MAGIC recent discoveries of gamma-ray binaries

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NextGenerationEU
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AGENCIA ESTATAL DE INVESTIGACIÓN

This work is part of the Project RYC2021-032991-I, funded by MICIN/AEI/10.13039/501100011033, and the European Union "NextGenerationEU"/RTRP.

Alicia López-Oramas (IAC)
for the MAGIC collaboration

Variable Galactic Gamma-Ray Sources (VI), Innsbruck, April 2023

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.

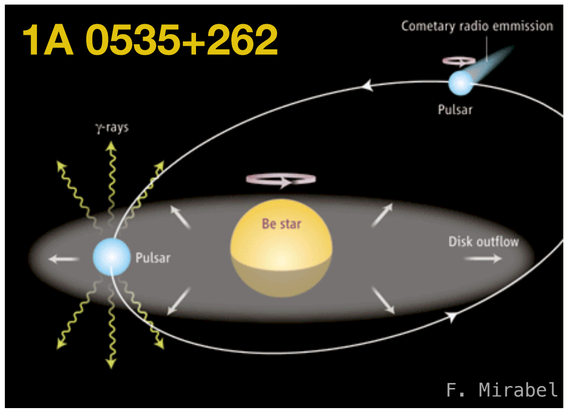
Energy: ~30 GeV - 100 TeV

Outline

Gamma-ray binaries

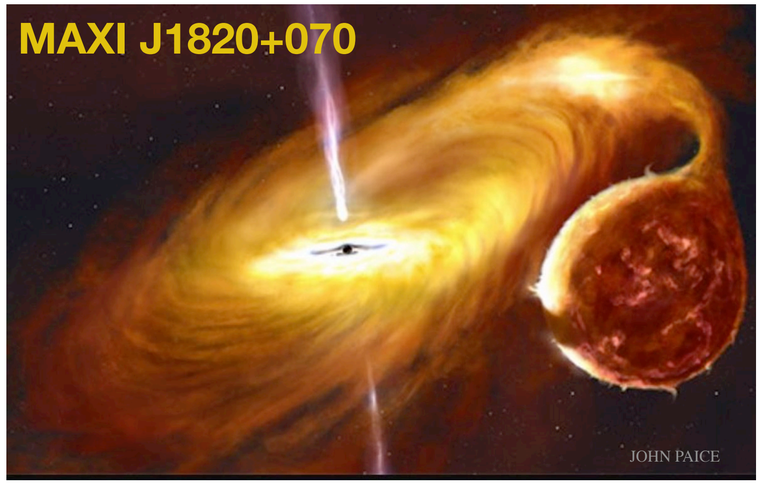
- Adams et al, (VERITAS, MAGIC and H.E.S.S. collaborations), "**Observation of the gamma-ray binary HESS J0632+057 with the H.E.S.S., MAGIC and VERITAS Telescopes**", 2021, ApJ, 923 241

Be/X-ray binaries



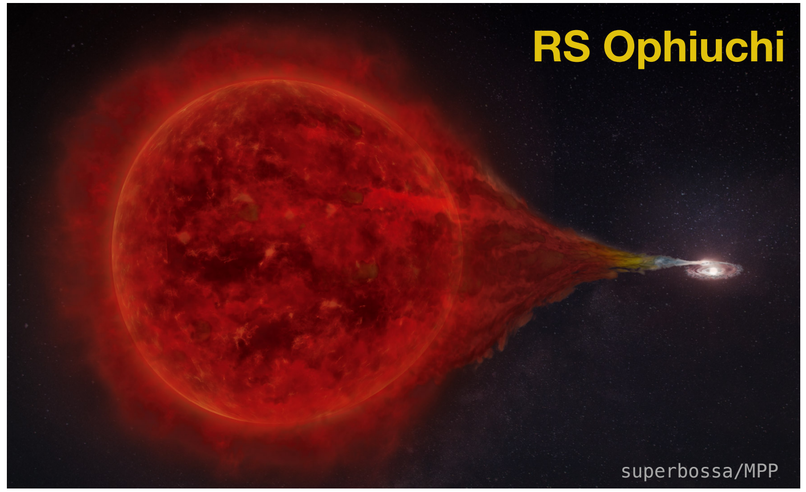
- Molina, López-Oramas, D. Hadasch and J. Hoang for the MAGIC Collaboration, **Recent MAGIC results on Galactic binaries**, Pos(ICRC2021)

Microquasars



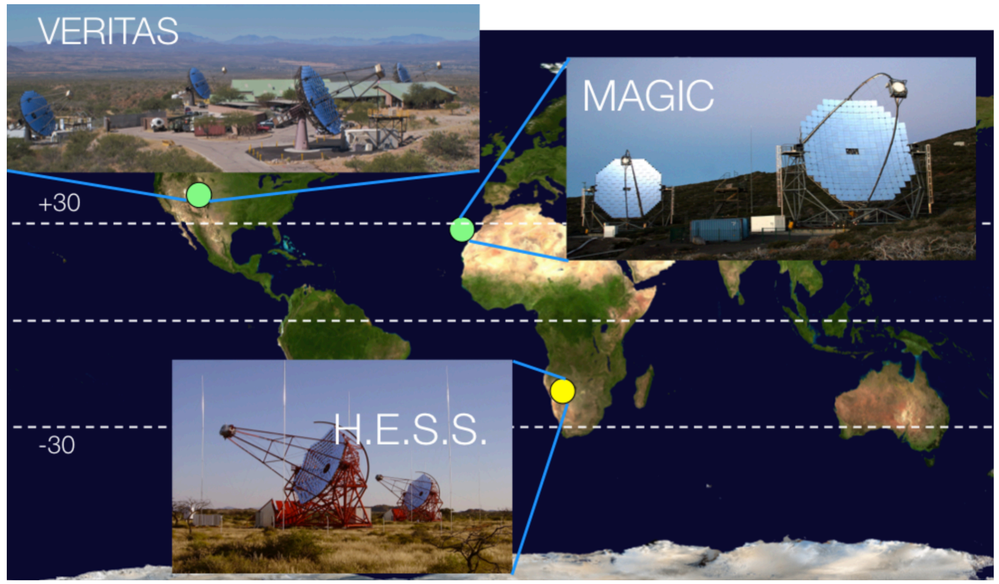
- Abe et al. (H.E.S.S., MAGIC and VERITAS), 2022, "**Gamma-ray observations of MAXI J1820+070 during the 2018 outburst** ", MNRAS, 517, 4736

Novae



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

HESS J0632+057 at VHE: joint effort



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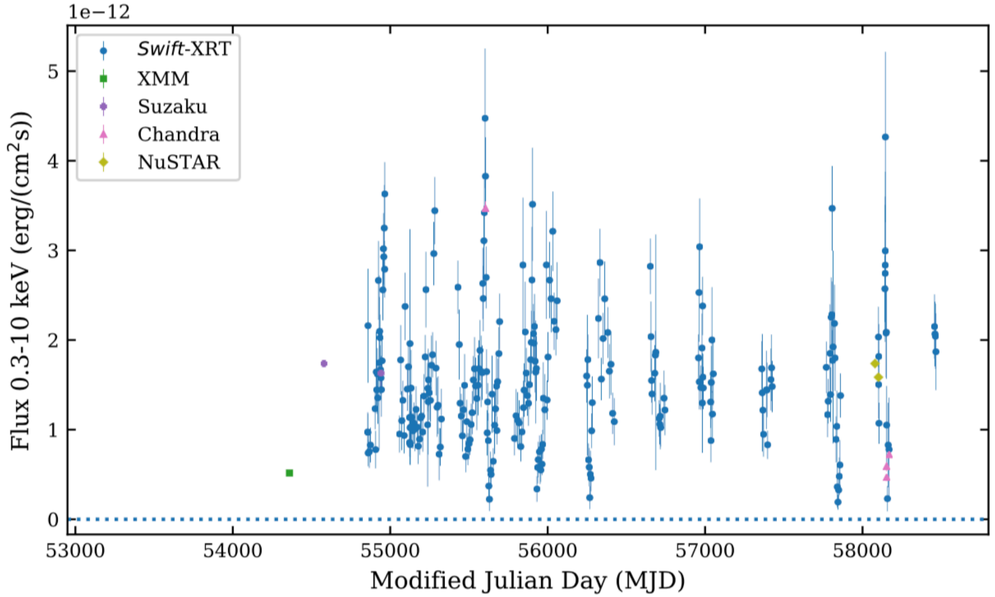
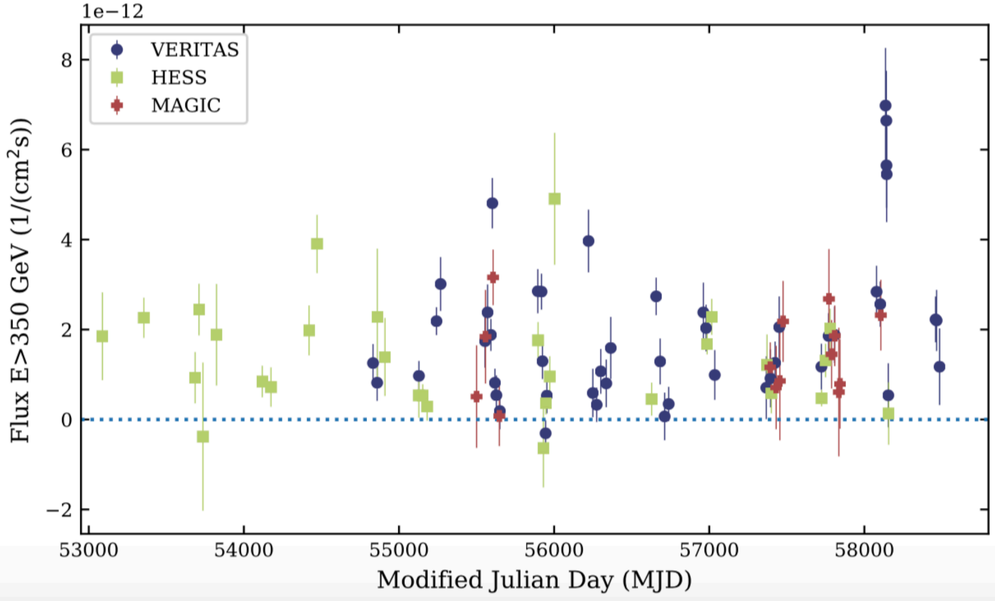


2004 ⟷ 2019



- **VHE**: **450 h of data over 15 years: 18 orbits**
- **X-rays**: Swift- XRT, XMM-Newton, Chandra and NuSTAR, also from Malyshev et al. (2019)
- **Optical**: HIDES (188 cm telescope at Okayama Astrophysical Observatory (OAO))and ESPaDOnS (Canada-France-Hawaii Telescope) spectrographs

Orbital period at TeV and lightcurve

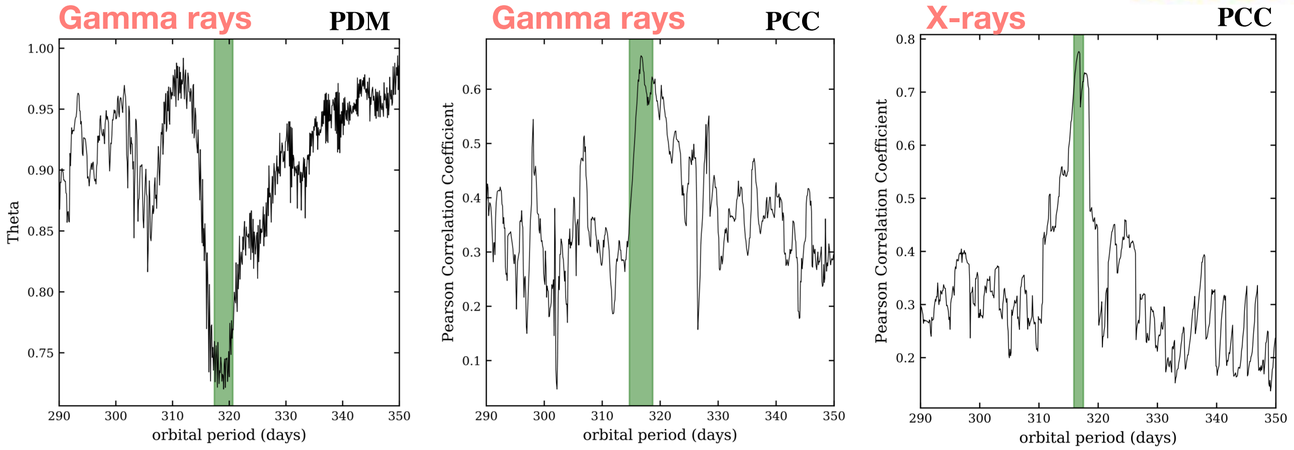
- We determine **for the first time**, the **orbital period at TeV:**

  316.7 ± 4.4(stat) ± 2.5(sys) days

  - In agreement with the 317.3 ± 0.7-day X-ray period

- Phase-averaged luminosity >1 TeV is ≈10^{32} erg s^{-1}:

  one of the faintest gamma-ray binaries known



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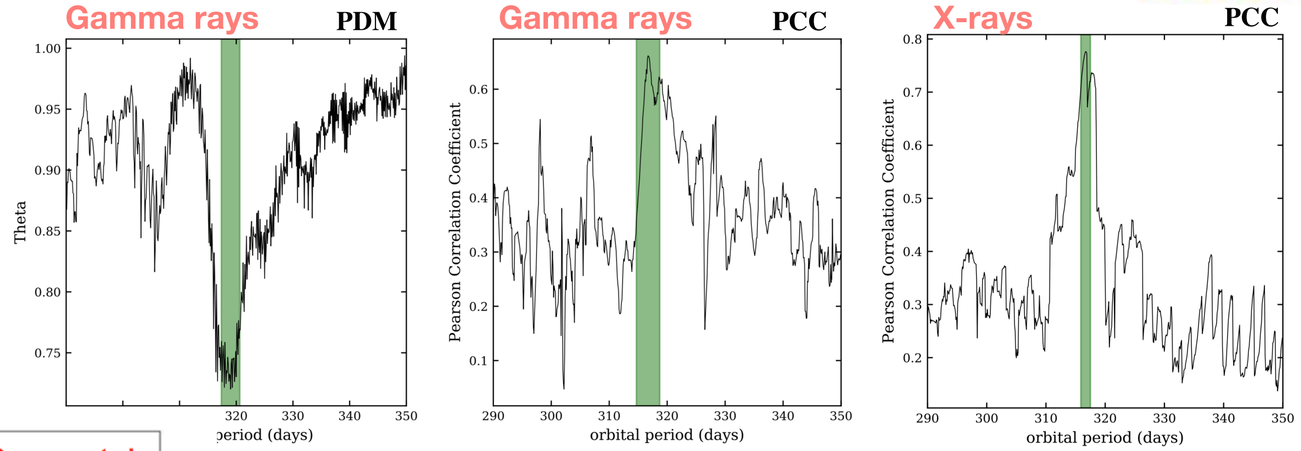
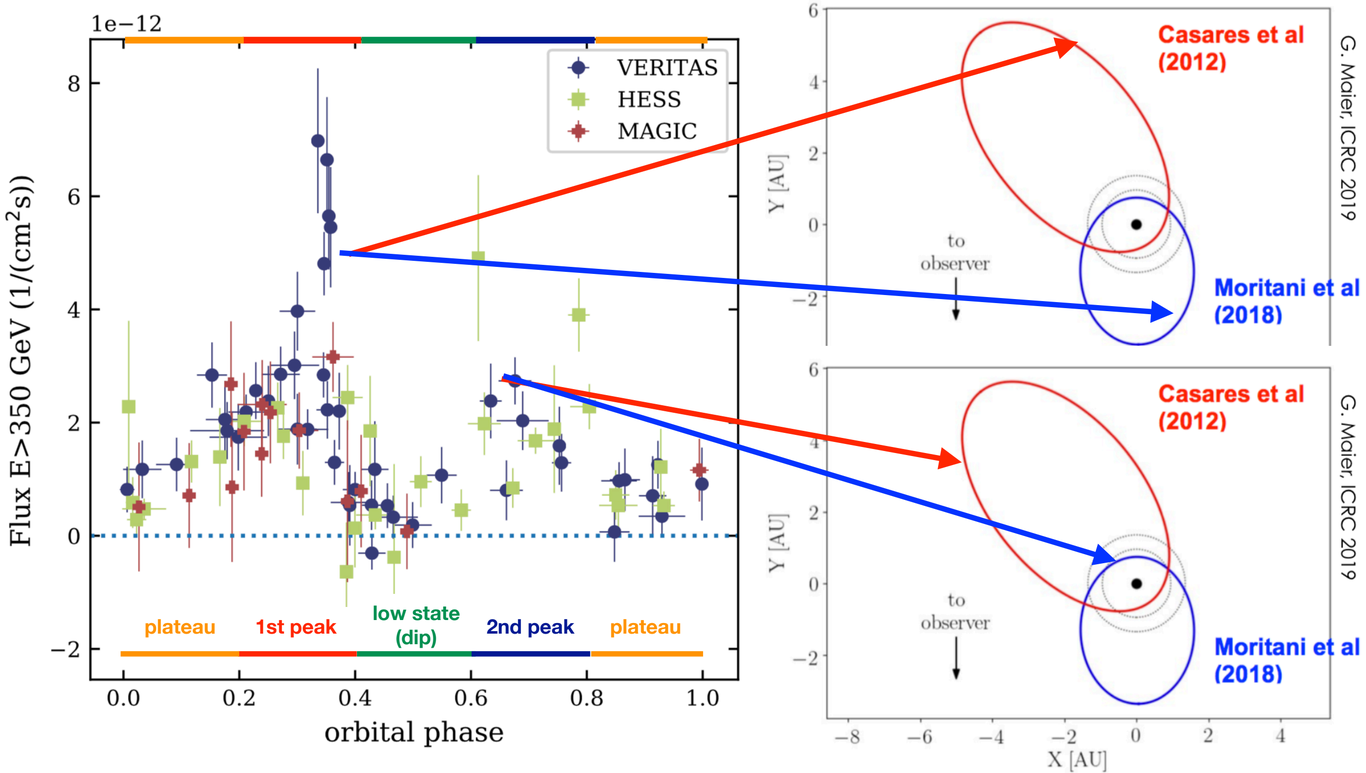
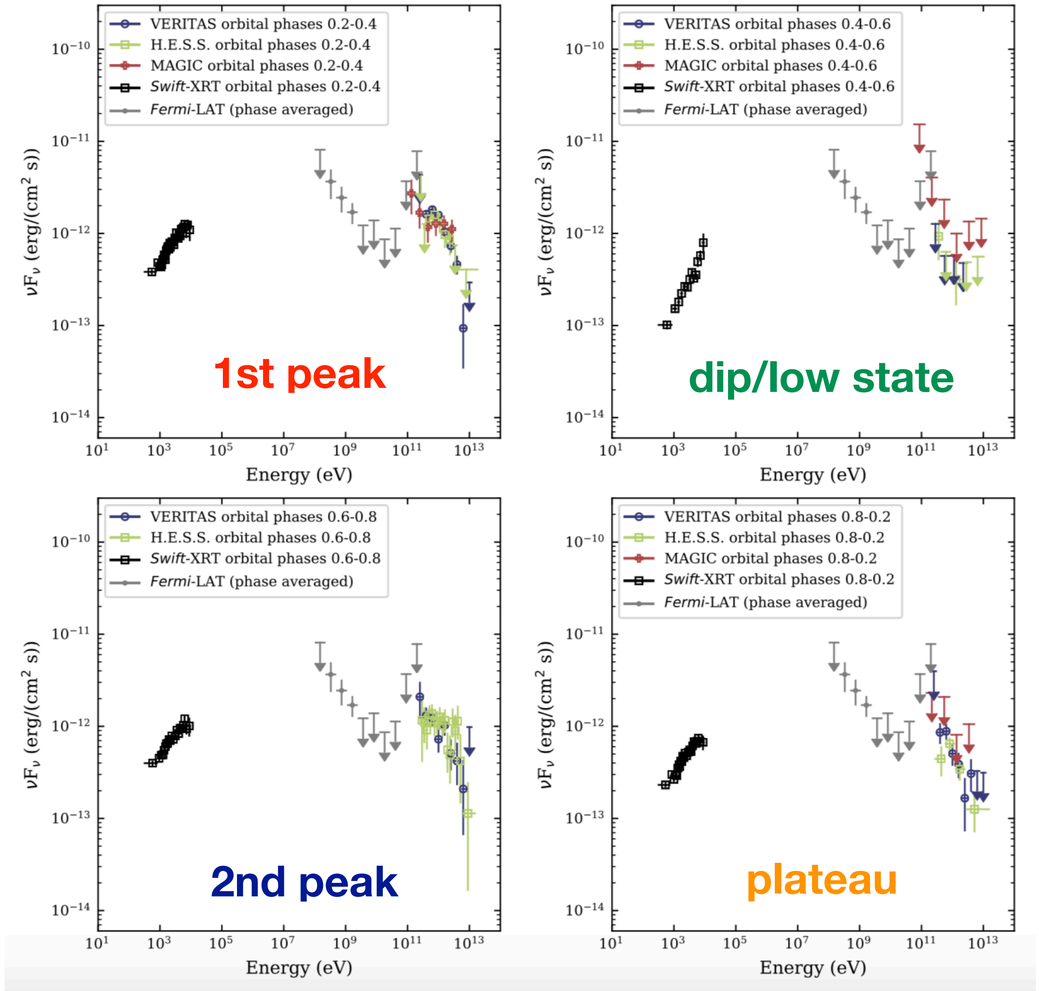
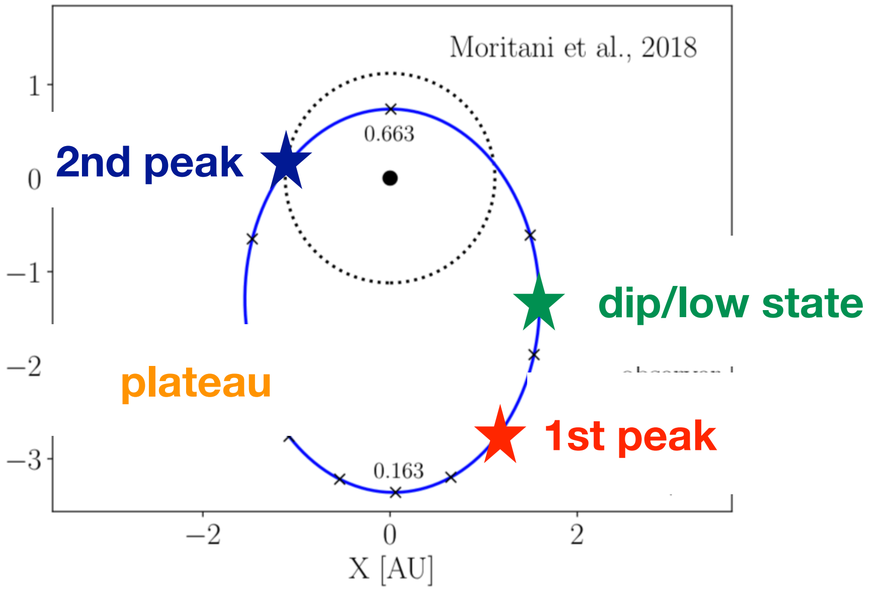




- Existence of **orbit-to-orbit variability**
- Strong variability of the VHE flux **on time scales of <20 days**
  - 2018: **detected on three individual nights** within one week of observations with >7σ per night
  - Flux incresed in 2011 and 2018:
    - Hα data (2018): size of the circumstellar disk had increased
- **No evidence for a super-orbital period**, as observed e.g., in LS I +61°303 (Ahnen et al. 2016)

SEDs and correlations





- VHE gamma- ray emission **extends beyond several TeV**
- **No sings of spectral variability**: spectral indices in the range 2.3–2.6
- Only **VERITAS** during the **phases 0.2–0.4** favors a PWEC **at 1.75 TeV**

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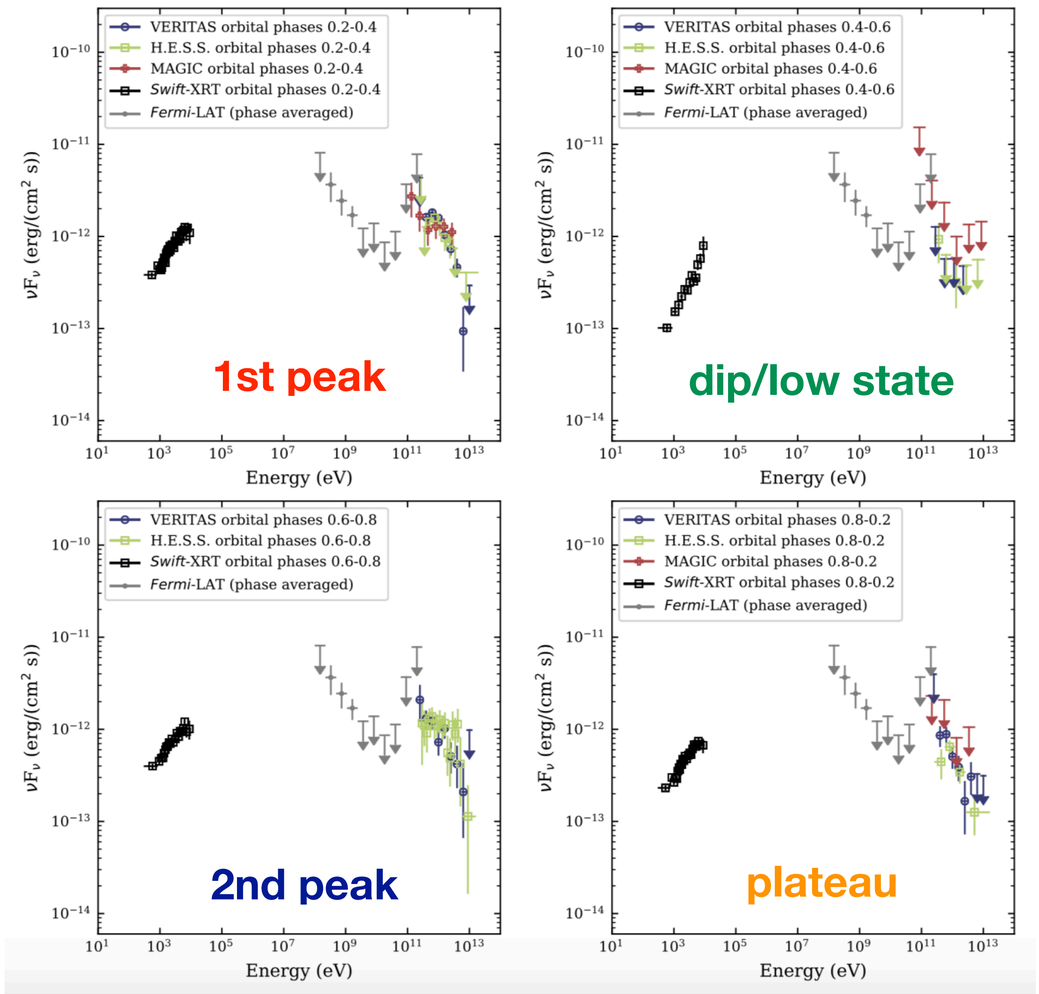

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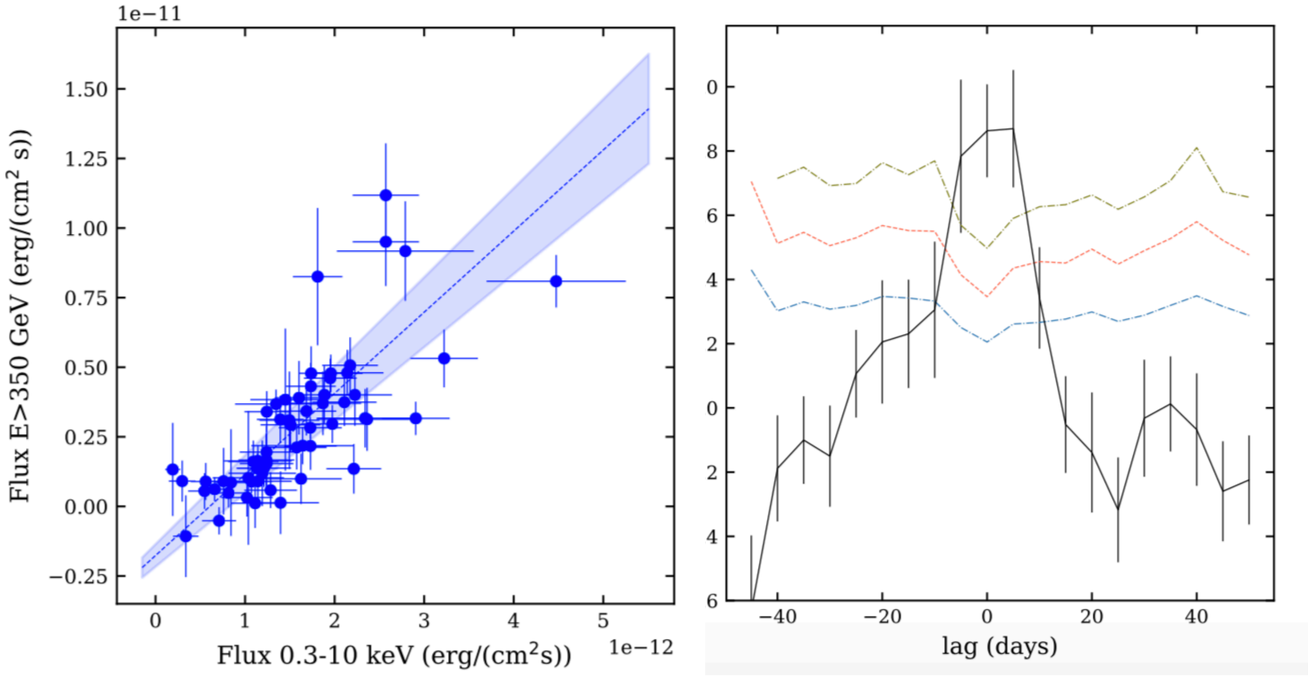
X-ray - gamma-ray correlation



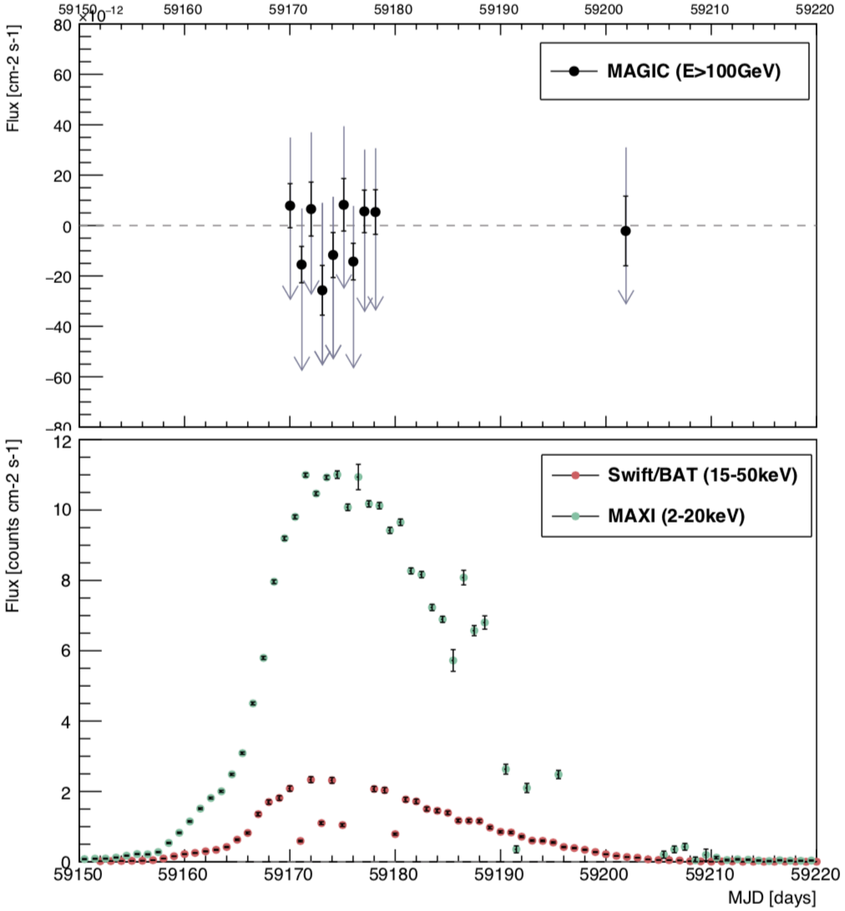
- **Strong correlation between X-ray and gamma rays**
  - **Gamma-to-xray ratio= 3 -> slight dominance of gamma-rays**
  - Emission in both bands is **produced by the same population of particles**
- **No time lag** is observed (although not probing time lags $\tau \leq 10$ days)
- **No optical-Xray / optical-gamma-rays correlations found**
  - Optical data obtained during five orbital periods(orbits 12–16)

1A 0535+262

- Be X-ray binary: massive Be star + pulsar (period:103.469 s)

- **Giant outburst on November 2020** (Mandal et al. 2020, Nakajima et al. 2020)
  - **Brighest X-ray flare**: 11 Crab level in the 15-50 KeV band
    - vs 8 Crab previous years
  - **Likely super-critical accretion** (Jaisawal et al. 2020)
  - **First time non-thermal radio detection** (J. van den Eijnden et al. 2020)
    - Coupled with X-ray
  - Reactivation on Feb 2021 (Mandal et al. 2021)

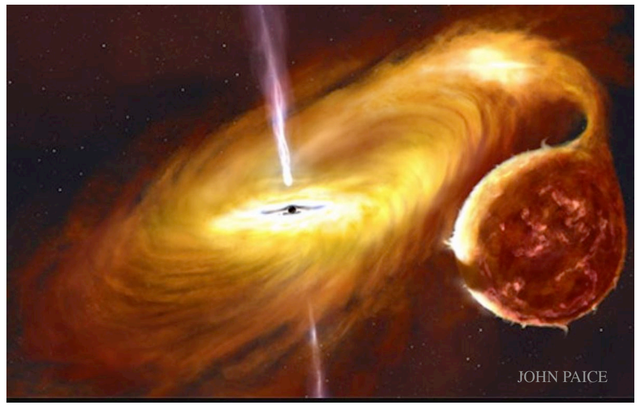
- **MAGIC** observations: November 17 - December 19, 2020
  - **No detection** (overal signigicance: 1.3 σ)
  - Integral flux UL (E>100 GeV): 5.0×10^{-12} cm^{-2} s^{-1}



Molina, López-Oramas, D. Hadasch and J. Hoang for the MAGIC Collaboration, Pos(ICRC2021)

MAXI J1820+070

- Black-hole low-mass X-ray binary, discovered in 2018 when undergoing an outburst:
  - ~4 Crabs (Del Santo & Segreto 2018; Shidatsu et al. 2019)
  - Radio emission throughout the whole outburst provides evidence for the **presence of jets**
    - Population of non-thermal particles (electrons and possibly positrons) emitting via the synchrotron mechanism.
  - Observed by MAGIC for 45 h (22.5h) between March and September 2018
    - Hard state, state transitions
  - **Joint campaign with H.E.S.S. and VERITAS**
    - **~ 60 h of observations**
    - **Covering full HS–SS–HS cycle**
  - No detection…



Source state	Experiment	Time (h)	Zenith angle (median) (°)
Hard State	H.E.S.S.	17.9	30–61 (33)
	MAGIC	14.2	21–58 (34)
	VERITAS	10.7	20–39 (28)
HS → SS	H.E.S.S.	4.0	30–38 (32)
	MAGIC	4.9	21–48 (27)
Soft State	H.E.S.S.	2.6	30–34 (31)
SS → HS	H.E.S.S.	1.8	37–53 (43)
	MAGIC	3.4	28–56 (41)
TOTAL	H.E.S.S.	26.3	30–61 (33)
	MAGIC	22.5	21–58 (32)
	VERITAS	10.7	20–39 (28)

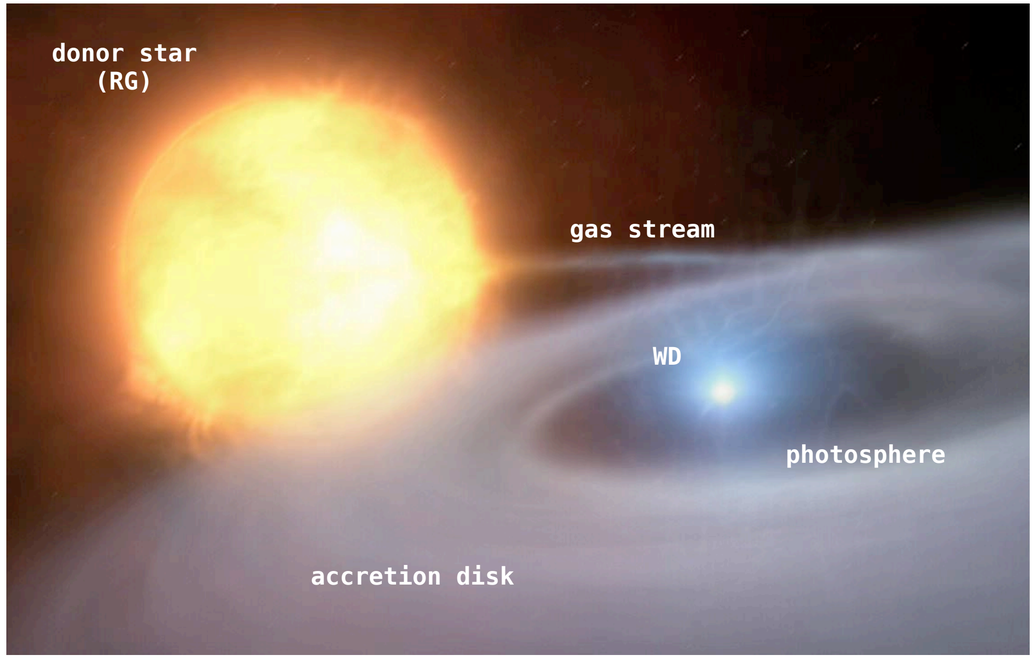
see: Edgar Molina
The 2018 flare of MAXI J1820+070: gamma rays and physical constraint
April 12, 12:20 h

Abe et al. (H.E.S.S., MAGIC and VERITAS), 2022, MNRAS, 517, 4736

Novae

- Novae are **thermonuclear explosions** caused by accumulation of material from **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 low-mass star
- Novae outbursts usually last from weeks to months
- Some novae show repeated outbursts within a human lifetime: **recurrent novae (RN)**



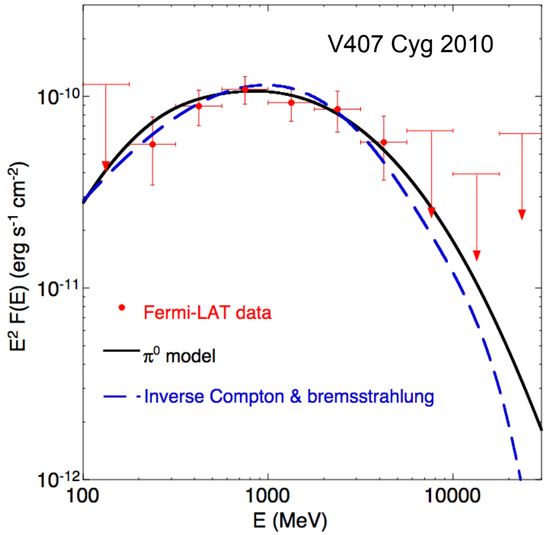
Credit: ESO / M. Kornmesser

see: Arnau Aguasca-Cabot
Novae at very-high-energy gamma rays: present and future
April 12, 12 h

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)

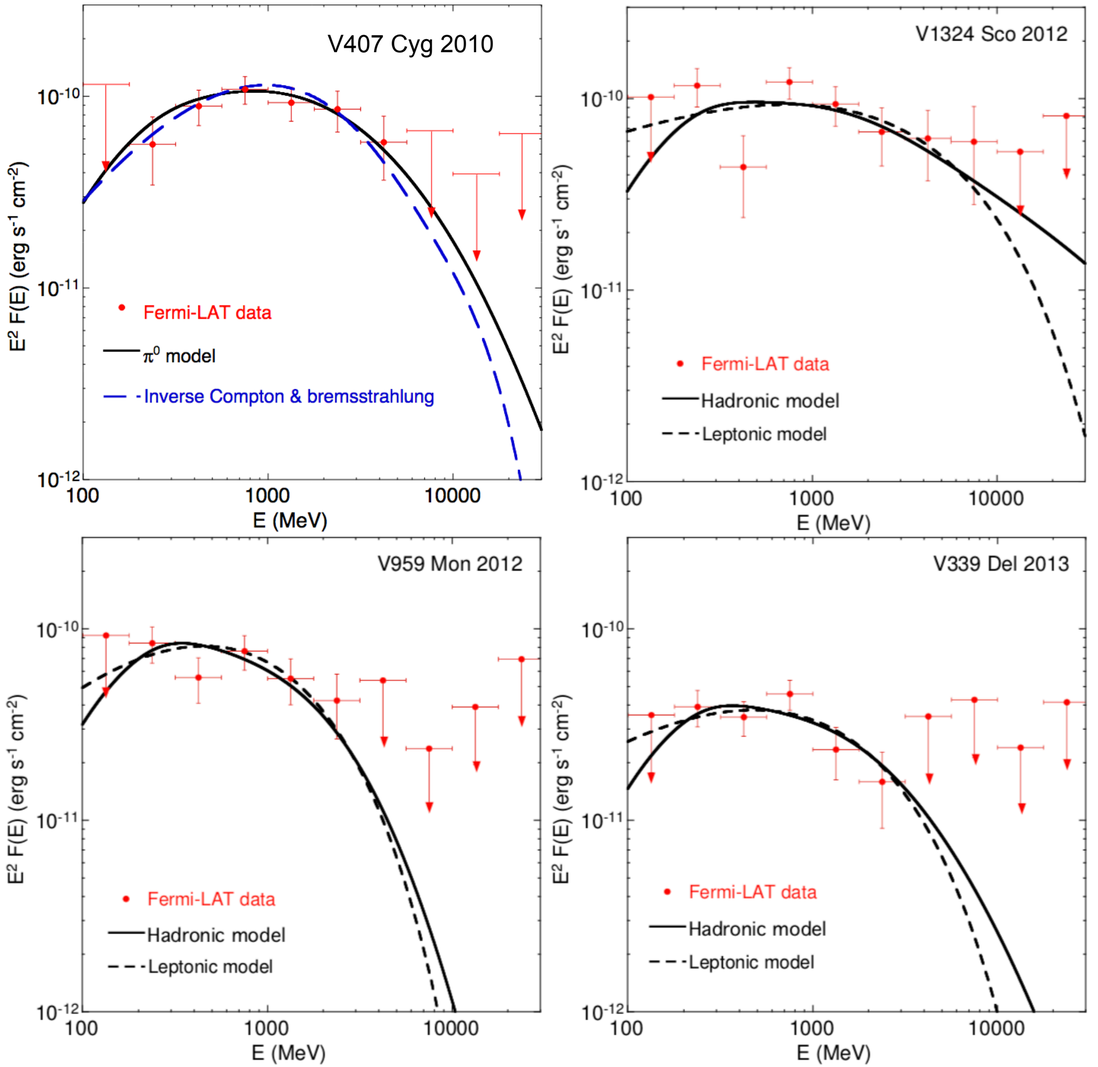
- **Novae established as HE emitters (HE, E>100 MeV)**



Fermi–LAT, Science, 2010

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 (WD+low-mass star) 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

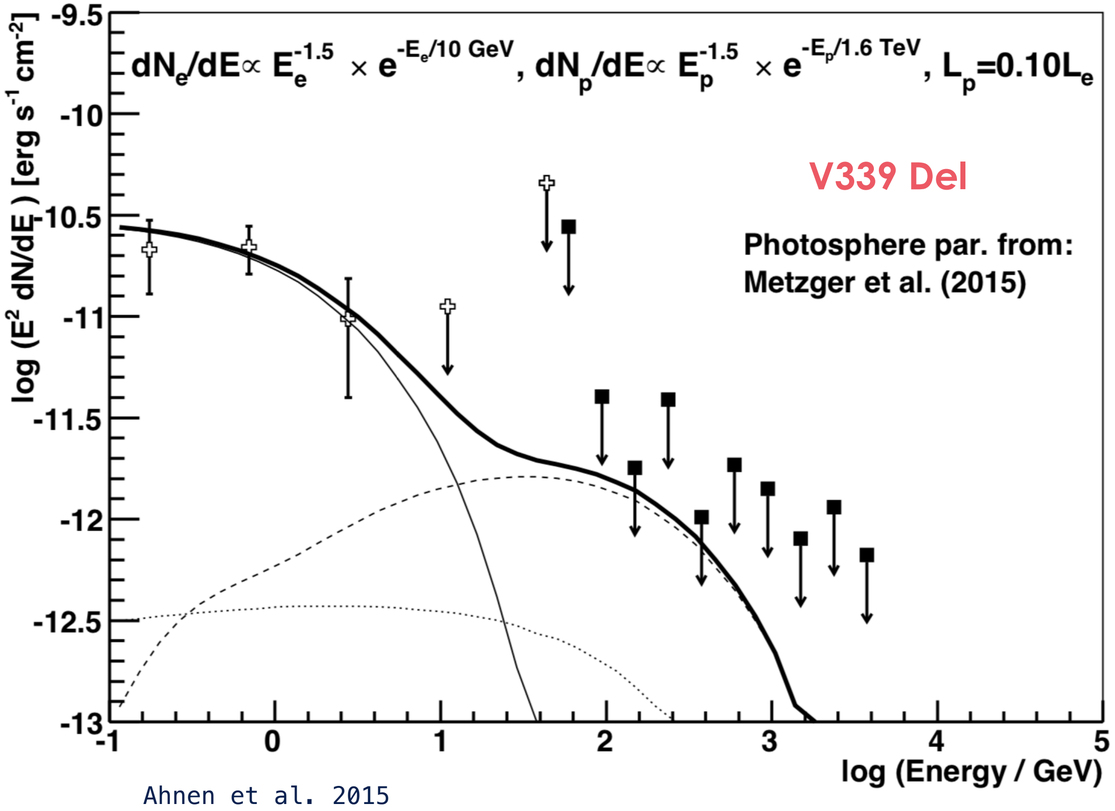


Fermi–LAT, Science, 2014

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

Searching for VHE emission

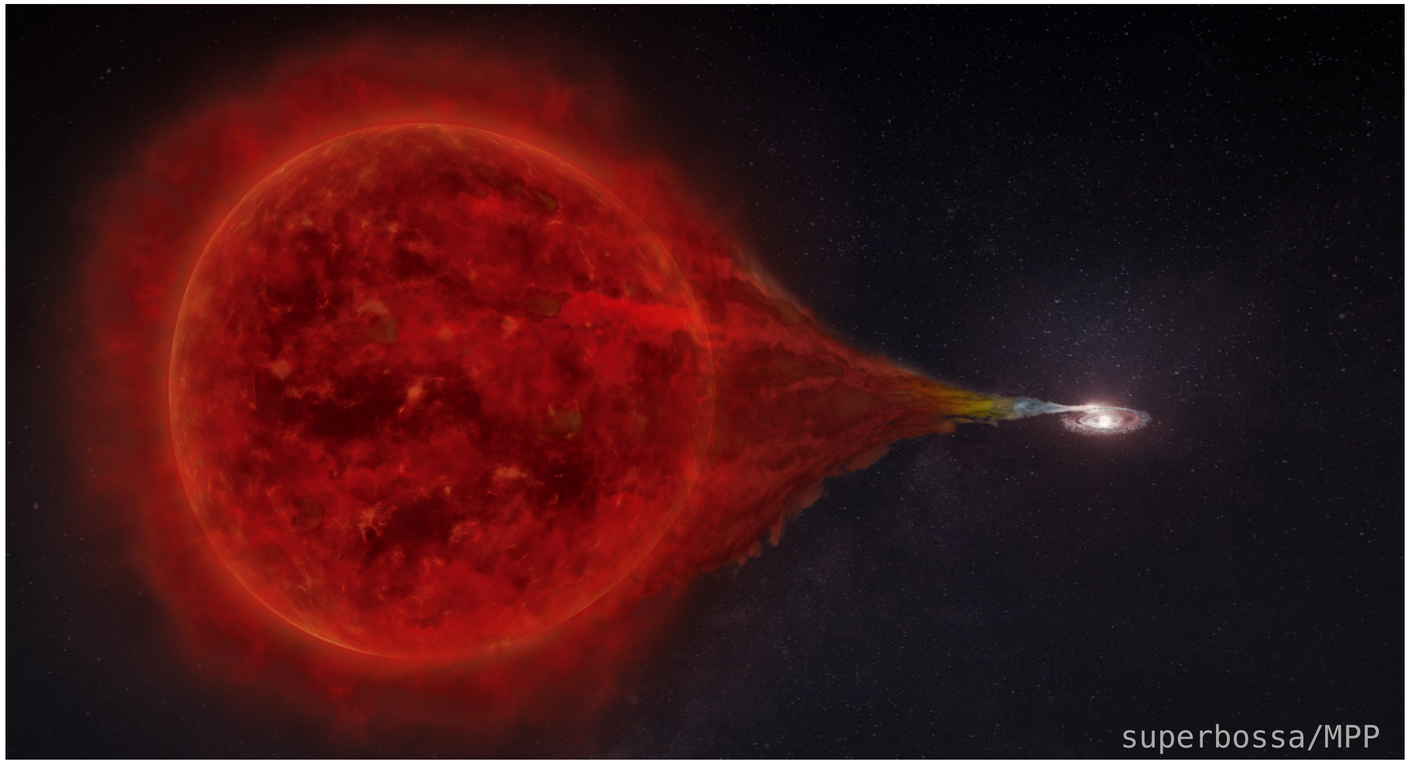
- **HE data alone is not enough** to disentangle electron and proton **acceleration models**
- Particles are accelerated in nova shock, **non-thermal processes** are at work
- **Protons can reach much higher energies due to lower energy losses** and thus possibly produce a second component detectable 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

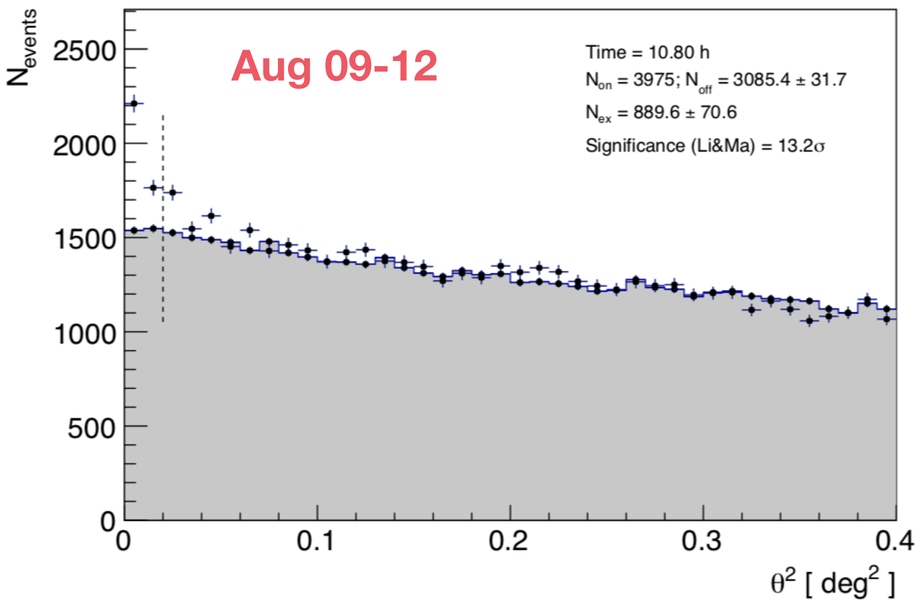
- RS Oph is a **recurrent symbiotic nova** which displays major **outbursts every ~15 years**
  - WD + M0-2 III RG star
    - M_{WD} = and M_{RG} = 0.68–0.80$M_{\odot}$
  - Distance: 2.45 pc (Rupen et. al. 2008)
    - Recent Gaia DR3: parallax distance of 2.69 ± 0.18 kpc
  - Nine eruptions between 1898 and 2021
    - **Latest outburst: August 2021**

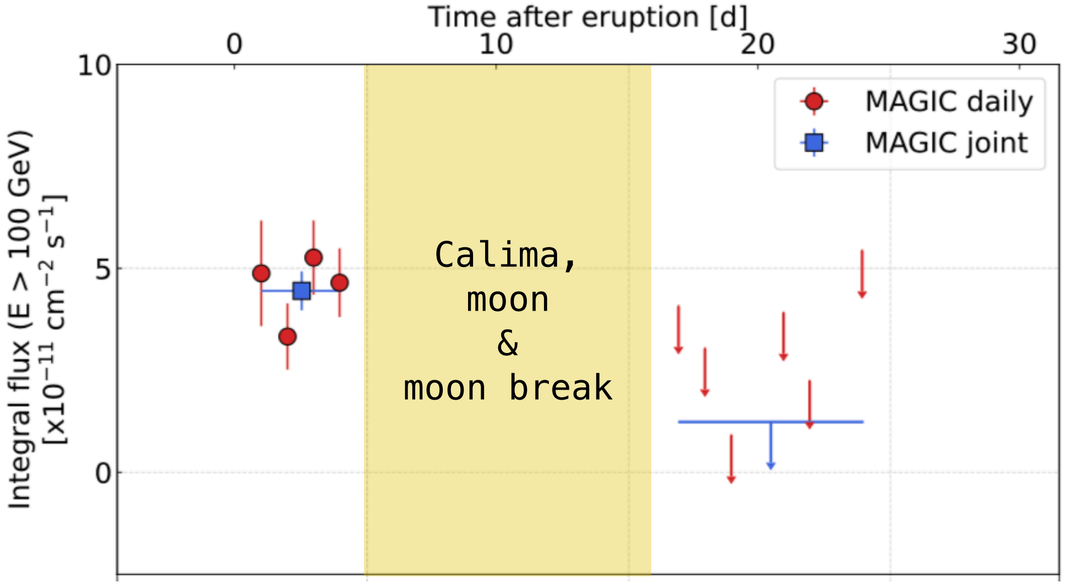


- **GeV emitter candidate:**
  - 2006 outburst of RS Oph detected by Swift/BAT could not be accounted by the decay of radioactive isotopes
  - Emission could be explained **via the production of non-thermal particles by diffuse shock acceleration** (Tatischeff et al. 2007)

MAGIC VHE 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**
- **Decrease** below the VHE detection limit **two weeks later**
- **Novae established as a new type of source of VHE emission**



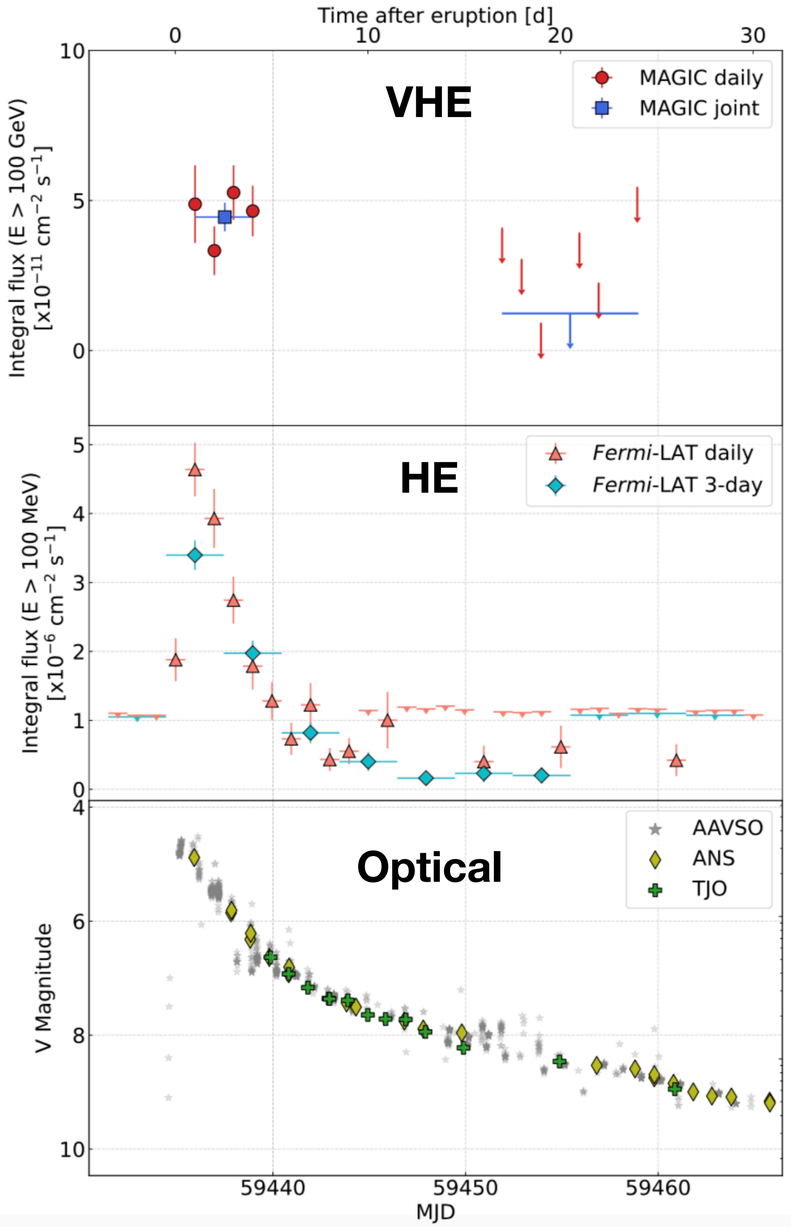


Acciari et al., Nature Astronomy, 2022
https://doi.org/10.1038/s41550-022-01640-z

MWL view

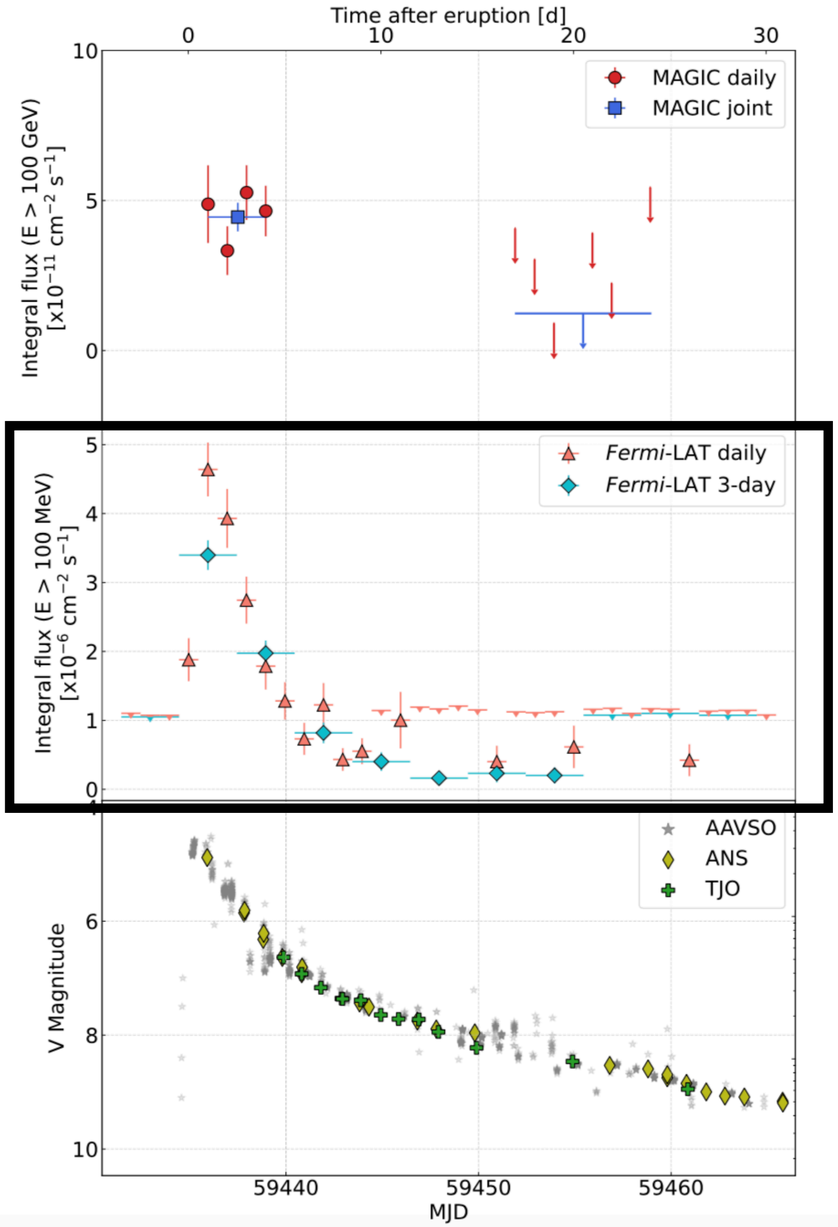
- The MAGIC observations reveal **VHE emission contemporaneous to the *Fermi*-LAT and optical maxima**
- Emission peaked at optical and MeV, but **VHE emission is** consistent with being **constant over the first 4 days**
- **First nova detected in the VHE regime**

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



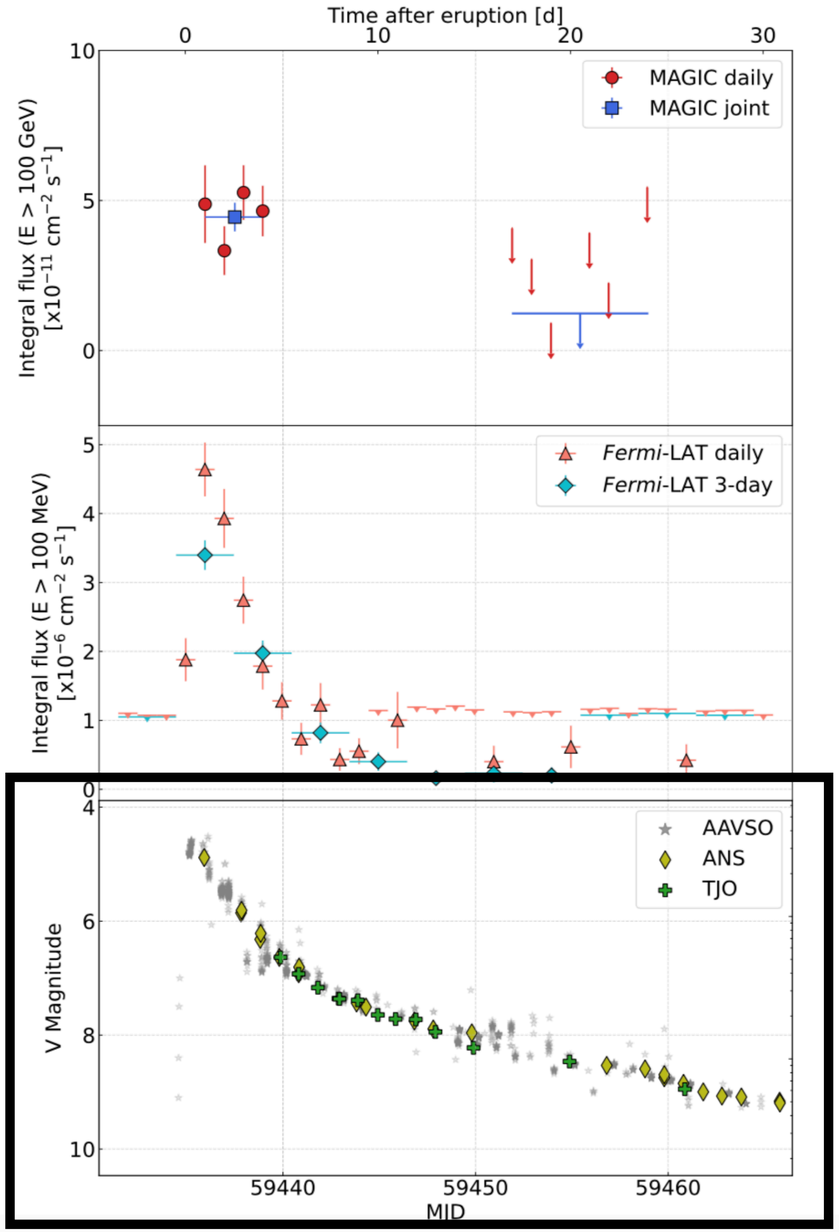
Fermi-LAT

- *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**



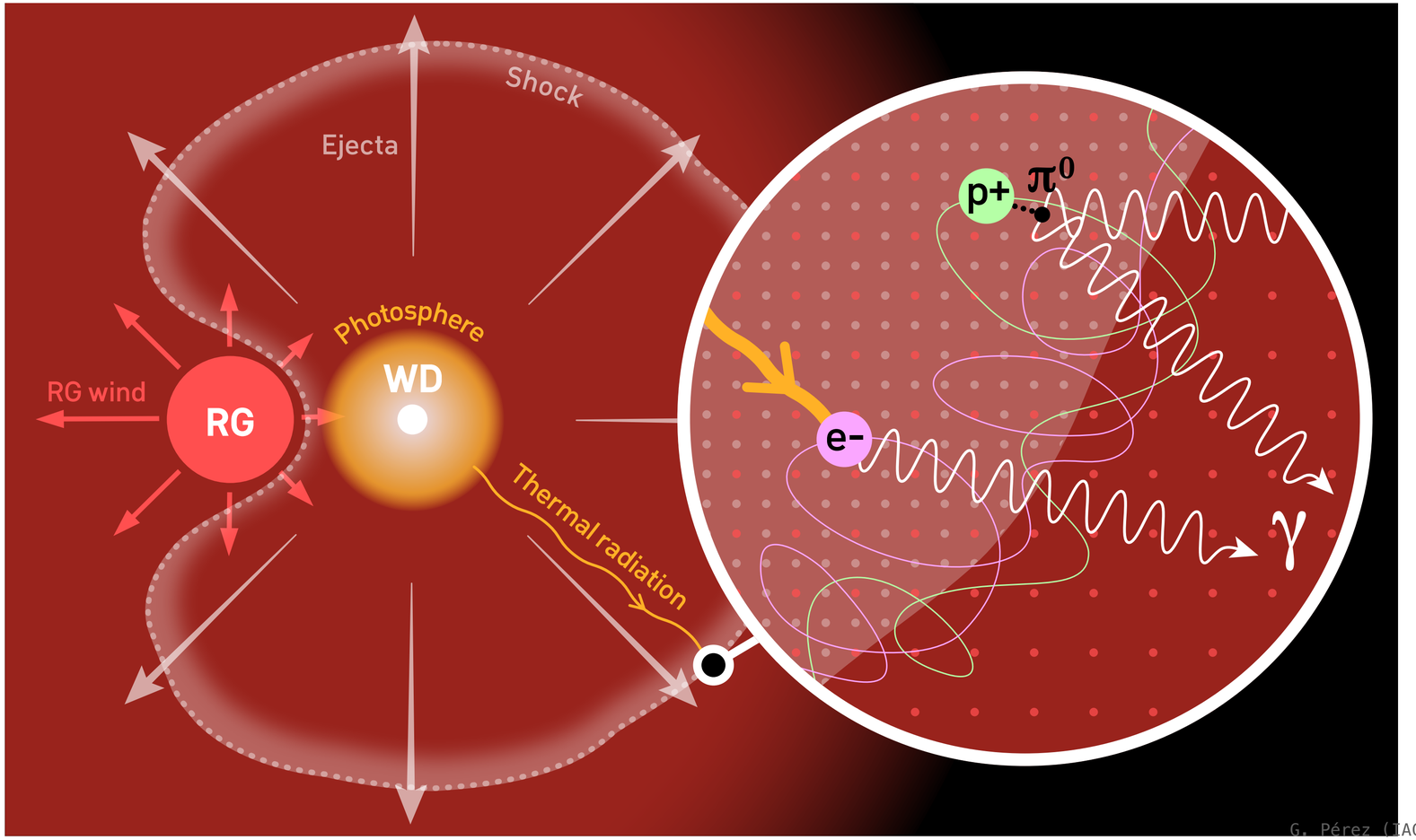
Optical

- **During the nova outburst the photospheric emission creates the dominant radiation field**
- Photometry
  - **TJO and ANS**
  - The emission*can be described by the **photosphere temperature dropping from T_{ph} = 10800 K to 7680 K and radius R_{ph} = 200 $R_\odot$**
    - Similar 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*



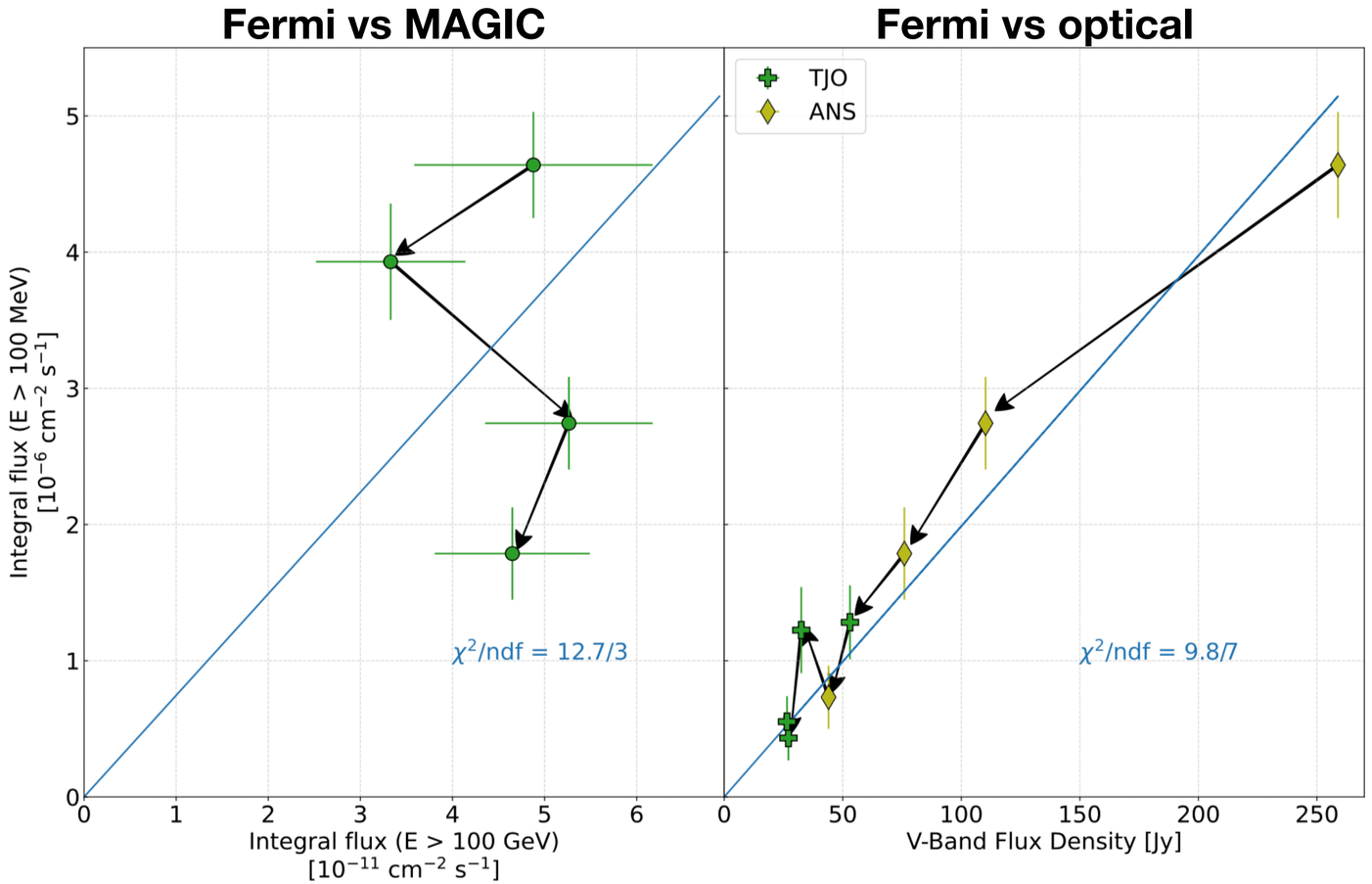
* during first 4 days

What's going on?



- **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

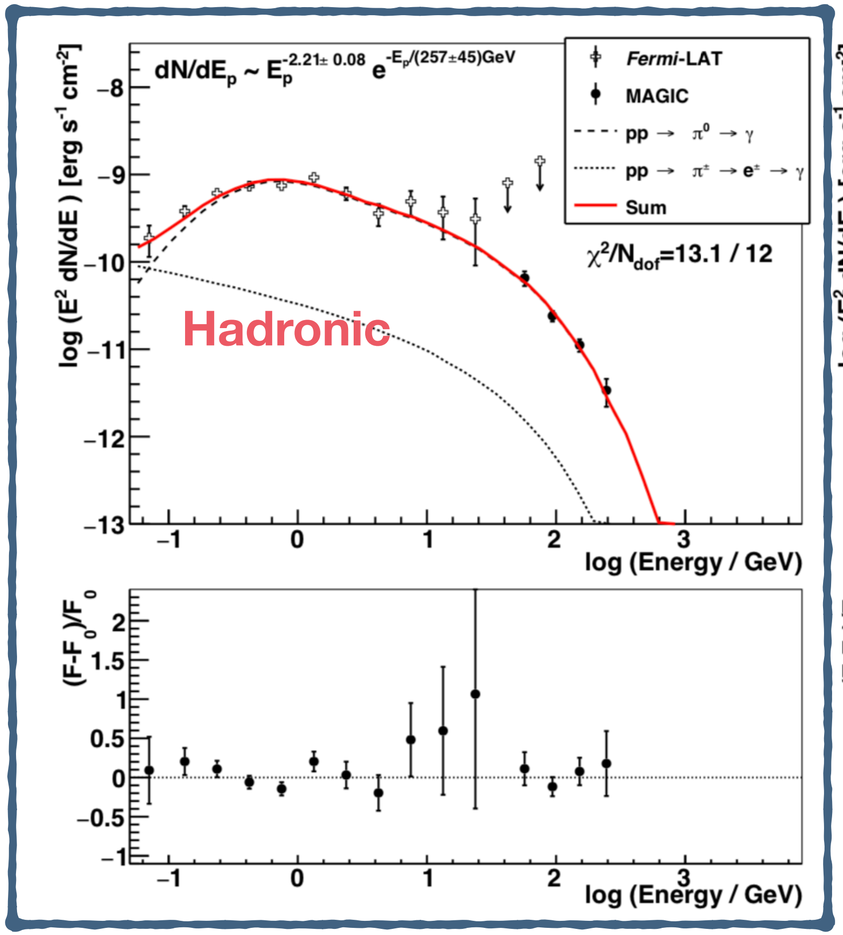


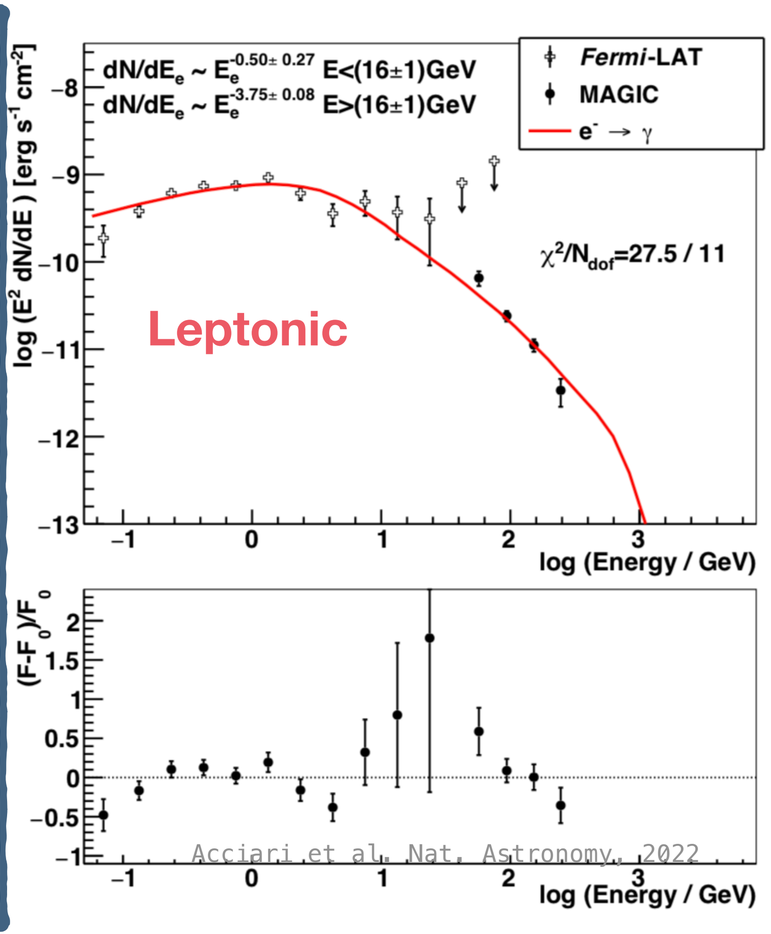
Acciari et al. Nat. Astronomy, 2022

- **VHE 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**

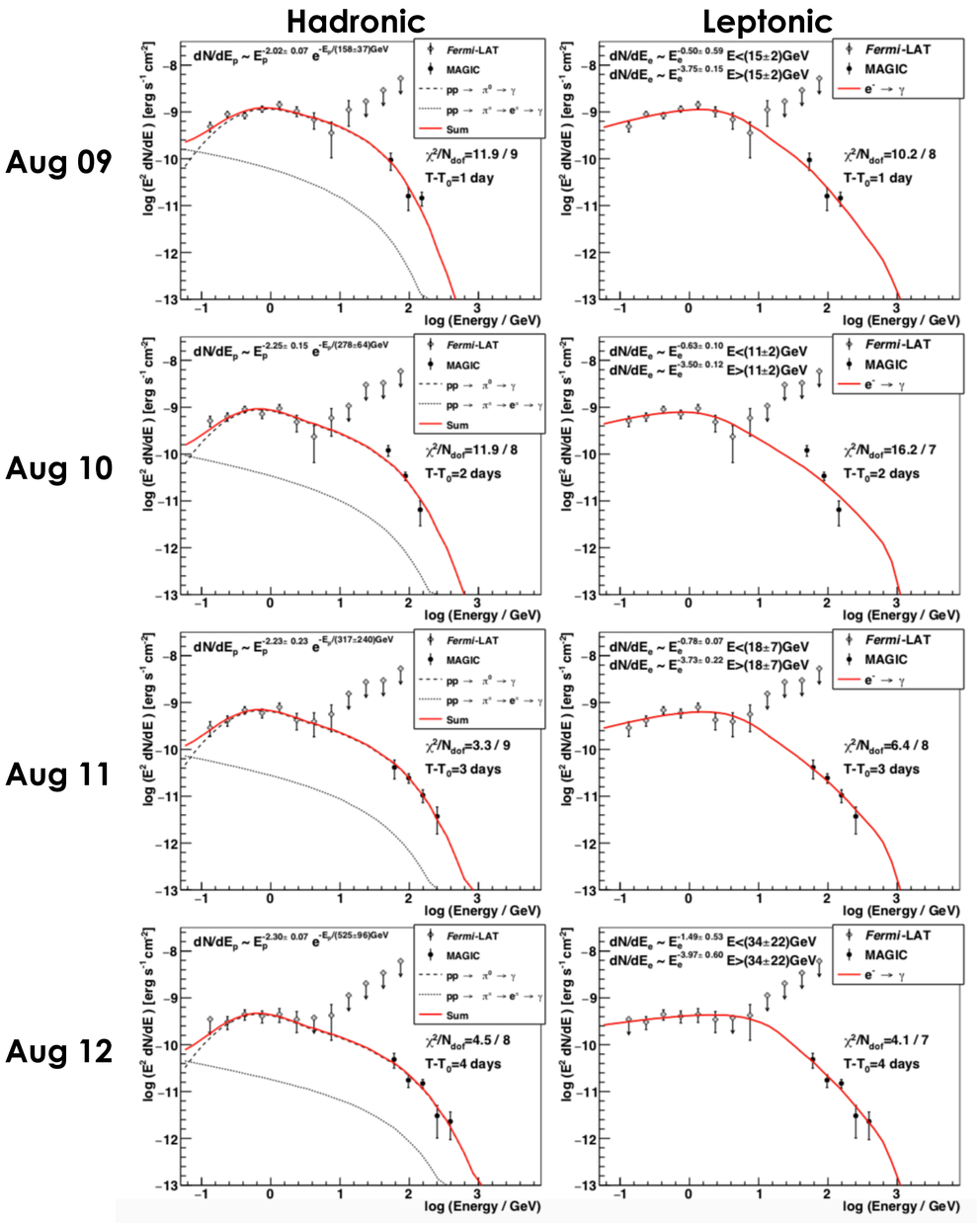
Gamma-ray modelling



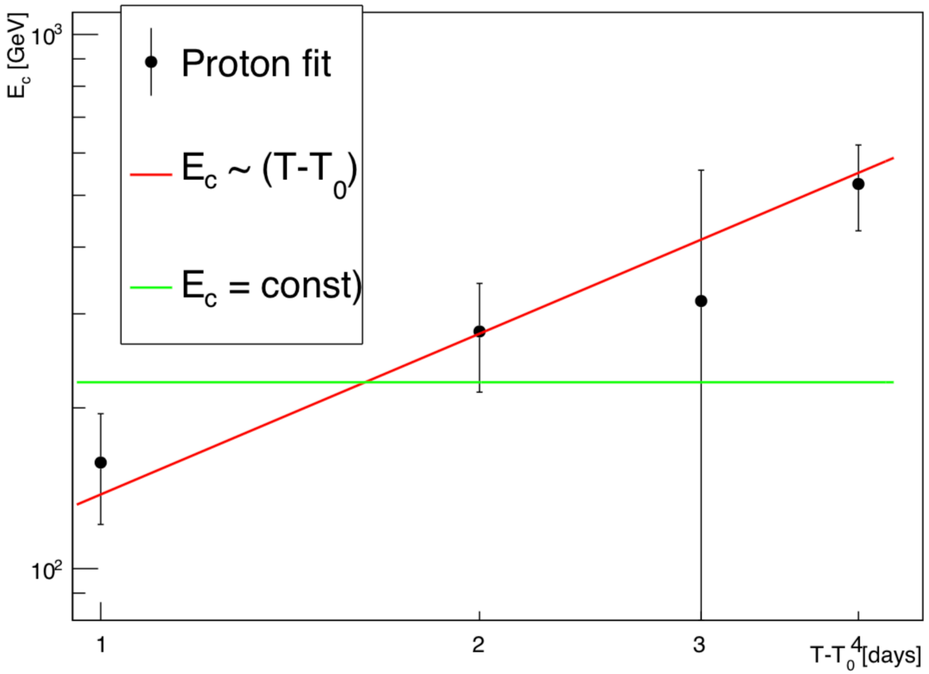


- **Joint Fermi-LAT +MAGIC** spectrum can be described as a **single**, smooth **component** spanning **from 50 MeV to 250 GeV**
- **Hadronic scenario is favored**

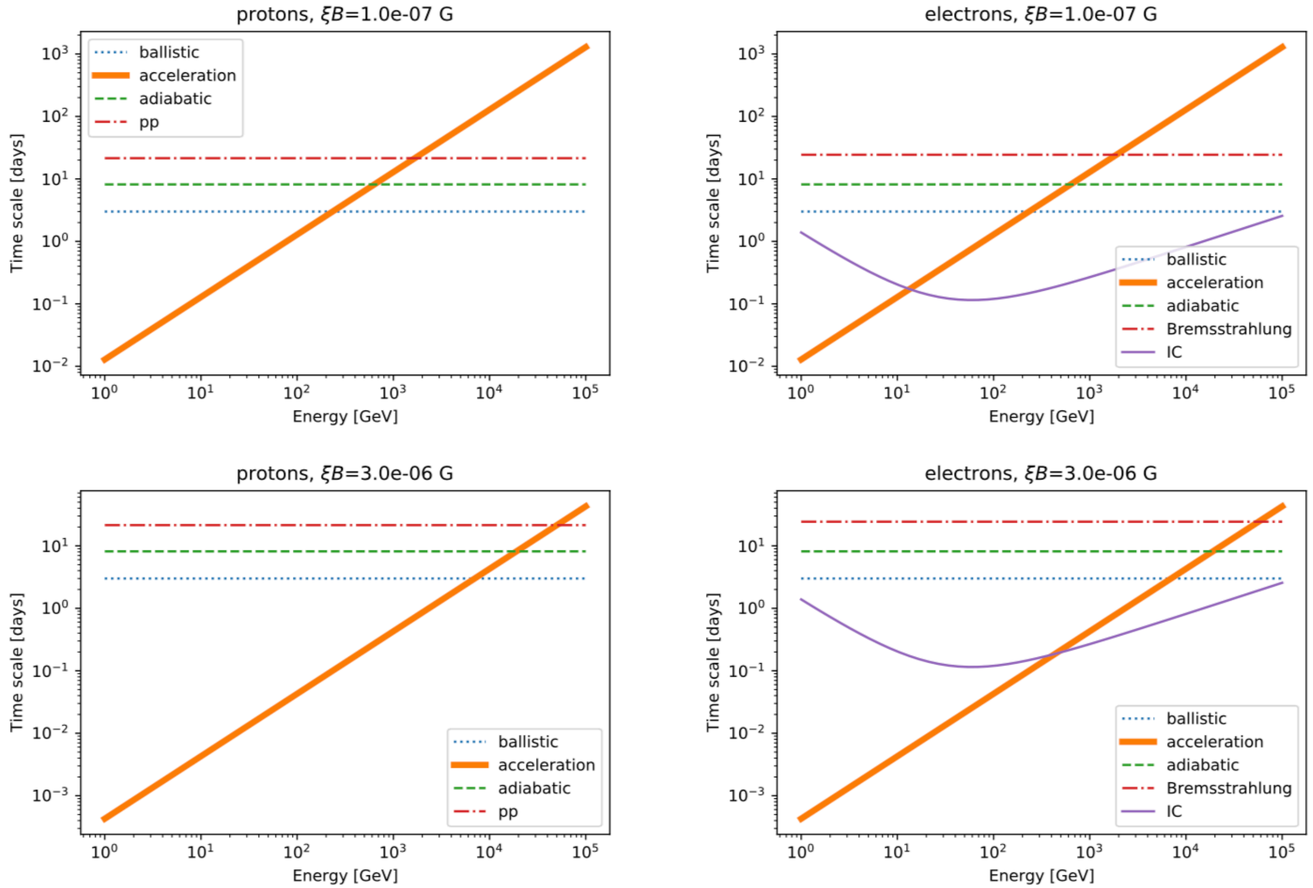
Gamma-ray modelling: daily proton acceleration



- **Daily SED**
  - **Hadronic scenario 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**

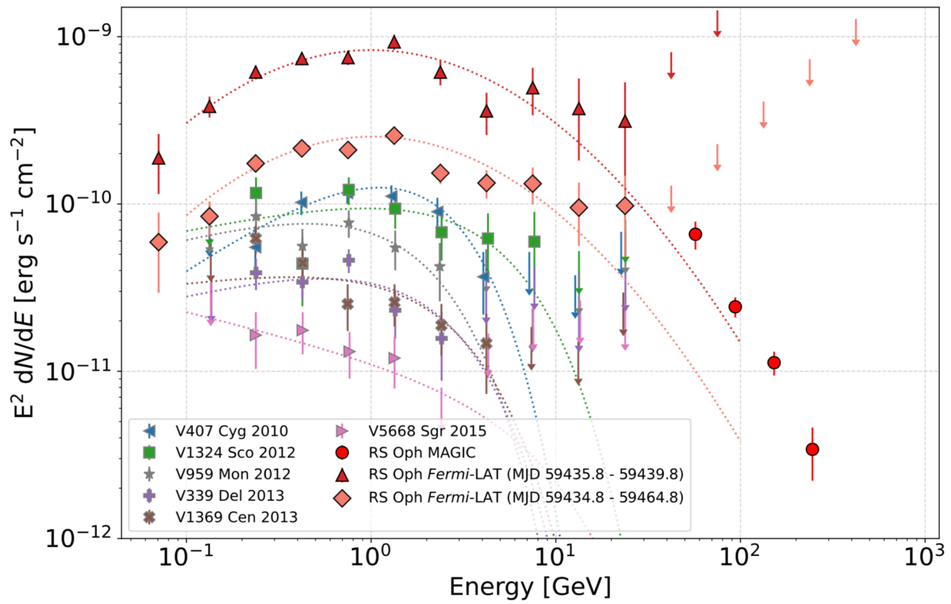


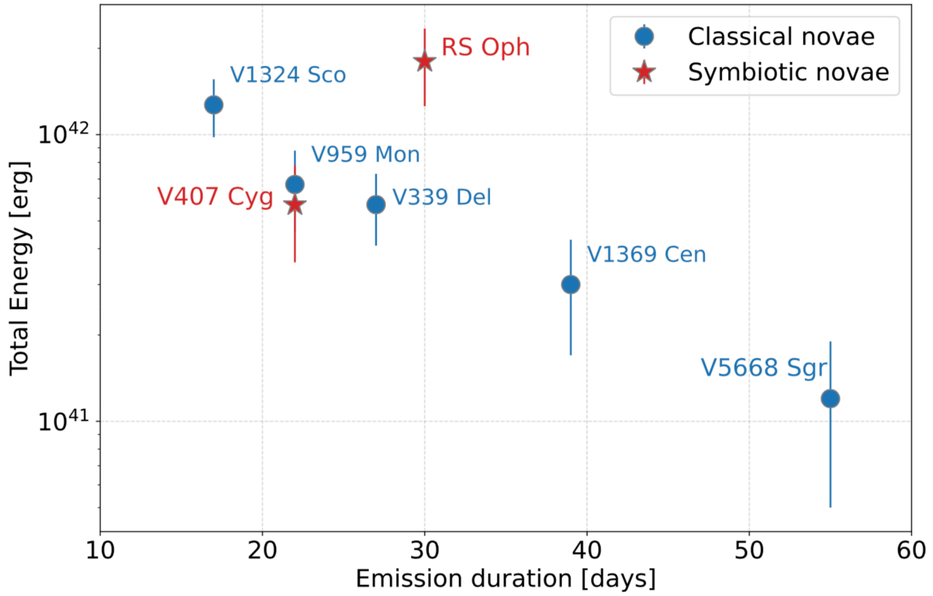
Supporting a hadronic scenario



- **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**

Comparison with other novae





- RS Oph is the nova with the **highest flux** and **brightest nova**
  - Almost two orders of magnitude larger than previously-detected eruptions
- **Comparison does not reveal any peculiarity** in the emission of RS Oph, except for its brightness

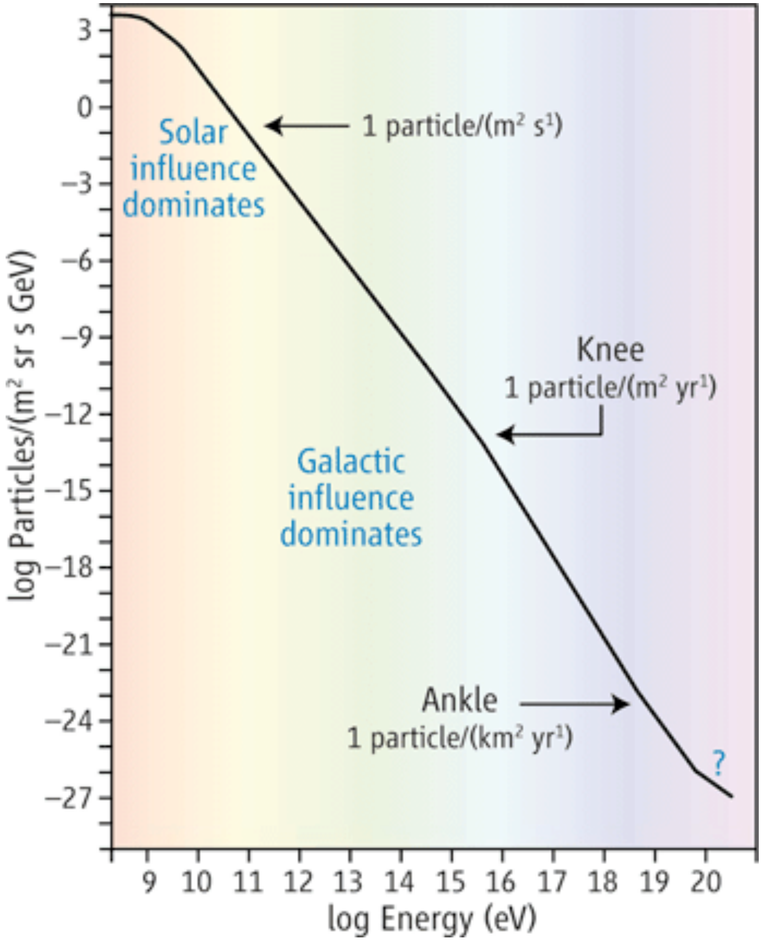
Galactic novae and cosmic rays

- **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

- **HESS J0632+057**:
  - **Deepest study at TeV energies** with H.E.S.S., MAGIC, and VERITAS, **comprising a total of 450 hr of data** spanning almost 15 years
  - For the first time, **the orbital period at TeV energies was determined,** yielding a value of **316.7 ± 4.4 days**.
  - Detailed lightcurve studies, **flux variability in <20 days.**
  - **No spectral variability**
  - **Strong correlation between X-rays and gamma-rays**: a **common origin of the radiation**
  - **Lack of correlation between Hα and X-rays or gamma-rays**
- **1 A 0535+262**: brightest X-ray flare in 2020
  - MAGIC observations **did not reveal any VHE signal**
- **MAXI J1820+070:**
  - Joint campaing H.E.S.S., MAGIC, and VERITAS
  - Covering **full HS-SS-HS cycle**: **no VHE detection**
- **RS Ophiuchi:**
  - 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 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**

Thanks

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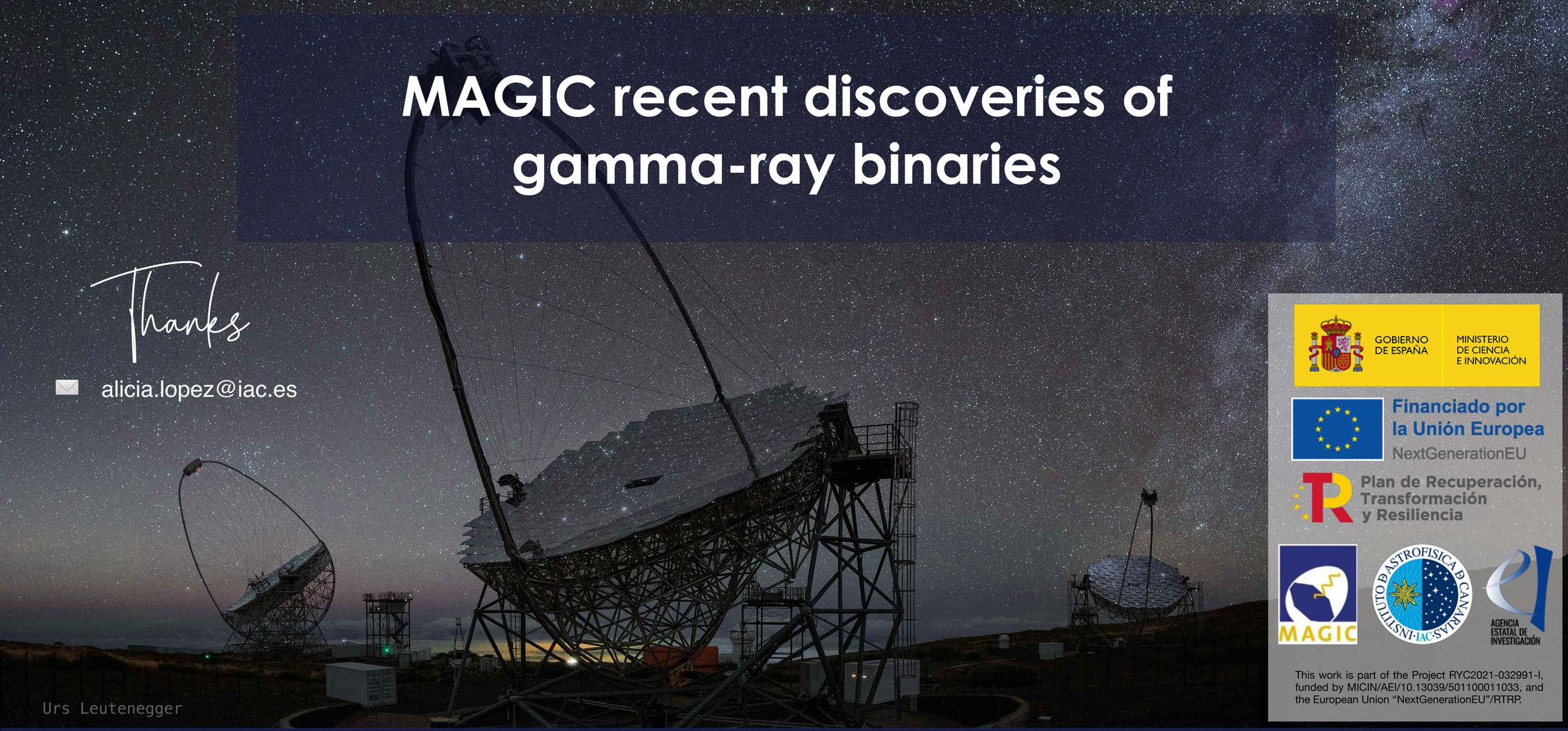
MAGIC recent discoveries of gamma-ray binaries



Thanks

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GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
Financiado por la Unión Europea
NextGenerationEU
Plan de Recuperación, Transformación y Resiliencia
MAGIC
INSTITUTO DE ASTROFISICA DE CANARIAS
AGENCIA ESTATAL DE INVESTIGACIÓN

This work is part of the Project RYC2021-032991-I, funded by MICIN/AEI/10.13039/501100011033, and the European Union "NextGenerationEU"/RTRP.

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for the MAGIC collaboration

Variable Galactic Gamma-Ray Sources (VI), Innsbruck, April 2023