Optical calibration of ASTRI Mini Array telescopes with muon rings

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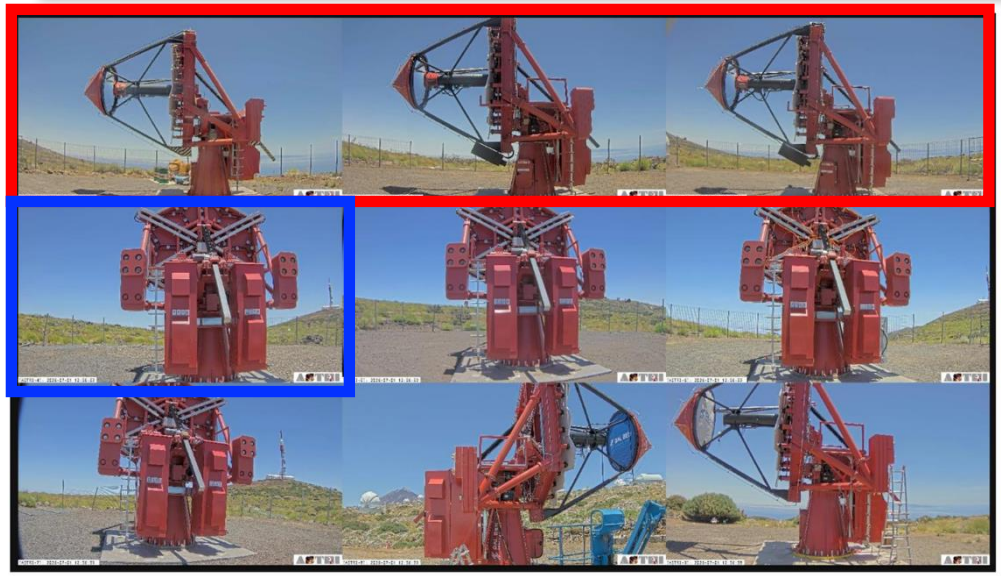
ASTRI Mini-Array

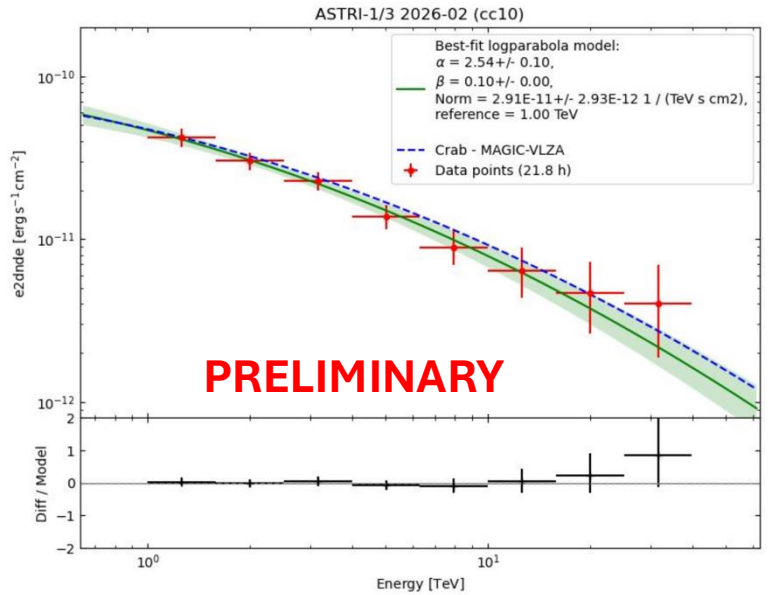


The status (**Tosti talk**)

- Array of nine Cherenkov telescopes under construction at the Teide Astronomical Observatory in Tenerife.
- All telescopes have been installed (see photos)
- ASTRI-1, ASTRI-2, and ASTRI-3 (boxed in red) are in commissioning and science verification phase.
- ASTRI-4 (boxed in blue) will become operational in the next few days,
- All the remaining telescopes are expected to be operative by spring 2027.

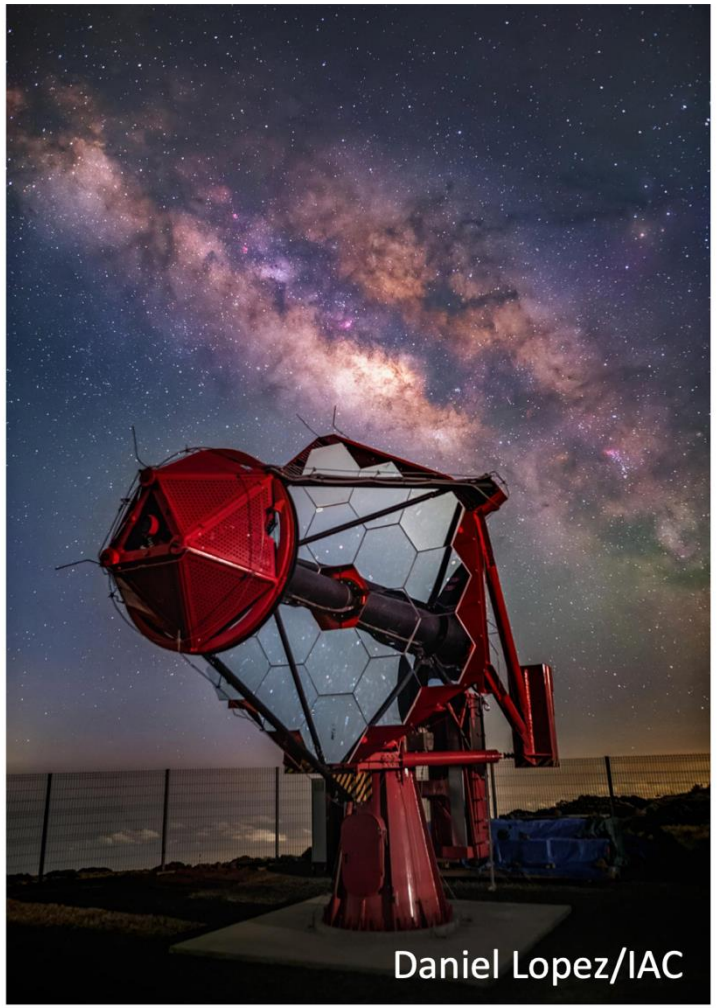
- working energy range 1–200 TeV
- spectral resolution of ~ 10% at 10 TeV
- spatial resolution of ~ 3' at 10 TeV.

Crab spectrum from ASTRI-1 and ASTRI-3 21.8 h observation fitted with a log parabola model. It is well in agreement with the spectrum detected by MAGIC (**Vercellone talk**).



Lombardi et al. SPIE 2026

ASTRI Mini-Array telescopes



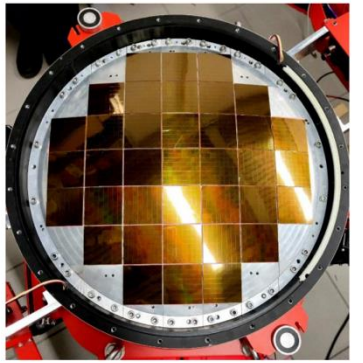
Optics (Sironi talk):

- the telescope adopts a compact dual-mirror Schwarzschild–Couder optical design
- the optical PSF has 80% of the signal within a single pixel (0.19º) up to an off-axis angles of ~4º.

Camera (Contino talk):

The camera is based on SiPMs arranged in 37 Photon Detection Modules (PDMs).

The front-end electronics operates in peak-detection mode, recording the maximum amplitude of HG and LG signals.
The pixel trigger time is also recorded.

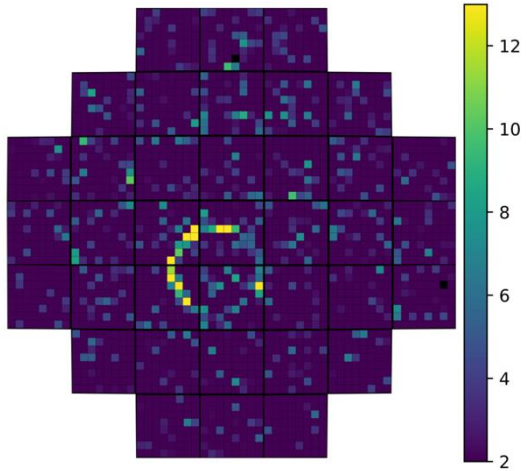


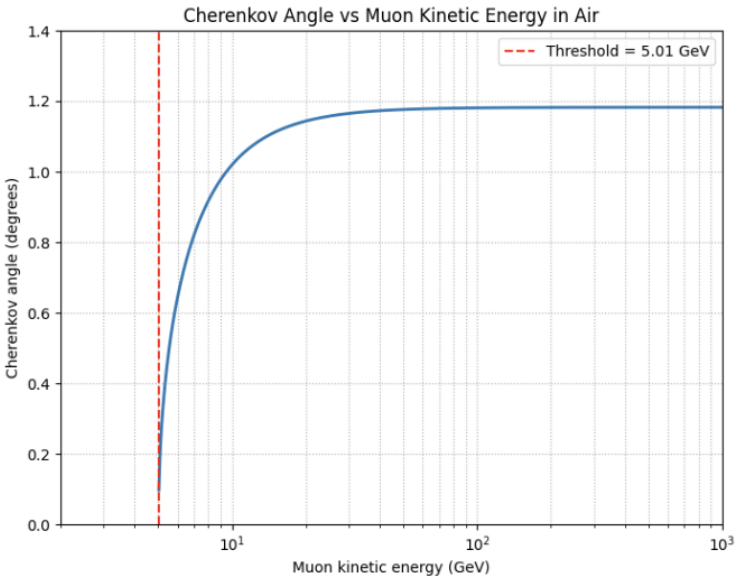
Calibration with muons: rationale

The end-to-end calibration of the ASTRI Mini-Array telescopes is performed using muon rings

Muons passing close to the telescope and traveling nearly parallel to its optical axis produce characteristic ring-shaped images.
Complete rings are observed when the muon hits the telescope primary mirror.

ASTRI-1 detected muon ring

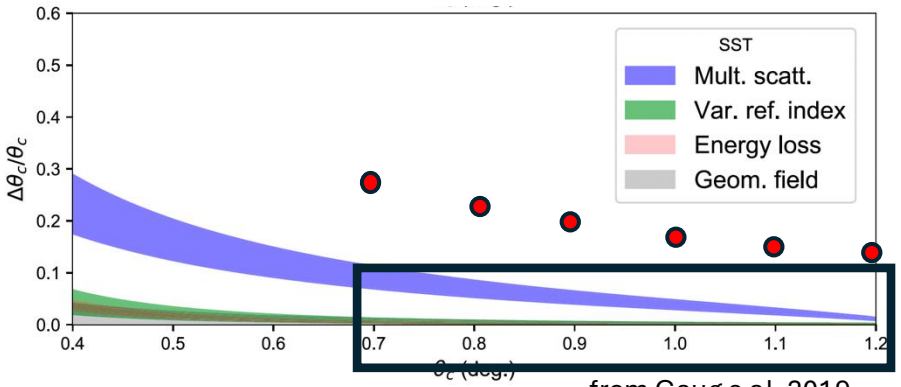




Information on the muons from the ring:

- the ring center gives the arrival direction of the muon
- the radius is determined by the Cherenkov angle, which depends on the muon energy as shown in the plot.

Calibration with muons: rationale



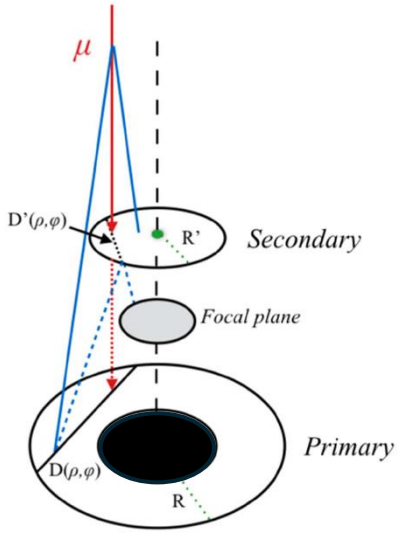
from Gaug e al. 2019

For ASTRI Mini-Array telescopes, the ring width is dominated by the optical PSF.

For the ASTRI calibration rings (radius >0.7°), the intrinsic Cherenkov angular spread (shown in the boxed region) is negligible compared with the camera pixel size (red dots).

The telescope end-to-end efficiency can be estimated from fitting the light distribution along the ring:

- the model adopted for the ASTRI telescopes is based on the Vacanti analytical formula (1994)
- the shadow of the secondary mirror is treated as a hole in the primary mirror.



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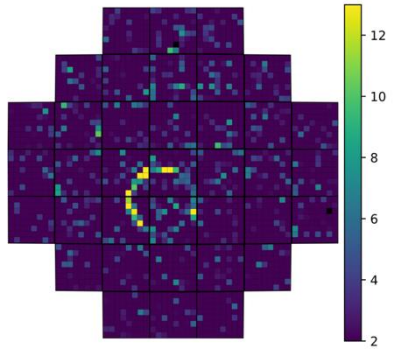
Calibration with muons: rationale



In summary:

- **muon rings allows to measure and monitor the telescope end-to-end efficiency and to monitor the optical (PSF)**
- **results can be used to eventually raise alerts to the hardware team**
- **results are used to fine-tuning MC simulations.**

Advantages:

- Muons generate shapes easily recognizable
- Muons are collected during the normal data taking
- The reconstruction of their parameters does no require dedicated simulations

Caveat:

- The muon Cherenkov emission spectrum is different from that produced by showers mainly because of the much lower atmospheric absorption
- The shadow of the structure musts is not considered leading to a slightly underestimation of the end-to-end efficiency

ASTRI Mini-Array calibration with muons: the software

A-MuSoft is the ASTRI Mini-Array code to reconstruct muon rings and evaluate the efficiency and the PSF

- identify the candidate muon events using both the size and the pixel trigger times.
- compute the coordinate of the ring centre and the ring radius
- apply further restrictive selections to identify events suitable for the calibration
- compute the ring width fitting the radial profile of the ring
- compute the telescope efficiency from the light distribution along the ring.

ASTRI Mini-Array calibration with muons: the software

- The muon analysis is performed in a semi-automatic way on the data collected each observing night
- It is currently running routinely for ASTRI-1 and ASTRI-2 and ASTRI-3
- It will be extended to all other telescopes as soon as they become operational

A more performant version of the code, completely integrated in the ASTRI Mini-Array calibration library (**astricaltools**) is under testing:

- It identifies the ring using a method based on a Hough-like transform applied to the pixel trigger times
- it computes both the ring width and the telescope efficiency at the same time performing a full 2D likelihood fit on the muon ring images

The results obtained with this new code are well in agreement with the first version ones.

Data Analysis

ASTRI-1 and ASTRI-3 observations acquired under good weather conditions have been calibrated and analyzed with A-MuSoft .

ASTRI-1	ASTRI-3
~500 runs from November 2024 to March 2026	~100 runs from January to February 2026

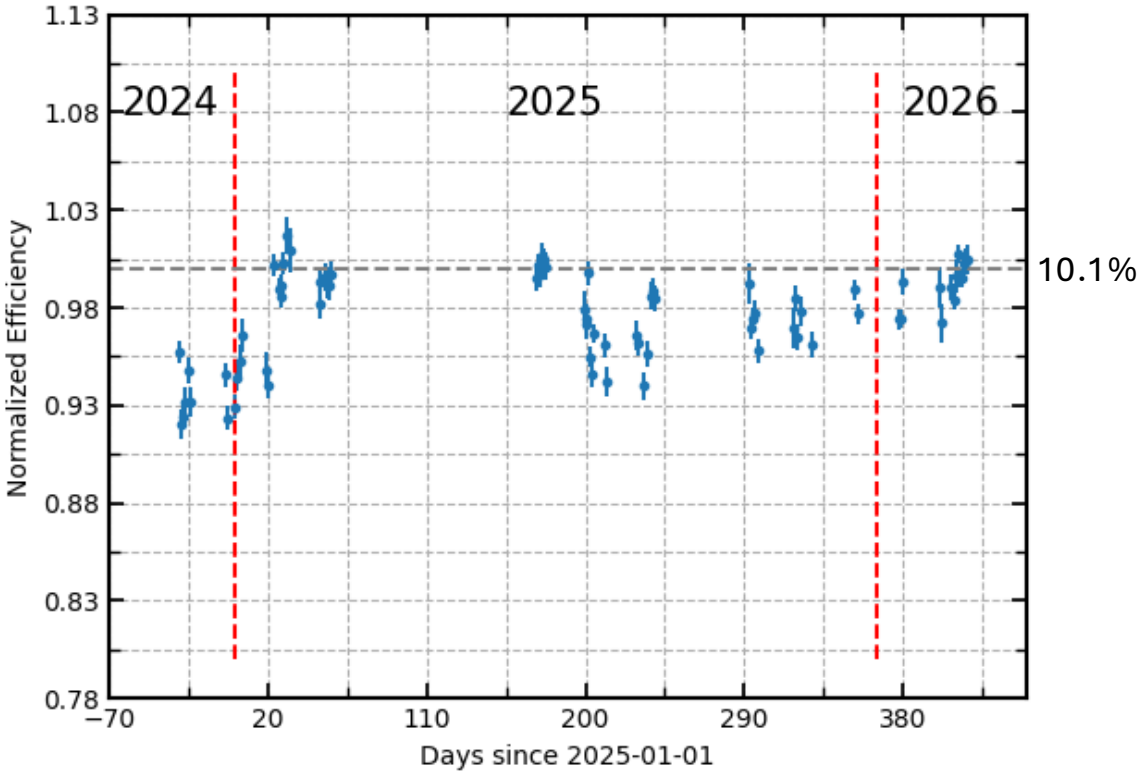
To improve the statistics, nightly averages were computed

- Efficiency and ring-width distributions were accumulated and fitted with Gaussian where:
  Mean → nightly average
  σ → nightly uncertainty

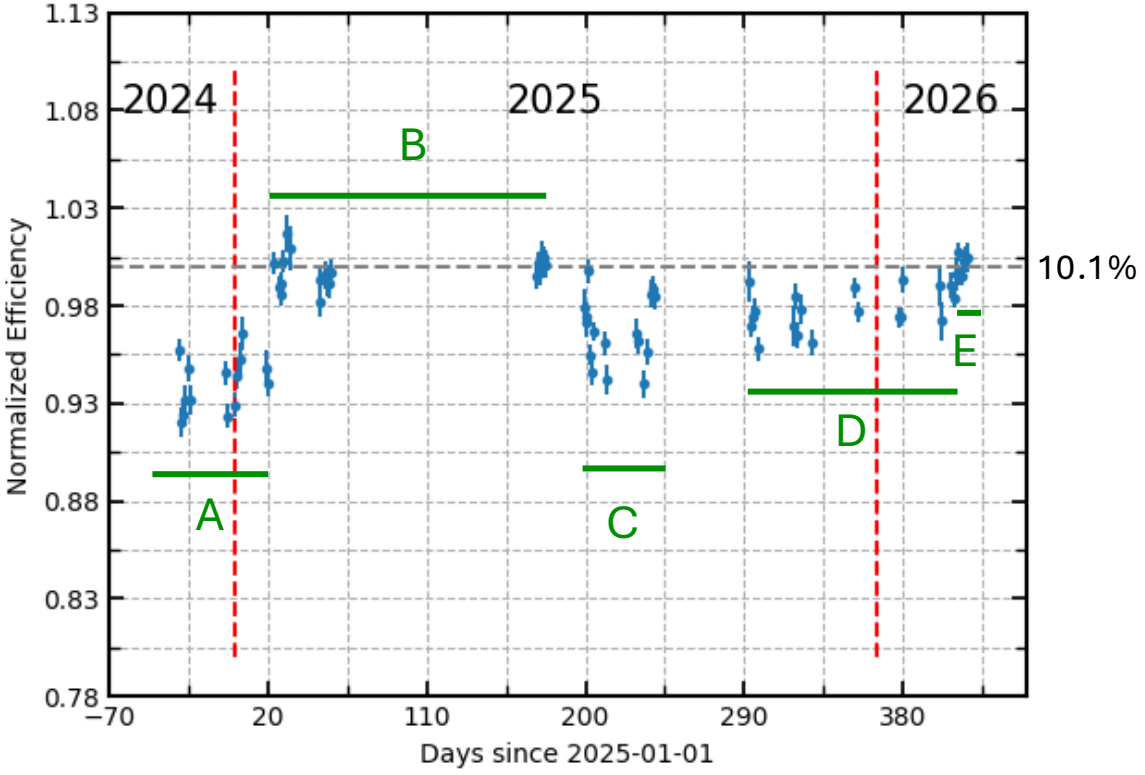
- Efficiency is normalized to an arbitrary reference value (10.1%): the ASTRI-1 average efficiency detected between January and June 2025 .

- Ring width expressed as the D80 (the diameter including 80% of the signal) is normalized to the pixel size (0.19°).

ASTRI-1 Efficiency

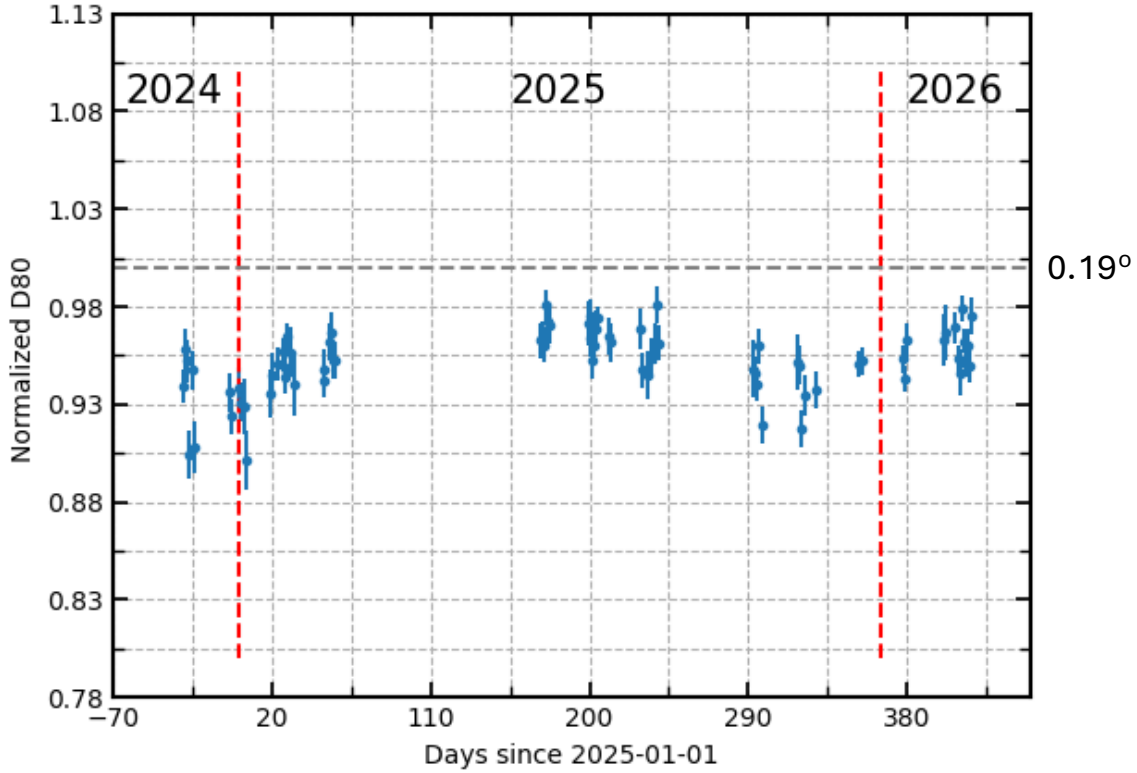


ASTRI-1 Efficiency

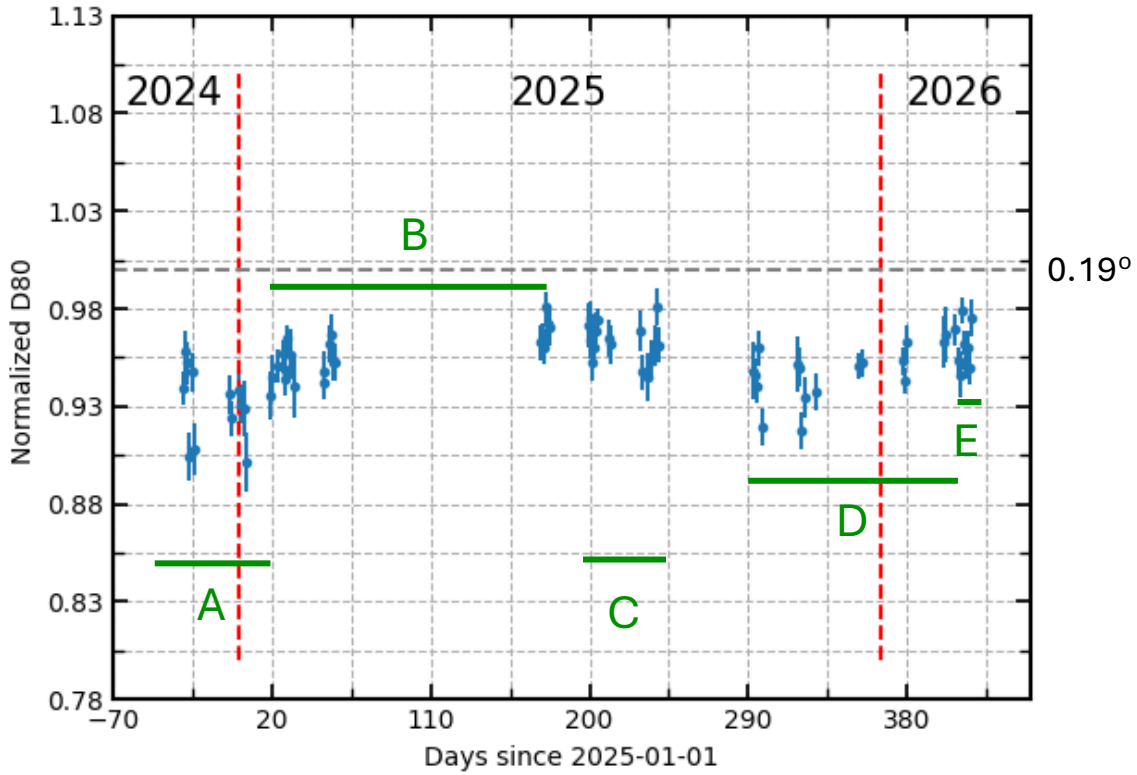


Normalized Efficiency	
Interval	Average
A (2024/12/01-2025/01/21)	0.94 ± 0.02
B (2025/01/28-2025/06/29)	1.00 ± 0.01
C (2025/07/19-2025/09/02)	0.97 ± 0.02
D (2025/10/17-2026/02/14)	0.98 ± 0.01
E (2026/02/16-2026/03/15)	1.00 ± 0.01

ASTRI-1 muon ring D80



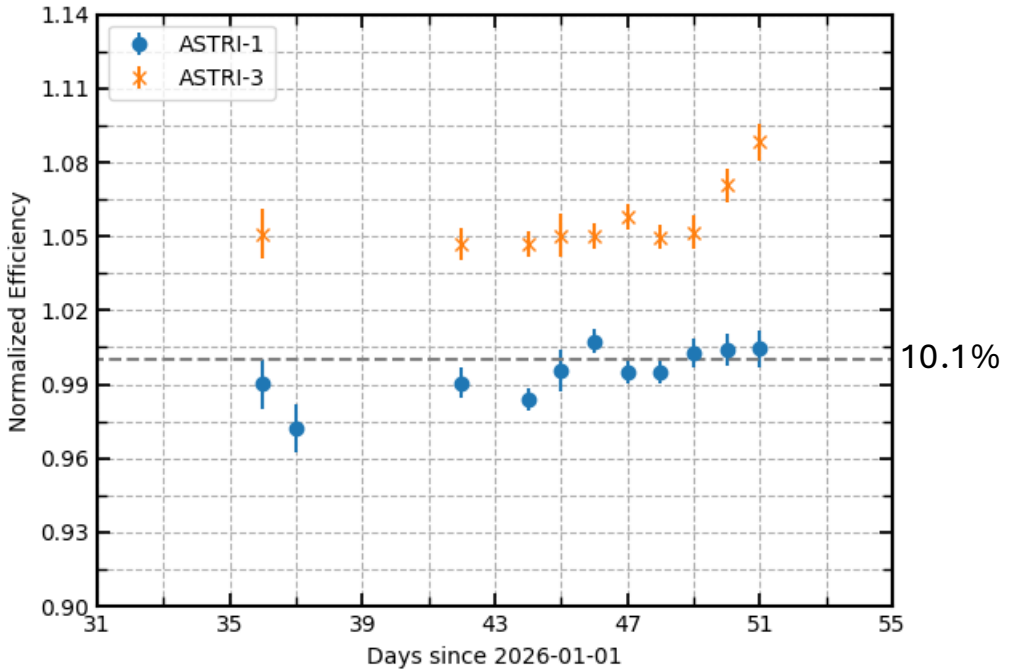
ASTRI-1 muon ring D80

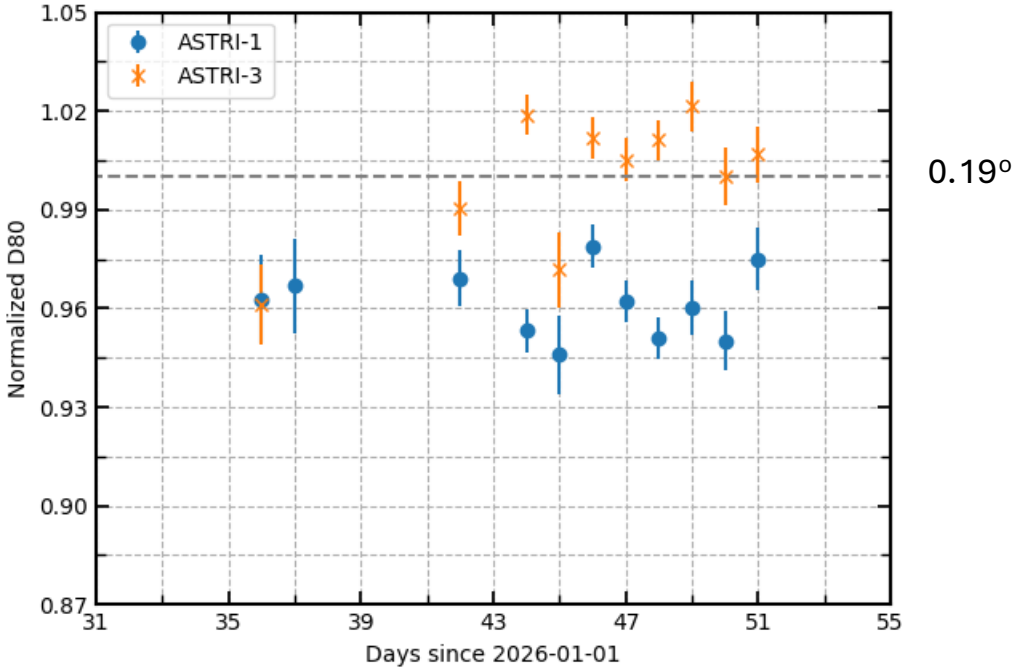


Normalized D80	
Interval	Average
A (2024/12/01-2025/01/21)	0.93 ± 0.02
B (2025/01/28-2025/06/29)	0.96 ± 0.01
C (2025/07/19-2025/09/02)	0.96 ± 0.01
D (2025/10/17-2026/02/14)	0.95 ± 0.01
E (2026/02/16-2026/03/15)	0.95 ± 0.01

No D80 significant variations along all the considered intervals. The average normalized D80 is 0.95 ± 0.02

ASTRI-3 Efficiency and D80





	Average Normalized Efficiency	Average Normalized D80
ASTRI-1	0.99±0.01	0.96±0.01
ASTRI-3	1.06±0.01	1.00±0.02

Conclusion

The muon analysis on the first two telescopes of ASTRI Mini- Array showed that:

- ASTRI-1 presented a maximum reduction in the end-to end efficiency of 6% in an interval where the mirror was particularly covered with dust
- No variation in the ASTRI-1 PSF was detected
- ASTRI-3 in the short interval analyzed showed an end-to-end efficiency higher that ~7% with respect to ASTRI-1
- The ASTRI-3 D80 is ~4% larger than the ASTRI-1 one but on average within one pixel

Absolute end-to-end efficiency measurements of all the telescopes are planned using the Illuminator.
These measurements will provide an independent validation of the efficiencies derived from the muon analysis.