The core science program of the ASTRI Mini-Array

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

TeVPA 2021, 25-29.10.2021

ASTRI: Astrophysics with Italian Replicating Technology Mirrors

ASTRI Mini-Array

See also Talk by S. Lombardi

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

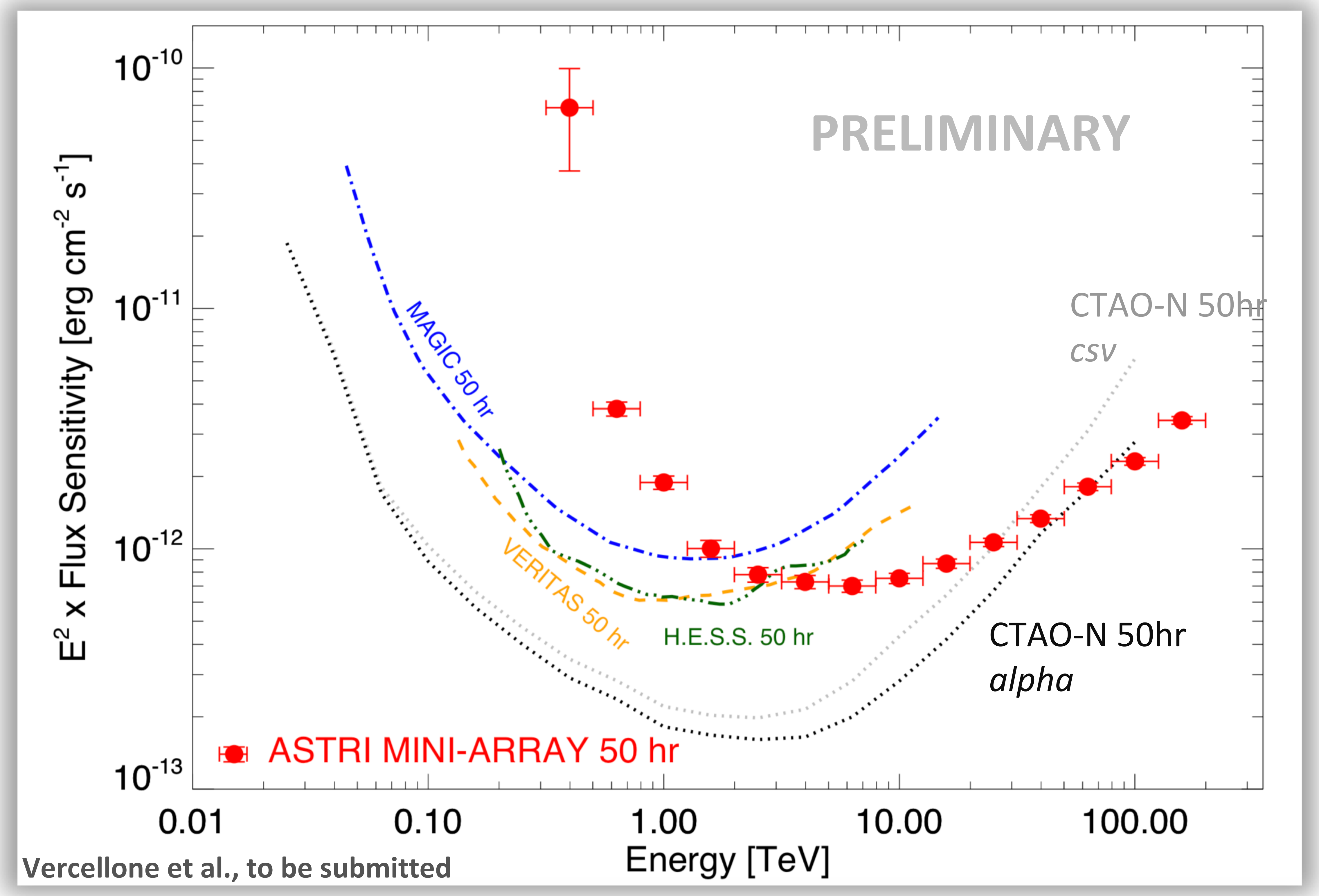
Being deployed at the *Observatorio del Teide* (Spain) in collaboration with IAC and FGG-INAF.

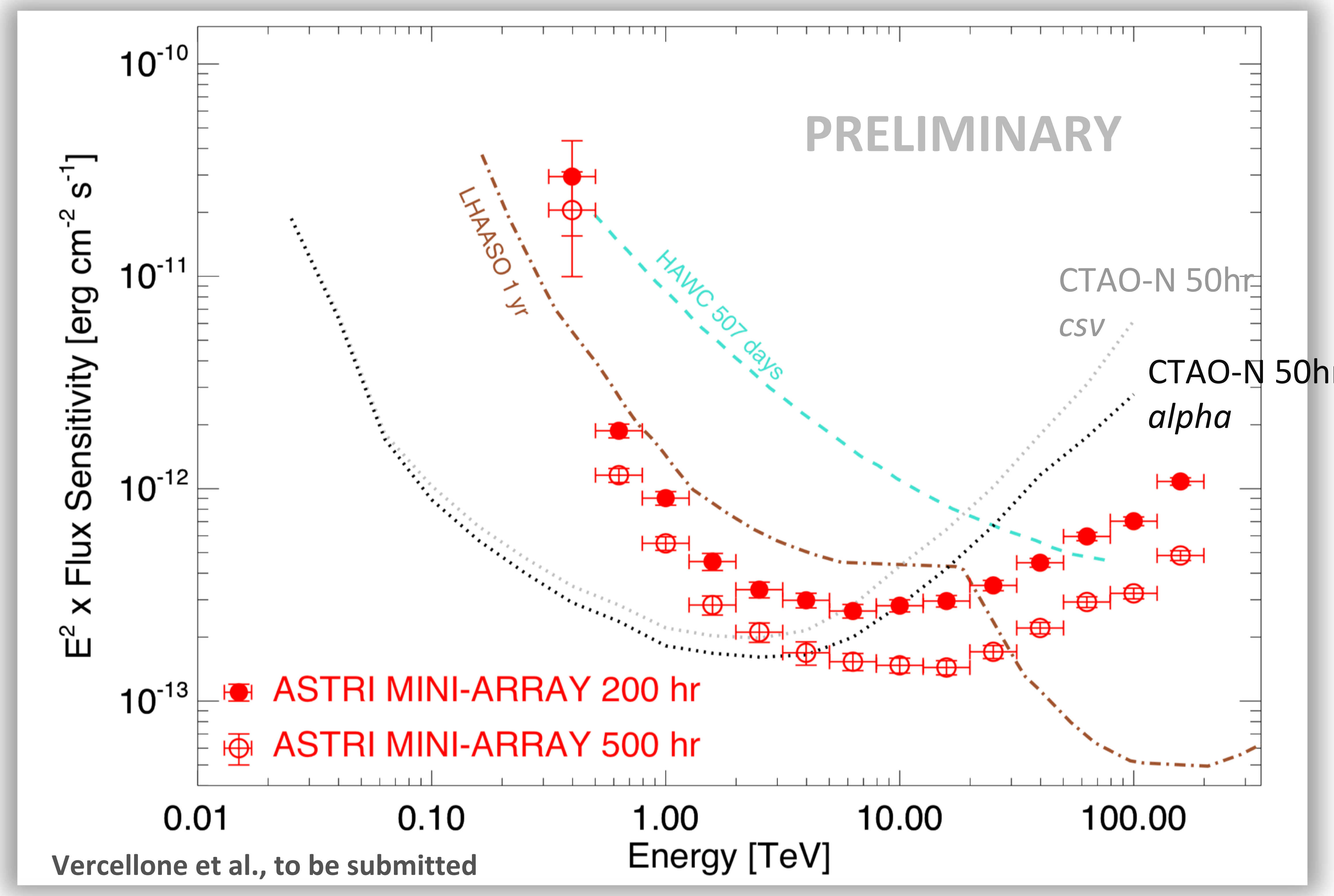
First 4 yr → *Core Science*, following 4 yr → *Observatory Science*. **Science operation → 2024**

The ASTRI Mini-Array – Performance

See also Talk by S. Lombardi

- 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

See also Talk by S. Lombardi

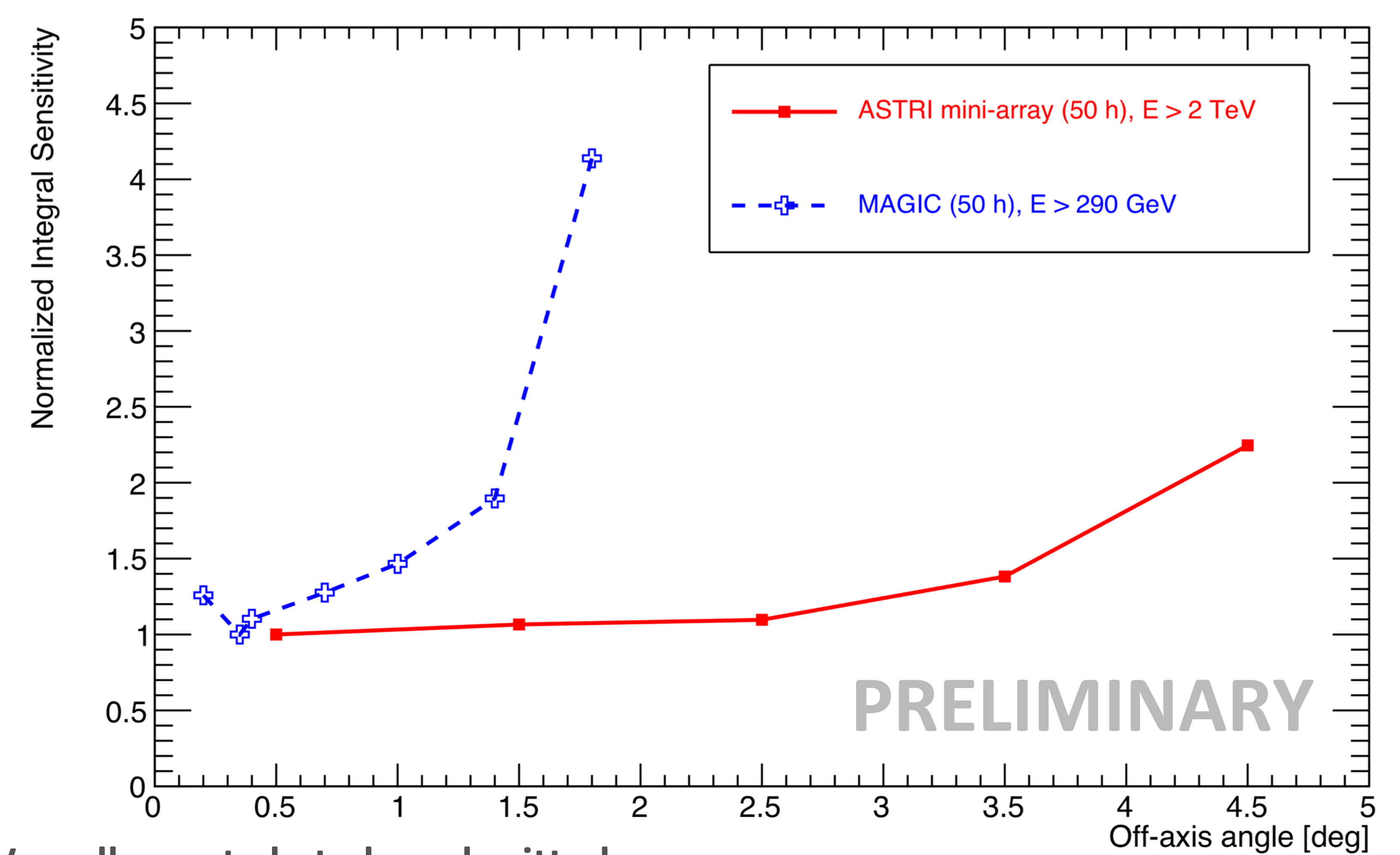
PRELIMINARY

	ASTRI Mini-Array	MAGIC	VERITAS	H.E.S.S.	HAWC	LHAASO	Tibet ASγ
Altitude [m]	2,390	2,396	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

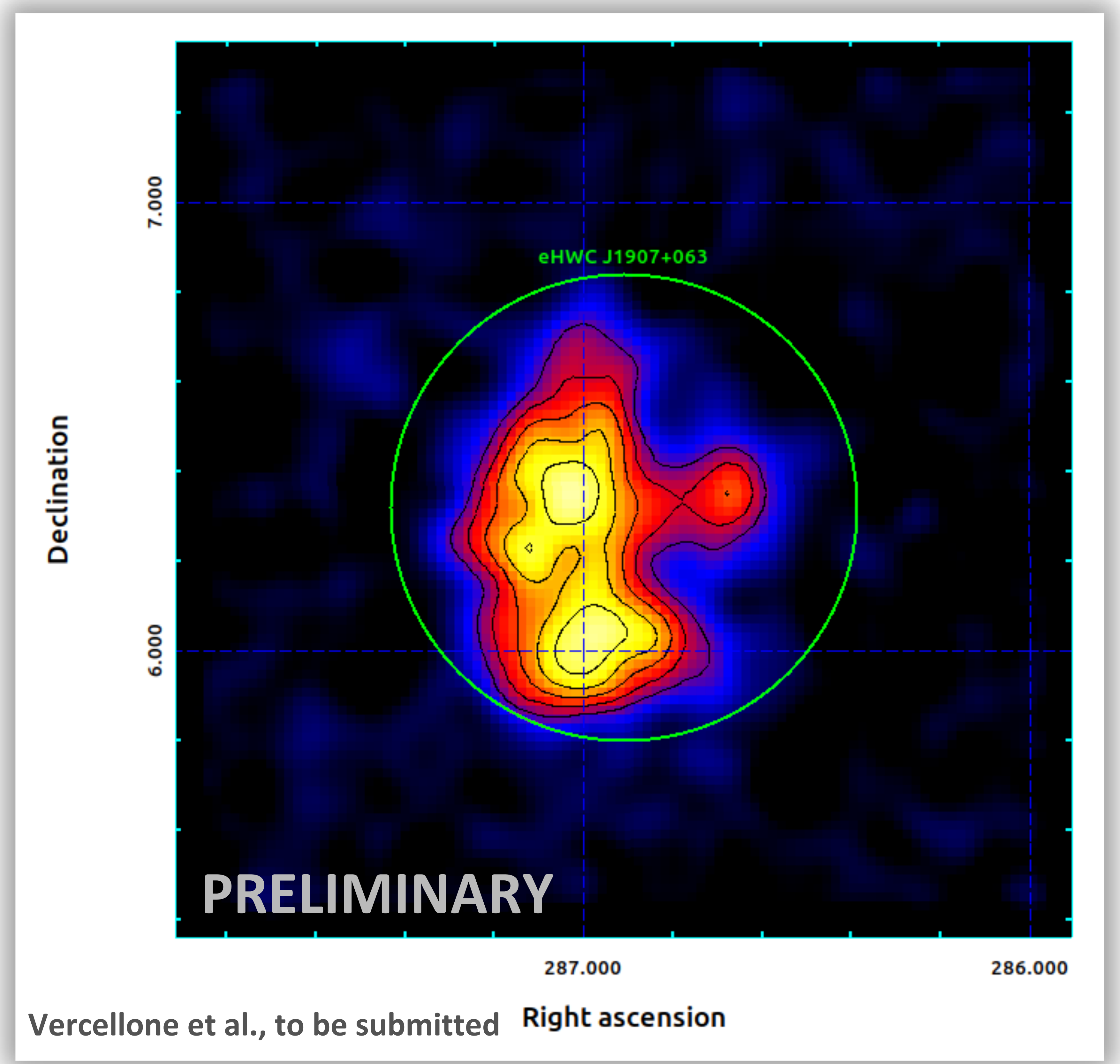
Energy/Angular resolution: ~10% / ~0.05° (E =10 TeV)
- Characterize extended sources morphology

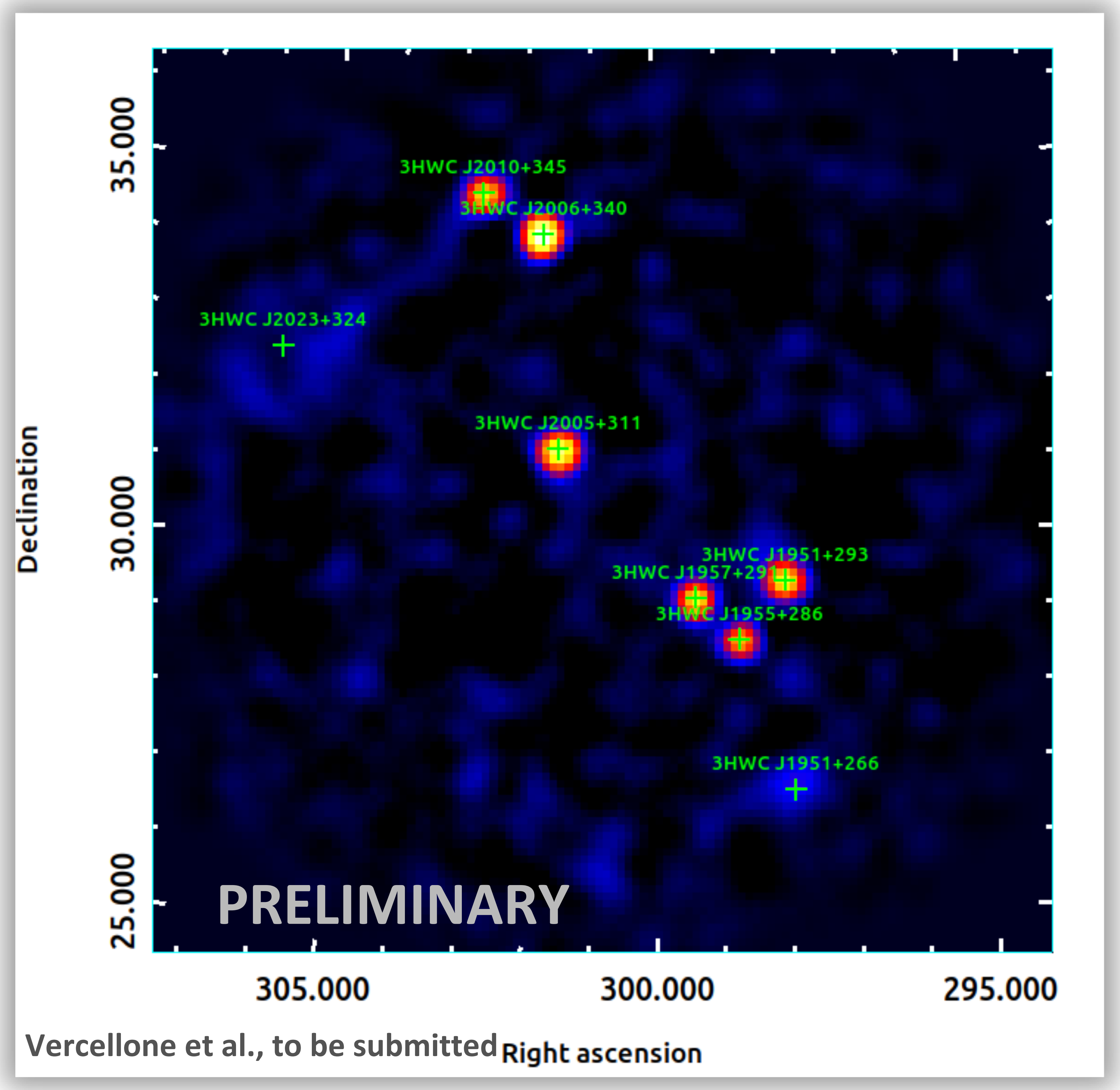
10° field of view with homogeneous off-axis performance
- Multi-target fields and extended sources
- Enhanced chance for serendipitous discoveries



Vercellone et al., to be submitted

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

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 LHAASO PeVatrons

ASTRI 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	$6.3^{+0.8}_{-0.7}$ ^{d}	$1.8 - 3.3^{k}$	—	
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	$1.8^{+1.7}_{-1.4}$ ^{l}	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 PeVatron sources, providing both the opportunity for **their precise identification** and important **information on their morphology**

The Pillars' concept

Mini-Array

First four years specific science topics → robust answers to a few **well-determined open questions**

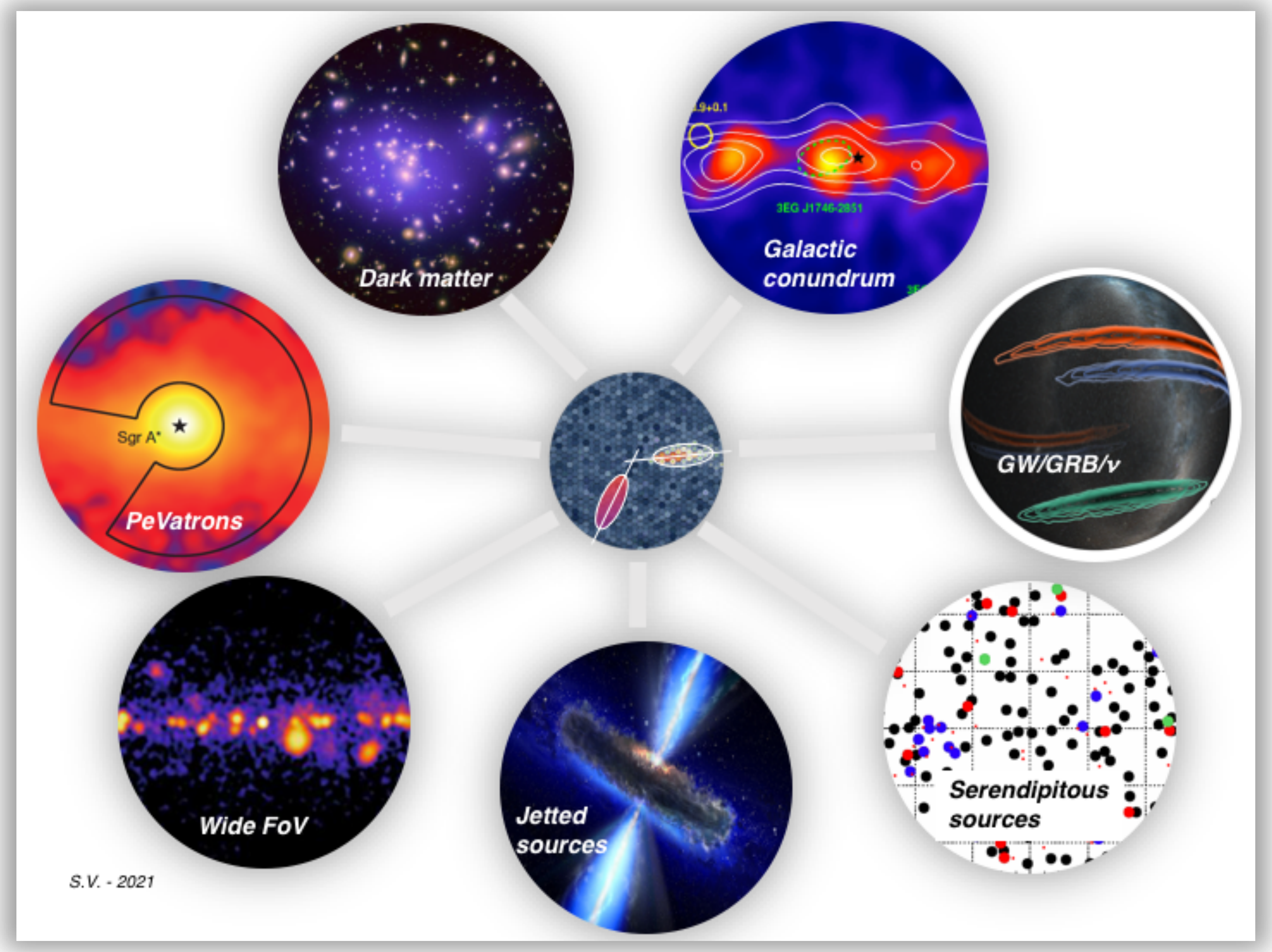
10° field of view →simultaneously **investigate more than one source** during the same pointing

Pillar 1 – The origin of cosmic rays

The quest for PeVatrons
Particle escape and propagation
High energy emission from Pulsar Wind Nebulae
Ultra High Energy Cosmic Rays from Starburst Galaxies

Pillar 2 – Cosmology and Fundamental Physics

TeV observations and constraints on the IR EBL
Probing intergalactic magnetic fields
Blazars as probes for hadron beams
Tests on the existence of axion-like particles
Lorentz Invariance violation studies
Indirect dark matter searches



Pillars' main scientific targets

Mini-Array

Pillar-1

Name PRELIMINARY	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

Pillar-2

Target IAU Name	Class	RA (J2000)	DEC (J2000)	Obs. time [hr]	ZA [deg]	Moon [%]	Strategy, analysis, notes PRELIMINARY
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.

PRELIMINARY

Vercellone et al., JHEAP, to be submitted

The Galactic Center – a challenge in a challenge

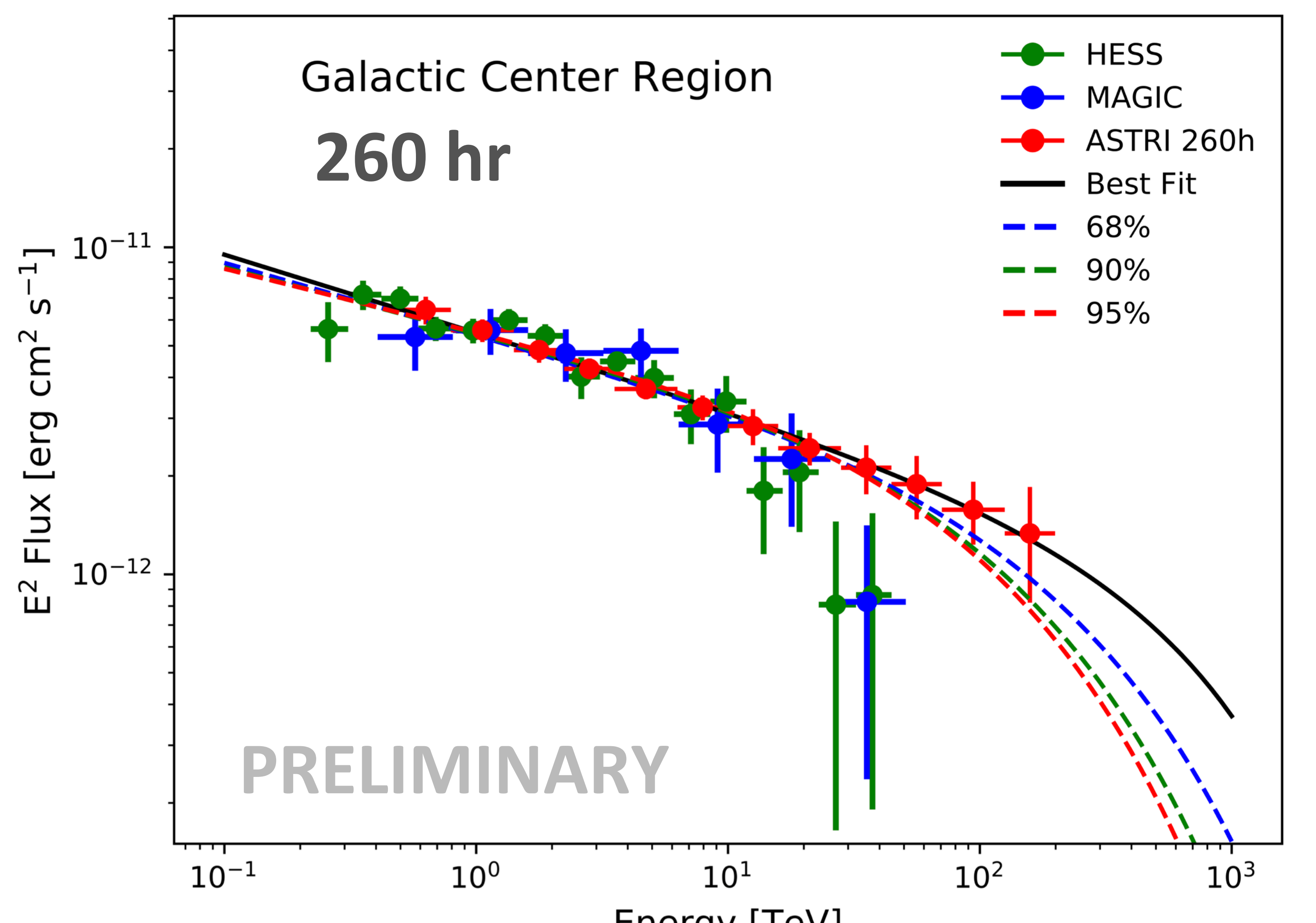
It is a complex region harbouring several potential sources of particle acceleration

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

Current IACTs detected **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



Vercellone et al., to be submitted

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 best fit cut-off at 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.

Cosmic-ray propagation: γ-Cygni

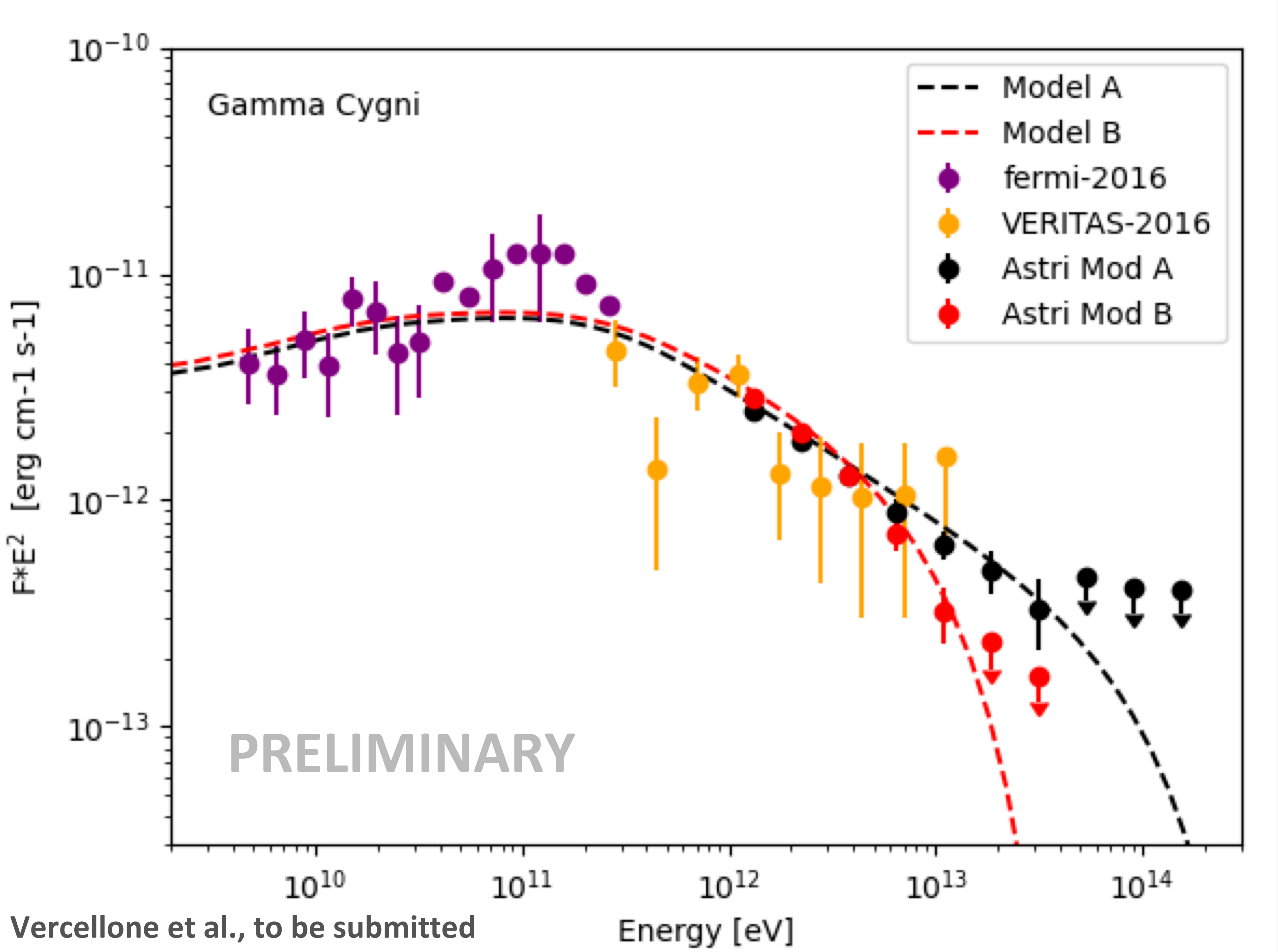
γ-Cygni (G78.2+2.1) is a middle-aged SNR located in the Cygnus region and discovered by VERITAS

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**



Vercellone et al., to be submitted

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

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

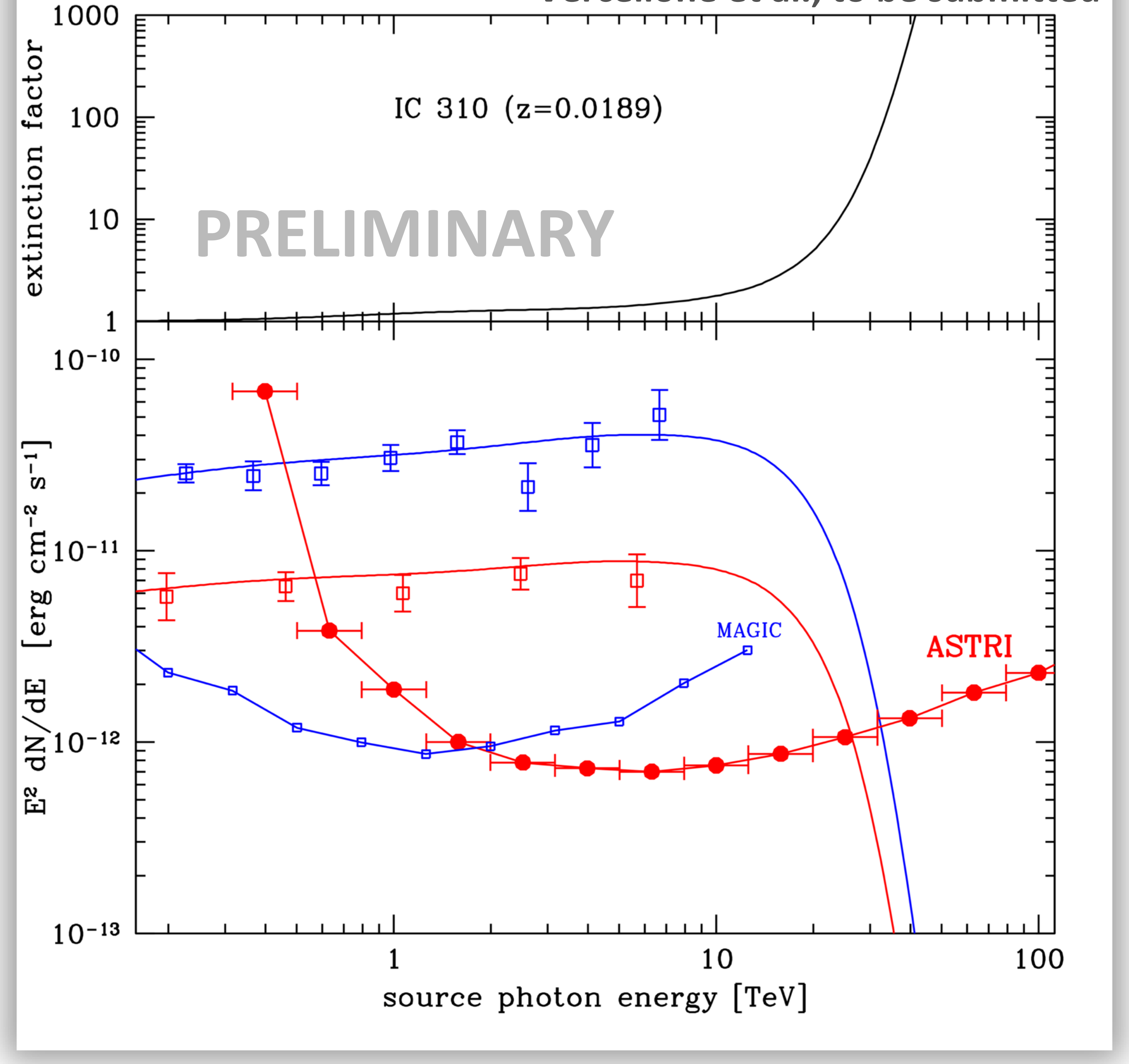
$$\lambda_{max} \sim 1.24 \times E_{TeV}\ [\mu m]$$

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

Vercellone et al., to be submitted



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

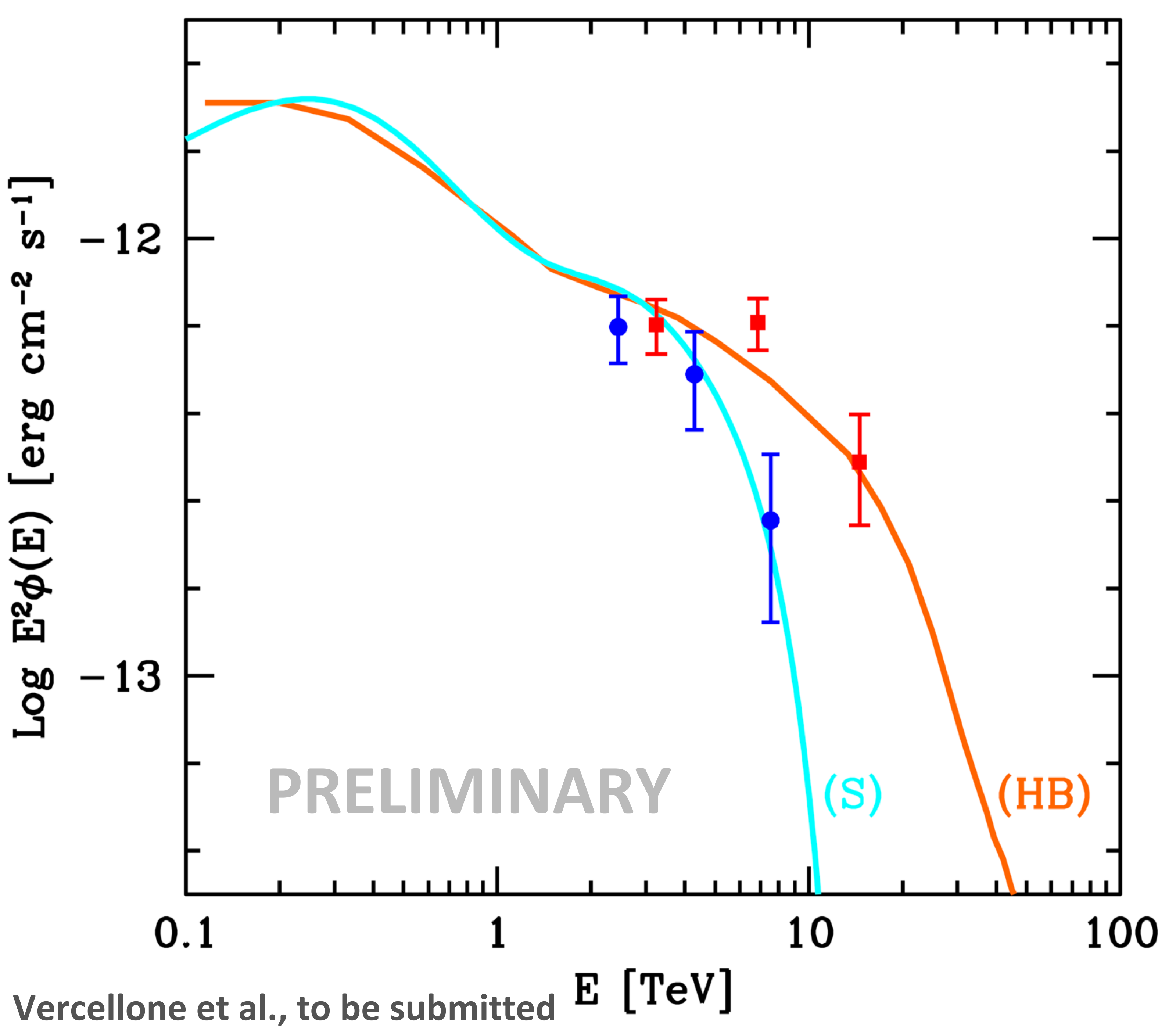
Fundamental physics – hadron beams

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**



Vercellone et al., to be submitted

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 significative detection up to 20 TeV with a deep (~250 hr) observation

Potential VHE synergies

- Both **MAGIC** and **CTAO-N** will be of paramount importance for the **study of GRBs,** as will be 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 **PSAs** 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

Core and Observatory science plan

ASTRI Mini-Array

Baseline

- We estimate about 1500 moonless hours/year at the Teide site
- This number has to be reduced because of, e.g., bad weather, maintanance, calibrations…
- We conservatively plan to dedicate **~1000 hours/year to scientific obervations**

Room for improvement

- ASTRI Mini-Array camera composed of SiPM, → **observations with a significant fraction of the Moon**, in addition to the 1000 hr/yr
- Main scientific goals focus on the multi-TeV energy band → we can **effectively perform observations at high (~60°) zenith angles**

Sources	Season	Dark hours
Galactic Center	May – June – July	300
VER J1907+062	September – October	300
G106.3+2.7	November – December	400

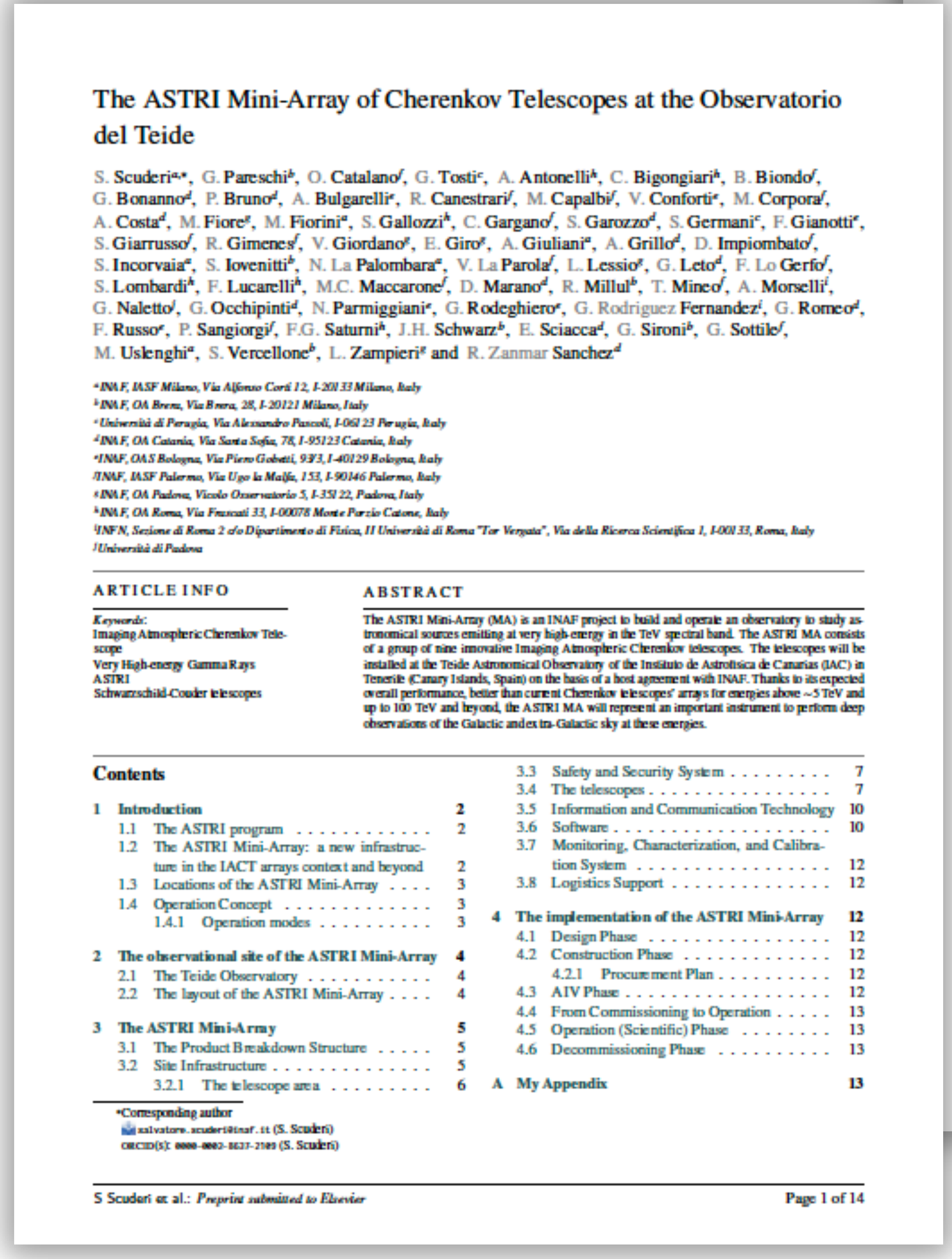
→

This example shows that we can observe **several sources per year** thanks to their different sky positions

We expect also **serendipitously detected sources**, thanks to the ASTRI Mini-Array wide field of view

To appear soon

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


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

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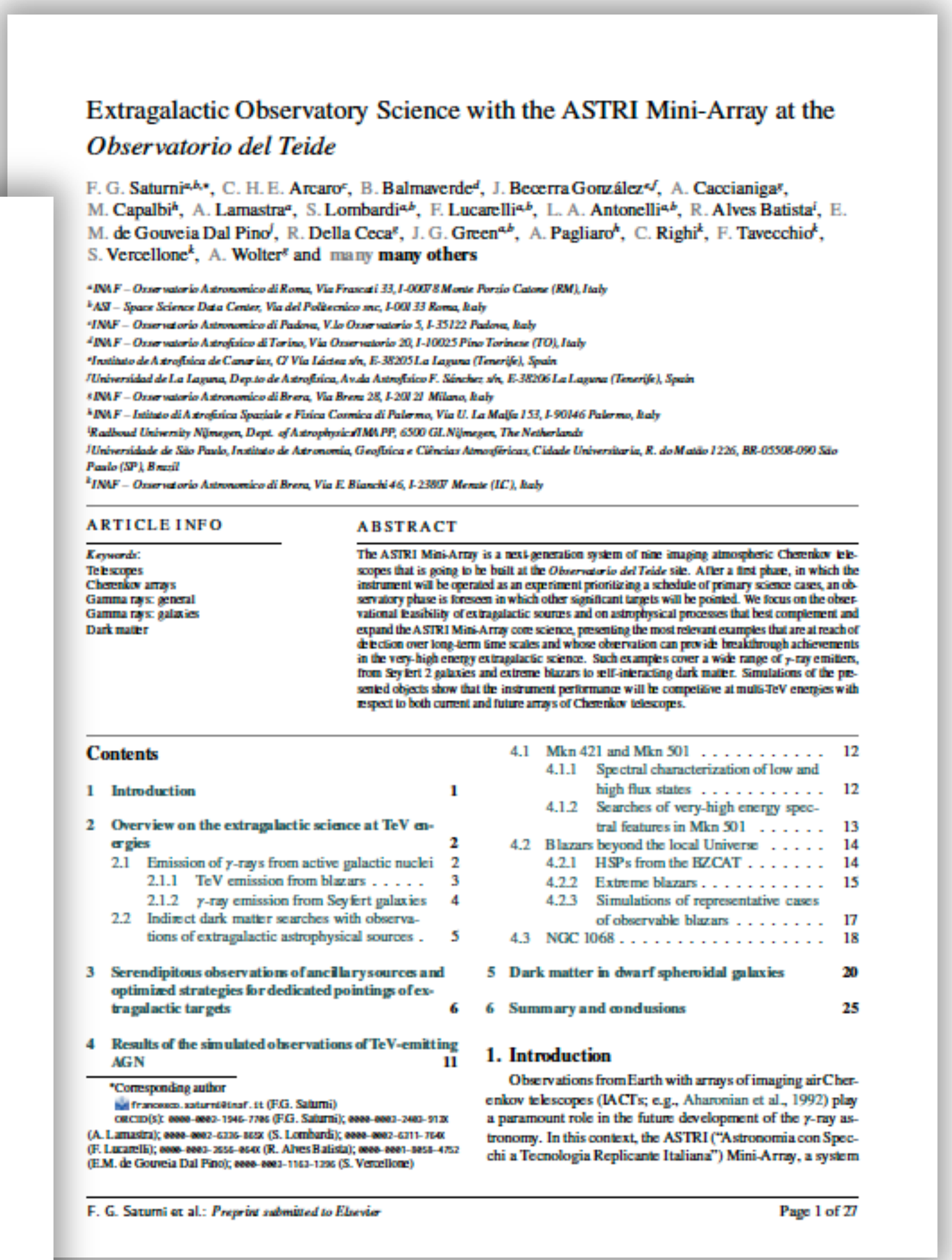
Extragalactic Observatory Science with the ASTRI Mini-Array at the *Observatorio del Teide*

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Summary

The ASTRI Mini-Array will start **scientific observations in 2024** 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

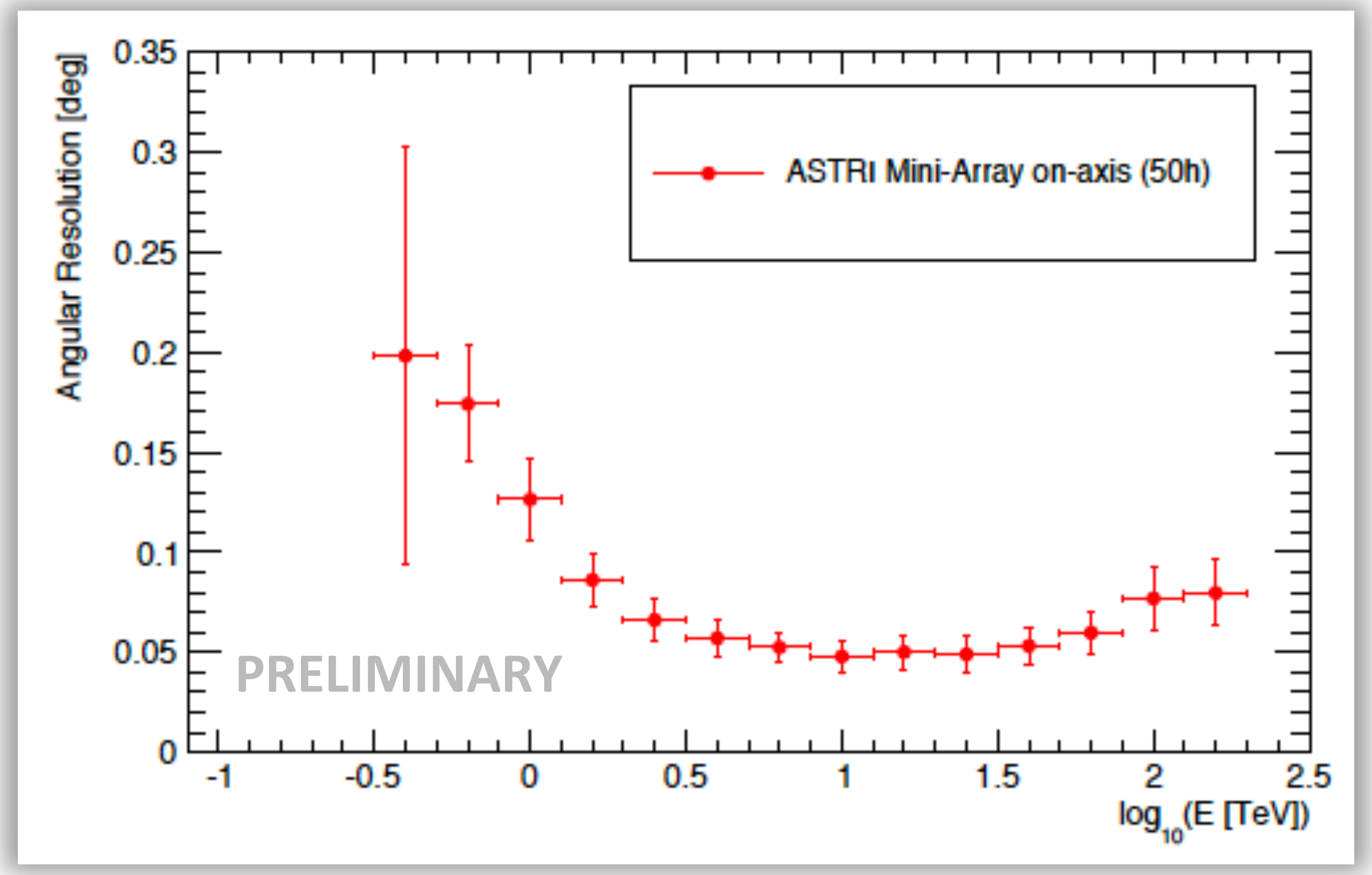
Its **3' angular resolution** at 10 TeV will allow us to perform detailed morphological studies of extended sources

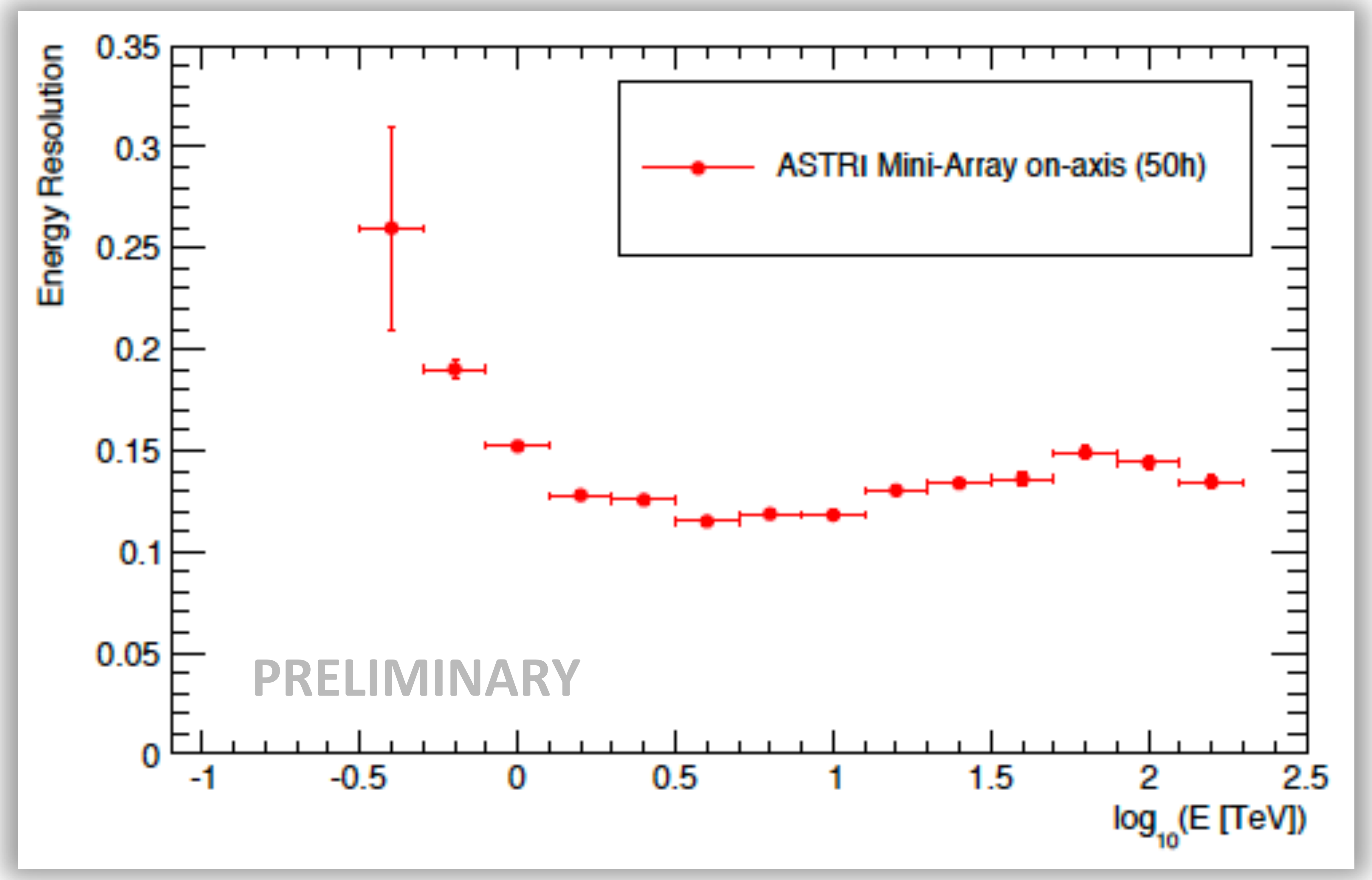
Its **sensitivity extending above 100 TeV** will make it the most sensitive IACT in the energy range 5-200 TeV in the Northern hemisphere

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

BKUP

BKUP


Angular Resolution [deg]
ASTRI Mini-Array on-axis (50h)
PRELIMINARY
log10(E [TeV])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