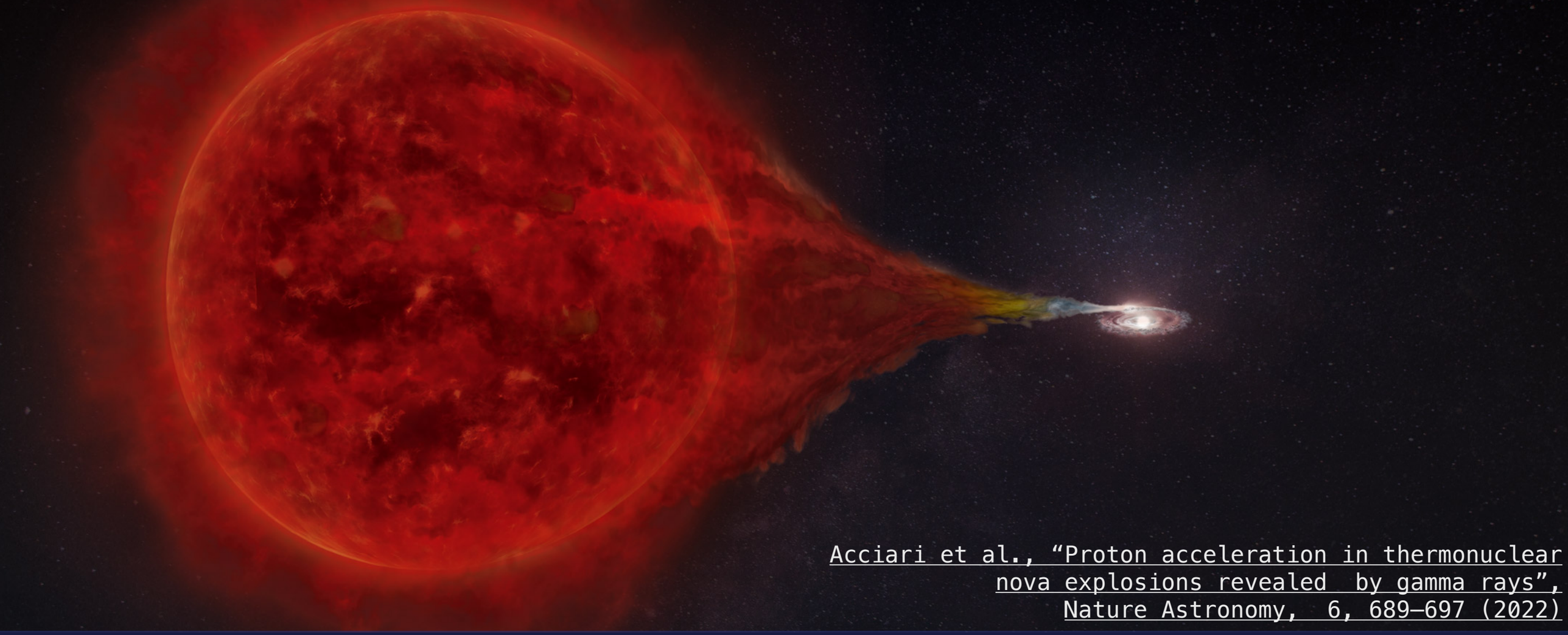
γ 2022
7th Heidelberg International Symposium on
High Energy Gamma-Ray Astronomy
Barcelona, July 4-8 2022

Gamma-ray emission of **hadronic origin** from **nova RS Oph** revealed by **the MAGIC telescopes**



Acciari et al., "Proton acceleration in thermonuclear nova explosions revealed by gamma rays", Nature Astronomy, 6, 689–697 (2022)

Alicia López-Oramas (IAC)
Vandad Fallah Ramazani, David Green, Francesco Leone, Rubén López-Coto, Julian Sitarek
for the MAGIC collaboration

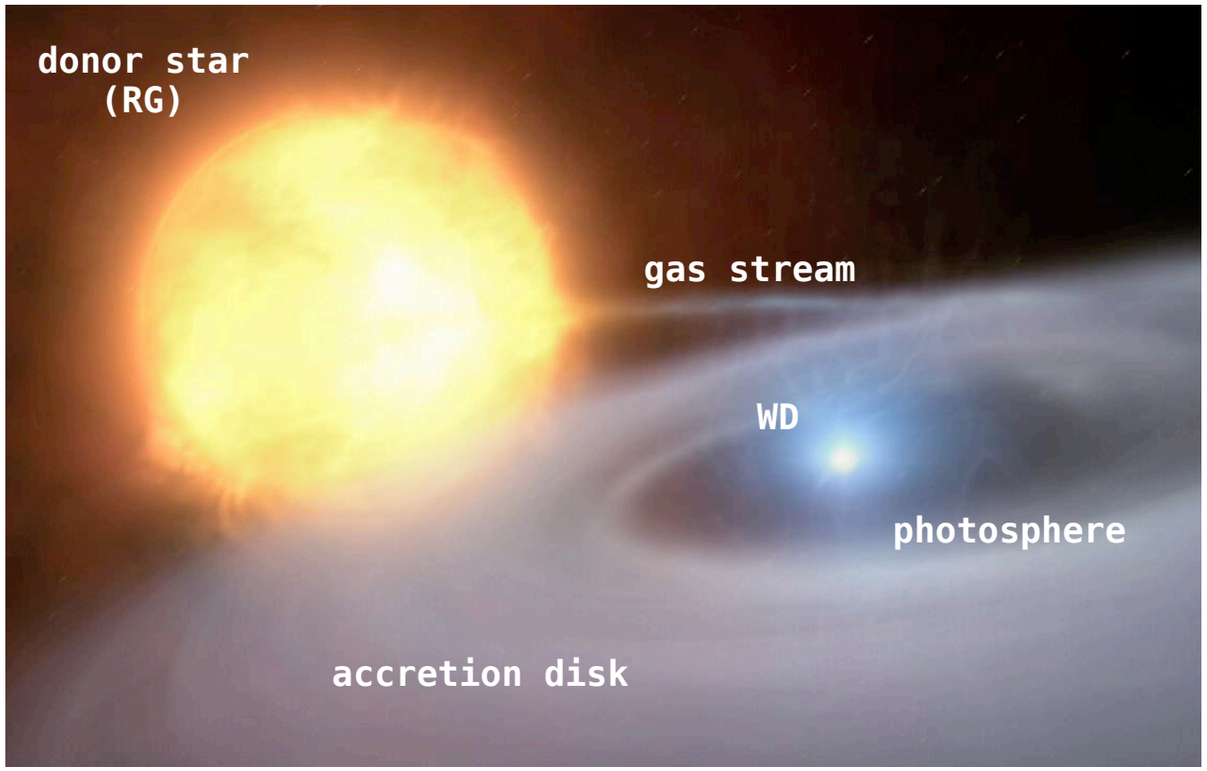
7th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy, July 2022

Novae

- Novae are **thermonuclear explosions** caused by accumulation of material from a **donor star** on a surface of a **white dwarf (WD)**

- Classification depening on the donor star:
  - **Symbiotic binary:** the donor star is a **red giant (RG).** The **WD is immersed in the RG wind**
  - **Classical novae:** the donor is a main sequence star

- Novae outbursts usually last from weeks to months



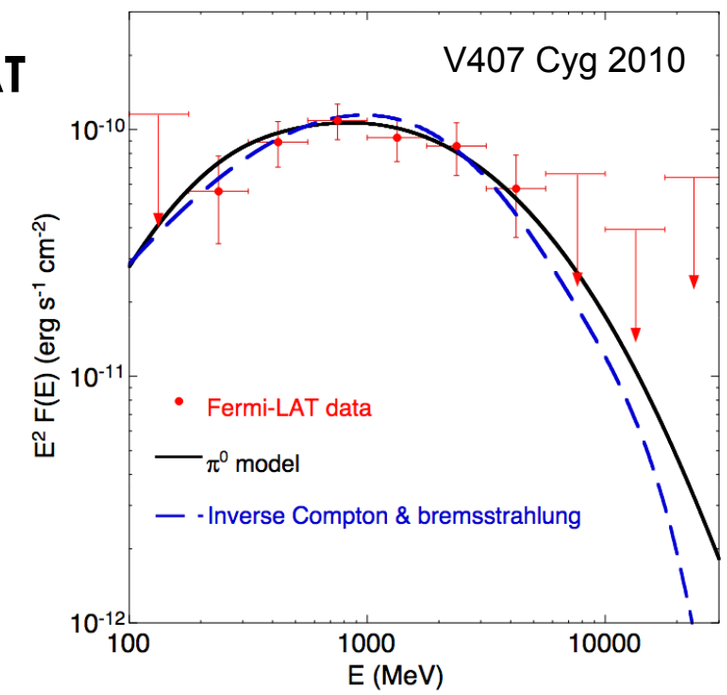
Credit: ESO / M. Kornmesser

- Some novae show repeated outbursts within a human lifetime: **recurrent novae (RN)**

Novae: sources of HE gamma rays

- The first nova to be detected by ***Fermi*-LAT** was the **symbiotic** system V407 Cyg (*Fermi*–LAT, Science, 2010)

- **Novae established as HE emitters (HE, E>100 MeV)**



Novae: sources of HE gamma rays

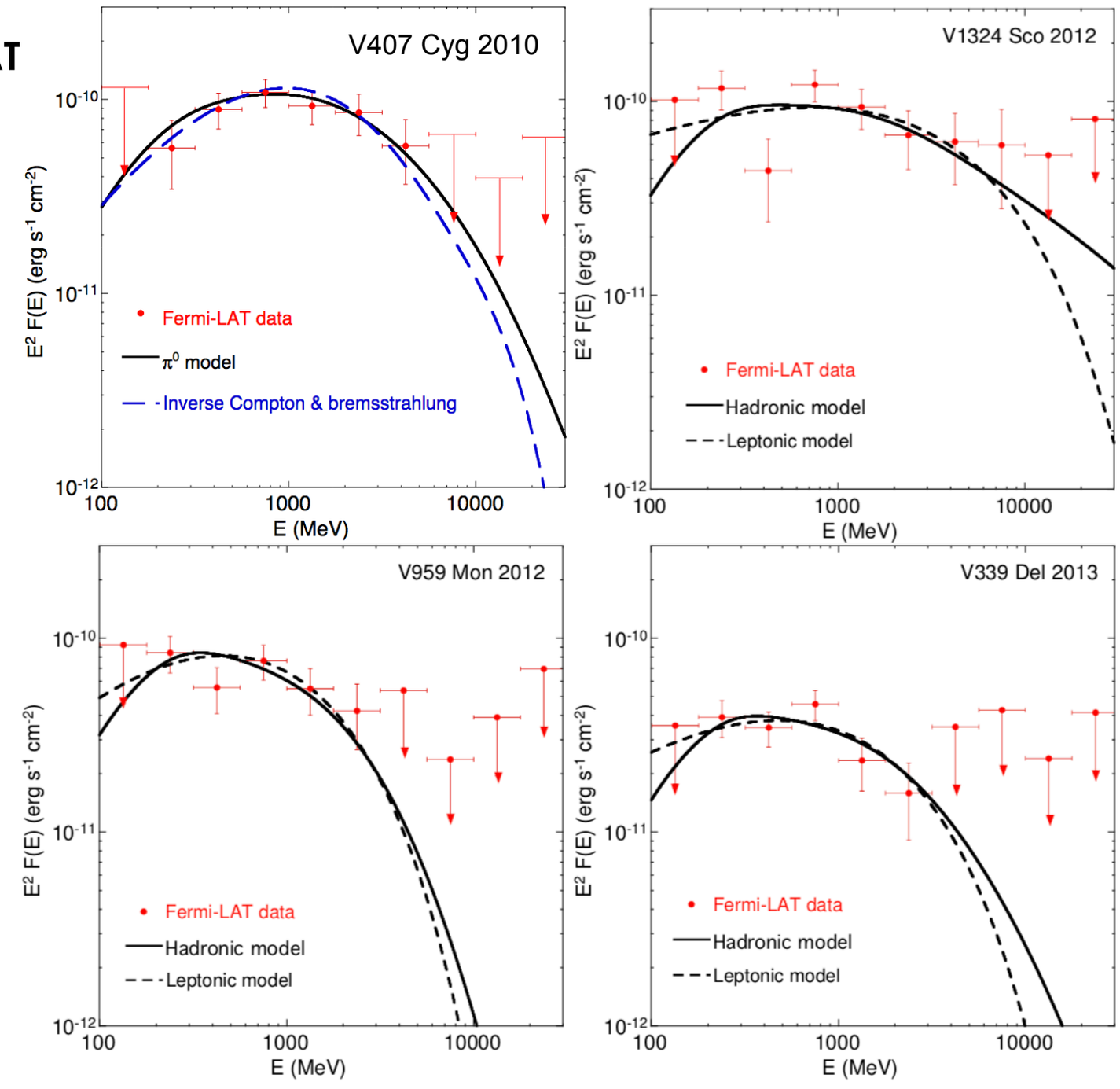
- The first nova to be detected by ***Fermi*-LAT** was the **symbiotic** system V407 Cyg (*Fermi*–LAT, Science, 2010)

- **Novae established as HE emitters (HE, E>100 MeV)**

- **Classical** novae are also **sources of HE gamma rays** (*Fermi*–LAT, Science, 2014)

- Emission could be explained with either **pp interaction** or **leptonic models** (IC+Brems.)

- SED measured up to 6 – 10 GeV



Fermi–LAT, Science, 2014

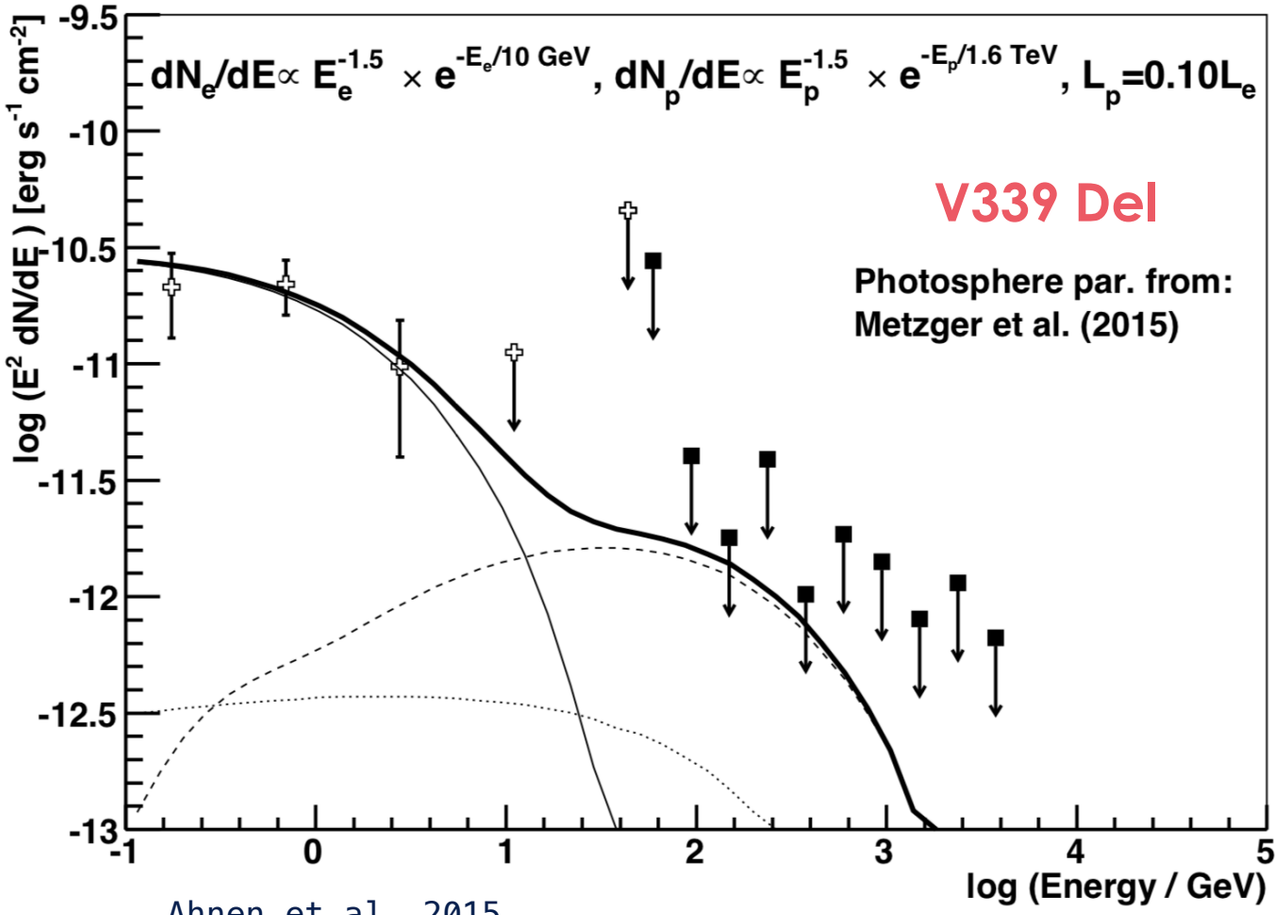
Are novae very-high-energy (VHE, E>100 GeV) emitters?

The MAGIC telescopes

- Two Imaging Air Cherenkov telescopes of 17 m of diameter
- Roque de los Muchachos observatory (La Palma, Canary Islands, Spain); 2200 m a.s.l.
- Energy threshold ~50 GeV

Search for VHE emission

- **HE data alone is not enough** to disentangle electron and proton **acceleration models**
- Particles are accelerated in nova shock, **non-thermal processes** are at work
- **Protons can reach much higher energies due to lower energy losses** and thus possibly produce a second component detectable by IACTs
- IACTs had searched for a VHE component in novae for more than a decade (Aliu et al. 2012, Ahnen et al. 2015)



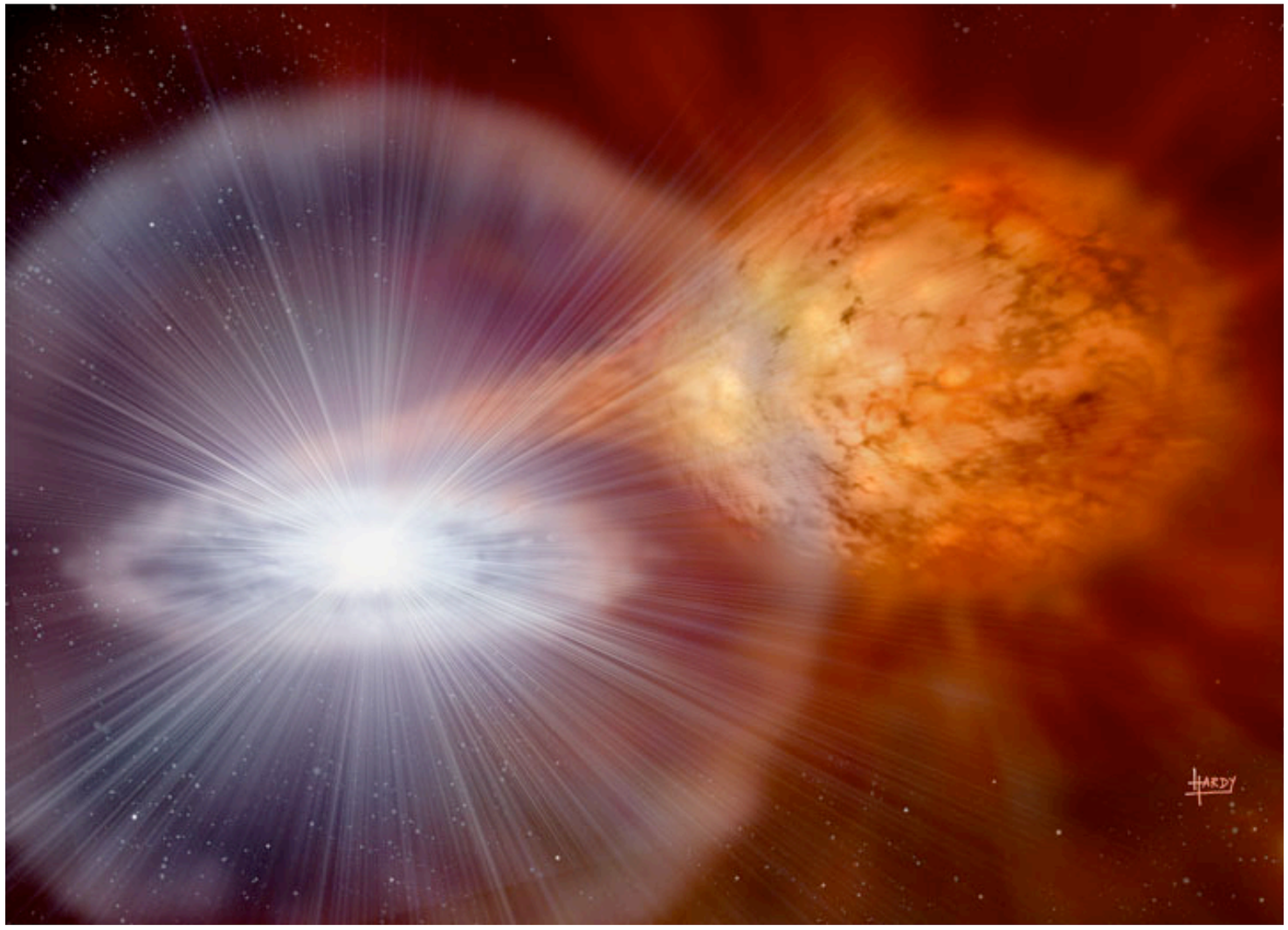
Ahnen et al. 2015

RS Ophiuchi

Antonio González (Cielos-LaPalma.com)

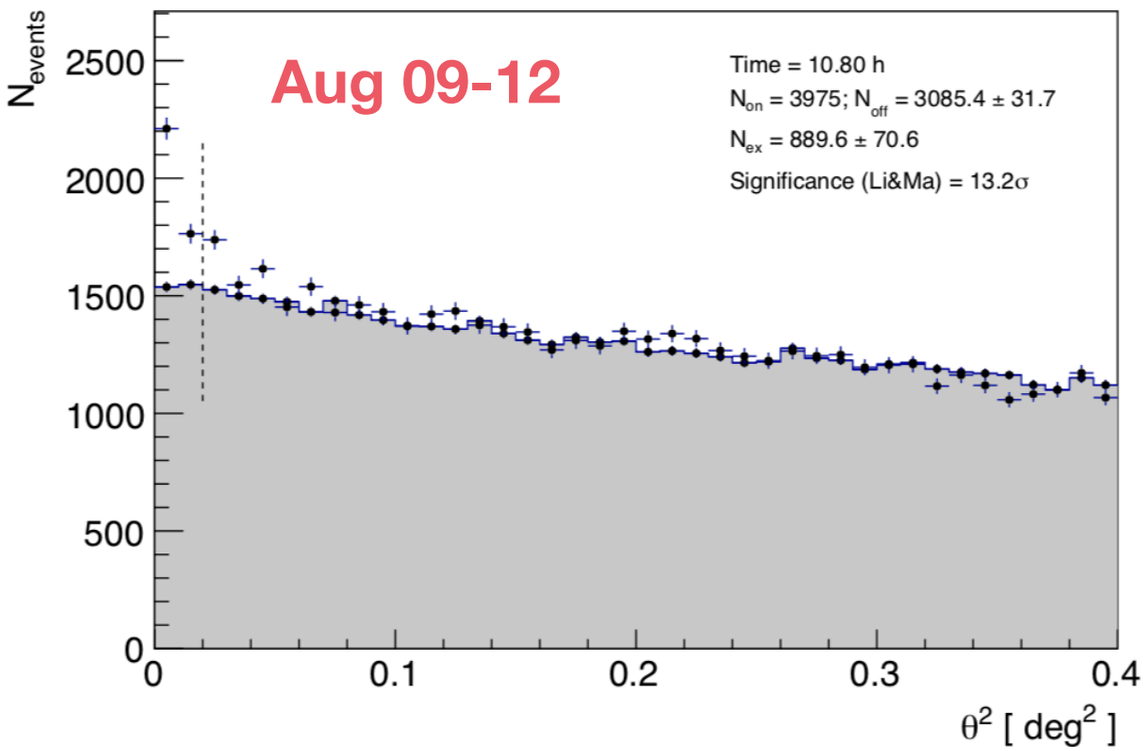
RS Ophiuchi

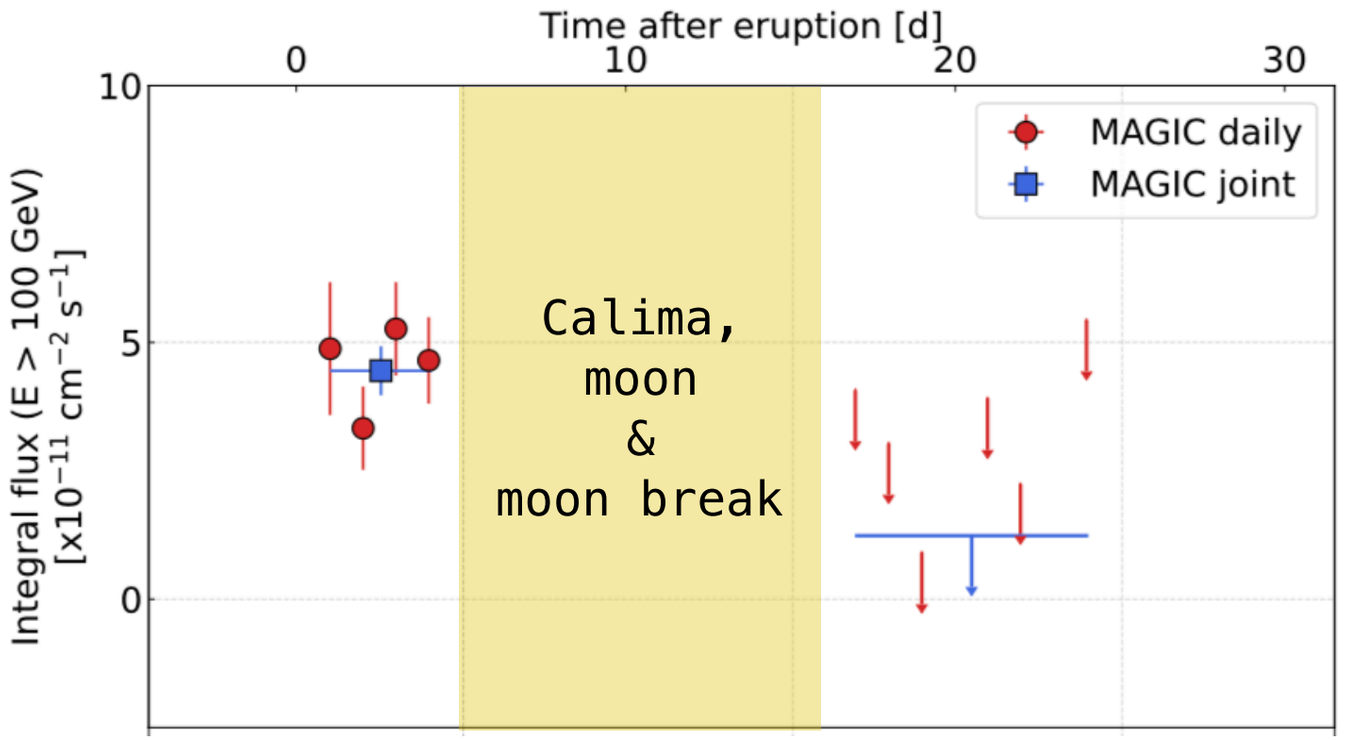
- RS Oph is a **recurrent symbiotic nova** for which 9 outbursts have been recorded since 1898
  - WD + M0-2 III RG star
    - M_{WD} = 1.2–1.4$M_{\odot}$ and M_{RG} = 0.68–0.80$M_{\odot}$ (Brandi et al. 2009)
  - **Latest outburst: August 2021**
- Type Ia SN progenitor candidate



MAGIC detection

- The **first four days** of MAGIC observations (August 09-12) yield a **VHE signal** with a **significance of 13.2σ** (Acciari et al. Nat. Astronomy, 2022)
  - 34 h observed, 21.4 h after quality cuts (zenith angle range: 36° - 60°)
  - **Energy threshold of the analysis: ~60 GeV**
- **Decreased** below the VHE detection limit **two weeks later**
- **Novae established as a new type of source of VHE emission**



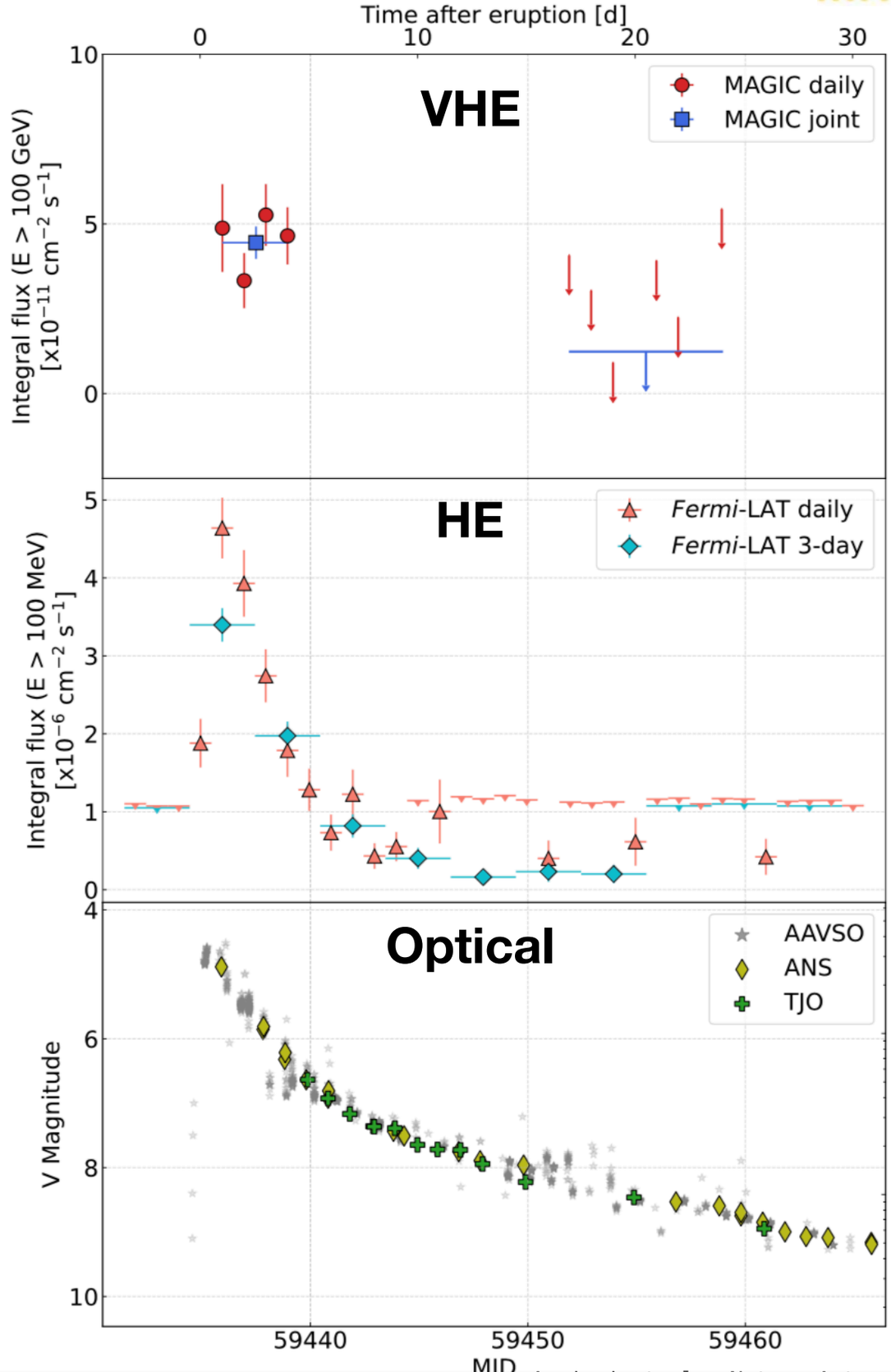


Acciari et al., Nature Astronomy, 2022
https://doi.org/10.1038/s41550-022-01640-z

MWL view

- The MAGIC observations reveal **VHE emission contemporaneous to the *Fermi*-LAT and optical maxima**
- Emission peaked at optical and MeV, but **VHE emission is** consistent with being **constant over the first 4 days**
- **First nova detected in the VHE regime**

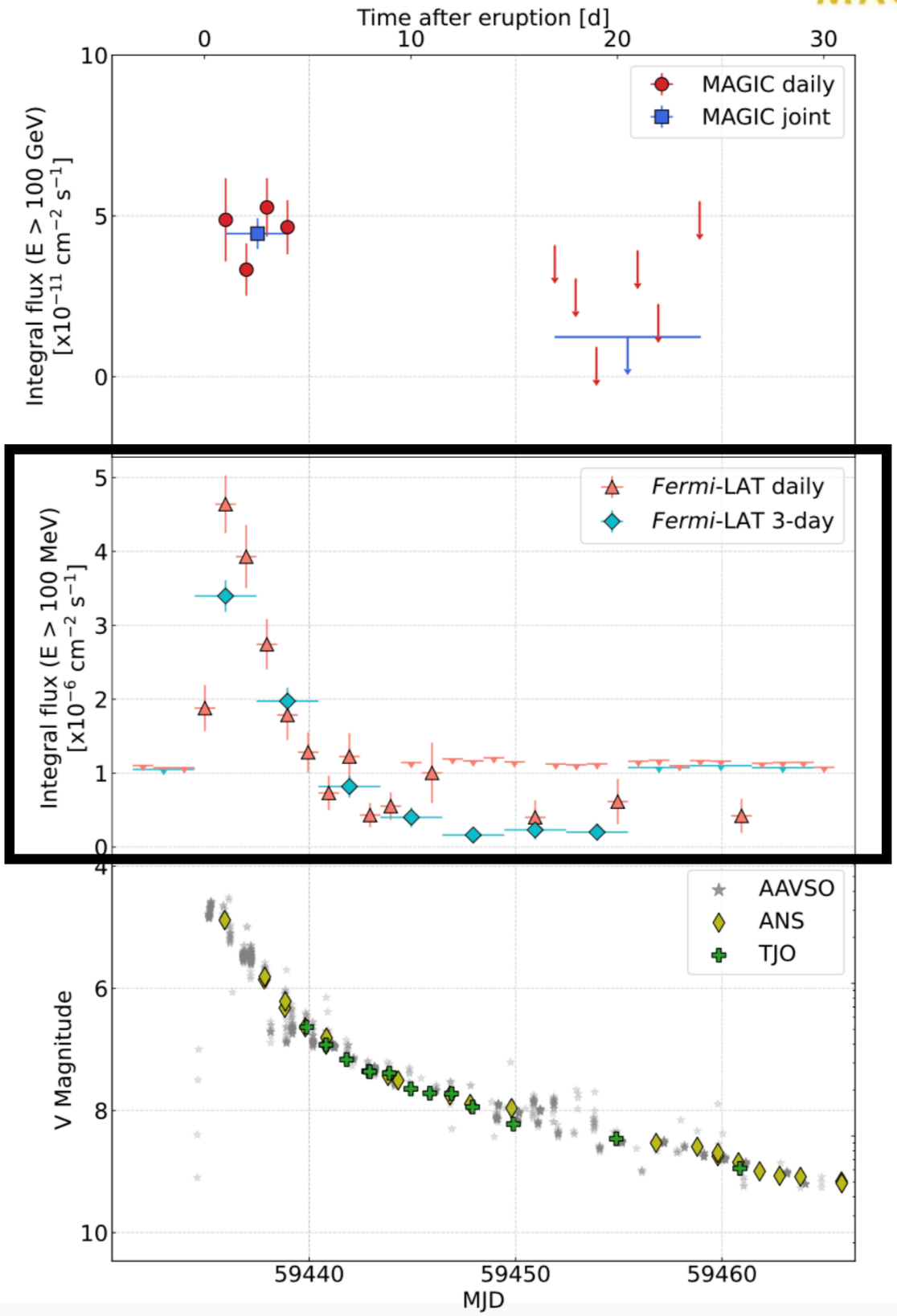
Novae established as a new type of source of VHE gamma rays



Acciari et al., Nature Astronomy, 2022

Fermi-LAT analysis

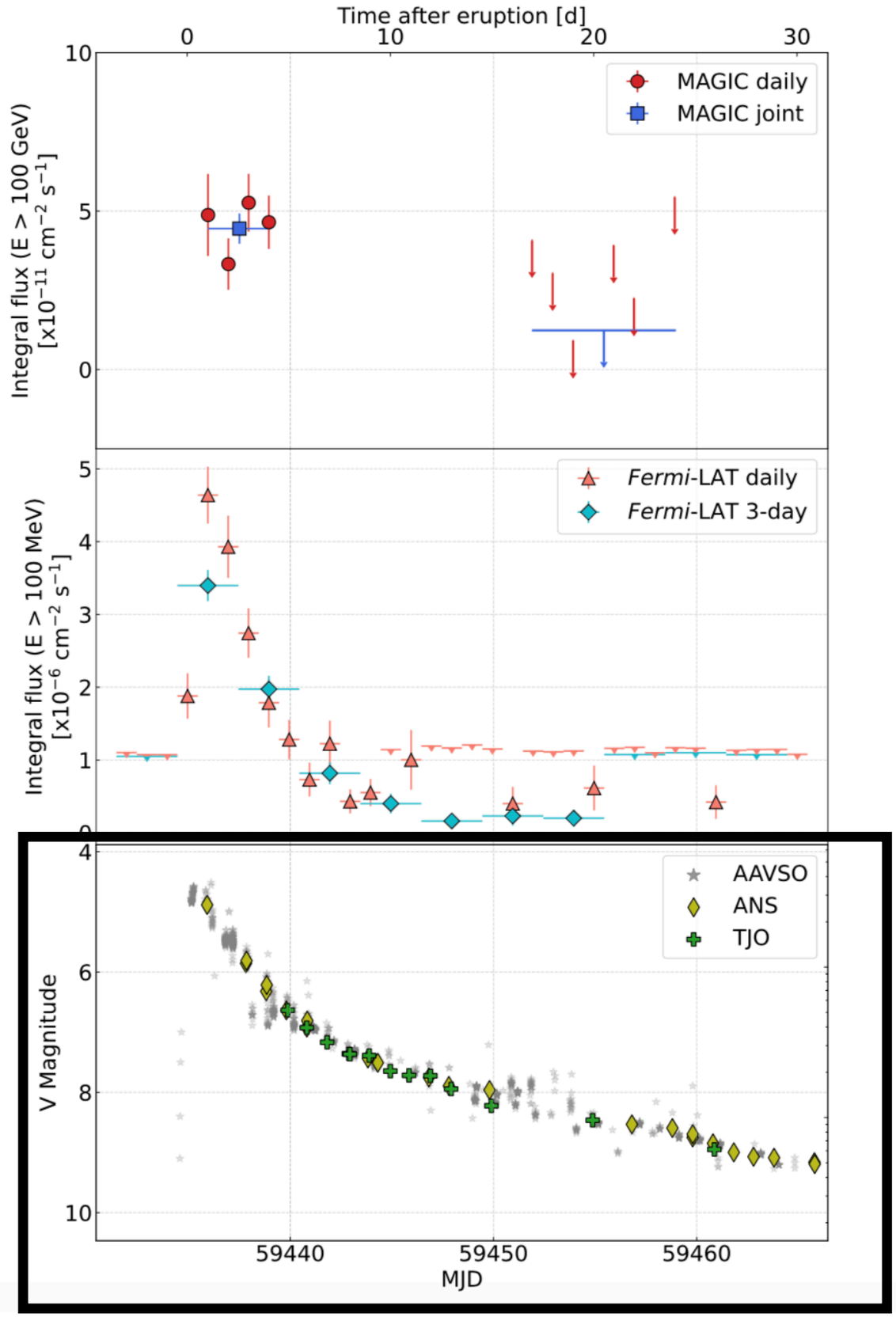
- *Fermi*-LAT: 1-day and 3-day LC (E: 0.1-.1000 GeV)
  - 1-day LC: **exponential decay with halving time of (2.20 ± 0.18) days**



Acciari et al., Nature Astronomy, 2022

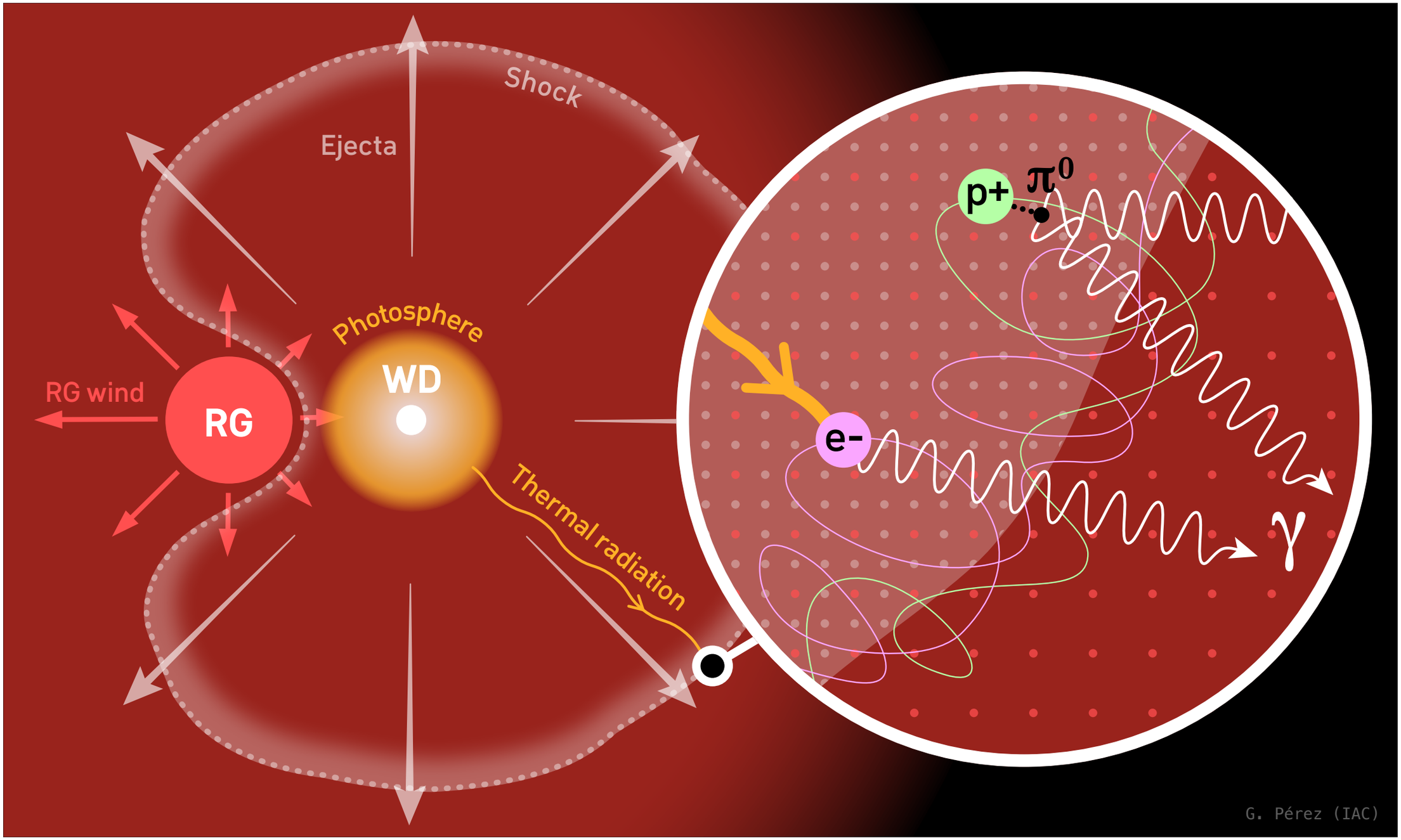
Optical

- **During the nova outburst the photospheric emission creates the dominant radiation field**
- Photometry
  - **TJO and ANS**
  - Similar parameters to those from 2006 outburst
- Spectroscopy:
  - **Varese 0.84 m and Catania 0.91 m telescopes**
  - 4500 ± 250 km s^{-1} for the ejecta expansion at the earliest stage*



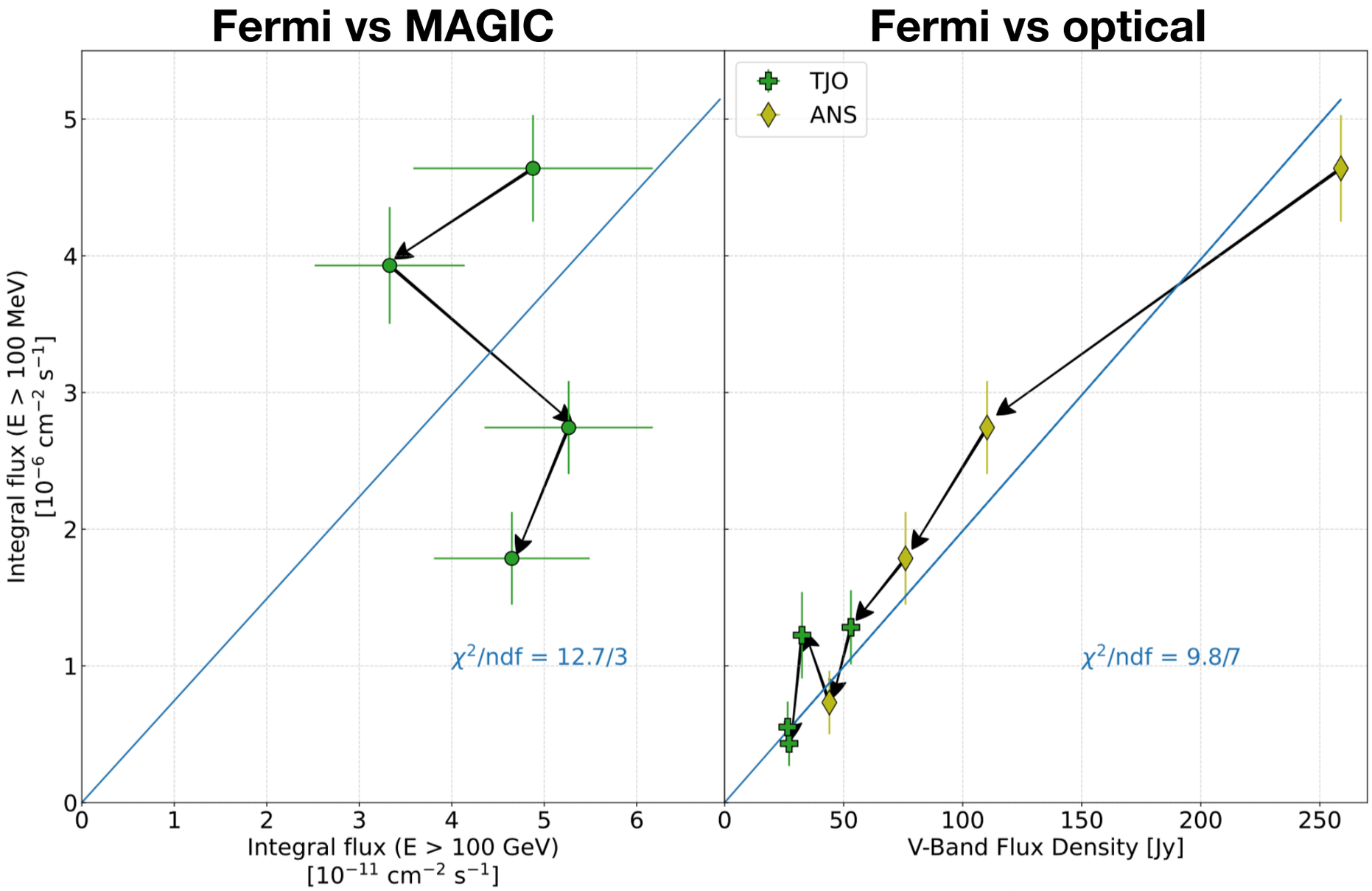
Acciari et al., Nature Astronomy, 2022

RS Ophiuchi



- **Protons**: pp interaction on **nova ejecta** (with some contribution from RG wind)
- **Electrons**: IC on thermal radiation of the **WD photosphere**
- Modeling: particles are injected and either **cool down completely (electrons)** or we gather their emission during the **acceleration time (protons)**

MWL flux evolution

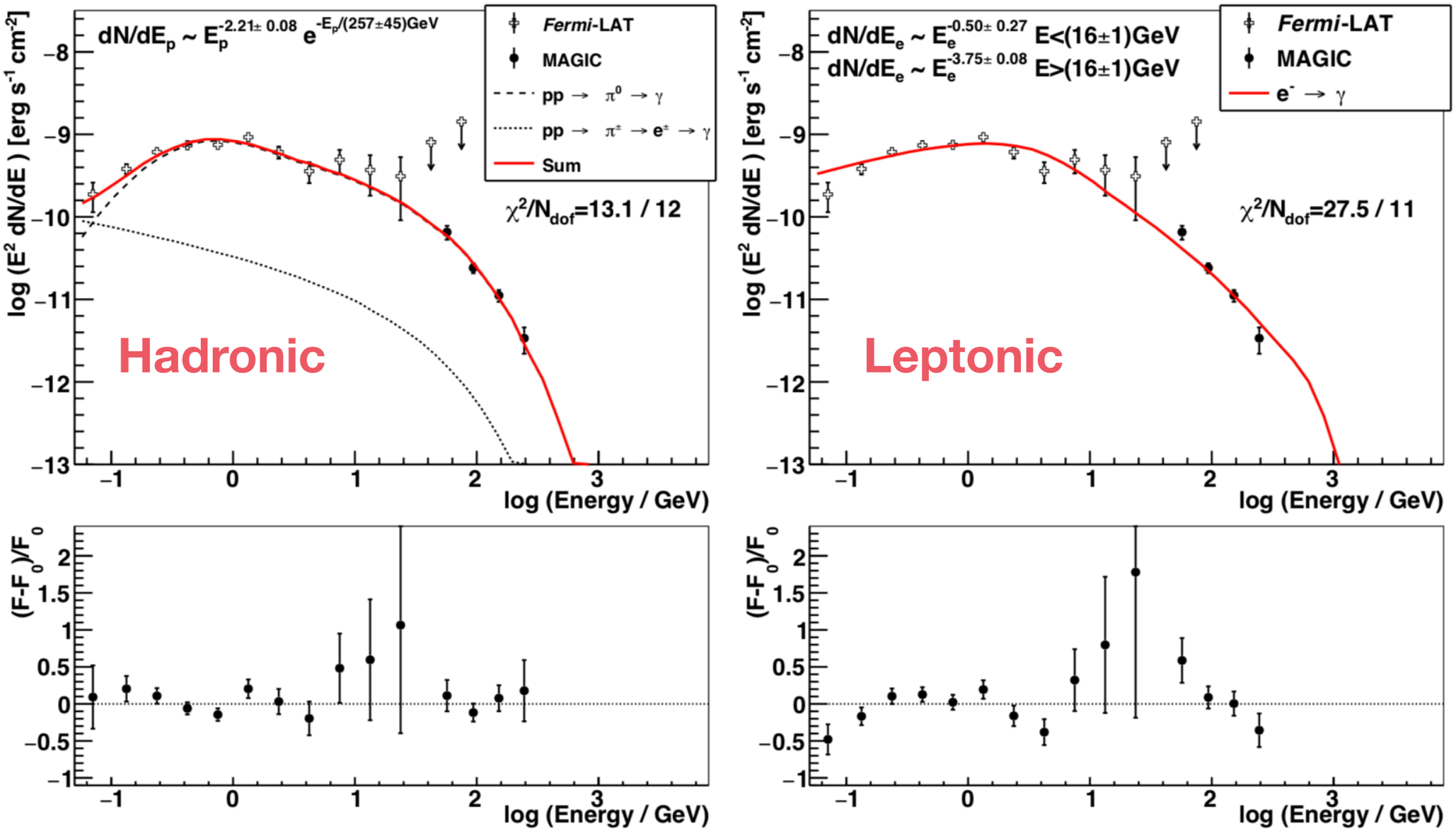


Acciari et al. Nat. Astronomy, 2022

- **VHE (integral flux) rougly flat, while HE decays faster**: can be explained as **hardening of the emission** during its decay
- **HE and optical** emission show **similar decay**: **not compatible with IC** model
  - IC emission should decay faster (due to increase of distance to photosphere)

- **Protons are favored**

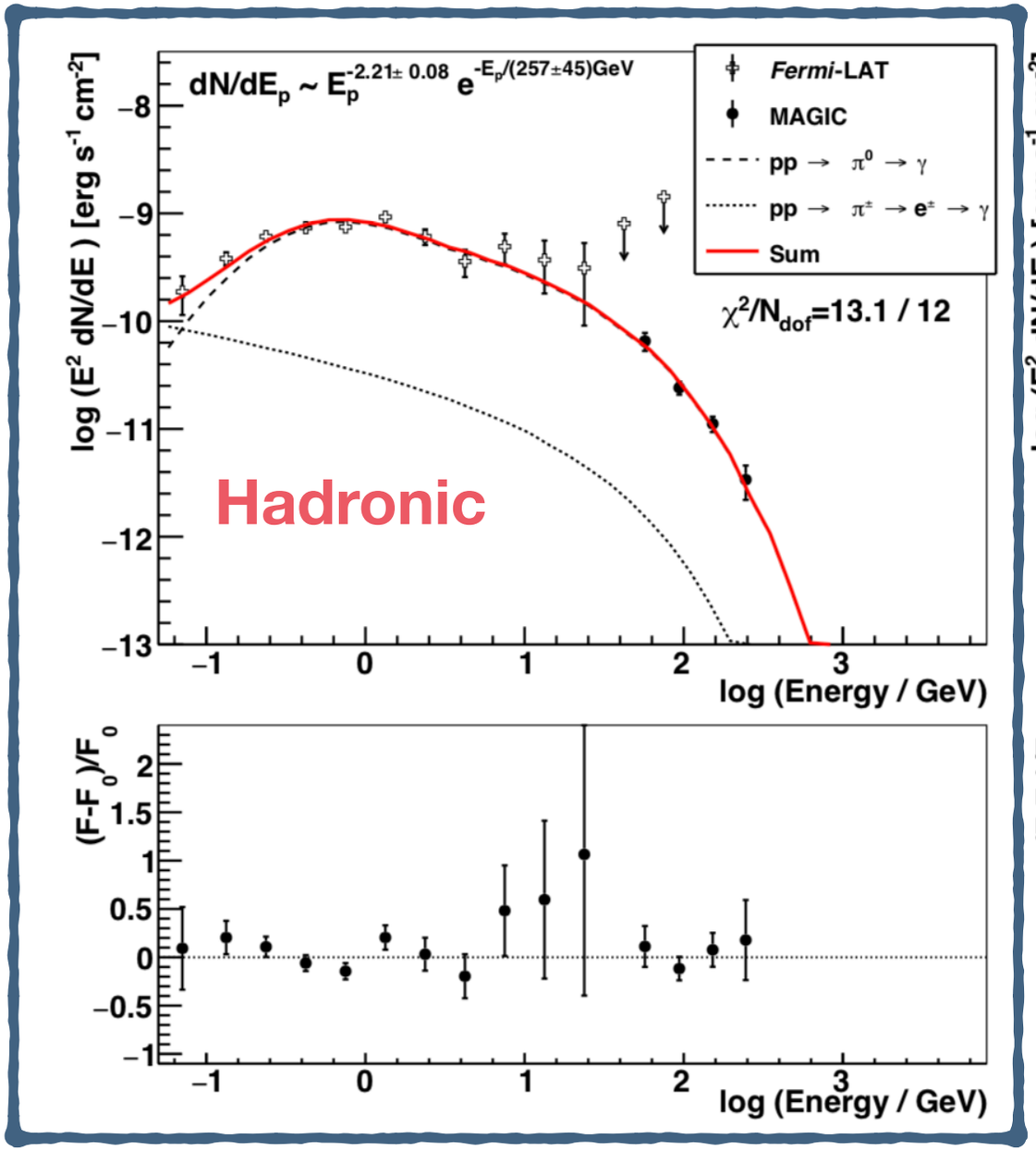
Gamma-ray modelling

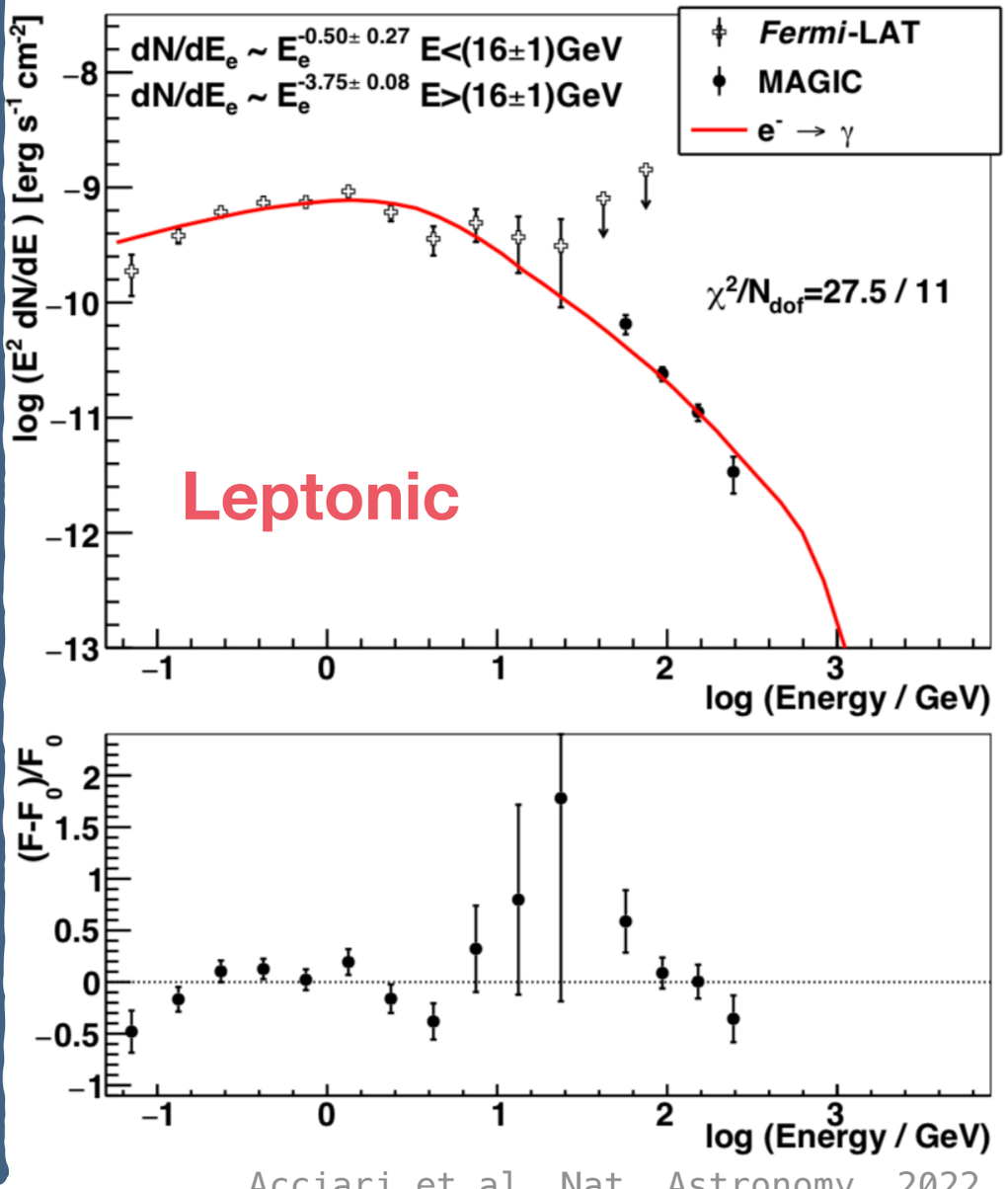


Acciari et al. Nat. Astronomy, 2022

- **Joint Fermi-LAT +MAGIC** spectrum can be described as a **single**, smooth **component** spanning **from 50 MeV to 250 GeV**

Gamma-ray modelling

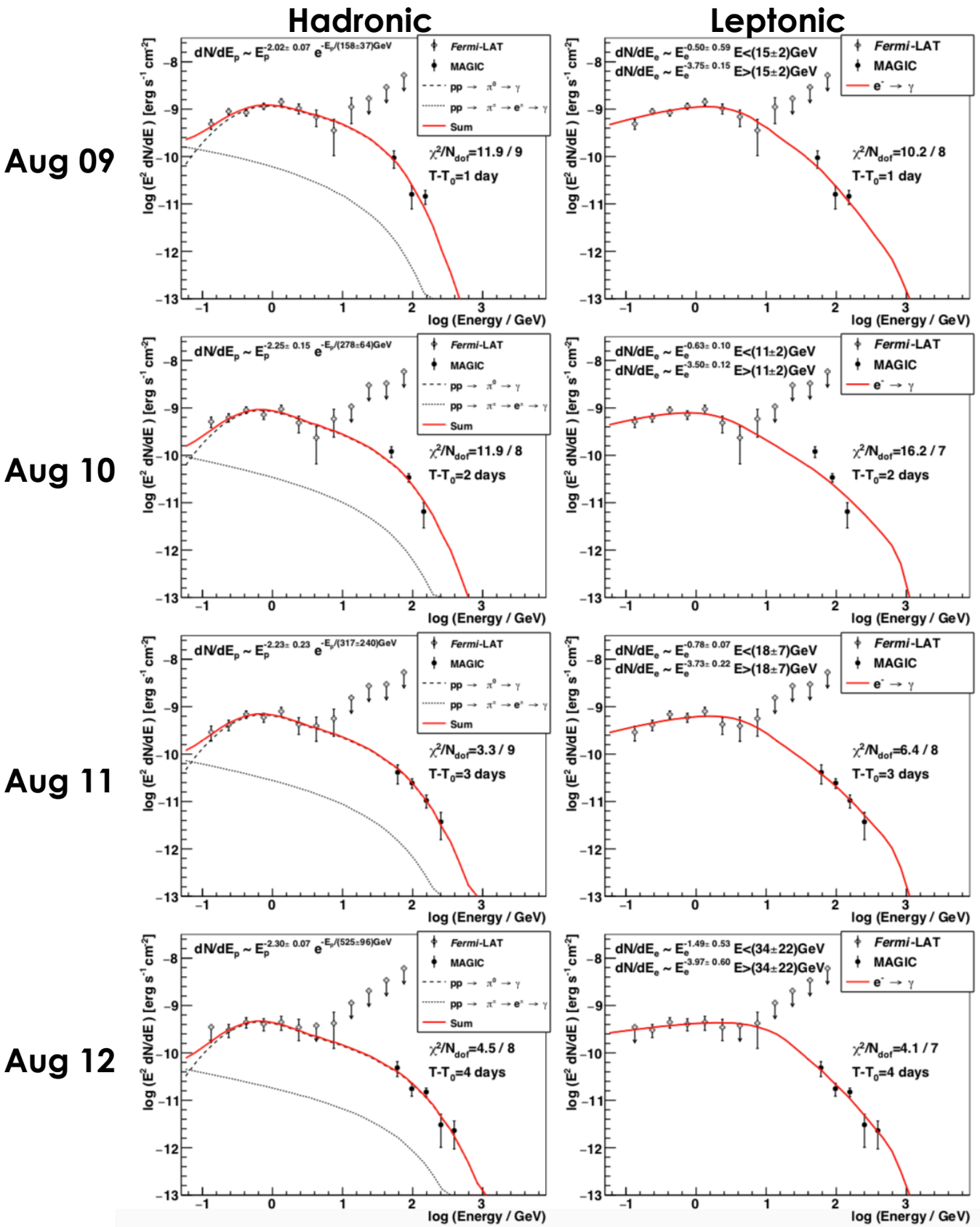




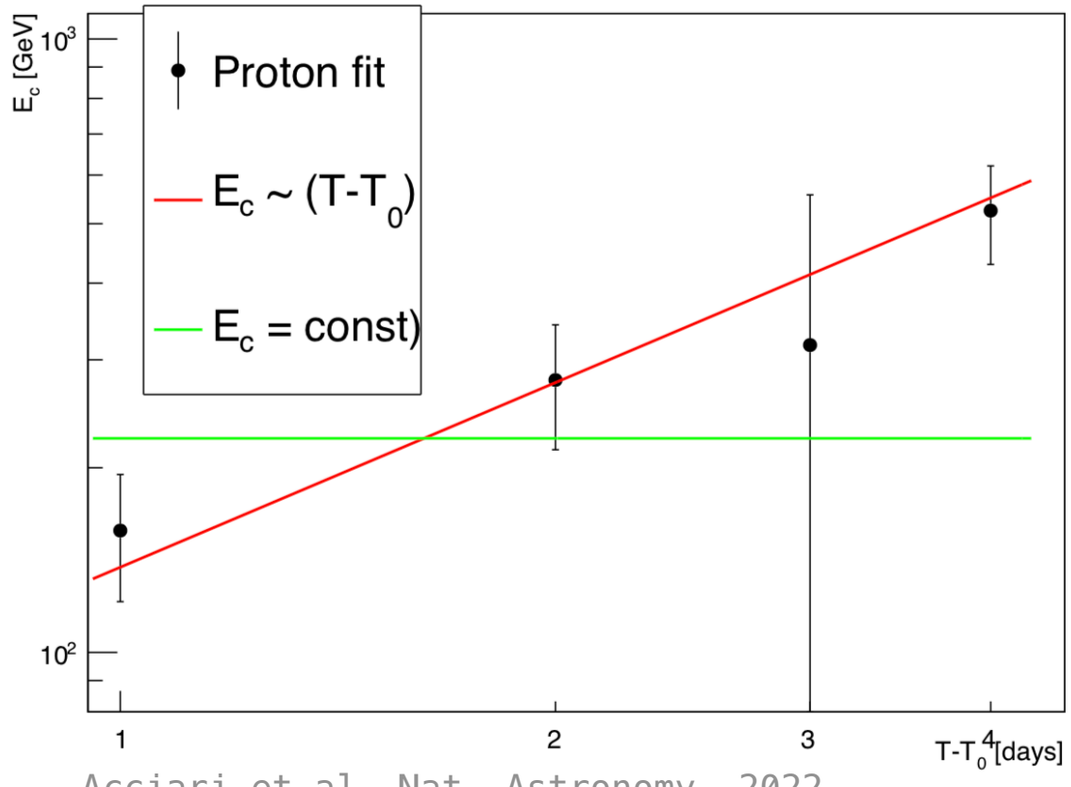
Acciari et al. Nat. Astronomy, 2022

- **Joint Fermi-LAT +MAGIC** spectrum can be described as a **single**, smooth **component** spanning **from 50 MeV to 250 GeV**
- **Hadronic scenario is favored**

Modelling: daily proton acceleration

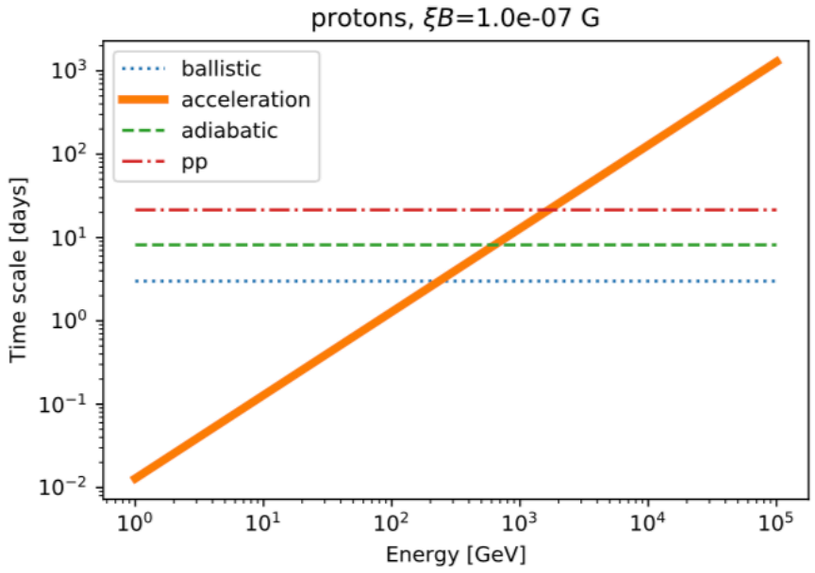


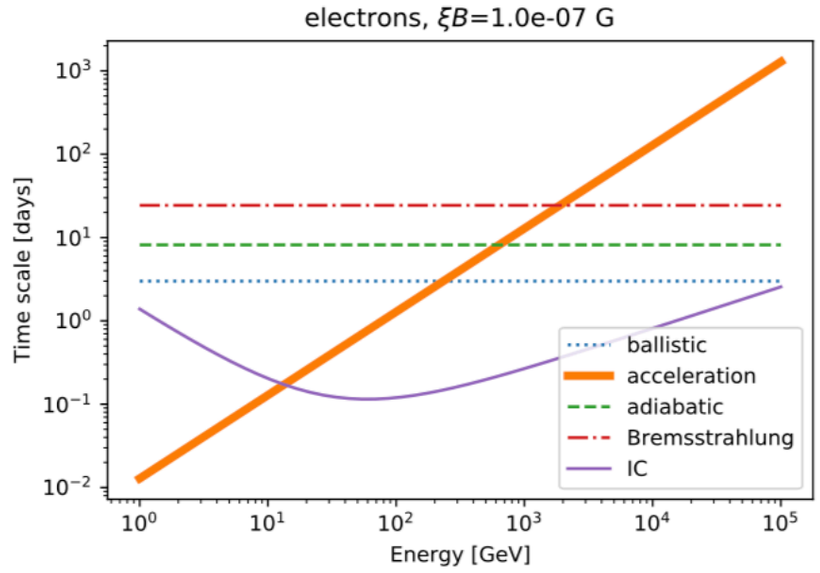
- **Daily SED**
  - **Hadronic scenario is again favored**
- **Increase of the cut-off energy with time:** hint of spectral hardening
  - In line with the expectations from the cooling and acceleration timescales
  - **Hadronic scenario favored**

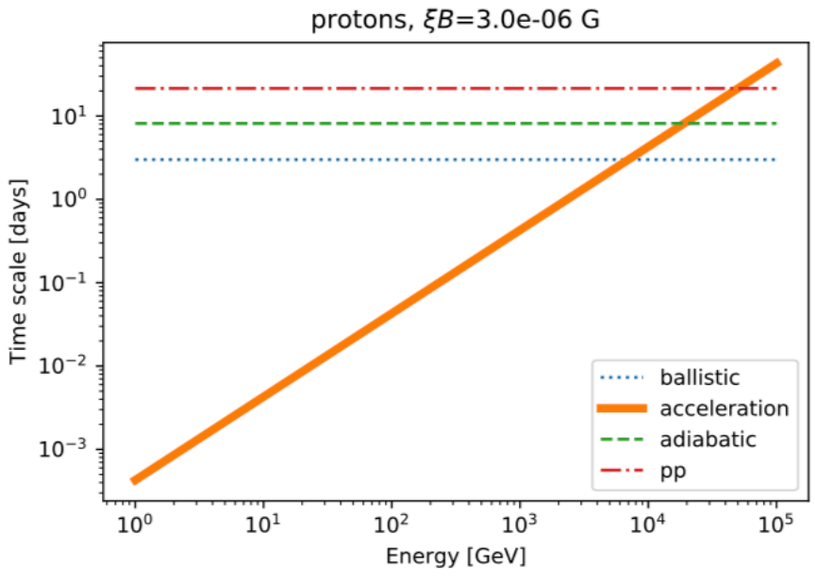


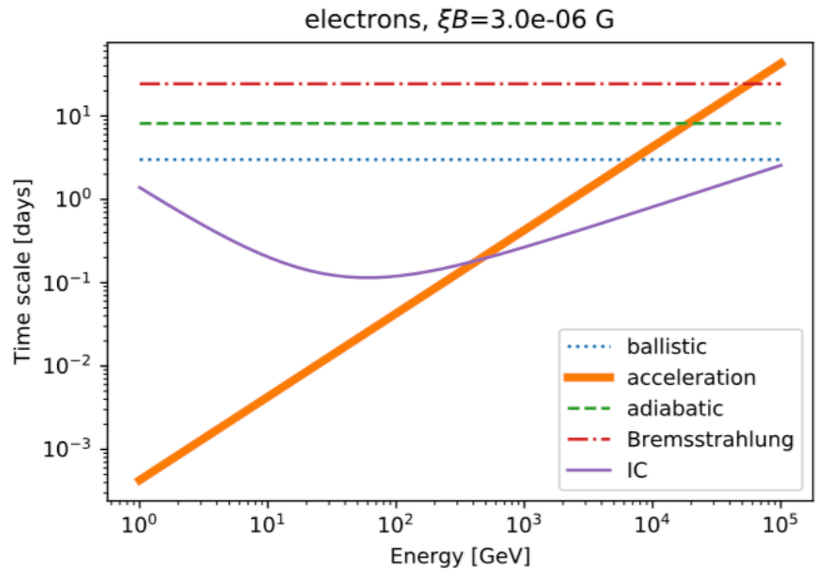
Acciari et al. Nat. Astronomy, 2022

Supporting a hadronic scenario





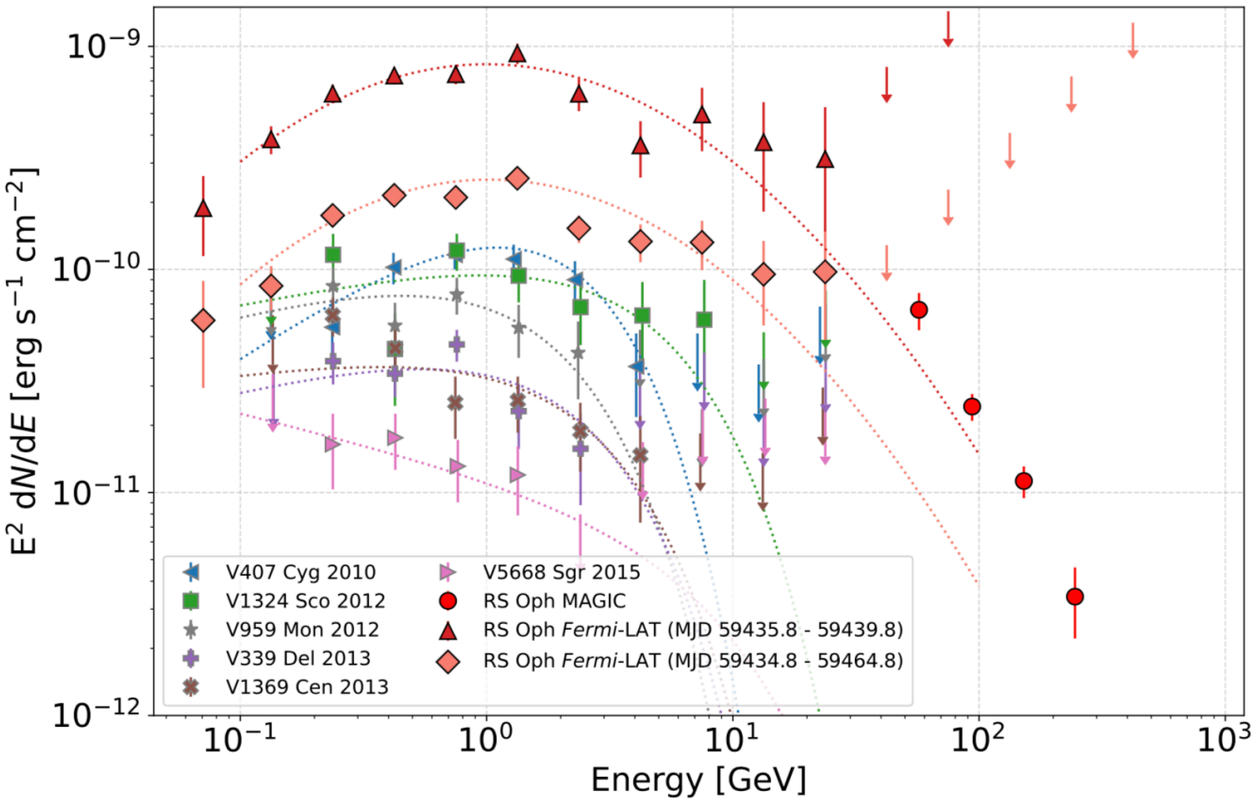


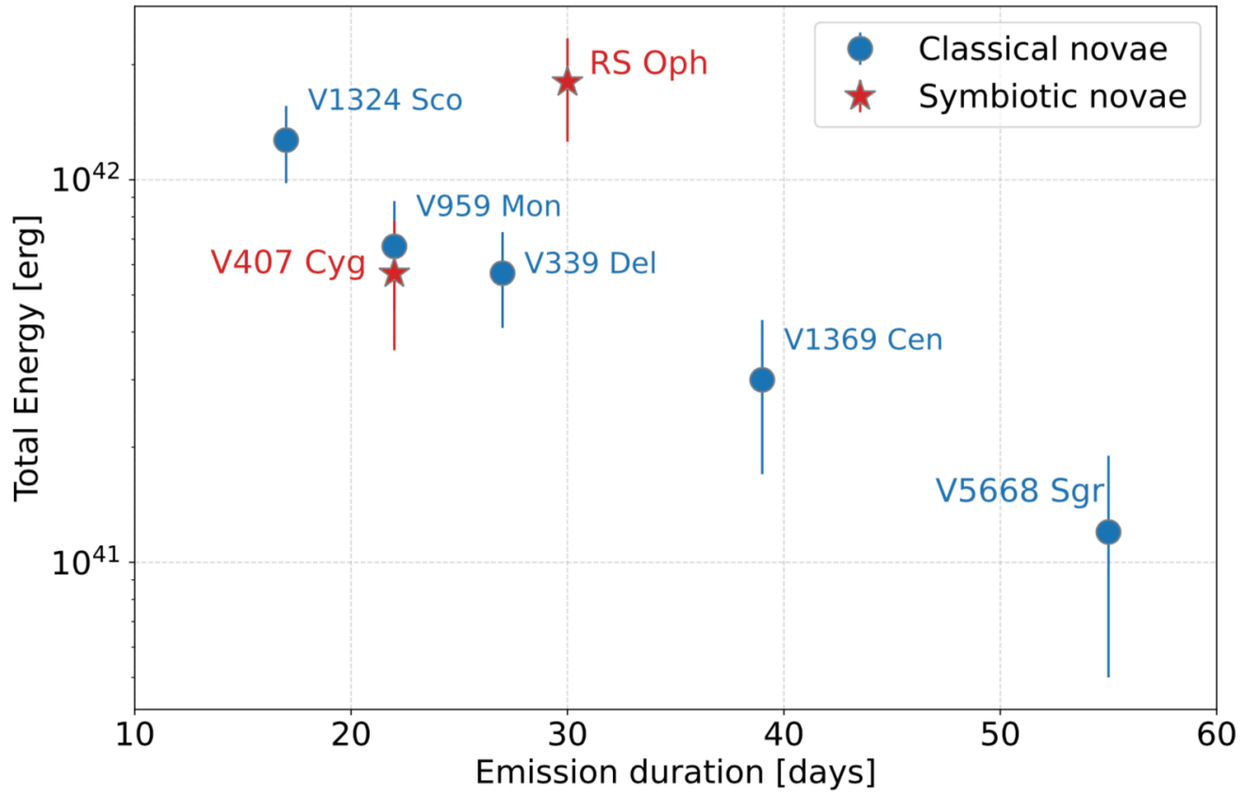


Acciari et al. Nat. Astronomy, 2022

- **Protons have slow cooling**, Emax determined by acceleration time
- **Electrons show fast cooling** on IC:
  - Two orders of magnitude **stronger acceleration and larger B needed** to reach the same energies
- **Protons are favored**

RSOph vs other novae





Acciari et al. Nat. Astronomy, 2022

- RS Oph is the nova with the **highest GeV flux** (close distance) and **brightest nova**
- **Comparison does not reveal any peculiarity** in the emission of RS Oph, except for its brightness

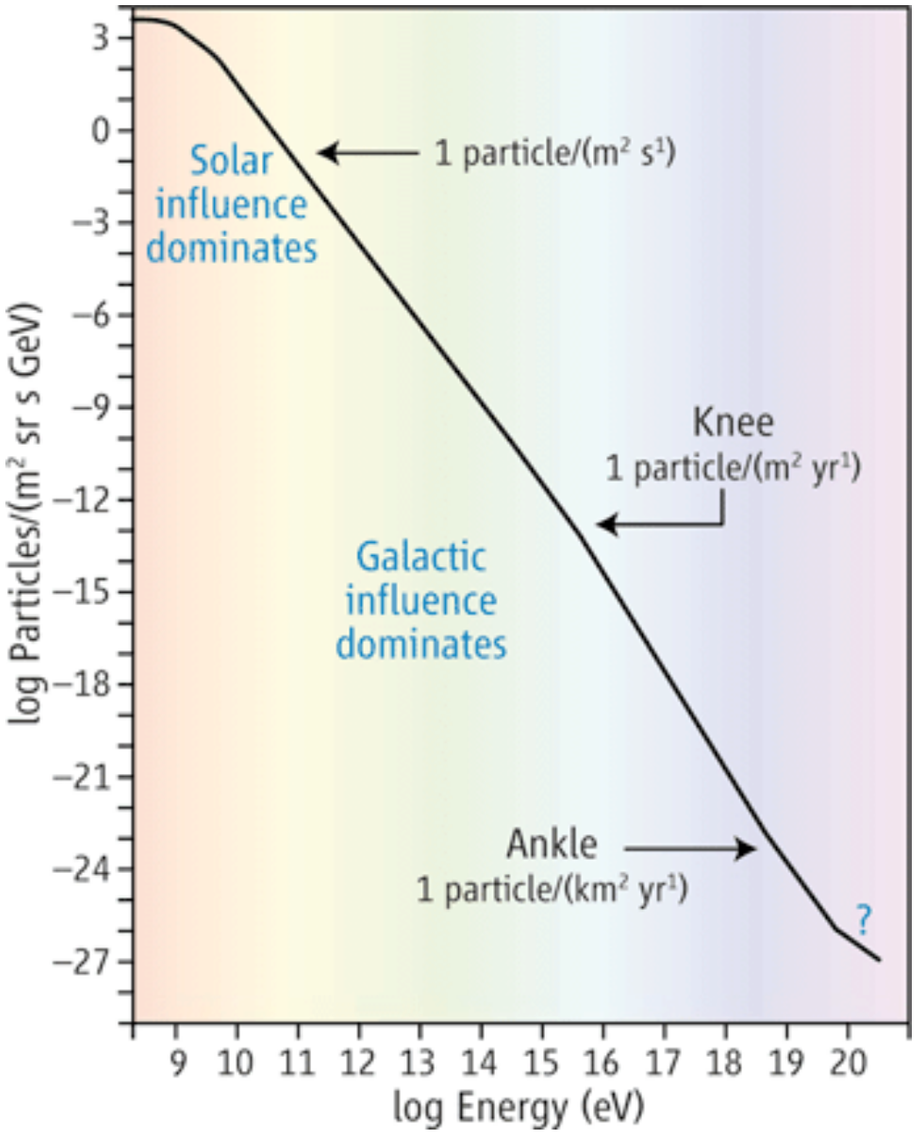
Galactic novae and Cosmic Rays

- **Accelerated protons will eventually escape the nova shock** carrying away most of their obtained energy. Such protons can **contribute to the Galactic Cosmic Ray sea**

- Using the CR energetic derived for RS Oph (~ 4.4 × 10^{43} erg): <**0.2% of the contribution from supernovae**

- Despite the small contribution to the overall CR sea, **novae would significantly increase the CR density in its close environment**: E_density(nova)>E_density(CR)

- In the case of **recurrent novae, protons will accumulate in a ~10 pc bubble** with enhanced CR density



Extracted from Dulgig, Science 2020

Summary

- The August 2021 outburst of RS Oph introduces a **new class of sources as VHE gamma-ray emitters: (recurrent symbiotic) novae**

- **Hadronic scenario (proton acceleration) is strongly favored by MAGIC+*Fermi*-LAT gamma-ray observations**

- **Galactic cosmic ray budget:** protons can escape the nova shock and contribute to the cosmic ray sea in their **close neighborhood creating bubbles of increased density (<10 pc)**

- RS Oph is the **brightest and most luminous nova**

Acciari et al. Nature Astronomy, 6, 689–697 (2022)

Summary

- The August 2021 outburst of RS Oph introduces a **new class of sources as VHE gamma-ray emitters: (recurrent symbiotic) novae**

- **Hadronic scenario (proton acceleration) is strongly favored by MAGIC+*Fermi*-LAT gamma-ray observations**

- **Galactic cosmic ray budget:** protons can escape the nova shock and contribute to the cosmic ray sea in their **close neighborhood creating bubbles of increased density (<10 pc)**

- RS Oph is the **brightest and most luminous GeV nova**

- Open questions:
  - Are classical novae also VHE emitters?
  - Is the VHE emission in RSOph related to is recurrent nature?

- **Next goal: detect the first classical nova at VHE!**

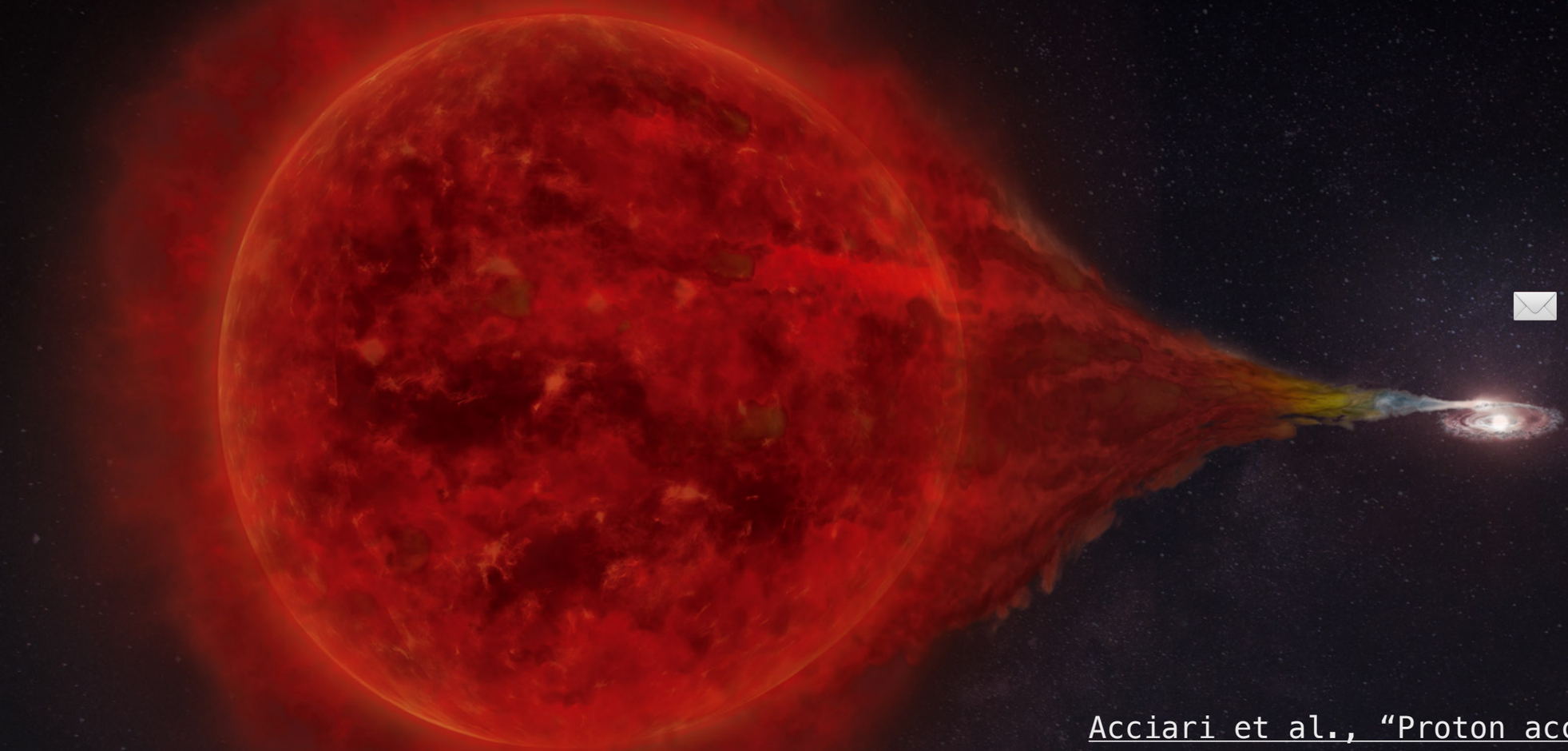
Thanks

alicia.lopez@iac.es

Acciari et al. Nature Astronomy, 6, 689–697 (2022)

γ 2022
7th Heidelberg International Symposium on
High Energy Gamma-Ray Astronomy
Barcelona, July 4-8 2022

Gamma-ray emission of **hadronic origin** from **nova RS Oph** revealed by **the MAGIC telescopes**



Thanks

alicia.lopez@iac.es

Acciari et al., "Proton acceleration in thermonuclear nova explosions revealed by gamma rays", Nature Astronomy, 6, 689–697 (2022)

Alicia López-Oramas (IAC)
Vandad Fallah Ramazani, David Green, Francesco Leone, Rubén López-Coto, Julian Sitarek
for the MAGIC collaboration

7th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy, July 2022