MAGIC
Major Atmospheric
Gamma Imaging
Cerenkov Telescopes

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Hadronic origin of gamma-ray emission from nova RS Oph revealed by the MAGIC telescopes

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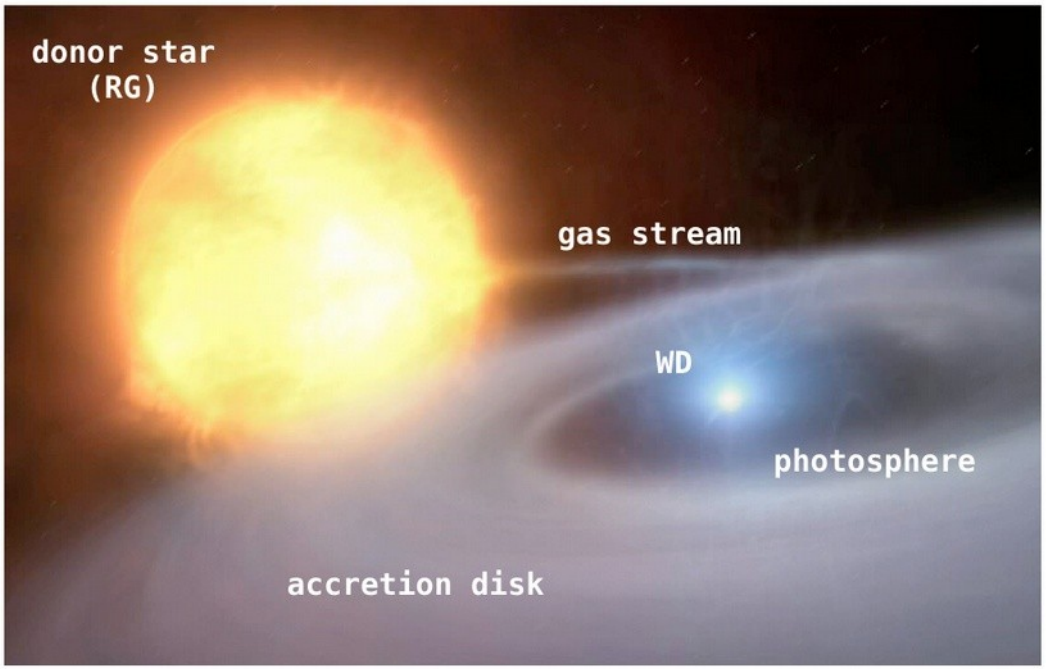
Novae

- Novae are cataclismic variable binary systems of white dwarf (WD) and a donor star.
- Mass transfer from the donor star causes thermonuclear explosions of the hydrogen accumulated on the WD.
- **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**.

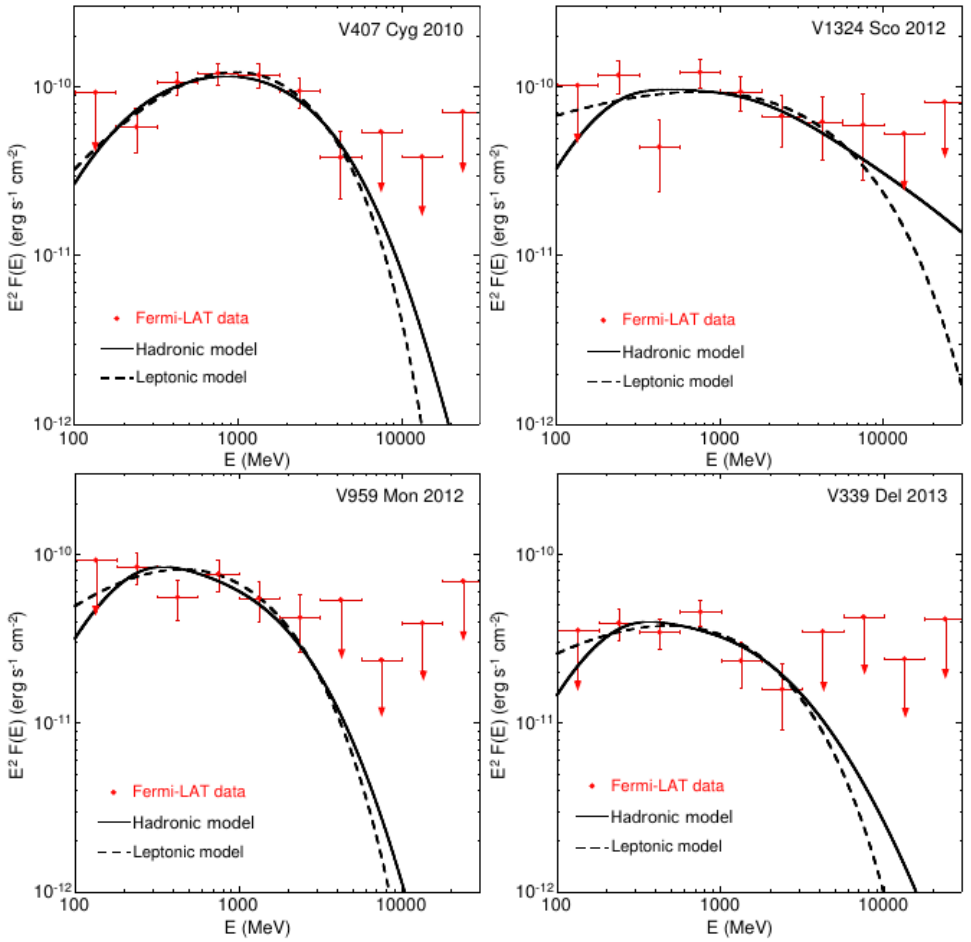


Credit: ESO / M. Kornmesser

- Due to high optical brightness (some are visible with a naked eye) they have been studied for centuries
- Optical emission lasts for weeks/months

Gamma-ray novae

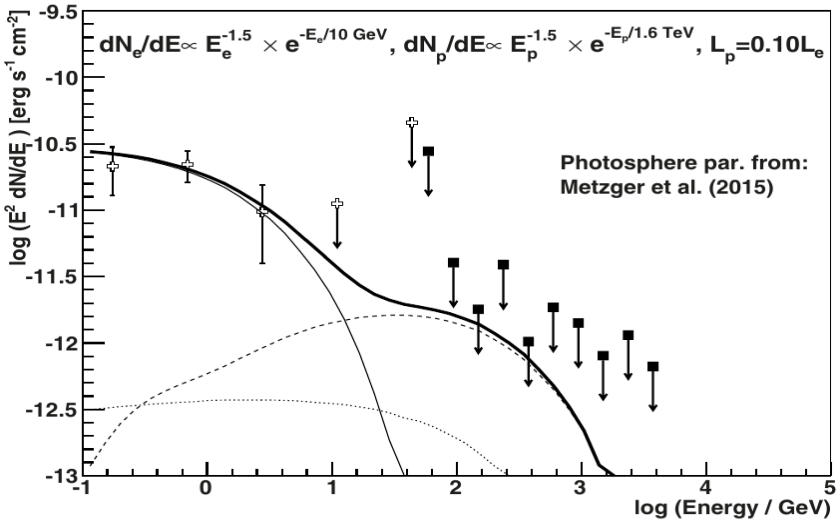
- Shock waves connected with novae outbursts produce conditions favorable for acceleration of charged particles
- Ambient matter and radiation fields serve as a target for those accelerated particles – mechanism for gamma-ray production
- GeV gamma-ray emission from novae was discovered by Fermi-LAT, first from a symbiotic nova, and then from a bunch of classical novae
- The emission could be measured only up to a few GeV and its origin was not clear – both leptonic and hadronic models were consistent with the data



Ackermann et al., 2014

MAGIC Nova follow-up program

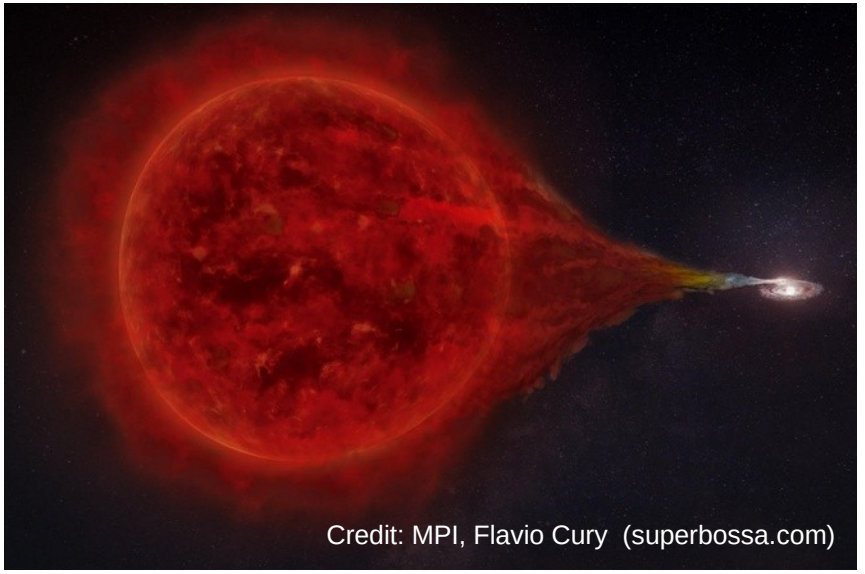
- Motivated by the GeV detection of emission from novae.
- Triggers based on GeV detection or on bright optical emission
- The first decade of the program resulted in observations of a few novae – no detection, but limits on a hadronic emission in sub-TeV range were put
- And in August 2021 …



Ahnen et al. 2015

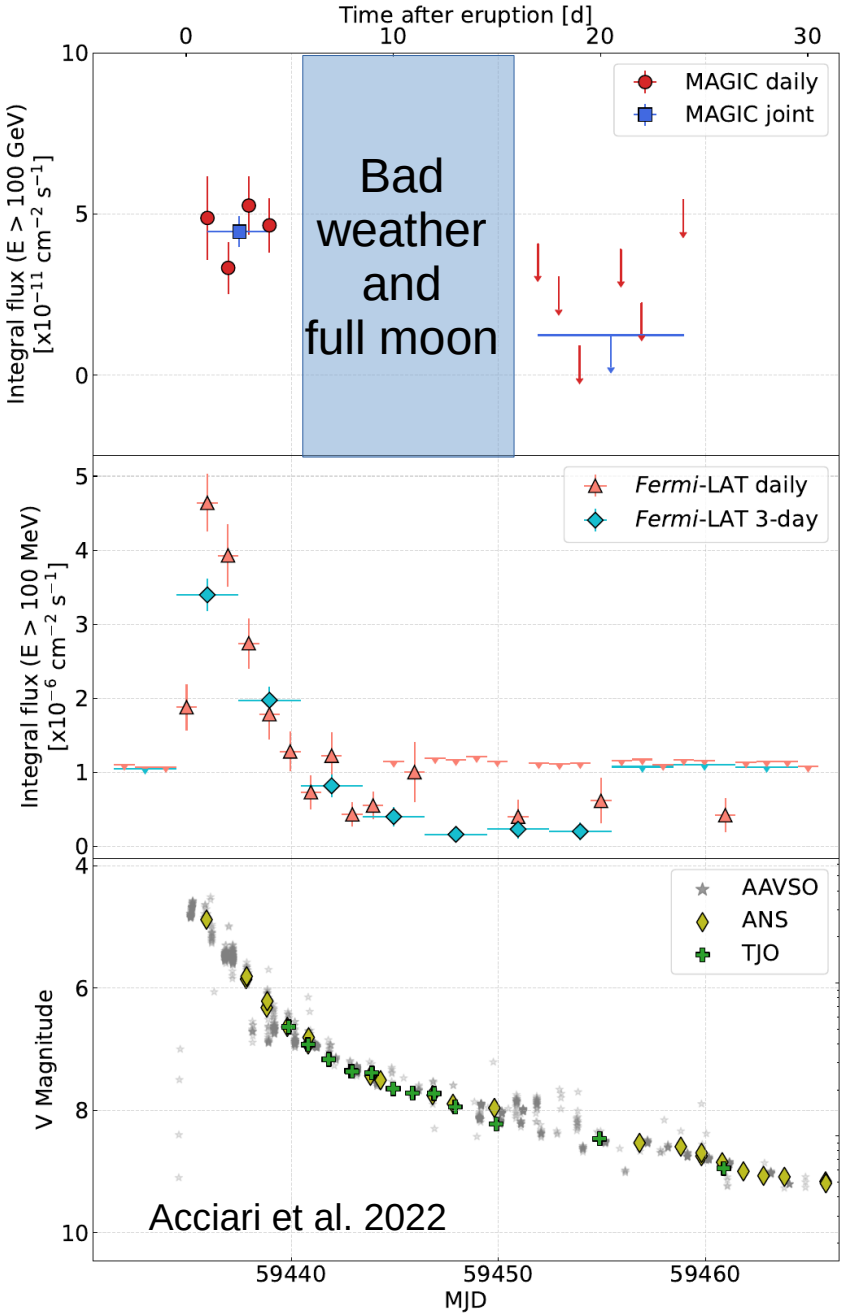
RS Ophiuchi

- 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) and MAGIC (Acciari et al. 2022)
- Different distance estimates: used 2.45 kpc (Rupen et al., 2008)
- **The first nova detected in VHE gamma rays**

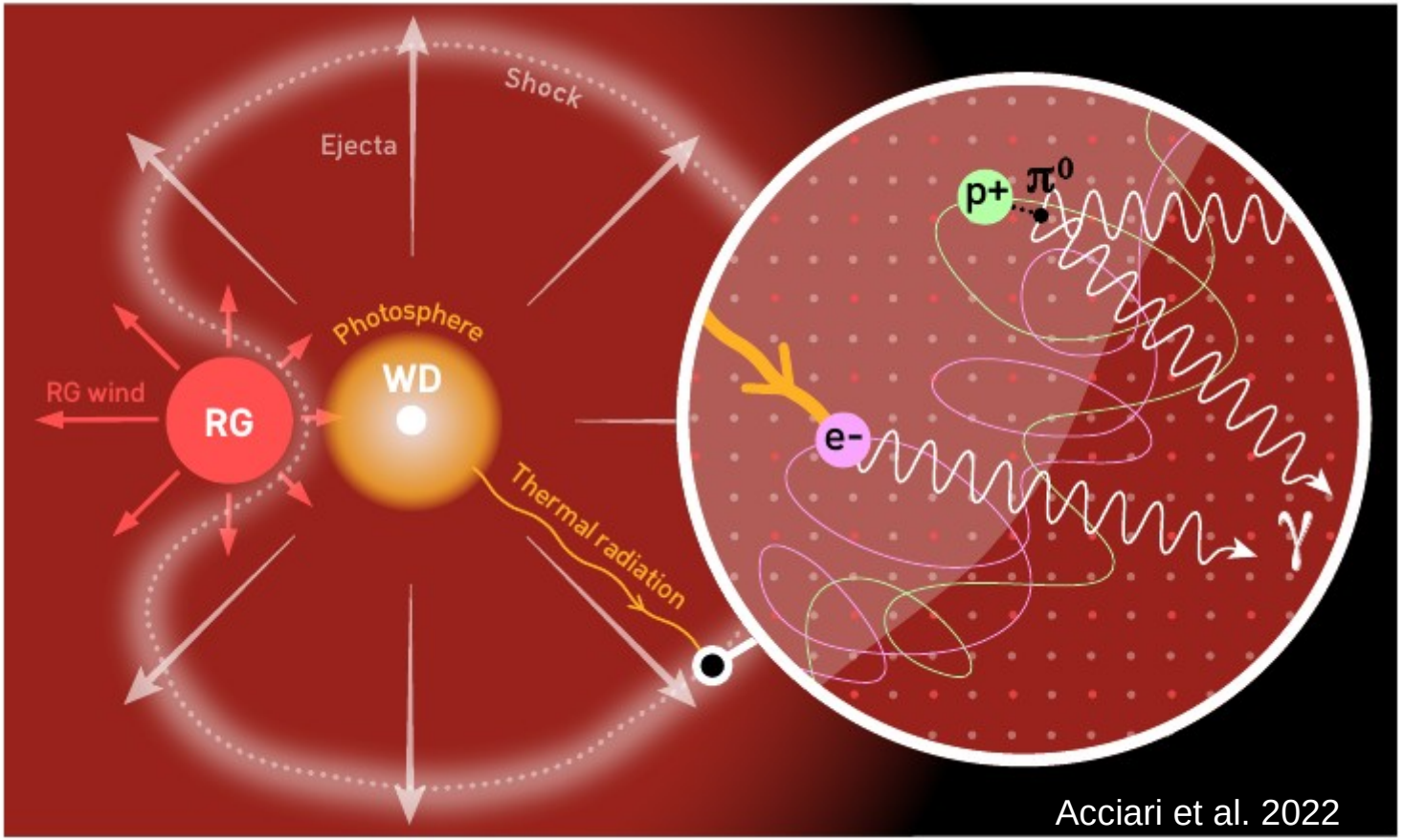


MAGIC observations of RS Oph

- 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

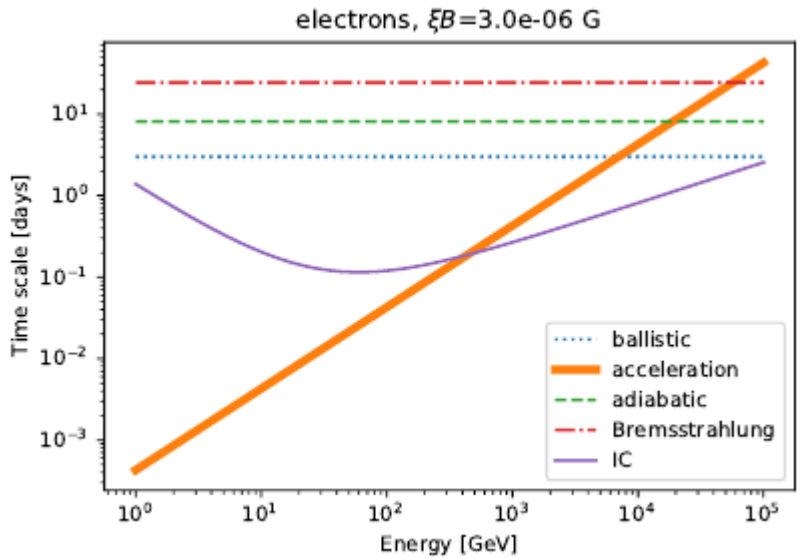


Environment in the nova

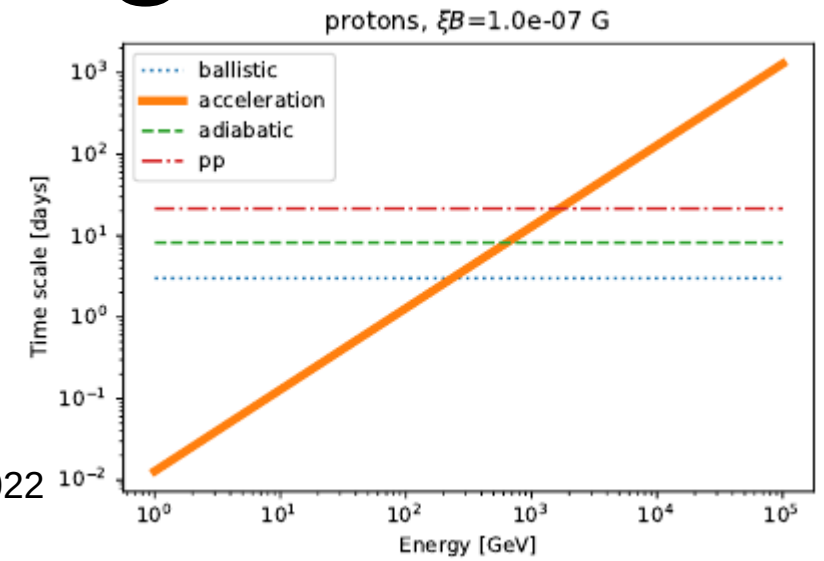


Possibility to accelerate both electrons and protons.
Which are responsible for the VHE gamma-ray emission?

Modeling

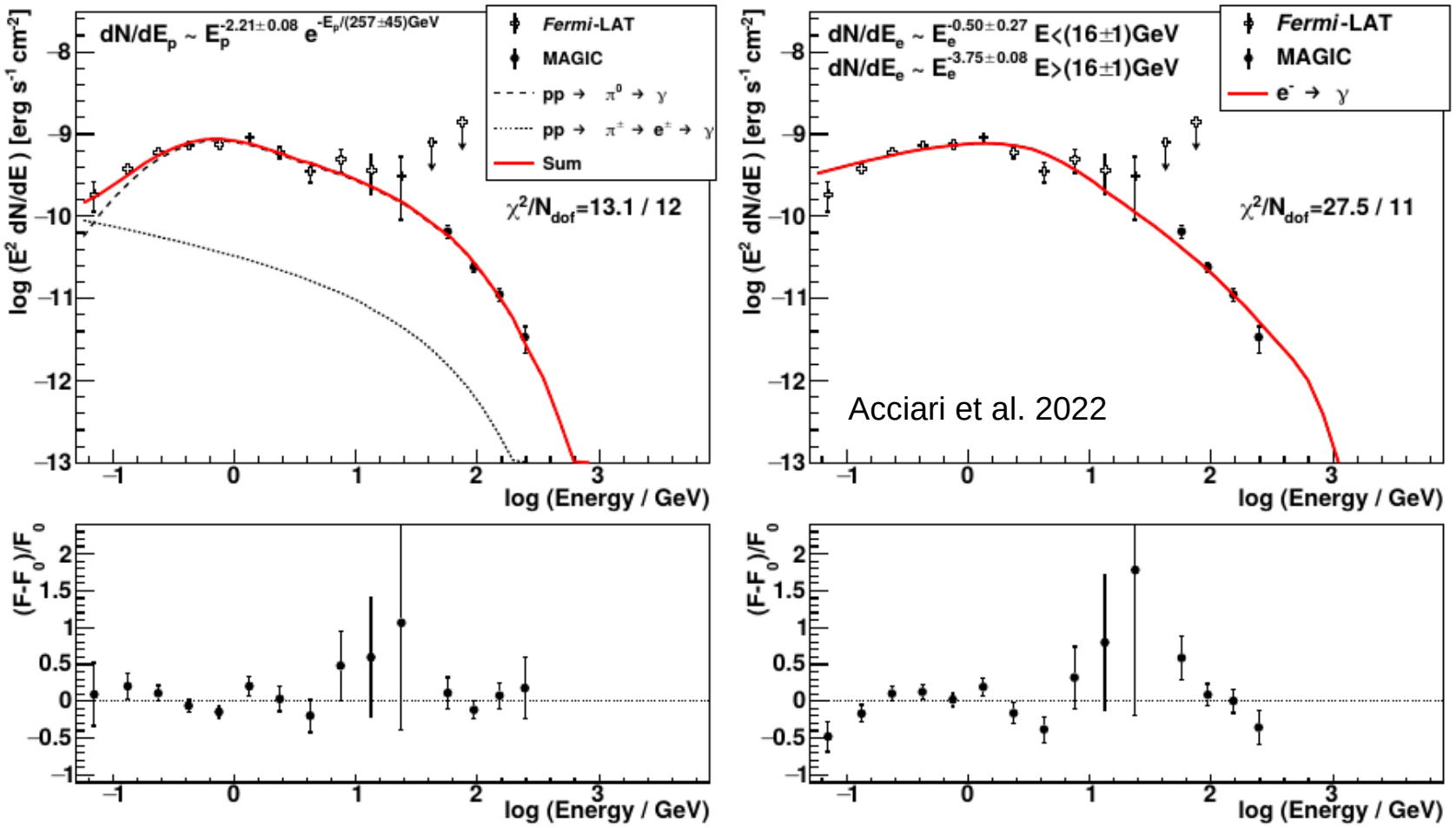


Acciari et al. 2022



- 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

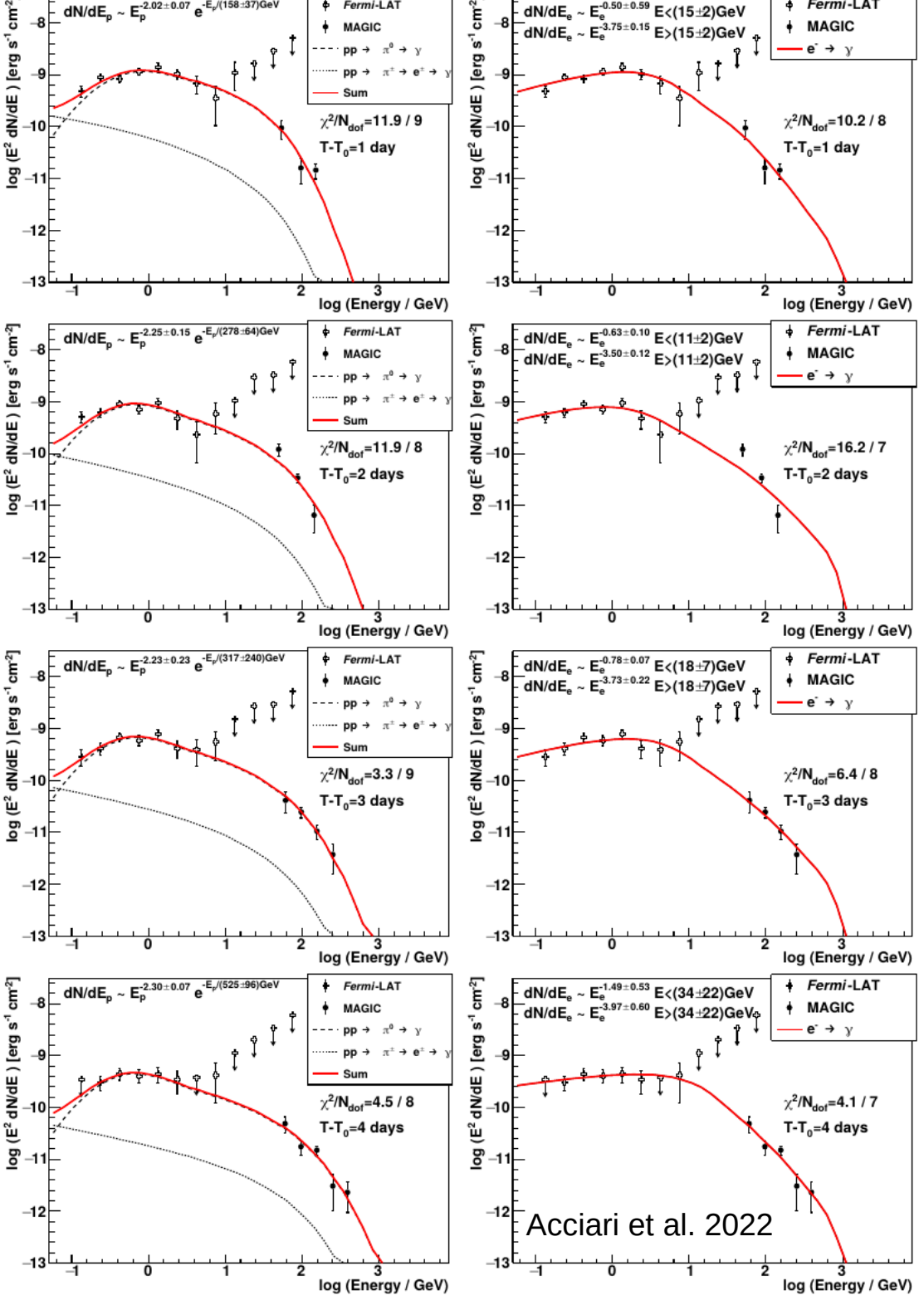
Protons vs electron models



- 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**

Daily fits

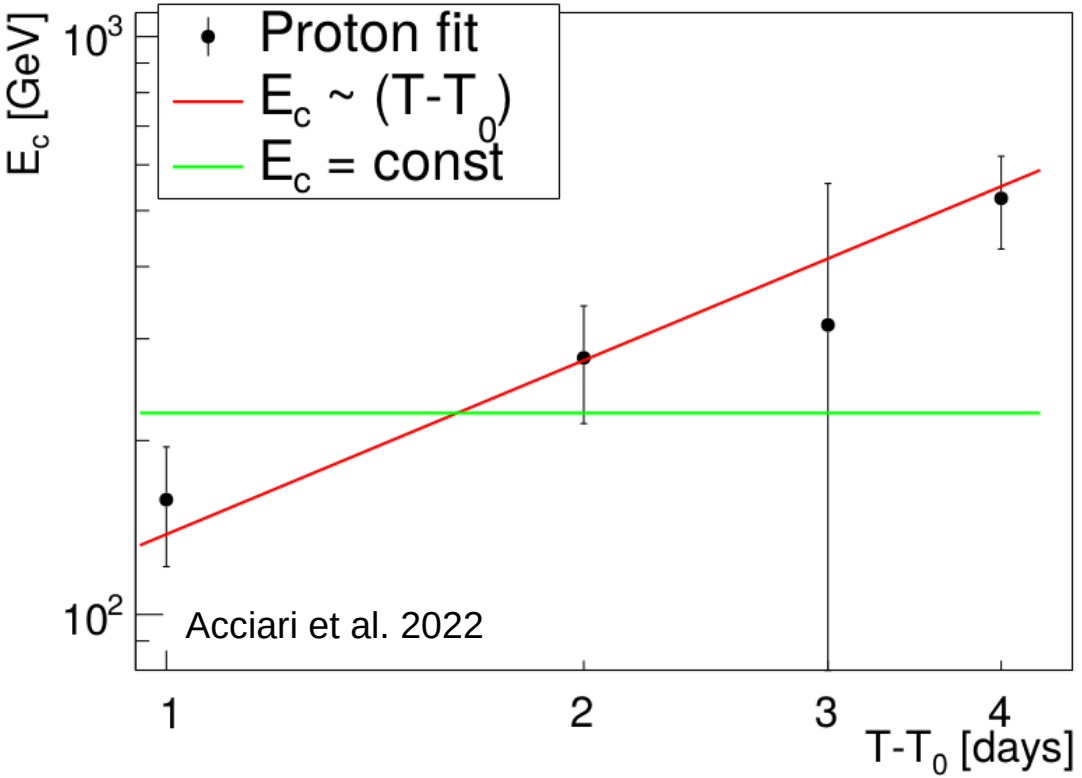
- The same modeling was done on day-by-day basis
- Similar preference for hadronic model



Acciari et al. 2022

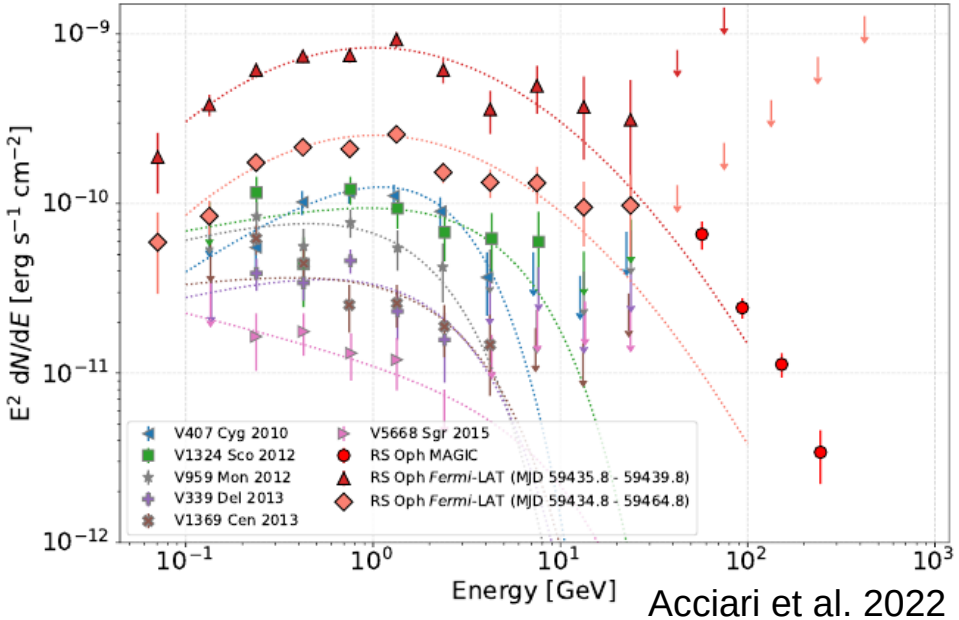
Proton maximum energy evolution

- Daily fits to the hadronic model show 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**

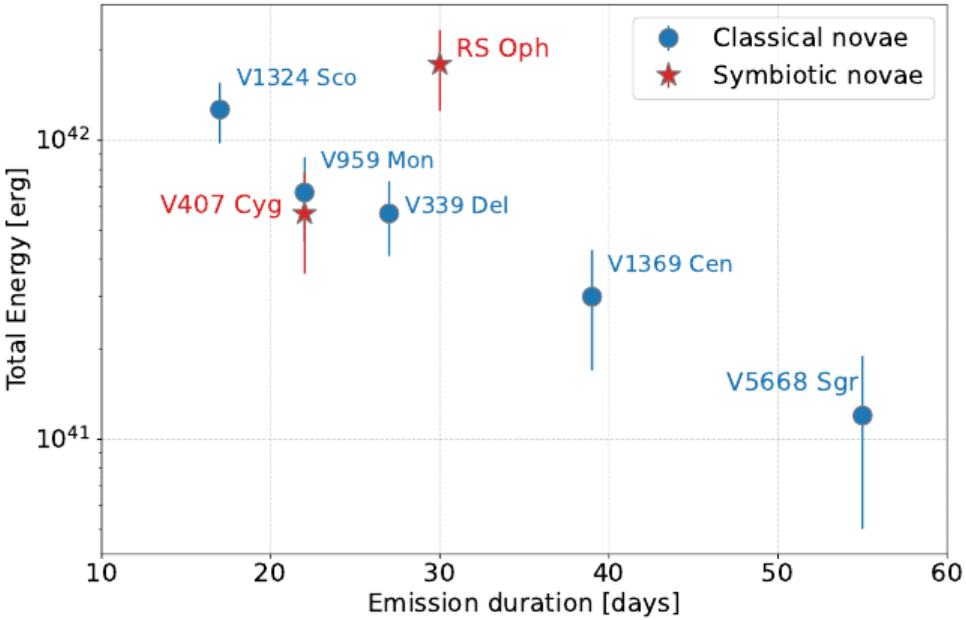


What is special about RS Oph ?

- Recurrent symbiotic nova (*Fermi*-LAT detection of novae also started with symbiotic ones)
- The brightest GeV nova so far:
  - relatively close distance
  - Also intrinsically the most energetic
- Very likely to detect further novae – just need long enough exposures



Acciari et al. 2022



Energetics and CRs

- Proton model requires significant (but still plausible) fraction of the nova kinetic energy:

$$\epsilon = \frac{E_{p,nova}}{E_k} = 0.22 \left(\frac{M_{ej}}{10^{-6} M_\odot} \right)^{-2} \left(\frac{v_{sh}}{4500\,\mathrm{km\,s^{-1}}} \right) \left(\frac{d}{2.45\mathrm{kpc}} \right)^{-2} \frac{h}{0.1}$$

- Most of this energy is carried away by escaping protons
- The contribution to global Galactic CR sea is however small (<~0.2%)
- The nova (in particular recurrent) can however create local blobs of increased CR density with size of O(1-10pc)

Conclusions

- RS Oph is the first detected VHE gamma-ray nova
- Interpretation of MAGIC data showed for the first time that the gamma-ray emission of novae is of hadronic origin
- Most of the proton energy is carried away into Galactic CRs, but only small constribution compared to SNe
- RS Oph is the brightest GeV nova seen so far – more novae are likely in reach of being detected. Will we detect also classical novae?