The ASTRI Mini-Array Core Science Program

Stefano Vercellone – INAF Osservatorio Astronomico di Brera
for the ASTRI Project

γ2022 Symposium, 04-08.07.2022

ASTRI: Astrophysics with Italian Replicating Technology Mirrors

Mini-Array

See Talk by A. Giuliani

ASTRI-Horn Prototype

INAF-led Project funded by Italian Ministry of Research

End-to-end prototype 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)

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 yr → *Core Science*, following 4 yr → *Observatory Science*. **Science operation → Q1 2025**

The JHEAP suite

Mini-Array

Set of 4 papers published on the «Journal of High Energy Astrophysics»

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], B. Biondo[f], M. Boettcher[r], G. Bonar… P. Bruno[d], A. Bulgarelli[e], R. Canestrari[f], M. Capalbi[f], M.Cardillo[k], V. Conforti[e], G. … M. Corpora[f], A. Costa[d], G. Cusumano[f], A. D'Aì[f], E. de Gouveia Dal Pino[l], R. D… E. Escribano Rodriguez[o], D. Falceta-Gonçalves[s], C. Fermino[l], M. Fiori[j,g], V. … …orini[a], S. Gallozzi[h], C. Gargano[f], S. Garozzo[d], S. Germani[c], A. Ghedina[o], F. C… …arrusso[f], R. Gimenes[f,l], V. Giordano[d], A. Grillo[d], C. Grivel Gelly[o], D. Impic… …ardona[d], S. Incorvaia[a], S. Iovenitti[b], A. La Barbera[f], N. La Palombara[a]… A. Lamastra[h], L. Lessio[g], G. Leto[d], F. Lo Gerfo[f], M. Lodi[o], S. Lombard… …Lucarelli[h], M.C. Maccarone[f], D. Marano[d], E. Martinetti[d], S. Me… …cciché[d], R. Millul[b], T. Mineo[f], G. Morlino[q], A. Morselli[i], G. Naletto[j,g], G. Nicotra … N. Parmiggiani[e], G. Piano[k], F. Pintore[f], E. Poretti[o], B. Olmi[q], G. Rodeghiero[e], G. …guez Fernandez[i], P. Romano[b], G. Romeo[d], F. Russo[e], P. Sangiorgi[f], F.G. Saturni[h], J.H. Schwarz[b], E. Sciacca[d], G. Sironi[b], G. Sottile[f], A. Stamerra[h], G. Tagliaferri[b], V. Testa[h], G. Umana[d], M. Uslenghi[a], S. Vercellone[b], L. Zampieri[g] and R. Zanmar Sanchez[d]

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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], M. Böt… G. Brunetti[n], A. A. Compagnino[e], S. Crestan[o,p], A. D'Aì[e], M. Fiori[h,f], G. Galanti[o], … E. M. de Gouveia Dal Pino[q], J. G. Green[b], A. Lamastra[b,g], M. Landoni[a], F. Luca… …orlino[c], B. Olmi[r,c], E. Peretti[s], G. Piano[d], G. Ponti[a,t], E. Poretti[a,u], P. Romano[a], F. C… …Scuderi[o], A. Tutone[b], G. Umana[v], J. A. Acosta-Pulido[l,m], P. Barai[q], A. Bonanno[v] … P. Bruno[v], A. Bulgarelli[w], V. Conforti[w], A. Costa[v], G. Cusumano[e], M. Del Sa… …l Valle[q], R. Della Ceca[a], D. A. Falceta-Gonçalves[q], V. Fioretti[w], S. Germani[x,y], … …opez[l,m], A. Ghedina[u], V. Giordano[v], M. Kreter[k], F. Incardona[v], S. Iovenitti[a], A. L… N. La Palombara[o], V. La Parola[e], G. Leto[v], F. Longo[z,aa], A. López-Oramas[l,m], M. C. … …one[e], S. Mereghetti[o], R. Millul[a], G. Naletto[f], A. Pagliaro[e], N. Parmiggiani[w], C. Righi[a], J. C. Rodríguez-Ramírez[q], G. Romeo[v], P. Sangiorgi[e], R. Santos de Lima[q], G. Tagliaferri[a], V. Testa[b], G. Tosti[x,y], M. Vázquez Acosta[l,m], N. Żywucka[k,ab], P. A. Caraveo[o] and G. Pareschi[a]

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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. L… Palombara[d], A. Paizis[d], G. Piano[e], F. G. Saturni[f,g], A. Tutone[a,h], A. Belfiore[d], M. C… S. Crestan[d], G. Cusumano[a], M. Della Valle[i,j], M. Del Santo[a], A. La Barbera[a], … S. Lombardi[f,g], S. Mereghetti[d], G. Morlino[b], F. Pintore[a], P. Romano[k], S. V… …Antonelli[f], C. Arcaro[l], C. Bigongiari[f], M. Böettcher[m], P. Bruno[n], A. Bulgarelli[o], … …Costa[n], E. de Gouveia Dal Pino[p], V. Fioretti[o], S. Germani[q], A. Ghedina[r], V. Giordano… …ardona[n], G. Leto[n], F. Longo[s,t], A. López Oramas[u], F. Lucarelli[f,g], B. Olmi[v], A. Pagliaro[a], N. Parmiggiani[o], G. Romeo[n], A. Stamerra[f], V. Testa[f], G. Tosti[o,q], G. Umana[n], L. Zampieri[e], P. Caraveo[d] and G. Pareschi[k]

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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… M. Capalbi[k], A. Lamastra[a], S. Lombardi[a,b], F. Lucarelli[a,b], R. Alves Batista[l] …onelli[a,b], E. M. de Gouveia Dal Pino[m], R. Della Ceca[j], J. G. Green[a,b], A. Pagliaro[k], … Tavecchio[n], S. Vercellone[n], A. Wolter[j], E. Amato[o], C. Bigongiari[a,b], M. Böttch… …etti[p], P. Bruno[q], A. Bulgarelli[r], M. Cardillo[s], V. Conforti[r], A. Costa[q], G. Cusu… …oretti[r], S. Germani[t], A. Ghedina[u], V. Giordano[q], A. Giuliani[v], F. Incardona[q], A. … G. Leto[q], F. Longo[w,x], G. Morlino[o], B. Olmi[y], N. Parmiggiani[r], P. Romano[n], G. Ro… A. Stamerra[a], G. Tagliaferri[n], V. Testa[a], G. Tosti[j,t], P. A. Caraveo[v] and G. Pareschi[n]

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Topic of this talk

ASTRI Mini-Array

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

JHEAP, 2022, 35, 1

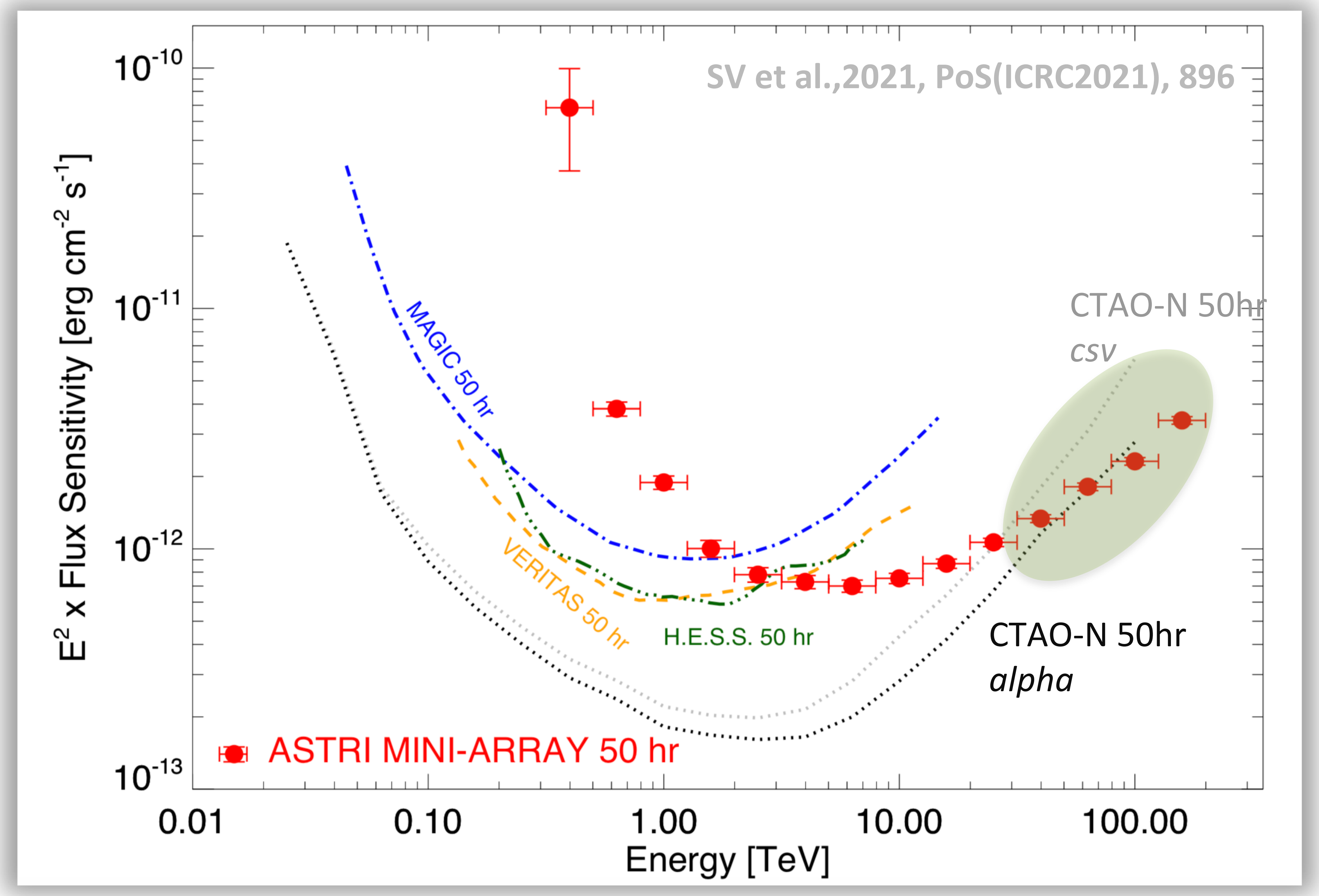
S. Vercellone[a,*], C. Bigongiari[b], A. Burtovoi[c], M. Cardillo[d], O. Catalano[e], A. Franceschini[f], S. Lombardi[b,g], L. Nava[a], F. Pintore[e], A. Stamerra[b], F. Tavecchio[a], L. Zampieri[h], R. Alves Batista[i], E. Amato[c,j], L. A. Antonelli[b,g], C. Arcaro[h,k], J. Becerra González[l,m], G. Bonnoli[a], M. Böttcher[k], G. Brunetti[n], A. A. Compagnino[e], S. Crestan[o,p], A. D'Aì[e], M. Fiori[h,f], G. Galanti[o], A. Giuliani[o], E. M. de Gouveia Dal Pino[q], J. G. Green[b], A. Lamastra[b,g], M. Landoni[a], F. Lucarelli[b,g], G. Morlino[c], B. Olmi[r,c], E. Peretti[s], G. Piano[d], G. Ponti[a,t], E. Poretti[a,u], P. Romano[a], F. G. Saturni[b,g], S. Scuderi[o], A. Tutone[b], G. Umana[v], J. A. Acosta-Pulido[l,m], P. Barai[q], A. Bonanno[v], G. Bonanno[v], P. Bruno[v], A. Bulgarelli[w], V. Conforti[w], A. Costa[v], G. Cusumano[e], M. Del Santo[e], M. V. del Valle[q], R. Della Ceca[a], D. A. Falceta-Gonçalves[q], V. Fioretti[w], S. Germani[x,y], R. J. García-López[l,m], A. Ghedina[u], V. Giordano[v], M. Kreter[k], F. Incardona[v], S. Iovenitti[a], A. La Barbera[e], N. La Palombara[o], V. La Parola[e], G. Leto[v], F. Longo[z,aa], A. López-Oramas[l,m], M. C. Maccarone[e], S. Mereghetti[o], R. Millul[a], G. Naletto[f], A. Pagliaro[e], N. Parmiggiani[w], C. Righi[a], J. C. Rodríguez-Ramírez[q], G. Romeo[v], P. Sangiorgi[e], R. Santos de Lima[q], G. Tagliaferri[a], V. Testa[b], G. Tosti[x,y], M. Vázquez Acosta[l,m], N. Żywucka[k,ab], P. A. Caraveo[o] and G. Pareschi[a]

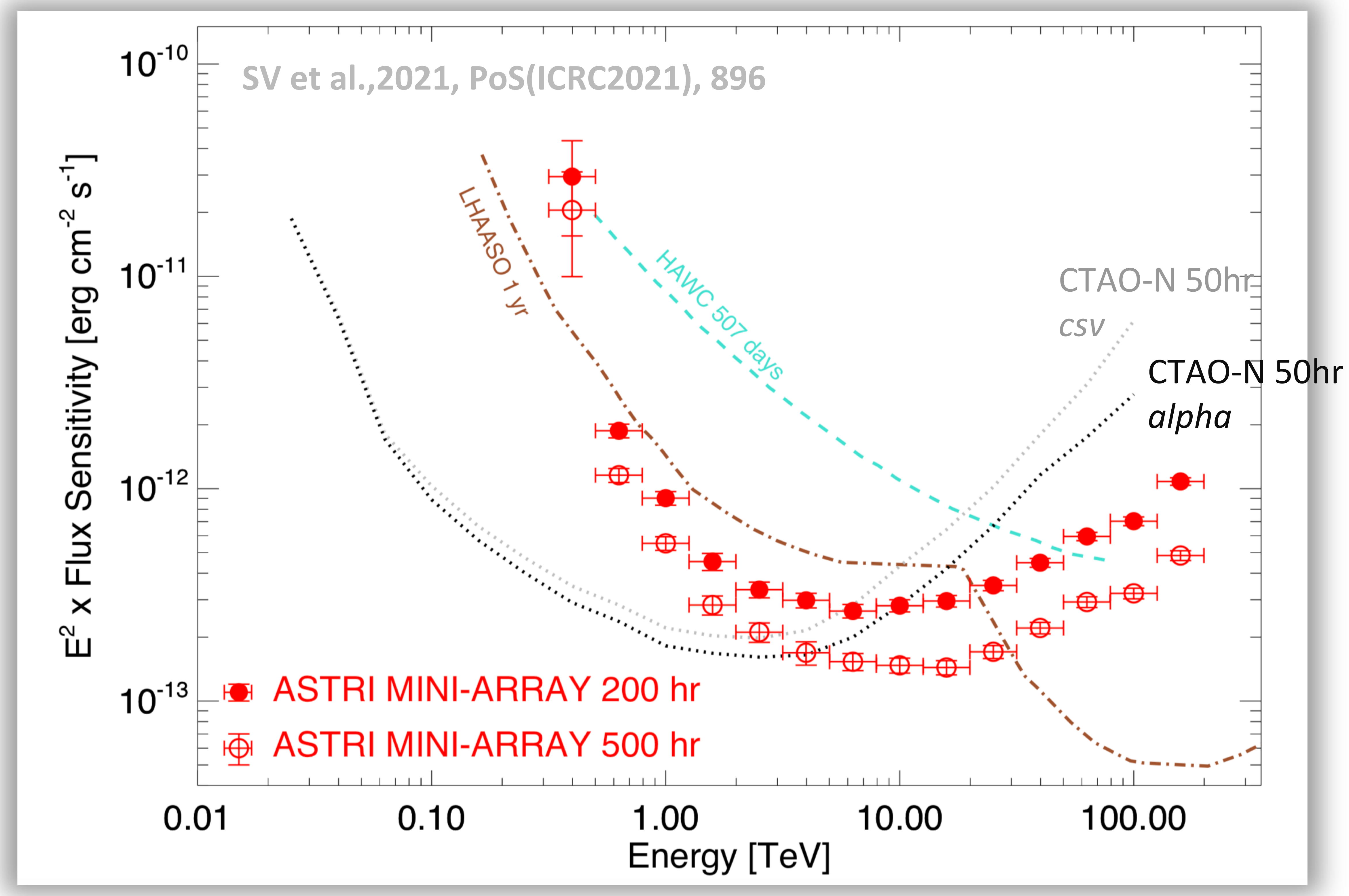
https://doi.org/10.1016/j.jheap.2022.05.005

The ASTRI Mini-Array – Performance

- We extend current IACTs **differential sensitivity up to several tens of TeV and beyond**

- Investigate possible spectral features at VHE, such as the presence of **spectral cut-offs** or the detection of emission at several tens of TeV expected from **Galactic PeVatrons**





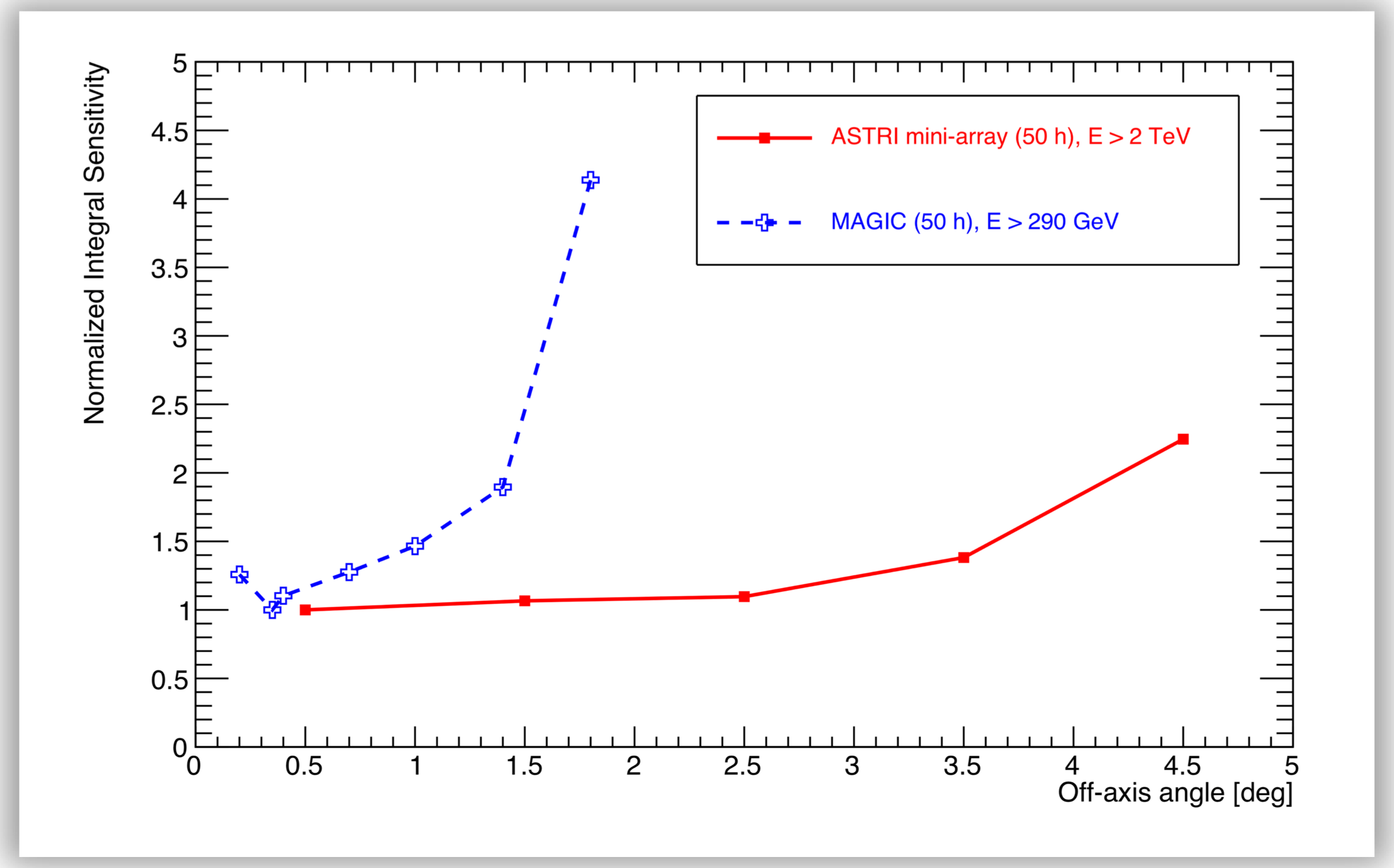
The ASTRI Mini-Array – Performance

	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 $\gtrsim$ 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



The Pillars' concept

Mini-Array

First 4 years
Specific science topics

10º FoV
Several sources in a single pointing

Pillar 1
The origin of cosmic rays

PeVatrons
Particle propagation
PWN HE emission
UHECR from SB galaxies

Pillar 2
Fundamental physics

IR EBL constraints
Probing IGMF
Blazars & hadron beams
ALP & LIV

Pillars' main scientific targets

Pillar-1

Name	RA (deg)	Dec (deg)	Type	Zenith Angle[1] (deg)	Visibility[2] (hr/yr)
Tycho	6.36	64.13	SNR	35.8	410+340
Galactic Center	266.40	-28.94	Diffuse	57.2	0+180
VER J1907+062	286.91	6.32	SNR+PWN	22	400+170
SNR G106.3+2.7	337.00	60.88	SNR	32.6	460+300
γ-Cygni	305.02	40.76	SNR	12.5	460+160
W28/HESS J1800-240B	270.11	-24.04	SNR/MC	51.6	0+300
Crab	83.63	22.01	PWN	6.3	470+170
Geminga	98.48	17.77	PWN	10.5	460+170
M82	148.97	69.68	Starburst	41.4	310+470

See Talk by A. Giuliani

Pillar-2

Target IAU Name	Class	RA (J2000)	DEC (J2000)	Obs. time [hr]	ZA [deg]	Moon [%]	Strategy, analysis, notes
IC 310	Radio gal.	03 16 43.0	+41 19 29	50-100	45	25	Better suited for ToO observations of high states
M87	Radio gal.	12 30 47.2	+12 23 51	50-100	45	25	Better suited for ToO observations of high states
Mkn 501	Blazar	16 53 52	+39 45 38	50-100	45	25	Better suited for ToO observations of high states

Target IAU Name	Class	RA (J2000)	DEC (J2000)	Obs. time [hr]	ZA [deg]	Moon [%]	Strategy, analysis, notes
Mkn 501	Blazar	16 53 52.2	+39 45 36.6	50-100	45	25	LIV, ALP. Better suited for ToOs in high states.
1ES 0229+200	Blazar	02 32 48.6	+20 17 17.5	200	45	25	HB, LIV, ALP. Almost steady source, possible "fill in" target.

These lists of sources reflect the science knowledge **at the time of writing** this paper

We expect **to improve these lists** according to the new findings from both IACTs and EASs

The Pillars' concept

Mini-Array

See Poster by M. Cardillo

Pillar 1
The origin of cosmic rays

PeVatrons
Particle propagation
PWN HE emission
UHECR from SB galaxies

The LHAASO Sources at ~PeV energies

Mini-Array

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}	

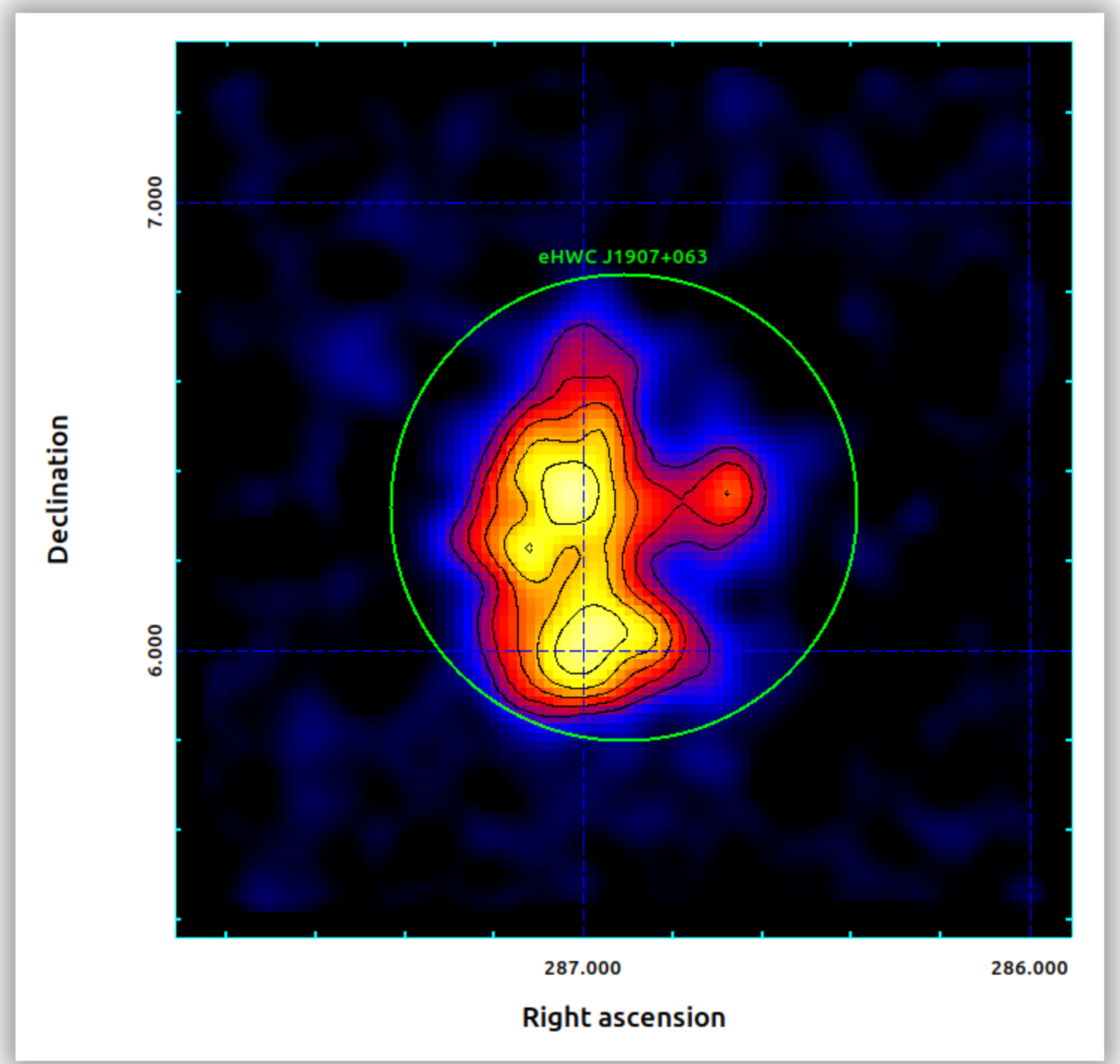
Discovery of **12 sources emitting at several hundreds of TeV**, up to 1.4 PeV

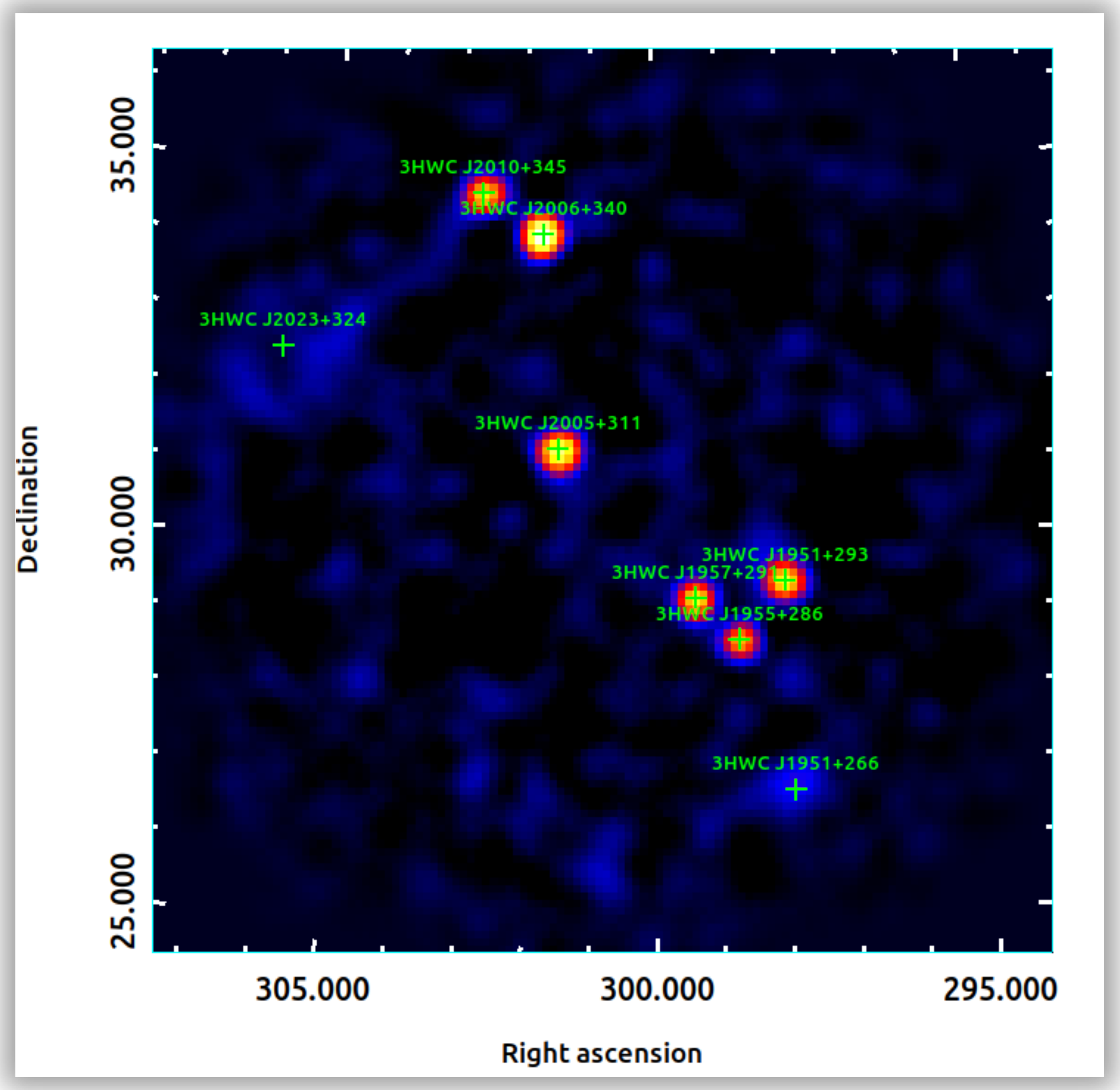
Crab apart, the majority of remaining sources represent **diffuse γ-ray structures with angular extensions up to 1°**, and all of them are located along the Galactic plane

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**

Angular resolution and large field of view





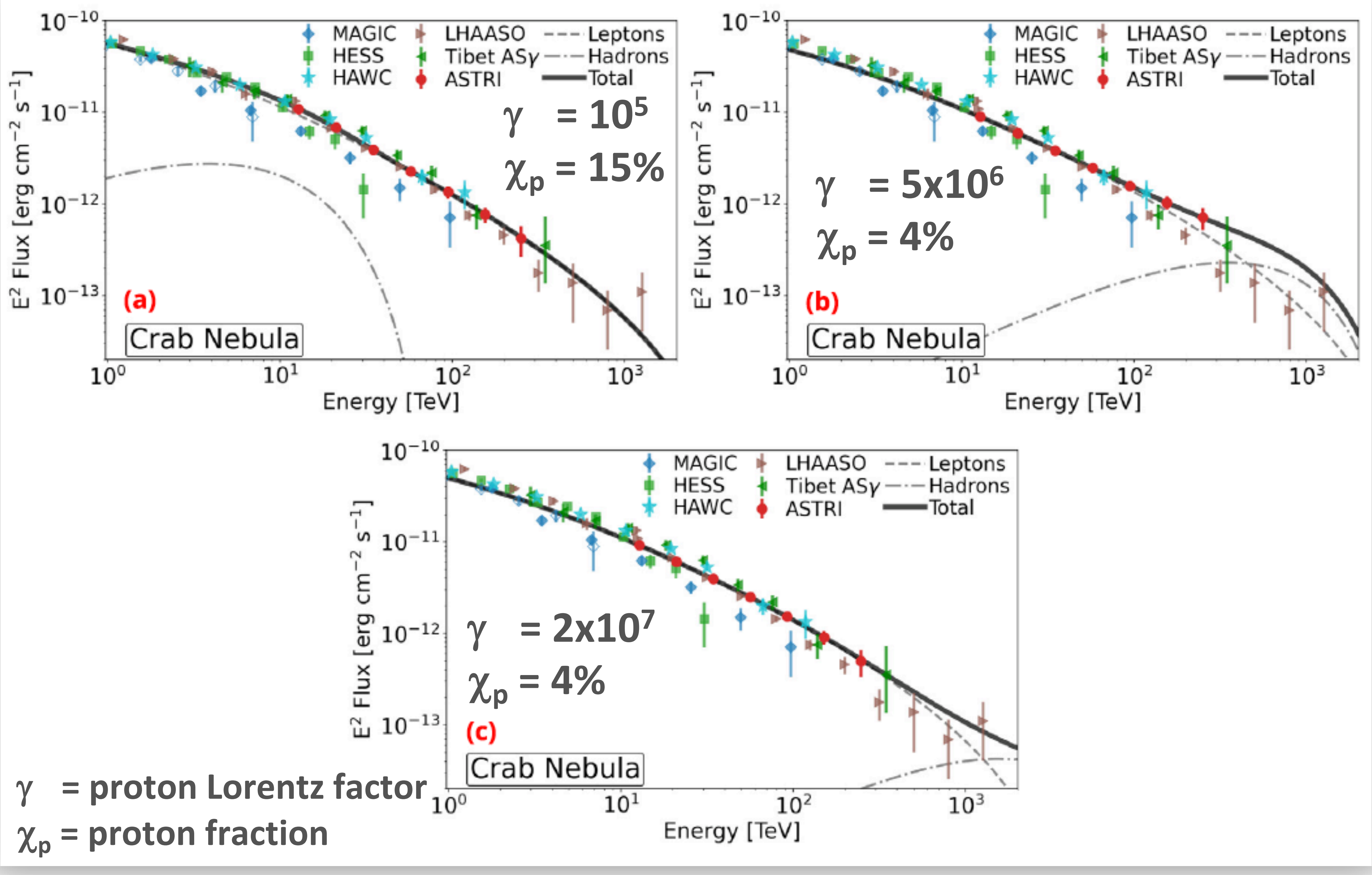
ASTRI Mini-Array **200 hr simulation (up to E~200 TeV)** of the region **of the Galactic source 2HWC J1908+063**. The light green circle marks the ~ 0.52° HAWC error-box for E > 56 TeV

See Talk by S. Crestan

ASTRI Mini-Array **200 hr simulation of the Cygnus Region**. Green crosses mark the positions of the 3HWC sources in a 10° × 10° field of view

The Crab – a leptonic PeVatron?

Mini-Array



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 over-all 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**

Cosmic-ray propagation: γ-Cygni

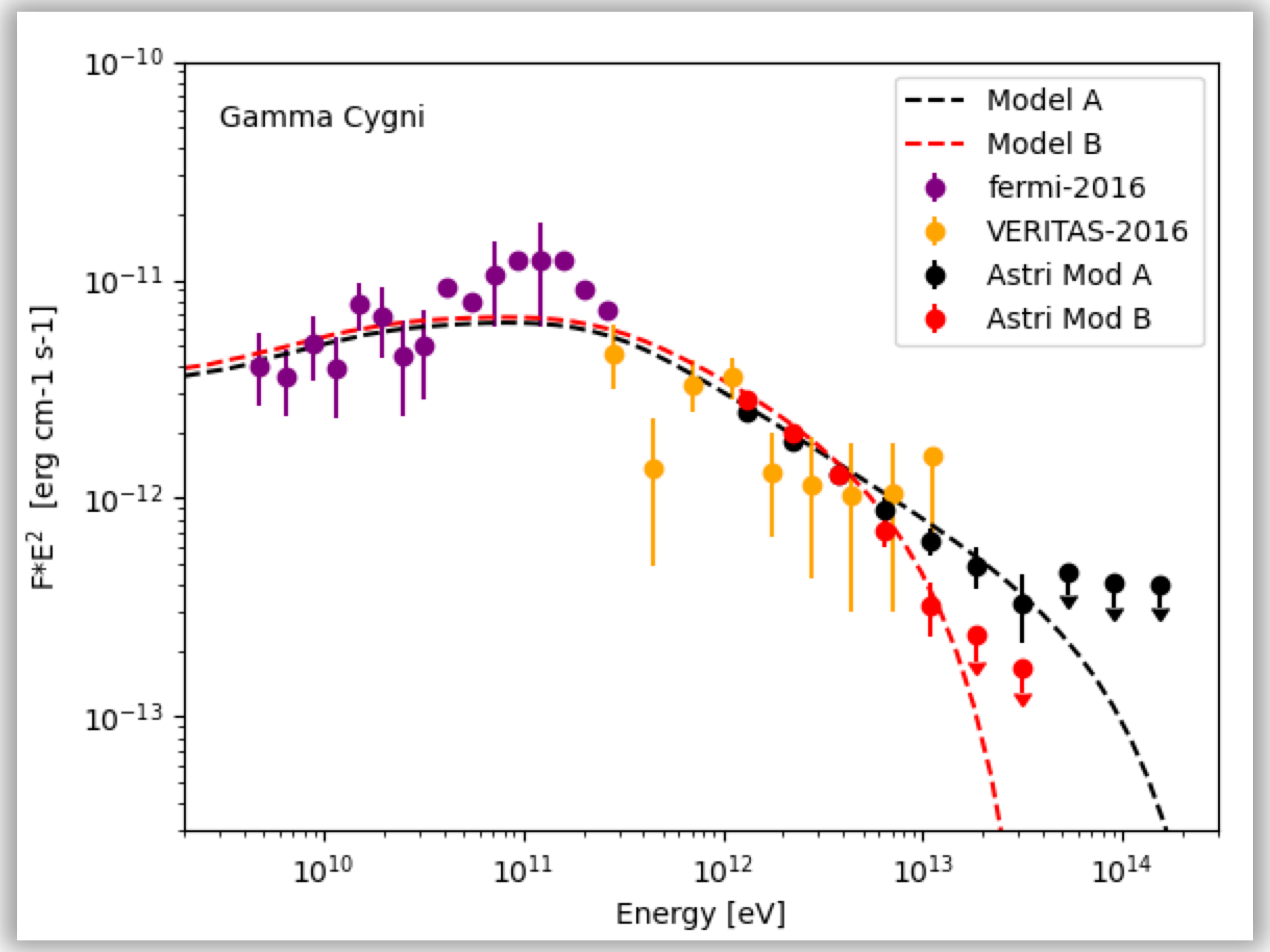
γ-Cygni (G78.2+2.1) is a middle-aged SNR located in the Cygnus region and discovered by VERITAS

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

The Pillars' concept

Pillar 2
Fundamental physics

IR EBL constraints
Probing IGMF
Blazars & hadron beams
ALP & LIV

EBL studies in the IR regime

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

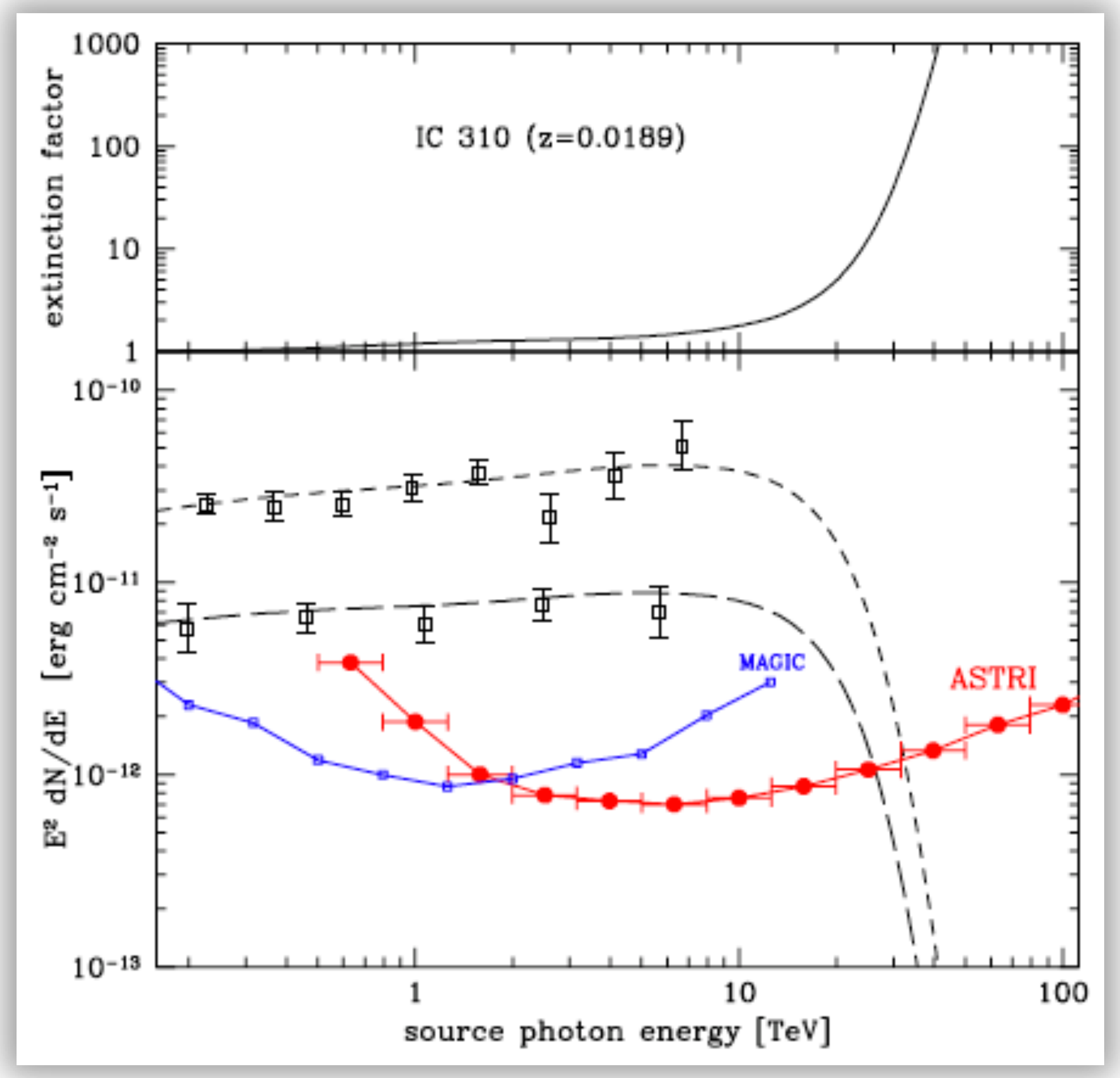
Best candidates to constrain the EBL up to $\lambda \sim 100\mu m$:

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

Fundamental physics – hadron beams

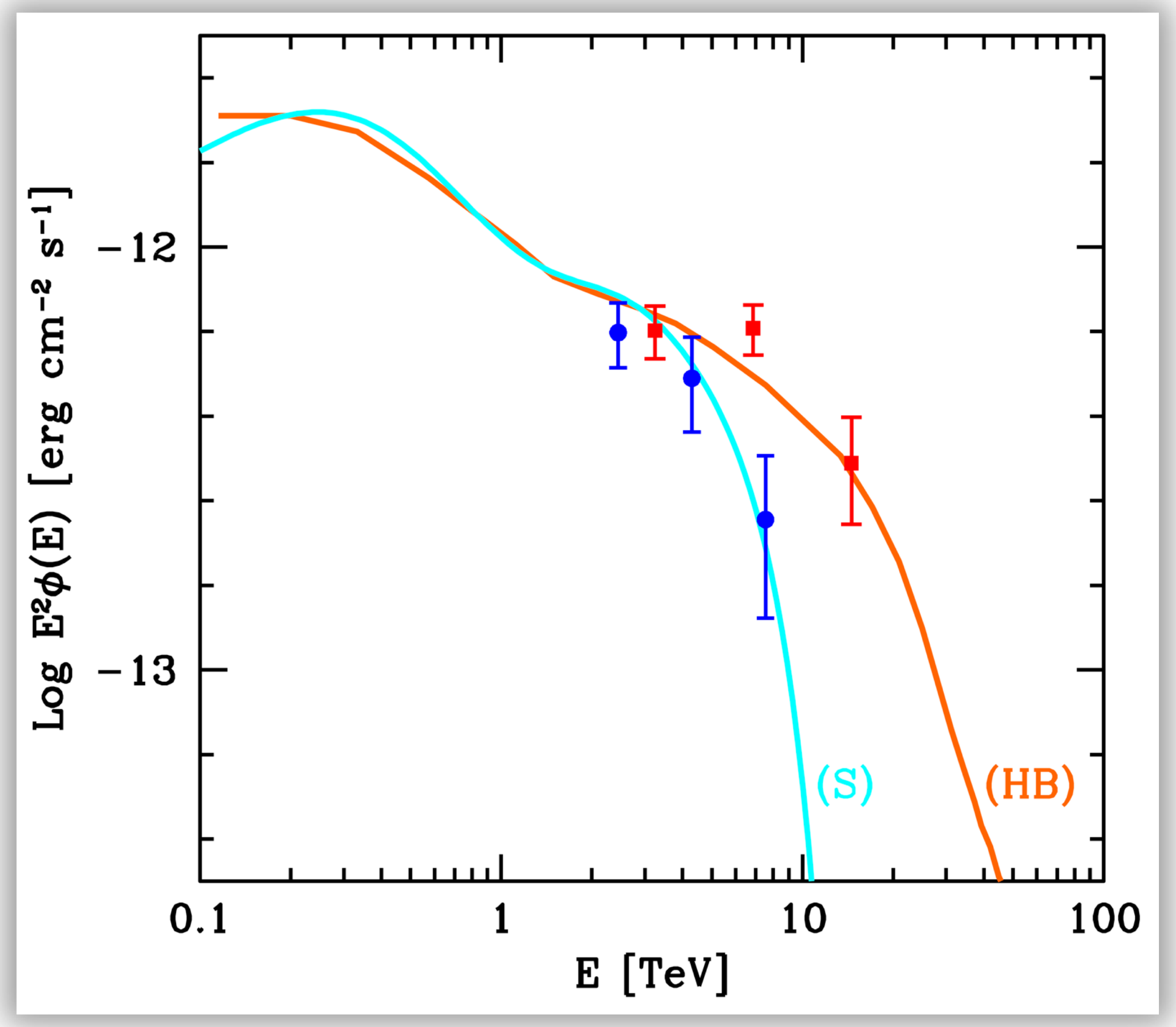
Mini-Array

Relativitic 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 > 10TeV) 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

Synergies

Synergies
The MWL panorama

Canary Island
IACTs & PSAs
From radio to gamma

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

Summary

The ASTRI Mini-Array will start **scientific observations in Q1 2025** from the *Observatorio del Teide* with a 4 (core science) + 4 (observatory science) year programme

Its **10° field of view** will allow us to investigate both extended sources (e.g., SNRs) and crowded/rich fields (e.g., the Galactic Center) with a single pointing

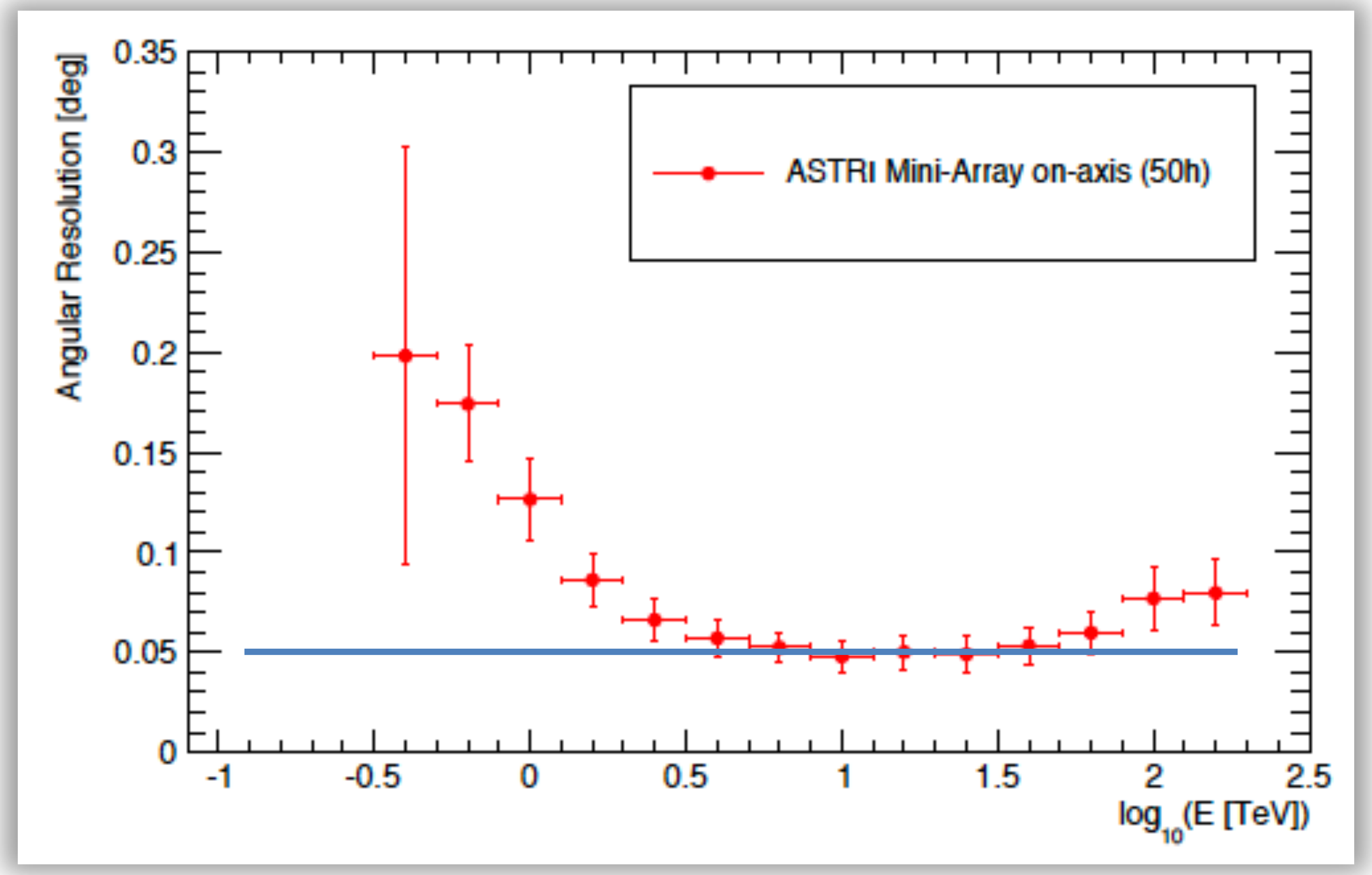
Its **3' angular resolution** at 10 TeV will allow us to perform detailed morphological studies of extended sources

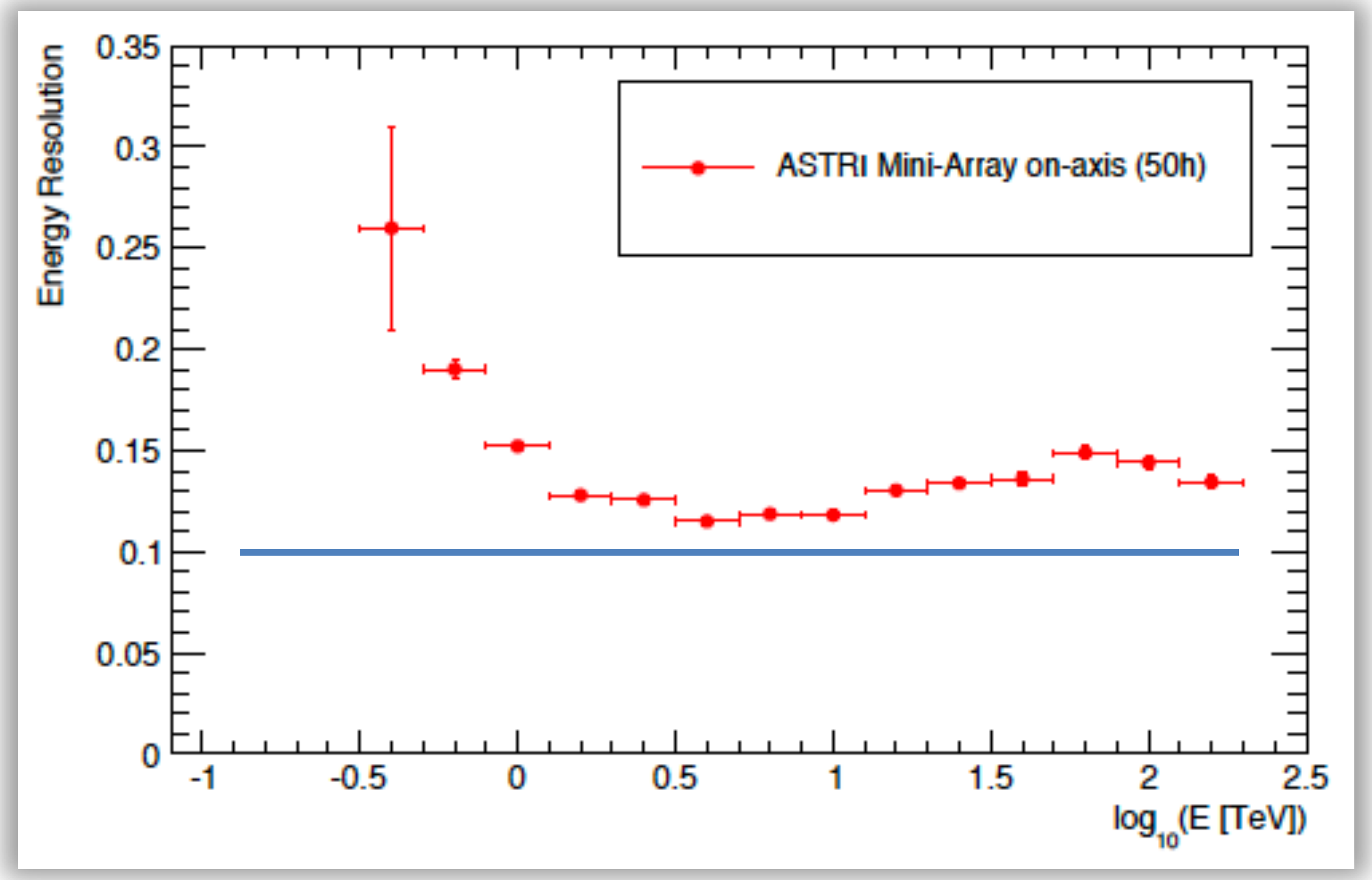
Its **sensitivity extending above 100 TeV** will make it the most sensitive IACT in the energy range 5-200 TeV in the Northern hemisphere

It will **join together** the ***very high-energy domain*** typical of EASs with the ***precision domain*** (excellent angular and energy resolutions) typical of IACTs

EXTRA SLIDES

Angular and Energy resolution





The Galactic Center – a challenge in a challenge

Mini-Array

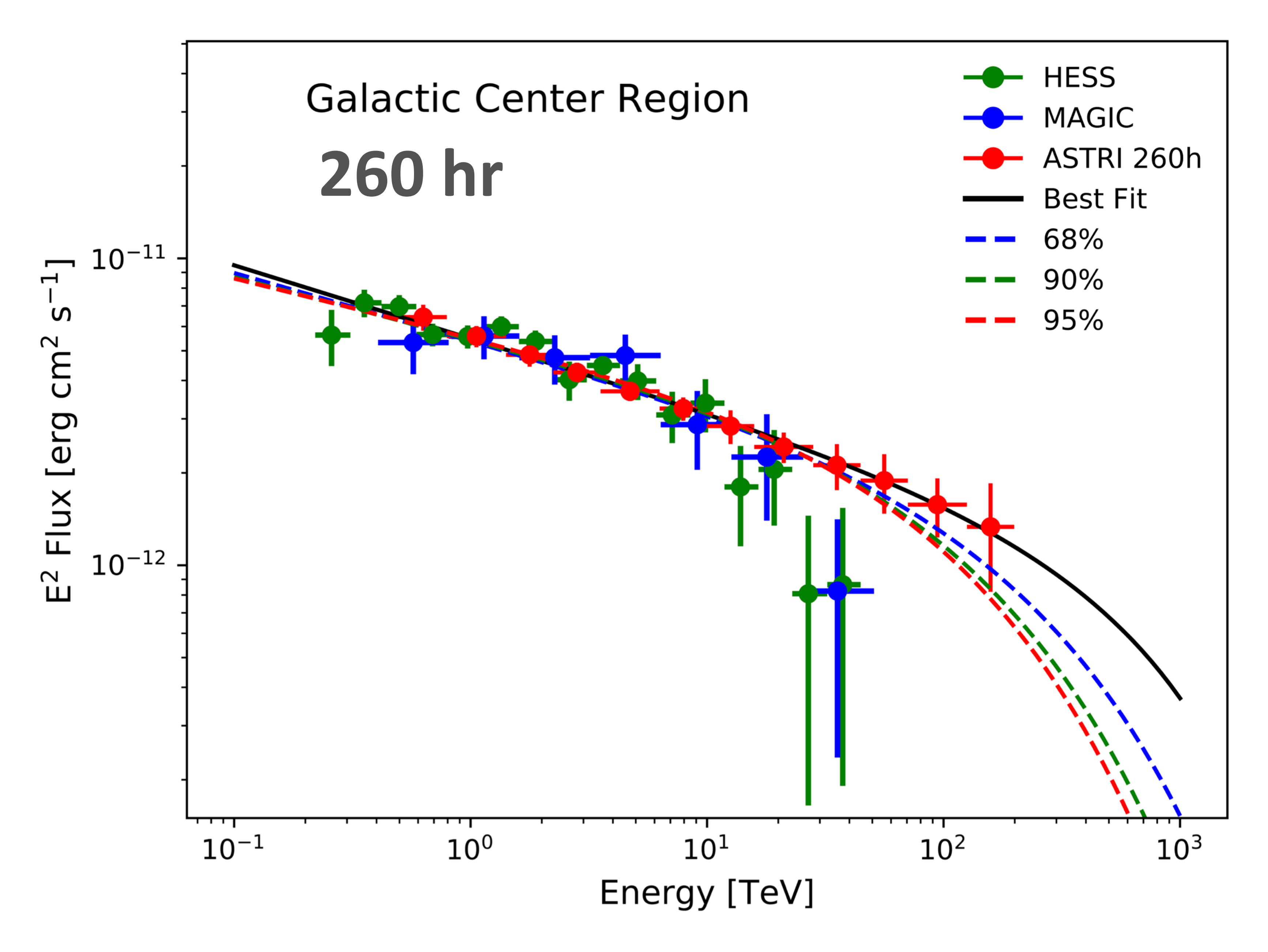
It is a complex region harbouring several potential sources of particle acceleration

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.

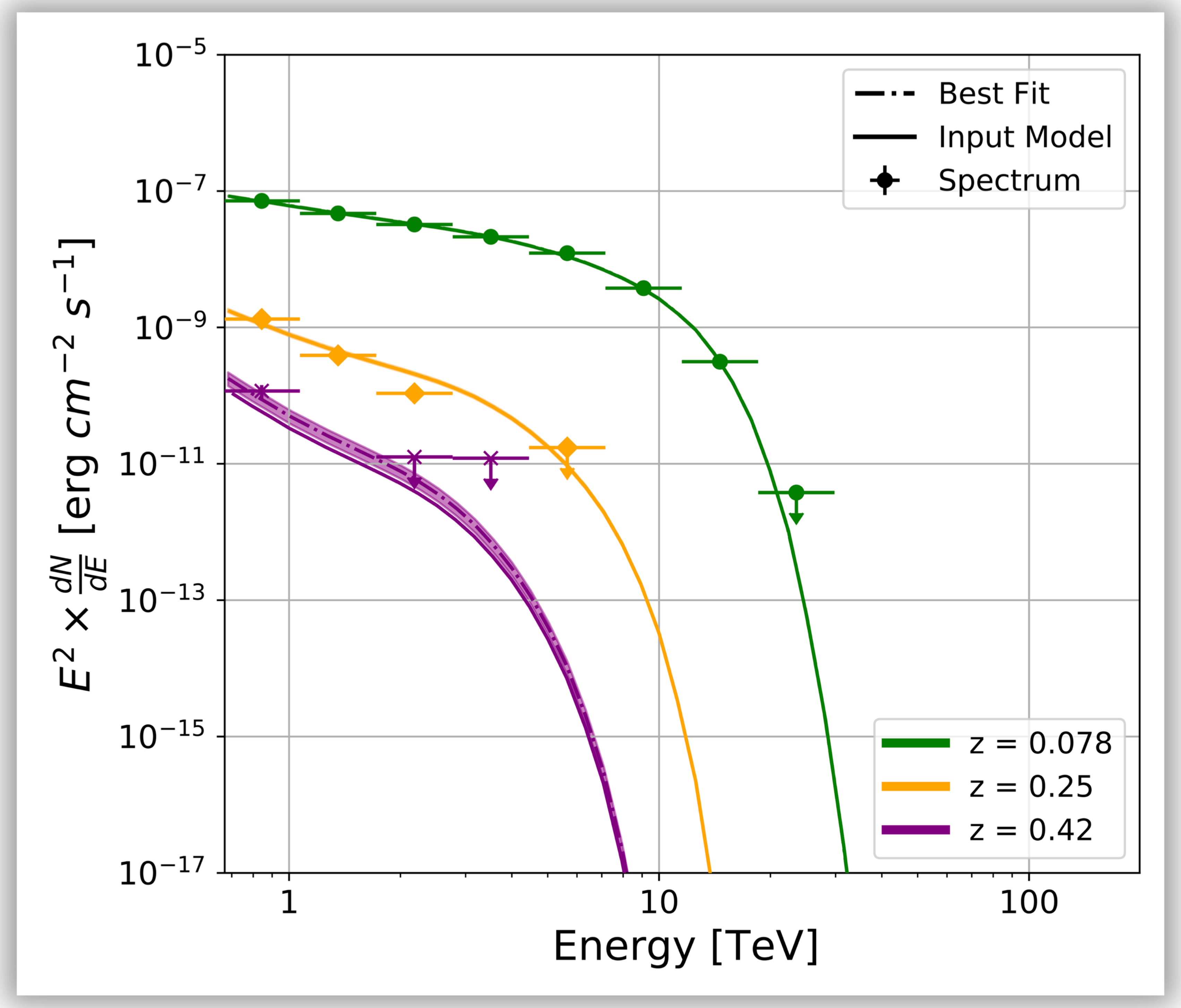
Gamma-ray bursts

- 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)

The multi-wavelength landscape

ASTRI 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 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

From *Core* Science to *Observatory* Science

For the first 4 years the ASTRI Mini-Array will be run as an experiment

It will be dedicated to the Core Science Topics

Smooth transition towards an Observatory period

Build-up on the experience and results from the Core Science

Open to observational proposals from the scientific community