Overview on ASTRI activities in Rome

S. Lombardi et al. – INAF-OAR and ASI-SSDC
for the ASTRI Project

VHE Rome meeting – 10/05/2023

ASTRI Rome group

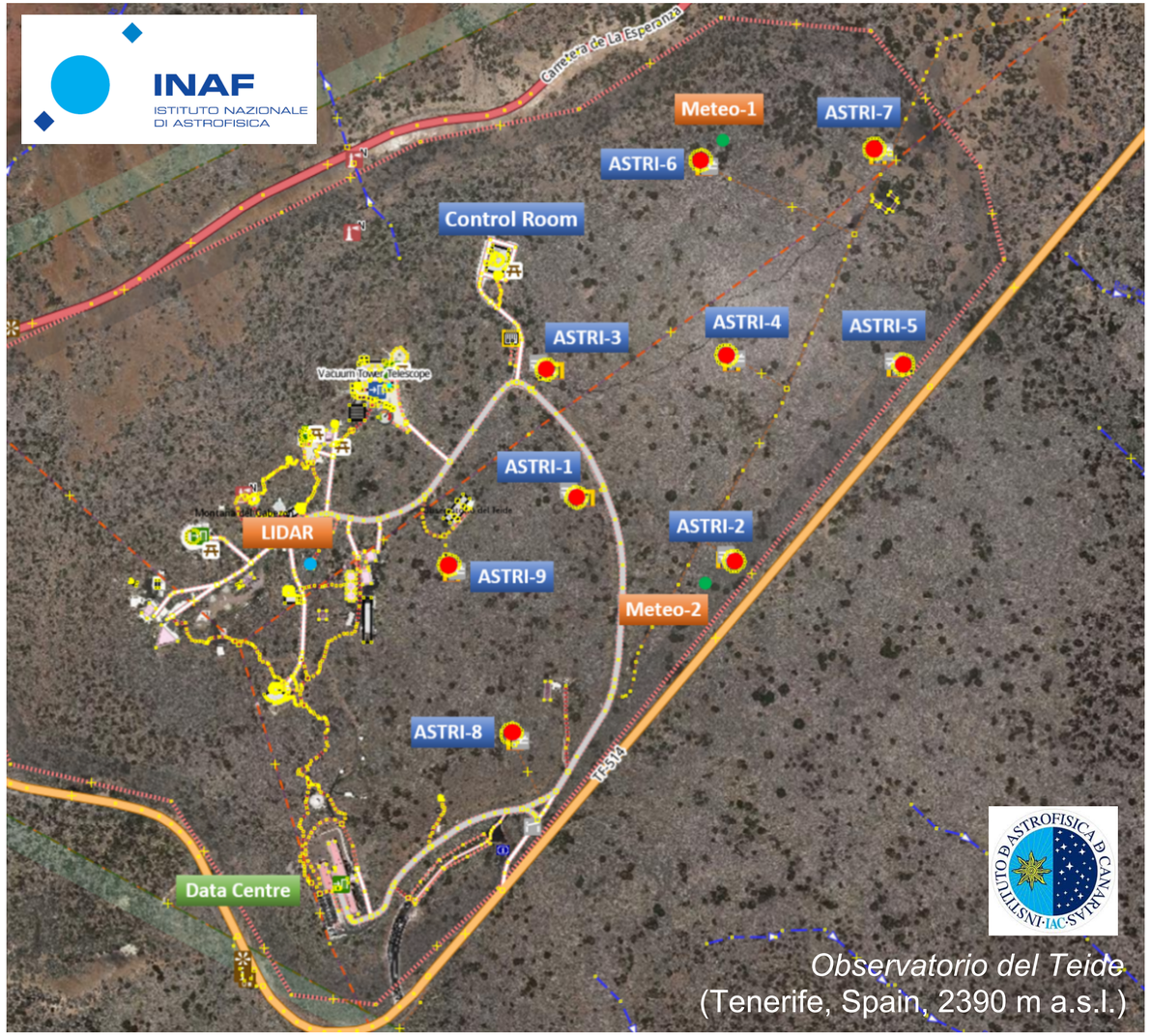
Lucio Angelo Antonelli, Ciro Bigongiari, Martina Cardillo, Alessandro Carosi, Elena Fedorova, Federico Fiordoliva, Stefano Gallozzi, Alessandra Lamastra, Saverio Lombardi, Fabrizio Lucarelli, Michele Mastropietro, Pietro Oliva, Francesco Gabriele Saturni, Antonio Stamerra, Antonio Tutone, Francesco Visconti, Georgios Zacharis

Both technical and scientific activities carried out!

In-depth and long-term experience in Cherenkov Telescopes

The ASTRI Mini-Array @ Teide Observatory

- **9 improved ASTRI-Horn-like telescopes**
- **Under construction** at the *Observatorio del Teide* (Tenerife, Spain, 2390 m a.s.l.), in collaboration with *Instituto Astrofísico de Canarias* (IAC)
- **First 3 operating telescopes by spring 2024**; Full array completion within a few years
- **Being developed in all its aspects**, from design/ implementation of all HW/SW components to dissemination of final scientific products
- INAF – IAC hosting agreement (**~4+4 years**)
- Unprecedented performance and wide FoV for observations at **TeV/multi-TeV energy scale**
- **Important synergies** with other Northern ground-based gamma-ray facilities (LHAASO, HAWC, VERITAS, MAGIC, LSTs, CTAO-N)



Observatorio del Teide
(Tenerife, Spain, 2390 m a.s.l.)

The ASTRI Mini-Array Science Operations

- **First 3/4 years ➔ Core Science:** **Vercellone, S. et al., JHEAP 35, 1 (2022)**
  - Array operated as an experiment (not as an observatory)
  - Core Science Program developed by ASTRI Science Team
  - Pillar Topics: Origin of Cosmic Rays and Fundamental Physics
  - Few selected targets / Deep exposures (~200 hr)
  - Science beyond VHE astronomy ➔ Stellar Intensity Interferometry
  - Possibility of MoUs with other γ-ray facilities for joint observations

- **Afterwards ➔ Observatory Science:** **D'aì, A. et al., JHEAP 35, 139 (2022)** **Saturni, F. G. et al., JHEAP 35, 91 (2022)**
  - Observing proposals from a wider scientific community
  - Broader scientific cases, with main focus on the multi-TeV domain:
    - Galactic sources: wide FoV ➔ multi-target fields
    - Extragalactic sources: survey of a few promising targets at > ~10 TeV
    - Fundamental physics: studies on LIV, EBL, Axion-Like Particles, …
    - Direct Measurement of Cosmic Rays
    - Time Domain and Multimessenger Astrophysics

Galactic targets:
- SNRs / PeVatrons / SNRs interacting with MCs
- PWNe / TeV Halos
- Gamma-ray binaries

Extragalactic targets:
- Extreme BL Lacs
- Radio galaxies
- Starburst galaxies

Fundamental physics:
- Lorentz invariance violation / Axion-like particles / Hadron beams in AGN jets
- EBL
- Dark Matter

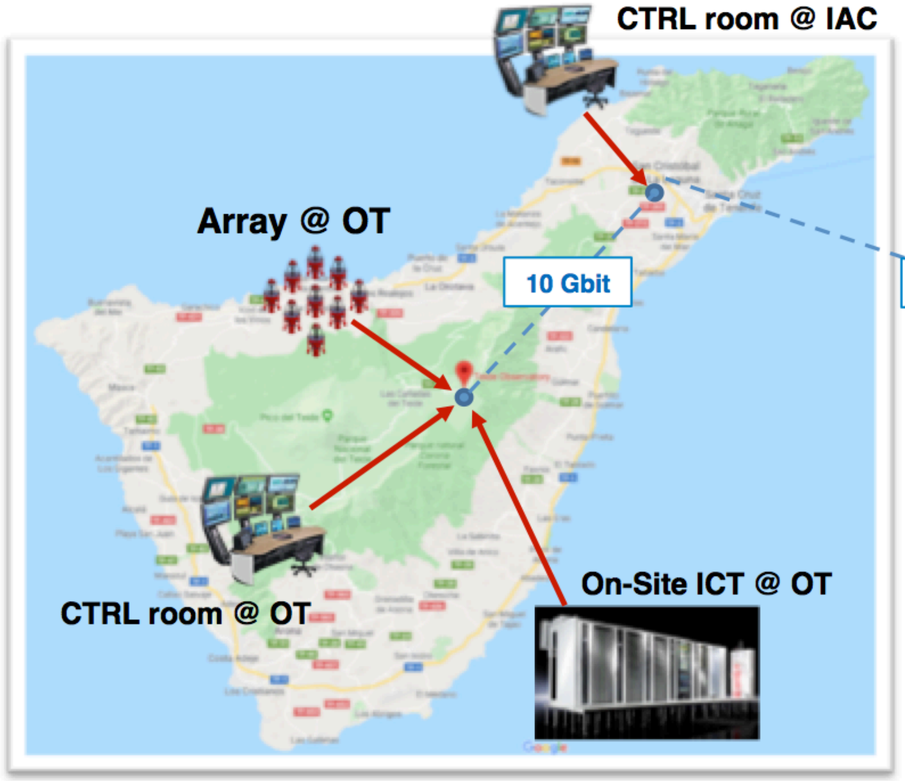
The ASTRI Mini-Array Operation Sites

The ASTRI Mini-Array at Tenerife:

- Telescope Array & auxiliaries (*Observatorio del Teide* - OT)
- Local Control Room @ THEMIS building (OT)
- On-site Data Centre @ IAC Teide Residencia (OT)
- Array Operation Center @IACTEC in La Laguna

The ASTRI Mini-Array in Italy:

- Data Center @INAF in Rome
- Remote Array Operation Centers (any INAF Institute involved)

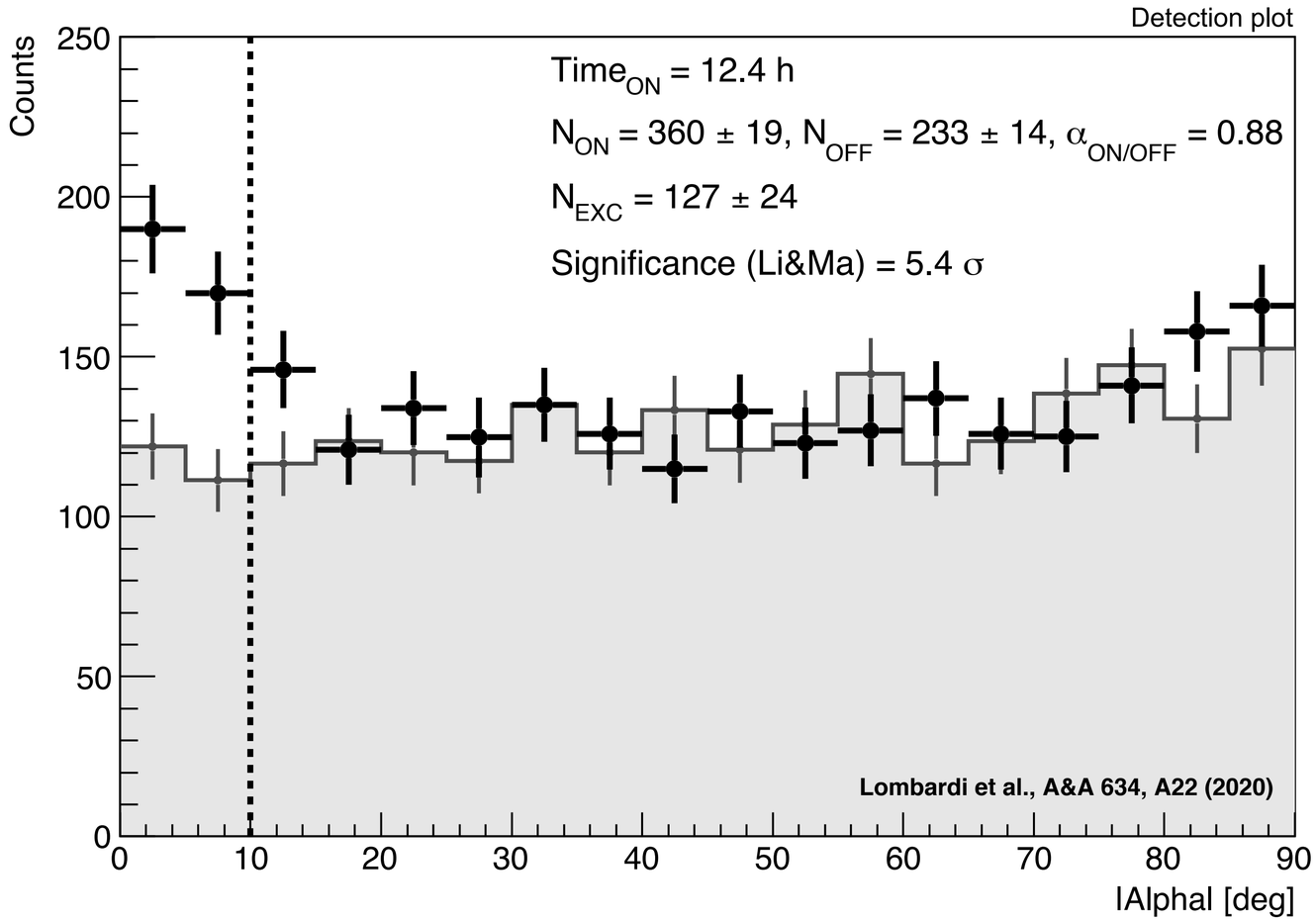


Main ASTRI activities in Rome

- **ASTRI Mini-Array:**
  - Software System (management)
  - Data Processing System (responsible)
  - Simulation System (responsible)
  - Archive System (responsible)
  - Offsite ICT – ASTRI Data Center in Rome (responsible)
  - Science Support System (responsible)
  - Transient Handler and Science with ASTRI Mini-Array (responsible)
  - Galactic and Extragalactic Science with ASTRI Mini-Array (relevant contributors)
  - ASTRI Speaker's and Publication Office (ASPO) (management)

(+ main activities related to the ASTRI-Horn telescope on Mt. Etna)

Main achievements, so far… (I)

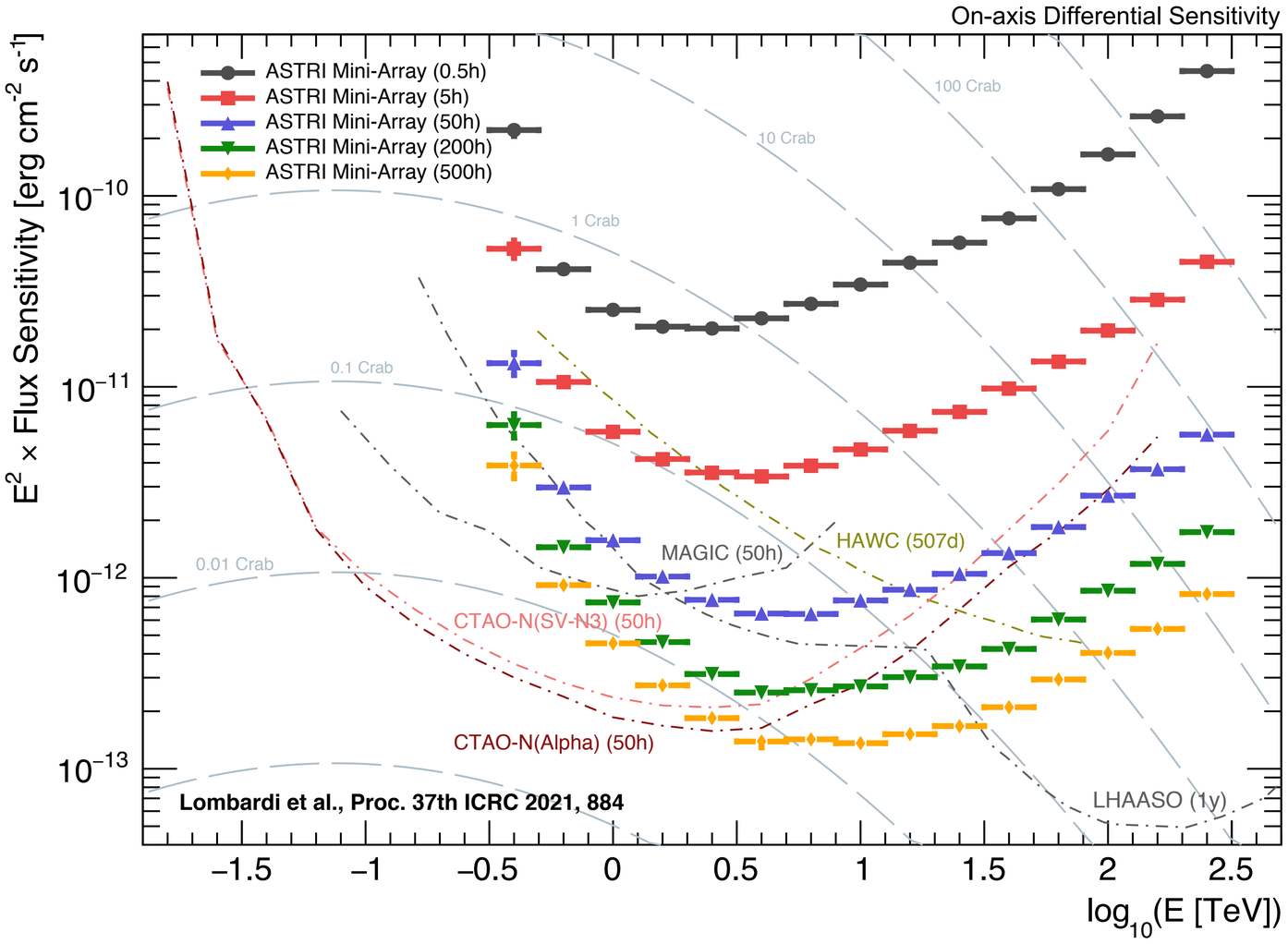


ASTRI-Horn Crab Nebula detection:

- Real data taken with ASTRI-Horn (December 2018)
- Analysis using `A-SciSoft` software package (single-telescope pipeline)
- First detection of a gamma-ray source with a Cherenkov telescope in dual-mirror Schwarzschild-Couder configuration

➔ *This achievement has represented an important step towards the validation of the dual-mirror optical design for ground-based gamma-ray astronomy applications*

Main achievements, so far… (II)



ASTRI Mini-Array performance and IRFs:

- Monte Carlo data from ASTRI-MA-Prod2_20deg (2021)
- Analysis using `A-SciSoft` software package (end-to-end array MC data pipeline)
- Full assessment of ASTRI Mini-Array performance and generation of IRFs for scientific studies: https://doi.org/10.5281/zenodo.6827882

➔ *The achieved results have demonstrated the significant ASTRI Mini-Array capabilities for observations at TeV / multi-TeV energy scale, in synergy with present- and next-generation gamma-ray observatories in the Northern Hemisphere*

Main achievements, so far… (III)

Journal of High Energy Astrophysics
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The ASTRI Mini-Array of Cherenkov telescopes at the Observatorio del Teide

S. Scuderi [a] ✉, A. Giuliani [a], G. Pareschi [b], G. Tosti [c], O. Catalano [f], E. Amato [p], L.A. Antonelli [h], J. Becerra Gonzàles [m], G. Bellassai [d], C. Bigongiari [h, u], B. Biondo [f], M. Böttcher [n], G. Bonanno [d], G. Bonnoli [b], P. Bruno [d], A. Bulgarelli [e], R. Canestrari [f], M. Capalbi [f] … R. Zanmar Sanchez [d]

Journal of High Energy Astrophysics
Volume 35, August 2022, Pages 1-42

ASTRI Mini-Array core science at the *Observatorio del Teide*

S. Vercellone [a] ✉, C. Bigongiari [b], A. Burtovoi [c], M. Cardillo [d], O. Catalano [e], A. Franceschini [f], S. Lombardi [b, g], L. Nava [a], F. Pintore [e], A. Stamerra [b], F. Tavecchio [a], L. Zampieri [h], R. Alves Batista [i], E. Amato [c, j], L.A. Antonelli [b, g], C. Arcaro [h, k], J. Becerra González [l, m], G. Bonnoli [a] … G. Pareschi [a]

Journal of High Energy Astrophysics
Volume 35, August 2022, Pages 91-111

Extragalactic observatory science with the ASTRI mini-array at the *Observatorio del Teide*

F.G. Saturni [a, b] ✉, C.H.E. Arcaro [c, d, e, f], B. Balmaverde [g], J. Becerra González [h, i], A. Caccianiga [j], M. Capalbi [k], A. Lamastra [a], S. Lombardi [a, b], F. Lucarelli [a, b], R. Alves Batista [l], L.A. Antonelli [a, b], E.M. de Gouveia Dal Pino [m], R. Della Ceca [j], J.G. Green [a, b, n], A. Pagliaro [k], C. Righi [o], F. Tavecchio [o], S. Vercellone [o] … G. Pareschi [o]

Journal of High Energy Astrophysics
Volume 35, August 2022, Pages 139-175

Galactic observatory science with the ASTRI Mini-Array at the *Observatorio del Teide*

A. D'Aì [a] ✉, E. Amato [b], A. Burtovoi [b], A.A. Compagnino [a], M. Fiori [c], A. Giuliani [d], N. La Palombara [d], A. Paizis [d], G. Piano [e], F.G. Saturni [f, g], A. Tutone [a, h], A. Belfiore [d], M. Cardillo [e], S. Crestan [d], G. Cusumano [a], M. Della Valle [i, j], M. Del Santo [a], A. La Barbera [a] … G. Pareschi [k]

Backup slides

ASTRI: Astrophysics with Italian Replicating Technology Mirrors

ASTRI-Horn Prototype

INAF-led Project funded by Italian Ministry of Research

End-to-end prototype of the 4-m class telescopes in the framework of CTA Observatory; installed and operational on Mount Etna volcano (Sicily, Italy)

First detection of a gamma-ray source (Crab Nebula) above 5σ **with a dual-mirror, Schwarzschild-Couder Chrenkov telescope** (Lombardi et al., 2020)

Dedicated to **Guido Horn D'Arturo**, precursor of the segmented astronomical mirrors technique

Array of 9 ASTRI telescopes

INAF-led Project with international partners: Univ. of Sao Paulo/FPESP (Brazil), North-West Univ. (S. Africa), IAC (Spain), FGG, ASI/SSDC, Univ. of Padova, Perugia and INFN

Being deployed at the *Observatorio del Teide* (Spain) in collaboration with IAC and FGG-INAF.

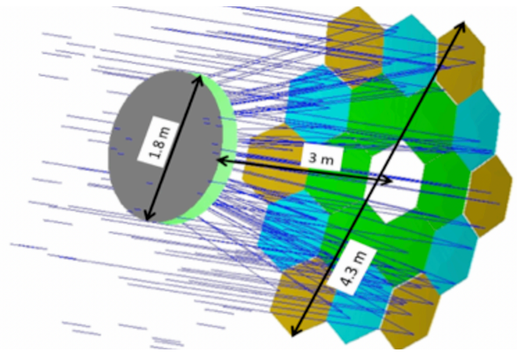
First 4 years → *Core Science*, following 4 → *Observatory Science.* **Science operation → 2025**

The ASTRI-Horn telescope

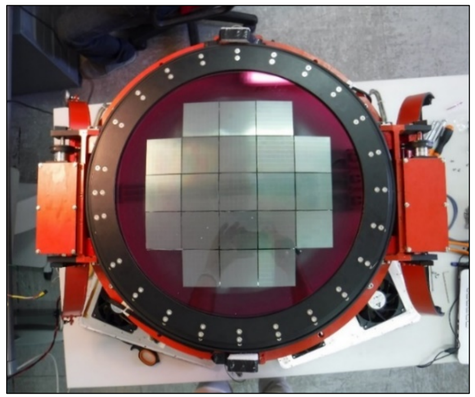
Installed @ INAF Observatory in Serra La Nave (Mt. Etna, Italy, 1740 m a.s.l.)

Dedicated to **Guido Horn D'Arturo**, precursor of the segmented astronomical mirrors technique

- **Technological demonstrator with an end-to-end approach** (HW and SW validation through actual Cherenkov observations)
- **Dual-mirror Schwarzschild-Couder design**:
  - Primary Mirror (M1): ⌀ 4.3 m (18 segments)
  - Secondary Mirror (M2): ⌀ 1.8 m (monolithic)
  - Optimal PSF (≤ 0.19°) across entire FoV
  - Post calibration pointing precision ≤ 7 arcsec
  - Reduced plate scale (37.5 mm/°) ➔ use of SiPMs



- **SiPM Cherenkov camera**:
  - Fast front-end electronics based on CITIROC ASICs
  - 7×7 mm SiPM sensors (Hamamatsu Photonics)
  - 1344 pixels (21 modules of 8×8 pixels)
  - Angular pixel size: 0.19° (≥ optical PSF)
  - Field of View: ~8°



- **Performance**:
  - Energy threshold: ~1 TeV
  - Energy/Angular resolution: ≤ 25% / ≤ 0.15°
  - Sensitivity: 1 Crab @ 5σ in few hours

Main ASTRI activities in Rome

- **ASTRI-Horn prototype:**
  - Observation schedules and data taking
  - Data reduction and analysis of real data
  - Monte Carlo production and validation
  - Data archiving
  - Data exploitation (mainly for validation purposes)
  - …

The Data Processing, Simulation, Archive Systems

- **Data Processing System**

Collection of software components in charge of preparing, calibrating, reducing, and analyzing raw Cherenkov data acquired during the observations up to the generation of high-level science-ready data and automated science products. Also in charge of providing suitable data check and calibration products, as well as performing data reduction of the Stellar Intensity Interferometry Instrument data.

- **Simulation System**

Collection of software components in charge of generating all simulated data needed for the ASTRI Mini-Array Project. Design and development phase: MC simulations used to optimize the telescope positions in the array, to fully characterize the (scientific) performance of the system, and to define and test data analysis methods. Commissioning and operation phase: used to provide auxiliary inputs for real data reconstruction (LUTs) and system response (IRFs).

- **Archive System**

Software (and hardware) service that provides storage and organization for all persistent information (data, data products, and metadata) generated for and by the ASTRI Mini-Array systems and defined by the Mini-Array Data Models. The system plays a central role in the whole observing life-cycle of the array, which goes from observation preparation and execution, to data processing and dissemination of the high-level science-ready data and automated science products to the Science Users.

SPIE Paper 12189-27 (Proc. SPIE2022)

The Data Processing, Simulation, and Archive Systems of the ASTRI Mini-Array Project

S. Lombardi – INAF-OAR and ASI-SSDC

for the ASTRI Project

Fabrizio Lucarelli, Ciro Bigongiari, Stefano Gallozzi, Martina Cardillo, Michele Mastropietro, Francesco Gabriele Saturni, Francesco Visconti, Lucio Angelo Antonelli, Andrea Bulgarelli, Milvia Capalbi, Osvaldo Catalano, Antonio Alessio Compagnino, Vito Conforti, Silvia Crestan, Giancarlo Cusumano, Antonino D'Aì, Stefano Germani, Andrea Giuliani, Simone Iovenitti, Valentina La Parola, Maria Concetta Maccarone, Teresa Mineo, Davide Mollica, Antonio Pagliaro, Nicolò Parmiggiani, Matteo Perri, Fabio Pintore, Salvatore Scuderi, Gino Tosti, Stefano Vercellone, and Luca Zampieri

(DPS Working group)

Data Processing System: main components

- ## Stereo Event Builder (SEB)

Software component that performs the off-line stereo array trigger of the Cherenkov events recorded by the telescopes of the ASTRI Mini-Array. The array trigger acts on information sent by each triggered telescope (like the trigger timestamps and the telescope status) to select Cherenkov shower signatures using stereoscopic information. (See *Germani et al., Paper 12183-66.*)

- ## Cherenkov Data Pipeline (CDP)

Software component that performs data reduction of the Cherenkov events observed by the ASTRI Mini-Array. Main goal: reconstruct the physical characteristics of the astrophysical gamma rays (and background cosmic rays) from the raw Cherenkov data collected by the ASTRI Mini-Array telescopes during the observations of the scientific targets. Usage of the **`A-SciSoft`** *software package.*

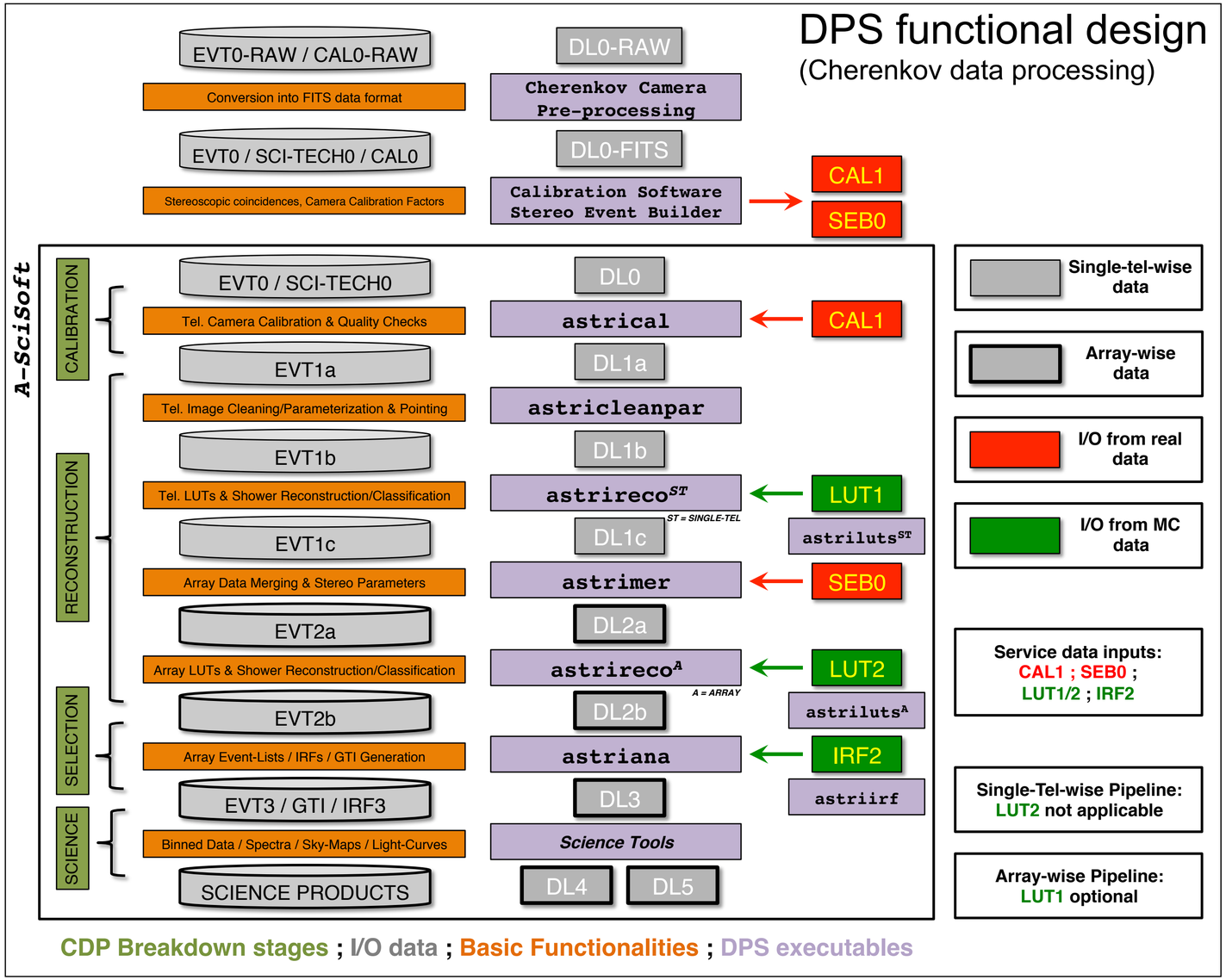
- ## Intensity Interferometry Data Pipeline (IIDP)

In charge of performing data reconstruction and scientific analysis of the Stellar Intensity Interferometry Instrument (SI3).
(See *Zampieri/Rodeghiero et al., Paper 12183-14.*)

- ## Calibration Software

Collection of software tools that reduces and analyzes all the data produced during the calibrations of the system. It provides suitable calibration factors for the calibration of Cherenkov data.

Data Processing System: Cherenkov data flow



- **Cherenkov Camera Pre-Processing:** all Cherenkov raw data converted in FITS data format (adopted as common I/O data format for each DPS subsystem);
- **Calibration Software:** generation of suitable calibration factors for Cherenkov data calibration;
- **Stereo Event Builder:** identification of stereoscopic Cherenkov events induced by the same extensive air shower;
- **Cherenkov Data Pipeline:** end-to-end Cherenkov data reduction (`A-SciSoft` software package) up to high-level science-ready data (DL3) and standard scientific products (DL4/5)
  - Calibration (DL0 ➔ DL1)
  - Reconstruction (DL1 ➔ DL2)
  - Selection (DL2 ➔ DL3)
  - Science* (DL3 ➔ DL4/5)

  *external Science Tools: `Gammapy` and `ctools`

2 end-to-end scientific data processing levels:
- **short-term** pipeline (for scientific quick-look)
- **long-term** pipeline (for consolidated products)

Lombardi et al., SPIE Conference Series 9913, 991315 (2016)
Lombardi et al., SPIE Conference Series 10707, 107070R (2018)

A-SciSoft status

A-SciSoft (v0.5.6)

https://www.ict.inaf.it/gitlab/astri/data-processing/ascisoft

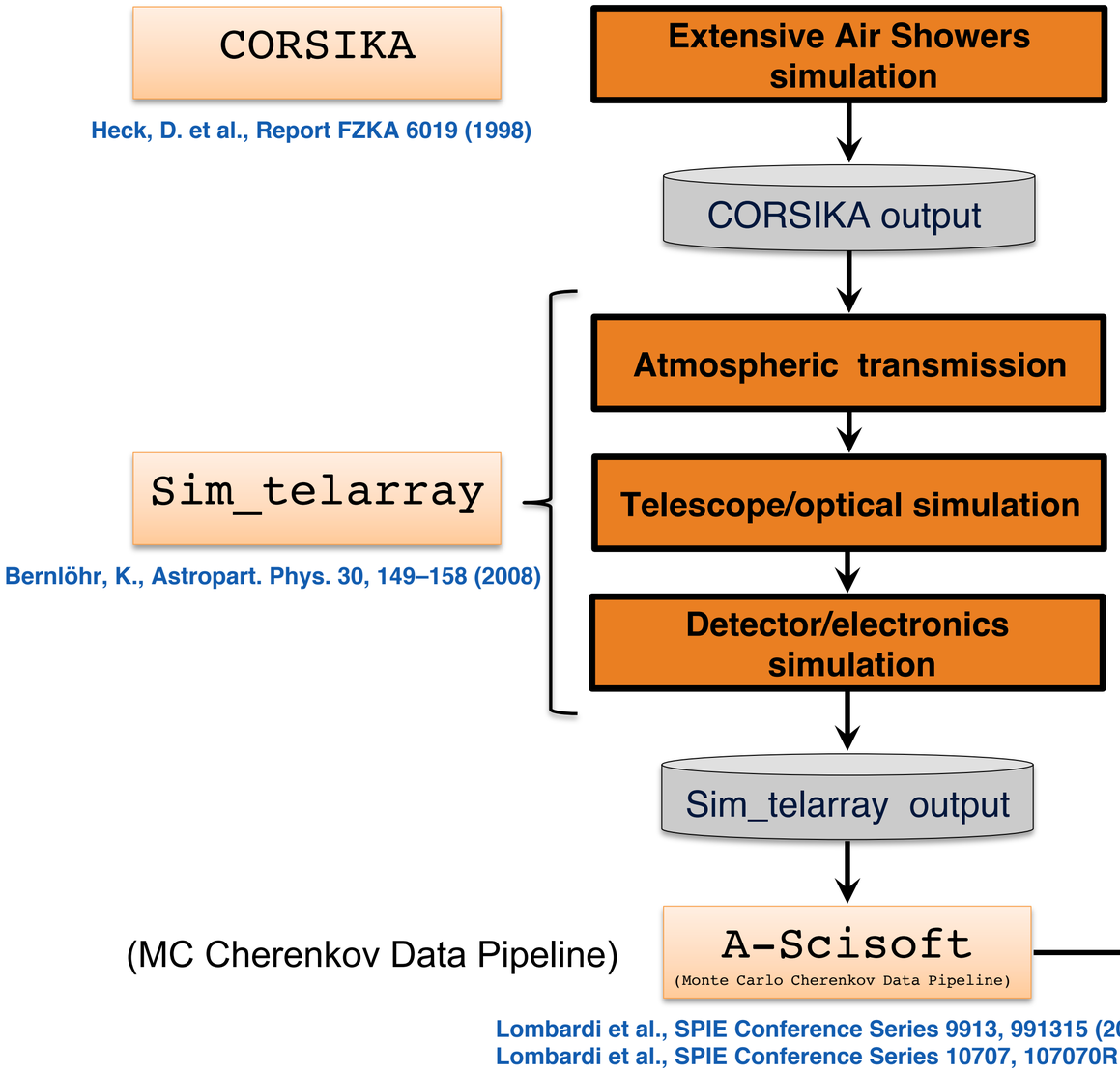
Status:

- Reduction of ASTRI-Horn real data (custom analysis, up to DL1c)
- End-to-end MC pipeline (still, workaround code for IRF3 generation)
- External ad-hoc tools for data quality checks, diagnostics (at different DLs)

Main Applications (so far):

- Detection of the Crab Nebula with ASTRI-Horn (December 2018)
- Data analysis of 2022-2023 ASTRI-Horn data
- Regular MC data reduction and analysis for
  - Mini-Array performance assessment
  - Mini-Array IRF3 production

Simulation System: simulation chain



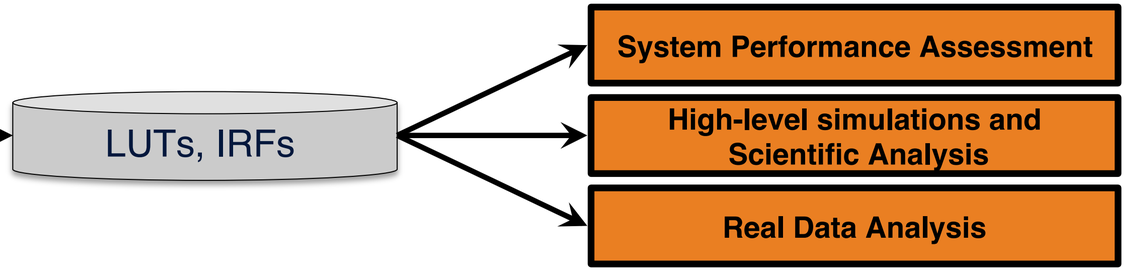
Simulation of:

- gamma and background (p, e^-, He,…) species
- Zenith and Azimuth angles
- Telescope positions in the array
- Geomagnetic field (@ array site)
- Atmospheric density profile

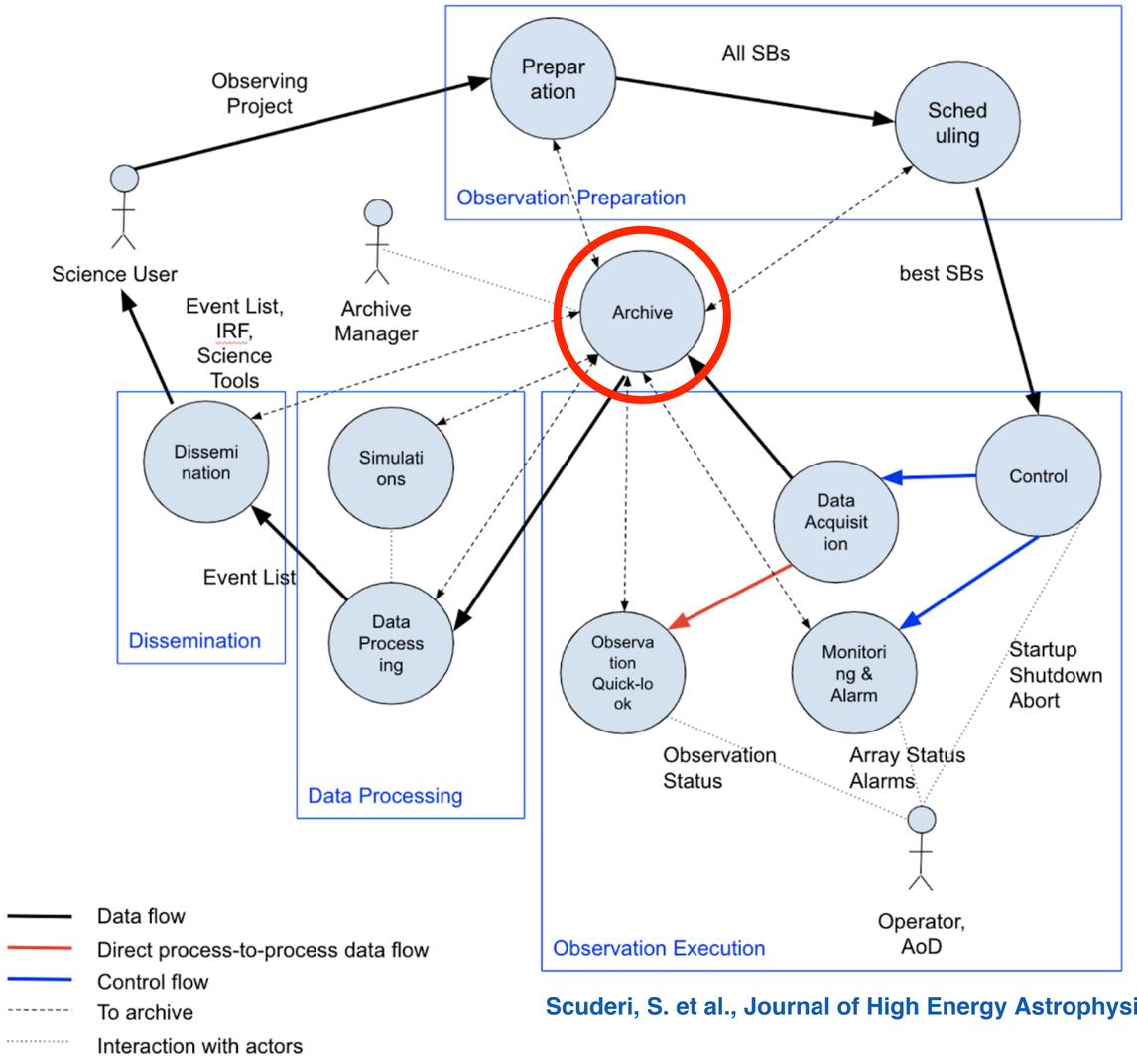
- Atmospheric extinction (← MODTRAN®)

- Ray Tracing (← Mirror reflectivity)

- SiPM response (← PDE Single Photo Electron Response)
- Camera Electronics (← SlowShaper)
- Trigger (← FastShaper)



Archive System: physical units



- **ASTRI Mini-array Archive System**
  - plays a **central role** in the whole observing life-cycle of the array
  - shall guarantee **long-term data preservation and access**
  - shall manage:
    observation plans; science data;
    monitoring/alarm/logging data; system configurations

2 separated physical units (10 Gbit/s connected):

- ***On-Site Archive System:***
  - @Teide Observatory (Tenerife, Spain)
  - Archive System for temporary storage (~1 week) and services
  - On-site ICT (*see Gianotti et al., Paper 12189-53*)
- ***Off-Site Archive System:***
  - @Rome (Italy)
  - Archive System for long-term data storage and services
  - Off-site ICT ➔ **ASTRI Data Center**

Scuderi, S. et al., Journal of High Energy Astrophysics 35, 52–68 (2022)