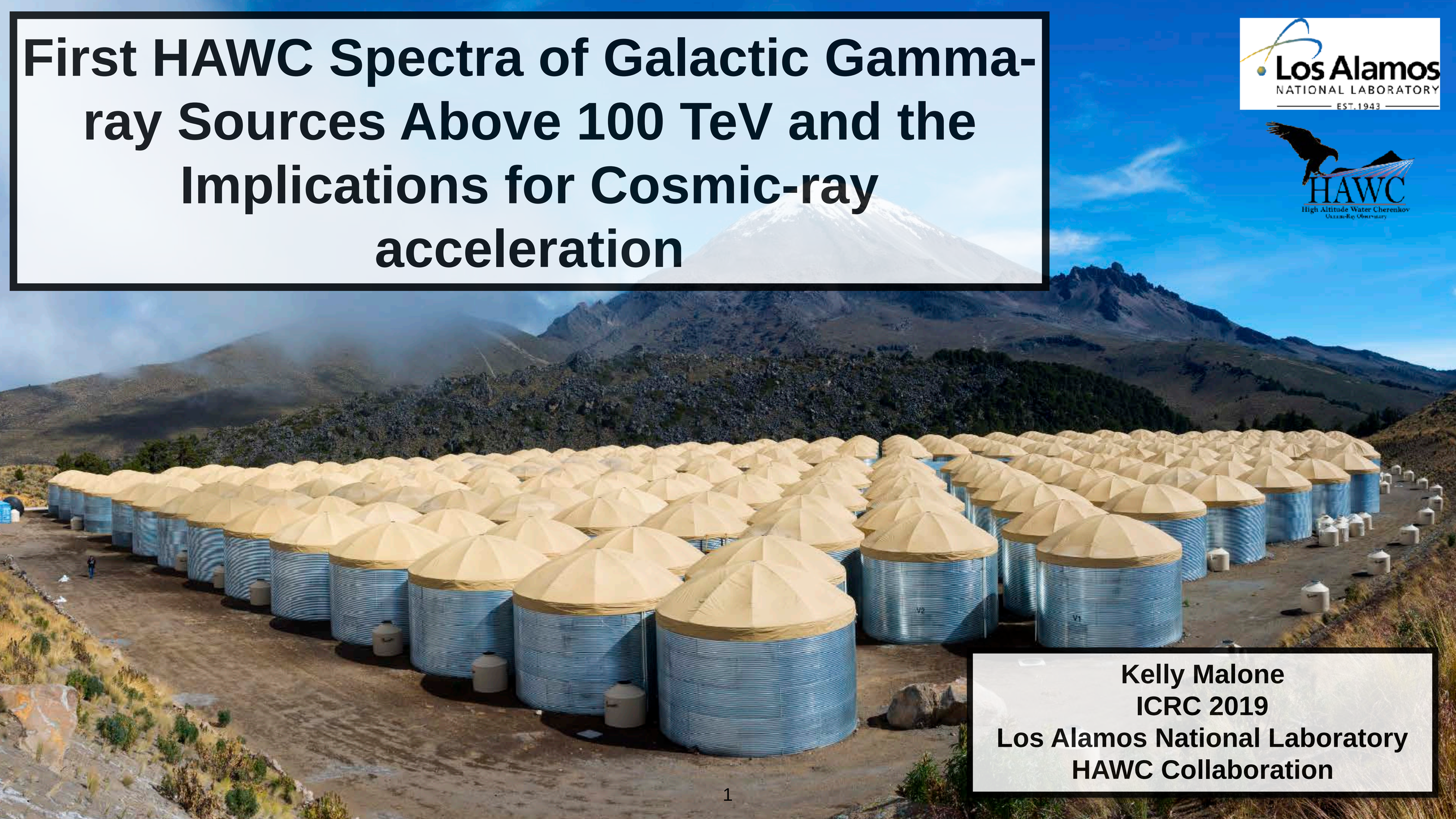
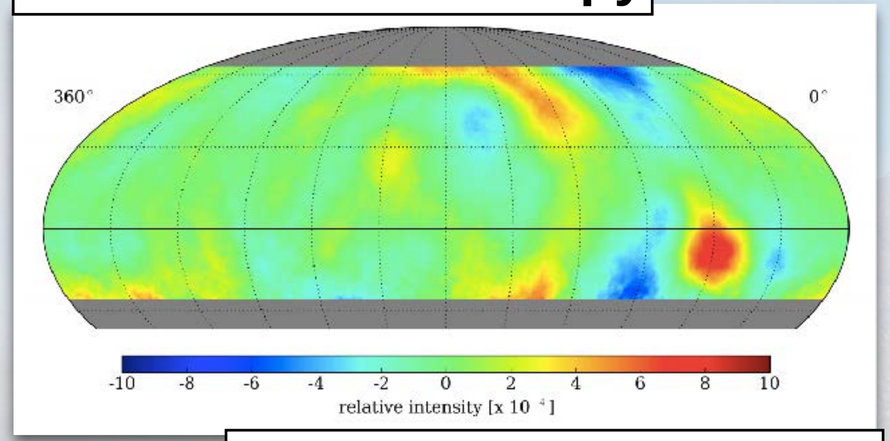
First HAWC Spectra of Galactic Gamma-ray Sources Above 100 TeV and the Implications for Cosmic-ray acceleration



Kelly Malone
ICRC 2019
Los Alamos National Laboratory
HAWC Collaboration

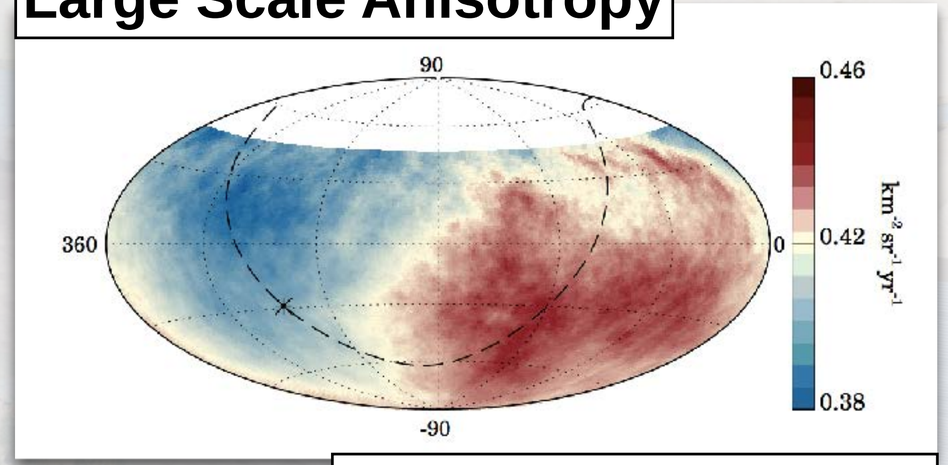
Sources of cosmic rays

Small Scale Anisotropy

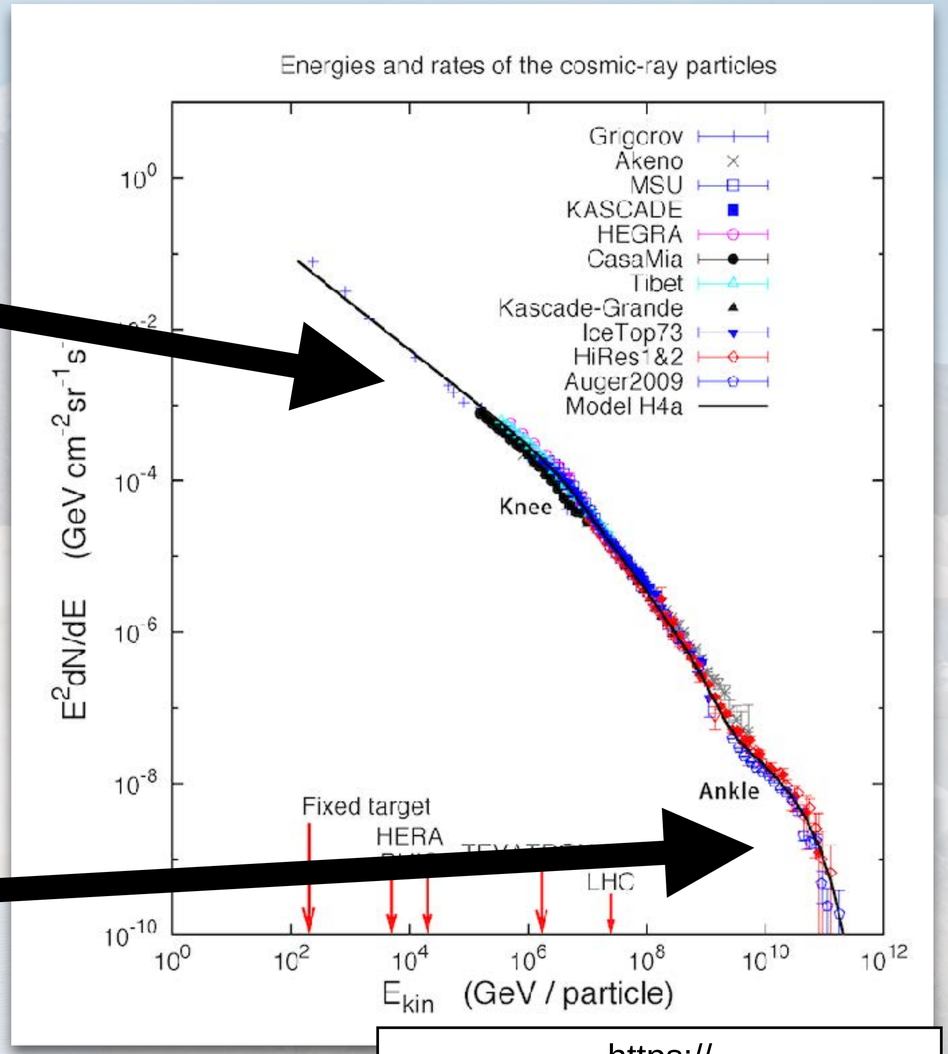


HAWC Collaboration, Astrophys. J (2014)

Large Scale Anisotropy



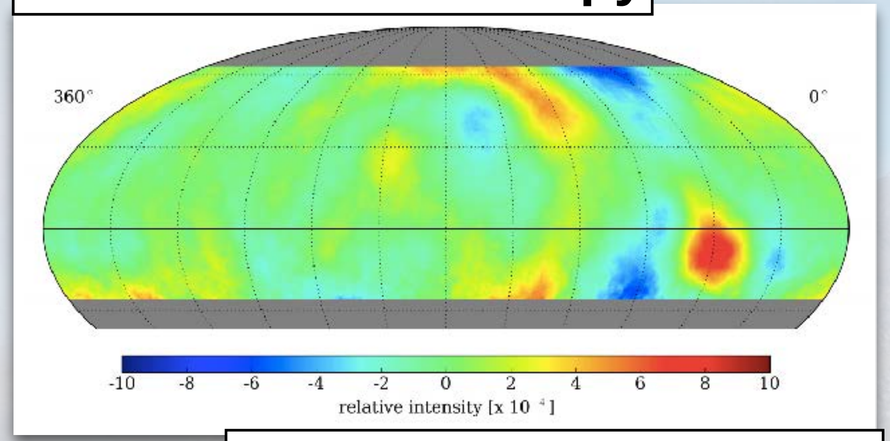
Auger Collaboration, Science (2017)



https://masterclass.icecube.wisc.edu/en/icetop/measuring-cosmic-rays

Sources of cosmic rays

Small Scale Anisotropy



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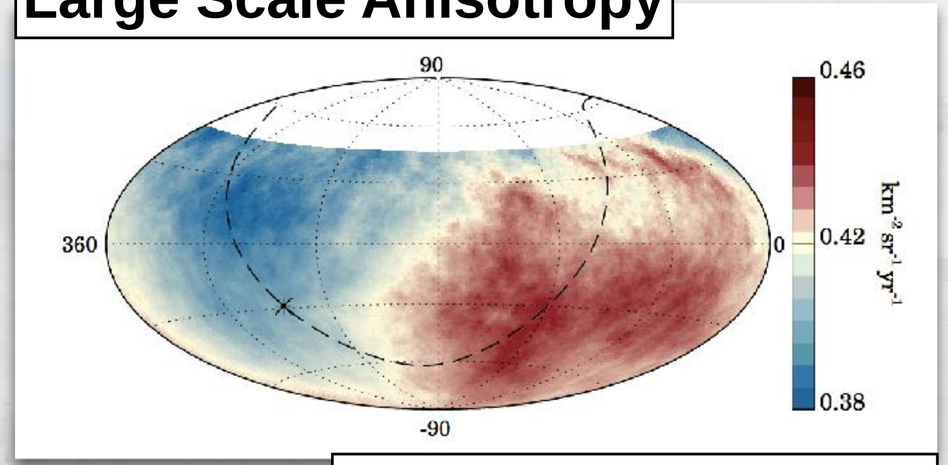
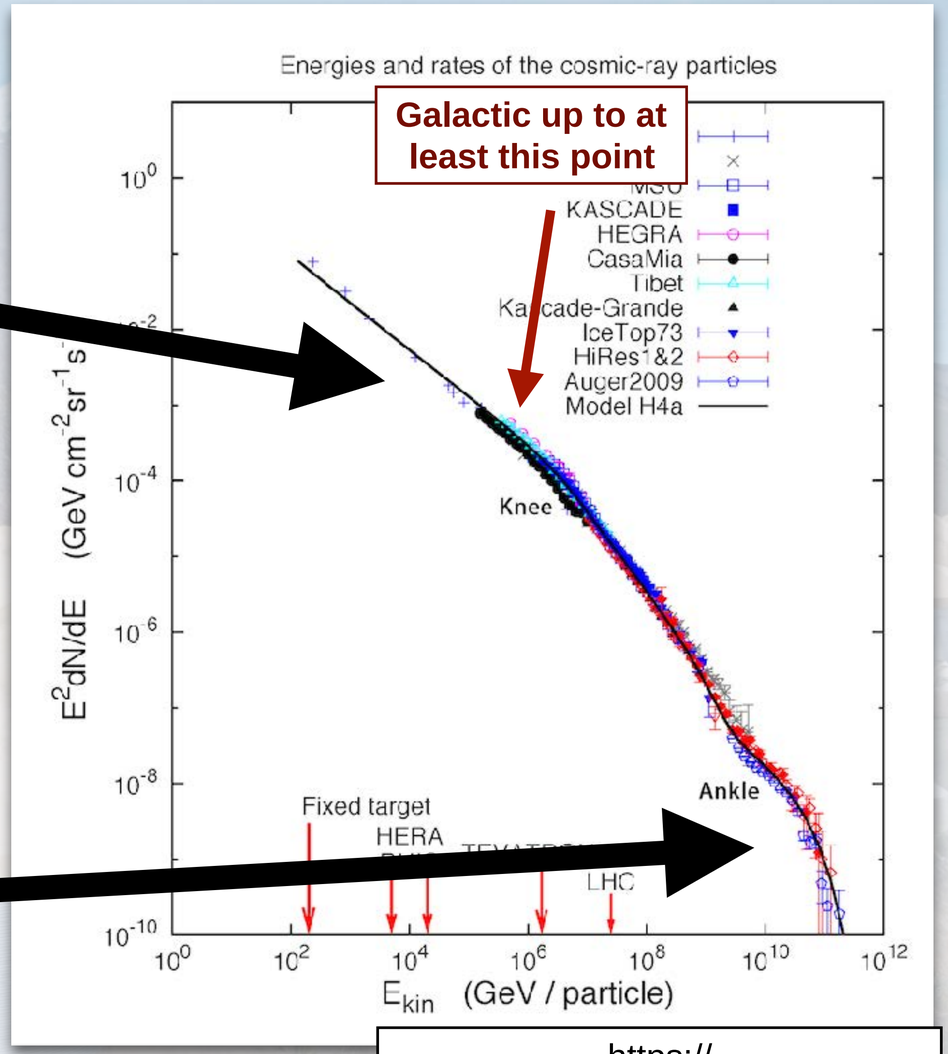


Auger Collaboration, Science (2017)



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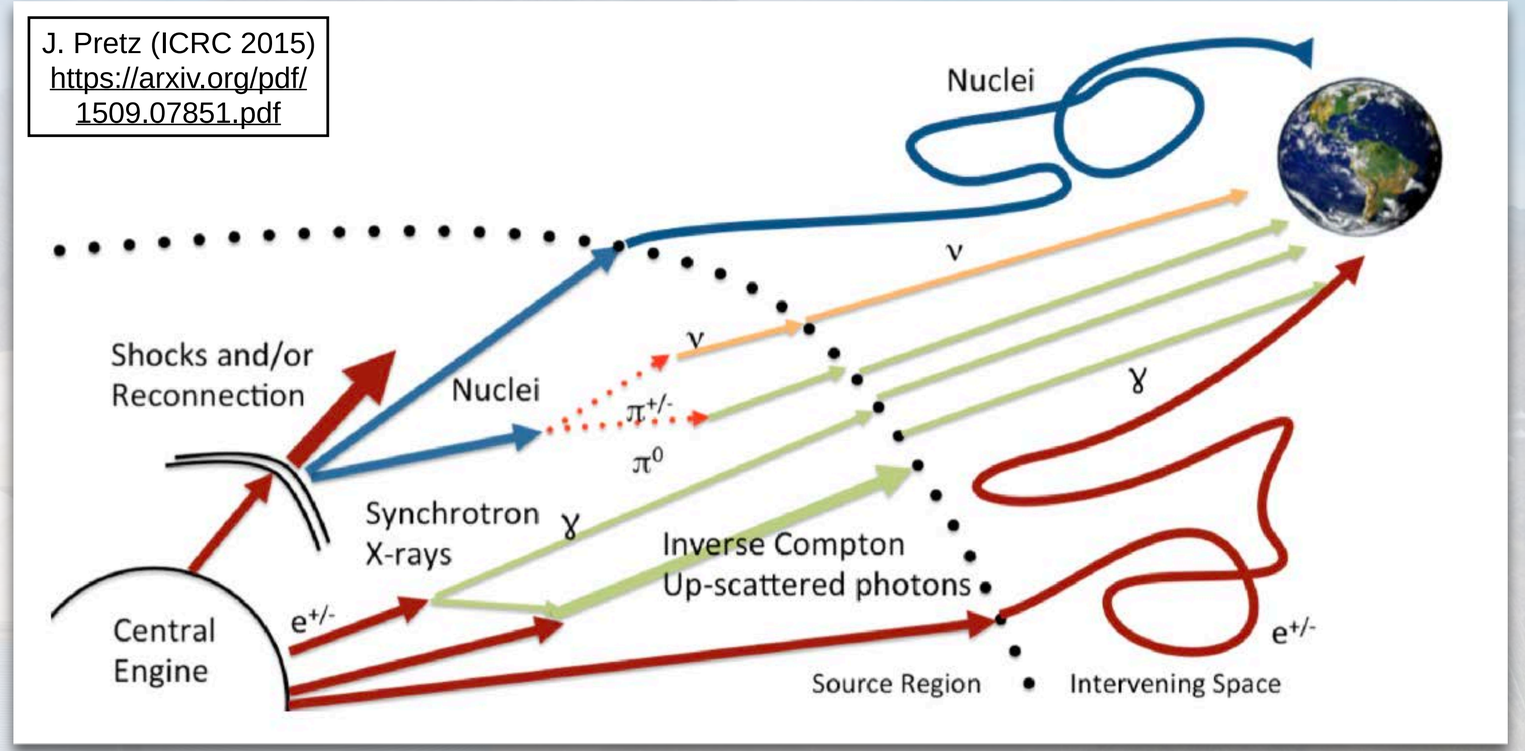
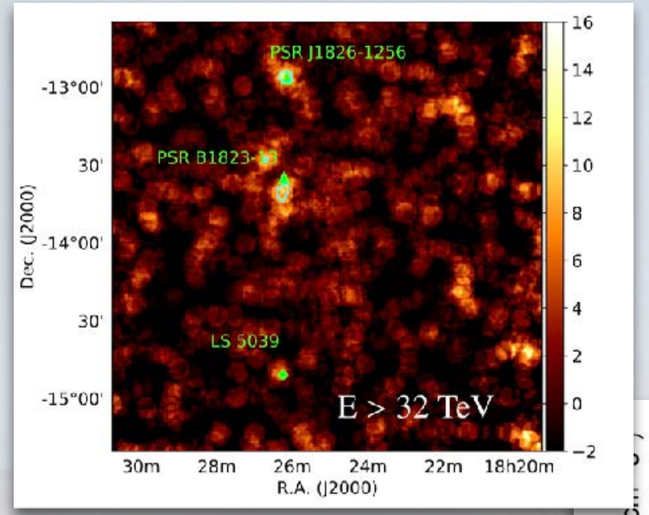
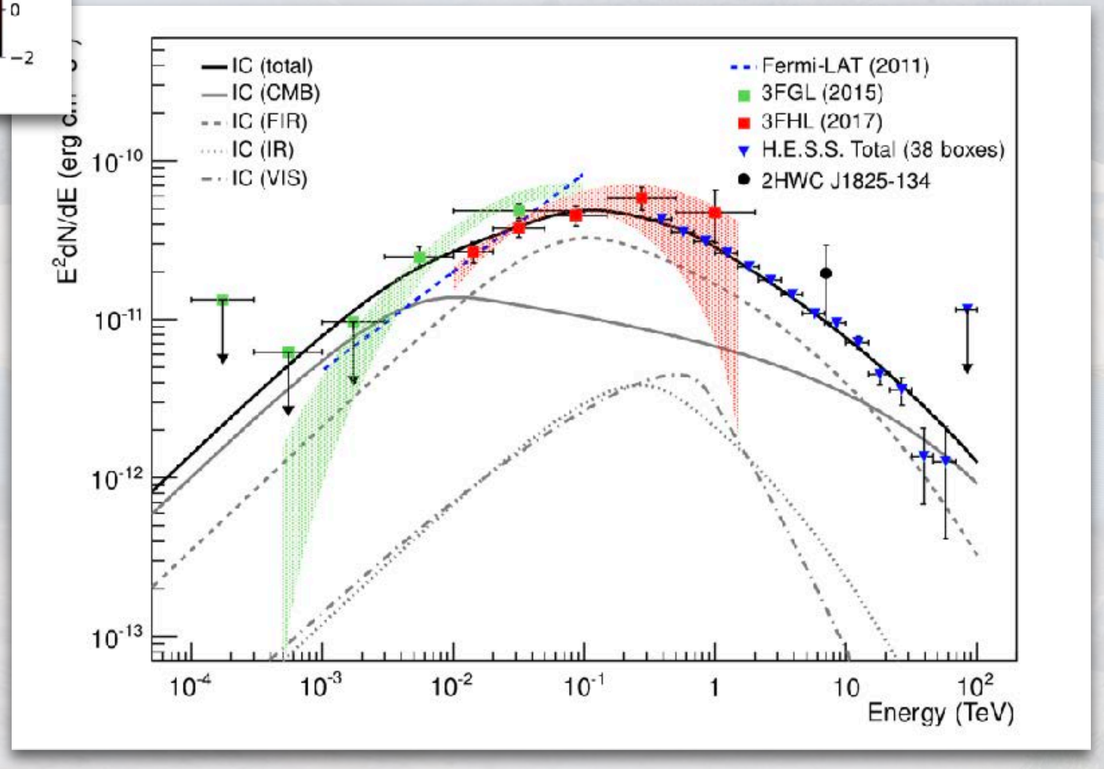
Gamma-ray production from cosmic rays

- Hadronic
- CRs interact with environment, pions are created
- $\pi_0 \rightarrow 2\gamma$
- Gamma rays are an order of magnitude less energetic than cosmic ray. (1 PeV CR creates ~100 TeV gamma ray)
- “PeVatron” spectrum would extend to ~100 TeV without any spectral break or cutoff
- Hard spectrum



Other sources emitting at the highest energies





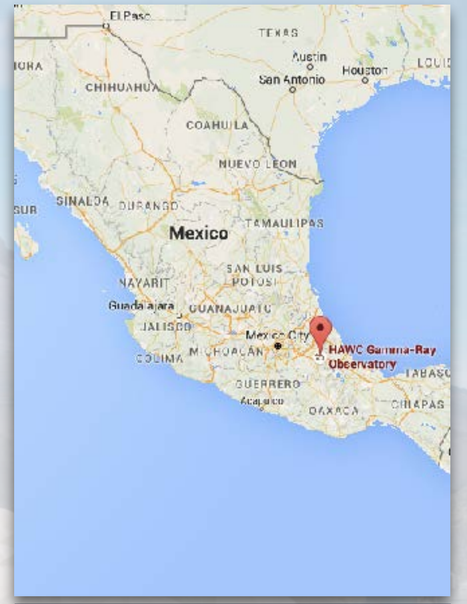
HESS Collaboration, A&A (2019)

- Leptonic
- TeV gamma rays created via inverse Compton scattering
- Klein Nishina effects result in changing spectral index with energy
- At least least two PWN previously known to emit above ~50 TeV in energy (the Crab Nebula, HESS J1825-137)

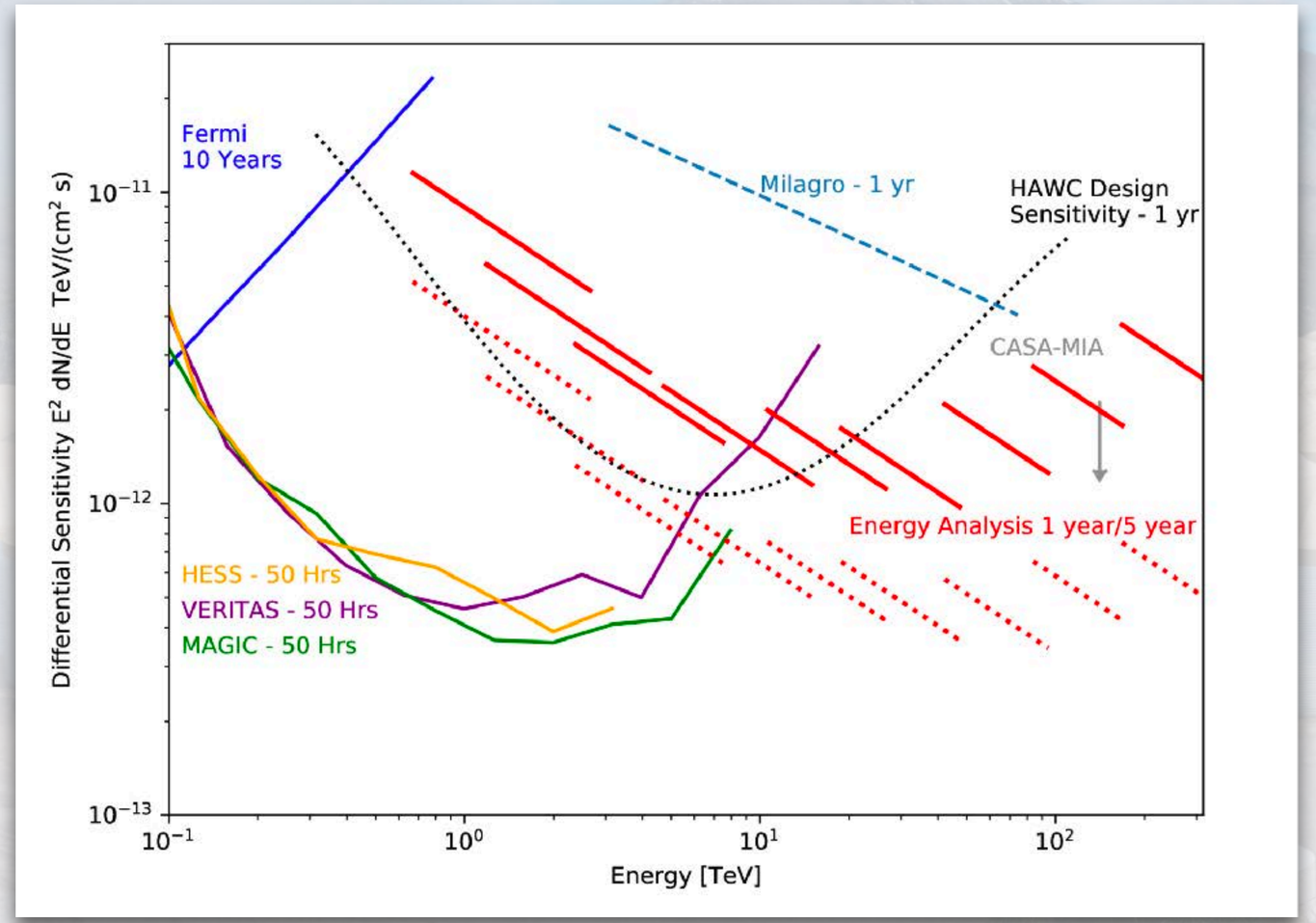
Introduction to HAWC

HAWC with Pico de Orizaba in the background

Number of tanks	300 (4 PMTs/200,000 L of water in each)
Area	22,000 m^2
Location	Puebla, Mexico (19° North)
Altitude	4100 m
Duty Cycle	> 95%
Coverage	2/3 of sky per day
Sensitivity	300 GeV to > 100 TeV
Angular resolution	> 0.1 degrees

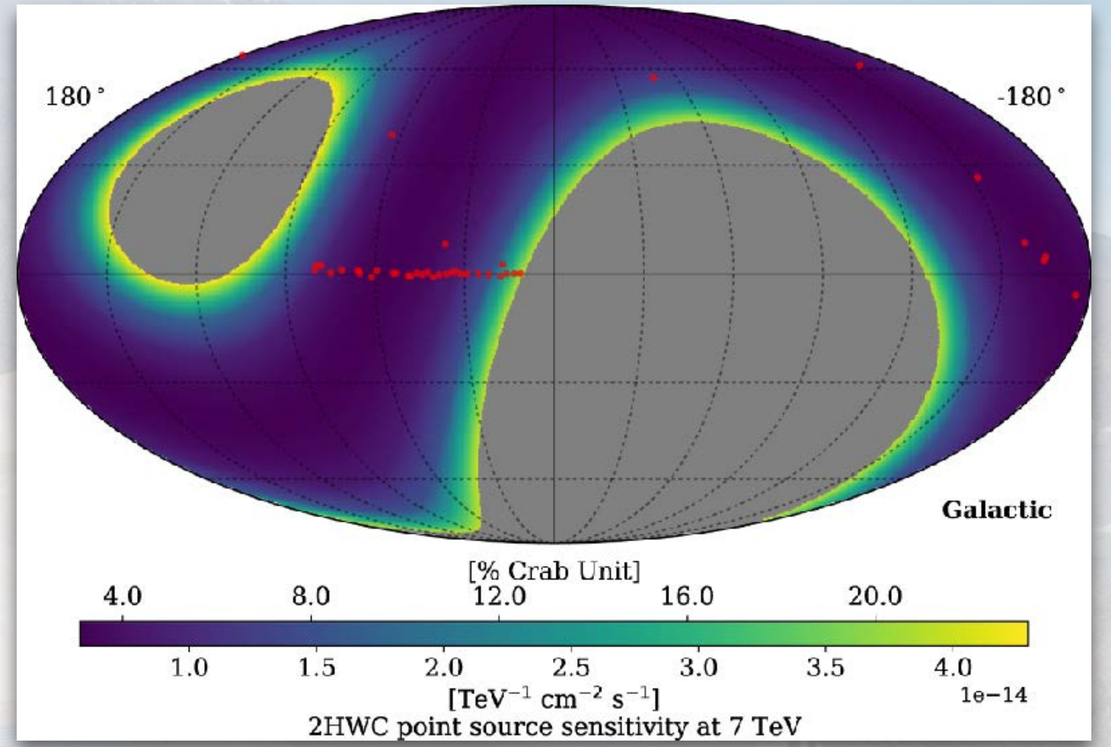


Above 10 TeV, HAWC is the most sensitive currently-operating experiment in the world. New energy estimators increase the dynamic range of the experiment



High-energy catalog search method

- Similar to 2HWC catalog construction (ApJ 2017), but recently developed energy-estimation algorithms allow for searches above specific energy thresholds. Ground parameter energy estimator used here
- TS maps of the highest-energy sky created using likelihood framework
  - Two energy thresholds: > 56 TeV and > 100 TeV
  - Power law spectrum assumed with a variety of different morphologies (point-like and extended)
- Hotspots where TS > 25 identified. Must be separated from nearby local maxima by $\Delta\sqrt{(TS)} > 2$.



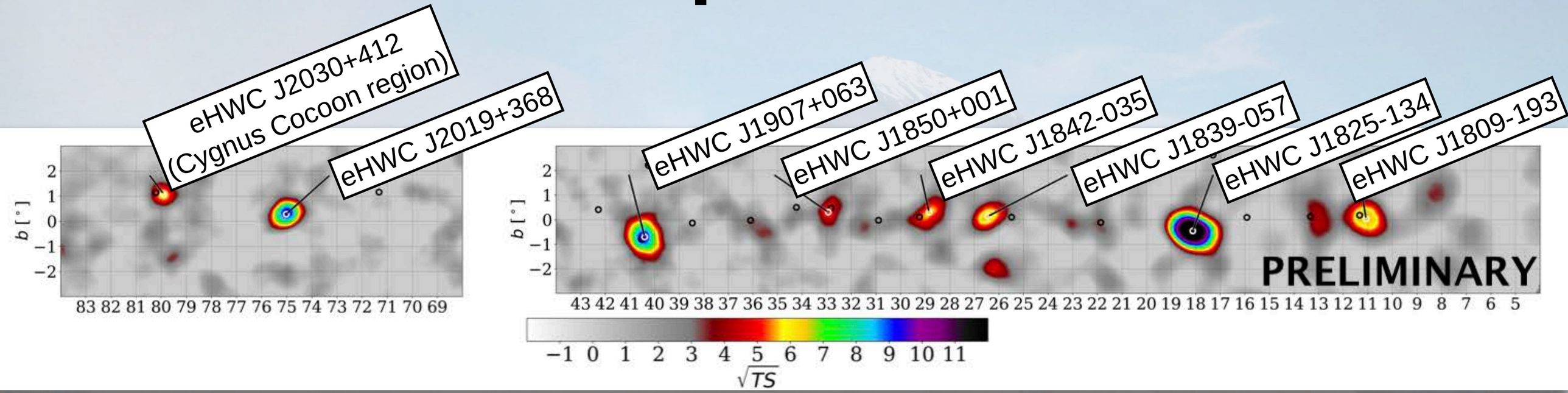
HAWC point source sensitivity
ApJ 2017 / https://arxiv.org/abs/1702.02992

High-energy catalog search results

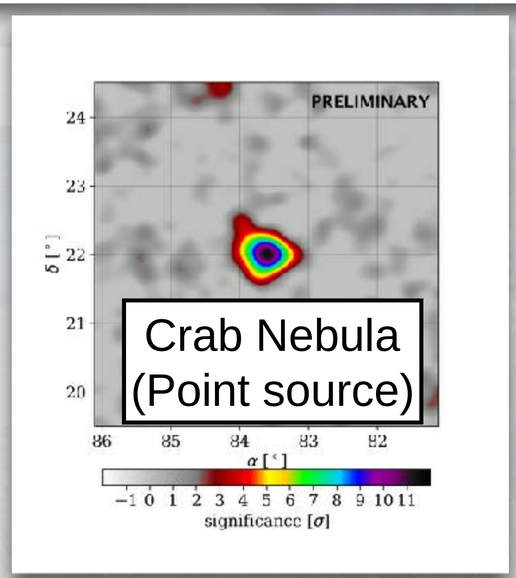
Highlighted sources emit above 100 TeV

Source name	RA (deg.)	Dec (deg.)	Gaussian width above 56 TeV (deg)	Nearest 2HWC source	Distance to 2HWC source (deg.)
eHWC 0534+220 (Crab)	83.61 +/- 0.02	22.00 +/- 0.03	Point source	Crab	0.03
eHWC J1809-193	272.46 +/- 0.13	-19.34 +/- 0.14	0.34 +/- 0.13	2HWC J1809-190	0.30
eHWC J1825-134	276.40 +/- 0.06	-13.37 +/- 0.06	0.36 +/- 0.05	2HWC J1825-134	0.07
eHWC J1839-057	279.77 +/- 0.12	-5.71 +/- 0.10	0.34 +/- 0.08	2HWC J1839-057	0.96
eHWC J1842-035	280.72 +/- 0.15	-3.51 +/- 0.11	0.39 +/- 0.09	2HWC J1844-032	0.44
eHWC J1850+001	282.59 +/- 0.21	0.14 +/- 0.12	0.37 +/- 0.16	2HWC J1849+001	0.20
eHWC J1907+063	286.91 +/- 0.10	6.32 +/- 0.09	0.52 +/- 0.09	2HWC J1908+063	0.16
eHWC J2019+368	304.95 +/- 0.07	36.78 +/- 0.04	0.20 +/- 0.05	2HWC J2019+367	0.02
eHWC J2030+412	307.74 +/- 0.09	41.23 +/- 0.07	0.18 +/- 0.06	2HWC J2031+415	0.34

Inner Galactic plane above 56 TeV



- 1038 days of data
- Map assumes 0.5 degree disk as the spatial morphology
- All sources in the Galactic plane remain extended above 56 TeV



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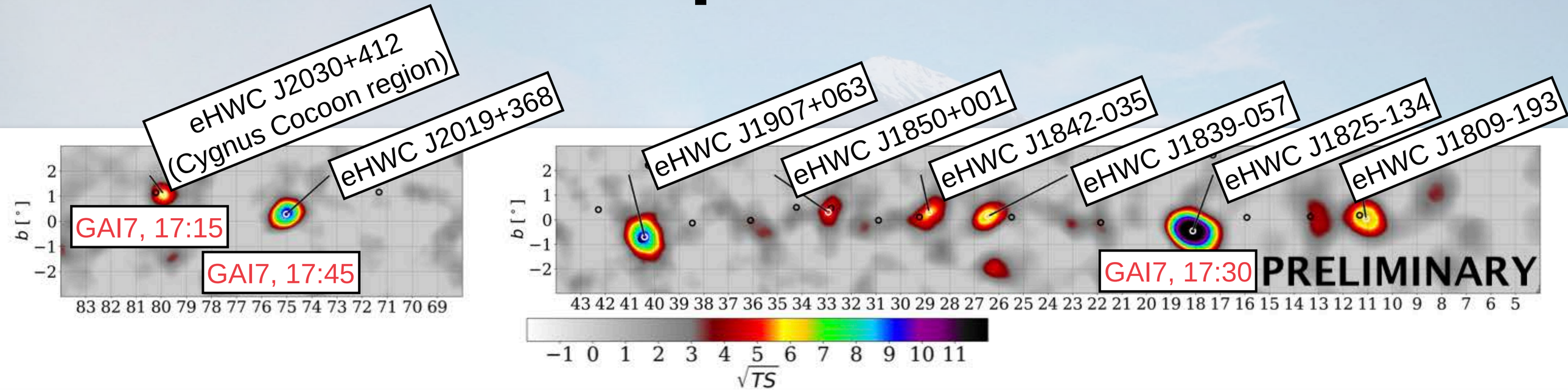

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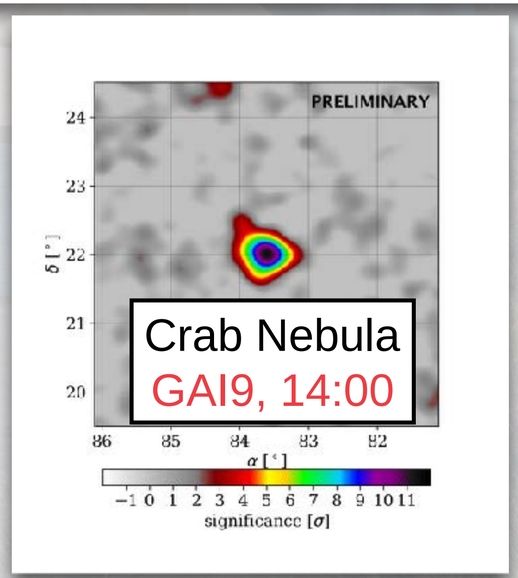

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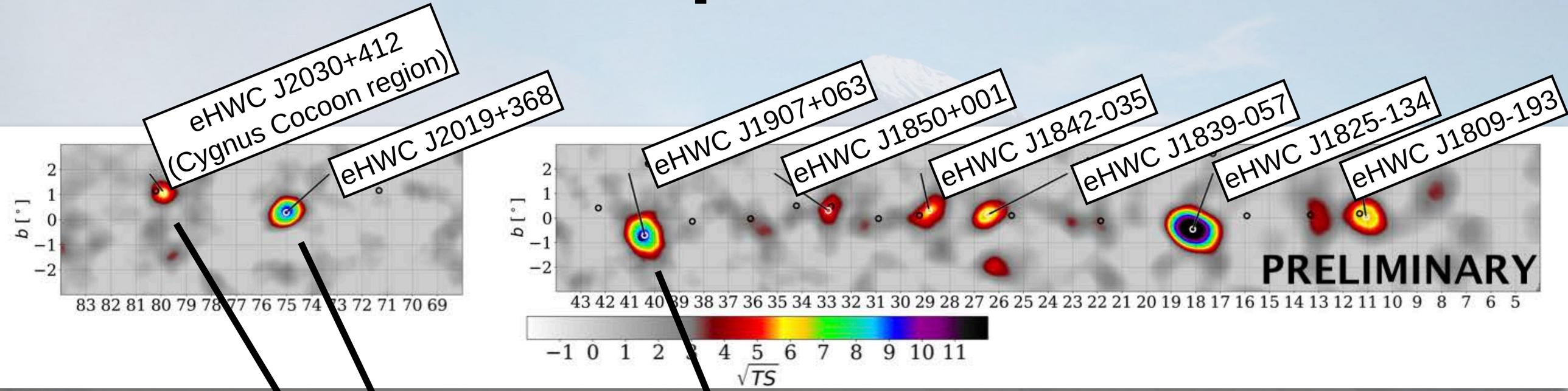
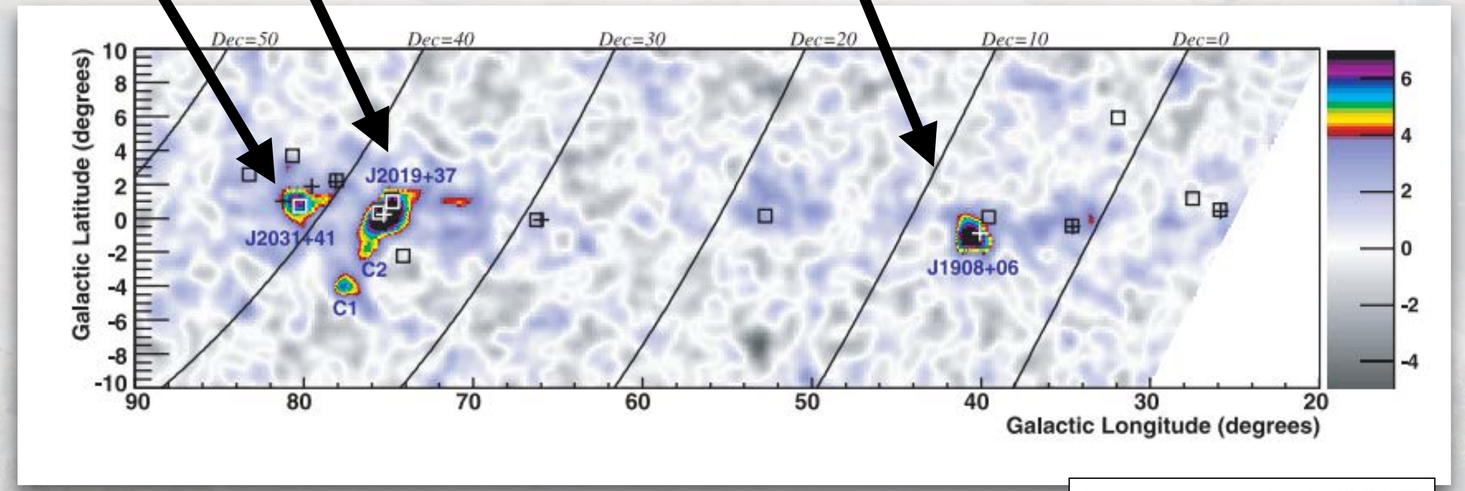
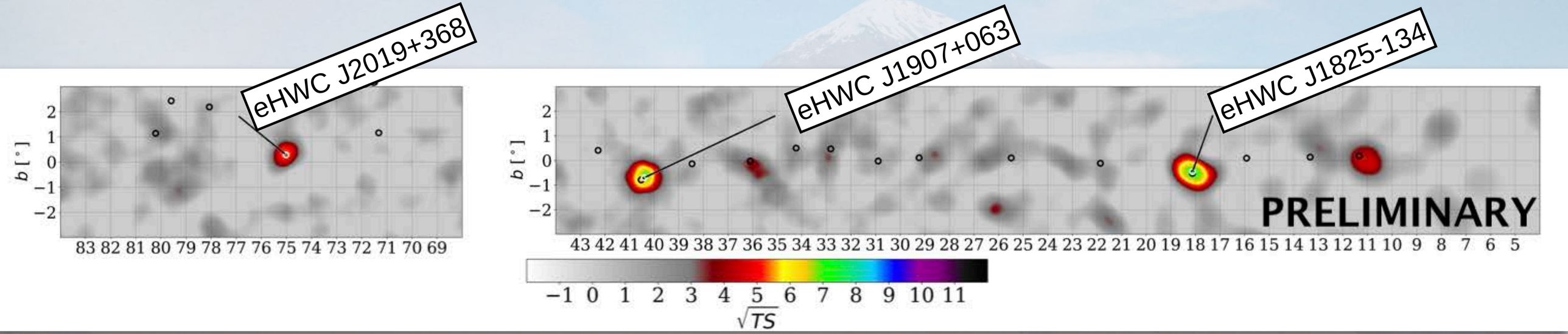




Areas of emission coincident with the Milagro Galactic plane map (median energy ~20 TeV)

Abdo et al., ApJ (2007)

Inner Galactic plane above 100 TeV



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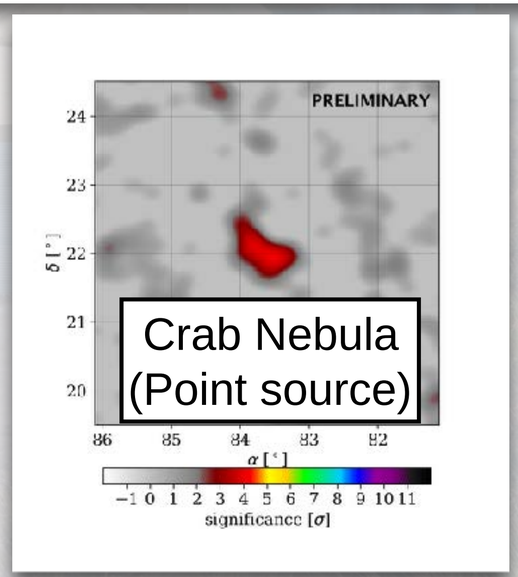
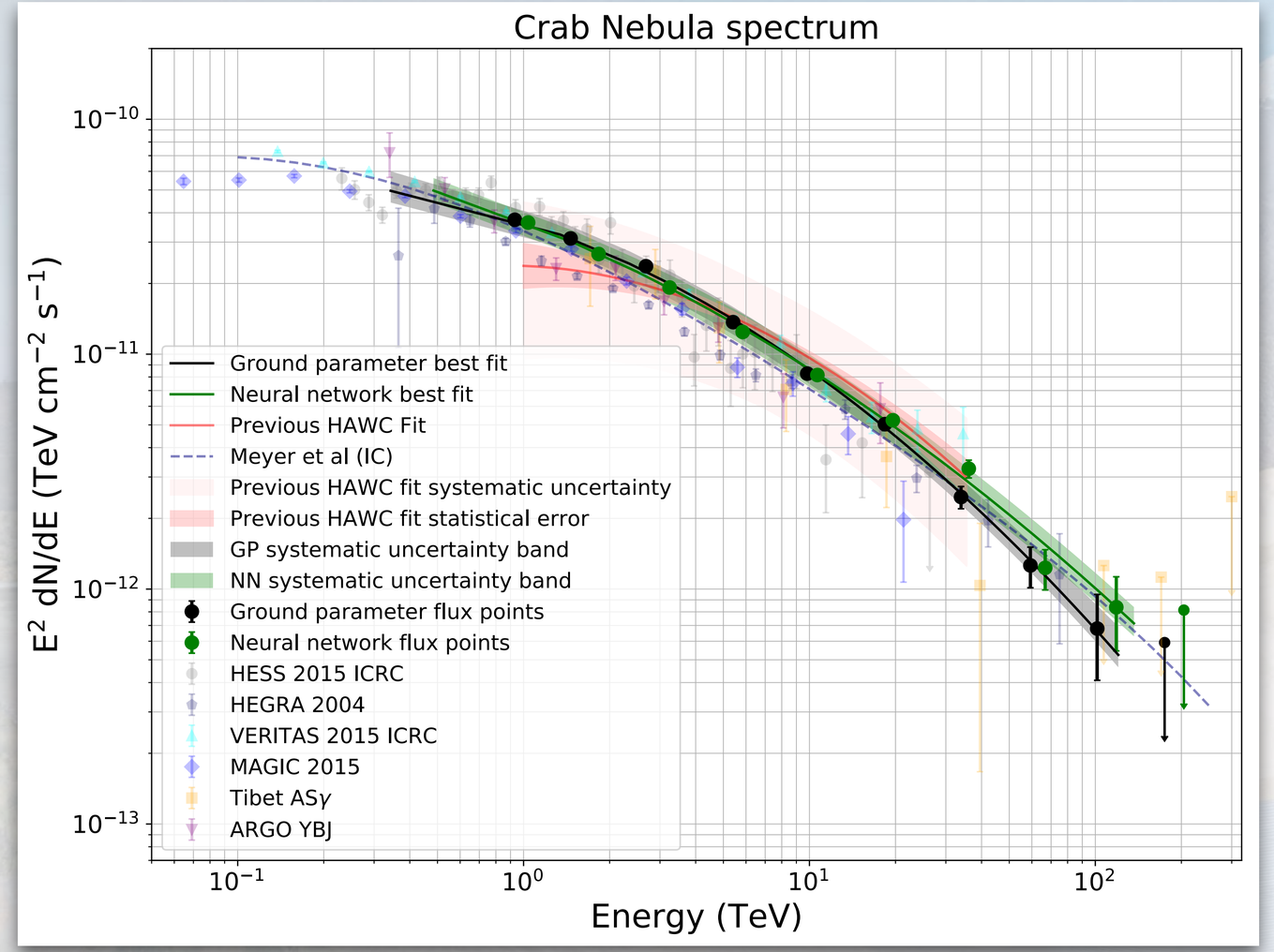


Crab spectra

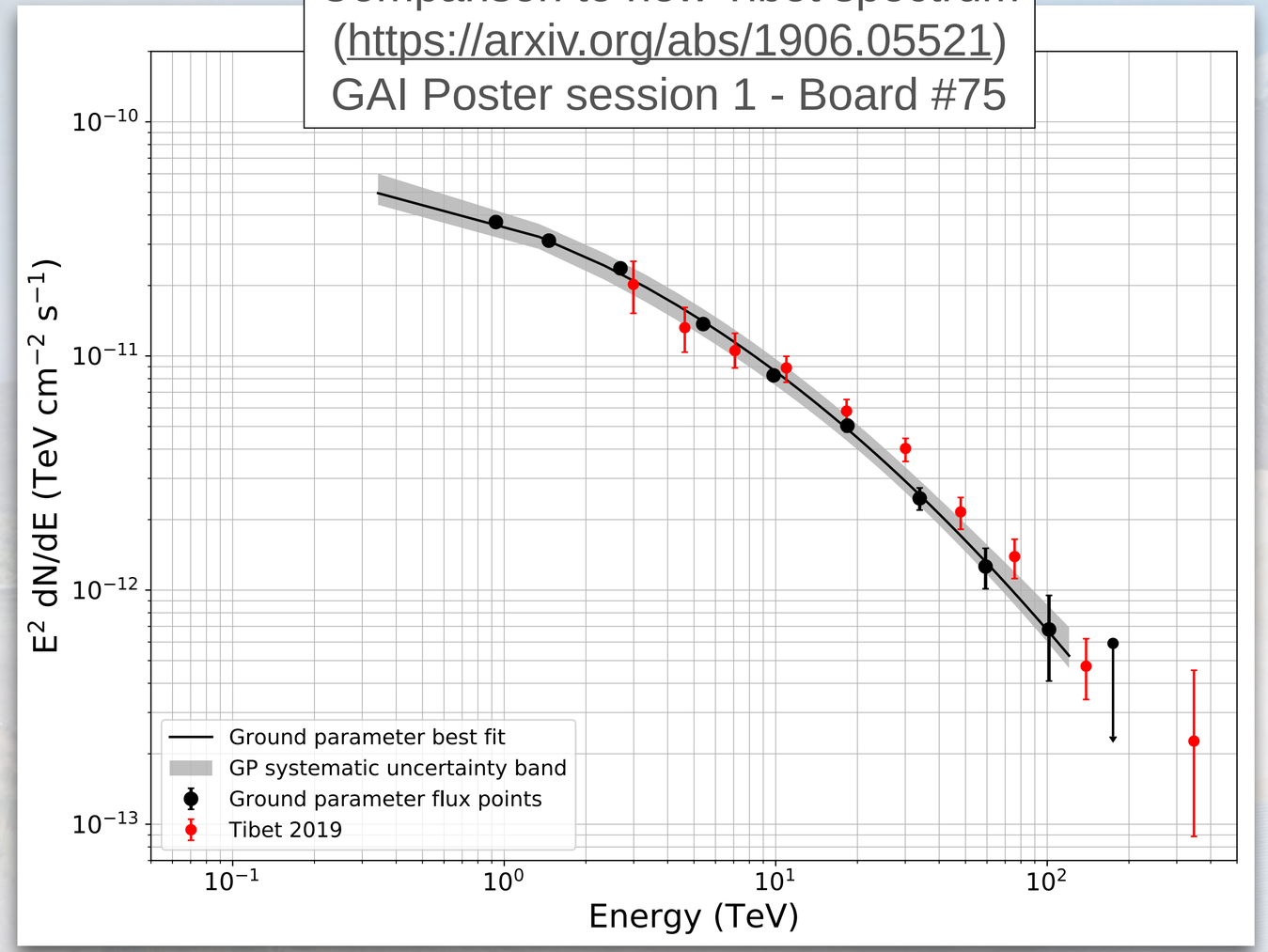


- 837 day dataset
- Two independent energy estimation methods agree within statistical uncertainties
- Agree well with IACTs in energy range with overlapping sensitivity

https://arxiv.org/abs/1905.12518
Accepted by ApJ

Crab spectra

Comparison to new Tibet spectrum
(https://arxiv.org/abs/1906.05521)
GAI Poster session 1 - Board #75



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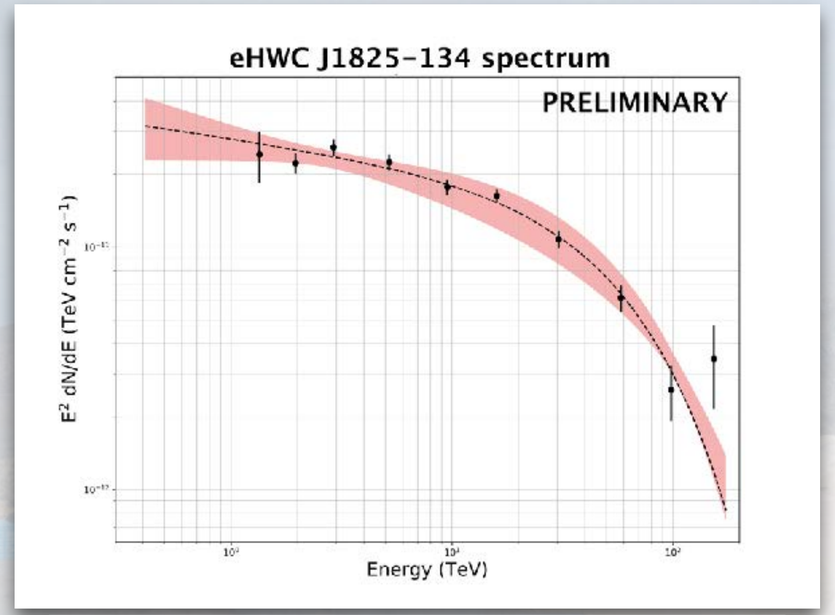
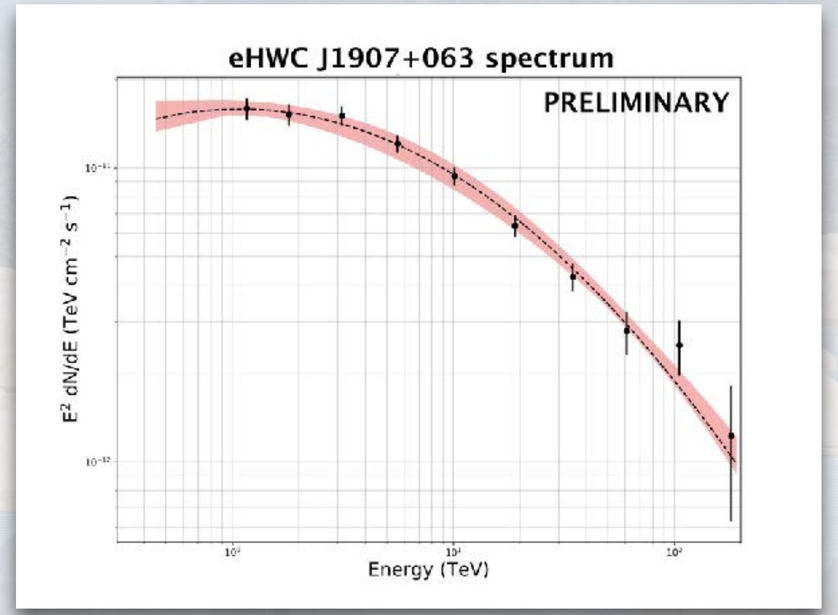
Spectra of the 3 sources that emit above 100 TeV

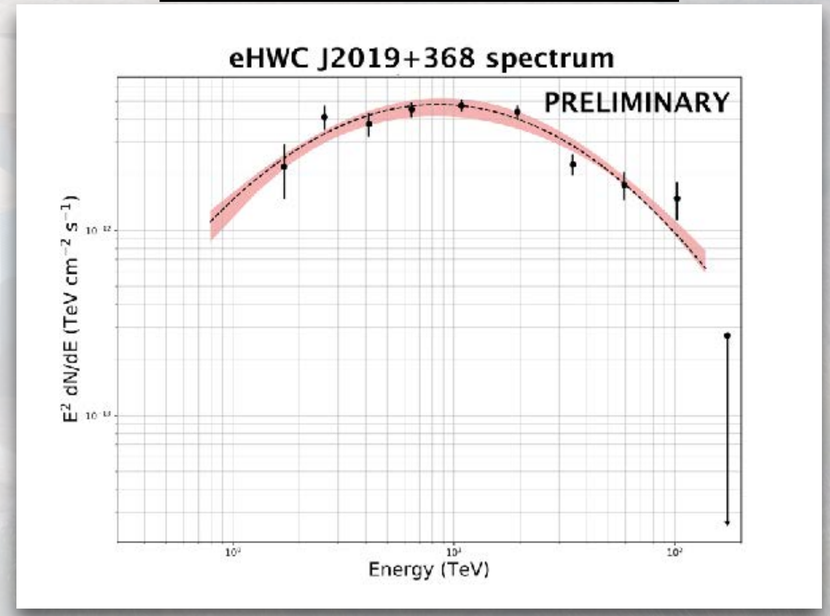


eHWC J1825-134
(Overlap with both HESS J1825-134 and HESS J1826-130)



eHWC J1907+063
(MGRO J1908+06)

eHWC J2019+368
(Cygnus region)



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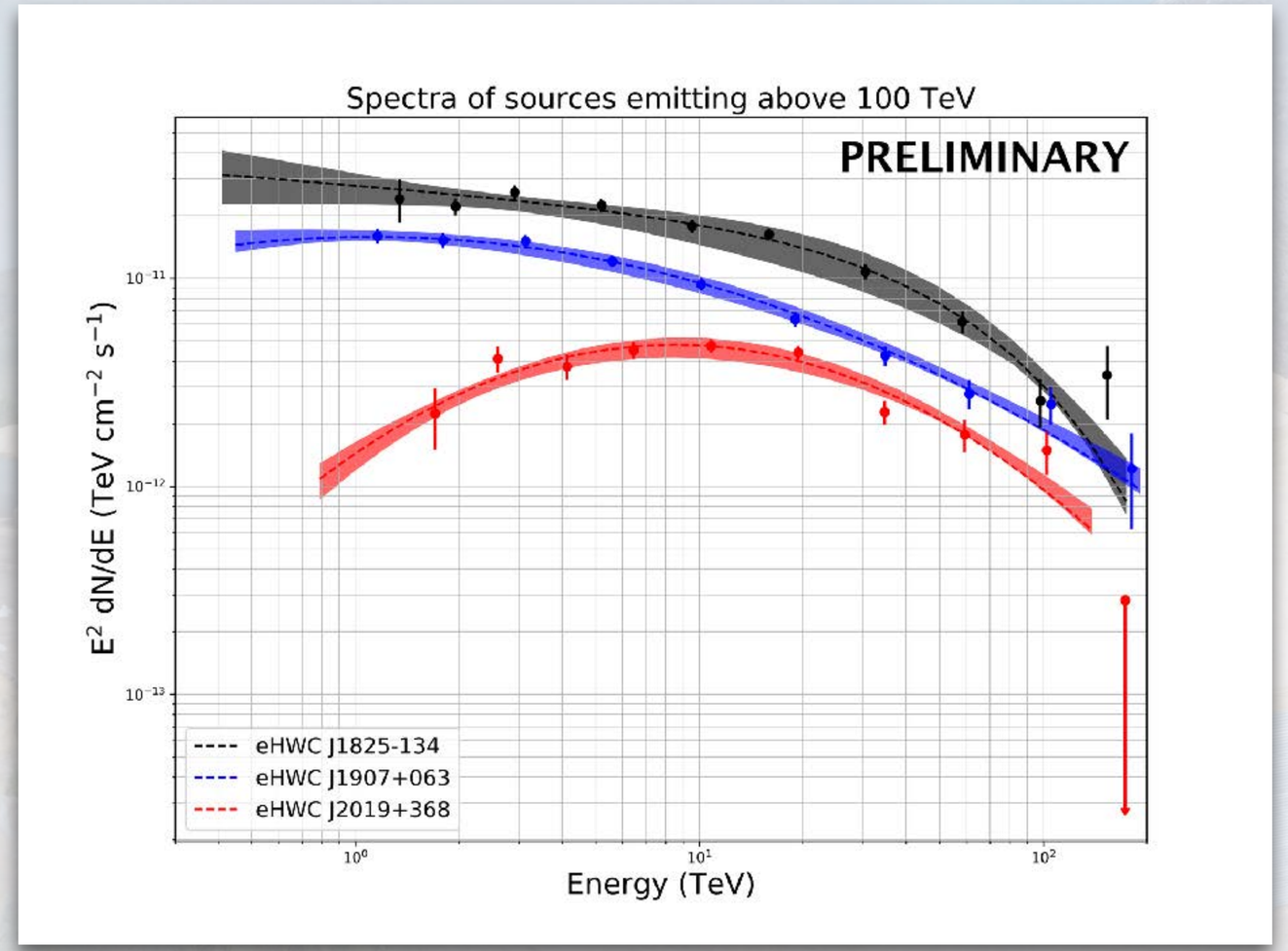


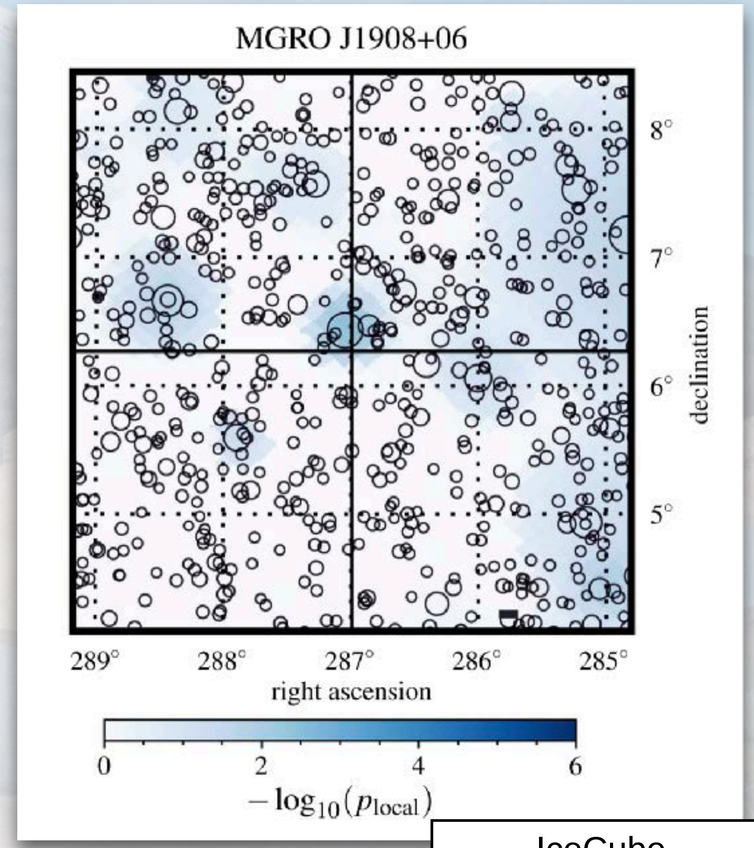
- Spectra of the three highest-energy sources are different
- Roughly the same flux at 100 TeV
  - Possibly selection bias due to HAWC's sensitivity
- More talks on highest-energy HAWC photons and implications:
  - J. Linnemann, 14:00 on July 30, GAI9
  - H. Martinez-Huerta, 17:00 on July 31, GAI11

Possible emission mechanisms

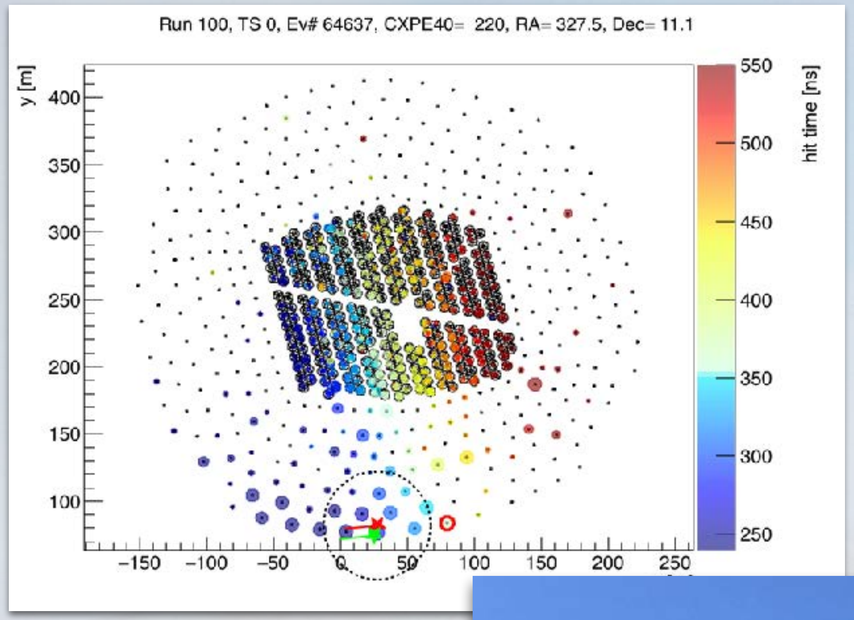
- **Leptonic**
  - All of these sources have at least one ATNF pulsar within 0.5 degree.
  - Pulsar with $\dot{E} > 10^{36}$ erg/s present for all but one high energy source; characteristic ages of < ~50 kyr
- **Hadronic**
  - SNRs and/or molecular clouds
  - Many of these sources have been hypothesized as promising neutrino targets by IceCube

Multi-messenger analyses

- Neutrinos seen in coincidence with a PeVatron candidate would unambiguously indicate hadronic component
- MGRO J1908+06 has one of the best p-values in IceCube point source searches, although still consistent with background-only hypothesis
- Sub-dominant fraction of IceCube neutrinos Galactic. Joint analysis with this dataset could still be interesting



IceCube, European Physics Journal (2019)



HAWC upgrade

- Outrigger array operational
- Will soon have data with at least 2x sensitivity to gamma rays above 10 TeV.
- Could lead to more detections above 50 TeV
- More in talk by V. Marandon, 14:45 on July 26, GAI3
- Poster by V. Joshi and H. Schoorlemmer, GAI poster session #1

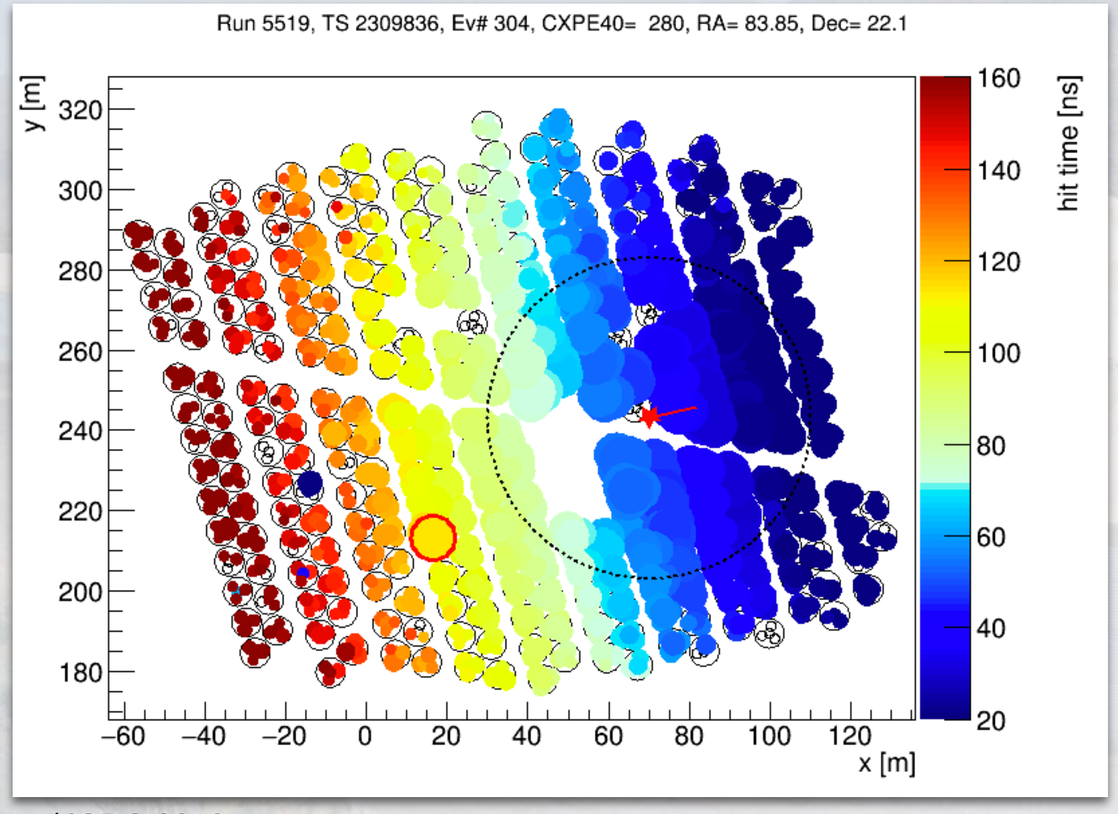
Conclusion

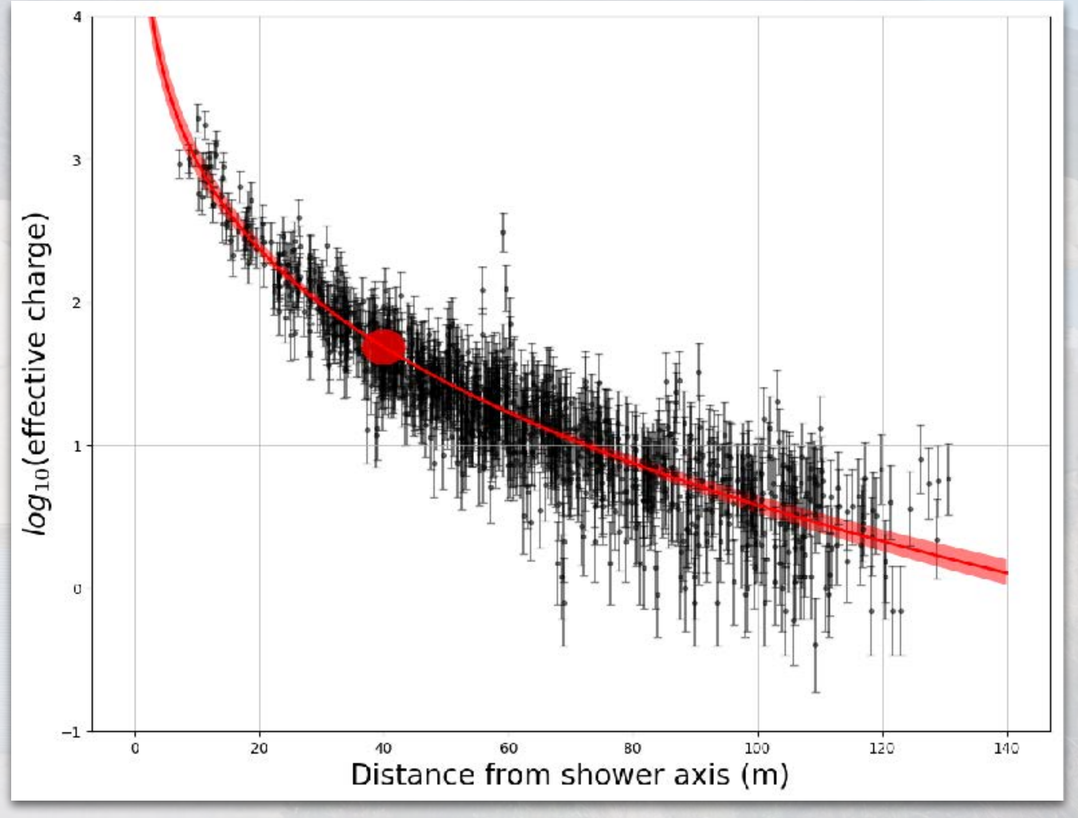
- HAWC has sensitivity above 50 TeV and see many sources above this threshold
- Three sources extend above 100 TeV. This is the highest-energy source catalog to date.
- Cannot distinguish between emission mechanisms at this time.
- Recently installed outrigger array will increase sensitivity in this energy range
- Multimessenger studies with neutrinos will be important, as well as multi-wavelength with other energies

Backup slides

Event-by-event energy estimation

- Recently developed event-by-event energy estimation algorithm allows HAWC to easily distinguish between 10 TeV and 100 TeV gamma rays
- Previously published HAWC papers relied on a rudimentary energy variable that lost dynamic range above 10 TeV





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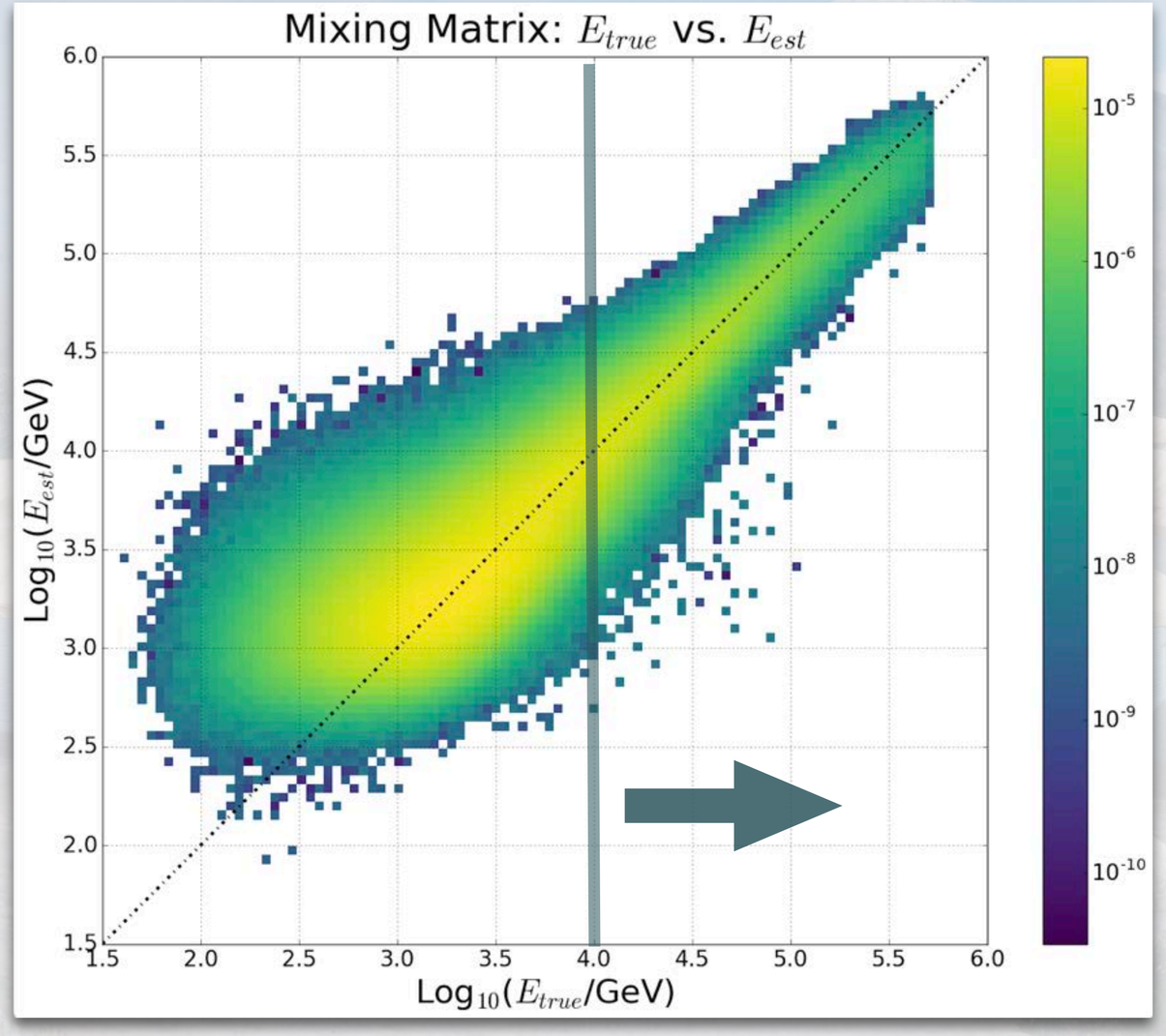

Performance best above 10 TeV, where showers are largest