Status of the Monte Carlo simulations of the ASTRI Mini-Array at Tenerife

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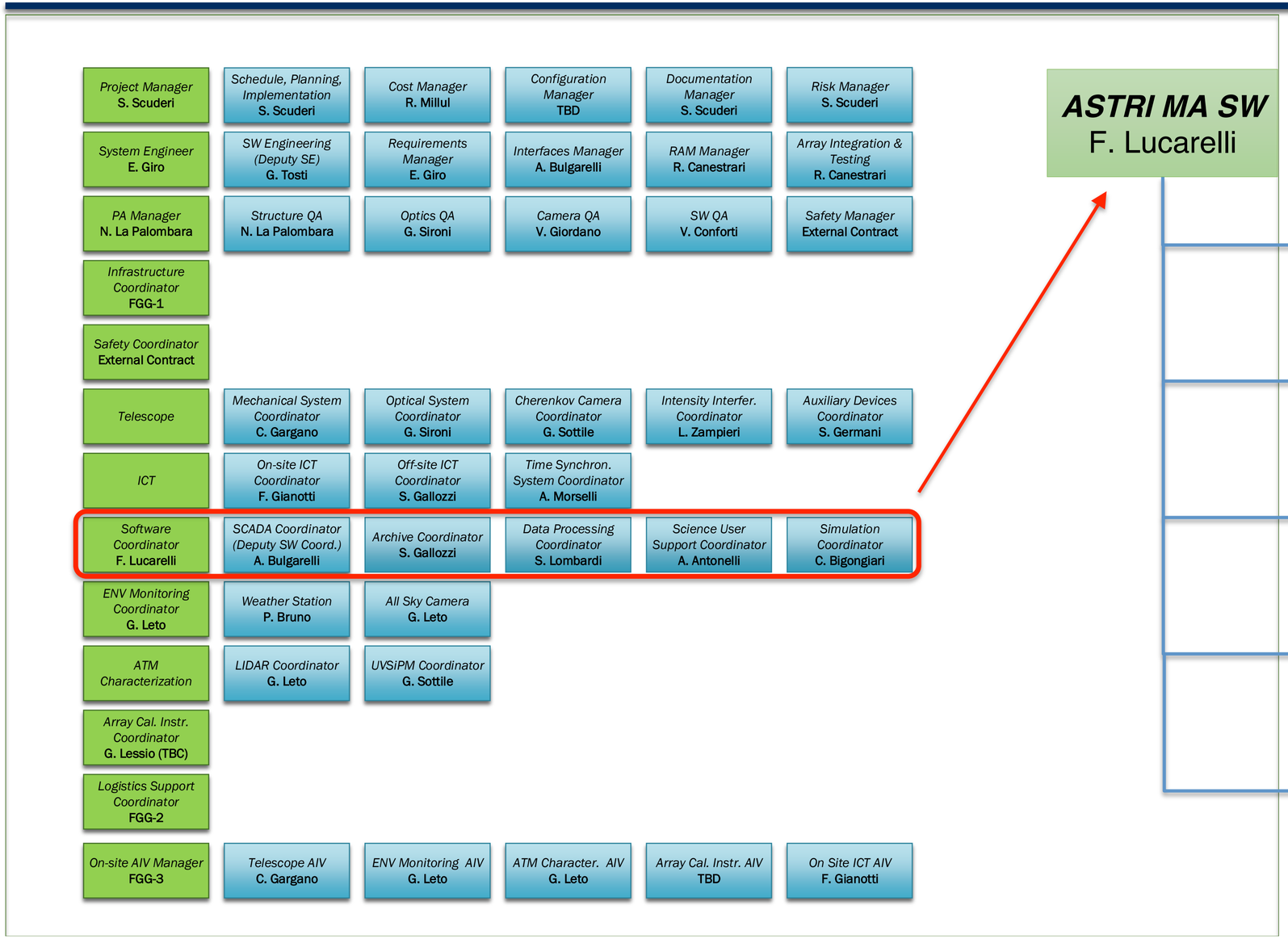
for the ASTRI Project

ASTRI Project Committee Meeting, 25/02/2022

Outline

- ASTRI Monte Carlo simulation chain
- ASTRI Monte Carlo data reduction and analysis chain
- Available Monte Carlo simulations @Teide
- Key performance features
- Monte Carlo simulation activities
- Summary

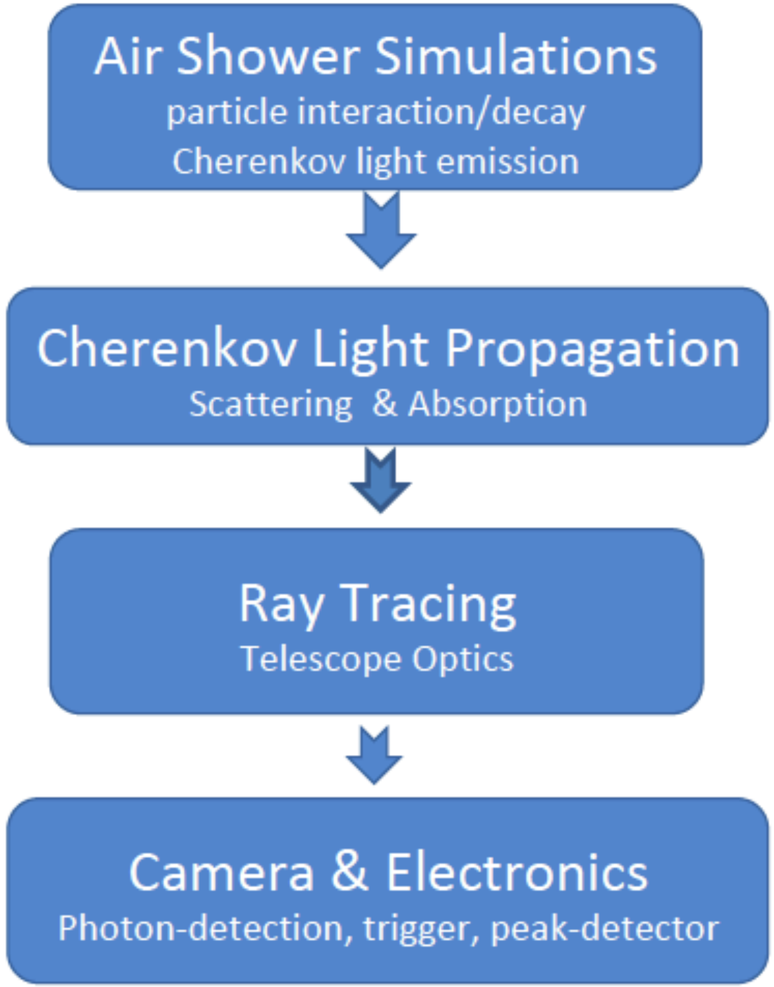
ASTRI Mini-Array – Software WP



ASTRI MA SW
F. Lucarelli

- **SCADA**
  A. Bulgarelli
  (deputy SW coord.)
- **Archive**
  S. Gallozzi
- **Data Processing**
  S. Lombardi
- **Science Support System**
  A. Antonelli
- **Simulations**
  C. Bigongiari

ASTRI Mini-Array – Simulation chain (I)



CORSIKA

https://www.iap.kit.edu/corsika/index.php

Used version **6.99** for a long time
(same as CTA Prod4)
Moved to version 7.74

Sim_telarray

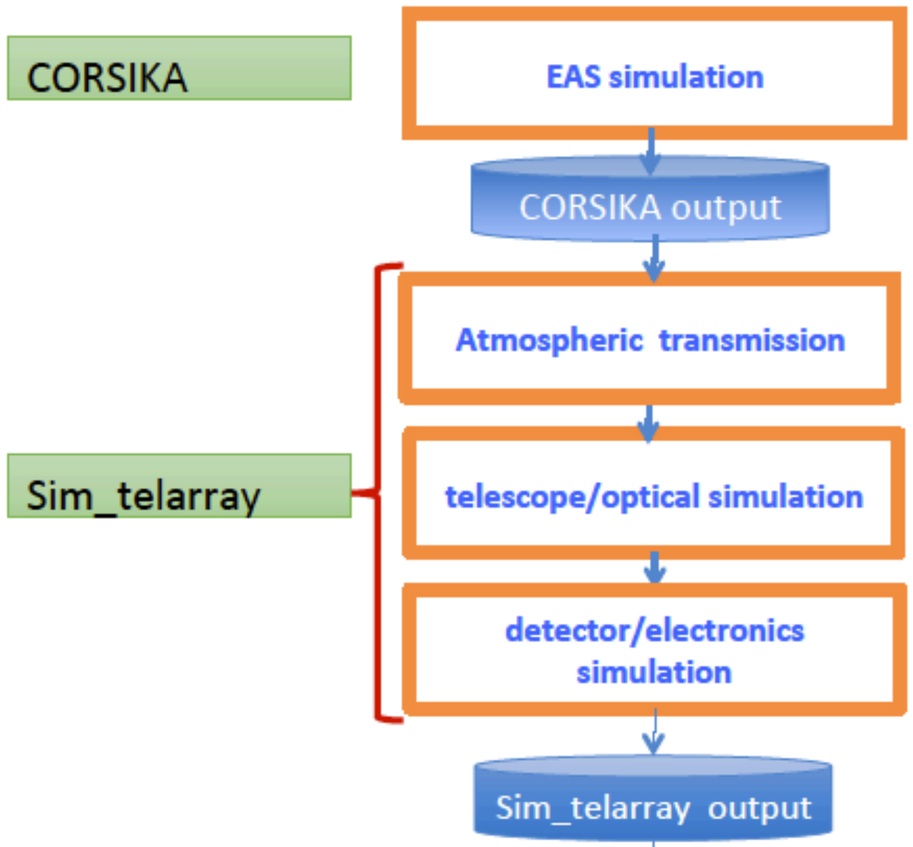
https://www.mpi-hd.mpg.de/hfm/CTA/MC/Software/

Using version **2018.11.07** for a long time
(same as CTA Prod4)
Moved to version 2021.12.25

Stay aligned to CTA and exploit some new features

Credits: C. Bigongiari

ASTRI Mini-Array – Simulation chain (II)



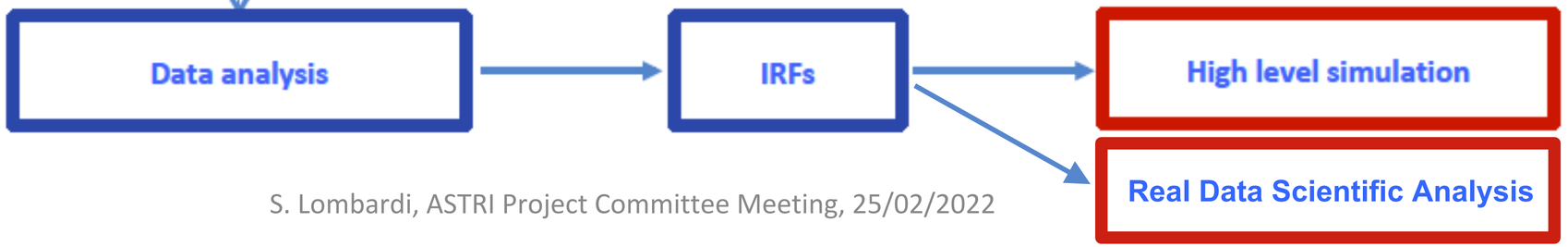
- γ and bkg (p, e^-, He,...)
- Azimuth & Zenith angles
- Telescope positions
- Geomagnetic field
- Atmospheric density profile

- Atmospheric extinction ← MODTRAN

- Ray Tracing ← Mirror reflectivity

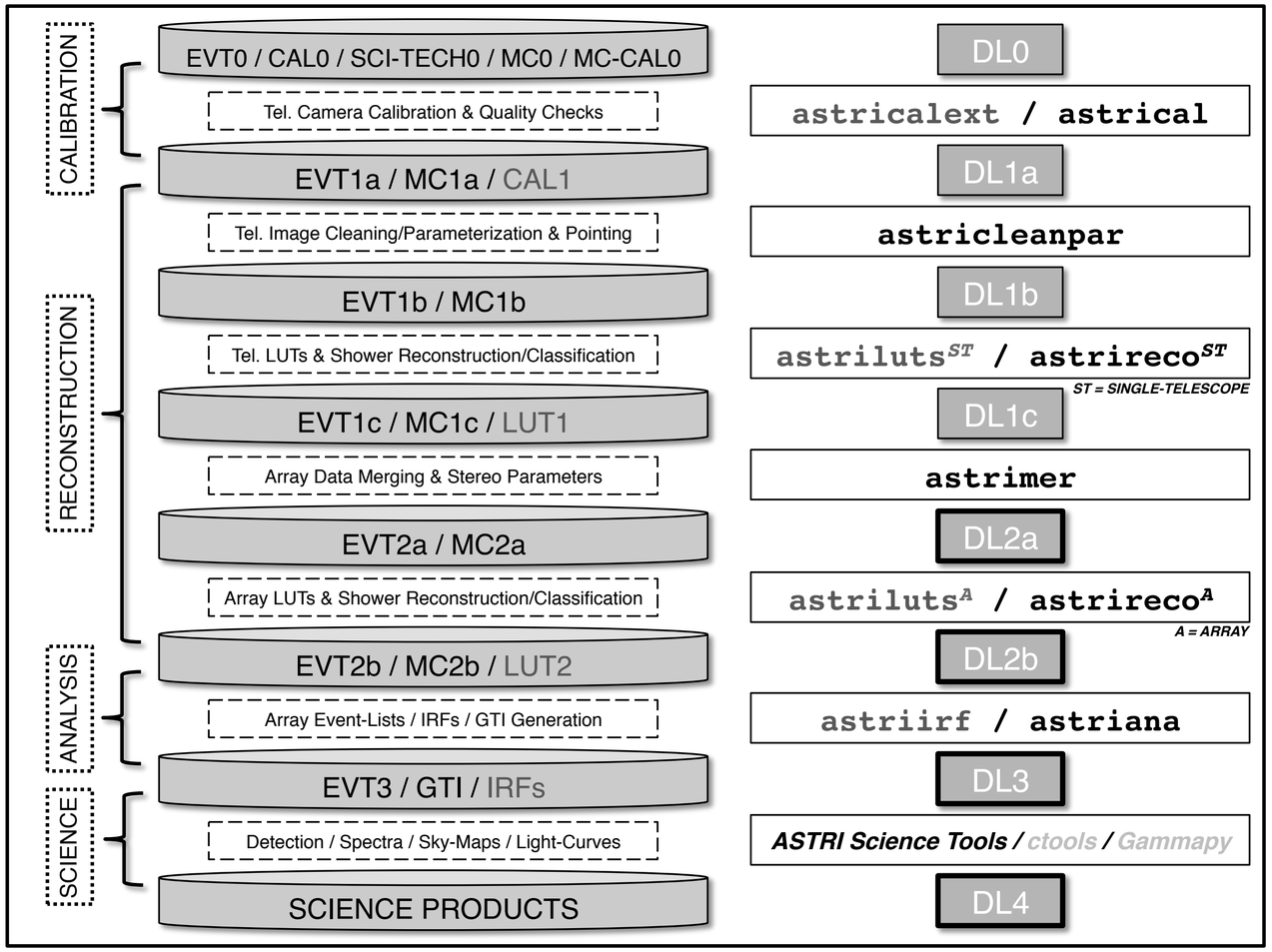
- SiPM ← PDE SinglePhotoElectronResponse
- Camera Electronics ← SlowShaper
- Trigger ← FastShaper

We store on disk both CORSIKA and Sim_telarray output



Credits: C. Bigongiari

ASTRI Mini-Array – Data reduction and analysis chain



Functional design layout of the ASTRI data reduction and scientific analysis software package (***A-SciSoft***). From left to right, functional breakdown stages are shown as dotted boxes, I/O data as grey cylinders (black: main pipeline I/O data; grey: auxiliary I/O data), basic software functionalities as dashed boxes, data levels as grey boxes (thin: telescope-wise data; thick: array-wise data), and data processing executables as solid boxes. The external packages for the scientific analysis, i.e. *ctools* and *Gammapy*, are written in bright grey.

SPIE 991315 (2016); SPIE 107070 (2018)

A-SciSoft (ASTRI Scientific Software, aka **astripipe**)

- End-to-End pipeline from RAW data (DL0) to Science Products (DL4)
- FITS data format from DL0 to DL4
- *C++/Python* (pipeline and auxiliary modules)
- Single-telescope and array data reduction and analysis
- Monte Carlo data reduction and analysis (so far extensively tested)
- Real data reduction and analysis (so far tested with ASTRI-Horn telescope)
- Scientific analysis from DL3 to DL4 with external science tools (`Gammapy` and `ctools`)

ASTRI Mini-Array – Available MC Simulations @Teide

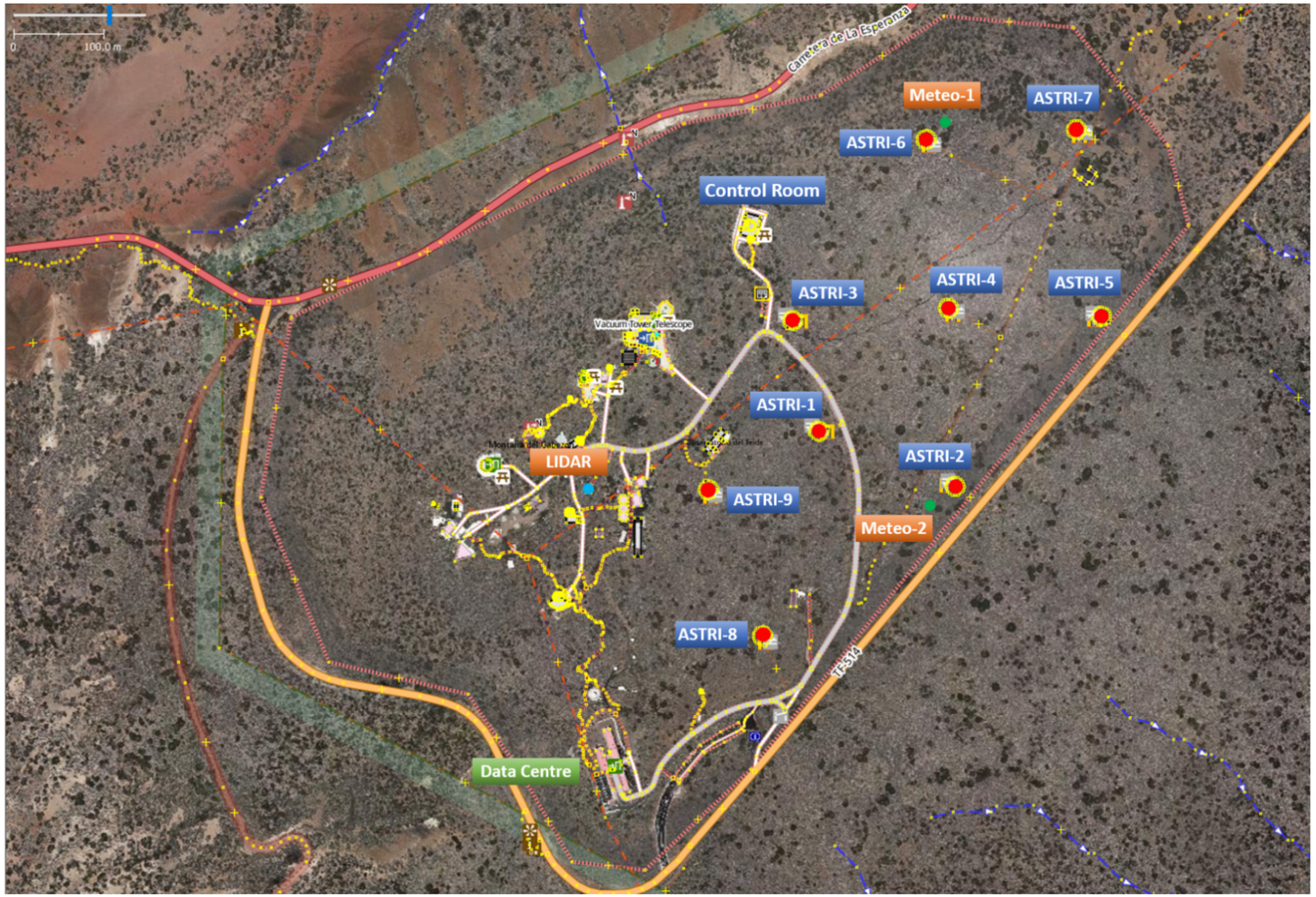
- "Prod1-Teide" Monte Carlo production (2020) (provisional telescope positions)

PARTICLE	Emin [TeV]	Emax [TeV]	Spectral Slope	IPmax [m]	View Cone [deg]	Zenith [deg]	Azimuth [deg]	Number of Simulated Runs	Number of Simulated Showers per Run	Number of Simulated Showers
GammaPointlike	0.1	330	-1.5	2000	0	20	180	1000	10000	10^7
GammaDiffuse	0.1	330	-1.5	2400	10	20	180	5000	20000	10^8
Electron	0.1	330	-1.5	2400	10	20	180	5000	20000	10^8
Proton	0.1	600	-1.5	2400	10	20	180	50000	20000	10^9
TOTAL								**61000**		**1.21×10^9**

- "Prod2-Teide" Monte Carlo production (2021) (final telescope positions; higher MC statistics)

PARTICLE	Emin [TeV]	Emax [TeV]	Spectral Slope	IPmax [m]	View Cone [deg]	Zenith [deg]	Azimuth [deg]	Number of Simulated Runs	Number of Simulated Showers per Run	Number of Simulated Showers
GammaPointlike	0.1	330	-1.5	2000	0	20	180	2×2000	10000	4×10^7
GammaDiffuse	0.1	330	-1.5	2400	10	20	180	2×10000	20000	4×10^8
Electron	0.1	330	-1.5	2400	10	20	180	2×5000	20000	2×10^8
Proton	0.1	600	-1.5	2400	10	20	180	2×50000	20000	2×10^9
TOTAL								**134000**		**2.64×10^9**

ASTRI Mini-Array – Final Telescope Layout



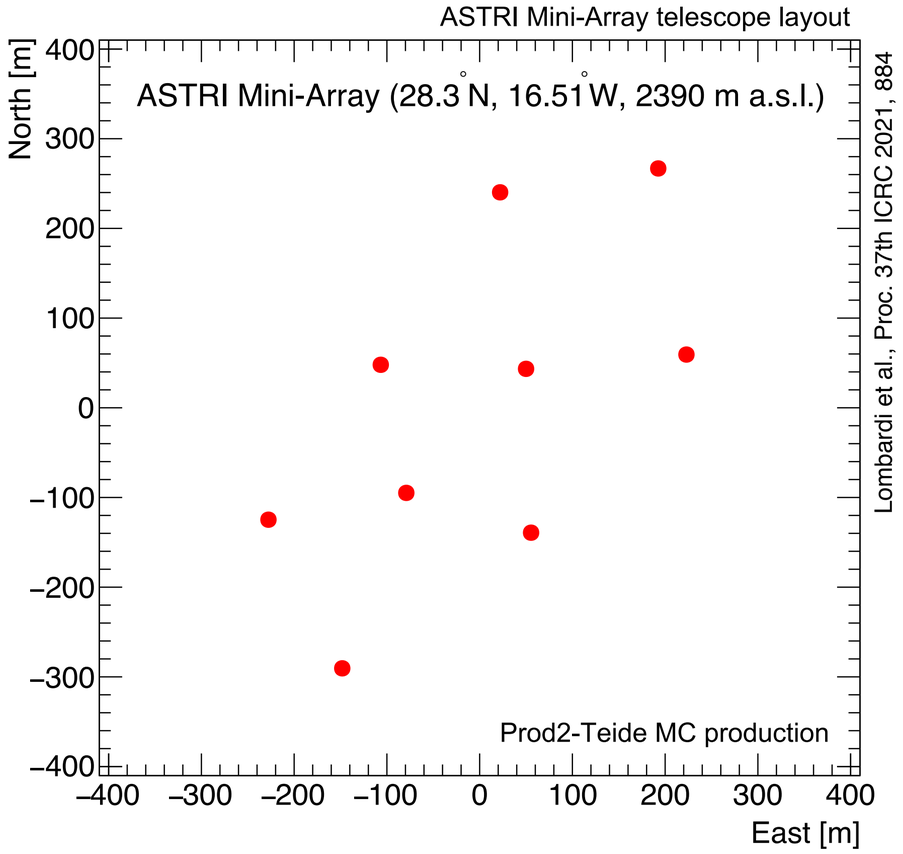
TELID	TELX [m]	TELY [m]	TELZ [m]
ASTRI-1	-77.590	-99.710	26.000
ASTRI-2	56.190	-138.500	15.000
ASTRI-3	-108.380	49.290	31.000
ASTRI-4	52.920	42.520	23.000
ASTRI-5	223.750	55.450	25.000
ASTRI-6	26.220	245.690	18.000
ASTRI-7	198.410	265.710	9.000
ASTRI-8	-149.800	-291.800	43.150
ASTRI-9	-221.730	-128.640	26.000

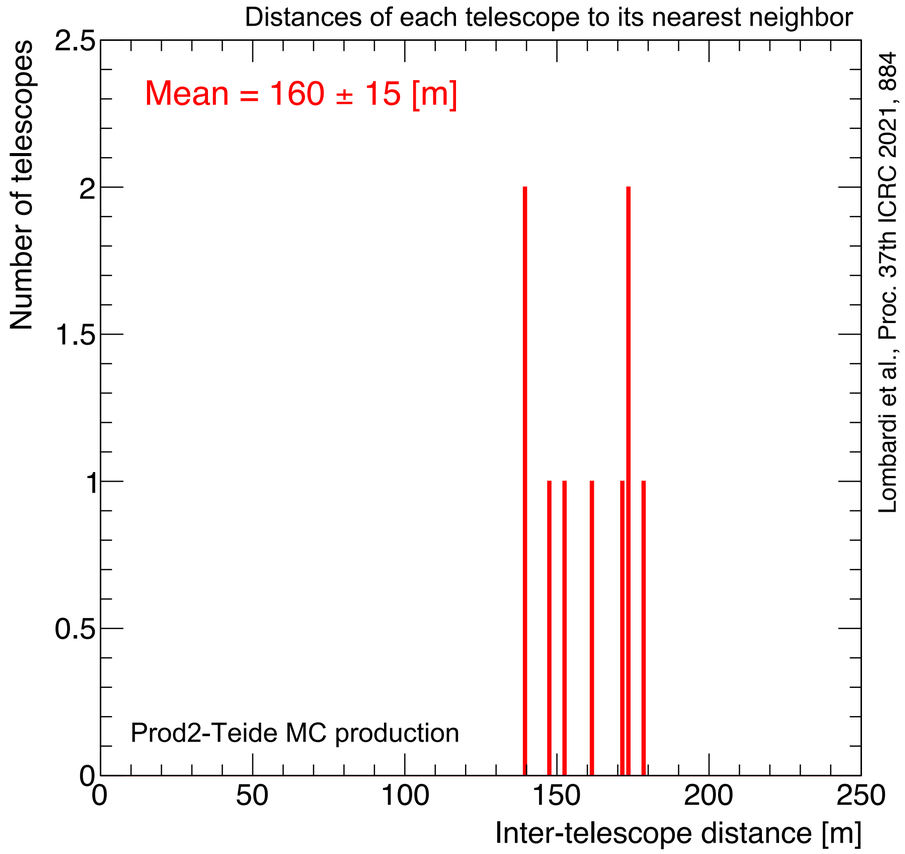
2D intertelescope distances

Tel	ASTRI-1	ASTRI-2	ASTRI-3	ASTRI-4	ASTRI-5	ASTRI-6	ASTRI-7	ASTRI-8	ASTRI-9
ASTRI-1	0.000	139.290	152.148	193.034	338.940	360.663	457.939	205.214	147.015
ASTRI-2	139.290	0.000	249.697	181.050	256.306	385.357	428.500	256.774	278.095
ASTRI-3	152.148	249.697	0.000	161.442	332.187	238.097	375.443	343.596	210.968
ASTRI-4	193.034	181.050	161.442	0.000	171.319	204.917	266.423	390.980	323.618
ASTRI-5	338.940	256.306	332.187	171.319	0.000	274.243	211.781	510.022	482.018
ASTRI-6	360.663	385.357	238.097	204.917	274.243	0.000	173.350	565.578	449.001
ASTRI-7	457.939	428.500	375.443	266.423	211.781	173.350	0.000	657.318	576.220
ASTRI-8	205.214	256.774	343.596	390.980	510.022	565.578	657.318	0.000	178.312
ASTRI-9	147.015	278.095	210.968	323.618	482.018	449.001	576.220	178.312	0.000

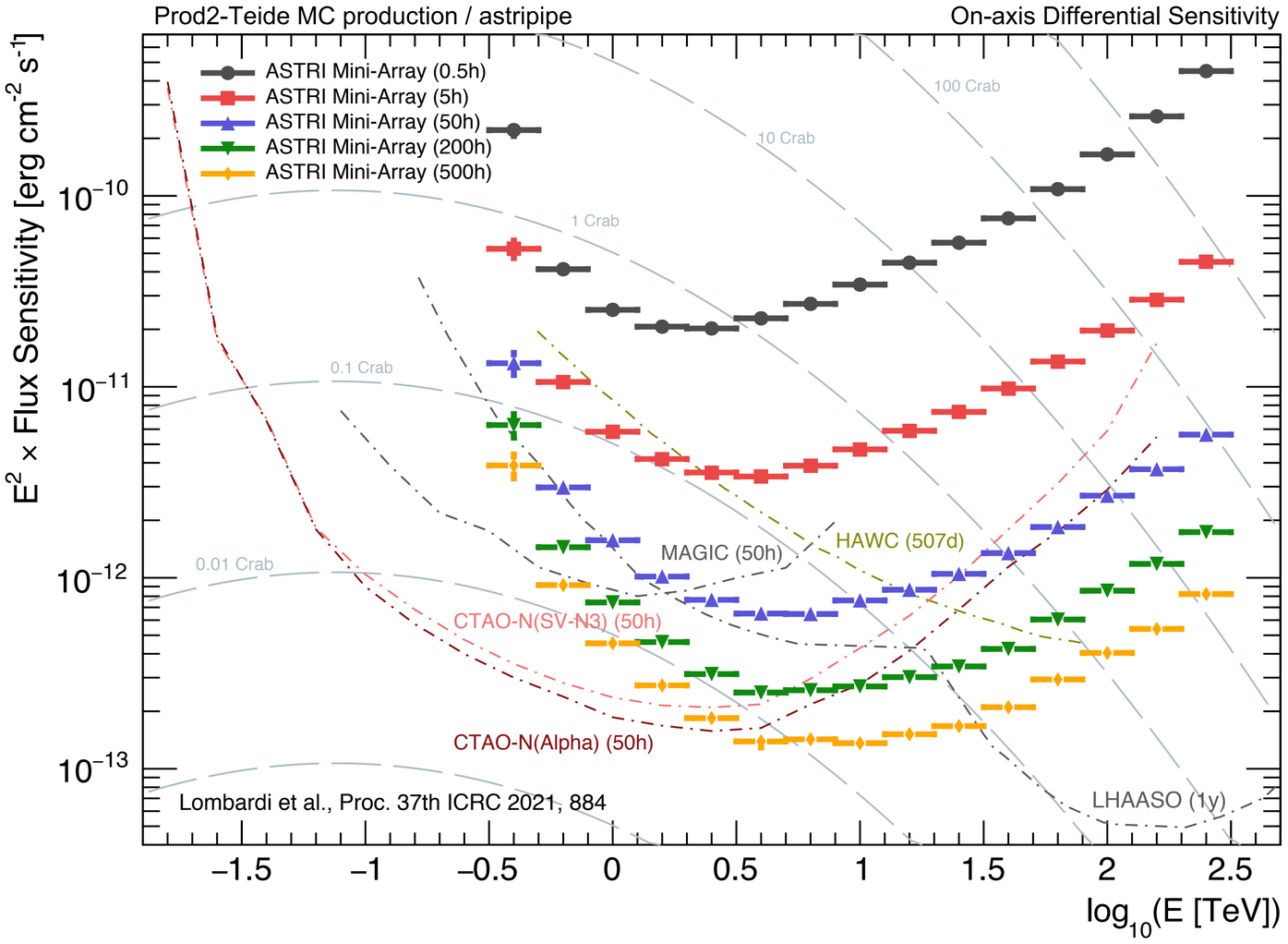
ASTRI Mini-Array – Final Telescope Layout

- Telescope positions ➔ trade-off between performance and site constraints
- Telescope next-neighbor distance: ~160 m ➔ enhanced sensitivity at TeV / multi-TeV energy scales





ASTRI Mini-Array – Key Performance Features



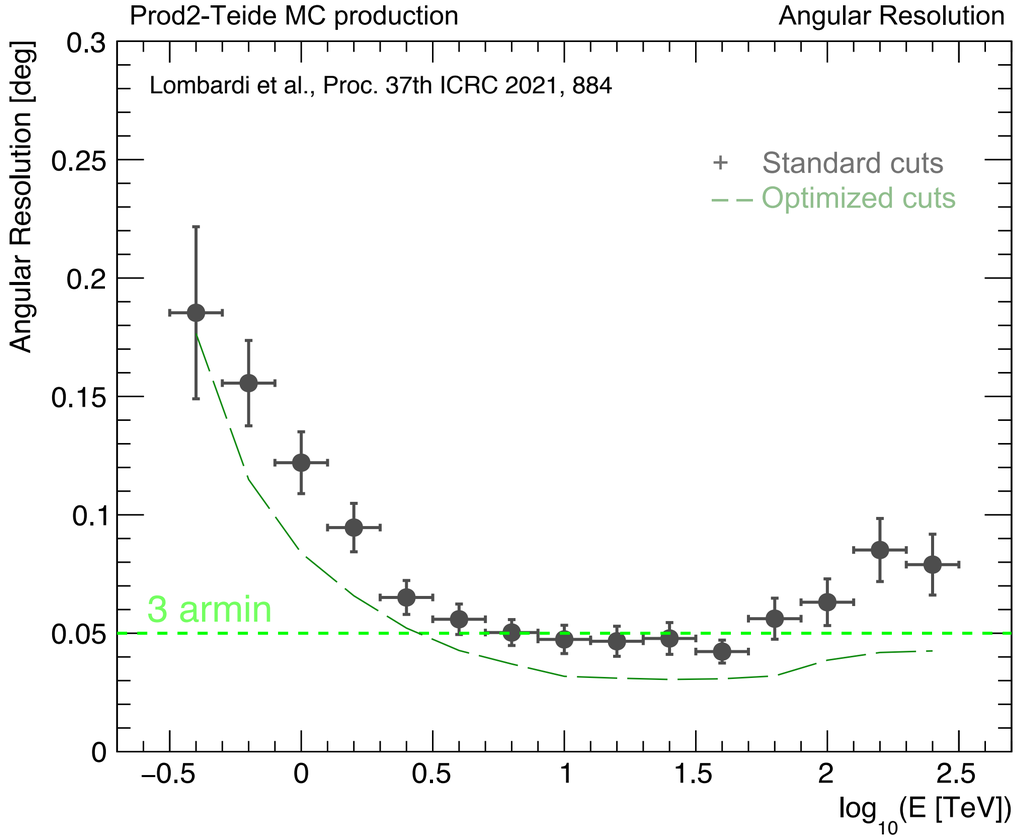
ASTRI Mini-Array Differential Sensitivity:

- Better than present-generation IACTs above a few TeV
- Comparable to CTAO-N(Alpha) above a few tens of TeV
- Surpassed by HAWC (507 days) and LHAASO (1 year) sensitivity above a few tens of TeV, BUT substantially better angular/energy resolution at those energies

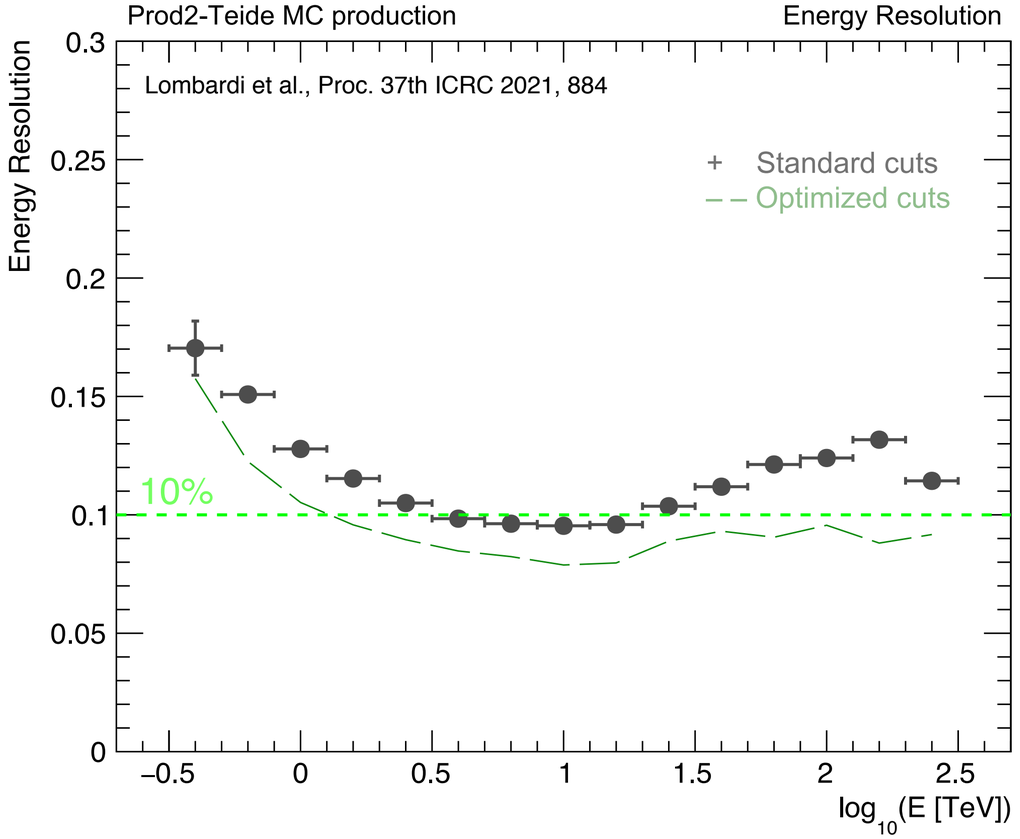
➔ *ASTRI Mini-Array fully functional complement at the TeV / multi-TeV energies to present- and next-generation gamma-ray observatories in the Northern Hemisphere*

ASTRI Mini-Array – Key Performance Features

Angular resolution: ~0.05° (3 arcmin) above a few TeV ➔ *important for morphological studies of sources detected by HAWC and LHAASO in the multi-TeV regime*



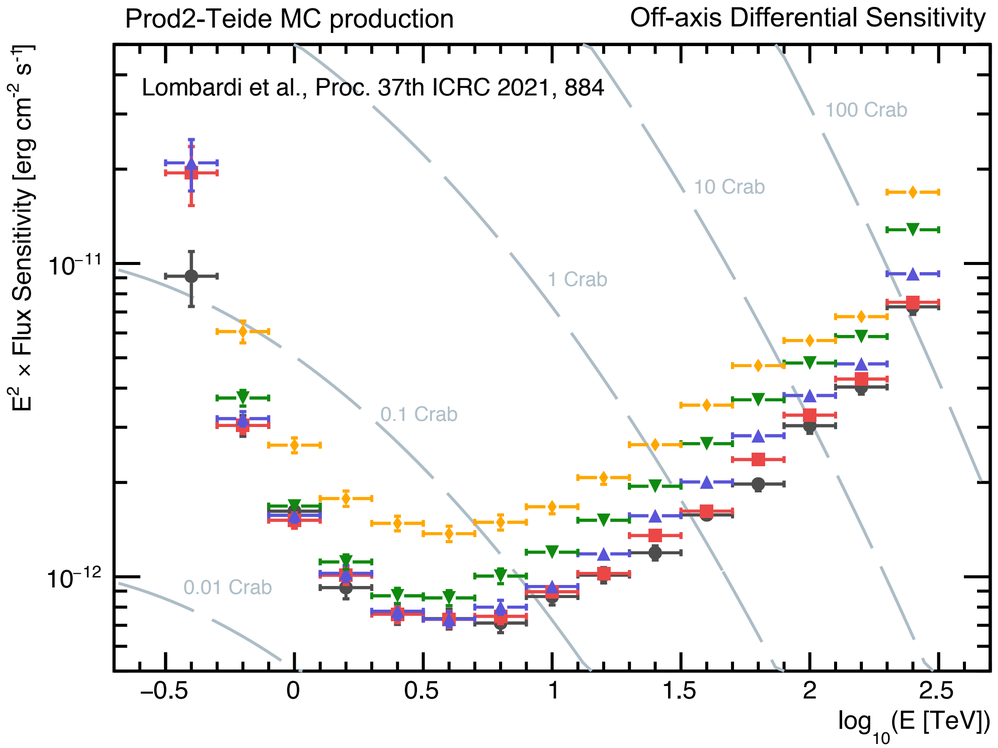
Energy resolution: ~10% above a few TeV ➔ *important for spectral studies (e.g. cut-off, bumps, …) in the TeV / multi-TeV regime*

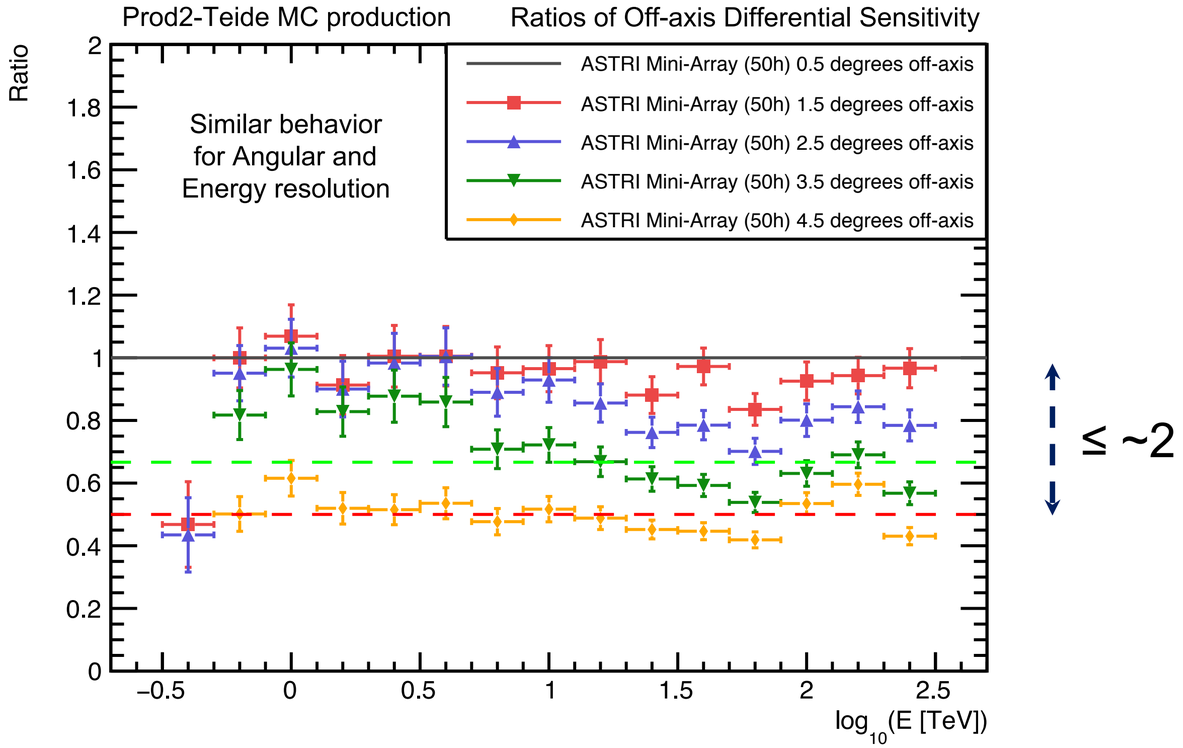


ASTRI Mini-Array – Key Performance Features

Off-axis Performance: almost homogeneous acceptance (within a factor ~2) over ~10° FoV

➔ *important for simultaneous multi-target observations / extended sources / large surveys of the sky / enhanced chance for serendipitous discoveries*





ASTRI Mini-Array – Key Performance Features

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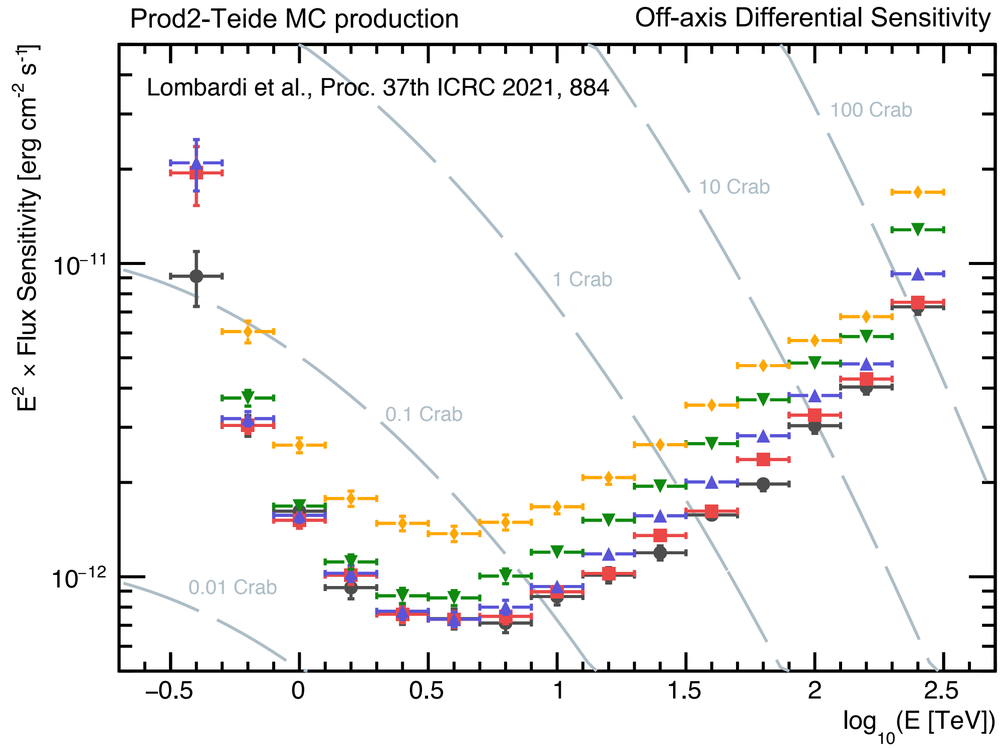
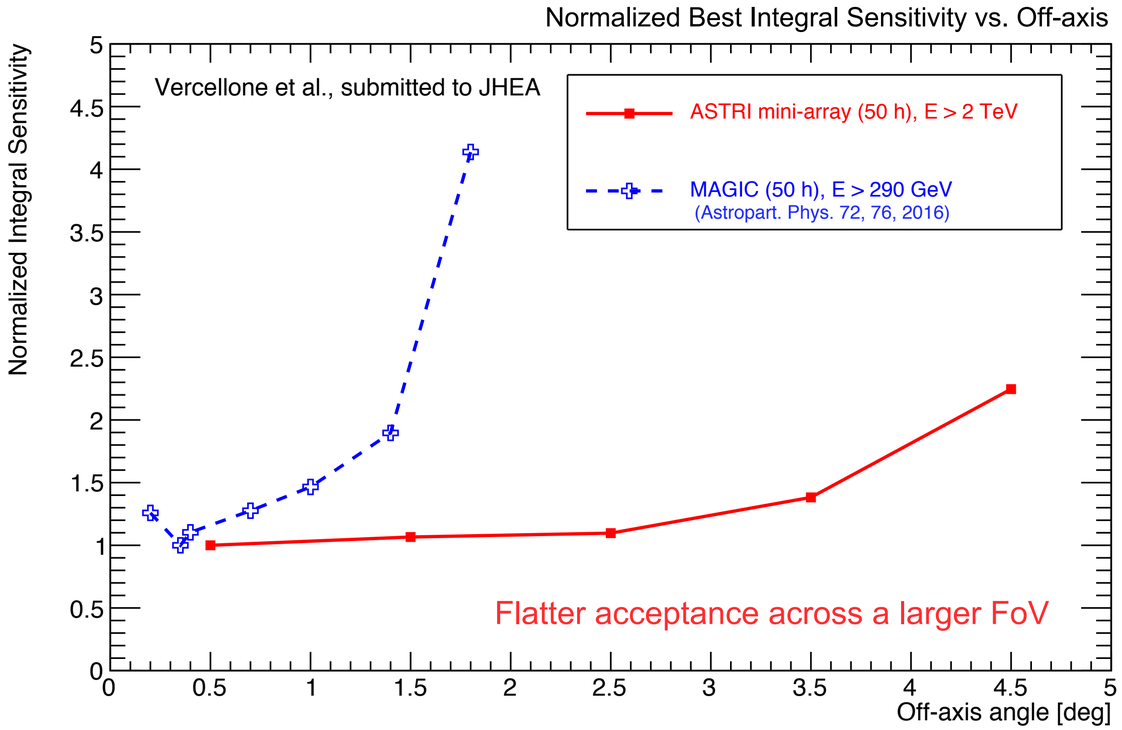
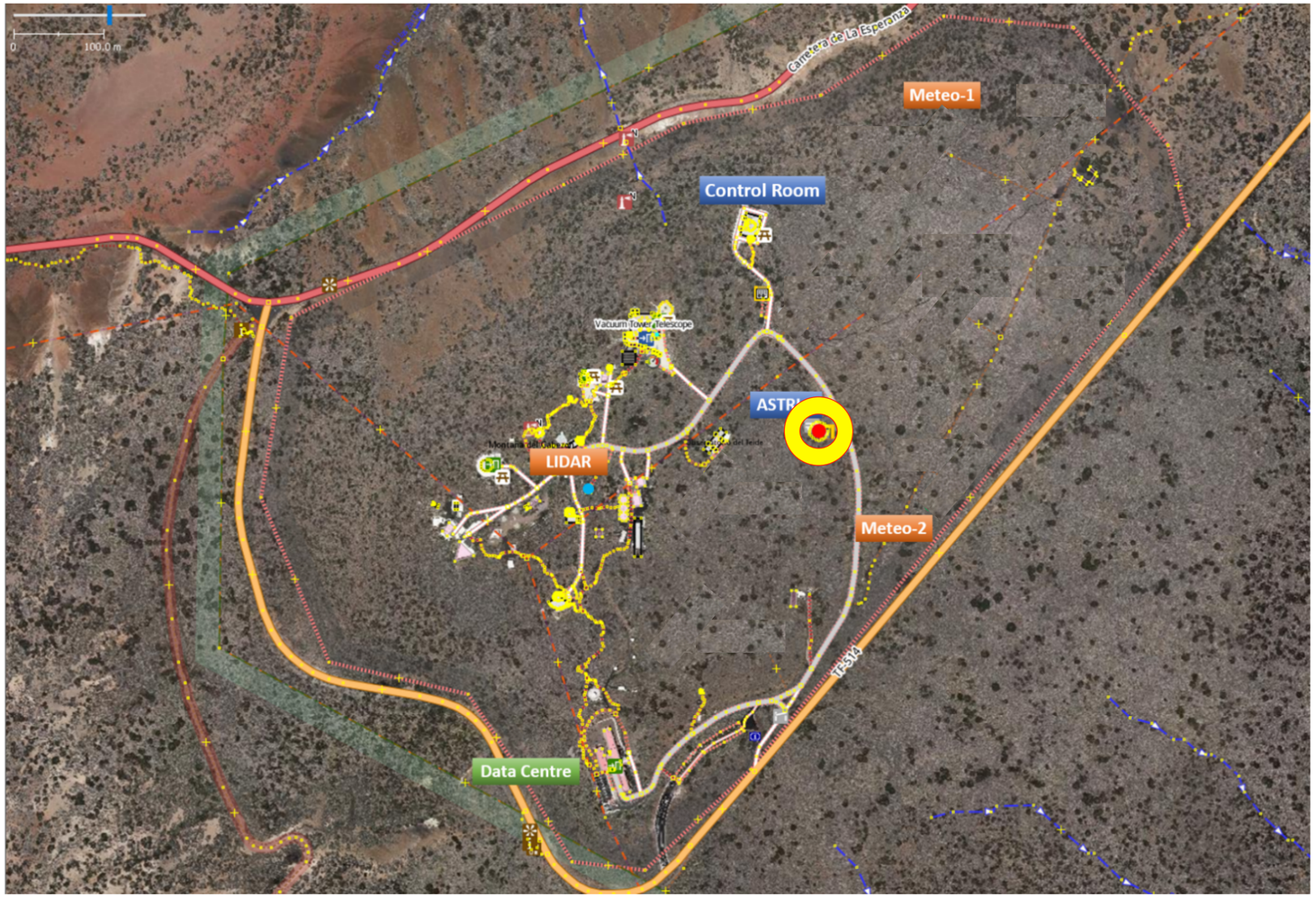




ASTRI Mini-Array – Phase 1.5



TELID	TELX [m]	TELY [m]	TELZ [m]
ASTRI-1	-77.590	-99.710	26.000

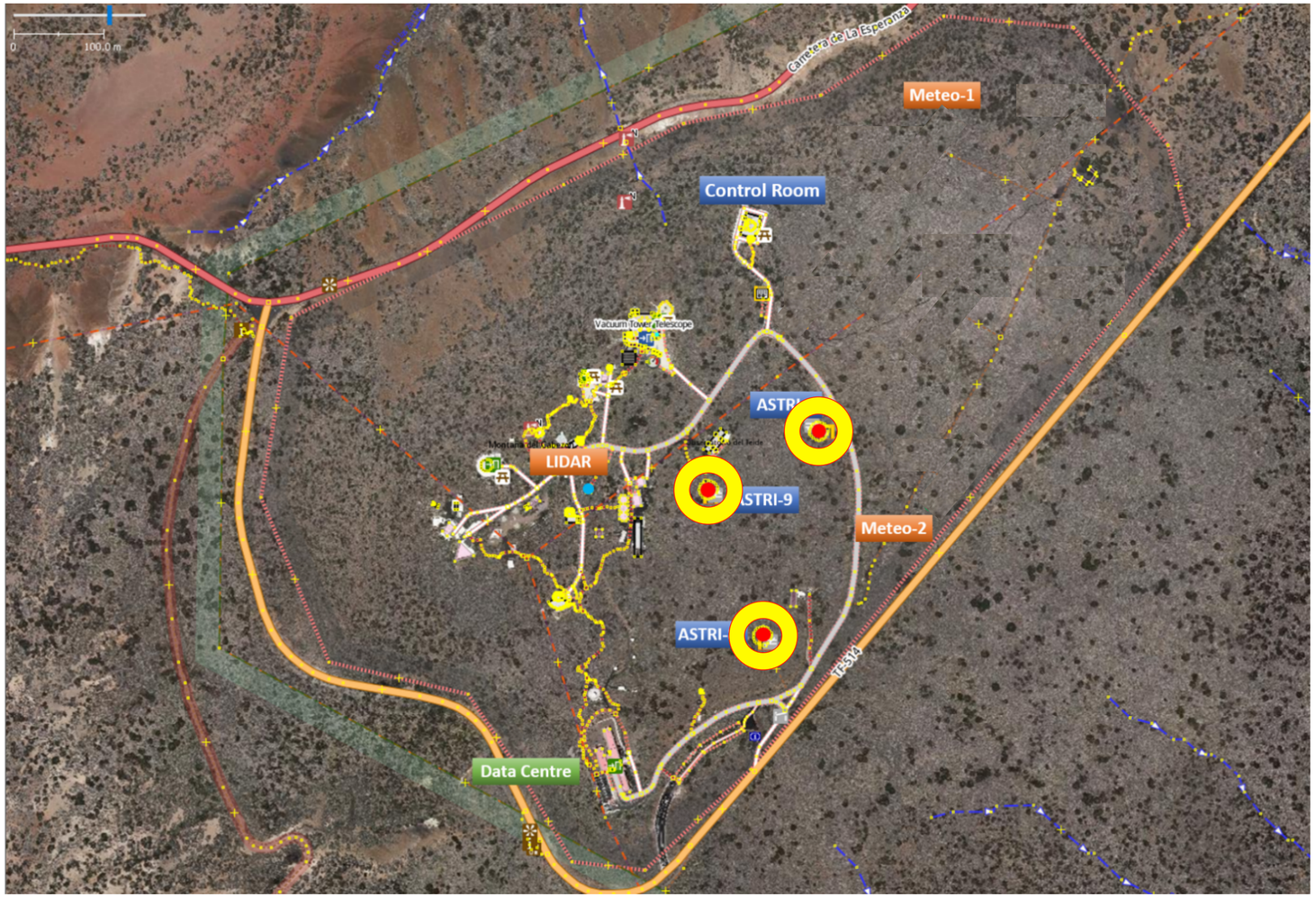
2D intertelescope distances

Tel	ASTRI-1
ASTRI-1	0.000

Phase 1.5 site implementation
(ASTRI-INAF-PLA-2000-004)

ASTRI-1

ASTRI Mini-Array – Phase 2



TELID	TELX [m]	TELY [m]	TELZ [m]
ASTRI-1	-77.590	-99.710	26.000
ASTRI-8	-149.800	-291.800	43.150
ASTRI-9	-221.730	-128.640	26.000

2D intertelescope distances

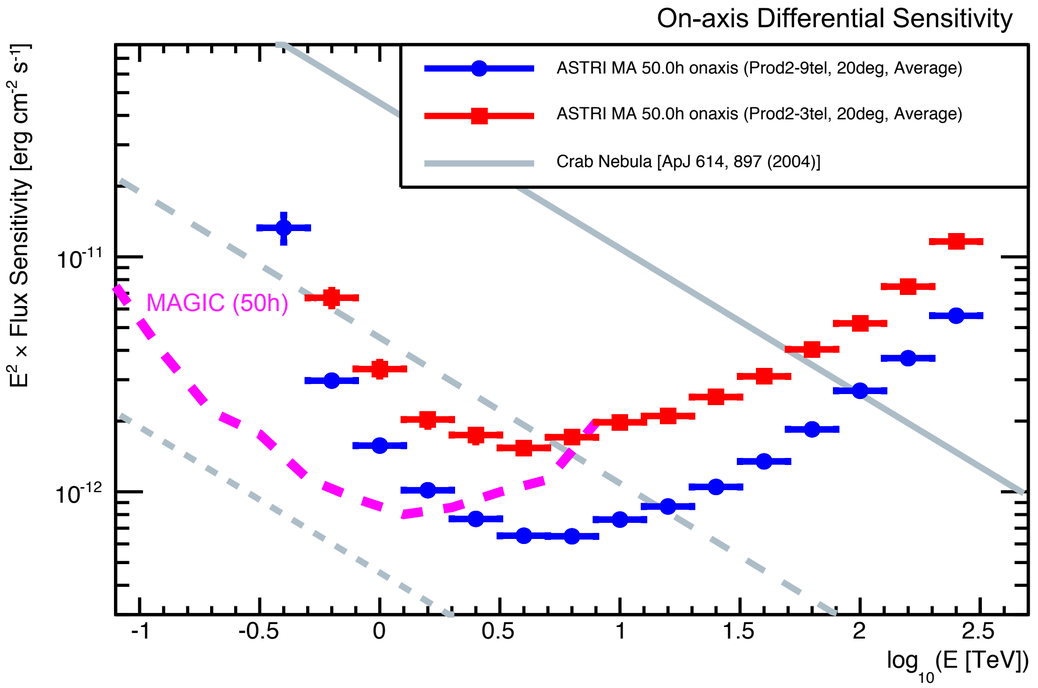
Tel	ASTRI-1	ASTRI-8	ASTRI-9
ASTRI-1	0.000	205.214	147.015
ASTRI-8	205.214	0.000	178.312
ASTRI-9	147.015	178.312	0.000

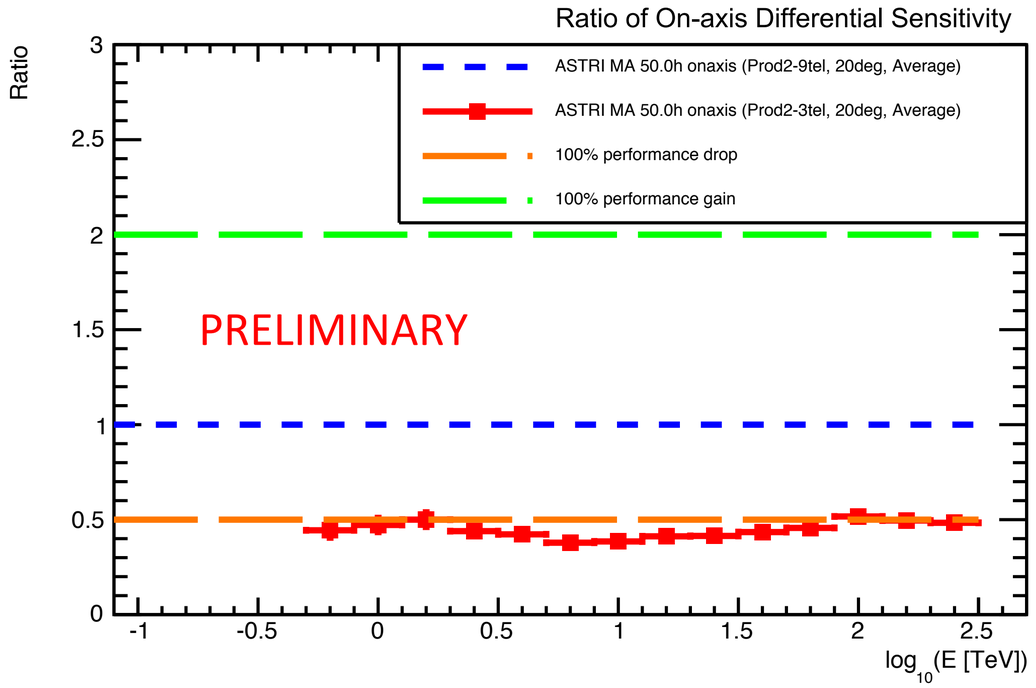
Phase 2 site implementation
(ASTRI-INAF-PLA-2000-004)

ASTRI-1
ASTRI-8
ASTRI-9

ASTRI Mini-Array – Phase 2 performance

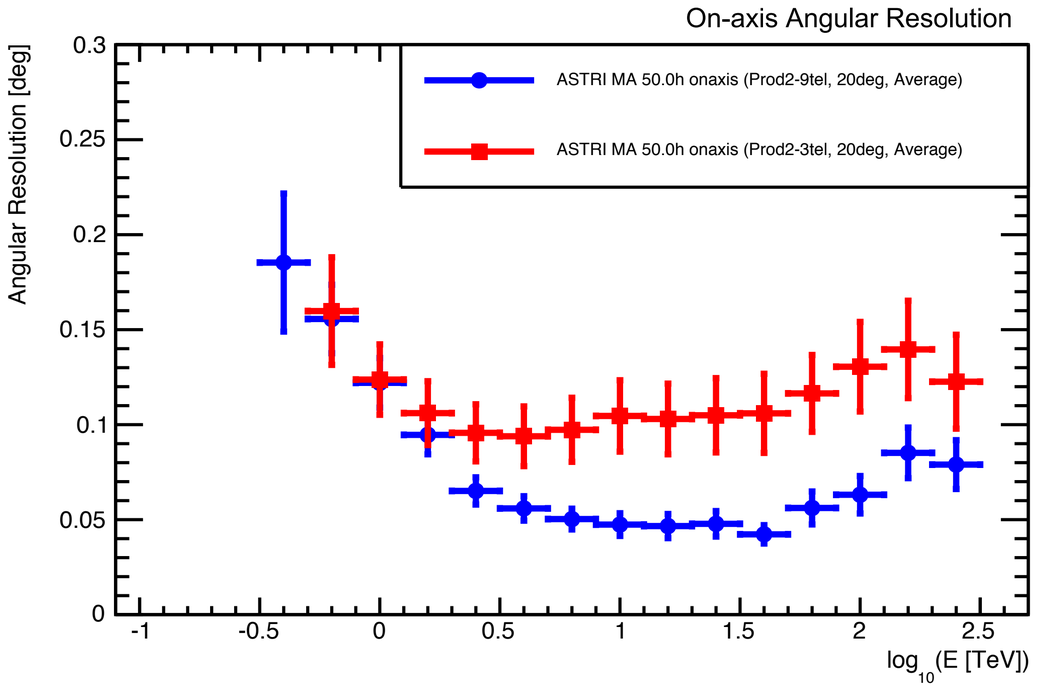
- Full Array (9 telescopes)
- Phase 2 (3 telescopes)

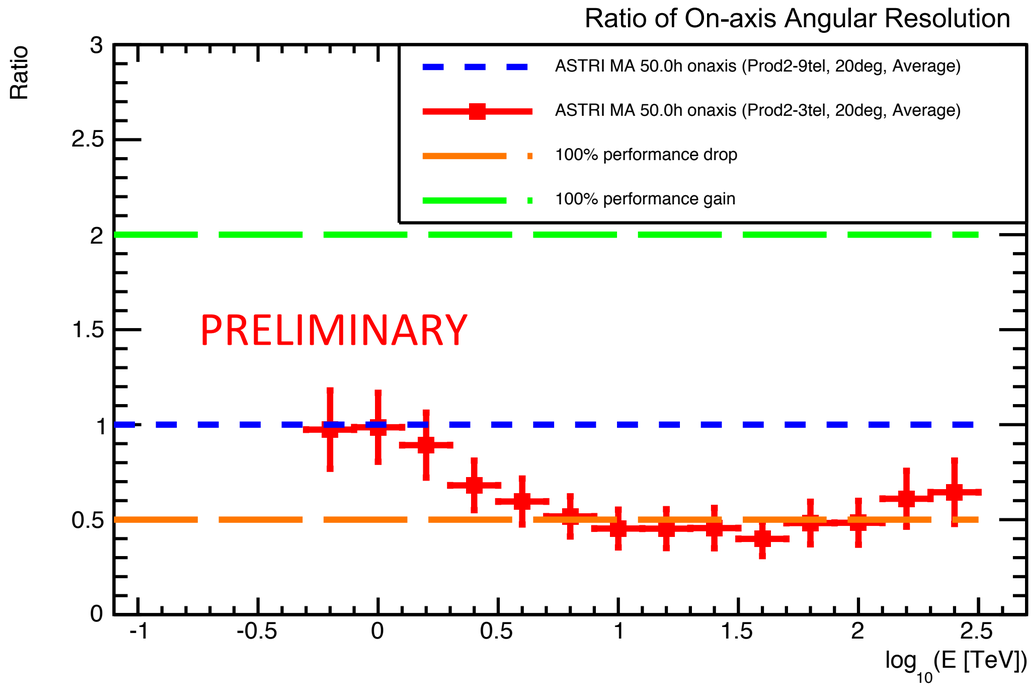




ASTRI Mini-Array – Phase 2 performance

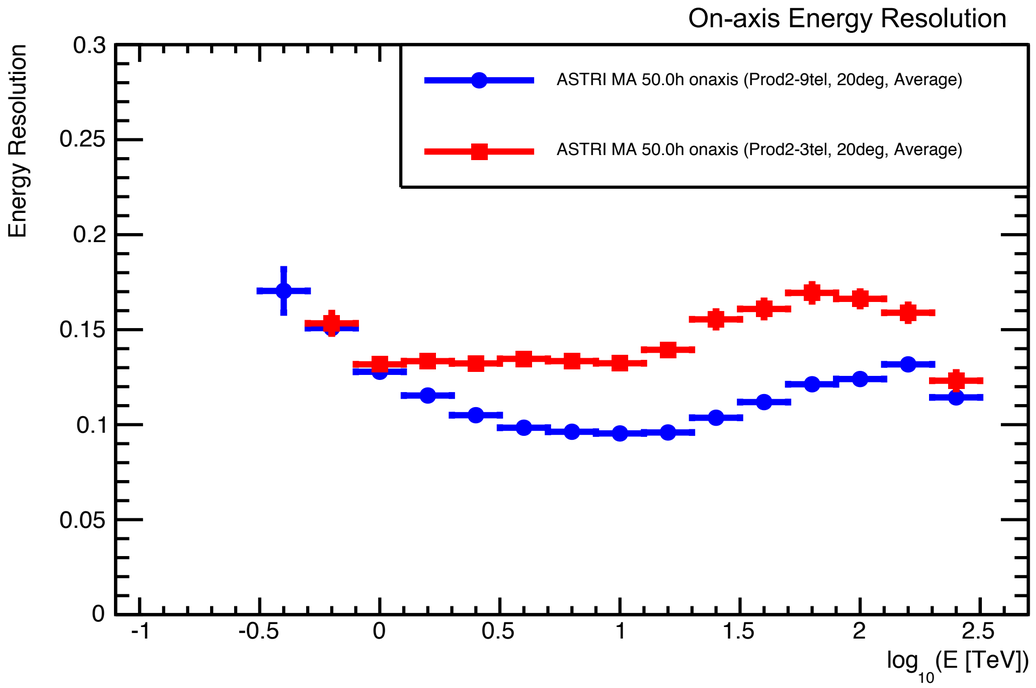
- Full Array (9 telescopes)
- Phase 2 (3 telescopes)

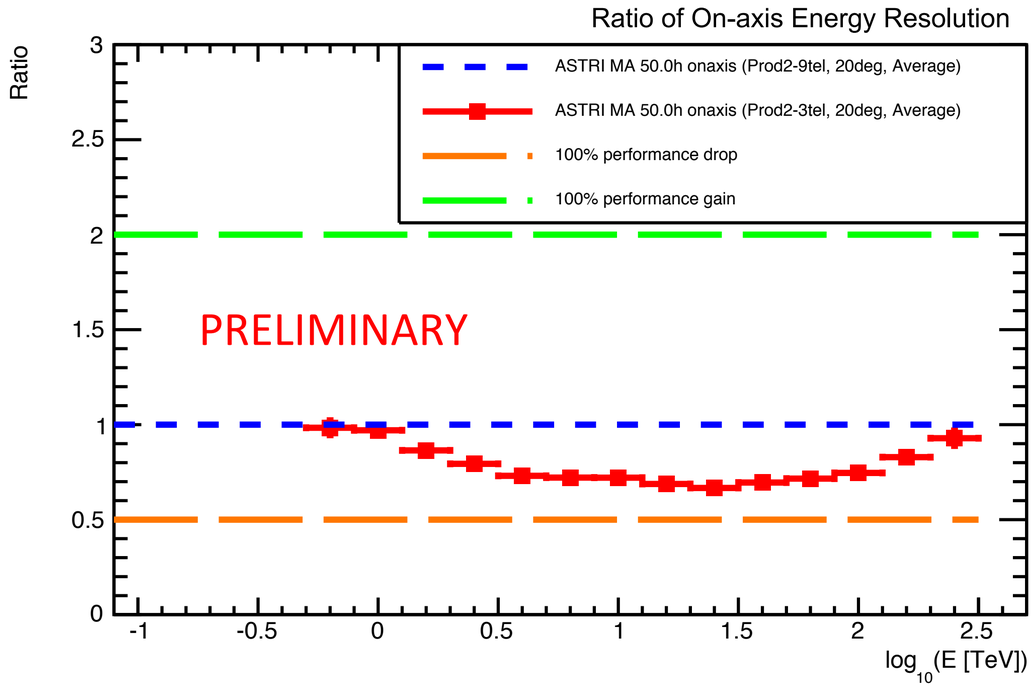




ASTRI Mini-Array – Phase 2 performance

- Full Array (9 telescopes)
- Phase 2 (3 telescopes)





ASTRI Mini-Array – Current MC Simulation activities

- Massive Monte Carlo production at High Zenith Angles (ZA):
  - ZA = 60 deg
  - 4 Azimuth: North, South, East, West
  - Realistic NSB (in dark condition)
  - **Assessing the ASTRI Mini-Array performance at high zenith angles**
  - Scientific use cases: Galactic Center, …

“Prod2_Teide_60deg” (ongoing)

- Monte Carlo production at Low ZA with different NSB levels:
  - From Prod2_Teide CORSIKA outputs
  - ZA = 20 deg
  - 2 Azimuth: North, South
  - Realistic NSB at different Moonlight levels
  - **Assessing the ASTRI Mini-Array performance under Moonlight conditions**
  - Evaluating the maximum duty cycle achievable by the system

“Prod2_Teide_NSB” (preliminary phase)

ASTRI Mini-Array – Current MC Simulation activities

- Massive Monte Carlo production at Serra La Nave (ASTRI-Horn telescope):
  - 10 deg < ZA < 40 deg
  - Continuum Azimuth distribution
  - Realistic NSB (in dark condition)
  - Revised atmospheric profile and geomagnetic field model
  - **Validation of the ASTRI (single-telescope) simulation chain**

“Prod2_SLN”
(preliminary phase)

- Massive Monte Carlo production at Medium Zenith Angles (ZA):
  - ZA = 40 deg
  - 4 Azimuth: North, South, East, West
  - Realistic NSB (in dark condition)
  - **Assessing the ASTRI Mini-Array performance at medium zenith angles**
  - Scientific use cases: many …

“Prod2_Teide_40deg”
(planned)

- Noticeable “ancillary” Monte Carlo productions:
  - Monte Carlo production for Illuminator (Calibration System WP)
  - Monte Carlo production for Stereo Event Trigger (DPS WP)

“Prod1_ILL” (delivered)
“Prod1_SEB” (planned)

Summary

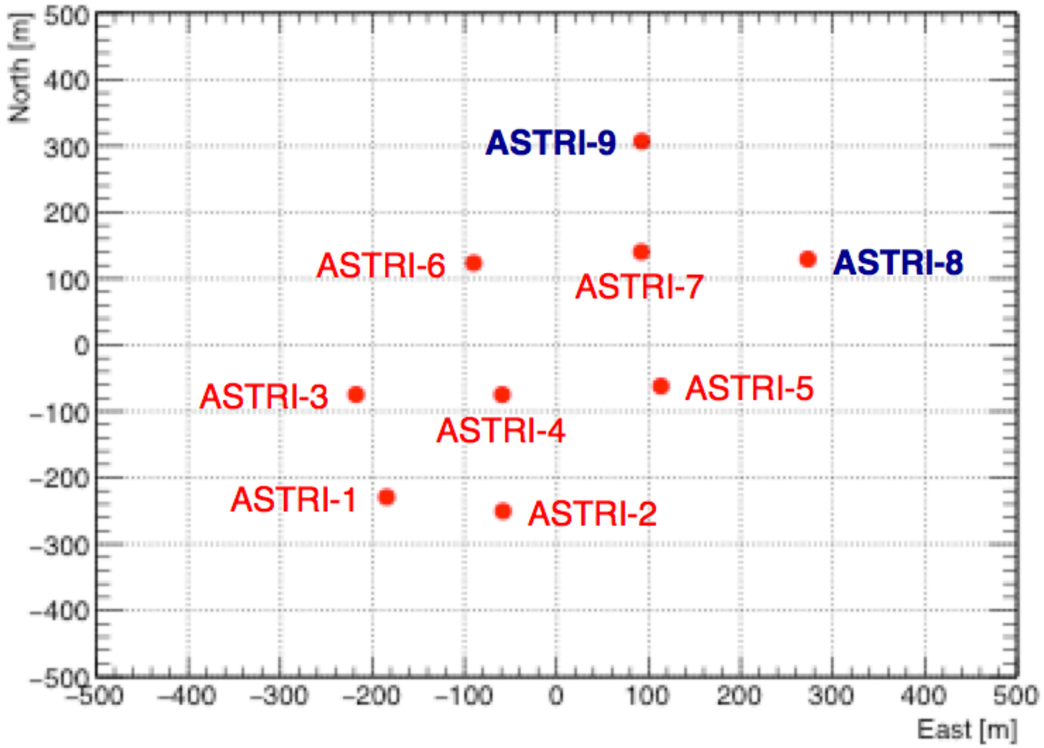
- ASTRI Monte Carlo Simulation chain in place (still being optimized)
  - Revision of CORSIKA and Sim_telarray configurations ongoing
  - Implementation of realistic NSB levels (at different Alt-Az positions) and of HW response to them
  - Check of Geomagnetic field and Atmospheric profile ongoing
- ASTRI Monte Carlo Data reduction and analysis chain in place (still being optimized)
  - Robust standard analysis methods implemented (new reconstruction methods foreseen)
  - Room for improvement of overall analysis performance
- 2 Massive MC productions @Teide available and used to assess key performance features
- Next Massive MC productions to assess performance under higher ZA and Moonlight conditions
- First (single-telescope) validation foreseen (at the moment) with upcoming ASTRI-Horn data
- Intense activities ongoing in both MC Simulations and Data Processing WGs
- Detailed working plan to achieve an efficient data reduction and analysis of first real data taken @Teide (in Phase 1.5 & 2) under discussion

Backup slides

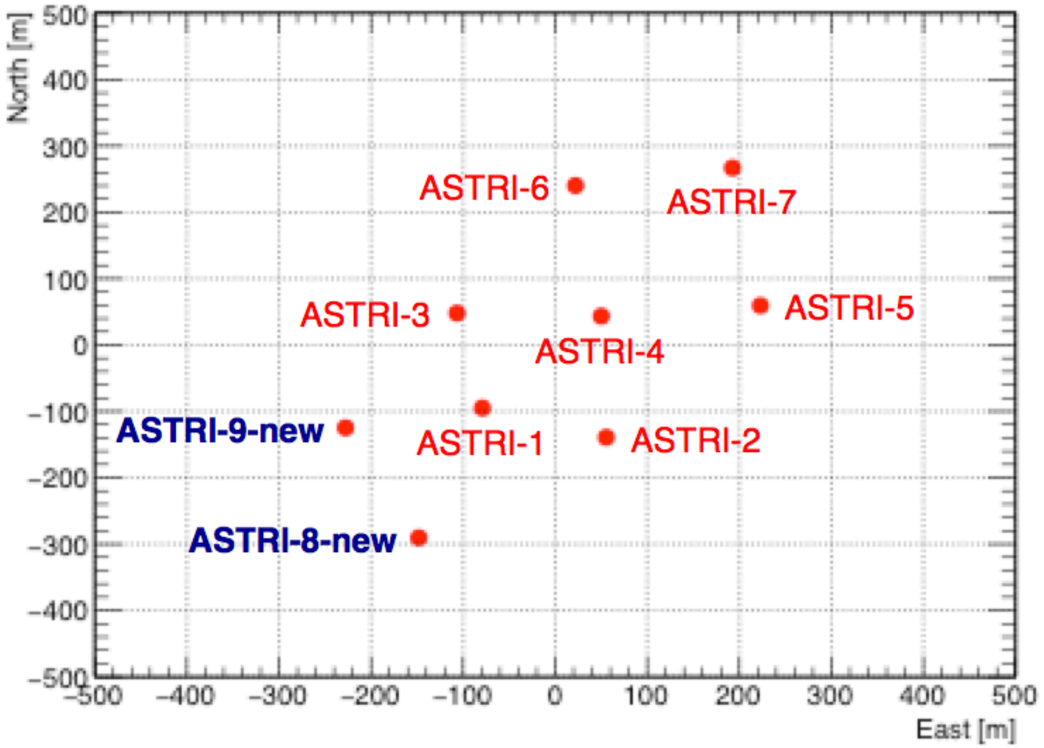
Prod1 vs. Prod2

Mini-Array

Prod1-Teide

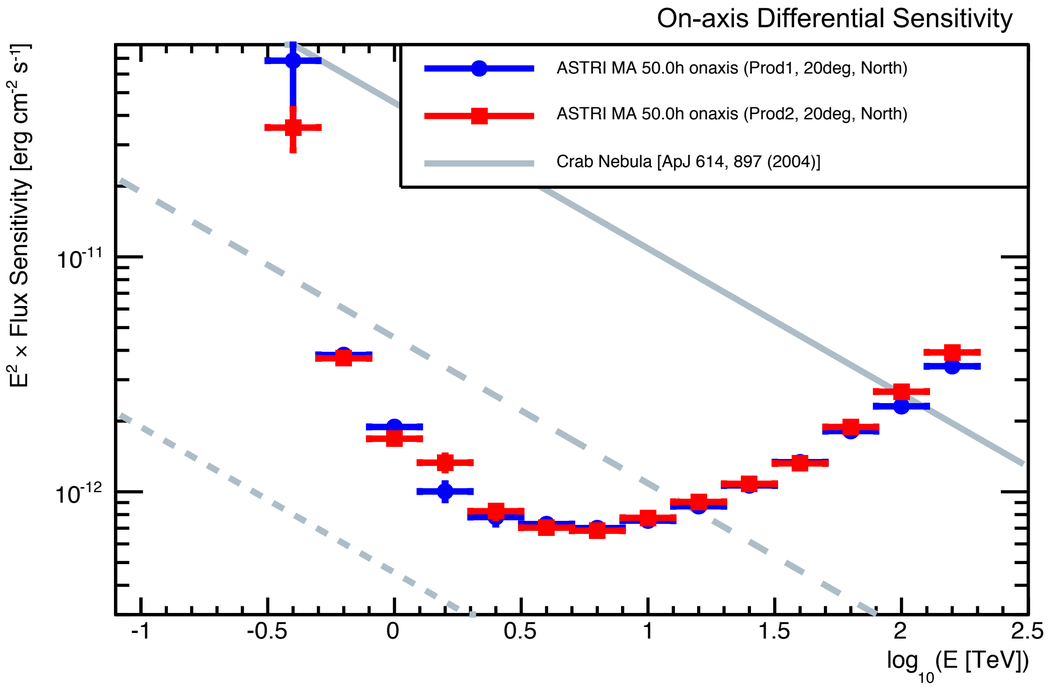


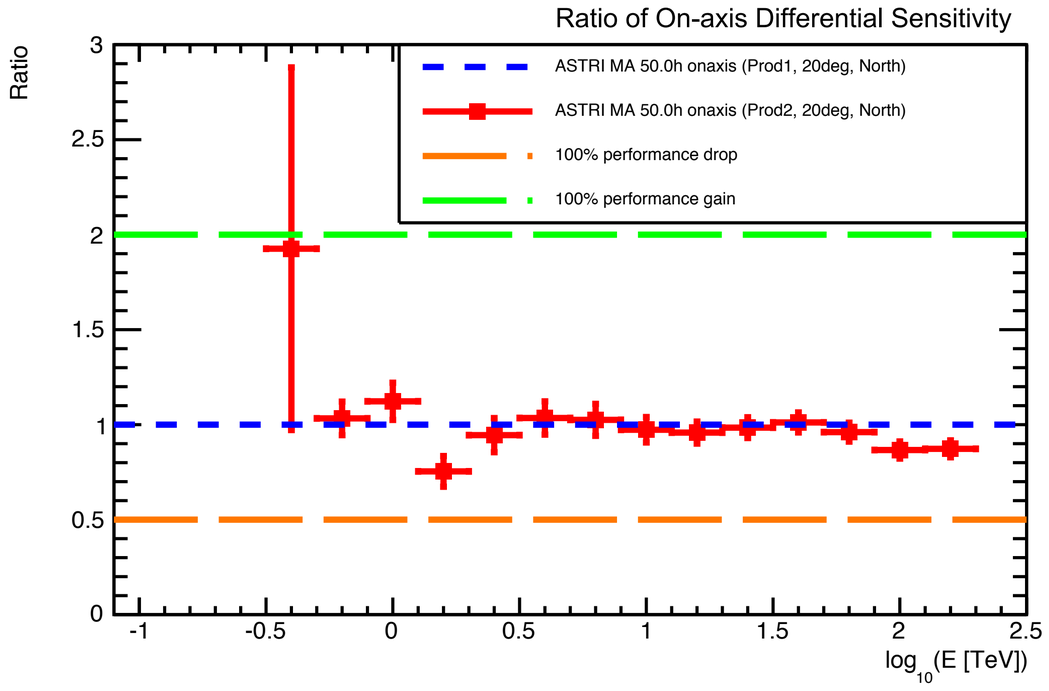
Prod2-Teide



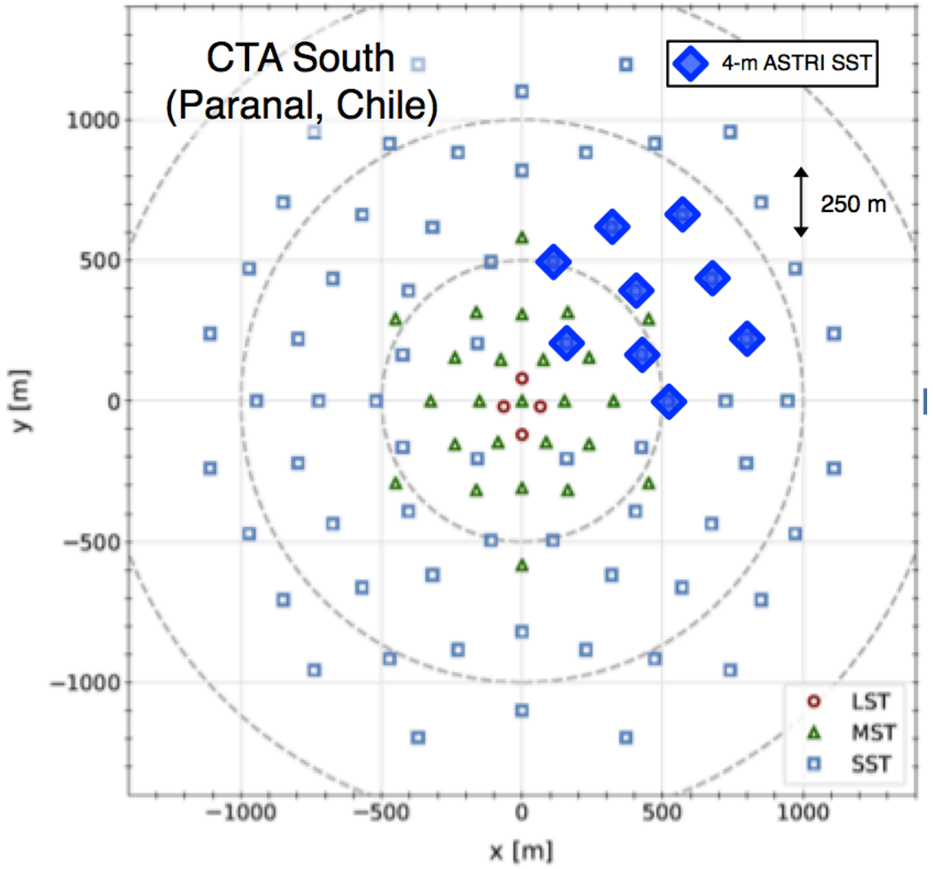
Prod1 vs. Prod2

- Full Array (Prod1-Teide)
- Full Array (Prod2-Teide)

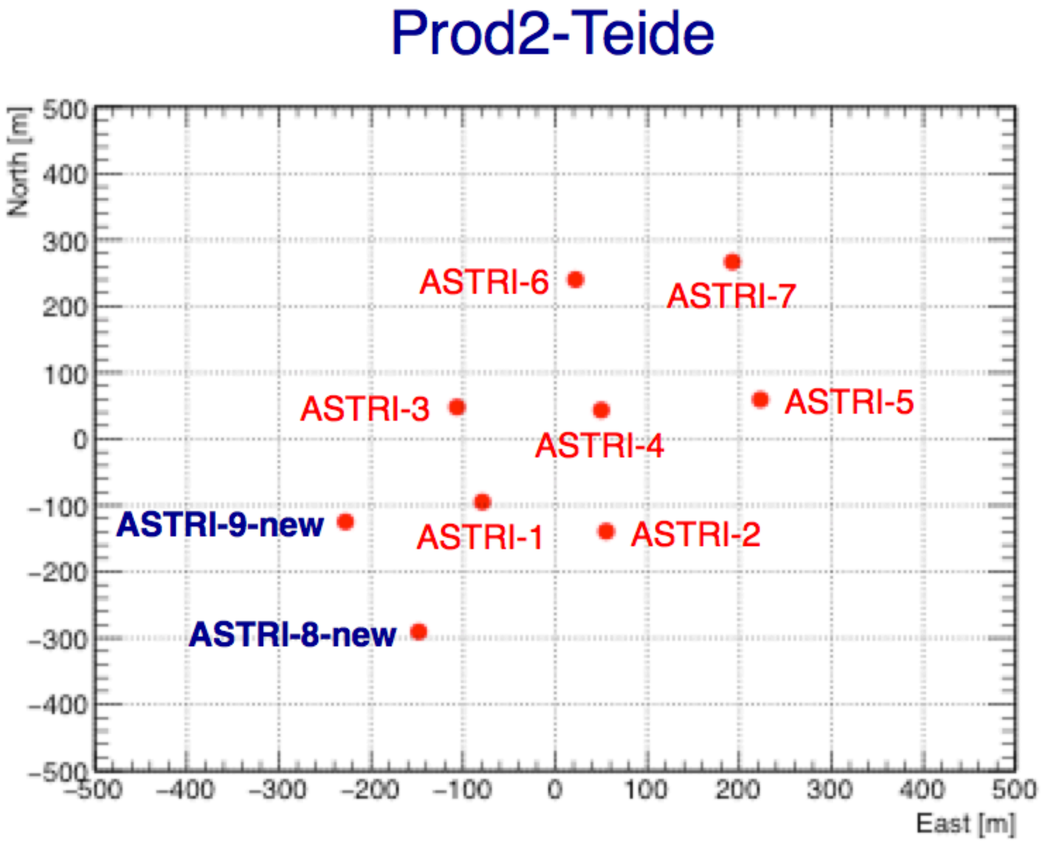




Paranal vs. Teide

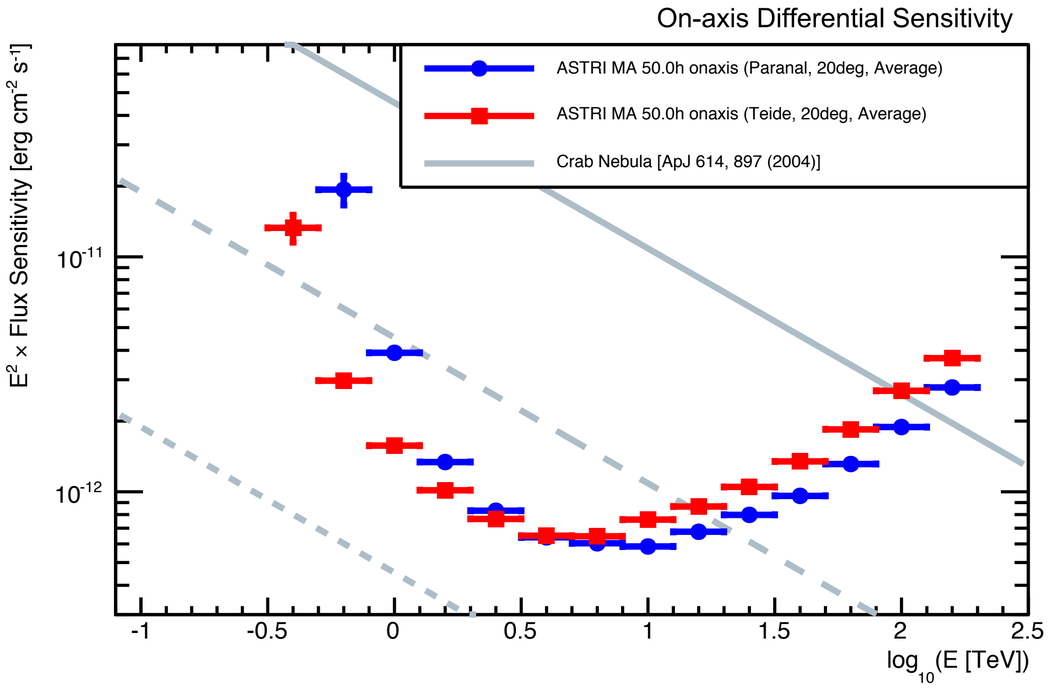


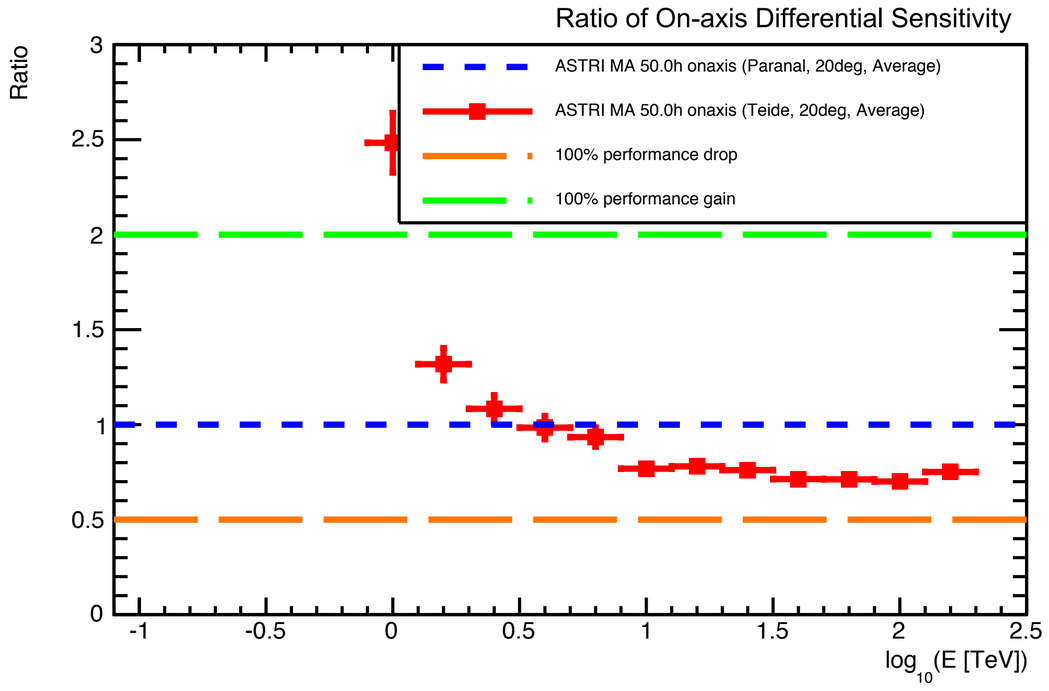
Acharya et al., the CTA Consortium, Astropart. Phys., 111, 35 (2019)



Paranal vs. Teide

- Full Array (@Paranal)
- Full Array (@Teide)





Data reduction and analysis consistency check

- Full Array (Prod1-Teide, `astripipe`)
- Full Array (Prod1-Teide, `eventdisplay`)