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Filming the evolution of symbiotic novae with VLBI

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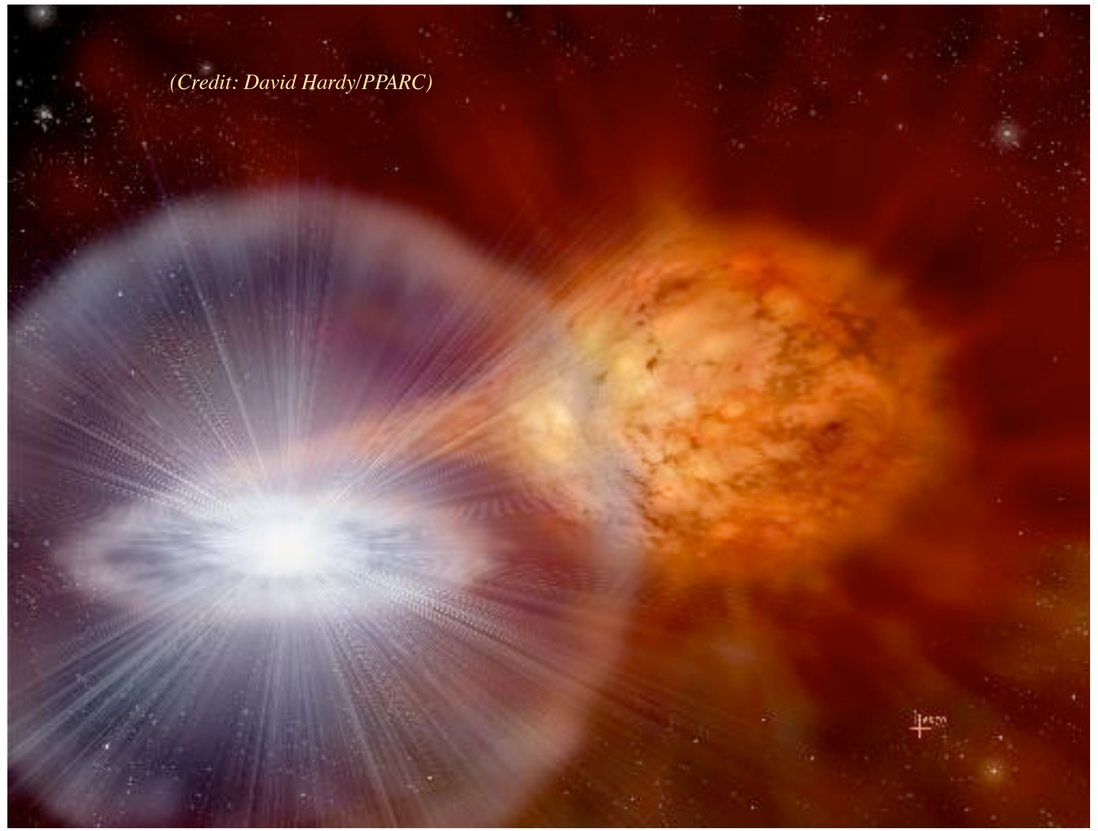
V407 Cyg: Giroletti et al. 2020, A&A 638

RS Oph: Munari et al. 2022, A&A 666

CTAO Science Symposium 2024, Bologna Teatro Duse, 16 April

Symbiotic novae

- The WD companion is a pulsating red giant (RG)
- The nova ejecta expand through its dense wind
- Rare systems, typically recurring on human time scales:
  - observing landscape changes dramatically from outburst to outburst!
  - latest events: 2010 V407 Cyg, 2021 RS Oph

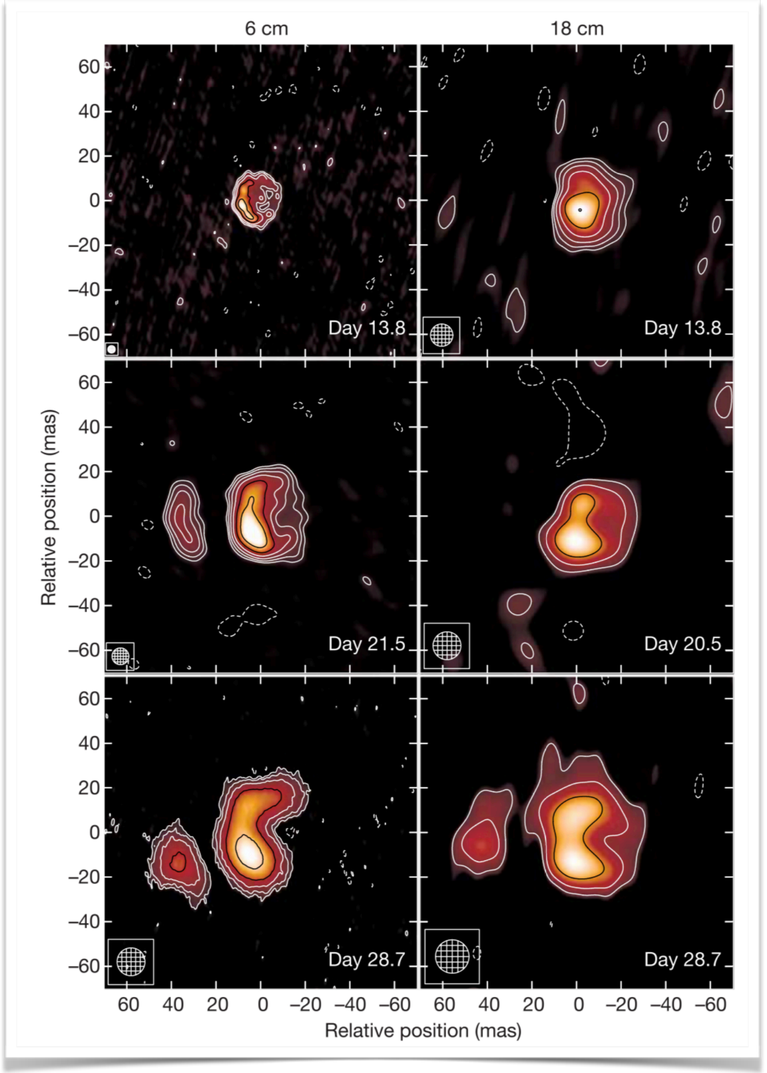


Very Long Baseline Interferometry (VLBI)

- Synchronise radio telescopes as far apart as d~10000 km
- Achieve angular resolution θ=λ/d~1 mas (1AU@1kpc)
- Filters out diffuse low brightness temperature emission and reveals compact structures (typically, non-thermal)
- Main arrays: VLBA, EVN, LBA, EHT 

V407 Cyg and RS Oph

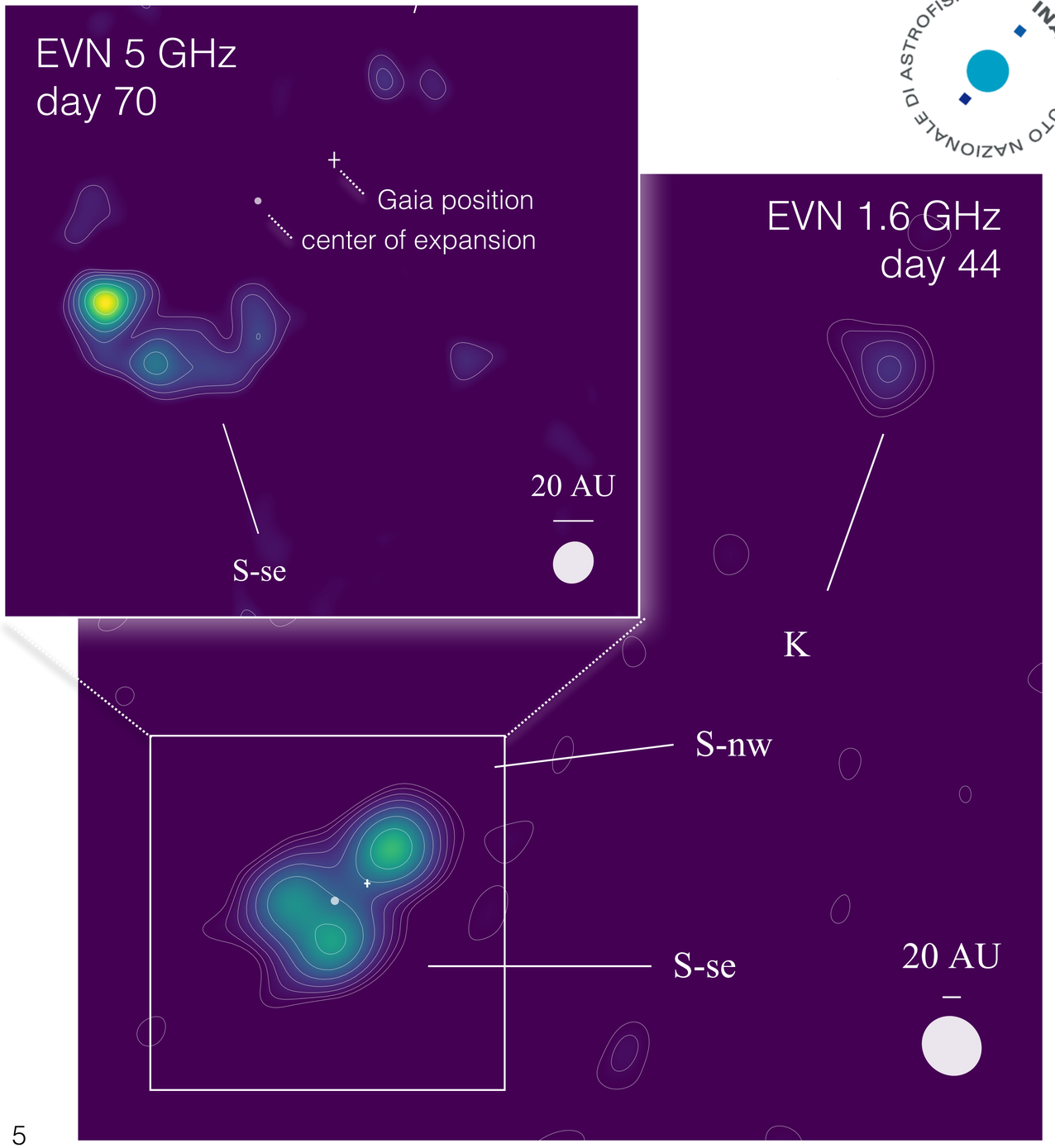
- Similar distance (~2.7 kpc)
- **V407 Cyg** has much longer orbital period (up to ~100 vs 1.3 years)
- Since 1898, ~8 **RS Oph** outbursts, ~3 **V407 Cyg's**
- VLBI observations of **RS Oph**'s outbursts in 1985 and 2006 indicate non-thermal nature of (part of) the emission, asymmetric jet-like structure
- **V407 Cyg** first nova detected in gamma rays (in 2010, by Fermi-LAT)
- **RS Oph** first nova detected in VHE (in 2021, by MAGIC and H.E.S.S.)



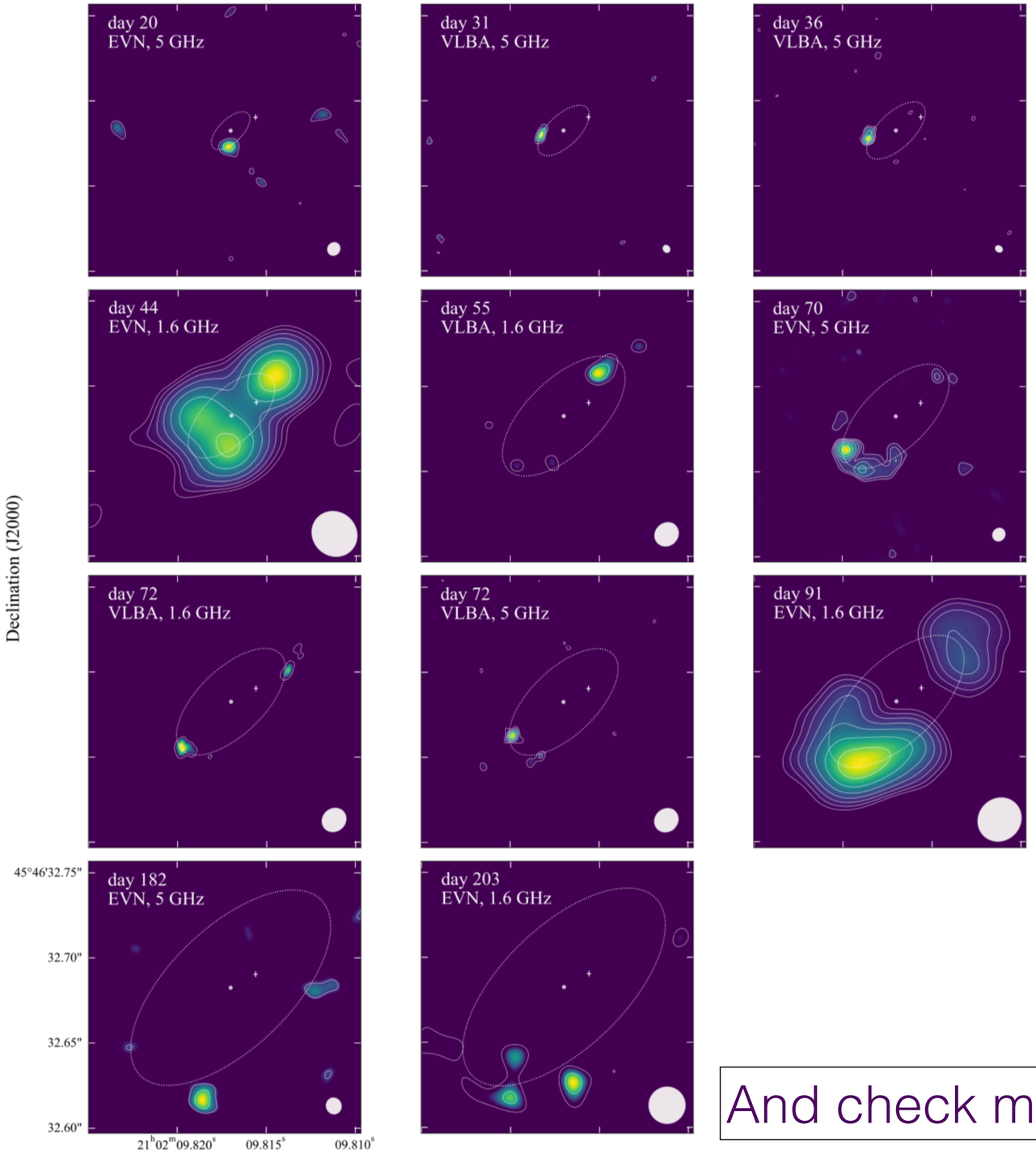
O'Brien et al. (2006 Nature)

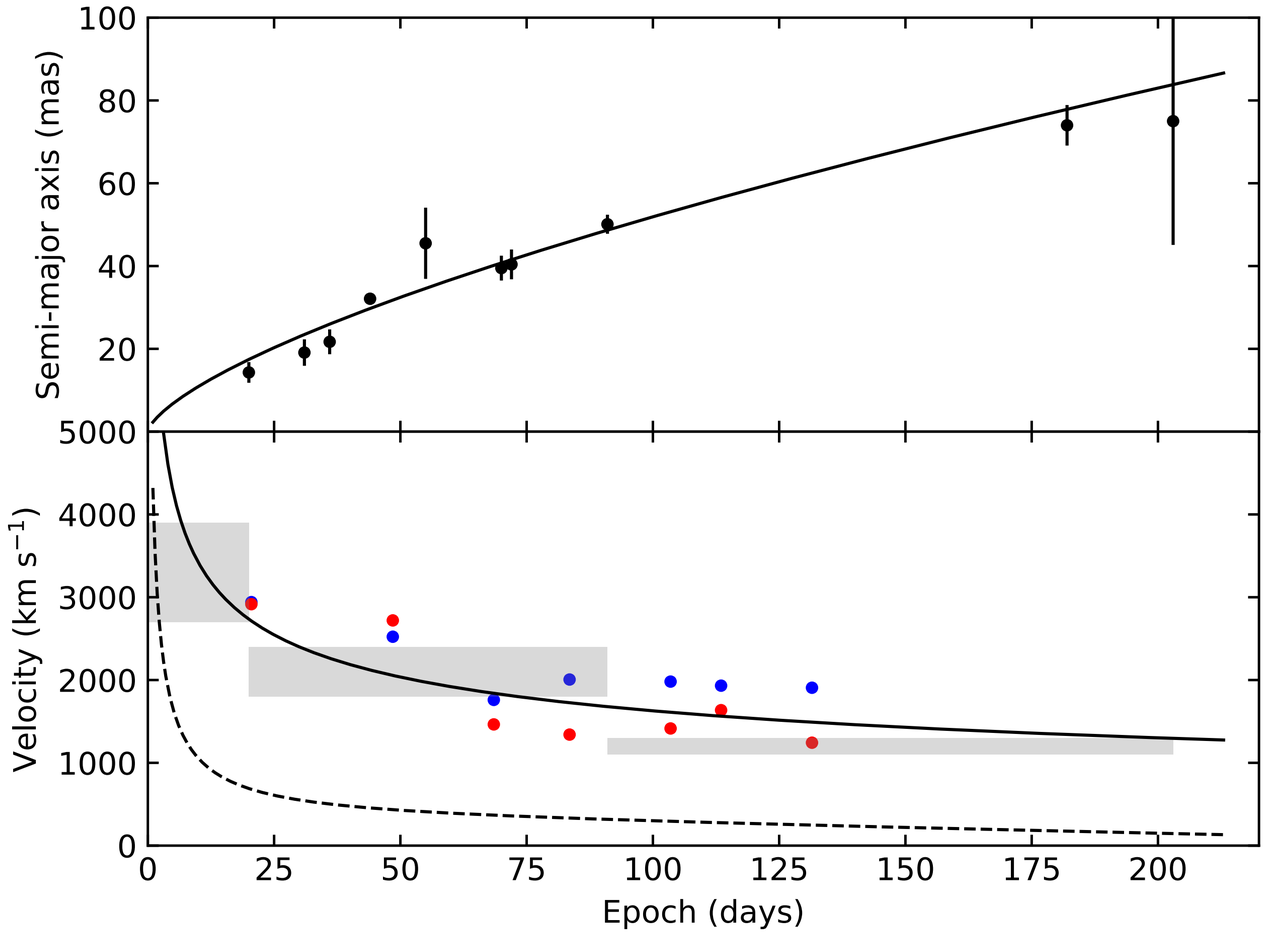
V407 Cyg VLBI campaign

- 16 observations between 20 and 200 days after outburst
- Initially shell-like structure, then bipolar outflow
- A faraway, much slower feature
- Rising ($S_\nu \sim \nu^{+1.0}$) spectrum, large T_b
- Velocity starting at ~3000 km s^{-1}, then decreasing as $v \sim t^{-0.32}$



V407 Cyg summary





And check movie at https://fb.watch/rjpjjuCEsO/

RS Oph, 2021 nova

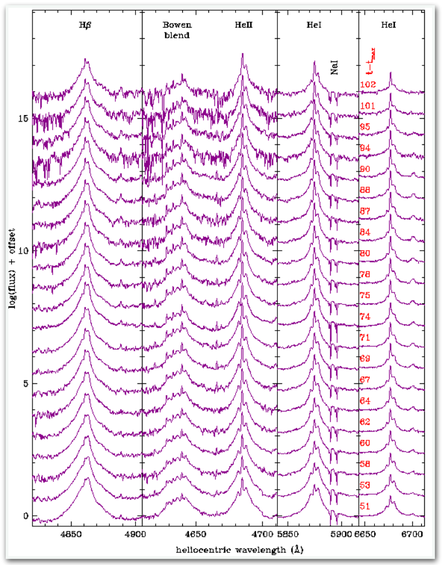
Discovered in optical on 2021 Aug 8

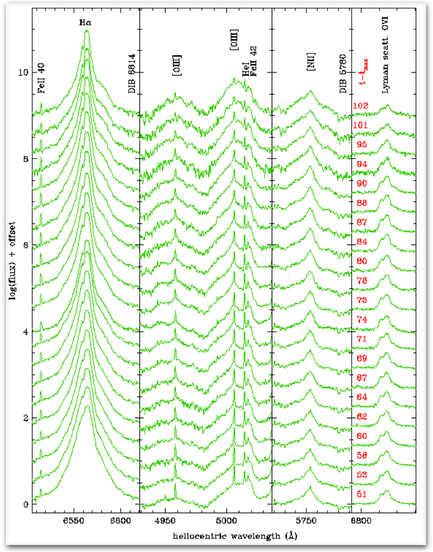
Promptly reported in MeV/ GeV domain by *Fermi*-LAT

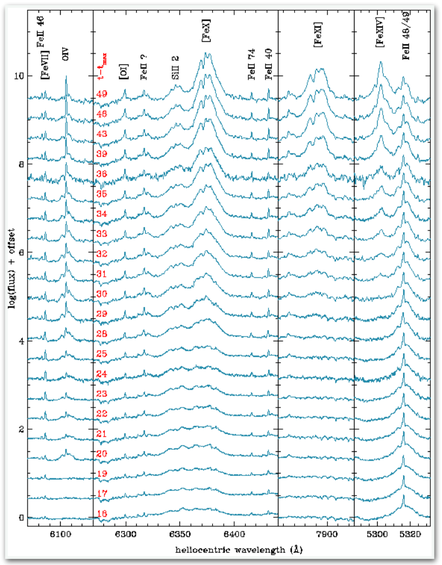
Very rich optical spectroscopy datasets

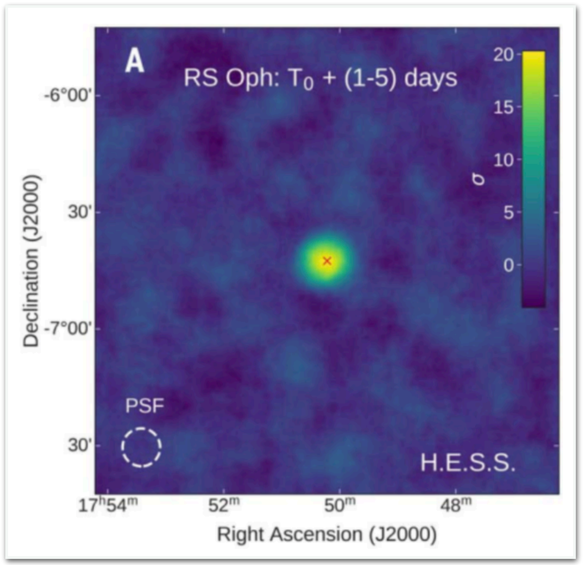
Detected also by MAGIC, H.E.S.S. at VHE

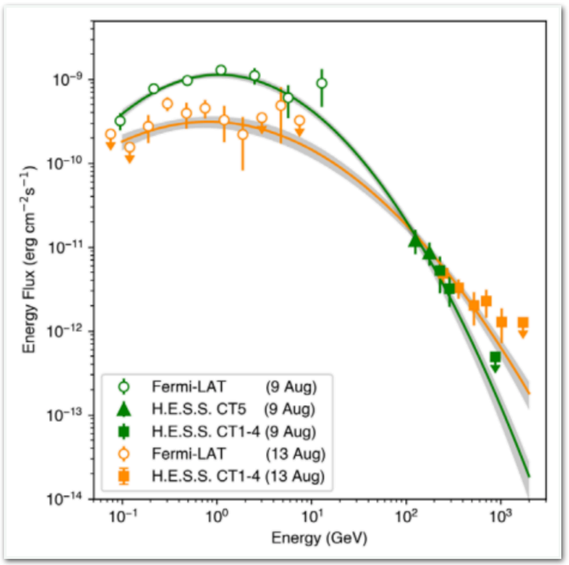
Fast rise in radio reported by e-Merlin, MeerKAT, AMI-LA, VLA











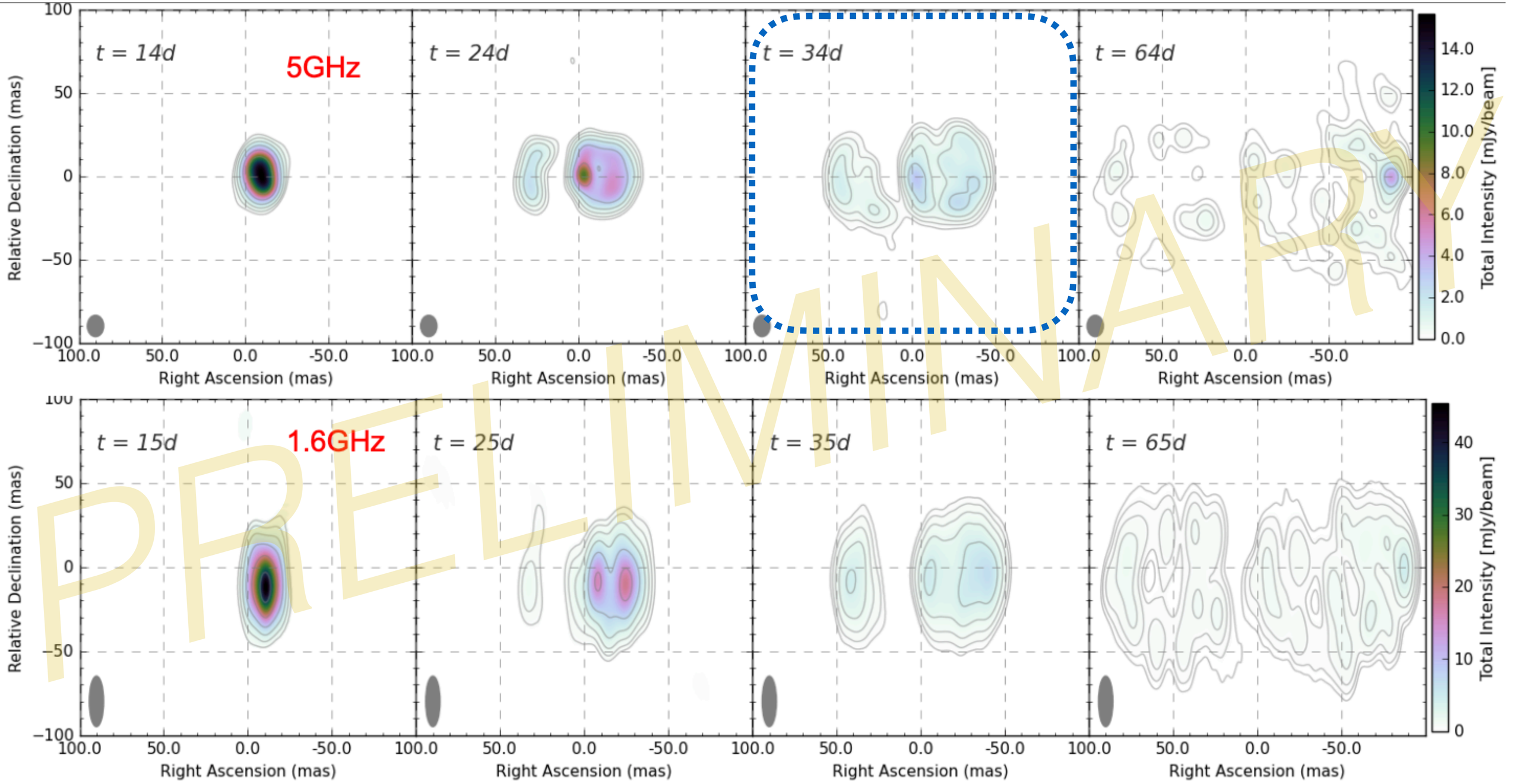
Munari & Valisa 2022

H.E.S.S. collaboration 2022
Acciari et al., 2022

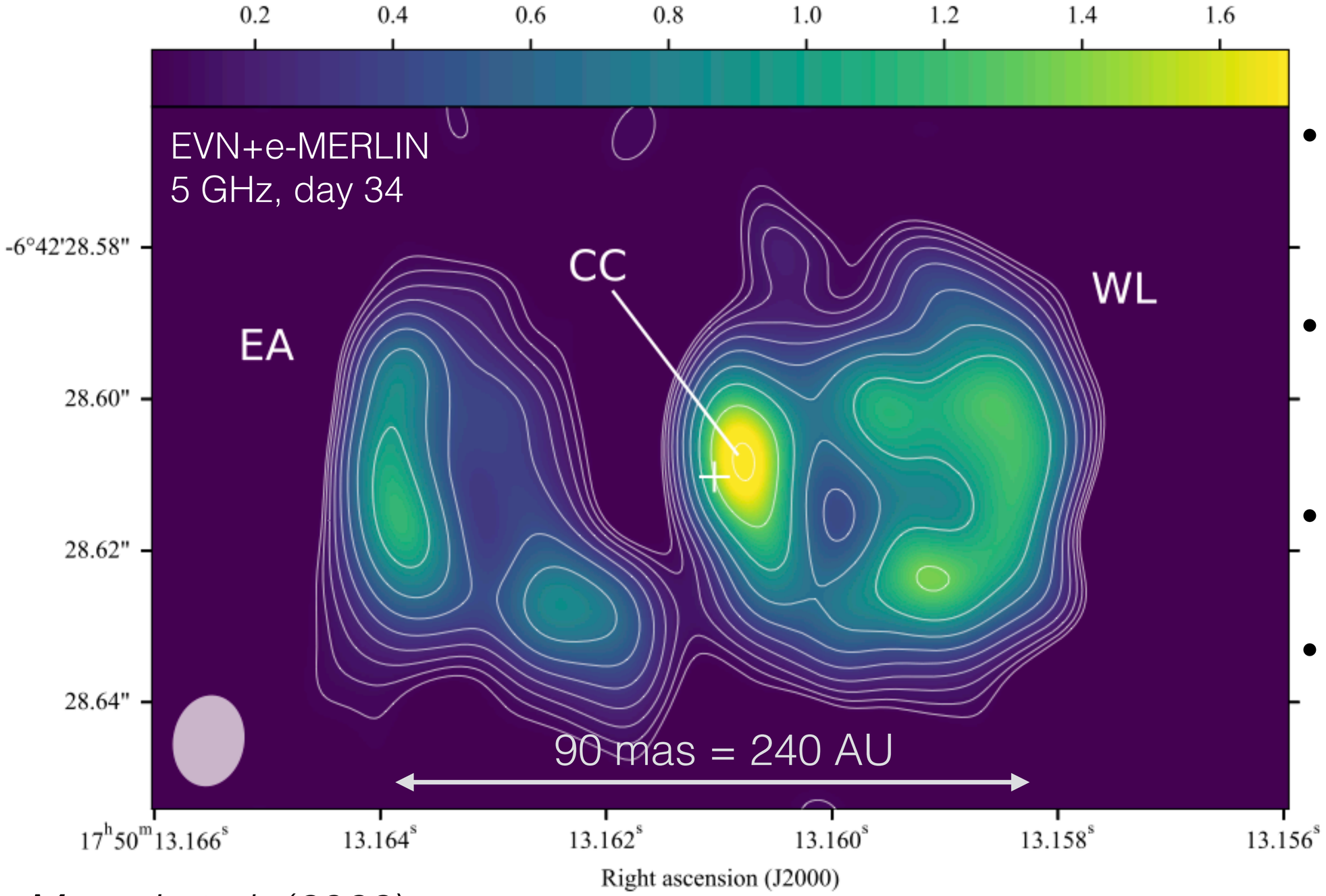
The EVN+e-MERLIN campaign

- Challenges:
  - Source evolving rapidly
  - Dual-frequency necessary
  - Out-of-session observations without notice …in the middle of the summer!
- However:
  - 5x2x8 hr observations (1.6, 5 GHz)
  - *t*=14/15, 24/25, 34/35, 49/50, 64/65 days

the 76-metre Lovell Telescope at Jodrell Bank taking part in the Sept-2nd EVN observation (courtesy of Tim O'Brien).



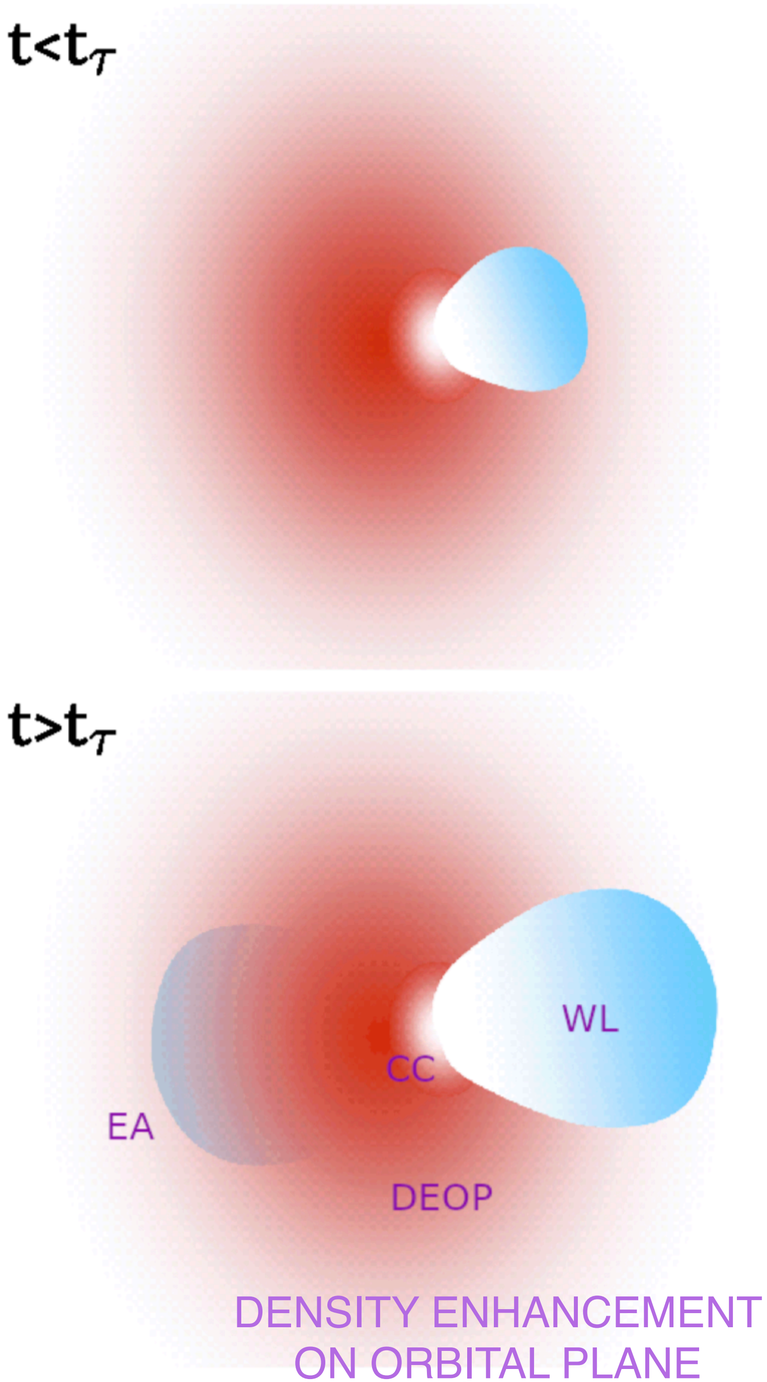
Lico et al. in prep.



- White cross is Gaia position (d=2.7 kpc)
- Emission on either side, with shell-like structure
- Total flux density S=20 mJy
- Radio luminosity 1.7×10^{13} W Hz^{-1} (8.5×10^{29} erg s^{-1})

Munari et al. (2022)

A simple sketch



- Situation very similar to 2006, but with much more detail
- DEOP confines the ejecta primarily within a bipolar structure perpendicular to orbital plane
- Non-thermal radio emission originates at shock interface between the fast expanding lobes and the pre-existing RG slow wind
- Sometimes around t=20d, EA crosses the τ_V=1 position and becomes detectable (in both outbursts)
- Combination of optical spectroscopy and VLBI imaging provide v_{eje} =7550(±150) km s^{-1}, i=54°(±1)

Munari et al. (2022)

Future perspectives

- 9 more EVN datasets and a full 1-yr e-Merlin light curve to analyse - study of:
  - the loci of shock-acceleration
  - separate thermal and non-thermal emission regions
  - distinguish free expansion from deceleration induced by the sweep-up of the RG wind

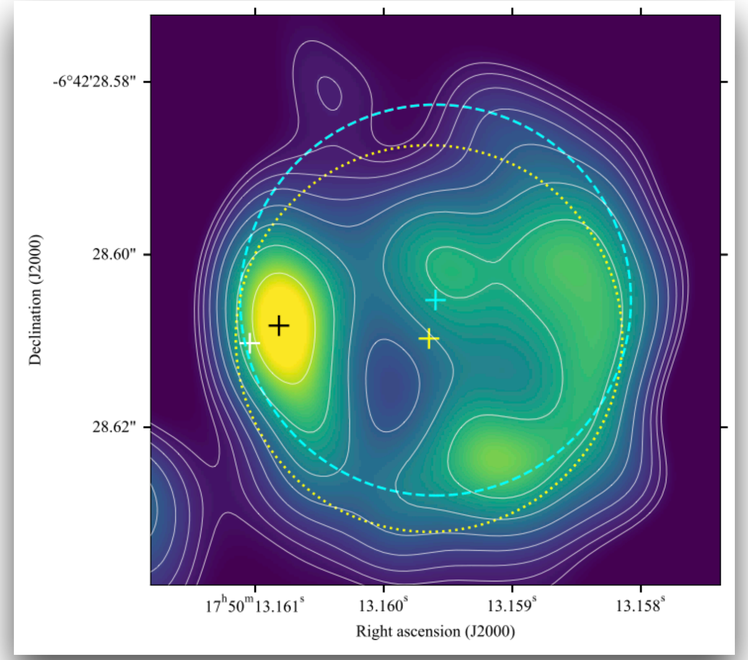
Lico et al. in prep.

- And we are looking forward to **T CrB**!
  - about 3 times closer: brighter, faster!
  - previous outbursts in 1866 and 1946 (V=2mag)
  - super active phase & dip similar indicate action soon (Munari+16, Schaefer+23)

VLBA, EVN+e-MERLIN proposals

Take home messages

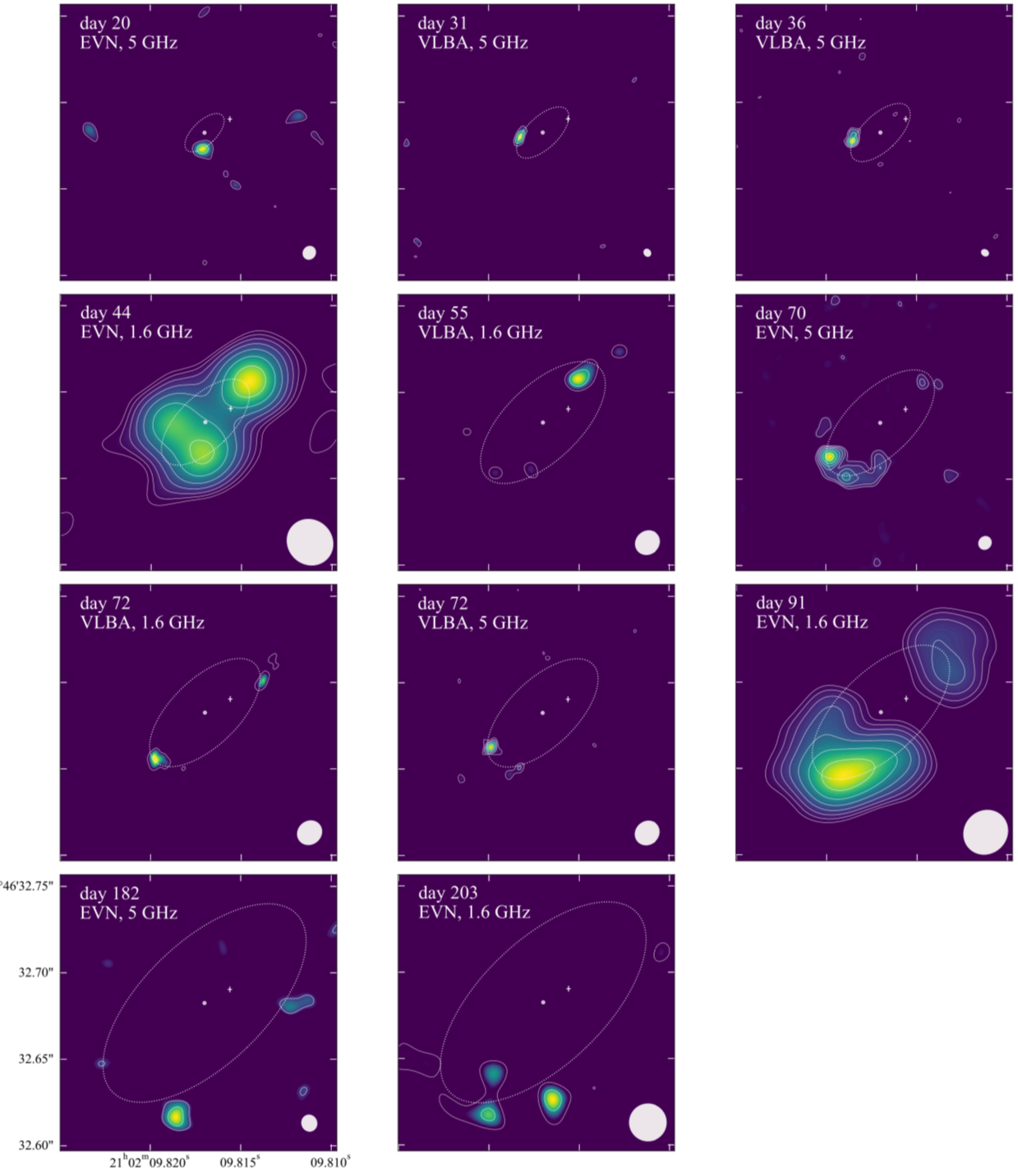
1. VLBI provided direct imaging of expansion of bipolar ejecta along polar axis in V407 Cyg, RS Oph
2. Radio interferometry, from ~100 MHz to ~100 GHz, is increasing its performance steadily: LOFAR, MeerKAT, VLA, ALMA, and more - waiting for SKAO
3. VLBI is often the only technique for a resolved imaging and to directly reveal structural evolution also in other accreting systems (XRB, GW counterparts, FRB, AGN etc.)

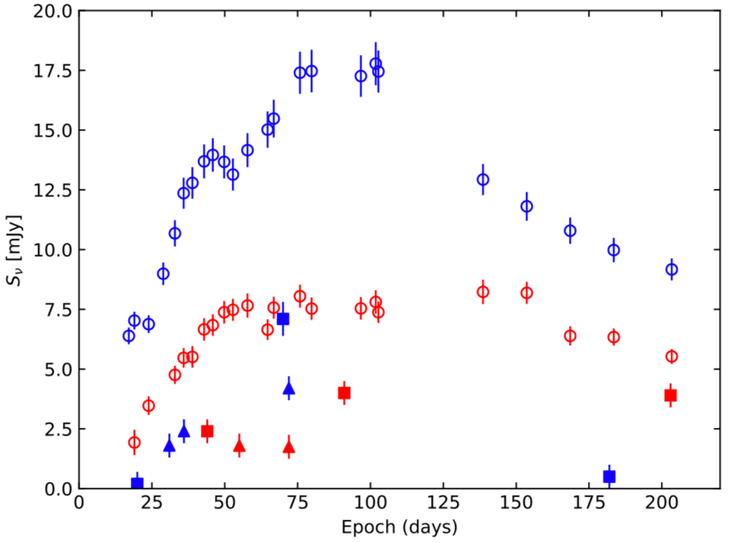


Giroletti, Munari et al. 2020, A&A 638

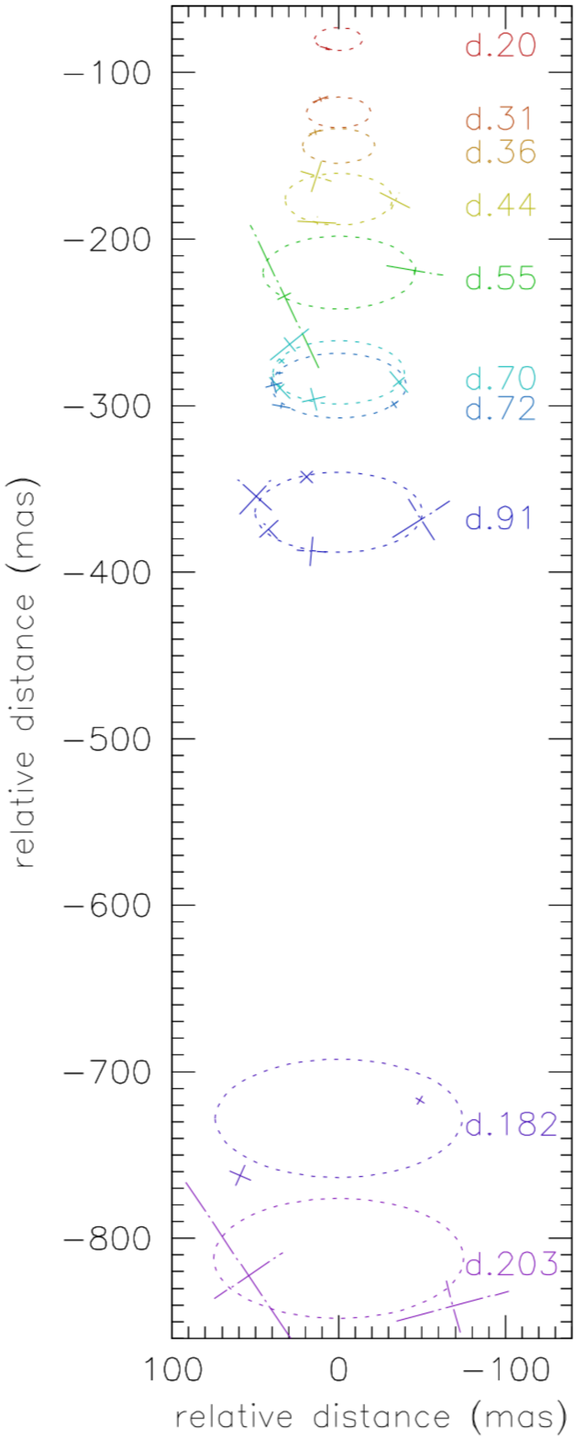
Munari, Giroletti et al. 2022, A&A 666

V407 Cyg additional plots





g. 4. V407 Cyg light curve with VLA (empty circles, from omiuk et al. 2012) and VLBI (filled symbols) data from the present per: filled squares and triangles represent EVN and VLBA data, spectively. Red indicates 1.6 GHz (1.8 GHz for the VLA data) and ue indicates 5 GHz.



First results

Astronomy & Astrophysics manuscript no. paper
September 27, 2022

LETTER TO THE EDITOR

Radio interferometric imaging of RS Oph bipolar ejecta for the 2021 nova outburst

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ABSTRACT

The recurrent nova and symbiotic binary RS Oph erupted again in August 2021 for its eighth known outburst. We observed RS Oph 34 days after the outburst at 5 GHz with the European VLBI Network (EVN). The radio image is elongated over the east–west direction for a total extension of about 90 mas (or about 240 AU at the *Gaia* DR3 distance $d = 2.68^{+0.17}_{-0.15}$ kpc), and shows a bright and compact central component coincident with the *Gaia* astrometric position, and two lobes east and west of it, expanding perpendicular to the orbital plane. By comparing with the evolution of emission-line profiles on optical spectra, we found the leading edge of the lobes to be expanding at ~7550 km s^{-1}, and i=54° as the orbital inclination of the binary. The 2021 radio structure is remarkably similar to that observed following the 2006 eruption. The obscuring role of the density enhancement on the orbital plane (DEOP) is discussed in connection to the time-dependent visibility of the receding lobe in the background to the DEOP, and the origin of the triple-peaked profiles is traced to the ring structure formed by the nova ejecta impacting the DEOP.

- Munari, Giroletti, et al. (2022, A&A 666)
- https://arxiv.org/abs/2209.12794
- Analysis of EVN epoch 3 at 5 GHz (t=34 d)
- Comparison with optical spectra - and 2006 outburst

From optical spectroscopy:

$v_{eje} \cos i$=4450 km s-1

From radio extension:

$v_{eje} \sin i$~6100 km s-1

Therefore:

v_{eje} =7550(±150) km s-1

i=54°(±1)

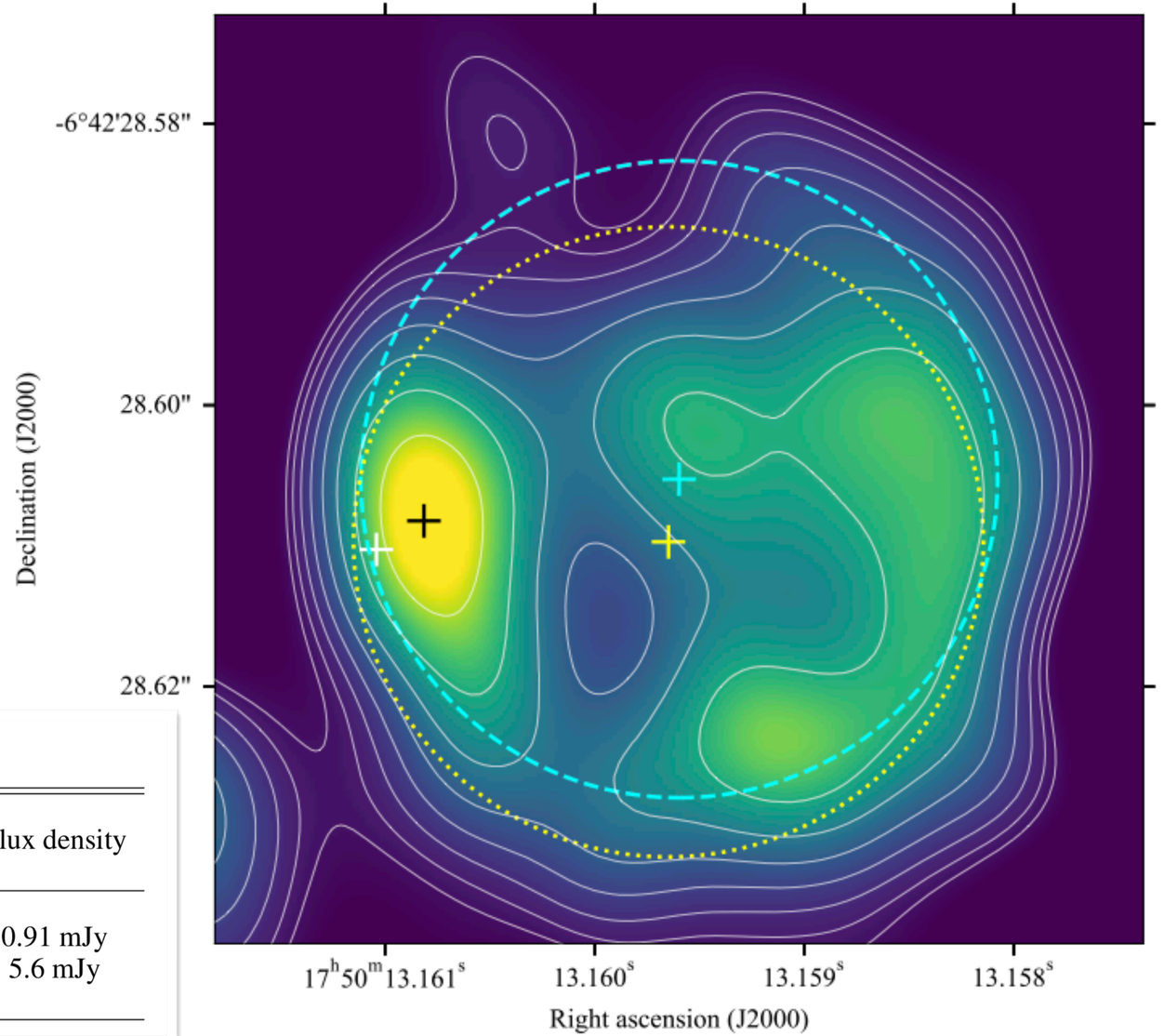


Table 1. Results of fitting the delta and ring components as shown in the right panel of Figure 1.

Component	Type	RA	Dec	Radius	Flux density
CC	delta	17h50m13.1608s	−06d42′28.6082″	- -	0.91 mJy
WL	ring	17h50m13.1596s	−06d42′28.6053″	22.5 mas	5.6 mJy

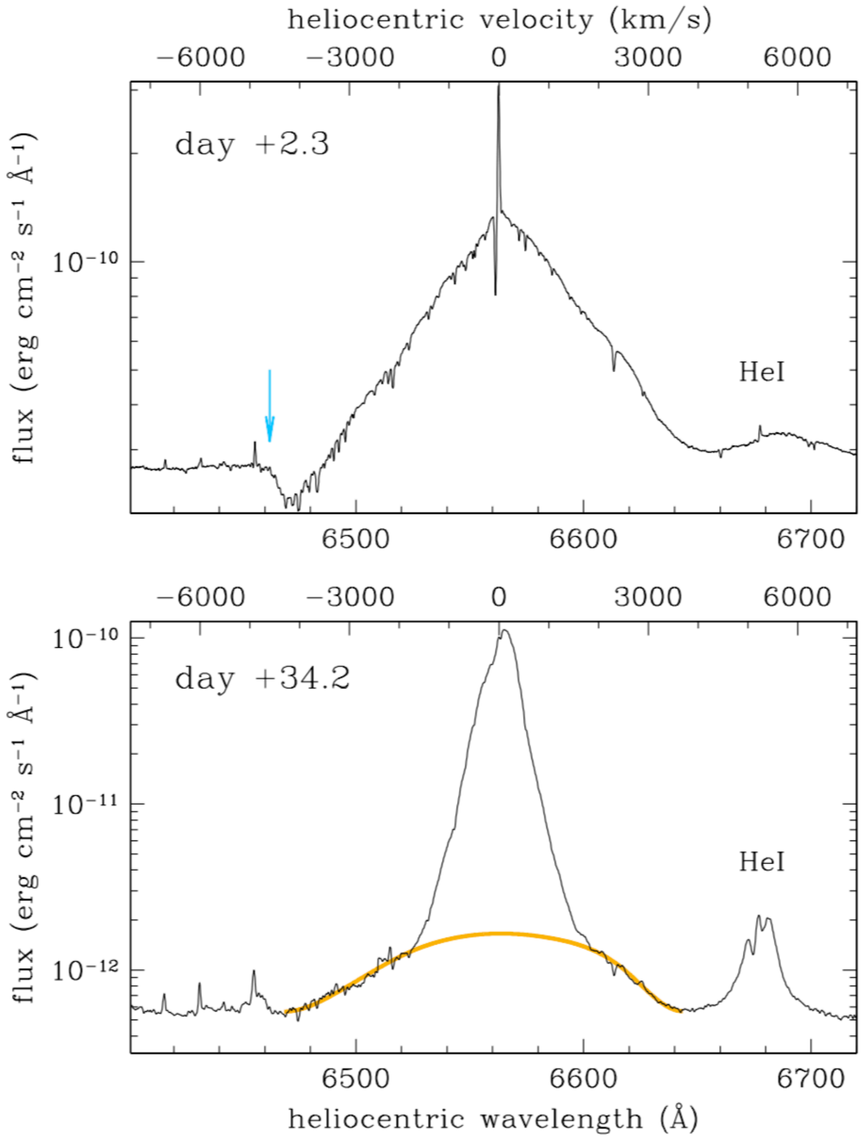


Fig. 3. Sample Hα profiles of RS Oph (from data in Munari & Valisa 2022) early in the outburst and at the time of our EVN radio imaging (see sect 3.3 for details). Heliocentric radial velocities are given at the top of the panels. The arrow in the top panel marks the -4700 km s^{-1} terminal velocity of the P-Cyg absorption, while the orange line in the lower panel is a fit to the broad pedestal extending up to -4200 km s^{-1}.

- Opposite orbital phase in 2006 and 2021 (0.26 vs 0.73)
- Orbital period 1.26d (vs >100yr for V407 Cyg)
- Binary separation 1.48 AU (<1 mas)

V407 Cyg and RS Oph

	V407 Cyg	RS Oph
Distance	2.7 kpc	2.7 kpc
P_{orb}	40-100 yr (sep 7-30 AU)	1.3 years
R_{orb}	7-30 AU	1.5 AU
n outbursts since 1900	3	8

Epoch 1

beam 5.5masx4.6mas
peak 5.7 mJy/beam
total f.d. 43 mJy
l.c.: 1.0 mJy/beam

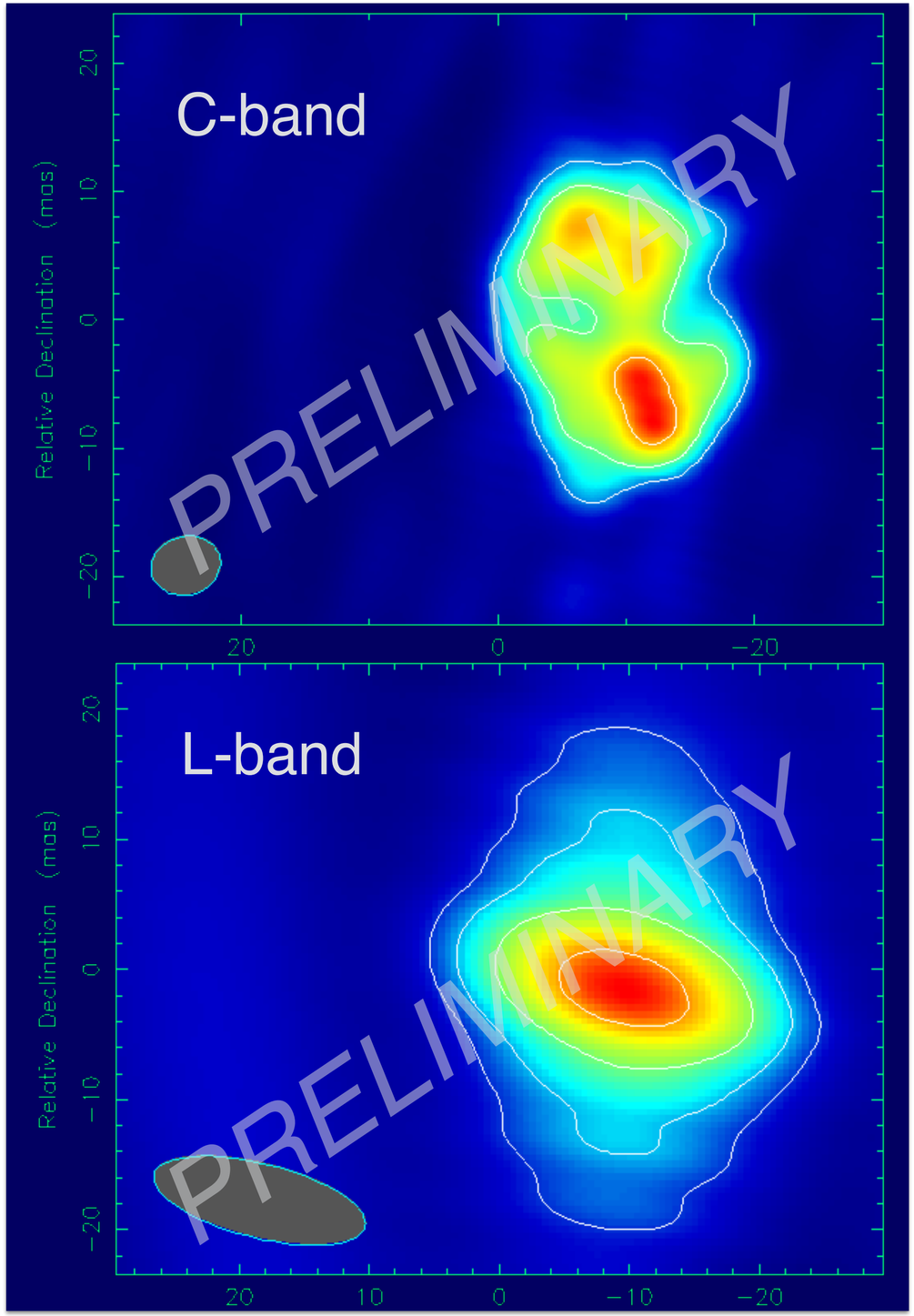
t=14-15 d

Total extension ~20 mas (28 AU)

Entirely to the West

$S_\nu \sim \nu^{+0.5}$

beam 19masx4.5mas
peak 27.2 mJy/beam
total f.d. 25 mJy
l.c.: 2.7 mJy/beam



Epoch 2

beam 10masx6mas
peak 7.3 mJy/beam
total f.d. 44 mJy
l.c.: 0.3 mJy/beam

t=24-25 d

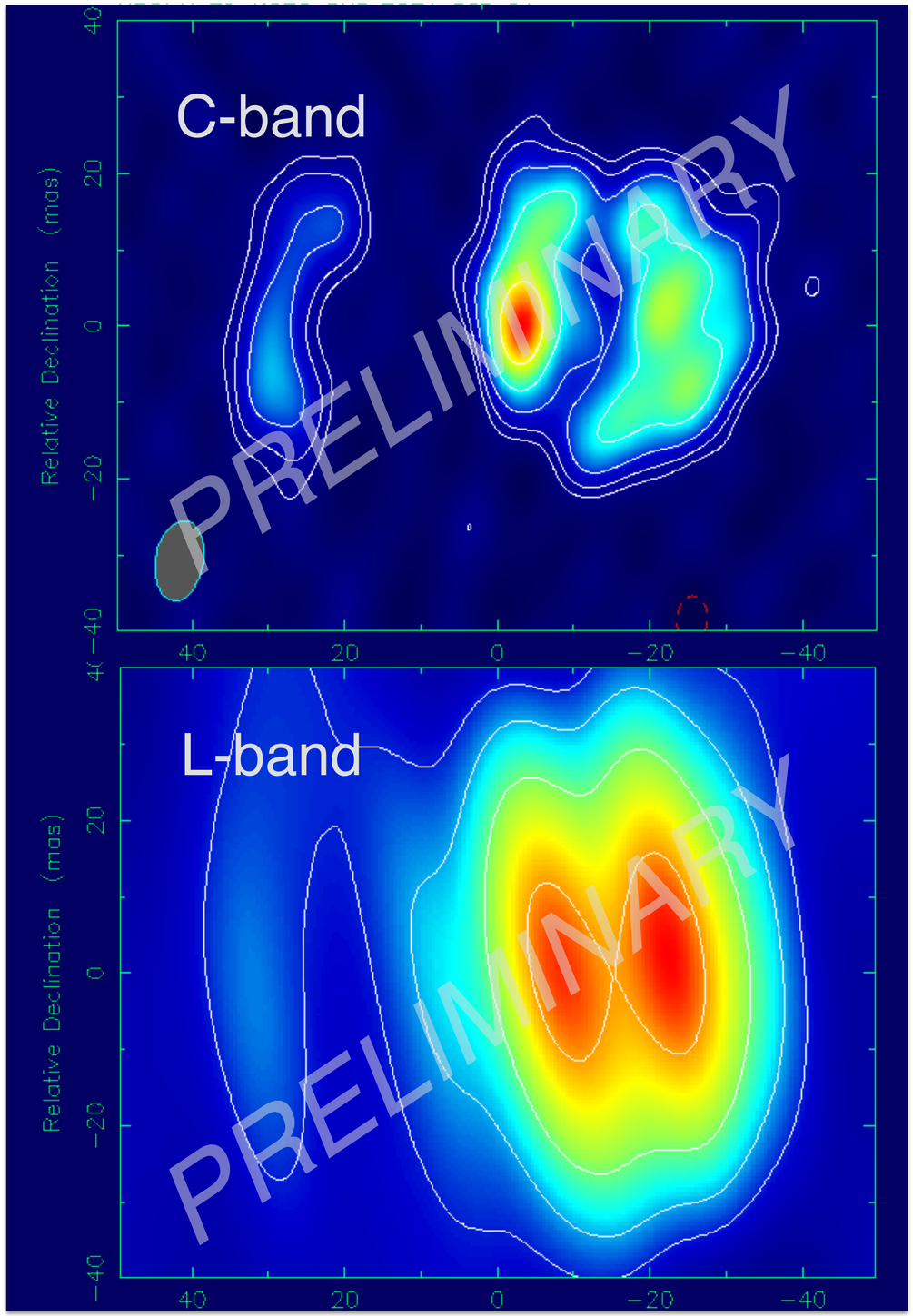
Total extension ~60 mas (84 AU)

Eastern emission appears

Spectrum turns over

$S_\nu \sim \nu^{-0.4}$

beam 44masx11mas
peak 20.7 mJy/beam
total f.d. 67 mJy
l.c.: 2.1 mJy/beam



Epoch 2

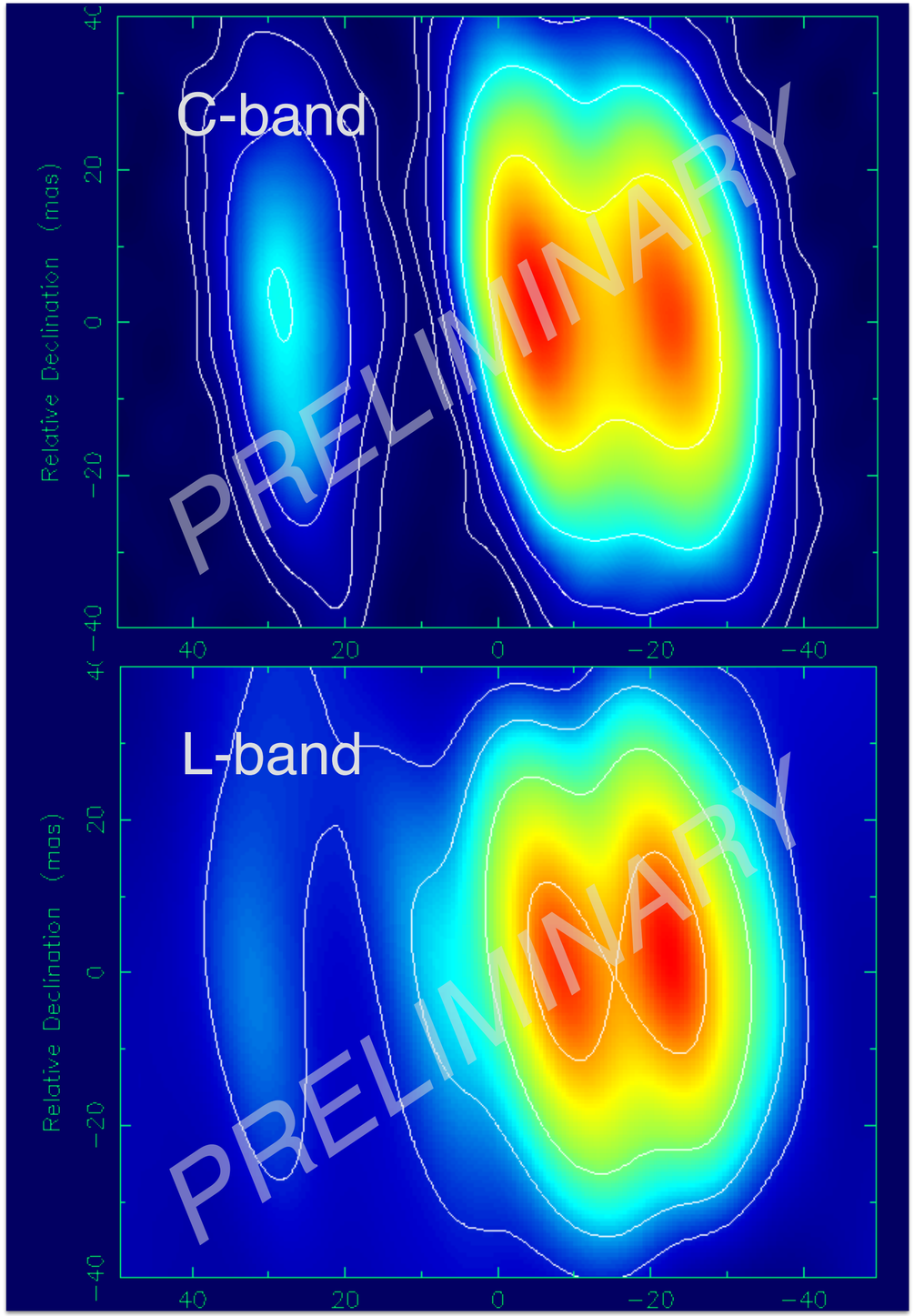
(convolved with same beam)

t=24-25 d

Total extension ~60 mas (84 AU)

Eastern emission appears

comp	$S_{1.6}$	S_5	α
E	10 mJy	6.7 mJy	-0.4
C	16 mJy	16 mJy	0.0
W	36 mJy	22 mJy	-0.4



Epoch 3

(with e-Merlin baselines!)

beam 12masx9mas
peak 2.0 mJy/beam
total f.d. 20 mJy
l.c.: 0.2 mJy/beam

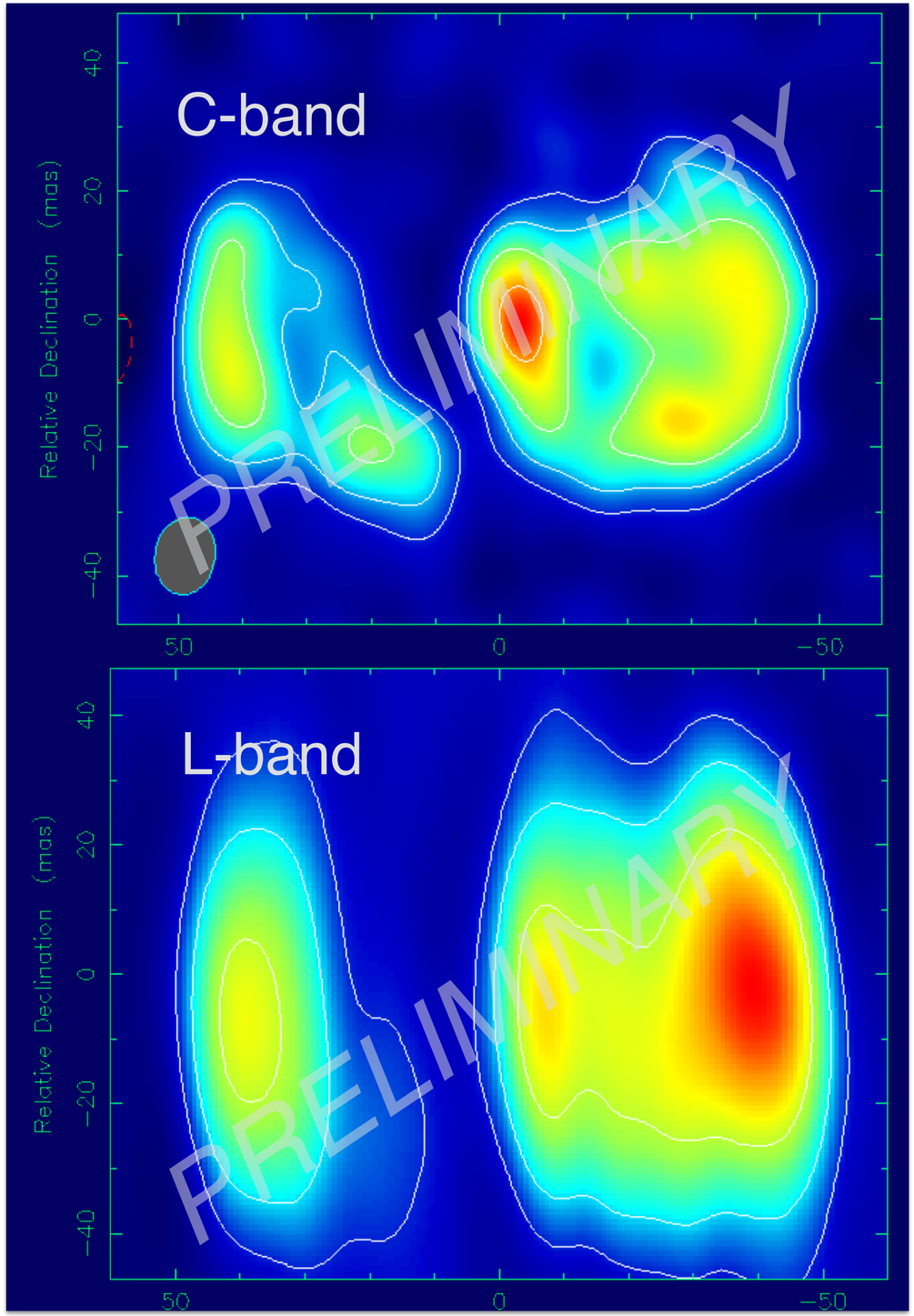
t=34-35 d

Total extension ~80 mas (112 AU)

Rich structure on both sides

$S_\nu \sim \nu^{-1.0}$ (total)

beam 34masx9mas
peak 8.5 mJy/beam
total f.d. 62 mJy
l.c.: 1.1 mJy/beam



Epoch 3

(with e-Merlin baselines!)
(convolved with same beam)

t=34-35 d

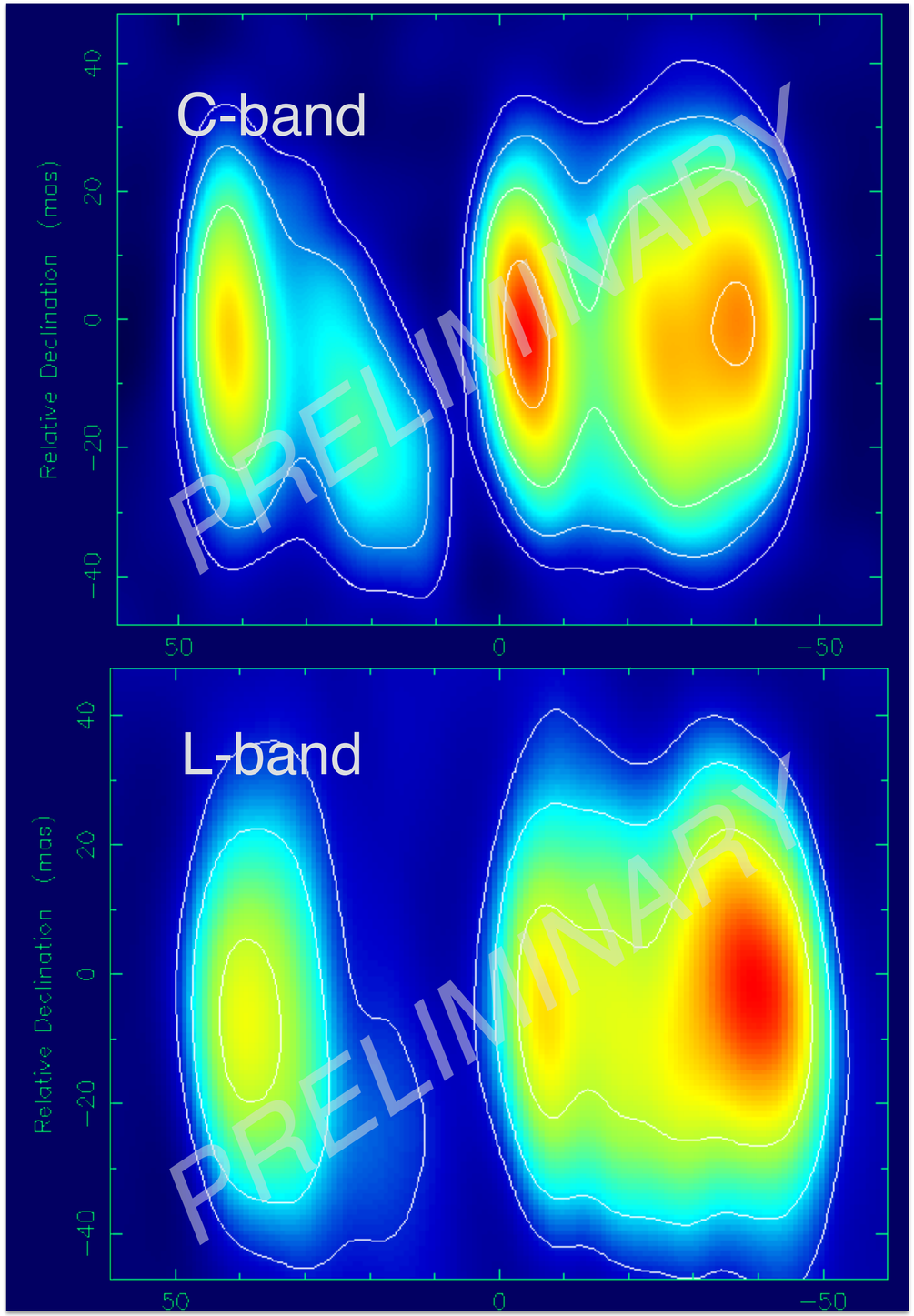
Total extension ~80 mas (112 AU)

Rich structure on both sides

$S_\nu \sim \nu^{-1.0}$ (total)

flat-standing-compact core

steep-advancing-structured outflows



Epoch 4

t=49-50 d

e-MERLIN WIDAR correlator hardware problem

still… an indication that the source is expanding

might eventually recover something about the most compact structures (in progress)

BUMMER

😢

Epoch 5

(with e-Merlin baselines)

beam 11masx9mas
peak 1.9 mJy/beam
total f.d. 15 mJy
l.c.: 0.08 mJy/beam

t=64-65 d

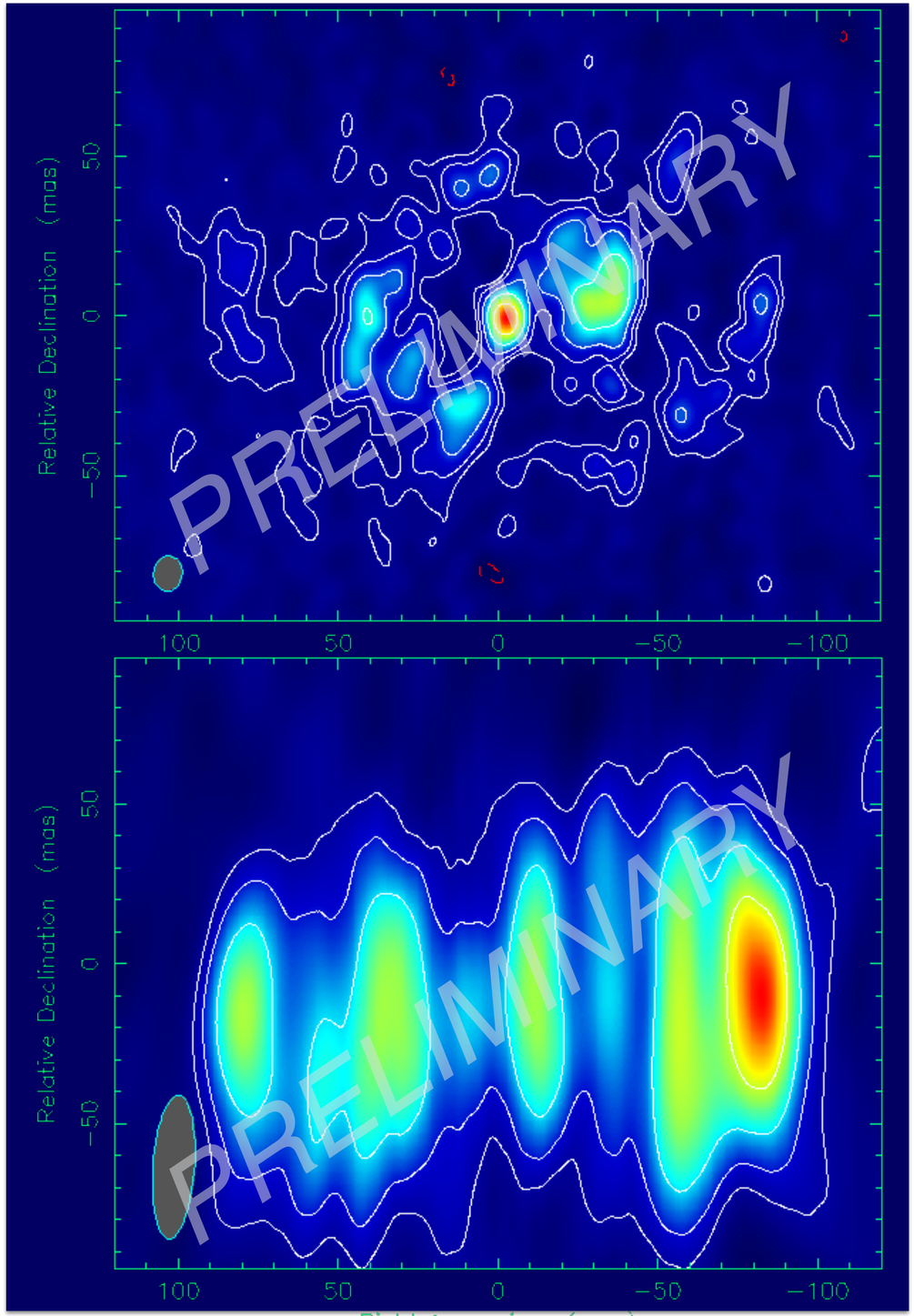
Total extension ~180 mas (250 AU)

Central compact component

Outer structure heavily resolved out

New components starting to appear

beam 45masx13mas
peak 4.1 mJy/beam
total f.d. 34 mJy
l.c.: 0.3 mJy/beam



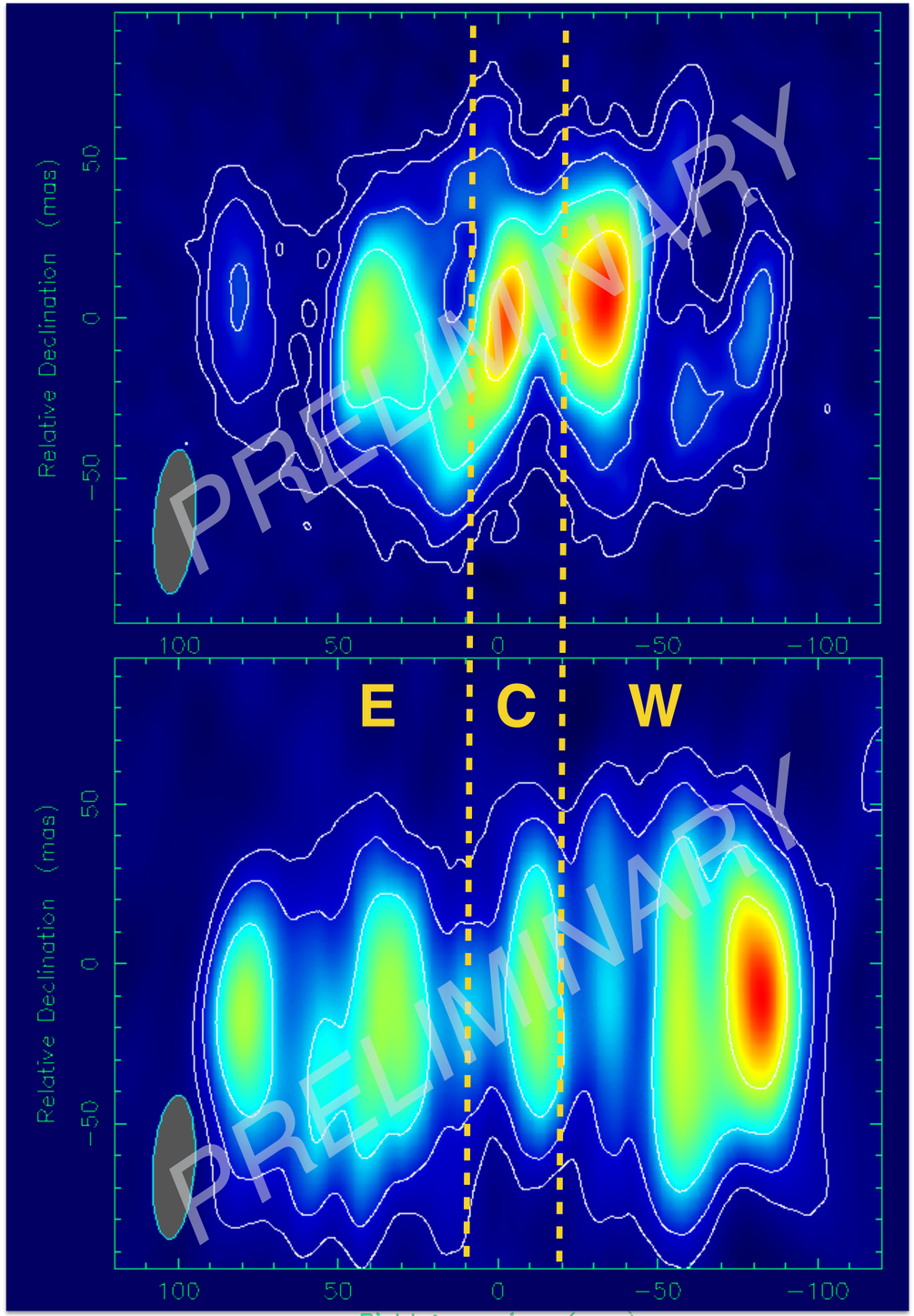
Epoch 5

(with e-Merlin baselines)
(convolved with same beam)

t=64-65 d

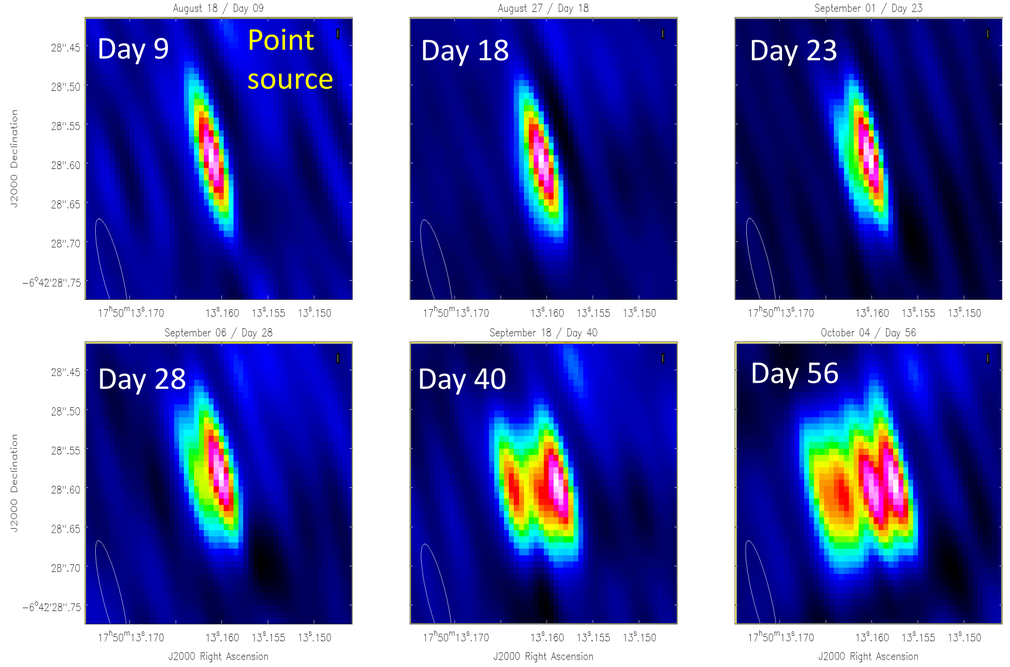
Flat “core”, steep “lobes”,
spatially resolved study
still in progress

region	$S_{1.6}$	S_5	α
E	16 mJy	7.2 mJy	-0.7
C	4.6 mJy	3.3 mJy	-0.3
W	19 mJy	6.9 mJy	-0.9



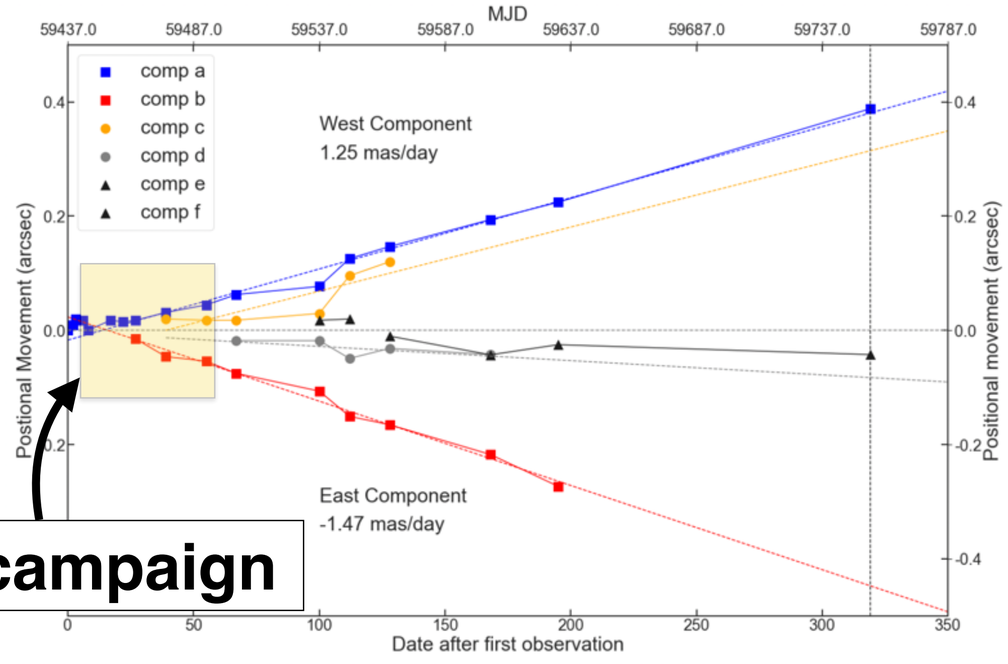
e-Merlin radio imaging

- e-MERLIN has imaged the expanding remnant from outburst in Aug 2021 to June 2022
- Imaging reveals multi-component bipolar expansion east-west as hinted at in 1985 and seen in 2006
- Resolved components are still being detected 316 & 319 days after outburst
- The expansion appears linear, but some components have faded and early times need more angular resolution



PRELIMINARY

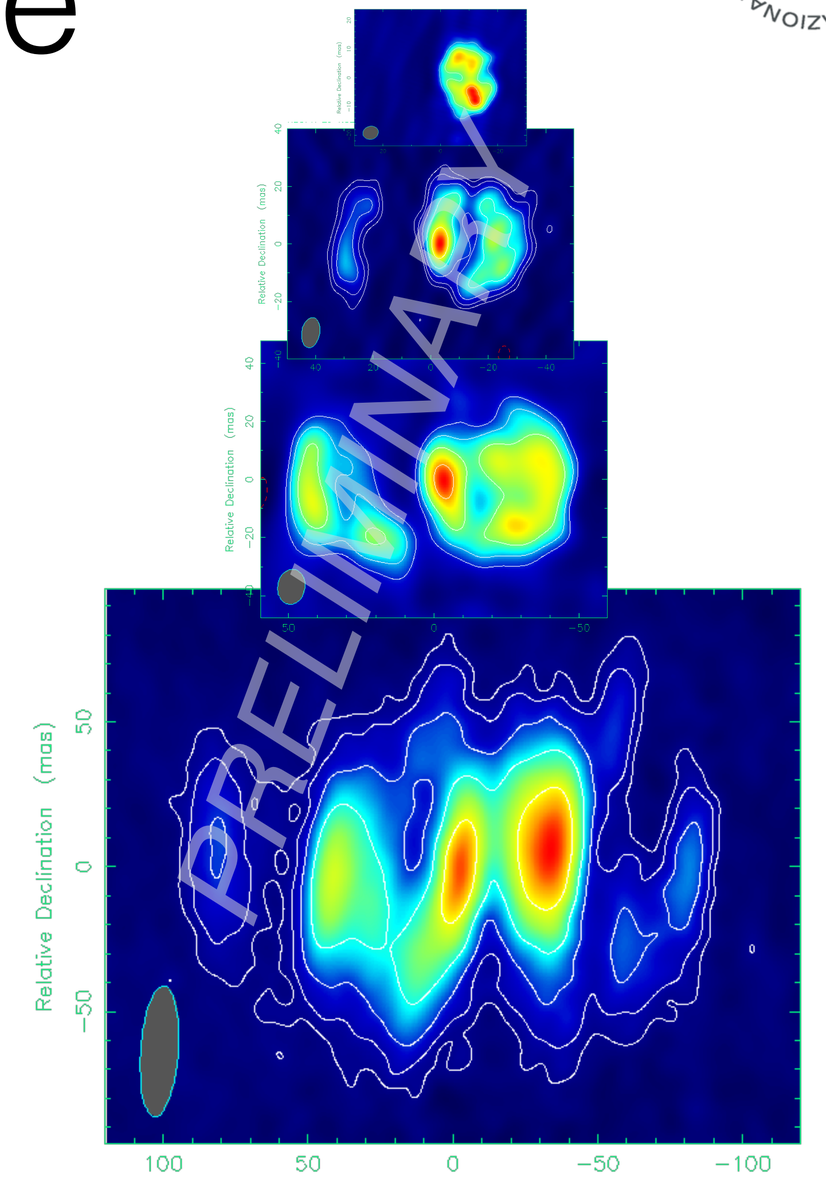
courtesy of
T. O'Brien,
D. Williams



EVN campaign

~~Take home~~ *Preliminary* message

- EVN+e-Merlin performed well under quite extreme circumstances
- RS Oph is well detected, with bipolar (yet asymmetric) emission
- Significant similarities with 2006 episode
- Further analysis of VLBI data and comparison with e-Merlin and MWL results will shed light on physics (shocks, geometry, medium, …)



EVN follow-up

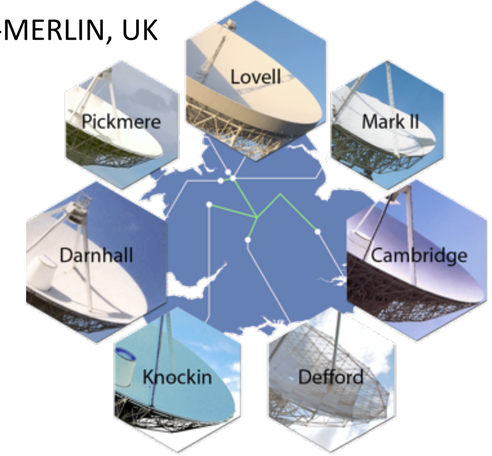
- Goals:
  - identify the loci of shock-acceleration and separate thermal and non-thermal emission regions (through spatially resolved study of Tb and α)
  - determine the geometrical configuration of the ejecta (outflow along the orbital plane or along the polar axis, exploiting opposite orbital phase)
  - distinguish free expansion from deceleration induced by the sweep-up of the RG wind (through measurement of velocity profile)

- Challenges:
  - Source evolving rapidly
  - Dual-frequency necessary
  - Out-of-session observations without notice
  - …in the middle of the summer!

Radio observations of the 2021 outburst with AMI-LA and e-MERLIN

Dave Williams & Tim O'Brien
(JBCA, University of Manchester)
Also VLA, MeerKAT and LOFAR with collaborators.

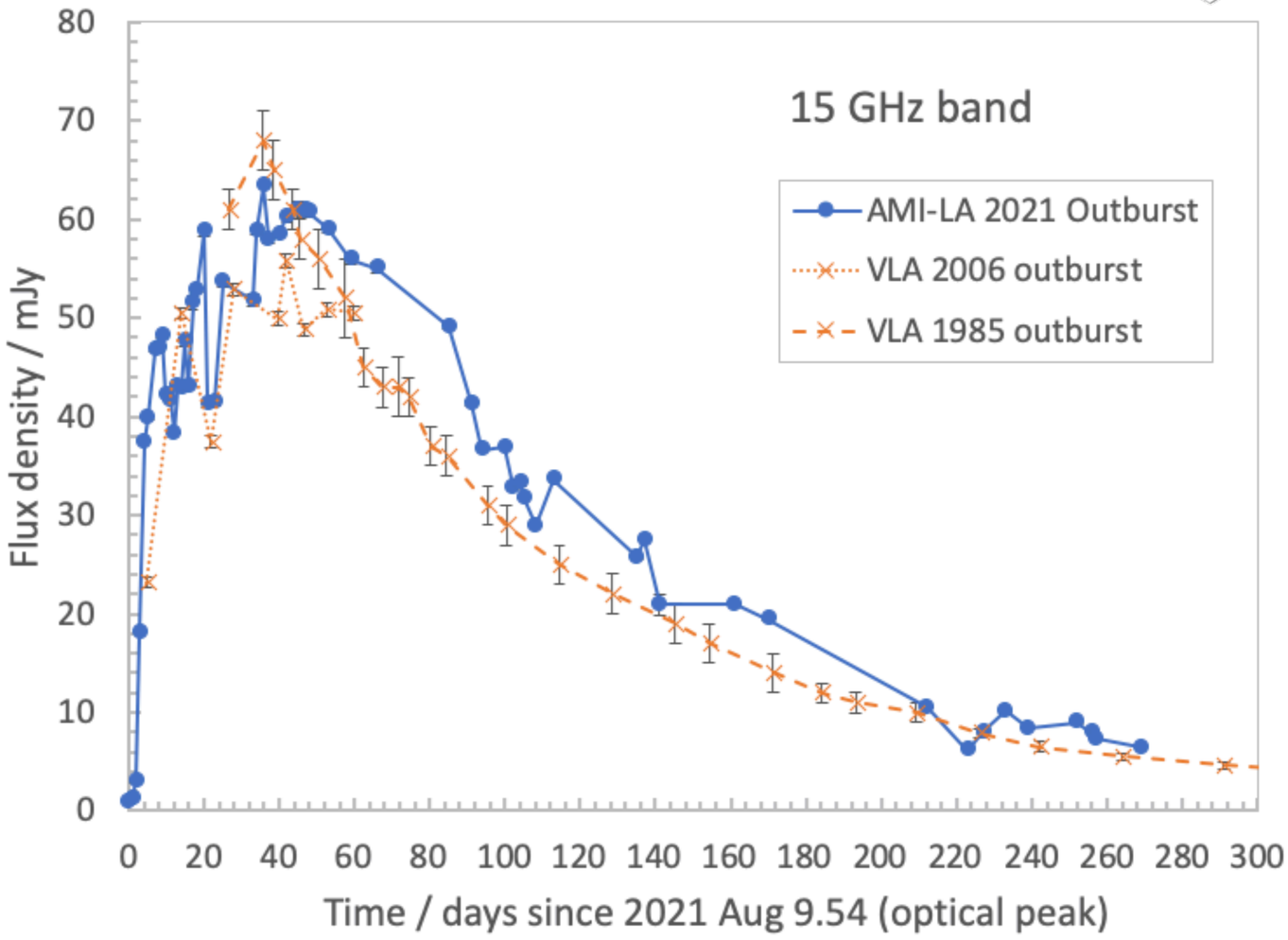

AMI-LA, Cambridge, UK – Photo by Cmglee



For example, at right are AMI-LA flux densities in 15.5 GHz band from optical peak on 9th August 2021 to May 2022.

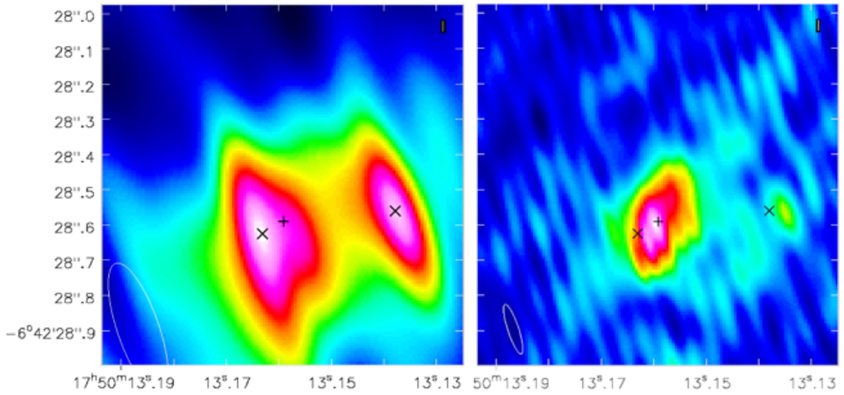
Also shown for comparison are data in similar band from VLA for the 2006 and 1985 outbursts.

Note very sharp rise just after optical peak first seen in 2006 (Eyres et al 2006), has now been confirmed and observed at several wavelengths.

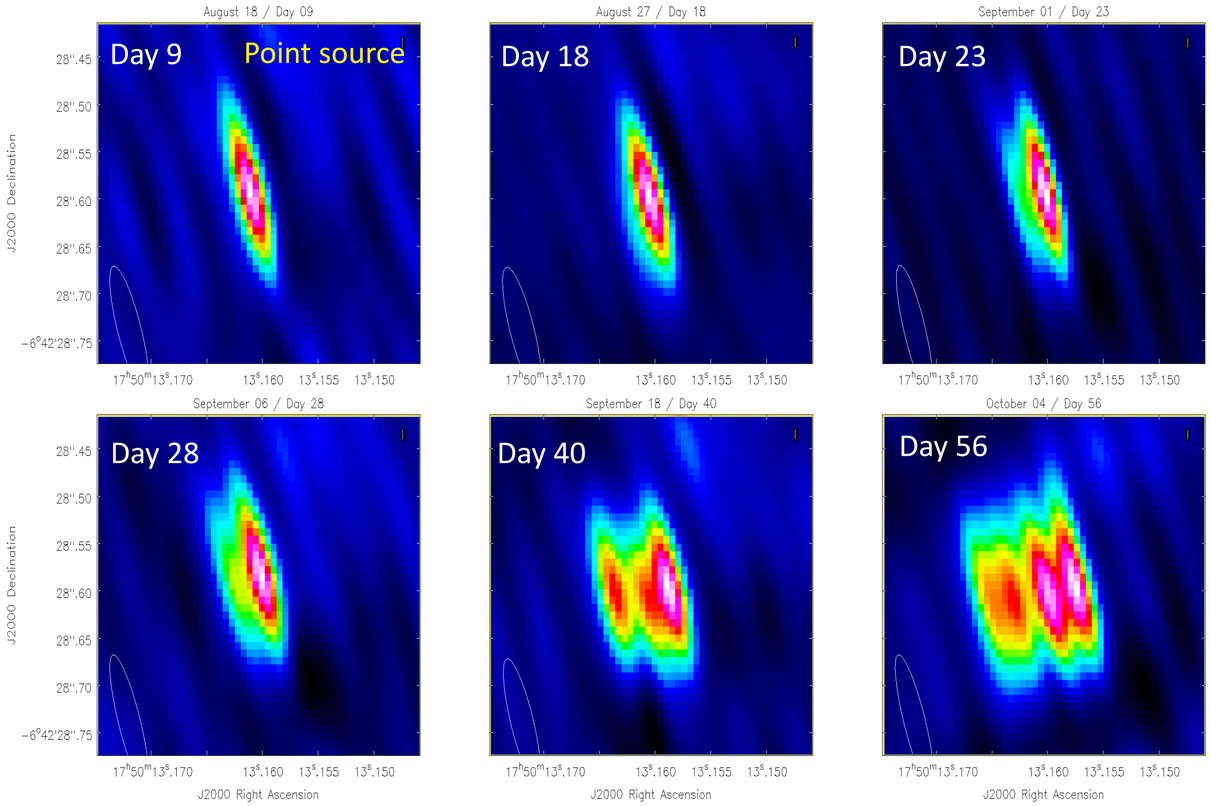


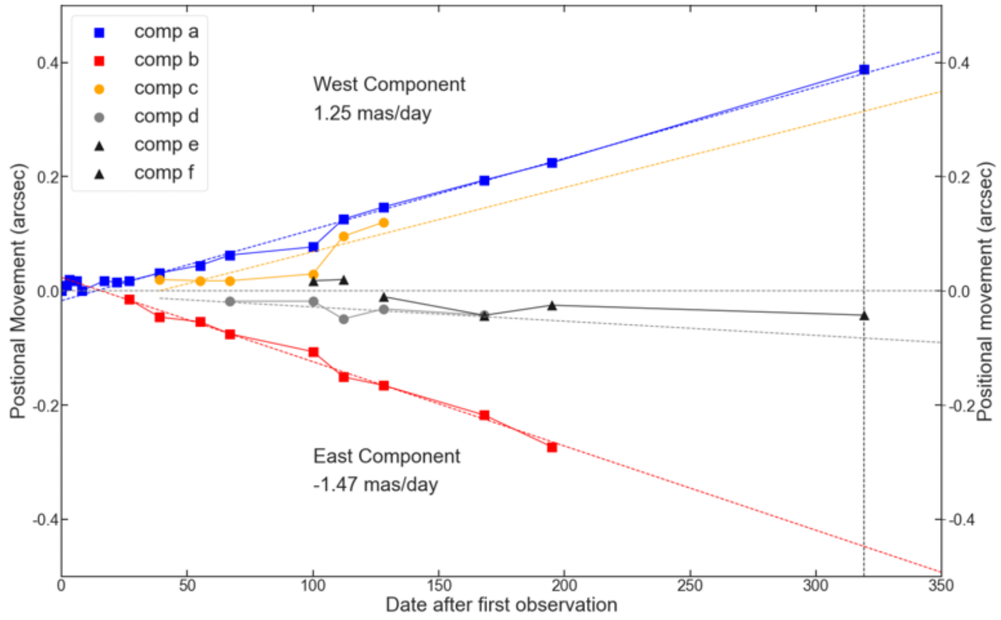
Radio imaging with e-MERLIN

e-MERLIN has imaged the expanding remnant from outburst in Aug 2021 to June 2022.
Imaging at 5 GHz shown at right reveals multi-component bipolar expansion east-west as hinted at in 1985 and seen in 2006.
Resolved components are still being detected e.g. 1.4 GHz image at left and 5 GHz at right from 2022 June 21 & 24 (316 & 319 days after outburst).



The expansion appears remarkably linear, see right, with velocities of around 1.47 (east) and 1.25 (west) mas/day. Equivalent to 4070 and 3470 km/s at a distance of 1.6 kpc.
Note the eastern components have now faded (with the inner one having stalled), whereas the western one continues its linear expansion.





H.E.S.S.

- picca dopo LAT, tempo che ci vuole per riempire la coda di alte energie delle particelle accelerate
- preferisce hadronic perché il leptonic richiede frazione di energia in relativistic electron too large (>1%)
- if it works, and can be extended to supernovae, supports origin of cosmic rays
- several parameters require radio imaging (indeed based on 2006 VLBI observations); shock velocity at late times

Early Radio

https://www.astronomerstelegram.org/?read=14849

- Following multi-wavelength reports of a new outburst of the recurrent nova RS Ophiuchi, we requested observations with AMI-LA at 15.5 GHz, e-MERLIN at 5 GHz and MeerKAT at 1.28 GHz. AMI-LA observations started on 2021-08-09.77 and 2021-08-10.77 and each epoch lasted for 4 hours. We detect RS Oph at a flux density of 0.80+/-0.08 mJy on 2021-08-09.77 and 1.50+/-0.15 mJy on 2021-08-10.77. The image noise levels were 0.15mJy/beam on 2021-08-09.8 and 0.2mJy/beam on 2021-08-10.8, respectively.
- The e-MERLIN observations started on 2021-08-10.60 and lasted 12 hours, we detect RS Oph at a flux density of 0.38 +/- 0.06 mJy with an image noise of 40 uJy/beam.
- MeerKAT detects RS Oph at a flux density of 0.29 +/- 0.03 mJy, with an image noise of 12 uJy/beam.
- The previous earliest detection of radio emission from RS Oph in outburst was 4.4 days after the peak of the visual light curve (Eyres et al. 2009). All of the detections presented here were obtained ~2 days after the start of the outburst and are the earliest radio detections of this source in outburst.