Tenth International Fermi Symposium

9th-15th October 2022

Revealing time-resolved hadronic particle acceleration in the recurrent nova RS Ophiuchi with H.E.S.S.

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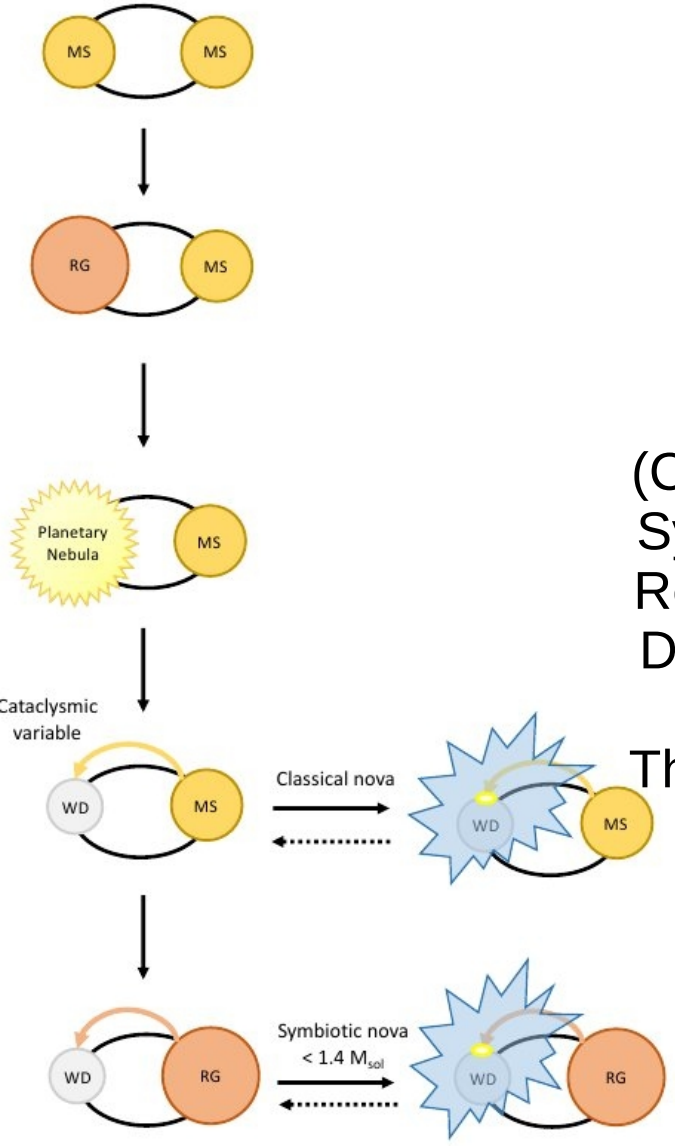


Novae

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

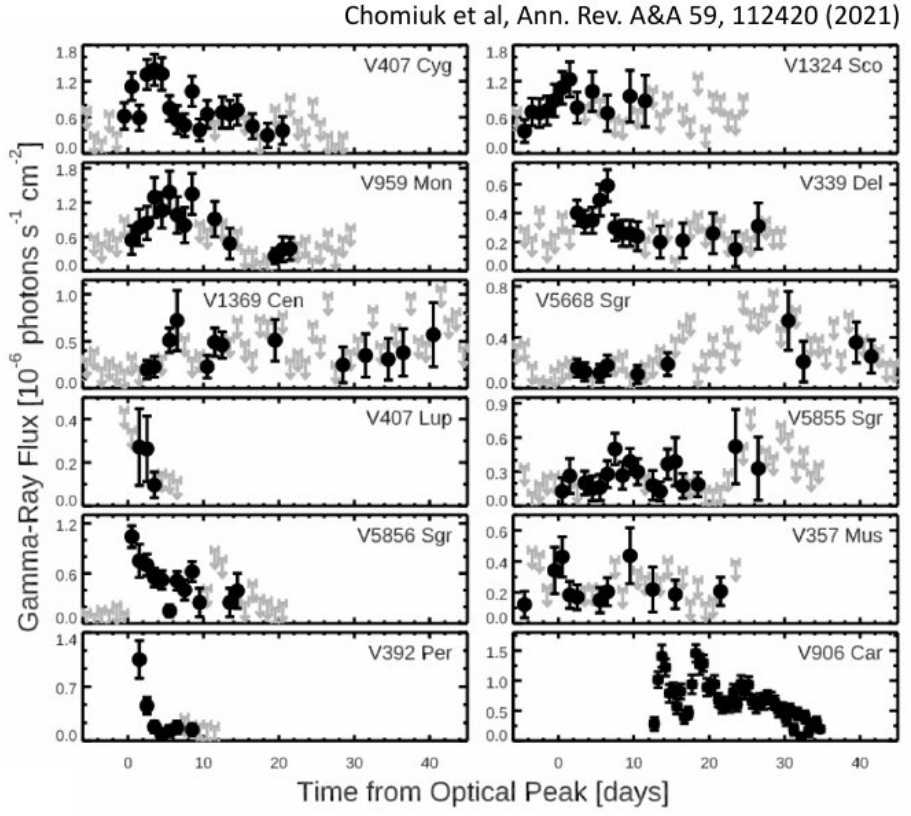
Gamma-ray emission from Novae

LAT discovery
Particle acceleration at shocks:
interaction with dense wind (external)
or of fast ejecta with slower material (internal)

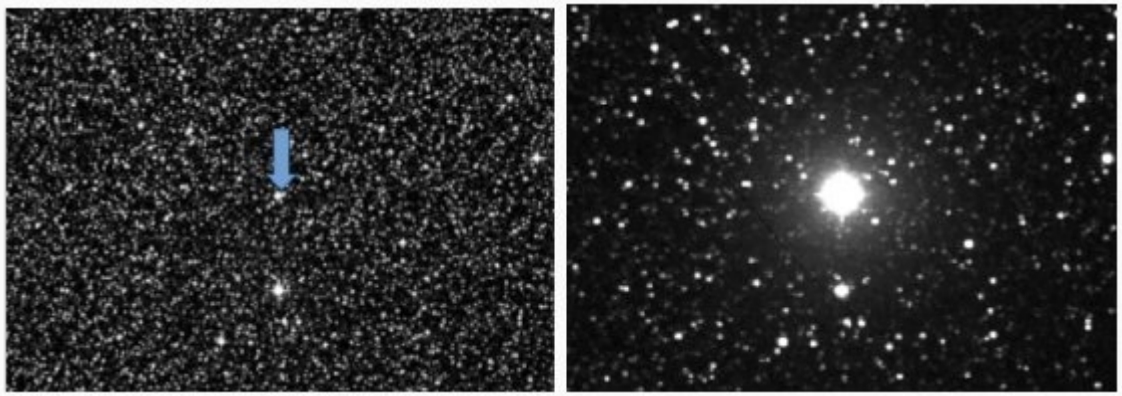
17 novae detected in gamma-rays
by Fermi-LAT by 2021

Typical duration days to weeks
Typical spectral cut-off ~1-10 GeV

Classical and symbiotic/recurrent novae



RS Ophiuchi

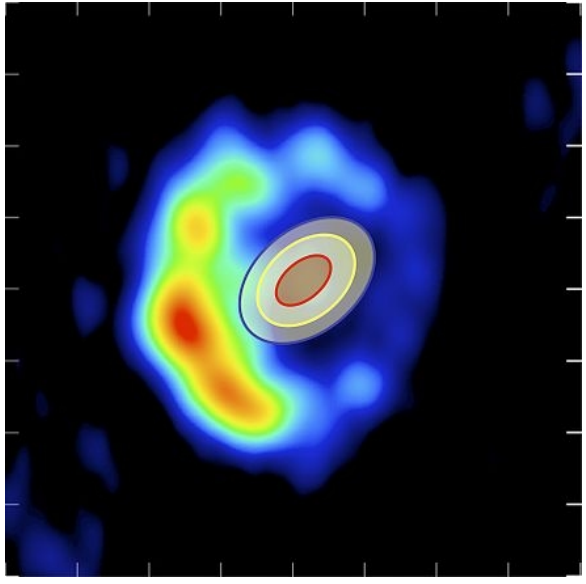


1st Galactic VHE transient source:
RS Ophiuchi – 2021 flare

A well-known recurrent nova
at a distance of ~1.4 kpc.

About 9 outbursts since 1898.
~ 15 years recurrence rate.

2006 outburst observed with HESS
(very poor observing conditions)
Non-detection matches 2021 fluxes.



The 2021 outburst

Gamma-ray detection has been anticipated
Recurrence ~ 9 – 25 years, last explosion 2006

HESS triggered observation of Novae based on
- de-absorbed flux
  (scaling of optical and gamma flux)
- high expansion velocities
  (strong shocks)
- LAT detection
- recurrent novae are looked-out for.

RS Ophiuchus matched all criteria:

HESS – arXiv: 2202.08201
Science, 376, 77 (2022)
LAT – arXiv: 2207.02921
ApJ, 935, 44 (2022)
MAGIC – arXiv: 2202.07681
Nat. Ast. 6, 689, 2022
Radio-VLBI – arXiv: 2209.12794
A&A, in press, 2022

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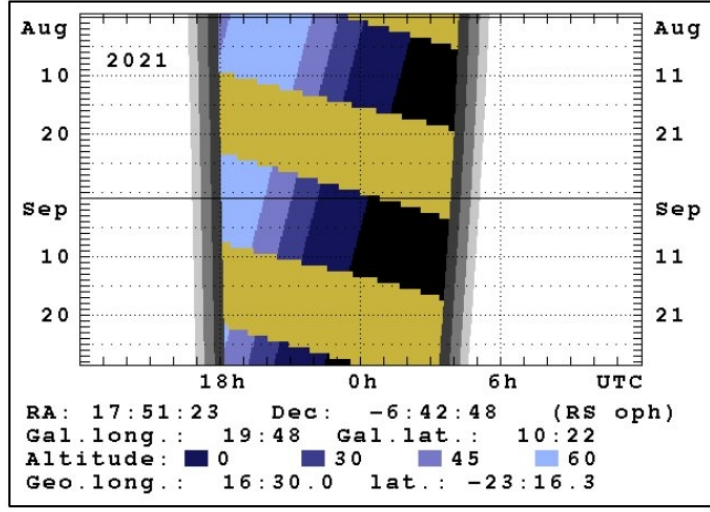
m_V ~ 5
(AAVSO, 8th Aug 22:20 UTC)
≥ 2600 km/s
(ATel #14838, 9th Aug)
(ATel #14834, 9th Aug)
expected

RS Ophiuchus matched all criteria:

Start observations August 9

RS Oph observations



Observing Sequence:

August 8 – announcement @ 22:20
– not on a channel that is automatically screened.

Noted at 23:30 → RS Oph setting and below 30 elevation → no observation

Observations commenced 18:17 UTC on 09/08/21

Continued nightly until 13/08/21
Enforced break due to high moonlight

Observations resumed from 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

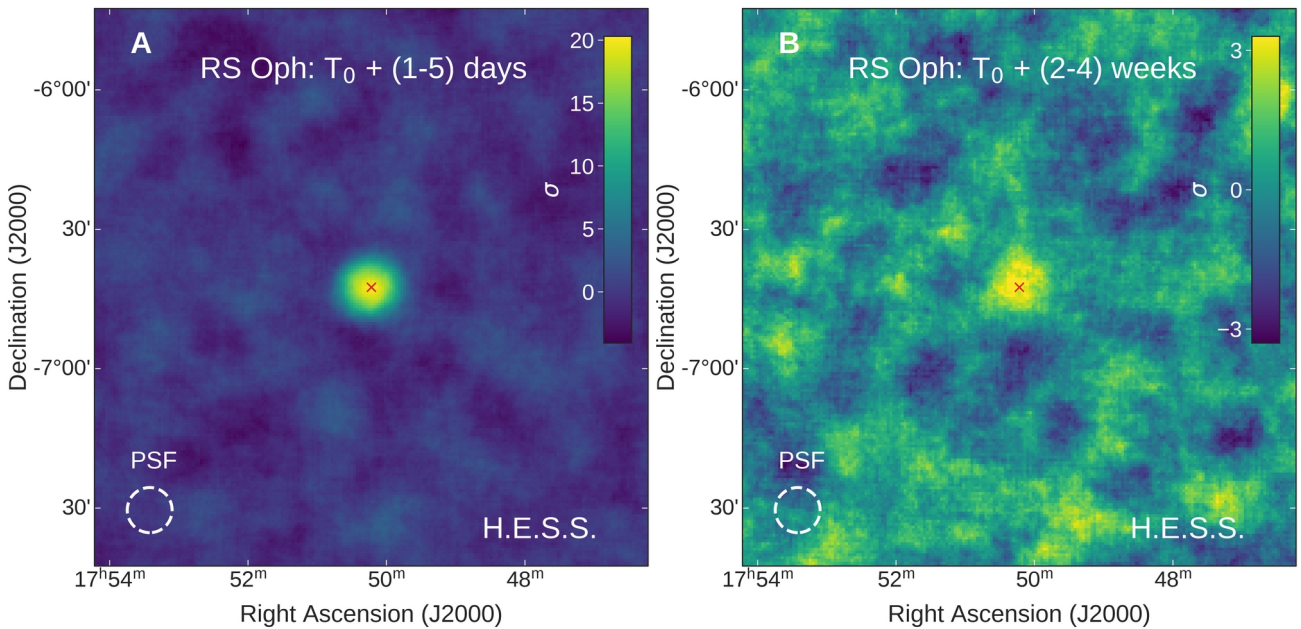
Referred to by ATel #: 14845, 14846, 14848, 14849, 14851, 14855, 14857, 14858, 14860, 14882, 14885, 14886, 14894, 15169

Detection

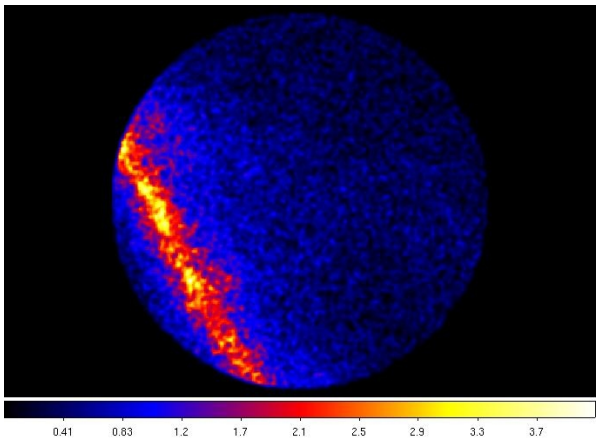
H.E.S.S. Detection
at > 6 sigma on each night
of first five nights.

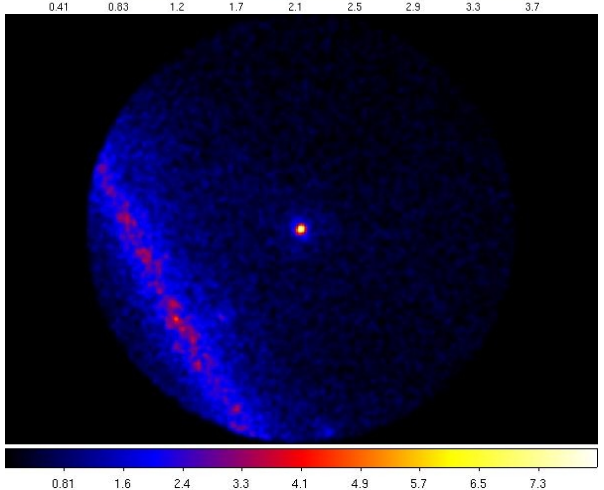
Parts of the data were
affected by poor weather
(reduced transparency).

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)

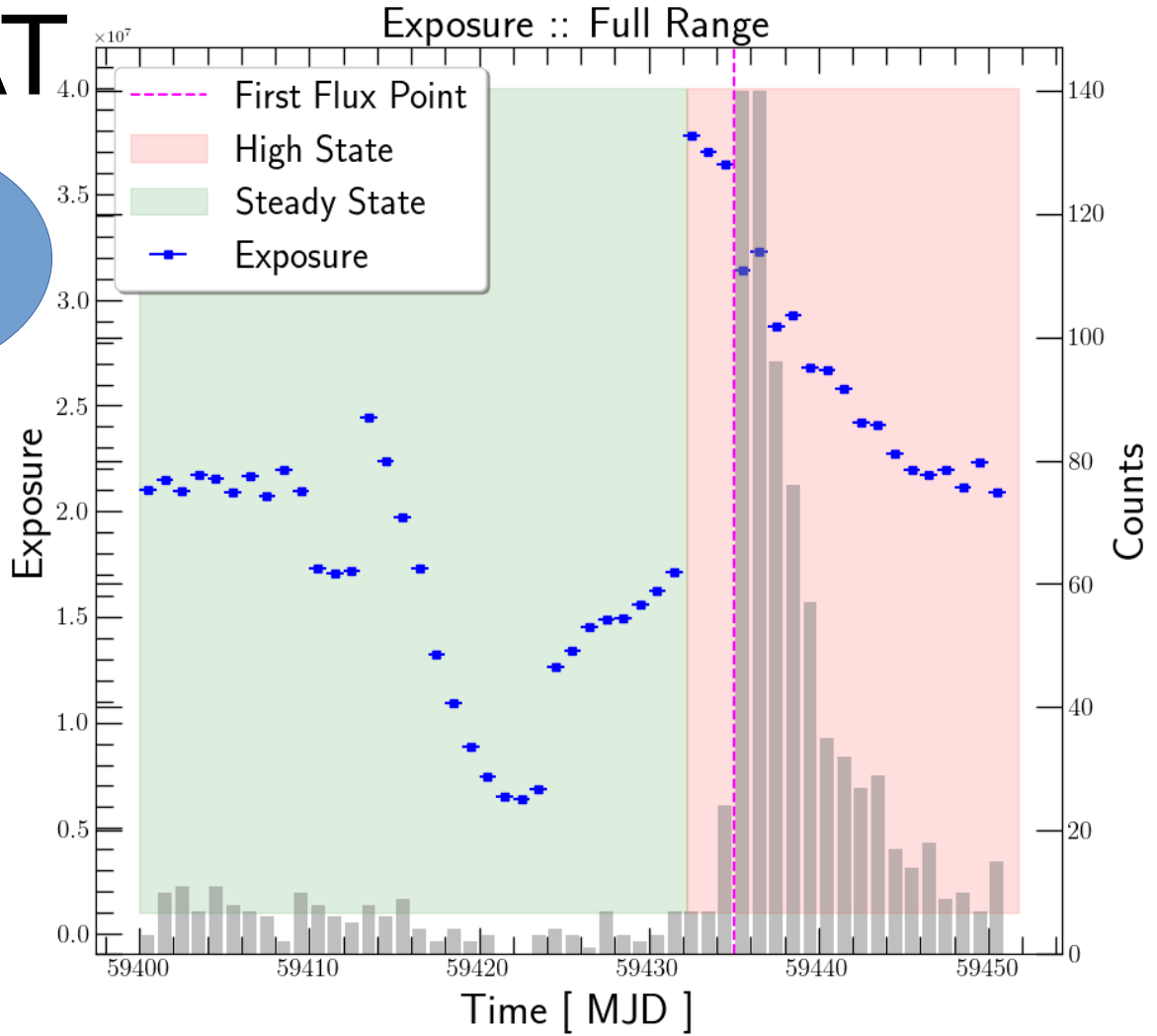


RS Oph with LAT

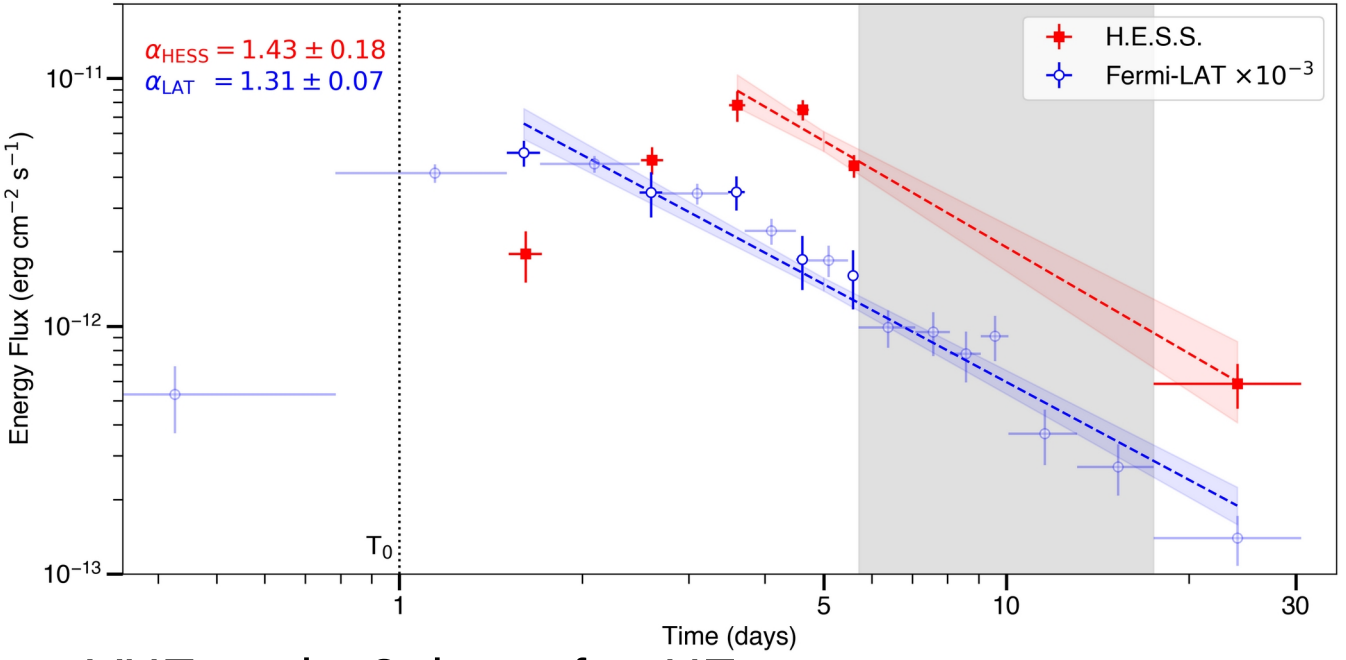




LAT saw it coming



Temporal Evolution

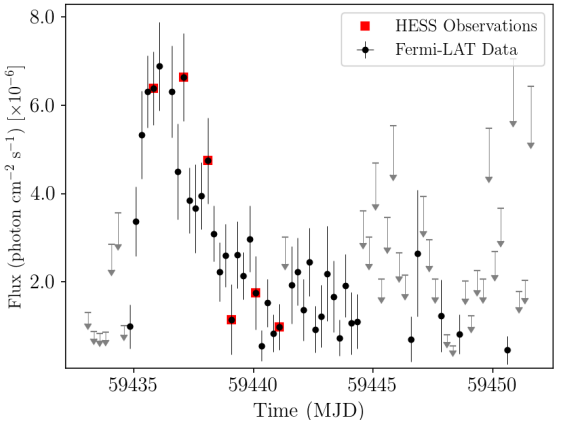


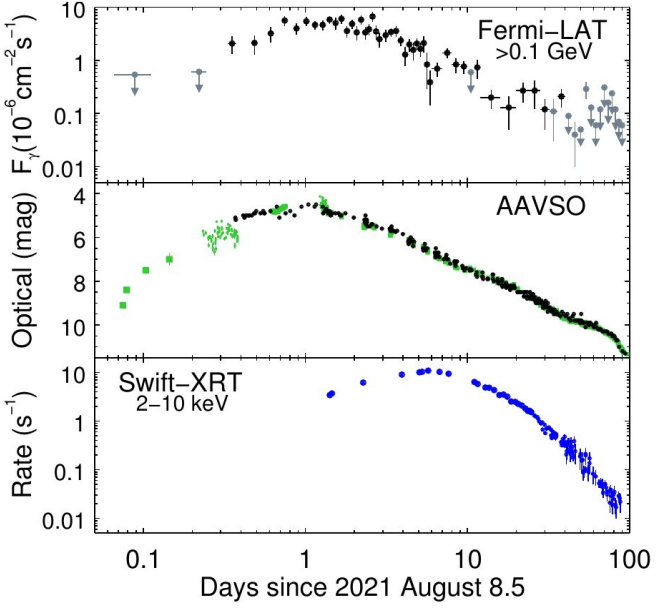
VHE peaks 2 days after HE

Exponential rise/decay in opt, HE, VHE

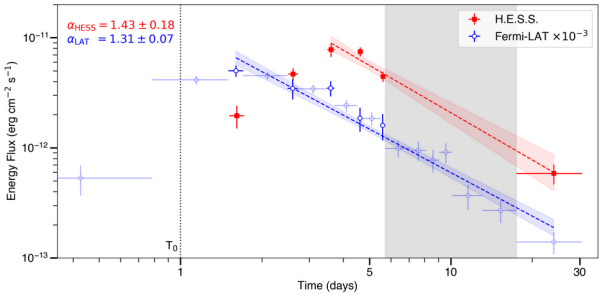
HESS, 2022

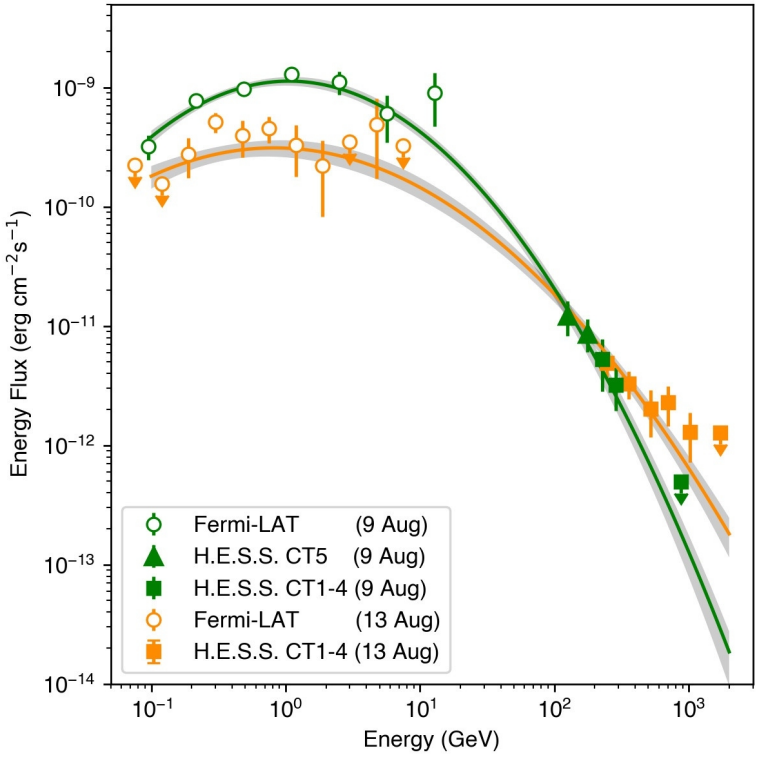
Cheung et al., 2022

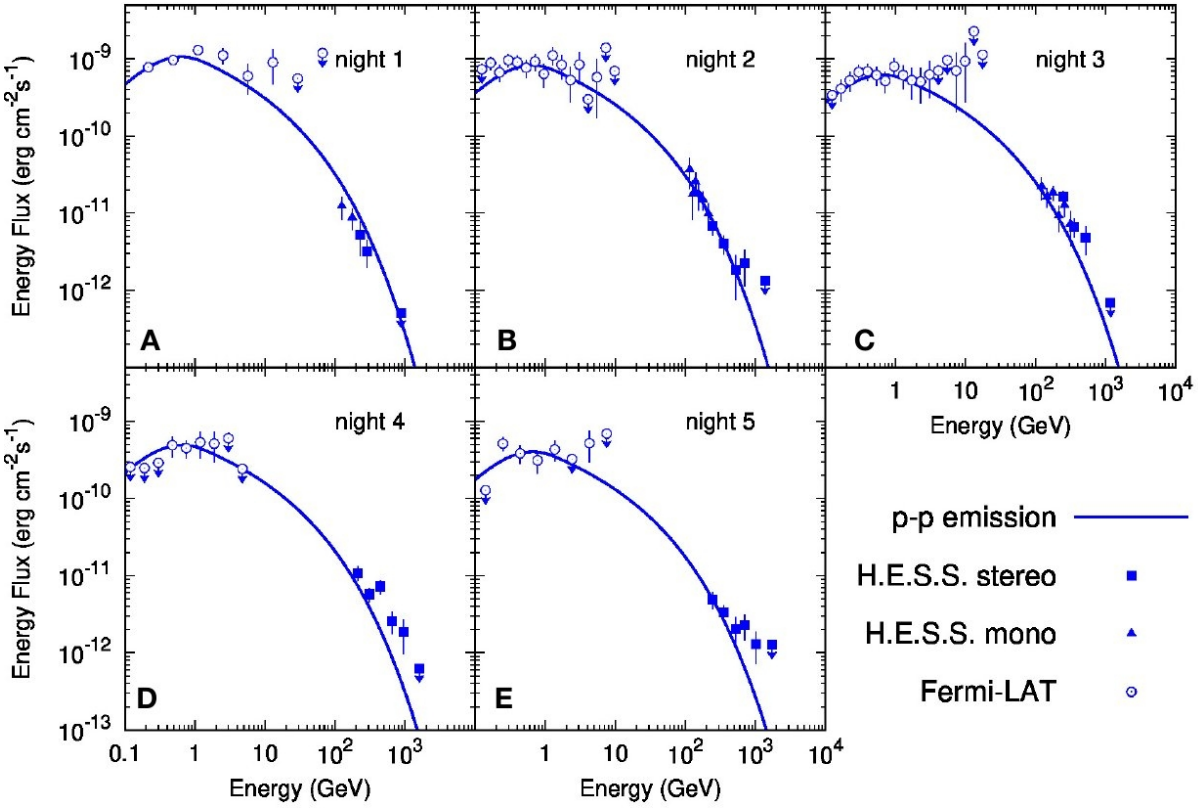




Gamma-SED

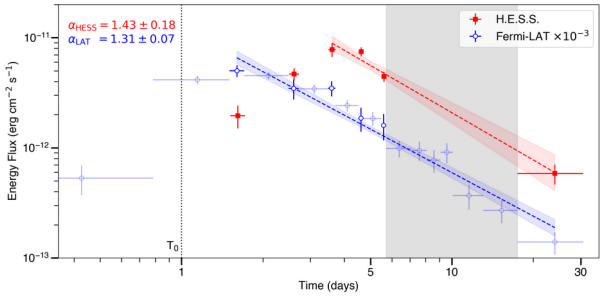

$\alpha_{HESS} = 1.43 \pm 0.18$
$\alpha_{LAT} = 1.31 \pm 0.07$
H.E.S.S.
Fermi-LAT ×10⁻³
Energy Flux (erg cm⁻² s⁻¹)
Time (days)
T₀


Energy Flux (erg cm⁻² s⁻¹)
Energy (GeV)
Fermi-LAT (9 Aug)
H.E.S.S. CT5 (9 Aug)
H.E.S.S. CT1-4 (9 Aug)
Fermi-LAT (13 Aug)
H.E.S.S. CT1-4 (13 Aug)


night 1
night 2
night 3
night 4
night 5
A
B
C
D
E
Energy Flux (erg cm⁻² s⁻¹)
Energy (GeV)
p-p emission
H.E.S.S. stereo
H.E.S.S. mono
Fermi-LAT

Spectral evolution

Over the first five days, Fermi-LAT flux reduces and HESS flux hardens.



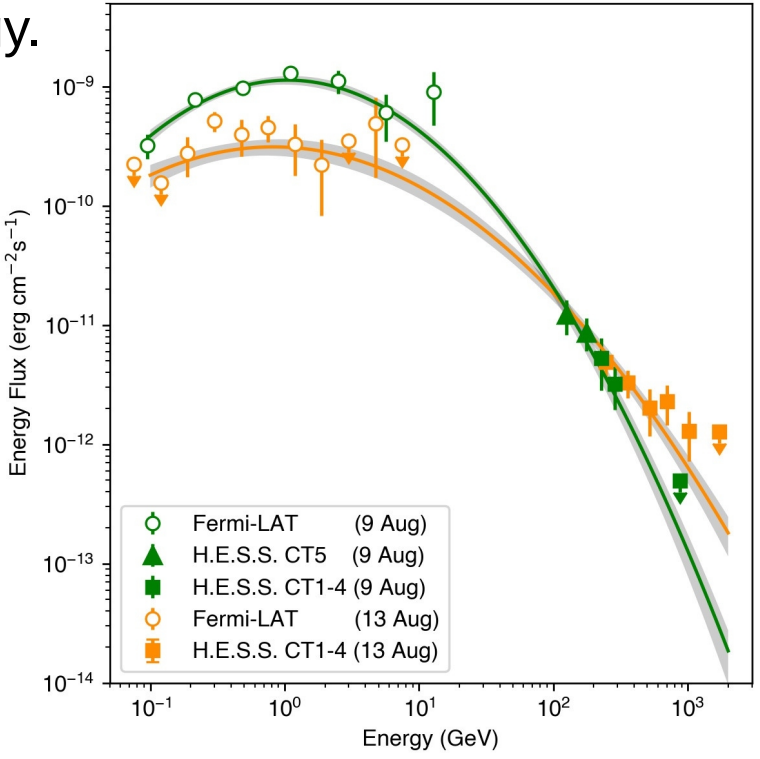
It takes time to reach the theoretical maximum energy.

Either: time taken before radiative cooling dominates acceleration,
or: particles become sufficiently energetic to escape the shock (confinement limit, Bell et al 2013).

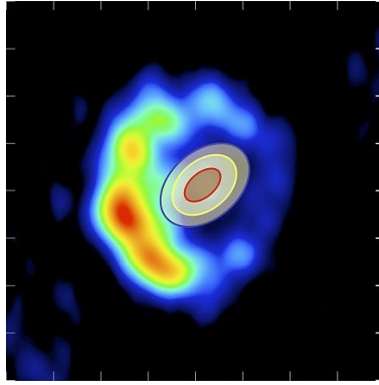
$$E_{max} = 1.5|Z|\left(\frac{\xi_{esc}}{0.01}\right)\left(\frac{\dot{M}/v_{wind}}{10^{11}\ \mathrm{kg\ m^{-1}}}\right)^{1/2}\left(\frac{u_{sh}}{5000\ \mathrm{km\ s^{-1}}}\right)^{2}\ \mathrm{TeV}$$

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

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



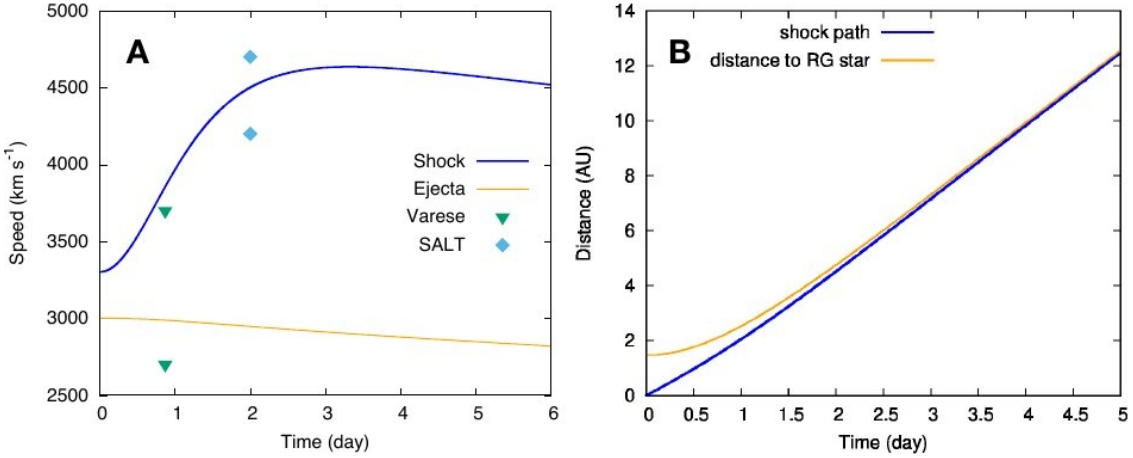
Acceleration in shocks

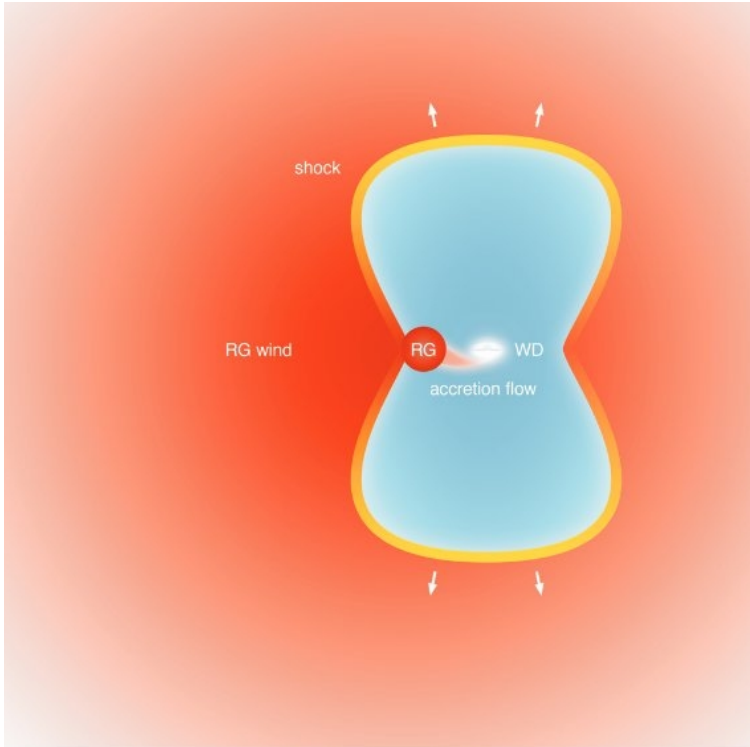


Asymmetric expansion observed during 2006 outburst

Fast shock expands into red giant wind.
(Spectroscopic monitoring: 4000 − 5000 km/s during first week (ATel #14852), SWIFT temperatures).

Diffusive shock acceleration at fast shocks.





Particle acceleration

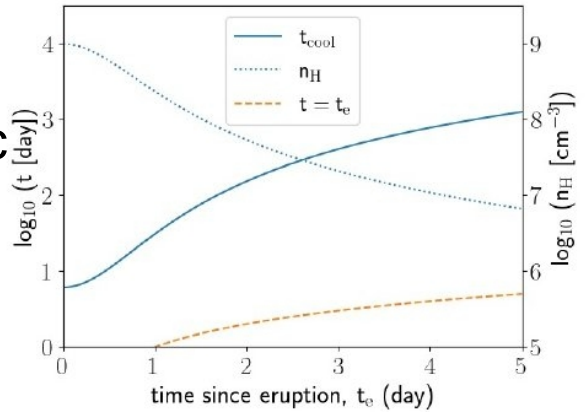
Cooling time > expansion time → forward shock is adiabatic

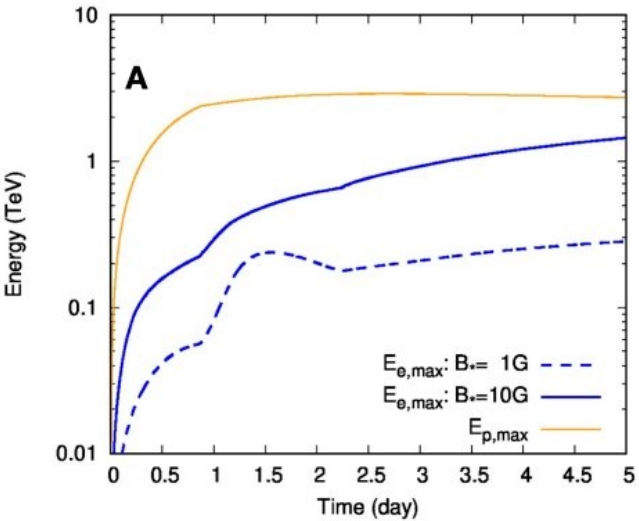
Maximum energy saturates at confinement limit for protons.

Escaping particles drive turbulent B-field amplification:

$$E_{\max} < \frac{qc\xi_{\rm esc}}{20}\sqrt{\frac{\dot{M}}{v_{\rm w}}}\left(\frac{u_{\rm sh}}{c}\right)^2$$

Decrease in energy loss rate with radius increases maximum energy for electrons.





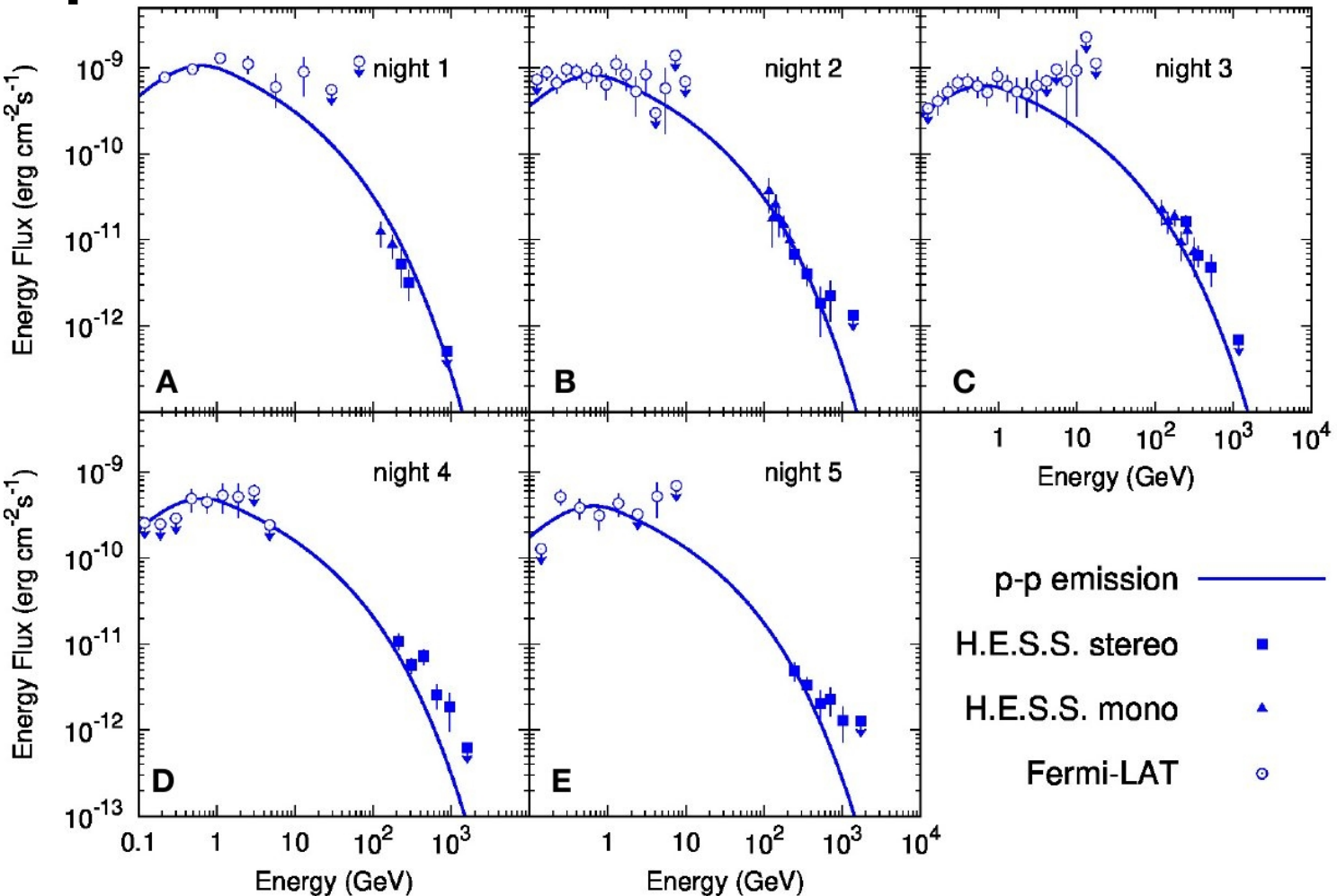
Nova RS Ophiuchi: A simple model

Collisions in dense gas downstream and/or IC scattering of Nova photons.

Leptonic model requires > 1% conversion efficiency, inconsistent with injection.

Hadronic scenario preferred:
Shock expands in decreasing density profile.
Total kinetic energy ~ 10^{43}erg, 10% of this accelerates CR.
Peak delay due to finite acceleration time of > 1TeV photons
This continuously fills 1pc^3 with CR, sub-average diffusion will raise local density

Spectra in hadronic scenario

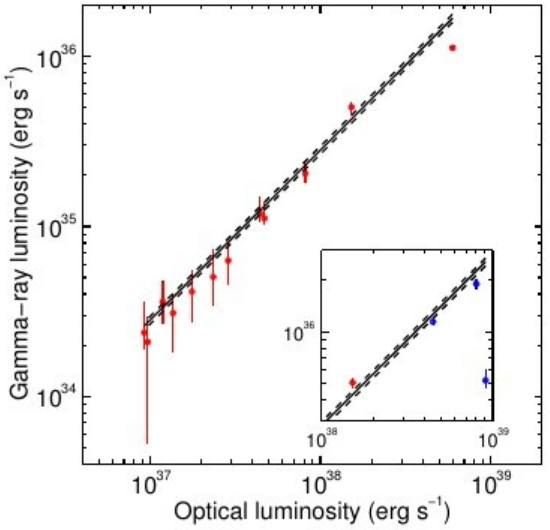


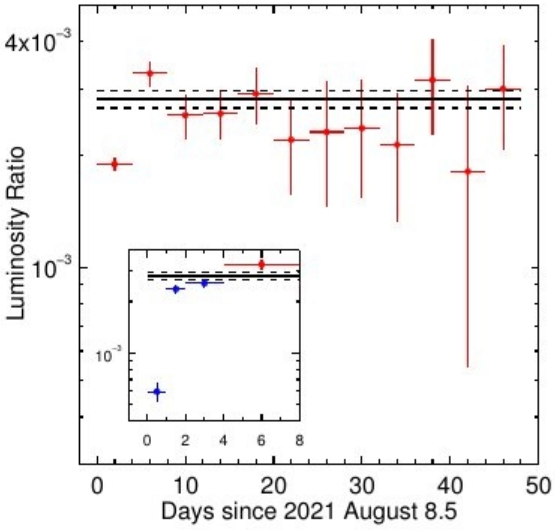
Absorption

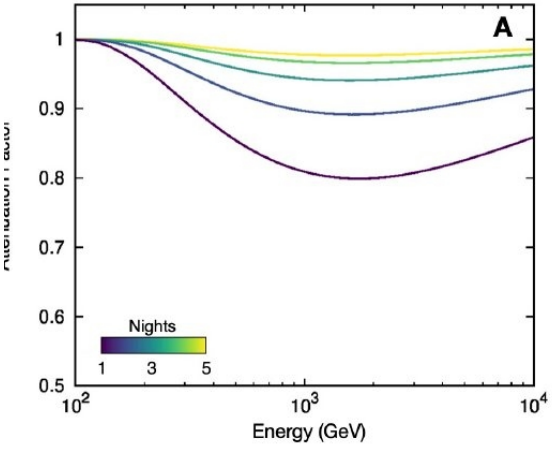
Close match of HE – optical fluxes implies minor attenuation after day 1

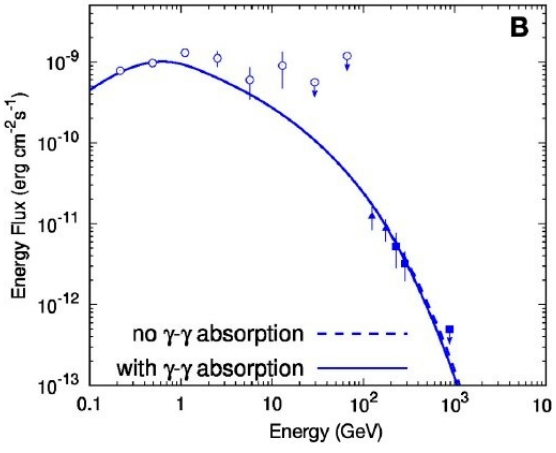
For an assumed distance of 1.4 kpc attenuation due to nova photon fields is insufficient to account for the observed spectral hardening (minor below ~ 1TeV).

Discrepancies to attenuation assumed by MAGIC collaboration.



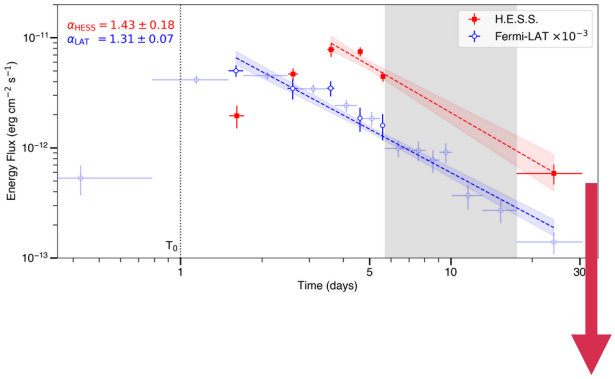


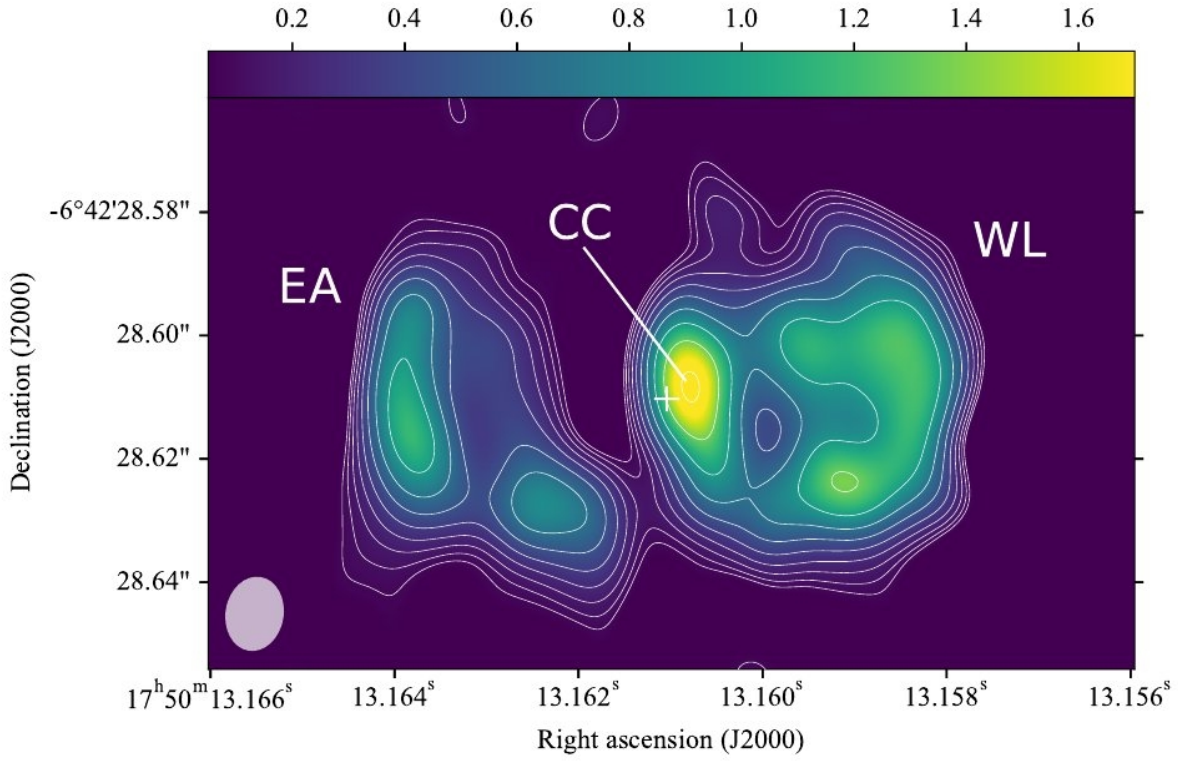


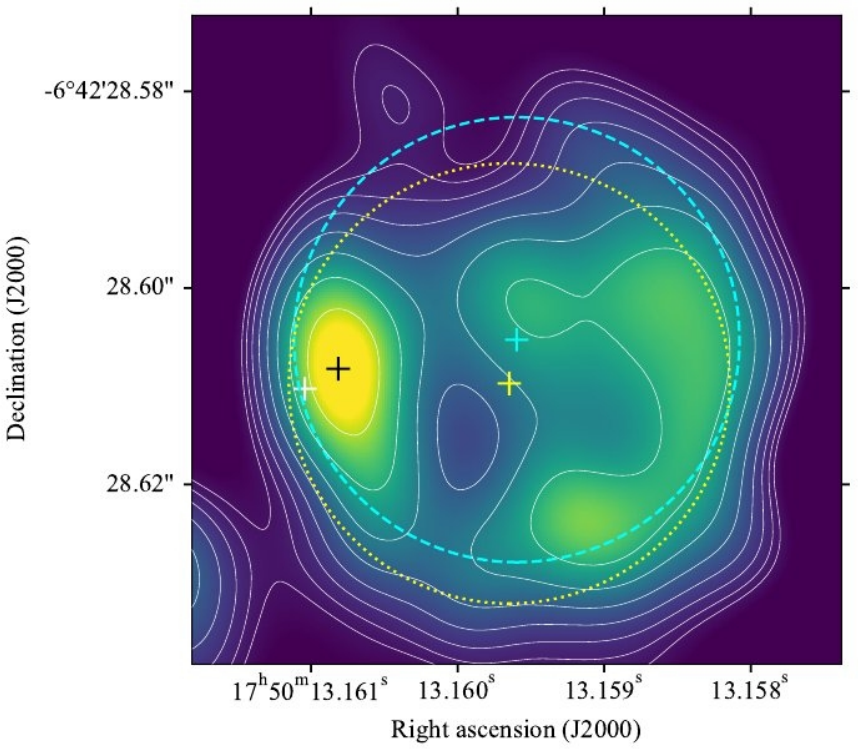


Seeing is believing

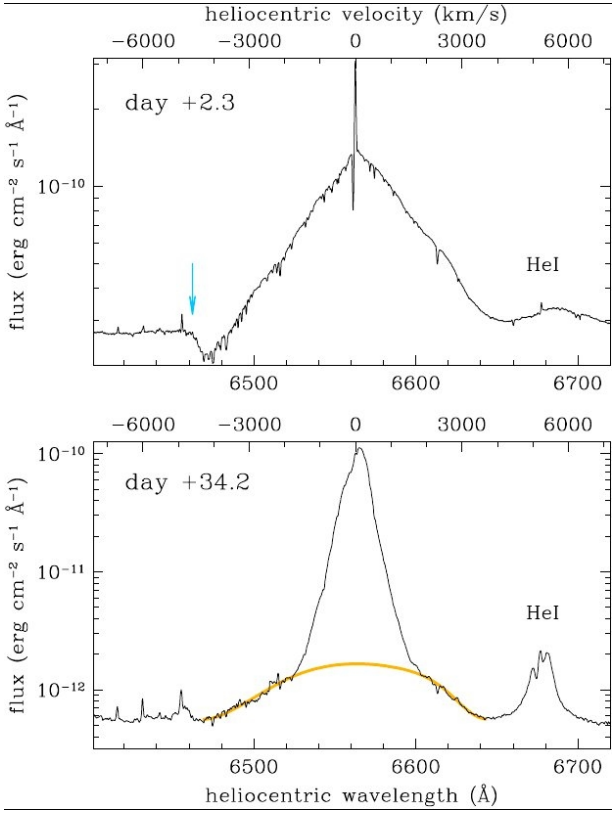
Munari et al., 2022, A&A: EVN + *e*-Merlin

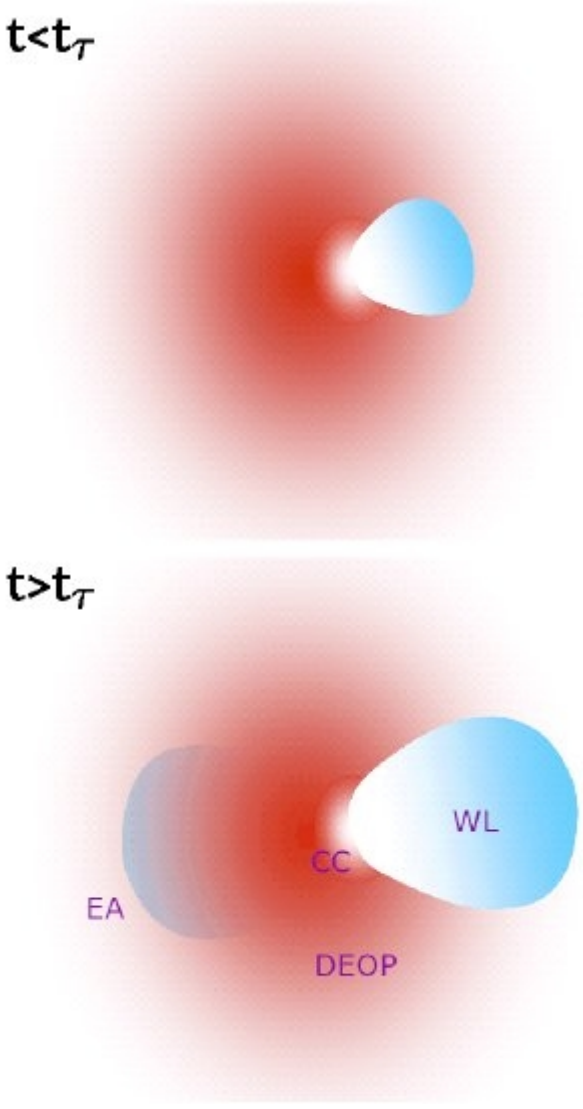


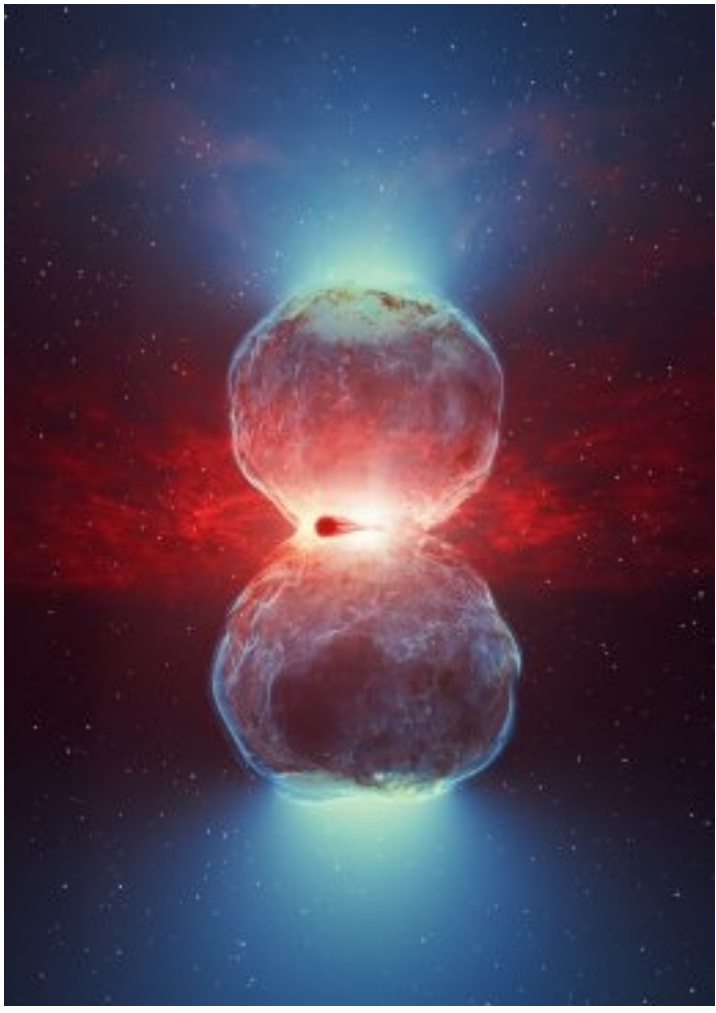




Cartoon


heliocentric velocity (km/s)
−6000
−3000
0
3000
6000
day +2.3
flux (erg cm⁻² s⁻¹ Å⁻¹)
10⁻¹⁰
HeI
6500
6600
6700
day +34.2
10⁻¹⁰
10⁻¹¹
10⁻¹²
HeI
heliocentric wavelength (Å)


t<t_T
t>t_T
WL
CC
EA
DEOP



Cosmic Rays

Particle acceleration in dense wind environments
→ max energy ~ a factor 100 x higher than seen in previous novae.

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