



# The core science program of the ASTRI Mini-Array

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for the ASTRI Project

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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  $5\sigma$  **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**

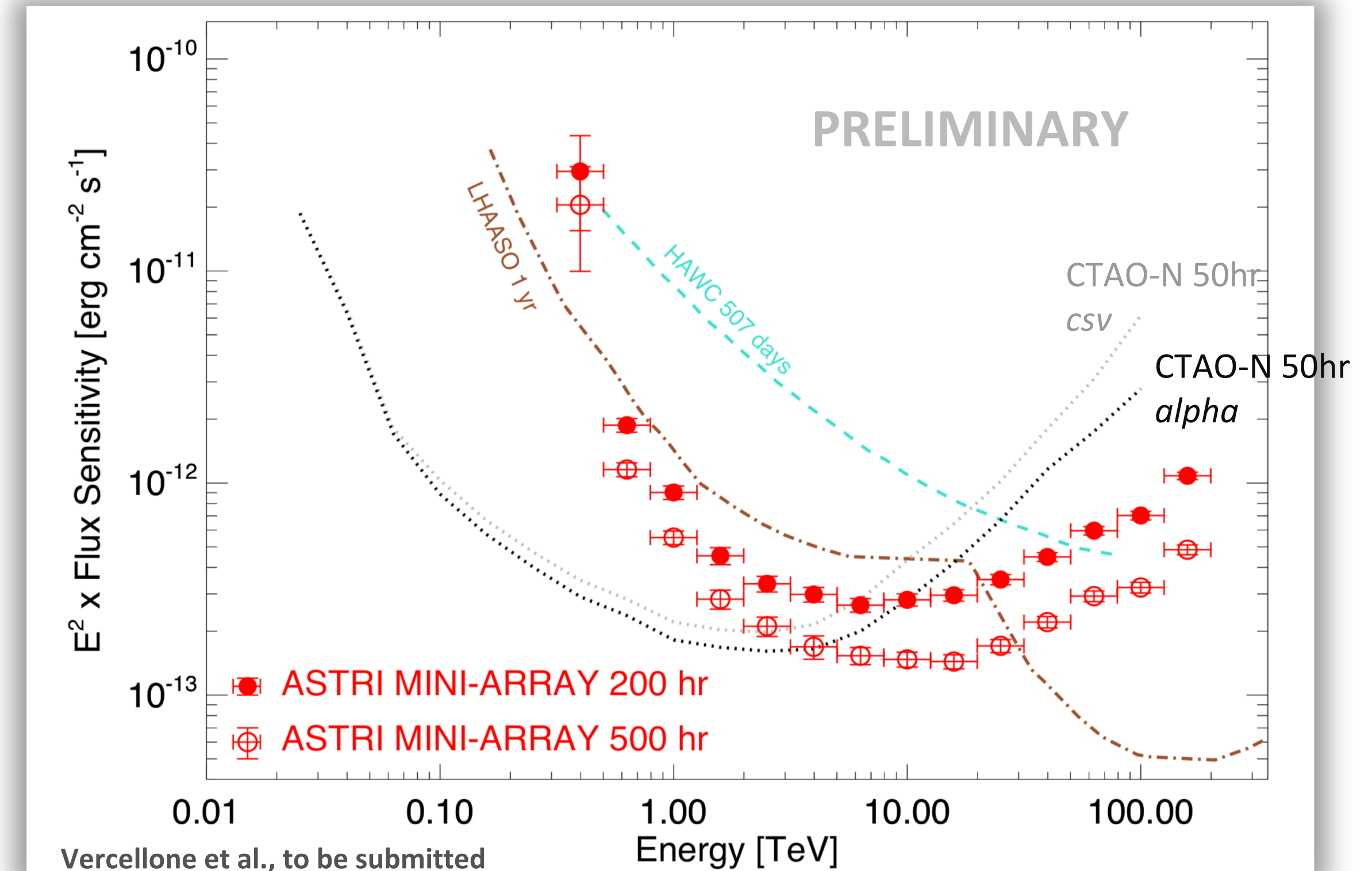
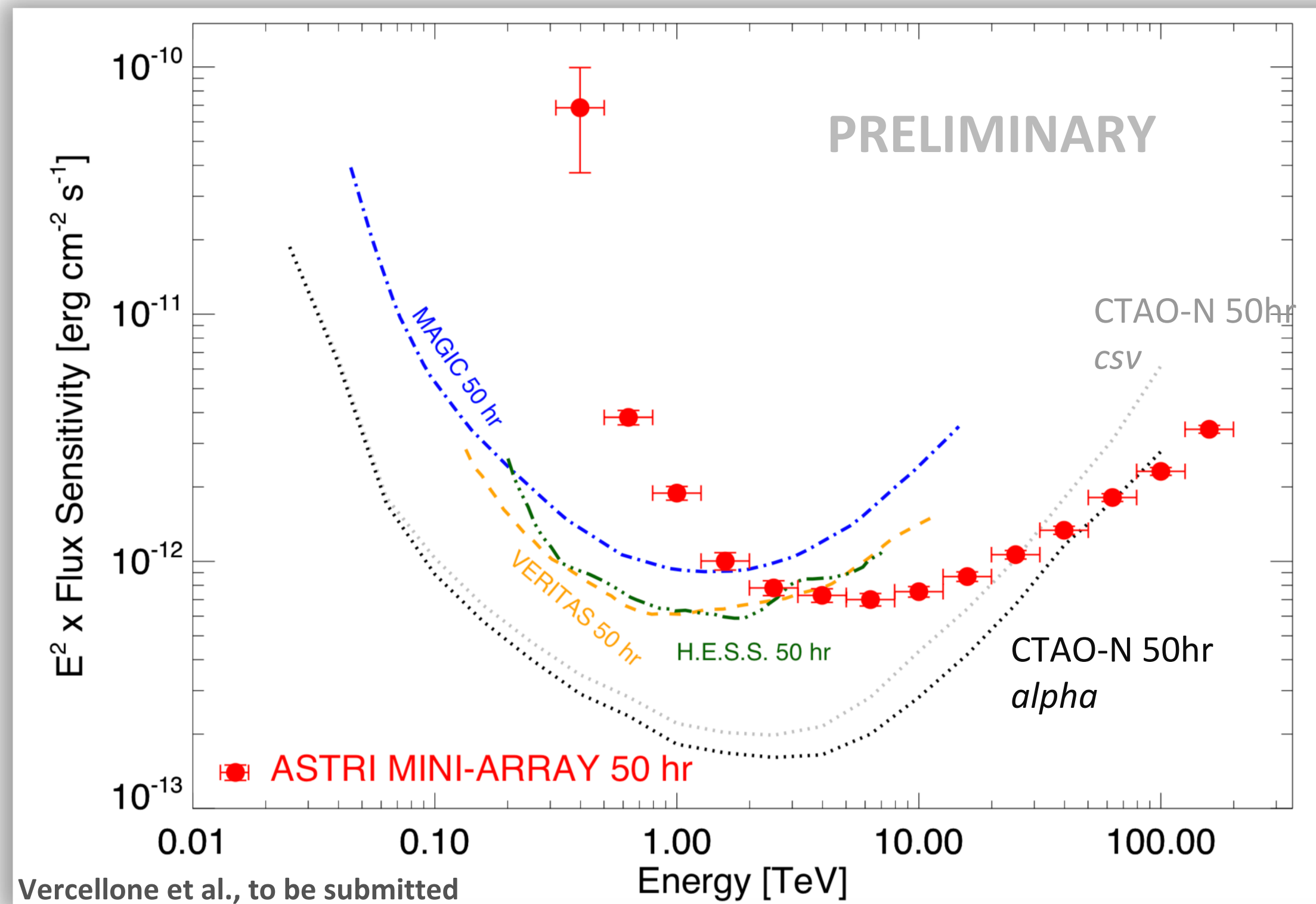




# The ASTRI Mini-Array – Performance

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 AS $\gamma$
Altitude [m]	2,390	2,396	1,268	1,800	4,100	4,410	4,300
FoV	$\sim 10^\circ$	$\sim 3.5^\circ$	$\sim 3.5^\circ$	$\sim 5^\circ$	2 sr	2 sr	2 sr
Angular Res.	$0.05^\circ$ (30 TeV)	$0.07^\circ$ (1 TeV)	$0.07^\circ$ (1 TeV)	$0.06^\circ$ (1 TeV)	$0.15^\circ$ (10 TeV)	$(0.24\text{--}0.32)^\circ$ (100 TeV)	$\sim 0.2^\circ$ (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

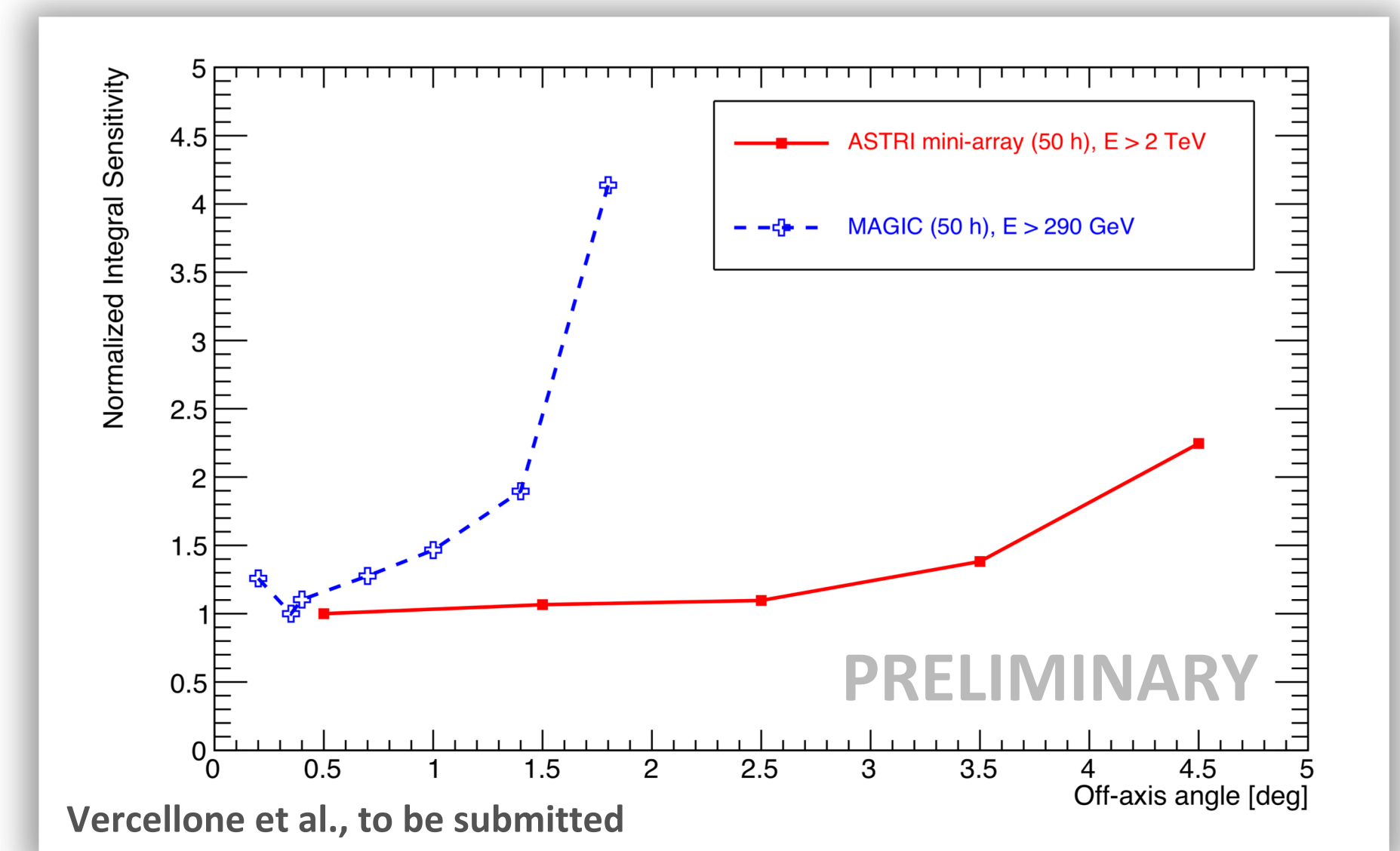
**Energy/Angular resolution:  $\sim 10\%$  /  $\sim 0.05^\circ$  ( $E = 10$  TeV)**

Characterize extended sources morphology

**$10^\circ$  field of view with homogeneous off-axis performance**

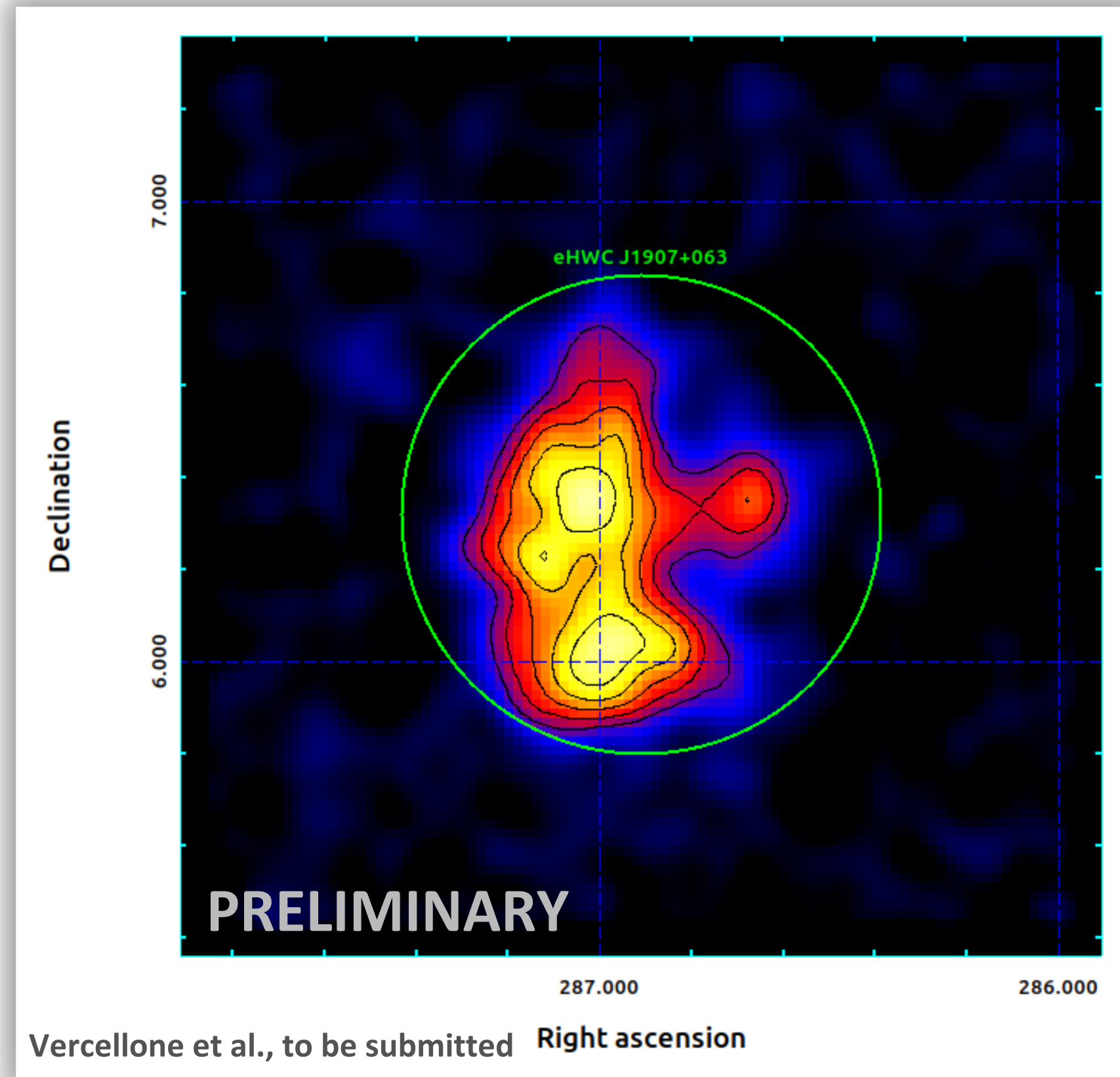
Multi-target fields and extended sources

Enhanced chance for serendipitous discoveries

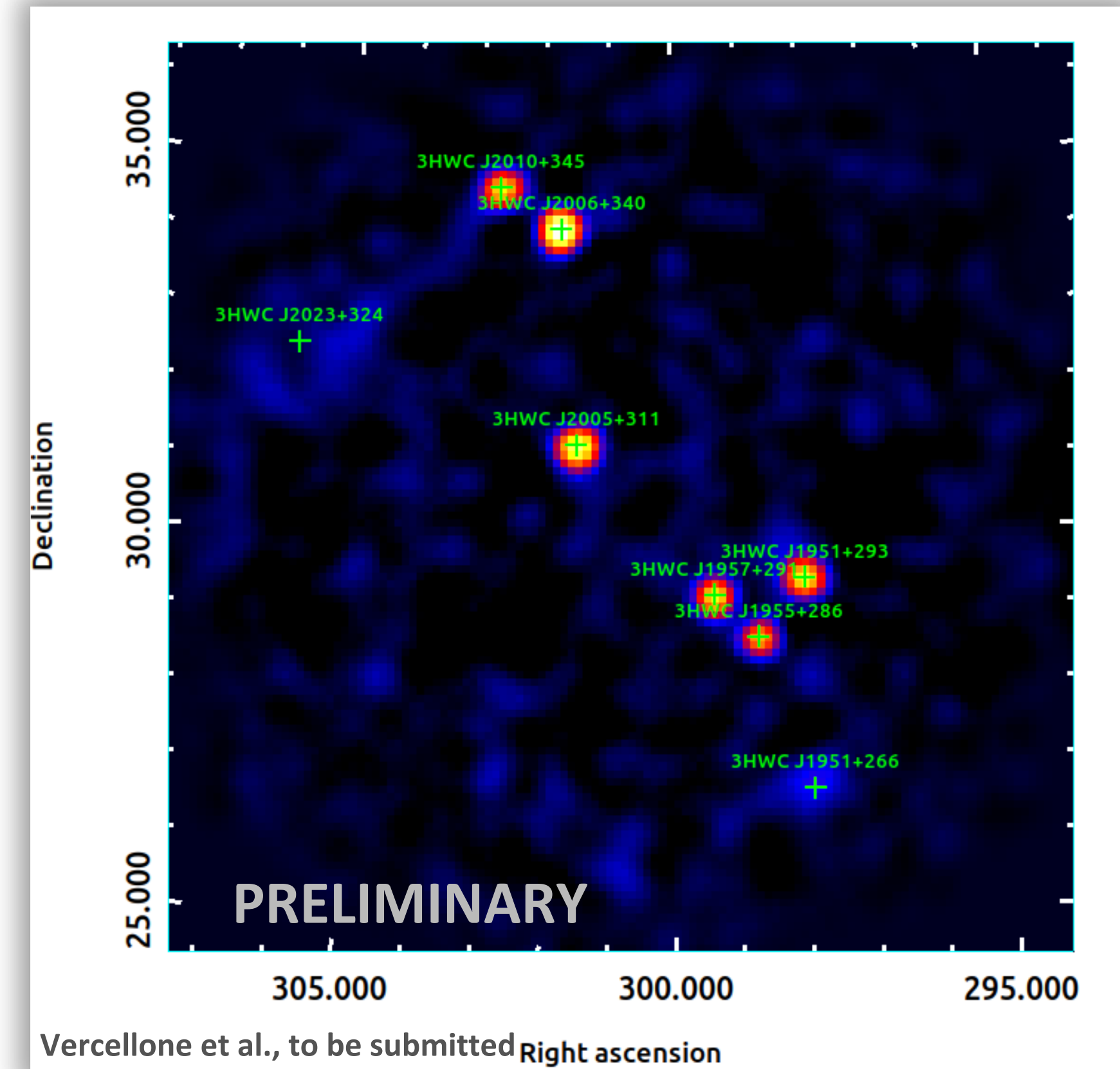




# Angular resolution and large field of view



ASTRI Mini-Array **200 hr simulation (up to  $E \sim 200$  TeV)** of the region **of the Galactic source 2HWC J1908+063**. The light green circle marks the  $\sim 0.52^\circ$  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  $10^\circ \times 10^\circ$  field of view



# The LHAASO PeVatrons

Cao et al., 2021, Nature

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

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**

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

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

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



# The Pillars' concept

**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

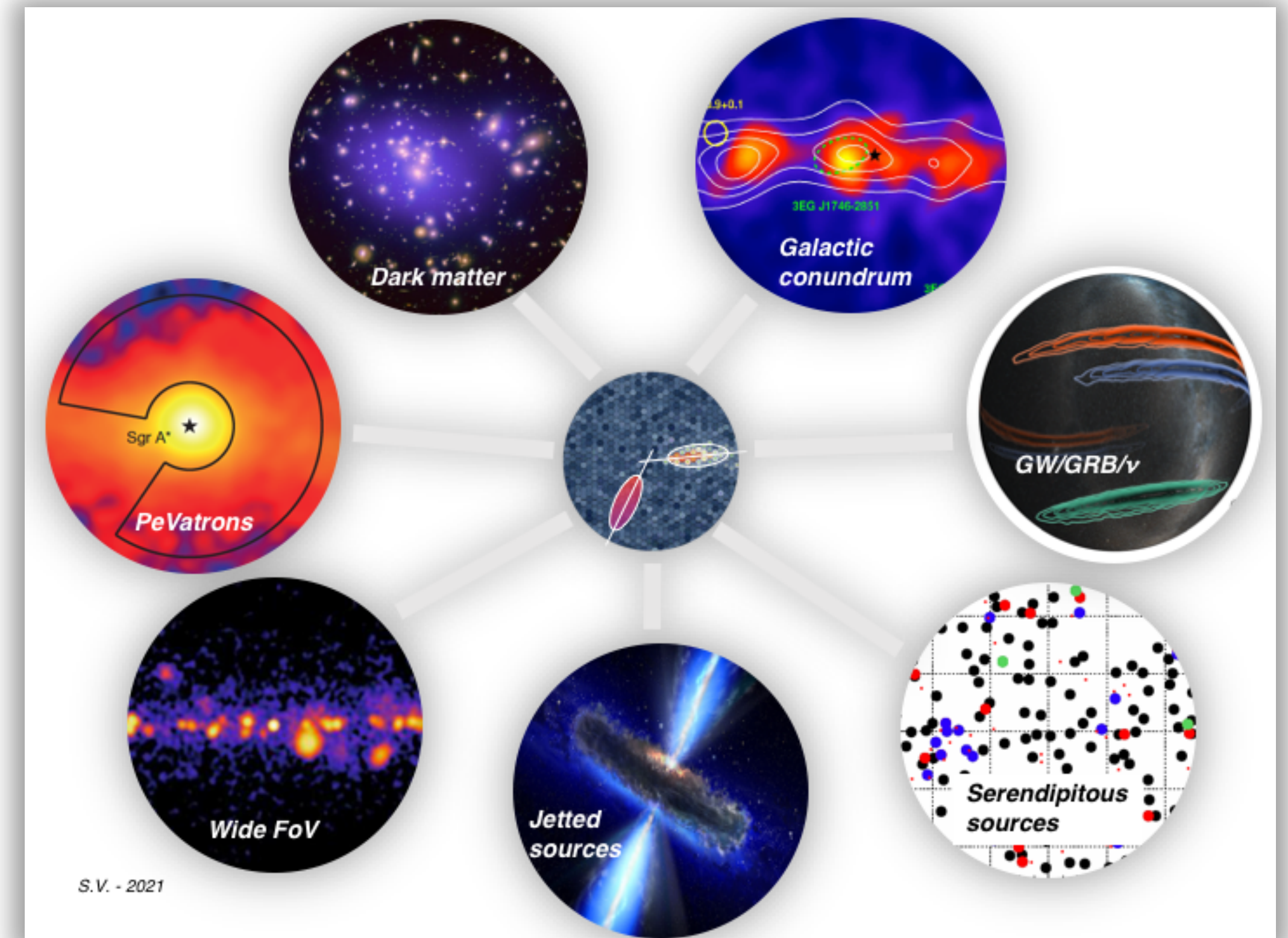
Probing intergalactic magnetic fields

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



## Pillar-1

Name	RA	Dec	Type	Zenith Angle <sup>1</sup>	Visibility <sup>2</sup>
PRELIMINARY	(deg)	(deg)		(deg)	(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
$\gamma$ -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	Class	RA (J2000)	DEC (J2000)	Obs. time	ZA	Moon	Strategy, analysis, notes
IAU Name				[hr]	[deg]	[%]	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	Class	RA (J2000)	DEC (J2000)	Obs. time	ZA	Moon	Strategy, analysis, notes
IAU Name				[hr]	[deg]	[%]	
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

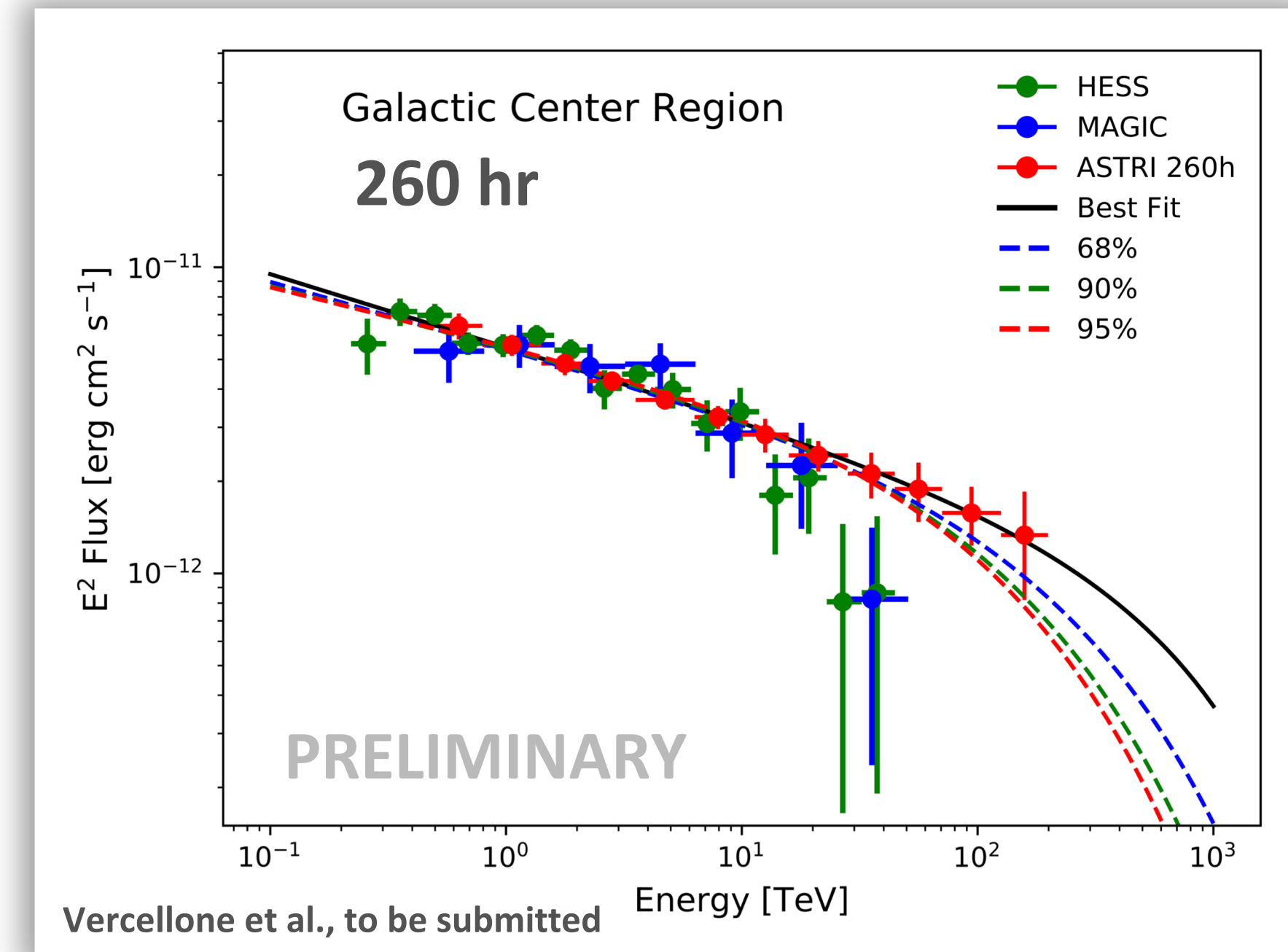
It is a complex region harbouring several potential sources of particle acceleration

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



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: $\gamma$ -Cygni

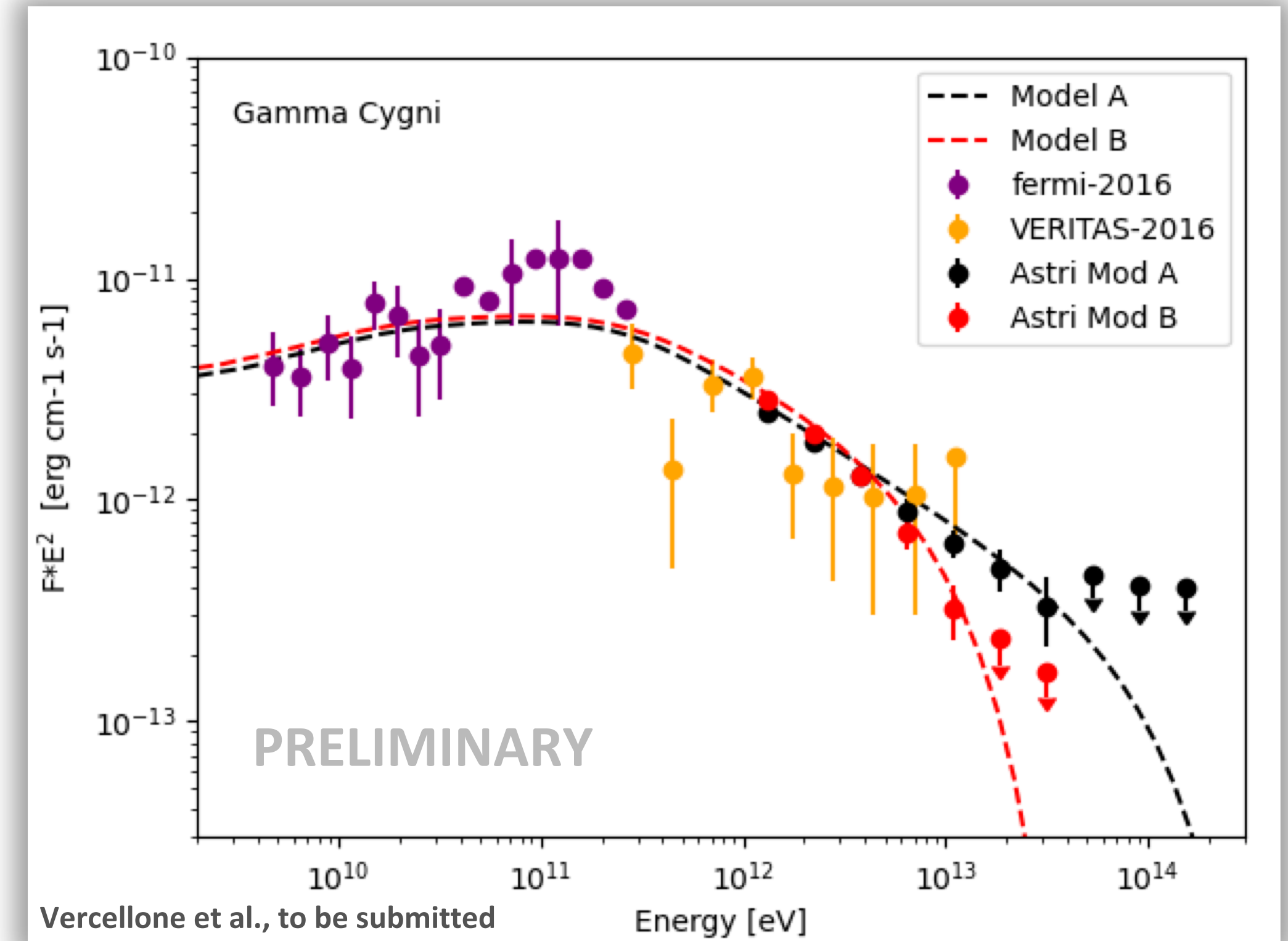
$\gamma$ -Cygni (G78.2+2.1) is a middle-aged SNR located in the Cygnus region and discovered by VERITAS

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



# 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

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

Measurements in the **(10-30)TeV energy band probe the EBL in the  $\sim(10-30)\mu\text{m}$  regime**, otherwise inaccessible

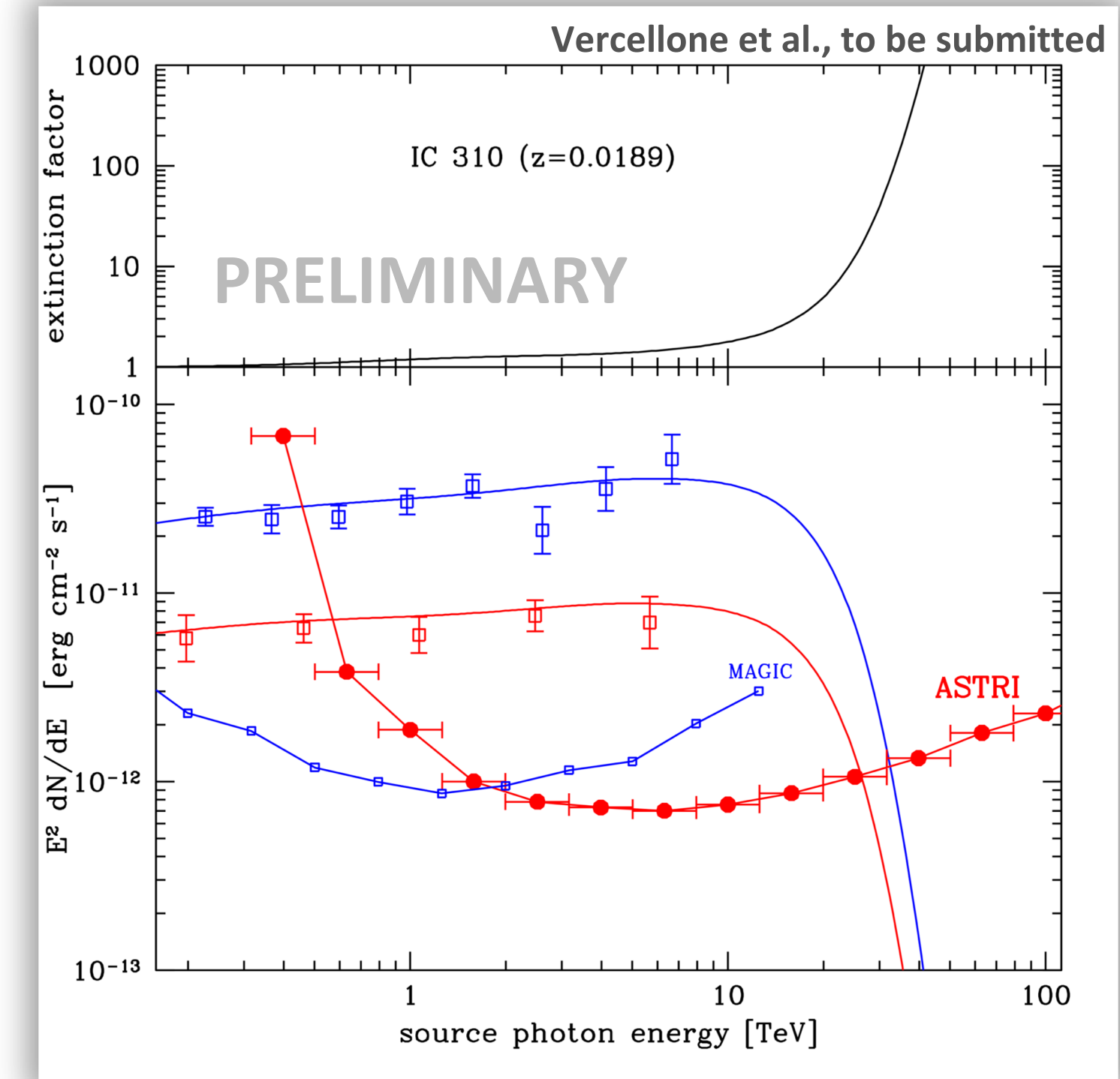
**Best candidates to constrain the EBL up to  $\lambda \sim 100\mu\text{m}$ :**

**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,  $5\sigma$  differential sensitivity



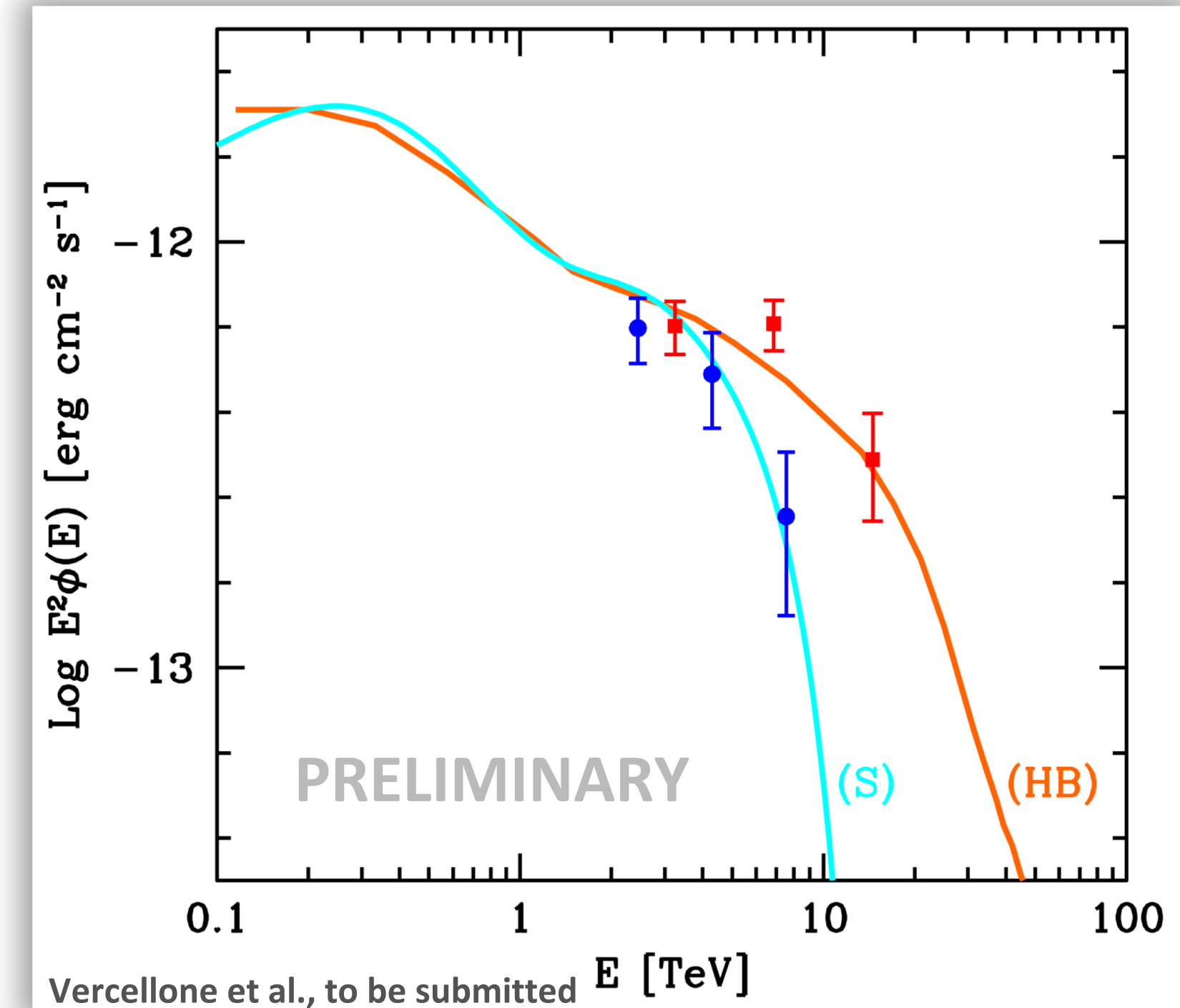
# Fundamental physics – hadron beams

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  $\gamma$  and  $\nu$ .
- Because of the reduced distance,  $\gamma$  experience a less severe EBL absorption
- **The observed gamma-ray spectrum extends at energies much higher ( $E > 10\text{TeV}$ ) 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 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 AS $\gamma$  extended energy range



# Core and Observatory science plan

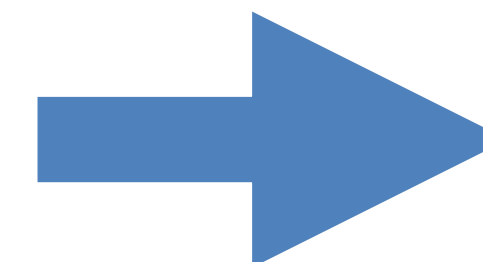
## Baseline

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

## 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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#### ABSTRACT

The ASTRI Mini-Array (MA) is an INAF project to build and operate an observatory to study astronomical sources emitting at very high-energy in the TeV spectral band. The ASTRI MA consists of a group of nine innovative Imaging Atmospheric Cherenkov telescopes. The telescopes will be installed at the Teide Astronomical Observatory of the Instituto de Astrofísica de Canarias (IAC) in Tenerife (Canary Islands, Spain) on the basis of a host agreement with INAF. Thanks to its expected overall performance, better than current Cherenkov telescopes' arrays for energies above  $\sim 5$  TeV and up to 100 TeV and beyond, the ASTRI MA will represent an important instrument to perform deep observations of the Galactic and extra-Galactic sky at these energies.

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#### ABSTRACT

The ASTRI (Astronomia con Specchi a Tecnologia Replicante Italiana) Project led by the Italian National Institute for Astrophysics (INAF) is developing and will deploy at the *Osservatorio del Teide* a mini-array (ASTRI Mini-Array) composed of at least nine telescopes similar to the small-size dual-mirror Schwarzschild-Couder telescope (ASTRI-Hot) currently operating on the slopes of Mt. Etna in Sicily. The ASTRI Mini-Array will surpass the current Cherenkov telescope array differential sensitivity above a few tens of GeV, extending the energy band well above hundreds of TeV. This will allow us to explore a new window of the electromagnetic spectrum, by combining the sensitivity performance with excellent angular and energy resolution figures. In this paper we describe the Core Science that we will address during the first four years of operation, providing examples of the breakthrough results that we will obtain when dealing with current open questions, such as the acceleration of cosmic rays, cosmology and fundamental physics and the new window, for the TeV energy band, of the time-domain astrophysics.

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

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#### ABSTRACT

The ASTRI Mini-Array will be composed of nine imaging atmospheric Cherenkov telescopes at the *Osservatorio del Teide* site. The array will be best suited for astrophysical observations in the 0.5-200 TeV range with an angular resolution of few arc-minutes and an energy resolution of  $\sim 13\%$ . A core-science programme in the first four years will be devoted to a limited number of key targets, addressing the most important open scientific questions in the very-high-energy domain. At the same time, thanks to a wide field-of-view of about  $6^\circ$  radius, ASTRI Mini-Array will observe many additional field sources, which will constitute the basis for the long-term observatory programme that will eventually cover all the accessible sky. In this paper, we review different astrophysical Galactic environments, e.g. pulsar wind nebulae, supernova remnants, and gamma-ray binaries, and show the results from a set of ASTRI Mini-Array simulations of possible field VHE sources made to highlight the expected performance of the array and the important additional observatory science that will complement the core-science programme.

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

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#### ABSTRACT

The ASTRI Mini-Array is a next-generation system of nine imaging atmospheric Cherenkov telescopes that is going to be built at the *Osservatorio del Teide* site. After a first phase, in which the instrument will be operated as an experiment prioritizing a schedule of primary science cases, an observatory phase is foreseen in which other significant targets will be pointed. We focus on the observational feasibility of extragalactic sources and on astrophysical processes that best complement and expand the ASTRI Mini-Array core science, presenting the most relevant examples that are at reach of detection over long-term time scales and whose observation can provide breakthrough achievements in the very-high energy extragalactic science. Such examples cover a wide range of  $\gamma$ -ray emitters, from Seyfert 2 galaxies and extreme blazars to self-interacting dark matter. Simulations of the presented objects show that the instrument performance will be competitive at multi-TeV energies with respect to both current and future arrays of Cherenkov telescopes.

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#### 1. Introduction

Observations from Earth with arrays of imaging air Cherenkov telescopes (IACTs; e.g., Aharonian et al., 1992) play a paramount role in the future development of the  $\gamma$ -ray astronomy. In this context, the ASTRI (“Astronomia con Specchi a Tecnologia Replicante Italiana”) Mini-Array, a system



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





