The life cycles of stars:
What VLBI can tell us

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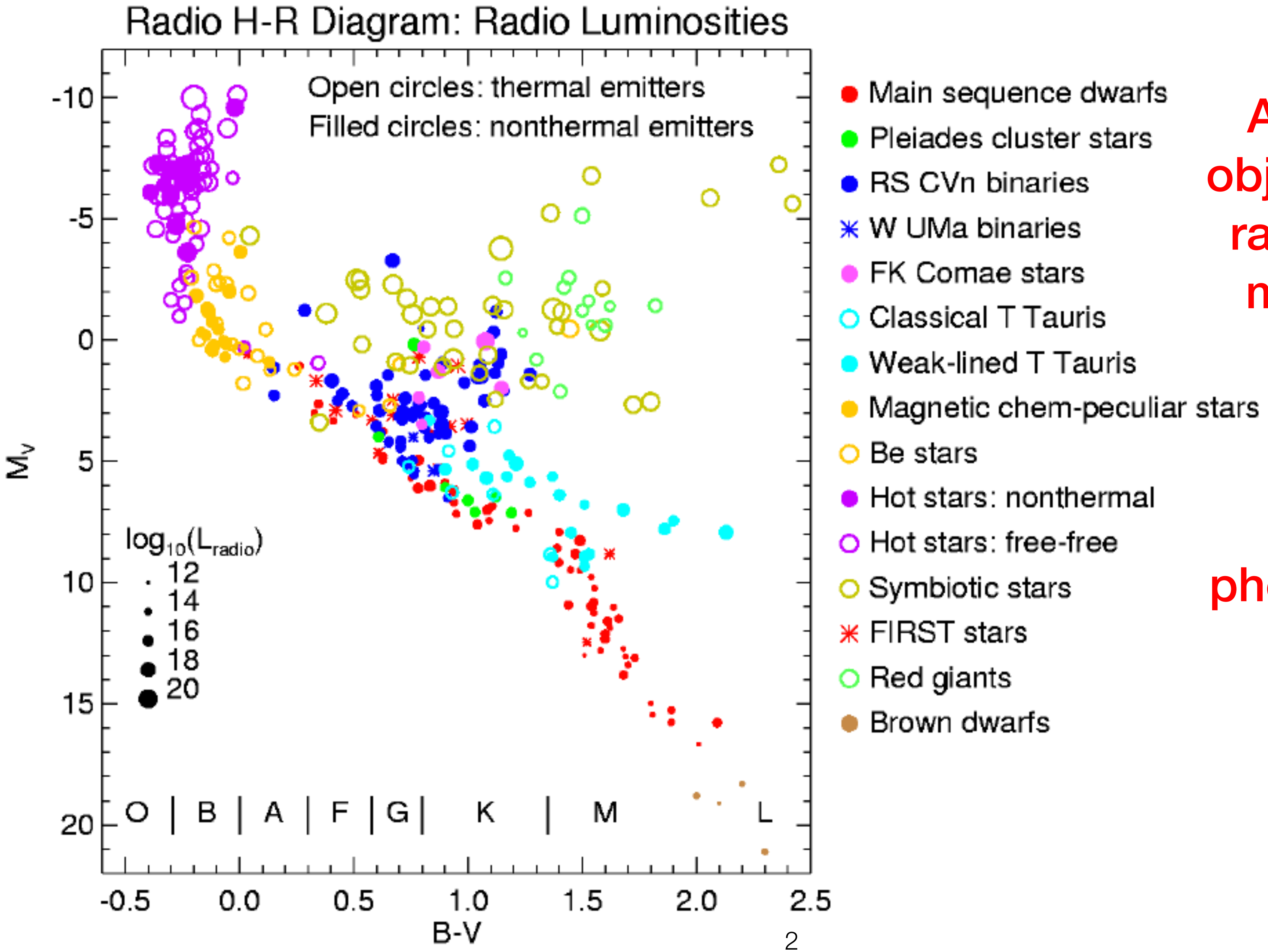
Space, Earth and Environment, Chalmers

Radio detections in HR diagram

Stephen White (Güdel ARAA 2002)



A diversity of object types and radio emission mechanisms,

&

rich in phenomenology.

Sensitivity & Resolution

This relation filters out what is detectable using VLBI in the radio HR diagram:

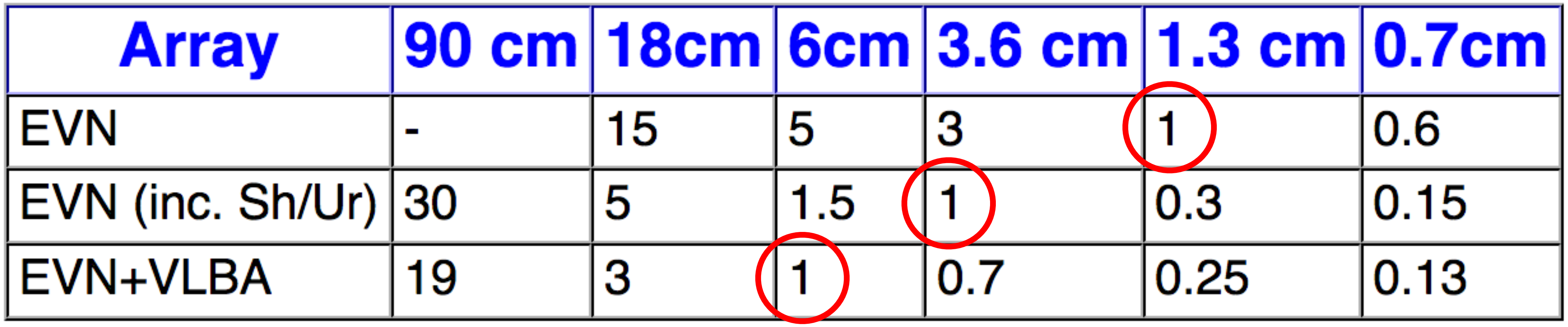
$$T_{\mathrm{b}} = 1.36 \times 10^{6} \left[\frac{S}{\mathrm{mJy/beam}}\right] \left[\frac{\lambda}{\mathrm{cm}}\right]^{2} \left[\frac{\mathrm{mas}}{\theta}\right]^{2} \ \mathrm{K}$$

We can expect the requirement of high brightness temperatures in order to resolve structures or perform astrometry at mas level!

Sensitivity & Resolution

A rich variety of VLBI setups: VLBA, EVN, Global, HSA, etc. (for future AVN, SKA-VLBI).

I have chosen the following table (maximum resolution in mas) as an illustrating example:



Array	90 cm	18cm	6cm	3.6 cm	1.3 cm	0.7cm
EVN	-	15	5	3	1	0.6
EVN (inc. Sh/Ur)	30	5	1.5	1	0.3	0.15
EVN+VLBA	19	3	1	0.7	0.25	0.13

1 mas at 1 kpc: 1 AU
1 mas at 100 pc: 20 R_{sun}
1 mas at 10 pc: 2 R_{sun}

Sensitivity & Resolution

	Band	S [μJy/beam] 8 hours	θ_b [mas]	T_b [MK]
EVN	L (Sh/Ur)	5.5	4	0.2
	C (Sh/Ur)	3.8	1.5	0.06
	K	17	1	0.04
Global (Y27/Gb)	L	1.9	2.5	0.13
	C	1.3	1	0.06
	K	3.7	0.25	0.14

Based on the EVN calculator and 1024 Mb/s and 2048 Mb/s in the L and C and K bands, respectively.

Radiation mechanisms & Phenomena

The wealth of radiation mechanisms mean that a wealth of different phenomena can be observed.

Incoherent:	**Bremsstrahlung (or free-free), thermal, broad,**	$T_b \approx 10^4$ K
	Gyro-resonance, thermal, features, polarized,	$T_b \approx 10^7$ K
	Gyro-synchrotron, non-thermal, broad, polarized,	$T_b \approx 10^9$ K
	Synchrotron, non-thermal, broad, polarized,	$T_b \approx 10^{12}$ K
Coherent:	**Electron cyclotron maser, features, polarised,**	$T_b < 10^{20}$ K
	Plasma emission, features, polarised,	$T_b < 10^{18}$ K
	Maser line emission, features, polarised,	high T_b

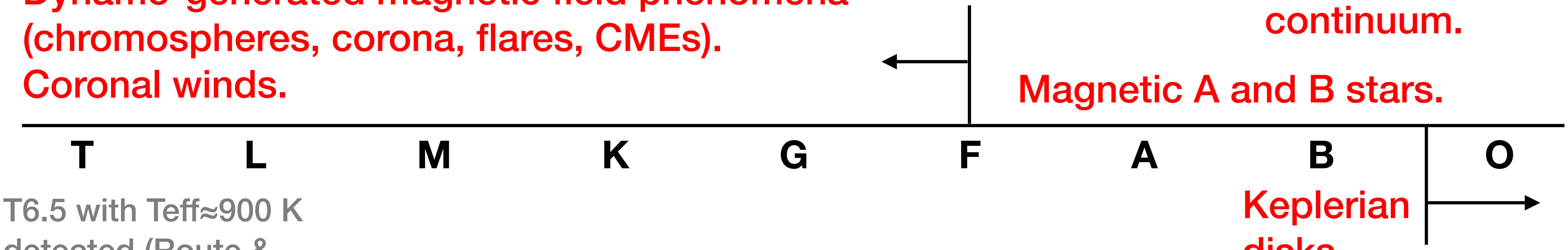
- **A blessing, but also a curse.**
- **Often difficult to discriminate between the different radiation mechanisms.**
- **High-spatial resolution observations can play a crucial role in this context.**

Radio stars

"If we put the Sun at the distance of the nearest star, we would not be able to detect it as a radio source",
α Cen, ALMA, ATCA

Pre-MS stars of all masses:
active stars, accretion disks, jets, outflows, winds.

Massive ionized winds driven by radiation pressure on lines or in continuum.



Dynamo-generated magnetic field phenomena (chromospheres, corona, flares, CMEs).
Coronal winds.

Magnetic A and B stars.

T6.5 with Teff≈900 K detected (Route & Wolszczan 2012)

Keplerian disks of Be stars.

WR
LBV

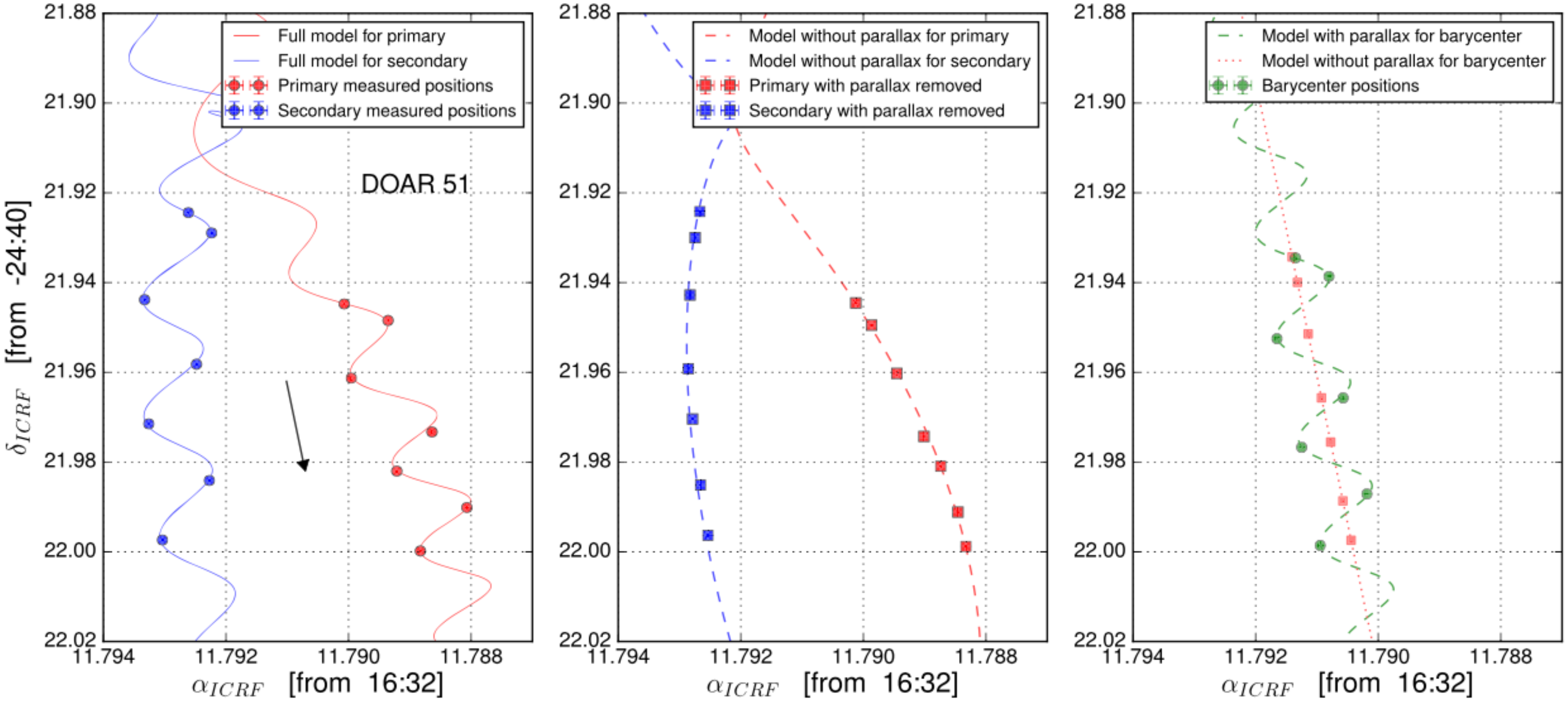
Post-MS of all masses:
active stars, massive cool winds driven by radiation pressure on dust.
WD pulsars

I can only give a “smörgåsbord” of what can be done by observing stars using the VLBI technique.

(essentially a non-maser talk)

Astrometry

Astrometry gives distances, orbits, dynamical masses, …



Ortiz-Leon et al. (2017)
VLBA

Distances to star clusters

L1688,	**d=137.3 +/- 1.2 pc**	**(Ortiz-Leon et al. 2017a)**	
Serpens/W40,	**d=137.3 +/- 1.2 pc**	**(Ortiz-Leon et al. 2017b)**	
Pleiades,	**d=136.2 +/- 1.2 pc**	**(Melis et al. 2014)**	**~~Hipparcos~~**

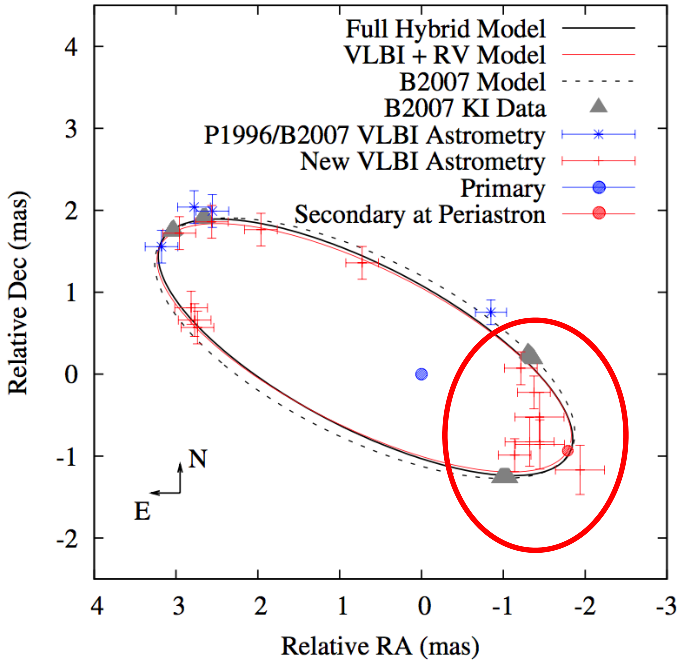
Extremely important for calibrating stellar model theory to get the distance accurately determined.

Pre-MS evolution

Evolution models, magnetospheres, outflows

Test of stellar pms models based on dynamical masses

HD160934 A/c, 0.70+/-0.07 Msun and 0.45+/-0.04 Msun.
AB Dor A/C, 0.89+/-0.08 Msun and 0.09+/-0.008 Msun.
Azulay et al. (2017a,b), EVN, LBA

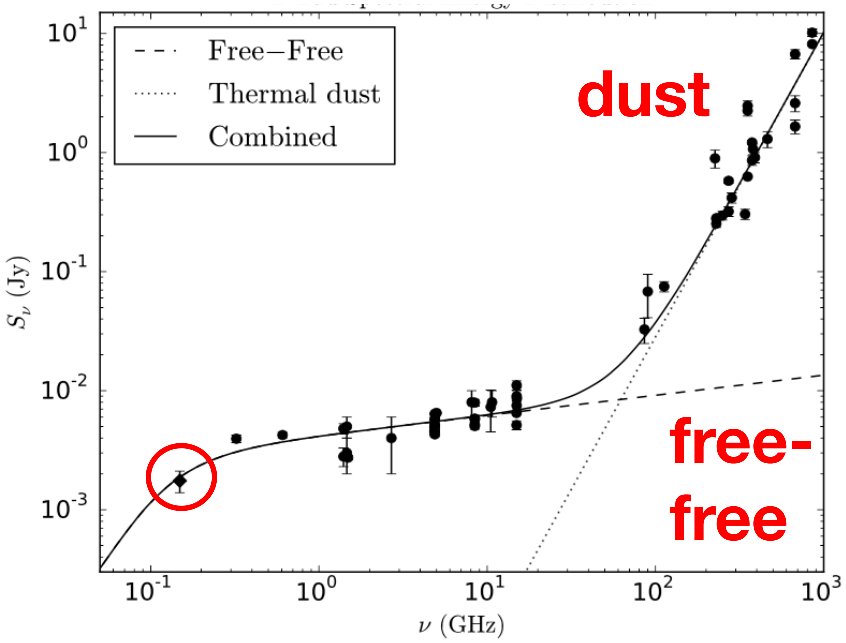


Magnetospheric structure

V744 Tau A, both stars radio brighter at periastron (dynamical masses, distance).
Torres et al. (2012), VLBA

Outflow characteristics

T Tau Sb, free-free turn-over frequency determined (n_e, M_{ion}, and EM).
Choughlan et al. (2017), LOFAR



The cool MS

Ultra-cool dwarfs (late M, BD)

About 10% of observed UCDs are radio-detected; detection rate increases with rotation rate, decrease with spectral class.

ECM emission from T7.5 BD ($T_{eff} \approx 900$ K), $T_b > 10^{11}$ K and $B \approx 2$ kG.
Route & Wolszczan (2015), Arecibo.

The magnetic activity appears changed from being driven by solar-like locally strong magnetic fields to more large-scale magnetospheric current systems (even auroral-type coronae).

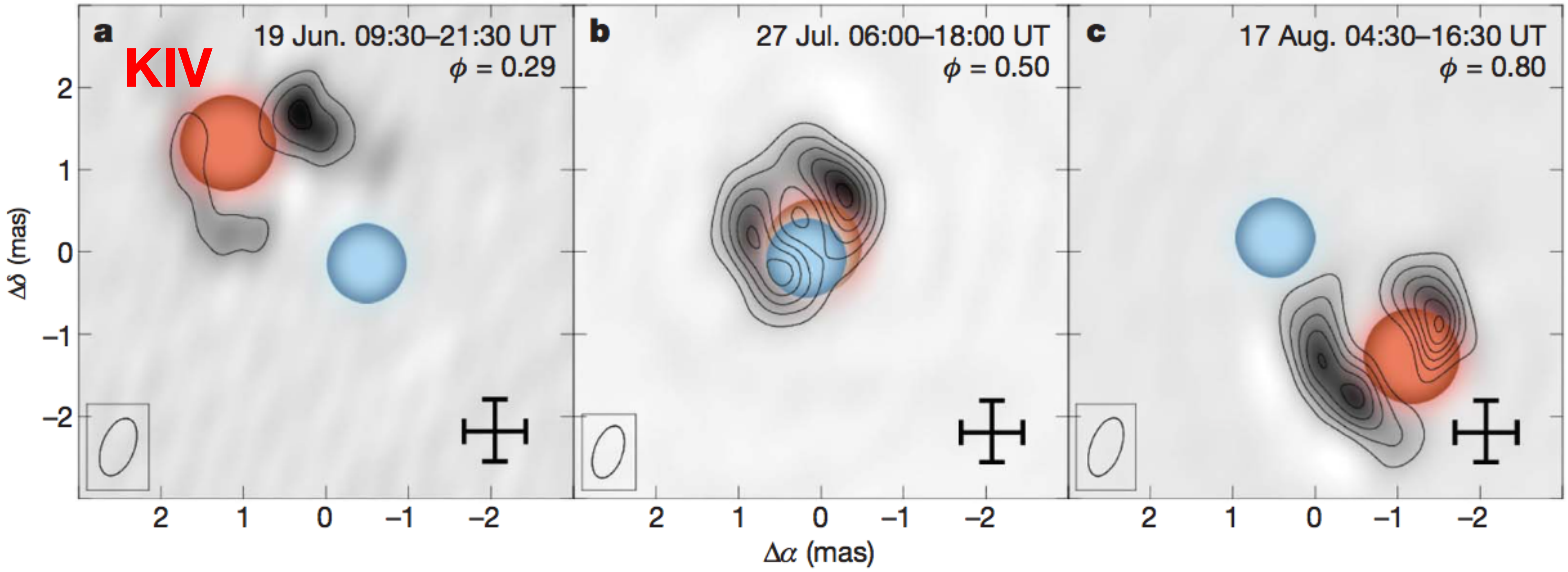
Two UCDs [L0+L1.5 (12 pc) & M9 (11 pc)]: quiescent gyro-synchrotron emission ($T_b \approx$ few x 10^9 K), dipolar field, and ECM pulses.
Lynch et al. (2015), VLA.

UCD system [equal mass M7.5 binary +L7 (16 pc)] and detect gyro-synchrotron emission turn-over frequency ($B \approx$ few kG in binary).
Guirado et al. (2018), VLA + EVN.

Coronal structure

Coronal loop structure of Algol (KIV + B8). Both stars have magnetic fields due to tidally locked rotation (KIV is radio active).

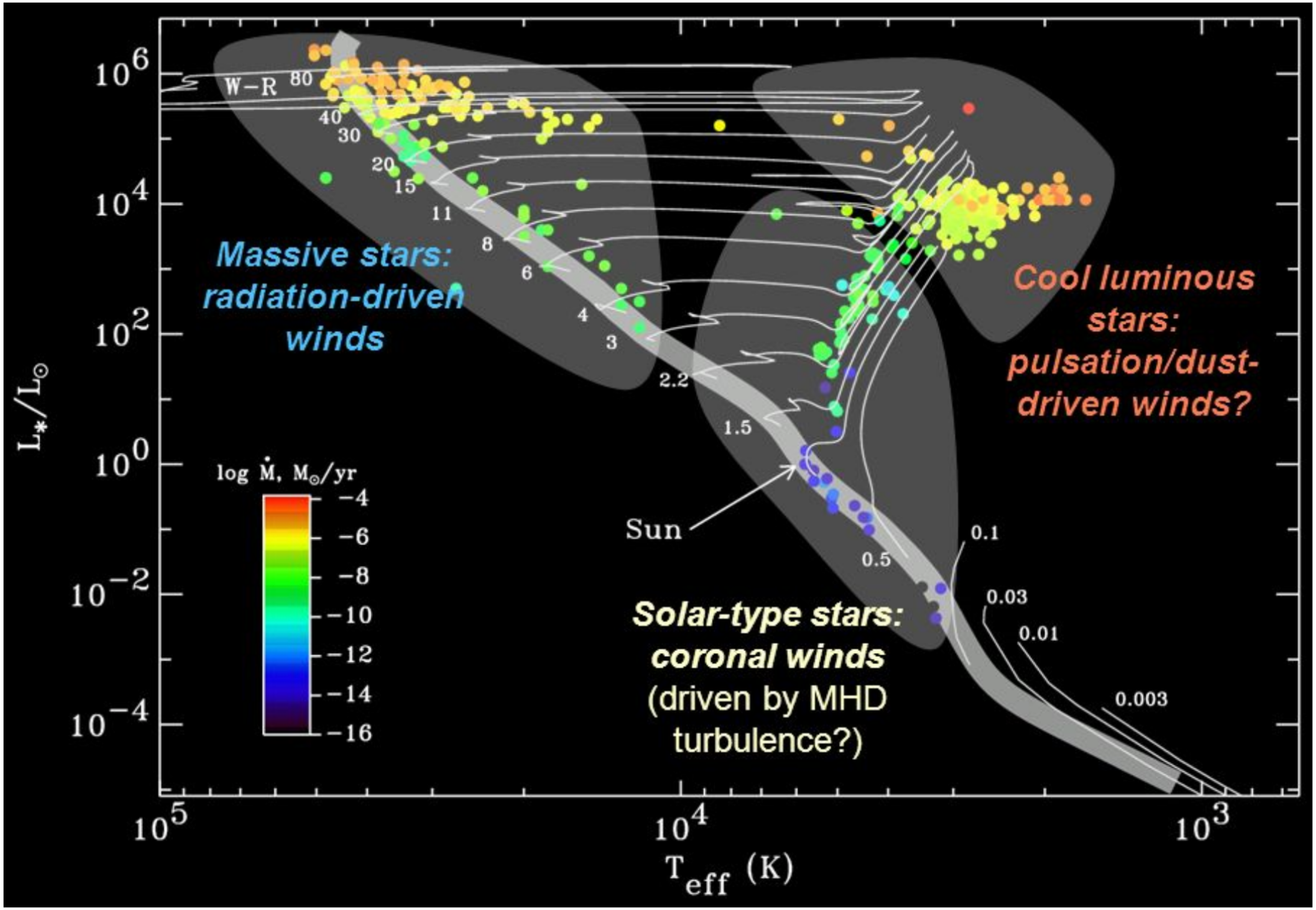
Peterson et al. (2010), HSA



Star-sized coronal loop structure that is affected by the magnetic field of the companion.

Stellar winds

Stellar winds of different types and driving mechanisms exist throughout the HR diagram, and they affect evolution of the stars and/or their surroundings.

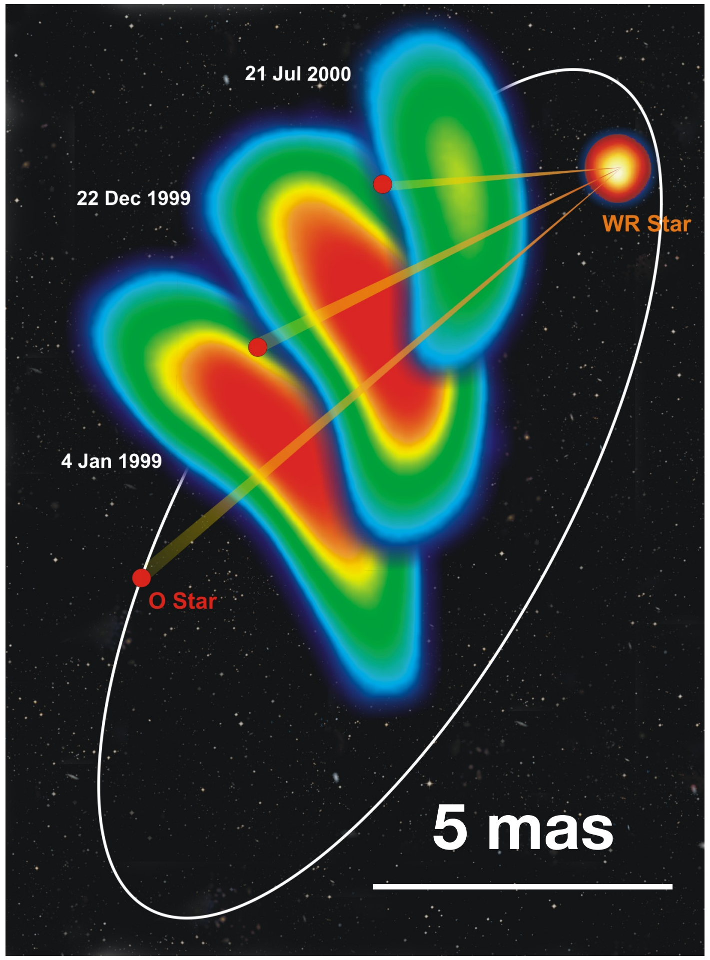


Massive stars: ionized winds

Difficult to observe the thermal winds using VLBI.
Would be very interesting to determine “clumpiness” since it is crucial for mass-loss-rate estimates!

Colliding winds produce non-thermal emission.
WR140, WC7 - O4-5 binary, 7.9 yr period, eccentric orbit.
Complicated SED evolution with time.
Dougherty et al. (2005), VLBA.

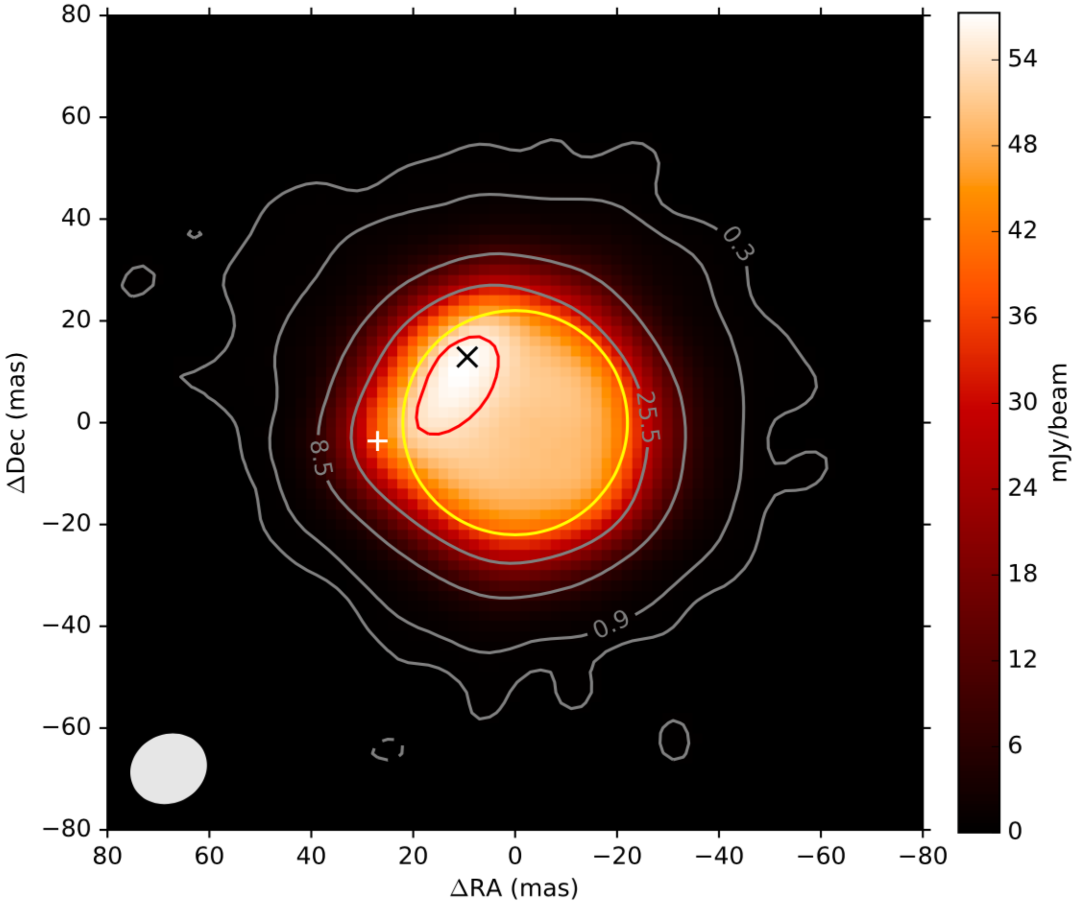
η Car is of this type.



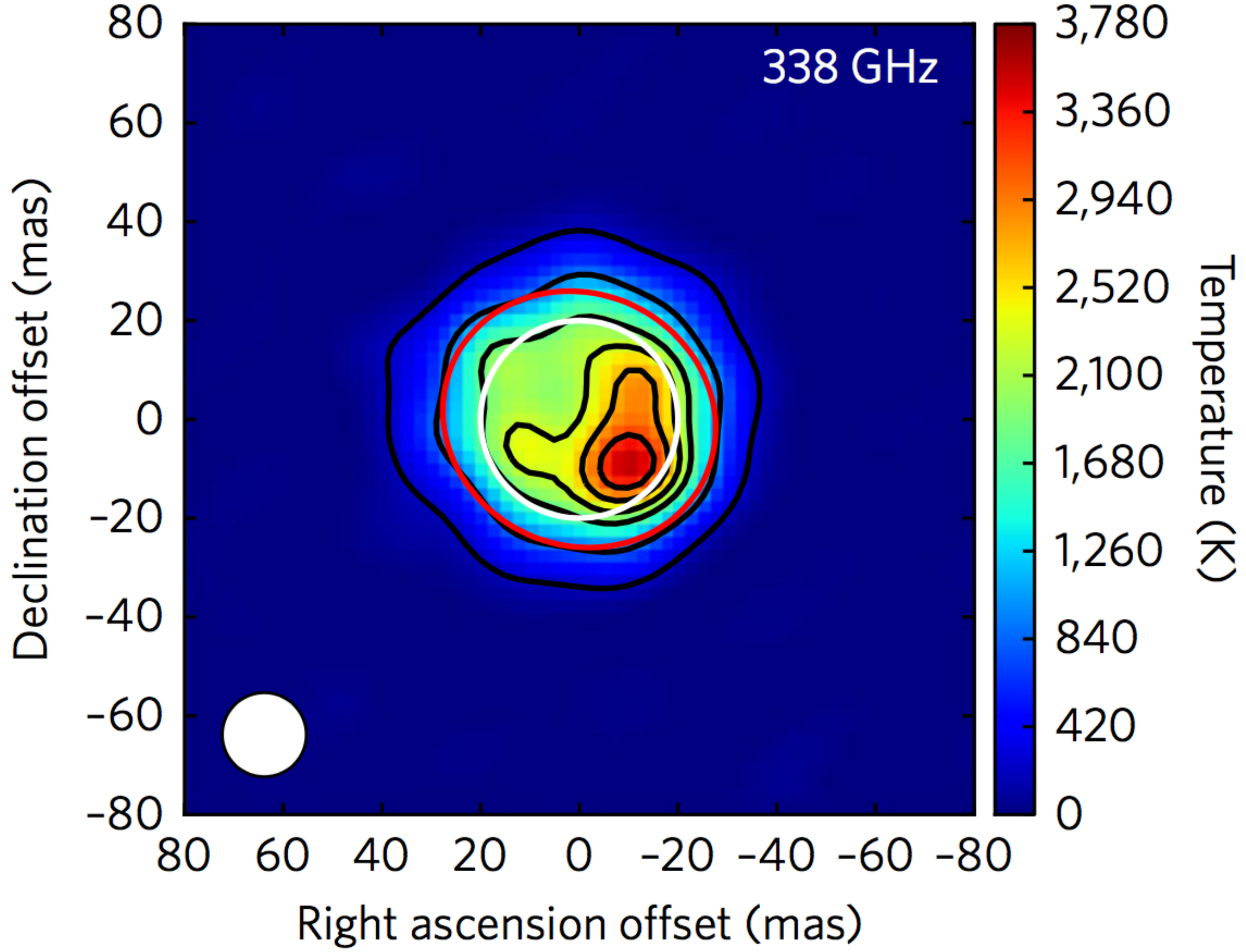
Evolved stars
AGB & RSG

Surface structures: star spots

Betelgeuse, RSG



W Hya, AGB



$T_b \approx$ 3800 K, size 20x8 mas

O'Gorman et al. (2017), ALMA

$T_b \approx$ 3800 K & 5400 K, sizes < 40 mas

Richards et al. (2012), eMERLIN

$T_b >$ 53000 K, size < 3 mas

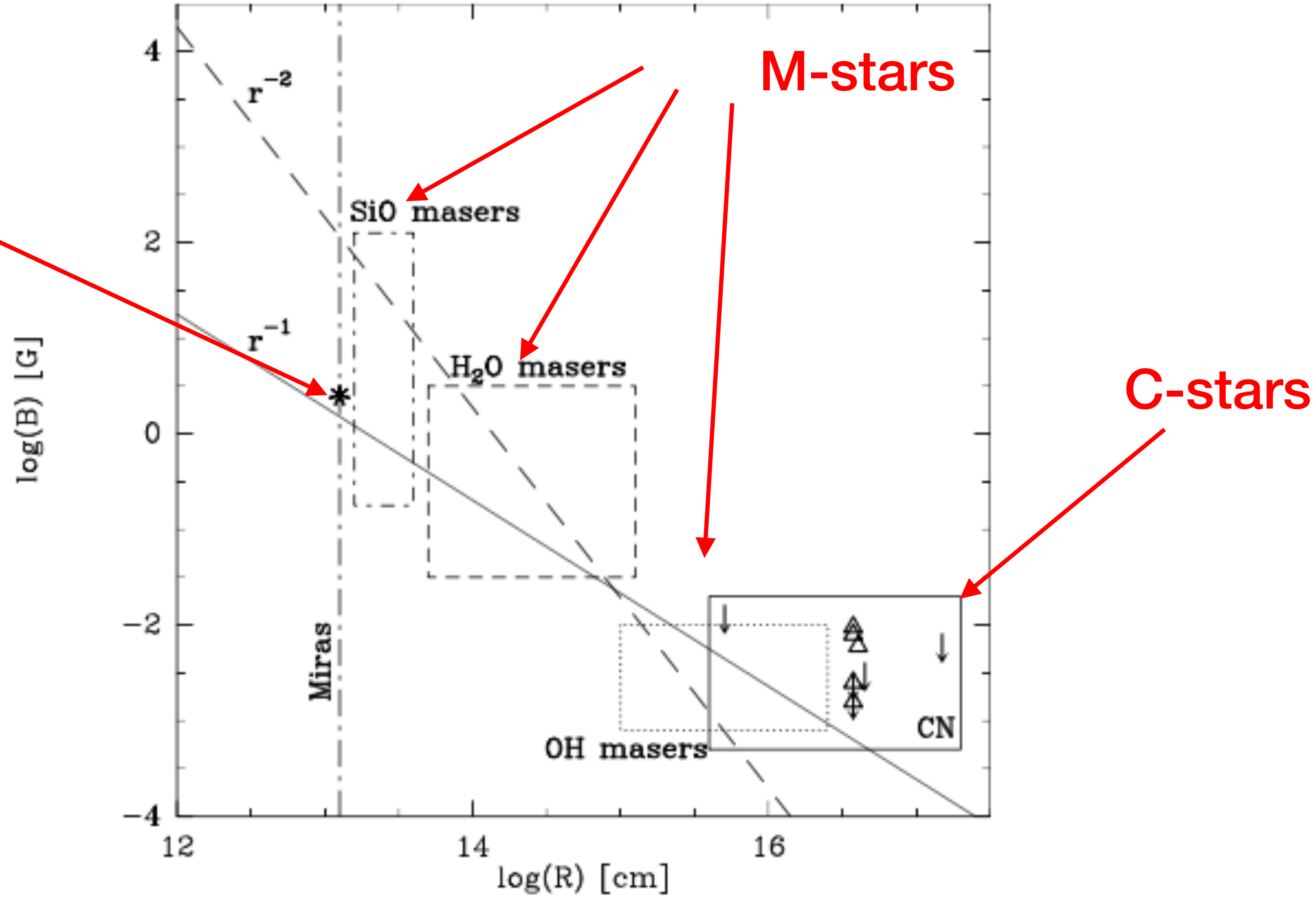
Vlemmings et al. (2017), ALMA

What is the cause of the local heating, and effects on mass loss & chemistry?

Magnetic fields

Stellar magnetic fields may affect nucleosynthesis, mass-loss characteristics, transition to PNe, etc.

Only measured value
for an AGB star
(χ Cyg, an S-star)



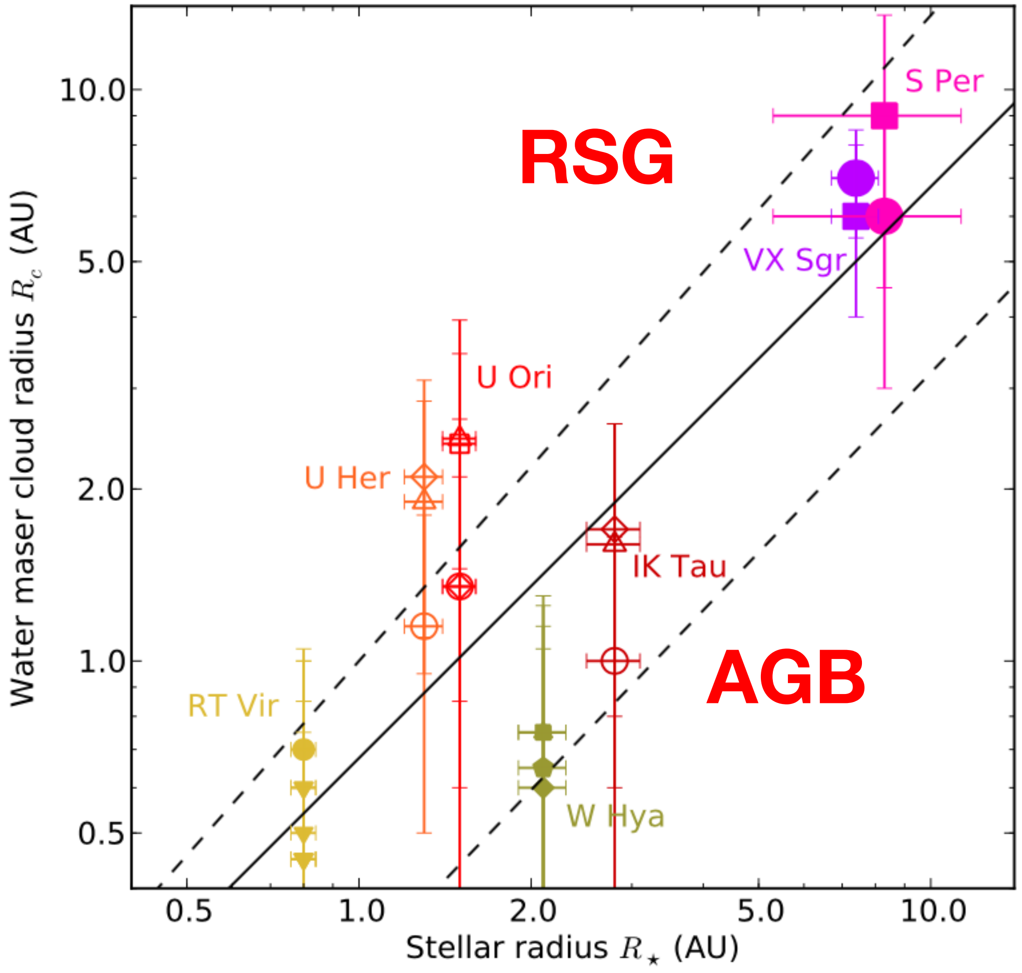
Vlemmings, IAU Symp. 287, 31 (2012)
Duthu et al., A&A 604, A12 (2017)

Cool winds

Mass-loss-rate estimates for, and the chemistry of, cool winds around AGB stars and RSGs are very dependent on the “clumpiness” of the circumstellar medium.

VLBI has provided information through observations of maser spot sizes, but the relation between clump and maser spot size is not simple.

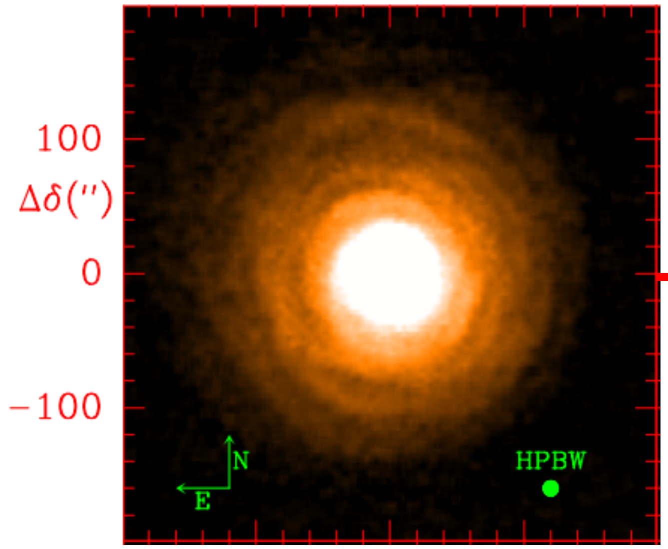
H_2O 22 GHz masers
Richards et al. (2012), MERLIN



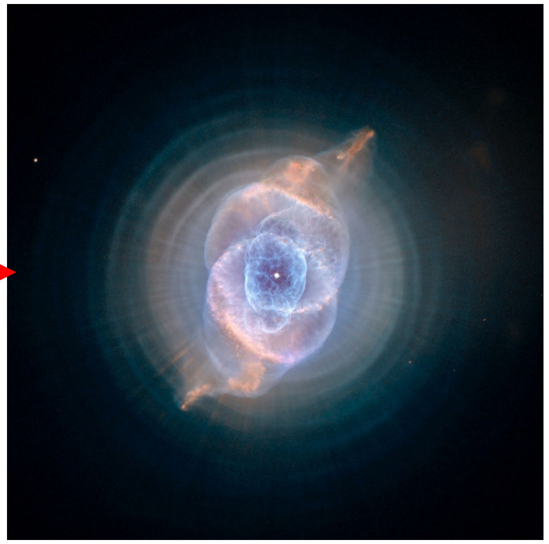
Towards planetary nebulae

VLBI observations of a water-fountain source, W43A, believed to be in transition from AGB to PN.

IRC+10216

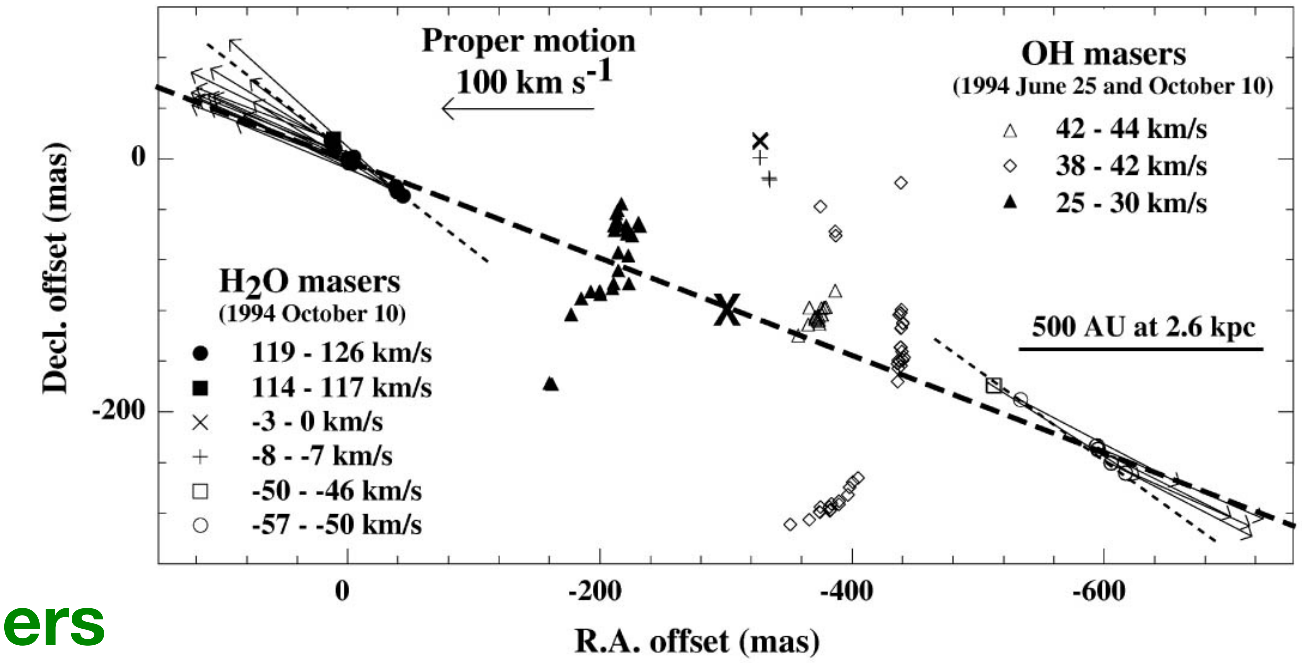


Cat's eye nebula



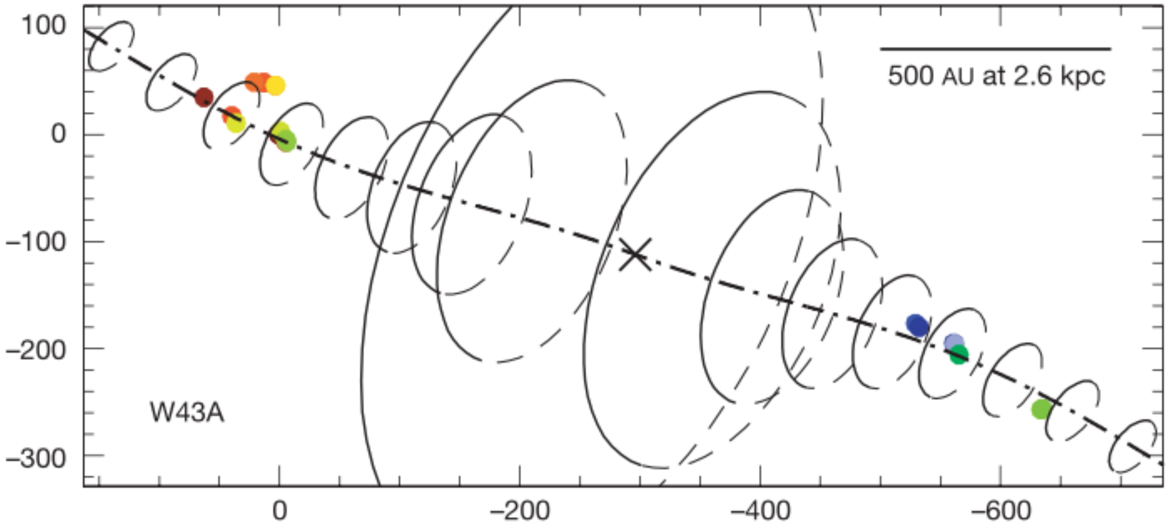
Collimated outflow

Imai et al. (2002), W43A, VLBA



Magnetic field strengths from H_2O masers

Vlemmings et al. (2006), W43A, VLBA



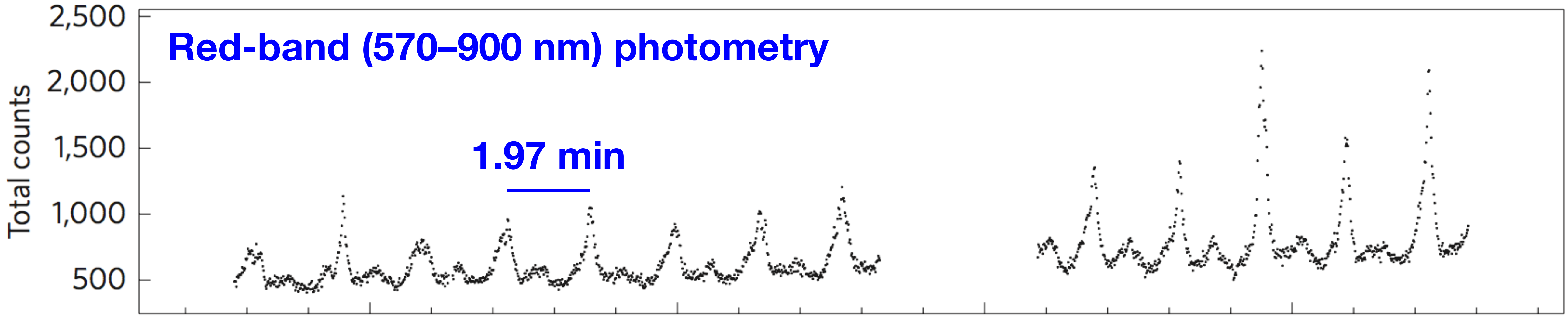
The morphological change is believed to be associated with binarity, magnetic fields, and the emergence of jets.

Binaries

WD pulsar

Marsch et al. (2016) and Buckley et al. (2017) provide evidence for the first WD pulsar, driven by the rotation of the WD, in the AR Sco binary system (WD + dM5).

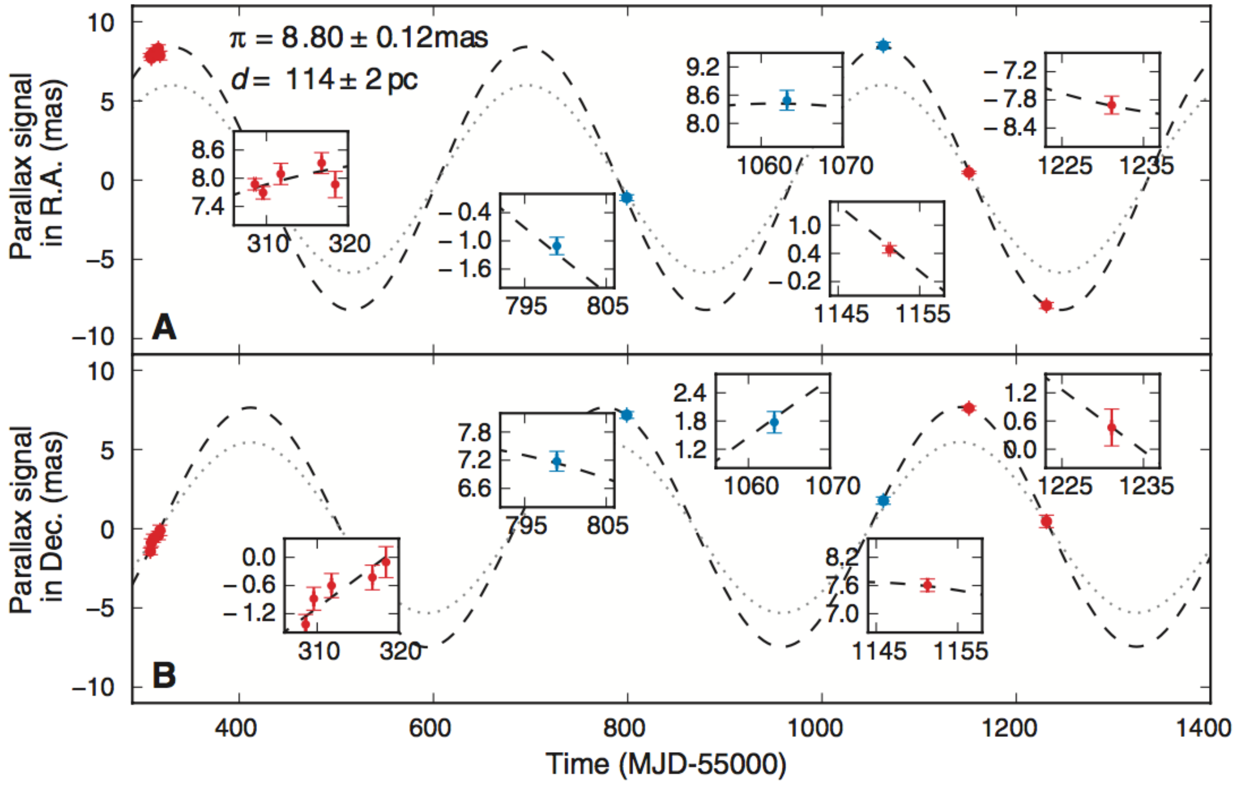
The radiation is synchrotron emission (radio - IR - optical).



VLBI can provide distance, orbit, masses, and morphology.

Novae

Dwarf novae (WD + comp.)
Mechanism?

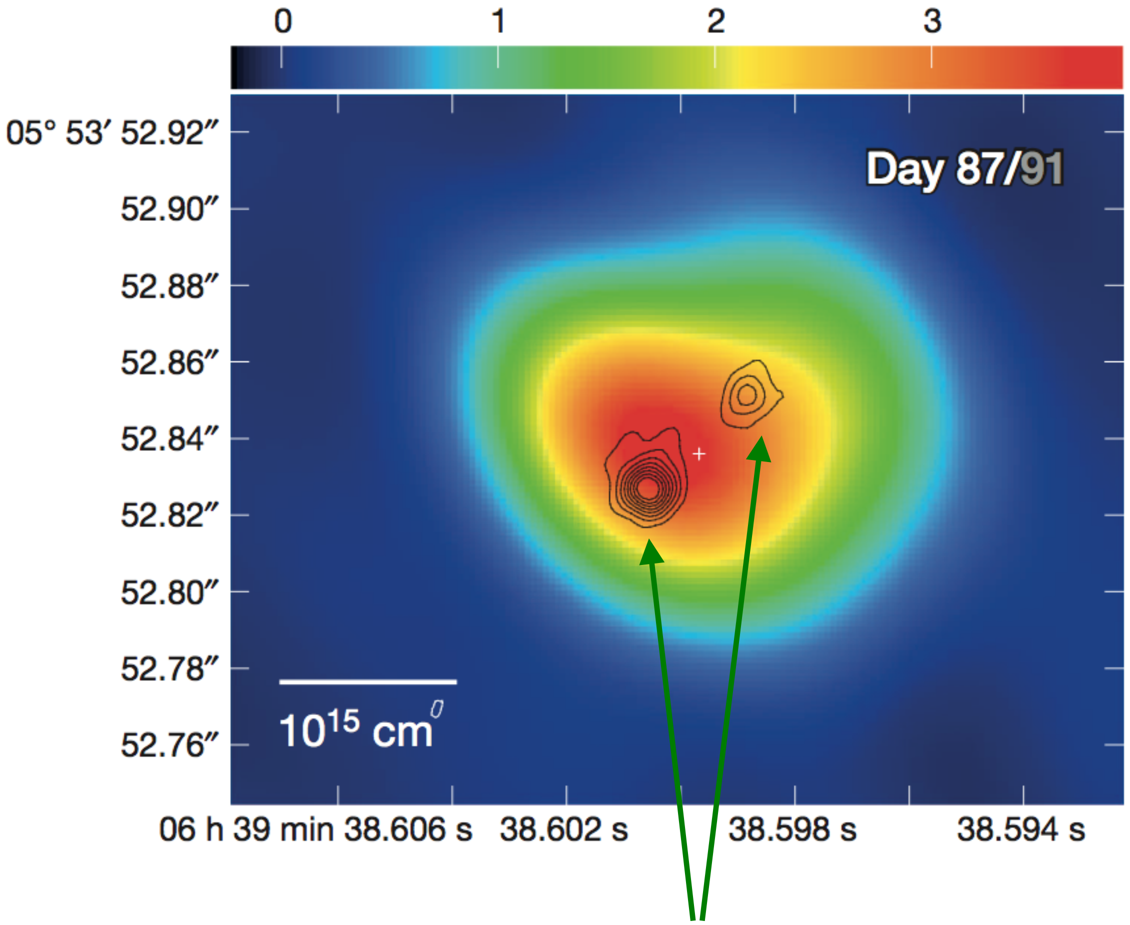


SS Cyg: VLBI distance (114+/-2 pc) gives support for accretion disk theory.

(HST distance 159 +/- 12 pc!)

Miller-Jones et al. (2013), VLBA, EVN.

Classical novae (WD + comp.)
Ejection mechanism unknown!
Often γ-ray transients.



V959 Mon: Ejecta shaped by the binary, expanding non-thermal components.

Chomiuk et al. (2014), VLA, EVN.

Conclusions

VLBI observations provide:

- **Astrometric measurements: crucial for a wide variety of studies.**
- **Radiation mechanism identification (T_b estimates), Turn-over frequencies of free-free, gyro-synchrotron, …**
- **Source imaging: non-thermal components at mas-scales**
- **Very high sensitivity — Even thermal emission**
  Surface structures
  Wind clumpiness
  Coronal winds (FYSP, …)
  Flares, CMEs (habitability)