# Recent developments in the ASTRI Project simulation system

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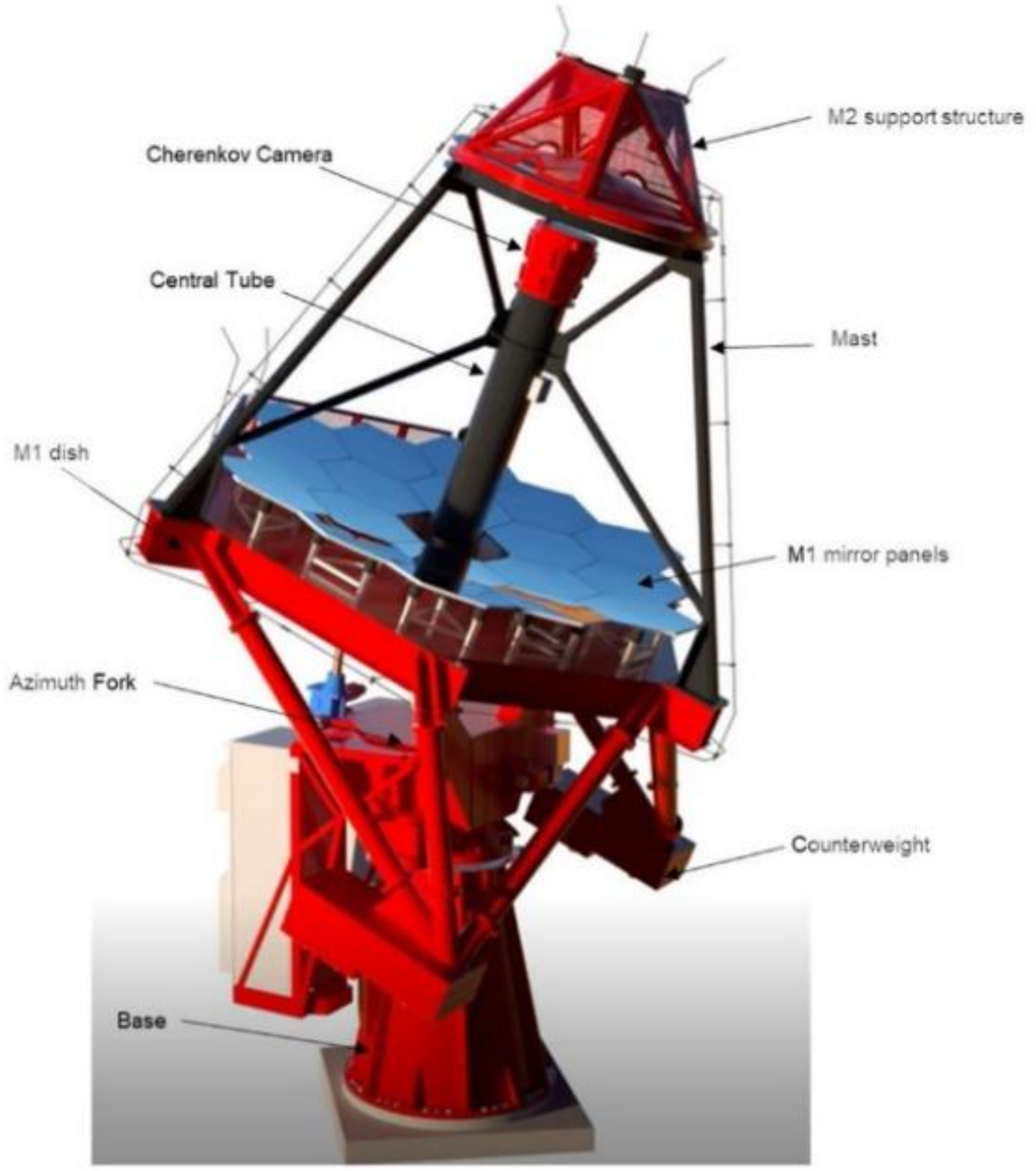
for the ASTRI Project

**From nine to forty: the SST telescopes and gamma-ray science with ASTRI and CTAO, July 20-24, 2026**

# The ASTRI Project

Mini-Array

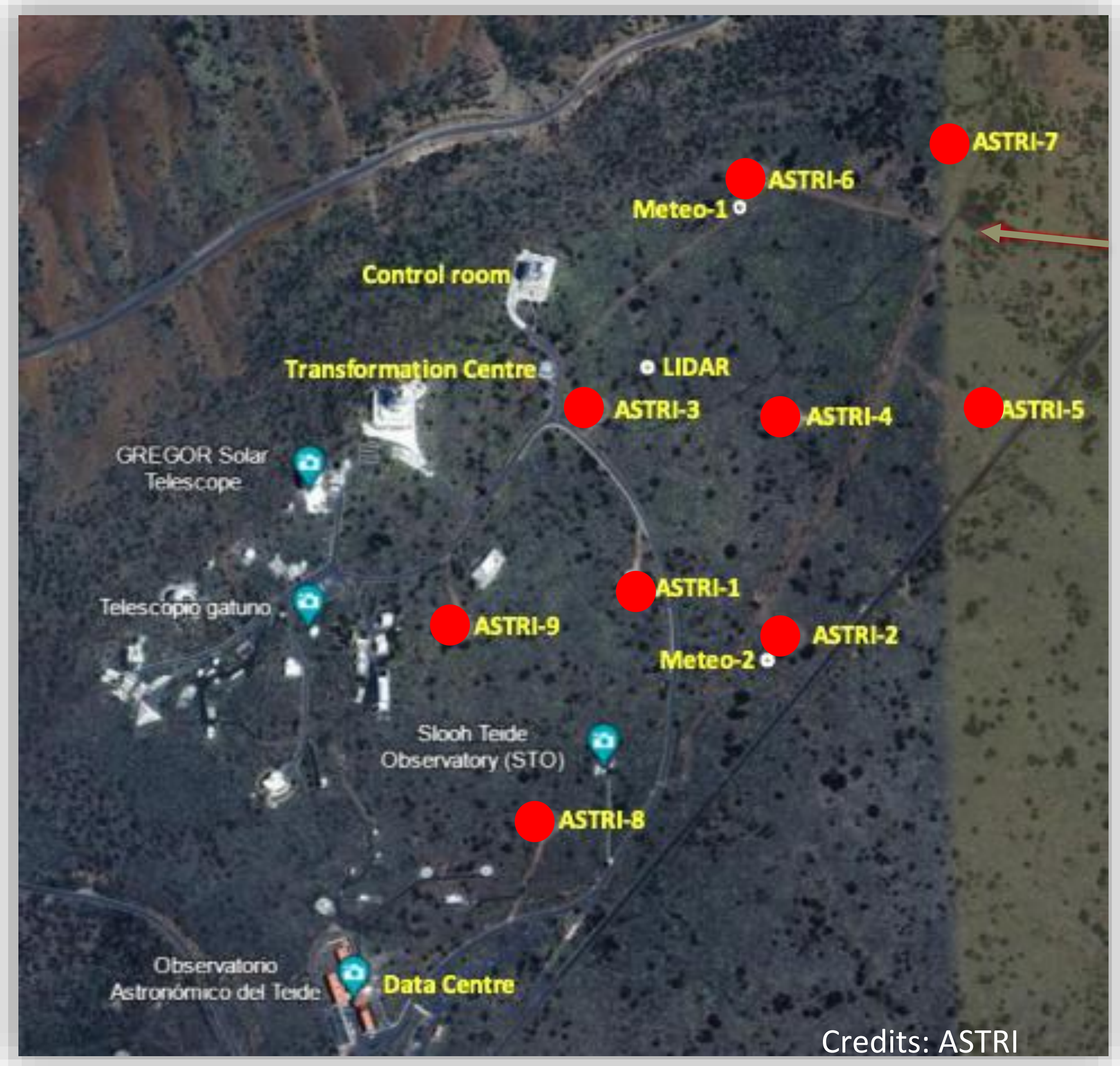
- *Astrofisica con Specchi a Tecnologia Replicante Italiana* (ASTRI; *"Astrophysics with Italian Replicating Technology Mirrors"*).
- Istituto Nazionale di AstroFisica (INAF; National Institute of AstroPhysics)-led project funded by Italian Ministry of Research, in the framework of Cherenkov Telescope Array Observatory (CTAO) Small Size Telescopes (SSTs).
- Innovative dual-mirror, Schwarzschild-Couder (SC) optical configuration, Imaging Atmospheric Cherenkov Telescopes (IACTs).
- Features:
  - ~4m mirror diameter.
  - Angular resolution up to 0.05deg.
  - Energy resolution of ~10-15%.
  - Large field of view (FoV) 10.5deg.
  - Small plate-scale camera made of Silicon PhotoMultipliers (SiPMs) detectors with 7x7 mm pixels.




Pictorial view of an ASTRI IACT.

# The ASTRI-Mini Array

- Array of 9 IACTs under deployment at the "Observatorio del Teide (OT)", ~2400m a.s.l., in Tenerife (Canary islands, Spain).
  - 3 telescopes (ASTRI-1, ASTRI-2, and ASTRI-3) already acquiring data.
- More than 200 researchers belonging to INAF, Italian Universities, Istituto Nazionale di Fisica Nucleare (INFN; National Institute of Nuclear Physics), etc.
- Observations at multi-TeV energies (1-200 TeV).
- Important synergies with other Northern ground-based gamma-ray facilities such as Large High Altitude Air Shower Observatory (LHAASO), Major Atmospheric Gamma Imaging Cherenkov telescopes (MAGIC), CTAO-North, etc.
- See G. Tosti's talk for more datails.

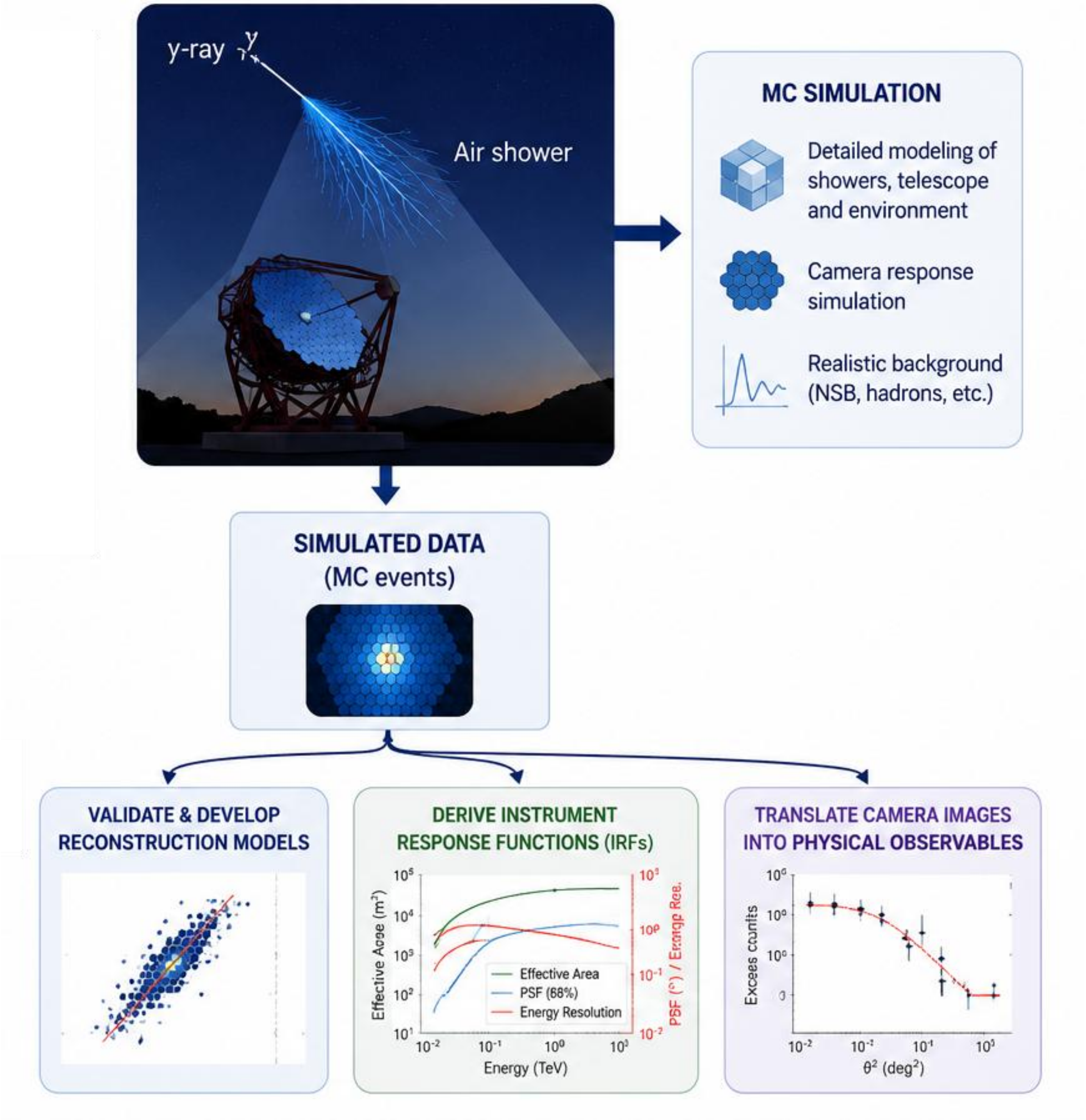



ASTRI-Mini Array location.

# Why Monte Carlo (MC) Simulations?

Monte Carlo (MC) simulations are used during:

- Commissioning to validate the instrument and develop reconstruction models.
- Science operation to derive the response of the system to $\gamma$-ray astrophysical observations by means of the generation of appropriate instrument response functions (IRFs).
- Data analysis: translate camera images into physical observables.



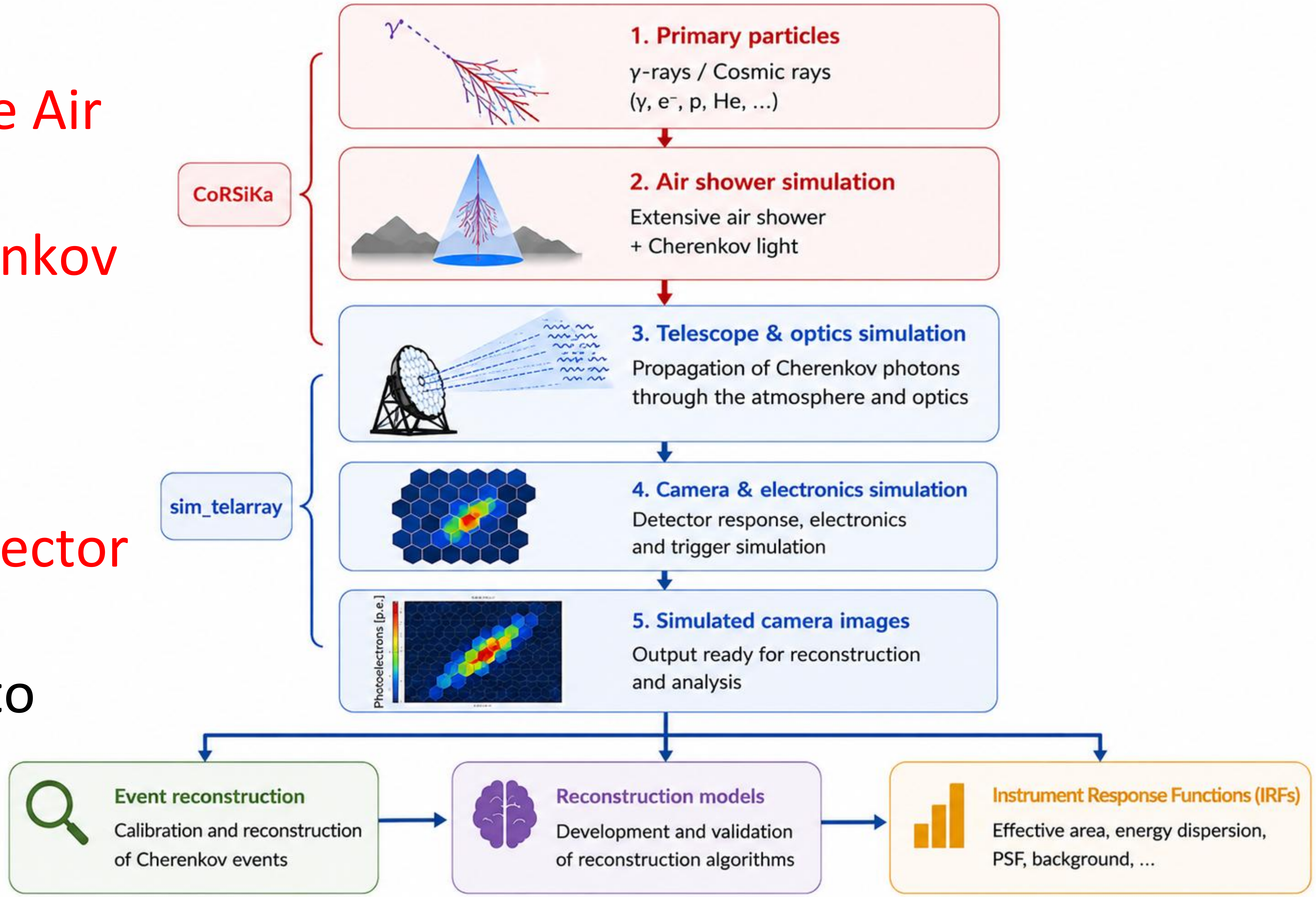
# Simulation pipeline

**CoRSiKa** (Heck et. al. 1998)

- Simulates atmospheric Extensive Air Showers (EAS).
- Models the production of Cherenkov light.

**sim_telarray** (Bernlöhr 2008)

- Simulates the telescope and detector response.
- Converts Cherenkov photons into detector event images.



# Simulation configuration

Mini-Array

Accurate simulations of the ASTRI Mini-Array require the proper configuration of both CORSIKA and sim_telarray, involving nearly 300 simulation parameters..

**CORSIKA**

- Observation level.
- Telescope positions.
- Geomagnetic field.
- Atmospheric density profile.
- Primary incoming direction.
- Primary impact point.
- Energy range & spectral index.
- Many other technical parameters.

**sim_telarray**

- Telescope pointing.
- Atmospheric extinction.
- Telescope geometry.
- Mirror reflectivity.
- Camera geometry.
- SiPM.
- Trigger.
- Readout.
- Many other technical parameters.

# CoRSiKa configuration: Geomagnetic field

- The geomagnetic field deflects charged secondary particles, modifying the EAS development and the Cherenkov light distribution.
- The geomagnetic field has been estimated by geomag 7.0 (Alken et al., 2021) .

  -Input:

  Latitude:28.303017 deg

  Longitude: -16.506095 deg

  Altitude: 2338.00m

-Output:

H=3.2µT, Z=2.3 µT


E:\data\My Data\Lavoro\Casa

```
28.303017

Enter the decimal longitude (-180 to 180) (- for Western hemisphere).
-16.506095

 Model: IGRF2020
 Latitude: 28.30 deg
 Longitude: -16.51 deg
 Altitude: 2338.00 meters
 Date of Interest:  2022.00

 ----------------------------------------------------------------------------
  Date        D          I          H        X        Y        Z        F
  (yr)    (deg min)  (deg min)     (nT)     (nT)     (nT)     (nT)     (nT)
 2022.00   -4d  20m   36d  26m  31037.6  30948.7  -2347.3  22908.8  38576.5
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  Date        dD         dI        dH       dX       dY       dZ       dF
  (yr)     (min/yr)   (min/yr)  (nT/yr)  (nT/yr)  (nT/yr)  (nT/yr)  (nT/yr)
 2022.00      9.7       -3.9      35.3     41.7     85.2    -28.1     11.7
 ----------------------------------------------------------------------------

 Enter
    0) to quit.
    1) to select a new model input file.
    2) to compute for a new point using same data file.

  ==> |
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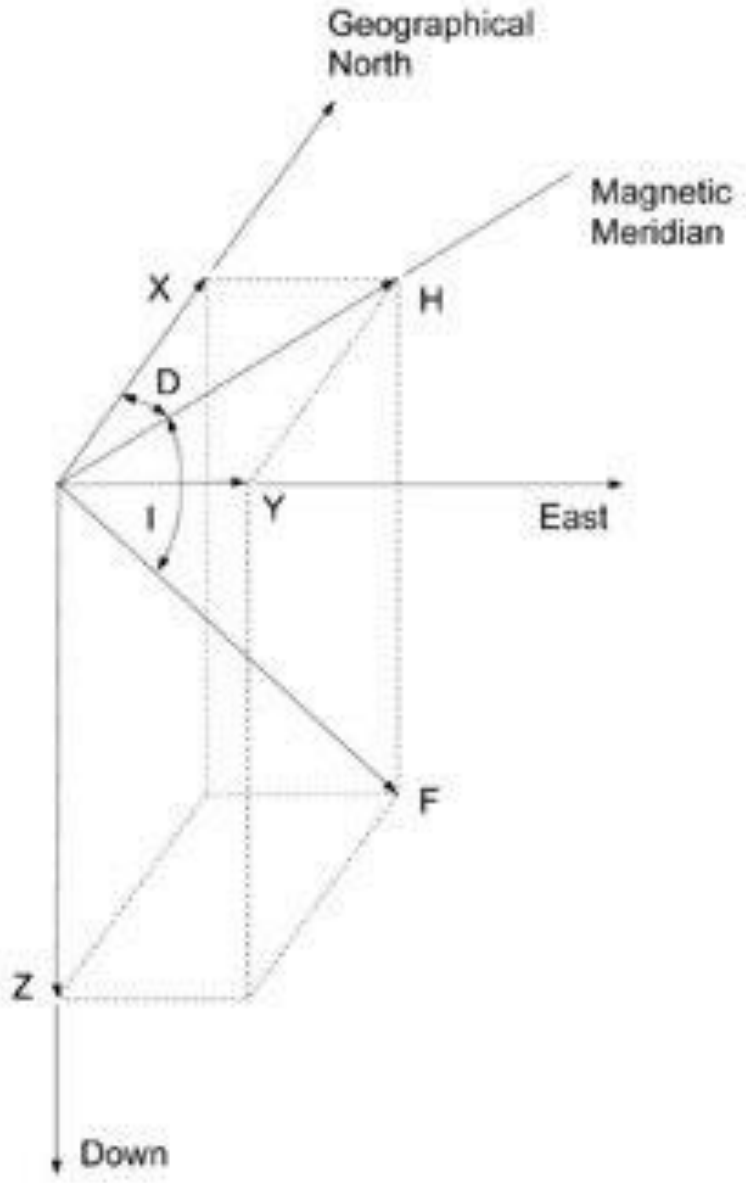
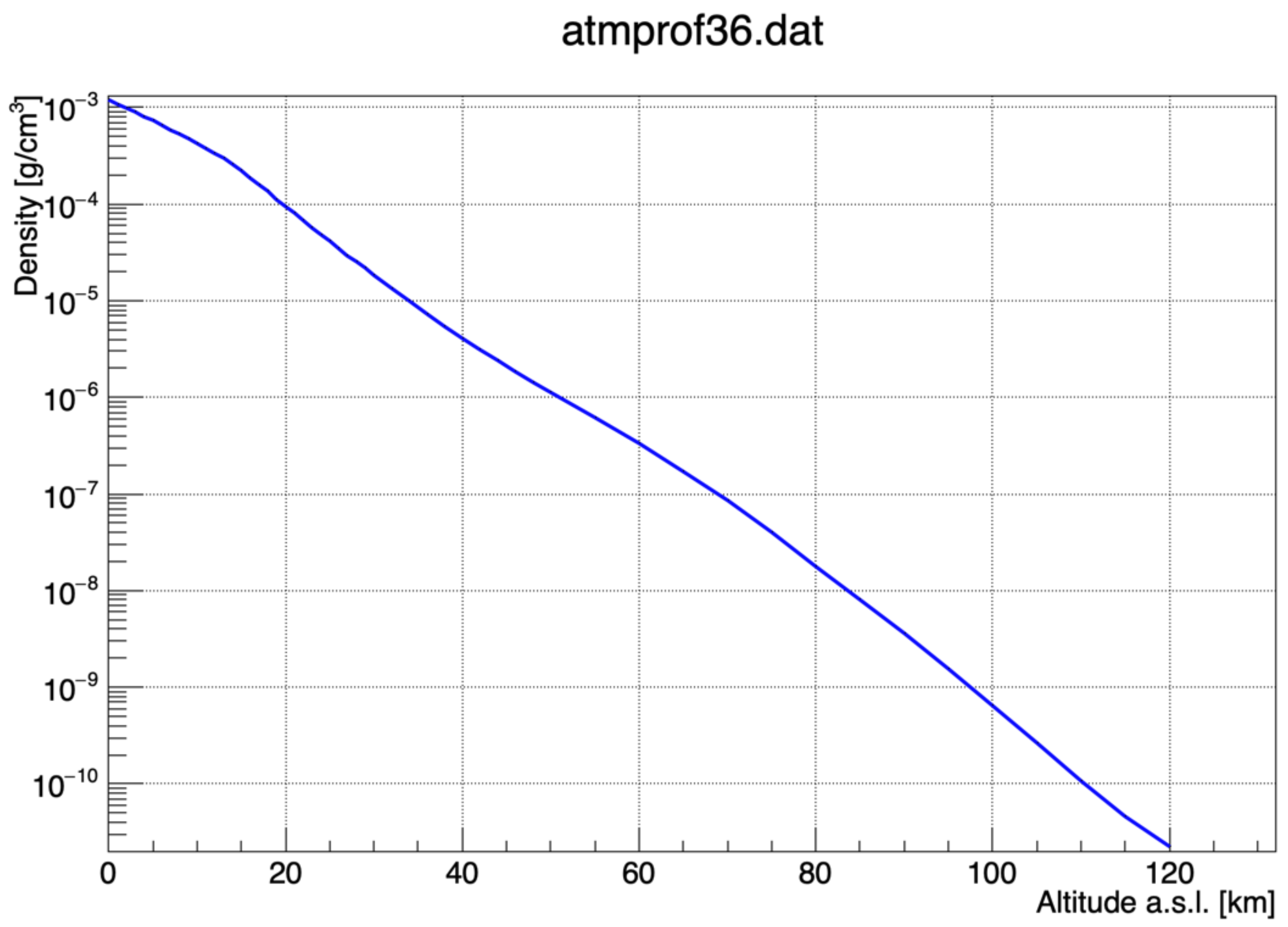


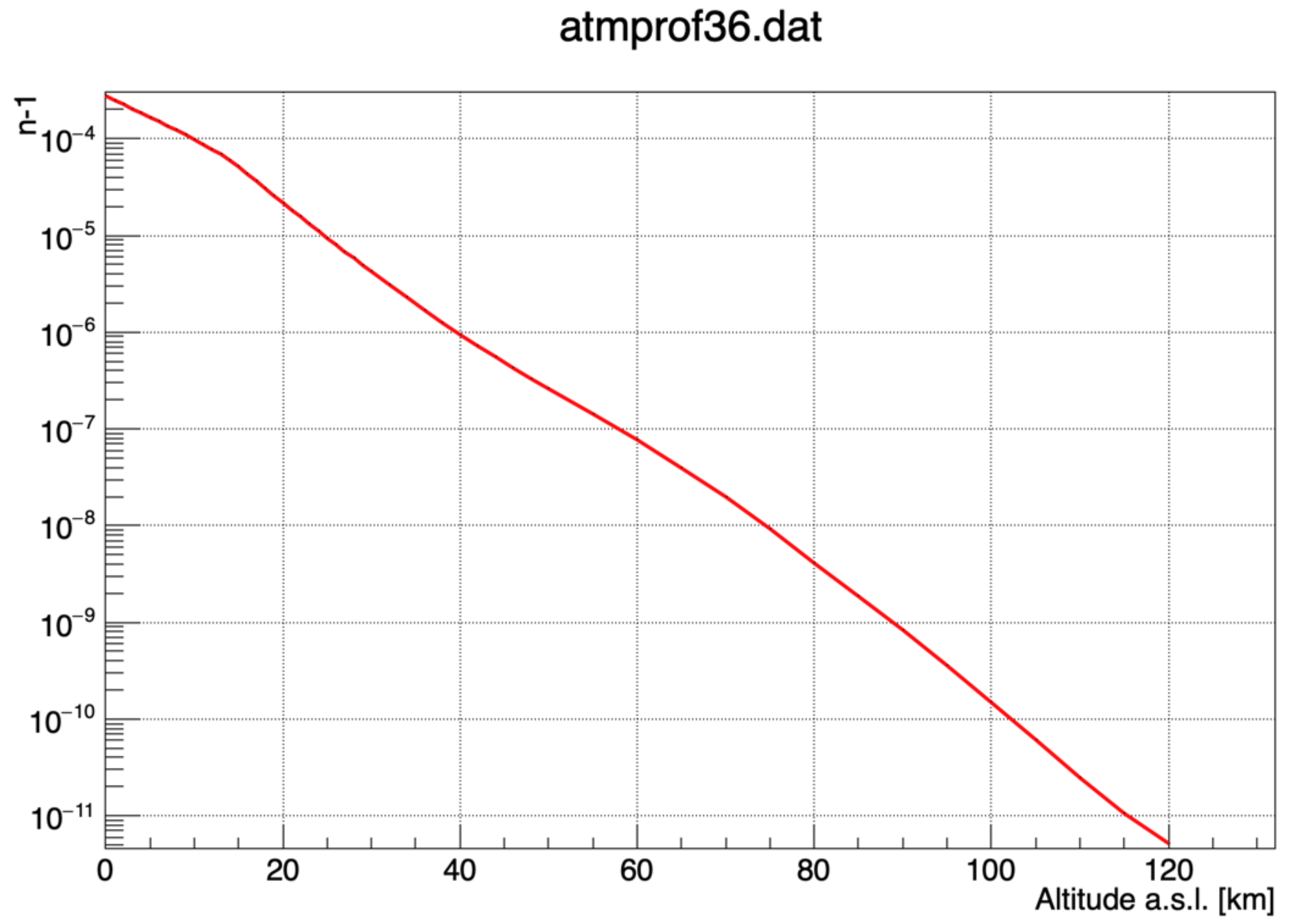
# CoRSiKa configuration: Atmopheric density and refractive index

- Atmospheric density profile is computed to determine the amount of matter traversed by shower particles.
- The air refractive index profile is also needed to compute:
  - -The Cherenkov emission angle $\cos\theta_c = \dfrac{1}{n\beta}$
  - -The Cherenkov photon yield:

$$\frac{d^2N}{dxd\lambda} = \frac{4\pi^2 z^2 e^2}{hc\lambda^2}\left(1 - \frac{1}{n^2\beta^2}\right) = \frac{2\pi z^2}{\lambda^2}\alpha \sin^2\Theta_C$$

- We adopted the atmprof36.dat atmospheric model provided with the corsika_sim_telarray package.



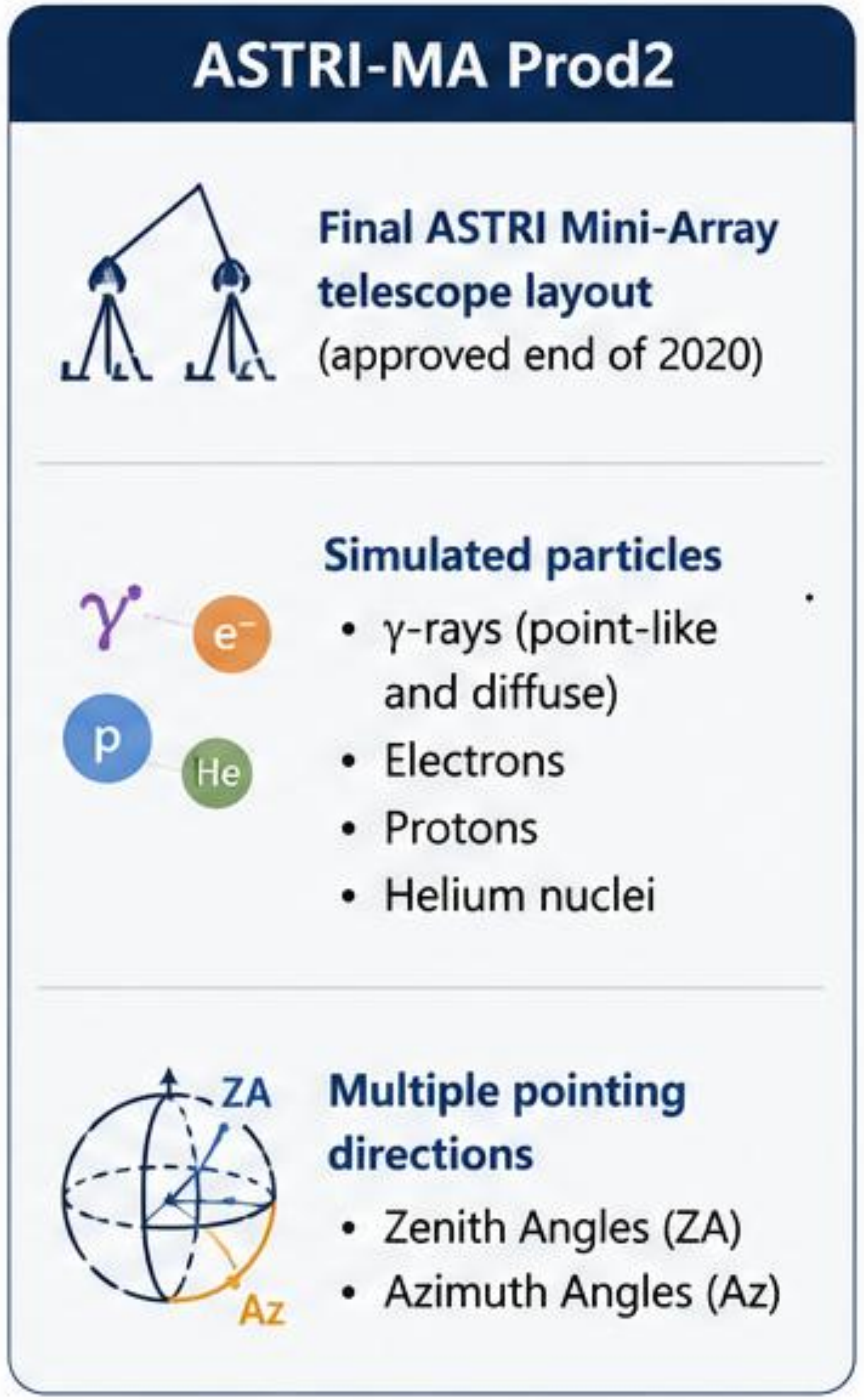
# ASTRI-Mini Array Prod-2 simulations

Mini-Array

- Large-scale CoRSiKa production:
  - -Point-like and diffuse γ-rays.
  - -Electrons.
  - -Protons.
  - -Helium nuclei.
- Power-law energy spectrum:

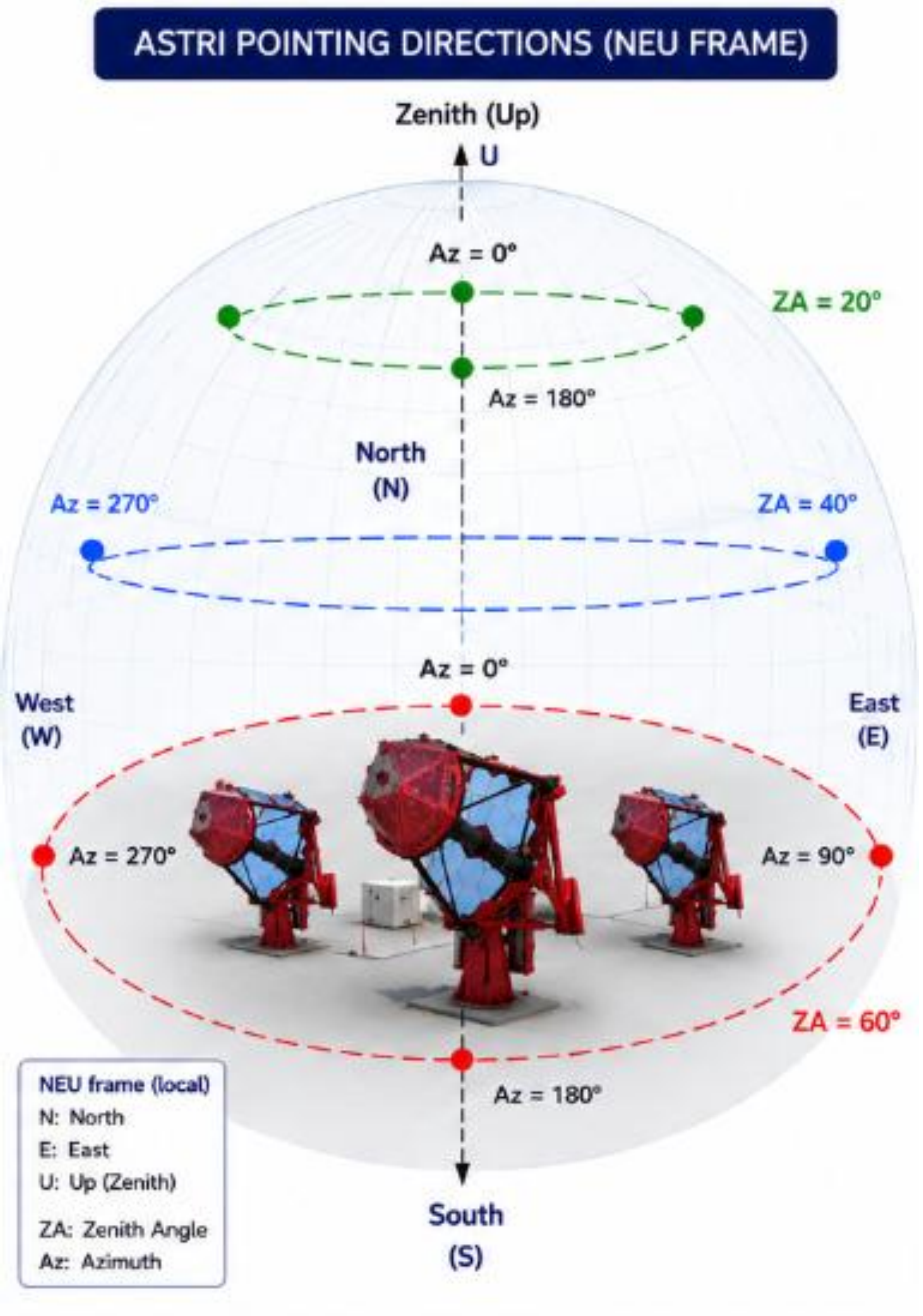
$$\frac{dN}{dE} \propto E^{-1.5}$$

- Final telescope layout (2020).
- Simulations performed for multiple Zenith and Azimuth angles.



# ASTRI-Mini Array Prod-2 simulations

- Pointing directions North-Est-Up (NEU) frame:
  - -ZA=20°, AZ=0°,180°.
  - -ZA=40°, AZ=90°,270°.
  - -ZA=60°, AZ=0°,90°,180°,270°.
- Directions choosen to reproduce the Crab Nebula trajectory.
- Goal: Provide sufficient MC statistics over the full energy range while reproducing the observing conditions of the ASTRI- Mini Array.



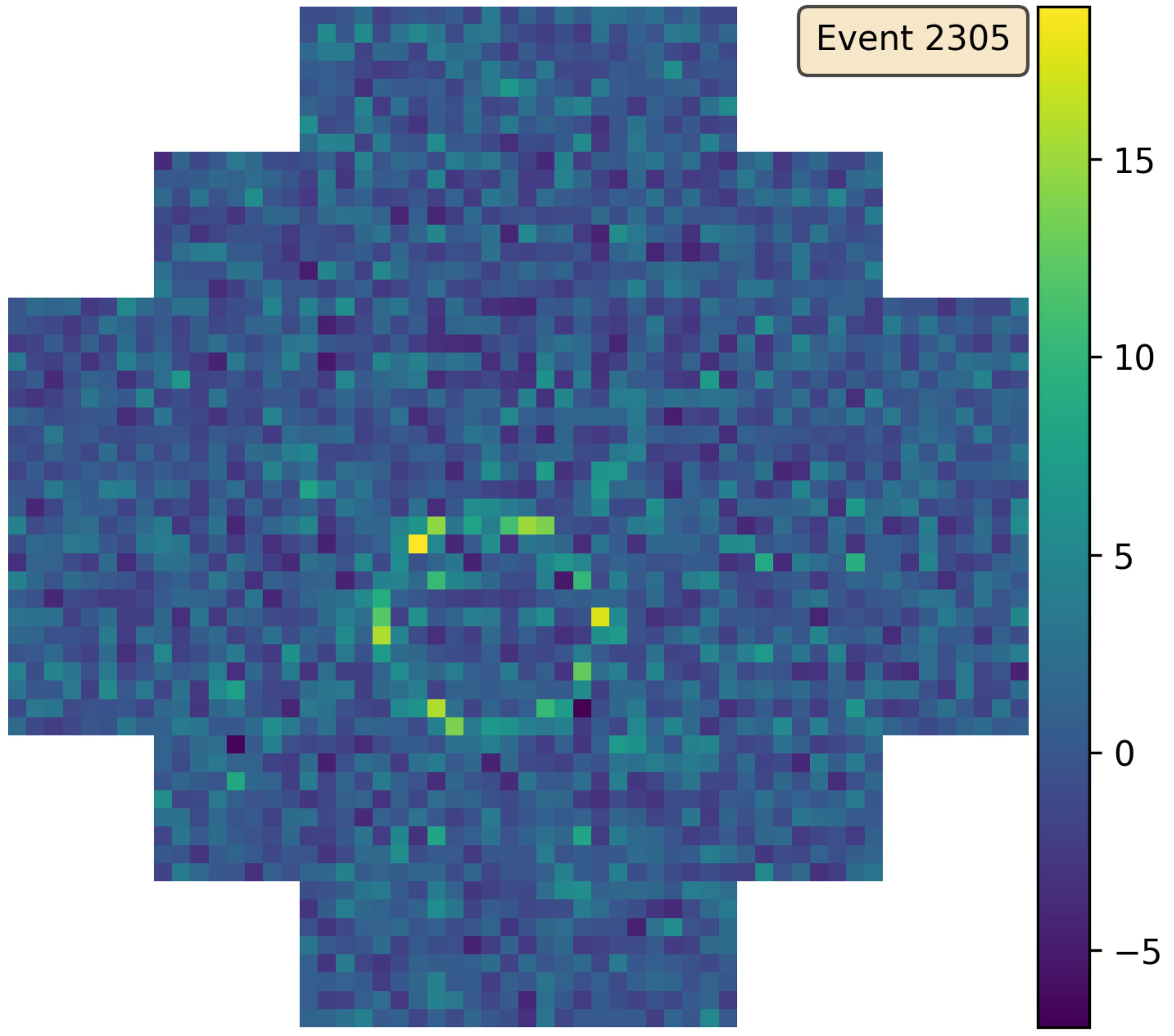
# ASTRI-Mini Array Prod-2 simulations

| Particle type | Spectral slope | Energy range (TeV) | View-cone radius (deg) | Scatter radius (m) | Azimuth (deg) | Zenith angle (deg) | No. of simulated showers |
|---|---|---|---|---|---|---|---|
| | | | ASTRI-MA Prod2_20deg | | | | |
| Photons (point-like) | −1.5 | 0.1 – 330 | 0 | 3200 | 0/180 | 20 | $4 \times 10^7$ |
| Photons (diffuse) | −1.5 | 0.1 – 330 | 10 | 3200 | 0/180 | 20 | $4 \times 10^8$ |
| Electrons | −1.5 | 0.1 – 330 | 10 | 3200 | 0/180 | 20 | $2 \times 10^8$ |
| Protons | −1.5 | 0.1 – 660 | 10 | 3200 | 0/180 | 20 | $2 \times 10^9$ |
| Helium nuclei | −1.5 | 0.12 – 750 | 10 | 3200 | 0/180 | 20 | $1.2 \times 10^8$ |
| | | | ASTRI-MA Prod2_40deg | | | | |
| Photons (point-like) | −1.5 | 0.16 – 530 | 0 | 4000 | 90/270 | 40 | $4 \times 10^7$ |
| Photons (diffuse) | −1.5 | 0.16 – 530 | 12 | 4000 | 90/270 | 40 | $4 \times 10^8$ |
| Electrons | −1.5 | 0.16 – 530 | 12 | 4000 | 90/270 | 40 | $2 \times 10^8$ |
| Protons | −1.5 | 0.16 – 1060 | 12 | 4000 | 90/270 | 40 | $2 \times 10^9$ |
| Helium nuclei | −1.5 | 0.16 – 2120 | 12 | 4000 | 90/270 | 40 | $1.2 \times 10^8$ |
| | | | ASTRI-MA Prod2_60deg | | | | |
| Photons (point-like) | −1.5 | 0.5 – 800 | 0 | 6000 | 0/90/180/270 | 60 | $4 \times 10^7$ |
| Photons (diffuse) | −1.5 | 0.5 – 800 | 14 | 6000 | 0/90/180/270 | 60 | $4 \times 10^8$ |
| Electrons | −1.5 | 0.5 – 800 | 14 | 6000 | 0/90/180/270 | 60 | $2 \times 10^8$ |
| Protons | −1.5 | 0.5 – 1600 | 14 | 6000 | 0/90/180/270 | 60 | $2 \times 10^9$ |
| Helium nuclei | −1.5 | 0.5 – 3200 | 14 | 6000 | 0/90/180/270 | 60 | $1.2 \times 10^8$ |

Main CORSIKA simulation parameters for the ASTRI Mini-Array MC production at the Observatorio del Teide.

# ASTRI-Mini Array Prod-2 calibration simulations

- Events for camera calibration (dark, laser,   and pedestal) to provide the complete reduction and analysis of the first scientific data suitable IRFs for evaluating the system performance.
- Muon-initiated events for the analysis of muon rings  to estimate and monitor the overall optical throughput and optical point-spread function (PSF).
- Light emission by an illuminator that will serve as a cross-calibration device for the ASTRI telescopes.

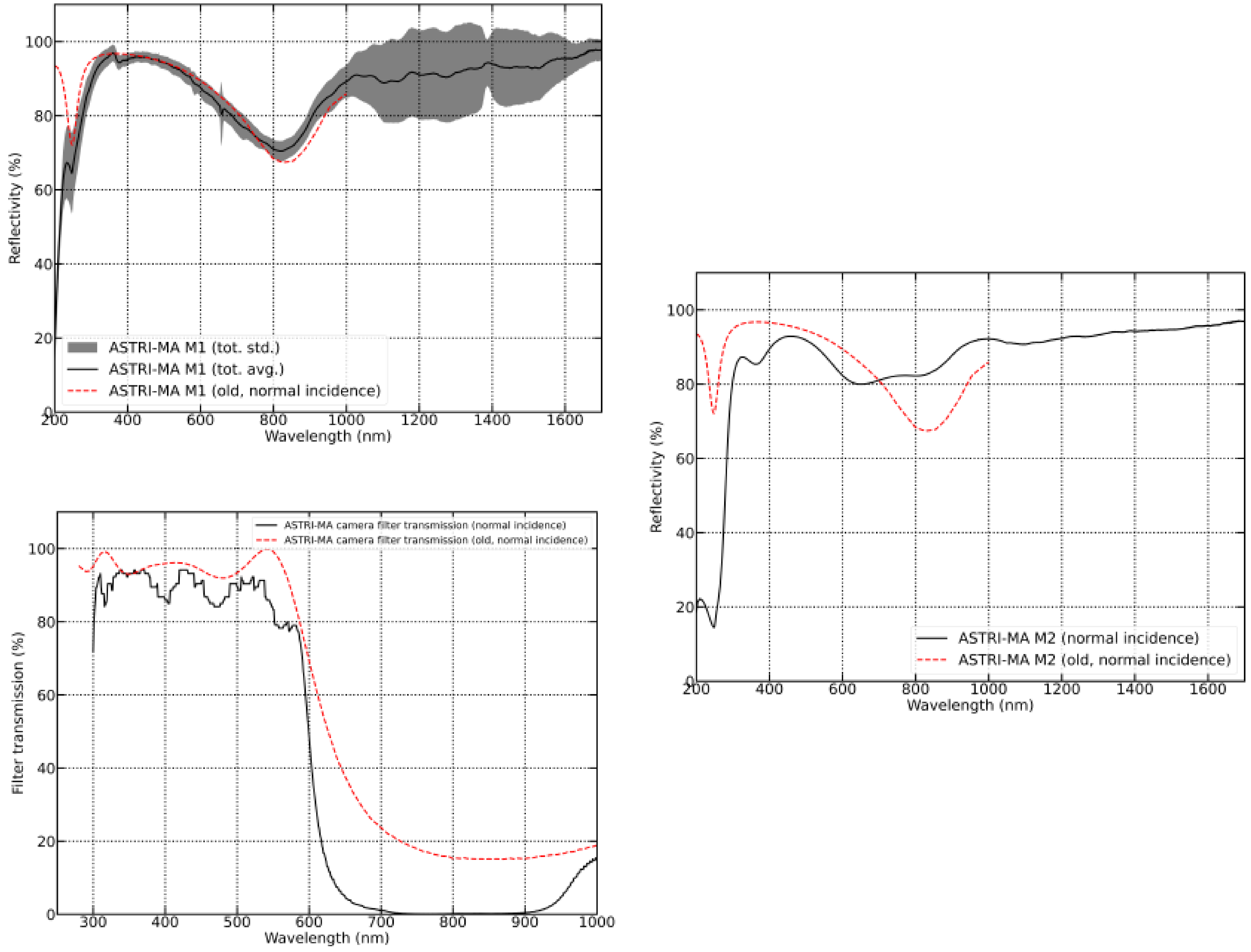



Muon ring.

# sim_telarray configuration: optical and detector parameters

Optical and detector parameters have been implemented in sim_telarray to provide a realistic simulation of the telescopes e.g.:

- Differential reflectivity of primary and secondary mirrors.
- Differential camera filter trasmission.
- Detector response based on measured High Gain (HG)/Low Gain (LG) waveforms and calibrated SiPM single-photoelectron (SPE) spectra.




Primary (top) and secondary (middle) mirrors reflectivity, and camera filter trasmission (bottom).

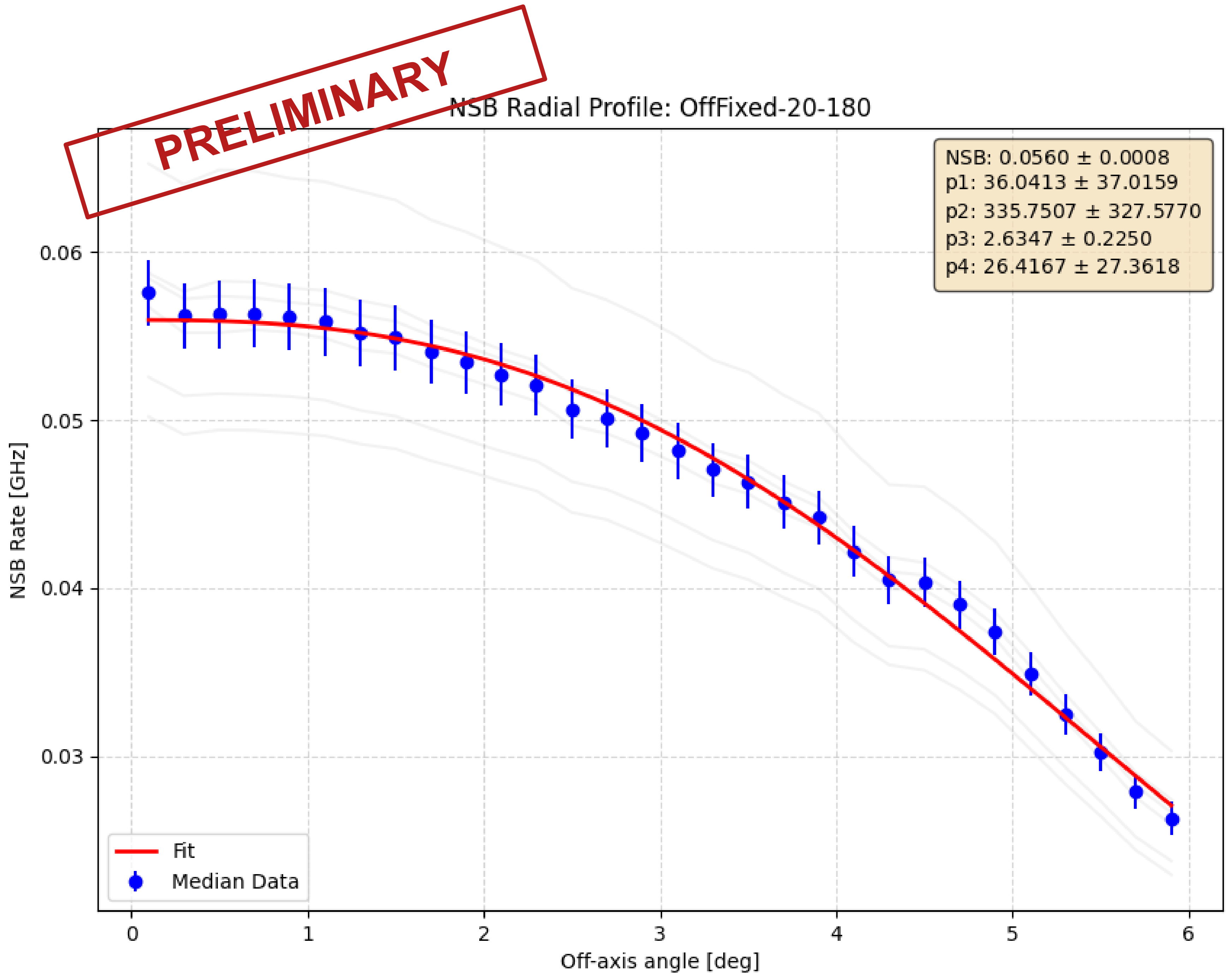
# sim_telarray configuration: Night Sky Background (NSB)

Night Sky Background (NSB) consists of all background light detected by the telescopes, distinct from the transient Cherenkov signal.

- Increases the camera background noise.
- Affects the energy threshold and trigger performance.
- Contributes to systematic uncertainties in observations.
- Influences the thermal load of the camera.
- Determines the capability to operate under partial moonlight conditions.

Realistic NSB model is essential for detector simulations and performance evaluations.

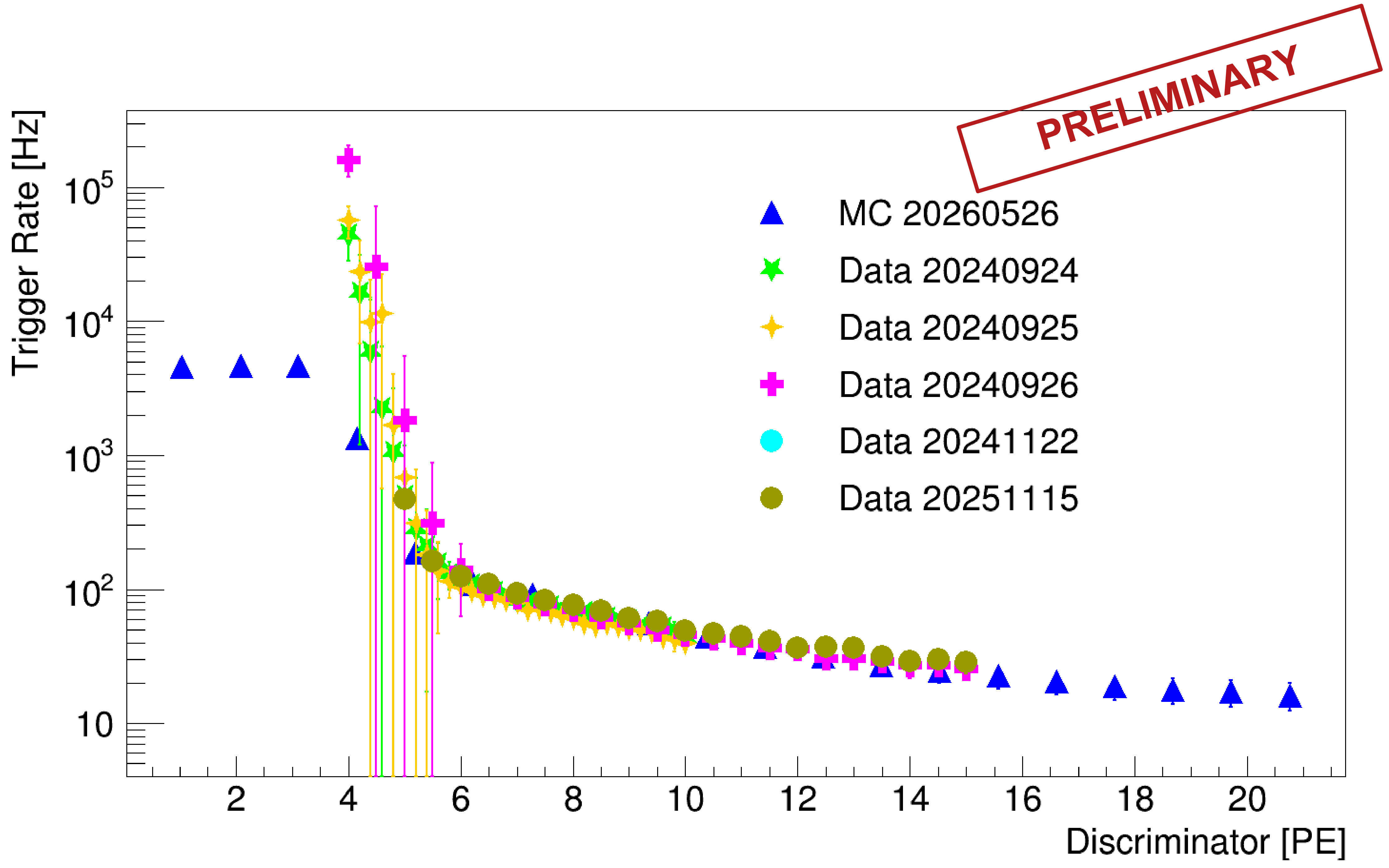
Dedicated code has been developed to estimate the NSB based on real data observations.




NSB estimated for ASTRI-3 at Z=20°, AZ=180°.

# Validation of MC simulations: Trigger rate

- The trigger rate is estimated using proton and helium MC files.
- Events reweighted to the physical Cosmic Rays (CRs) spectra.
- Detector geometrical acceptance determined by the maximum core distance Rmax.
- The total reweighted distribution of background events is normalized to reproduce the physical flux over the full energy interval.

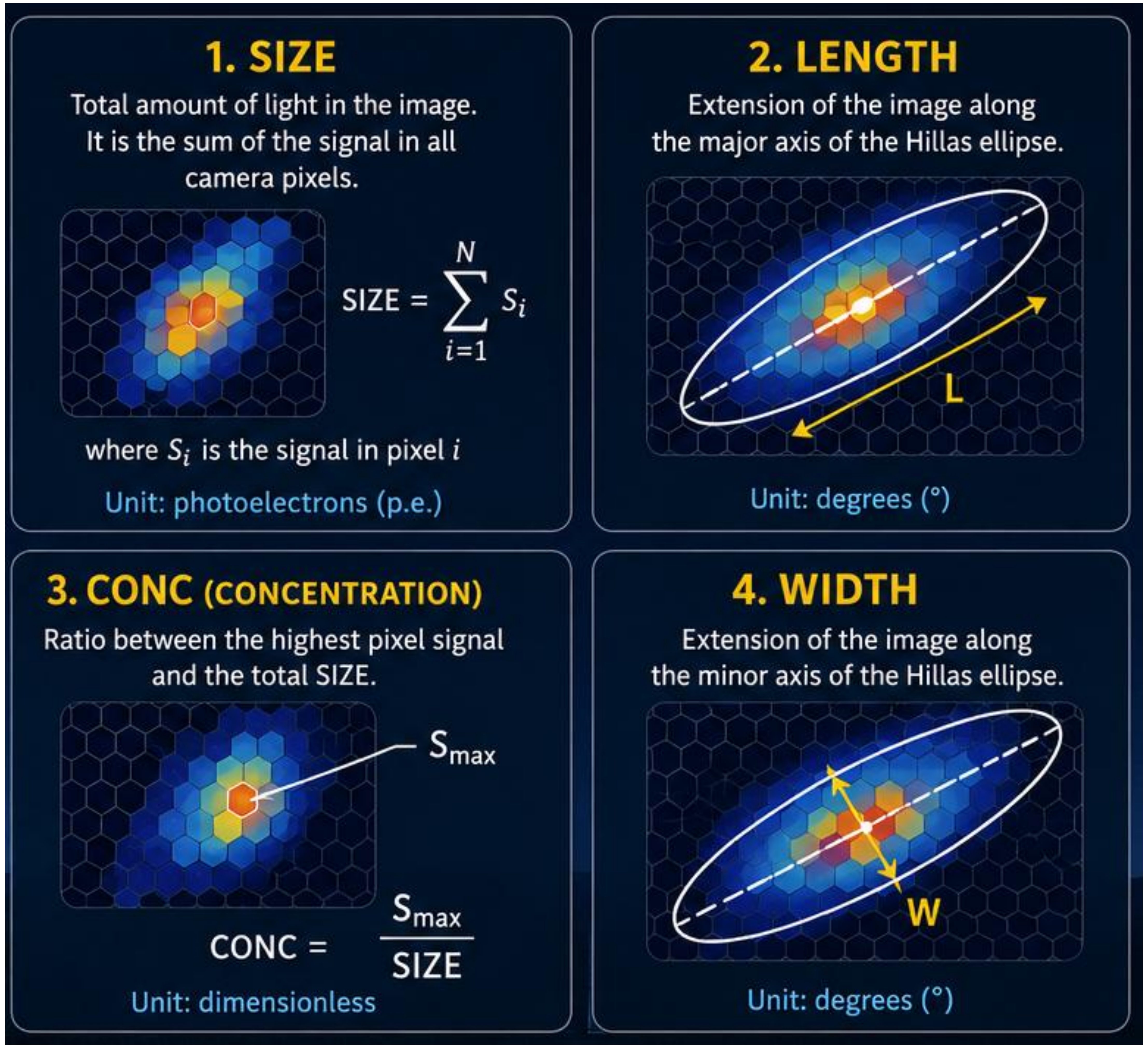



ASTRI-1 trigger scan. MC comparison with real data.

# Validation of MC simulations: Background events Hillas parameters

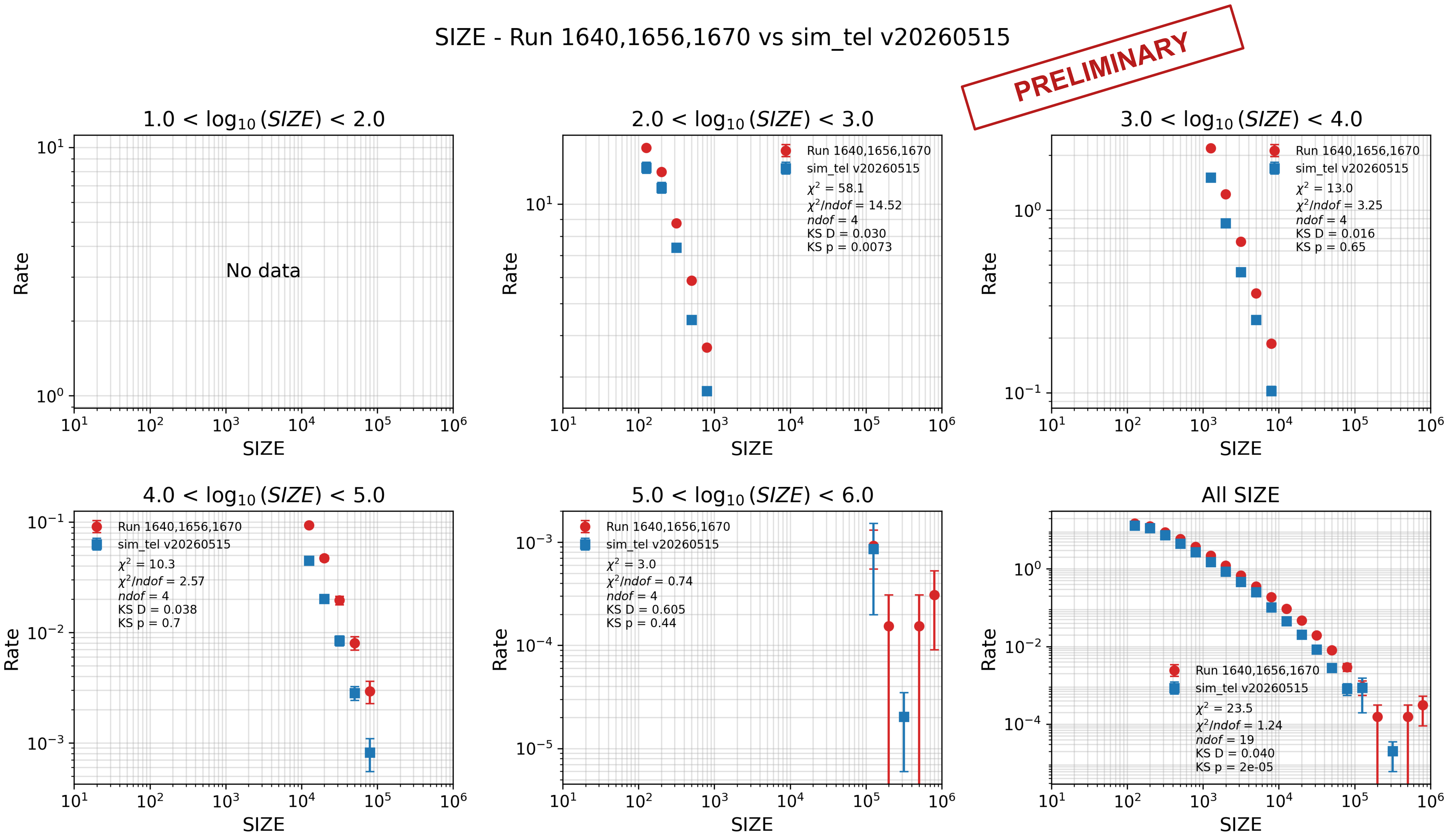
Mini-Array

- Background Hillas parameters (Size, Lenght, Width, and Conc) are extracted from simulated (p+He) and real data.
- MC events are reweighted.
- For each Hillas parameter, normalized distributions are built from both real data and MC.
- Quality cuts Size>100, width>0, leakage<0.1 and numisland<2 are applied.
- Compatibility is assessed using $\chi^2$ and Kolmogorov-Smirnov (KS) tests and by inspecting the relative percent residuals.



# Validation of MC simulations: Background events
# Hillas parameters

SIZE - Run 1640,1656,1670 vs sim_tel v20260515



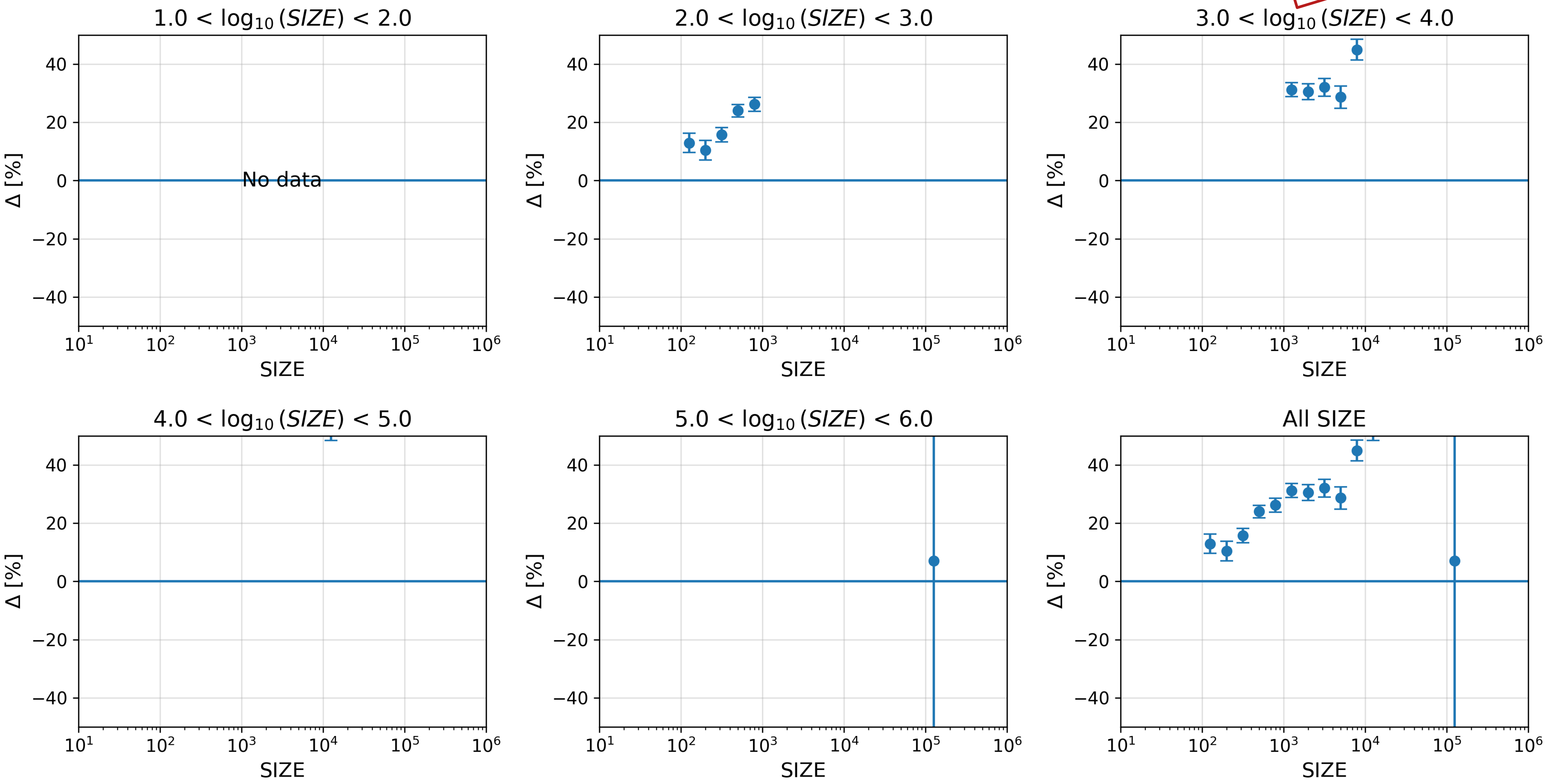

ASTRI-1 size distribution. MC comparison with real data (Z=20°, AZ=180°).

# Validation of MC simulations: Background events Hillas parameters

Mini-Array

SIZE percent difference - (Run 1640,1656,1670 - sim_tel v20260515)/Run 1640,1656,1670

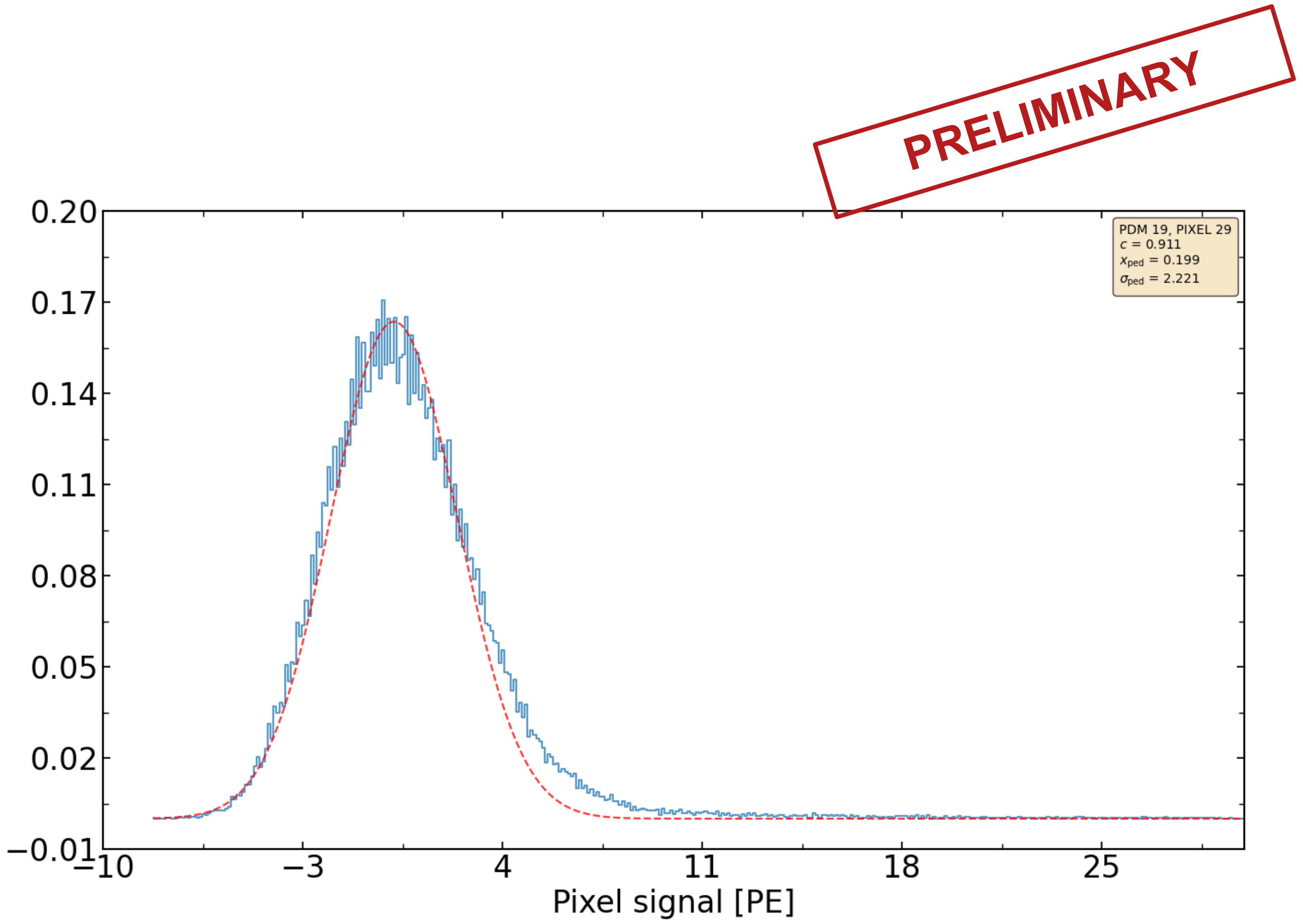
PRELIMINARY




ASTRI-1 percentage difference of size distribution. MC comparison with real data (Z=20°, AZ=180°).

# Validation of MC simulations: Pedestal

- Pedestal represents the baseline signal measured in the absence of physical events, mainly due to electronic noise and the contribution of the NSB.
- Pedestal width, is a key parameter for the instrument sensitivity at low energies, since it determines how effectively faint Cherenkov signals can be discriminated from fluctuations of the baseline.
- To estimate the pedestal width we use calibration events and perform a Gaussian fit to the pedestal distribution of each pixel, extracting the mean value and the standard deviation.

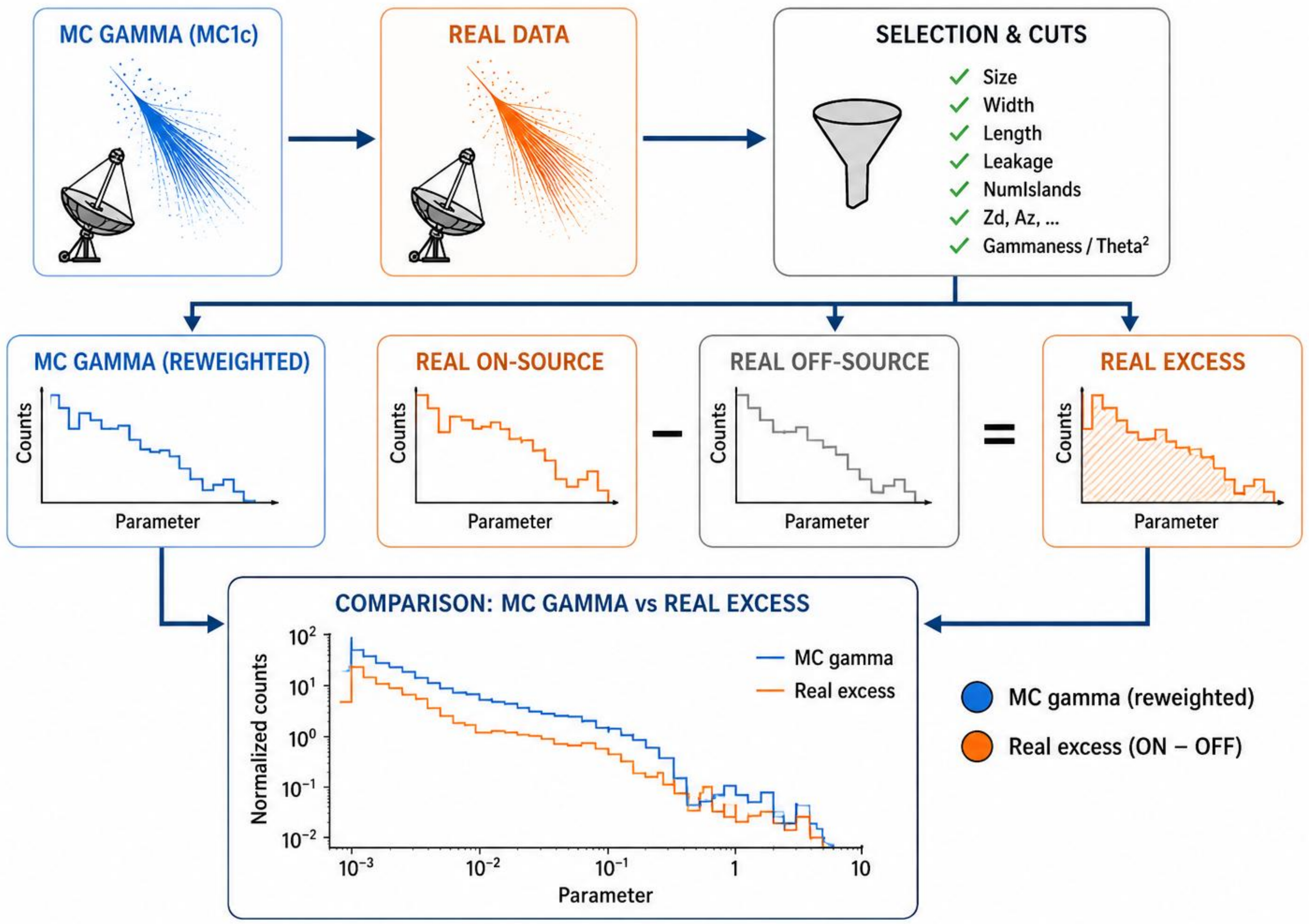



ASTRI-1 MC pedestal distribution fit.

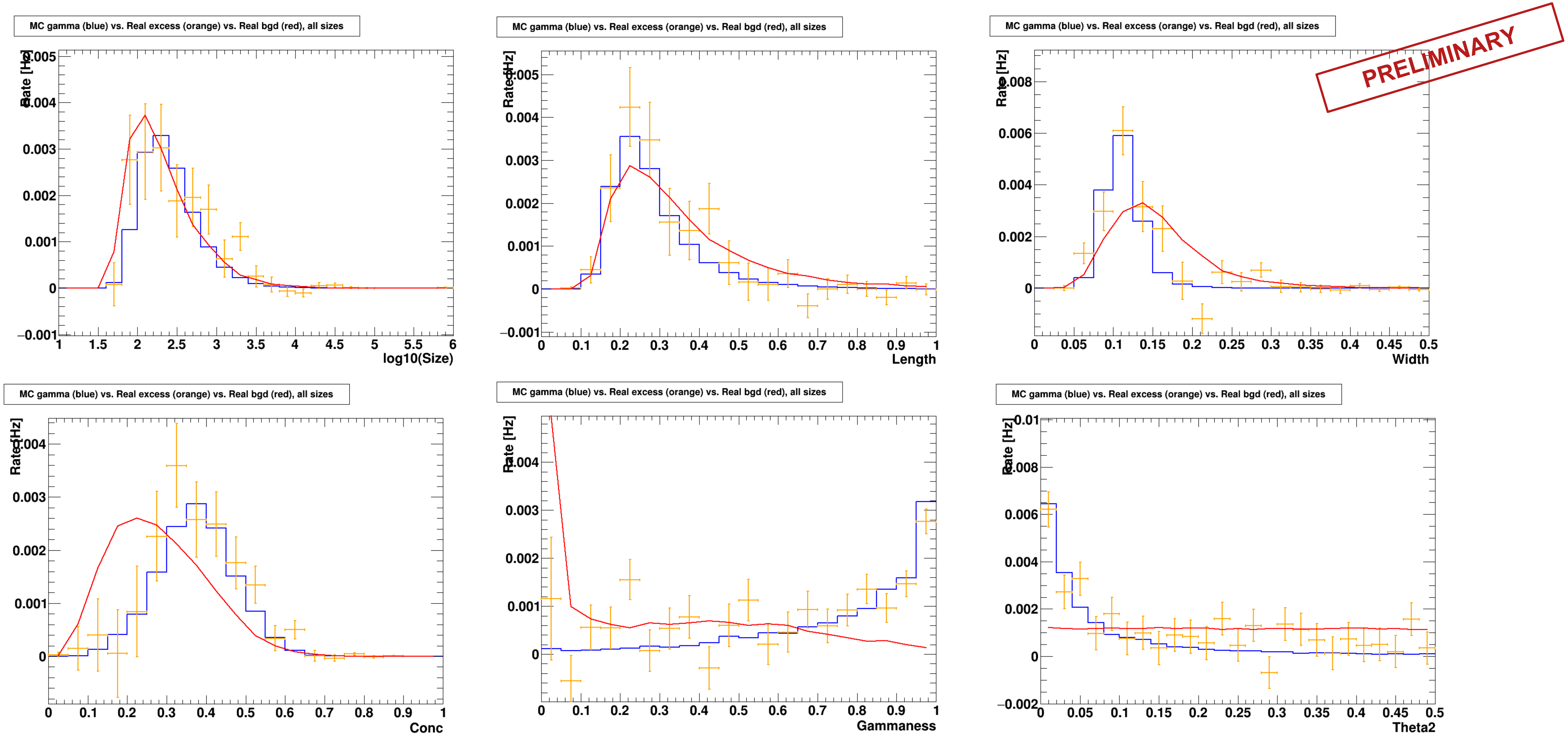
# Validation of MC simulations: Gamma-rays excess

Mini-Array

- Hillas parameter distributions are extracted from MC γ events and real Crab observations.
- Quality cuts are applied (Size, Width, Length, etc.).
- For Theta², the Gammaness cut is computed from a fixed gamma efficiency, while for the other parameters a Theta² cut is applied.
- MC gamma events are reweighted and normalized.
- Real γ-ray excess distributions are obtained by subtracting the OFF-source background from the ON-source data.



# Validation of MC simulations: Gamma-rays excess

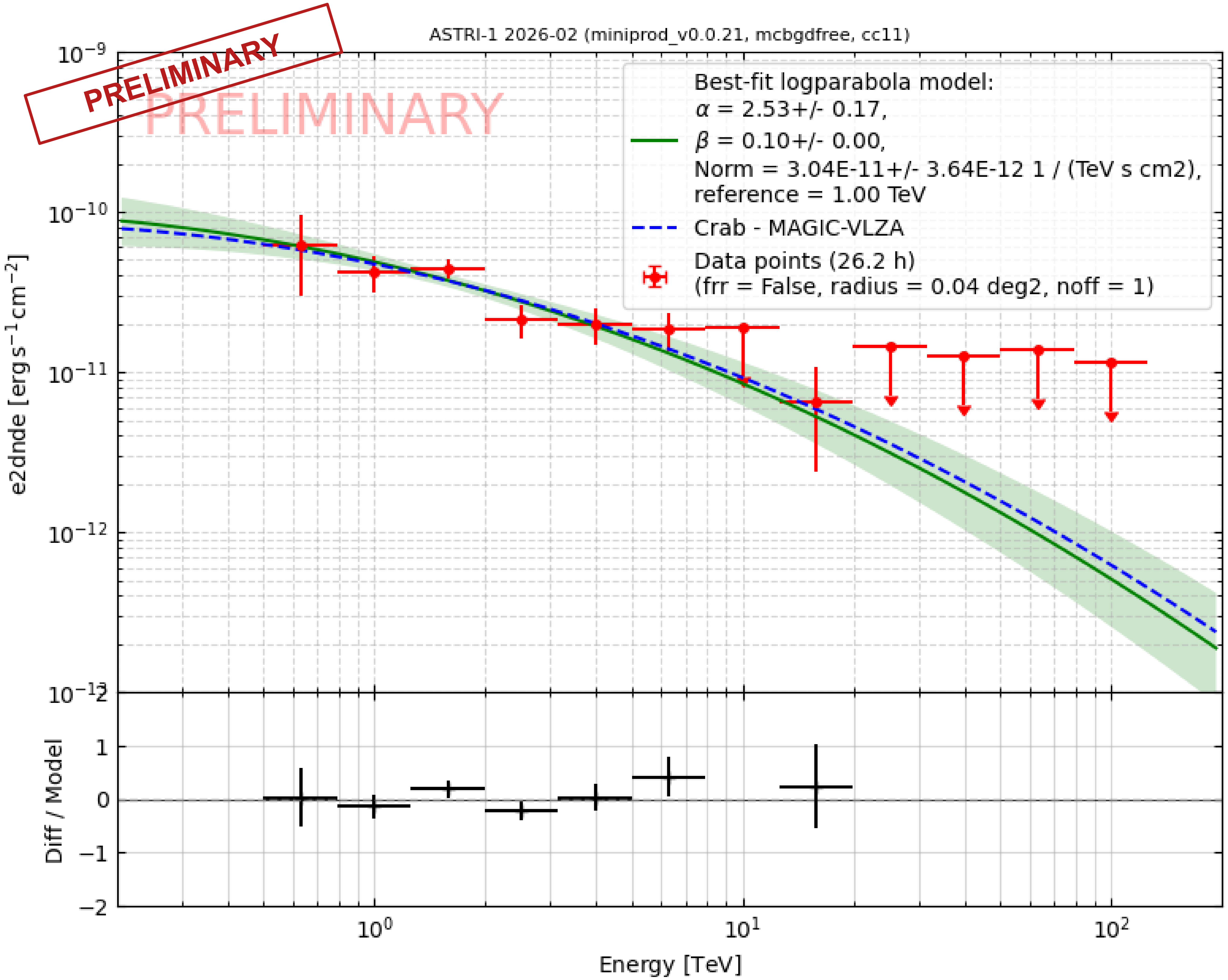



ASTRI-1 gamma-rays excess MC comparison with real data.

# Crab Nebula spectrum

Mini-Array

- MC gamma events are used to provide suitable IRFs (Effective Area, PSF, Energy Dispersion) for spectral analysis.
- Reconstructed γ-ray excesses are used to derive the differential energy spectrum of the Crab Nebula.
- The measured spectral energy distribution (SED) is fitted with a log-parabola model.




Crab Nebula spectrum using ASTRI-1 observations.

# Conclusions

- A comprehensive MC production has been developed for the ASTRI Mini-Array.
- The simulation chain has been updated to reproduce the final detector configuration:
  - -Telescope positions.
  - -Optical model.
  - -Electronics.
  - -NSB.
- Dedicated calibration simulations support:
  - -Camera calibration.
  - -Muon analysis.
  - -Telescope cross-calibration.
- Validation against real ASTRI data currently on-going.