Revealing time-resolved hadronic particle acceleration in the recurrent nova RS Ophuichi

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for the H.E.S.S. collaboration

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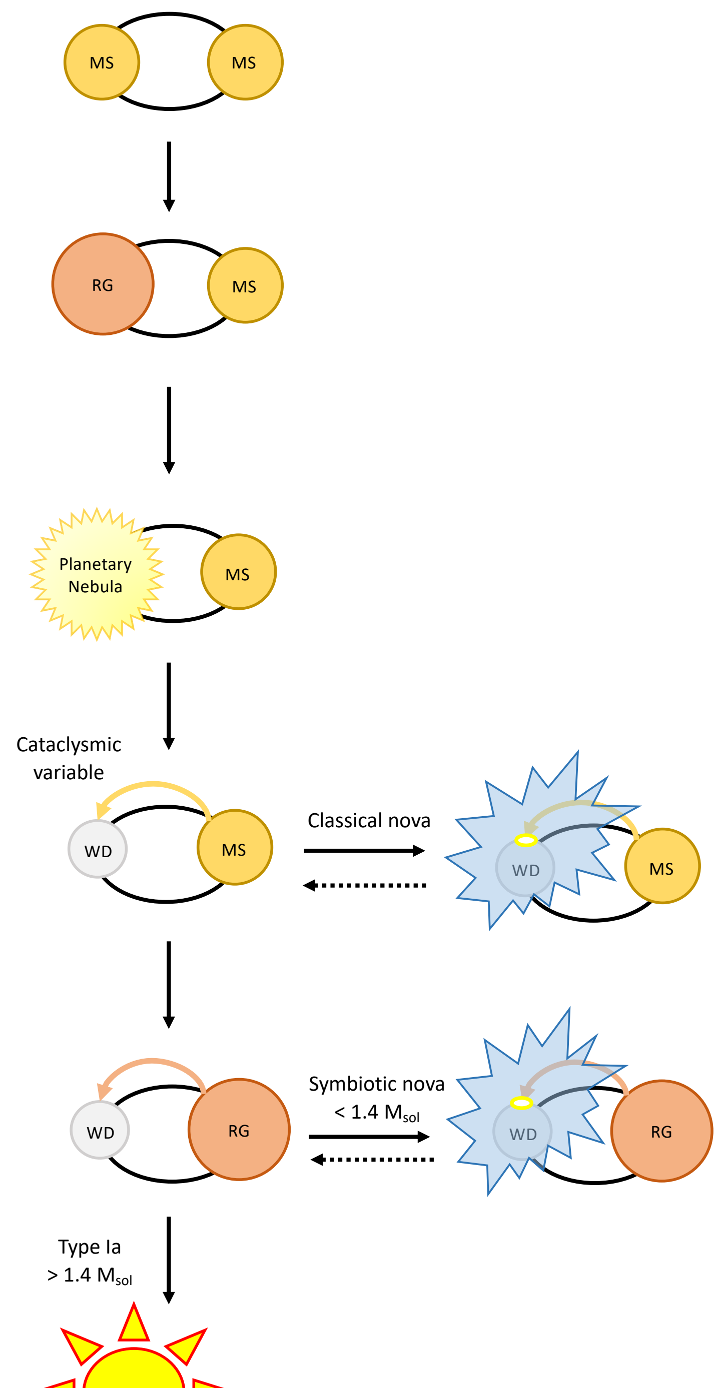
ecap

Introduction to Novae

- Novae – outbursts from accreting binary systems (White Dwarf + massive donor):
  - (Classical) Novae → outbursts from cataclysmic variables
  - Symbiotic Novae → red giant / "evolved" donor star
  - Recurrent Novae → multiple observed outbursts
  - Dwarf Novae → mini-outbursts (not thermonuclear)
- Thermonuclear explosion ignited on surface of white dwarf
- Increase in optical brightness $\Delta m_V \sim 8$ to 15
- Typical optical duration weeks to months



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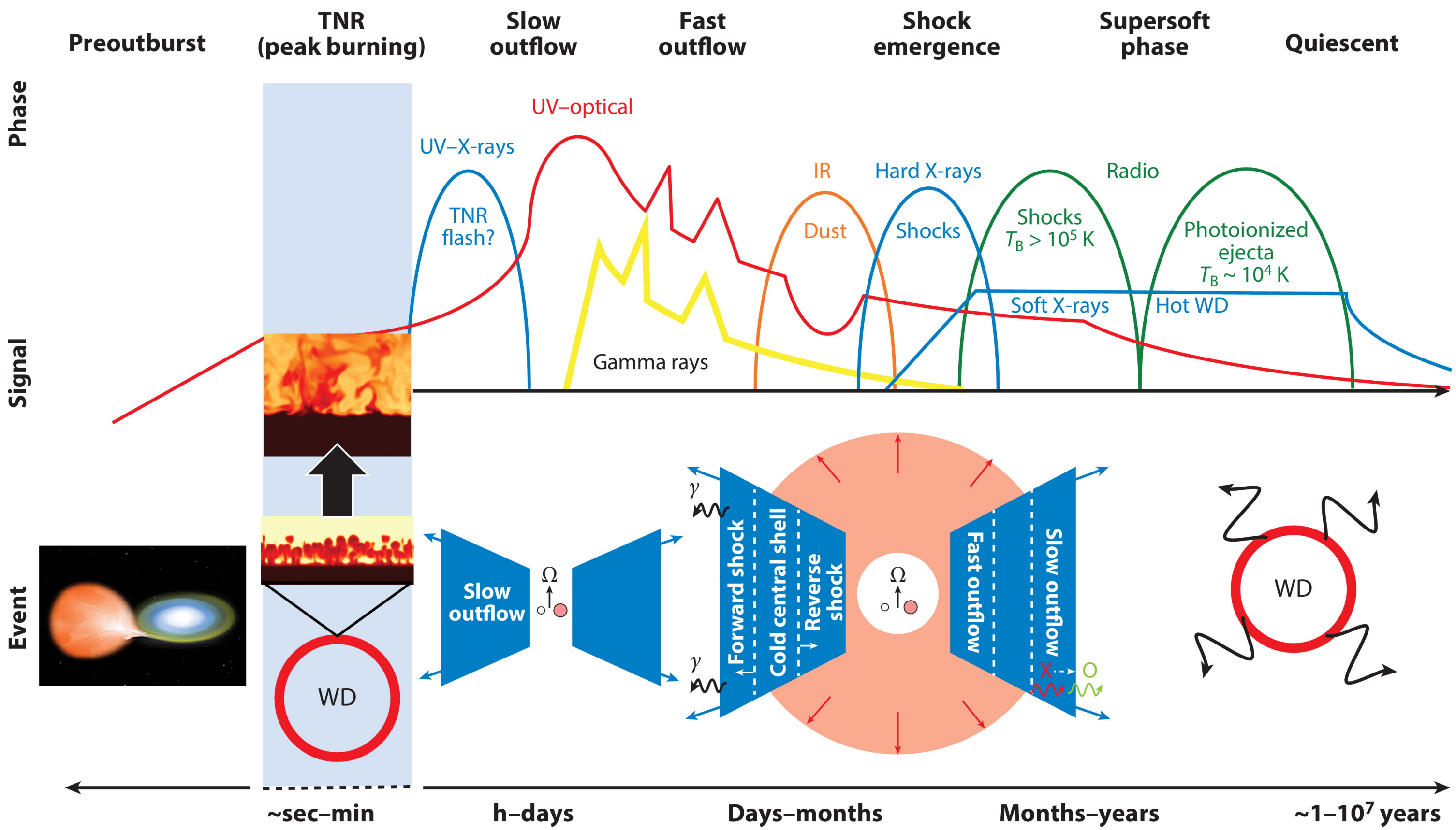
Evolution of a nova outburst



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

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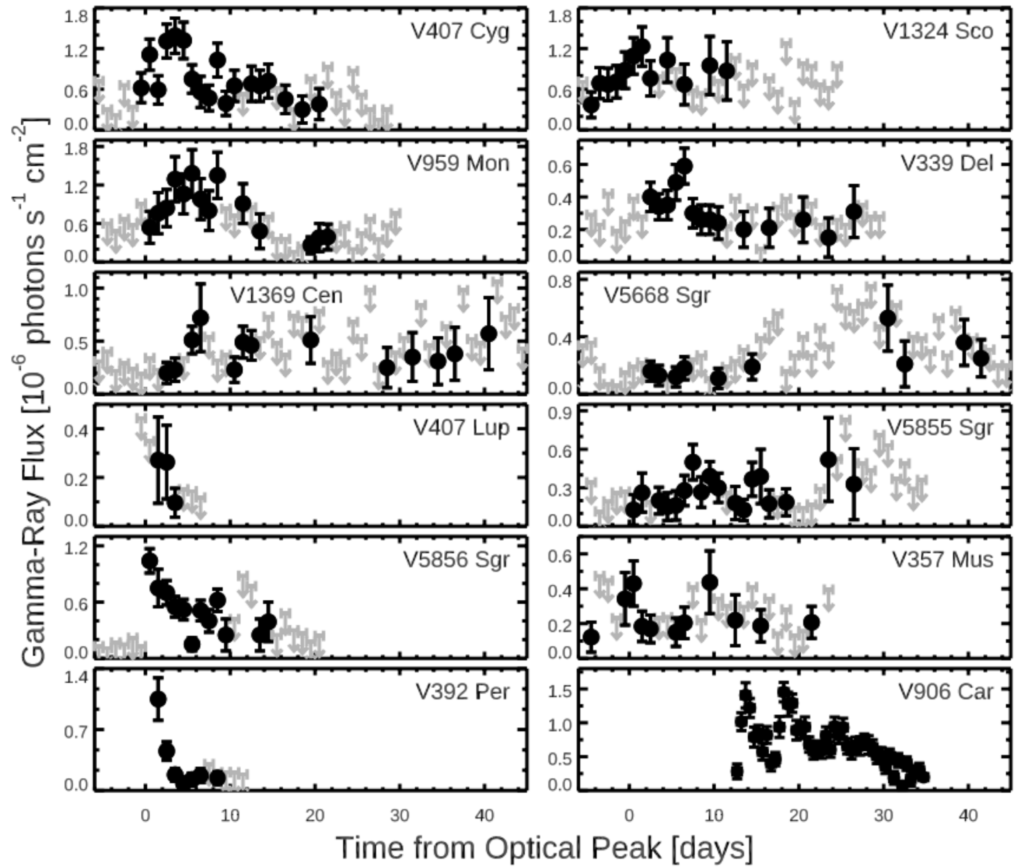
Novae in gamma-rays

- Particle acceleration at shocks → interaction with dense wind (external) or of fast ejecta with slower material (internal)

Chomiuk et al, Ann. Rev. A&A 59, 112420 (2021)



- 17 novae detected in gamma-rays by Fermi-LAT so far
- Typical duration days to weeks
- Typical spectral cut-off ~1-10 GeV

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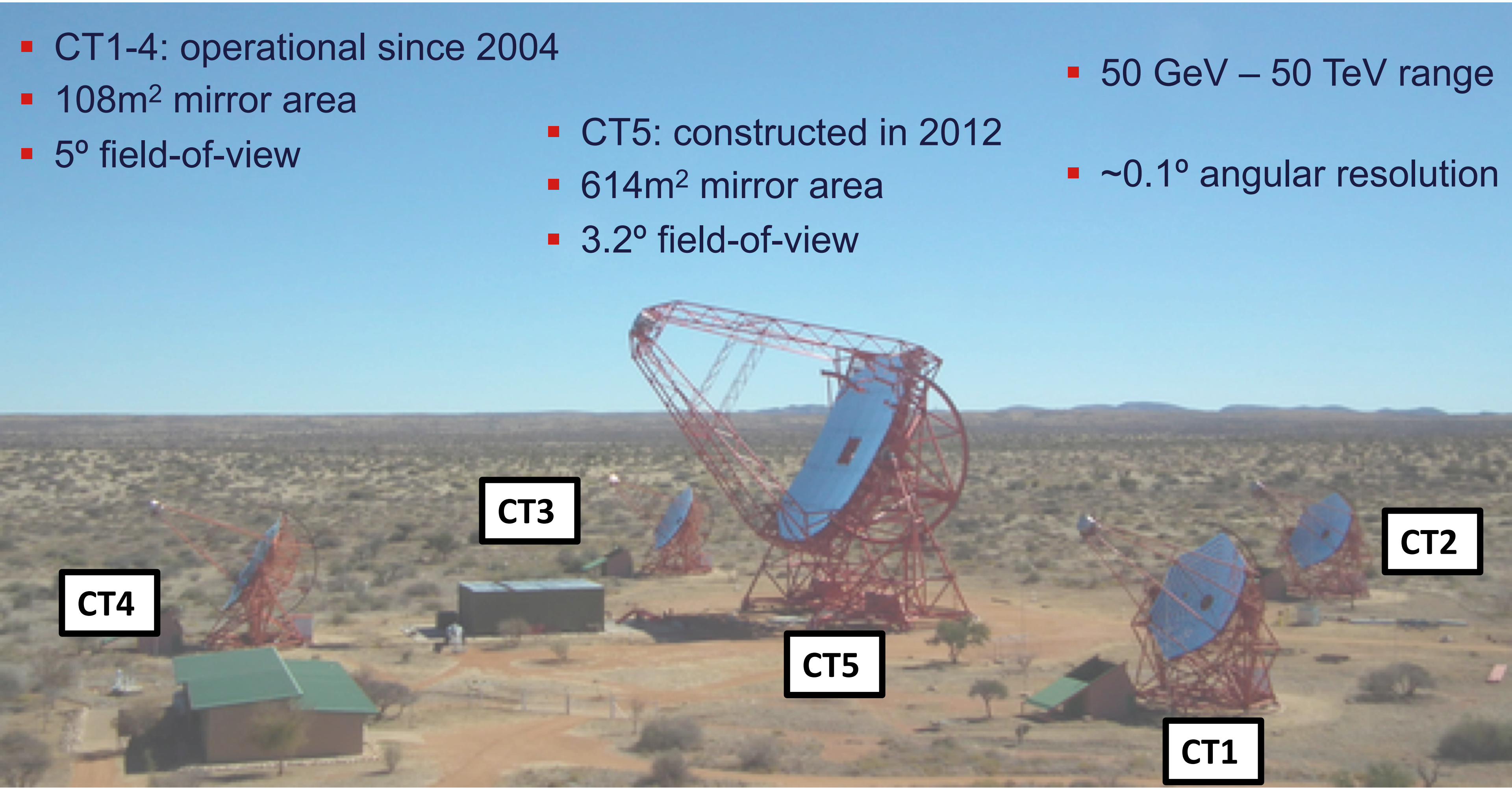
Introducing RS Ophiuchi

- Binary system comprised of white dwarf and red giant at ~1.4 kpc distance
- Quiet state $m_v = 12.5$
- Semi-regular explosions observed since 1898
  most recently in 12th February 2006 and **8th August 2021** reaching $m_v = 4.6$
- Post-2006: asymmetric expansion at 5.5 days from infrared interferometric observations
  Chesneau et al. A&A **464**, 119 (2007)

Introducing H.E.S.S.

Array of five IACTs in Khomas Highlands, Namibia



- CT1-4: operational since 2004
- 108m² mirror area
- 5º field-of-view

- CT5: constructed in 2012
- 614m² mirror area
- 3.2º field-of-view

- 50 GeV – 50 TeV range
- ~0.1º angular resolution

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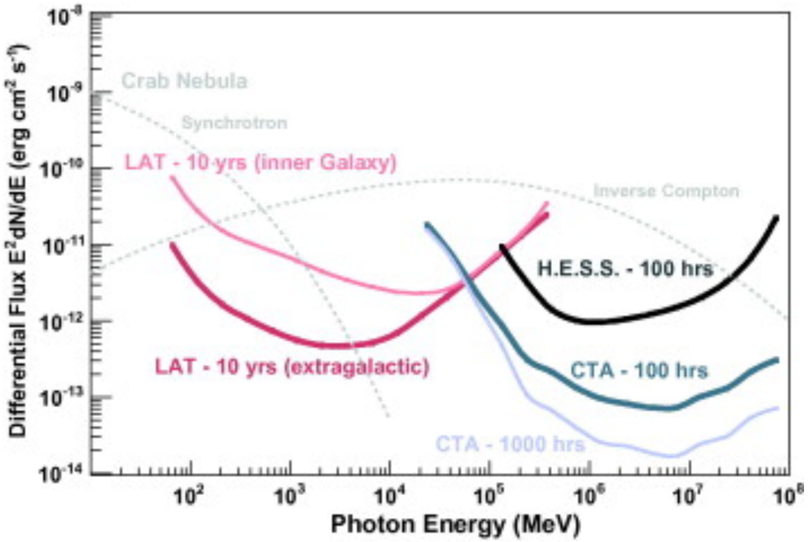
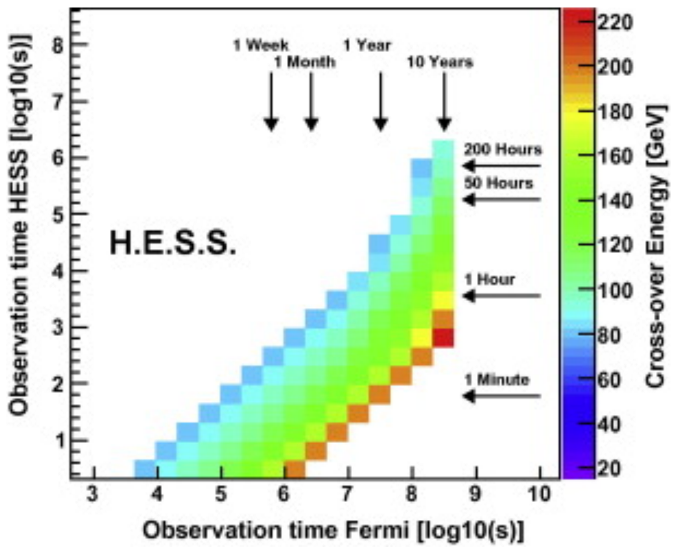
Instrument performance

- Fermi-LAT satellite and IACTs as highly complementary facilities
- Cross-over energy depends on exposure





Funk & Hinton, Astropart Phys 43 (348-355), 2013

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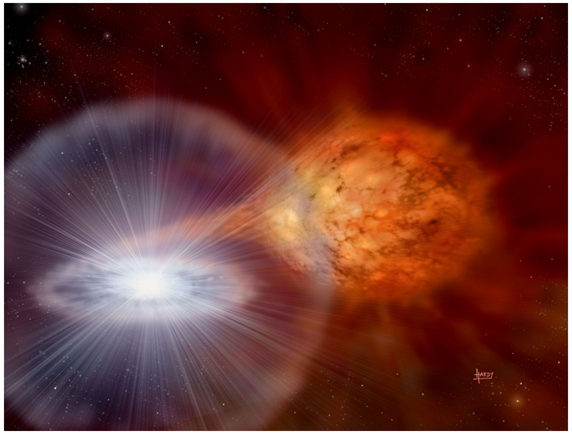
- Trigger criteria for novae:
  - Optical magnitude, $m_V \leq 9$
  - Fast ejecta velocity ≥ 1500 km/s
  - Associated Fermi-LAT detection
- Known recurrent novae also to be observed whenever they enter outburst
- Most novae only match 1-2 criteria
- RS Oph → fulfilled **all** criteria (rare)

- RS Oph in 2021:
  - $m_V \sim 5$ (AAVSO, 8th Aug 22:20 UTC)
  - ≥ 2600 km/s (Atel #14838, 9th Aug 15:00 UTC)
  - **~6 sigma** (ATel #14834, 9th Aug 05:00 UTC)
- Is a known recurrent nova



AAVSO++ → community notified by amateur astronomers

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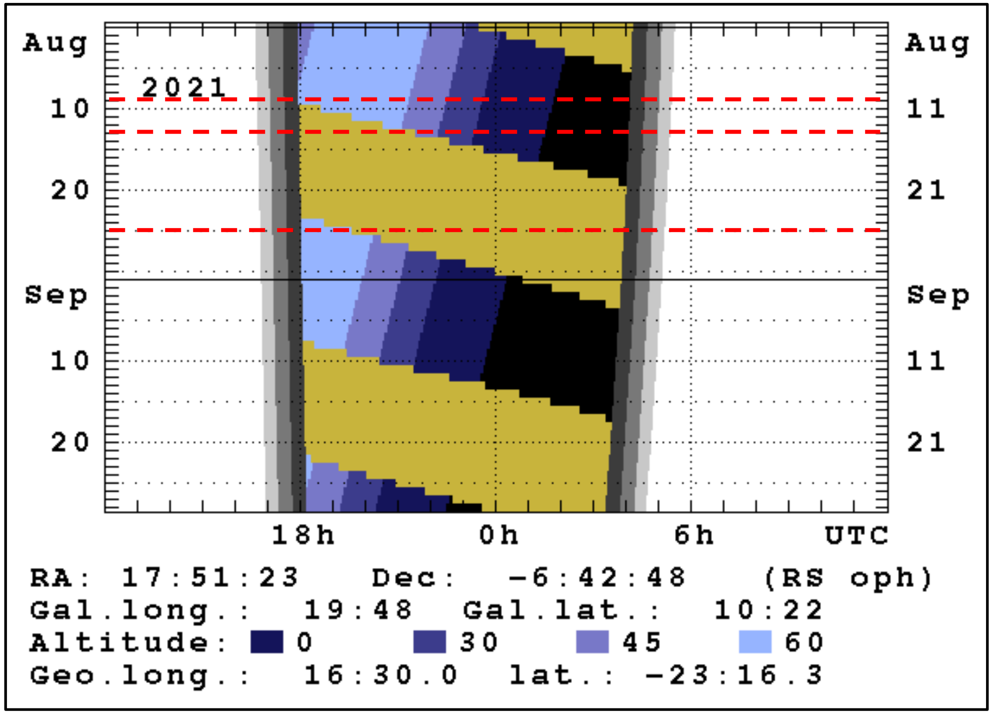
Observations of RS Oph



- Restricted by:
  - Elevation above horizon
  - Ambient sky brightness (e.g. background moonlight)
  - Time of year (luck)

- Observations commenced 18:17 UTC on 09/08/21
- Continued nightly until 13/08/21
  Enforced break due to high moonlight
- Observations resumed from 17:48 UTC 25/08/21

Detection of VHE gamma-ray emission from the recurrent nova RS Ophiuchi with H.E.S.S.

ATel #14844; *Stefan J. Wagner, for the H. E.S. S. collaboration*

*on **10 Aug 2021; 18:34 UT***

Credential Certification: Stefan J. Wagner (swagner@lsw.uni-heidelberg.de)

Subjects: Gamma Ray, >GeV, TeV, VHE, Binary, Nova

Referred to by ATel #: 14845, 14846, 14848, 14849, 14851, 14855, 14857, 14858, 14860, 14882, 14885, 14886, 14894, 15169

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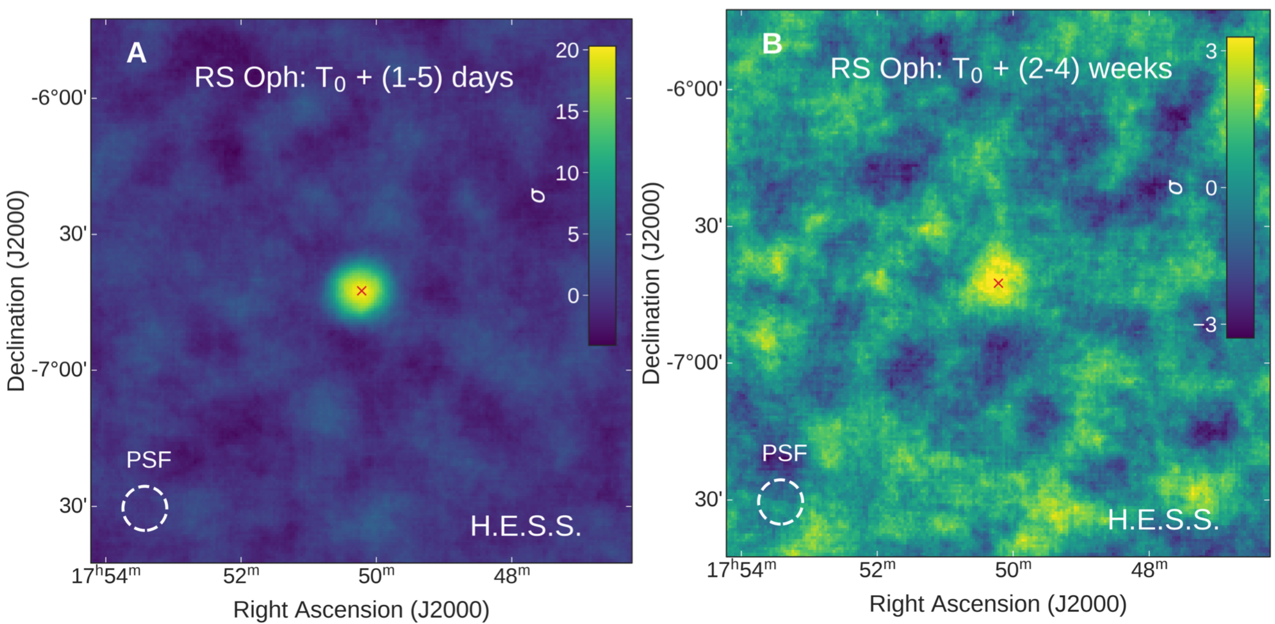
H.E.S.S. detection of RS Oph

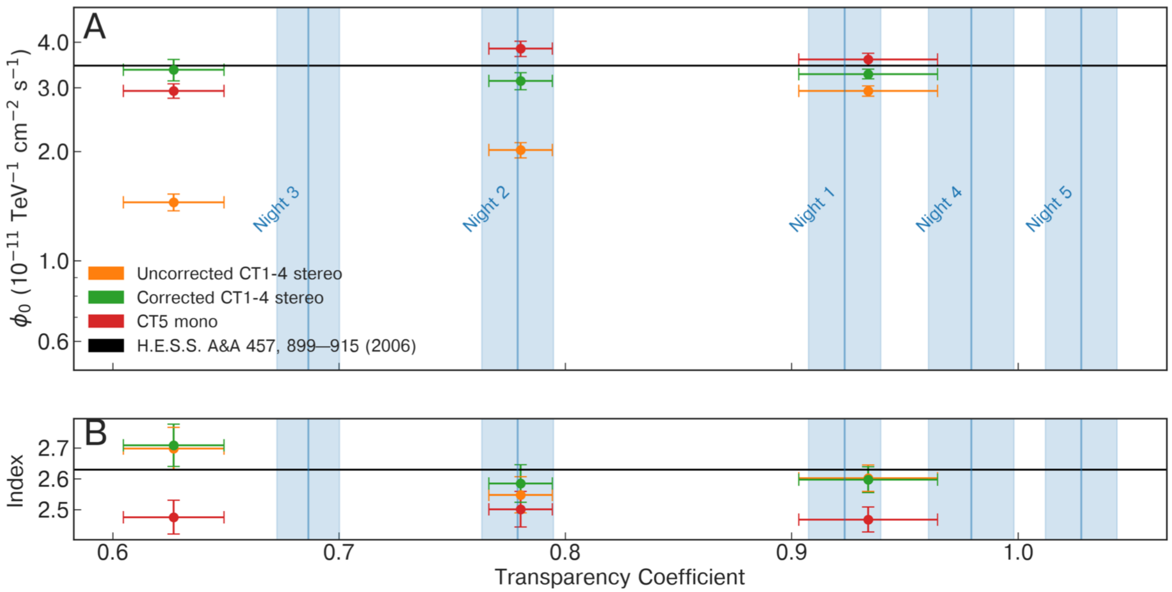
- Detection at > 6 sigma on each night of first five nights
- Signal at ~3 sigma level in ~15 hours of data accumulated between 17 and 31 days post-outburst

Night	T_{obs} (UTC)	Livetime (hours)	Significance (σ)
09 Aug. 2021	18:17:40	3.2	5.8 (6.4)
10 Aug. 2021	17:53:46	3.7 (2.8)	9.0 (7.1)
11 Aug. 2021	17:44:08	3.7	9.8 (9.6)
12 Aug. 2021	18:17:12	2.3	13.6
13 Aug. 2021	17:44:43	2.8	10.5 (9.4)
25 Aug. – 07 Sep. 2021	17:48:03; 19:47:31	14.6 (13.4)	3.3 (2.3)



Atmospheric correction

- Challenging data quality
- Variable and degraded atmospheric transparency
- Correction based on scaling instrument response for the atmospheric transparency
  Hahn et al Astropart. Phys **54** 25-32 (2015)
- Validated on Crab Nebula data
  → reproduces the correct flux

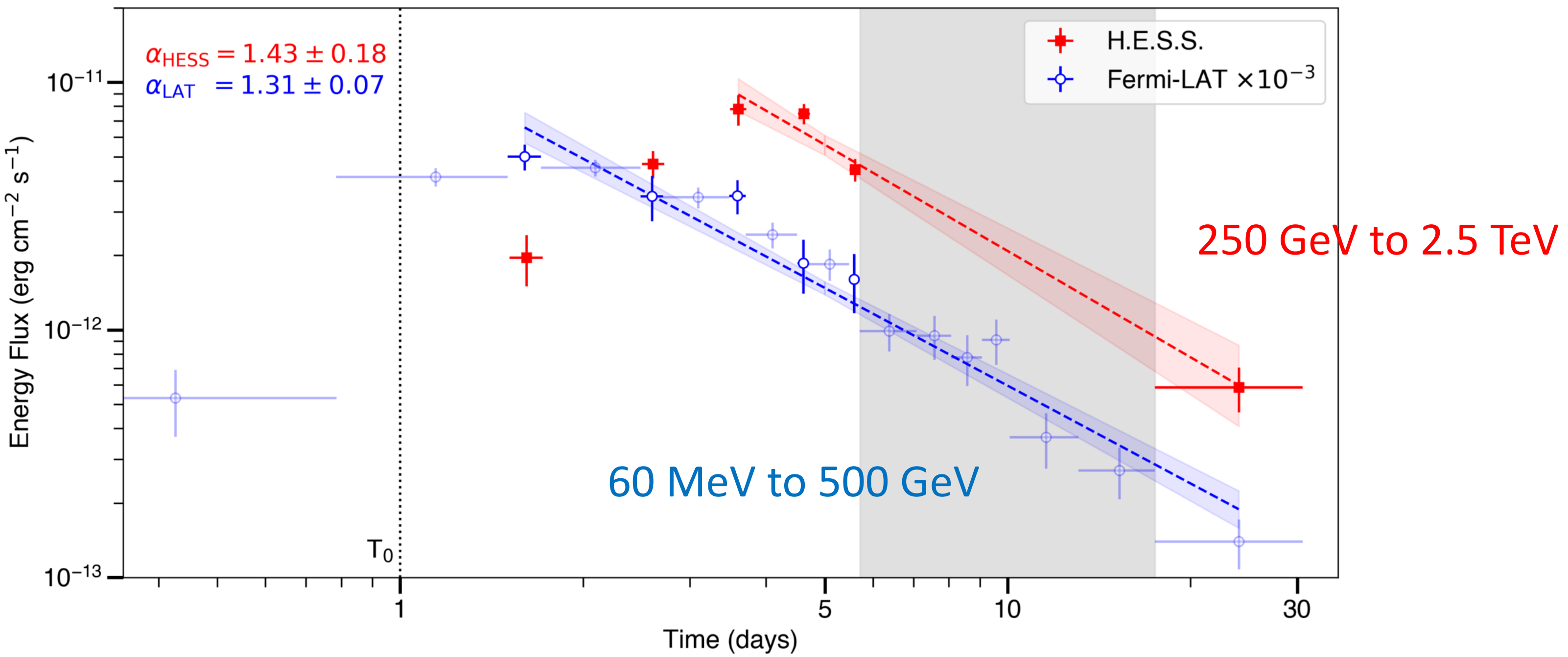


Night	T_{obs} (UTC)	Livetime (hours)	Significance (σ)	Atmospheric transparency	NSB noise level
09 Aug. 2021	18:17:40	3.2	5.8 (6.4)	0.90	1.0
10 Aug. 2021	17:53:46	3.7 (2.8)	9.0 (7.1)	0.80	1.0
11 Aug. 2021	17:44:08	3.7	9.8 (9.6)	0.65	1.0
12 Aug. 2021	18:17:12	2.3	13.6	1.00	1.5
13 Aug. 2021	17:44:43	2.8	10.5 (9.4)	1.10	2.5
25 Aug. – 07 Sep. 2021	17:48:03; 19:47:31	14.6 (13.4)	3.3 (2.3)	0.96	1.0

Gamma-ray flux decay

- Optical peak occurred at T_0 = 59435.25 (MJD)
- Fermi-LAT gamma-ray peak flux
- VHE gamma-ray flux peak seen by H.E.S.S. is delayed by ~ 2 days

- Consistent decay slope after peak flux is attained



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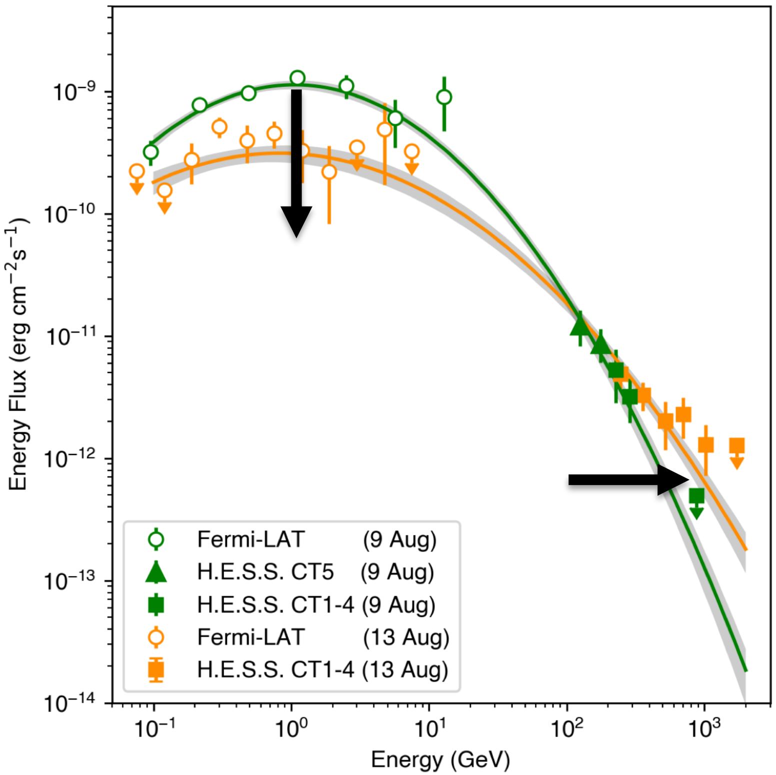

Spectral evolution

- Over the first five days, Fermi-LAT flux reduces and HESS flux hardens
- It takes time to reach the theoretical maximum energy
- Either: cooling limited (leptonic)
- Or: confinement limited (hadronic)

  until particles become sufficiently energetic to escape the shock

$$E_{\max} = 1.5|Z|\left(\frac{\xi_{\rm esc}}{0.01}\right)\left(\frac{\dot{M}/v_{\rm wind}}{10^{11}\ \mathrm{kg\ m^{-1}}}\right)^{1/2}\left(\frac{u_{\rm sh}}{5000\ \mathrm{km\ s^{-1}}}\right)^{2}\ \mathrm{TeV}$$

- For RS Oph:
  E_{max} ~10 TeV for 1% efficiency and

$$\dot{M}/v_{\rm wind} = 6\times10^{11}\ \mathrm{kg\ m^{-1}}$$

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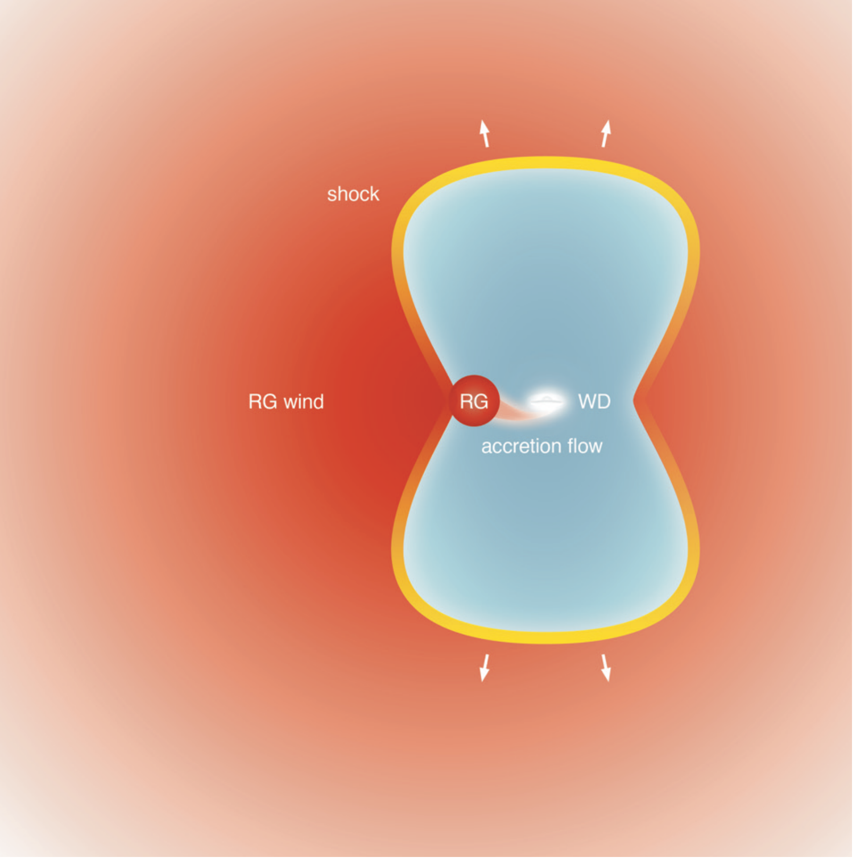
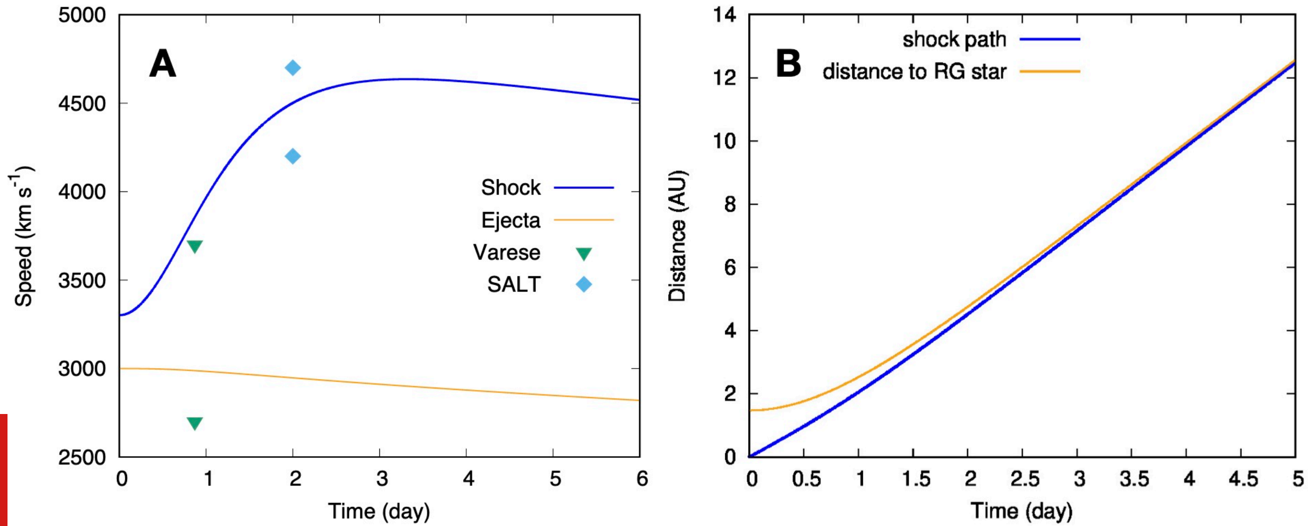


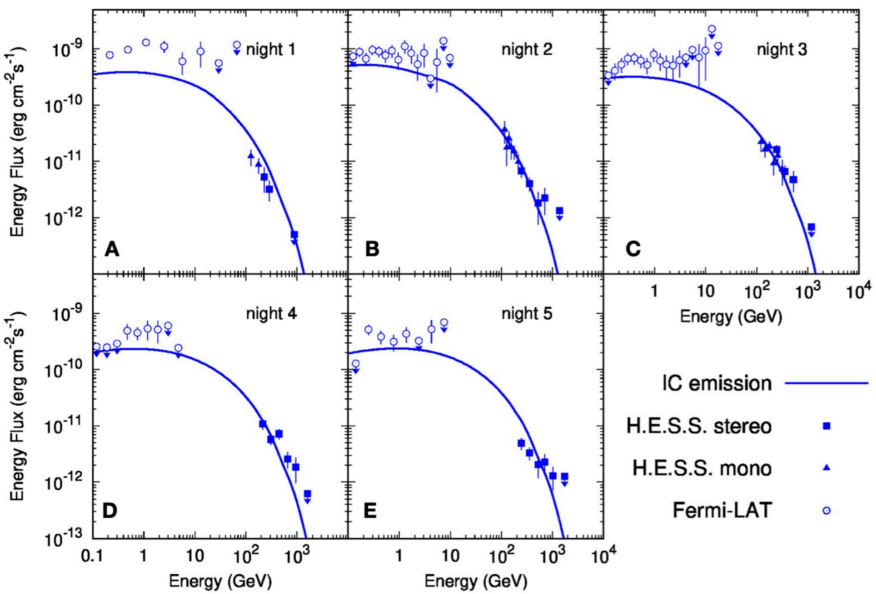
Shock expansion

- Asymmetric expansion (images and interferometric observations post-2006 outburst)
- Fast shock – velocities from spectroscopy.
  From HST images post-2006 outburst, consistently several 1000 km/s over several months



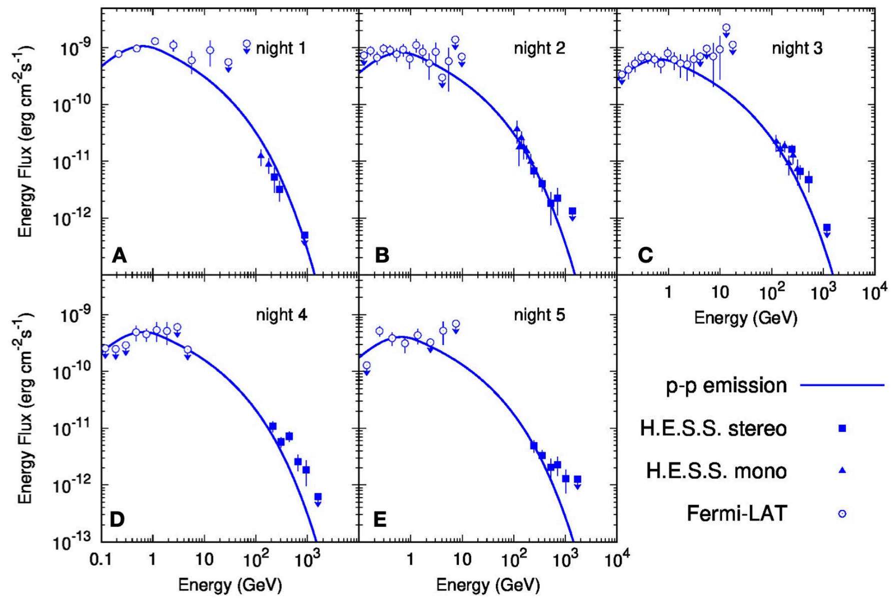
Leptonic scenario

- Inverse Compton scattering
- Need efficient acceleration and scattering
- Need > 1% efficiency
  → cannot be realised
  (e^- to ion ratio << 10^{-2})



Hadronic scenario

- Neutral pion decay
- Need ~10% of energy into accelerating protons



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Interpretation: implications

- Particle acceleration in dense wind environments → ~ a factor 100 x higher energy than seen in previous novae with E_{max} ~1-10 TeV
- Hadronic scenario preferred via energy efficiency arguments
- Resulting local cosmic ray density is ~0.1 eV/cm^3
  → for recurrent novae, quasi-continuous injection could lead to local cosmic ray enhancement
  → provided diffusion coefficient is suppressed compared to Galactic average
- Theoretical limit for maximum energy via diffuse shock acceleration reached.
- If results scale up to supernovae, findings support that PeV cosmic rays originate in supernova remnants

Summary & outlook

https://www.science.org/doi/10.1126/science.abn0567

- The first nova event detected at TeV energies → won't be the last
- Strong signal enables time-resolved analysis

- Rich multiwavelength and multi-instrument dataset

→ Swift, Fermi-LAT, HESS, MAGIC, LST...
→ see e.g. next talk by David Green

- Looking forward to images and results on RS Oph from many facilities in the near future

- Looking forward to many more novae in future, including with CTA...

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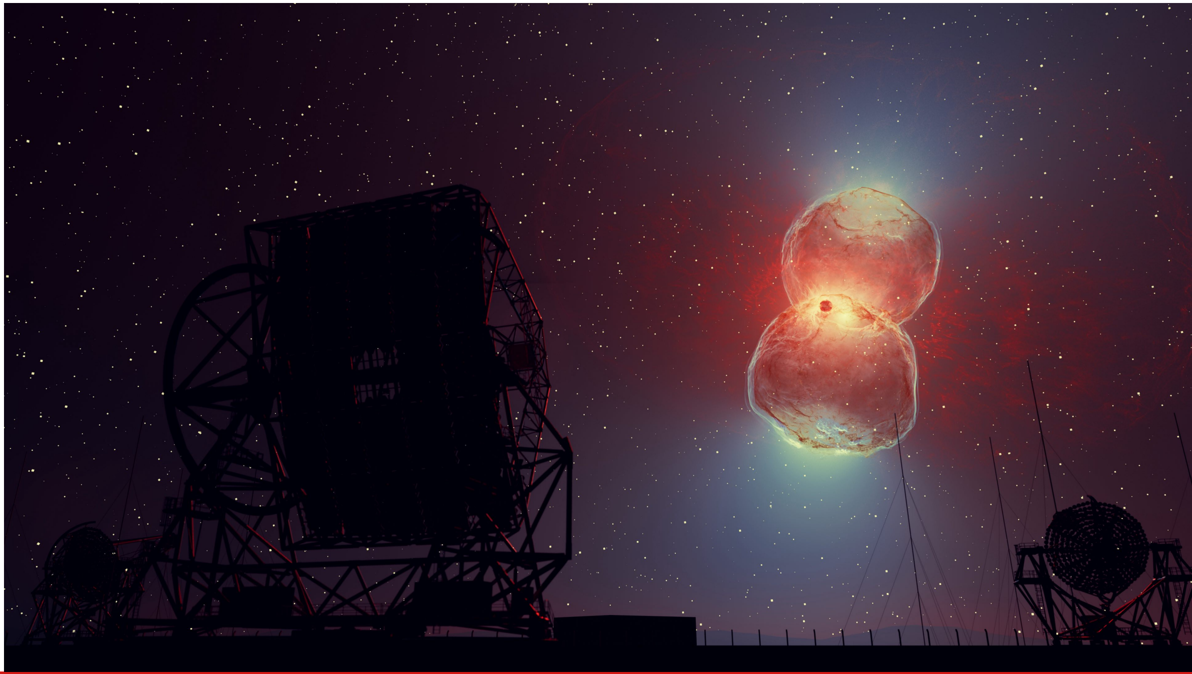

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Thanks for your attention

Any Questions?

Video released for 1 year anniversary:

https://youtu.be/XE3mapcBboc

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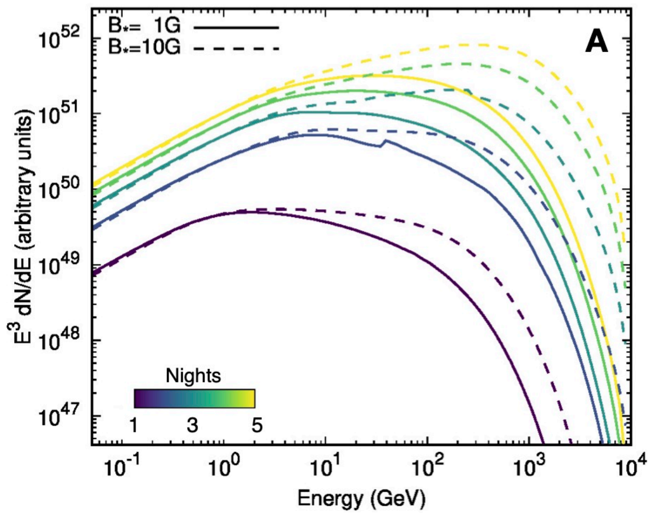
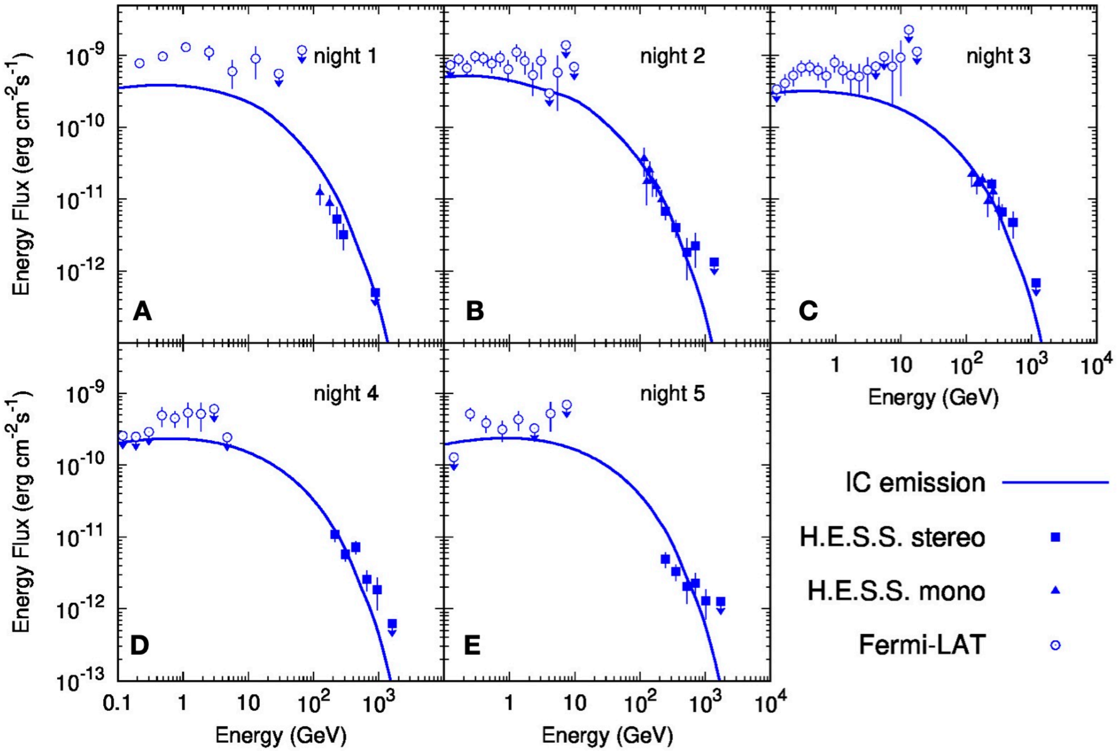
DFG Deutsche Forschungsgemeinschaft
German Research Foundation

Interpretation: leptonic scenario

- Efficient acceleration – close to Bohm limit – required (radiative losses)
- Efficient scattering → strong self-generated magnetic fluctuations
  → an energetic hadronic component.
- Peak delay due to energy-dependent cooling rates in time-dependent photon fields
- Need > 1% energy into electrons





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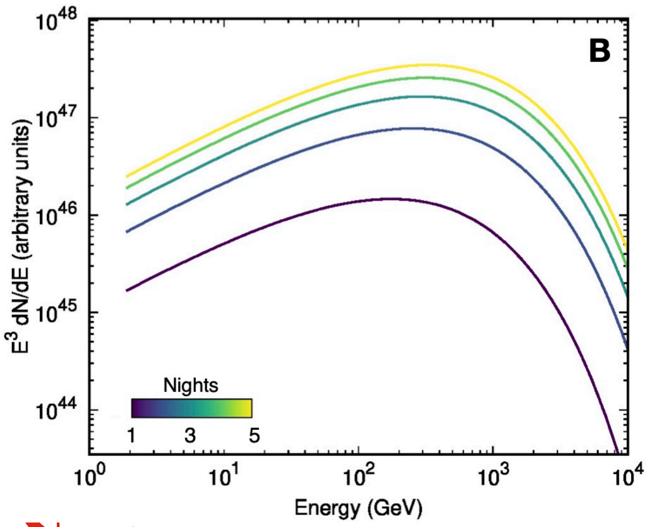
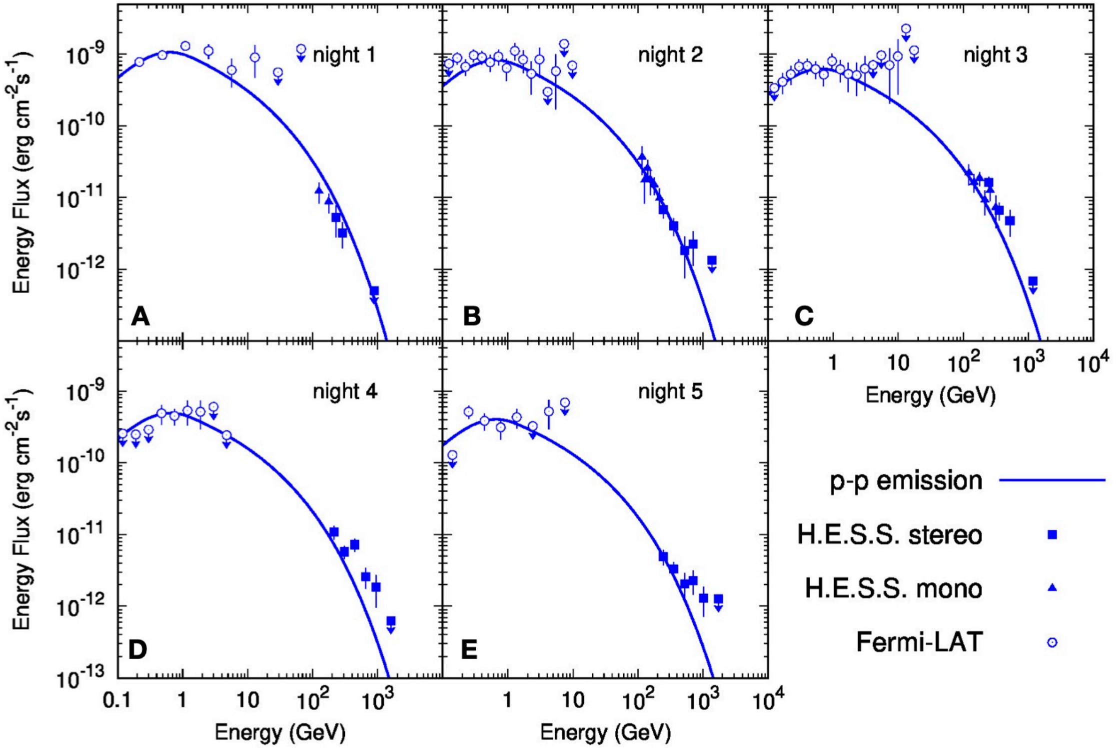
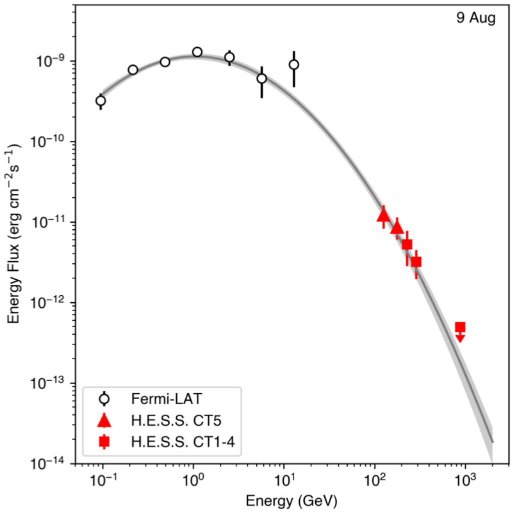
Interpretation: hadronic scenario

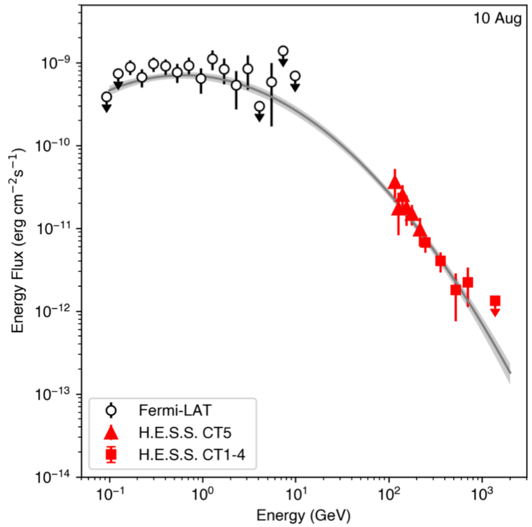
- Expanding shock in decreasing density profile
- ~10% of energy goes into accelerating protons
- Peak delay due to finite acceleration time of > 1 TeV protons
- cf > 1% energy into electrons
  but e^- to ion ratio << 10^{-2}
- >1% efficiency cannot be realised
- Prefer hadronic scenario

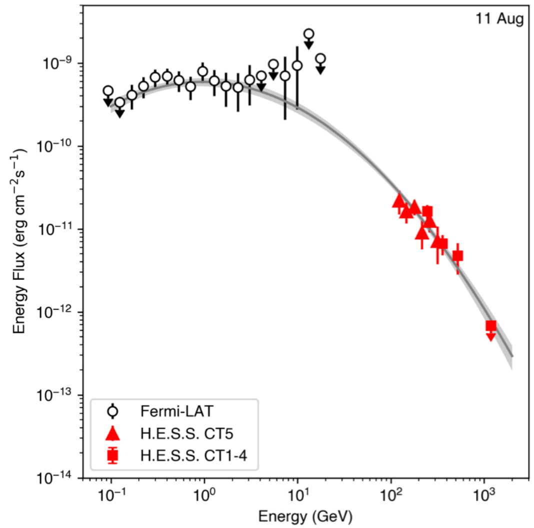




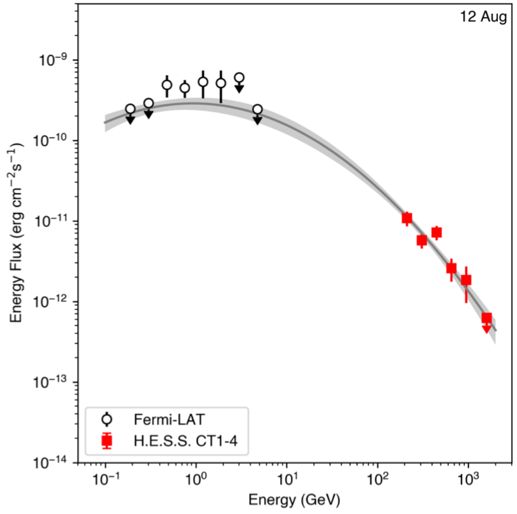
Spectral evolution

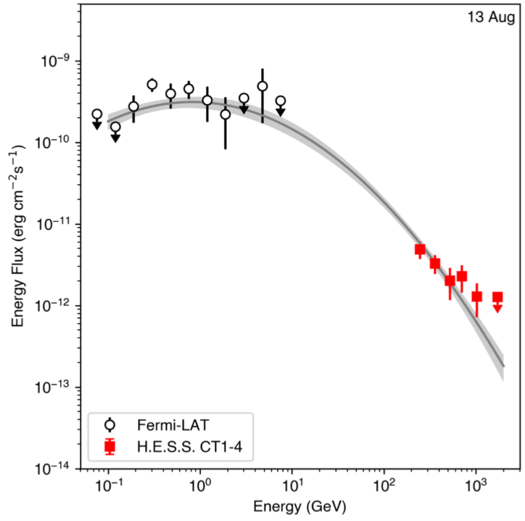


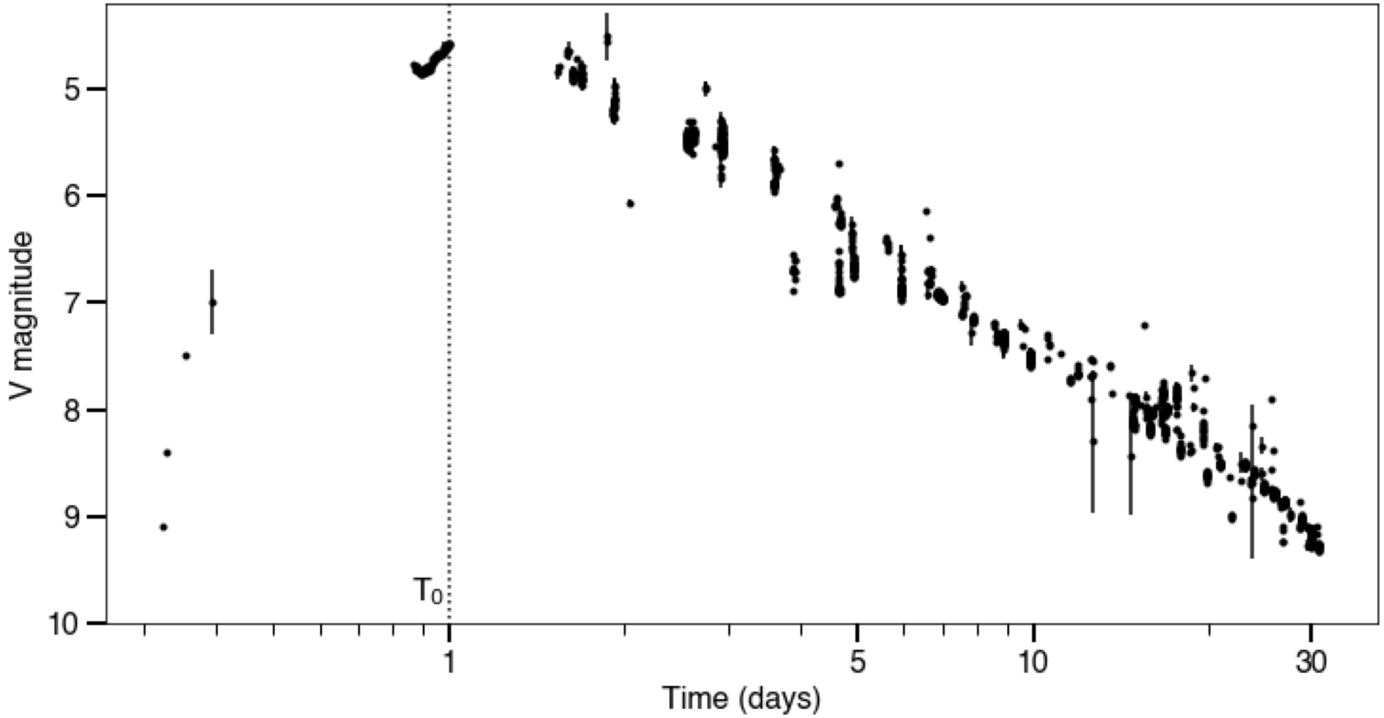




Data set	ϕ_0 [10^{-4} TeV^{-1} cm^{-2} s^{-1}]	E_0 [GeV]	α	β
09 Aug. 2021	7.06 ± 0.58	1.0	1.98 ± 0.04	0.19 ± 0.01
10 Aug. 2021	4.27 ± 0.43	1.0	2.12 ± 0.05	0.13 ± 0.01
11 Aug. 2021	3.69 ± 0.42	1.0	2.01 ± 0.06	0.13 ± 0.01
12 Aug. 2021	1.79 ± 0.32	1.0	2.02 ± 0.09	0.11 ± 0.02
13 Aug. 2021	1.94 ± 0.32	1.0	2.05 ± 0.07	0.12 ± 0.02







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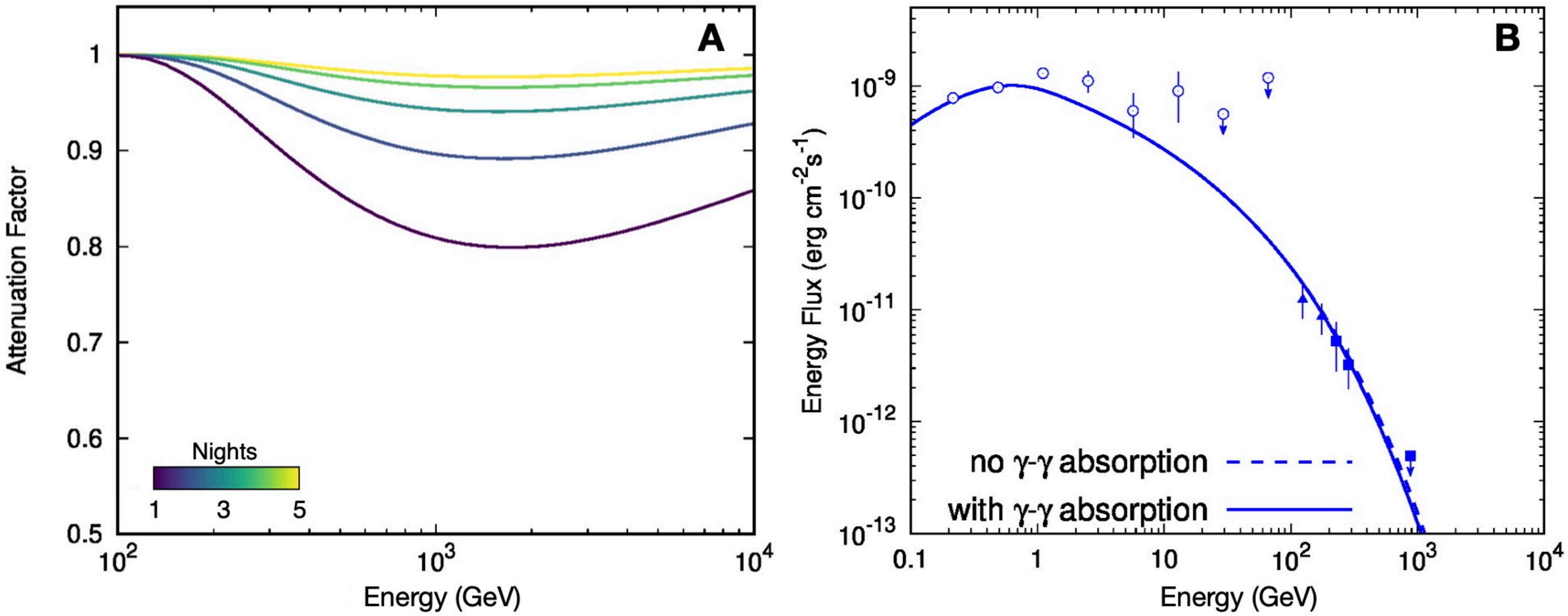
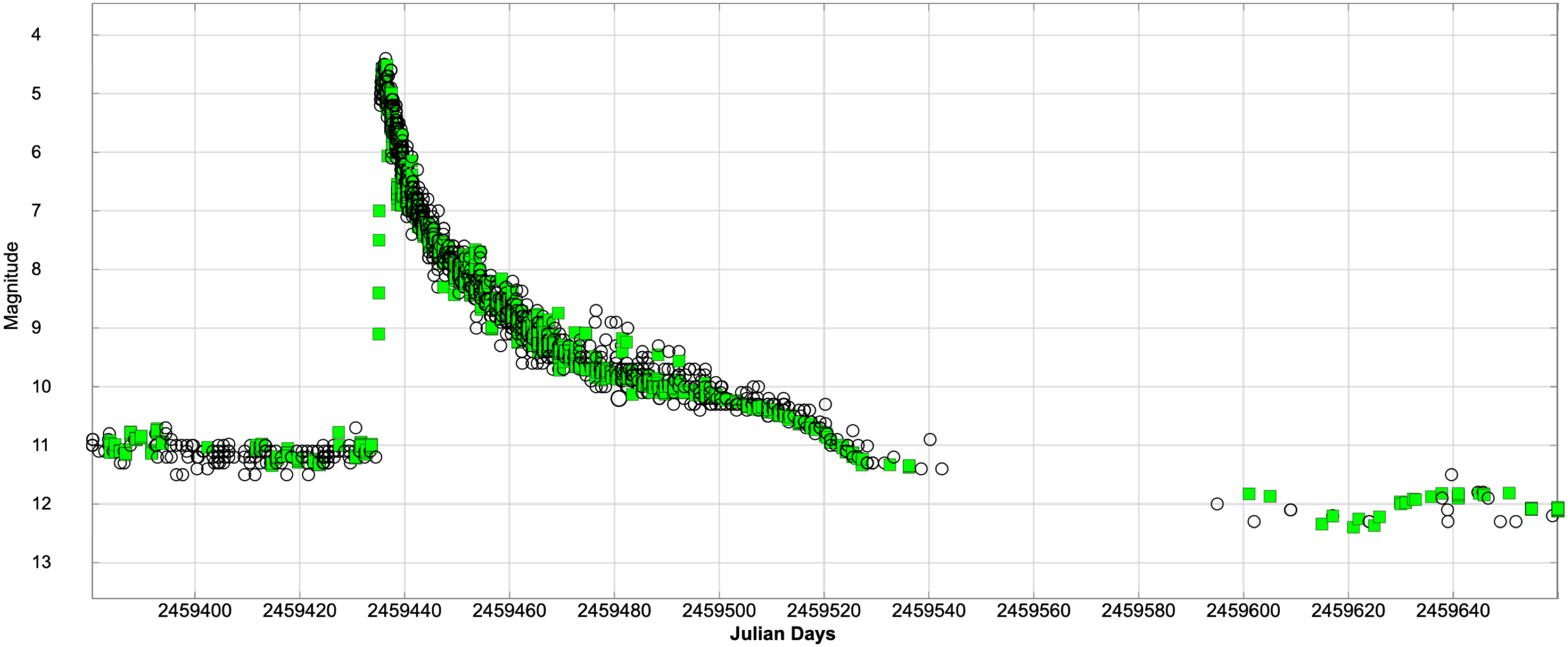
Gamma-gamma attenuation

- For the adopted distance of 1.4 kpc
- Attenuation due to nova photon fields is insufficient to account for the observed spectral hardening (minor below ~ 1TeV)



AAVSO


Magnitude
4
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2459540
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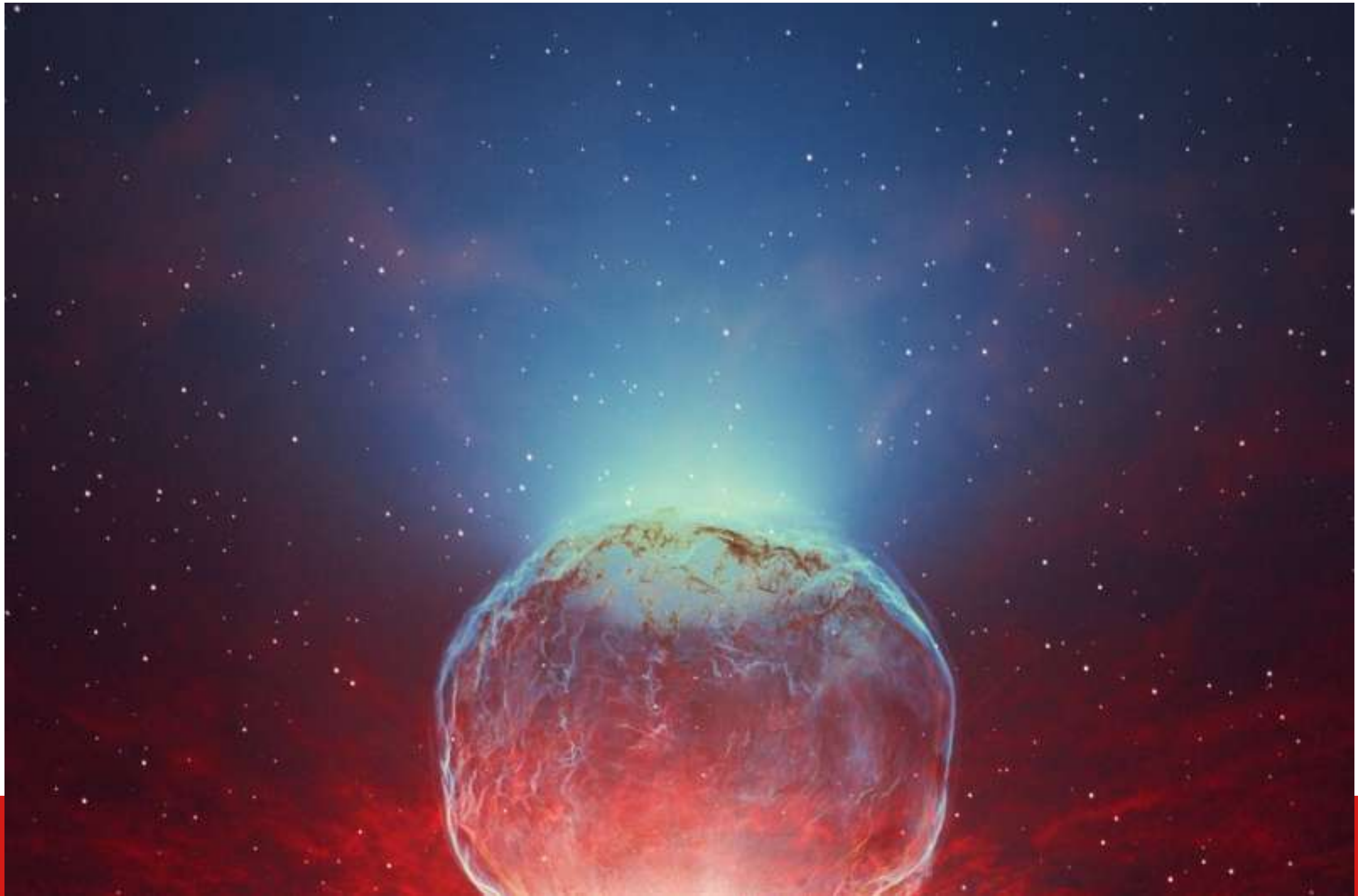
2459600
2459620
2459640
Julian Days

- Visuals motivated by:
  Booth et al. MNRAS **457** 822-835 (2016)



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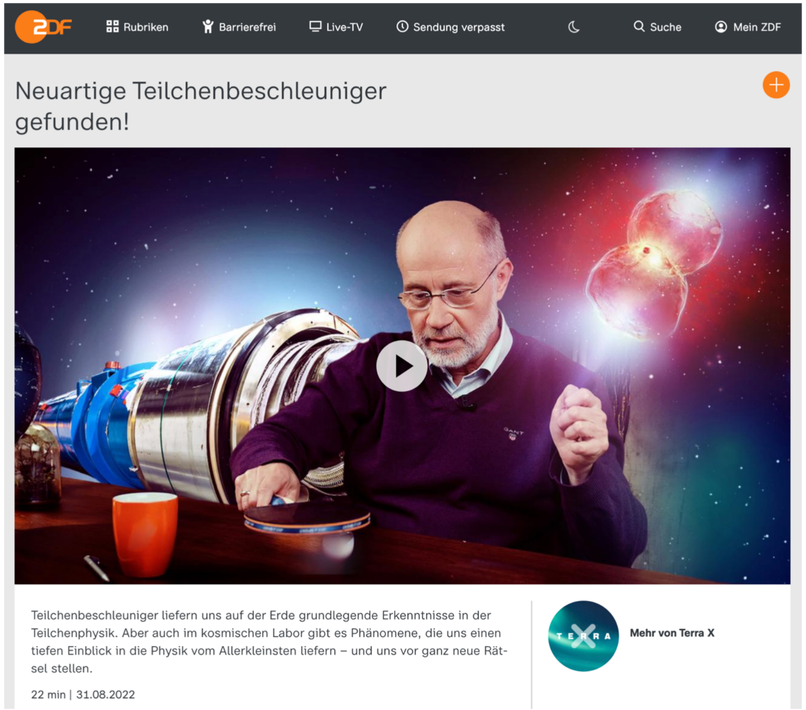

https://www.zdf.de/dokumentation/terra-x/lesch-und-co-neuartige-teilchenbeschleuniger-gefunden-100.html#xtor=CS5-95#xtor=CS5-95

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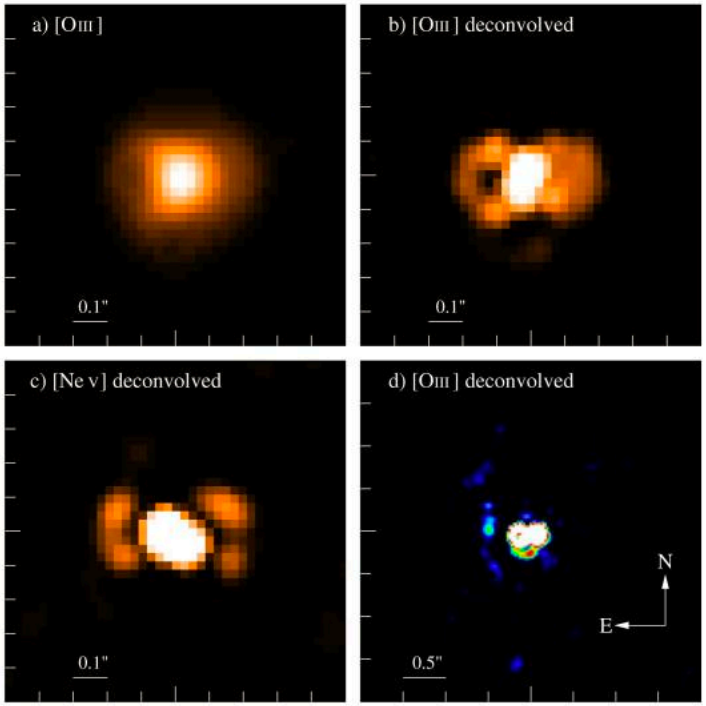

Figure 1. *HST* ACS/HRC narrow-band Epoch 1 images of RS Oph. (a) PSF-subtracted [O III] λ5007 Å image clearly showing extended emission at subarcsecond size scales particularly in the east-west direction; (b) results of deconvolution of the [O III] λ5007 Å RS Oph PSF-subtracted image with the PSF star, showing a double ring structure; (c) same as (b), but for [Ne V] λ3426 Å and using a TinyTim PSF; (d) deeper, larger area view of (b), showing an arc-like feature to the east and a southern blob of emission.