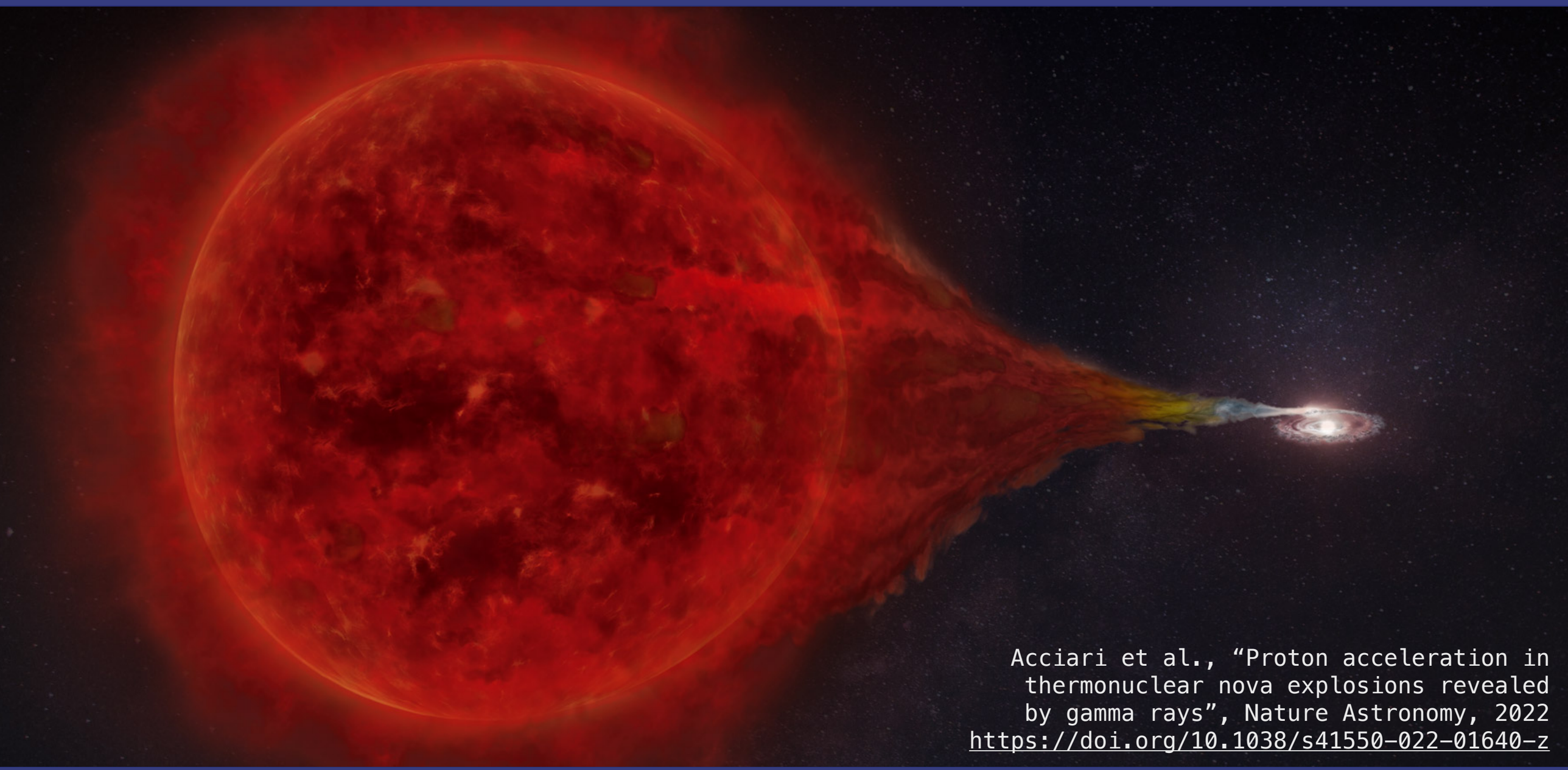
RS Ophiuchi: the first nova detected at very high energies



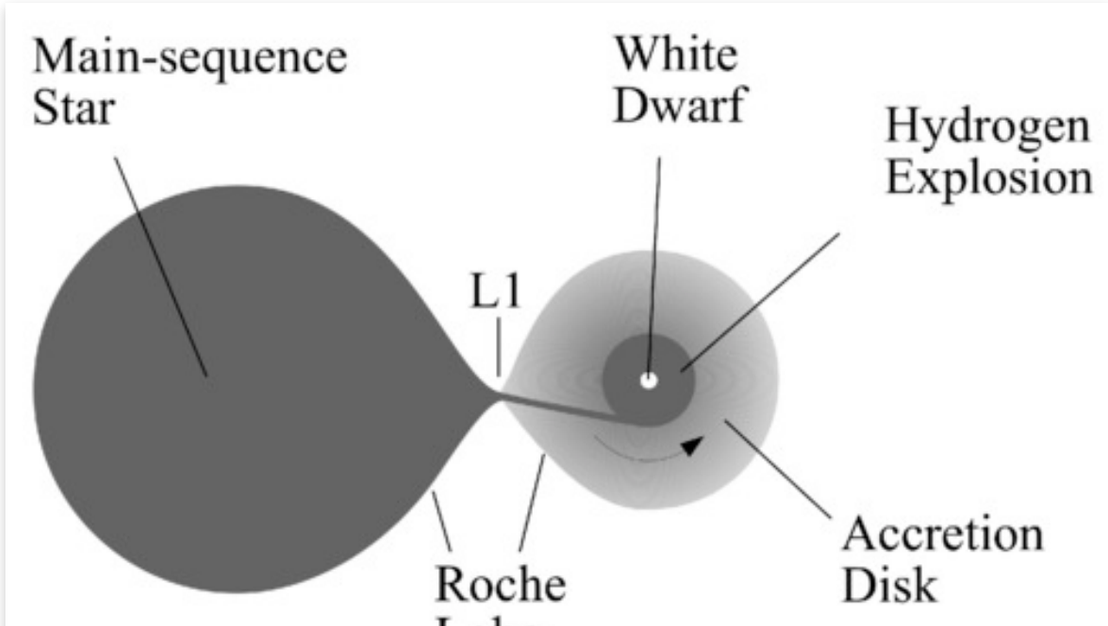
Acciari et al., “Proton acceleration in thermonuclear nova explosions revealed by gamma rays”, Nature Astronomy, 2022
https://doi.org/10.1038/s41550-022-01640-z

Alicia López Oramas
Instituto de Astrofísica de Canarias
ICRR Seminar, April 27, 2022

Novae

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

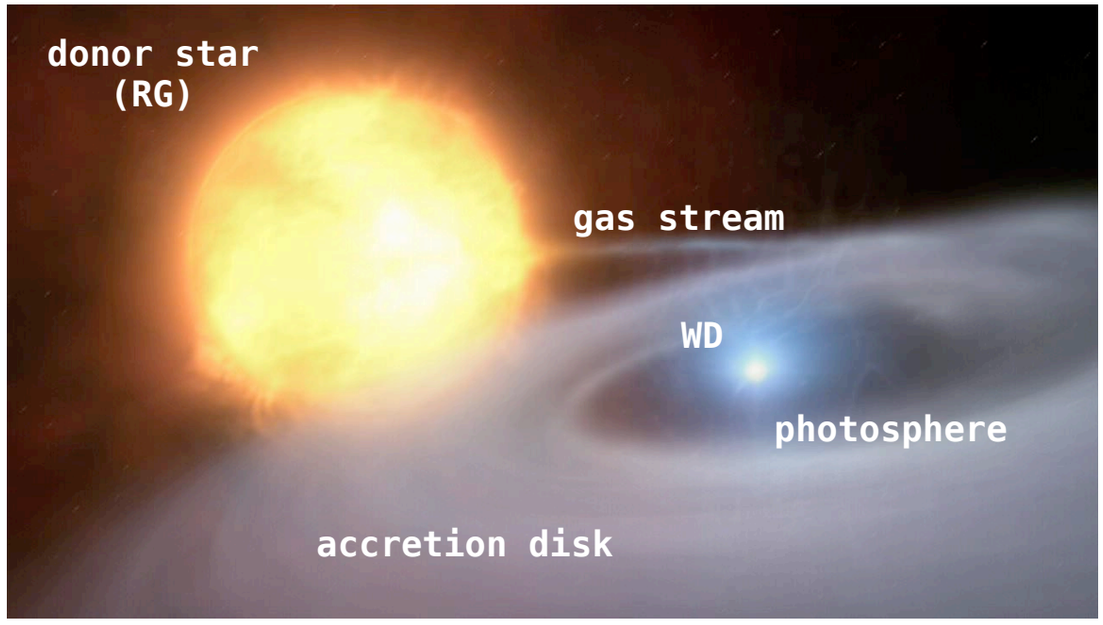
- Classification depening on the donor star:
  - **Symbiotic binary:** the donor star is a **red giant (RG).** The **WD is immersed in the RG wind**
  - **Classical novae:** the donor is a low-mass star



- Novae outbursts usually last from weeks to months

- Largerly studied in optical, radio and X-rays for decades

- Named after *stella novae (new star)*



Credit: ESO / M. Kornmesser

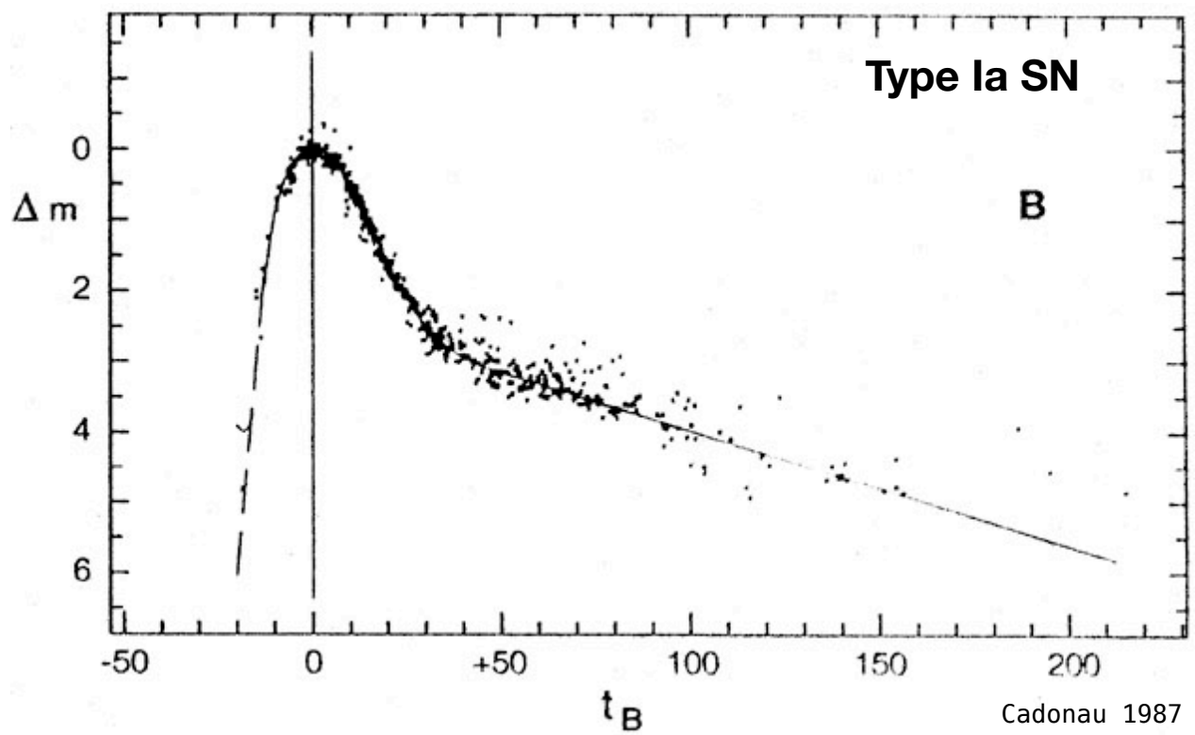
Novae

- **System is not disrupted after the nova event** -> cycle restarts

- Most novae detected only once:
  - Outburst once every (hundreds of) thousand years

- Some novae show repeated outbursts within few years/human lifetime: **recurrent novae (RN)**
  - 10 known RN in the Galaxy with repetition rate <100 years
  - For a **symbiotic nova to be RN**, the **WD must be massive** (≥1.1 M⊙)

- Only if the **WD exceeds the Chandrasekhar limit** ($M>1.44M_{\odot}$) -> **supernova type IA**

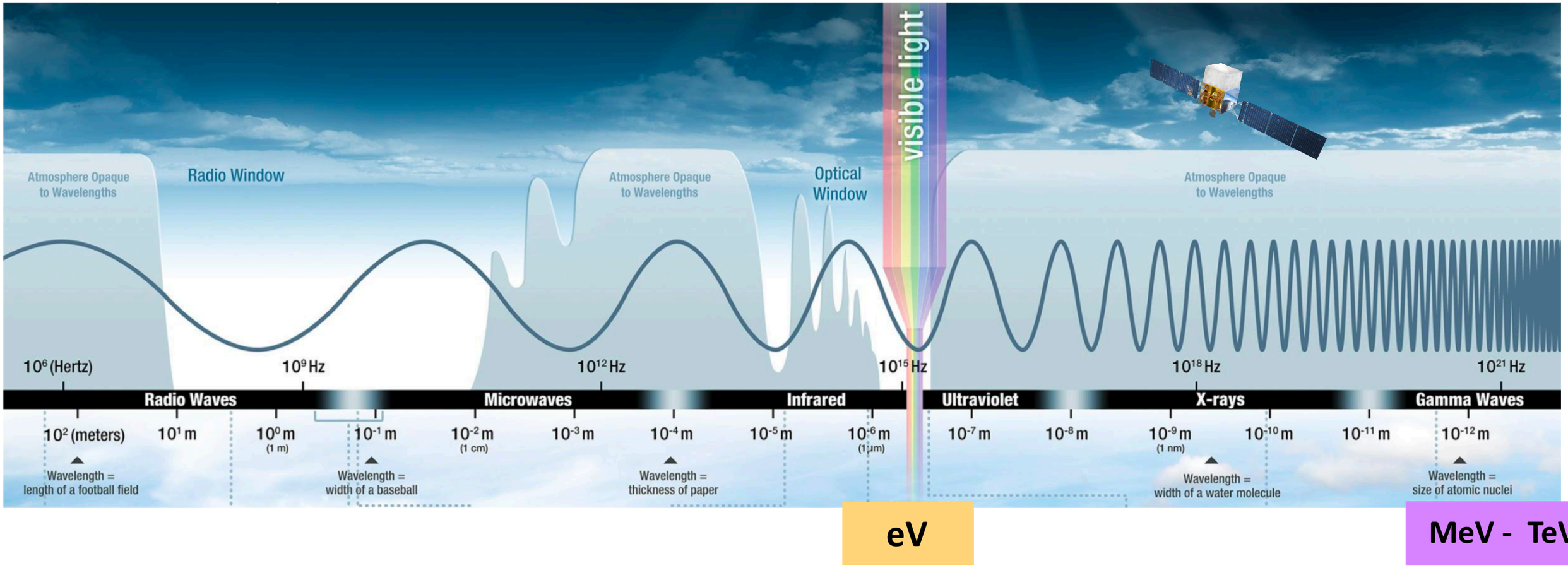


Cadonau 1987

Gamma-ray emitters?

Gamma-ray astronomy: basic concepts

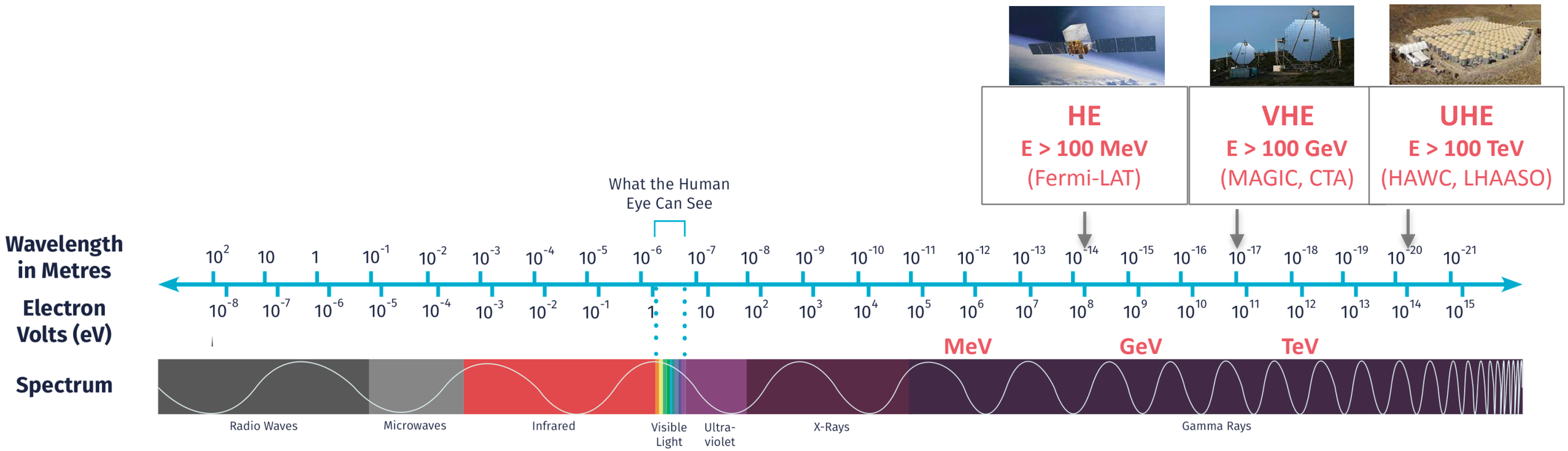
Gamma rays



eV

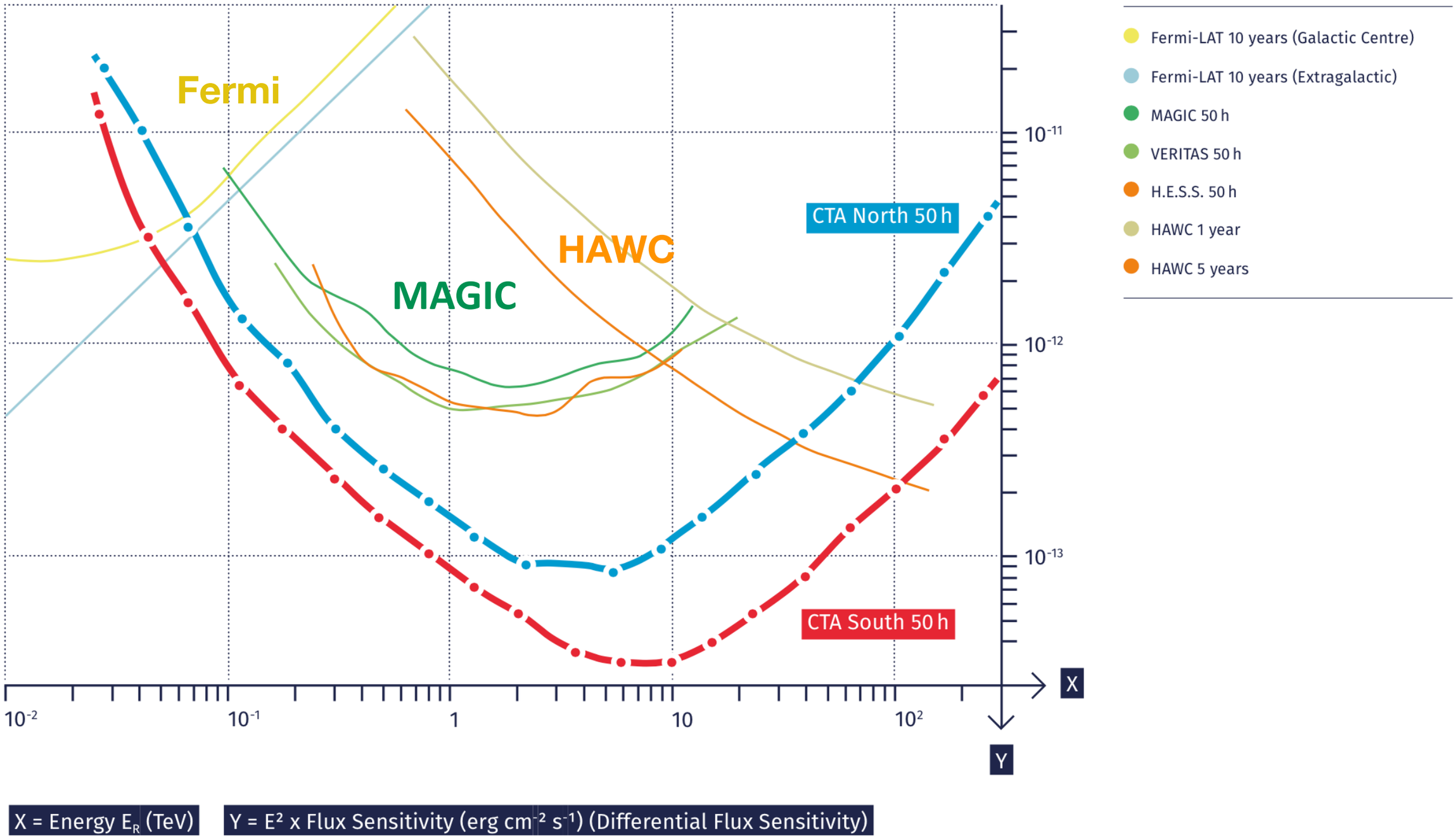
MeV - TeV

Gamma rays



- High energy **(HE) > 100 MeV** -> satellites (Fermi-LAT)
- Very high energy **(VHE) > 100 GeV** -> **Cherenkov telescopes** (**MAGIC**, VERITAS, H.E.S.S., CTA)
- Ultra high energy **(UHE) > 100 TeV** -> Detectors (LHAASO, HAWC)

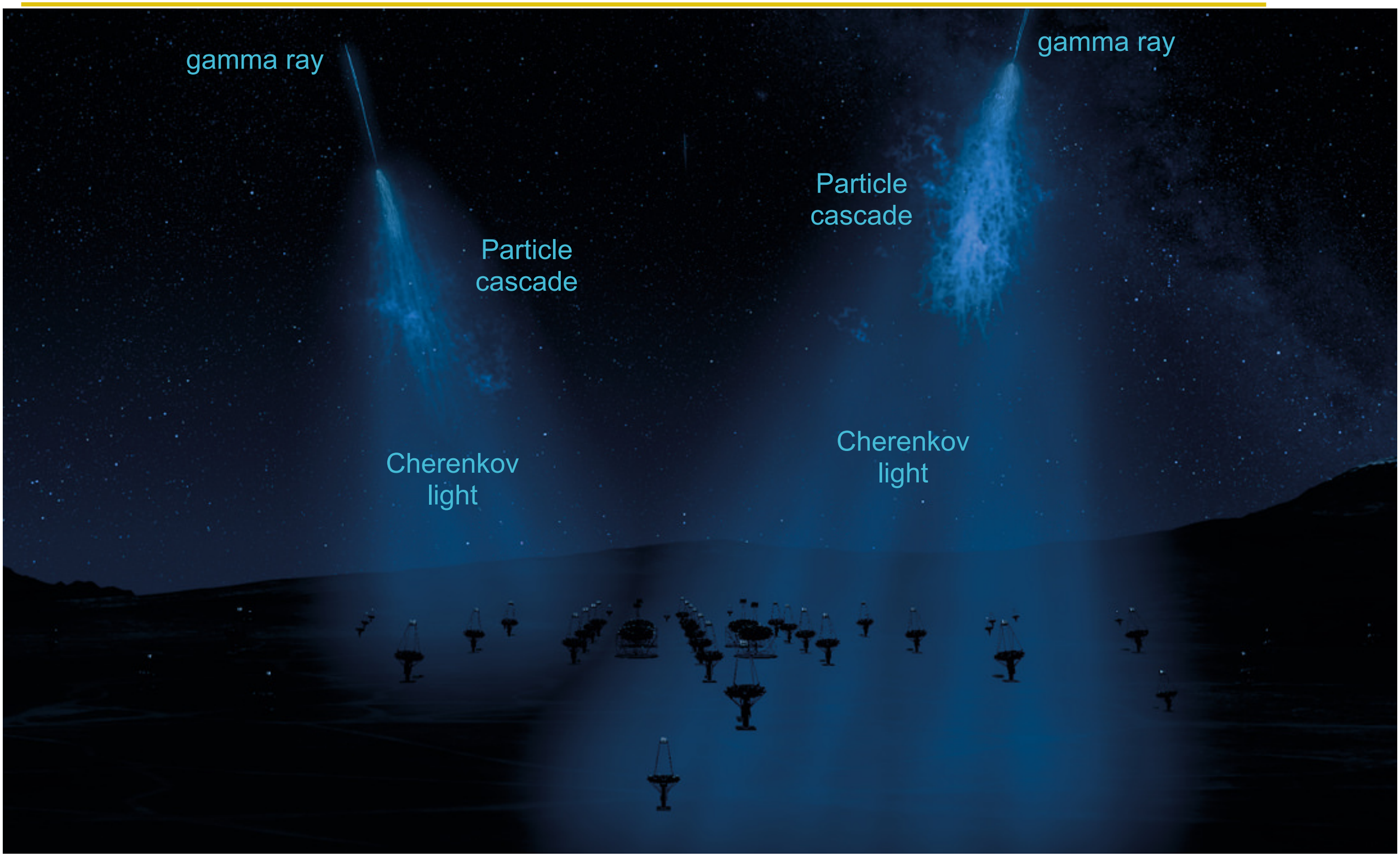
Gamma rays



X = Energy E_R (TeV)

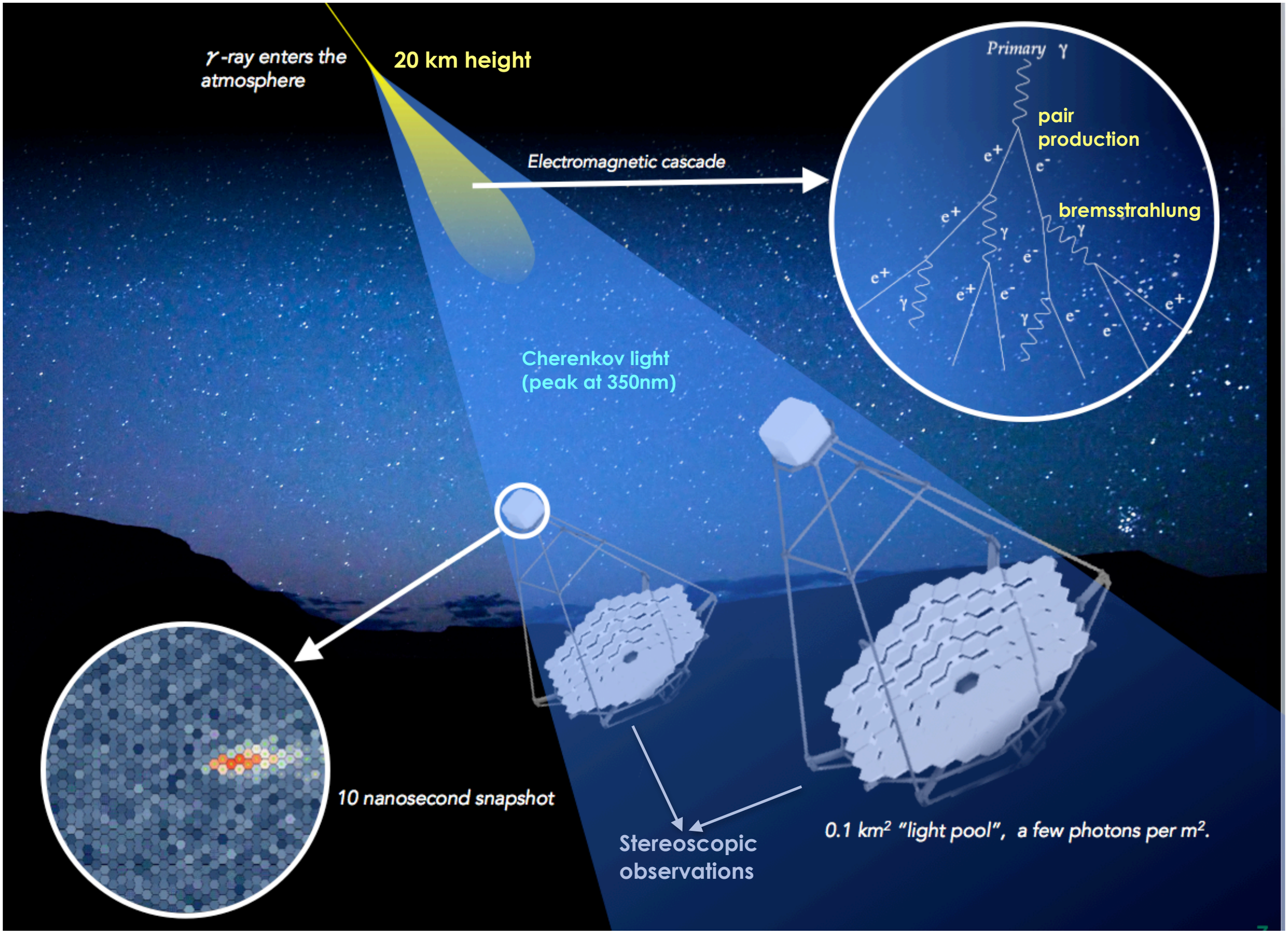
Y = E^2 x Flux Sensitivity (erg cm^{-2} s^{-1}) (Differential Flux Sensitivity)

Cherenkov technique



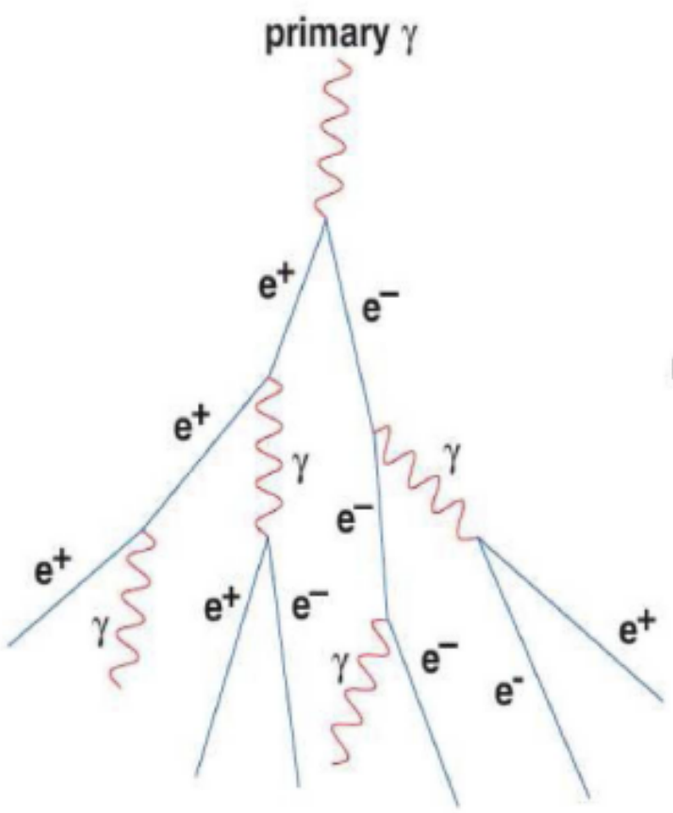
- **Indirect observation** of VHE gamma rays via detection of **Cherenkov (~350nm) flashes (few ns)**

Gamma rays

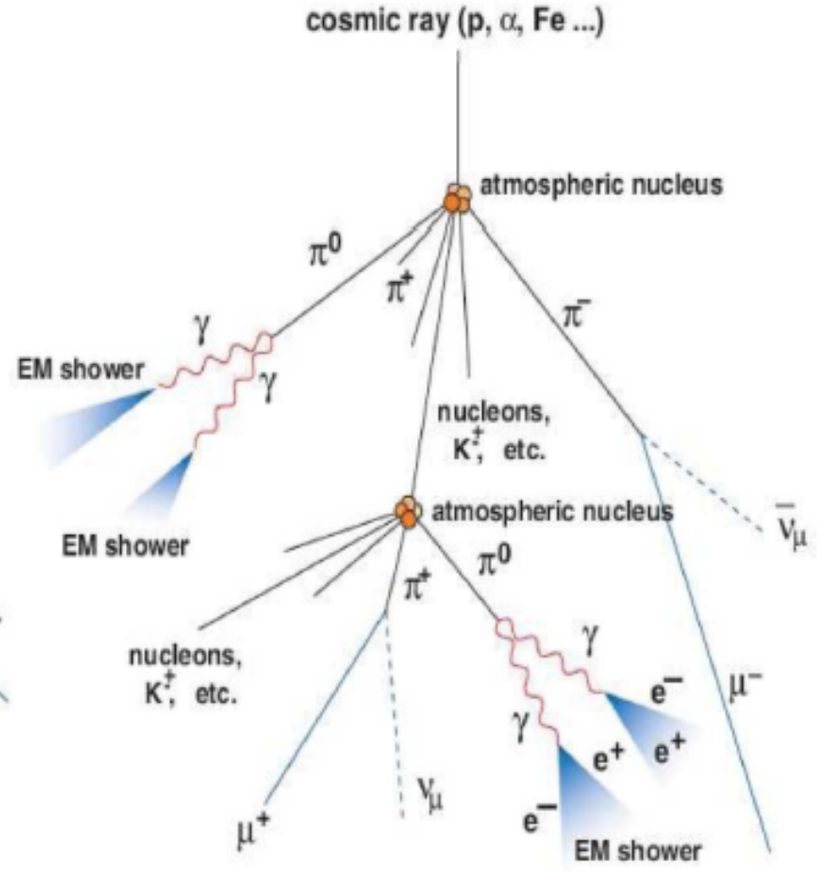

γ-ray enters the atmosphere
20 km height
Electromagnetic cascade
Primary γ
pair production
bremsstrahlung
Cherenkov light (peak at 350nm)
10 nanosecond snapshot
Stereoscopic observations
0.1 km² "light pool", a few photons per m².

Cherenkov technique

Electromagnetic Shower



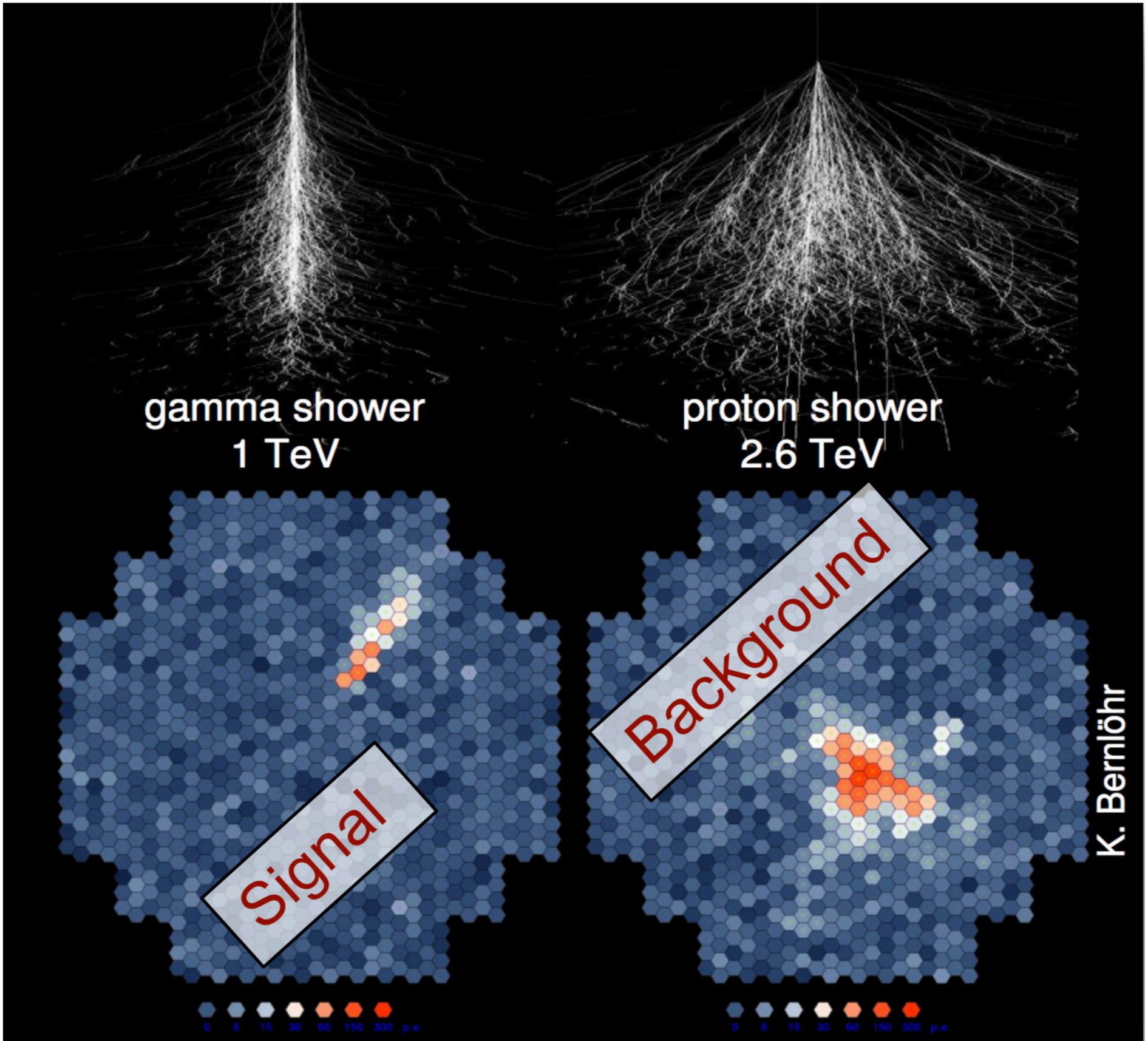
Hadronic Shower



Pair production + bremsstrahlung

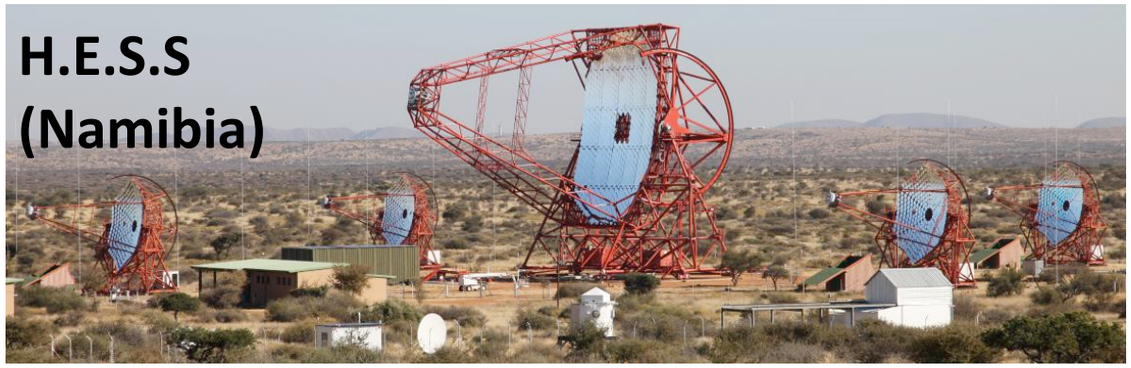
Hadronic interaction + sub-showers

Cherenkov technique

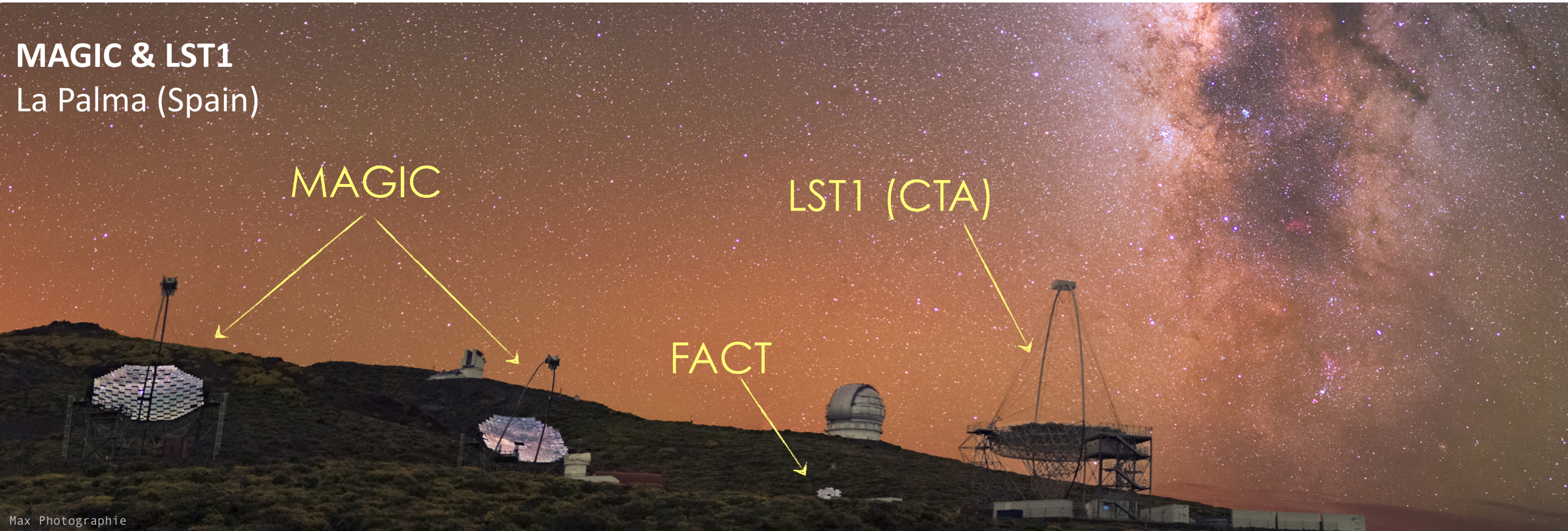


Cherenkov technique

- **Indirect observation** of VHE gamma rays via detection of **Cherenkov (~350nm) flashes (few ns)**
- Characteristics:
  - Large dish size (Φ=12-24m)
  - Highly sensitive pixelized camera (PMTs)
  - Fast trigger system and readout electronics

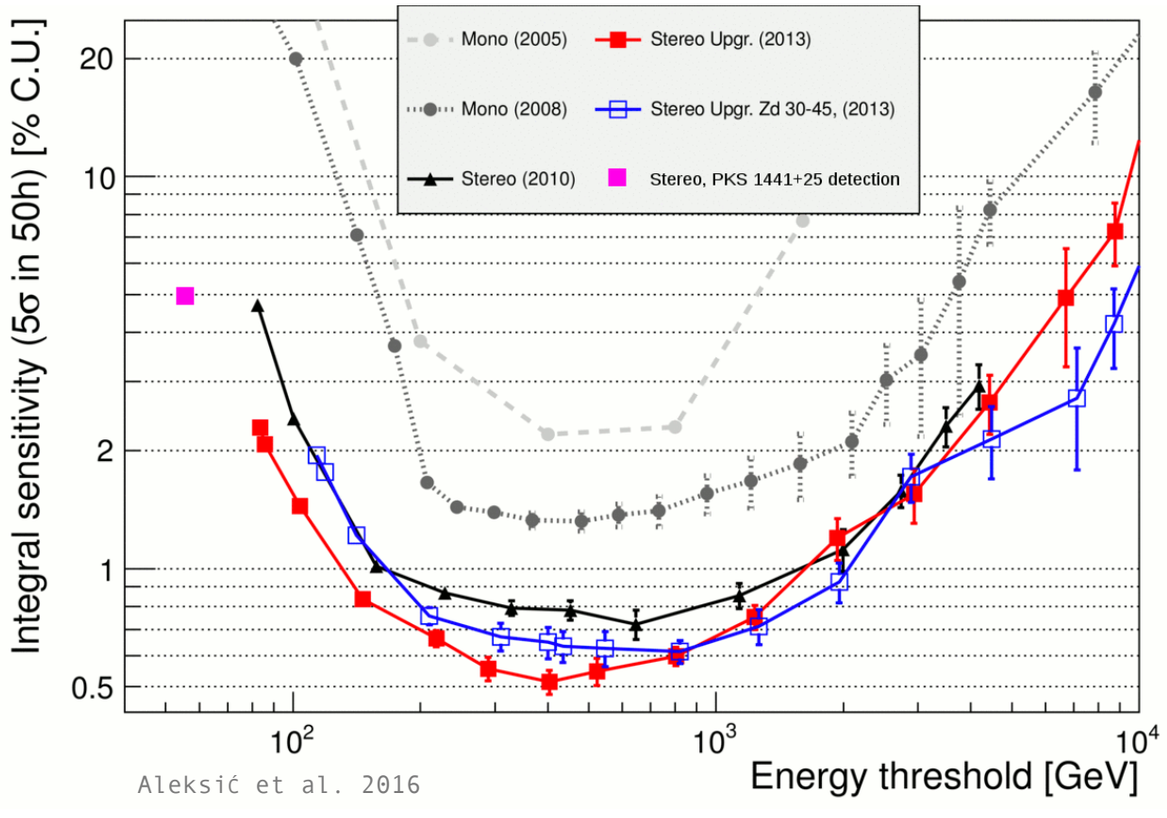


MAGIC & LST1
La Palma (Spain)



The MAGIC telescopes

- Two telescopes, 17 m diameter
- Roque de los Muchachos observatory @2200 m a.s.l.
- Energy threshold ~50 GeV
- VLA technique -> 100 TeV (Crab)
- Integral sensitivity E >290 GeV: (0.67 ± 0.04)% of Crab Nebula flux in 50 hours (Aleksić et al. 2016)



Gamma-ray emitters?
HE counterpart

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 are established as HE emitters**
  - Emission could be explained with either **pp interaction model** (on RG wind for a symbiotic binary) or **leptonic models (IC+Brems.)**

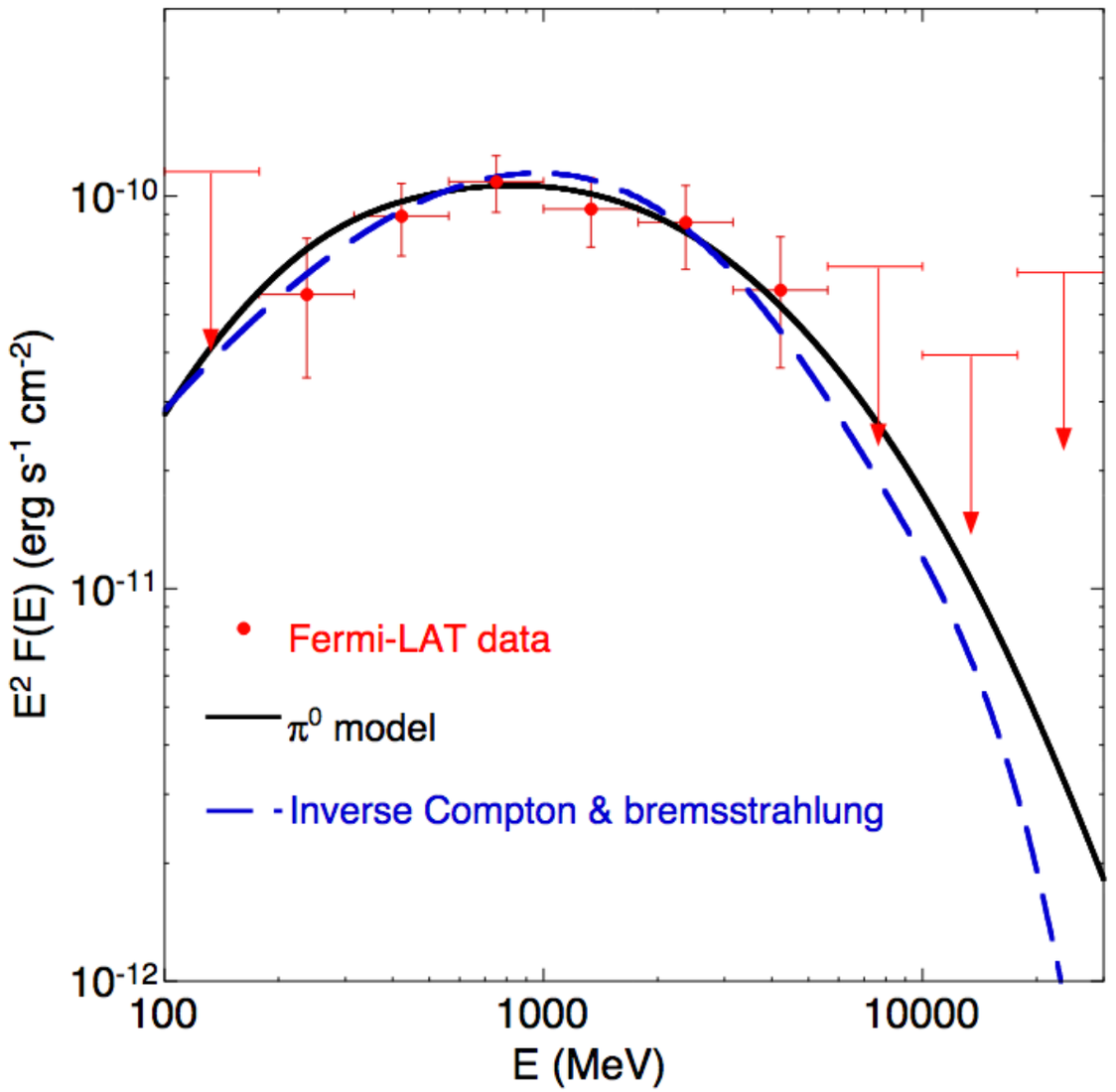


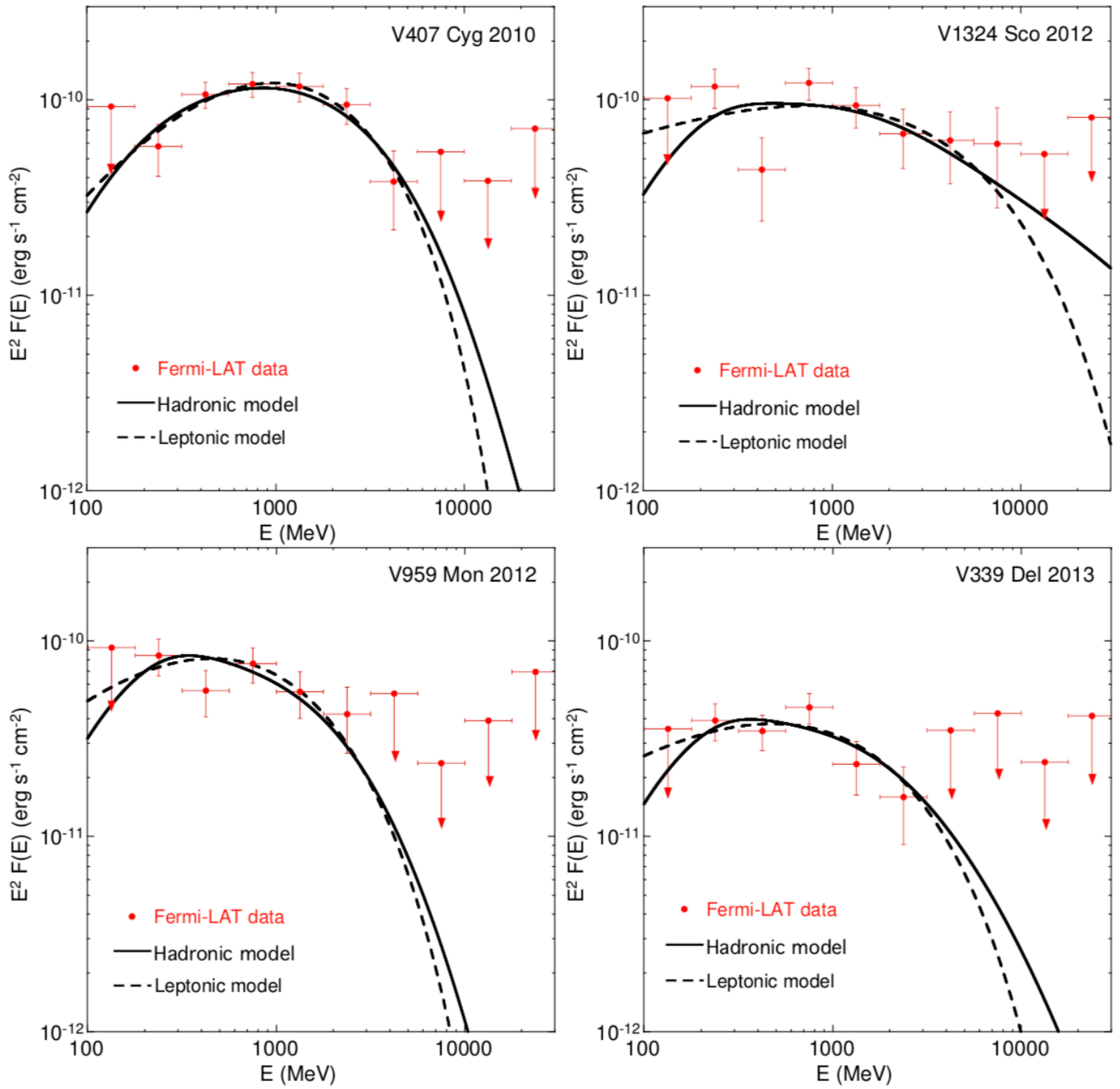
Fig. 3. SED of V407 Cyg in MeV/GeV γ-rays measured by the *Fermi*-LAT over the period 10 March 18:00 – 29 March 00:00 2010. Vertical bars indicate 1σ statistical errors, arrows indicate 2σ upper limits, and horizontal bars indicate energy ranges. The best-fit π^0 (black solid line) and leptonic (blue dashed line) models are indicated.

Fermi-LAT, Science, 2010

Novae: sources of HE gamma rays

- **Classical** novae (WD+low-mass star) are also **sources of HE gamma rays** (Fermi–LAT, Science, 2014)

- Most of the Fermi-detected novae **show a cut-off** in their SED
  - All spectra of gamma-ray novae have been measured only up to 6 – 10 GeV

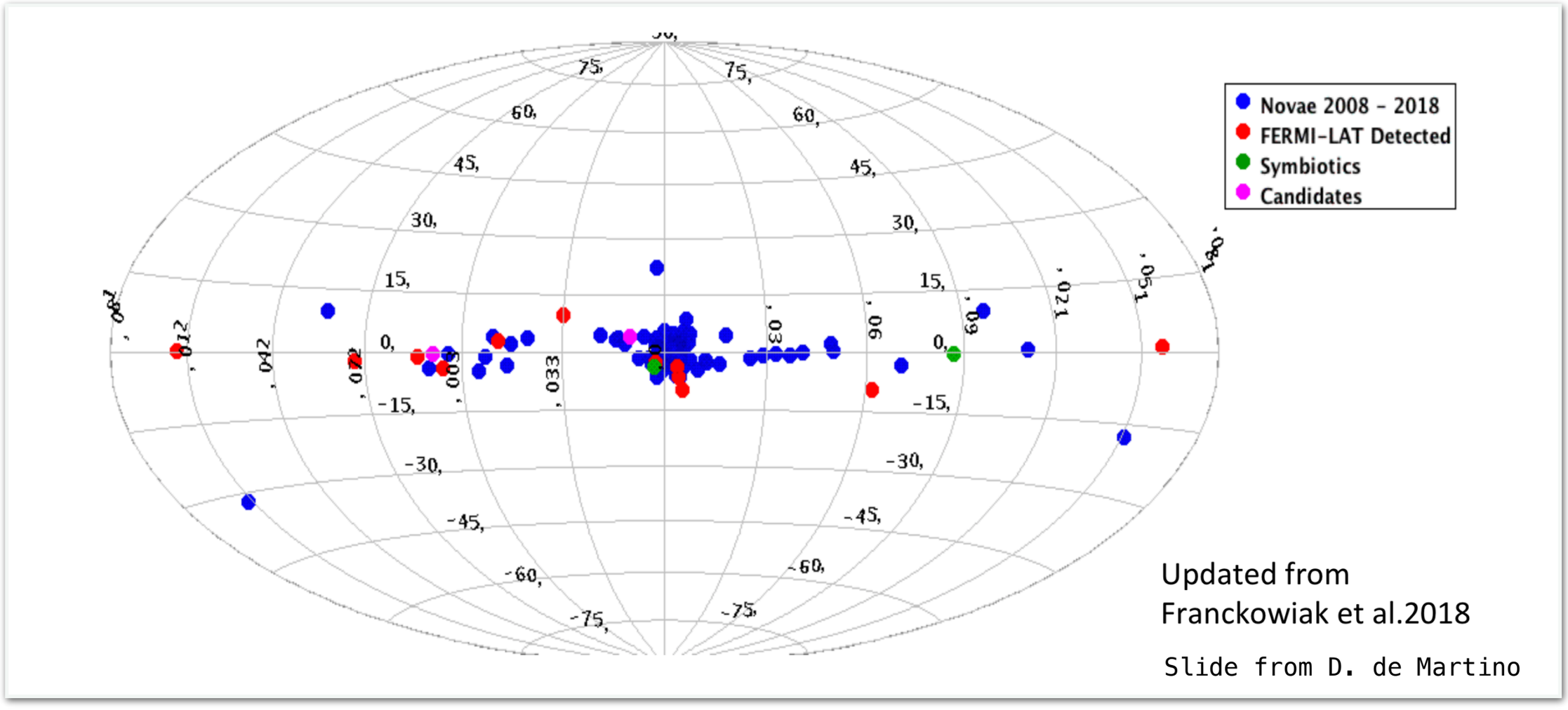


Fermi–LAT, Science, 2014

Novae: sources of HE gamma rays

- Up to know, total of 17 HE novae* (+5 hints)

- Can novae emit VHE radiation?



Updated from
Franckowiak et al.2018

Slide from D. de Martino

*https://asd.gsfc.nasa.gov/Koji.Mukai/novae/latnovae.html
** Plot not fully updated

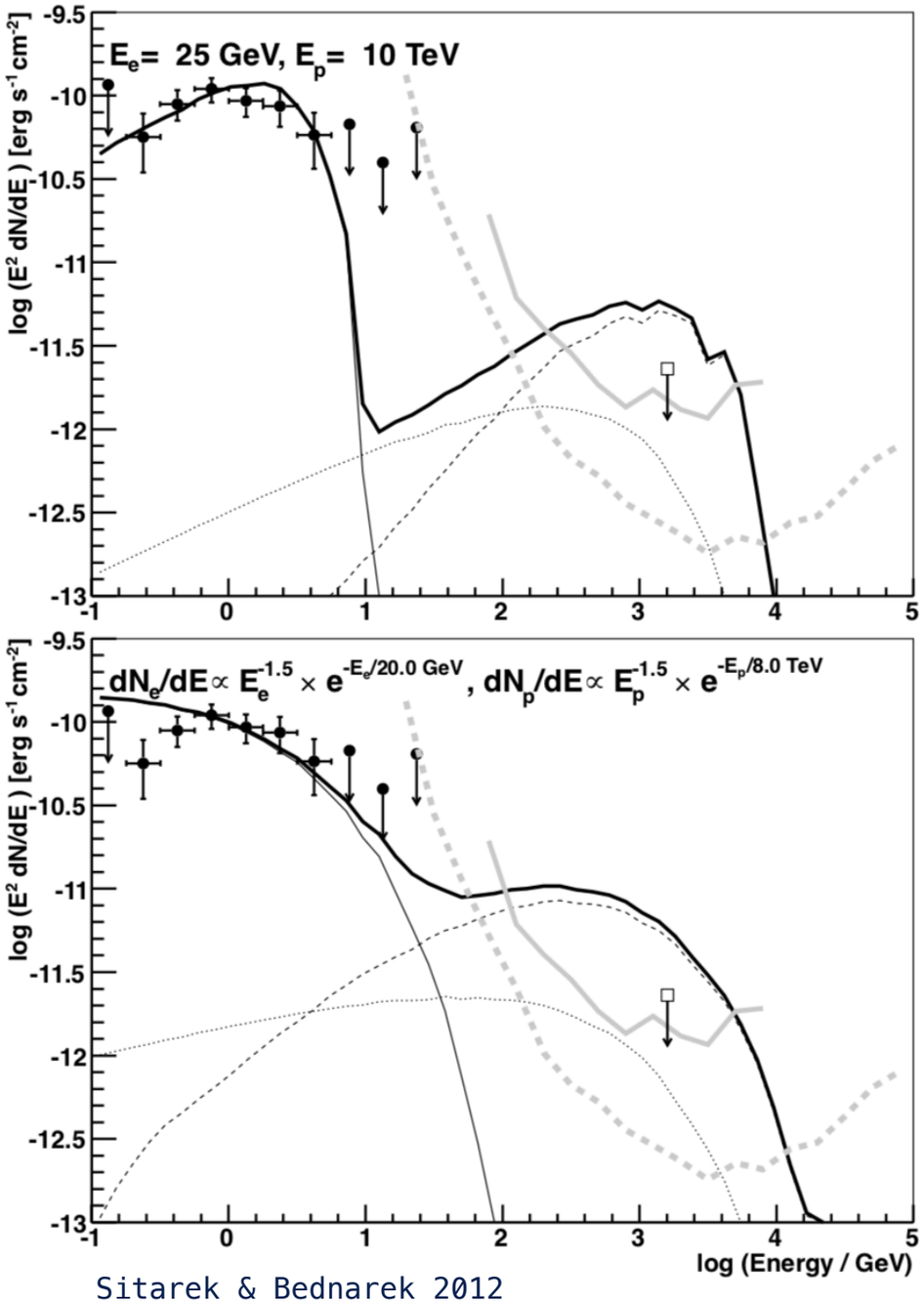
Gamma-ray emitters?
VHE counterpart

Search for VHE emission: motivation

- 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

- Several models expect VHE emission in novae (Sitarek & Bednarek 2012, Metzger et al. 2016, Tatischeff et al. 2007)



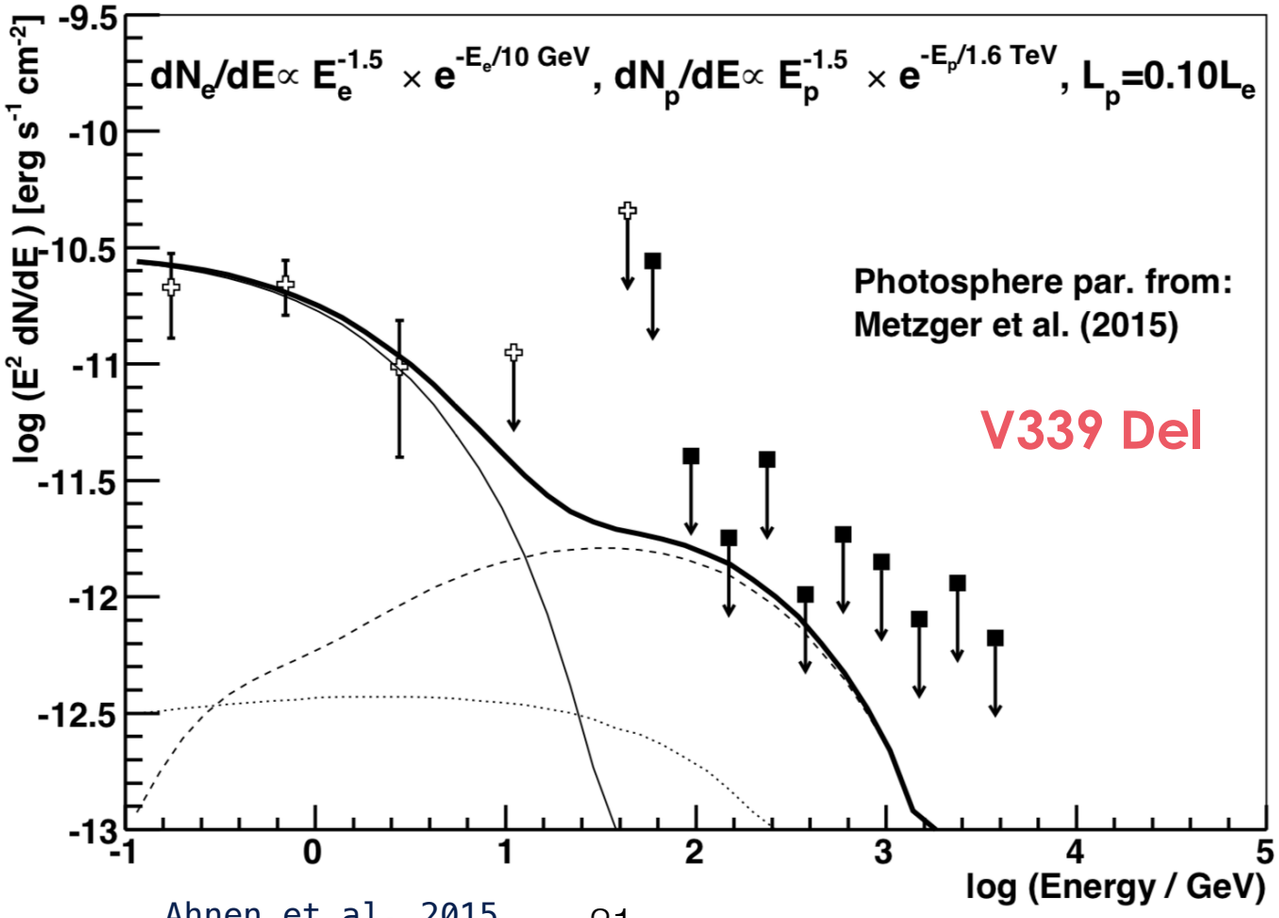
Sitarek & Bednarek 2012

Search for VHE emission

- IACTs have searched for a VHE component in novae
  - **HE data alone is not enough** to disentangle electron and proton **acceleration models**

- VERITAS observations of symbiotic nova V407 Cygni reported **ULs** (Aliu et al. 2012)

- MAGIC **searching for novae for over 10 years** (Ahnen et al. 2015)
  - **ULs** on (contemporaneously Fermi-LAT detected) classical nova V339 Del
  - **ULs** to the GeV and TeV emission of symbiotic nova YY Her and dwarf nova ASASSN-13ax



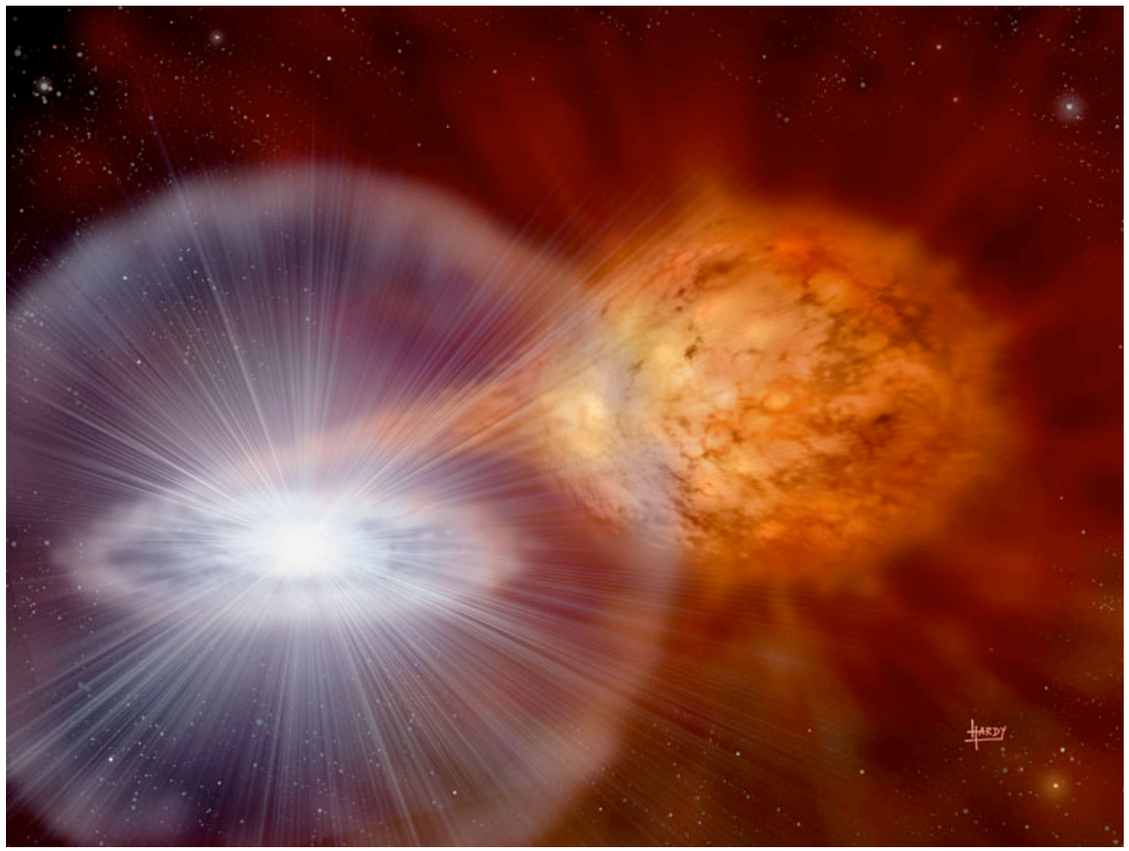
Ahnen et al. 2015

RS Ophiuchi

Antonio González (Cielos-LaPalma.com)

RS Ophiuchi

- RS Oph is a **recurrent symbiotic nova** which displays **major outbursts every 14.7 years**
  - M0-2 III RG star + WD
  - $M_{WD} = 1.2–1.4 M_{\odot}$ and $M_{RG} = 0.68–0.80 M_{\odot}$
  - Nine eruptions between 1898 and 2021
    - Latest outburst: August 2021
  - Distance: 2.45 kpc (applied in this work), but values ~1.4 – 4.3 kpc (with various caveats) are reported in the literature

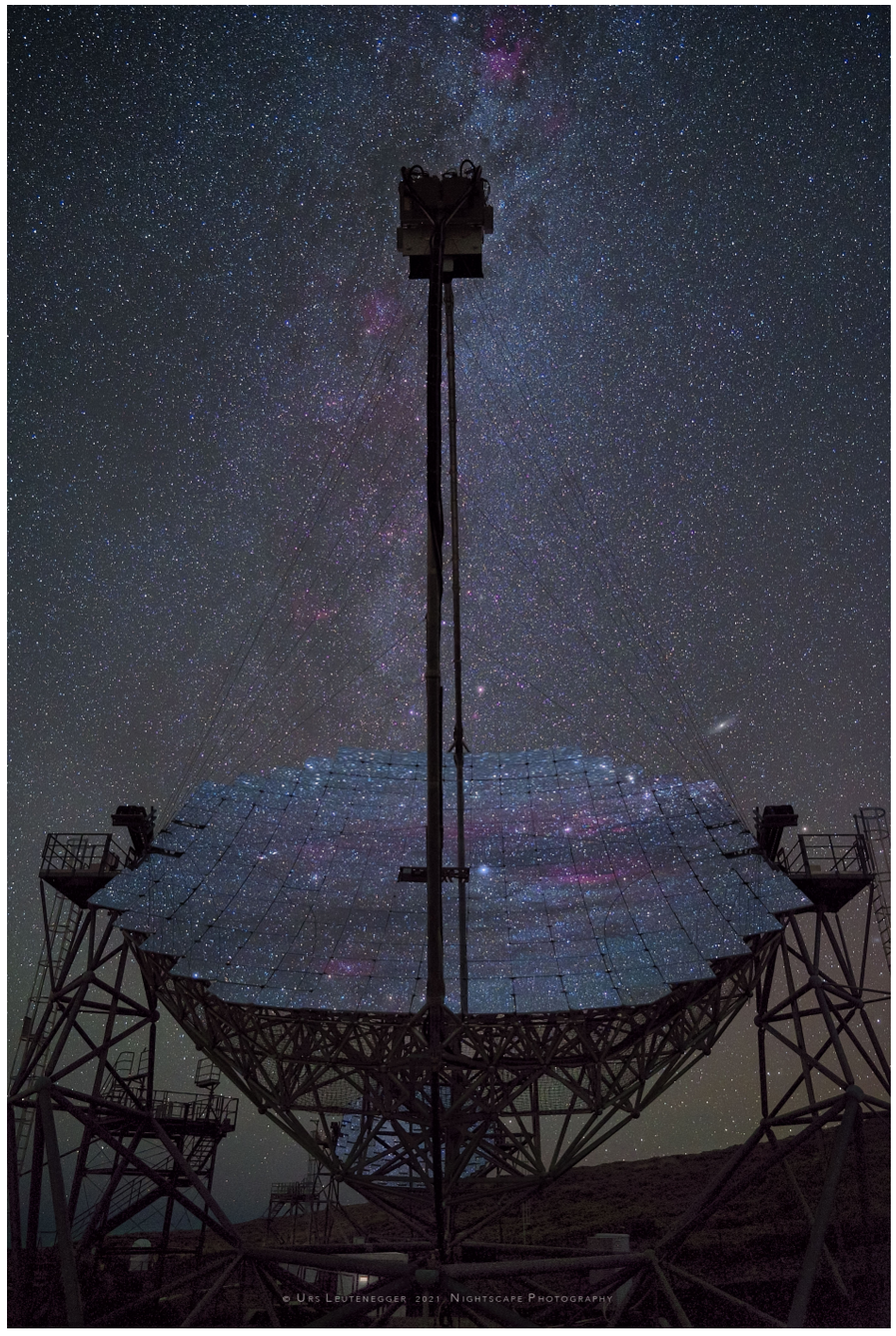


- **GeV emitter candidate**:
  - 2006 outburst of RS Oph detected by Swift/BAT could not be accounted by the decay of radioactive isotopes
  - Emission could be explained **via the production of non-thermal particles by diffuse shock acceleration** Tatischeff et al. 2007)

- **Type Ia Supernova progenitor candidate**

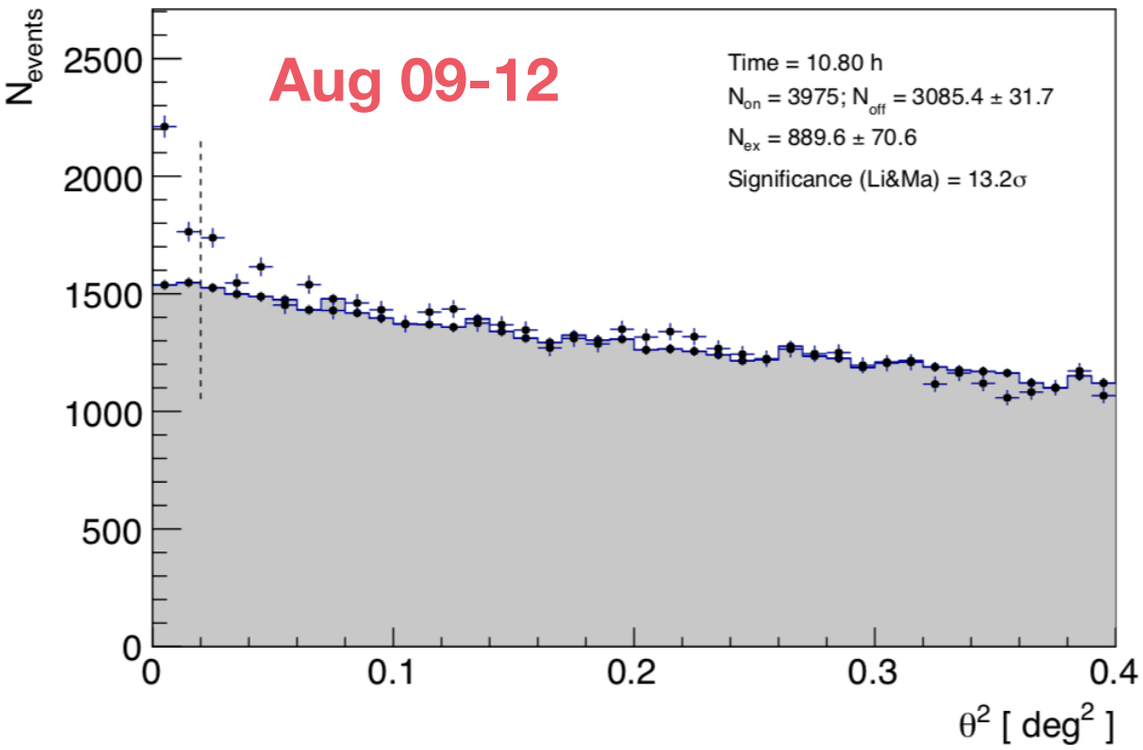
RS Oph at VHE

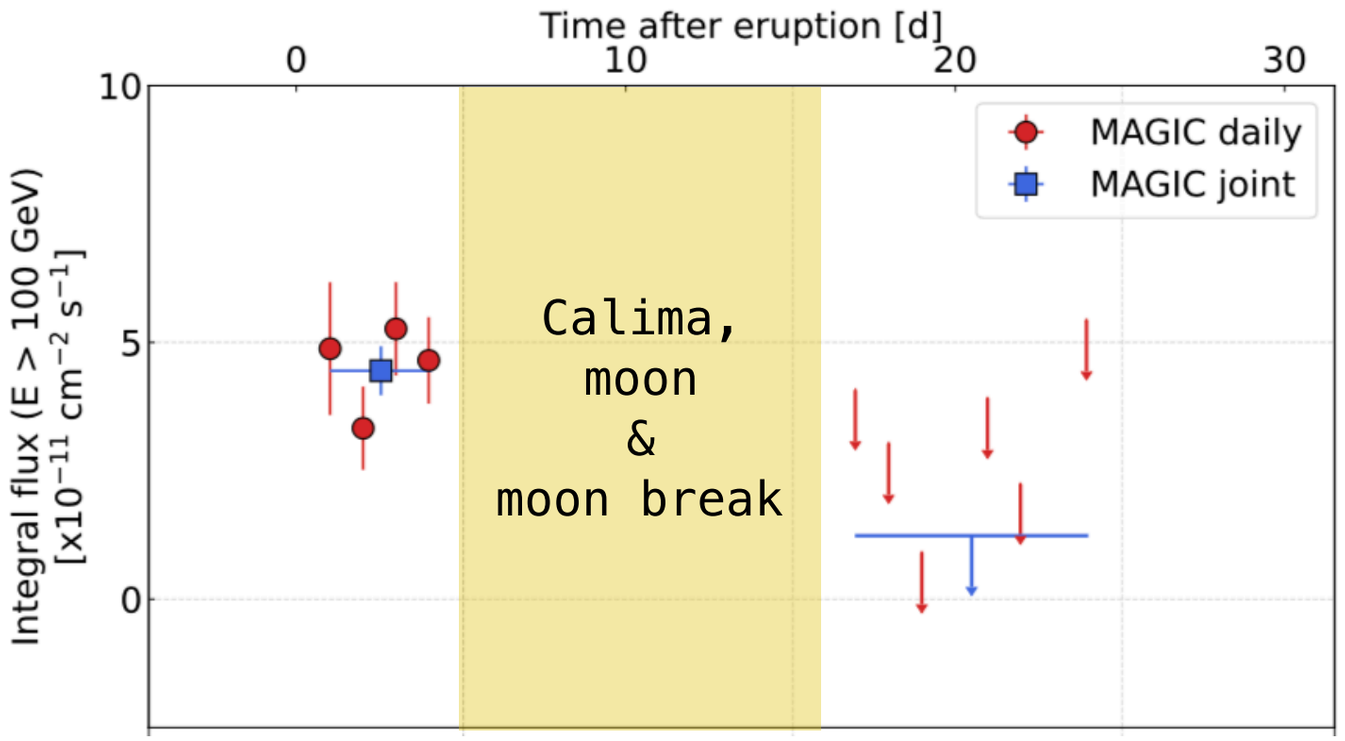
- **Latest outburst: August 08, 2021**
  - Aug 08, 22:20 UT: RS Oph in outburst
  - Aug 09, 00:35 UT: Optical notice (Geary, vsnet-alert 26131, Aug 8, 22:21 UT)
  - Aug 09, 05:05: Fermi-LAT reports discovery at >100 MeV(ATel 14834)
  - Aug 09 12:23 UT: MAGIC ToO request
  - Aug 09, 18:17 UT: H.E.S.S. starts observations
  - Aug 09, 22:27 UT: MAGIC starts observations
    - Triggered via Target of Opportunity
  - Aug 10, 2021; 18:34 UT: H.E.S.S. reporsts discovery at VHE on(ATel #14844)



MAGIC detection

- The **first four days** of MAGIC observations (August 09-12) yield a **VHE signal** with a **significance of 13.2 σ** (Acciari et al. Nat. Astronomy, 2022)
  - 34 h observed, 21.4 h after quality cuts
  - Zenith angle range: 36° - 60°
  - Dedicated low-energy procedure with a special signal extraction and image cleaning (MaTaJu)
  - Energy threshold of the analysis is ~60 GeV
- Bad weather prevented the detection on following days
- Emission completely disappeared after moon break
- **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

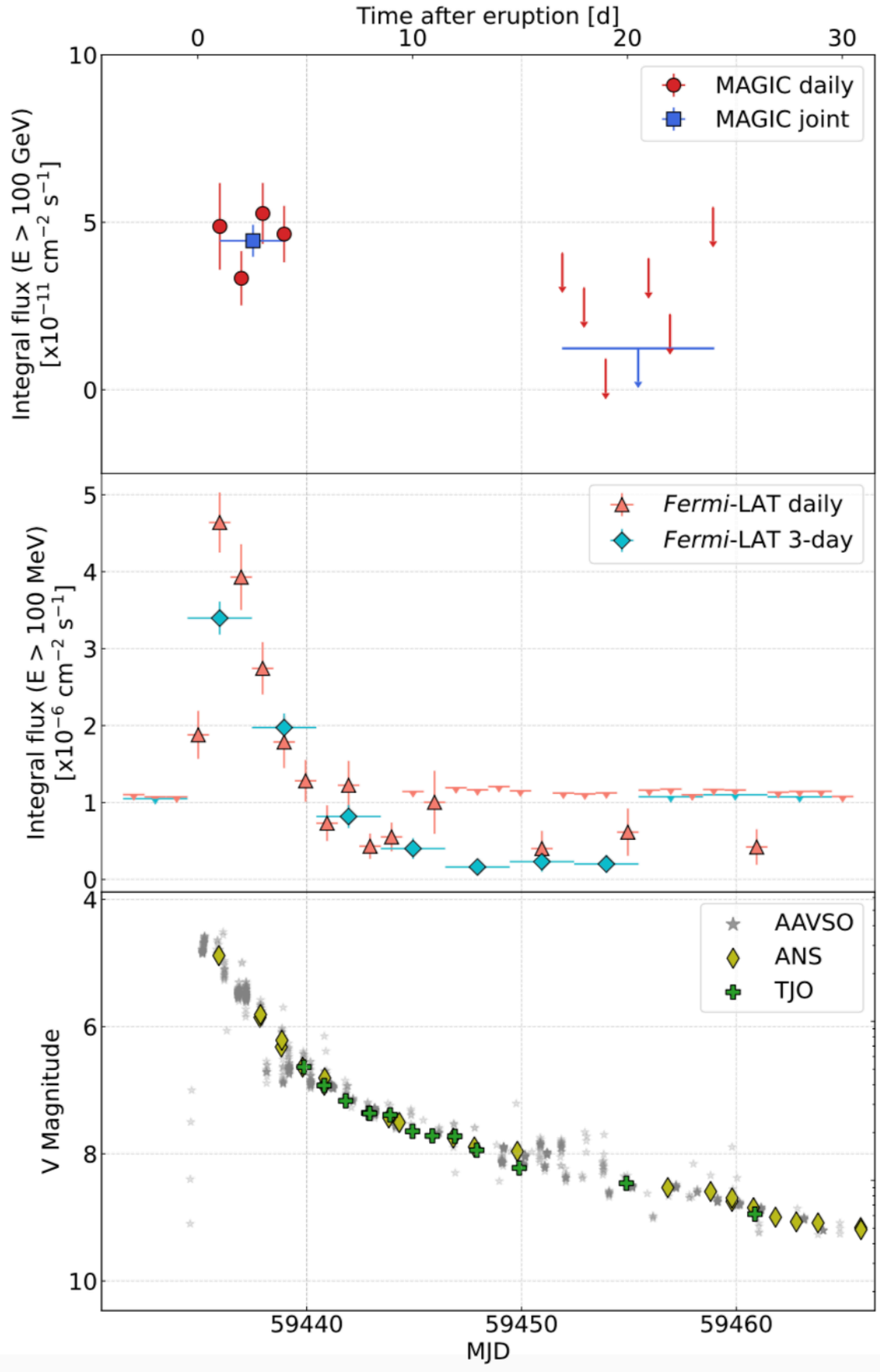
MWL view

- The MAGIC observations reveal **VHE emission contemporaneous to the Fermi-LAT and optical maxima**, and a **decrease** below the VHE detection limit **two weeks later**

- Emission peaked at optical and MeV, but **VHE emission is** consistent with being **constant over the fi 4 days**

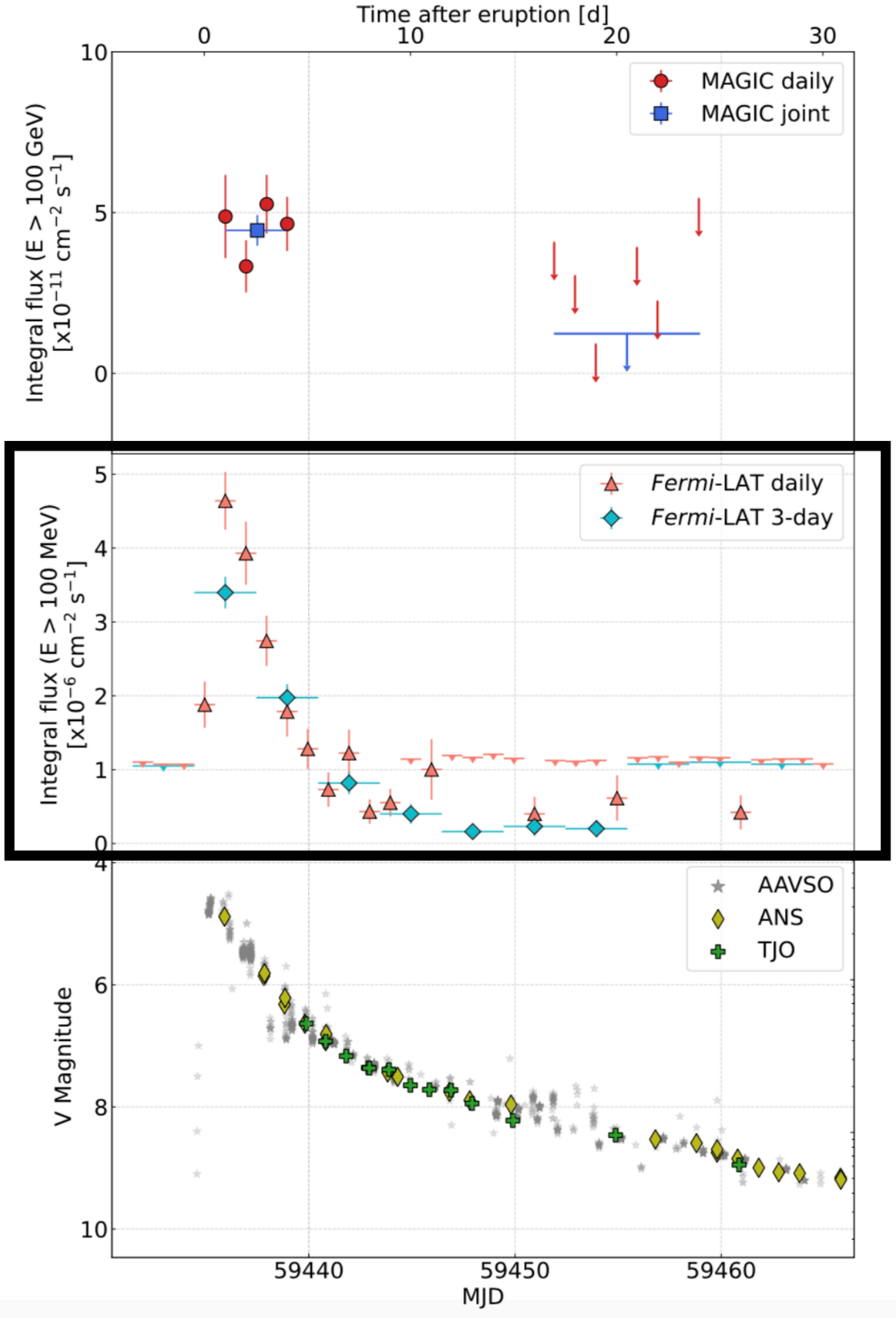
- **Fast decay at HE**
  - 2.2 day halving timescale in Fermi-LAT

- Signal decay in optical



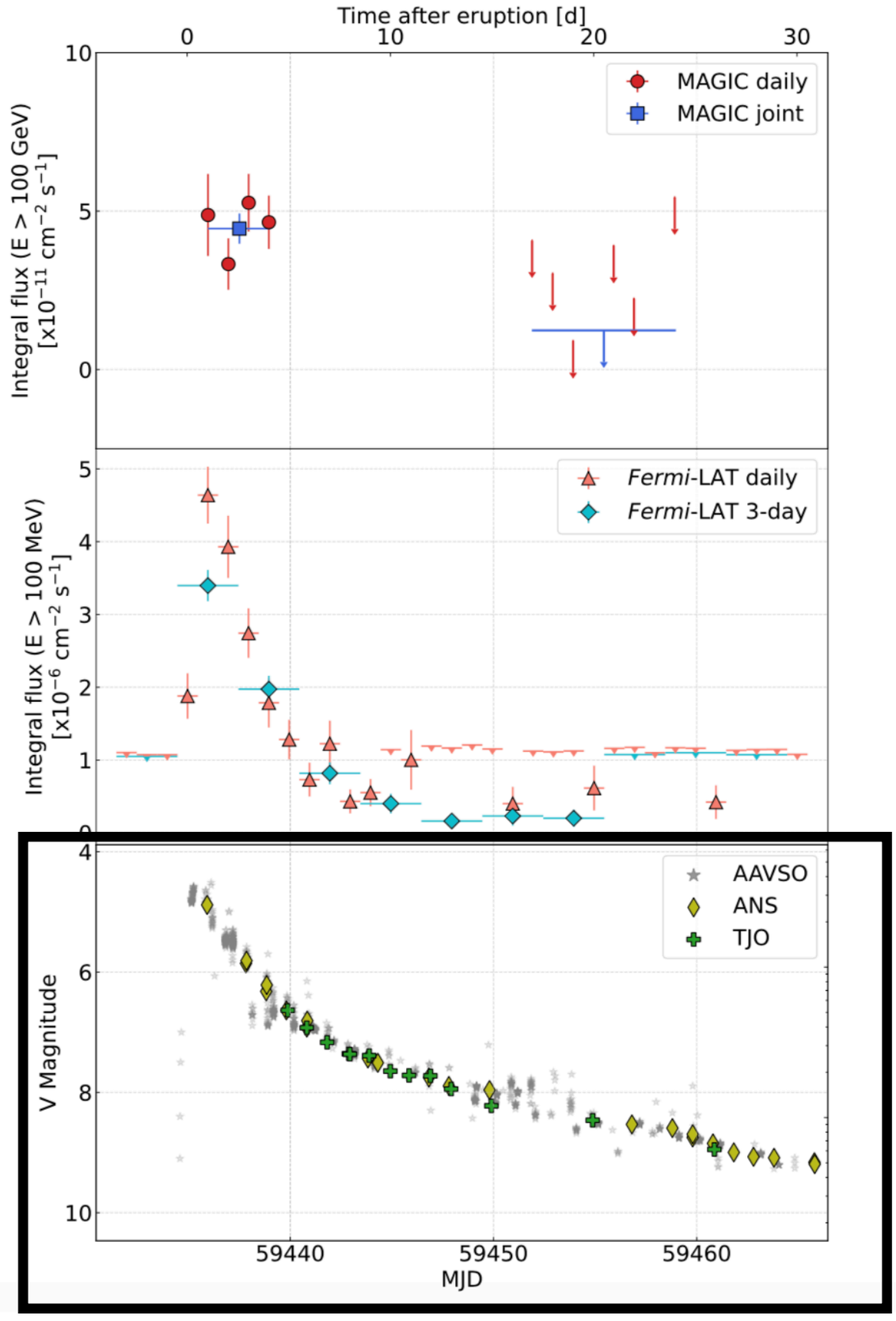
Fermi-LAT analysis

- 1-day and 3-day LC (MJD 59431.45 to 59461.45)
  E: 0.1 GeV to 1,000 GeV
  - 1-day LC (MJD 59435.45–59444.45) can be well fitted with **an exponential decay with halving time of (2.20 ± 0.18) days**
- For the combined first four days (MJD 59435.45–59439.45) -> E range starting at 0.05 GeV



Optical

- **During the nova outburst the photospheric emission creates the dominant radiation field**
- Photometry
  - Performed with **TJO and ANS telescopes**
  - During the first 4 days (contemporaneous with MAGIC) the emission can be described* by the **photosphere temperature dropping from T_{ph} = 10,800 K to 7,680 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**
  - **4,500 ± 250 km s^{-1}** for the ejecta expansion at the earliest stage (during the VHE gamma-ray detection by MAGIC).

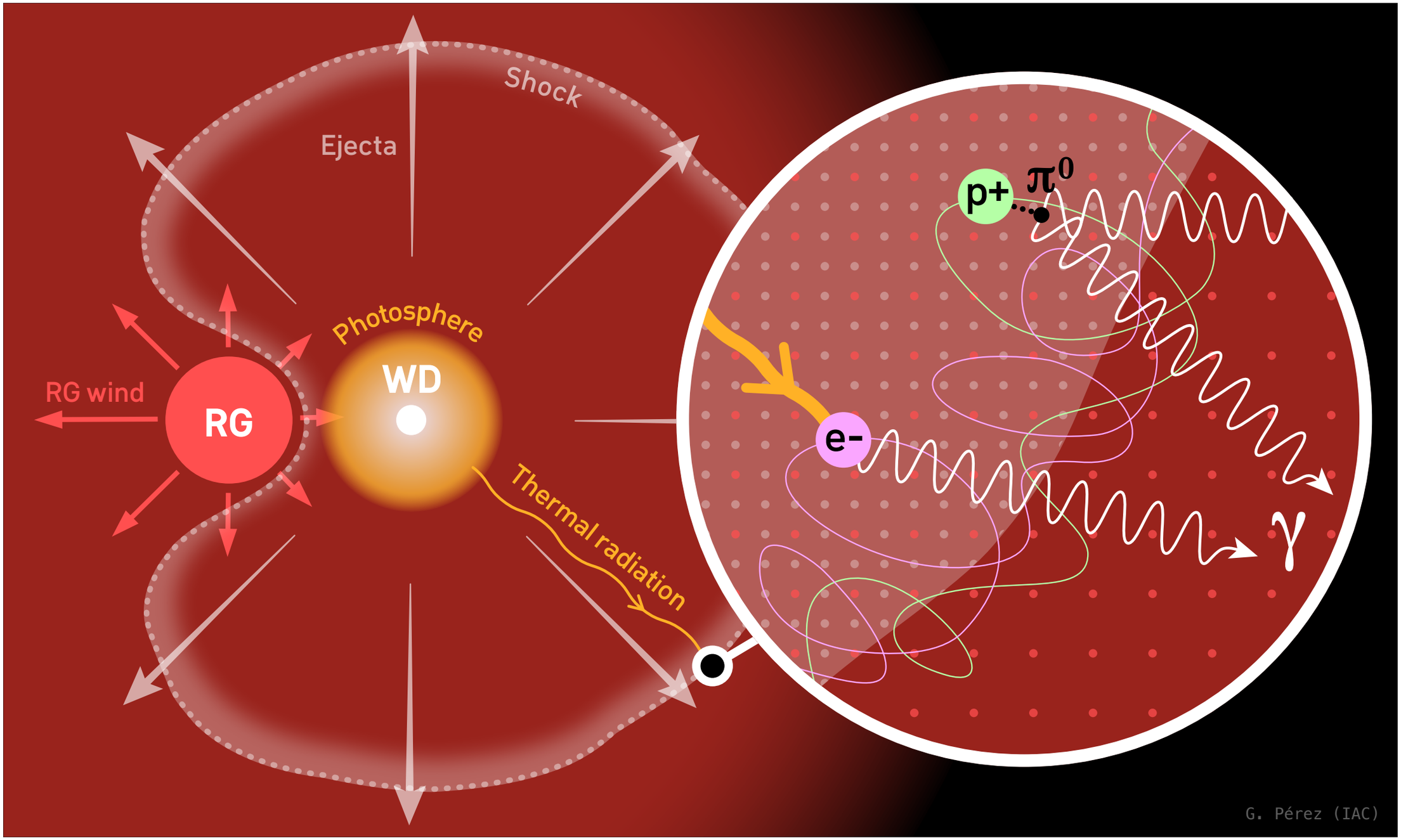


* consider an approximation of the radiation field, in the context of gamma-ray emission, and no conclusion on the evolution of these two parameters should be drawn.

RS Ophiuchi

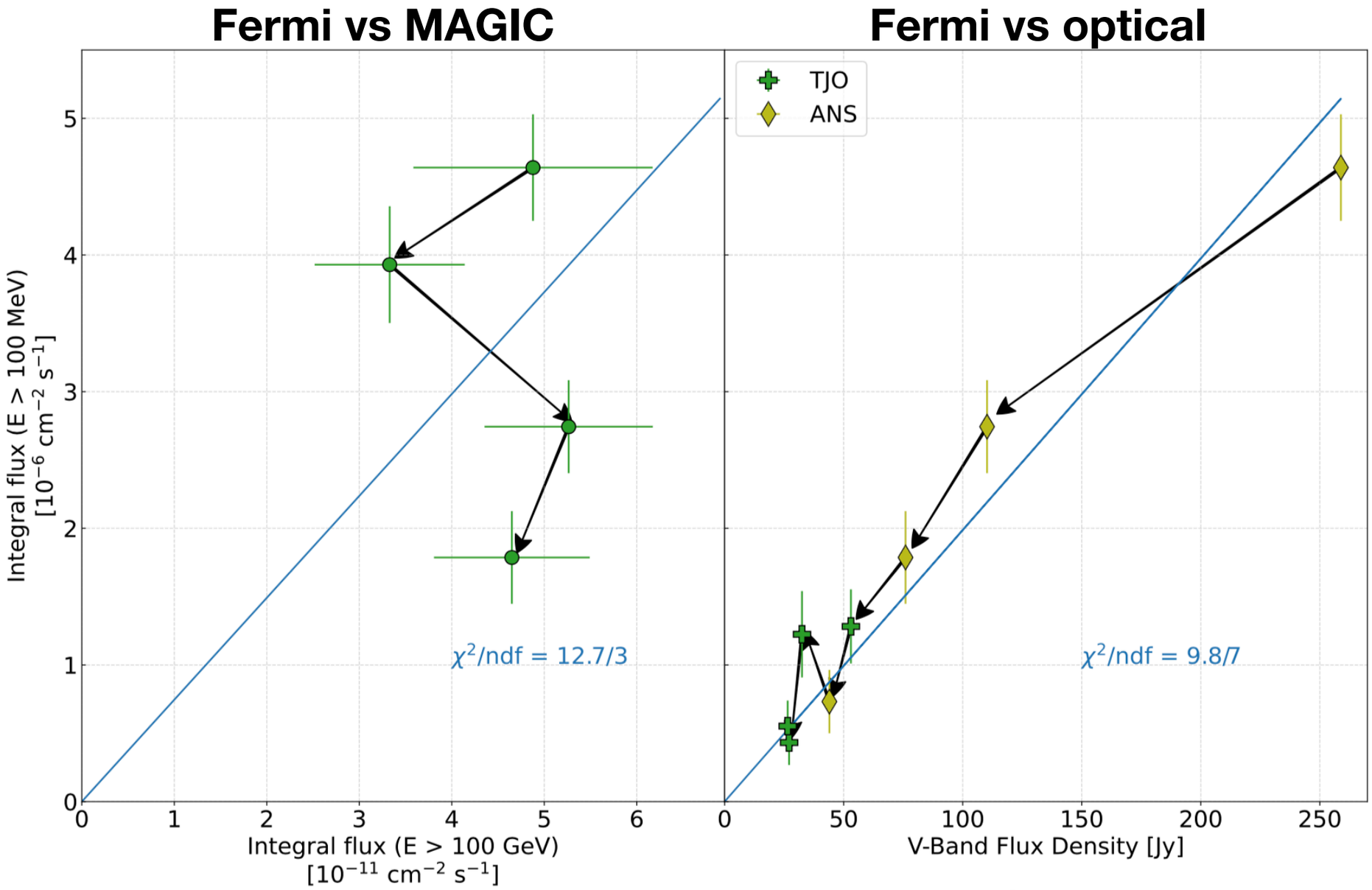
superbossa.com/MPP

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)**

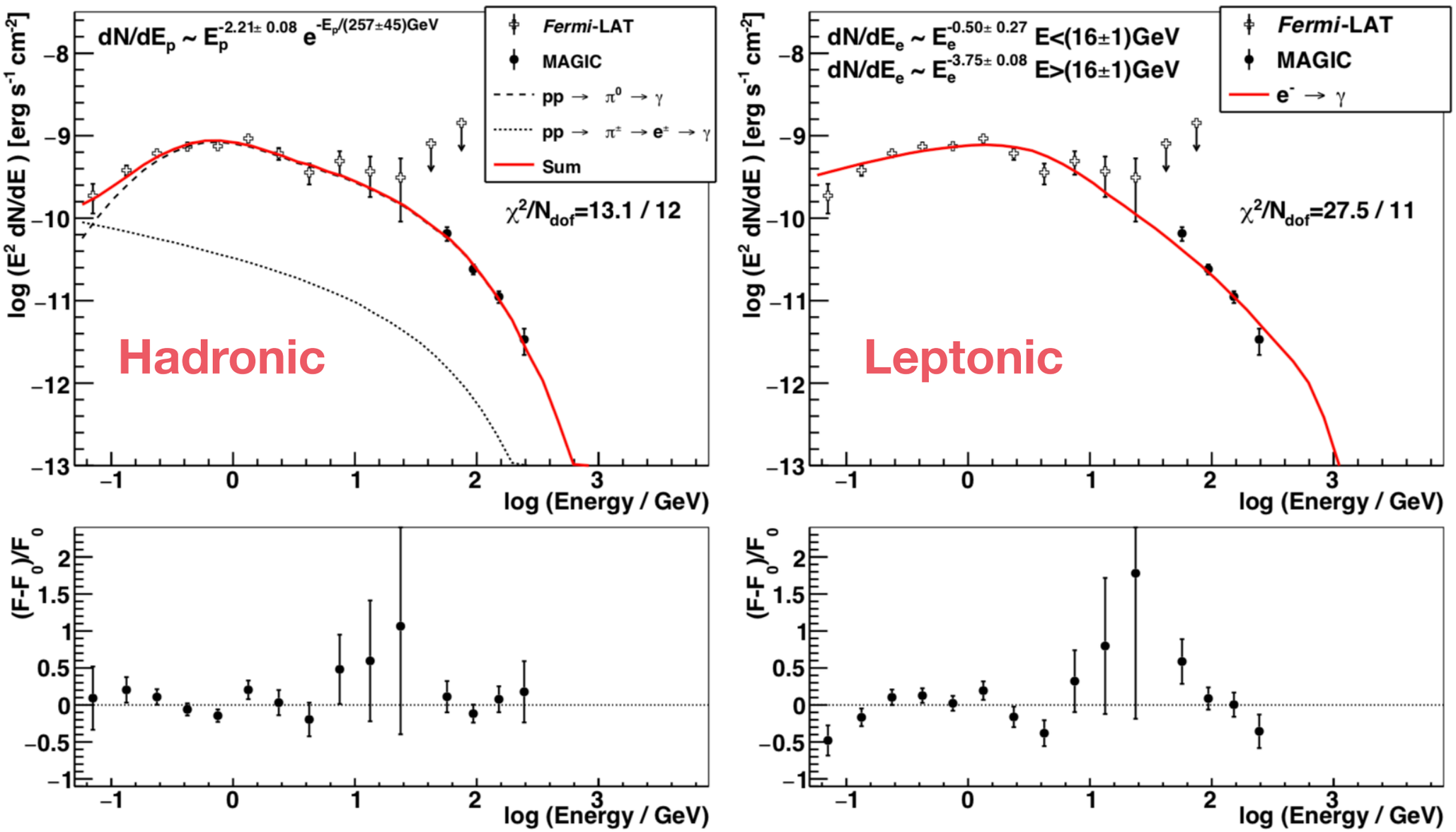
MWL flux evolution



Acciari et al. Nat. Astronomy, 2022

- **VHE 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**

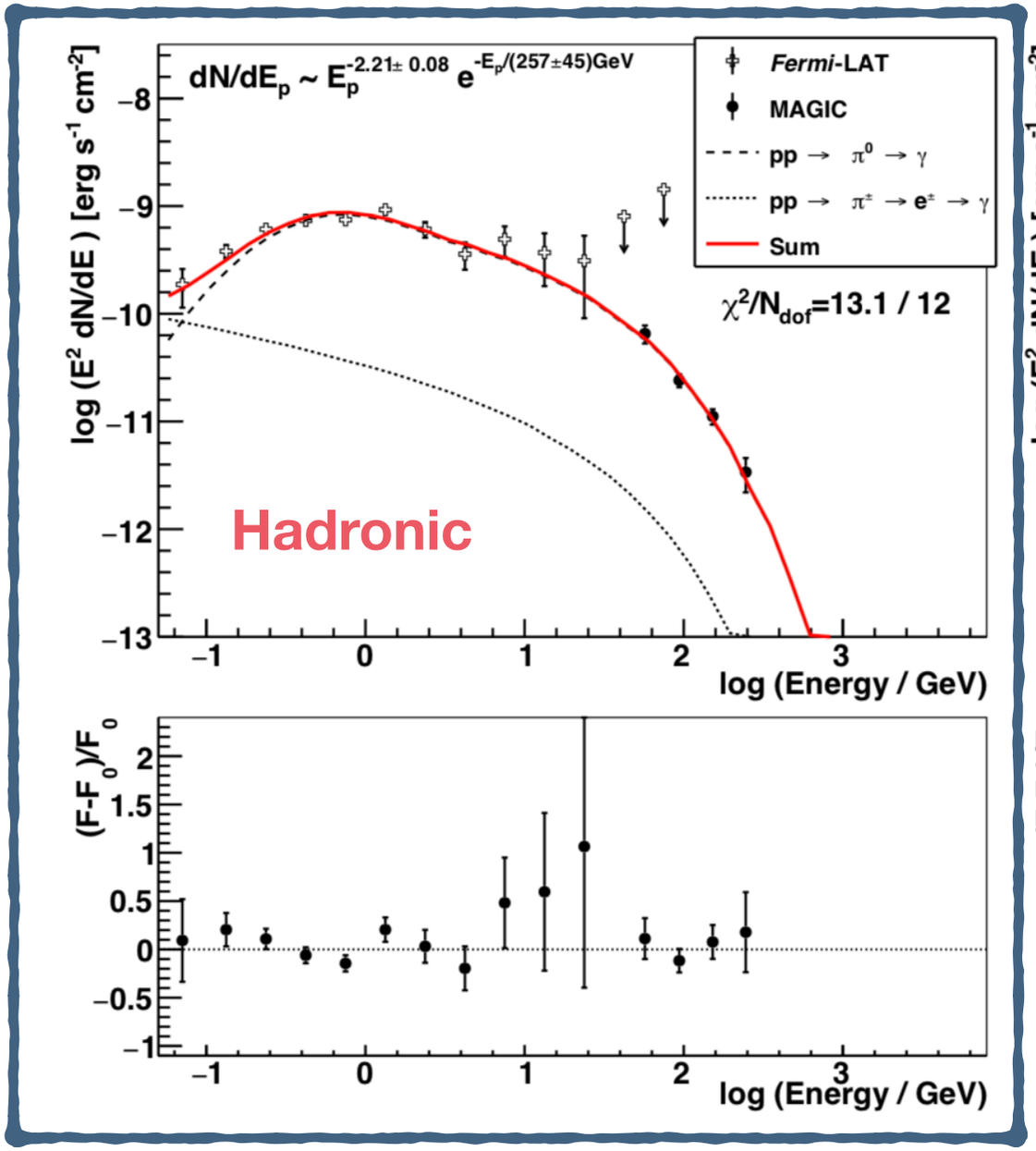
Modelling

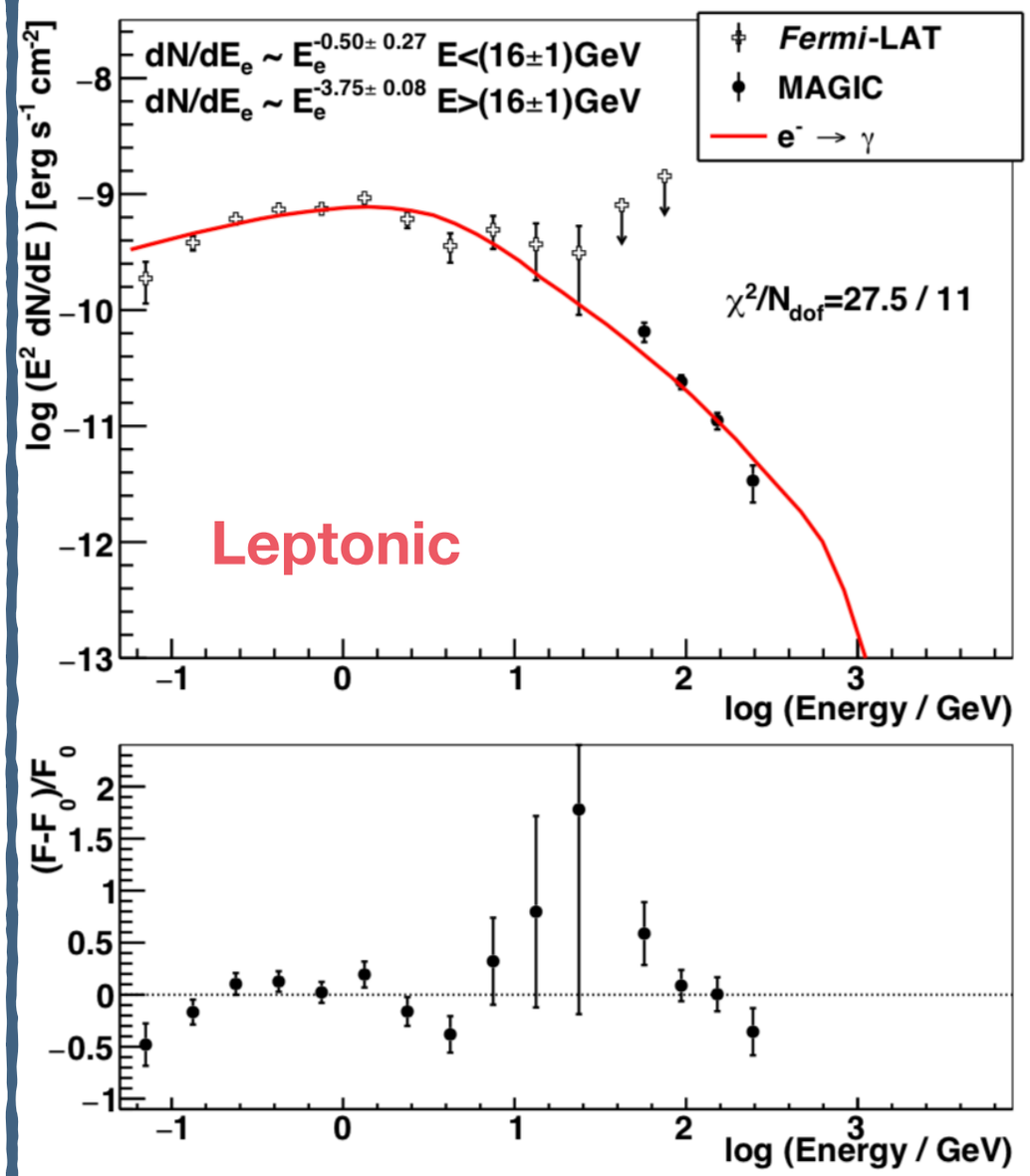


Acciari et al. Nat. Astronomy, 2022

- **Joint Fermi-LAT +MAGIC** spectrum can be described as a **single**, smooth **component** spanning **from 50 MeV to 250 GeV**
- RS Oph spectrum averaged **over the first four days** of the outburst, modeled within **hadronic (left panel)** or **leptonic (right panel)** scenario. Model based on `Sitarek & Bednarek 2012`

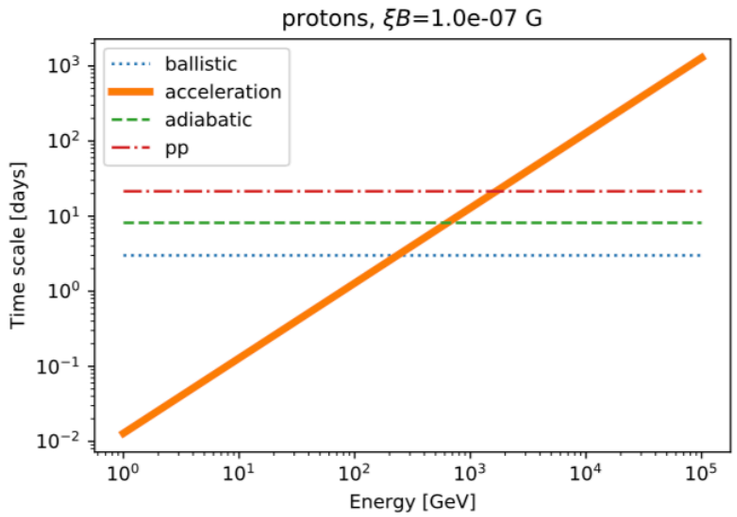
Modelling: proton acceleration

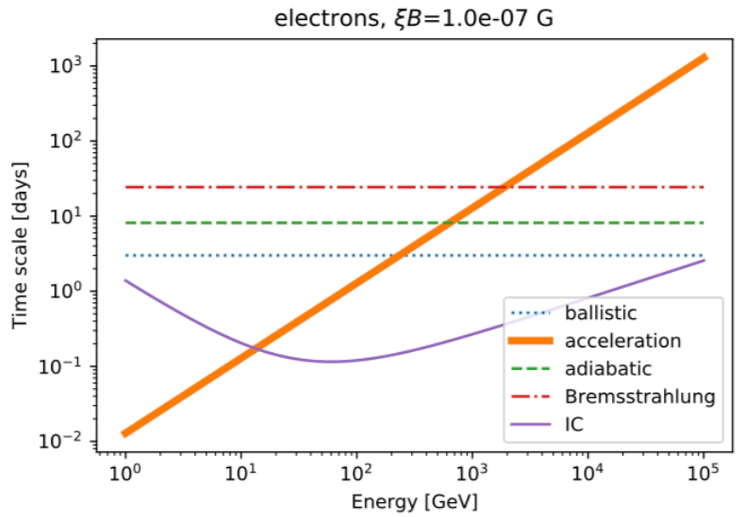


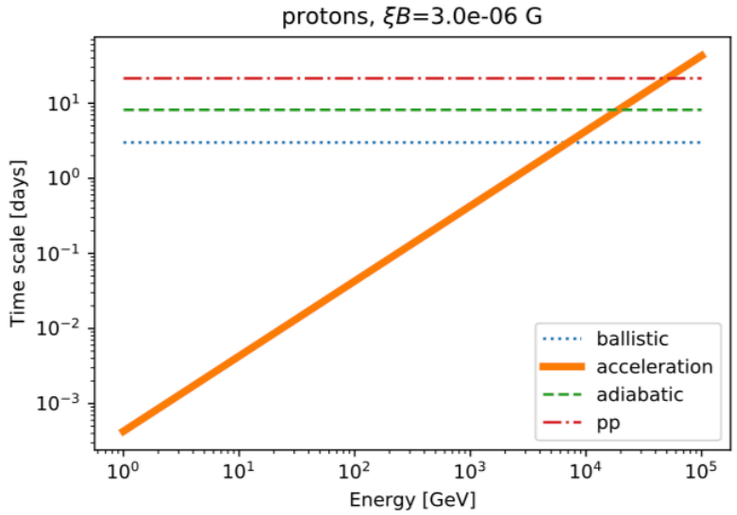


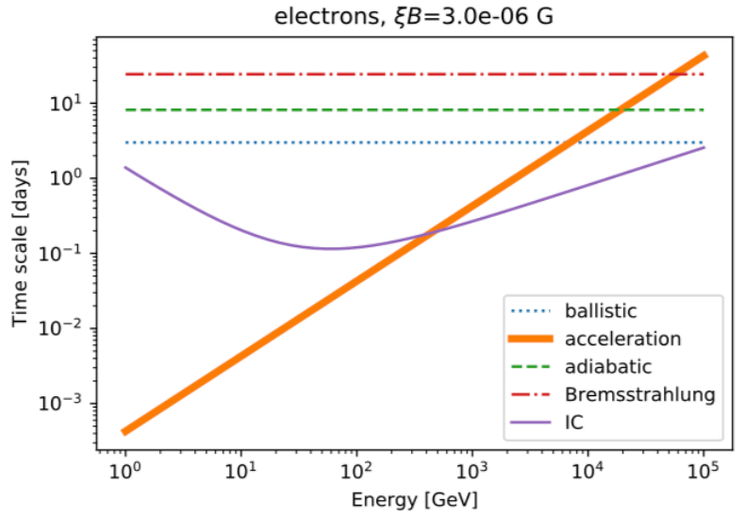
- **Hadronic scenario is favored**
  - **Better χ^2 of the fit** (AIC test gives electrons only 4.7 x 10^{-4} times as likely as protons)
  - Hadronic scenario favored:
    - Protons injected with **standard -2 slope** spectrum with a cut-off, while electrons would need a ad-hoc strong spectral break

Supporting a hadronic scenario



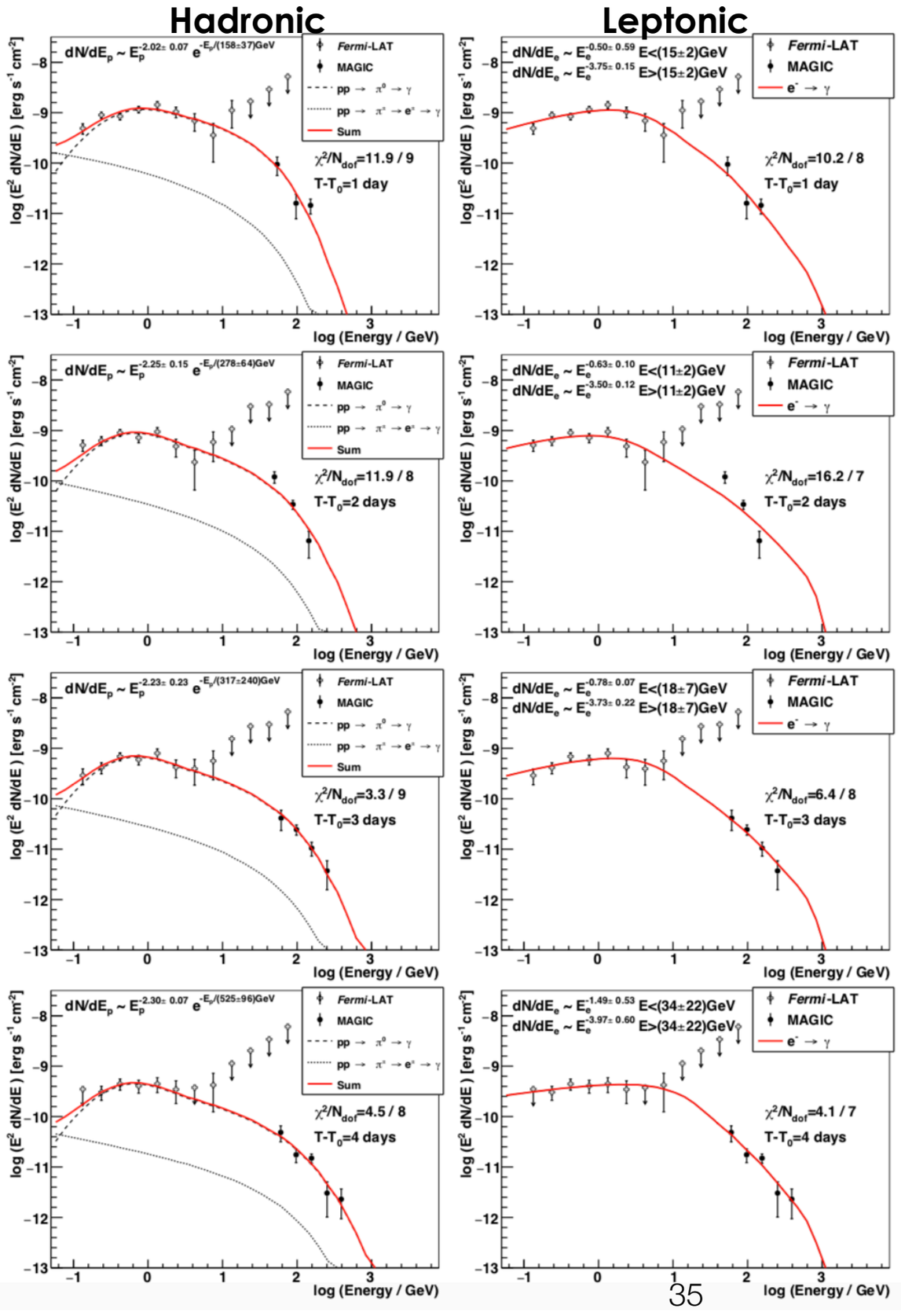






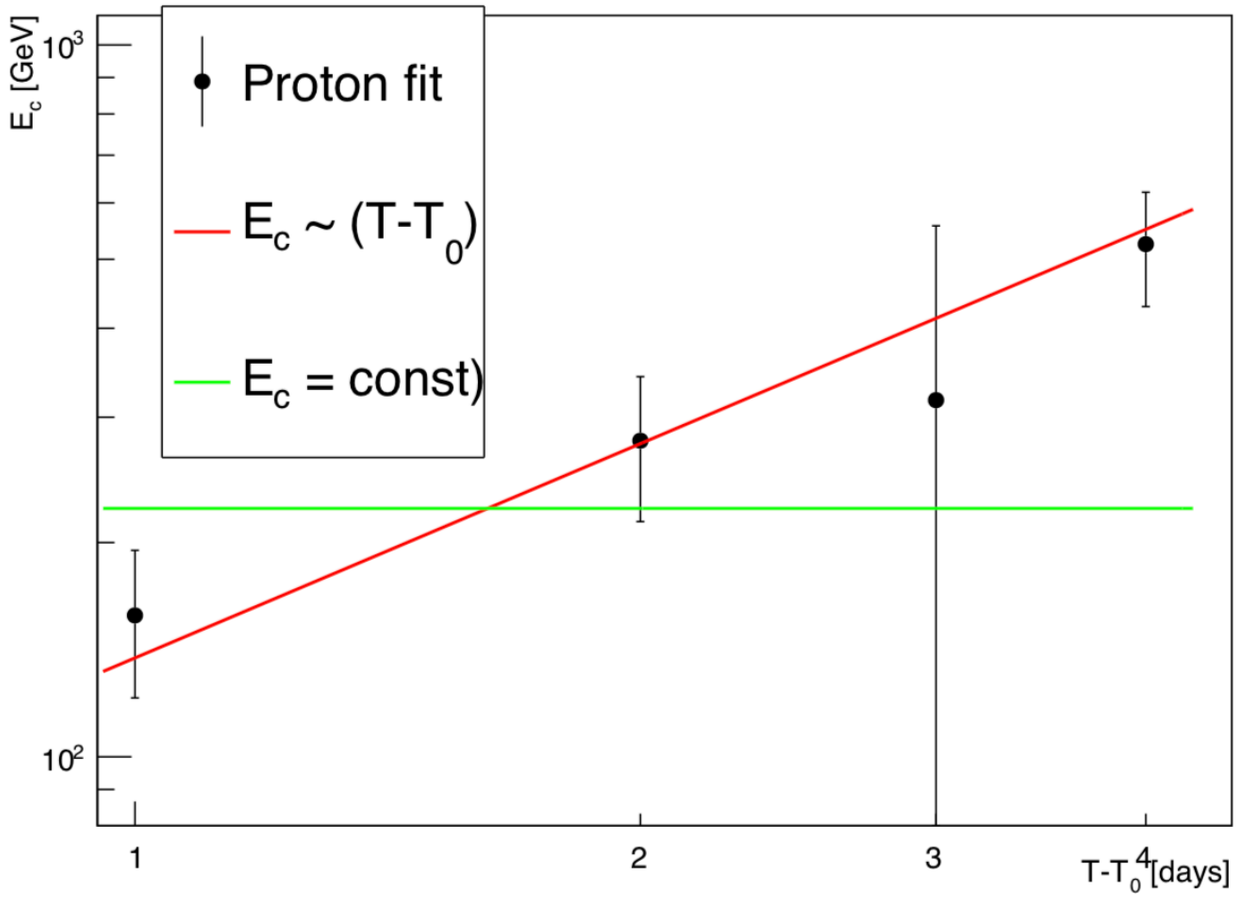
- **Protons have slow cooling**, Emax determined by acceleration time
- **Electrons show fast cooling** on IC: 2 orders of magnitude stronger acceleration to reach the same energies
  - Larger B required to accelerate e-
- In order to accelerate p+ up to energies of a few hundred GeV, $\xi B \gtrsim 10^{-7}$ G
  - If electrons are accelerated in the same conditions, they can reach energies of only ~ 10 GeV
- **Protons are favored**

Modelling: daily proton acceleration



- **Hadronic scenario favored** daily
- **Increase of the cut-off energy with time**

Supporting a hadronic scenario



- **Spectral hardening**
- **Increase in maximum energy of protons** from modeling (increase of cut-off): behaviour **in line with the expectations from the cooling and acceleration time scales**
  - Due to low cooling losses of protons, their maximum energies are mainly determined by the duration of the acceleration
  - Increase of maximum proton energies could last until the shock is drained up from its energy, or is slowed down by the interstellar medium
  - Constant value can be excluded
- **Hadronic scenario is favored**

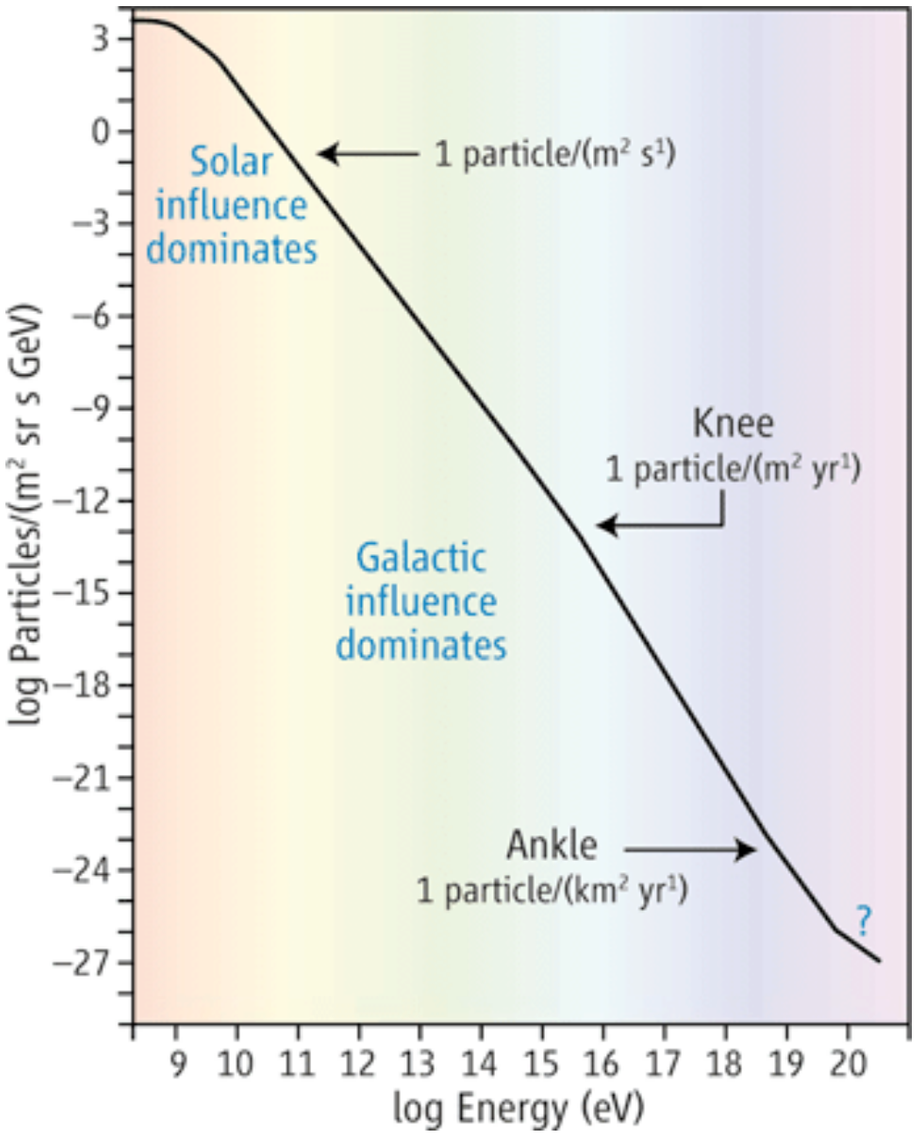
Galactic novae and Cosmic Rays

- **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**

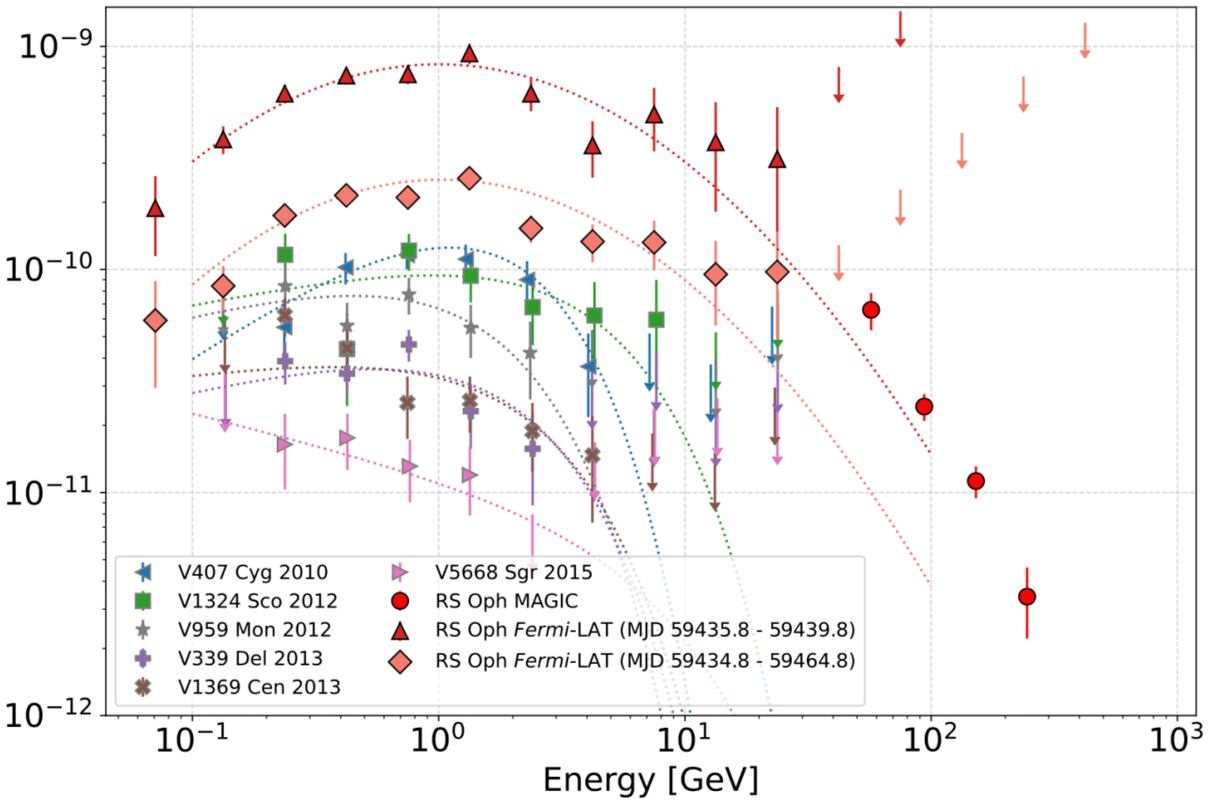
- Despite the small contribution to the overall CR sea, **novae would significantly increase the CR density in its close environment**: E_density(nova)>E_density(CR)

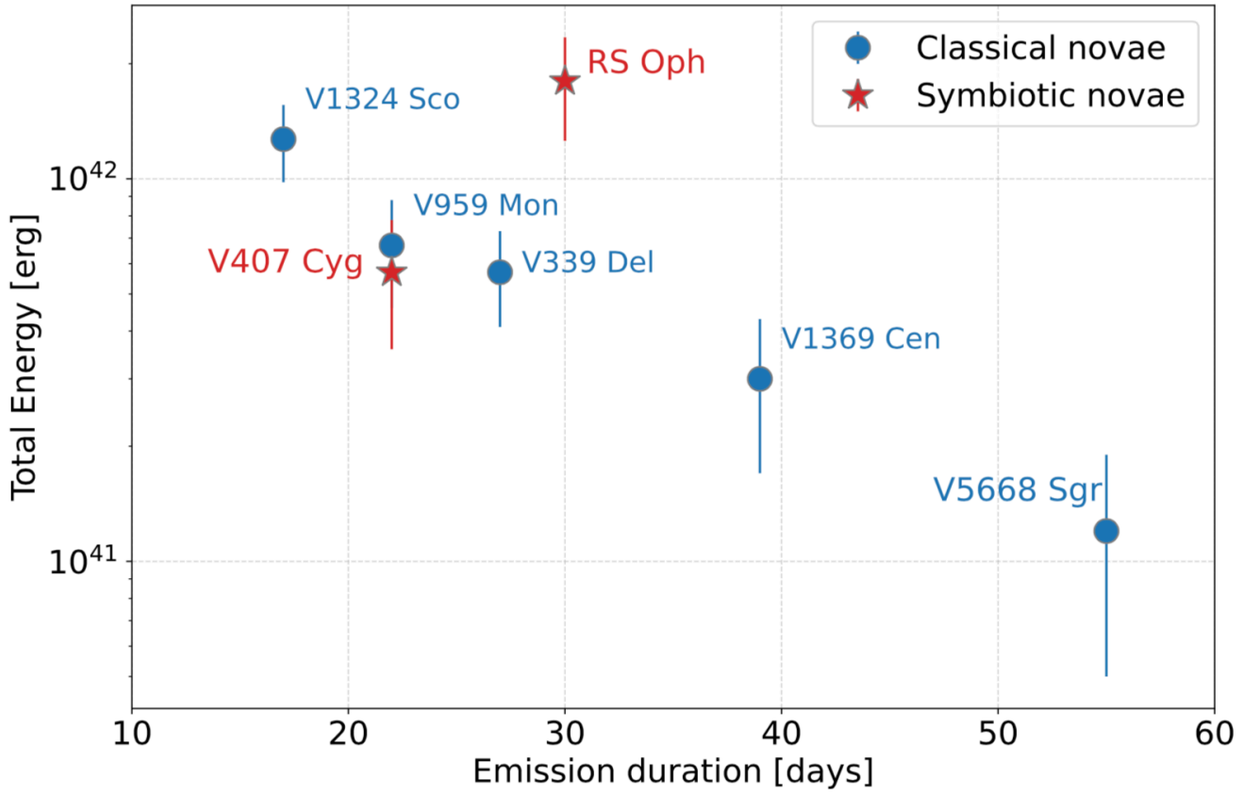
- In the case of **recurrent novae, protons will accumulate in a ~10 pc bubble** with enhanced CR density



Extracted from Dulgig, Science 2020

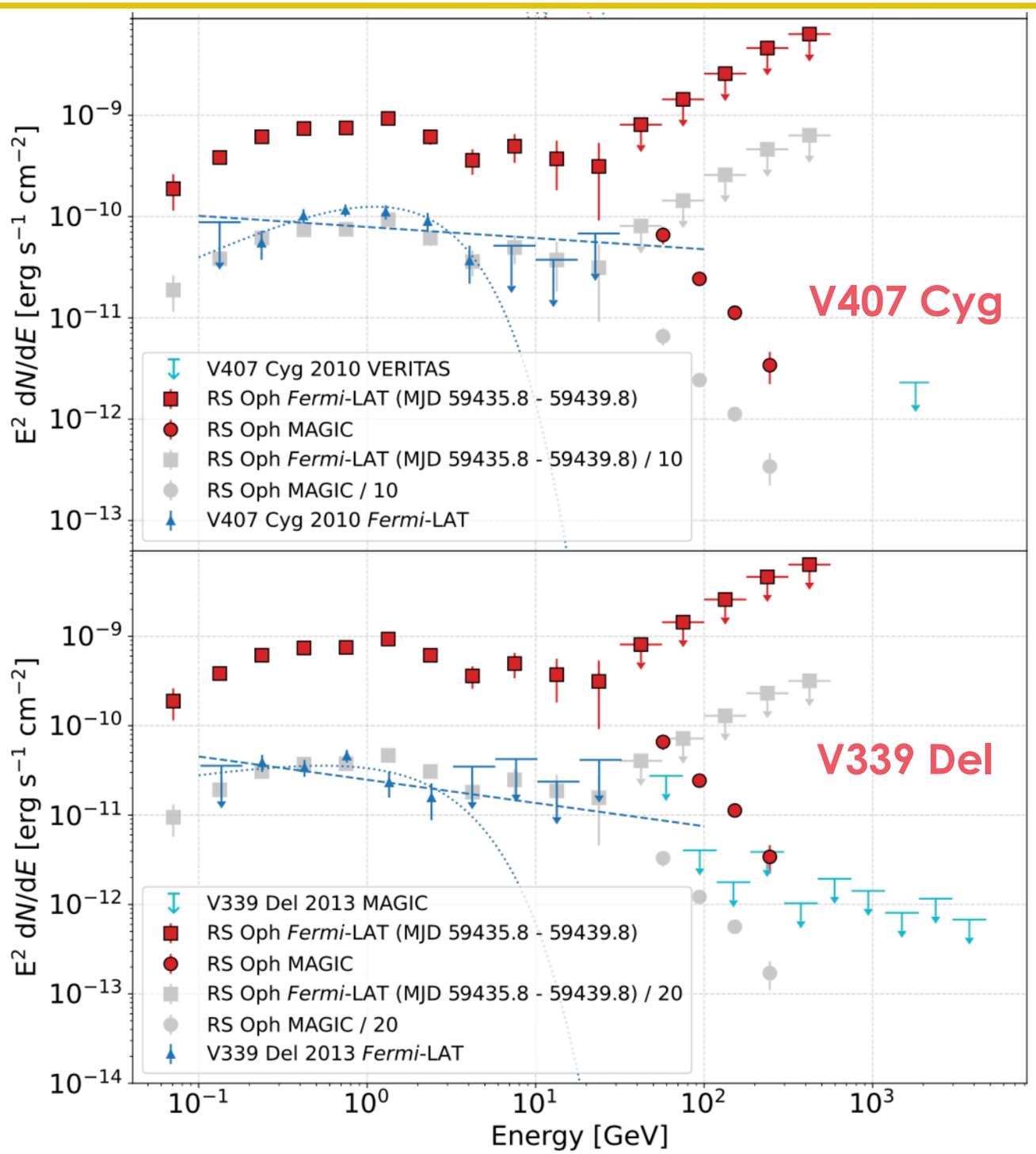
RSOph vs other novae





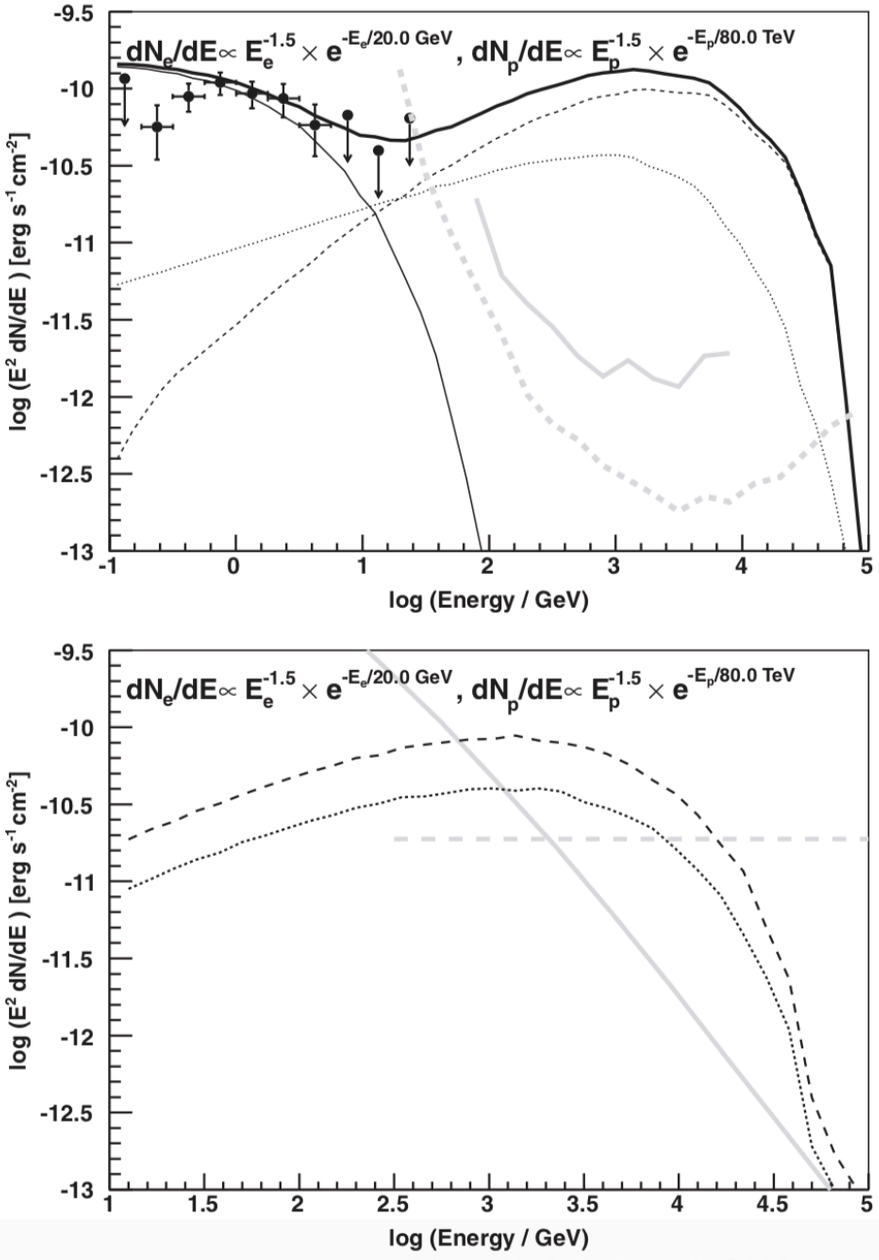
- RS Oph is the nova with the **highest flux** and **brightest nova** observed by *Fermi*- LAT
  - The flux corresponding to the simultaneous data and the average flux during the whole eruption are almost two orders of magnitude larger than previously-detected eruptions.
- **Comparison does not reveal any peculiarity** in the emission of RS Oph, except for its brightness.

RSOph vs other novae

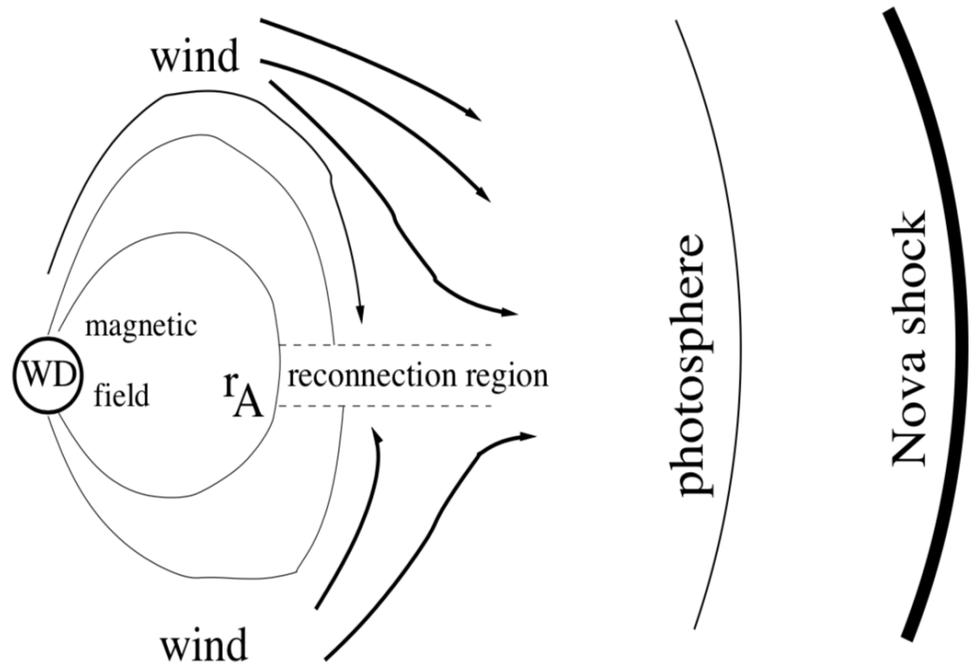


- Scaling RS Oph to V337 Del and V407 Cyg level, previous MAGIC and VERITAS ULs not be able to constrain RS Oph- like emission
- Previous novae may have been emitting at the same level as RS Oph, but maybe telescopes did not have the needed the sensitivity to detect them.

Neutrinos prediction in novae



Sitarek & Bednarek 2012



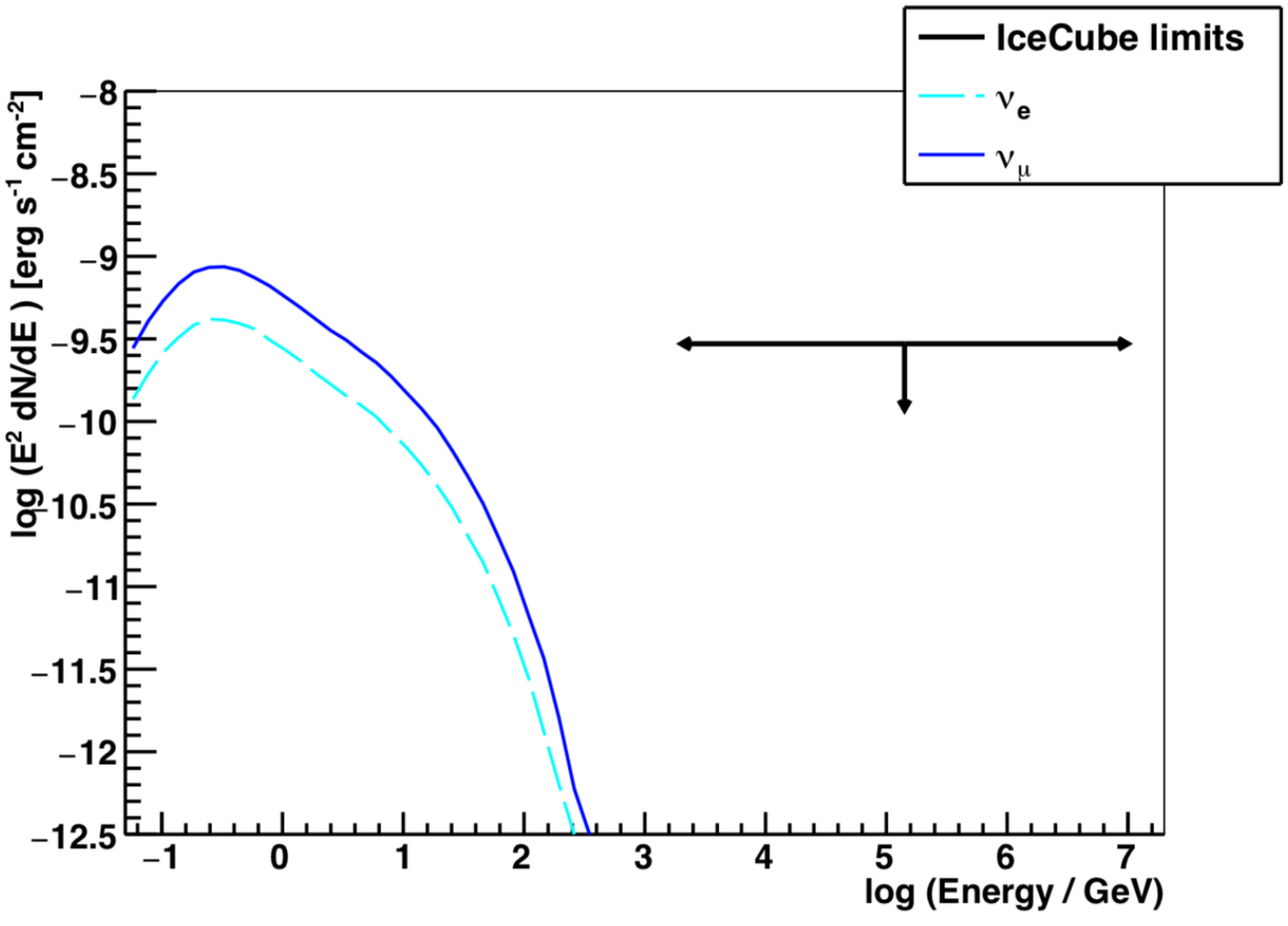
Bednarek & Smialkowski 2022

- Prediction **VHE and neutrino emissions from symbiotic nova** explosions (V407Cygni-like)(Sitarek & Bednarek 2012)

- Production of **neutrinos in collisions of relativistic protons with the matter of the fast wind from the WD** (Bednarek & Smialkowski 2022)

Neutrinos from RS Oph?

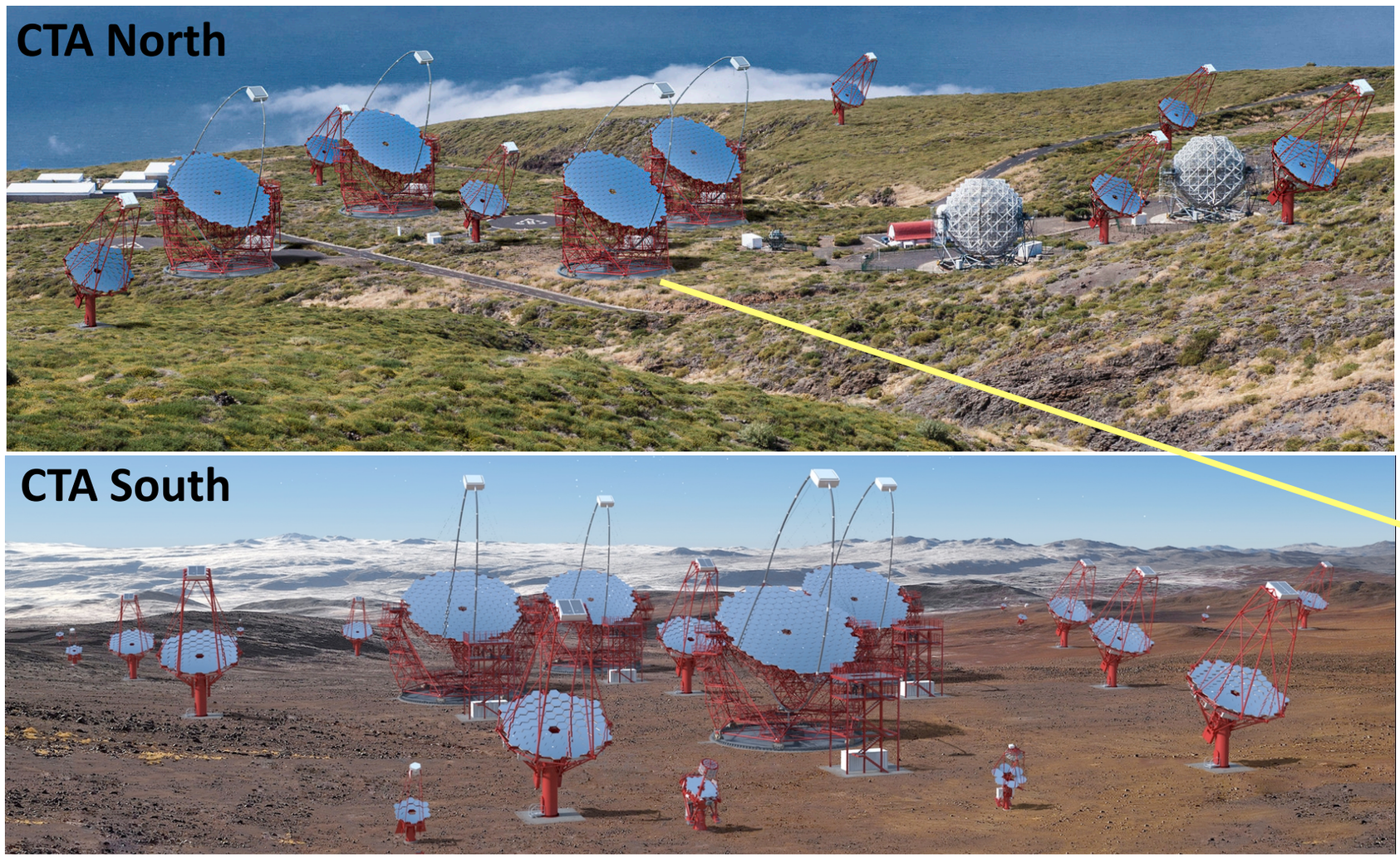
- **No signal detected by IceCube** in the 3 first days (Pizzuto et al. ATel #14851)
- We calculated the neutrino emission corresponding to the proton model and compared it with limits from the IceCube Collaboration
  - Protons reach only sub-TeV energies-> the **predicted neutrino emission does not reach energies higher than those of protons** and these limits cannot constrain the model

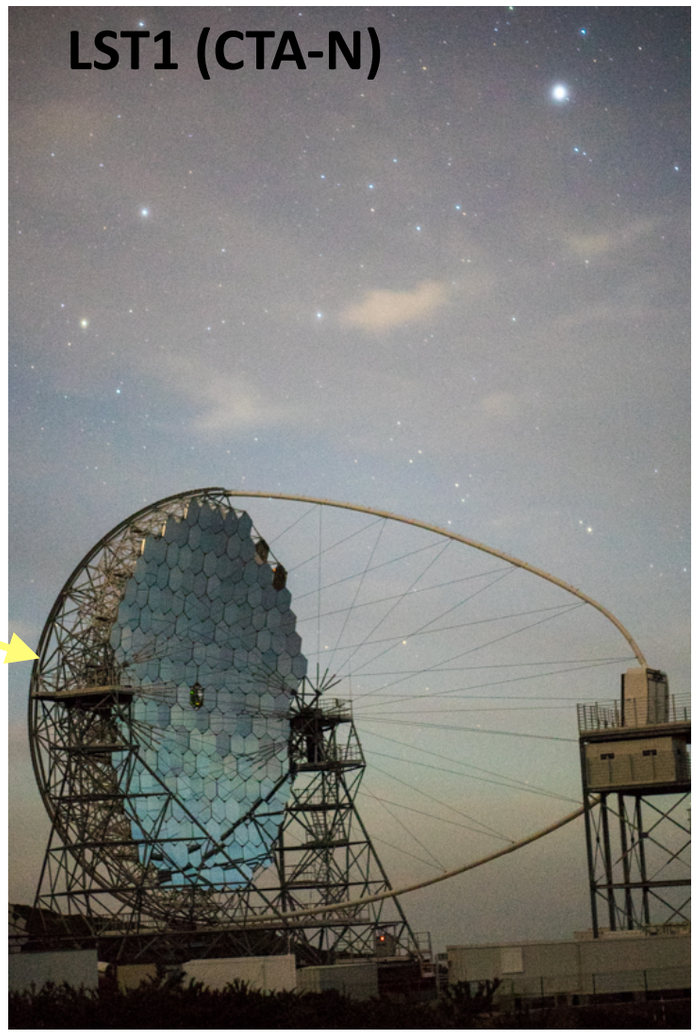


- Could SuperKamiokande have detected neutrino emission from RS Oph?
  - No: low collection area at the GeV energies the expected number of events is only of the order of 5×10^{-7}.

Cherenkov Telescope Array

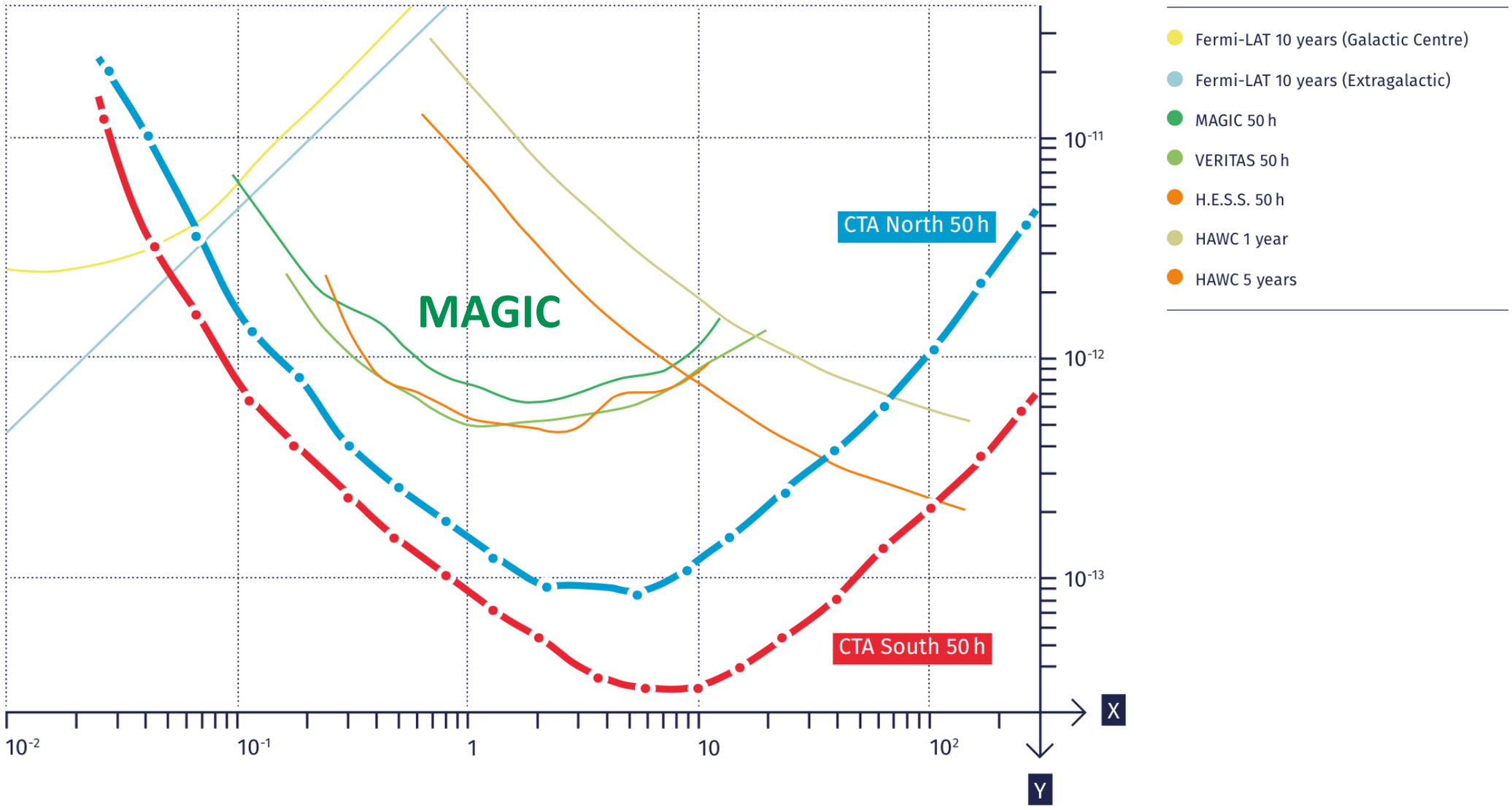
- Future ground-based gamma-ray observatory
- Two array sites: **CTA-North** (La Palma, Spain) **& CTA-South** (Chile)
- **Three clases of telescopes** sensitive to different energies
    - First Large Size Telescope (LST1) already under commissioning at La Palma





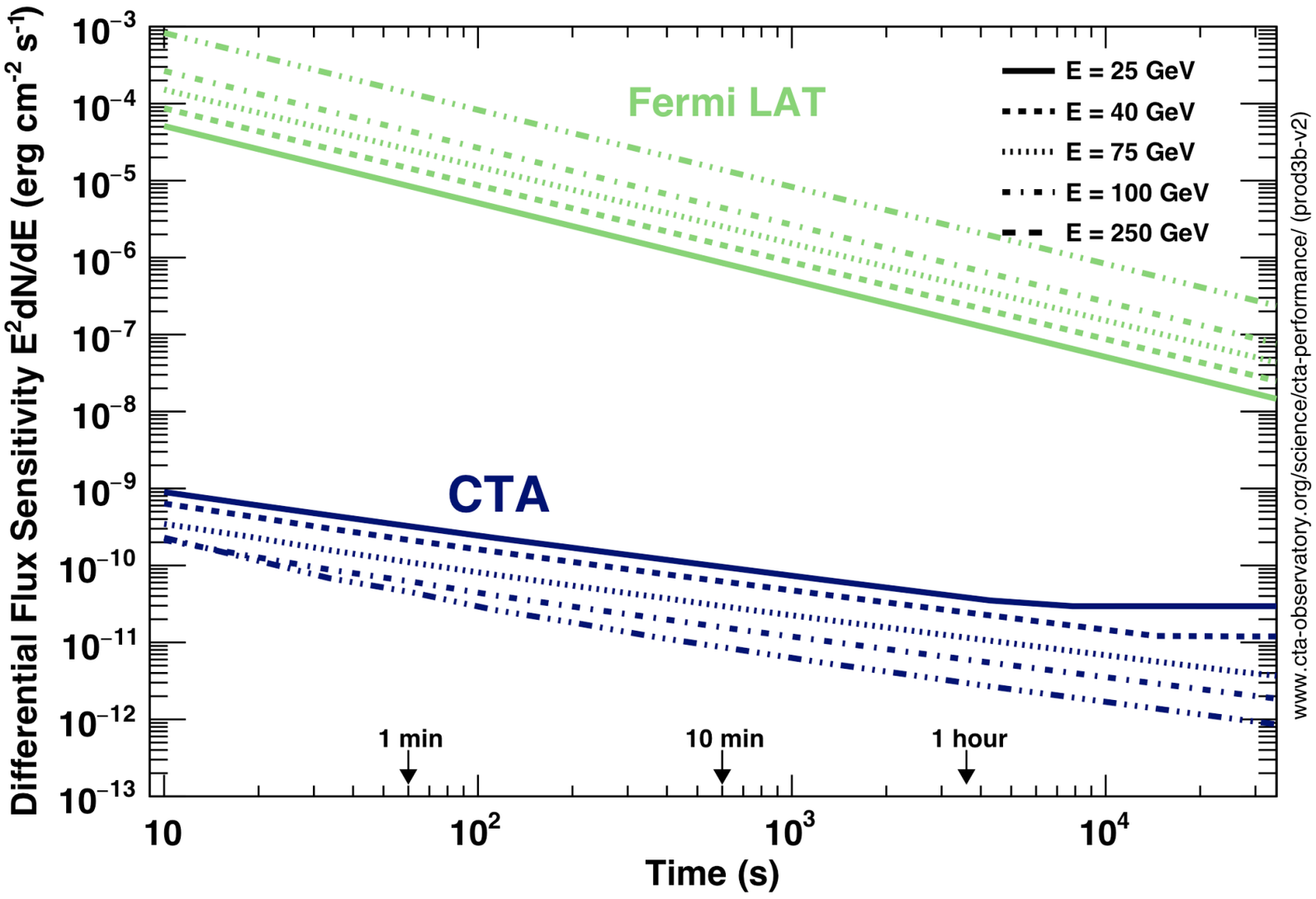
Credit: Gabriel Pérez Diaz (IAC)

Cherenkov Telescope Array



- **Improve current sensitivity** of instruments: by **an order of magnitude**
- **Enlarge the energy range** : almost **four decades** in energy.
- **Improve energy and angular resolution**

Cherenkov Telescope Array



- Unprecedent sensitivity at short timescales: perfect for transient detection! (arXiv:2106.03621v1)

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 favored by 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**

- 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

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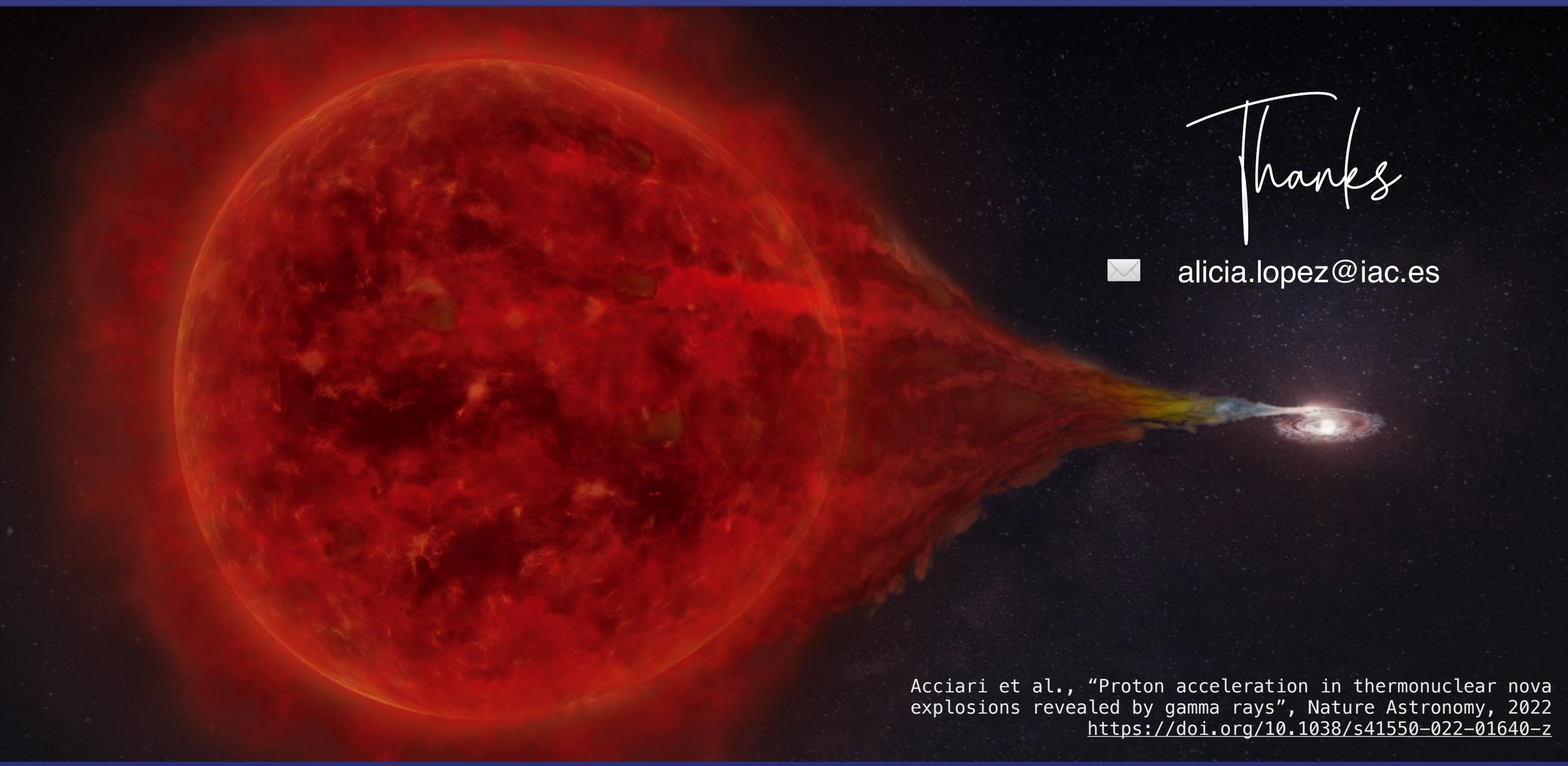
Acciari et al., “Proton acceleration in thermonuclear nova explosions revealed by gamma rays”, Nature Astronomy, 2022 https://doi.org/10.1038/s41550-022-01640-z

RS Ophiuchi: the first nova detected at very high energies



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