Filming the evolution of symbiotic novae with VLBI: the 2021 explosion of RS Oph

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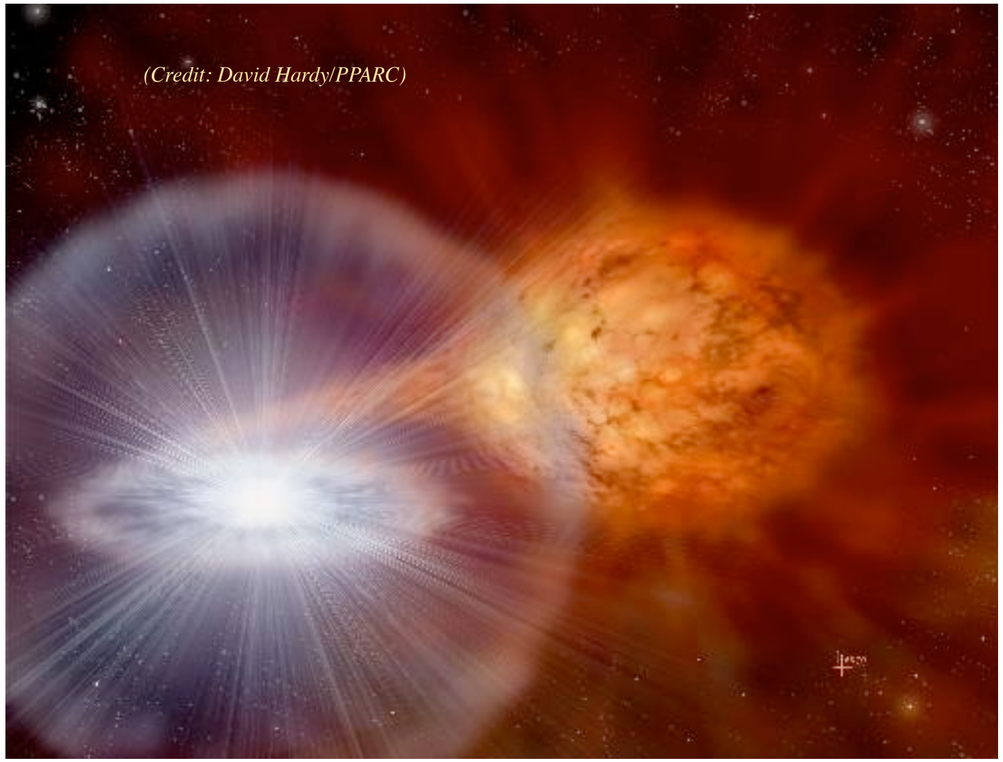
with U. Munari, T. O'Brien, B. Marcote, D. Williams, P. Woudt, P. Veres, J. Yang

15th EVN Symposium, Cork, Ireland, 2022 July 14th

About novae

- Novae are thermonuclear outbursts in binary systems containing an accreting white dwarf (WD)

- Accreted material accumulates until pressure at base of accreted shell produces thermonuclear ignition; result is ejection of shell, expanding into surroundings

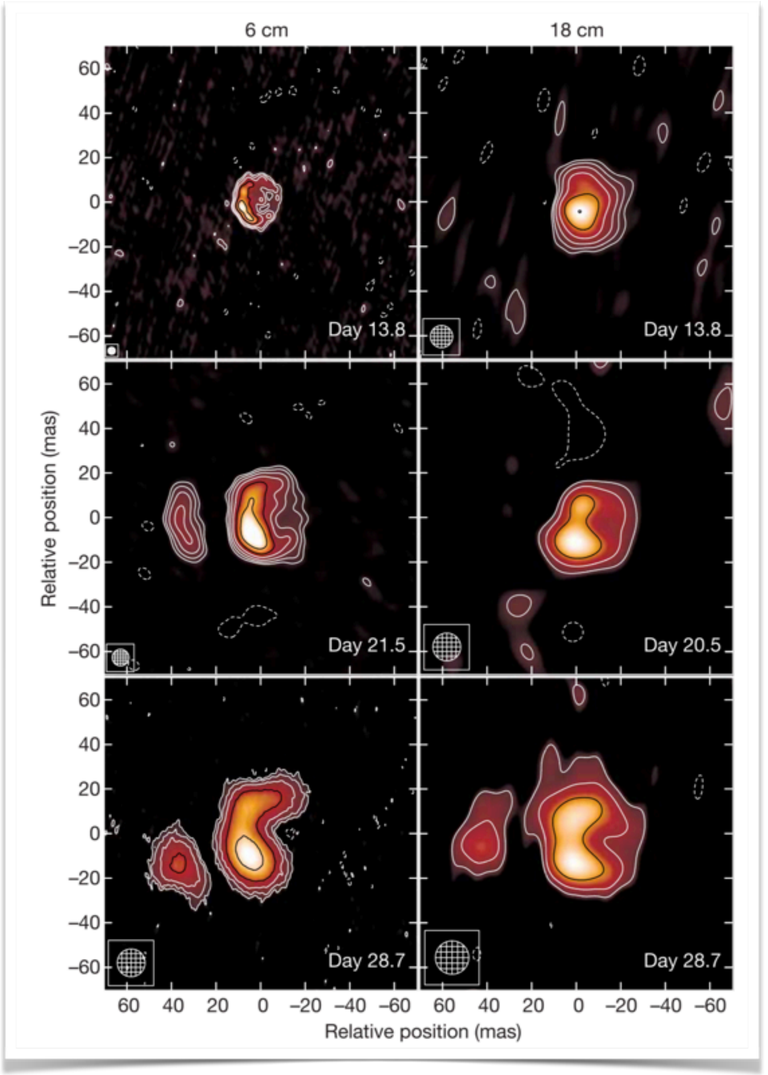


- Classical novae: the WD companion is a main sequence star

- Symbiotic novae: the companion is a pulsating red giant (RG); the nova ejecta expand in its denser wind

Symbiotic novae, VLBI, and high energy

- Rare systems, typically recurring on human time scales
- RS Oph - outbursts in 1985 and 2006
- V407 Cyg - outburst in 2010, first episode of *any* nova detected in gamma rays
- Growing evidence of shock acceleration in RG wind



O'Brien et al. (2006 Nature)

V407 Cyg summary

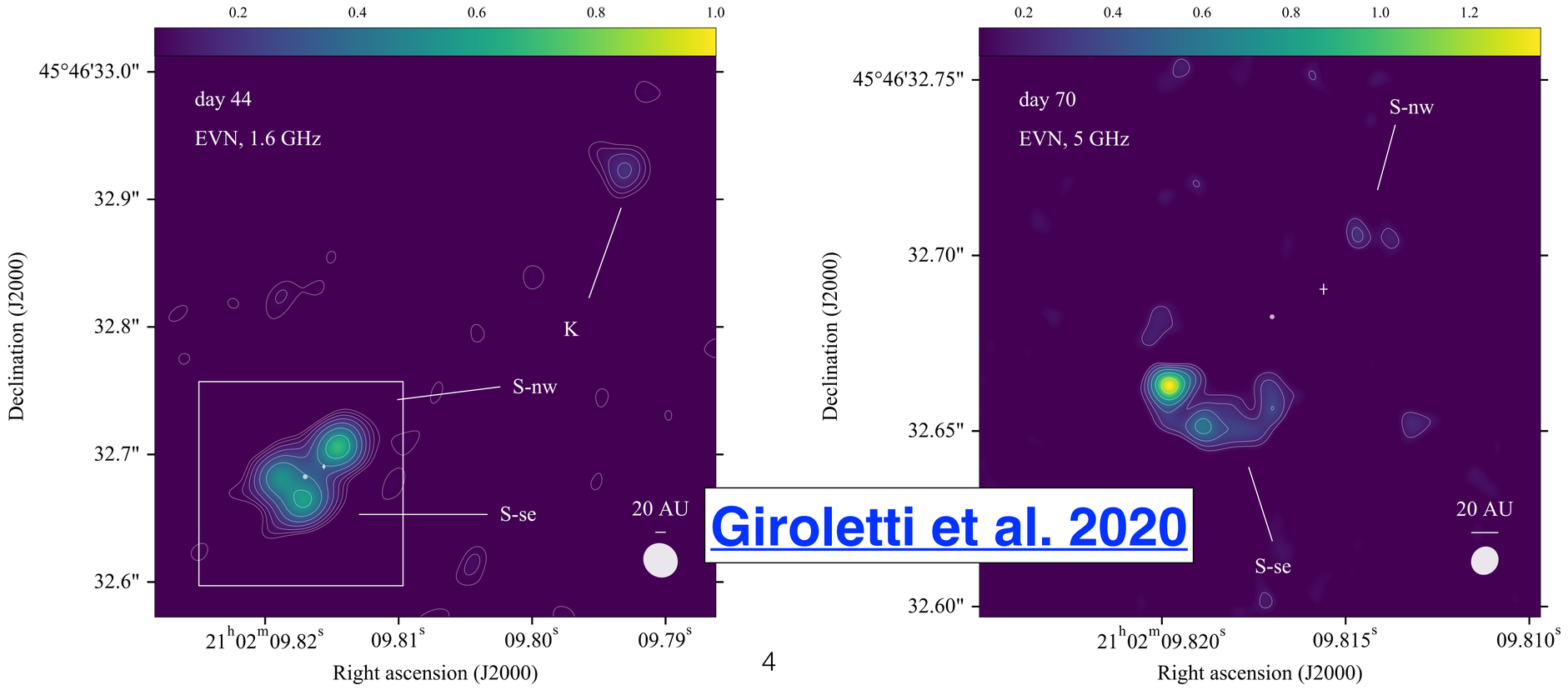
6 EVN epochs, between 20 and 200 days from nova

Initially shell-like structure, then bipolar outflow

Rising ($S_\nu \sim \nu^{+1.0}$) spectrum, large T_b

Velocity starting at ~3000 km s^{-1}, then decreasing as $v \sim t^{-0.32}$

Constraints on orientation and features from past activity



Giroletti et al. 2020

RS Oph, 2021 nova

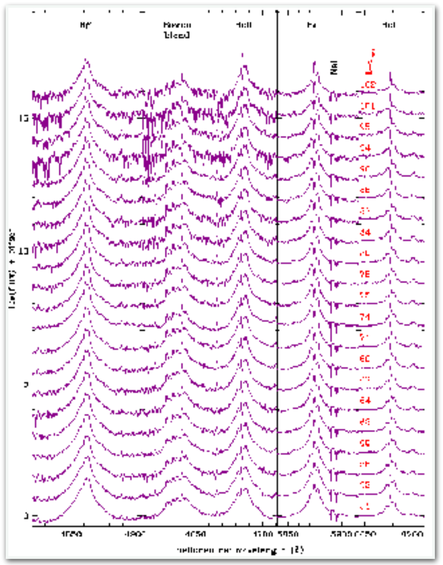
Discovered in optical on 2021 Aug 8

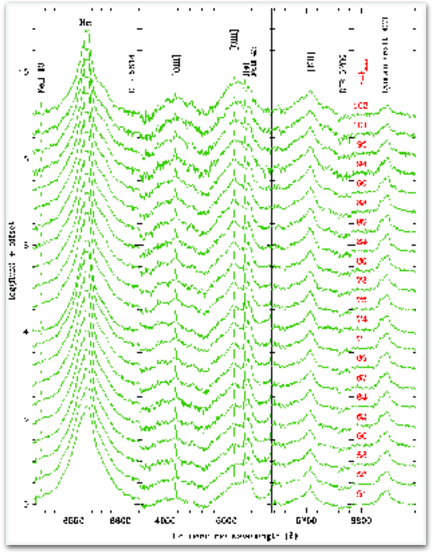
Promptly reported in MeV/ GeV domain by *Fermi*-LAT

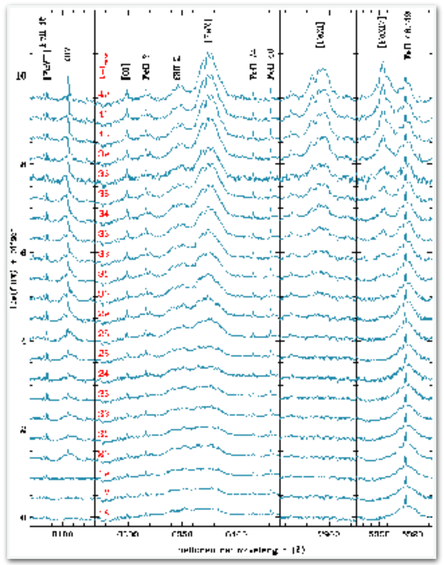
Very rich optical spectroscopy datasets

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

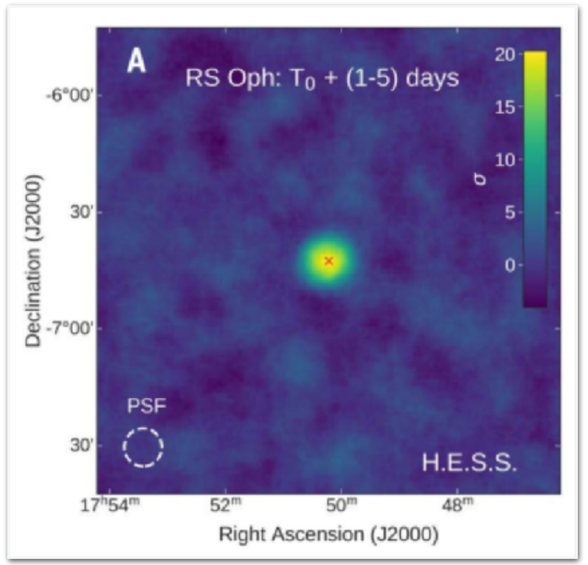
Fast rise in radio reported by e-Merlin, MeerKAT, AMI-LA, VLA

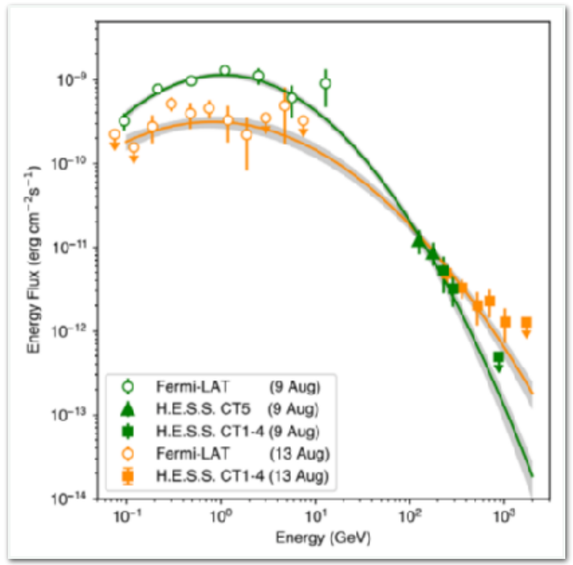






Munari & Valisa 2022





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

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!

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    the summer!

EVN Officers and Directors

JIVE Support Scientists

my collaborators, especially J. Yang

The RG012 campaign

Code	Date	Days from T0	Freq	Notes
A	Aug 22	14	5 GHz	
B	Aug 23	15	1.6 GHz	only 5 Eu + Hh
C	Sep 1	24	5 GHz	
D	Sep 2	25	1.6 GHz	
E	Sep 11	34	5 GHz	with e-Merlin
F	Sep 12	35	1.6 GHz	with e-Merlin
G	Sep 26	49	5 GHz	with e-Merlin
H	Sep 27	50	1.6 GHz	with e-Merlin
I	Oct 11	64	5 GHz	with e-Merlin
J	Oct 12	65	1.6 GHz	with e-Merlin

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

Epoch 1

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

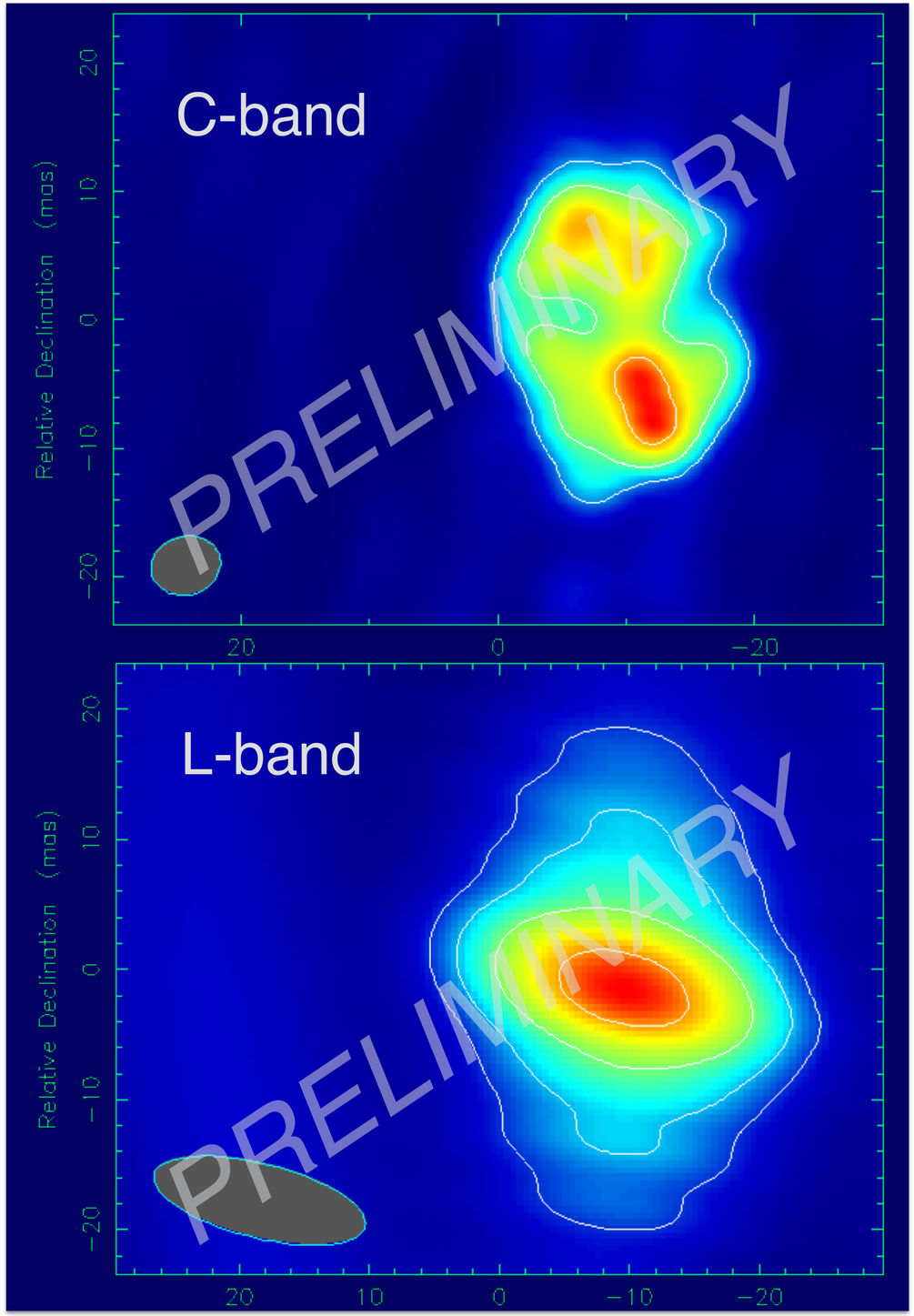
t=14-15 d

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

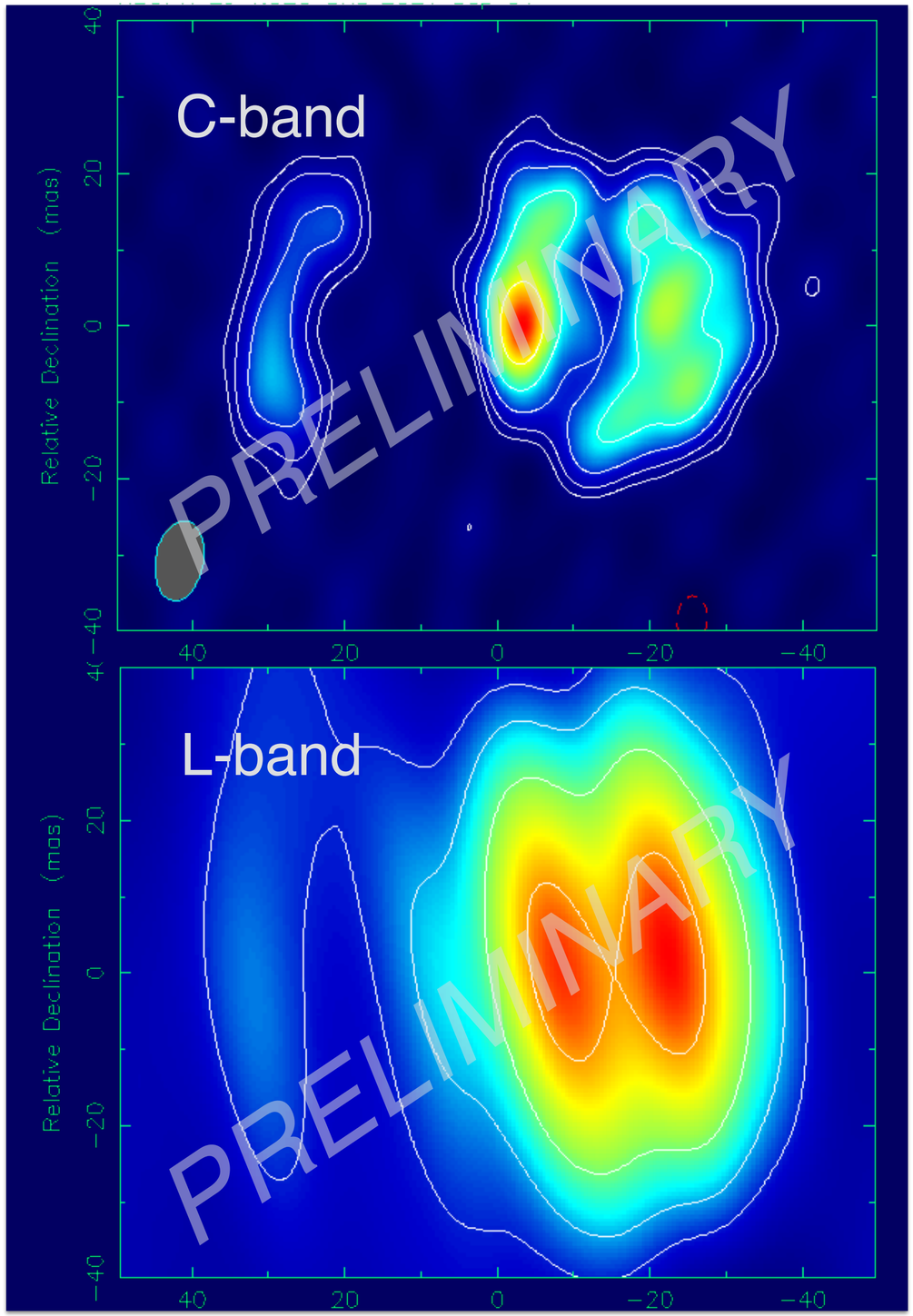
Total extension ~60 mas (84 AU)

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

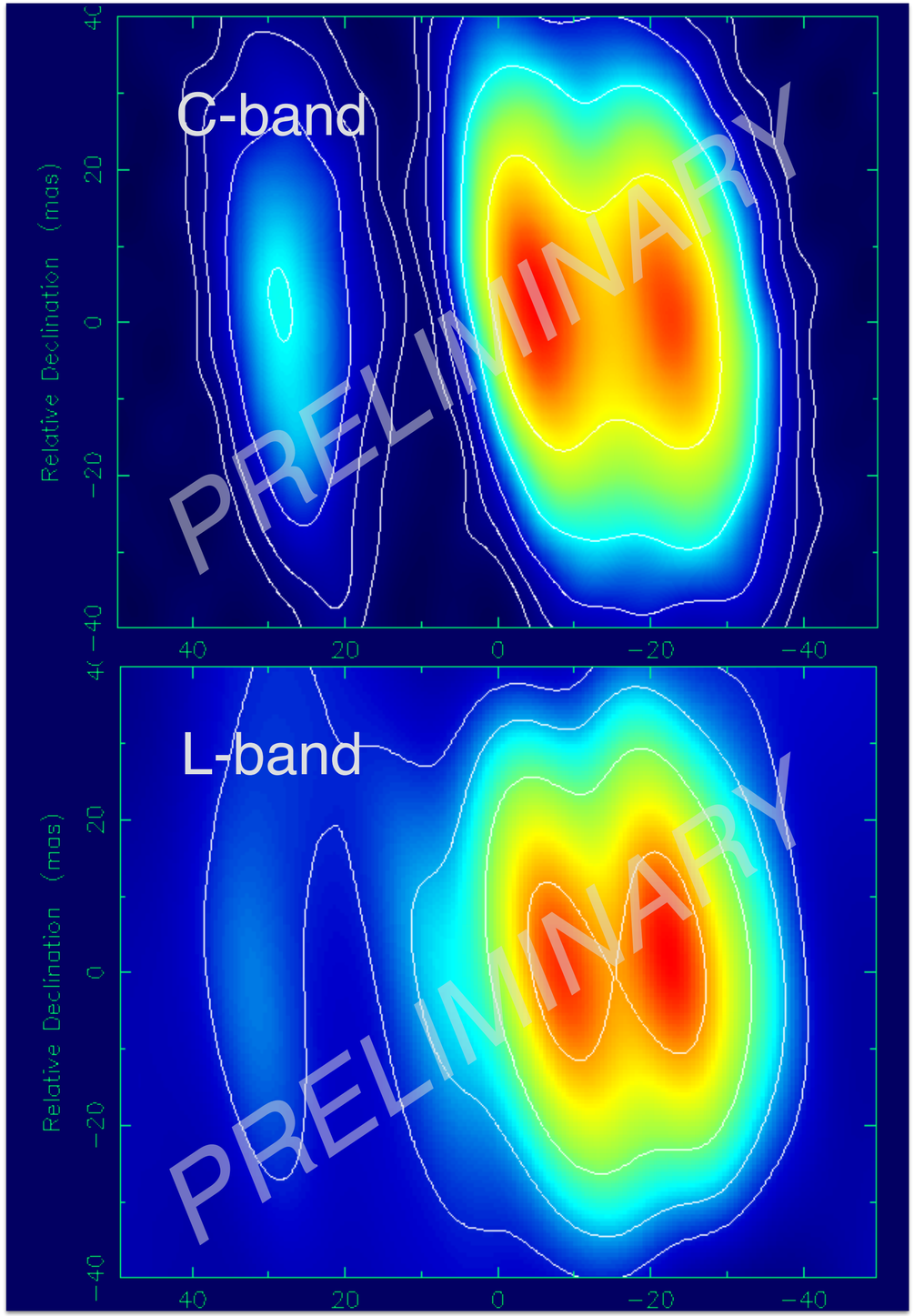
(convolved with same beam)

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

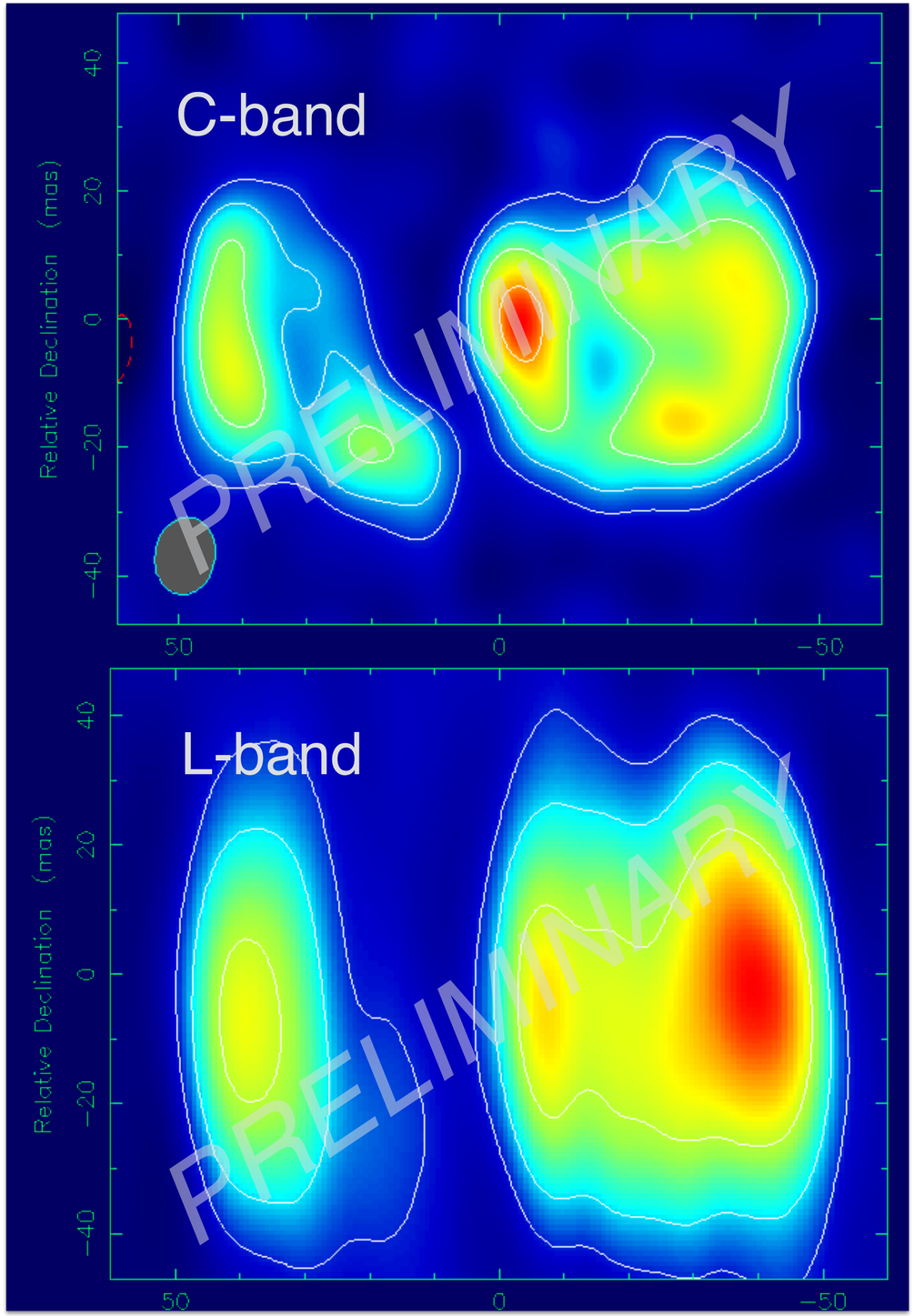
t=34-35 d

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

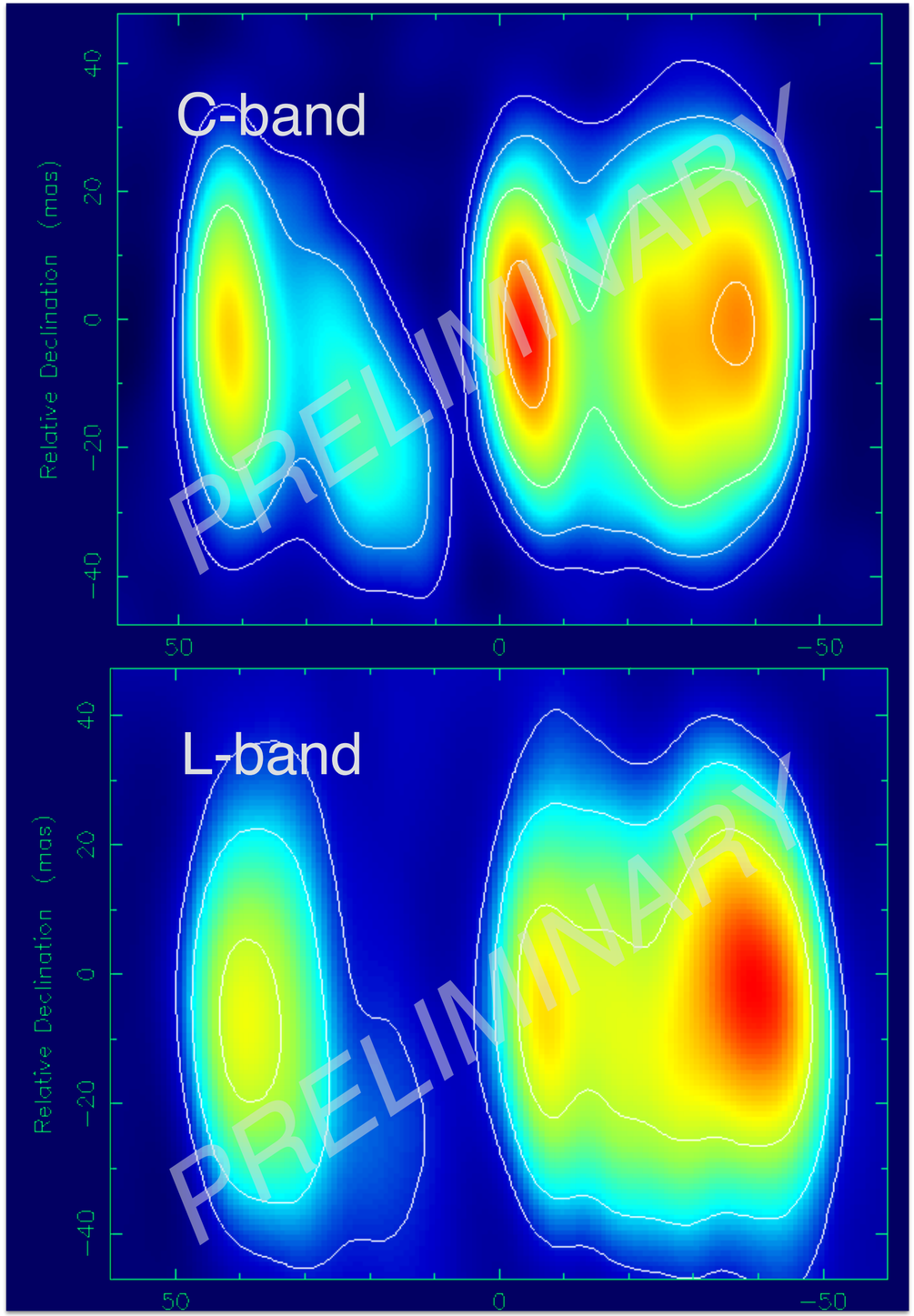
Total extension ~80 mas (112 AU)

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

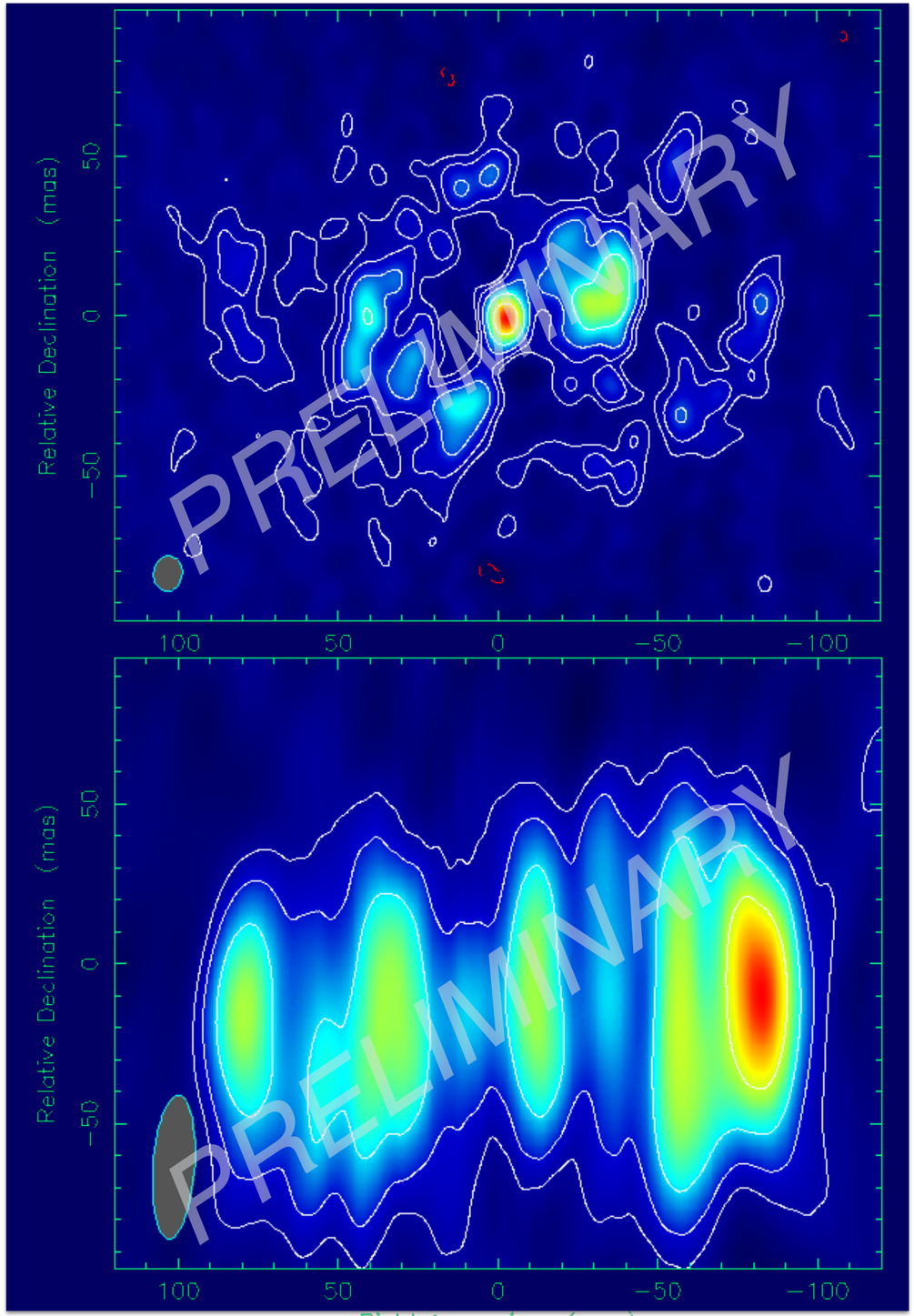
Total extension ~180 mas (250 AU)

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



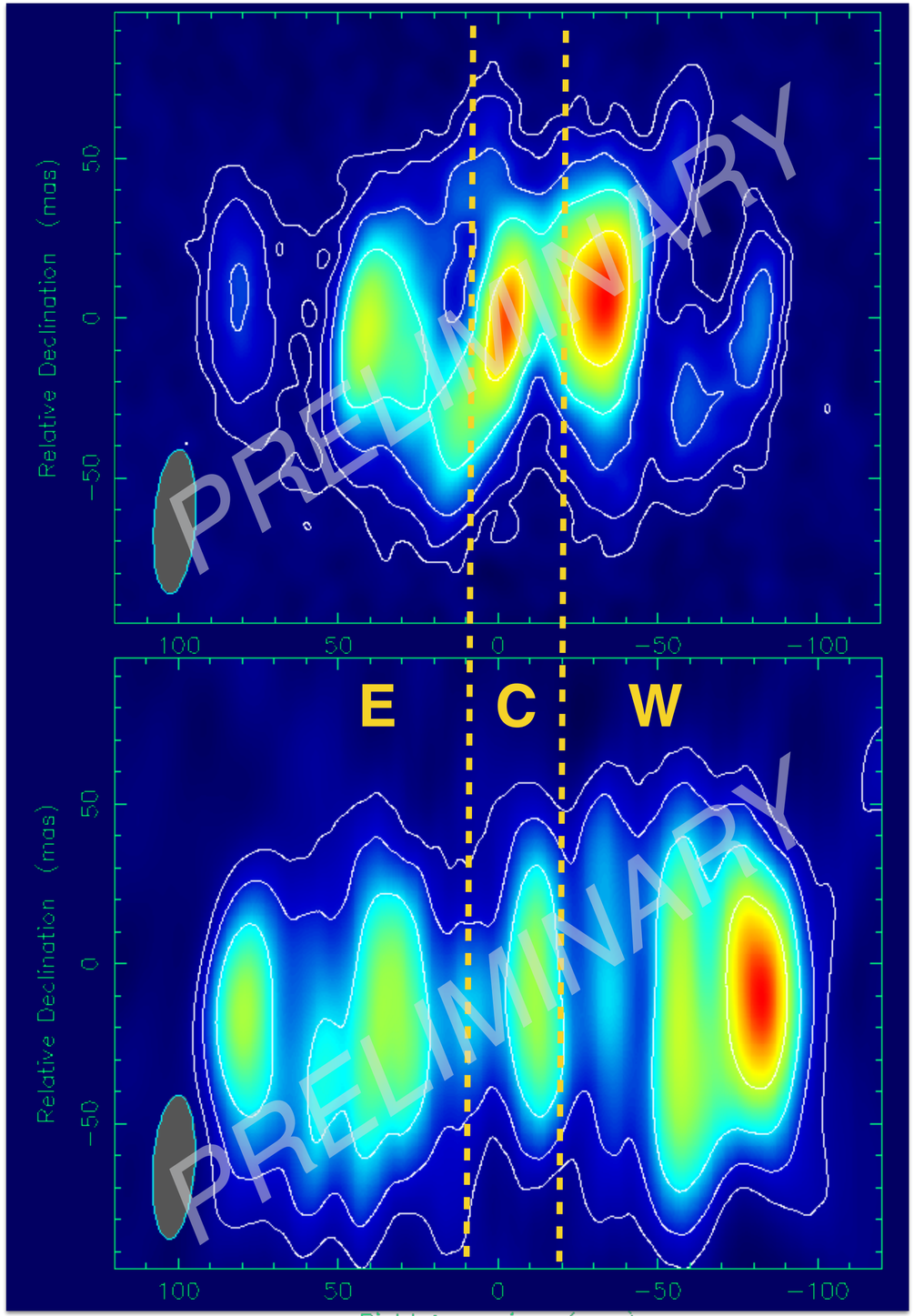
Epoch 5

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

t=64-65 d

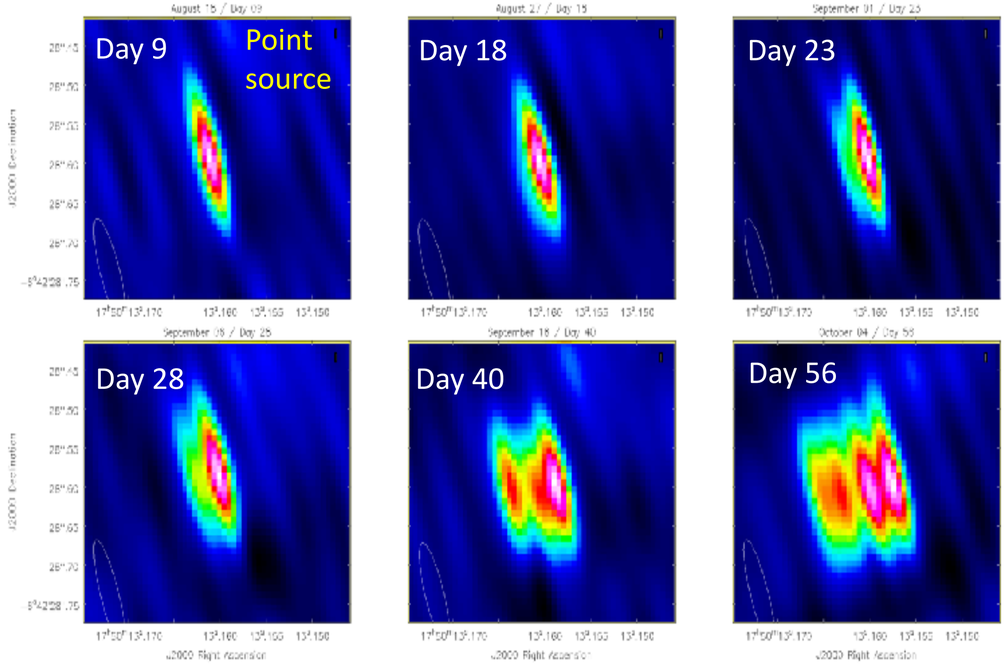
Flat “core”, steep “lobes”,
spatially resolved study
still in progress

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



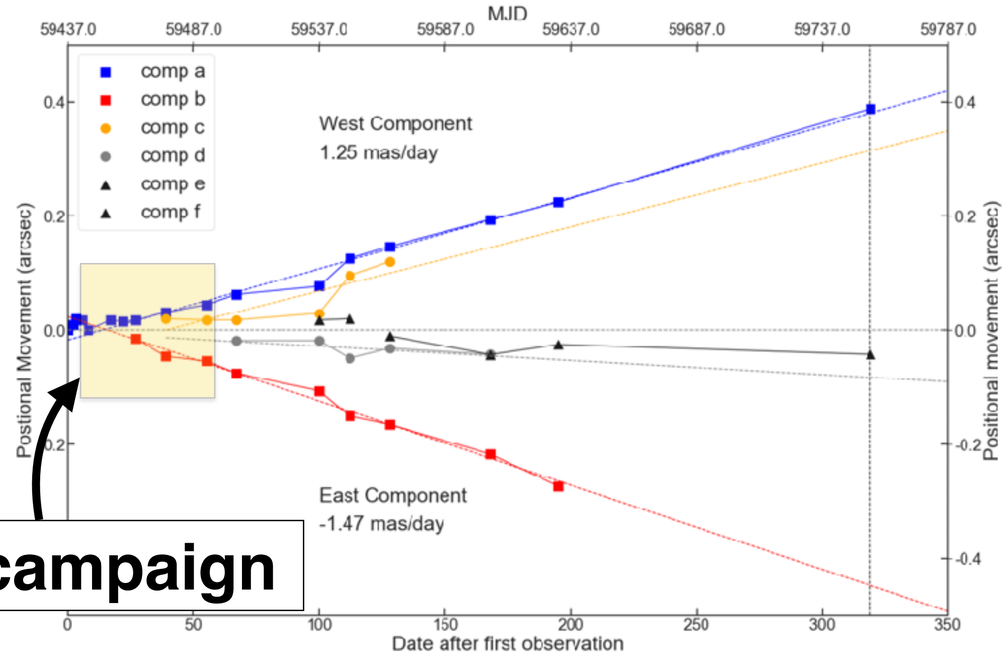
e-Merlin radio imaging

- 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

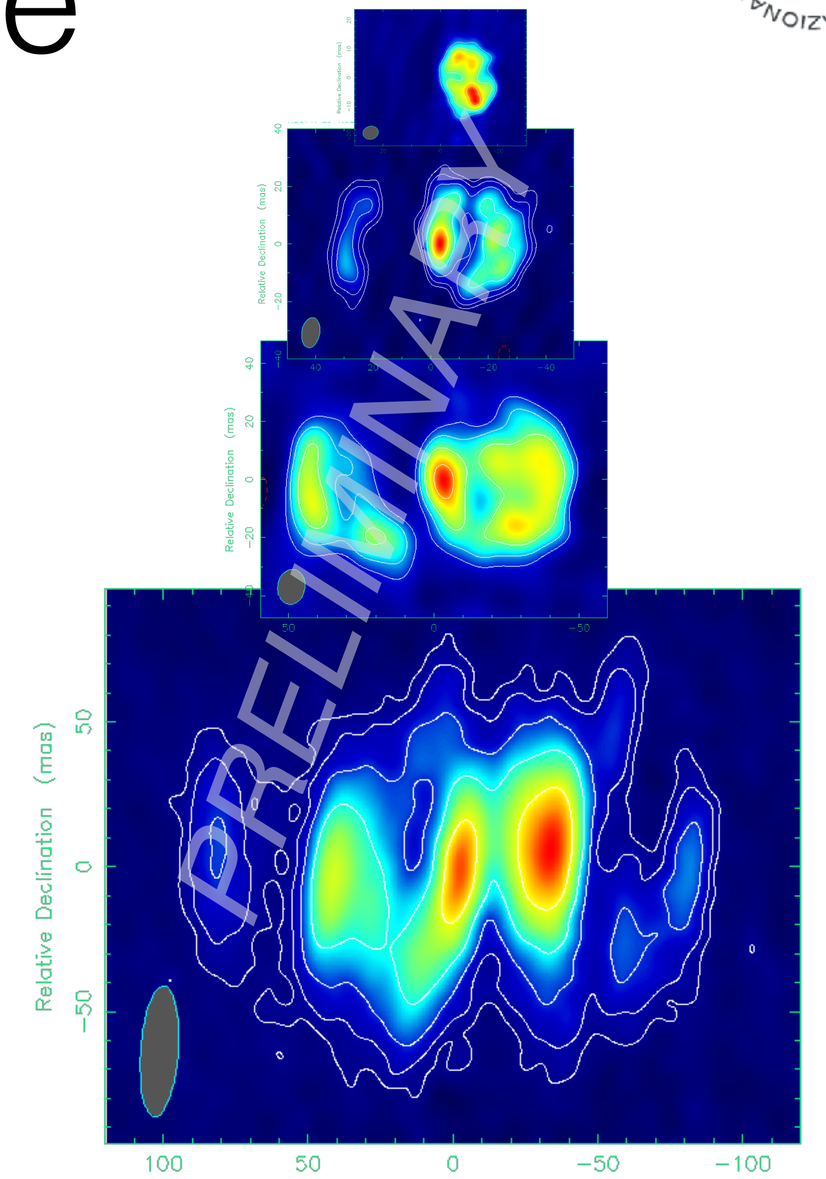
courtesy of
T. O'Brien,
D. Williams



EVN campaign

Preliminary ~~Take home~~ message

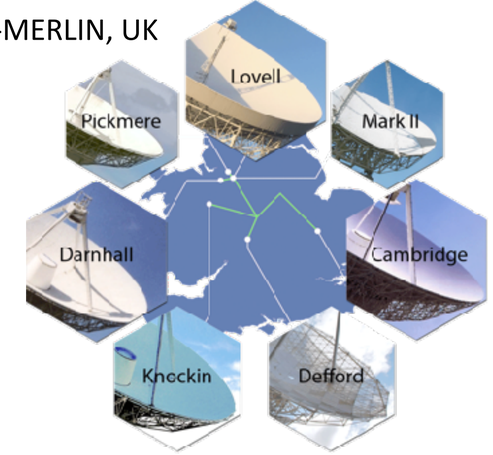
- EVN+e-Merlin performed well under quite extreme circumstances
- RS Oph is well detected, with bipolar (yet asymmetric) emission
- Significant similarities with 2006 episode
- Further analysis of VLBI data and comparison with e-Merlin and MWL results will shed light on physics (shocks, geometry, medium,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



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.

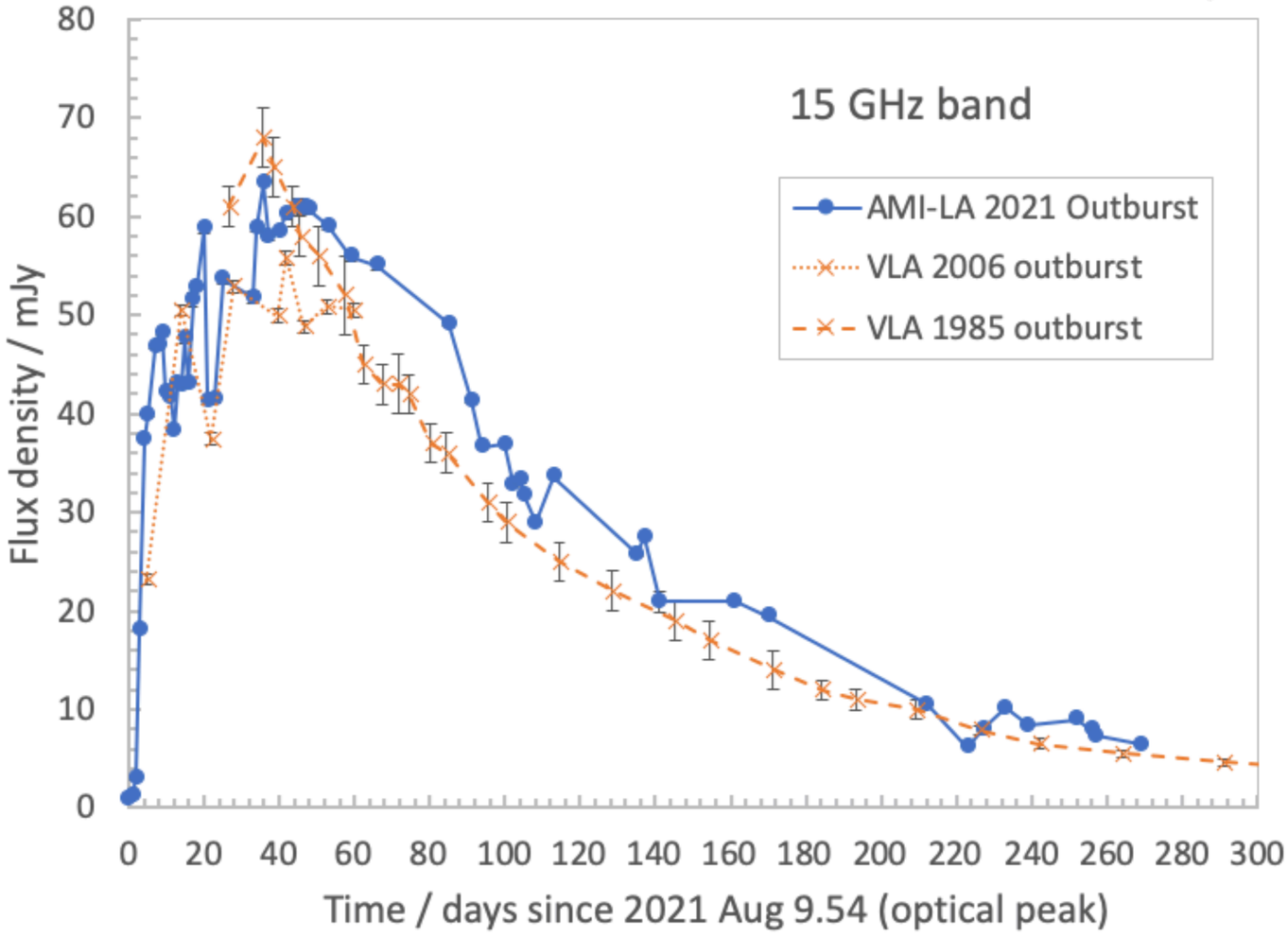

AMI-LA, Cambridge, UK – Photo by Cmglee



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.

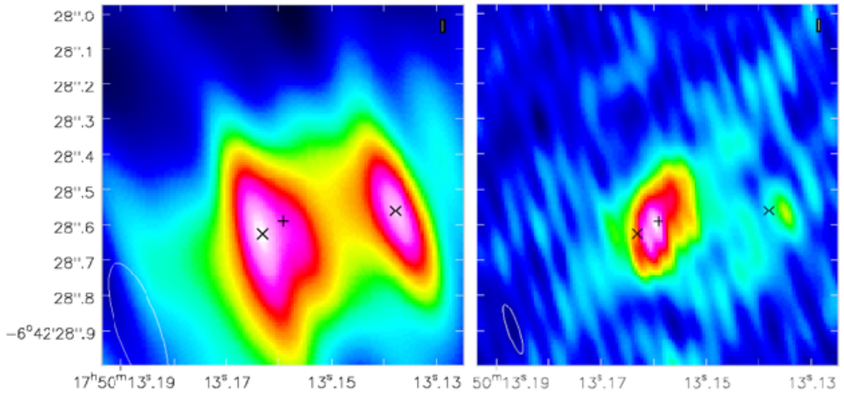


Radio imaging with e-MERLIN

e-MERLIN has imaged the expanding remnant from outburst in Aug 2021 to June 2022.

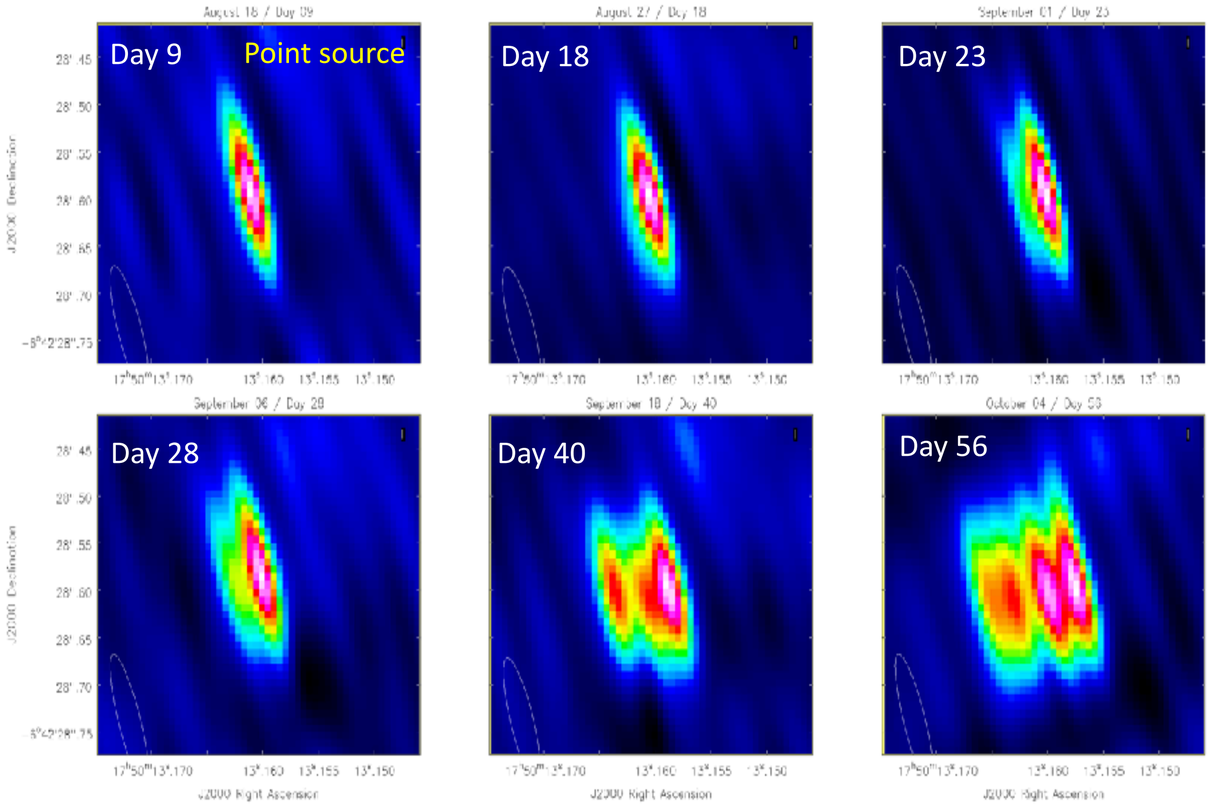
Imaging at 5 GHz shown at right reveals multi-component bipolar expansion east-west as hinted at in 1985 and seen in 2006.

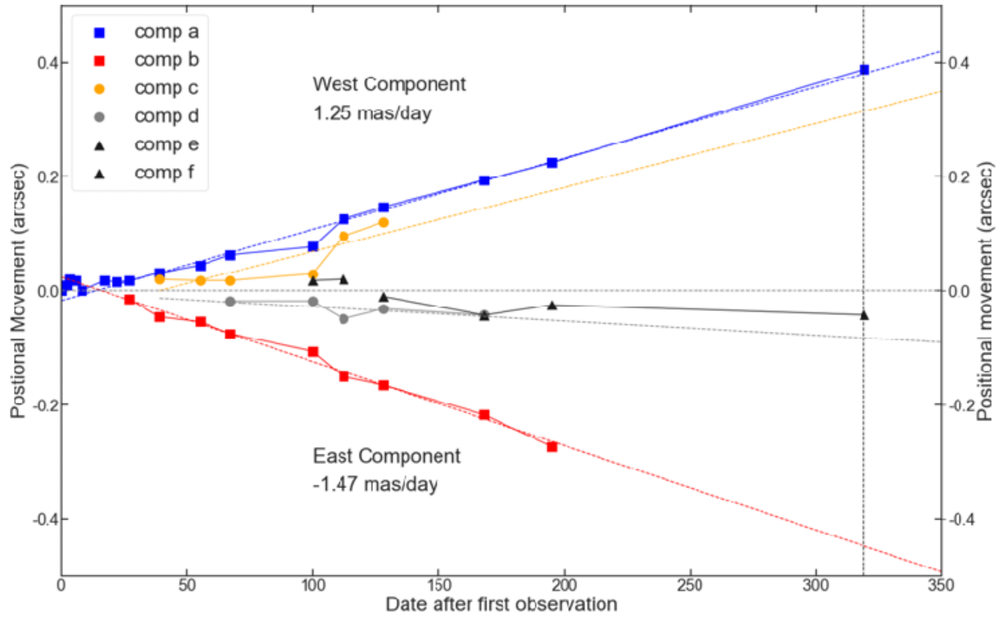
Resolved components are still being detected e.g. 1.4 GHz image at left and 5 GHz at right from 2022 June 21 & 24 (316 & 319 days after outburst).



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.