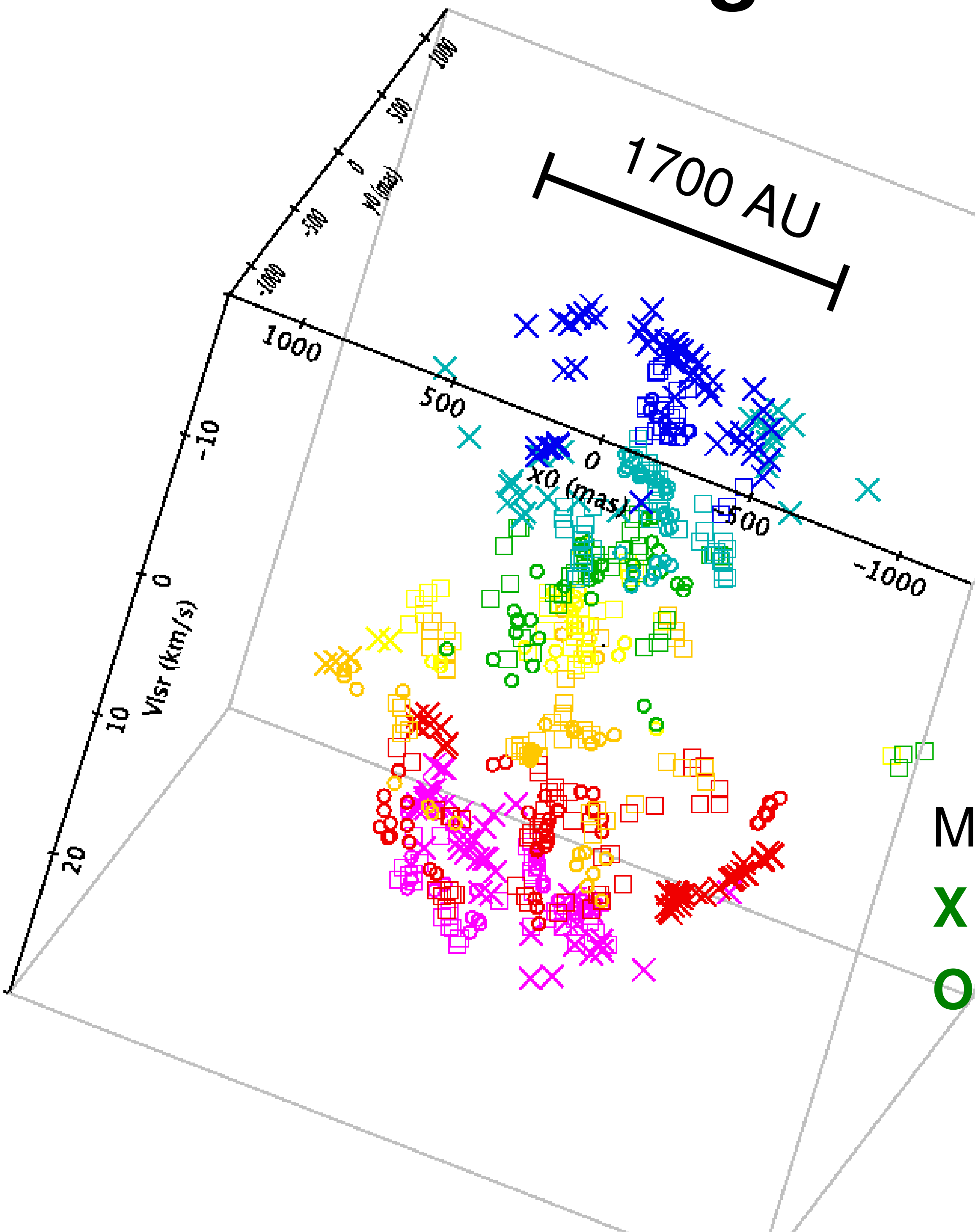


VX Sgr masers at mas resolution



- OH 1612 MHz masers at 800-2000 au (65-170 $R_\star$)
- H_2O masers at 95-325 au (8-27 $R_\star$)
- SiO masers within 3 $R_\star$
- OH mainlines overlap H_2O and 1612 MHz

VX Sgr 3D model



- Measure V_{LSR} and angular position in orthogonal directions
  - Solve quartic equation including acceleration
  - Display and rotate us-ing VO tool TopCat

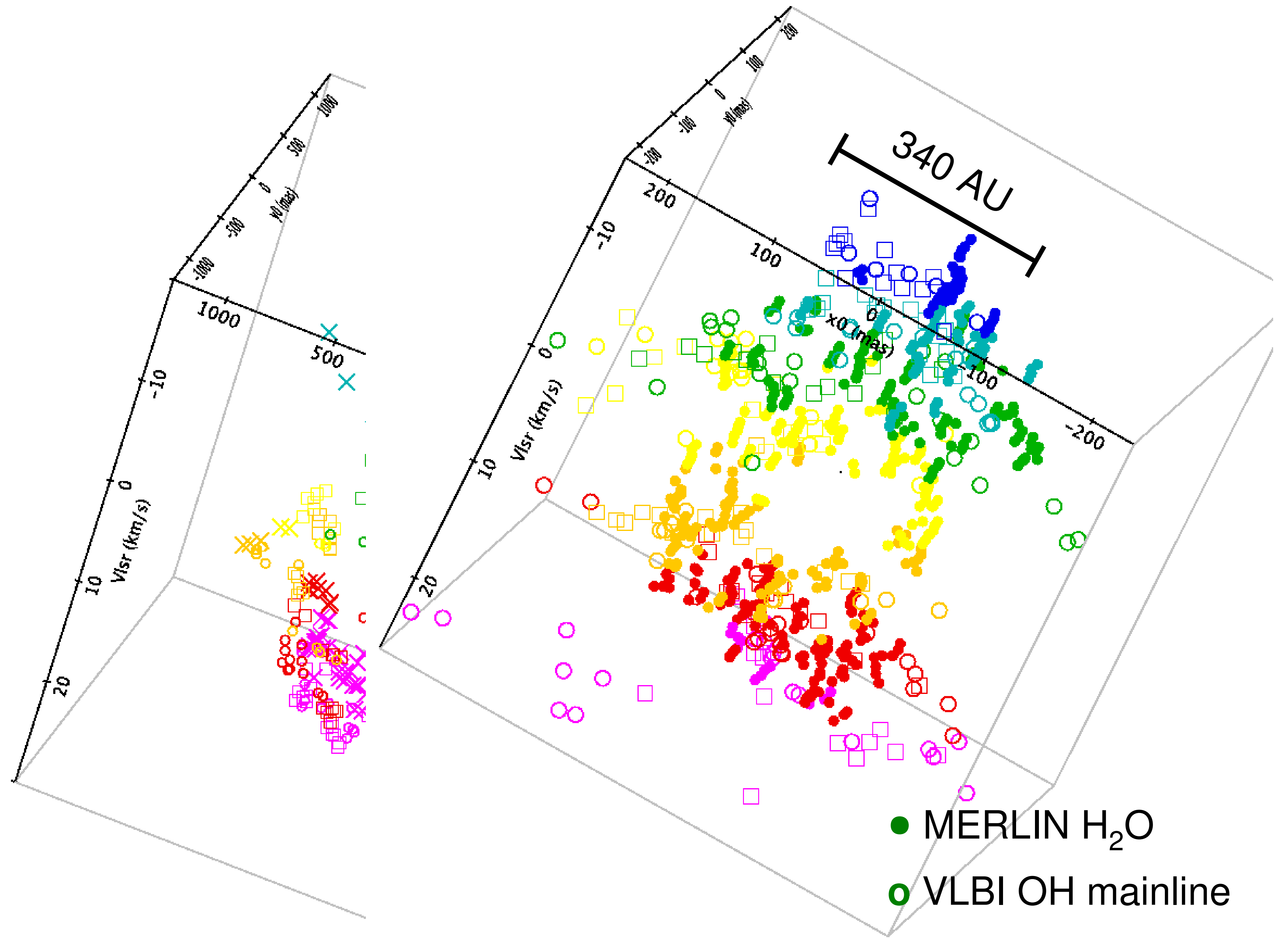
MERLIN

X 1612 MHz OH

O Mainline OH

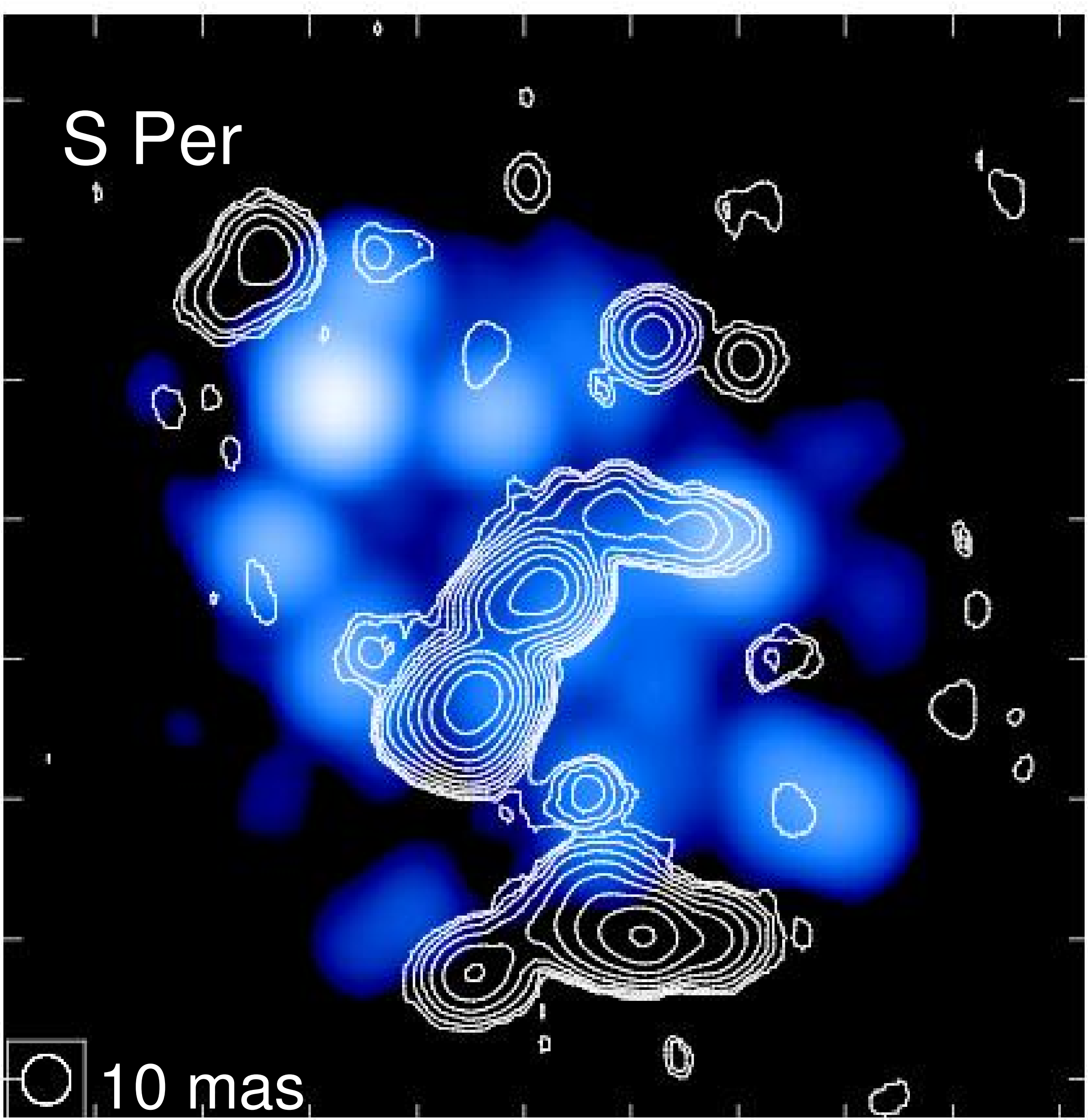
- MERLIN H_2O

o VLBI OH mainline



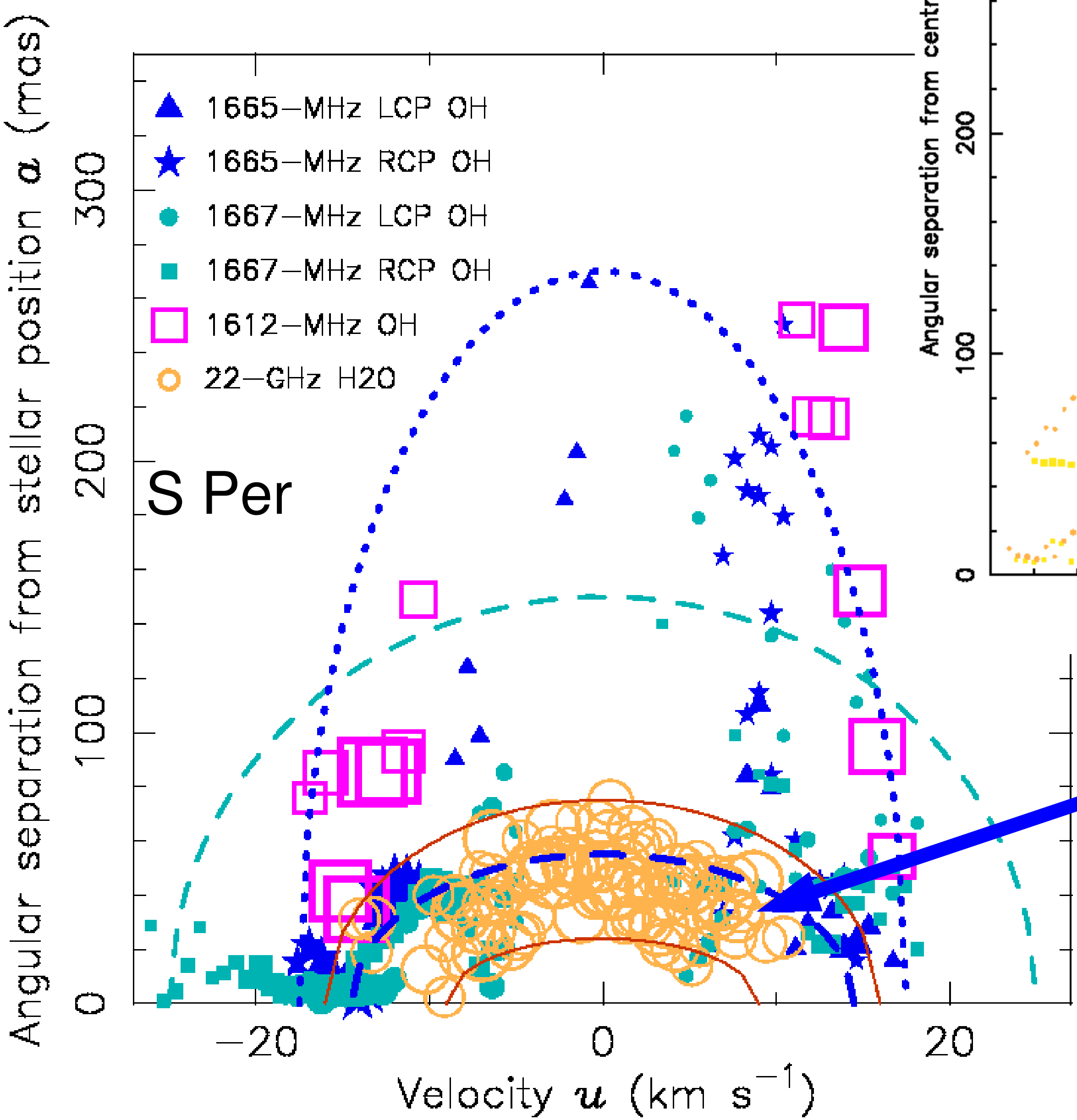
340 AU
MERLIN H_2O
VLBI OH mainline
Vlsr (km/s)
x0 (mas)
y0 (mas)

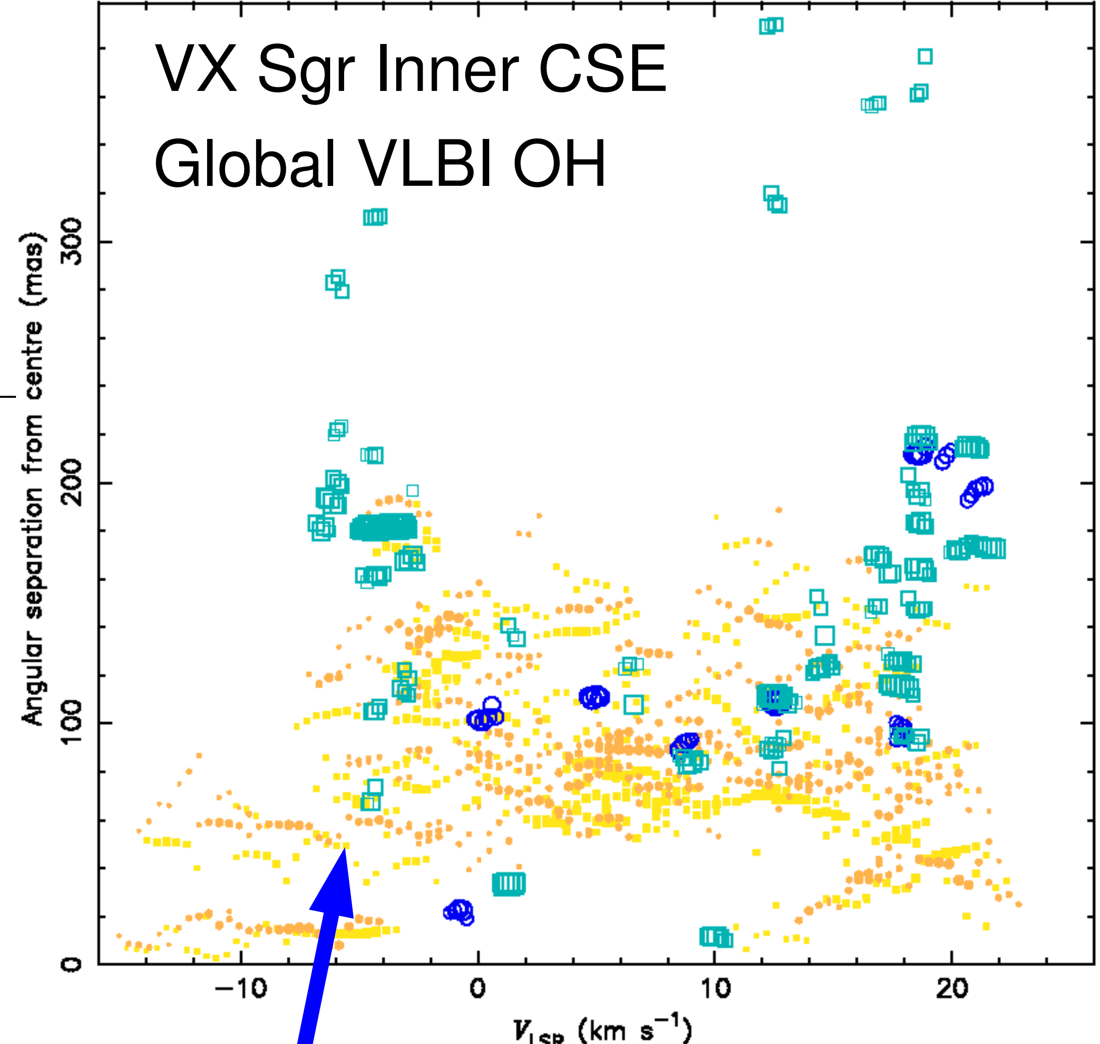
RSG OH mainlines interleave H_2O



- MERLIN H_2O (blue)
- EVN/global main-line OH (contours)
  - *Masheder et al.*
- OH mainlines inter-leave H_2O
  - Near-by, but not identical distribution
- Only ground-state OH detected
  - T_{OH}~500 K max?
  - T_{H2O} ~1000 K ?

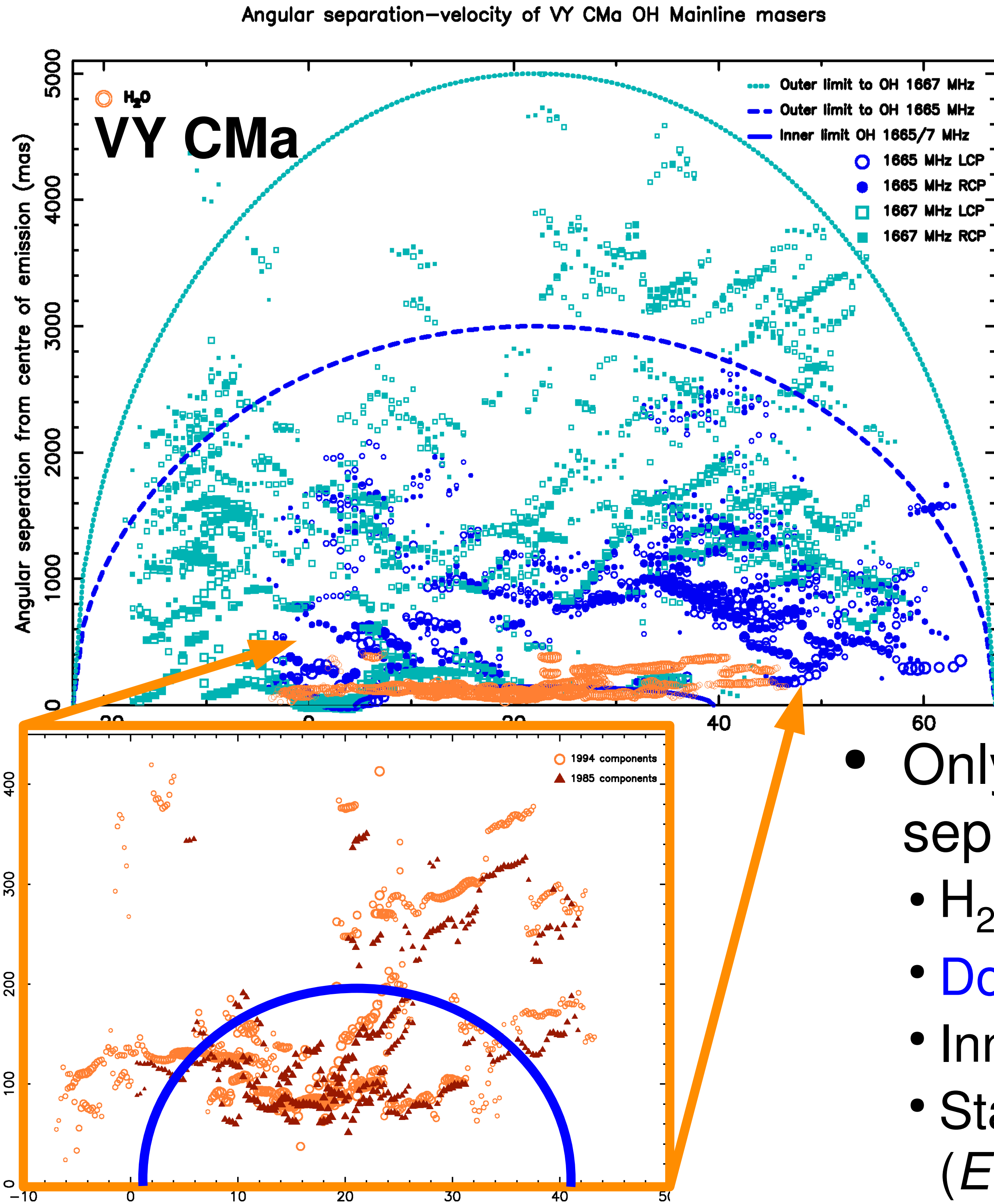
RSG overlapping maser shells





- OH reaches >25 km/s
  - *Inner OH mainlines overlap H_2O !!*
- VX Sgr similar
  - *Double OH mainline shells*

3/4 RSG overlap

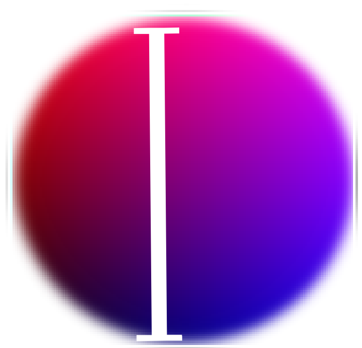


- **VY CMa** OH 1667 (& 1612) MHz shell huge
  - v_o **>40 km/s**
  - r_o **>7000 AU**
- **H_2O overlaps OH r_i**
- Only **NML Cyg** shells are well-separated
  - H_2O and OH bipolar
  - Double OH mainline shell
  - Inner shell faster
  - Star 'recently' got brighter? (*Etoka & Diamond 03*)

Measuring 'true' maser cloud size

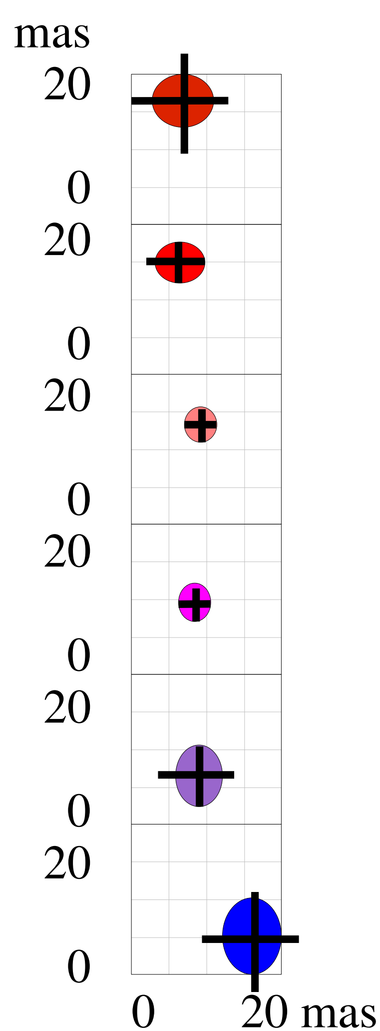
Cloud properties

Cloud *D*=18 AU at 1 kpc

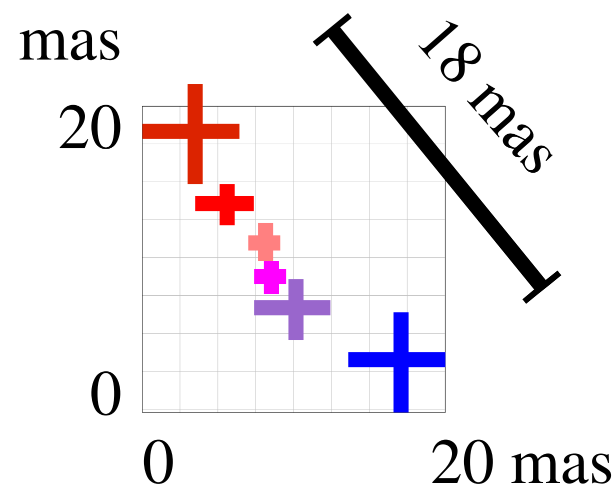


1.2 km/s total line width

Channel maps every 0.2 km s^{-1}



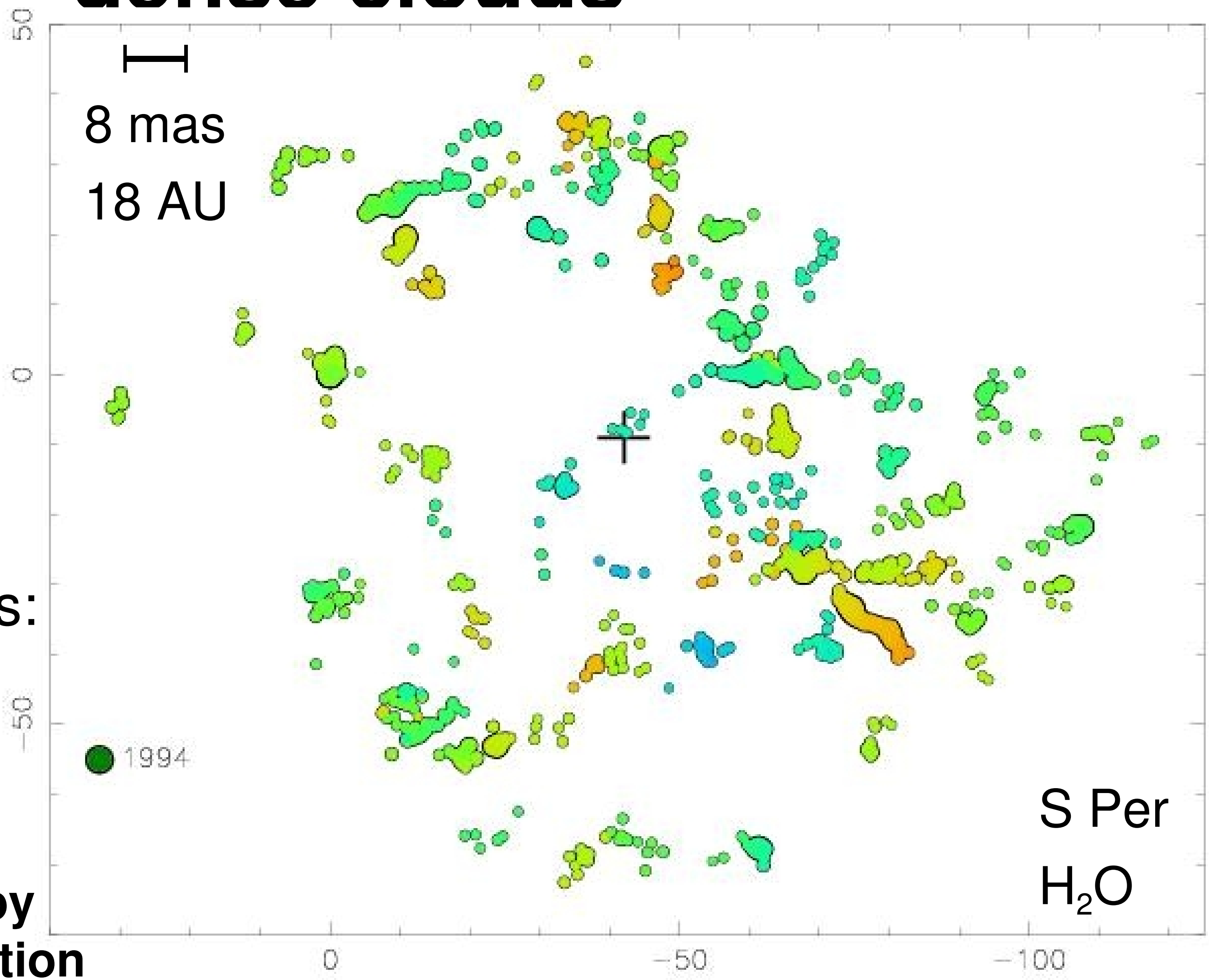
Component measurements



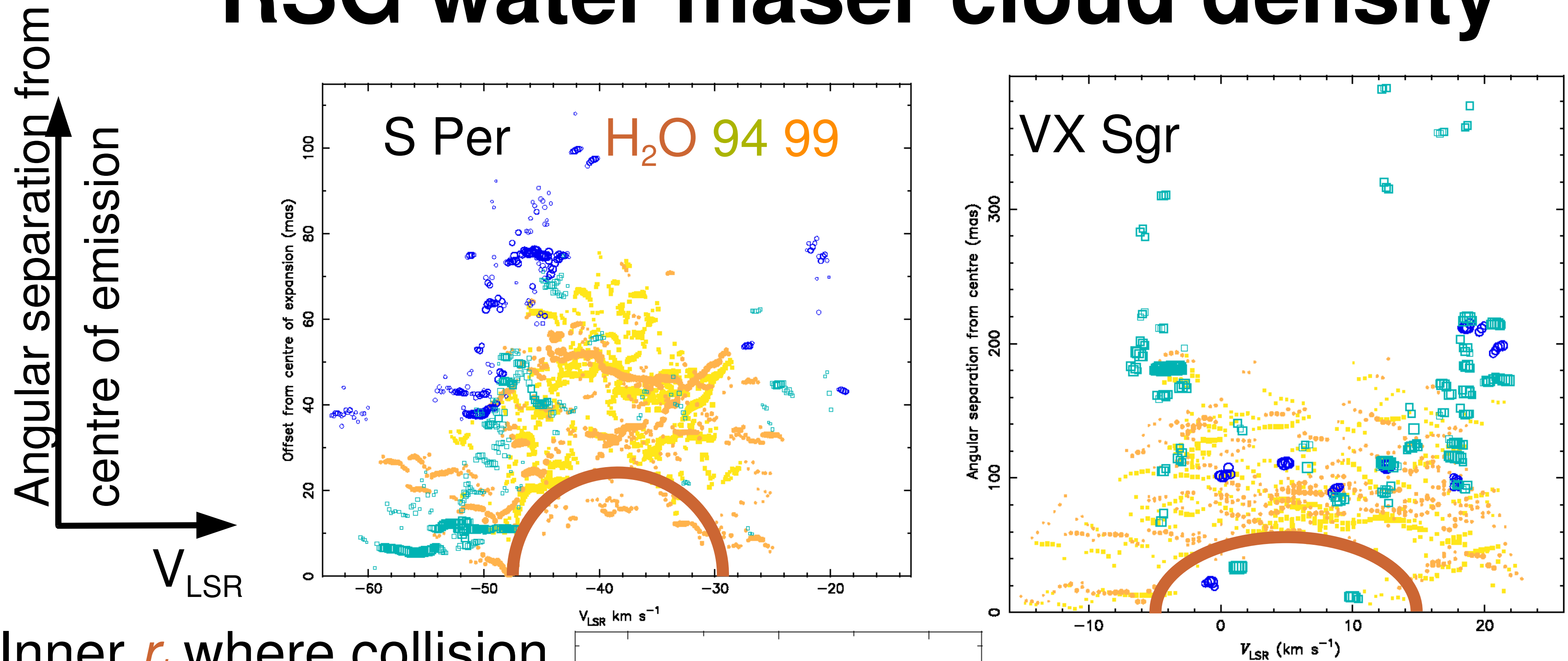
Largest angular separation *across all channels* is *actual* cloud size (18±5 mas)
(to limits of sensitivity)

Water masers concentrated in dense clouds

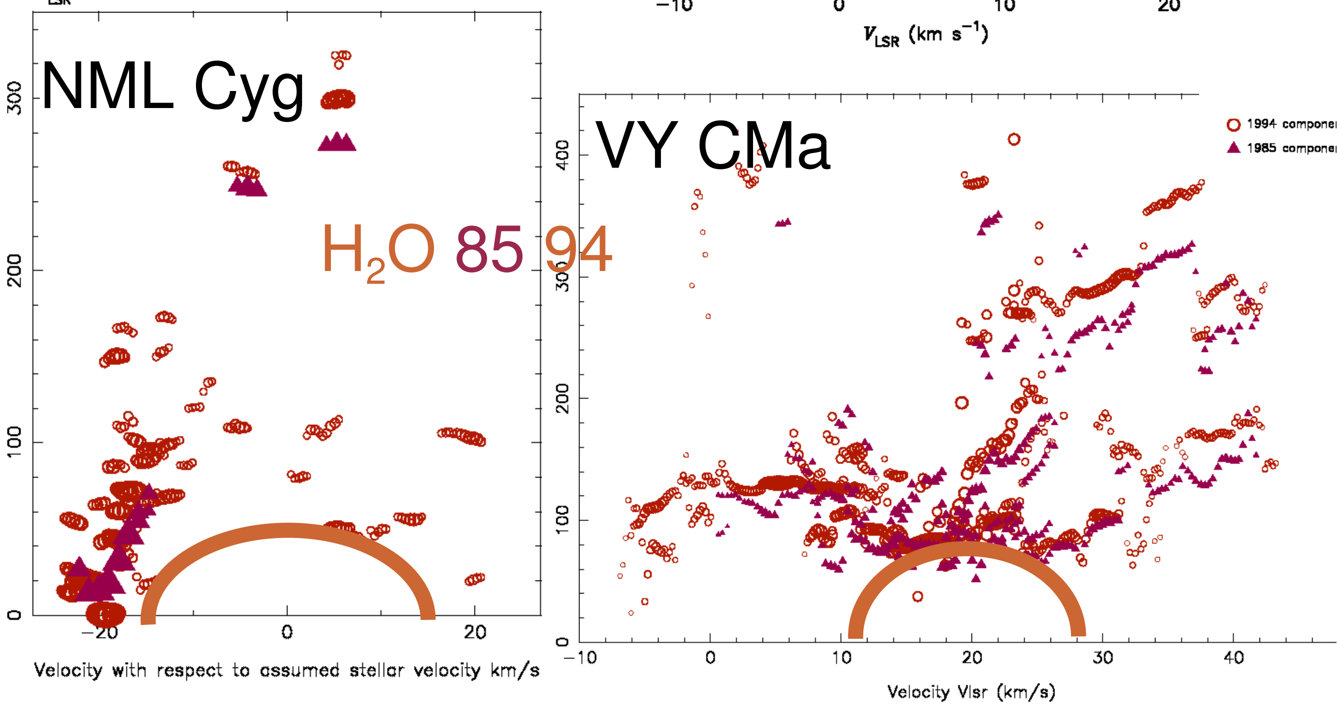
- Masers span 1-2 km/s, few mas
- Typical R_{cloud}:
  - AGB 1-2 AU
  - RSG 10-15 AU
    - $R_{\mathrm{cloud}} \propto R_{\star}$
    - **Cloud size set at stellar surface?**
- Many RSG clouds:
  - $2R_{\mathrm{cloud}}$ > maser gain length
  - $\Delta V_{\mathrm{cloud}} > \Delta V_{\mathrm{th}}$
    - **Clouds defined by density/composition**



RSG water maser cloud density



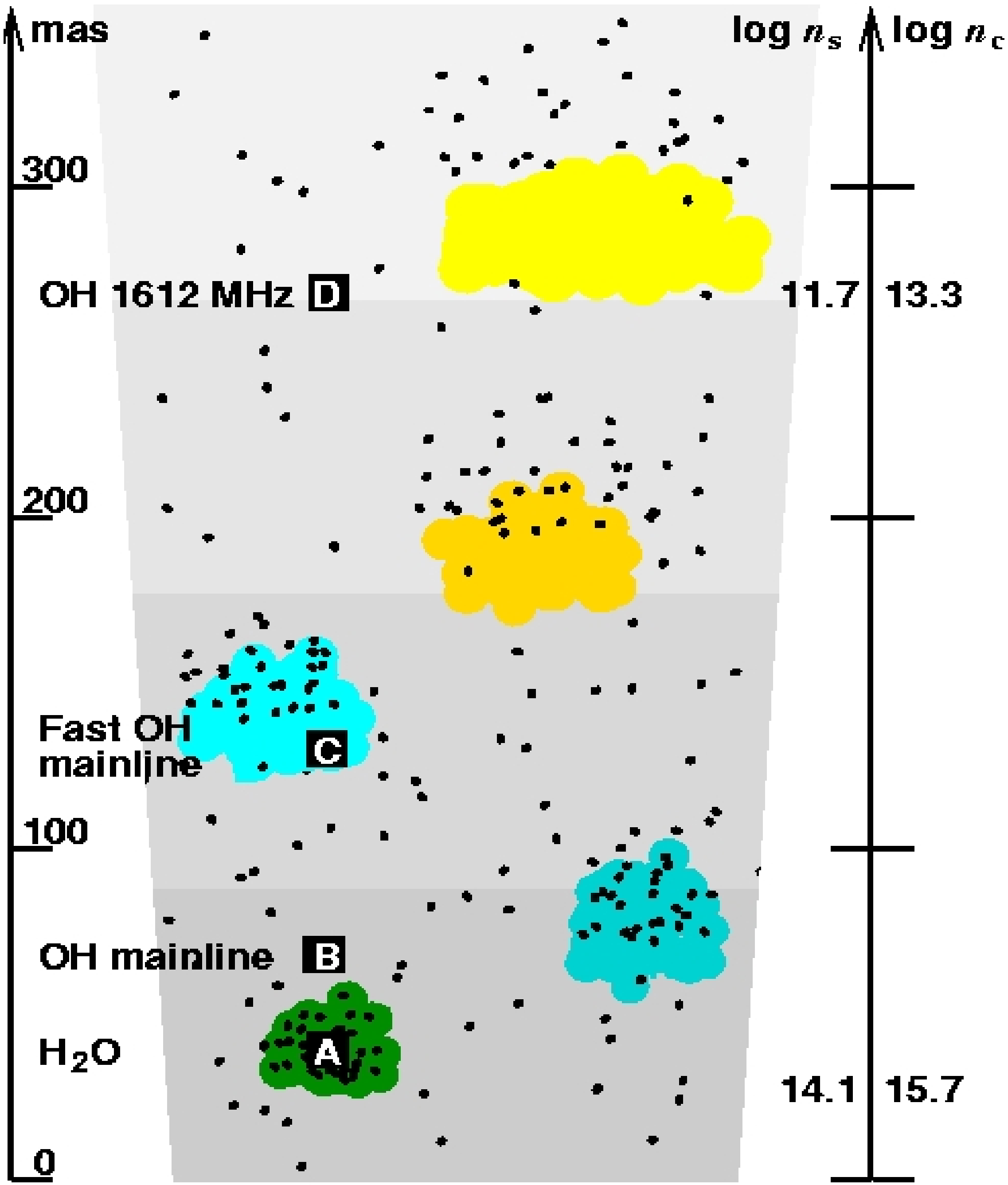
- Inner r_i where collision rate quenches maser (*Cooke&Elitzur 85*)
- $n_q(r_i)$ ~5x10^{15} m^{-3}
  - >>$n(r_i)$ $\dot{M}$(CO, IR)
  - H_2O clouds 10-100x overdense



Clumpy, inhomogenous CSE

- Water maser clouds dusty, rapidly accelerated
  - Require n [$5\text{x}10^{15}$, 10^{14}] m^{-3}, T [1300, 500] K (*Cooke & Elitzur*)
- Water maser clouds over-dense: $n_{\text{(H2O cloud)}}$ ~50x $n_{\text{(OH gas)}}$
  - Consistent with better acceleration, tangential beaming
- OH mainlines emanate from surrounding gas
  - Require $n < 10^{14}$ m^{-3}, T <500 K (*Gray*)
- *Over-dense, over-temperature clumps survive shell crossing times of decades (AGB stars)/a century (RSG)??*
- Water clumps have stronger magnetic field
  - B_{H2O} (*Vlemmings et al.*) ~5 x B_{OH} @ equivalent distance
    - Frozen-in $B \propto n^{\sim 0.3 - 0.5}$ (*Mouschouvias 87*)
- Cloud radius ~1 AU (AGB), 10 AU (RSG) (~$R_\star$)
  - Extrapolating to stellar surface would imply birth size ~0.1$R_\star$

More melon than onion?



A) H_2O clumps dustier, better accelerated
  - Tends to tangential beaming

B) Interleaving gas supports OH mainlines near star
  - Mixed, mainly radial beaming

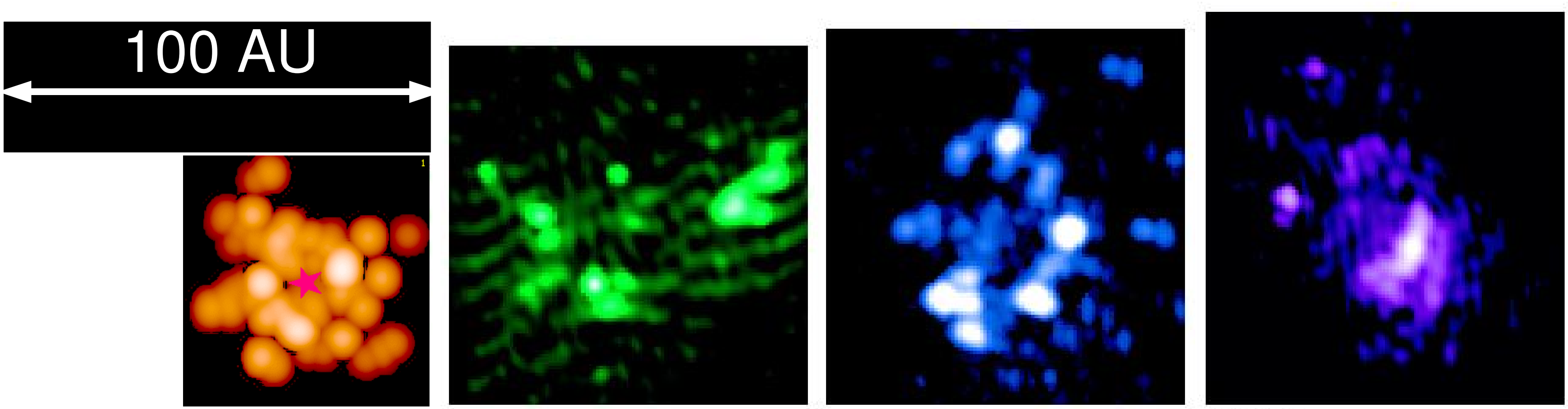
C) Some H_2O & OH mainlines reach high velocities
  - Can overshoot OH 1612
  - At different latitudes?

D) OH 1612 further out
  - Needs ~steady velocity
  - Radial beaming

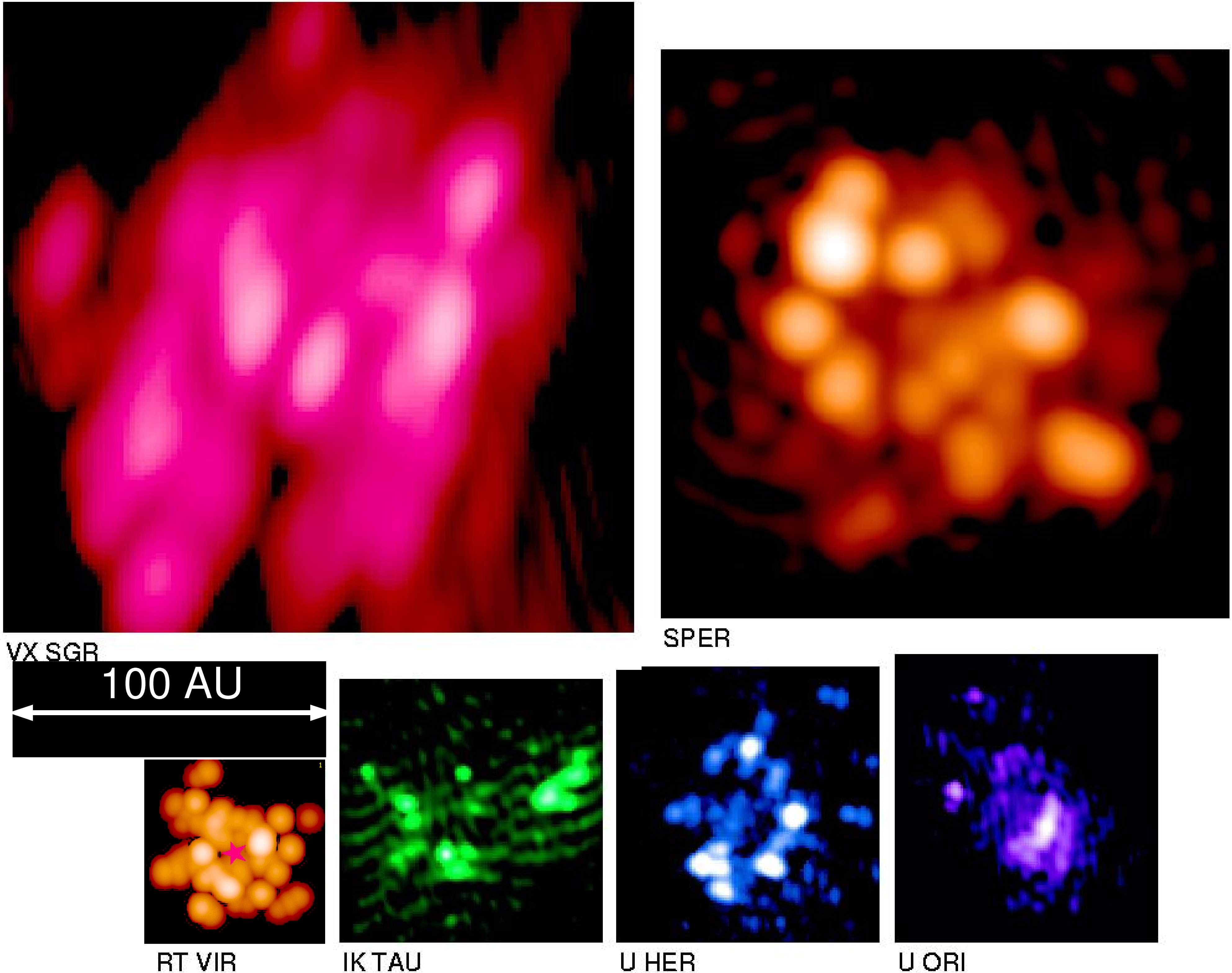
RSG and AGB

H_2O masers

- RSG $M_{\star} \gtrsim 10\ M_{\odot}$
  - End up as SNe
- AGB lower mass
  - Most end as PNe
- H_2O shell outer radii several tens of $R_{\star}$

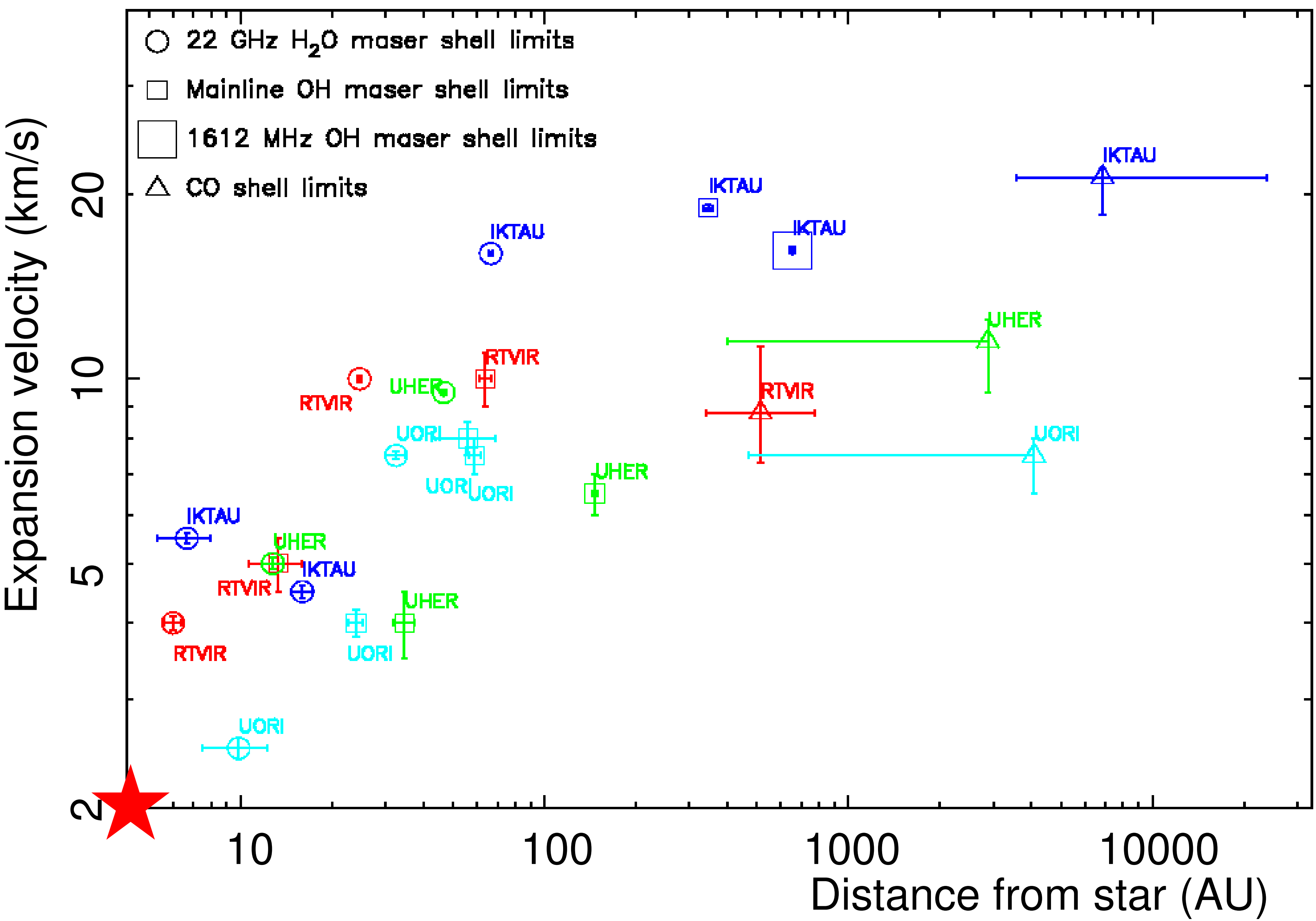


RT VIR IK TAU U HER U ORI



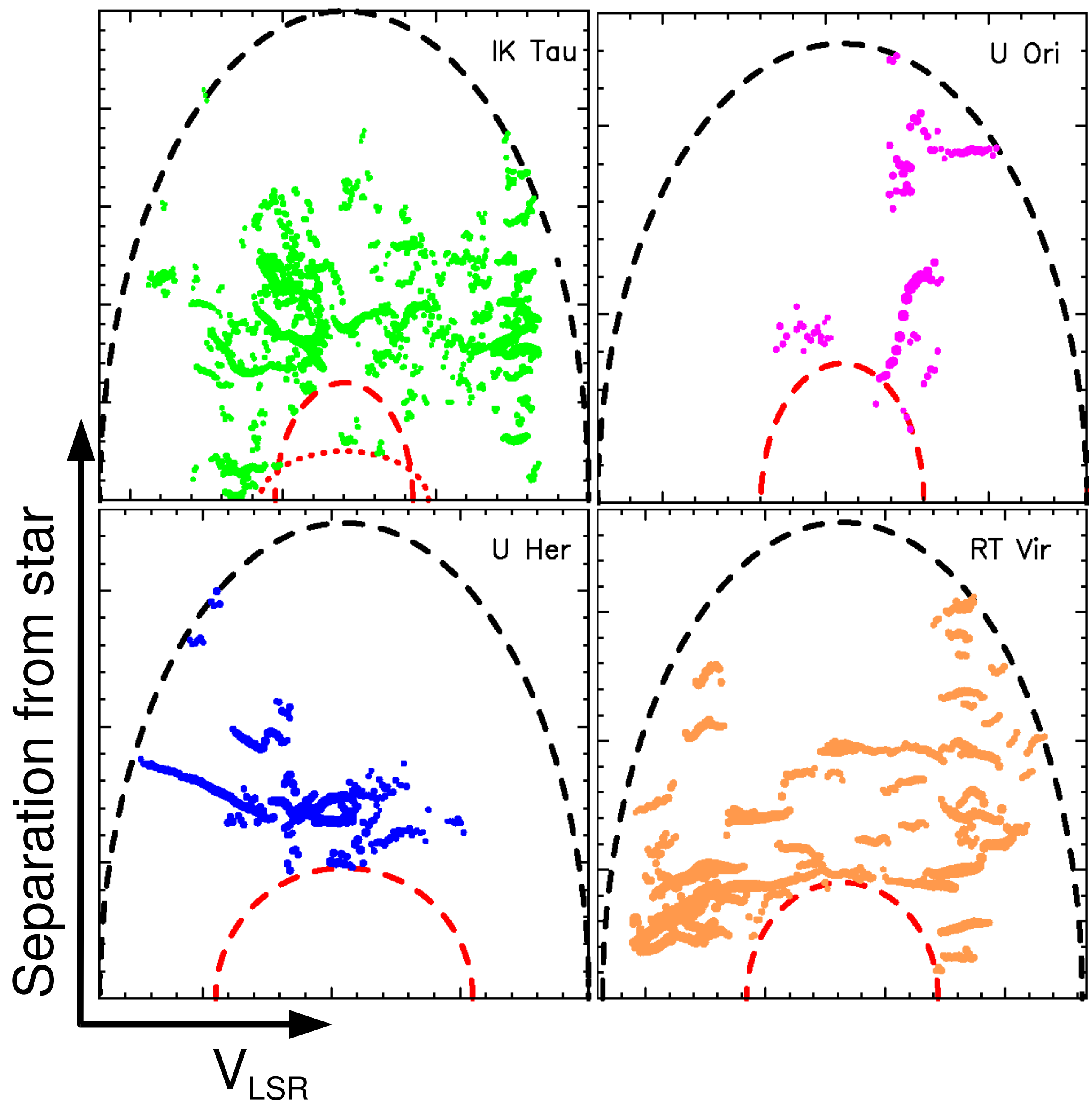
VX SGR
SPER
100 AU
RT VIR
IK TAU
U HER
U ORI

AGB wind acceleration

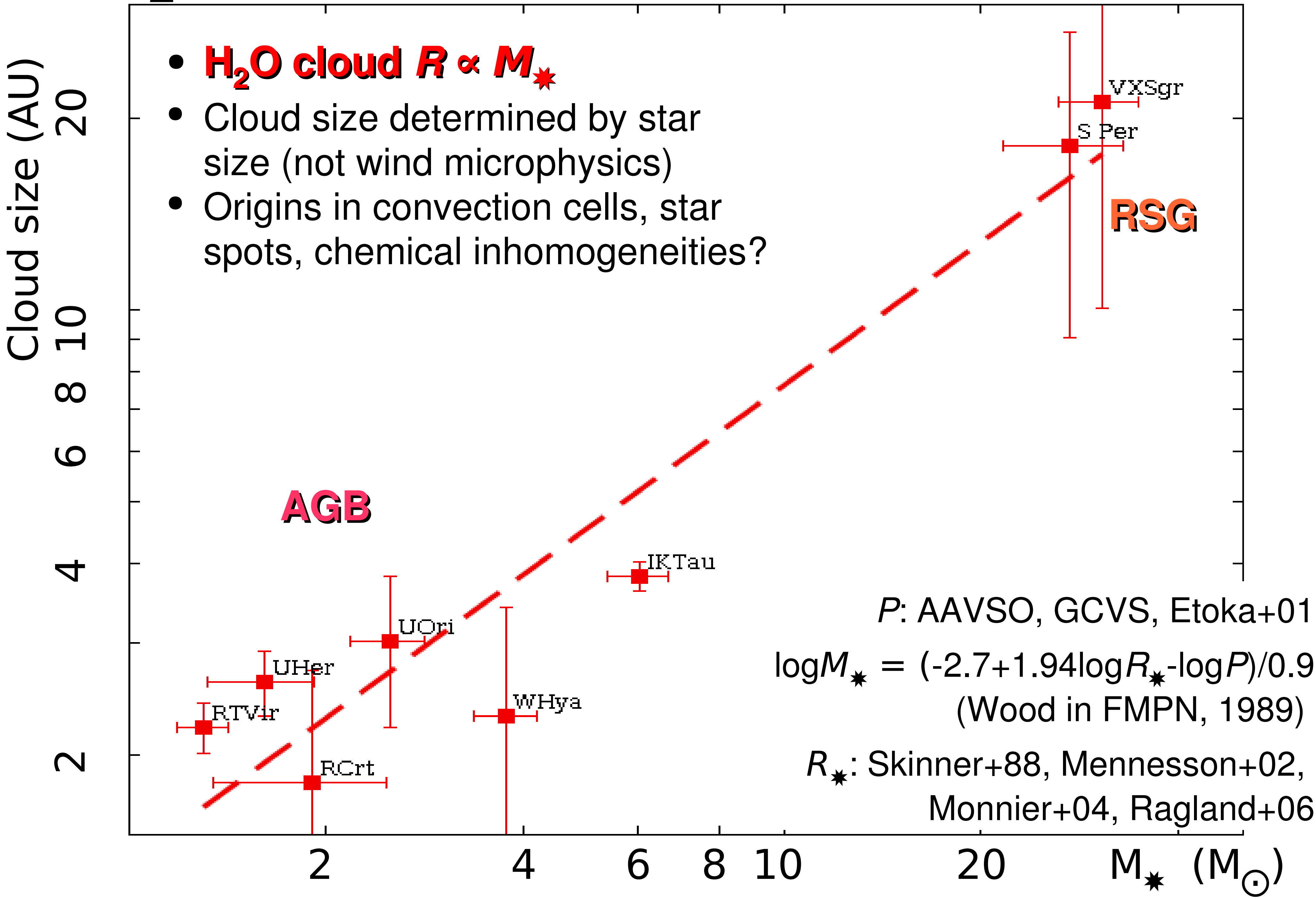


AGB maser cloud density

- Fit maser shell limits
- Inner radius r_i
  - ~5 AU (AGB)
  - ~50-100 AU (RSG)
- n_q at H_2O r_i implies $\dot{M}$ 10-100 x CO, IR values
- **H_2O clouds ~50x overdense**
- 20- 100 per shell
  - Filling factor ≲1%
  - 1-few clouds / period
- r_o 25 - 500 AU



H_2O maser cloud size/Stellar mass

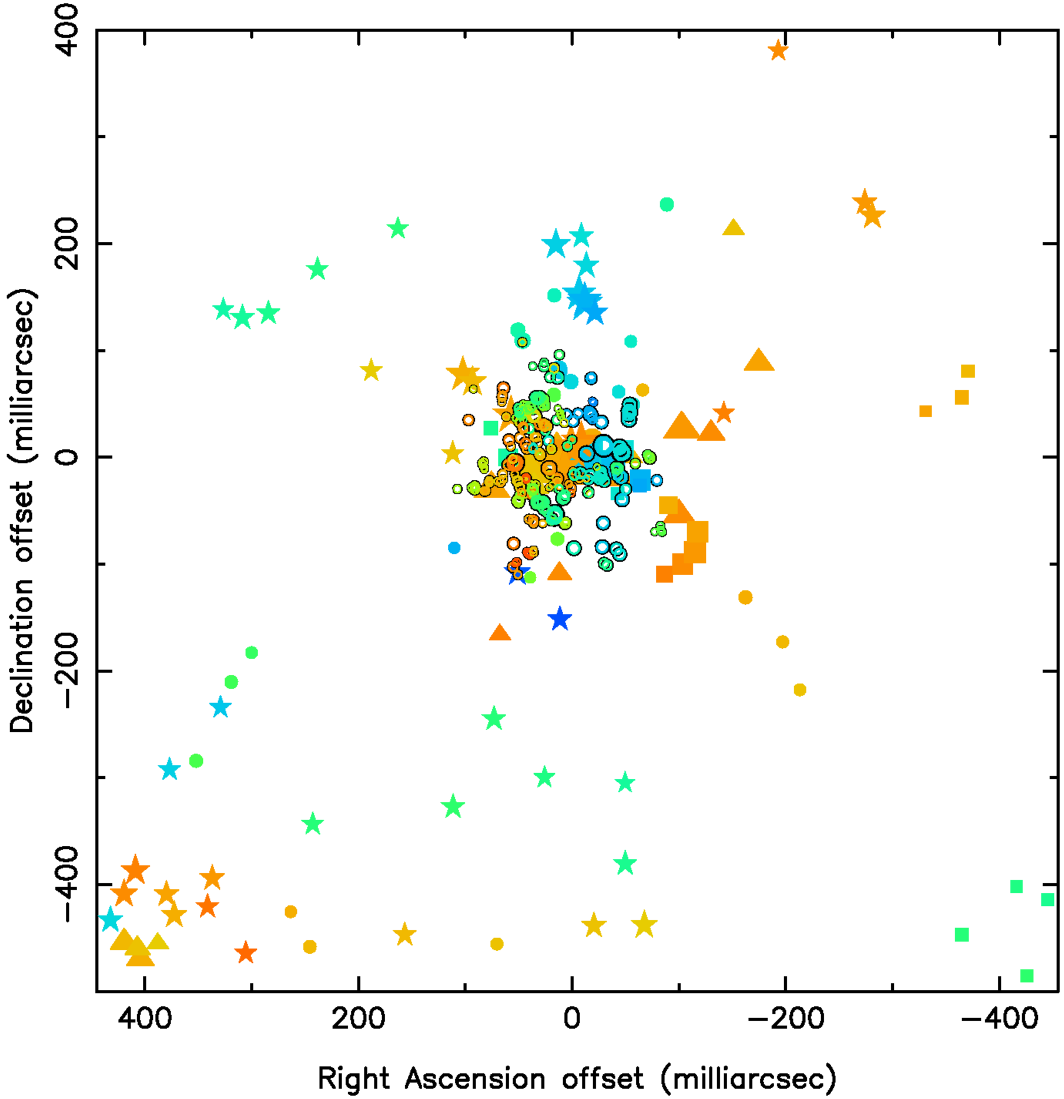


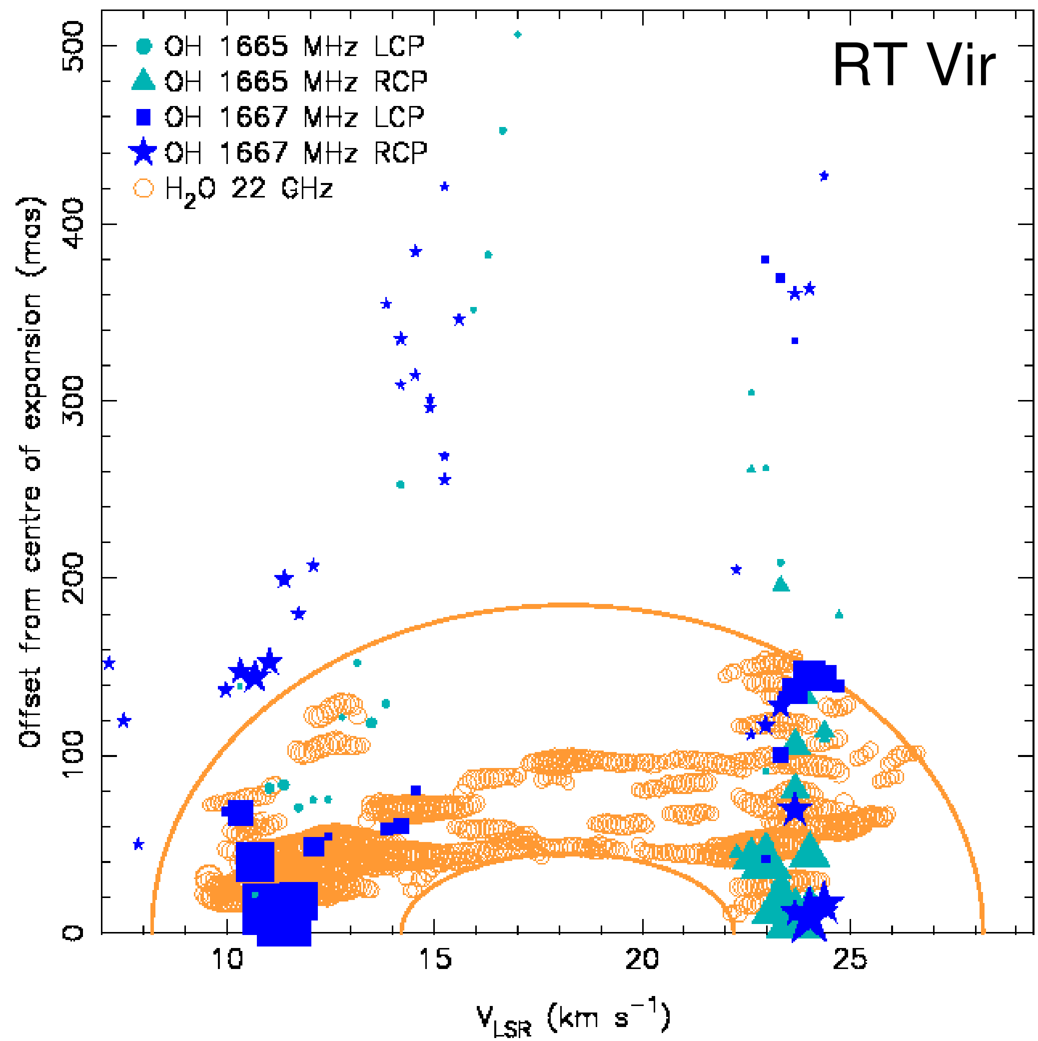
OH mainline/H_2O overlap on AGB?

- RT Vir SRb at 133 pc

o H_2O ★ OH mainlines

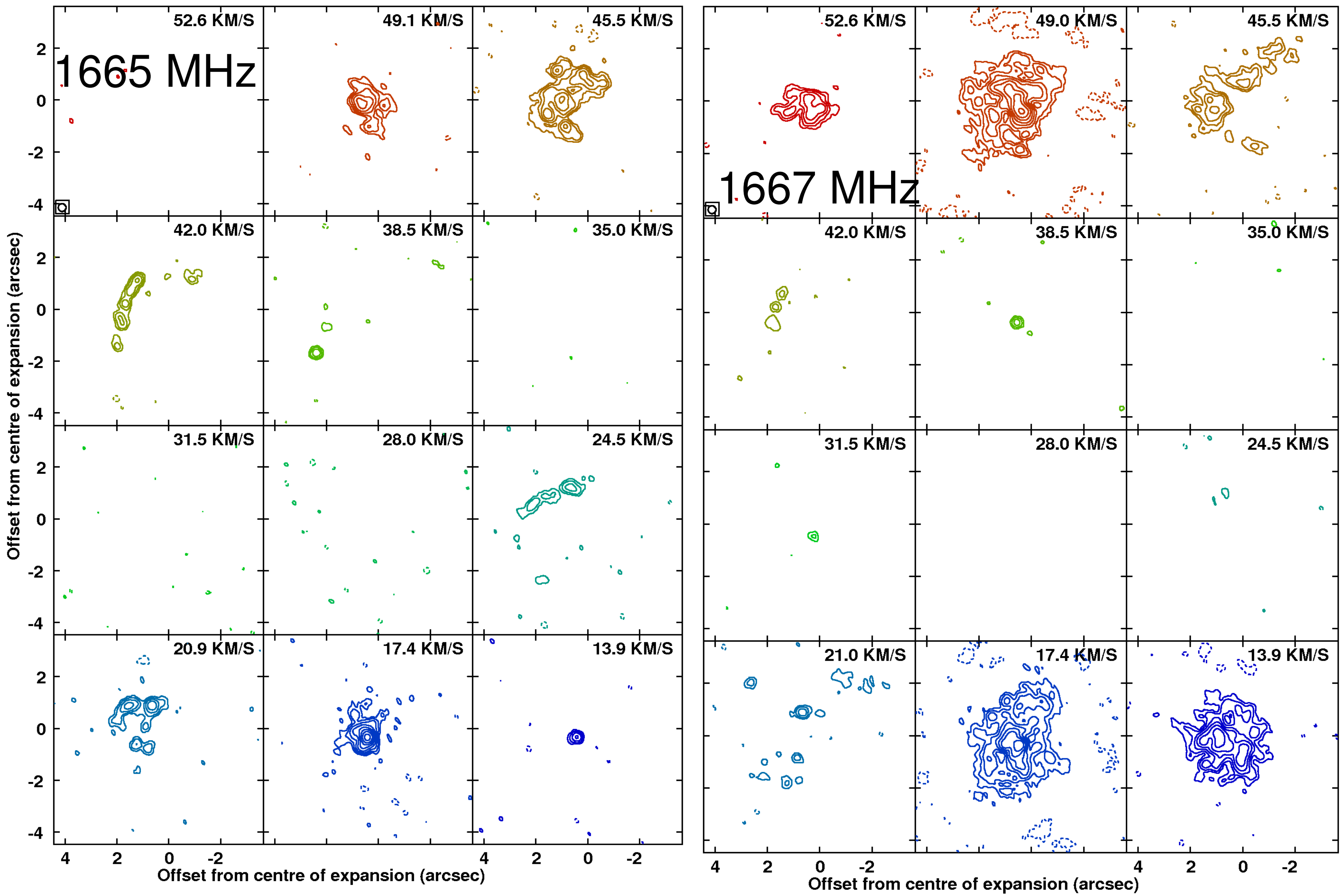
- MERLIN resolves overlap





Hint of overlap in IK Tau 1667 MHz

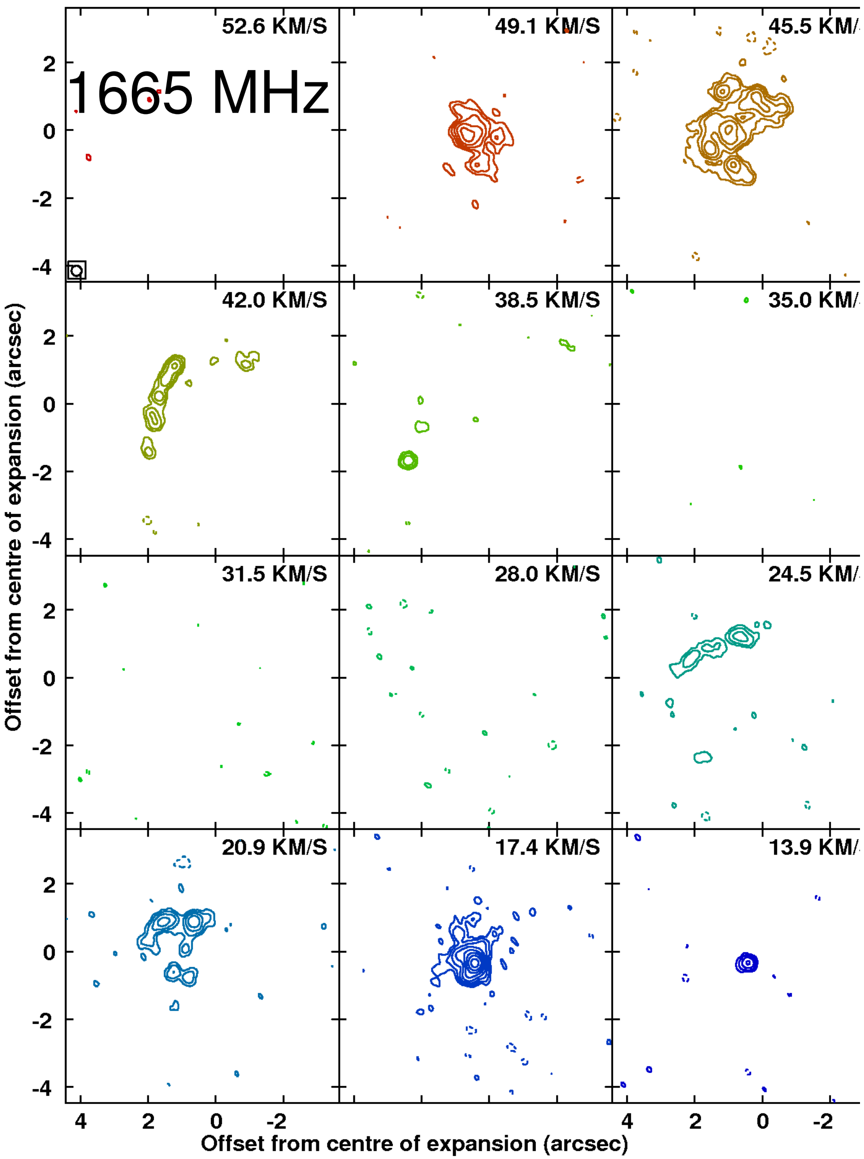
IK Tau: Sum emission for sensitivity: by velocity ...

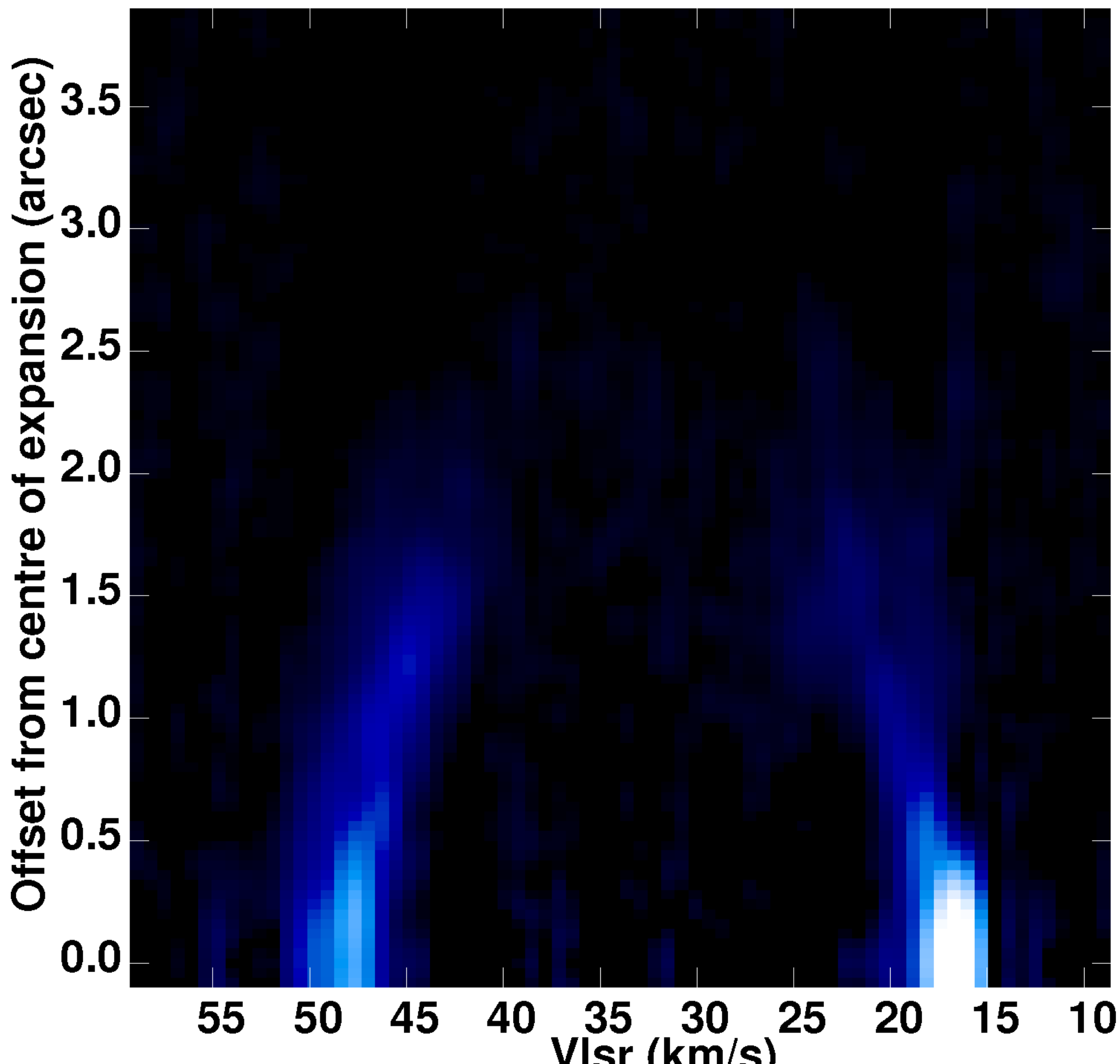


Hint of overlap in IK Tau 1667 MHz

IK Tau: Sum emission for sensitivity: by velocity ...

and by angle

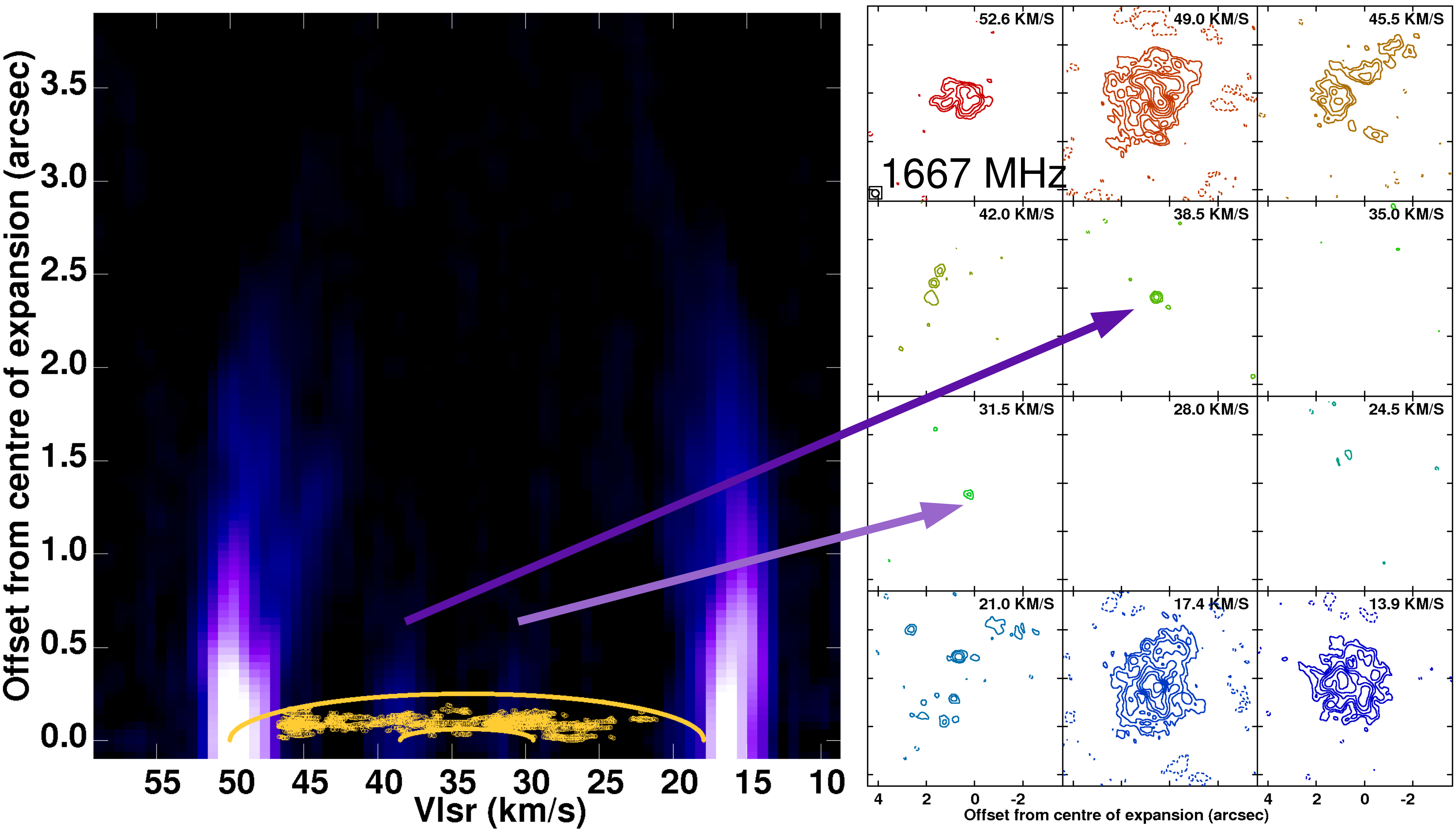




Hint of overlap in IK Tau 1667 MHz

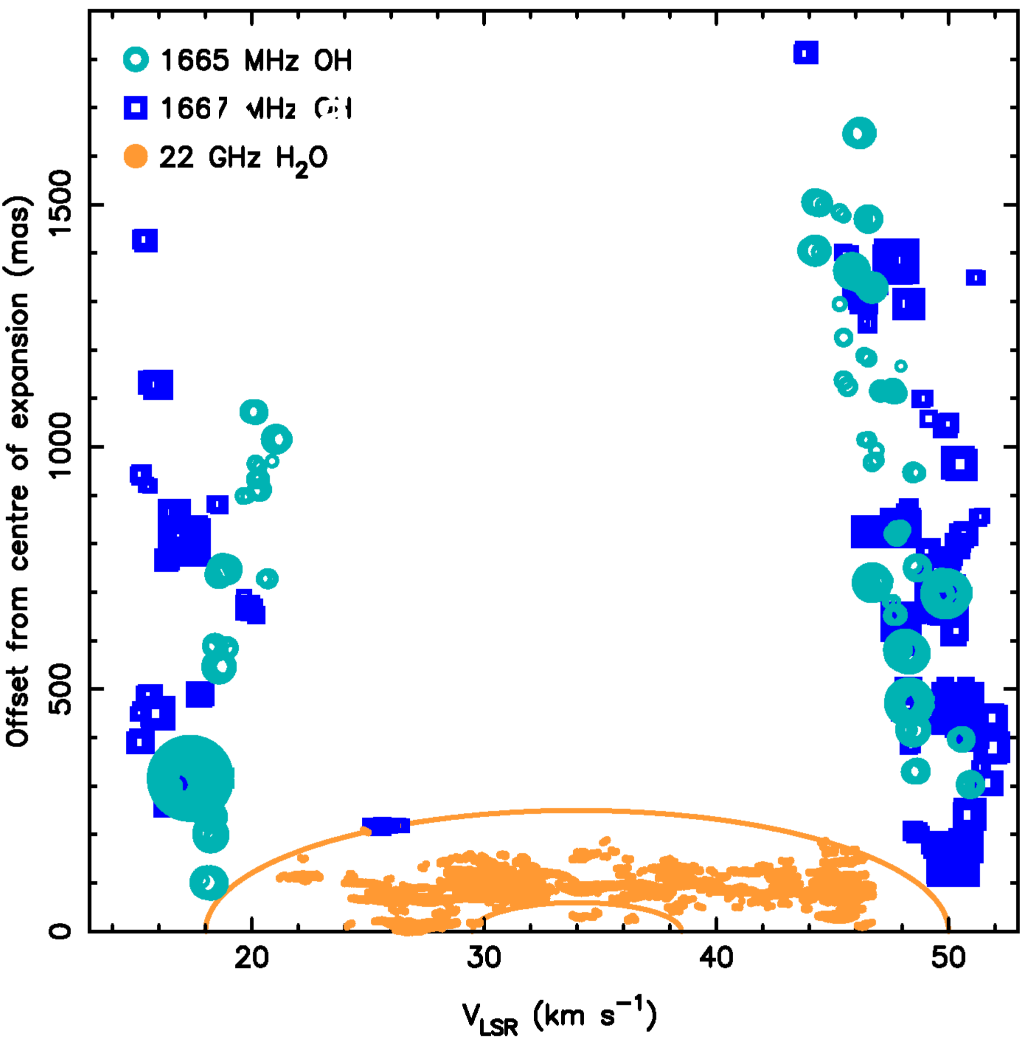
IK Tau: Sum emission for sensitivity: by velocity ...

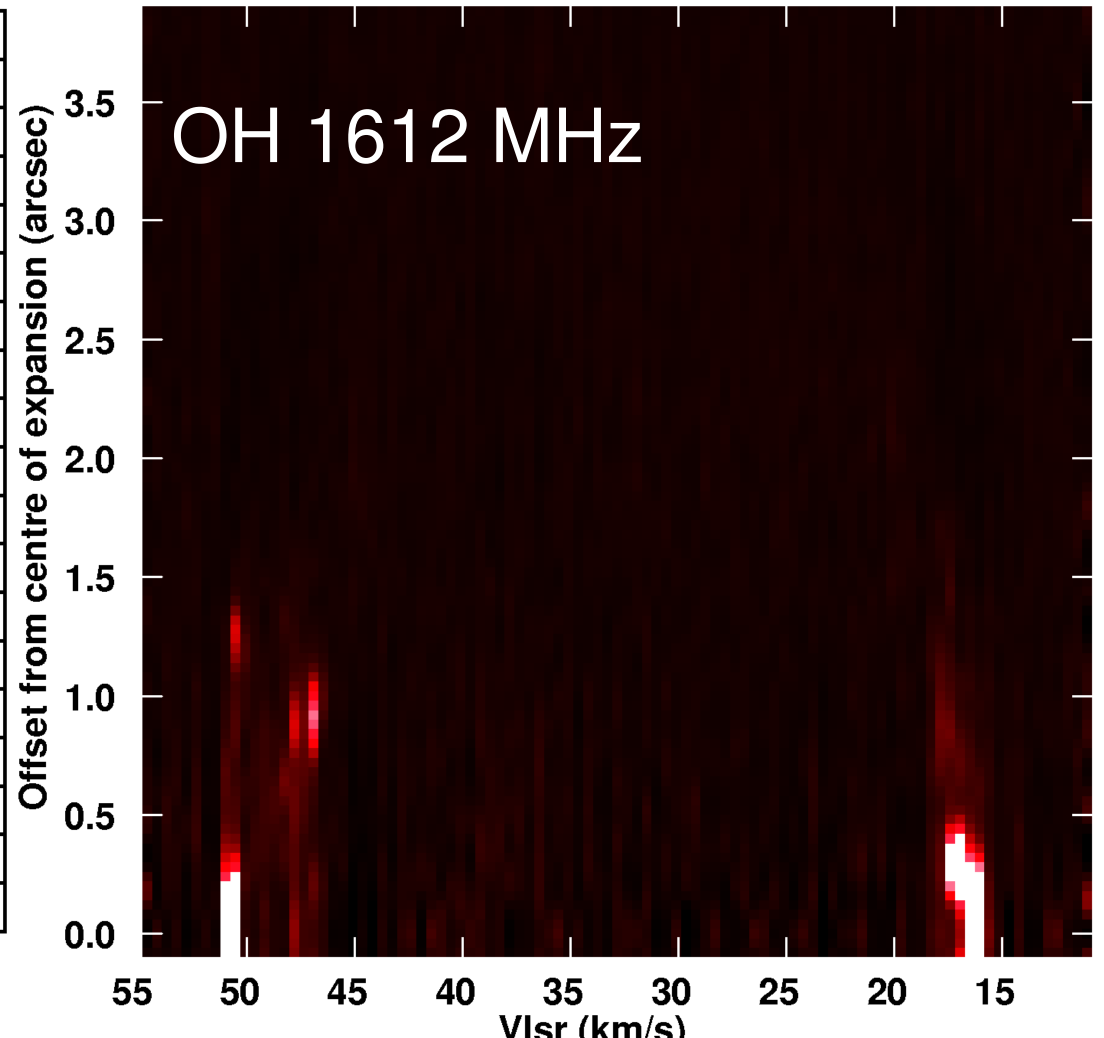
Inner 1667 MHz still there!



IK Tau

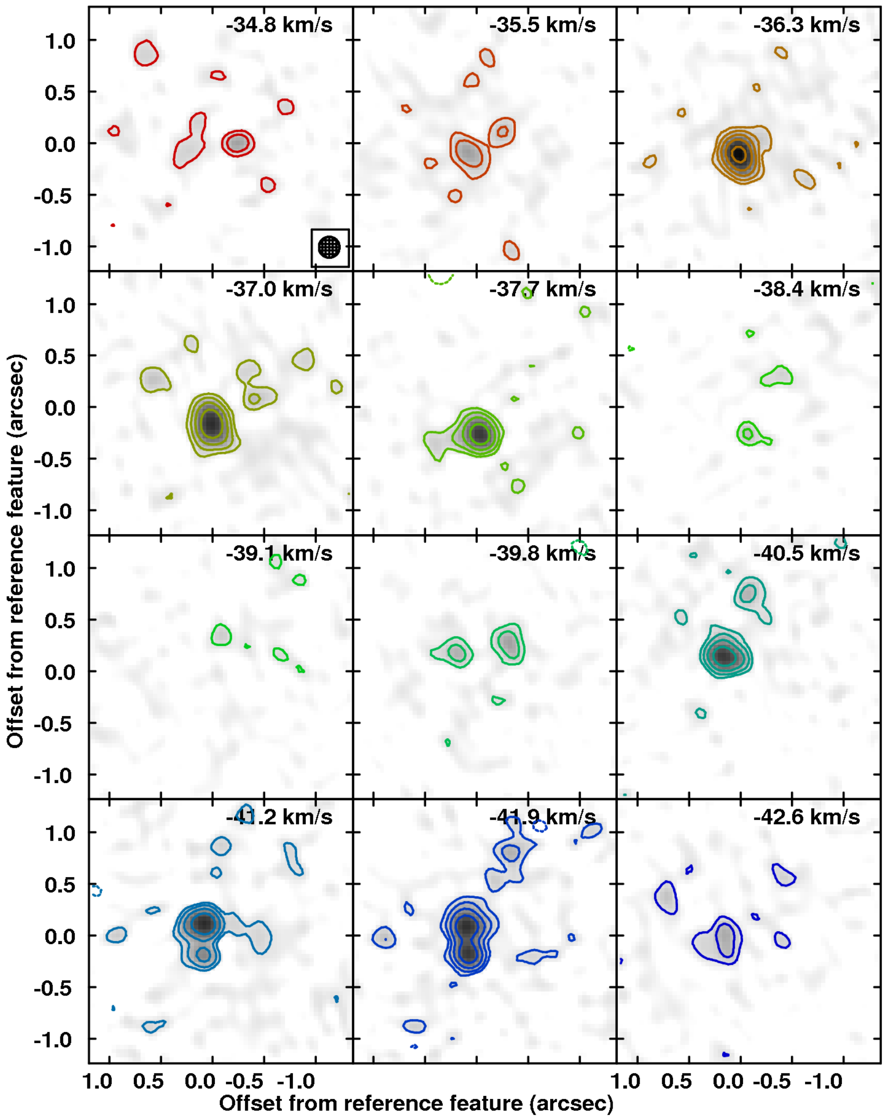
- EVN OH at edge of H_2O
  - Much resolved out?
  - But MERLIN 2001 << 1993
- Mira - but very bipolar OH?
- OH 1612 MHz still outside

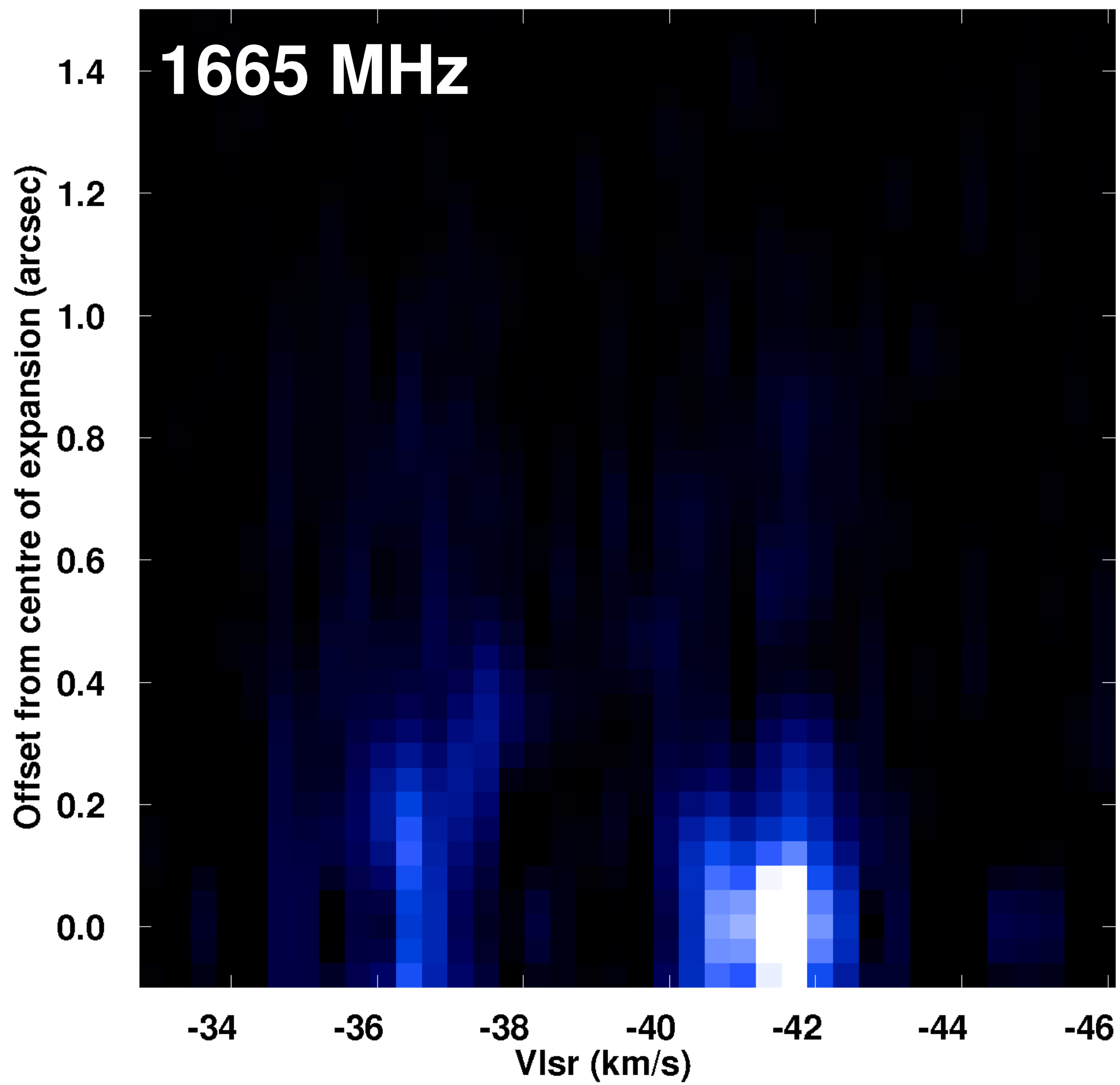




U Ori MERLIN

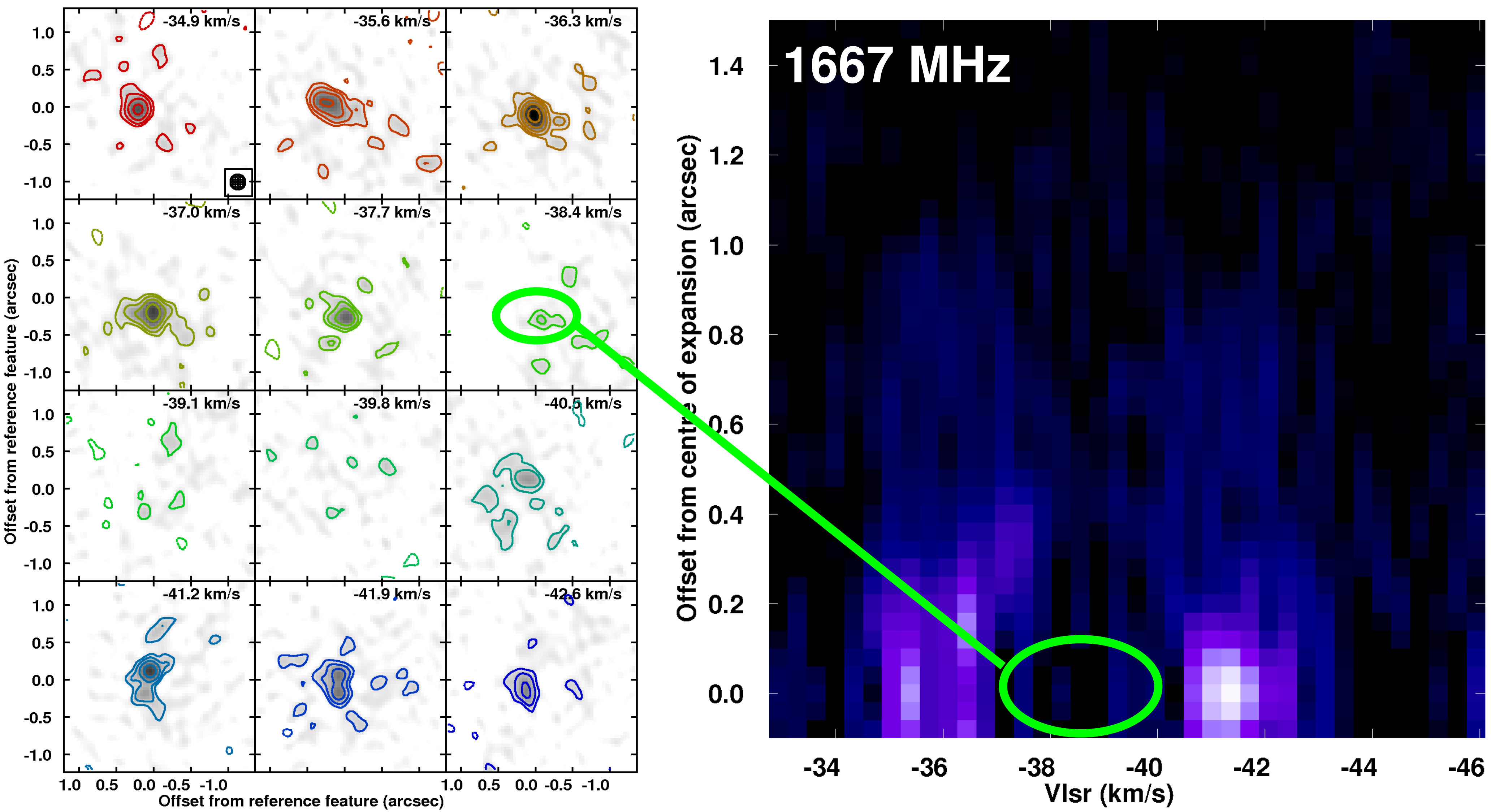
- Mira, 266 pc, OH mostly mainline
  - Transient 1612-MHz probably a flare from inner CSE





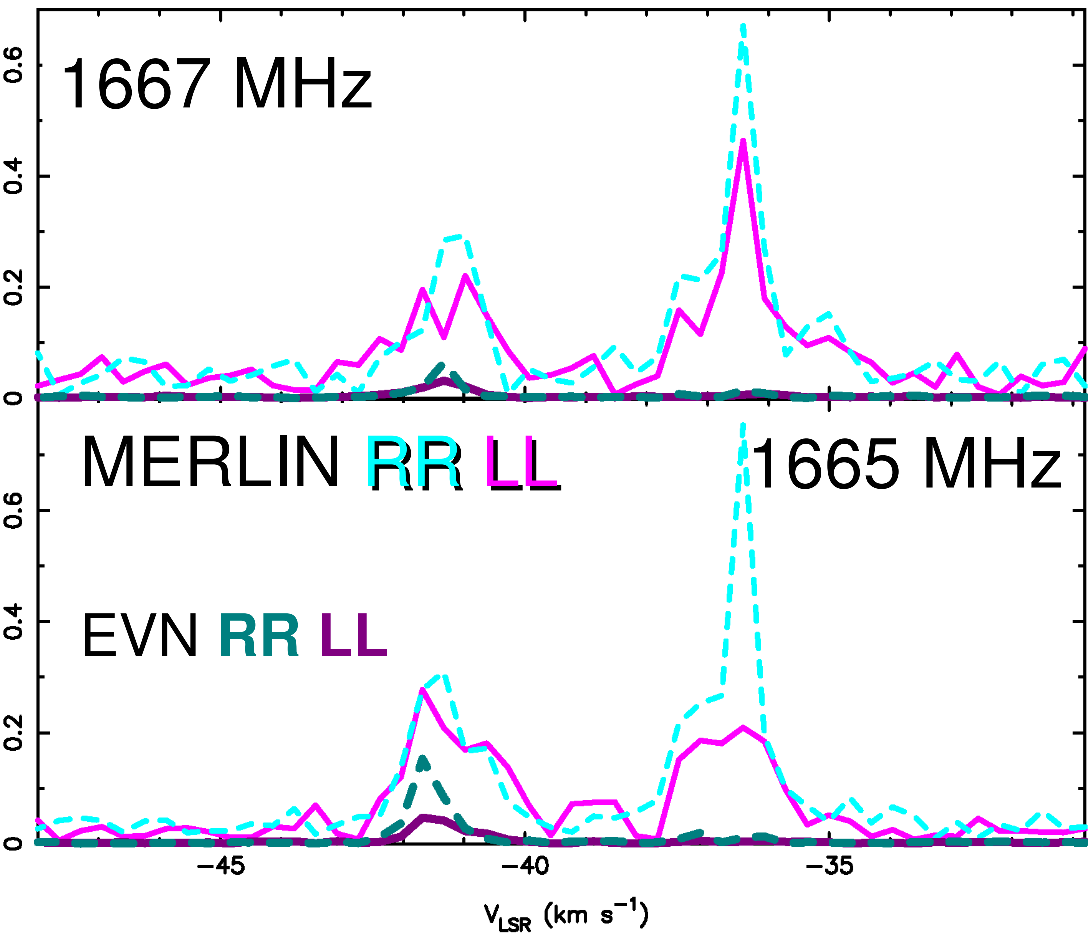
U Ori MERLIN

- Fairly well-filled, stable OH mainline shell (*Chapman+91*)
- Trace of inner emission

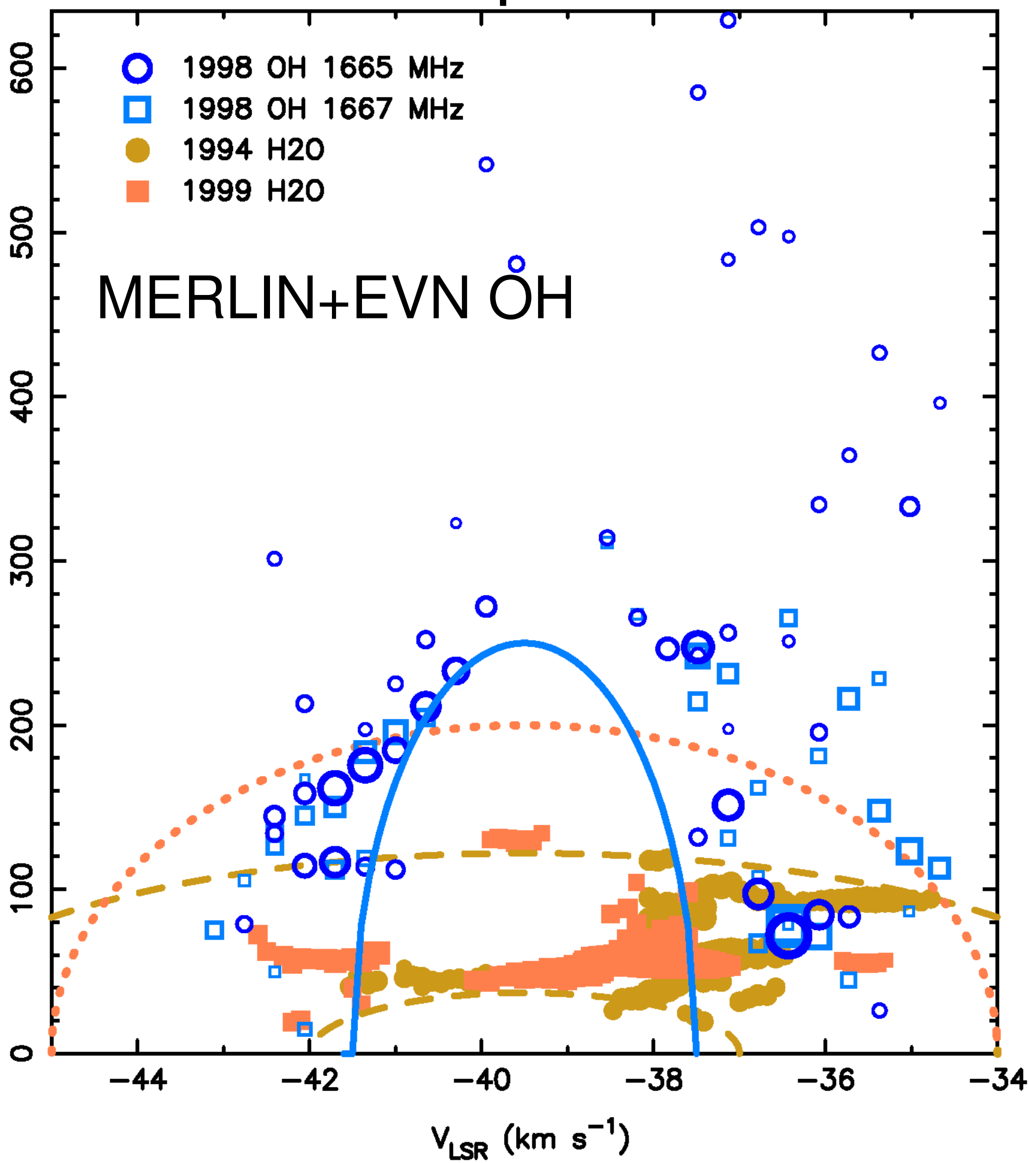


U Ori MERLIN+EVN

- MERLIN+EVN observed OH within 3 months
- Several MERLIN runs - little variability

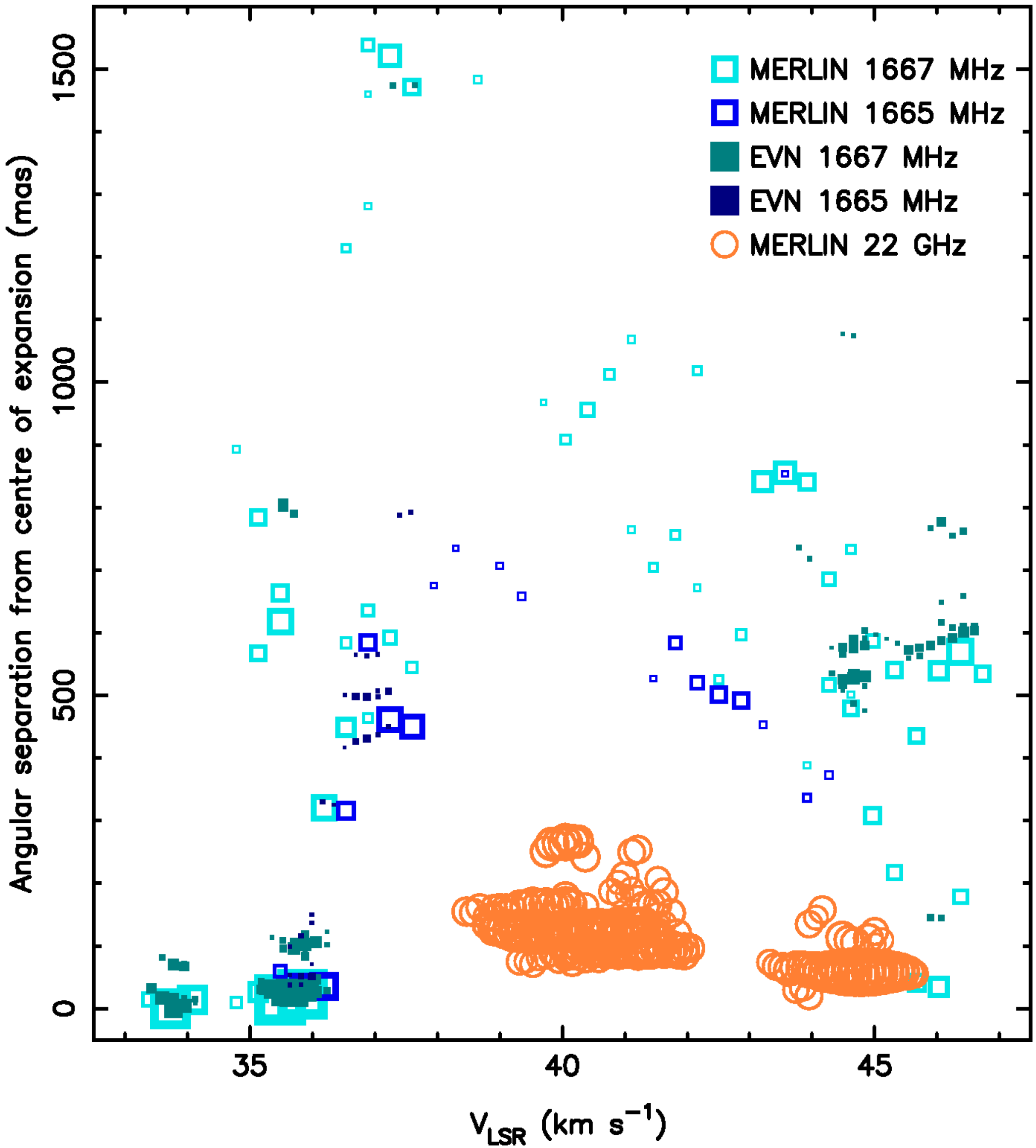


- Combined data show a little overlap?



W Hya separate?

- SRa, ~100 pc
- Dec -28
  - MERLIN σ_{pos} large!
- MERLIN OH *Szymczak+ 1998*
  - EVN confirms (if assume aligned)
- H_2O *Yates*
  - More epochs to come
  - Ovelap in velocity but probably not in position



CSEs with water/OH mainline overlap

RSG AGB	dM/dt CO/IR ($M_\oplus$ yr^{-1})	H_2O shell r_i (AU)	OH shell r_i (AU)	H_2O shell r_o (AU)	dM/dt 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})
S Per	3−60	55	80	165	(930)	100	18 (44)	15−20
VX Sgr	5−80	95	130	320	(190)	100	21	10−15
VY CMa	70-115	75	300	600	(3220)	54+	--	>60?
U Ori	~0.08	9	25	32.5	(8.3)	14	3	~0.03
RT Vir	~0.05	6	15	25.6	(5.1)	55	2.2	~0.05

- *H_2O clouds much denser than surroundings*
  - $n_{H2Ocloud}$ 30-100x n_{OHgas}
- OH mainline r_i < H_2O r_o
- H_2O maser cloud filling factor less than a few %
  - Solves mass loss rate discrepancy
- **OH comes from less dense gas around and outside H_2O clouds**

Why don't OH mainlines overlap H_2O around all RSG/AGB stars?

Four RSG: VX Sgr, S Per, VY CMa, NML Cyg

- All with SiO, H_2O, OH mainline and 1612-MHz masers
- VX Sgr, S Per, VY CMa overlap
- NML Cyg H_2O bipolar, inner OH faster, no overlap
  - More evolved? Excited OH detected.

Four AGB: SR: RT Vir, W Hya Mira: U Ori, IK Tau

- RT Vir-U Ori-IK Tau-W Hya: strong-some-little-no overlap
- Only IK Tau has well-resolved outer OH 1612-MHz
  - Others show faint/flaring emission (e.g. *Etoka et al. 03*)
- IK Tau had strong, biconical OH mainlines, now fading
- IK Tau, RT Vir bright H_2O with persistent? asymmetries
  - U Ori, W Hya H_2O no obvious preferred direction
  - W Hya outer detatched OH mainline shell? (*Etoka+00*)

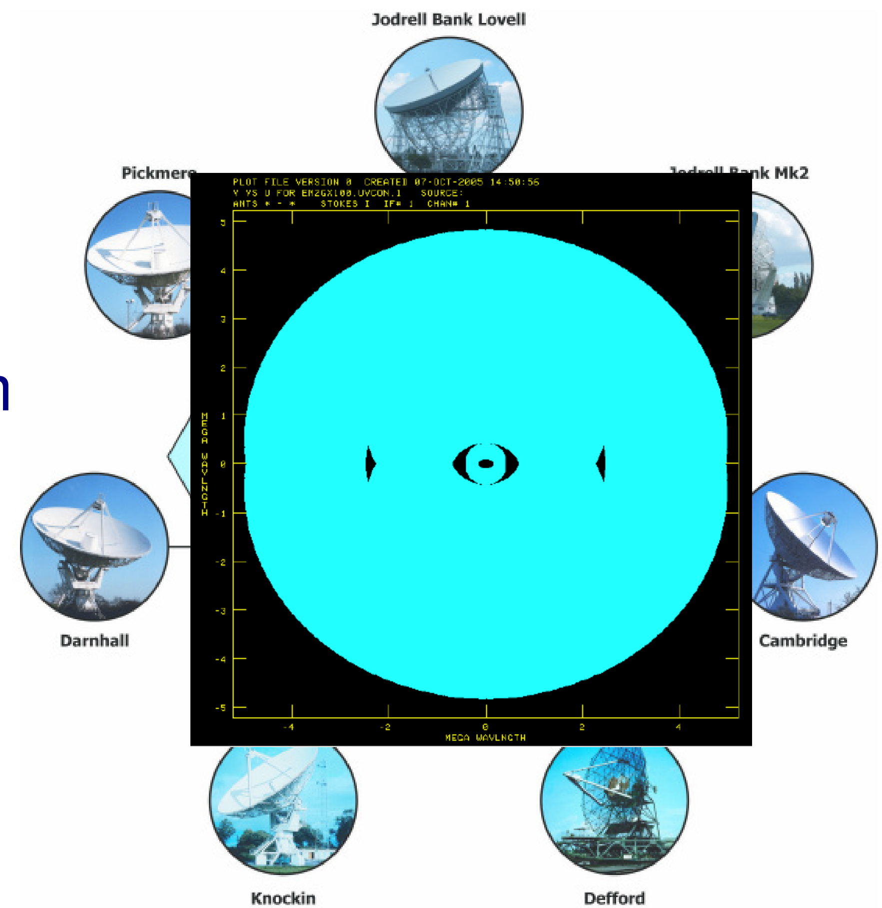
Observational requirements

- Clumping scales, cloud survival determine:
  - Wind chemistry, ionisation, magnetisability, acceleration
  - Molecular structure of material returned to ISM, future SF
  - Accuracy of mass-loss estimates
- Multiple epochs
  - Proper motions for 3D structure
  - Transient excitation effects v. persistent asymmetry
- High resolution and sensitivity
  - Resolve sub-mas components for maser physics
  - 100-mas scale weak extended emission (as in SFR)

- e-MERLIN+EVN ideal
  - +Global VLBI for RSG
  - +EVLA for close AGB
  - Good N-S baselines - Noto - invaluable
- Phase-referencing - align different species/epochs
- Full polarization at <100 m/s spectral resolution
- Adequate velocity span & resolution

e-MERLIN is coming

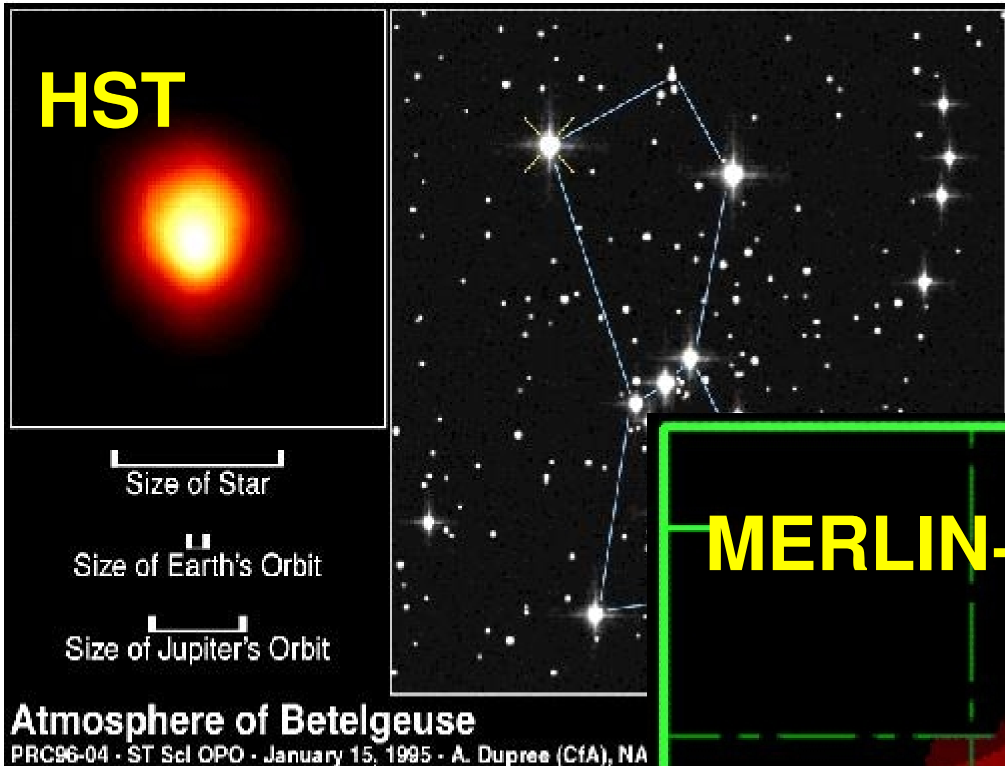
- MERLIN since 1992
  - 10-200-mas resolution @1.2-25 cm
  - Full polarization, >20' f.o.v. @ 21 cm
  - Max. b/w 16 MHz - 60 μJy/12 hr
- *e*-MERLIN 2 GHz opt fibre b/w
  - New receivers, hard/software
    - Lovell upgrade
  - 10-30x continuum sensitivity
    - σ_{rms} 2 μJy/beam/12 hr around λ 6 cm
    - σ_{rms} 15 μJy/beam/12 hr around 1.3 cm
    - ~Filled aperture @λ> 4cm!
  - Sub-mas ICRF astrometry
  - Rapid frequency changes
  - 1000s km/s, multiple spectral lines
- Run by JBCA, Manchester University
  - Funded by STFC, NWDA, other Uni's



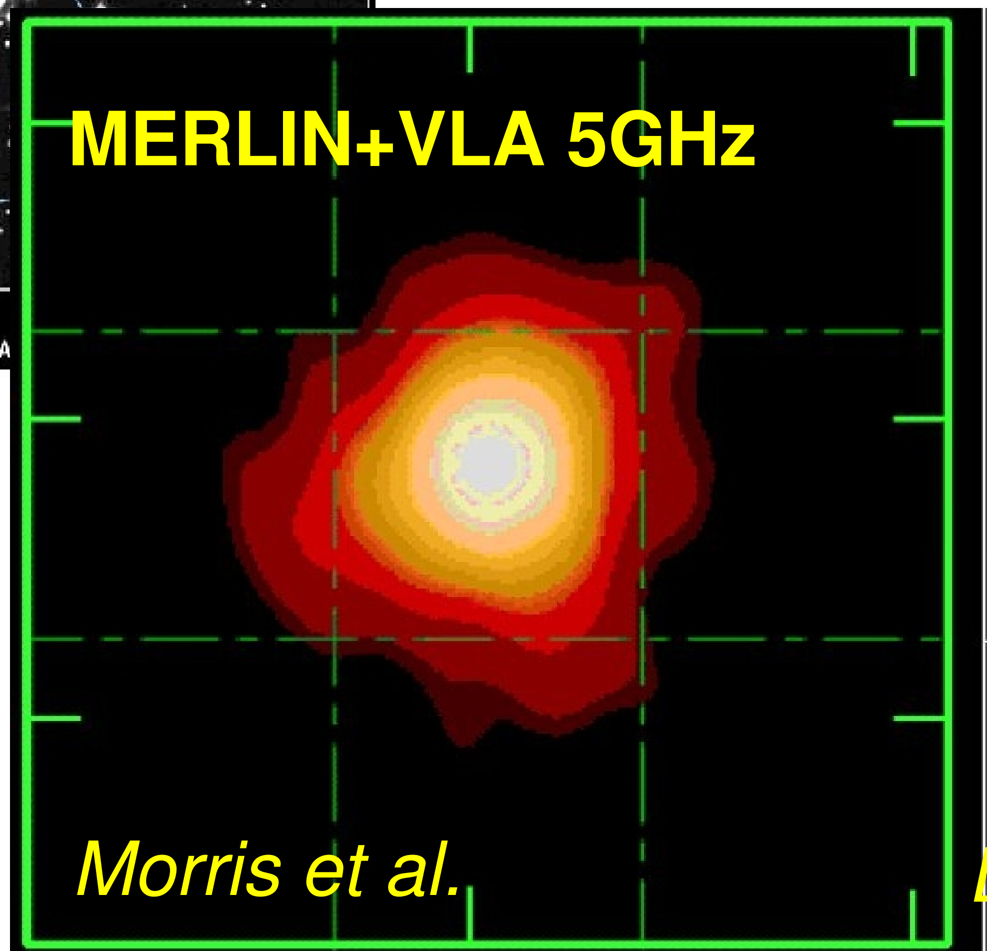
eMERLIN

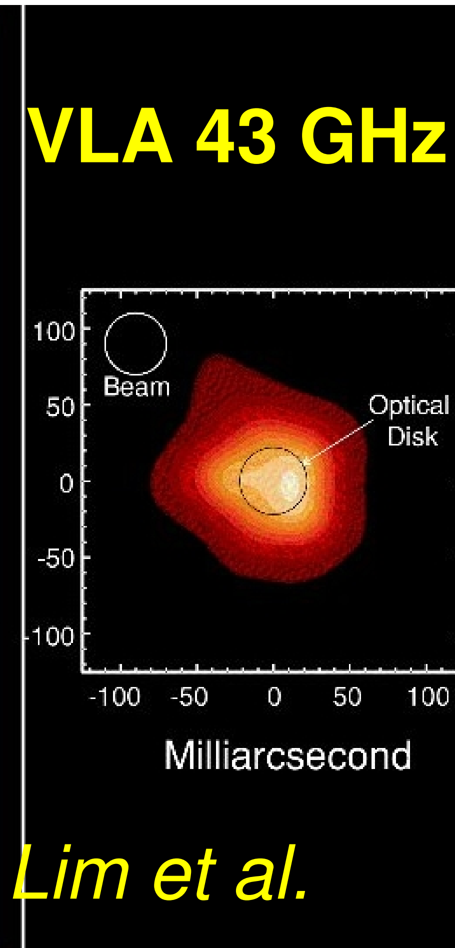
- Incremental devel-opment
  - Full ops 2009-10

Mass loss from the stellar surface



- α Ori lumpy, aspherical
- RSG clouds 5-10% $R_{\star}$ at birth
  - Star spots?
  - Chemical inhomogeneity?





- *e*-MERLIN, EVLBI
  - Image the star *and* its masers
- ALMA
  - Track the dust as it forms

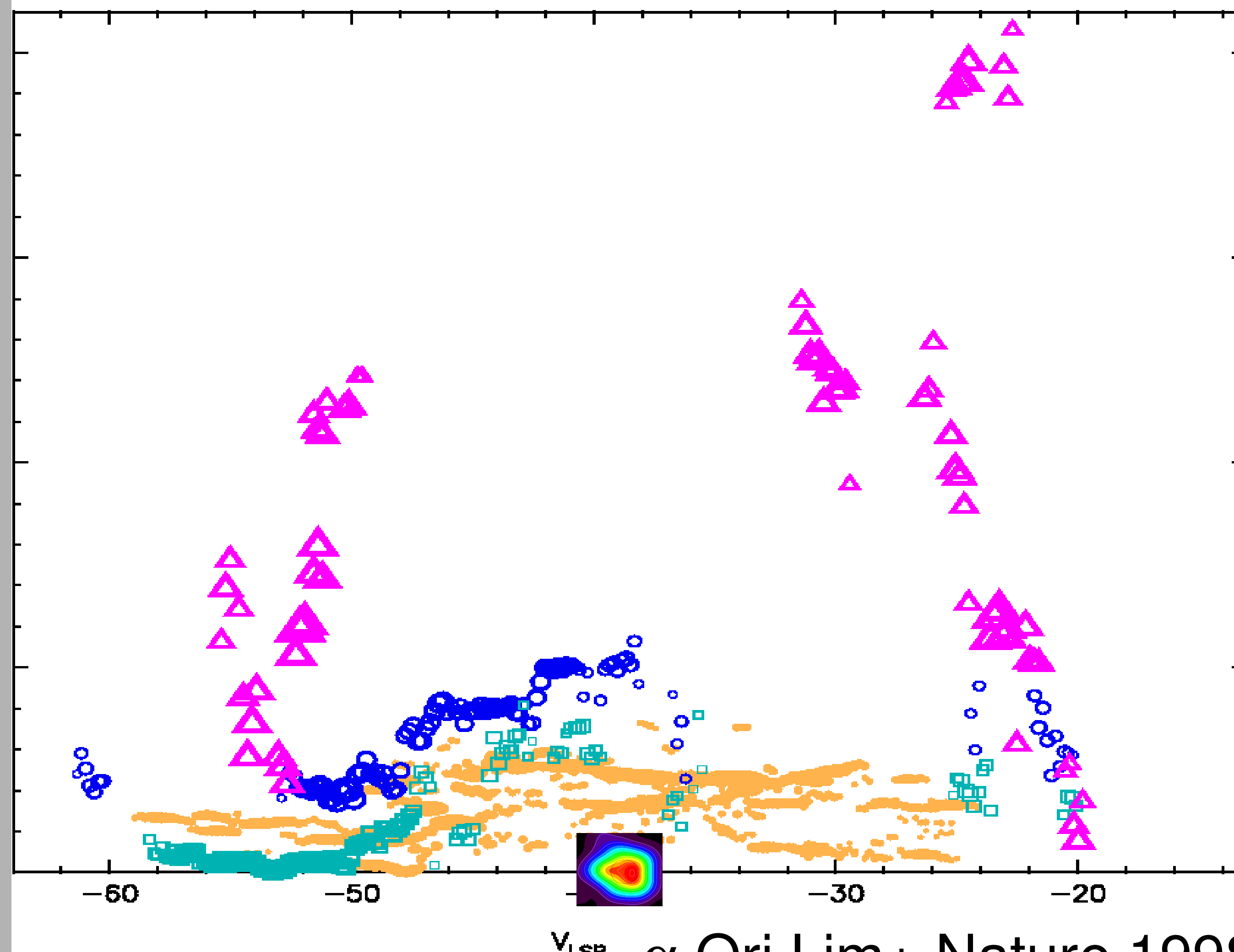
Track AGB/RSG wind from photosphere to ISM

(part of 'radio H-R' legacy group)

eMERLIN

Legacy Project

- **1612 MHz masers**
  - ***e-MERLIN, EVN***
- **OH 1665/7 MHz masers**
  - ***e-MERLIN, EVN***
- **H_2O masers**
  - ***e-MERLIN***
- **Dust**
  - ***ALMA, VLTI***
- **SiO masers**
  - ***VLBA***
- **Star radio photosphere**
  - ***e-MERLIN (+ALMA, VLTI...)***



α Ori Lim+ Nature 1998

Where	What	How study	What with	Year
$R_\star$ few AU, spots $R_\star/10$?	Photosphere 2500 K, star spots	Optical, IR, 5-25 GHz	eMERLIN/EVN, ALMA, VLTI	0
SiO masers 2-5 $R_\star$	2000 K gas small clumps	43, 86 GHz polarization	VLBA (Diamond)	1 – 4 (monthly)
Dust forms 4 – 5 $R_\star$	1000 – 1500 K clumps? shells?	IR/sub-mm	ALMA, VLTI, MROI	4 – 15?
H2O masers 5-25 $R_\star$	500 – 1500 K $R_\star$dense clumps	22 GHz polarization	eMERLIN/ EVN	5 – 25 (few mn)
OH mainline 8 – 100 $R_\star$	200 – 500 K diffuse gas	1.6 GHz polarization	eMERLIN/EVN/ global VLBI	8 and later
OH 1612MHz 50 – 100 $R_\star$	50 – 150 K tranquil gas	1.6 GHz polarization	eMERLIN/ EVN	Follow outer H2O