VHE gamma-ray novae: RS Oph modelling & CTAO perspectives

Arnau Aguasca-Cabot, P. Bordas, D. Green, Y. Kobayashi, R. López-Coto, M. Ribó, and J. Sitarek on behalf of the CTAO LST Project

VGGRS VII

06/05/2025

CTAO | LST COLLABORATION

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EXCELENCIA MARÍA DE MAEZTU 2020–2024

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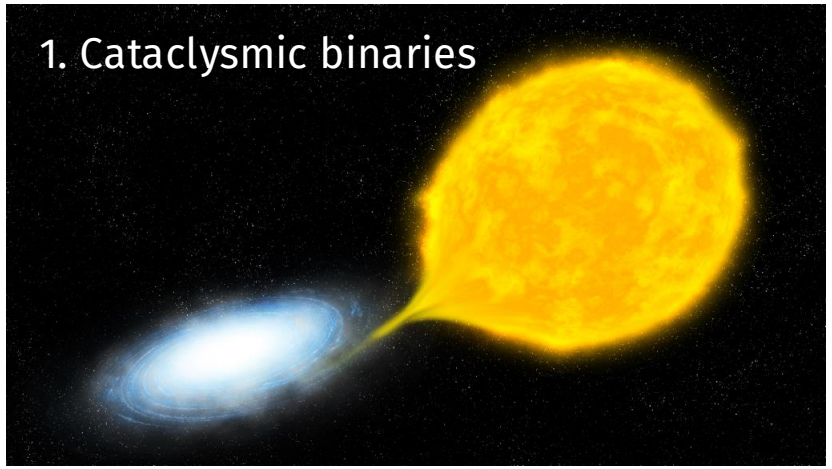
Novae

Nova *(stella nova):*

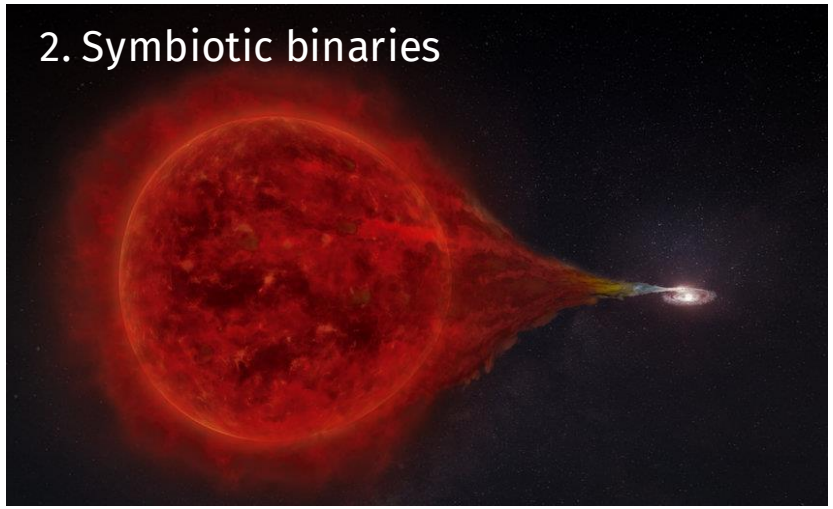
Thermonuclear runaway explosion on the surface of a white dwarf in a binary system

- Types of systems:
  1. Cataclysmic binaries (classical novae)
     - White dwarf and main sequence star
  2. Symbiotic binaries (symbiotic “embedded” novae)
     - White dwarf and red giant (Mira star)

- Mass transfer (Roche-lobe overflow and/or wind-driven)

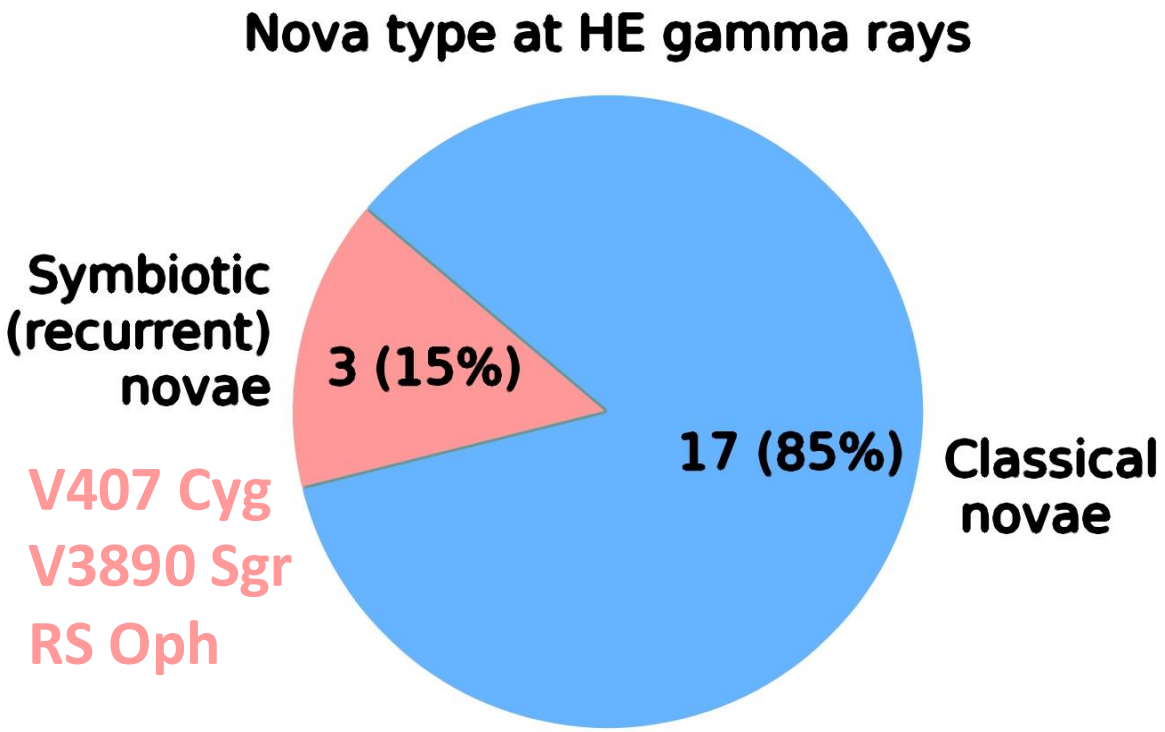


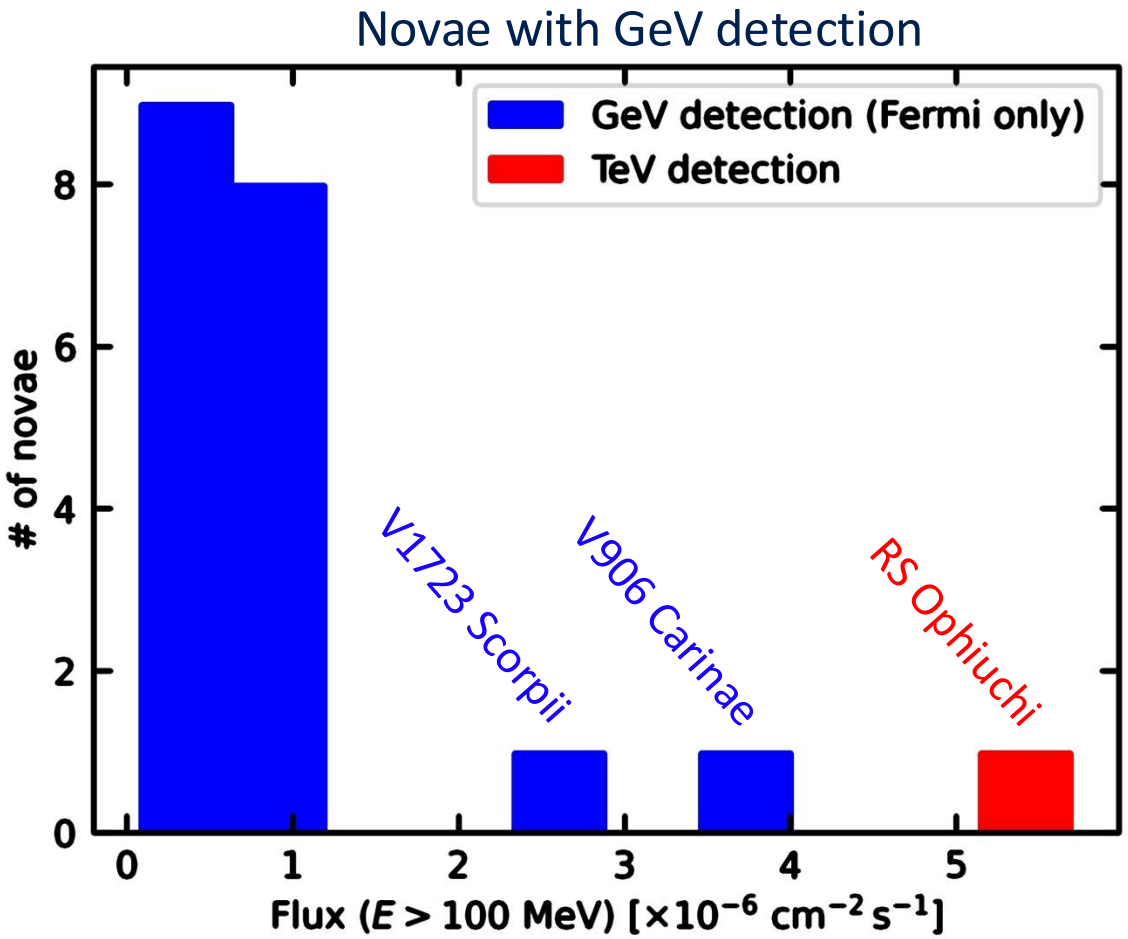
Credit: NASA/SOFIA/L. Proudfit



Credit: superbossa.com / MPP

Novae at HE gamma rays





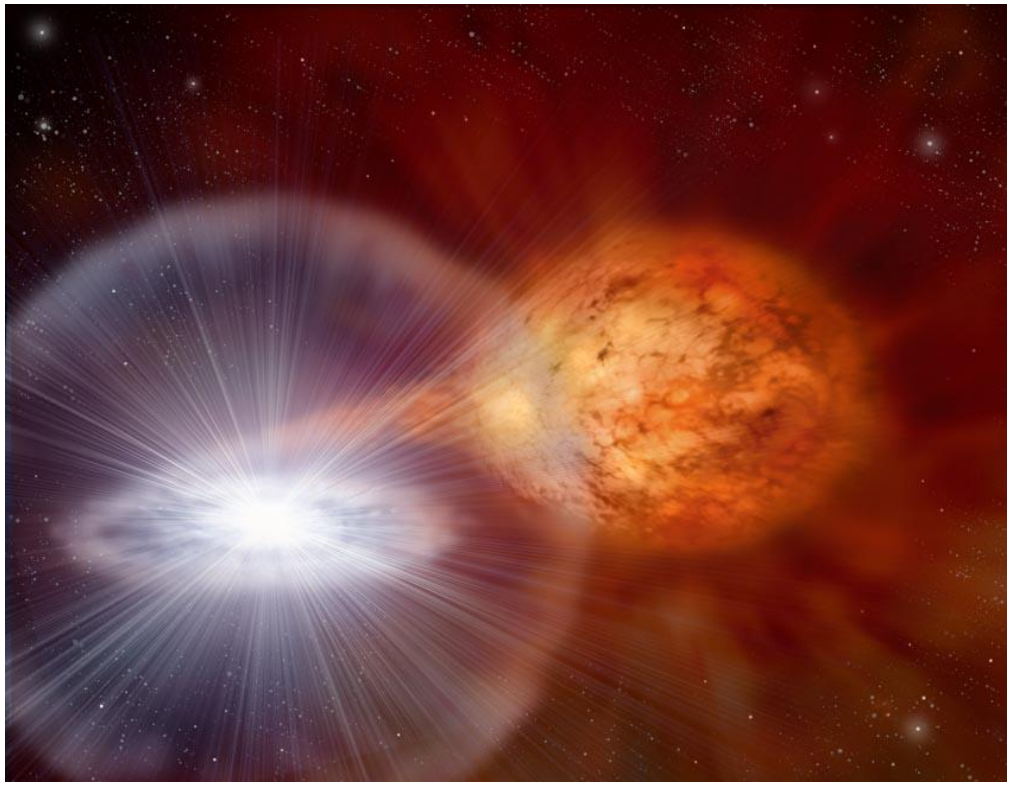
Data: https://asd.gsfc.nasa.gov/Koji.Mukai/novae/latnovae.html, last view on April 13th, 2025.

Novae : RS Ophiuchi (RS Oph)

- Symbiotic binary at $d \sim 2.45$ kpc
  (Gaia Collaboration 2023, Rupen et al. 2008)
  White dwarf embedded in the RG wind

- Recurrent nova outbursts every 9 to 27 years
  Recurrent nova

- August 2021 outburst: the first detection of a nova at TeV γ rays
  (H.E.S.S. Collaboration 2022, Acciari et al. 2022, Abe et al. 2025)
  - H.E.S.S.
  - MAGIC
  - LST-1



Credit: David A.Hardy/ www.astroart.org & PPARC.

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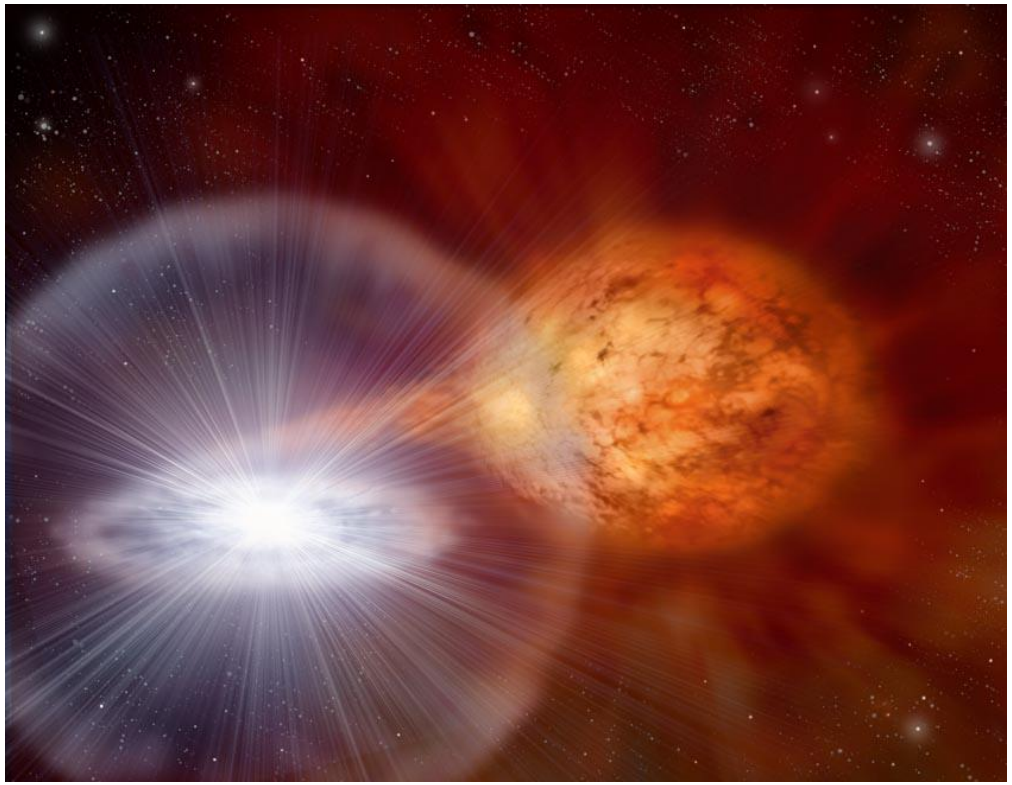

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The first Large-Sized Telescope (LST-1)

- The Large-Sized Telescopes (LSTs) are the **largest telescope** type of the future Cherenkov Telescope Array Observatory

- LSTs for tens to hundreds of GeV

Large mirror area $\sim 400\ \mathrm{m}^2$

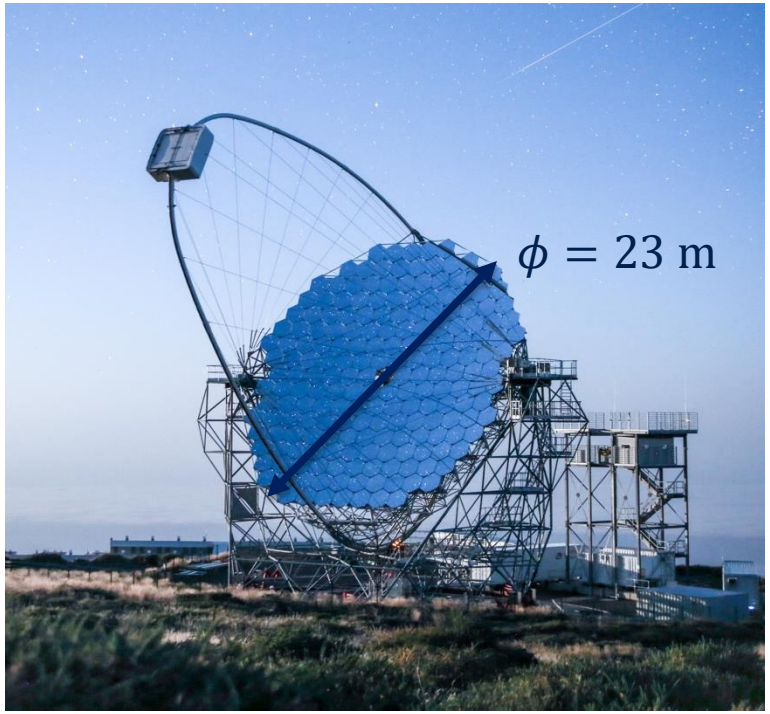
+

Efficient Photomultiplier tubes

=

Low energy threshold: 20 GeV

The first LST in La Palma: LST-1



RS Oph at gamma rays : LST-1

- **Detection** of RS Oph with LST-1 in 6.35 h **within the first four days**
- **No detection** using **data 21 days after t_0**

Date (yyyy-mm-dd)	t-t_0 (days)	Observation time after cuts (h)
2021-08-09	0.97	1.43
2021-08-10	1.97	2.68
2021-08-12	3.97	2.24
2021-08-29	21.01	0.97
2021-08-30	21.97	1.52
2021-09-01	24.05	0.32
2021-09-02	24.98	1.27

Right after outburst

After moon break

t_0 = 59434.93 MJD (Geary 2021, VSNET 26131)

RS Oph at gamma rays : IACTs + *Fermi*-LAT

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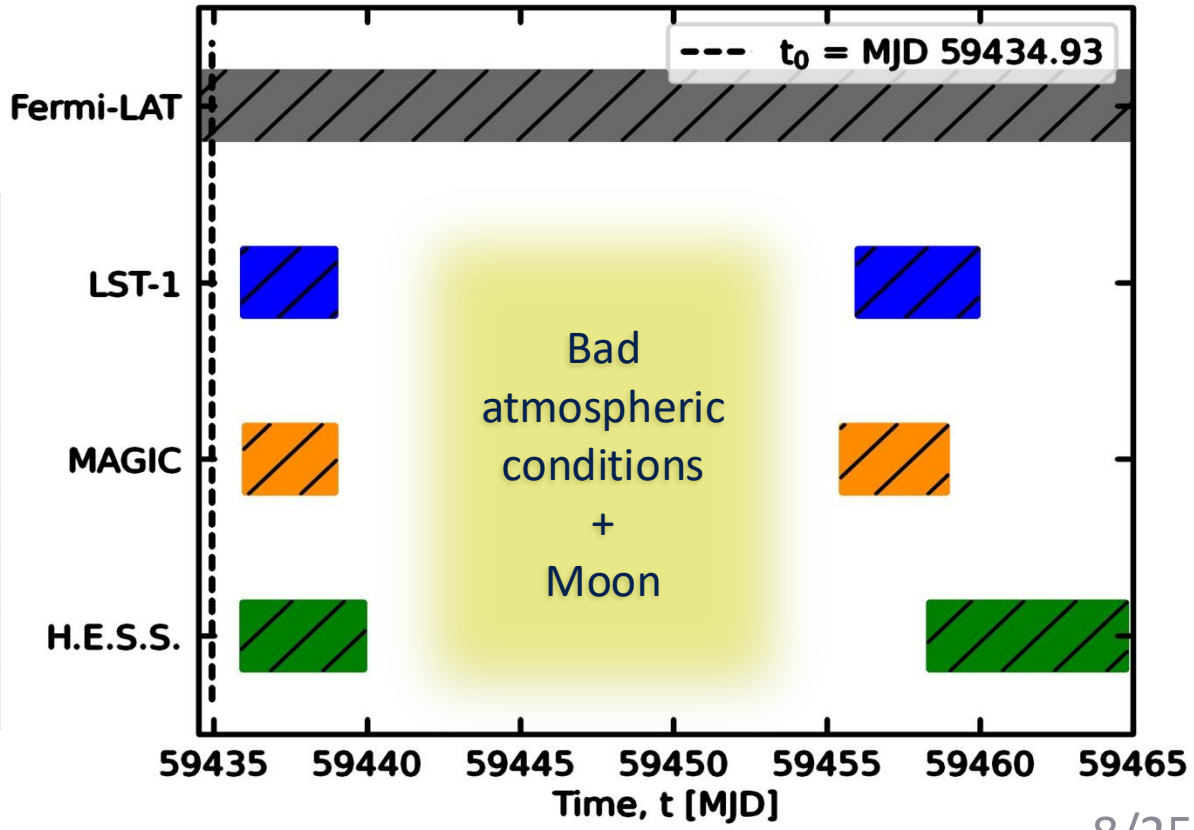
Hatched region = discontinuous observations



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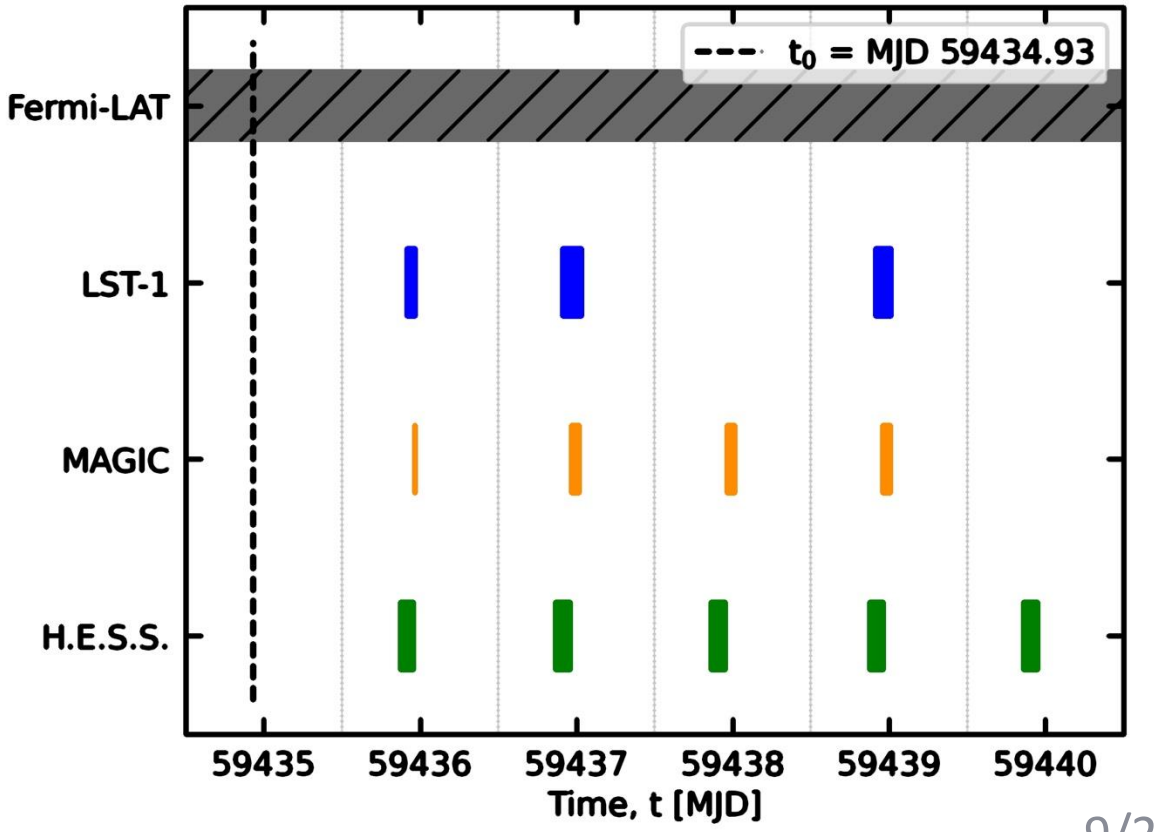

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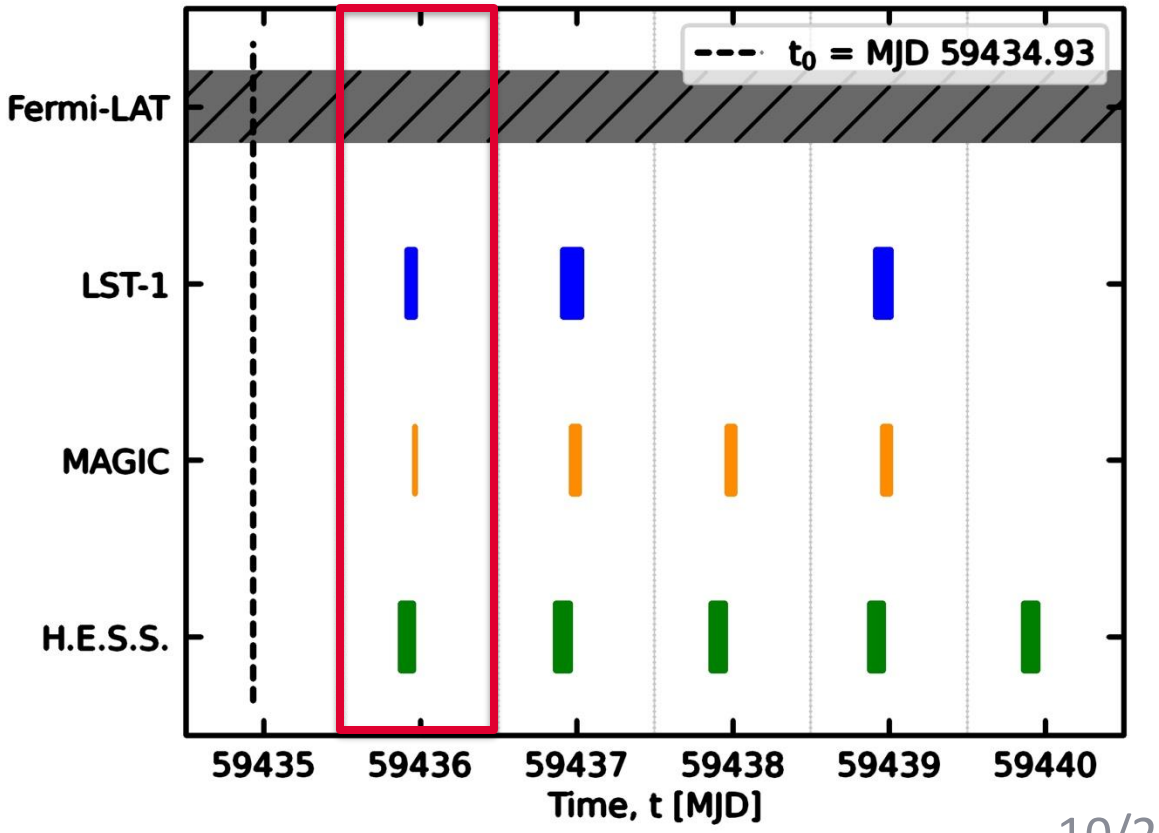
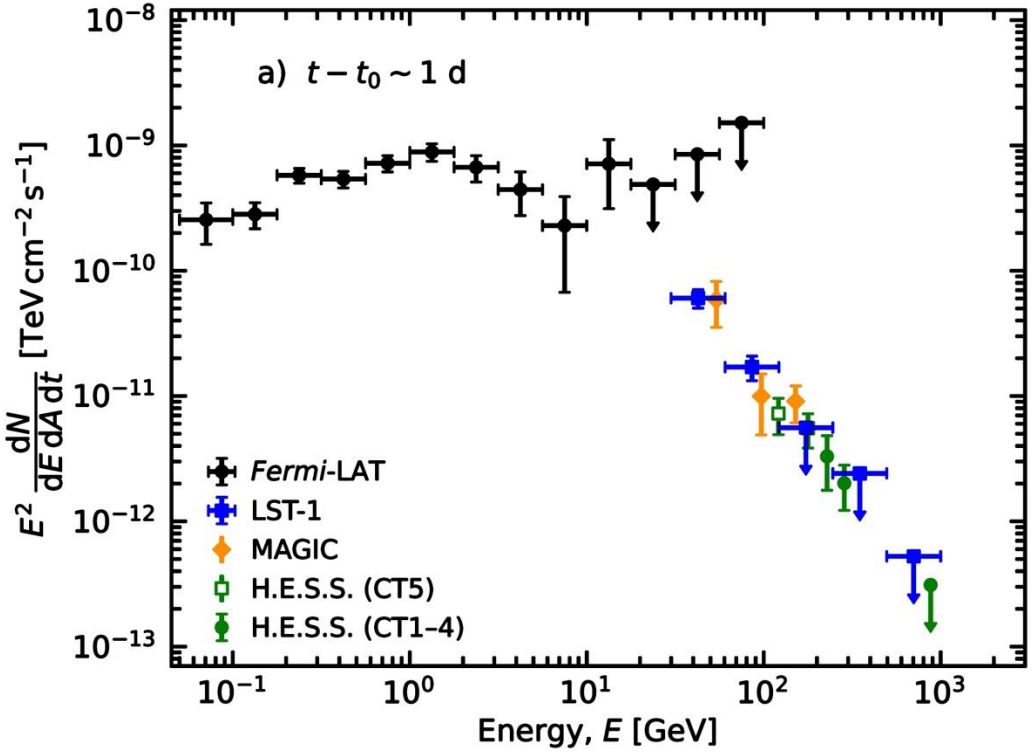


RS Oph at gamma rays : SED

- The SED presents curvature from HE to VHE gamma rays



Source: Abe et al. 2025, A&A, 695, A152

RS Oph at gamma rays : SED

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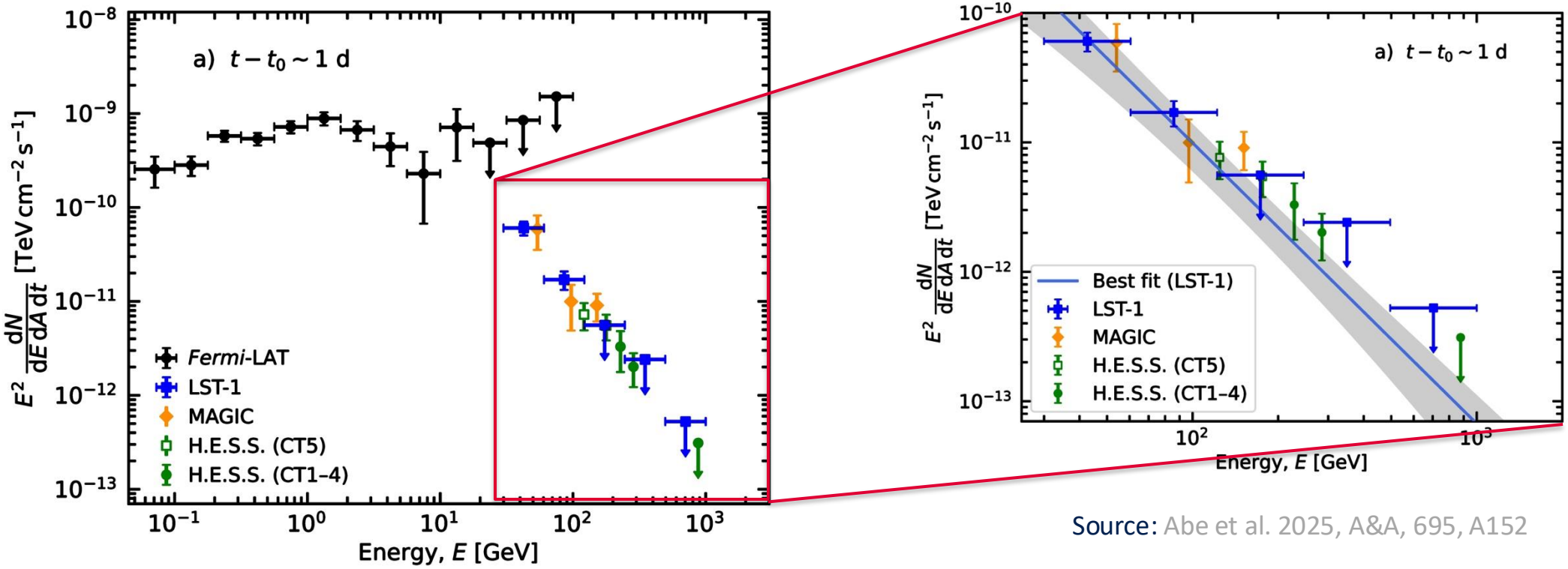
- Soft emission at VHE gamma rays ($\Gamma \sim -4$)



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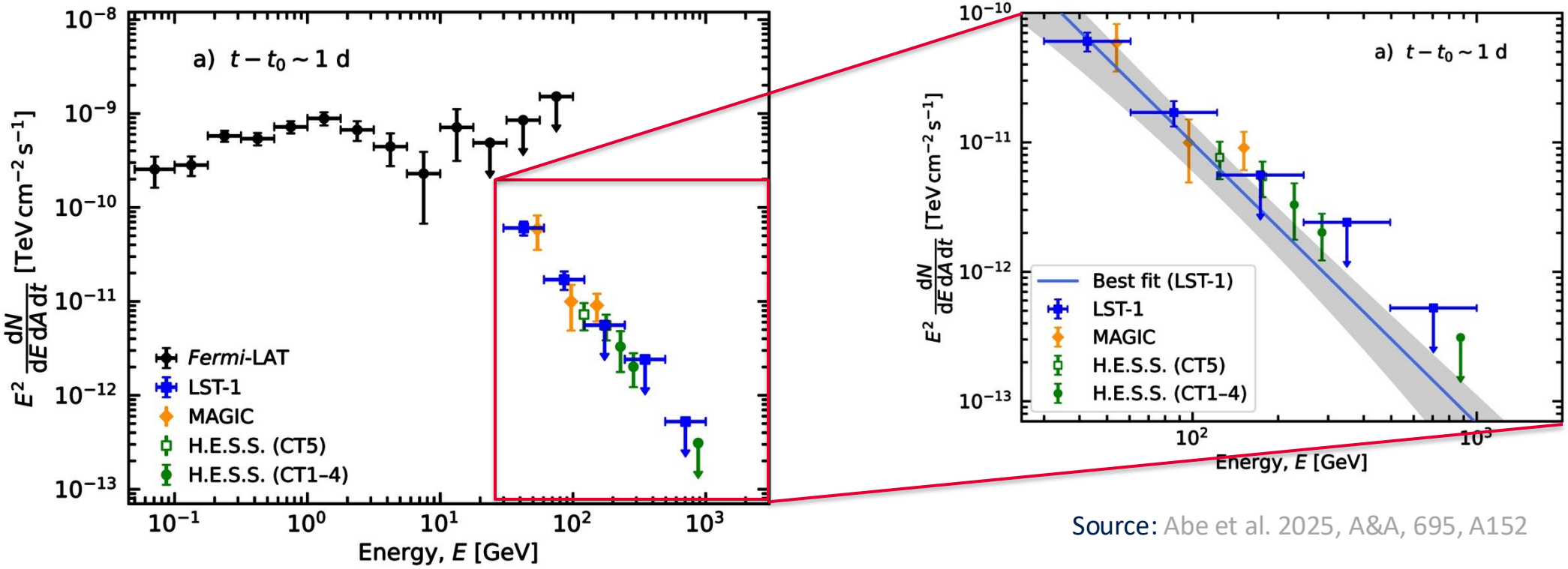
- Soft emission at VHE gamma rays ($\Gamma \sim -4$)
- Emission evolves with time



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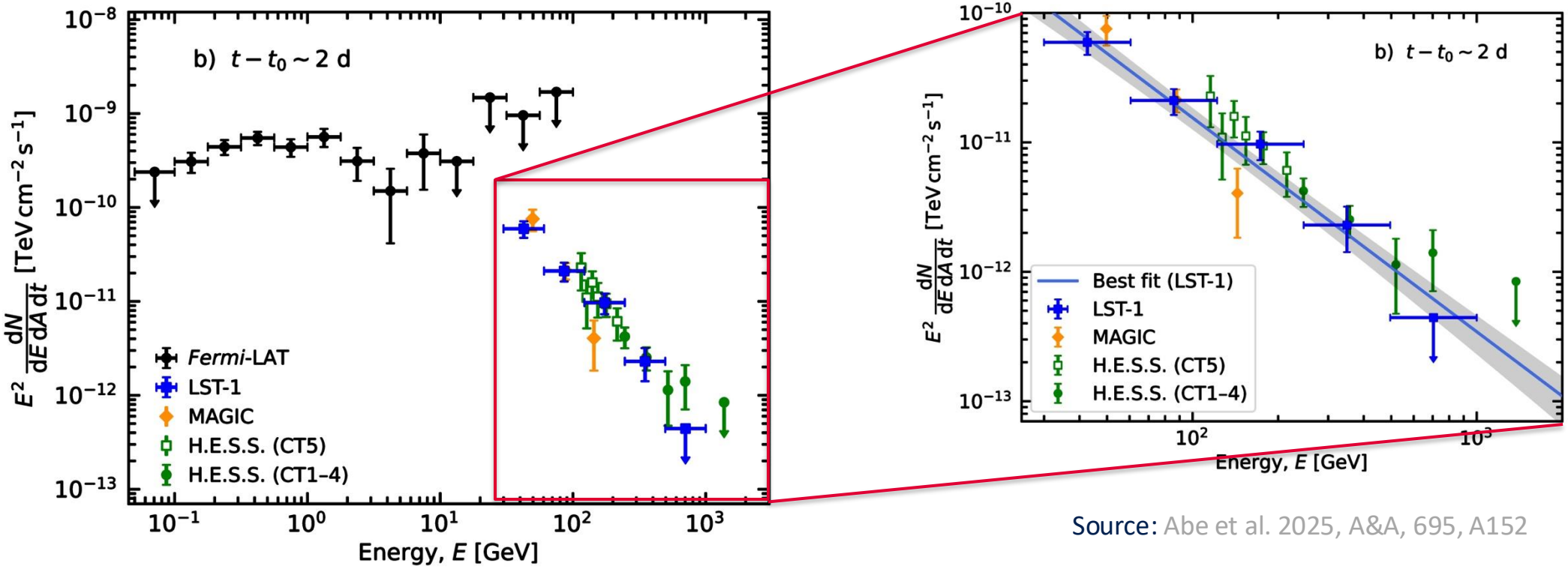

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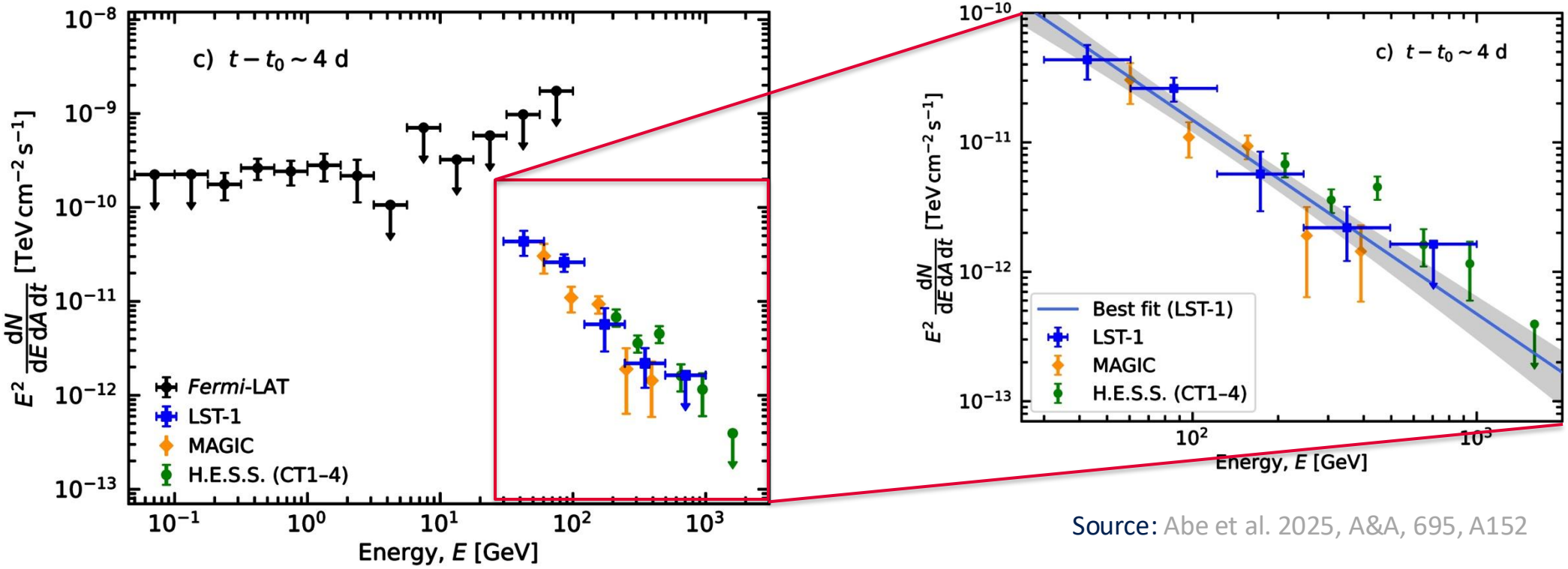

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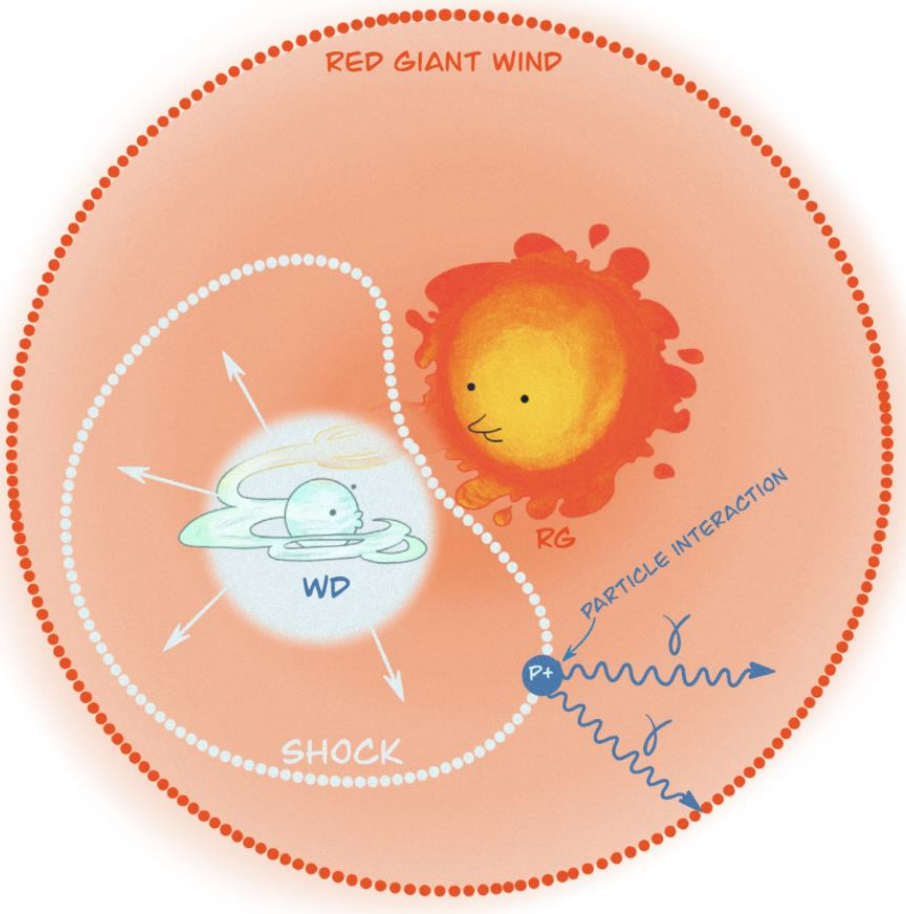
HE-VHE gamma-ray modelling

- Gamma ray emission modelled with **hadronic and leptonic model**
  - The same model framework as in Acciari et al. (2022)
    - Spherical shell structure
- Obtain a precise energy spectrum of the injected particles
  - Use daily SED points from *Fermi*-LAT, LST-1, MAGIC and H.E.S.S.



Credit: M. I. Bernardos

Modelling : hadronic vs leptonic scenario

* **AICc** = Akaike information criterion with second-order small-sample bias adjustment

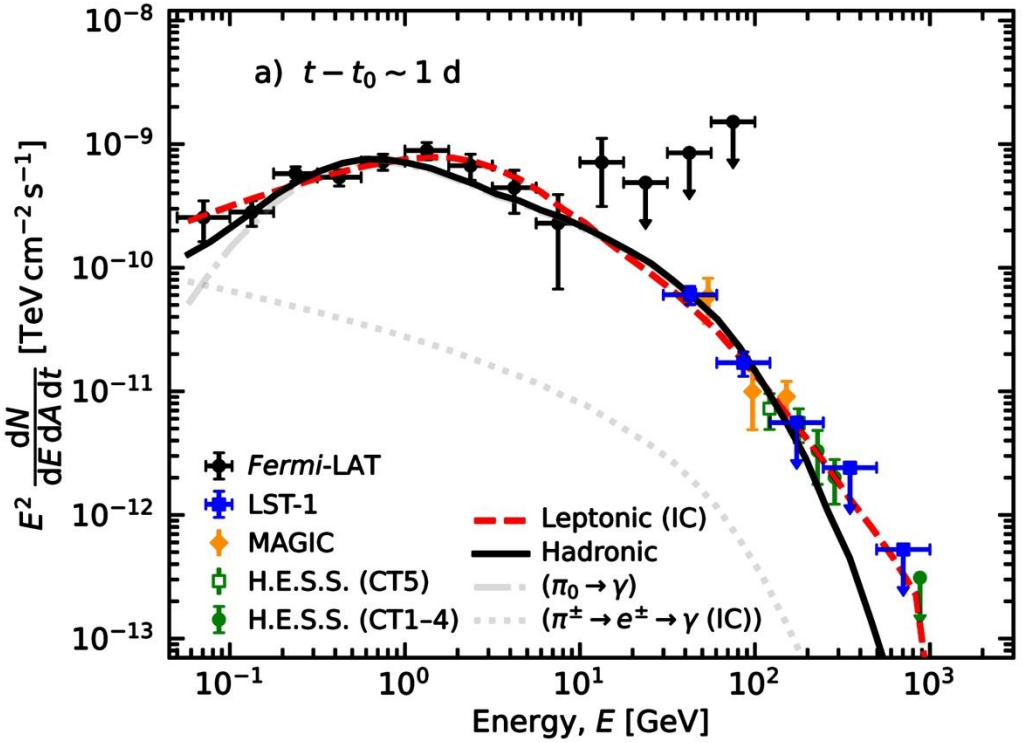
Hadronic model

- A **Power-law with cutoff** (E_{cp}) particle spectrum reproduces the emission
- E_{cp}: 0.26±0.08 TeV → 1.6±0.6 TeV

Leptonic model

- Need **broken power-law** particle spectrum to fit the SED curvature
- Best-fit parameter values **less preferable** based on DSA

No preference between models based on fit statistics (hadronic: ΔAICc=0.8, leptonic: ΔAICc=0)



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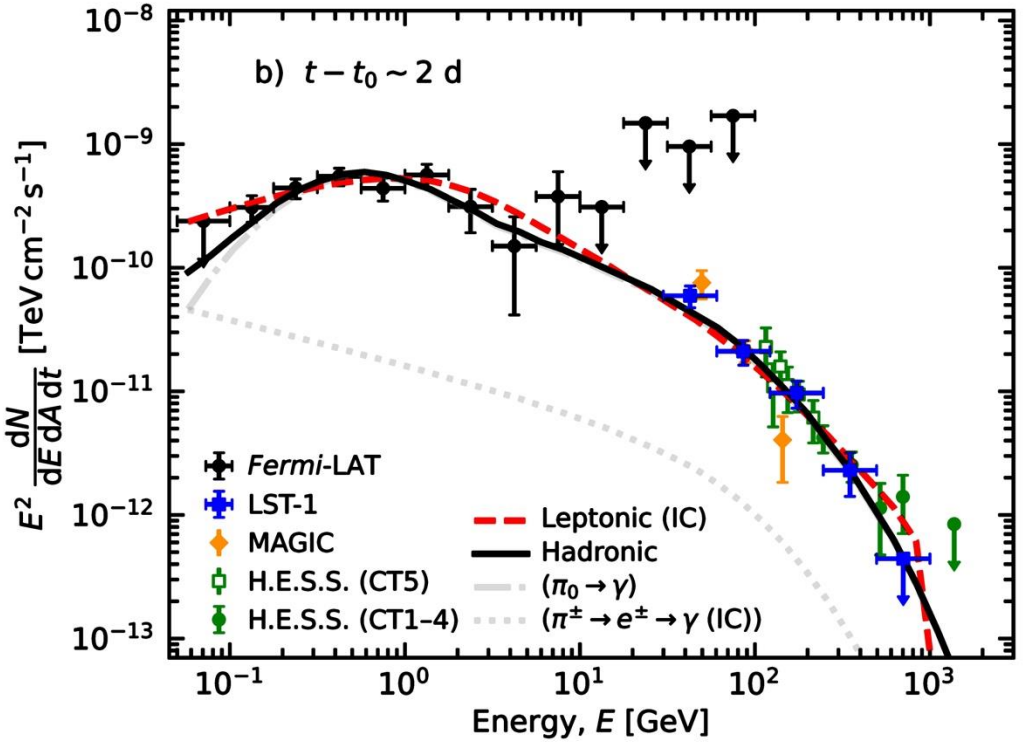

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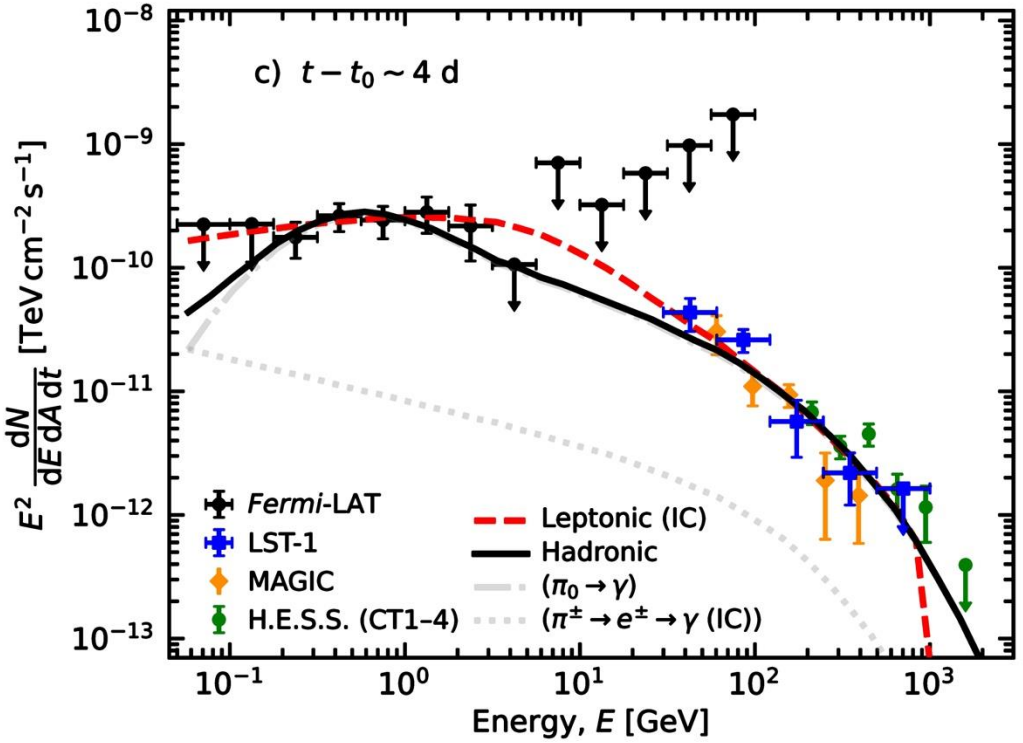

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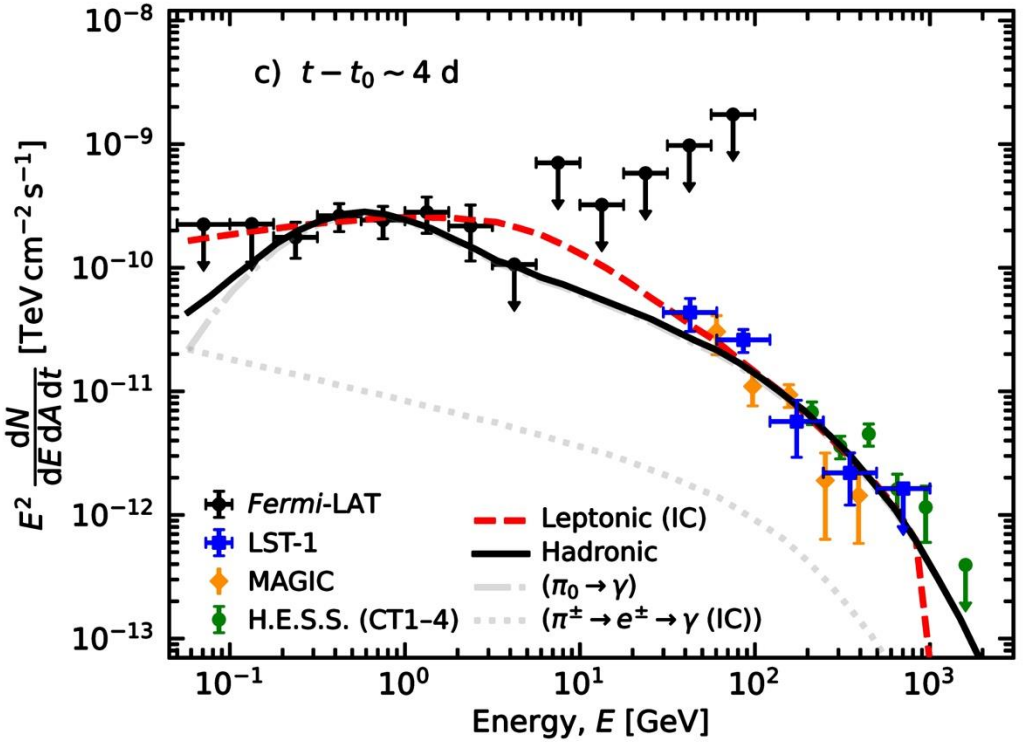

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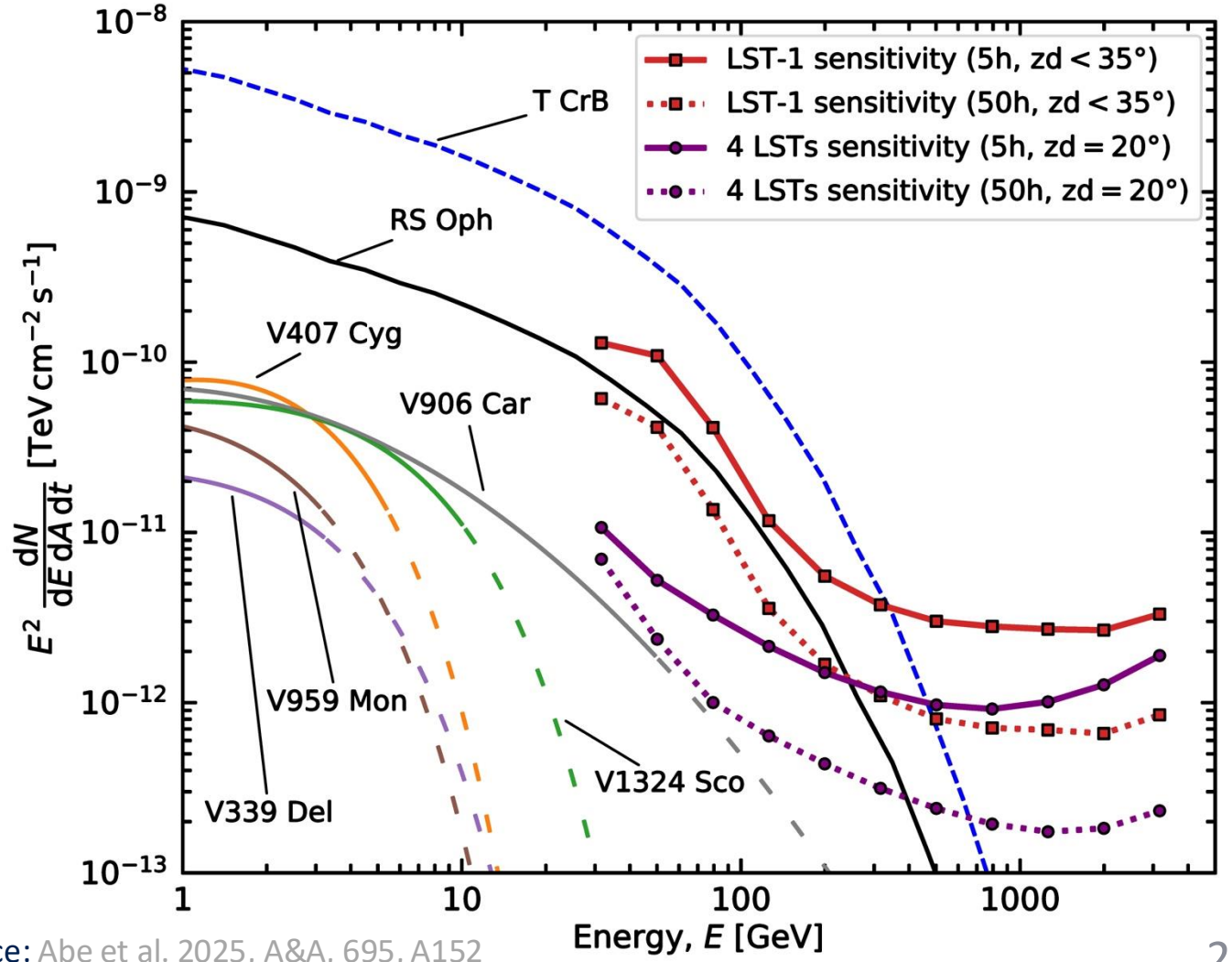
Some open questions : Do all novae behave the same?

- RS Oph: Bright gamma-ray emission due to its binary configuration?
  - Massive WD + Red Giant
  - ~10 known members
- Can classical novae produce gamma rays up to TeV energies?
  - V906 Car is the brightest classical nova at HE gamma rays so far



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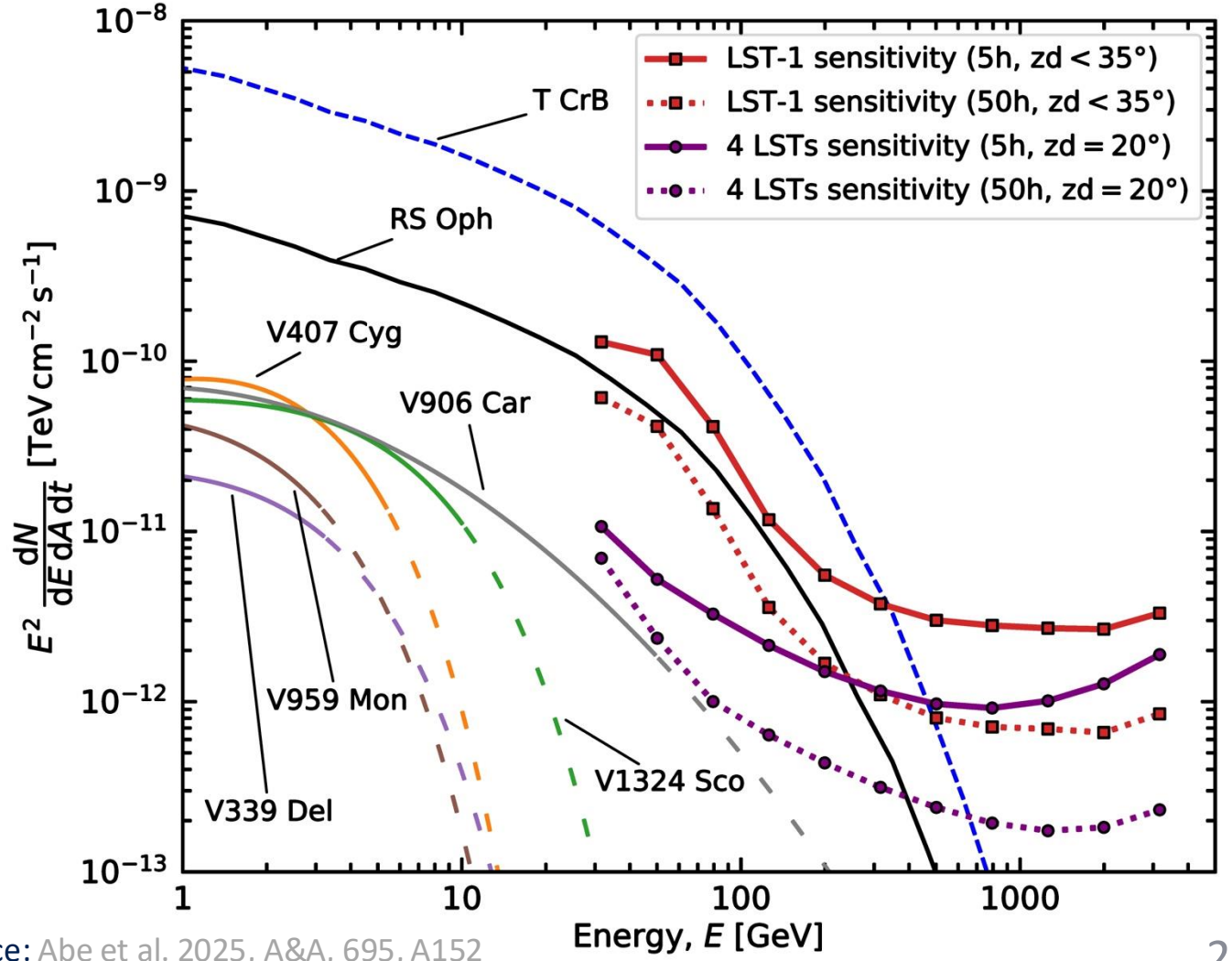
Some open questions : Do all novae behave the same?

Spectral energy distribution for RS Oph, T CrB (expected), V906 Car and the first novae detected with *Fermi*-LAT

- Solid lines: fit to data
- Dashed lines: fit extrapolation



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Some open questions : Do all novae behave the same?

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- Parameter space study for novae considering typical
  - Shock density values
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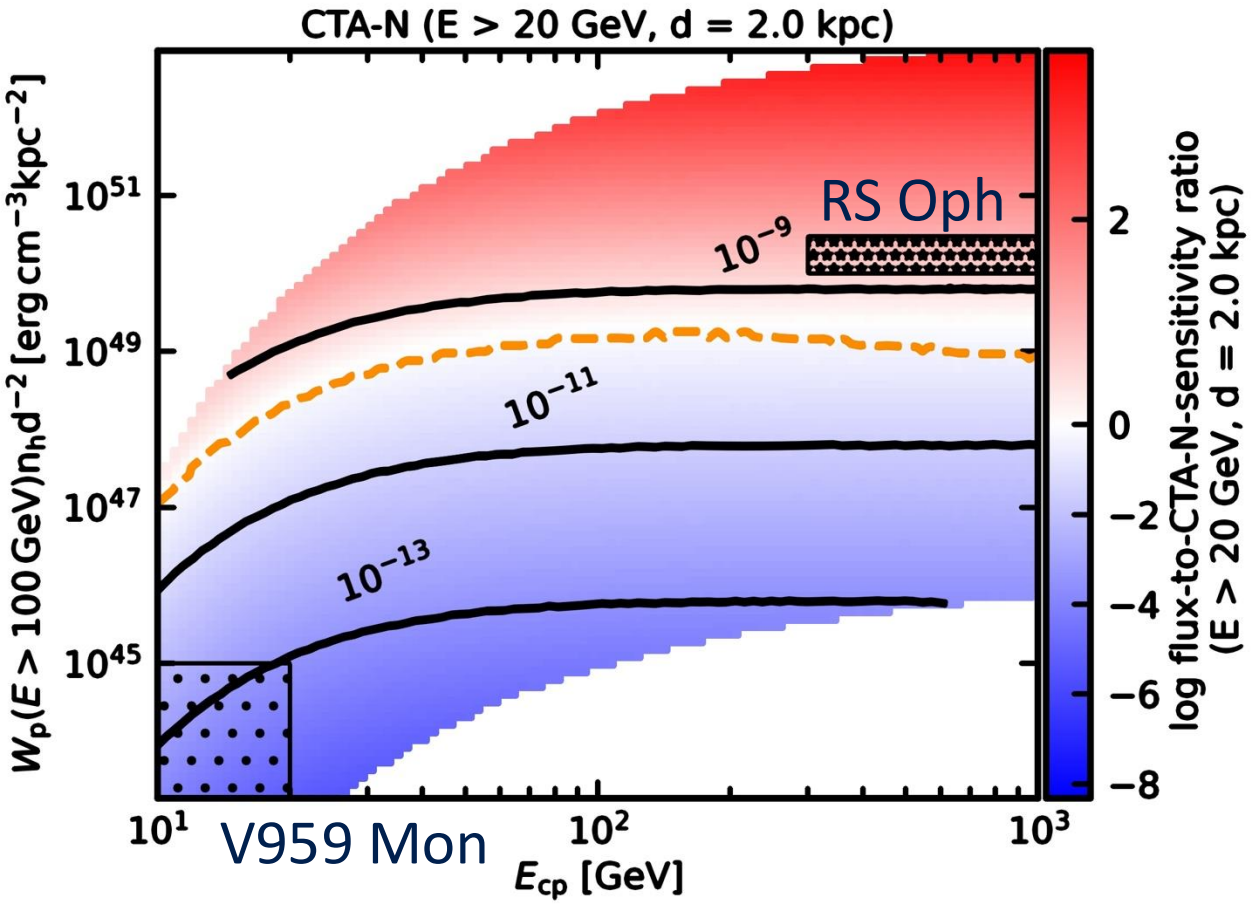

Source: K. Abe, et al. MNRAS. In press (2025)

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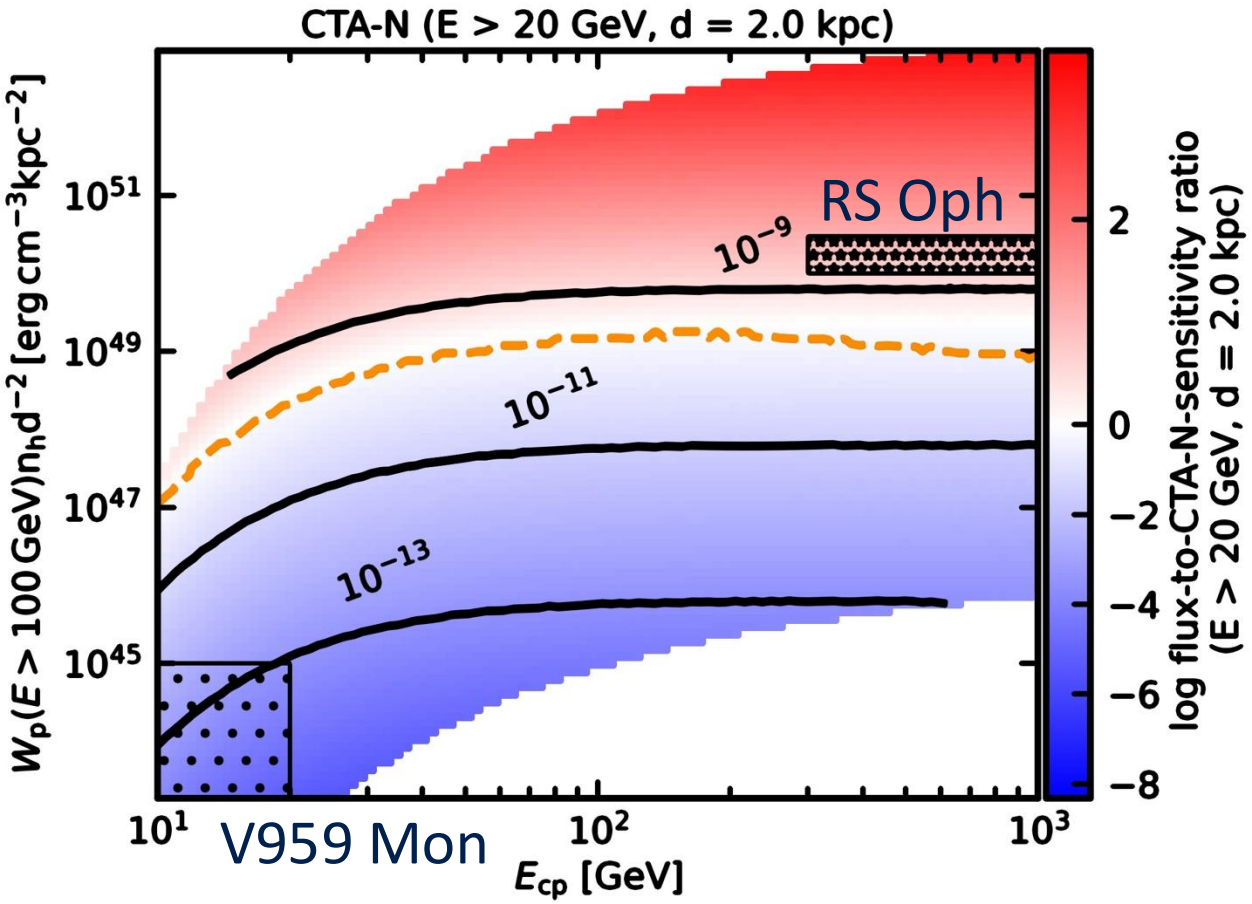
- CTAO* detects ~30% of the combinations
  - CTAO-N outperforms CTAO-S with 10% more detections



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* Alpha configuration

Conclusions

- The hadronic scenario is preferred over the leptonic scenario
  based on the simpler particle spectrum with the most complete γ-ray spectrum

- Cutoff energy increases from (0.26±0.08) TeV to (1.6±0.6) TeV between day 1 and day 4
  Temporal evolution due to finite particle acceleration of the protons to reach TeV

- The LST array will play a major role in detecting faint novae and increasing their discovery rate
  LSTs/CTAO may constrain physical parameters of the VHE nova phenomena, disentangle between single/multiple shocks in a hadronic/lepton-hadronic scenario, and answer open questions such as symbiotic recurrent vs classical novae

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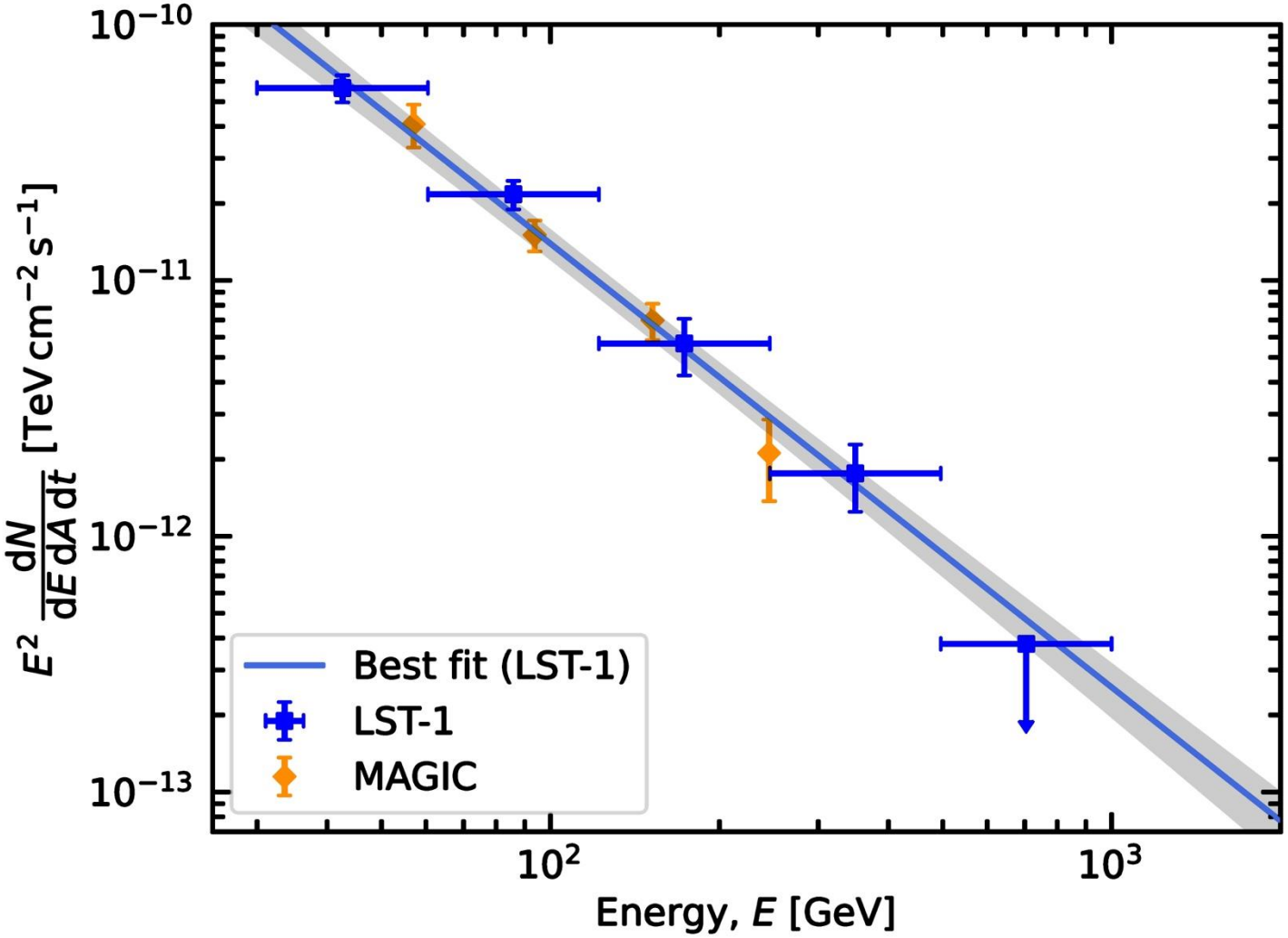
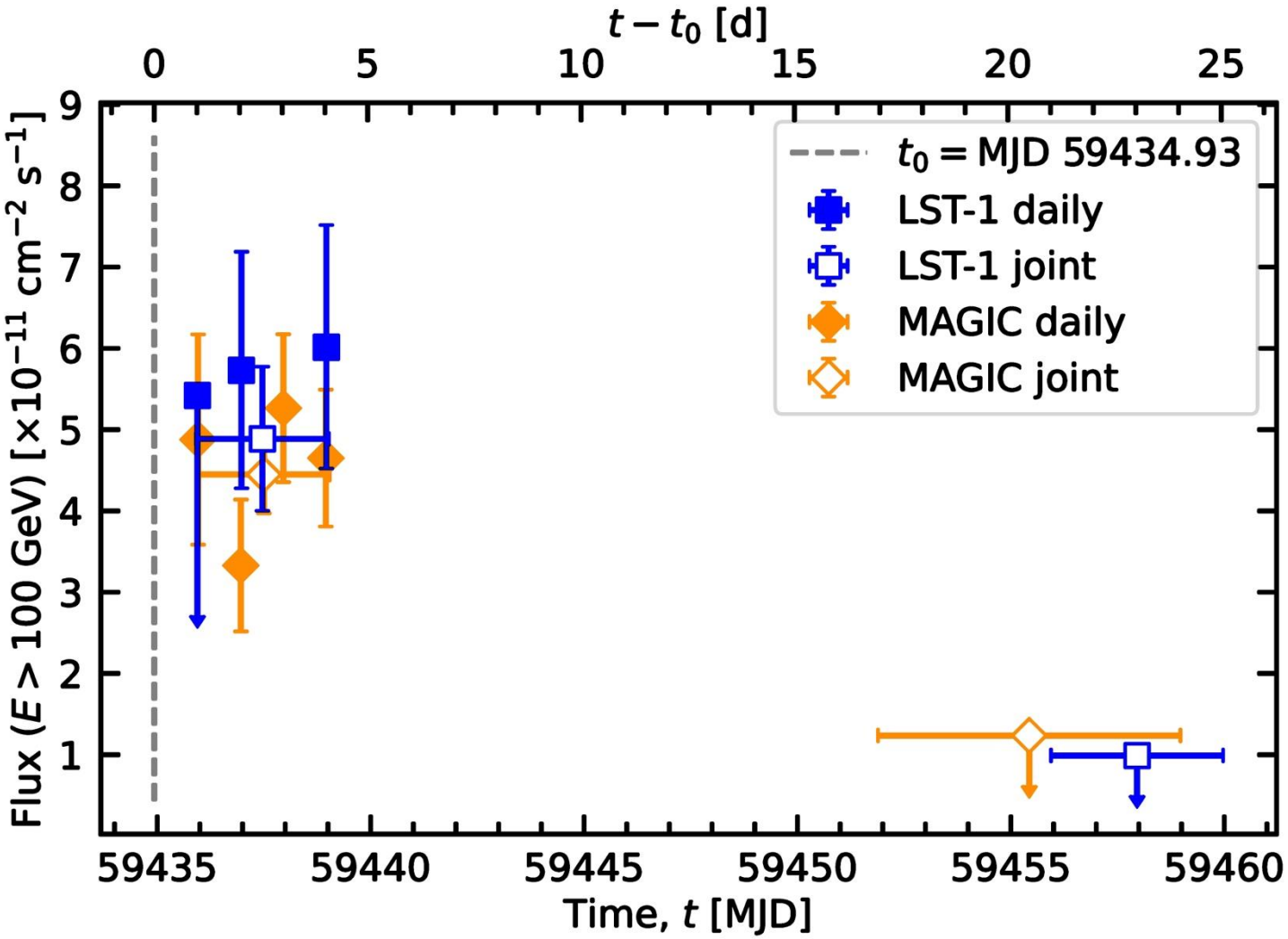
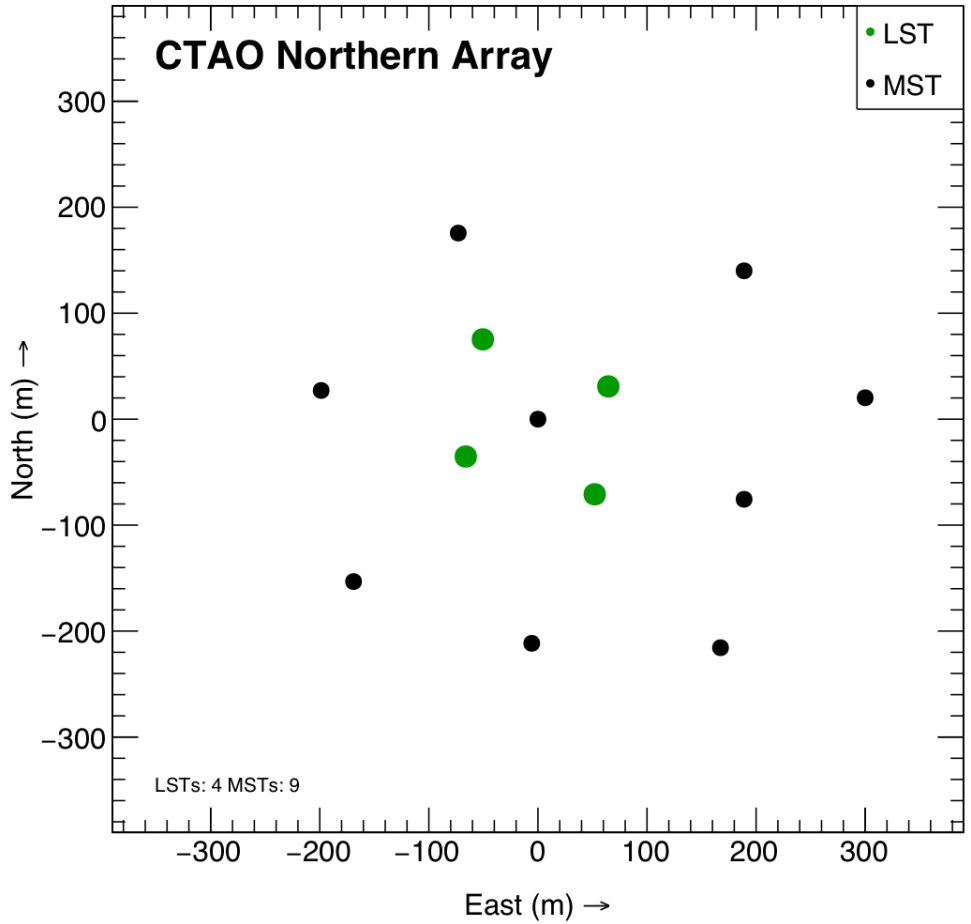
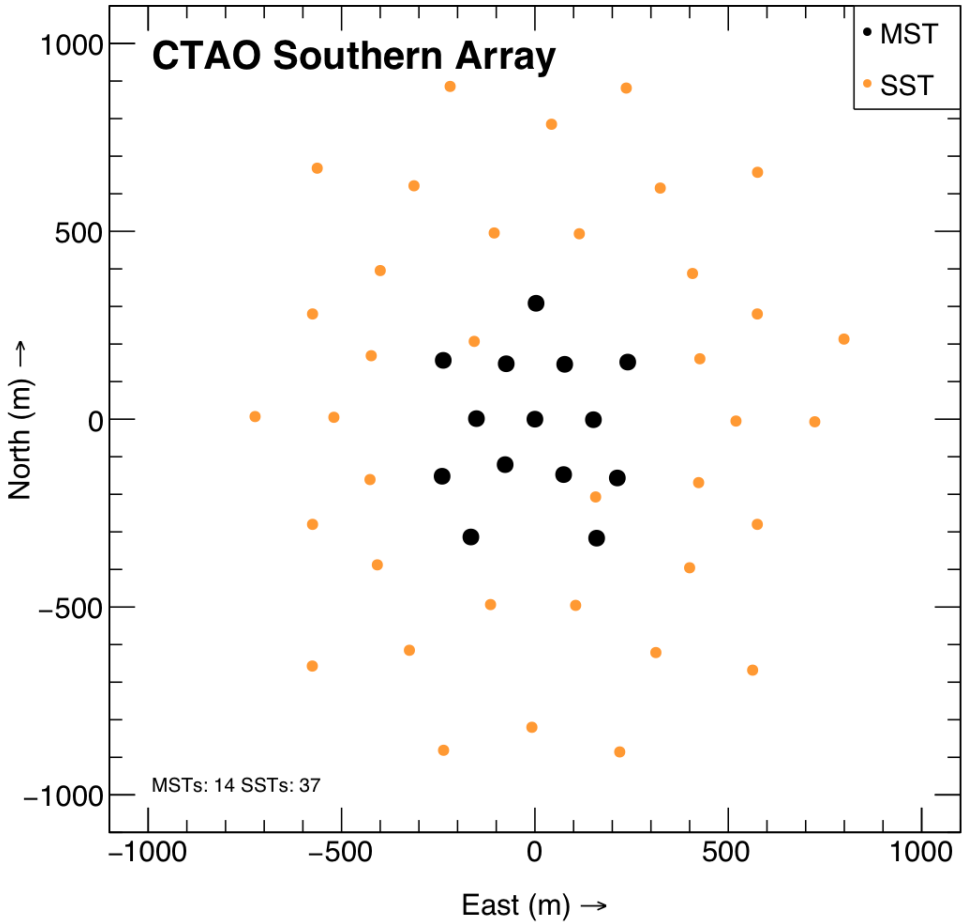


Back up: Light curve



Back up: Alpha configuration CTAO



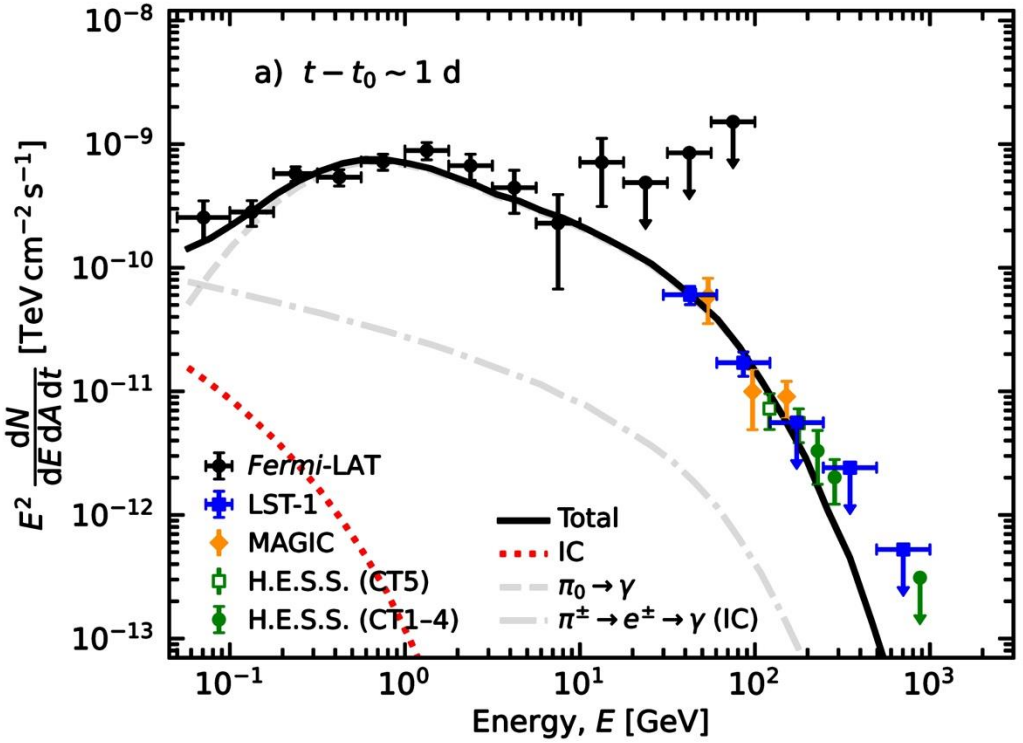


Back up: lepto-hadronic model

Lepto-hadronic model

- Poorly constrained.
- More data and modelling would be required

No preference between models based on fit statistics (lepto-hadronic: ΔAICc=8.5)



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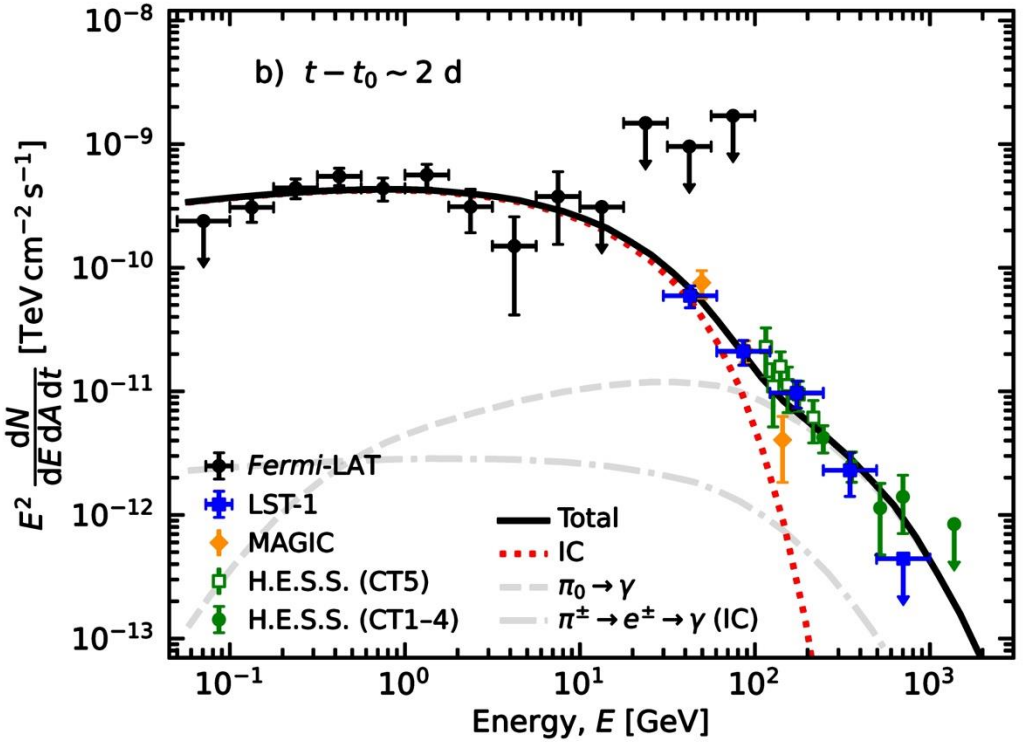

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