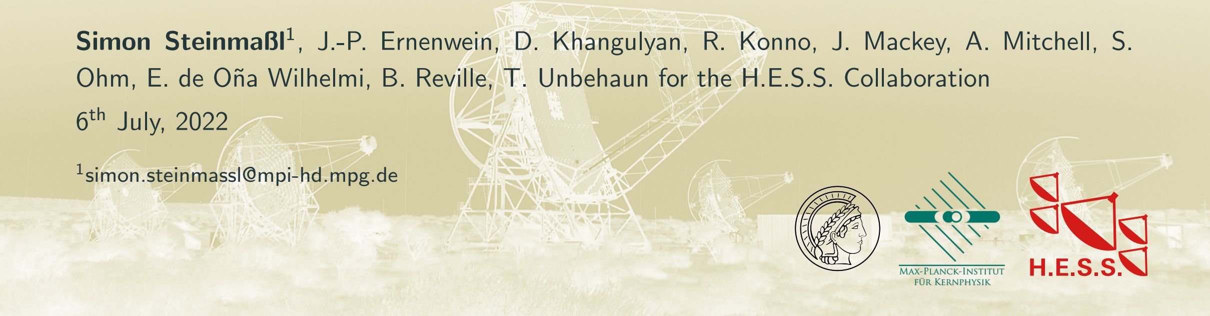
Revealing time-resolved particle acceleration in the recurrent Nova RS Ophiuchi

7th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy

Simon Steinmaßl[1], J.-P. Ernenwein, D. Khangulyan, R. Konno, J. Mackey, A. Mitchell, S. Ohm, E. de Oña Wilhelmi, B. Reville, T. Unbehaun for the H.E.S.S. Collaboration

6th July, 2022

[1]simon.steinmassl@mpi-hd.mpg.de



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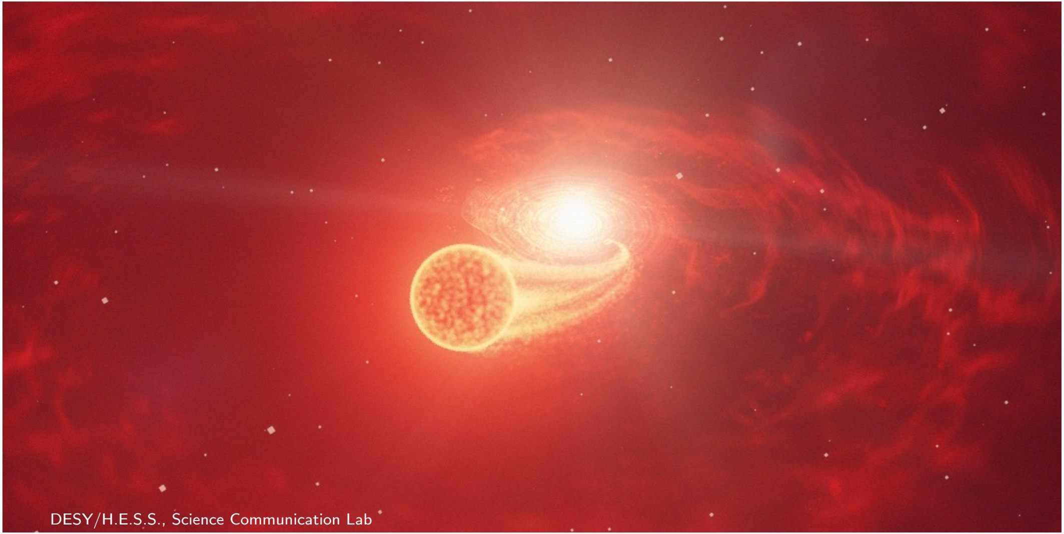
H.E.S.S.

RS Ophiuchi - First nova detected in very high energies (VHE)

DESY/H.E.S.S., Science Communication Lab

RS Ophiuchi - A white dwarf - red giant accreting binary system



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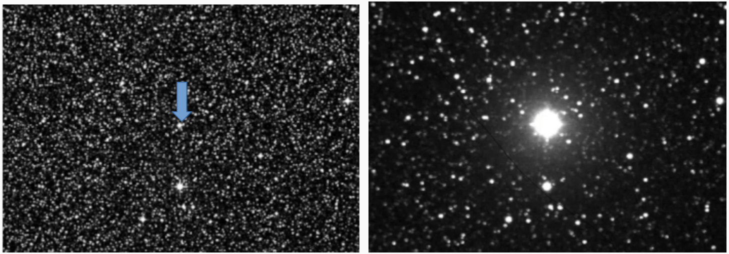
RS Ophiuchi -The 2021 outburst



https://skyandtelescope.org/astronomy-news/recurrent-nova-rs-ophiuchi-just-blew-its-top/

- $\sim$ 1.4 kpc from Earth (Barry et al., 2008)
- Reports of a new outburst on 8th Aug 2021, 22:20 UTC (AAVSO)

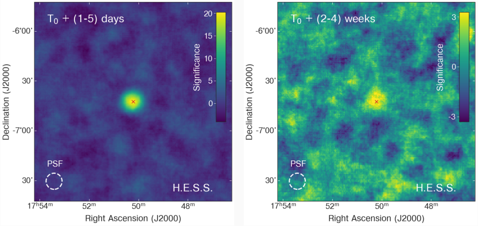
H.E.S.S. Nova ToO	Criterion	RS Oph
Ejecta velocity	$\geq$ 1500 km/s	$\geq$ 2600 km/s (Atel #14838) ✓
Visual magn.	$m_v \leq 9$	$m_v = 4.5$ (AAVSO) ✓
Fermi LAT det.	Yes	6σ (ATel #14834) ✓

Trigger

H.E.S.S. observations starting on 9th Aug, 18:17 UTC

RS Ophiuchi - H.E.S.S. detection results

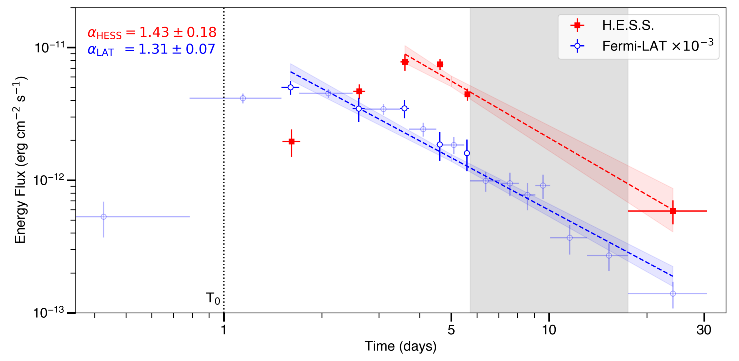
Night	T_{obs} (UTC)	Livetime (hours)	Significance (σ)
09 Aug. 2021	18:17:40	3.2	5.8 (6.4)
10 Aug. 2021	17:53:46	3.7 (2.8)	9.0 (7.1)
11 Aug. 2021	17:44:08	3.7	9.8 (9.6)
12 Aug. 2021	18:17:12	2.3	13.6
13 Aug. 2021	17:44:43	2.8	10.5 (9.4)
25 Aug. – 07 Sep. 2021	17:48:03; 19:47:31	14.6 (13.4)	3.3 (2.3)



H.E.S.S. Collaboration, 2022 (`https://doi.org/10.1126/science.abn0567`)

- Independent analysis in
  - Stereo with the four 12m telescopes
  - Mono with the 28m telescope (upgraded in 2019)
- Detection in real time analysis triggered observations in the following nights (Atel #14844)
- Detected by H.E.S.S. in each of the first 5 nights individually - followed by observation break due to moon
- Observations again from 25th Aug to 7th Sep
- 3 sigma signal in cumulated nights after the moon break

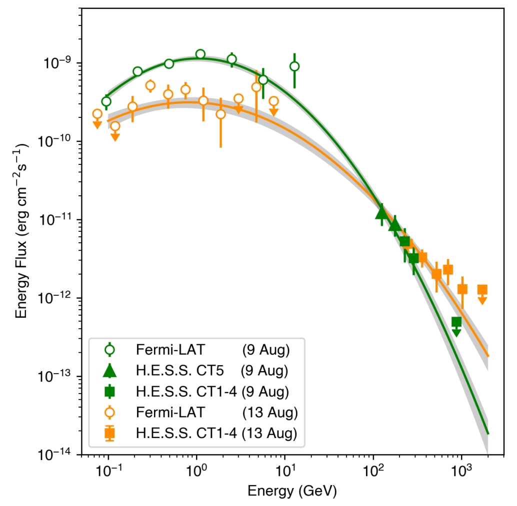
RS Ophiuchi - Light curve results



H.E.S.S. Collaboration, 2022

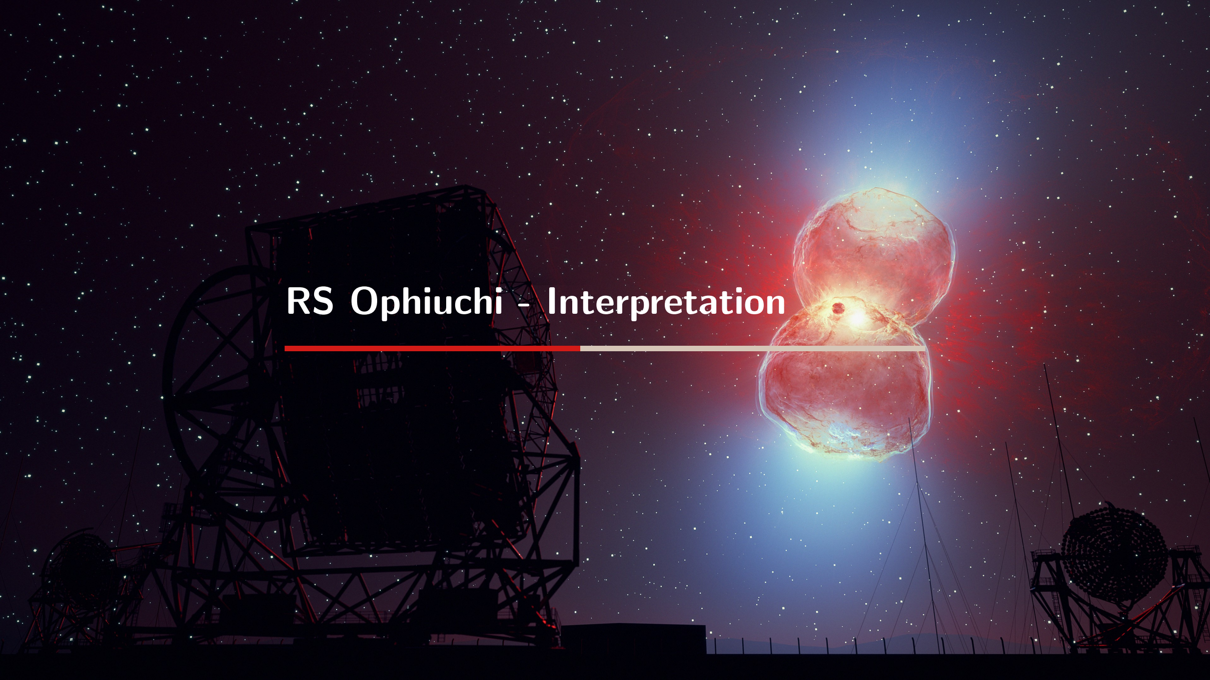
- H.E.S.S. flux between 250 GeV and 2.5 TeV
- Fermi flux between 60 MeV and 500 GeV
- Peak H.E.S.S. flux:
  - 3 days after optical peak (T_0)
  - 2 days after Fermi LAT maximum
- Comparable decay slope
- γ-ray emission still visible after $\sim$ 20 days

RS Ophiuchi - Spectral results



- Combined spectral fits to Fermi and H.E.S.S. data on nights 1-5 individually (with log-parabola)
- Smooth spectral behaviour over whole energy range
- General trend: (Fermi) flux level decreases, parabola widens
- Light curve and spectrum suggest single component for gamma rays for the whole time span

H.E.S.S. Collaboration, 2022



RS Ophiuchi - Interpretation

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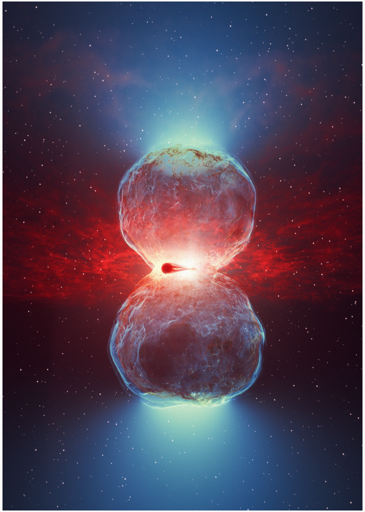


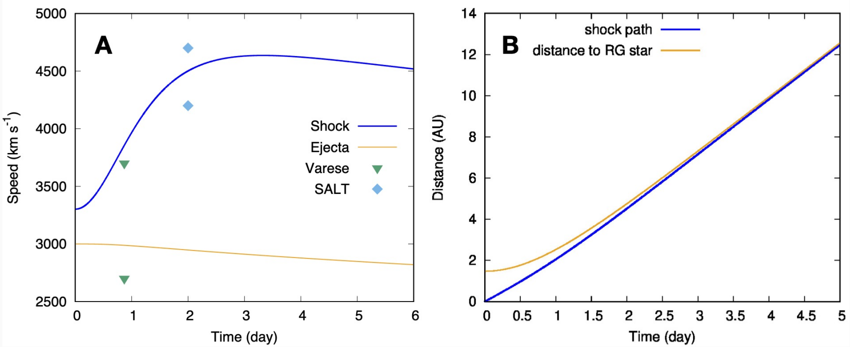
- Shock velocity: 4000 – 5000 $\mathrm{km/s}$ for first week from spectroscopy (ATel #14852)
- Consistent with observations from 2006 outburst (for several months)
- Quasi-spherical shock
  - Expanding into the open wind of the red giant
  - Pinched at binary orbital plane (Booth et al., 2016)

→ Particles undergo diffusive shock acceleration

Image Credit: DESY/H.E.S.S., Science Communication Lab

RS Ophiuchi - 1D hydrodynamical model

- Describes motion of ejecta and dynamics of forward shock (radius & speed)
- Changing enviroment (e.g. decreasing upstream density)
- Hadronic & leptonic scenario tested with single-zone model



H.E.S.S. Collaboration, 2022

RS Ophiuchi - Maximum energy

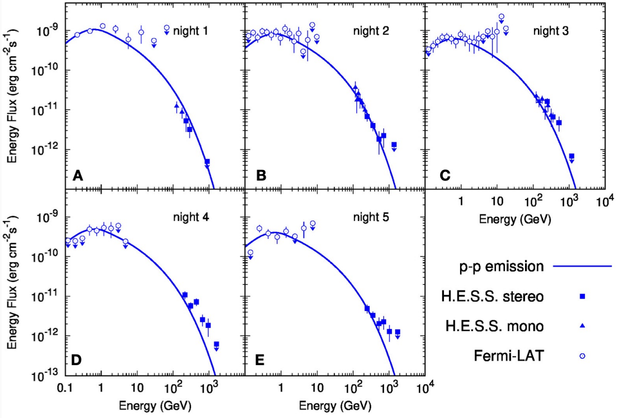
Confinement limit (Bell et al. 2013)

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

- Efficiency parameter ξ_{esc}: fraction of energy density flux processed by the shock & lost to the upstream escaping energetic particles - typically $\sim 1\%$
- $\dot{M}$ mass-loss rate, v_{wind} wind velocity of red giant, u_{sh} shock velocity
- For RS Oph: $\dot{M}/v_{\mathrm{wind}} = 6 \times 10^{11}\,\mathrm{kg\,m^{-1}}$, $u_{\mathrm{sh}} = 4000 - 5000\ \mathrm{km\ s^{-1}}$

$\Rightarrow E_{max} \approx 1 - 10$ TeV

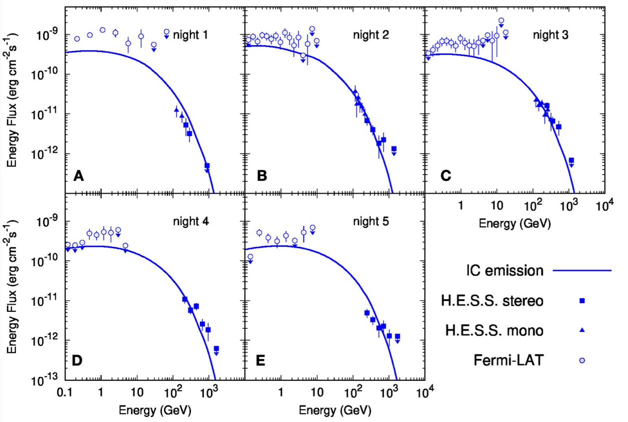
RS Ophiuchi - Hadronic scenario



H.E.S.S. Collaboration, 2022

- Confinement limit is the dominant constraint for protons
- Measured fluxes imply $> 10\%$ of internal energy to accelerate protons
- Delay in Fermi vs. H.E.S.S. peak = finite acceleration time
- Hadronic model consistent with spectral evolution observed

RS Ophiuchi - Leptonic scenario



H.E.S.S. Collaboration, 2022

- Electron acceleration must overcome strong radiative (IC) losses
- Difference in Fermi vs. H.E.S.S. spectral slopes due to energy dependent cooling rates
- BUT: Requires efficiency $> 1\%$ - significantly higher than theories of injection at high-Mach number shocks predict (e.g. Malkov & Drury, 2001)

Conclusion

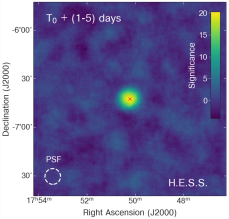
Hadronic scenario preferred

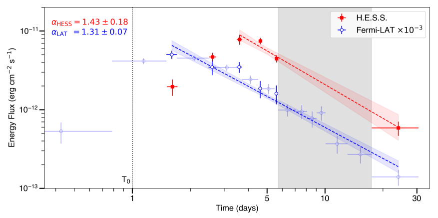
RS Ophiuchi - VHE implications

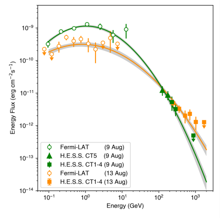
- Acceleration to TeV energies possible in novae! (1st time observed)
- Total energy release: $\sim 10^{43}$ erg with large fraction converted to relativistic protons & heavier nuclei
- In case of RS Oph: recurrent injection of cosmic rays could lead to local CR enhancement
- But contribution of novae sub-dominant to average Galactic cosmic ray population
- Theoretical limit for maximum energy via diffuse shock acceleration reached
- Extremely efficient accelerator → if extrapolated could explain PeV cosmic rays from supernovae

RS Ophiuchi - Conclusions & outlook

- First nova seen in the VHE regime - hopefully more to come!
- Strong signal allows time resolved analysis
- Combined Fermi & H.E.S.S. analysis suggests single component for gamma rays
- Gamma ray emission with
  - Most likely hadronic origin
  - Extremely efficient acceleration to $E_{max} \approx 1 - 10$ TeV



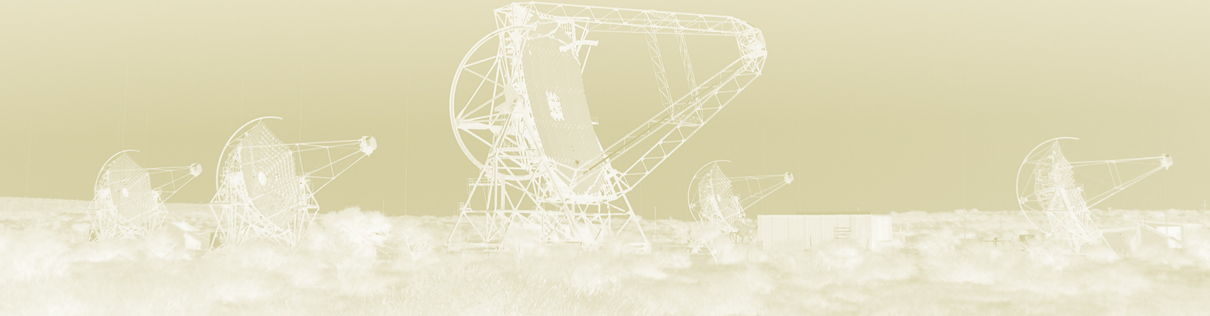




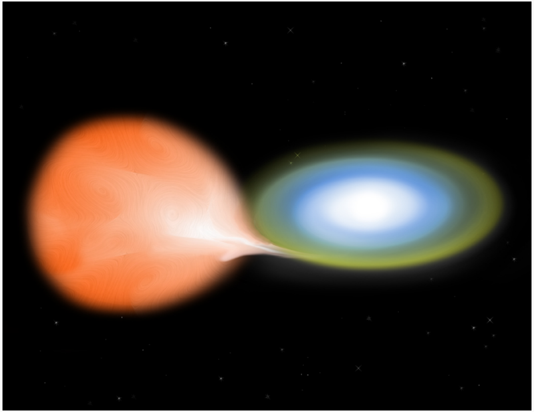
Thanks for listening!

Any Questions?

Backup



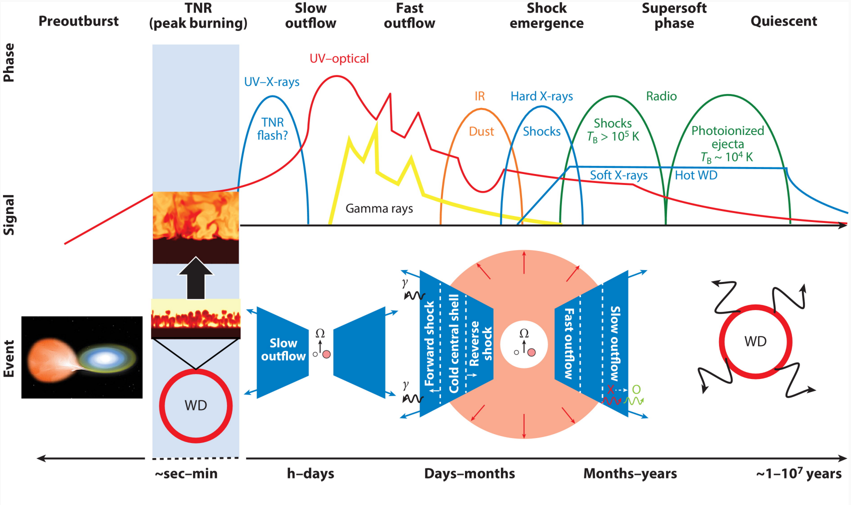
Backup slides - Novae



Credit: NASA/CXC/M.Weiss

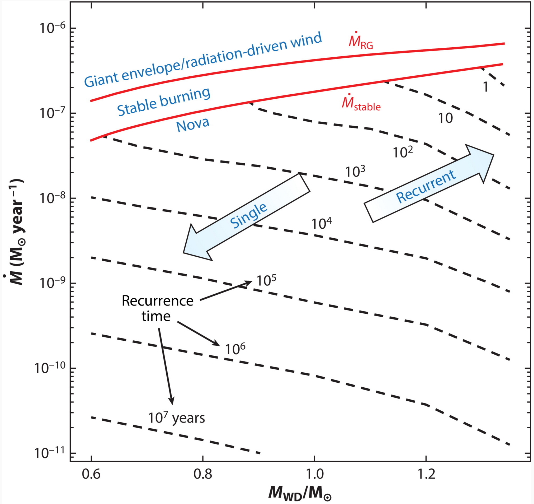
- Prerequisites:
  - Binary system of white dwarf and stellar companion (cataclysmic variables or symbiotic binaries)
  - Accretion flow from companion to WD
  - Accumulation of accreted layer on surface of WD
- Eruption due to (runanway) thermonuclear fusion of accreted material
- Eventual ejection of accreted layer
- Can be recurrent process

Backup slides - Nova schematic timeline



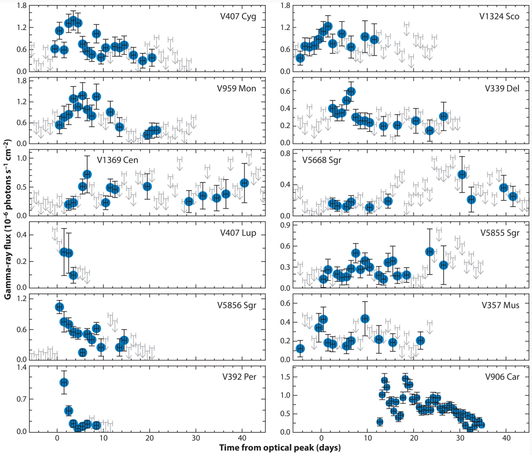
Chomiuk L, et al. 2021
Annu. Rev. Astron. Astrophys. 59:391–444

Backup slides - Recurrence



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

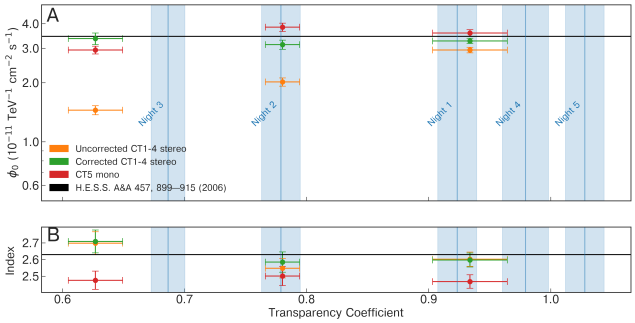
Backup slides - Fermi-LAT detections of novae



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

- Standard picture: thermal emission as driving force
- First detection of nova by Fermi LAT in 2010 - big surprise
- Fermi LAT has detected 17 novae so far → there must be non thermal processes / shocks involved
- Typical cut-off at 1-10 GeV & lasting up to a few weeks

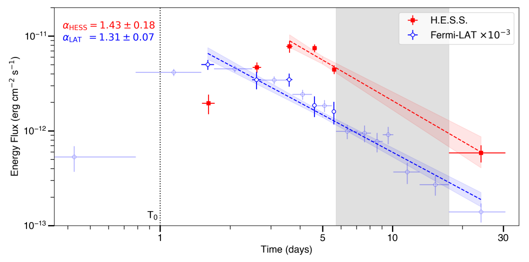
Backup Slides - Analysis challenges

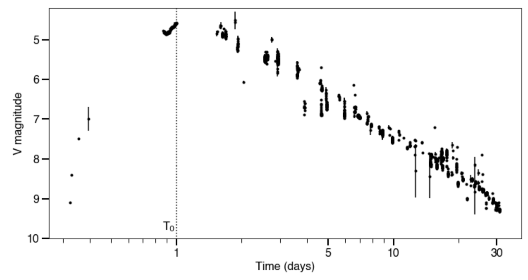


H.E.S.S. Collaboration, 2022

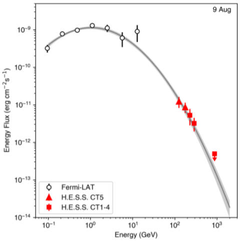
- Challenging analysis due to
  - non optimal & varying atmospheric conditions
  - varying night sky background
- Correction scheme using the atmospheric transparency coefficient
- Checks on Crab run lists categorized by atmospheric transparencies
  → correction validated

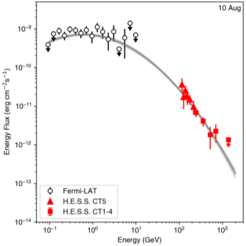
Backup slides - LC with optical

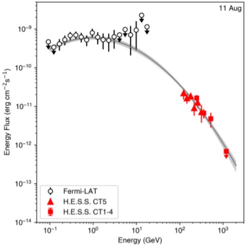


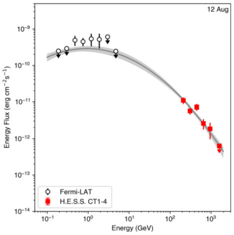


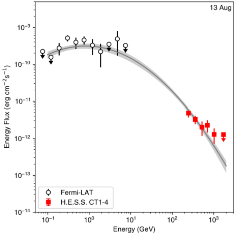
Backup slides - Spectral Evolution

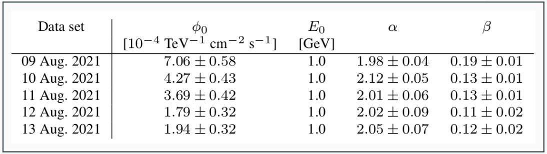






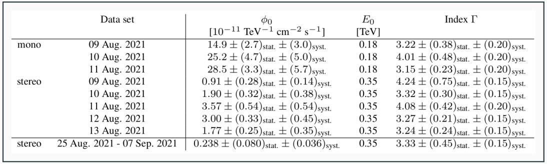






Data set	ϕ_0 [10^{-4} TeV^{-1} cm^{-2} s^{-1}]	E_0 [GeV]	α	β
09 Aug. 2021	7.06 ± 0.58	1.0	1.98 ± 0.04	0.19 ± 0.01
10 Aug. 2021	4.27 ± 0.43	1.0	2.12 ± 0.05	0.13 ± 0.01
11 Aug. 2021	3.69 ± 0.42	1.0	2.01 ± 0.06	0.13 ± 0.01
12 Aug. 2021	1.79 ± 0.32	1.0	2.02 ± 0.09	0.11 ± 0.02
13 Aug. 2021	1.94 ± 0.32	1.0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

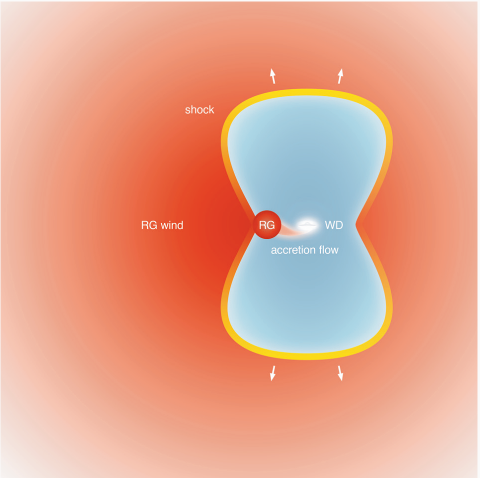
Fermi + H.E.S.S.



Data set		ϕ_0 [10^{-11} TeV^{-1} cm^{-2} s^{-1}]	E_0 [TeV]	Index Γ
mono	09 Aug. 2021	$14.9 \pm (2.7)_{\rm stat.} \pm (3.0)_{\rm syst.}$	0.18	$3.22 \pm (0.38)_{\rm stat.} \pm (0.20)_{\rm syst.}$
	10 Aug. 2021	$25.2 \pm (4.7)_{\rm stat.} \pm (5.0)_{\rm syst.}$	0.18	$4.01 \pm (0.48)_{\rm stat.} \pm (0.20)_{\rm syst.}$
	11 Aug. 2021	$28.5 \pm (3.3)_{\rm stat.} \pm (5.7)_{\rm syst.}$	0.18	$3.15 \pm (0.23)_{\rm stat.} \pm (0.20)_{\rm syst.}$
stereo	09 Aug. 2021	$0.91 \pm (0.28)_{\rm stat.} \pm (0.14)_{\rm syst.}$	0.35	$4.24 \pm (0.75)_{\rm stat.} \pm (0.15)_{\rm syst.}$
	10 Aug. 2021	$1.90 \pm (0.32)_{\rm stat.} \pm (0.38)_{\rm syst.}$	0.35	$3.32 \pm (0.30)_{\rm stat.} \pm (0.15)_{\rm syst.}$
	11 Aug. 2021	$3.57 \pm (0.54)_{\rm stat.} \pm (0.54)_{\rm syst.}$	0.35	$4.08 \pm (0.42)_{\rm stat.} \pm (0.20)_{\rm syst.}$
	12 Aug. 2021	$3.00 \pm (0.33)_{\rm stat.} \pm (0.45)_{\rm syst.}$	0.35	$3.27 \pm (0.21)_{\rm stat.} \pm (0.15)_{\rm syst.}$
	13 Aug. 2021	$1.77 \pm (0.25)_{\rm stat.} \pm (0.35)_{\rm syst.}$	0.35	$3.24 \pm (0.24)_{\rm stat.} \pm (0.15)_{\rm syst.}$
stereo	25 Aug. 2021 - 07 Sep. 2021	$0.238 \pm (0.080)_{\rm stat.} \pm (0.036)_{\rm syst.}$	0.35	$3.33 \pm (0.45)_{\rm stat.} \pm (0.15)_{\rm syst.}$

H.E.S.S. only

Backup slides - Model schematic



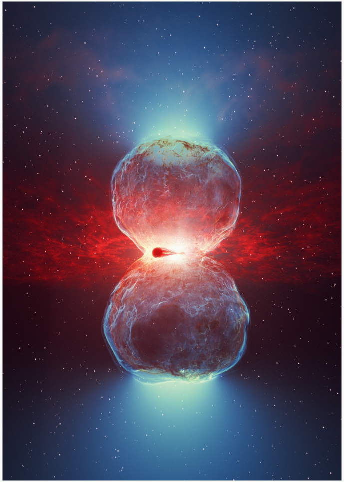
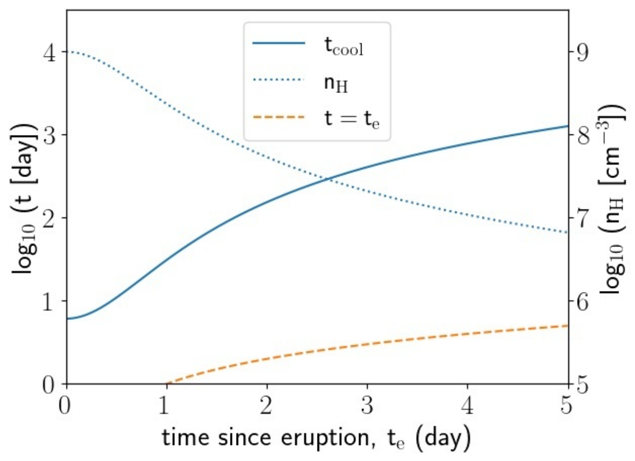


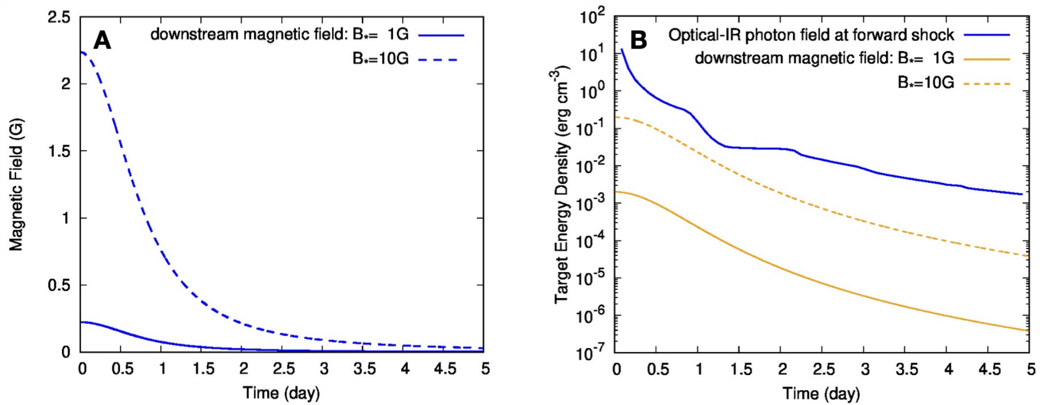
Image Credit: H.E.S.S.,2022 & DESY/H.E.S.S., Science Communication Lab

Backup slides - Cooling times



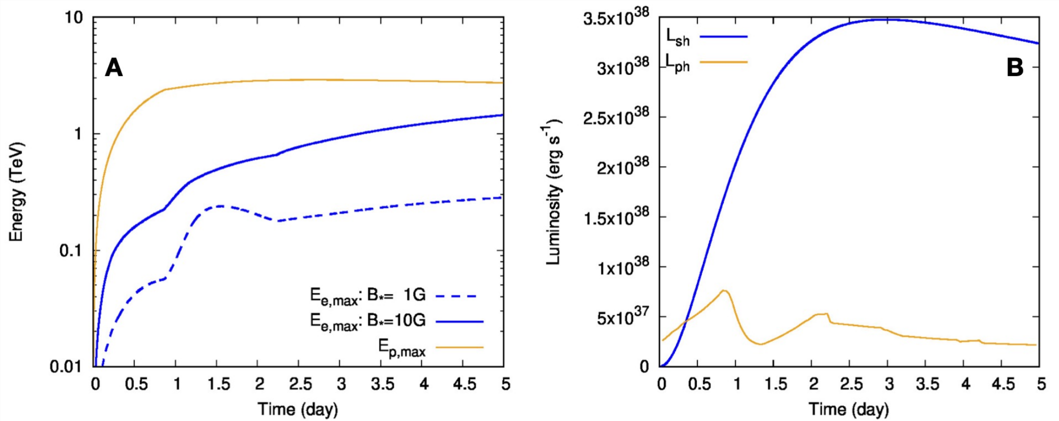
H.E.S.S. Collaboration, 2022

Backup slides - Magnetic field and photon field evolution



H.E.S.S. Collaboration, 2022

Backup slides - Particle energy and luminosity evolution

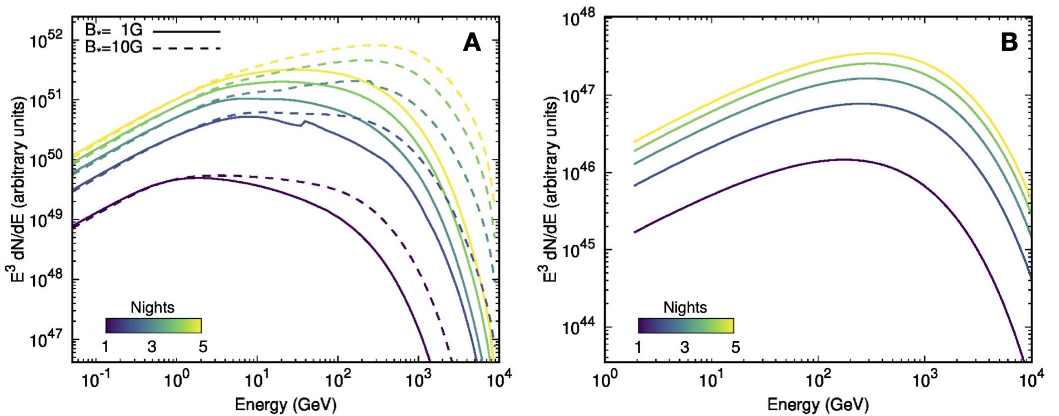


H.E.S.S. Collaboration, 2022

Backup slides - Particle spectra evolution

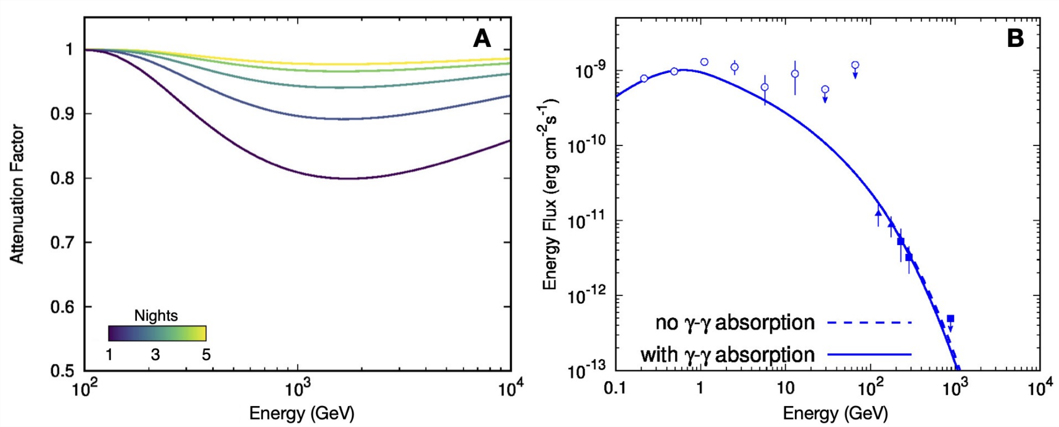
Electrons

Protons



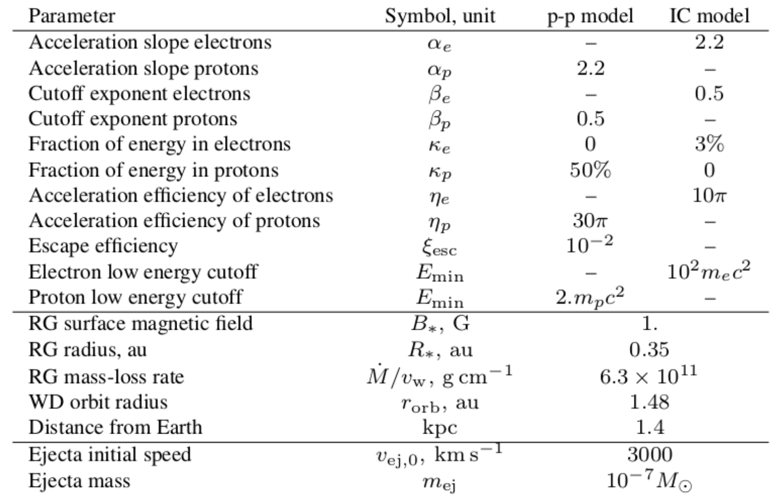
H.E.S.S. Collaboration, 2022

Backup slides - Attenuation



H.E.S.S. Collaboration, 2022

Backup slides - Model parameters



Parameter	Symbol, unit	p-p model	IC model
Acceleration slope electrons	α_e	–	2.2
Acceleration slope protons	α_p	2.2	–
Cutoff exponent electrons	β_e	–	0.5
Cutoff exponent protons	β_p	0.5	–
Fraction of energy in electrons	κ_e	0	3%
Fraction of energy in protons	κ_p	50%	0
Acceleration efficiency of electrons	η_e	–	10π
Acceleration efficiency of protons	η_p	30π	–
Escape efficiency	$\xi_{\rm esc}$	10^{-2}	–
Electron low energy cutoff	$E_{\rm min}$	–	$10^2 m_e c^2$
Proton low energy cutoff	$E_{\rm min}$	$2.m_p c^2$	–
RG surface magnetic field	B_*, G	1.	
RG radius, au	R_*, au	0.35	
RG mass-loss rate	$\dot{M}/v_{\rm w}$, $\rm g\,cm^{-1}$	6.3×10^{11}	
WD orbit radius	$r_{\rm orb}$, au	1.48	
Distance from Earth	kpc	1.4	
Ejecta initial speed	$v_{\rm ej,0}$, $\rm km\,s^{-1}$	3000	
Ejecta mass	$m_{\rm ej}$	$10^{-7} M_\odot$	