The High Altitude Water Cherenkov (HAWC) Gamma-Ray Observatory, Mexico and the PeVatrons

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19th Rencontres du Vietnam, Theory meeting experiment, January 2023

OUTLINE

1.- Gamma-Ray Astrophysics and Pevatrons

2.- The High Altitude Water Cherenkov (HAWC) Observatory

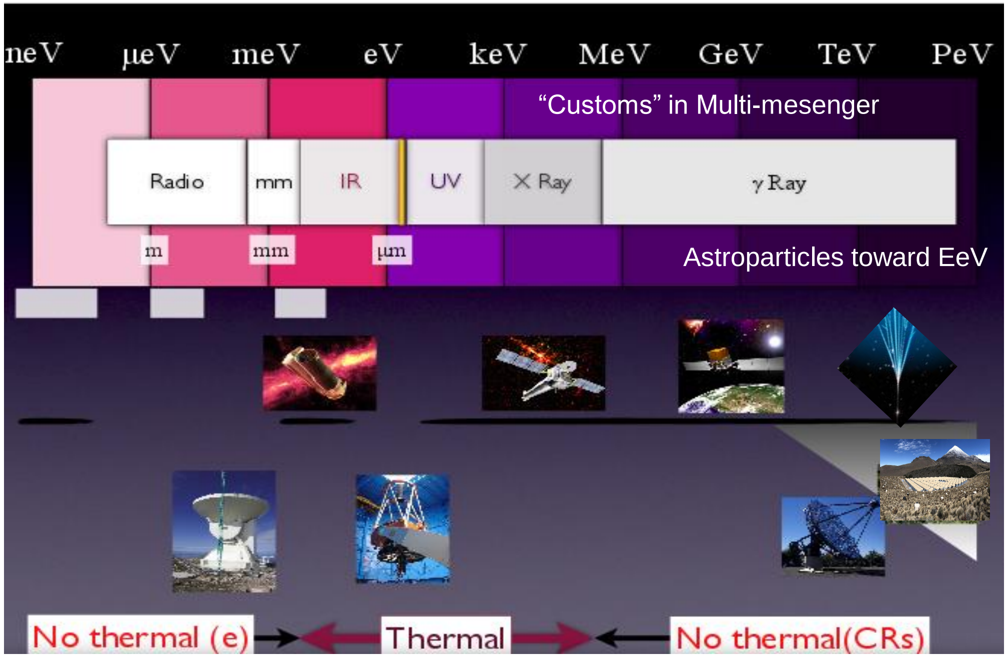
3.- HAWC meets PeVatrons

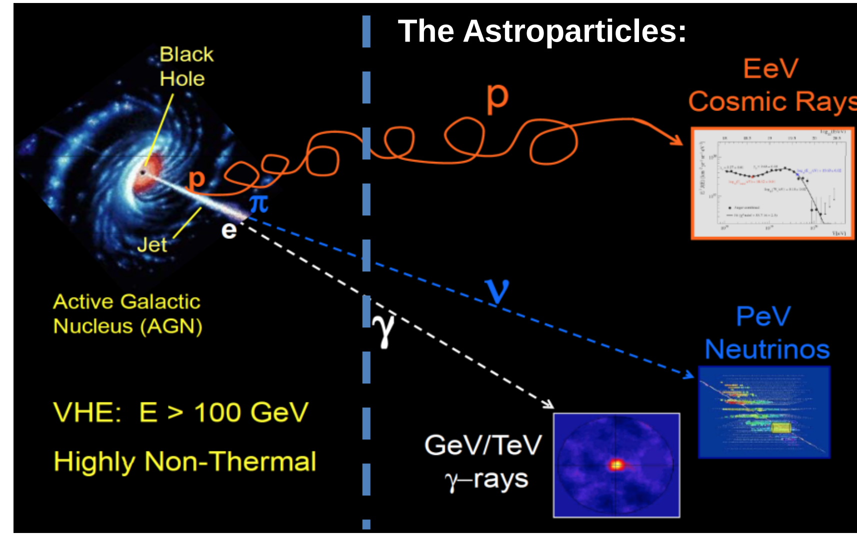
4.- Future and open questions

1.- Gamma-Ray Astrophysics and PeVatrons

Gamma-Ray (GR) Astronomy: From GeV to (sub) PeV

Nature's Particle Accelerators are Gamma-Ray Sources





The Energy is the Key: LHC (~ 10TeV), Nature (to EeV)

Energy range:

- LE or MeV → 0.1—100 MeV
- HE or GeV → 0.1—100 GeV
- VHE or TeV → 0.1—100 TeV
- UHE or PeV → 0.1—100 PeV

Revolutions in the GRA (XXI Century):

1.- NASA-Fermi (GeV era)
2.- Maturity of the second generation of observatories in the XXI century: IACTs, WCDs, Scintillators (TeV era)
3.- UHE and PeVatrons (PeV era)

Gamma-Ray Astronomical + Man Made (e.g LHC) TeVatrons ⟺ **Origin of cosmic rays**

< 1 PeV ⇒ Galactic
> 1 Eev ⇒ X-Galactic
In between **Transition (?)**

What is the maximum energy that nature accelerates particles in the Galaxy?

Gamma-Ray nature (hadronic or leptonic)

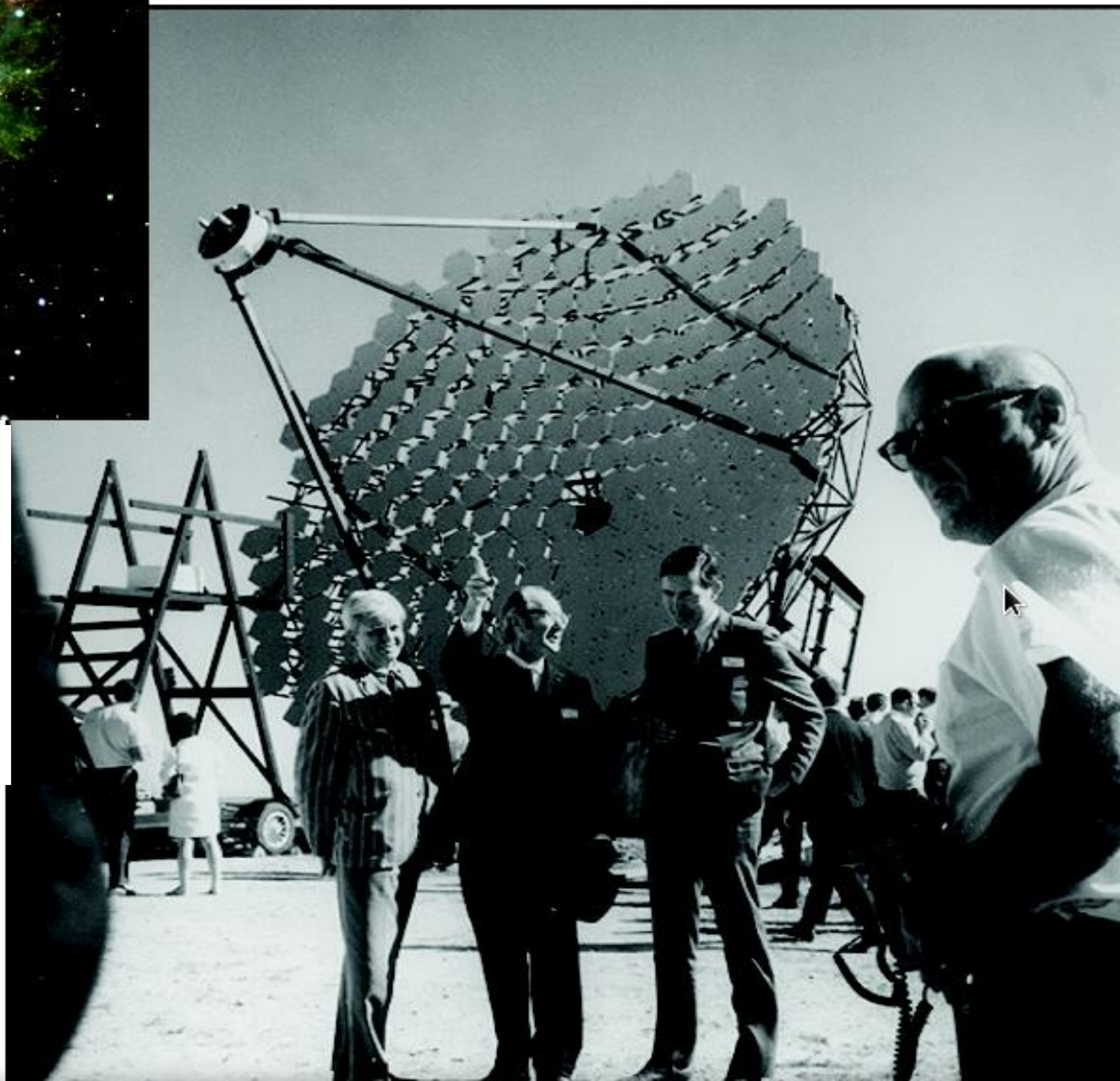
⟺ **PeV Astronomy** ⟺ **Cosmic Rays**

- CR sources (what, where)
- How we can identify them?
- Acceleration mechanism?
- Effects on propagation?
- Isotropy (?)
- Chemical composition?

1/4.- Gamma-Ray Astrophysics and PeVatrons

The Birth of the VHE Gamma Ray Astrophysics (TeV)

The first successful full detection of the gamma-ray emission above 0.7 TeV from the Crab nebula in 1989 by the Whipple collaboration: 5 sigma in 50 hrs (159 pixel camera + Hillas image analysis)



A.E. Chudakov and G.T. Zatsepin (1961). Crimea Obs. (1961.1963)

The upper limit obtained by Chudakov was proof of the direct acceleration of electrons in the Crab Nebula (1961)

UHE γ-ray Astronomy:

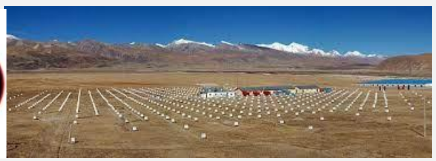
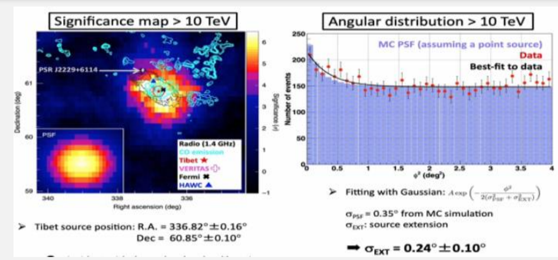
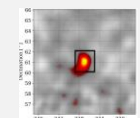
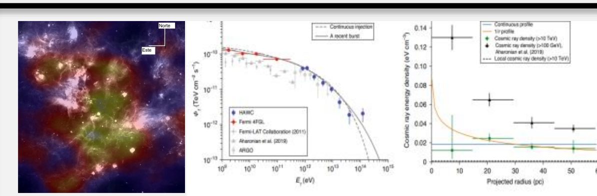
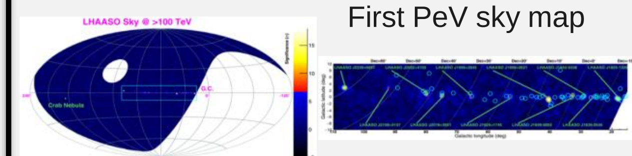
2021: A new window in Astronomy: A transition from Tevatrons:

Gamma-Ray Ultra-High Energy (E >100 TeV).

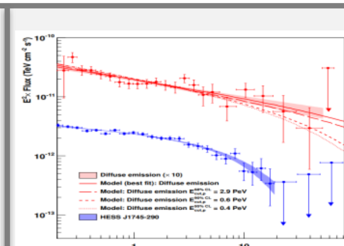
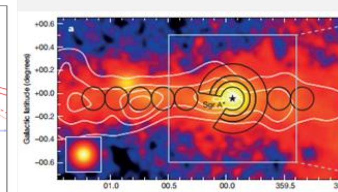
If we detect energies > 100 TeVs (gamma rays) from astronomical sources (*accelerator*), the expected particle acceleration is > 1 PeV (energy per beam**).**

The rise of the PeV era (Pevatrons)

Time-line Observationally speaking (high energy sensitivity):

High sensitivity observatory (By year pub.)	Remarkably Contribution Object: reference and year	Results	Comments and Remarks
Tibet AS γ  **Energy range: Beyond 100 TeV**	SNR G106.3+2.7 Nature Astronomy, 5, 460 (2021) Published: 2021/03/06 Confirmation as PeVatron		HAWC Coll. ApJL, 896, L20 (2020):  Crab Nebula paper: PRL, 123, 051101 (2019)
HAWC High Altitude Water Cherenkov Gamma-Ray Observatory  **Energy range: 100 GeV to 100 TeV**	Cygnus Cocoon (FERMI-LAT) Nature Astronomy, 5, 465 (2021) Published: 2021/04/06 Star-Clusters as PeVatron		Star forming región at Cygnus-X: Cyg-OB2 Association Crab Nebula paper: ApJ, 881, 134 (2019)
LHAASO 高海拔宇宙线观测站  **Energy range: 0.1 TeV to 0.1 EeV**	North Sky (> 1.4 PeV) Nature, 594, 33 (2021) Published: 2021/05/17 Sky map and 12 PeV candidates (galactic)	First PeV sky map 	Crab Nebula as PeVatron: **Science, 373, 425 (2021/07/08)**

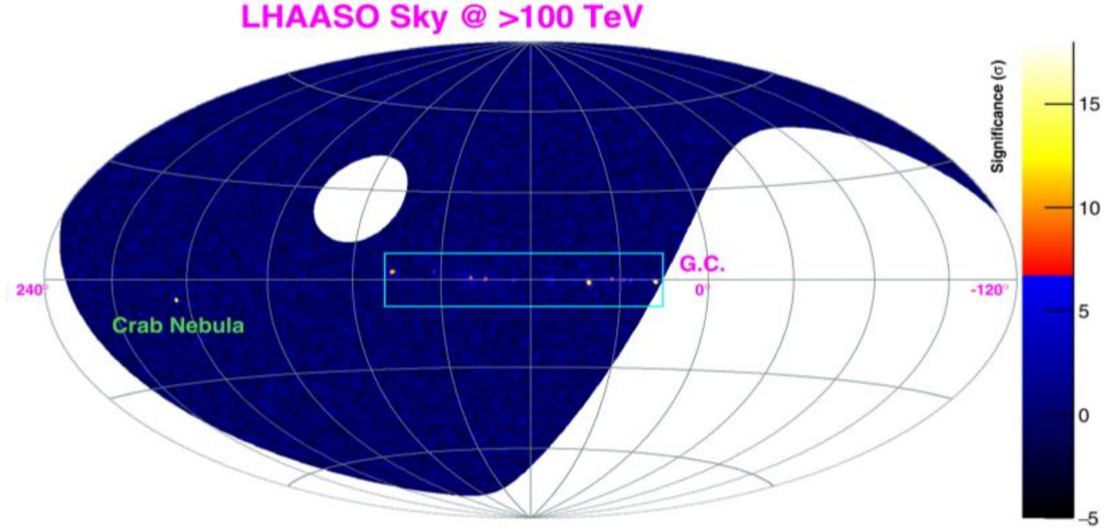
Reference work where the term "PeVatron" was coined by first time in 2016 (Obs+predictions):

Energy range:10s of GeV to 10s of TeV. H.E.S.S. 	Galactic Center Study Nature, 531, 476 (2016) Published: 2016/03/16 Suggesting Sag. A* black hole could be the PeVatron	 	This work is the first robust detection of a VHE cosmic hadronic accelerator As PeVatron, HESS refer to hadrons Previous GC observations by IACTs HESS: 2004, 2066 MAGIC: 2006, 2016 VERITAS: 2011

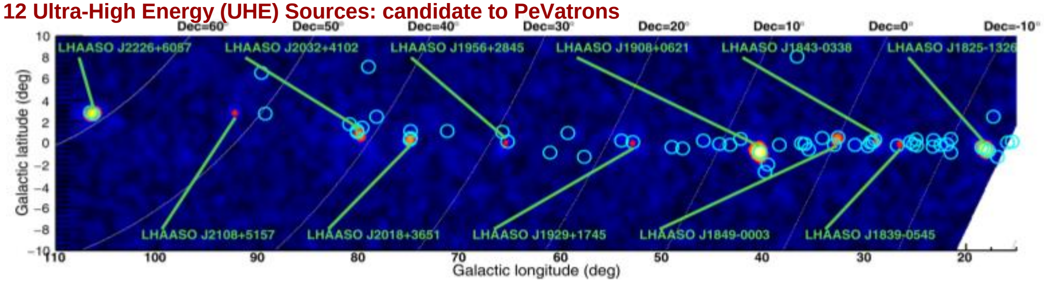
Pevatron: (2021)

Particle accelerators boosting energy of protons to the PeV domain without a sharp cutoff up to 1 PeV

An astronomical object that can produce particles upto the knee (3 PeV) without a visible cut-off



12 Ultra-High Energy (UHE) Sources: candidate to PeVatrons



Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26\ _{-0.10}^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71\ _{-0.07}^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

"I think leptonic and hadronic accelerators are equally interesting and equally important. And in fact, it s virtually certain that all hadronic accelerators are also leptonic accelerators. Understand co-acceleration is of crucial importance"

Paolo Lipari (ICRC 2021 at GR-Indirect discussion session)

- No consensus on the definition yet (2021): An astronomical object that can accelerate particles at PeV energies.

2022: An astronomical object (accelerator) able to accelerate particles at energies > 1 PeV

- The main conflict point is: Only hadrons?. (ICRC 2021 discussion at GR-indirect).

LPeV for PWNe, and HPeV for individual SNR and stellar winds (v > 0.01; B > 0.01 G)?

To date, there is a high debate about hadronic PeVatrons associated with SNR.

- Three conditions to confirm a PeVatron: (Discussion between conveners and the rapporteur of session 55: UHE gamma rays and *PeVatron in ICRC 2021)*

a) An acceleration at PeV (emission > 100 TeV is not enough to claim a Pevatron; e.g. Crab and some leptonic sources)
b) Molecular Gas Environment,
c) Neutrino detection--coincidence (true)

2023: X-Ray Observations covering all PeVatrons candidates are crucial (to constrain leptonic emission)

2.- The High Altitude Water Cherenkov (HAWC) Observatory in Mexico

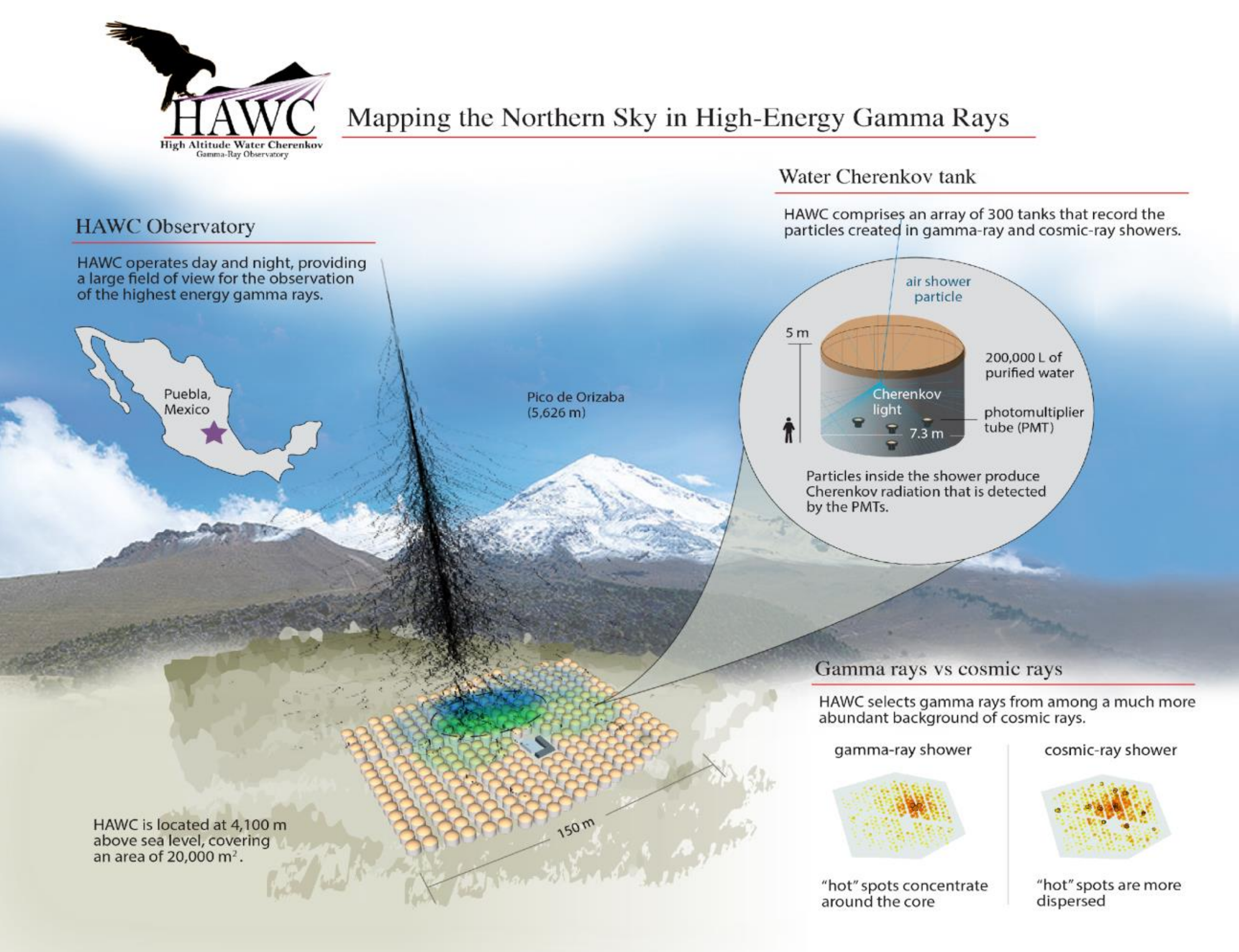
The High Altitude Water Cherenkov (HAWC) Observatory at México

Latitude: 18°59.7’N
Longitude: 97°18.6’W

2/4.- The HAWC observatory at México

The HAWC Collaboration

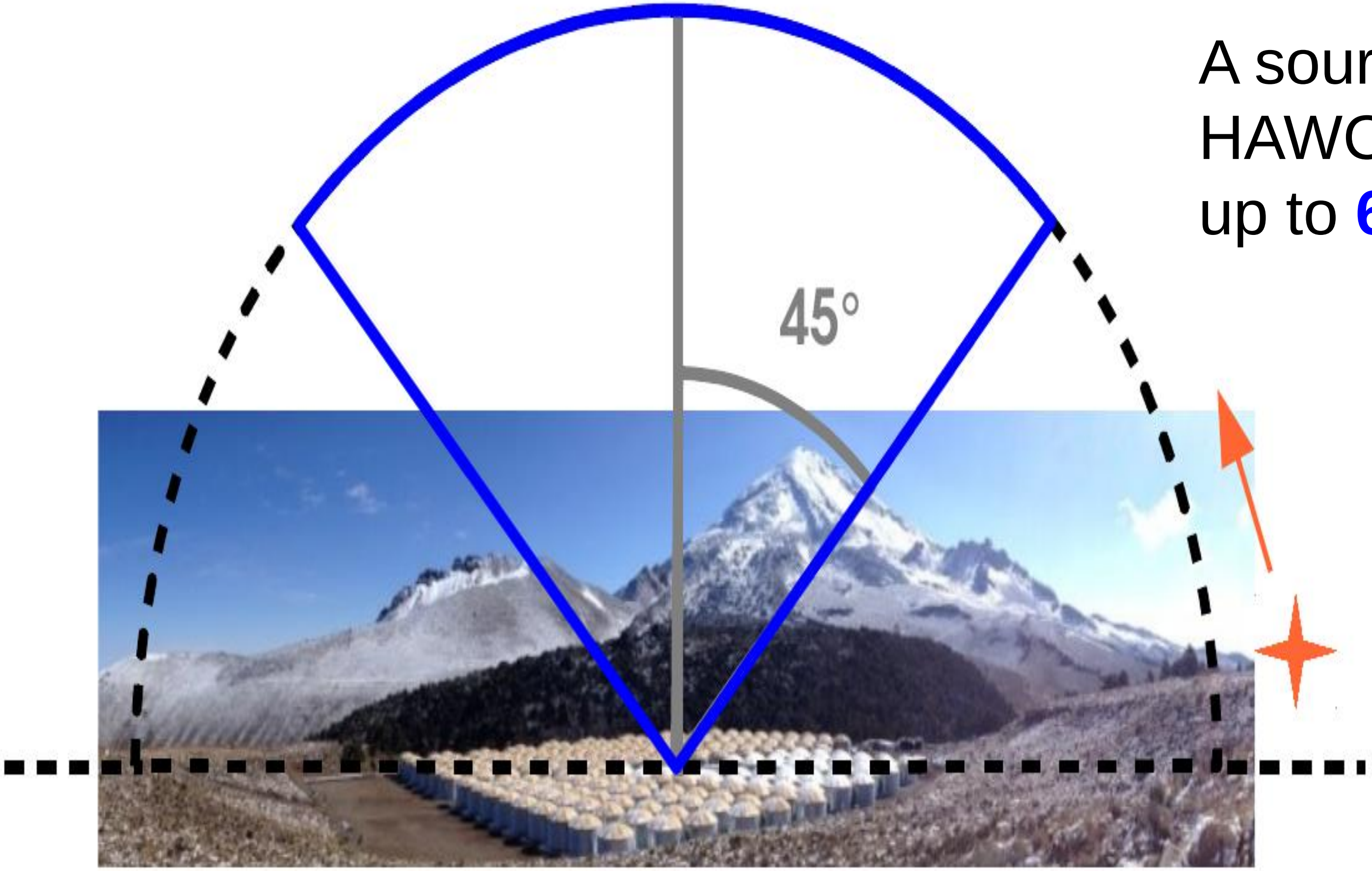
México	**Estados Unidos**	**Europa**	
Instituto Nacional de Astrofísica, Óptica y Electrónica	University of Maryland	Max Planck Institute für Kernphysik, Heidelberg	Alemania
Universidad Nacional Autónoma de México	Los Alamos National Laboratory	F. Alexander Universität, Erlangen	Alemania
Instituto de Astronomía UNAM	George Mason University	Institute of Nuclear Physics, Cracovia	Polonia
Instituto de Ciencias Nucleares UNAM	Georgia Institute of Technology	INFN & Universita di Padova	Italia
Instituto de Física UNAM	Michigan State University	IFIC - Universidad de Valencia	España
Instituto de Geofísica UNAM	Michigan Technological University		
Benemérita Universidad Autónoma de Puebla	Pennsylvania State University	**Asia**	
Centro de Investigación y Estudios Avanzados	NASA GSFC	University of Seoul	Corea del Sur
Instituto Politécnico Nacional	Stanford University	Shanghai Jiao Tong University	China
Centro de Investigación en Cómputo	University of California Santa Cruz	Chulalongkorn University	Tailandia
Instituto de Física	University of California Irvine		
Universidad Autónoma de Chiapas	University of New Hampshire	**América Latina**	
Universidad Autónoma del Estado de Hidalgo	University of New Mexico	Universidad de Costa Rica	Costa Rica
Universidad de Guadalajara	University of Rochester		
Universidad Michoacana de San Nicolás de Hidalgo	University of Utah		
Universidad Politécnica de Pachuca	University of Wisconsin		



	Milagro	HAWC
Detector Area	3500 m^2 /2100 m^2	20,000 m^2
Time to 5σ on the Crab	120 days	5hrs
Median Energy	4 TeV	1 TeV
Angular Resolution	$0.40^0 - 0.75^\circ$	$0.25^\circ - 0.50^\circ$
Energy Resolution at 5 TeV	140%	72%
Energy Resolution at 50 TeV	85%	35%
Hadron Rejection efficiency at 10 TeV	90%	>99.5%
Q for gamma/hadron rejection	1.6	5
Time to detect 5 Crab flare at 5σ	5 days	10 minutes
Eff. Area at 100 GeV	5 m^2	100 m^2
Eff. Area at 1 TeV	10^3 m^2	$20x10^3$ m^2
Eff Area at 10 TeV	$20x10^3$ m^2	$50x10^3$ m^2
Eff Area at 50 TeV	$70x10^3$ m^2	$70x10^3$ m^2
Volume of Universe where $3x10^{-6}$ erg/cm^2 GRB is detectable	7 Gpc^3	47 Gpc^3
Flux Sensitivity to a Crab-like source (1 year) (5σ detection)	625 mCrab	45 mCrab

The High Altitude Water Cherenkov (HAWC) Observatory at México

Field of view down to ~45° from zenith:
Scanning 2/3 of the sky each day through the rotation of the Earth

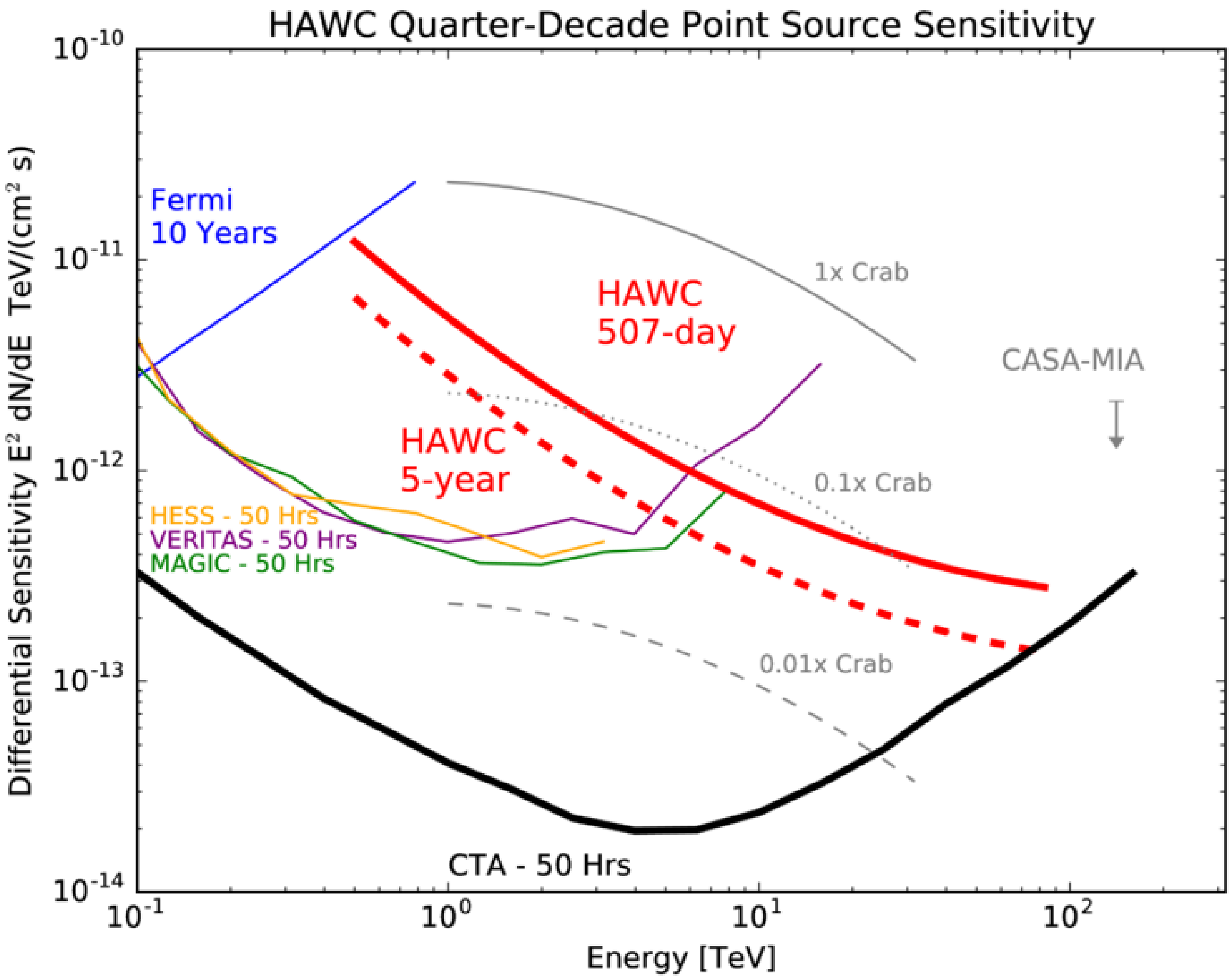


A source is visible for HAWC
up to **6 hours per day**

2/4.- The HAWC observatory at México

The High Altitude Water Cherenkov (HAWC) Observatory at México

Survey > half the sky to: 40mCrab [5σ] (1yr) or <20mCrab [5σ] (5yr)



Instantaneous sensitivity about 15-20x less than IACTs:

- ~2-3x from Angular Resolution
- ~5x from energy threshold.

Exposure (sr yrs) is 2000-4000x higher.

~1500 hrs/src/yr

For hard or extended sources, HAWC improves relative to IACTs

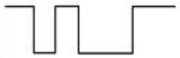
2/4.- The HAWC observatory at México

HAWC Collaboration
Nucl. Instrum. Meth. A 888 (2018) 138-46

Photo-multiplier Tube

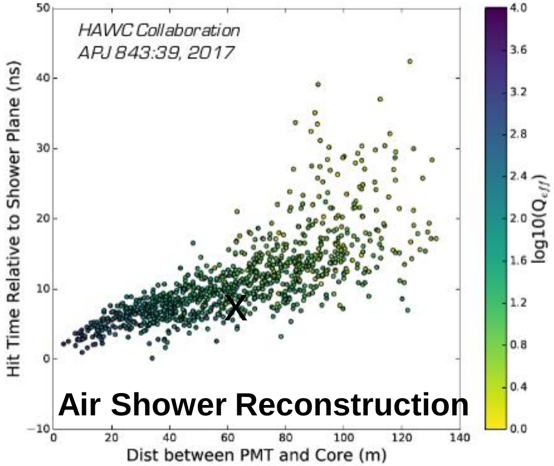
Data adquisition

Custom Front-End Electronics
Pick-off circuits and discriminators.

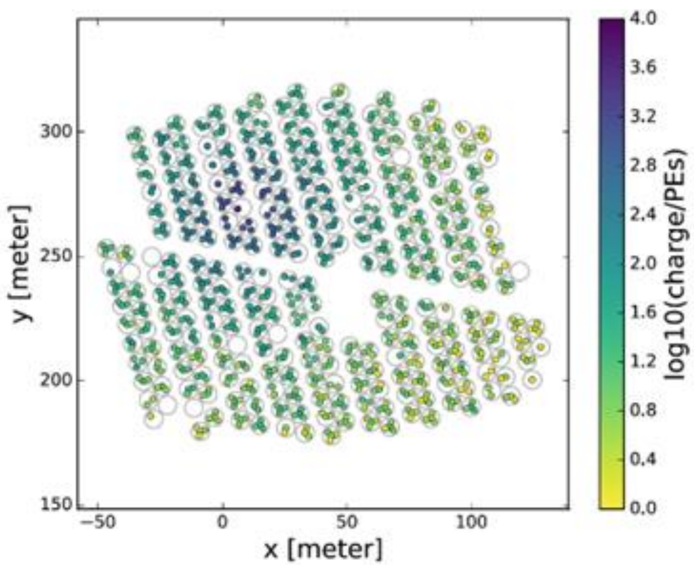


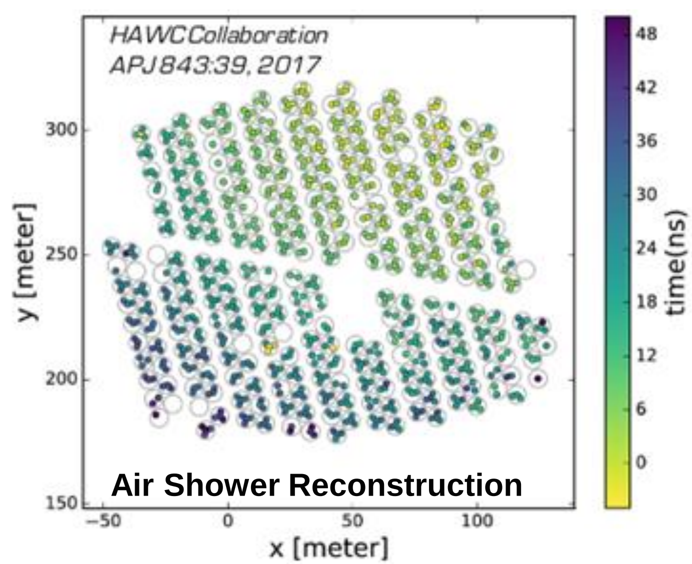
CAEN Vx1190 Time-to-Digital Converters

- The system is based on measuring the ToT (Time over Threshold)
- HAWC uses the TDCs as continuous recorders of edge timing: the experiment acquires and transmits all of the TDC-digitized edges to a computer farm
- The trigger happens at software level: a PMT multiplicity trigger



- Display of the arrival time distributions of a shower consistent with a gamma-ray from the Crab
- By precisely taking into account the shower curvature it is possible to get an angular resolution of up to 0.15°

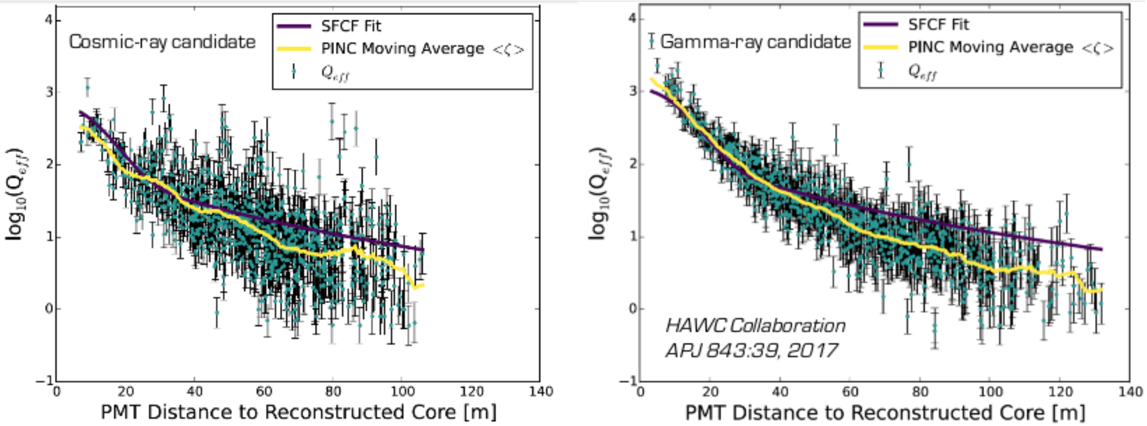




- ✓ Arrival Direction determined by relative timing (~1ns precision) of Cherekov Light Pulses observed in tanks
- ✓ Primary Energy determined by "size" of shower.
- ✓ Lateral distribution and curvature of shower front gives more information about energy
- ✓ Cosmic Ray Background rejection from clumpiness of shower 'footprint'

2/4.- The HAWC observatory at México

Credit Hermes Leon and HAWC Collaboration



Gamma / Hadron Rejection

$CxPE_{40}$: Largest Q_{eff} outside a radius of 40 m from the shower core

N_{hit}: Number of PMT hits during the air shower

$$\mathcal{C} = \frac{N_{hit}}{CxPE_{40}}$$

For hadronic showers C is small

PINCness (**P**arameter for **I**dentifying **N**uclear **C**osmic rays)

$$\mathcal{P} = \frac{1}{N}\sum_{i=0}^{N}\frac{(\zeta_i - \langle\zeta_i\rangle)^2}{\sigma^2_{\zeta_i}}$$

$\zeta_i = \log_{10}(Q_{\mathrm{eff,i}})$

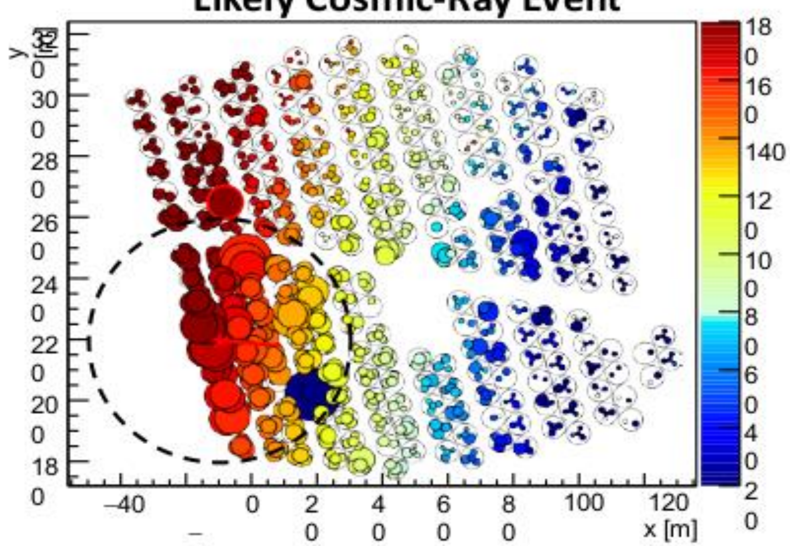
$\langle\zeta_i\rangle$: Average of all PMTs contained in an annulus of width 5m containing the hit

σ_{ζ_i} : Obtained from a sample of strong gamma-ray candidates from the Crab

For hadronic showers $\mathcal{P}$ is large

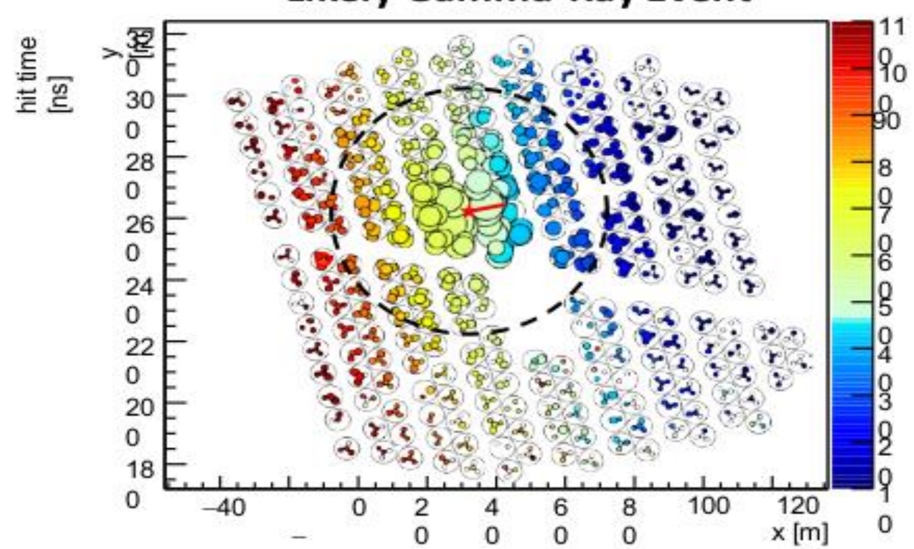
"Clumpiness" ➔ Hadron

Likely Cosmic-Ray Event



"Smoothness" ➔ Photon

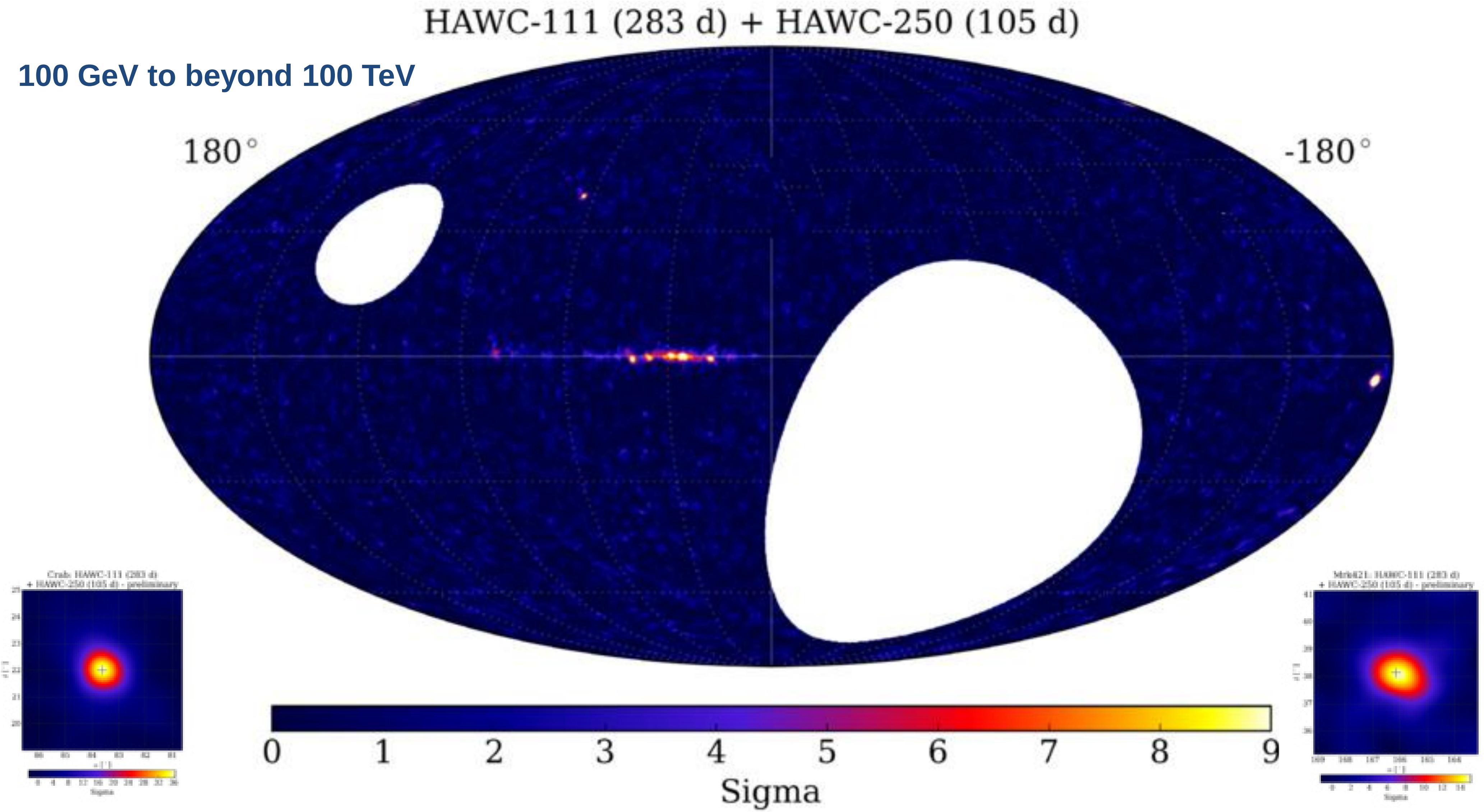
Likely Gamma-Ray Event



HAWC Gamma-Ray Sky Map (Historical result)

Galactic coordinates map with zoom on Crab (36 sigma) and Mrk421 (15 sigma)

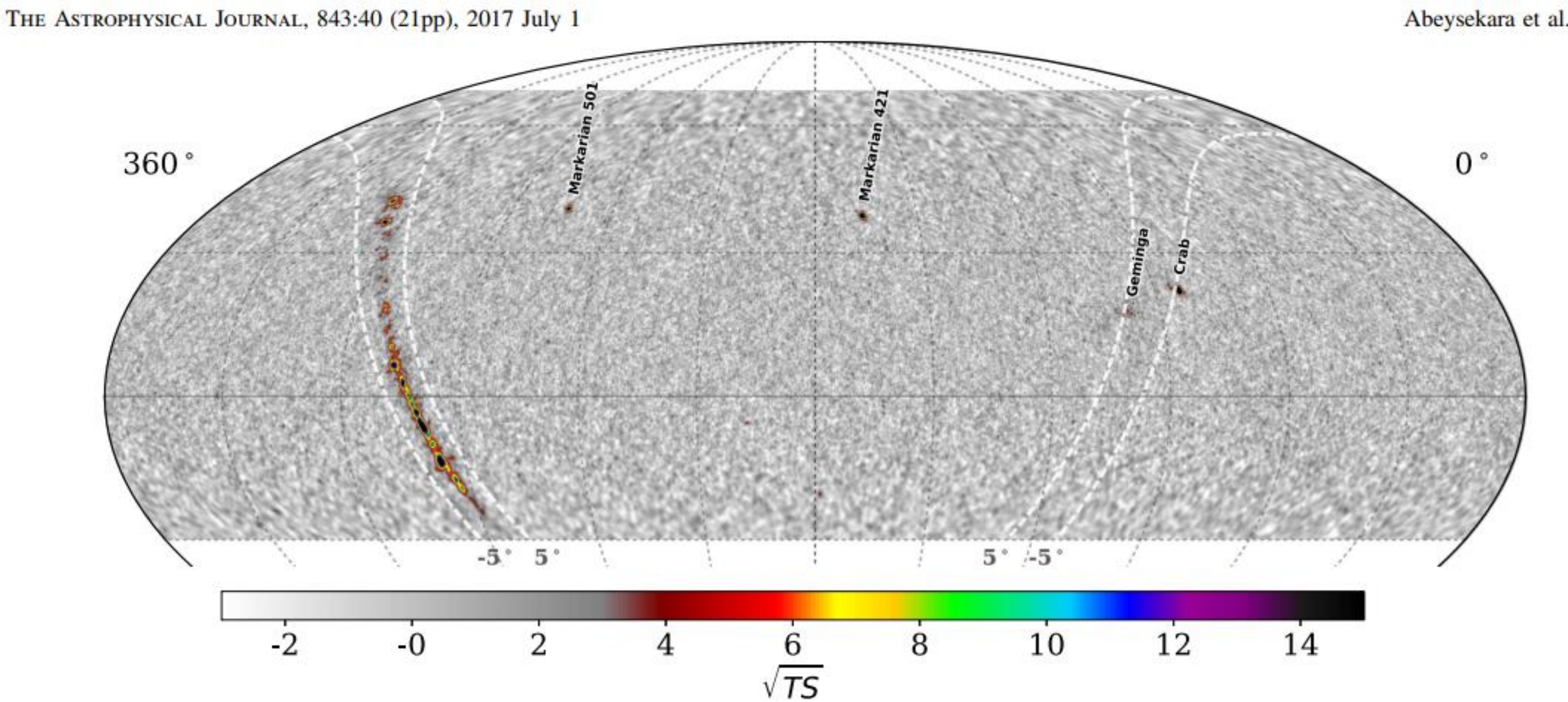
100 GeV to beyond 100 TeV



2/4.- The HAWC observatory at México

HAWC Gamma-Ray Sky Map and sources E > 56 TeV

Equatorial coordinates map



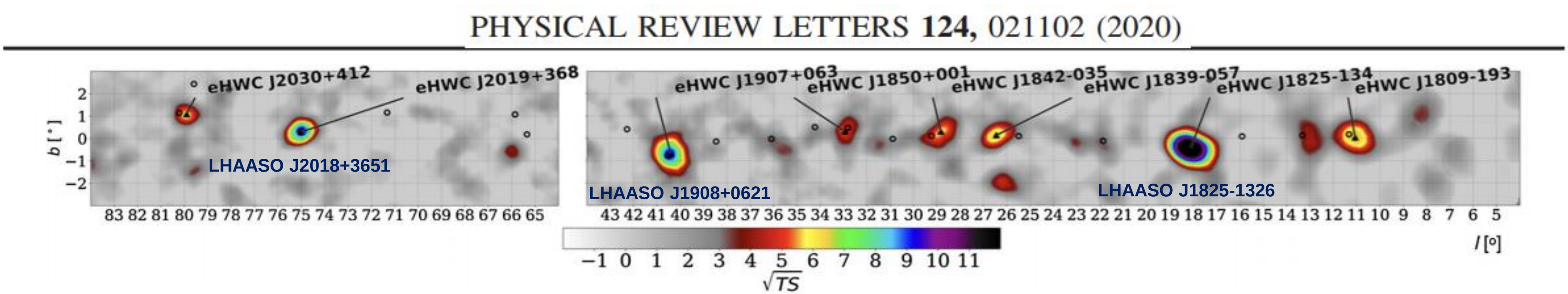
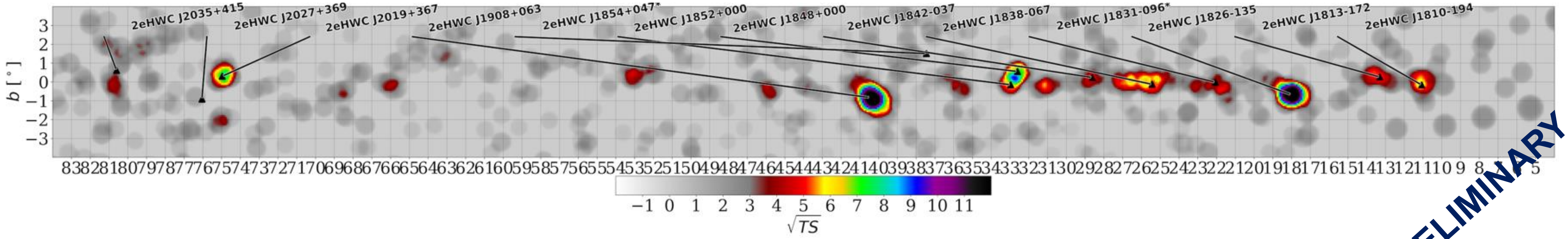


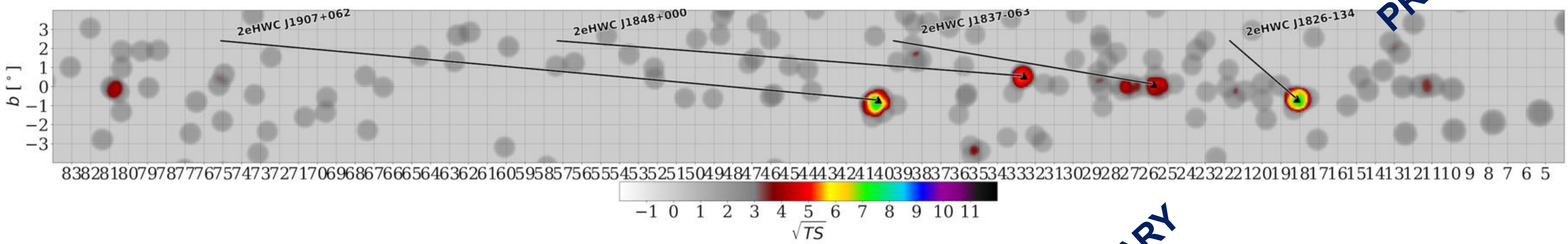
FIG. 1. $\sqrt{TS}$ map of the galactic plane for $\hat{E} > 56$ TeV emission. A disk of radius 0.5° is assumed as the morphology. Black triangles denote the high-energy sources. For comparison, black open circles show sources from the 2HWC catalog.

HAWC Gamma-Ray Sky Map and sources E > 56 TeV

0.5 degrees extended sources above 100 TeV



PRELIMINARY



0.5 degrees extended sources above 177 TeV

PRELIMINARY

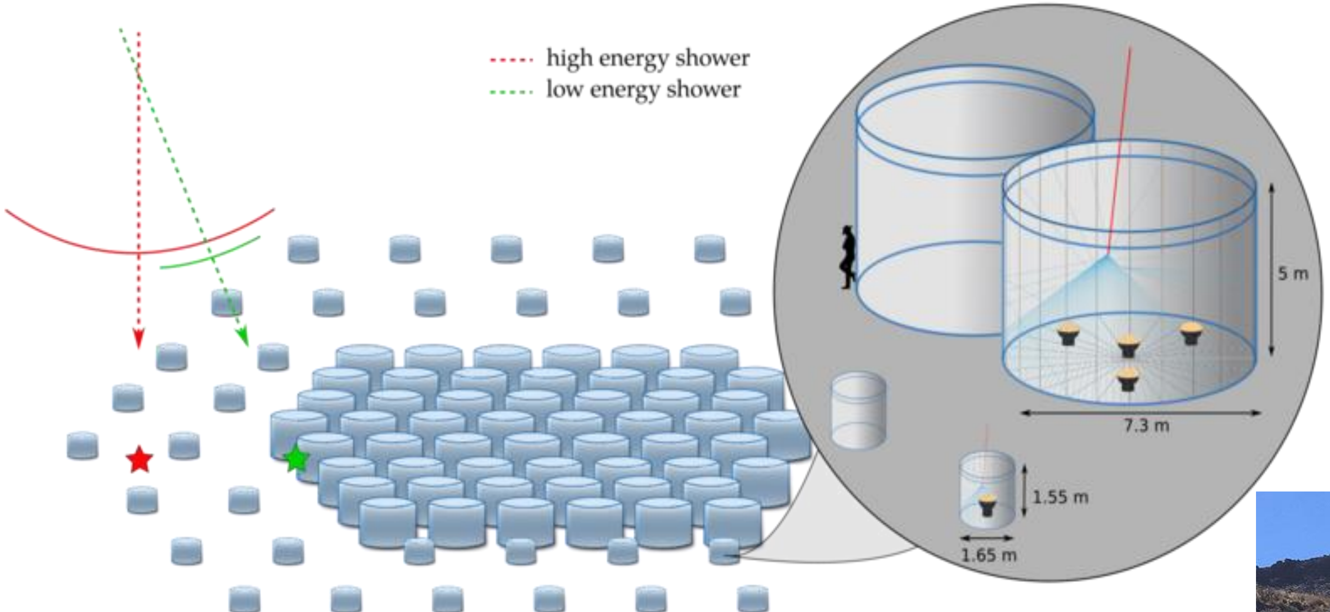
3 PWN and 1 unidentified. Predominance of Leptonic?

HAWC upgraded (Outriggers era starting in 2023):

The outriggers array consist of 345 smaller plastic roto-molded WCDs (2500 liters) covering an area 4 times HAWC primary detector

Enhanced Sensitivity above 10 TeV
(e.g., 3 to 4 times the sensitivity at 50TeV)

Accurately determine core position for showers off the main tank array.



Increase effective area above 10 TeV by ~4x

2/4.- The HAWC observatory at México

3.- HAWC Meet Pevatrons

Despite LHAASO sources being cataloged by HAWC, historically speaking, not considering the G106.3+2.7 case (see section 4), and in a robust way, HAWC meet PeVatrons formally at Cygnus region (2021)

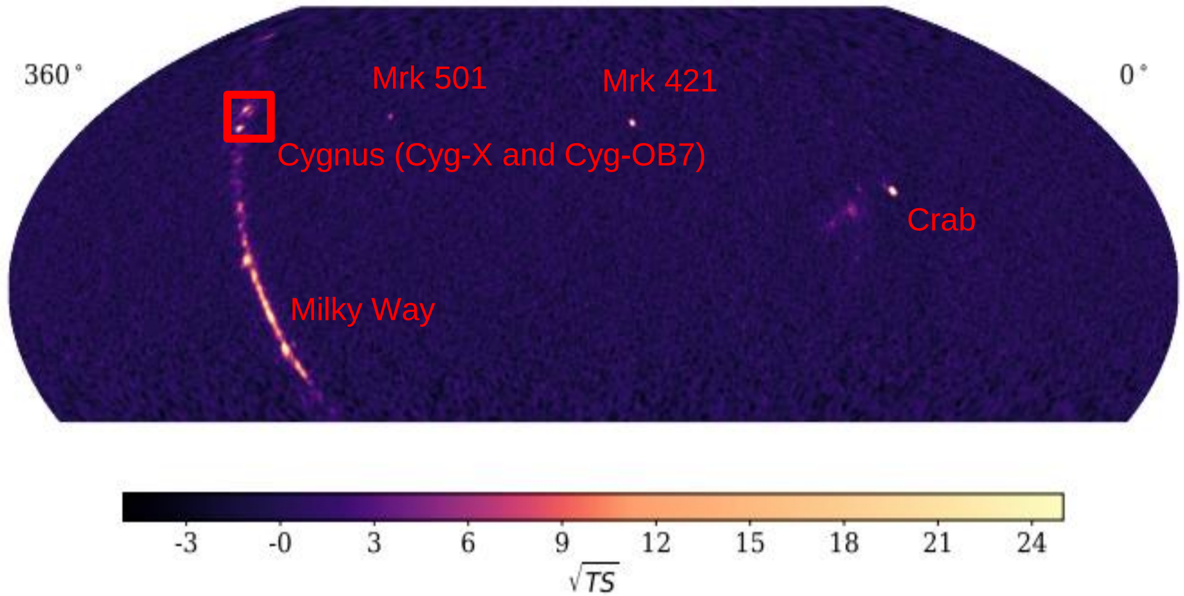
LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)[a]	L_s (erg/s)[b]	Potential TeV Counterpart[c]
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2^d	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	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,
Cygnus region	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,
Cygnus region	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	—	— Cygnus region	—	—	—	—
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}	

3/4.- The HAWC observatory at México

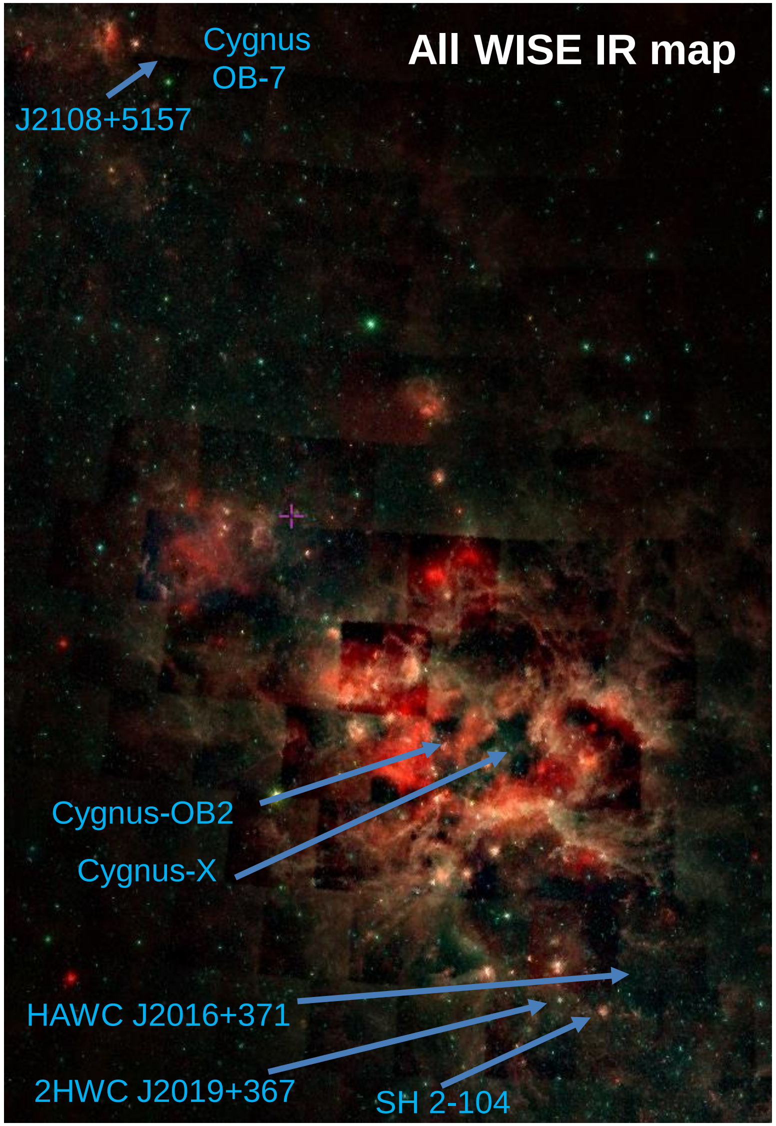
HAWC Gamma-Ray Sky Map (Third Catalog, 2020): HAWC meet PeVatrons formally and in robust way at Cygnus region (2021)

Equatorial coordinates map

100 GeV to beyond 100 TeV



HAWC Collaboration; Albert, et al., The Third HAWC Catalog of Very-high-energy Gamma-Ray Sources, ApJ, 905, 76 (2020), doi: 10.3847/1538-4357/abc2d8



2HWC J2019+367 was associated with the PWN Dragonfly
HAWC J2016+371 was associated with the SNR CTB 87

A. Albert *et al.*, ApJ, 911, 143 (2021)

In contributions to PeVatrons topic, to date, the HAWC's jewel in the Crown is the Cygnus Cocoon: (Massive star clusters)

Published by HAWC Collaboration on March, 11, 2021, at Nature Astronomy, 5, 465; Binita Hona's PhD (2021), Michigan State University (MSU).

Star-Forming *Regions like Cygnus-X related with OB star associations as Cyg-OB2, are galactic sources of cosmic rays, not only the PSR, PWN, SNR, and related objects.*

Cygnus-Cocoon, W43, and Sh 2-104, are the only (massive) star cluster + star-forming regions in the LHAASO catalog (2021),. The others candidates are most PSR, SNR, and one unidentified (J2108+5057).

***In the LHAASO catalog, Cygnus Cocoon rules in massive stellar content and could be considered as a reference in PeVtrons. Besides, it meets the conditions to be associated with a neutrino candidate and molecular environment*.**

arXiv:2105.07242v2 [astro-ph.HE] 15 Jul 2021

Observation of photons above 300 TeV associated with a high-energy neutrino from the Cygnus Cocoon region

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(Carpet–3 Group)

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(Received May 15; Revised July 3; Accepted July 15, 2021)

Submitted to ApJL

ABSTRACT

Galactic sites of acceleration of cosmic rays to energies of order 10^{15} eV and higher, dubbed PeVatrons, reveal themselves by recently discovered gamma radiation of energies above 100 TeV. However, joint gamma-ray and neutrino production, which marks unambiguously cosmic-ray interactions with ambient matter and radiation, was not observed until now. In November 2020, the IceCube neutrino observatory reported an $\sim$ 150 TeV neutrino event from the direction of one of the most promising Galactic PeVatrons, the Cygnus Cocoon. Here we report on the observation of a 3.1-sigma (post trial) excess of atmospheric air showers from the same direction, observed by the Carpet-2 experiment and consistent with a few-months flare in photons above 300 TeV, in temporal coincidence with the neutrino event. The fluence of the gamma-ray flare is of the same order as that expected from the neutrino observation, assuming the standard mechanism of neutrino production. This is the first evidence for the joint production of high-energy neutrinos and gamma rays in a Galactic source.

1. INTRODUCTION

Recent observations of astrophysical gamma rays above 100 TeV established the existence of various Galactic sources, both point-like (Abeysekara et al. 2019a,b, 2020; Albert et al. 2020; Albert et al. 2021; Cao et al. 2021) and diffuse (Amenomori et al. 2021). ... tions of neutrinos co-produced with these gamma rays would unambiguously point to their hadronic origin.

It is an intriguing question whether some of the high-energy (above TeV) astrophysical neutrinos (Aartsen et al. 2013a,b; for recent reviews, see e.g. Ahlers & Halzen 2018; Palladino et al. 2020) come from Galac-

The History of Pevatrons: HAWC and the Cygnus Cocoon

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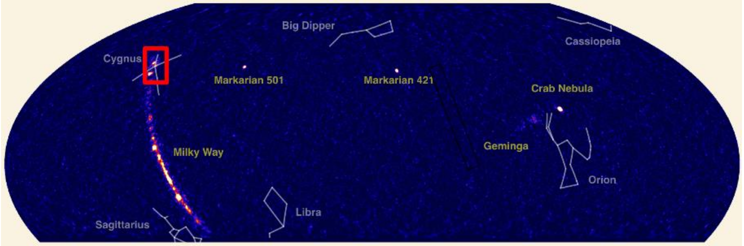
https://doi.org/10.1038/s41550-021-01318-y

Credit: Binita Hona (U. Utah)



A Cocoon of Freshly Accelerated Cosmic Rays Detected by Fermi in the Cygnus Superbubble

M. Ackermann[1], M. Ajello[1], A. Allafort[1], L. Baldini[2], J. Ballet[3], G. Barbiellini[4,5], D. Bastieri[6,7], A. Belfiore[8], R. Bellazzini[2], B. ...
+ See all authors and affiliations

Science 25 Nov 2011:
Vol. 334, Issue 6059, pp. 1103-1107
DOI: 10.1126/science.1210311

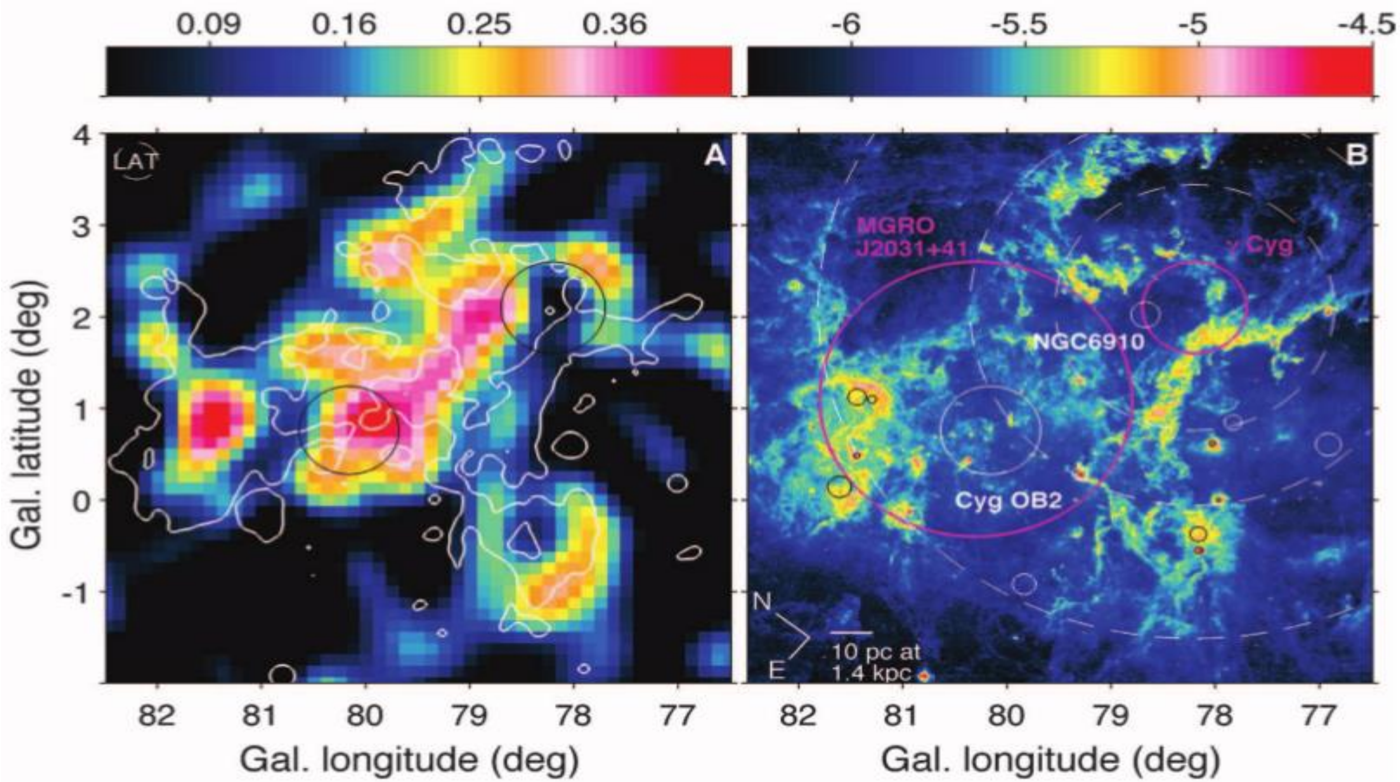
One of the most massive OB associations in our Galaxy

Consists about ~120 type O stars

Age: 1 to 7 Myrs

Stellar wind power of a few 10^{39} erg/sec maintained for at least 2 Myrs *(Lozinskaya et al. 2002)*

Motivation of studying this particular location



(RA, Dec): (307.17°, 41.17°)

Attributed to a Cocoon of freshly accelerated CRs

OB2 association as a possible source of CRs in the cocoon

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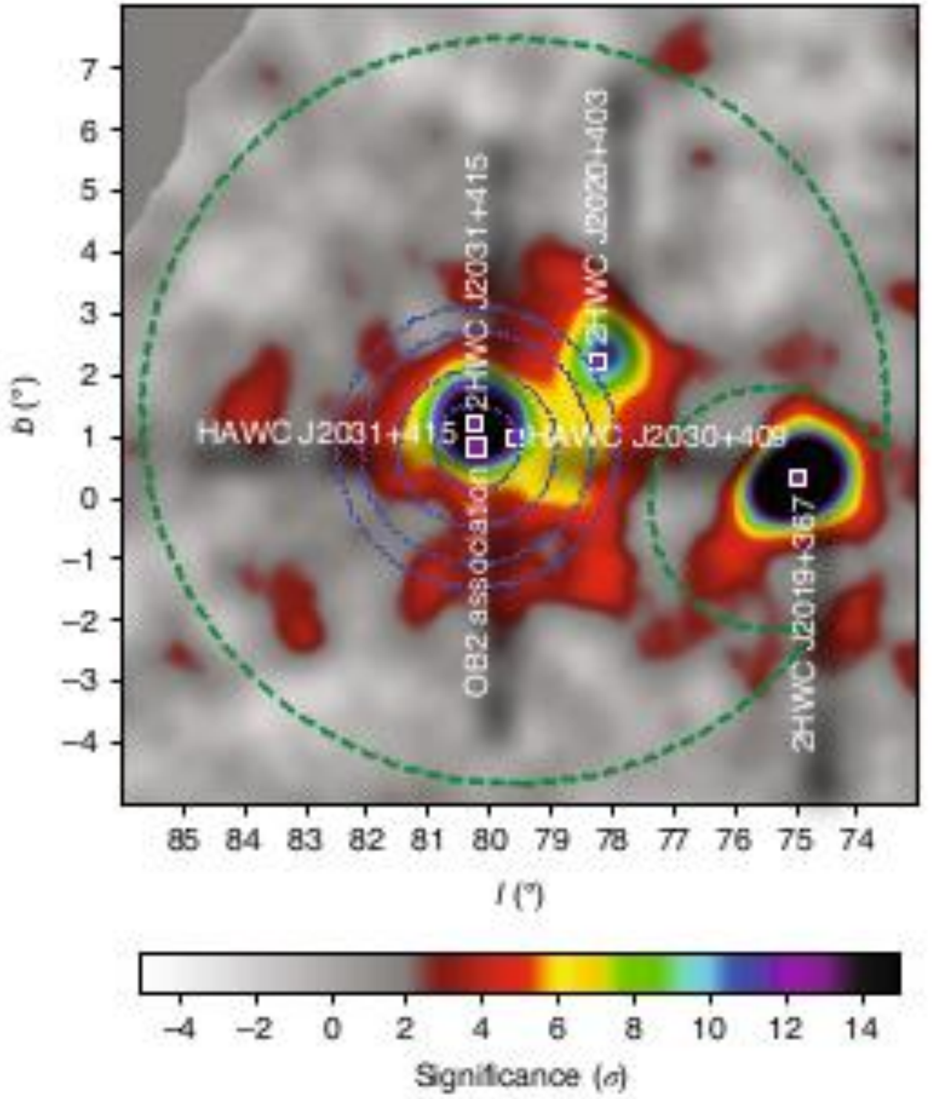
Credit: Binita Hona (U. Utah)



- Significance map with 1343 days of GP data
- Green Contour region of interest (ROI), 2HWC J2019+367 masked in the ROI

Sources	2HWC Catalog	HAWC Location (RA, Dec)
PWN	HAWC J2031+415	307.89°, 41.58°
Cocoon	**HAWC J2030+409**	**307.65°, 40.93°**
Gamma Cygni SNR	2HWC J2020+403	305.16°, 40.37°

3/4.- The HAWC observatory at México

The History of Pevatrons: HAWC and the Cygnus Cocoon

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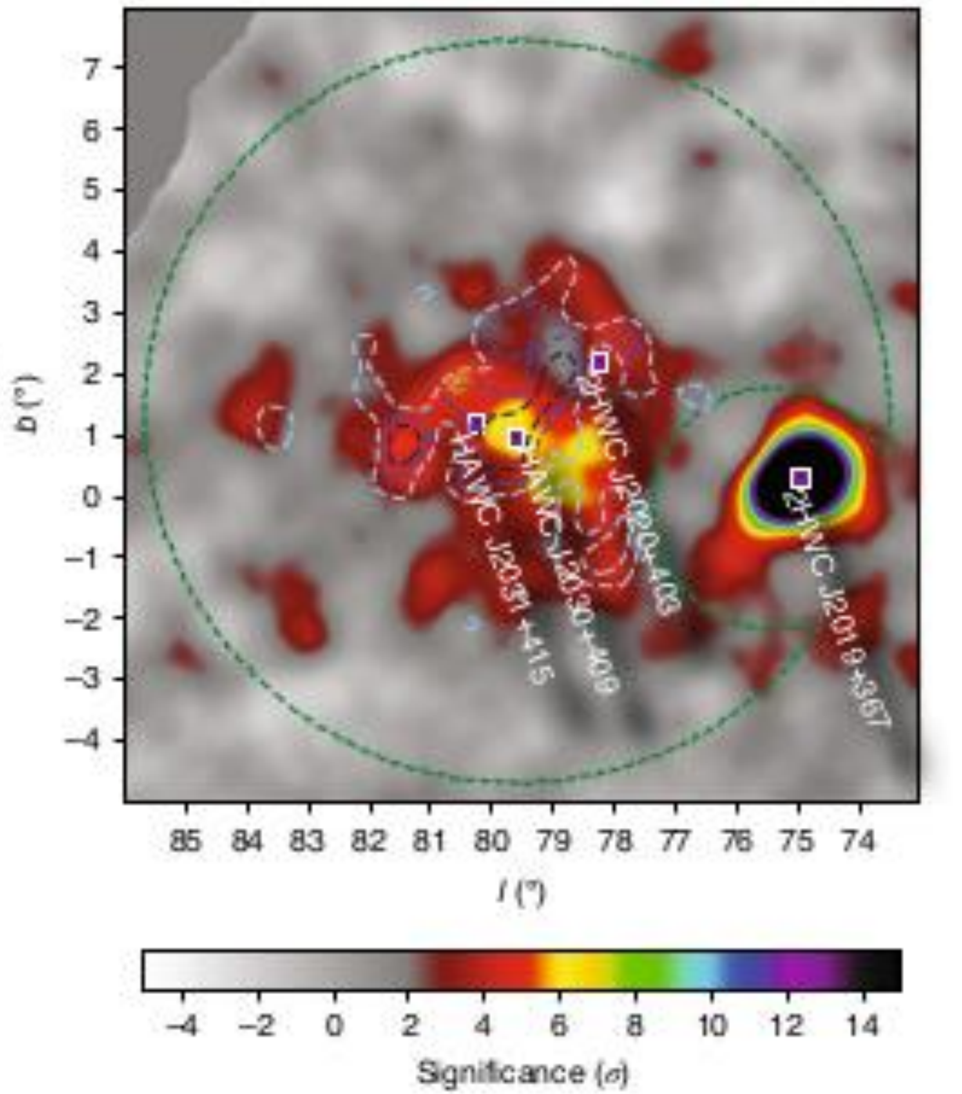

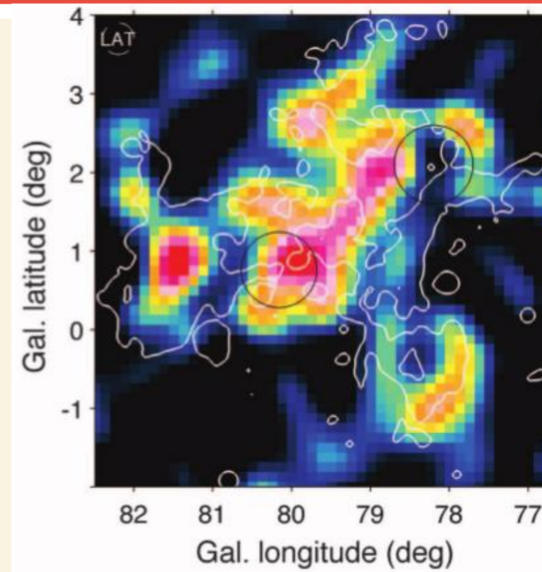

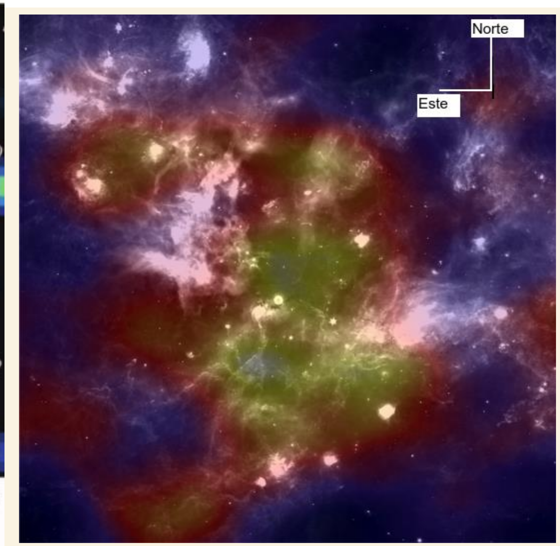

- Significance Map after subtracting the HAWC PWN and Gamma Cygni
- Light blue to dark blue contours are Fermi-LAT (RA, Dec) 0.16, 0.24, 0.32 photons/bin contours
- Cocoon significantly detected in HAWC data
- Morphology is described by a Gaussian width of $(2.12 \pm 0.16(stat.))°$
- Gaussian width is similar to reported by Fermi-LAT

3/4.- The HAWC observatory at México

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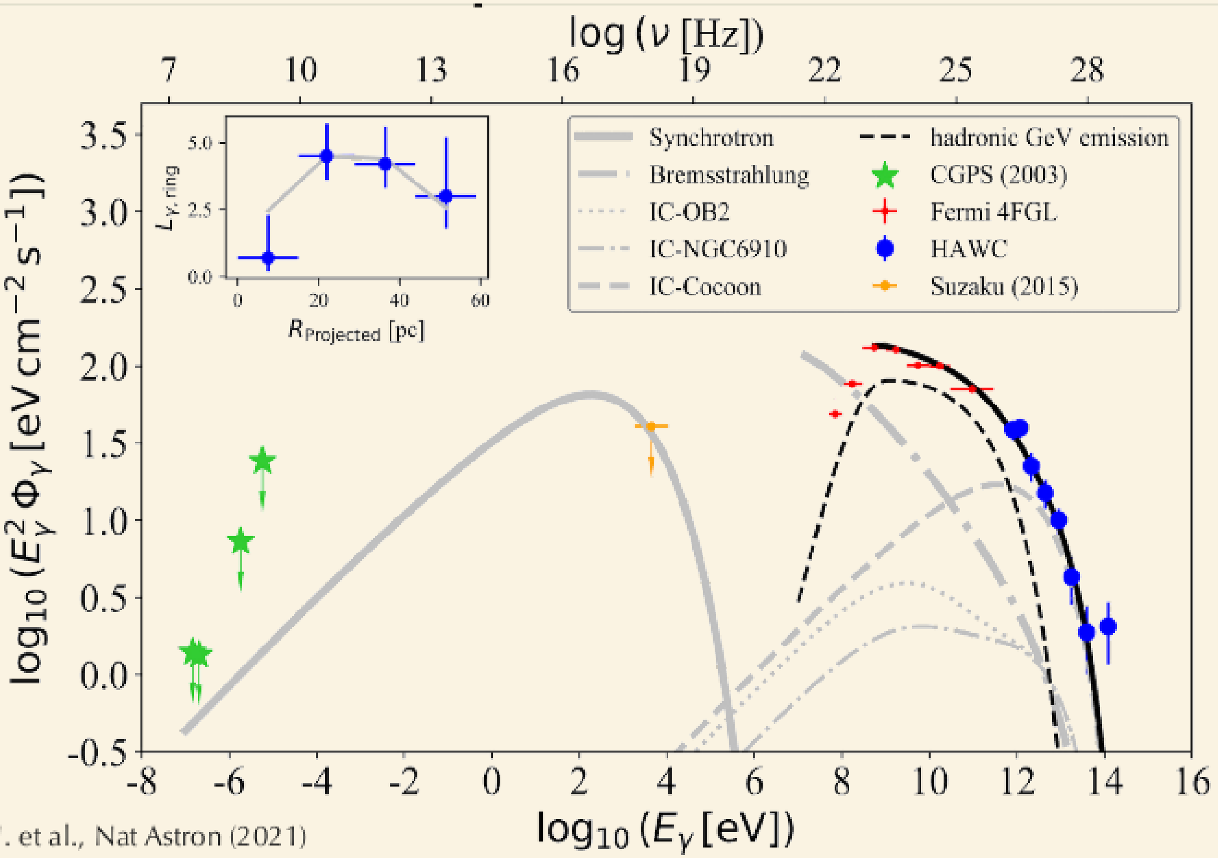
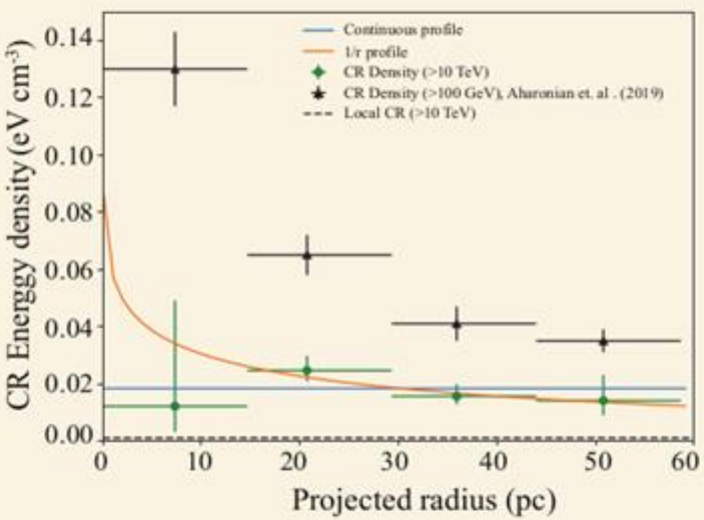


.U. et al., Nat Astron (2021)

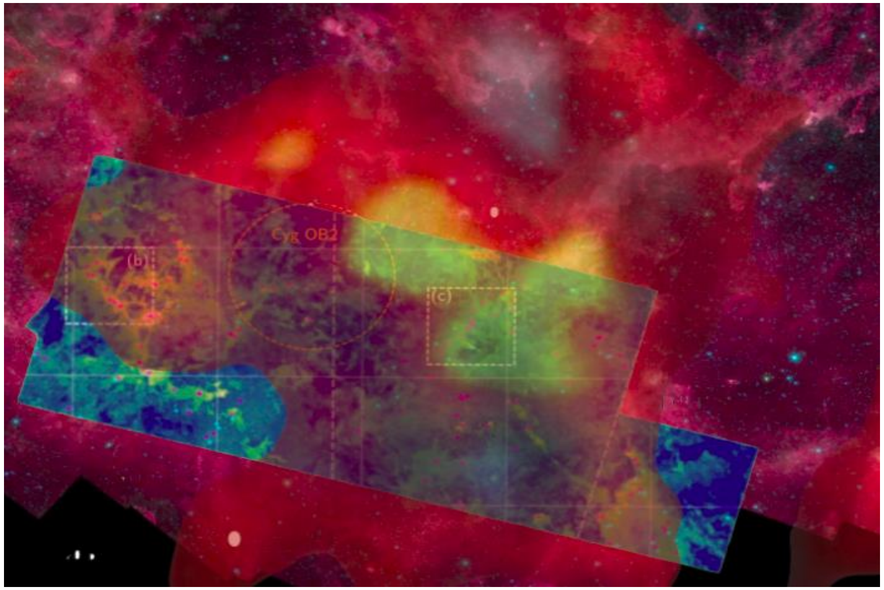


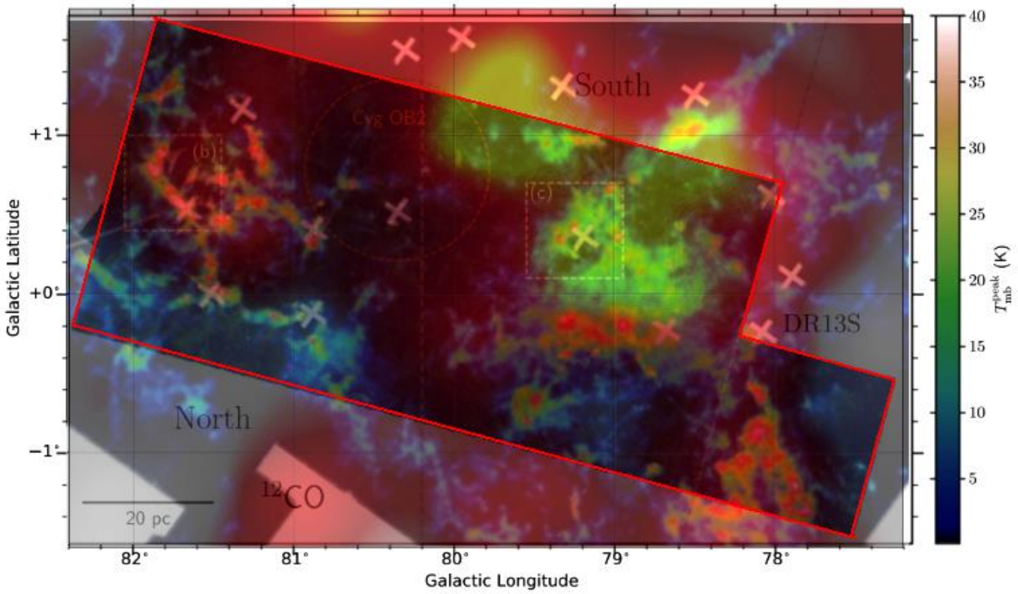
Rings (pc)	$L_\gamma(>0.7\mathrm{TeV})\mathrm{erg\,s^{-1}}$	$w_{CR}(>7\mathrm{TeV})\mathrm{eV/cm^3}$
$0 < r < 15$	0.7 - 0.5 + 1.6	0.016 - 0.012 + 0.037
$15 < r < 29$	4.5 -0.9 + 1.2	0.033 - 0.007 + 0.009
$29 < r < 44$	4.2 - 0.9 +1.4	0.019 - 0.004 + 0.006
$44 < r < 55$	3.0 -1.2 + 2.3	0.017 - 0.006 + 0.012

- Green circles: Projected CR density against the distance from the center of the OB2 association.
- Significantly detected above local CR (>10 TeV)
- Can be described by 1/r signature for continuous injection or constant profile for burst like injection
- Black triangles: CR density from *(Aharonian et. Al, Nature Astronomy, 2019)*

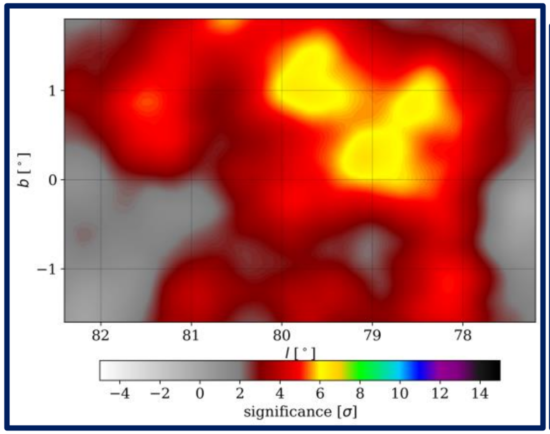
3/4.- The HAWC observatory at México

Molecular gas at Cygnus-X and Cygnus Cocoon

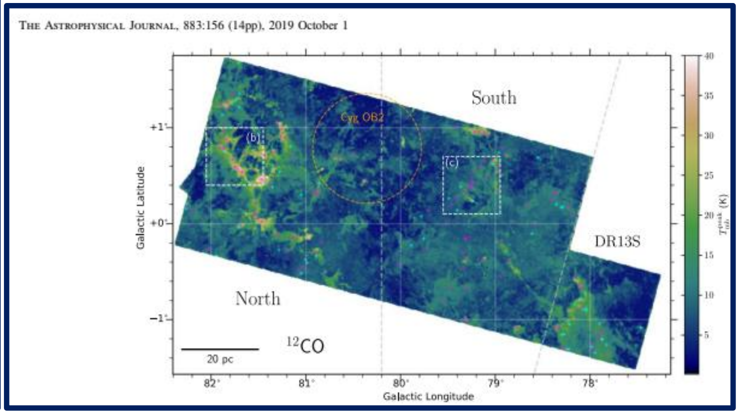




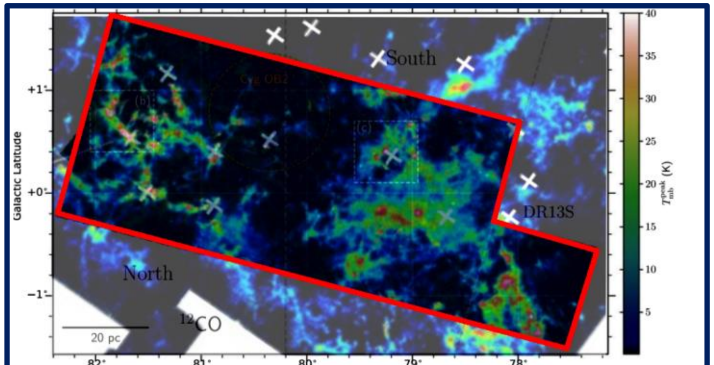
HAWC



Takekoshi et al. 2019, ApJ, 883, 156



Schneider et al. 2011, A&A, 529, A1



FCRAO 13CO(1-0)

3/4.- The HAWC observatory at México

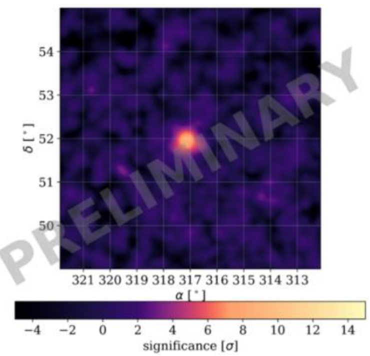
4.- The Future of HAWC in Science (PeVatrons):

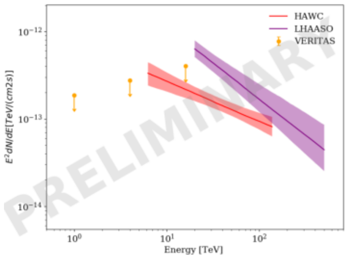
- **To study the PeVatrons of the HAWC catalog including OUTRIGGERS data.**
- **To date, analisis of next three sources are in progress:**

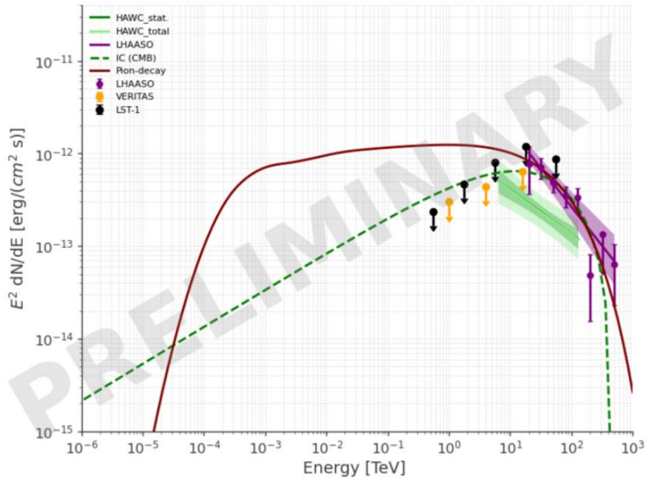
eHWC J1809-193 (HESS J1809-1917): An object identified as a PeVatron candidate not included on LHAASO catalog (2021). Possible associations are PSR J1809-1917 or G11.0-00. One way or another, the PeVatron seems to be related to PWN or SNR. Refer to APS 2023 meeting "HAWC Analysis of HESS J1809-193: a potential hadronic PeVatron?" by Rishi Babu (MTU Ph. D. Candidate).

LHAASO J2108+5157 (HAWC + Veritas Study)

A Jewel of the crown for LHAASO observatory





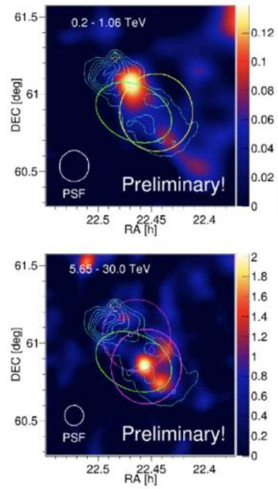


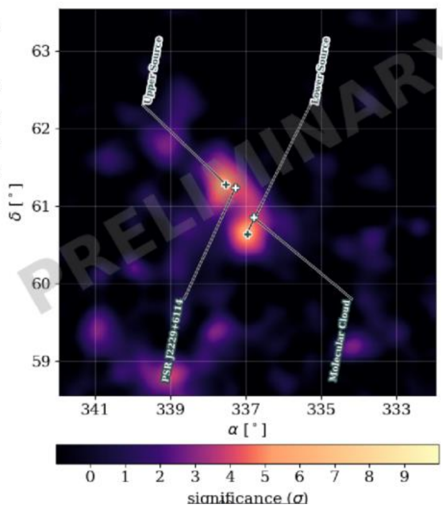
Associated with a molecular cloud, in Cygnus OB-7. Excellent place for a hadronic study.

SNR G106.3+2.7 (HAWC and MAGIC studies)

This impressive SNR is hard to claim as PeVatron

https://pos.sissa.it/395/796

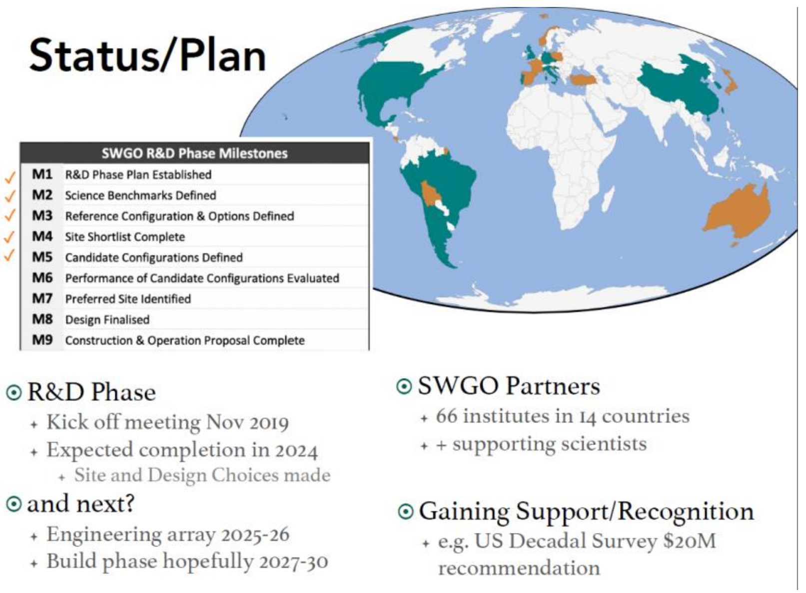


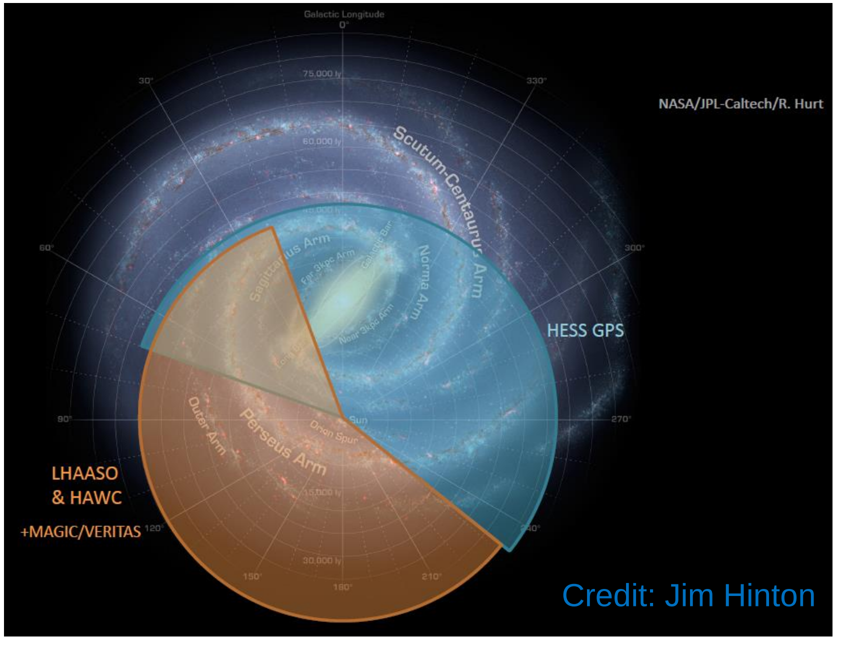


With better data HAWC resolve the inner emission of the first work (2020) in two sources: one related with a PWN (leptonic), and other related with a molecular cloud (hadrons). This result is observed by MAGIC too.

4.- The Future of HAWC: to share experience to build a new (complimentary) third-generation instrument:

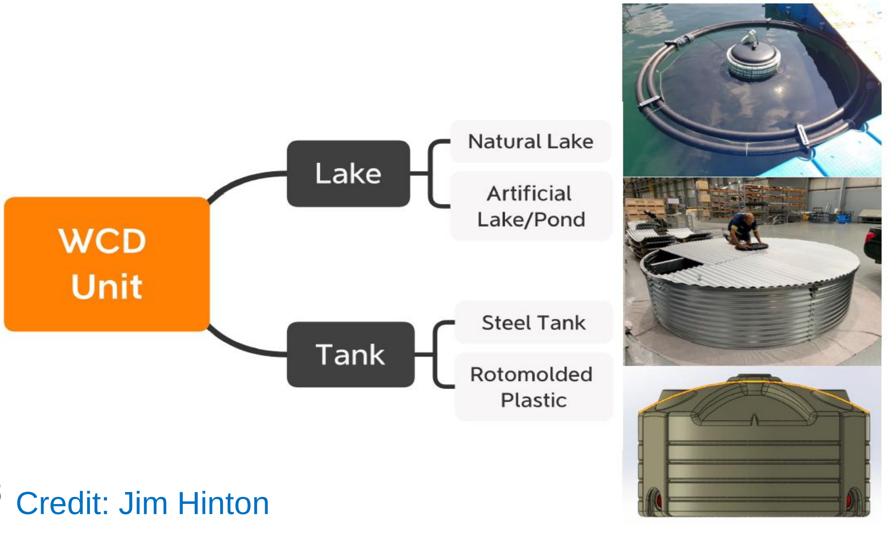
The Southern Wide-field Gamma-ray Observatory (SWGO)

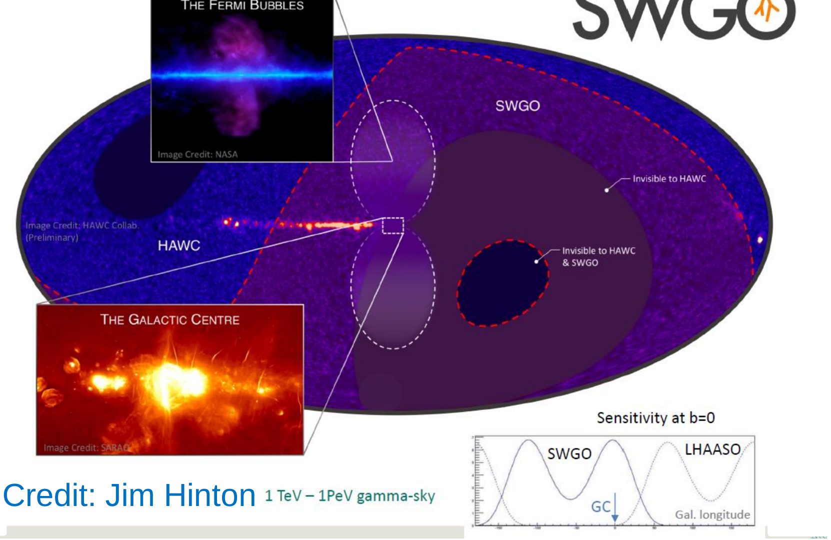




Credit: Jim Hinton

https://www.swgo.org/SWGOWiki/doku.php





Credit: Jim Hinton 1 TeV – 1PeV gamma-sky

 Credit: Jim Hinton

THANK YOU!.

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