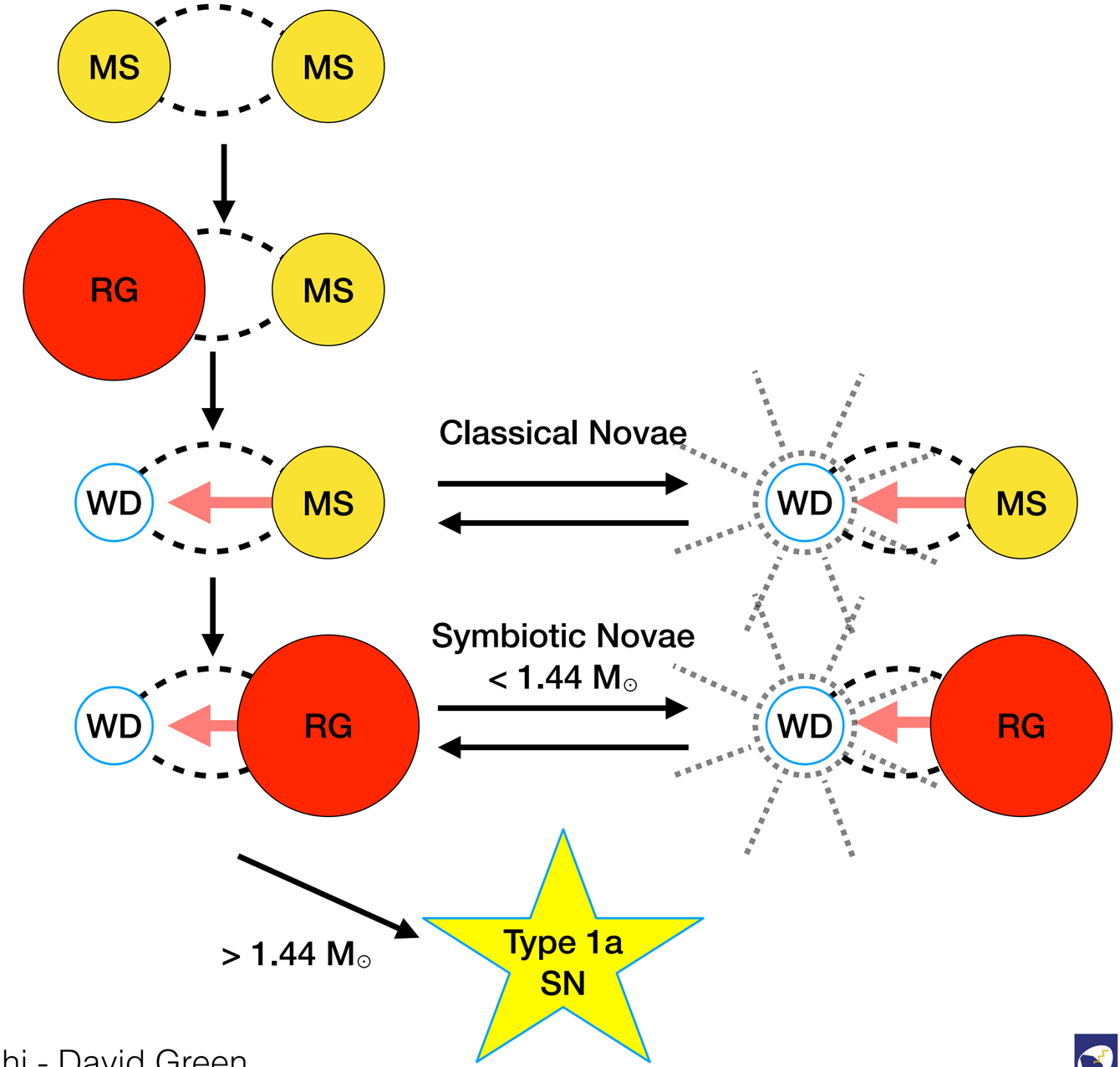
Very High Energy Gamma Rays from RS Ophiuchi

David Green (MPP)
Vandad Fallah Ramazani, Francesco Leone, Rubén López-Coto, Alicia López-Oramas, and Julian Sitarek
on behalf of the MAGIC Collaboration

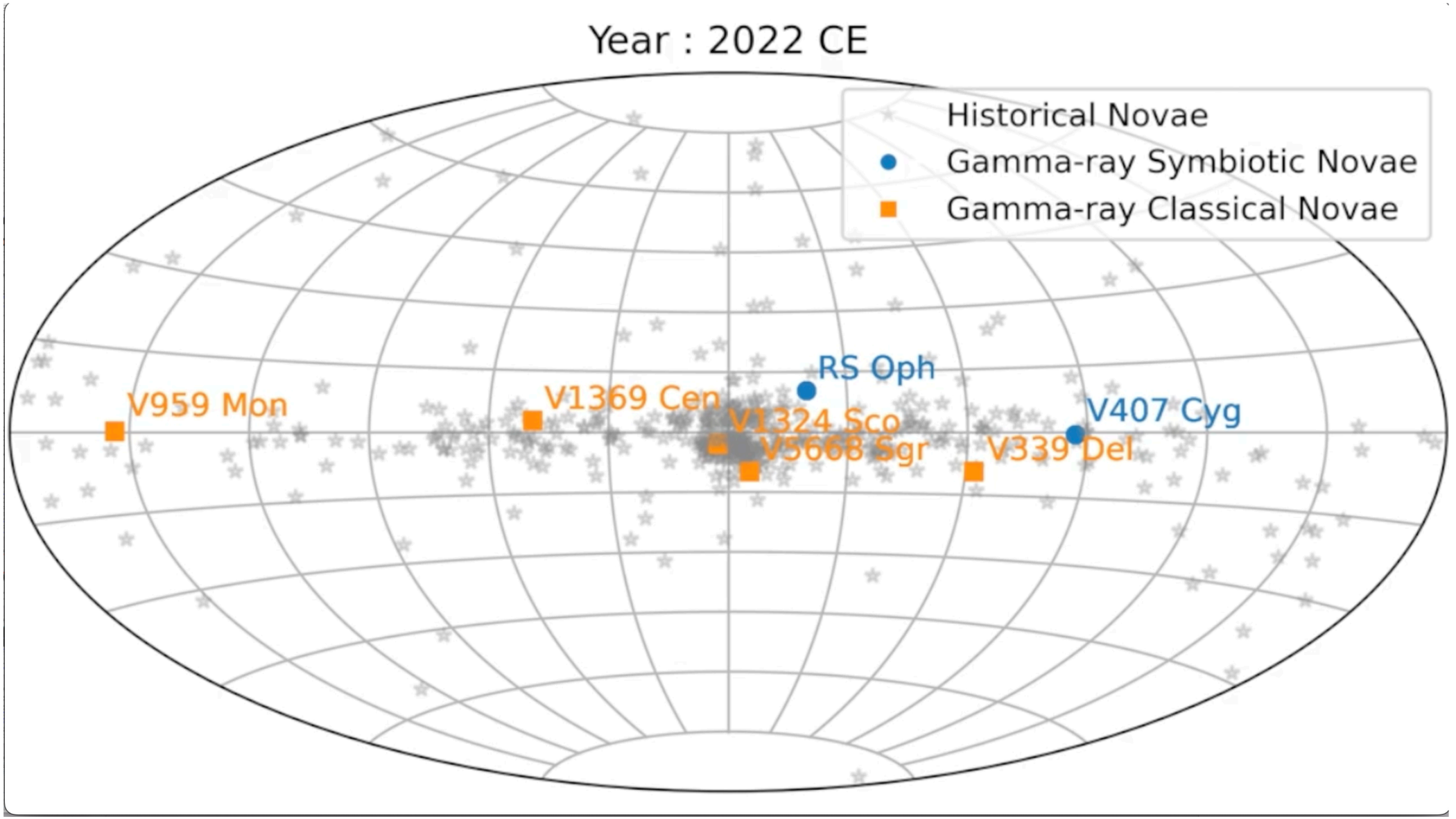
Credit: Daniel Lopez IAC

A Short Introduction to Novae

- Thermonuclear explosions caused by matter from a donor star collecting on a white dwarf surface in a binary system
- Matter on surface is in thermal equilibrium and eventually reaches fusion flashpoint
- Nova have a rate ~ 50 per year (Shafer, A. ApJ 2017)
- Various Classifications are adopted, in particular:
  - Classical -> MS donor star
  - Symbiotic -> Evolved donor star/RG
  - Recurrent -> Multiple observed outbursts
  - Dwarf -> mini-outbursts (thought to be AD instabilities)

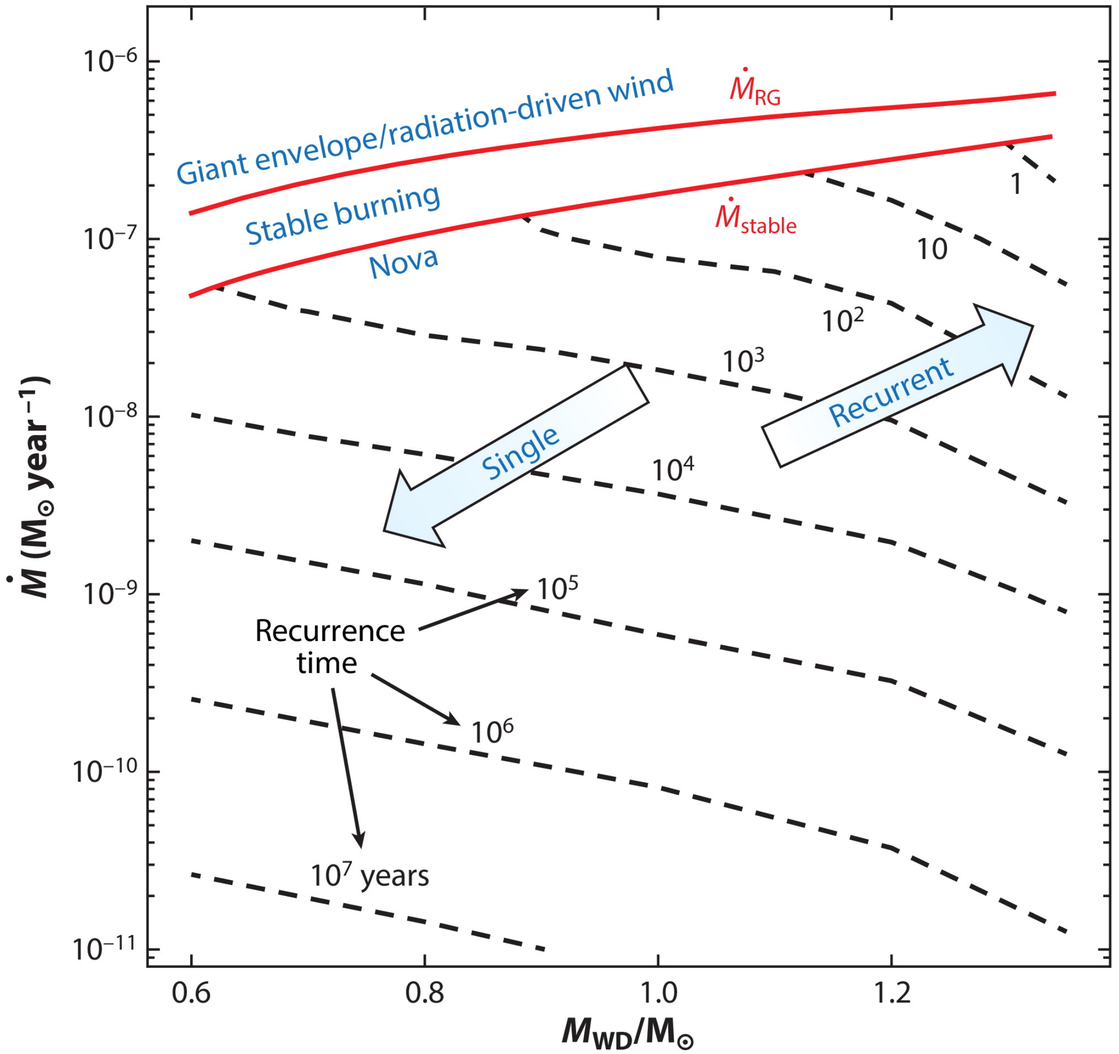


Historical Novae



Recurrent vs Classical

- Recurrent and classical are more an observational classification
- Since precision astronomy has only been around a few hundred years, only a few known nova are recurrent
- Recurrent nova such as RS Oph, are typically symbiotic and fill their Roche Lobes
- Larger mass loss rate (~10^{-7} $M_\odot$/yr) from Red Giant winds, create a dense environment surrounding WD



Chomiuk L, et al. 2021
Annu. Rev. Astron. Astrophys. 59:391–444

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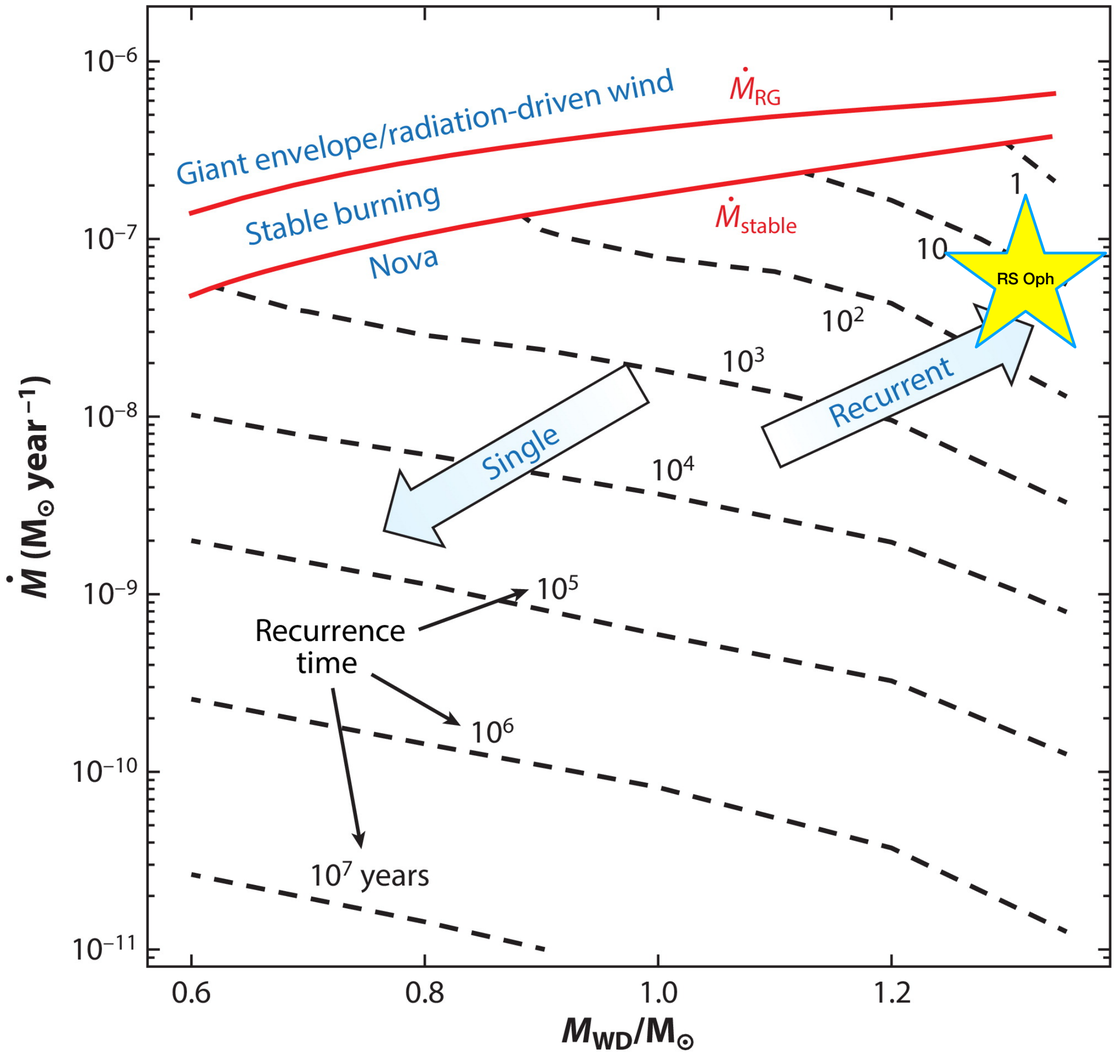

Chomiuk L, et al. 2021
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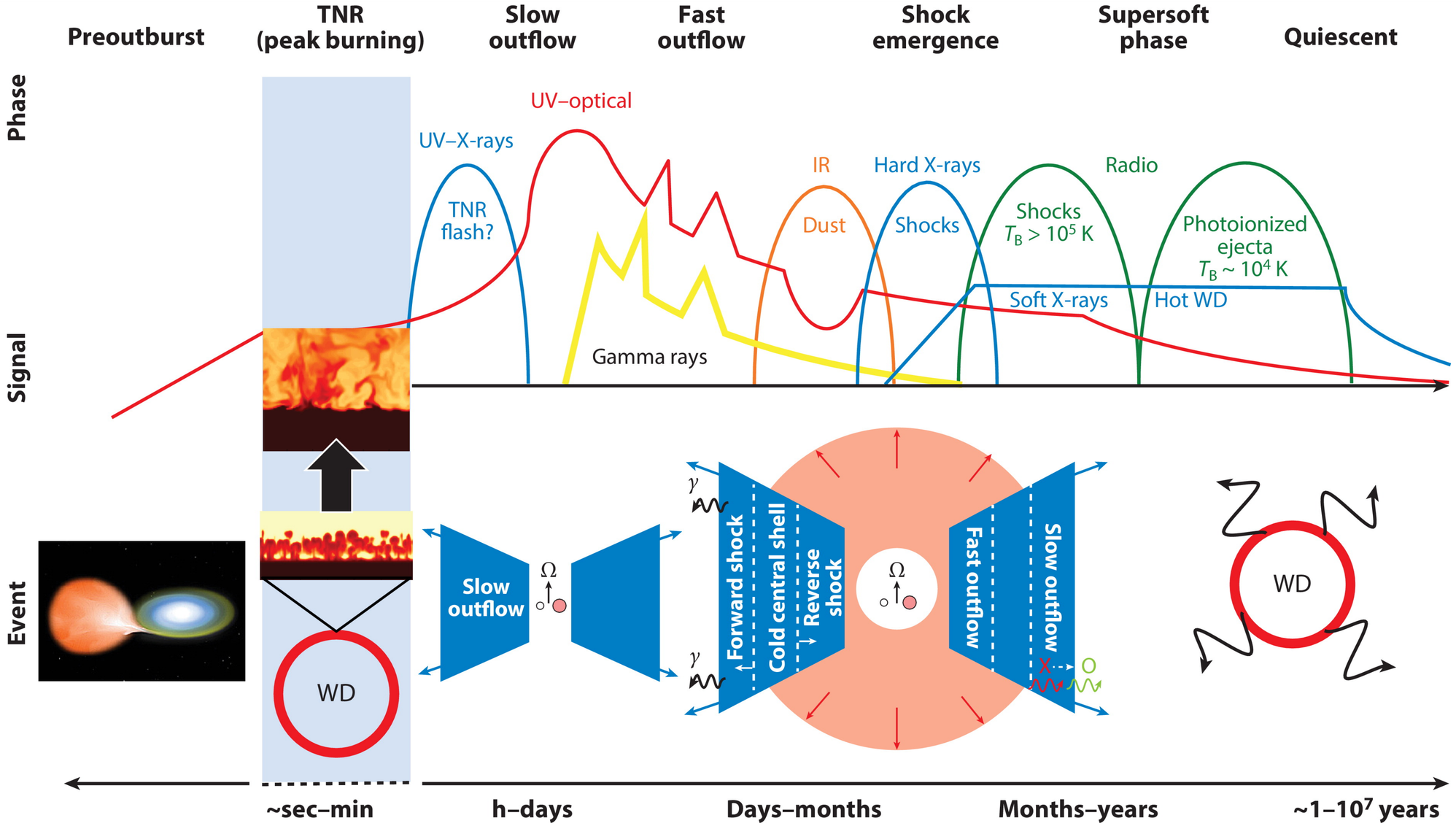
Full Spectrum Temporal Evolution



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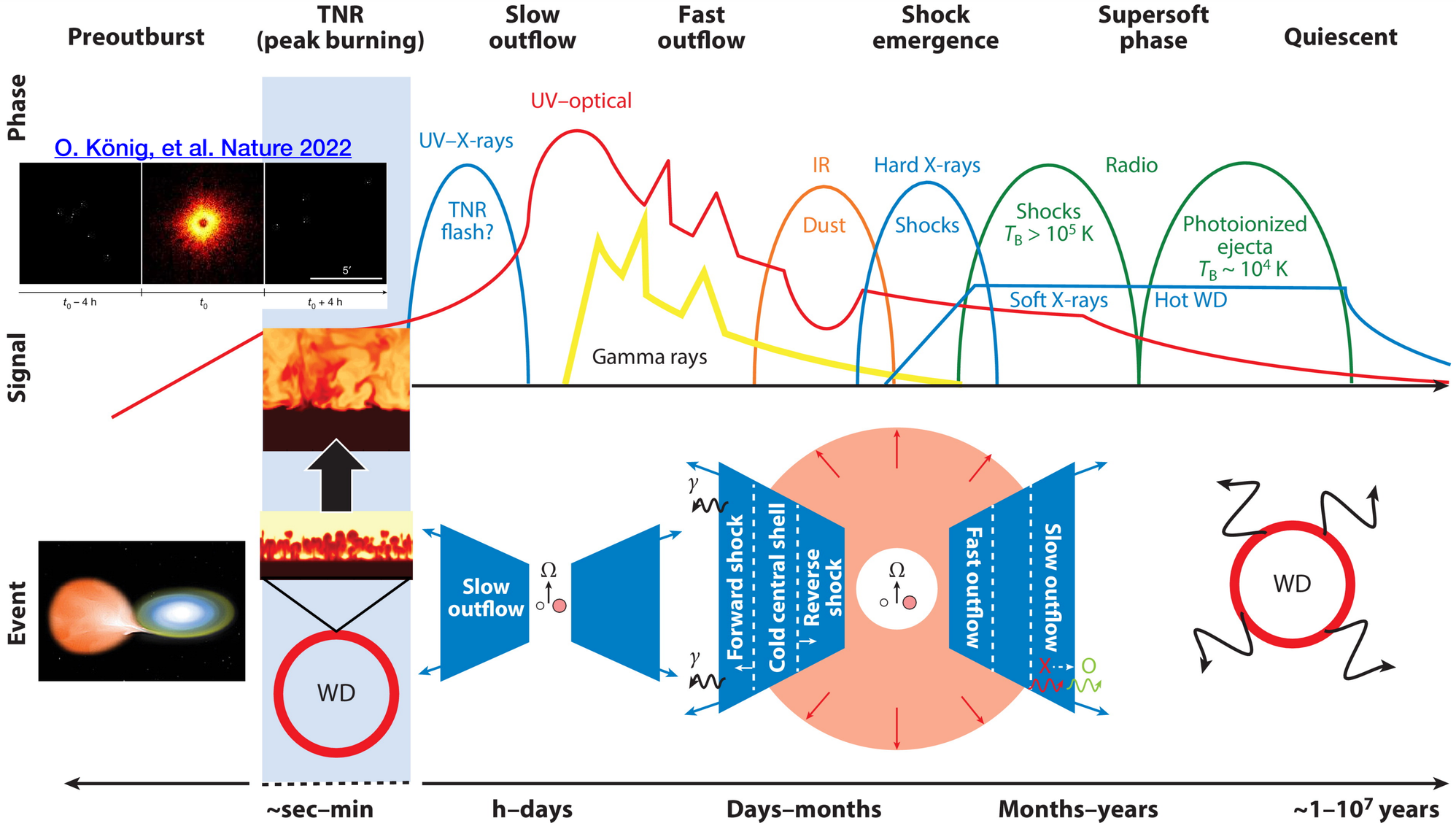
Full Spectrum Temporal Evolution



Chomiuk L, et al. 2021
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Novae: Known Sources for HE Gamma-ray Emission

- V407 Cyg was the first nova (symbiotic) detected in the high energy (HE) gamma-ray energy range (Fermi-LAT, Science 2010)
- Classical nova soon followed with in 2014 (Fermi-LAT, Science 2014)
- Unable to distinguish between Hadronic or Leptonic (IC + Brem) origins

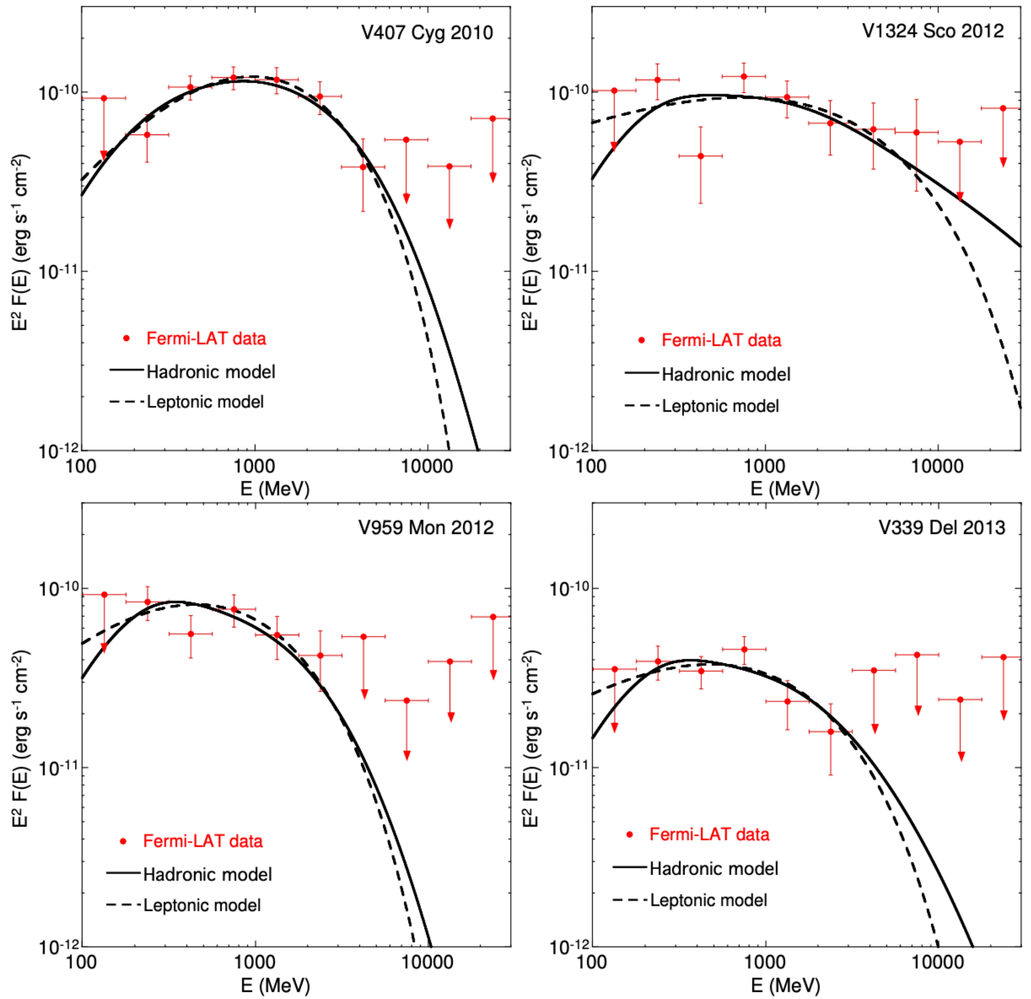
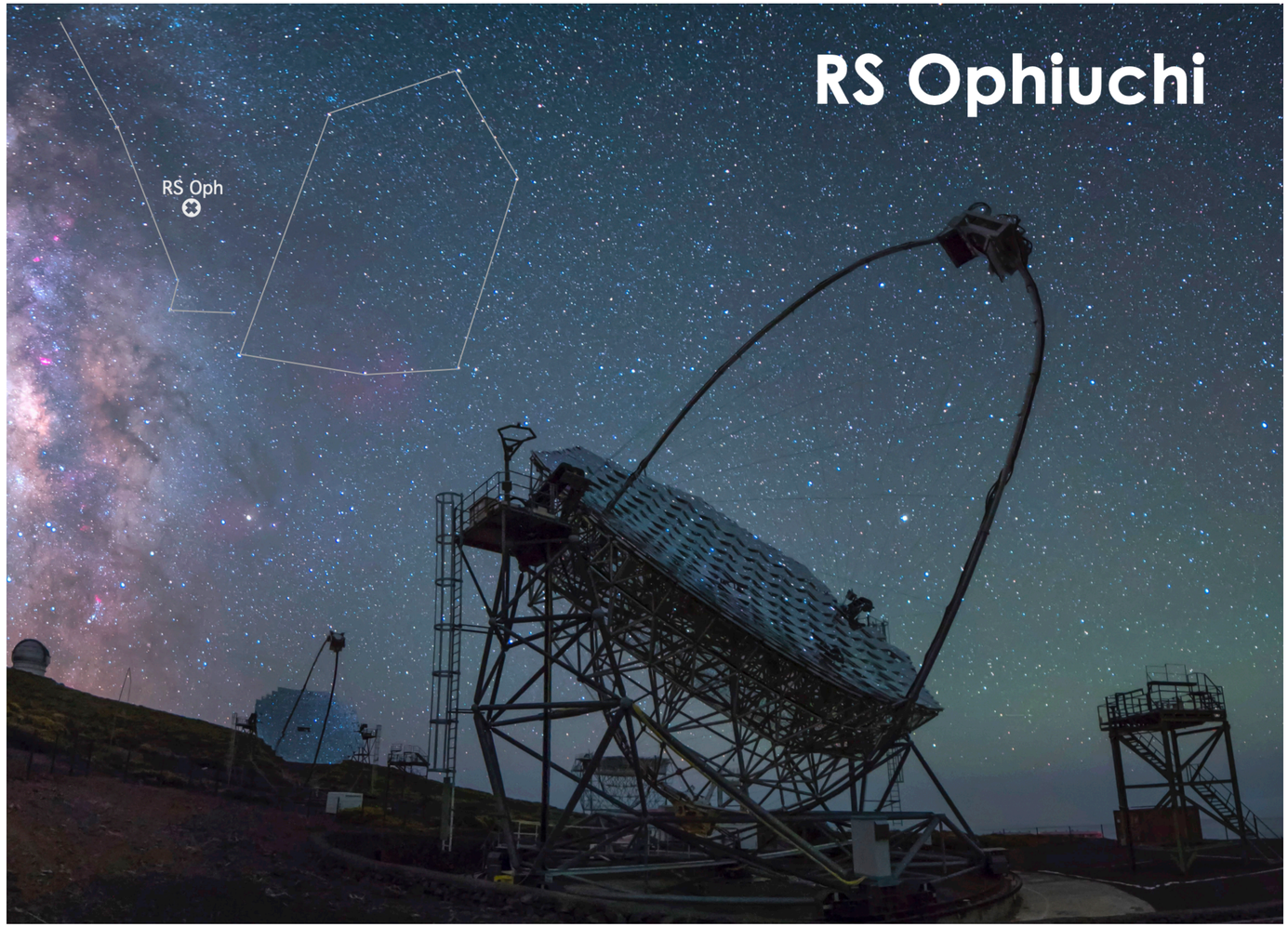


Fig. 3. Fermi-LAT >100 MeV average γ-ray spectra of the four novae over the full 17−27 day durations. Vertical bars indicate 1σ uncertainties for data points with significances $> 2\sigma$; otherwise, arrows indicate 2σ limits. The best-fit hadronic and leptonic model curves are overlaid.

(Fermi-LAT, Science 2014)

MAGIC Telescopes

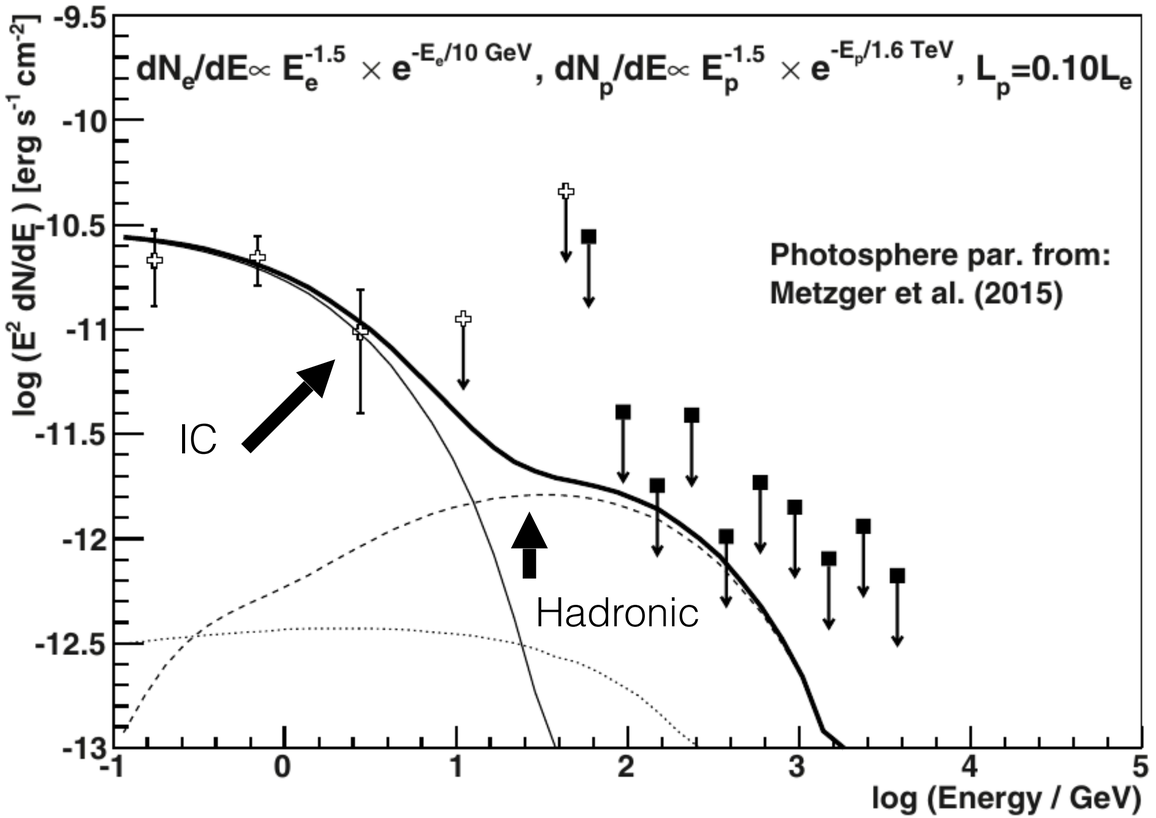
- Located at the Roque de los Muchachos observatory at La Palma, Canary Islands, Spain
- Two 17m diameter imaging atmospheric telescopes
- Specially designed to measure the lowest energies of the VHE regime (~50 GeV) and up to 10s of TeV



Picture credit: Antonio González

Novae with MAGIC

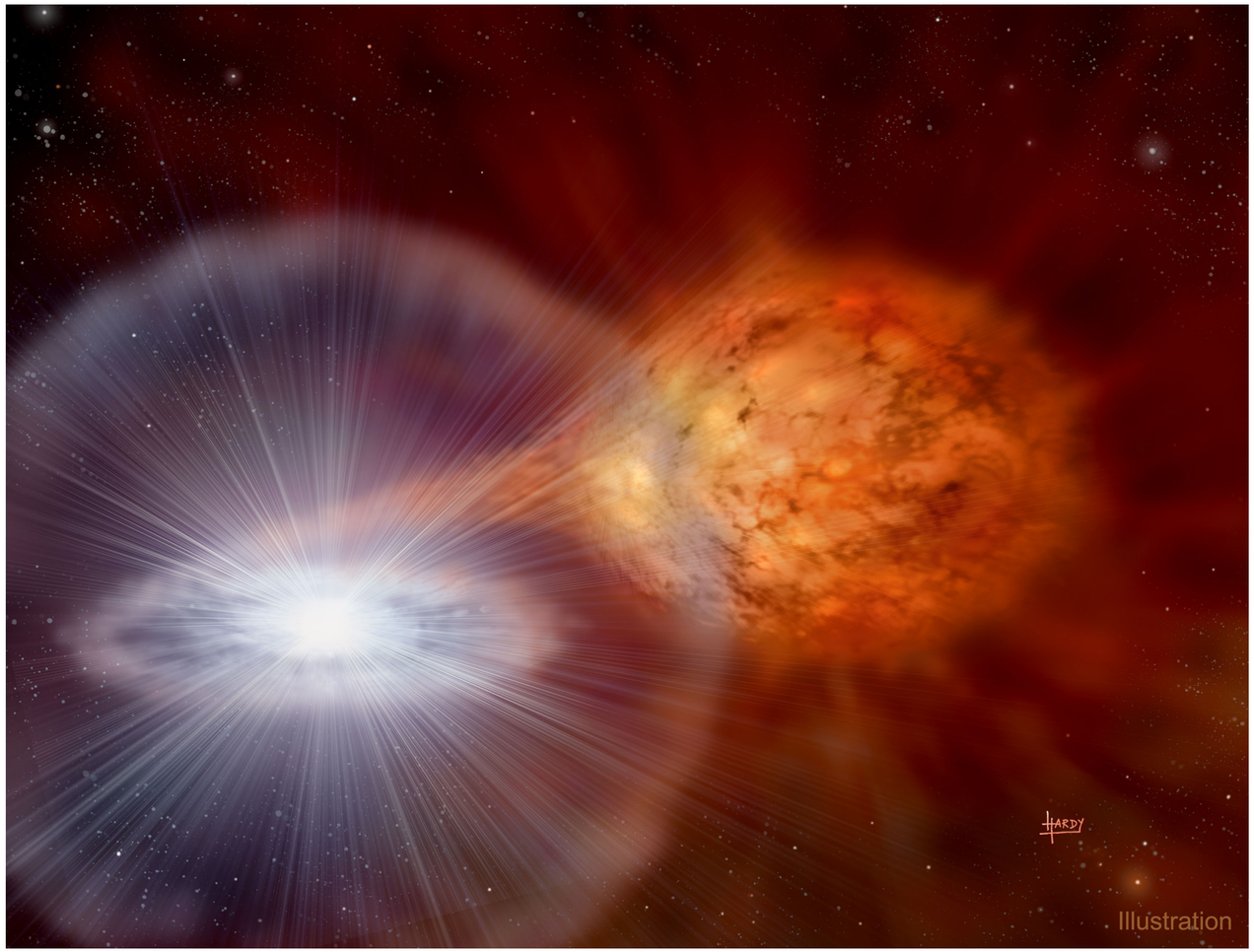
- MAGIC initiated a follow up program on novae in 2012
- VHE (>100 GeV) data is critical to understand emission mechanisms
- Constraining upper limits from V339 Del, 2013 eruption
- No VHE detection until RS Oph



MAGIC Coll., A&A, 582 (2015)

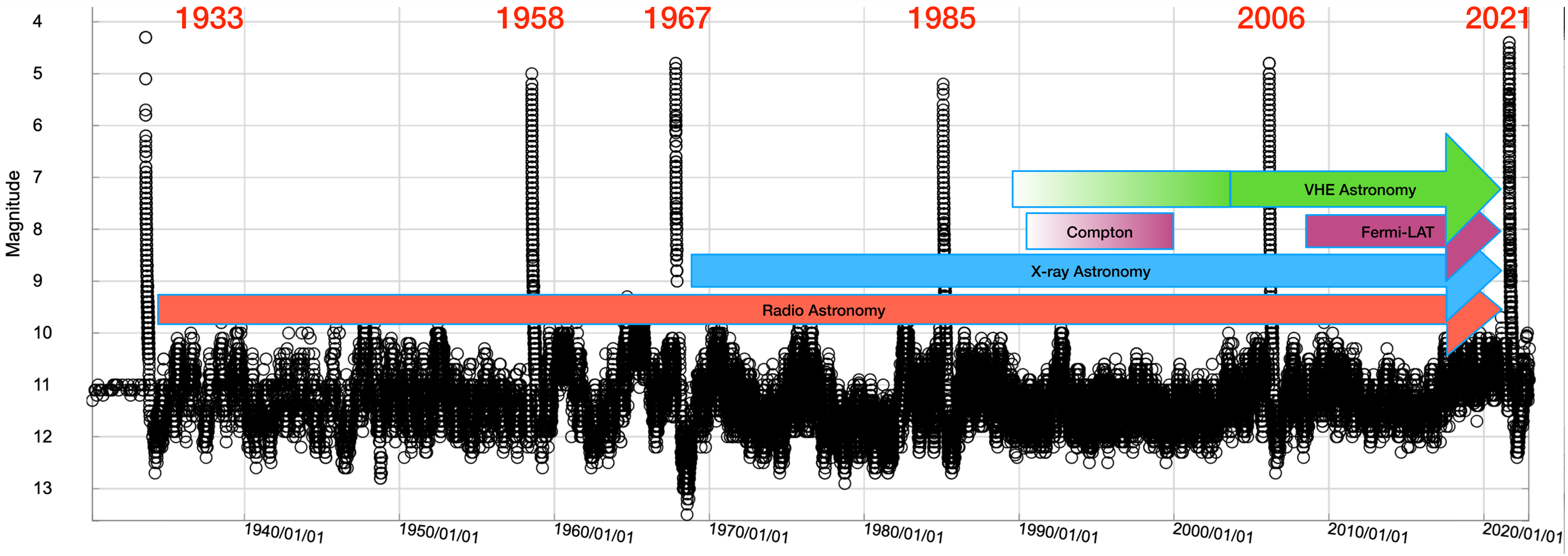
RS Ophiuchi

- Recurrent nova in a symbiotic binary
- WD (1.2–1.4$M_\odot$) + M0-2 III RG star (0.68–0.80$M_\odot$)
  Schaefer Astrophys. J. Suppl. Ser. 2010
- One of the most well studied recurrent nova
  - Recurrent rate ~ 15-20 years
  - Optically maximum m_V ~ 5,
    quiet state m_V ~ 12.5
- Distance debated, range from
  1.4 – 4.3 kpc with caveats for each
  - We used 2.45 ± 0.18 kpc, derived from Rupen et. al., ApJ 2008
  - In line with recent Gaia DR3 parallax measurement which derives a distance of 2.69 ± 0.18 kpc
    Gaia Col., A&A 2016, Gaia Col., 2022



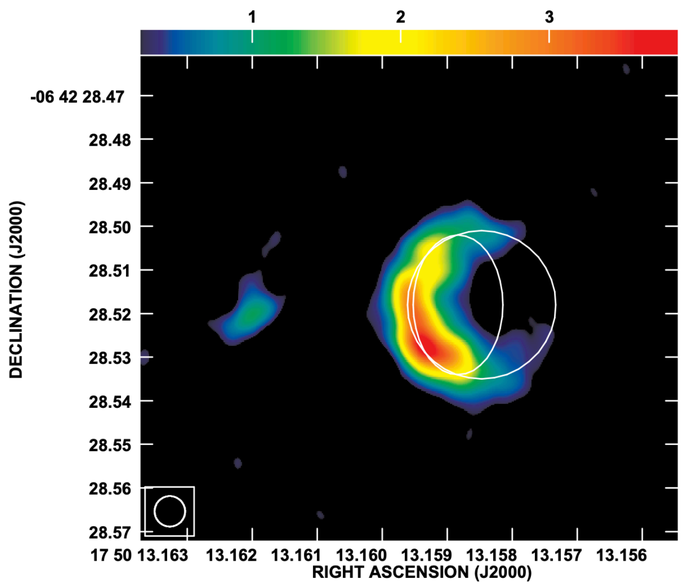
Credit: David A. Hardy

RS Ophiuchi



- Has major outburst every ~ 15 - 20 years
- 2021 outburst very well studied in almost all wavelengths

RS Ophiuchi 2006



Rupen et al. ApJ 2008

Fig. 2.— Tilted circular rings superposed on the 5.0 GHz image from day 20.8, for inclinations of 0°(face-on) and 50°, using radii of 31 and 29 milliarcseconds, respectively. The orbital inclination is thought to be ∼ 50° (Quiroga et al. 2003; Brandi et al. 2007). The color scale for the image ranges from 0.25 (black) to 3.865 (red) mJy beam^{-1}.

Bode et al. ApJ 2006

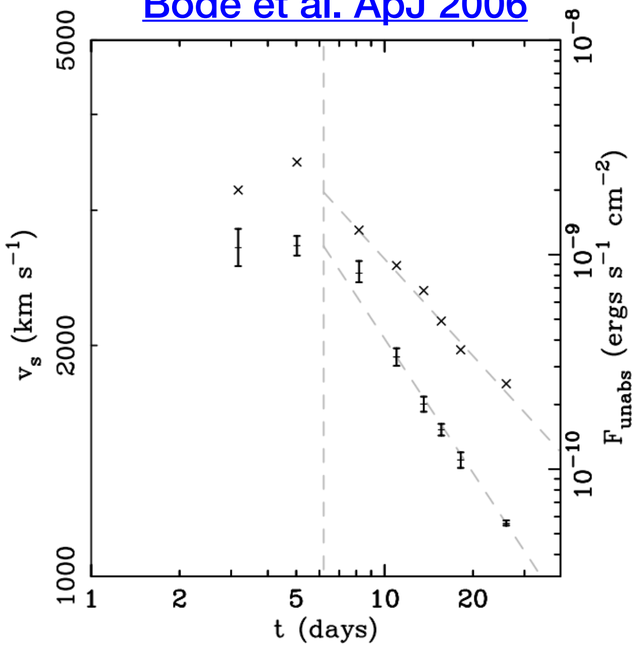


FIG. 4.—XRT-derived temporal behavior of the shock velocity, v_s (*points with error bars*), and unabsorbed (0.7–10 keV) flux, F_{unabs} (*crosses*; errors here are <5%). The diagonal dashed lines are power laws with index $\alpha = 0.6$ (for v_s points) and $\alpha = 1.5$ (for F_{unabs}; see text for details).

O'Brien et al, Nature 2006

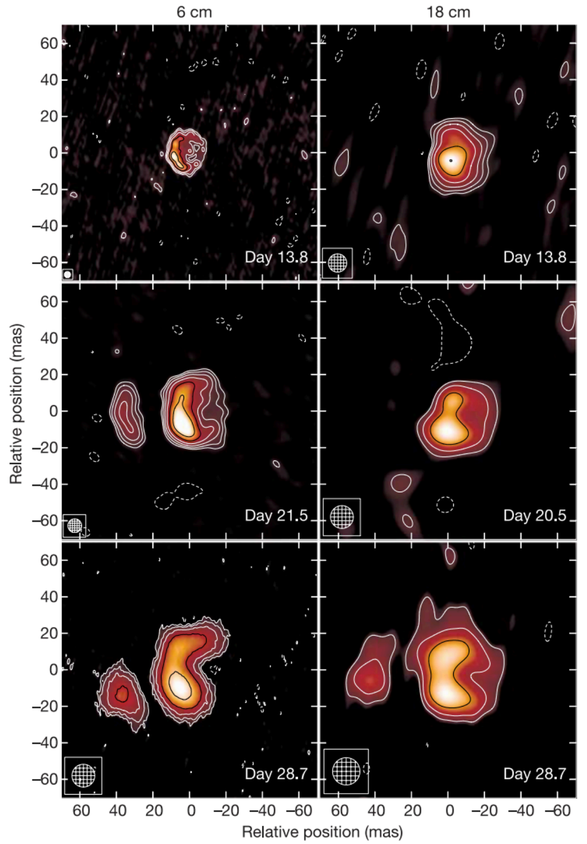


Figure 1 | High-resolution radio images of RS Oph. Images of RS Oph at wavelengths of 6 cm (left column) and 18 cm (right column) made with the VLBA on 2006 February 26 (day 13.8) and March 13 (day 28.7), and the EVN on March 5/6 (day 20.5/21.5). In each case, north is up and east is to the left, and the images are restored with the circular beams shown at lower left. The first 6-cm VLBA image has a resolution of 3.3 mas (5 AU at a distance of 1,600 pc) and a peak flux density of 4.7 mJy beam^{-1} corresponding to a brightness temperature of around 4×10^7 K. The contour levels are (−1, 1, 2, 4, 8, 16, 32) times a base level given by 227, 105 and 220 μJy beam^{-1} for the 6-cm images (in increasing time order), and 500, 900 and 900 μJy beam^{-1} for the 18-cm images.

- Last RS Oph outburst, Fermi-LAT had not launched
- Novae were not known to be gamma-ray emitters
- Tatischeff, V. & Hernanz, M. ApJL 2007, predicted GeV and VHE emission from RS Oph

RS Ophiuchi 2021

- Many telescopes had been anticipating RS Oph's eruption
- Optical Discovery by Brazilian Astronomer Alexandre Amorim (https://www.aavso.org/rs-ophiuchi) and confirmed by Keith Geary (vsnet-alert 26131) and Fermi-LAT ATel #14834
- MAGIC observations began on 9 Aug 22:30 UT

RS Ophiuchi

AAX
Affiliation: Nucleo de Estudo e Observacao Astronomica - Jose Brazilicio de Souza (Florianopolis, Brazil) (NEOA-JBS)
Sun, 08/08/2021 - 22:22

Dear friends,

RS Ophiuchi seems to be in outburst.

In August 8, 2021, at 21:55 UT I estimated it in magnitude 5.0.

An image was taken and it is at website:

http://www.geocities.ws/costeira1/img/20210808_2159ut.jpg

with regards,

AAX

RS Ophiuchi 2021

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- MAGIC - MAGIC Collab. Nat Astro 2022
- H.E.S.S. - H.E.S.S. Collab, Science 2022
- Fermi-LAT - Cheung, C.C , ApJ 2022
- Swift - Page K. L. MNRAS 2022
- XMM - Orio, M. ApJ 2022
- VLBI - Munari, U. A&A 2022

RS Ophiuchi 2021

Letter | Published: 14 April 2022

Proton acceleration in thermonuclear nova explosions revealed by gamma rays

V. A. Acciari, S. Ansoldi, L. A. Antonelli, A. Arbet Engels, M. Artero, K. Asano, D. Baack, A. Babić, A. Baquero, U. Barres de Almeida, J. A. Barrio, I. Batković, J. Becerra González, W. Bednarek, L. Bellizzi, E. Bernardini, M. Bernardos, A. Berti, J. Besenrieder, W. Bhattacharyya, C. Bigongiari, A. Biland, O. Blanch, H. Bökenkamp, ... P. Valisa + Show authors

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HOME > SCIENCE > VOL. 376, NO. 6588 > TIME-RESOLVED HADRONIC PARTICLE ACCELERATION IN THE RECURRENT NOVA RS OPHIUCHI

REPORT | GAMMA-RAY ASTRONOMY

Time-resolved hadronic particle acceleration in the re-current nova RS Ophiuchi

H.E.S.S. COLLABORATION*† Authors Info & Affiliations

THE ASTROPHYSICAL JOURNAL

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Fermi LAT Gamma-ray Detection of the Recurrent Nova RS Ophiuchi during its 2021 Outburst

C. C. Cheung[1], T. J. Johnson[2], P. Jean[3,4], M. Kerr[1], K. L. Page[5], J. P. Osborne[5], A. P. Beardmore[5], K. V. Sokolovsky[6,7], F. Teyssier[8], S. Ciprini[9,10] + Show full author list

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The Astrophysical Journal, Volume 935, Number 1

Citation C. C. Cheung *et al* 2022 *ApJ* **935** 44

DOI 10.3847/1538-4357/ac7eb7

JOURNAL ARTICLE

The 2021 outburst of the recurrent nova RS Ophiuchi observed in X-rays by the *Neil Gehrels Swift Observatory*: a comparative study

K L Page, A P Beardmore, J P Osborne, U Munari, J-U Ness, P A Evans, M F Bode, M J Darnley, J J Drake, N P M Kuin ... Show more

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Issue	A&A **Volume** 666, October 2022
Article Number	L6
Number of page(s)	5
Section	Letters to the Editor
DOI	https://doi.org/10.1051/0004-6361/202244821
Published online	30 September 2022

A&A 666, L6 (2022)

Letter to the Editor

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

U. Munari[1], M. Giroletti[2], B. Marcote[3], T. J. O'Brien[4], P. Veres[5], J. Yang[6], D. R. A. Williams[4] and P. Woudt[7]

Received: 27 August 2022 | **Accepted:** 21 September 2022

THE ASTROPHYSICAL JOURNAL

OPEN ACCESS

Shocks in the Outflow of the RS Oph 2021 Eruption Observed with X-Ray Gratings

Marina Orio[1,2], E. Behar[3], G. J. M. Luna[4,5,6], J. J. Drake[7], J. Gallagher[1], J. S. Nichols[7], J. U. Ness[8], A. Dobrotka[9], J. Mikolajewska[10], M. Della Valle[11,12]

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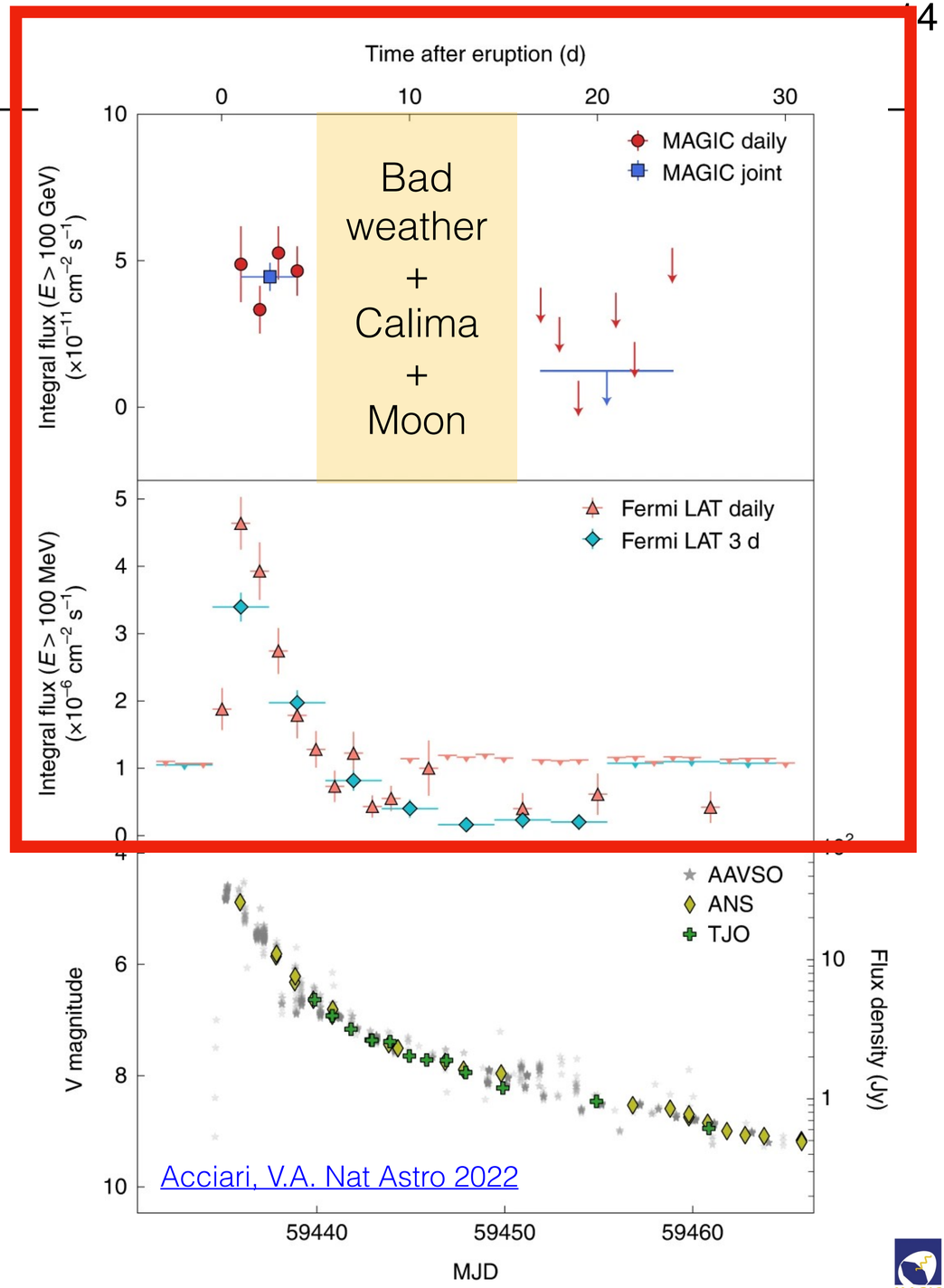
The Astrophysical Journal, Volume 938, Number 1

Citation Marina Orio *et al* 2022 *ApJ* **938** 34

DOI 10.3847/1538-4357/ac8f46

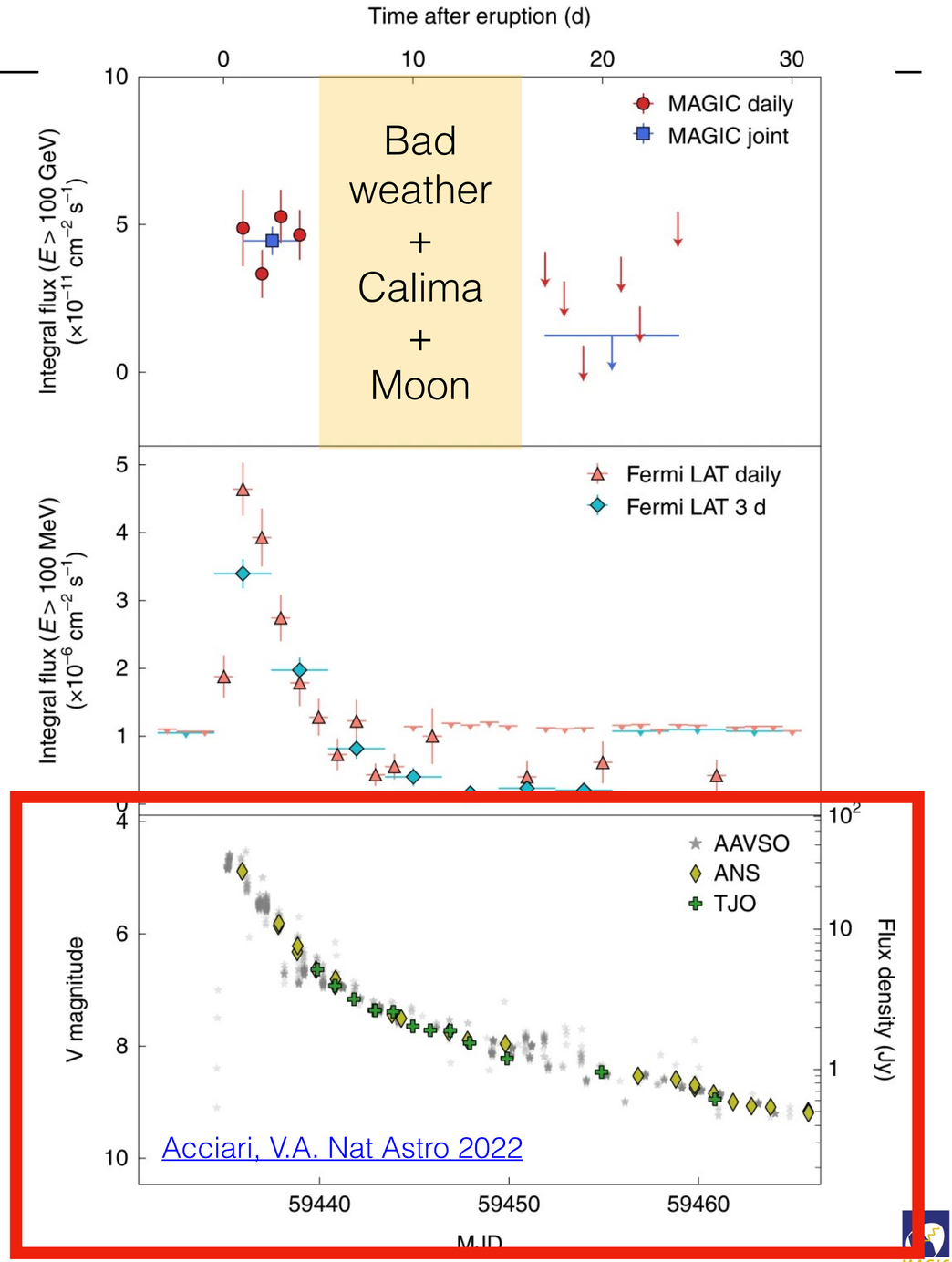
RS Ophiuchi in Gamma-rays

- HE shows rapid rise (brightest nova to date) and fall (exponential halving time (2.20 ± 0.18 days)
- The first four days of MAGIC observations (August 09-12) yield a VHE signal with a significance of 13.2σ
- No MAGIC detection as after August 25th (day 16 after outburst)
- VHE photon flux > 100 GeV constant over first 4 days while HE signal decreases by factor of <2



RS Ophiuchi in Optical

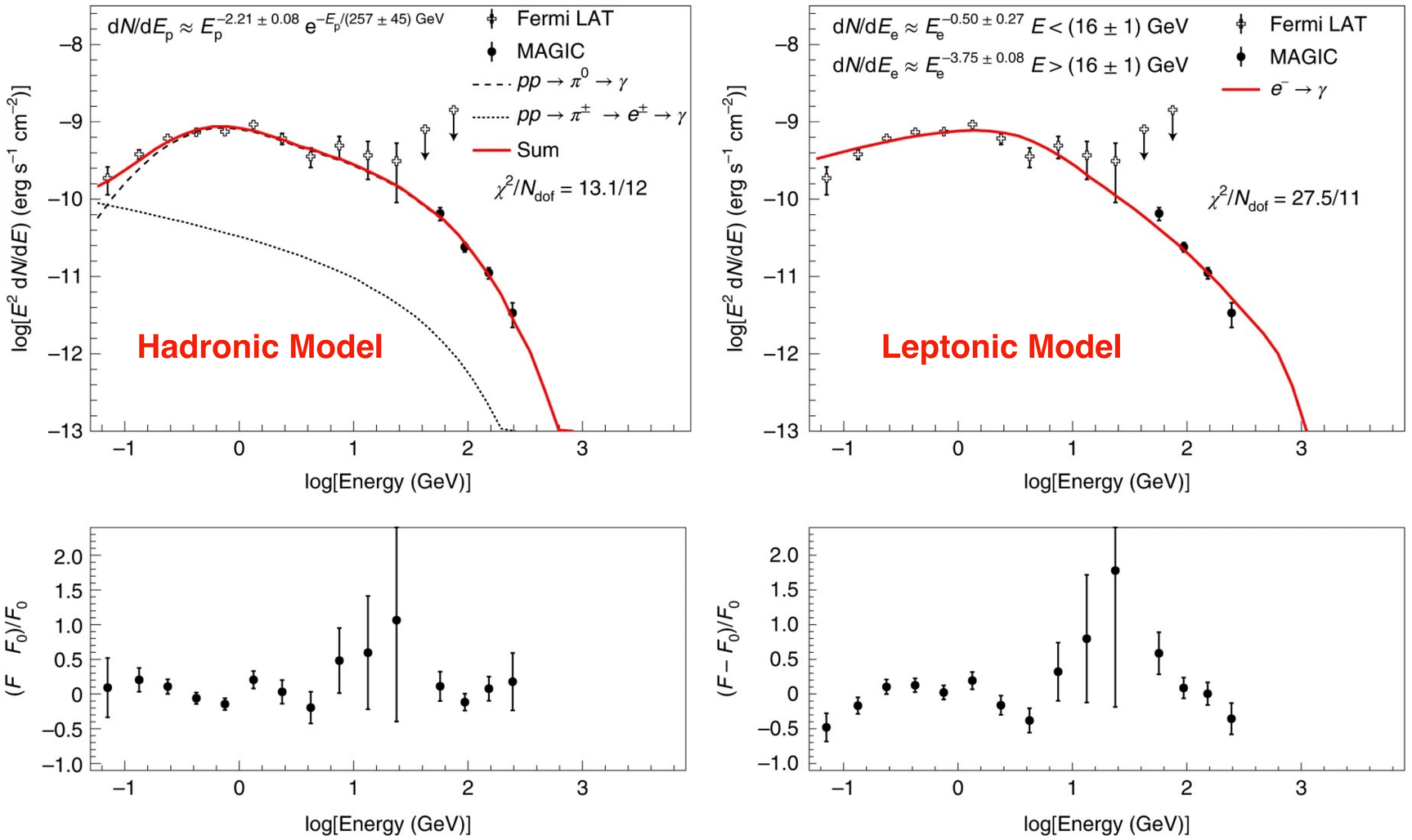
- Photometry:
  - TJO and ANS simultaneous data with MAGIC
  - Emission described with T_{ph} 10800K -> 7680 K and R_{ph} = 200 $R_\odot$
- Spectroscopy:
  - Varese 0.84 m and Catania 0.91 m telescopes
  - 4500 ± 250 km/s for ejecta expansion during first 4 days



Gamma-ray Modeling

- Time dependent modeling based from [MAGIC Coll., A&A, 582 (2015)]
- Hadronic model favored over leptonic model
- Hadronic model has natural CR index ~2
- Leptonic requires ad hoc break and fits poorly

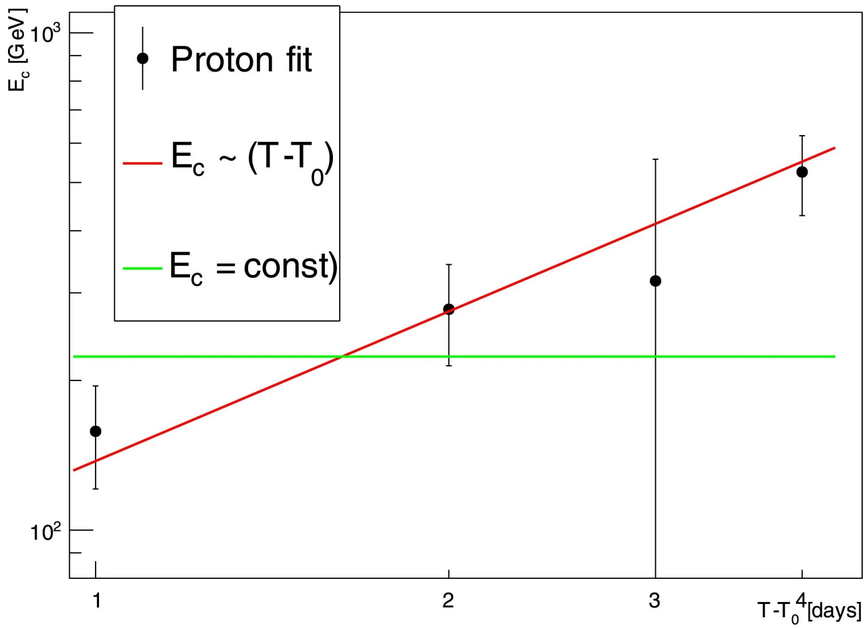
[Acciari, V.A. Nat Astro 2022]



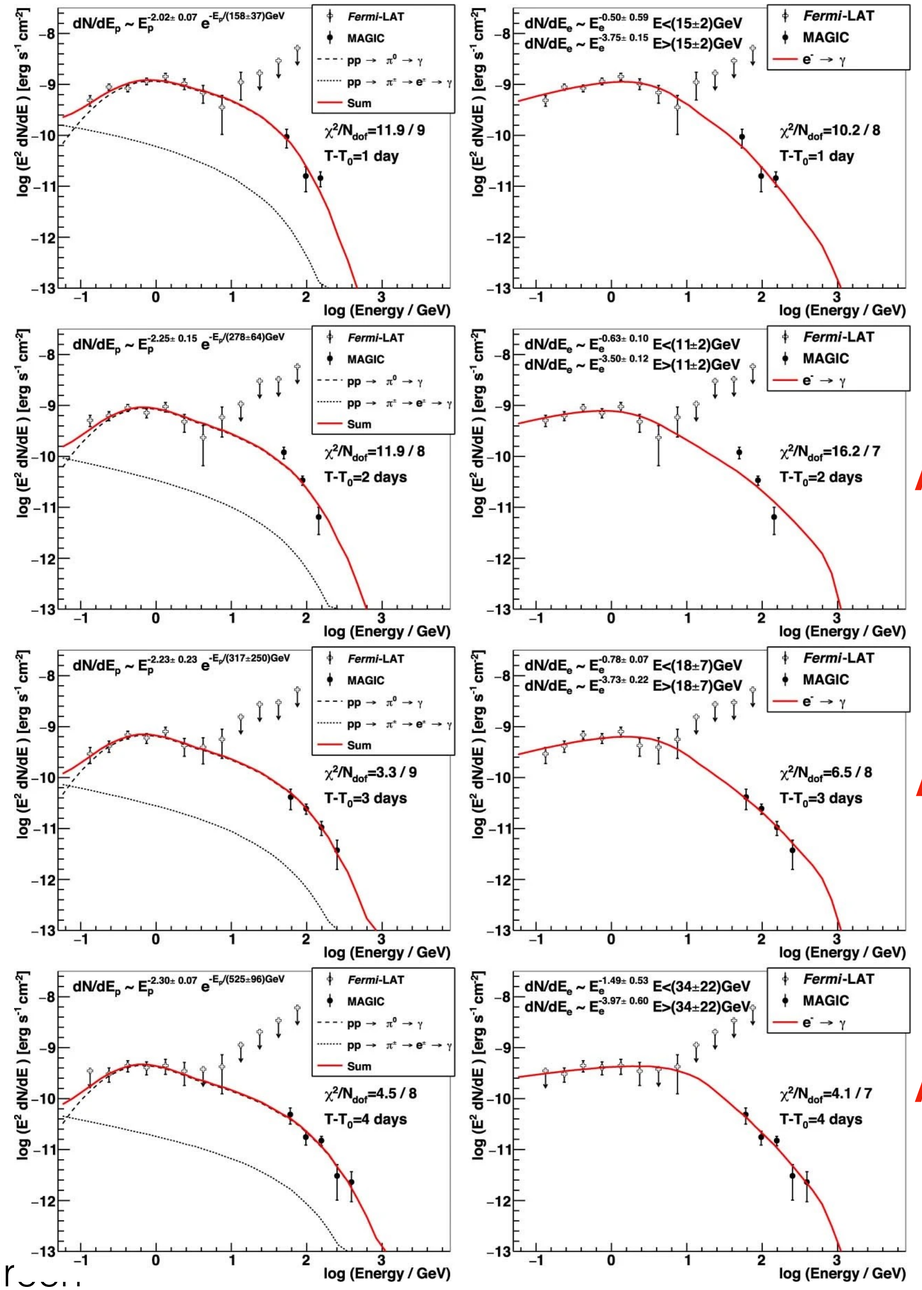
Daily Gamma-ray Modeling

Acciari, V.A. Nat Astro 2022

- Hadronic model preferred on the daily fits
- Slight indication of hardening (increase in maximum energy) vs time
- Inline with protons cooling slowly



Hadronic Model **Leptonic Model**



Aug 9th

Aug 10th

Aug 11th

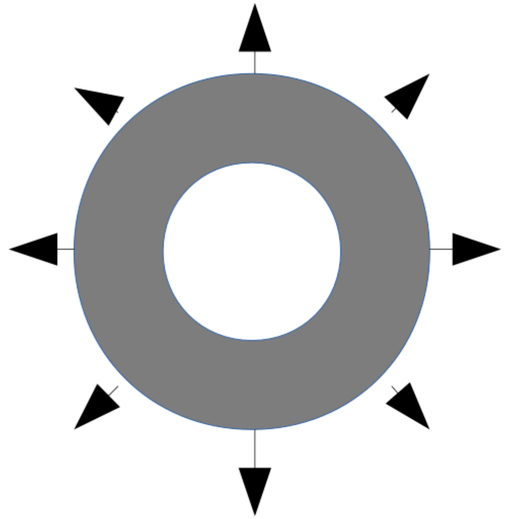
Aug 12th

Target for Protons

- **Expanding shell of ejecta** - Dominates emission

$$n_{ej} = \frac{M_{ej}}{4\pi h R_{sh}^3 m_p}$$

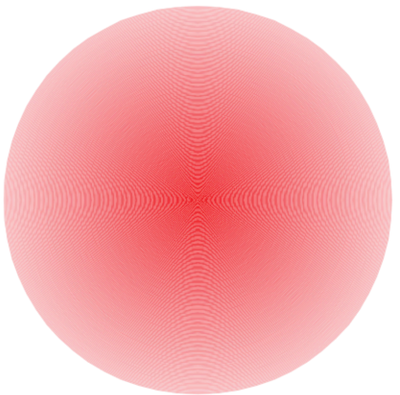
$$= 6.0 \times 10^8 \frac{M_{ej}}{10^{-6} M_\odot} \left(\frac{v_{sh}}{4500 \text{km s}^{-1}} \right)^{-3} \left(\frac{t}{3\text{d}} \right)^{-3} \left(\frac{h}{0.1} \right)^{-1} [\text{cm}^{-3}]$$



- **Red giant wind** - Contributes to ~20% of target material

$$n_{RG} = \frac{\dot{M}_{RG}}{4\pi R_{sh}^2 v_{RG} m_p}$$

$$= 1.1 \times 10^8 \frac{\dot{M}_{RG}}{5 \times 10^{-7} M_\odot/\text{yr}} \left(\frac{v_{sh}}{4500 \text{km s}^{-1}} \right)^{-2} \left(\frac{t}{3d} \right)^{-2} \left(\frac{v_{RG}}{10 \text{km s}^{-1}} \right) [\text{cm}^{-3}]$$



Energetics

- Proton model requires significant fraction (22%) of the nova's kinetic energy:

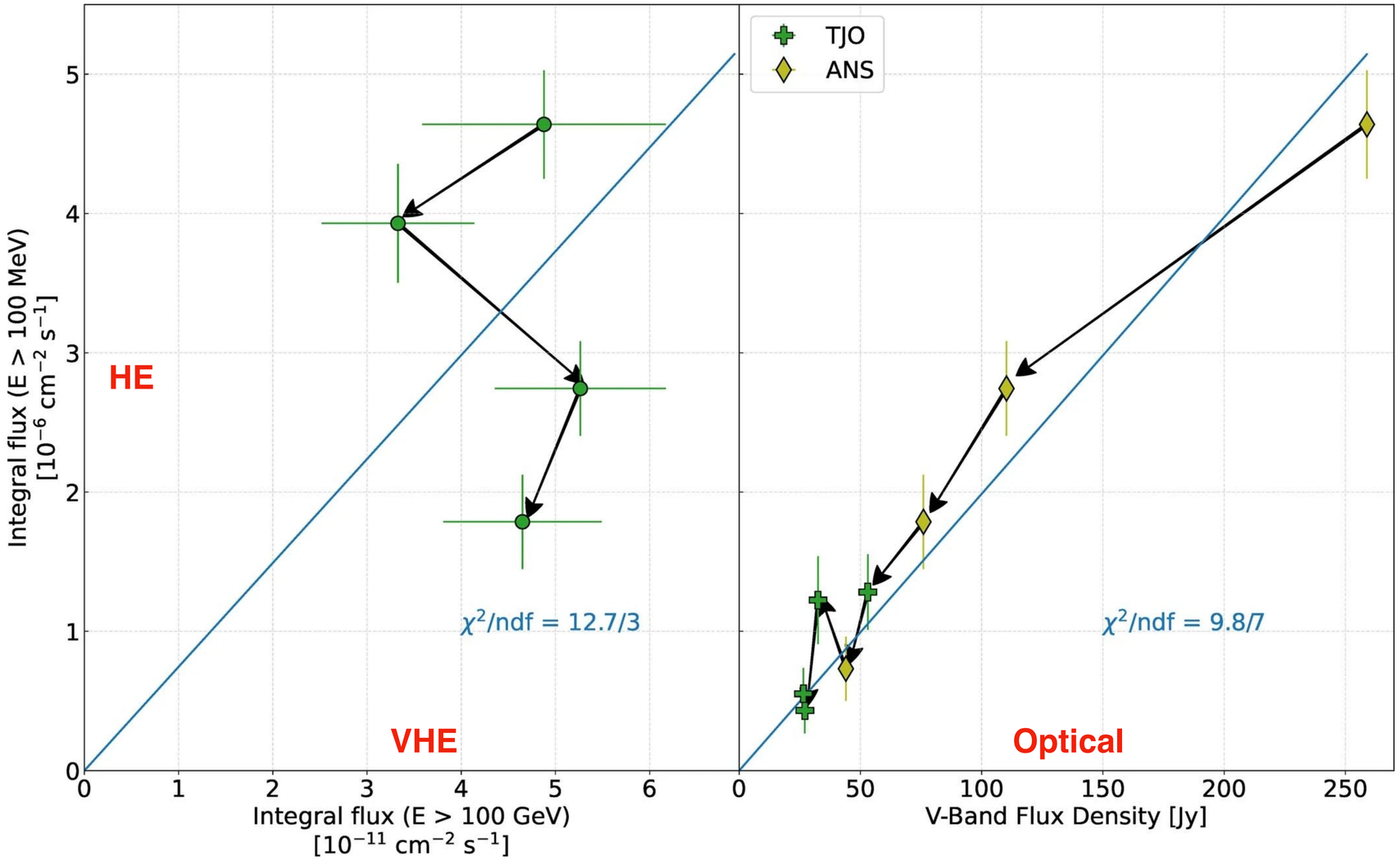
$$\epsilon = \frac{E_{p,nova}}{E_k} = 0.22 \left(\frac{M_{ej}}{10^{-6} M_\odot} \right)^{-2} \left(\frac{v_{sh}}{4500 \text{km s}^{-1}} \right) \left(\frac{d}{2.45 kpc} \right)^{-2} \frac{h}{0.1}$$

- Most of this energy is carried away by escaping protons

More Evidence for Protons

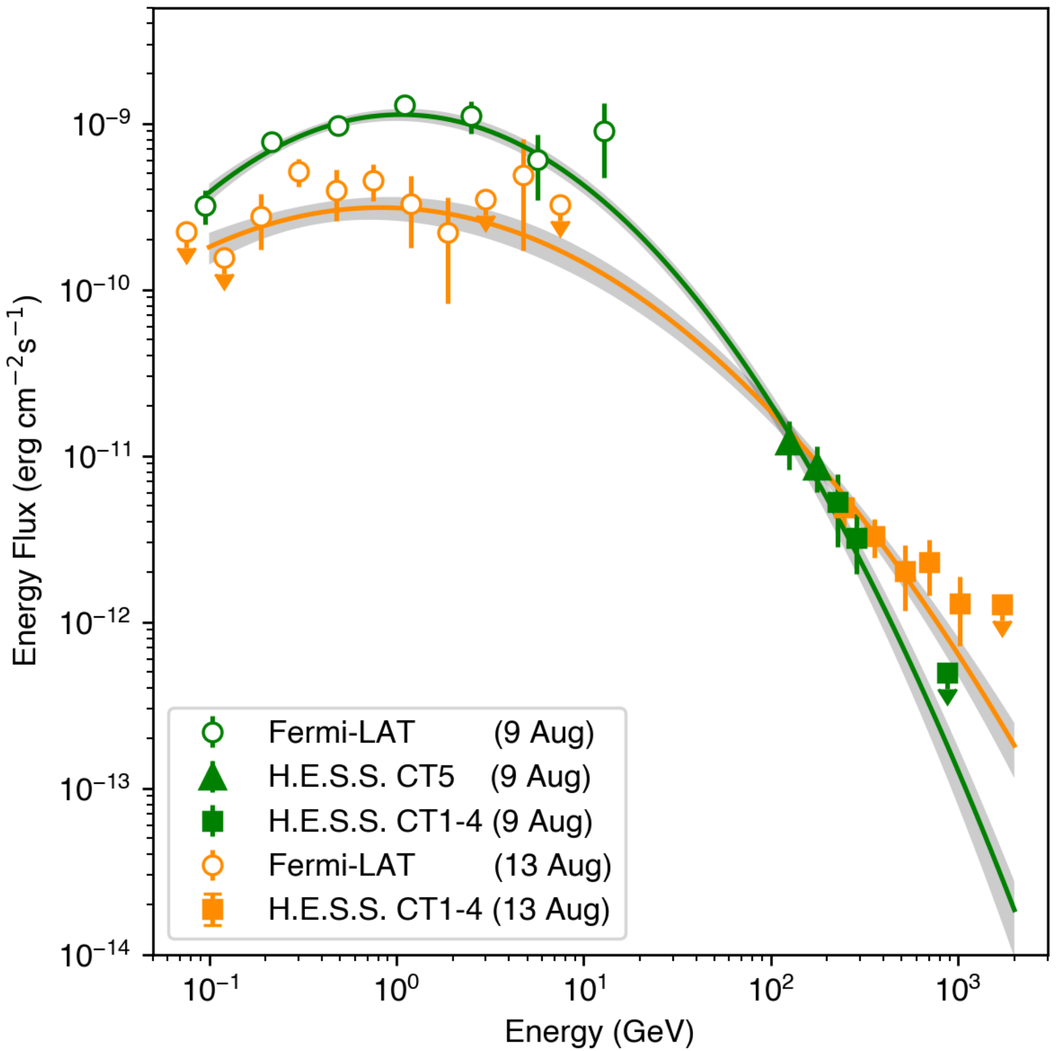
- Optical and HE emission follow similar decay
  - IC emission should decay fast due to shock expansion
- VHE emission seems stable
  - Hint of spectral hardening
  - Protons cool slowly + delayed emission

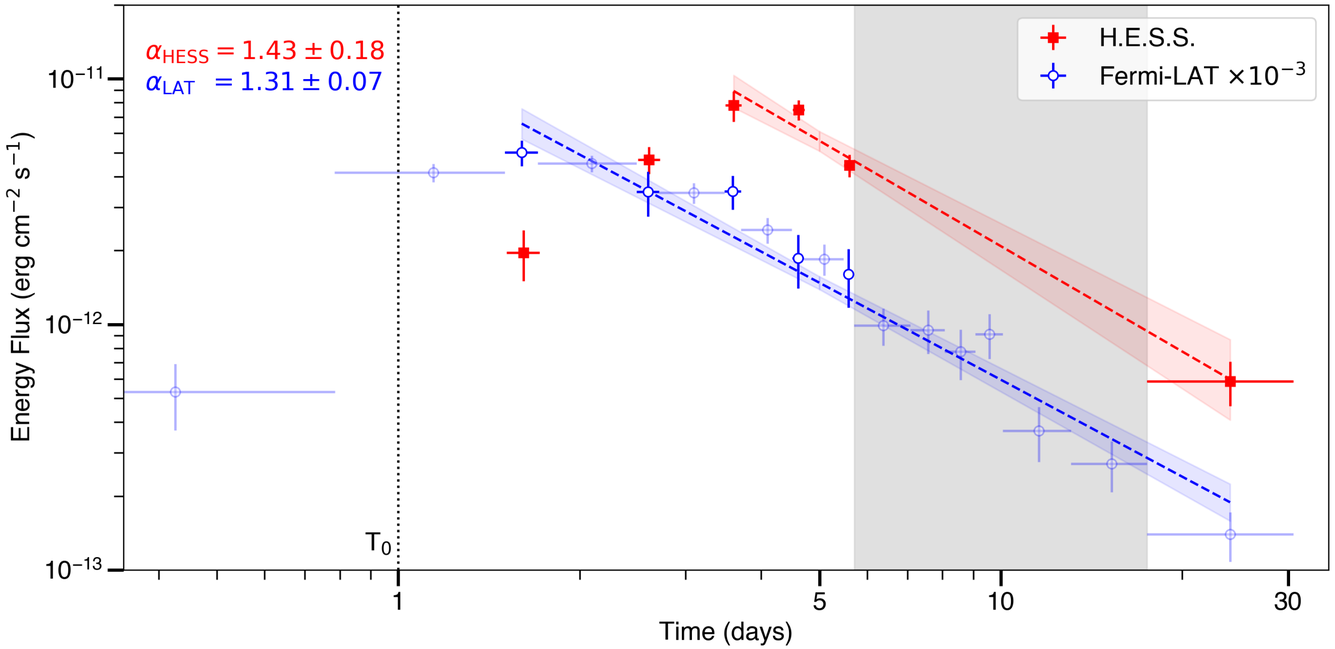
Acciari, V.A. Nat Astro 2022



Yet More Evidence for Protons

H.E.S.S. Collab, Science 2022

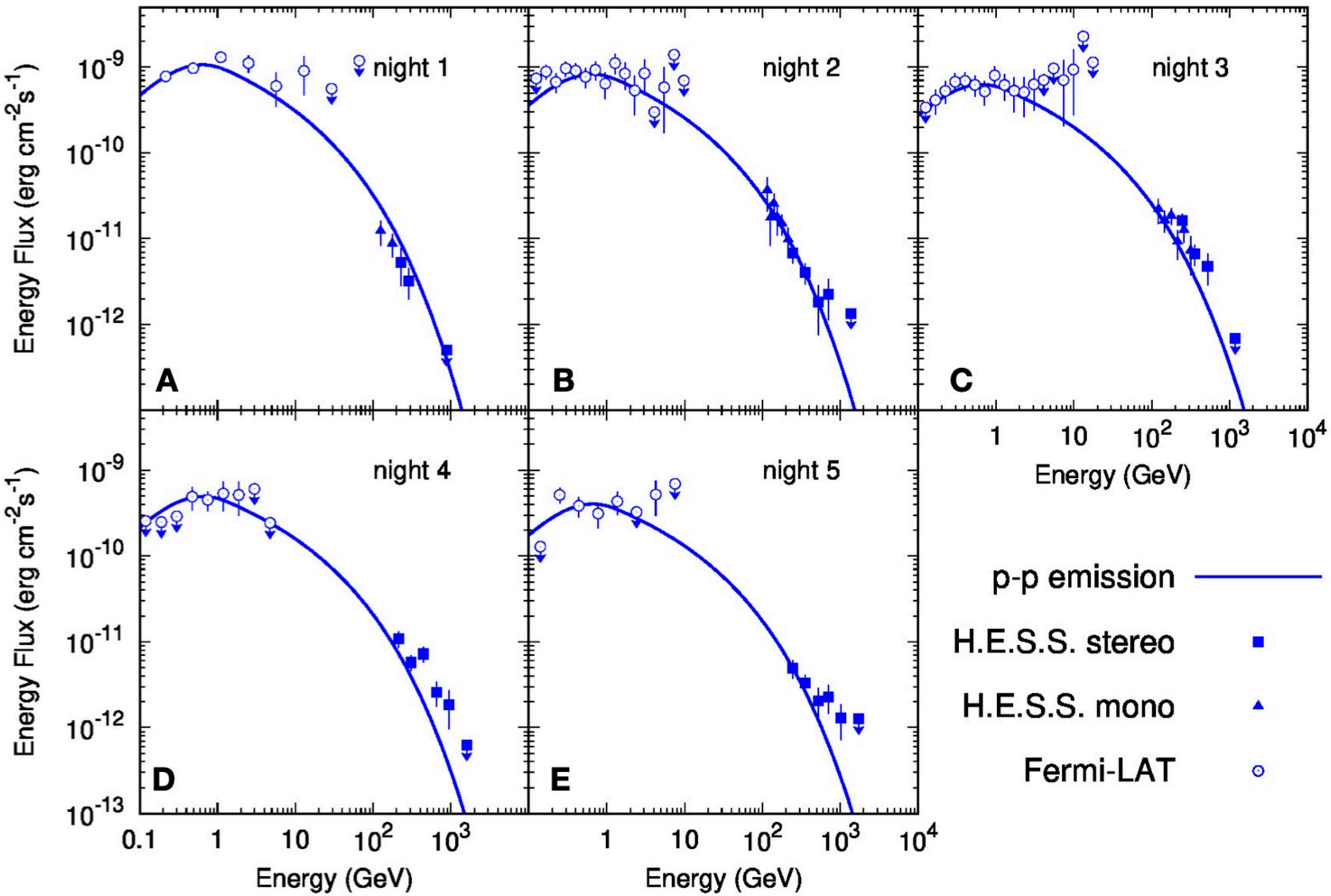




- H.E.S.S. observed RS Oph during early outburst
- Observations are for higher energies (Flux > 250 GeV)

Yet More Evidence for Protons

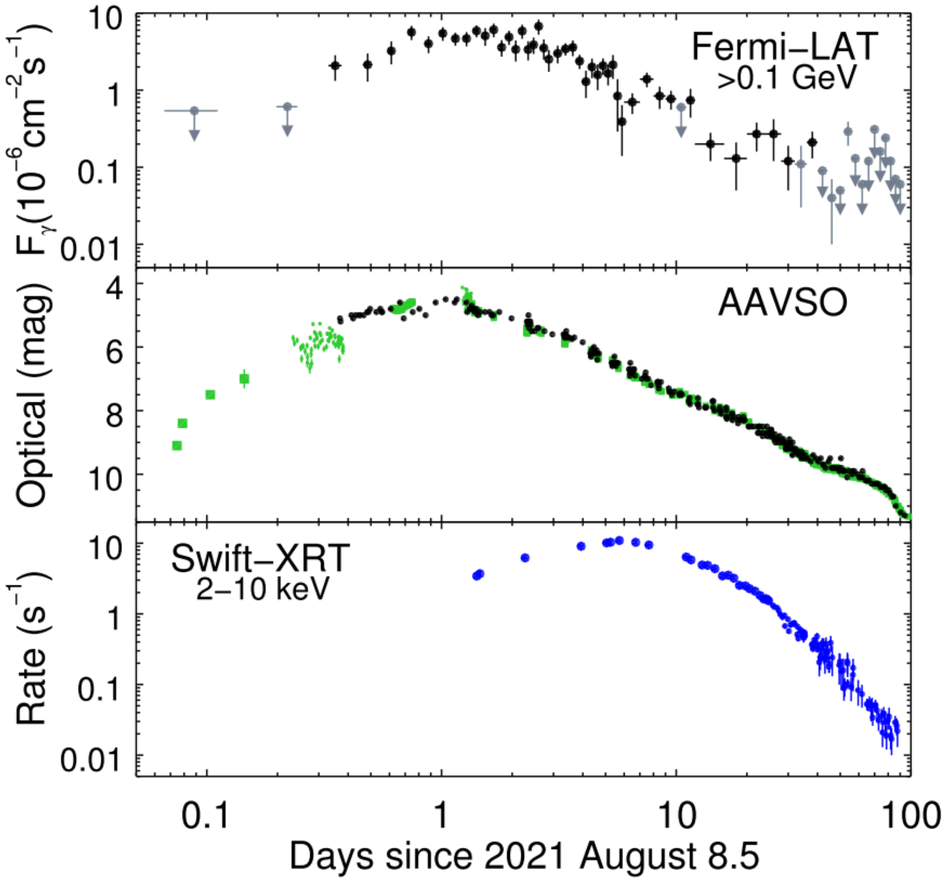
H.E.S.S. Collab, Science 2022



- H.E.S.S. model also prefers hadronic over leptonic
- Need ~50% of KE into protons

And Still More Evidence for Protons

Cheung, C.C , ApJ 2022



- Using the hadronic model proposed in Tatischeff, V. & Hernanz, M. ApJL 2007, able to reproduce the gamma-ray light curve
- Once again, hadronic model preferred over leptonic model

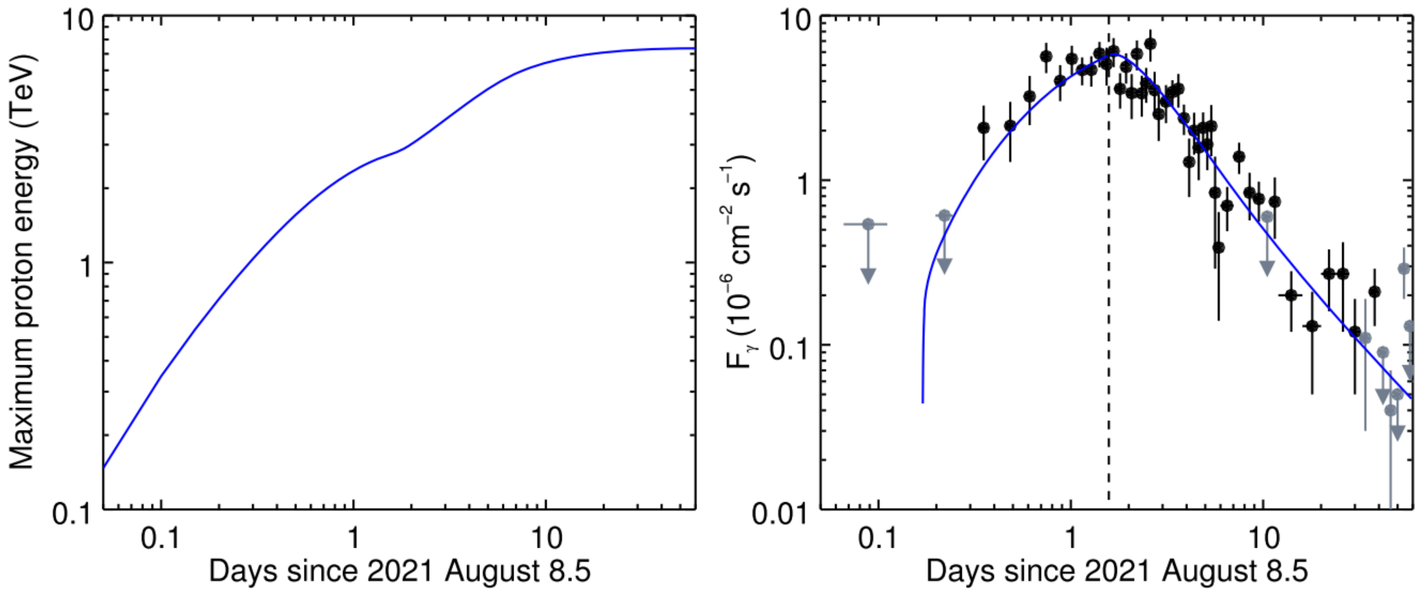
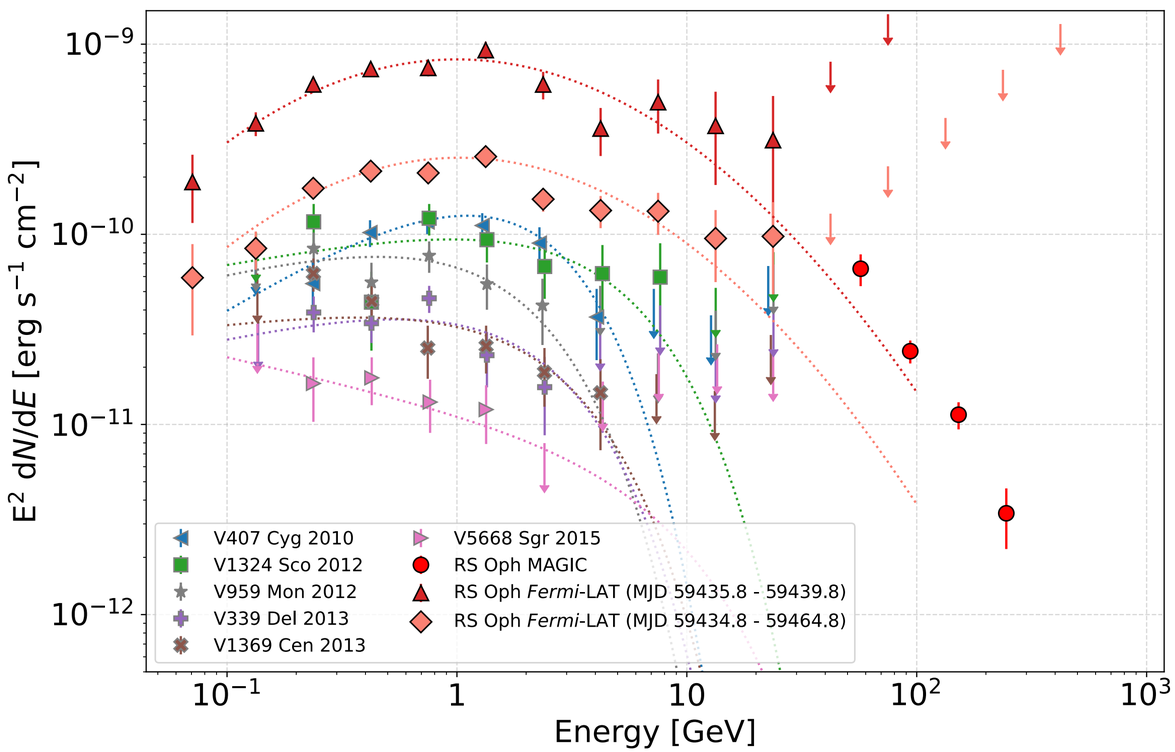
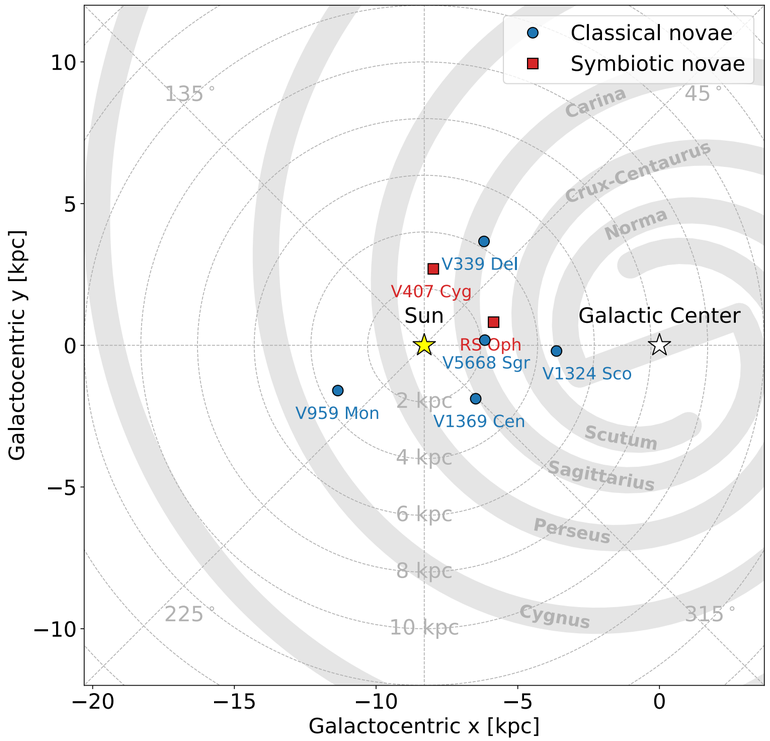


Figure 6. (Left): Maximum proton energy with time for the hadronic model for RS Oph 2021. (Right): Comparison of the hadronic model with the observed γ-ray flux light curve presented in Figure 2. The dashed line shows the date at which the ejecta reach the radius of 1.5×the binary separation (see text).

Context of other Gamma-ray Novae

Acciari, V.A. Nat Astro 2022

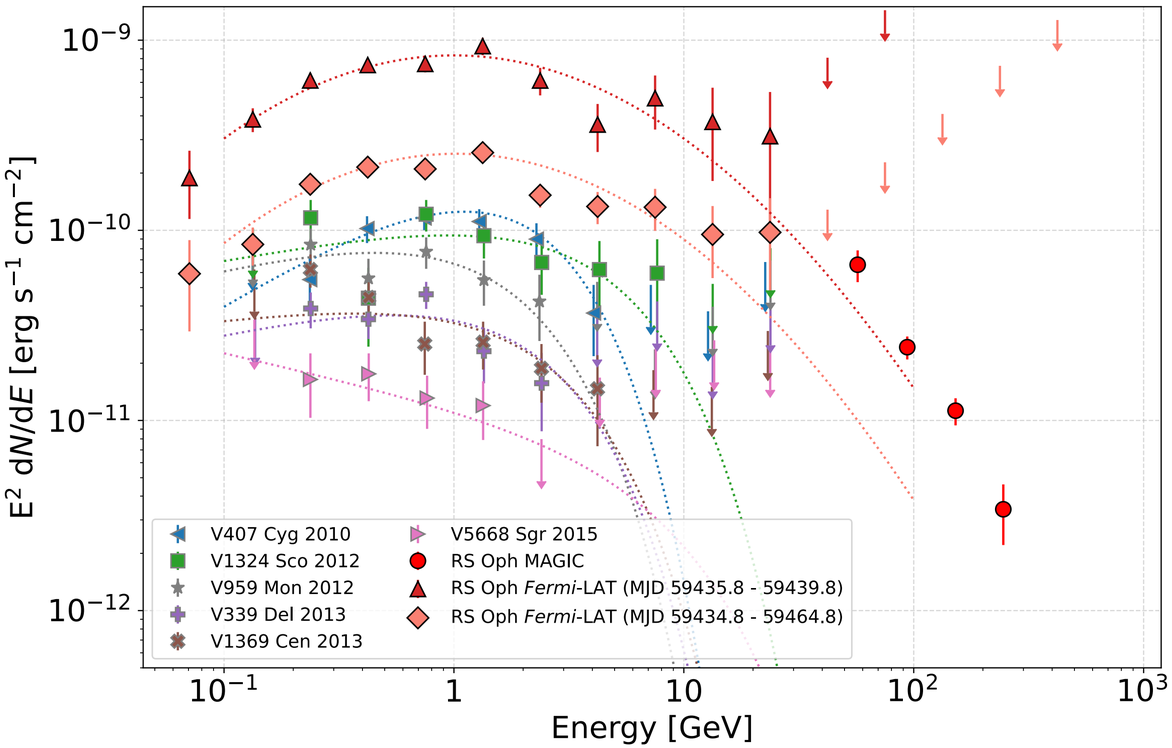


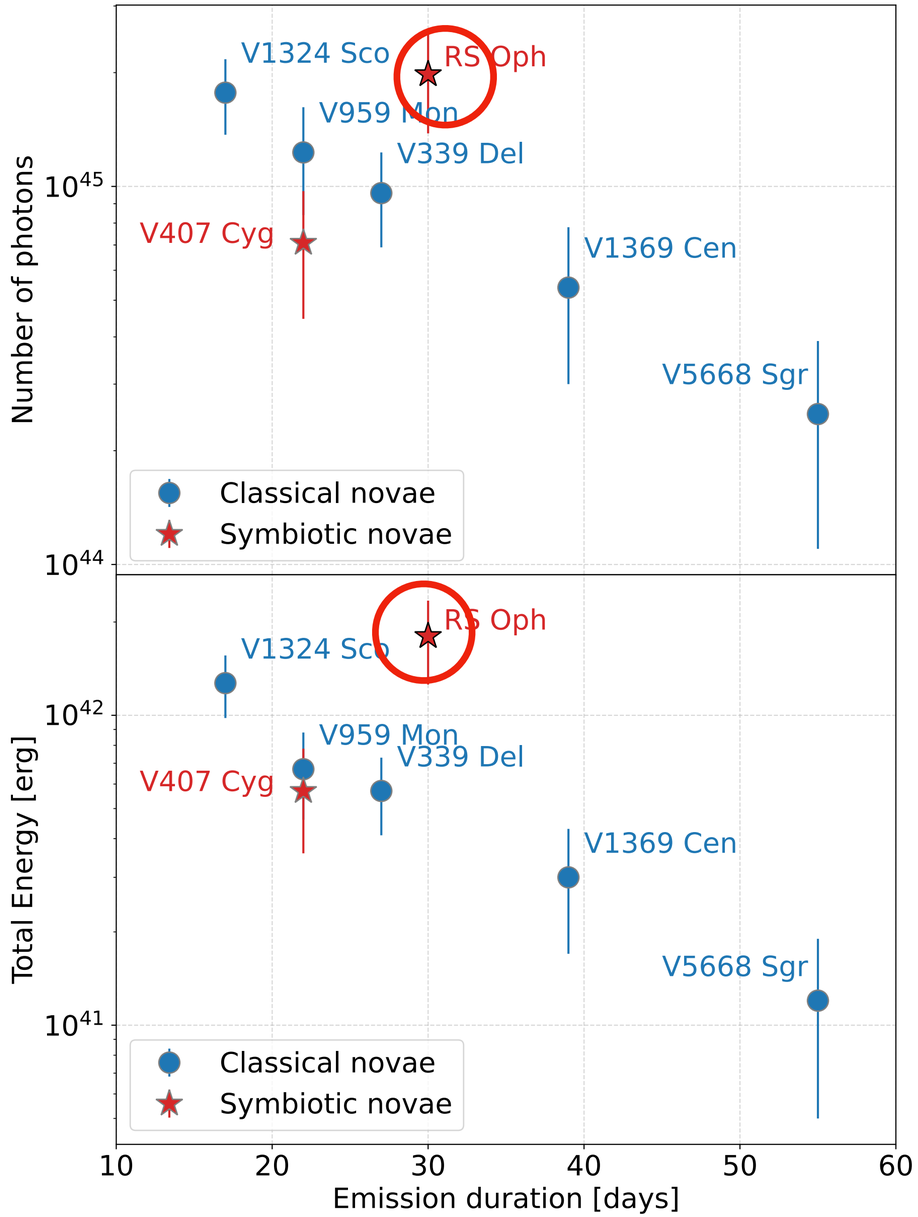


- RS Oph is of the highest flux of other gamma-ray novae

Context of other Gamma-ray Novae

Acciari, V.A. Nat Astro 2022





- Also intrinsically the brightest

Context of other Gamma-ray Novae

- Tricky to detect other novae at VHE energies
- Scaling RS Oph to V407 Cyg or V339 Del brightness, would have been below detection threshold of current generation IACTs
- More sensitive instruments required like the future CTA

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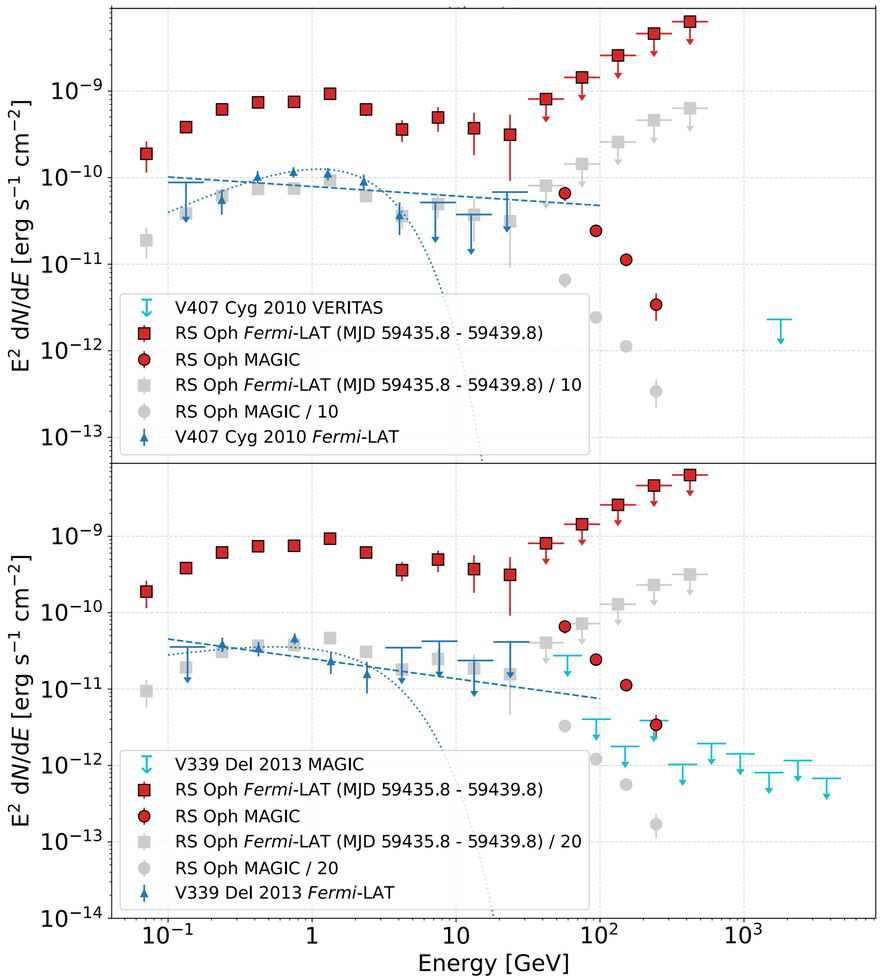
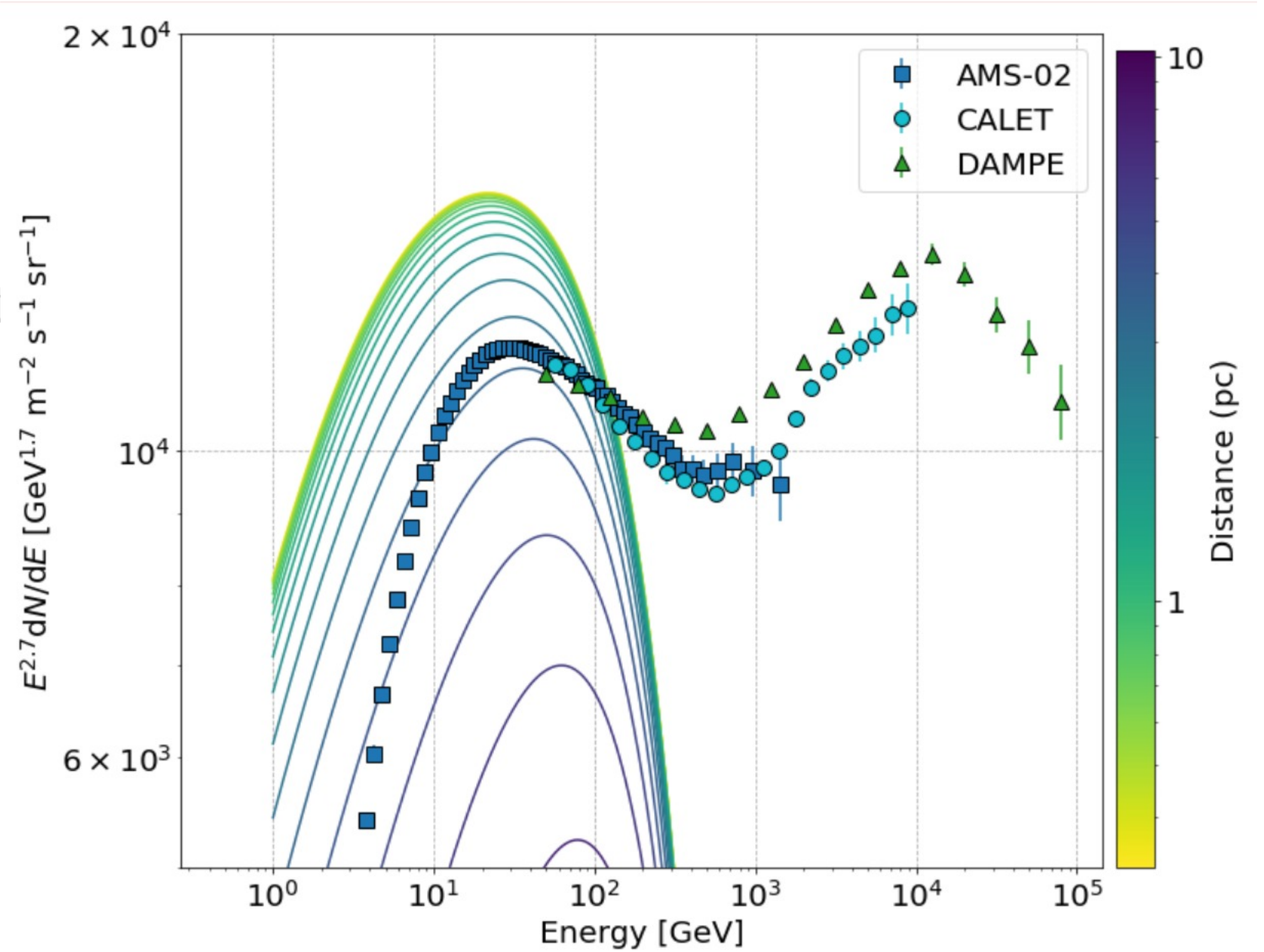


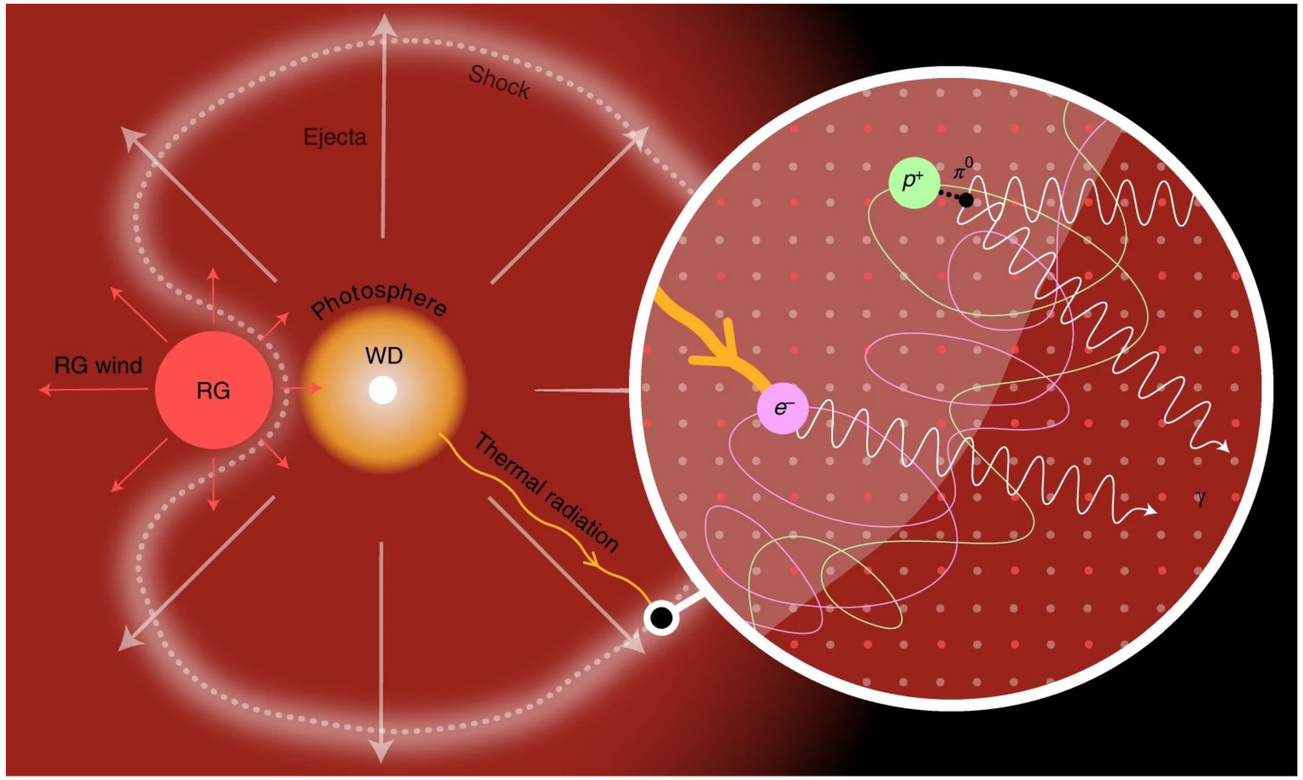
Galactic Cosmic Rays

- Protons can contribute to cosmic-ray population
  - Total contribution is < 0.2% compared to Supernova remnant
- Can dominate over ~ 1 pc radius
  - For frequent recurrent eruptions create a bubble with ~10 pc radius
  - Novae are not expected to contribute significantly to the measured CR spectrum



Conclusions

- Observations of the August 2021 outburst of RS Oph creates a new class of VHE emitters
- Hadronic emission favored by Optical + Fermi-LAT + MAGIC modeling
- Other measurements from Fermi-LAT and H.E.S.S. also prefer hadronic origins
- First evidence for hadronic origin of gamma-rays in novae



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