Perspectives on ASTRI observations of AGNs and connections with fundamental physics

Giorgio Galanti (INAF, IASF-Milano)
for the ASTRI Project

RICAP-24 Roma International Conference on AstroParticle Physics, 23-27/09/2024

ASTRI Mini-Array @ Teide Observatory

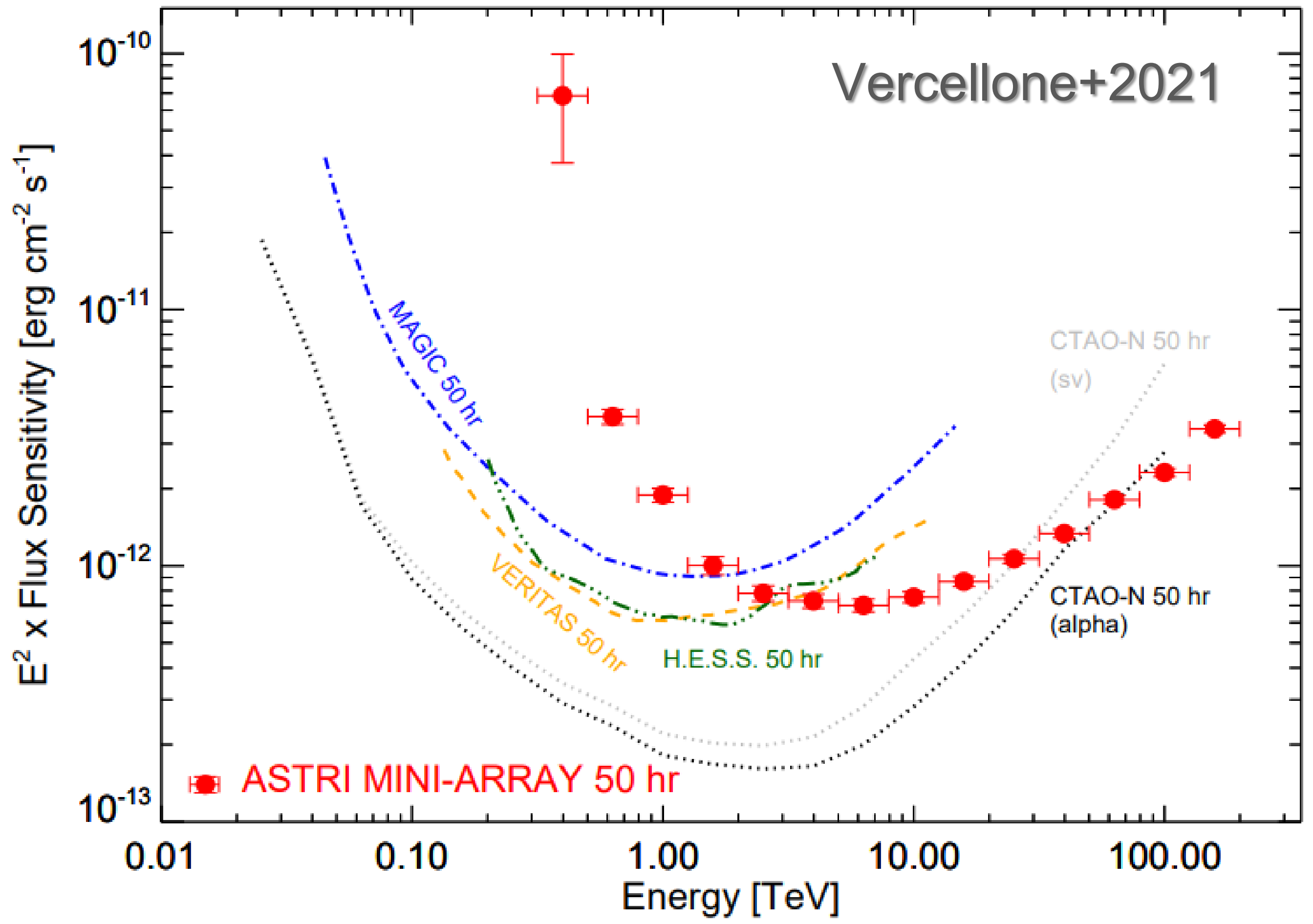
Mini-Array

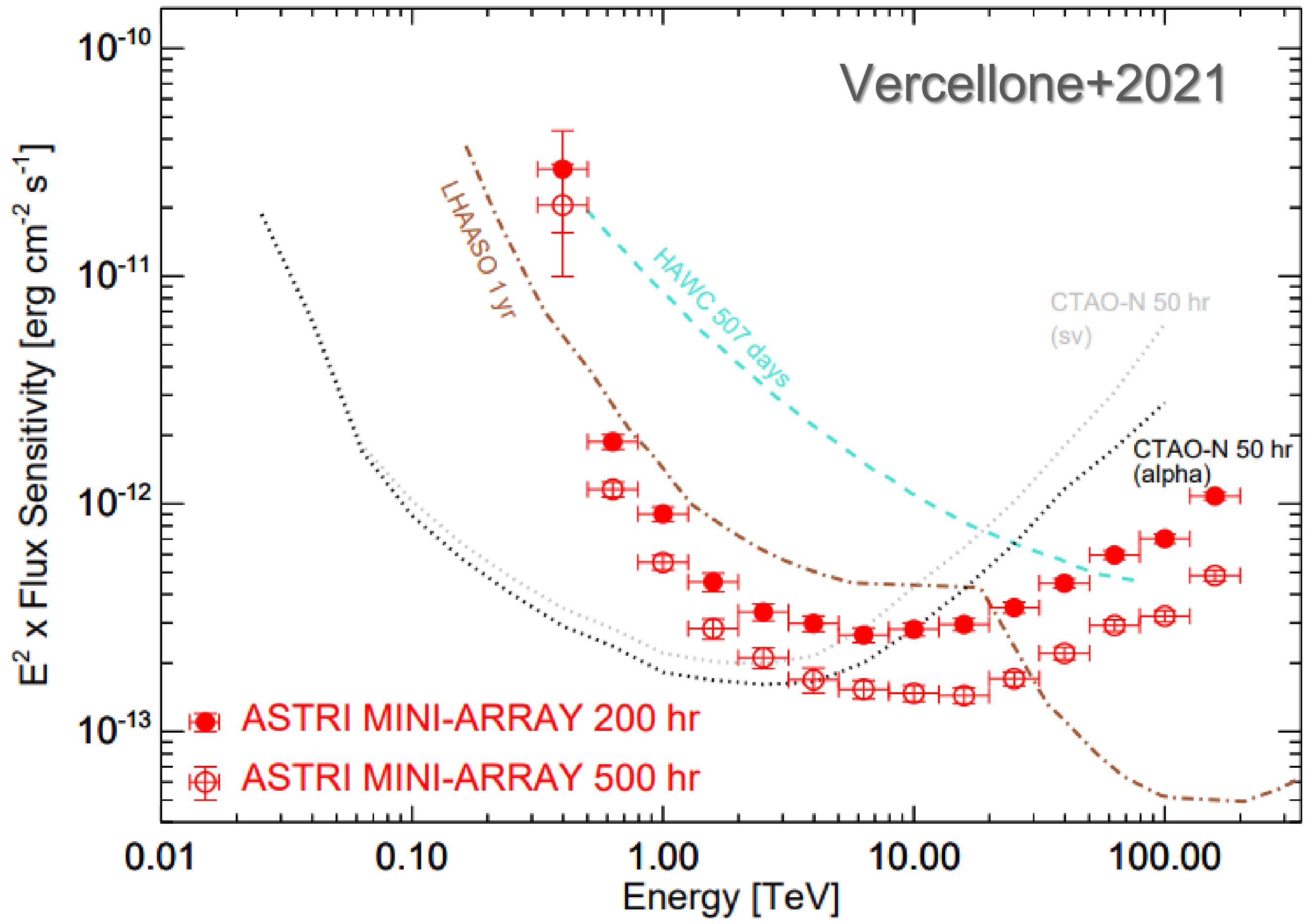
- Under construction at the Observatorio del Teide (Tenerife), in collaboration with IAC
- Being **developed in all its aspects**, from design/implementation of all HW/SW components to dissemination of final scientific products
- Unprecedented performance and wide FoV for observations at **multi-TeV energy scale**
- **Core Science Program** in the first 4 years
- **Important synergies** with other Northern ground-based gamma-ray facilities (LHAASO, HAWC, MAGIC, VERITAS, CTAO-N)

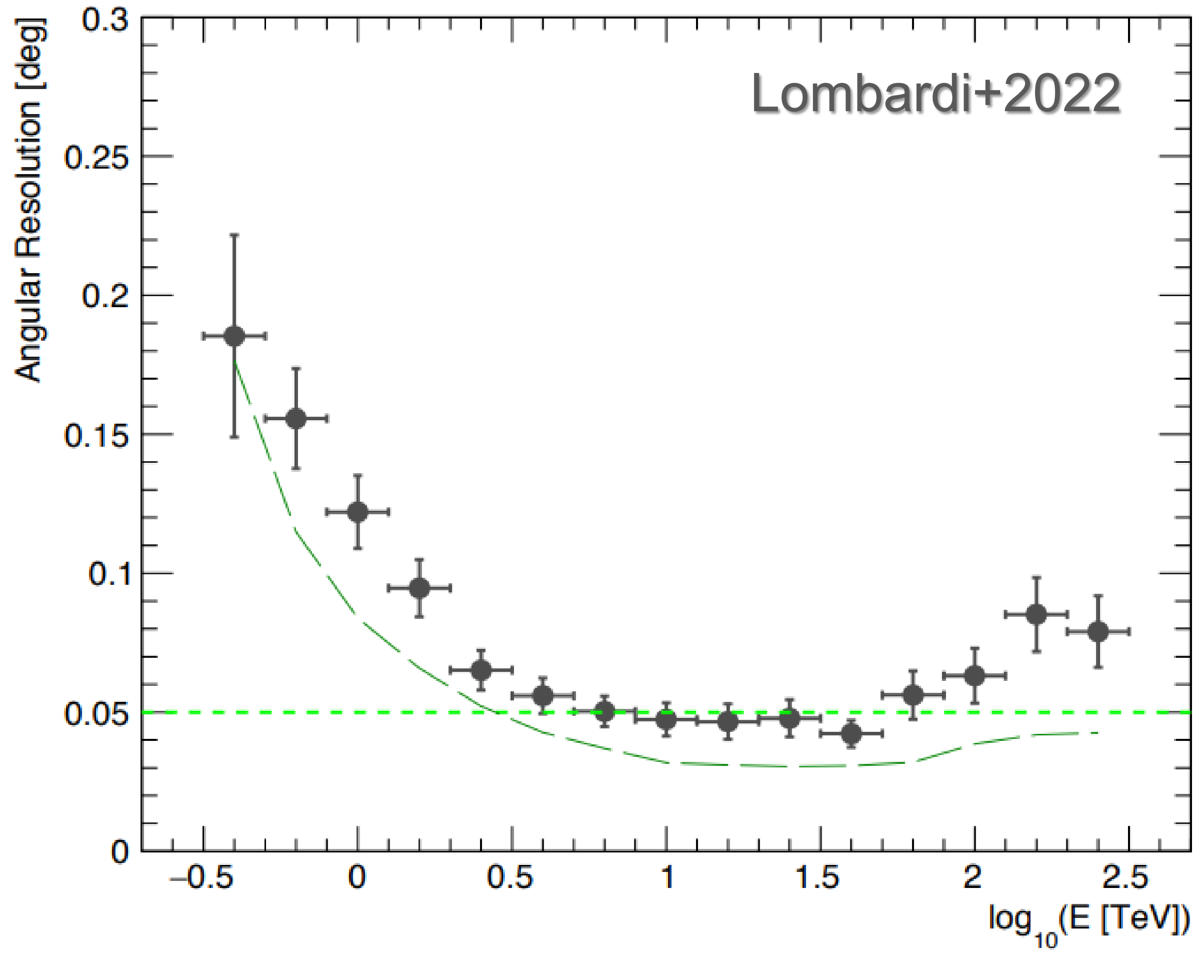
CREDITS : Adapted from Andrea Giuliani

ASTRI Mini-Array performance

- **Sensitivity:** better than that of current IACTs (*E* > a few TeV)
  - Extension of the spectra of already detected sources and/or measurement of cut-offs
- **Energy/Angular resolution:** ~10% / ~3‘ (*E* > a few TeV)
  - Characterization of the morphology of extended sources at the highest VHE





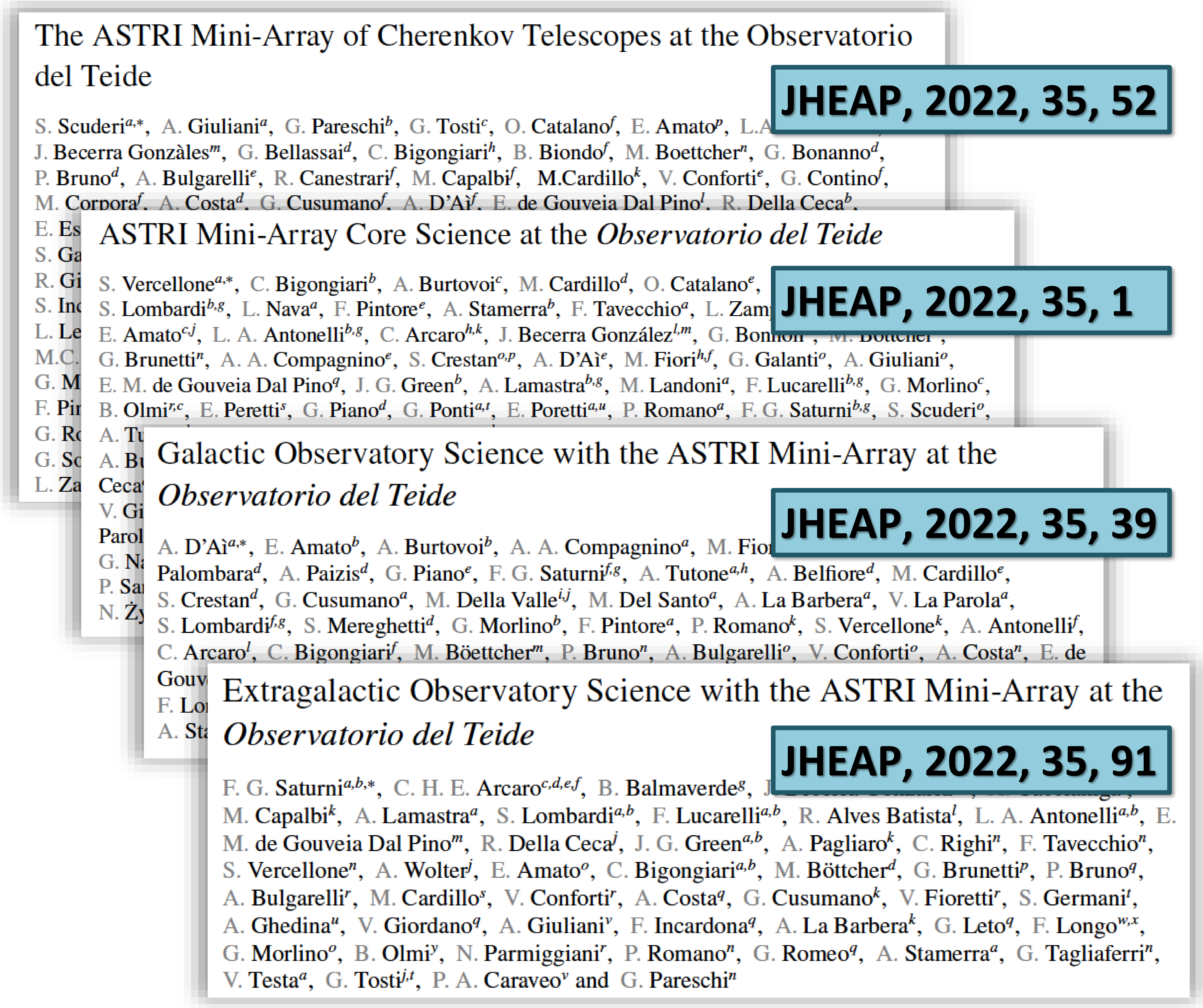


- **ASTRI Mini-Array** needs deep exposures -> focus on few sky fields
  - **Large field of view** (FoV) -> **several sources** in the FoV
  - Observations with moonlight -> increase of available time ~50–80 %
  - **Large zenith angle** -> **increase** of the **effective area** at high energy

CREDITS : Adapted from Andrea Giuliani

ASTRI Science: overview

- **Origin of Cosmic Rays**
  - PeVatrons
  - CR acceleration and propagation
  - Pulsar Wind Nebulae and TeV Halos
- **Fundamental Physics**
  - Intergalactic fields
  - Blazars
  - ALP, LIV, HB
- **Transient Follow-Up**
- **Non gamma-ray science**



ASTRI Science: overview

ASTRI Mini-Array

- **Origin of Cosmic Rays**
  - PeVatrons
  - CR acceleration and propagation
  - Pulsar Wind Nebulae and TeV Halos
- **Fundamental Physics**
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  - ALP, LIV, HB
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- **Non gamma-ray science**

The ASTRI Mini-Array of Cherenkov Telescopes at the Observatorio del Teide

JHEAP, 2022, 35, 52

ASTRI Mini-Array Core Science at the *Observatorio del Teide*

JHEAP, 2022, 35, 1

Galactic Observatory Science with the ASTRI Mini-Array at the *Observatorio del Teide*

JHEAP, 2022, 35, 39

Extragalactic Observatory Science with the ASTRI Mini-Array at the *Observatorio del Teide*

JHEAP, 2022, 35, 91

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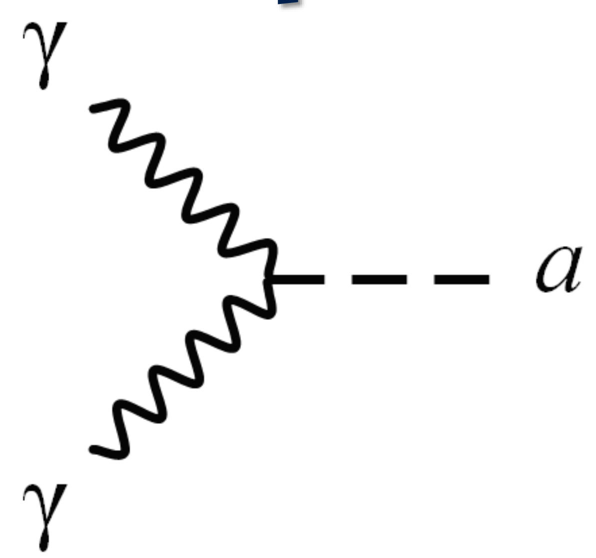
Axion-like particles (ALPs)

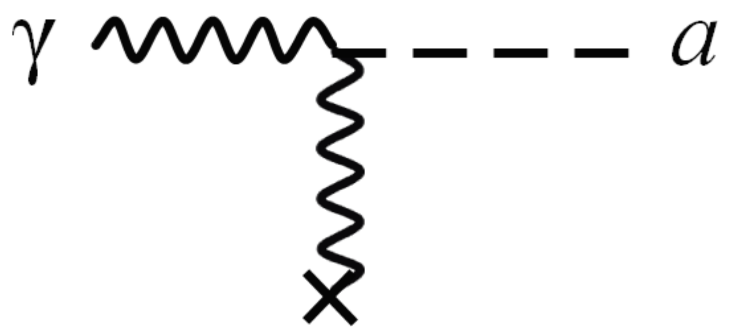
- Predicted by **String Theory**
- Very light particles ($m_a < 10^{-8}$ eV)
- Spin 0
- **Interaction with** two **photons** (coupling $g_{a\gamma\gamma}$)
- Subdominant interactions with other particles
- Possible candidate for dark matter
- Produce **spectral** and **polarization effects**

Two photons

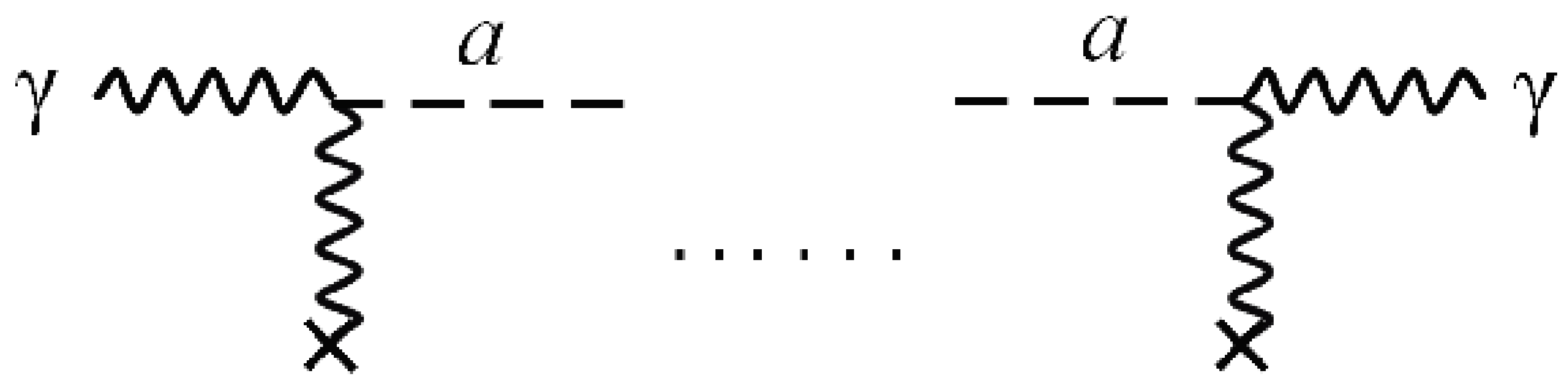


$$\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$$

In an external B field



Photon-ALP oscillations



ALPs in astrophysical contest

ASTRI Mini-Array

- ALPs very elusive in laboratory experiments (low coupling) → **astrophysical environment** is the **best opportunity** to study ALPs and ALP effects (*for free*)
- Photon/ALP beam with energy $E >> m_a$
- ALPs induce **modifications to astrophysical spectra**
  - For E < 10 GeV → negligible photon absorption due to EBL
    - **Photon-ALP interaction** produces effective **photon absorption**
  - For E > 10 GeV → photons absorbed by EBL ($\gamma\gamma \rightarrow e^+e^-$), **ALPs** are **not absorbed**
    - **Photon-ALP oscillations increase medium transparency**
- ALPs induce **modifications to photon polarization** (*birefringence*, *dichroism*)
- **HINTS** at ALP existence:
  - Explain FSRQs emission up to 400 GeV → Tavecchio, Roncadelli, Galanti, Bonnoli, Phys. Rev. D, 86, 085036 (2012)
  - Solve the redshift dependence of blazar spectra → Galanti, Roncadelli, De Angelis, Bignami, MNRAS 493, 1553 (2020)
  - GRB 221009A → Galanti, Nava, Roncadelli, Tavecchio, Bonnoli, Phys. Rev. Lett. 131, 251001 (2023)

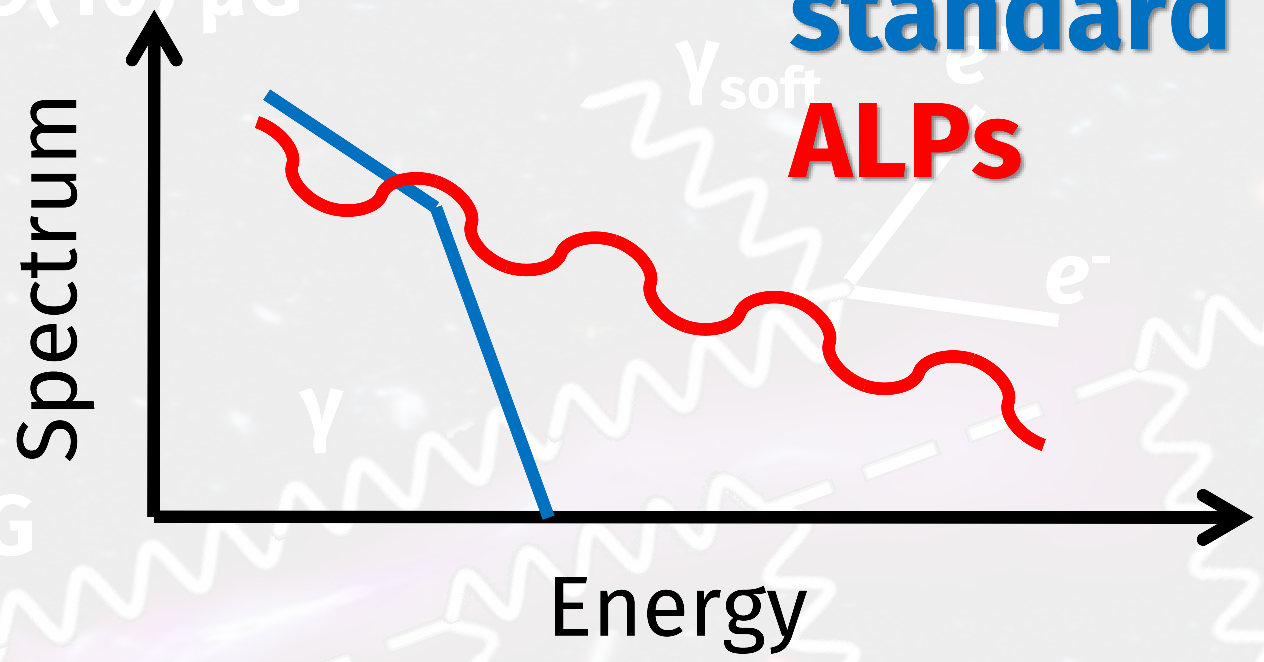

γ: photon
a: ALP
absorption: $\gamma + \gamma_{Soft} \rightarrow e^+ + e^-$
γ_{Soft}: EBL, BLR
$g_{a\gamma\gamma}$: γγa coupling
E: γ electric field
B: external magnetic field
$\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}$ E·B a
Milky Way:
Horns, Maccione, Meyer et al., Phys. Rev. D, 86, 075024 (2012)
Galanti, Tavecchio, Roncadelli, Evoli, MNRAS 487, 123 (2019)
$B_{MW} = O(1)$ μG
Host galaxy:
Galanti, Nava, Roncadelli, Tavecchio, Bonnoli, Phys. Rev. Lett. 131, 251001 (2023)
Levan et al., ApJL 946 L28 (2023)
$B_{host} = O(10)$ μG
γ_{soft}
e^+
e^-
γ
a
$B_{jet} = O(1\text{-}10^4)$ G
$B_{ext} = O(1)$ nG
Extragalactic space:
Mirizzi, Montanino, JCAP 12, 004 (2009)
Galanti, Roncadelli, Phys. Rev. D 98, 043018 (2018)
Galanti, Roncadelli, JHEAp, 20 1-17 (2018)
Source:
Tavecchio, Roncadelli, Galanti, Phys. Lett. B 744, 375 (2015)
Galanti, Nava, Roncadelli, Tavecchio, Bonnoli, Phys. Rev. Lett. 131, 251001 (2023)

γ: photon
a: ALP

absorption: $\gamma + \gamma_{Soft} \rightarrow e^{+} + e^{-}$
γ_{Soft}: EBL, BLR

SPECTRA

- **Standard physics**
  - photon absorption
- **With ALPs**
  - lower photon absorption
  - spectral irregularities



$g_{a\gamma\gamma}$: $\gamma\gamma a$ coupling
E: γ electric field
B: external magnetic field
$\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$

POLARIZATION

- **Standard physics**
  - unpolarized photon case
- **With ALPs**
  - modified polarization
  - partially polarized photons

Milky Way:
Horns, Maccione, Meyer et al., Phys. Rev. D, 86, 075024 (2012)
Galanti, Tavecchio, Roncadelli, Evoli, MNRAS 487, 123 (2019)
$B_{MW} = O(1)$ μG

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Levan et al., ApJL 946 L28 (2023)
$B_{host} = O(10)$ μG

$B_{jet} = O(1\text{-}10^4)$ G

$B_{ext} = O(1)$ nG

Extragalactic space:
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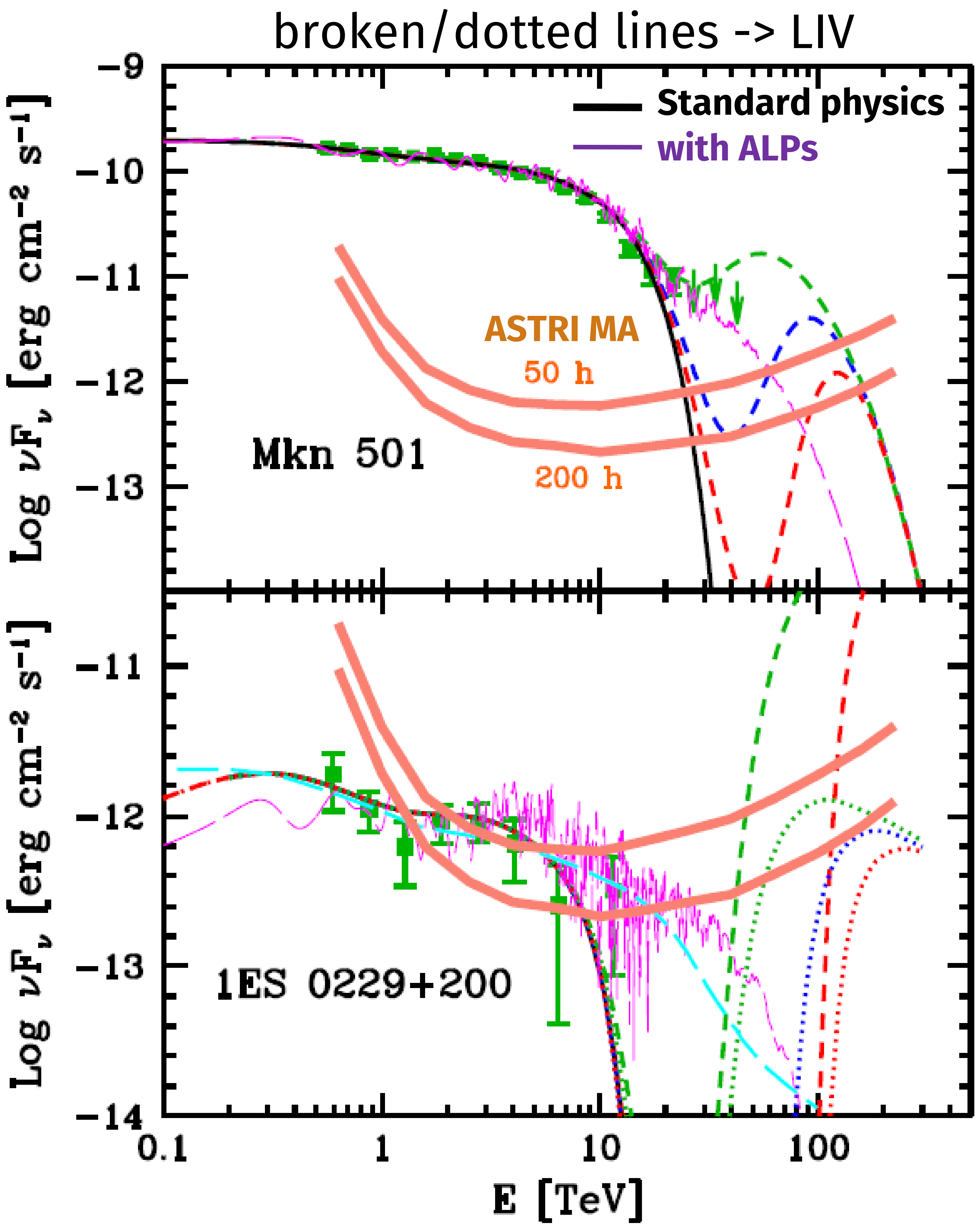
Galanti, Nava, Roncadelli, Tavecchio, Bonnoli, Phys. Rev. Lett. 131, 251001 (2023)

ALPs with the ASTRI Mini-Array

- **Markarian 501** & **1ES 0229+200** -> emission in the jet
- Low ALP mass m_a -> γ-a conversion in the **high-energy weak mixing** regime (QED and CMB dispersion effects)
- γ<->a oscillations in the jet, host galaxy, extragalactic space & Milky Way
- $B_{jet,0}$ = 0.5 G; B_{ext} = 1 nG
- $m_a = O(10^{-10})$ eV; $g_{a\gamma\gamma} = O(10^{-11})$ GeV^{-1}
- Detectable ALP induced effects:
  - **Spectral oscillations**
  - **Photon excess** above ~10 TeV

Vercellone et al. (ASTRI Collaboration), JHEAp 35, 1 (2022)



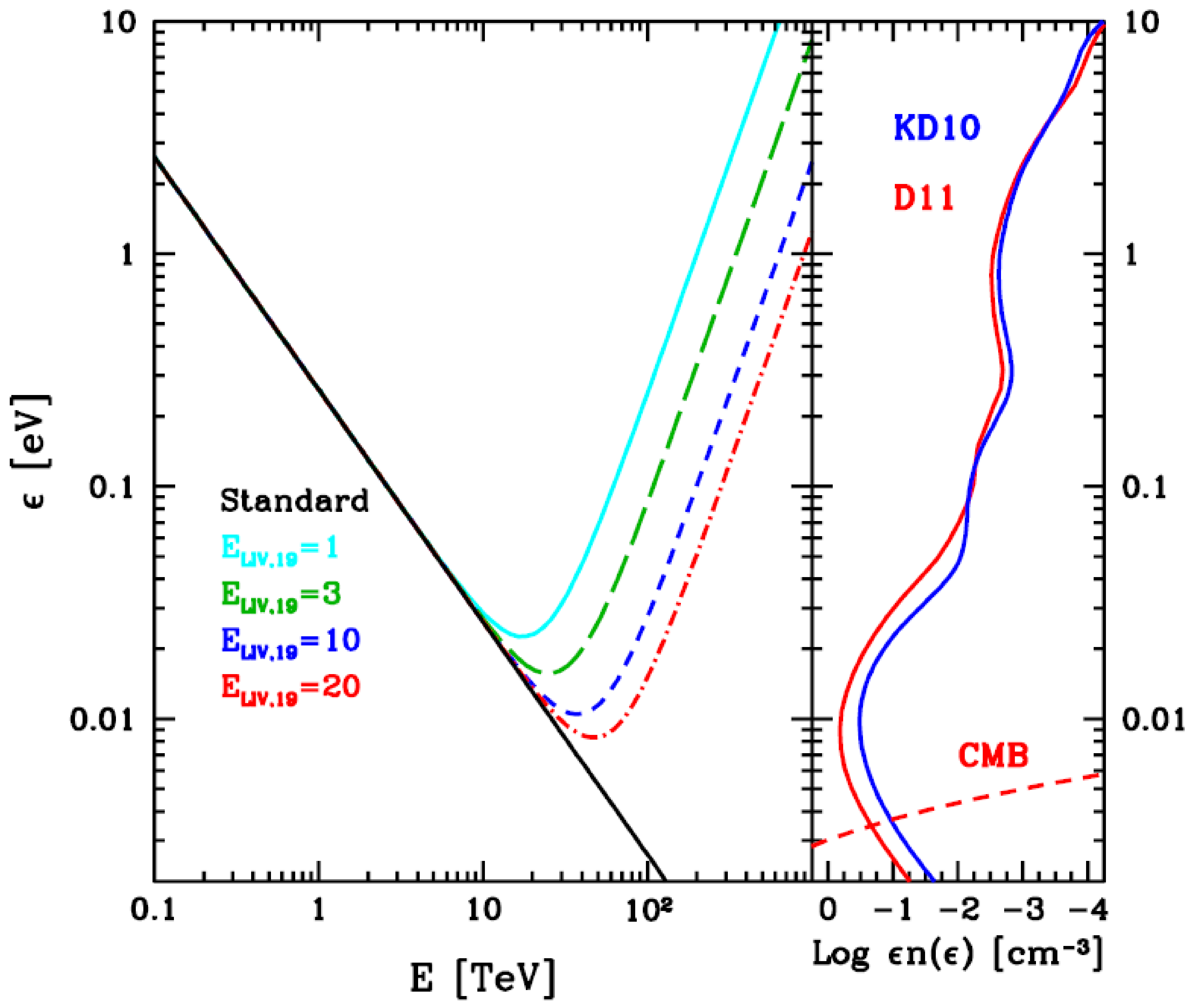
Lorentz Invariance Violation (LIV)

- Predicted by quantum gravity models for $E > 10^{19}$ GeV (Mattingly 2005)
- Effects on standard physics processes (Coleman&Glashow 1999; Jacobson+2003; Liberati 2013):
  - Photon decay
  - Photon splitting
  - **Modification of dispersion relations**
- **Modified photon dispersion relation**

$$E^2 - p^2 = -\frac{E^{n+2}}{E_{\mathrm{LIV}}^n}$$

E -> energy
p -> momentum
E_{LIV} -> LIV parameter

- → **Modification** of the **threshold** of the $\gamma\gamma \rightarrow e^+e^-$ process
  - Hundreds-TeV photons interact with optical/UV photons
  - **Smaller** photon absorption



Tavecchio & Bonnoli, A&A 585, A25 (2016)

LIV with the ASTRI Mini-Array

- **ASTRI Mini-Array** will **detect LIV** induced **effects** (if present):

- **Markarian 501** emitted spectrum:
  - power law with exponential **cutoff**

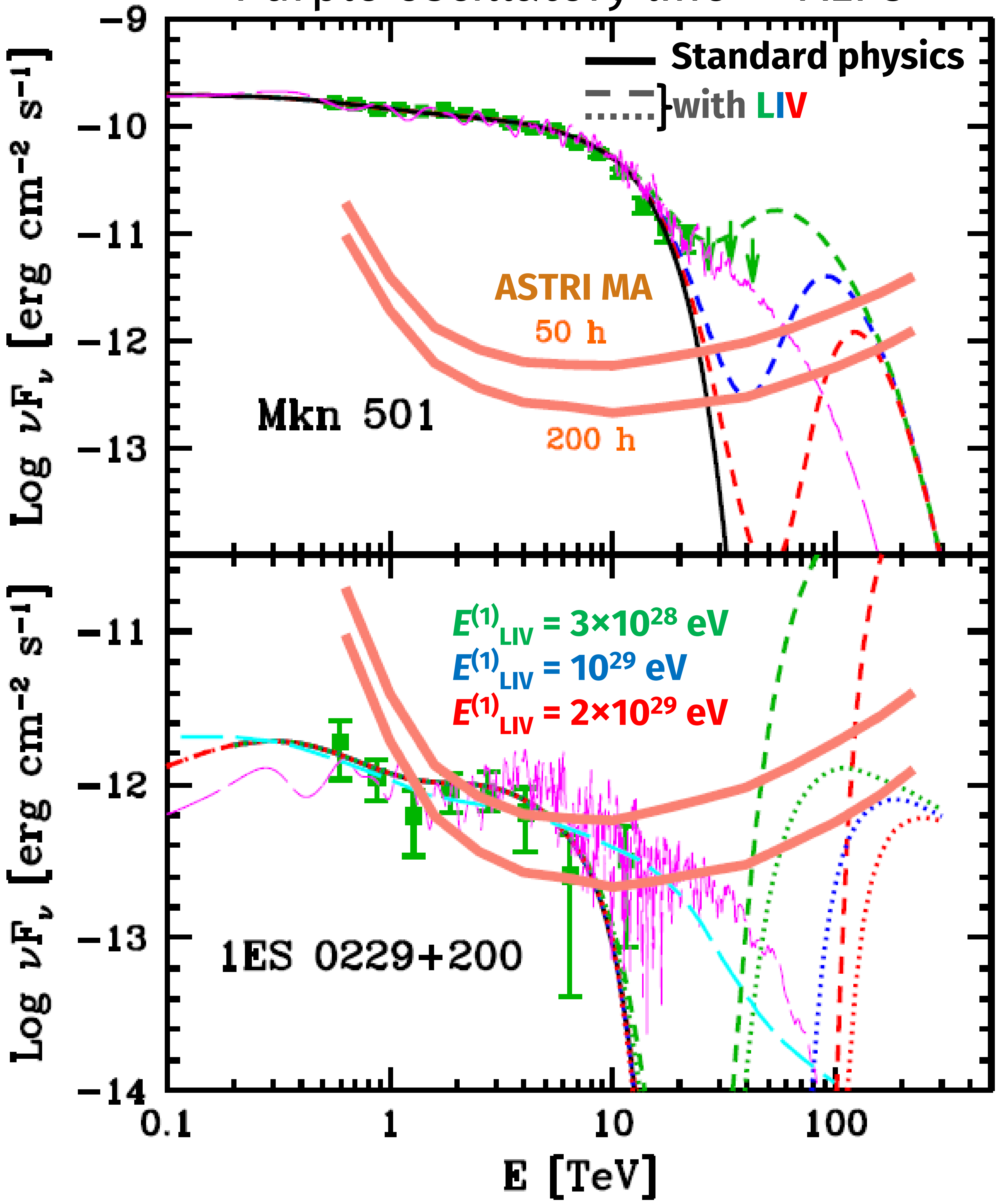
- **1ES 0229+200** emitted spectrum:
  - **unbroken** power law – – – –
  - **broken** power law ....

- **LIV effects** -> above ~50 TeV

- For **farther** sources:
  - **harder** emitted **spectrum** needed to observe LIV effects

Vercellone et al. (ASTRI Collaboration), JHEAp 35, 1 (2022)

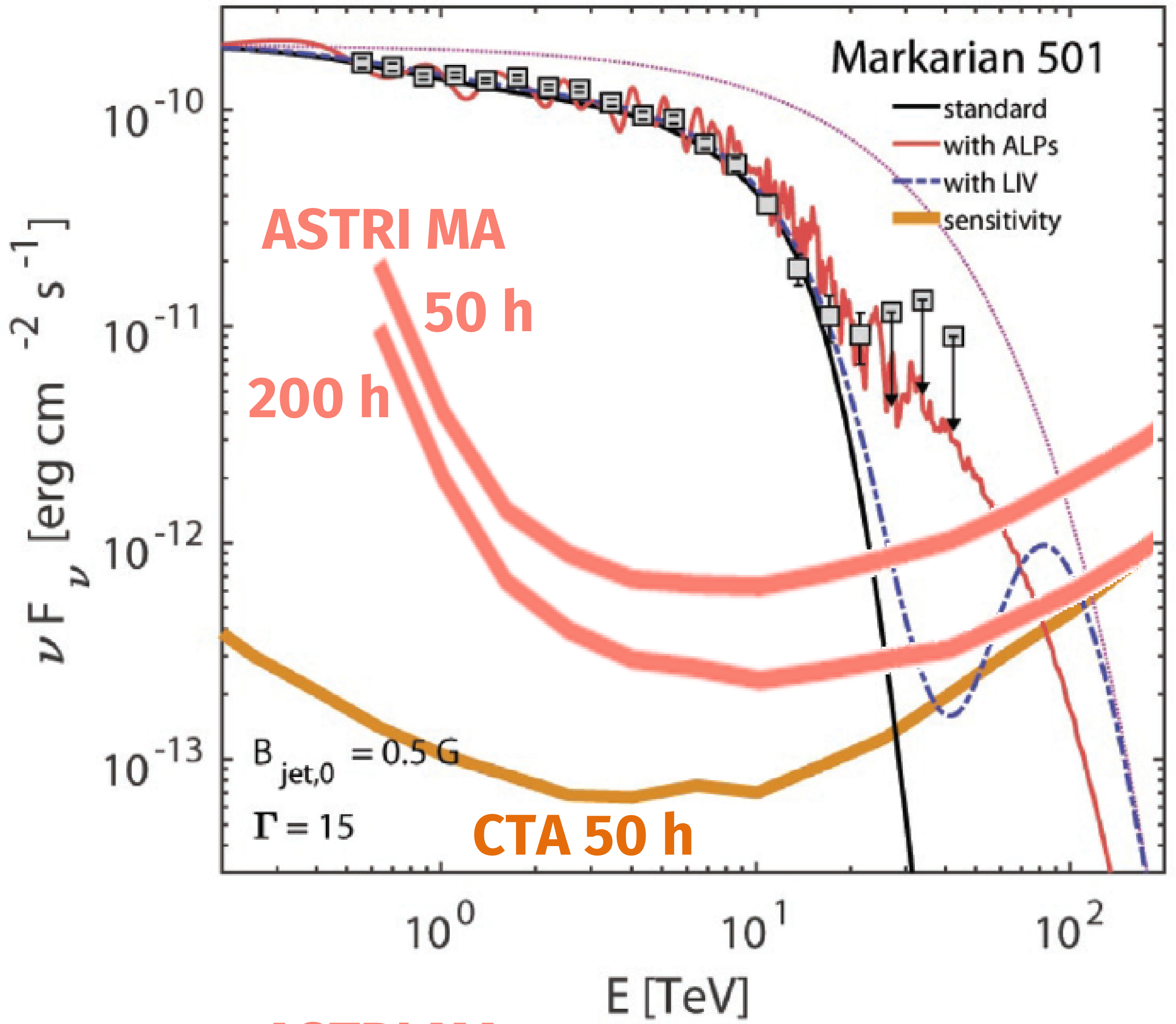
Purple oscillatory line -> ALPs

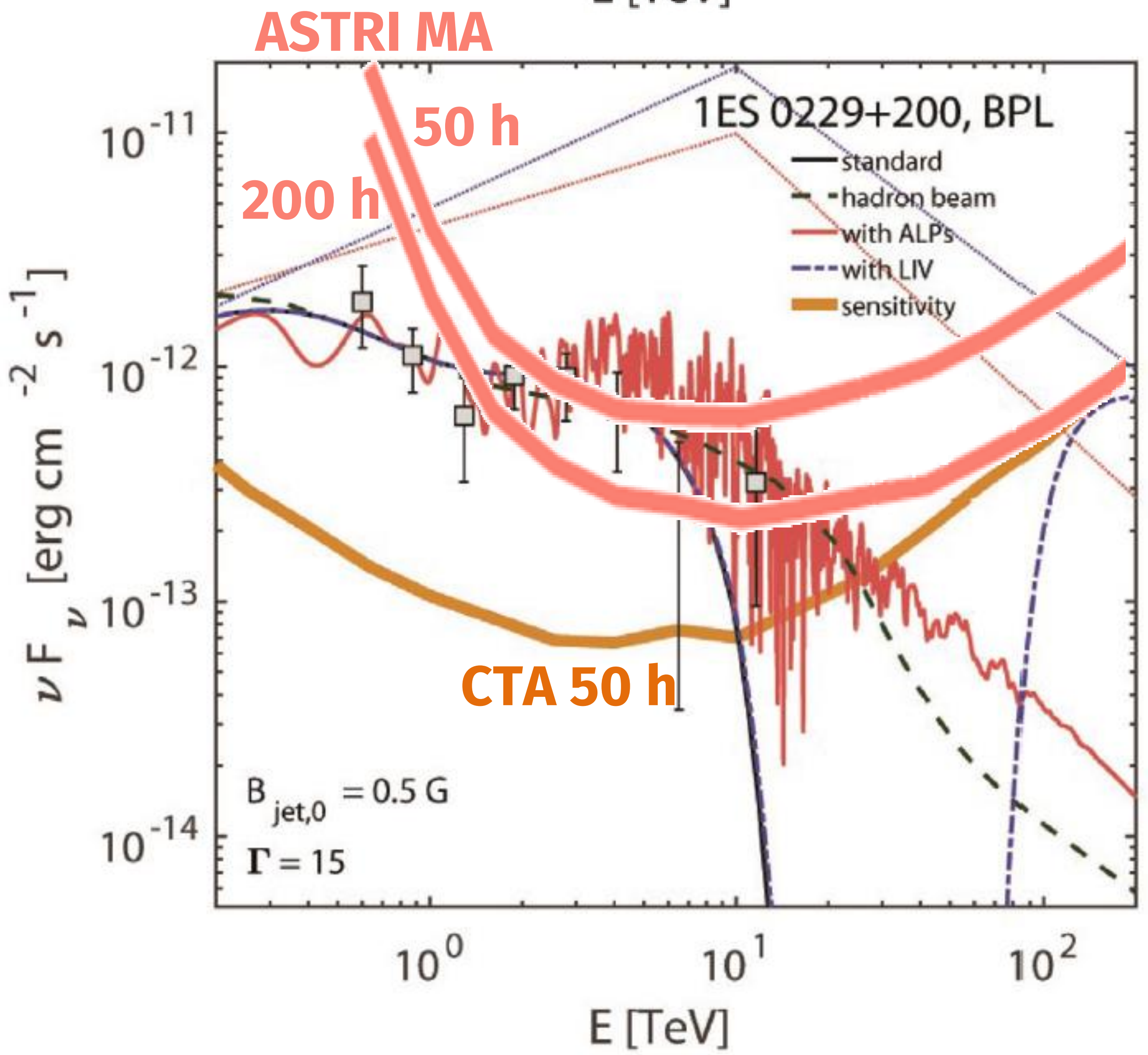


ALPs & LIV & hadron beam

- **ASTRI Mini-Array** can **detect** the **effects** induced by several models:
  - **ALPs** -> *photon excess* (above ~10 TeV) & *spectral oscillations*
  - **LIV** -> *photon excess* (above ~50 TeV)
  - **hadron beam** (**HB**, EM cascade of hadrons on background photons) -> *photon excess* (above ~10 TeV)
- **Markarian 501** -> ALPs, LIV, no HB (too variable)
- **1ES 0229+200** -> ALPs, LIV, HB
- **ASTRI Mini-Array** with the help of CTAO-N can **discriminate** among different models:
  - **ALPs only** predict **spectral oscillations**
  - CTAO-N -> more sensible at lower energies (0.2 – 2) TeV

Galanti, Tavecchio, Landoni, MNRAS 491, 5268 (2020)





GRB 221009A

ASTRI Mini-Array

- Extremely luminous Gamma Ray Burst (GRB) at redshift z = 0.151
- Observed by:
  - Fermi-GBM, Fermi-LAT (Fermi 2023), Swift (Williams+2023)
  - **LHAASO** at $E \simeq$ (13–18) TeV within 2000 s after the initial burst (LHAASO 2022, 2023a,b)
- **BUT strong EBL absorption** for $E \gtrsim$ 10 TeV at z = 0.151 within Conventional Physics (CP)

EBL	15 TeV		18 TeV		100 TeV		251 TeV	
	τ_{CP}	P_{CP}	τ_{CP}	P_{CP}	τ_{CP}	P_{CP}	τ_{CP}	P_{CP}
D	12.7	3×10^{-6}	19.4	4×10^{-9}	350	2×10^{-152}	9654	~0
G	9.4	8×10^{-5}	13.1	2×10^{-6}	246	2×10^{-107}	9502	~0
FR	10.1	4×10^{-5}	14.1	7×10^{-7}	333	2×10^{-145}	15411	~0
SL	12.8	3×10^{-6}	18.3	10^{-8}	220	3×10^{-96}	>9251	~0

τ_{CP} -> optical depth; P_{CP} -> photon survival probability
D -> EBL model by Domínguez et al., 2011
G -> EBL model by Gilmore et al. 2012
FR -> EBL model by Franceschini & Rodighiero 2017
SL -> EBL model by Saldana-Lopez et al. 2021

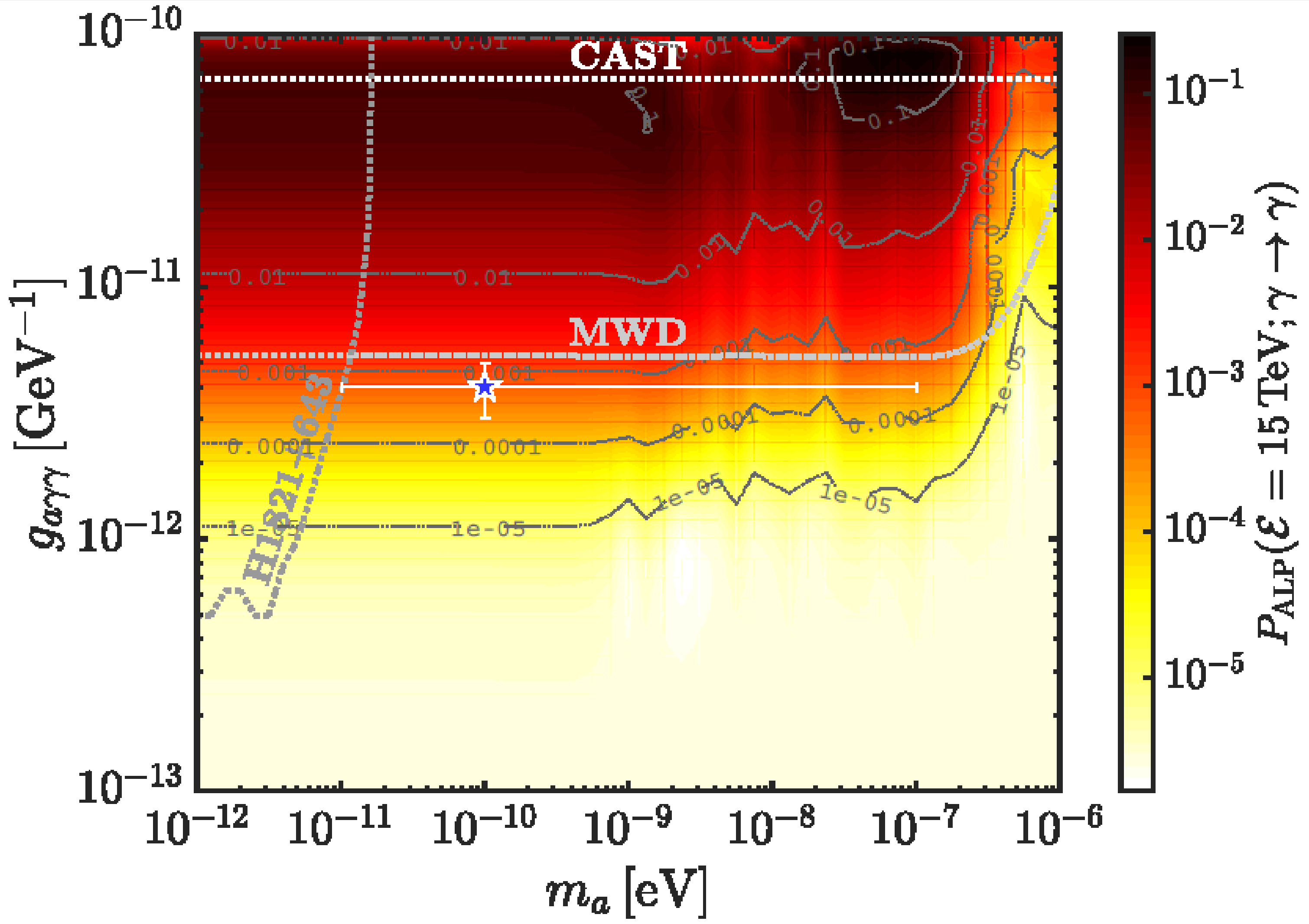
QUESTION:
How can we have detected this GRB up to $E \simeq$ (13–18) TeV?

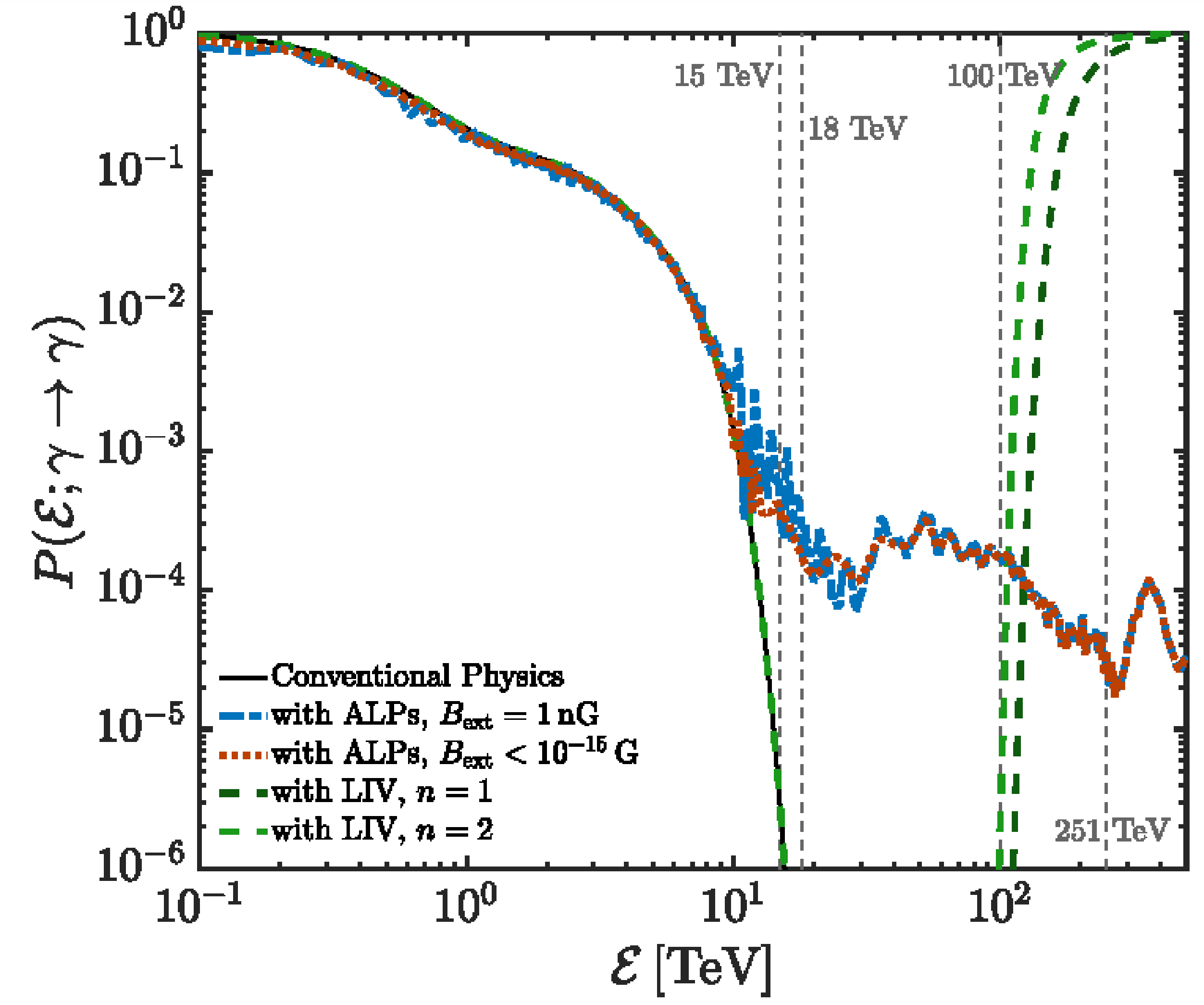
ANSWER:
with **axion-like particles (ALPS)** !!!

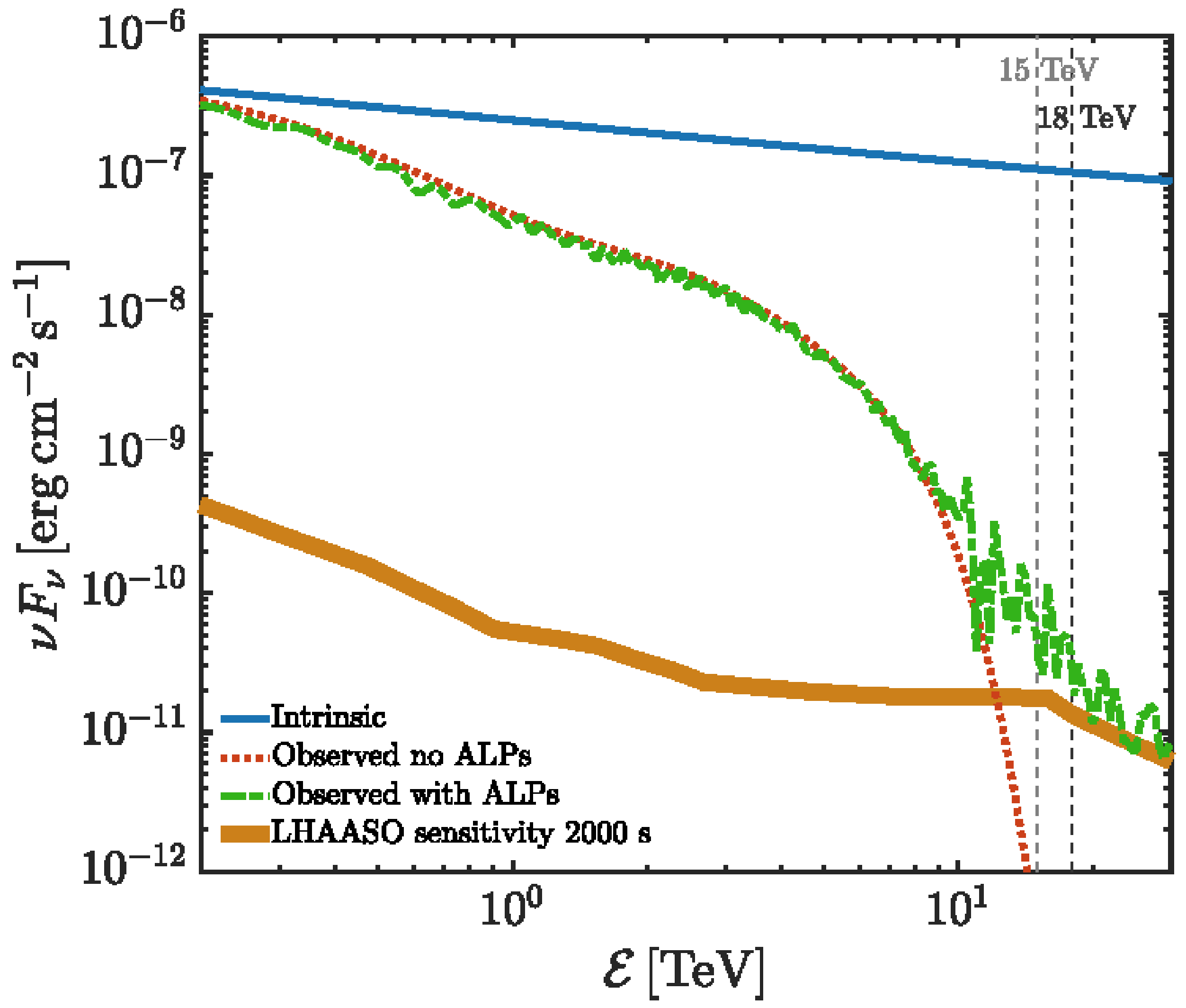
Galanti, Nava, Roncadelli, Tavecchio, Bonnoli, Phys. Rev. Lett. 131, 251001 (2023)

ALP hint from GRB 221009A

- **Photon-ALP mixing**
  - $g_{a\gamma\gamma} = (3 - 5) \times 10^{-12}$ GeV^{-1}
  - $m_a = (10^{-11} - 10^{-7})$ eV
- **LIV**
  - $E_{LIV,\, n=1} = 3 \times 10^{29}$ eV
  - $E_{LIV,\, n=2} = 5 \times 10^{21}$ eV







- Photon-ALP beam propagation in all crossed magnetized media
- **ALPs explain:**
  - LHAASO detection (LHAASO 2022)
  - GRB 221009A spectrum (LHAASO 2023a,b)

→ **hint at ALP existence**

- **LIV cannot explain** LHAASO event

Galanti, Nava, Roncadelli, Tavecchio, Bonnoli, Phys. Rev. Lett. 131, 251001 (2023)

- **ASTRI Mini-Array** might **detect** close **TeV GRBs** ($z < 0.4$)
  - **better energy resolution** with respect to LHAASO at ~10 TeV

The future

- **LHAASO** is expected to produce **new** exciting **observations** but with a **not so high energy resolution** (15% – 30% above 10 TeV):
  - Blazars
  - GRBs
  - …

- **ASTRI Mini-Array** can work in **synergy** with **LHAASO** with **better energy resolution** ($\lesssim$ 10%) at (1-100) TeV:
  - GRB 221009A -> could have had **better spectral characterization**
  - -> important **focus on GRBs** for **fundamental physics** studies
  - **possible solid conclusions** on **ALPs**, **LIV**, **HB**

- **Synergy** with **Fermi-LAT** & **Fermi-GBM** for a multi-wavelength analysis

- Possible **synergy** with polarimetric missions like **IXPE** (eXTP, NGXP, …) and **COSI** (e-ASTROGAM, AMEGO) to strengthen spectral results
  - **ALPs** & **LIV** produce detectable **polarization effects**

Conclusions

Mini-Array

- **ASTRI Mini-Array** -> fantastic observatory to perform studies on **fundamental physics**
- It will likely give us a final answer on **ALPs**, **LIV**, **HB**
- **Synergy** with **LHAASO**
- **Synergy** with **CTAO-N**
- **Synergy** with **Fermi-LAT** & **Fermi-GBM**
- **Synergy** with **IXPE** & **COSI**

Thank you

Backup slides

The ASTRI Mini-Array Project

Mini-Array

The ASTRI Mini-Array is a project whose purpose is to construct, deploy and operate an array of 9 Cherenkov telescopes of the 4 meters class at the Observatorio del Teide in Tenerife (Spain) in collaboration with IAC.

More than 150 researchers belonging to

- INAF institutes (IASF-MI, IASF-PA, OAS, OACT, OAB, OAPD, OAR)
- Italian Universities (Uni-PG, Uni-PD, Uni-CT, Uni-GE, PoliMi) & INFN
- Fundacion Galileo Galilei
- International institutions (IAC - Spain, University of Sao Paulo – Brazil, North-West University – South Africa, Université / Observatoire de Geneve CH).

Italian and foreign industrial companies are and will be involved in the ASTRI Mini-Array project with important industrial return.

CREDITS : Andrea Giuliani

The ASTRI Mini-Array operations

- Hosting agreement foresees 4 + 4 years of operations for the ASTRI Mini-Array starting from beginning of operations

- During the first 4 years of operations the array will be **run as an experiment**

- The ASTRI Science team will develop a strategy to **concentrate the observational time on a limited number of programs** with clearly identified objectives

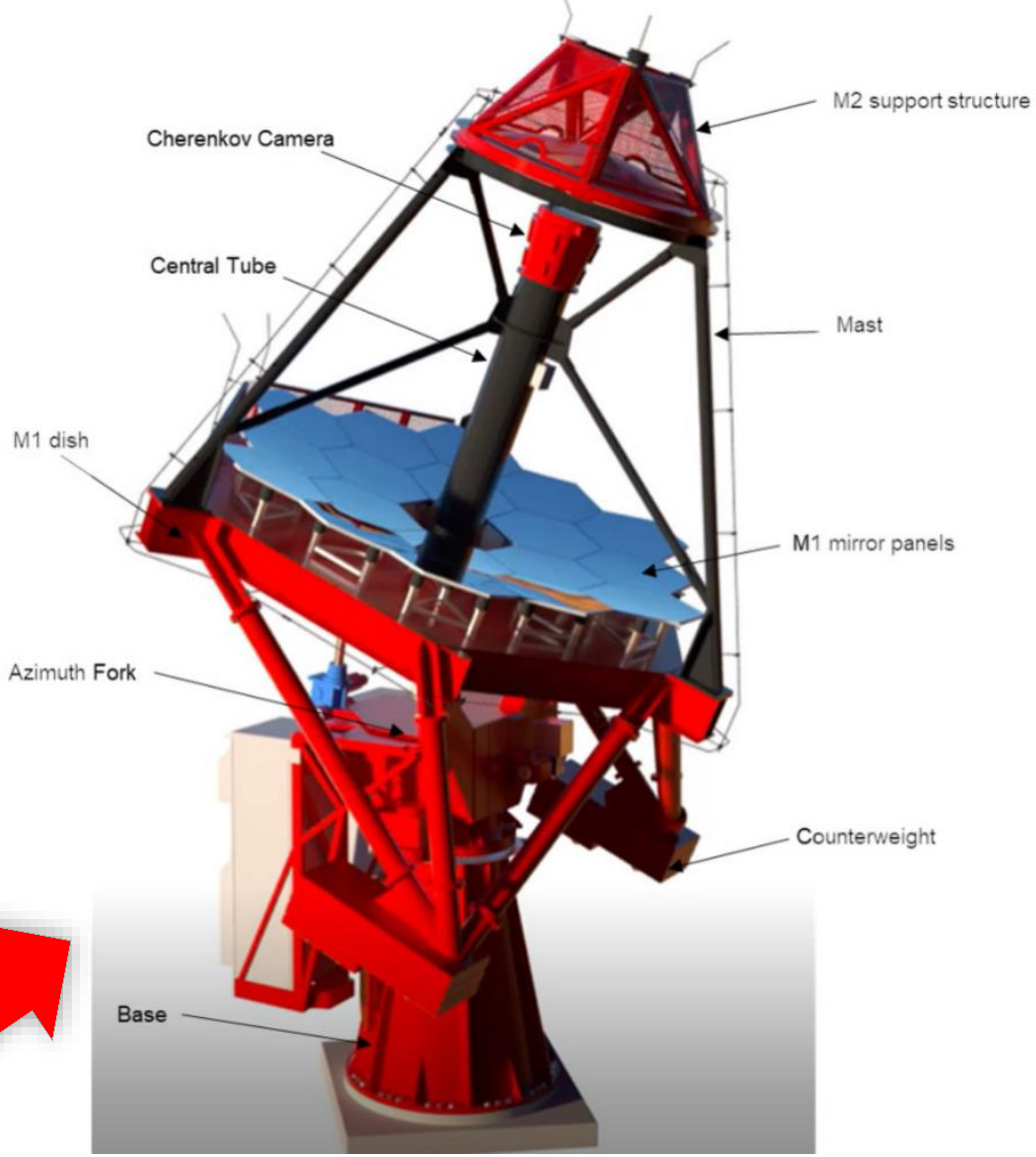
- After this initial period **the project will gradually move towards an observatory model** in which a fraction of the time will be assigned to scientific proposals through a Time Allocation Committee procedure

CREDITS : Andrea Giuliani

Telescope

- The current design of the ASTRI electromechanical structure is an evolution of the ASTRI-Horn prototype telescope.

- Electro-mechanical structure has been optimized in terms of mass, functionality and maintainability (mass has been reduced by 30%).



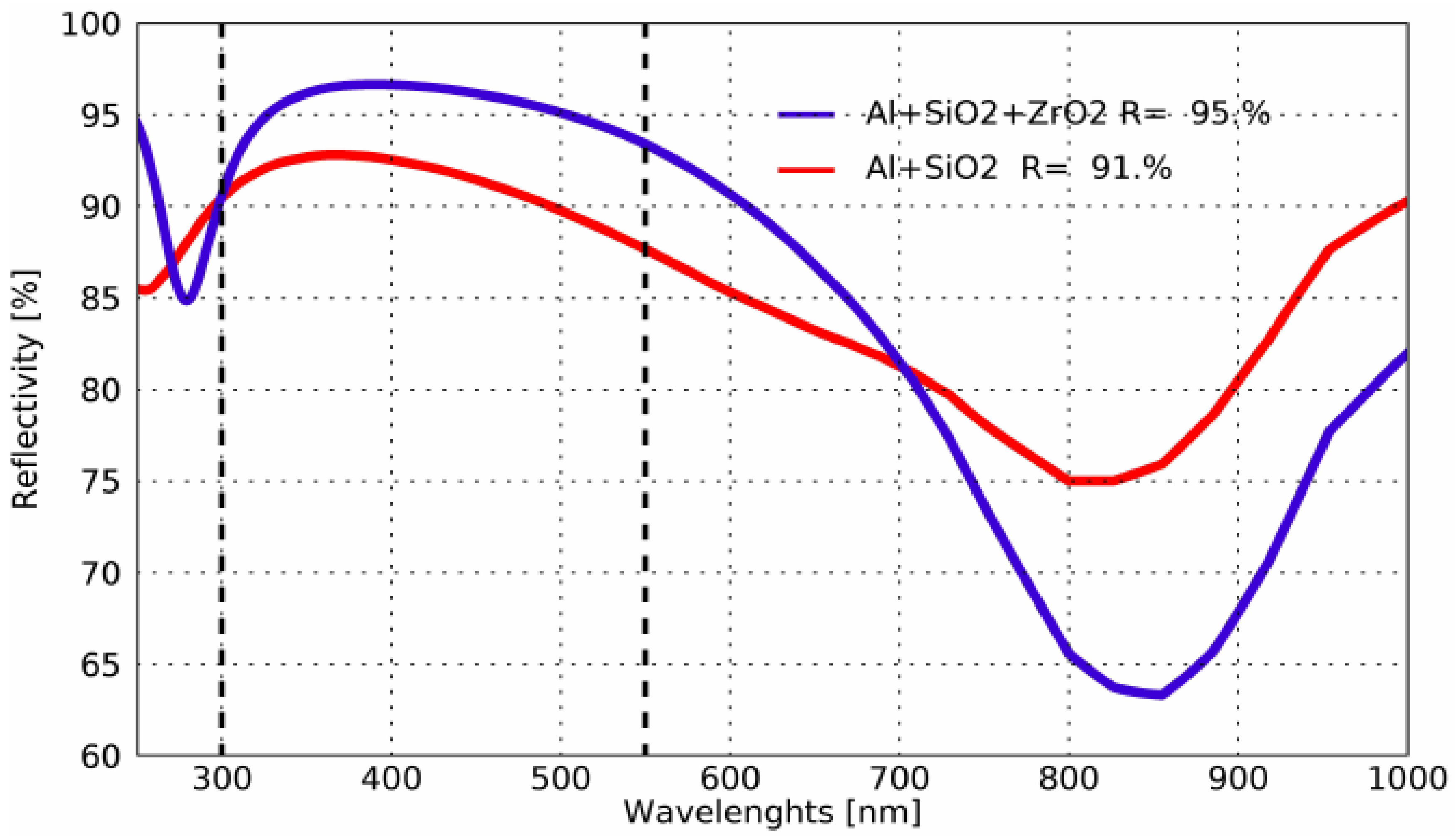
CREDITS : Andrea Giuliani

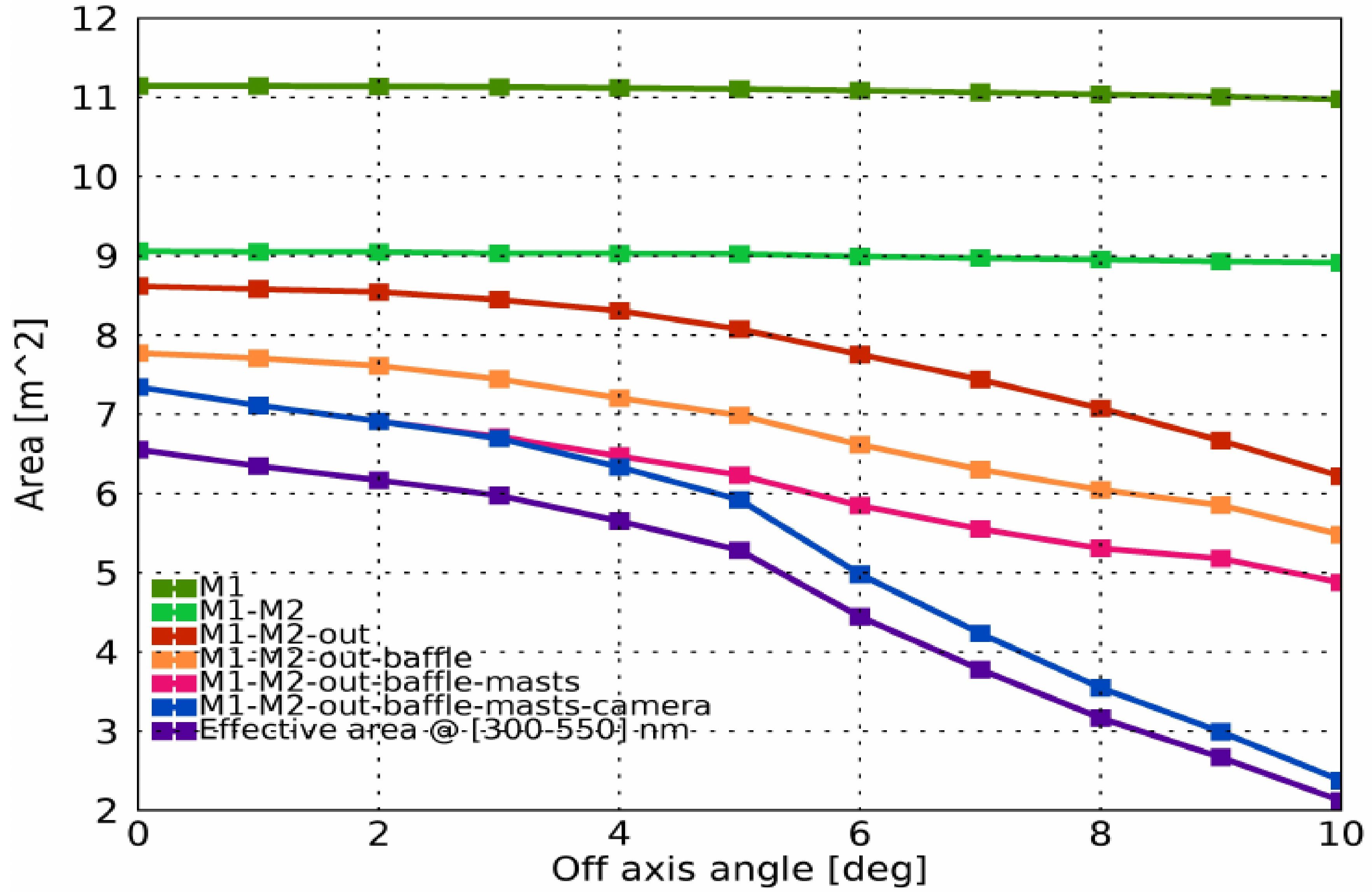
Optics

- The optical design is based on a modified (Vassiliev et al. (2007), see also Sironi (2017)) Schwarzschild-Couder configuration.

- This configuration allows better correction of aberrations at large incident angles even for small focal ratios and hence facilitates the construction of compact telescopes.

- This optical system enables good angular resolution across the entire field of view and allows reducing the focal length and therefore the physical pixel and overall camera size.



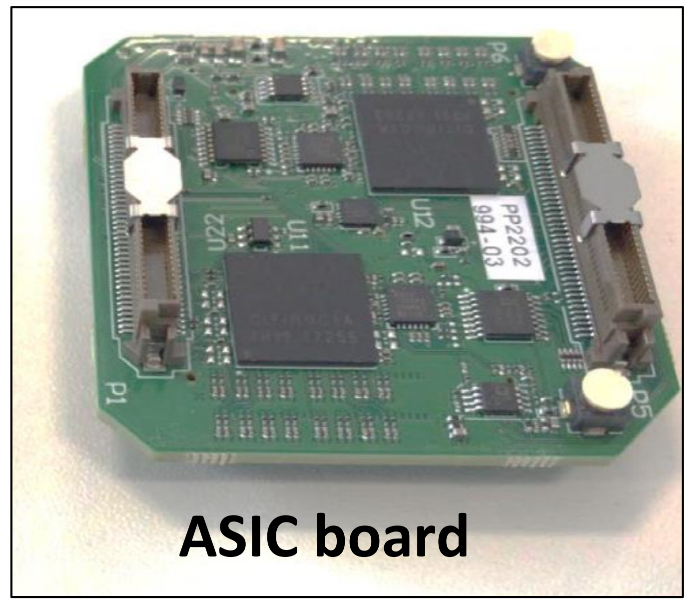


CREDITS : Andrea Giuliani

ASTRI Camera

ASTRI Mini-Array

SiPM matrices

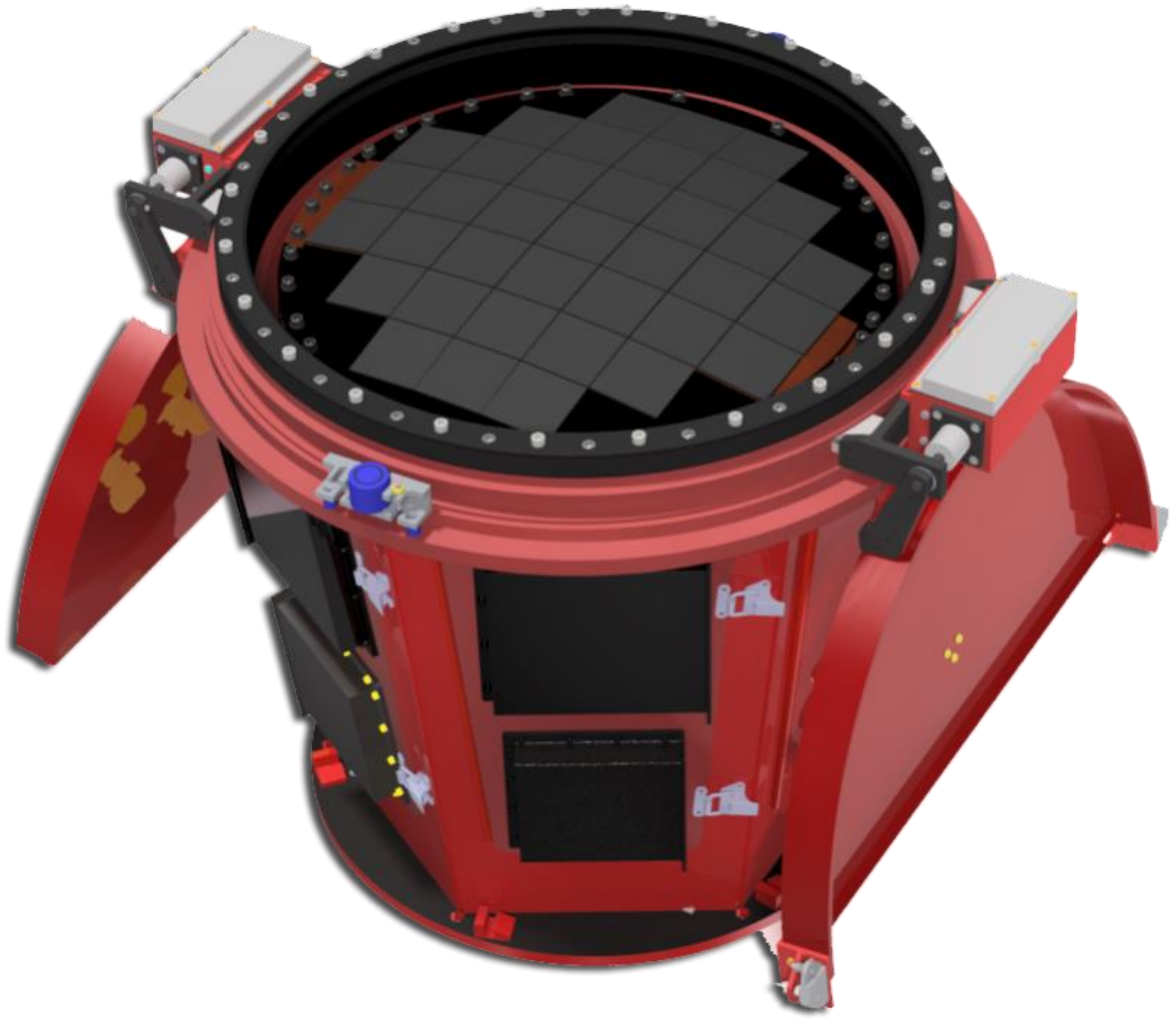


ASIC board

- The SiPM produced by Hamamatsu photonics (7x7 mm^2) grouped in matrices of 8x8 pixels
- 37 matrices are arranged to adapt to the curved focal plane of the telescope.
- innovative electronics for peak detection(CITIROC ASICS , WEEROC-INAF) ⇒ smalls mount of data
- Interferential filter as front window (Romeo et al. (2018) and Catalano et al. (2018)) that allows to reduce the contribution from the night sky background at wavelengths greater than 550 nm where the sensitivity of SiPM detector is still high.

CAEN Tools for Discovery

EIE GROUP



HAMAMATSU PHOTON IS OUR BUSINESS

CREDITS : Andrea Giuliani

ASTRI-1

ASTRI Mini-Array

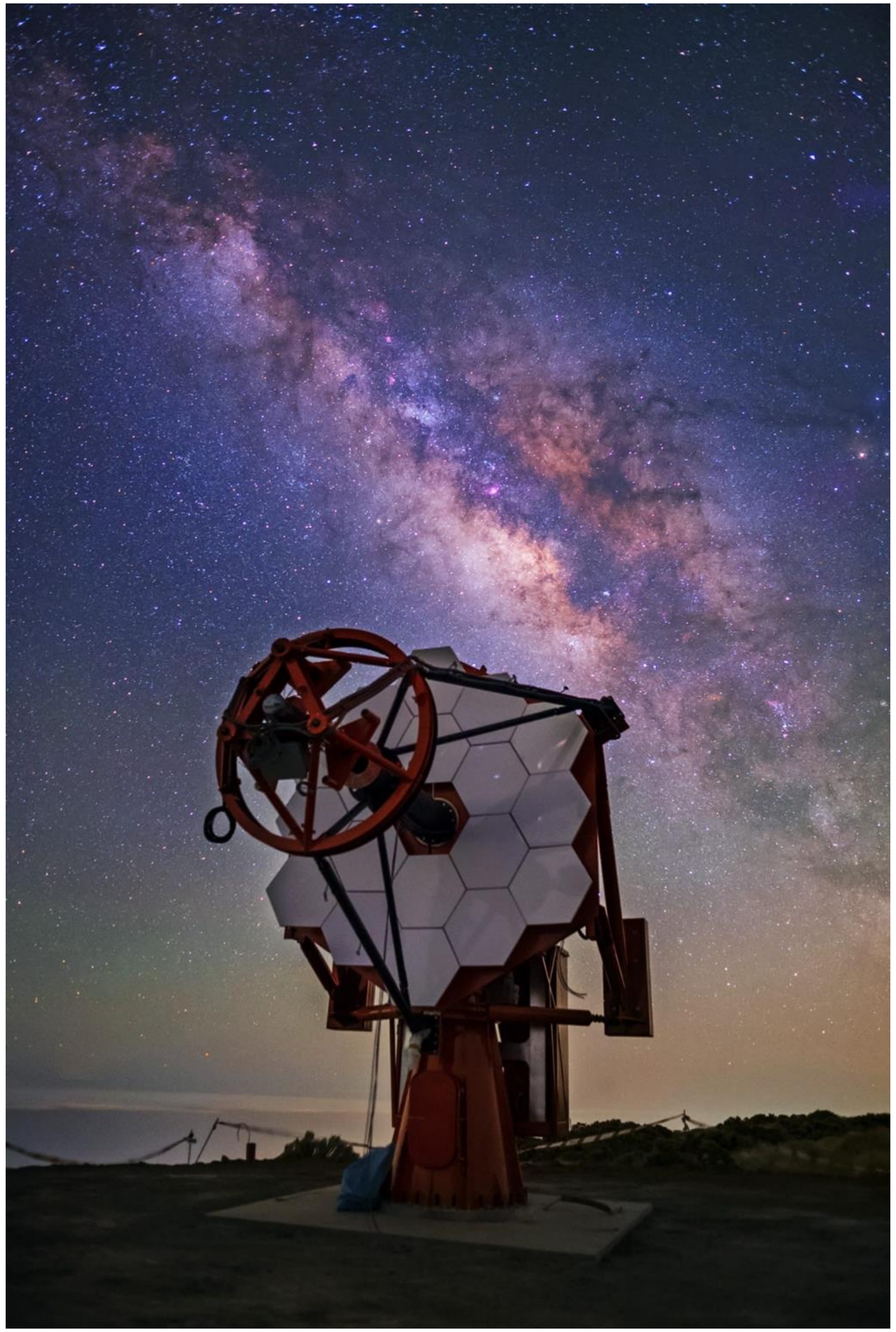


Photo CREDITS : Tommaso Marchiori and IAC

ASTRI Mini-Array performance

	ASTRI Mini-Array	MAGIC	VERITAS	H.E.S.S.	HAWC	LHAASO	Tibet ASγ
Altitude [m]	2,390	2,200	1,268	1,800	4,100	4,410	4,300
FoV	$\sim 10°$	$\sim 3.5°$	$\sim 3.5°$	$\sim 5°$	2 sr	2 sr	2 sr
Angular Res.	0.05° (30 TeV)	0.07° (1 TeV)	0.07° (1 TeV)	0.06° (1 TeV)	0.15° (10 TeV)	(0.24–0.32)° (100 TeV)	$\sim$ 0.2° (100 TeV)
Energy Res.	12% (10 TeV)	16% (1 TeV)	17% (1 TeV)	15% (1 TeV)	30% (10 TeV)	(13–36)% (100 TeV)	20% (100 TeV)
Energy Range	(0.3-200) TeV	(0.05-20) TeV	(0.08-30) TeV	(0.02-30) TeV	(0.1-200) TeV	(0.1-1,000) TeV	(0.1-1,000) TeV

Sensitivity: better than current IACTs (E $\gtrsim$ 3 TeV)

Extended spectrum and cut-off constraints

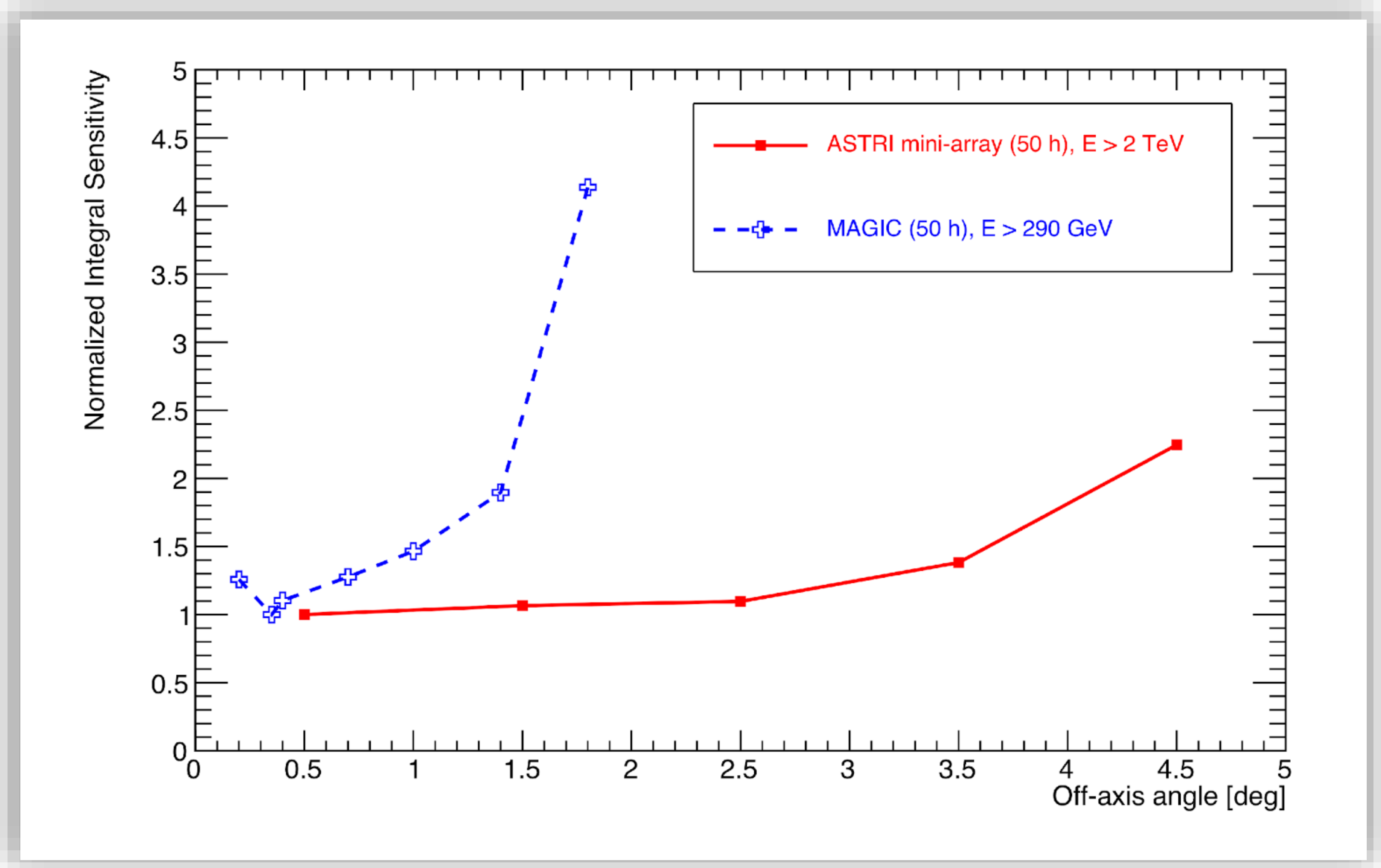
Energy/Angular resolution: ~10% / ~0.05° (E =10 TeV)

Characterize extended sources morphology

10° field of view with homogeneous off-axis performance

Multi-target fields and extended sources

Enhanced chance for serendipitous discoveries



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Strategic VHE synergies

ASTRI Mini-Array

- Both **MAGIC** and **CTAO-N** will be of paramount importance for their capability to investigate not only the local Universe, but also reaching **redshifts well beyond one**

- Both **MAGIC** and **CTAO-N** will allow us to extend the ASTRI Mini-Array spectral performance in the **sub-TeV regime**, with almost no breaks **from a few tens of GeV up to hundreds of TeV**

- The **EASs** detected several sources with **photons up to several hundreds of TeV**. Potential synergies are important to make use of the **ASTRI Mini-Array angular and energy resolution** in combination with the LHAASO, HAWC and Tibet ASγ extended energy range

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The multi-wavelength landscape

Mini-Array

- **MeerKat** and **ASCAP** (SKA precursors in the South) will allow us to investigate the Galactic Center and its features
- **LOFAR** (SKA precursor in the North) will open a new science window in the low-frequency radio band and monitor 2/3 of the sky nightly in Radio Sky Monitor mode, being an excellent radio transient factory
- **SRT** has already observed sources of interest for the ASTRI Mini-Array, such as W 44, IC 433 and Tycho, making it an excellent observatory for future synergies in the northern hemisphere
- **TNG** is located in La Palma and can be extremely useful for optical follow-up observations. The **WEBT Consortium** is dedicated to the observation of blazars, and it is fundamental for blazar SEDs. IAC also provides access to several optical telescopes on-site.
- **eROSITA/SRG**, **XMM-Newton**, **Chandra, NuSTAR and IXPE** will provide fundamental photometric, imaging, spectroscopic, and polarimetric data.
- **AGILE, Fermi, INTEGRAL, and *Swift*** will be extremely important for their large FoV and for the *Swift* ability to promptly react to transients

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