Evidence of 200 TeV photons from HAWC J1825-134.

Zoom NOI Seminar, Feb 2nd 2021

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HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

Outline

- The origin of highest energy cosmic rays in the Galaxy
- The HAWC detector
    - https://www.hawc-observatory.org/
- HAWC Highest Energy Sky
- Analysis of e-HWC J1825 region
- Interpretation of the results
- Future : Outriggers
- Conclusions

The Cosmic Ray Spectrum at Earth

- 90% protons, 9% helium, 1% electrons
- Almost featureless spectrum and isotropically distributed up to very high energies
- CRs up to the knee are believed to have a Galactic origin
- Galactic accelerators have to inject particles up to at least the knee at PeV (10^{15} eV) energies, maybe 10^{17} eV.
- The knee for protons might be earlier at about 400-500 TeV (ARGO Collaboration 2015).
- CR production rate = (0.3-1) 10^{41} erg/s or cosmic-ray energy density roughly 1 eV cm^{-3}
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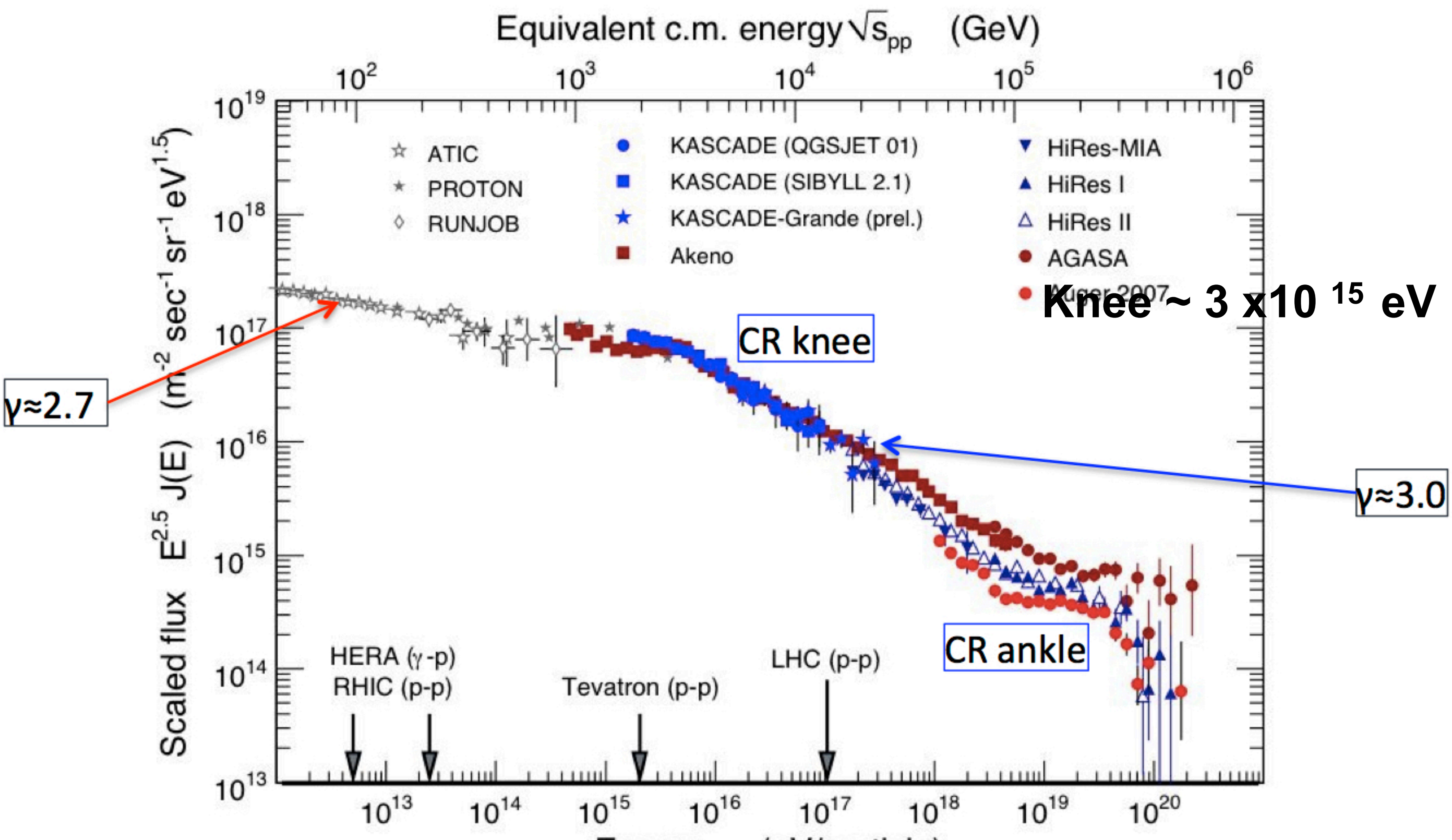


Relevant tests of candidate PeVatrons

- The candidate PeVatron emits VHE γ-ray. Its γ− ray spectrum is relatively hard and extends up at least several tens of TeV without a break

- The γ radiation is hadronic

- We can quantify the energetic input in accelerated protons

$$L_\gamma \propto W_p t^{-1} \propto W_p n$$

SNR Paradigm

- Theoretically SNRs provide adequate conditions to have efficient CR acceleration through Diffusive Shock Acceleration -> 10% efficiency and hard E^{-2} type particle spectrum continuing up to very high energies

- SN explosions provide the necessary amount of available energy – 10^{51} erg – to sustain the Gal CR population

- Is there any observational evidence of CR acceleration up to PeV energies in SNRs ?
- Can we constrain how much of the SN burst energy goes in CRs ? Can we prove that each SNR inject 10^{50} erg ?

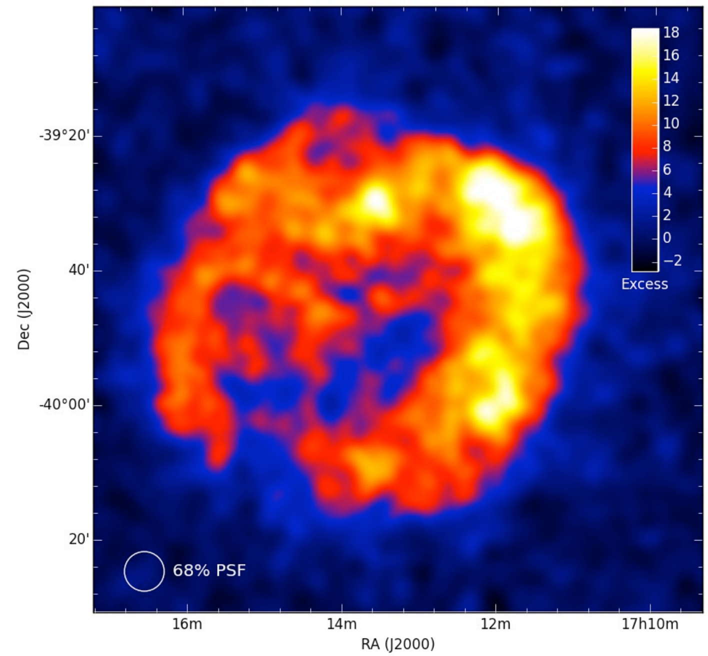
SNR RX J1713-3946

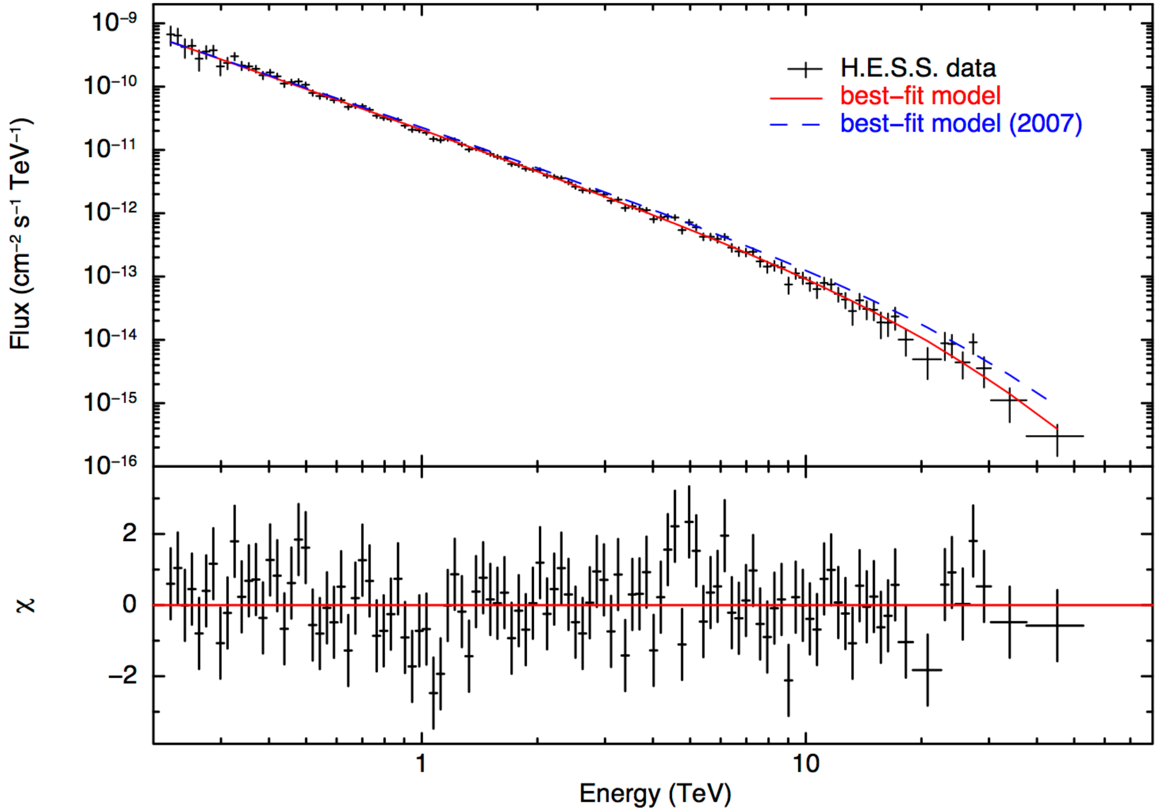
Young (~1.5 kyr) and nearby (~1 kpc) SNR

First, and brightest resolved TeV shell

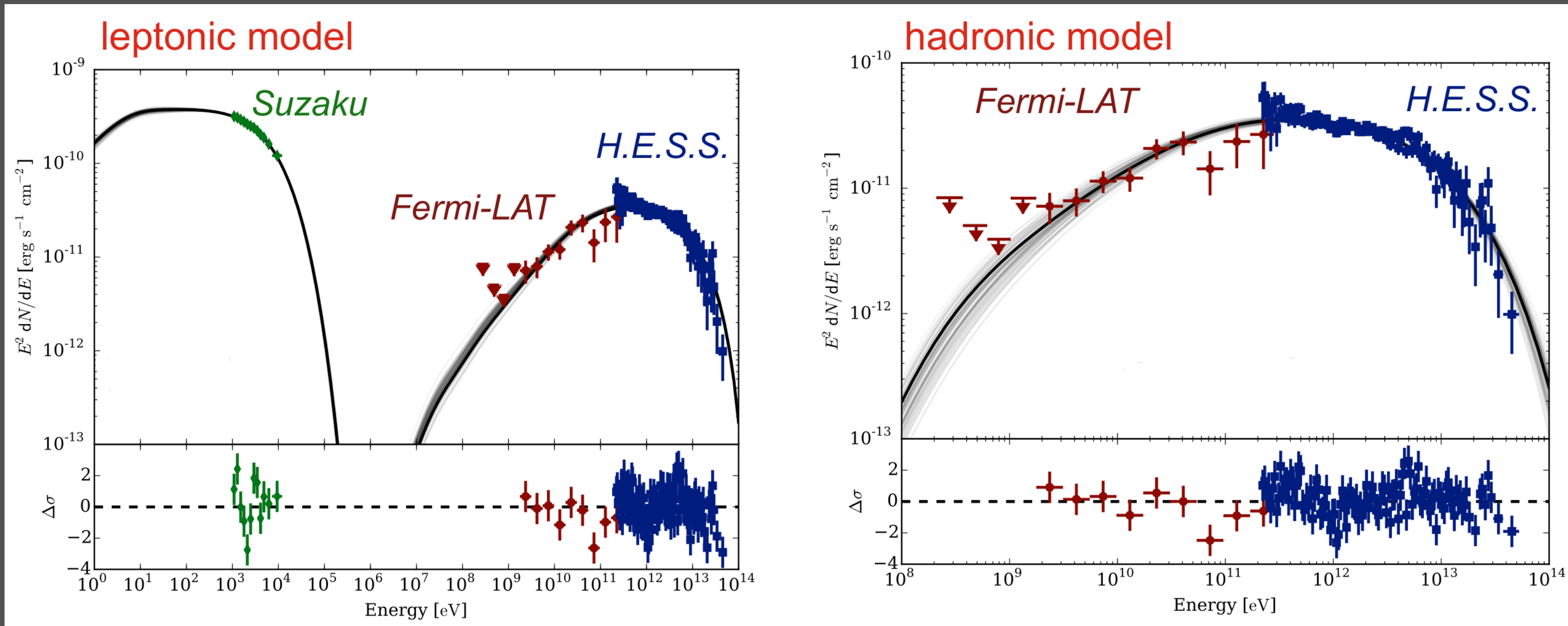
10 years of H.E.S.S. data

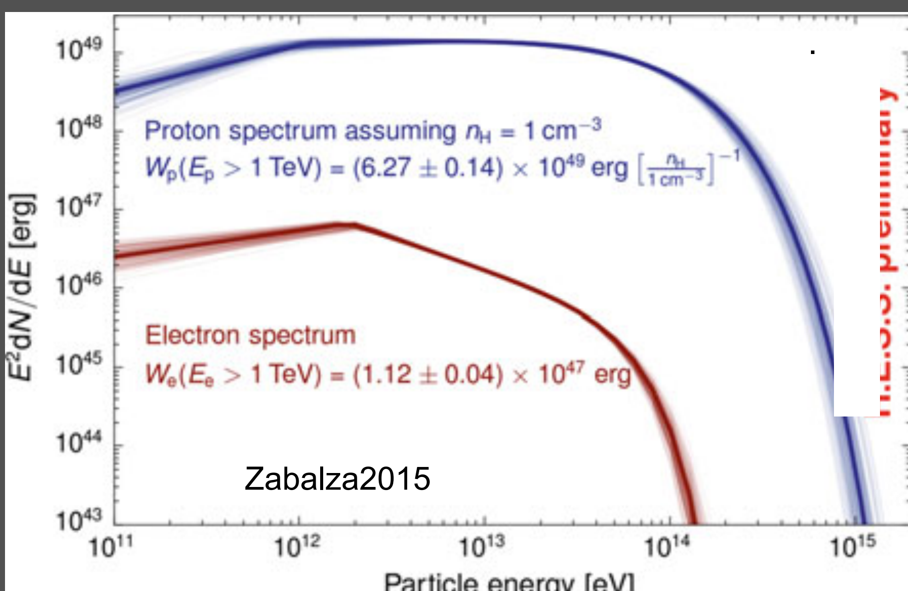
- Factor 2 improvement in statistics over last publication (> 27 000 γ's)
- Spectrum up to ~50 TeV: cuts off ~ 12 TeV





Hadronic or leptonic ?



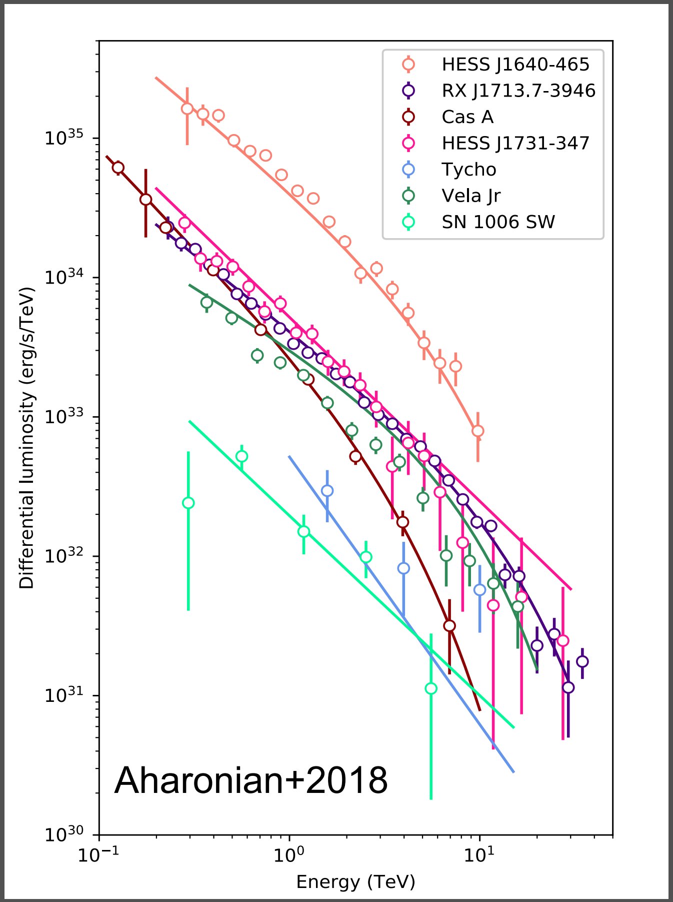


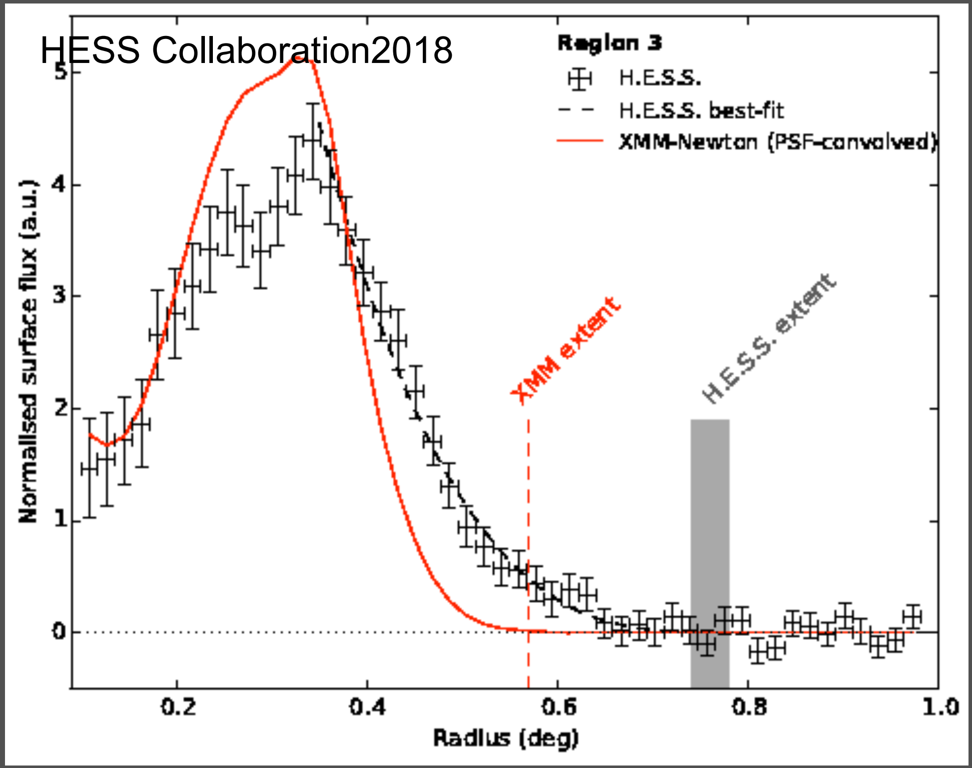
Both hadronic and leptonic can explain the GeV to TeV emission

The content in accelerated hadrons in unknown because of the uncertainty in the estimate of the gas density

Spectra of young SNRs

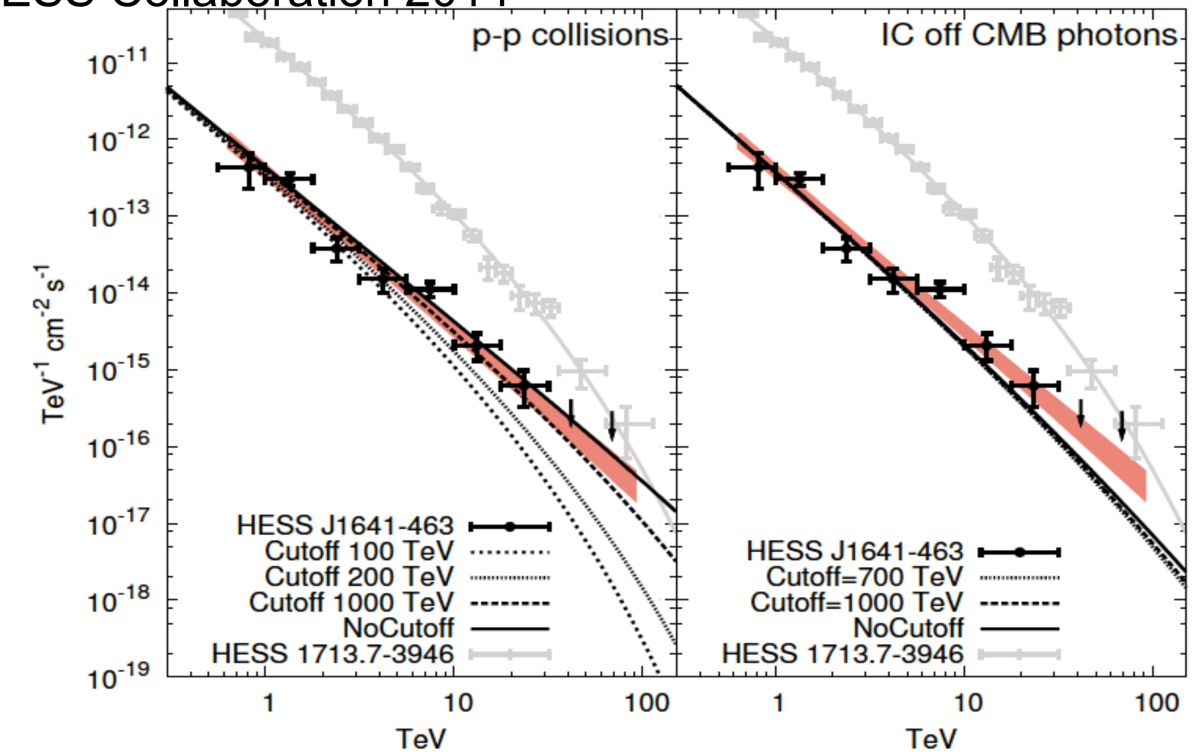
- Cutoffs in the spectra of famous young SNRs at few TeVs. Particle acceleration proceeds up to 100 TeV. No indication of particle acceleration proceeding up to the knee
- SNRs thought to act as PeVatrons only during the early phases. Small chance to detect SNRs when they are PeVatrons. Maybe PeVatron gamma-ray signatures from nearby clouds illuminated by runaway CRs

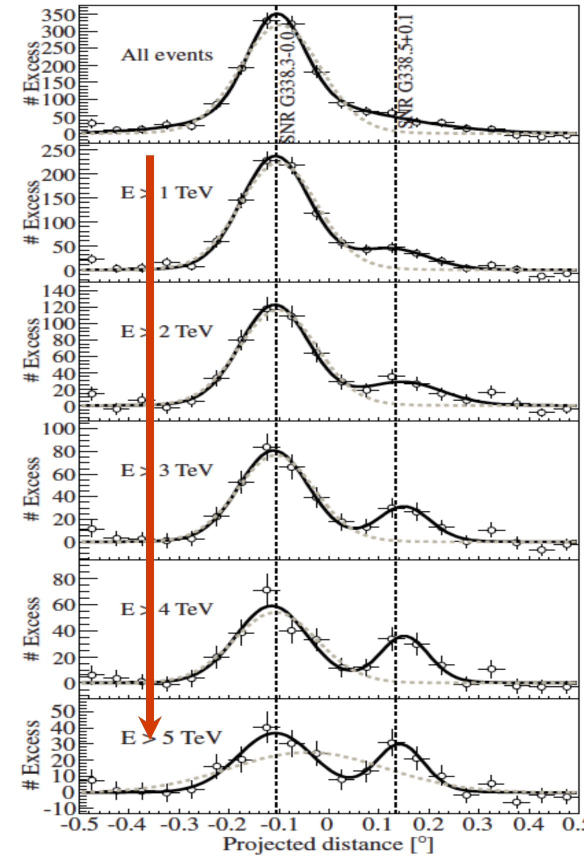




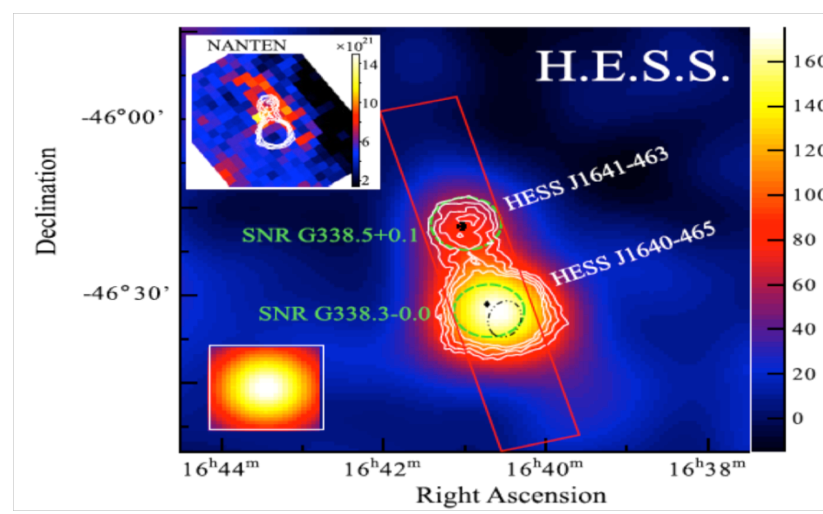
Runaway cosmic rays ?

HESS Collaboration 2014

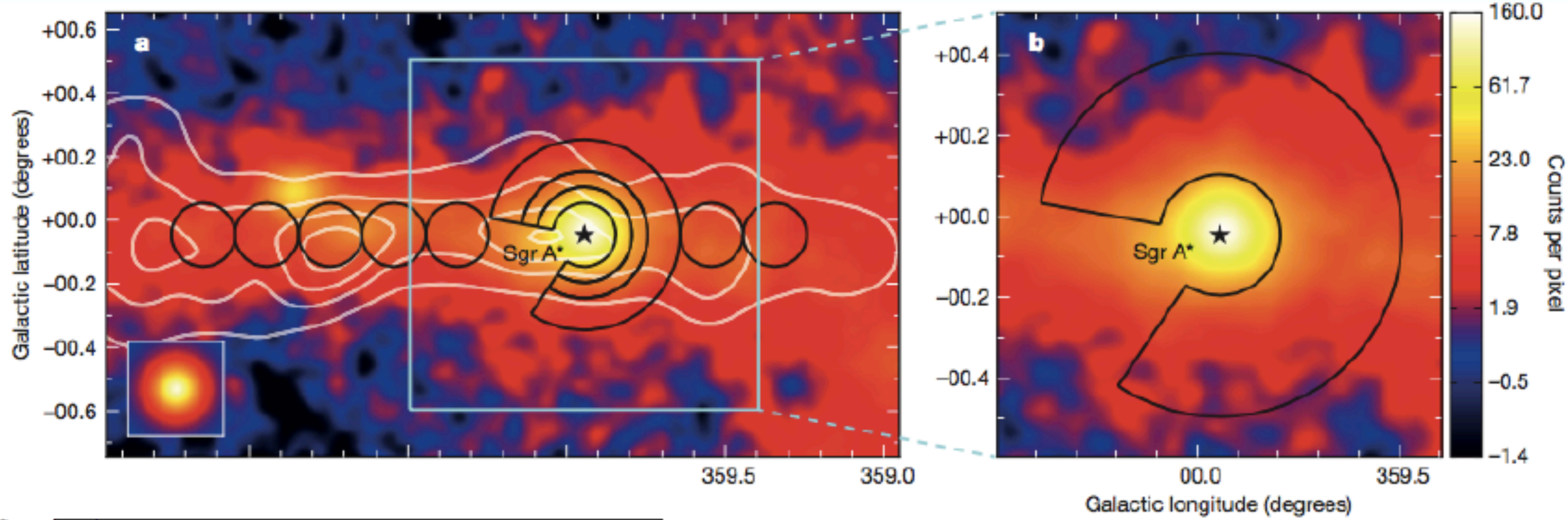


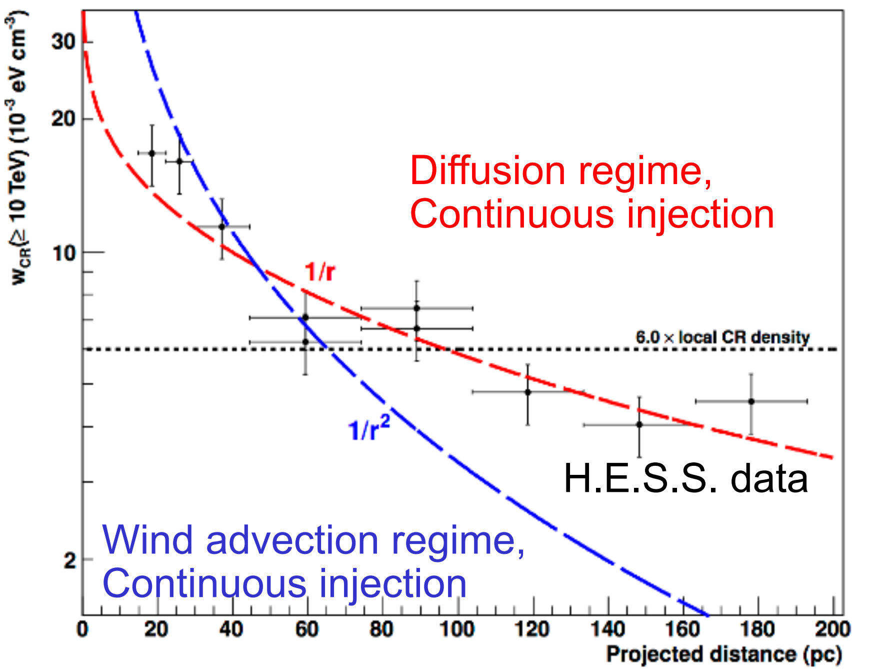


- Very hard spectrum, index 2.07
- No preference for a cutoff
- Data points until 20 TeV
- Lower limit on proton cutoff energy: 100 TeV
- Wp = 10^{50} n^{-1} erg
- Leptonic scenario implies particle spectra up to at least 700 TeV
- Several sources like HESS J1641–463 needed



GC PeVatron : Morphological studies





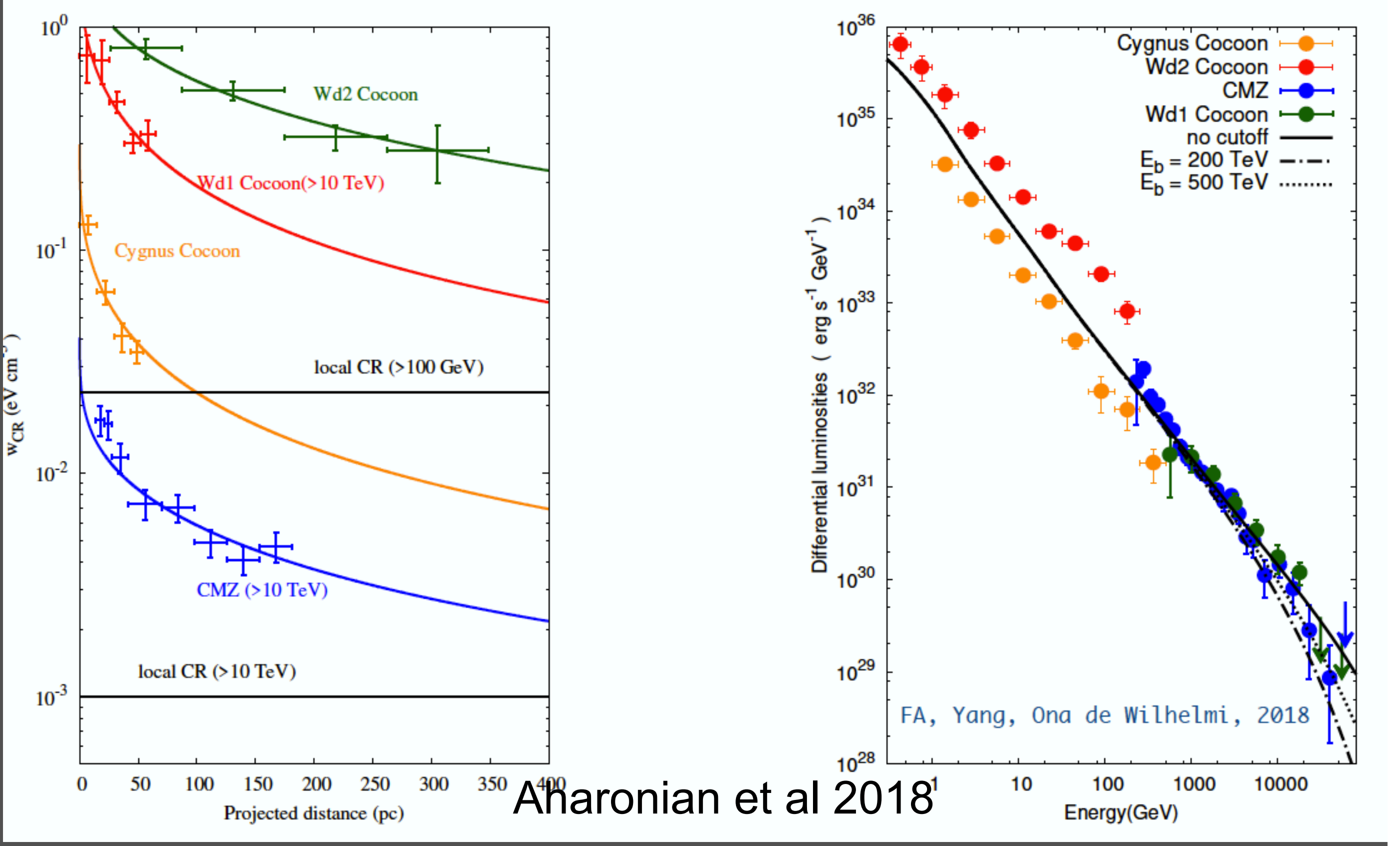
- Emission profile consistent with propagation of protons accelerated continuously from a region < 10 pc from GC
- Current bolometric lum of Sgr A* is 100-1000 times less than required to support CR population. PeVatron more powerful in the past ? Other PeVatrons in the Galaxy ?

Young Stellar Clusters

Extended gamma-ray emissions around young star clusters (50 ~ 200 pc). Gamma-ray luminosity ~ 1e36 erg/s.

Each source has hard spectrum ~ 2.2, without cutoff

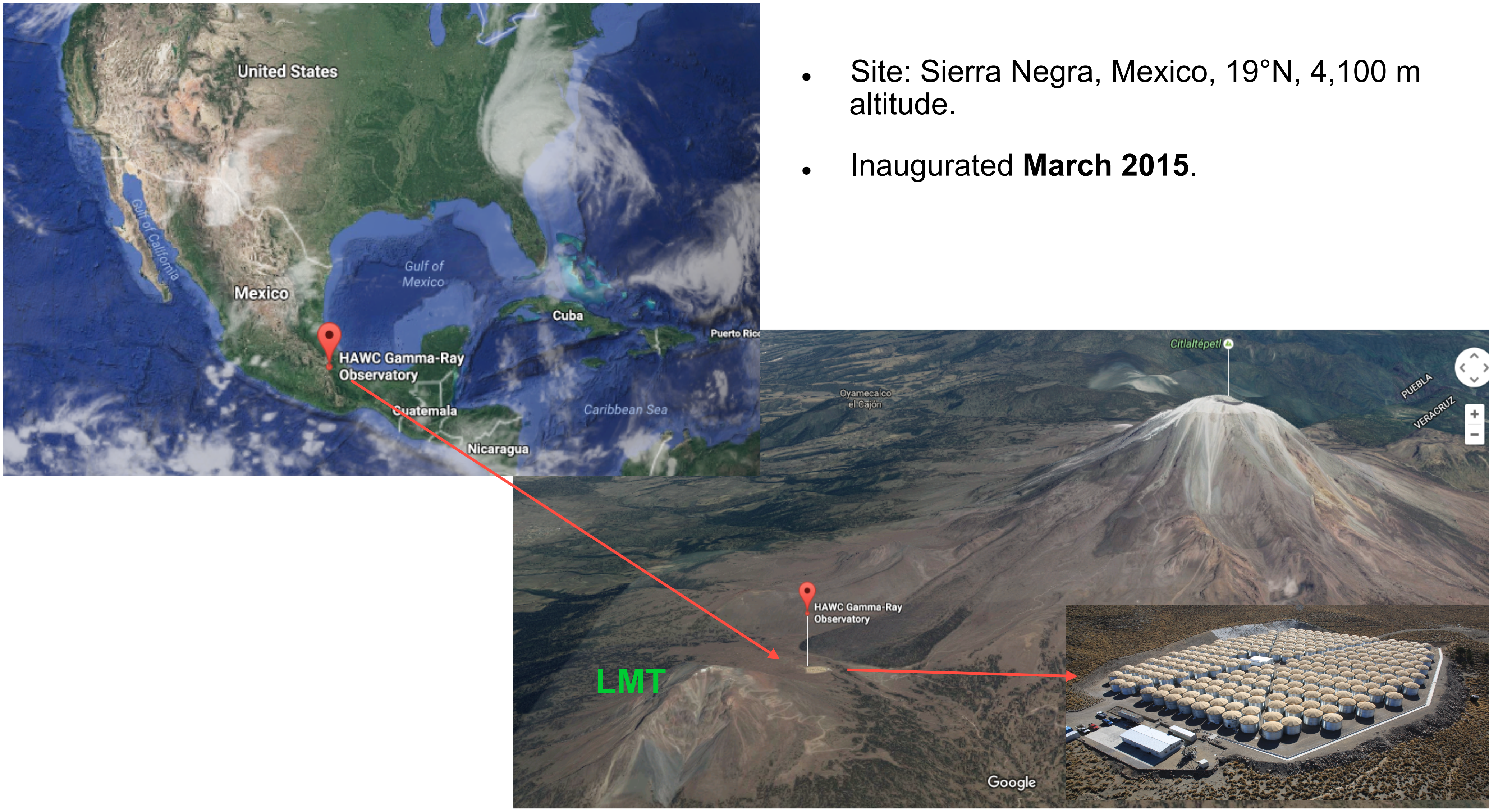
CR distribution derived by gamma-ray profile and gas distributions. 1/r profile implies a continuous injection in the lifetime of clusters

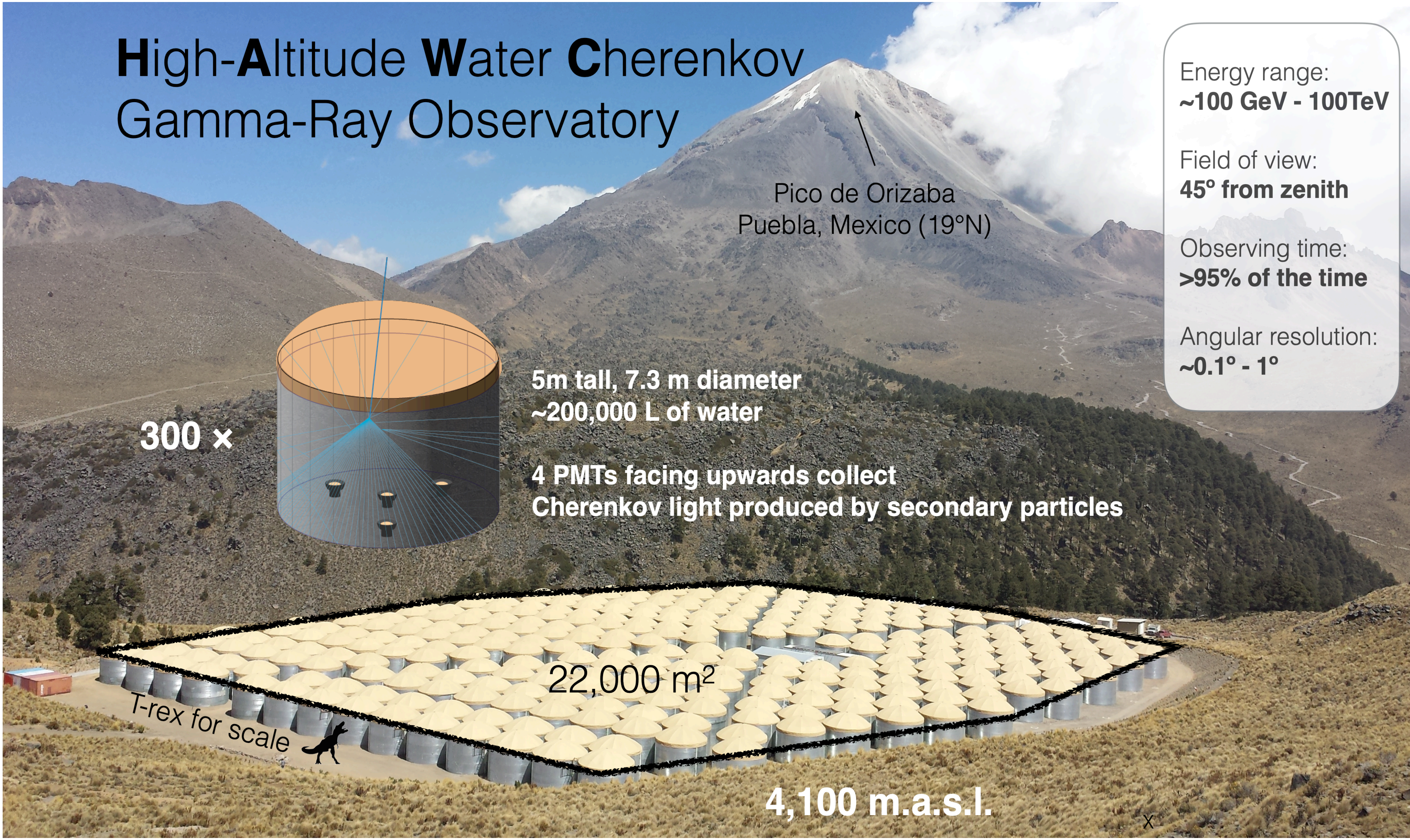


Aharonian et al 2018

The HAWC Detector

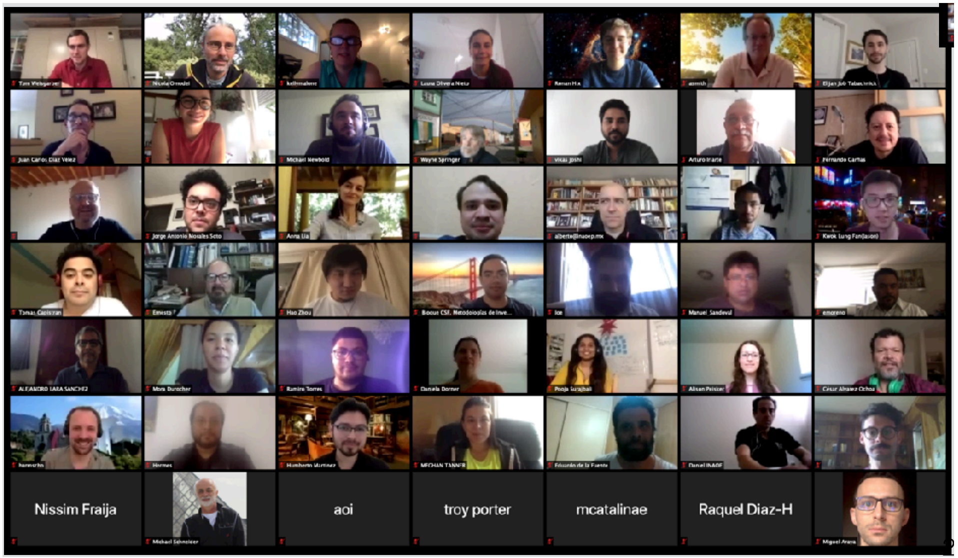
- Site: Sierra Negra, Mexico, 19°N, 4,100 m altitude.
- Inaugurated **March 2015**.





- **Instantaneous FOV 2sr. Daily 8sr (66% of the sky).**

Zoom on HAWC



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University of Wisconsin
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University of New Hampshire
Pennsylvania State University
University of New Mexico
Michigan Technological University
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Michigan State University
University of Rochester

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Universidad Nacional Autónoma de México (UNAM)
Instituto de Física
Instituto de Astronomía
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Centro de Investigación en Computación – IPN

Europe
IFJ-PAN, Krakow, Poland
Max-Planck Institute for Nuclear Physics

HAWC Water Cherenkov Detectors

- The WCDs are filled with 200,000 l of purified water. The particles from the shower induce **Cherenkov** light in **water,** detected by the 4 PMTs.

Steel frame construction

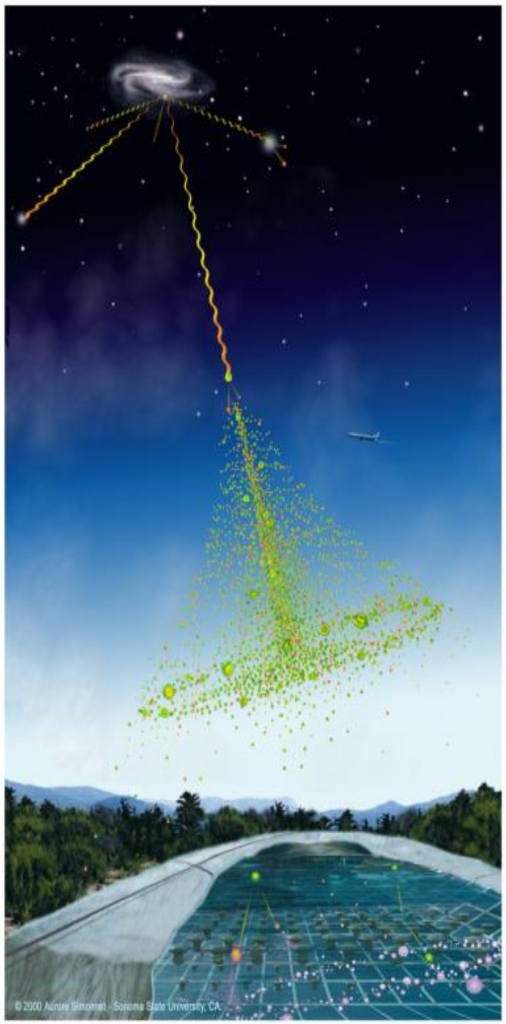
Large plastic bag container

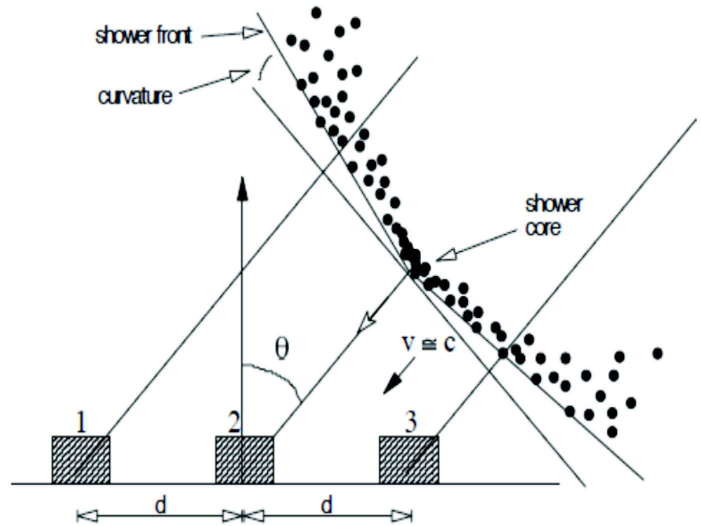
Water trucks filling the tanks

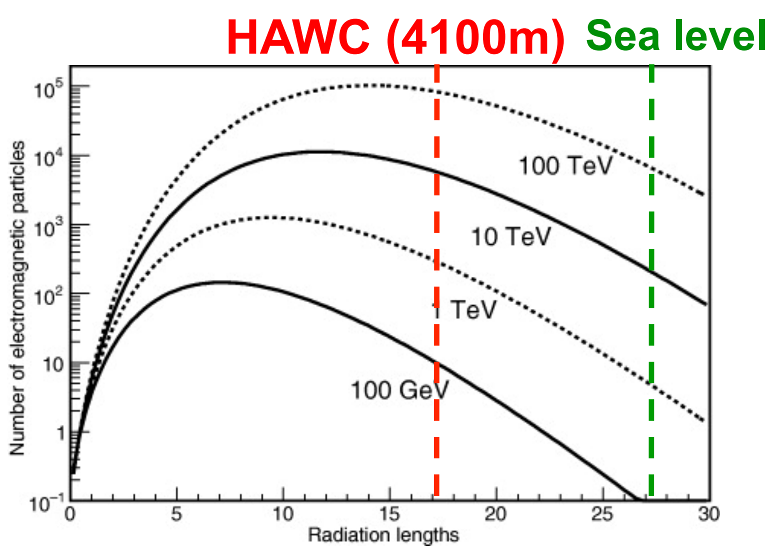
8-inch 10-inch PMTs

3900 tanker truck trips needed

Detection Technique







- The particle detectors are tanks full of water. Particles from the shower pass through the water and induce Cherenkov light detected by PMTs.
- High altitude means closer to the shower maximum

The reconstruction of the events Involves determining:

Direction of the Event

Likelihood of an event to be γ

Size of the Event

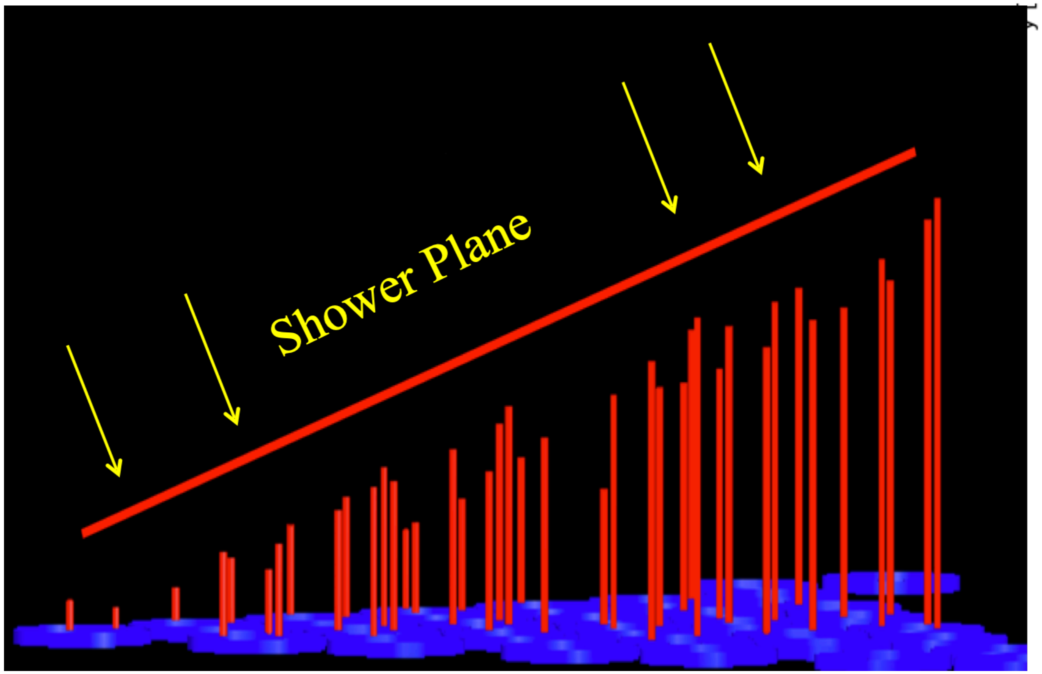
Direction reconstruction

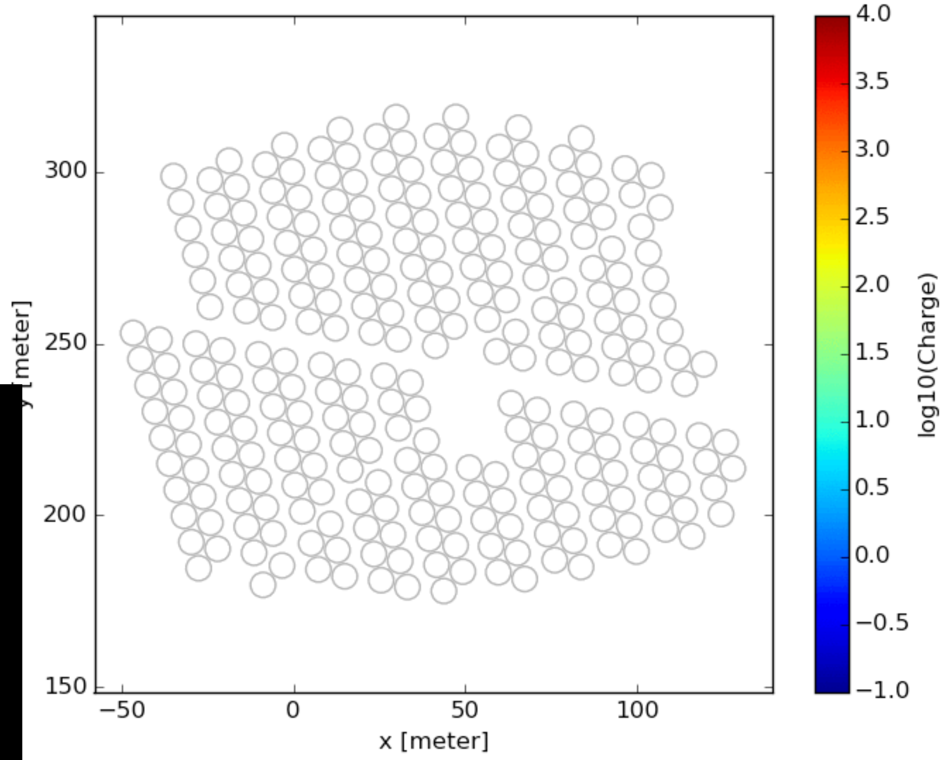
The concentration of secondary particles is highest along the trajectory of the original primary particle, termed the air shower core.

Determining the position of the core on the ground is key to reconstructing the direction

At first order, we fit a plane to the relative timing of each PMT

Sub-nanosecond precision is needed

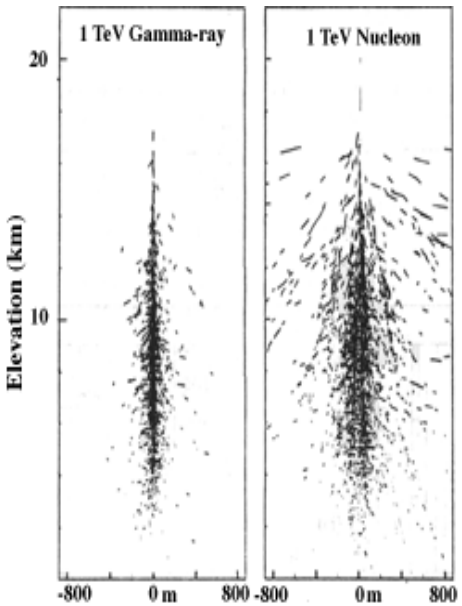




Gamma-Hadron Separation

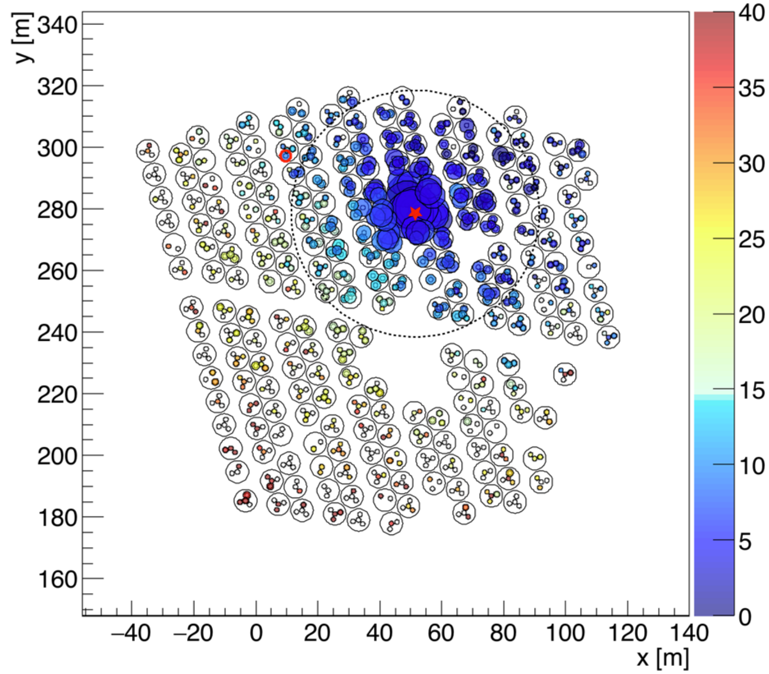
Simulation

Gamma **Hadron**



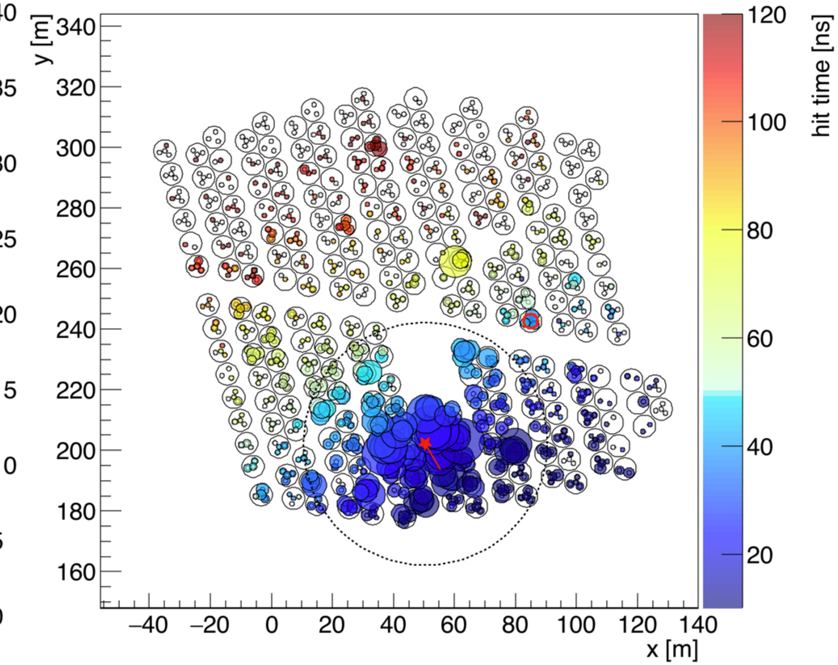
HAWC Data

Likely Gamma Ray



HAWC Data

Hadron Shower

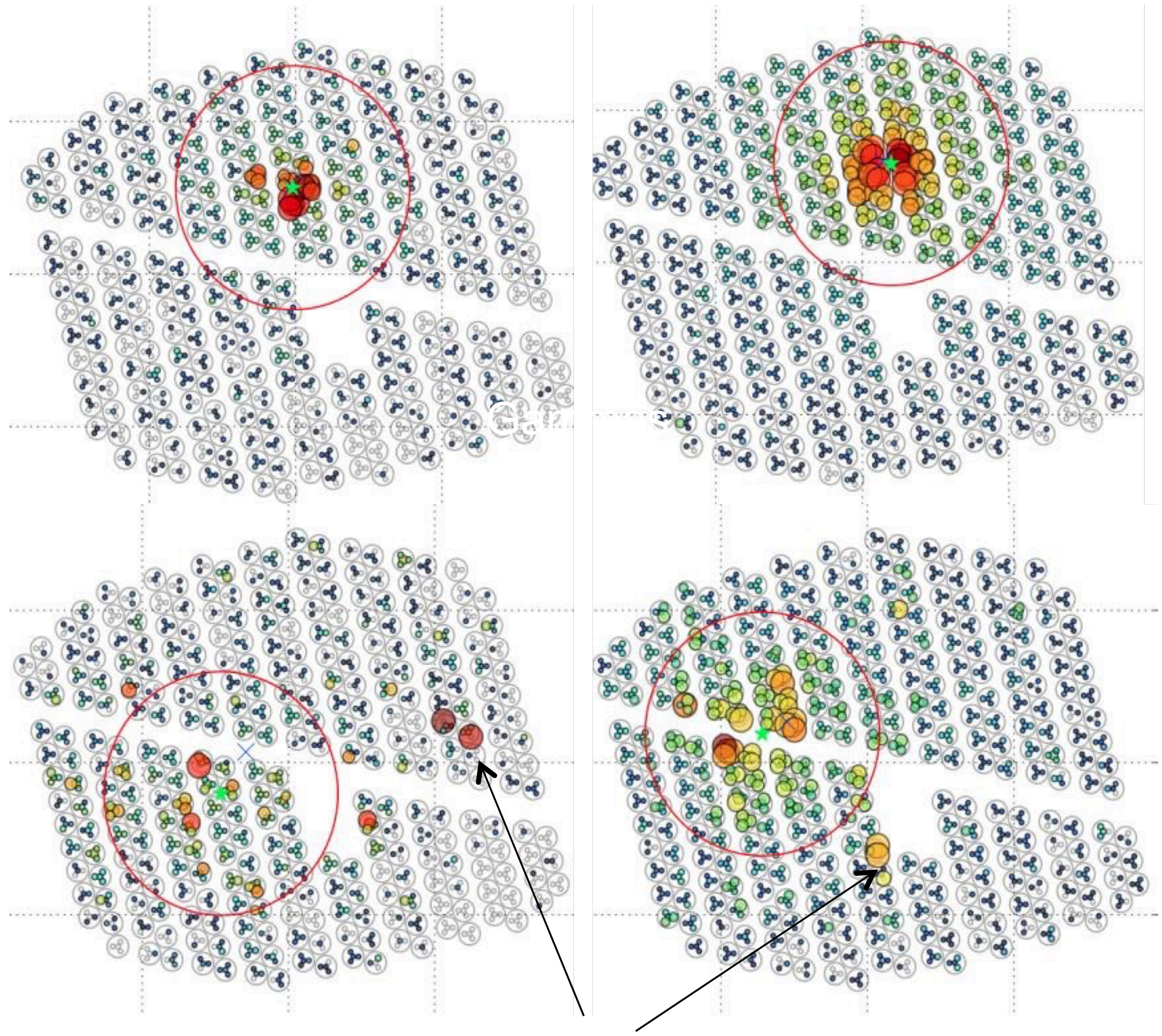


- Main background is hadronic CR, e.g. 400 γ/day from the Crab vs 15k CR/s.
- Gamma/hadron can be discriminated based on the event footprint on the detector: gamma-ray showers are more compact, cosmic rays showers tend to "break apart”
- Showers appear quite different particularly above several TeV..

Montecarlo Shower Simulation

Gammas

Protons

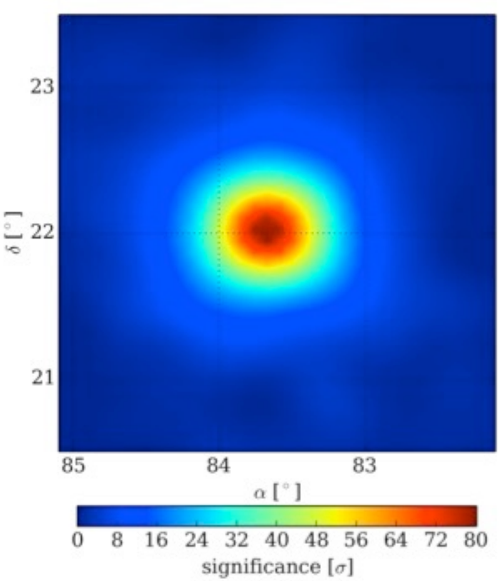


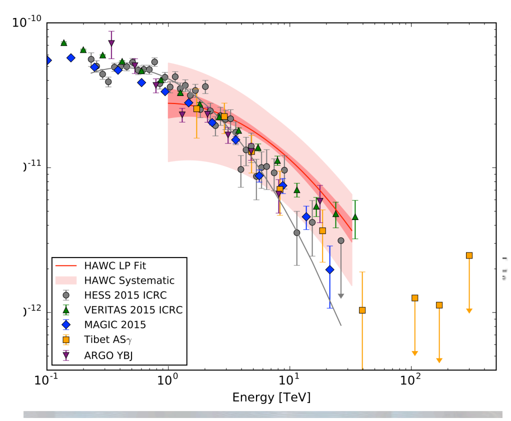
Energy deposited away from the core

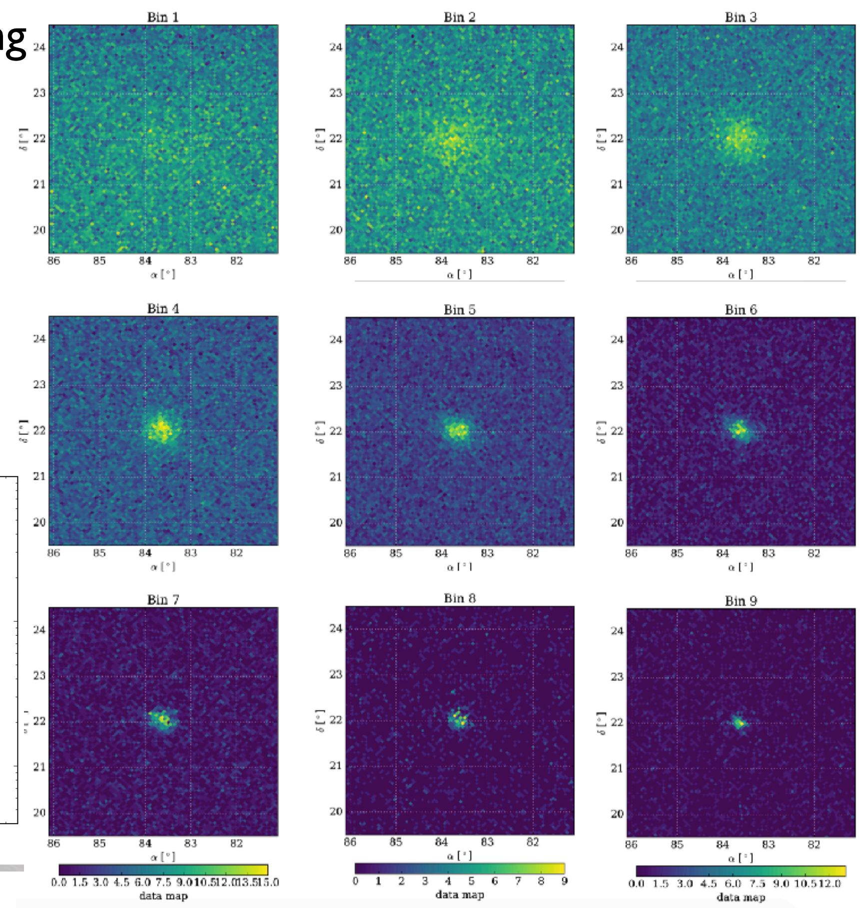
Searching for sources with HAWC

- Events are sorted by size in *n* bins (corresponding to a characteristic energy, S/N ratio and PSF)
- A likelihood framework incorporating detector response and source model tests the presence of sources in the *n* maps

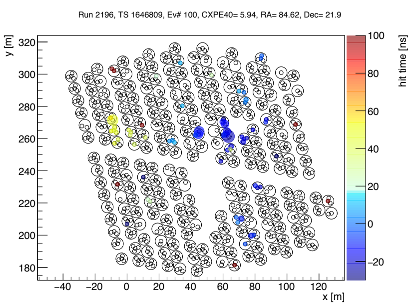
CRAB



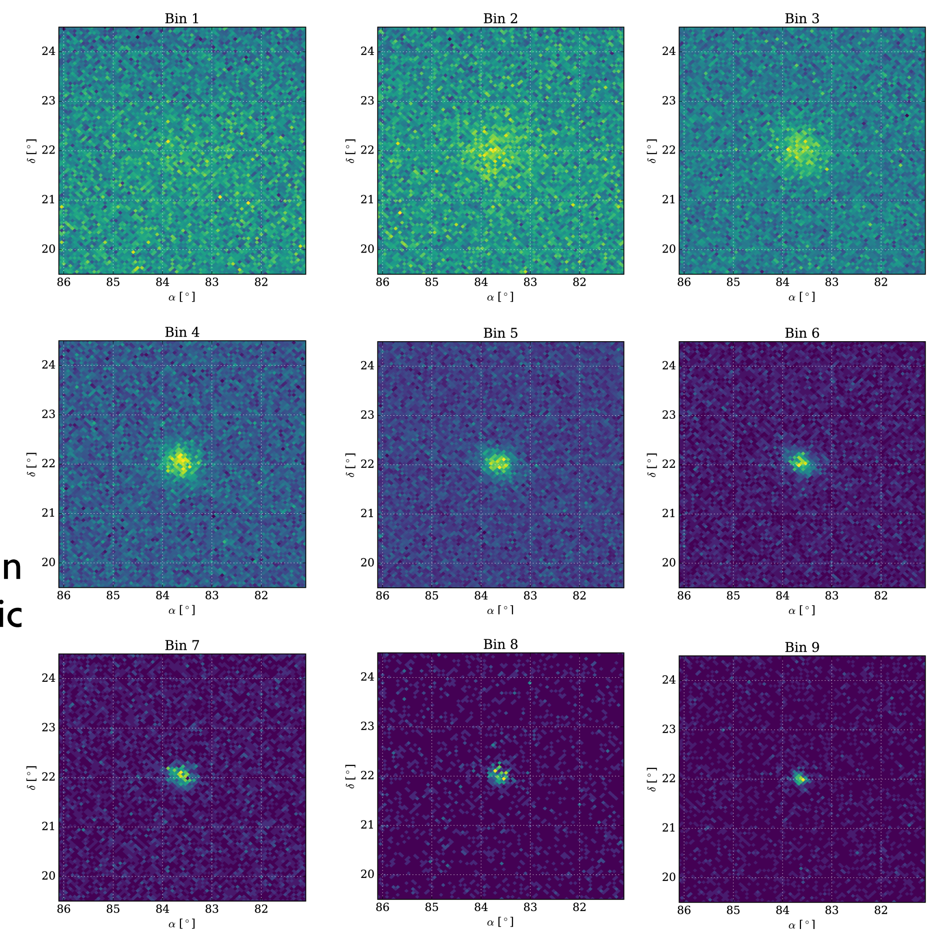




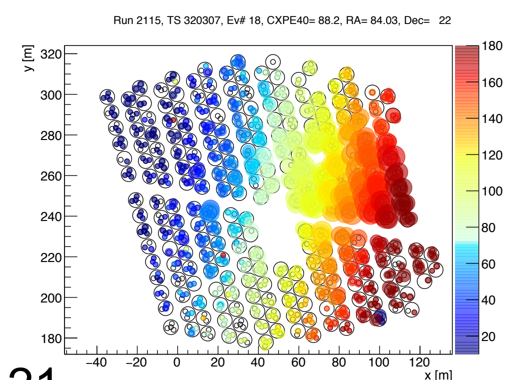
HAWC Sensitivity



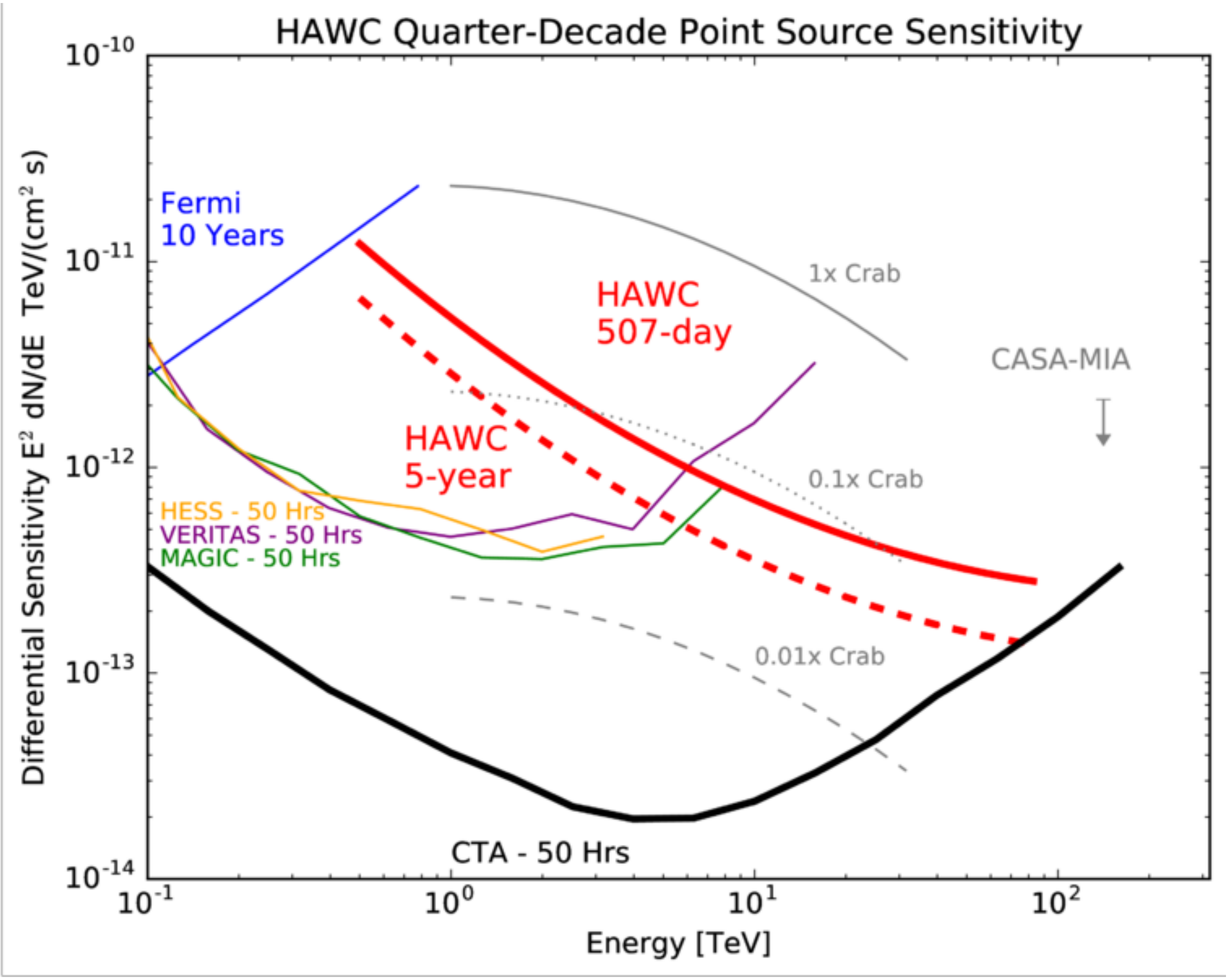
CRAB



The bigger the shower the:
the better the angular resolution
the better the background rejectic
the higher the energy
the fewer the events



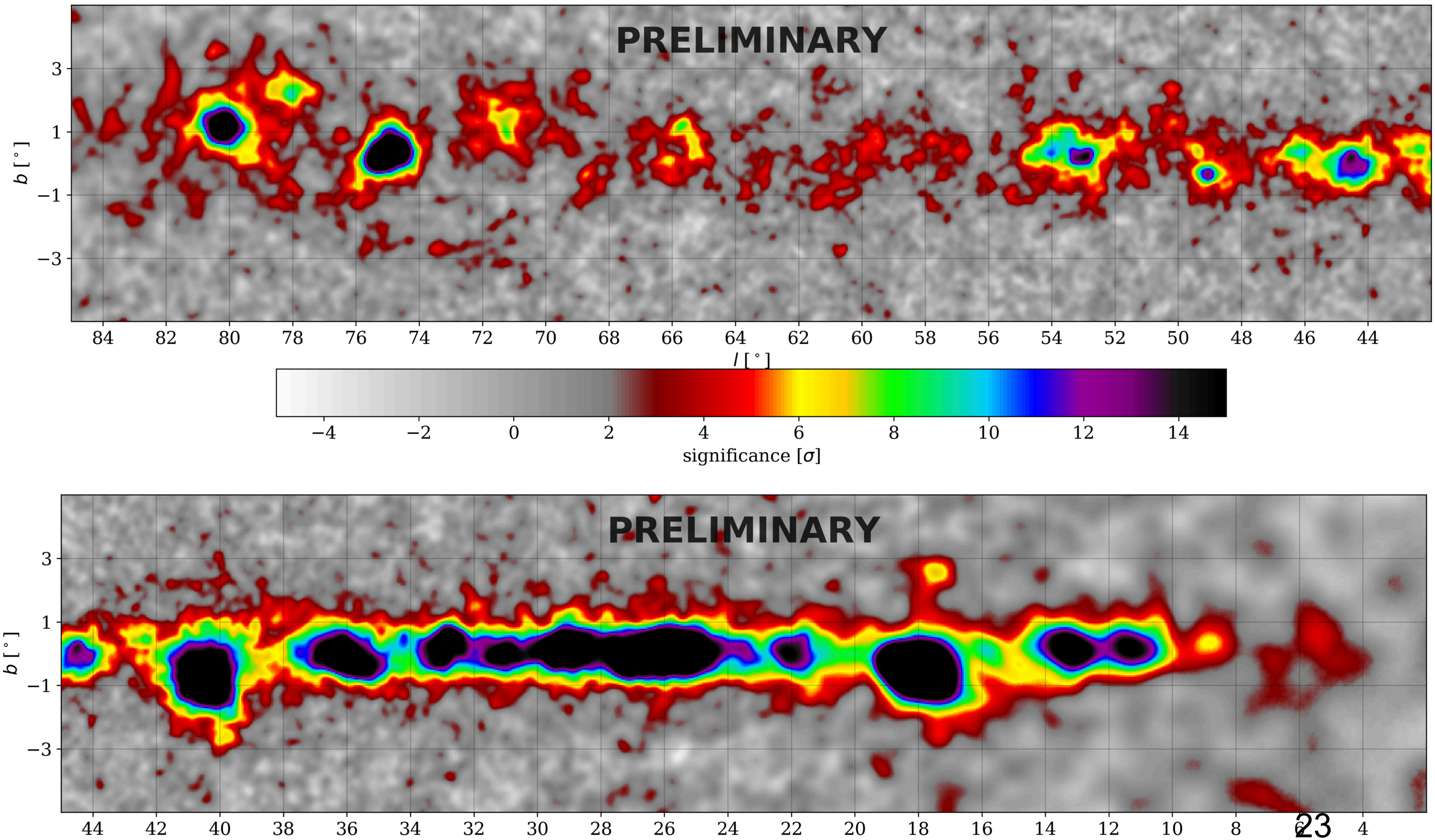
HAWC Sensitivity



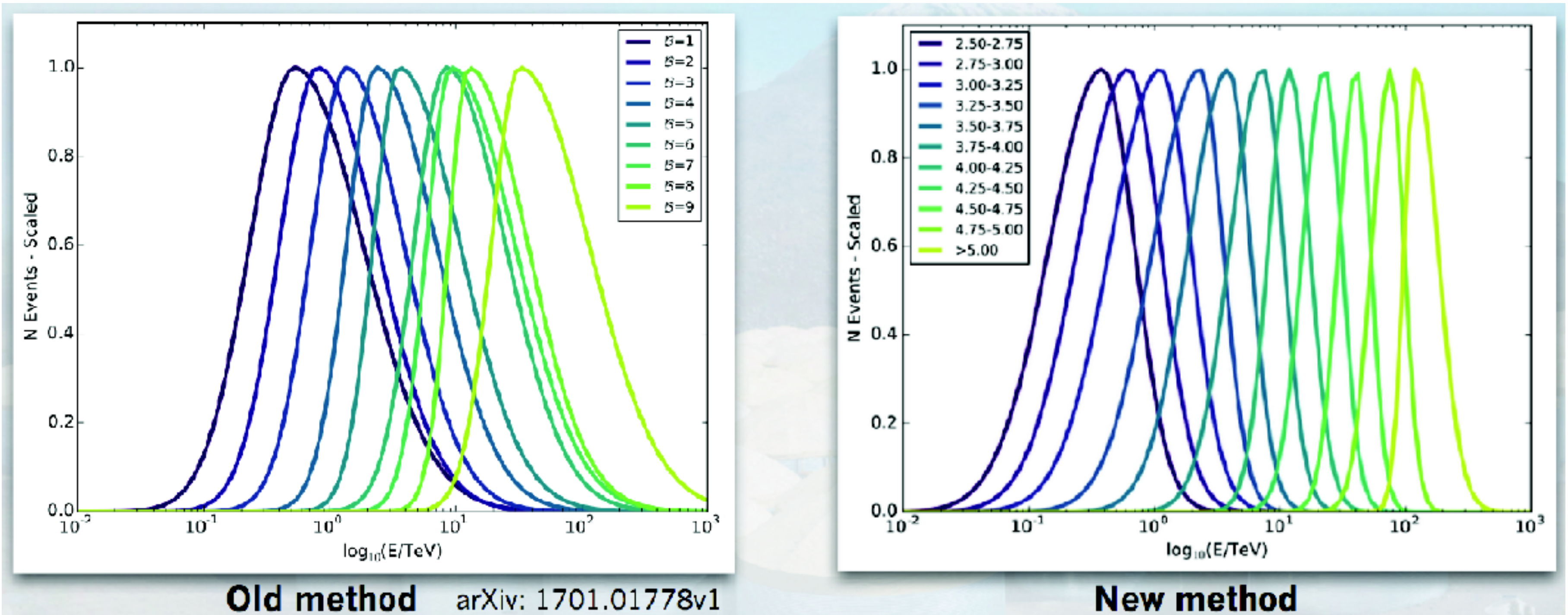
HAWC Collaboration+17

- Instantaneous sensitivity 15-20x less than IACTs.
- Exposure (sr/yr) is 2000-4000x higher than IACTs.
- Above 10 TeV HAWC 1-yr sensitivity is comparable to 50h observation by an IACT.
- Survey > half the sky to: 40 mCrab [5 σ] (1yr) <20 mCrab [5 σ] (5yr)

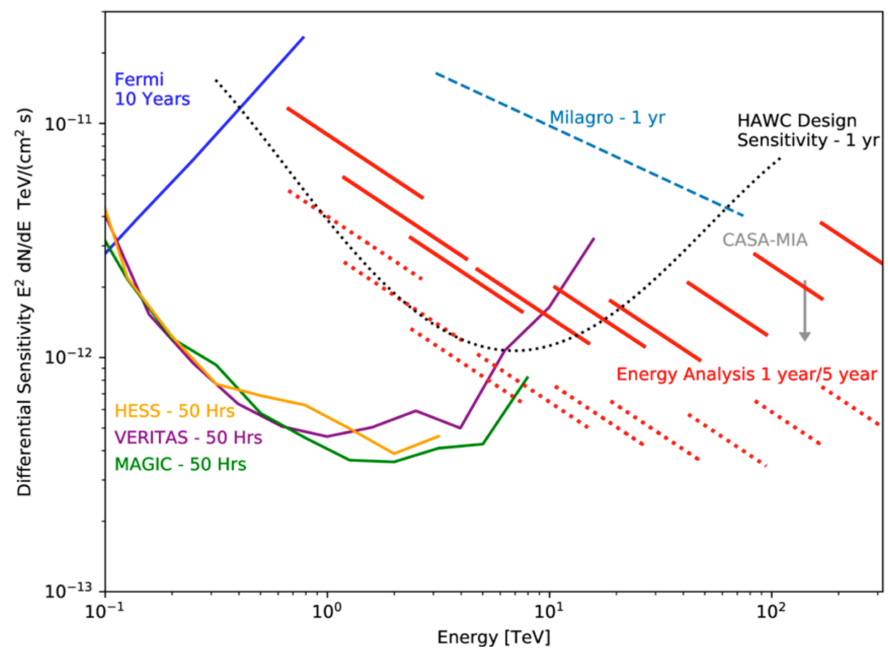
HAWC maps after 1543 days



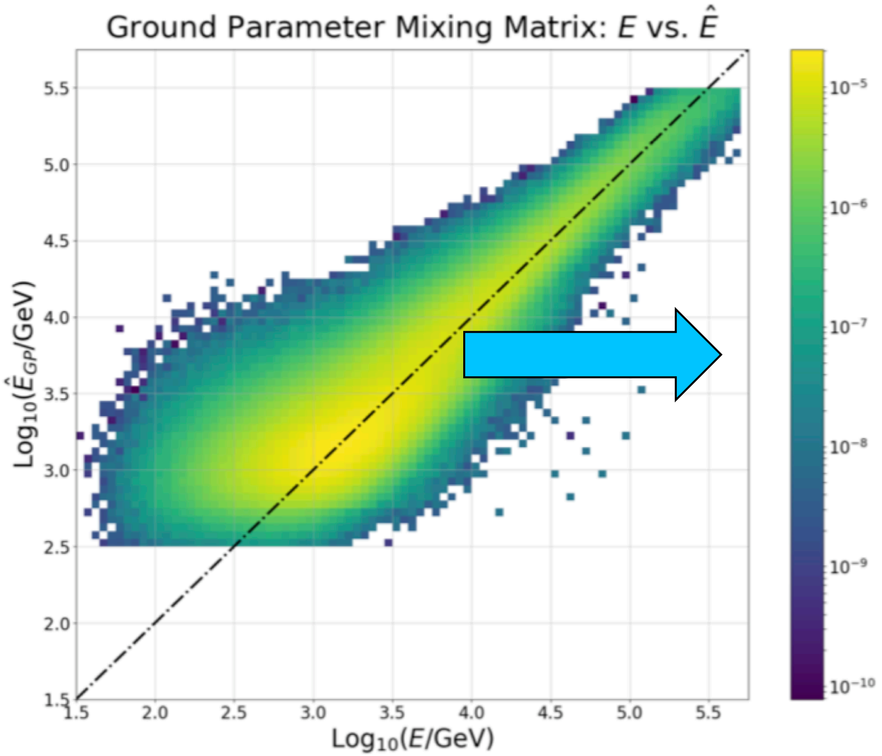
Event by event Energy Estimator

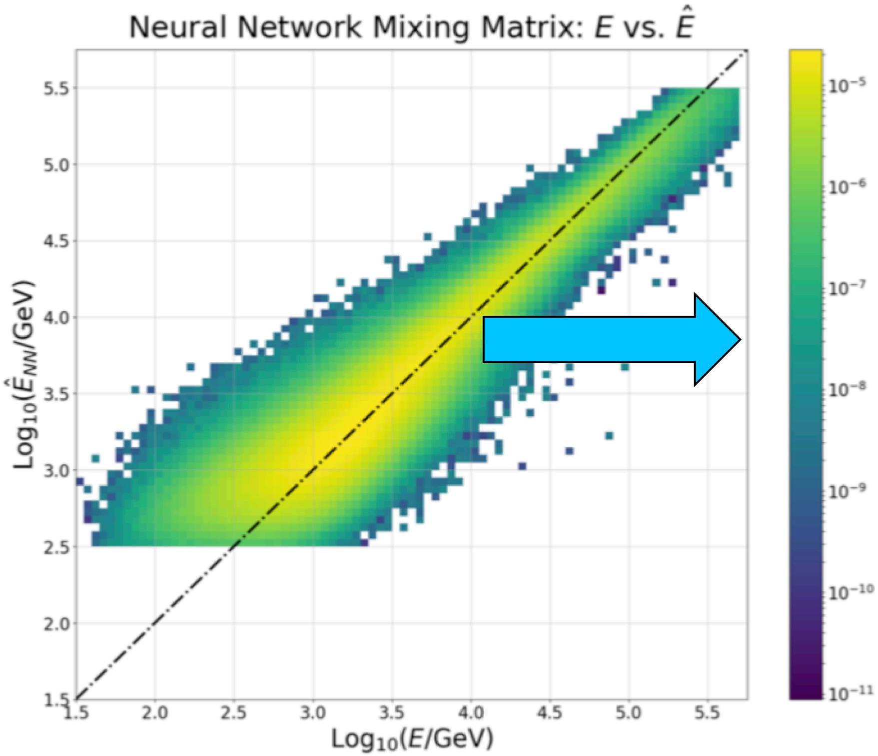


- Spectral analysis is paramount when understanding the physics of the emission
- Previously the number of PMT seeing lights as energy proxy. No difference between 10 and 50 TeV events
- Event-by-event energy estimation algorithm to distinguish between 10 and 100 TeV photon
- Previously published HAWC papers did not use this algorithm



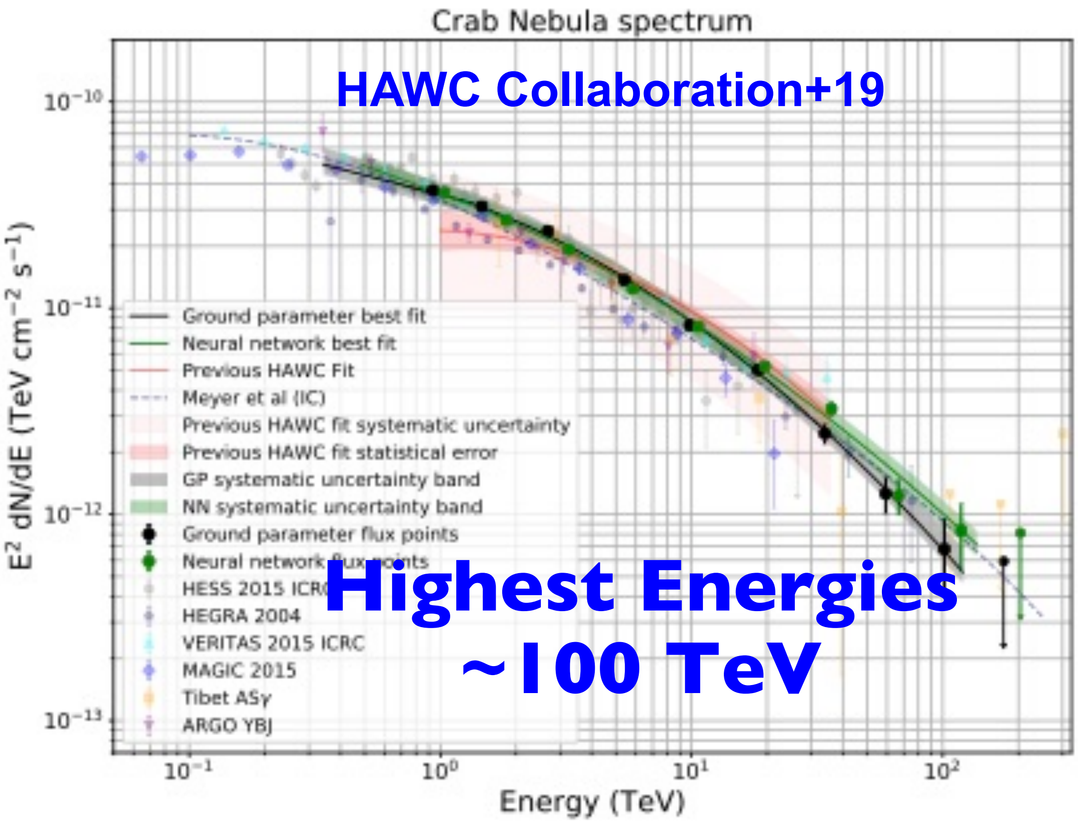
Breaking degeneracy of highest Energy Events: Energy Estimators





Kelly Malone & Sam Marinelli

The Crab Spectrum at the highest energies



Two independent energy estimation algorithms (grey and green points/ bands above)

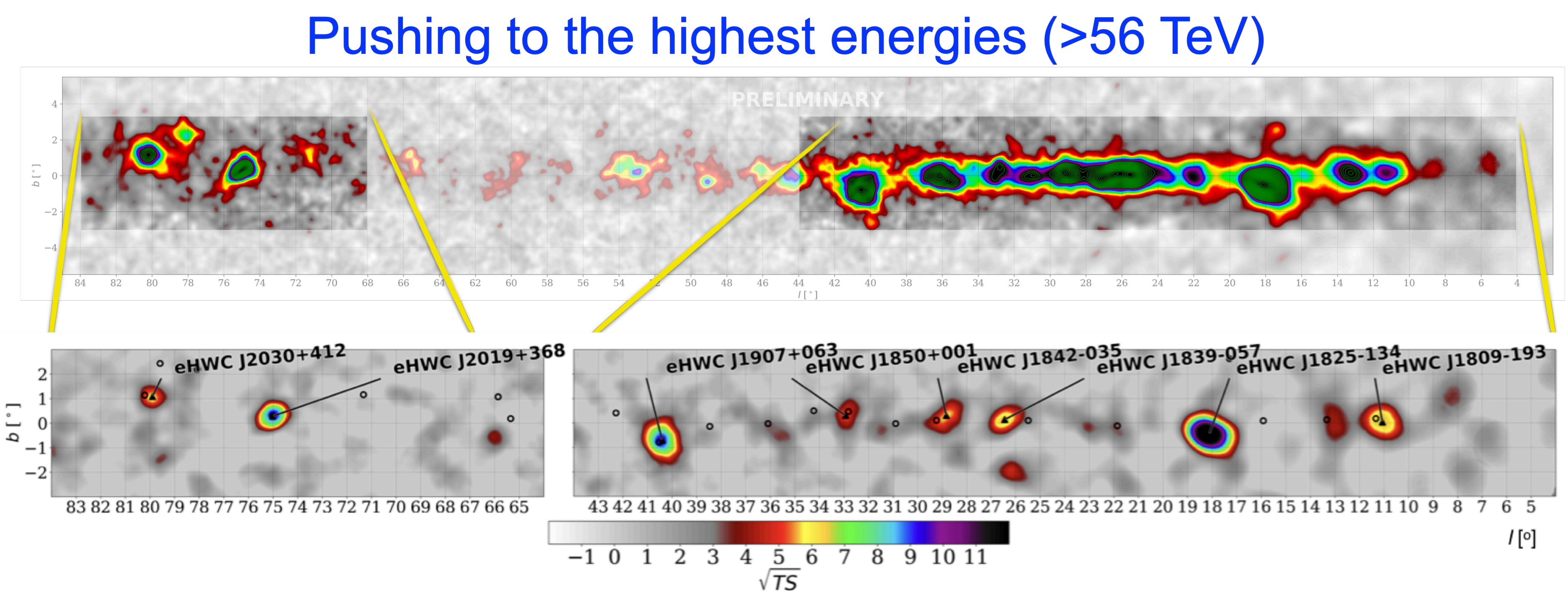
837 day dataset

Good agreement at lower energies with previous HAWC paper (ApJ 2007) and IACT measurements

First Crab spectra that goes past 100 TeV in reconstructed energy

The Crab spectrum obtained with the GP method (black) and NN method (green). The error bars on the flux points are statistical only The shaded grey and green shaded bands denote systematic uncertainties.

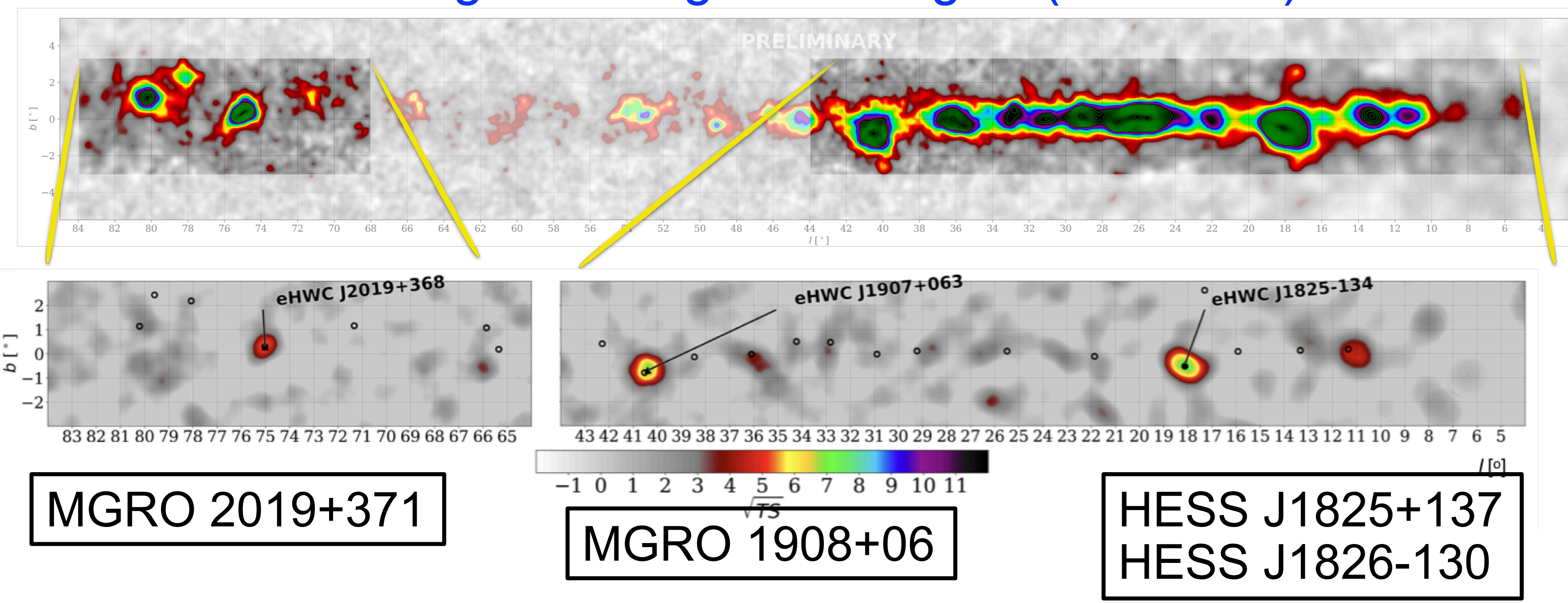
Highest Energy Skymaps (1039 days)



Acceleration mechanisms: hadronic or leptonic?
Each source has a pulsar within 0.5 deg from the HAWC position
Correlation with neutrinos?
Detailed studies of the sources

Highest Energy Skymaps

Pushing to the highest energies (>100 TeV)

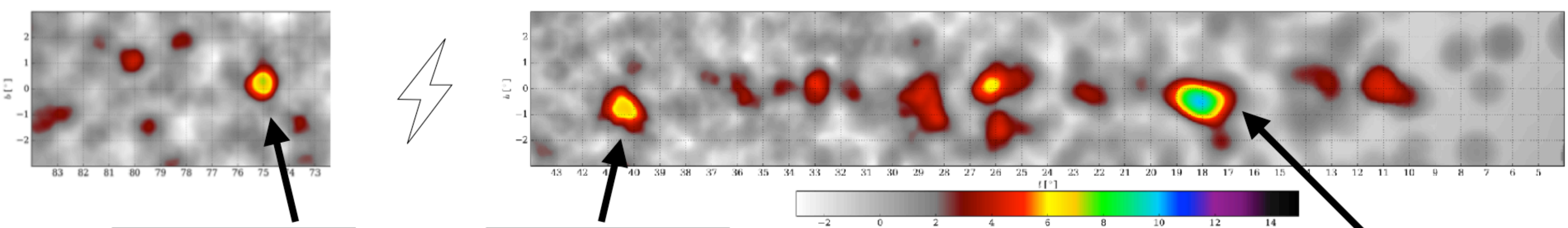


HAWC Collaboration+19

The Galaxy above 100 TeV

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

Galactic Plane, > 56 TeV (0.5 degree extended source assumed)

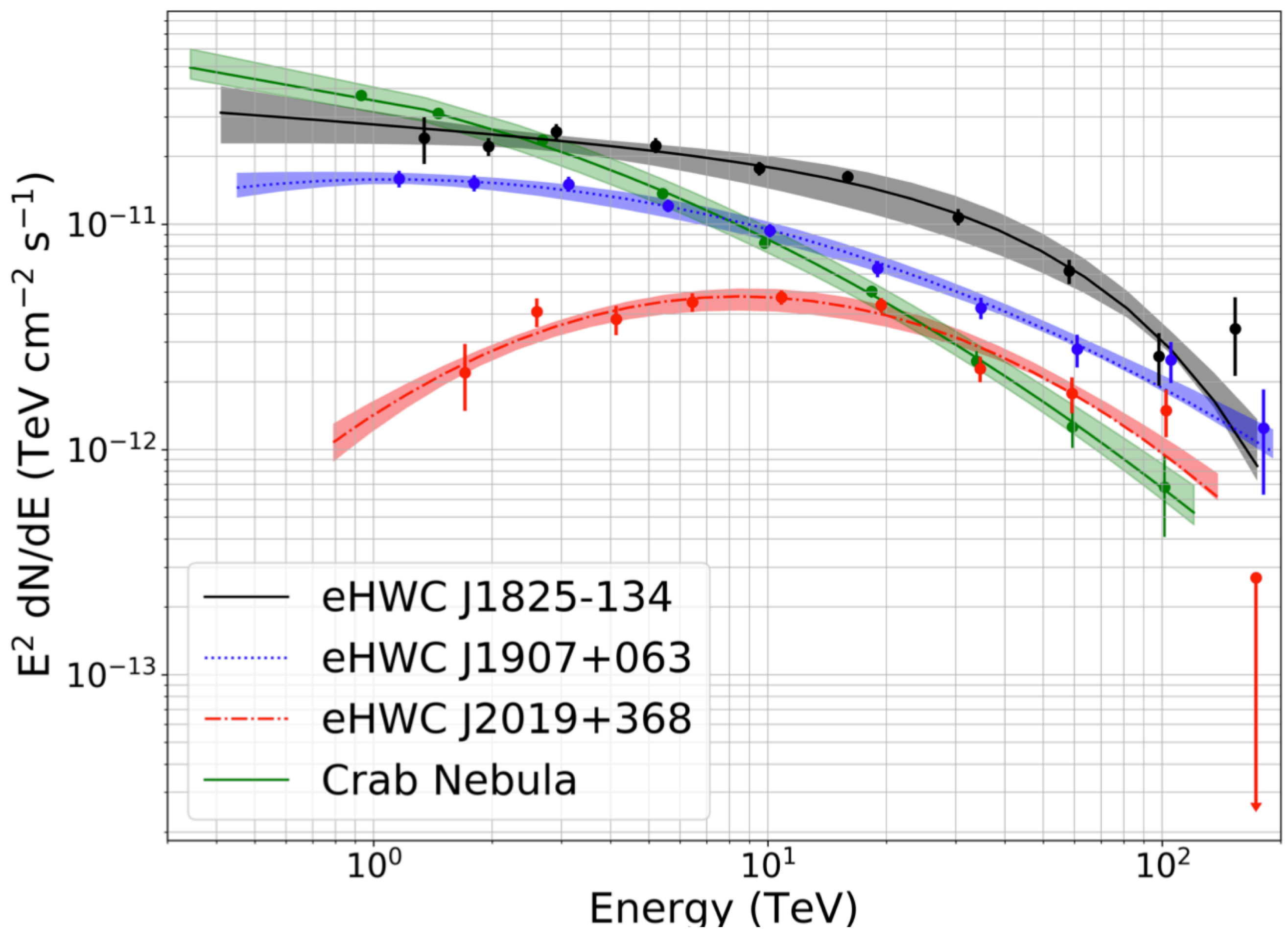


MGRO 2019+371

MGRO 1908+06

HESS J1825+137
HESS J1826-130

The Galaxy above 100 TeV: Spectra

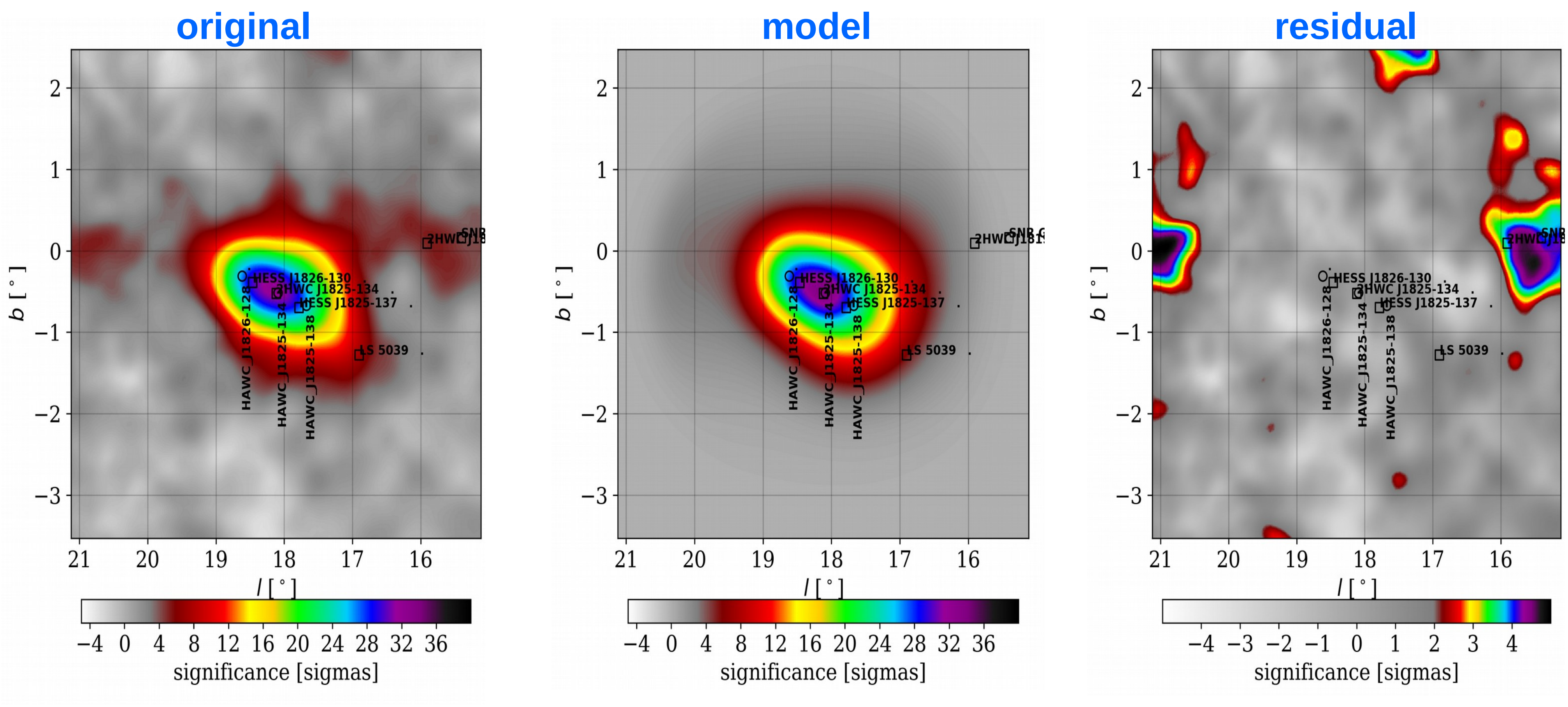


Source	$\sqrt{TS}$	Extension (^{o})	ϕ_0 (10^{-13} TeV cm^2 s)$^{-1}$	α	E_{cut} (TeV)	PL diff
eHWC J1825-134	41.1	0.53 ± 0.02	2.12 ± 0.15	2.12 ± 0.06	61 ± 12	7.4

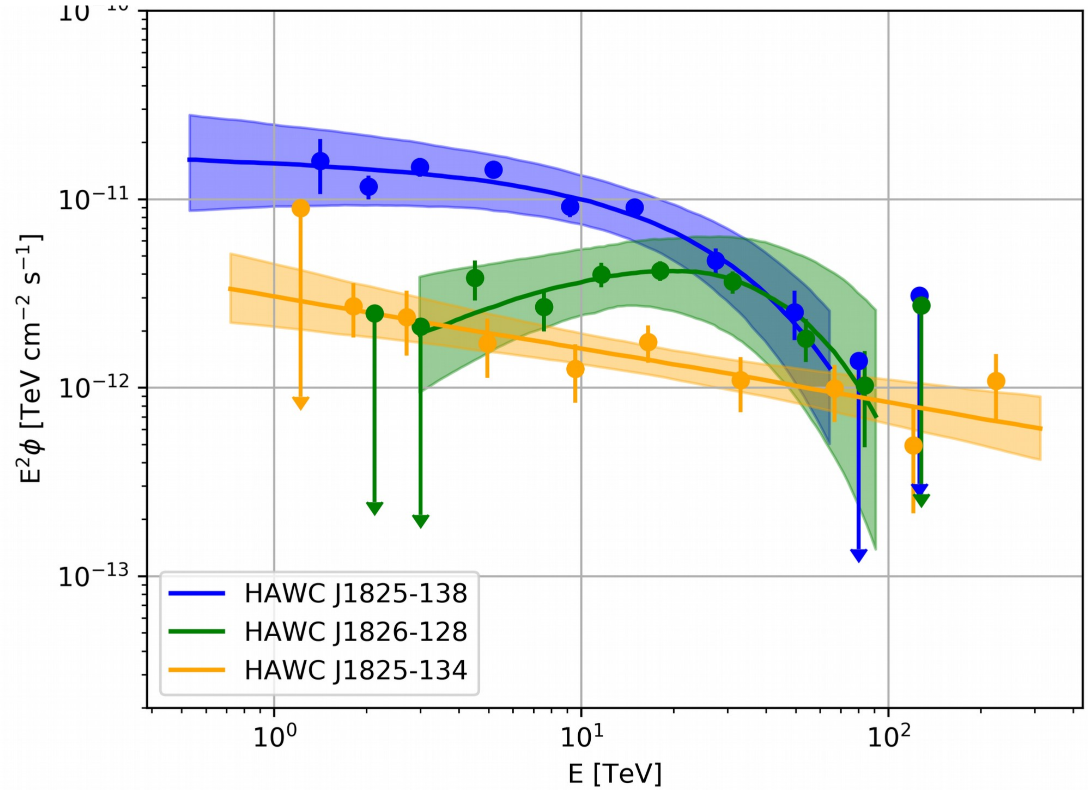
Source	$\sqrt{TS}$	Extension (^{o})	ϕ_0 (10^{-13} TeV cm^2 s)$^{-1}$	α	β	PL diff
eHWC J1907+063	37.8	0.67 ± 0.03	0.95 ± 0.05	2.46 ± 0.03	0.11 ± 0.02	6.0
eHWC J2019+368	32.2	0.30 ± 0.02	0.45 ± 0.03	2.08 ± 0.06	0.26 ± 0.05	8.2

The region of eHWC J1825

- **The best modeling of the region was with 3 sources**: 2 extended (Gaussian) sources (PL*Ecut spectrum) + 1 point source (SPL).
- We included also a GDE Gaussian template (width fixed, SPL spectrum) covering galactic longitudes from 16-21 deg.
- LS5039 is within the ROI of 2.5 deg but **was not included** in the fit since the TS~3.



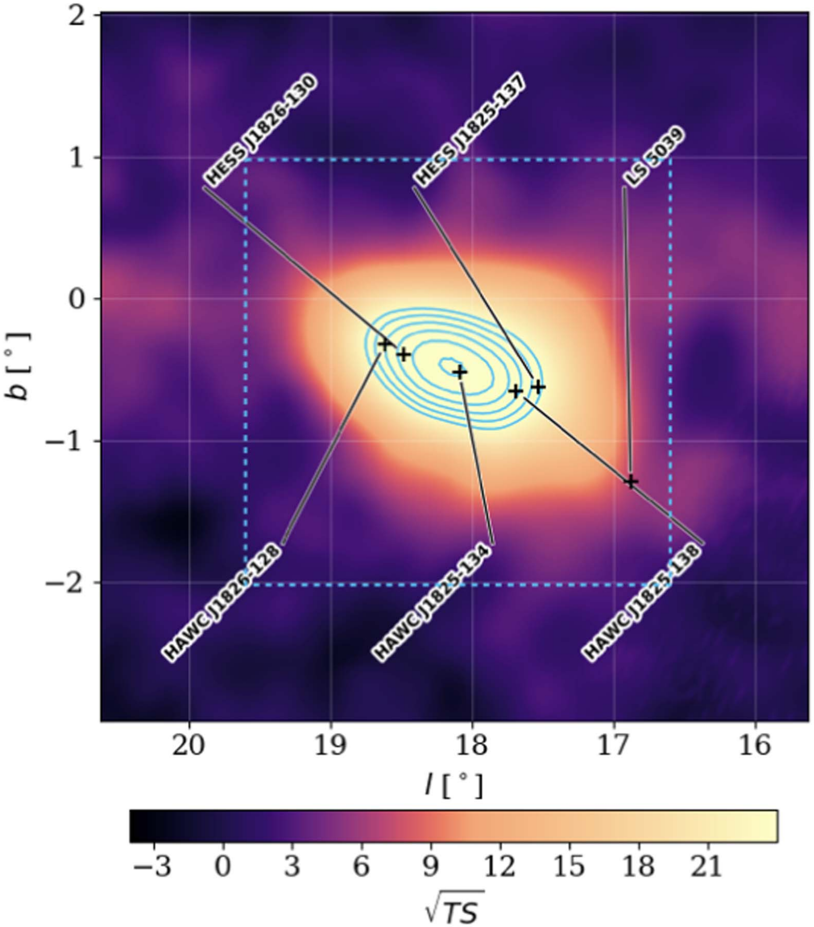
Spectra of the three sources in the region

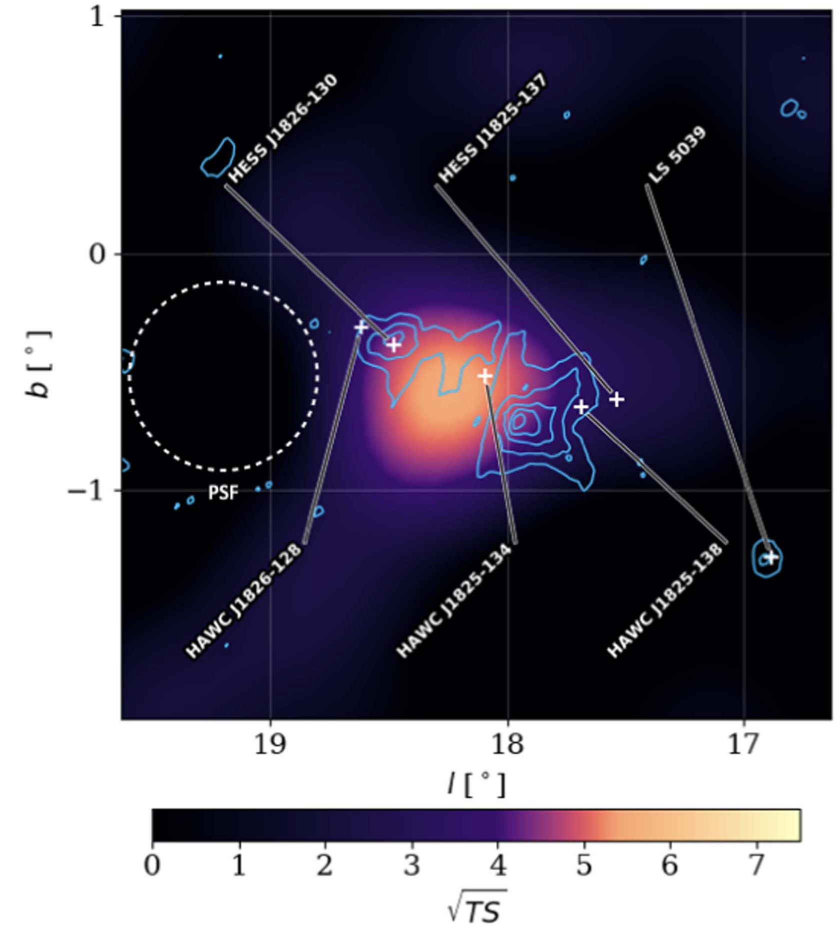


HAWC J1825-138		HAWC J1826-128		HAWC J1825-134	
Emin (TeV)	Emax	Emin	Emax	Emin	Emax (1 / 2 / 3 σ)
0.53	64	3.0	91	0.72	**312 / 209 / 163**

- Points with TS>4, otherwise U.L.
- E range with "1σ" method, as in the Crab 2017 paper. Tested also 2σ and 3σ.
- Systematics on Emax for HAWC J1825-134:
  312 +19 -15 TeV
  209+37-9 TeV
  163+16-14 TeV
- **HAWC J1825-134 emits above 200 TeV at 95% C.L.** (including systematics) and does not show a clear cut-off in the spectrum

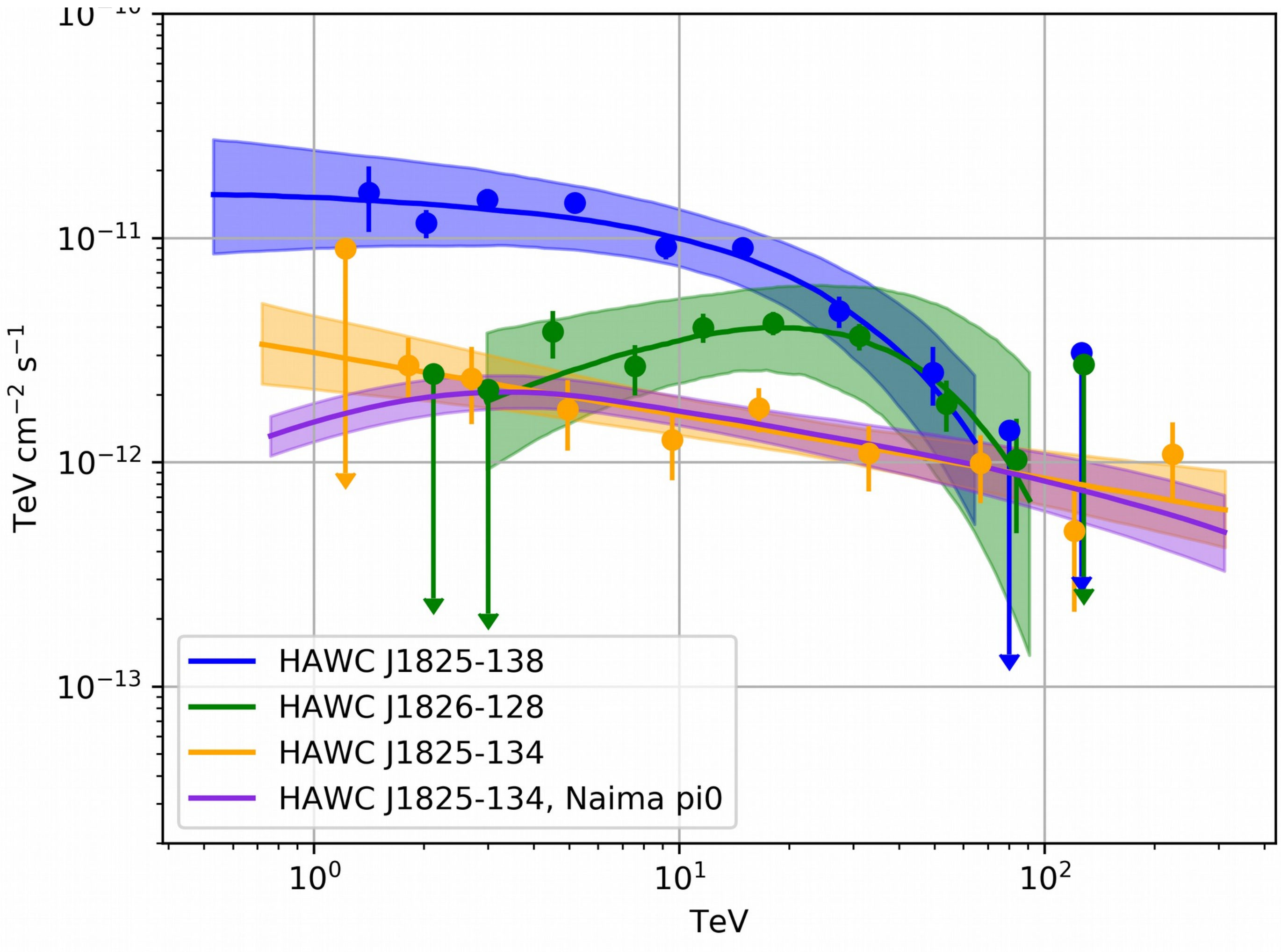
HAWC Collaboration, ApJL 907, 2021





source	RA (deg)	dec (deg)	σ [deg]	N(18TeV) 10^{-14} [cm^{-2} TeV^{-1} s^{-1}]	index	E_{cut} [TeV]	TS
HAWC J1825-138	276.38 ± 0.04	-13.86 ± 0.05	0.47 ± 0.04		-2.02 ± 0.15		142
HAWC J1826-128	276.50 ± 0.03	-12.86 ± 0.04	0.20 ± 0.03		-1.2 ± 0.4		83
HAWC J1825-134	276.44 ± 0.03	-13.42 ± 0.04	--		-2.28 ± 0.12	--	38

Particle Population



Results from the fit, using a simple power law for the particle spectrum (pp):

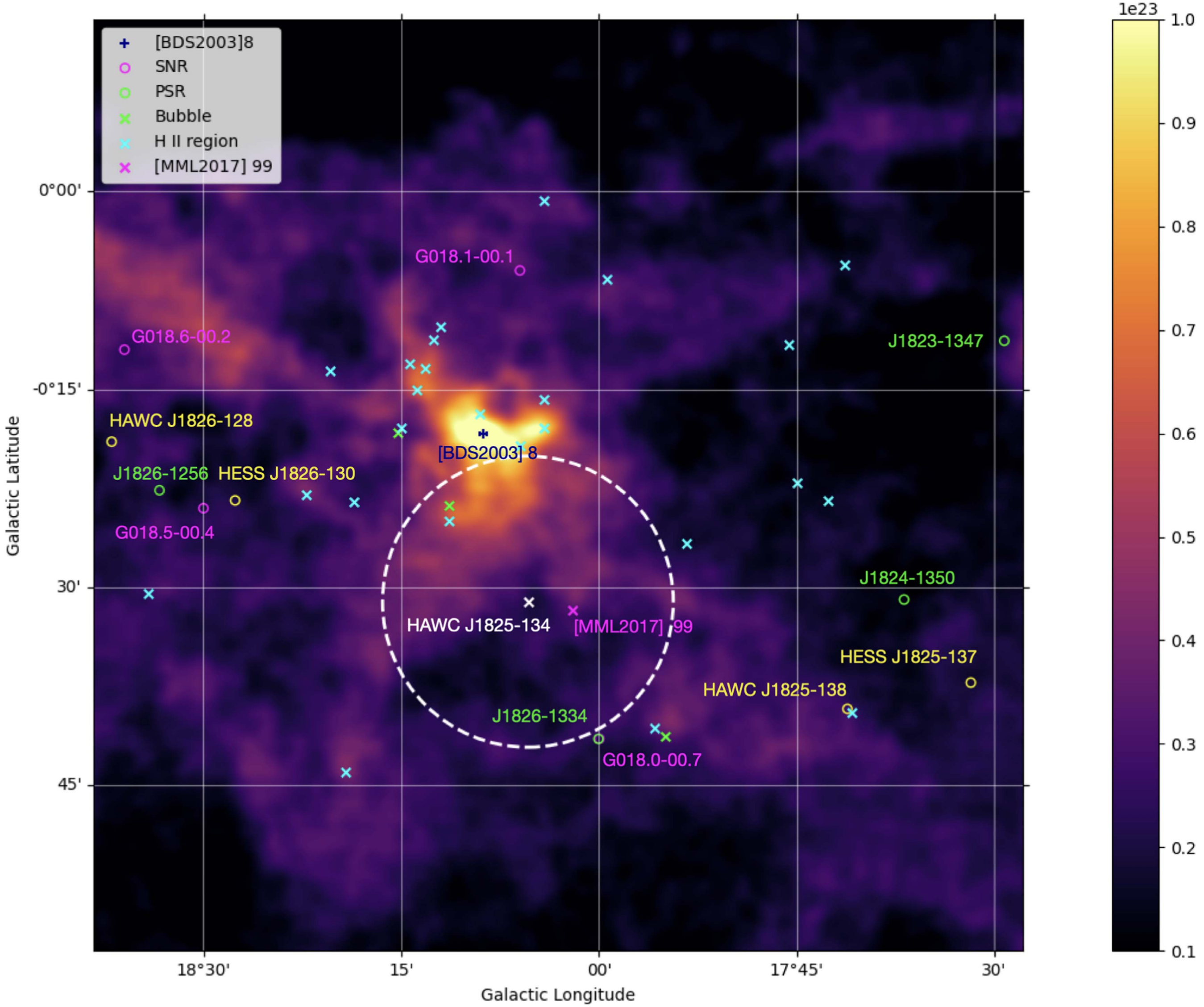
Wp= (5.1 +0.8−0.7) x 10^{58} keV = (8.2 +1.3-1.1) x 10^{49} erg

index= 2.30 ± 0.12

<u>Information used for the fit:</u>

$E_{p,min}$ = 10 TeV
$E_{p,max}$ = 100 PeV
n (density) = 1 cm^{-3}
distance = 4 kpc

Looking for counterparts



Leptonic mechanism

- **Parental electron spectrum without cutoff**

Median electron energy 500 TeV

- **Acceleration of electrons in close SNRs**

$t_{acc} = D(E)/v_{sh}^2$ where v_{sh} is typically 2000 km/s in SNRs and for Bohm diffusion $t_{acc} = 1.5\ 10^5\ (B/1\,\mu G)^{-2}\ (Ee/\ 500\ TeV)^{-1}\ (v_{sh}/\ 2000\ km/s)^{-2}$ yr > t_{age}

Magnetic field amplification causes synchrotron cooling
$t_{-cool} = (B/100\ \mu G)^{-2}\ (Ee/\ 500\ TeV)^{-2}$ yr << t_{acc}

- **Acceleration in close pulsars and transport**

Magnetic field : $B = 100\ \mu G\ (n/10^4\ cm^{-3})^{0.5} = 27\ \mu G$ if n = 700. Travelled distance of the electrons d is proportional to n. If n=700 cm^{-3}, d = 4pc. Cooling time and travelled distance are proportional to $(n/10^4\ cm^{-3})^{-1}$

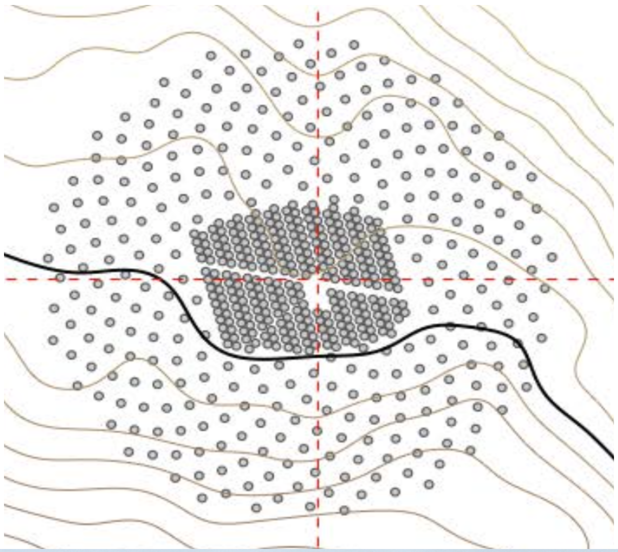
Even changing the fit position n > 600 cm^{-3} within half a degree from the source, and B>24 mG and travelled distance d<5pc if the particles travel at light-speed. The diffusion coefficient is likely orders of magnitude lower in HII regions such as J1825-134, so d << 5pc .

IC likely excluded !

Hadronic mechanism

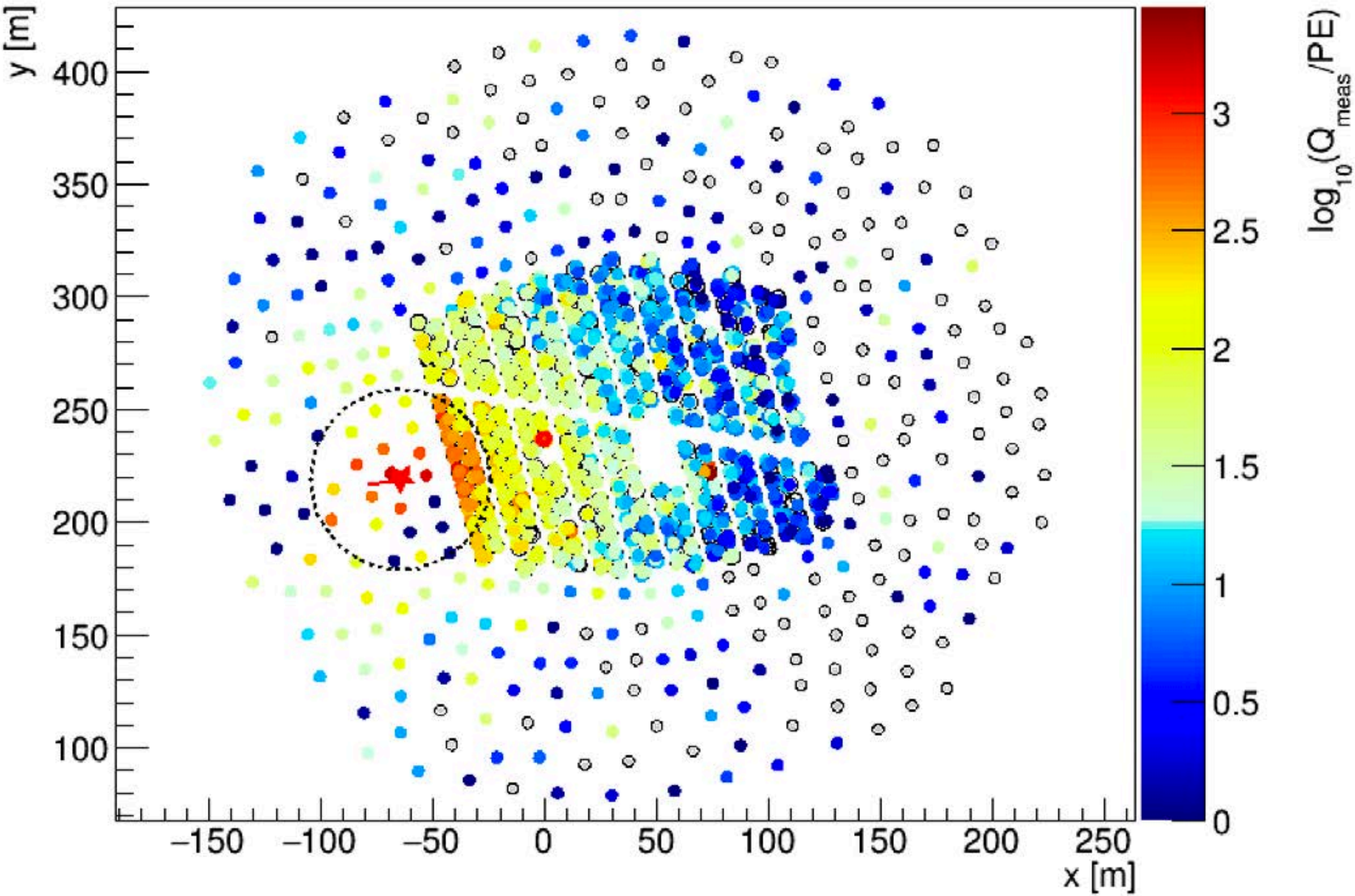
- **Gamma-ray spectrum extending beyond 200 TeV**
  - Proton spectrum -2.3 extending beyond PeV energies without a break or cutoff
- **Gamma-ray luminosity and local gas density**
  - CR energy density : 0.3 eV/cm3 above 10 TeV, roughly 300 times the local CR density
  - Total budget in protons : W_p = 8 x 10^{49} n^{-1} erg W_p= 2 x 10^{47} ergs for n = 700 cm^3
- **Gamma-ray morphology : J1825-134 associated with a dense gas region**
  - Possible CR PeVatrons :
    - young star cluster BDS2003 8 (roughly 5 10^{38} erg/s, age 10^6 yr). Coincident with dense gas region, hosting several HII regions, bubbles and cloud clumps
    - local SNRs. Though these SNRs are not young and particles of PeV energies would have since left the whole region even if D strongly suppressed
    - Pulsars as hadron accelerators energetically difficult.Spin down luminosity 10^{36} erg/s and age = 15-20 kyr, then 10^{48} ergs available

HAWC with Outrigger

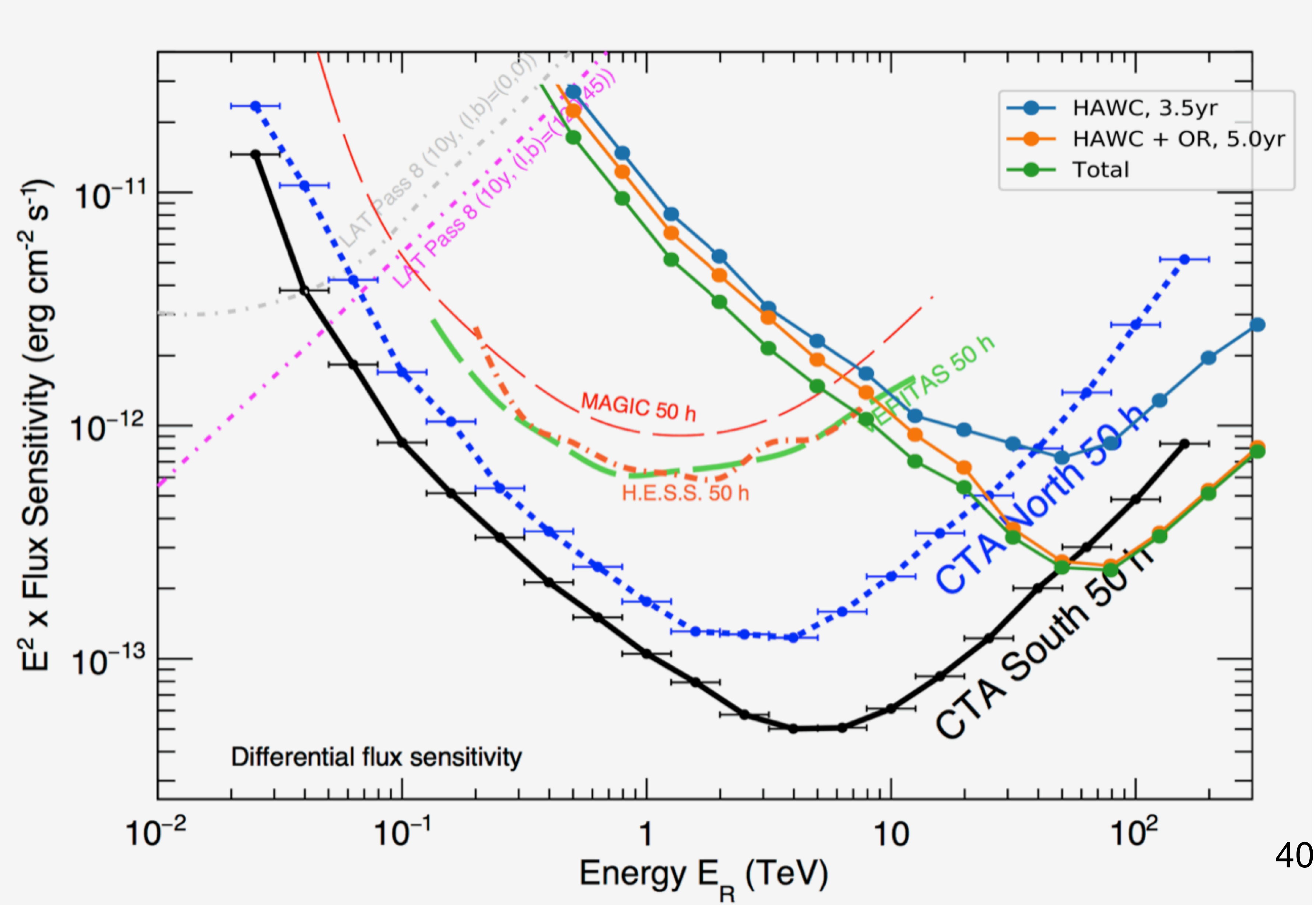


- HAWC has added more detectors to enhance the sensitivity above 10 TeV.
- Outriggers help to accurately determine core position for showers off the main tank array.
- Funded by LANL LDRD, Max Planck Institute in Heidelberg, and CONACyT in Mexico
- Gives angle and energy reconstruction for showers that trigger HAWC but have the core outside the HAWC array
- Expands total effective area by a factor of ~4 above ~10TeV with the addition of 350 outrigger tanks
- 100% operational and taking data since August 2018, but we're still refining calibration, reconstruction and analysis algorithms
- HAWC already detects multiple sources greater than 100 TeV. Outriggers will increase this number of sources and characterize their spectra.

Run 8541, TS 1600070, Ev# 185, CXPE40= 649, RA= 119.9, Dec= 14.7



HAWC + Outriggers Sensitivity

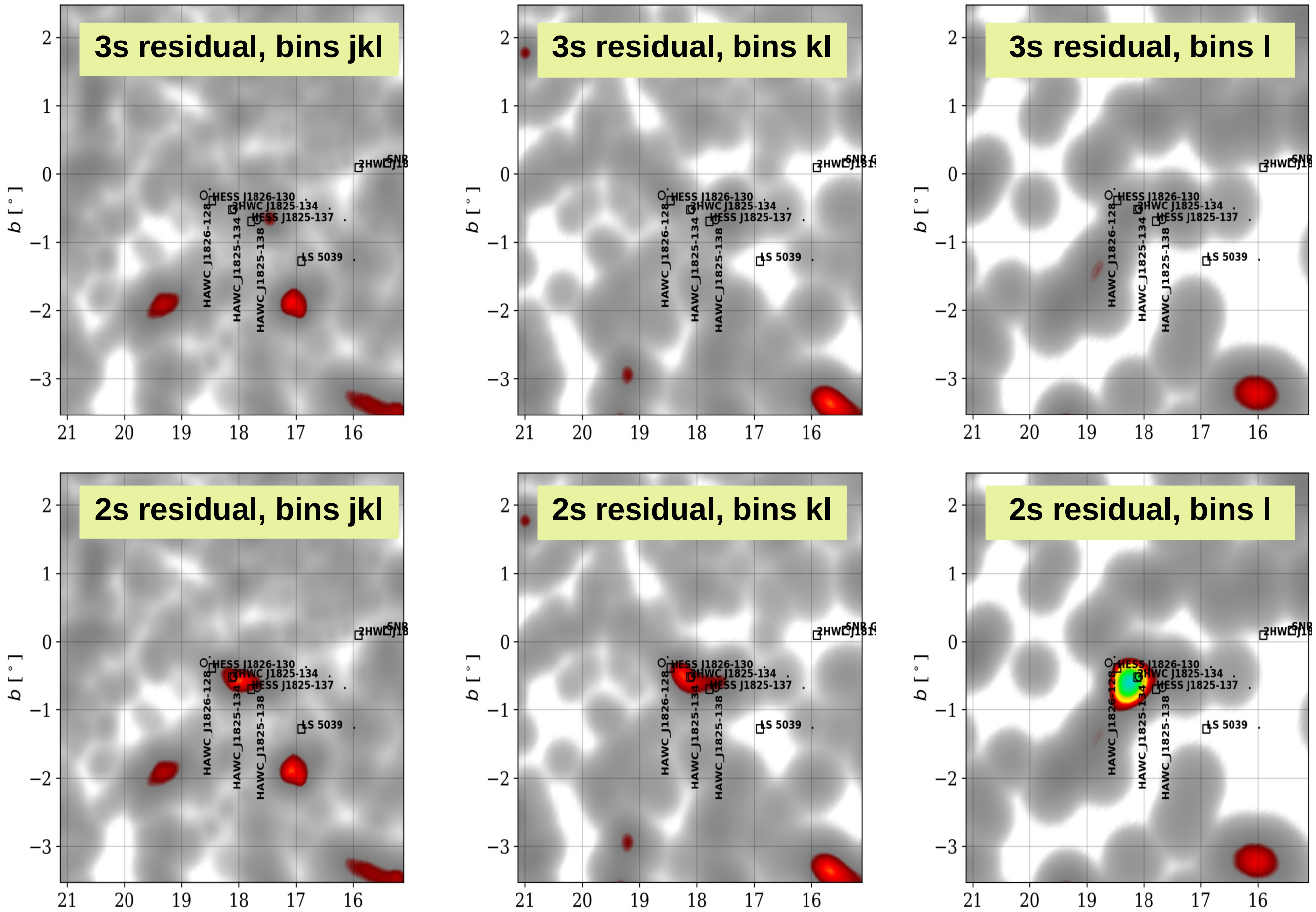


Conclusions and Outlook

- Discovery of a source with datapoints up to 200 TeV, not in the cutoff region
- Electrons unlikely to emit such radiation
- Emission is associated with a giant molecular cloud
- Protons up to at least 1 PeV likely responsible for the emission
- HAWC J1825-134 is a direct gamma-ray signature of a CR PeVatron, maybe associated to a star cluster (https://www.space.com/powerful-particle-accelerator-molecular-cloud)
- Currently working on an analysis including outriggers

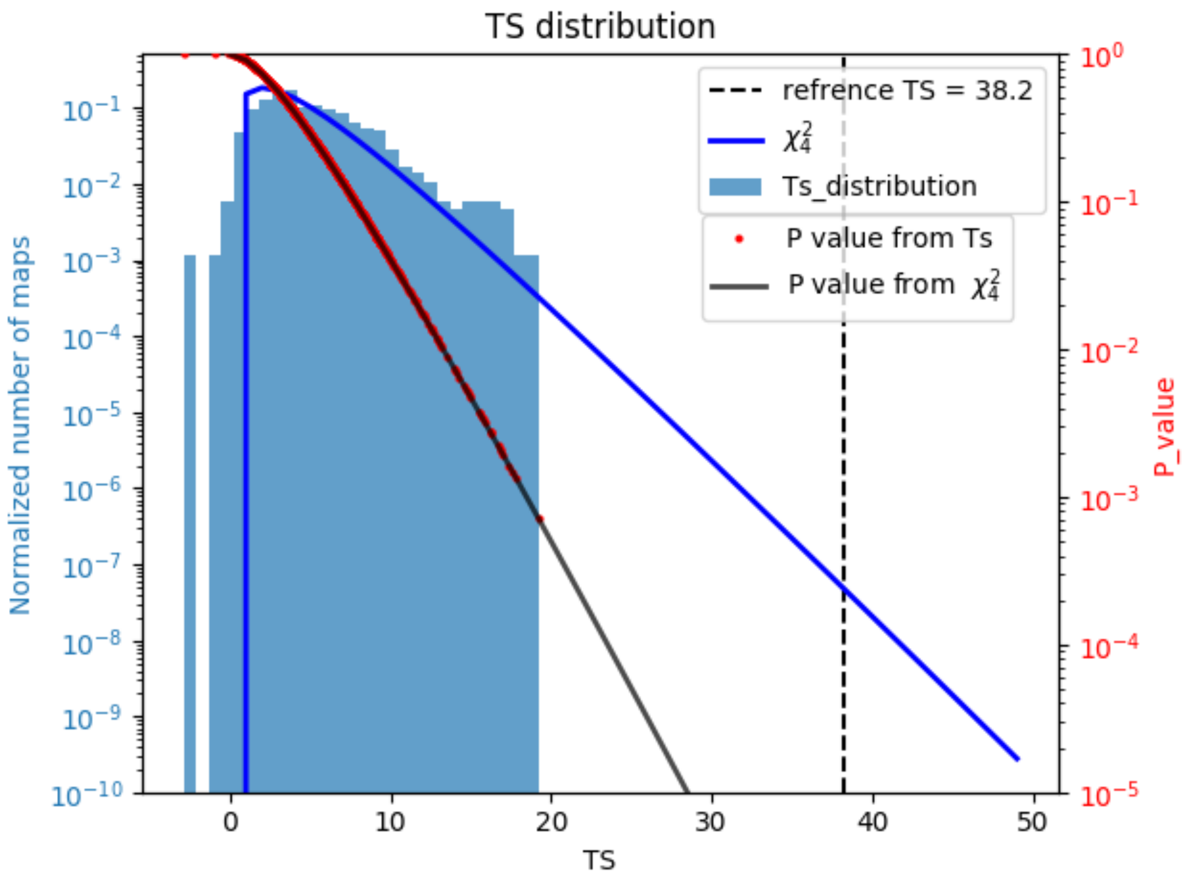
Backup Slides

Residuals


3s residual, bins jkl
3s residual, bins kl
3s residual, bins l
2s residual, bins jkl
2s residual, bins kl
2s residual, bins l
HESS J1826-130
2HWC J1825-134
HESS J1825-137
LS 5039
HAWC_J1826-128
HAWC_J1825-134
HAWC_J1825-138
b [°]

3-Source vs 2-Source Model

- The 3-source model is preferred with ΔTS = 38 when compared to 2-source model.
- What is the probability of that being a fluctuation?
- We generated a set of maps with 2 source + Poisson fluctuation, and then fit them with the two models.
- The TS histogram is well described by a χ^2 with 4 DoF.
- **We didn't reach the ΔTS observed in any of the ~1k simulated samples.**
- **Extrapolating the p-value at ΔTS=38 is ~10^{-7}, so >5σ**



E dependence J1825

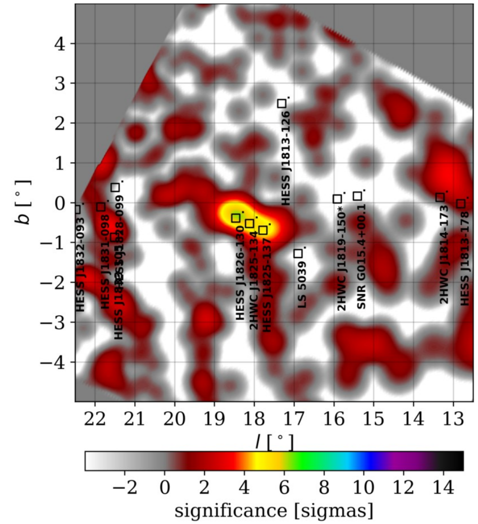
- Free Norm and size. Position fixed. Other sources fixed.

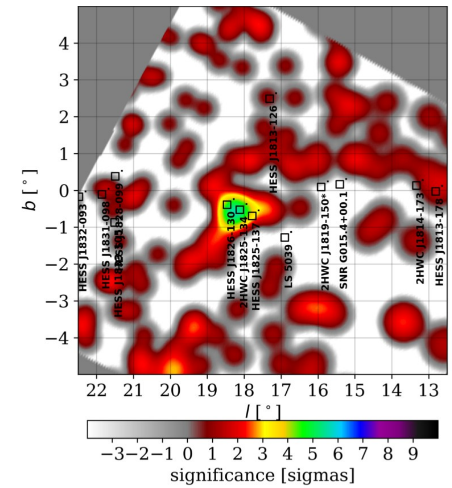
HAWC J1825-138 (H.E.S.S. J1825)				
bins	**E (TeV)**	**width [deg]**	**N(18TeV) 10^{-14} [cm^{-2} TeV^{-1} s^{-1}]**	**TS**
all	1-300	0.42 ± 0.03	4.1 ± 0.3	532
cdef	1-10	0.45 ± 0.04	4.8 ± 0.3	248
ghi	10-56	0.41 ± 0.04	3.9 ± 0.4	270
jkl	>56	**0.18 ± 0.13**	3.5 -1.0 +1.4	20

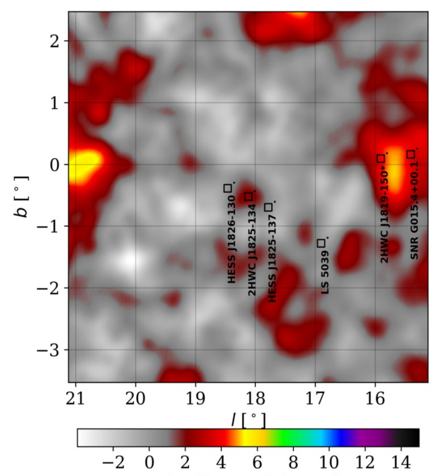
Source smaller in the last 3 bins but also it vanishes and has large uncertainty.

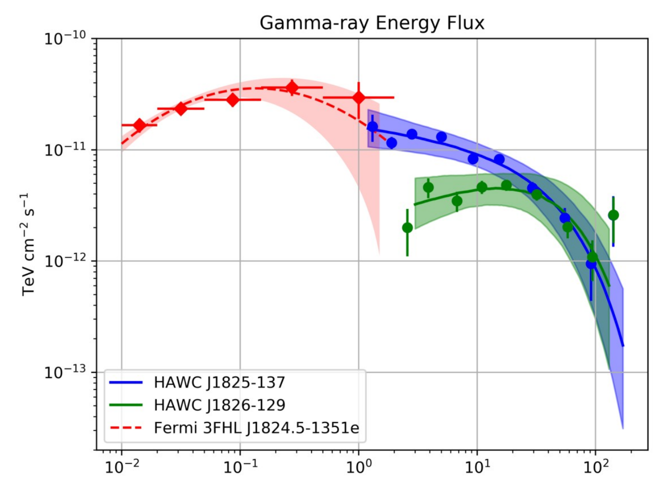
New modeling: extra source

- Motivation:
  - We have a residual of ~2σ in the middle of the 2 claimed sources.
  - We have an upper fluctuation flux point in the last E bin (bin l).
  - The significance maps from bin k to bin l suggest a transition 2→1 source.
- If a new source exists it should:
  - Have a spectrum around -2 and without a clear Ecutoff.
  - Overtake the other 2 at 100 TeV.
  - Probably small extension/PS by looking at the residuals.

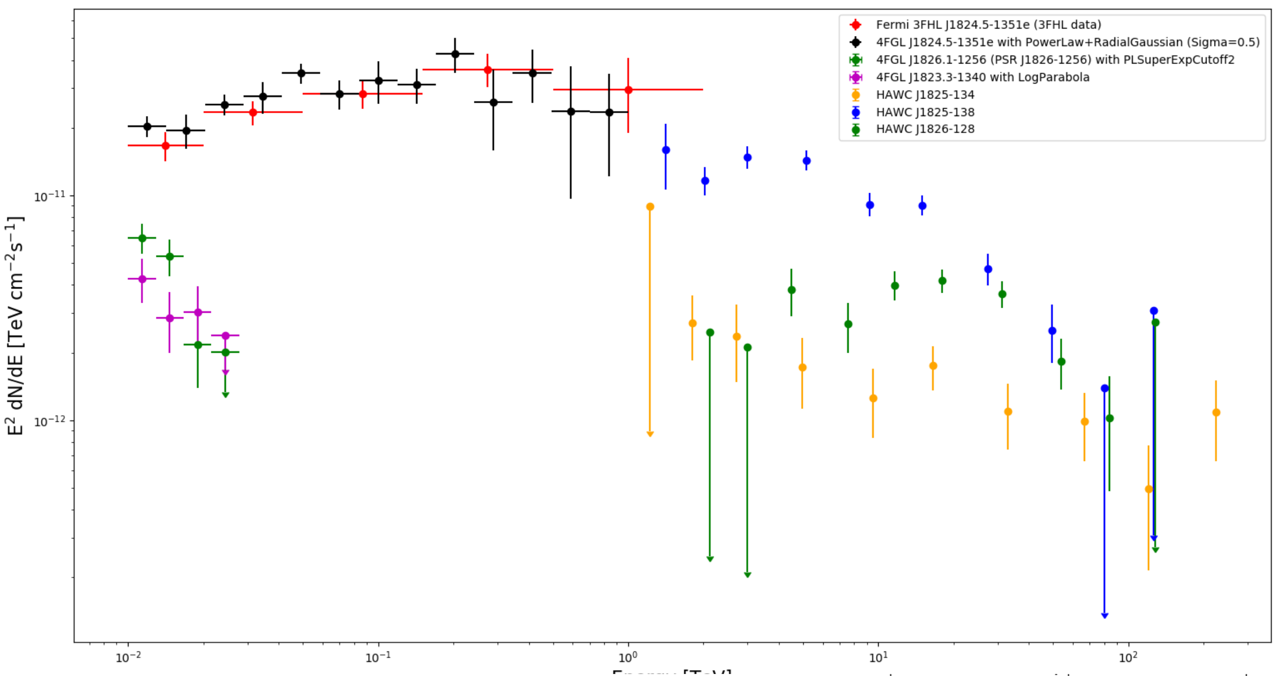




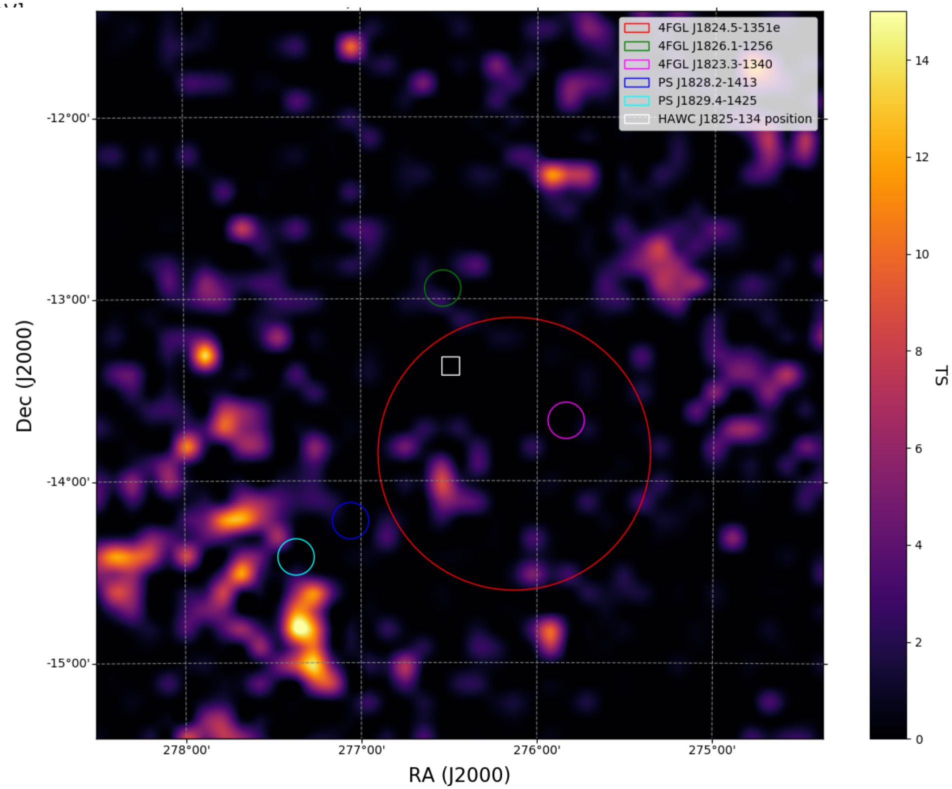




Fermi Analysis



Vardan



Quantifying the clumpiness: Compactness

$$C = Nhit / CxPE40$$

CxPE40 is the effective charge measured in the PMT with the largest effective charge outside a radius of 40 meters from the shower core. Nhit is the number of hit PMTs during the air shower. CxPE40 is typically large for a hadronic event, so C is small.

Albert et al, 2017

Quantifying the clumpiness: Pincness

$$P = 1/N \sum_{i=1,N} (\zeta_i - \langle \zeta_i \rangle)^2 / \sigma_{\zeta i}^2$$

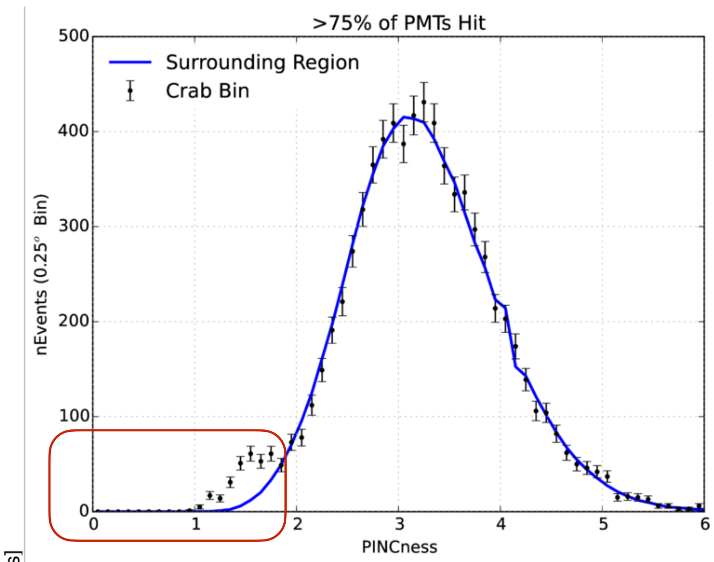
P is defined using the **lateral distribution function of the air shower**.

Each of the PMT hits, i, has a measured **effective charge Qeff,i.** P is computed using the logarithm of this charge ζ_i=log10(Qeff,i).

For each hit, an expectation is assigned $\langle \zeta_i \rangle$ by averaging the ζ_i in all PMTs contained in an annulus containing the hit, with a width of 5 meters, centered at the air shower core.

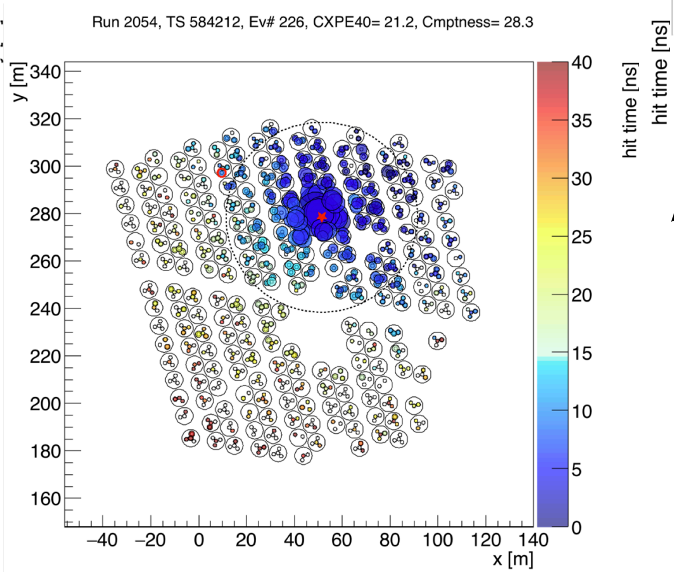
The higher the accumulated charge within the ring the more likely the event is a hadron.

Background Rejection

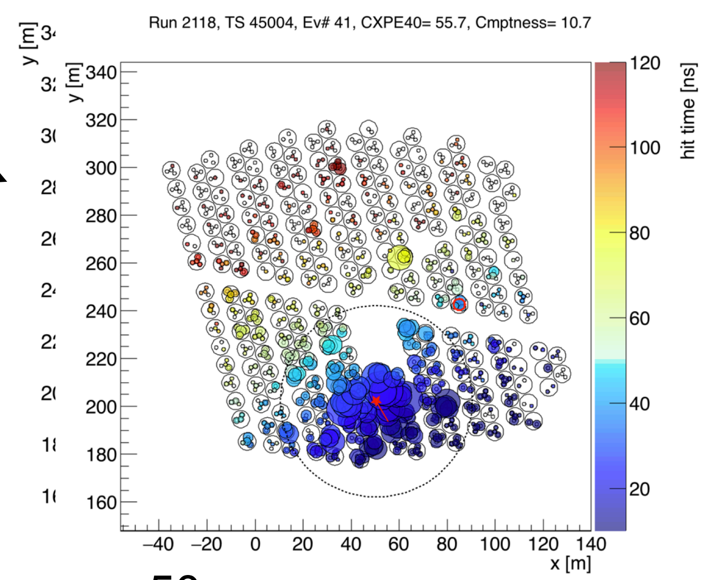


>99.9% rejection
for large showers

Likely gamma shower

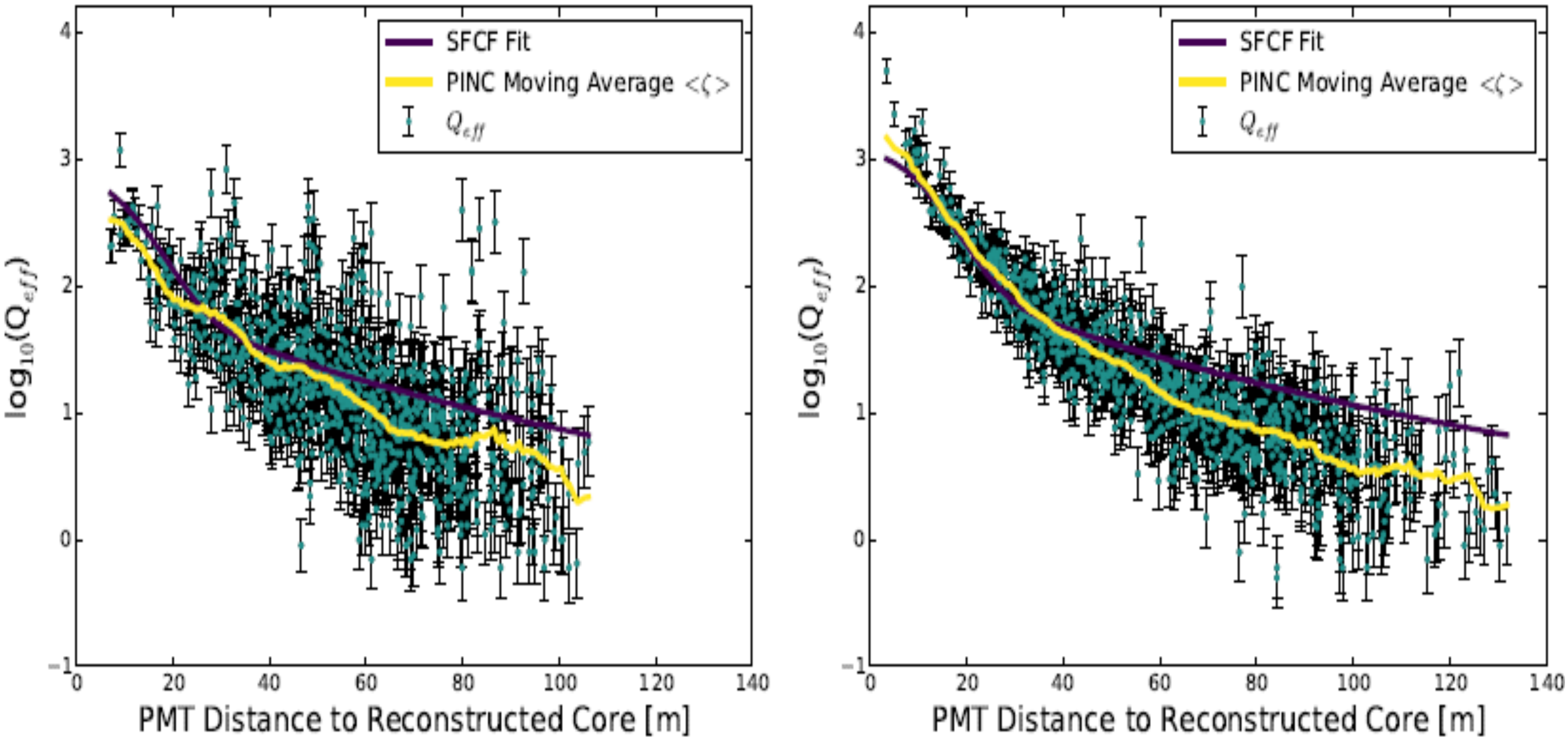


Likely hadron shower



Albert et al, 2017

γ/h separation



Lateral distribution functions of an obvious cosmic ray (left) and a photon candidate from the Crab Nebula (right).The cosmic ray has isolated high-charge hits far from the shower core due to penetrating particles in the hadronic air shower. These features are absent in the gamma-ray shower.

Cuts used in analysis

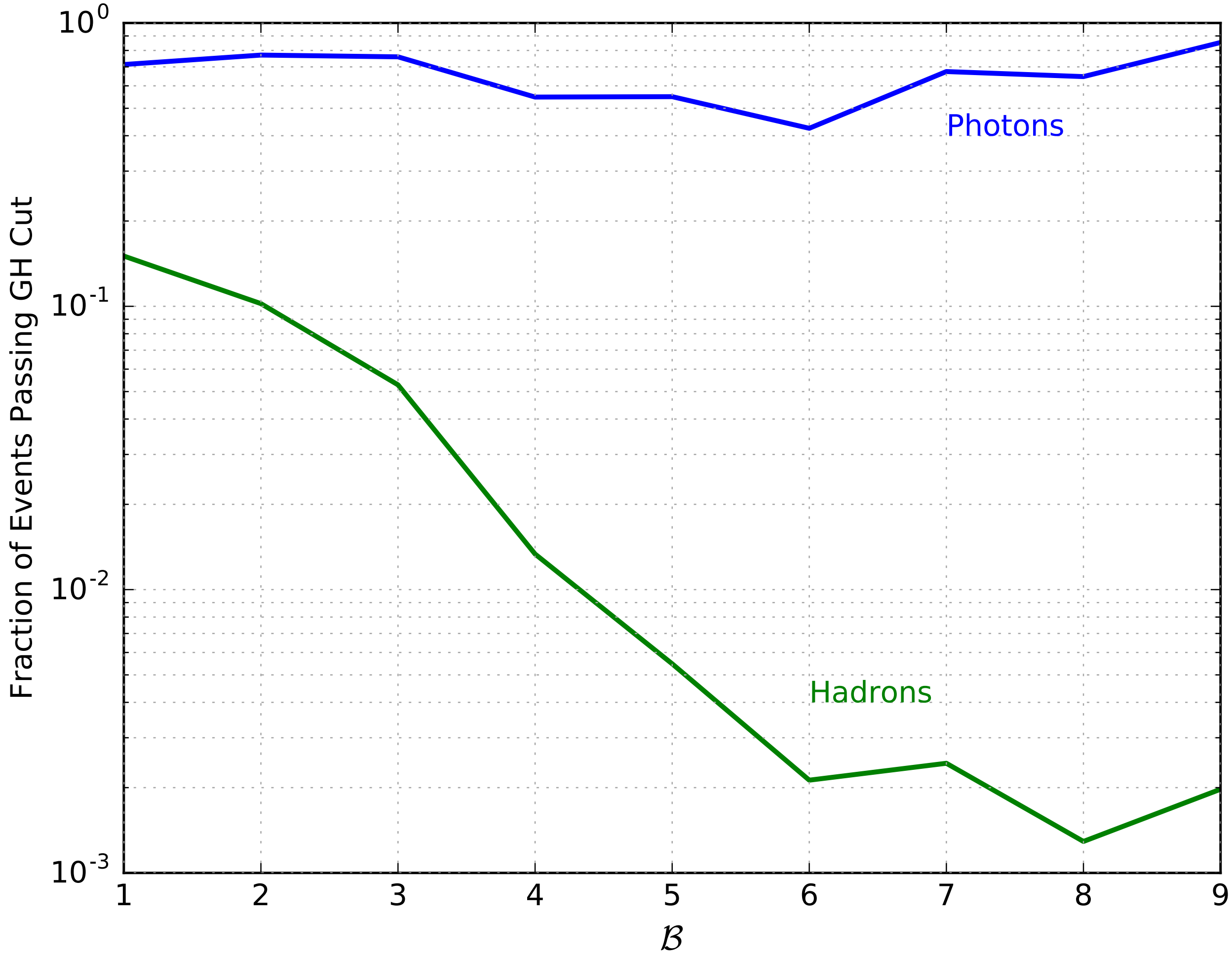
$\mathcal{B}$	f_{hit}	ψ_{68}	$\mathcal{P}$ Maximum	$\mathcal{C}$ Minimum	Crab Excess Per Transit
1	6.7 - 10.5%	1.03	<2.2	>7.0	68.4 ± 5.0
2	10.5 - 16.2%	0.69	3.0	9.0	51.7 ± 1.9
3	16.2 - 24.7%	0.50	2.3	11.0	27.9 ± 0.8
4	24.7 - 35.6%	0.39	1.9	15.0	10.58 ± 0.26
5	35.6 - 48.5%	0.30	1.9	18.0	4.62 ± 0.13
6	48.5 - 61.8%	0.28	1.7	17.0	1.783 ± 0.072
7	61.8 - 74.0%	0.22	1.8	15.0	1.024 ± 0.053
8	74.0 - 84.0%	0.20	1.8	15.0	0.433 ± 0.033
9	84.0 - 100.0%	0.17	1.6	3.0	0.407 ± 0.032

The cuts are chosen to maximize the statistical significance with which the Crab is detected in the first 337 days of the 507-day dataset, leaving the resting days to obtain the Crab spectra without optimisation. The two spectra differ by 10%, assumed as one of the systematics.

Albert et al, 2017

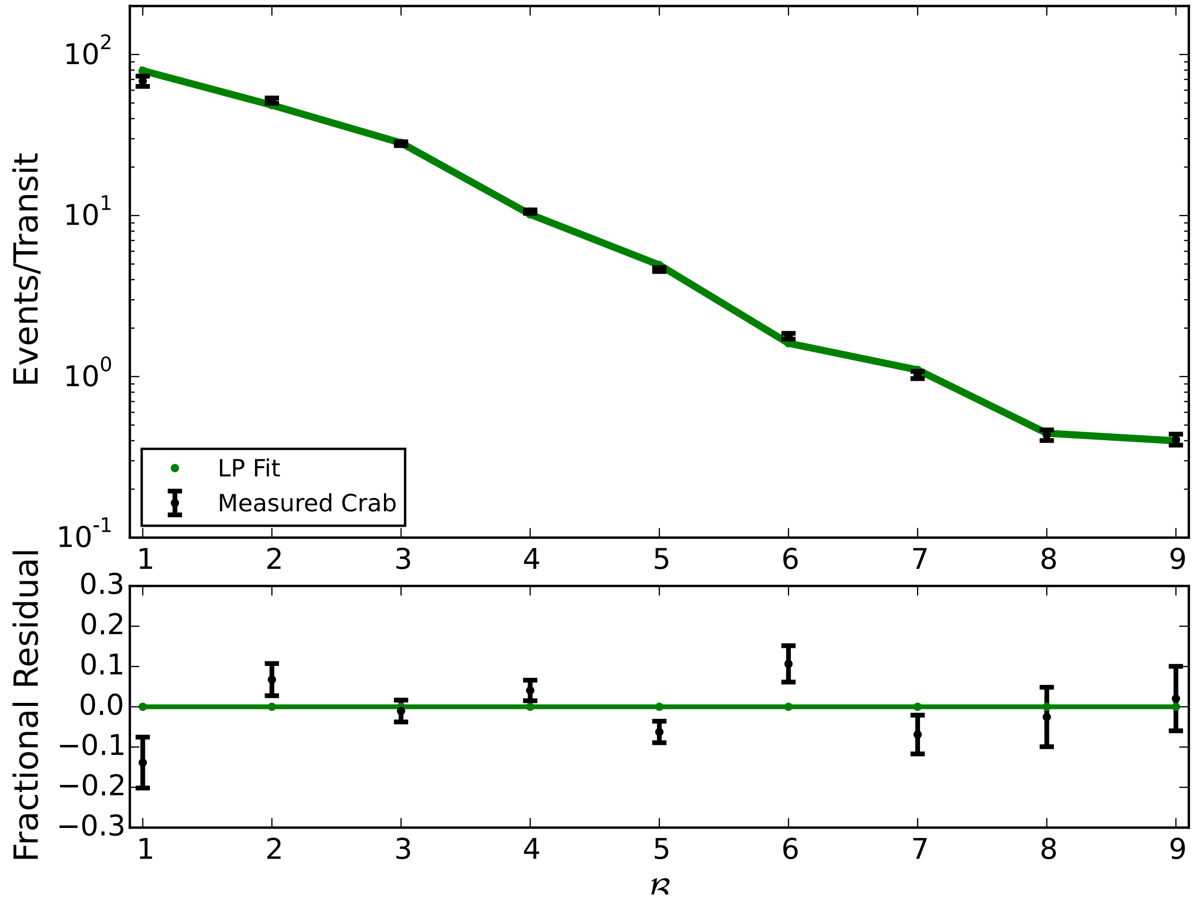
Cut Efficiency

Albert et al, 2017



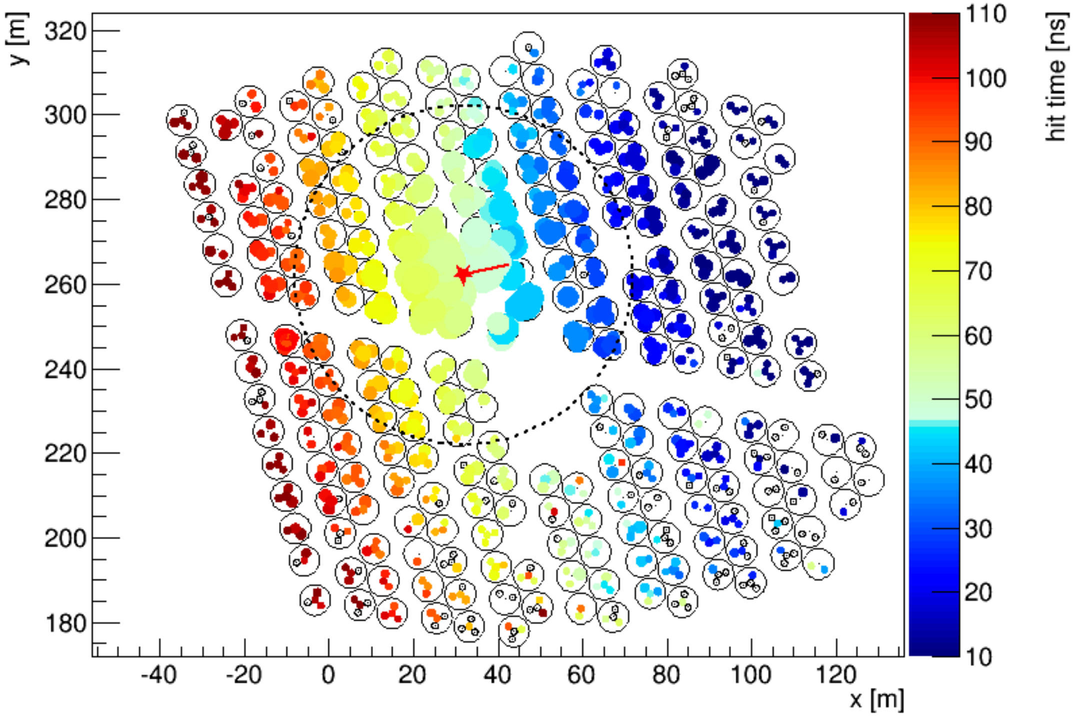
The figure shows the fraction of gamma rays and background hadron events passing photon/hadron discrimination cuts as a function of the event size, $\mathcal{B}$. Good efficiency for photons is maintained across all event sizes with hadron efficiency approaching 1×10^{-3} for high-energy events.

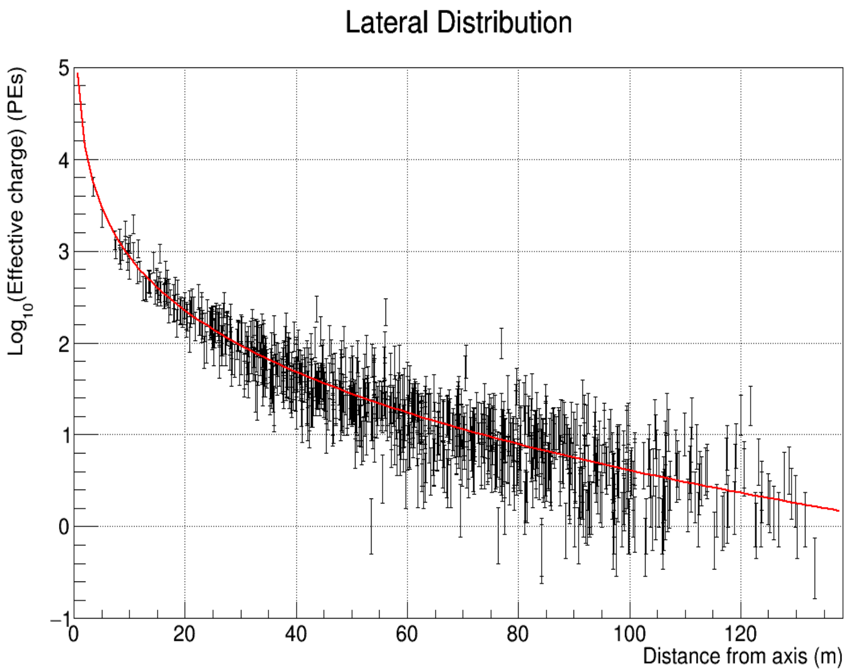
Number of photons from Crab



The figure shows the measured, background-subtracted number of photons from the Crab in each B bin. To get the total number of photons, the signal from the Crab is fit for each B separately. The measurements are compared to prediction from simulation assuming the Crab spectrum is at the HAWC measurement. The fitted spectrum is a good description of the data, with no evidence of bias in the residuals.

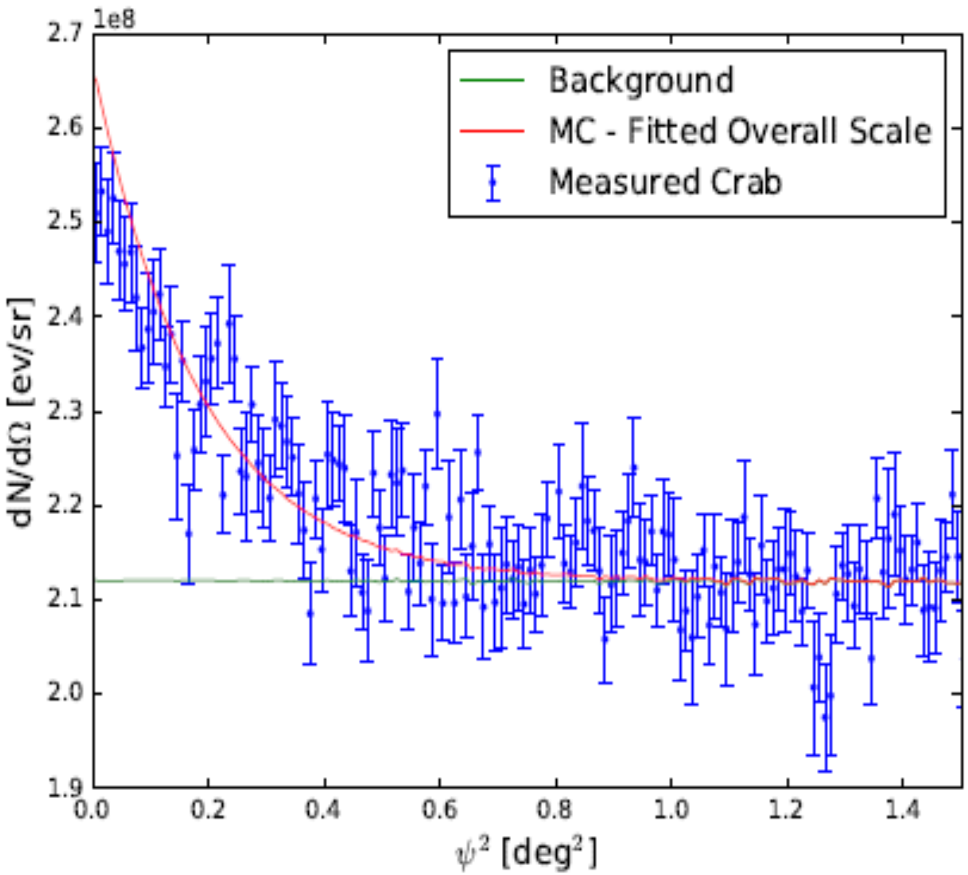
Crab gamma-ray candidate



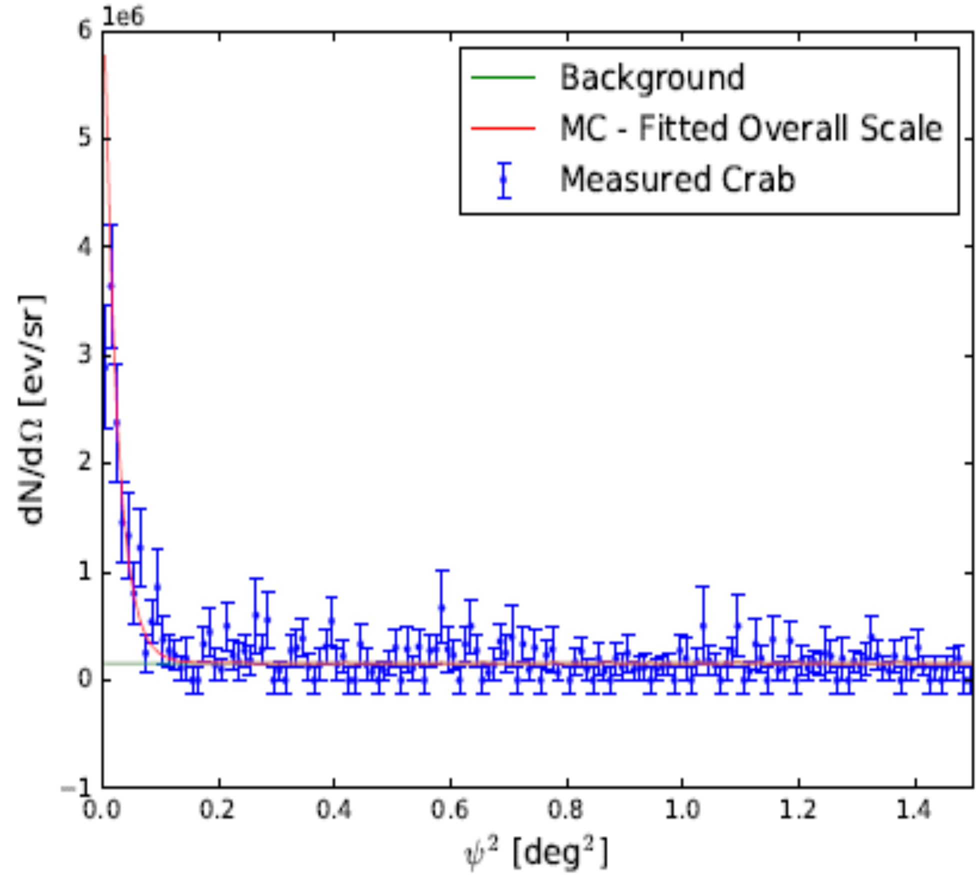


- Event reconstructed within 0.4° of the Crab Nebula.

Angular Resolution

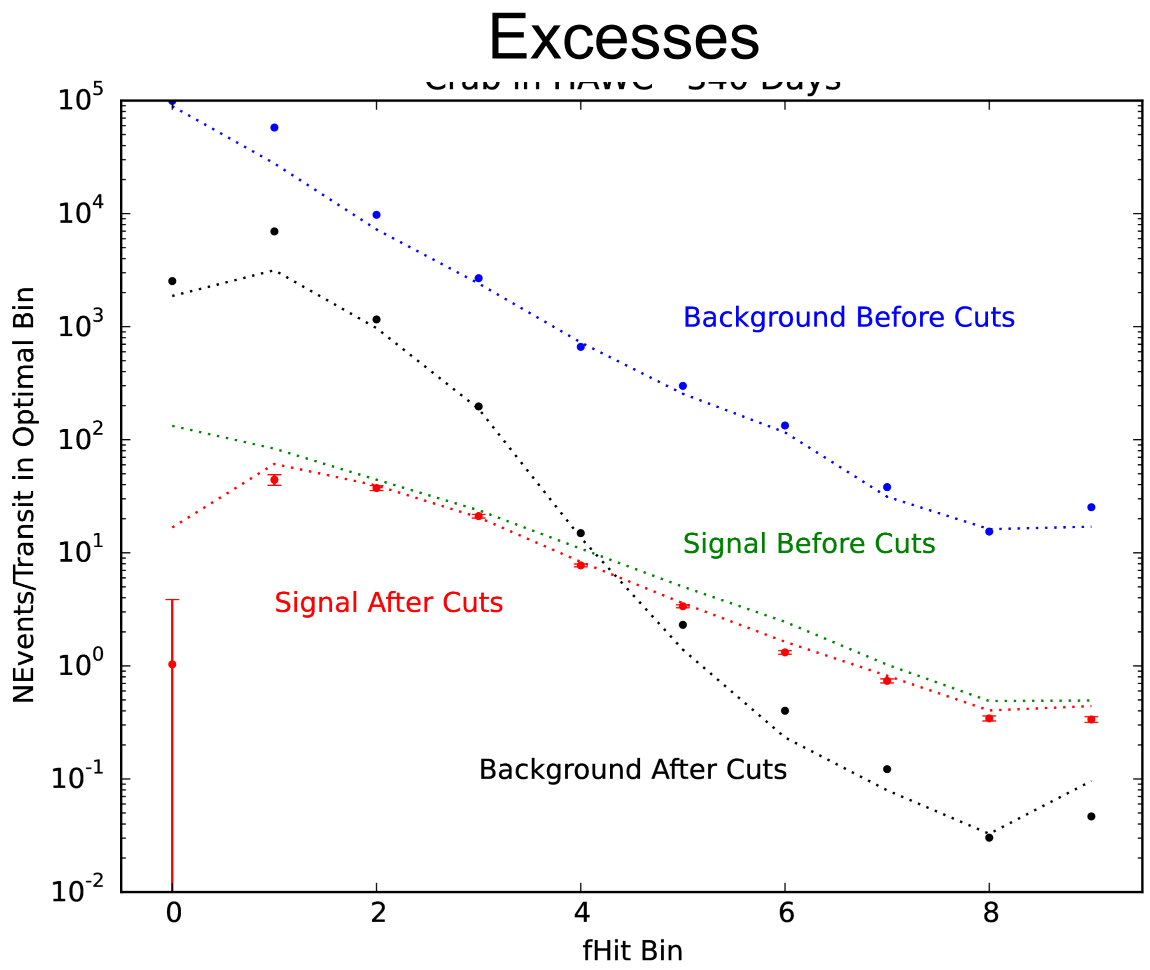


(c) $\mathcal{B} = 3$ Angular Profile



(d) $\mathcal{B} = 8$ Angular Profile

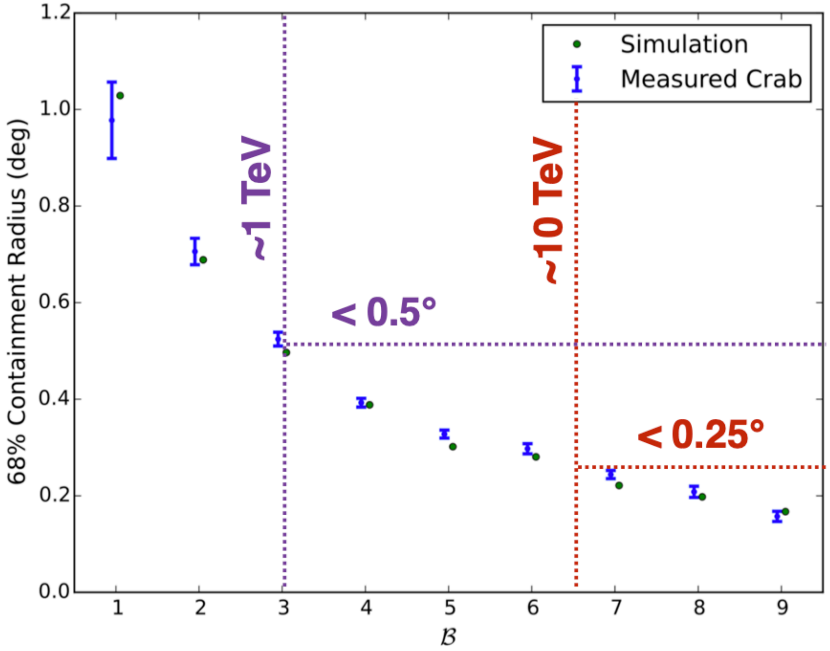
Signal and background before and after cuts



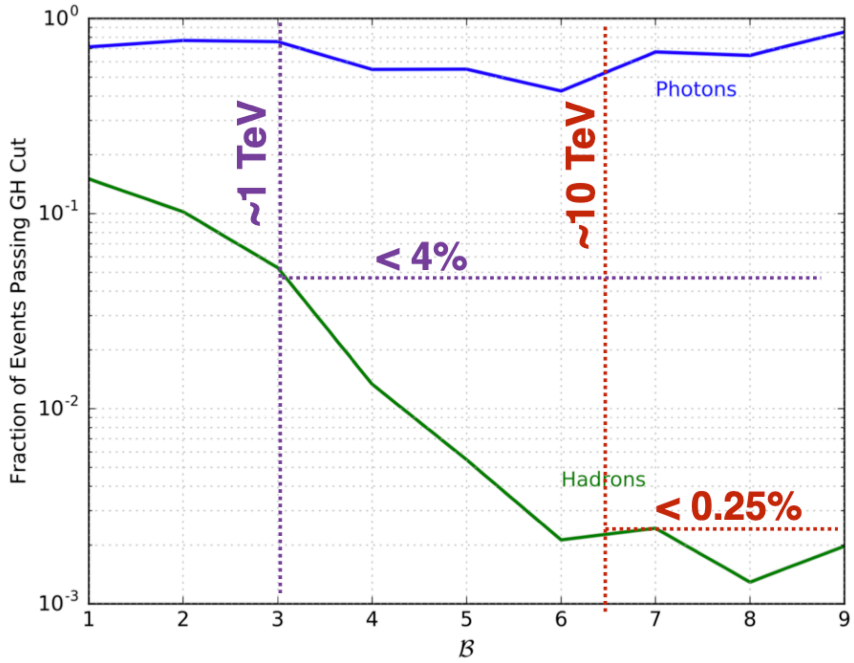
σ = signal/sqrt(background) on Crab per transit: 5-7 integrated over all energy bins.
In 1128 days we have 162 σ, which roughly scales with square root of time and gives 5 σ/day

Summary on reconstruction

Angular resolution



Gamma / Hadron - Cut efficiency



A. U. Abeysekara, *et al*, *ApJ*, **843**, 2017 / `arXiv:1701.01778`