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

Arnau Aguasca-Cabot

Alessandro Carosi, Alice Donini, Susumu Inoue, Yuri Sato, Monica Seglar-Arroyo, Kenta Terauchi, Pol Bordas and Marc Ribó for the CTAO-LST Project

Gamma 2024

2024-09-05

CTAO LST COLLABORATION

ICCUB Institut de Ciències del Cosmos UNIVERSITAT DE BARCELONA

UNIVERSITAT DE BARCELONA

IEEC Institut d'Estudis Espacials de Catalunya

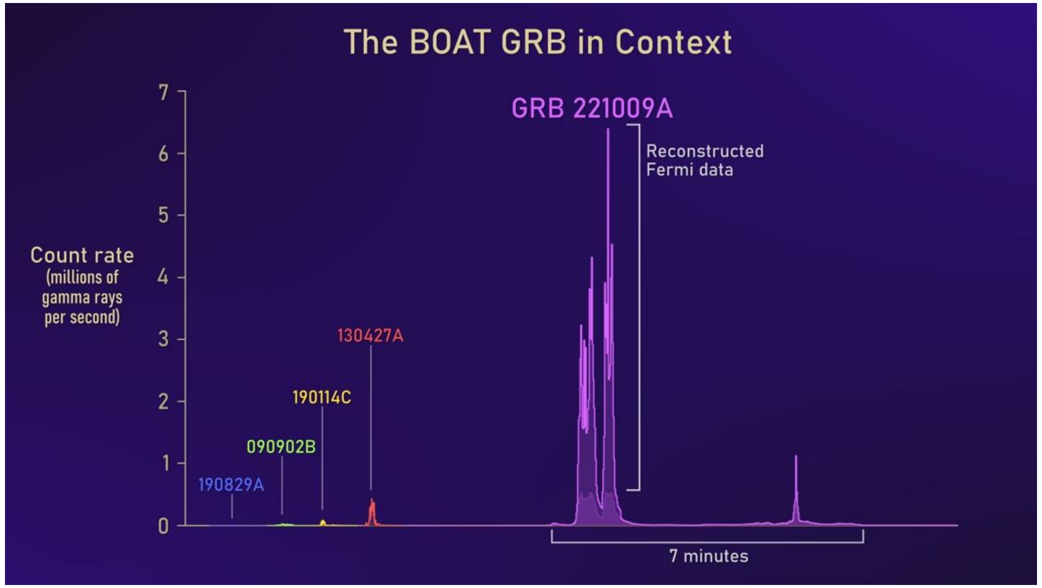
GRB 221009A

- The brightest of all time (BOAT) GRB
  - Rate of ≤ 1 event every 1000 years
    (Williams et al. 2023)

- The first GRB with detection of the VHE afterglow onset
  - Peak energy flux* $= 10^5$ Crab
    (LHAASO Collaboration 2023)

- Evidences of a structured jet
  (e.g. Zhang et al. 2023, Ren et al. 2024, Zheng et al. 2024)

- Burst during bright moonlight
  - Challenging for Imaging Atmospheric Cherenkov Telescopes (IACTs)



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

*Energy flux between 0.3 – 5 TeV

The Large-Sized Telescope prototype (LST-1)

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

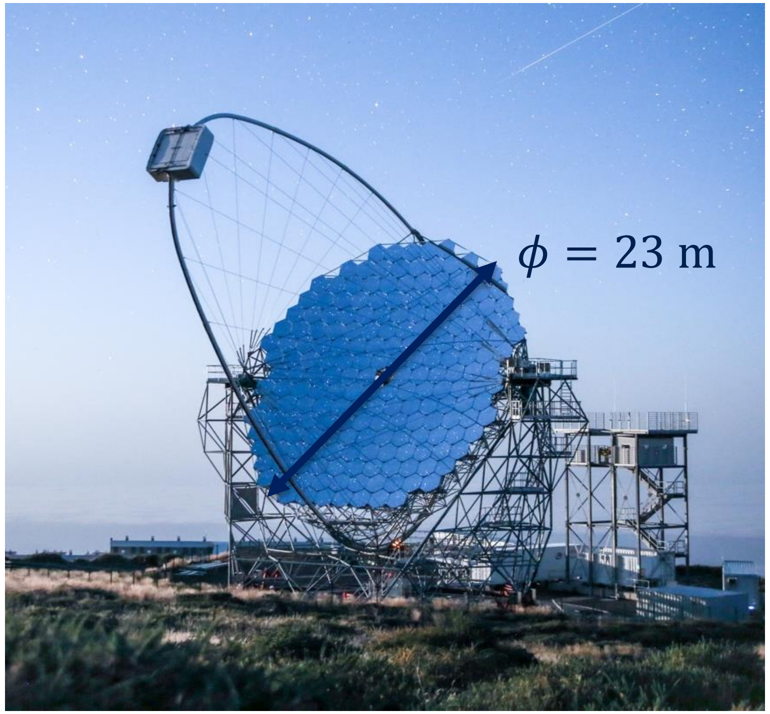
- LSTs are ideal for GRBs

Fast re-positioning speed: 180° in 20 s

Low energy threshold: 20 GeV

4.5° field-of-view camera

The first LST in La Palma: LST-1



LST-1 observations

- LST-1 observed GRB 221009A
  - Data taking under different observation conditions

(orange)	very strong moon conditions
(yellow)	strong moon conditions
(blue)	dark conditions

Date (YYYY-MM-DD)	$T - T_0$ (d)	Min. zenith (deg)	Max. zenith (deg)	Observation time (h)
2022-10-10	1.33	31	54	1.75
2022-10-12	3.33	34	52	1.42
2022-10-15	6.30	25	52	0.80
2022-10-16	7.32	34	65	2.35
2022-10-17	8.30	28	60	2.41
2022-10-23	14.30	34	61	2.01
2022-10-25	16.33	45	59	1.18
2022-10-26	17.32	42	58	1.42

Burst trigger T_0 = 2022-10-09 13:16:59.99 UTC (Lesage et al. 2023)

LST-1 observations

- LST-1 observed GRB 221009A
  - Data taking under different observation conditions
  - Follow-up observations begin on T_0 + 1.33 d

(very strong moon conditions colour)	very strong moon conditions
(strong moon conditions colour)	strong moon conditions
(dark conditions colour)	dark conditions

Date (YYYY-MM-DD)	$T - T_0$ (d)	Min. zenith (deg)	Max. zenith (deg)	Observation time (h)
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2022-10-17	[illegible]	[illegible]	[illegible]	2.41
2022-10-23	14.30	34	61	2.01
2022-10-25	16.33	45	59	1.18
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First observations of GRB 221009A by an IACT

Burst trigger T_0 = 2022-10-09 13:16:59.99 UTC (Lesage et al. 2023)

LST-1 analysis

- GRB 221009A observations require a dedicated analysis scheme

Moon observations (~3 h)

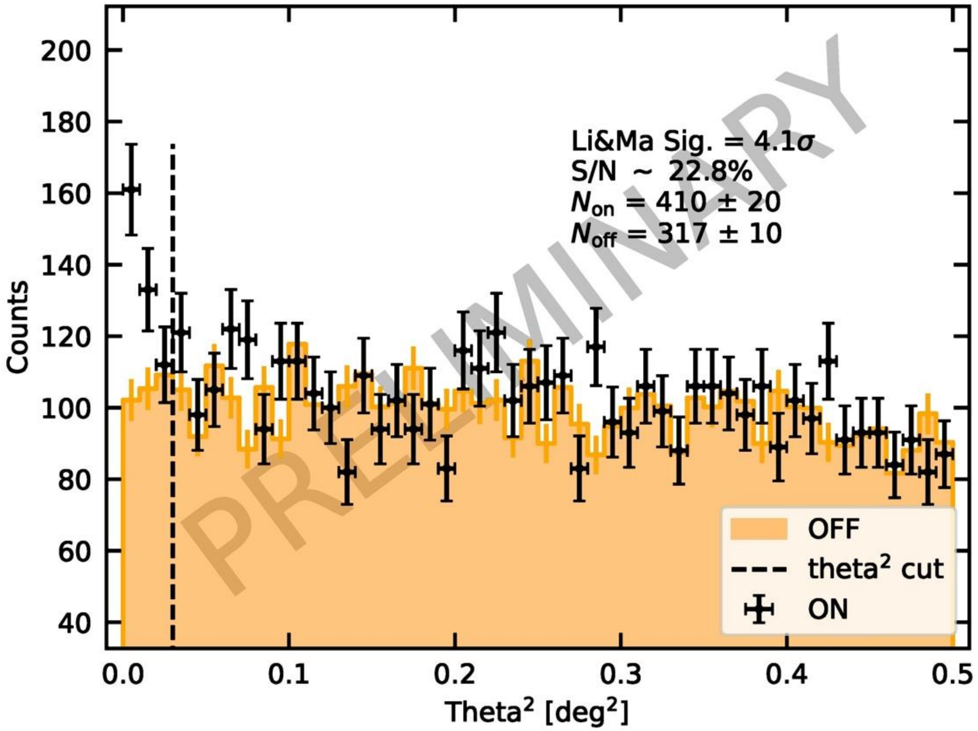
- **Degradation** of the telescope performance
- **Tailored** analysis
- Energy threshold of **hundreds** of GeV

Dark observations (~10 h)

- Best performance at hundred GeV
- Standard analysis
- Energy threshold of **tens** of GeV

Angular distribution

- **Hint of detection** in the GRB 221009A direction on Oct. 10 (T_0 + 1.33 d)
  - Statistical significance*: ~4σ
  - Compatible results using two independent analysis chains
- Excess compatible with background afterwards
  - Both for Oct. 12 and later times



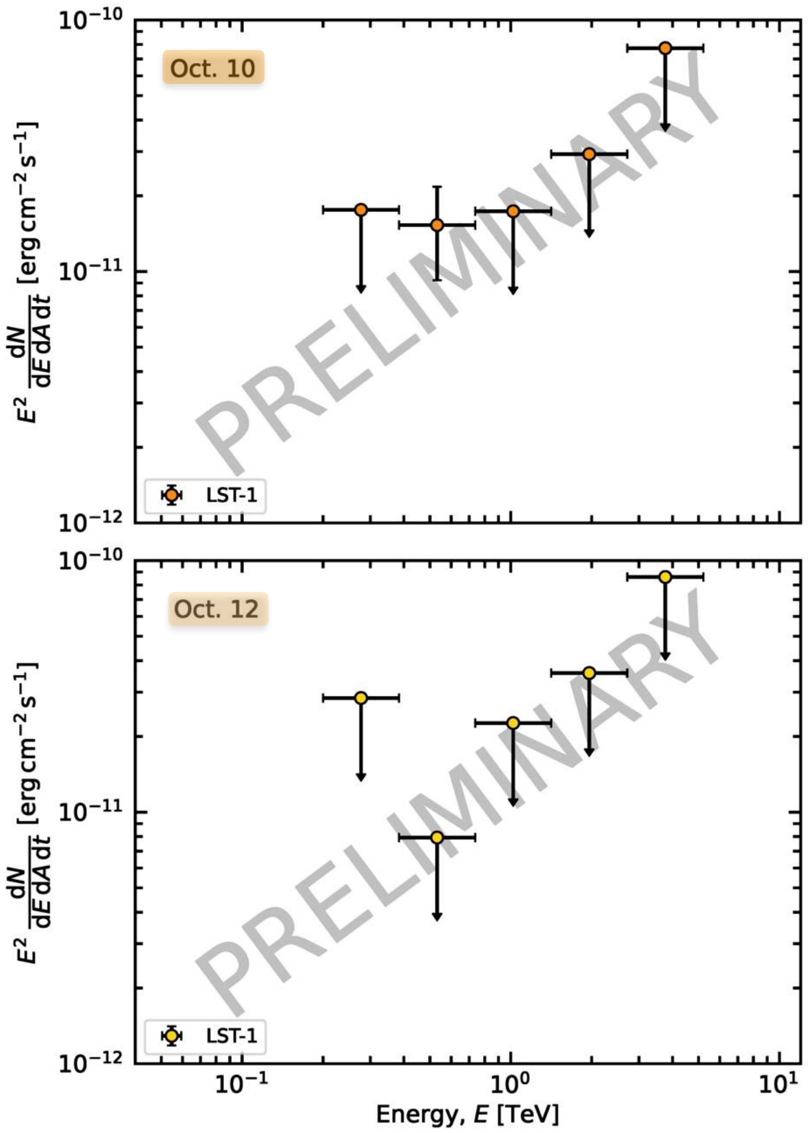
θ^2-plot for the moon data (Oct. 10)

*Equation 17, Li & Ma 1983

Spectral results : moon analysis

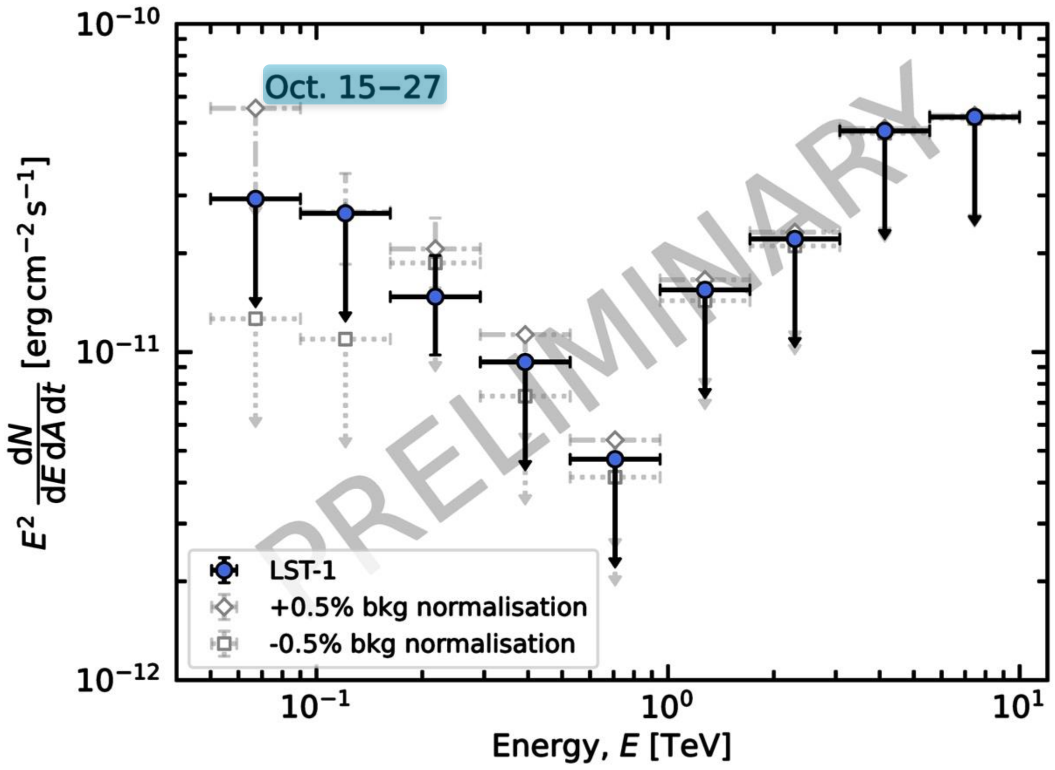
- 1-D spectral analysis
- Assumed spectral model
  - Power law with EBL attenuation ($z = 0.151$)
  - Intrinsic spectral index fixed at $\Gamma = -2$
- **Deep** differential flux **upper limits** (ULs)
- Lower energy bound at 200 GeV

SEDs during the moon period



Spectral results : dark analysis

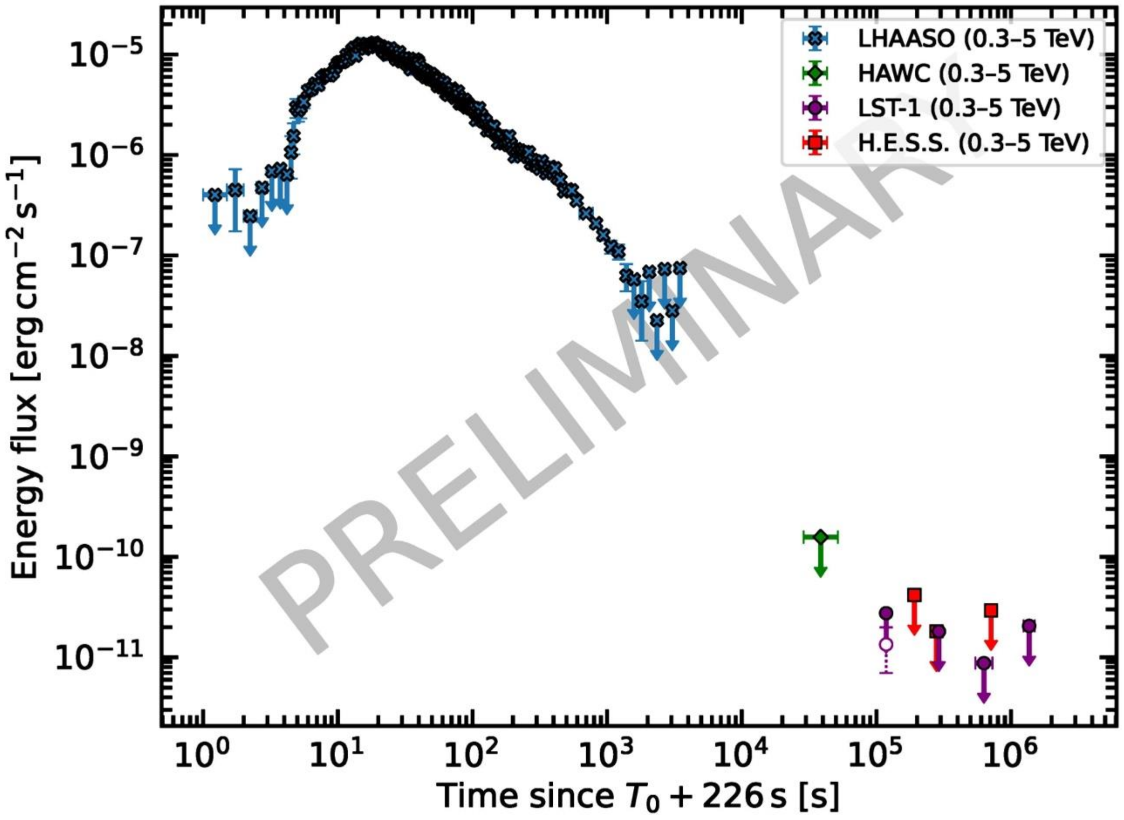
- Lower energy bound at **50 GeV**
- Background normalisation as a possible source of systematics
  - Estimated systematics: $\pm 0.5\%$
  - Maximum effect at low energies
  - Negligible effect for the moon analysis



SED during the dark period

Light curve

- LST-1 constrains the emission as early as T_0 + 1.33 d (~10^5 s)
- LST-1 bridges the HAWC and H.E.S.S. ULs
- Energy flux ULs at the level of 10^{-11} erg cm^{-2} s^{-1} between $E = [0.3, 5]$ TeV
  - An order of magnitude deeper than HAWC, comparable with H.E.S.S.



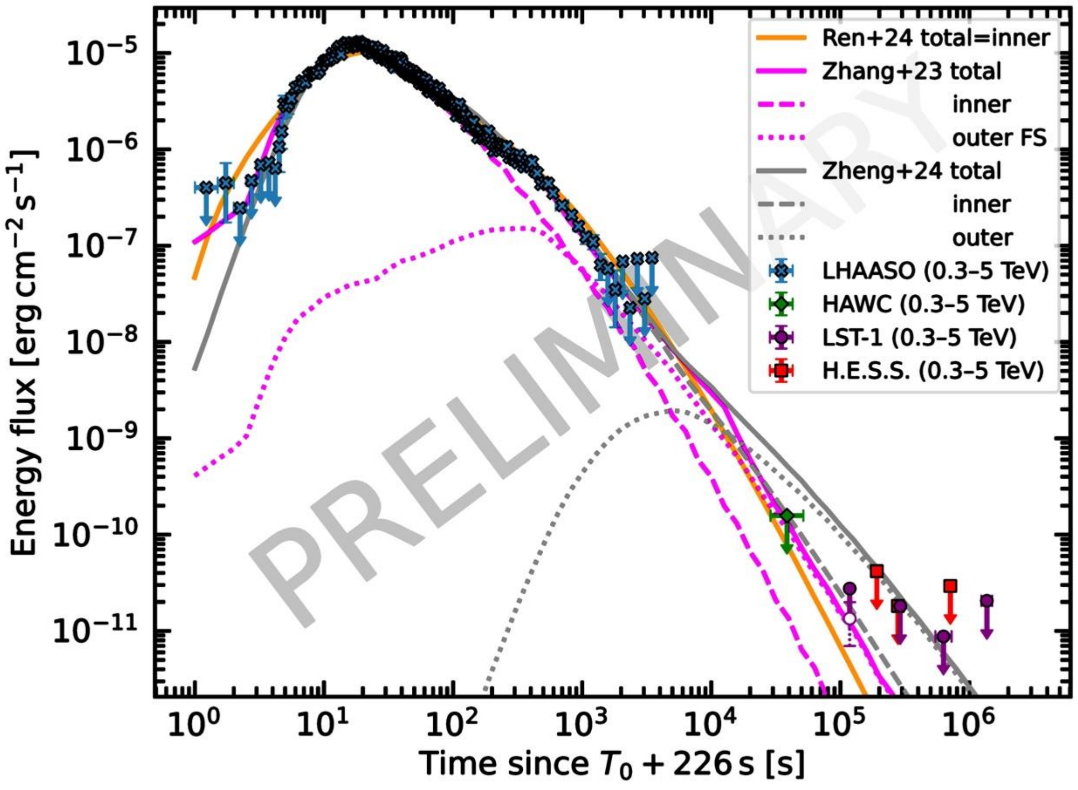
LST-1 light curve using moon and dark data

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 emission is real …
  - Does the VHE emission come from the inner or the outer component?

- Late-time TeV emission is **mean-ingful** to constrain the jet structure



Conclusions

- LST-1 observations provide valuable information after T_0 + 1.33 d
  - Observation campaign under diverse observing conditions
- Hint of detection at 4σ on Oct. 10 with LST-1
  - Validated using two independent analysis chains
  - Results compatible with background afterwards
- The “early” LST-1 data with HAWC and H.E.S.S. constraints are key
  - Relevant for constraining the emission of jet models at late times

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LST-1 analysis

- GRB 221009A observations require a dedicated analysis scheme

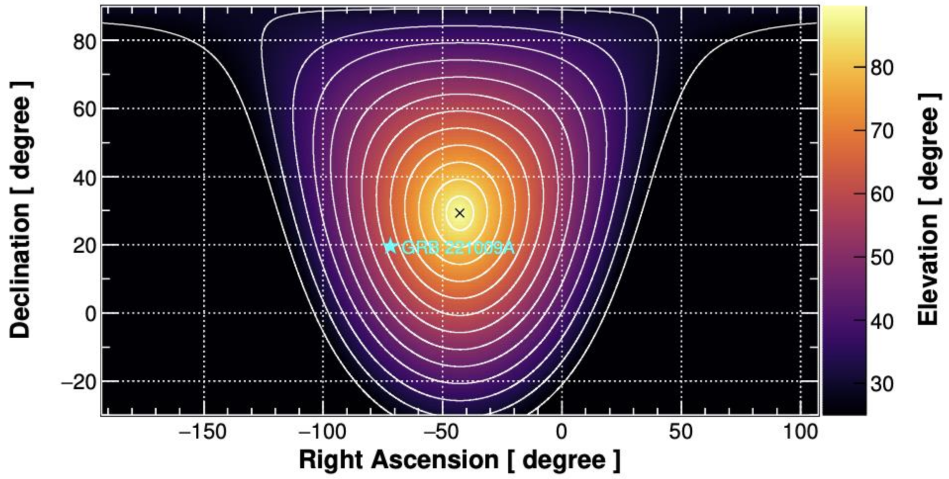
Moon observations (~3 h)

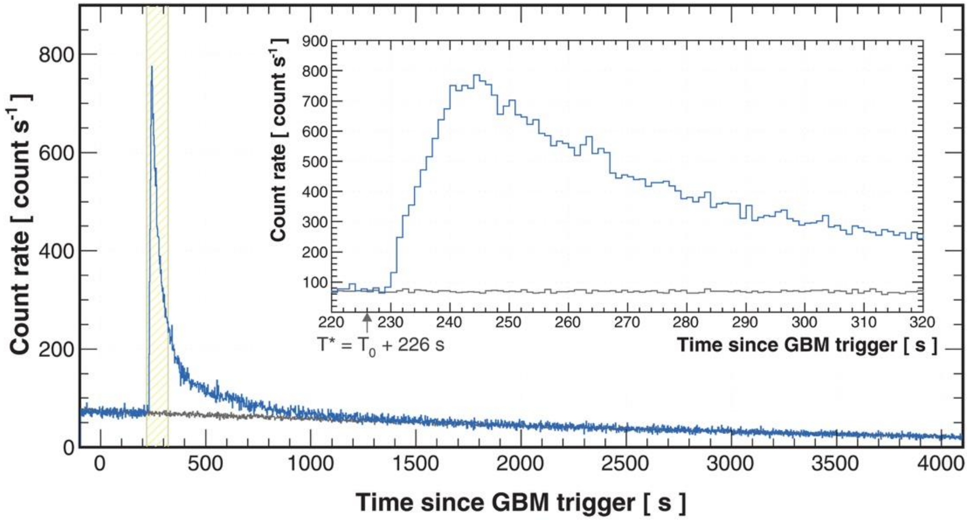
- Degradation of the telescope performance
- **Tailored** analysis
- Energy threshold of **hundred** GeV

- Better calibration
- Optimised signal extractor
- Optimised image cleaning
- Observation-by-observation analysis

LHAASO observations of GRB 221009A

- GRB 221009A occurred within the field of view of LHAASO
  – First GRB detection by a water Cherenkov
- GRB 221009A was detected with LHAASO with a high statistics
  – More than 60,000 photons at E > 0.2 TeV
- Photons detected up to E~13 TeV
  – The most energetic photon recorded from a GRB





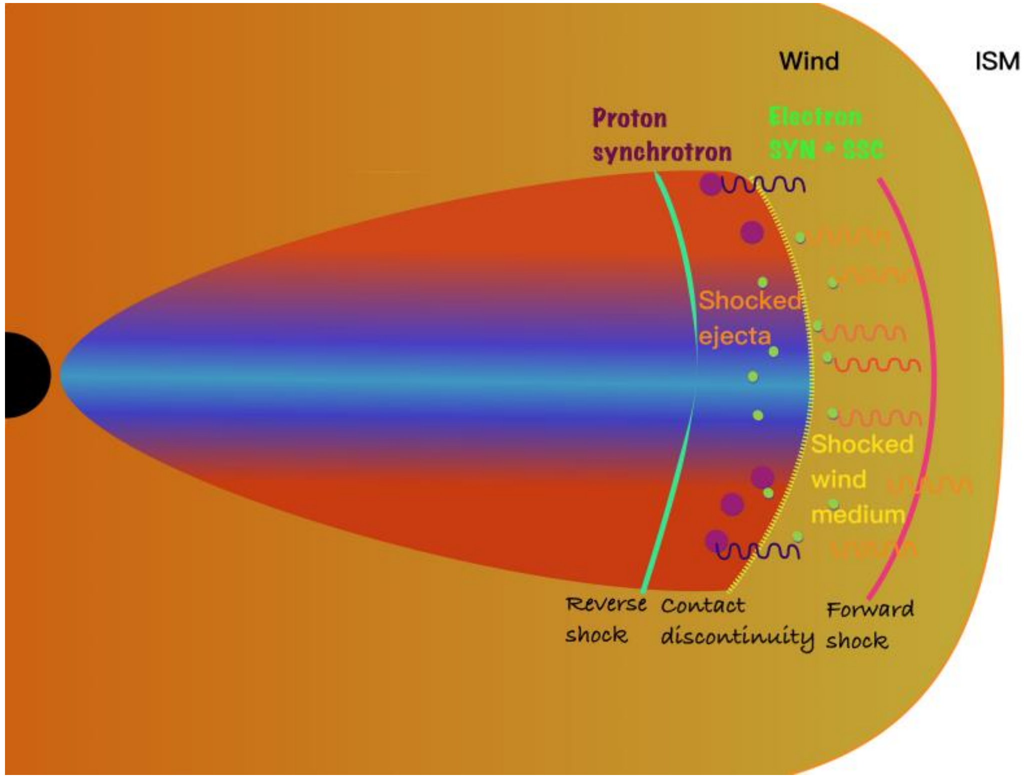
LHAASO Collaboration 2023

Structured jet and environment

- Structured jet components
  - Narrow top-hat core
  - Structured-wide wing

- Stratified CMB density profile
  - ISM + wind environment

$$n(r) = \begin{cases} n_0, & r < r_c \\ Ar^{-2}, & r \geqslant r_c. \end{cases}$$



Zhang et al. 2023

Validation of the LST-1 results

- An extensive validation of the LST-1 results has been performed both for the moon and dark periods
  - Independent cross-check analysis for each period
  - Two independent analysis chains at the low-level analysis

Analysis chain	
Source-independent analysis	→ Results in this talk (CTAO standard analysis)
Source-dependent analysis	→ Assume source position at the GRB 221009A location