# Study of the variable VHE gamma-ray emission of bright AGN with LST-1

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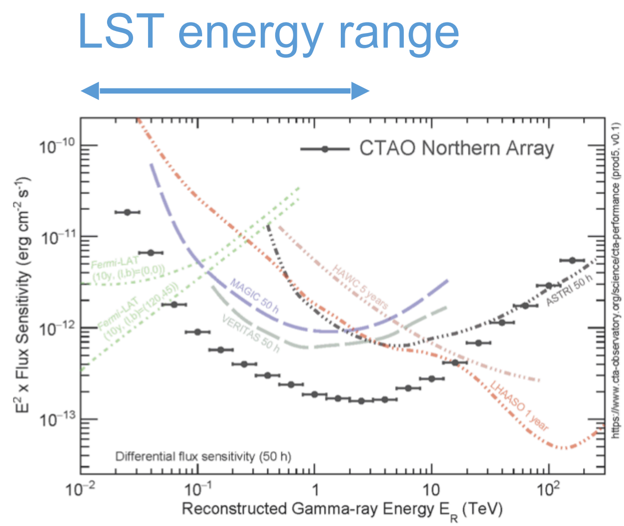
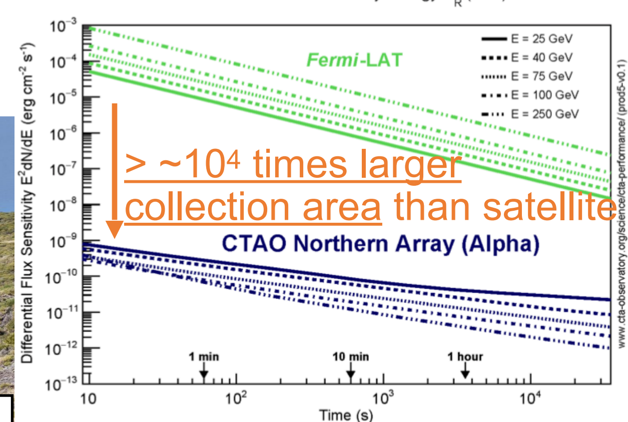
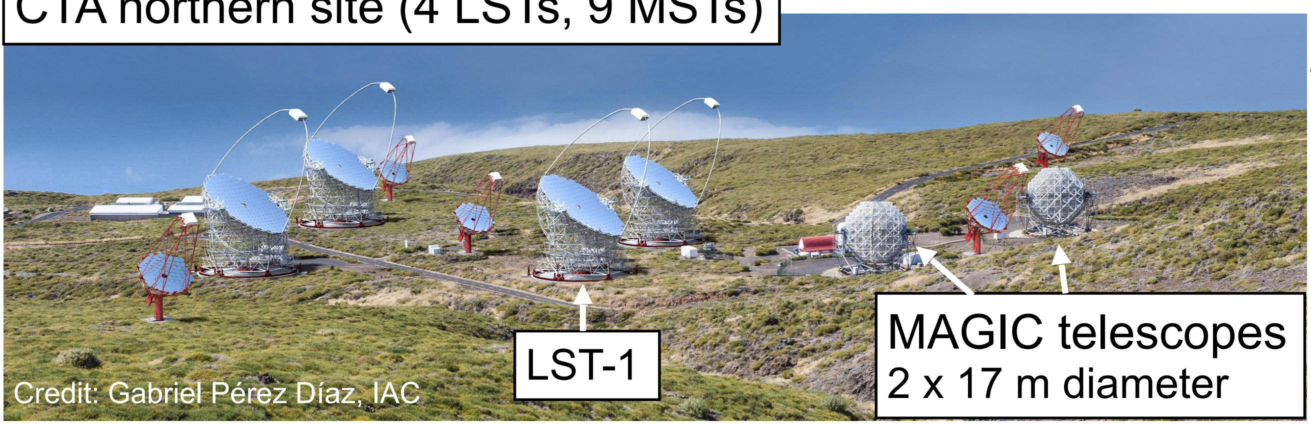
# Cherenkov Telescope Array (CTA)

- New gamma-ray observatory under construction
- 4 LSTs will be set at the northern site in La Palma, Spain, alongside 9 MSTs.
- Compared to current telescopes,
  - 10 times better sensitivity
  - 10 times wider energy range: 20 GeV – 300 TeV
- We started LST-1 operation from 2018.



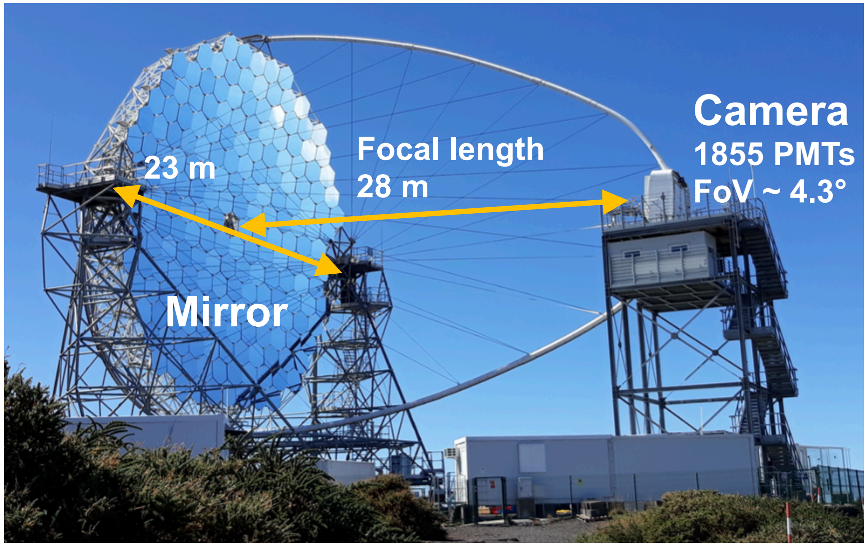

CTA northern site (4 LSTs, 9 MSTs)



# CTA large-sized telescope (LST)

- 23 m diameter: over 400 m² mirror area
- Targeting an energy threshold ~20 GeV
- Stereo observations at **lowest energy ever observed from ground**
- Ability to reposition to any point in the sky within 20 seconds
- Ideal for fast transients and soft sources

AGN flare, GRB, pulsars, …




High sensitivity down to tens of GeV

→ **lack of absorption** from photon-photon interactions with extragalactic background light (EBL)

# Active Galactic Nuclei (AGN) observation with LST-1

- AGN constitute the most populous class of sources in the extragalactic very-high-energy (VHE; E > 100 GeV) sky.
- Detecting more VHE AGN at different energies and distances is crucial for a better understanding of their emission mechanisms.

- More than 150 hours of bright AGN data taken in 2020-2022:

  Near sources ($z < 0.03$): Mrk 421, Mrk 501, 1ES 1959+650

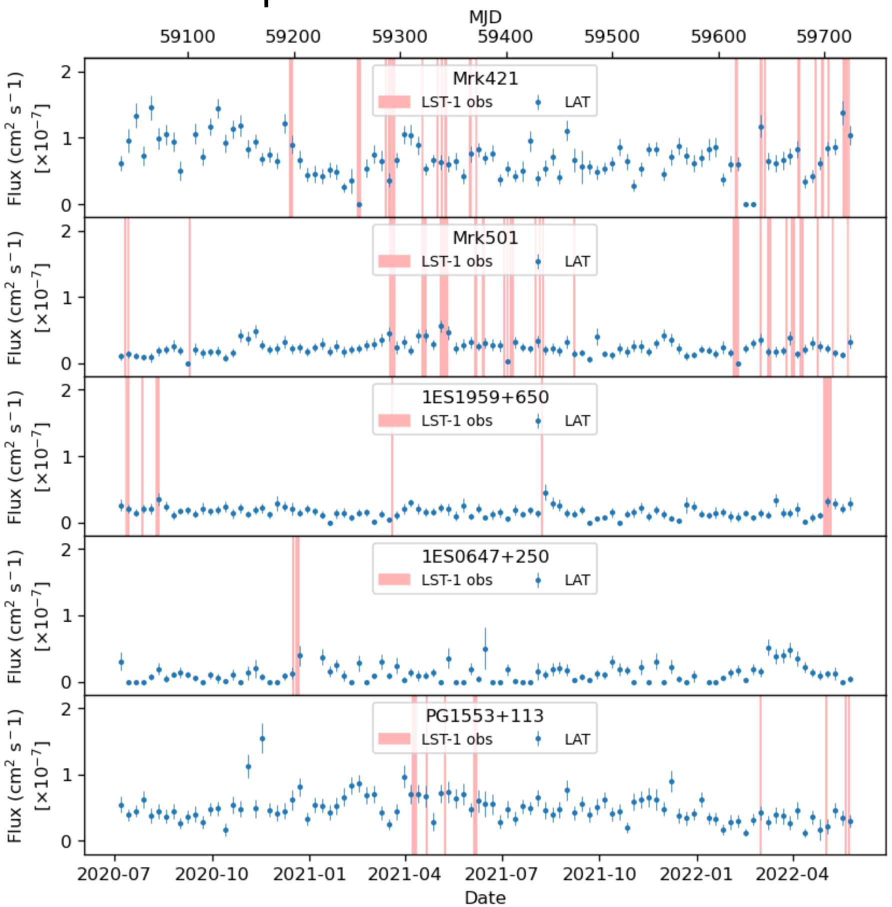
  Distant sources ($z \sim 0.45$): 1ES 0647+250, PG 1553+113

- We present results on spectral variability from above observations:
- Time-resolved (Bayesian block) spectra for near sources
- Comparison and joint-fit with Fermi-LAT spectra

# Observation condition

| Source | Observation date | Redshift | Observation time before/after cut (h) | Detection significance ($\sigma$) |
|---|---|---|---|---|
| Mrk 421 | 2020 Dec. 12 - 2022 May 23 | 0.031 | 68.5 / 31.9 | 53 |
| Mrk 501 | 2020 July 10 - 2022 May 22 | 0.034 | 67.2 / 39.7 | 21 |
| 1ES 1959+650 | 2020 July 11 - 2022 May 5 | 0.048 | 21.3 / 11.8 | 13 |
| 1ES 0647+250 | 2020 Dec. 16 - 2020 Dec. 21 | 0.45±0.05 | 8.8 / 8.2 | 7 |
| PG 1553+113 | 2021 Apr. 8 - 2022 May 23 | 0.433 | 12.2 / 9.9 | 16 |

Fermi light curve
with LST-1 time period




- More than 150 hours of LST-1 data accumulated in commissioning period: 2020-07 - 2022-05
- Dark data under good weather condition are selected.
- In LST-1 data period, Mrk 421, Mrk 501, 1ES 1959+650 had flux variability.

# Analysis condition

- Standard LST analysis with dedicated analysis tool *cta-lstchain v0.9.12/13* and *Gammapy v1.0/1.1*
- Spectral analysis for a point source
- Two different MC simulations separated with zenith and azimuth angles

Training: train reconstruction algorithms

Testing: obtain effective area, cut condition

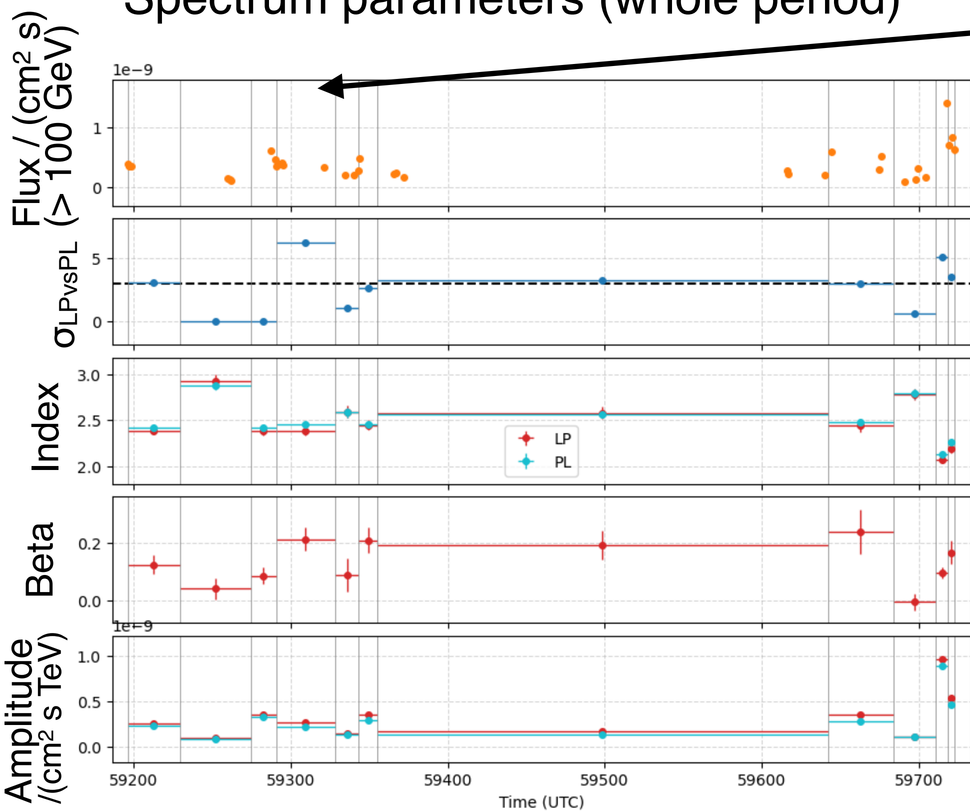
- Spectrum energy threshold: 25 GeV (Zd < 35 deg), 100 GeV (> 35 deg)
- Light curve energy threshold: 100 GeV
- Spectrum fit: preferred one from Power-law (PL), Log-parabola (LP), Power-law with exponential cut-off (ECPL)
- Gammaness and theta cut: energy-dependent (efficiency 80%)
- EBL model: Domínguez (2011)

# Bayesian block analysis

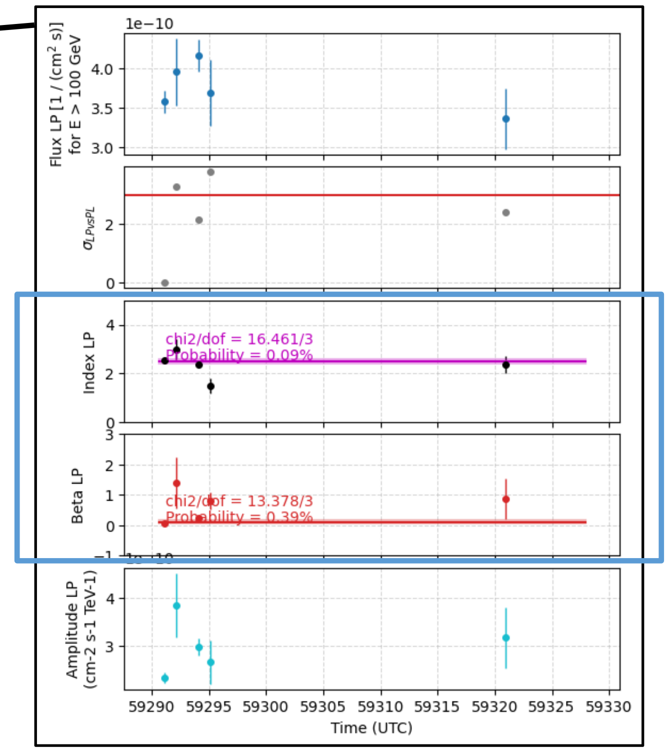
Mrk 421 data

- Fit spectrum of each night data and obtain day-by-day flux
- Select Bayesian blocks with false alarm probability 3σ
- Check that spectral parameter variability in each block is within 3σ

Spectrum parameters (whole period)




Day-by-day spectrum parameters (block 3)



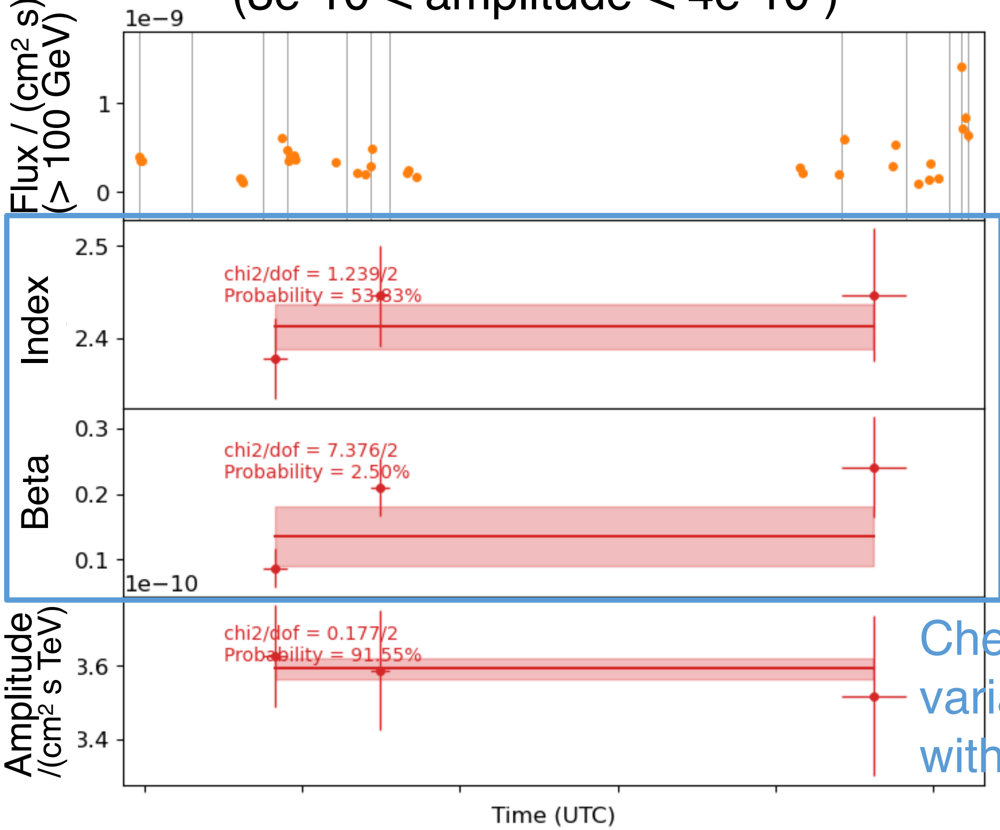

Check variability within 3σ

# Bayesian block analysis

Mrk 421 data

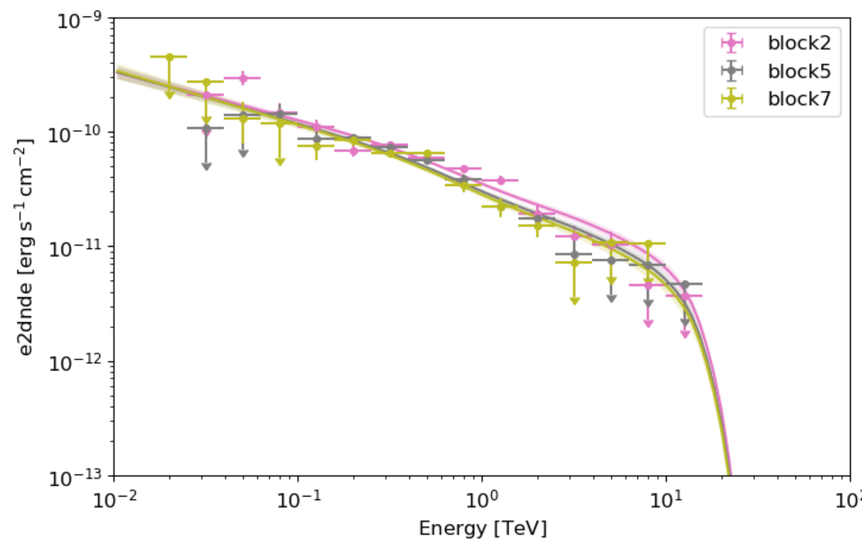
- Select blocks with similar amplitude
- Check that spectral parameter variability between the blocks is within 3σ

Spectrum parameters in high flux state
(3e-10 < amplitude < 4e-10 )




Check variability within 3σ

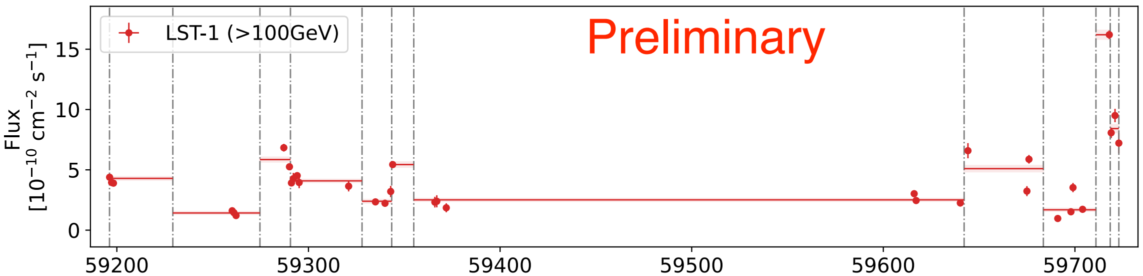
Spectra in high flux state




-> merge spectra in same state as typical spectra

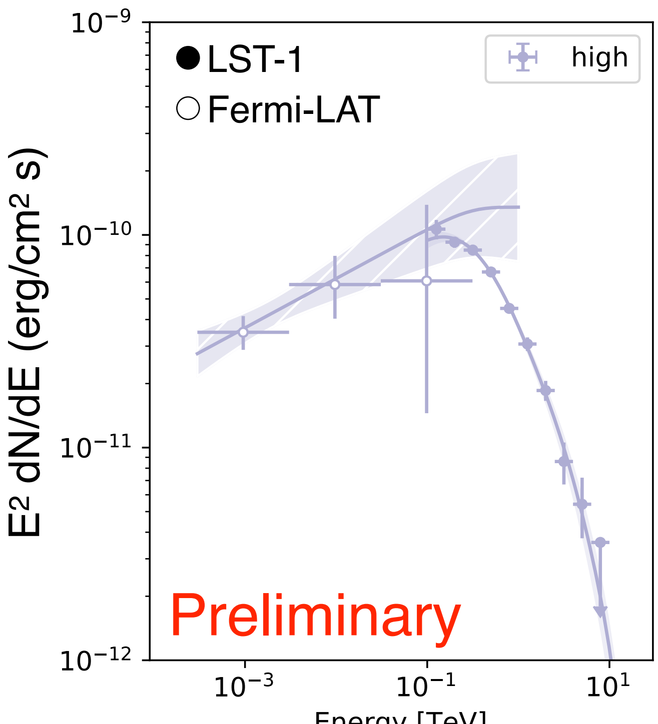
# Results: Mrk 421

Night-wise light curve




- 11 blocks are identified in the dataset

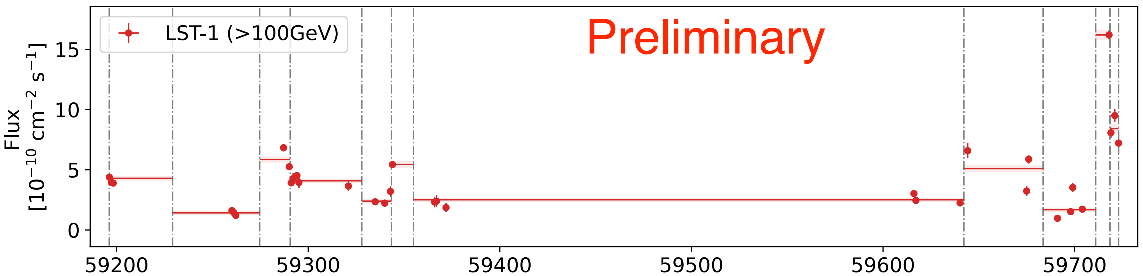
Energy spectra in high state



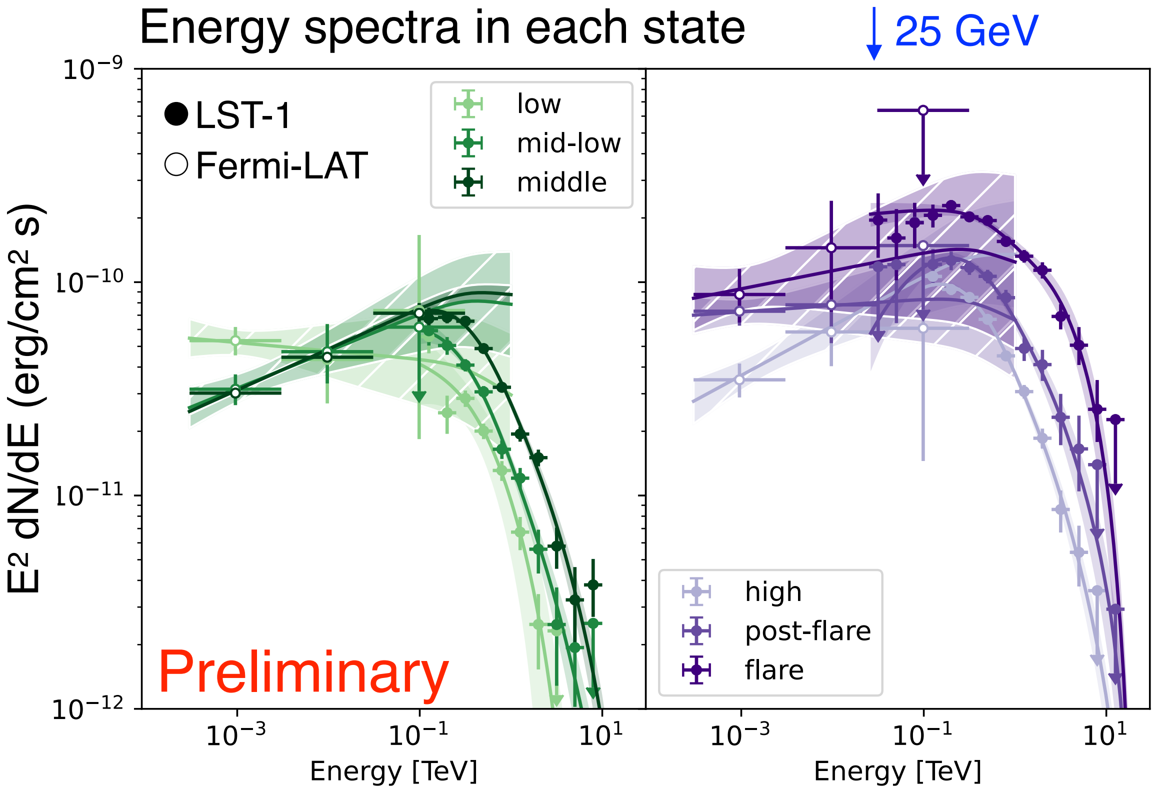

- LST-1 spectrum and Fermi-LAT spectrum simultaneous to LST-1 observation (power-law + EBL)
- Good agreement between both results

# Results: Mrk 421

Night-wise light curve




Energy spectra in each state



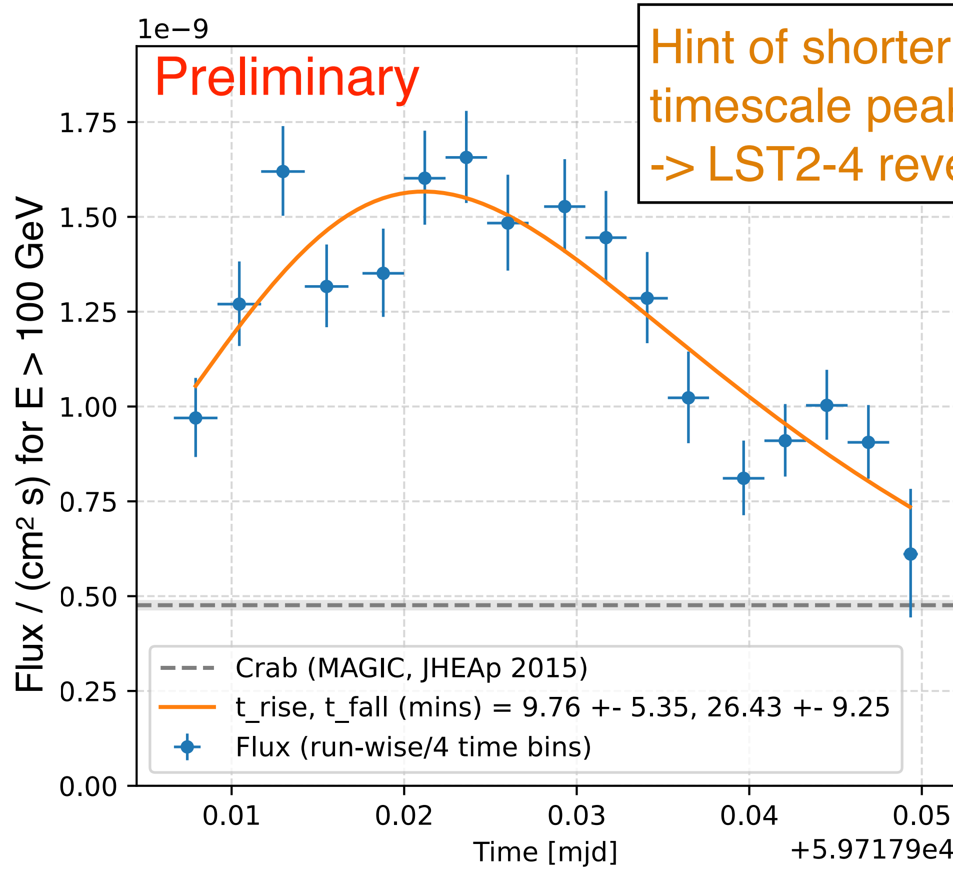

- 6 merged blocks are identified out of 11 blocks
- Fermi-LAT spectra simultaneous to LST-1 observations show good agreement between both results
- LST-1 is highly sensitive to gamma-ray sources with time variation above 25 GeV for low-Zd observation

# Results: Mrk 421 flare light curve

- Flare on 2022-05-18 (0.91 hours data)
- ~3x brighter than Crab at > 100 GeV
- Doubling time scale (Zhang et al. (1999)): t_var = 9.07 ± 6.68 min.
- Rise and fall time (min.):

  t_rise = 9.76 ± 5.35

  t_fall = 26.43 ± 9.25




Emission region size

$$R \leq \frac{c t_{\rm var} \delta}{1+z}$$

δ: Doppler factor

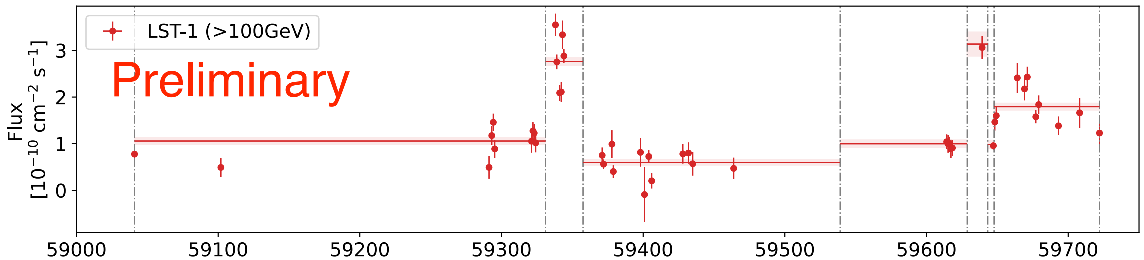
*z:* redshift of the source

- Assuming δ = 10-50, using $t_{var}$ ~ 10-30 min., z = 0.031,

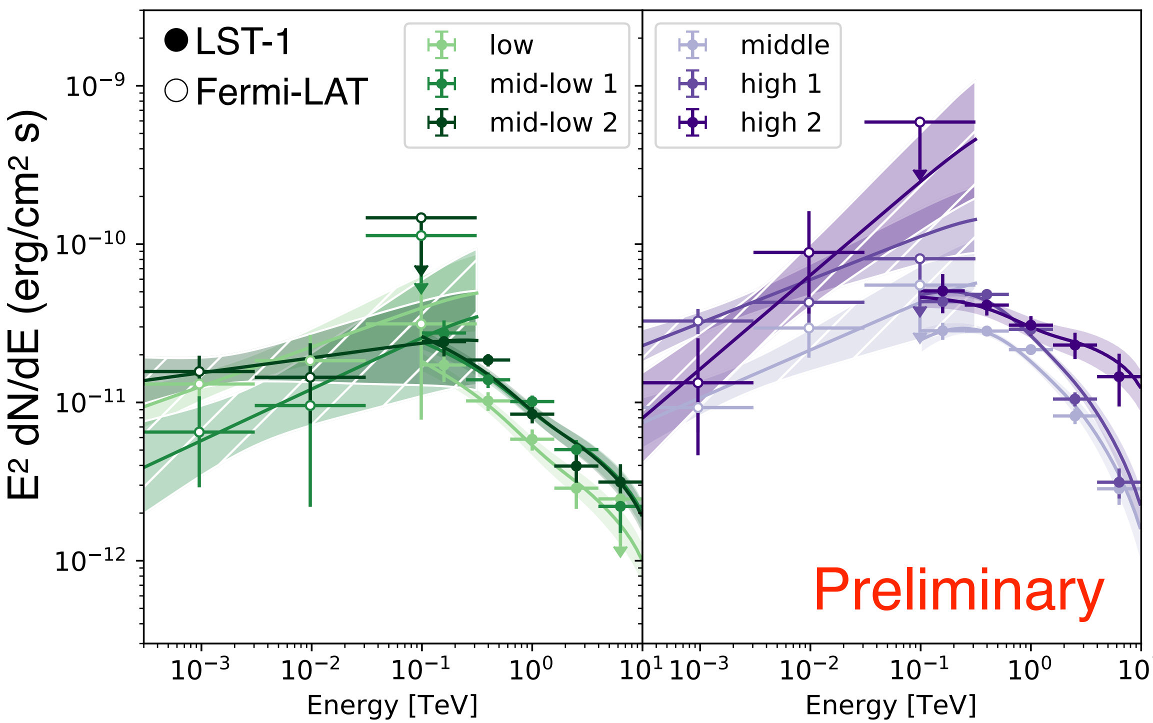
R < ~0.2-3 x $10^{15}$ cm

# Results: Mrk 501

Night-wise light curve



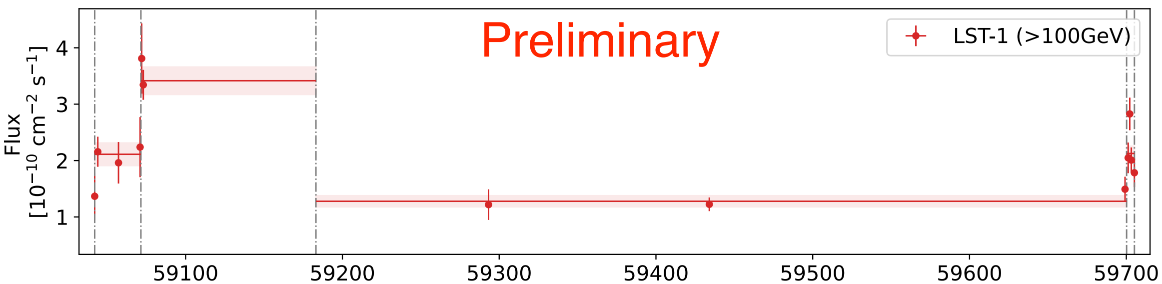

Energy spectra in each state



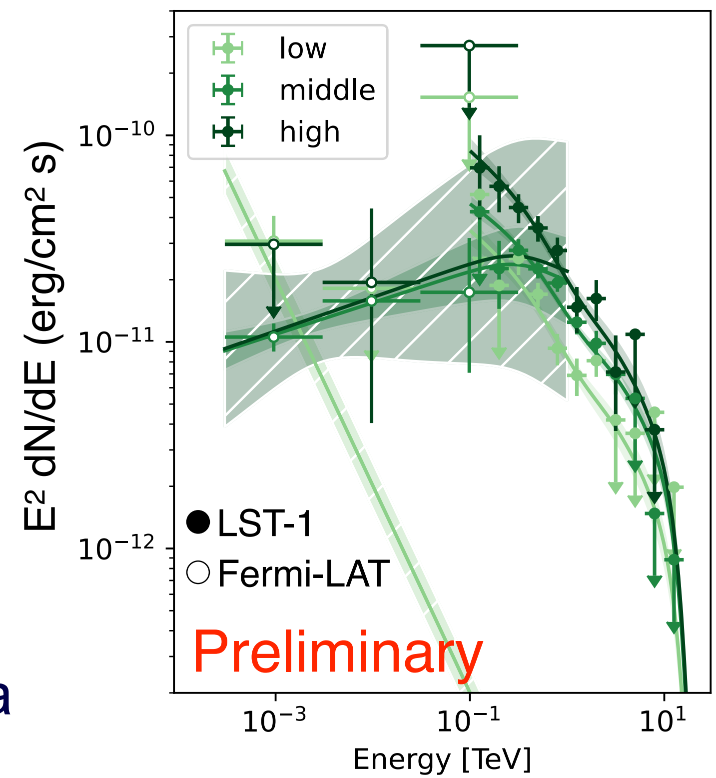

- 6 merged blocks are identified out of 7 blocks
- Less than Crab Nebula flux
- Fermi-LAT spectra data points are comparable to LST-1 in all states.

# Results: 1ES1959+650

Night-wise light curve

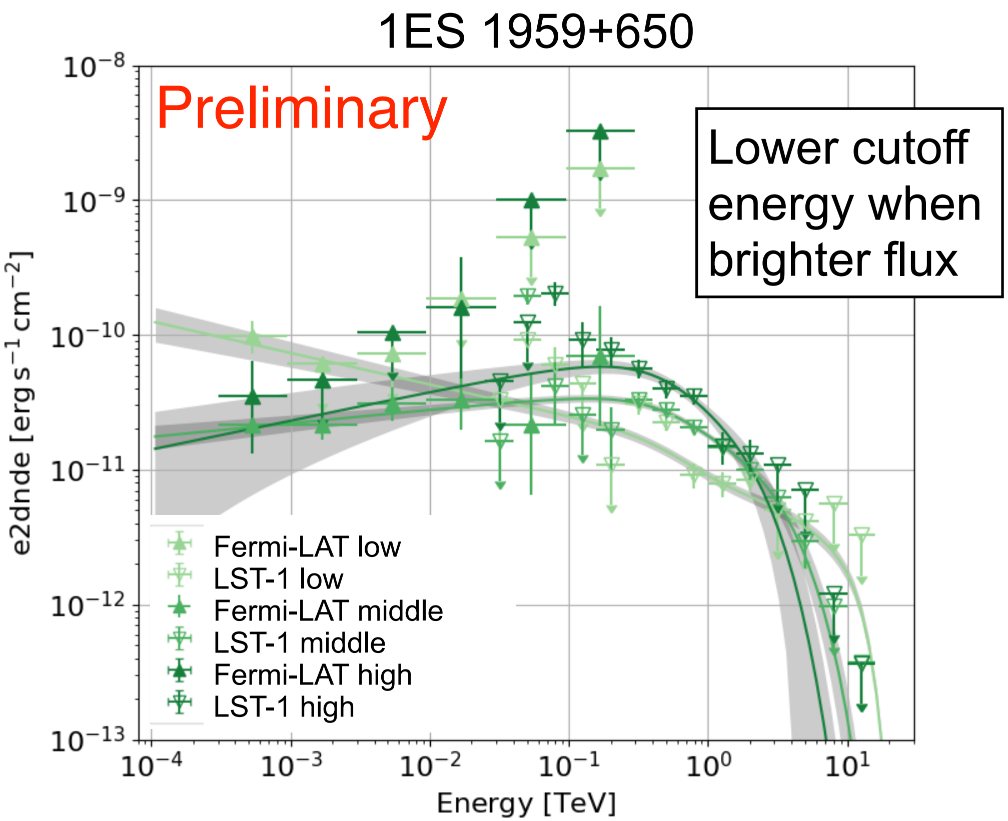



Energy spectra in each state




- 3 merged blocks are identified out of 4 blocks
- Less than Crab Nebula flux
- For low state, statistics of Fermi-LAT data simultaneous to LST-1 observations (~ 6 hours) are too small to fit the spectrum.

# Results: Joint-fit analysis




- Joint-fit with Fermi-LAT data using dedicated Gammapy-based pipeline *Asgardpy v0.4.4*
- Obtained clearer gamma-ray spectrum model without gaps
- Joint-fit method can reveal gamma-ray spectra even when Fermi data have low statistics.

# Conclusion

- We studied spectral variability of several well-known AGN using LST-1 commissioning data accumulated in 2020-2022.
- We applied Bayesian block to Mrk 421, 501, 1ES1959+650 data and the blocks were merged by checking spectrum parameters vary < 3σ.
- LST-1 spectra show good agreement with Fermi-LAT and prove that LST-1 is highly sensitive to gamma-ray sources with time variation above ~25 GeV for low-Zd observation.
- Mrk 421 flare measured in May 2022 showed flux doubling time scale is 10-30 min. -> Emission region size is ~0.2-3 x $10^{15}$ cm
- Joint-fit method can obtain gamma-ray spectra without gaps even when Fermi data have low statistics.

- These results foresee an exceptional performance of AGN detection with LST-1 and CTAO in the future.