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Moon shadow in the EEE data

EEE group of ITI Marconi di Pontedera

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EEE Marconi - Pontedera (Pisa)

Motivation

We were inspired by the following article of the:
Large High Altitude Air Shower Observatory (LHAASO)

This detector is similar to EEE for cosmic ray detection (area ~1.5 km^2 located @~3000 m of altitude) but in addition LHAASO can trace back high energy gamma rays (thanks to 3 underground pools filled with 3 10^5 liters of water for Cerenkov radiation detection)

Journal of Physics:
Conference Series

PAPER • **OPEN ACCESS**

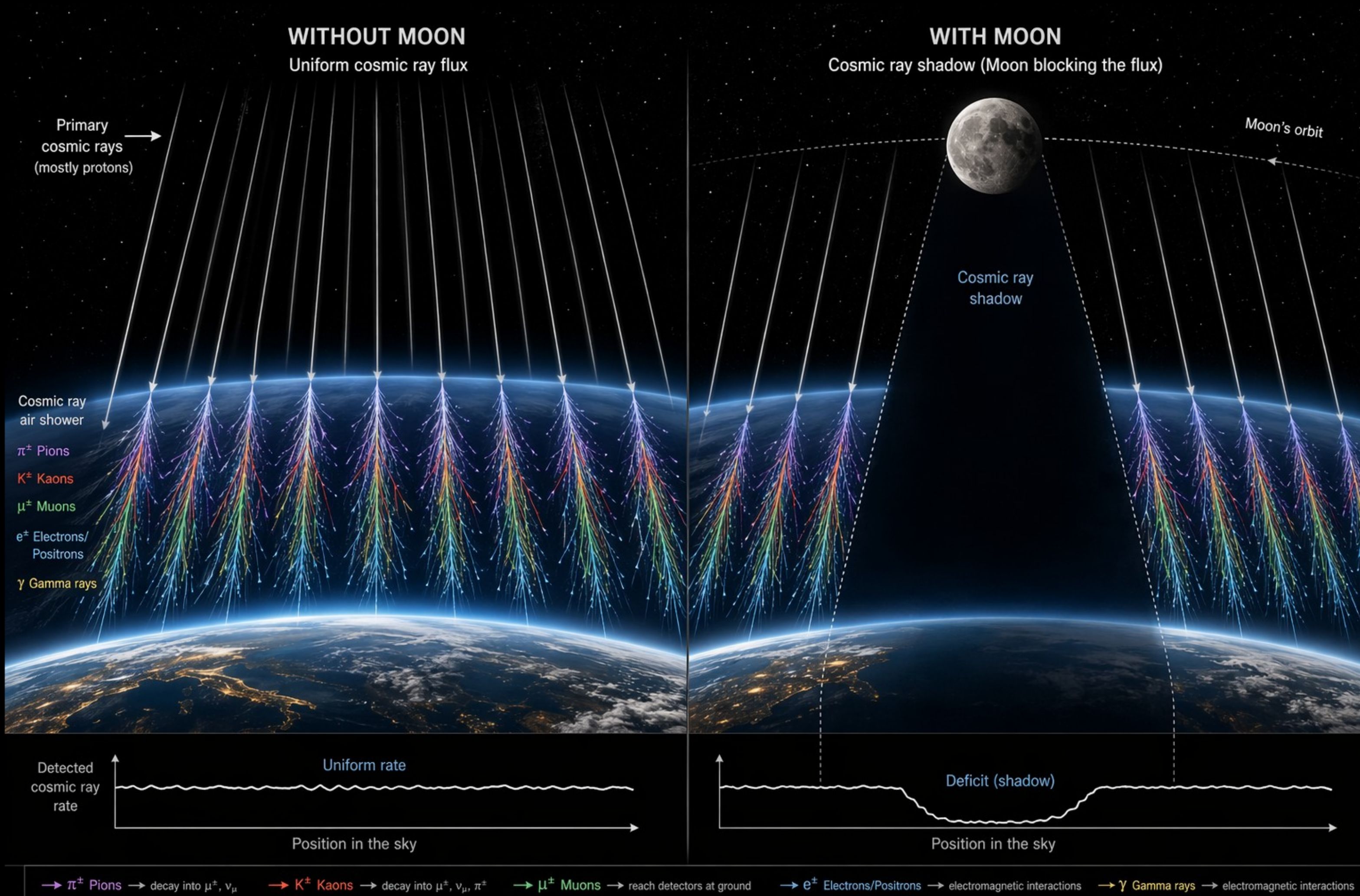
Analysis of Moon shadow from 2021-2022 LHAASO WCDA Data

To cite this article: J Maburee *et al* 2023 *J. Phys.: Conf. Ser.* **2653** 012026

View the article online for updates and enhancements.

The idea

We are not able to reconstruct primary vertex but maybe we can indirectly detect a deficit of primary cosmic ray coming from specific directions (those of the moon along it's apparent motion in the sky)



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Moon features relevant for this analysis

Diameter: 3 475 km (Earth: 12 742 km)

Distance @ perigee (Closest): ~363 300 km
Distance @ apogee (Farthest): ~405 500 km
Takes ~2 weeks to travel from perigee to apogee and back

Sidereal Period (Orbit relative to stars): 27.322 days
Synodic Period (Full Moon → Full Moon): 29.530 days

IMPORTANT:

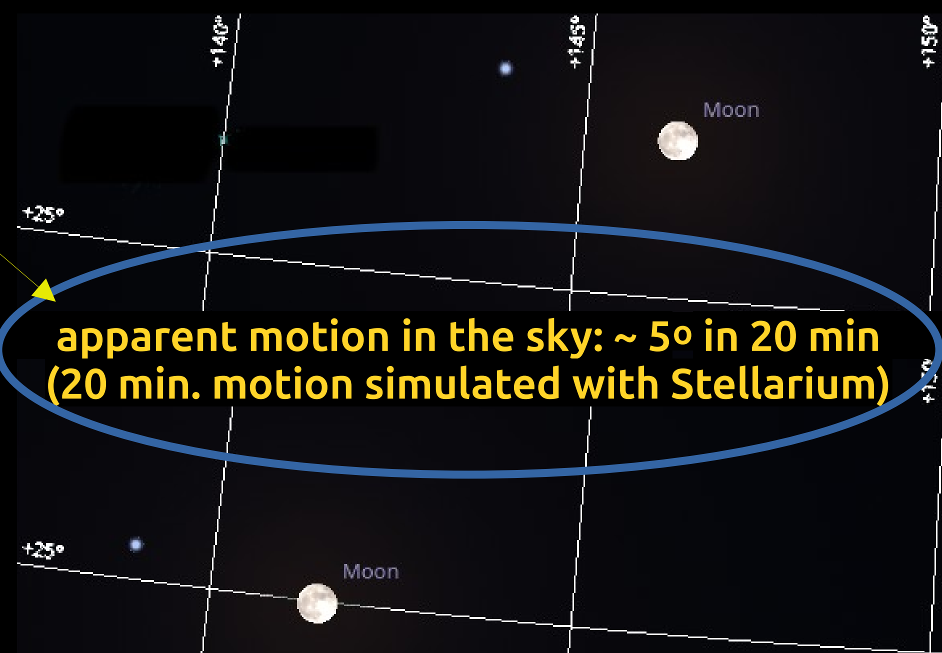
→ small (BUT ~ CONSTANT) angle
→ DIFFICULT←

→ need to account for the apparent motion in the sky

Apparent size in the Sky: ~0.5°
@perigee: 0.48°
@apogee: 0.56°

Rotation (same side to Earth, tidally locked):
on its axis once every 27.322 day
orbit eccentricity: 0.055

RELEVANT FOR THE ANALYSIS



apparent motion in the sky: ~ 5° in 20 min
(20 min. motion simulated with Stellarium)

Cosmi-Ray Moon shadow on Earth

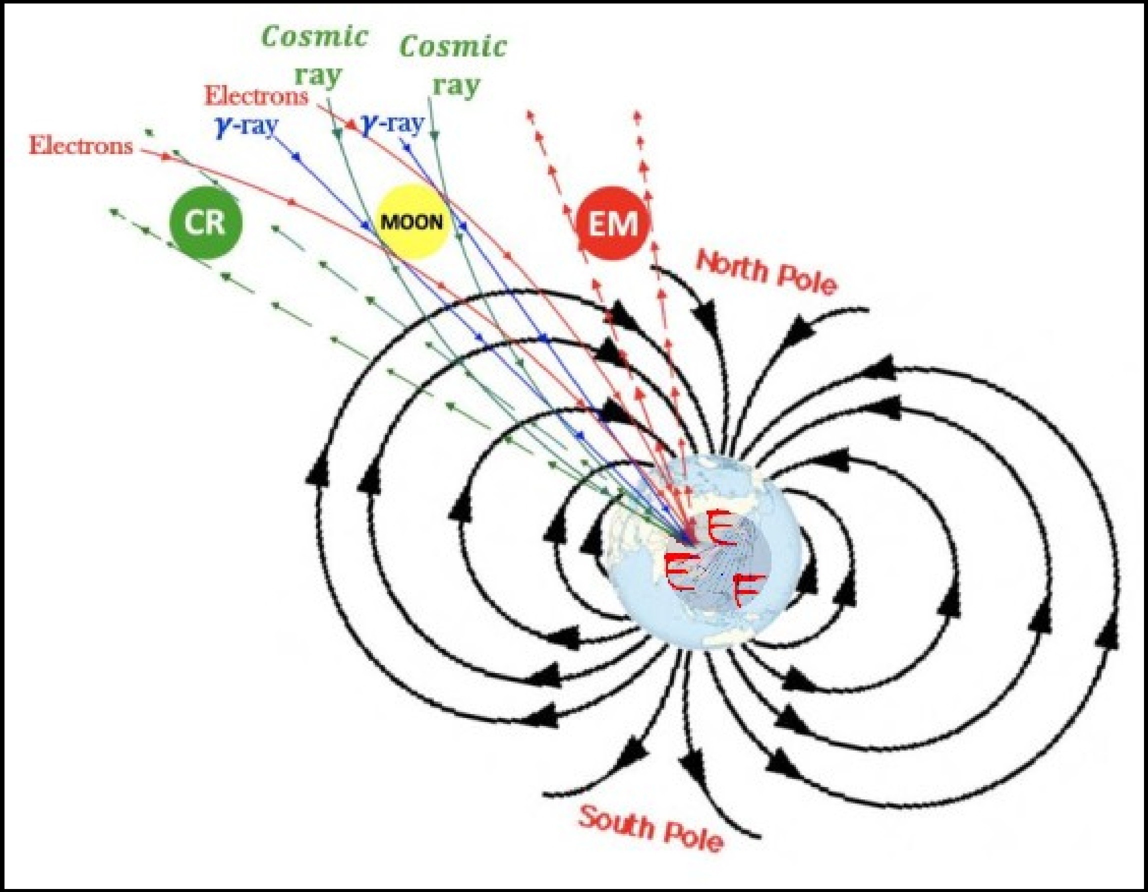
Different types of cosmic-ray particles behaves differently
as they travel through the Earth's magnetic field:

-- [Gamma rays] being uncharged cast the Moon's shadow accurately (but → <u>not accessible in EEE data</u>)
-- [Positively charged particles] like p^+, μ^+ deflect and shift the Moon's shadow
-- [Negatively charged particles] e^-, μ^- experience an opposite deflection and shift

EXPECTED RESULT:

→ no rate in the position of the moon

→ 2 regions with a deficit of events
since the Moon produces "holes"
in the cosmic-ray map



Analysis goals

Combine data from multiple EEE stations

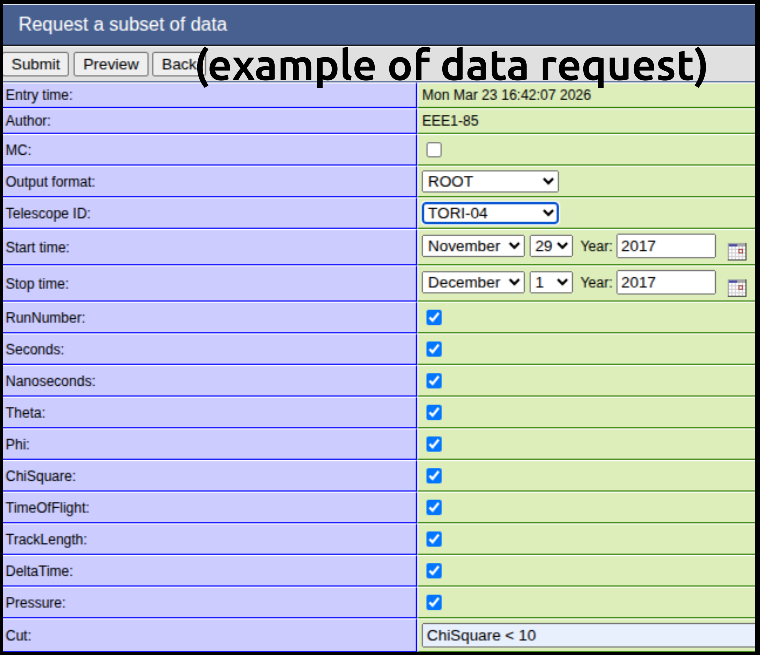
Reconstruct muon arrival directions

Convert times and coordinates properly

Compute Moon position event-by-event

Produce:

→ ON map (signal region near Moon position within radius $R = 6^{o}$)
→ OFF map (background same sky region Moon position shifted ahead in transit time by $\Delta t = 20$ minutes or ~ $R = 5^{o}$)
→ Difference map (ON – OFF)
→ Significance map (using Li & Ma estimator)

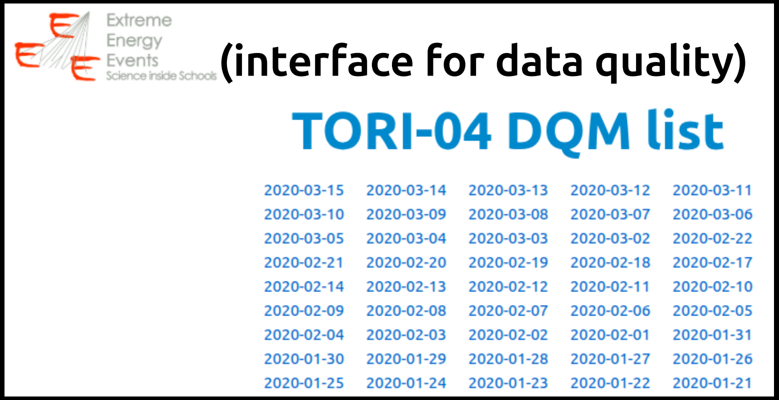


Request a subset of data

Submit | Preview | Back

Entry time:	Mon Mar 23 16:42:07 2026
Author:	EEE1-85
MC:	☐
Output format:	ROOT
Telescope ID:	TORI-04
Start time:	November 29 Year: 2017
Stop time:	December 1 Year: 2017
RunNumber:	☑
Seconds:	☑
Nanoseconds:	☑
Theta:	☑
Phi:	☑
ChiSquare:	☑
TimeOfFlight:	☑
TrackLength:	☑
DeltaTime:	☑
Pressure:	☑
Cut:	ChiSquare < 10

(example of data request)



2020-03-15	2020-03-14	2020-03-13	2020-03-12	2020-03-11
2020-03-10	2020-03-09	2020-03-08	2020-03-07	2020-03-06
2020-03-05	2020-03-04	2020-03-03	2020-03-02	2020-02-22
2020-02-21	2020-02-20	2020-02-19	2020-02-18	2020-02-17
2020-02-14	2020-02-13	2020-02-12	2020-02-11	2020-02-10
2020-02-09	2020-02-08	2020-02-07	2020-02-06	2020-02-05
2020-02-04	2020-02-03	2020-02-02	2020-02-01	2020-01-31
2020-01-30	2020-01-29	2020-01-28	2020-01-27	2020-01-26
2020-01-25	2020-01-24	2020-01-23	2020-01-22	2020-01-21

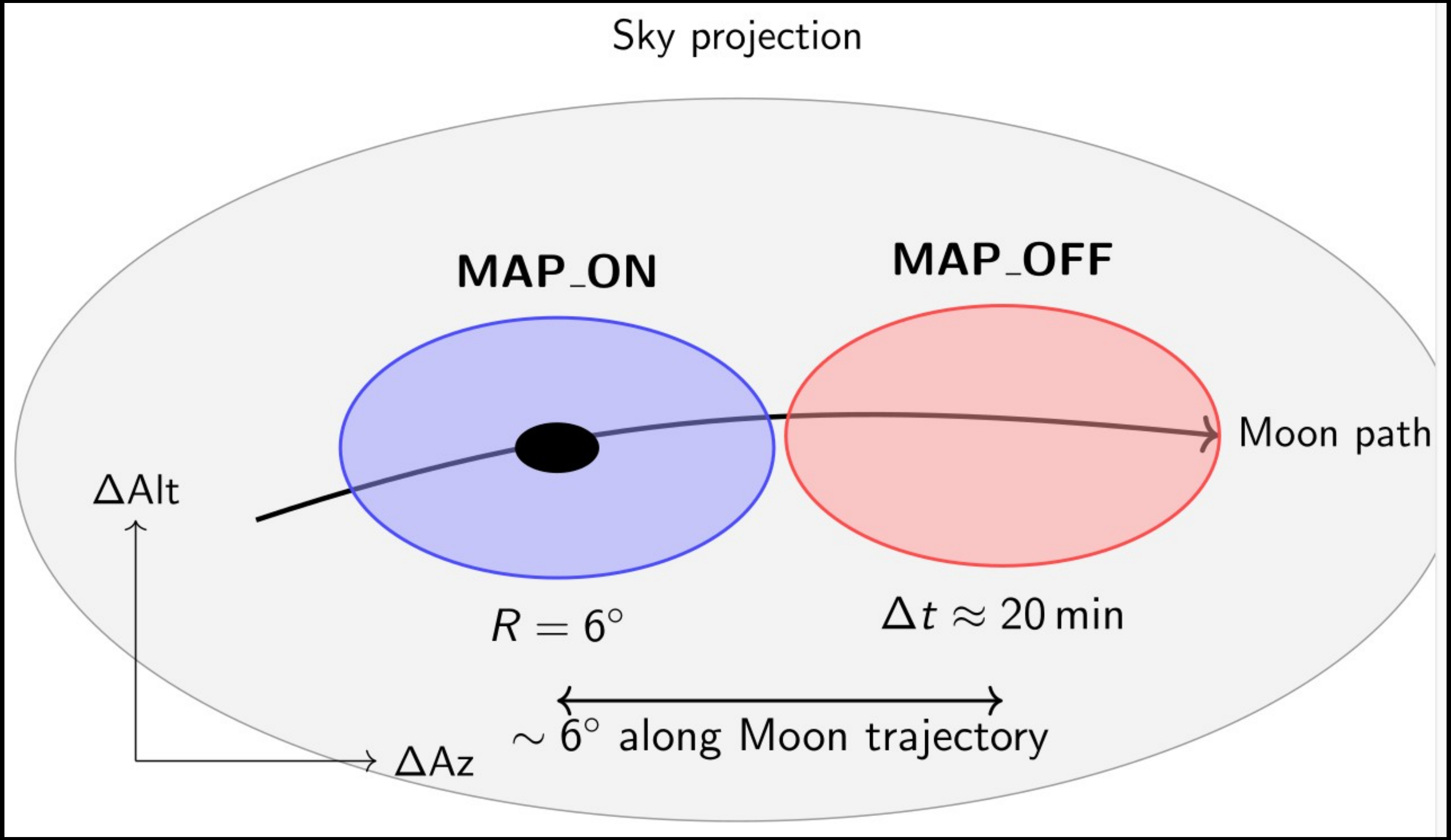
(interface for data quality)

Event Selection - each event must satisfy:
$\chi 2 < 10$ (reject badly reconstructed tracks)

NB: EEE Longitudinal acceptance = ~58.1^{o}

Analysis key idea

Key idea:
Same detector acceptance and same sky exposure
ON_map contains = (background + Moon shadow)
OFF_map contains = (only background)
Difference map (ON – OFF) = (Moon shadow)



Errors: what's the Li & Ma estimator ?

How to know/judge if what we are doing is right ? → We need to estimate an error

The "mean standard deviation" would be: $\frac{N_{\text{on}} - N_{\text{off}}}{\sqrt{N_{\text{off}}}}$ but is not optimal in this case

Since is not valid at low statistics, it ignores the Poisson nature of events counting and does not include exposure normalization (the Cosmic Rays $\cos^2(\theta)$ dependence)

The "mean standard deviation" (i.e. significance) is computed using the Li & Ma method developed by Ti-Pei Li and Yu-Qian Ma (1983) for statistical analysis in high-energy astrophysics: valid for Poisson statistics, correct for low counts and able to accounts for different exposures

$$S = \sqrt{2\left[N_{\text{on}} \ln\left(\frac{1+\alpha}{\alpha}\frac{N_{\text{on}}}{N_{\text{on}}+N_{\text{off}}}\right) + N_{\text{off}} \ln\left((1+\alpha)\frac{N_{\text{off}}}{N_{\text{on}}+N_{\text{off}}}\right)\right]}$$

N_on : counts in signal region
N_off : counts in background region
α : exposure ratio between ON and OFF (we used α =1)

ChatGPT contribution

What reported so far are all indications taken from the LHAASO article

But we needed AI help of ChatGPT to setup the analysis code (that was out of reach for us)

ChatGPT suggested a further improvement:

angular Normalization of Cosmic Ray Flux

The cosmic ray flux is not isotropic in θ:

Implication:
More muons arrive near zenith
Fewer near horizon

$$\frac{dN}{d\Omega} \propto \cos^2\theta$$

Correction applied in code:

Purpose:
Flatten angular distribution
Remove detector + physical bias
Ensure ON and OFF maps are comparable

$$w = \frac{1}{\cos^2\theta}$$

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Moon shadow: analysis summary

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Summary of the analysis carried on data provided by various EEE-telescopes in various years (2017, 2018 and 2025) and periods ranging from 3 days to about 7 months:

(1st raw - all considered stations) BOLO-01, BOLO-02, BOLO-03, BOLO-04, AREZ-01, BARI-01, ALTA-01, CATA-01, SAVO-02, CAGL-03, TORI-04;

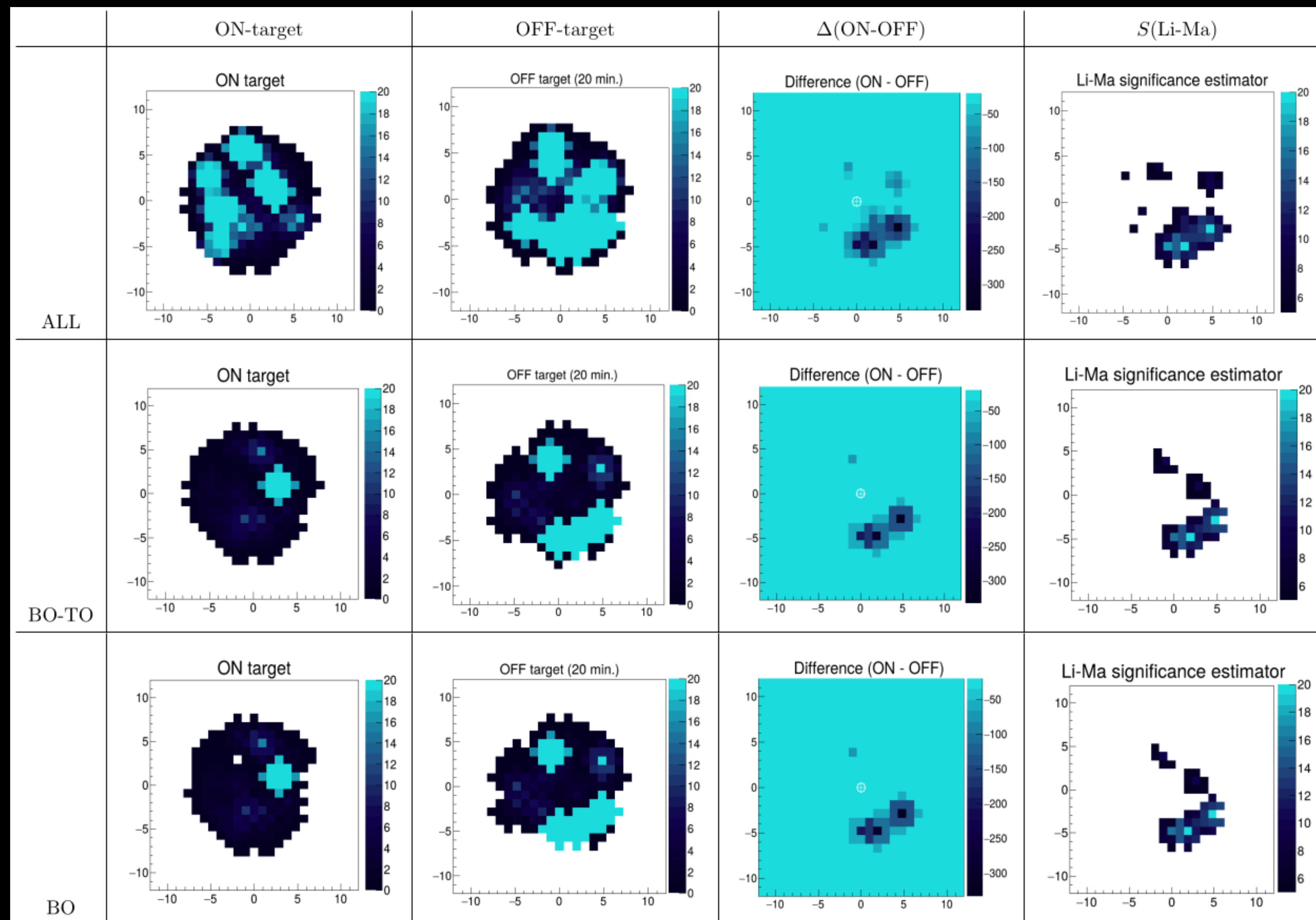
(2nd raw - 5 stations) BOLO-01, BOLO-02, BOLO-03, BOLO-04,TORI-04;

(3rd raw stations from a single town) BOLO-01, BOLO-02, BOLO-03, BOLO-04

NOTICE:

with more EEE-telescopes
→→ LESS ← ←
detector pointing
angular reconstruction
(timing accuracy ?...)

with less EEE-telescopes
→→ MORE ← ←
detector pointing
angular reconstruction



April 2026

Moon shadow: analysis result

For the reasons illustrated before our best result is obtained with:
enough statistic (~7 months)
From a single town (Bologna with the EEE-telescopes: BOLO-01, BOLO-02, BOLO-03, BOLO-04)

NOTICE:

the WHITE pixel

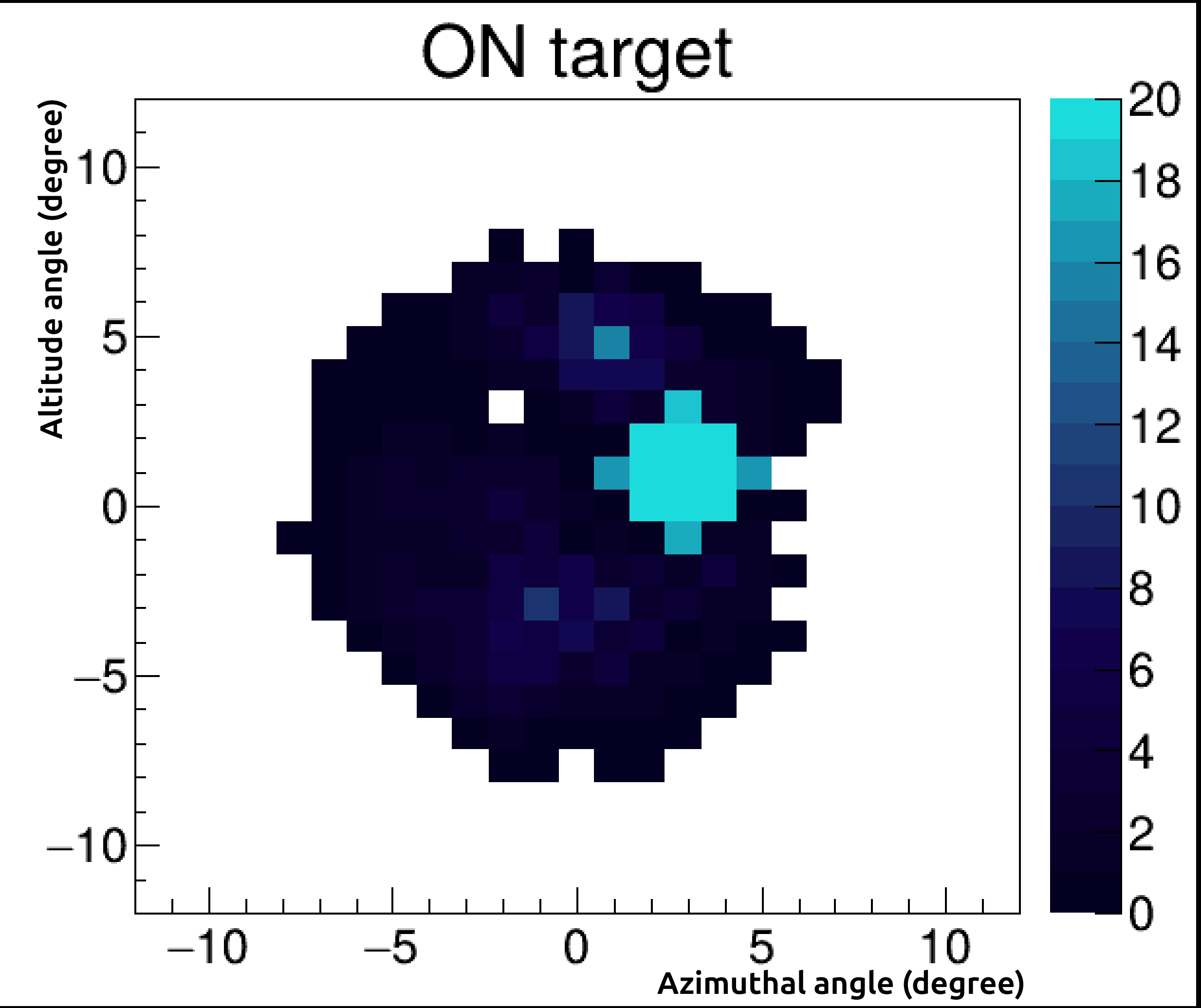
in the ON_target map

means NO-DATA

→that pixel could be the Moon←

Align-error:

(Az, Alt) ~ (-2°, 3°)
→ supposed to be in (0,0)



Moon shadow: analysis result

For the reasons illustrated before our best result is obtained with:
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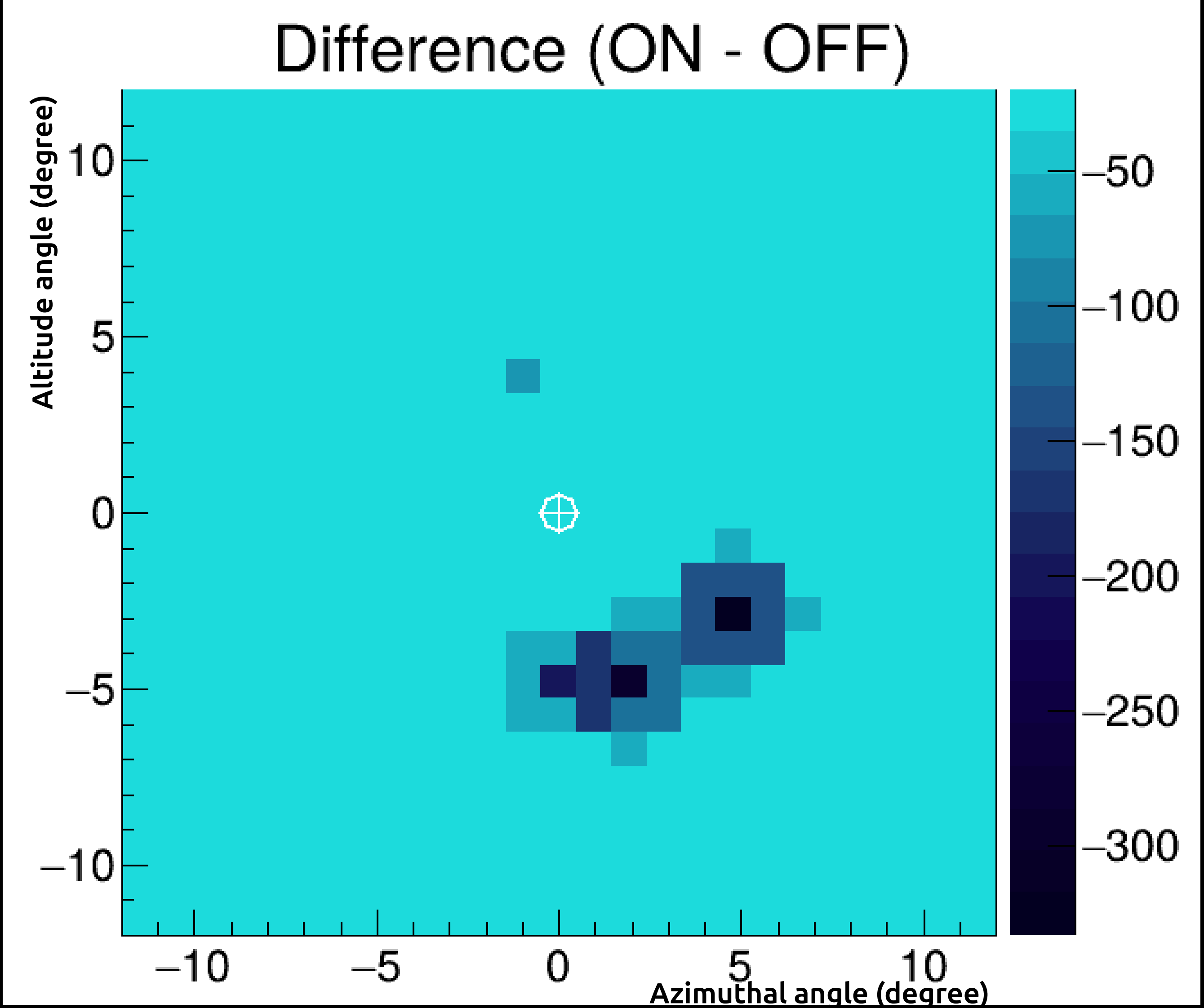
From a single town (Bologna with the EEE-telescopes: BOLO-01, BOLO-02, BOLO-03, BOLO-04)

the WHITE circle is where we expected the Moon to be (the plot is centered on Moon position)

But we know from the previous plot that the single dark blue pixel in

(Az, Alt) ~ (-1°,4°)
Is the Moon

The 2 dark-blue regions could be the (expected) shadows of the Moon (less CR flux from those 2 regions)



April 2026

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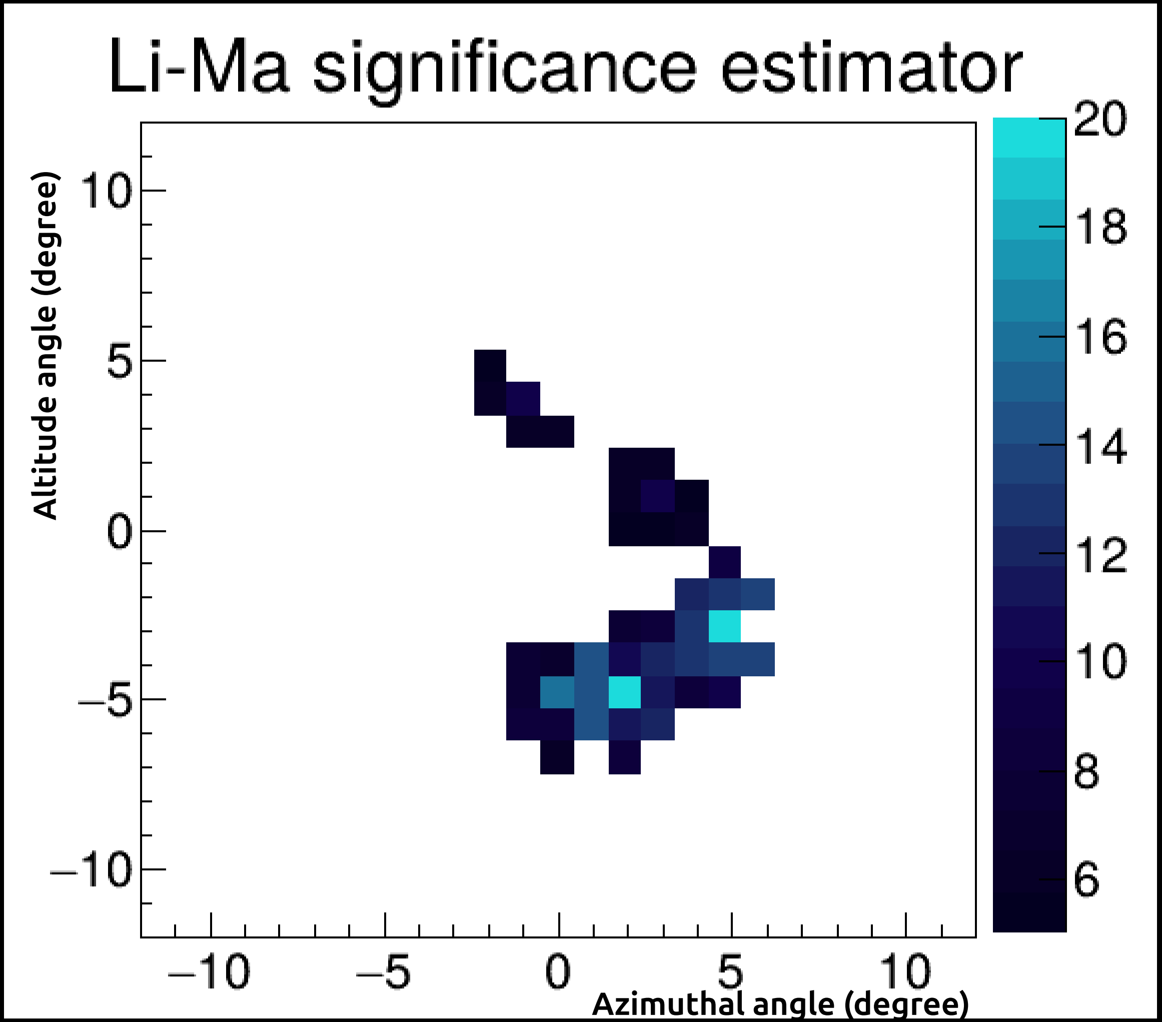
For the reasons illustrated before our best result is obtained with:
enough statistic (~7 months)
From a single town (Bologna with the EEE-telescopes: BOLO-01, BOLO-02, BOLO-03, BOLO-04)

The 2 light-blue spots @:

(Az, Alt) ~ (2°, -5°)
(Az, Alt) ~ (5°, -3°)

Seems to confirm an high significance (likelihood) for the 2 expected shadows of the Moon



Conclusions

→ This analysis showed the limits (in alignment/angular reconstruction/timing) of the EEE detector when used as an array of detectors (the all-sites plots have a poor quality)

→ At the same time the analysis showed instead how the EEE detector works well in the local-group configuration (the single data-set from the Bologna telescopes was good)

→ Very promising that in the ON_target hit map we have a single pixel without events: this could indeed be the spot of the Moon (also the angular dimensions are compatible)

→ We will continue to study the energy dependence of the 2 spots of Moon shadows as suggested in the LHAASO article

[References]:

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-- Study of the influence of the buildings on secondary cosmic rays measurements performed with EEE Project telescopes
M.Campana -- Univ. Salento – Thesis
-- ChatGPT

Thanks !