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Highlight results with the First Large-Sized Telescope (LST-1)

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CSIC Institute of Space Sciences | EXCELENCIA MARÍA DE MAEZTU

Overview

- Description of the instrument
  - First Large-Sized Telescope (LST-1)
- Pulsars

  Crab Pulsar [A&A, 690, A167 (2024)]

  Geminga Pulsar [A&A, 698, A283 (2025)]
- Galactic center
- Extragalactic sources

  OP313, BL Lac, …
- Transient Sources

  Gamma-ray bursts: GRB221009 (BOAT) [ApJL 988, L42 (2025)]

  Novae: RS Ophiuchi [A&A 695A, 152A (2025)]

credit: Moritz Huetten

Cherenkov telescope array observatory

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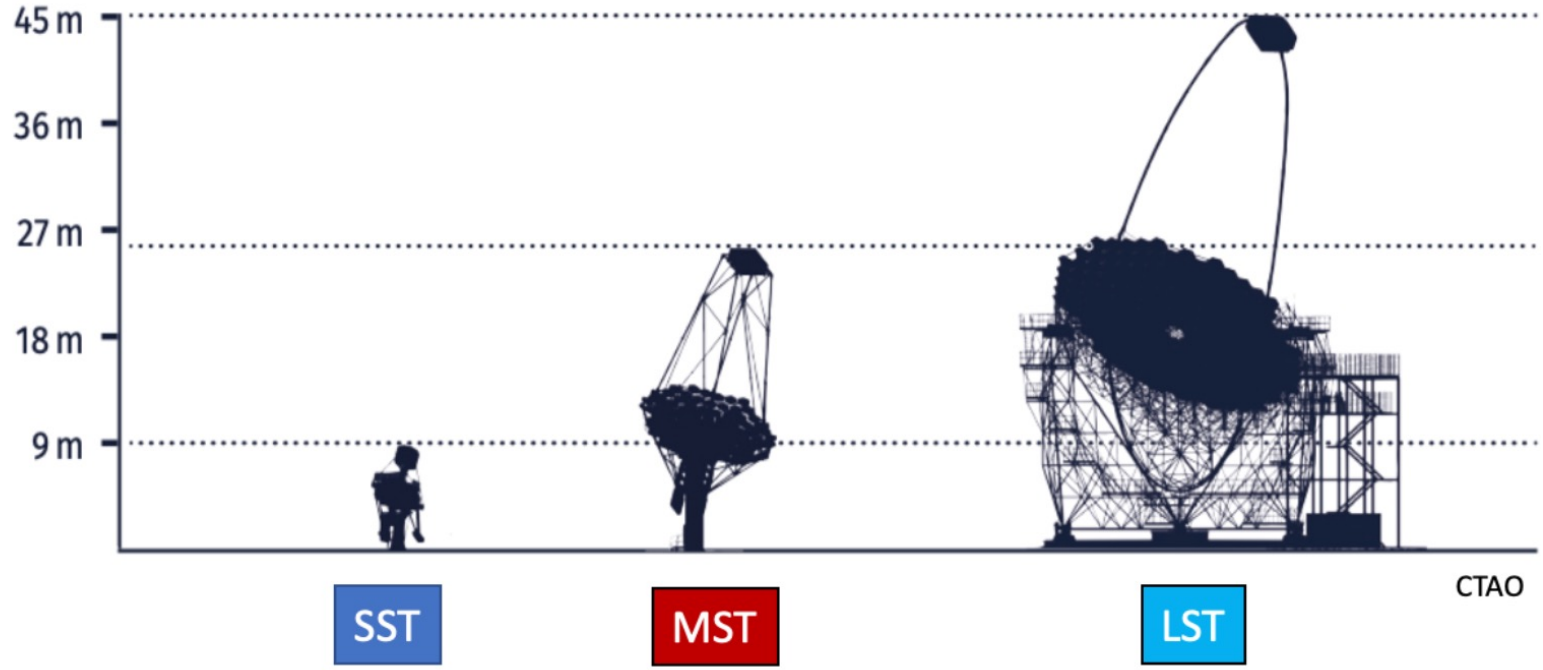
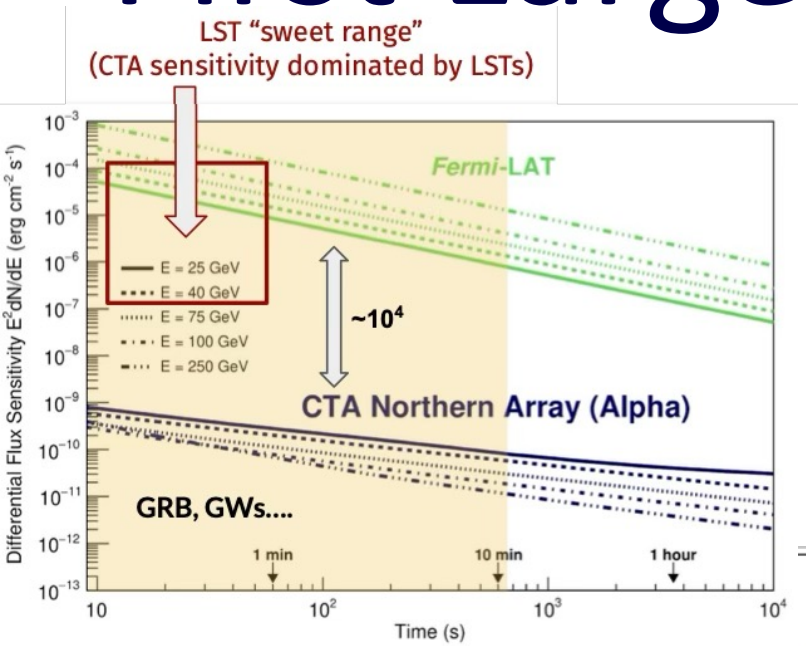


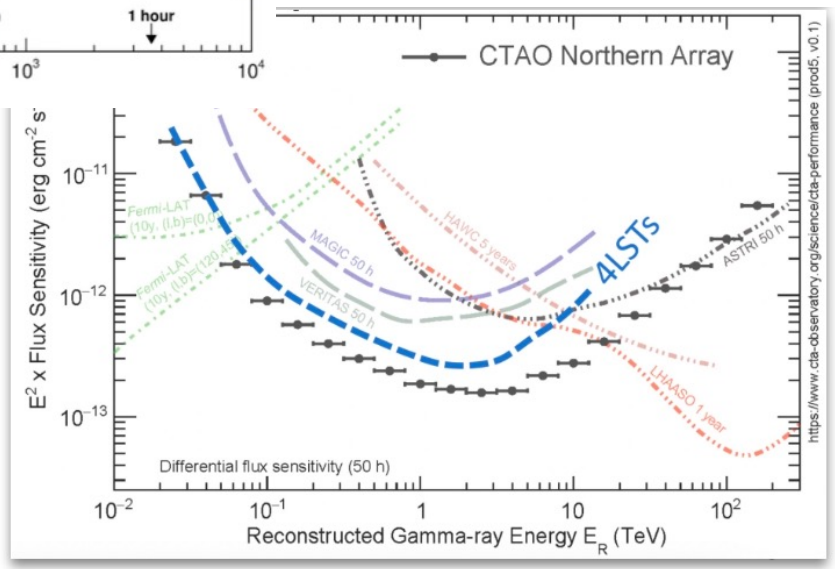
Small-Sized Telescope (SST)
Precision measurements in a still little explored energy range
100TeV range largely unexplored

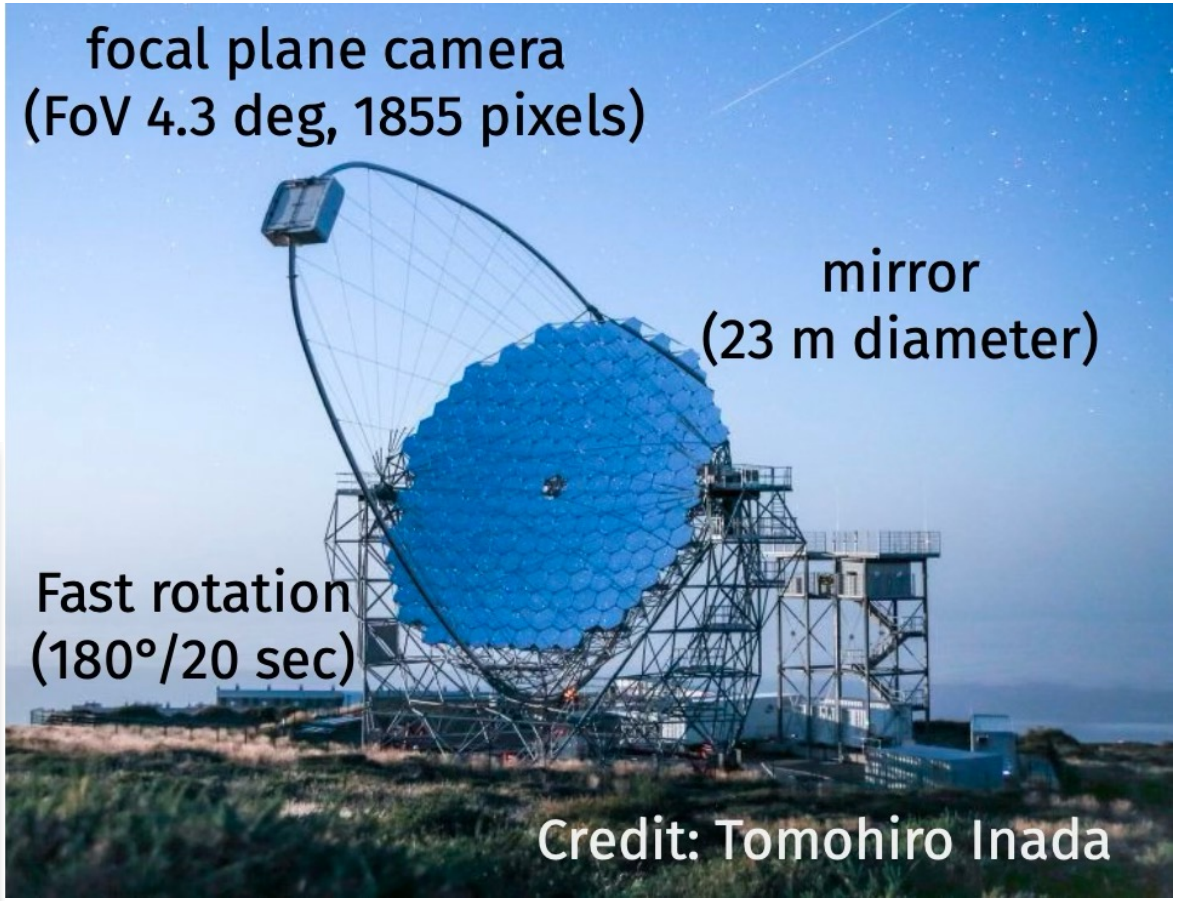
Medium-Sized Telescope (MST)
Deepest sensitivity ever
Arcmin angular resolution
Large FoV
Surveys & precision studies

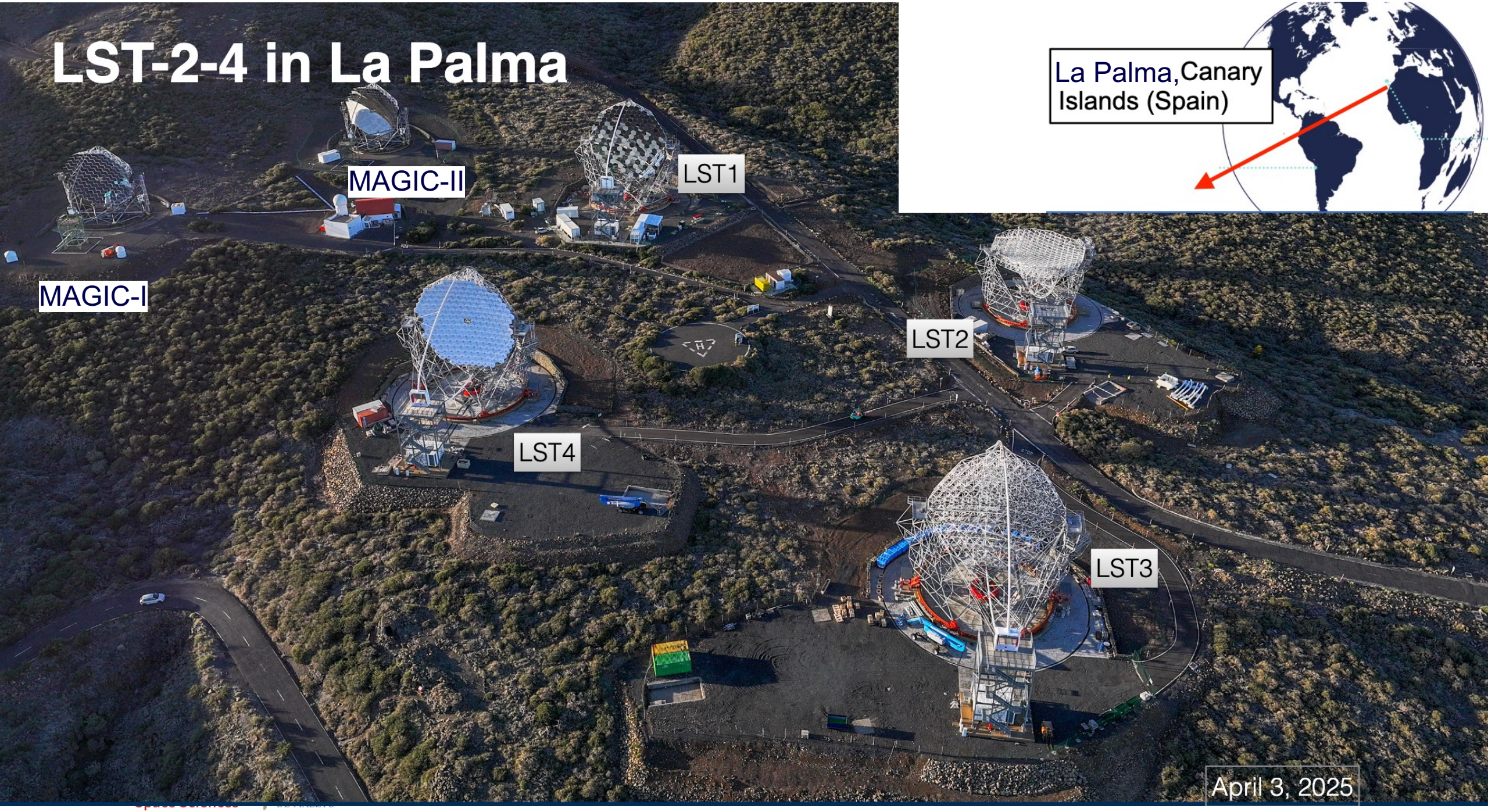
Large-Sized Telescope (LST)
Lowest energies (tens of GeV)
Cosmological sources
Deepest sensitivity for short timescales
Time domain largely unexplored

First Large-Sized Telescope LST-1

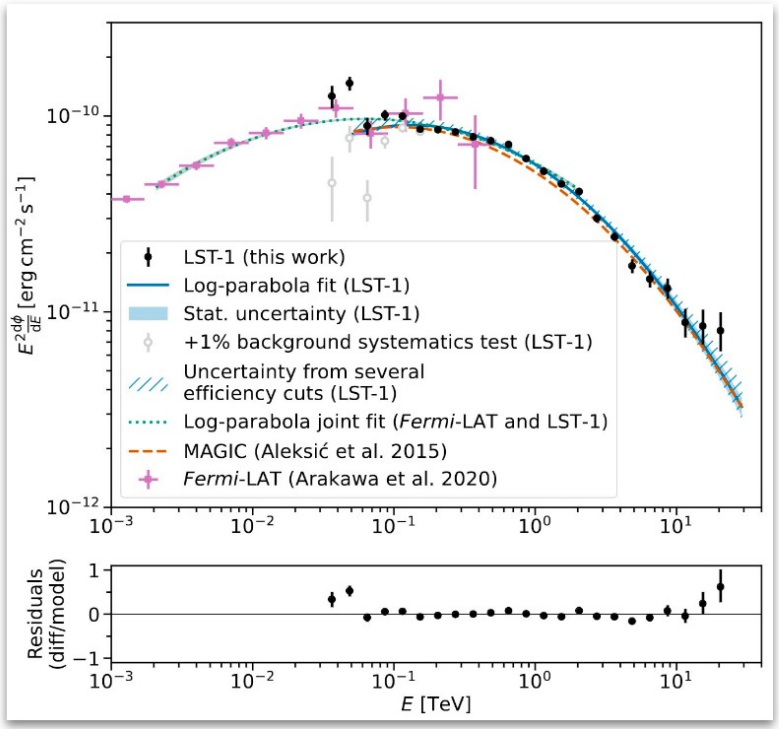


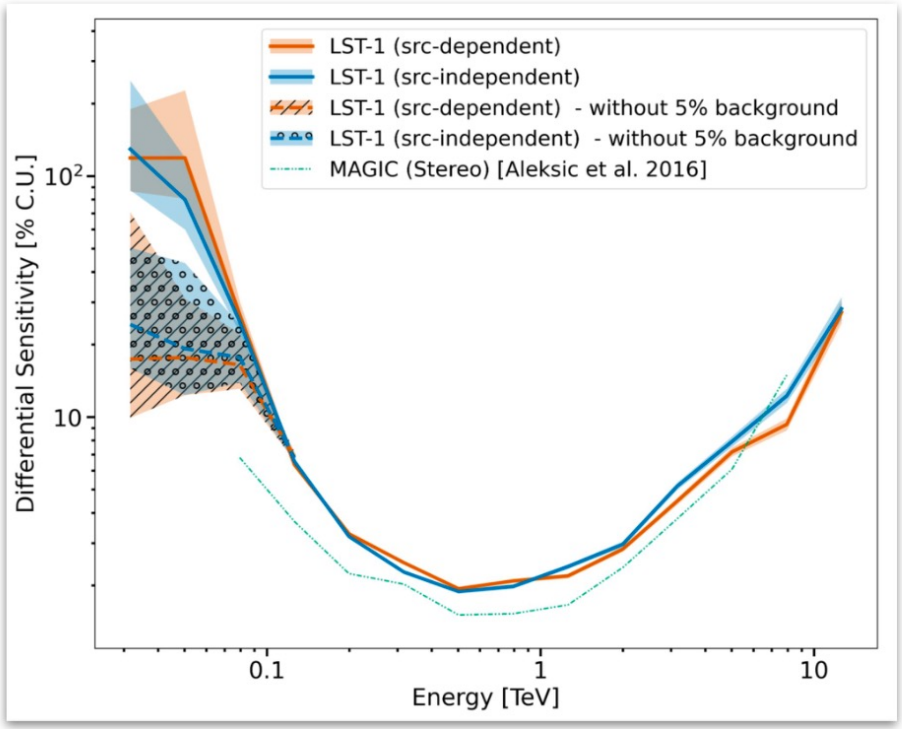





LST-2-4 in La Palma
La Palma,Canary Islands (Spain)
MAGIC-II
LST1
MAGIC-I
LST2
LST4
LST3
April 3, 2025

LST-1: Performance





Performance evaluated with observations on Crab Nebula

Abe, H., et al.: ApJ, 956:80 (2023)

- Sensitivity evaluated with real Crab data: energy range widened to lower energy compared to MAGIC (SED measured down to 30 GeV)
- MAGIC (stereo system) ~1.5 x better sensitivity than LST-1 (mono) - As expected by the difference between mono and stereo systems
- Systematics from background begin to dominate below 50 GeV → will be reduced with stereo trigger

The LST collaboration

https://www.lst1.iac.es/collaboration.html

- 11 countries, 29 groups
- LST is a large part of CTAO
- World-wide effort
- Costbook value: 15 M€ / telescopes (with FTE, no inflation…)
- 4 LSTs in the north, 2-3 in the south?

Galactic Science

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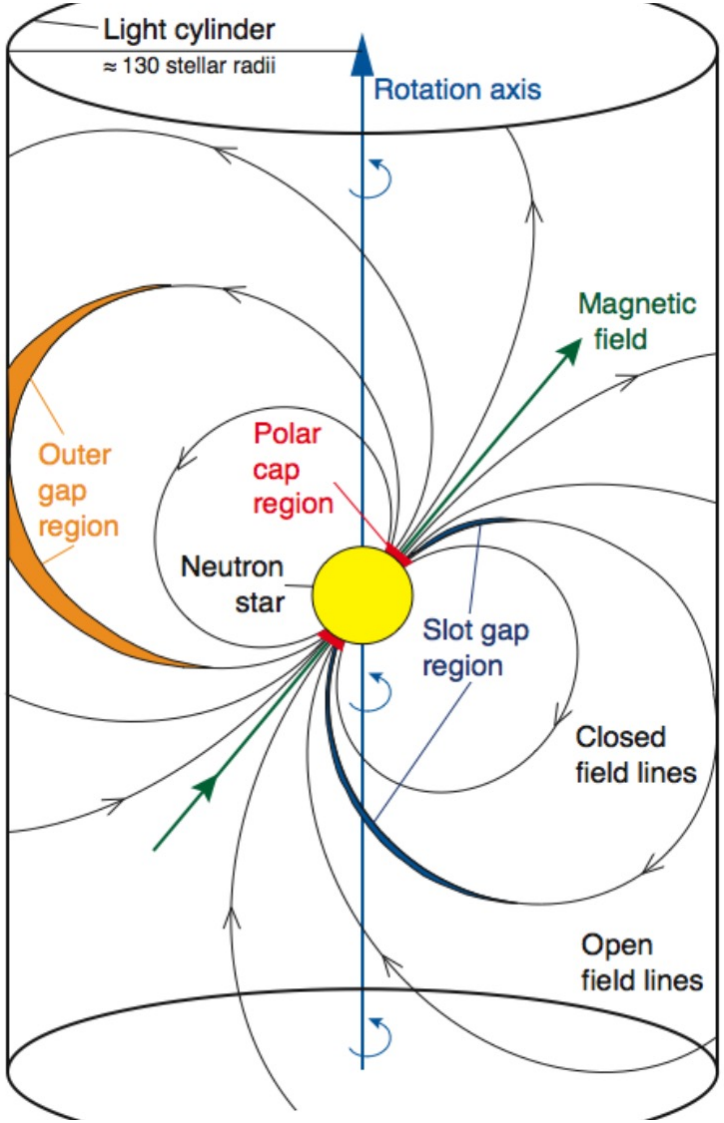
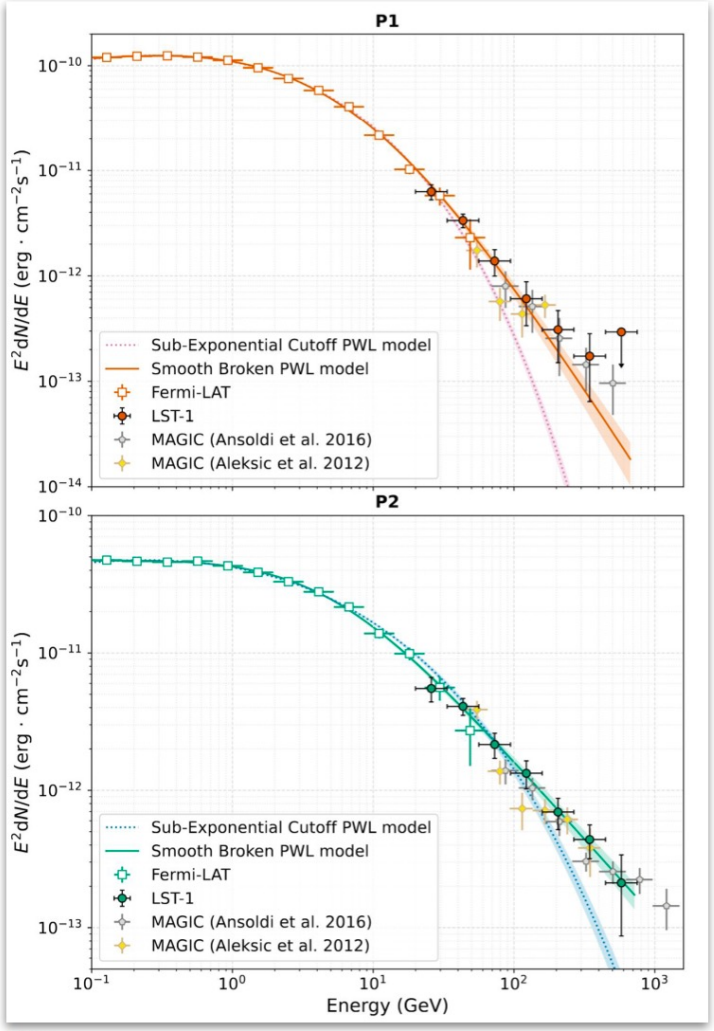
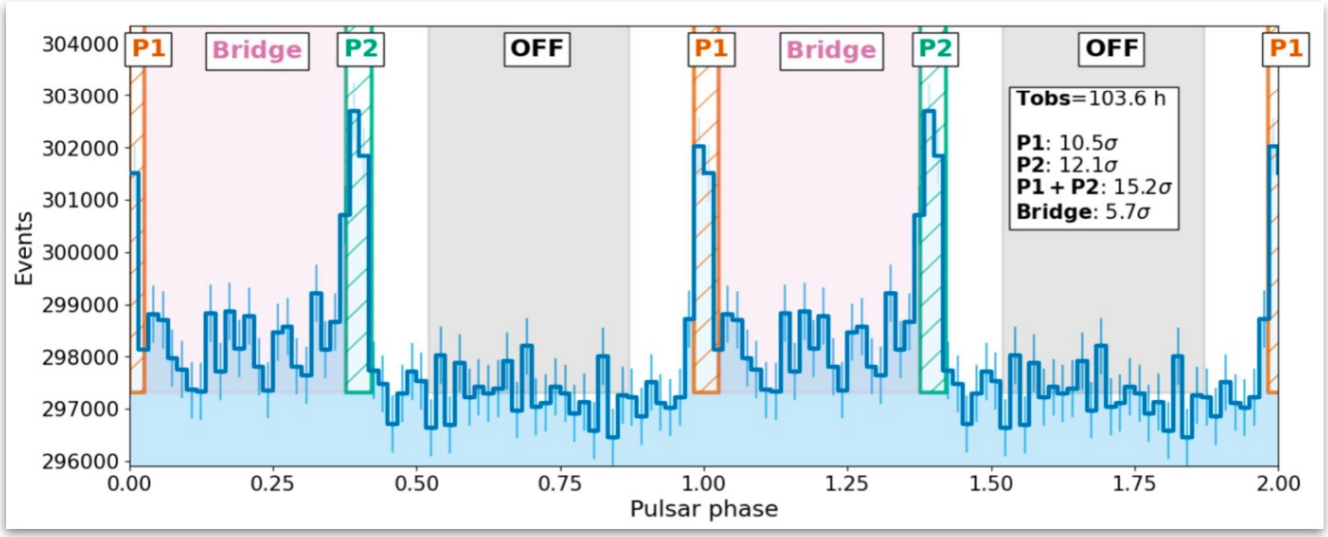
Pulsars

- Almost 340 pulsars detected at high energies.
  (Third *Fermi*-LAT Catalog of Gamma-ray Pulsars)
- Only three detected at very high energies.
  Crab, Vela and Geminga pulsar: pulsed emission detected by H.E.S.S., MAGIC and VERITAS up to TeV.
  → Challenge for current curvature radiation models.
  → Polar cap as emission region excluded.
- Emission mechanism at very high energies?



Crab pulsar





A detailed study of the very-high-energy Crab pulsar emission with the LST-1
A&A, 690, A167 (2024)

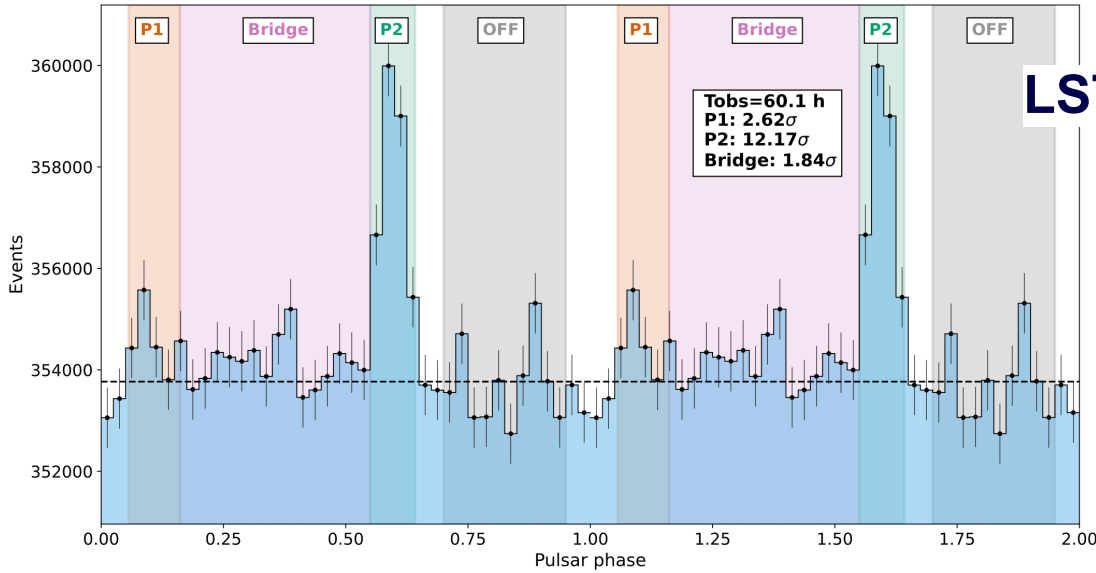
Detection of Crab Pulsar:

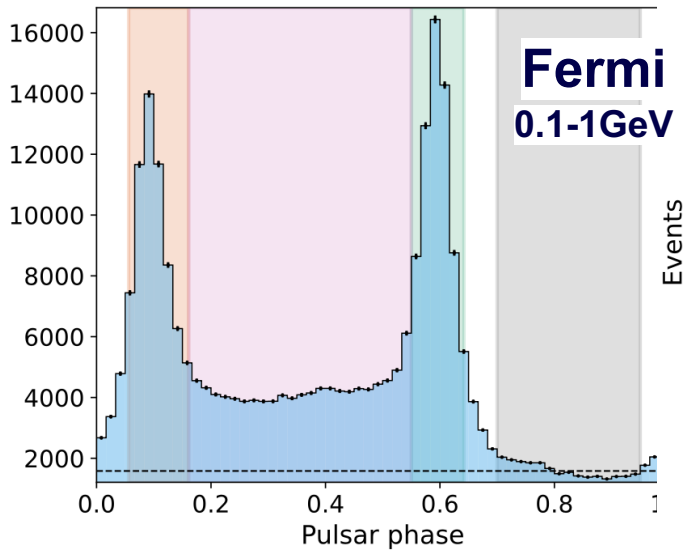
- Source physics + telescope performances (threshold, cross-calibration, energy resolution…)
- Clear detection of P1 and P2 → **Ethr down to ~20 GeV**
- Smooth transition between *Fermi*-LAT and LST-1

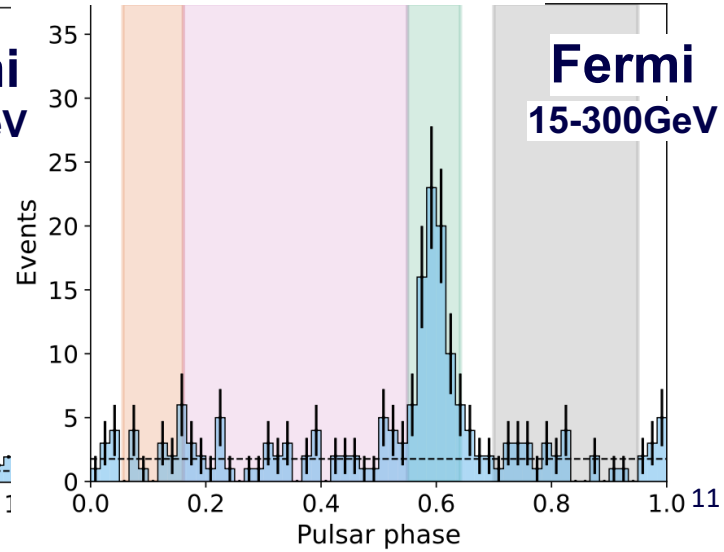
Geminga pulsar (PSR J0633+1746)

- Soft spectrum source
  → Detection of Geminga confirms the good performance in the 15-30 GeV band, one of the main scientific drivers of LST
- LST-1: 12σ in 60 hours for P2
- MAGIC: 6.3σ in 80 hours for P2
  [A&A, 643, L14 (2020)]
- LST-1: Hints for P1 and bridge emission

  For detection more sensitive instrument (4LSTs) needed.



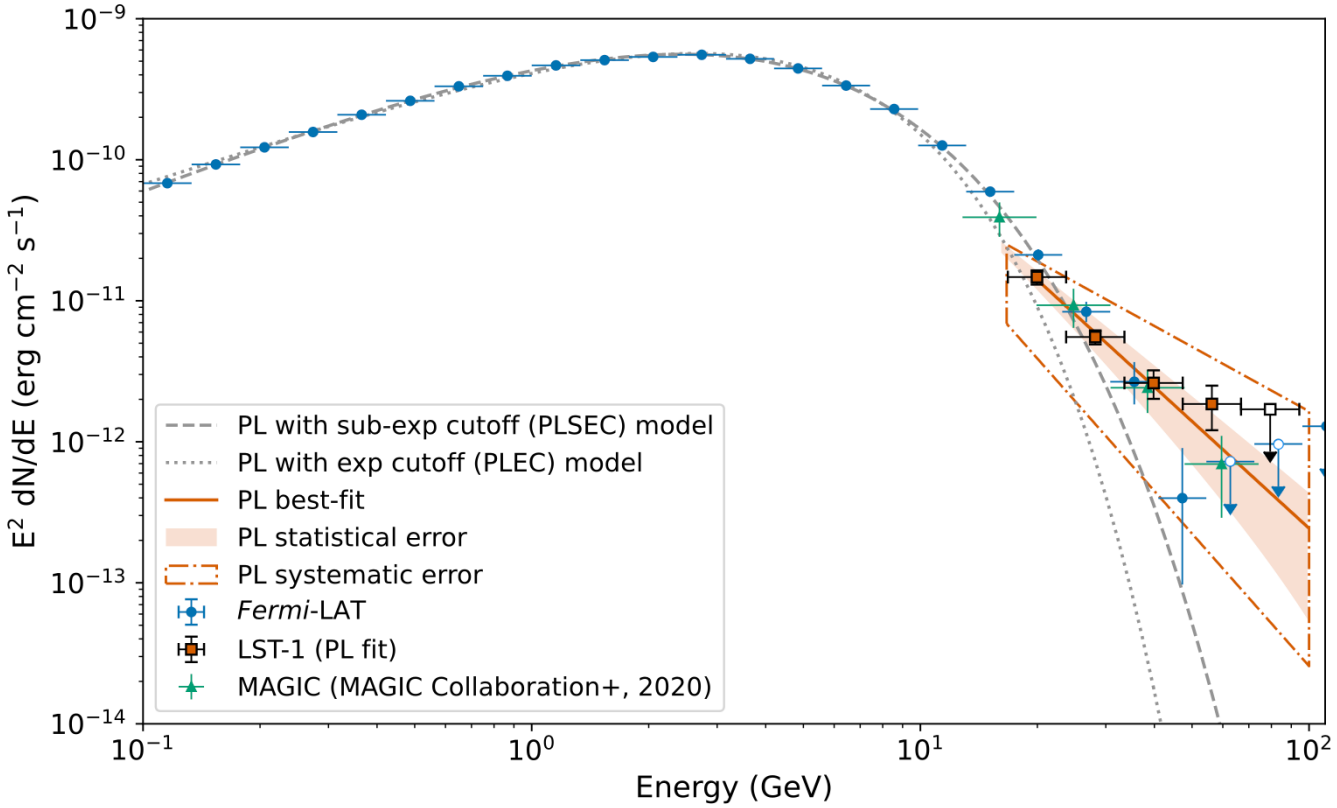




[A&A, 698, A283 (2025)]

Geminga pulsar (PSR J0633+1746)

- Spectral energy distribution of P2 in the [20, 95] GeV range
  Power law with spectral index
  $$\Gamma = (4.5 \pm 0.4_{\mathrm{stat}})^{+0.2_{\mathrm{sys}}}_{-0.6_{\mathrm{sys}}}$$
- Joint fit LST-1 and *Fermi*-LAT
  - Exponential cut-off model rejected over sub-exponential cut-off
  - Still not correct description of the spectrum
- Test of curvature in high-energy end
  - Negative for LST-1 maybe due to limited statistics
- Joint dataset: log parabola favored over power-law, effect decreasing with minimum energy set as starting point of the fit increases.

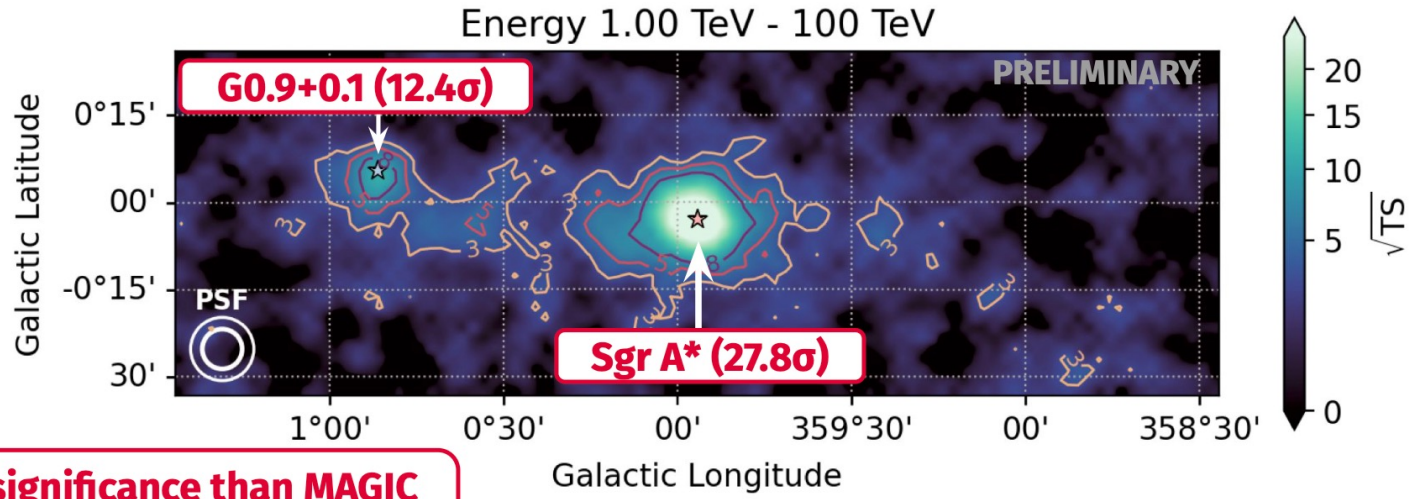


Galactic Center

- 39 hours taken at high zenith angles (Zd > 58 deg) .
- Spatially-resolved spectral fit with *gammapy*.

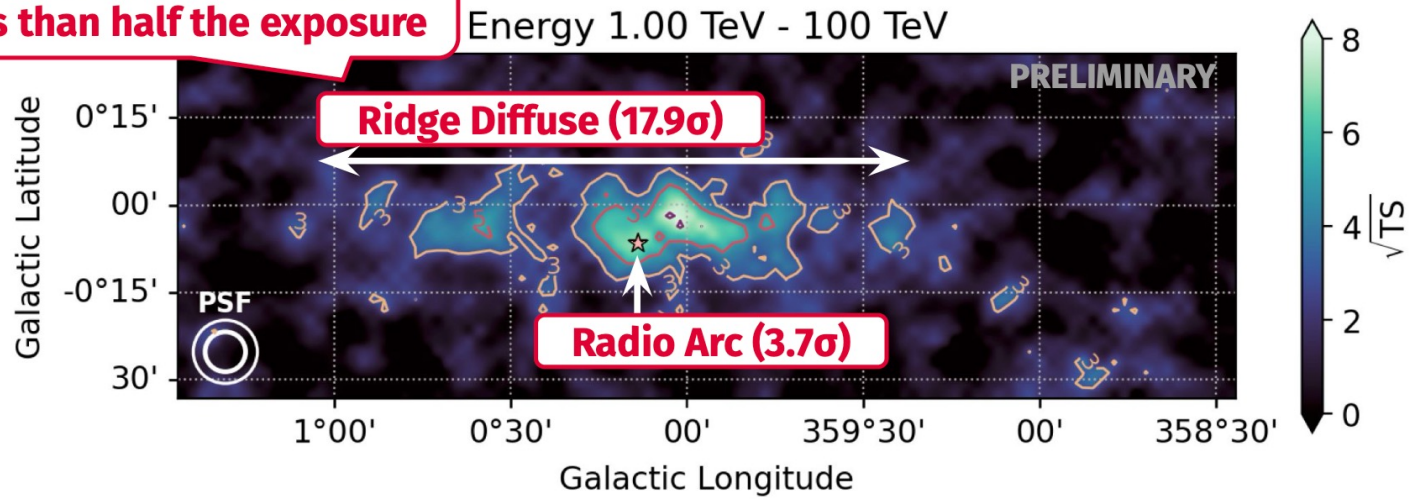
Source	Spatial	Spectral
Sgr A*	Point-like (Gaussian)	Power Law with Exp. Cutoff
G0.9+0.1	Point-like (Gaussian)	Power Law
Arc	Point-like (Gaussian)	Power Law
Ridge Diffuse	Template	Power Law with Exp. Cutoff

TS Map

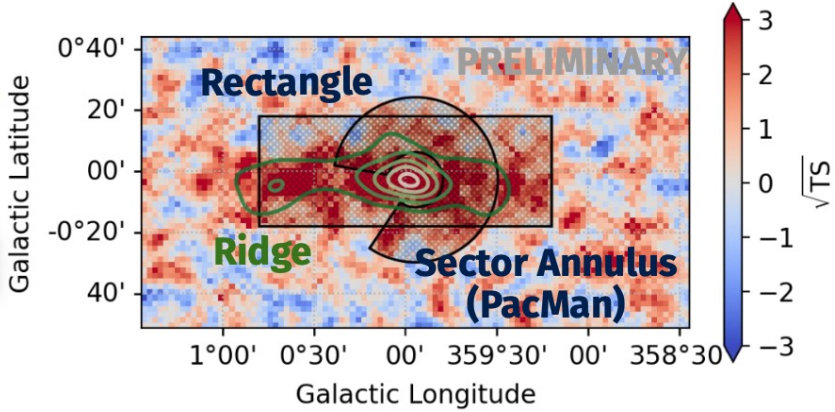


Higher significance than MAGIC with less than half the exposure

Sgr A* & G0.9+0.1 subtracted

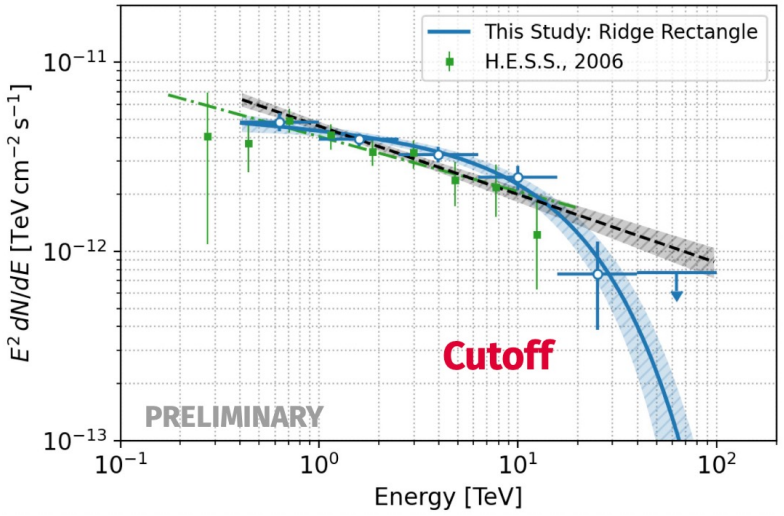


Galactic Center



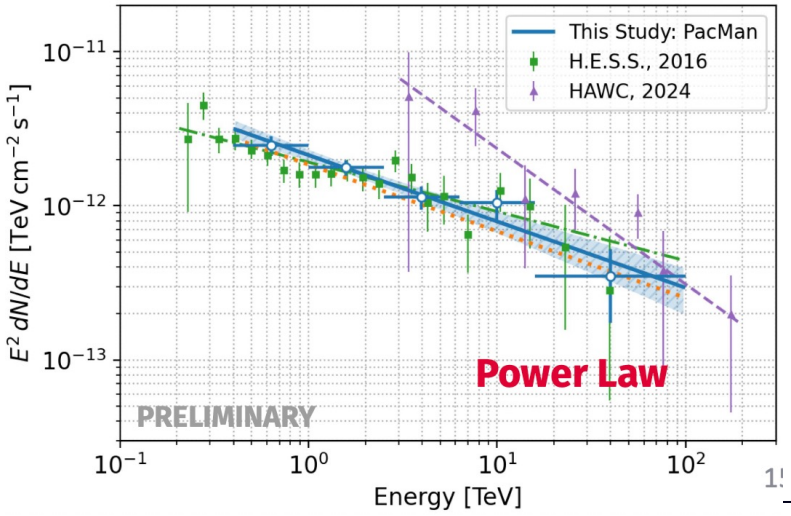
Rectangular Region

|l| < 0.8 deg (~±120 pc) & |b| < 0.3 deg, used in HESS 2006
cutoff at Ecut ~ 19 TeV favored with 3.7σ



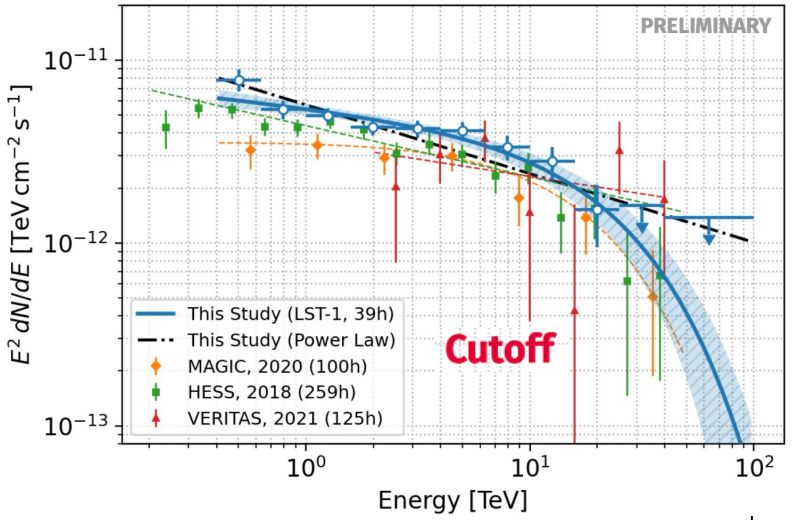
Sector Annulus Region (PacMan)

between 0.15-0.45 deg (20-60 pc), used in HESS 2016
No sign of cutoff, Ecut > 46 TeV (90% C.L.)



Ridge Diffuse

Spectral cut-off at ~24 TeV preferred with 2.8σ against pure power law, 3D (E-l-b) Likelihood Analysis.



- Spectral cutoff of the diffuse ridge emission.
- No sign of cutoff in the 20-60 pc region, suggesting a presence of PeVatron?
- This study provides an implication, for the first time in the TeV regime, that diffuse emissions in the region have a spatial variation in spectral curvature.

Extra-Galactic Science

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Active Galactic Nuclei (AGN)

- 84 blazars are detected up to 2024.

  Flat Spectrum Radio Quasar (FSRQ): optical emission lines.

  BL Lac: weak or no optical emission lines.

  10 are FSRQ and 74 are BL Lac.

- Spectral Energy Distribution: double-peaked.

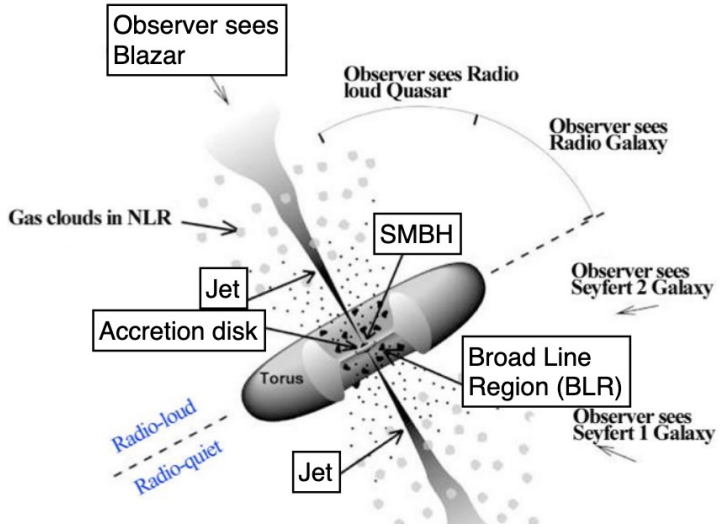
  Low-energy peak (radio - X-ray) –> synchrotron radiation from electrons in the jets.

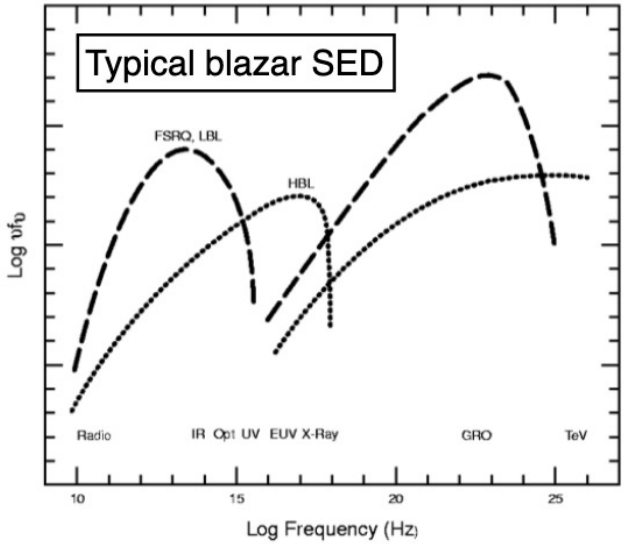
  High-energy peak (X-ray - TeV): under debate.

  - Inverse Compton with synchrotron photons (Synchrotron-Self-Compton; SSC)

  - Inverse Compton with seed photons outside the jet (External Compton; EC)

  - Hadronic process

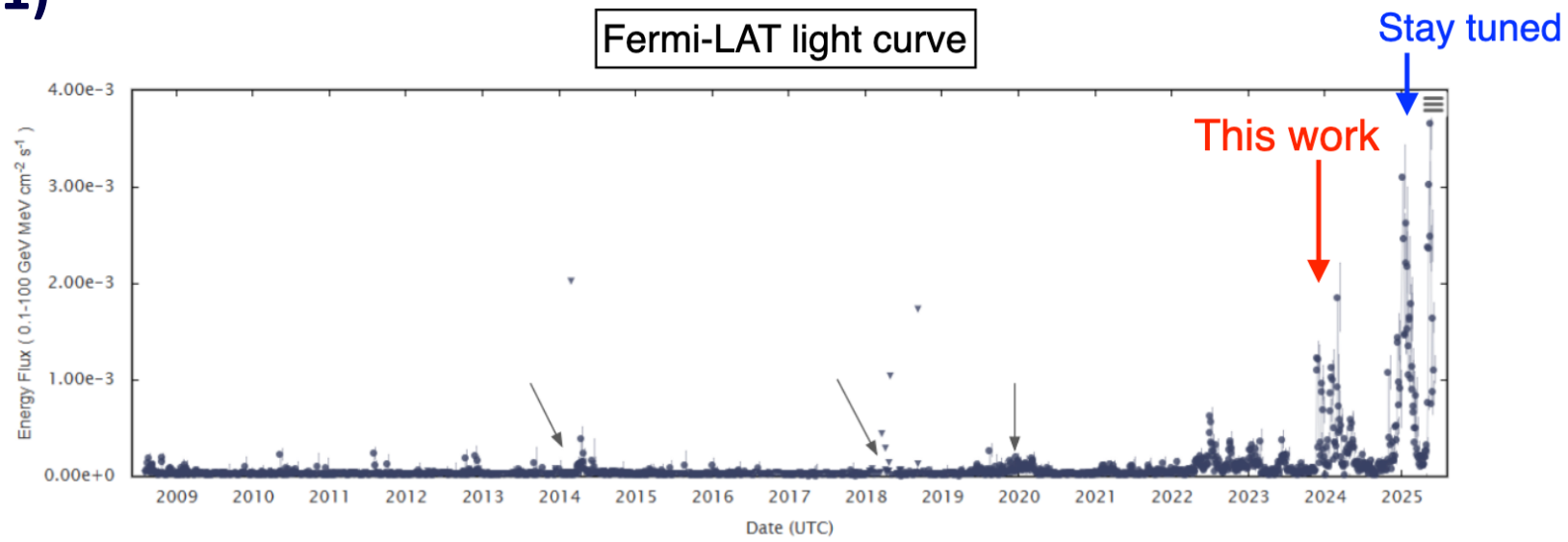




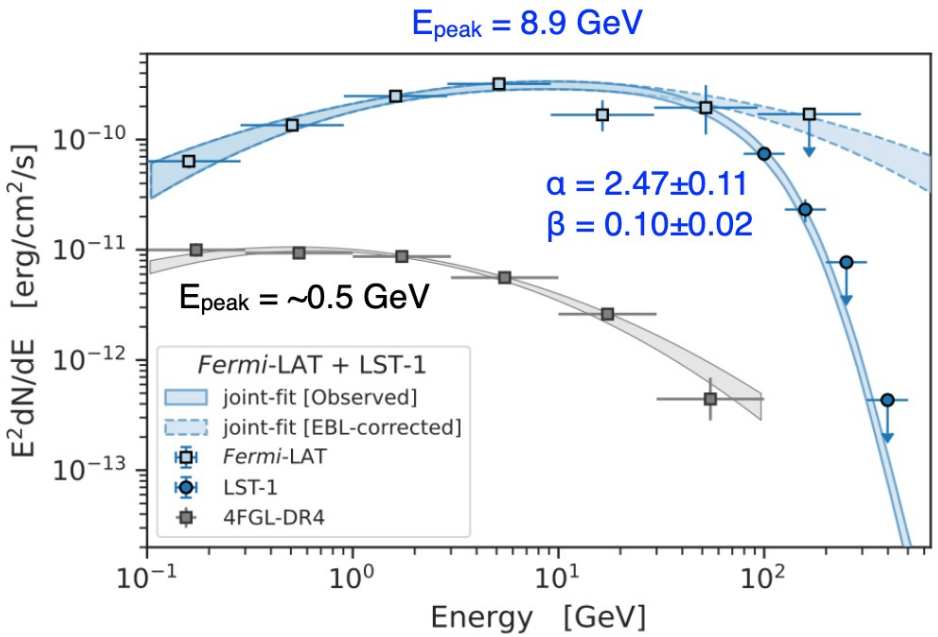
FSRQ OP313

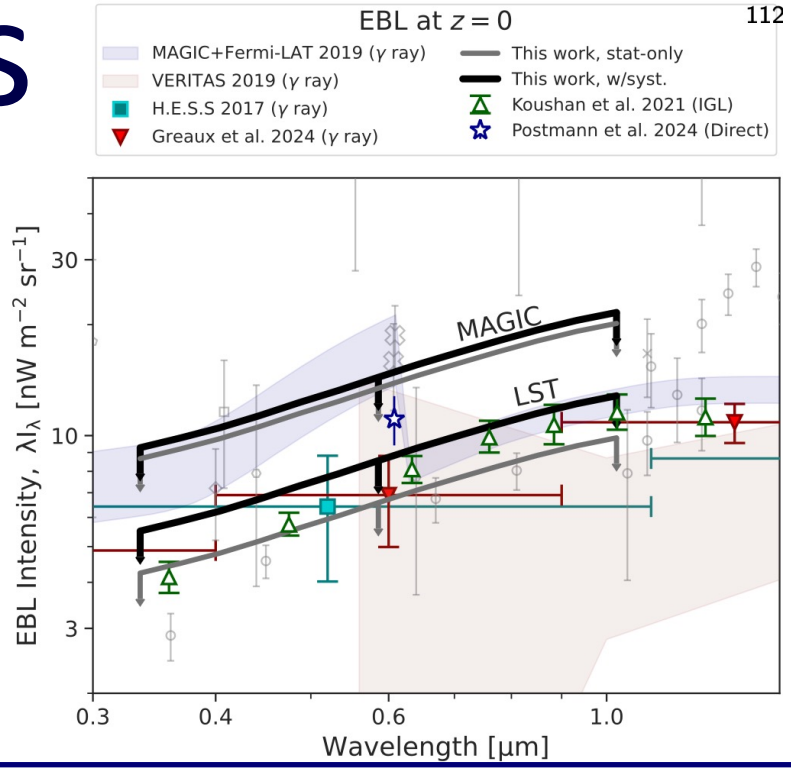
- High redshift z=0.997 (**furthest blazar ever**)—> gamma-ray absorption by EBL —> challenging for the sensitivity of current-generation Cherenkov telescopes.

  First detection at very high energies (VHE) with the LST-1 in December 2023 (ATel #16381)



SED & EBL constraints





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[Paper under review]

- Fermi-LAT + LST-1 joint fit of high state in December
- EBL model: Saldana-Lopez et al. (2021)
- Well-fitted with Log-Parabola and exponential cutoff.
- Peak energy shifted ~10 times higher during flare.

- γ -ray attenuation by Extragalactic Background Light:

$F_{obs} = \exp(-\alpha\, \tau(z, E_\gamma)) \times F_{int}$

$\tau(z, E_\gamma)$: optical depth, α: scaling factor

→ EBL intensity constrained: $\lambda I_\lambda < 6.72$ nW m^2 sr^{-1} ($\lambda = 0.6$ μm)

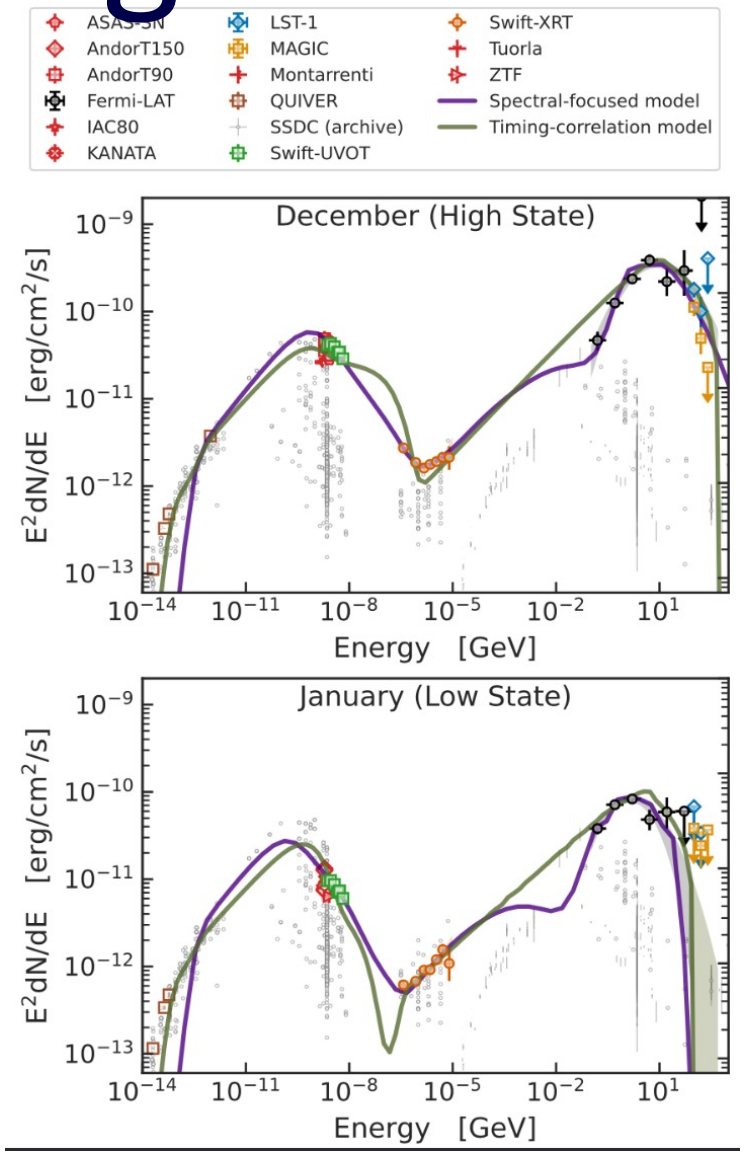
→ **Good agreement with integrated galaxy light estimates.**

Broad band SED modeling

- **Two-zone leptonic scenario** (near and far from super-massive black hole).
  - Including external seed photons from Broad Line Region and Dust Torus and Accretion Disk.
  - SSC and EC models.
- Spectral focused model

  Aims to carefully reproduce SED --> balanced EC emission from each component.
- Timing-correlation model

  Adopts single emitting zone beyond optical/UV, considering time-correlation between UV, X and γ-rays → less accurate.
- Difference between December and January states can be explained by difference in the electron distribution shape.



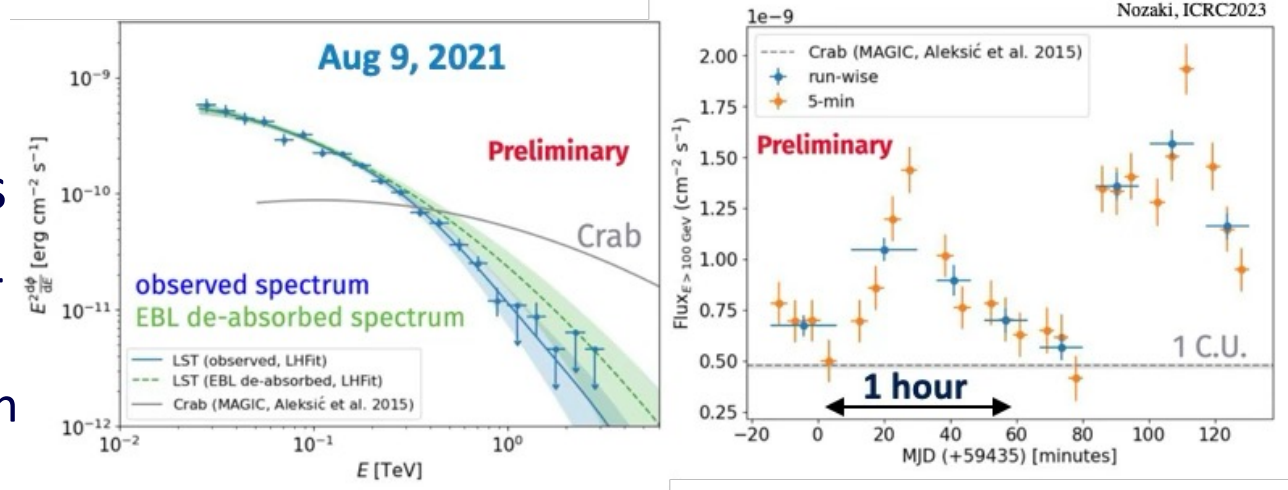
[Paper under review]

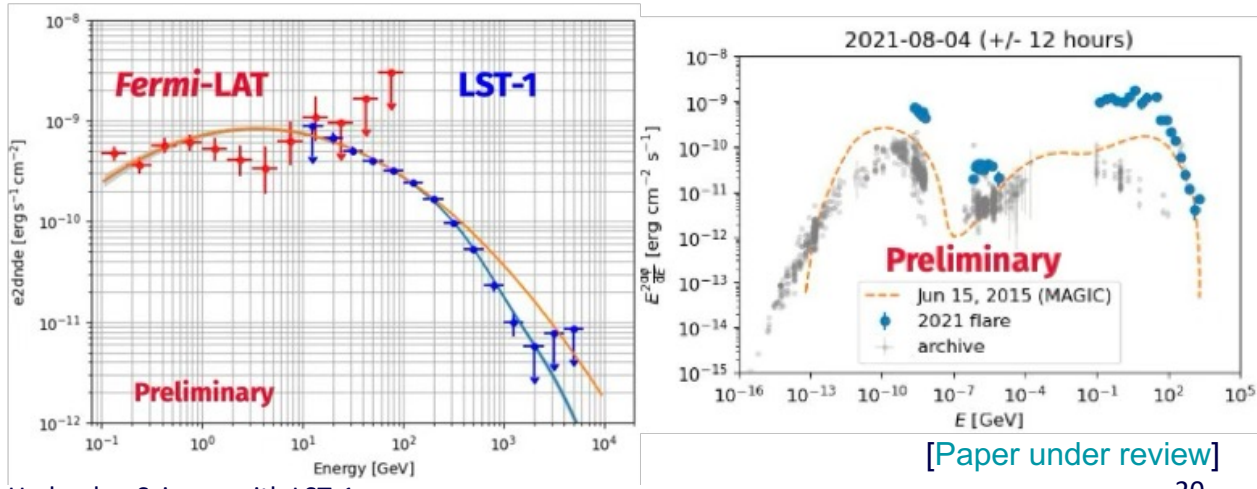
BL Lac flare

- Intermediate-synchrotron-peak BL Lac type object (z=0.069)
- VHE γ-ray emission only during high states
- LST observed flare of BL Lac: 17.6h in July-Aug 2021

  Significant intra-night flux variability (>100 GeV) on Aug 9
- Fast variability indicates small size of emission region

  $R < ct_{var}$ $\delta \sim 10^{15}$cm
- Joint binned likelihood analysis of *Fermi*-LAT and LST-1 data: smooth connection





[Paper under review]

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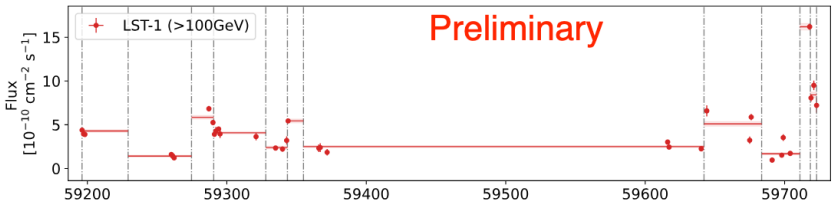
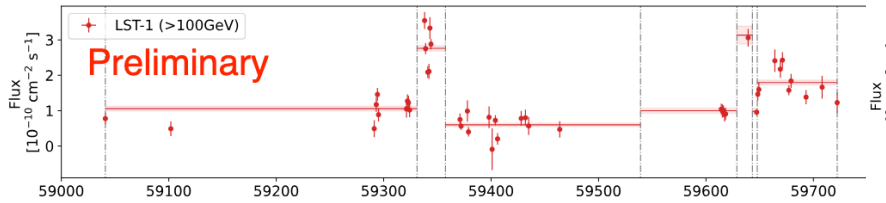
AGN Zoo: Monitoring

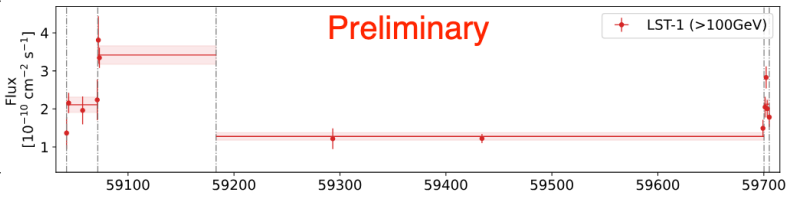
Mrk421: Low flux variability. Hint of shorter timescales -> LST2-4 reveal

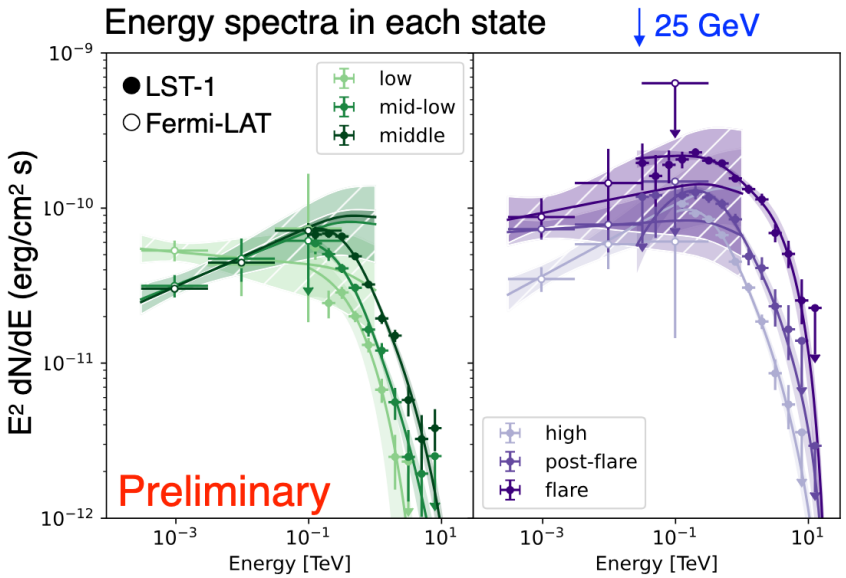
Mrk501: Fermi-LAT spectra comparable to LST-1 ones.

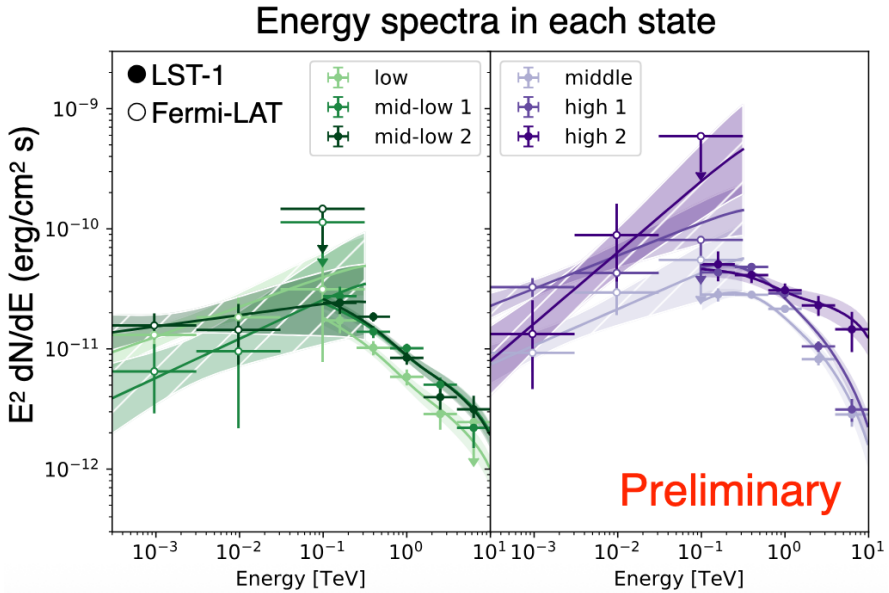
1ES1959+650: Joint-fit method can reveal γ-ray spectra even when Fermi data have low statistics.

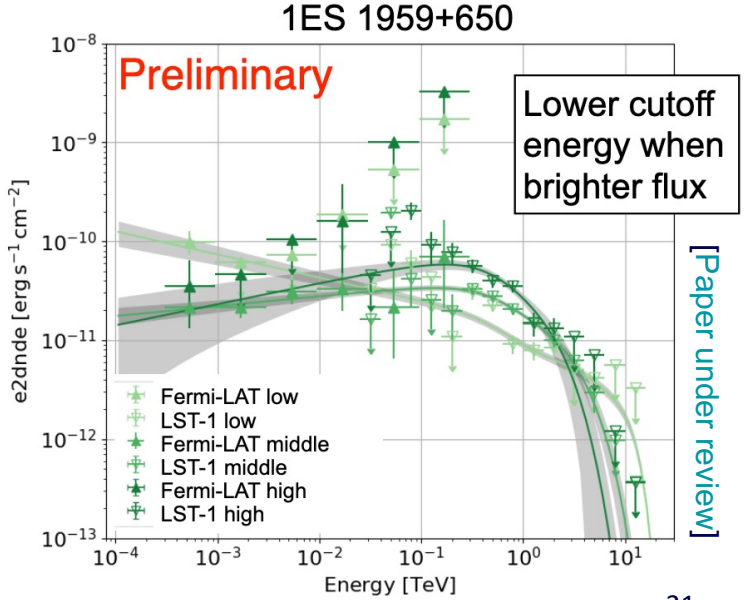












[Paper under review]

Transient Sources

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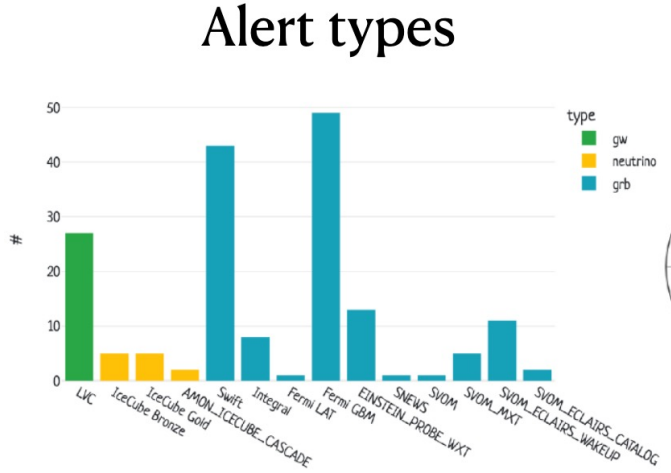
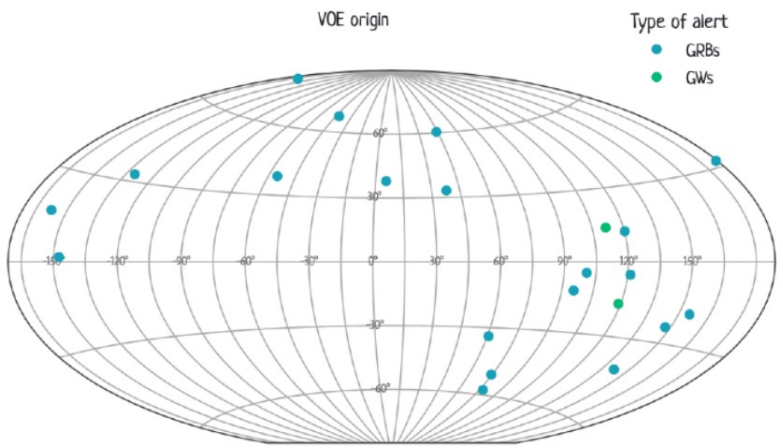
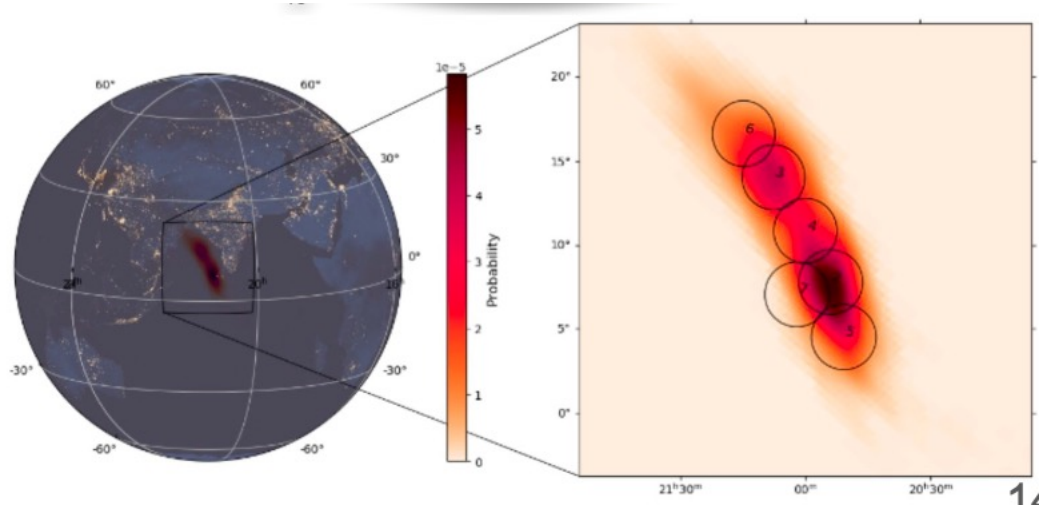
Transients Follow-up

- **LST is built for transients!** First follow-up started at the end 2020.
  - Dedicated **Transient Handler** and automatic follow up procedure implemented.
  - Handles **automatically** alerts in the order of ~ 10s seconds-min.
  - Large uncertainty alerts (i.e., GW) handled by *tilepy* [M. Seglar-Arroyo et al., ApJS 274, 1 (2024)]
  - Since the end of 2023, a total of 22 alerts have been followed by LST-1: GRBs are the largest of these, with 20 observed alerts (~ 48 h) and two GW sources (~ 3.3 h).

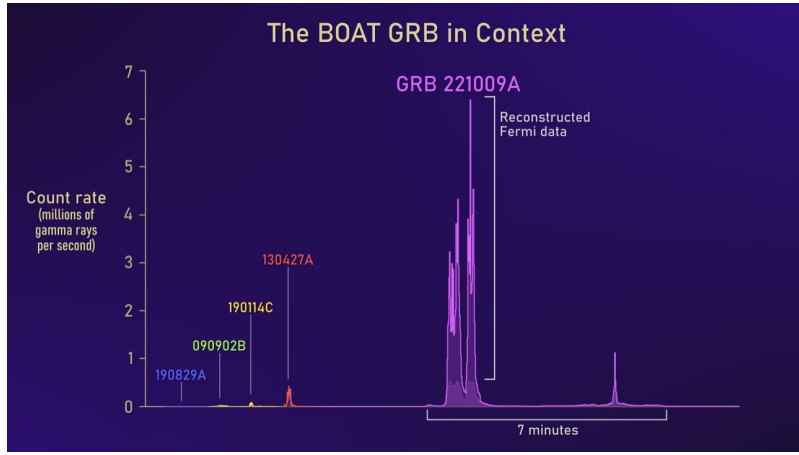




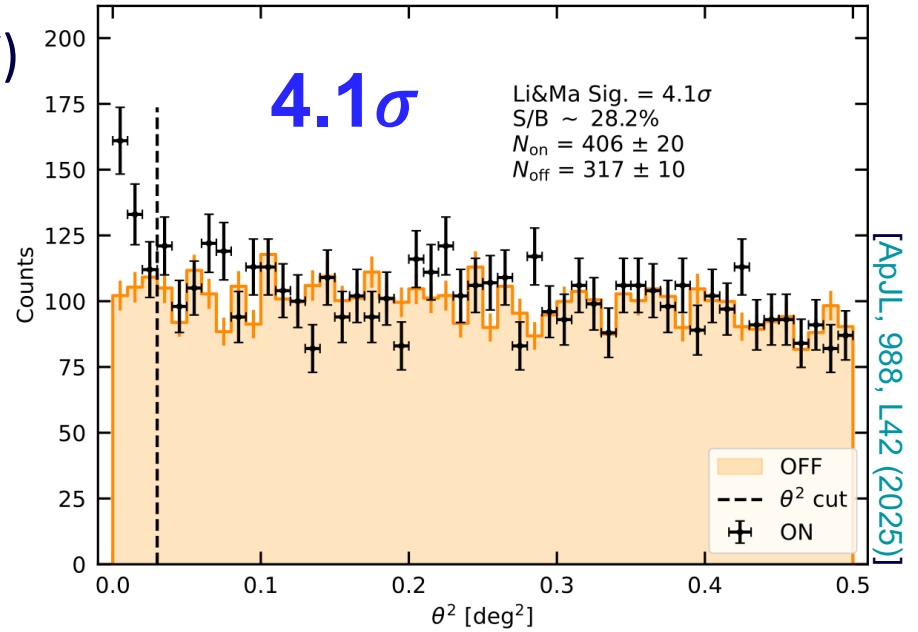


GRB 221009A: The BOAT

- "Brightest of all time" (BOAT) GRB: ≤ 1 event every 1000 years [Williams et al. (2023)]
  E_{iso} ~ $2x10^{54}$ erg; z = 0.151
- First GRB with detection of the VHE afterglow onset [LHAASO collaboration 2023)]
  Peak energy flux = 10^5 Crab (Energy flux between 0.3 – 5 TeV)
- **LST-1 follow-up observations** began at **T_0 + 1.33 d** (2022/10/10 ~21:34 UTC)
  Bright moonlight → special settings in data taking & analysis
- Hint of detection on first night: ~4σ
  Excess compatible with background afterwards



NASA's Goddard Space Flight Center and Adam Goldstein (USRA)

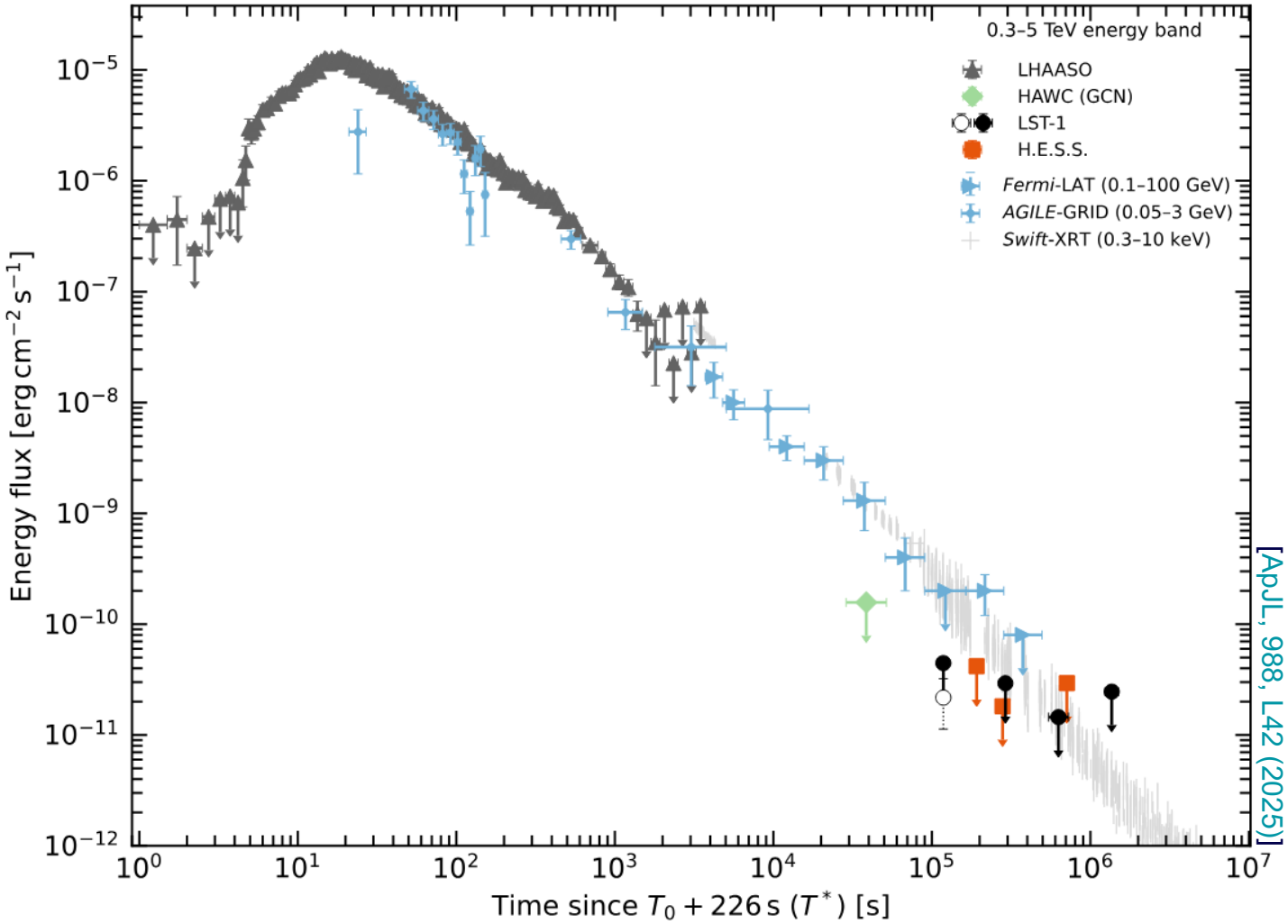


[ApJL, 988, L42 (2025)]

BOAT: Light curve

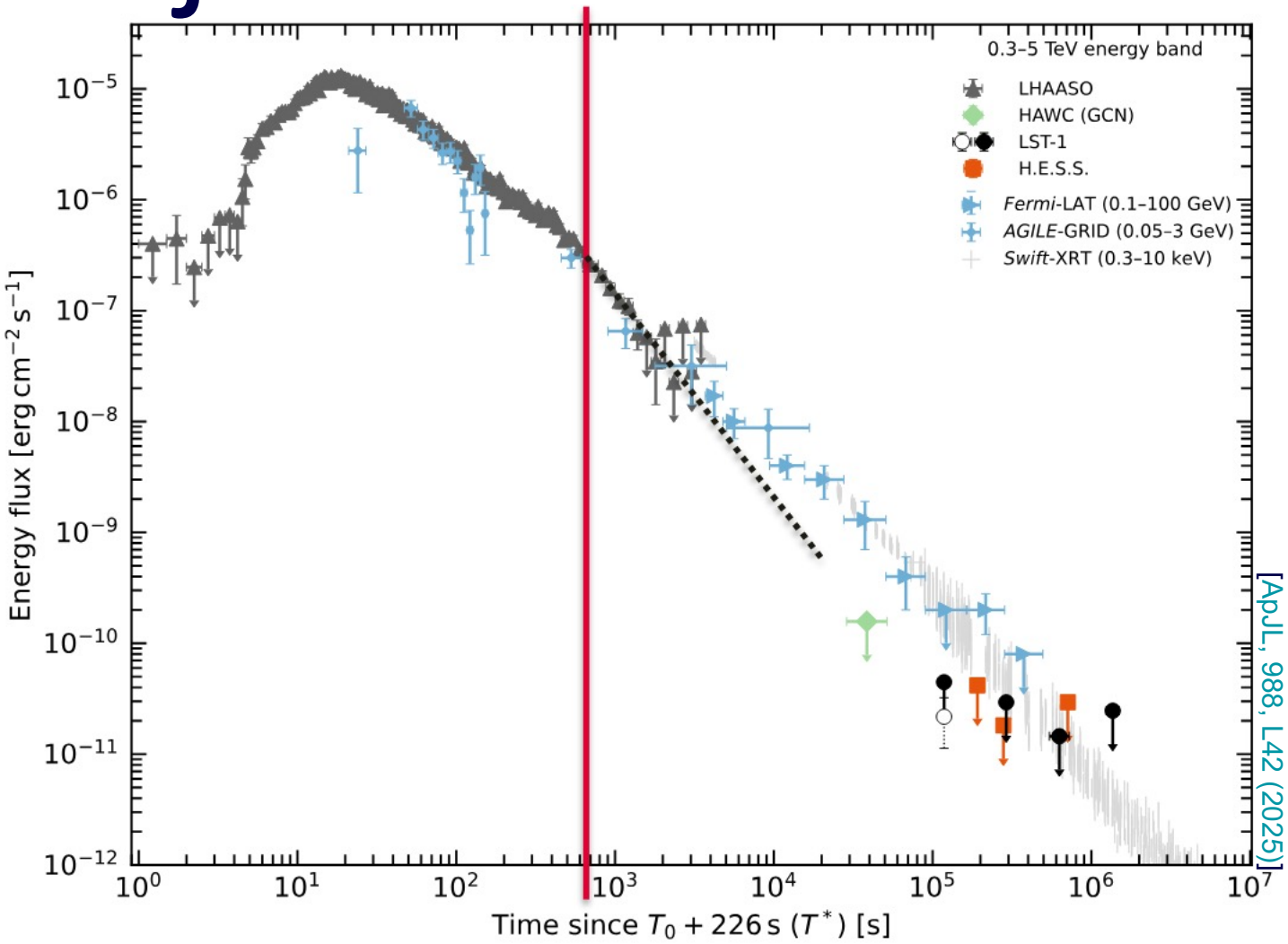
- LST-1 constrains emission as early as T0 + 1.33 d (~10^5 s)
- LST-1 bridges the HAWC and H.E.S.S. UIs
- Energy flux ULs at the level of 10^{-11} erg cm^{-2} s^{-1} between E = [0.3, 5] TeV

  Order of magnitude deeper than HAWC, comparable with H.E.S.S.



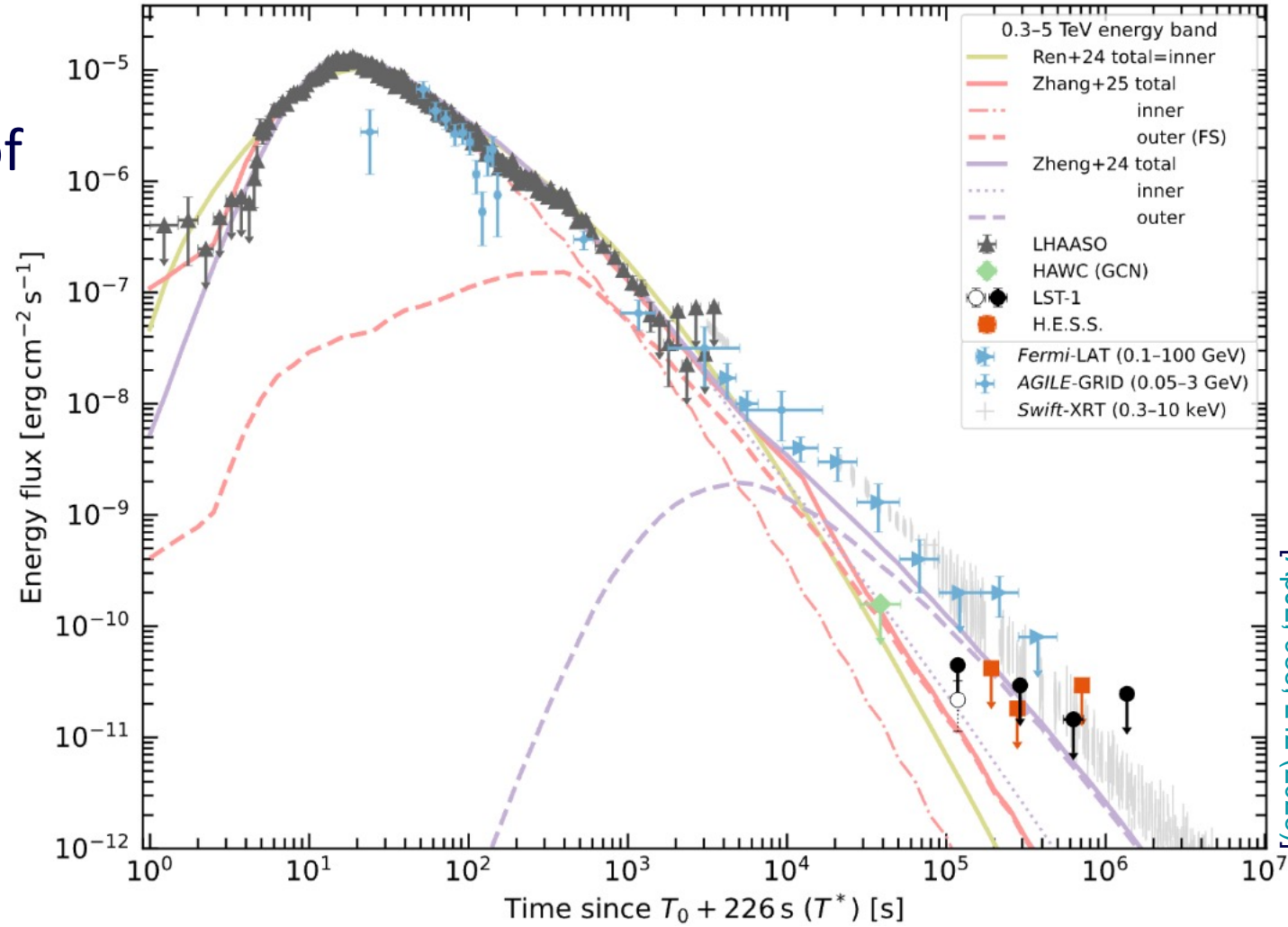
BOAT: Structured jet

- LHAASO: achromatic break at T* + 670 s (jet break)
  Jet opening angle of 0.6 deg [LHAASO Collaboration 2023]
- The decay at other bands after the jet break are shallower than LHAASO
- The emission at later times likely origins from a separated region surrounding the inner 0.6 deg jet
  → Structured jet
  → Alternative interpretations: L. Foffano et al. (2024) and D. Khangulyan et al. (2024).



BOAT: Modelling

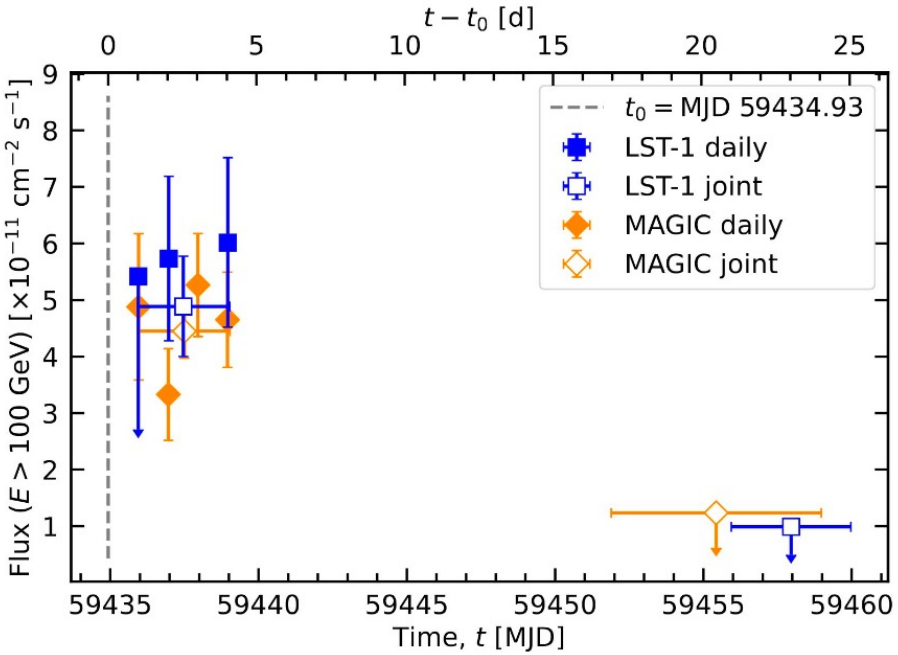
- LST-1 provides substantial constraints to realistic models of structured jet afterglows
  LST-1 ULs can rule out parts of the parameter space
- Assuming the detection hint is real …
  Does the VHE emission come from the inner or the outer component?
- Late-time TeV emission is meaningful to constrain the jet structure



[ApJL, 988, L42 (2025)]

RS Ophiuchi Nova

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



- 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 y
  - For a symbiotic nova to be RN, the WD must be massive (≥1.1 M ⊙) (if M > 1.44 M ⊙ → Sn Ia)

Observation day	Γ	ϕ_0 [10^{-10} TeV^{-1} cm^{-2} s^{-1}]
Day 1	−4.2 ± 0.3	3.3 ± 1.3
Day 2	−3.65 ± 0.13	5.9 ± 1.0
Day 4	−3.50 ± 0.15	5.9 ± 1.1
Day 1, 2 and 4	−3.73 ± 0.10	5.2 ± 0.7

RS Oph is a recurrent symbiotic nova which displays major outbursts every 14.7 years

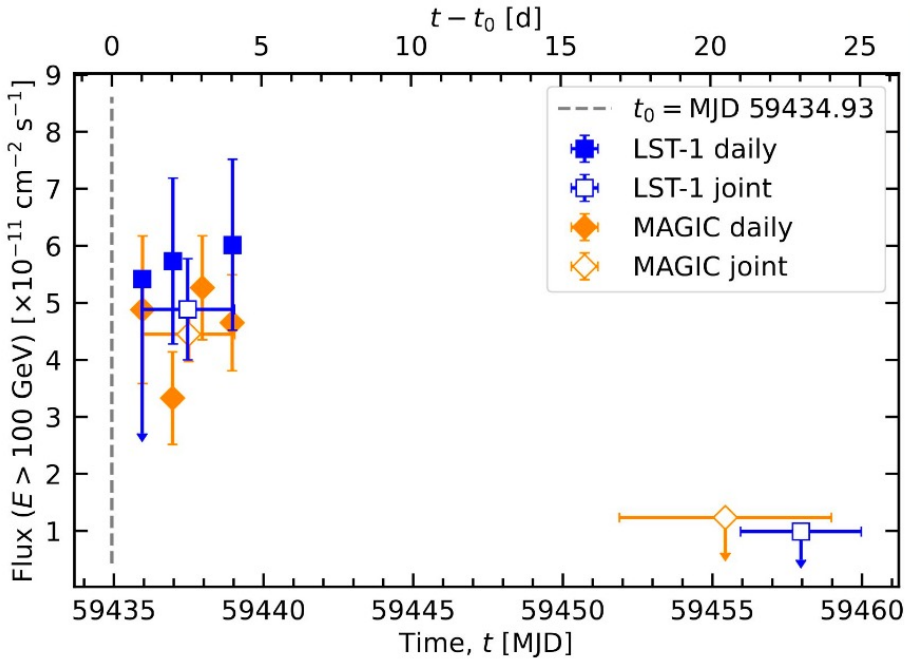
Observed and detected on August 2021 by both MAGIC and LST-1

Novae established as a new type of VHE emitters

[A. Carosi VHEGAM 2025]

RS Ophiuchi Nova

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



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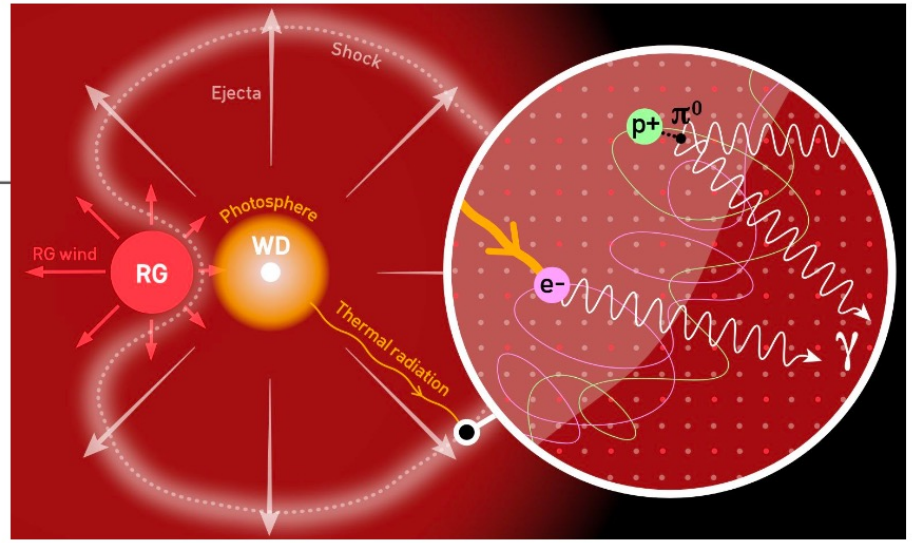
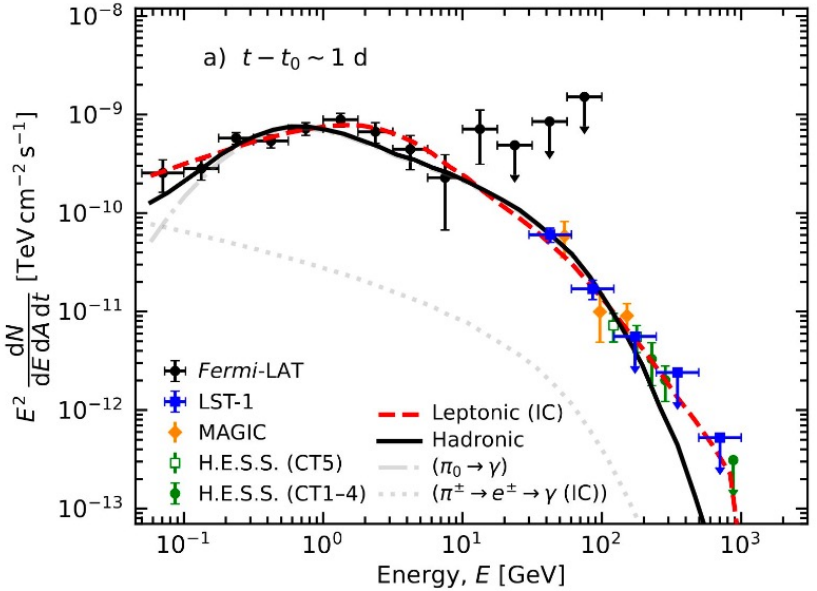
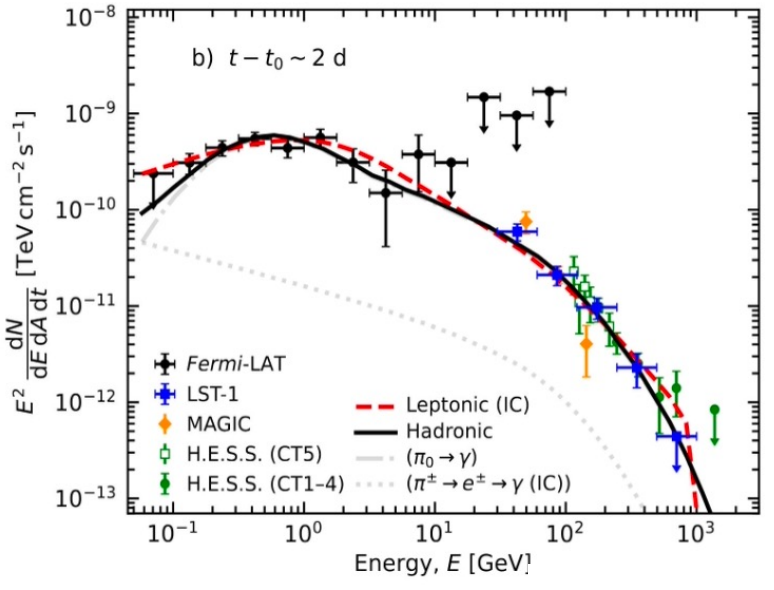


LST Coll. 2025, A&A, 695A.152A
MAGIC Coll. 2022, Nat Astron 6, 689

- Evidence for a spectral hardening as novae evolves and increase in cutoff energy
- Hadronic model preferred

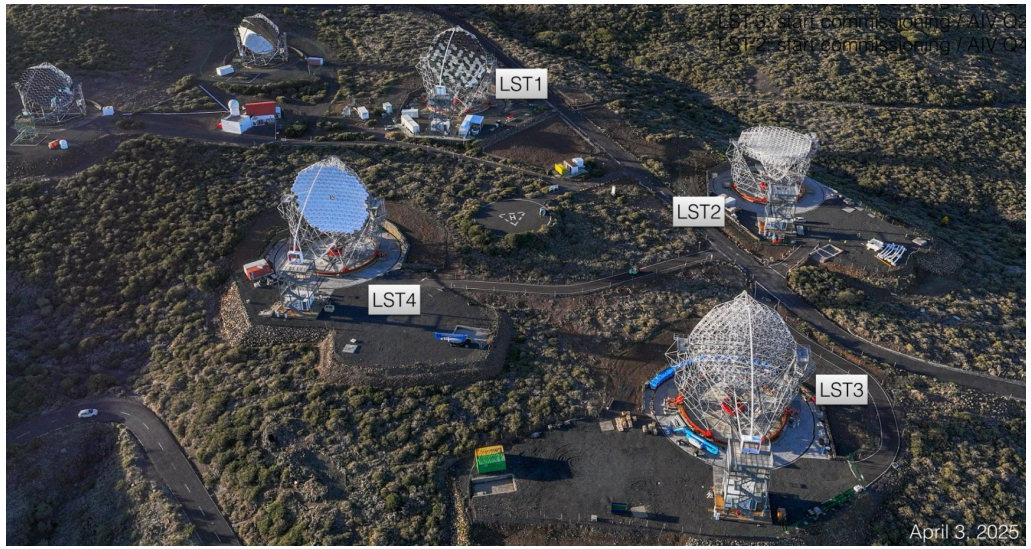




[A. Carosi VHEGAM 2025]

Summary

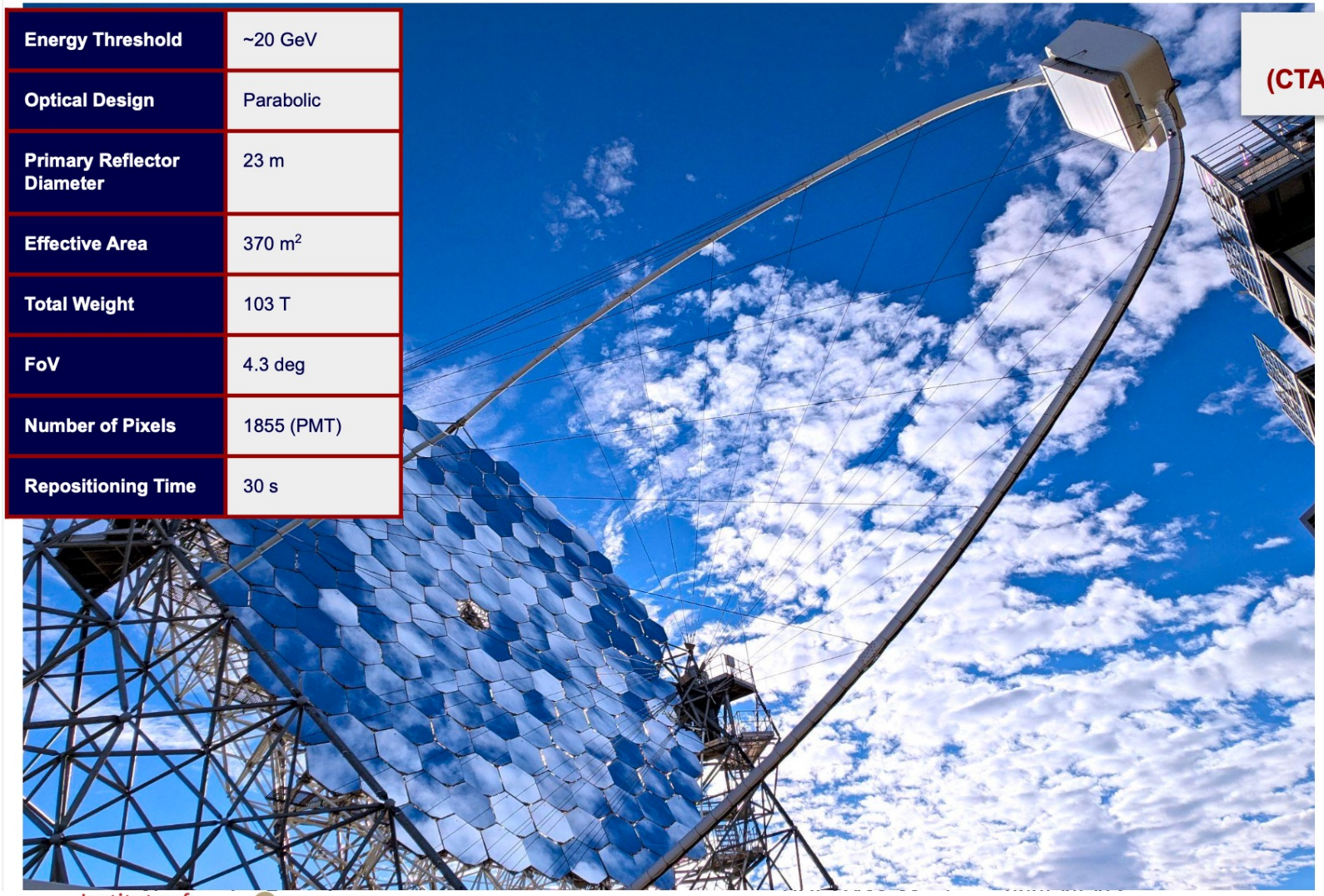
- The prototype telescope LST-1 was inaugurated at the CTAO Northern Array site in La Palma in 2018.
- LST-1 Science program has been established and is growing rapidly.
  Cycle III of observations has recently started in a joint-mode with MAGIC.
- Observations and results cover a wide range of scientific targets (Galactic sources, transients, TeV Blazars, FSRQs…)....and that's not all!
  Many other results not mentioned here such as fundamental physics study, dark matter, LIV, interferometry….
- Future ahead: moving forward to the LSTs array soon!



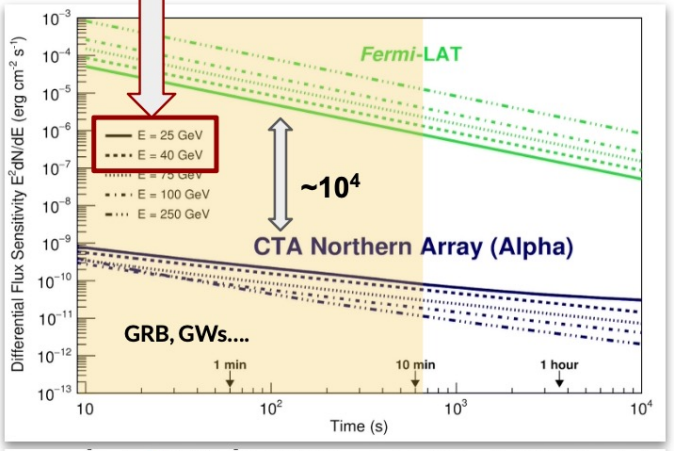
CTAO | LST COLLABORATION

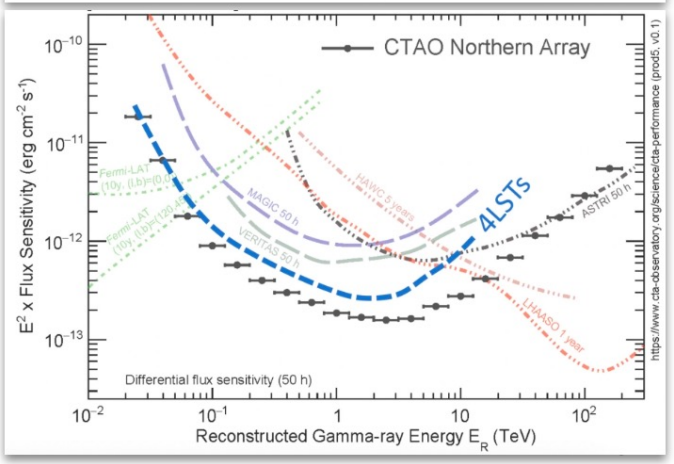
First Large-Sized Telescope LST-1

Energy Threshold	~20 GeV
Optical Design	Parabolic
Primary Reflector Diameter	23 m
Effective Area	370 m^2
Total Weight	103 T
FoV	4.3 deg
Number of Pixels	1855 (PMT)
Repositioning Time	30 s



LST "sweet range"
(CTA sensitivity dominated by LSTs)





A. Carosi@VHEGAM2025

Pulsar summary

Crab pulsar

- Energy dependecy of the peaks.
  P2 more significant at VHE than P1.
- Bridge emission visible.
  Spectra for all regions computed.
- Smooth transition between *Fermi*/LAT and LST-1 data that points
  → Emission being produced by a single population of electrons.
- Acceleration region still unclear.

Geminga pulsar

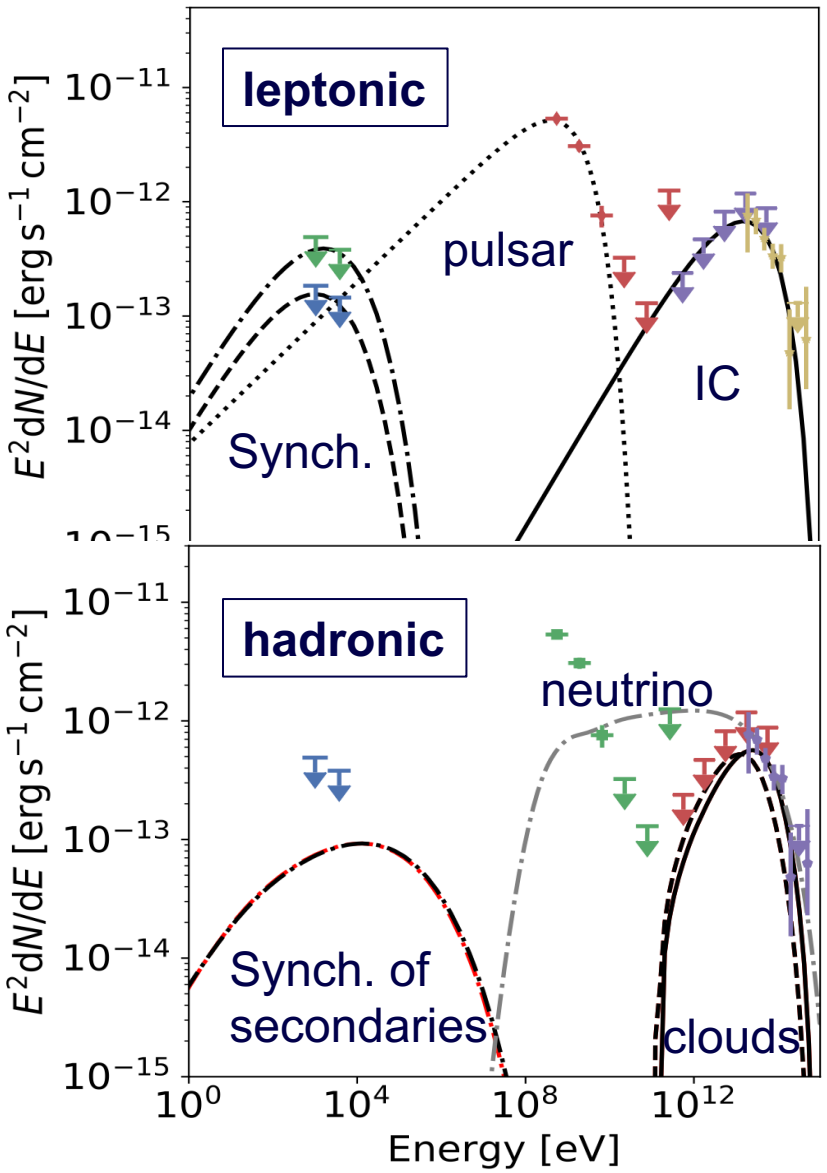
- Hints for P1 and bridge emission thanks to low energy threshold of LST-1.
  For detection more sensitive instrument (4 LSTs) needed.
- More pulsar detections to come specially with more LSTs.

LHAASO J2108+5157

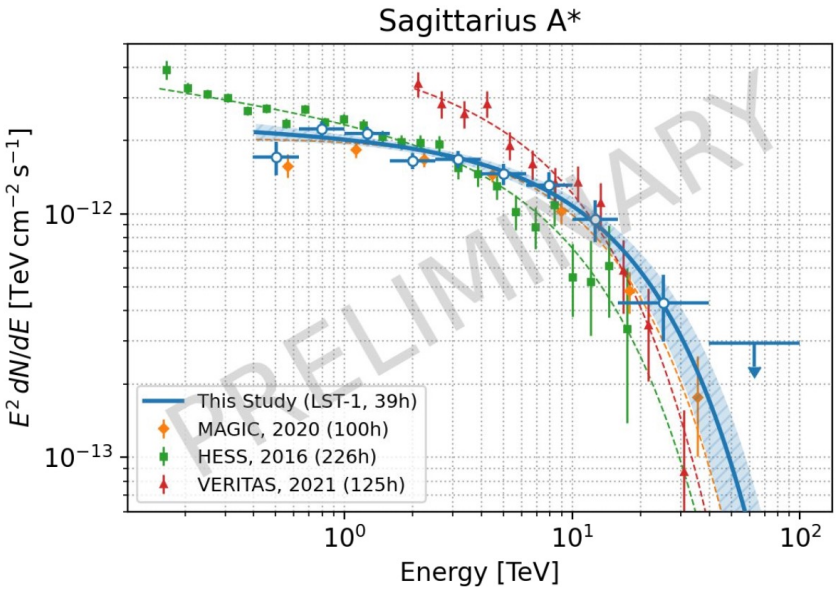
Unidentified source

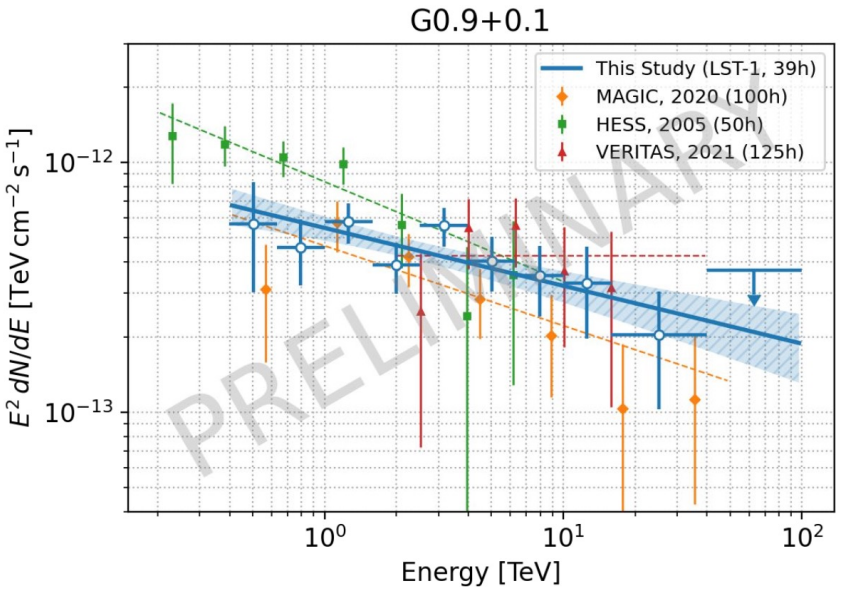
- First gamma-ray source directly discovered in the ultra-high energy (UHE) band (~100 TeV)
- ~91 hours observations with LST-1.
- No X-ray nor VHE counterpart (3.7σ in the few TeV band) → constraining upper limits achieved.
- Future CTAO observatory or deeper X-ray observation → distinguish PWN and TeV-halo hypotheses
- Interesting candidate for future neutrino experiments of sufficient sensitivity.

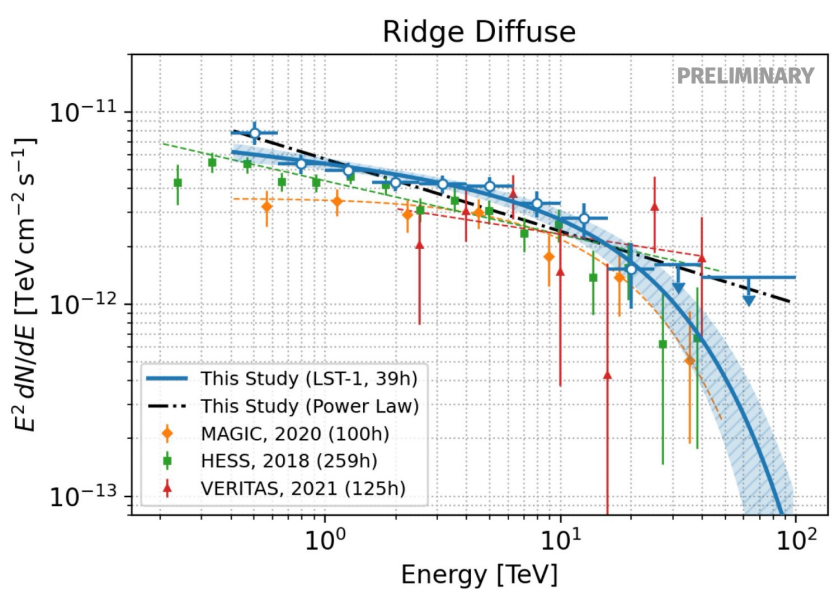
Abe, S., et al.: A&A 673, A75 (2023)



Galactic Center





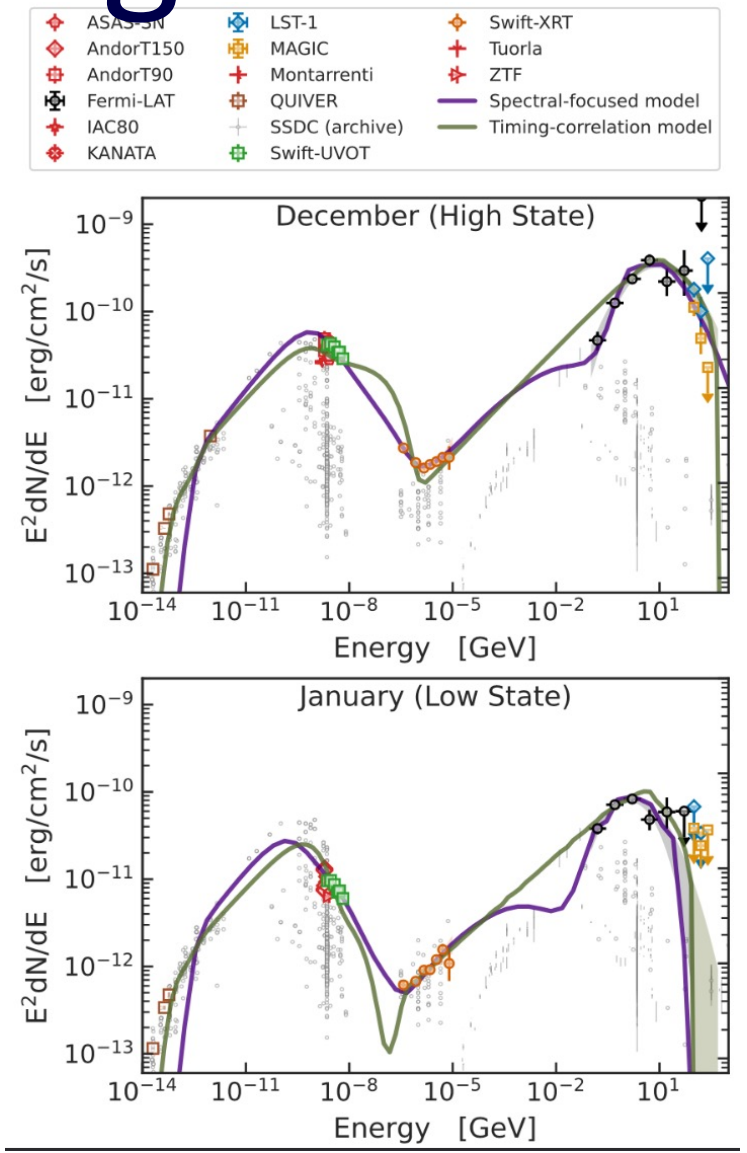


- LST-1 results consistent with prior studies.
- Cutoff not been seen in G0.9+0.1, despite the 4.8σ cutoff significance for Sgr A*.

Total diffuse emision favors cutoff at 24 TeV with 2.8σ, consistent with MAGIC results.

Broad band SED modeling

- **Two-zone leptonic scenario** (near and far from super-massive black hole).
  - Gamma-ray is produced via SSC and EC in **near zone** ($D_{H,near}$ = 2 ×10^{16} cm).
  - Radio/optical emission comes from synchrotron radiation in **far zone** ($D_{H,far}$ = 2.9×10^{17} cm).
  - Including external seed photons from Broad Line Region and Dust Torus.
- Difference between December and January states can be explained by difference in the electron distribution shape.



Galactic Center

This study provides an implication, for the first time in the TeV regime, that diffuse emissions in the region have a spatial variation in spectral curvature.

	HESS (2016, 2018)	MAGIC (2020)	VERITAS (2021)	LST-1 (This Study)
Sectoral Annulus (a.k.a. PacMan)	Power Law Ecut > 60 TeV (90% C.L.)	Not Reported	Not Reported	Power Law Ecut > 46 TeV (90% C.L.)
total ridge	Power Law Ecut: Not Reported	Ecut ~ 20 TeV, 2σ	Power Law Ecut > 10 TeV (95% C.L.)	Ecut ~ 24 TeV, 2.8σ (3.7σ from rectangle)
CR longitudinal profile: $r^{-\alpha}$	alpha = 1.10 ± 0.12	alpha = 1.2 ± 0.3	Not Reported	alpha = 1.21 ± 0.11
Zenith Angle	Low Zd	Large Zd	Large Zd	Large Zd
Field of View	5.0 deg	3.5 deg	3.5 deg	4.5 deg