


# HAWC: Pevatrons and Star Formation Regions


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ICRR Seminar, August, 2, 2021

# Eduardo de la Fuente Acosta

Bs. Sc. Physics at Universidad de Guadalajara, Mexico

M. Sc. in Astronomy at Instituto de Astronomia of UNAM

Ph. D. in Physics at Universidad de Guadalajara, Mexico with especiality in Radio Astronomy

Postdoc at INAOE Nat. Lab in México, working on HAWC since its origin in 2007

Sabbatical stay on 2021 at ICRR to work in Alpaca and Hyper-Kamiokande, to boost the participation of Mexico.

# OUTLINE

1.- Astroparticles and Gamma-Ray  Astronomy

2.- Ultra-High Energy (UHE) Gamma-Ray (GR) Astronomy and the Pevatrons

3.- Towards the UHE-GR: The HAWC TeV GR Observatory

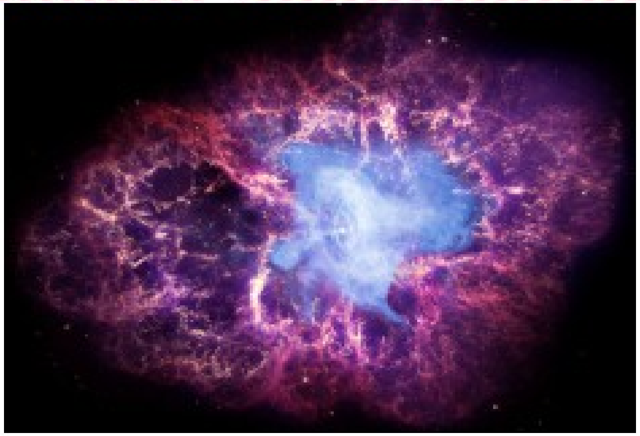
4.- HAWC and the Cygnus cocoon: Stars meets Pevatrons

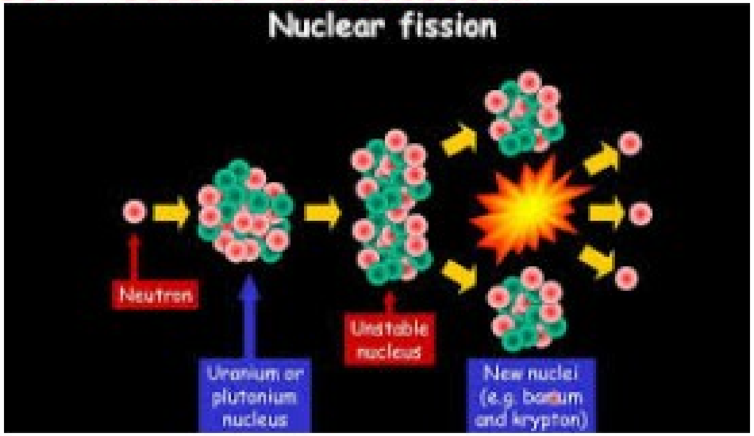
5.- Looking for Pevatrons: Starting a new study in Cygnus

6.- General conclusion: A new epoch on HEP

# Astroparticles and Gamma-Ray Astronomy

## High Energy Physics / Particle Physics can be divided in:






1.- ACCELERATOR PHYSICS 2.- ASTROPARTICLES 3.- NUCLEAR PHYSICS

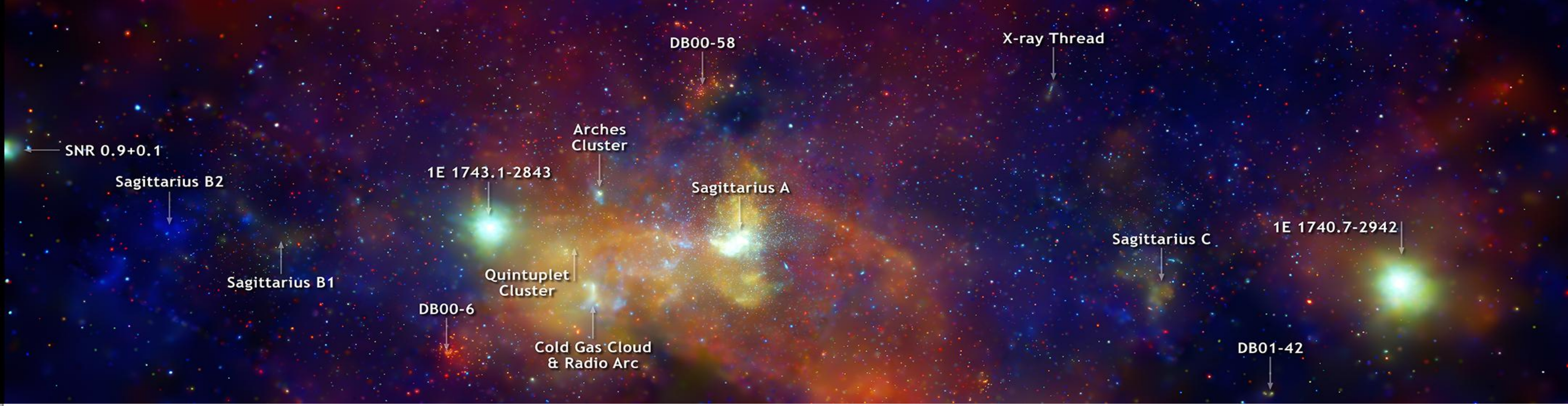
**Particle Accelerators:**
**1.- Artificial, and 2.- Natural**

**Large Hadron Collider, (LHC)Geneva $7x10^{12}$ eV**

**THE ENERGY IS THE KEY**

**Nature accelerates cosmic rays to $3x10^{20}$ eV**

**HAWC: Pevatrons and Star Formation Regions**




1.- GAMMA RAY (GR)
2.- COSMIC RAYS (CR)
3.- NEUTRINOS

-QUESTIONS TO ANSWER:

1.- ORIGIN (Where are they from?)

2.- IDENTITY (What are they?),

3.- ACCELERATION (How do they get their energy), and

4.- PROPAGATION (What happend on their way)

- HOW: By measuring their

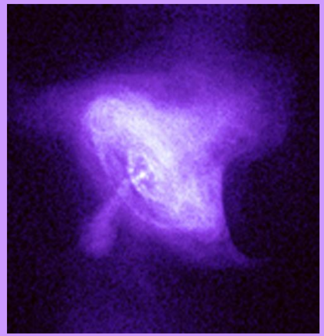
1.- ENERGY SPECTRUM
2.- COMPOSITION
3.- ARRIVAL DIRECTION

EXTREME ENERGIES in
EXTREME ENVIROMENTS
(Astronomical places)

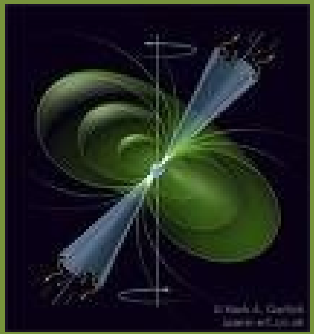
# Nature's Particle Accelerators are Gamma-Ray Sources

Galactic

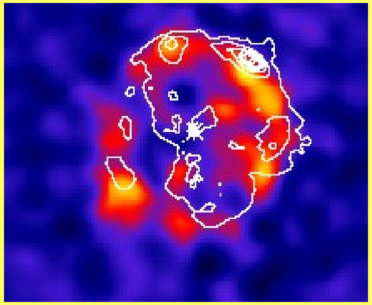
Pulsars Wind Nebula



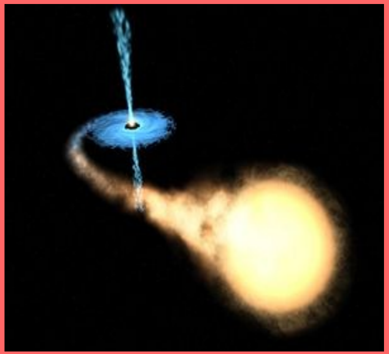
Pulsars



Supernova Remnant

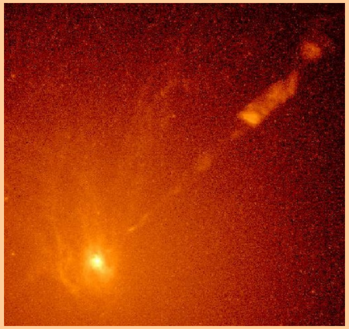


X-ray Binaries



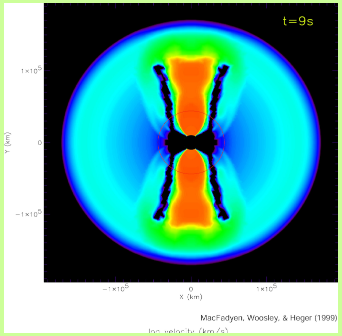
ExtraGalactic

Active Galactic Nuclei

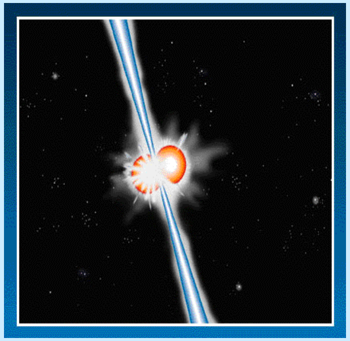


Starburst Galaxies

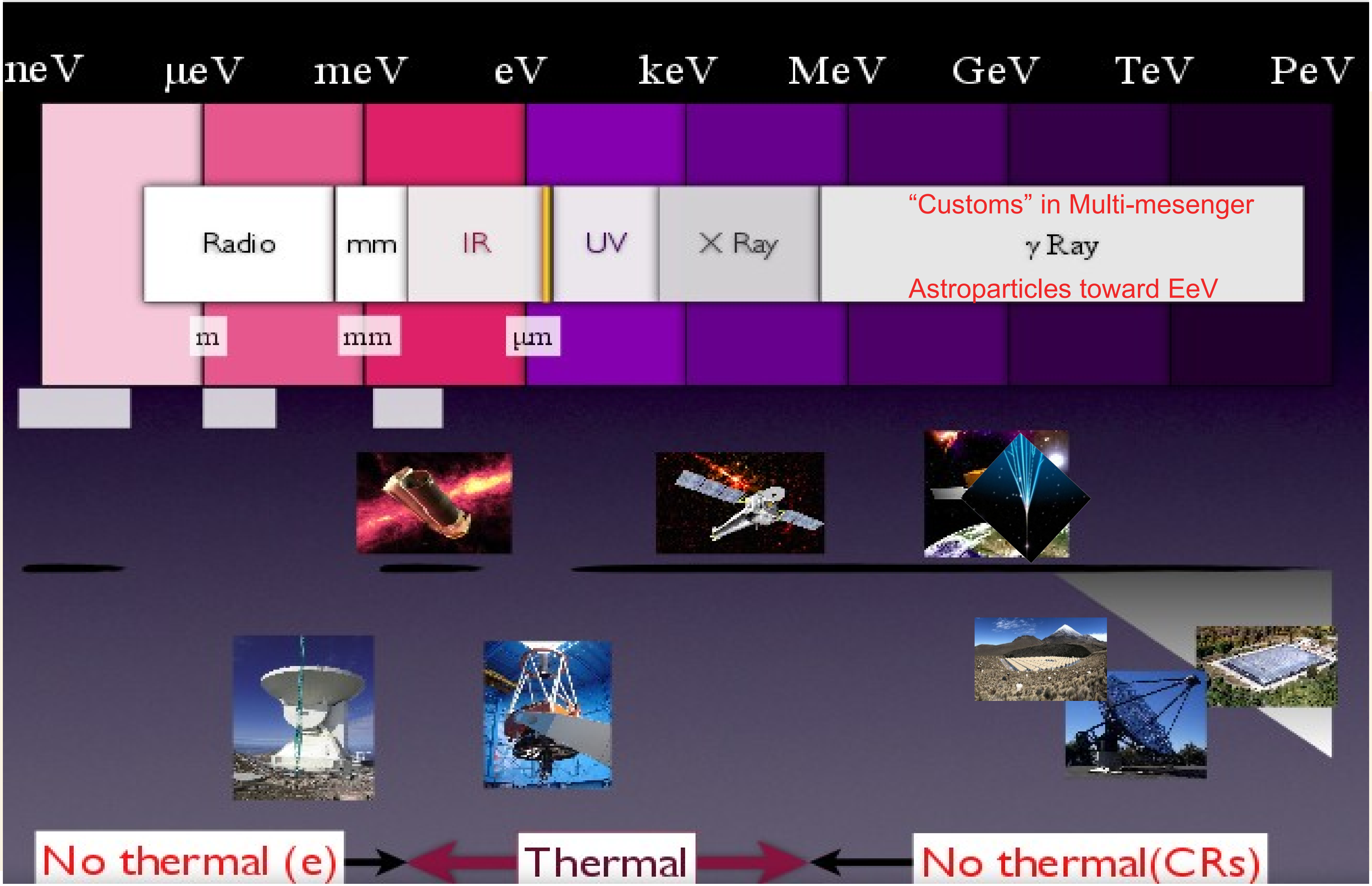
Long Gamma-Ray Burst




Short Gamma-Ray Burst



# Gamma-Ray (GR) Astronomy - Astroparticles

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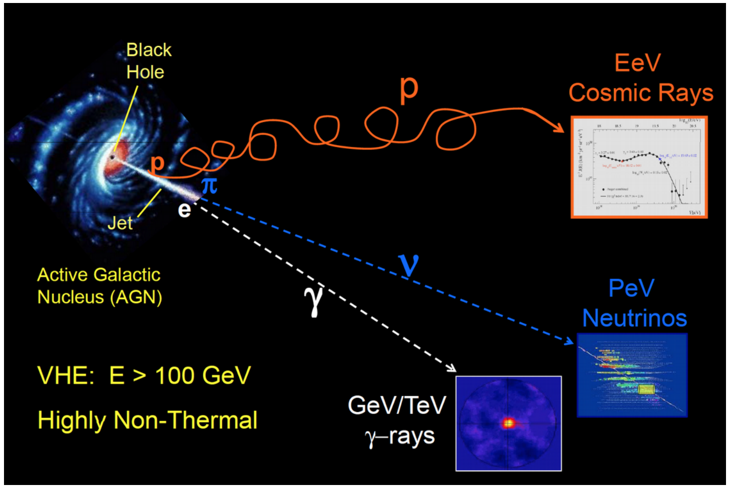
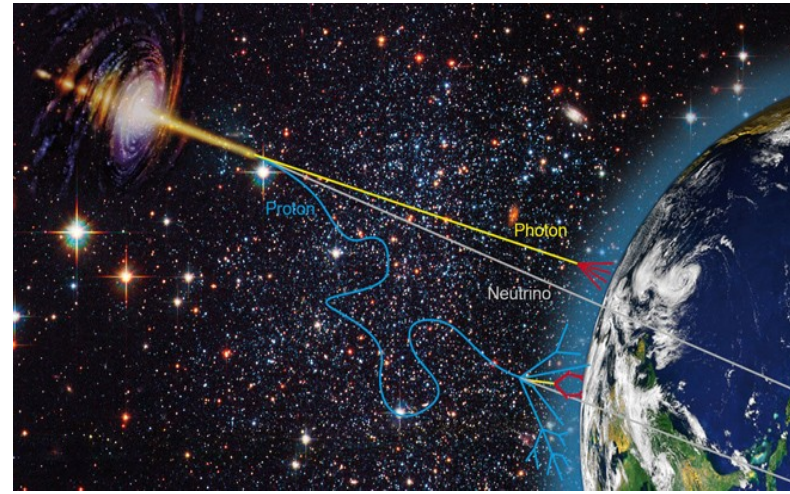
# Gamma-Ray Astronomy and Accelerators (Friends)



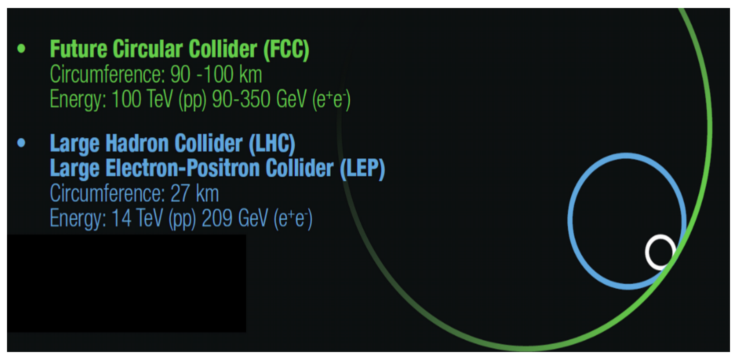

## ASTROPARTICLES:

1.- Gamma rays
2.- Cosmic rays
3.- Neutrinos




**Gamma-Ray Astronomical Tevatrons**

**Gamma-Ray Astronomy**




| | | | |
|---|---|---|---|
| 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 |

**Origin of cosmic-ray:**

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

- **Tevatron**
  Circumference: 6.2 km
  Energy: 2 TeV ($p\bar{p}$)

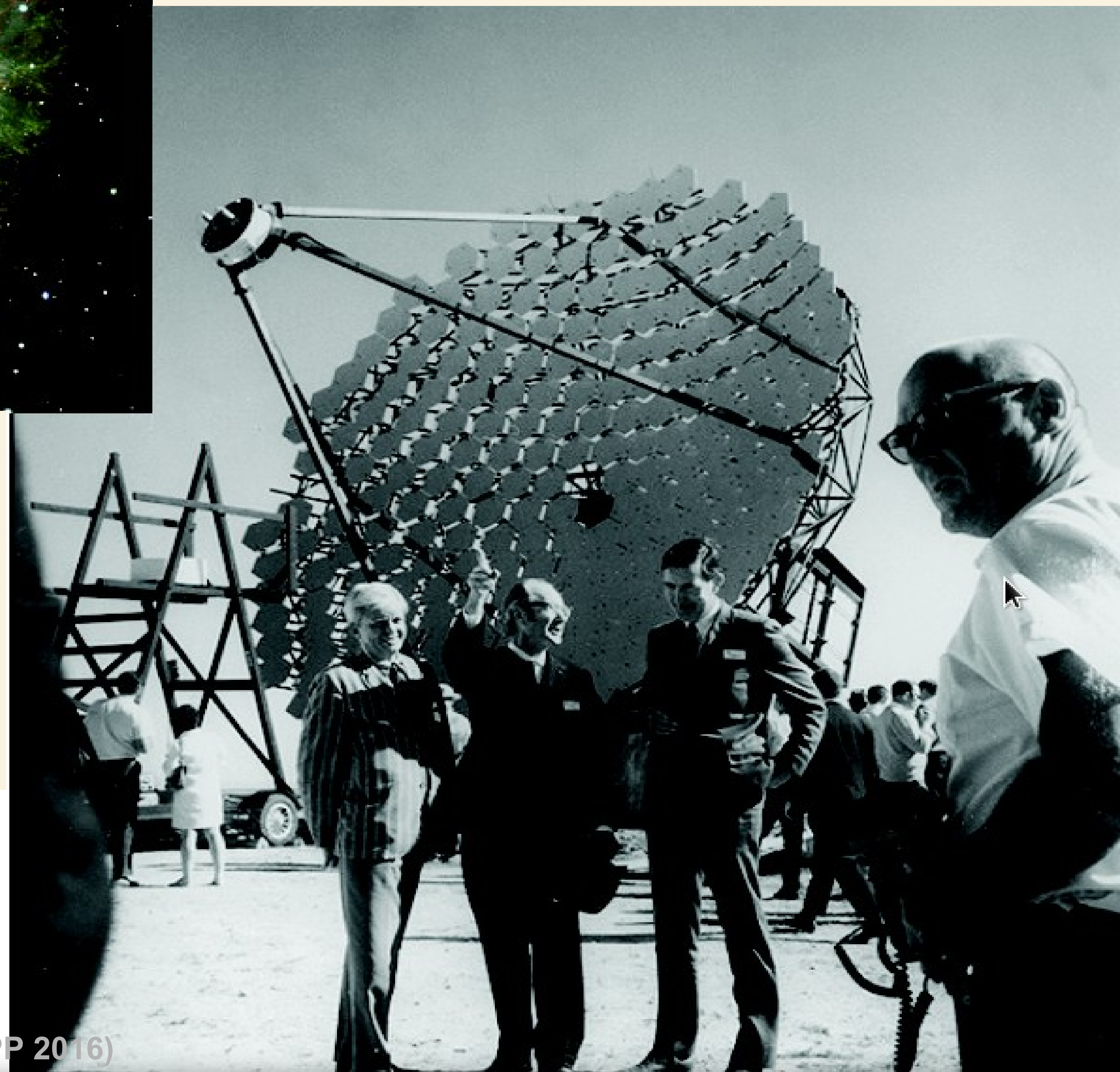
**Revolutions in the GR Astronomy:**

1.- Chereknov Obs. Maturity (TeV era)
2.- NASA-Fermi (GeV era)
3.- UHE and PeVatrons (PeV era)

**PeV Astronomy**

# The Birth of the VHE Gamma Ray Astrophysics

- The first success 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 a proof of direct acceleration of electrons in the Crab Nebula (1961)

# UHE γ-ray Astronomy:

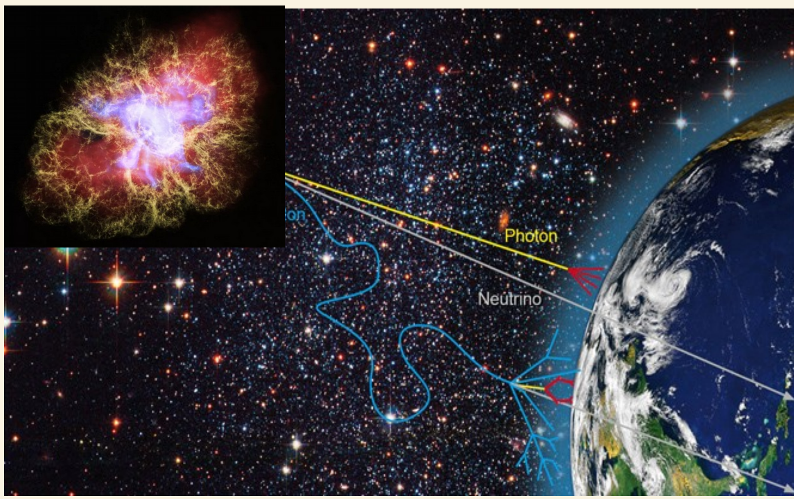
2021: A new window in Astronomy:

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

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

CONCLUSION: A new hot topic:

**The rise of the PeV era (Pevatrons)**




To date three high sensitivity observatories:

1.- High Altitude Water Cherenkov (HAWC)
2.- Tibet AS gamma
3.- Large High Altitude Air Shower (LHAASO)

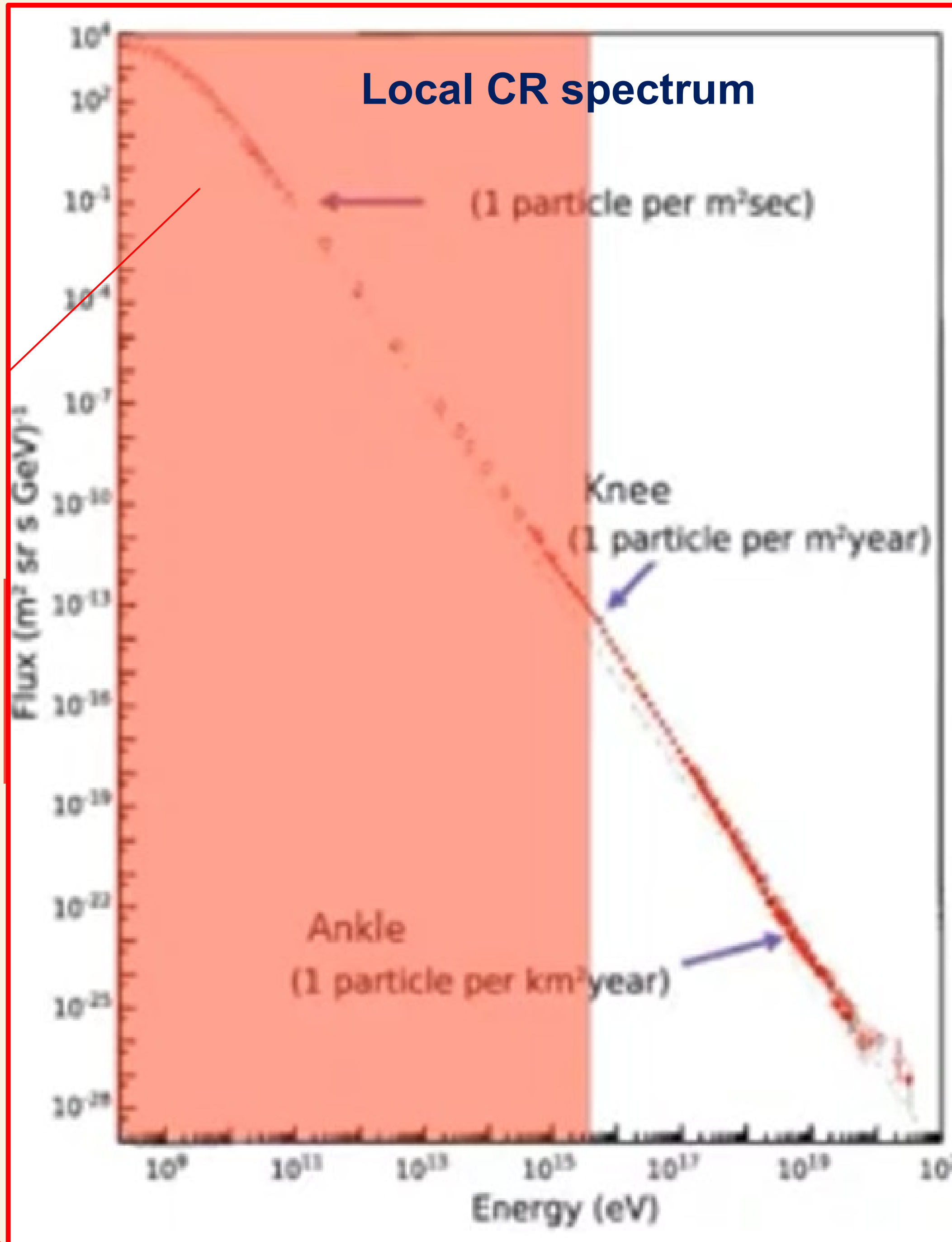
Between 2014-2021

- Which are the CR sources?
- How we can identify them?
- What acceleration mechanism?
- Effects on CR propagation?
- Isotropy (?)
- Chemical composition?

# Pevatrons

**CR ← → link with gamma rays and NEUTRINOS (HADRONIC Models) via**

**ENERGY DENSITY of the local CR spectrum**

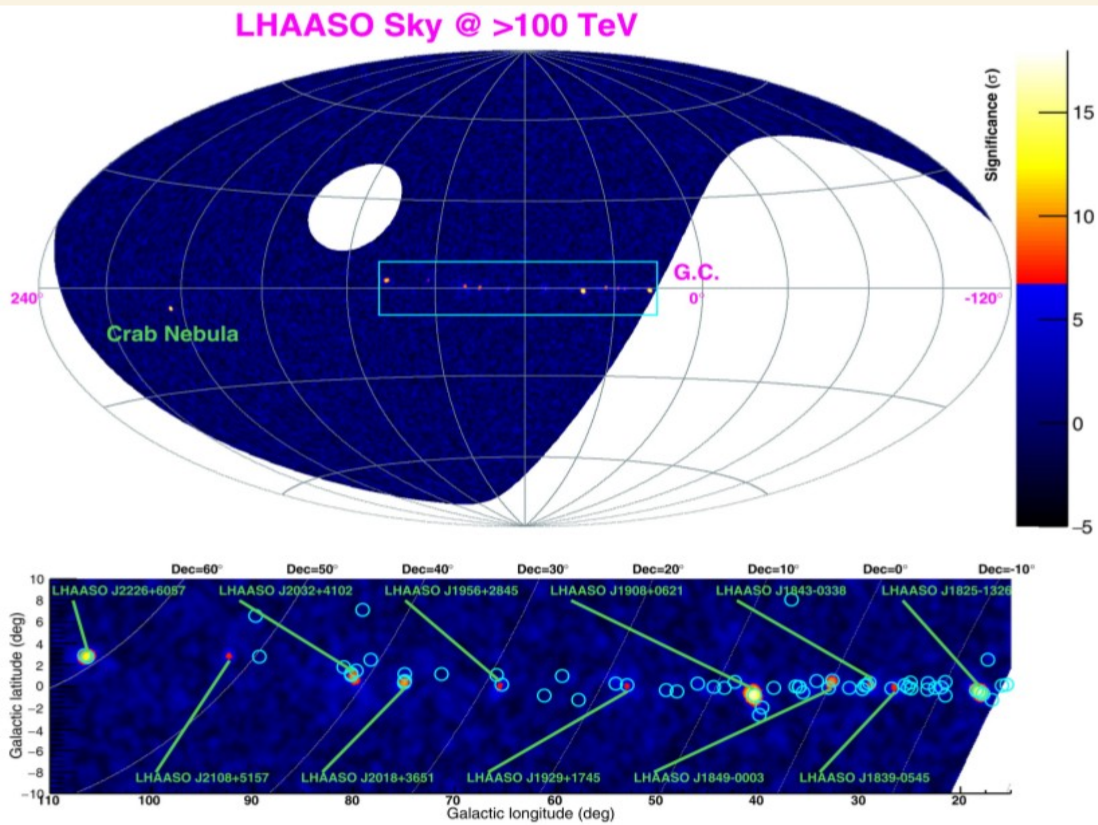


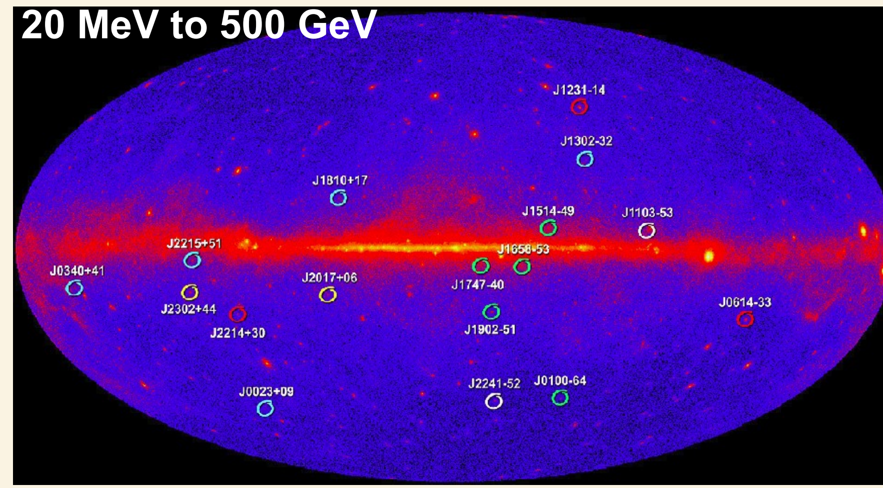
# Pevatron: (2021)

**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**

**No consensus in defintion yet (2021): An astronomical object that can accelerate particles at PeV energies. The conflic point is:  Only Hadrons?. (ICRC 2021).  LPev for PWNe, and HPev for individual SNR and stellar winds with v > 0.01 c and provided B > 0.01 G**




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

**Credit too:**

**Astronomical Tevatrons**

HAWC High Altitude Water Cherenkov Gamma-Ray Observatory

Tibet AS γ

## HAWC: Pevatrons and Star Formation Regions

Seminar at ICRR-Utokyo, August, 2, 2021

Dr. Eduardo de la Fuente Acosta (CUCEI-UdeG)

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# The History of Pevatrons (candidates): Timeline

## 1.- Galactic Center

**PeVatron term (observationally) in 2016**

**Pevatron (HESS refer to hadrons or protons)**

**Extreme particle accelerators that can reach such PeV energies**

Published: 16 March 2016

# Acceleration of petaelectronvolt protons in the Galactic Centre

HESS Collaboration

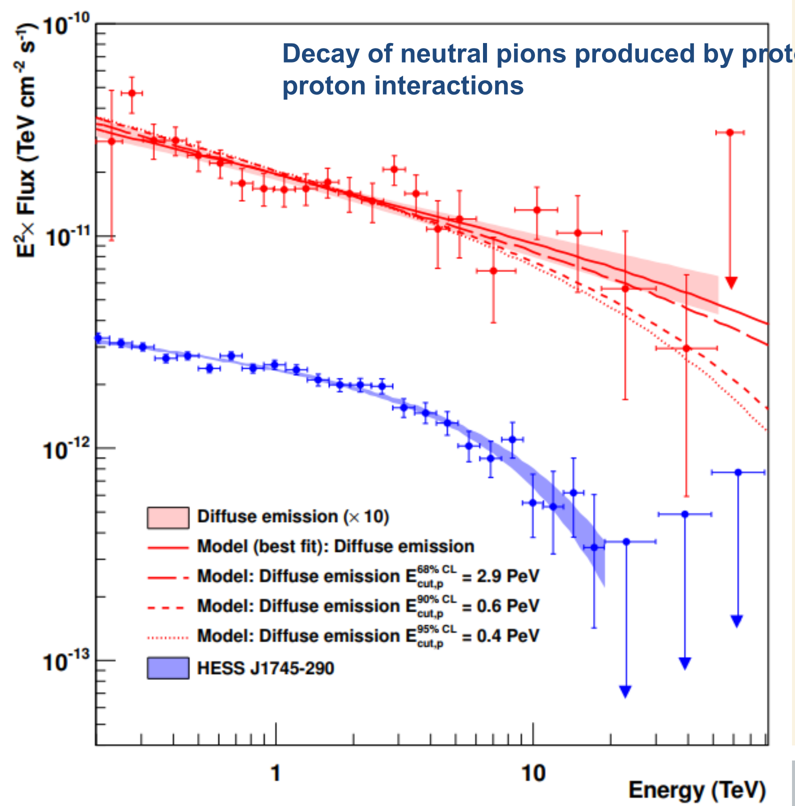
*Nature* **531**, 476–479 (2016) | Cite this article

This is the first robust detection of a VHE cosmic hadronic accelerator which operates as a source of PeV particles (a ‘PeVatron’).

They propose that the supermassive black hole Sagittarius A* is linked to this PeVatron.

**HESS array of Telescopes energy range:10s of GeV to 10s of TeV.**

**Decay of neutral pions produced by proton-proton interactions**




**White controus: molecular CS. Black: CR density**

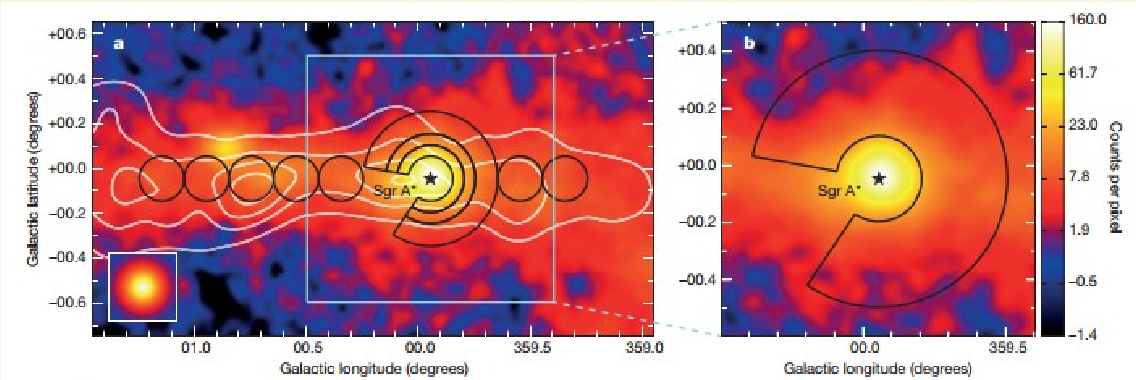
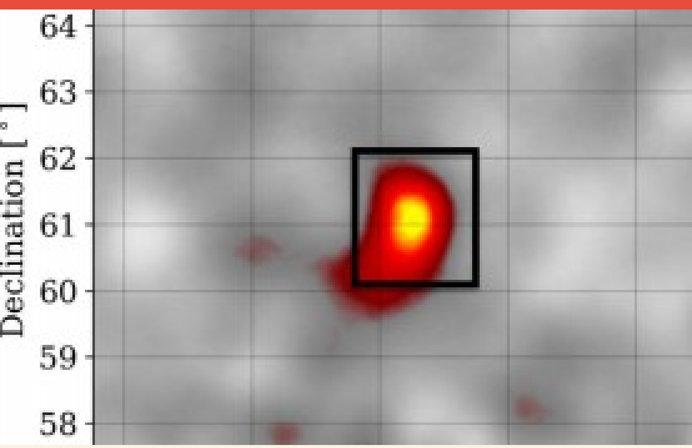
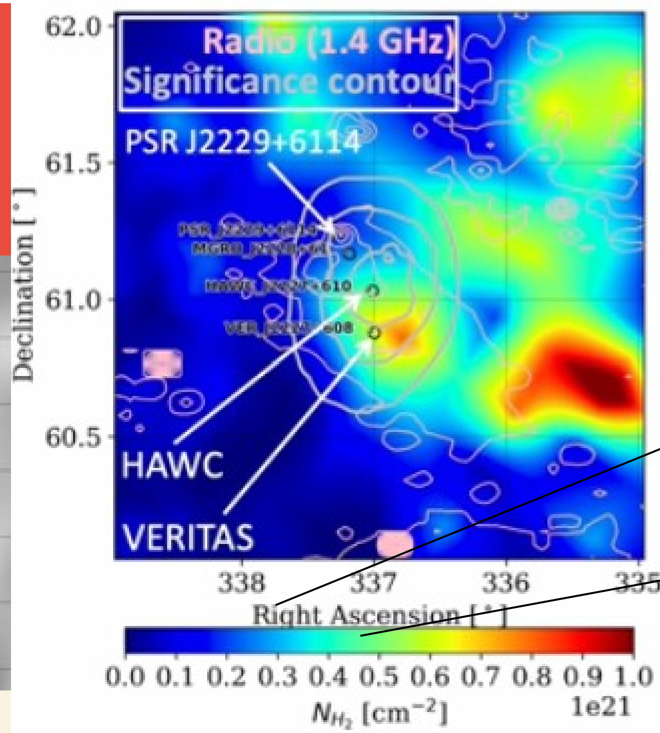



**Figure 1 | VHE γ-ray image of the Galactic Centre region.** The colour scale indicates counts per 0.02° × 0.02° pixel. **a**, The black lines outline the regions used to calculate the cosmic-ray energy density throughout the central molecular zone. A section of 66° is excluded from the annuli (see Methods). White contour lines indicate the density distribution of molecular gas, as traced by its CS line emission[30]. Black star, location of Sgr A*. Inset (bottom left), simulation of a point-like source. The part of the image shown boxed is magnified in **b**. **b**, Zoomed view of the inner ~70 pc and the contour of the region used to extract the spectrum of the diffuse emission.

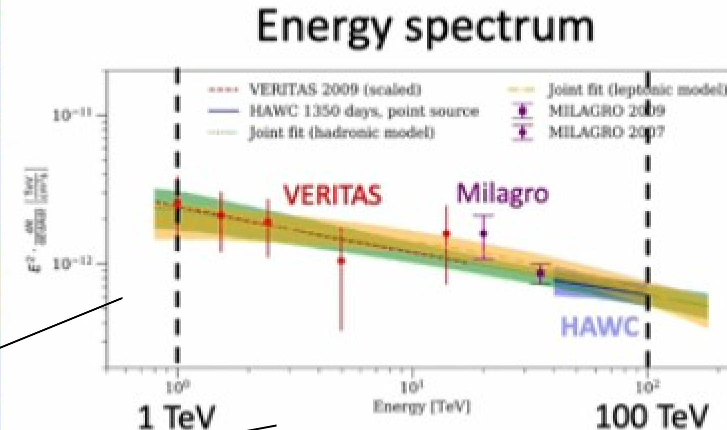
# The History of Pevatrons (candidates): Timeline

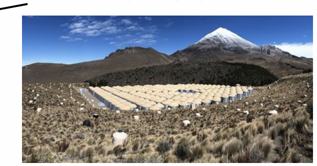
## 2.- SNR G106.3+2.7




HAWC Coll. ApJL, 896, L20 (2020)



**nature astronomy**

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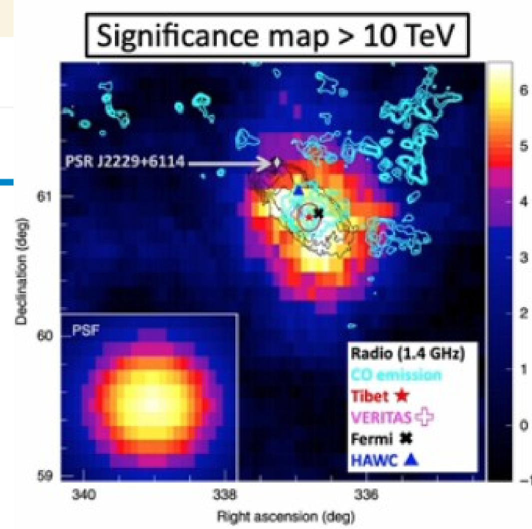
Letter | Published: 01 March 2021

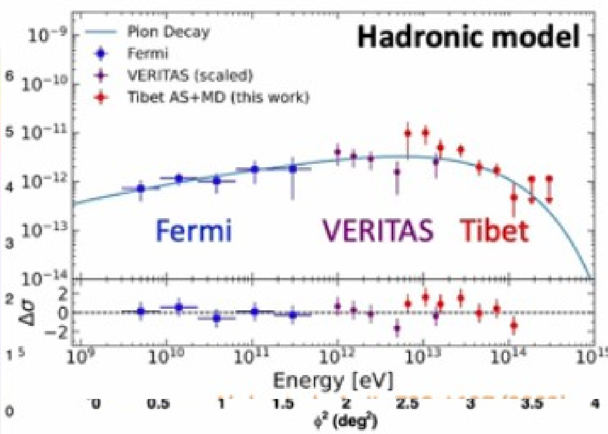
## Potential PeVatron supernova remnant G106.3+2.7 seen in the highest-energy gamma rays

The Tibet ASγ Collaboration

*Nature Astronomy* **5**, 460–464 (2021) | Cite this article




➤ Tibet source position: R.A. = 336.82°±0.16°
Dec = 60.85°±0.10°




| | $\alpha$ | $E_{cut}$ (TeV) |
|---|---|---|
| leptonic | $2.30^{+0.08}_{-0.07}$ | $190^{+127}_{-66}$ |
| hadronic | $1.79^{+0.08}_{-0.09}$ | $499^{+382}_{-180}$ |

nature



## The History of Pevatrons (candidates): Timeline

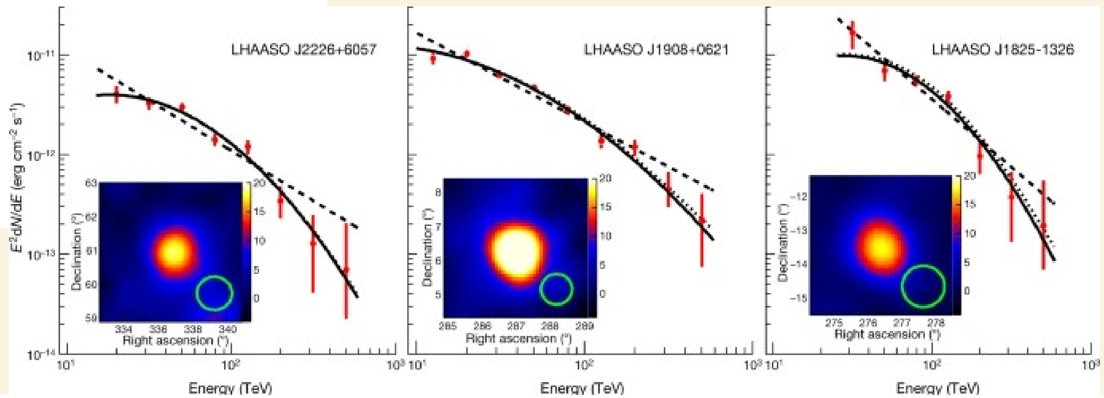
3.- Cygnus Cocoon
4 to 13- LHAASO + Crab

Article | Published: 17 May 2021

# Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

Zhen Cao, F. A. Aharonian, […]X. Zuo

*Nature* **594**, 33–36 (2021) | Cite this article




| 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) |

## FUTURE AND NEEDS OF PEVATRONS

**Conclusion: Open Topic.**

**WAIT THE THIRD DECADE OF XXI CENTURY**

- **Emerging of Southern Observatories like ALPACA, CTA, SWGO**
- **More resolution, not only sensitive.**
- **Constrain on Hadronic or Leptonic**

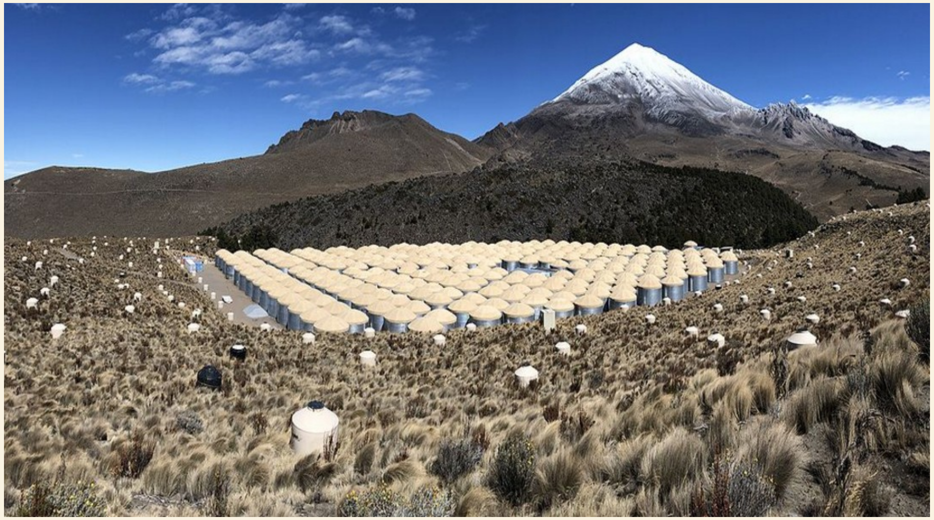
**Question: What is the maximum energy that nature accelerates particles in the Galaxy?**

***"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)***

**THUS TOWARDS THE UHE GR, ALLOW ME TO TALK ABOUT:**

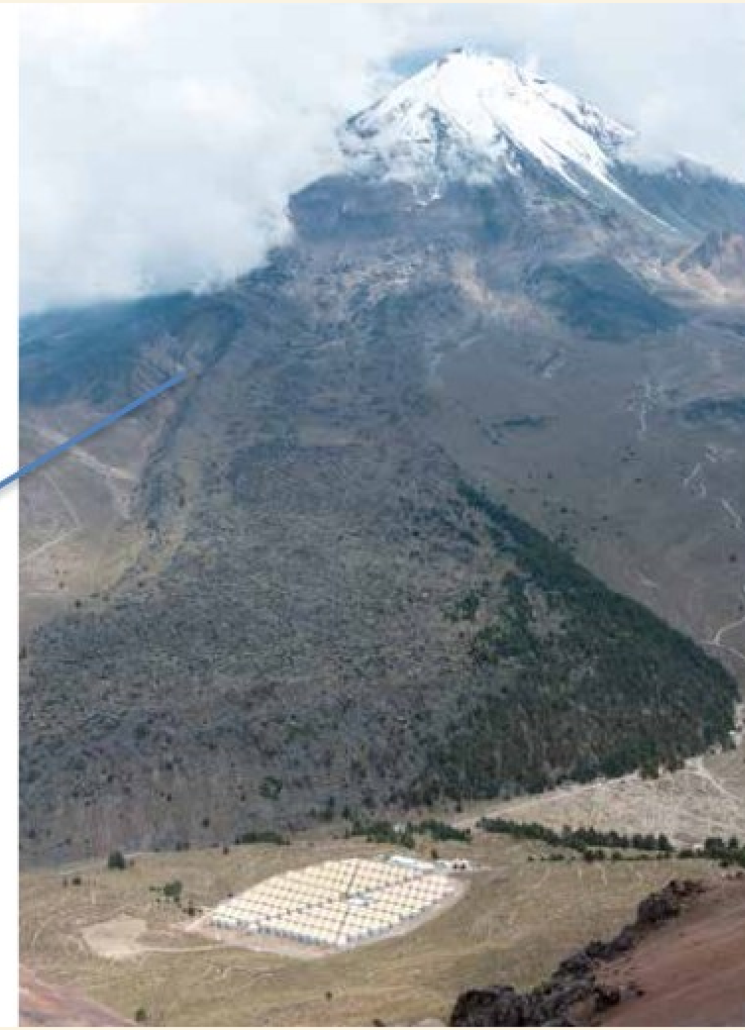
# The HAWC TeV Gamma Ray Observatory



ICRR Seminar, August, 2, 2021

# The High Altitude Water Cherenkov (HAWC) Observatory at México


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



HAWC: Pevatrons and Star Formation Regions

# The HAWC Collaboration

## Mexico

Instituto Nacional de Astrofísica, Óptica y Electrónica
Universidad Nacional Autónoma de México
- Instituto de Astronomía UNAM
- Instituto de Ciencias Nucleares UNAM
- Instituto de Física UNAM
- Instituto de Geofísica UNAM

Benemérita Universidad Autónoma de Puebla
Instituto Politécnico Nacional
- Centro de Investigación y Estudios Avanzados
- Centro de Investigación en Cómputo - IPN

Universidad Autónoma de Chiapas
Universidad Autónoma del Estado de Hidalgo

Universidad de Guadalajara

Universidad Michoacana de San Nicolás de Hidalgo

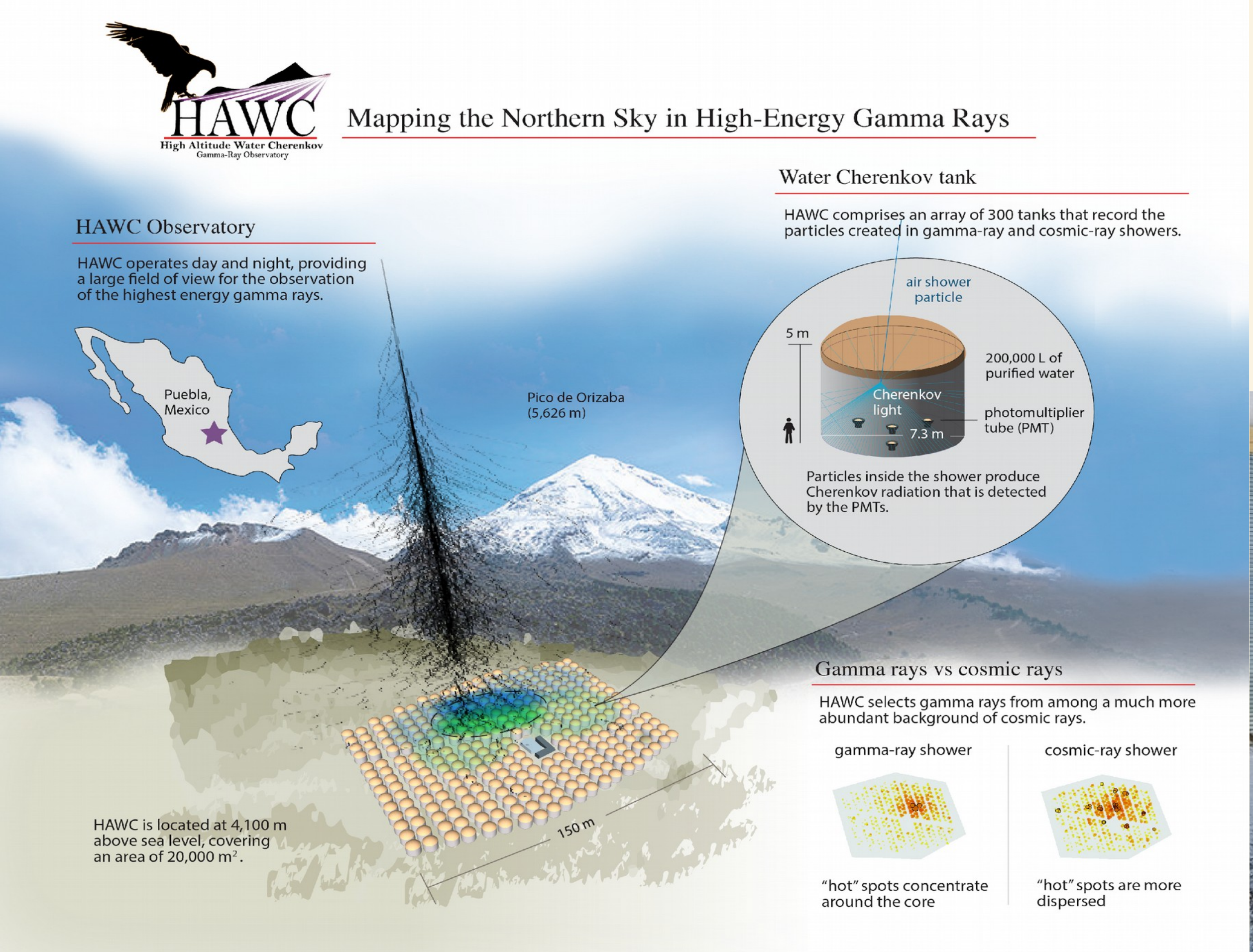
Universidad Politécnica de Pachuca

## United States

Los Alamos National Lab
University of Maryland
Georgia Institute of Technology
Michigan State University
Michigan Technological University
Pennsylvania State University
NASA GSFC
University of New Mexico
University of Rochester
University of Utah
University of Wisconsin

## Europe and (Costa Rica)

Max Planck Institute, Heidelberg
Univeristy of Costa Rica
Krakow Nuclear Institute, Poland

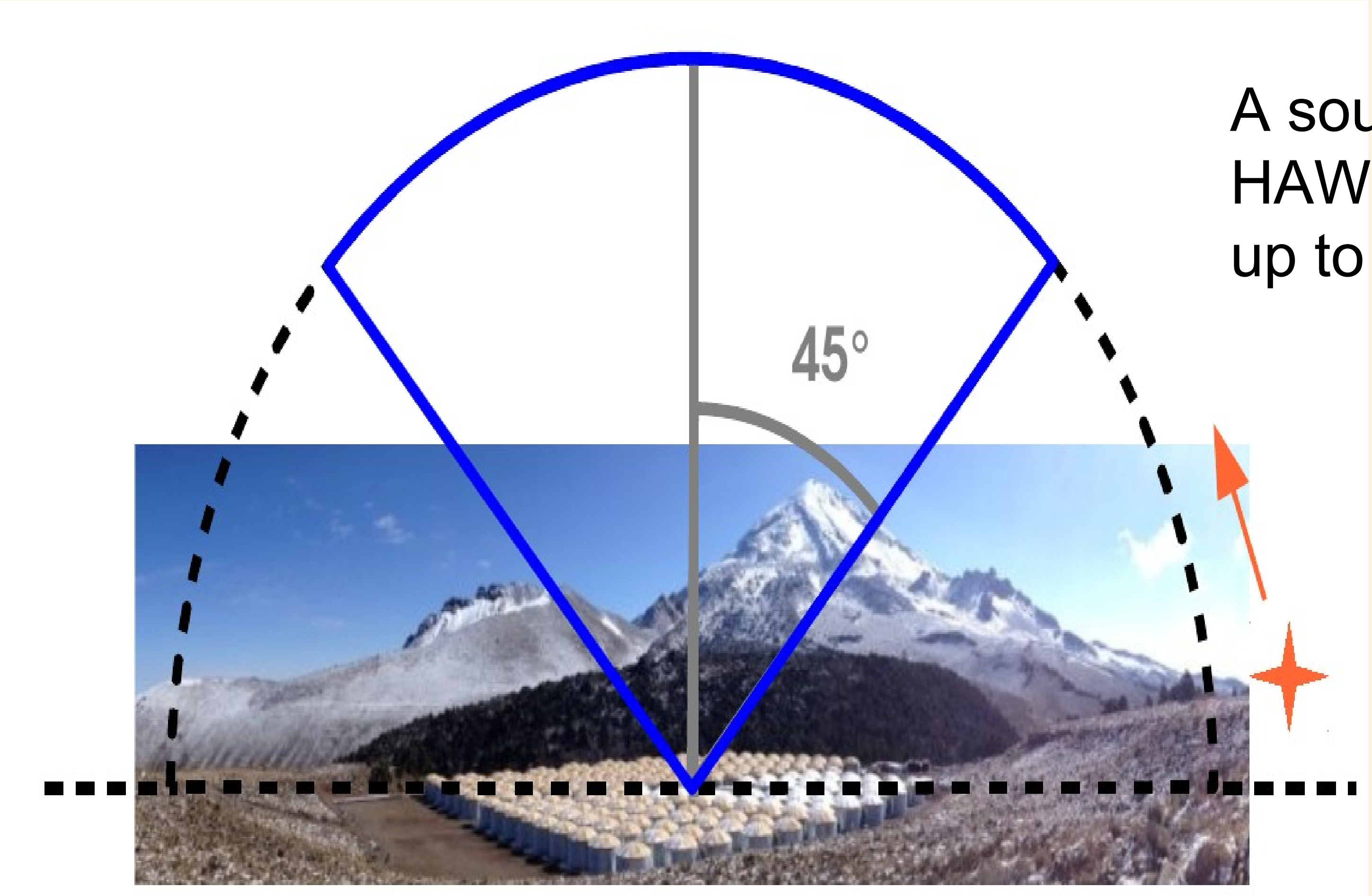





| | Milagro | HAWC |
|---|---|---|
| Detector Area | 3500 $m^2$ /2100 $m^2$ | 20,000 $m^2$ |
| Time to 5σ on the Crab | 120 days | 5hrs |
| Median Energy | 4 TeV | 1 TeV |
| Angular Resolution | $0.40^\circ - 0.75^\circ$ | $0.25^\circ - 0.50^\circ$ |
| Energy Resolution at 5 TeV | 140% | 72% |
| Energy 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 | $10^3$ $m^2$ | $20\times10^3$ $m^2$ |
| Eff Area at 10 TeV | $20\times10^3$ $m^2$ | $50\times10^3$ $m^2$ |
| Eff Area at 50 TeV | $70\times10^3$ $m^2$ | $70\times10^3$ $m^2$ |
| Volume of Universe where $3\times10^{-6}$ 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**

# The High Altitude Water Cherenkov (HAWC) Observatory at México

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

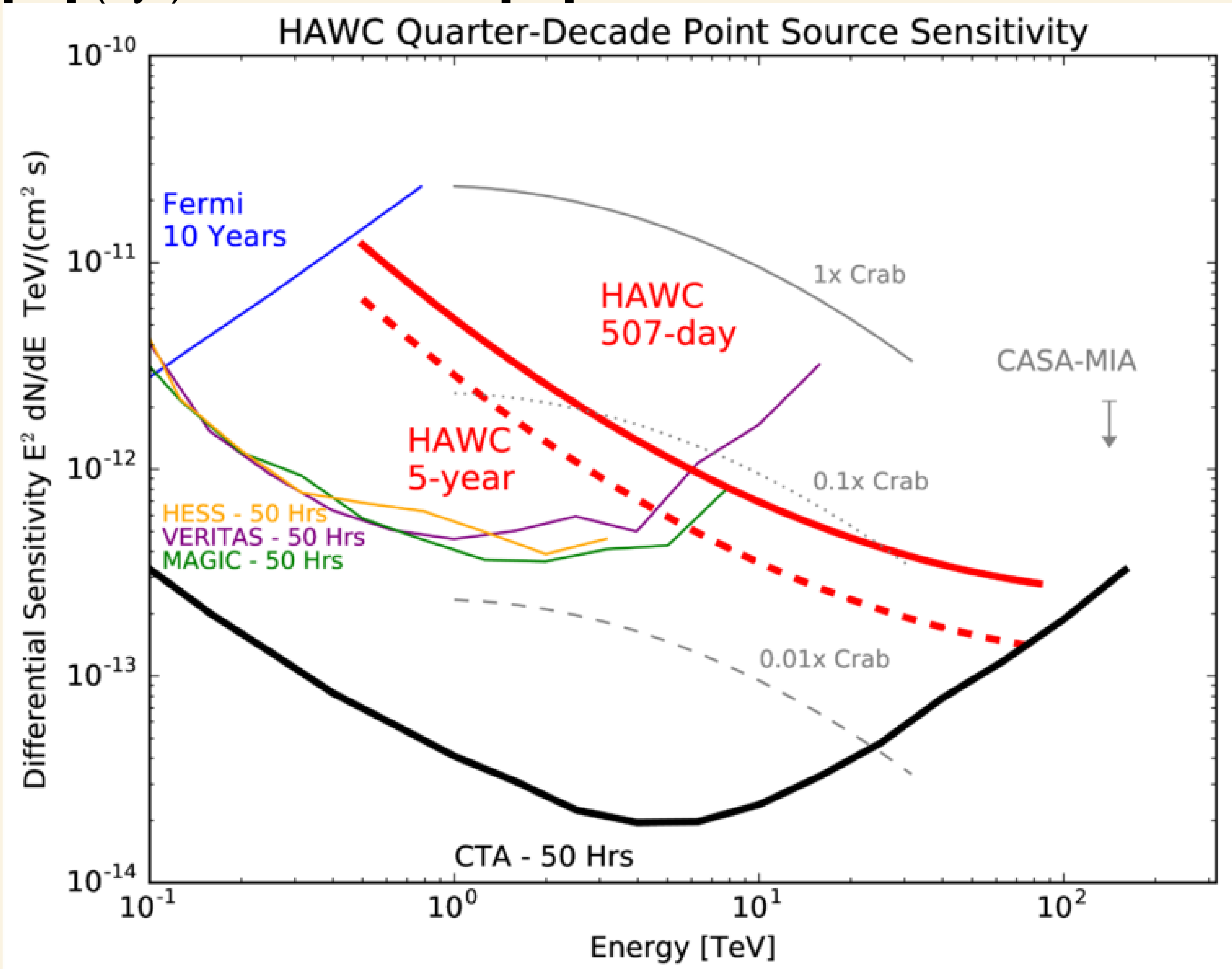
Instantaneous sensitivity about 15-20x less than IACTs:

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

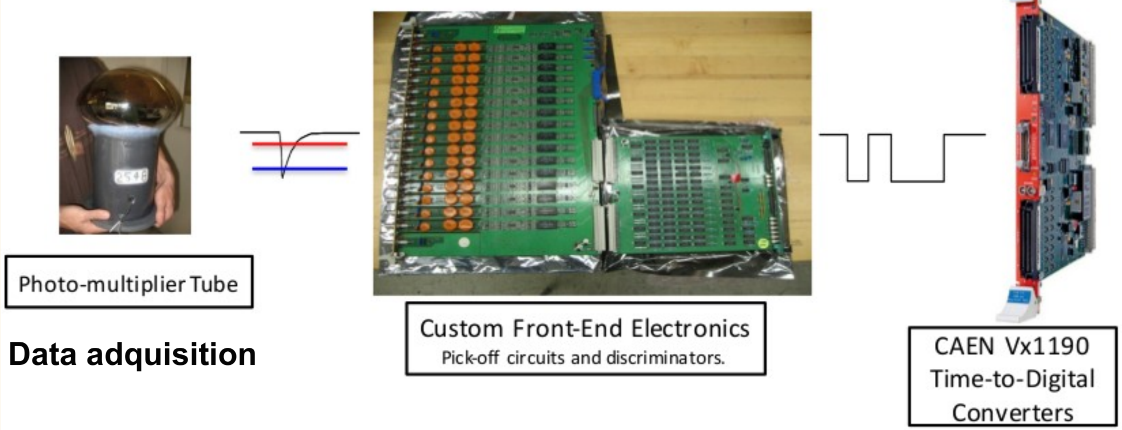
Exposure (sr yrs) is 2000-4000x higher.

~1500 hrs/src/yr

For hard or extended sources, HAWC improves relative to IACTs

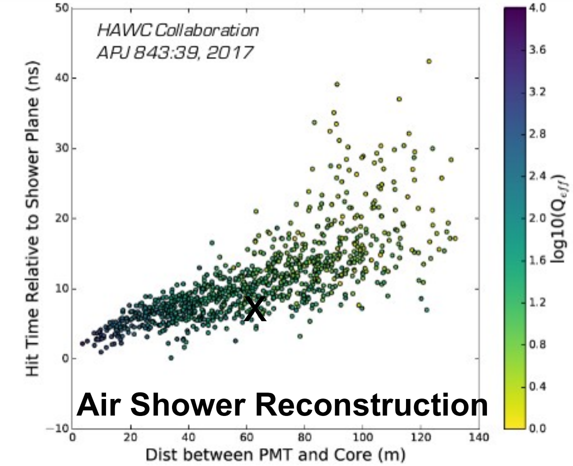


HAWC Collaboration
Nucl. Instrum. Meth. A 888 (2018) 138-46

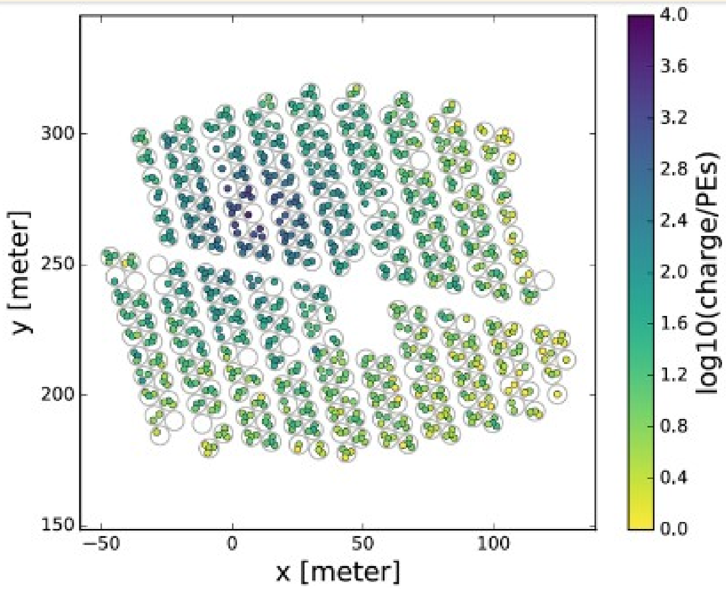


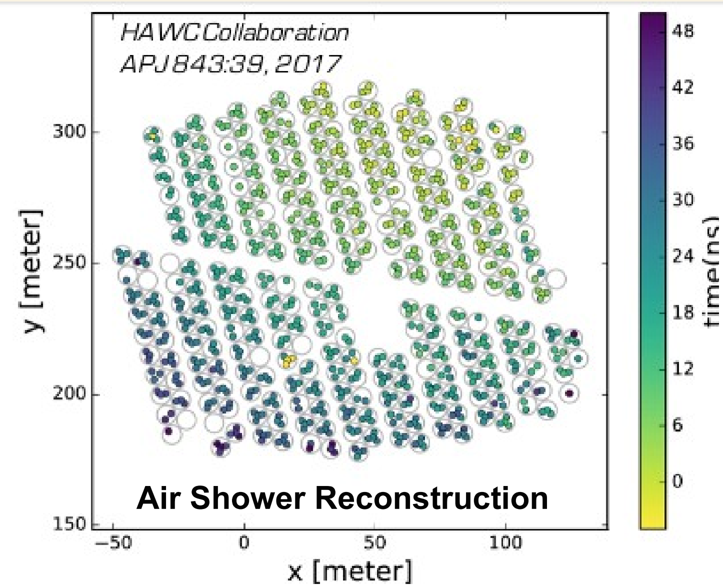

**Data adquisition**

- 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°



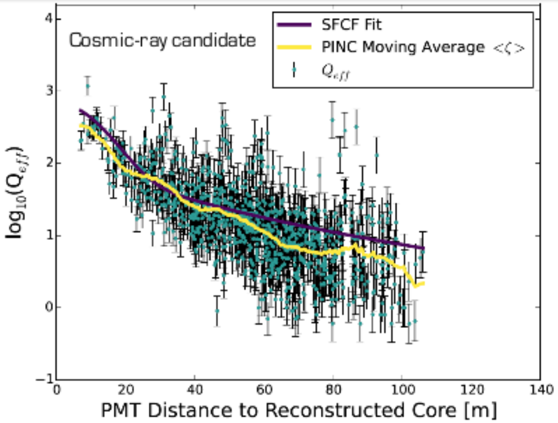



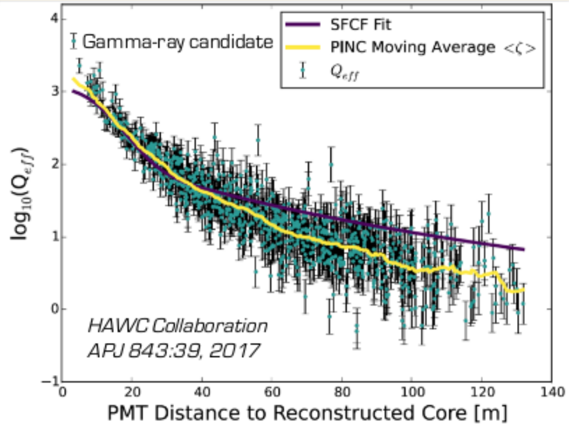

- ✓ Arrival Direction determined by relative timing (~1ns precision) of Cherekov Light Pulses observed in tanks
- ✓ Primary Energy determined by "size" of shower.
- ✓ Lateral distribution and curvature of shower front gives more information about energy
- ✓ Cosmic Ray Background rejection from clumpiness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

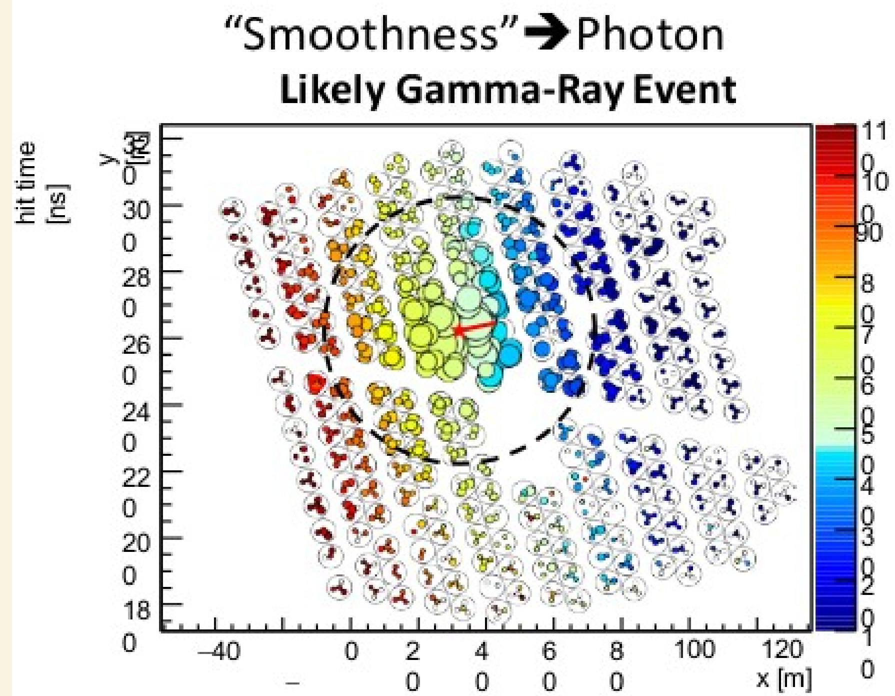
| Step | Description | Hit selection |
|---|---|---|
| 1 | Calibration | |
| 2 | Hit selection | |
| 3 | Center of mass core reconstruction | Selected hits |
| 4 | SFCF core 1st pass | Selected hits |
| 5 | Direction 1st pass | Selected hits |

| Step | Description | Hit selection |
|---|---|---|
| 6 | SFCF 2nd pass | SH within 50 ns of 1st plane |
| 7 | Direction 2nd pass | SH within 50 ns of 1st plane |
| 8 | Compactness, $C$ | SH within 20 ns of 2nd plane |
| 9 | PINCness, $\mathcal{P}$ | SH within 20 ns of 2nd plane |

# Gamma / Hadron Rejection



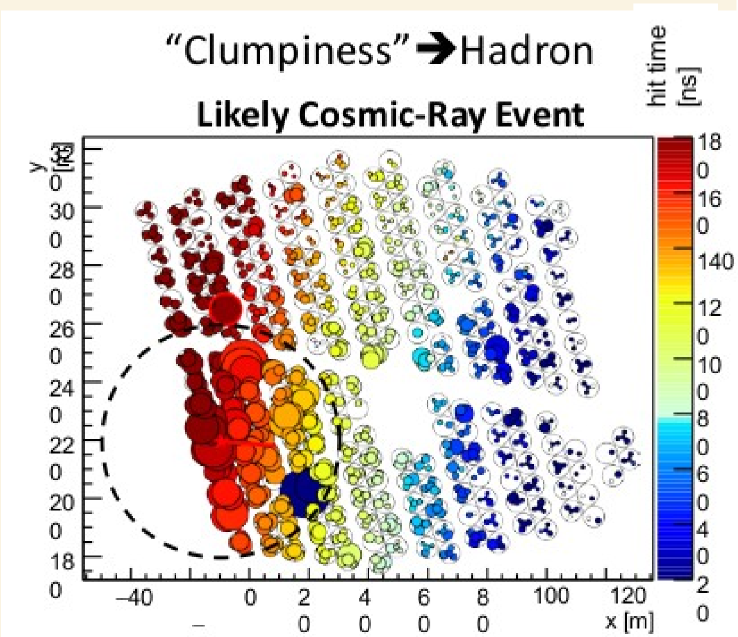



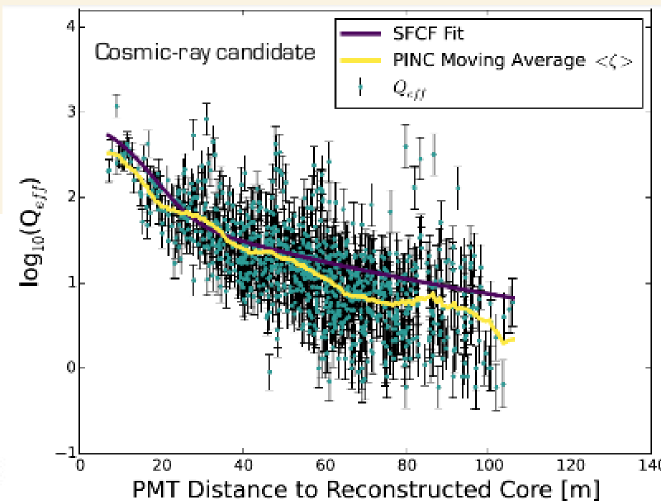

$CxPE_{40}$: Largest $Q_{eff}$ outside a radius of 40 m from the shower core

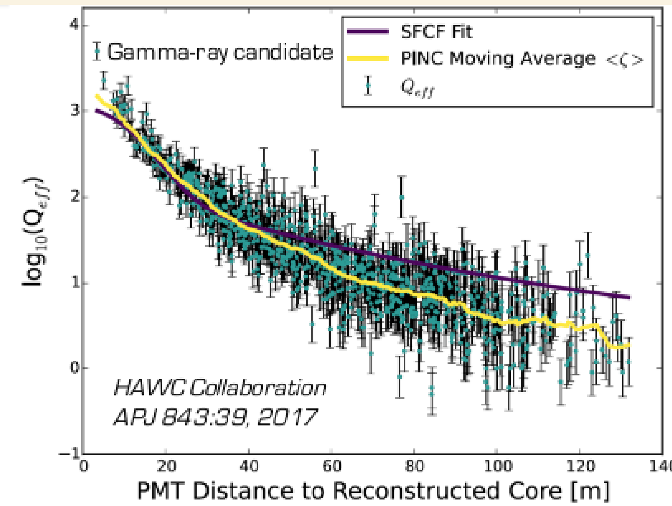
$N_{hit}$: Number of PMT hits during the air shower

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

For hadronic showers $\mathcal{C}$ is small




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

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

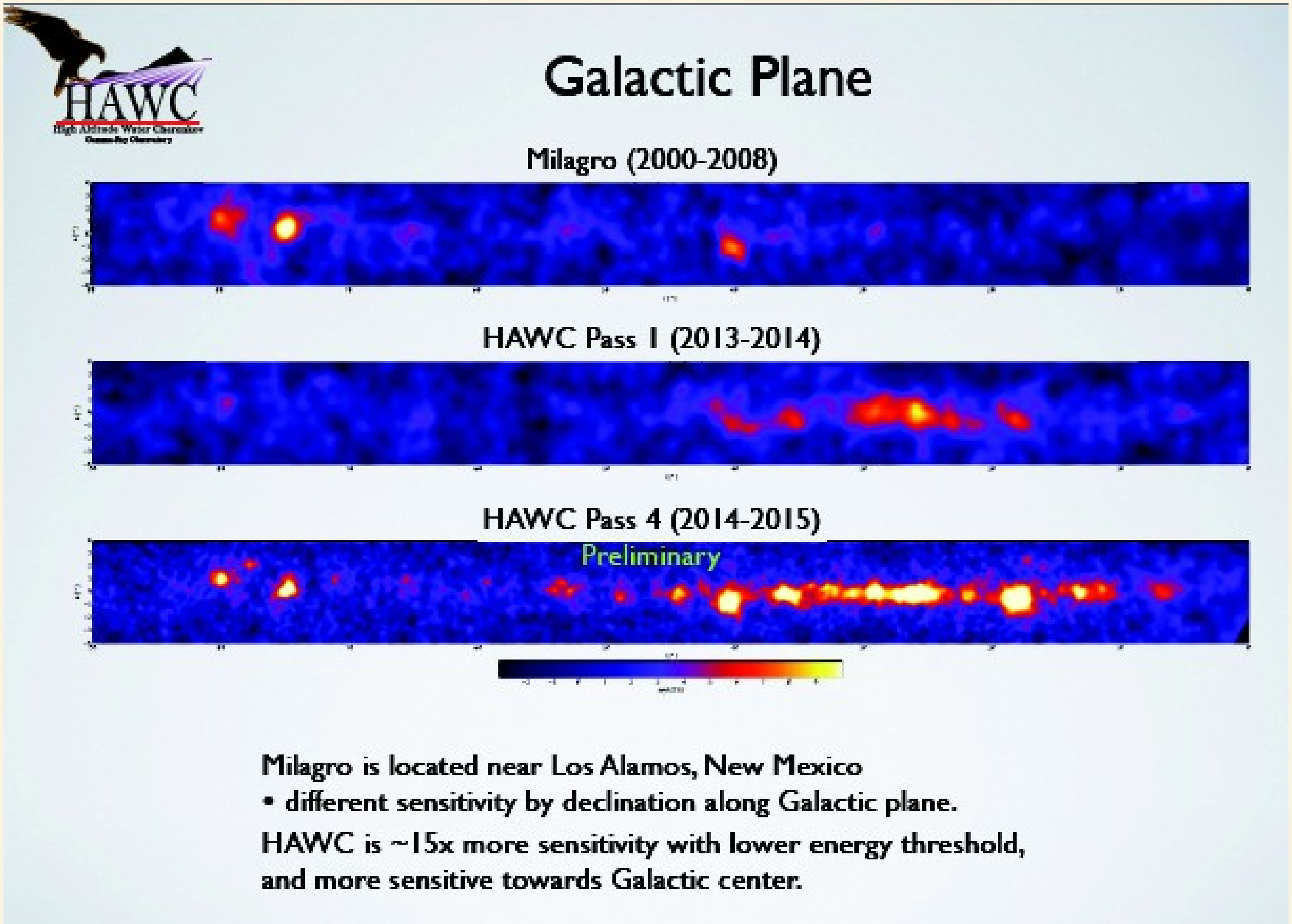
$\zeta_i = \log_{10}(Q_{\mathrm{eff,i}})$

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

$\sigma_{\zeta_i}$ : Obtained from a sample of strong gamma-ray candidates from the Crab

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

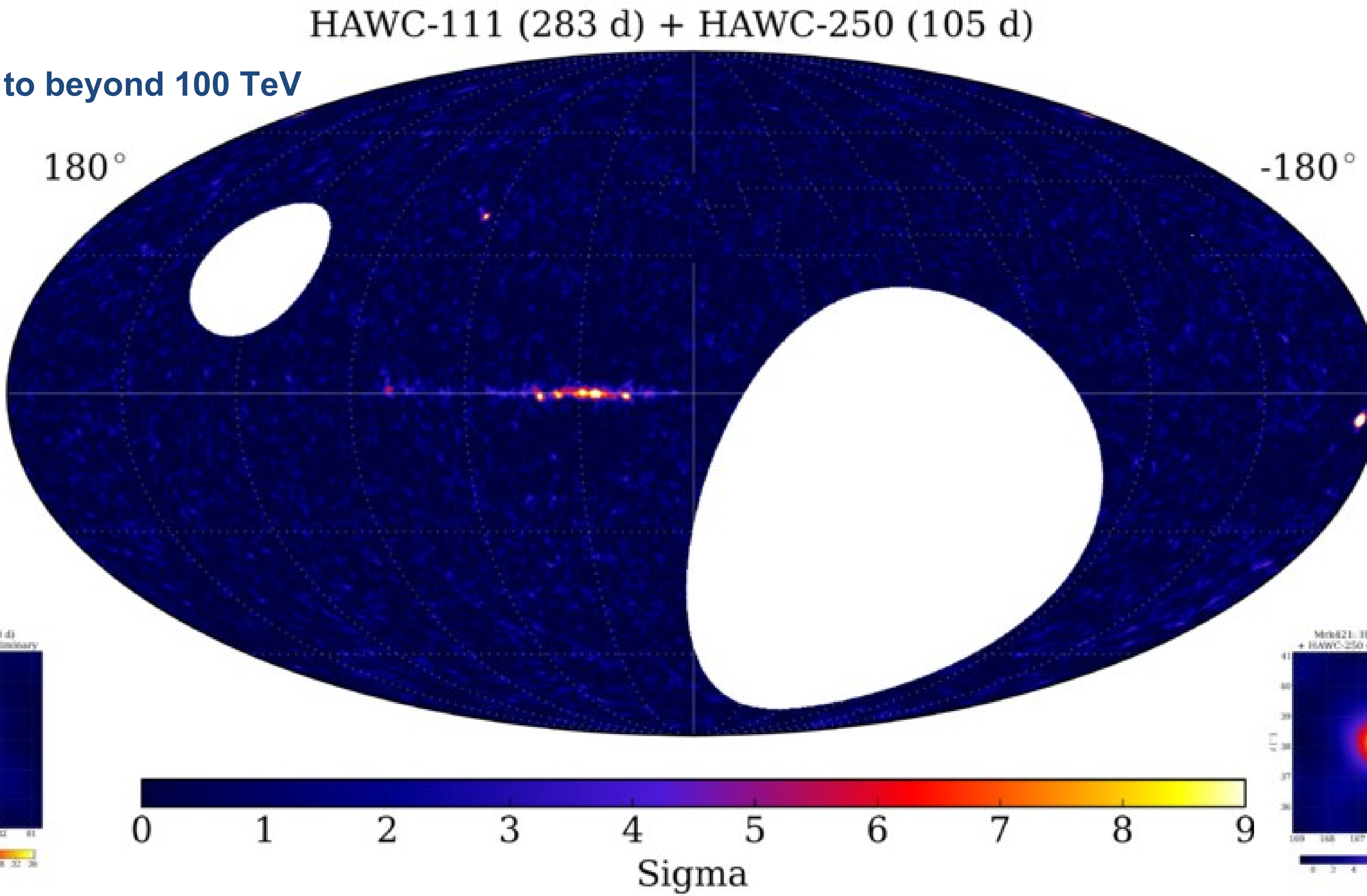
# The High Altitude Water Cherenkov (HAWC) Observatory at México: Results in context

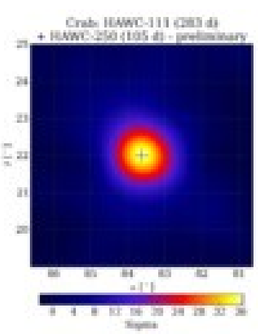


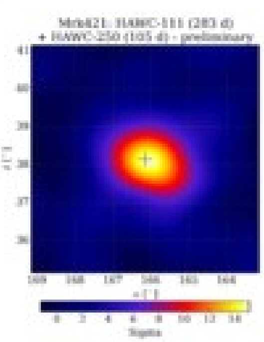
# The High Altitude Water Cherenkov (HAWC) Observatory at México: Results in context

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

**100 GeV to beyond 100 TeV**



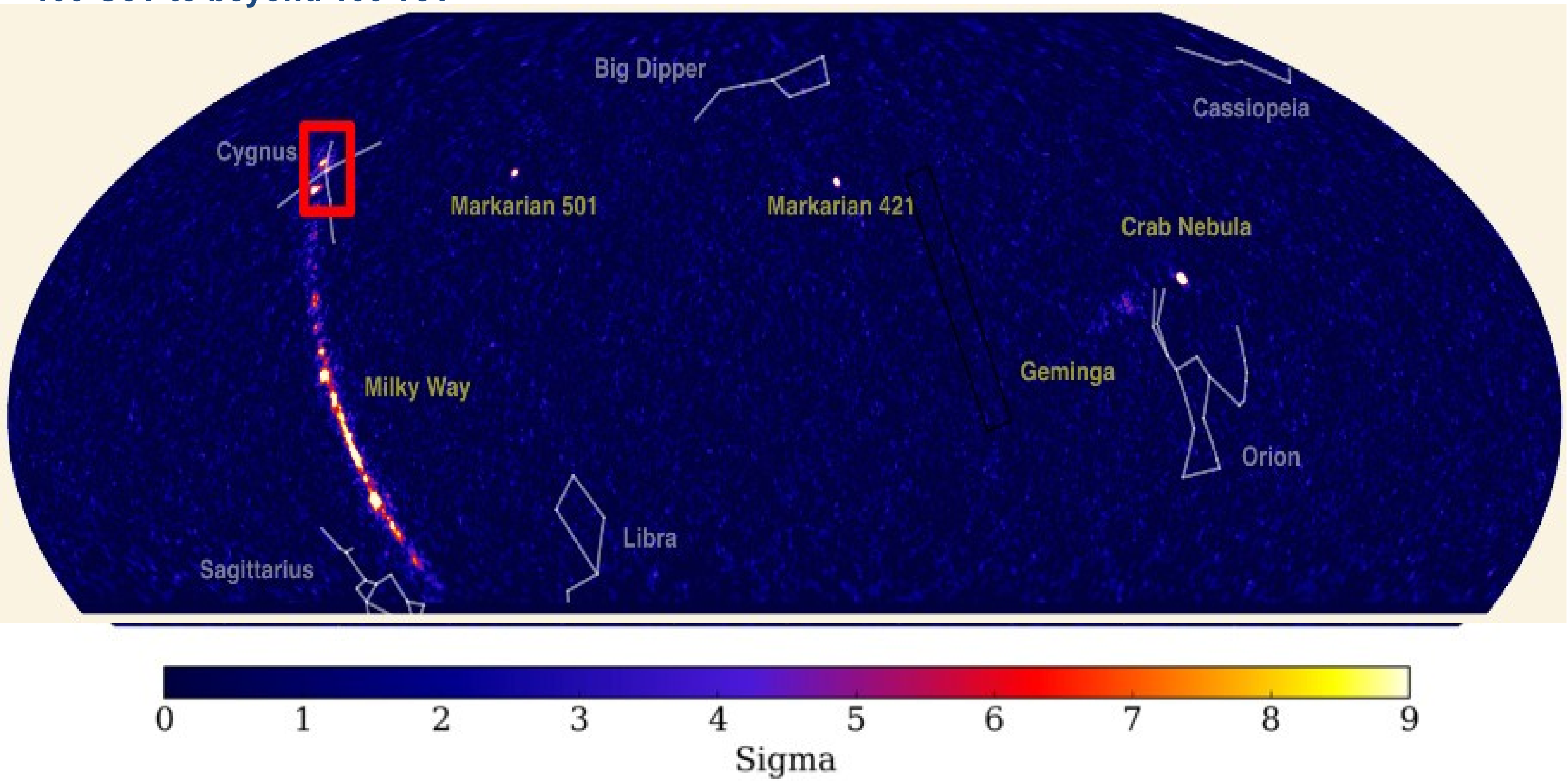





## HAWC: Pevatrons and Star Formation Regions

# The High Altitude Water Cherenkov (HAWC) Observatory at México: Results in context

100 GeV to beyond 100 TeV




HAWC: Pevatrons and Star Formation Regions

# The High Altitude Water Cherenkov (HAWC) Observatory at México: Results in context

THE ASTROPHYSICAL JOURNAL, 843:40 (21pp), 2017 July 1 Abeysekara et al.

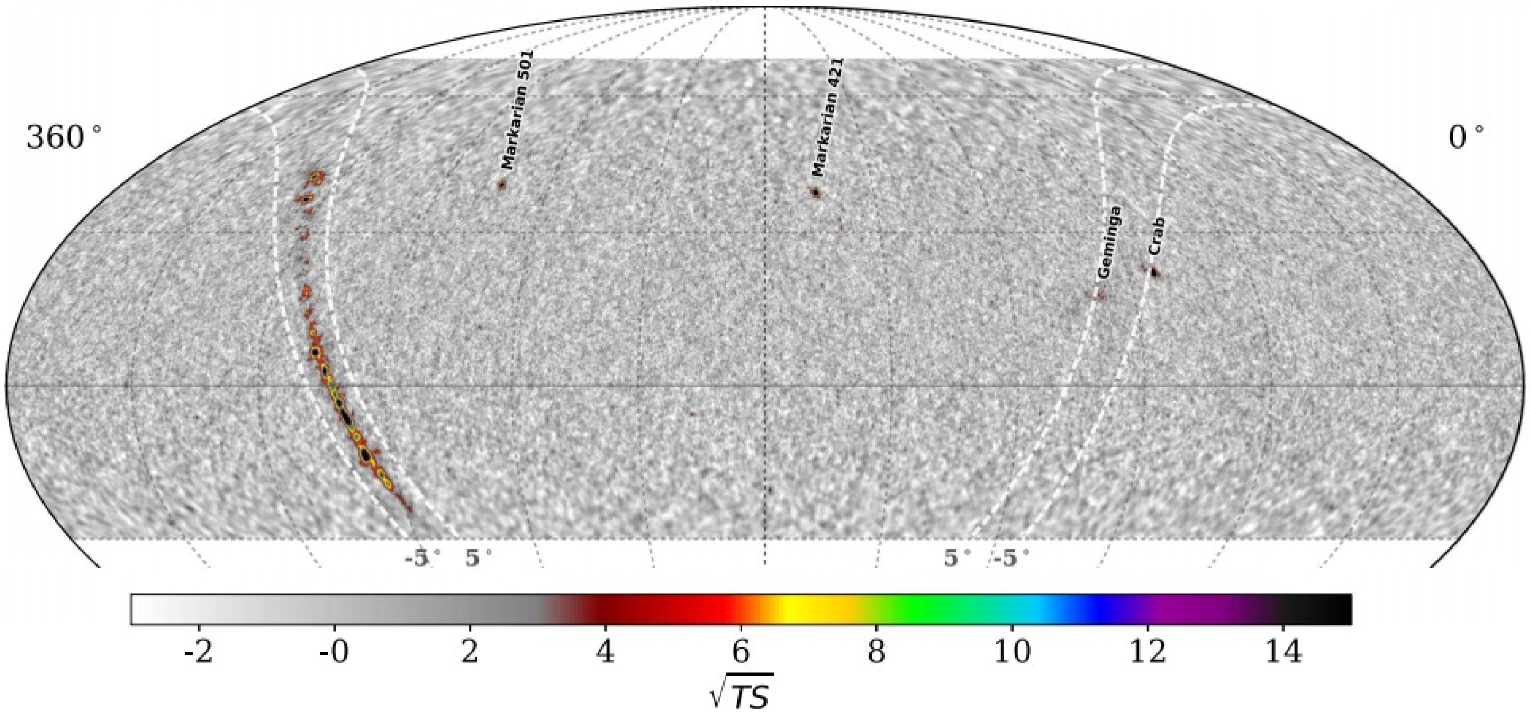



**Figure 3.** Equatorial full-sky TS map, for a point source hypothesis with a spectral index of −2.7. Black graticule corresponds to the equatorial coordinate system, and white lines indicate Galactic latitudes ±5°.

PHYSICAL REVIEW LETTERS **124**, 021102 (2020)

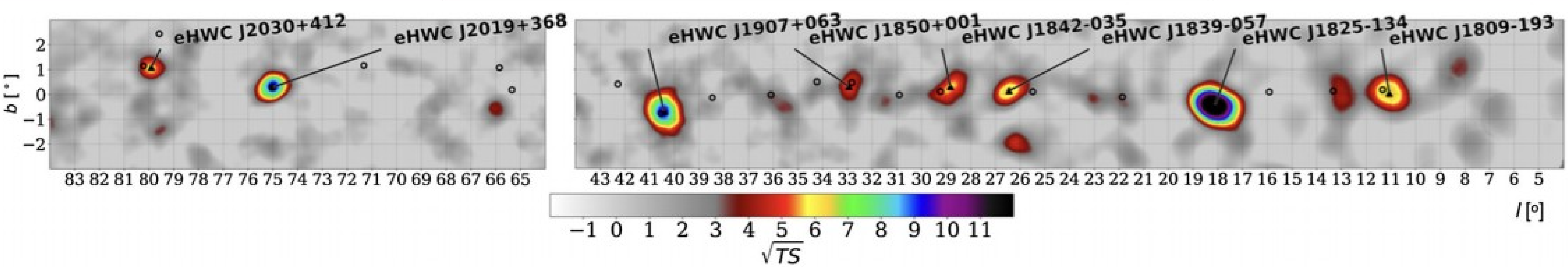



FIG. 1. $\sqrt{\mathrm{TS}}$ map of the galactic plane for $\hat{E} > 56$ TeV emission. A disk of radius 0.5° is assumed as the morphology. Black triangles denote the high-energy sources. For comparison, black open circles show sources from the 2HWC catalog.

# HAWC: Results in context: Astronomical TeVatrons

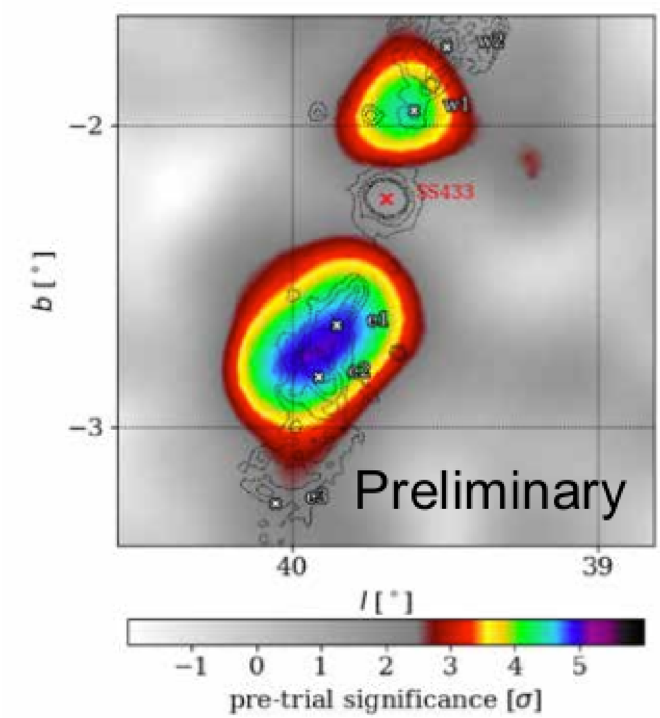
Letter | Published: 03 October 2018

**Very-high-energy particle acceleration powered by the jets of the microquasar SS 433**

A. U. Abeysekara, A. Albert, […]H. Zhou

*Nature* **562**, 82–85 (2018) | Cite this article

- HAWC observation of SS433 is the first direct proof of particle acceleration to > 100TeV in jets
  - Jets are observed edge-on so the gamma rays are not Doppler boosted to higher energies or higher luminosities
  - Hadronic acceleration disfavored due to extreme energetics required
  - Electrons radiate synchrotron x-rays and magnetic field is then given by the electron energy determined by HAWC
  - Acceleration does not happen at the black hole because the cooling time of the electrons is too short to make the observed gamma-rays



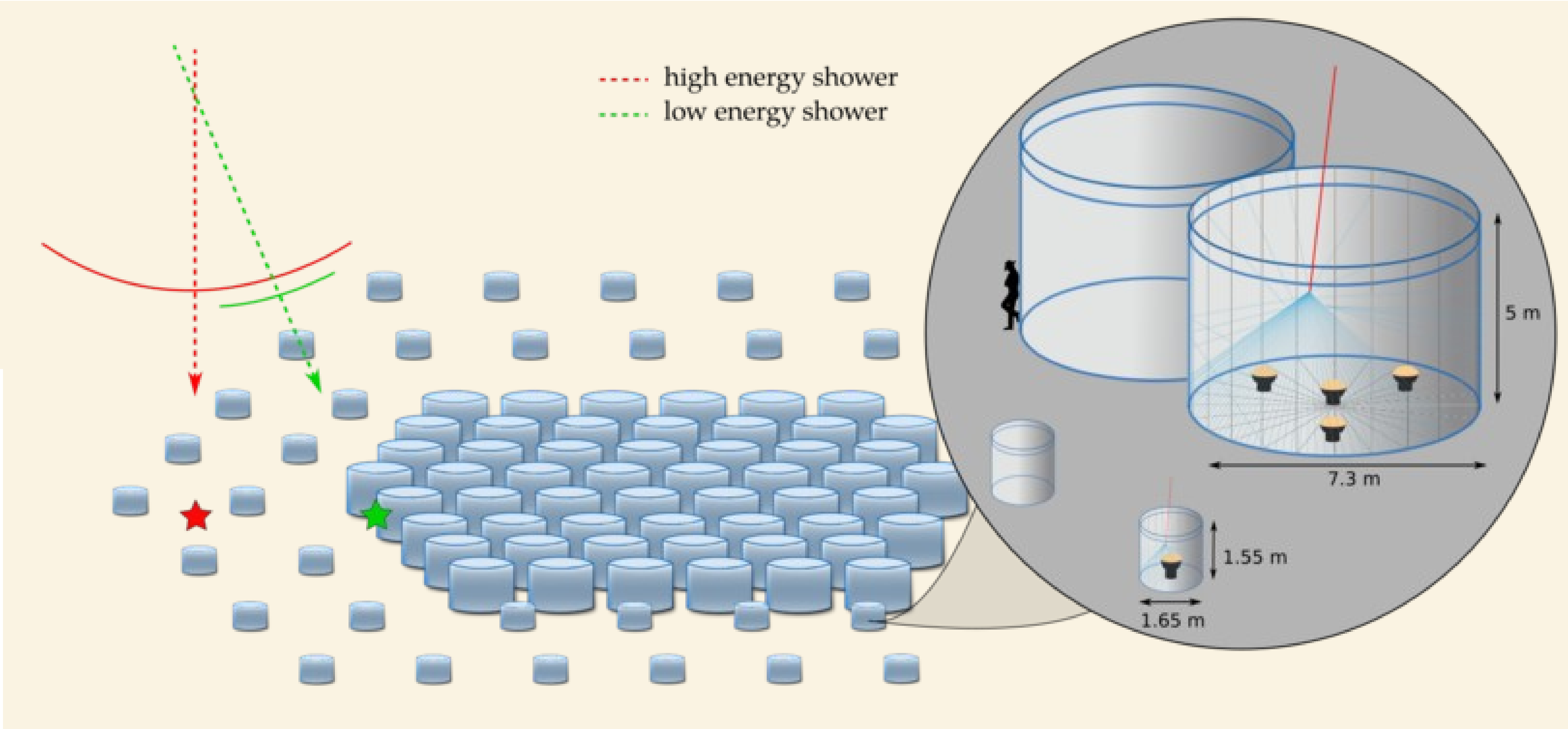

HAWC significance with the overlay of x-ray contours showing the jet lobes and not the black hole.

# The High Altitude Water Cherenkov (HAWC) Observatory at México: Future (Outriggers)

Enhanced Sensitivity above 10 TeV

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

Increase effective area above 10 TeV by ~4x



*“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)*

One starts: *To* distinguish between *leptonic and hadronic*

“Among the *PeVatron candidates, the Cygnus cocoon is one of the favorite and perhaps* more reliable because of its Neutrino coincidence, molecular gas environment, and accelerations at least 1.4 *PeVs ( 2021 and starting)”.*

“Three conditions for a *Pevatron: 1.- Neutrino Coincidence by Icecube, 2.- Acceleration at PeVs, 3.- Molecular gas environment”*

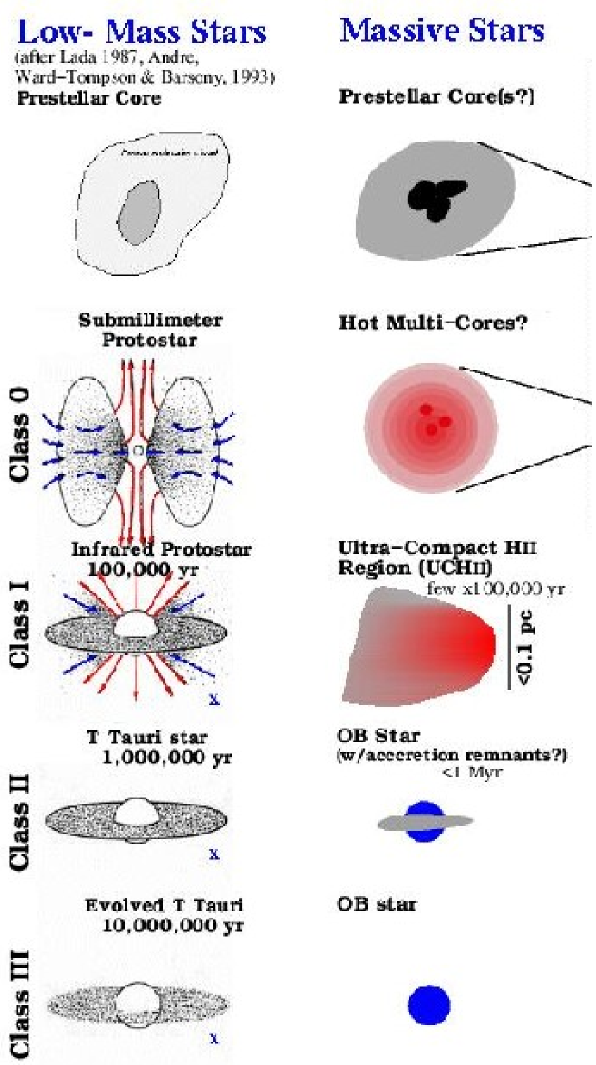
Discussion between conveners and the rapporteur of the session 55: UHE gamma rays and *PeVtron in ICRC 2021*

# HAWC and the Cygnus Cocoon: (Massive) Stars living or in formation (?) meet Pevatrons via molecular gas ?.

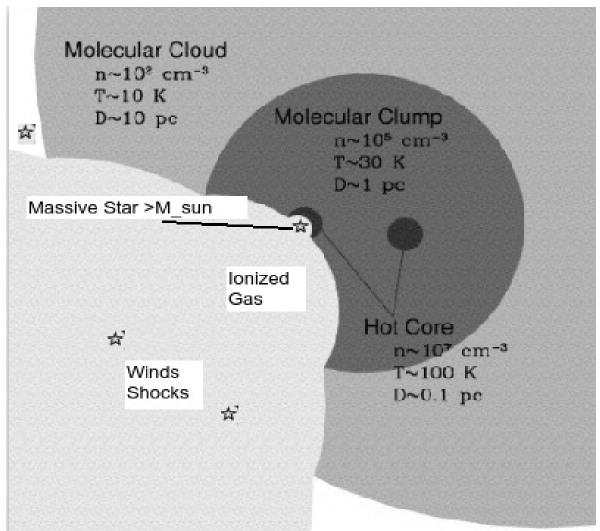
Star-Forming *Regions like Cygnus are galactic sources of cosmic rays, not only the pulsars, PWN, and related objects.*

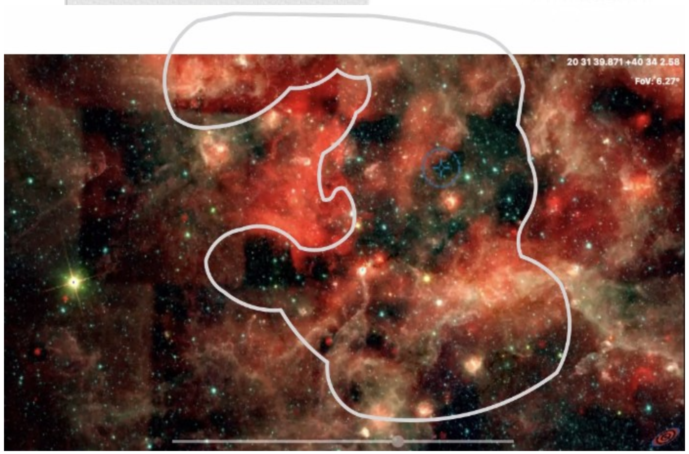
On *LHAASO list, Cygnus is the only star formation region. The others are SR, PWN, and a dark nebula*.

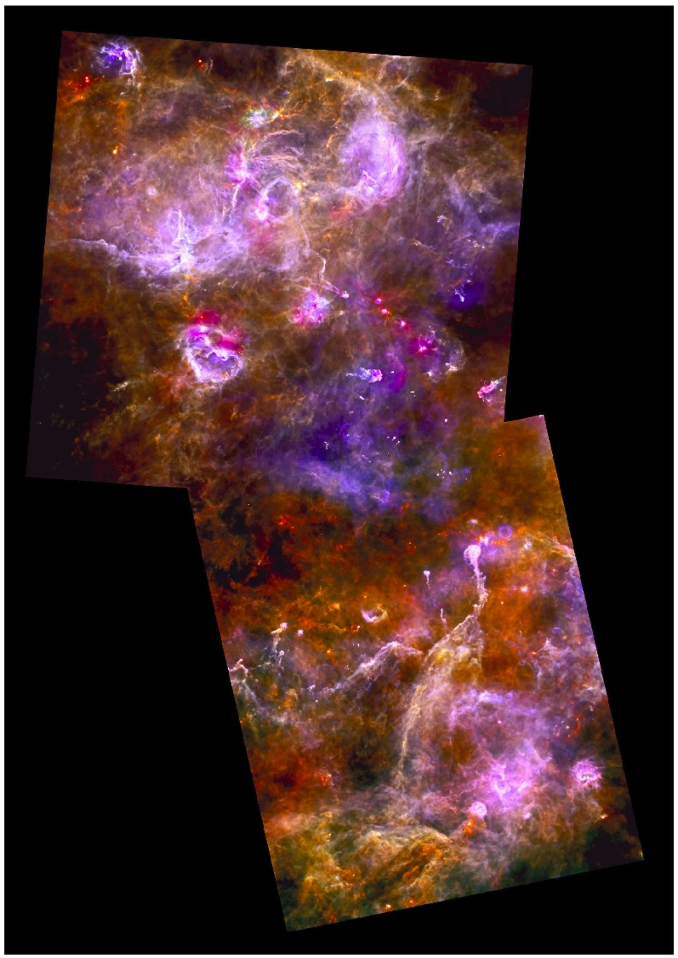
- Stars meet PEVATRON via DEATH OF MASSIVE STARS (> 8 M_sun): SNRs ←Plerions→ PWNs
- (MASSIVE) Stars as MAIN SEQUENCE objects Meets PEVATRON via WINDS and SHOCKS (? )
- Stars in FORMATION meets PEVATRONS via (MASSIVE) Young Stellar Objects (YSOs)?, or by STELLAR WINDS and SHOCKS OF MASSIVE STARS ?.




## Cygnus Cocoon is the best place to find answers





(blue = 70 μm, green = 160 μm, red = 500 μm, all maps are absolutely calibrated) of

# HAWC: Pevatrons and Star Formation Regions


Seminar at ICRR-Utokyo, August, 2, 2021

Dr. Eduardo de la Fuente Acosta (CUCEI-UdeG)

“Among the *PeVatron candidates, the Cygnus cocoon is one of the favorite and perhaps* more reliable because of its Neutrino coincidence, molecular gas environment, and accelerations at least 1.4 *PeVs ( 2021 and starting)”.*

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Discussion between conveners and the rapporteur of the session 55: UHE gamma rays and *PeVtron in ICRC 2021*

# Cygnus Cocoon; First Condition to be a Pevatron

# Neutrino Coincidence (Icecube)

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

D. D. Dzhappuev [1], Yu. Z. Afashokov [1], I. M. Dzaparova [1,2], T. A. Dzhatdoev [3,1], E. A. Gorbacheva [1], I. S. Karpikov [1], M. M. Khadzhiev [1], N. F. Klimenko [1], A. U. Kudzhaev [1], A. N. Kurenya [1], A. S. Lidvansky [1], O. I. Mikhailova [1], V. B. Petkov [1,2], E. I. Podlesnyi [4,3,1], V. S. Romanenko [1], G. I. Rubtsov [1], S. V. Troitsky [1], I. B. Unatlokov [1], I. A. Vaiman [4,3], A. F. Yanin [1], Ya. V. Zhezher [1,5] and K. V. Zhuravleva [1]

(Carpet–3 Group)

[1] *Institute for Nuclear Research of the Russian Academy of Sciences, 60th October Anniversary Prospect 7a, Moscow 117312, Russia*
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[4] *Physics Department, M. V. Lomonosov Moscow State University, Moscow 119991, Russia*
[5] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Kashiwanoha, 5-1-5, 277-8582, Japan*

(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-

"Among the *PeVatron candidates, the Cygnus cocoon is one of the favorite and perhaps* more reliable because of its Neutrino coincidence, molecular gas environment, and accelerations at least 1.4 *PeVs ( 2021 and starting)".*

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Discussion between conveners and the rapporteur of the session 55: UHE gamma rays and *PeVtron in ICRC 2021*

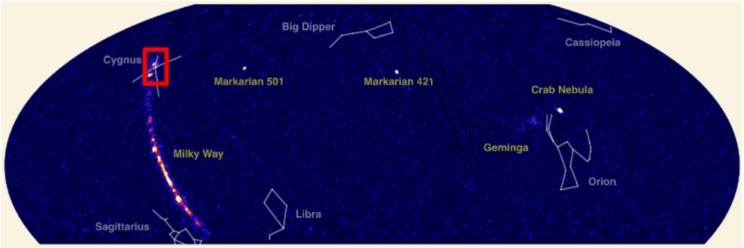
# Cygnus Cocoon; Second Condition to be a Pevatron

## Acceleration at PeVs (UHE Gamma-ray emission)

# The History of Pevatrons: HAWC and the Cygnus Cocoon

nature astronomy
LETTERS
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

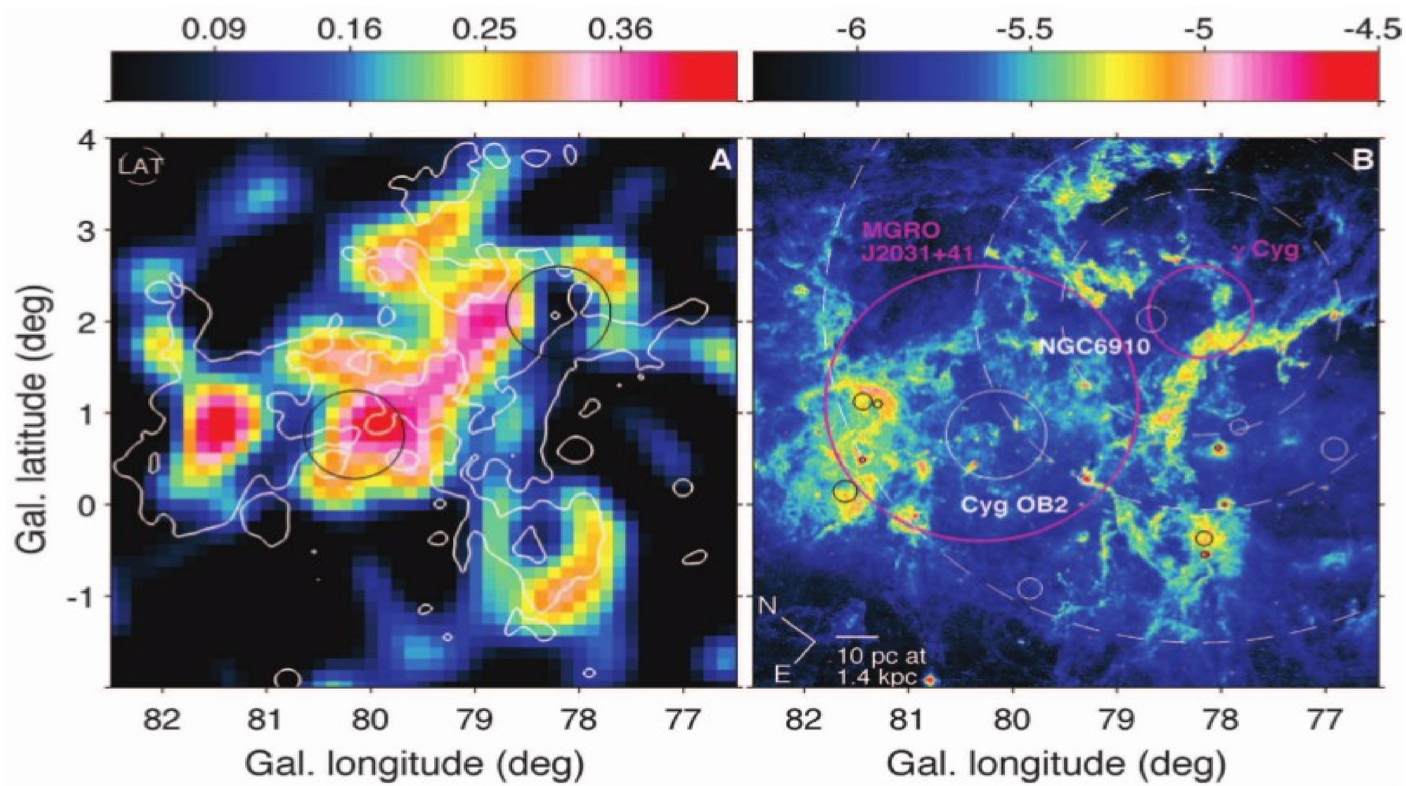
Stellar wind power of a few $10^{39}$ erg/sec maintained for at least 2 Myrs *(Lozinskaya et al. 2002)*

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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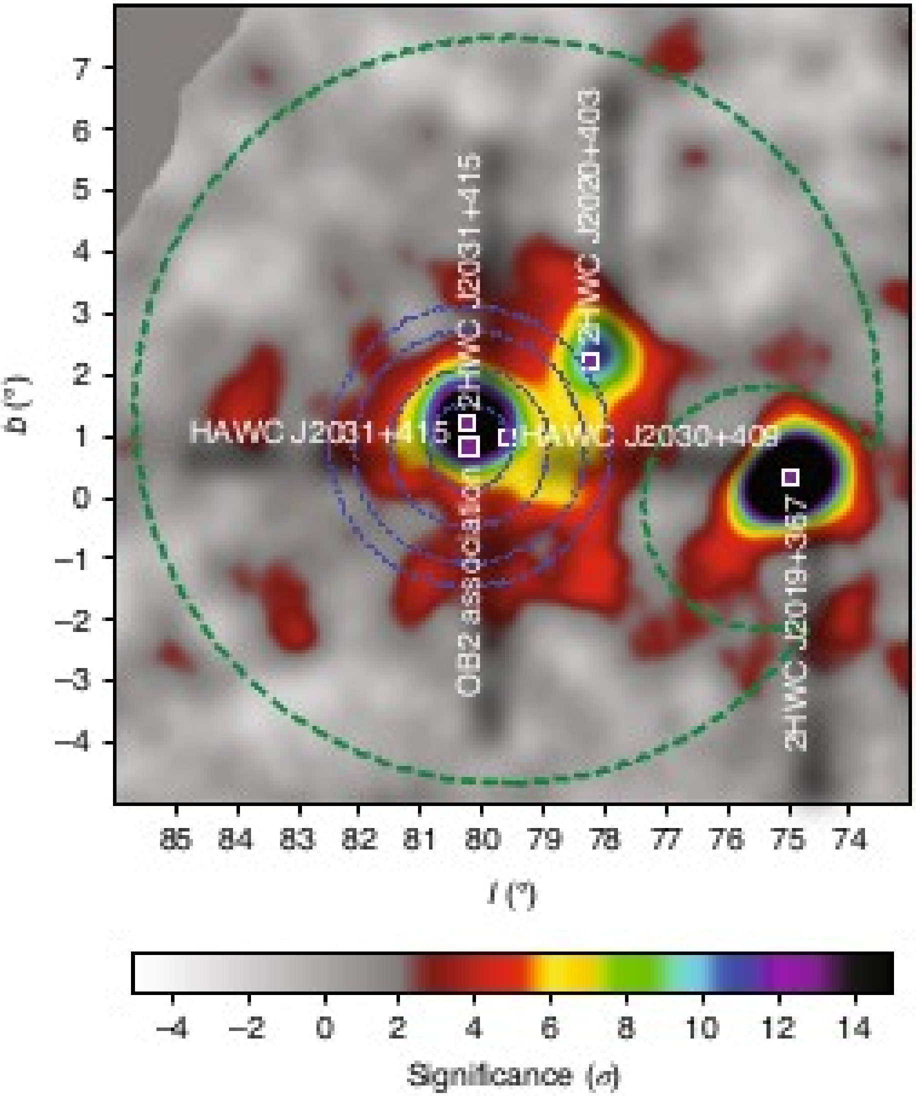


- Significance map with 1343 days of GP data
- Green Contour region of interest (ROI), 2HWC J2019+367 masked in the ROI

| 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° |

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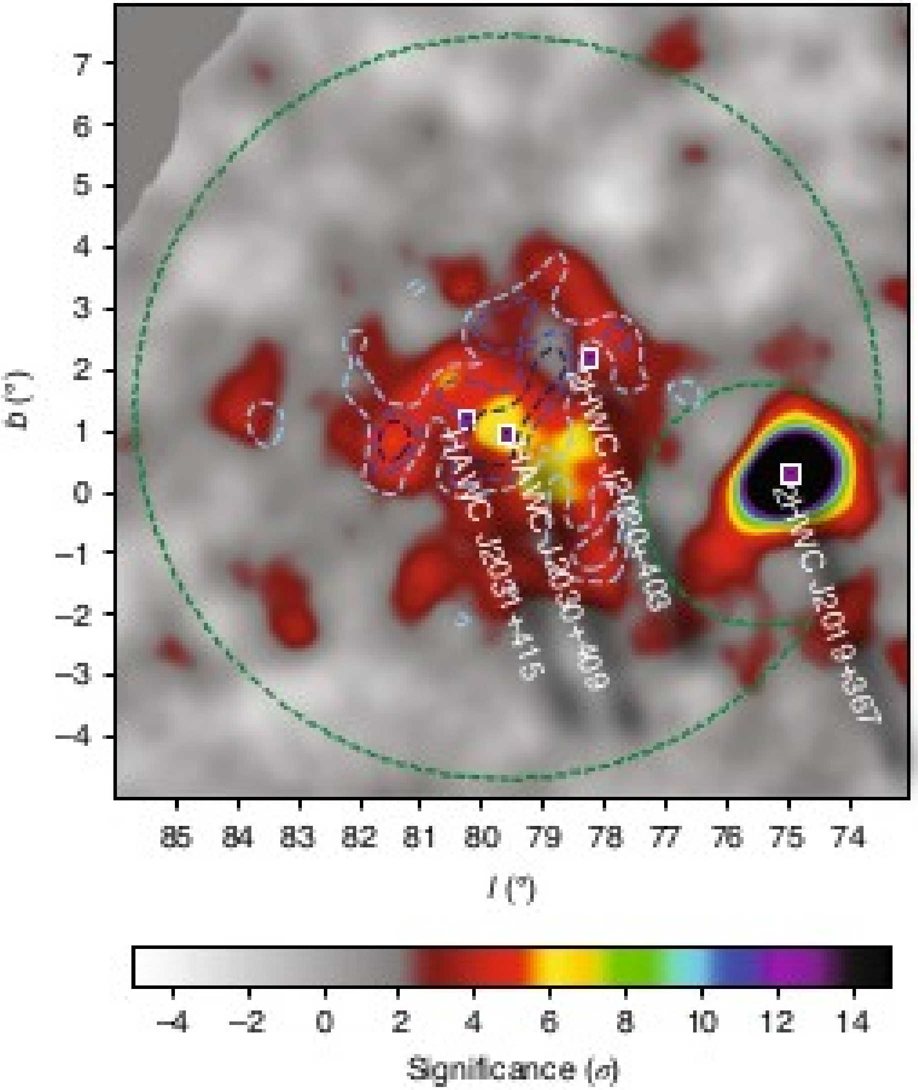


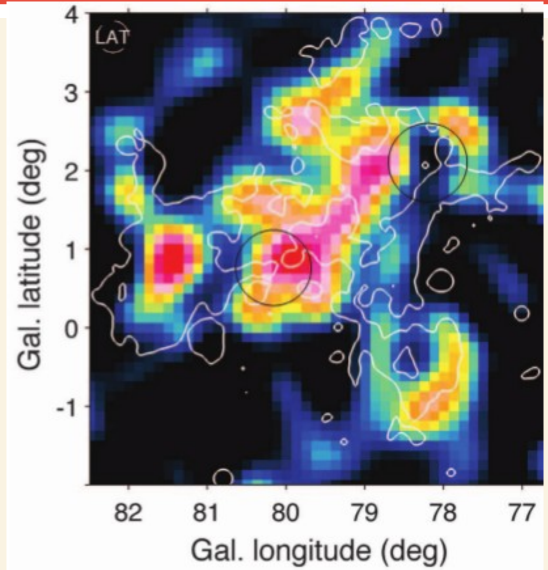


- Significance Map after subtracting the HAWC PWN and Gamma Cygni
- Light blue to dark blue contours are Fermi-LAT (RA, Dec) 0.16, 0.24, 0.32 photons/bin contours
- Cocoon significantly detected in HAWC data
- Morphology is described by a Gaussian width of $(2.12 \pm 0.16(\text{stat.}))°$
- Gaussian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

# The History of Pevatrons: HAWC and the Cygnus Cocoon

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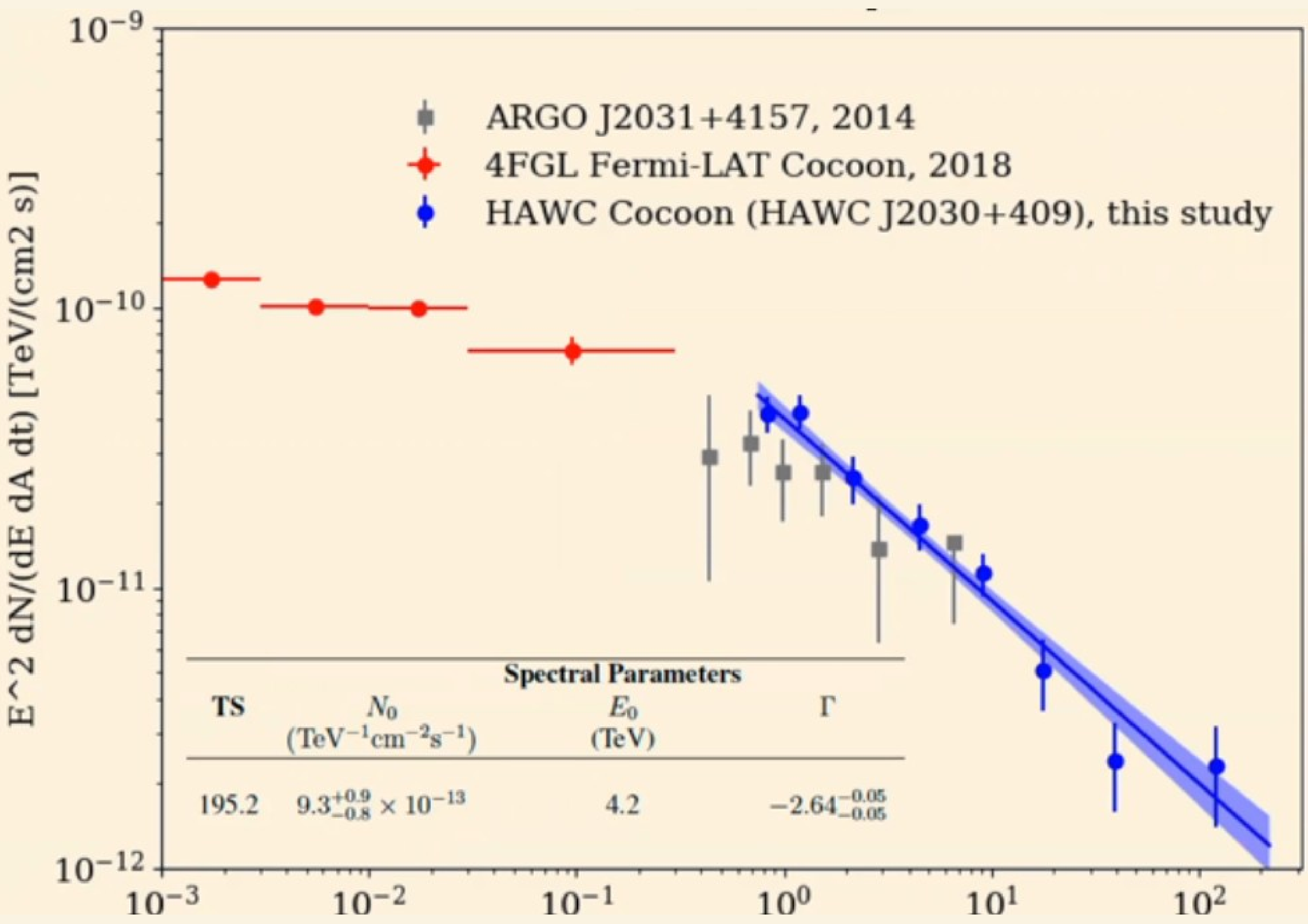


Spectrum extends from 0.75 TeV to ~ 200 TeV

Spectral index of -2.64 compared to -2.1 observed for GeV spectrum

# The History of Pevatrons: HAWC and the Cygnus Cocoon

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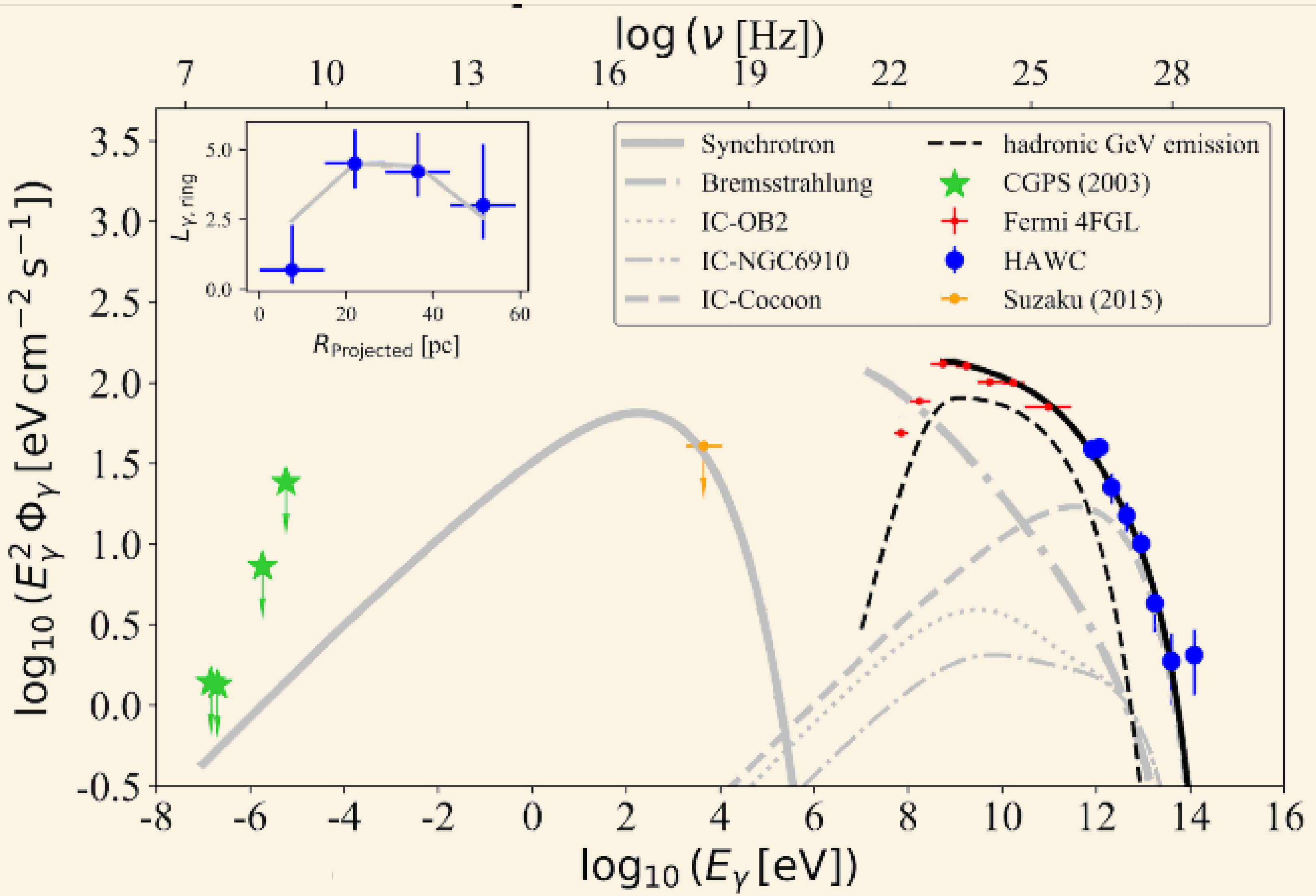
Credit: Binita Hona (U. Utah)




## HAWC: Pevatrons and Star Formation Regions

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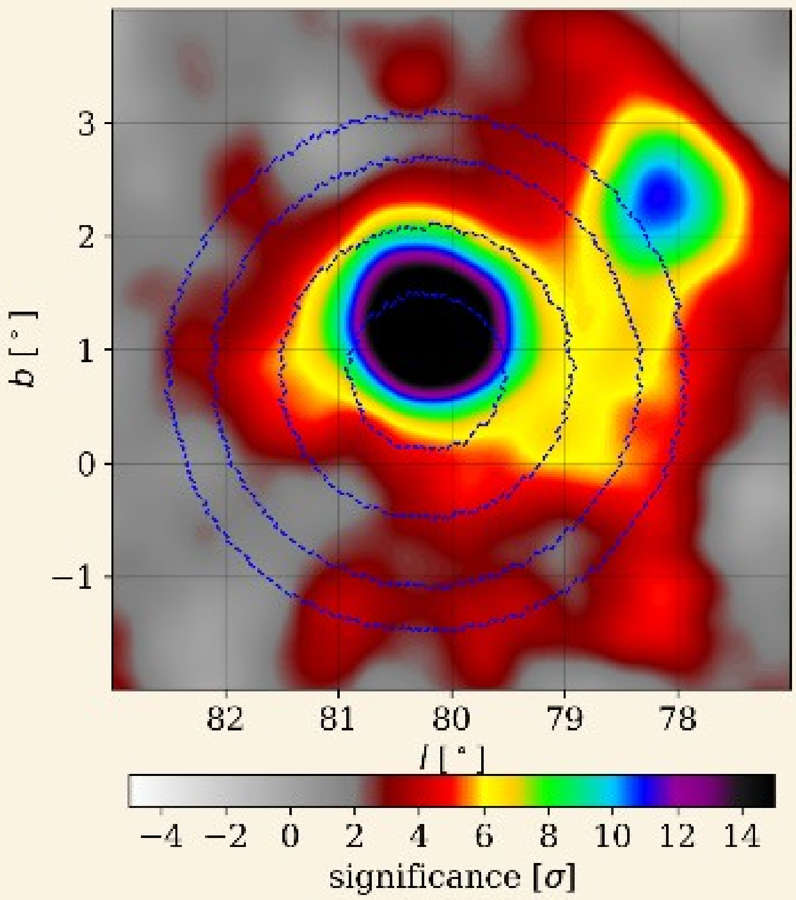


- CR density, $w_{CR}(> 10E_\gamma) = 1.8 * 10^{-2} \left(\frac{\eta}{1.5}\right)^{-2} \frac{L_\gamma(\geq E_\gamma)}{10^{34}\ \mathrm{erg\ s^{-1}}} \left(\frac{M}{10^6 M_\odot}\right)^{-1}$
  *(Aharonian et. Al, Nature Astronomy, 2019)*

  $L_\gamma$ = Luminosity
  M = Gas Mass
  $\eta$ = 1.8 (presence of heavier than Hydrogen nuclei)

- Four rings ( [0:15] pc, [15:29] pc, [29:44] pc and [44:55] pc) centered at the position of OB2 association (308.3, 41.3)°

- $L_\gamma = 4\pi I_{ring}.\, d^2$,

  $I_{ring}$ =Integrated flux of each ring
  d = 1.5 kpc

# The History of Pevatrons: HAWC and the Cygnus Cocoon

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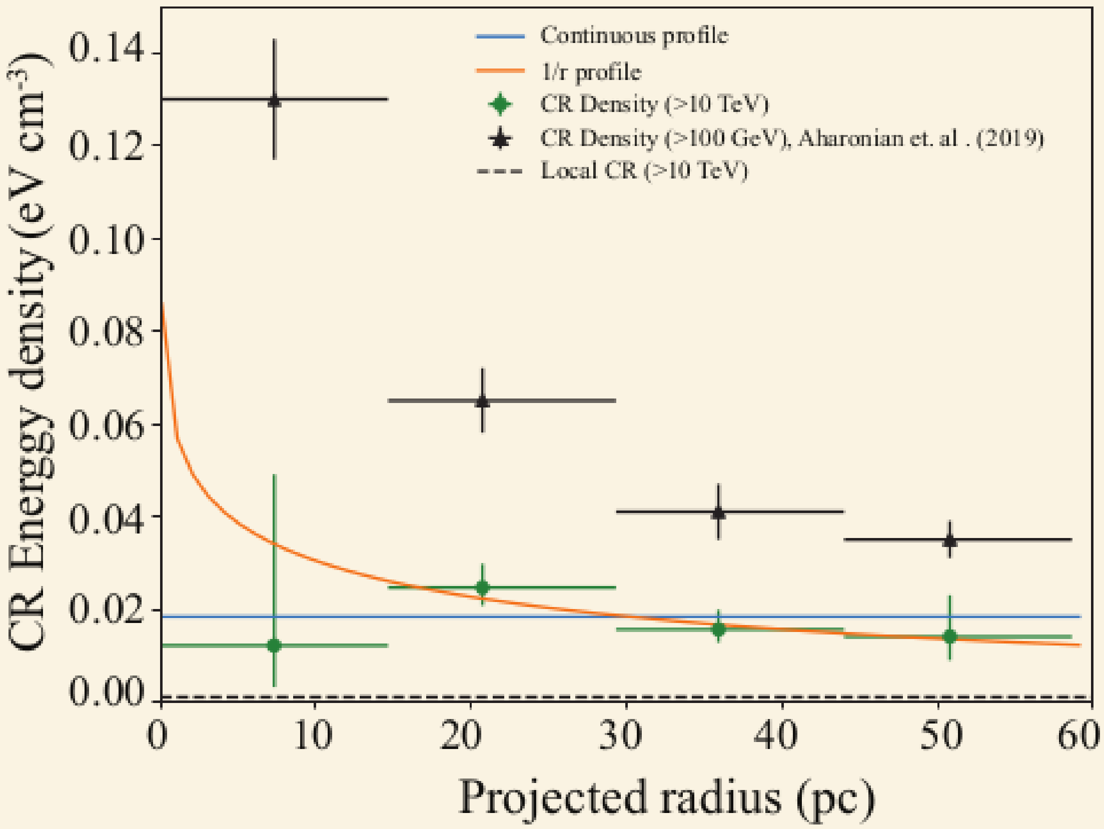


| Rings (pc) | $L_\gamma(>0.7\text{TeV})\text{erg s}^{-1}$ | $w_{CR}(>7\text{TeV})\text{eV/cm}^3$ |
|---|---|---|
| $0 < r < 15$ | 0.7 - 0.5 + 1.6 | 0.016 - 0.012 + 0.037 |
| $15 < r < 29$ | 4.5 -0.9 +1.2 | 0.033 - 0.007 + 0.009 |
| $29 < r < 44$ | 4.2 - 0.9 +1.4 | 0.019 - 0.004 + 0.006 |
| $44 < r 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

# The History of Pevatrons: HAWC and the Cygnus Cocoon

nature astronomy LETTERS
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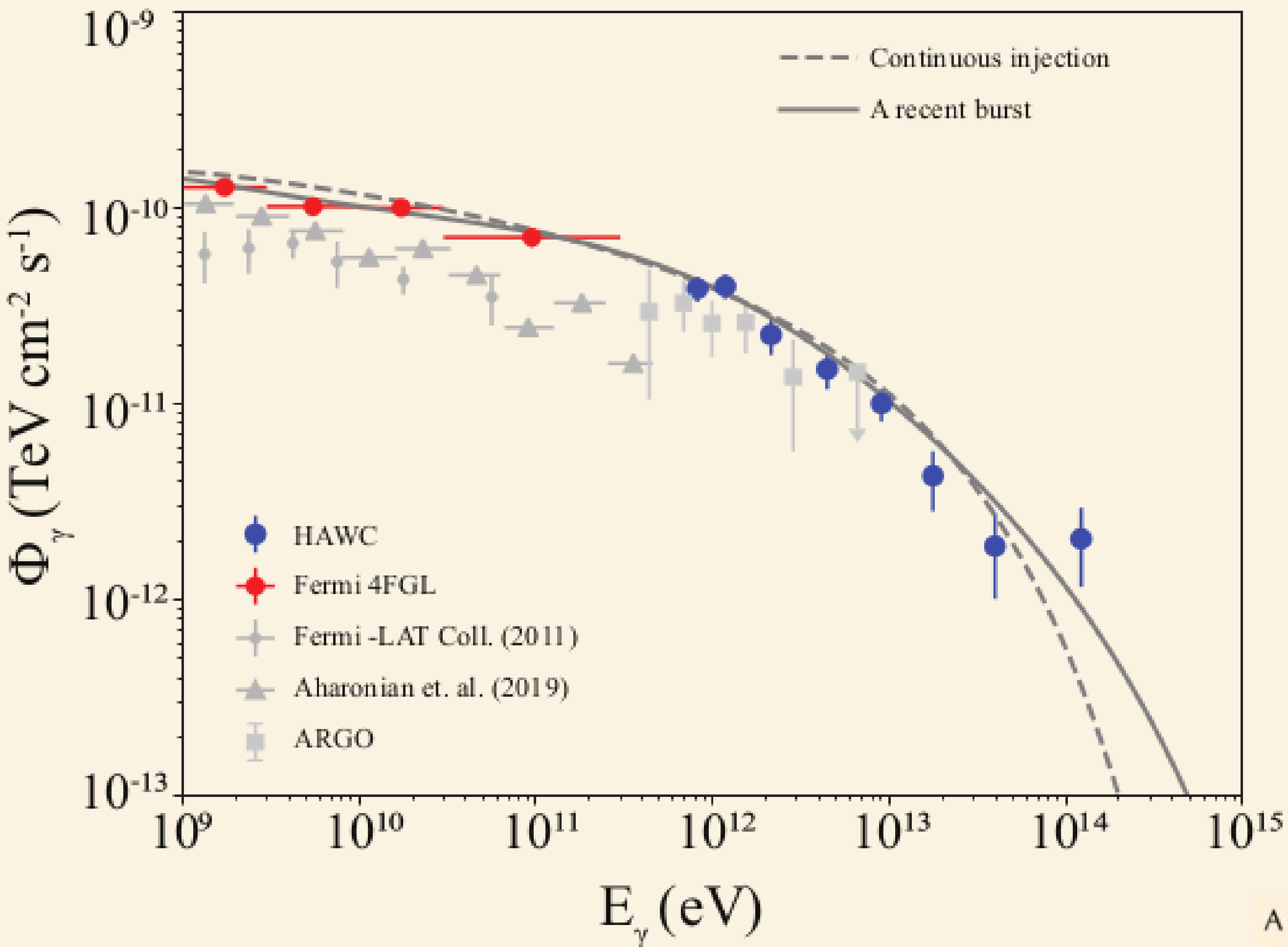


- **Burst Scenario**
  $P(> 1\text{GeV}) \sim 4 \times 10^{37}$ erg/s
- **Steady Scenario**
  $P(> 1\text{GeV}) \sim 7 \times 10^{36}$ erg/s
- In OB2, wind power of a few $10^{39}$ erg/s maintained for at least 2 Myrs.
- Acceleration efficiency:
  - 4% (Burst Scenario)
  - 1% (Steady Scenario)

A spectral softening above TeV,
- leakage of CRs from the superbubble (Burst Scenario)
- a cutoff in the CR injection spectrum (Steady Scenario)

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# Cygnus Cocoon; Third Condition to be a Pevatron

## Molecular Enviroment : n($H_2$) via CO ($^{12}CO$, $^{13}CO$, and $C^{18}O$)

ICRR Seminar, August, 2, 2021

# The History of Pevatrons: HAWC and the Cygnus Cocoon

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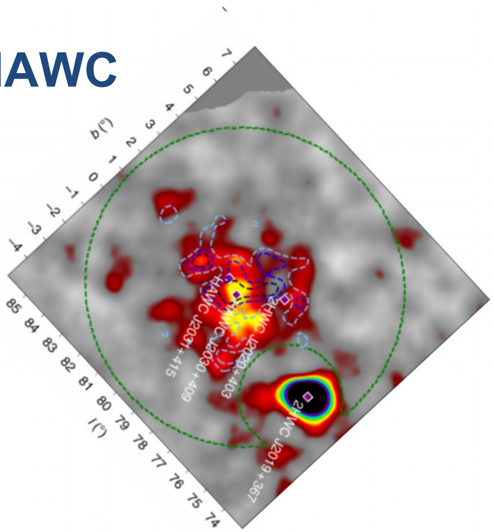
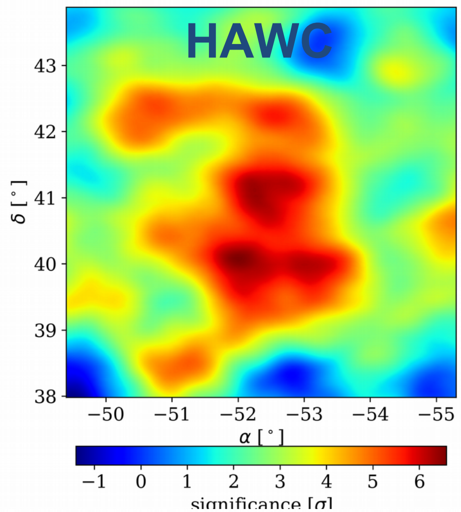
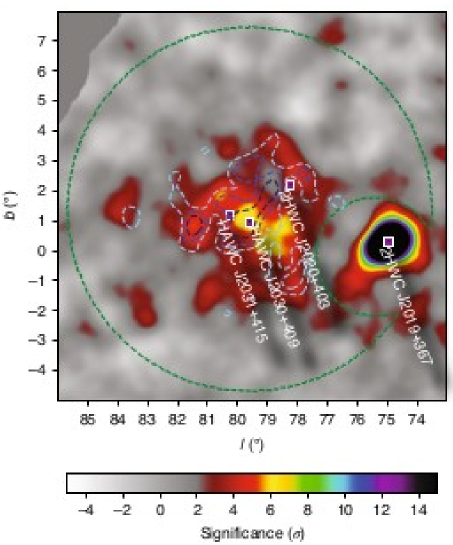
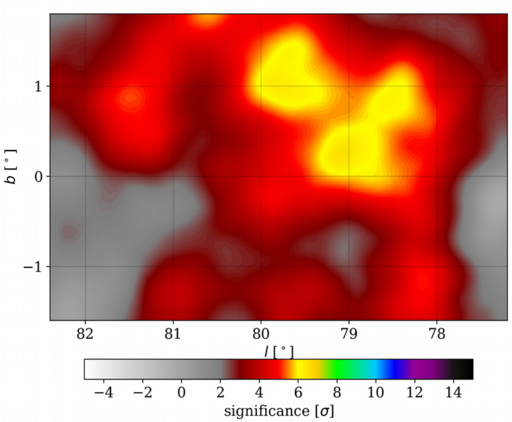
https://doi.org/10.1038/s41550-021-01318-y

HAWC

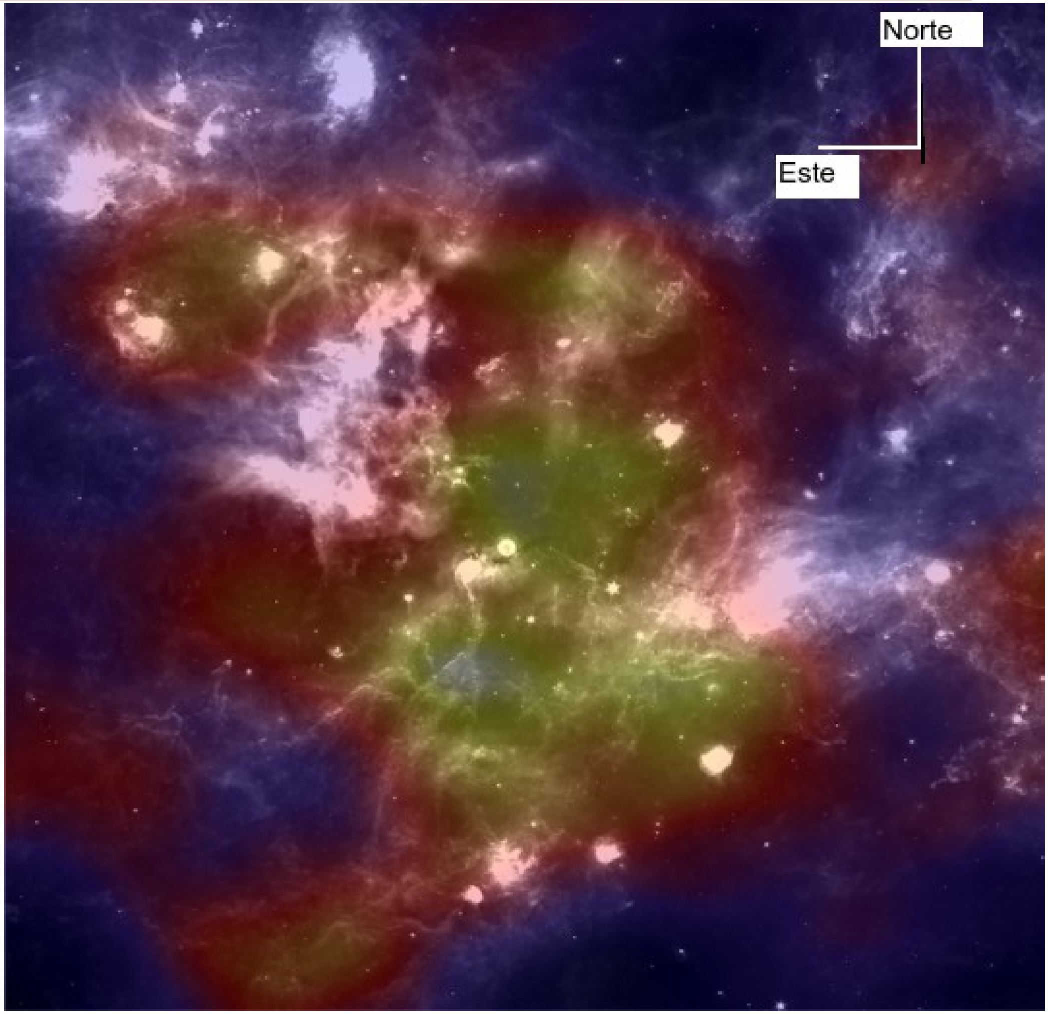





HAWC




**HAWC plus Spitzer-MIPS at 24 microns: Dust, Young Stellar Objects, embedded star clusters**

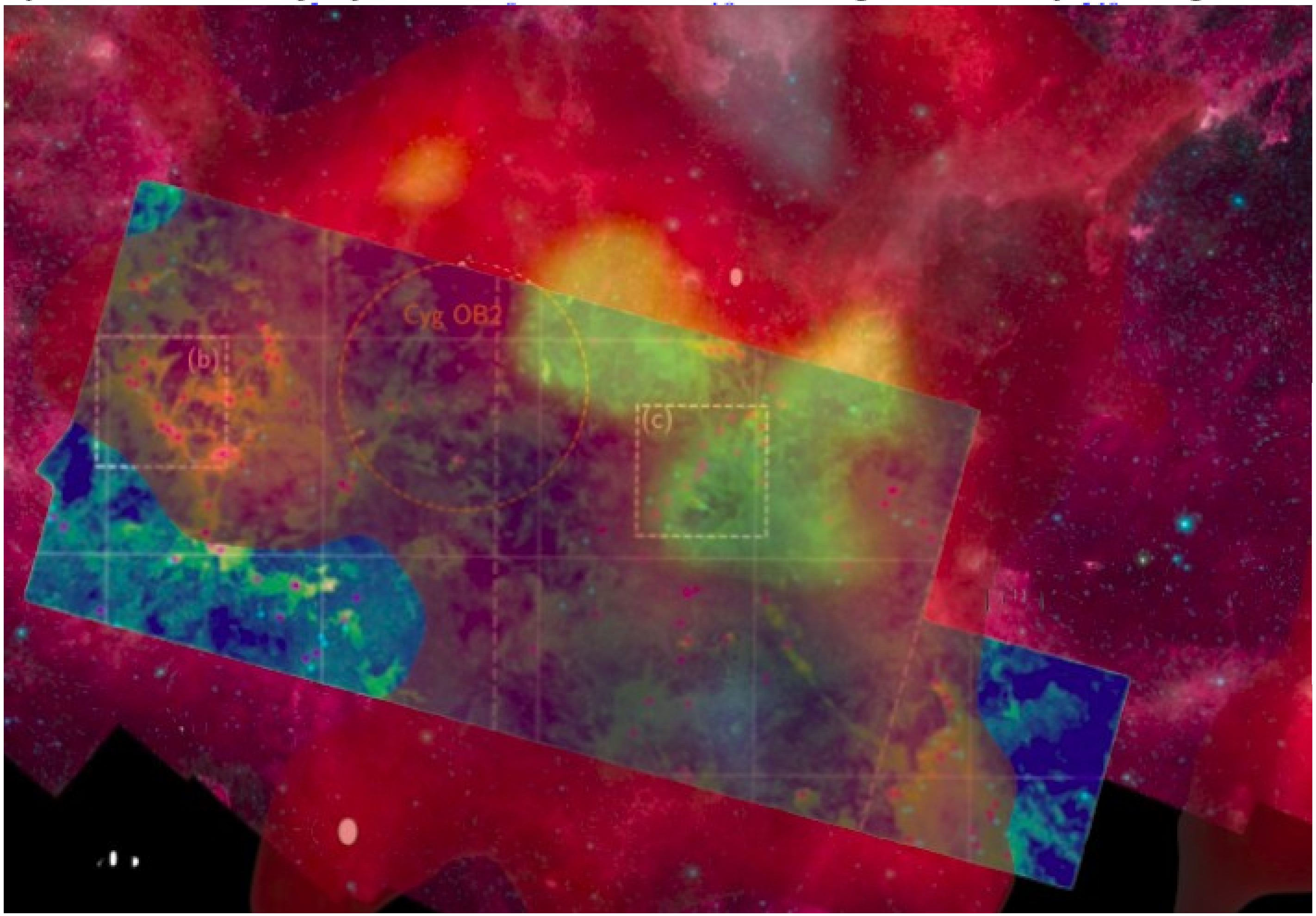
## HAWC: Pevatrons and Star Formation Regions

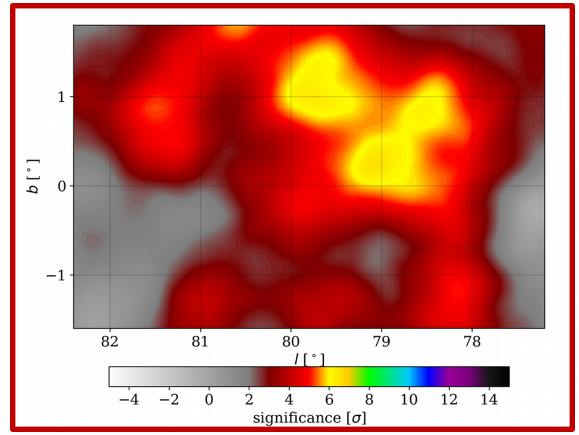
Work to do in the ICRR, starting in 2021, in a colaboration between ICRR-UTokyo and UdeG-Mexico (on GR Astronomy), using the experience obtaine with Tibet AS-Gamma and HAWC Observatories in the Cygnus Cocoon.

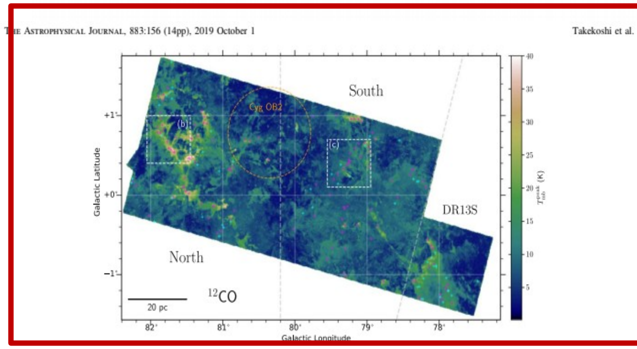
## Pevatrons on Star Forming Regions (SFRs)

**Nobeyama 45 m Cygnus-X CO Survey. II. Physical Properties of C$^{18}$O Clumps**

Tatsuya Takekoshi[1,2], Shinji Fujita[3], Atsushi Nishimura[4], Kotomi Taniguchi[5,6], Mitsuyoshi Yamagishi[7],




**MODELLING ON THE GAMMA RAY EMISSION**

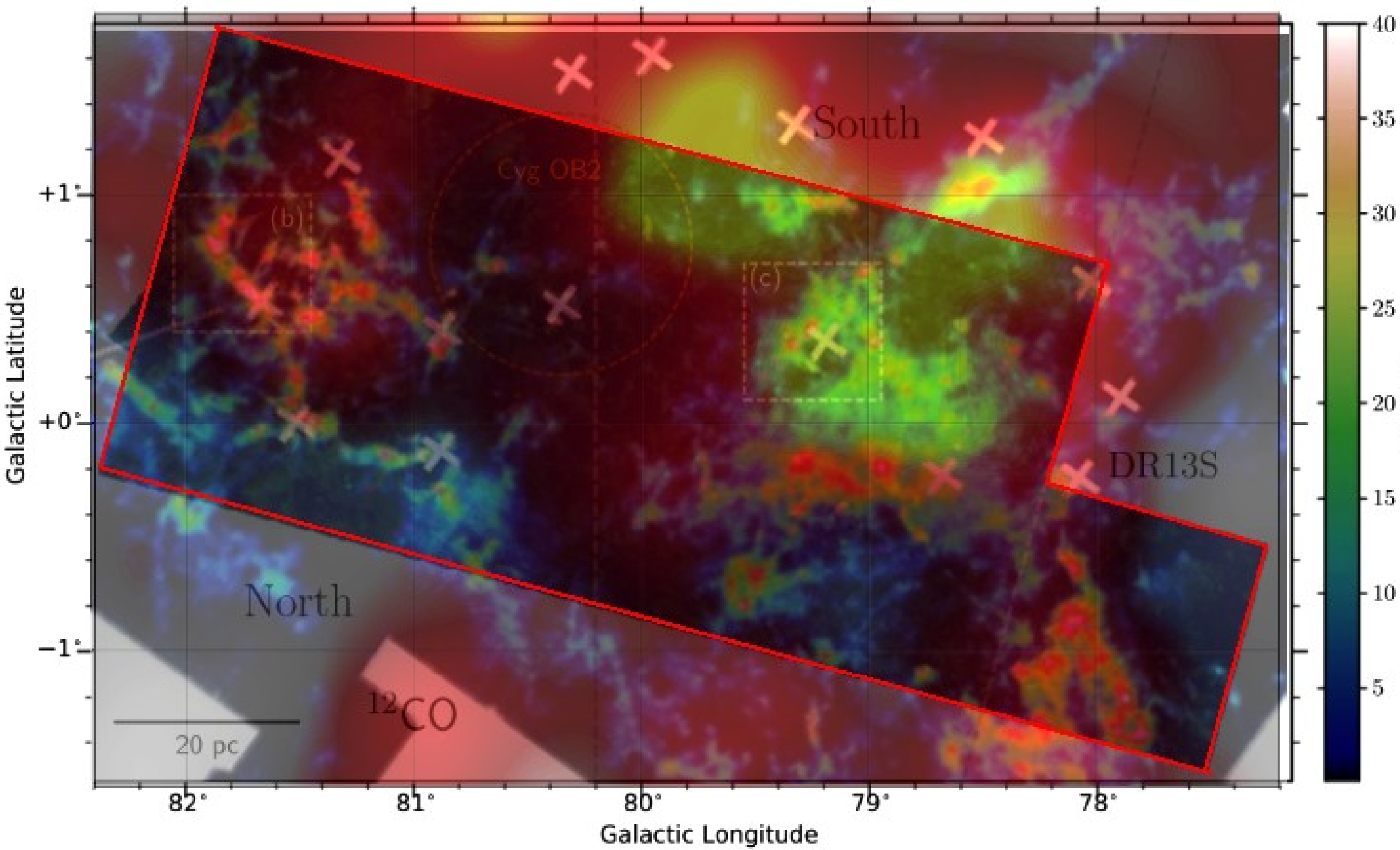
# HAWC: Pevatrons and Star Formation Regions

Seminar at ICRR-Utokyo, August, 2, 2021

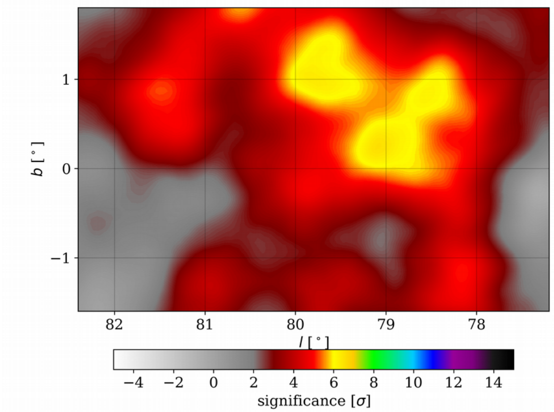
Dr. Eduardo de la Fuente Acosta (CUCEI-UdeG)

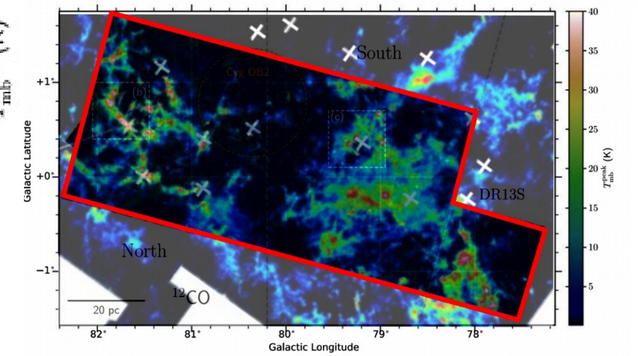
**Work to do in the ICRR, starting in 2021, in a colaboration between ICRR-UTokyo and UdeG-Mexico (on GR Astronomy), using the experience obtaine with Tibet AS-Gamma and HAWC Observatories in the Cygnus Cocoon.**

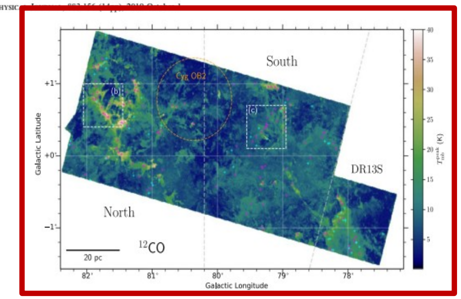
## Pevatrons on Star Forming Regions (SFRs)




13CO from Schneider et al. (2011) + HAWC




# HAWC: Pevatrons and Star Formation Regions

Seminar at ICRR-Utokyo, August, 2, 2021

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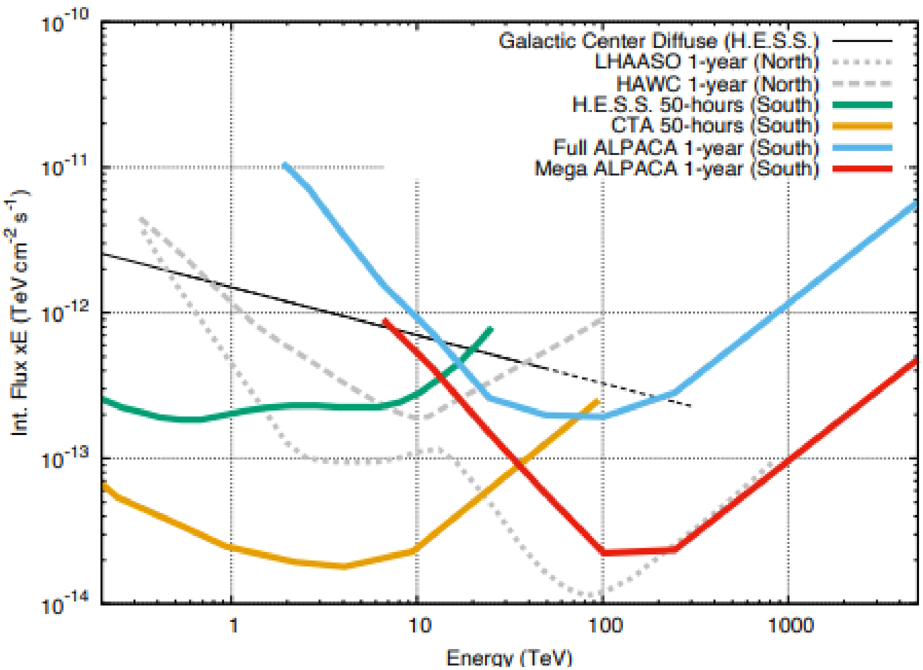
**GENERAL CONCLUSION:** A new epoch in the High Energy Physics is emergening. The PeV era on Astronomy is emerging too, both in 2021, all thanks to the Astroparticles, and the UHE GR Astronomy

Understand Pevatrons is crucial, lets see the evolution of the topic in the ICRC 2023 at Osaka.

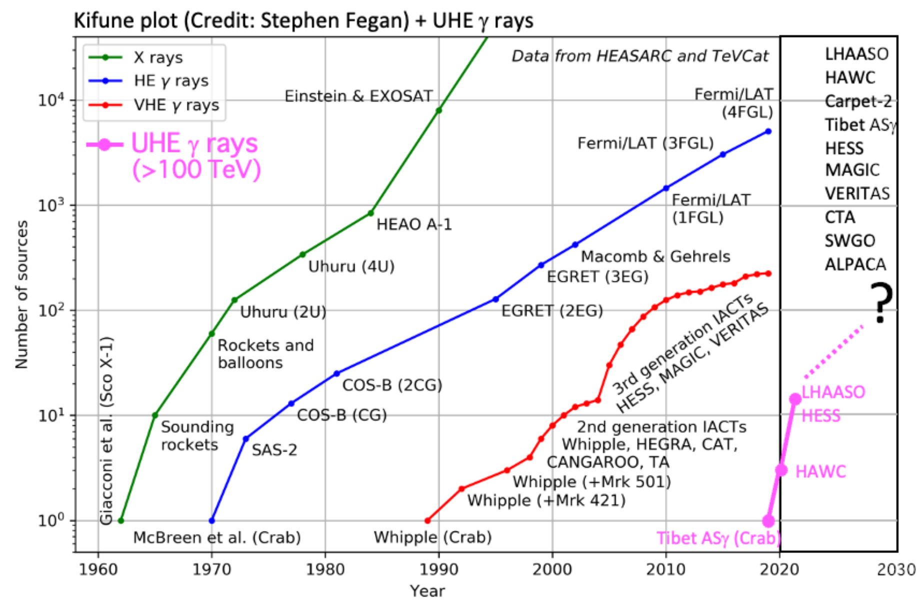
**We need to better the sample; the southern sky is more rich in Pevatrons: SFRs, SNRs, PWNe; and UHE GR sources than the north sky. More. WAIT for ALPACA observatory in Chacaltaya, Bolivia (sensitivity) and CTA.**




**Current status of ALPACA for exploring sub-PeV gamma-ray sky in Bolivia**

https://pos.sissa.it/395/733/pdf

T. Sako[a] on behalf of the ALPACA Collaboration




Draw the "Kifune" plot - the integral number of high energy sources detected as a function of year - in the style of a plot developed by Tadashi Kifune (for example http://adsabs.harvard.edu/abs/1996NCimC..19..953K).
The data for the number of X-ray and HE (GeV) gamma-ray sources come from a page on HEASARC maintained by Stephen A. Drake (retrieved 2017-09-28) : https://heasarc.gsfc.nasa.gov/docs/heasarc/headates/how_many_xray.html
The data for the number of VHE (TeV) gamma-ray sources is from TeVCat maintained by Deirdre Horan and Scott Wakely (retrieved 2017-09-28) : http://tevcat.uchicago.edu/

Kifune plot: the number of detected sources as a function of time (1960) (ICRC 2021)

# HAWC: Pevatrons and Star Formation Regions


# THANK YOU!.

**Dr. Eduardo de la Fuente Acosta**

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Institute for Cosmic Ray Research (ICRR), University of Tokyo (Sabbatical)

eduardo.delafuente@academicos.udg.mx