ASTRI Astrofisica con Specchi a Tecnologia Replicante Italiana

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

Universidade de São Paulo

NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT

ASTRI Mini-Array @Teide: observing the gamma-ray sky up to 100 TeV

Giovanni Pareschi – INAF on behalf of ASTRI Team

INSTITUTO DE ASTROFISICA DE CANARIAS · IAC ·

telescopio nazionale galileo

Fundación Galileo Galilei INAF, Fundación Canaria - Telescopio Nazionale Galileo

- ASTRI Project background
- ASTRI Prototype
- ASTRI mini array

ASTRI - Astrofisica con Specchi a Tecnologia Replicante Italiana

Astrophysics with Mirrors via Italian Replication Technology

Name given by Nanni Bignami

ASTRI was born as a "flagship project" funded by the Italian Ministry of University and Scientific Research with the l aim to design, realize and deploy:

a) an innovative end-to-end prototype of the 4 meters class wide-field telescopes to be tested in an astronomical site (INAF – Catania on Etna Volcano);
b) a mini-array of telescopes based on the new technology, aiming also to early science in the 1-100 TeV energy window.

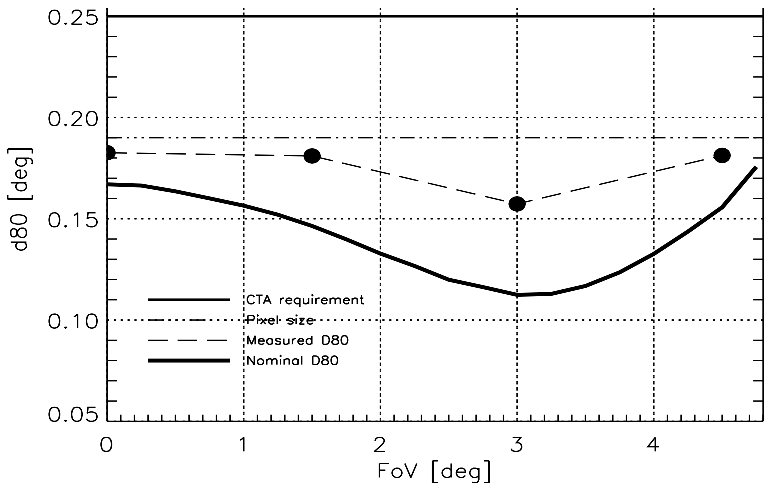
ASTRI will also pave the way to INAF participation in CTA

He's not fat, he's just big boned!

Mechanical Structure

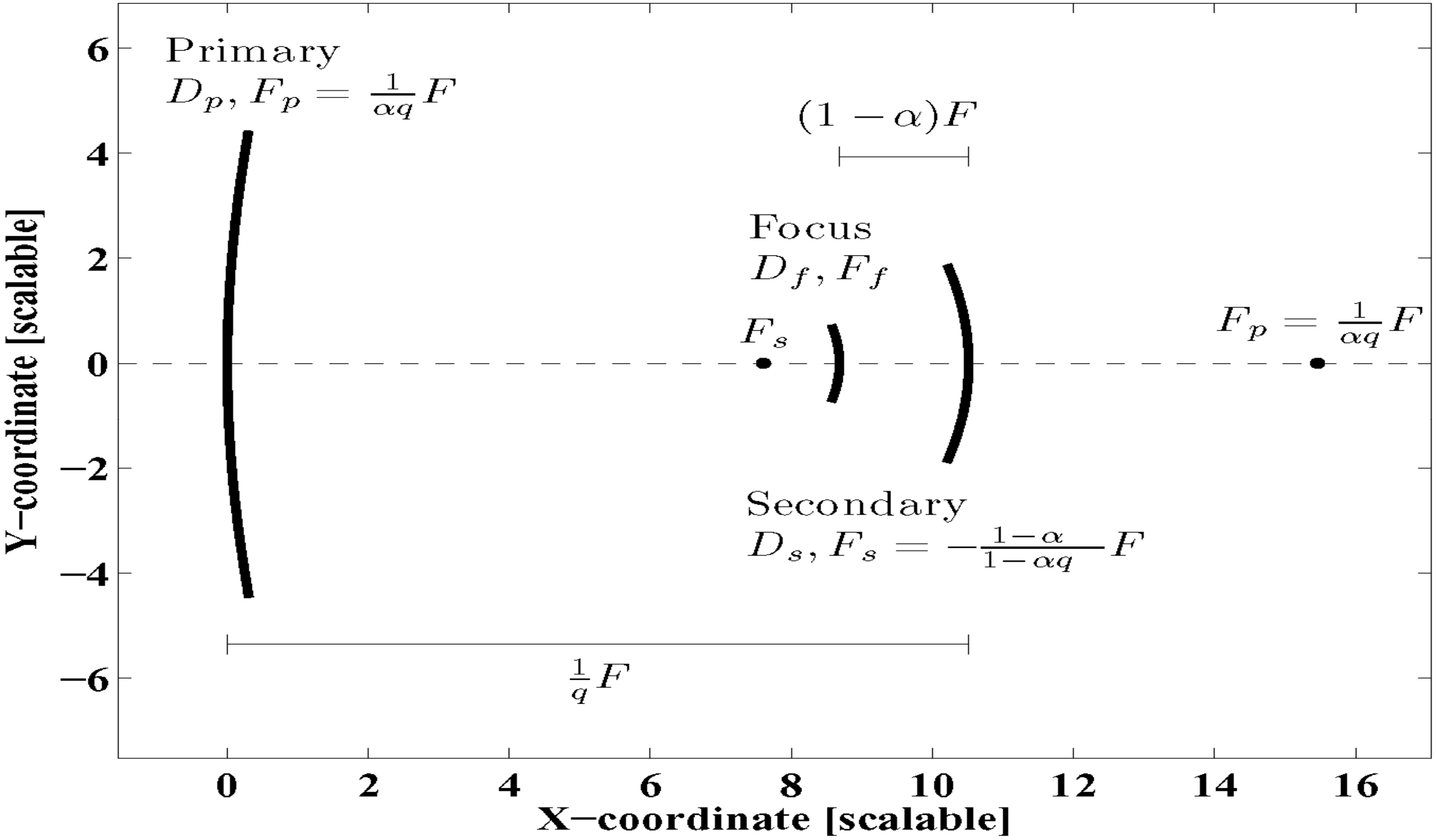
Dimensions & Mass	
Height of the Telescope (pointing horizontally & vertically)	7.5 m & 8.6 m
Radius of free area for Az. Movements	5.3 m
Total Mass of the prototype	19000 kg
Tracking & Pointing	
Driver Encoder Precision	2 arcsec
Tracking Precision	<0.1°
P	

Polynomial design developed by P. Conconi



Aplanatic Telescope

Vladimir Vassiliev recovered the configuration for Cherenkov telescopes. Thanks!



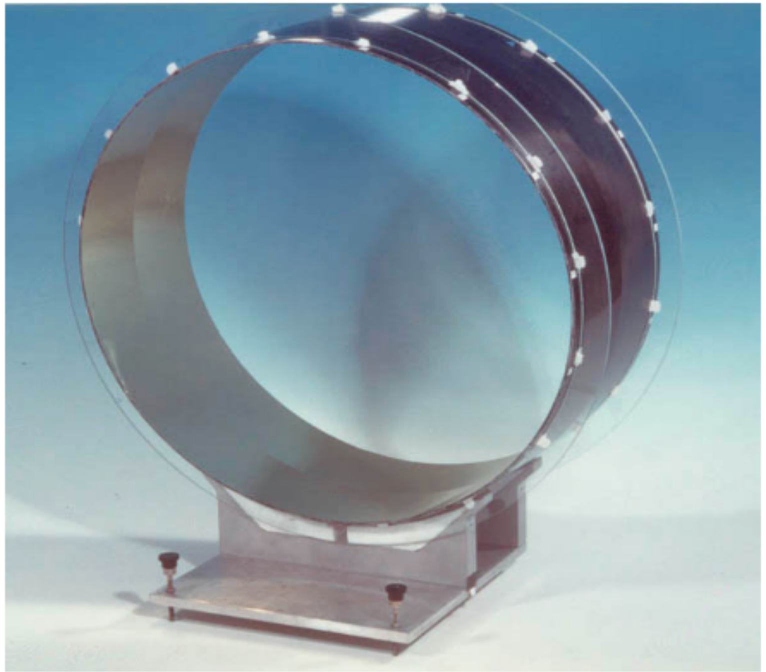
Generalized Schwarzschild theorem:

"For any geometry with reasonable separations between the optical elements, it is possible to correct n primary aberrations with n powered elements." (1905)

Karl Schwarzschild

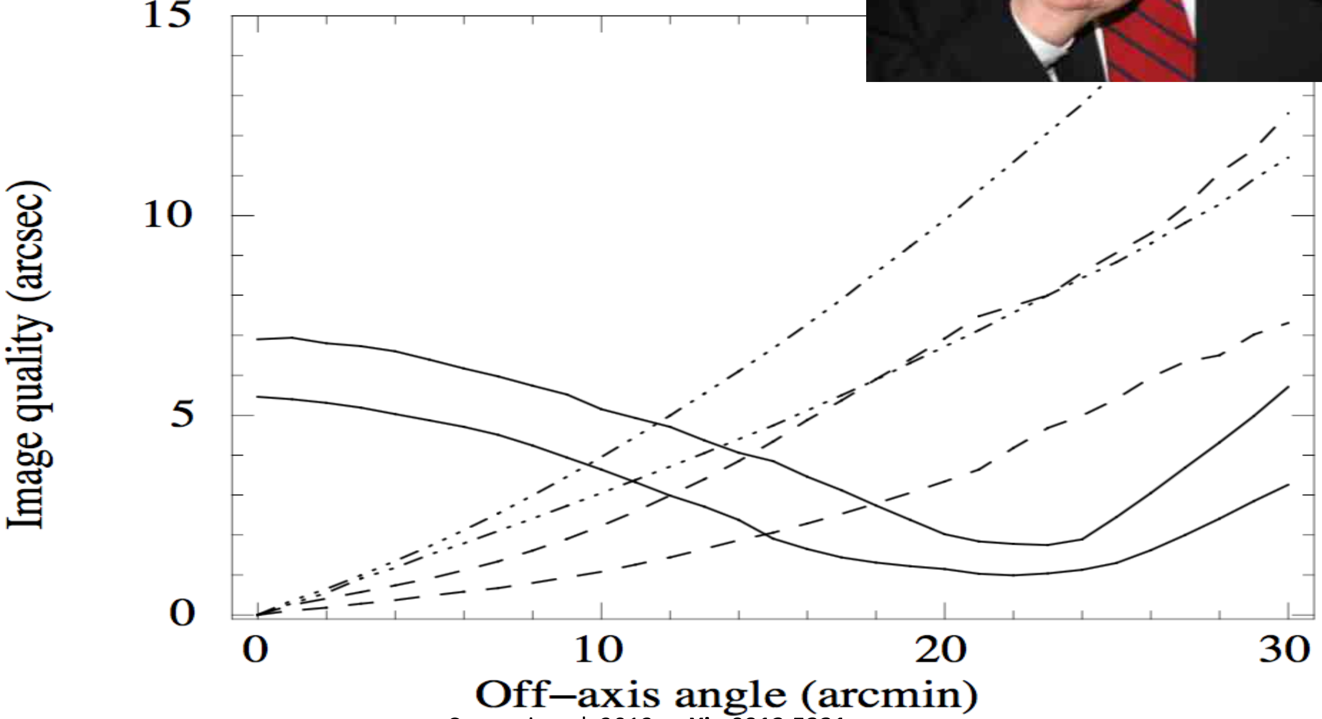
Karl Schwarzschild (1873–1916)

2010: Conconi et al. applied polynomial solution to design an X-ray telescope with a resolution of 5’’ on a field of 1°



Polynomial design of SC grazing incidence optics elaborated by P. Conconi (2010), after first Riccardo’s suggestion (1991) …and many interaction with him

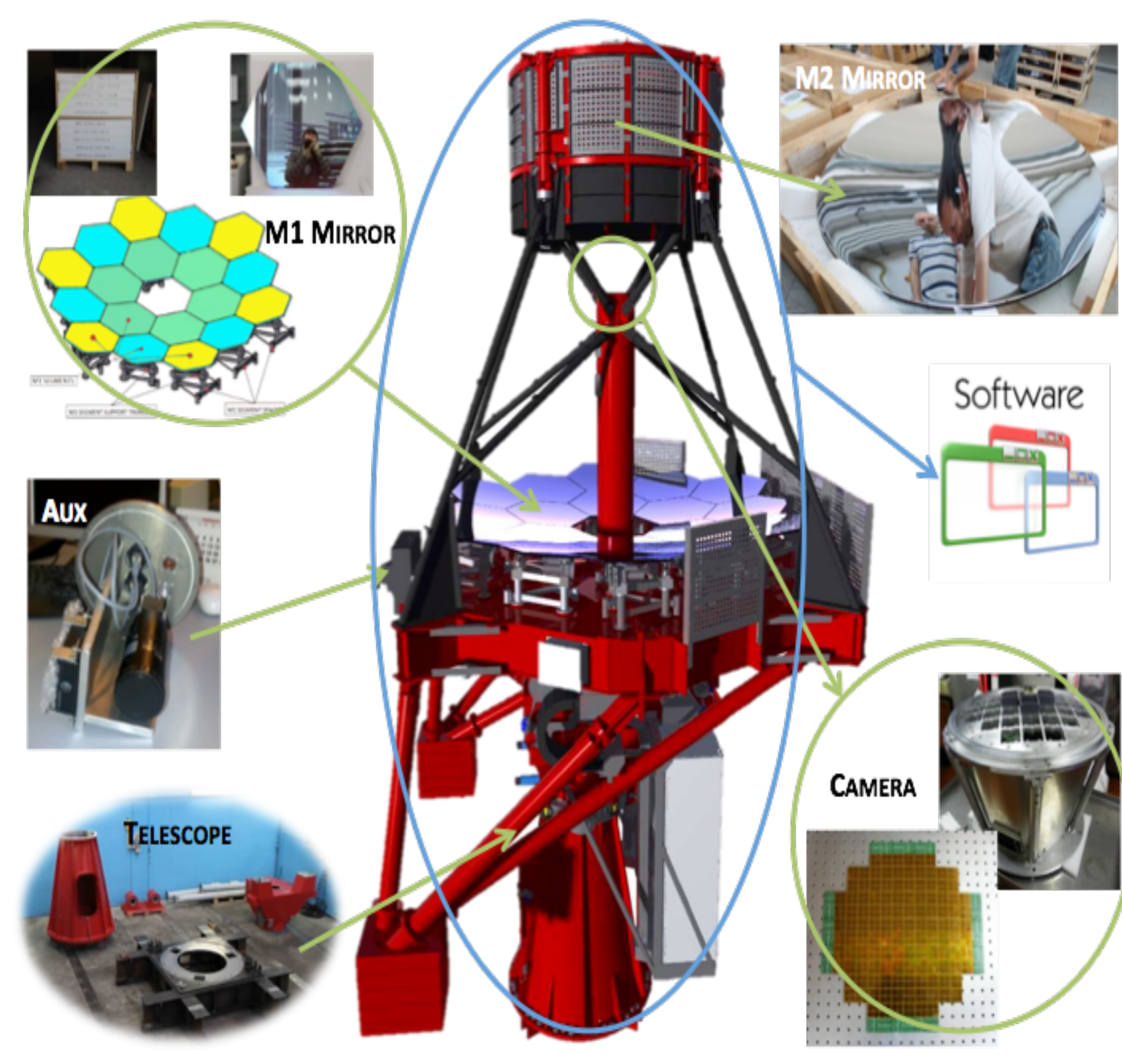
Study for WFXT



Conconi et al. 2013, **arXiv:0912.5331**

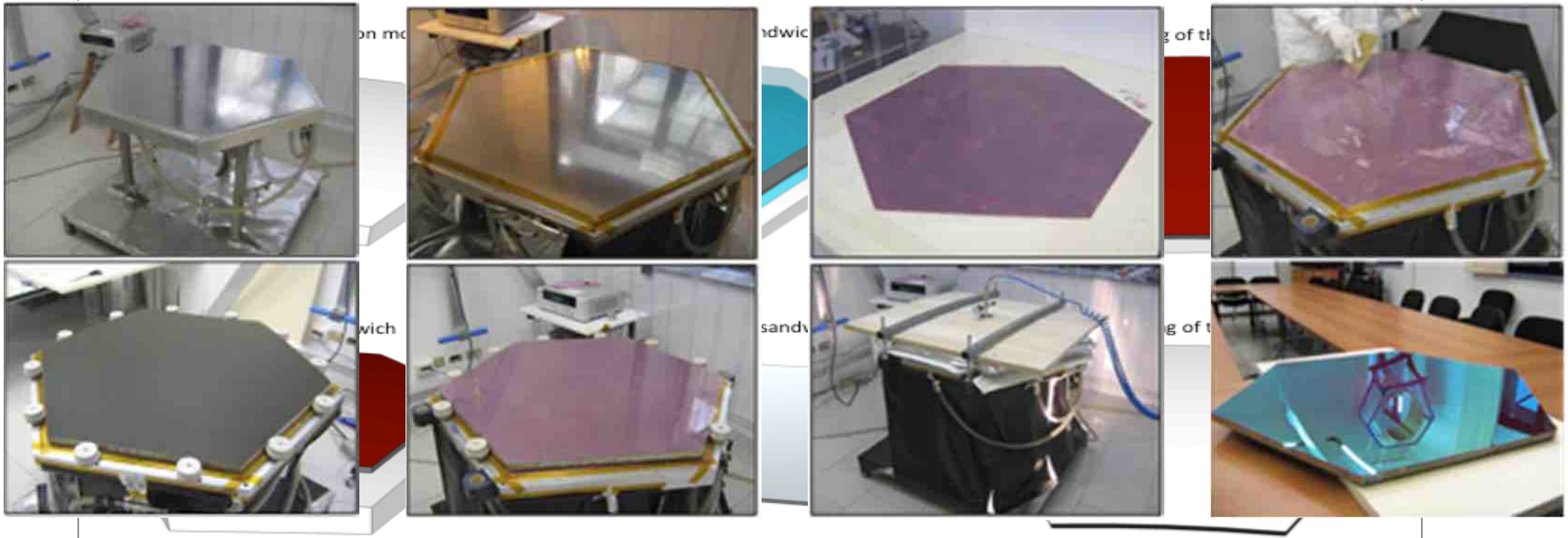
ASTRI SST-2M prototype end-to-end

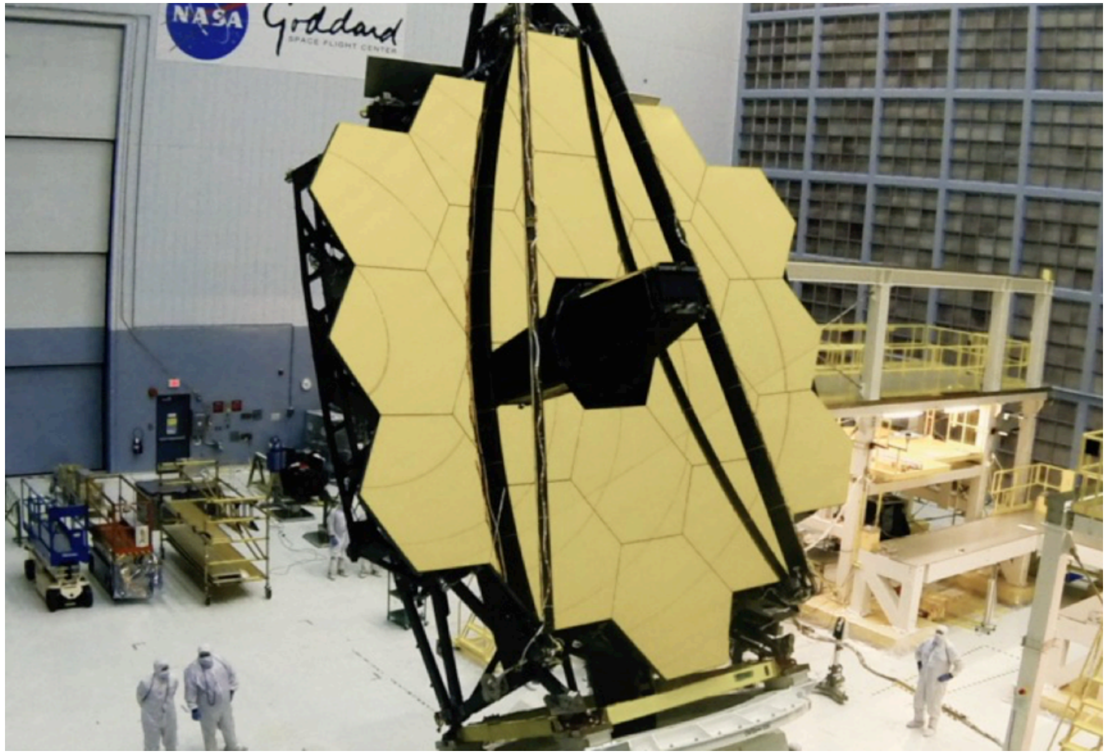
- Test of new technologies
- Test of the dual mirror approach for Cherenkov astronomy
- Development of a new camera (entarily developed in INAF!) with low data rate and consumption
- Debug of the entire system! ➔ **increase of reliability for array**



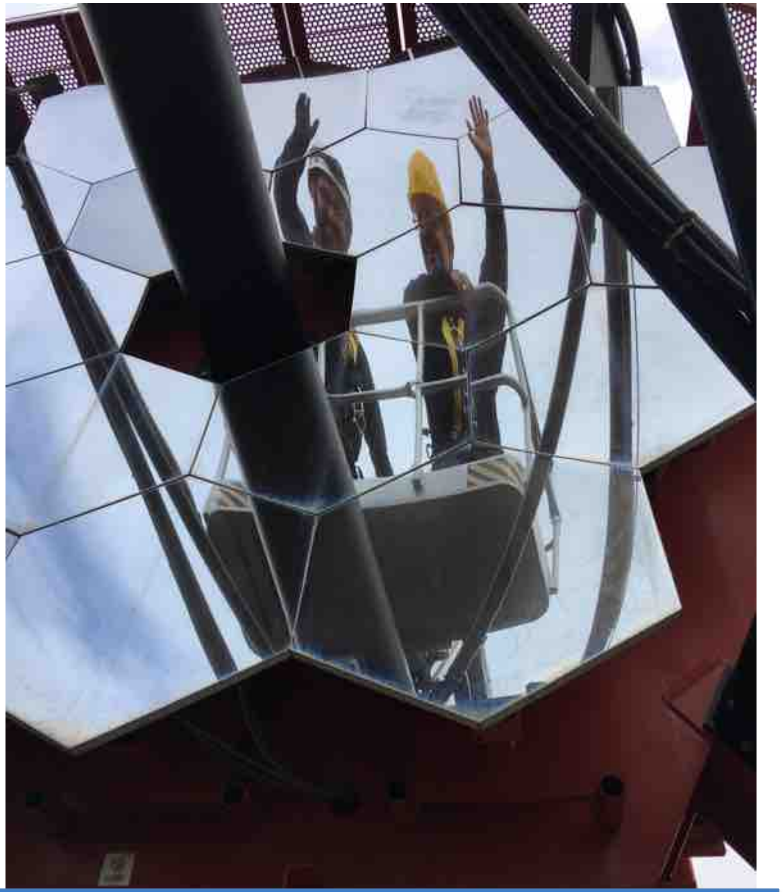
Mirror replication technology

Glass Cold-Shaping technology





Credits: NASA



JWST, reflecting suface cost: ➔ 2 M$/m^2$

ASTRI, reflecting surface cost: ➔ 0.002 M$/m^2$

24th September 2014

Inauguration of the prototype @ INAF-Catania mountain station in Serra La Nave placed at 1725 meters on the Etna volcano

ASTRI - HORN: Dedication to Horn D’Arturo

10th of November 2018

Dedication of ASTRI prototype telescope to Guido Horn D’Arturo inventor of the segmented astronomical mirrors

Weeroc + INAF

PDM: CITIROC ASIC

The first batch of CITIROC ASICs is ready

INAF has the Intellectual Property of the design

CITIROC is available as:

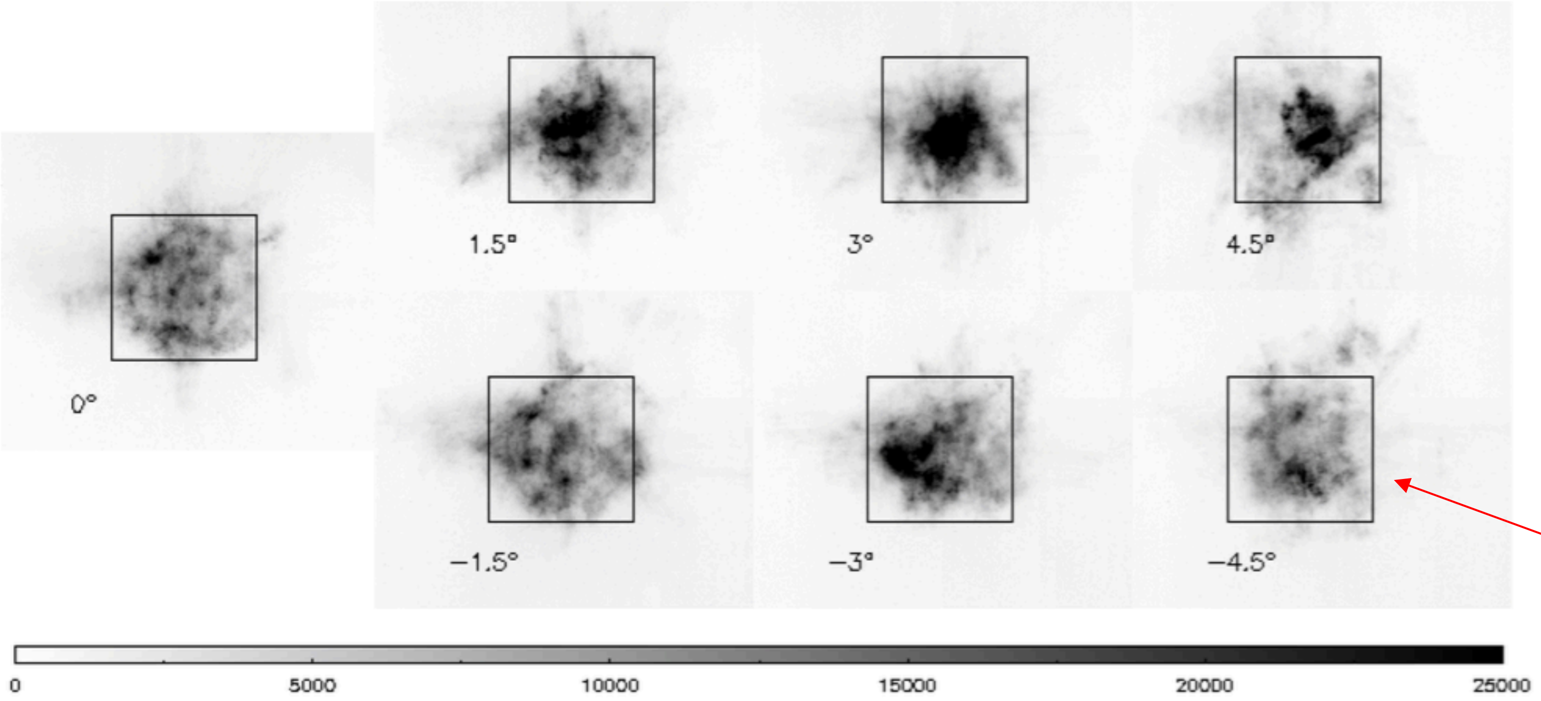
- LQFP160 case
- Naked die 4.1 x 4.1 mm^2

ASTRI Prototype: PSF across the field of view

Astronomy & Astrophysics manuscript no. a˙a˙paper˙optical˙quality˙ver3˙arXiv
September 28, 2017

First optical validation of a Schwarzschild Couder telescope: the ASTRI SST-2M Cherenkov telescope

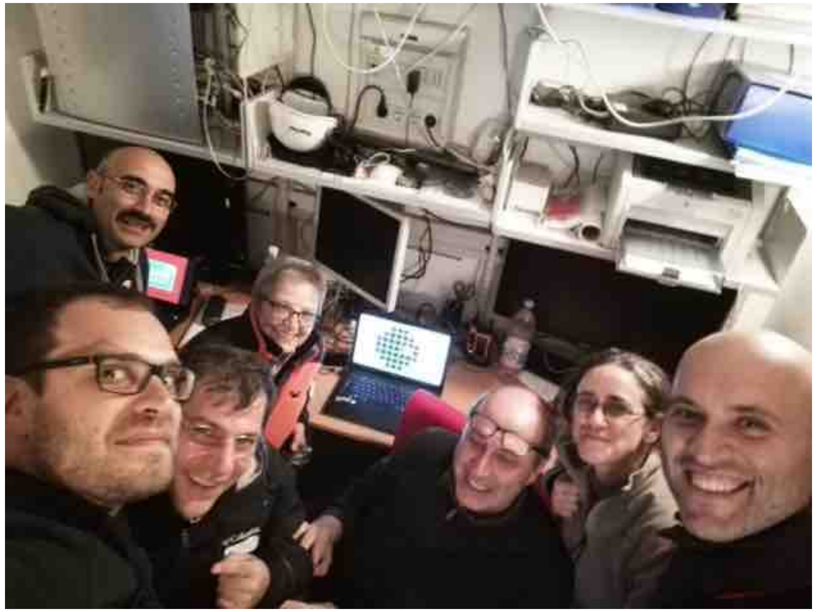
E. Giro[1,2], R. Canestrari[2], G. Sironi[2], E. Antolini[3], P. Conconi[2], C.E. Fermino[4], C. Gargano[5], G. Rodeghiero[1,6], F. Russo[7], S. Scuderi[8], G. Tosti[3], V. Vassiliev[9], and G. Pareschi[2]

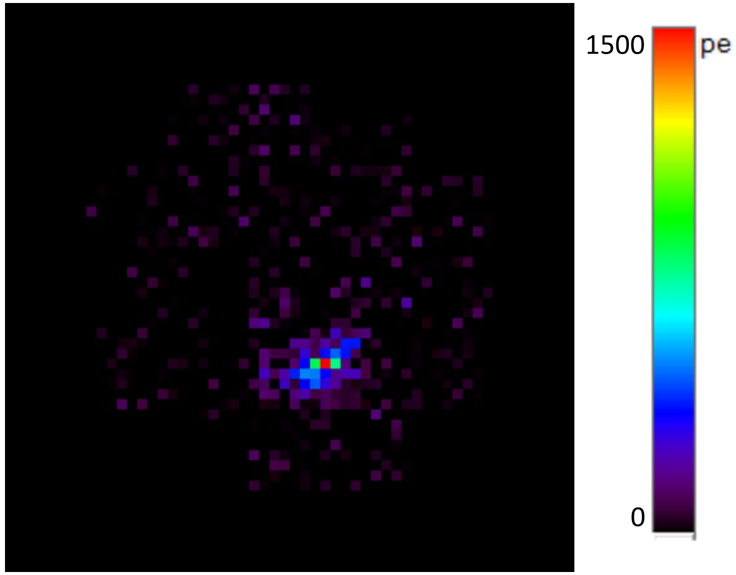


FoV position (deg)	D80 (mm)
4.5	6.72
3.0	6.32
1.5	7.28
0.0	6.86
-1.5	6.32
-3.0	5.50
-4.5	6.90

SiPM pixel linear dimension:
7 mm → 11.2 arcmin

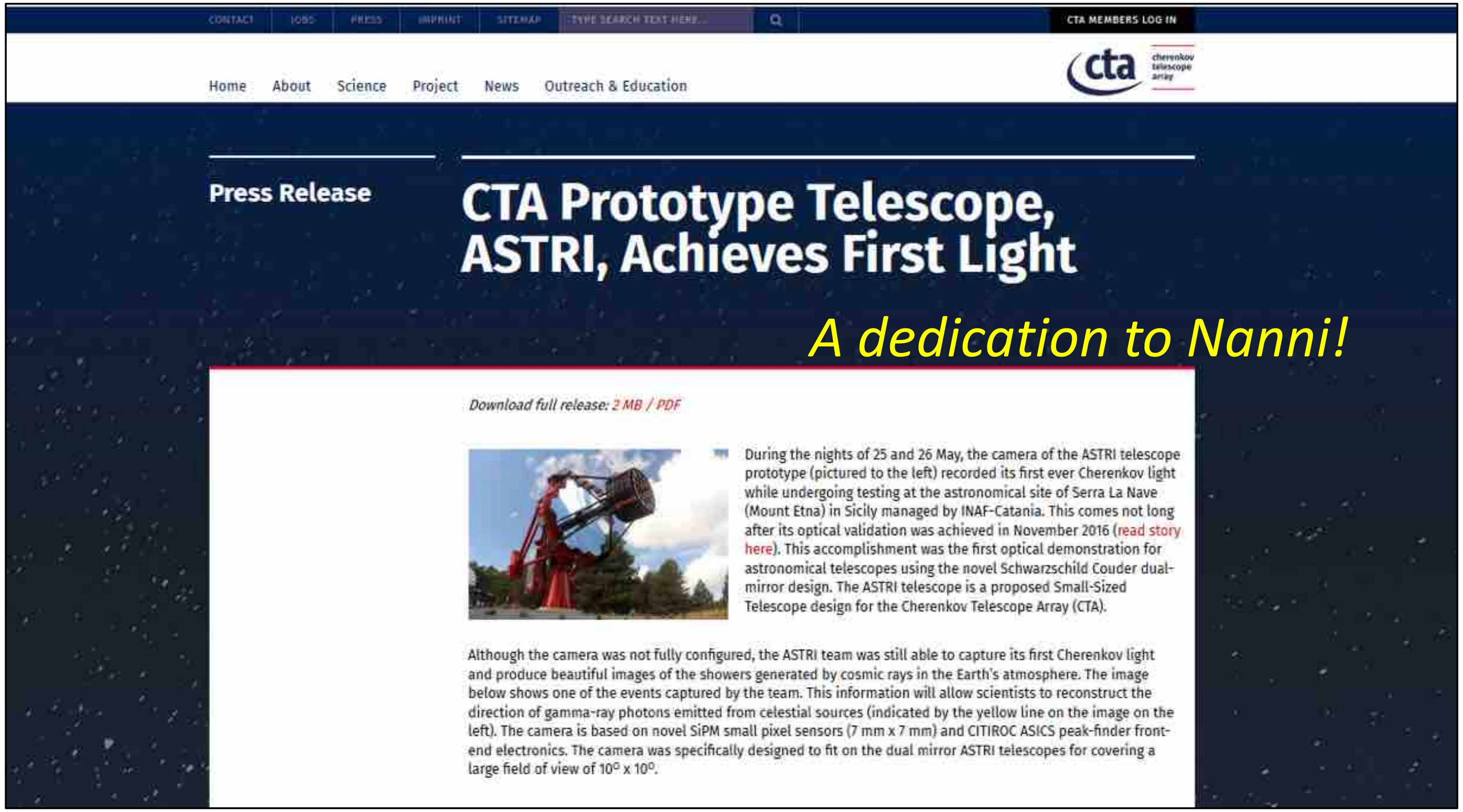
ASTRI - HORN: ASTRI camera first Cherenkov Light





25th of May 2017

First Cherenkov light with the ASTRI camera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cta cherenkov telescope array

Press Release

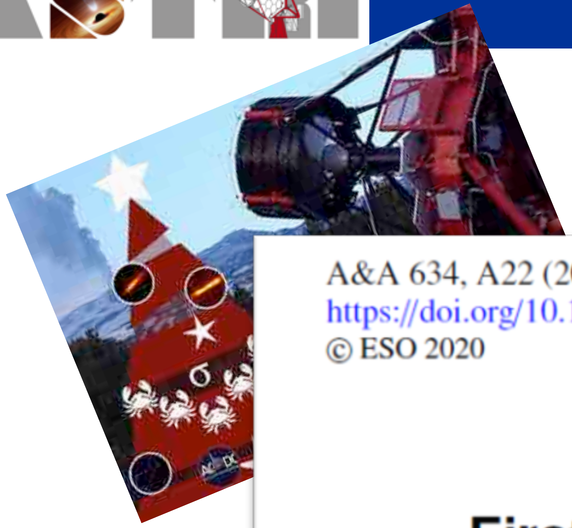
CTA Prototype Telescope, ASTRI, Achieves First Light

Download full release: 2 MB / PDF

During the nights of 25 and 26 May, the camera of the ASTRI telescope prototype (pictured to the left) recorded its first ever Cherenkov light while undergoing testing at the astronomical site of Serra La Nave (Mount Etna) in Sicily managed by INAF-Catania. This comes not long after its optical validation was achieved in November 2016 (read story here). This accomplishment was the first optical demonstration for astronomical telescopes using the novel Schwarzschild Couder dual-mirror design. The ASTRI telescope is a proposed Small-Sized Telescope design for the Cherenkov Telescope Array (CTA).

Although the camera was not fully configured, the ASTRI team was still able to capture its first Cherenkov light and produce beautiful images of the showers generated by cosmic rays in the Earth's atmosphere. The image below shows one of the events captured by the team. This information will allow scientists to reconstruct the direction of gamma-ray photons emitted from celestial sources (indicated by the yellow line on the image on the left). The camera is based on novel SiPM small pixel sensors (7 mm x 7 mm) and CITIROC ASICS peak-finder front-end electronics. The camera was specifically designed to fit on the dual mirror ASTRI telescopes for covering a large field of view of 10° x 10°.

A dedication to Nanni!



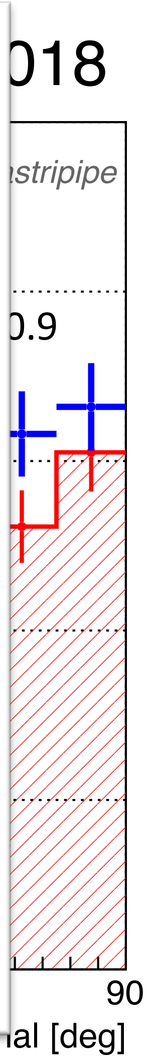
Observations between 5th and 11th december 2018

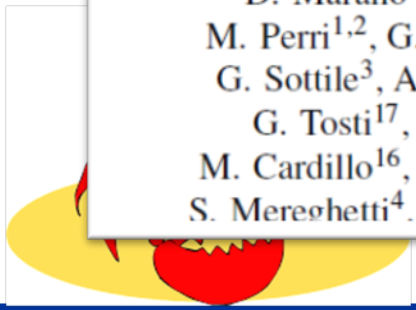
A&A 634, A22 (2020)
https://doi.org/10.1051/0004-6361/201936791

Astronomy & Astrophysics

First detection of the Crab Nebula at TeV energies with a Cherenkov telescope in a dual-mirror Schwarzschild-Couder configuration: the ASTRI-Horn telescope

S. Lombardi[1,2,⋆], O. Catalano[3,⋆], S. Scuderi[4,⋆], L. A. Antonelli[1,2], G. Pareschi[5], E. Antolini[6], L. Arrabito[7], G. Bellassai[8], K. Bernlöhr[9], C. Bigongiari[1], B. Biondo[3], G. Bonanno[8], G. Bonnoli[5], G. M. Böttcher[10], J. Bregeon[11], P. Bruno[8], R. Canestrari[3], M. Capalbi[3], P. Caraveo[4], P. Conconi[5], V. Conforti[12], G. Contino[3], G. Cusumano[3], E. M. de Gouveia Dal Pino[13], A. Distefano[4], G. Farisato[14], C. Fermino[13], M. Fiorini[4], A. Frigo[14], S. Gallozzi[1], C. Gargano[3], S. Garozzo[8], F. Gianotti[12], S. Giarrusso[3], R. Gimenes[13], E. Giro[14], A. Grillo[8], D. Impiombato[3], S. Incorvaia[4], N. La Palombara[4], V. La Parola[3], G. La Rosa[3], G. Leto[8], F. Lucarelli[1,2], M. C. Maccarone[3], D. Marano[8], E. Martinetti[8], A. Miccichè[8], R. Millul[5], T. Mineo[3], G. Nicotra[15], G. Occhipinti[8], I. Pagano[8], M. Perri[1,2], G. Romeo[8], F. Russo[3], F. Russo[12], B. Sacco[3], P. Sangiorgi[3], F. G. Saturni[1], A. Segreto[3], G. Sironi[5], G. Sottile[3], A. Stamerra[1], L. Stringhetti[4], G. Tagliaferri[5], M. Tavani[16], V. Testa[1], M. C. Timpanaro[8], G. Toso[4], G. Tosti[17], M. Trifoglio[12], G. Umana[8], S. Vercellone[5], R. Zanmar Sanchez[8], C. Arcaro[14], A. Bulgarelli[12], M. Cardillo[16], E. Cascone[18], A. Costa[8], A. D'Aì[3], F. D'Ammando[12], M. Del Santo[3], V. Fioretti[12], A. Lamastra[1], S. Mereghetti[4], F. Pintore[4], G. Rodeghiero[14], P. Romano[5], J. Schwarz[5], E. Sciacca[8], F. R. Vitello[8], and A. Wolter[5]





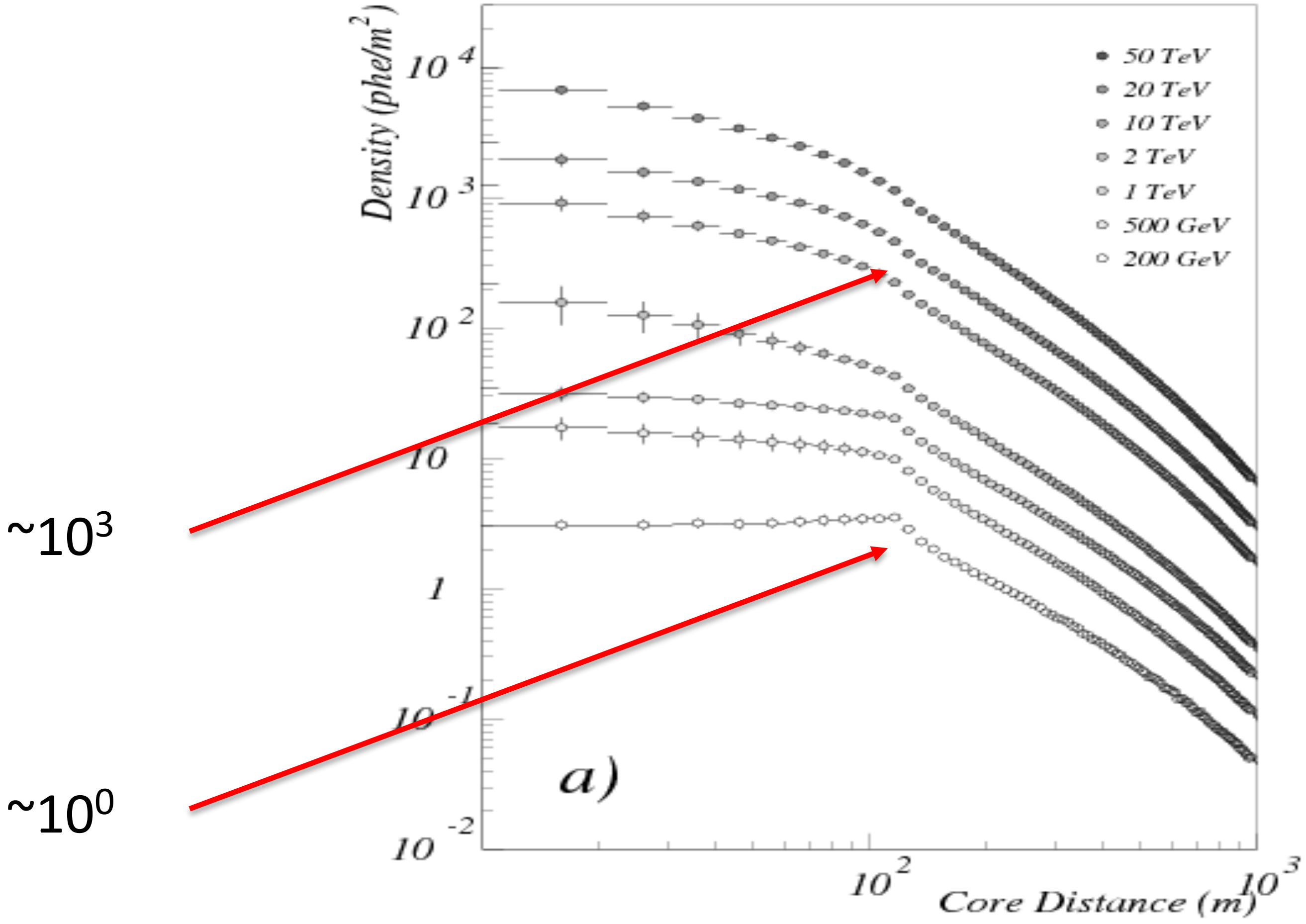
ASTRI mini-array: The next step of the program

The ASTRI mini-array will be a new pathfinder of the arrays of Cherenkov telescopes

- **INAF commitment with the Italian government and international partners (University of Sao Paulo/FPESP - Brazil, North-West University - South Africa)**
- **Dedicated funding**
- **It will composed by 9 ASTRI telescopes, evolution of the ASTRI-Horn prototype successfully implemented and tested**
- **It will deployed at the Teide Observatory (Canary Islands) in collaboration with IAC**

Cherenkov light and pool versu energy

Radial profile of Cherenkov light originated from an electromag-netic shower initiated by a gamma ray:

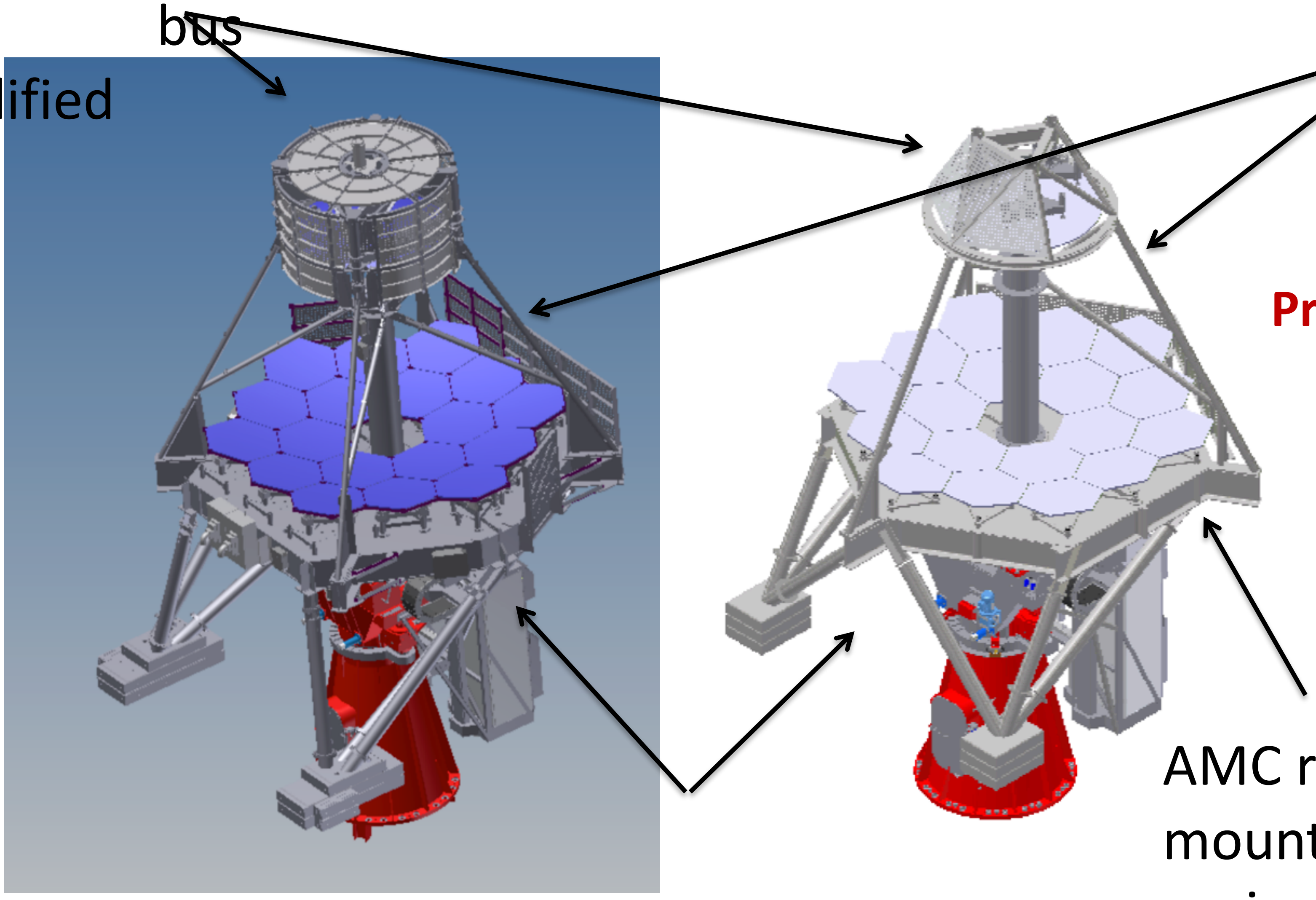


ASTRI: a new pathfinder of the arrays of Cherenkov telescopes

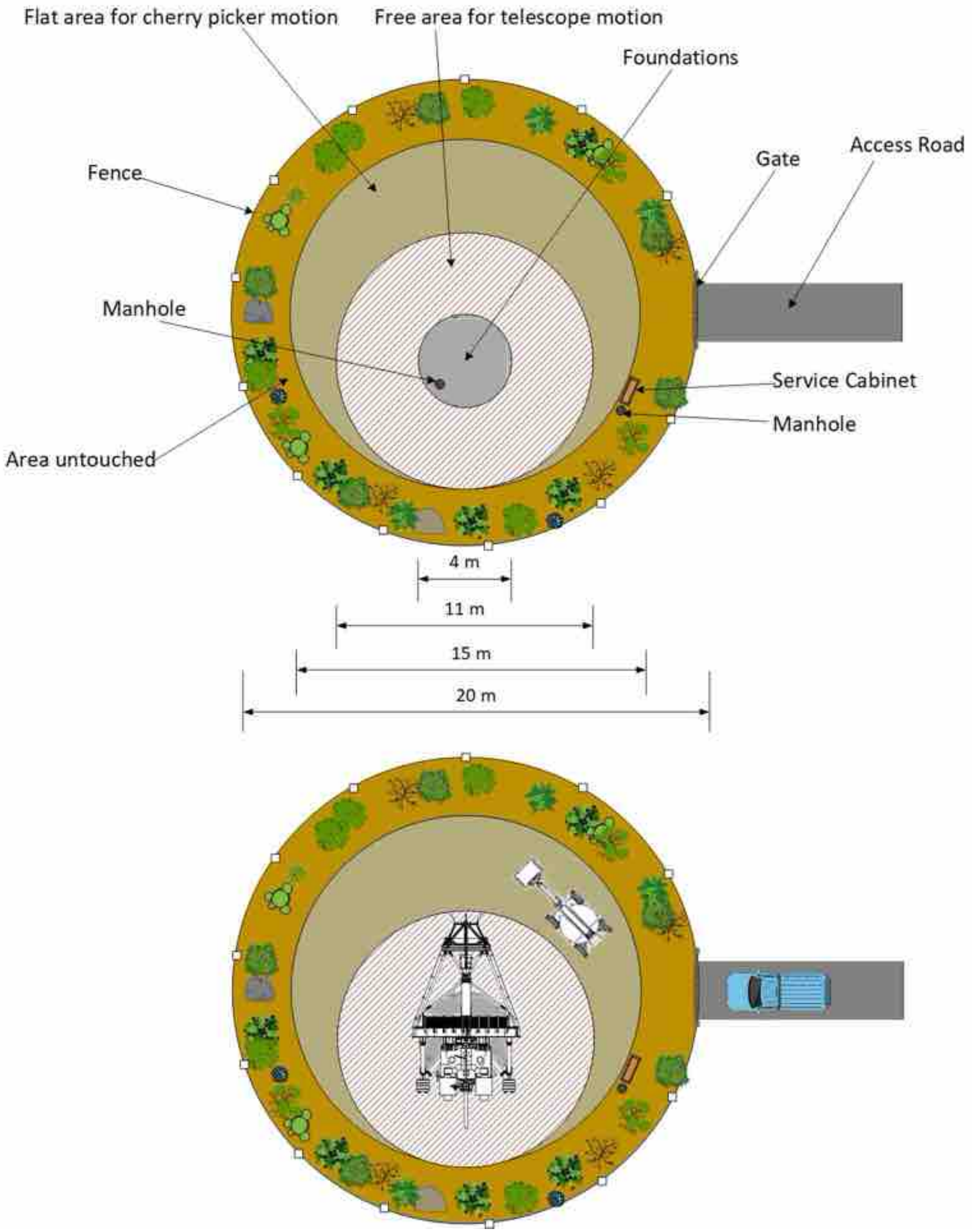
On June 12nd 2019, in La Laguna (Tenerife, Spain) Prof. Nichi D'Amico, President of the Italian National Institute for Astrophysics (INAF), and Prof. Rafael Rebolo Lopez, Director of the Instituto de Astrofisica de Canaries, signed a Record of Understanding to enter a detailed negotiation on a technical and programmatic basis aimed to install and operate the ASTRI Mini-Array at the Observatorio del Teide

INAF and IAC Representatives on the Teide Observatory site

ASTRI Pre-production activities: Design Consolidation

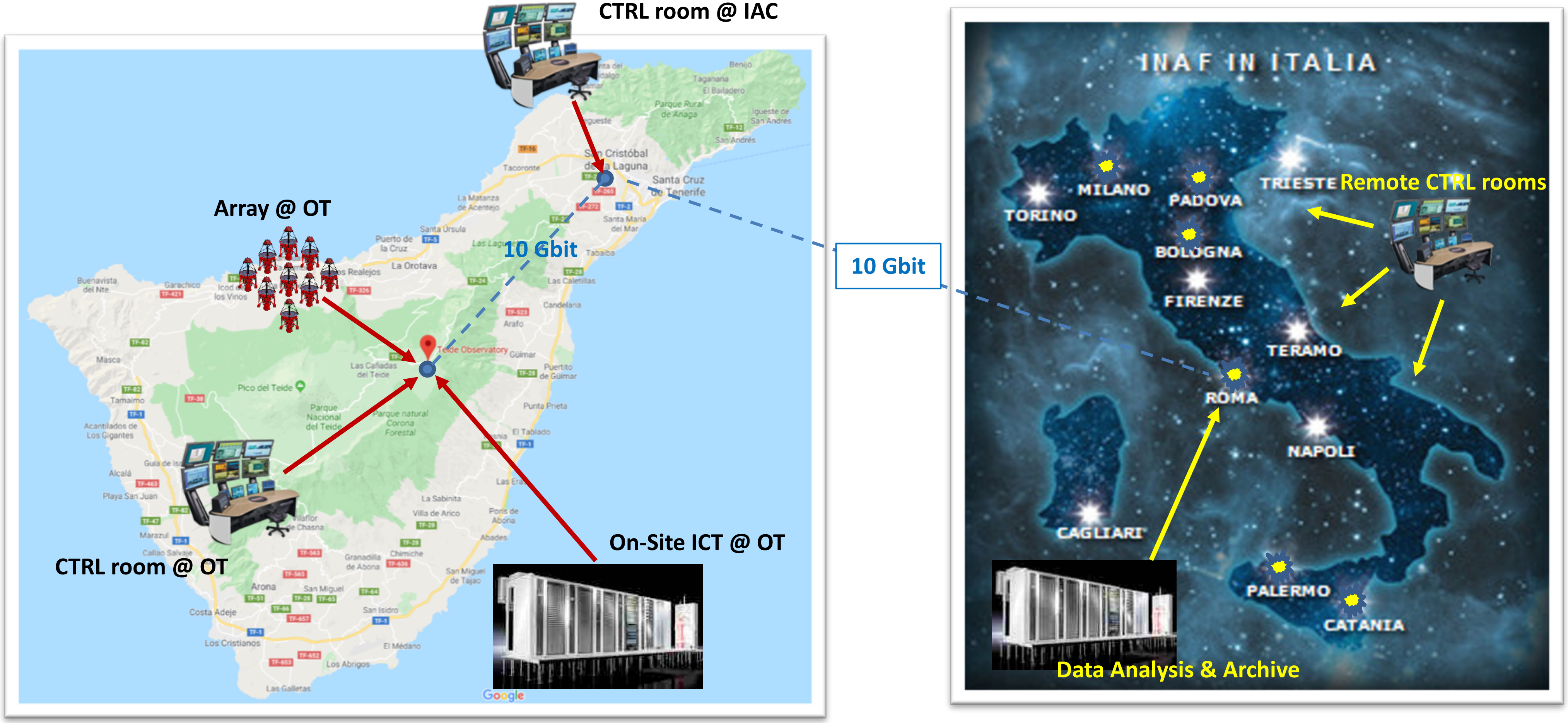


Scheduled production of the first telescope for the end of the year



Site ready to host the first telescope in one year

ASTRI mini-array: The physical layout



- **It will be developed in order to be operated, after the commissioning phase, remotely.**
- **Data analysis will be performed off-site (3 TeraBytes/night)**

Science Operations 1/2

- During the first years of operations the ASTRI mini array will be run as **an experiment** and not as an observatory

- The ASTRI Science team will develop a strategy to concentrate the ASTRI observational time on a limited number of programs with clearly identified objectives. This will produce an observation schedule that will span several months at a time.

- No real time analysis of the data is foreseen but only a data quality check. Data analysis policy adopted will then be next day processing.

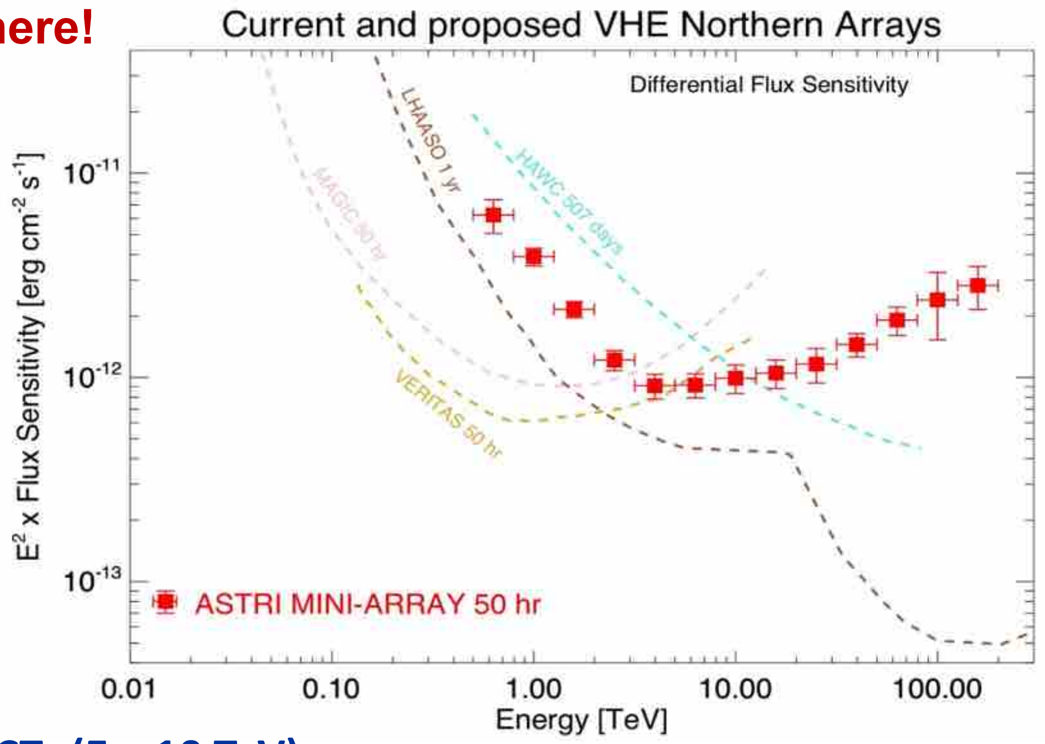
Science Operations 2/2

- No array trigger (stereo trigger) will be implemented at the site. Any search for Cherenkov events detected in coincidence by more than one telescope will be performed via software off-line at the Rome Data Center.

- No subarray operation is foreseen for the ASTRI mini array.

- Night Science operation is controlled from a control room located in La Laguna @ IAC (possibly also from TNG and Italy, TBC), so no people are required to be present at the mini array site during the night. A control room will be also available at the mini array site at the Themis Observatory (TBC) and will be mainly used during commissioning and science verification or in case of other special activities.

Science at very high gamma ray energy in the northern hemisphere!



Expected performance:

- **Sensitivity: better than current IACTs (E > 10 TeV):**
  - Possibility to extend the spectra of already detected sources and/or measure cut-offs
  - Possibility to characterize the morphology of extended sources at the highest VHE
- **Energy/Angular resolution: < ~10% / < ~ 0.1° (E > ~ 10 TeV)**
- **Wide FoV (3 ° diameter in gamma rays 5% sens), with homogeneous off-axis acceptance**
  - Optimal for multi-target fields, surveys, and extended sources
  - Enhanced chance for serendipity discoveries

ASTRI mini-array: energy resolution

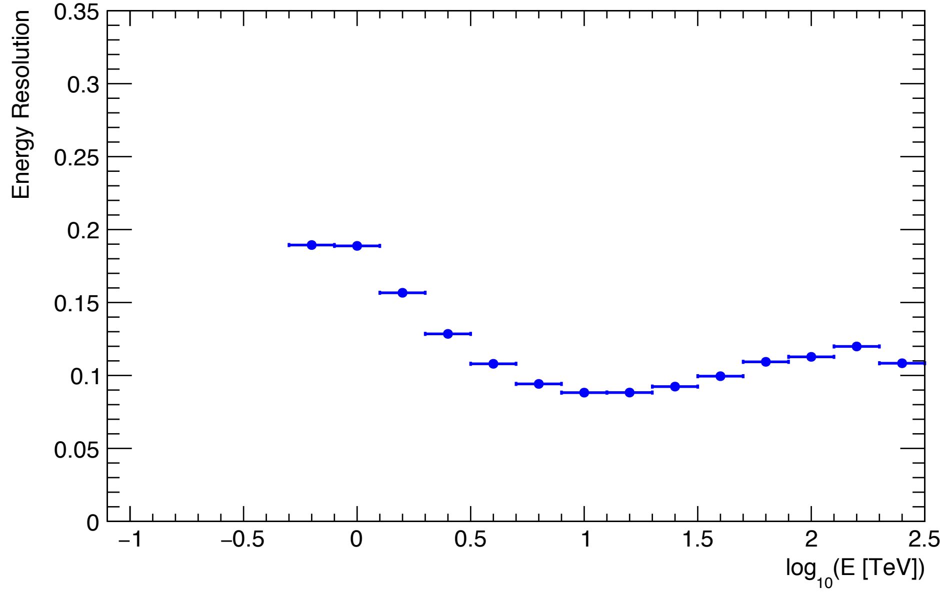


Figure 2: On-axis energy resolution of the ASTRI Mini-Array as a function of the energy between ≃ 0.1 TeV and ≃ 300 TeV.

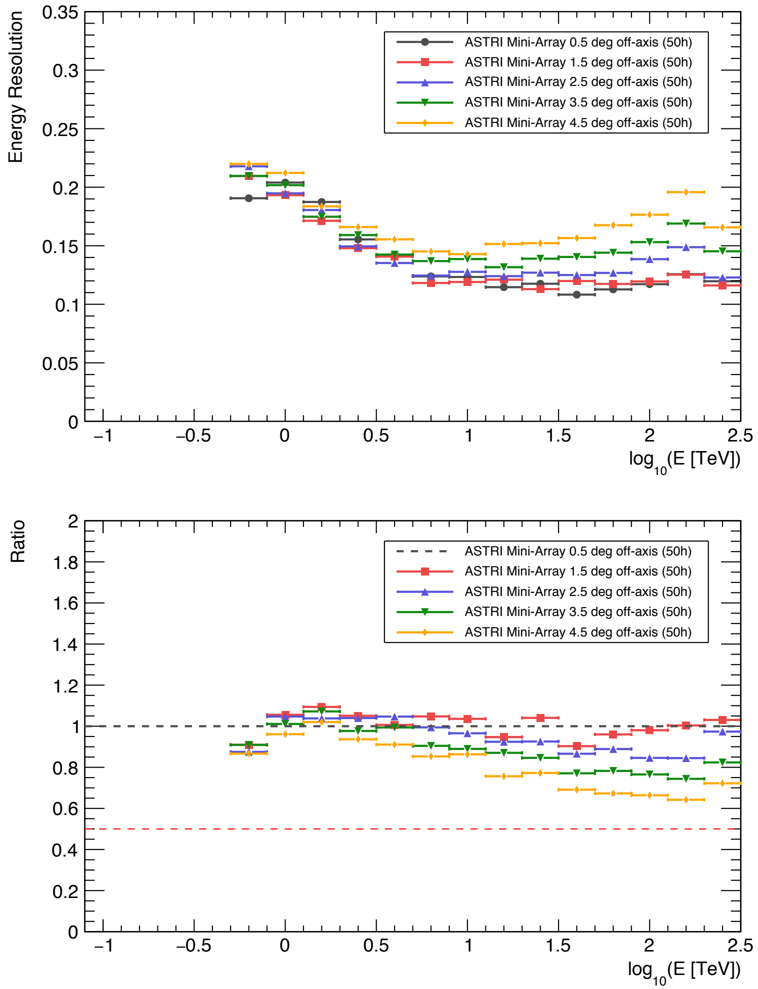
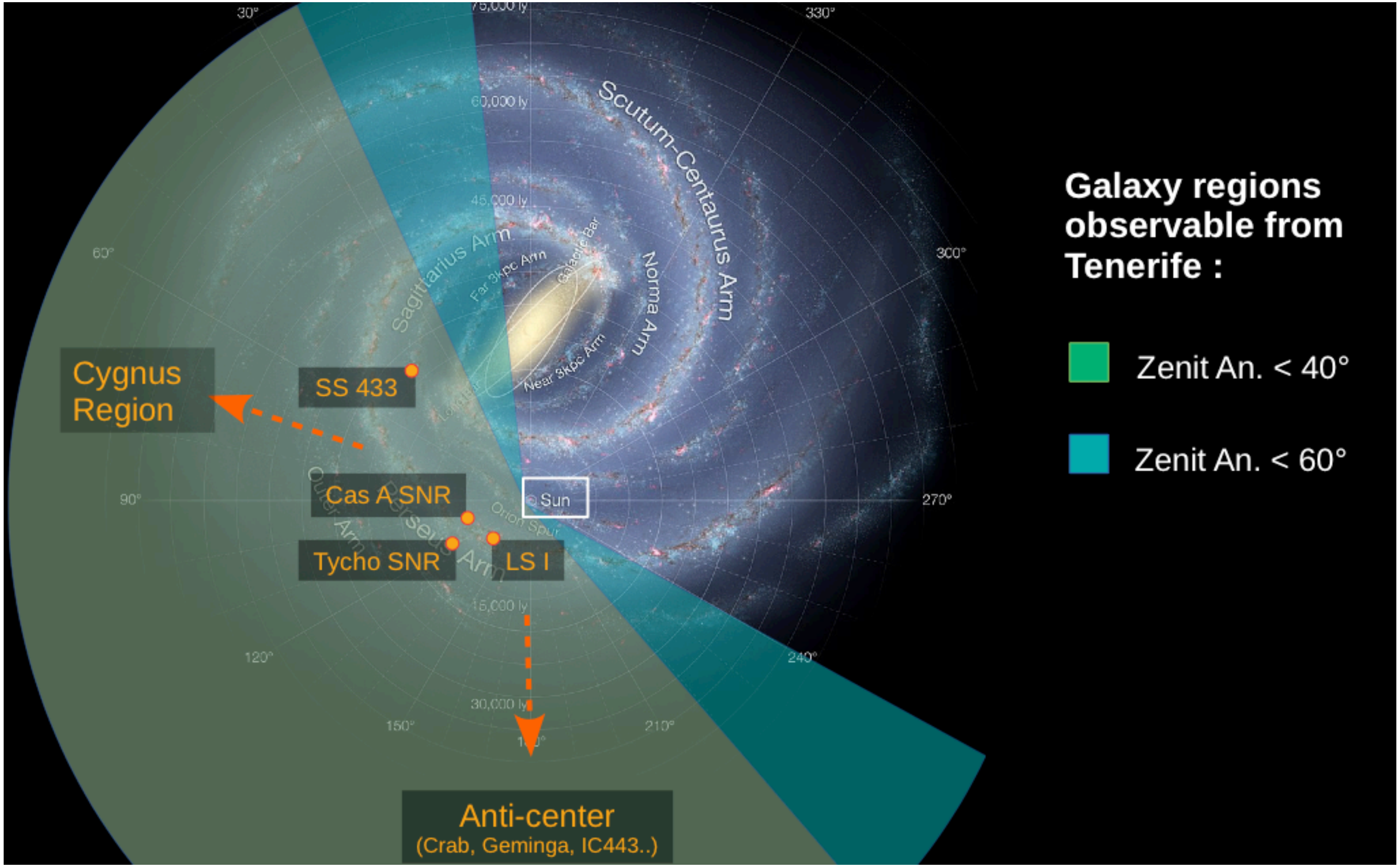


Figure 6: *Top*: Off-axis energy resolution of the ASTRI Mini-Array as a function of the energy between 10^{-1}≃ 0.1 TeV and $10^{2.5}$≃ 300 TeV for 5 source off-axis bins between 0° and 5°. *Bottom*: Energy resolution ratios with respect to the energy resolution achieved in the first considered off-axis bin (from 0° to 1°). The ratio is calculated so that higher values correspond to better performance. The dashed, thin red line represents the 50% performance drop.

Table 6

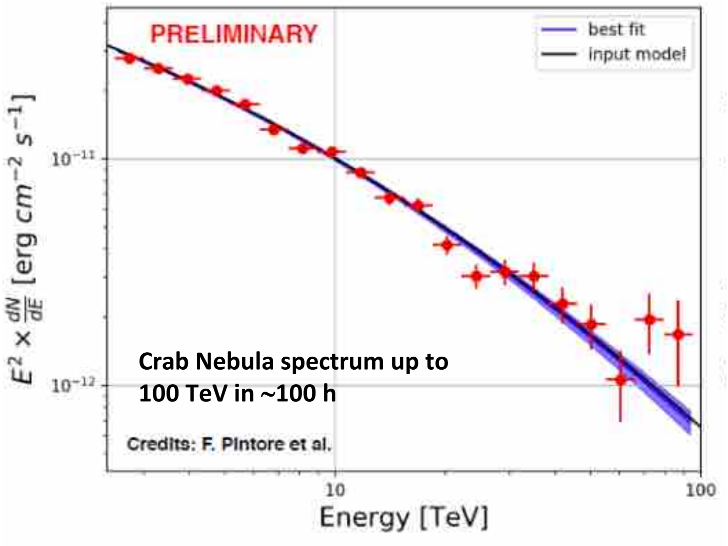
Summary of the performance of the current main imaging atmospheric Cherenkov telescope arrays and water Cherenkov detectors. **References.** ASTRI Mini-array: this work. MAGIC: Aleksić et al. (2016). VERITAS: Holder et al. (2006) and https://veritas.sao.arizona.edu. H.E.S.S.: Aharonian et al. (2006a). HAWC: Abeysekara et al. (2017c,b). LHAASO: Cao (2010). **Notes.** [a]: as a function of the event size. [b]: w.r.t. on axis at 3°. [c]: w.r.t. on axis at 2°. [d]: for ZA $\geq 35\,^{\circ}$.

	ASTRI Mini-Array	**MAGIC**	**VERITAS**	**H.E.S.S.**	**HAWC**	**LHAASO**
Location	28° 18′ 04″ N	28° 45′ 22″ N	31° 40′ 30″ N	23° 16′ 18″ S	18° 59′ 41″ N	29° 21′ 31″ N
	16° 30′ 38″ W	17° 53′ 30″ W	110° 57′ 7.8″ W	16° 30′ 00″ E	97° 18′ 27″ W	100° 08′ 15″ E
Altitude [m]	2,390	2,396	1,268	1,800	4,100	4,410
FoV	9.6°	$\sim 3.5°$	$\sim 3.5°$	$\sim 5°$	2 sr	2 sr
Angular Res.	$\sim 0.07°$ (10 TeV)	0.04° (1 TeV)	0.08° (1 TeV)	$< 0.1°$	(0.2–1)°[a]	$\sim xx°$ (10 TeV)
Energy Res.	(10-15)% (10 TeV)		17% (1 TeV)	10%	30% (10 TeV)	xx% (10 TeV)
Energy Range	(0.6-200) TeV		(0.85-30) TeV	(0.2-30) TeV	(0.1-100) TeV	(0.1-1,000) TeV
Sensitivity Drop	50%[a]			$< 40\%$[b]	Factor > 5[c]	Factor $> xx$[d]


Galaxy regions observable from Tenerife :
Zenit An. < 40°
Zenit An. < 60°
Cygnus Region
SS 433
Cas A SNR
Tycho SNR
LS I
Sun
Anti-center
(Crab, Geminga, IC443..)
Scutum-Centaurus Arm
Norma Arm
Sagittarius Arm
Far 3kpc Arm
Near 3kpc Arm
Galactic Bar
Perseus Arm
Outer Arm
Orion Spur
30°
60°
90°
120°
150°
210°
240°
270°
300°
330°
60,000 ly
45,000 ly
15,000 ly
30,000 ly

Core science program in the first ~2/3 years (detailed strategy under definition):

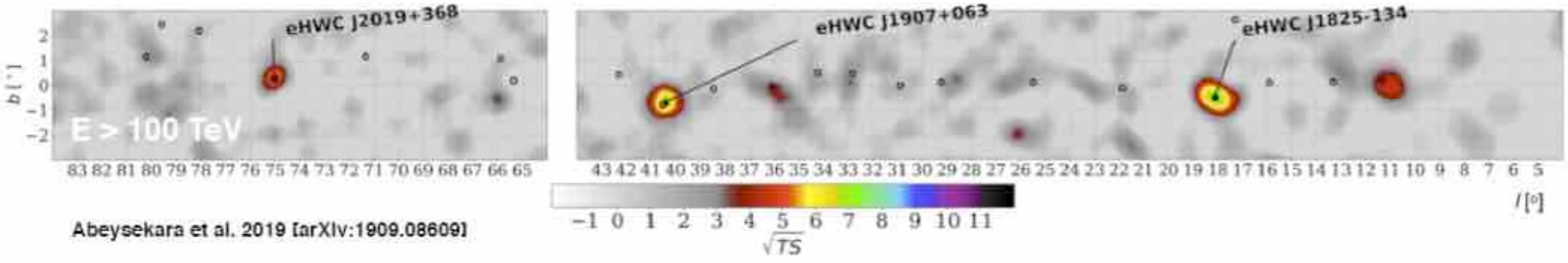
- Restricted number of targets/deep exposures (>~ 200 h) → strong scientific cases
- Galactic sources: wide FoV → multi-target fields
- Extragalactic sources: survey of a few promising targets at > ~10 TeV scale
- Fundamental physics: studies on LIV, EBL, Axion-Like Particles, …
- Science beyond VHE astronomy also envisaged → Stellar Intensity Interferometry



Crab Nebula spectrum up to 100 TeV in ~100 h

Synergies with current VHE Northern Arrays:

- Observations of HAWC and LHAAZO sources with higher angular/energy resolution
- Simultaneous observations with MAGIC and LSTs will be possible



Abeysekara et al. 2019 [arXiv:1909.08609]

Table 2
List of selected γ-ray sources relevant for the study of CR origin, observable from the Observatorio del Teide and studied with ASTRI-MA simulations

Name	RA (deg)	Dec (deg)	Type	Zenith Angle[1] (deg)	Visibility[2] (hr/yr)	Flux[3](1 TeV) (10^{-13} TeV^{-1}cm^{-2}s^{-1})	Index	Section
Tycho	6.36	64.13	SNR	35.8	410+340	1.71	2.28	4.1.1
Galactic Center	266.40	-28.94	Diffuse	57.2	0+180	36	2.32	4.1.2
eHWC 1907+063	286.91	6.32	SNR+PWN	22	400+170	0.85(7 TeV)	2.33	4.1.3
SNR G106.3+2.7	337.00	60.88	SNR	32.6	460+300	1.15 (3 TeV)	2.29	4.1.3
γ-Cygni	305.02	40.76	SNR	12.5	460+160	20 (whole SNR) 12 (hot-spot)	2.37	4.2.1
W28/HESS J1800-240B	270.11	-24.04	SNR/MC	51.6	0+300	7.5	2.4 - 2.55	4.2.2
Crab	83.63	22.01	PWN	6.3	470+170	*	*	4.3.1
Geminga	98.48	17.77	PWN	10.5	460+170	*	*	4.3.2
M82	148.97	69.68	Starburst	41.4	310+470	2.02 (no CO) 2.74 (w CO)	2.2	4.4

[1]This is the culmination angle reachable at Teide from the source.
[2]Maximum available hours of visibility in moonless conditions calculated for one year of observations and for two zenith angle intervals [0-45°]+[45°-60°].
[3] Flux and index are the one of the input model used in the simulation. See the text for the references.
* For these sources, we adopted an input model not previously reported in literature. See text for more details.

Examples of Galactic sources that will be investigated with the ASTRI Mini-Array.

The ASTRI Mini-Array will allow us to explore the almost unexplored region above a few tens of TeVs.

ASTRI Mini-Array will be fundamental to resolve the particle acceleration in these sources.

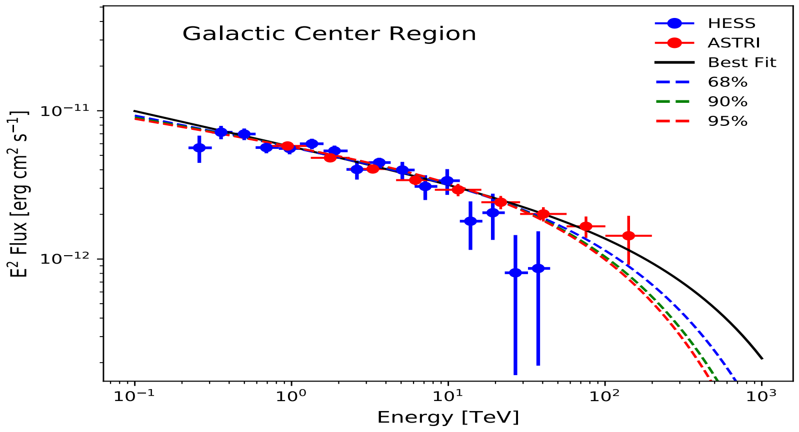


Figure 12: Galactic Center region: HESS (blue points) and ASTRI-MA (260 hr; red points) spectra fitted with a proton population with a best fit cut-off at 50 PeV (black solid line). The blue, green and red solid lines indicates the 68% (20 PeV), 90% (0.9 PeV) and 95% (0.8 PeV) confidence level for the cut-off, respectively.

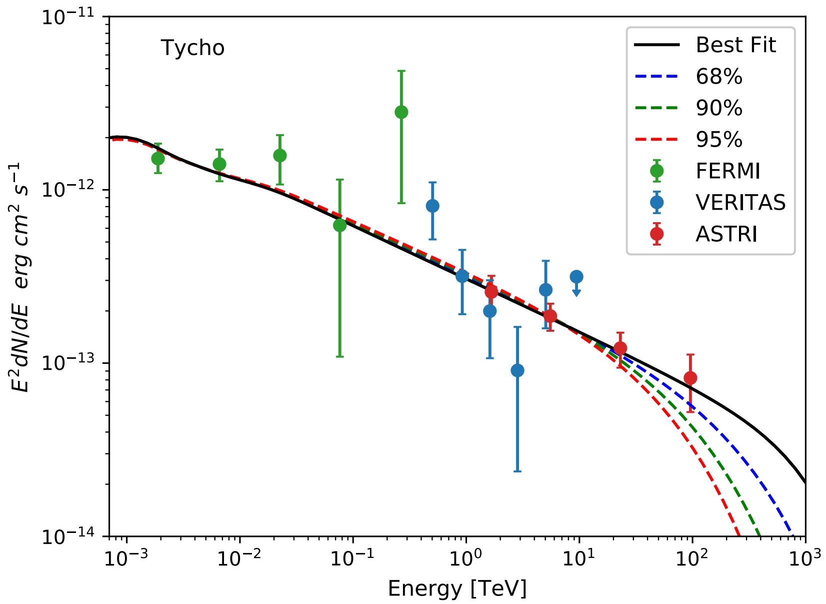


Figure 10: Tycho SNR: γ-ray data from Fermi-LAT (green), VERITAS (orange) (Archambault et al., 2017) and ASTRI-MA simulations (red) for 500 hr of observations. The blue lines show the PL fit with cut-off energies of 0.46, 0.73, 3.4 PeV (corresponding to 95, 90 and 68% of confidence levels).

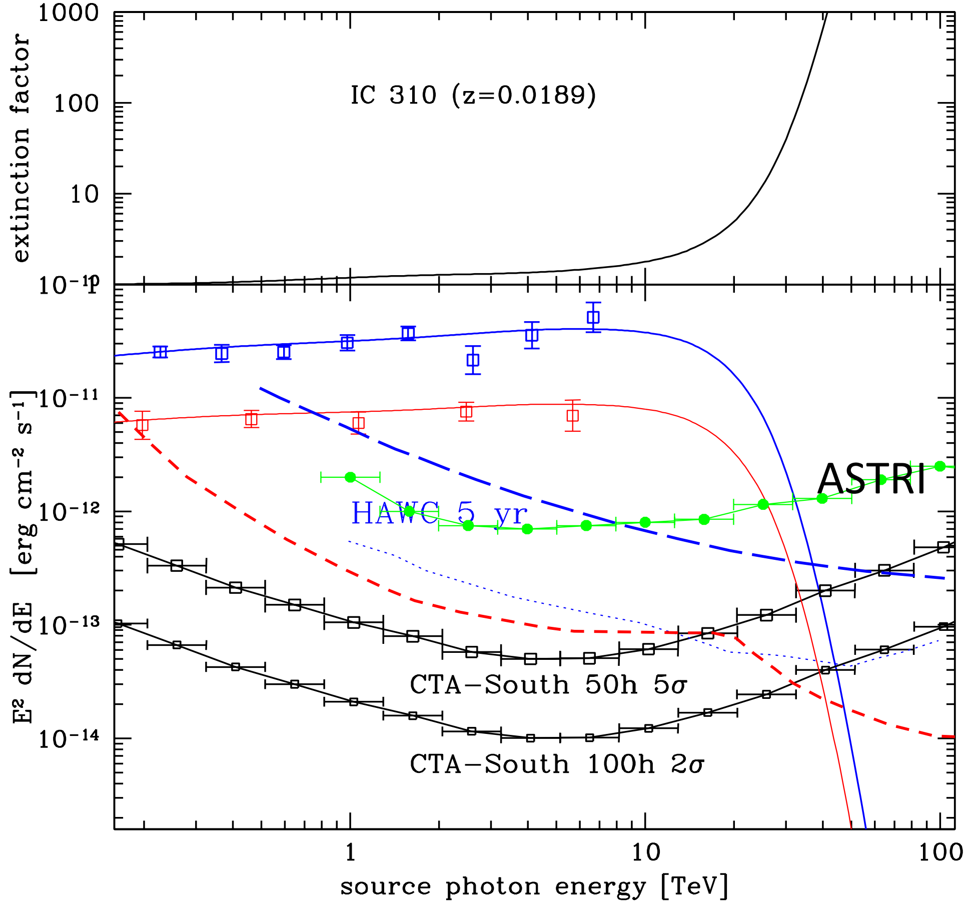
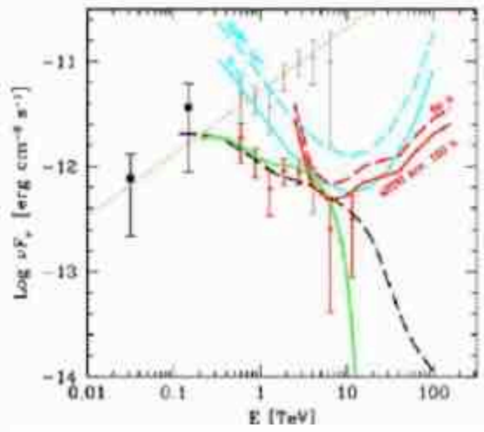
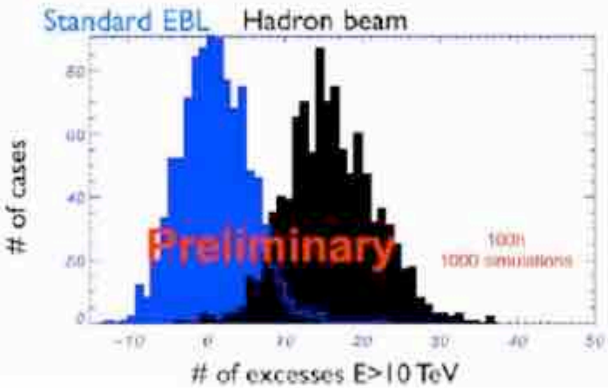
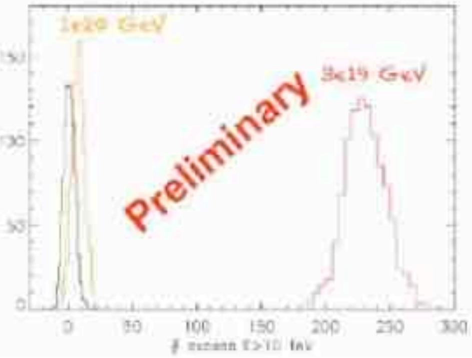


Figure 22: The upper panel reports the e^{τ} extinction factor for photon-photon interaction on EBL at the IC 310 source distance. Bottom panel reports data-points for two stages of the source, a flare in blue and high-state in red, together with best-fitting curves including EBL extinction. The green points mark the ASTRI Mini-Array 50 hours 5σ limit and the red dashed line is the foreseen LHAASO 5-yrs sensitivity.

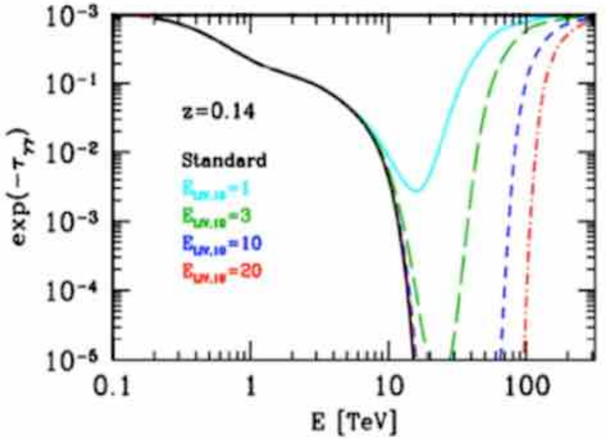
Observation of a few blazars will allow to investigate acceleration processes, to discriminate emission mechanisms (leptonic/adronic), transparency of the region (related to neutrinos and UHECR)
Furthemore the same object could be used for studies of EBL or fundamental physics as hadron-beam, axion-like particles or Lorentz invariance violation.







Discrimination of the photon-induced and proton-induced cascade spectra with the ASTRI Mini array for the 1ES 0229+200 E-HBL



γ- γ opacity for a blazar at redshift z = 0.14. Black solid line is the expected optical depth for standard γ- γ interaction with the EBL while the coloured lines are the expected depth in the presence of quantum gravity effects at various orders.

CREDITS: F. Tavecchio/ F. Lucarrelli /INAF Milano - Roma

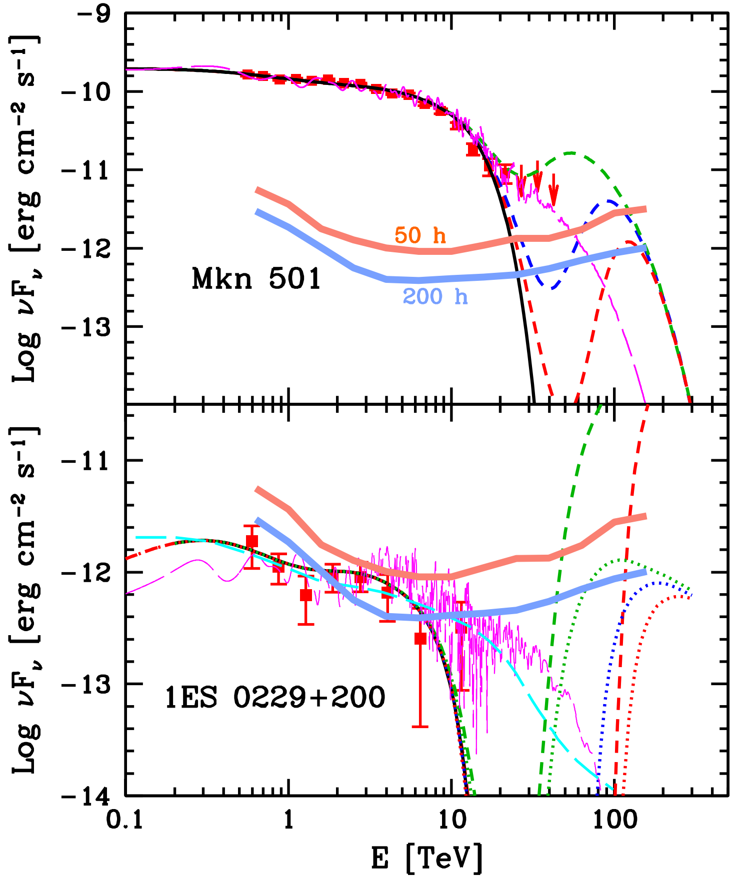


Figure 27: Upper panel: VHE spectrum of Mkn 501 measured by HEGRA during the extreme outburst in 1997 (red triangles). The black solid curve reports an intrinsic cut-off power-law spectrum absorbed by interaction with EBL. The magenta long-dashed line shows the observed spectrum assuming mixing of photons with ALPs (from Galanti et al. 2020). The dashed curves report the observed spectrum assuming an intrinsic cut-off power-law spectrum and LIV occurring at different energy scales (from Tavecchio and Bonnoli 2016). Lower panel: as above for the case of 1ES 0229+200. For the LIV case we consider the intrinsic spectrum described by an unbroken (short dashed) or a broken (dotted) power law (see Tavecchio and Bonnoli 2016 for details). In both panels the orange and blue thick lines show the expected sensitivity of the ASTRI Mini-Array for 50 hours and 200 hours of exposure.

ASTRI and detection of CR PEV hadrons

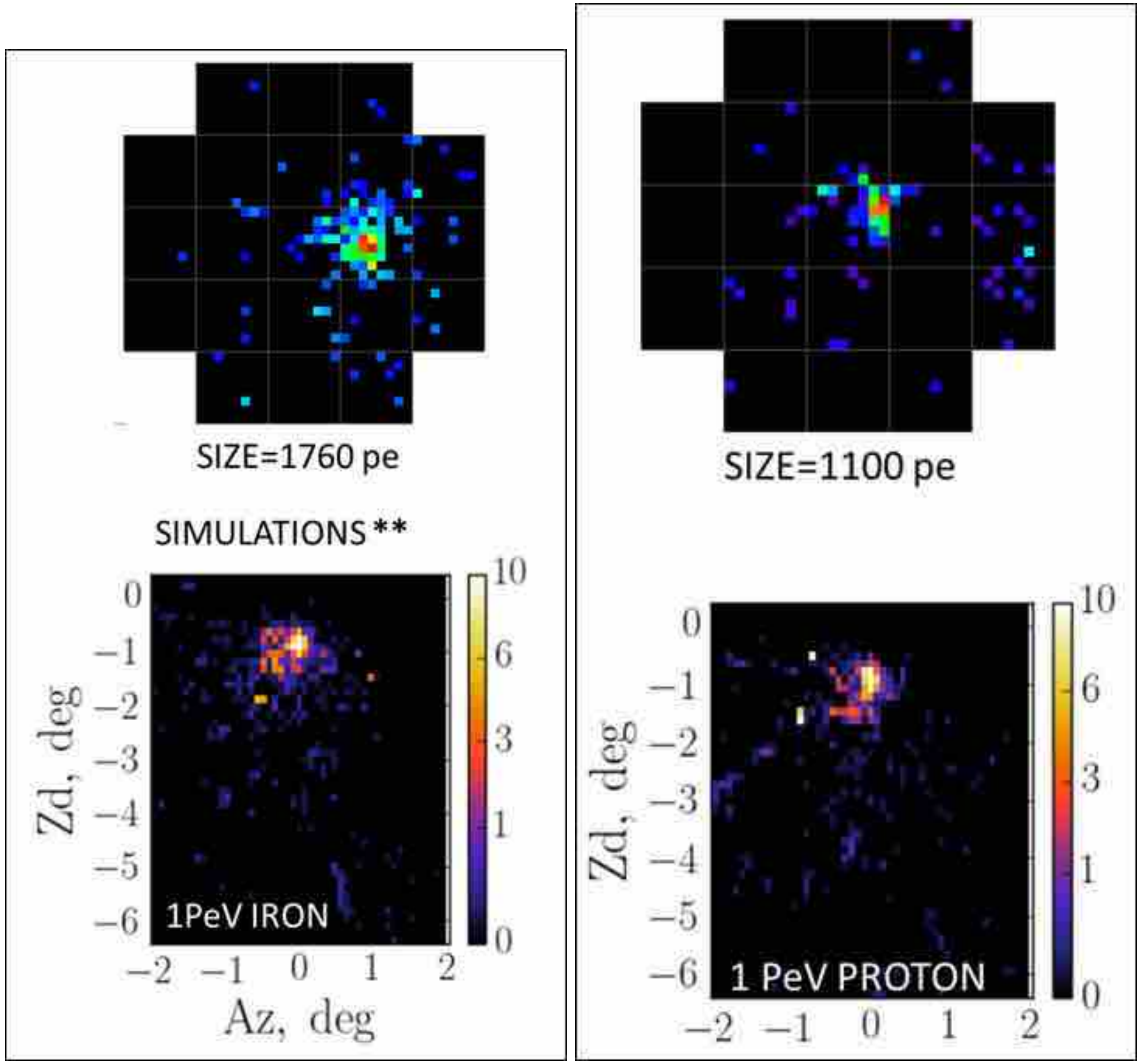
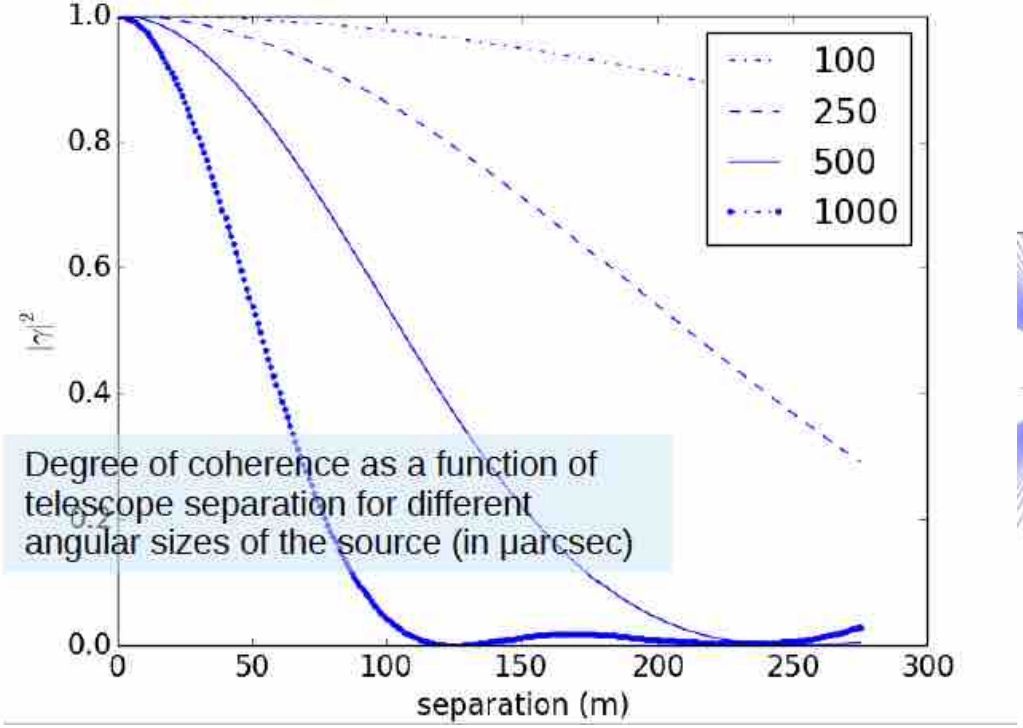


Figure 38: Images of the two detected events. The size is here calculated summing image-pixels greater than 6pe.

ASTRI mini-array: not only for VHE astronomy

ASTRI Miniarray envisages the scientific potential of Stellar Intensity Interferometry for achieving optical imaging with resolution of ~100 microarcseconds.

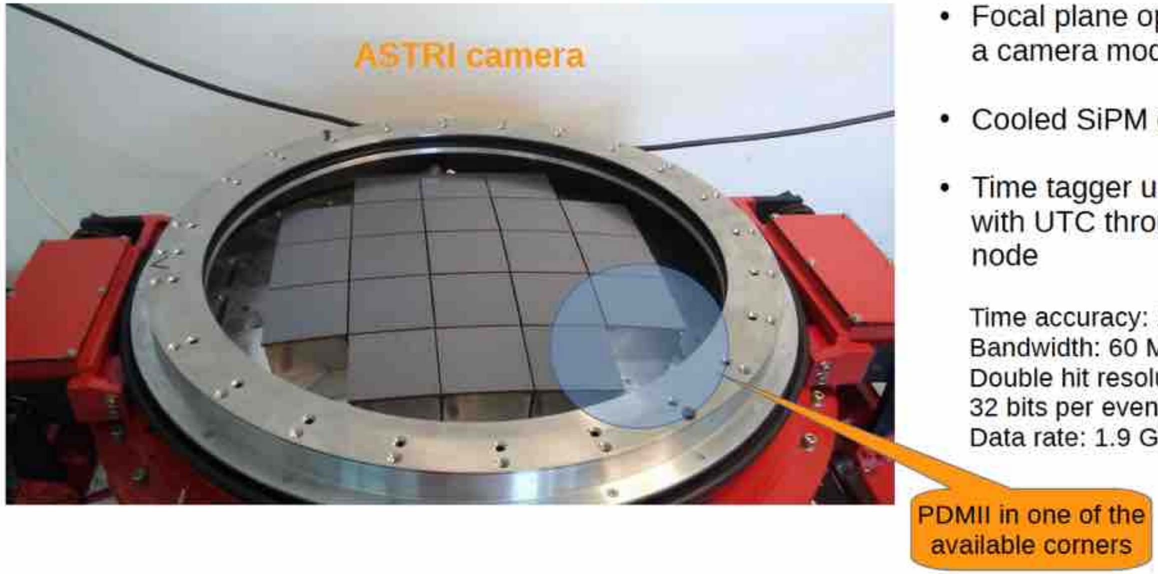
Resolution capabilities (~200 m sep.): sub-marcsec
Baselines for image reconstruction: 72 (for 9 tel.)



Degree of coherence as a function of telescope separation for different angular sizes of the source (in μarcsec)

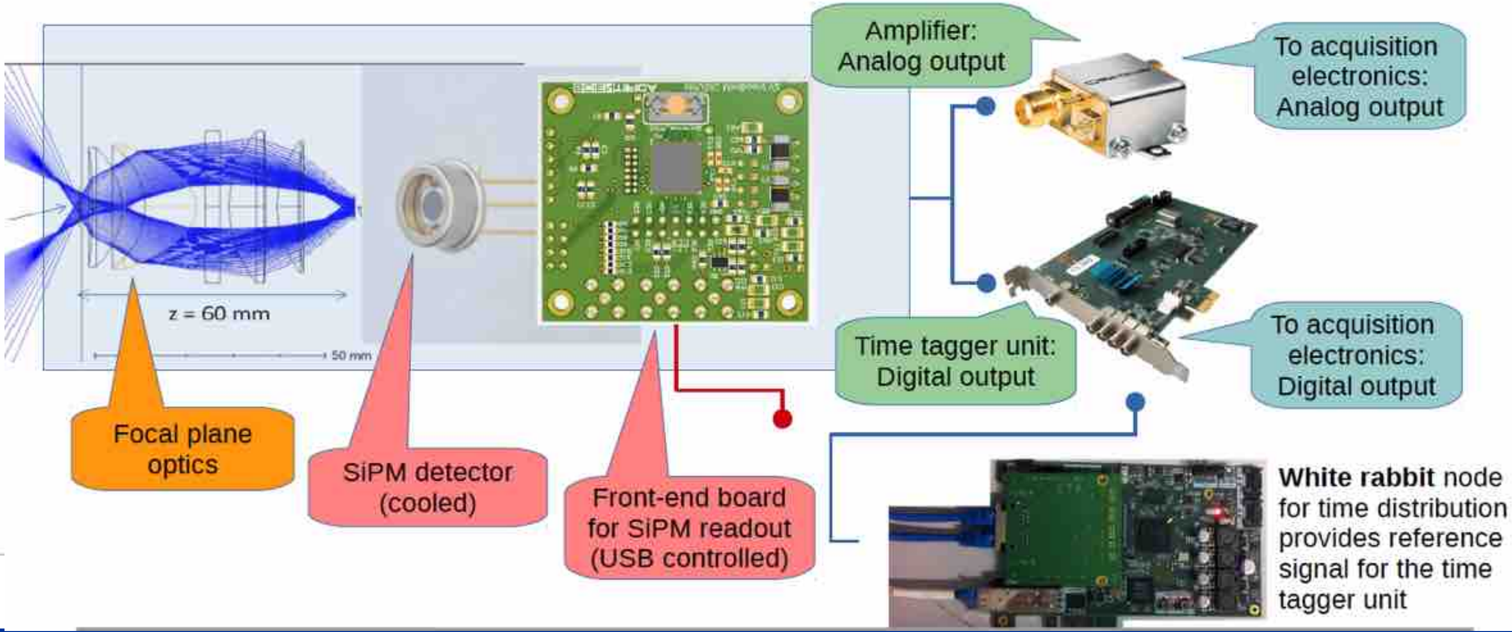
CREDITS: L. Zampieri – INAF Padova

PDMII and acquisition electronics: Requirements



- Focal plane optics fits inside a camera module
- Cooled SiPM detector
- Time tagger unit synchronized with UTC through a White Rabbit node

Time accuracy: 1 ns
Bandwidth: 60 Mhits/s
Double hit resolution: 1 ns
32 bits per event
Data rate: 1.9 Gbit/s



Title: ASTRI mini-array schedule
Date: Mon 04/05/20
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ASTRI Mini-Array Construction Project

ID	Task Name	Start	Finish	Duration
0	**ASTRI Mini-Array**	**Wed 22/06/16**	**Thu 13/10/2:**	**1647 days**
1	**Infrastructure**	**Mon 09/03/20**	**Fri 23/07/21**	**360 days**
9	**Telescopes**	**Wed 22/06/16**	**Thu 13/10/22**	**1647 days**
80	**Software**	**Thu 04/07/19**	**Wed 24/08/2:**	**820 days**
87	**Environmental Monitoring Syste**	**Mon 06/04/20**	**Fri 11/12/20**	**180 days**
90	**Calibration System**	**Mon 04/05/20**	**Fri 17/09/21**	**360 days**
94	**Atmospheric Characterization System**	**Mon 08/06/20**	**Mon 17/01/22**	**421 days**
101	**On Site Integration & Verificatio**	**Mon 05/04/21**	**Thu 15/09/22**	**379 days**