

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

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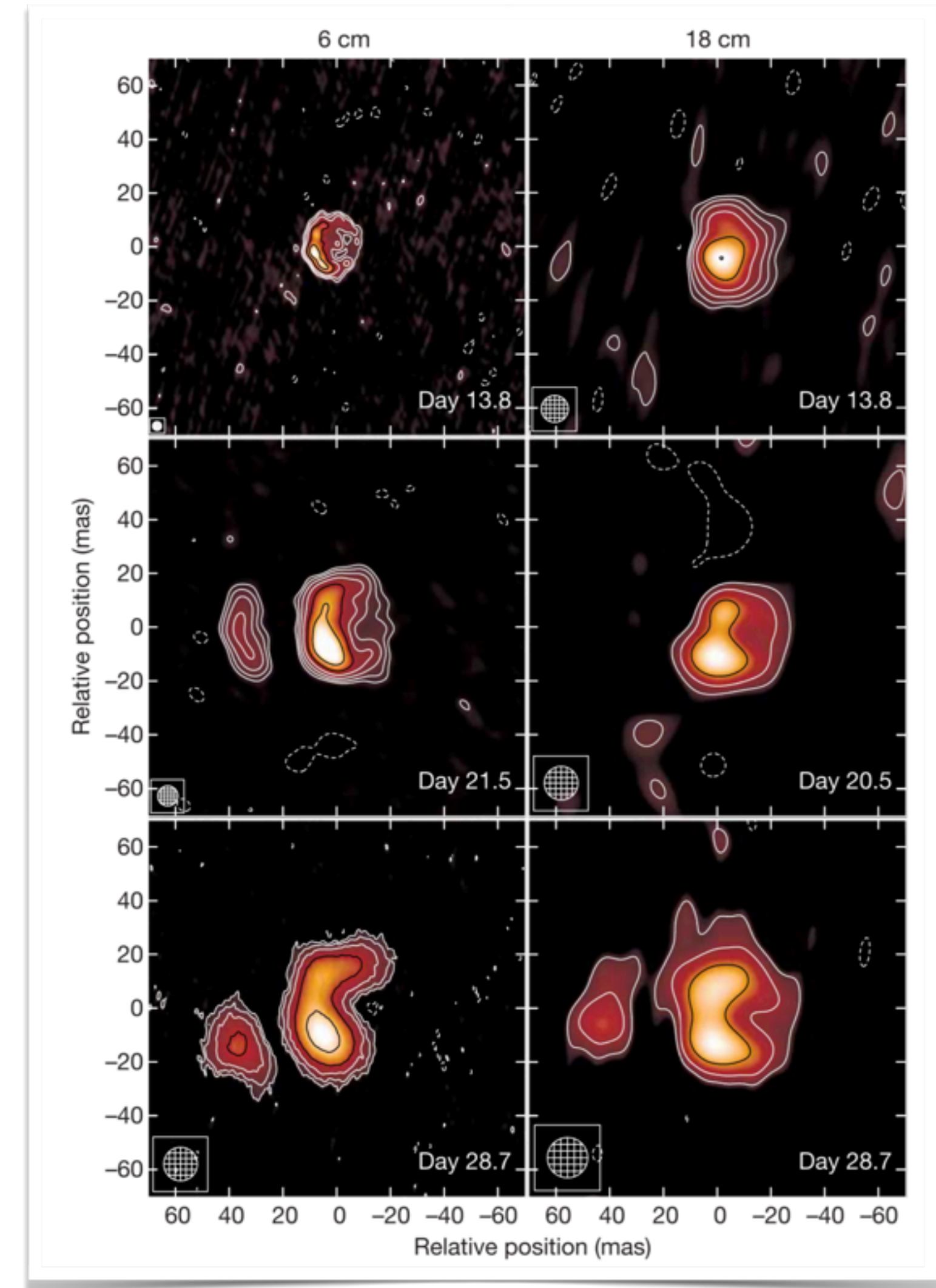
About novae

- 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

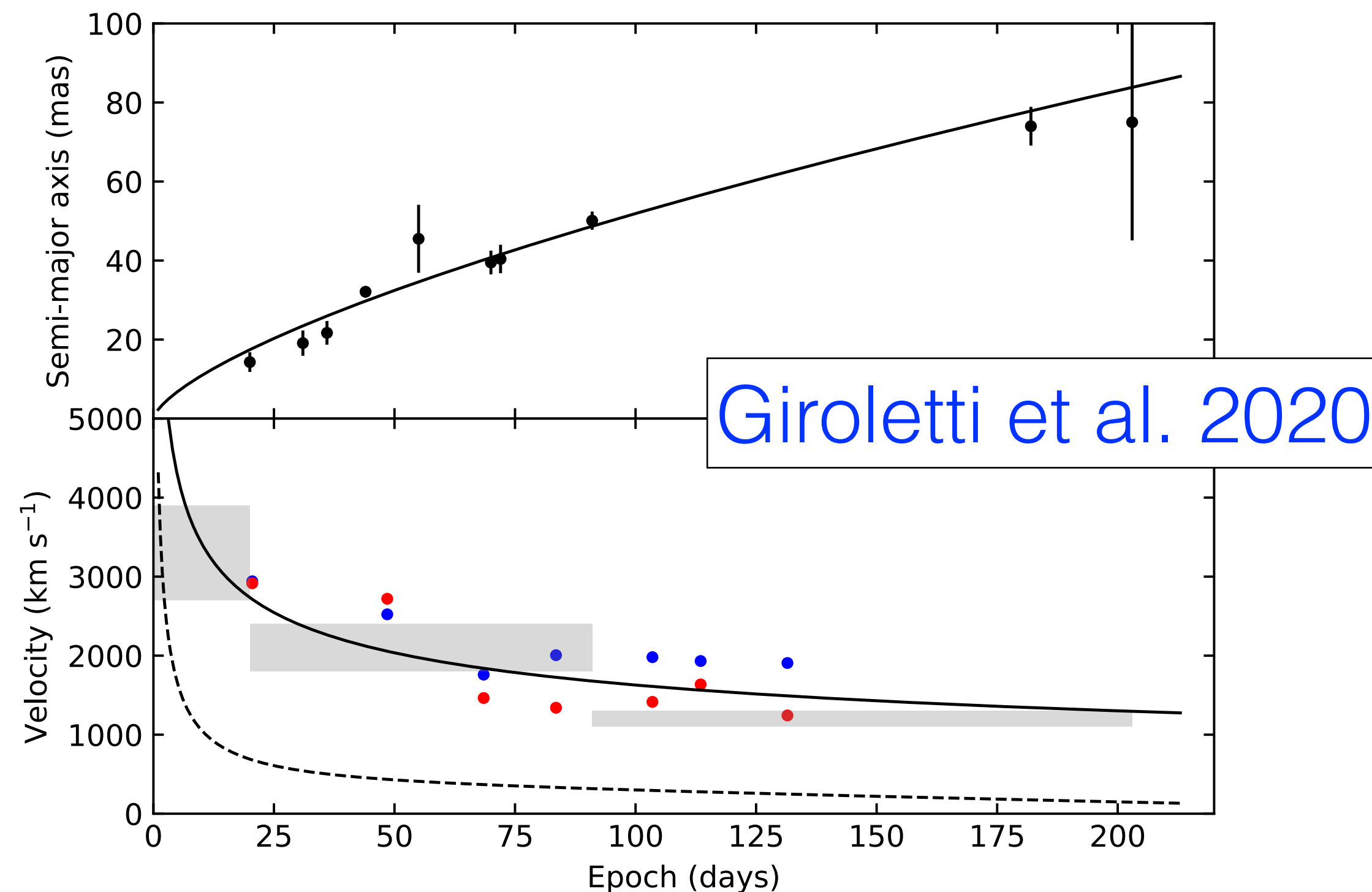
- Rare systems, typically recurring on human time scales
- RS Oph - outbursts in 1985 and 2006
- V407 Cyg - outburst in 2010, first episode of *any* nova detected in gamma rays
- Growing evidence of shock acceleration in RG wind



O'Brien et al. (2006 Nature)

V407 Cyg summary

- The first nova ever detected in gamma rays (Abdo et al. 2010)
... and my only previous appearance at a CNOCC (Ferrara 2013)
- VLBI campaign reveals non-thermal emission from bipolar outflow, with $v_0 \sim 3000 \text{ km s}^{-1}$ and decreasing as $v \sim t^{-0.32}$



RS Oph, 2021 nova

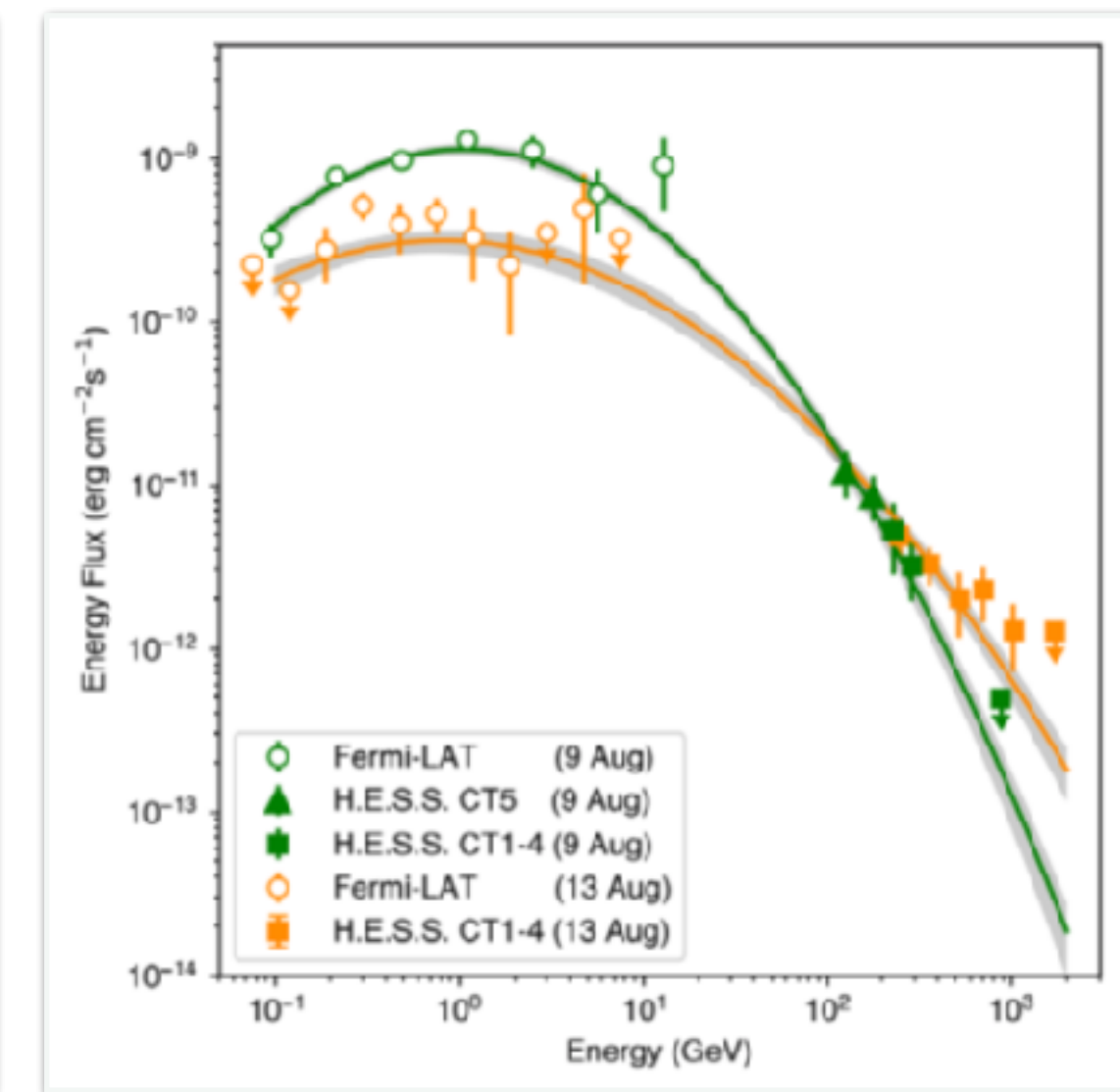
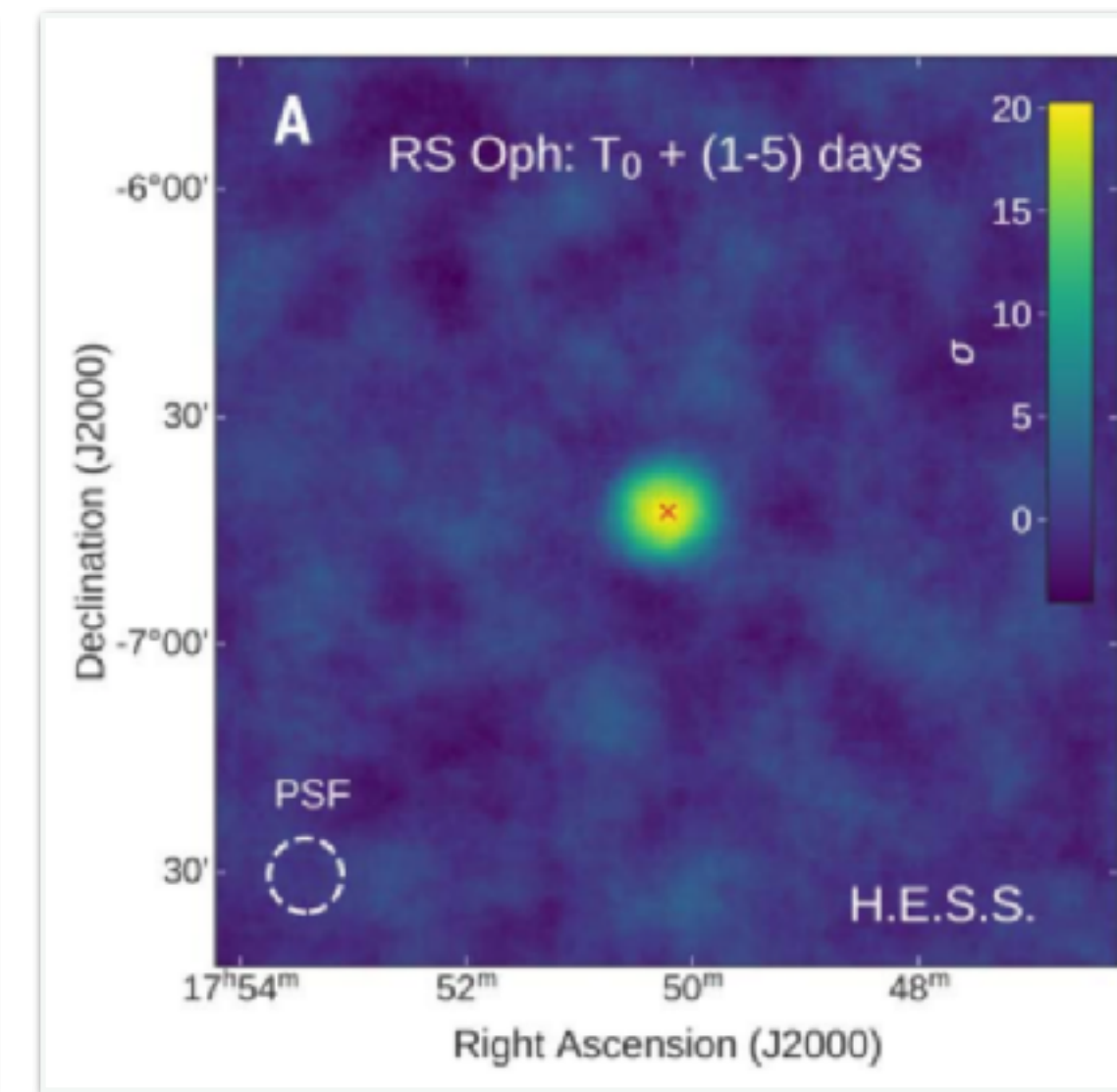
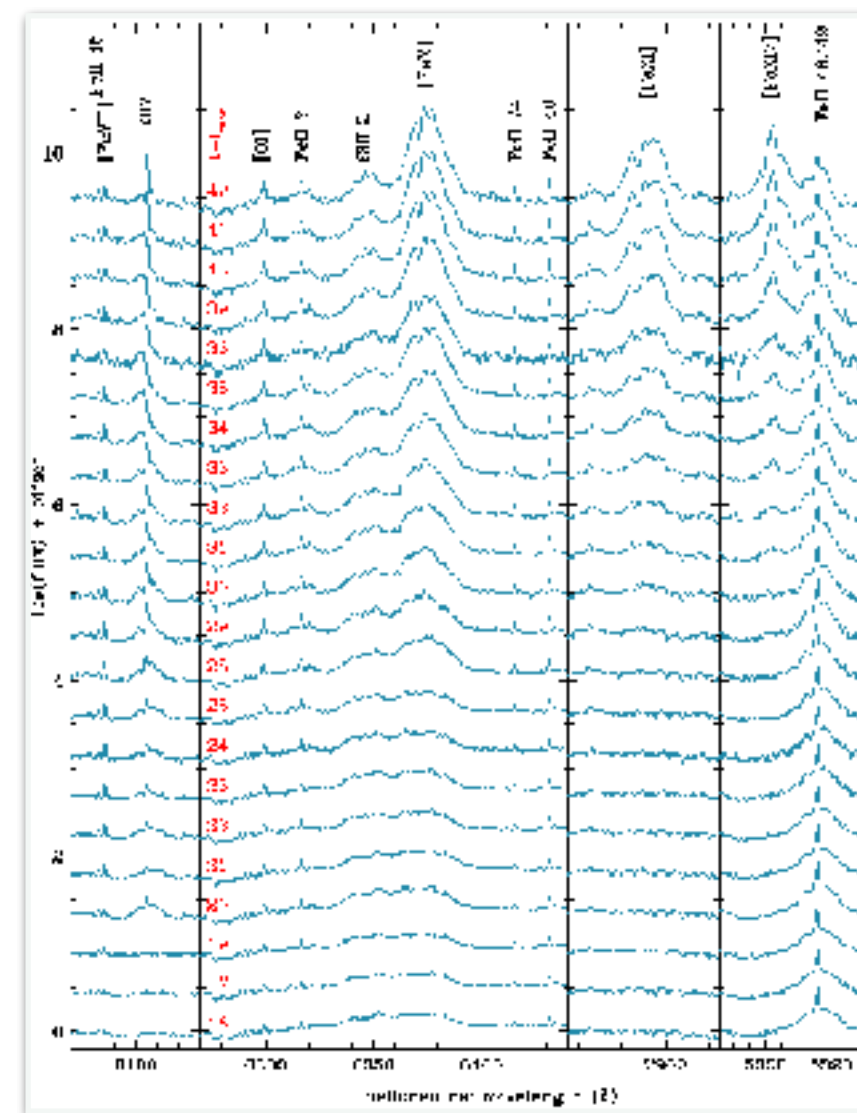
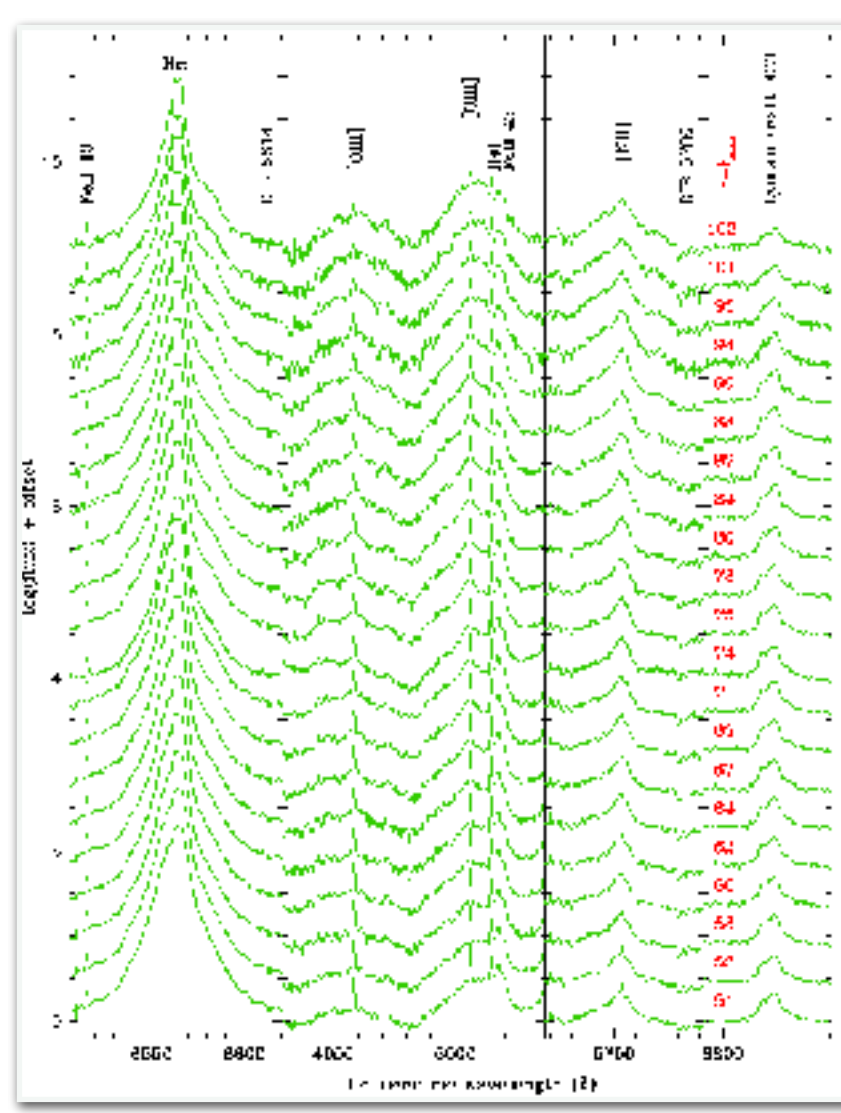
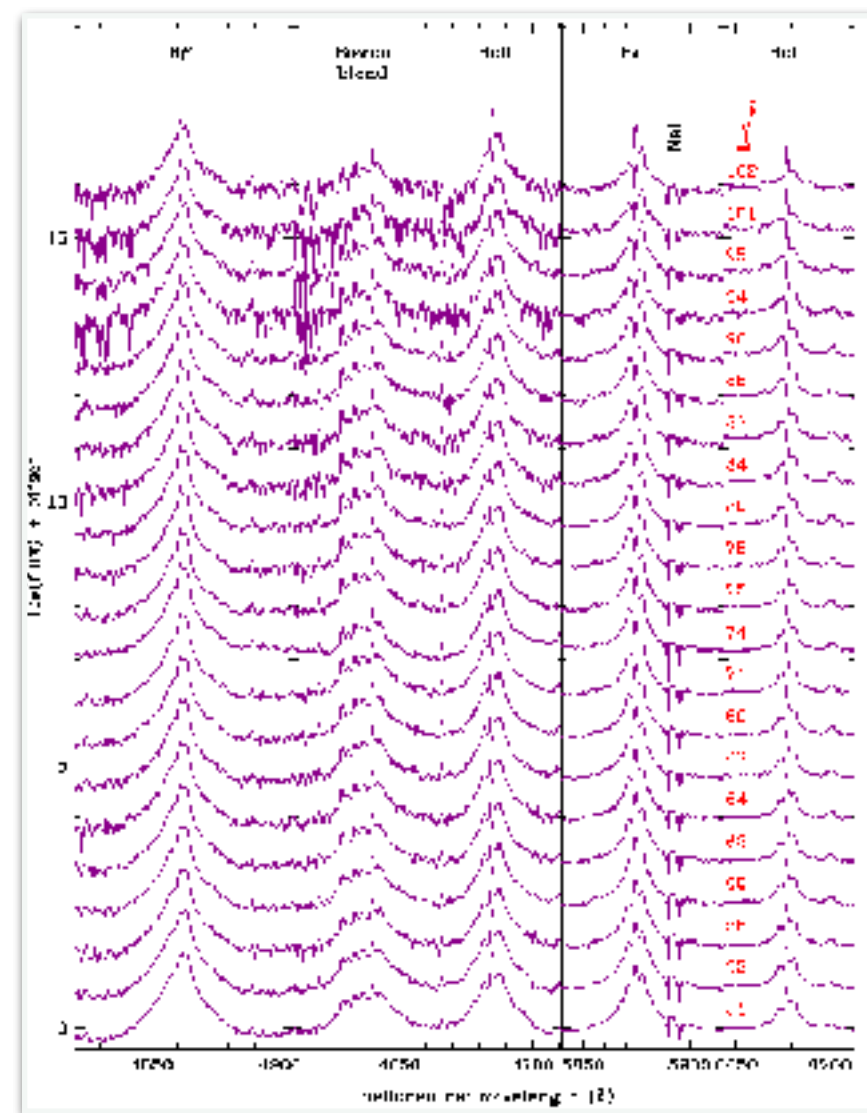
Discovered in optical on
2021 Aug 8

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

A challenging VLBI 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).

First results

Astronomy & Astrophysics manuscript no. paper
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LETTER TO THE EDITOR

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

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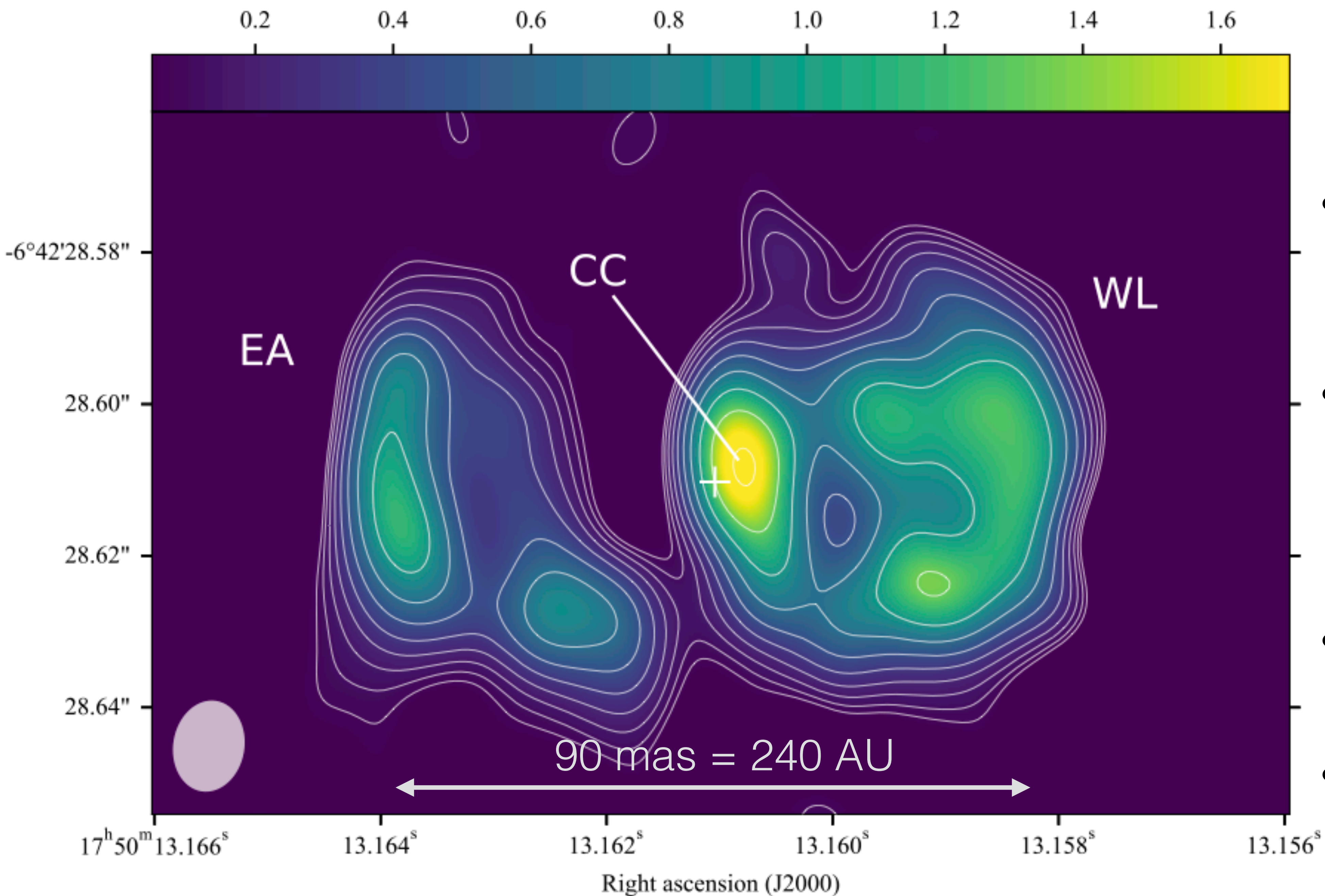
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ABSTRACT

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 $\sim 7550 \text{ km s}^{-1}$, and $i=54^\circ$ 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.

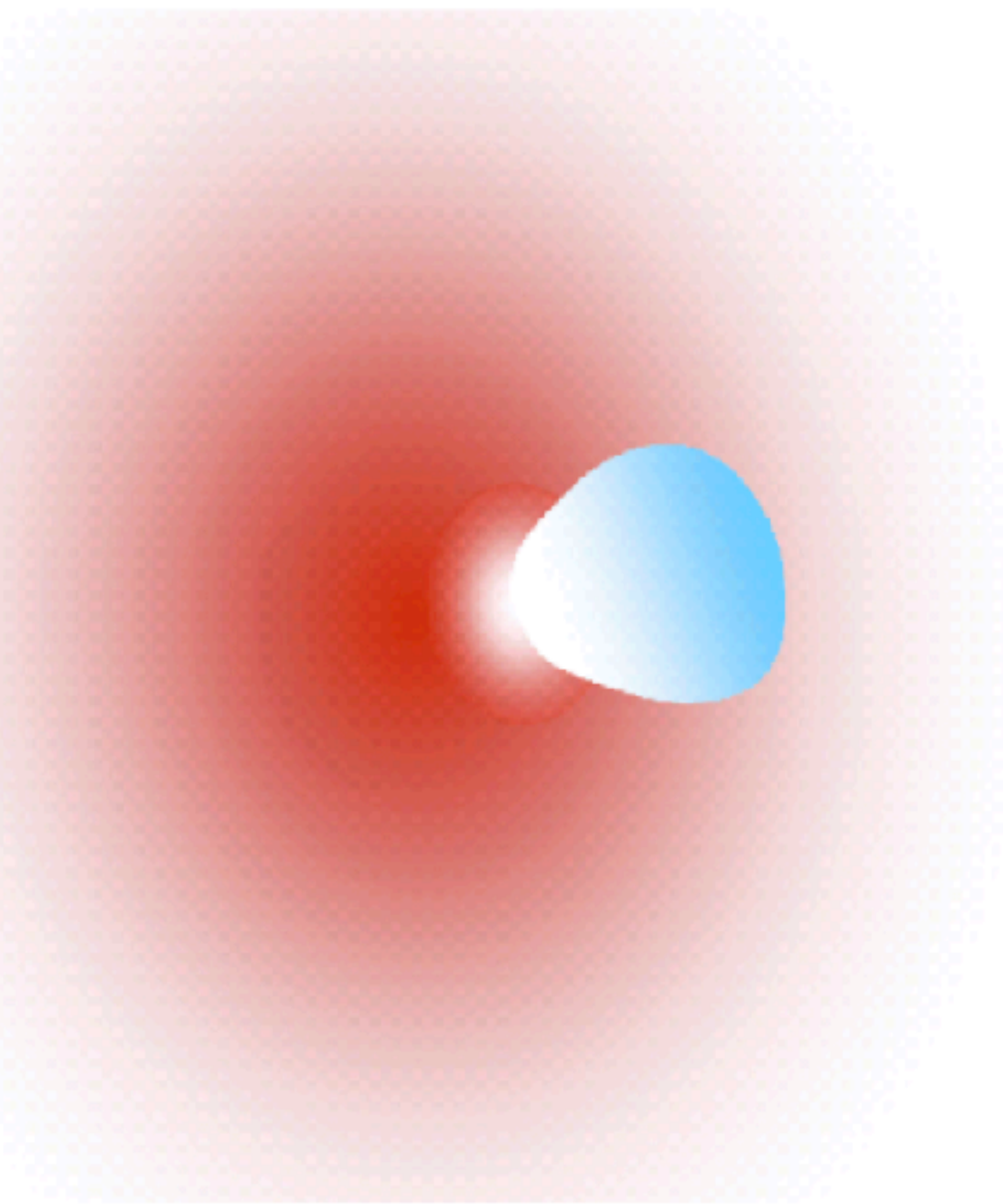
- Munari, Giroletti, et al.
A&A in press
- <https://arxiv.org/abs/2209.12794>
- Analysis of EVN epoch 3 at 5 GHz ($t=34 \text{ d}$)
- Comparison with optical spectra - and 2006 outburst



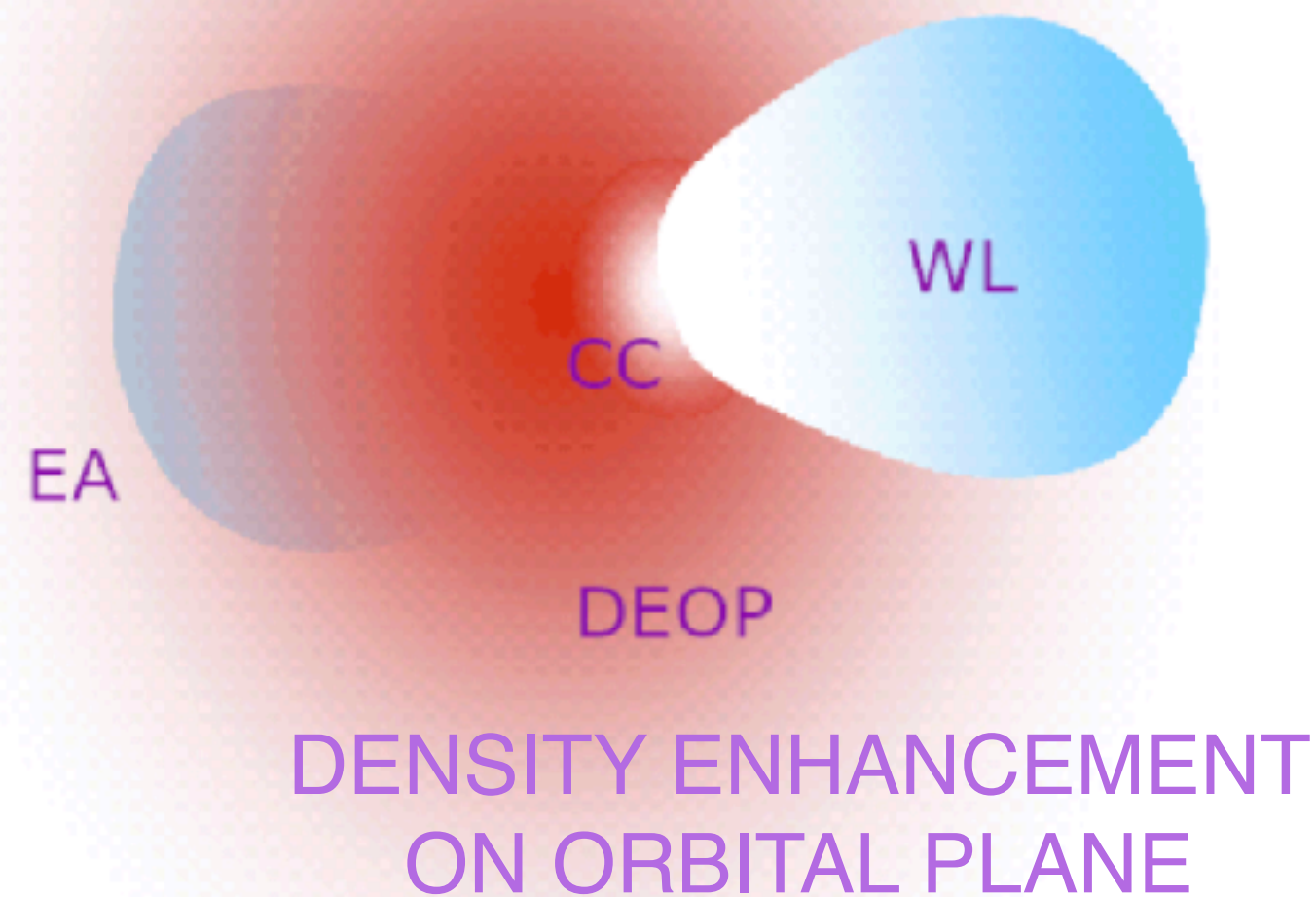
- White cross is Gaia position ($d=2.7$ kpc)
- Emission on either side, with shell-like structure
- Total flux density $S=20$ mJy
- Radio luminosity $1.7 \times 10^{13} \text{ W Hz}^{-1}$

A simple sketch

$t < t_\tau$



$t > t_\tau$

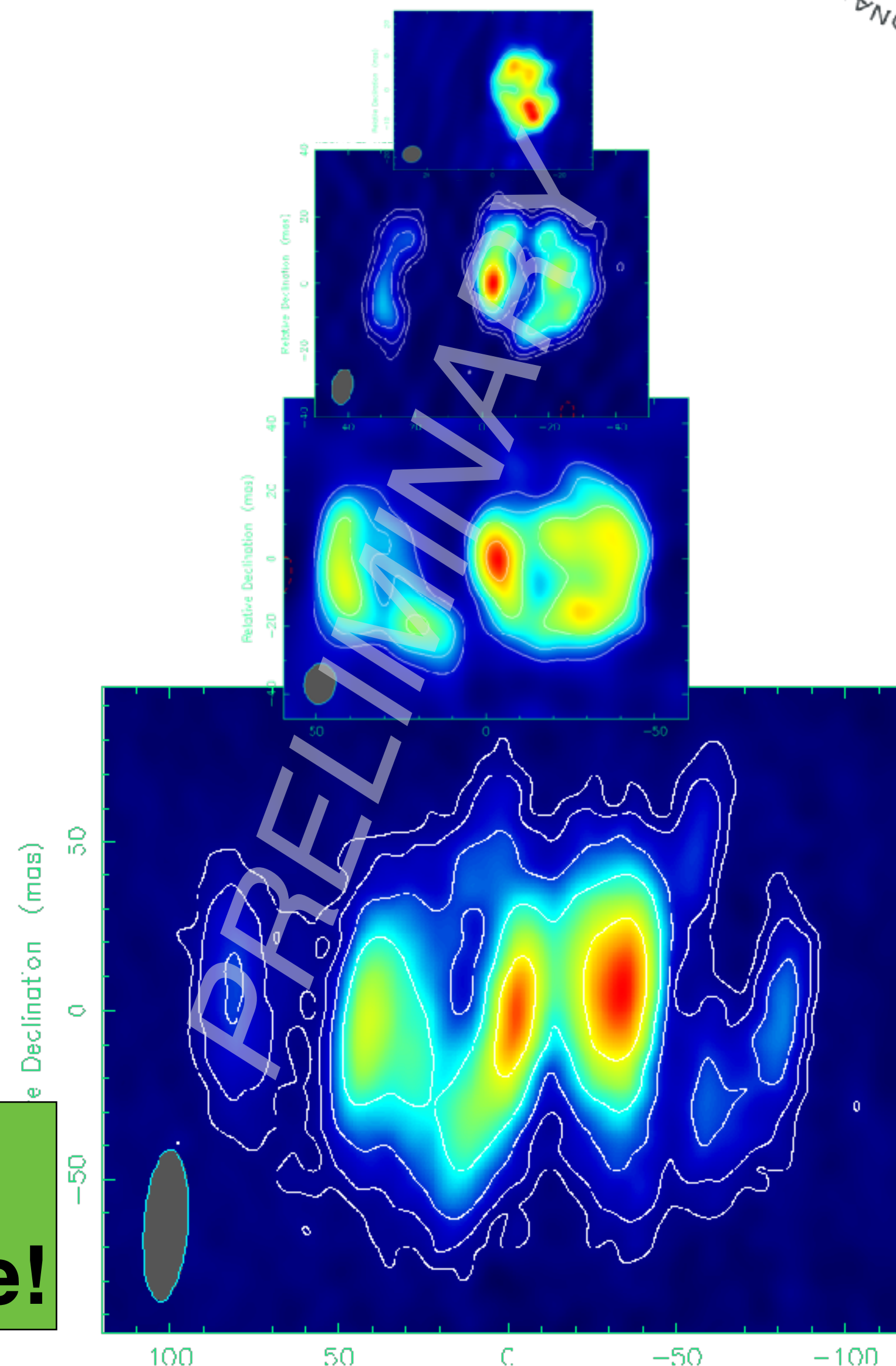


- Situation very similar to 2006, but with much more detail
- DEOP confines the ejecta primarily within a bipolar structure perpendicular to orbital plane
- Non-thermal radio emission originates at shock interface between the fast expanding lobes and the pre-existing RG slow wind
- Sometimes around $t=20d$,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

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

**We are looking for a motivated post-doc.
Call will be out as soon as INAF grant is available!**



Conclusions

1. VLBI provided direct imaging of expansion of bipolar ejecta along polar axis in 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!
- VLBI is often the only technique for a resolved imaging and to directly reveal structural evolution
 - INAF is upgrading its radio telescopes over this whole frequency range (through PON and PNRR)
 - Transient/compact object studies can greatly benefit from this resource: XRB, GW, FRB, etc.

