# Science Pillars of the ASTRI Mini-Array


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


**ASTRI Project Committee, 29.11.2021**

# The “Fab Four” 

**Paper – I (Scuderi et al):** ***The ASTRI Mini-Array of Cherenkov Telescopes at the Observatorio del Teide***
We present a detailed description of the ASTRI Project, namely the ASTRI Mini-Array technological solutions and suggest a possible observing plan, based on the sources discussed in Paper – II **[see Salvo’s + Gino’s + Andrea’s talks]**.

**Paper – II (Vercellone et al):** ***ASTRI Mini-Array Core Science at the Observatorio del Teide***
We discuss the science themes that we will investigate during the first 3 to 4 years of the ASTRI Mini-Array observing life, when it will be run as an experiment by the ASTRI Mini-Array collaboration. Most of this presentation is devoted to a discussion of a few of them.

**Paper – III (D’Ai’ et al):** ***Galactic Observatory Science with the ASTRI Mini-Array at the Observatorio del Teide***
***&***
**Paper – IV (Saturni et al):** ***Extra-galactic Observatory Science with the ASTRI Mini-Array at the Observatorio del Teide***

We report the expected results on Galactic and extra-galactic sources, respectively, that the ASTRI Mini-Array will achieve during its observatory phase, i.e. after the completion of the core science observing period.

# To appear soon

## The ASTRI Mini-Array Core Science Paper

- Resubmitted to internal reviewers
- Waiting for the sign-in procedure

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


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ABSTRACT


The ASTRI (Astrofisica con Specchi a Tecnologia Replicante Italiana) Project led by the Italian National Institute for Astrophysics (INAF) is developing and will deploy at the *Observatorio del Teide* a mini-array (ASTRI Mini-Array) composed of nine telescopes similar to the small-size dual-mirror Schwarzschild-Couder telescope (ASTRI-Horn) 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 tera-electronvolt (TeV), extending the energy band well above hundreds of TeV. This will allow us to explore a new window of the electromagnetic spectrum, by convolving 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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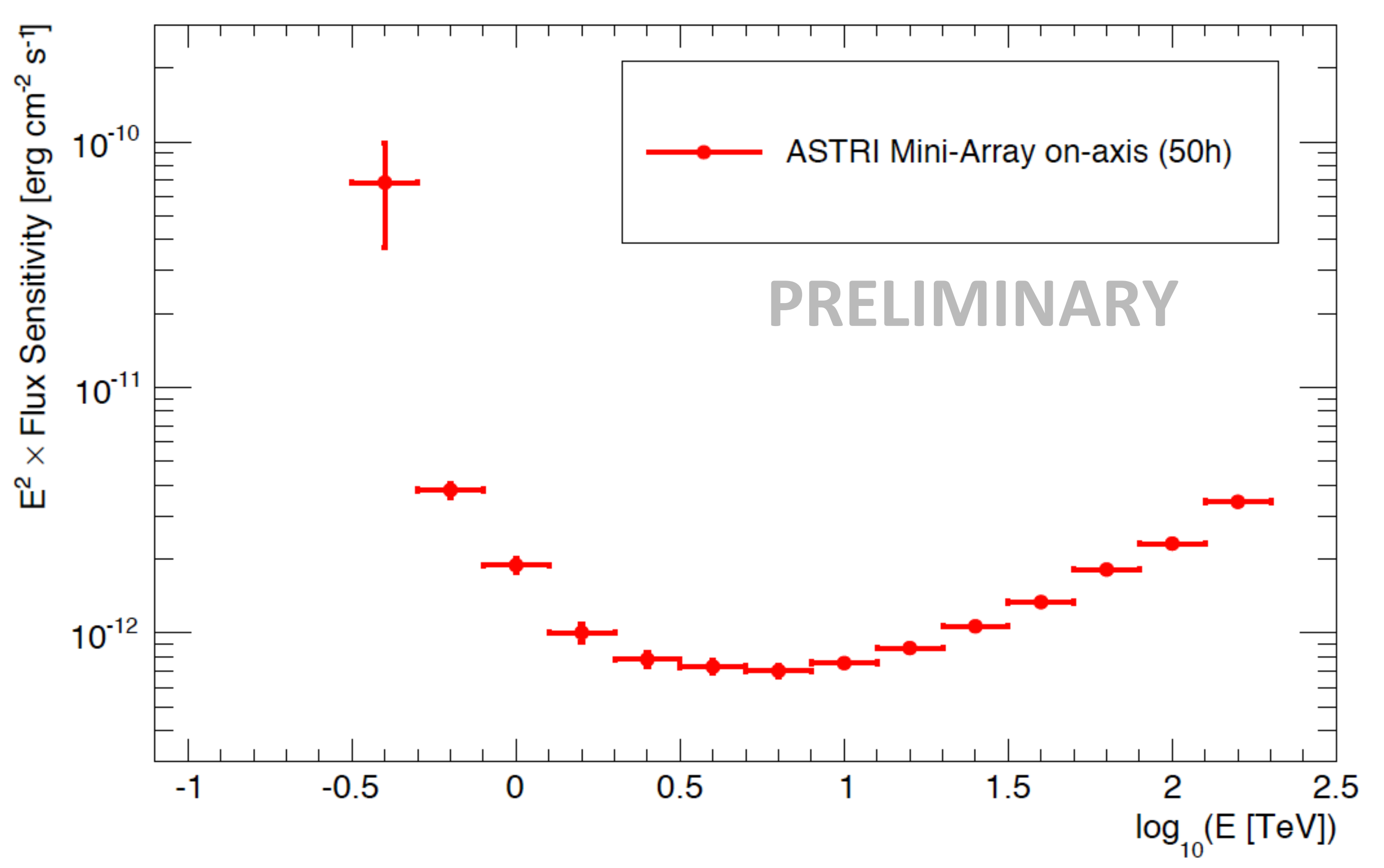
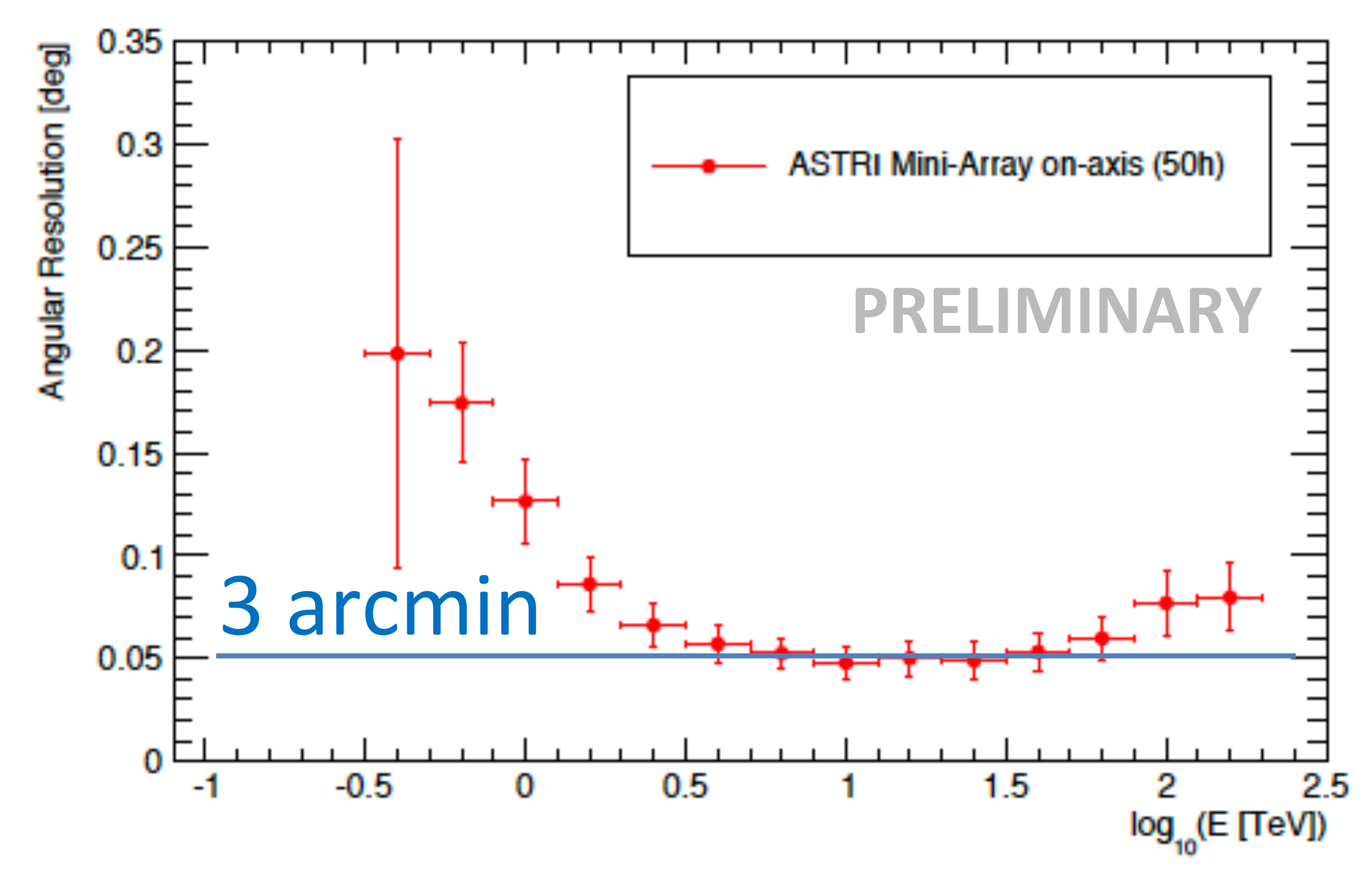
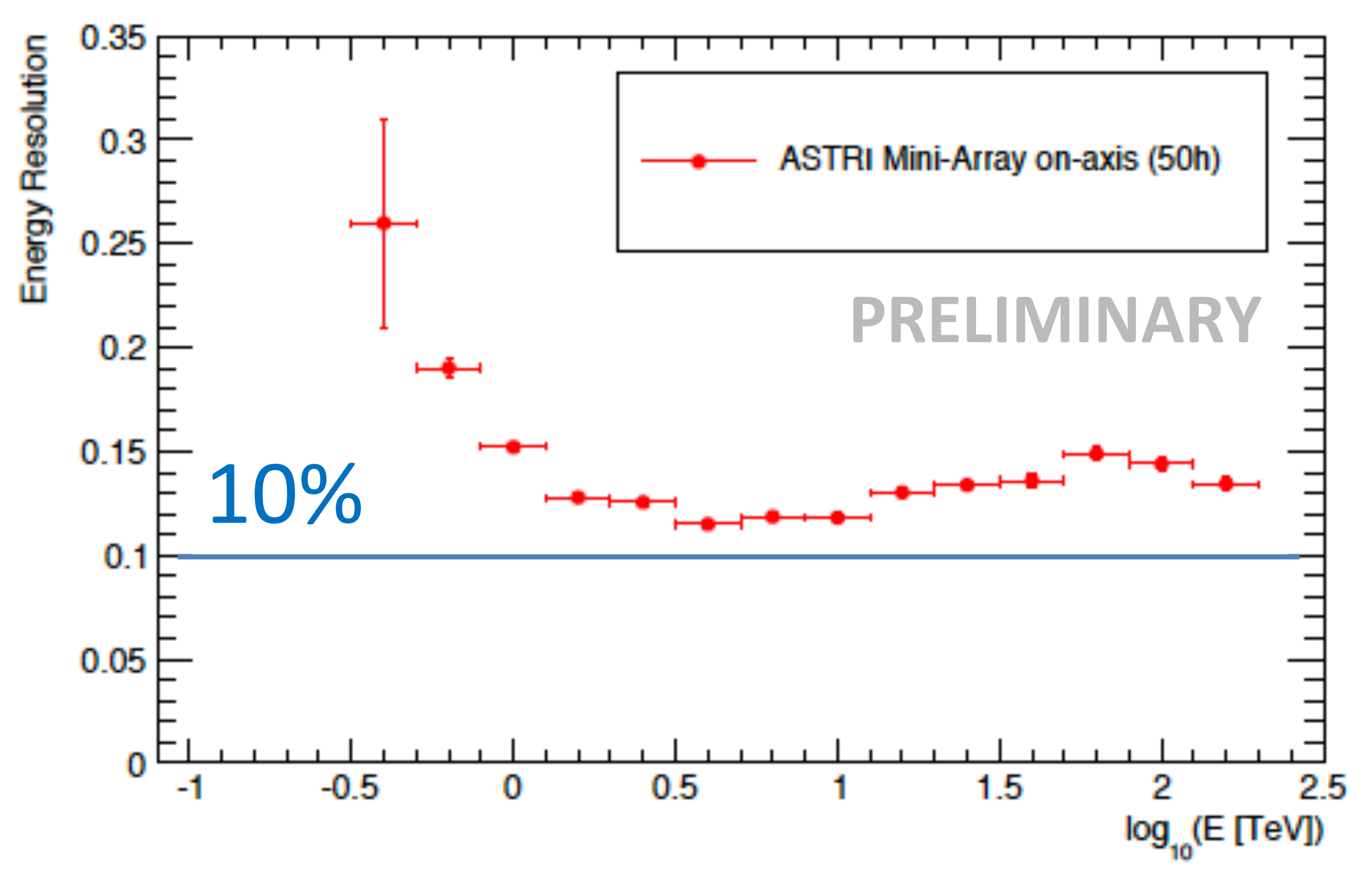


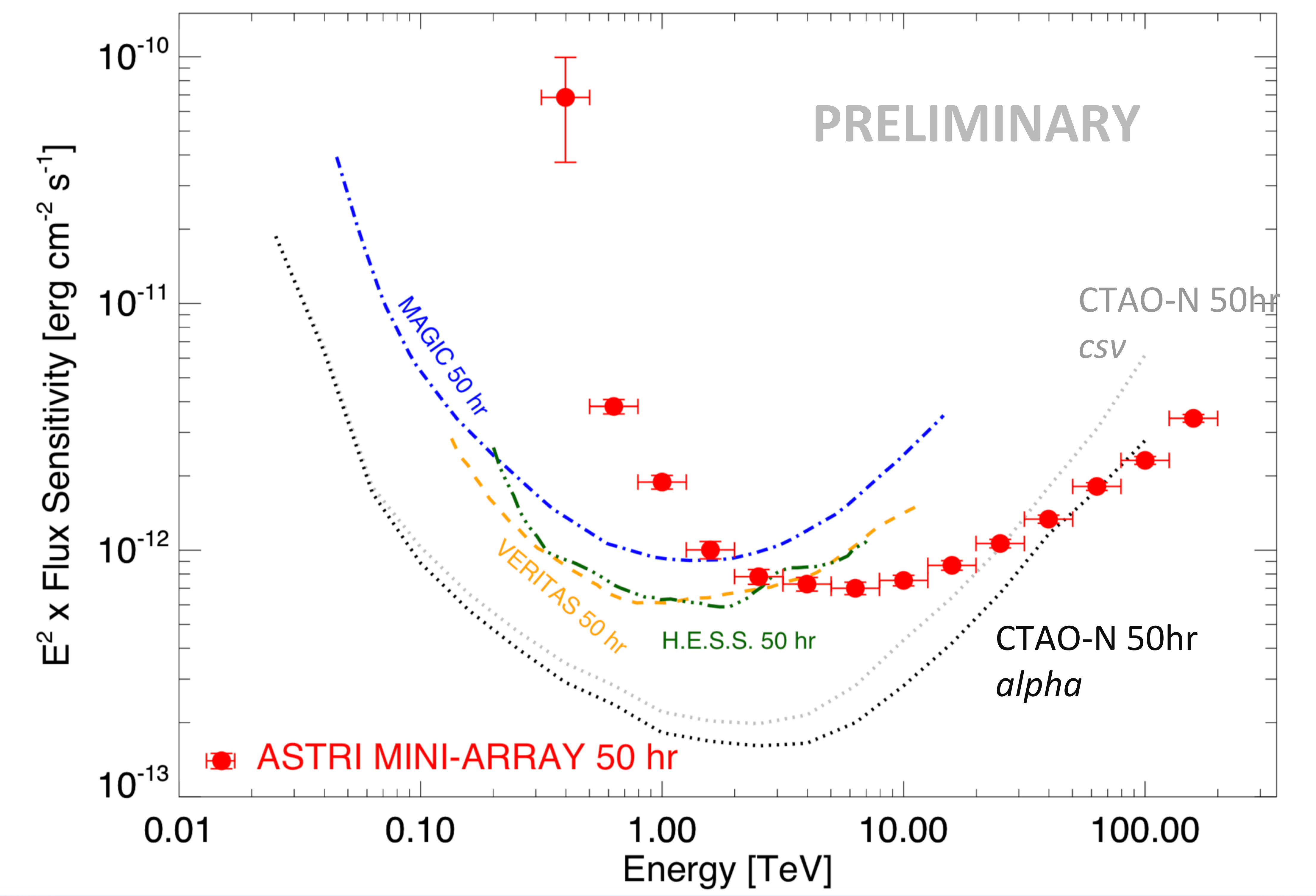



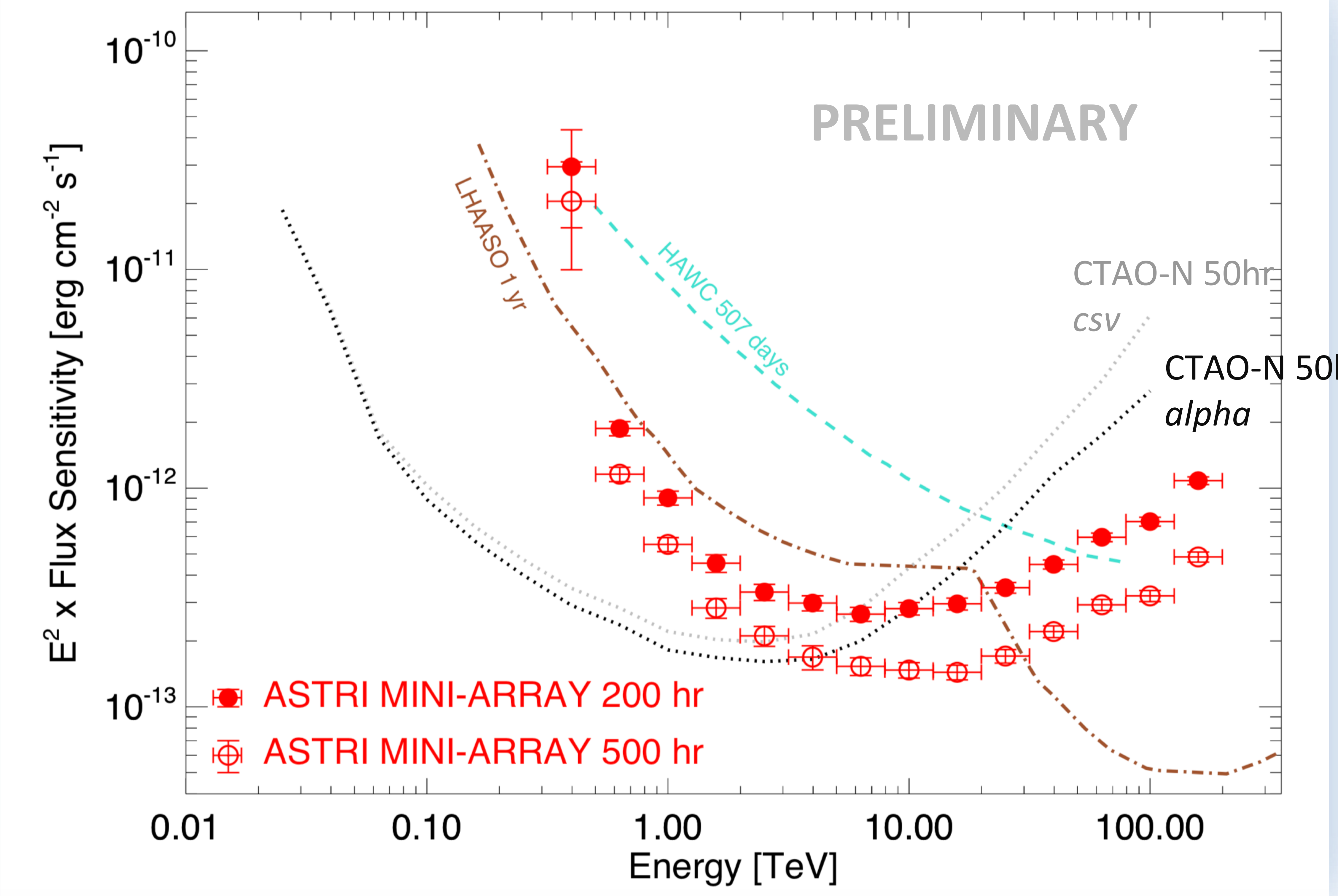

- The **off-axis performance** remains in the entire energy range within a **factor of ~1 (~2) of the on-axis performance up to ~3°(~5°)**

- It allows the system to preserve a performance close to the best one over a wide field of view of several squared degrees.

# 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

| 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** | $\sim 10°$ | $\sim 3.5°$ | $\sim 3.5°$ | $\sim 5°$ | 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 | (0.1-1,000) 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

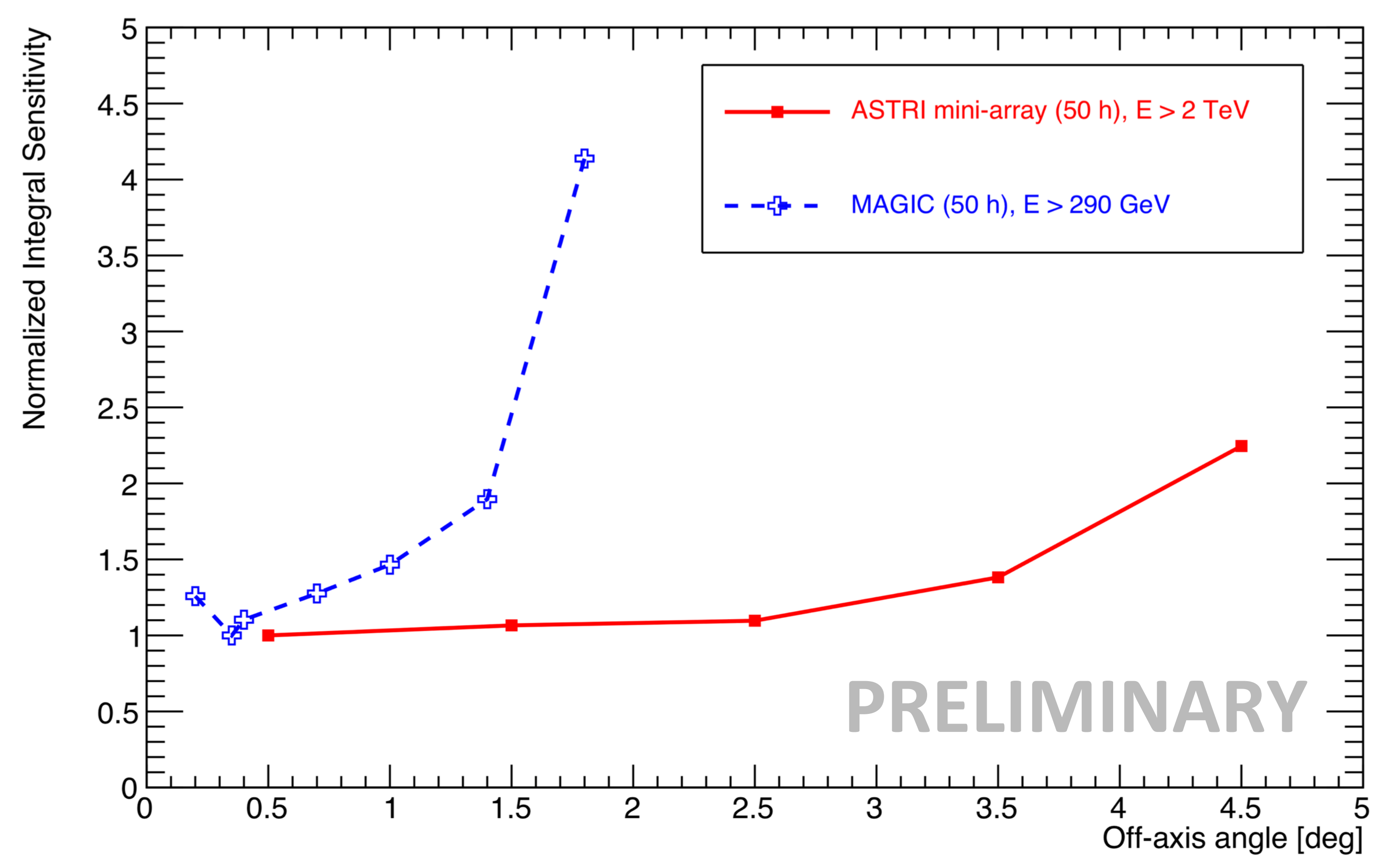
**Energy/Angular resolution: ~10% / ~0.05° (E =10 TeV)**

Characterize extended sources morphology

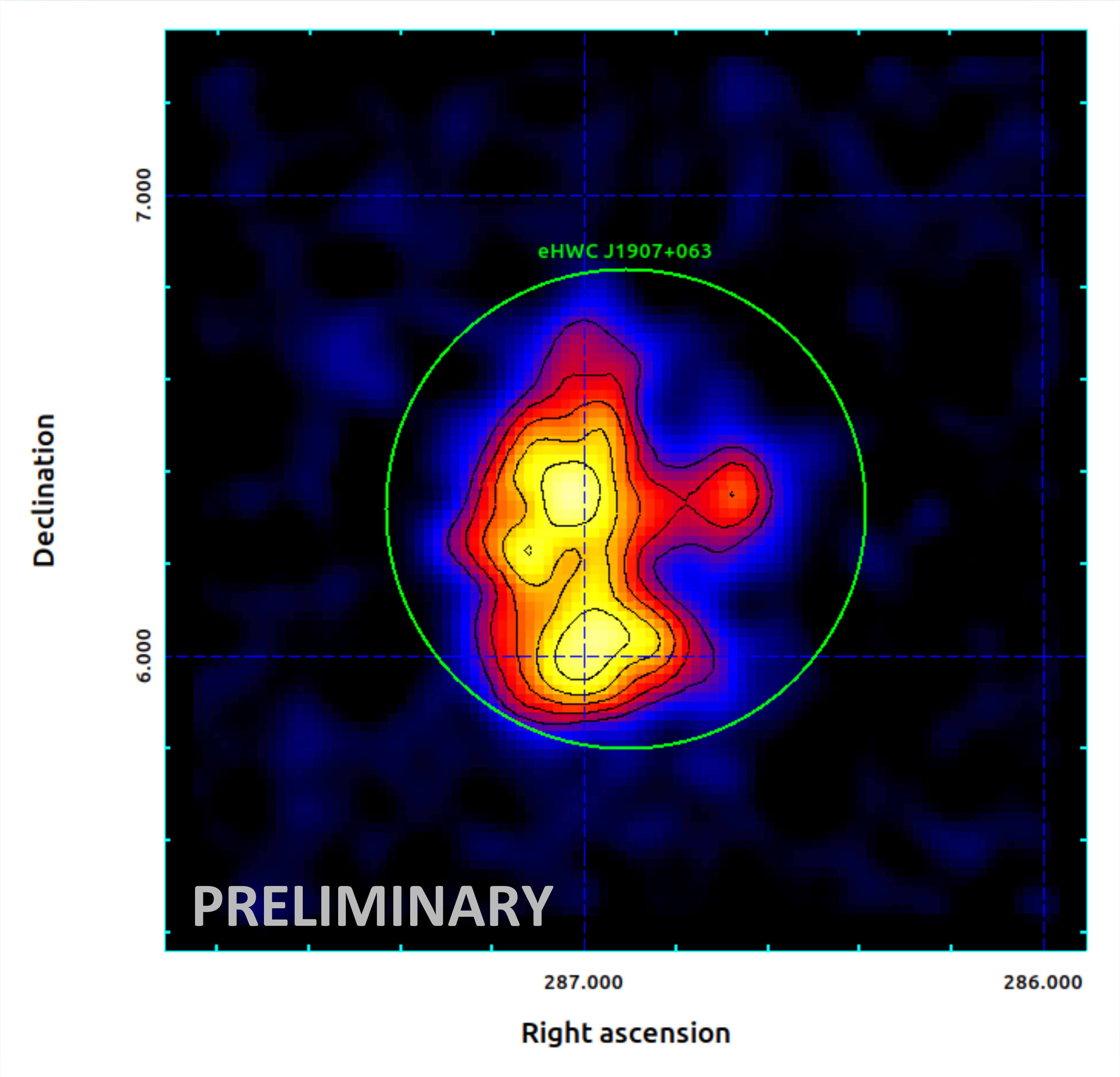
**10° field of view with homogeneous off-axis performance**

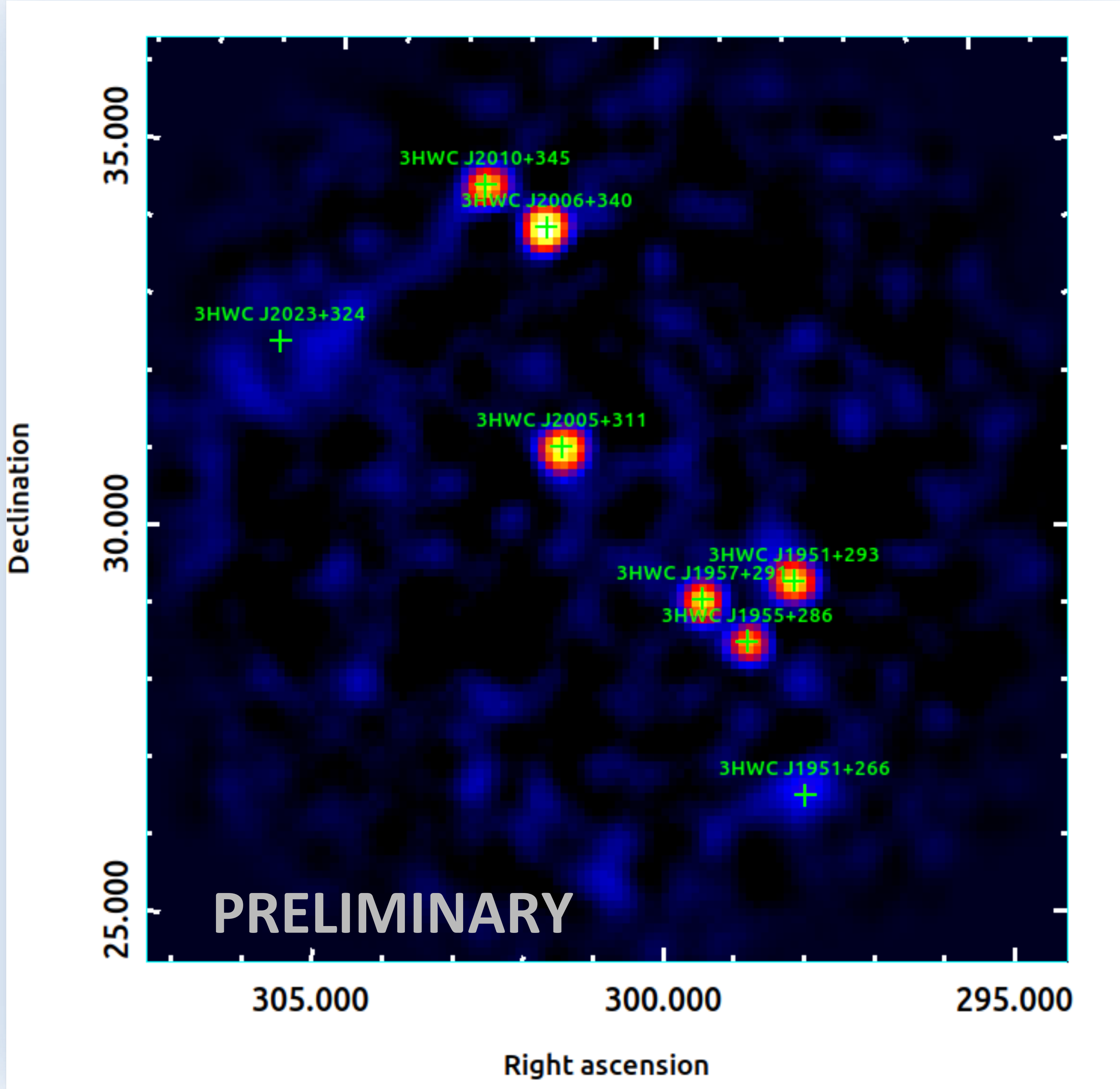
Multi-target fields and extended sources

Enhanced chance for serendipitous discoveries



# 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 $\sim 0.52°$ 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 $10° \times 10°$ field of view

# The LHAASO PeVatrons

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 | $4.5 \times 10^{38}$ | 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, |
| | PSR J1826-1256 | PSR | 1.6 | 14.4 | $3.6 \times 10^{36}$ | 2HWC J1825-134 |
| LHAASO J1839-0545 | PSR J1837-0604 | PSR | 4.8 | 33.8 | $2.0 \times 10^{36}$ | 2HWC J1837-065, HESS J1837-069, |
| | PSR J1838-0537 | PSR | $1.3^{e}$ | 4.9 | $6.0 \times 10^{36}$ | HESS J1841-055 |
| 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, |
| | PSR 1907+0602 | PSR | 2.4 | 19.5 | $2.8 \times 10^{36}$ | ARGO J1907+0627, VER J1907+062, |
| | PSR 1907+0631 | PSR | 3.4 | 11.3 | $5.3 \times 10^{35}$ | 2HWC 1908+063 |
| LHAASO J1929+1745 | PSR J1928+1746 | PSR | 4.6 | 82.6 | $1.6 \times 10^{36}$ | 2HWC J1928+177, 2HWC J1930+188, |
| | PSR J1930+1852 | PSR | 6.2 | 2.9 | $1.2 \times 10^{37}$ | 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 | $3.4 \times 10^{35}$ | 2HWC J1955+285 |
| | SNR G66.0-0.0 | SNR | $2.3 \pm 0.2^{d}$ | — | — | |
| LHAASO J2018+3651 | PSR J2021+3651 | PSR | $1.8^{+1.7\ l}_{-1.4}$ | 17.2 | $3.4 \times 10^{36}$ | 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 | $1.40 \pm 0.08^{o}$ | — | — | TeV J2032+4130, ARGO J2031+4157, |
| | PSR 2032+4127 | PSR | $1.40 \pm 0.08^{o}$ | 201 | $1.5 \times 10^{35}$ | 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 | $0.8^{p}$ | $\sim 10^{p}$ | $2.2 \times 10^{37}$ | |

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 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 Pillars' concept

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

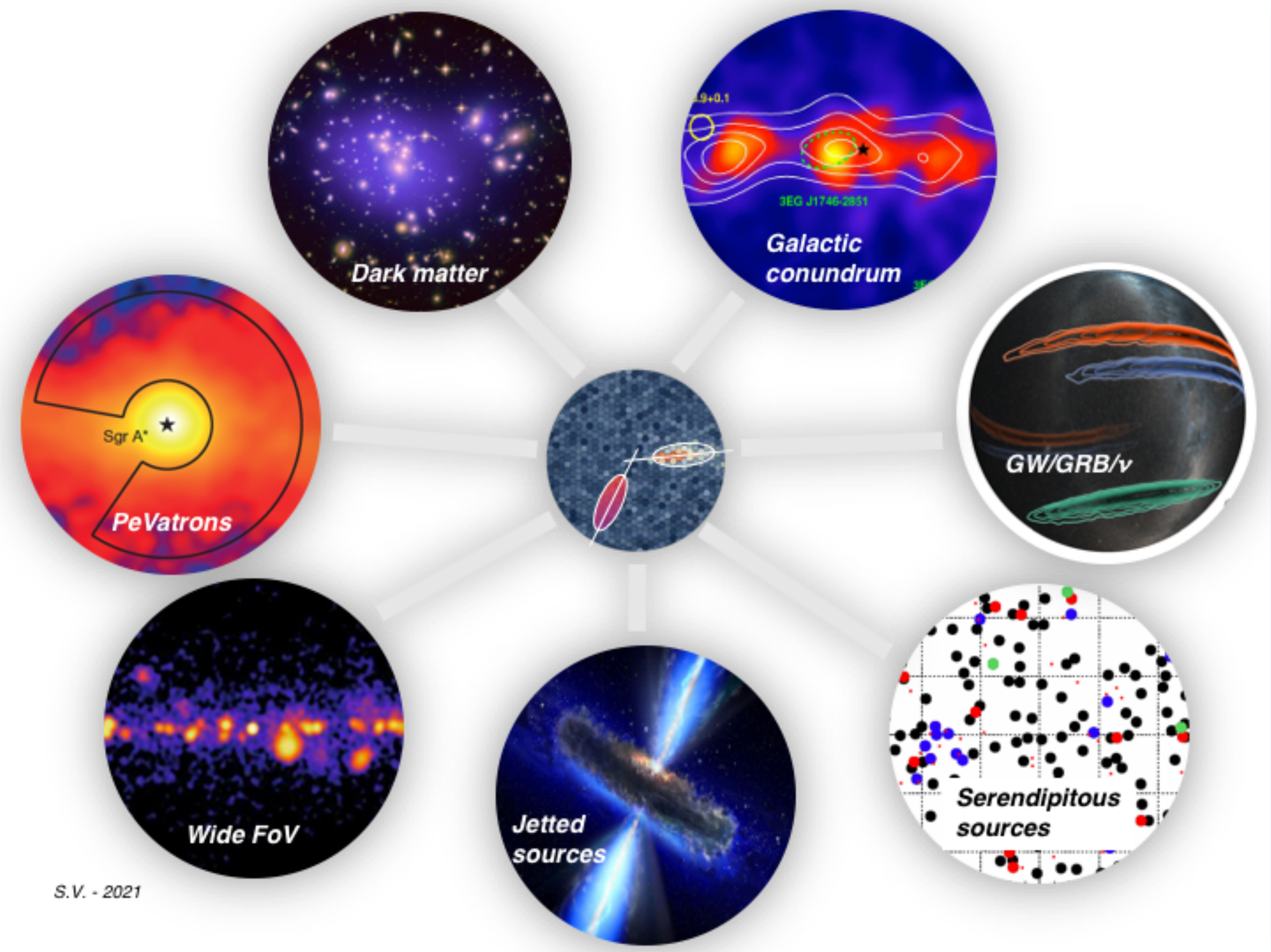
**10° field of view** →simultaneously **investigate more than one source** during the same pointing

## 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



# Pillars' main scientific targets

Mini-Array

## Pillar-1

| Name | RA | Dec | Type | Zenith Angle[1] | Visibility[2] |
|---|---|---|---|---|---|
| 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 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 PRELIMINARY |
|---|---|---|---|---|---|---|---|
| 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. |

[see Andrea's talk for a preliminary observing plan]

# The Galactic Center – a challenge in a challenge

Mini-Array

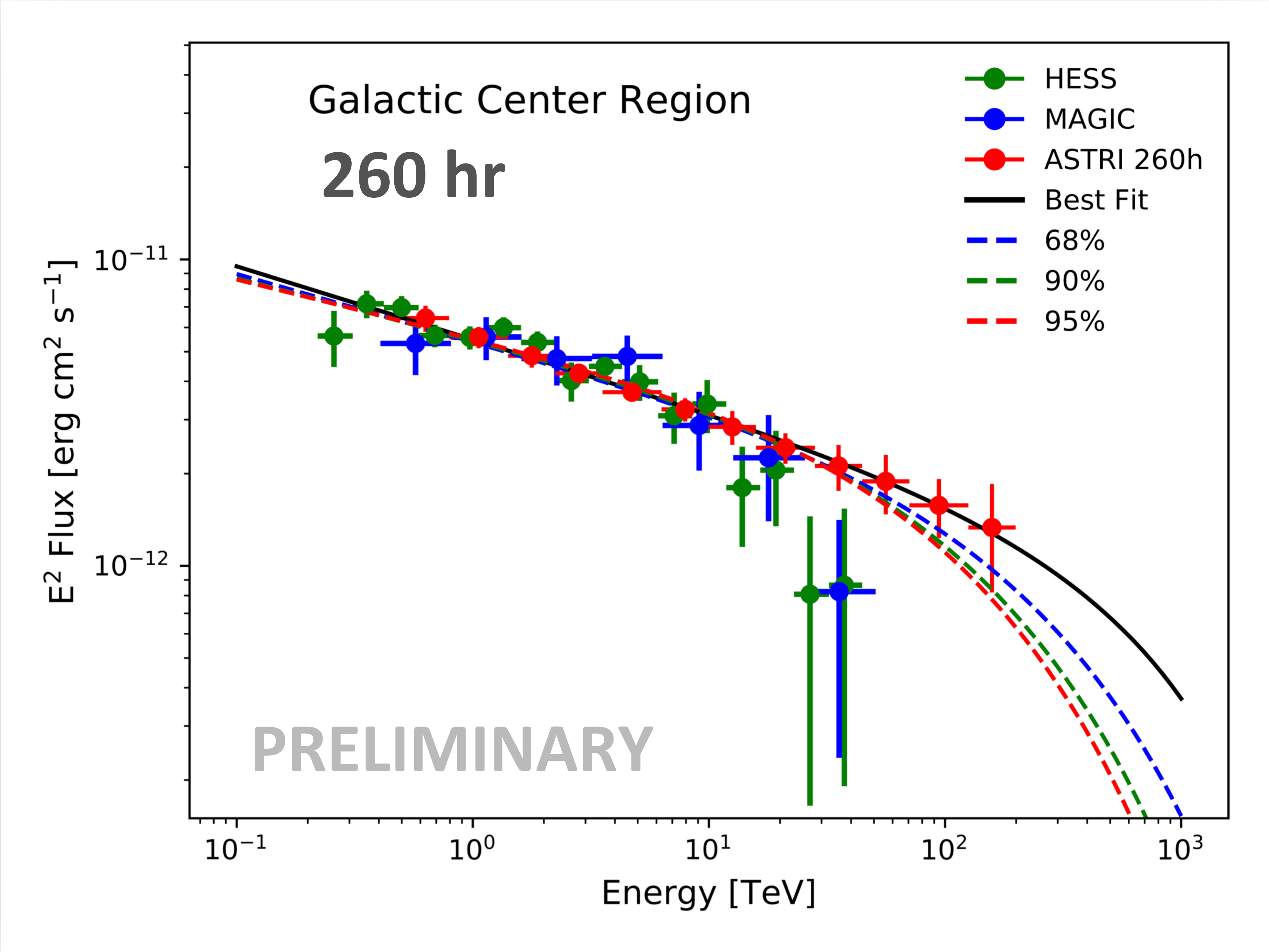
It is a complex region harbouring several potential sources of particle acceleration

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

Current IACTs detected **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

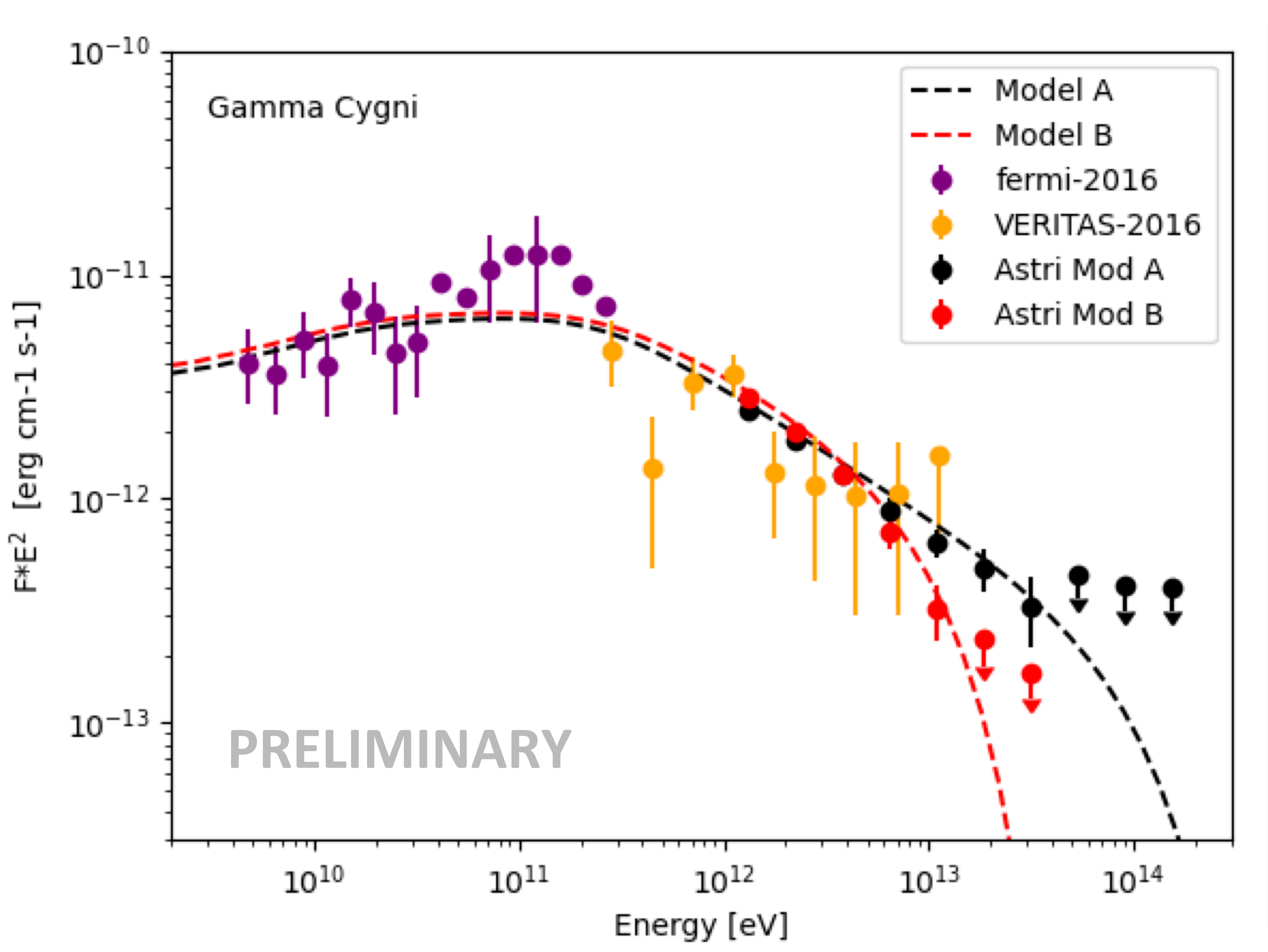
$\gamma$-Cygni (G78.2+2.1) is a middle-aged SNR located in the Cygnus region and discovered by VERITAS

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

ASTRI Mini-Array

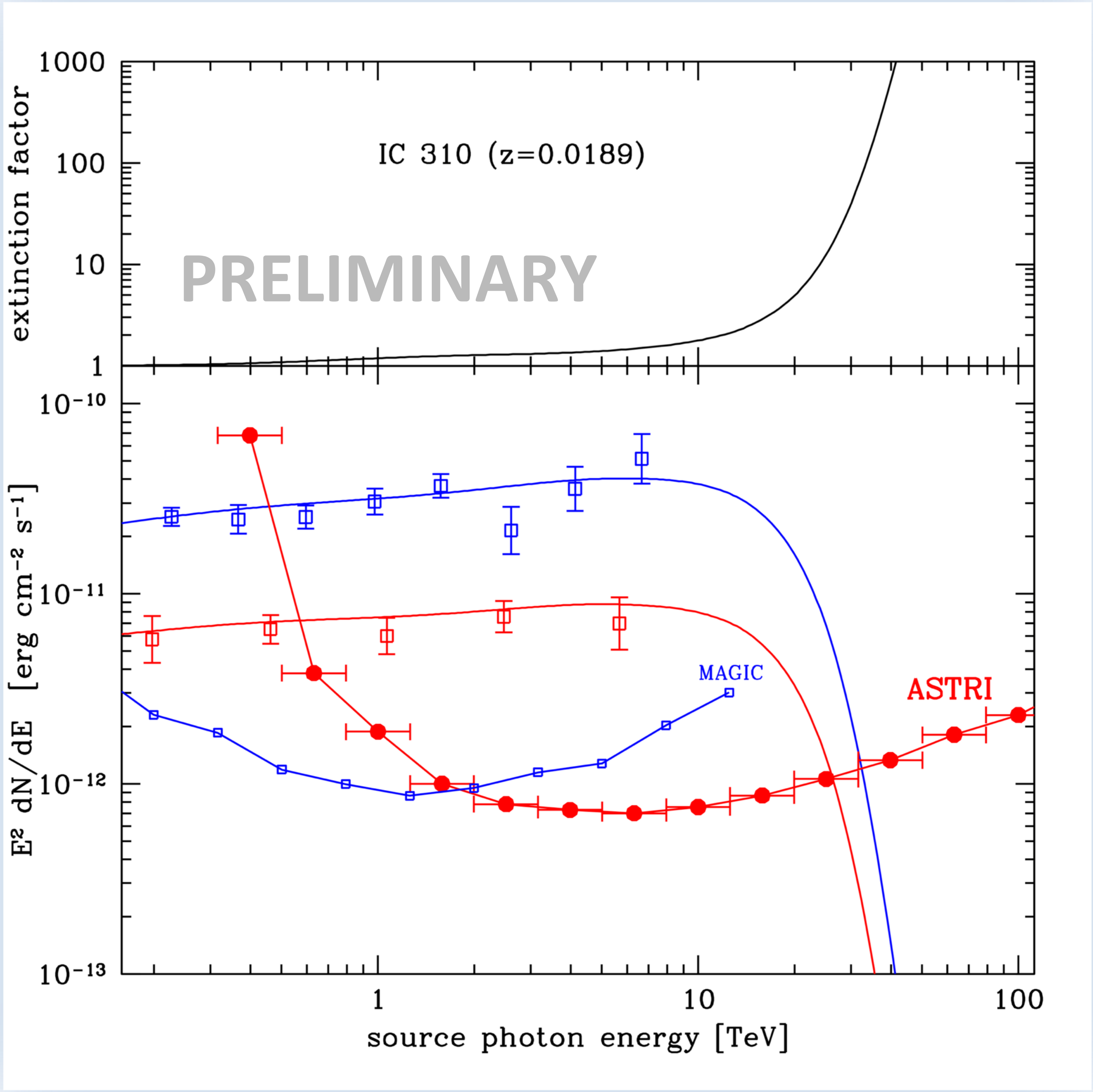
From the mid-IR to the far-IR, where the IR background intensity is maximal, EBL direct measurements are prevented by the overwhelming dominance of local emission from both the Galaxy and our Solar system

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

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 $\lambda \sim 100\mu m$:**

- **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, 5$\sigma$ differential sensitivity

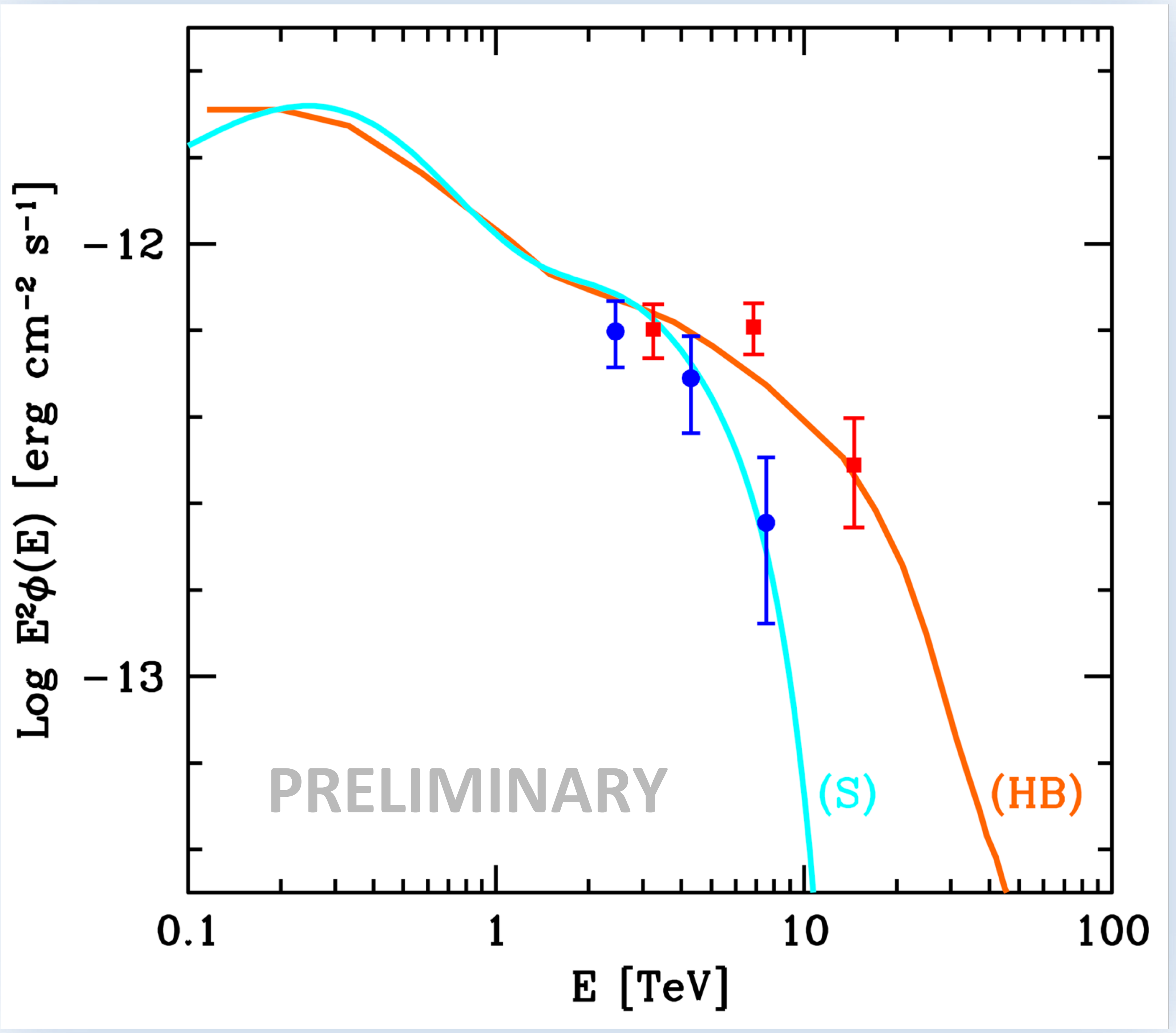
# Fundamental physics – hadron beams

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 $\gamma$ 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 > 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 significative detection up to 20 TeV with a deep (~250 hr) observation**

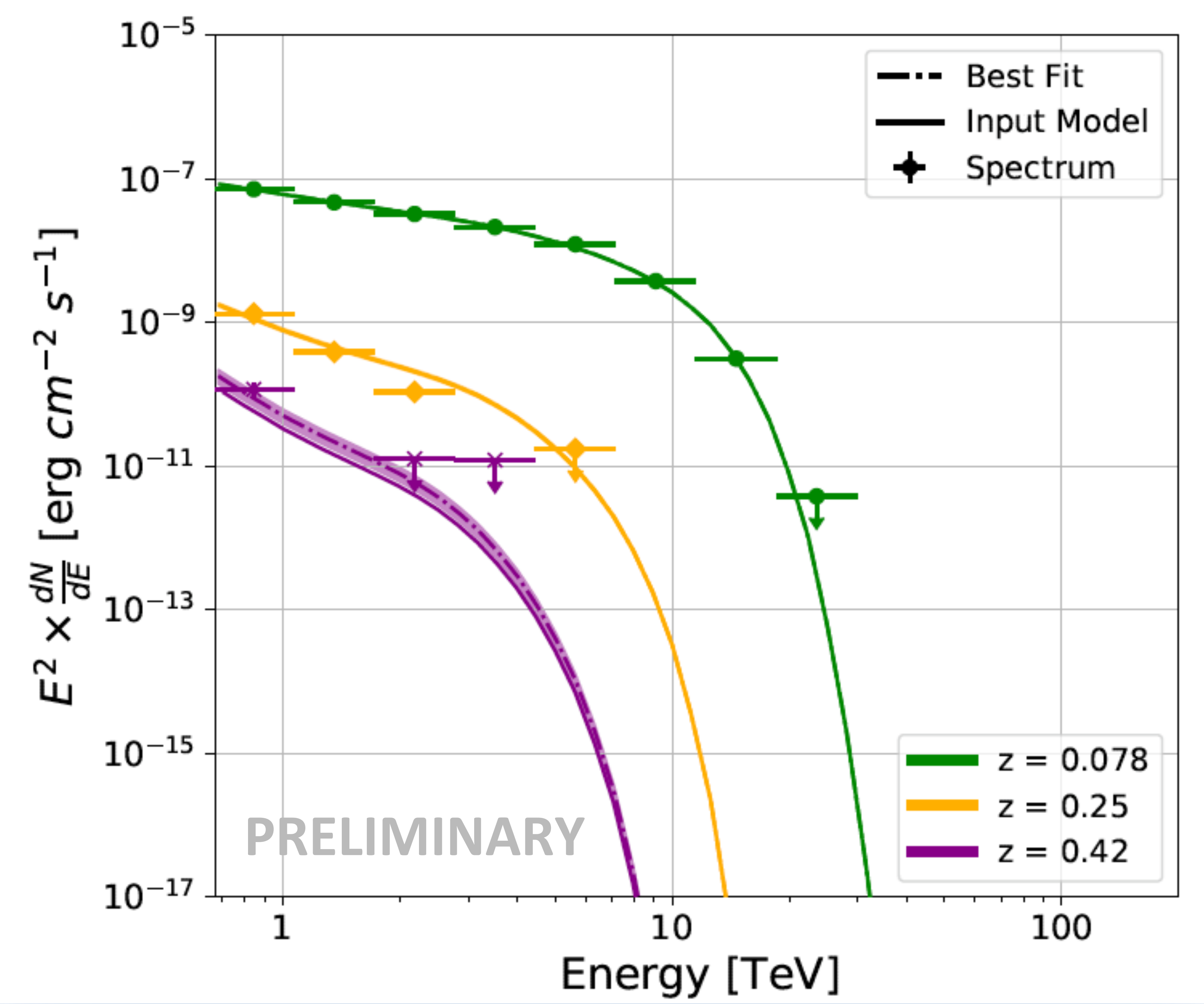
# Time-domain astrophysics – GRB

The detection by the MAGIC telescopes of GRB190114C (z = 0.42) revealed the presence of a new and energetically relevant component in GRBs, likely **SSC emission, extending into the TeV energy range.**

We used GRB190114C as a template to simulate the emission from GRBs at shorter distances: z = 0.078 (corresponding to the redshift of GRB 190829A, detected by H.E.S.S.), and the intermediate redshift z = 0.25.

To simulate the response of the ASTRI Mini-Array in the three different cases, we considered an observation starting 200 s after the burst and lasting 600 s.

**The expected number of follow-ups on observable GRBs is ~ 1 per month.**




The **ASTRI Mini-Array can**

- detect emission from a GRB 190114C-like event
- confirm afterglow emission at E >1 TeV from close GRBs at redshift smaller than ~0.4
- measure the spectral cutoff, either originated by the EBL absorption or intrinsic, if greater than ~1 TeV

# UHECR & Stellar Intensity Interferometry

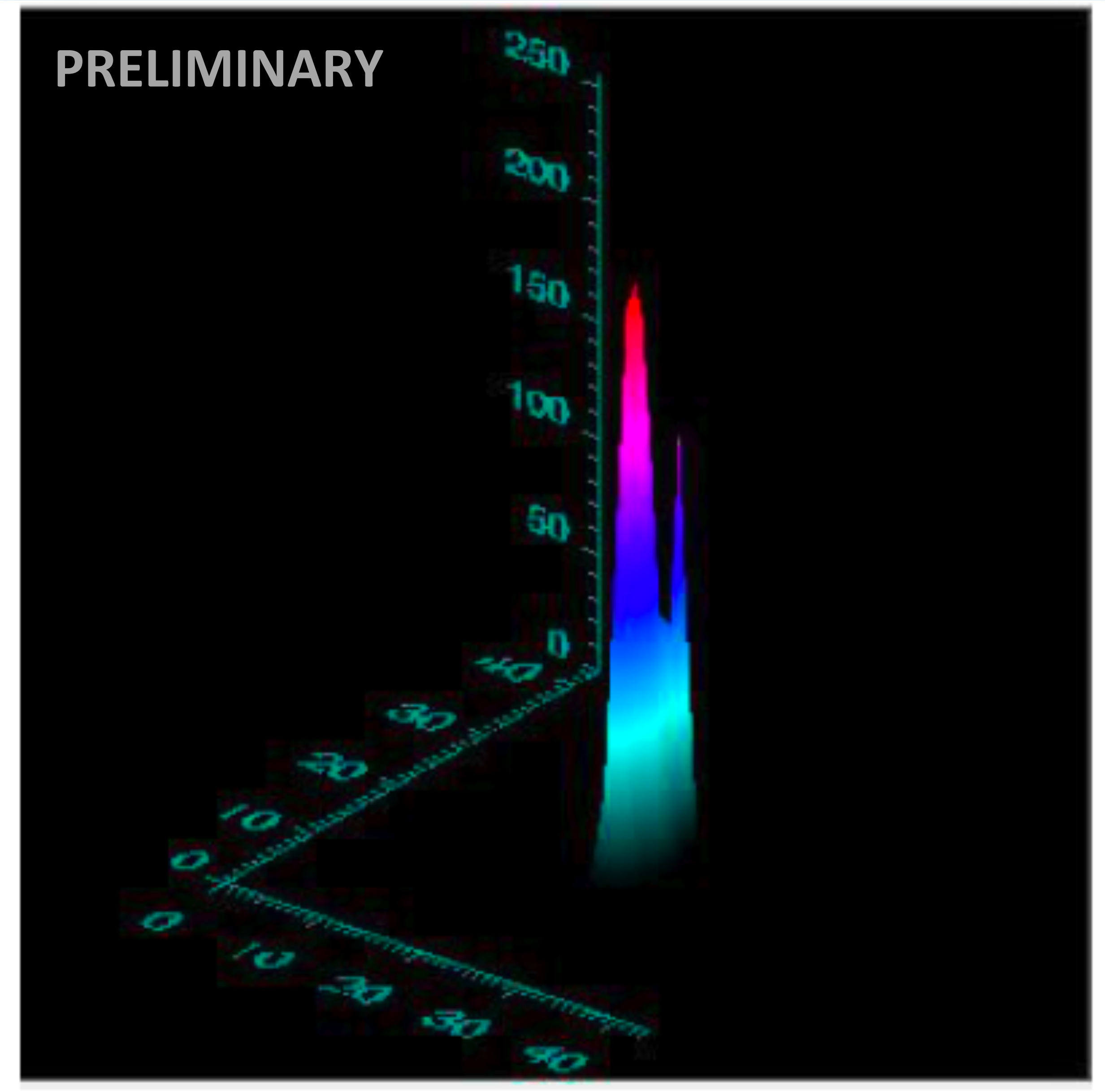
ASTRI Mini-Array

## UHECR

More than 99% of the observable component is hadronic in nature, it is recorded during normal observations and it could be used to perform UHECR direct measurements. The more efficient method for investigating heavy nuclei relies on the identification of a **single high intensity pixel in the camera images**, which lies between the reconstructed shower direction and the center of gravity of the shower.

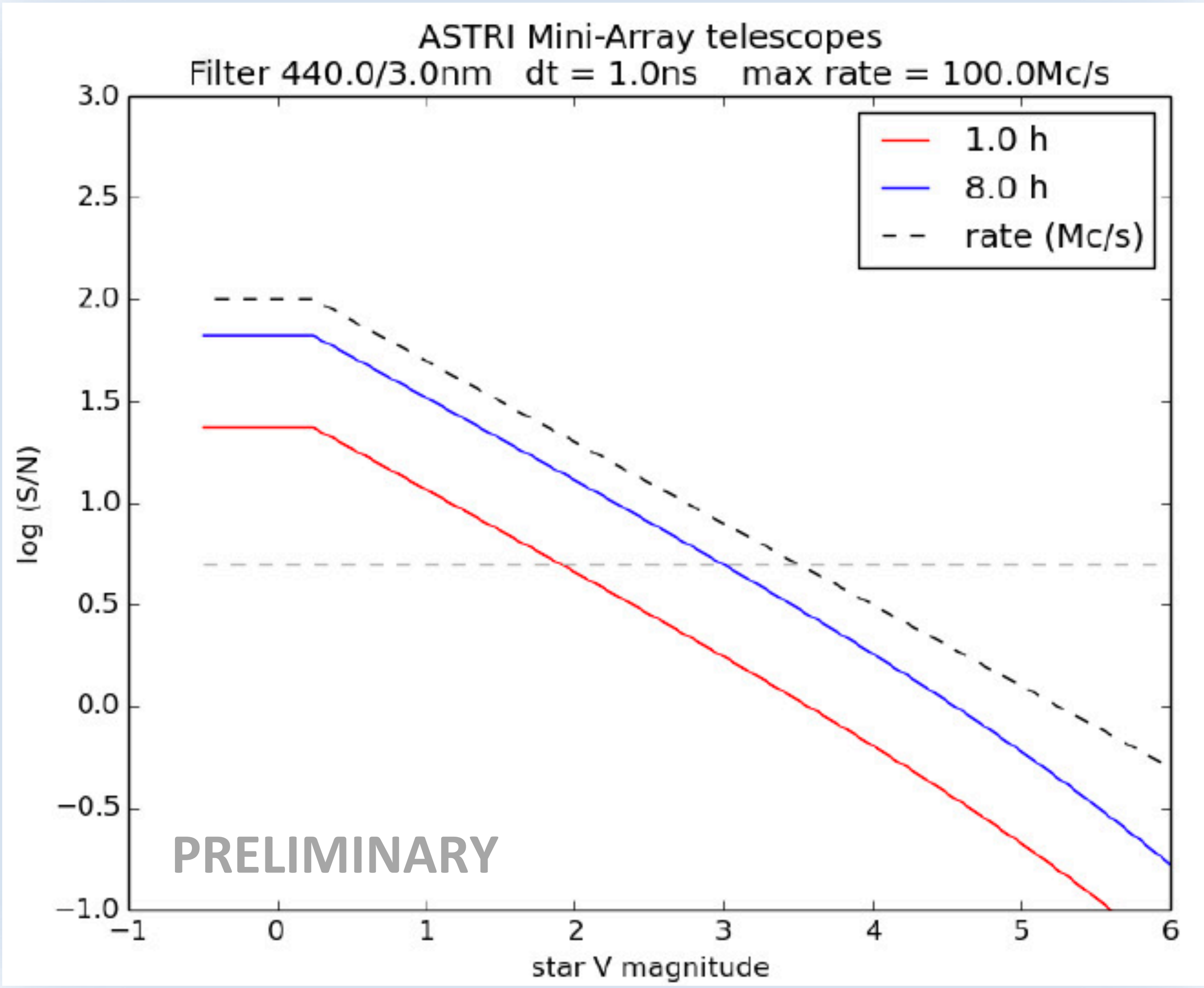
Event recorded in the **ASTRI-Horn camera.**

A single bright pixel is outside the main Cherenkov image.




## Stellar Intensity Interferometry

The ASTRI Mini-Array equipped with a SII instrument will provide the first images of bright Galactic stars with sub-mas angular resolution. **Stars with magnitude V< 3 are observable with the ASTRI Mini-Array telescopes with a S/N> 5, for an exposure time of < 8 hours**. With 240 h/yr we then expect to be able to observe 3-8 bright and 14 average stars per year. **[See Luca's talk]**



# To appear soon

## GAL
## &
## EGAL
## observatory papers

- Resubmitted to internal reviewers
- Waiting for the sign-in procedure

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

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Gamma rays: general
Gamma rays: galaxies
Dark matter

ABSTRACT

The ASTRI Mini-Array is a next-generation system of nine imaging atmospheric Cherenkov telescopes that is going to be built at the *Observatorio 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.

**Contents**



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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 composed by 9 ASTRI Small-Sized Telescopes (SSTs) originally proposed as a precursor for the Southern site of the



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 *Observatorio del Teide* site. The array will be best suited for astrophysical observations in the 1-200 TeV range with an angular resolution of few arc-minutes and an energy resolution of ~ 10%. 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° 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.

**Contents**



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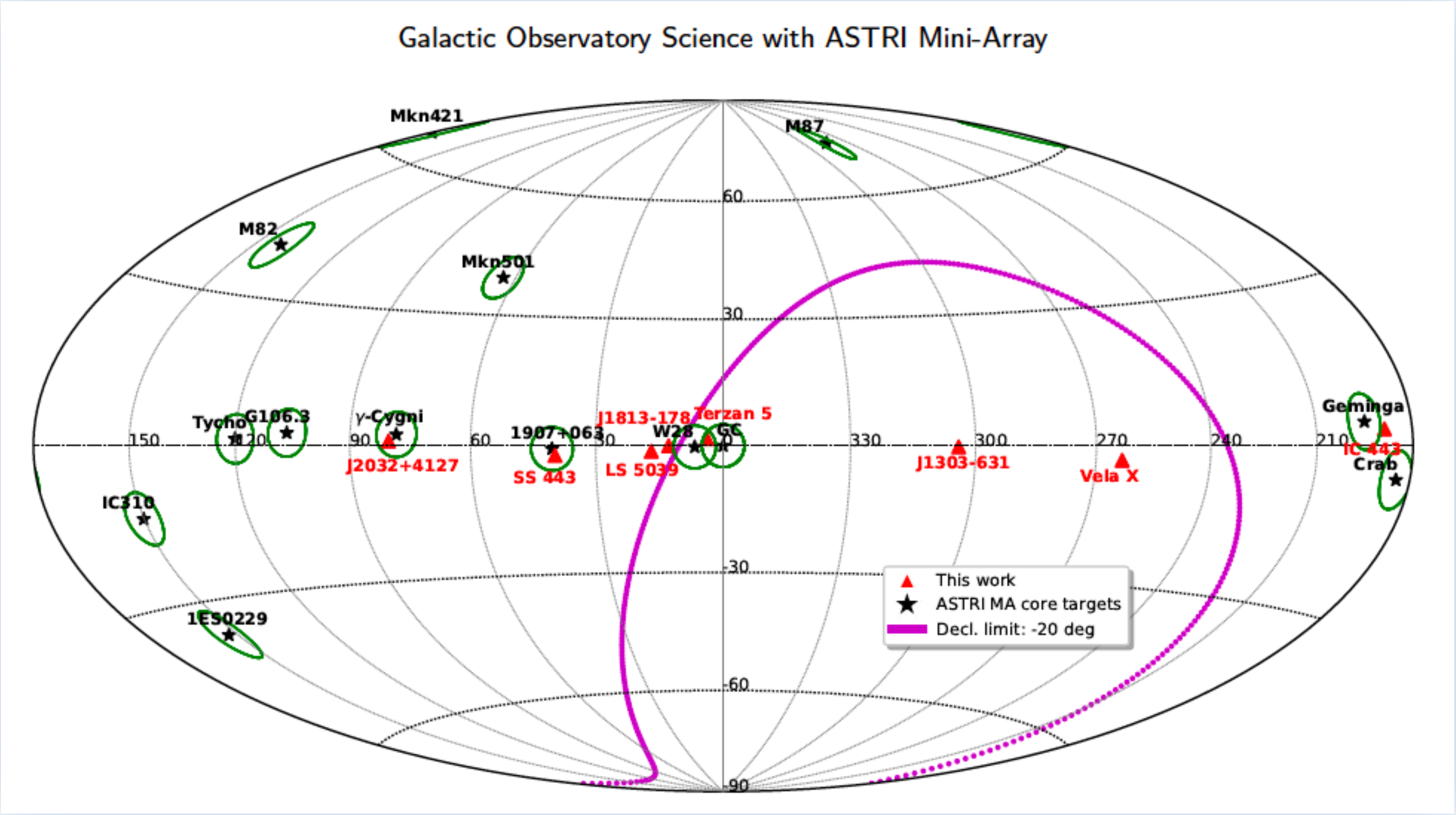
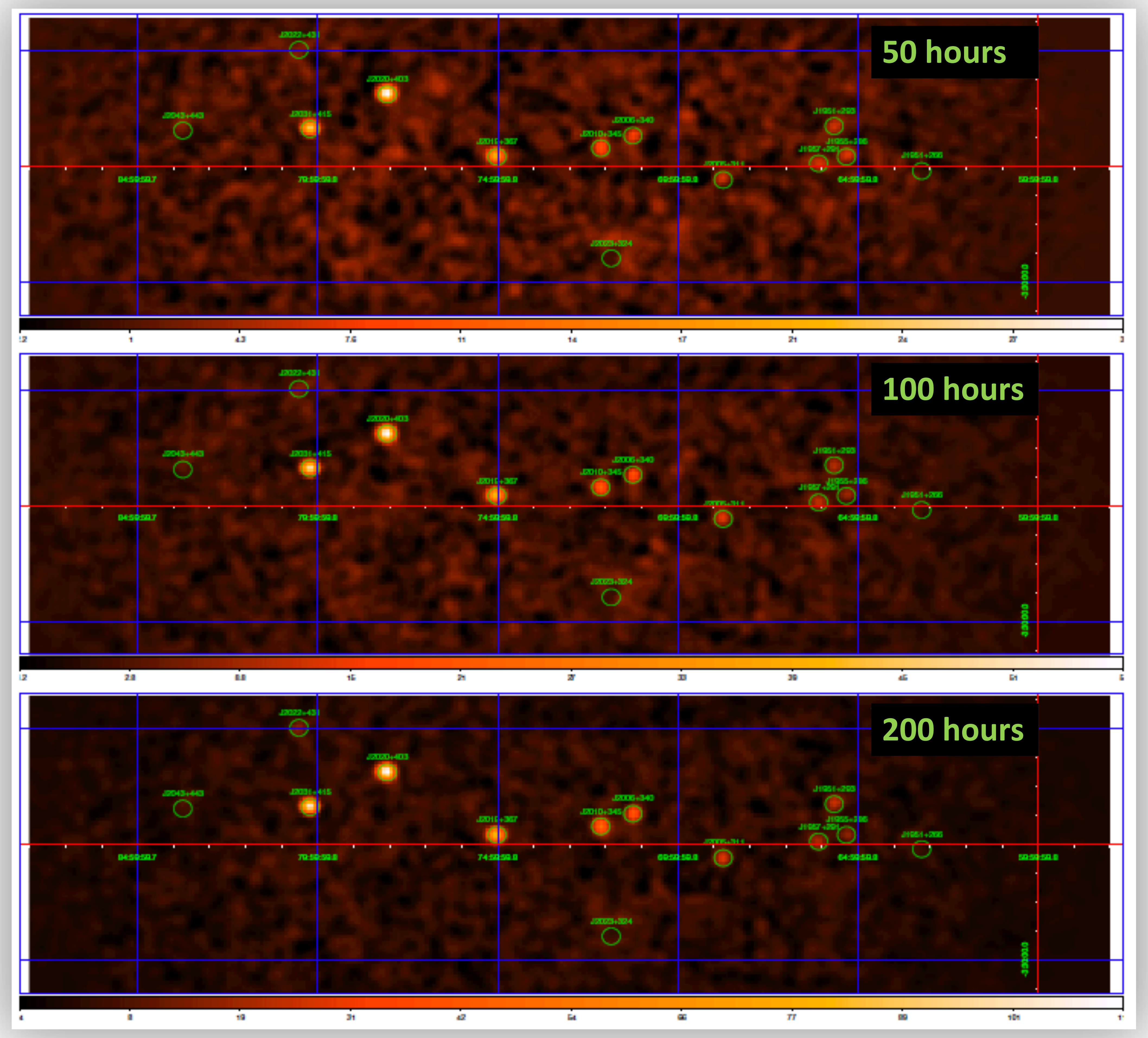
# Glimpse on Galactic Obs. Science



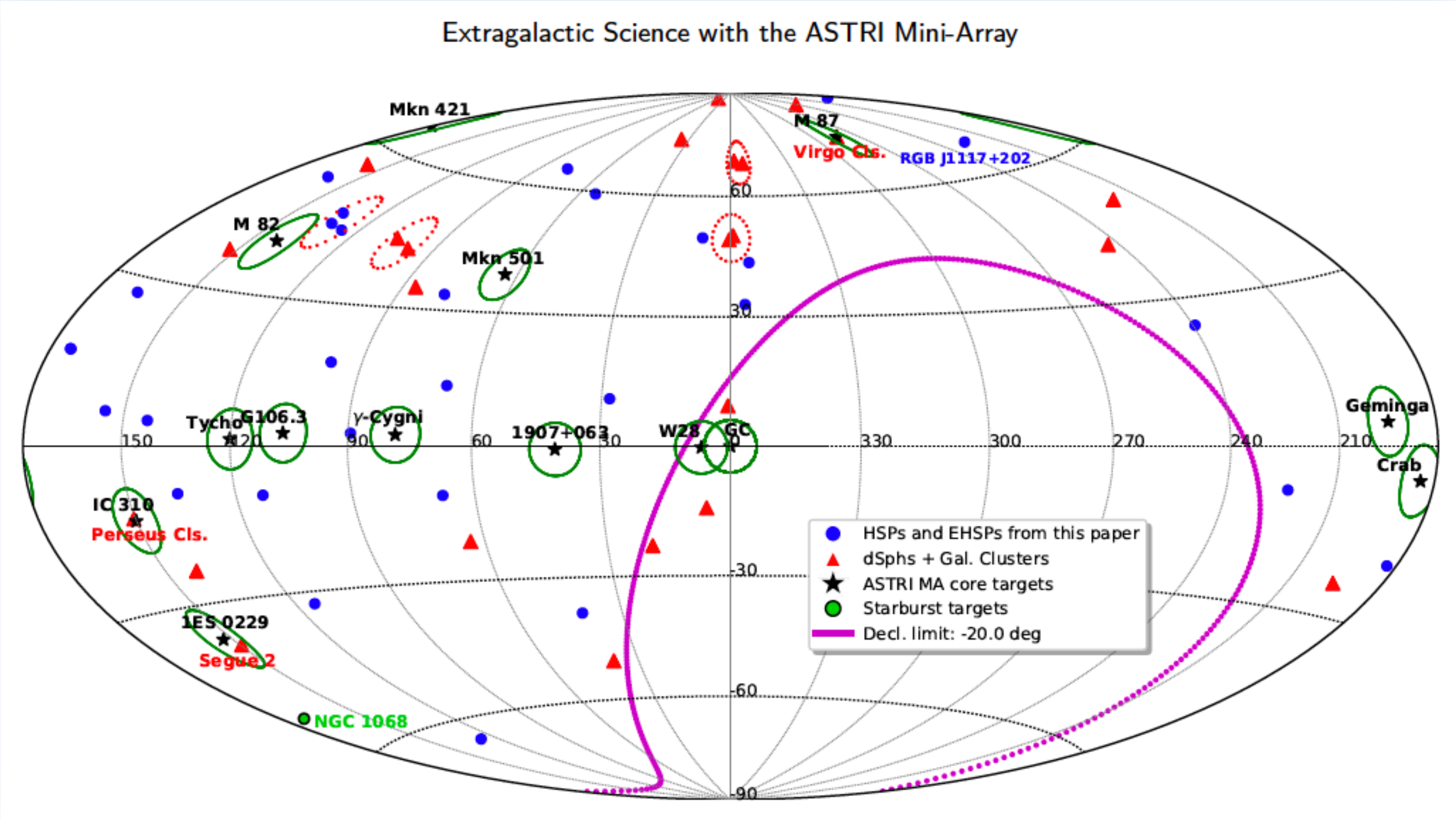

Scan of the Cygnus Region at different $T_{exp}$

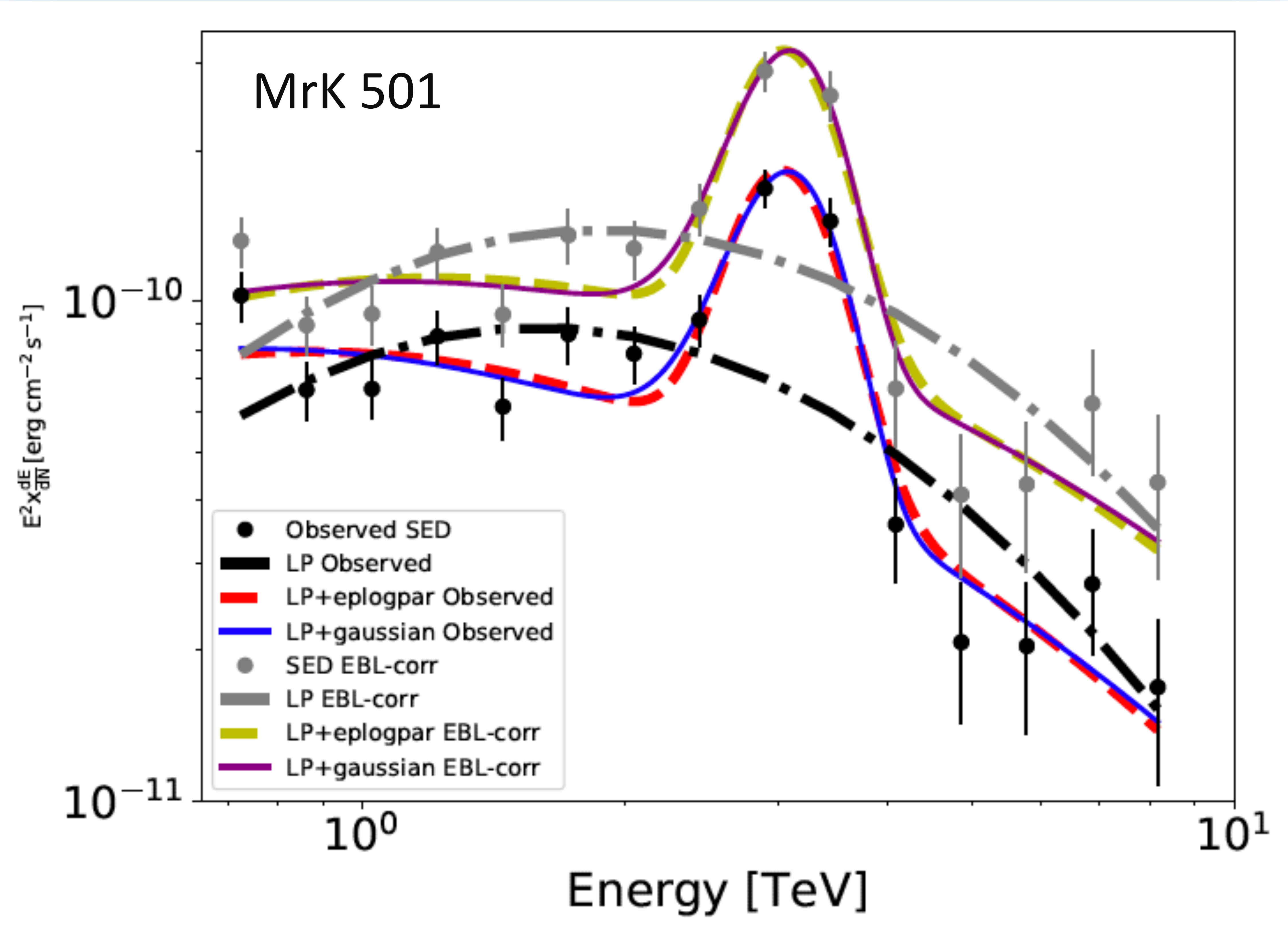
Possible topics

- Gamma-ray binaries
- Micro-quasars
- Peculiar PWNe and SNRs
- Serendipitous sources
- **Galactic Plane scans**

# Glimpse on Extra-galactic Obs. Science

Mini-Array




Possible topics

- TeV emission from Seyferts
- Constraints on dark matter
- Extreme blazars
- Serendipitous sources
- **Newly-discovered spectral features**

1 h of simulated data taking clearly shows the ability of the ASTRI Mini-Array to fully detect a spectral feature of the type hinted in the MAGIC data [MAGIC Collaboration, 2020. A&A 637, A86]

# Potential VHE synergies

- **MeerKat and ASCAP** (SKA precursors in the South) will allow 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. **Several telescopes are also accessible at the IAC site** (Las Cumbres Global Observatory, the STELLA Robotic telescopes, the PIRATE telescope, the Liverpool Robotic Telescope and the Gran Telescopio de Canarias). The **WEBT Consortium** is dedicated to the observation of blazars in the radio, millimetre, infrared and optical wavelength, fundamental for blazar SEDs
- **INTEGRAL** and **NuSTAR** will allow us to complement and extend the spectral performance of **eROSITA**, **XMM-Newton** and **Chandra**, while **IXPE** will open the X-ray polarimentry window
- **Swift, AGILE** and **Fermi** will be extremely important for their large FoV and for the Swift ability to promptly react to transients

# 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**

- **Particle showers arrays (PSAs)** detected several sources with **photons up to several hundreds of TeV**. 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

# 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