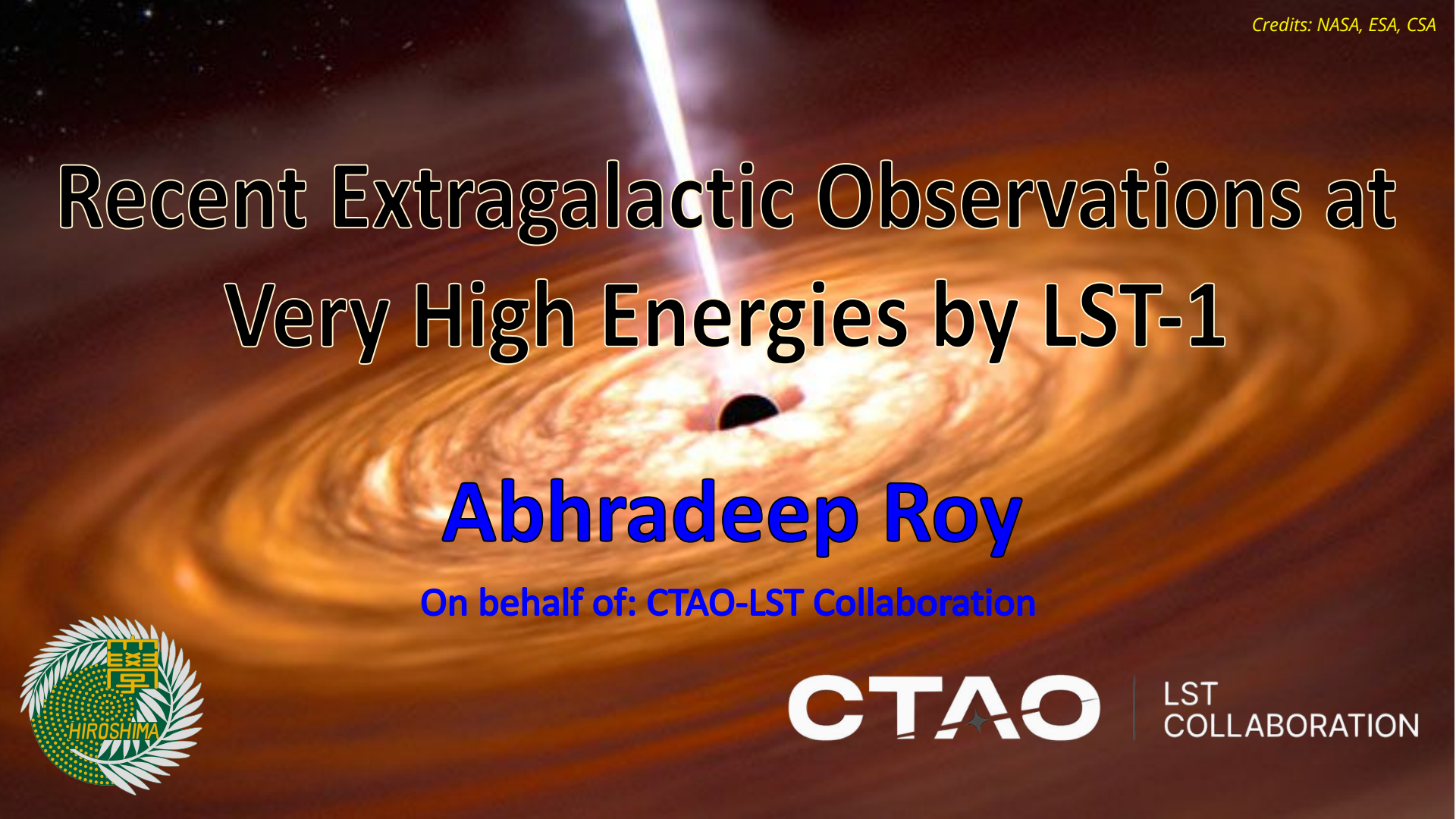



# Recent Extragalactic Observations at Very High Energies by LST-1

**Abhradeep Roy**

On behalf of: CTAO-LST Collaboration

HIROSHIMA

CTAO | LST COLLABORATION

# Outline

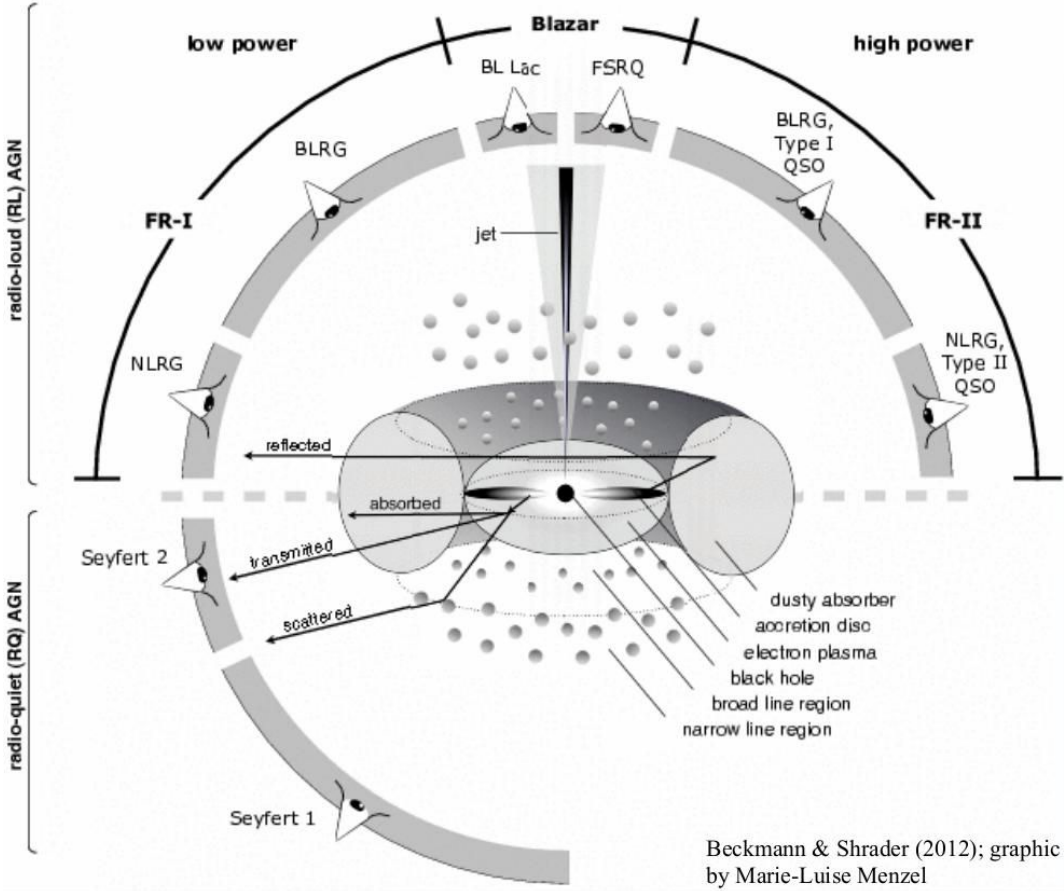
1. Motivation
2. The Large Sized Telescope-1
3. Observed blazars
   a. Mrk 421
   b. Mrk 501
   c. 1ES 1959+650
   d. BL Lac

   Nearby sources ($z < 0.1$)

   e. 1ES 0647+250
   f. PG 1553+113
   g. OP 313

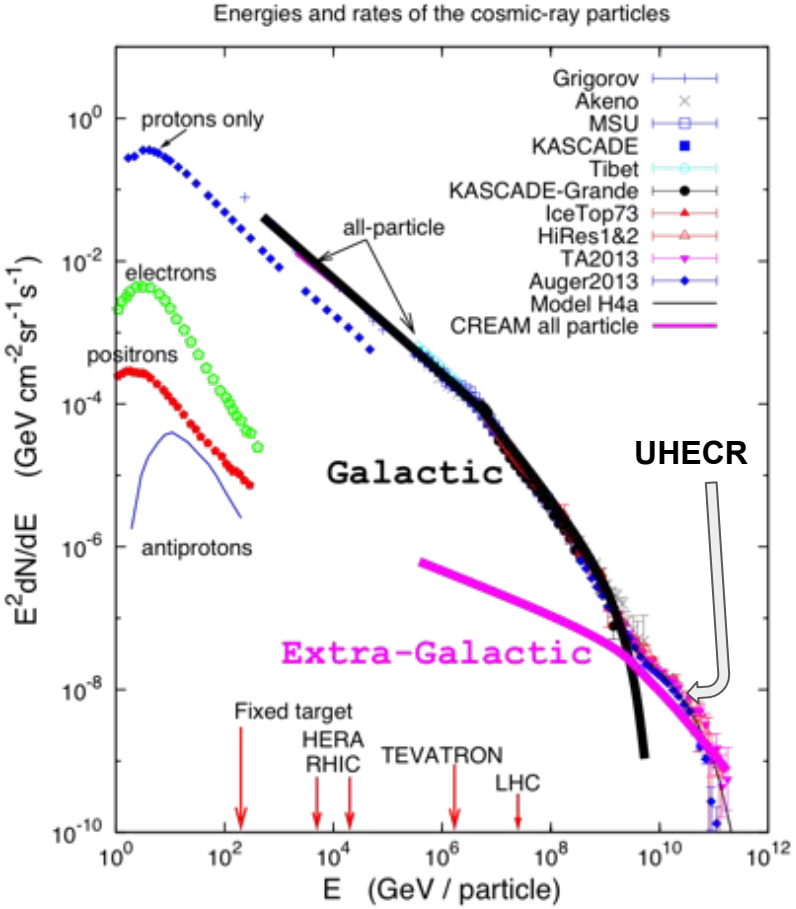
   Distant sources ($z > 0.4$)

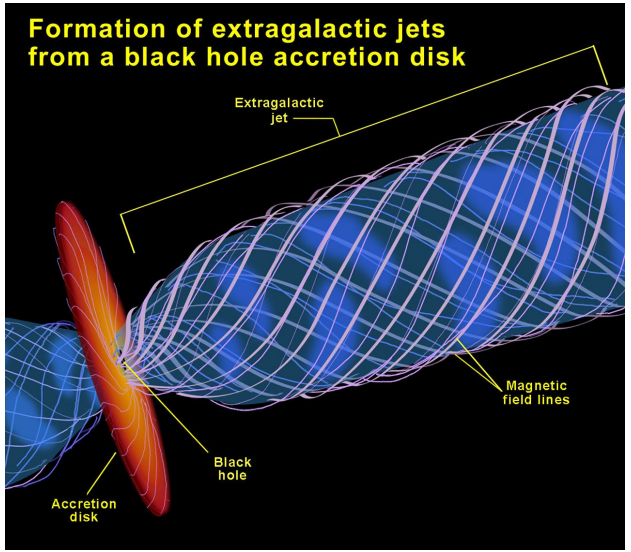
   h. 1ES 1218+304
4. Summary

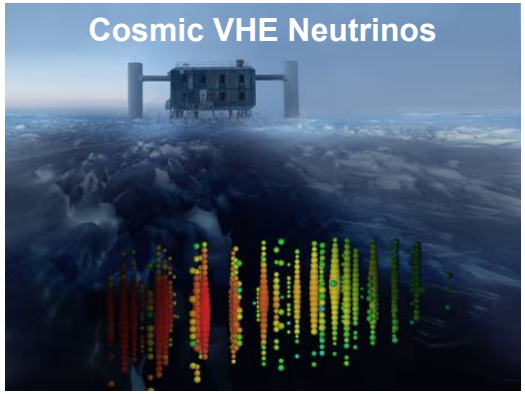



Beckmann & Shrader (2012); graphic by Marie-Luise Menzel

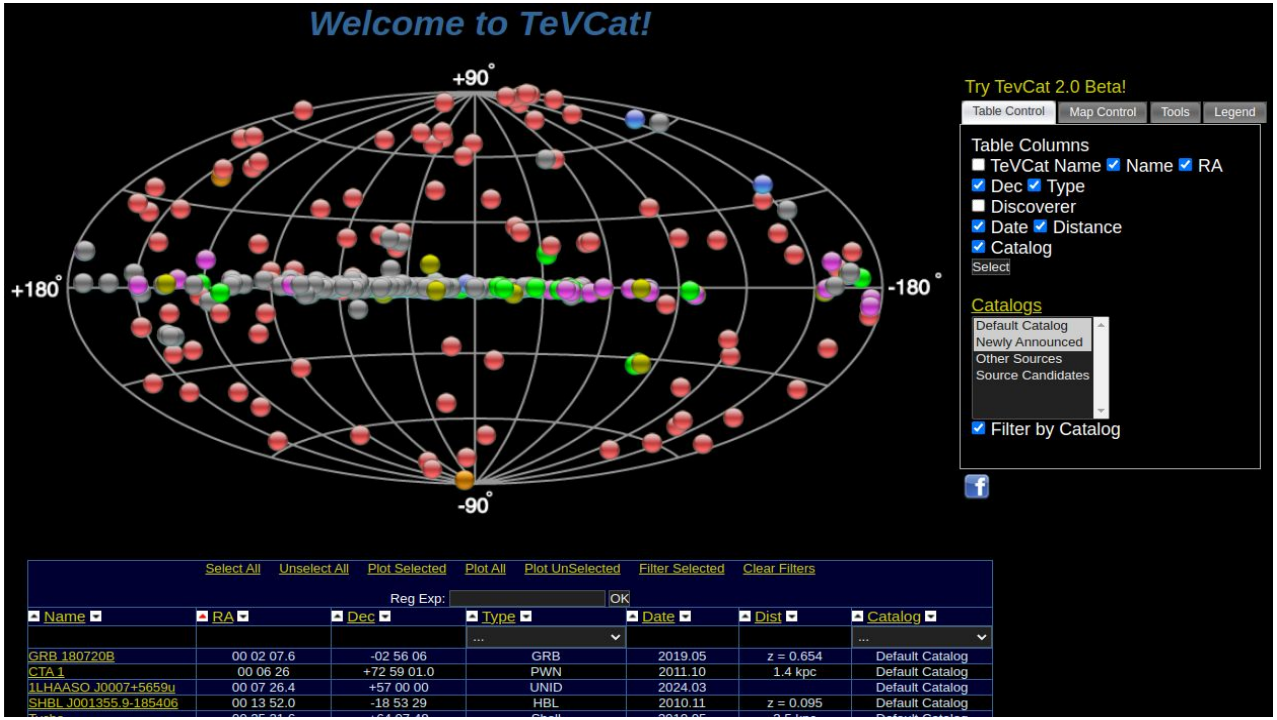
# Motivation behind Extragalactic Observations



# The Extragalactic Sky at VHE



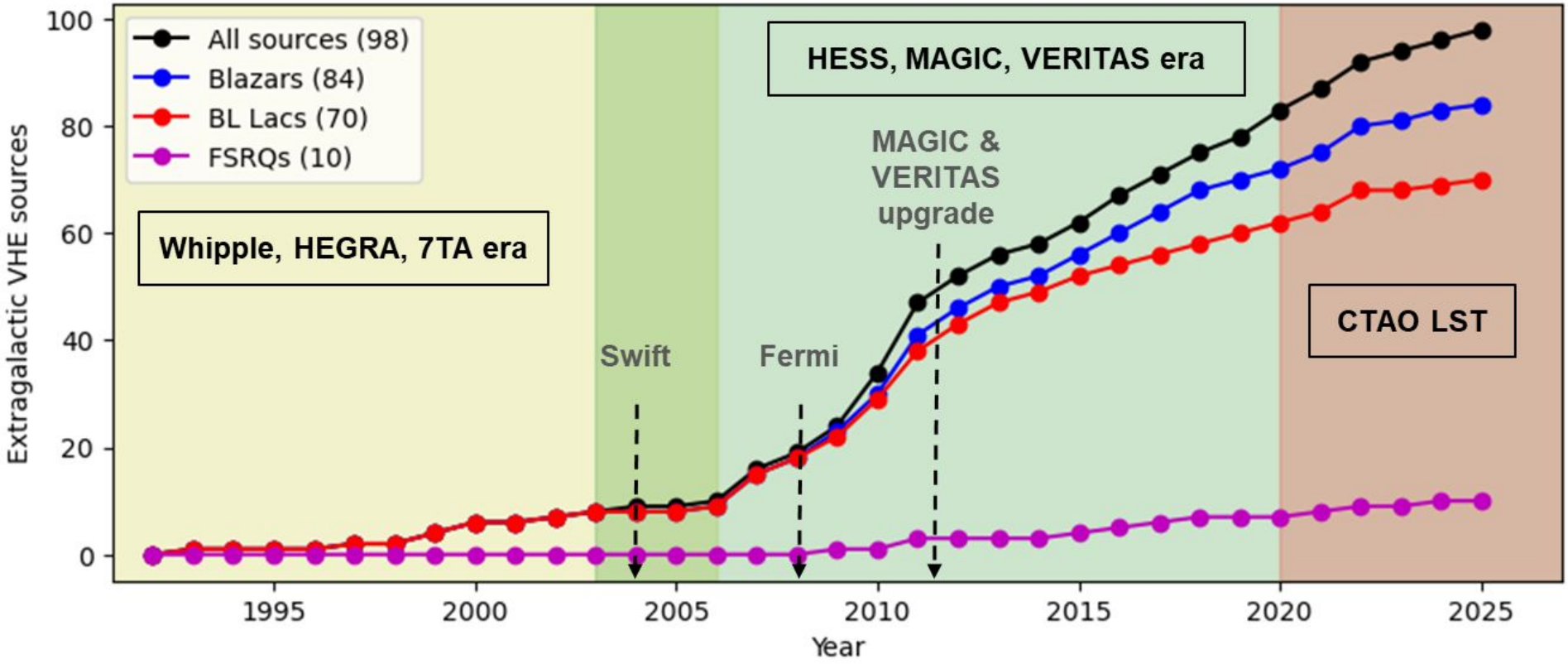

http://tevcat.uchicago.edu/

Or

http://tevcat2.uchicago.edu/

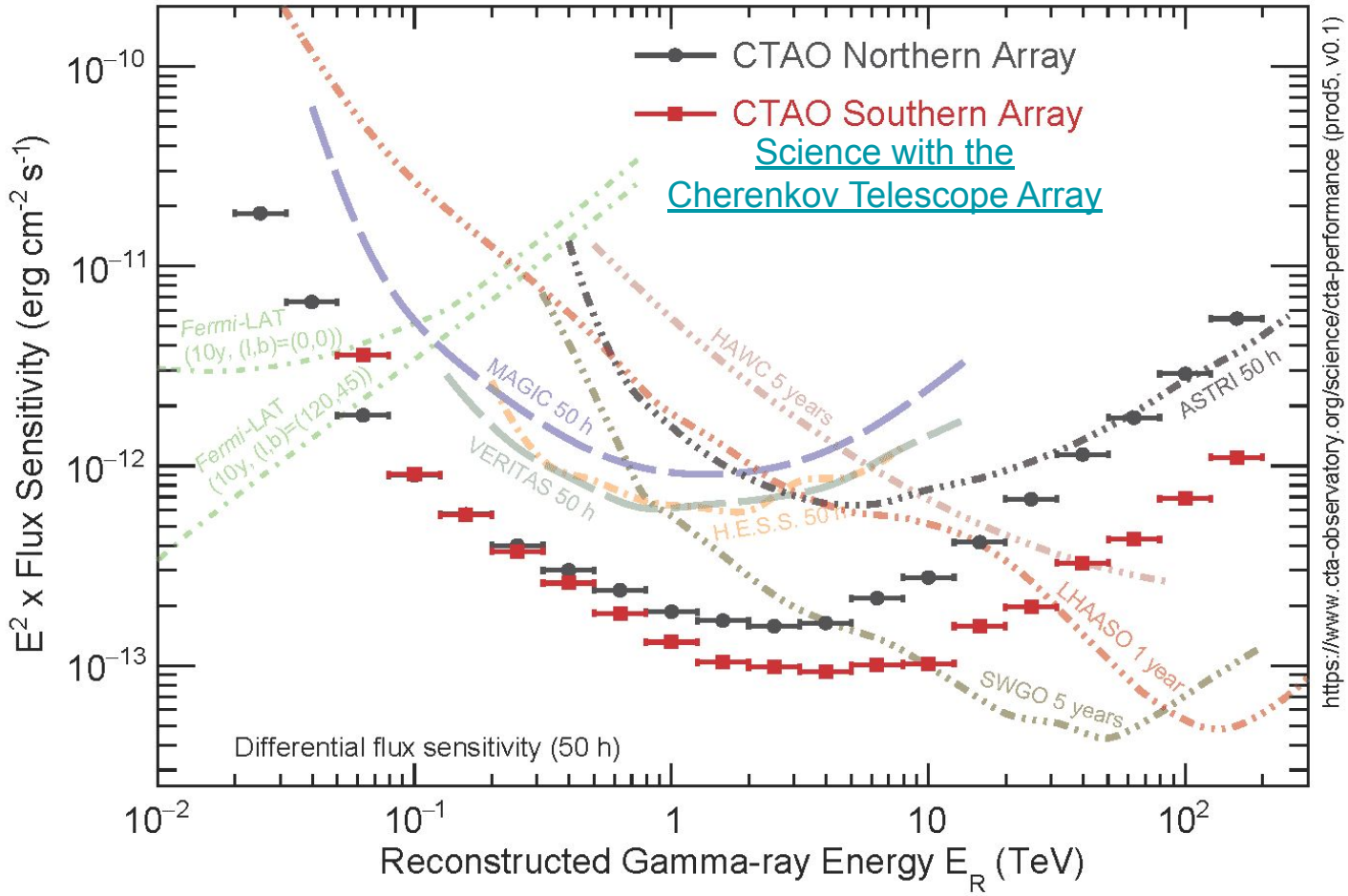
- Total VHE sources: 308
- Extragalactic sources: 98
  - AGN (88)
  - Starburst galaxies (3)
  - GRB (7)

# The Extragalactic Sky at VHE with CTA-LST

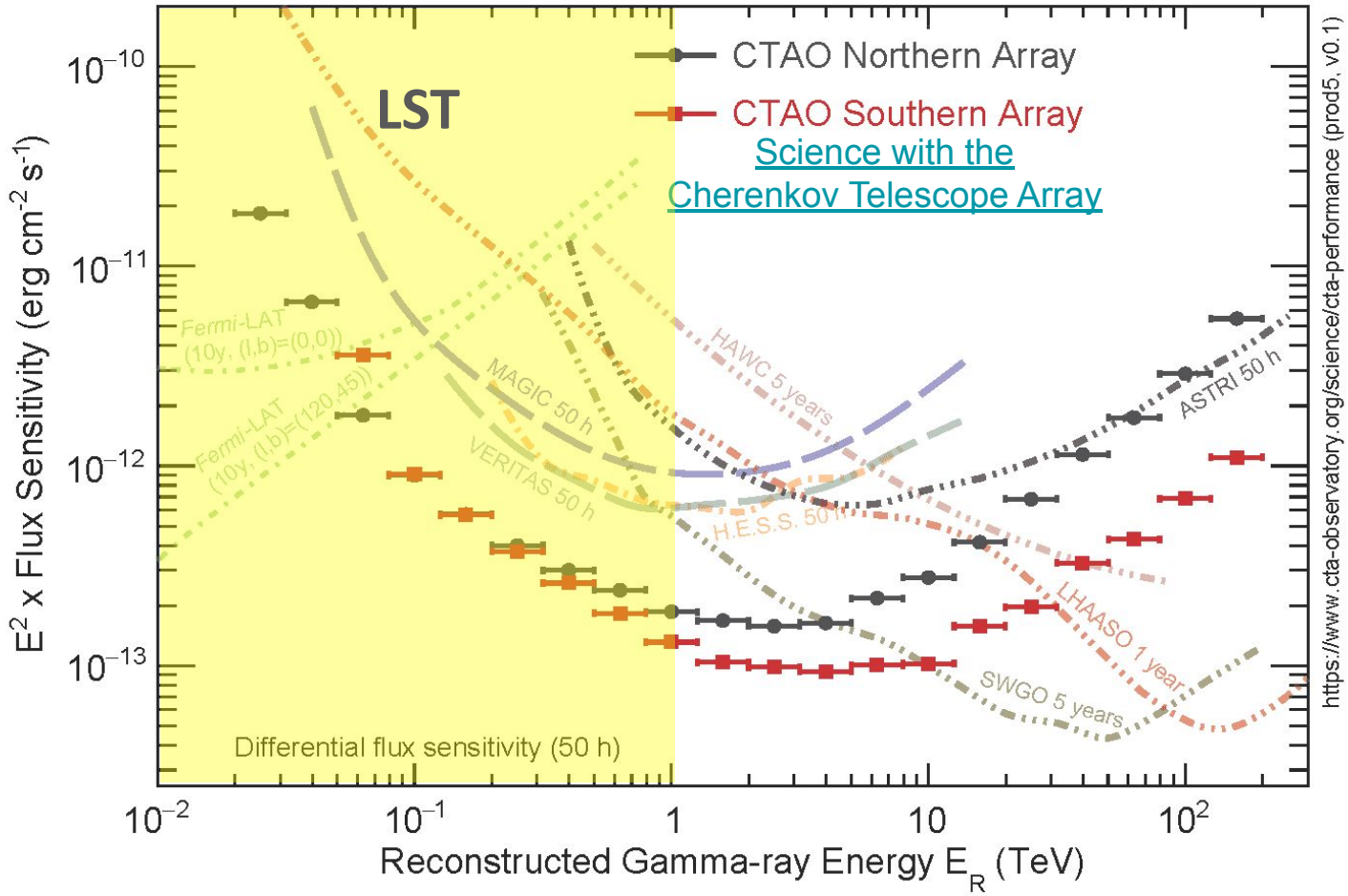


# The Extragalactic Sky at VHE with CTA-LST

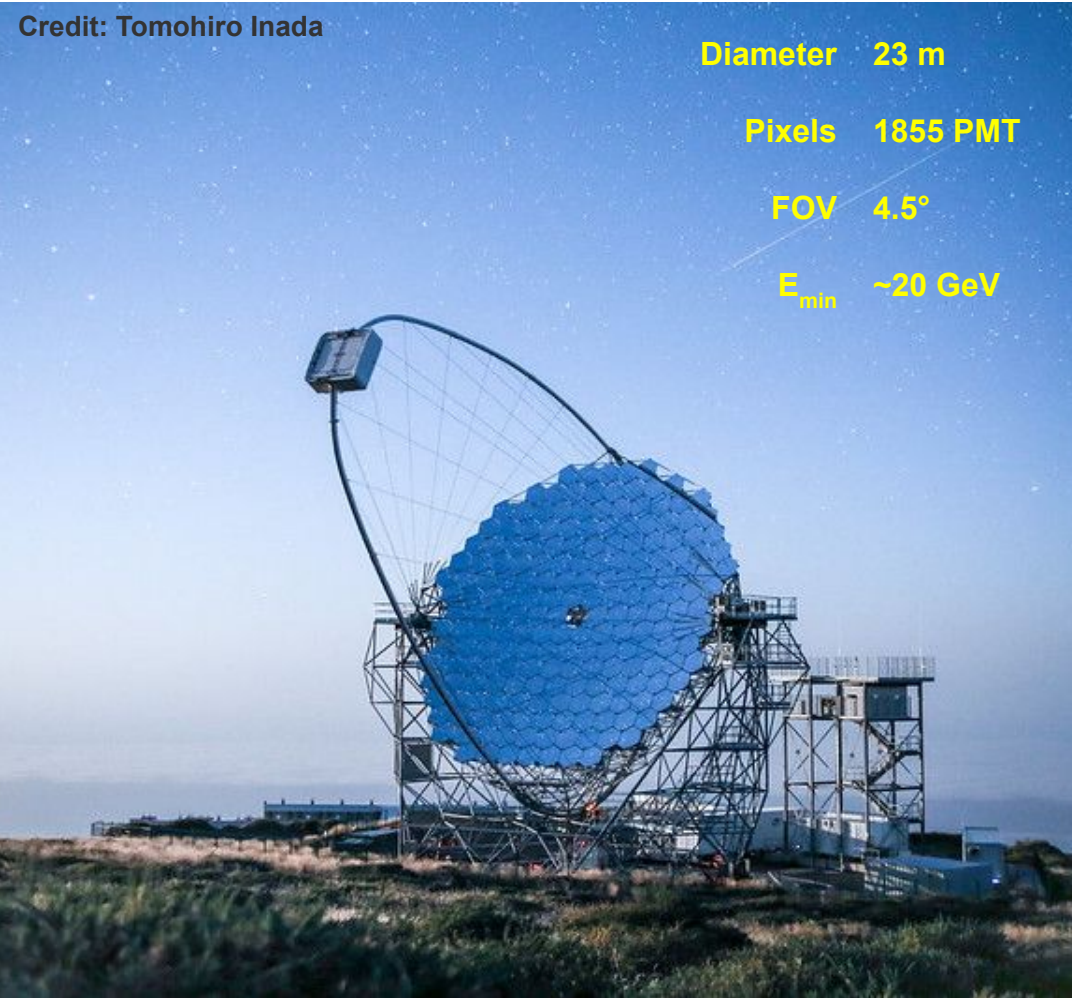


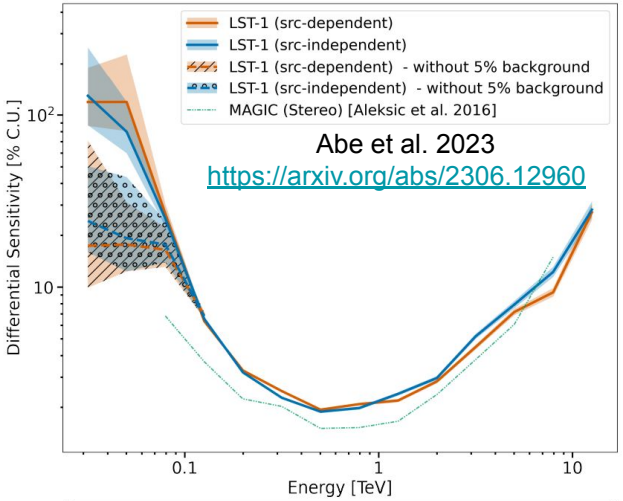


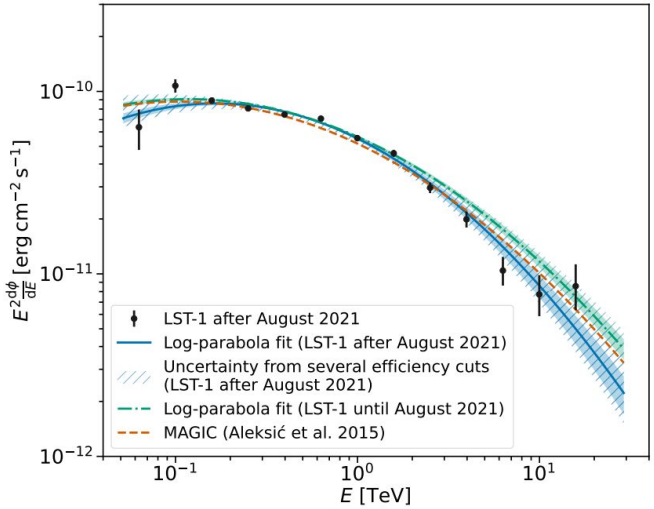
# The Extragalactic Sky at VHE with CTA-LST



# The Large Sized Telescope-1



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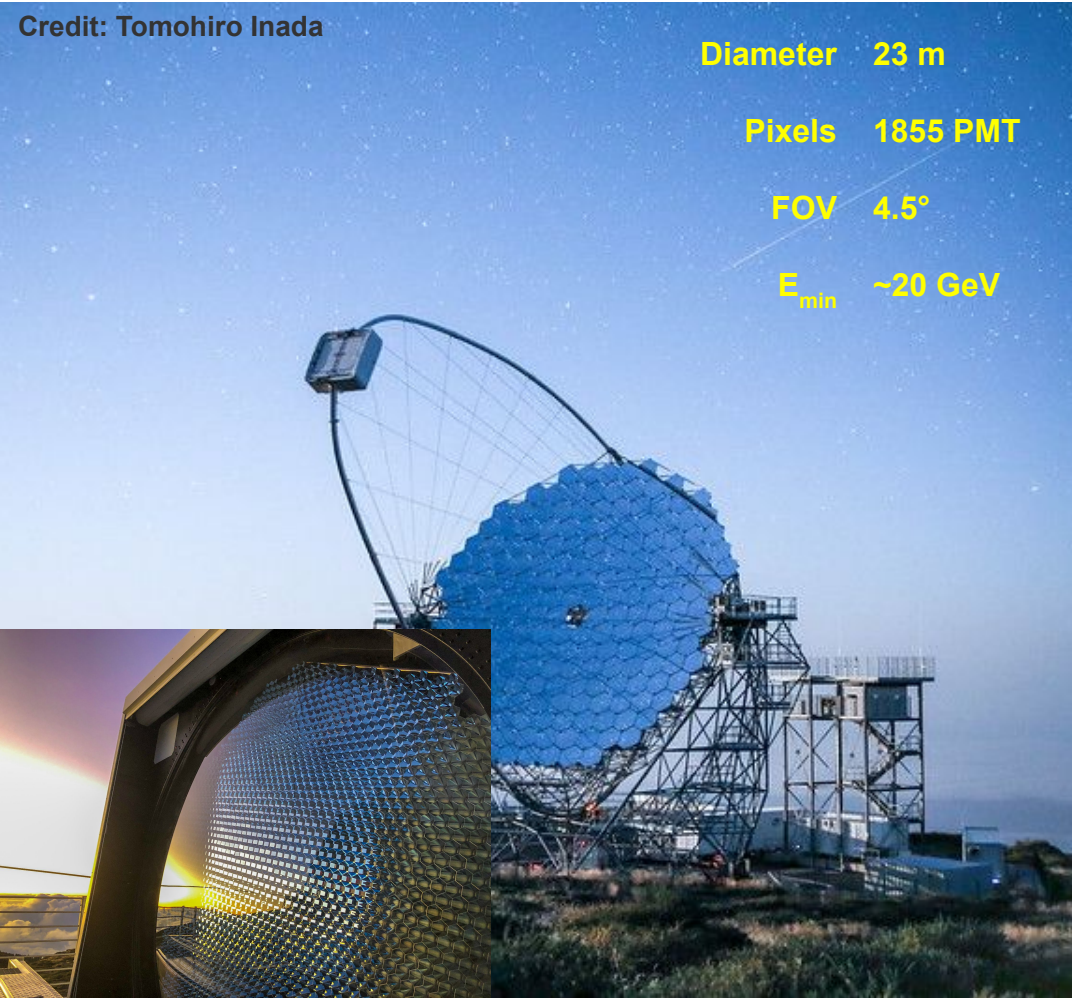
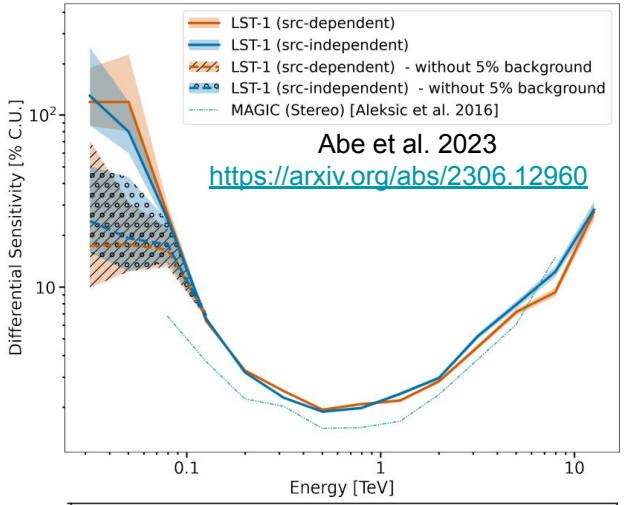
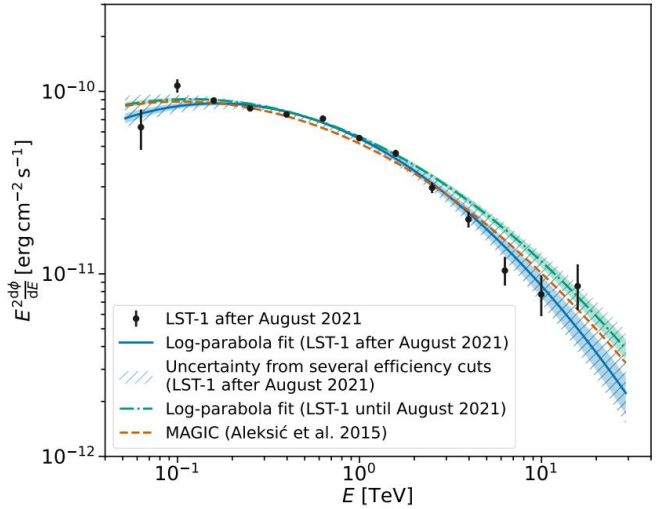
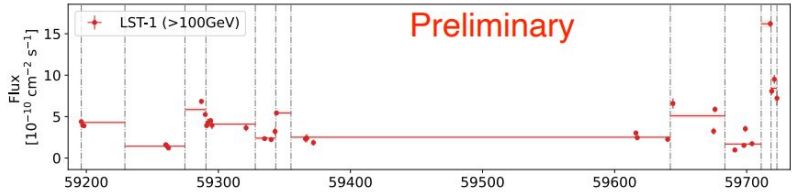


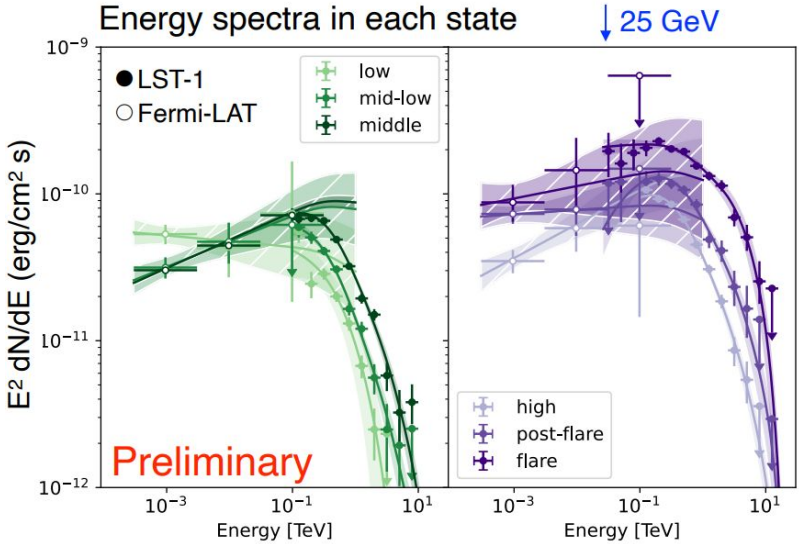



# Mrk 421 (z = 0.031)

- ➔ Observation time: 31.9 hrs (2020 to 2022)
- ➔ Detection significance: 53σ
- ➔ Bayesian blocks to identify states of activity




*Credit: Ryuji Takeishi (TeVPA 2024)*

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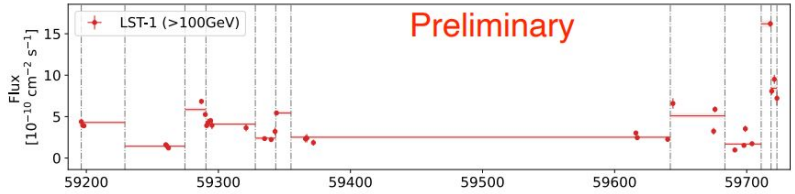
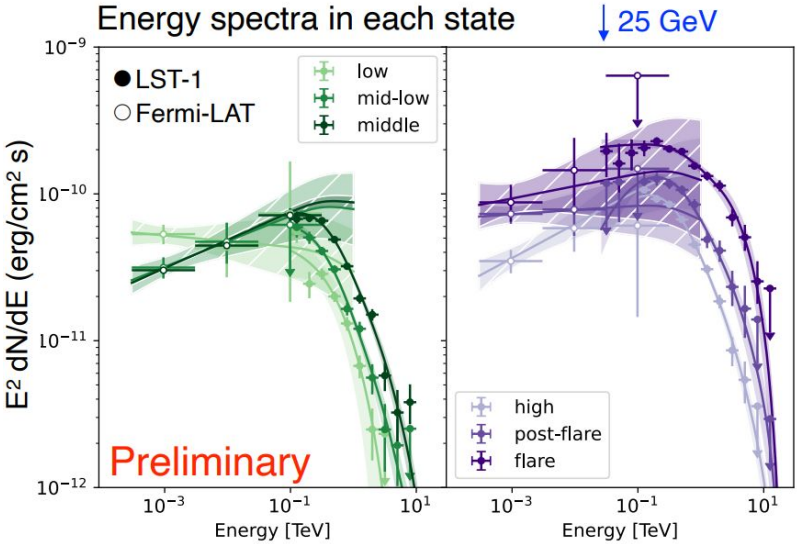
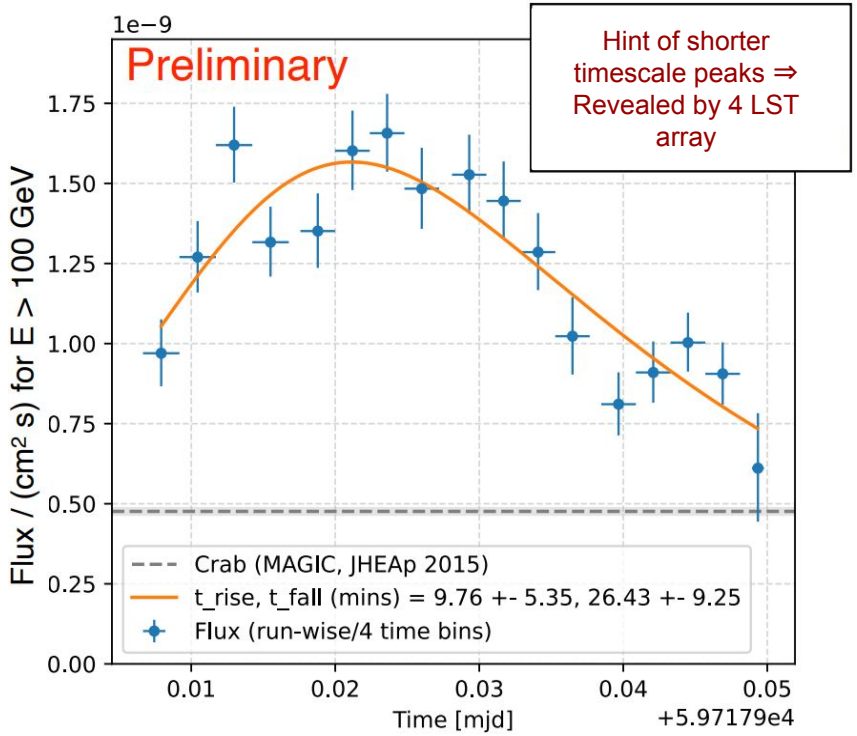



- ➔ Flare on 2022-05-18 (~3 crabs at >100 GeV)
- ➔ Fast variability observed during flare.
- ➔ Rise time: ~10 min, Fall time: ~26 min
- ➔ Compact emission region: $0.2 - 3 \times 10^{15}$ cm




*Credit: Ryuji Takeishi (TeVPA 2024)*

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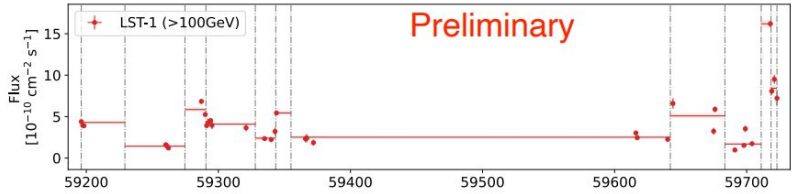


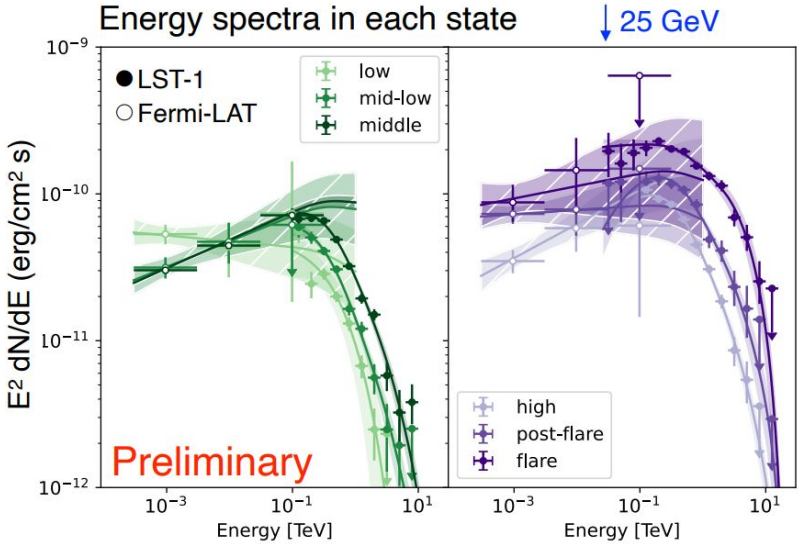


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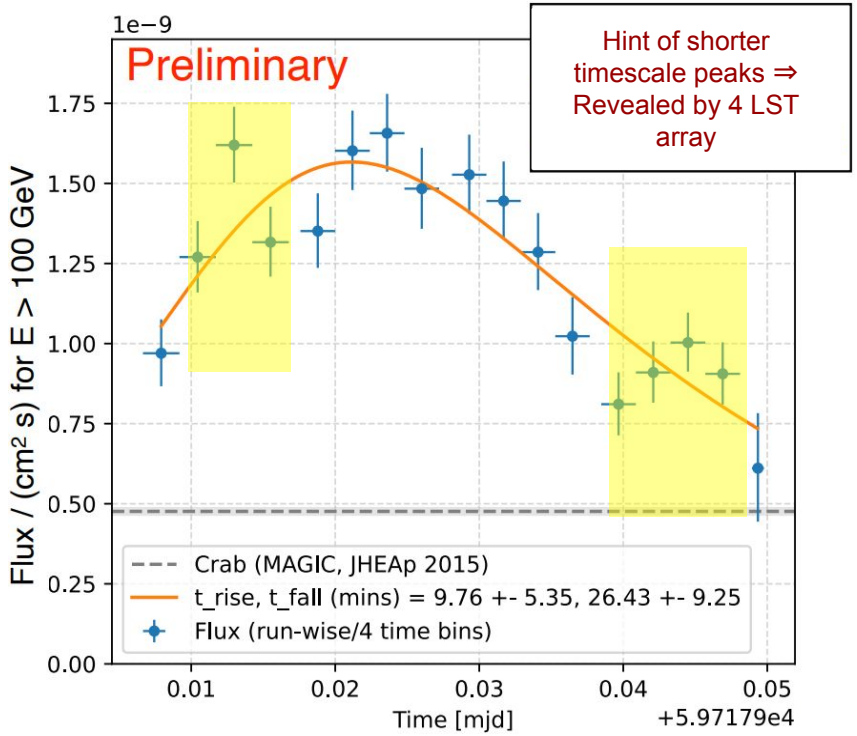
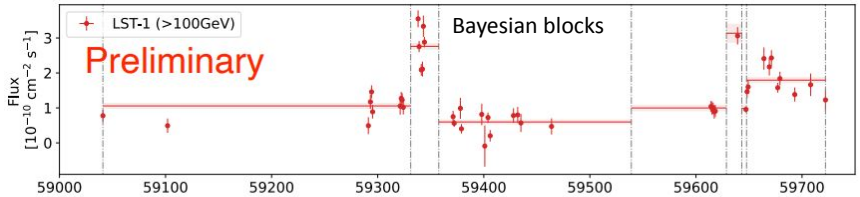
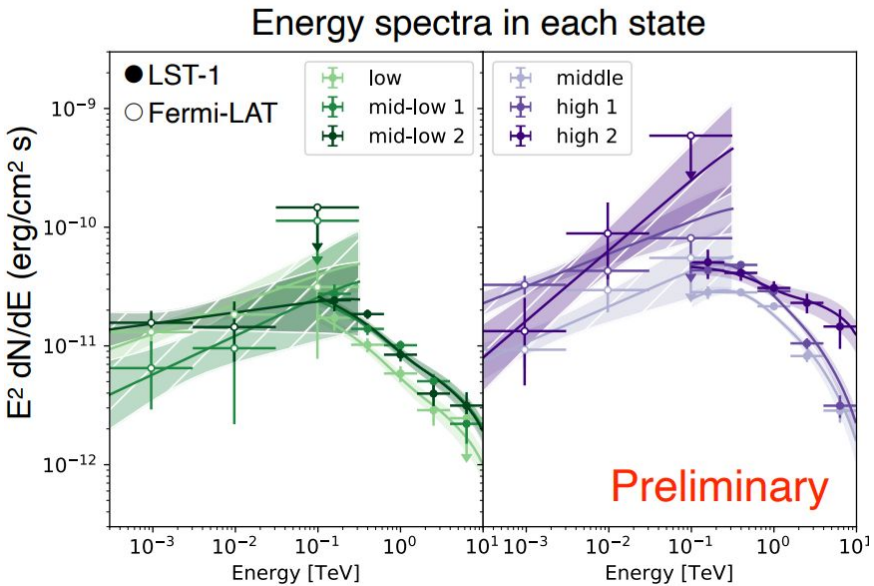



*Credit: Ryuji Takeishi (TeVPA 2024)*

# Mrk 501 (z = 0.034)

- ➔ Observation time: 39.7 hrs (2020 to 2022)
- ➔ Detection significance: 21σ




*Credit: Ryuji Takeishi (TeVPA 2024)*

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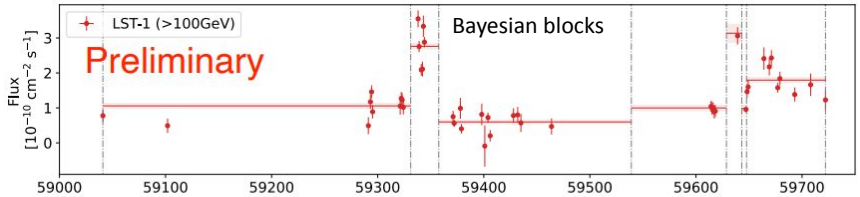
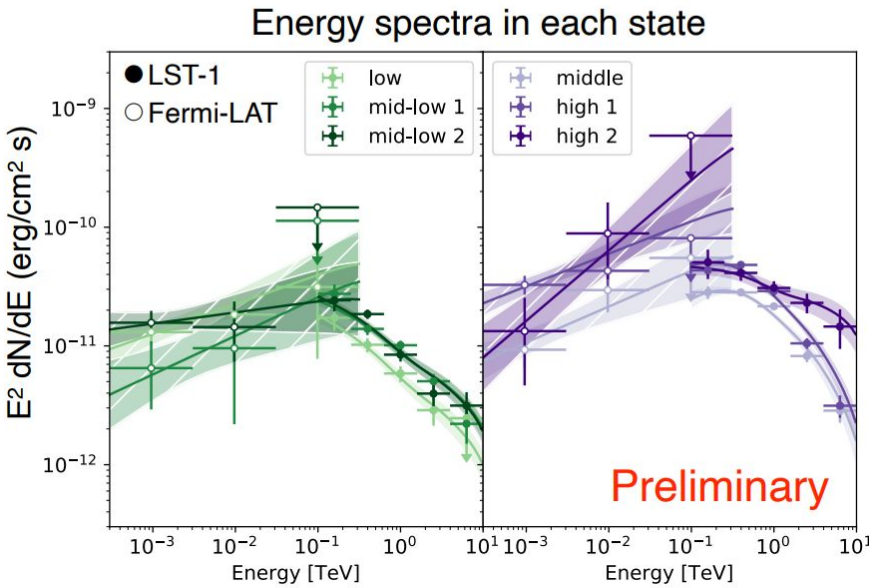
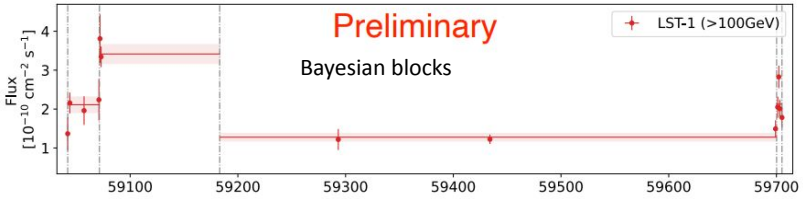
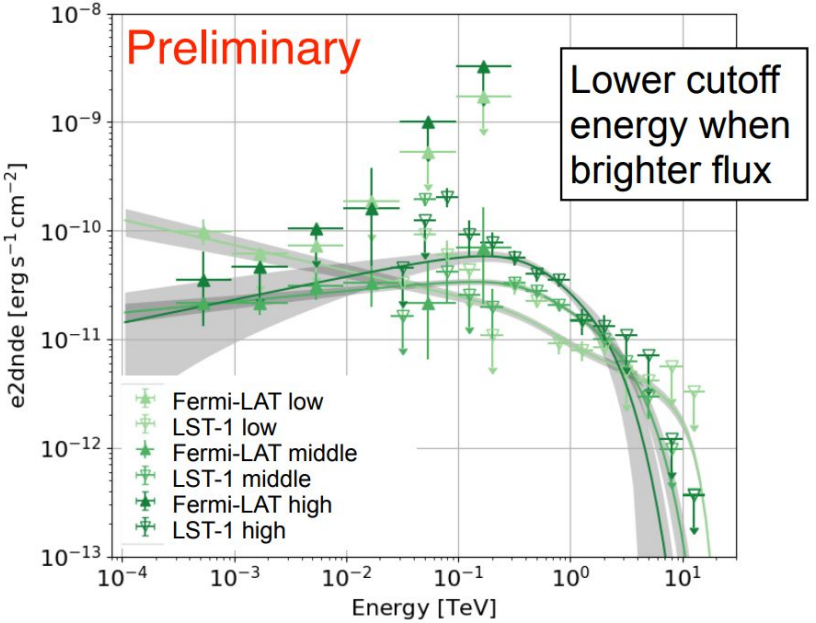



# 1ES 1959+650 (z = 0.048)

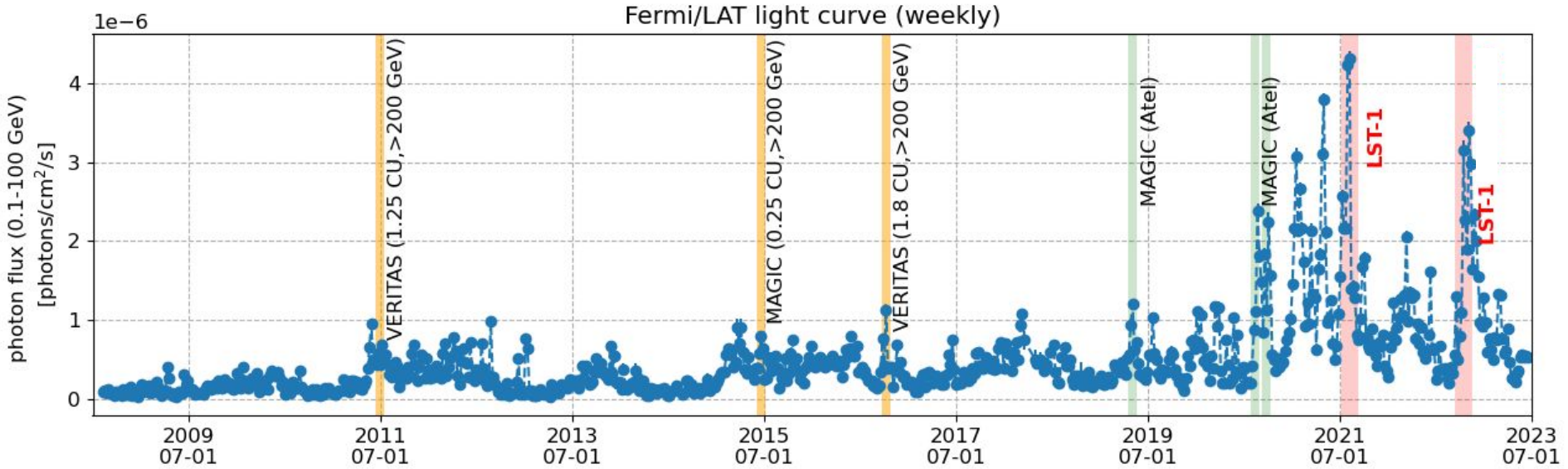
- ➔ Observation time: 11.8 hrs (2020 to 2022)
- ➔ Detection significance: 13σ




*Credit: Ryuji Takeishi (TeVPA 2024)*

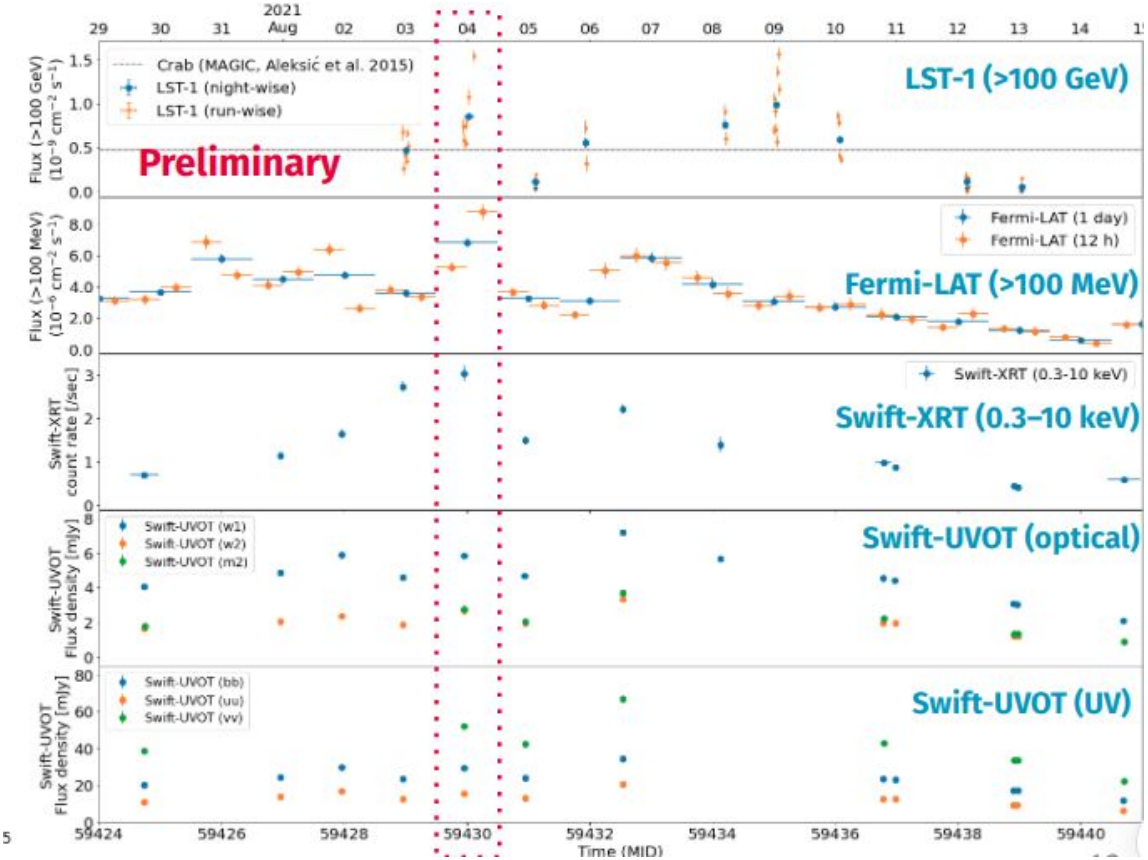
# BL Lac (z = 0.07)




➔ Two major flares in 2021 and 2022, brightest emission ever observed from BL Lac in VHE.

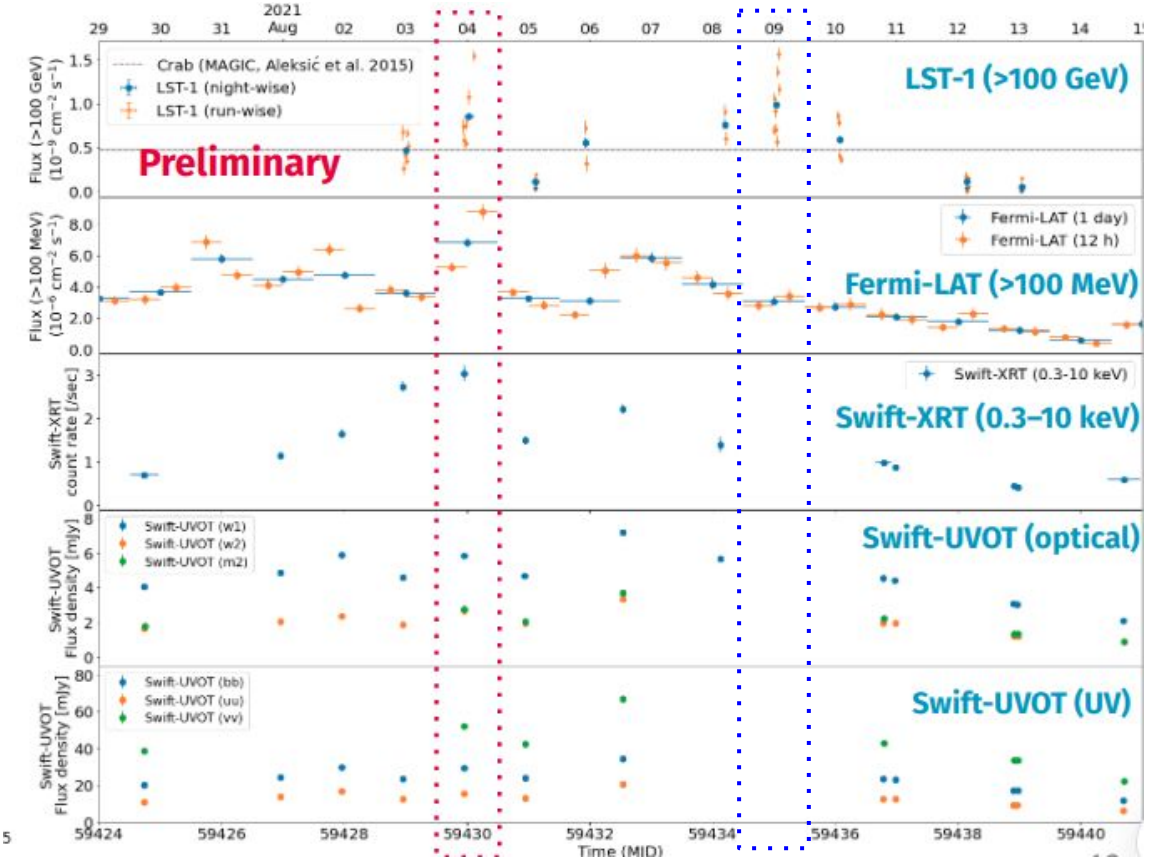
*Credit: Seiya Nozaki (ICRC 2023)*

# BL Lac (z = 0.07) in 2021

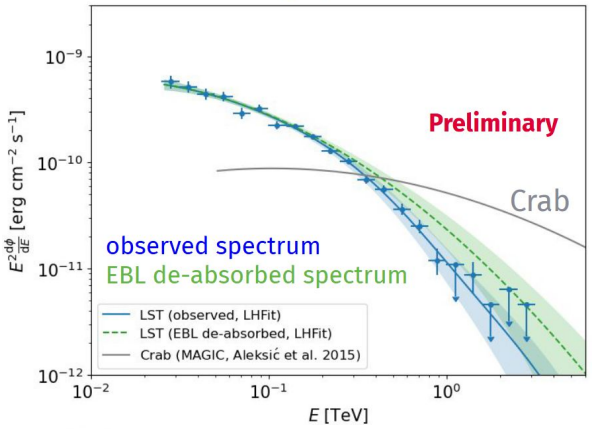


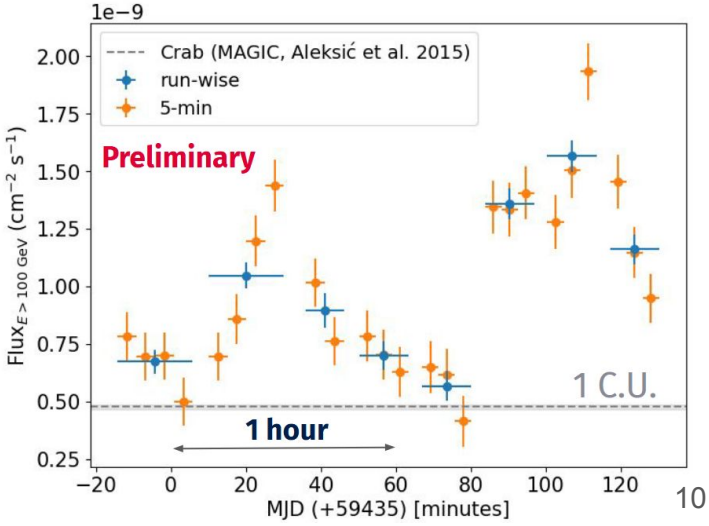

*Credit: Seiya Nozaki (ICRC 2023)*

# BL Lac (z = 0.07) in 2021




Aug 9, 2021



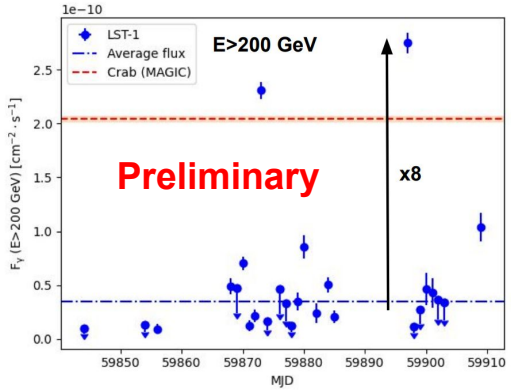



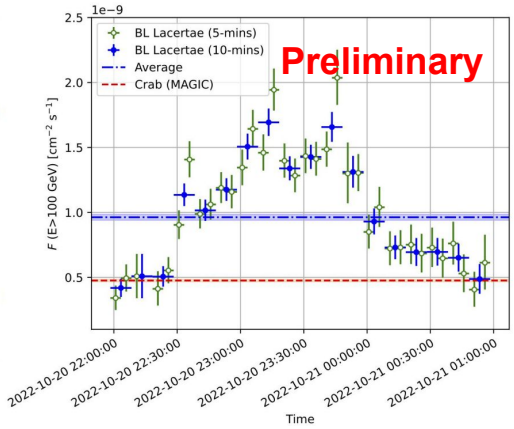

*Credit: Seiya Nozaki (ICRC 2023)*

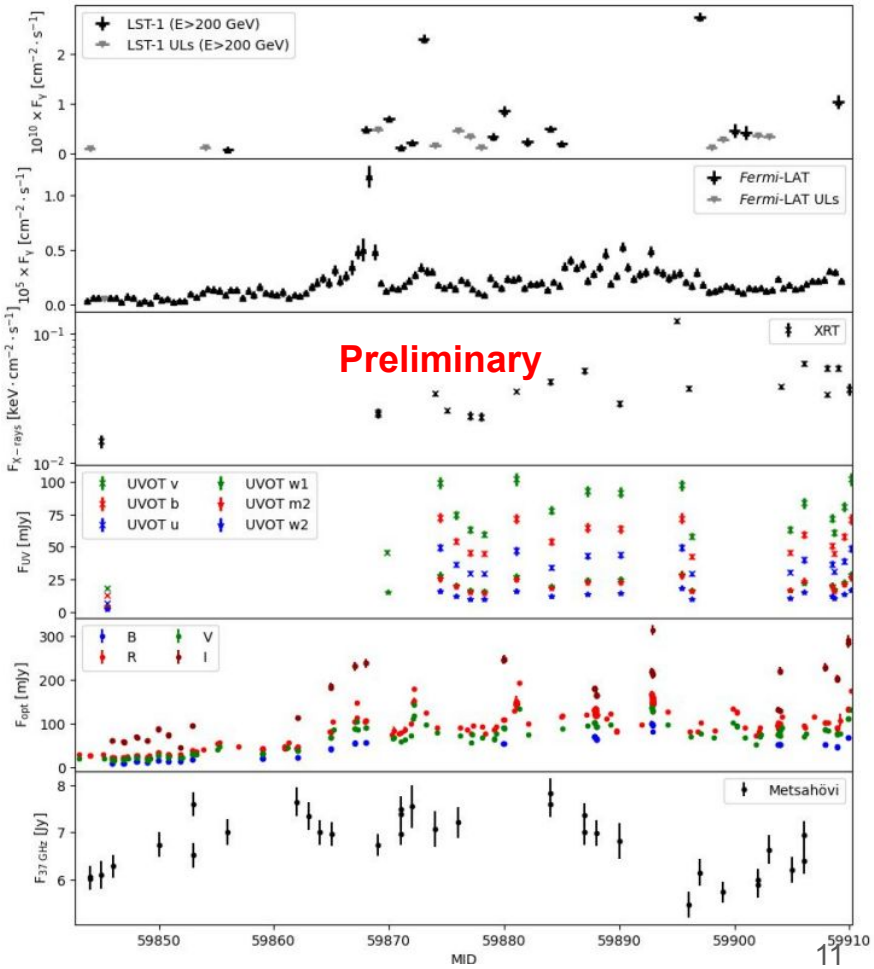
# BL Lac (z = 0.07) in 2022

- 36 hours of good quality data ⇒ 28σ significance (>100 GeV).
- Brightest night: 20 Oct. (40σ) & 13 Nov. (27σ).
- Flux peaking above 2 C.U.

- Short timescale variability:
  - Rise time = 22 ± 3 min
  - Decay time = 34 ± 5 min
  - Region ($\delta$ = 30 – 50) ≃ $10^{15}$ cm.



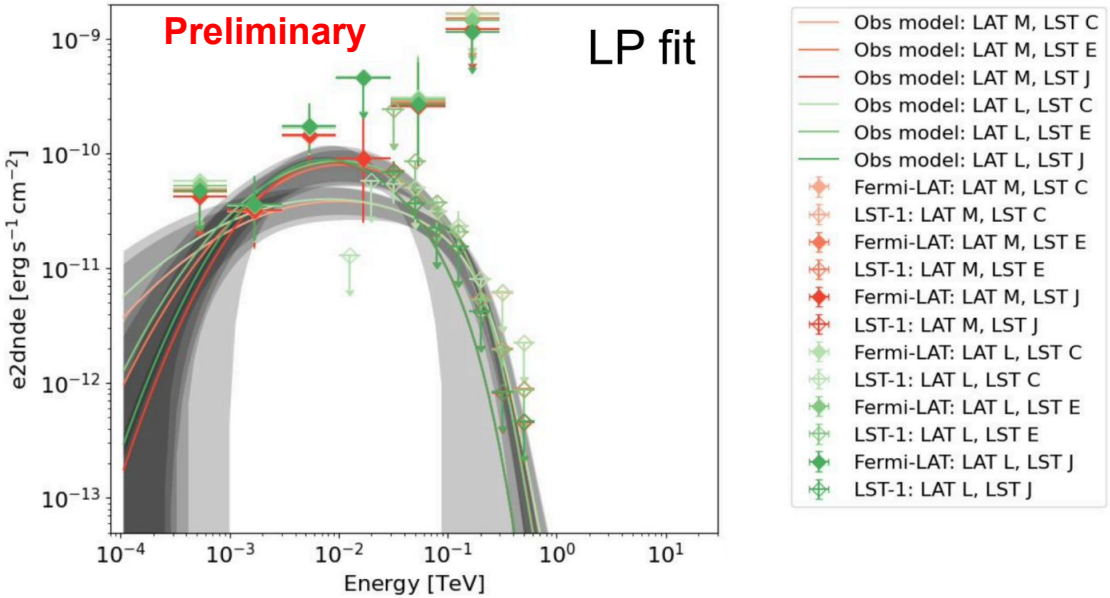




*Credit: Jorge Otero-Santos (SEA 2024)*

# 1ES 0647+250 (z = 0.45)

- ➔ Observation time: 8.2 hrs (2020 to 2022)
- ➔ Detection significance: 7σ
- ➔ Joint Fermi-LAT + LST1 fit performed




*Credit: Ryuji Takeishi (TeVPA 2024)*

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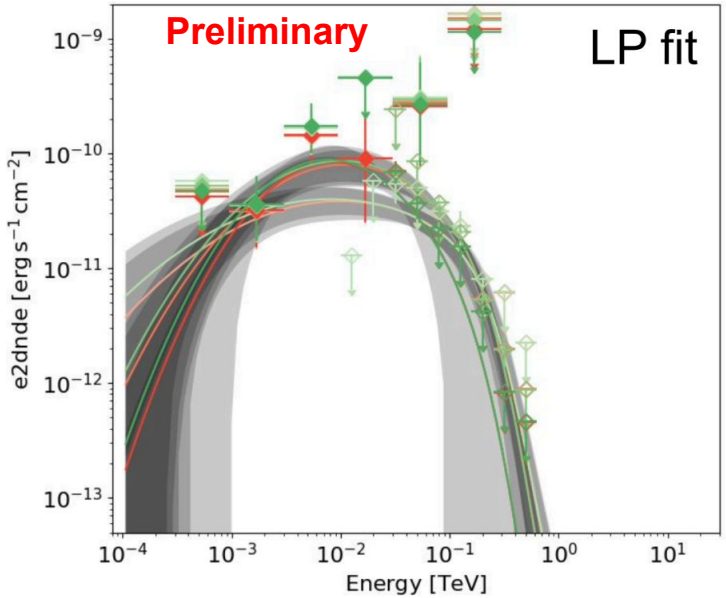
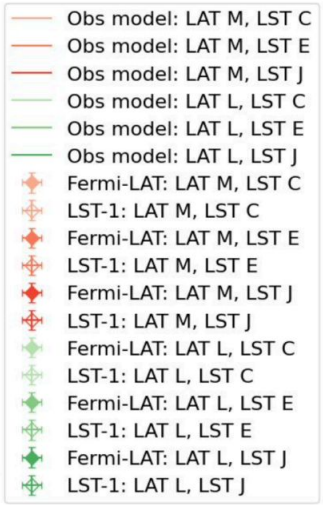
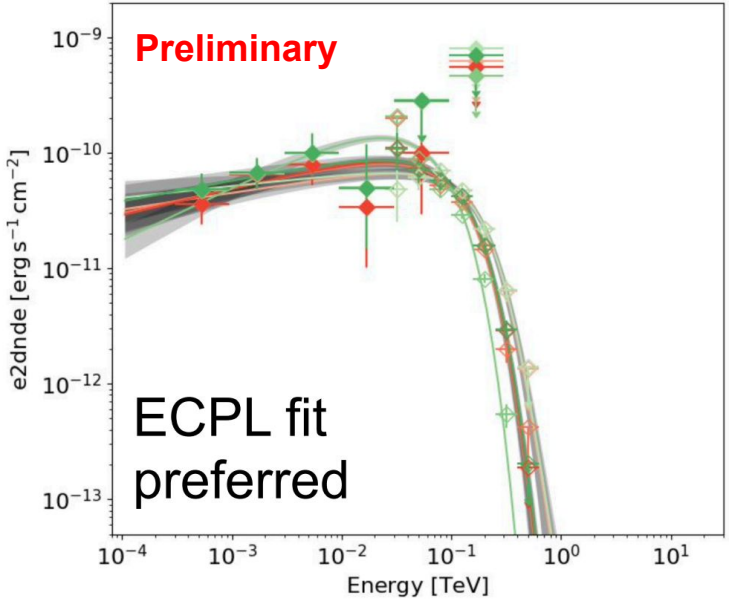



# PG 1553+113 (z = 0.433)

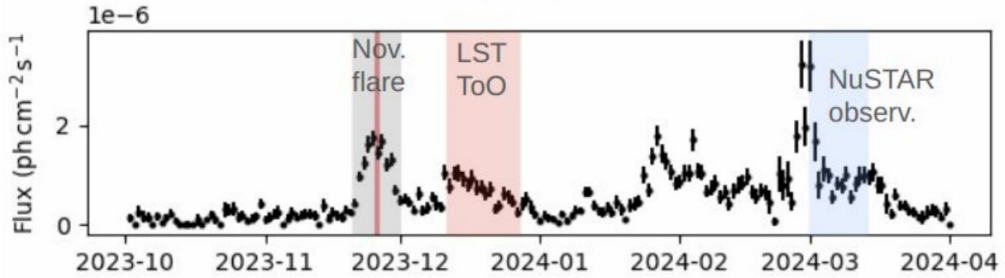
- ➔ Observation time: 9.9 hrs (2020 to 2022)
- ➔ Detection significance: 16σ
- ➔ Joint Fermi-LAT + LST1 fit performed

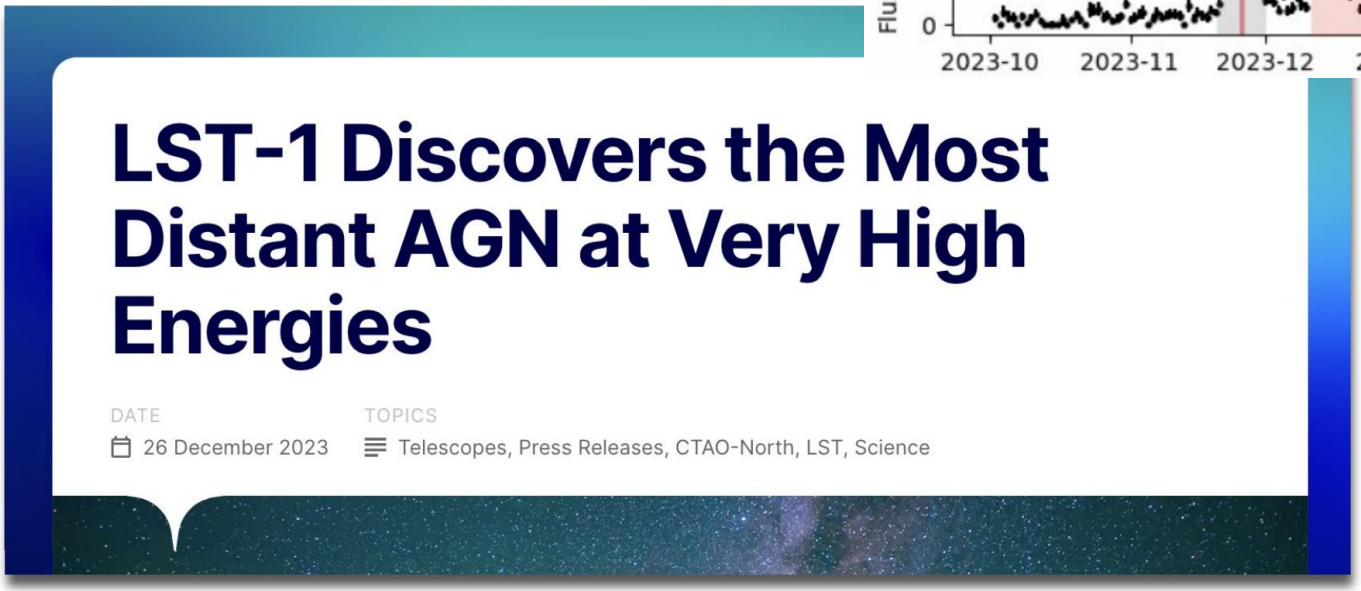



*Credit: Ryuji Takeishi (TeVPA 2024)*

# OP 313 (z = 0.997)

- ➔ **The most distant quasar detected in VHE by LST1** (ATel #16381).
- ➔ Only 10th FSRQ in VHE.
- ➔ LST-1 observation started on December 9.
- ➔ Pointing zenith angle >30 deg. Energy threshold 40 GeV.




*Credit: Mireia Nievas (TeVPA 2024)*

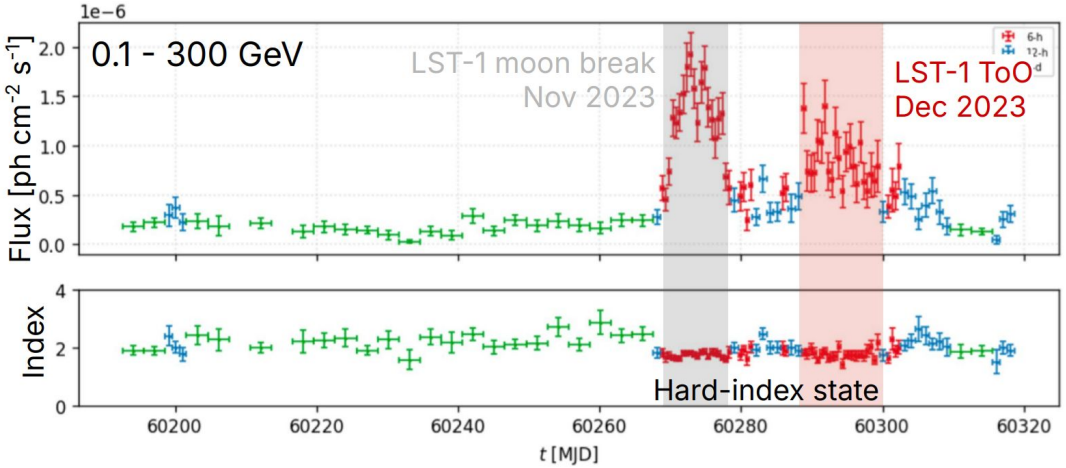
# OP 313 (z = 0.997)

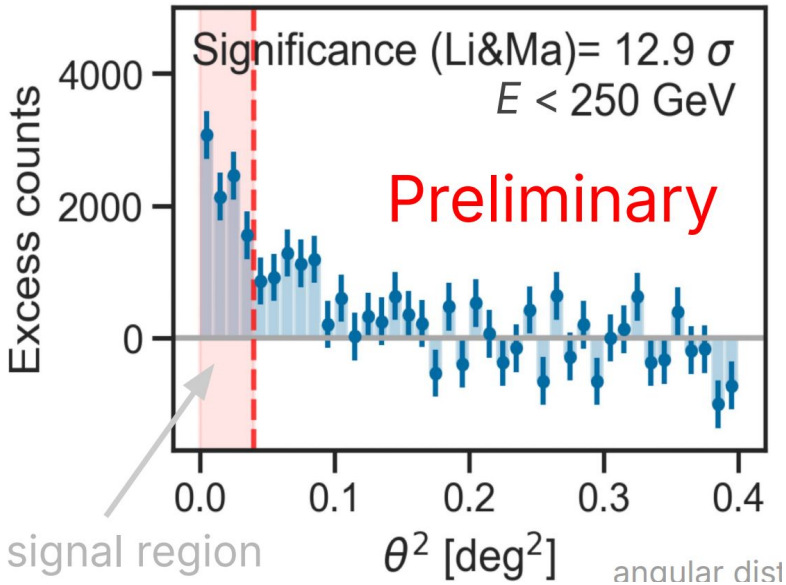
- **The most distant quasar detected in VHE by LST1** (ATel #16381).
- Only 10th FSRQ in VHE.
- LST-1 observation started on December 9.
- Pointing zenith angle >30 deg. Energy threshold 40 GeV.
- Observation time: 15 hrs (During flare in December 2023)
- Detection significance: 13σ
- Flux = 0.28 Crabs (>100 GeV)
- Multiple ongoing projects: variability, EBL, MWL etc.

**First detection of VHE gamma-ray emission from FSRQ OP 313 with LST-1**

ATel #16381; *Juan Cortina (CIEMAT) for the CTAO LST collaboration*
*on **15 Dec 2023; 14:31 UT***
*Credential Certification: Juan Cortina (Juan.Cortina@ciemat.es)*

Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, AGN, Blazar, Quasar

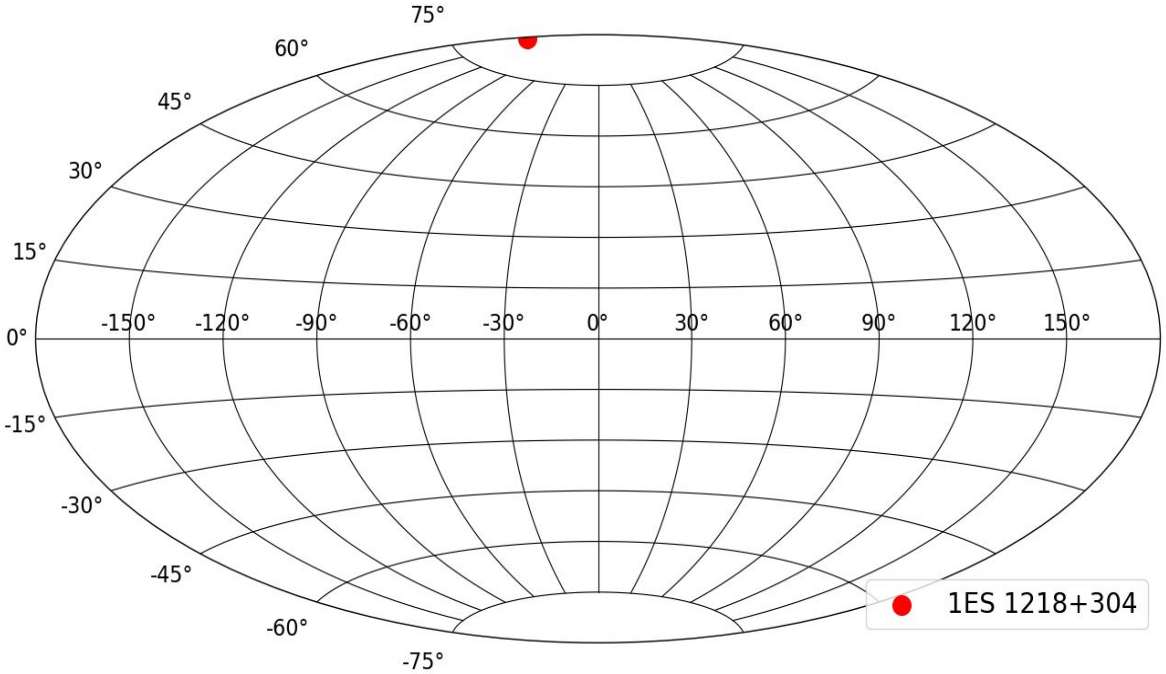



*Credit: Mireia Nievas (TeVPA 2024)*

# 1ES 1218+304 (z = 0.182)

- ➔ High-energy peaked BL Lac – TeV discovery by MAGIC on 2006-05 (Albert et al. 2006)
- ➔ VHE variability observed by VERITAS (Acciari et al. 2010)
- ➔ Observed spectral index ~3.0 (MAGIC and VERITAS)




More details: TeVCat Gamma-Ray Source Summary: 1ES 1218+304

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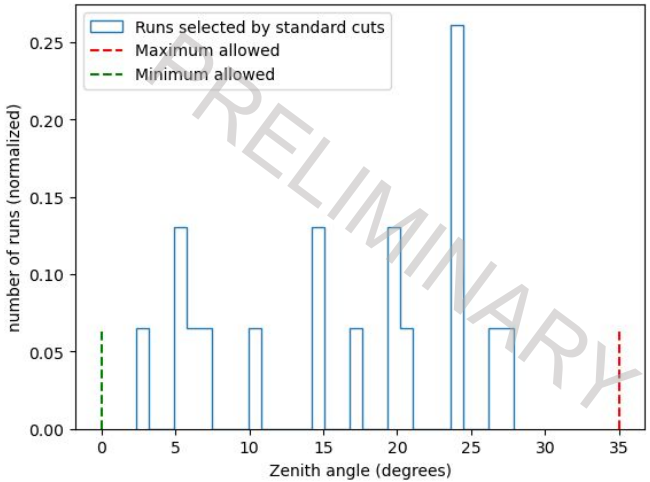
- ➔ VHE variability observed by VERITAS (Acciari et al. 2010)
- ➔ Observed spectral index ~3.0 (MAGIC and VERITAS)

**LST-1 Observation**

- ➔ **Period:** 2023-02-28 to 2023-04-12
- ➔ **Duration:** 18 hours – 40% in moonlight (Rejected by standard cuts!)
- ➔ **Tools:** lstchain-v0.10.11 (DL1 to DL3) ⟶ gammapy-1.1 (post DL3)

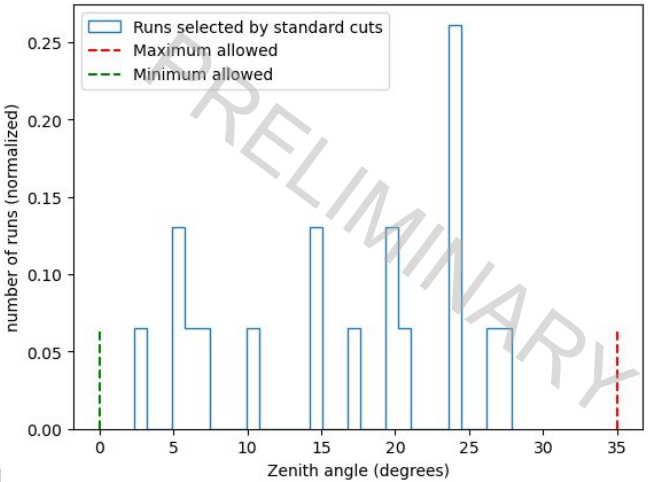


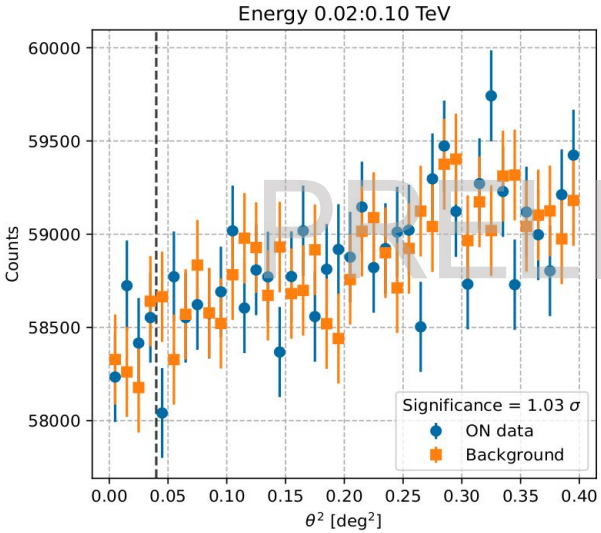
# 1ES 1218+304 (z = 0.182)

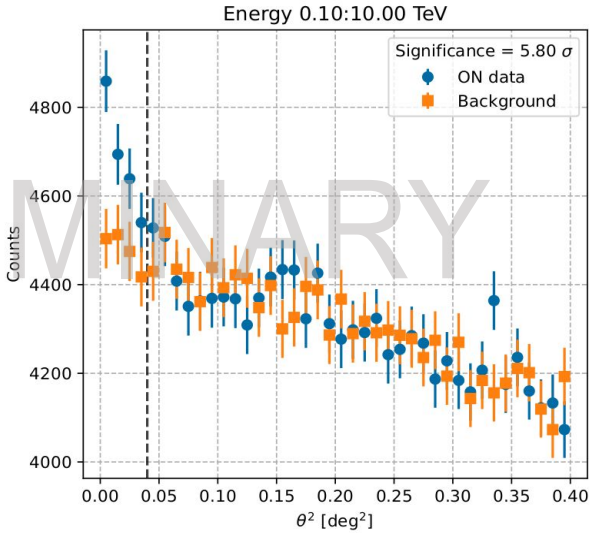
- ➔ High-energy peaked BL Lac – TeV discovery by MAGIC on 2006-05 (Albert et al. 2006)
- ➔ VHE variability observed by VERITAS (Acciari et al. 2010)
- ➔ Observed spectral index ~3.0 (MAGIC and VERITAS)

**LST-1 Observation**

- ➔ **Period:** 2023-02-28 to 2023-04-12
- ➔ **Duration:** 18 hours – 40% in moonlight (Rejected by standard cuts!)
- ➔ **Tools:** lstchain-v0.10.11 (DL1 to DL3) ⟶ gammapy-1.1 (post DL3)






**Source Detection:**

- ➔ Selected duration by quality cuts: 4.4h
- ➔ Energy-dependent dynamic gammaness cut with 70% efficiency.
- ➔ Detection with 5.8σ significance.

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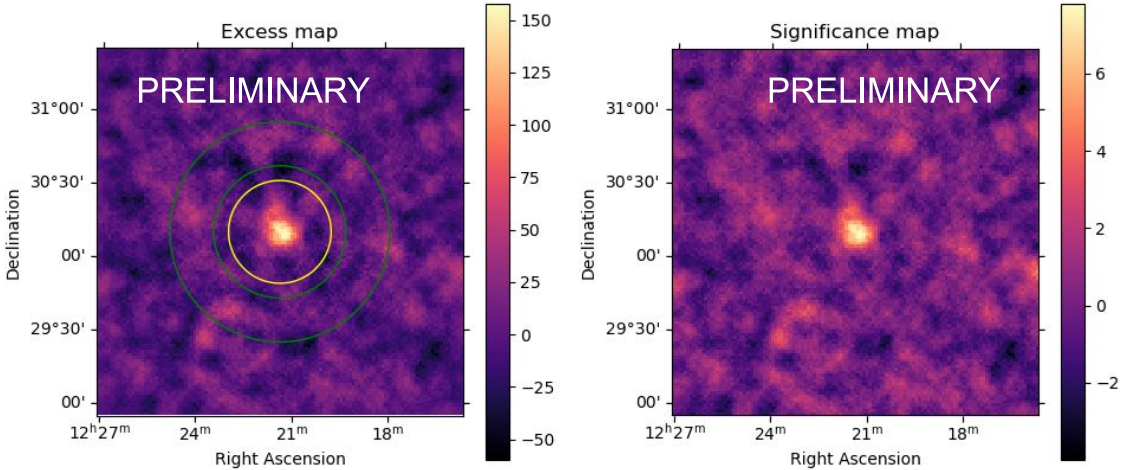
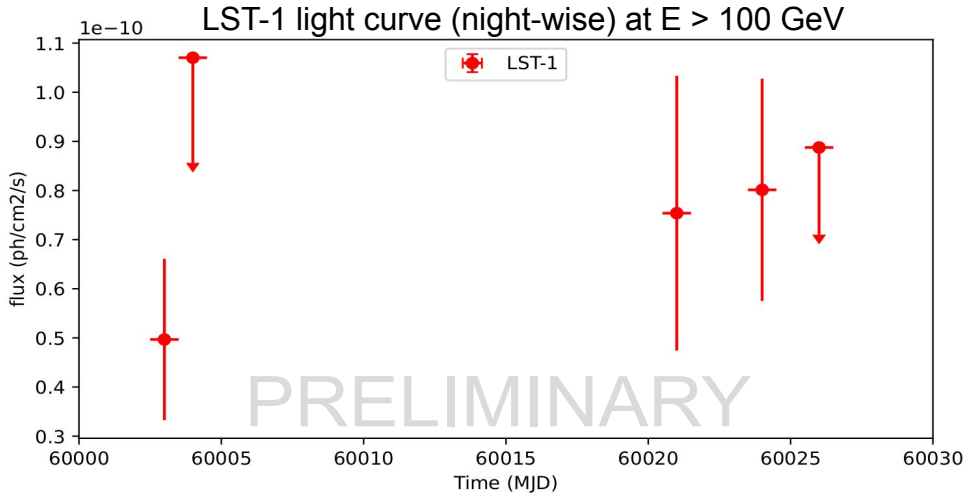
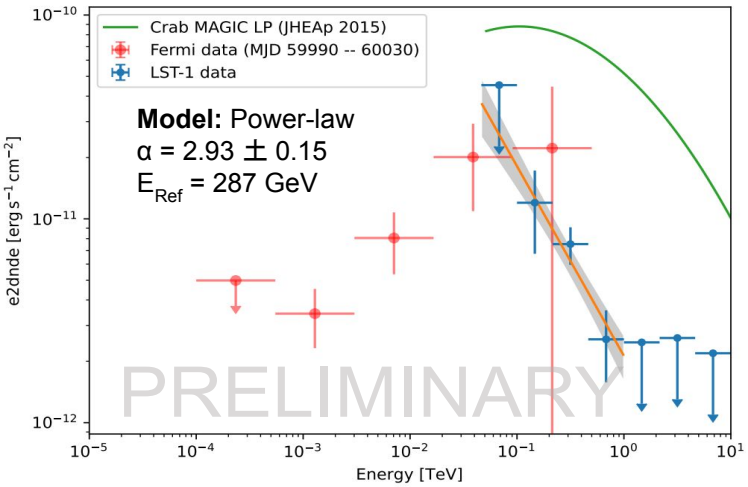
- ➔ Flux (> 100 GeV) ≃ 12 % Crab
- ➔ VHE spectral slope is comparable to literature.
- ➔ Flux variability study is not possible.



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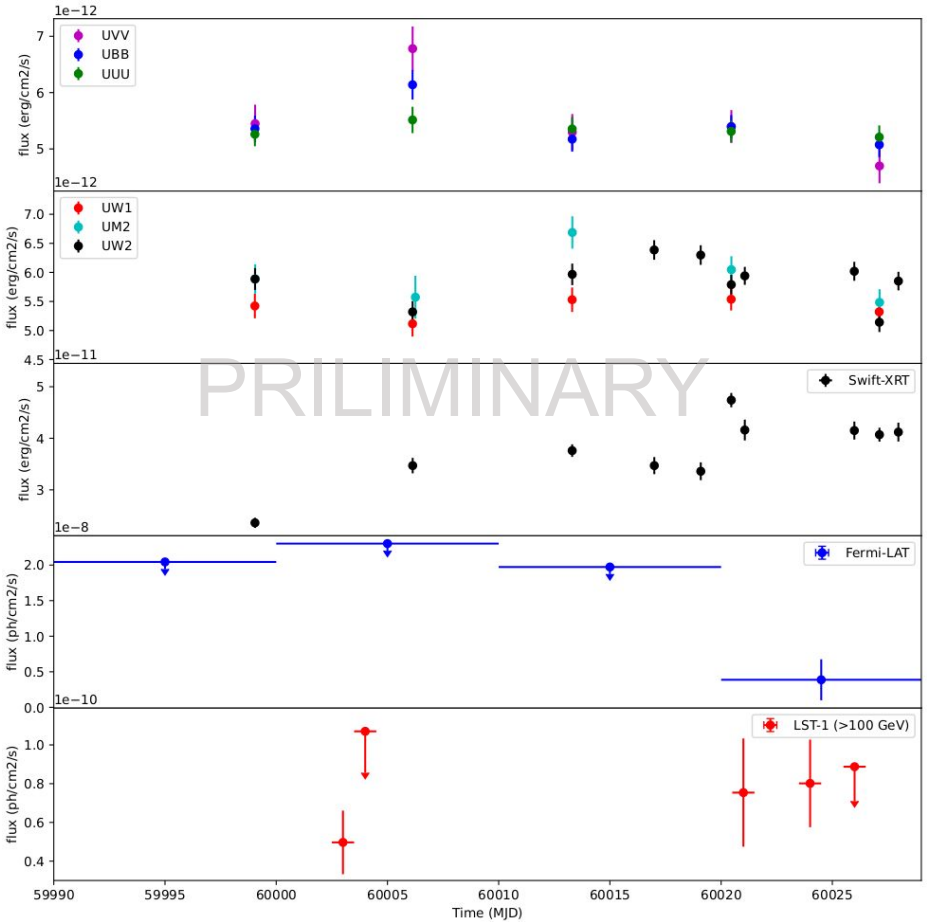



## Multi-wavelength lightcurves

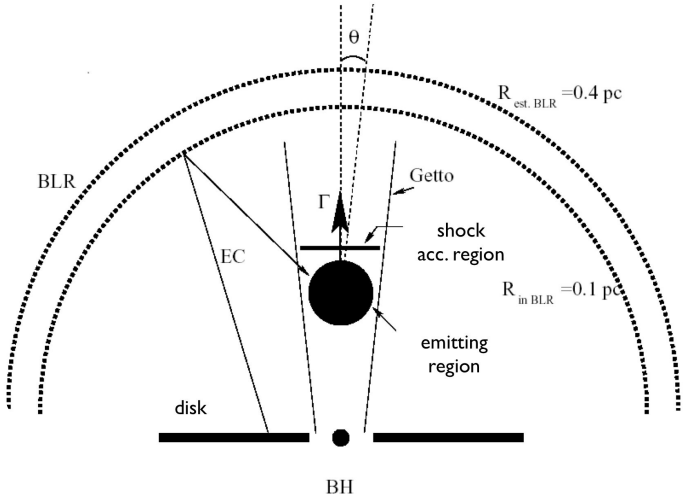
- 10 Swift observations.
- Optical-UV data from Swift-UVOT filters.
  - Galactic reddening and extinction correction
- Swift-XRT (0.3 to 10 keV)
  - Corrected for pile-up effect.
  - Correction for neutral Hydrogen column density during modelling.
- Fermi-LAT (100 MeV to 500 GeV)
  - Low emission state
  - Kept 1ES 1215+303 free during modelling
  - Spectral index ~1.59
- No significant variability observed in gamma-rays
  - No time-resolved SED study
  - One overall average SED

# 1ES 1218+304 (z = 0.182)

- Quasi-simultaneous Swift-UVOT, Swift-XRT and Fermi-LAT data.
- Leptonic Synchrotron Self-Compton model with a spherical emission zone.
- $t_{var} \lesssim 1$ day [Sato et al. 2008, Acciari et al. 2010].
- Log-parabolic particle energy distribution:

$$f(\gamma) = (\gamma/\gamma_0)^{-(s+r\log(\gamma/\gamma_0))}$$

- **Fixed parameters:** R = 2.5 × $10^{16}$ cm; δ = 20
- EBL absorption: Franceschini et al. 2008



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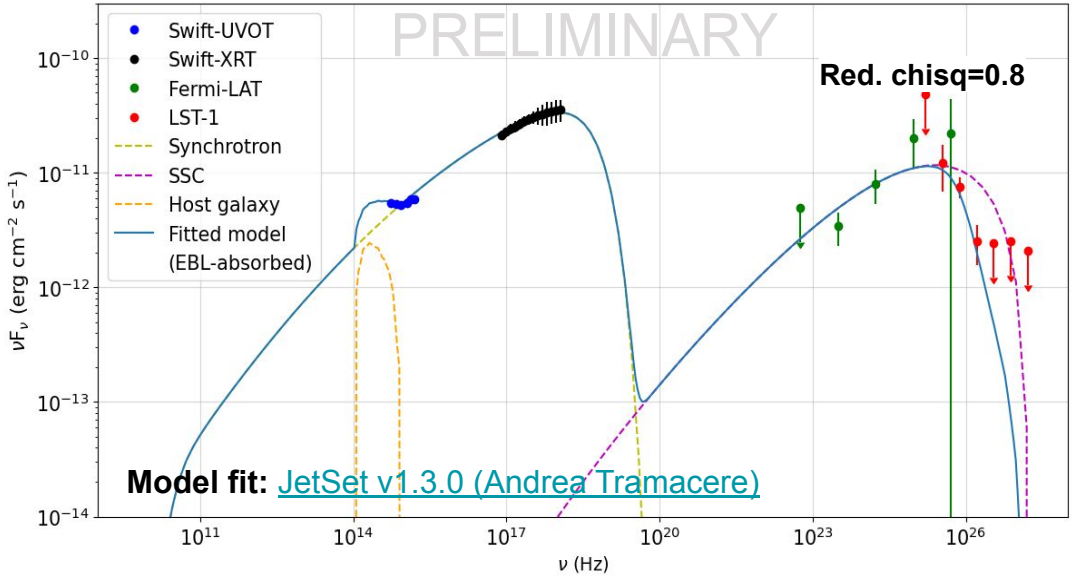


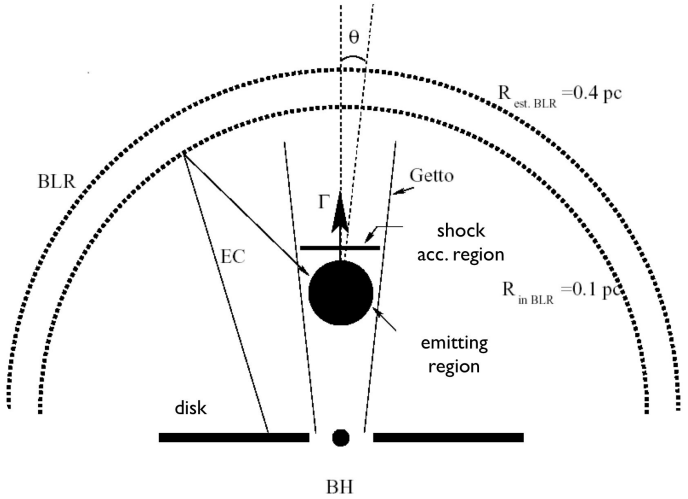


**SED model parameters:**

| | |
|---|---|
| Particle density, N | = 12.7 ± 1.9 $cm^{-3}$ |
| Magnetic field, B | = 0.09 ± 0.01 G |
| Index, s | = 2.17 ± 0.04 |
| Curvature parameter, r | = 0.13 ± 0.02 |
| Minimum Lorentz factor, $\gamma_{min}$ | = 44 ± 7 |
| Maximum Lorentz factor, $\gamma_{max}$ | = (9 ± 1) × $10^5$ |
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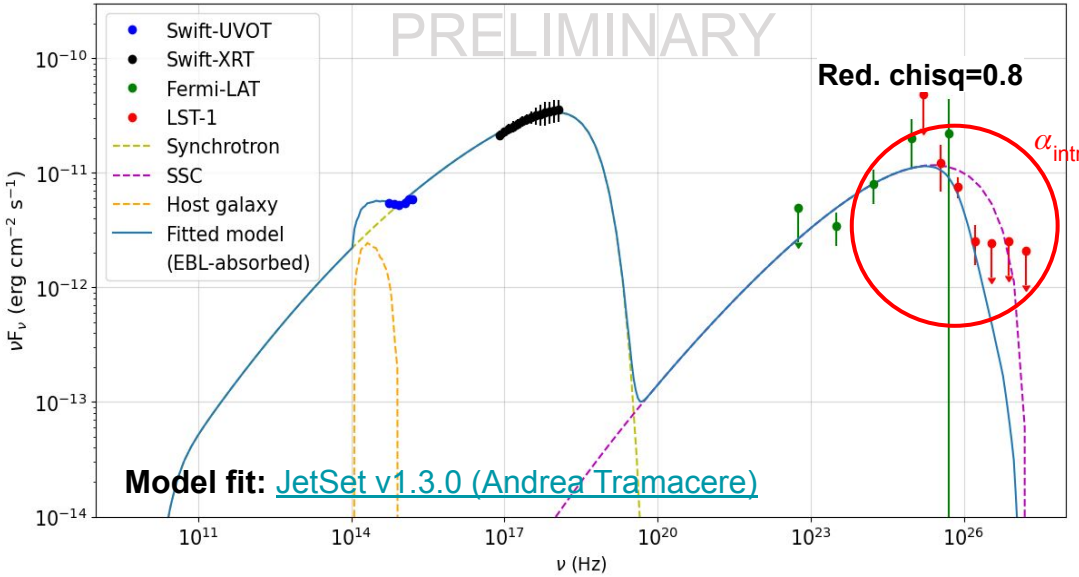


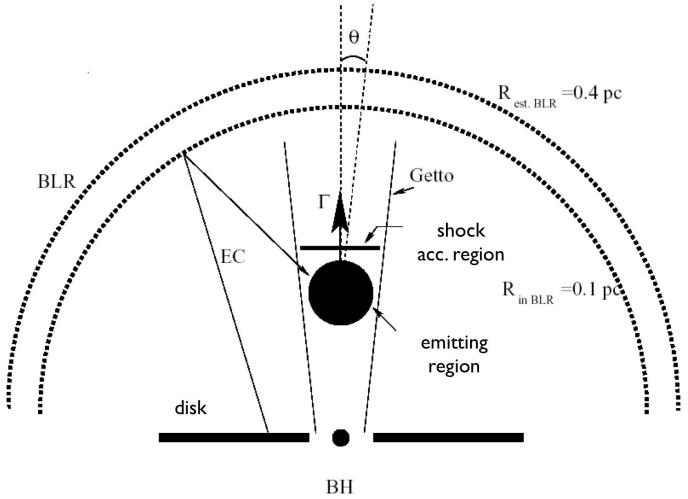


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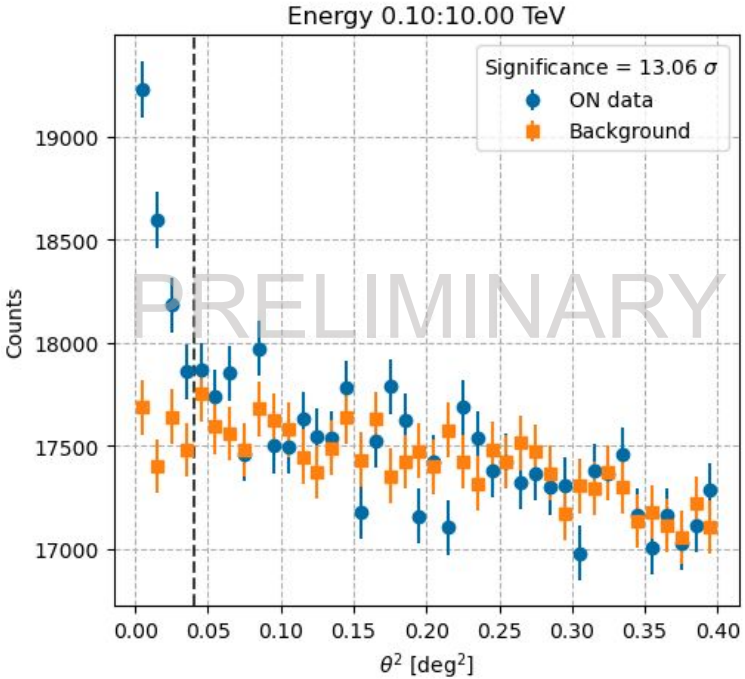
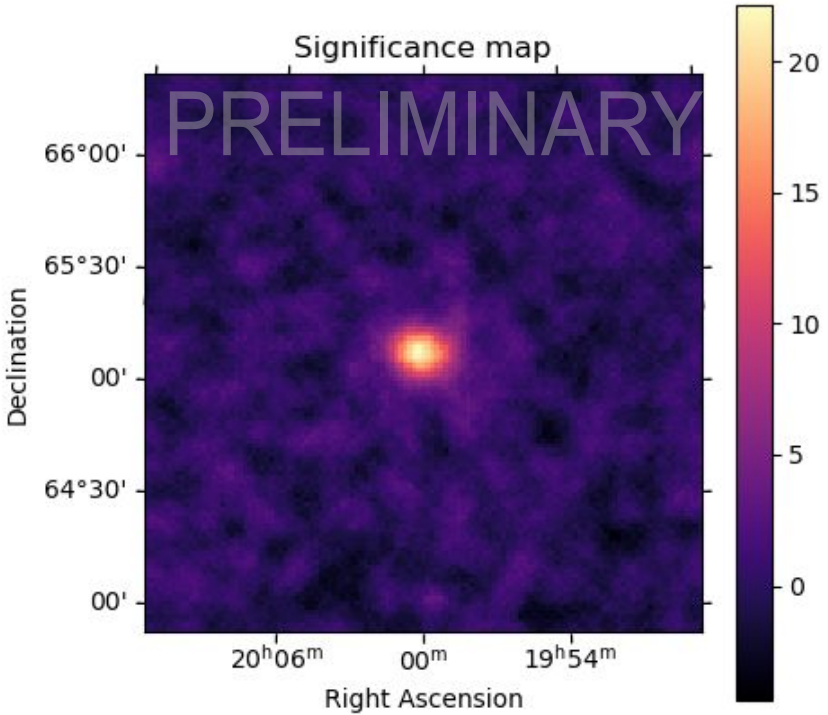
# 1ES 1959+650 (z = 0.048)

- ➔ LST1 observations since May, 2022.
- ➔ Standard data quality cut: 5.63 hrs (total obs = 20 hrs).
- ➔ Detection significance 13σ.



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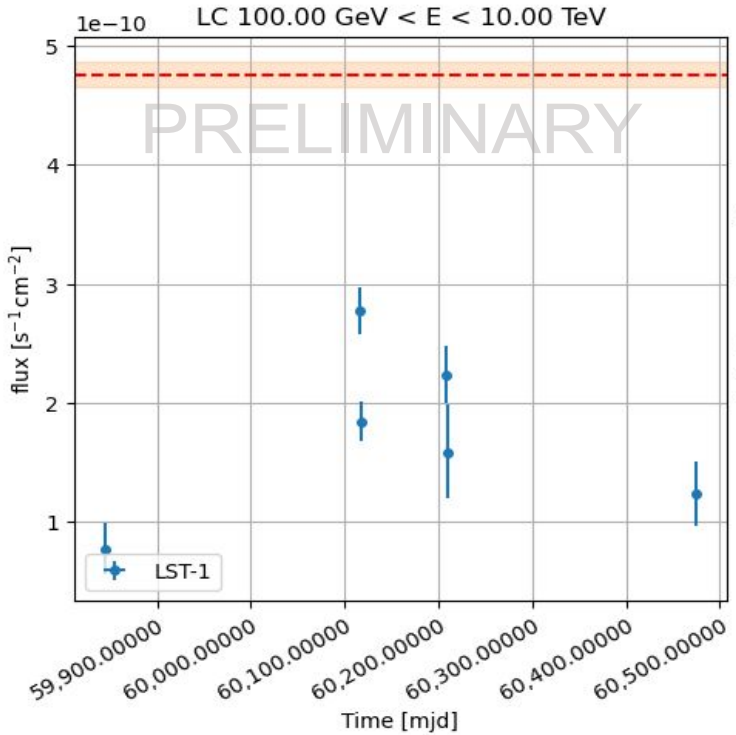


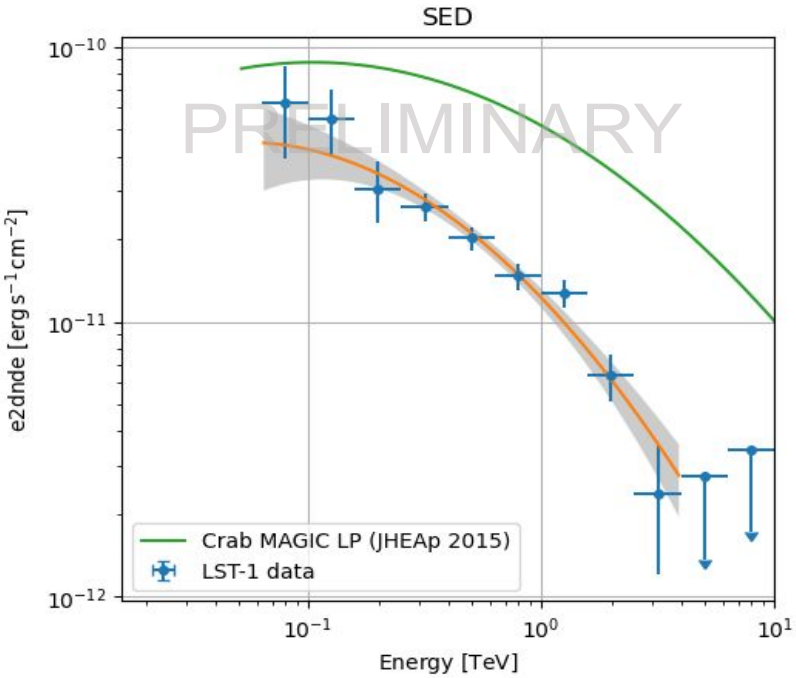

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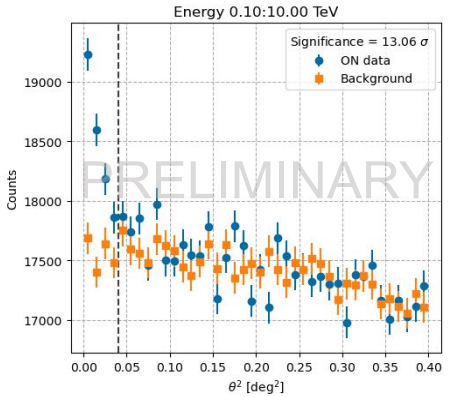
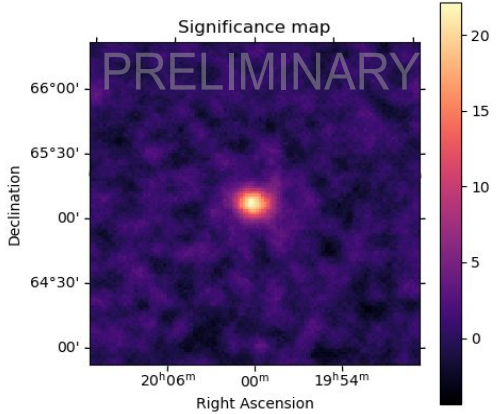
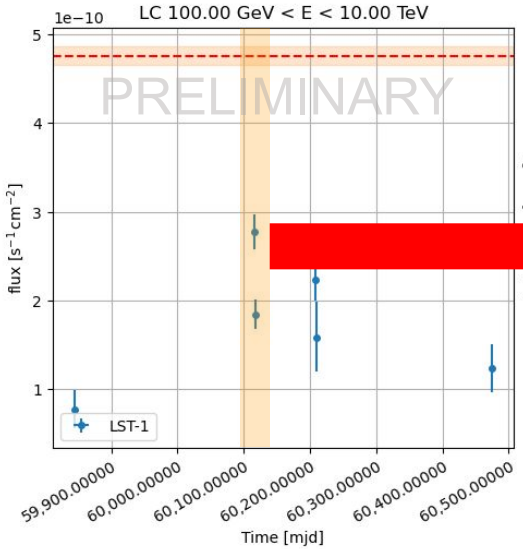
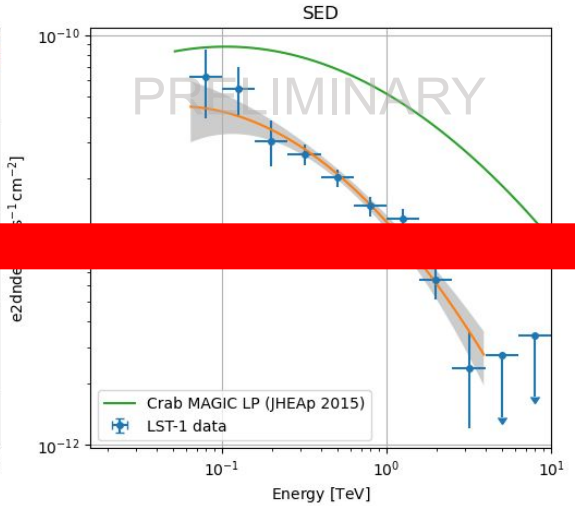
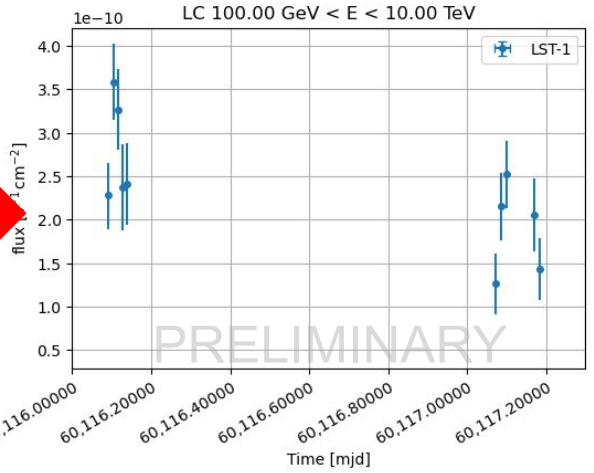
- ➔ Detection significance 13σ.
- ➔ Similar flux level as 2020 – 2022 period (~40% Crab).
- ➔ Hint of intraday variability.
- ➔ Shortest flux doubling timescale, $t_{var}$ = 26 min
- ➔ Assuming δ = 10 – 50, emission region size, $R \lesssim$ $(0.4 – 2) \times 10^{15}$ cm.
- ➔ Time-resolved broadband SED might be interesting.



# Summary

- Spectral variability study of well-known AGN with LST1 data in 2020 – 2022.
- Good agreement between simultaneous Fermi-LAT and LST-1 spectrum.
- Sensitive to variable gamma-ray sources above 25 GeV for low zenith observations.

- Detection of OP 313, the highest redshift (z = 0.997) FSRQ till date.
  - Several projects on OP 313 are ongoing.

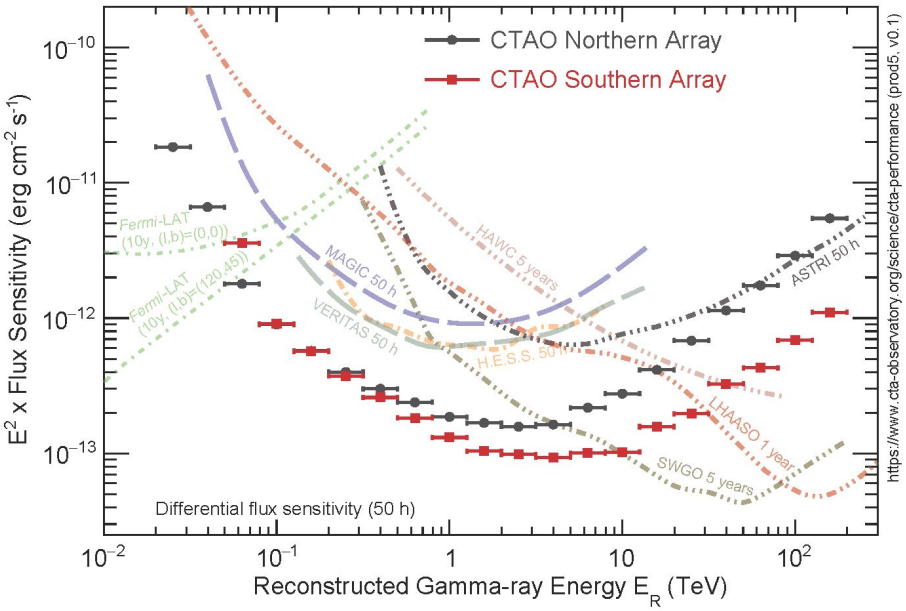
- Detection of 1ES 1218+304 with 4.4 hours of LST1 observation
  - Comparable VHE spectral index
  - Multiwavelength SED modelling
  - Diffusive shock acceleration is viable

- Ongoing projects:
  - BL Lac: LST-1 observation of flares in 2021 and 2022.
  - OP 313: VHE flux variability, MWL SED, BLR study, EBL
  - PG 1553+113: IDV

- My involvements:
  - MAGIC + LST1 joint observations of 1ES 1218+304
  - Multiwavelength study of 1ES 1959+650

- Future: 4 LSTs coming soon – new EGAL sources.

## Looking forward…



# Backup Slides

# The Extragalactic Sky at VHE with CTA-LST