100 TeV Gamma-Ray Observation with Extensive Air Shower Arrays

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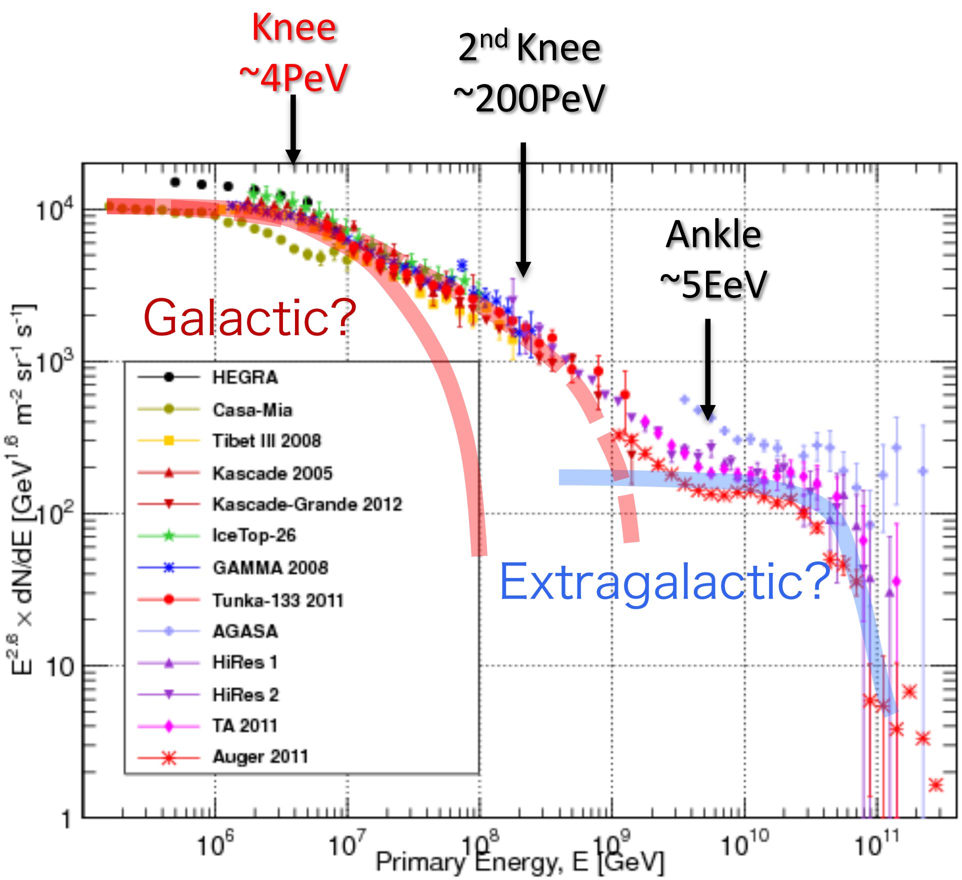
Outline

- Introduction
- Recent results:
  - Tibet results
  - HAWC results
- How to identify PeVatron?
- Projects in southern hemisphere

Galactic Cosmic-Ray Origin



Gaisser et al. Front.Phys.(Beijing) 8 (2013) 748

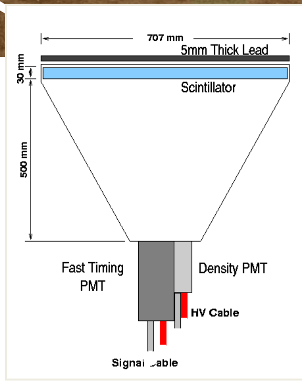
- ✓ Cosmic-ray origins of Knee
  SNR?? Galactic Center?
  → PeVatrons

- ✓ Gamma-Ray Observation
  PeV protons produces
  ~100 TeV γ rays via π^0 decay
  (p + ISM → π^0 → 2γ)
  → Hard spectral index (–2) beyond 100 TeV (+ Molecular Cloud)

Different features from
Inverse Compton γ rays by HE electrons

100 TeV energy window is a key to identify Galactic CR origins!

Tibet Air Shower Array



- Site: Tibet (90.522°E, 30.102°N) 4,300 m a.s.l.

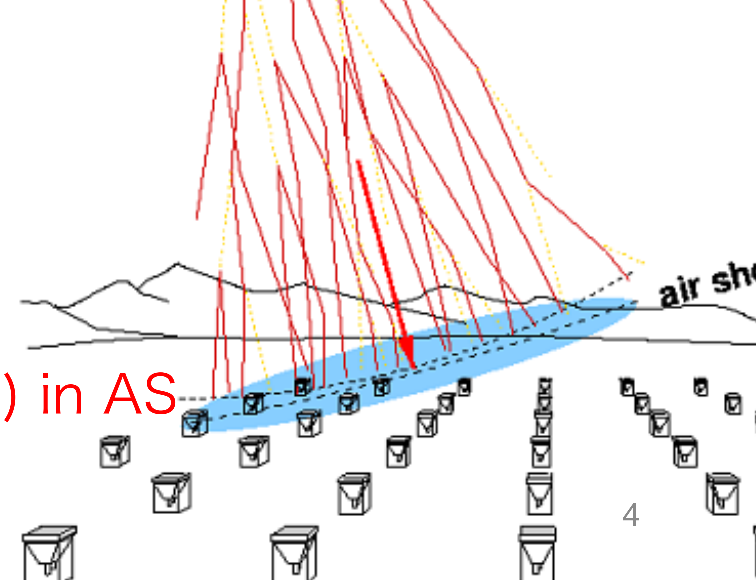
<u>Present Performance</u>

# of detectors	0.5 m² x 597
Covering area	~65,700 m²
Angular resolution	~0.5°@10TeV γ
	~0.2°@100TeV γ
Energy resolution	~40%@10TeV γ
	~20%@100TeV γ

→Observation of secondary (mainly $e^{+/-}$, γ) in AS

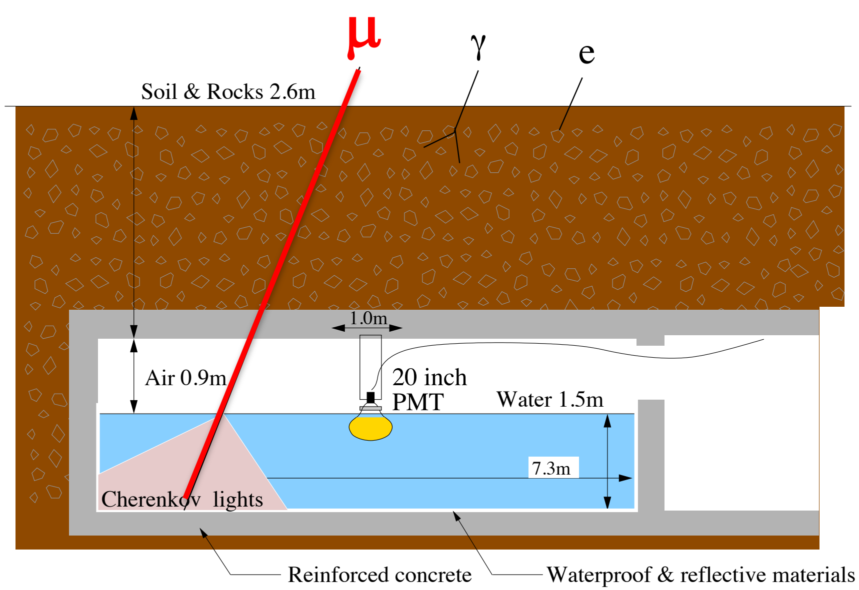
Primary energy : 2nd particle densities

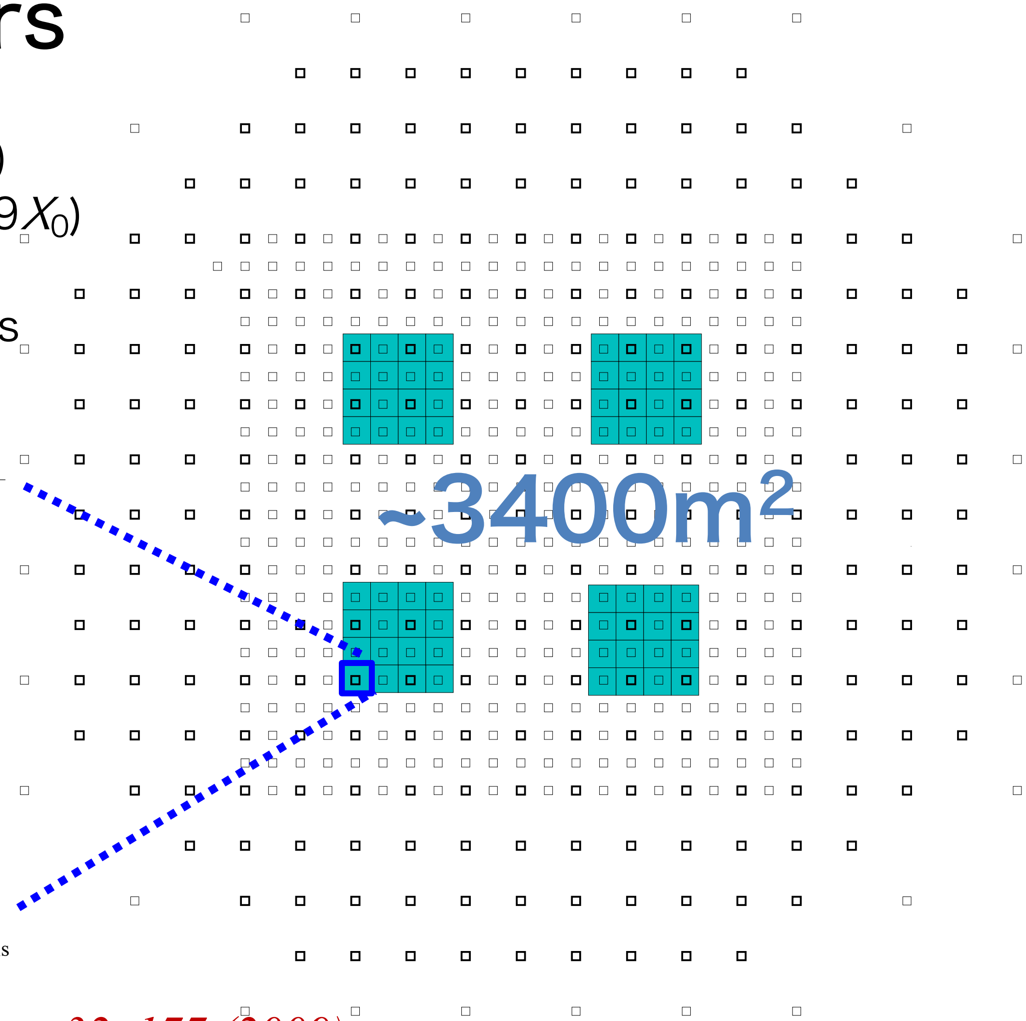
Primary direction : 2nd relative timings



Underground Water Cherenkov Muon detectors

- ✓ 4 pools, 16 units / pool
- ✓ 54m^2 in area ×1.5m in depth (water)
- ✓ 2.4m soil overburden (~515g/cm^2 ~9X_0)
- ✓ 20”ΦPMT (HAMAMATSU R3600)
- ✓ Concrete pools + white Tyvek sheets





Basic idea: T. K. Sako et al., Astropart. Phys. 32, 177 (2009)

Measurement of # of μ in AS → γ／CR discrimination

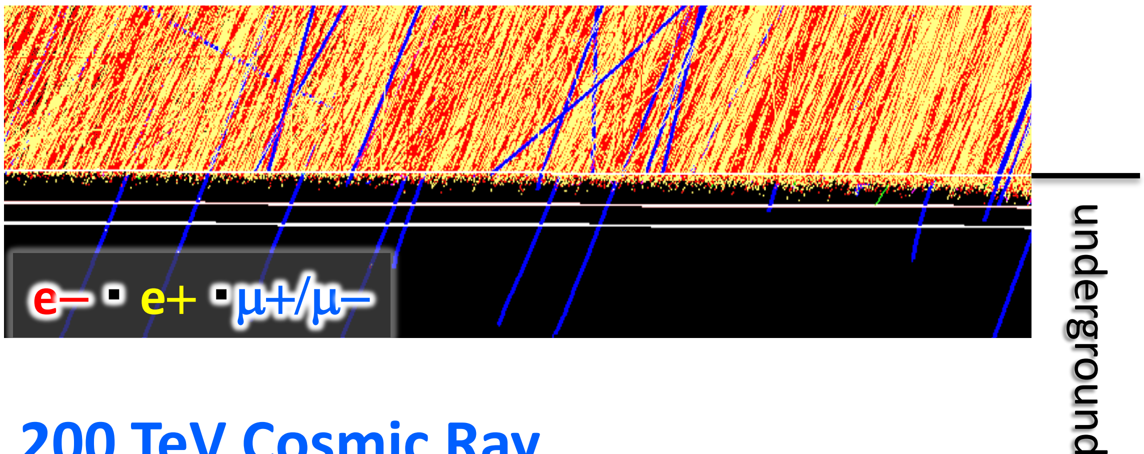
DATA: February, 2014 - May, 2017 Live time: 719 days

p/γ Separation

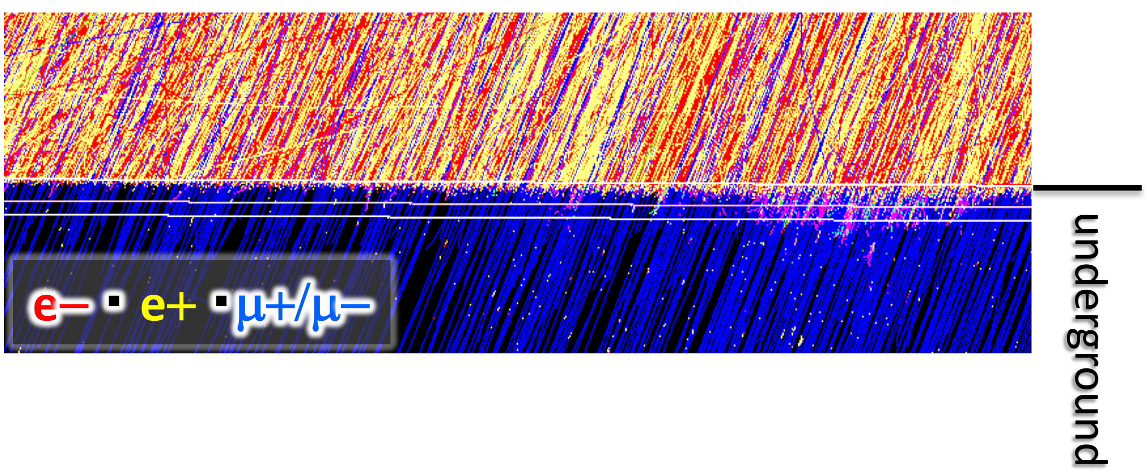
γ−ray induced AS → Muon less

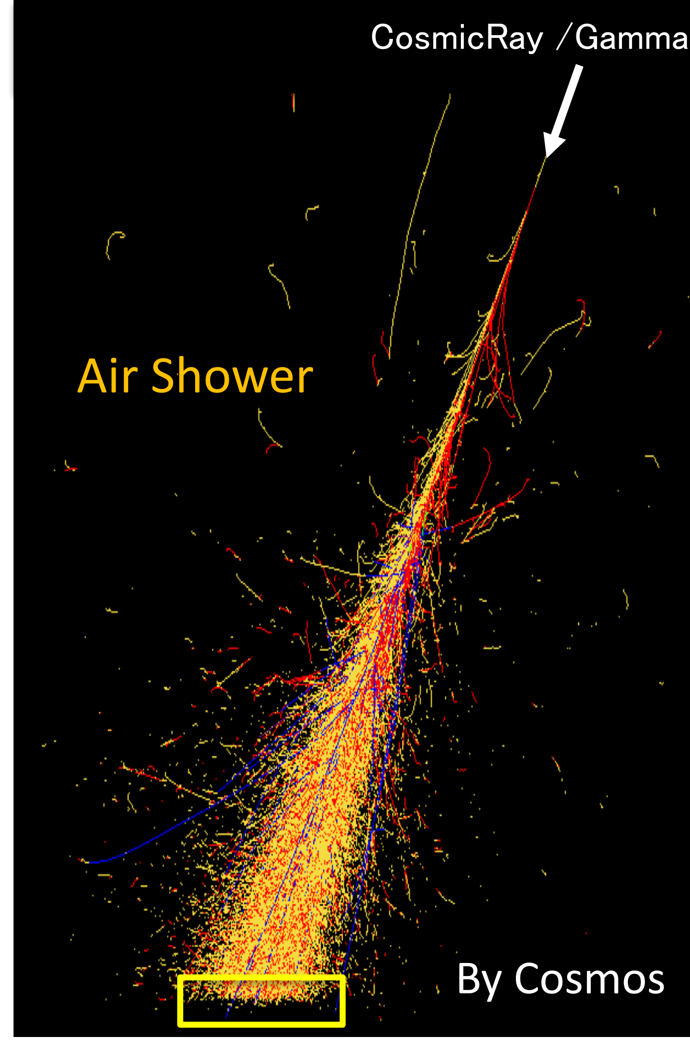
Muons penetrate to underground

200 TeV Gamma Ray



200 TeV Cosmic Ray





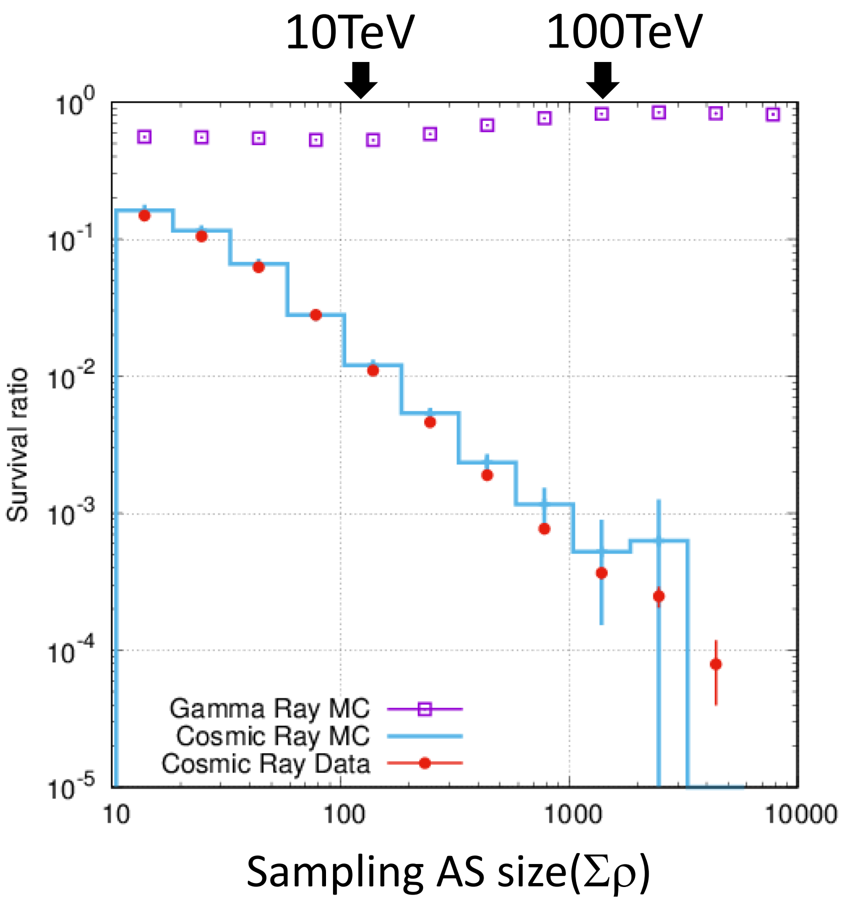
Enlarge around ground

E ($\Sigma\rho$) vs. $N\mu$ Plot

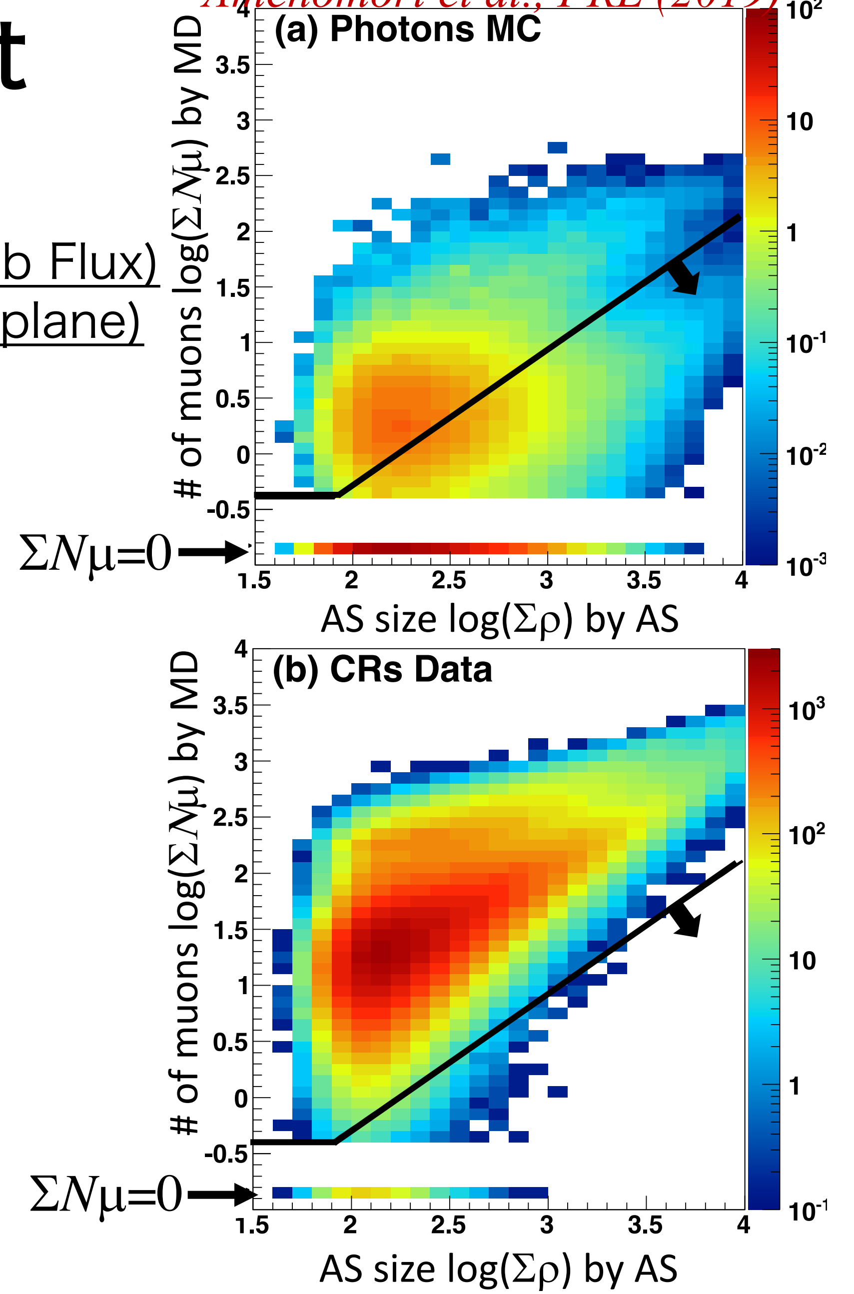
→Optimization of cut

Gamma: MC sample（Crab orbit & Crab Flux)

CR：DATA(excluding Crab and Galctic plane)

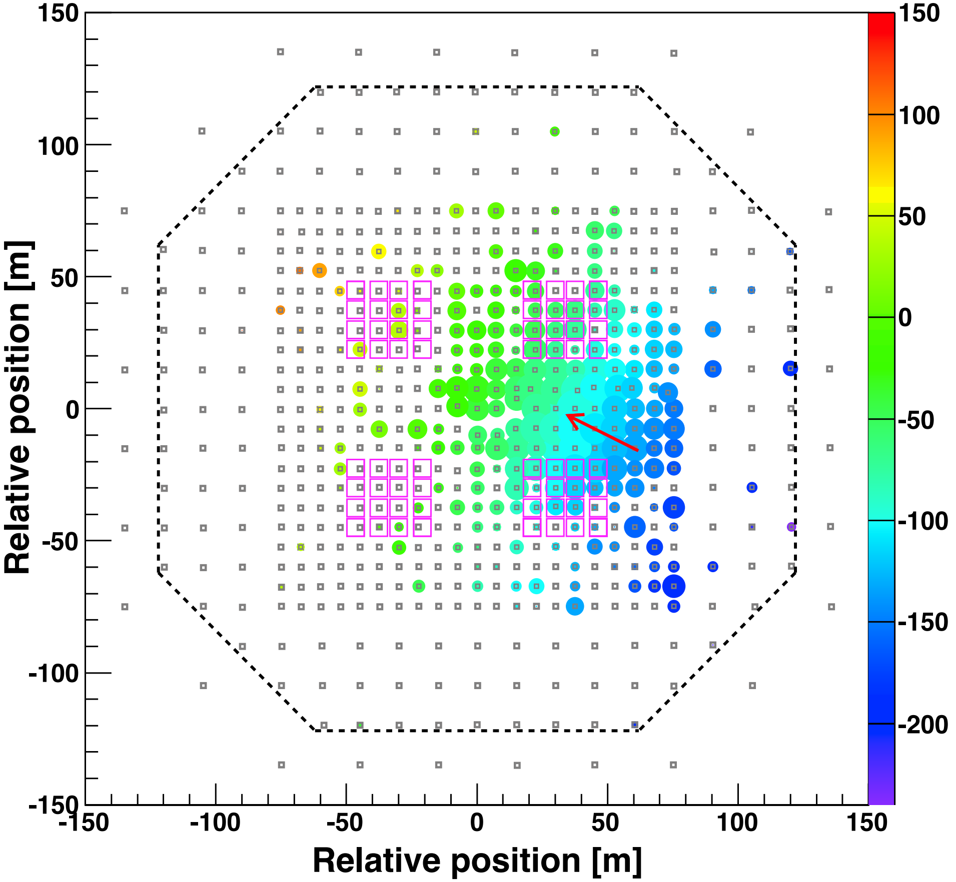


Amenomori et al., PRL (2019)



After Nμ cut,~99.9% CR rejection & ~90% γ efficiency @100 TeV

Gamma-like Event from the Crab

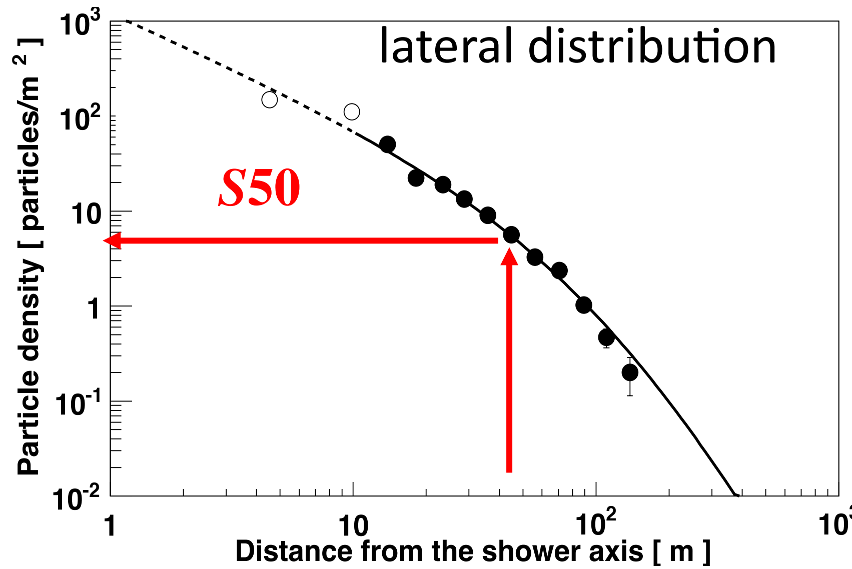


circle size ∝ log(# of detected particles)

circle color ∝ relative timing [ns]

Amenomori et al., PRL (2019)

Kawata et al, Exp. Astro., 44, 1 (2017)



fitting with NKG function

➡ E_{rec} ($S50$, θ)

$\Sigma\rho$ (from AS array) : 3256

$\Sigma N\mu$ (MD) : 2.3

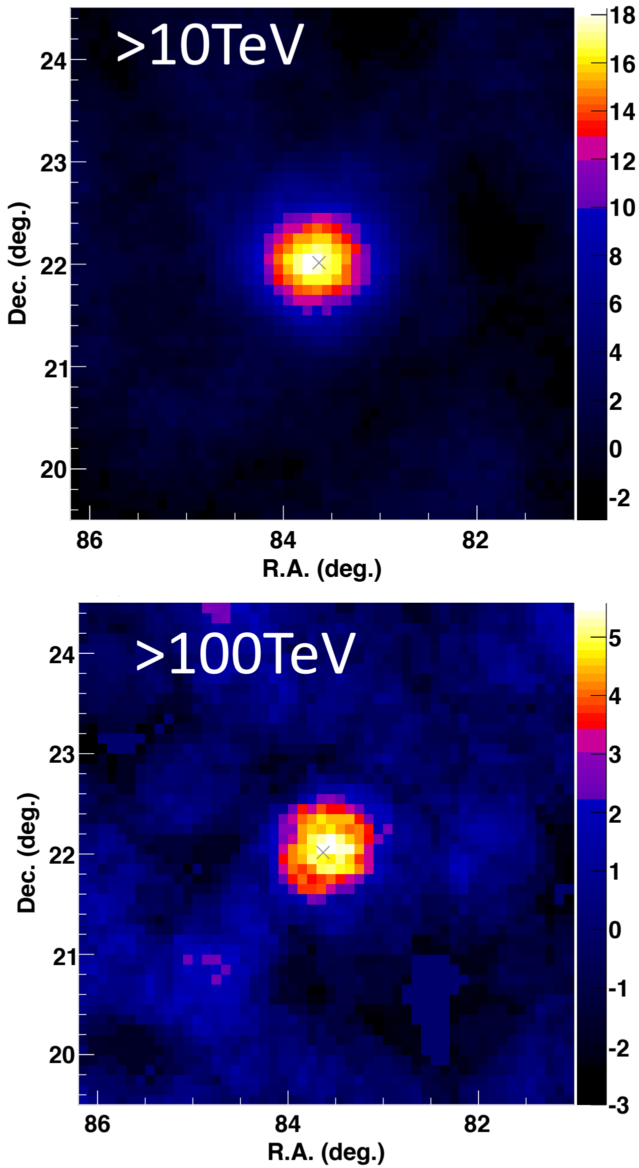
zenith angle : 29.8°

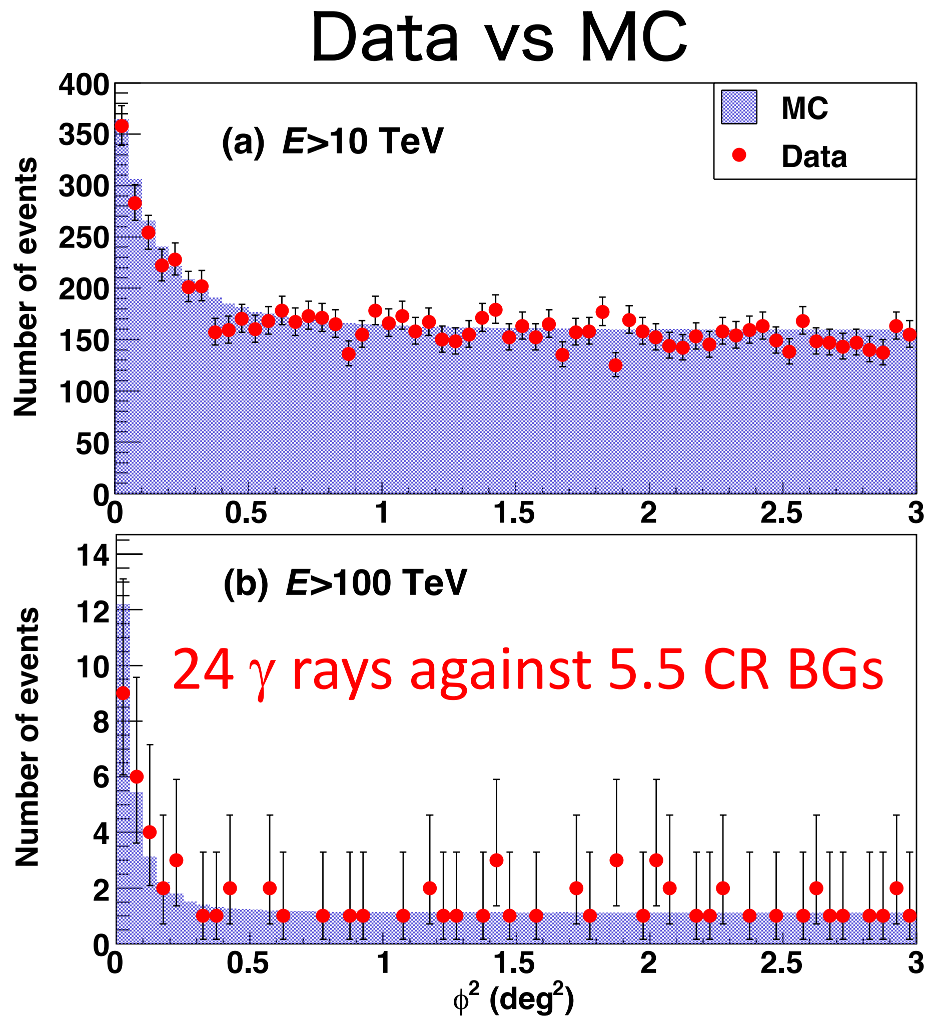
E_{rec} : 251^{+46}_{-43} TeV

S50 improves E resolutions (10 - 1000 TeV)

→ ~40%@10 TeV , ~20%@100 TeV

Gamma-ray Emission from Crab

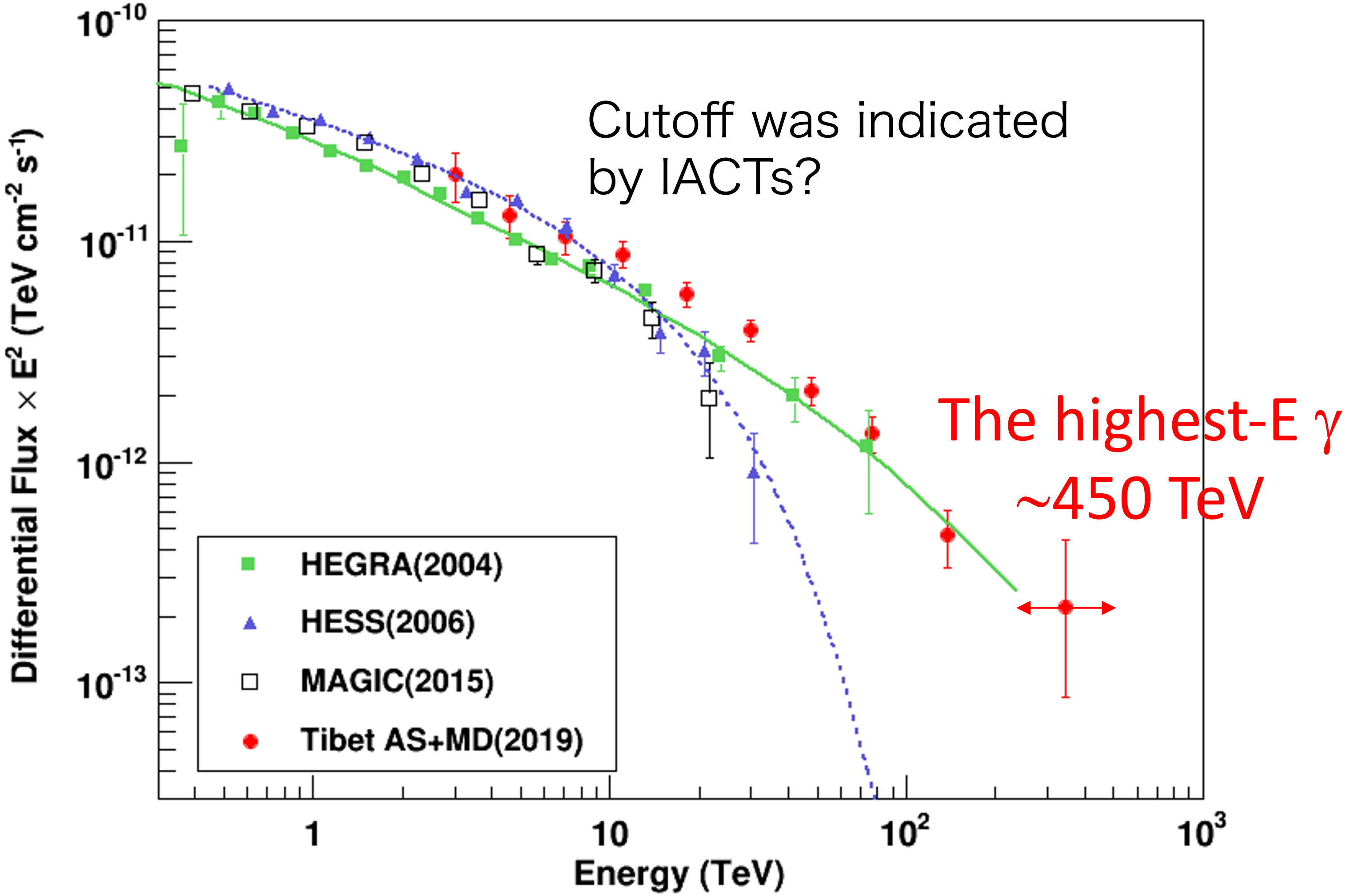




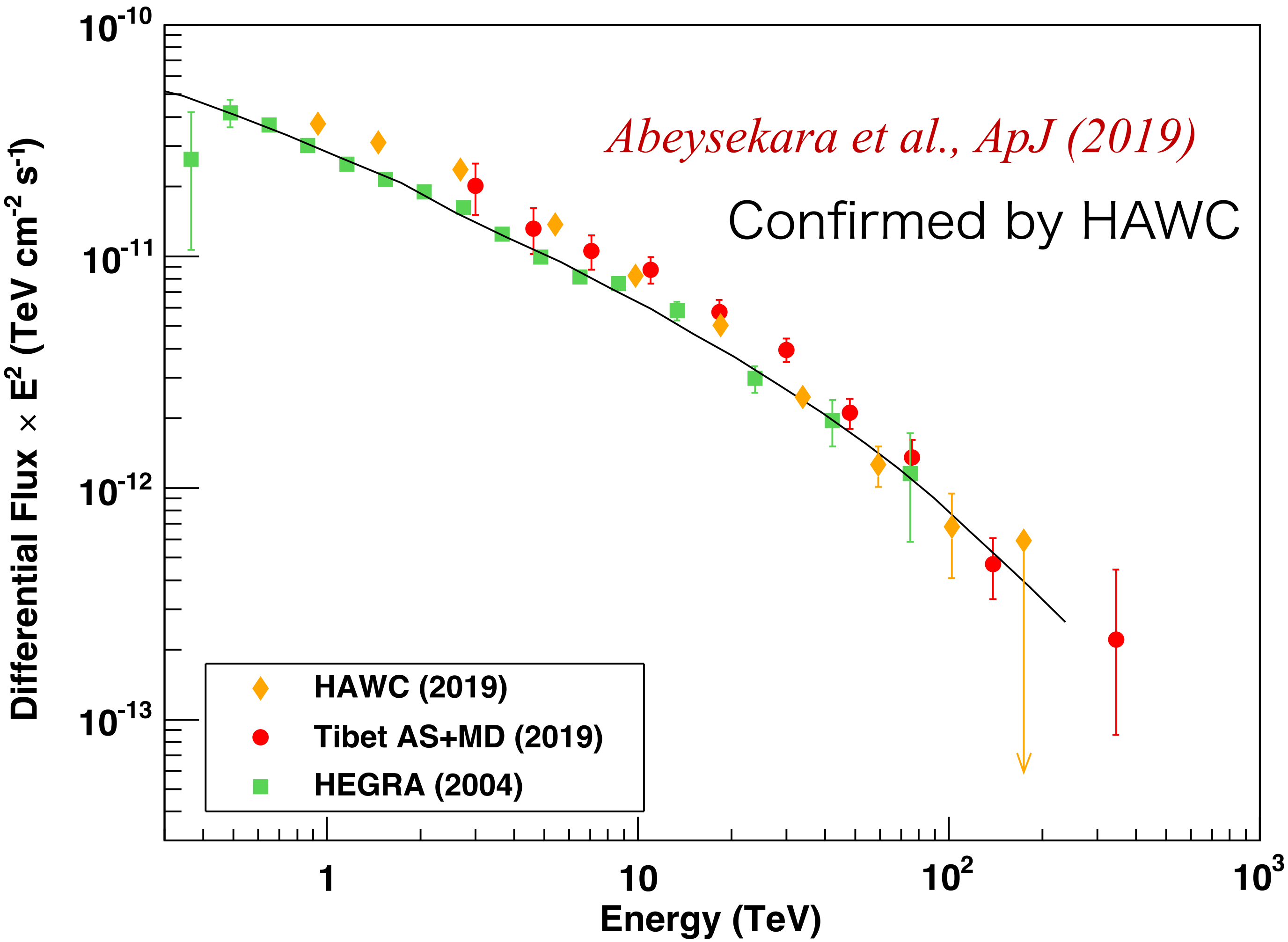
First Detection of Sub-PeV γ (5.6σ)

Amenomori et al., PRL
Supplemental Material (2019)

Energy spectrum of the Crab

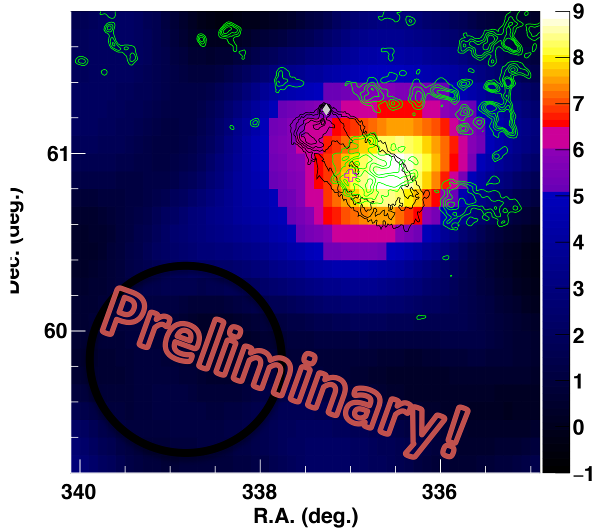


Comparison with HAWC

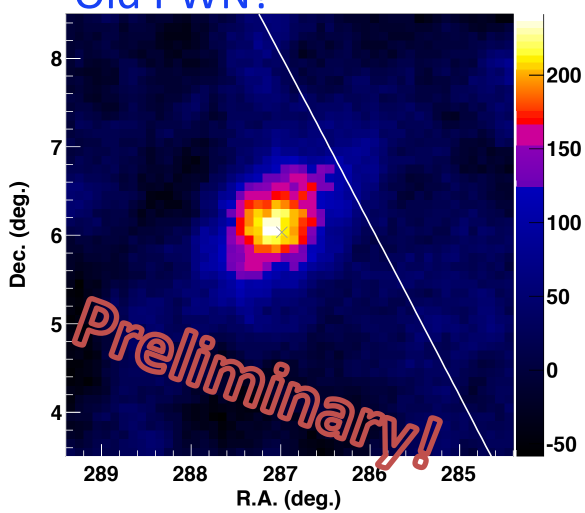


Extended Sources (>10 TeV)

SNR G106.3+2.7
Coincident with MC

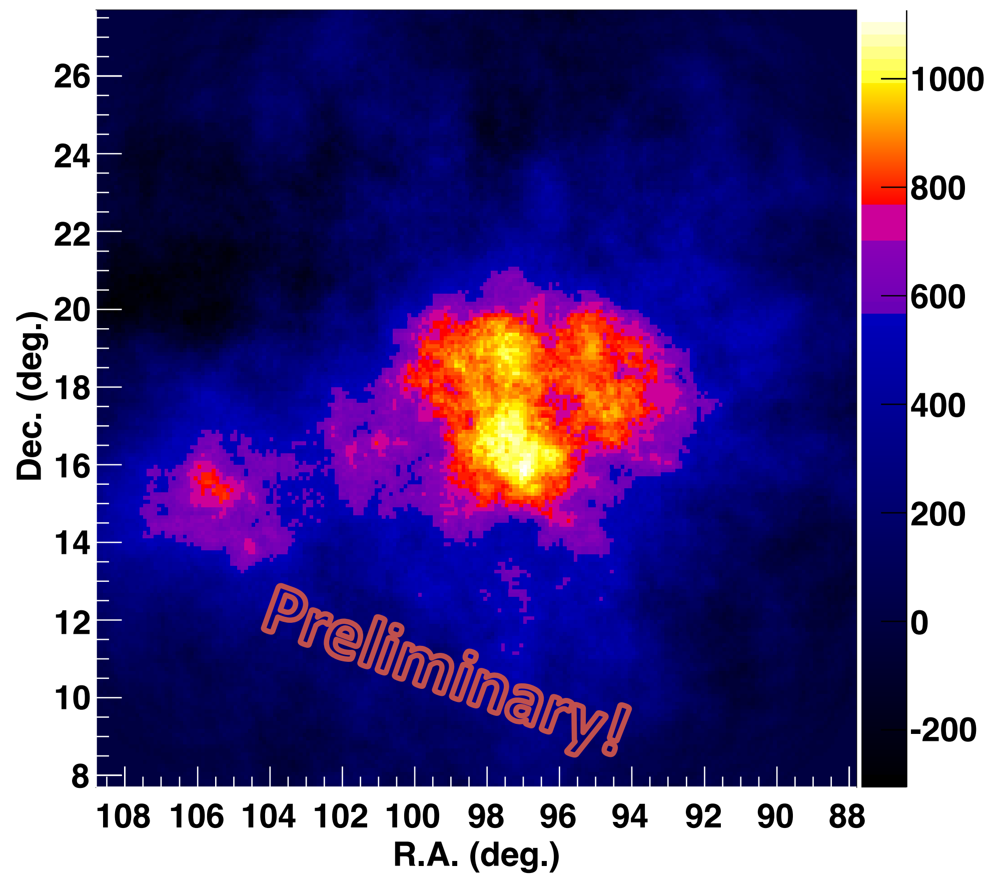


MGRO J1908+06
Old PWN?

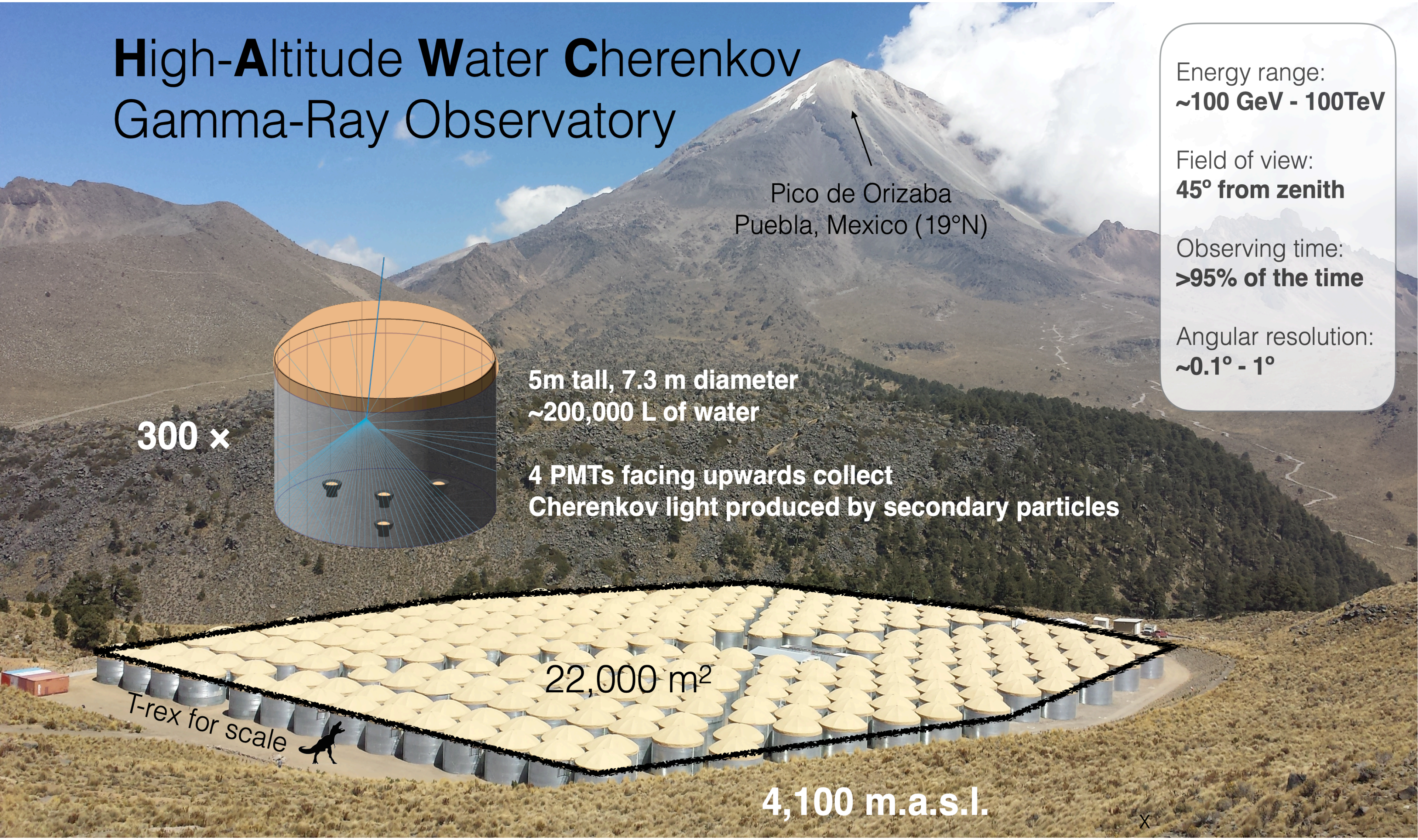


Geminga

Very extended > ~2^{o}



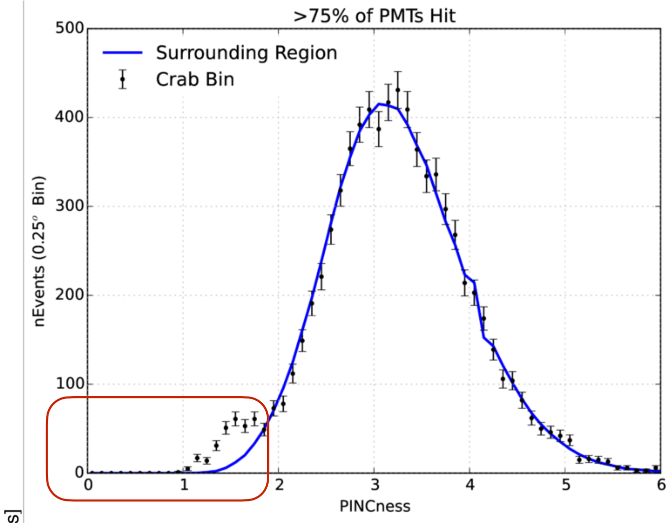
Spectra are under analysis



Site: Sierra Negra, Mexico, 19° N, 4,100 m altitude.

From Slides made by S. Casanova 2020

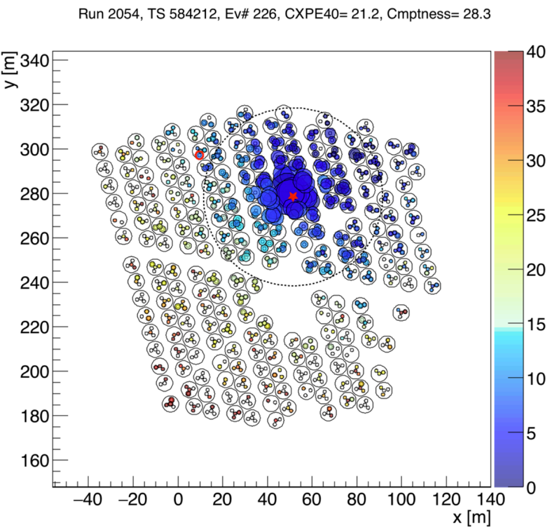
Discrimination γ/CRs in HAWC



>99.9% rejection for large showers

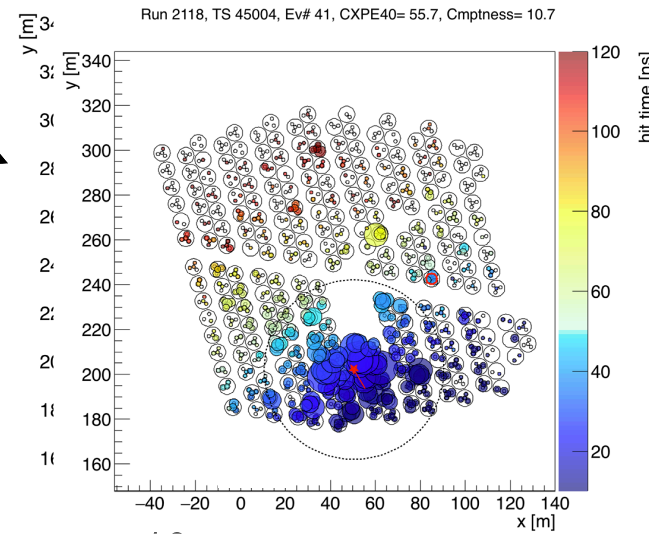
Gamma-like

Likely gamma shower



CR-like

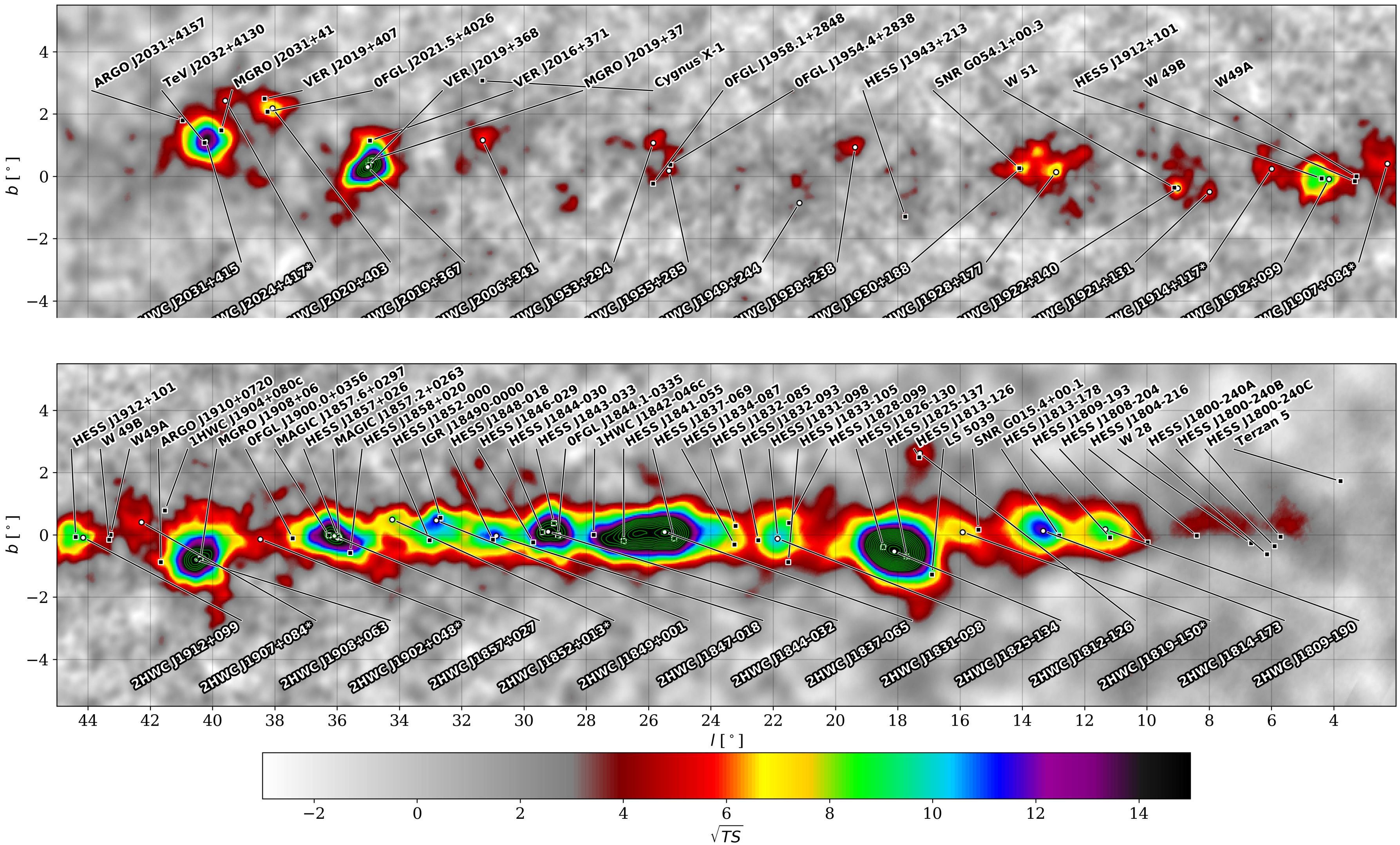
Likely hadron shower



From Slides made by S. Casanova 2020

Galactic Plane with HAWC (~TeV)

2nd HWC Catalog: Abeysekara et al, ApJ (2017)

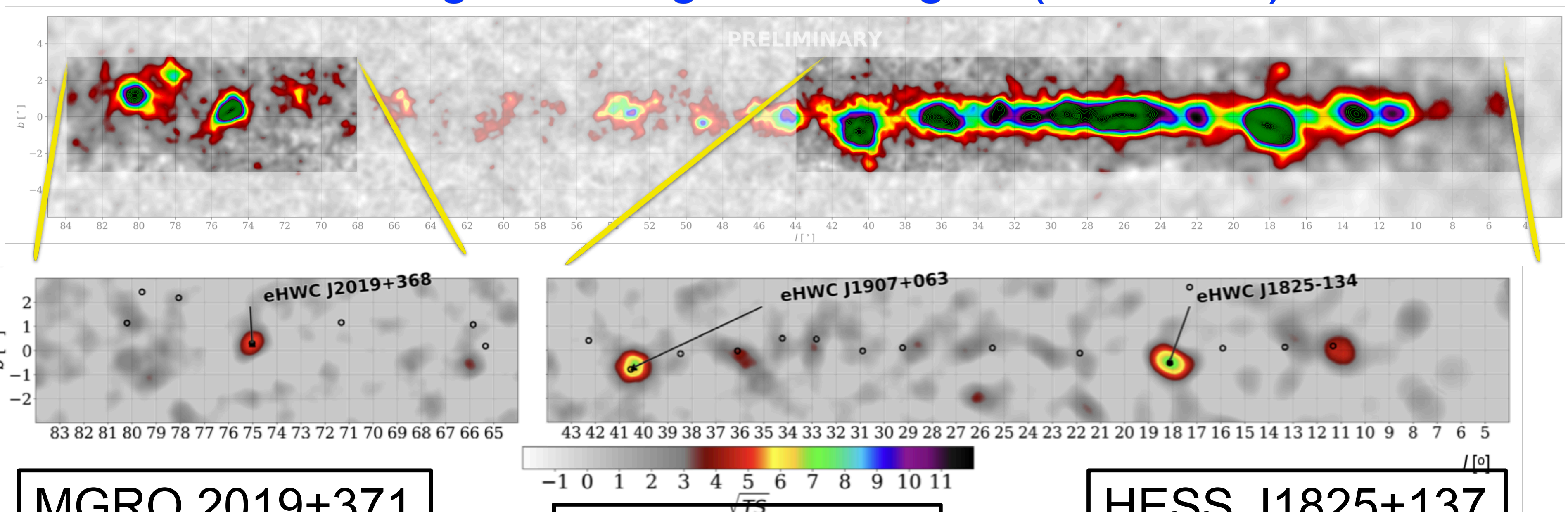


From Slides made by S. Casanova 2020

40 sources of which ¼ are new

100 TeV Observation with HAWC

Pushing to the highest energies (>100 TeV)



MGRO 2019+371

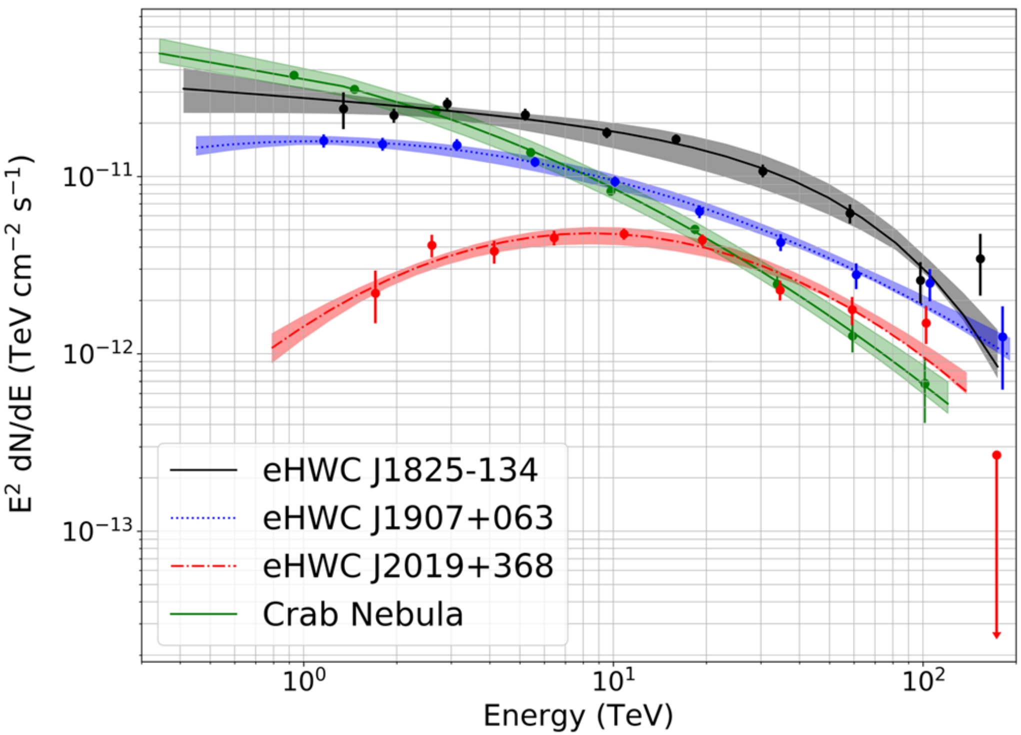
MGRO 1908+06

HESS J1825+137
HESS J1826-130

Abeysekara et al., PRL, 124, 021102 (2020)

From Slides made by S. Casanova 2020

Energy Spectra up to100 TeV



<u>eHWC J1825-134 (PWN?)</u>
PSR J1826-1334
PSR J1826-1256
A few SNRs …

<u>eHWC J1907+063 (PWN?)</u>
PSR J1907+0602
SNR G40.5-0.5

<u>eHWC J2019+368 (PWN?)</u>

✓ Hard spectral index (~ -2)
✓ Extended morphology

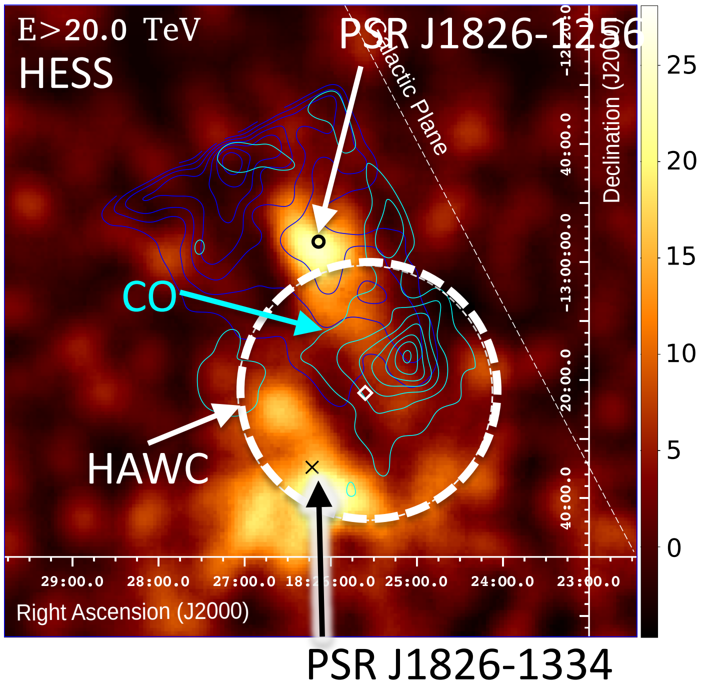
Source name	RA (°)	Dec (°)	Extension > 56 TeV (°)	F (10^{-14} ph cm^{-2} s^{-1})	$\sqrt{\mathrm{TS}}$ > 56 TeV	Nearest 2HWC source	Distance to 2HWC source(°)	$\sqrt{\mathrm{TS}}$ > 100 TeV
eHWC J0534 + 220	83.61 ± 0.02	22.00 ± 0.03	PS	1.2 ± 0.2	12.0	J0534 + 220	0.02	4.44
eHWC J1809 − 193	272.46 ± 0.13	−19.34 ± 0.14	0.34 ± 0.13	$2.4^{+0.6}_{-0.5}$	6.97	J1809 − 190	0.30	4.82
eHWC J1825 − 134	276.40 ± 0.06	−13.37 ± 0.06	0.36 ± 0.05	4.6 ± 0.5	14.5	J1825 − 134	0.07	7.33
eHWC J1839 − 057	279.77 ± 0.12	−5.71 ± 0.10	0.34 ± 0.08	1.5 ± 0.3	7.03	J1837 − 065	0.96	3.06
eHWC J1842 − 035	280.72 ± 0.15	−3.51 ± 0.11	0.39 ± 0.09	1.5 ± 0.3	6.63	J1844 − 032	0.44	2.70
eHWC J1850 + 001	282.59 ± 0.21	0.14 ± 0.12	0.37 ± 0.16	$1.1^{+0.3}_{-0.2}$	5.31	J1849 + 001	0.20	3.04
eHWC J1907 + 063	286.91 ± 0.10	6.32 ± 0.09	0.52 ± 0.09	2.8 ± 0.4	10.4	J1908 + 063	0.16	7.30
eHWC J2019 + 368	304.95 ± 0.07	36.78 ± 0.04	0.20 ± 0.05	$1.6^{+0.3}_{-0.2}$	10.2	J2019 + 367	0.02	4.85
eHWC J2030 + 412	307.74 ± 0.09	41.23 ± 0.07	0.18 ± 0.06	0.9 ± 0.2	6.43	J2031 + 415	0.34	3.07

Abeysekara et al., PRL, 124, 021102 (2020)

100 TeV Sources Resolved by IACTs

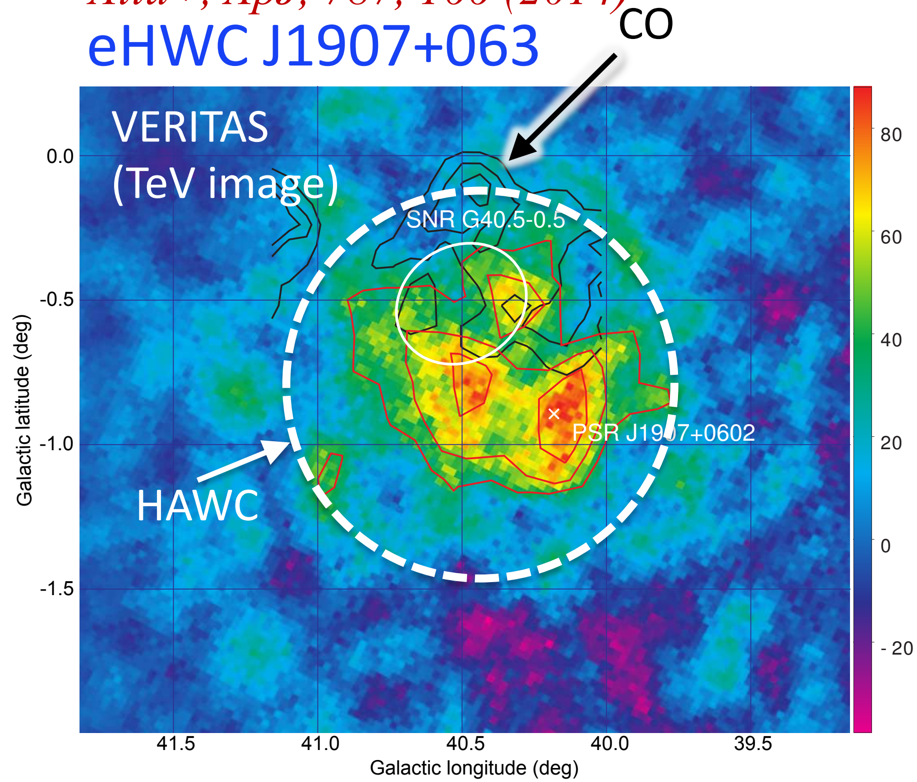
H.E.S.S., A&A, in press (2020)

eHWC J1825-134



Aliu+, ApJ, 787, 166 (2014)

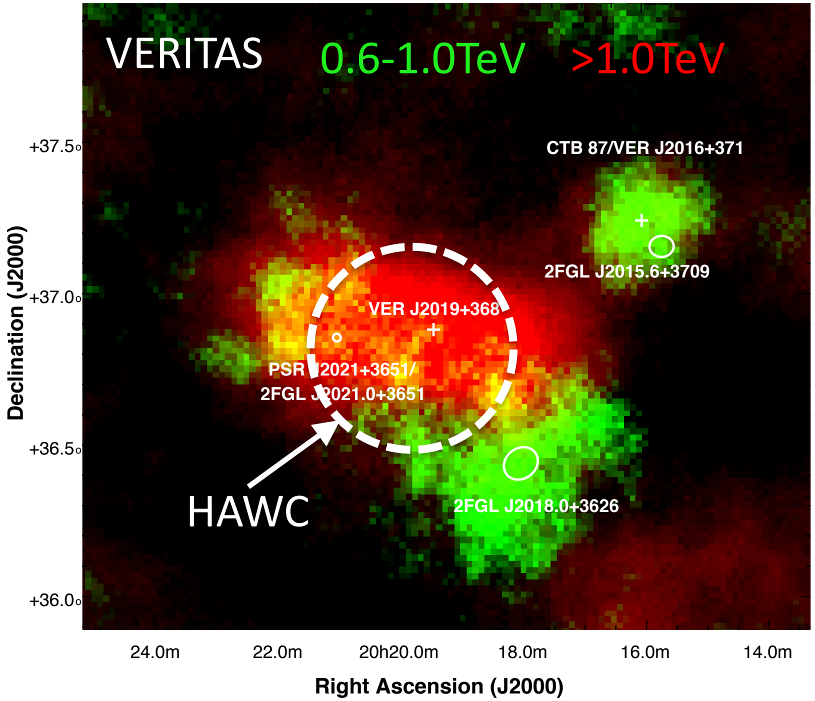
eHWC J1907+063



- ✓ Separated into two or more sources by IACTs
- ✓ Bright region around a pulsar → PWN?
- ✓ SNR is situated near source
- ✓ Molecular clouds (CO) are located near the source
- ✓ Hard spectral index $\alpha = \sim -2$

100 TeV Sources Resolved by IACTs

eHWC J2019+368 (Cygnus region) *Aliu+, ApJ, 788, 78 (2014)*



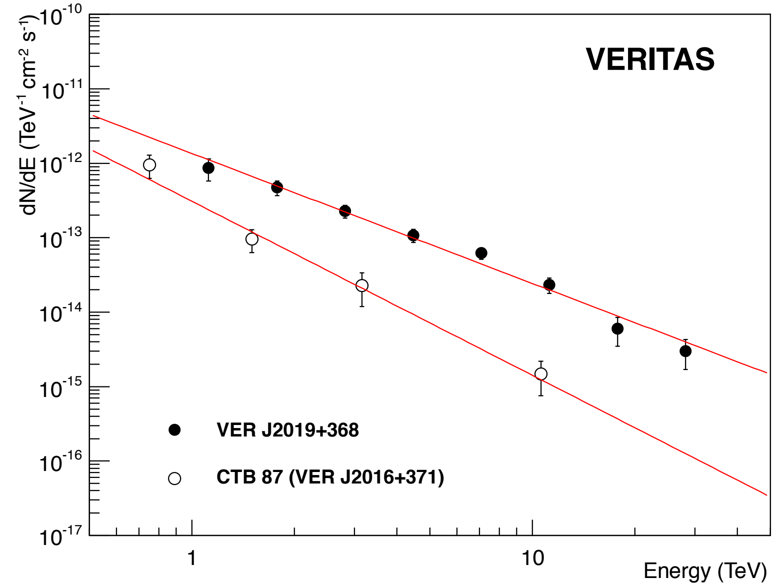


FIG. 3.— Differential energy spectrum of VER J2016+371/CTB 87 and VER J2019+368 as measured by VERITAS. The event excess in each bin have a statistical significance of at least 2σ.

- ✓ Separated into two or more sources by IACTs
- ✓ Bright region around a pulsar → PWN?
- ✓ SNR is situated near source
- ✓ Molecular clouds (CO) are located near the source
- ✓ Hard spectral index $\alpha = \sim -2$

PeVatron Candidate: SNR G106.3+2.7

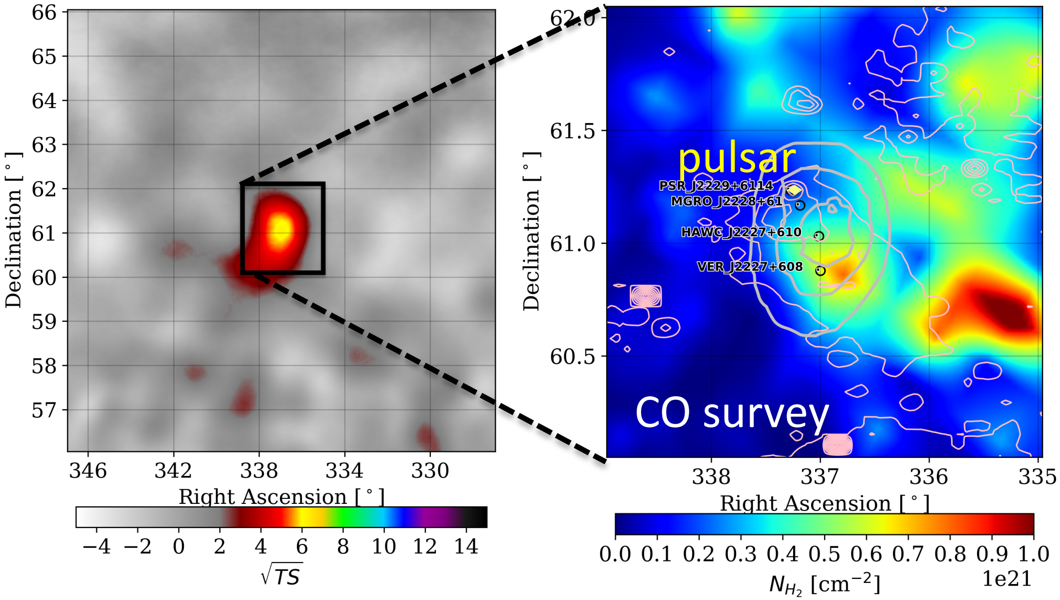
Albert+, ApJL (2020)

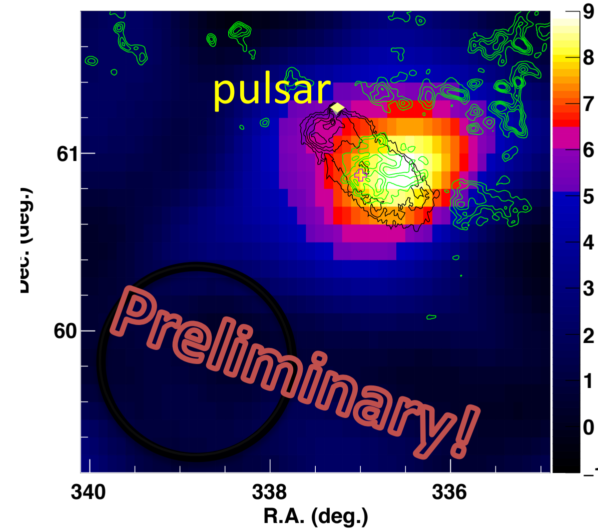
HAWC (>40TeV)

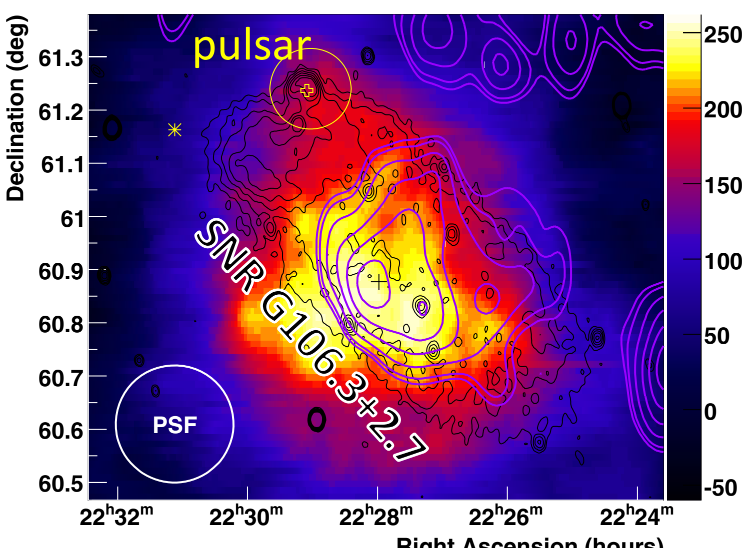
Molecular Clouds

Amenomori+, ICRC2019

Tibet AS+MD(>10TeV)







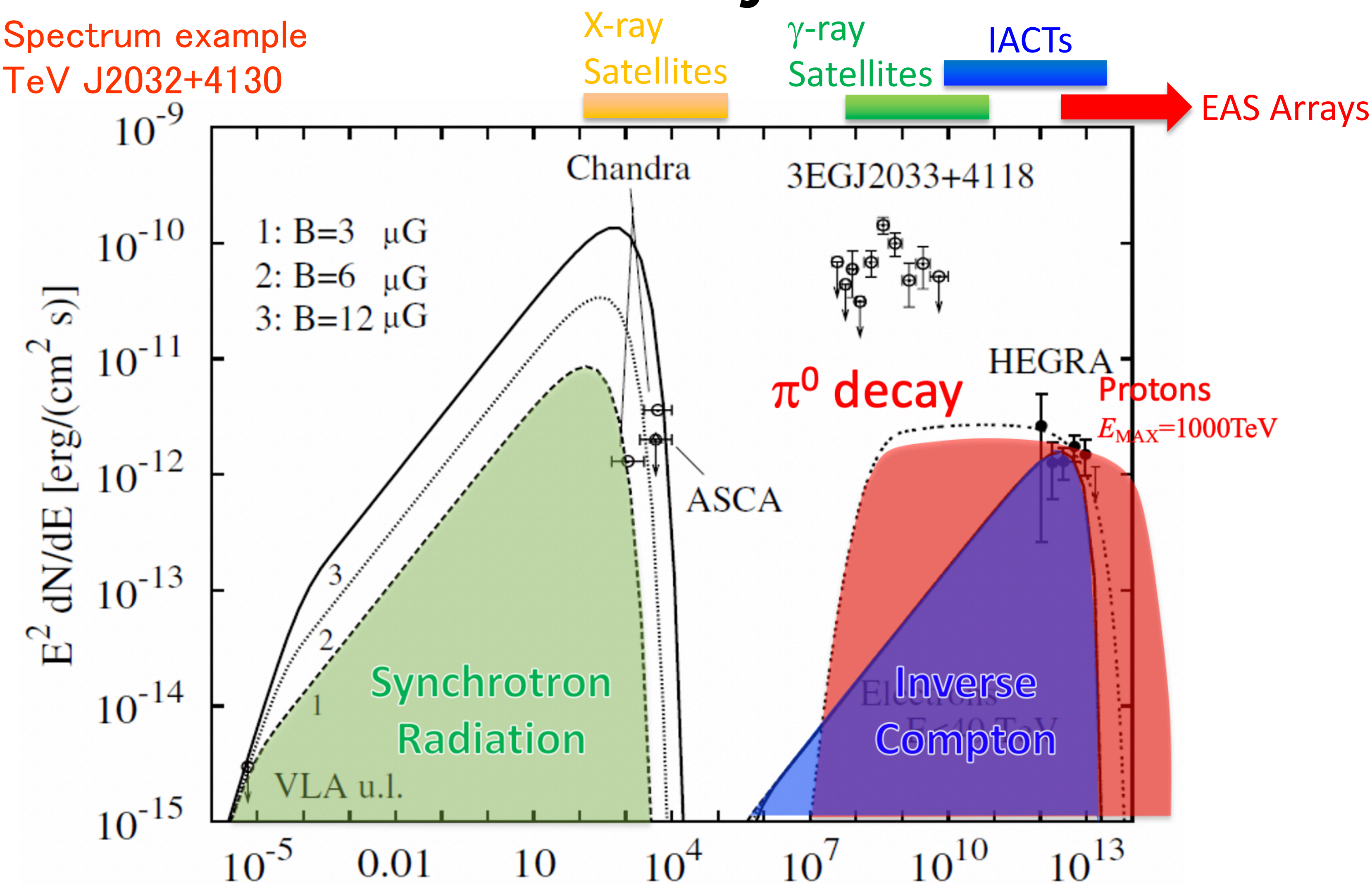
- ✓ Shell-type SNR near the pulsar
- ✓ γ-ray excess is coincident with MC
- ✓ Spectrum extends up to 100 TeV

VERITAS (>TeV)

Acciari+, ApJ (2019)

How to Identify PeVatron

Spectrum example
TeV J2032+4130



Aharonian et al, A&A, 431, 197 (2005)

→ Hard spectral index (–2)
beyond 100 TeV
(+ Molecular Cloud)

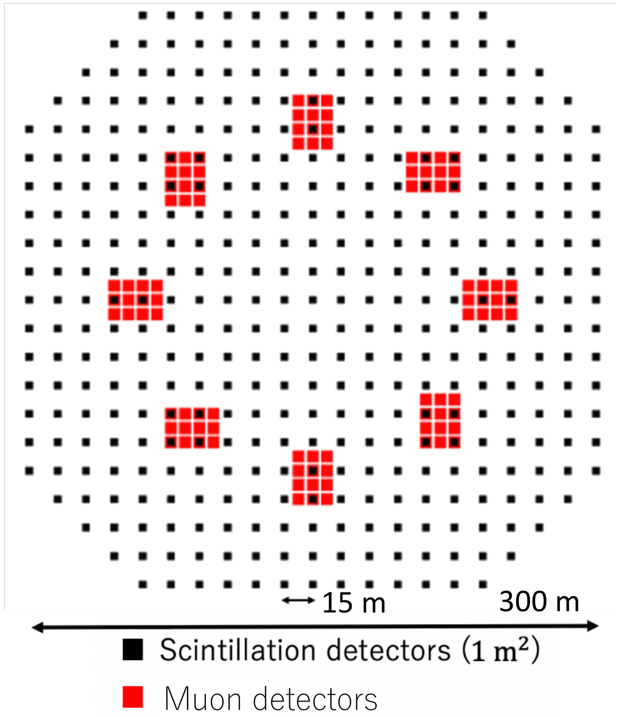
How to Identify PeVatron

- γ-ray beyond 100 TeV by Tibet, HAWC etc. in North,
  ALPACA, SWGO in south will come soon
- Spectral index $\alpha \sim -2$ in TeV by IACTs
- Coincident with molecular cloud observed by radio
- π^0 cutoff around 70 MeV by γ-ray satellites
- Dark in X-ray observation
- Deep observation by IACTs to resolve sources
- Coincident with HE neutrino by IceCube

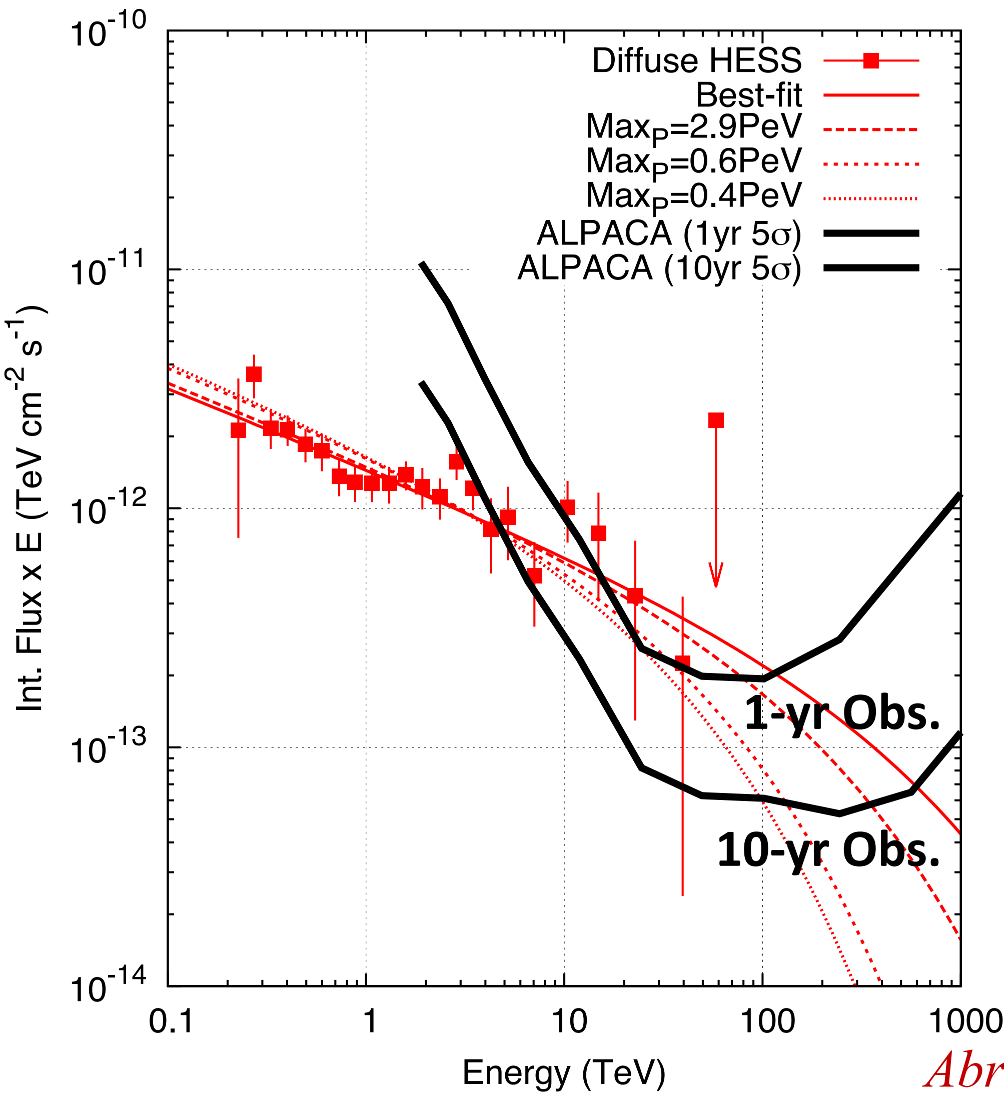
Multi-wavelength Multi-particle Observations

ALPACA Experiment in Bolivia

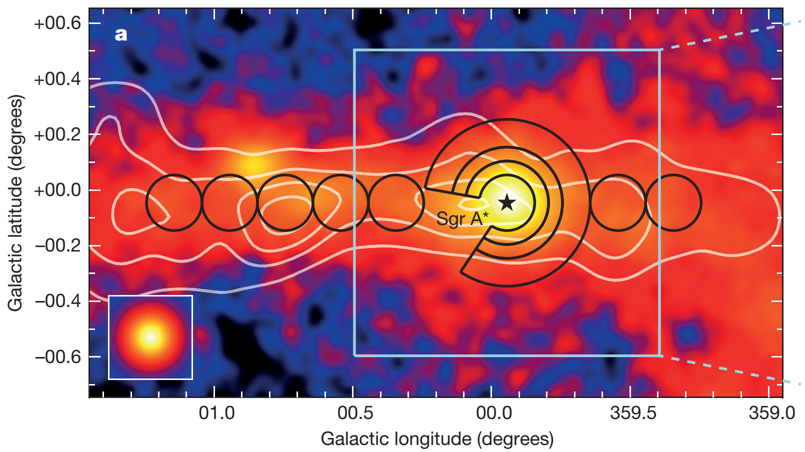
- ✓ International collaboration (Japan + Bolivia + Mexico)
- ✓ Mt. Chacaltaya in Bolivia 4740m asl
- ✓ Same type of detectors as Tibet ASγ (AS 83,000m^2 + MD 5,600m^2)
- ✓ Target energy : 5 – 1000 TeV
- ✓ Construction of prototype is ongoing (above picture)
- ✓ PeVatron search in the southern sky
  - Galactic center regions, diffuse gamma
  - DM search in the direction of G.C.
- ✓ Cosmic-ray anisotropy
- ✓ Sun's shadow monitor



Galactic Center Diffuse Emission



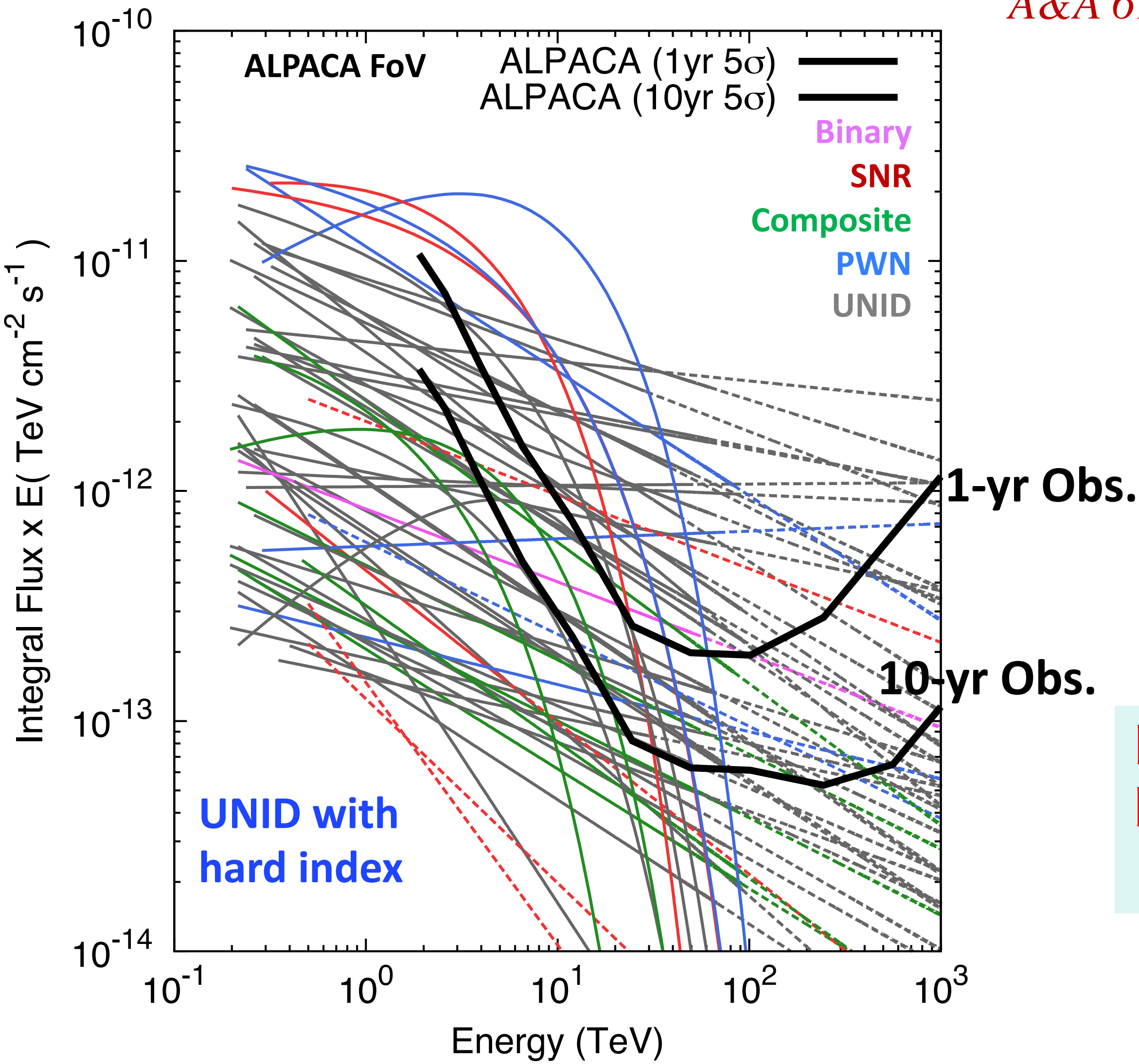
- ✓ Diffuse emission up to a few 10 TeV
- ✓ Hard spectral index
- ✓ Candidate for PeVatron
  → Sub-PeV γ observation!



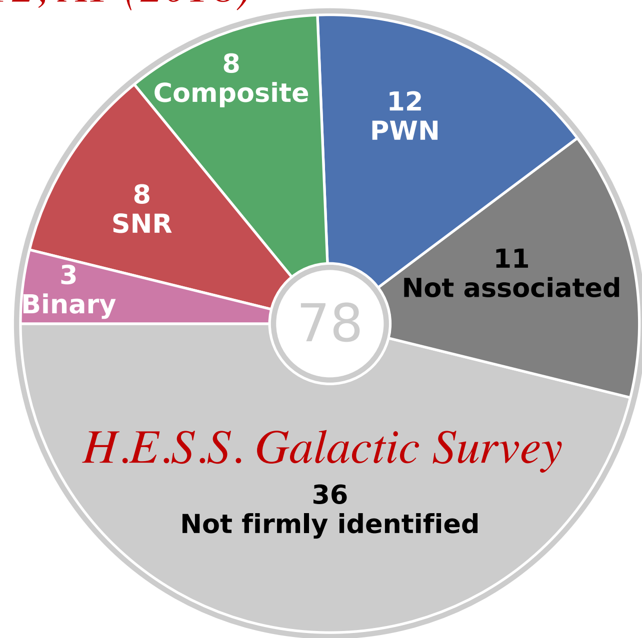
Abramowski+ (H.E.S.S.), Nature (2016)

"Acceleration of petaelectronvolt protons in the Galactic Centre"

Dark Accelerators



A&A 612, A1 (2018)



Hard spectral index (–2) beyond 100 TeV (+ Molecular Cloud)

30 sources >30TeV Search for PeVatrons

Status of Prototype Array: ALPAQUITA





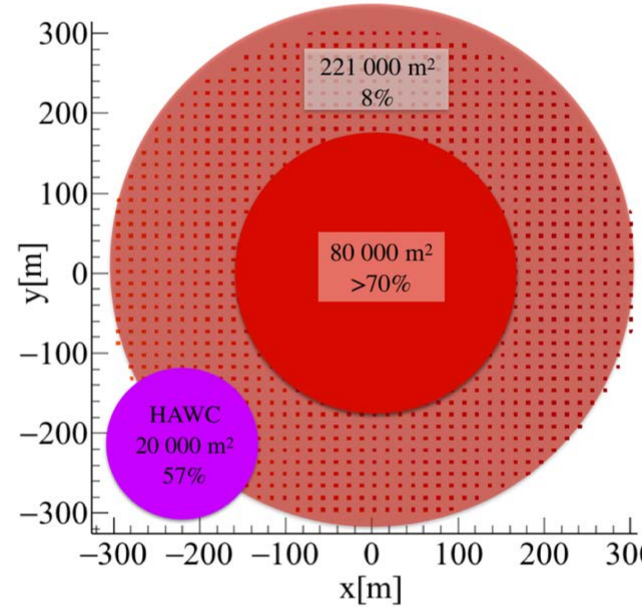


For details, please see the next talk

SWGO

www.swgo.org

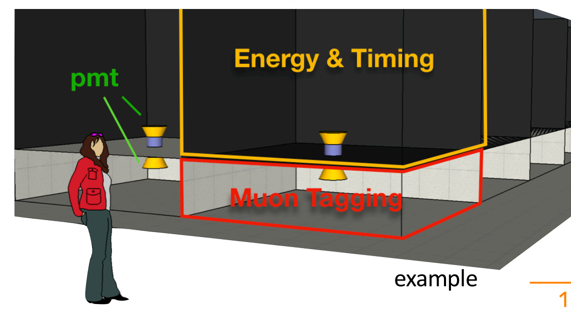
- ✓ Southern Wide FoV Gamma-ray Observatory
- ✓ New collaboration formed in July 2019
- ✓ Based on Water Cherenkov technique
- ✓ Site survey and simulation studies are ongoing



e.g.

Site?

- Detailed characterisation work started
  - → Shortlist by end 2020



- ✓ Ground-particle detection based high altitude (>4.4 km) γ-ray observatory latitude -15° to -30°
- ✓ Wide energy range: 100 GeV to 100 TeV

Summary

- The Tibet ASγ experiment first detected 100 TeV γ rays from an astrophysical source.
- HAWC found a few additional 100 TeV γ-ray sources with hard spectral index.
- Multi-wavelength, multi-particle observations will be important to identify PeVatrons in our Galaxy.
- In the southern hemisphere, ALPACA started the construction of a prototype detectors, and SWGO collaboration formed, and site survey is ongoing.

Personal Opinions

What's your targeted physics in next decades?

- Identify/understand cosmic-ray origin in our Galaxy (PeVatron)
- Heavy DM search in our Galaxy

What we need to accomplish?

- Wide FoV sky survey > 100 TeV in northern and southern hemispheres
- Multi-wavelength multi-particle observations