Resolving evolved Sun-like stars' mass loss

Anita Richards
UK ARC, JBCA, Manchester

with thanks to
Bains, Bartkiewicz, Diamond, Dinh Van Trung, Gray, Lekht, Lim, Mendoza, Murakawa, Rosa-Gonzalez, Szymczak, van Langevelde, Verhoelst, Vlemmings, Yates, Zijlstra et al.

RadioNet

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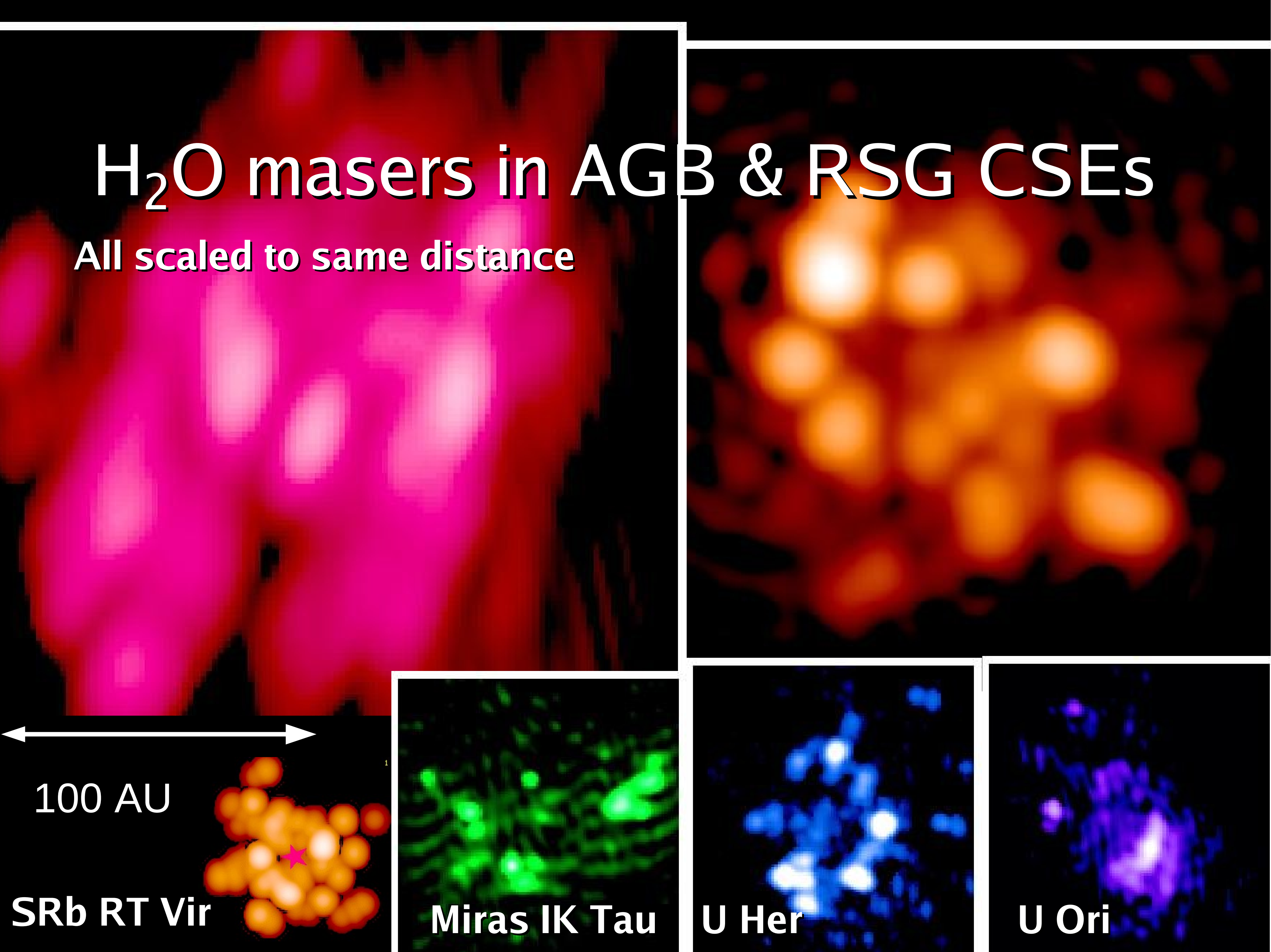
Sorry to come between us and dinner...

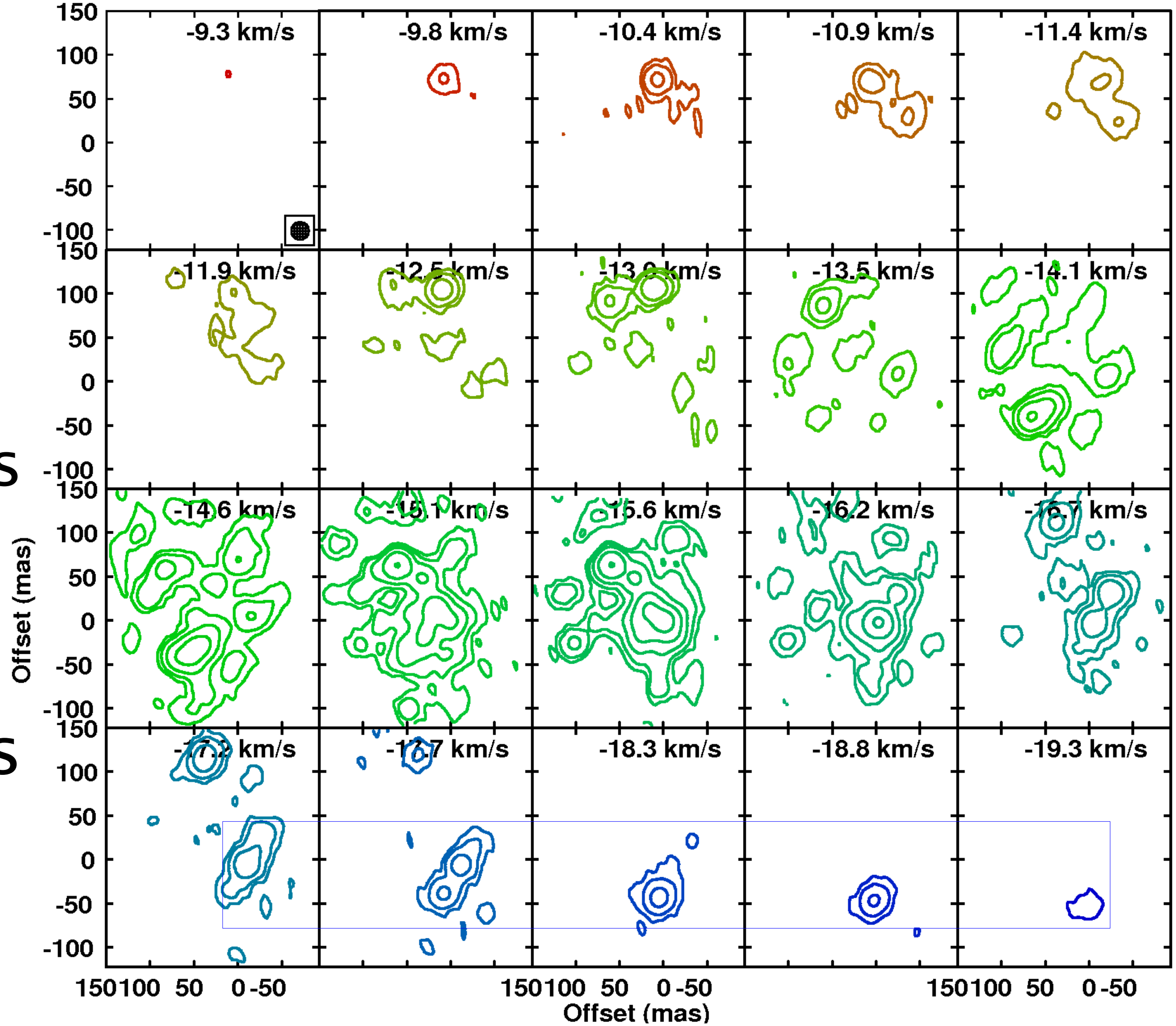
Overview

- Structure of 22-GHz H_2O masers in CSE
  - MERLIN+EVN H_2O and OH monitoring + single dish
    - 10+ Supergiants and AGB stars
  - Clumpy mass loss
  - Evidence for dust evolution
- Cloud size related to star size
  - Determined by stellar phenomena?
- Direct imaging of mass loss from star
  - *e*-MERLIN, EVLA, ALMA,VLTI, MROI...
  - Trace mass loss through maser and dust zones


H$_2$O masers in AGB & RSG CSEs
All scaled to same distance
100 AU
SRb RT Vir
Miras IK Tau
U Her
U Ori

Water maser shells

- AGB/RSG at few 100/1000 pc
  - MERLIN detects ~all 22-GHz masers
  - 0.1 km/s channels
  - Milli-arcsec resolution
- Trace position shifts
  - Typically 5-10 mas in ~1-2 km/s
  - Intensity rises then falls



U Her (Mira) 0.5 km/s smoothing

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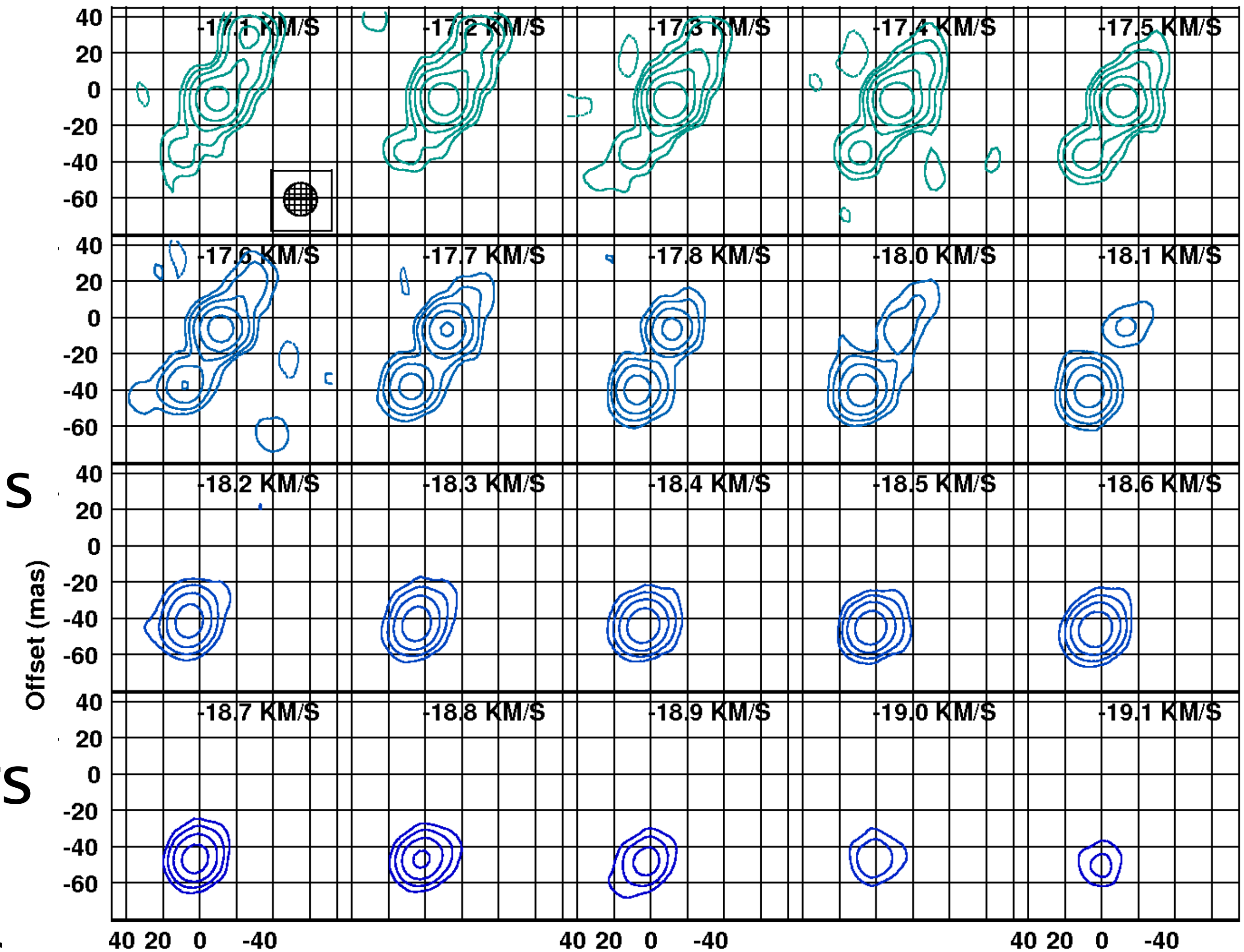
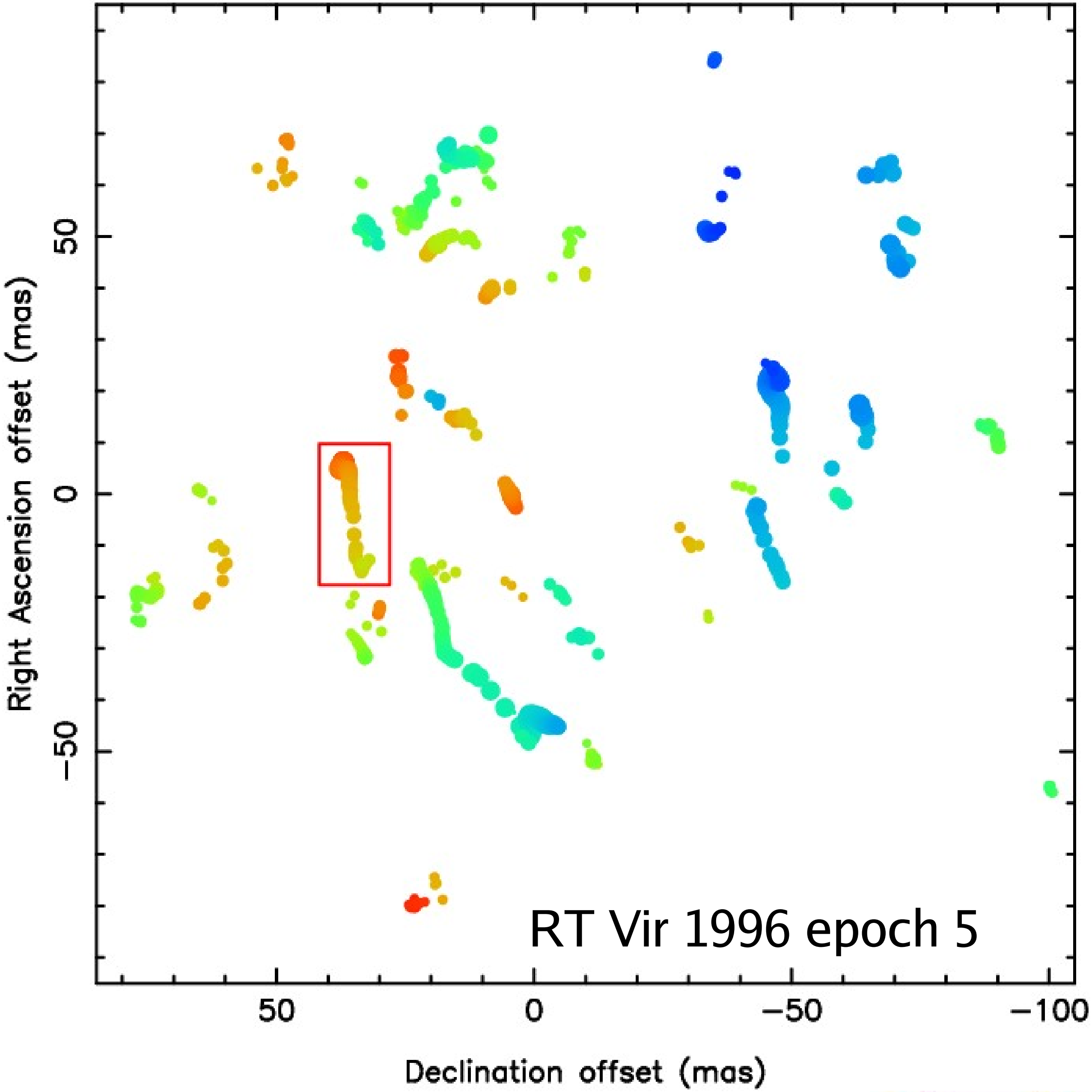


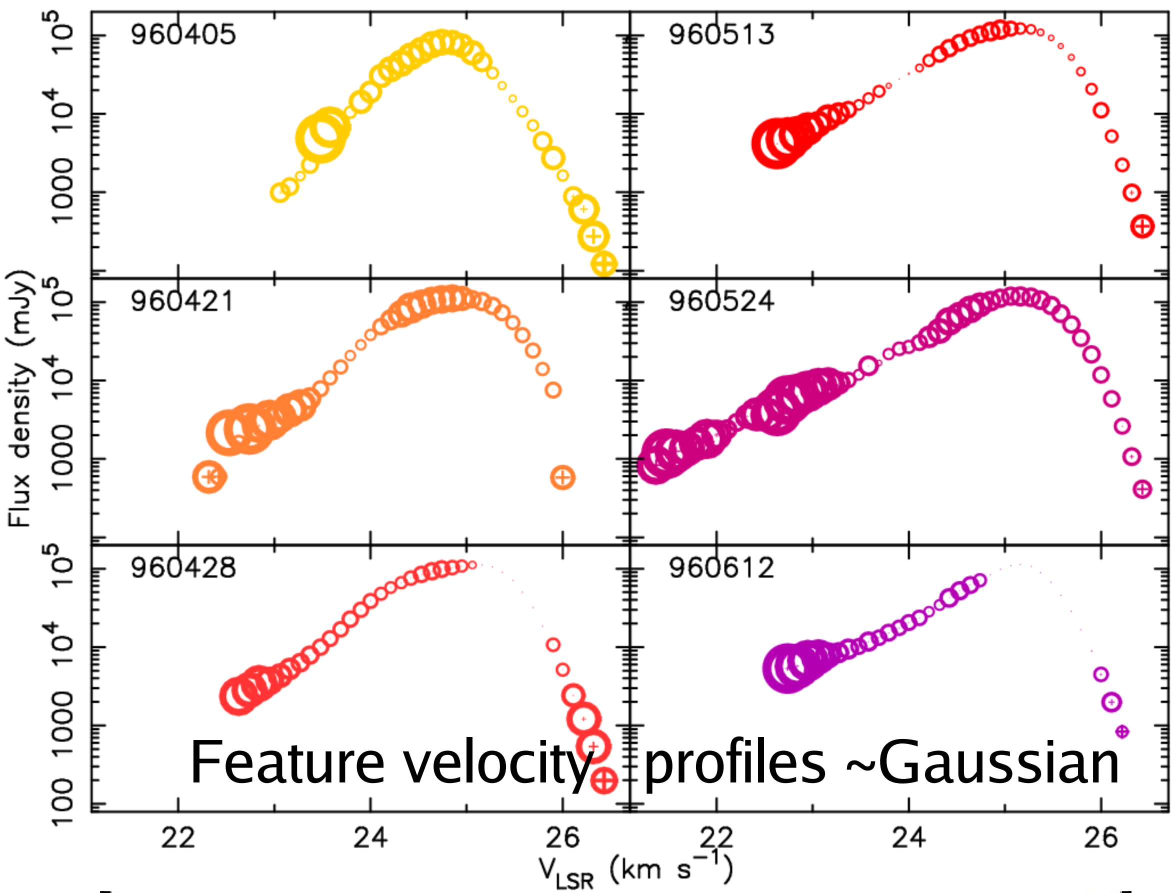
U Her 0.1 km/s resolution

Maser component structure

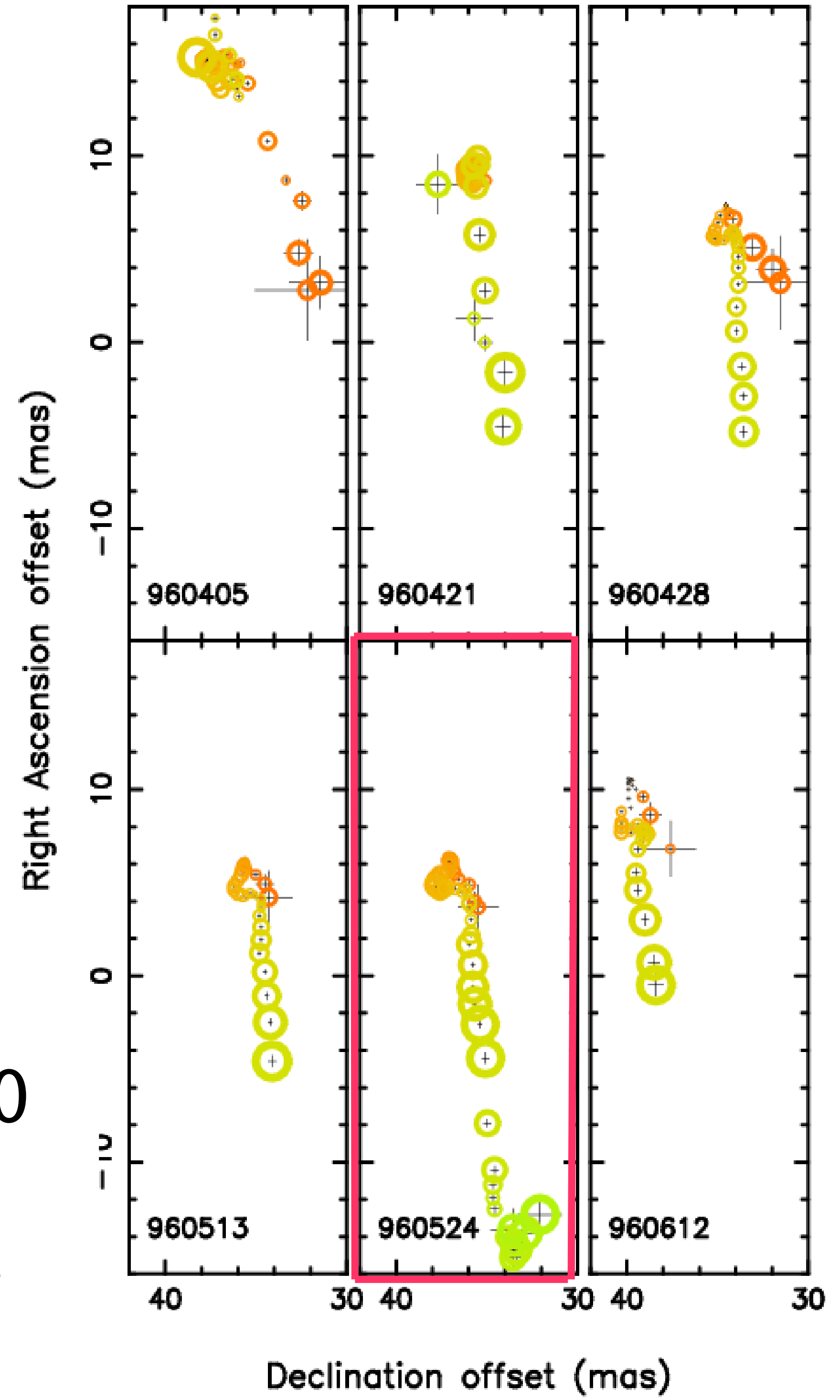
- Masers sample deepest column depth in channel δV
  - Grouped into clouds
  - Typical diameter RT Vir 1 –2 AU
    - No preferred direction of elongation
    - Clouds on average spherical?



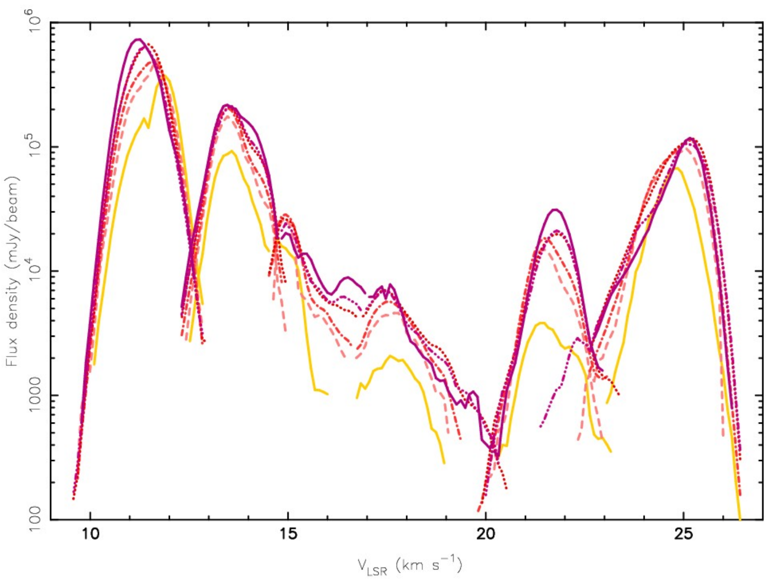
Maser clouds



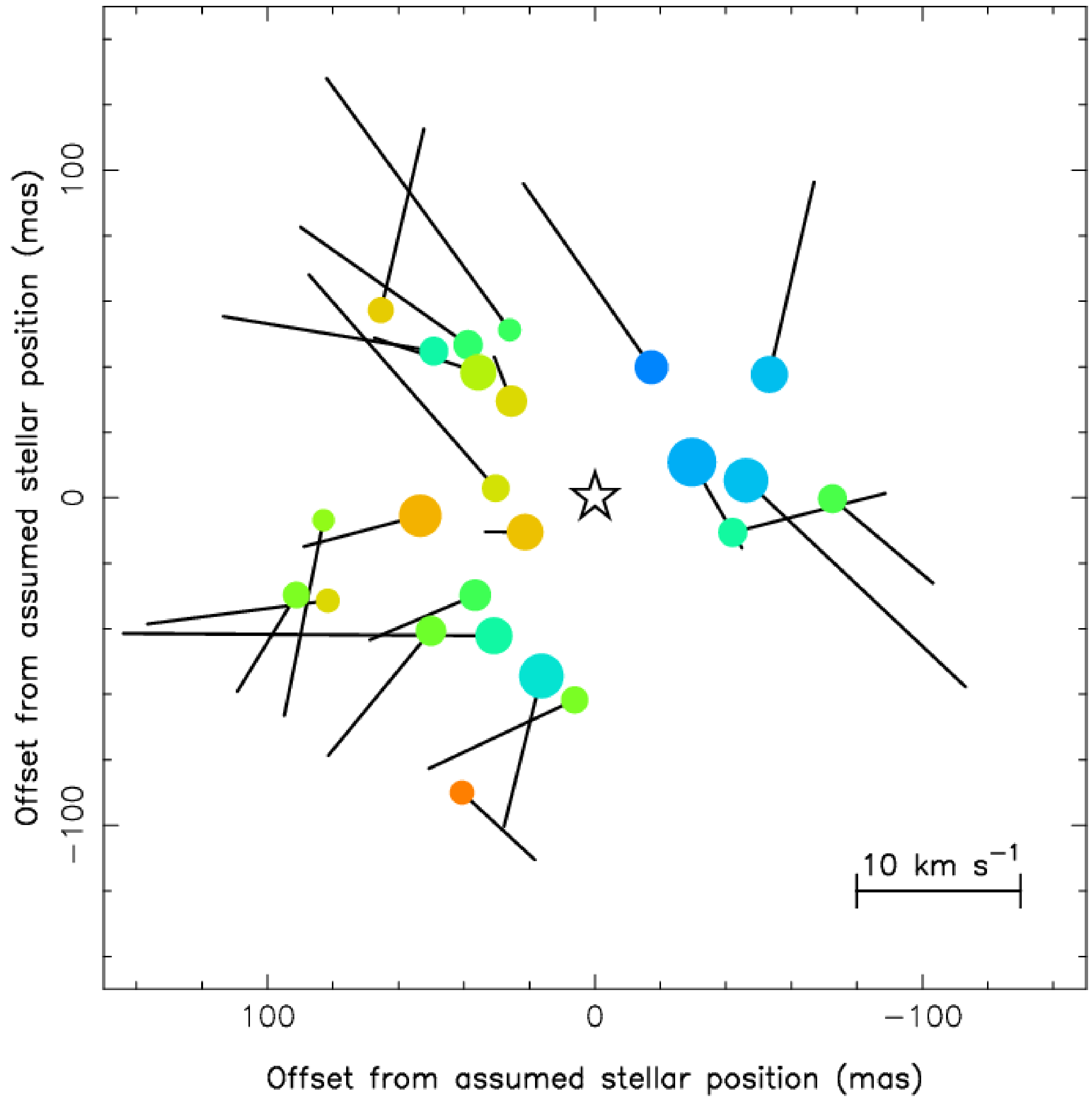
- RT Vir: 6 epochs observed in 10 weeks
  - 11 features seen at all epochs



Expansion and acceleration



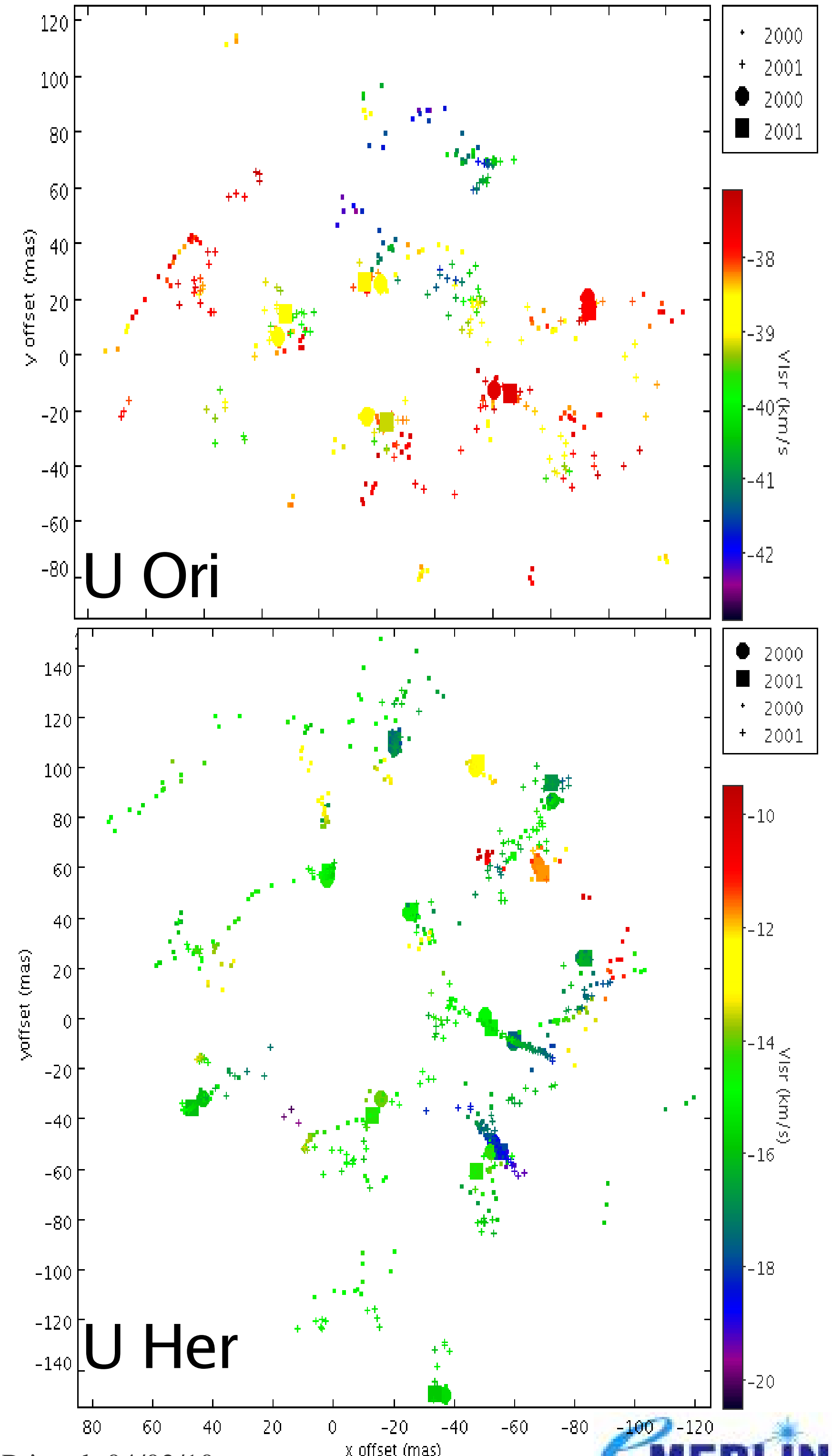
- V_{LSR}'s suggest radial expansion, acceleration
  - Proper motions consistent with V_{LSR}
  - No systematic rotation
  - Shell is elongated &/or has denser but faster equatorial belt



RT Vir cloud proper motions

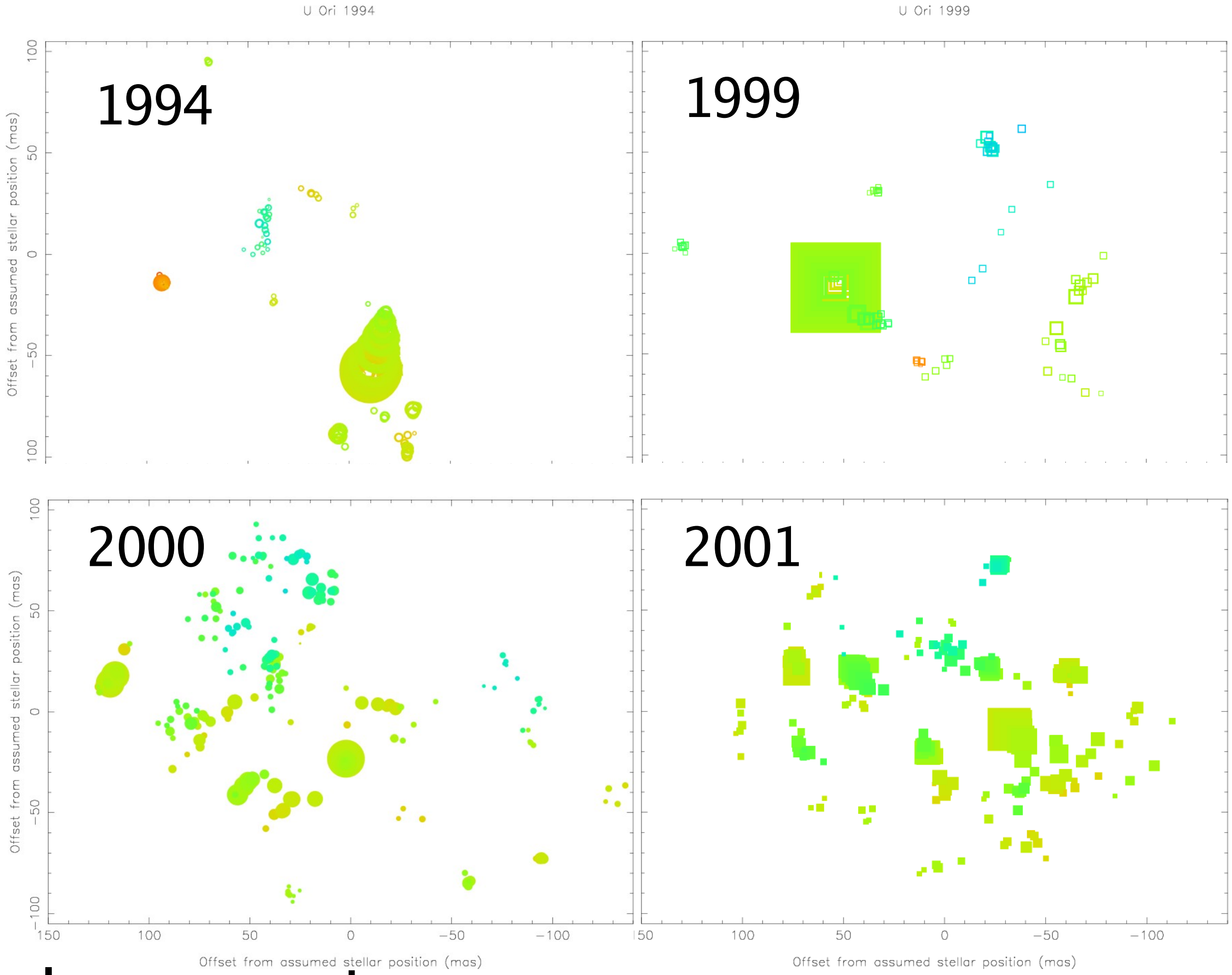
Maser survival

- IK Tau 1.5 yr expansion proper motions *Yates & Cohen 94*
- AGB maser features survive less than 2 yr
- U Ori: 5 clouds survive a year (**large symbols**)
  - no clear direction of motion
- U Her: **14 clouds matched** 2000 - 2001
  - Expansion 2.7(0.1) km/s
  - Rotation 0.3(0.1) km/s
    - Negligible rotation?

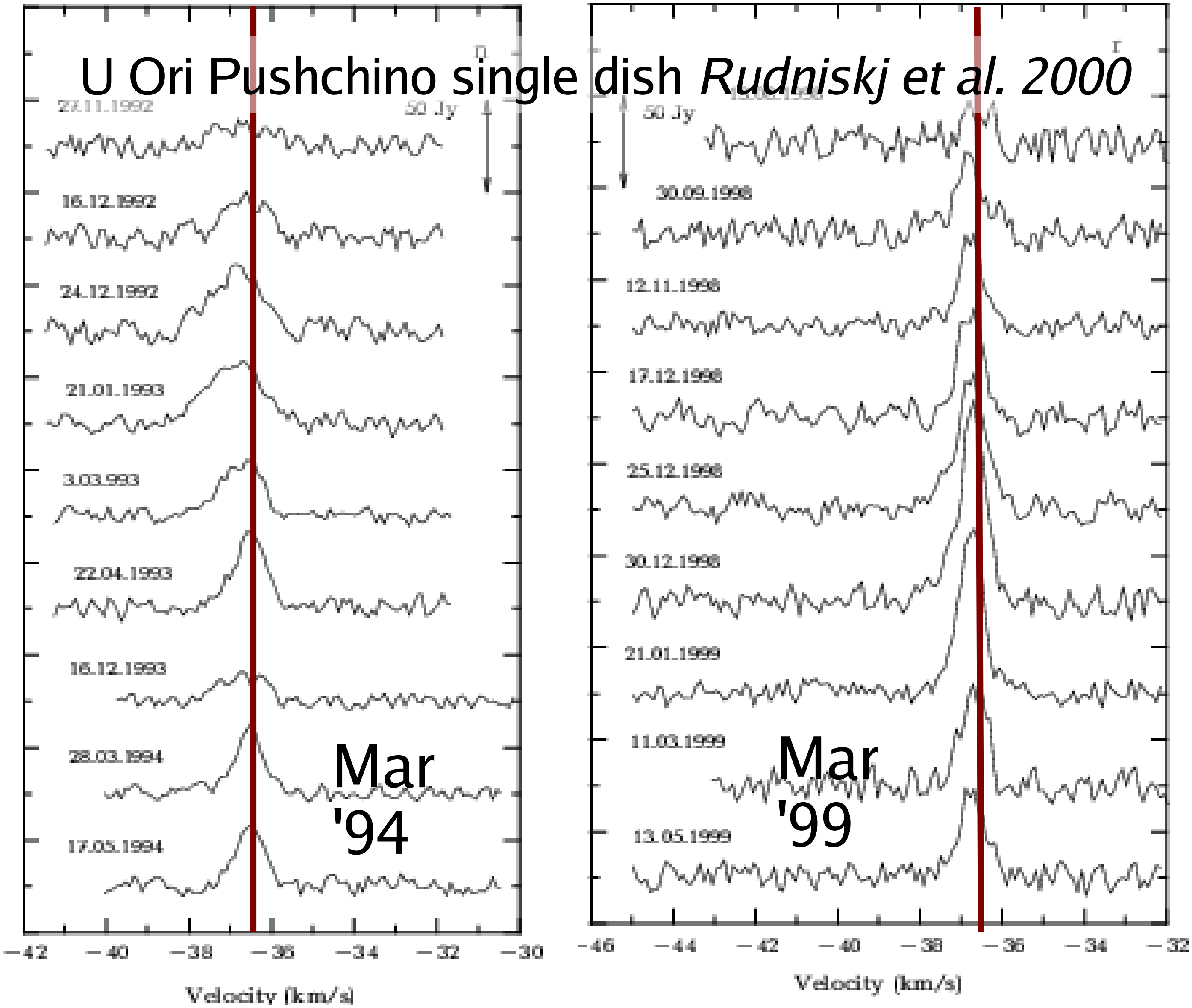


Maser variability

- U Ori shell 1994 elongated NE-SW
- Shape changes over the years
  - Masers dis/appear in different regions of shell
- Peaks at different position angles
  - But similar velocities and angular separations from centre of expansion



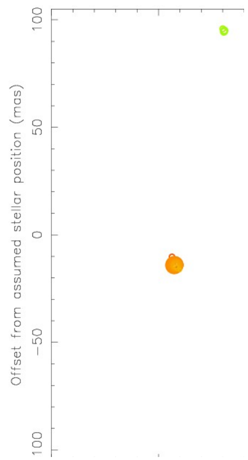
Cloud survival

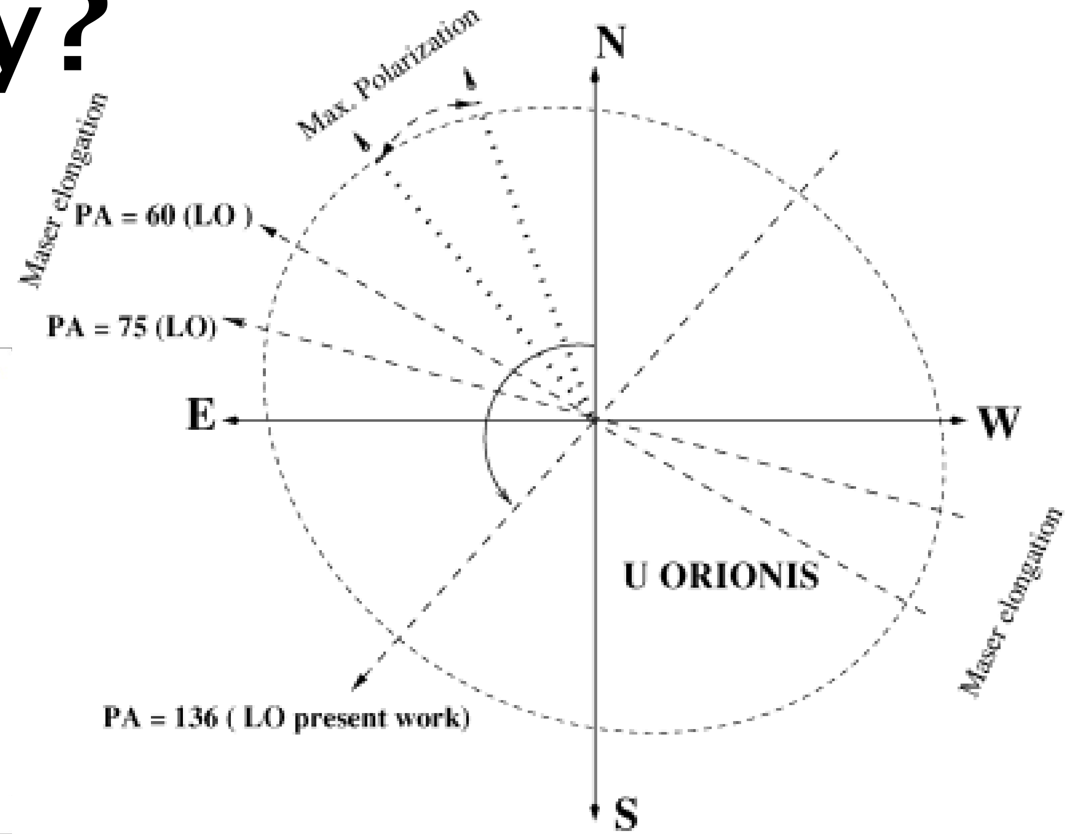


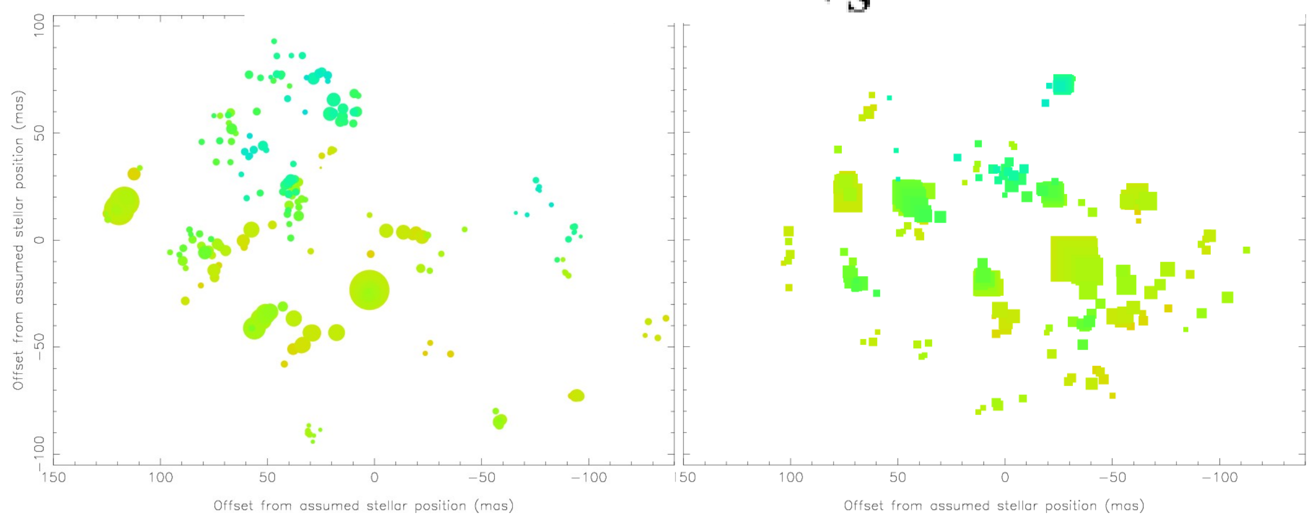
- AGB masers fade in <few yr
  - Cloud sound crossing time
- Shell crossing time >10 yr
  - Clouds must survive
- Masers wink on and off
  - Might see them from a different angle!

Stellar asphericity?

- VLTI talks
- U Ori 2000 lunar occultation 2μm
  - *Mondhal+ 2004*
- Is alignment coincidence?
  - Is shape persistent
- Need years of stellar shape monitoring
  - Astrometry vital
    - e.g. Pluzhnik et al. misaligned

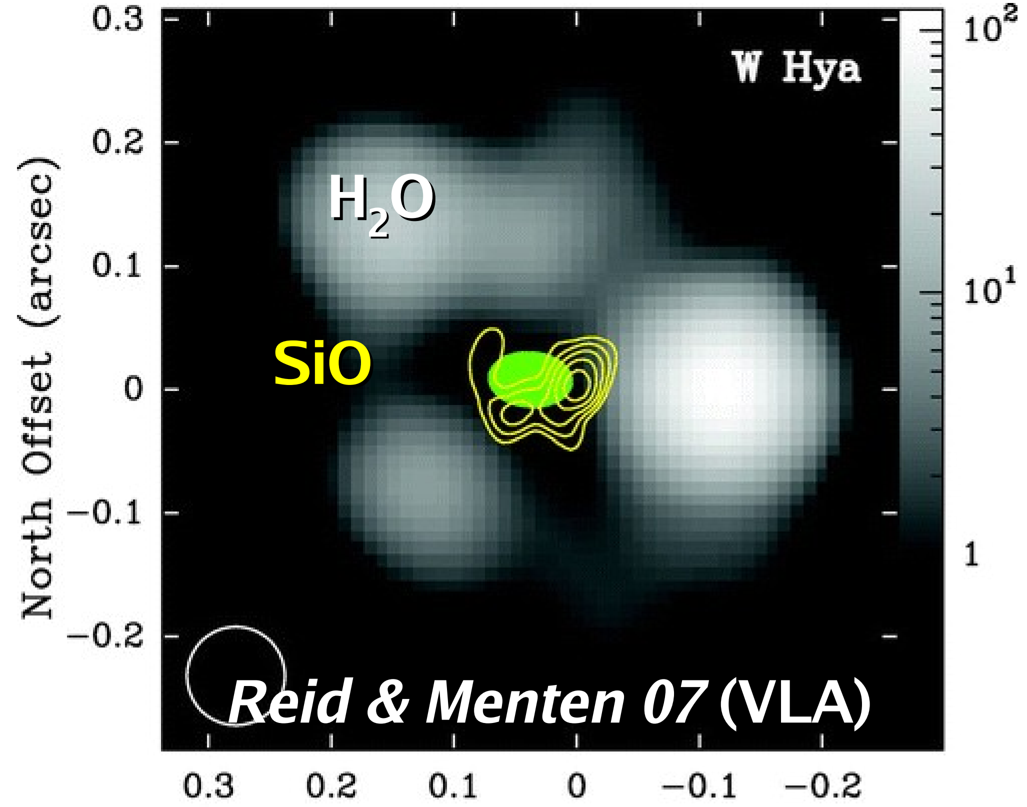


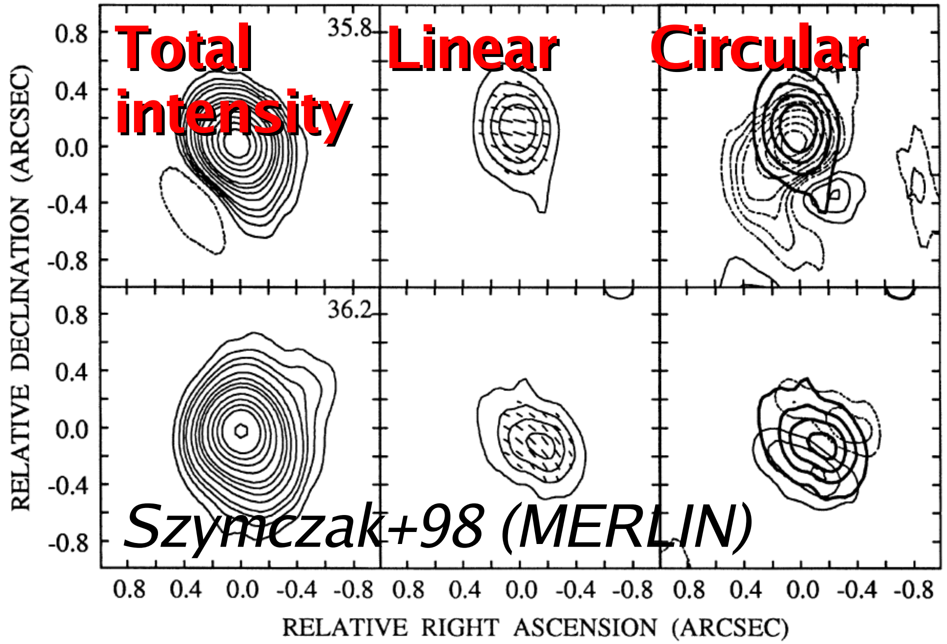




Magnetic axis?

- W Hya
  - Radio photosphere
    69 x 46 mas, PA 86°
    - Epoch 2000
  - OH mainline maser Zeeman splitting
    - Dipole?
  - Almost orthogonal magnetic axis
    - Epoch 1996
- Also see Szymczak, Vlemmings, Kemball, Diamond etc.
  - Hard to establish persistent orientation





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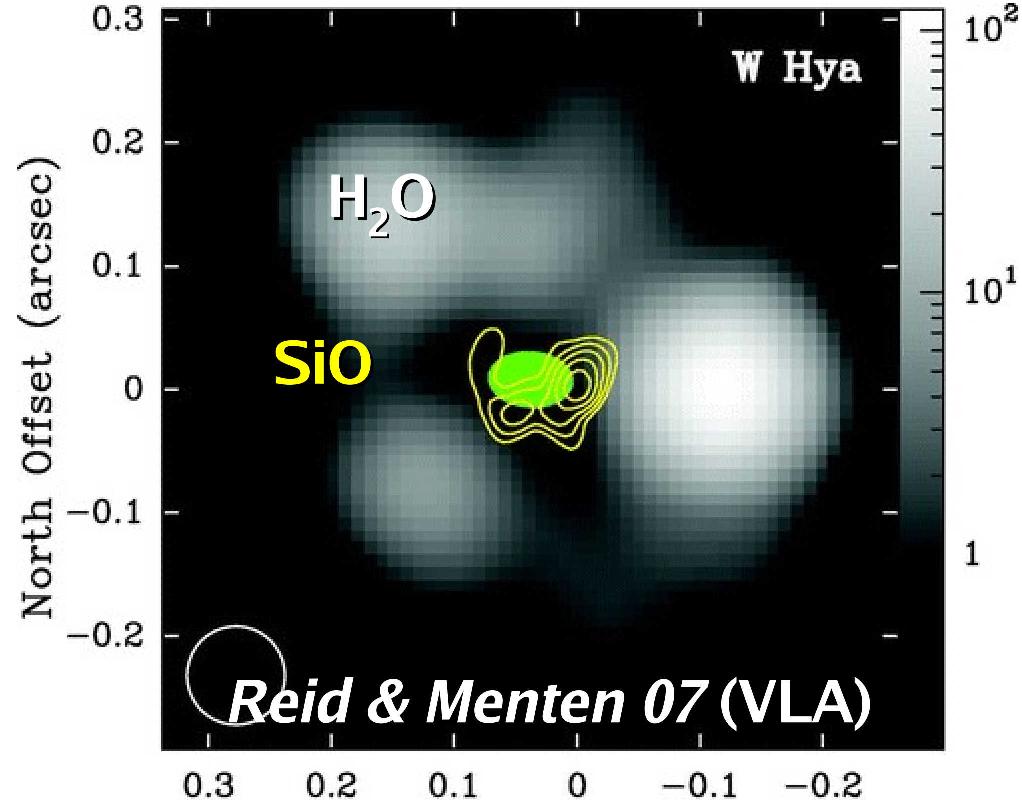
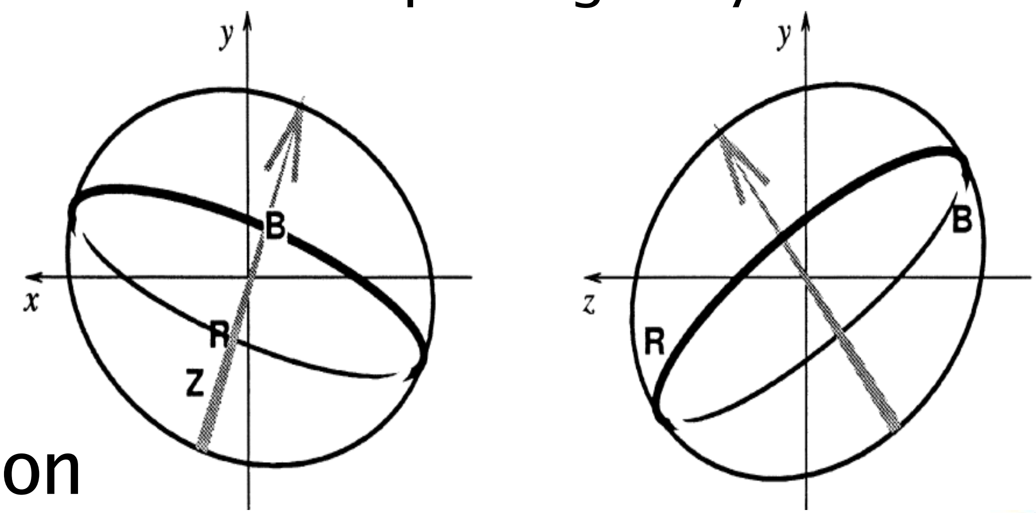
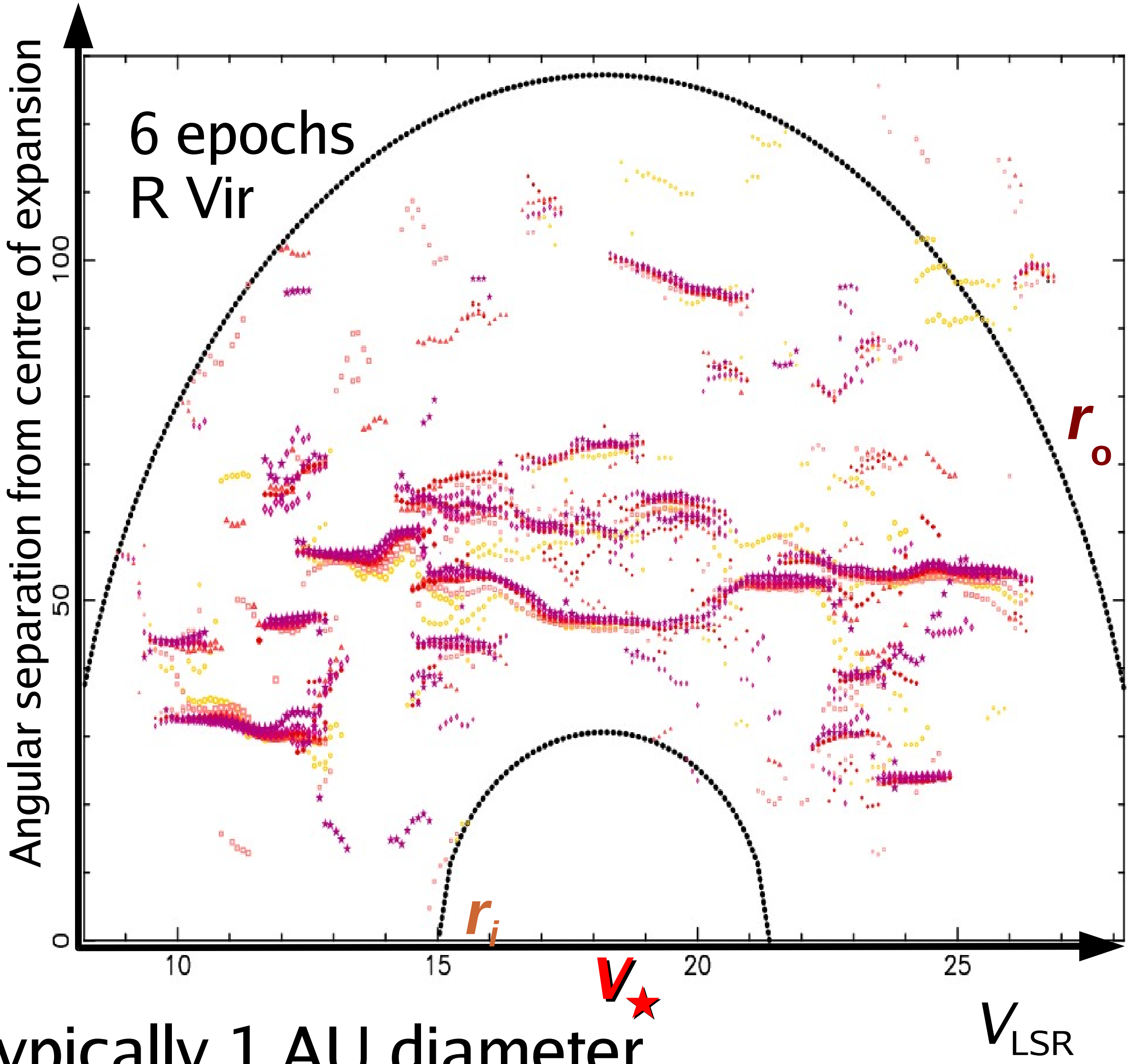


OH magnetic field ~0.6 mG, axis PA -20°
pointing away from us in N at 35°



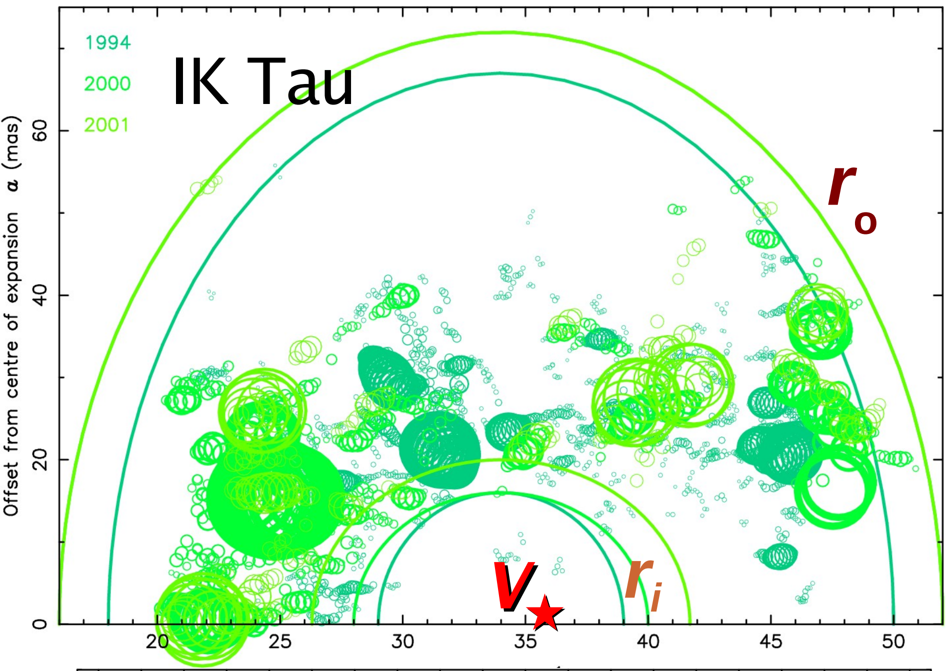
Water maser cloud density

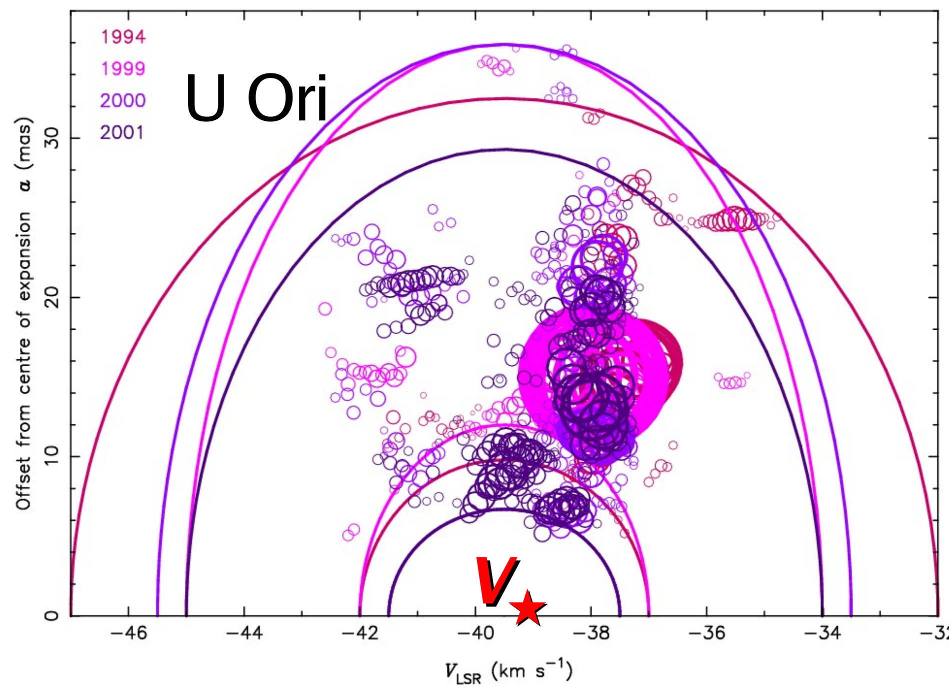
- Inner edge of maser shell r_i ~5 -10 AU
  - Collision rate quenches masing (*Cooke&Elitzur 85*)
  - Quenching density $n_q(r_i)$ ~5x10^{15} m^{-3}
  - >> wind density interpolated from CSE average
    - $n(r_i)$ $\dot{M}_{(CO, IR)}$ ~$10^{14}m^{-3}$

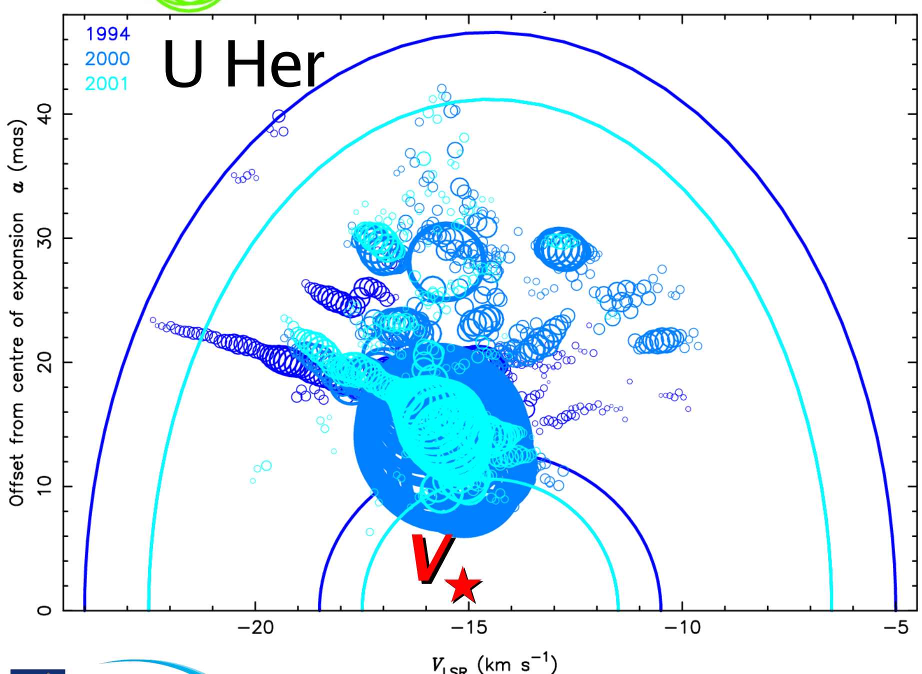


- RT Vir H_2O clouds typically 1 AU diameter
  - Clouds 50 –100 x overdense

AGB maser clouds







- R_o ~25 –50 AU
  - 10 - 100 maser clouds per shell
    - Filling factor ≲1%
  - Shell crossing time ~(few) decades
    - 1- few clouds / period

Maser cloud properties

Mira SRb	d*M*/dt CO/IR ($M_\oplus$ yr^{-1})	H_2O shell r_i (AU)	H_2O shell r_o (AU)	H_2O over-density	Number of H_2O clouds	H_2O cloud size <L>(AU)	OH shell r_i (AU)
U Ori	~0.08	9	34	100	15-30	2 –5	60
U Her	~0.12	11	45	240	35-45	2 –5	35
IK Tau	~9	17	70	45	40-250	2 –4	160
RT Vir	~0.05	5	22	115	40-60	1 –1.5	13

- H_2O clouds much denser than surroundings/OH gas
  - Filling factor ≲1%
- Cloud mass 0.01 –0.1 $M_\oplus$
  - 1- few clouds / period
  - 30% –95% of mass loss is in clouds

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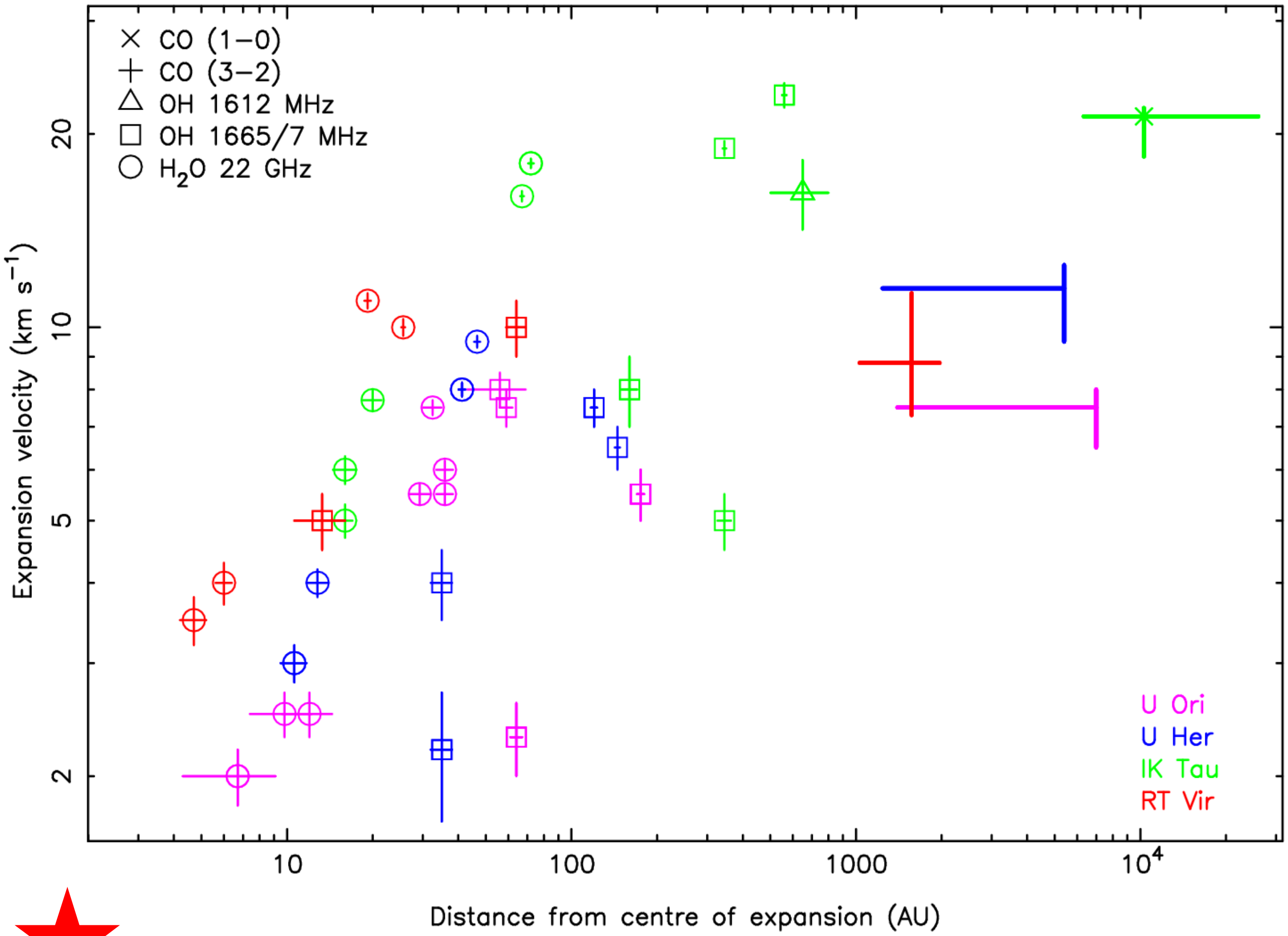
Dust-driven wind acceleration

- Bounds of resolved maser shells
  - CO outer limits
- Wind accelerates to 100s AU
  - Dust absorption coefficient increases
  - $\kappa_D \propto r$
    - *Chapman & Cohen 86*
  - IR shows dust properties evolve
    - *Verhoelst et al.*



Data: *Bains+ 2003*, tab. 1 refs, ongoing work

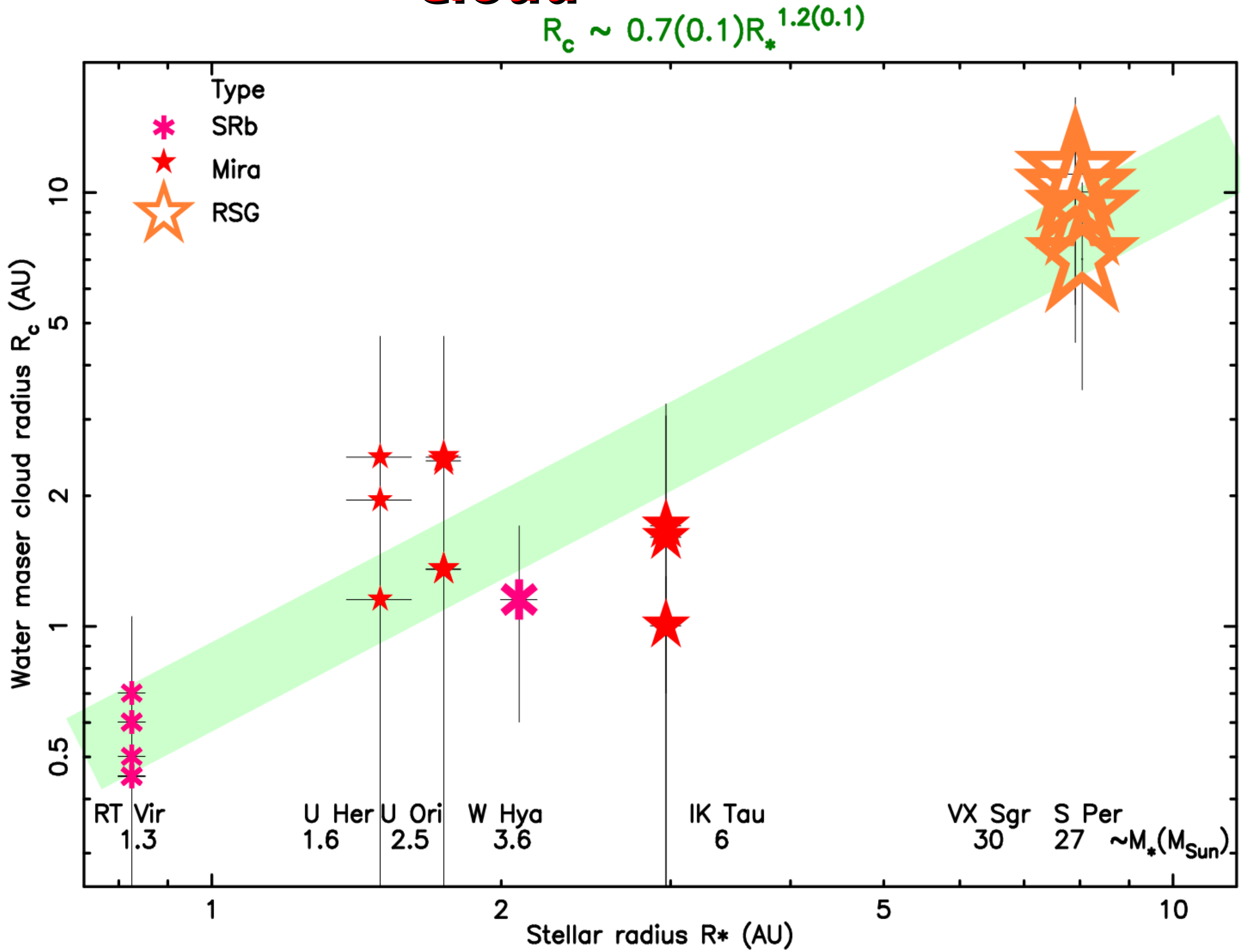
Maser results and prospects

- Kinematics
  - 0.1 km/s or better velocity resolution
  - Position accuracy ~ synthesized beam/SNR
    - 10 –100 μas VLBI –MERLIN
    - Proper motions in weeks: **full 3D structure,** distance
- Size and evolution of emitting material
  - Interpreting shapes is model-dependent
    - Distinctive amplification from shocks v. spheres
- Magnetic fields (stellar origin?) *Vlemmings*
- Evolutionary stage (rapid post-AGB changes)
- Physical conditions (model-dependent)
  - Constrain density, temperature, τ(pump/cascade photons)
    - Helps to have multiple transitions
  - ALMA: excited H_2O around 180, 300, 600 GHz...
    - Some inside dust formation radius, some outside

TX Cam (*Diamond & Kemball*)

- SiO masers within a few $R_\star$
- See Wittkowski et al. Posters
- Region probed by excited H_2O masers

H_2O maser $R_{cloud} \propto$ Stellar mass $M_\star$

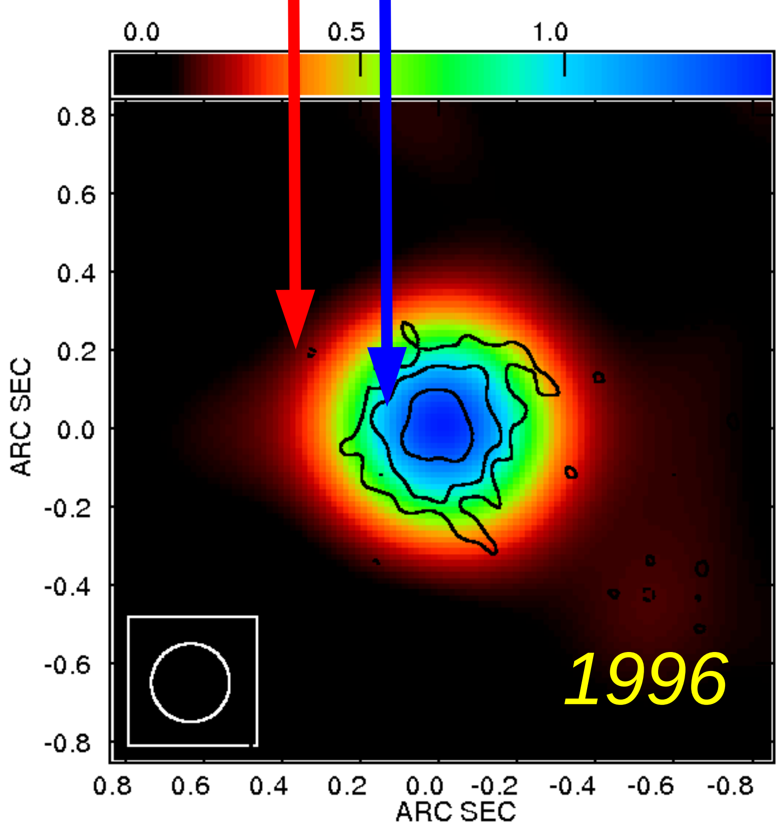


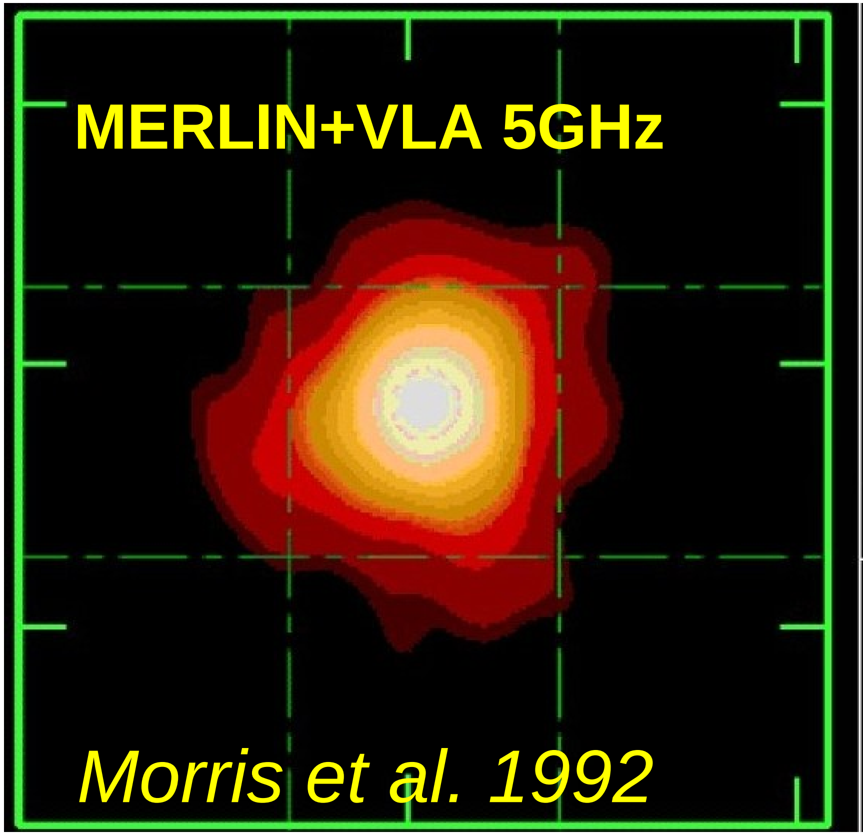
R_{cloud} set by star properties?

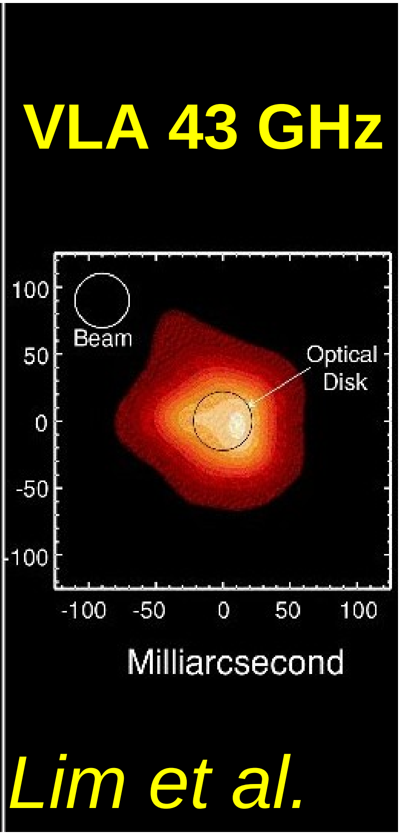
- Esimate Stellar mass *Wood 89*
  - $\log M_\star = (-2.7 + 1.94 \log R_\star - \log P) / 0.9$
  - *P*eriod from AAVSO, GCVS, *Etoka+01*
  - Measure stellar radius $R_\star$ from opt/IR interferometry
    - *Skinner+88, Mennesson+02, Monnier+04, Ragland+06*
- Cloud size is a function of stellar mass and radius
  - In water maser shell $R_c \sim 0.7 \pm 0.1\ R_\star^{1.2 \pm 0.1}$
- ***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 $M_\star$
  - $R_{cloud} \propto R_\star$ (birth radius $0.1 R_\star$ if outflow expands as r^{-2})

Resolving Betelgeuse

- Only well-resolved star (apart from Sun)
- VLA barely resolves at 5 GHz (colour scale)
  - Old MERLIN only detected hotspots at 5 GHz
  - Combined image shows details (contours)





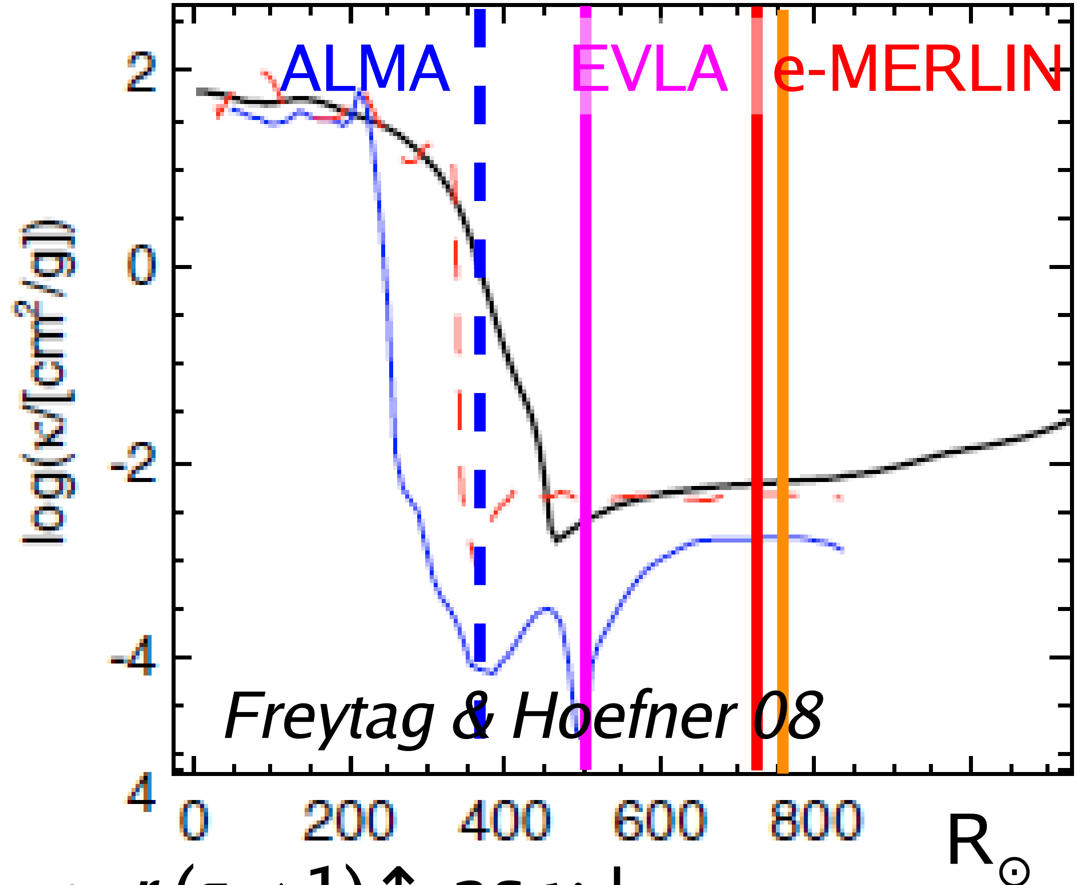


e-MERLIN + EVLA stellar imaging

- Beam 10-50 mas *e*-MERLIN &/or EVLA
  - K-band (21 - 26 GHz), Q-band (<50 GHz)
  - 10 - 100 resolution elements per star
    - Persistent axisymmetry would imply magnetic axis
    - Variations: convection or non-radial pulsations
- α Ori: 250 μJy/beam peaks @ 22 GHz
  - Need σ_{rms}< 17 μJy/beam to detect 20% fluctuations
  - e.g. 12 hr *e*-MERLIN, 1.5 hr EVLA per epoch
- AGB/ RSG: masers for calibration (*Reid & Menten*)
  - $R_\star$ 15-40 mas @22 GHz, 1 - few mJy total flux

Different ν's trace different layers

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



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

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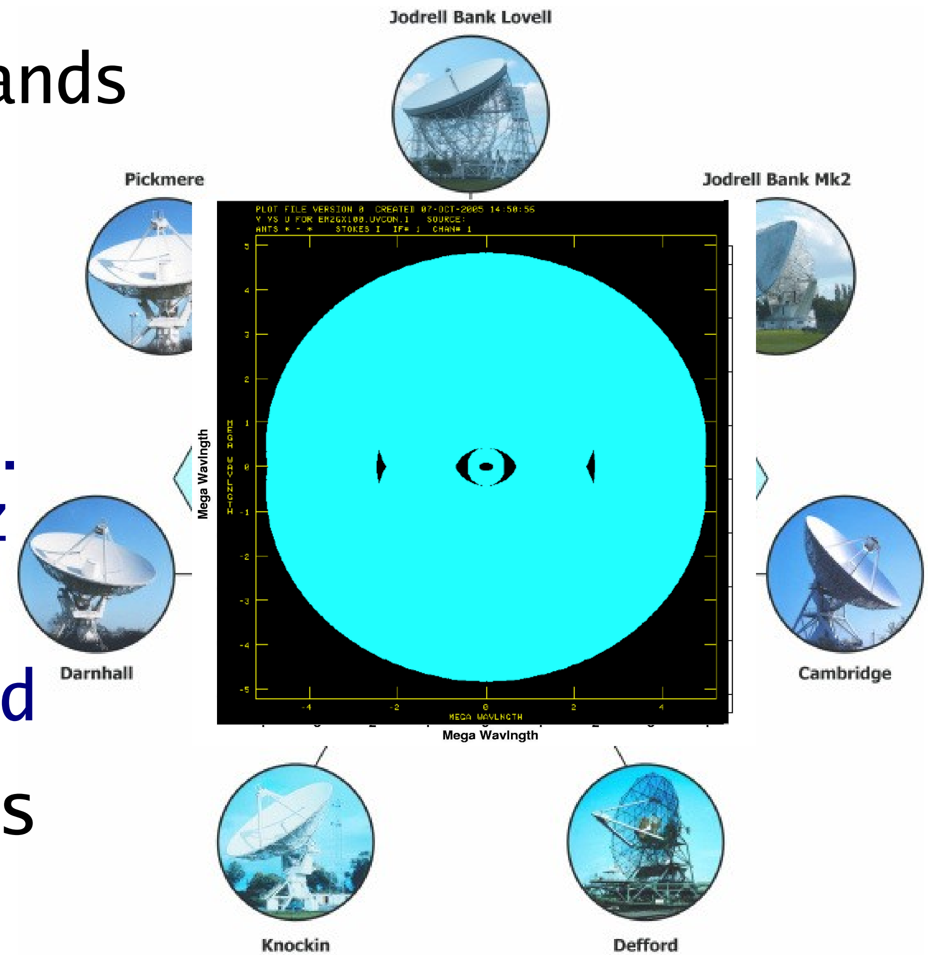
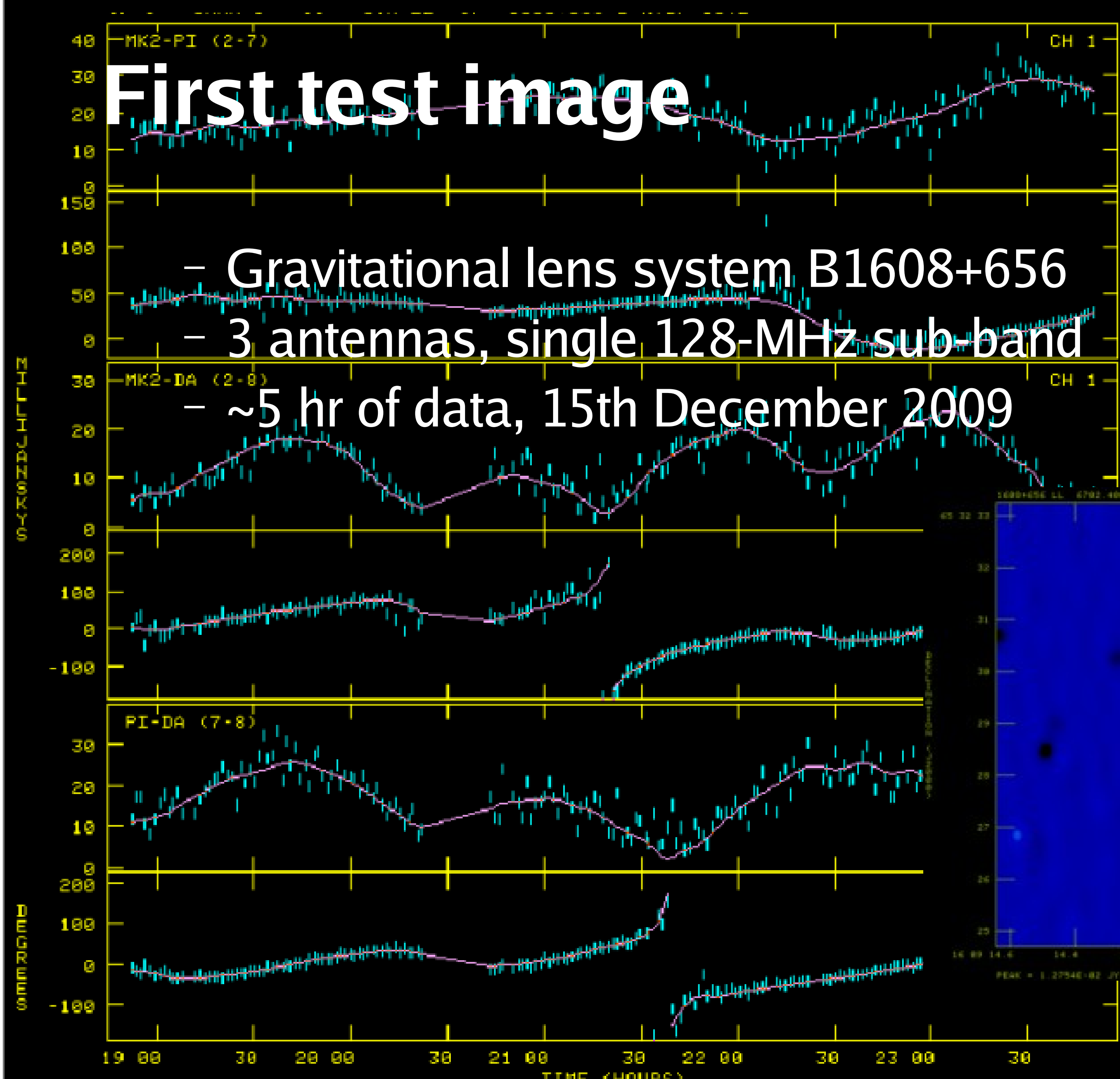
What is eMERLIN ?

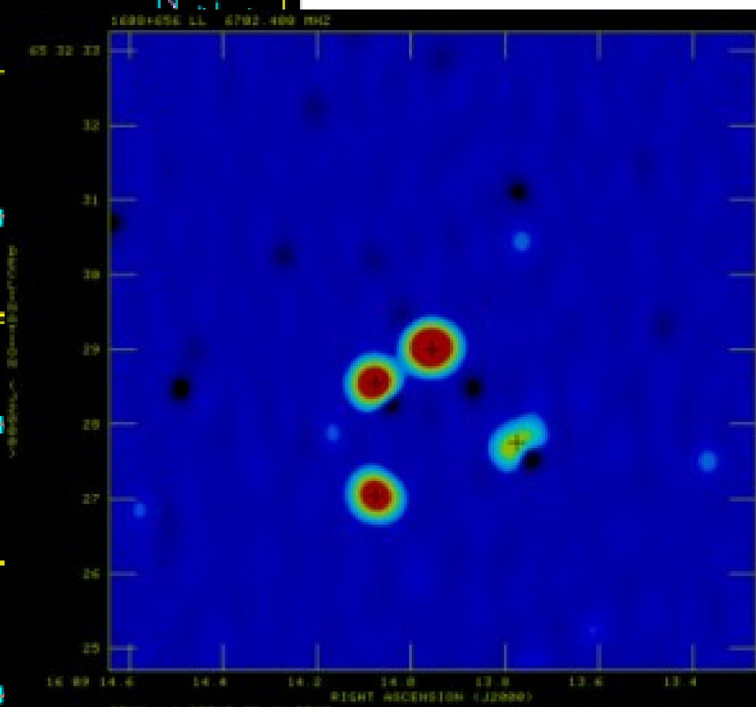
- UK radio interferometer
  - 1.3-1.7, 4-8, 21-26 GHz wavebands
    - λ 22 - 1.2 cm
  - 200 - 10 mas angular resolution
- *Upgrade to e-*MERLIN
  - Optical fibres, Rx, correlator etc.
  - 2 GHz bw ~fills aperture<8 GHz
  - μJy continuum sensitivity
  - Spectral line sensitivity >doubled
- 7 antennas, $\lesssim$217 km baselines
  - Five 25-m dishes, one 32-m
  - Upgraded Lovell 75-m at $\nu \lesssim$8 GHz



First test image

- Gravitational lens system B1608+656
- 3 antennas, single 128-MHz sub-band
- ~5 hr of data, 15th December 2009

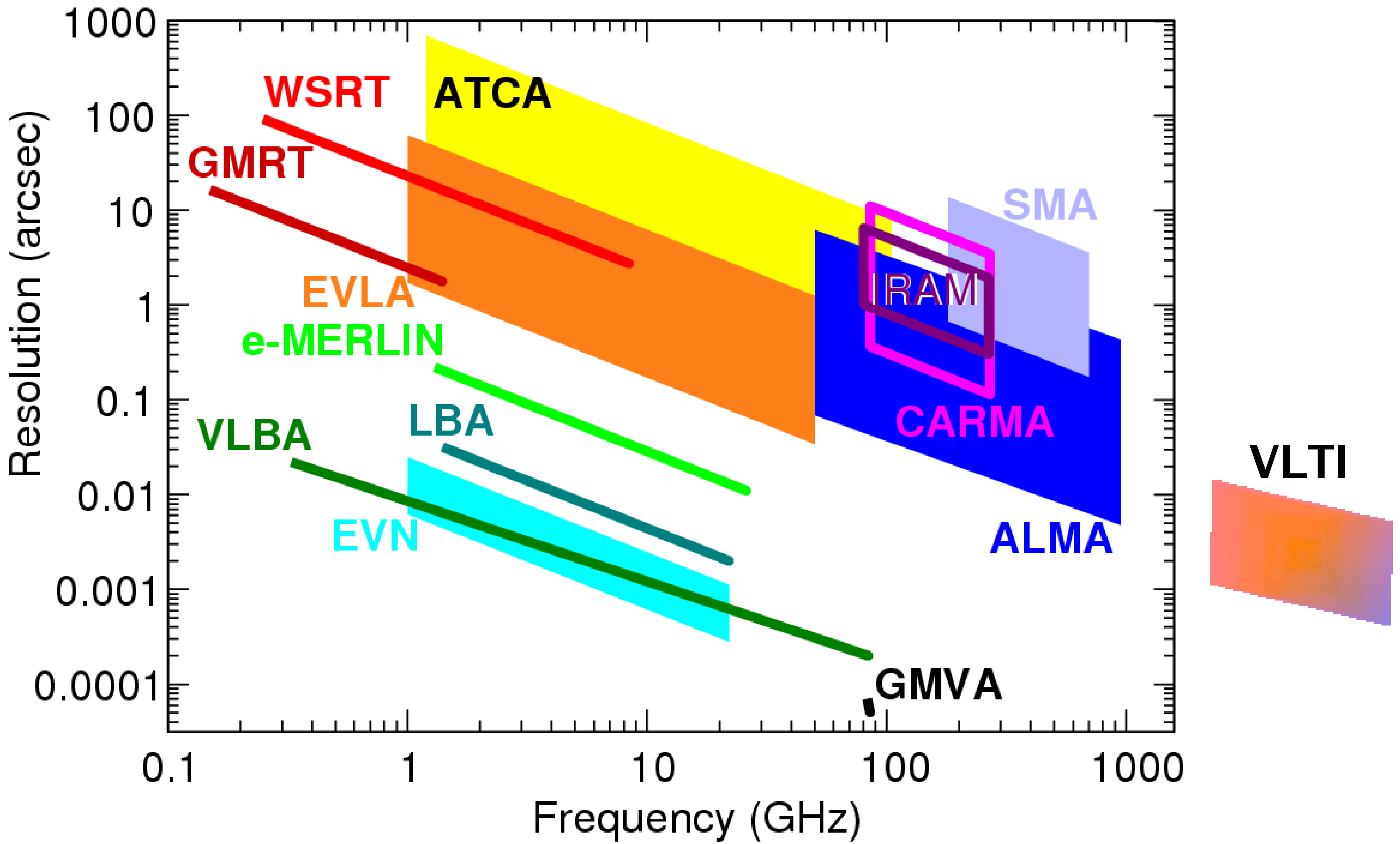




e -MERLIN capabilities

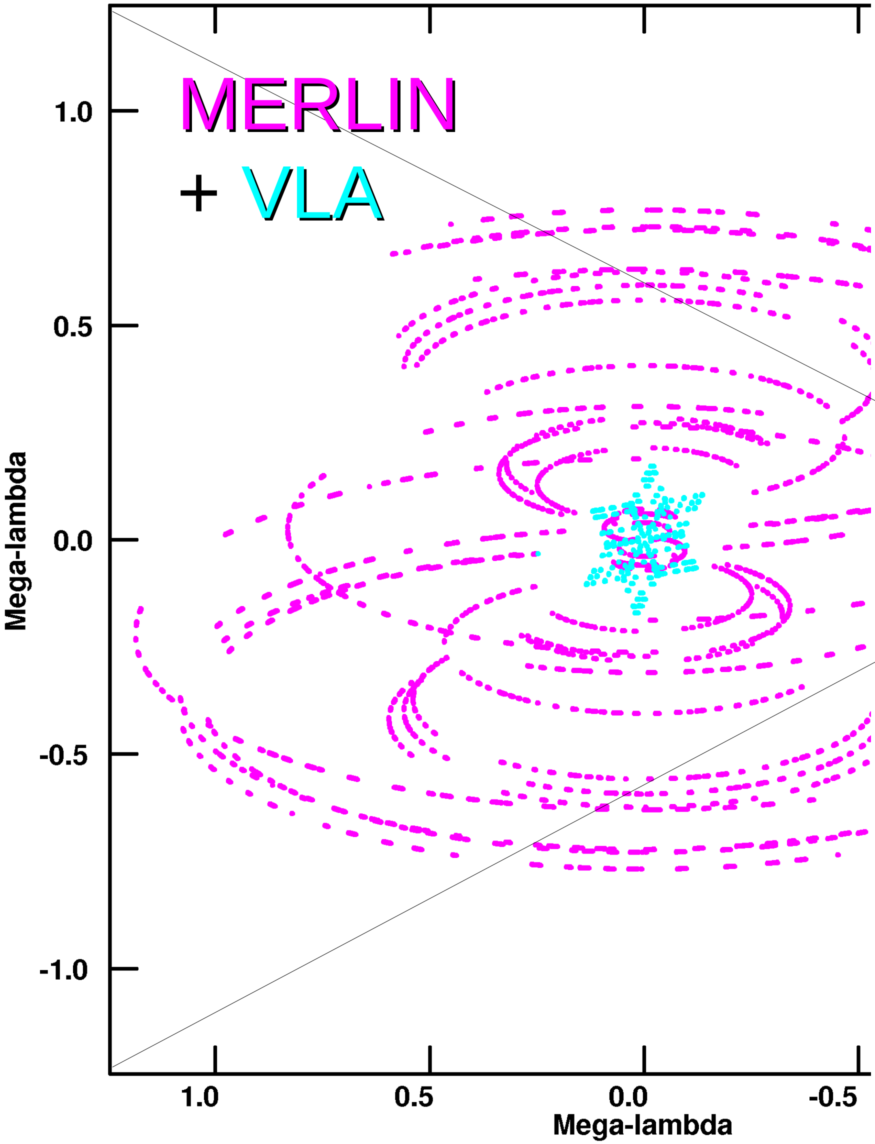
- Resolution matches HST/JWST/ALMA
  - Sub-mas ICRF astrometry, in-beam calibration
  - Full polarization
- 6 μJy 3-σ sensitivity in 12 hr at 4-8 GHz (2-GHz bw)
  - 40-mas resolution, up to 8-arcmin field of view
- ~15 μJy continuum sensitivity at other frequencies
- Spectral line sensitivity 7-20 mJy in 0.1 km/s
- Early science later this year
  - Open access (via UK PATT peer review)
  - Joint observations with EVN/ Global VLBI
- http://www.e-merlin.ac.uk

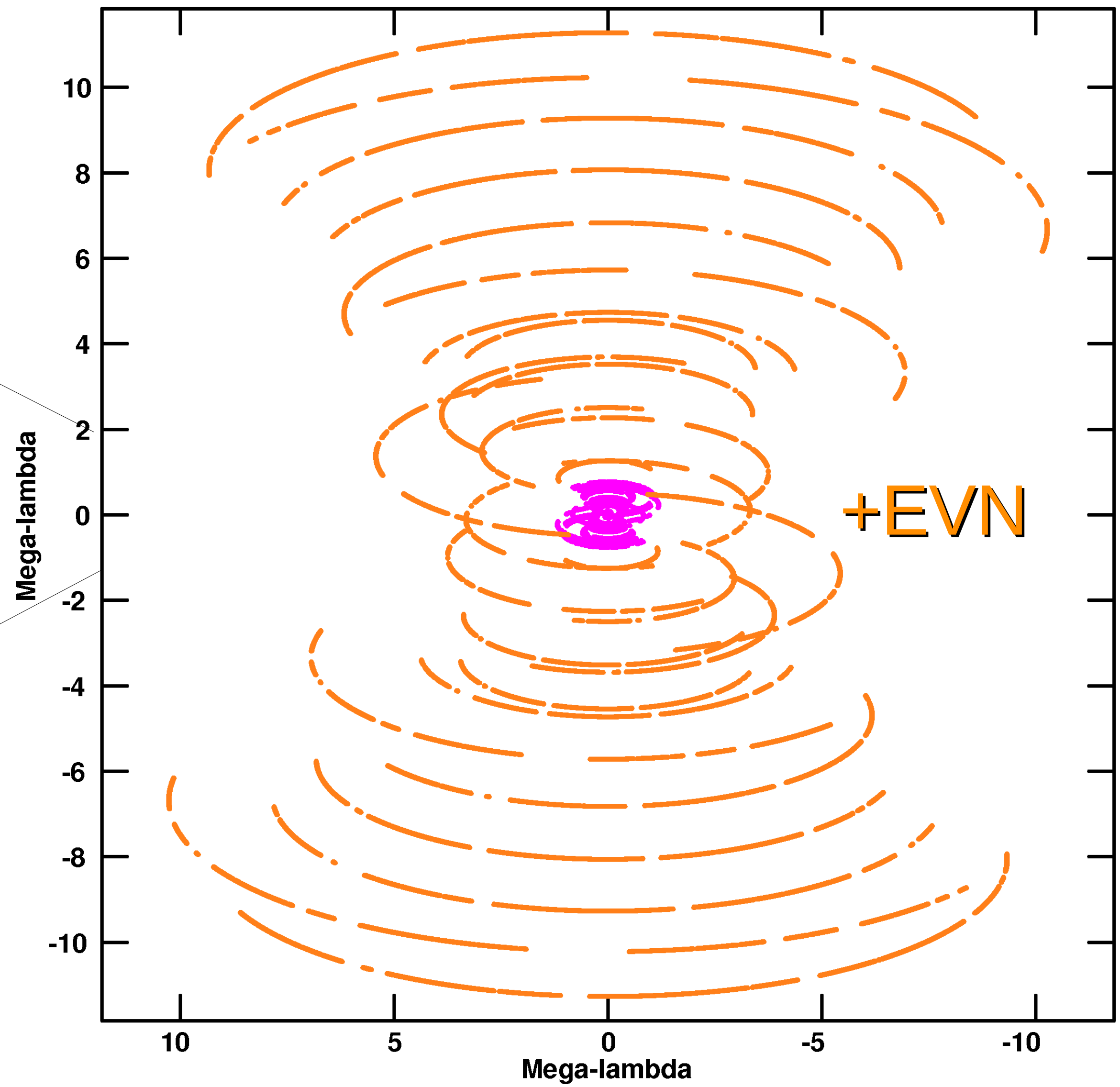
Radio array imaging capabilities



e-MERLIN complements EVLA, VLBI

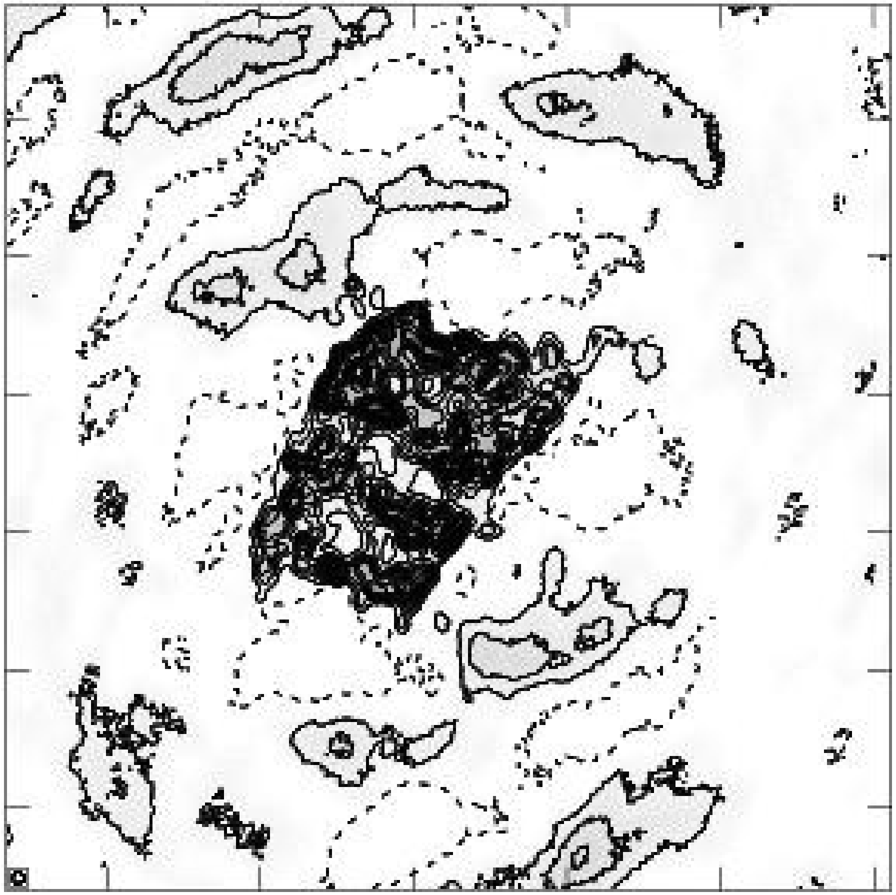
– Spectral line *uv* coverage at 1.6 GHz

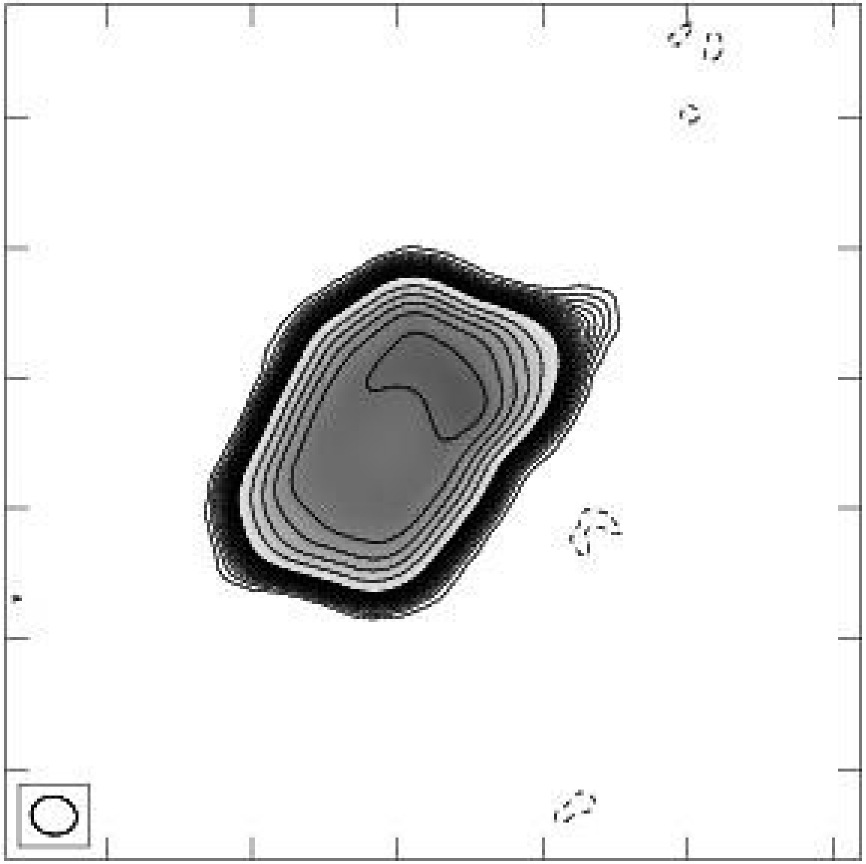




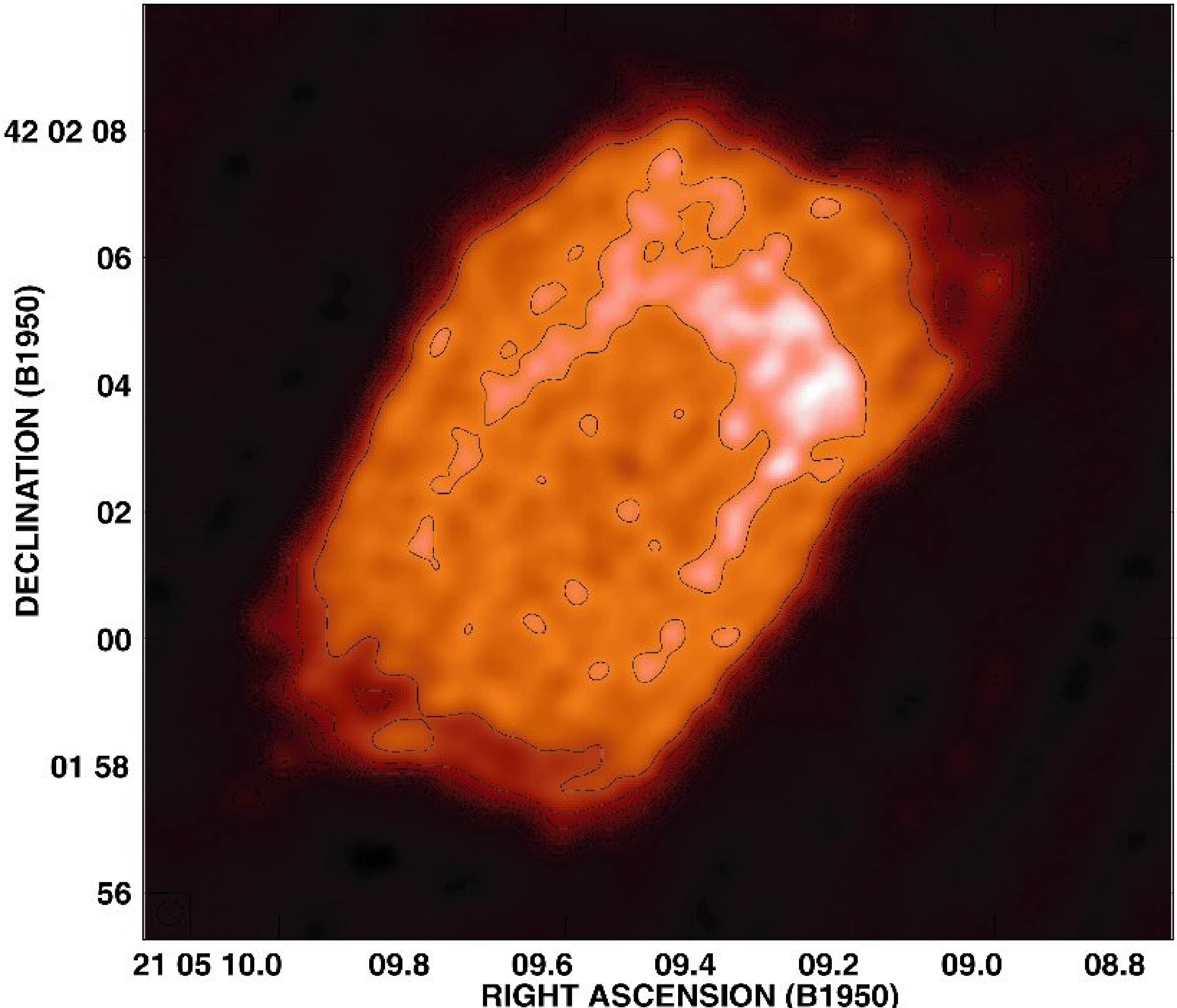
PNe in all their glory

- e-MERLIN+EVLA resolve α, T*e*, τ etc (*Zijlstra*)
- NGC 7027: MERLIN loses flux, VLA loses detail





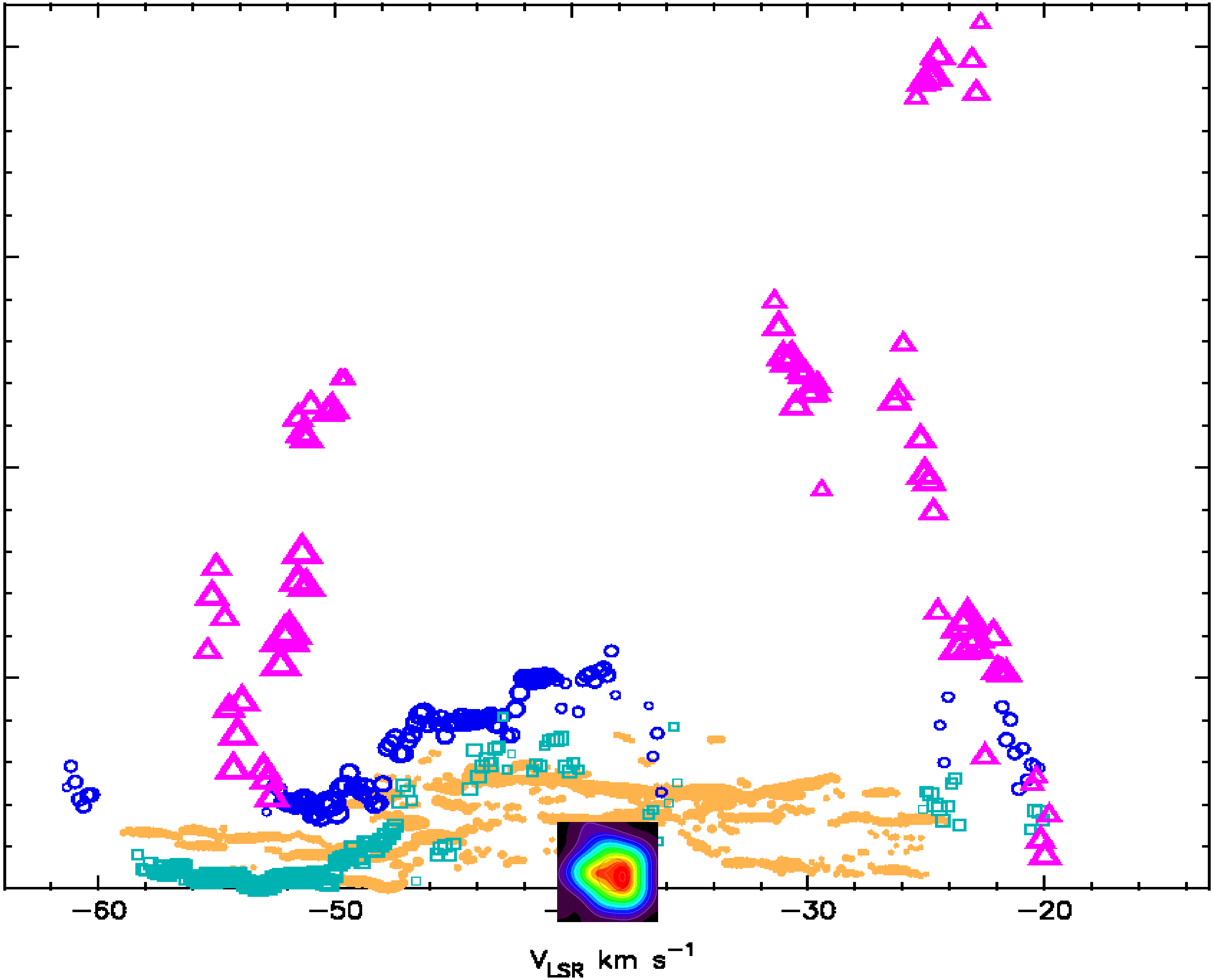
PNe in all their glory



MERLIN *and* VLA detect *and* re-solve full details (Bains et al.)

Track wind from photosphere to ISM

- 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 photo/ radiosphere
  - *e-MERLIN/ EVLA, VLTI, MROI*
  - *Different ν ≡ different depths*



Resolvable stellar continuum

Star	D (pc)	Type	$R_\star$ (mas)	R_{22} (mas)	H_2O?
W Hya	95	SR	21.3	**40**	y
η Gem	107	SR + G+M	6.3	12 - 10	n
o Cet	110	Mira + WD	22	35 - 30	faint
α Her	117	Mgiant + G + ?	16	25 - 20	n
CW Leo	130	C-RSG	35	*100+* - 50	n
RT Vir	133	SR	6.2	29 - 12	y
α Ori	190	RSG	23	**55**	n(?)
R Aqr	220	Symbiotic Mira	9	*18+* - 15?	faint
IK Tau	266	Mira	11.2	14 - 22	y
U Her	266	Mira	5.4	14 - 11	y
U Ori	266	Mira	6.7	14 - 13	y
VY CMa	1500	RSG	9.4	*19+* - 17	y
VX Sgr	1700	RSG	4.4	9 - 15	y
NML Cyg	2000	RSG	3.9	8 - 13	y
S Per	2300	RSG	3.5	7 - 12	y

- 22 GHz flux likely to be >60 μJy per 10-30 mas beam
- **Bold**: resolved *RM 97, Lim+98*
- *Italic*: may be wind contribution *Menten+06, Lipsky+05*

e-MERLIN capabilities

- Sub-mas ICRF astrometry, in-beam calibration
- Full polarization
- Resolution matches HST/JWST/ALMA
- μJy sensitivity in 12 hr

	L-band	C-band	K-band
GHz/cm	1.3-1.725 / 23-17.4	4.2-7.8 / 7.1-3.8	21.5-24.5 / 1.4-1.2
Ang. resol'n	220 - 110 mas	70 - 30 mas	13 - 8 mas
FoV	13 - 30 arcmin	4 - 7 arcmin	2 arcmin
Continuum	sensitivity /beam	sensitivity /beam	sensitivity /beam
	(max Δν /subband)	(max Δν /subband)	(max Δν /subband)
3σ 12 hr / 4 hr	14 μJy / 25 μJy	6 μJy / 10 μJy	15 μJy / 26 μJy

Spectral capabilities

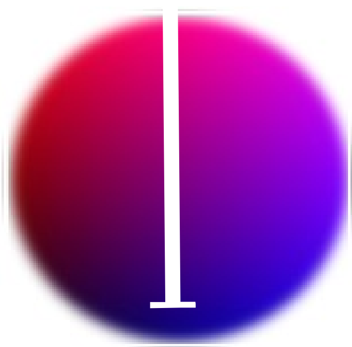
- Resolution $\delta\nu \geqq 2$ Hz ($\lambda/\delta\lambda \leqq 7\times10^8$ @ 21cm)
- Transfer calibration between lines and continuum
  - 2-3x better sensitivity due to better Rx & calibration
- Multiple lines and continuum simultaneously
  - Easy to match spectral configuration with EVLA/VLBI

Spectral	L-band	C-band	K-band
3σ 12 hr / 4 h	sensitivity /beam	sensitivity /beam	sensitivity /beam
Lines:	(per channel)	(per channel)	(per channel)
0.05 km/s	23 mJy / 40 mJy	10 mJy / 17 mJy	32 mJy / 55 mJy
3 km/s	2.9 mJy / 5 mJy	1.3 mJy / 2.2 mJy	4 mJy / 7 mJy
Continuum	(max Δν /subband)	(max Δν /subband)	(max Δν /subband)
12 subbands	17 μJy / 30 μJy	8 μJy / 14 μJy	17 μJy / 30 μJy

Measuring 'true' maser cloud size

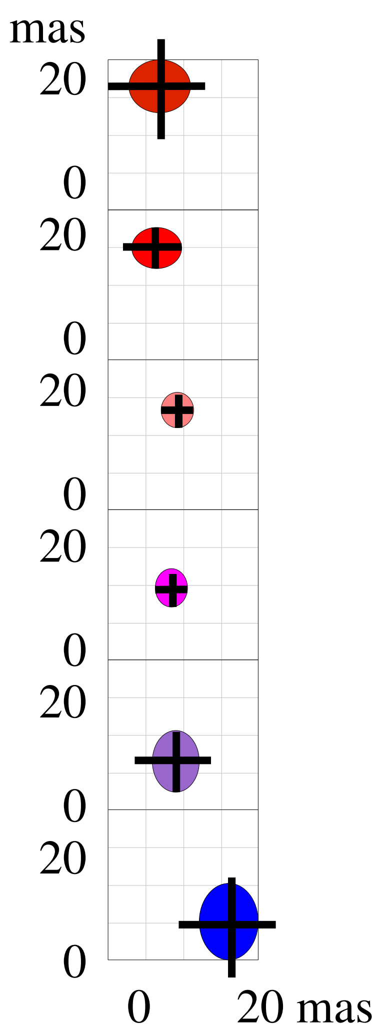
Cloud properties

Cloud *D*=18 AU at 1 kpc

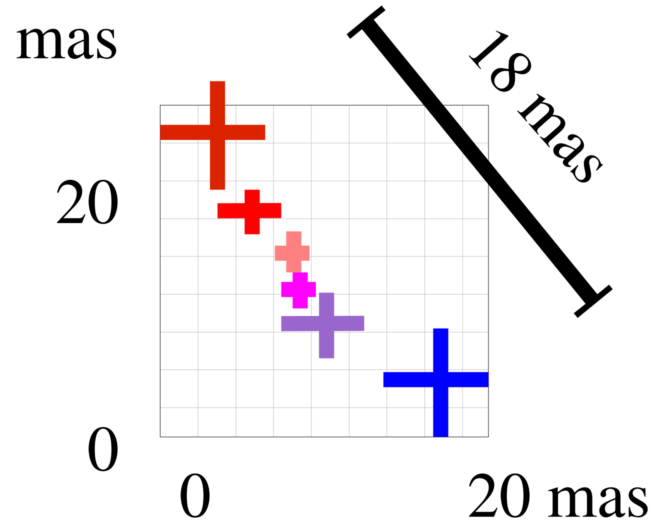


1.2 km/s total line width

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)