Science goals of the ASTRI Mini Array

A.Giuliani (INAF / IASF Milano)
for the ASTRI Project

HANDS ON THE EXTREME UNIVERSE WITH HIGH ENERGY GAMMA RAYS 2022

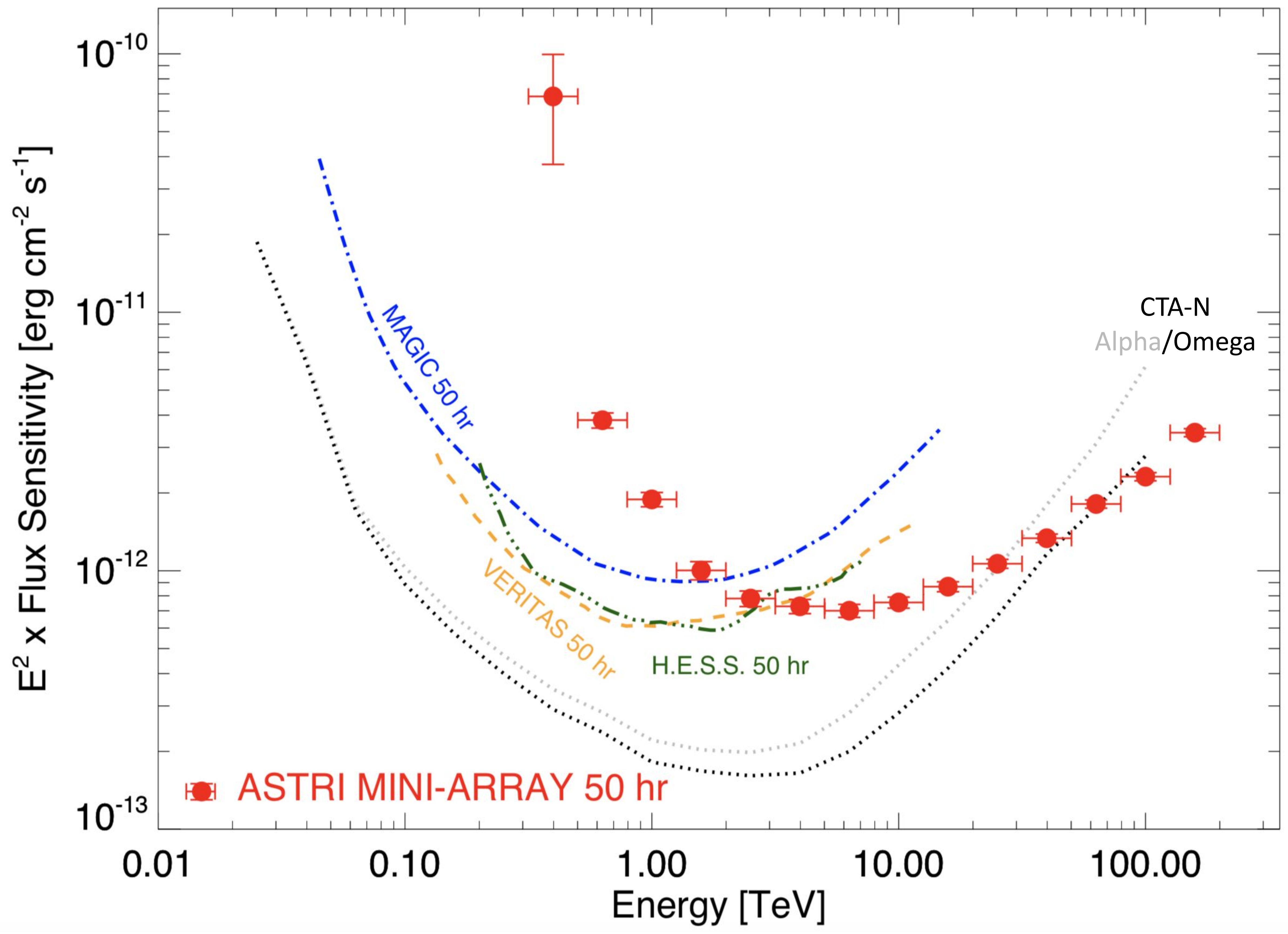
ASTRI Mini-Array @ Teide Observatory

…see G.Sironi's talk

- 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 3 years
- **Important synergies** with other Northern ground-based gamma-ray facilities (LHAASO, HAWC, MAGIC, VERITAS, CTAO-N)

ASTRI Performances

Mini-Array

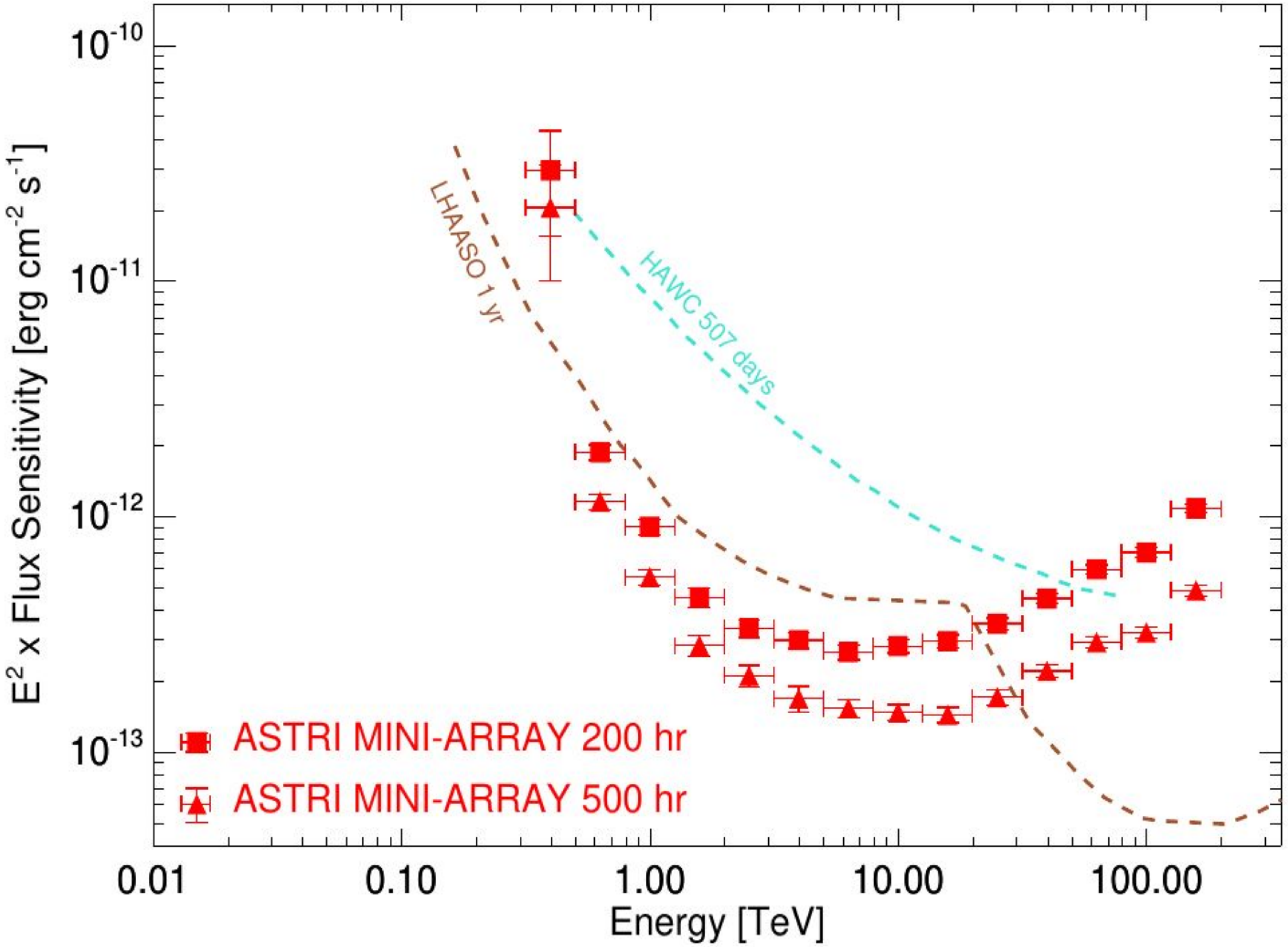


Expected performance

Sensitivity: better than that of current IACTs (E > a few TeV)

- Extend the spectra of already detected sources and/or measure cut-offs

ASTRI Performances



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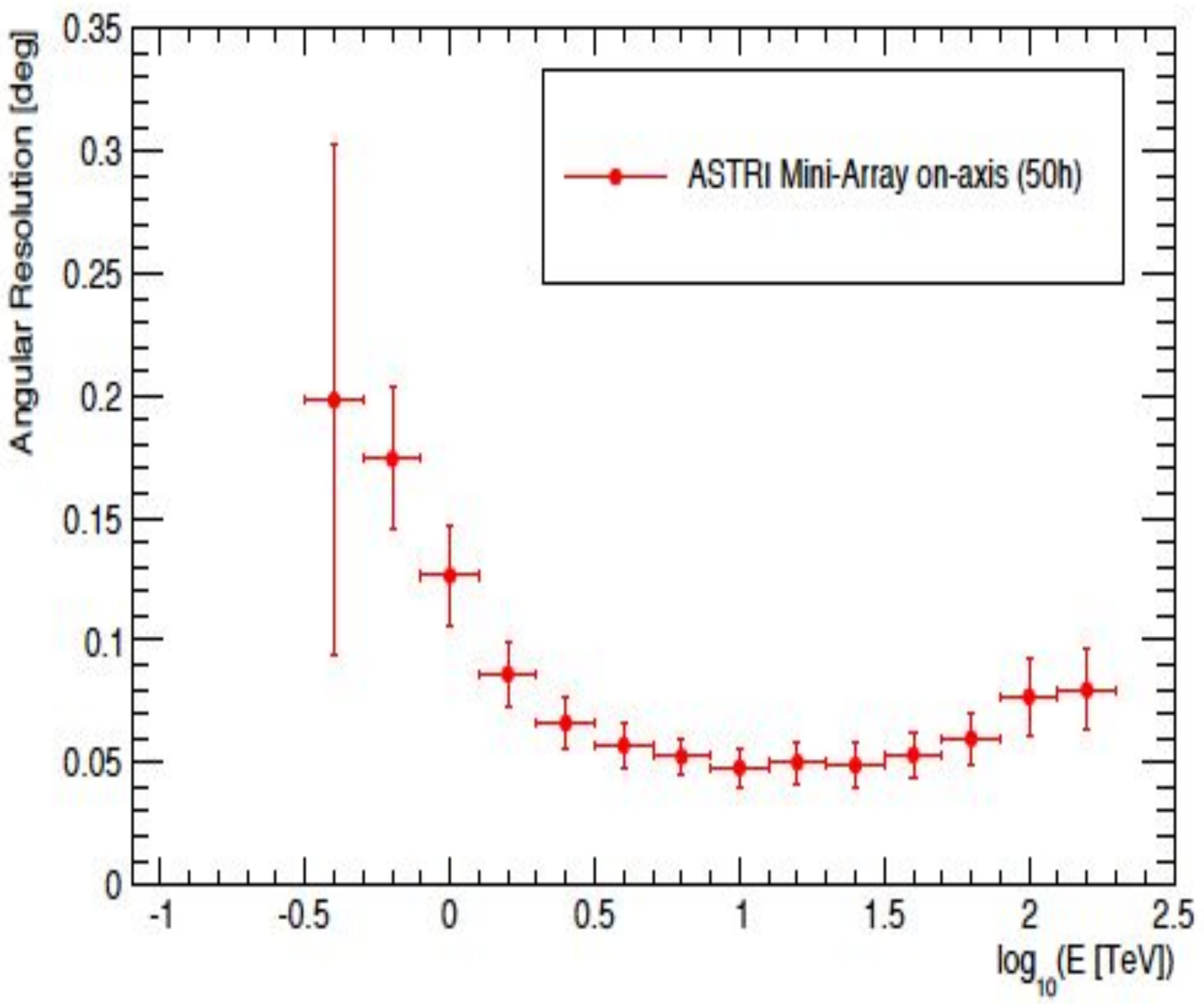

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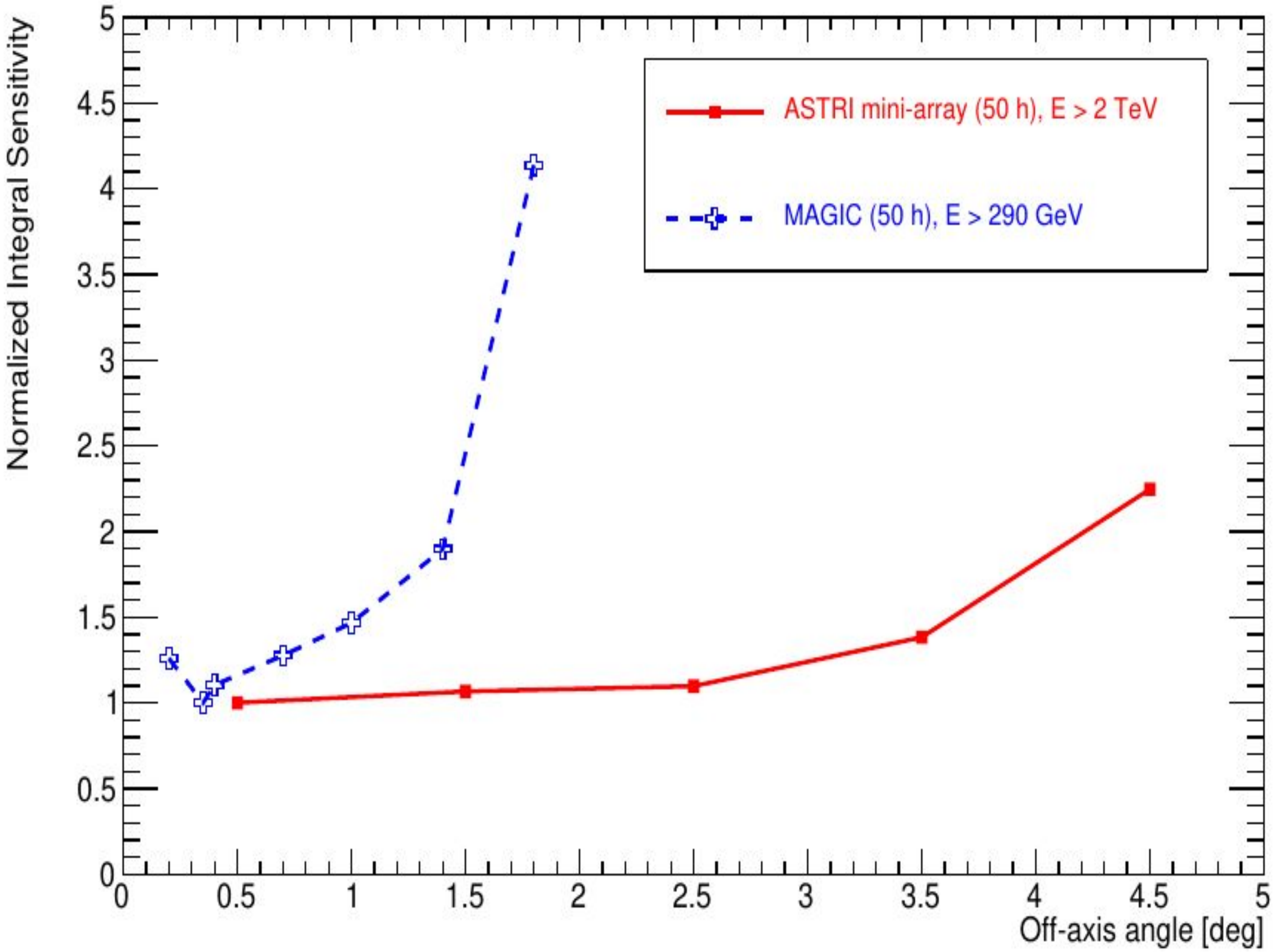
- Extend the spectra of already detected sources and/or measure cut-offs

Energy/Angular resolution: ~ 10% / ~ 3‘ (E > a few TeV)

- Characterize the morphology of extended sources at the highest VHE

ASTRI Performances



Expected performance

Sensitivity: better than that of current IACTs (E > a few TeV)

- Extend the spectra of already detected sources and/or measure cut-offs

Energy/Angular resolution: ~ 10% / ~ 3‘ (E > a few TeV)

- Characterize the morphology of extended sources at the highest VHE

Wide FoV (≥ 10°), with almost homogeneous off-axis acceptance

- Optimal for multi-target fields, surveys, and extended sources
- Enhanced chance for serendipity discoveries

ASTRI Science : overview

Origin of Cosmic Rays

- PeVatrons
- CRs Acceleration and Propagation
- Pulsar Wind Nebulae and TeV Halos

Fundamental Physics

- Intergalactic fields
- Blazars
- LIV and ALP

Transient Follow-Up

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*

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], S. Vercellone[n], A. Wolter[j], E. Amato[o], C. Bigongiari[a,b], A. Bulgarelli[r], M. Cardillo[s], V. Conforti[r], A. Costa[q], G. Cusumano[k], V. Fioretti[r], S. Germani[t], A. Ghedina[u], V. Giordano[q], A. Giuliani[v], F. Incardona[q], A. La Barbera[k], G. Leto[q], F. Longo[w,x], G. Morlino[o], B. Olmi[y], N. Parmiggiani[r], P. Romano[n], G. Romeo[q], A. Stamerra[a], G. Tagliaferri[n], V. Testa[a], G. Tosti[j,t], P. A. Caraveo[v] and G. Pareschi[n]

JHEAP, 2022, 35, 91

ASTRI Science : overview

Origin of Cosmic Rays

- **PeVatrons**

Follow-up of LHAASO Sources

Cao et al., 2021, Nature

LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)^a	L_s (erg/s)^b	Potential TeV Counterpart^c
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2^d	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	2HWC J1825-134
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069,
	PSR J1838-0537	PSR	1.3^e	4.9	6.0×10^{36}	HESS J1841-055
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3^f	$< 2^f$	—	HESS J1843-033, HESS J1844-030, 2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7^g	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5^h	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4^i	$\sim 10 - 20^j$	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	2HWC 1908+063
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188,
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	HESS J1930+188, VER J1930+188
	SNR G54.1+0.3	SNR	$6.3^{+0.8\ d}_{-0.7}$	$1.8 - 3.3^k$	—	
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2^d	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7\ l}_{-1.4}$	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	$3.3 \pm 0.3^m/4.0 \pm 0.5^n$	—	—	VER J2016+371
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08^o	—	—	TeV J2032+4130, ARGO J2031+4157,
	PSR 2032+4127	PSR	1.40 ± 0.08^o	201	1.5×10^{35}	MGRO J2031+41, 2HWC J2031+415,
	SNR G79.8+1.2	SNR candidate	—	—	—	VER J2032+414
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8^p	$\sim 10^p$	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8^p	$\sim 10^p$	2.2×10^{37}	

Discovery of **12 sources emitting at several hundreds of TeV**, up to 1.4 PeV

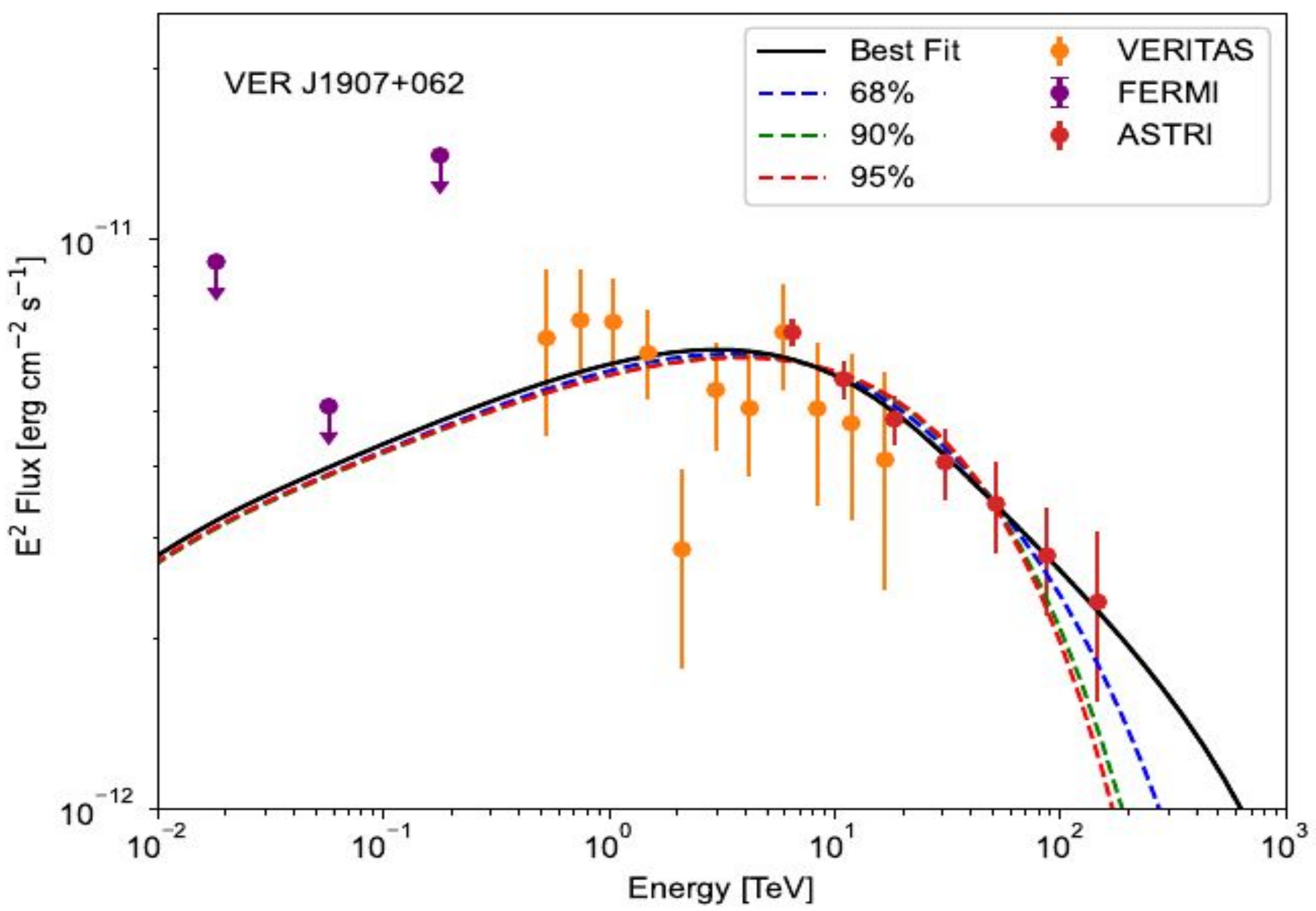
Crab apart, the majority of remaining sources represent **diffuse γ-ray structures with angular extensions up to 1°**, and all of them are located along the Galactic plane

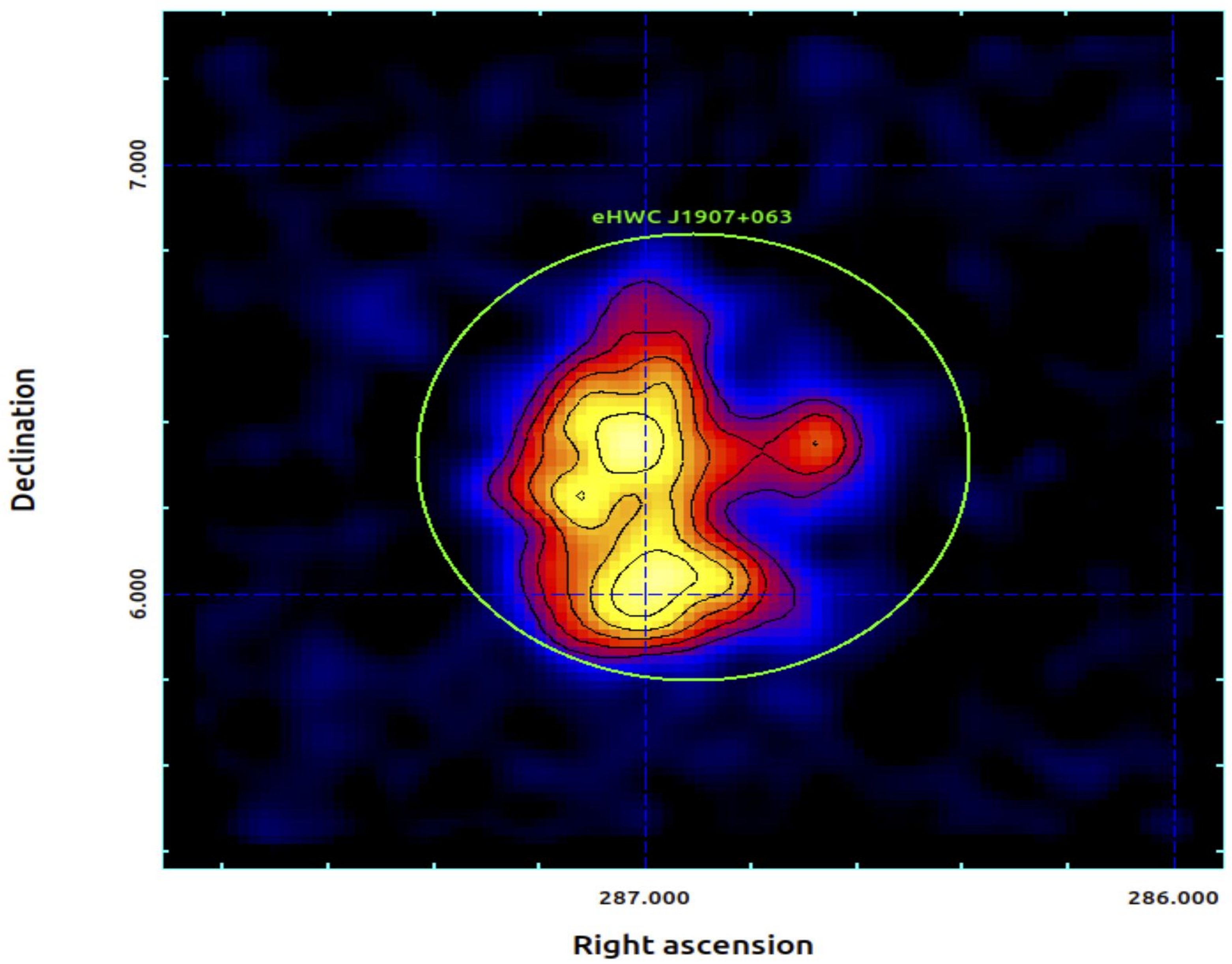
The **actual sources** responsible for the ultra high-energy γ-rays **have not yet been firmly localized and identified** (except for the Crab Nebula), leaving open the origin of these extreme accelerators

The **ASTRI Mini-Array** will investigate these and future UHE sources, providing both the opportunity for **their precise identification** and important **information on their morphology**

Follow up of LHAASO sources : the case of J1908+0621

ASTRI Mini-Array **200 hr simulation (up to E~200 TeV)** of 2HWC J1908+063

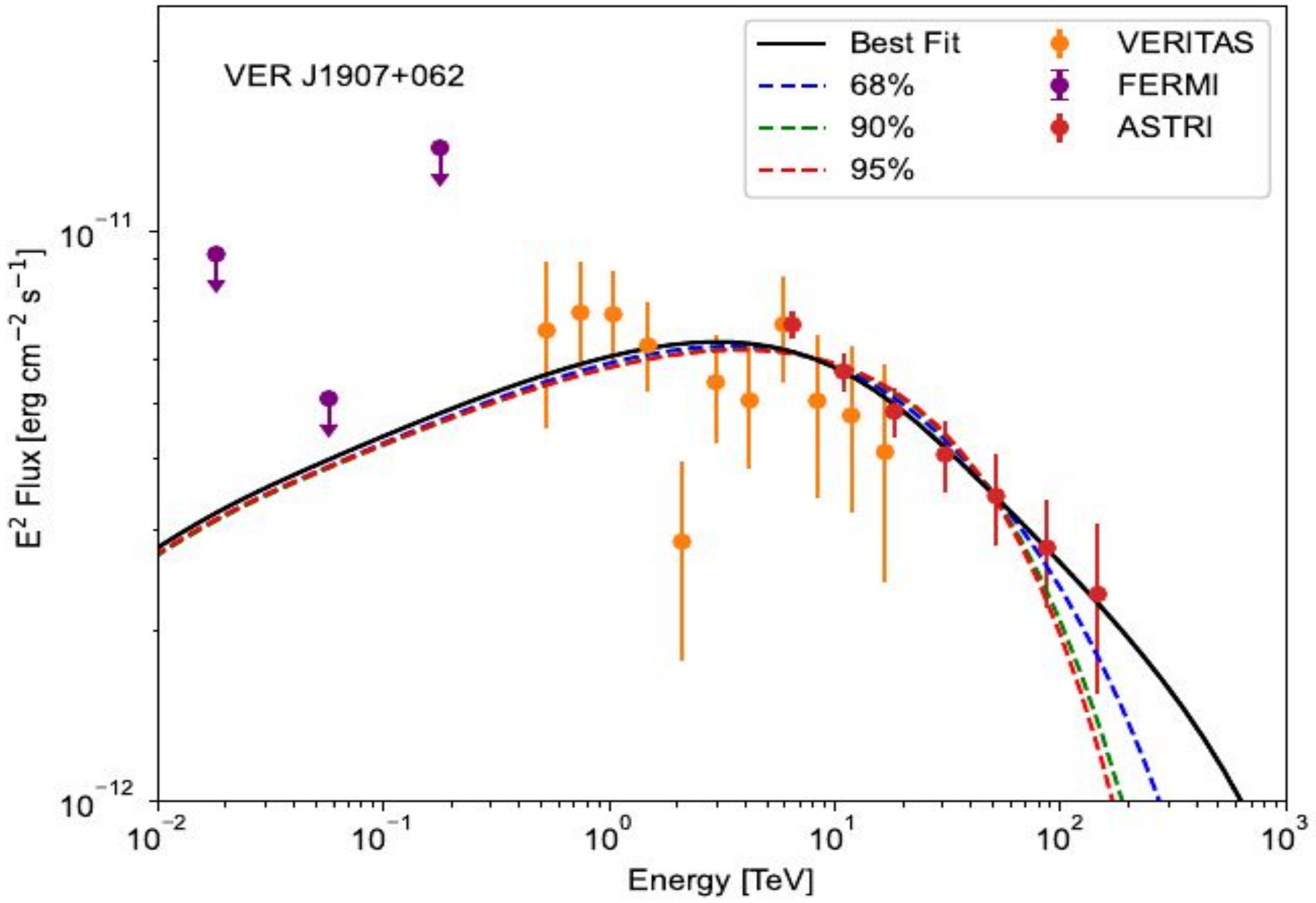


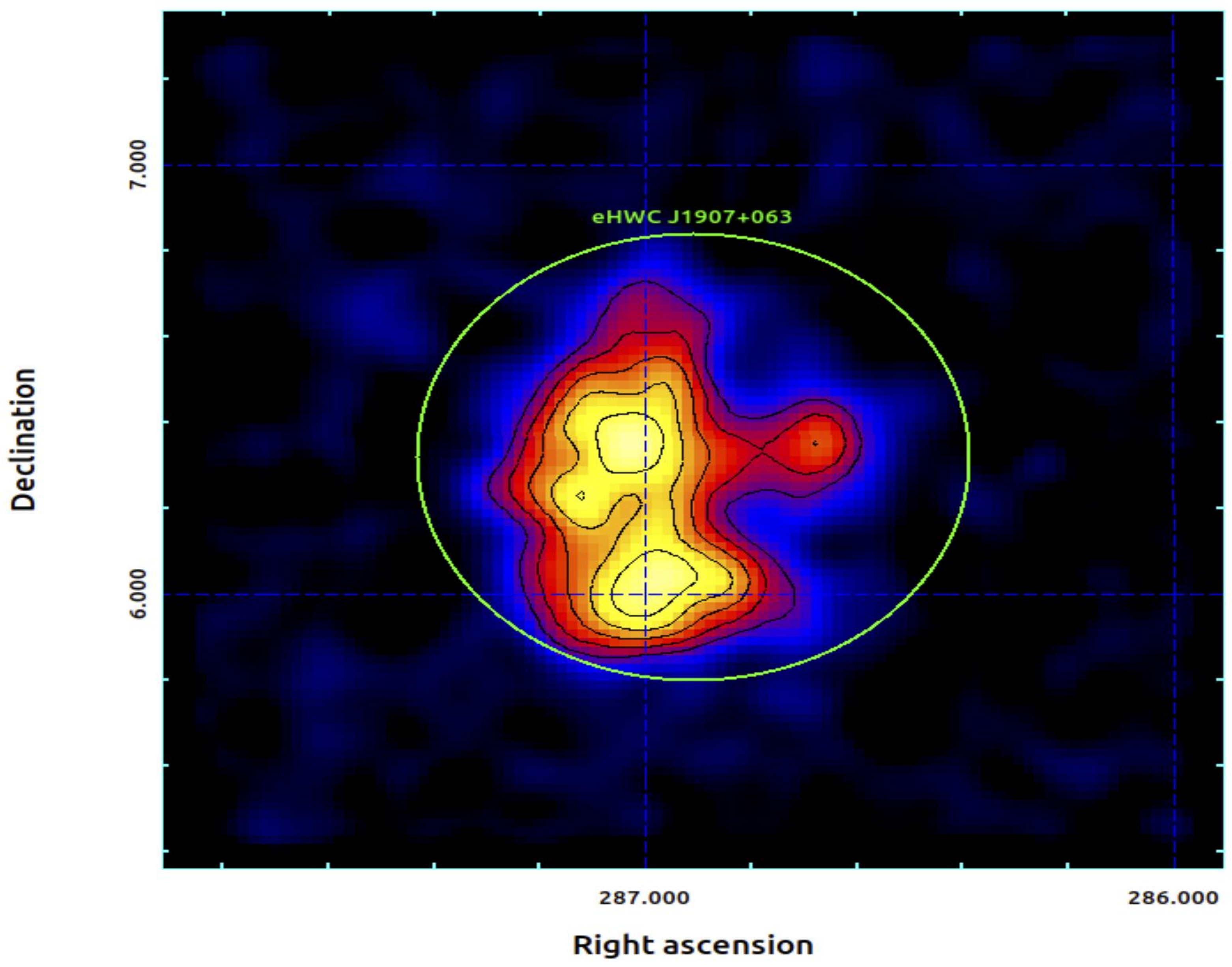


The light green circle marks the ~ 0.52° HAWC error-box

Follow up of LHAASO sources : the case of J1908+0621

ASTRI Mini-Array **200 hr simulation (up to E~200 TeV)** of **2HWC J1908+063**





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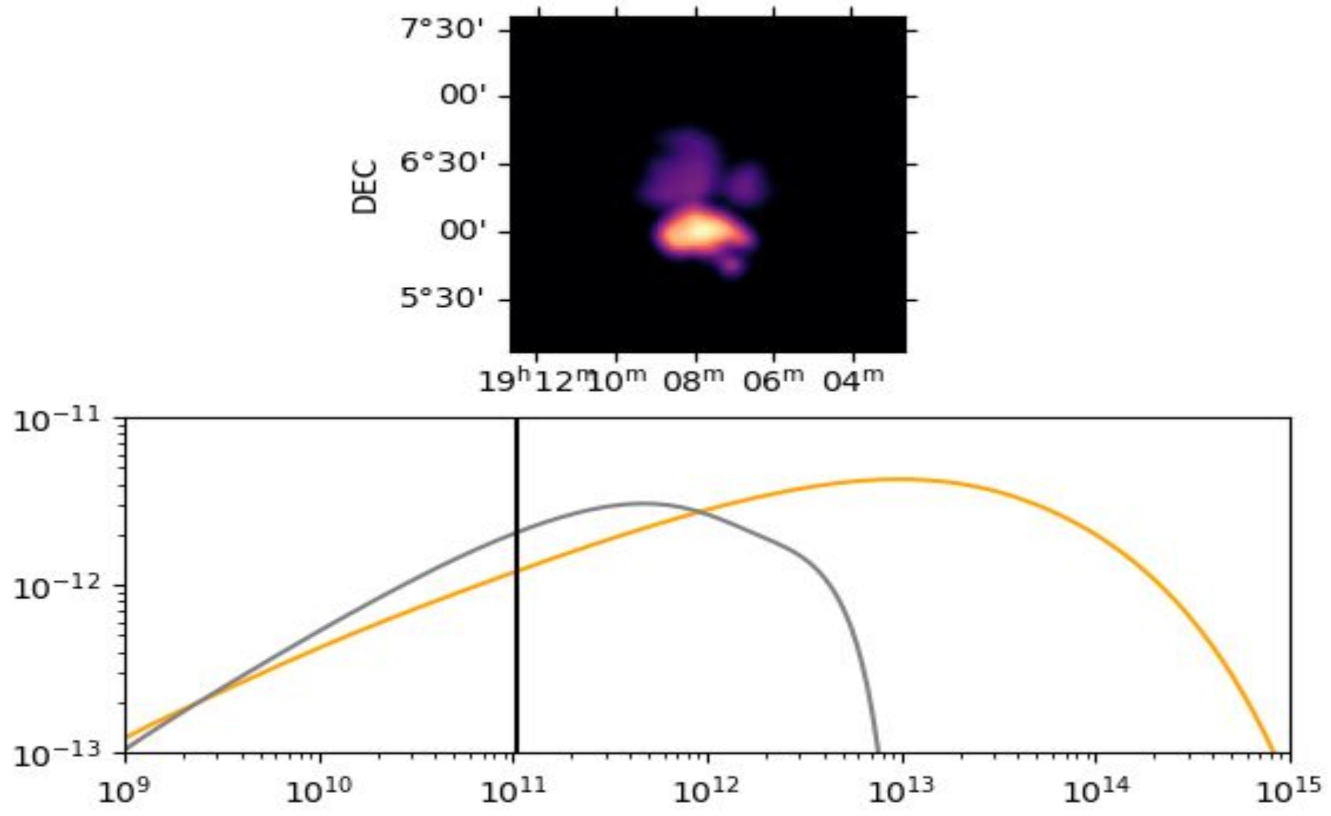
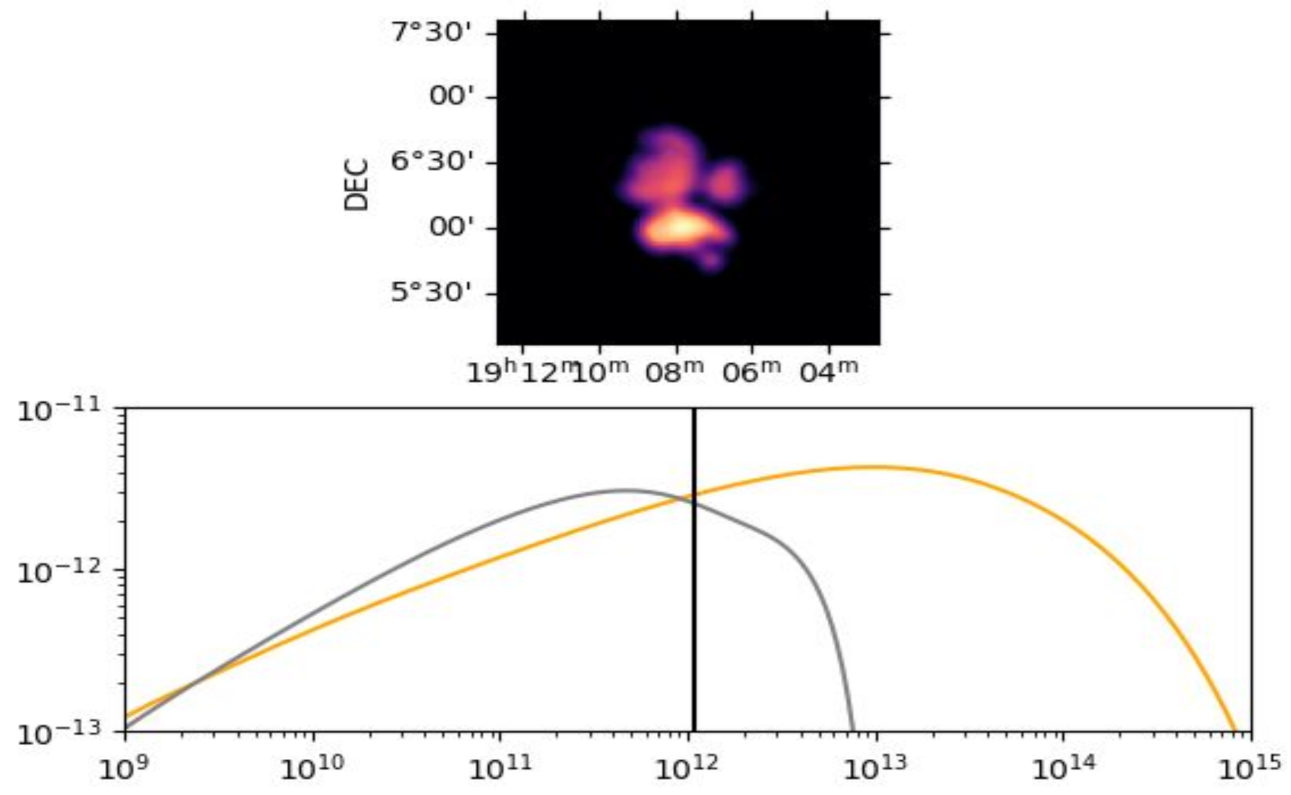
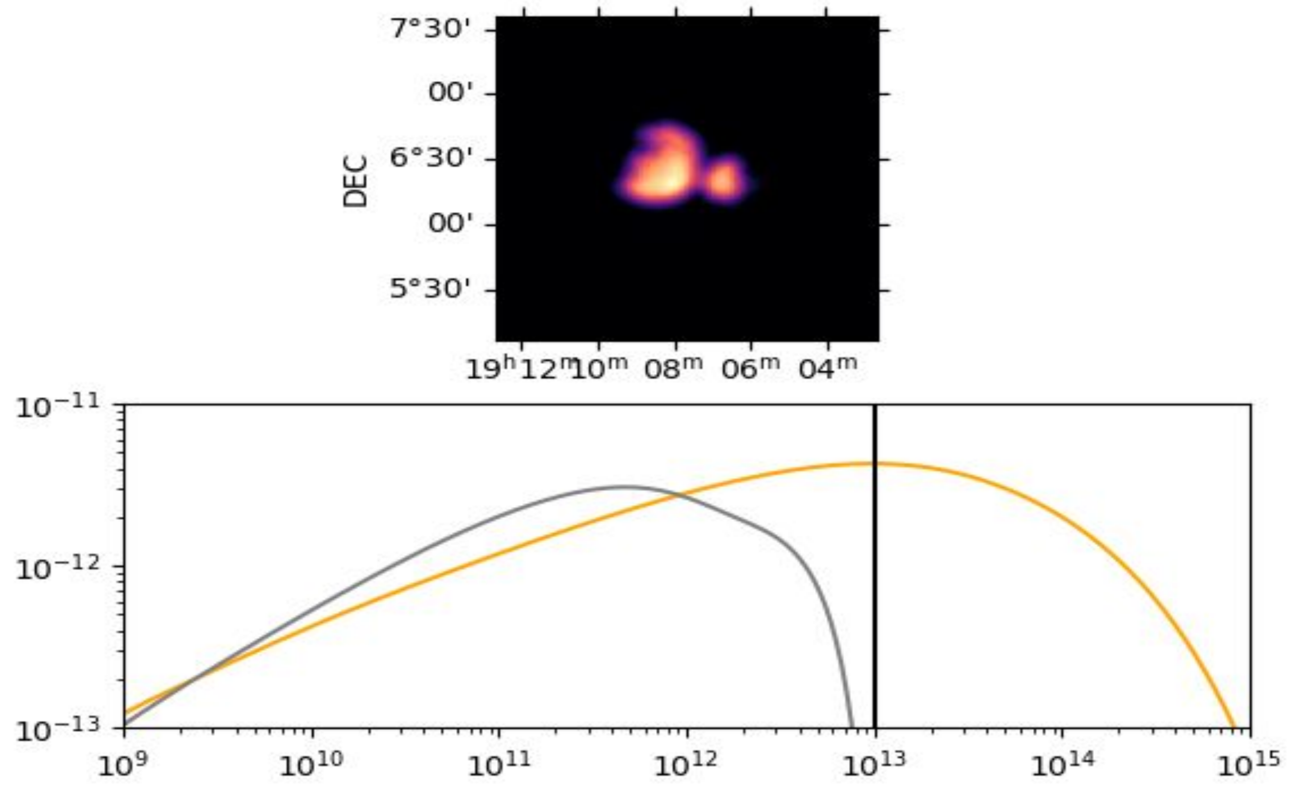






An Energy-dependent morphology (2 zone model)
can be **resolved by the ASTRI observations**

The Galactic Center – a challenge in a challenge

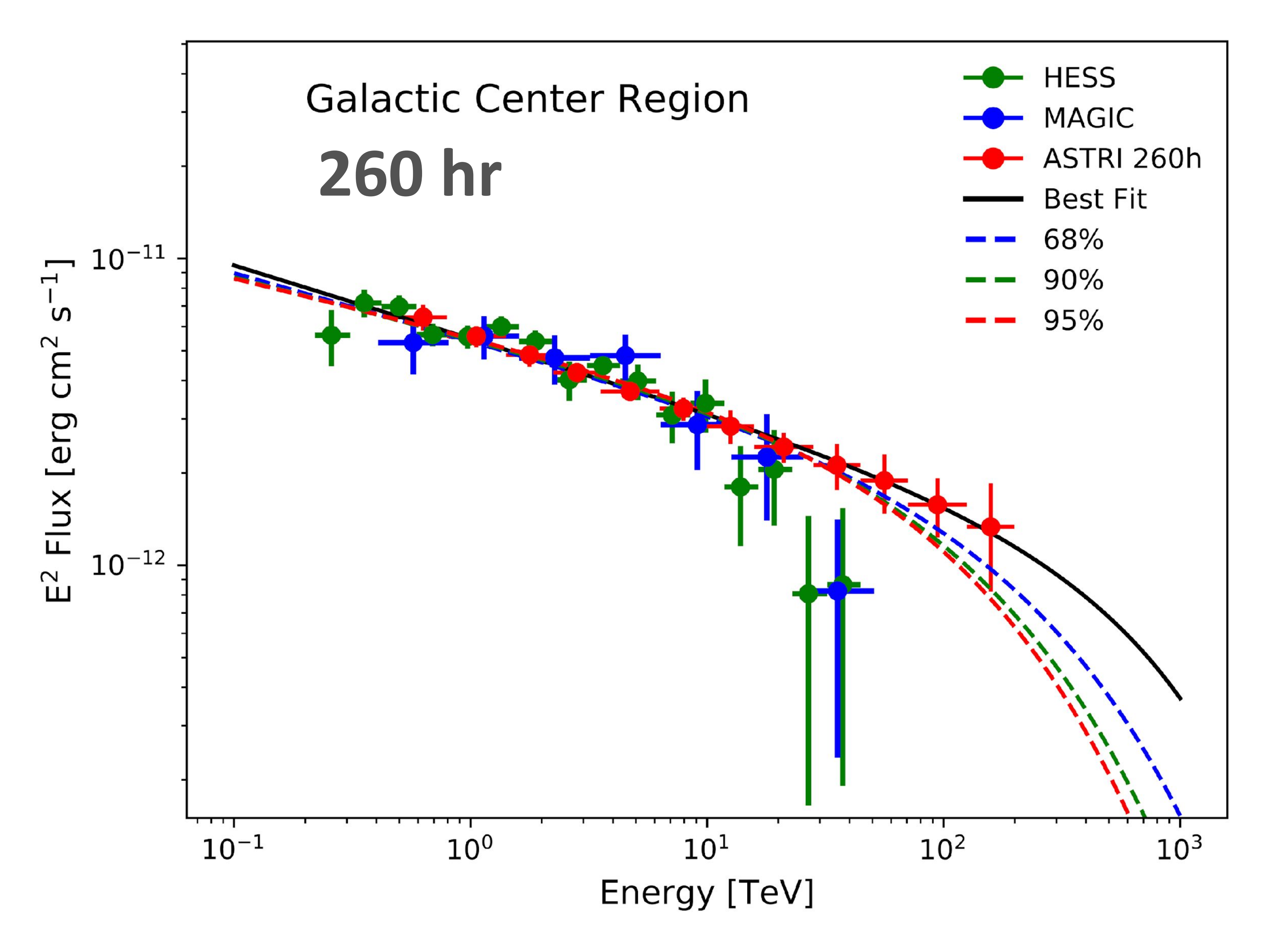
It is a complex region harbouring several potential sources of particle acceleration

It can be observed by the ASTRI Mini-Array only at high zenith angles

Current IACTs detected **non-variable emission with no significant cut-off up to a few tens of TeV**

ASTRI Mini-Array assets

- **the large FoV** will allow us to map the **whole GC region in a single observation**
- **the excellent angular resolution** could help us to **identify any HE source** among several candidates



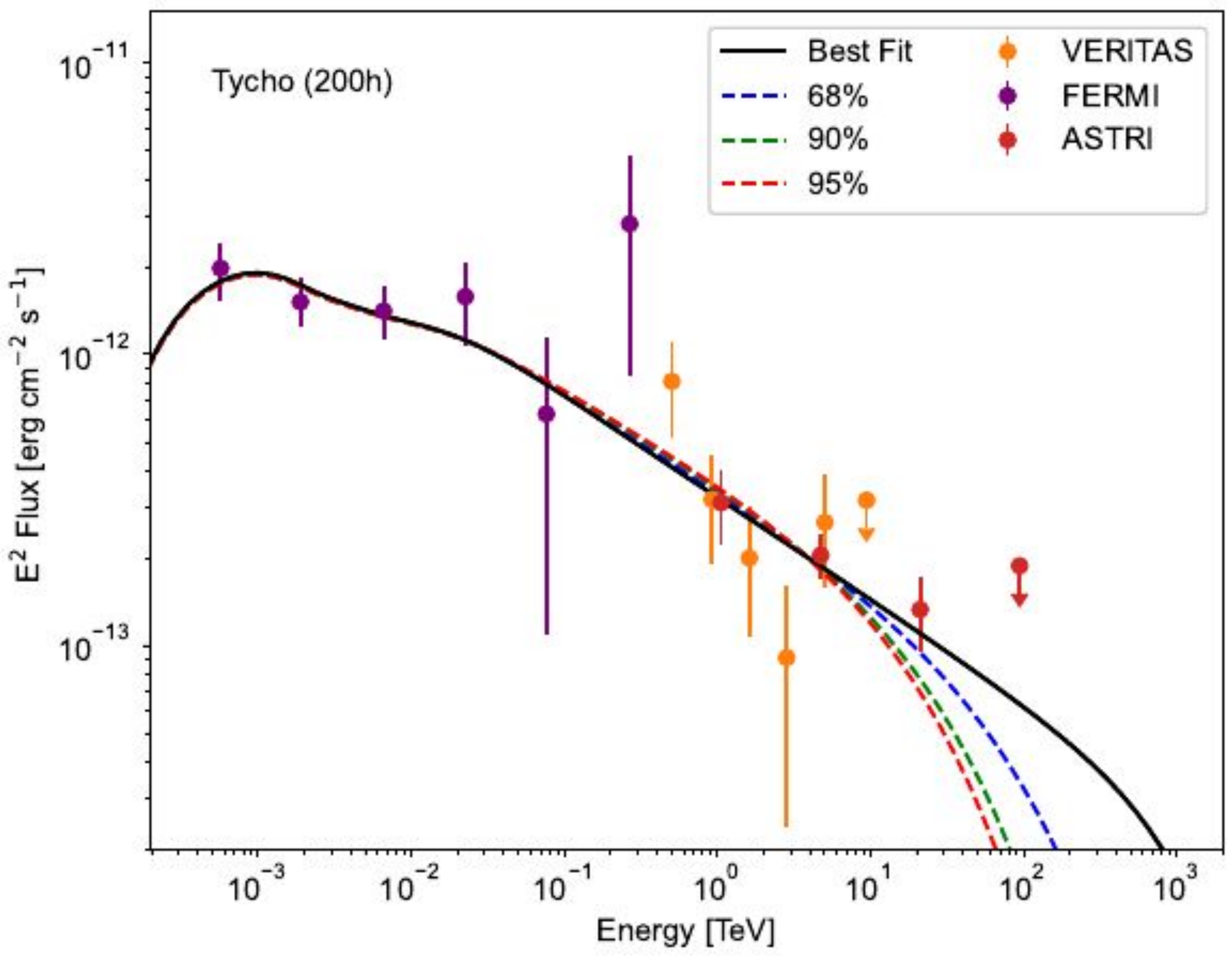
Spatial and spectral characterization of the inner Galactic Ridge emission (HESS Collab., 2018)

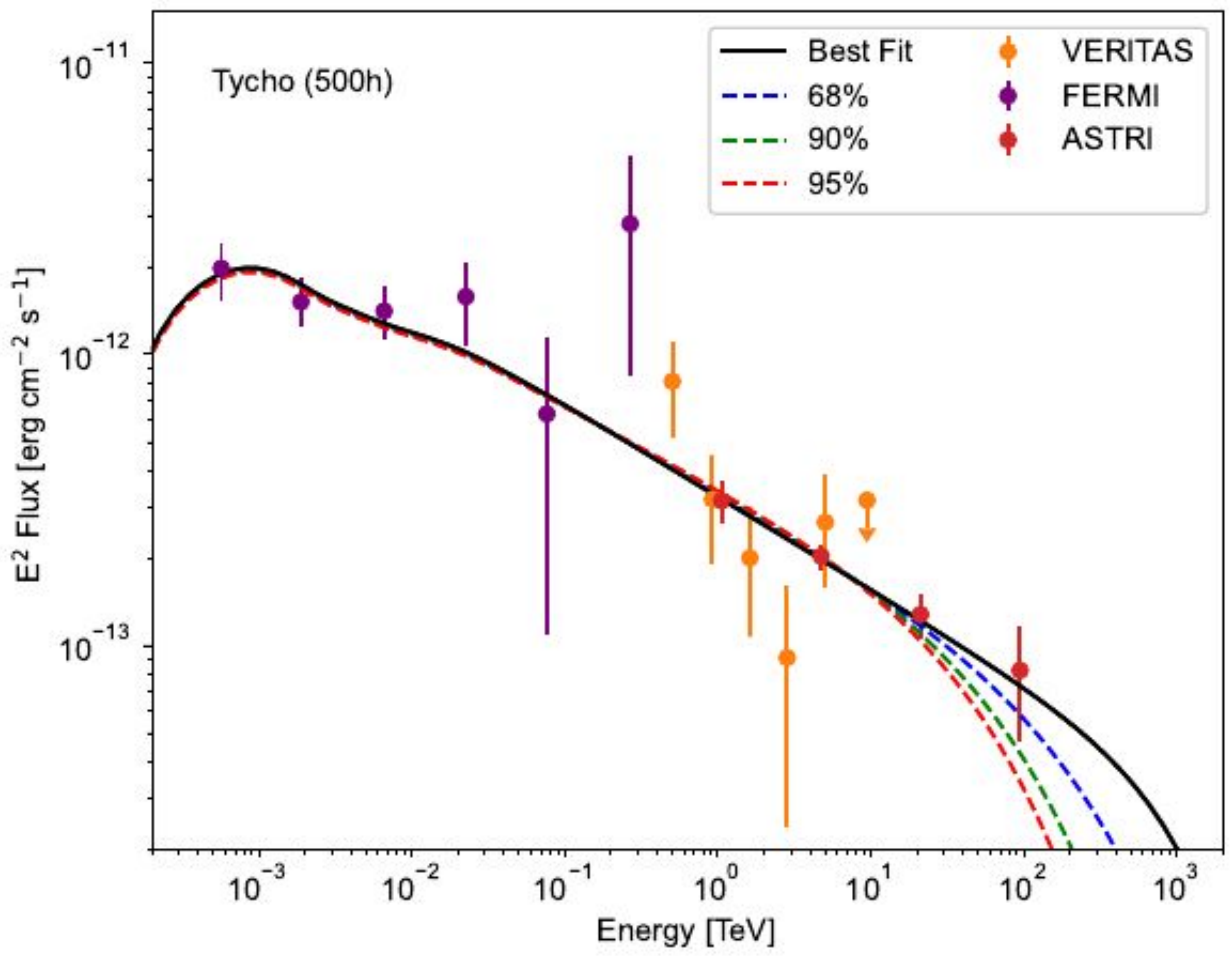
HESS, MAGIC and ASTRI spectra fitted with a proton population with a cut-off power-law with E_{cut} = 120 PeV

Exclude a cut-off in proton pop. below 3.5 PeV, 2.0 PeV, and 1.7 PeV at 68%, 90%, and 95% C.L.

Young SNRs

The ability in detecting cut-off in the VHE spectra has been tested simulating Tycho with a spectrum extending beyond 100 TeV





The dashed lines show the PL fit with cut-off energies of : **0.29, 0.41, 1.27 PeV**

The dashed lines show the PL fit with cut-off energies of : **0.85, 1.36, 3.96 PeV**

ASTRI Science : overview

Origin of Cosmic Rays

- **PeVatrons**
- **CRs Acceleration and Propagation**

Cosmic-ray propagation: γ-Cygni

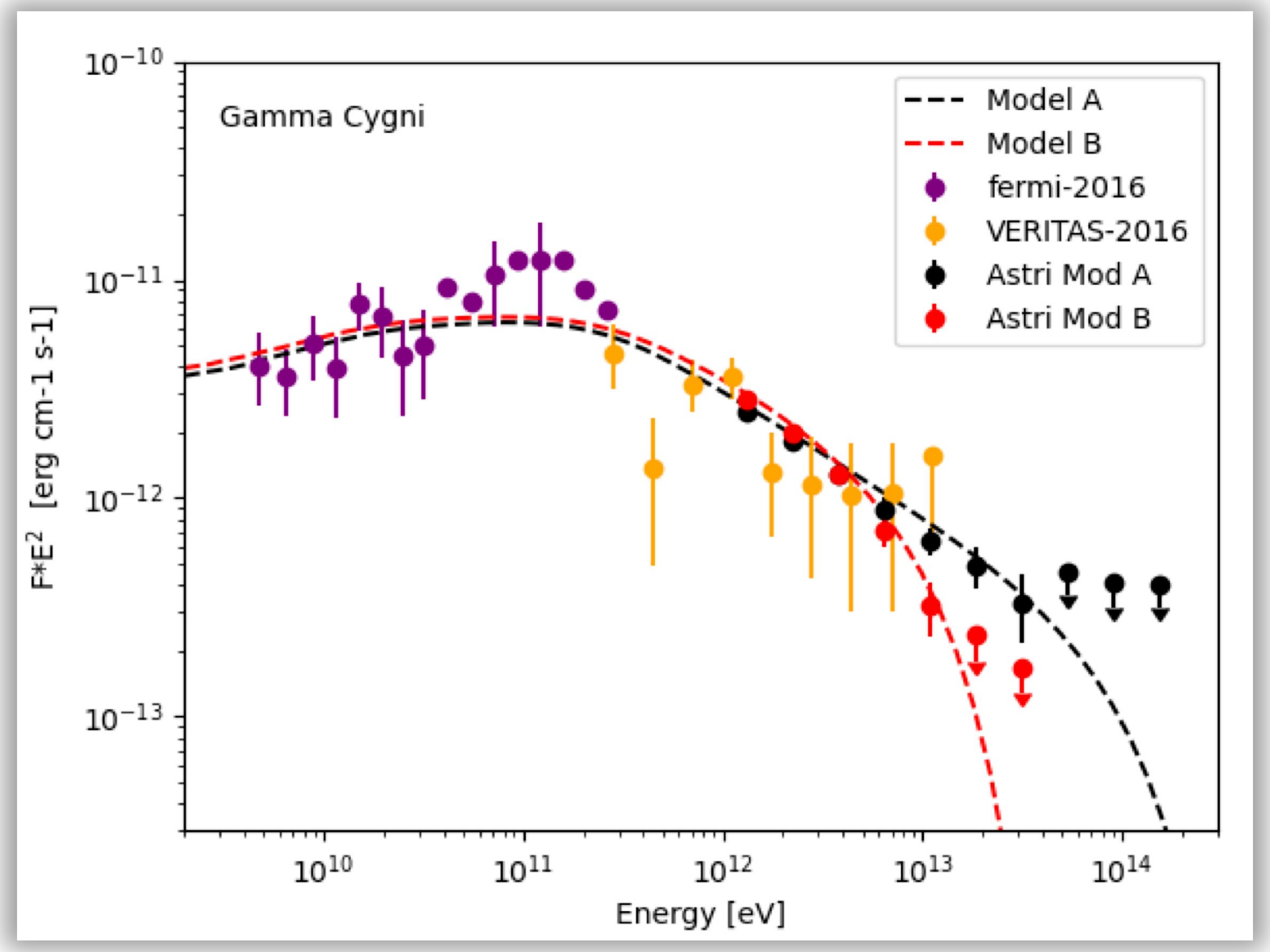
γ-Cygni (G78.2+2.1) is a middle-aged SNR located in the Cygnus region and discovered by VERITAS

HAWC observed this source, but HAWC's low angular resolution does not allow one to drive firm conclusion on the spatial structure

We simulated **2 possible spectral models** (A and B) fitting the combined Fermi-LAT and VERITAS data

The ASTRI Mini-Array will **constrain** some physical parameters such as the **maximum energy reached by protons** and the **diffusion coefficient**

Moreover, it will **investigate the VHE emission morphology**

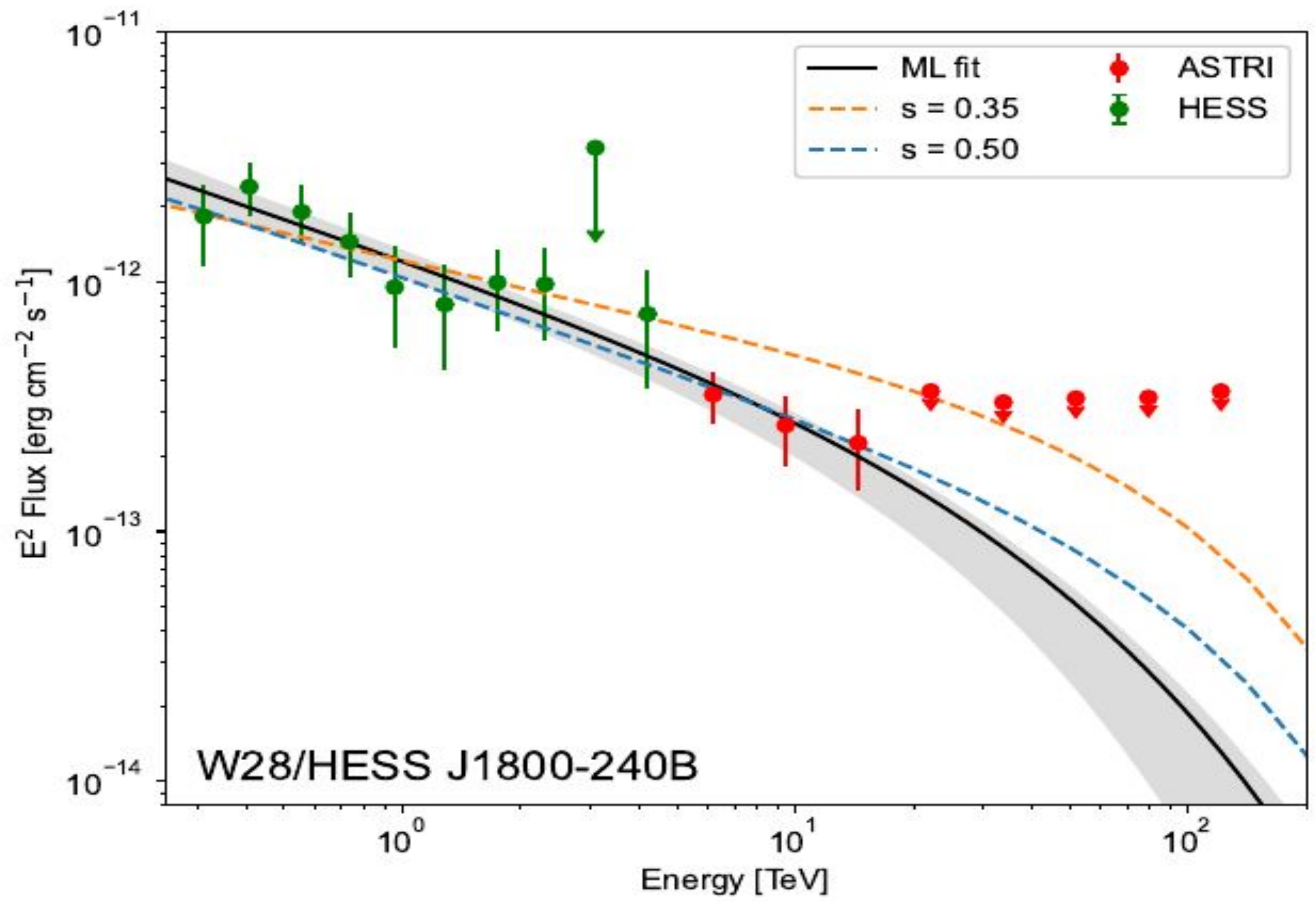


Black and red dots show the ASTRI Mini-Array simulations for model A and B, respectively, for 200 hr of exposure

Middle aged SNRs

Combining ASTRI and lower-energy data in order to constraining particle diffusion

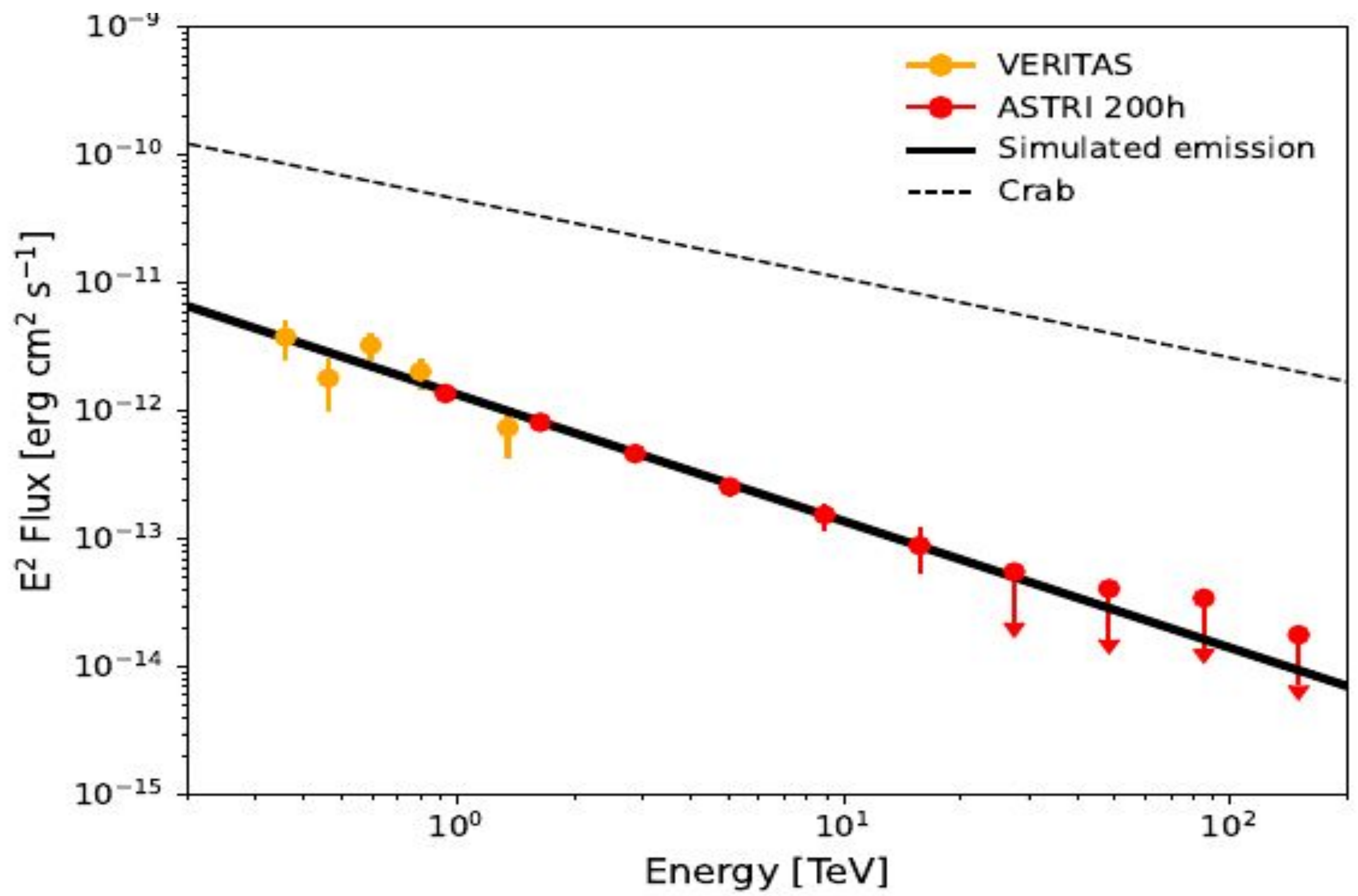
W 28



H.E.S.S. (green dots) and ASTRI Mini-Array simulations (red dots) for 200hr of exposure

ASTRI can discriminate between a diffusion index s = 0.35 versus s = 0.5

IC 443



γ-ray data from VERITAS (Acciari et al., 2009) (orange dots) and ASTRI Mini-Array (red dots).

The solid black line shows the best-fit model for the combined data-sets.

ASTRI Science : overview

Origin of Cosmic Rays

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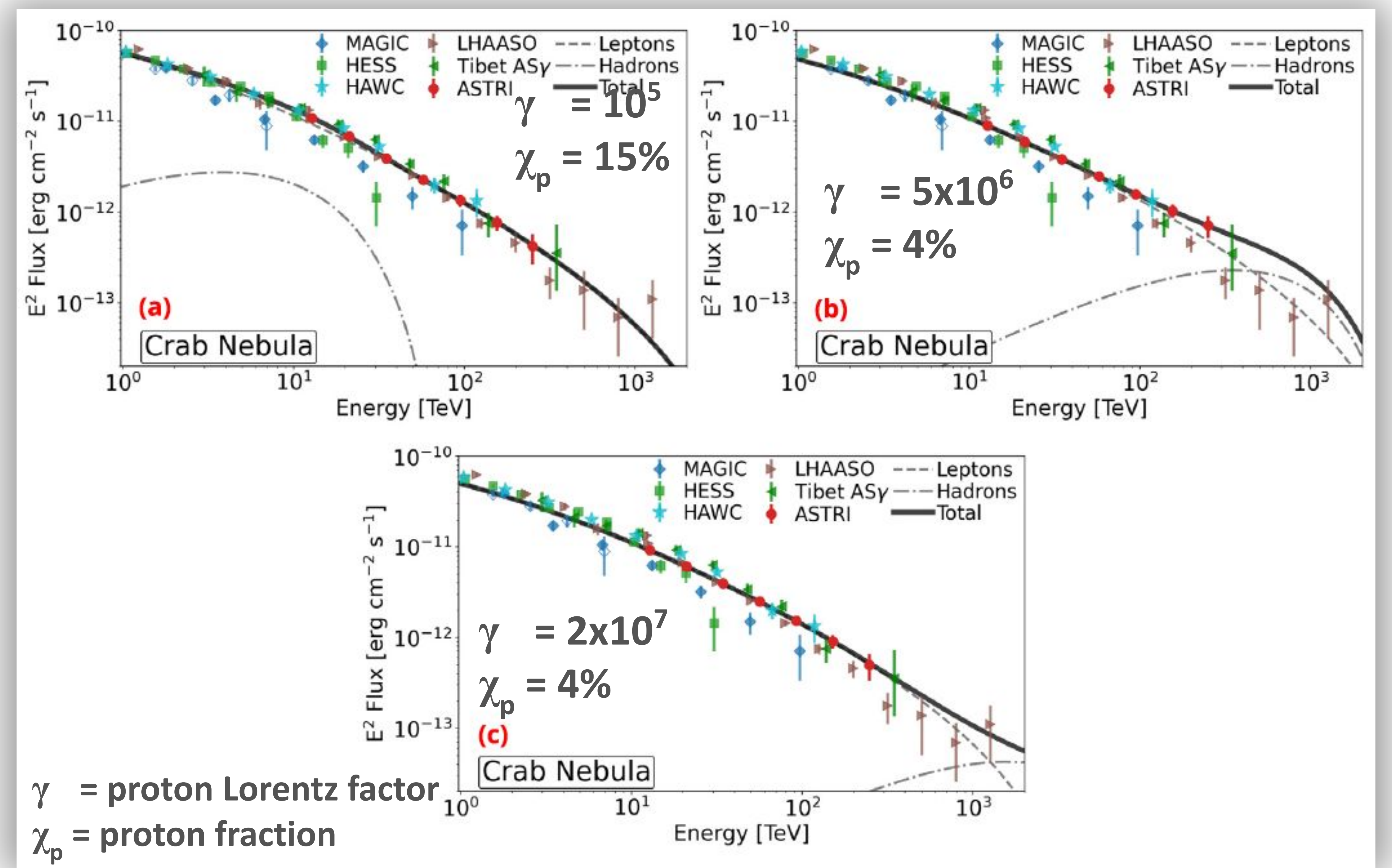
The Crab – a leptonic PeVatron?



The LHAASO data do not require a hadronic contribution, but cannot exclude it either.

As one can see from comparison of panel (b) and (c), **the ASTRI Mini-Array measurements in the 100-300 TeV range should definitely be able to provide constraints on the proton component**

Case (a)

- The hadronic component peaks below 10 TeV
- The leptonic component alone can very well reproduce the measurements by HAWC, Tibet AS-γ and LHAASO in the 1-400 TeV range

Case (b)

- In this case the overall spectrum is compatible with the highest energy data point by Tibet AS-γ and LHAASO, while LHAASO measurements in the 0.2-0.9 PeV range are over-predicted

Case (c)

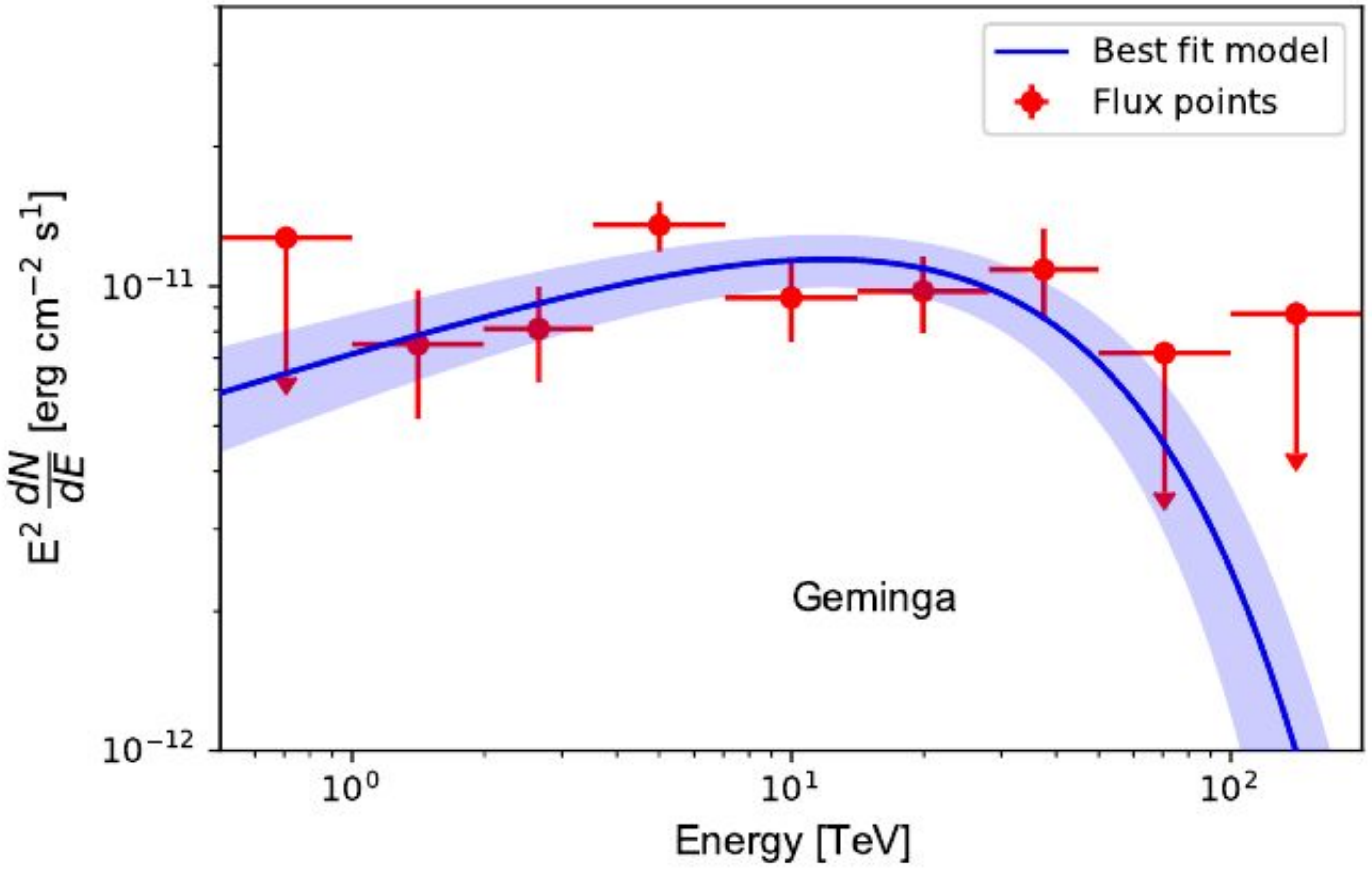
- In this case the model spectrum is compatible with all the available data. **All three plots highlight the excellent performance expected by the ASTRI Mini-Array (red symbols): the input spectrum is always recovered with very high accuracy with 500 hr of observations**

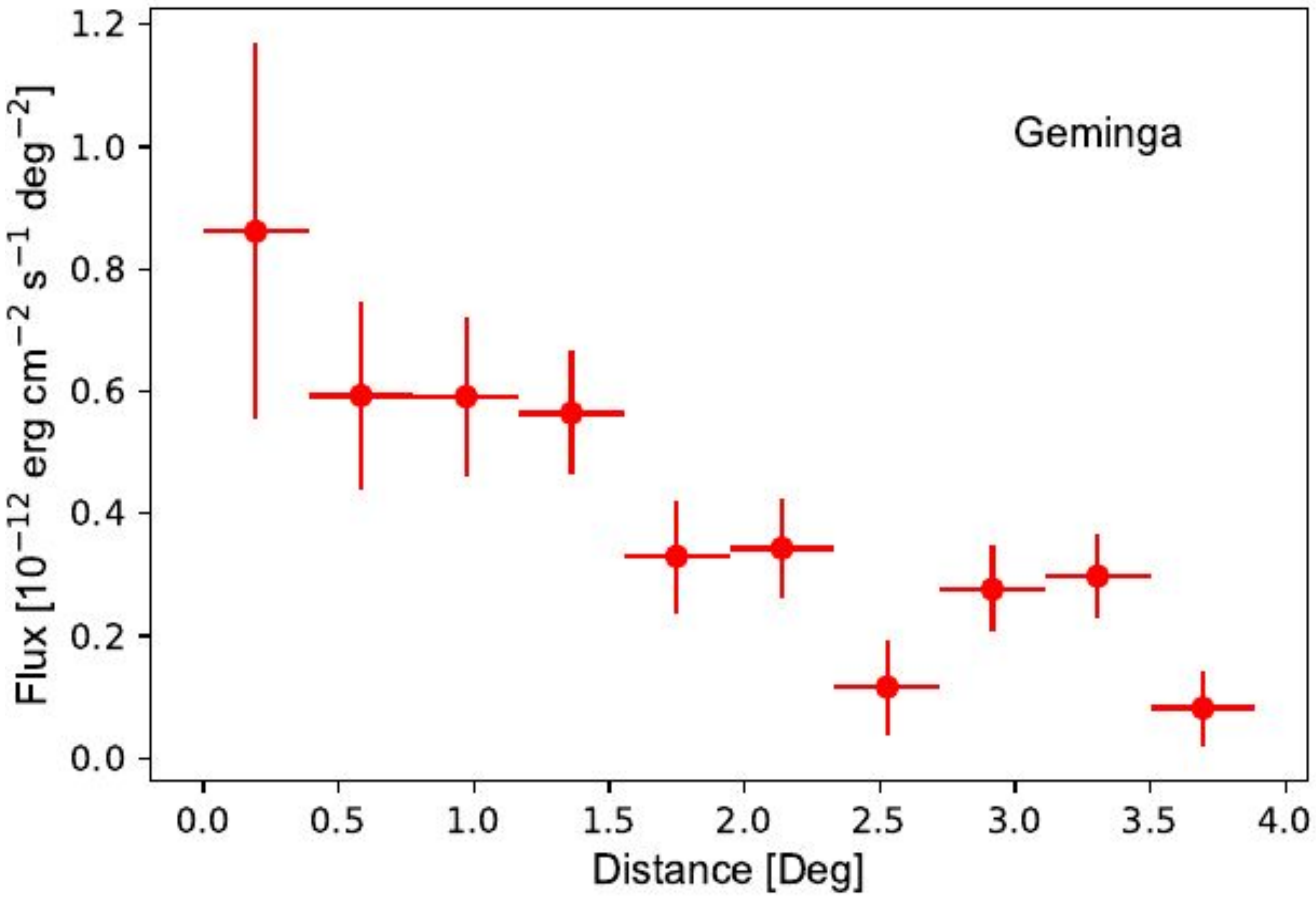
TeV Halos : the Geminga Halo

TeV halos are very large source (few degrees in diameter) with spectra peak in the multi-TeV range

→ ***Ideal case for ASTRI***

Tiling observations around the source position may be required in order measure the energy-dependent profile.





Simulation of an observation of the Geminga TeV Halo with ASTRI Mini-Array (200 hrs on source). Spectrum and radial profile

ASTRI Science : overview

Mini-Array

Origin of Cosmic Rays

- PeVatrons
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Fundamental Physics

- Intergalactic fields

EBL studies in the IR regime

Mini-Array

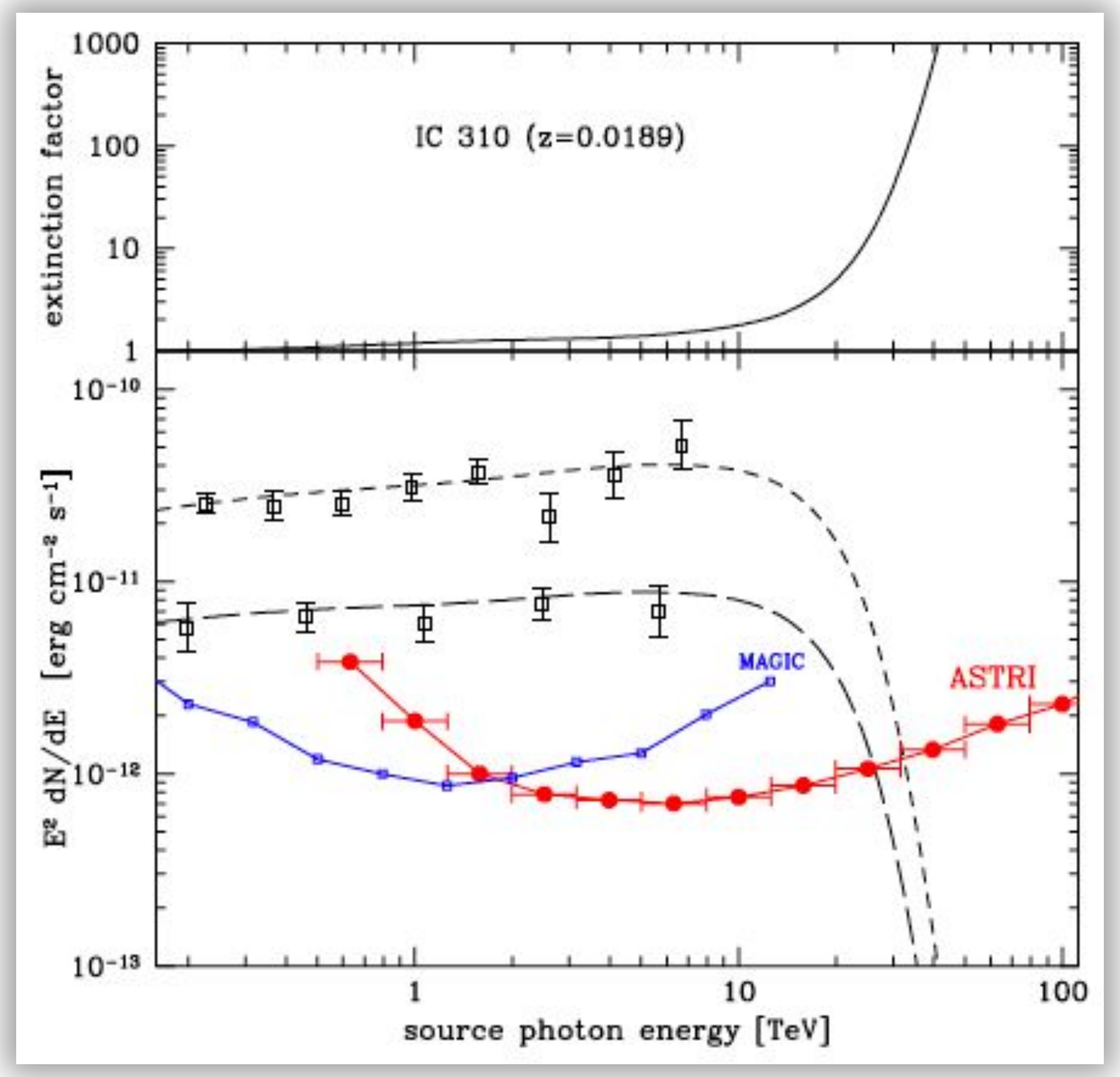
From the mid-IR to the far-IR, where the IR background intensity is maximal, EBL direct measurements are prevented by the overwhelming dominance of local emission from both the Galaxy and our Solar system

$$\lambda_{max} \sim 1.24 \times E_{TeV} \ [\mu m]$$

Measurements in the **(10-30)TeV energy band probe the EBL in the ~(10-30)µm regime**, otherwise unaccessible

Best candidates to constrain the EBL up to λ ~ 100μm:

- **low-redshift radio galaxies**
  - M 87, IC 310, Centaurus A
- **local star-bursting and active galaxies**
  - M 82, NGC 253, NGC 1068



Upper panel: extinction factor for photon-photon interaction on EBL at the IC 310 source distance.

Bottom panel: MAGIC (blue dots) and ASTRI Mini-Array (red dots) 50 hours, 5σ differential sensitivity

ASTRI Science : overview

Origin of Cosmic Rays

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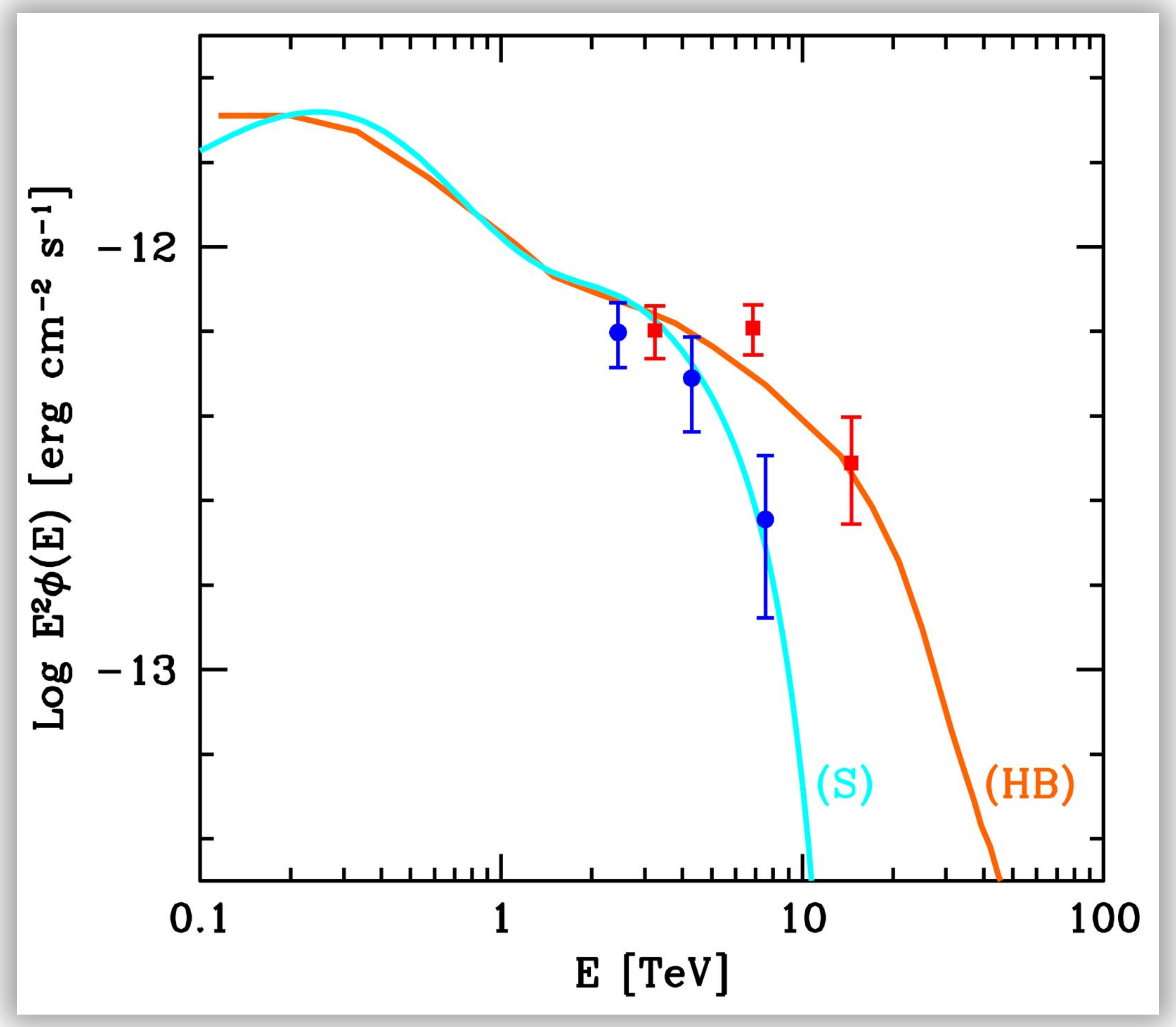
Hadron beams

Mini-Array

Relativistic jets from extreme BL Lacs could be one of the UHECR acceleration sites

Jets in extreme BL Lac objects could produce hadron beam (collimated beams of high-energy protons/nuclei)

While travelling towards the Earth
- UHECR lose energy through photo-meson and pair production
- these trigger the development of electromagnetic cascades producing γ and ν.
- Because of the reduced distance, γ experience a less severe EBL absorption
- **The observed gamma-ray spectrum extends at energies much higher (E > 10 TeV) than those allowed by the conventional EBL propagation**



Simulated VHE spectrum of 1ES 0229+220 for the standard (light blue, 200 hr) and hadron beam (red, 250 hr) scenarios

The ASTRI Mini- Array would be able to obtain a significant detection up to 20 TeV with a deep (~250 hr) observation

ASTRI Science : overview

Mini-Array

Origin of Cosmic Rays

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Fundamental Physics

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- LIV, ALP and DM

Transient Follow-Up

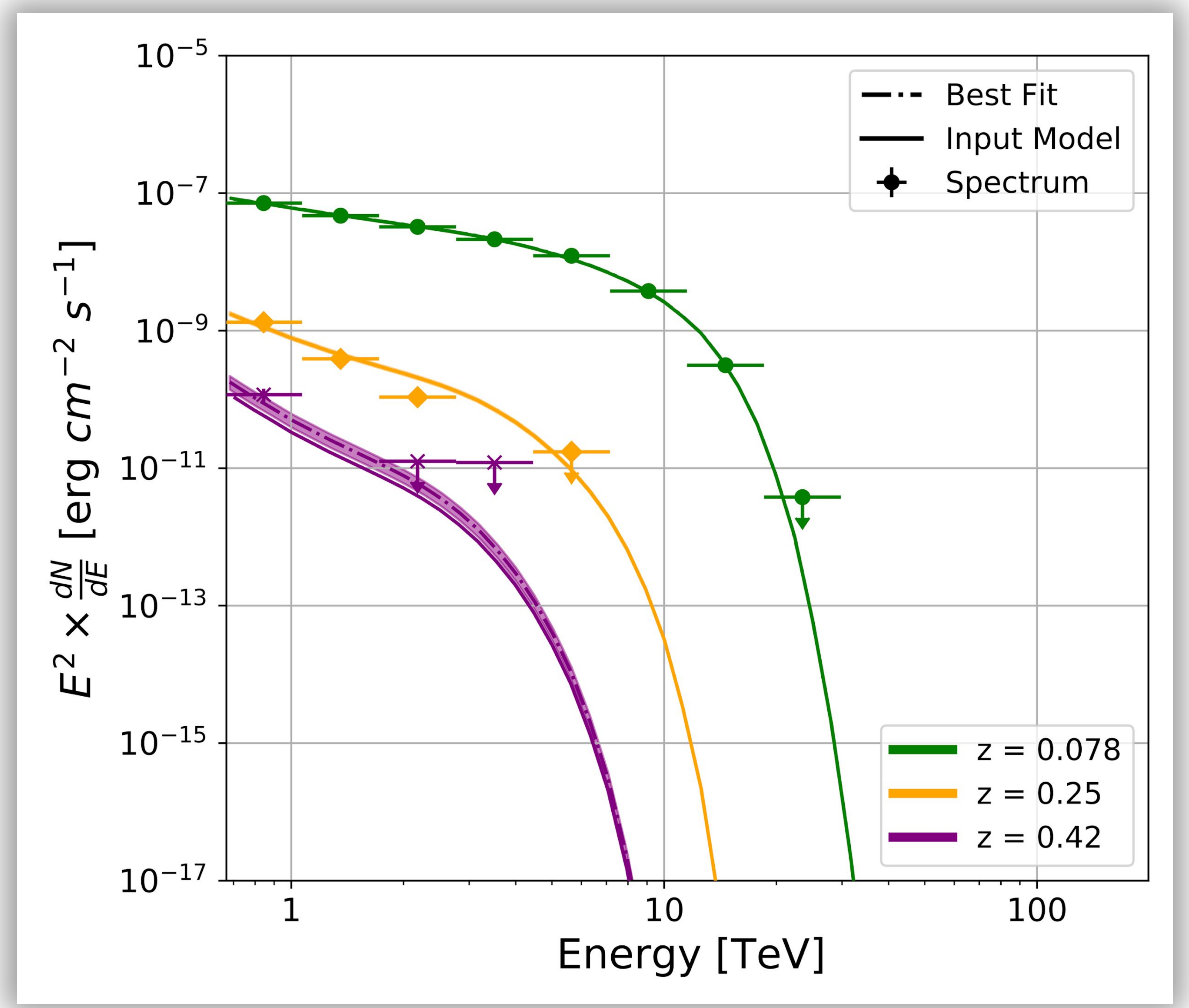
Gamma-ray bursts

- GRBs confirmed as a new class of TeV emitters thanks to the MAGIC detection of GRB 190114C (z=0.42)
- SSC component emerging in the TeV energy range

The ASTRI Mini-Array

- might have detected emission from GRB 190114C
- is able to confirm afterglow emission at E >1 TeV from close (z < 0.4) GRBs if observations start within the first tens of seconds up to few minutes from the onset of the burst
- can measure the spectral cut-off, either originated by the EBL absorption or intrinsic, if greater than 1 TeV

The expected number of follow-ups on observable GRBs is about than 1 per month



Simulation of the emission from three GRB 190114C-like bursts, at three different redshifts (z = 0.078, z = 0.25 and z = 0.42)

Strategic VHE synergies

- 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

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 3 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

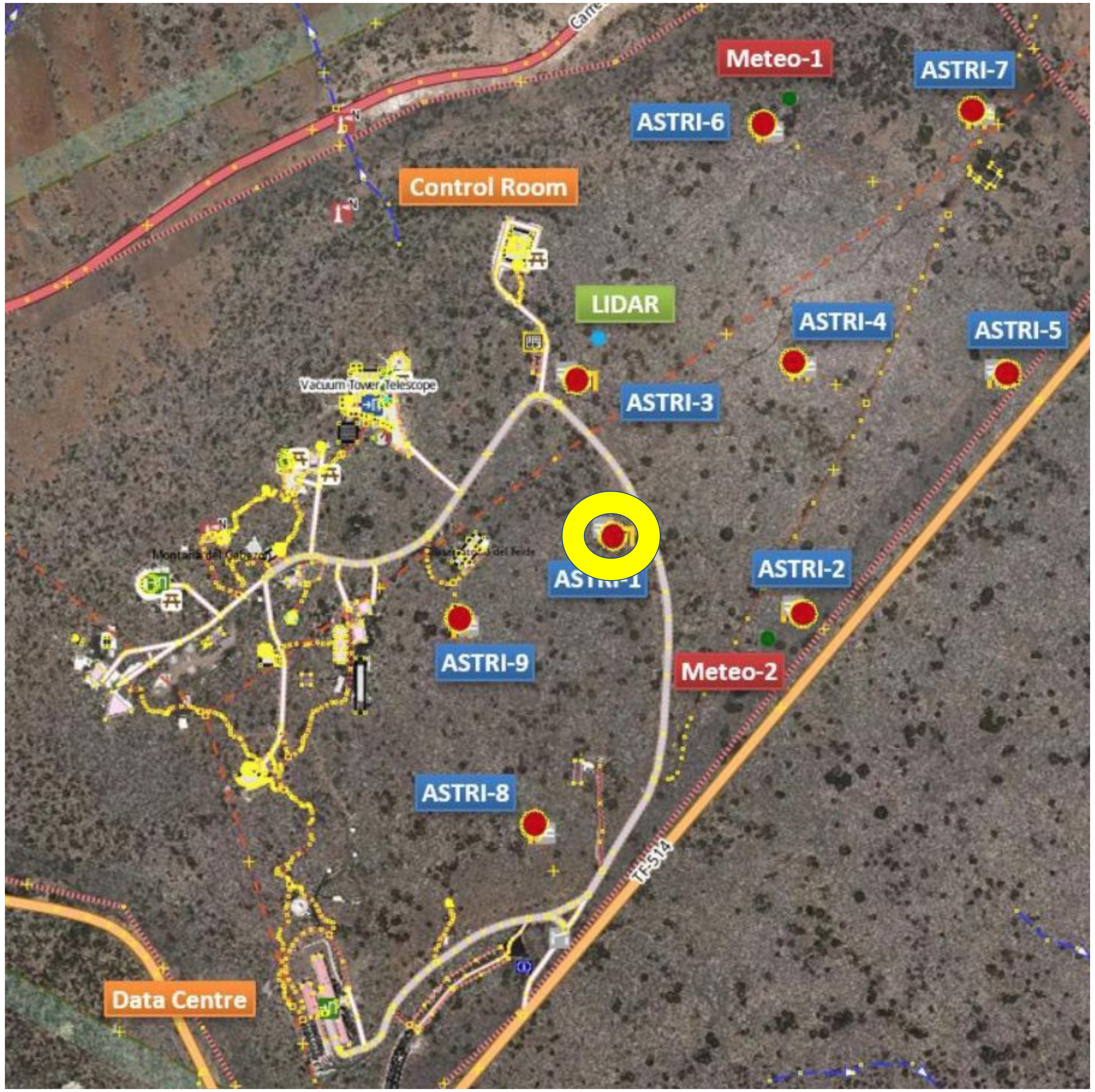
ASTRI Mini-Array - Schedule

June 2022

Phase 0

- 1 Telescope Structure
- m-ICT

Autumn 2022



ASTRI Mini-Array - Schedule

June 2022

Phase 0

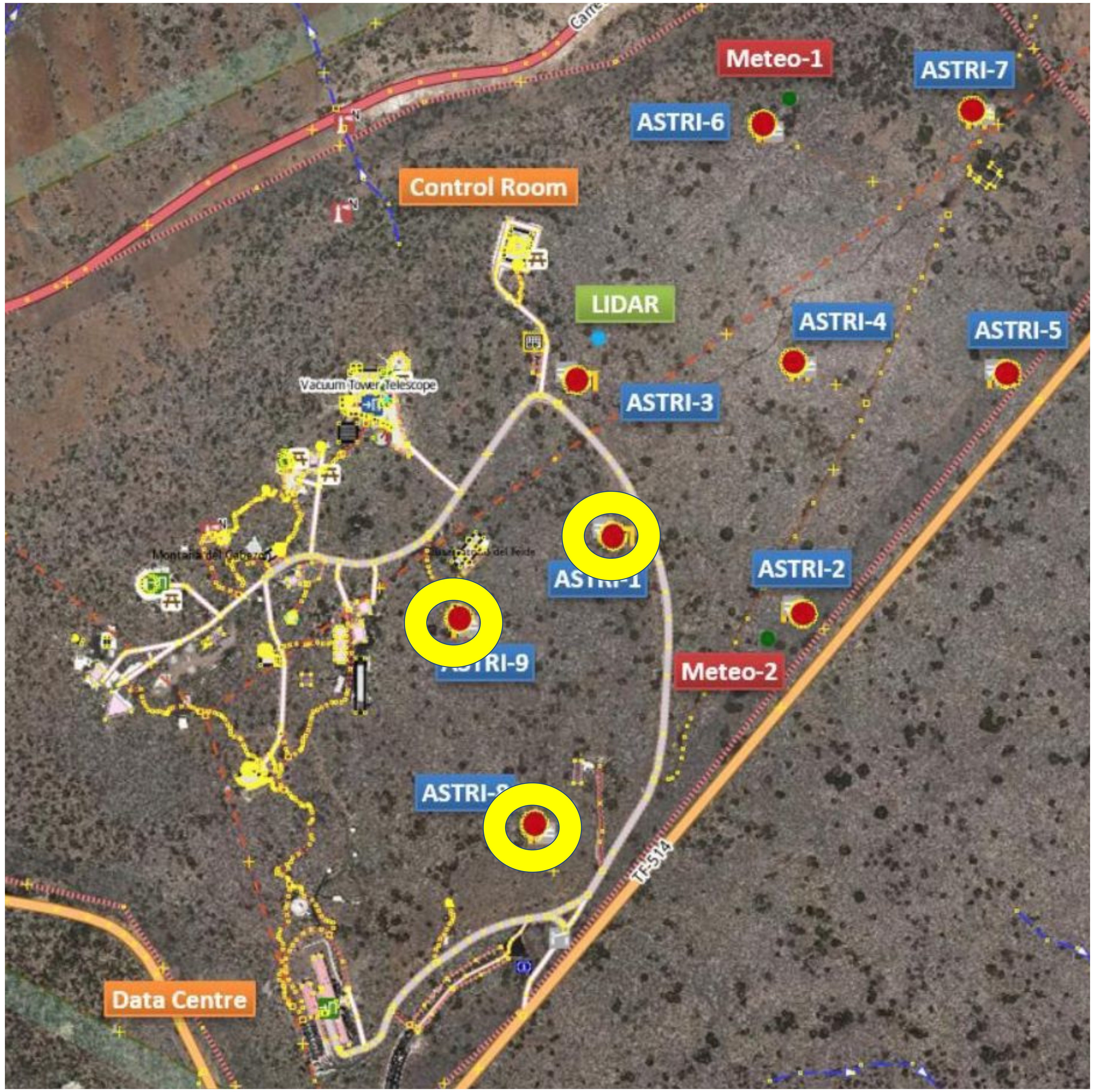
- 1 Telescope Structure
- m-ICT

Autumn 2022

Phase 1

- 3 Telescope Structures

Late Spring 2023



ASTRI Mini-Array - Schedule

June 2022

Phase 0
- 1 Telescope Structure
- m-ICT

Autumn 2022

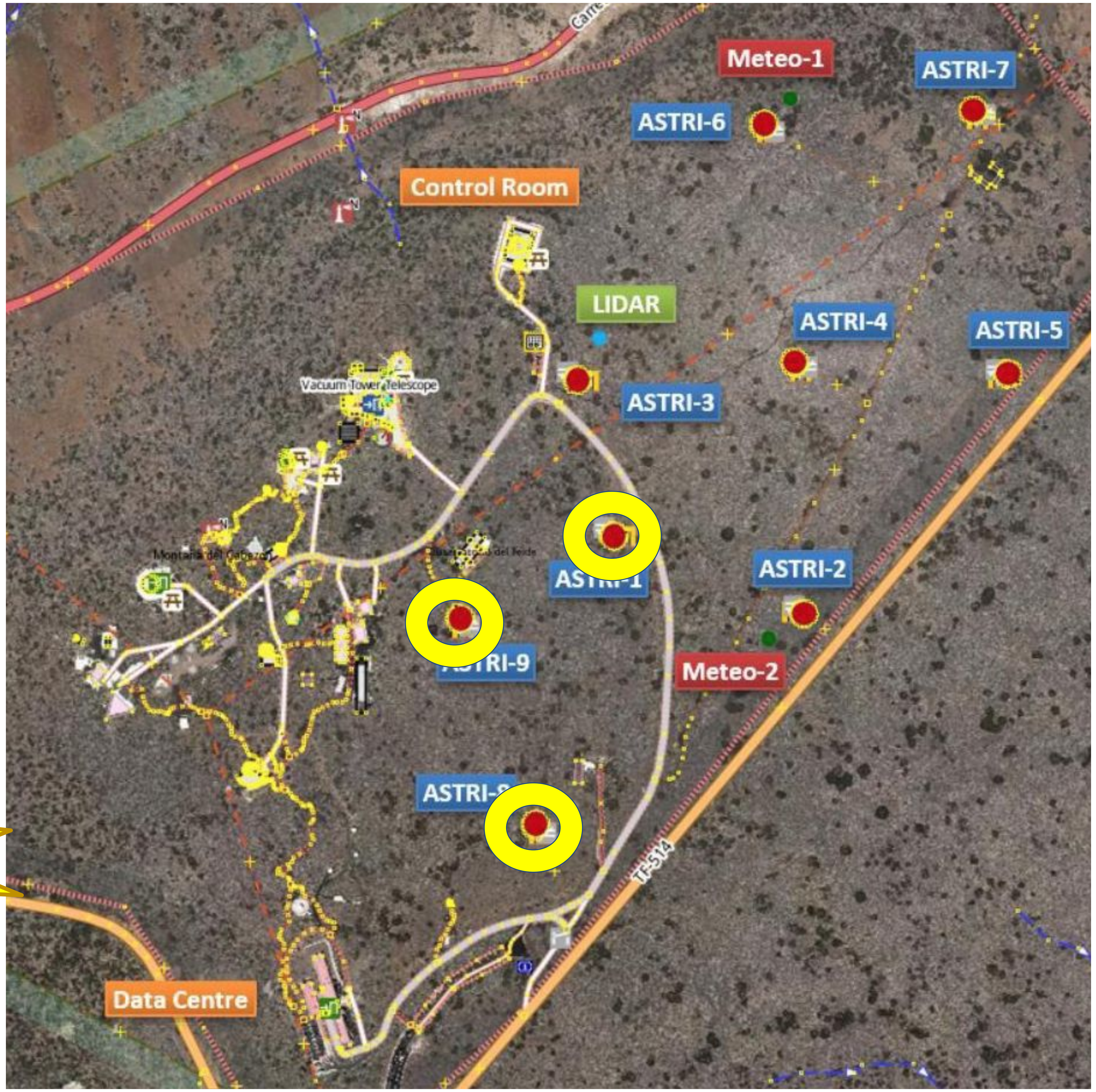
Phase 1
- 3 Telescope Structures

Late Spring 2023

Phase 2
- 3 Telescope Structures + Cameras

Autumn 2023

Early observations



ASTRI Mini-Array - Schedule

June 2022

Phase 0
- 1 Telescope Structure
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Autumn 2022

Phase 1
- 3 Telescope Structures

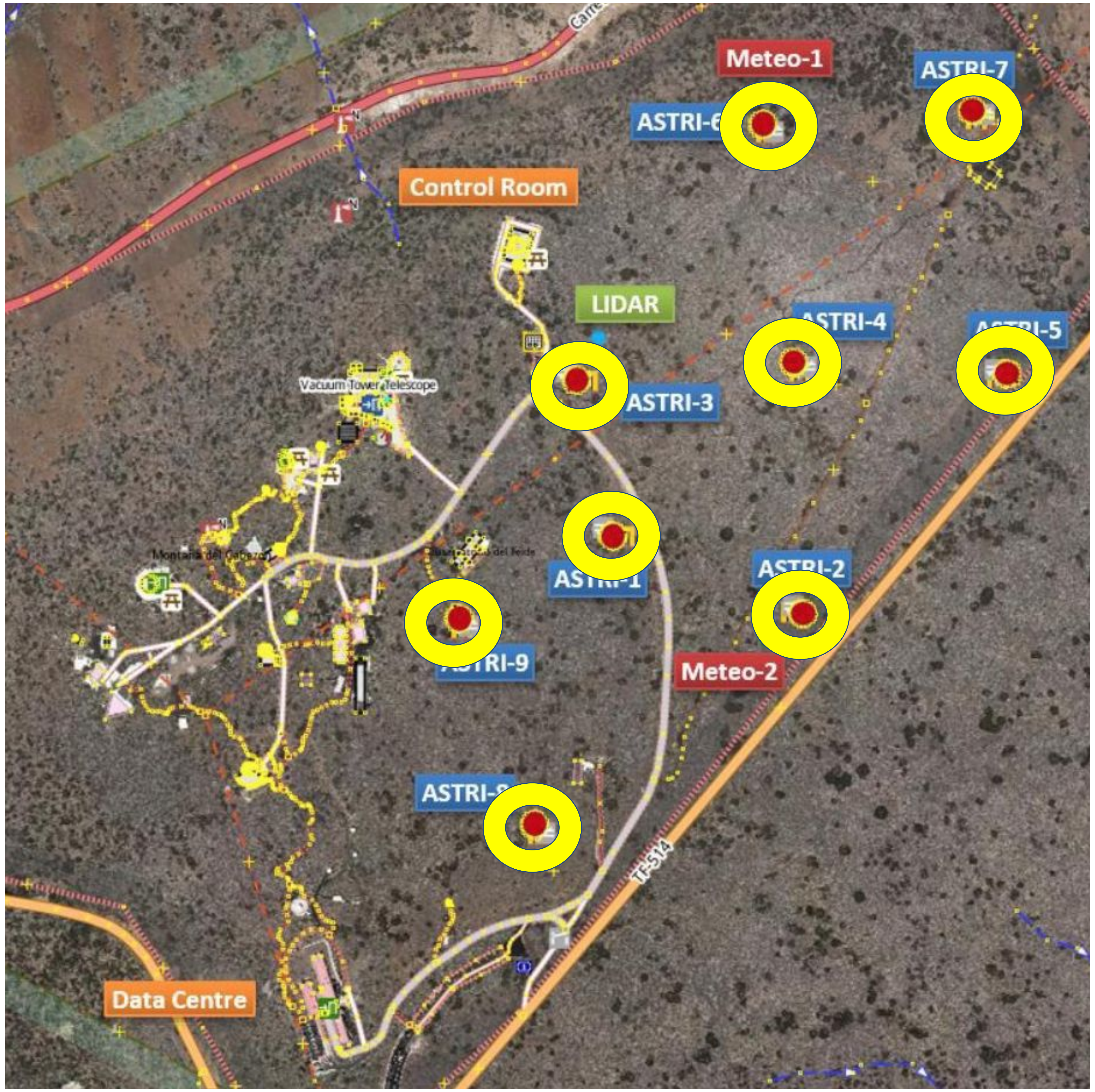
Late Spring 2023

Phase 2
- 3 Telescope Structures + Cameras

Autumn 2023

Phase 3
- Full Array

End of 2024



More at..

Astri web site : **http://www.astri.inaf.it/**

Science papers on **JHEAP, 2022, 35**

On socials, search for ***ASTRIgamma*** (FB and Instagram)

IRFs (gammapy and ctools compatible) available at :
https://zenodo.org/record/6827882

…THANK YOU !

Photo CREDITS Tommaso Marchiori

Backup slides

Observing Plan

Issue : Large exposures are required

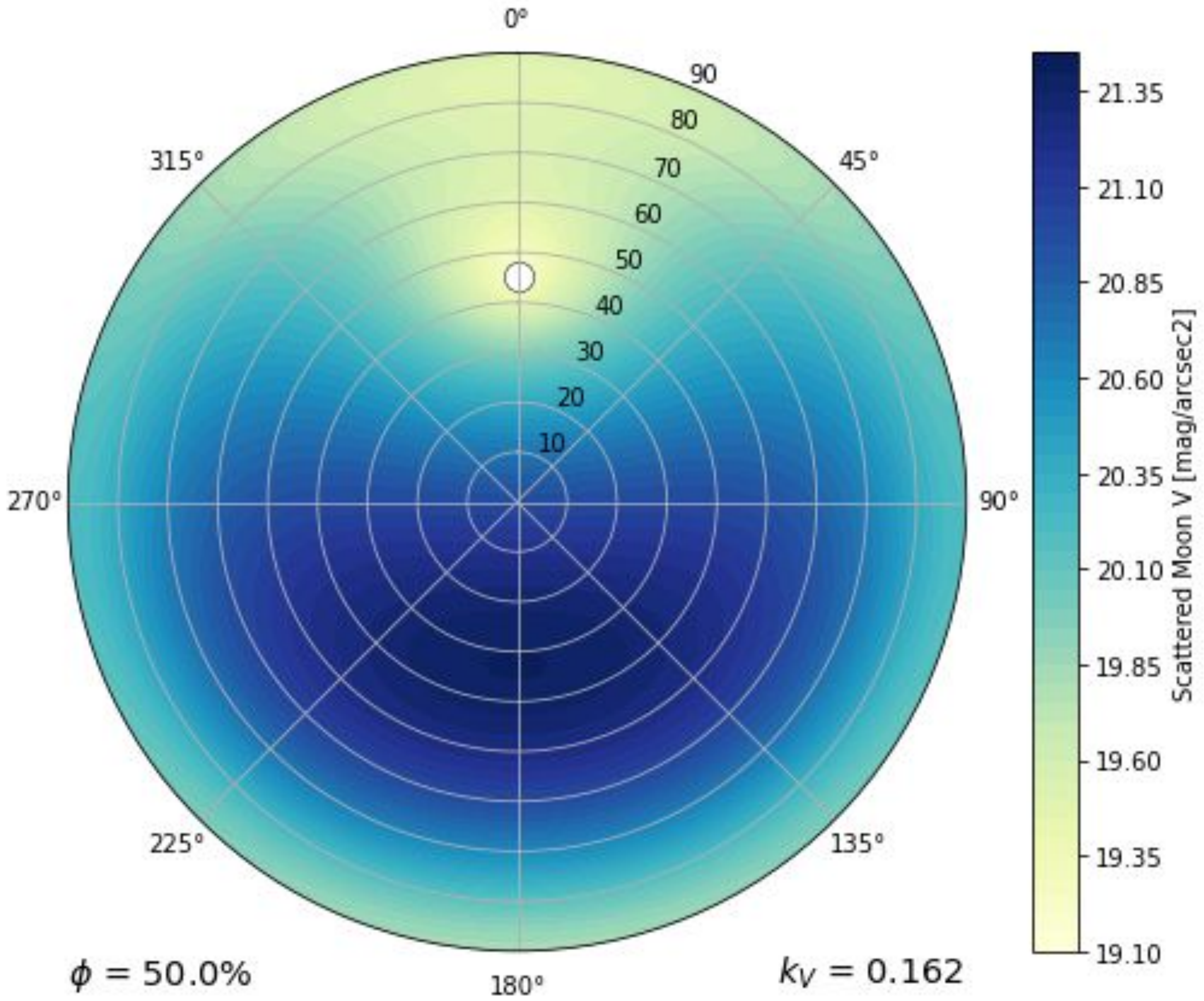
Strategy :

Focus on few sky fields → Long exposures

3 aces up the sleeve :

- Large FoV → Several sources in the FOV
- Large Z.A. → Increase Aeff @ high energies
- Observations with moonlight → ASTRI Camera can deal with high NSB

NSB with MoonLight

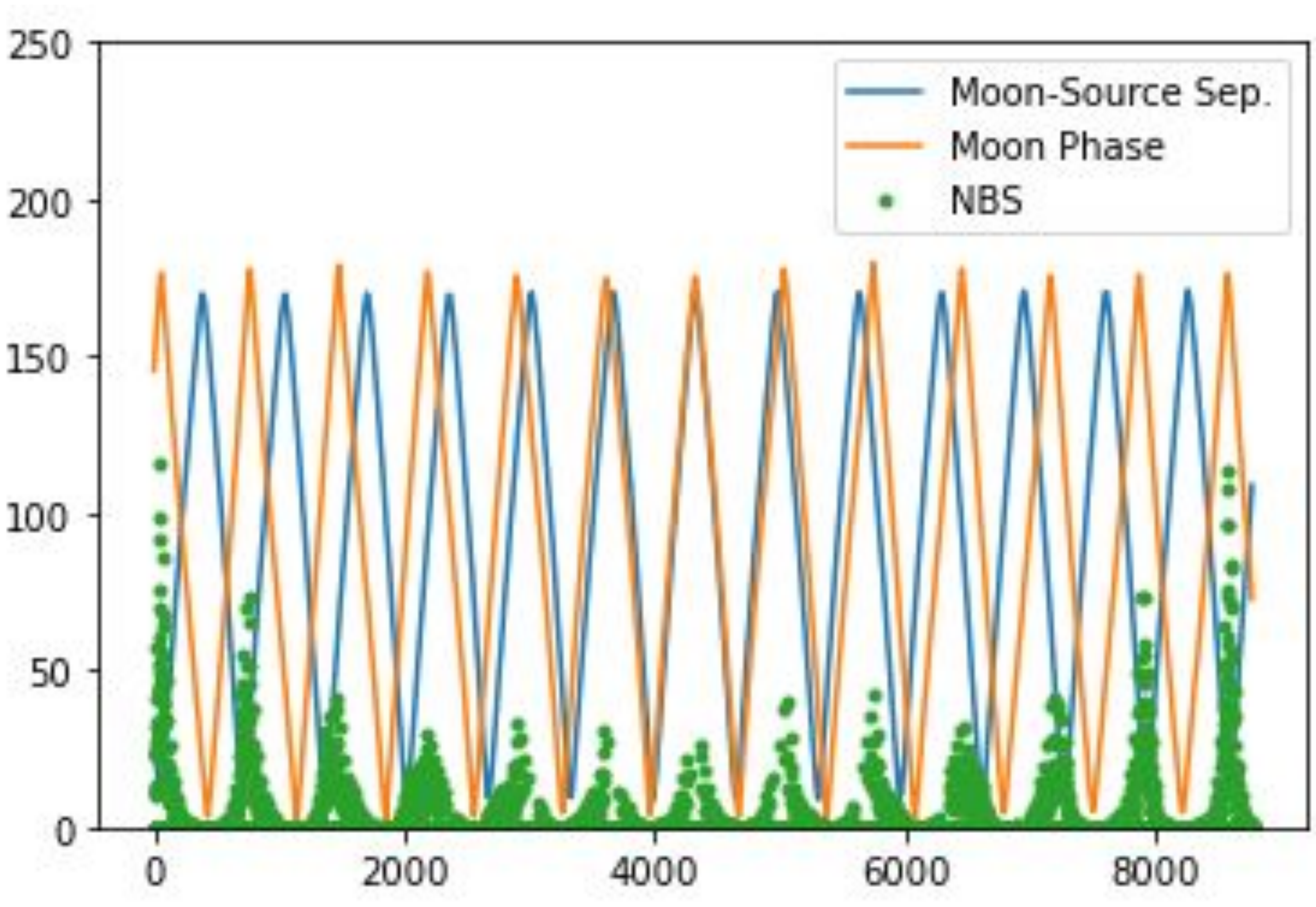


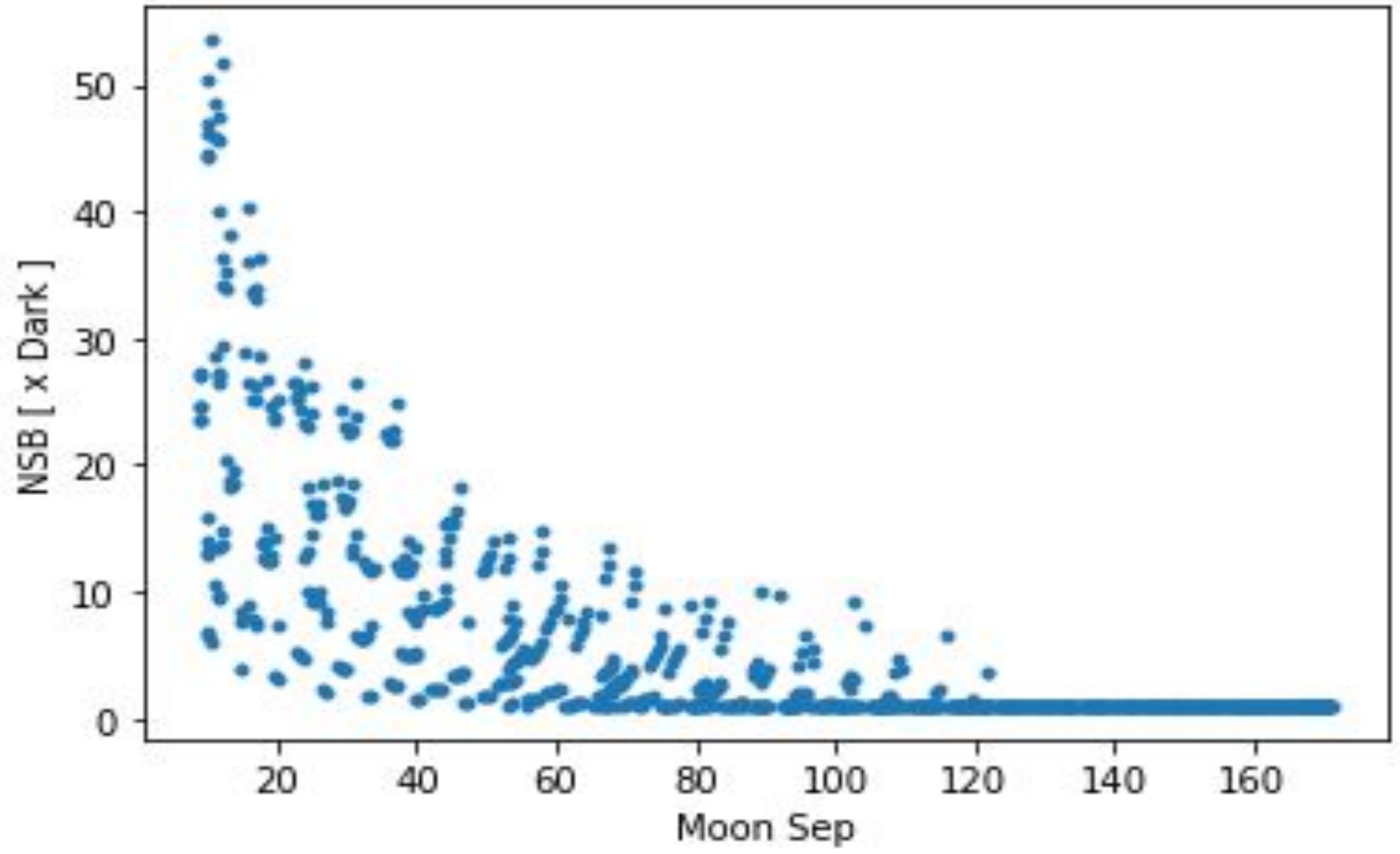
- SkyCalc
- SpecSim
  (https://specsim.readthedocs.io)
  Based on the model by
  Krisciunas&Schaefer

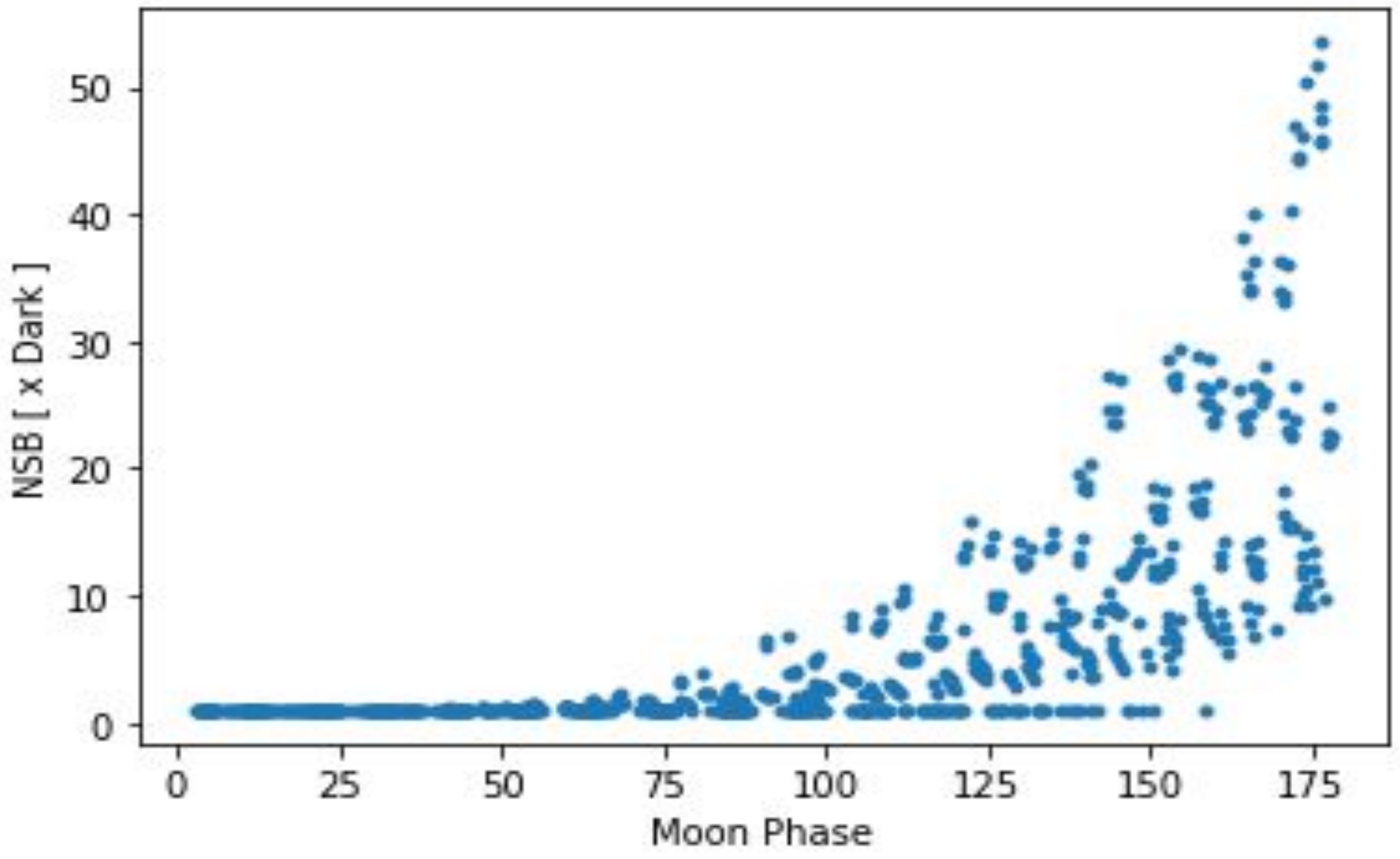
Brightness in V [mag/arcsec^2]

	SkyCalc	SpecSim	diff Fluxes
halfmoon_sep20	*20.04*	*20.03*	*0.9 %*
halfmoon_sep40	*20.47*	*20.52*	*4.7 %*
halfmoon_sep60	*20.68*	*20.75*	*6.7 %*
fullmoon_sep40	*18.33*	*18.30*	*2.8 %*

NBS with MoonLight – (the Geminga Halo)





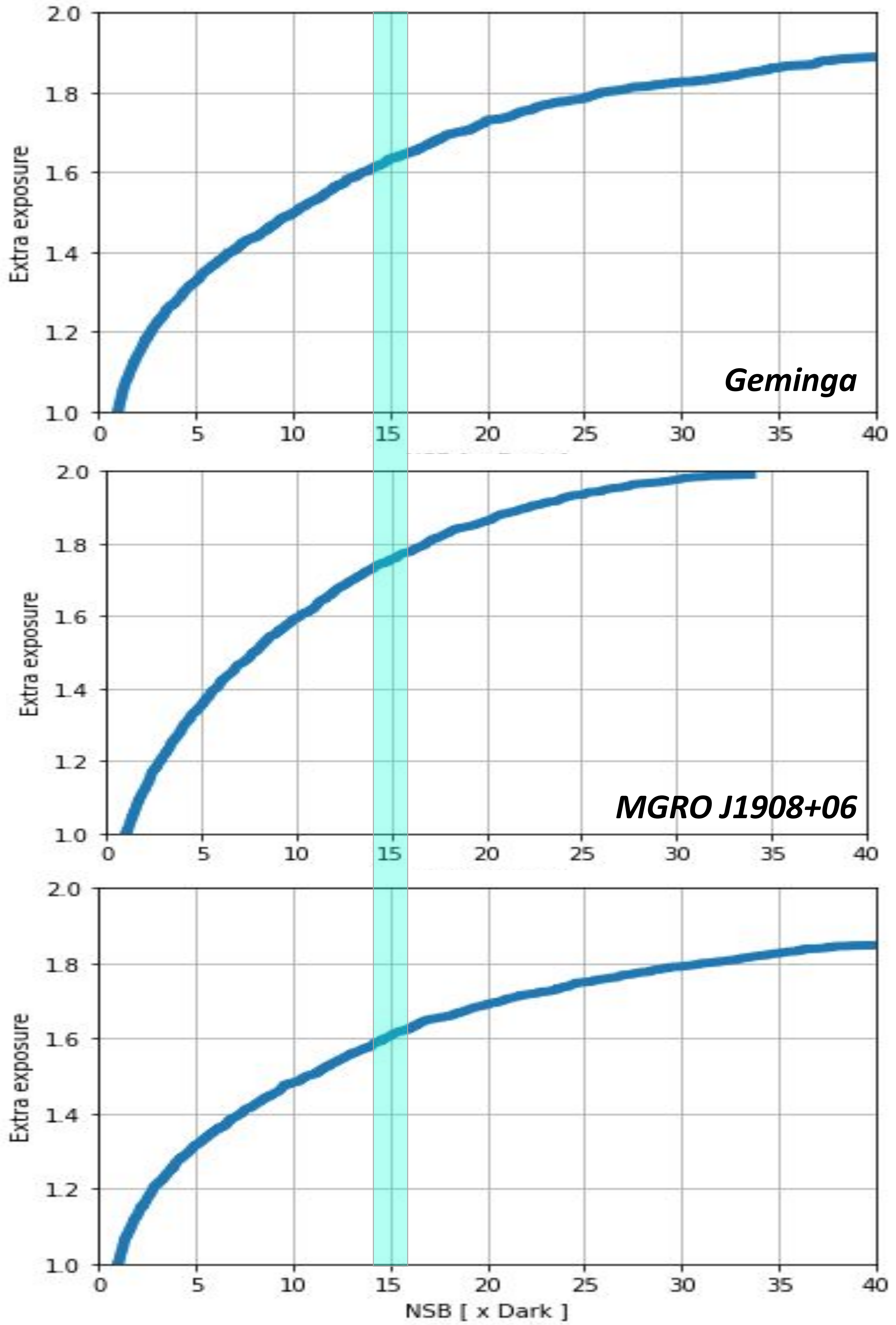


- For year 2026
- Dark : m_V= 21.55

Observation duty-cycle

Moonless Night Hours	1565 h
Fraction of clear nights (cloud coverage <20%)	0.79
Fractional loss due to bad weather	0.04
Fractional loss due to "Calima"	0.07
Average Annual Observation Time	1104 h

Setting 15 NSB as limit → AAOT ~ 1800 h



The 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 ≳ 3 TeV)

Extended spectrum and cut-off constraints

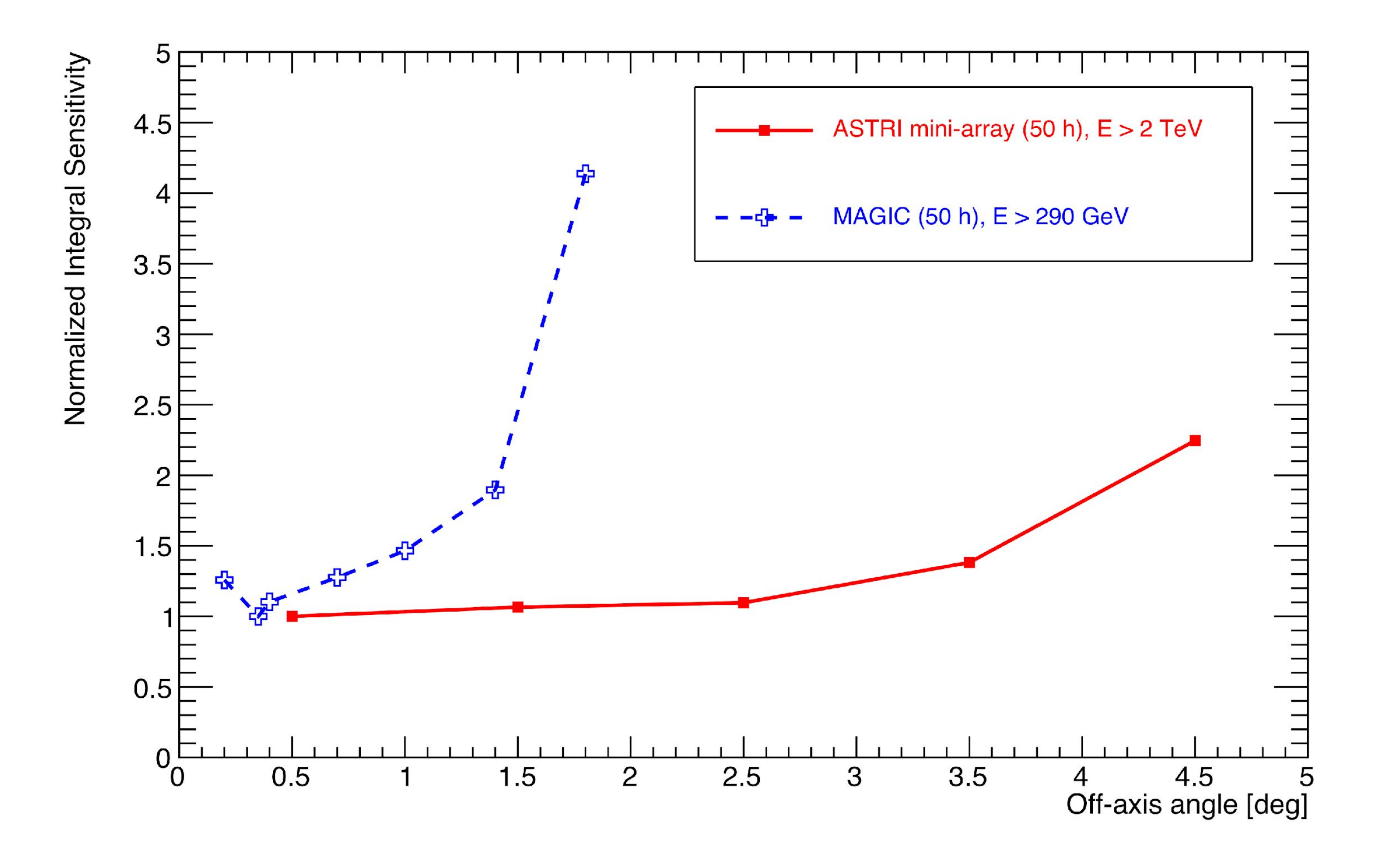
Energy/Angular resolution: ~10% / ~0.05° (E =10 TeV)

Characterize extended sources morphology

10° field of view with homogeneous off-axis performance

Multi-target fields and extended sources

Enhanced chance for serendipitous discoveries



The multi-wavelength landscape

- **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 interestest 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

The ASTRI Mini-Array Project

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.

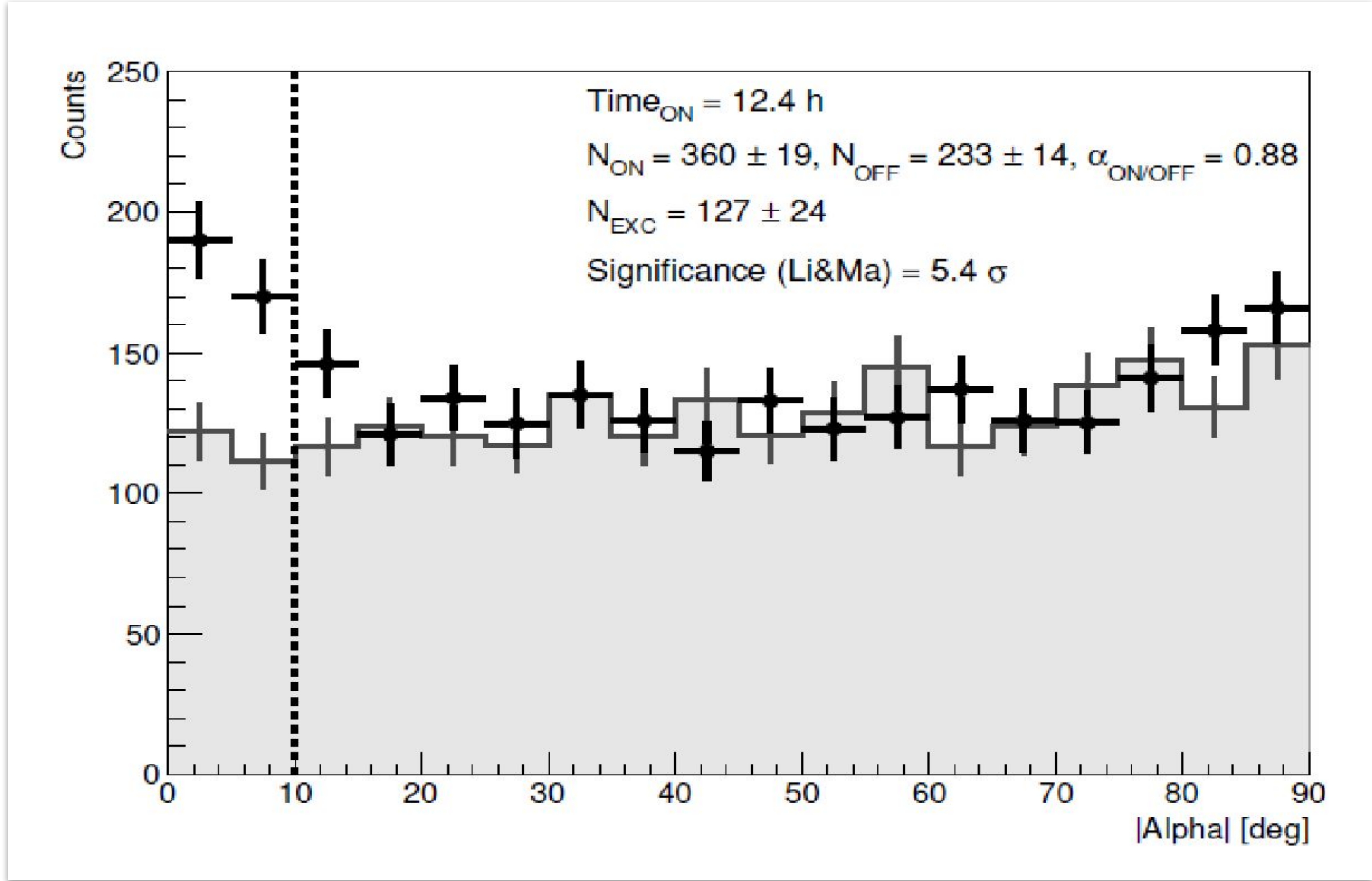
ASTRI HORN

ASTRI

(Astrofisica con Specchi a Tecnologia Replicante Italiana) was born as "Progetto Bandiera" funded by MIUR with the initial aim to design and realize an innovative end-to-end prototype of the 4 meters class telescopes in the framework of the CTA observatory

ASTRI-Horn.

ASTRI prototype at OACT in Serra La Nave, Etna Volcano



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

ASTRI Science

see ***S. Vercellone*** *talk and* ***M. Cardillo*** *poster*

Pillar 1 : **Origin of CRs**

- **PeVatrons**
- **CRs Propagation**
- **Pulsar Wind Nebulae**

Pillar 2 :
Cosmology and Fundamental Physics

Name	Type	Req. Exposure (Hrs)
Tycho Snr	SNR	400
Gal. Center	Diffuse	260
VER J1907	SNR+PWN	
G106.3+2.7	SNR	
γ-Cygni	SNR	
W28	SNR/MC	
M82	Starburst	
Crab	PWN	
Geminga	PWN	
IC 310	Radio gal	10-500
M87	Radio gal	10-500
Mkn 501	Blazar	5-500
1ES 0229+200	Blazar	200-250

Large exposures are required