LST-1 follow-up of the exceptionally bright gamma-ray burst GRB 221009A

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CTAO | LST COLLABORATION

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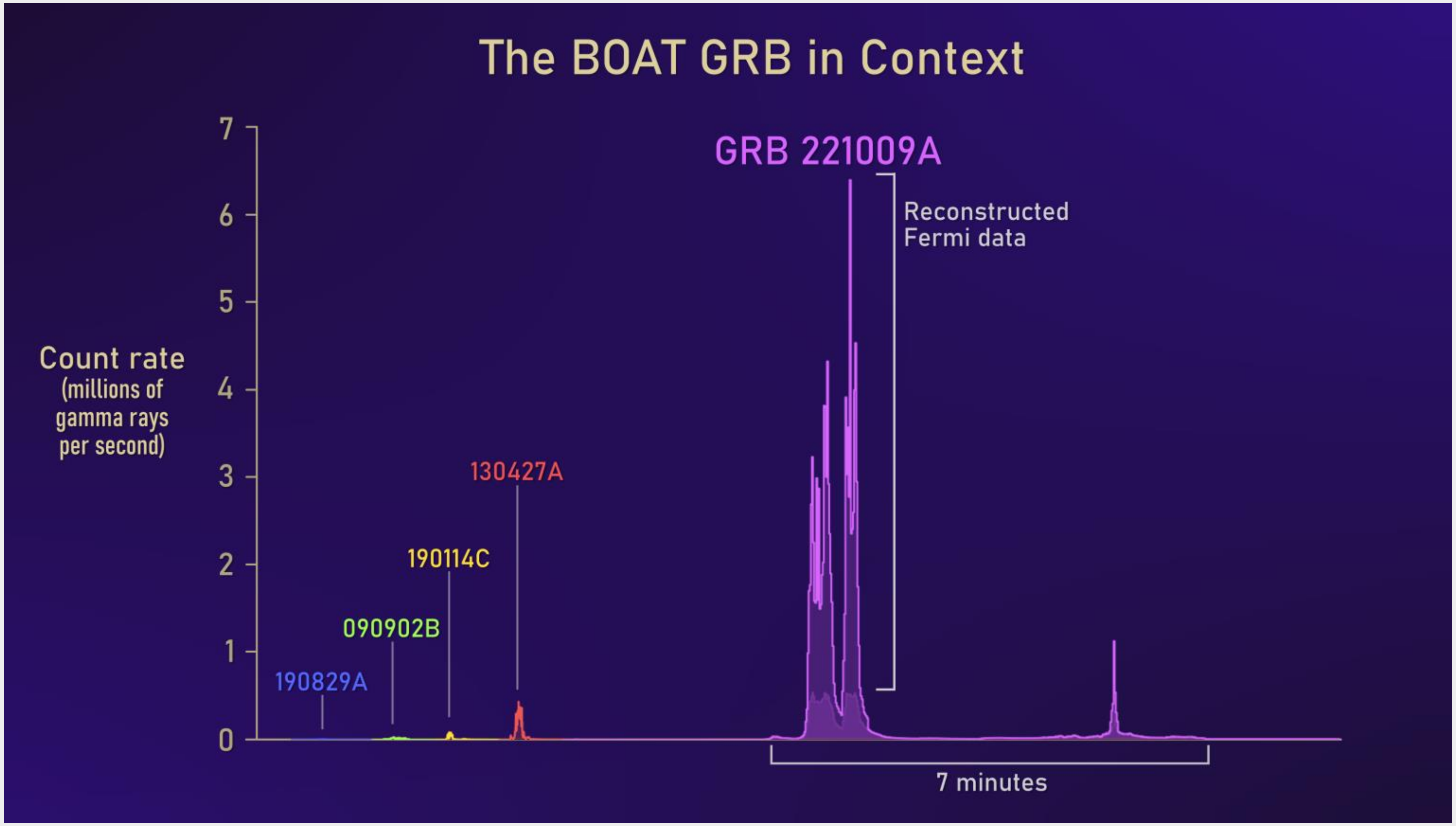
GRB221009A ~BOAT~

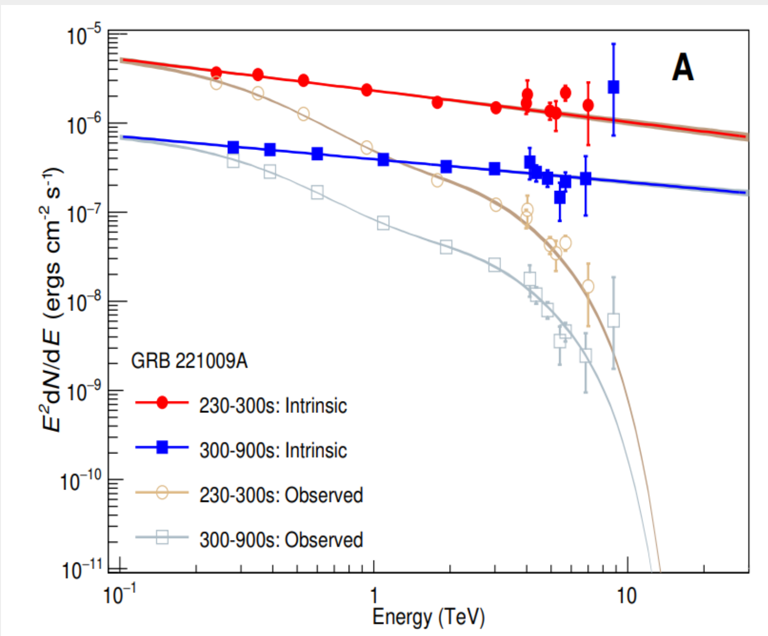
- Extremely bright GRB (**B**rightest **O**f **A**ll **T**ime)
    - Redshift z = 0.151 (724 Mpc)
    - $E_{\gamma,\mathrm{iso}} \approx 1.0 \times 10^{55}$ erg
    - Once-in-a-10,000-year event



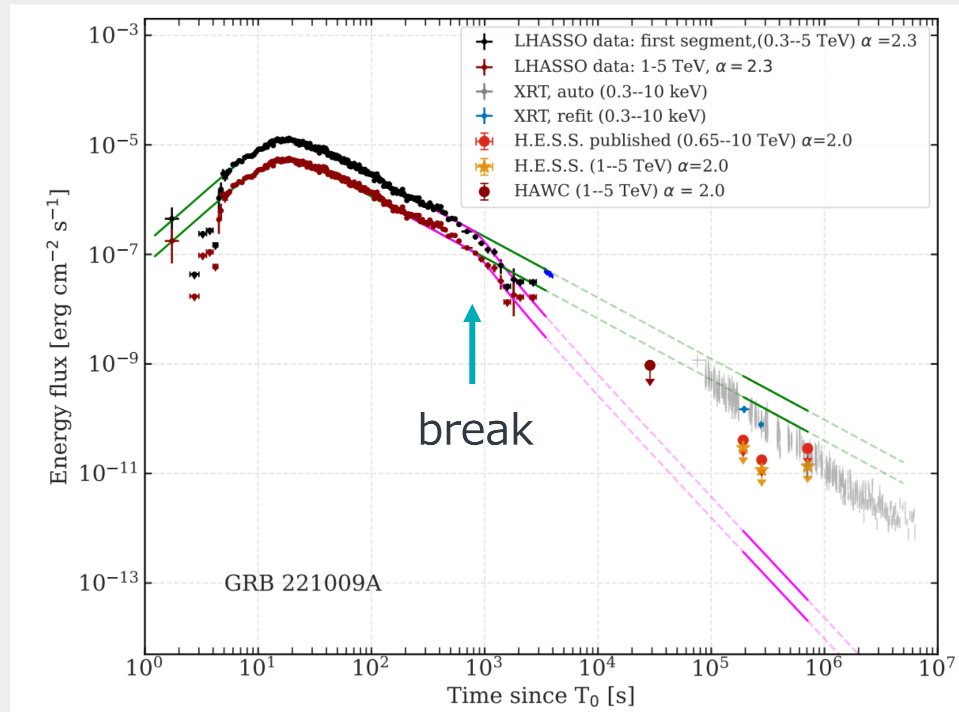
Credits: NASA's Goddard Space Flight Center and Adam Goldstein (USRA)

TeV Emission from GRB221009A

LHAASO Collaboration (2023)



J.D. Mbarubucyeye et al. (ICRC2023)



Detection up to 13 TeV by LHAASO experiment

Break in LHAASO lightcurve suggests a jetbreak

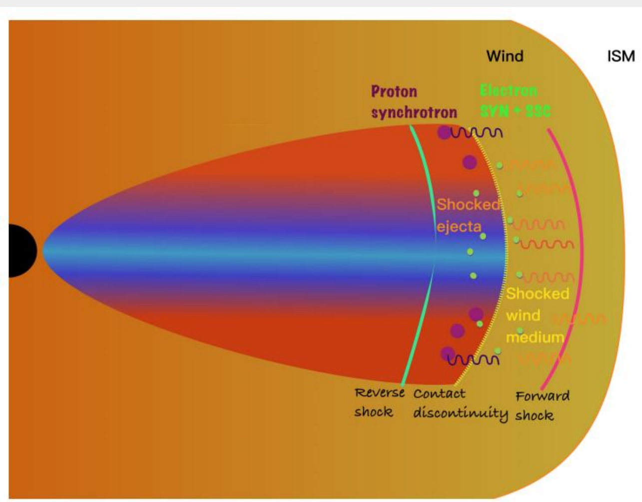
➡ Emission at >10^5 s comes from outer component of the jet?

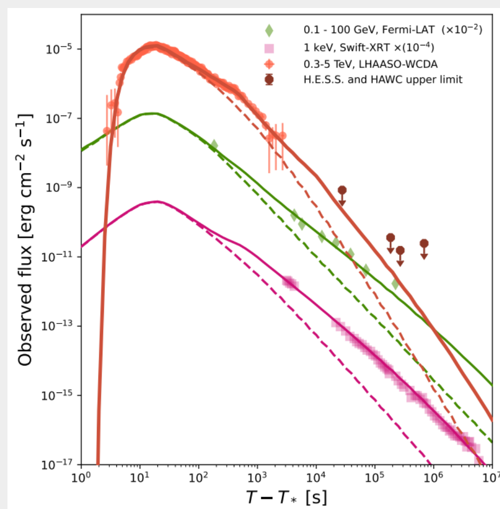
Structured Jet Model

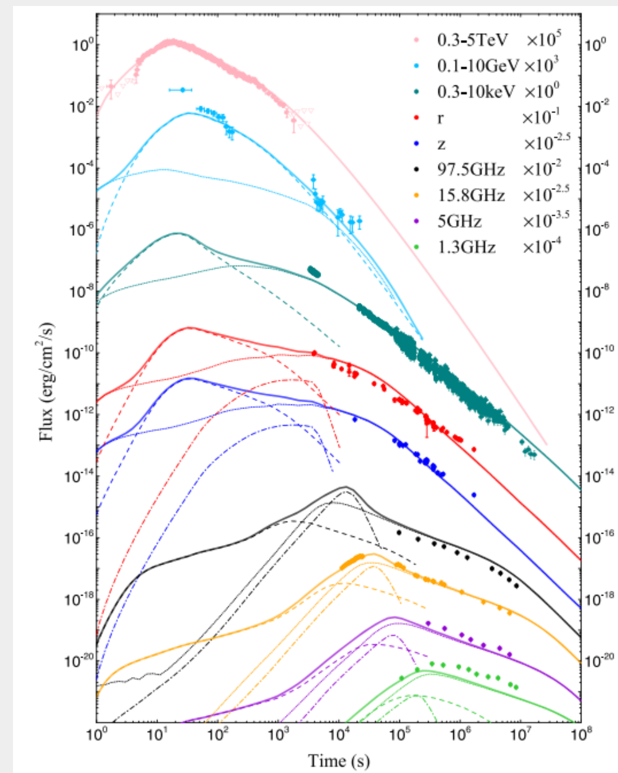
- Structured jet models are widely discussed to explain MWL data of GRB221009A
  - Narrow core + wide wing
  - Interesting comparison with GW/GRB 170817A (Explained by off-axis structured jet)

J. Ren et al. (2024)

B. T. Zhang et al. (2023; arXiv)







Latetime TeV observations provide clues to test different structured jet models

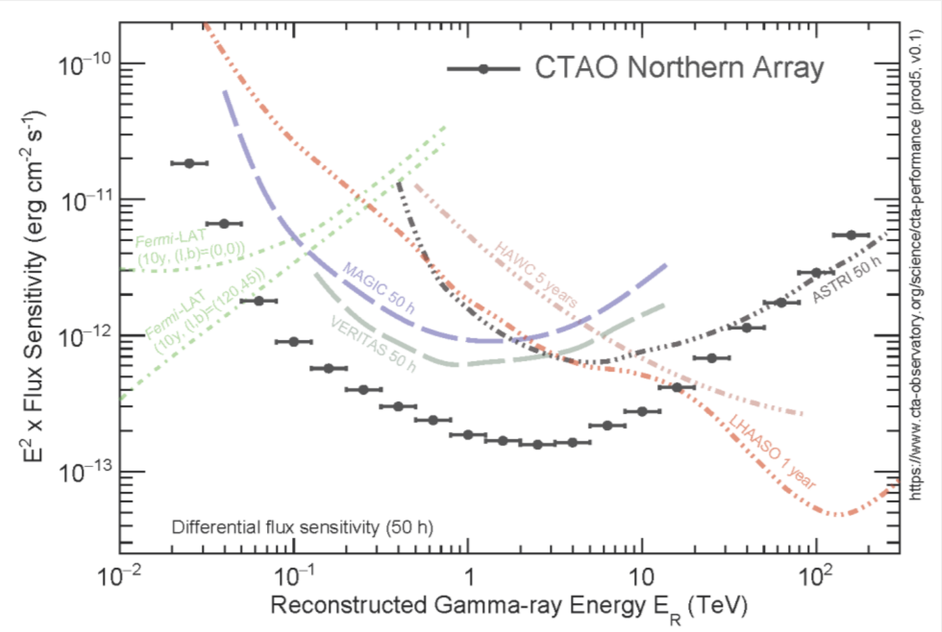
Cherenkov Telescope Array Observatory (CTAO)

- Cherenkov Telescope Array Observatory
  - Detect gamma rays by imaging air Cherenkov light
  - Cover wide energy range from 20 GeV to 300 TeV
  - 10 times better sensitivity compared to current IACT instruments

- CTAO consists of 3 types of telescopes
  - Large-Sized Telescope (LST) ← **This talk**
  - Medium-Sized Telescope (MST)
  - Small-Sized Telescope (SST)

CTAO North (Conceptional drawing)

Credit: Gabriel Perez Diaz

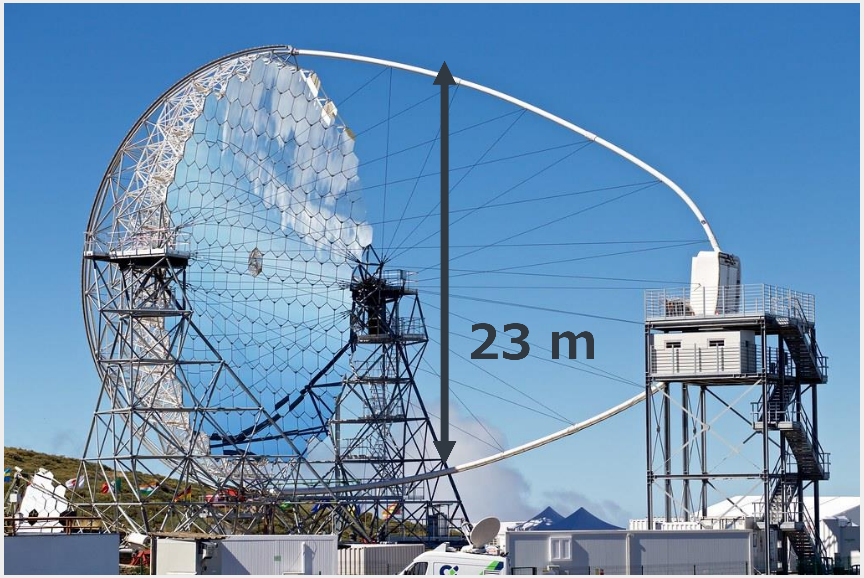


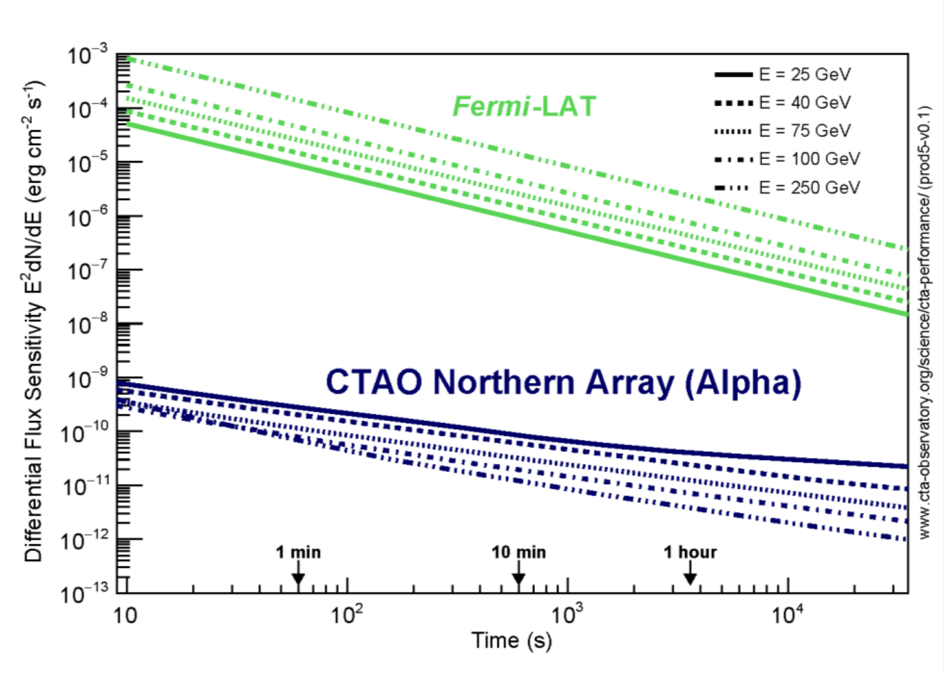
Large-Sized Telescope (LST)

- LSTs are optimized for observing transient and extragalactic sources
  - Low energy threshold (20 GeV)
  - Fast repositioning (< 20 s)
  - Better sensitivity on short timescales compared to Fermi-LAT

- The prototype of the LST (LST-1) started scientific operations since Oct. 2019 (H. Abe et al. 2023)

LST-1

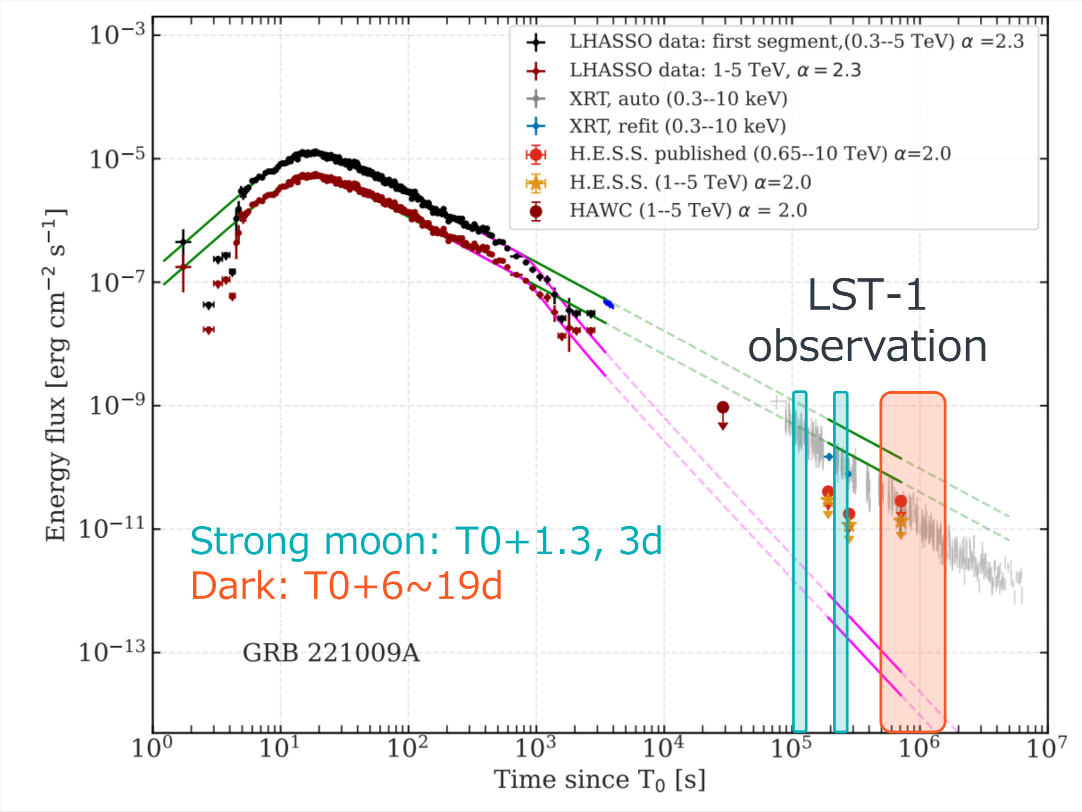




LST-1 Observation of GRB221009A

- LST-1 observation took place from 1.3 d to 19 d after the burst onset
  - The promptest observation among IACTs
  - ~3 h of strong moon time observation
  - ~10 h of dark time observation

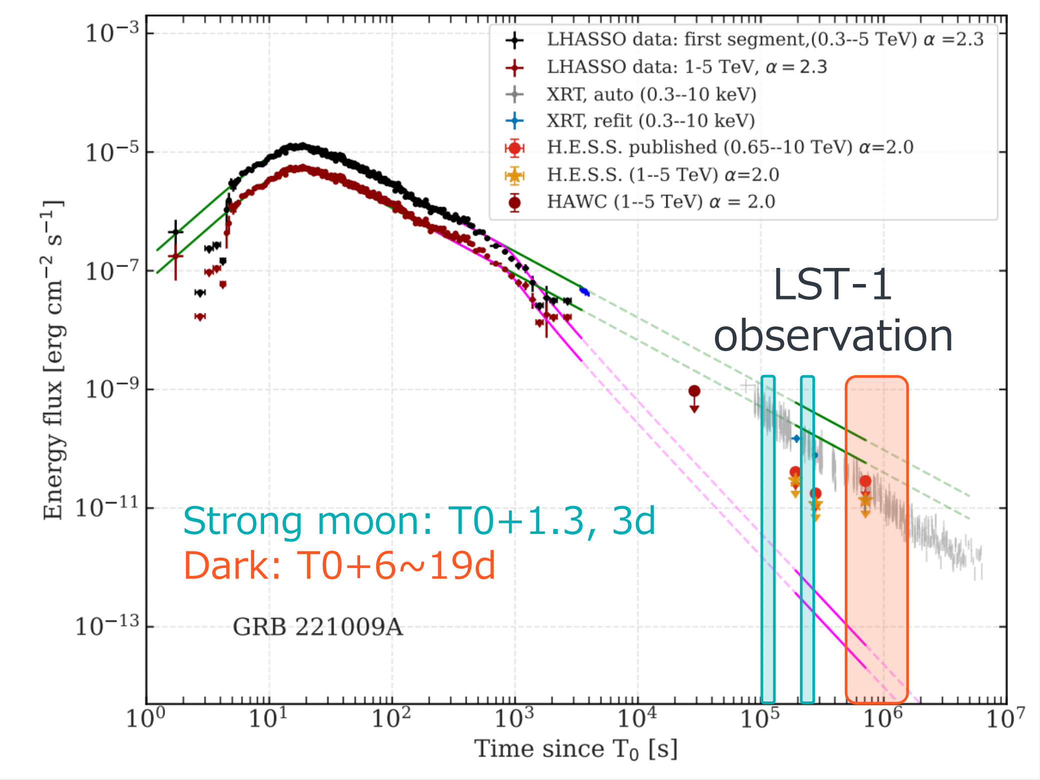
J.D. Mbarubucyeye et al. (ICRC2023)



LST-1 Observation of GRB221009A

- The observation includes both strong moon and dark time data
  - Moon (~3 h)
    - Dedicated analysis
    - Energy threshold: hundreds of GeV
  - Dark (~10 h)
    - Standard analysis
    - Energy threshold: tens of GeV

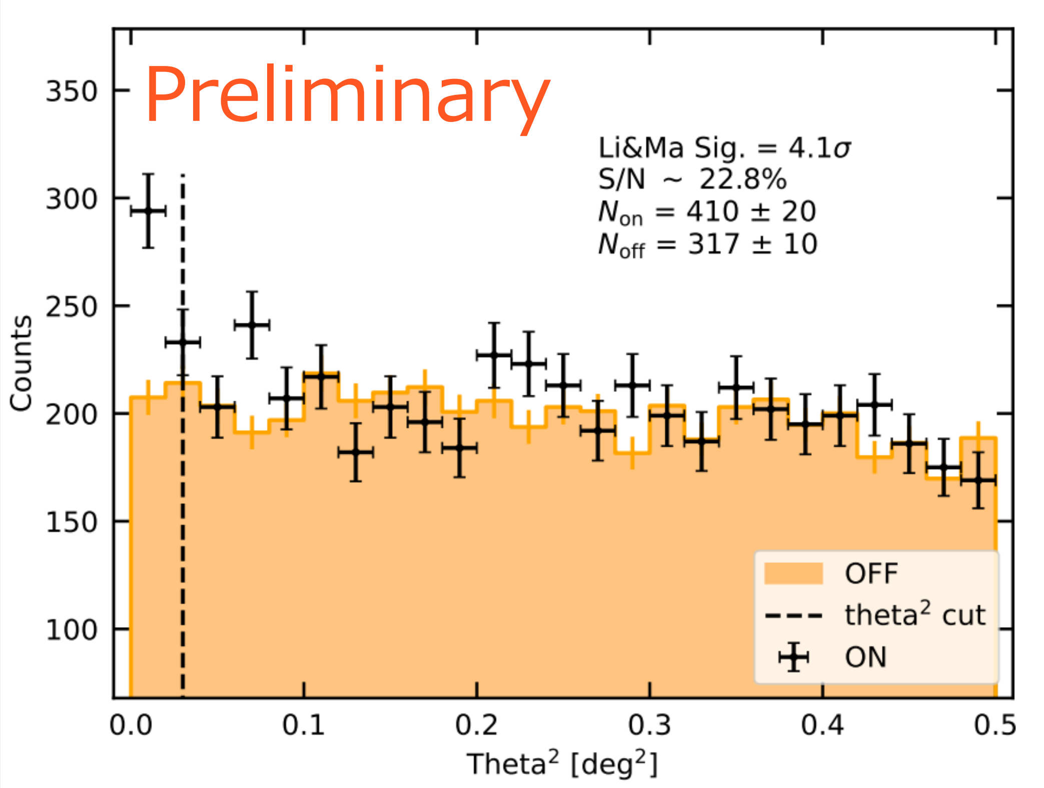
J.D. Mbarubucyeye et al. (ICRC2023)



Signal Search (Angular Distribution)

- A hint of detection with ~4 σ excess on Oct. 10 (1.3 d after the burst onset)
  - Consistent results are obtained with independent analysis methods

- No significant excess for Oct. 12 and later dark times



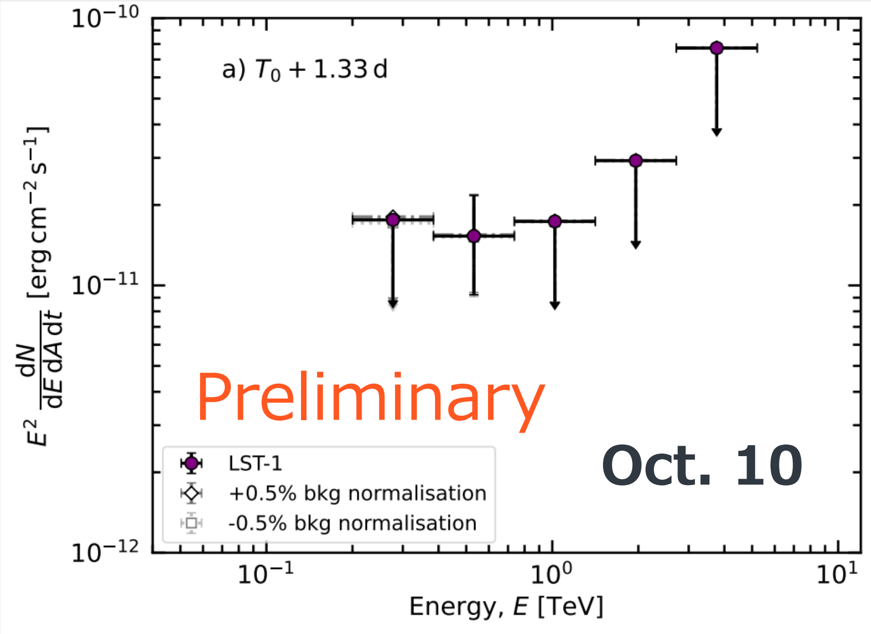
Theta: angular distance between gamma-ray like events and source position

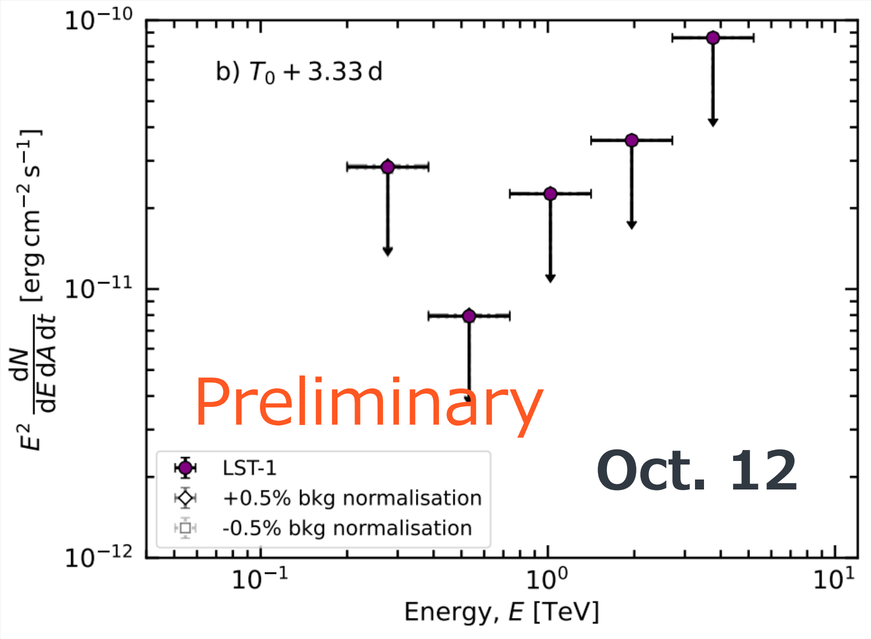
SED (Moon Data)

- 1D spectral analysis was performed with *gammapy*
  - SEDs shown below are **not** corrected for EBL absorption

- Power-law with EBL absorption was assumed for the spectral analysis
  - Intrinsic power-law index was fixed to 2.0
  - EBL model: Dominguez (z = 0.151)

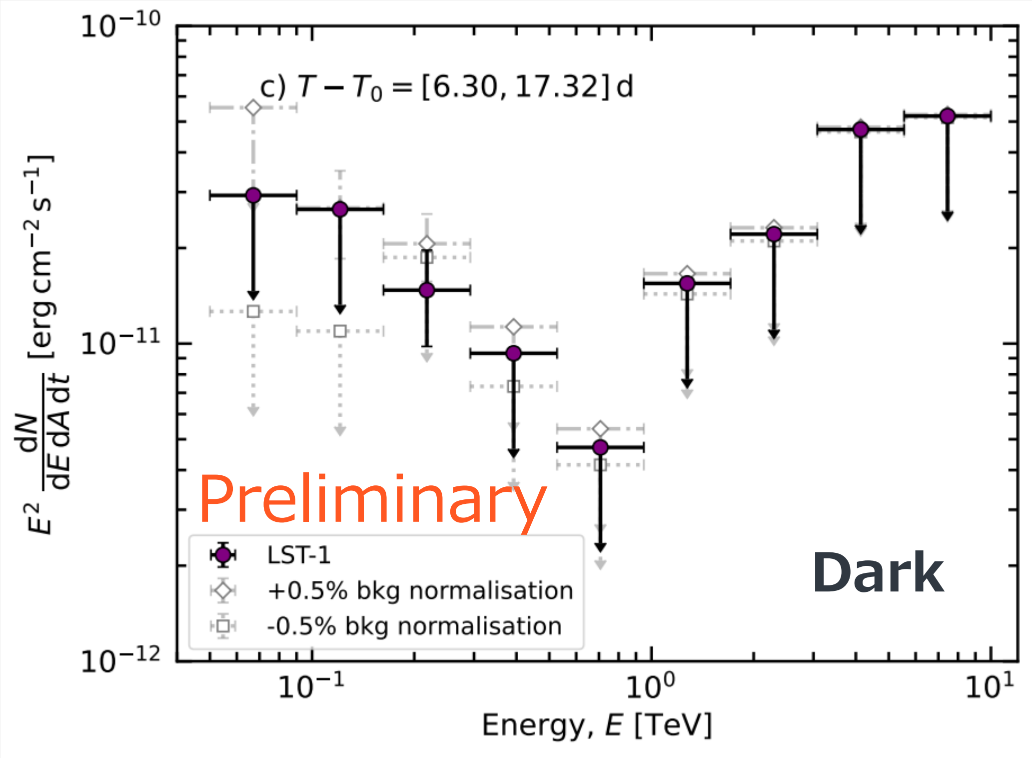
- Due to moonlight, the lower energy bound of SED is 200 GeV





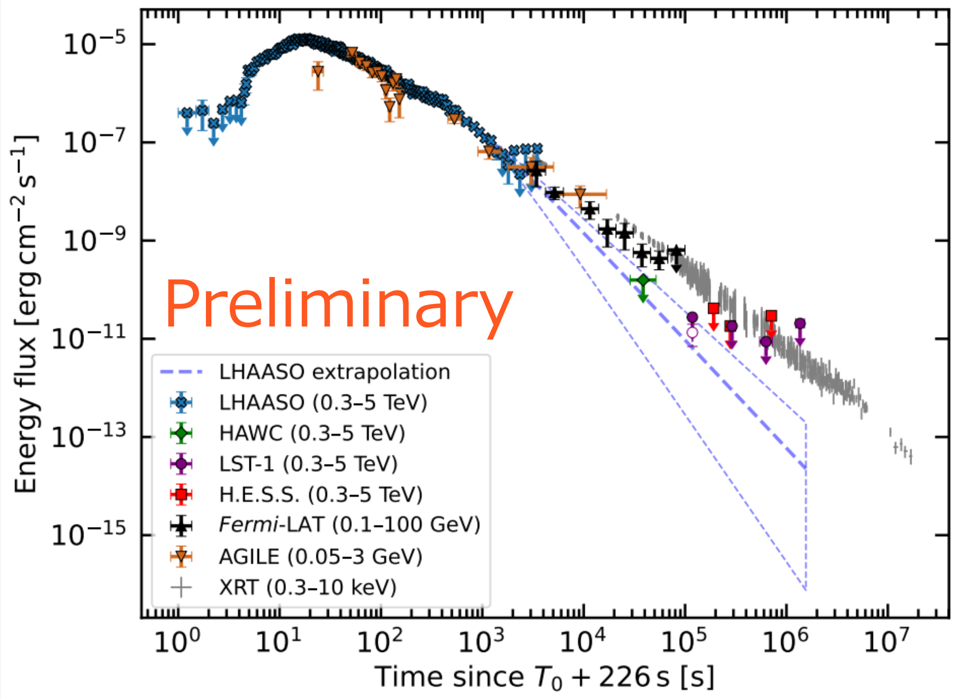
SED (Dark Data)

- No presence of the moon allowed computing SED down to 50 GeV
- Possible systematics on background normalization
  - ±0.5% systematics are taken into account based on LST-1 performance paper (H. Abe et al. 2023)
  - Effect gets larger as the energy decreases



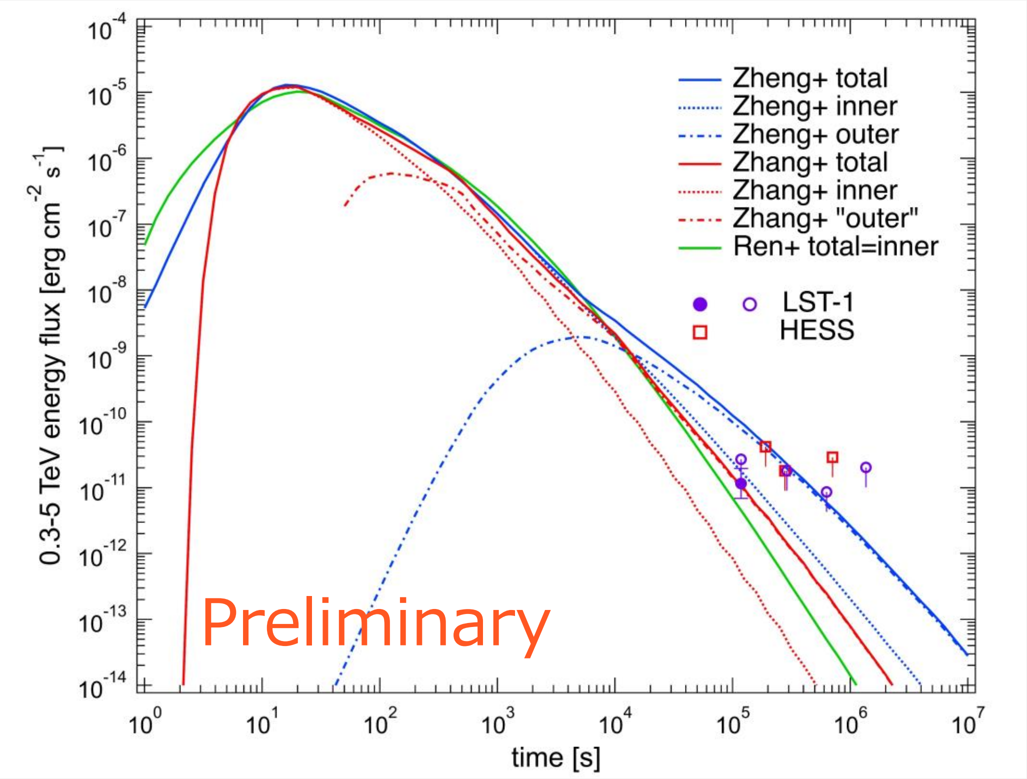
Light Curve

- LST-1 light curve shown below are corrected for EBL absorption
- LST-1 upper limits are compatible with H.E.S.S. upper limts
  - Earliest upper limits among IACTs (1.3 d after the burst onset)
- Assuming the excess on Oct. 10 ($\sim 10^5$ s) is real, it is consistent with extrapolation of LHAASO light curve
  - Model independent insight from LST-1 observations



Comparison with Modeling Results

- LST-1 upper limits disfavor the model reported by Zheng+24
  - At least parameter space is constrained
- Models by Zhang+23 and Ren+24 reproduce well the LST-1 signal, if we assume the signal is real
  - Ren+24: Latetime TeV emission from **inner jet** dominates
  - Zhang+23: Latetime TeV emission from **outer jet** dominates



Summary

- GRB221009A is an extremely bright GRB which occurred relatively close to Earth
  - Early TeV emission is detected by LHAASO
  - Structured jet models are discussed for explaining MWL data

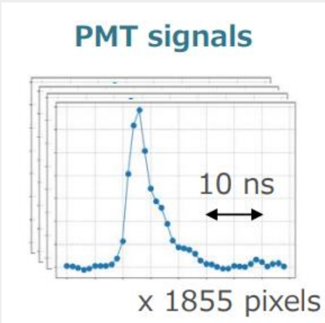
- LST-1 performed follow-up observations of GRB221009A from 1.3 d after the burst trigger
  - The promptest observation among IACTs

- LST-1 obtained a hint of detection with 4σ excess on Oct. 10
  - Validated with two independent analysis method

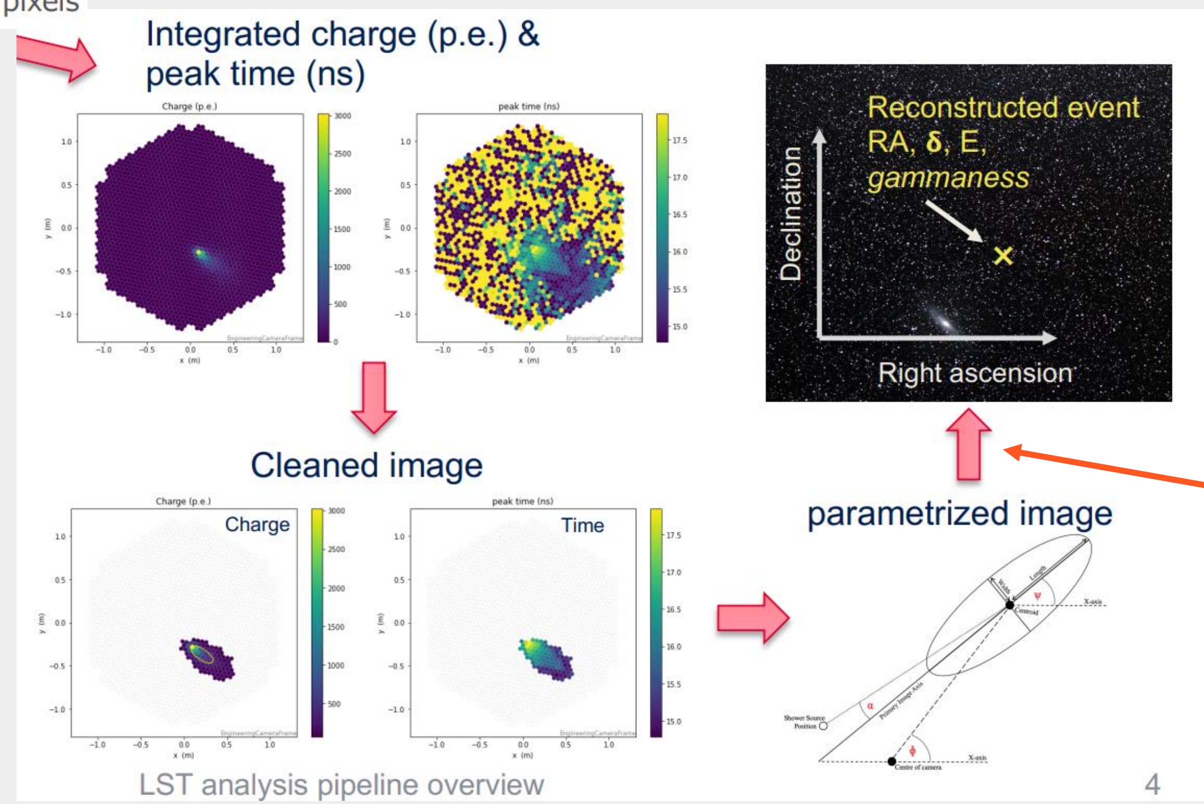
- LST-1 results test the structured jet models reported
  - LST-1 upper limits disfavor the model by Zheng+24
  - Models by Zhang+23 and Ren+24 reproduce well the LST-1 signal, if we assume the signal is real

Backup

Entire View of Analysis Flow



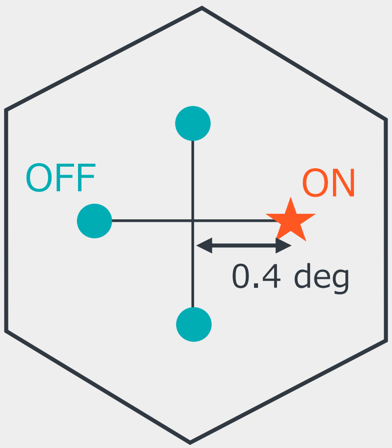
High level analysis



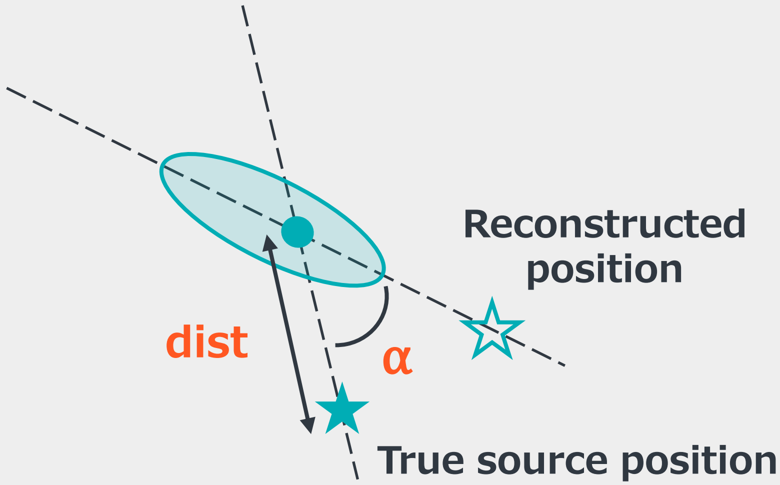
Machine Learning
(Random forest)

Analysis Method

Wobble observation



*α and dist are computed for each assumed source/OFF position



Source-**independent** Method

- Use reconstructed position of the source
- Valid for diffuse and point-like sources

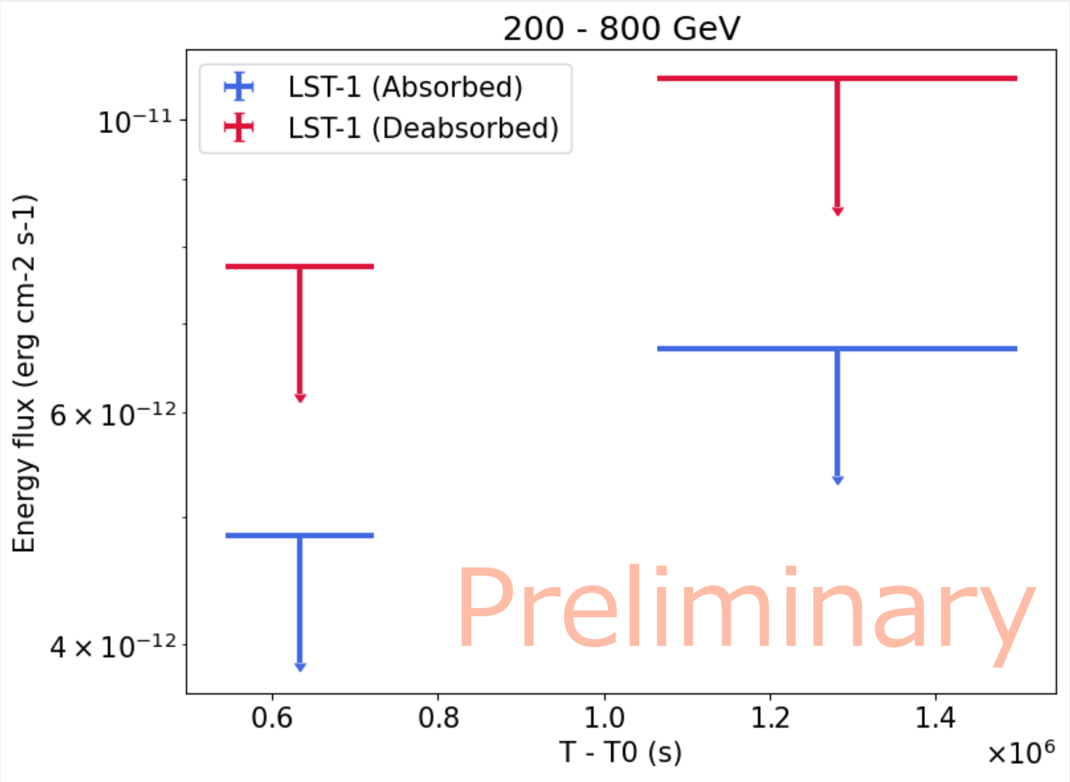
Source-**dependent** Method

- Use true position of the source
- Assume source/OFF positions
- Only valid for point-like sources

➡ Better energy resolution and smaller bias at low energies

LST-1 Lightcurve of GRB221009A

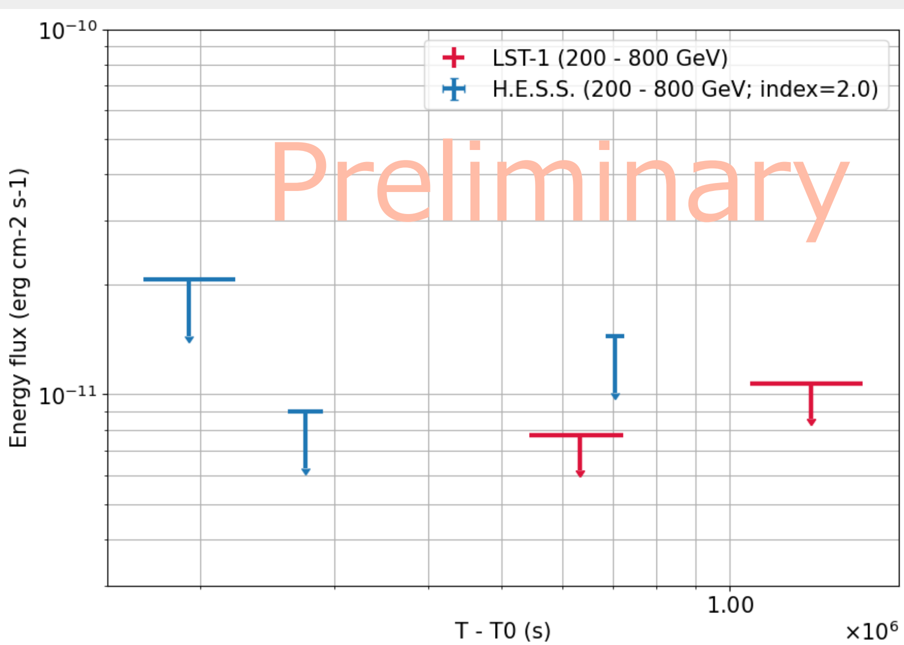
- Upper limits are calculated, considering the extragalactic background light (EBL) absorption
  - TeV photons interact with EBL in optical and infrared wavelength
  - Redshift z = 0.151
  - EBL model: Dominguez et al. (2011)



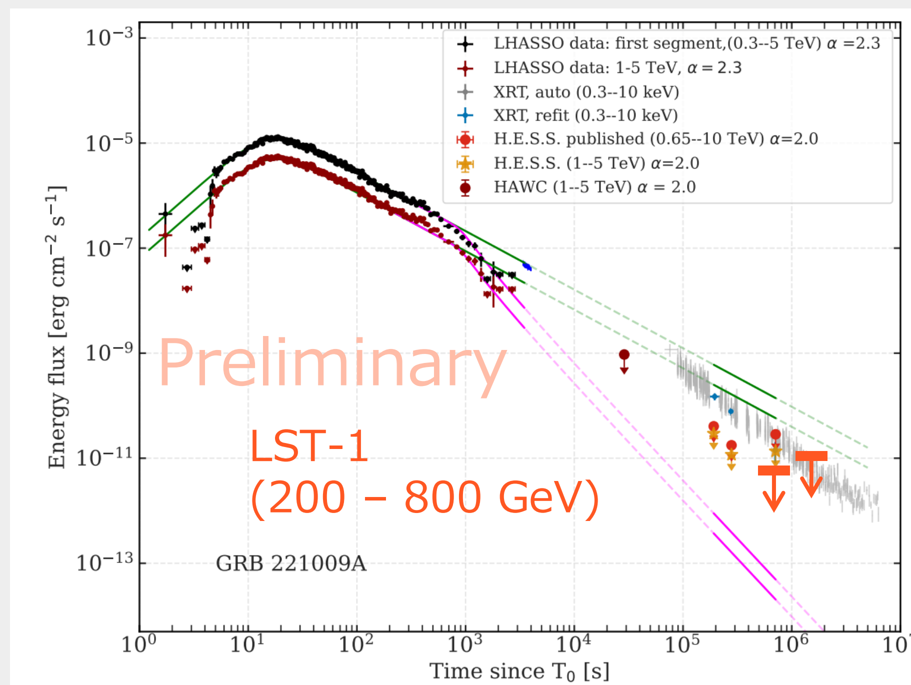
Comparison with Other Measurements

- H.E.S.S. upper limits are extrapolated to LST-1 energy range
  - Original energy range: 0.65 – 10 TeV (Assumed index = 2.0)
- LST-1 upper limits constrain models which predict TeV flux higher than extrapolation of the LHAASO lightcurve
  - cf.) Zheng et al. (arxiv:2310.12856)

F. Aharonian et al 2023 ApJL 946 L27

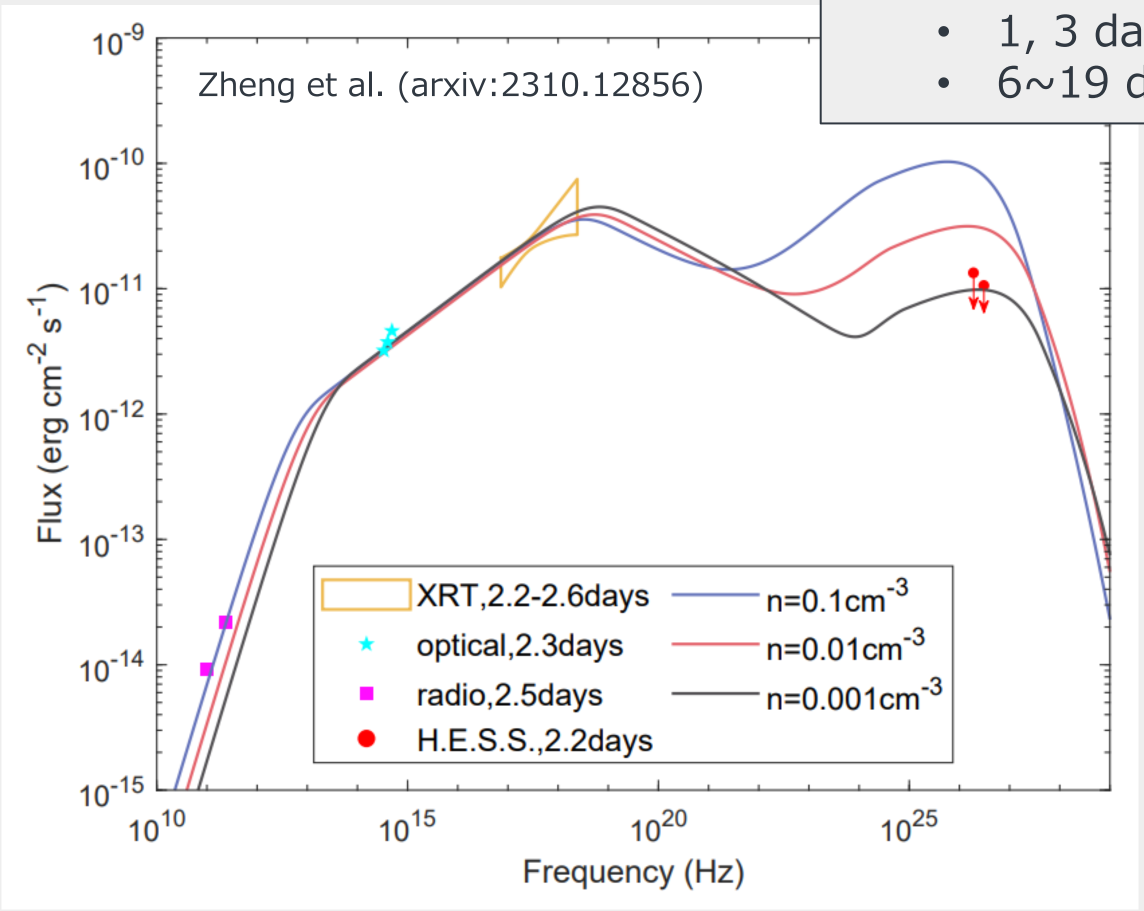


J.D. Mbarubucyeye et al. (ICRC2023)



Constrain Surrounding Environment

LST-1 observation:
- 1, 3 days (strong moon)
- 6~19 days (dark)



Latetime upper limits can be used to contrain density profile of interstellar medium or circumstellar medium

Zheng et al. (arxiv:2310.12856)

SED at T0+2.5 days

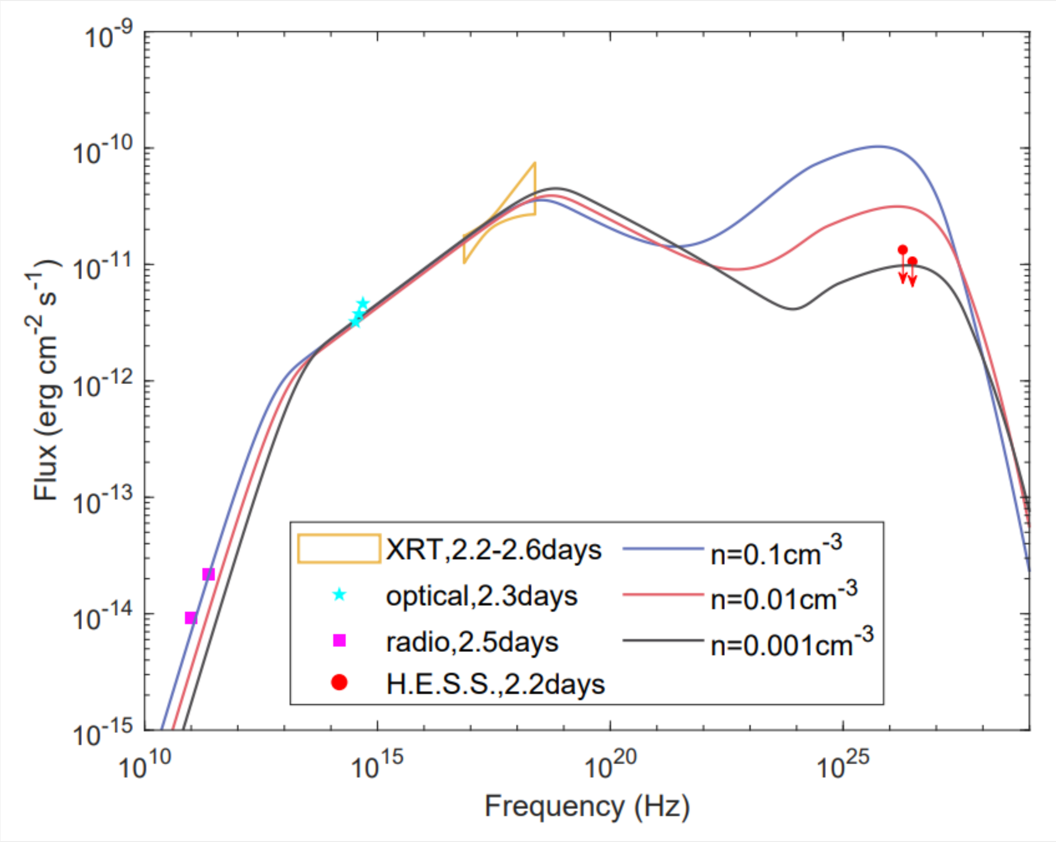
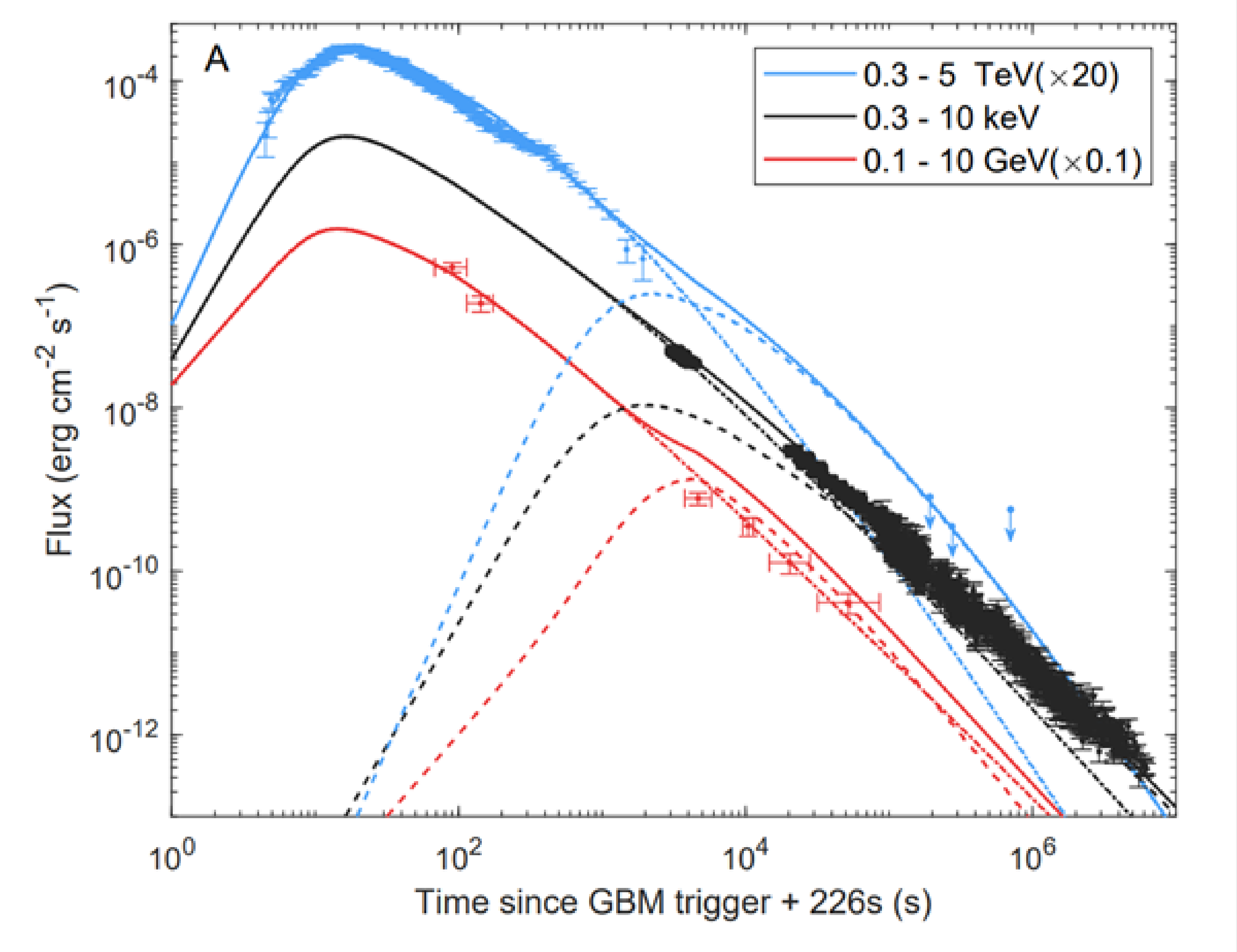


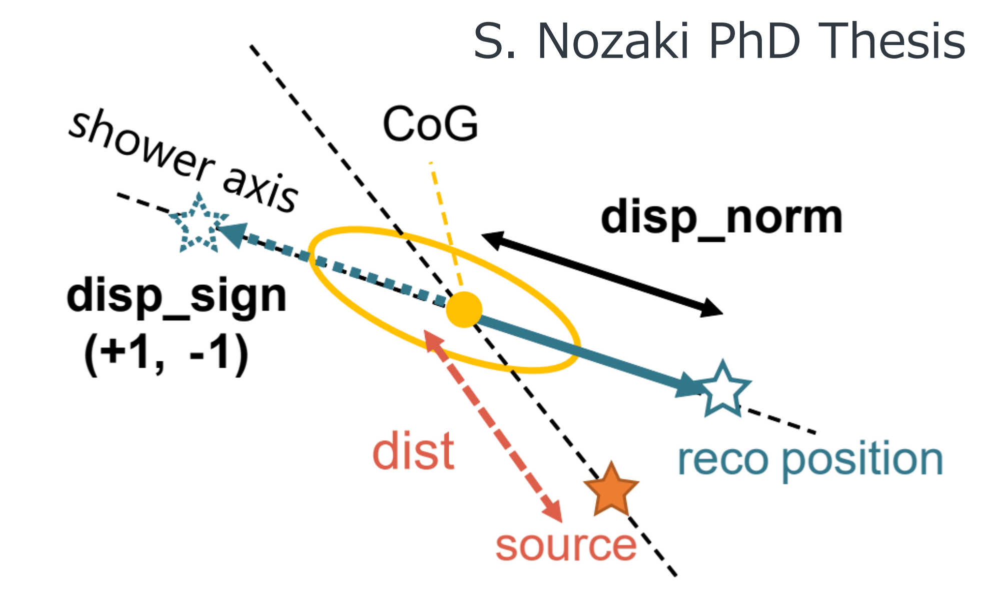
Figure 1. Spectra energy distribution of the afterglow emission at T_0+ 2.5 days. The red points denote the 95% C.L. upper limits from H.E.S.S. Collaborations. The blue, red and black lines represent the afterglow models with density $n_0 = 0.1\text{cm}^{-3}$, $n_0 = 0.01\text{cm}^{-3}$ and $n_0 = 0.001\text{cm}^{-3}$, respectively. The corresponding values of ϵ_B are 3×10^{-4}, 1×10^{-3} and 4×10^{-3}, respectively for the three lines. Other parameters are $E_{\text{II,iso}} = 2.2 \times 10^{53}$erg, $p = 2.4$, $\epsilon_\text{e} = 0.1$, and $\xi_e = 0.1$.

Zheng et al. (arxiv:2310.12856)

Lightcurve



*Energy range of H.E.S.S. upper limits: 0.65 – 10 TeV



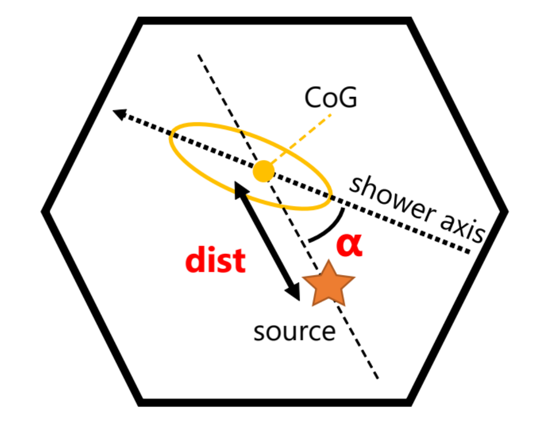


Fig. 9.2 Source-dependent parameters.

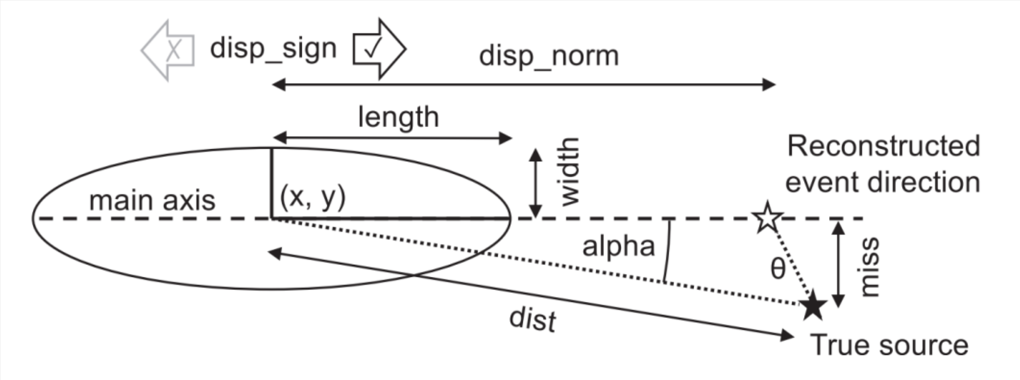
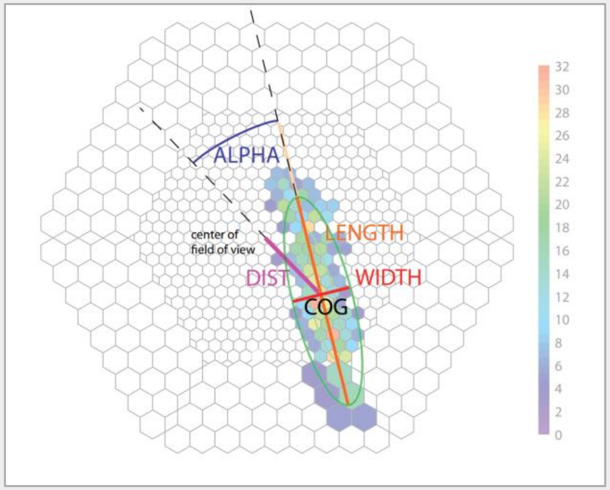
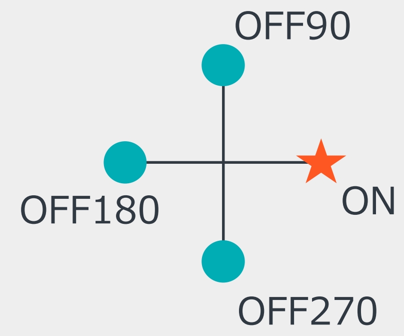


Figure 3. Definition of basic image parameters.

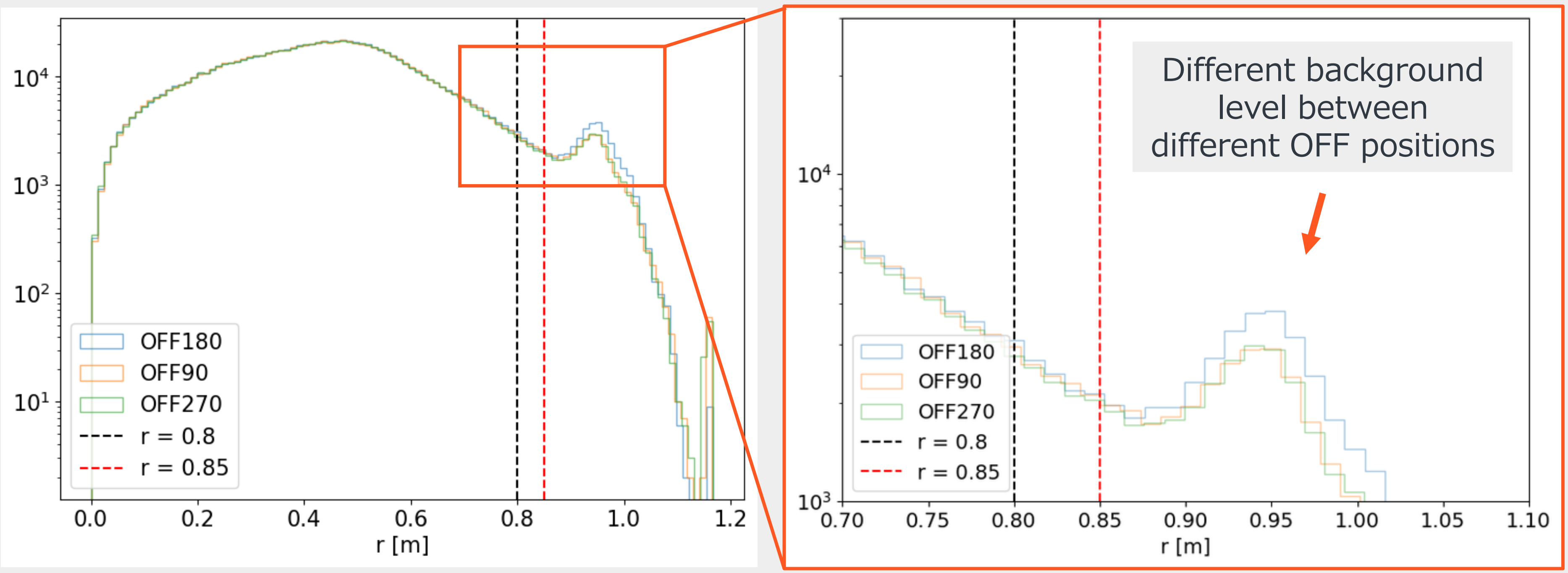


Investigation of Background Systematics

- **r** [m]: Distance between camera center and shower image gravity
- Bump feature can be seen in the distributions of r



Distribution of r parameter for OFF events
(α < 20 deg and event selection cut applied)



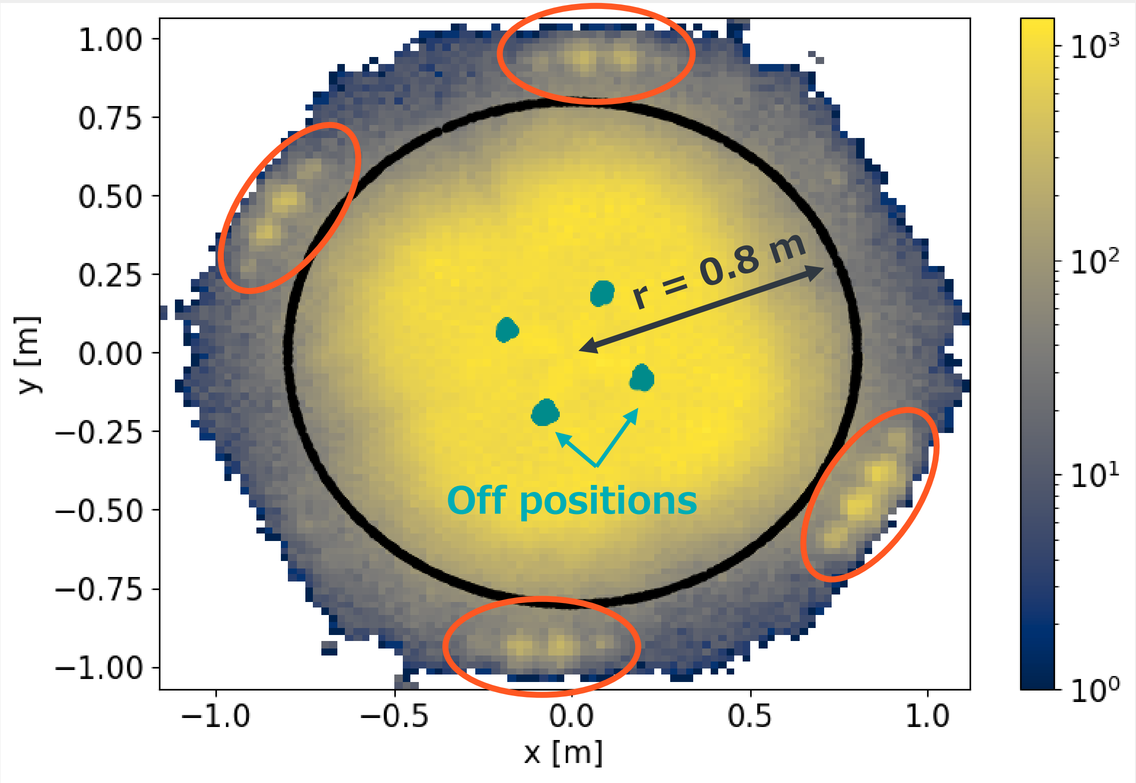
Events with r < 0.8 m (1.6 deg) are used for the analysis

Investigation of Background Systematics

- Strange spots can be seen in shower gravity map below
  - Still investigating the cause

Distribution of shower gravity for OFF events
(after event selection cuts applied)

r: Distance between camera center and shower gravity

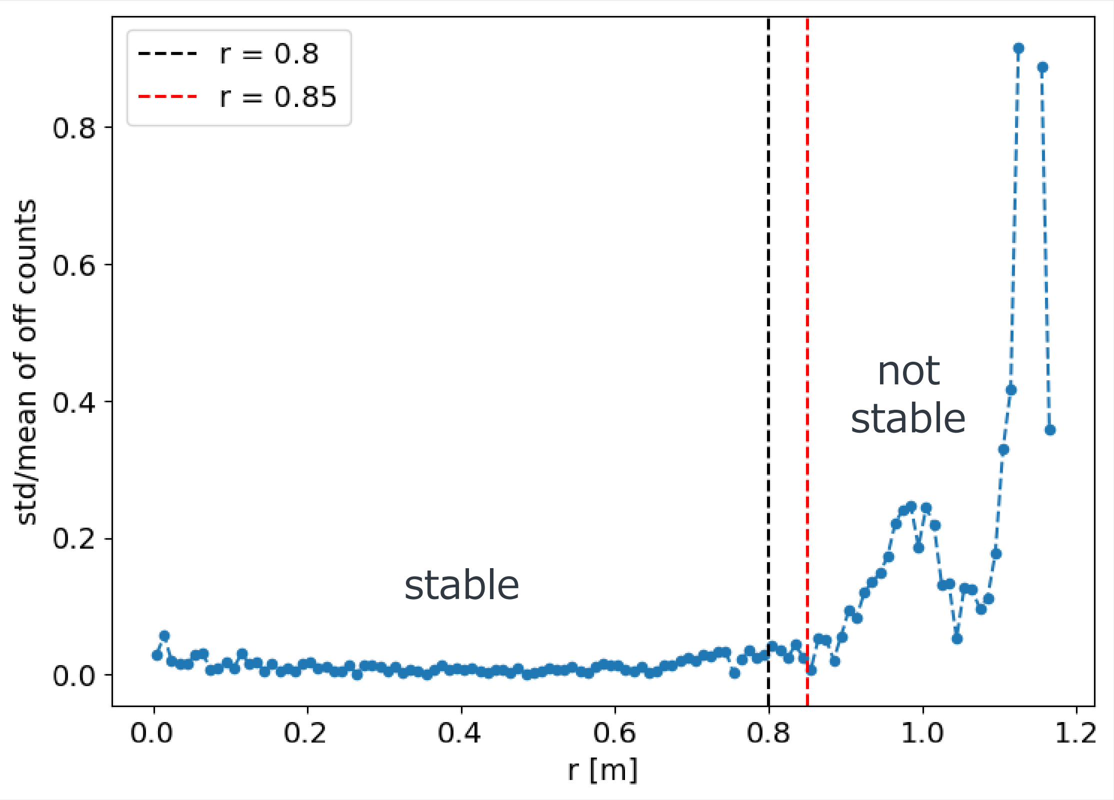


Events with r < 0.8 m (1.6 deg) are used for the analysis

Determine the cut in r

- Intensity > 50
- Alpha < 20 deg
- gh eff. = 80%
- Duplicated events removed

Standard deviation/mean of off counts (Noff = 3)



Cut of r < 0.8 is applied for later analysis