Efficient cosmic-ray acceleration in RS Ophuichi's 2021 outburst revealed by H.E.S.S.

Ruslan Konno, MMS Annual Meeting 2023, Weizmann Institute of Science, 2023-06-06

H. E. S. S. Collaboration et al., Science 376, 6588, 77-80, 2022

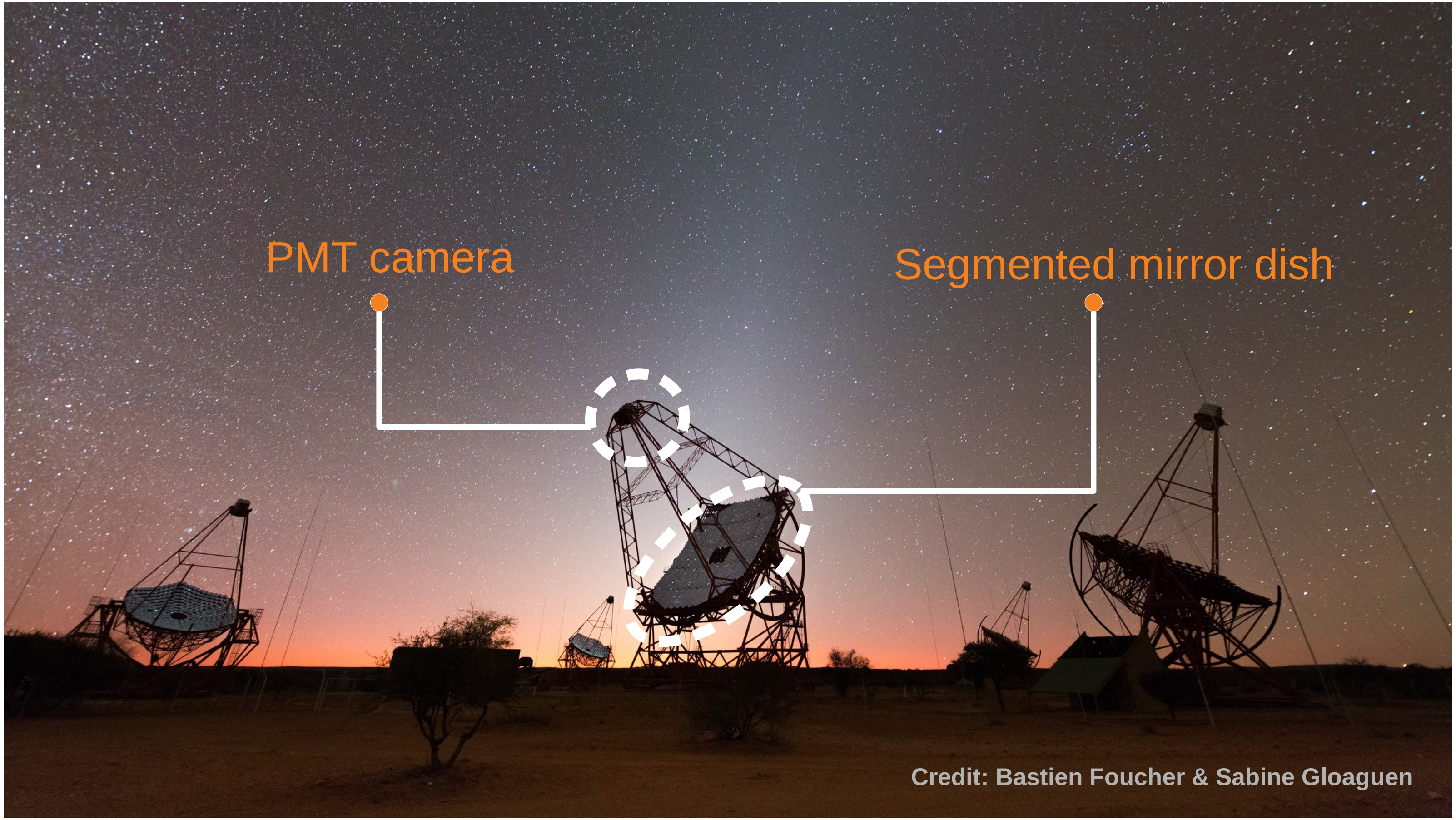
SCAN ME

H.E.S.S.

High Energy Stereoscopic System

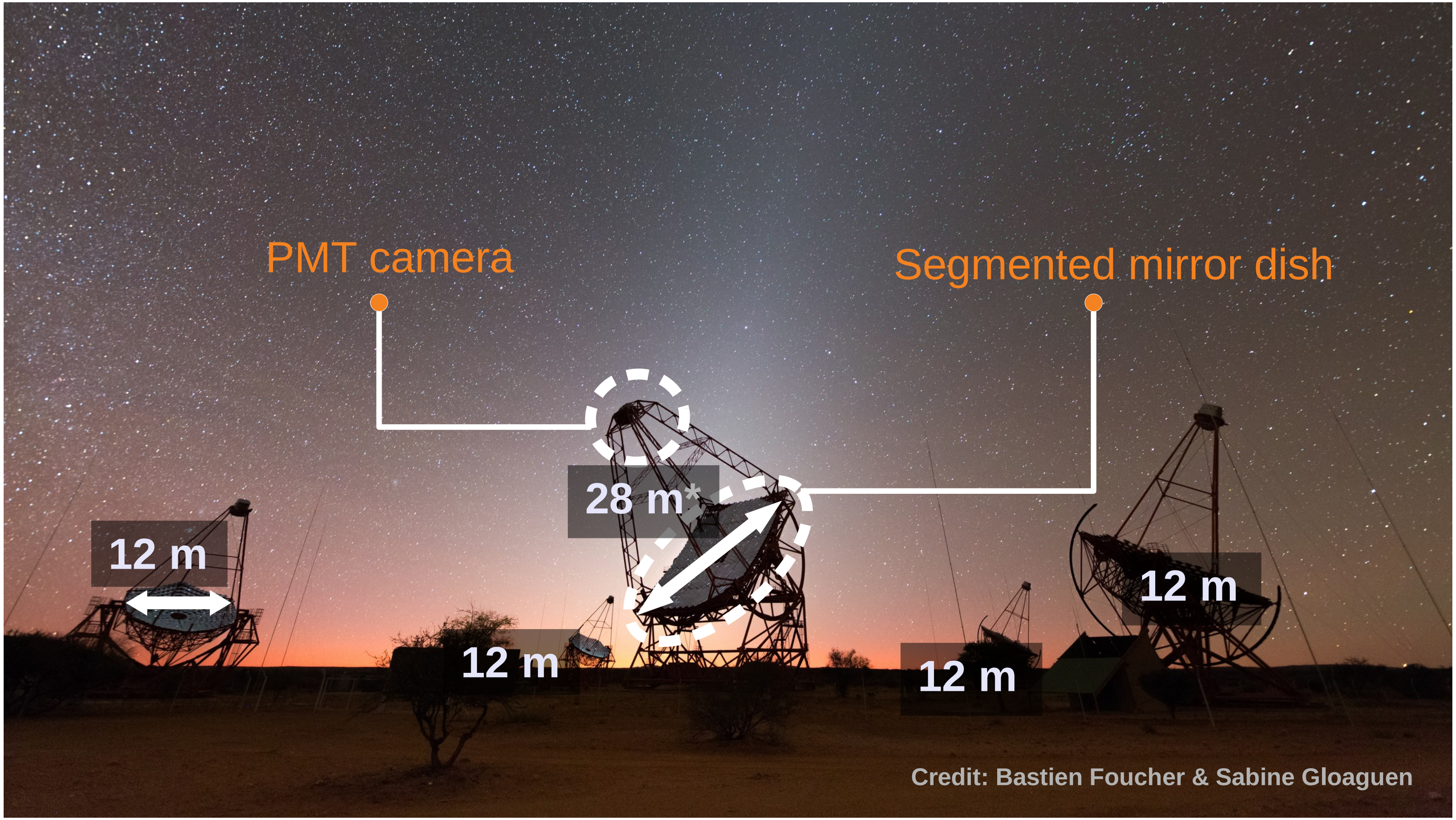
H.E.S.S.

High Energy Stereoscopic System



H.E.S.S.

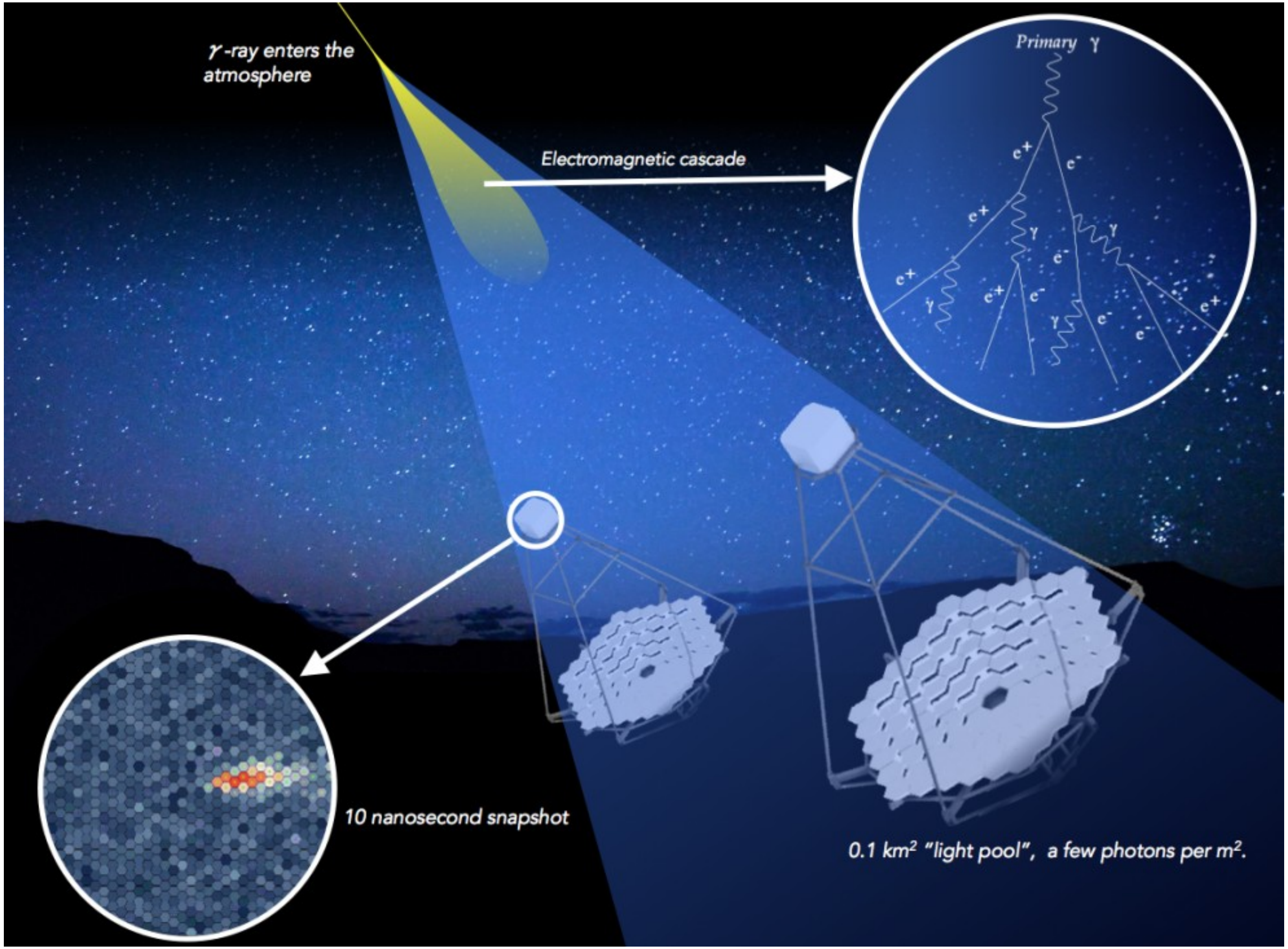
High Energy Stereoscopic System



*Effectively, is actually 32.6 m x 24.3 m.

IACTs

Imaging Atmospheric Cherenkov Telescopes



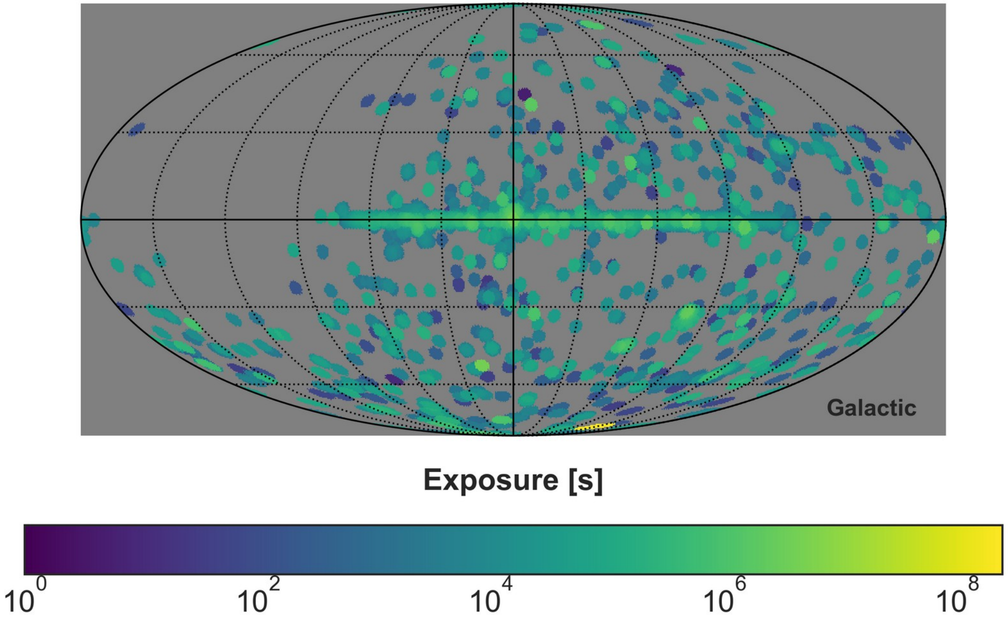
Credit: CTA

H.E.S.S.

Some characteristics

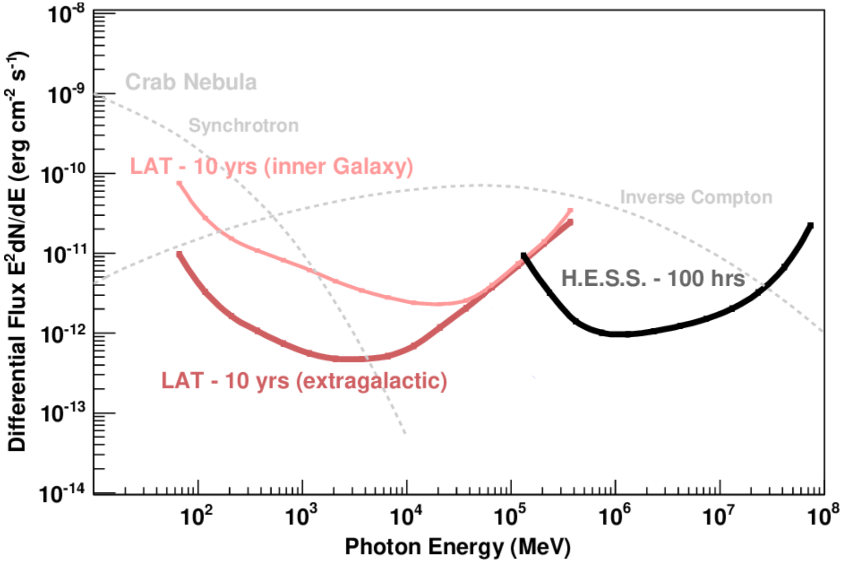
Sky coverage

- Site is in Namibia, Southern Africa
- Open to the Southern Sky
- FoV ~ 5 x 5 Deg^2



Sensitivity

- VHE* range (~50 GeV – ~50 TeV)
- 1 TeV core energy



Funk & Hinton, APh, 43, 348-355, 2013

* Very-High Energy

Introduction to Novae

- Transient phenomena originating in a binary containing a white dwarf (WD)
- WD accretes matter from companion until reaching critical mass
  → Ignition of a thermonuclear reaction → rapid expansion of hydrogen shell
- Increase in brightness $\Delta m \sim 8$ to 15
- Typical optical duration weeks to months
- Unlike SNe, progenitor survives and can erupt again → Recurrent Novae

Illustration: David A. Hardy.

Novae

Why interest in VHE γ rays?

- Clear indication of astrophysical shocks from radio & X-rays
  → particle acceleration

  [Hjielming et al., ApJ, 305L, 71H, 1986](#)

  [Mukai & Ishida, ApJ, 551, 1024M, 2001](#)

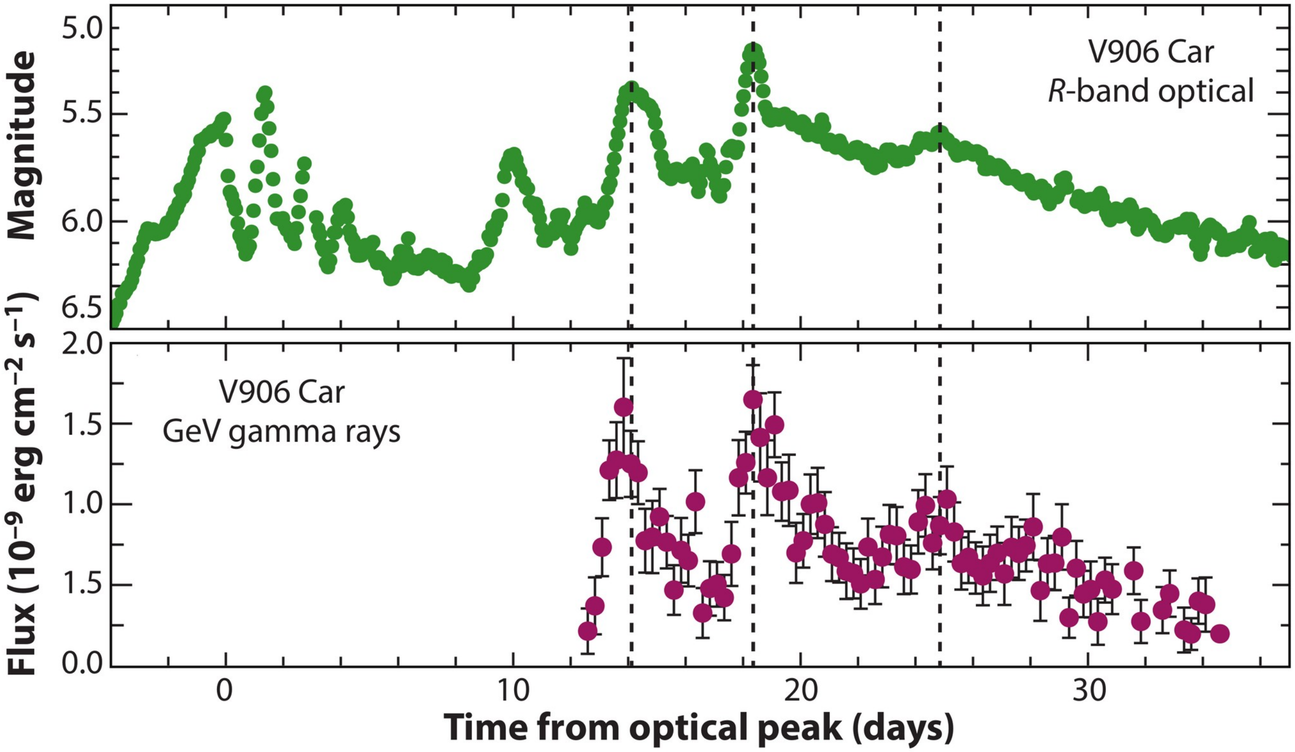
- Known emitters of HE* γ rays
  - >15 detected with Fermi-LAT so far

  [Franckowiak, A&A, 609A, 120F, 2018](#)

- Sources with similar shock physics seen in VHE (Eta Car)

  [H.E.S.S. Collaboration et al., A&A, 635, A167, 2020](#)

Optically bright novae can produce γ rays!



[Aydi et al., NatAs, 4, 776A, 2020](#)

* High Energy

RS Ophiuchi

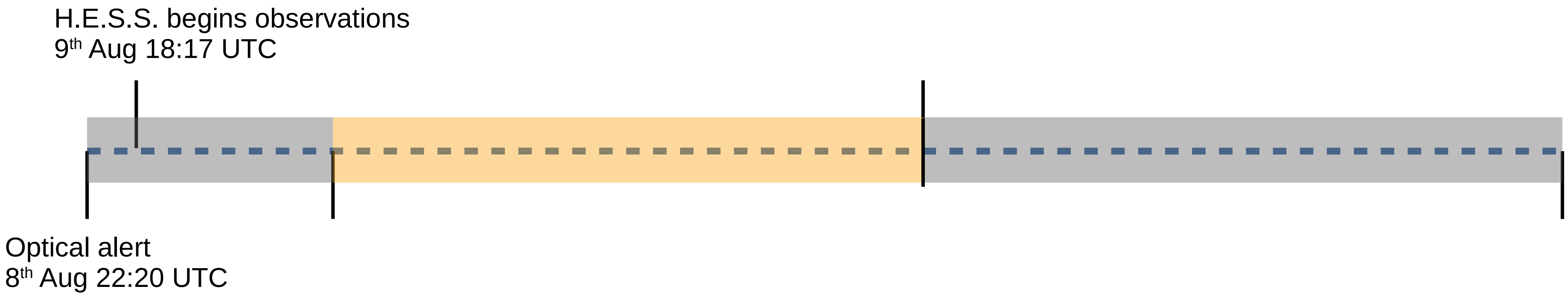
First Galactic VHE γ-ray transient

- RS Ophiuchi (RS Oph) is a well known recurrent nova with 7 recorded eruptions
  - Latest eruption in August 2021
  - Extensive MWL follow-up campaign with >30 ATels
- H.E.S.S. nova criteria
  - Optical magnitude $m_V < 9$
  - High ejecta velocity $v_{ej} > 1500$ km/s
  - Coincident Fermi-LAT detection
- RS Oph
  - ✓ $m_V \sim 5$ (AAVSO, 8th August 22:00 UTC)
  - ✓ $v_{ej} \geq 2600$km/s (ATel#143838, 9th August 15:00 UTC)
  - ✓ Fermi-LAT ~ 6σ (ATel#143834, 9th August 05:00 UTC)

First nova to meet all H.E.S.S. criteria!

RS Ophiuchi

Follow-up timeline



RS Ophiuchi

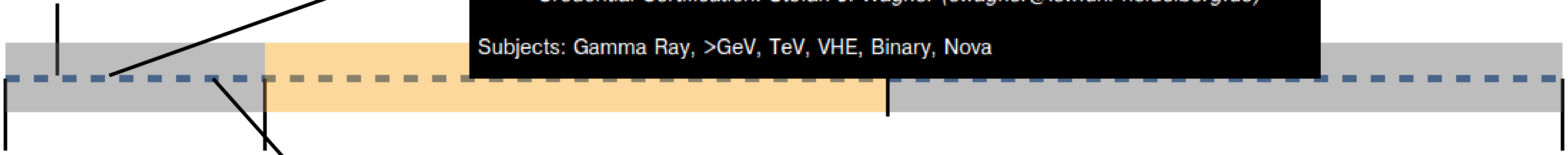
Follow-up timeline

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

H.E.S.S. begins observations
9th Aug 18:17 UTC



Optical alert
8th Aug 22:20 UTC

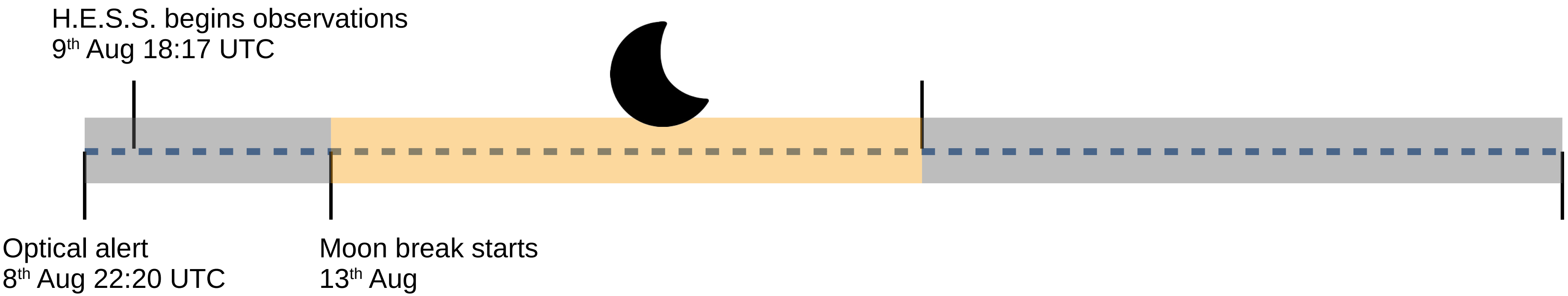
H.E.S.S. observations of soft spectrum VHE gamma-ray emission from the recurrent nova RS Ophiuchi

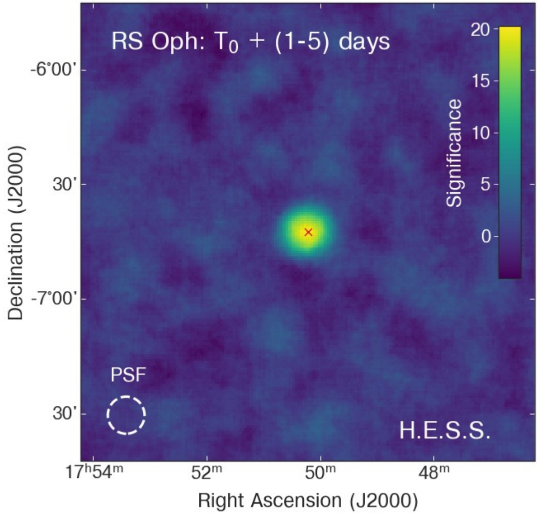
ATel #14857; *Stefan J. Wagner, for the H. E.S. S. collaboration*
on ***12 Aug 2021; 23:03 UT***
Credential Certification: Stefan J. Wagner (swagner@lsw.uni-heidelberg.de)

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

RS Ophiuchi

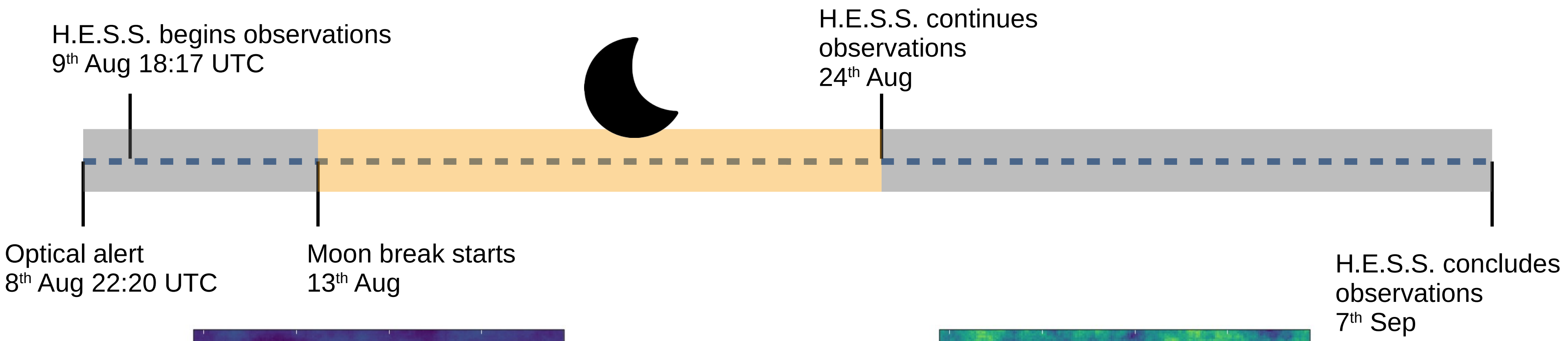
Follow-up timeline

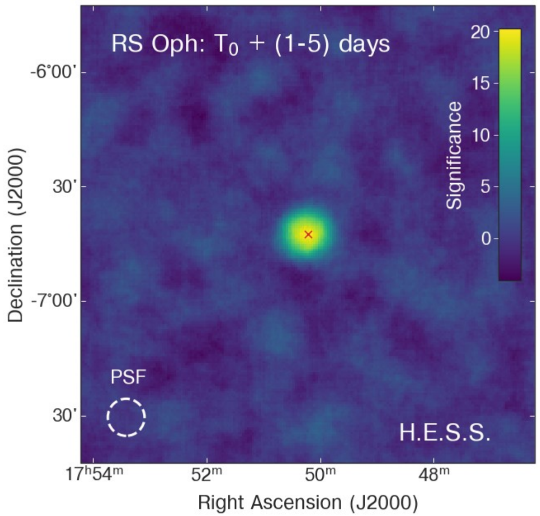


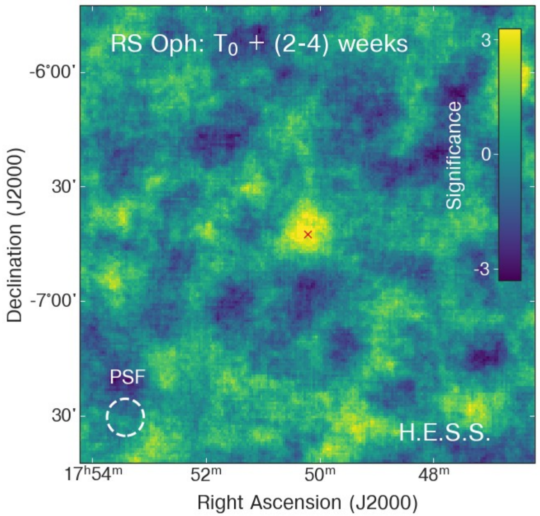


Night	$T_{\rm obs}$ (UTC)	Livetime (hours)	Significance (σ)
09 Aug. 2021	18:17:40	3.2	5.8 (6.4)
10 Aug. 2021	17:53:46	3.7 (2.8)	9.0 (7.1)
11 Aug. 2021	17:44:08	3.7	9.8 (9.6)
12 Aug. 2021	18:17:12	2.3	13.6
13 Aug. 2021	17:44:43	2.8	10.5 (9.4)

RS Ophiuchi
Follow-up timeline







RS Ophiuchi

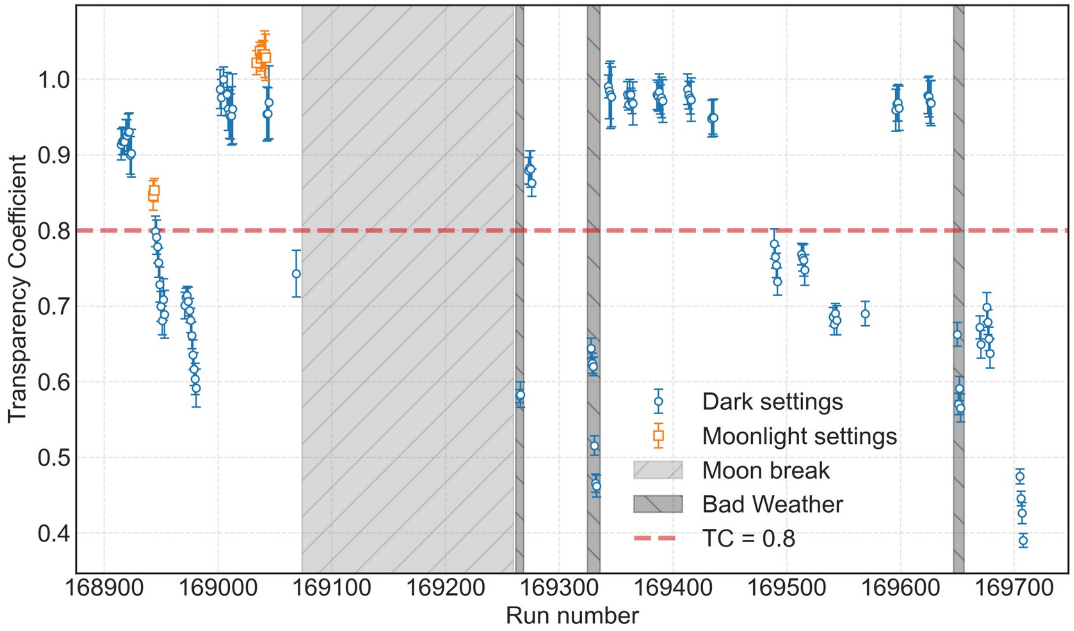
Challenging data set

- γ-ray reconstruction relies on simulations with an assumed atmospheric transparency
  - Reconstruction will be wrong when real atmosphere deviates from simulations

    → Standard cut: Discard data with 20% deviations

- RS Oph observations taken during seasonal biomass burning → Low atmospheric transparency
  - Save the data!

    → Novel approach: Atmospheric corrections

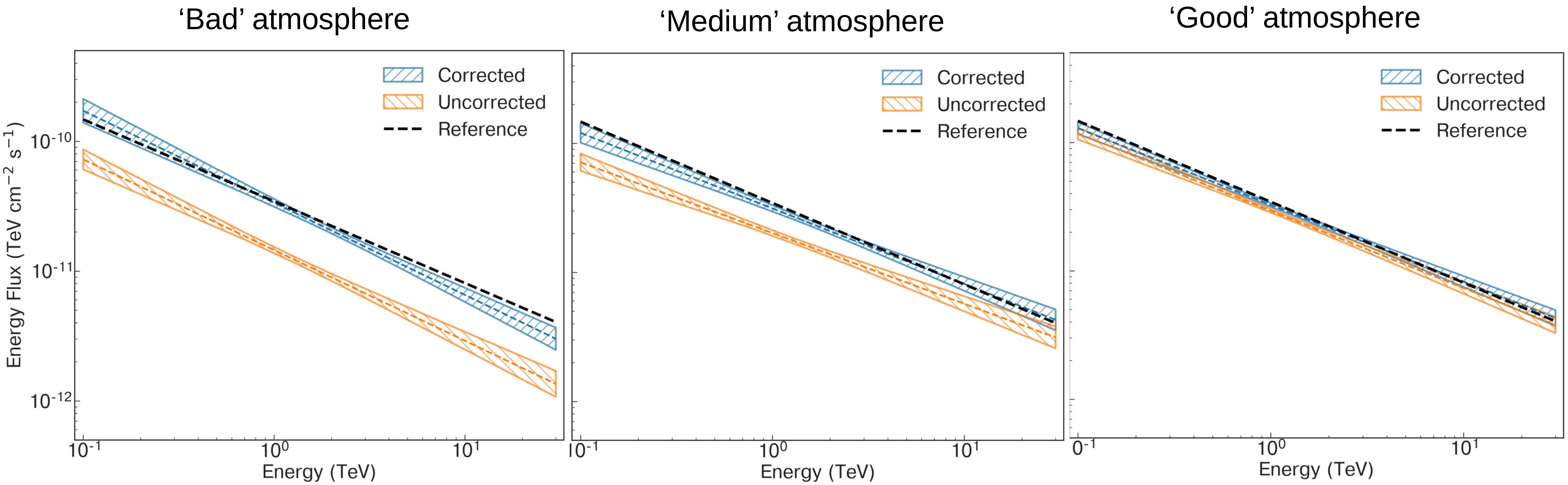


Atmospheric corrections

Crab study

- Cherenkov transparency coefficient: Ratio of Cherenkov photons not absorbed by the atmosphere.
  - Number of Cherenkov photons is ~linear to the energy of the γ-ray energy

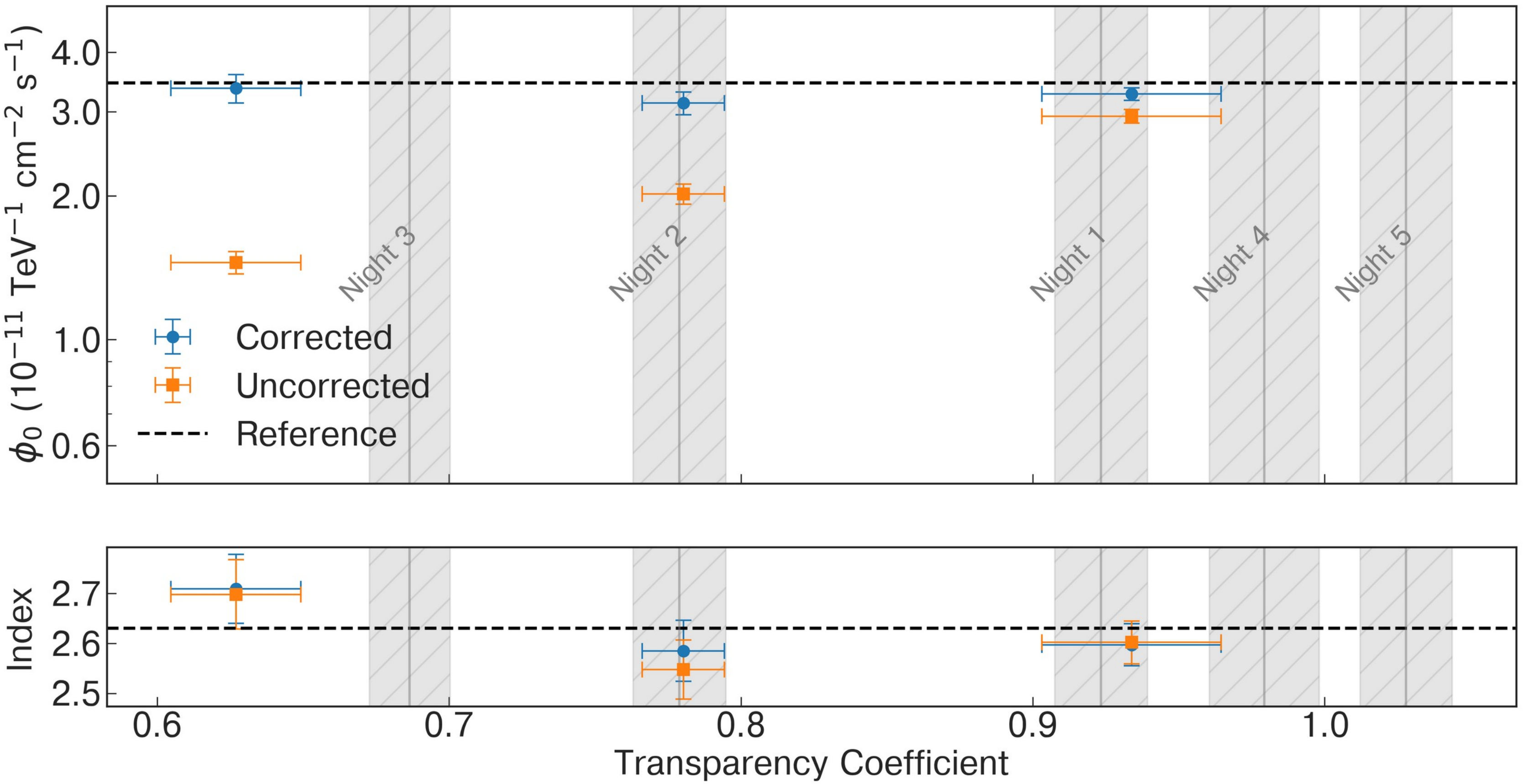
  → Correct the energy axes of the IRFs* with the transparency coefficient + test this on the Crab nebula

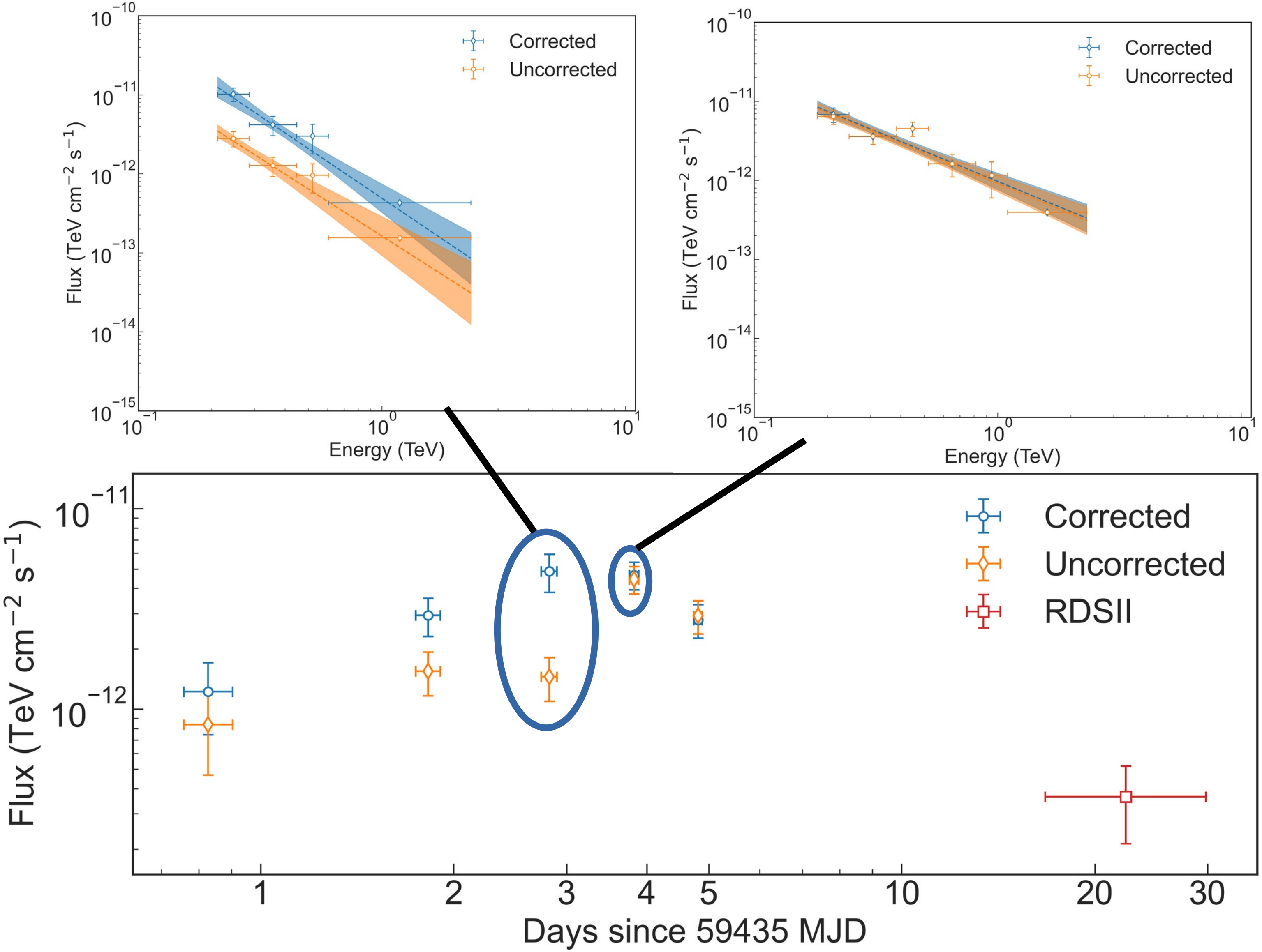


* Instrument Response Functions

Atmospheric corrections

Crab study



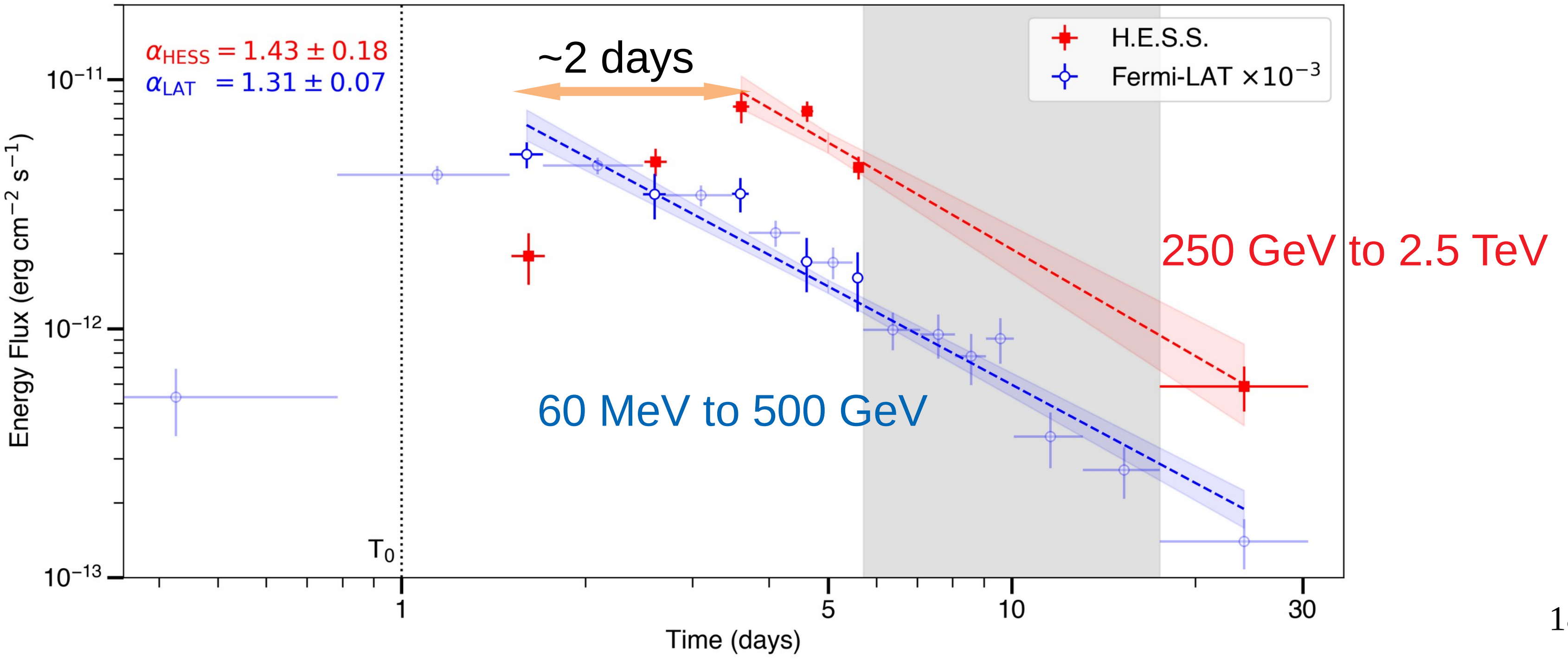


Corrected
Uncorrected
Flux (TeV cm^{-2} s^{-1})
Energy (TeV)
Corrected
Uncorrected
Flux (TeV cm^{-2} s^{-1})
Energy (TeV)
Corrected
Uncorrected
RDSII
Flux (TeV cm^{-2} s^{-1})
Days since 59435 MJD

RS Ophiuchi

HE & VHE γ-ray evolution

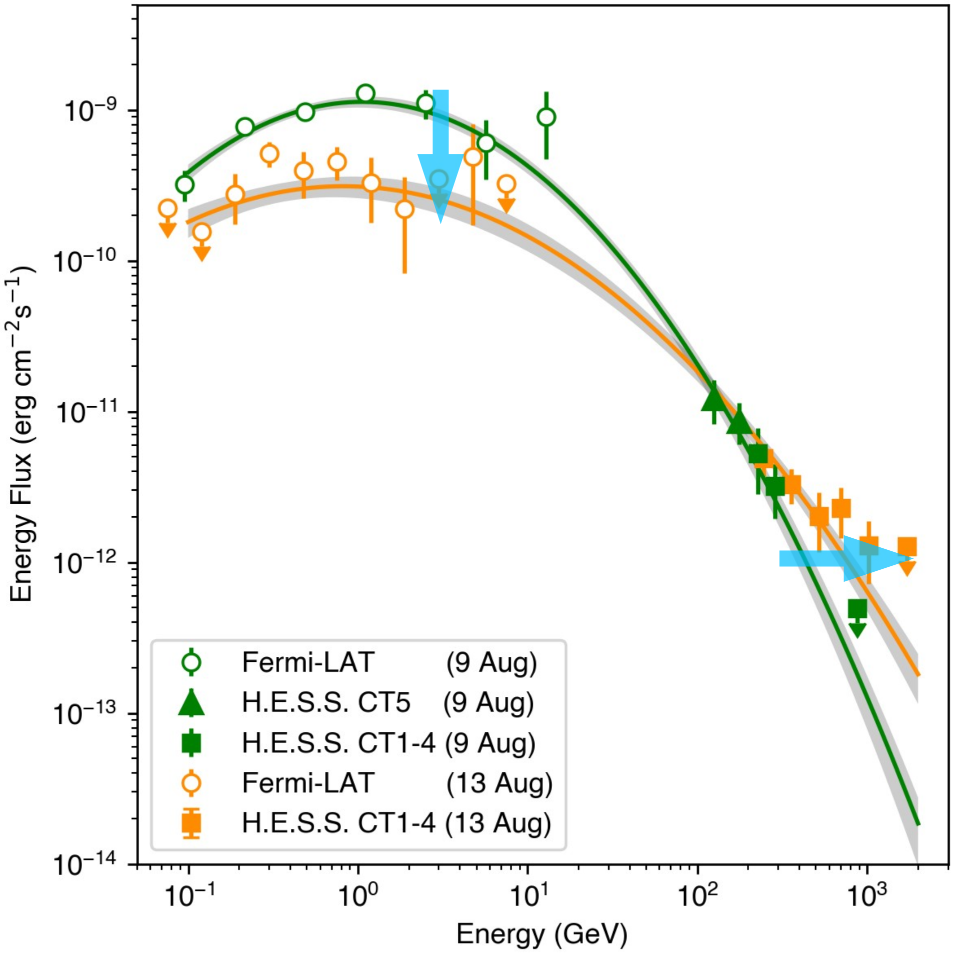
Consistent decay index → same physics
Offset between HE and VHE peaks ~2 days → energy is time-depend



RS Ophiuchi

γ-ray evolution

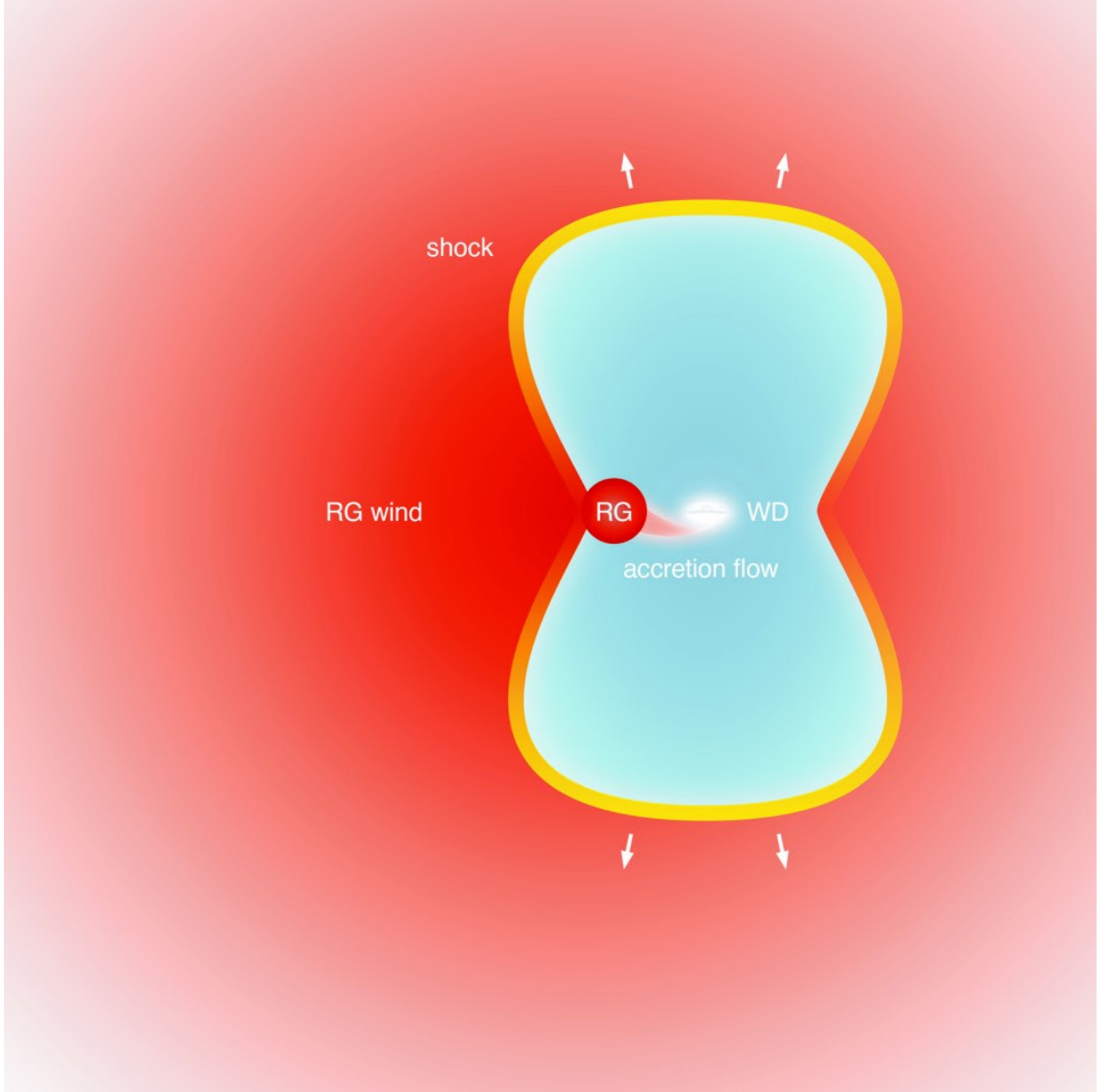
- Broadband γ-ray spectral energy distribution well described by parabola
- Parabola flattens over time
  - HE flux falls
  - VHE rises to higher energies
- Two possible scenarios
  1) Cooling limited – leptonic
  2) Confinement limited – hadronic



RS Ophiuchi

External shock model

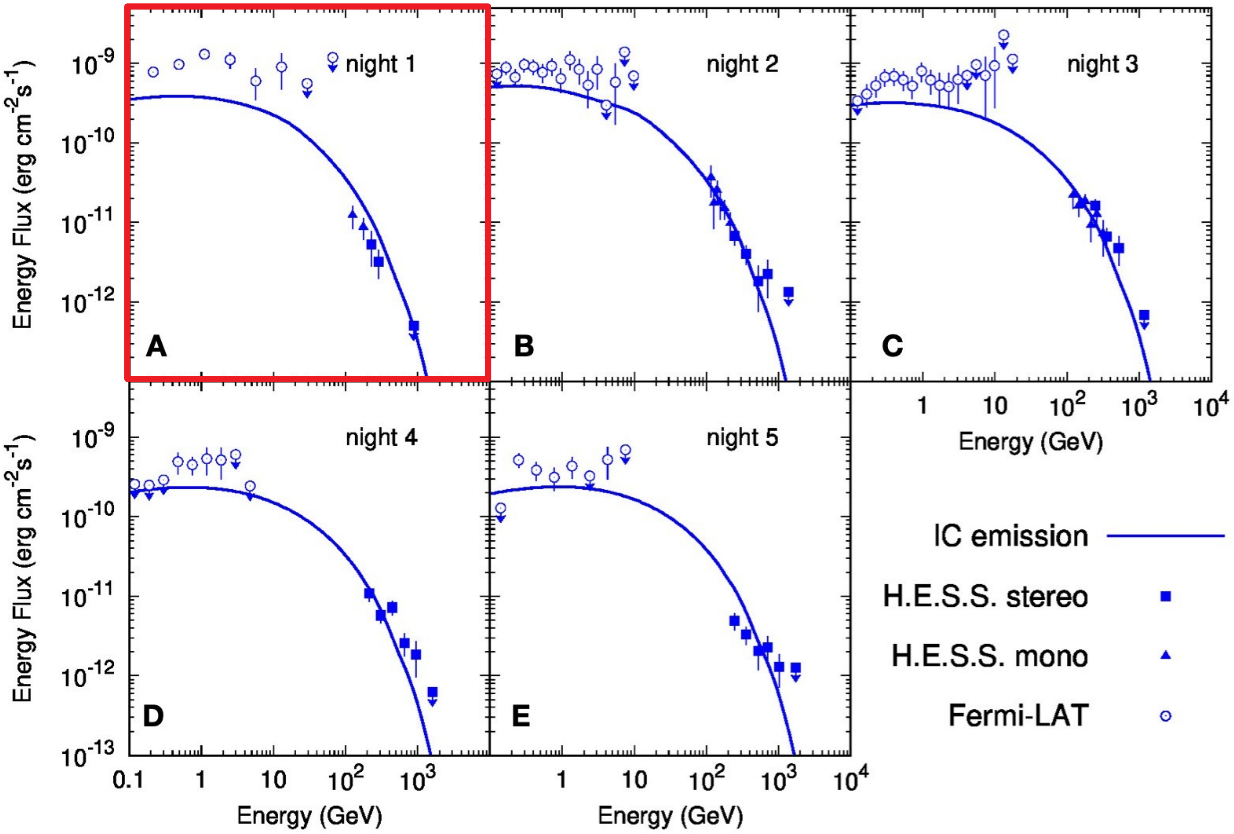
- Expansion pinched in orbital direction
- Collision between ejecta and companion wind
- Formation of external shocks perpendicular to orbital plane
- Diffusive shock acceleration and cooling of electrons and protons
- Shock evolution similar to cc-SNe



Leptonic scenario

- Dominant cooling process: Inverse Compton
- Insufficient to re-produce observed spectrum
- Matching the data requires acceleration efficiency > 1%

→Inconsistent with shock physics

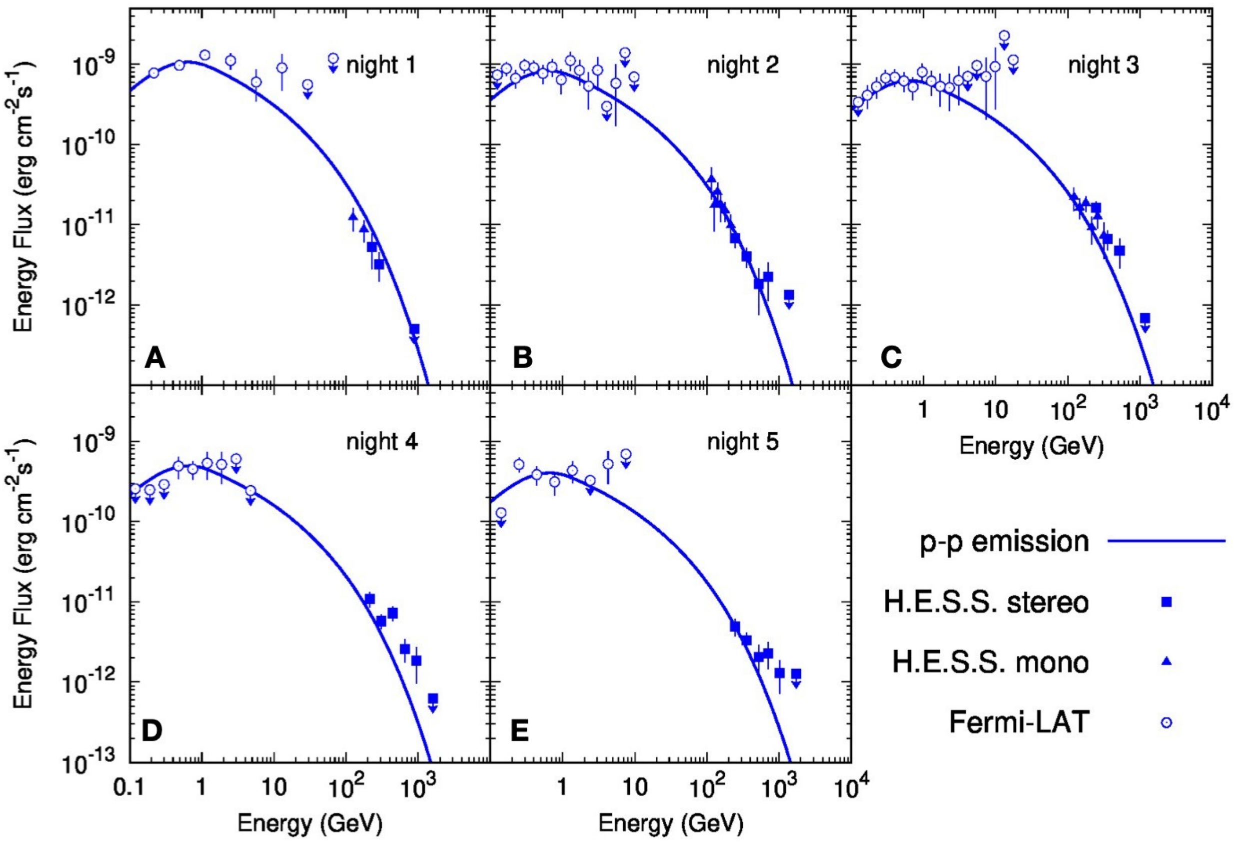


Hadronic scenario

- Dominant cooling process: π^0 decay
- Sufficient to re-produce observed spectrum
- Matching the data requires acceleration efficiency > 10%

→Consistent with shock physics

✓



Conclusion of H.E.S.S. (& MAGIC) detection

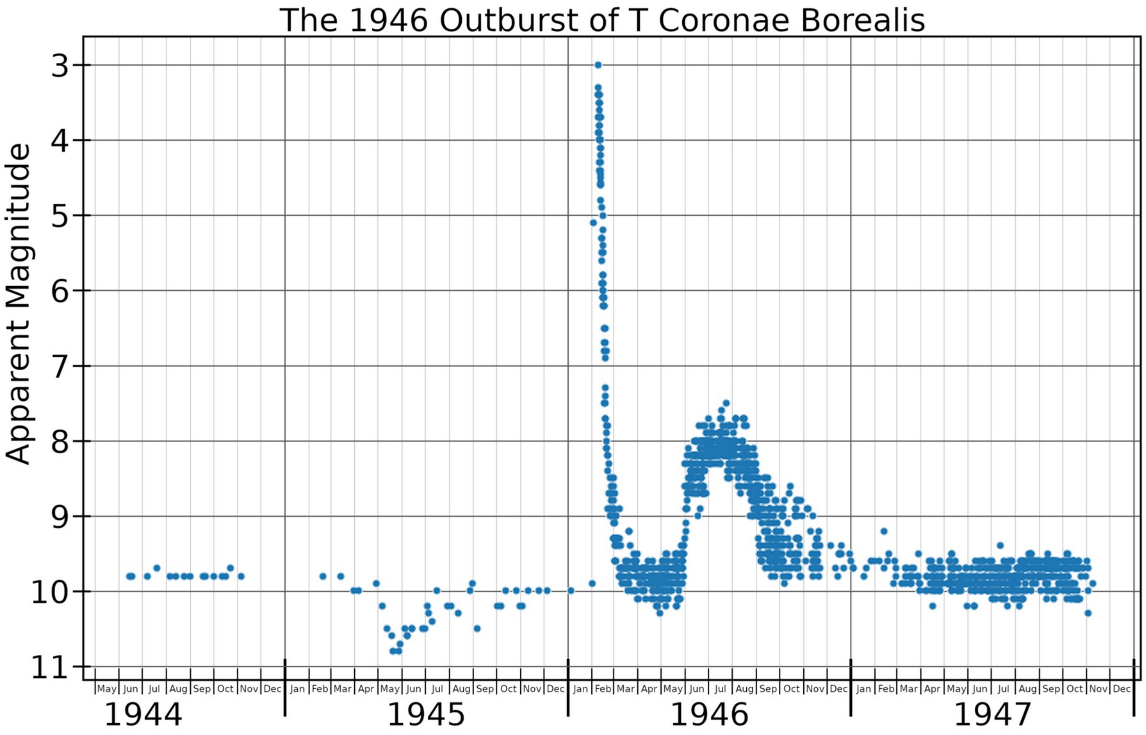
- New source class at VHE γ rays
- Time-resolved diffusive shock acceleration
- Acceleration at the theoretical limit in astrophysical shocks is possible
- Support for cc-SNe as potential PeVatrons
  - (similar but more extreme acceleration systems)

RS Ophuichi	
$\dot{M}$	$\sim 3\text{x}10^{-6}\ M_\odot\ \text{yr}^{-1}$
v_{wind}	~ 10 km/s
E	$\sim 10^{49}$ erg
M_{ej}	$\sim 10^{-6}\ M_\odot$

cc-Supernovae	
$\dot{M}$	$\sim 3\text{x}10^{-5}\ M_\odot\ \text{yr}^{-1}$
v_{wind}	~ 10 km/s
E	$\sim 10^{51}$ erg
M_{ej}	$\sim 10\ M_\odot$

Exciting event ahead

- T Coronae Borealis (T Crb) stated to erupt in 2025.5 ± 1.3
- ~80 year period
  - 1866 : 2 peak mag
  - 1946 : 3 peak mag
- Very close : ~806 pc



Credit: AAVSO

Back-up

DSA Model

protons

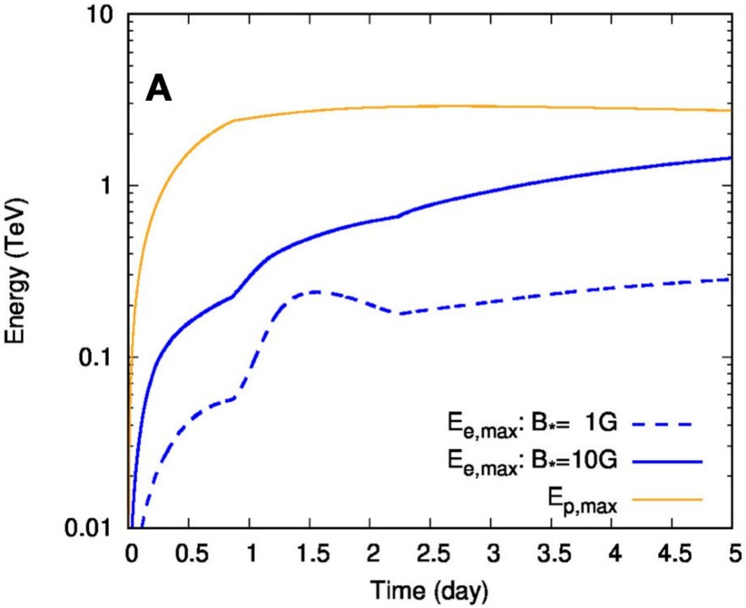
$$E_{\max} = 1.5\,|Z|\left(\frac{\xi_{\rm esc}}{0.01}\right)\left(\frac{\dot{M}/v_{\rm wind}}{10^{11}\,{\rm kg\,m^{-1}}}\right)^{1/2}\left(\frac{u_{\rm sh}}{5000\,{\rm km\,s^{-1}}}\right)\ {\rm TeV}$$

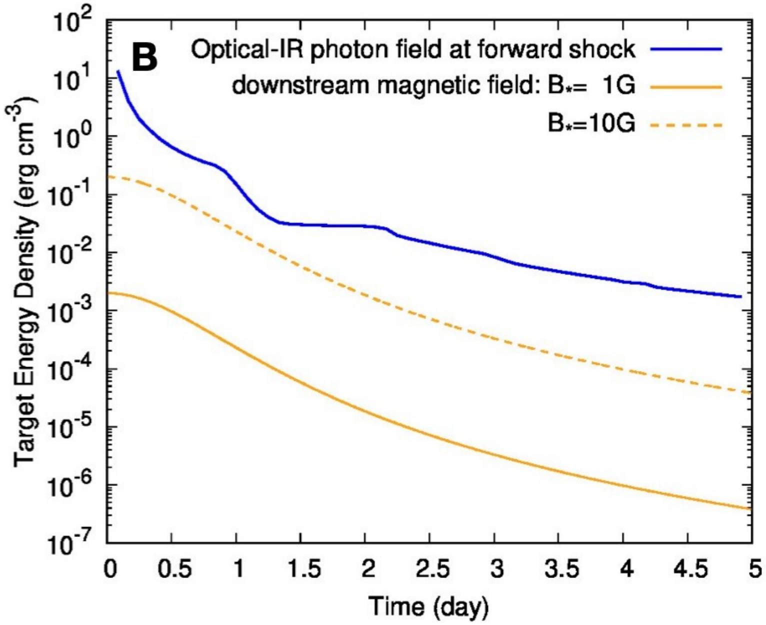
electrons

$$E_{\max} = 10\left(\frac{u_{\rm sh}}{5000\ {\rm km/s}}\right)\left(\frac{R_{\rm sh}}{\rm au}\right)\left(\frac{B_\star}{1\ {\rm G}}\right)\ {\rm TeV}$$

$$t_{\rm syn} \approx 400\left(\frac{E}{1\ {\rm TeV}}\right)^{-1}\left(\frac{B}{1\ {\rm G}}\right)^{-2}\ {\rm s}$$

$$t_{\rm IC,th} \approx 15\left(\frac{E}{1\ {\rm TeV}}\right)^{-1}\left(\frac{\omega_{\rm ph}}{1\ {\rm erg\ cm^{-3}}}\right)^{-1}\ {\rm s}$$





Systematics

Sub-dominant: Monte-Carlo extensive air shower hadronic interaction models, broken pixels of the Cherenkov cameras, and the live time of the data set

Dominant: Atmospheric parameters, Moonlight

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

Table S2: **Nightly spectral measurements of RS Oph.** Best-fitting nightly spectral parameters from H.E.S.S. assuming a power-law model of the form $\phi_0 \left(\frac{E}{E_0}\right)^{-\Gamma}$, with derived systematic uncertainties. E_0 is the reference energy, ϕ_0 is the amplitude at the reference energy and Γ is the spectral index.

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	$\dot{M}/v_{\rm w}$, 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	$v_{\rm ej,0}$, km s^{-1}	3000	
Ejecta mass	$m_{\rm ej}$	$10^{-7} M_\odot$	

Table S4: **Numerical model parameters.** Assumed parameters of the model used in equations (S3) through (S30) above, for the two cases of proton-proton (p-p) emission (see Figure S9) and a leptonic Inverse Compton (IC) model (see Figure S8) respectively.

Attenuation

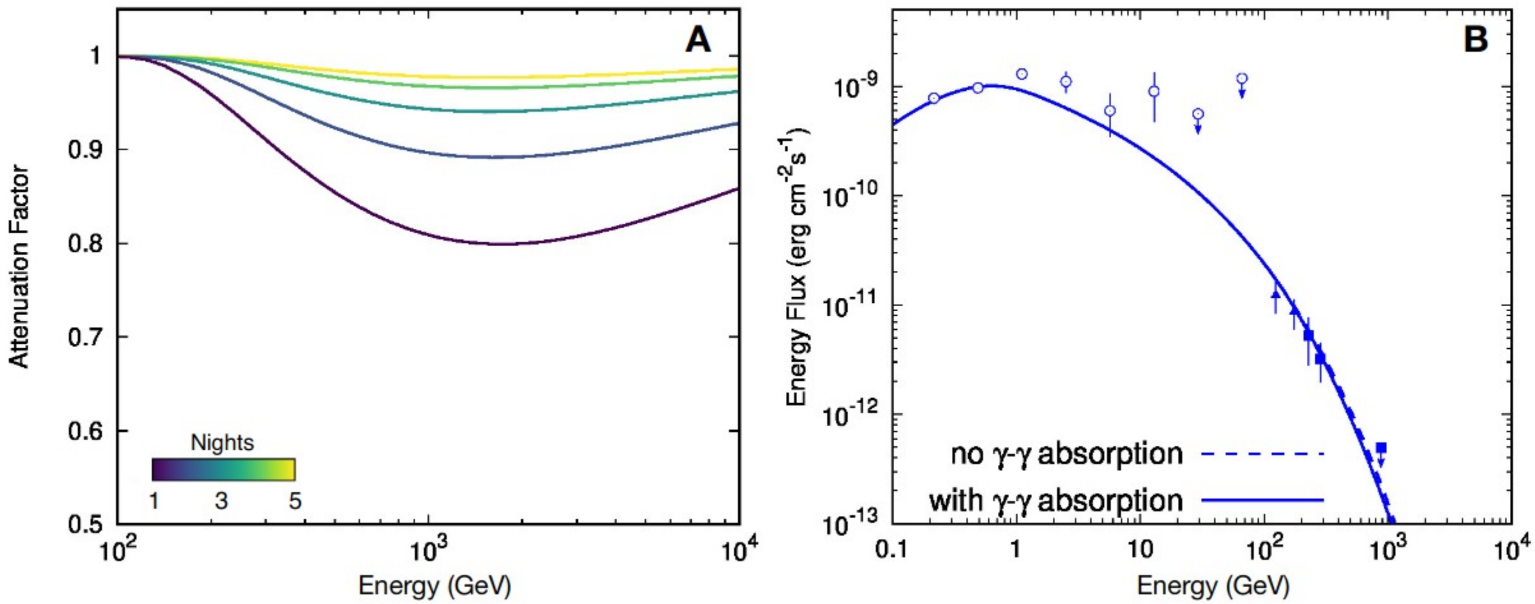
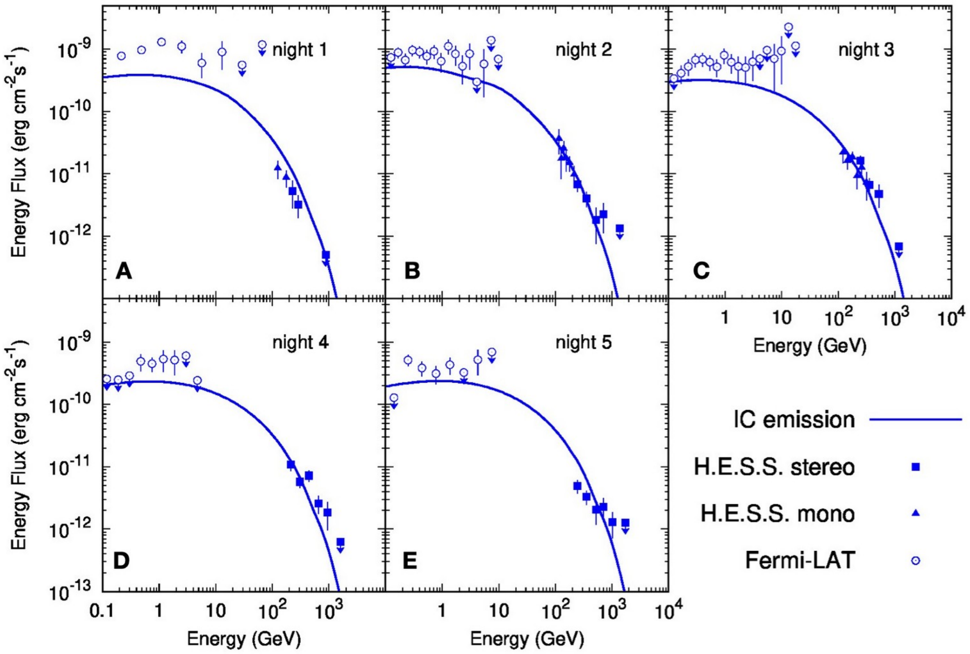
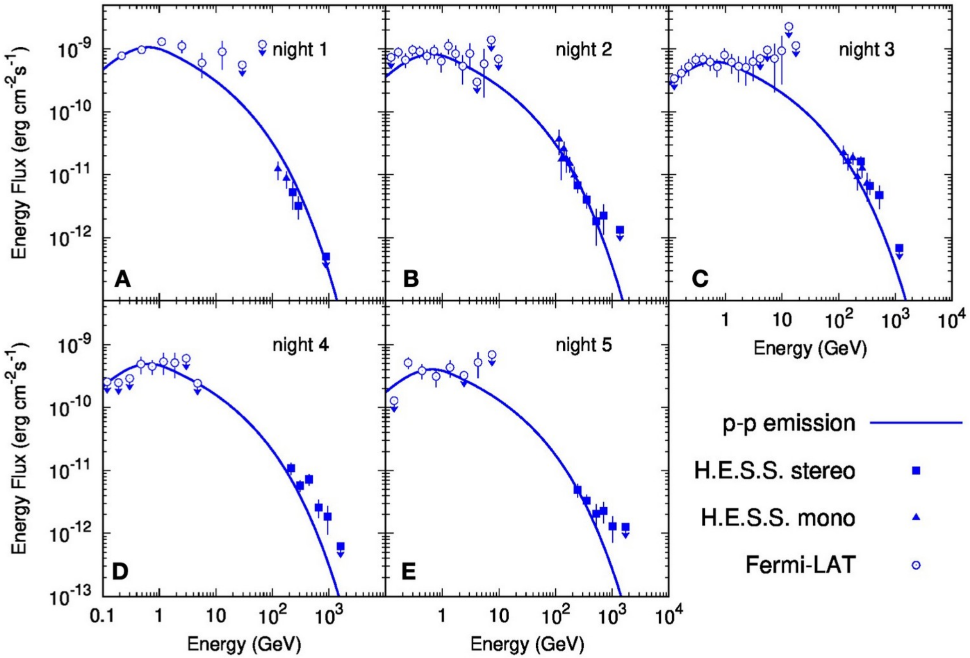


Figure S10: **Effect of gamma-gamma attenuation. A:** Attenuation factor due to the gamma-gamma absorption on the thermal photons produced by the explosion assuming a distance of 1.4 kpc. **B:** The impact of the gamma-gamma absorption on the emission spectrum from night 1 for the source assumed distance of 1.4 kpc. The data points are the same as in Fig. S9.



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



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