Recent Results from the HAWC Gamma Ray Observatory

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HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

instituto de astronomía
unam

UNIVERSIDAD NACIONAL AUTONOMA DE MEXICO
POR MI RAZA HABLARA EL ESPIRITU

The HAWC Collaboration

Institutions in Mexico

1. Benemérita Universidad Autónoma de Puebla (BUAP)
2. Centro de Investigación y de Estudios Avanzados (CINVESTAV)
3. Instituto Nacional de Astrofísica Óptica y Electrónica (INAOE)
4. Centro de Investigacion en Computacion, Instituto Politecnico Nacional (CIC-IPN)
5. Universidad de Guadalajara
6. Universidad Autónoma de Chiapas
7. Universidad Autónoma del Estado de Hidalgo
8. Instituto de Astronomía, Universidad Nacional Autónoma de México (IA-UNAM)
9. Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México (ICN-UNAM)
10. Instituto de Física, Universidad Nacional Autónoma de México (IF-UNAM)
11. Instituto de Geofísica, Universidad Nacional Autónoma de México (IGeof-UNAM)
12. Universidad Michoacana de San Nicolás de Hidalgo (UMSNH)
13. Universidad Politecnica de Pachuca

Institutions in the United States

14. California University of Pennsylvania
15. George Mason University
16. Georgia Institute of Technology
17. Los Alamos National Laboratory
18. Michigan State University
19. Michigan Technological University
20. NASA/Goddard Space Flight Center
21. NASA Marshall Space Flight Center
22. Pennsylvania State University
23. Stanford University
24. University of California, Irvine
25. University of Maryland
26. University of New Hampshire
27. University of New Mexico

Institutions in Europe

31. Erlangen Centre for Astroparticle Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany
32. IFJ-PAN, Krakow, Poland
33. National Institute for Nuclear Physics, Padova Division, Italy
34. Max-Planck-Institut für Kernphysik, Heidelberg, Germany

Institutions in South America

35. São Carlos Institute of Physics, University of São Paulo, Brazil

Institutions in Asia

36. Tsung-Dao Lee Institute & School of Physics and Astronomy, Shanghai Jiao Tong University
37. University of Seoul, South Korea
38. Sungkyunkwan University, South Korea

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

~10 years of operations.

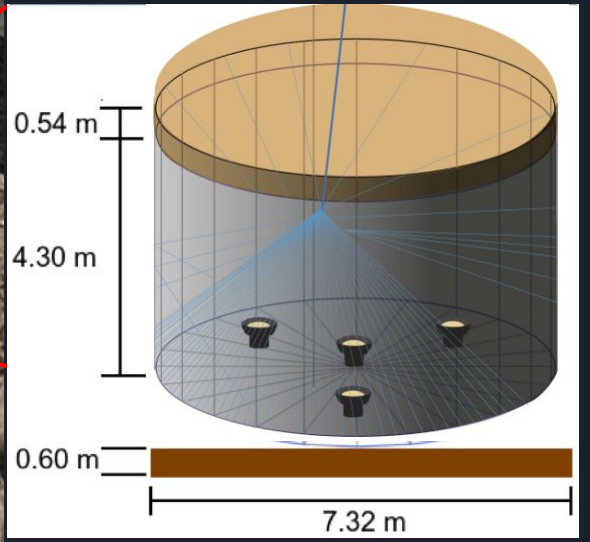
The HAWC Observatory

- Sierra Negra, Mexico
- 4000 m a.s.l.
- ~20,000 m^2
- 300 WCDs
- 345 outrigger detectors

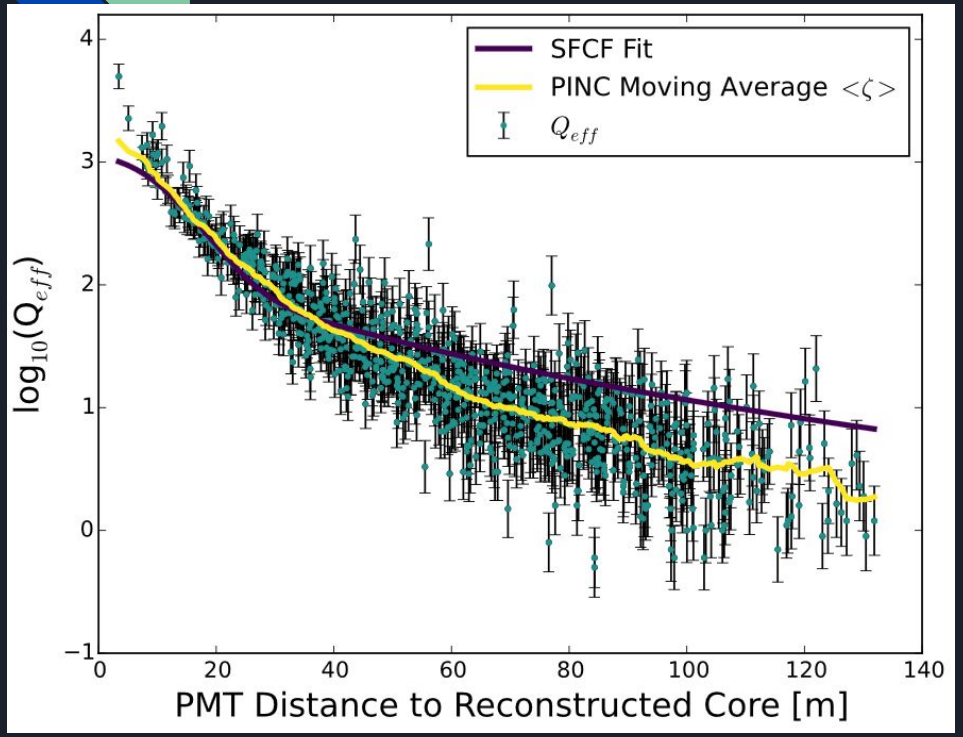
The HAWC Observatory

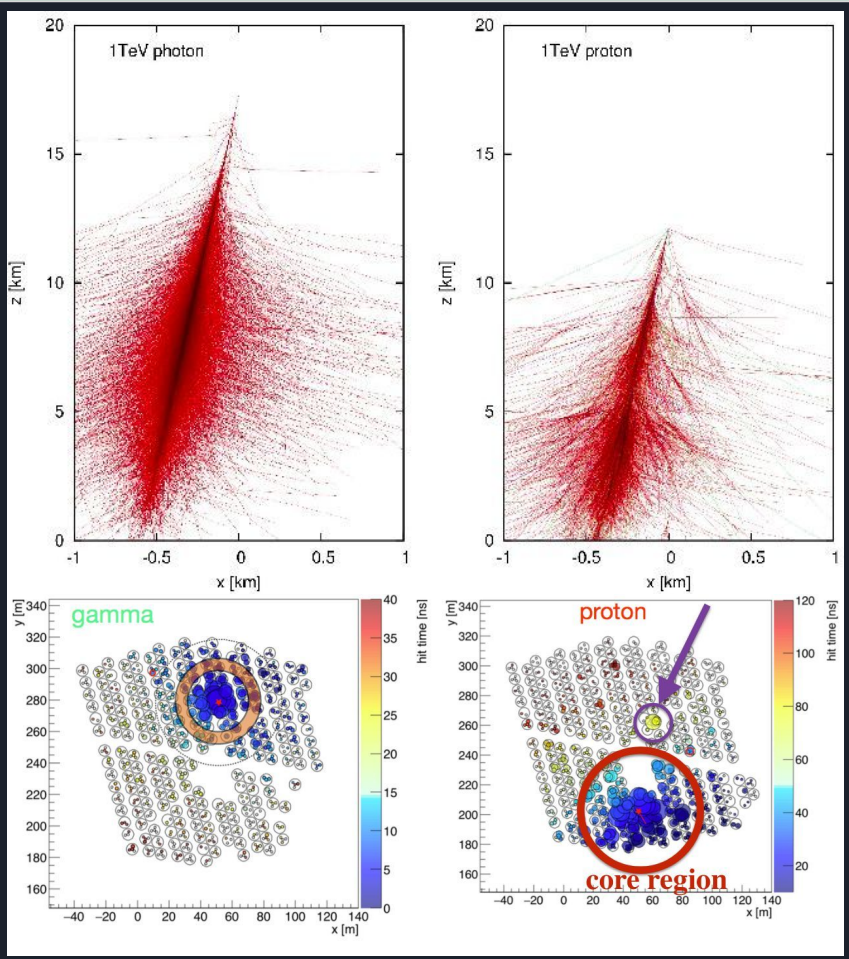
WCDs

- Diameter: 7.3 m
- Height: 4.8 m
- Water volume: 200,000 liters
- 4 PMTs

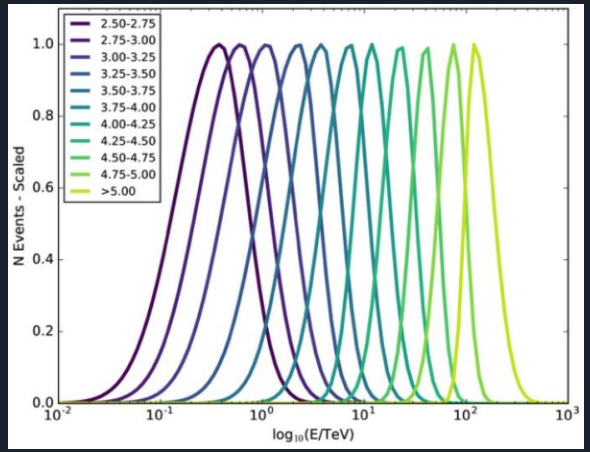


Gamma/Hadron Identification



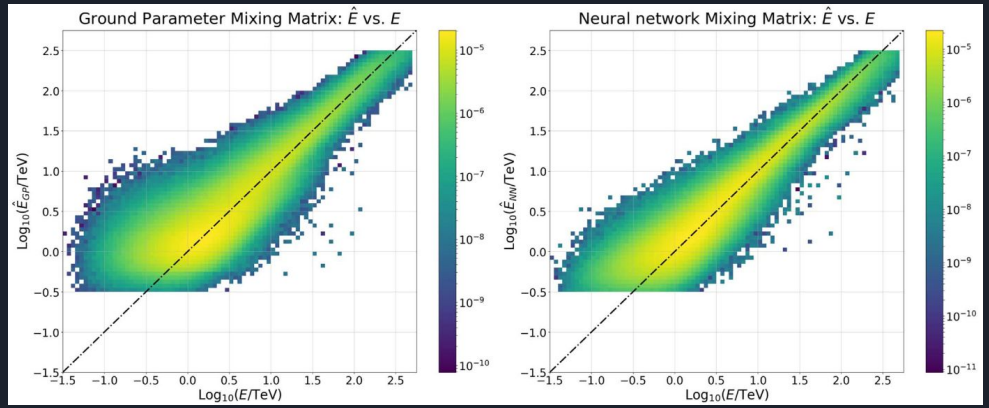


Energy Estimation



Energy Bins

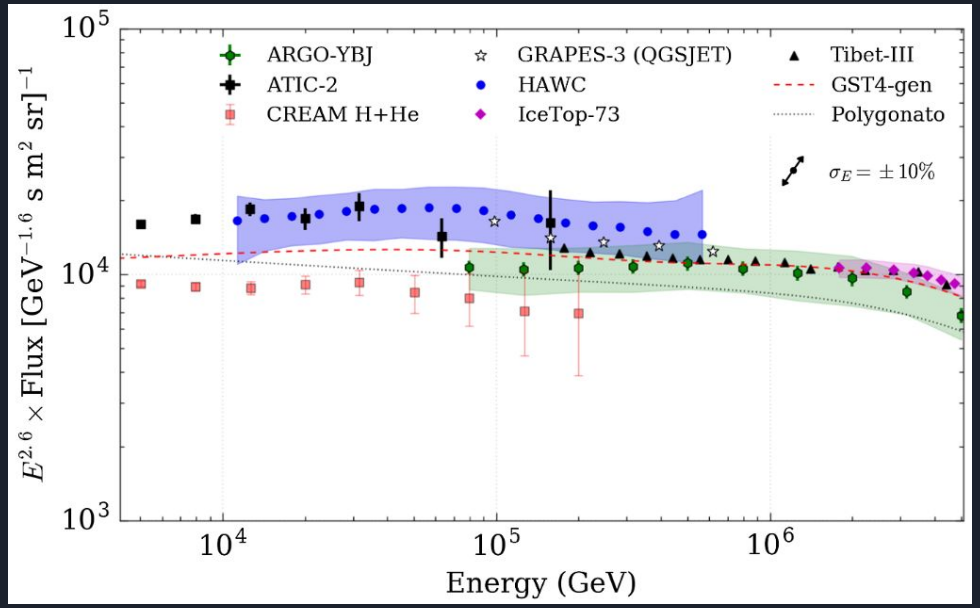
Bin	Low Energy (TeV)	High Energy (TeV)
a	0.316	0.562
b	0.562	1.00
c	1.00	1.78
d	1.78	3.16
e	3.16	5.62
f	5.62	10.0
g	10.0	17.8
h	17.8	31.6
i	31.6	56.2
j	56.2	100
k	100	177
l	177	316



Cosmic Rays Spectrum

All-particle Cosmic Ray Spectrum

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.96.122001

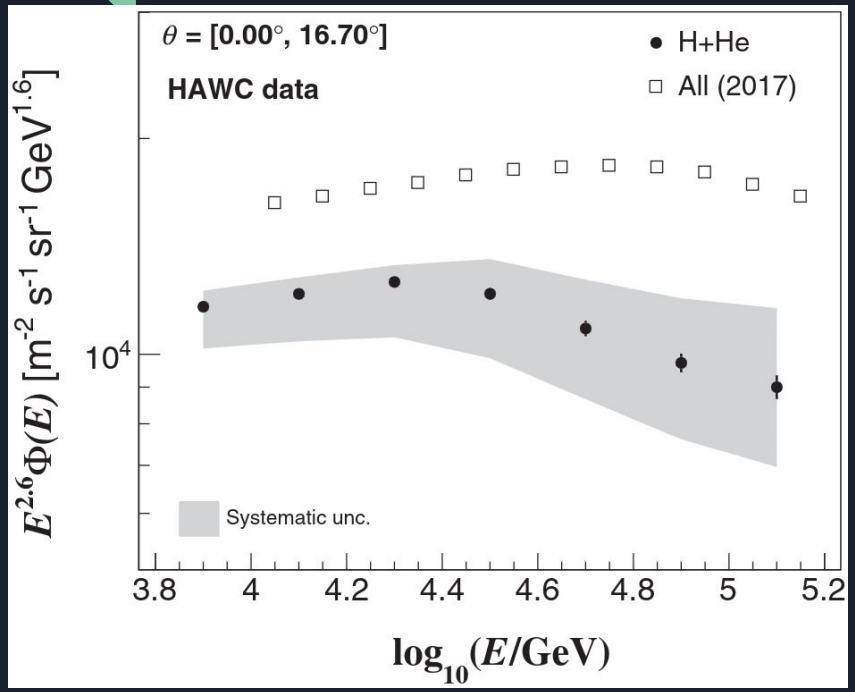


Phys. Rev. D 96, 122001 (2017)

- Agreement of HAWC cosmic ray spectrum with various experiments within systematic uncertainties (10–500 TeV)
- Evidence of a spectral break below 50 TeV
- HAWC's capability to extend ground-based air-shower arrays into energy ranges covered by direct detection experiments

p+He Spectrum (6 - 158 TeV)

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.105.063021

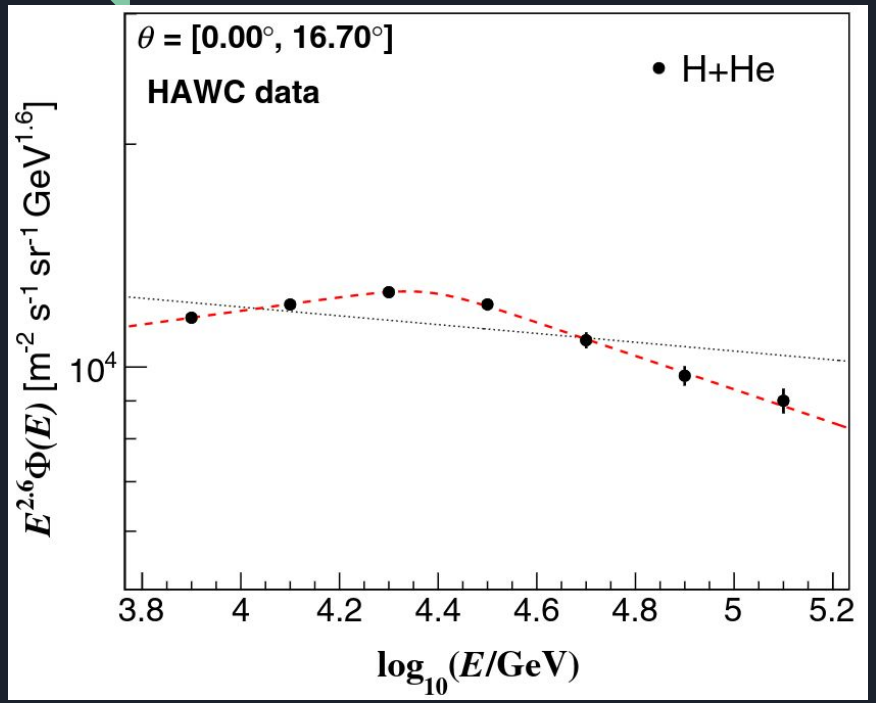


Phys. Rev. D 105, 063021 (2022)

- Confirms deviations from a plain power-law behavior in the 10–100 TeV energy interval.
- Previously reported by HAWC, now confirmed with a larger EAS dataset and improved MC simulations.

p+He Spectrum (6 - 158 TeV)

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.105.063021

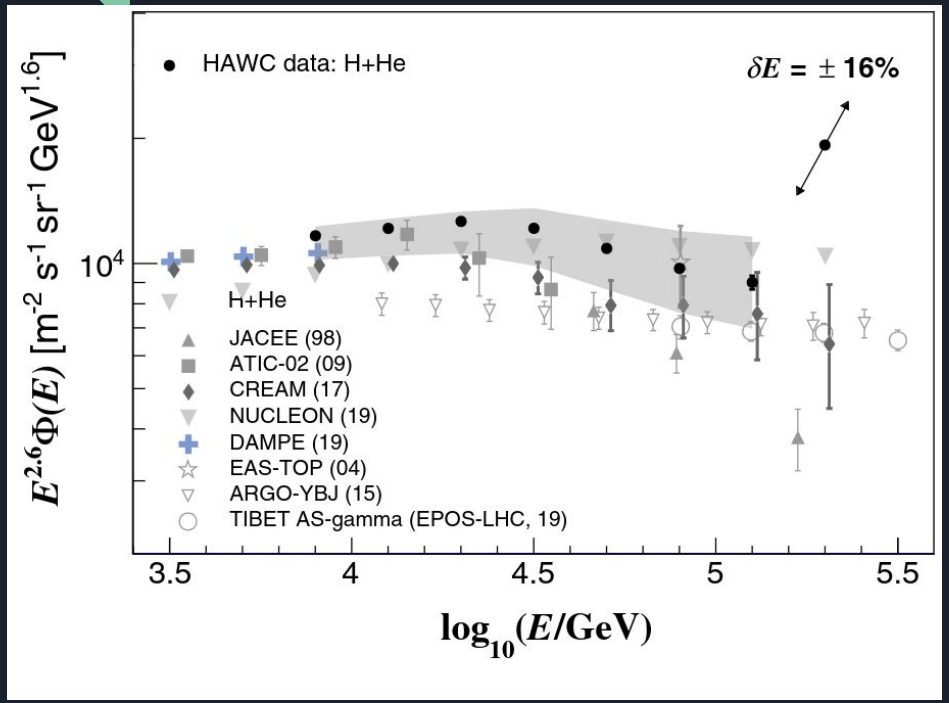


Phys. Rev. D 105, 063021 (2022)

- Break in the H + He spectrum near 24 TeV.
- Smooth decrease in the spectral index from $\gamma = -2.51 \pm 0.02$ to $\gamma = -2.83 \pm 0.02$.

p+He Spectrum (6 - 158 TeV)

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.105.063021



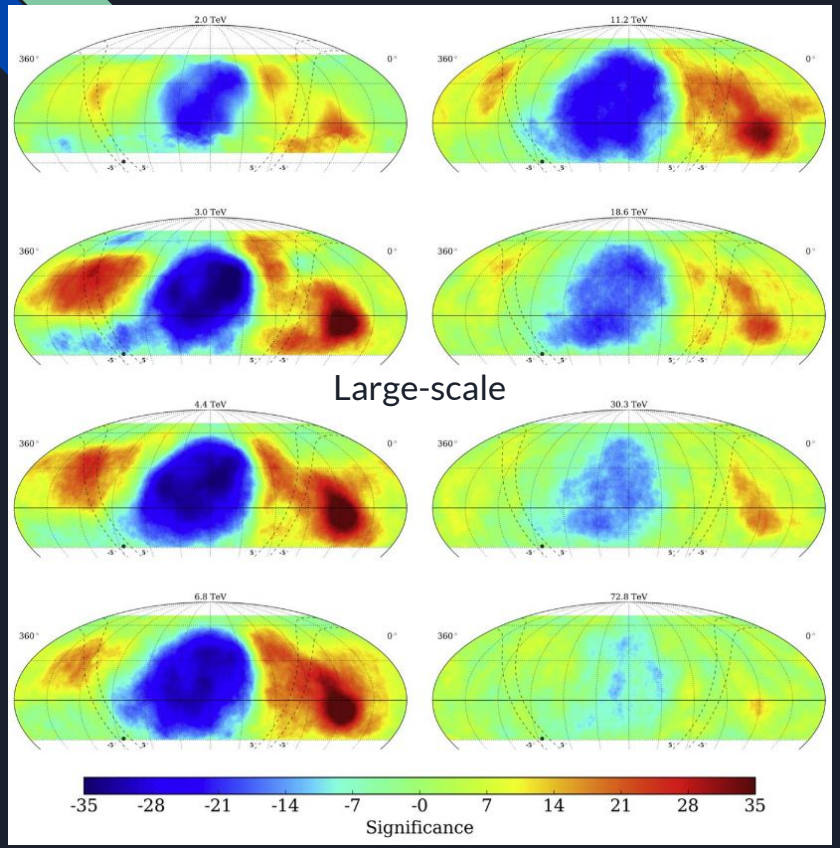
Phys. Rev. D 105, 063021 (2022)

- Consistent with ATIC-2, CREAM I-III, and NUCLEON.
- Agreement with DAMPE: softening in the spectrum at tens of TeV.

Anisotropies

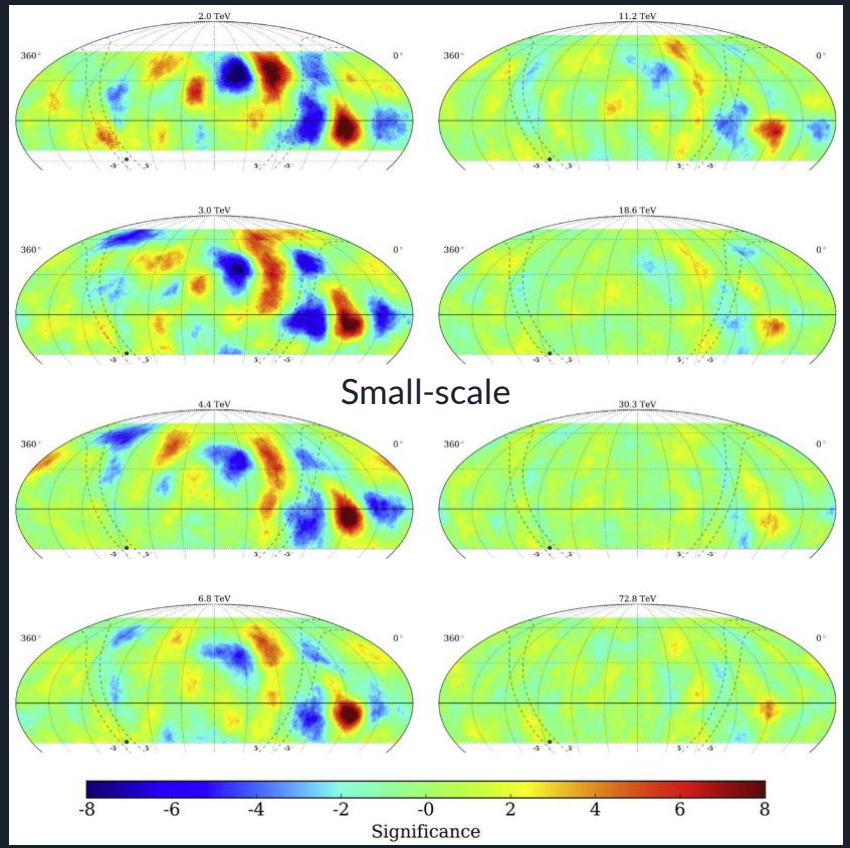
Observation of Anisotropy of TeV Cosmic Rays with Two Years of HAWC

https://doi.org/10.3847/1538-4357/aad90c



Large-scale

ApJ 865, 57 (2018)



Small-scale

ApJ 865, 57 (2018)

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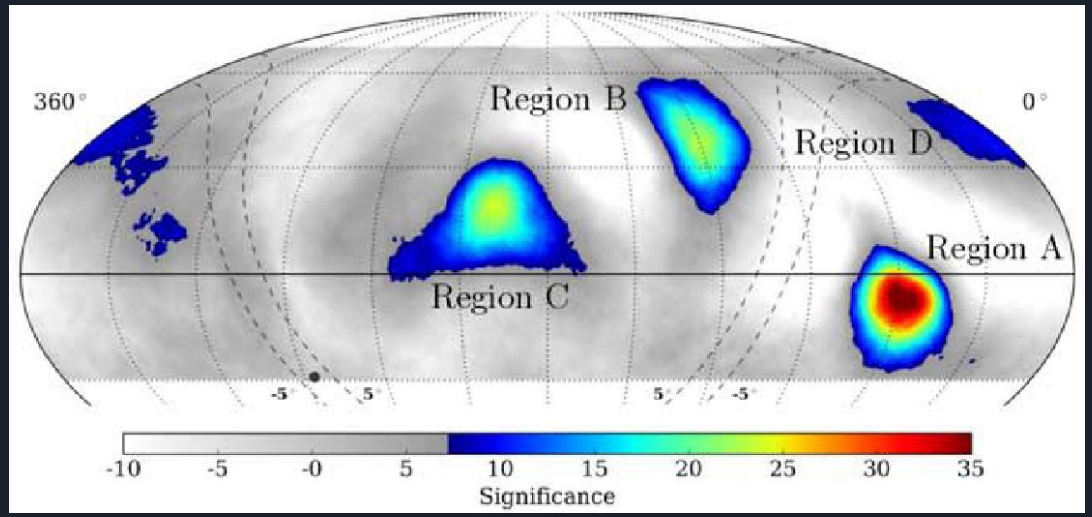
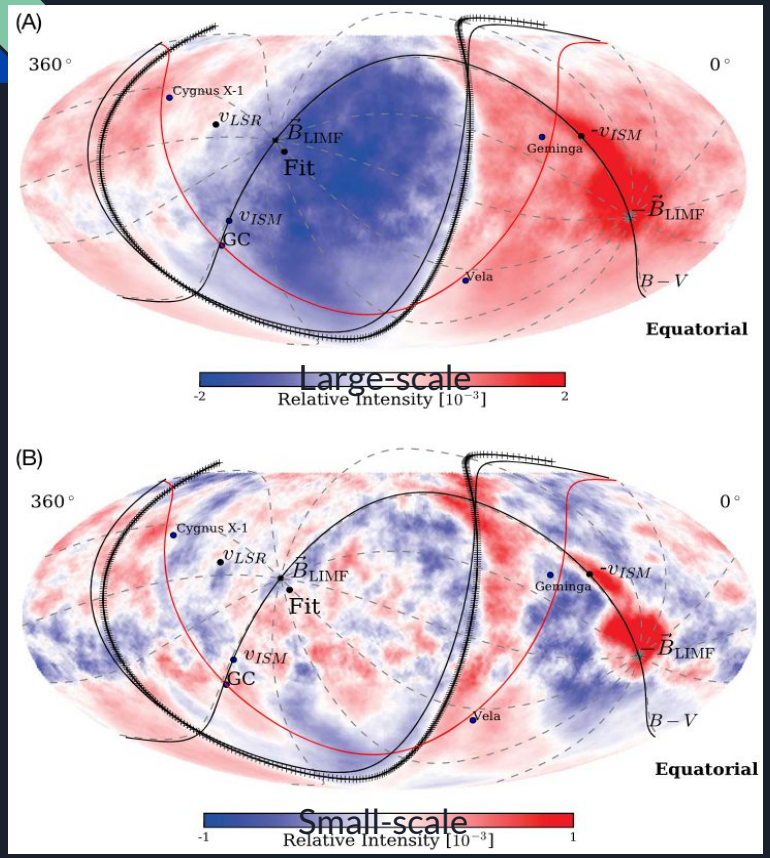


ApJ 865, 57 (2018)

- **Region A**: Most prominent feature, present at all energies, extent of ≈30°.
- **Region B**: Similar width in R.A. but elongated in declination.
- **Region C**: Relatively symmetric excess, extent of ≈30°.
- **Region D**: New excess, weaker than others, extent of ≈25° in declination, elongated in R.A.

All-sky Measurement of the Anisotropy of Cosmic Rays at 10 TeV and Mapping of the LIMF

https://iopscience.iop.org/article/10.3847/1538-4357/aaf5cc/meta



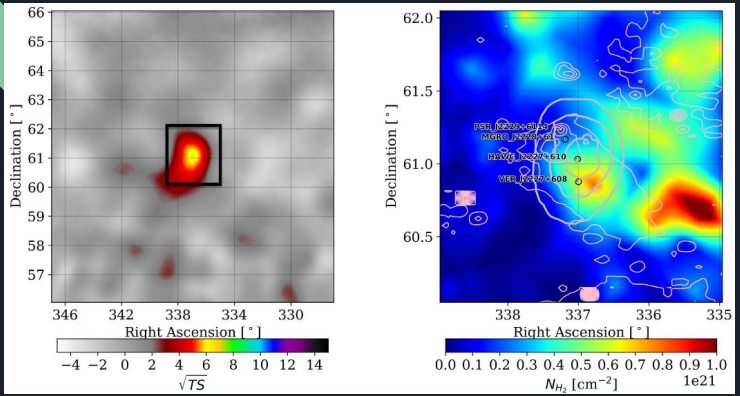
ApJ 871, 96 (2019)

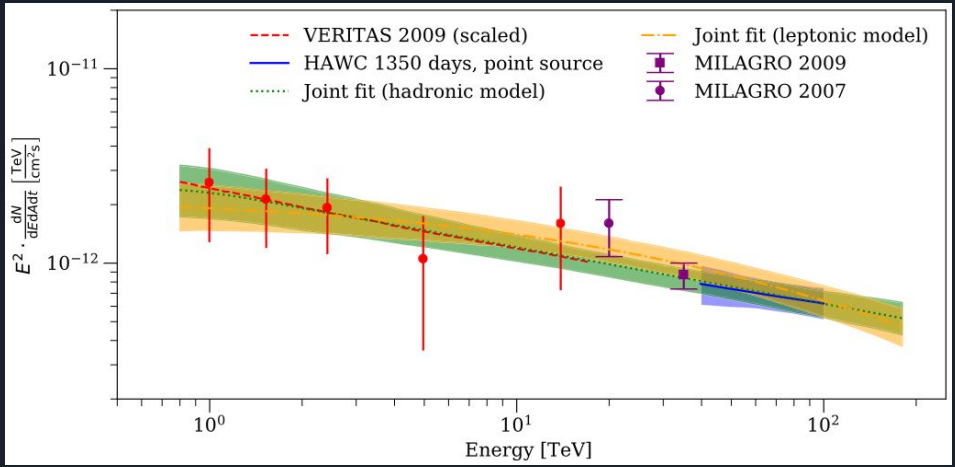
- First nearly full-sky map of cosmic ray arrival direction (HAWC and IceCube).
- Median energy of the cosmic rays is 10 TeV.
- The full-sky observation eliminates degeneracy between spherical harmonic components.
- Provides a tool to probe properties of particle diffusion and interstellar magnetic turbulence.
- Cosmic ray anisotropy is ordered along the local interstellar magnetic field (LIMF).

Cosmic Rays Accelerators

HAWC J2227+610 and Its Association with G106.3+2.7, a New Potential Galactic PeVatron

https://doi.org/10.3847/2041-8213/ab96cc



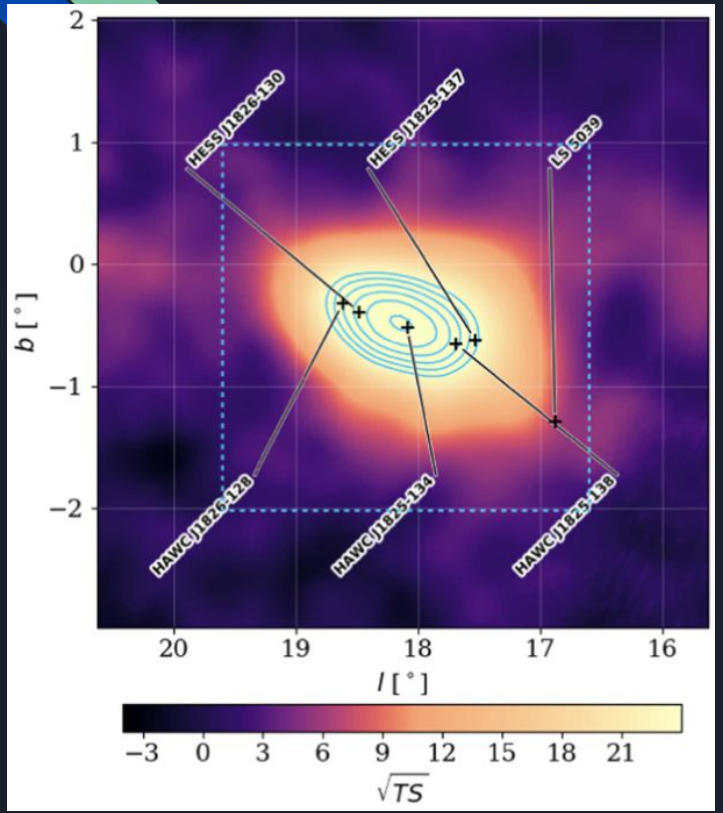


- No detected cutoff in the VHE gamma-ray energy spectrum yet.
- Gamma-ray cutoff is estimated to lie between 120 TeV and the PeV range.
- Detection of hard-spectrum gamma-ray emission up to more than 100 TeV from G106.3+2.7 region.
- Interpreted under both hadronic and leptonic emission models.
- If hadronic, the proton cutoff energy is above 800 TeV.
- Could be a Galactic PeVatron.
- The supernova shockwave potentially provides sufficient energy for the observed VHE gamma-ray emission.

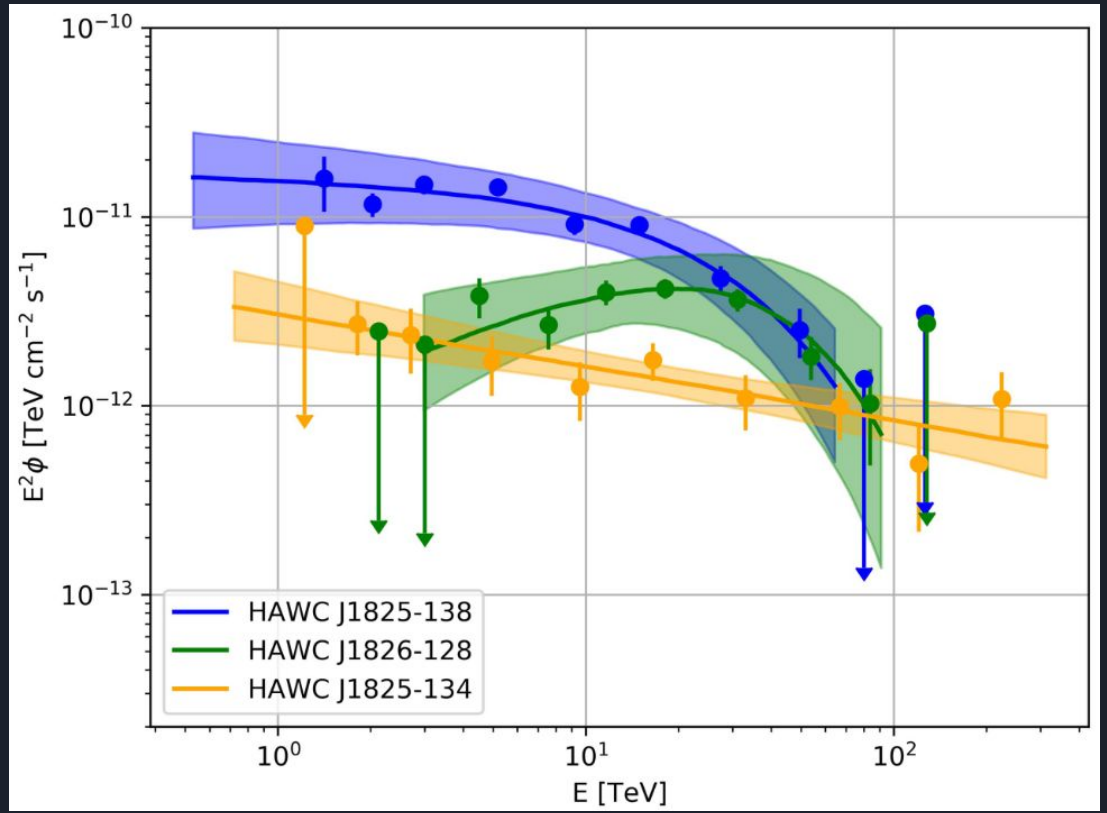
ApJ 896, L29 (2020)

Evidence of 200 TeV Photons from HAWC J1825-134

https://doi.org/10.3847/2041-8213/abd77b



ApJ 907, L30 (2021)



ApJ 907, L30 (2021)

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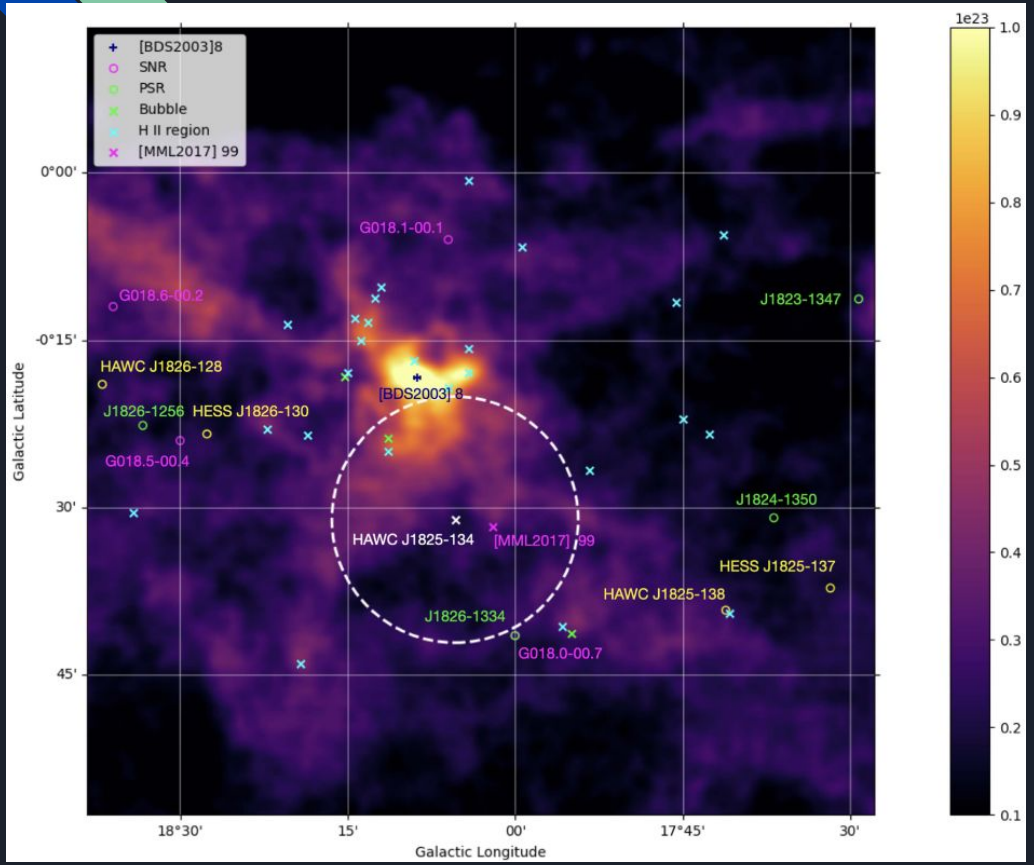
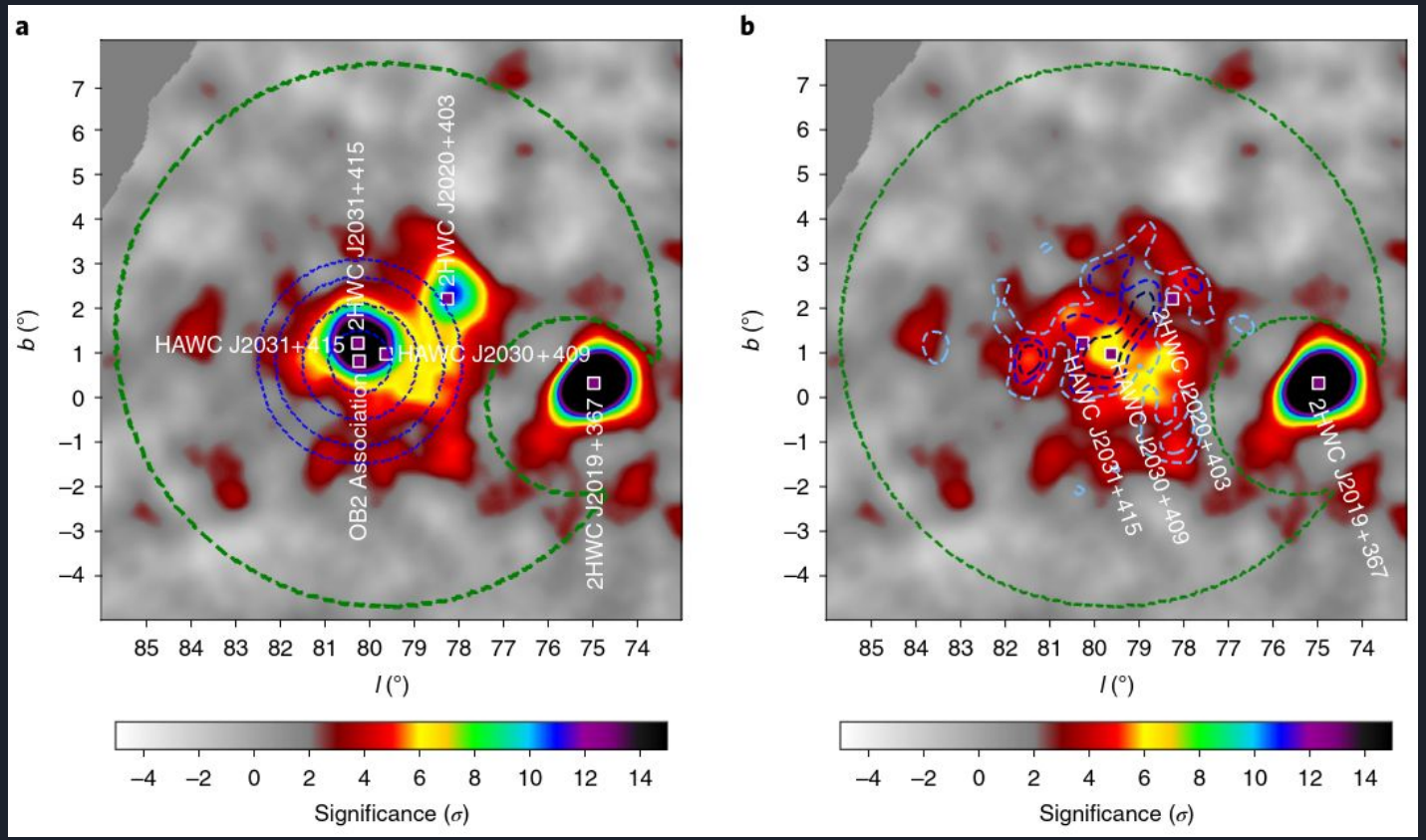


- Coincidence with the pulsar PSR J1826-1334 is not favored.
- Favored scenario: PeV cosmic-ray protons colliding with ambient gas.
- Coincides with a region of high density associated with the giant molecular cloud.
- Possible source of multi-PeV cosmic rays: young star cluster [BDS2003] 8.

ApJ 907, L30 (2021)

HAWC observations of the acceleration of very-high-energy cosmic rays in the Cygnus Cocoon

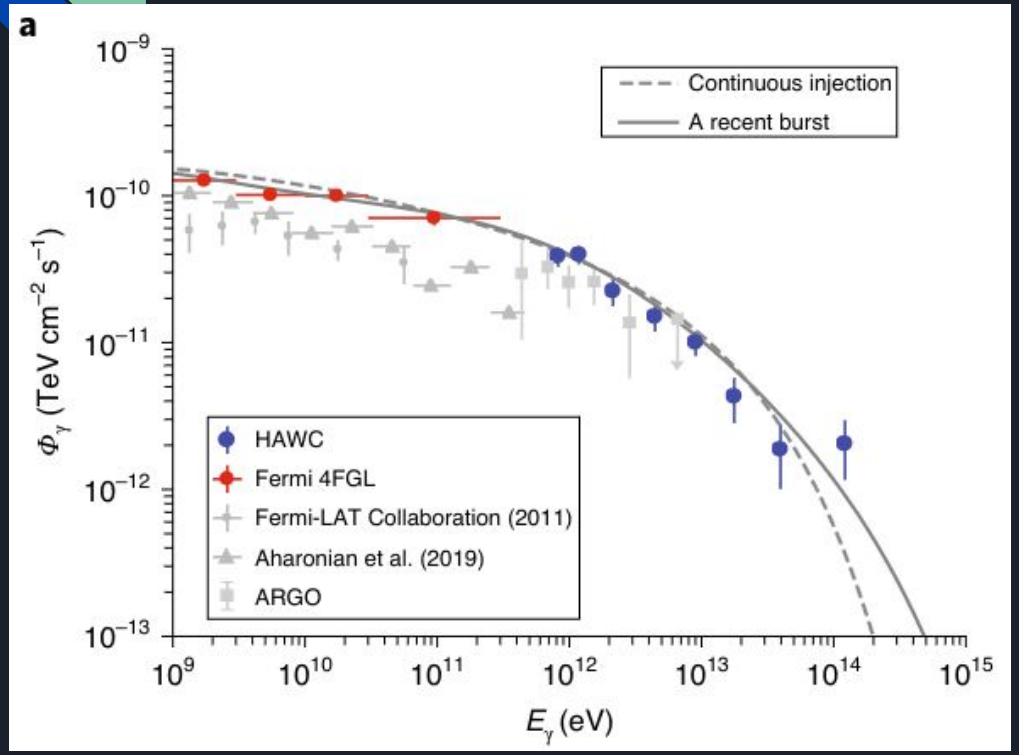
https://doi.org/10.1038/s41550-021-01318-y



Nat. Astron., 5:465–471,(2021)

HAWC observations of the acceleration of very-high-energy cosmic rays in the Cygnus Cocoon

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

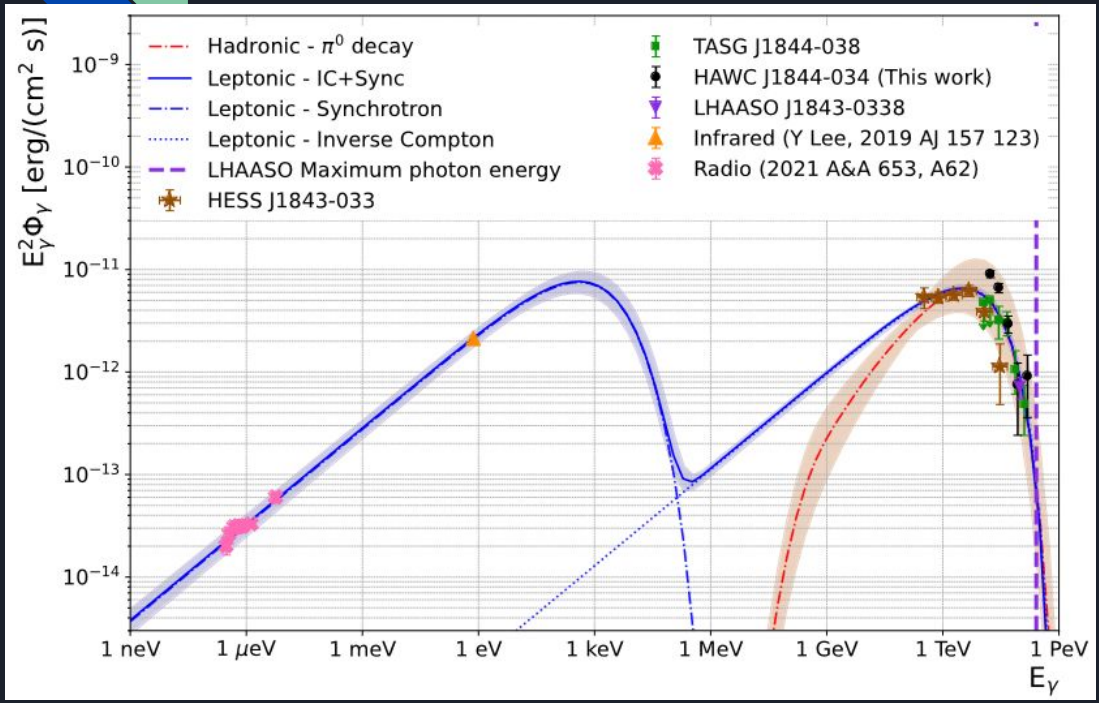


- Direct evidence of cosmic ray protons being accelerated above 100 TeV.
- The γ-ray spectrum does not harden above 1 TeV, contrary to simpler models of superbubble emission.
- Indicates a more complex mechanism for γ-ray emission in superbubbles.
- The Cygnus Cocoon could still be a PeVatron.

Nat. Astron., 5:465–471,(2021)

HAWC Study of the Very-high-energy γ-Ray Spectrum of HAWC J1844−034

https://doi.org/10.3847/1538-4357/ace967



Possible origin

- **Pulsar Association**: The location and energy budget make PSR J1844−0346 a strong candidate as the source of the observed γ-ray emission.
- **SNR Association**: Both hadronic and leptonic scenarios are plausible for SNR G28.6−0.1

ApJ, 954 205 (2023)

Other Cosmic Rays Related Papers

- Constraining p-bar/p ratio using Moon shadow: https://journals.aps.org/prd/pdf/10.1103/PhysRevD.97.102005
- Discovery of Gamma Rays from the Quiescent Sun with HAWC: https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.131.051201
- High-altitude characterization of the Hunga pressure wave with cosmic rays by the HAWC observatory: https://www.sciencedirect.com/science/article/pii/S0273117723007858
- Characterization of the background for a neutrino search with the HAW observatory: https://doi.org/10.1016/j.astropartphys.2021.102670
- Probing the Sea of Cosmic Rays by Measuring Gamma-Ray Emission from Passive Giant Molecular Clouds with HAWC: https://doi.org/10.3847/1538-4357/abfc47
- HAWC as a Ground-Based Space-Weather Observatory: https://link.springer.com/article/10.1007/s11207-021-01827-z
- Interplanetary magnetic flux rope observed at ground level by HAWC: https://iopscience.iop.org/article/10.3847/1538-4357/abc344
- High-altitude characterization of the Hunga pressure wave with cosmic rays by the HAWC observatory: https://doi.org/10.1016/j.asr.2023.09.049

Summary

- Many cosmic ray studies performed with conclusive results
- Analysis techniques are still being improved: incorporation of machine learning techniques improving energy estimation.
- Potential cosmic rays accelerators have been identified. (SNRs, bubbles, star clusters)
- Several new analysis in development and under Collaboration Review
  - “A measurement of the intensity spectrum of cosmic rays from 10^{13} to 10^{15} eV using HAWC.” – Under Collaboration review
  - “Cosmic Ray Composition dependent energy spectrum H,He and Heavy” – Analysis in progress
  - “Update on Cosmic Ray Anisotropies” – Analysis in progress (8 years of data)
  - “Testing the Molecular Cloud Paradigm for Ultra-High-Energy Gamma Ray Emission from the Direction of SNR G106.3+2.7” - Under Collaboration review