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Novae: a recent addition to very-high-energy gamma-ray sky

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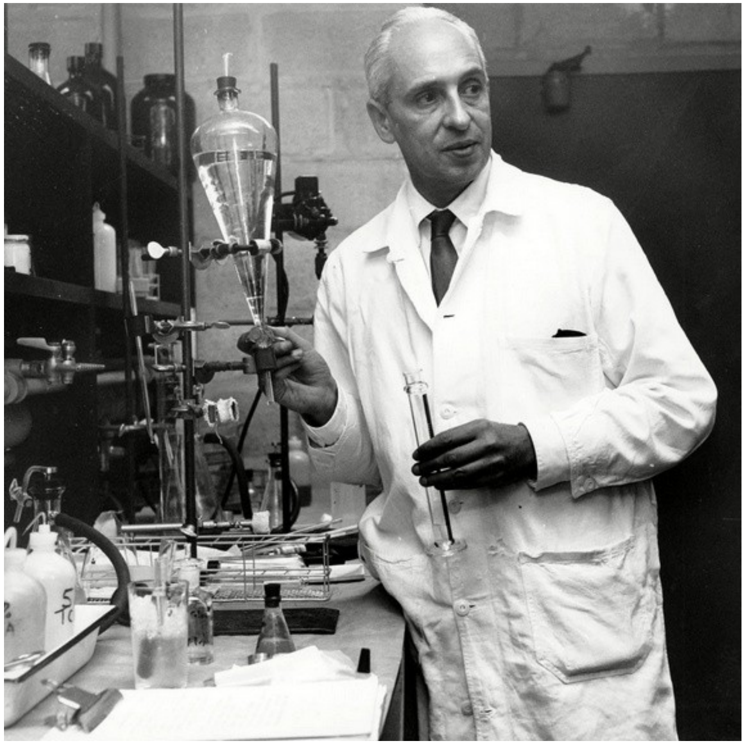
2026.02.06, IFAE Colloquium

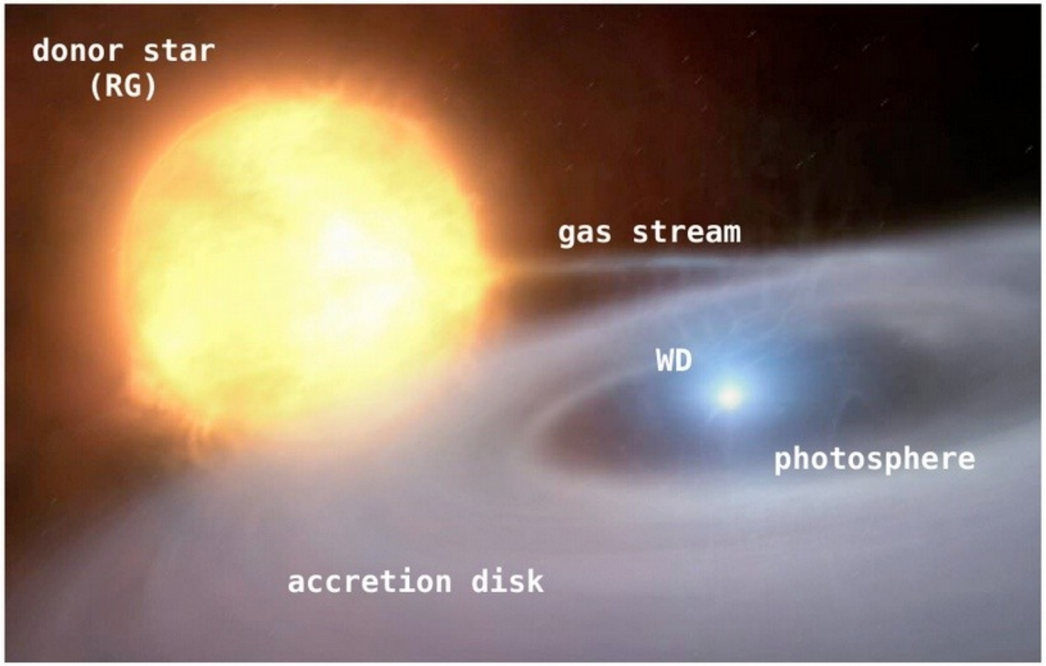
Thank you
Severo Ochoa de Albornoz



For allowing me to come back for some time to IFAE !

What are novae?

- Name “nova” comes from “new star”. Intense optical emission lasts for weeks/months.
- Due to high optical brightness (some are visible with a naked eye) they have been studied for centuries
- Novae are cataclysmic variable binary systems of white dwarf (WD) and a donor star.
- Mass transfer from the donor star causes thermonuclear explosion of the hydrogen accumulated on the WD.



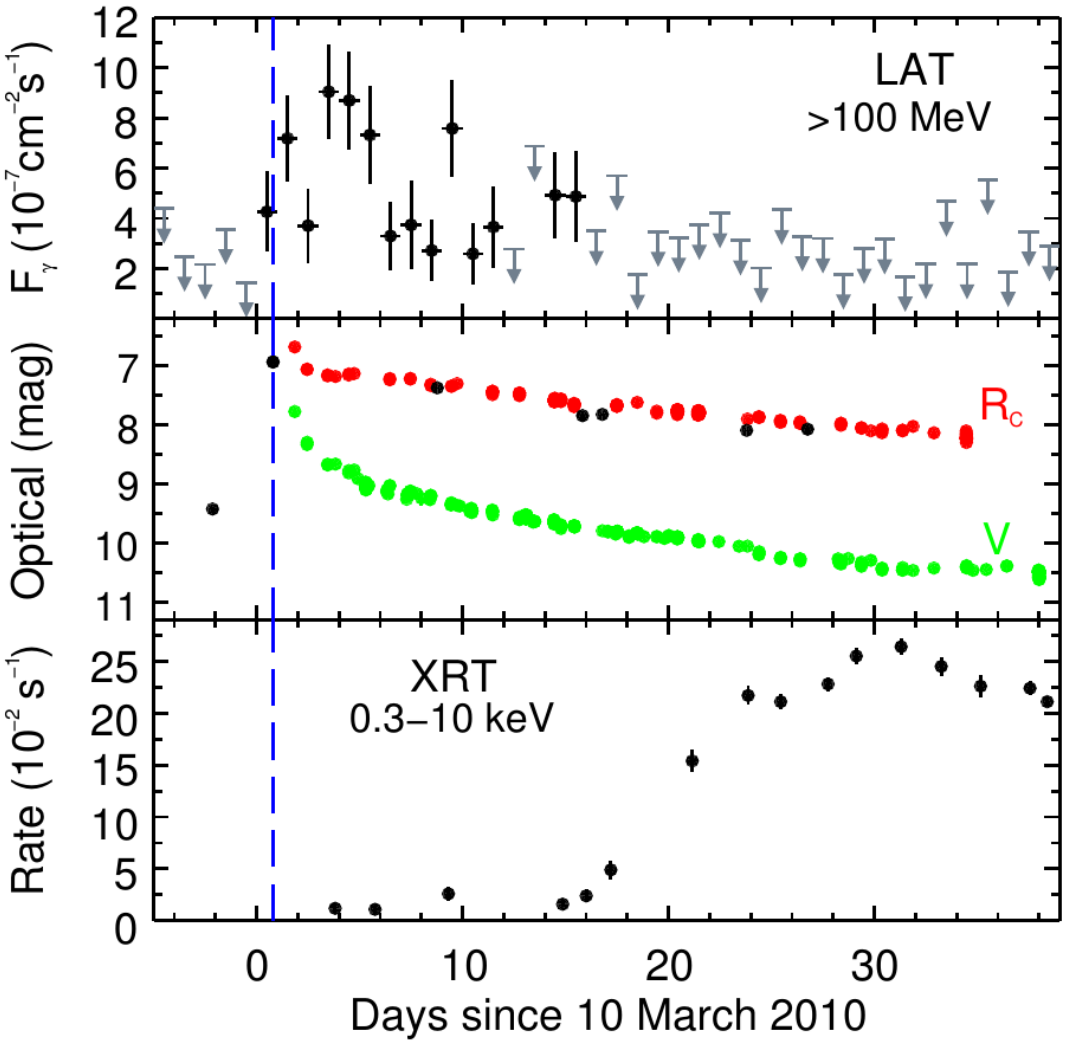
Credit: ESO / M. Kornmesser

Types of novae

- Observationally there are different types of nova, depending what kind of lines are seen from it (and also few types of objects with similar names, but which have little to do with novae).
- More fundamentally there are two classes of novae:
  - **Classical novae**: the donor star is a (low-mass) main sequence star
  - If the donor star is a RG, the system is immersed in its wind, creating a **symbiotic binary**.
- While most of novae should repeat, some of them have WD very close to the mass limit, causing repetition of outbursts in human lifespan (<100 years) – **recurrent novae**.

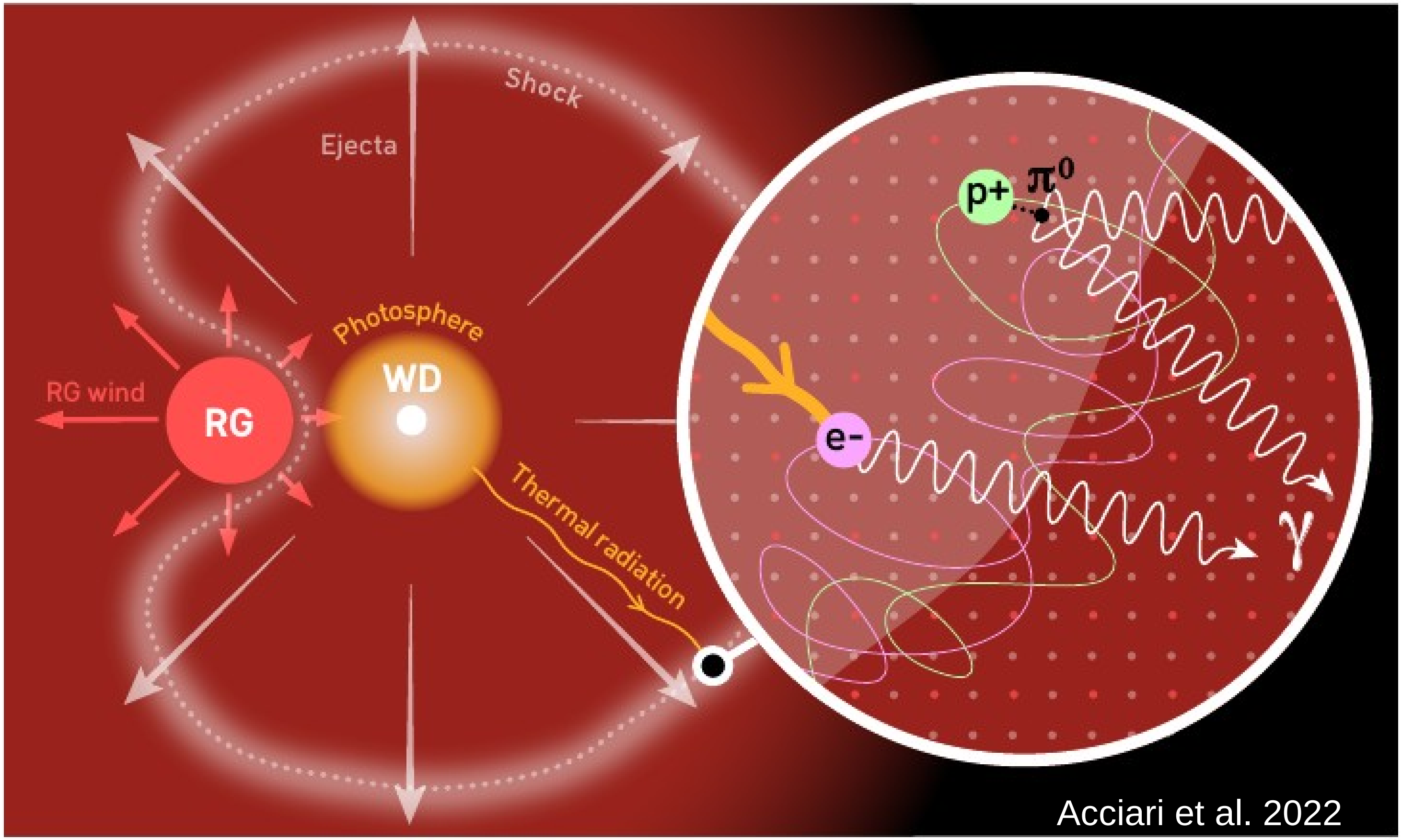
Gamma-ray emission from novae?

- The first novae seen in GeV (by Fermi-LAT) gamma rays was V407 Cyg
- V407 Cyg is a symbiotic binary
- The detection of first nova in gamma rays (while not completely unexpected) was quite a surprise!



Abdo et al. 2010

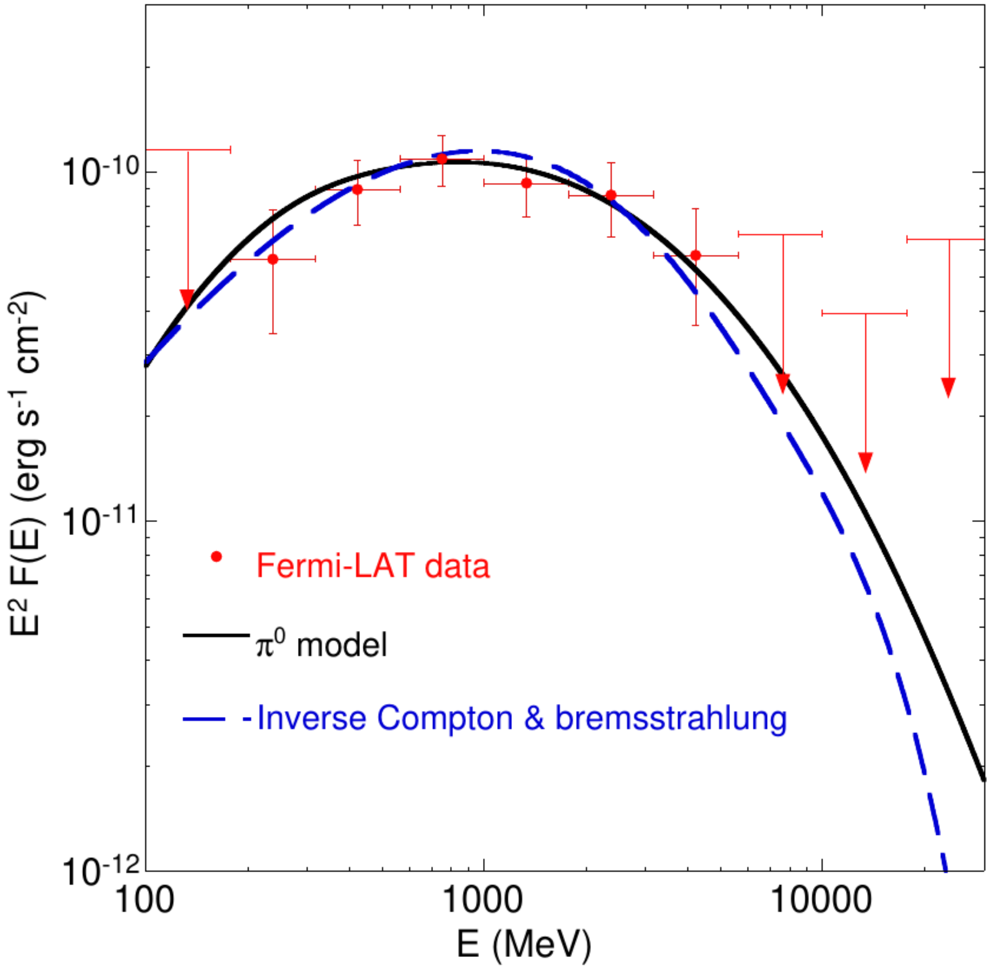
Environment in the nova



Possibility to accelerate both electrons and protons.
Which are responsible for the VHE gamma-ray emission?

Emission mechanism in novae: protons or electrons

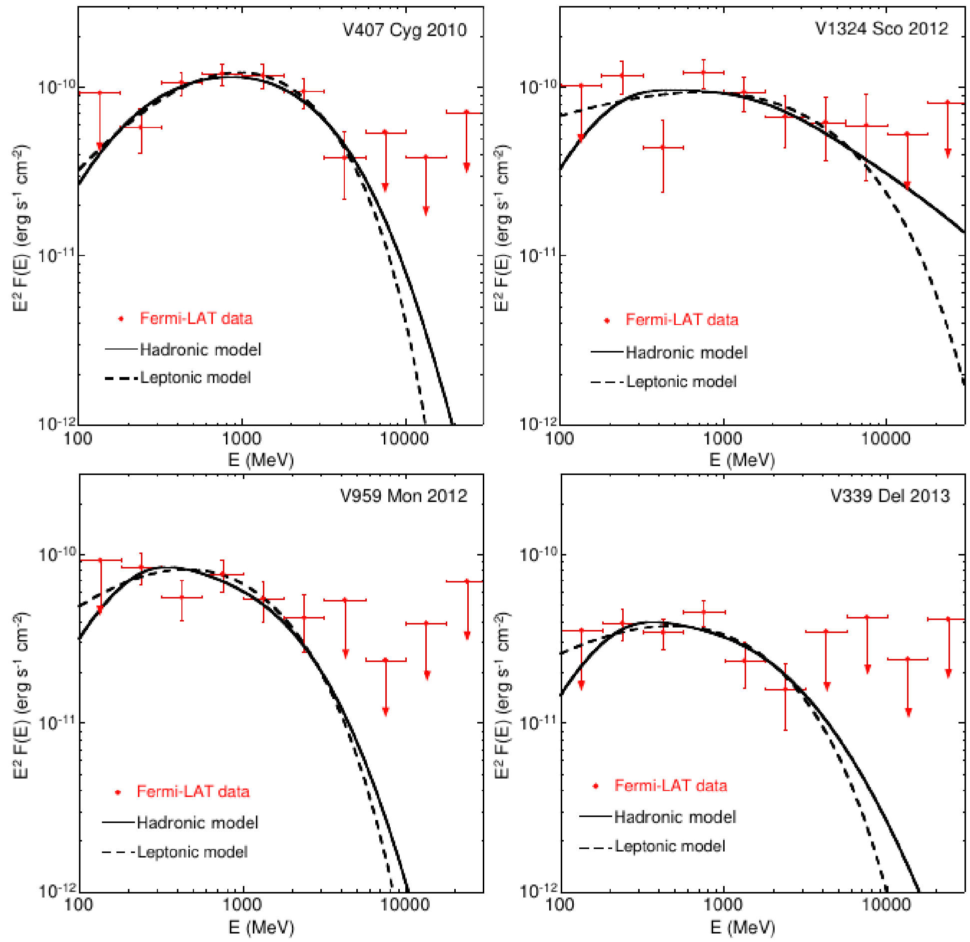
- Fermi-LAT data alone were not sufficient to disentangle the origin of the gamma-ray emission.
- Both leptonic and hadronic models were possible



Abdo et al. 2010

Further gamma-ray novae

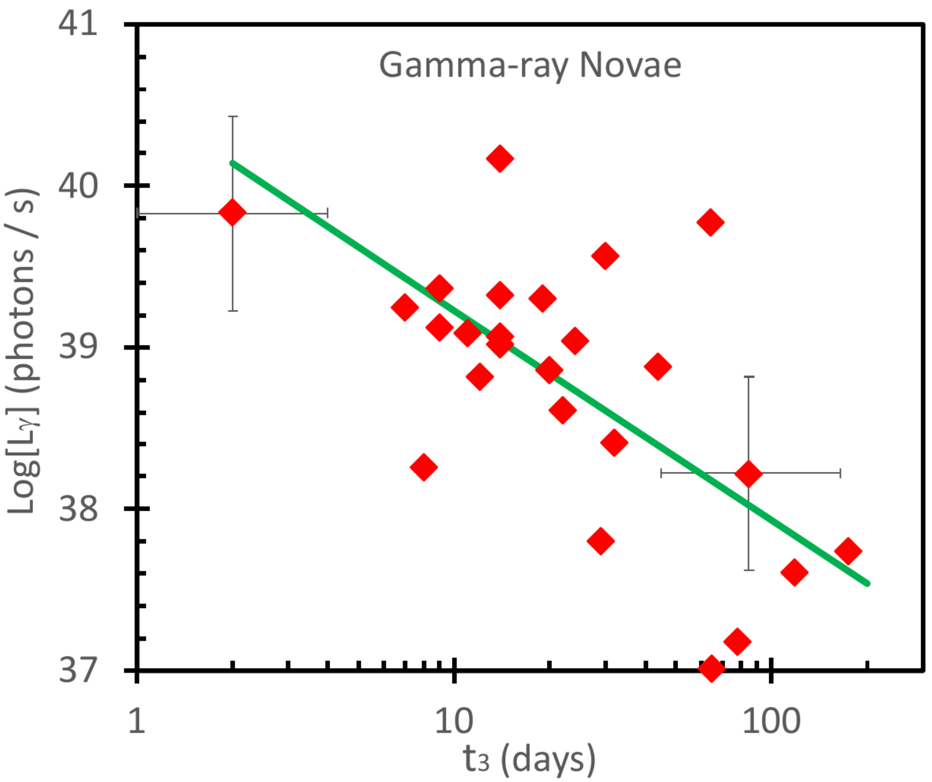
- After V407 Cygni a number of classical novae were detected by Fermi-LAT (now ~30)
- Shock waves connected with novae outbursts produce conditions favorable for acceleration of charged particles
- Ambient matter and radiation fields serve as a target for those accelerated particles – mechanism for gamma-ray production
- But the emission could be measured only up to a few GeV and both leptonic and hadronic models were still consistent with the data



Ackermann et al., 2014

Gamma-ray nova

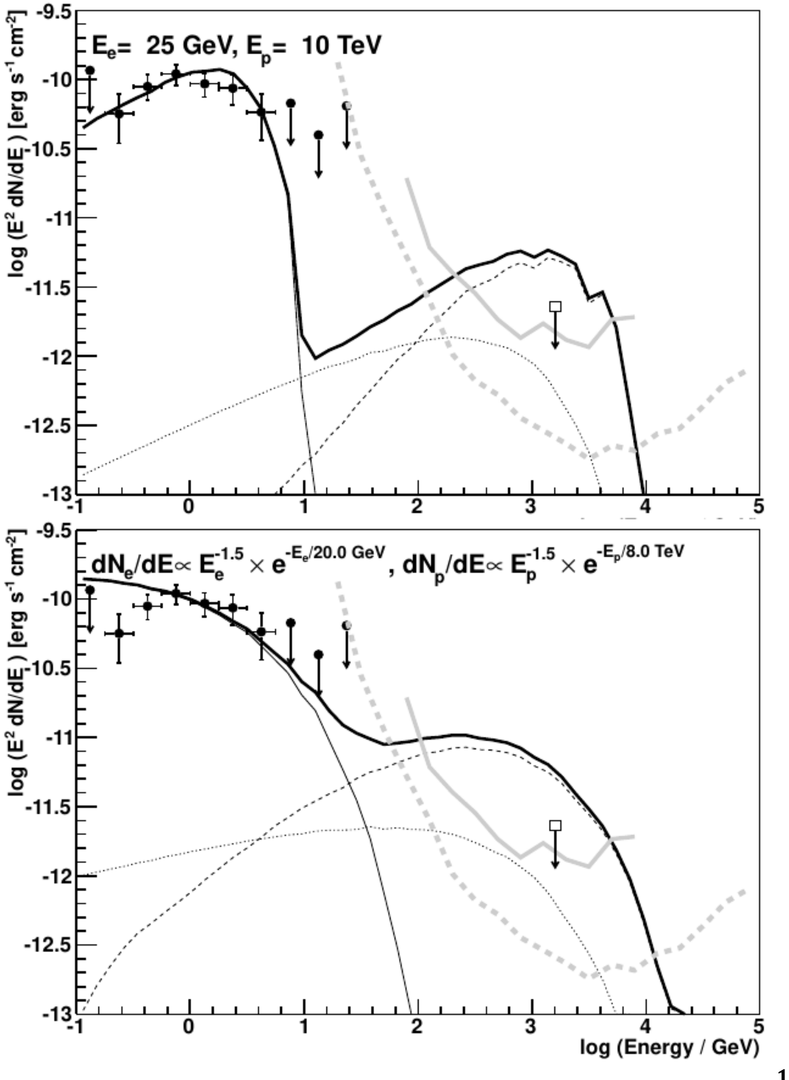
- Despite having a small population of GeV novae already, we do not understand their emission well.
- The novae parameters do not correlate with the gamma-ray brightness except of the t_3 decline time (for unknown reason)



Schaefer, 2025

And what if both electrons are protons are accelerated?

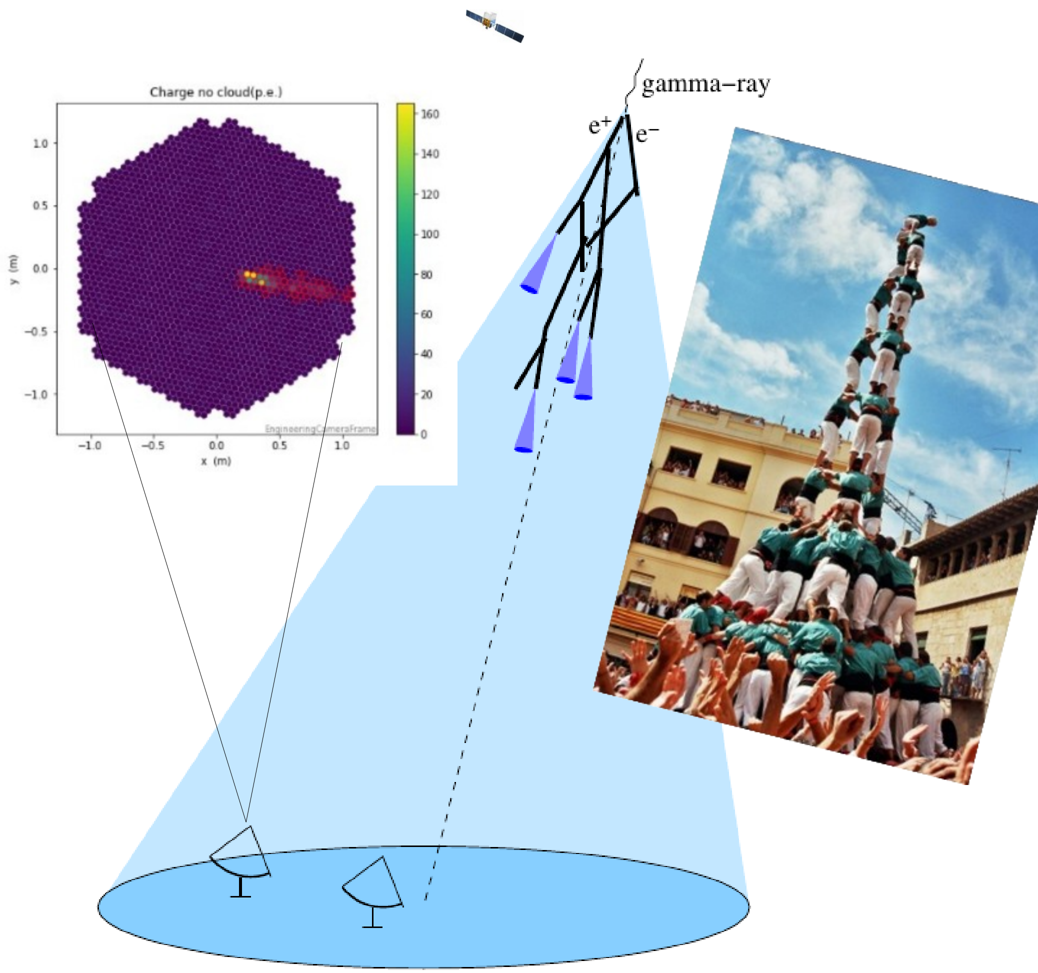
- The steepening of the GeV spectrum of V407 Cygni did not look too promissing for VHE range.
- But if the answer to “electrons OR protons” is “electrons AND protons” the emission would have a second component in TeV range.
- Follow-up project with MAGIC telescopes was started...



JS & Bednarek, 2012

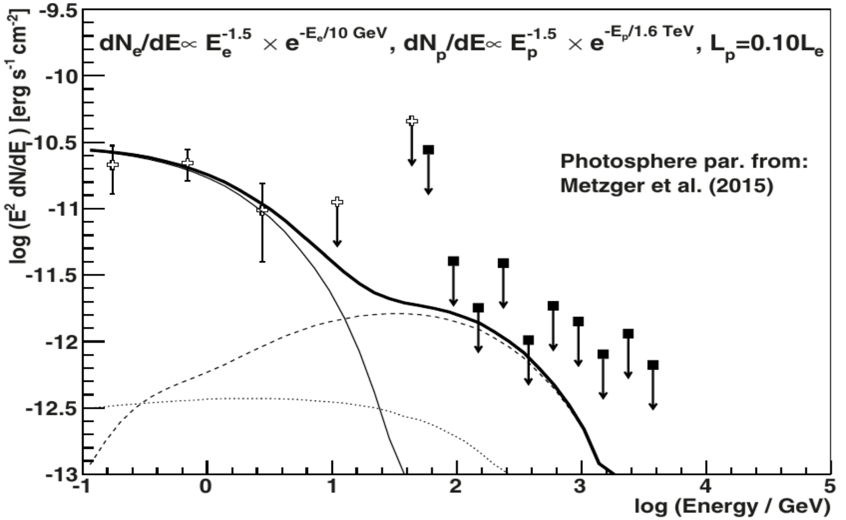
Going to higher energies

- Cherenkov telescopes gather light from the area with radius of ~120m illuminated by Cherenkov light induced by passage of the shower initiated by the primary gamma-ray
- Collection area is much larger even than physical size of the telescopes, and orders of magnitude larger than of satellite experiments
- Having Cherenkov telescope with large mirror area (MAGIC, LST, H.E.S.S.-II) allows observations also close to the top part of the Fermi-LAT energy range.



MAGIC novae follow-up program

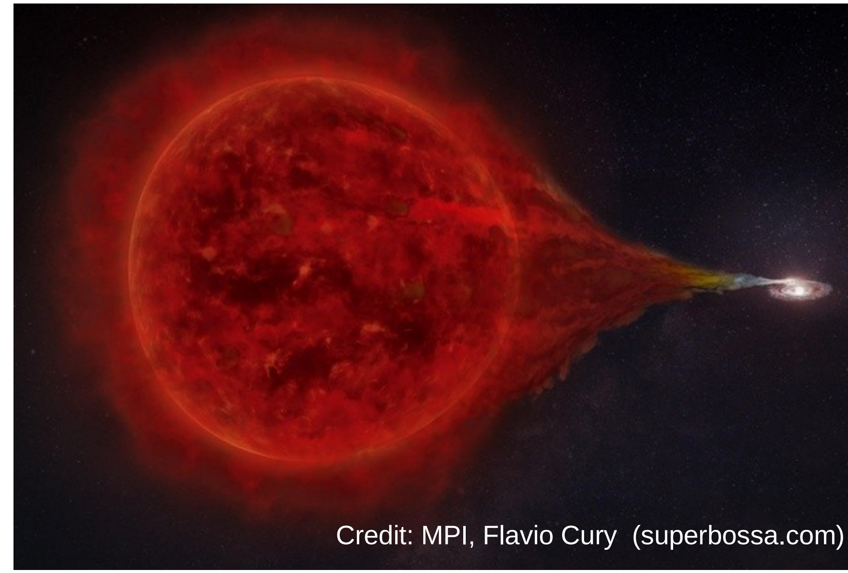
- Triggers based on GeV detection or on bright optical emission
- The first decade of the program resulted in observations of a few novae – no detection, but we put limits on a hadronic emission in sub-TeV range (in joint leptonic+hadronic model)
- And in August 2021 …



Ahnen et al. 2015

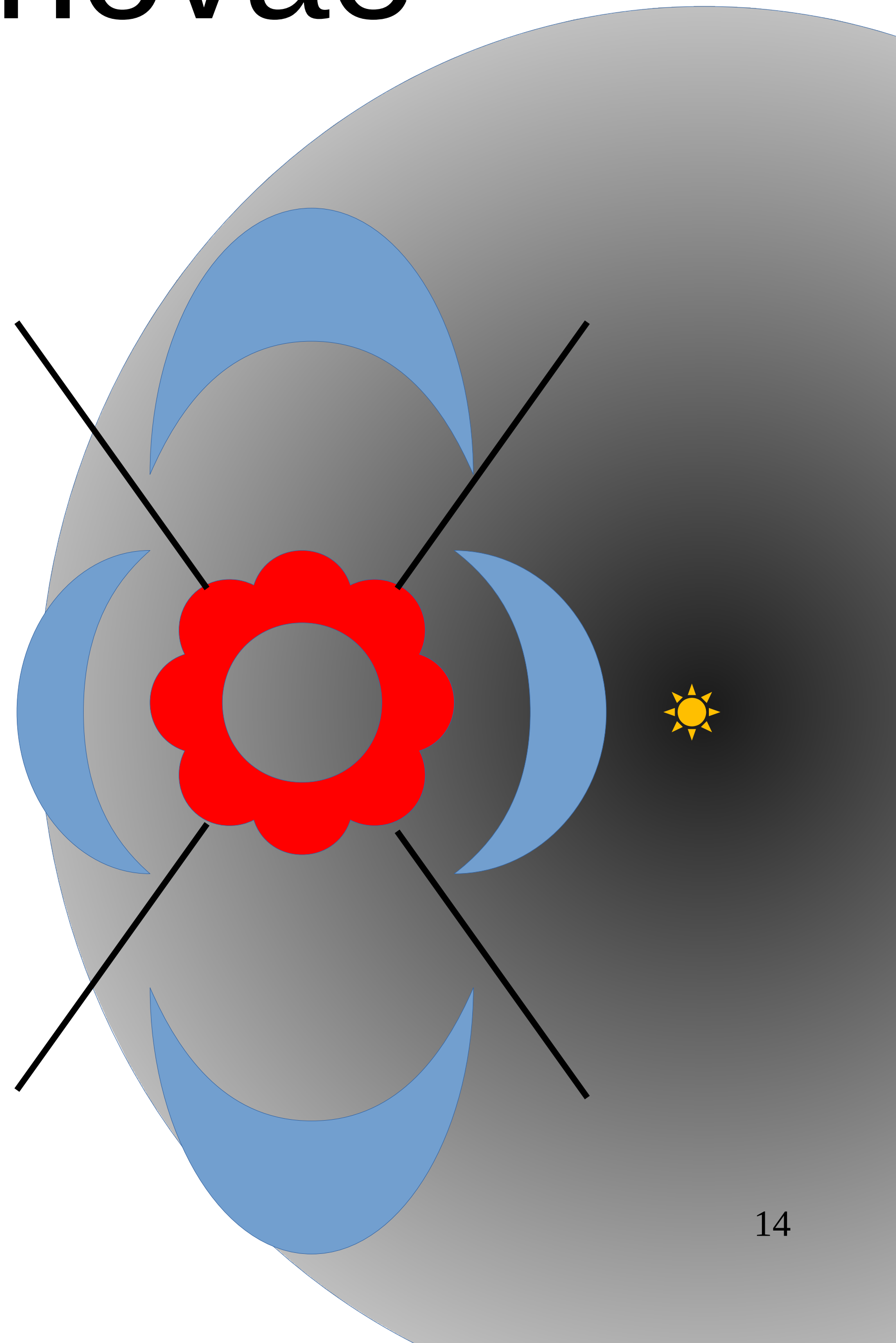
RS Ophiuchi

- Recurrent symbiotic novae with outbursts every ~15 years
- Latest outburst on 2021.08.8 UT ~22:20
- Independently followed and detected by H.E.S.S. (Aharonian et al. 2022), MAGIC (Acciari et al. 2022) and LST-1 (Abe et al. 2025)
- Distance somewhat uncertain, but about 2.45 kpc (Rupen et al., 2008)



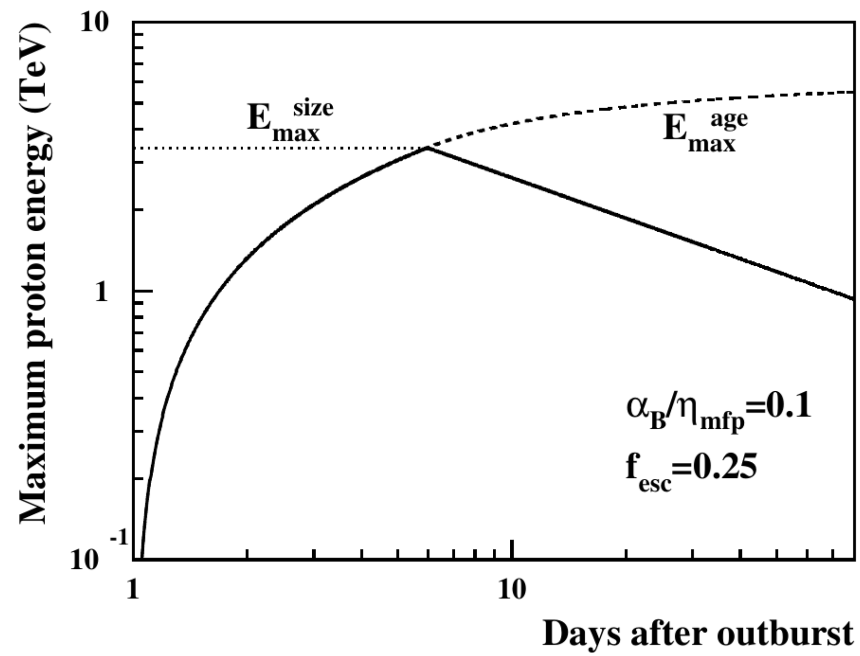
Shocks in novae

- The ejecta from the nova can produce shock on the surrounding matter (in particular in symbiotic systems)
- Observations of lines often show different speeds of outflows – internal shocks between outflow parts moving with different speeds are also possible.



Expectations from RS Oph

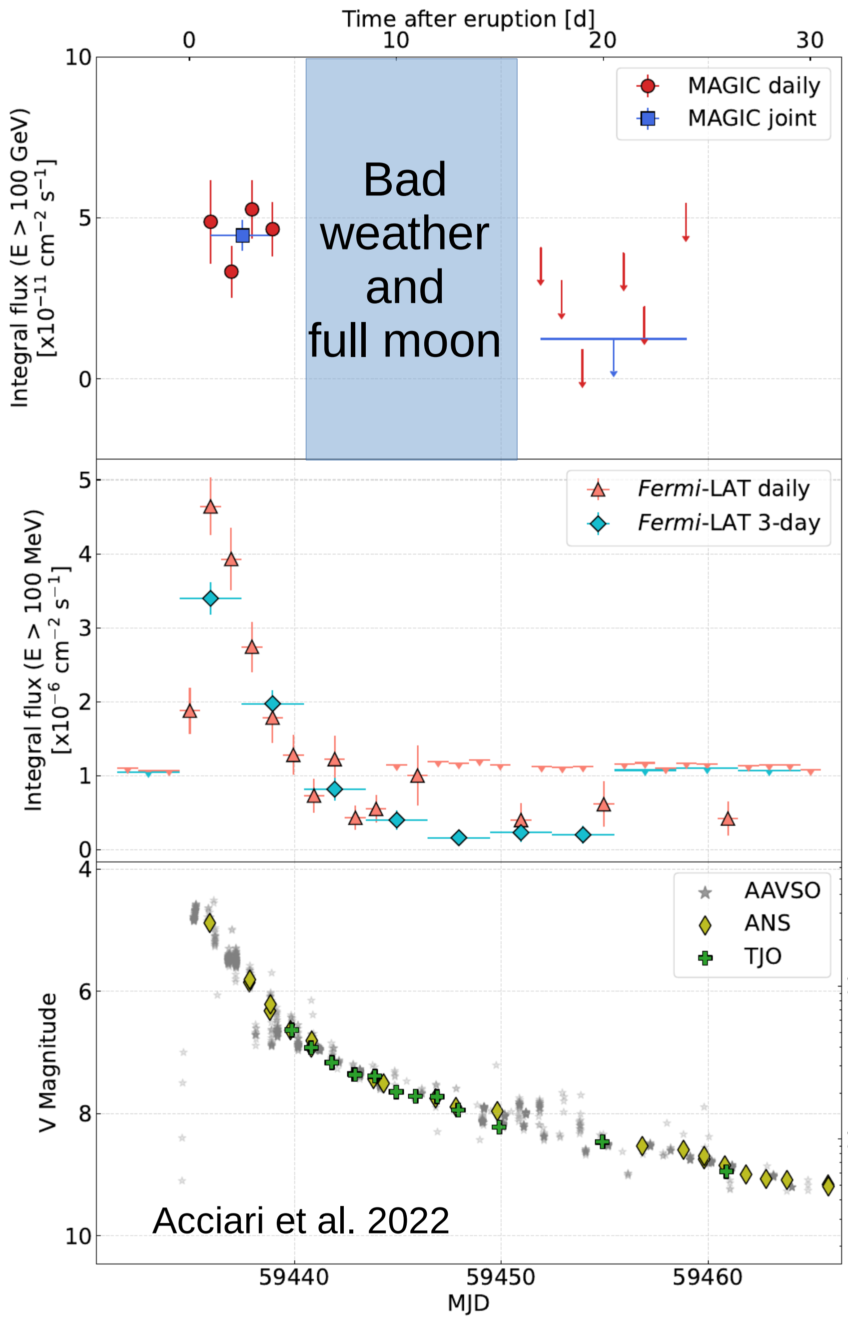
- After the previous explosion from 2006 it was already envisioned that TeV protons could be accelerated in the shock wave of the nova



Tatischeff and Hernanz 2007

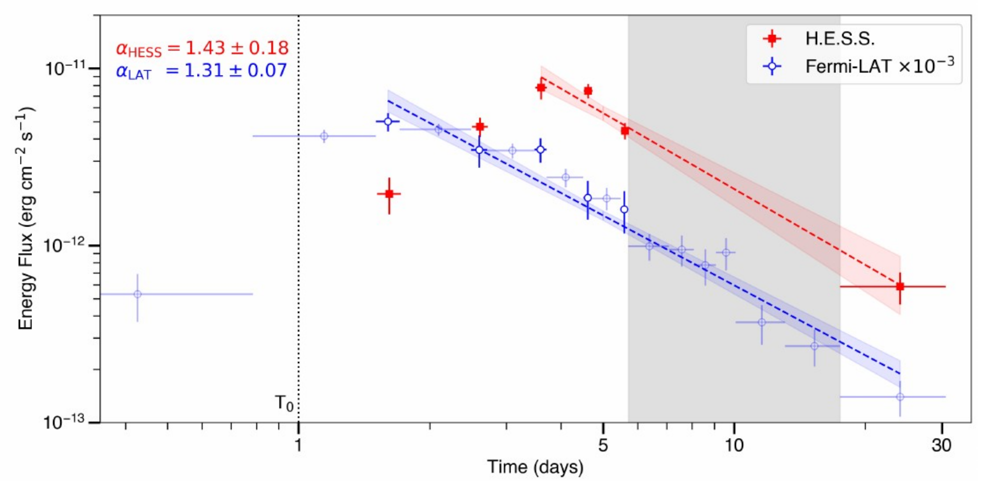
MAGIC observations of RS Oph

- **The first nova detected in VHE gamma rays**
- Daily observations (and SED measurement) from 1 day after the optical nova outburst
- VHE photon flux in the first 4 days consistent with a constant (rapid decrease in optical and GeV fluxes)
- Observations after two weeks showed that the emission dropped below the detection limit



H.E.S.S. view of RS Oph

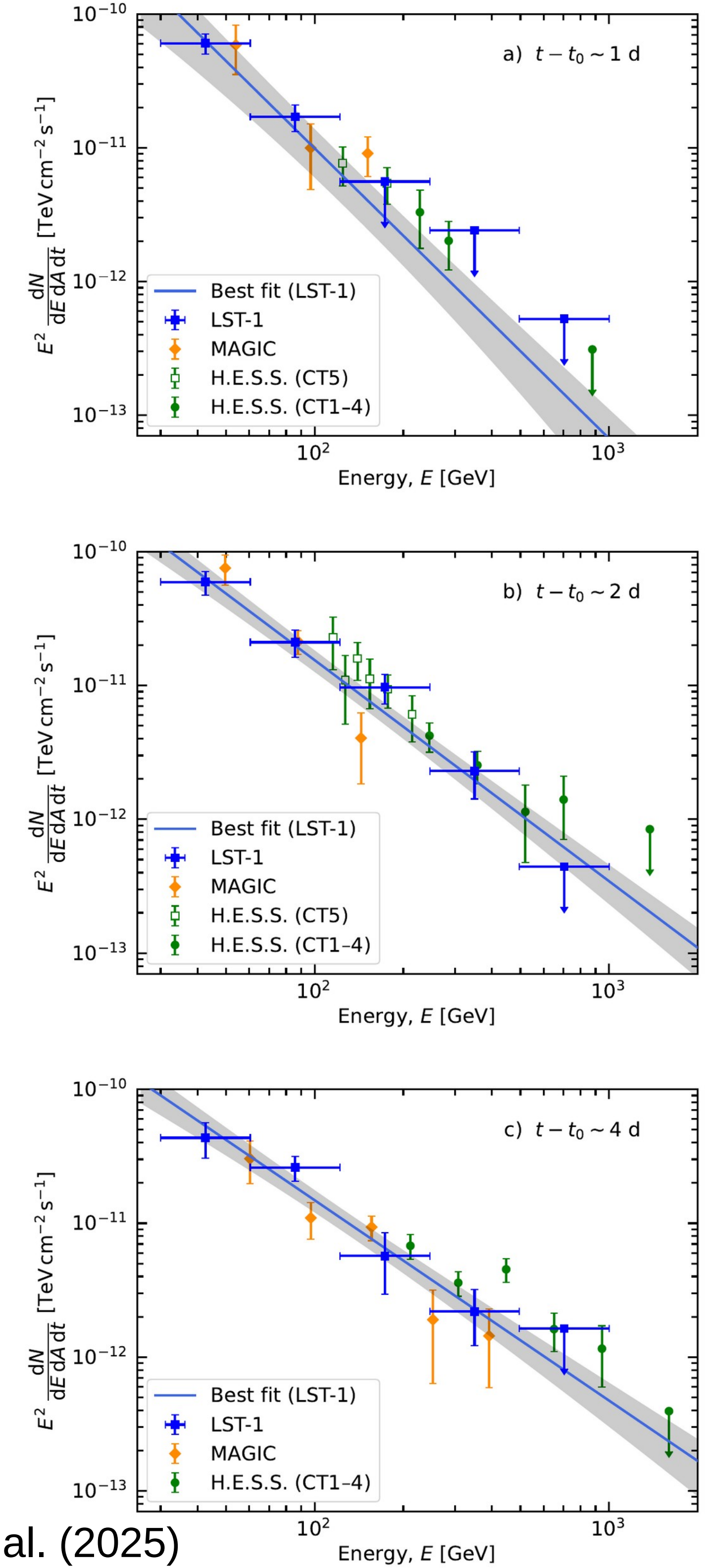
- H.E.S.S. telescopes also claimed some emission after ~20 days, however the flux uncertainty is large (and could also be just a fluctuation)



(H.E.S.S. Coll.) Aharonian et al. 2022

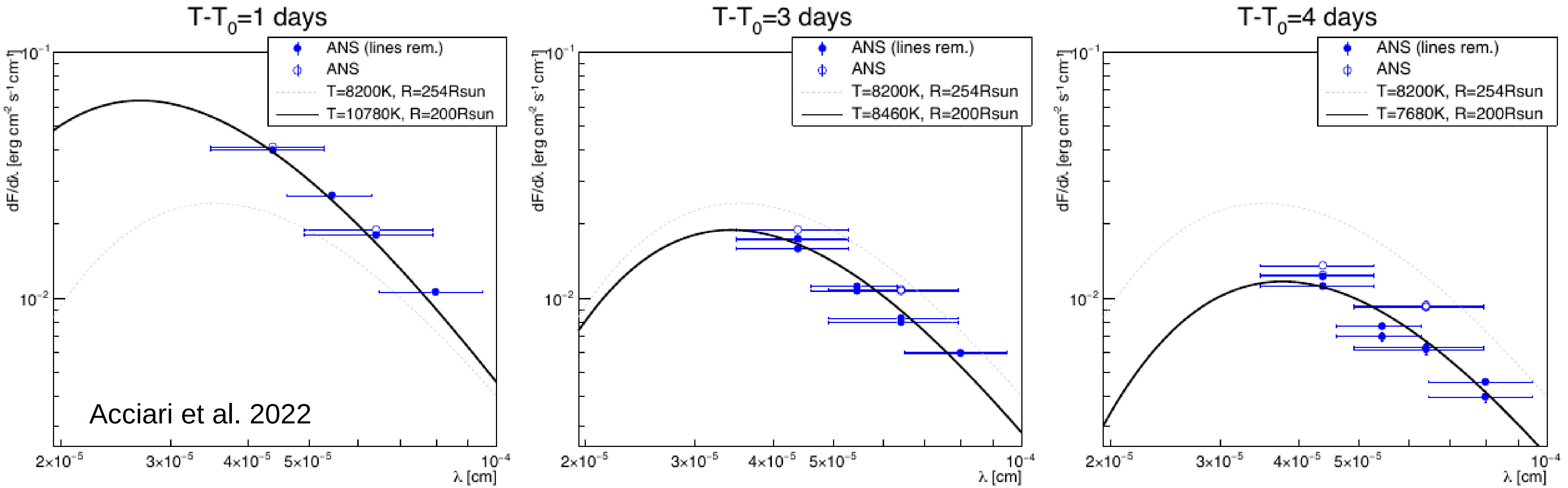
All Cherenkov telescopes

- The spectra of MAGIC, H.E.S.S. and LST-1 observed at different days are roughly in the same ballpark



Abe et al. (2025)

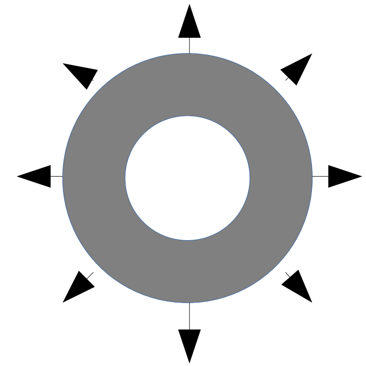
Photosphere radiation field



- Photosphere considered as a black body with the varying temperature – in the first days dominates over the RG radiation by a factor of 100.
- Fit with photometry measurements (corrected for the effect of lines)
- Simplified model, but sufficient for evaluation of the radiation field for gamma ray production and absorption

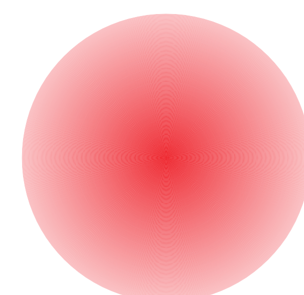
Target for pp interactions

- Expanding shell of ejecta (dominating):



$$n_{ej} = \frac{M_{ej}}{4\pi h R_{sh}^3 m_p} = 6.0\times10^8 \frac{M_{ej}}{10^{-6} M_\odot} \left(\frac{v_{sh}}{4500\,\mathrm{km\,s^{-1}}}\right)^{-3} \left(\frac{t}{3\,\mathrm{d}}\right)^{-3} \left(\frac{h}{0.1}\right)^{-1} [\mathrm{cm}^{-3}]$$

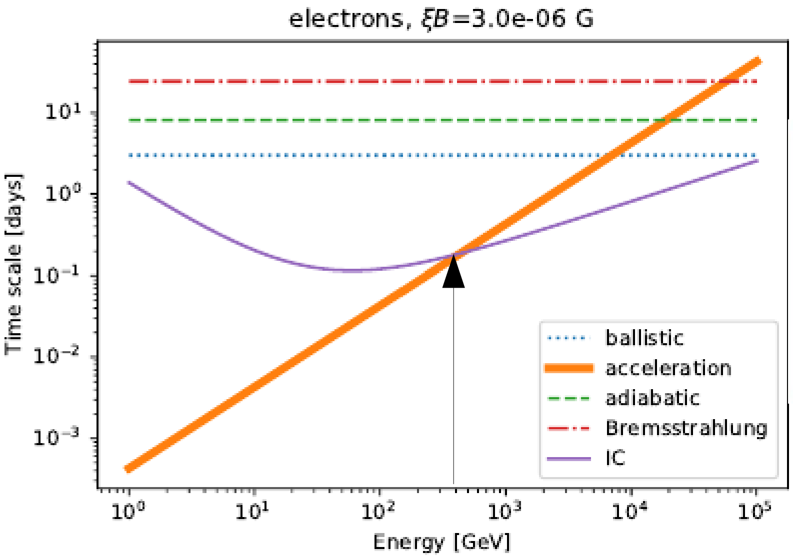
- Red giant wind, of the order of 20% contribution:

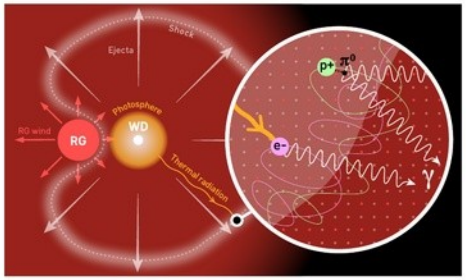


$$n_{RG} = \frac{\dot{M}_{RG}}{4\pi R_{sh}^2 v_{RG} m_p}$$

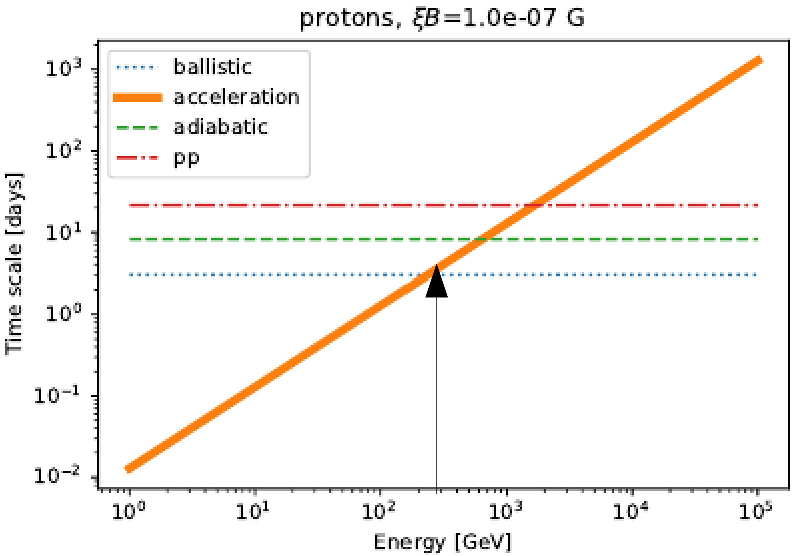
$$= 1.1\times10^8 \frac{\dot{M}_{RG}}{5\times10^{-7} M_\odot/\mathrm{yr}} \left(\frac{v_{sh}}{4500\,\mathrm{km\,s^{-1}}}\right)^{-2} \left(\frac{t}{3\,\mathrm{d}}\right)^{-2} \left(\frac{v_{RG}}{10\,\mathrm{km\,s^{-1}}}\right)^{-1} [\mathrm{cm}^{-3}]$$

Acceleration and energy losses



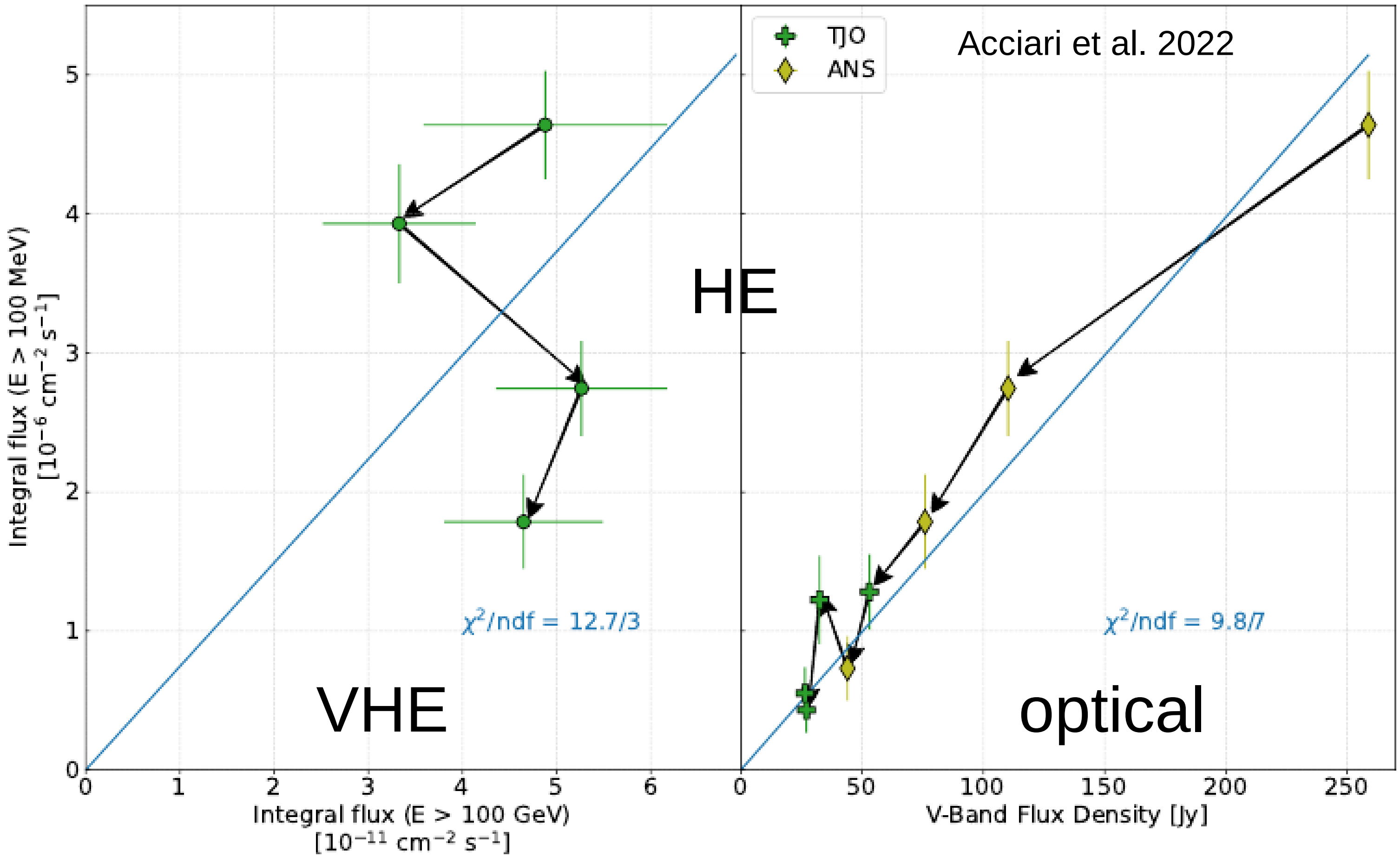


Acciari et al. 2022



- Electron scenario:
  - IC emission on the photosphere radiation field
  - Fast cooling of electrons (**varying electron distribution during emission is taken into account!**)
  - Bremsstrahlung subdominant w.r.t. IC
- Proton scenario:
  - pp interactions on ejecta (and also on some wind matter)
  - Little energy losses:
    - maximum energy limited by acceleration time (expected to raise as the nova progresses)
    - Most of the proton energy will be carried away from the nova – contribution to Galactic CRs

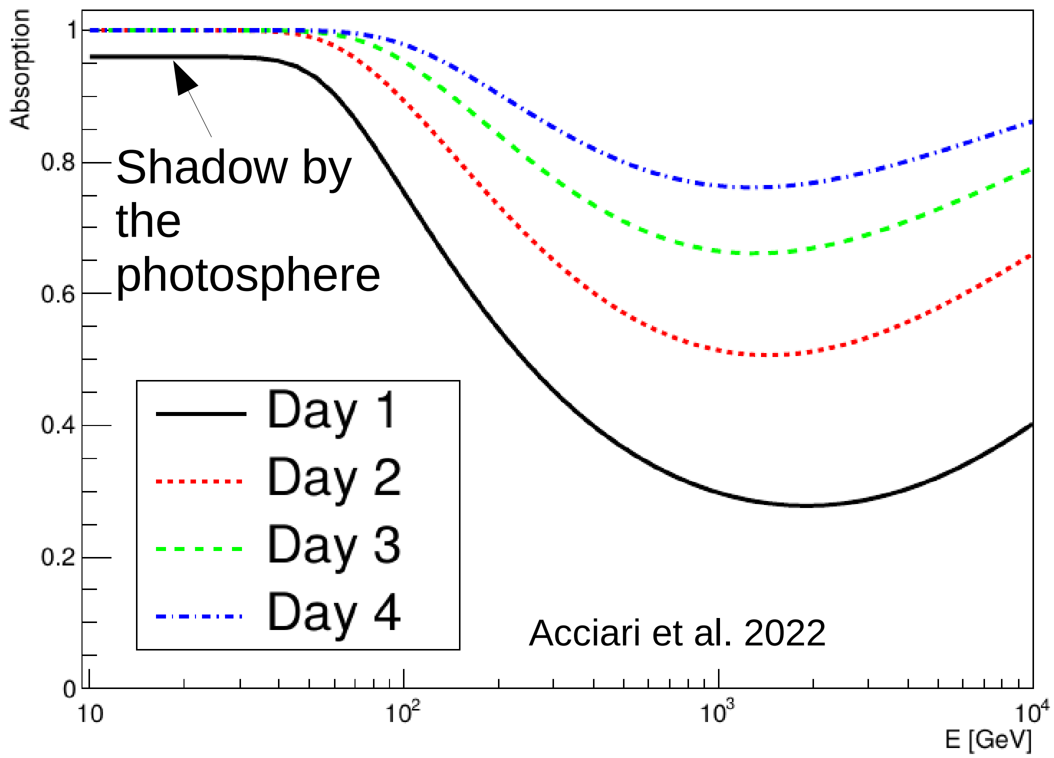
GeV vs TeV, GeV vs optical



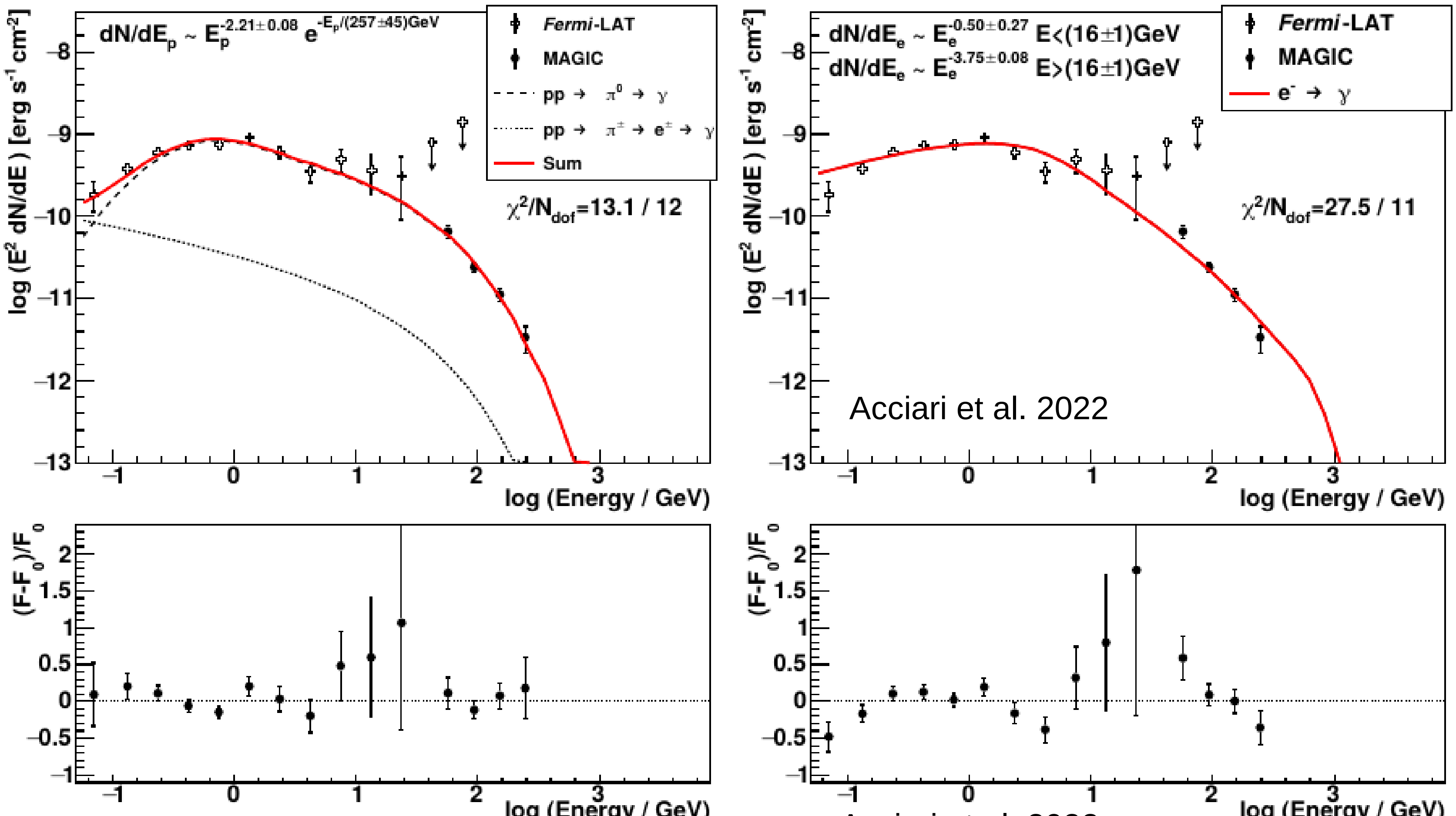
- Decaying GeV emission of Fermi-LAT with roughly constant VHE flux seen in MAGIC shows hints of hardening of the gamma-ray emission
- While optical and GeV emission follow similar decay this does not directly support IC scenario – due to shock propagation the radiation field seen by electrons will decay faster

Absorption of gamma rays

- Photosphere radiation can absorb the produced gamma rays, however this effect is only important in the very first days, and even then most of the gamma rays below a few hundred GeV is able to escape



MAGIC+Fermi-LAT data: Proton vs electron models

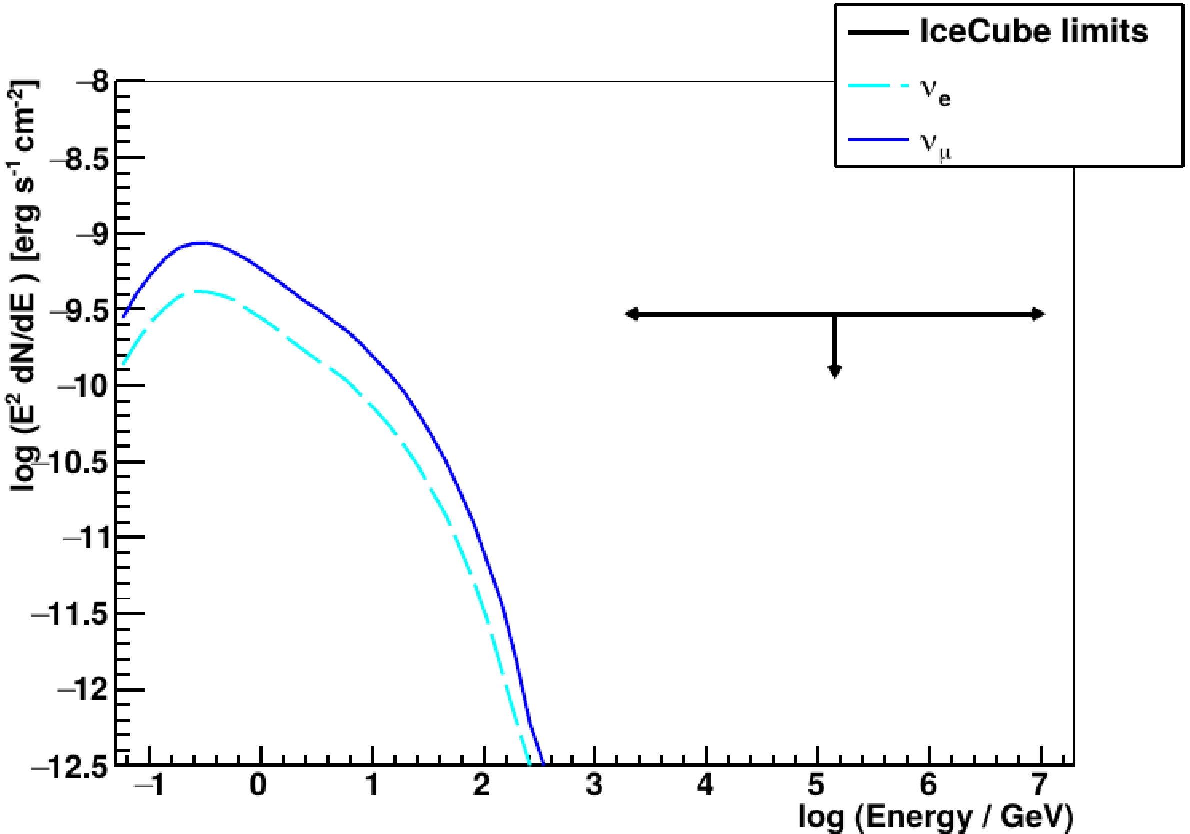


Acciari et al. 2022

- Electron model needs peculiar **injection** spectrum (with intrinsic, non-cooling, break) – **preference for protons**
- AIC test: electron model is only 4.7 x 10^{-4} times as probable as proton model – **another preference for protons**

Neutrino emission?

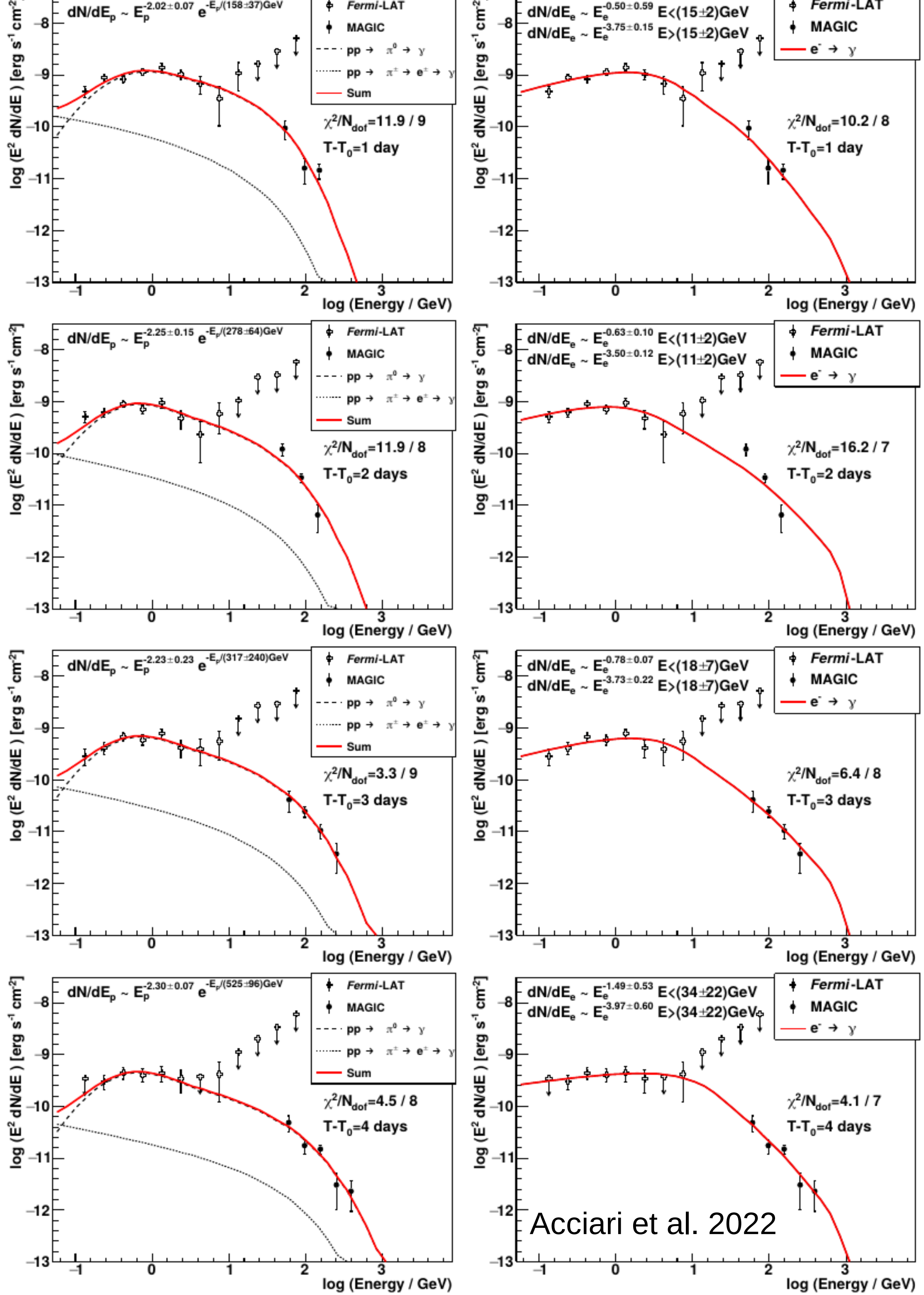
- The protons accelerated in the nova do not reach high enough energies to be detectable by Ice Cube.
- For low energy experiments (SuperKamiokande) the fluxes are too low to be detected (expected number of neutrinos ~5 x 10^{-7})



Acciari et al. 2022

Daily fits

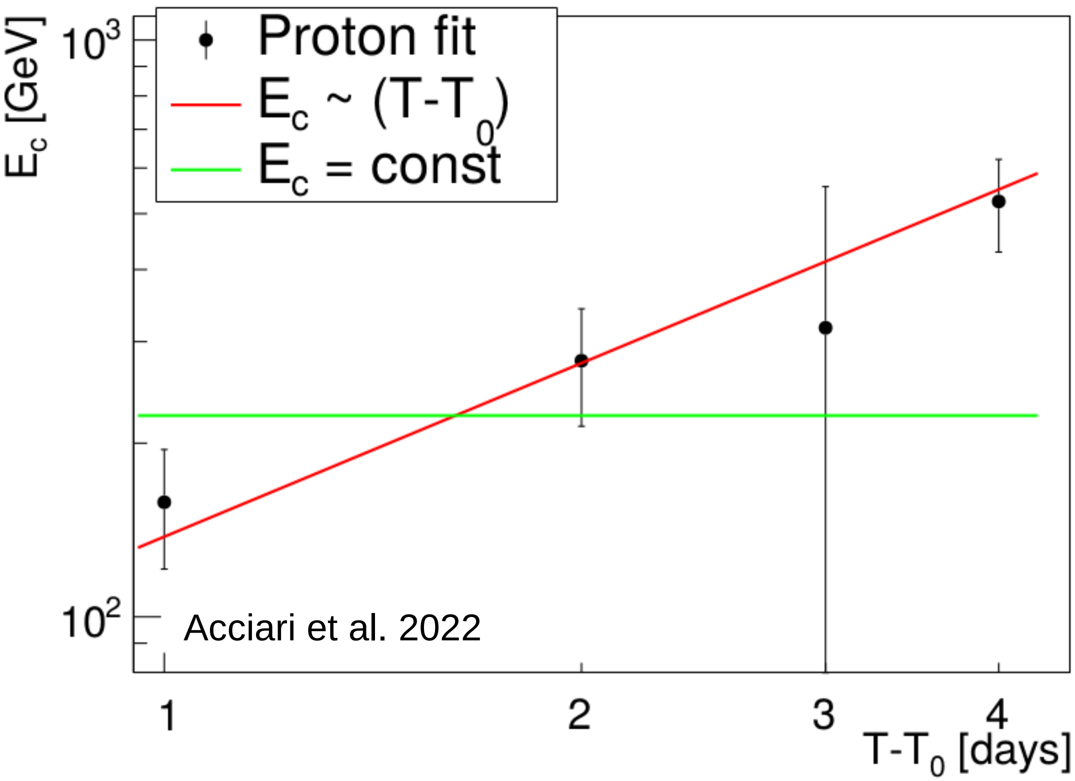
- The same modeling was done on day-by-day basis
- Similar preference for hadronic model



Acciari et al. 2022

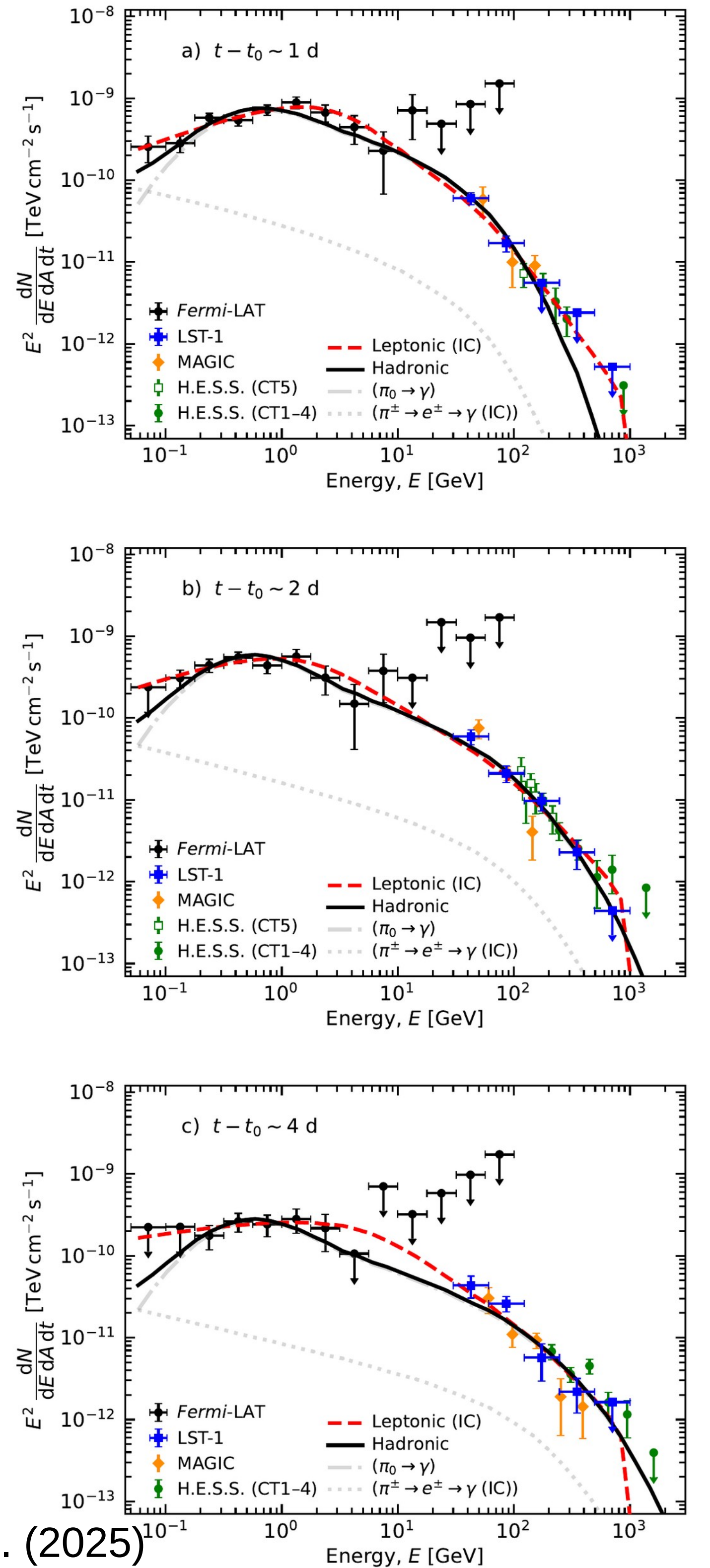
Proton maximum energy evolution

- Daily fits to the hadronic model show an increase (consistent with linear relation) of the maximum proton energy.
- Such linear relation is expected in acceleration-time dominated scenario
- **Self consistency further supporting protons**



Joint fit of all IACT data

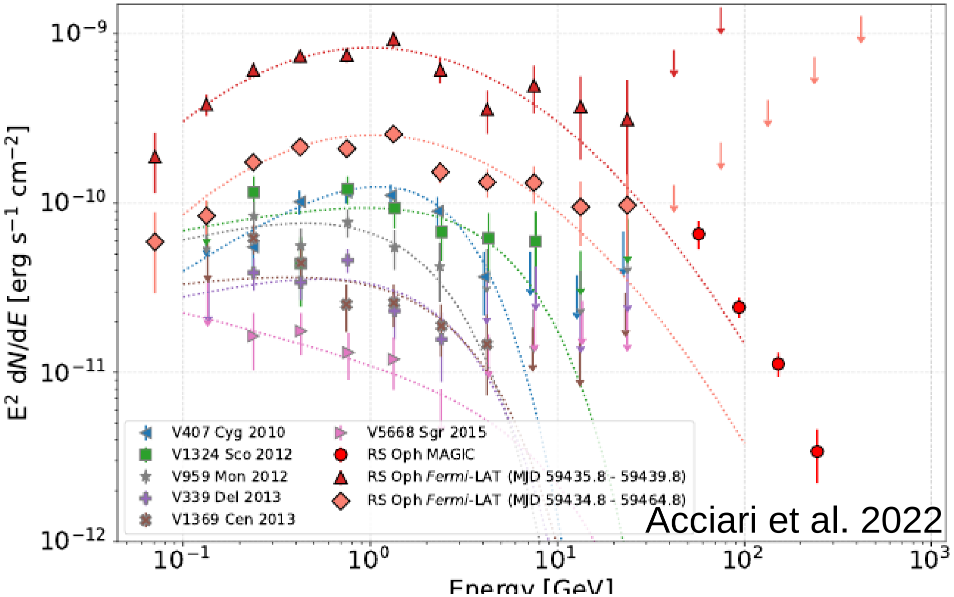
- Contrary to single telescope data, stacking all the measurements (Fermi-LAT+H.E.S.S. +MAGIC+LST-1) there is no clear statistical preference for the hadronic model over leptonic
- The latter however is requiring extreme electrons spectral shape.

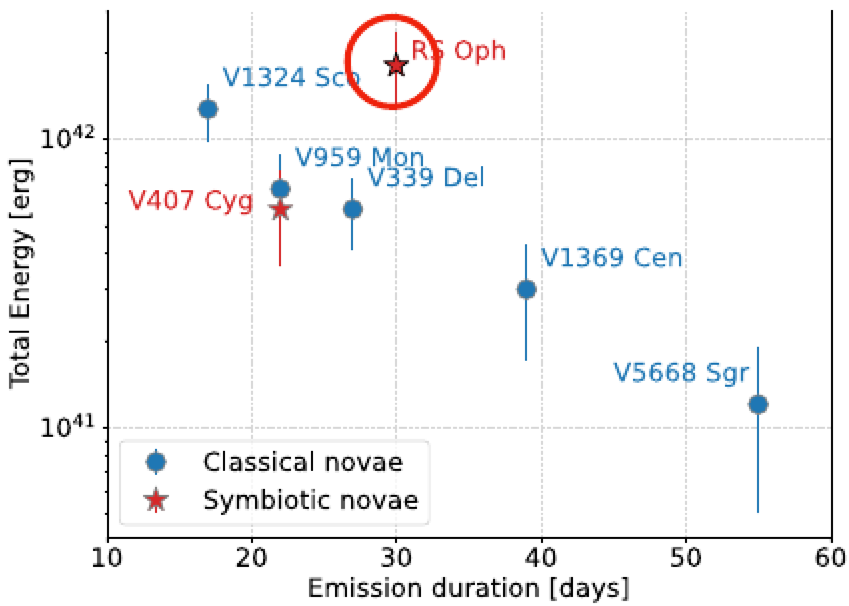


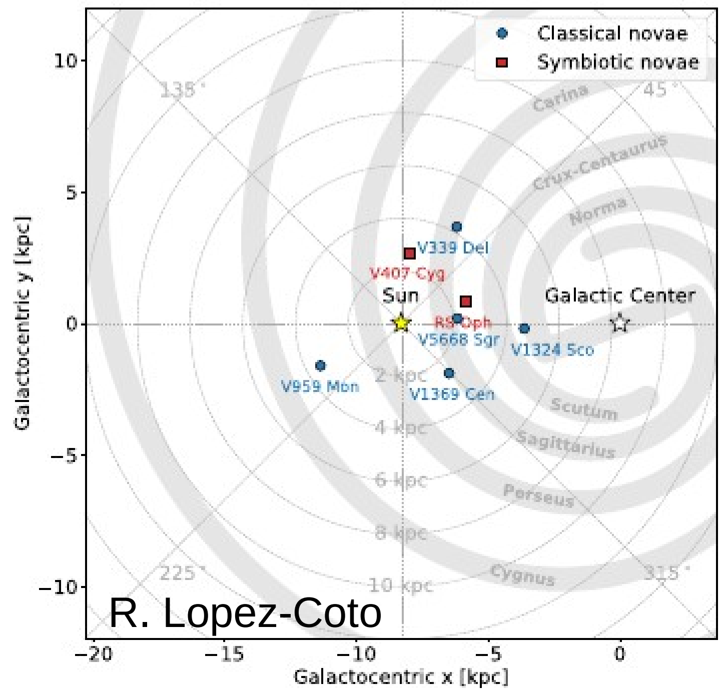
Abe et al. (2025)

What is special about RS Oph ?

- RS Oph is the brightest GeV nova observed so far
  - relatively close distance
  - also intrinsically the most energetic

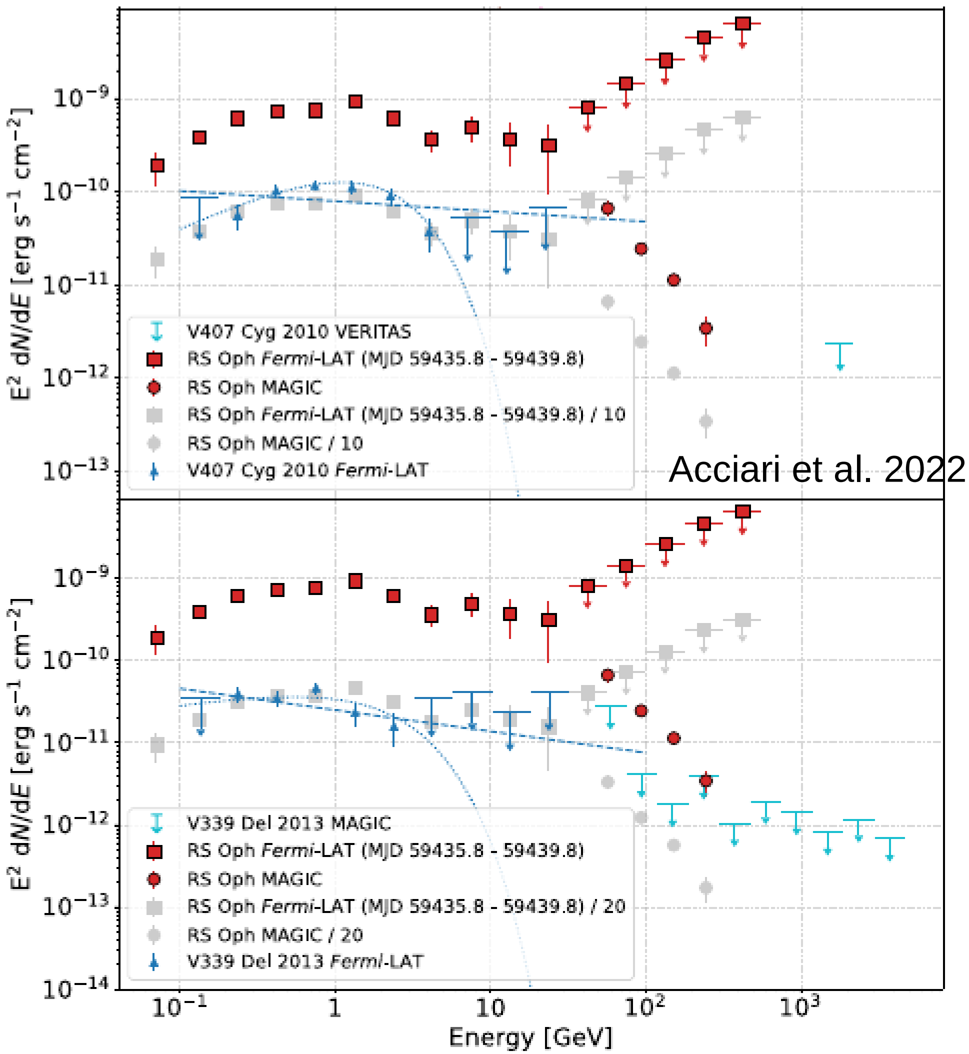






Will we detect other novae?

- Scaling the gamma-ray emission of RS Oph to the level of other novae the obtained upper limits on V407 Cyg and 339 Del are consistent with a similar emission scenario
- Further novae are likely to be detected – provided that long enough exposures are performed
- Recurrent symbiotic nature of the nova is not necessary to explain the TeV emission. *Fermi*-LAT detection of novae also started with symbiotic ones – will the next TeV nova be classical one?



Acciari et al. 2022

Energetics and CRs

- Proton model requires significant (but still plausible) fraction of the nova kinetic energy ~20%
- Most of this energy is carried away by escaping protons
- The contribution to global Galactic CR sea is however small (<~0.2%)

$$\text{Novae energy rate} = E_{p,nova} \times \text{nova rate} = 2.2 \times 10^{45}[\text{erg/year}]$$

$$\text{Supernovae energy rate} = 0.1 \times E_{\text{SN}} \times \text{supernova rate} = 2 \times 10^{48}[\text{erg/year}]$$

- The nova (in particular recurrent) can however create local blobs of increased CR density with size of O(1-10pc)

$$E_{\text{dens,nova,recurrent}} = \frac{3E_{p,nova} \times 10^4}{4\pi R^3_{\text{recurrent}}}$$

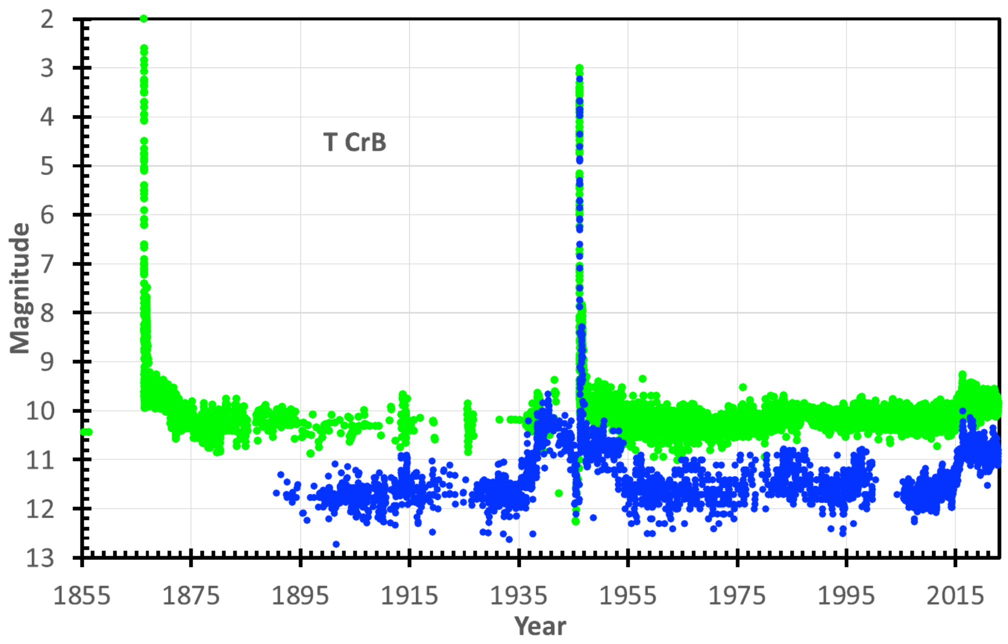
T Coronae Borealis (TCrB,Blaze Star)

- TCrB is a similar recurrent symbiotic nova like RS Oph, however located much closer
- It erupts every ~80 years, the last noted explosions were in 1217, 1787, 1866 and 1946
- It is ~0.9 kpc away, three times closer than RS Oph: expected flux should be an order or magniture higher

Credit: vito technology inc.

TcrB – early notice before the explosion?

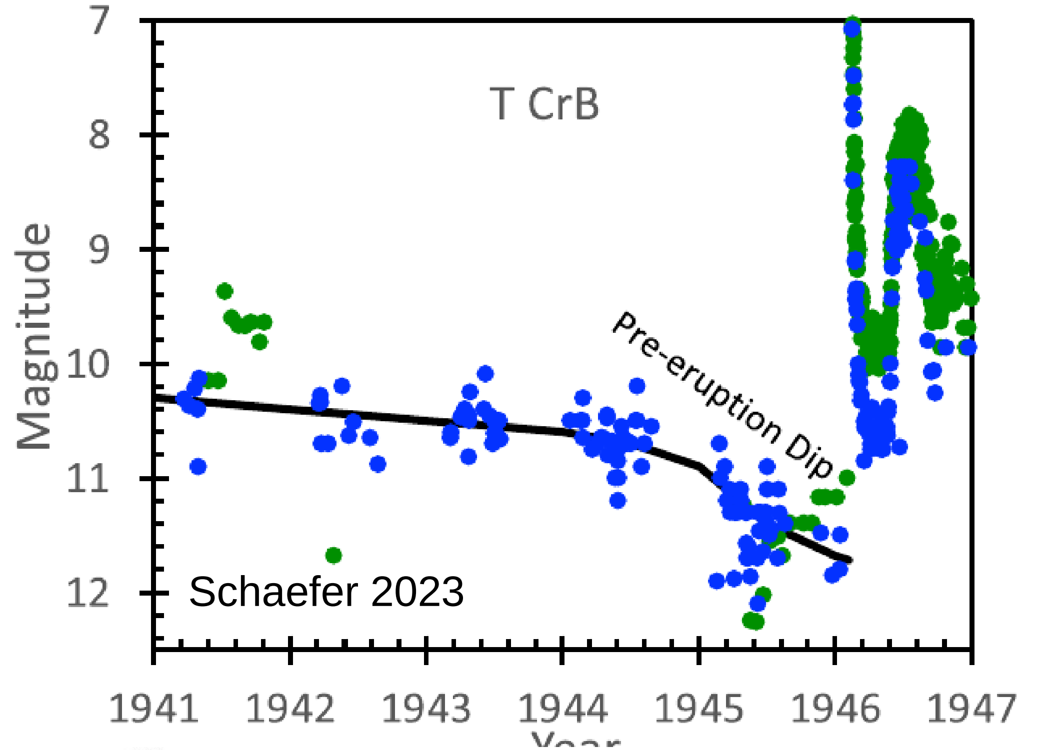
- Before 1946 a 10-year long optical high state was seen – **another started in 2015!**
  from the high state the next eruption should happen 2025.5 +-1.3

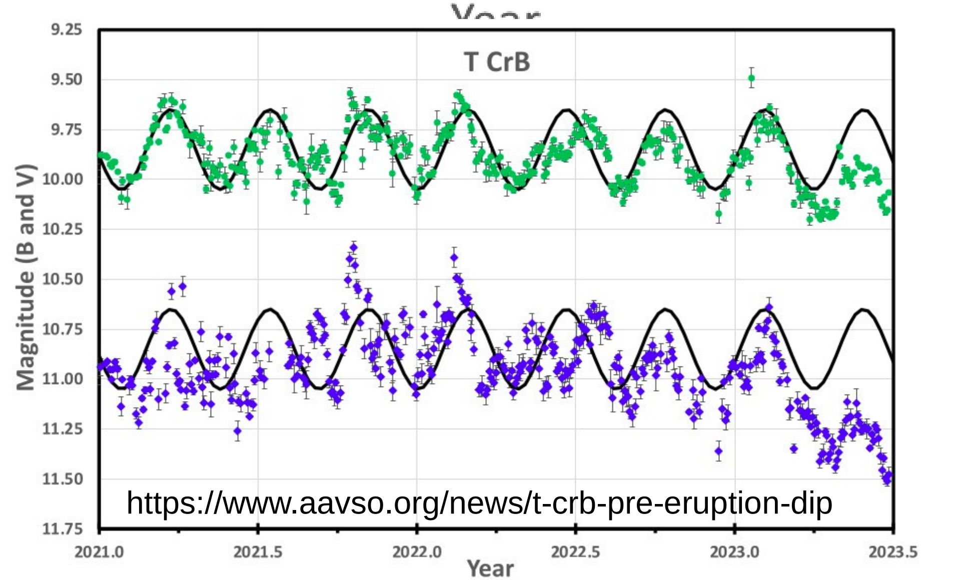


Schaefer 2023

TCrB – the dip

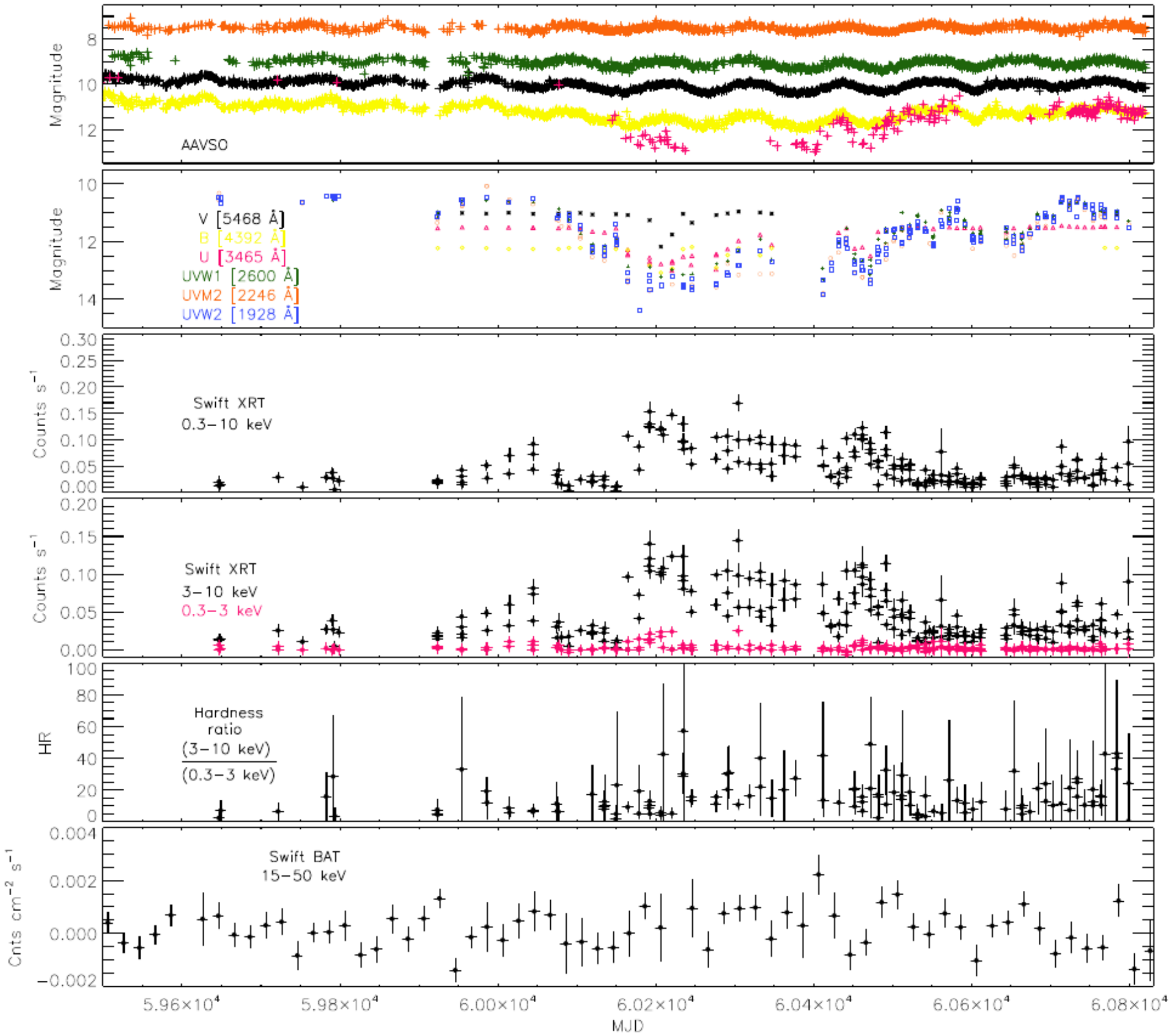
- The dip (discovered by Peltier in 1945) due to dust extinction gives an early warning about explosion
- The dip appeared in March/April 2023, resulting in estimate 2024.4+-0.3, (which did not happen...)





The evolution of the dip

- The emission partially recovered after the dip and shown another smaller dip.



Pei et al. 2025

T Coronae Borealis (TCrB,Blaze Star)

- The changes of the optical emission in the recent years show that likely the eruption is imminent
- We keep on waiting keeping the telescopes ready

Conclusions

- The novae were first shown as GeV emitters and recently also VHE gamma-ray emitters.
- RS Oph is the first detected VHE gamma-ray nova
- Interpretation of VHE gamma-ray data prefer hadronic origin of the emission.
- Most of the proton energy is carried away into Galactic CRs, but only small contribution compared to SNe

- Sometimes you need to be persistent (it took MAGIC a decade to detect the first nova)

Wish list for the next months/years

- TCrB – once in the lifetime event that will allow us to measure with high accuracy TeV emission of a recurrent nova, and track its evolution.
  - Would it behave like RS Oph?
  - Would a hadronic model also work for it?
- Detections or very strong constraints on the emission from classical novae:
  - are they also VHE emitters?
  - Is the presence of the dense RG wind of symbiotic novae important or will classical ones work the same way? Will they be described by hadronic model?

Thank you for your attention!

Backup

Distance estimates

Distance [kpc]	Method	
1.6	H I absorption measurements	Hjellming et al 1986, Bode(1987)
$1.4^{+0.6}_{-0.2}$	Several estimations	Barry et al (2008)
2.45 ± 0.37*	Expansion velocity	Rupen et al (2008)
3.1 ± 0.5	Requirement of RG filling its Roche lobe	Barry et al (2008)
4.3 ± 0.7	Light curve	Schaefer (2009)
2.68 ± 0.16	Parallax	Gaia Collaboration et al. (2018)

Spectral fit results

MAGIC-only

MJD	f_0 [10^{-10} TeV^{-1}cm^{-2}s^{-1}]	α	$\chi^2/\mathrm{N_{dof}}$
59435.94 - 59435.98	$5.0^{+1.3}_{-1.5}$	$3.92^{+0.51}_{-0.68}$	5.6/5
59436.89 - 59437.04	$3.73^{+0.92}_{-0.94}$	$4.71^{+0.34}_{-0.42}$	5.1/5
59437.89 - 59438.03	$5.03^{+0.81}_{-0.80}$	$3.70^{+0.28}_{-0.32}$	3.6/5
59438.88 - 59439.02	$4.83^{+0.77}_{-0.77}$	$3.78^{+0.25}_{-0.28}$	10.3/5
59435.94 - 59439.02	$4.66^{+0.47}_{-0.48}$	$4.07^{+0.18}_{-0.20}$	5.9/5

MAGIC + *Fermi*-LAT

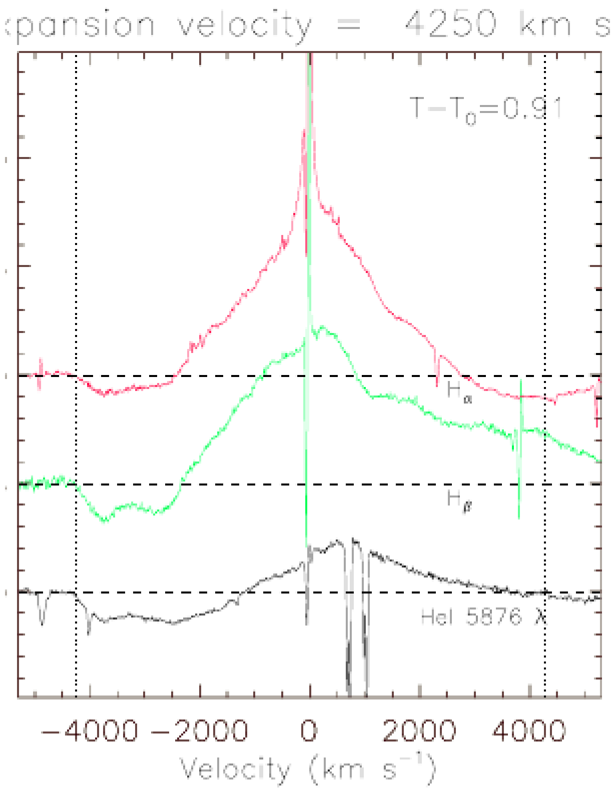
MJD	f_0[10^{-10}TeV^{-1}cm^{-2}s^{-1}]	α	β	$\chi^2/\mathrm{N_{dof}}$
59435.94 - 59435.98	5.4 ± 1.3	3.86 ± 0.13	0.194 ± 0.019	6.1/6
59436.89 - 59437.04	4.54 ± 0.78	3.73 ± 0.11	0.175 ± 0.020	16.4/6
59437.89 - 59438.03	5.37 ± 0.85	3.64 ± 0.12	0.173 ± 0.020	3.7/6
59438.88 - 59439.02	5.00 ± 0.78	3.44 ± 0.14	0.147 ± 0.027	10.8/6
59435.94 - 59439.02	5.08 ± 0.45	3.697 ± 0.059	0.175 ± 0.010	9.3/6

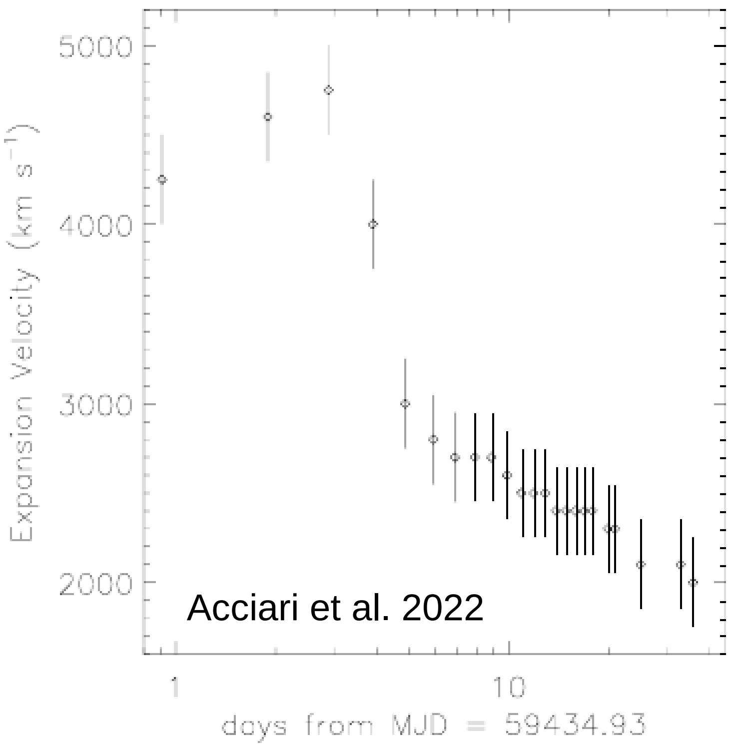
MAGIC telescopes

- Two 17-m diameter telescopes located at La Palma, Spain
- Energy range: from a few tens of GeV to a few tens of TeV
- Sensitivity
  - Long exposures: ~0.7% of the Crab Nebula flux above 300 GeV in 50 hr
  - Follow-up of transients: ~10% C.U. above 100 GeV in 1 hr

Large collection area and low energy threshold make MAGIC a perfect follow-up instrument for follow-up of low-energy alerts

Shock propagation velocity





- Estimated the velocity of the expanding envelope from the shape of the optical lines.
- In the first days the shock speed is ~ 4500 km/s

Applying the same model to H.E.S.S. + *Fermi*-LAT data

- Using 1st and 5th day spectra from H.E.S.S. Collaboration et al 2022.
- Similar conclusion – better description with a hadronic model