Recent HAWC results and future developments

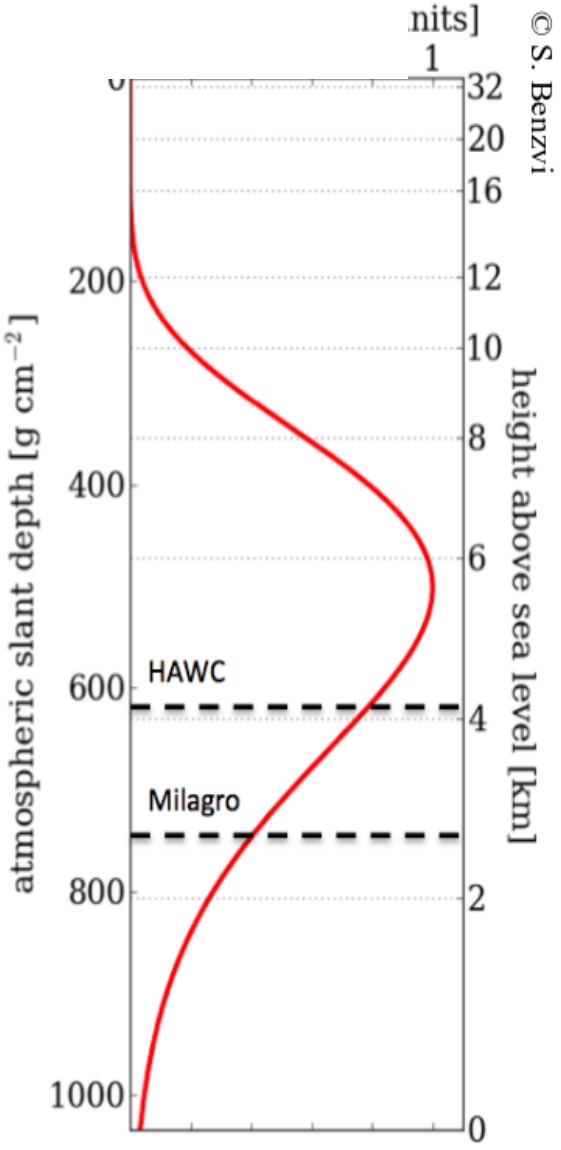
Gamma Ray Astrophysics with CTA
Sexten, July 24th-28th 2017

Sabrina Casanova, IFJ-PAN & MPIK

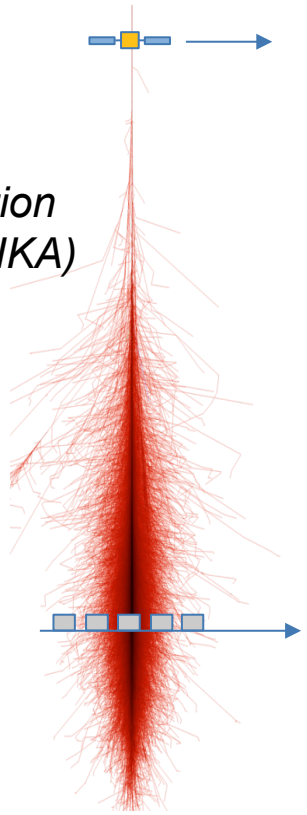
Outline

- The HAWC detector
- The sky seen by HAWC
  - 2HWC Catalog
  - Extended regions (Fermi bubbles, Cygnus Region, Geminga)
  - The Galaxy above 50 TeV
  - Search for extragalactic transients
- Future Developments
  - Outtriggers
  - Beyond HAWC : High sensitivity EAS array in the CTA era

High Energy Gamma-Ray Detectors



Simulation (CORSIKA)



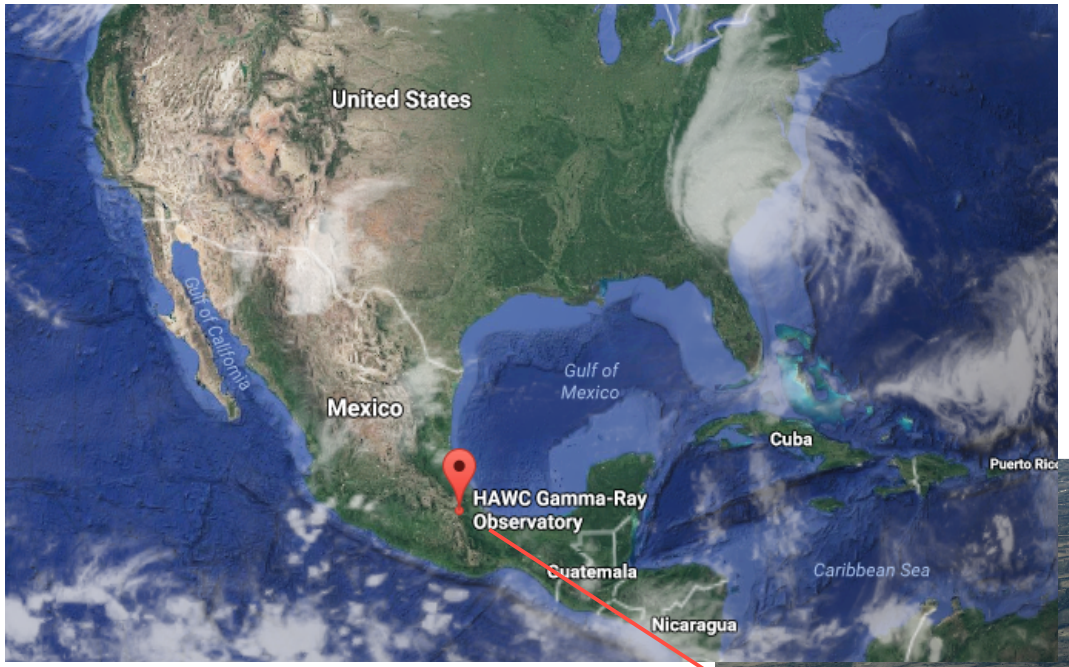
Satellite Detector

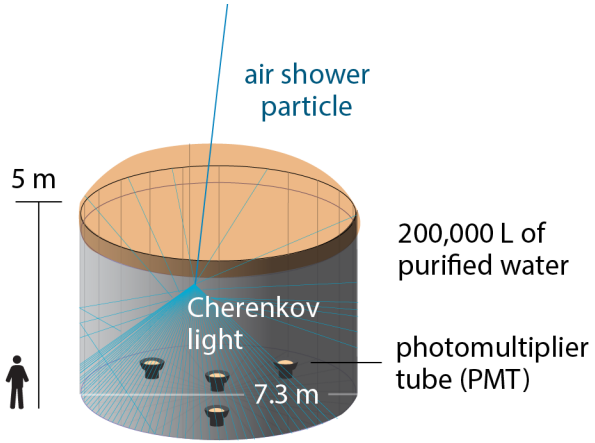
Extensive Air Shower (EAS) Detector

Imaging Atmospheric Cherenkov Telescope (IACT)

The HAWC Detector

- Site: Sierra Negra, Mexico, 19°N, 4,100 m altitude.
- **Instantaneous FOV 2sr. Daily 8sr (66% of the sky).**
- **Duty cycle >90%.**
- 300 WCDs covering 22,000m^2 area.
- Inaugurated **March 2015**.





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.

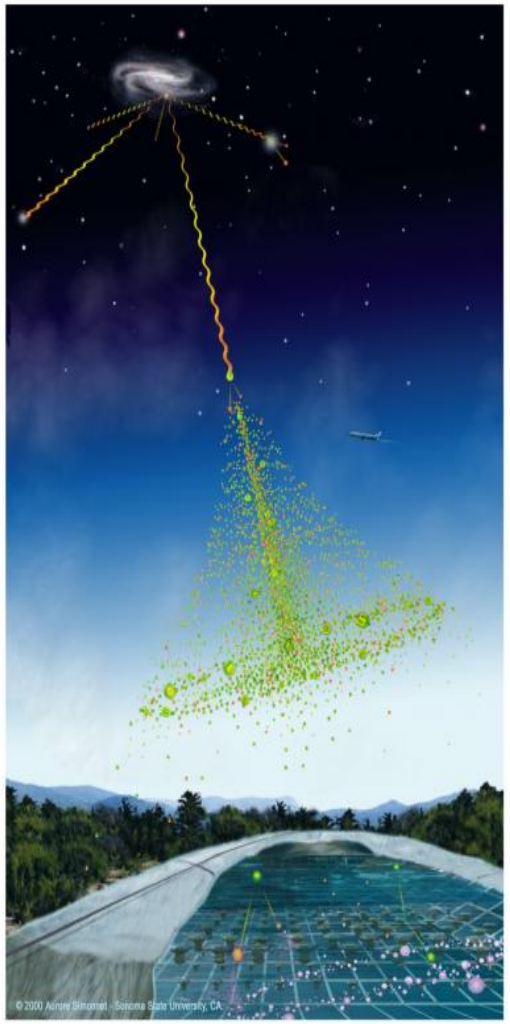
Steel frame construction

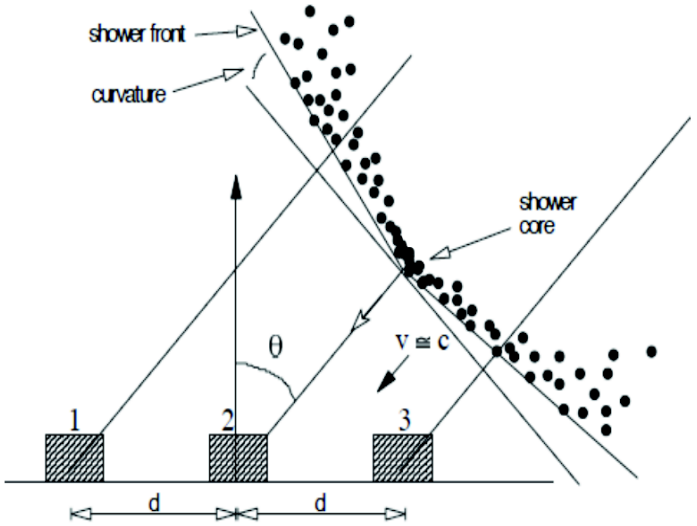
Large plastic bag container

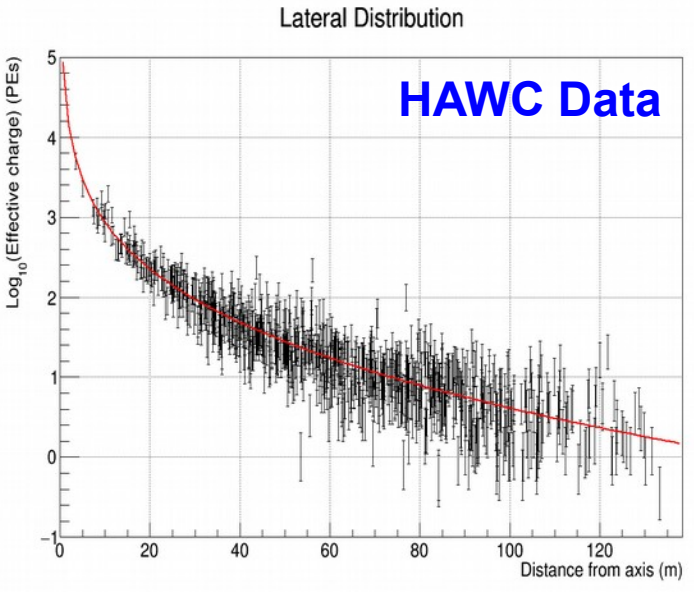
Water trucks filling the tanks

8-inch 10-inch PMTs

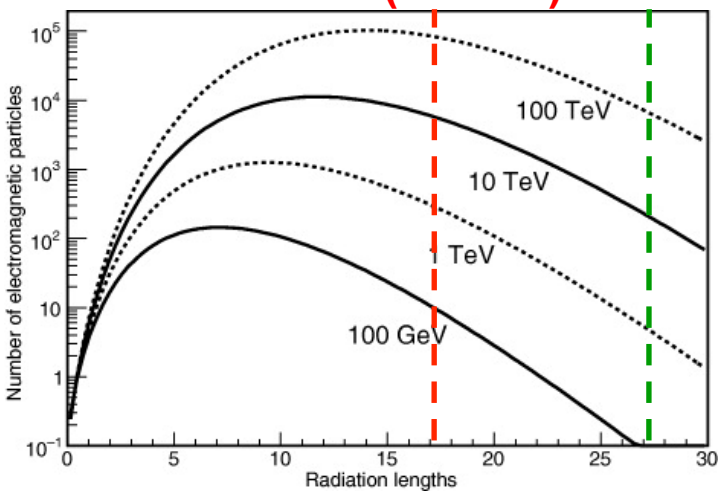
Detection Technique







HAWC (4100m) Sea level

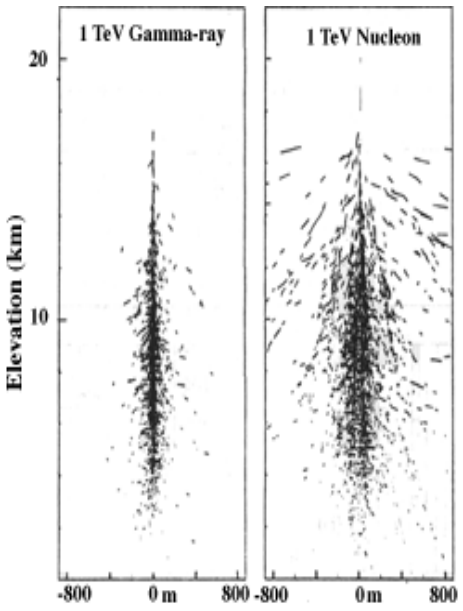


- The particle detectors are tanks full of water. Particles from the shower pass through the water and induce Cherenkov light detected by PMTs.
- High altitude means closer to the shower maximum.

Gamma-Hadron Separation

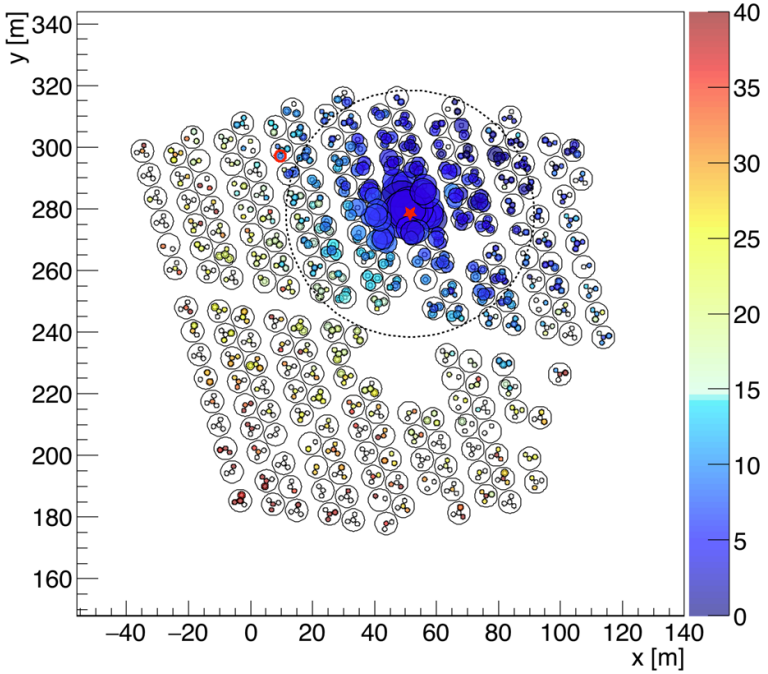
Simulation

Gamma **Hadron**



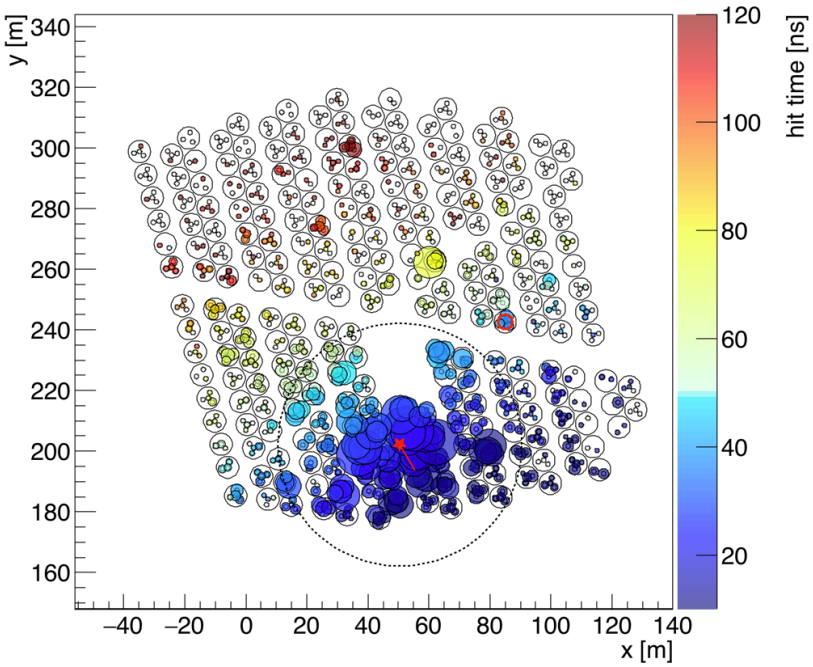
HAWC Data

Likely Gamma Ray



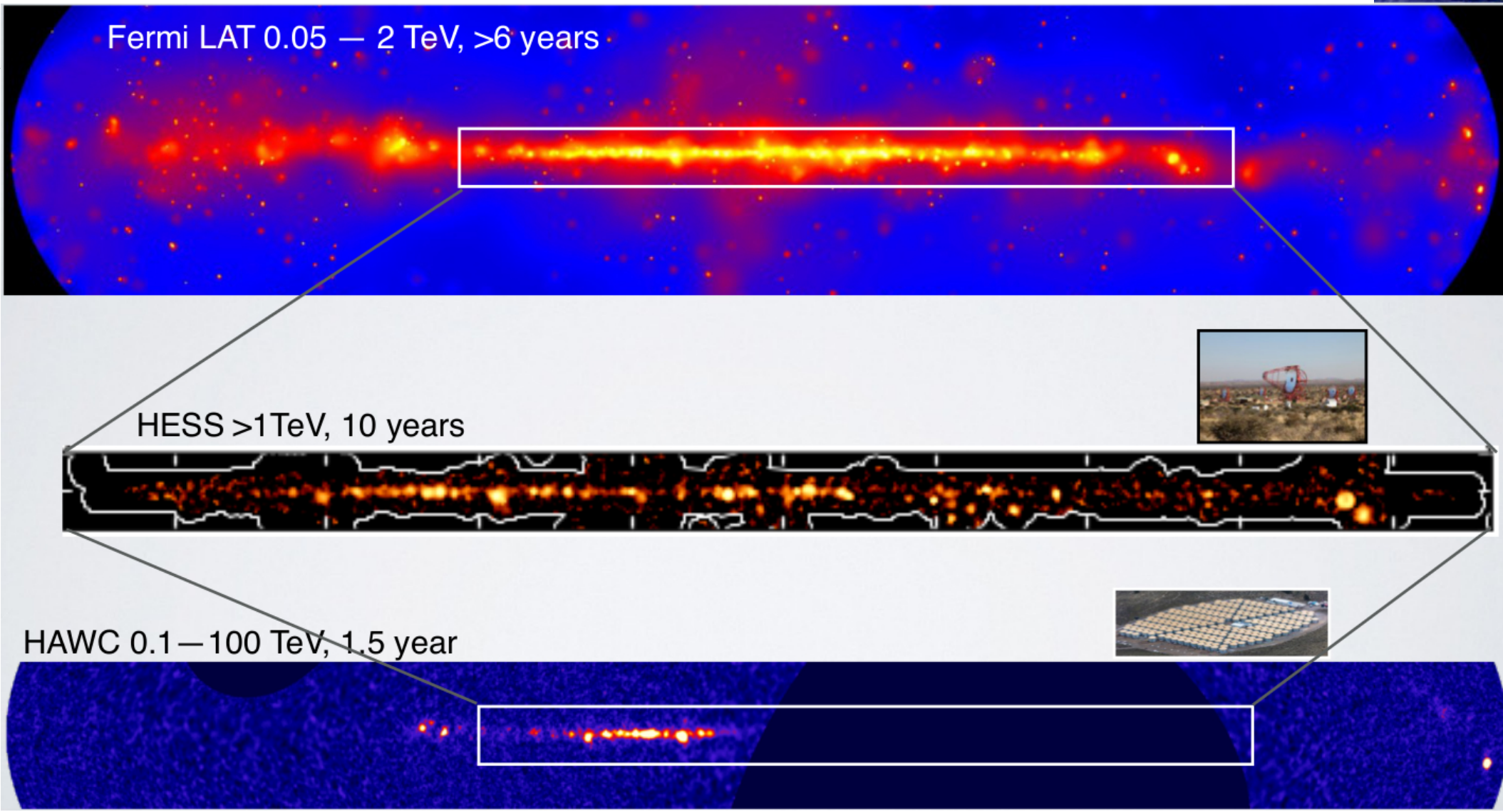
HAWC Data

Hadron Shower

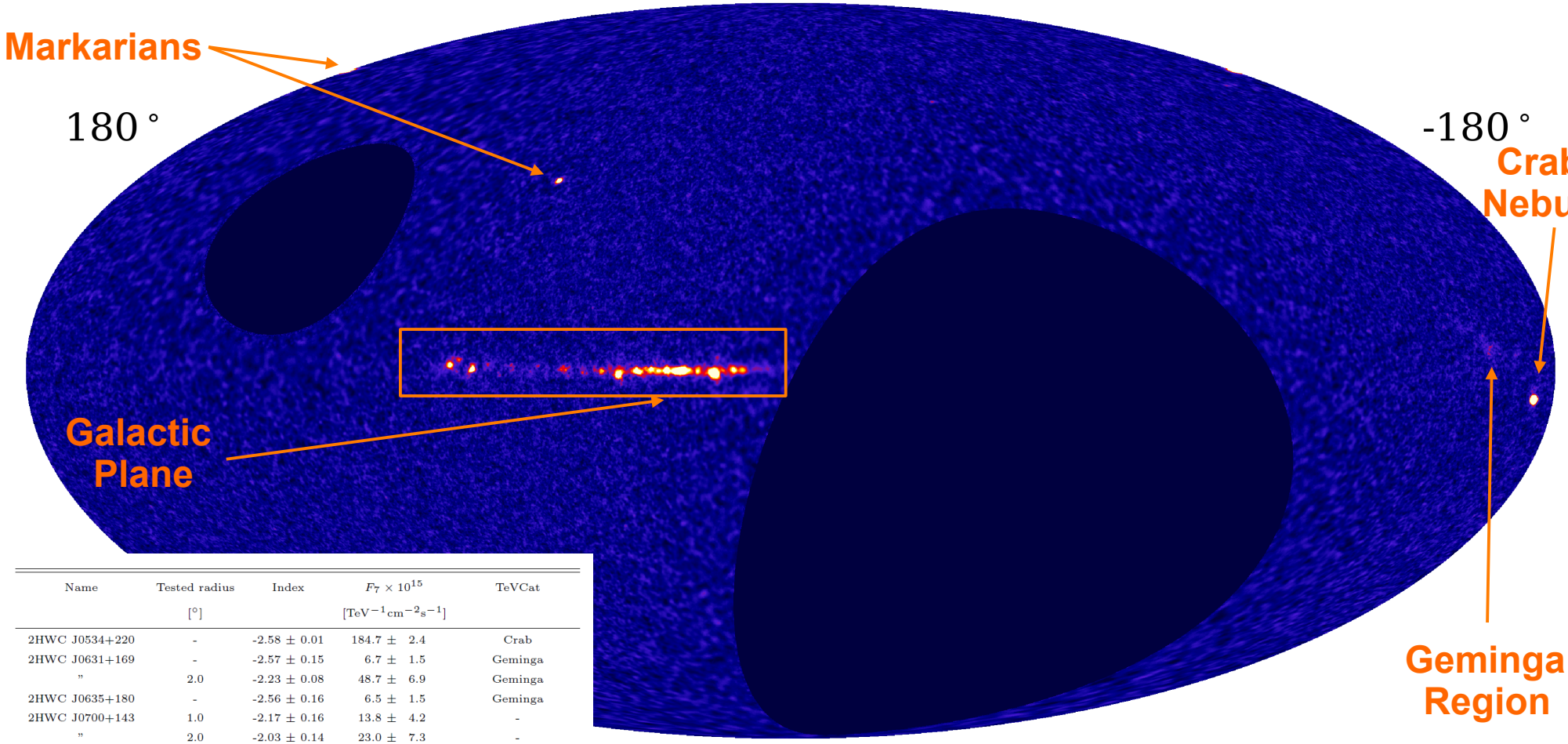


- Main background is hadronic CR, e.g. 400 γ/day from the Crab vs 15k CR/s.
- Gamma/hadron can be discriminated based on the event footprint on the detector: gamma-ray showers are more compact, cosmic rays showers tend to "break apart".

The gamma-ray Galactic Plane



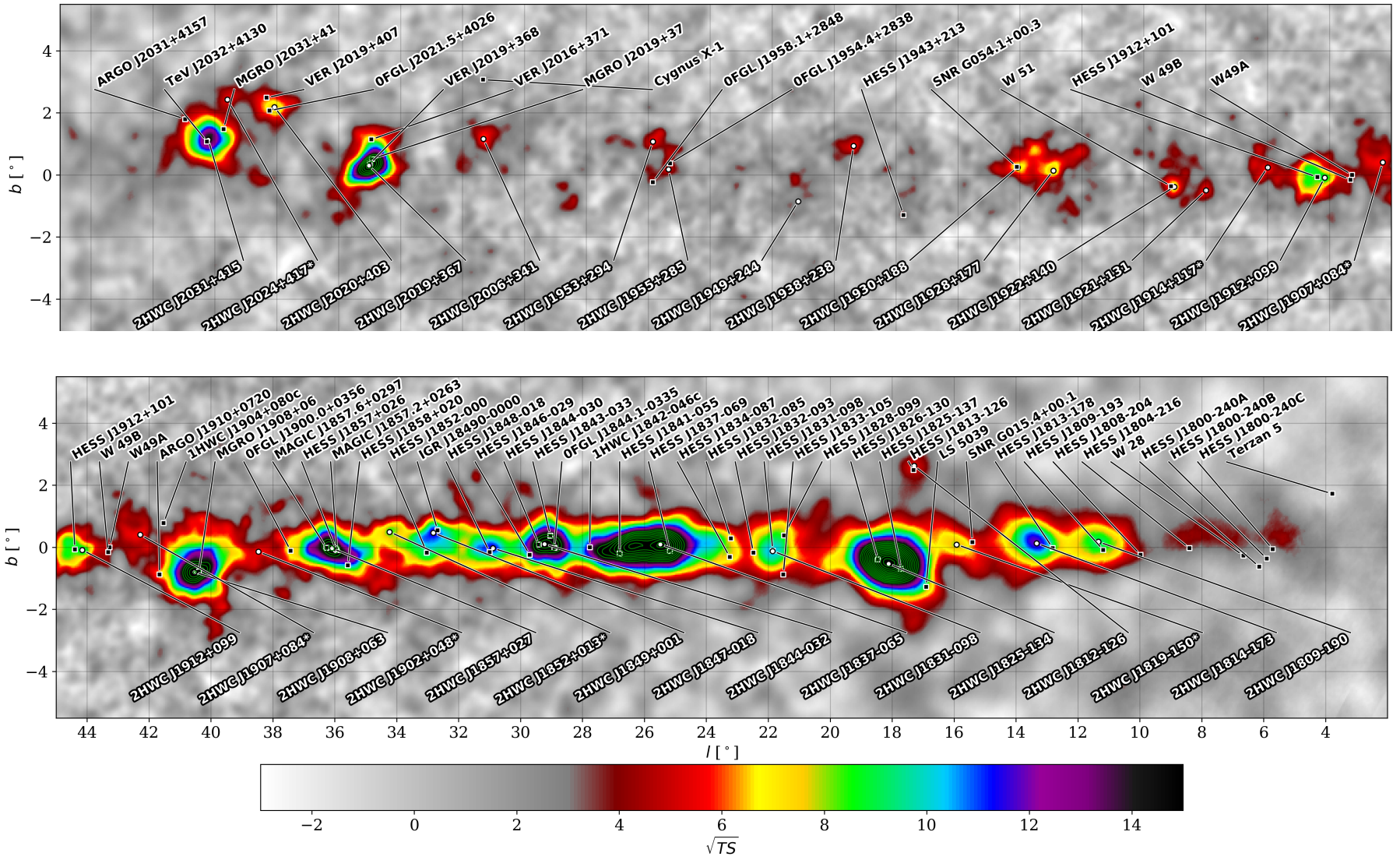
2th HAWC Catalog



Name	Tested radius [°]	Index	$F_7 \times 10^{15}$ [TeV^{-1}cm^{-2}s^{-1}]	TeVCat
2HWC J0534+220	-	-2.58 ± 0.01	184.7 ± 2.4	Crab
2HWC J0631+169	-	-2.57 ± 0.15	6.7 ± 1.5	Geminga
”	2.0	-2.23 ± 0.08	48.7 ± 6.9	Geminga
2HWC J0635+180	-	-2.56 ± 0.16	6.5 ± 1.5	Geminga
2HWC J0700+143	1.0	-2.17 ± 0.16	13.8 ± 4.2	-
”	2.0	-2.03 ± 0.14	23.0 ± 7.3	-
2HWC J0819+157	0.5	-1.50 ± 0.67	1.6 ± 3.1	-
2HWC J1040+308	0.5	-2.08 ± 0.25	6.6 ± 3.5	-
2HWC J1104+381	-	-3.04 ± 0.03	70.8 ± 2.9	Markarian 421
2HWC J1309-054	-	-2.55 ± 0.18	12.3 ± 3.5	-
2HWC J1653+397	-	-2.86 ± 0.04	56.5 ± 2.7	Markarian 501
2HWC J1809-190	-	-2.61 ± 0.11	80.9 ± 15.1	HESS J1809-193
2HWC J1812-126	-	-2.84 ± 0.16	27.4 ± 5.7	HESS J1813-126
2HWC J1814-173	-	-2.61 ± 0.09	88.4 ± 13.0	HESS J1813-178
”	1.0	-2.55 ± 0.07	151.6 ± 18.8	HESS J1813-178
2HWC J1819-150*	-	-2.88 ± 0.10	59.0 ± 7.9	SNR G015.4+00.1
2HWC J1825-134	-	-2.58 ± 0.04	138.0 ± 8.1	HESS J1826-130
”	0.9	-2.56 ± 0.03	249.2 ± 11.4	HESS J1826-130
2HWC J1829+070	-	-2.69 ± 0.17	8.1 ± 1.7	-
2HWC J1831-098	-	-2.80 ± 0.09	44.2 ± 4.7	HESS J1831-098

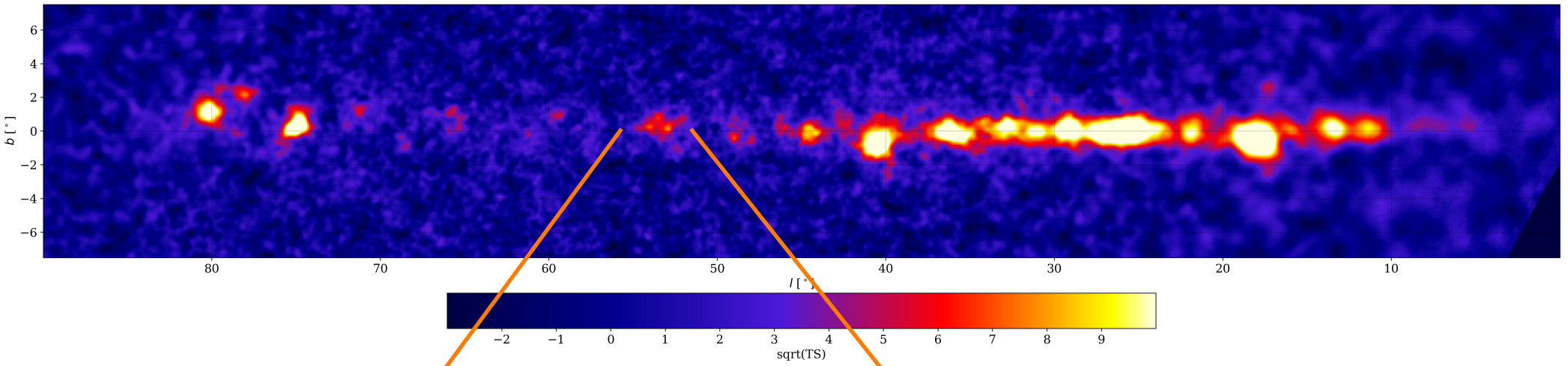
Abeysekara et al, ApJ, 2017

2nd HAWC Catalog



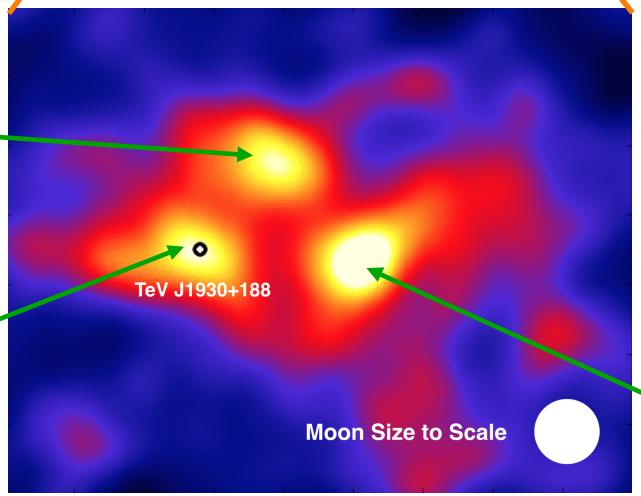
40 sources of which ¼ are new

The Galactic Plane seen by HAWC



Candidate source:
Association unclear

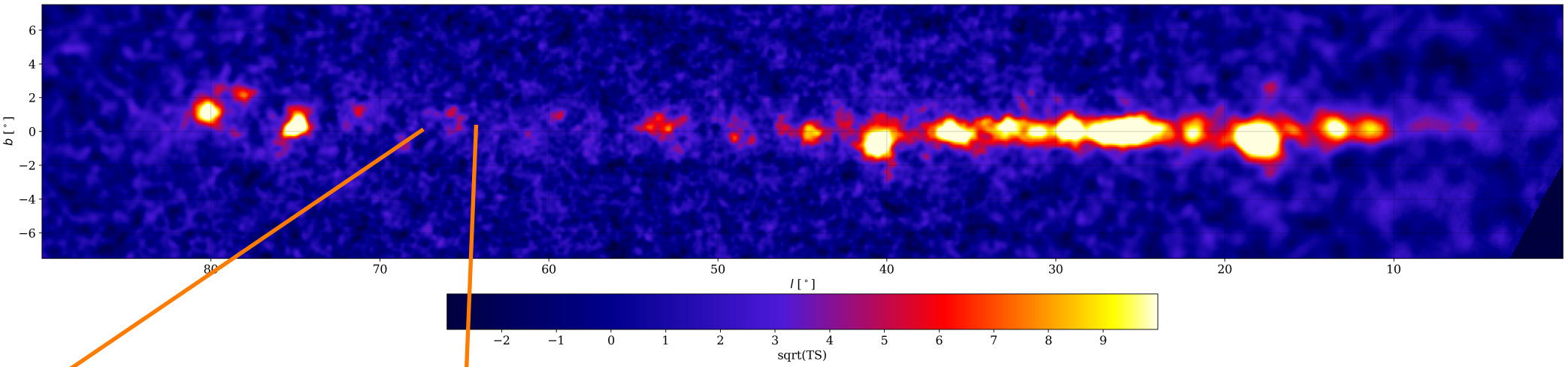
Supernova remnant with very energetic pulsar

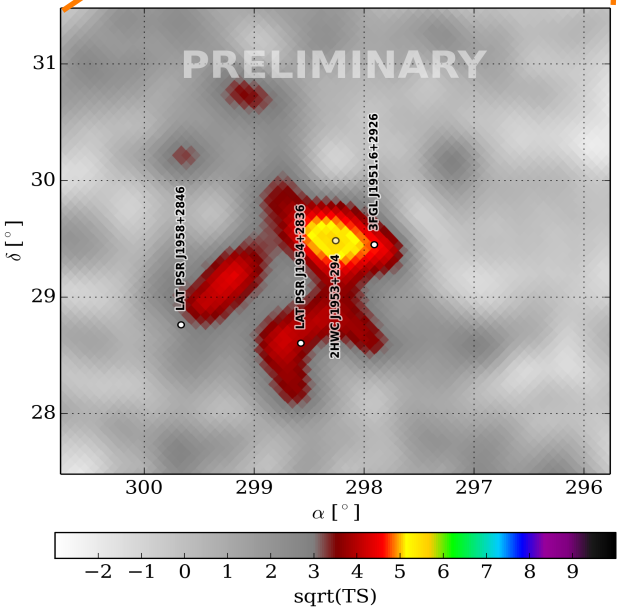


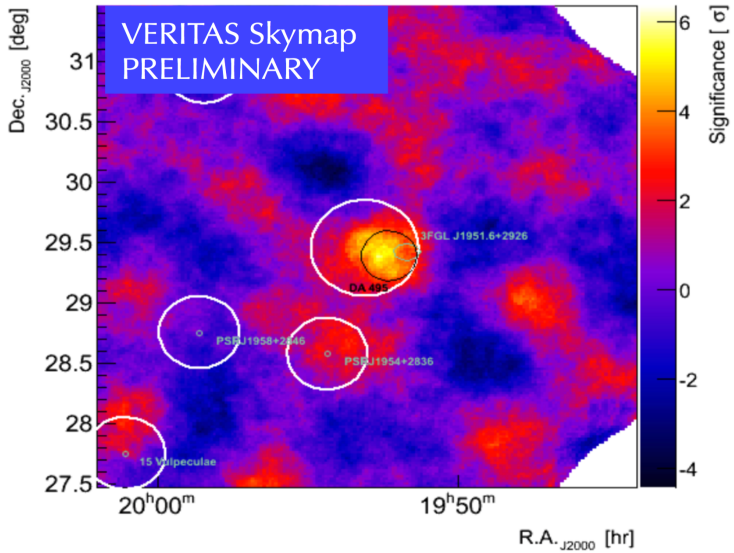
- Preliminary catalog was shared with MoU partners.
- Various sources coincident with TeVCat.
- Several w/o counterpart.

New source: Pulsar ~8kpc away

New Source Confirmed







No previously known TeV source.

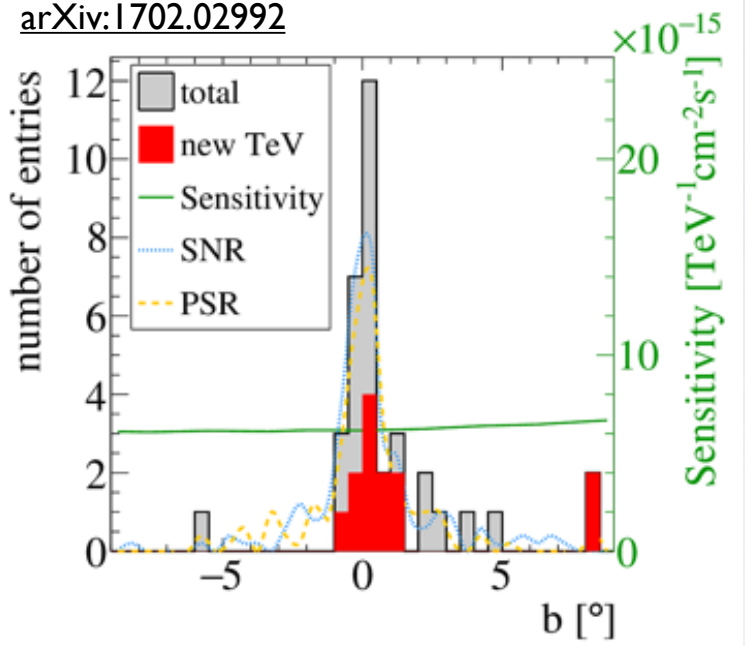
New analysis by VERITAS, archival plus new data, **source confirmed**.

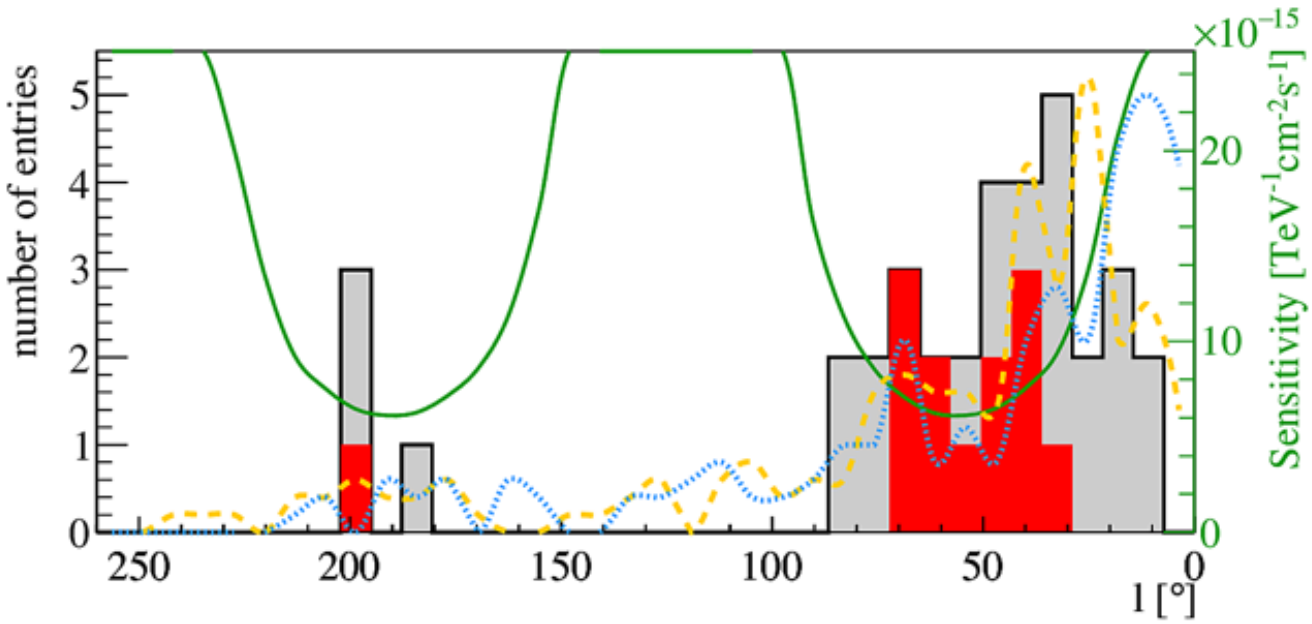
Tentative association

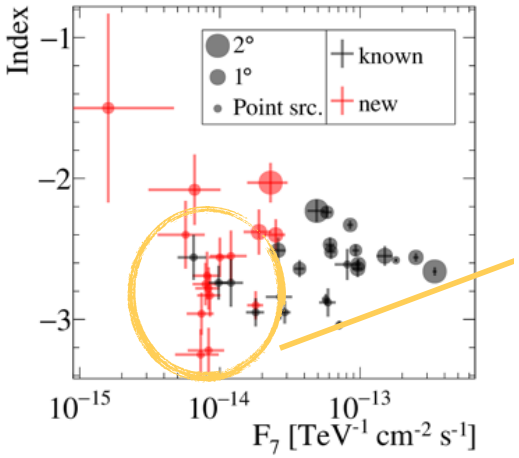
- 3FGL J1951.6+2926
- PWN DA 495 seen in X-rays

HAWC source distribution

arXiv:1702.02992





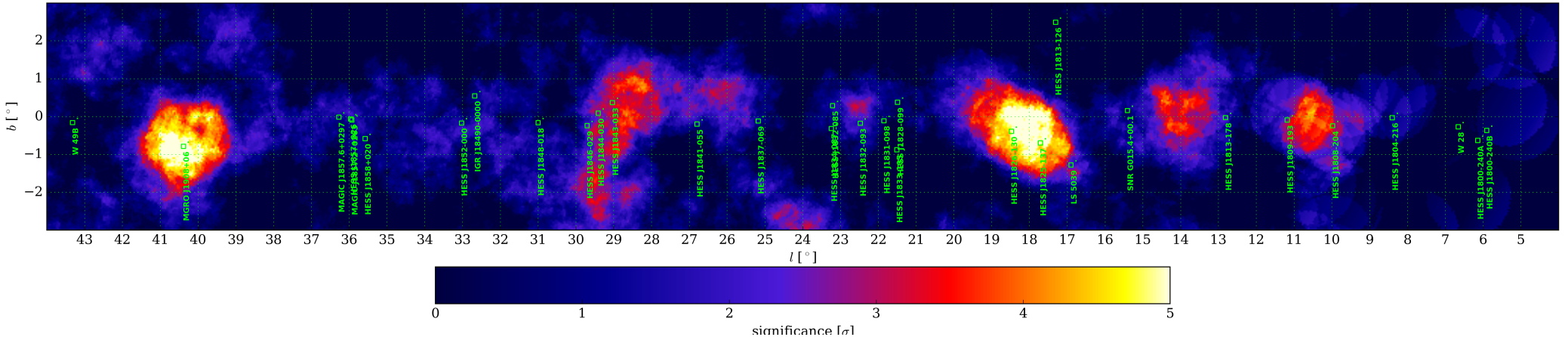


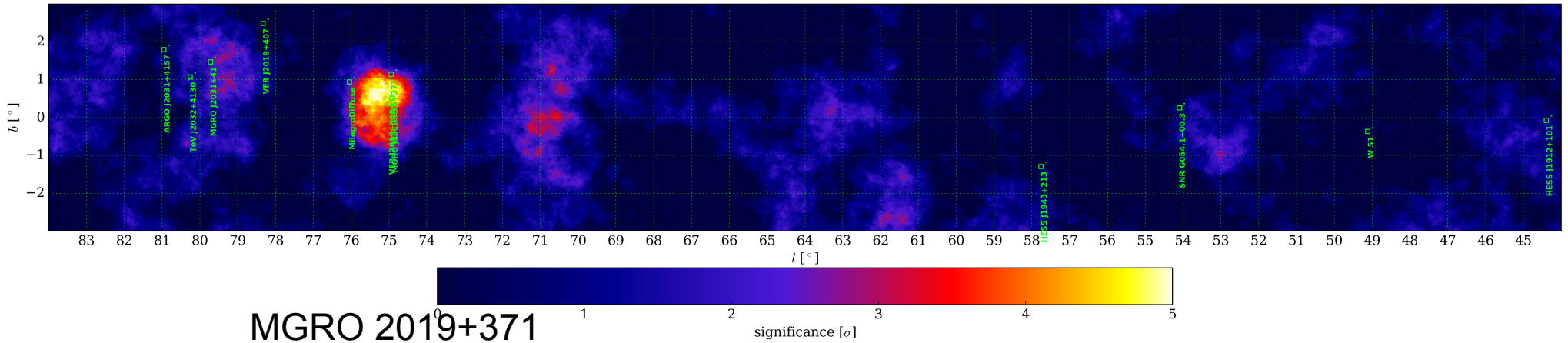
Good candidates for observations with
high resolution and high sensitive IACTs (MOUs)

HAWC sky above 50 TeV

MGRO 1908+06

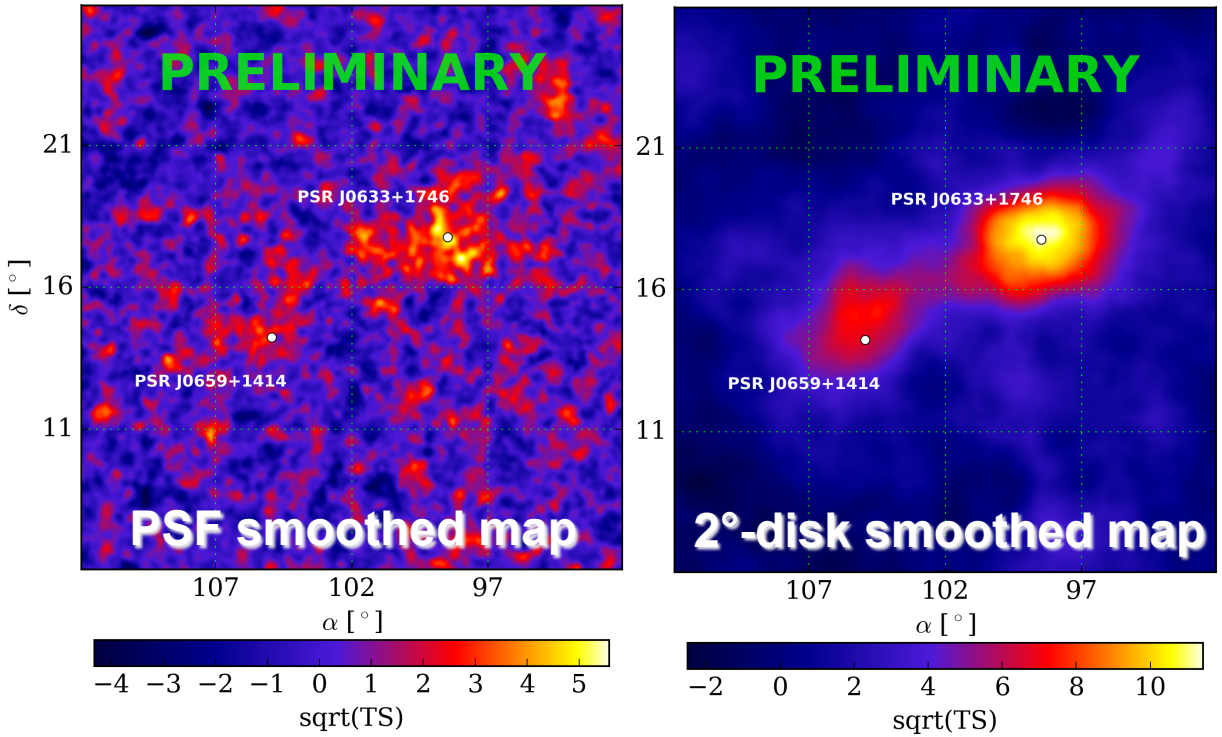
HESS J1825+137
HESS J1826-130

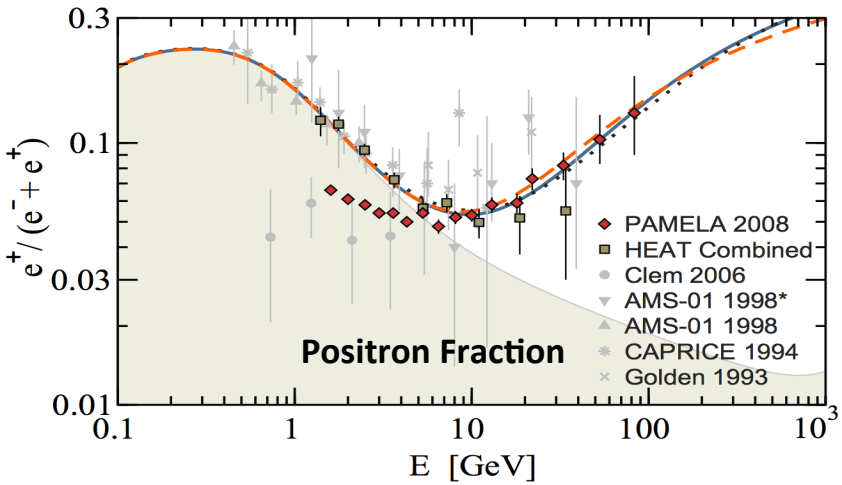




MGRO 2019+371

Geminga Region



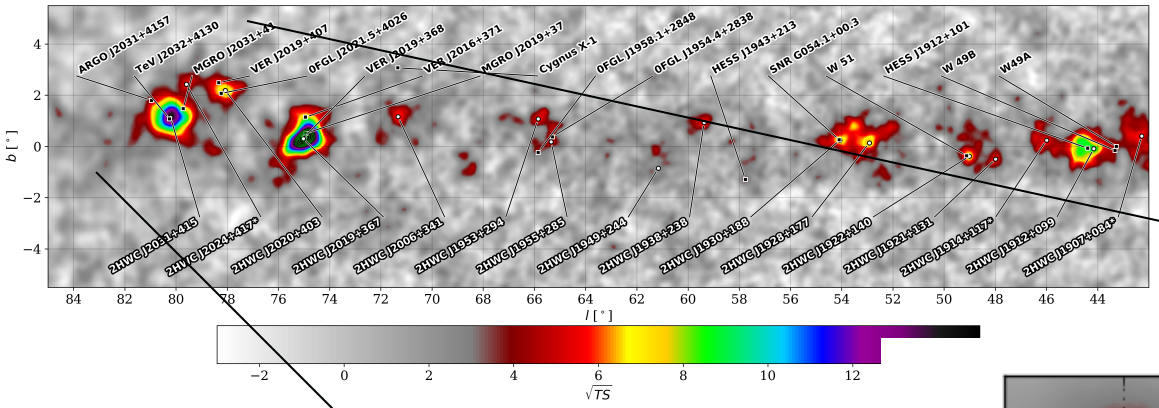


Aharonian+1995, Yuksel+2009

Paper submitted to Science!

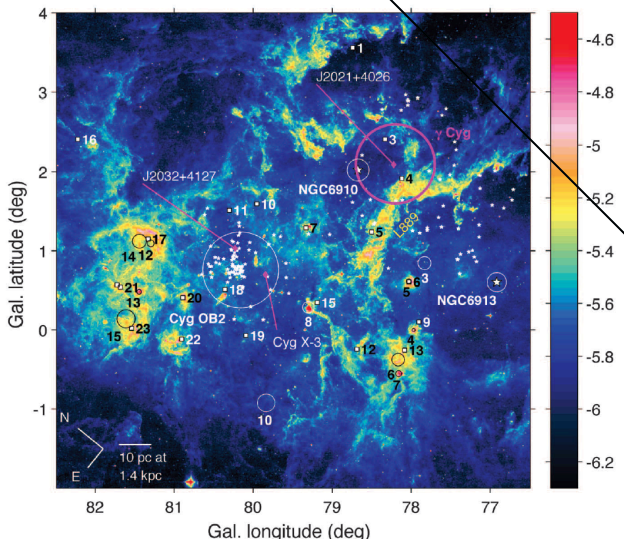
- Confirmation (~12σ pre-trial) of Geminga (PSR J0633+1746) by HAWC.
- Evidence (~7σ pre-trial) of a new extended source near PSR B0656+14.
- Both pulsars, similar in age and distance, were suggested as contributors of the positron fraction.
- **A very interesting region to be explored with the CTA small size telescopes.**

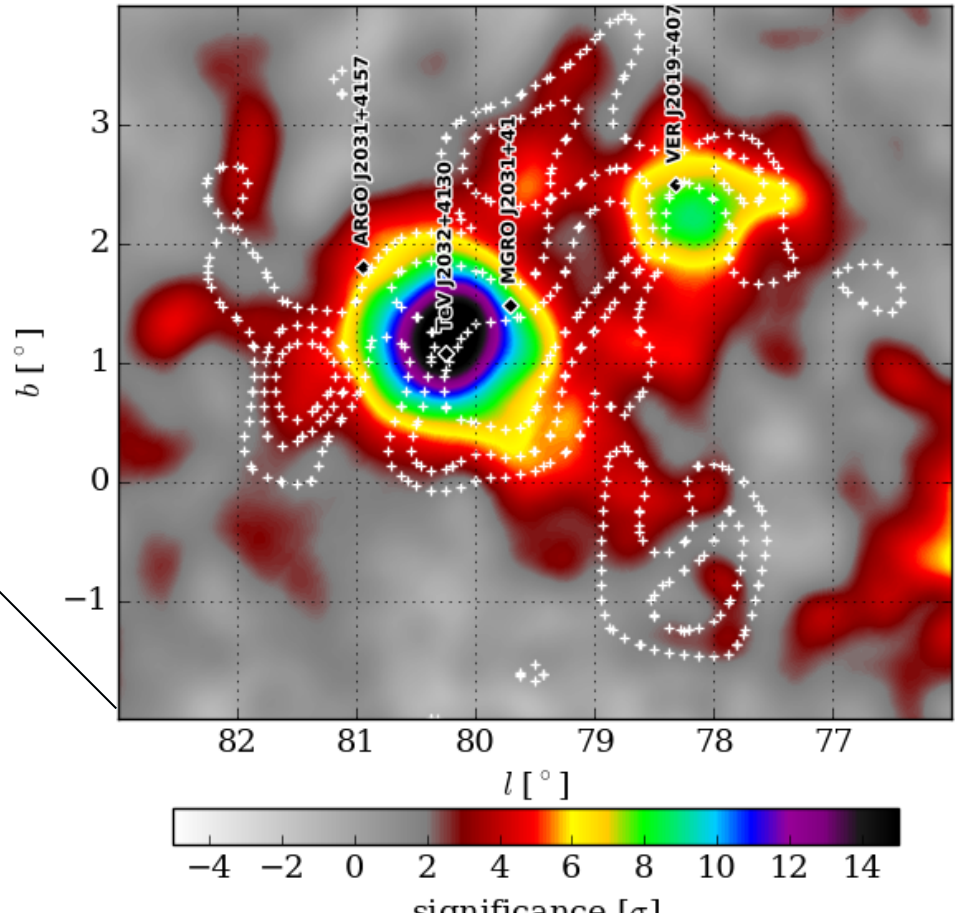
The Cygnus Cocoon Region



Fermi detected hard and extended emission from Cygnus X, between OB2 and Gamma Cygni SNR

Cocoon of freshly accelerated CRs





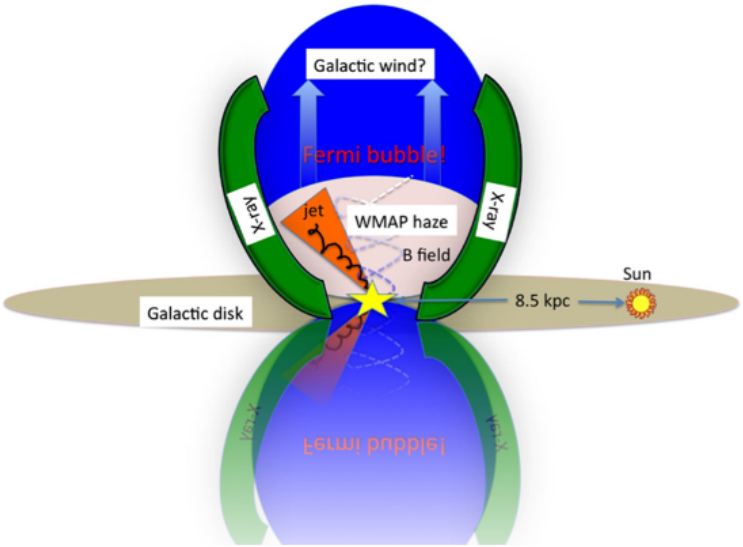
Fermi bubbles

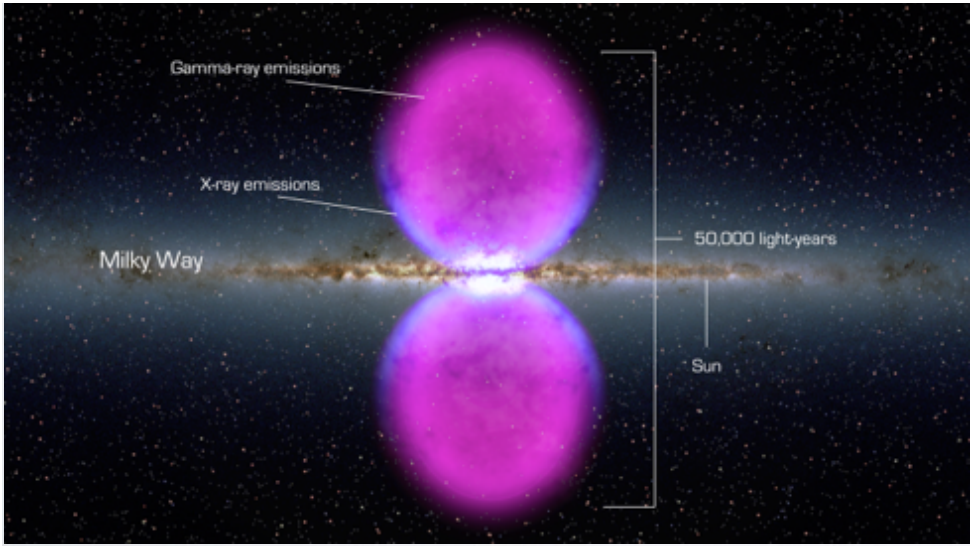
Large scale, non-uniform structures extending above and below the Galactic center.

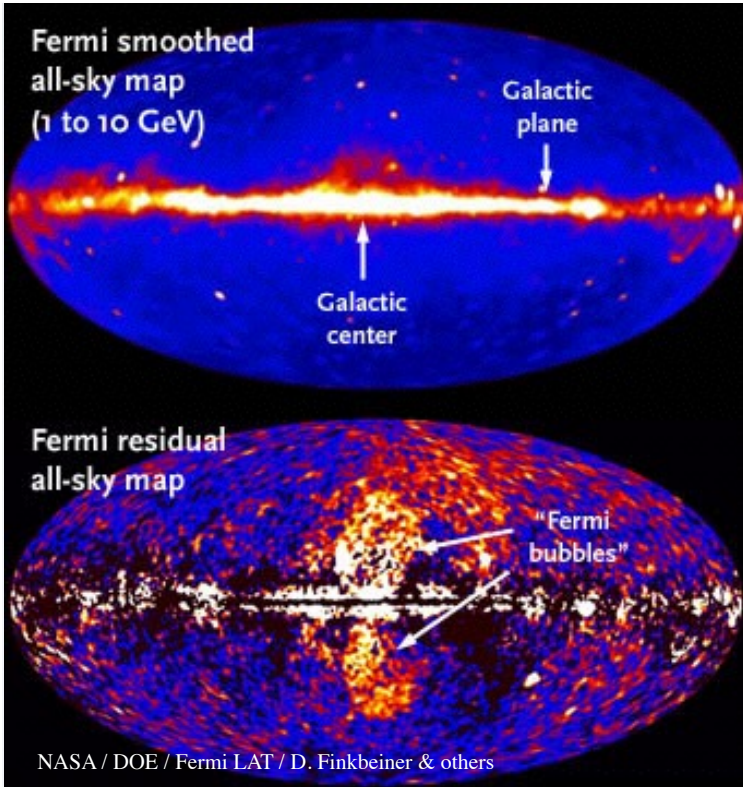
Edges line up with X-ray features.

Correlate with microwave excess (WMAP haze)

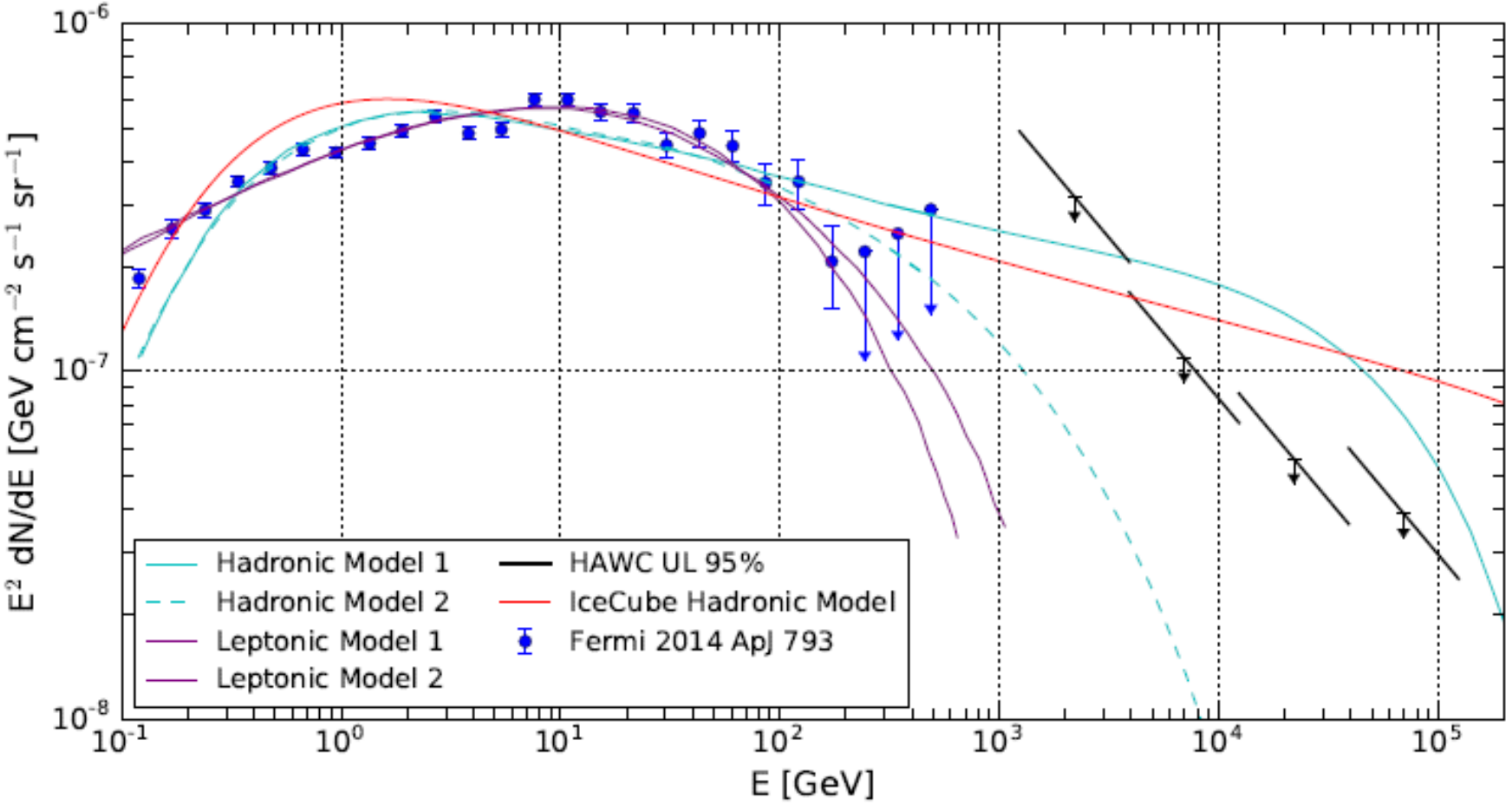
Both hadronic and leptonic model fit Fermi LAT data.







Fermi Bubbles



Abeysekara et al, ApJ, 2017

Active Galactic Nuclei are Variable

PRELIMINARY

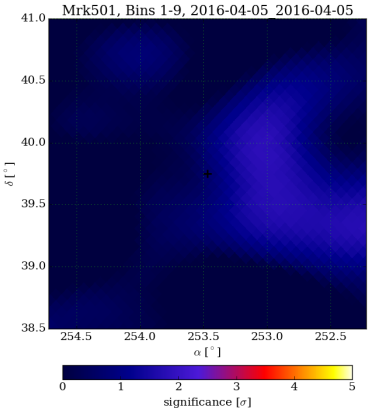
First HAWC Alert

HAWC detection of increased TeV flux state for Markarian 501

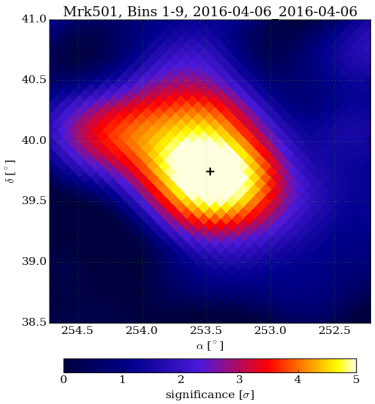
ATel #8922; *Andrés Sandoval (IF-UNAM), Robert Lauer (UNM), Joshua Wood (UMD) on behalf of the HAWC collaboration*
on 7 Apr 2016; 23:38 UT
Credential Certification: C. Michelle Hui (c.m.hui@nasa.gov)

Subjects: Gamma Ray, TeV, VHE, Request for Observations, AGN, Blazar

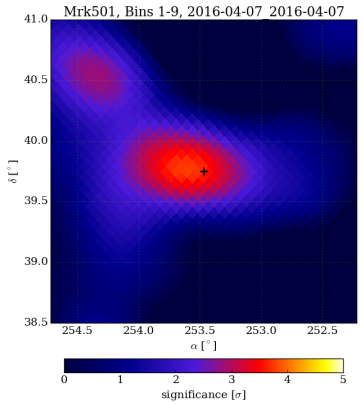
Paper on online flare monitoring in preparation!



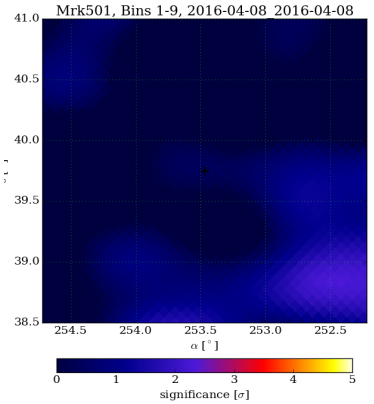
April 5, 2016



April 6, 2016



April 7, 2016



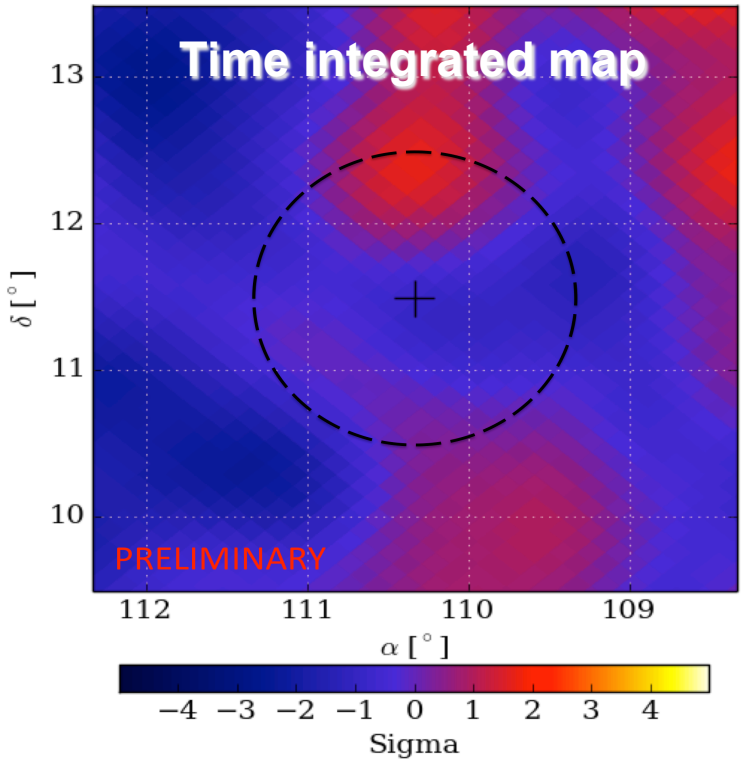
April 8, 2016

- HAWC is already providing prompt notification of flaring activity.
- First Astronomer's Telegram sent on April reporting a Mkr 501 flare (~2 Crab units for 2 days).
- Monitoring all gamma-ray sources visible to HAWC every day.

HAWC Multi-Messenger: IceCube Neutrinos

IceCube Event follow-up

- Highest energy (2.6 PeV) pointed astrophysical track-like event.
- June 11, 2014, 4:54 UTC. (RA,Dec) = (110.3, 11.5)
- HAWC-111 live (pass1). Several hours out of HAWC's FOV.
- Searches:
  - Integrated dataset (Steady, Aug 2013-May 2015)
  - Next Day / Prior Day
  - ±2 and ±5 days around the event.
  - All searches consistent with cosmic-ray background.

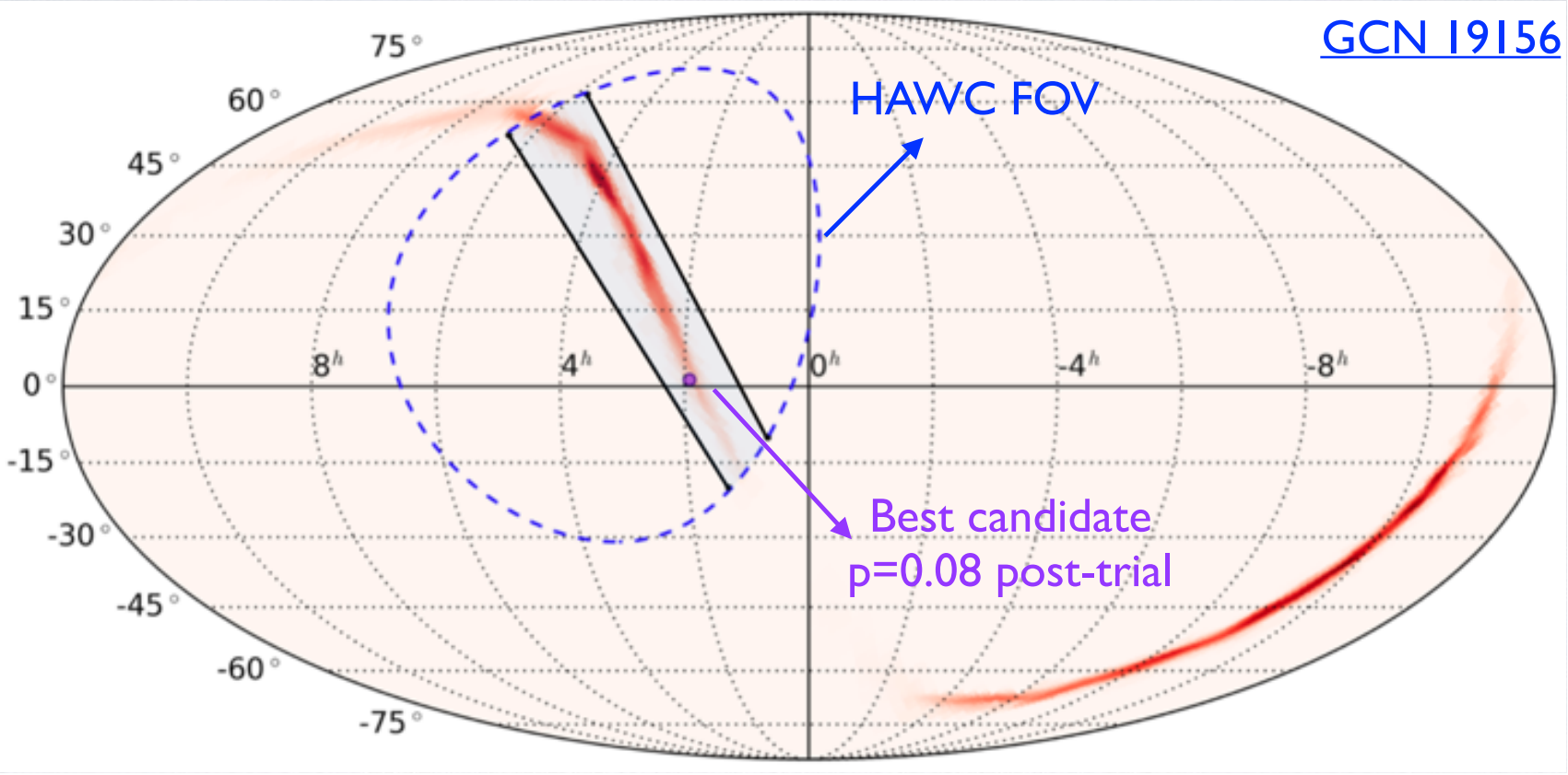


The steady neutrino flux, assuming it is evenly divided among N_s sources (IceCube, PRL 2014), should be detectable in HAWC in a year if photons are not attenuated.
We can set constraining limits on every IceCube event in the HAWC FOV.

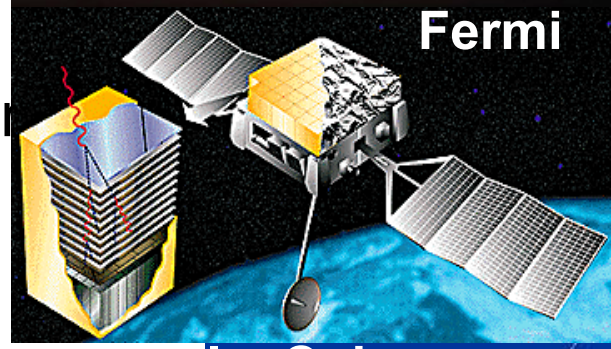
IceCube ATel: #7856
HAWC Follow-up ATel: #7868

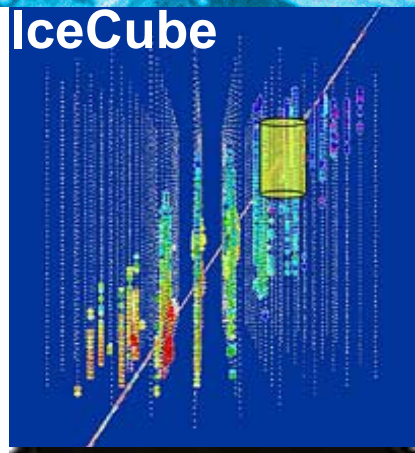
HAWC Multi-Messenger: LIGO Gravitational Waves

- **GW151226**, 2015-12-26 03:38:53 UTC, • z=0.09 +0.03 -0.04
  • 14.2M⊙ + 7.5M⊙ ➡20.8M⊙
- Analysis under MoU with LIGO. HAWC field of view covered a large part of the localization contour at time of coincidence. Real-time all-sky GRB search: 4 sliding windows (0.1, 1, 10, 100 seconds)
- No significant detection.
  GCN circular: http://gcn.gsfc.nasa.gov/gcn3/19156.gcn3



HAWC&ParticleAstrophysics





Complements TeV IACTs

- Identifies new and flaring sources for follow up observation of morphology and sub TeV spectr
- Extends TeV spectra to higher energies

Complements GeV All Sky Survey

- Monitors 1000s of Fermi GeV sources at higher energies

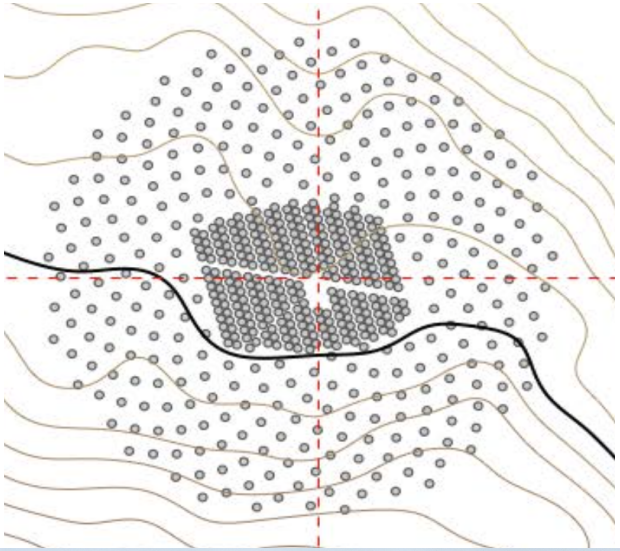
Complements TeV neutrino observations

- Identifies new and flaring TeV sources to improve the sensitivity and interpretation of blind searches

Complements Advanced LIGO

- Simultaneous observations of nearby, short GRBs from ns-ns inspiral

Future Developments



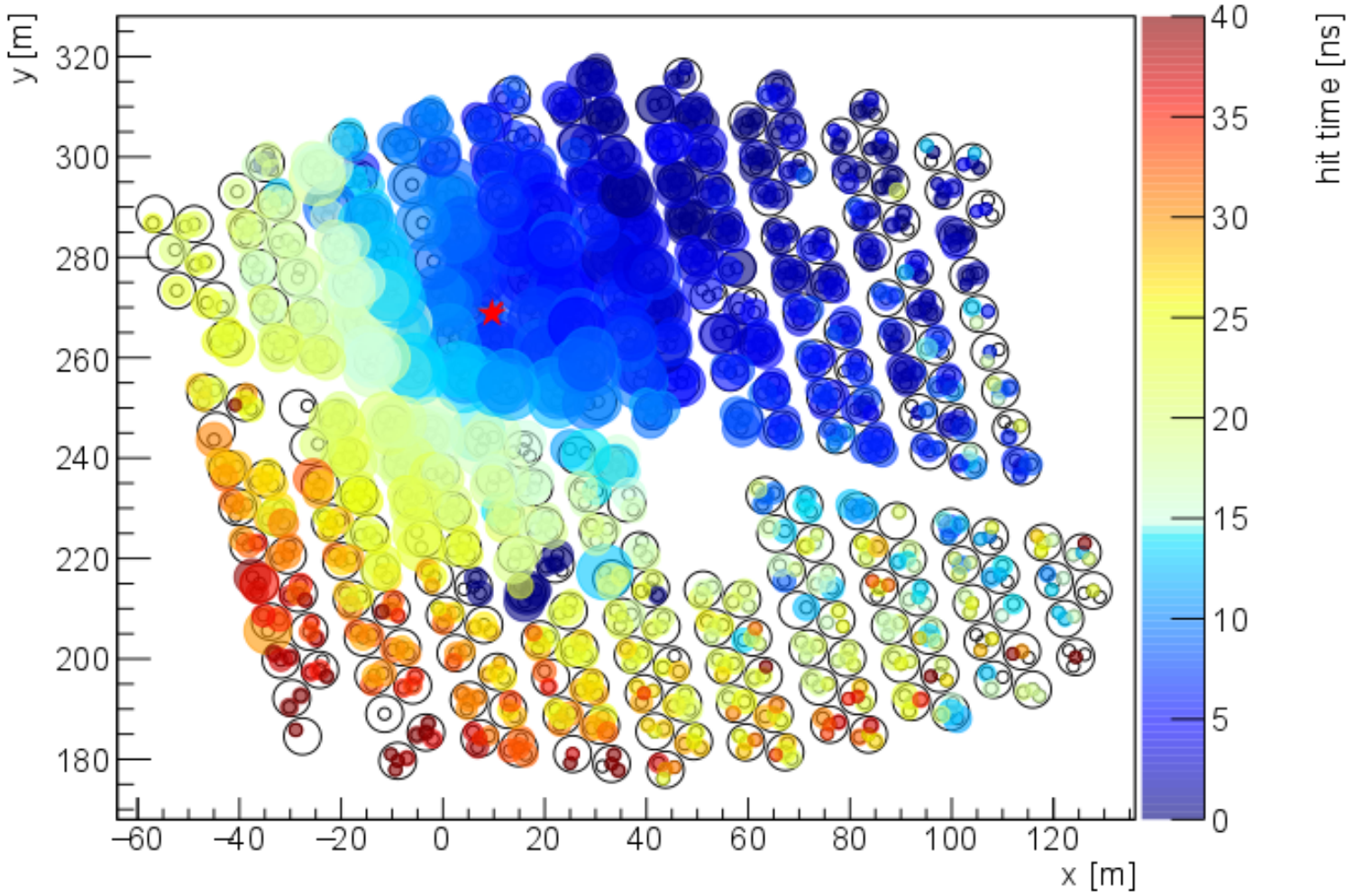
Near future:

- HAWC is adding more detectors to enhance the sensitivity above 10 TeV.
- Outriggers will help to accurately determine core position for showers off the main tank array.
- Increase effective area above 10 TeV by 3-4x
- Plans for ~300 tanks of 2500 liter tanks (1/80 HAWC tank).
- Funded by LANL, Mexico, MPIK. Tank deployment and firsts tests ongoing.

Future:

- Working together with other scientists on a future wide field-of-view TeV observatory for the Southern Hemisphere that **will complement CTA in the south**.
- Expected improvements: higher altitude, larger area, better hadronic rejection, better shower sensitivity.

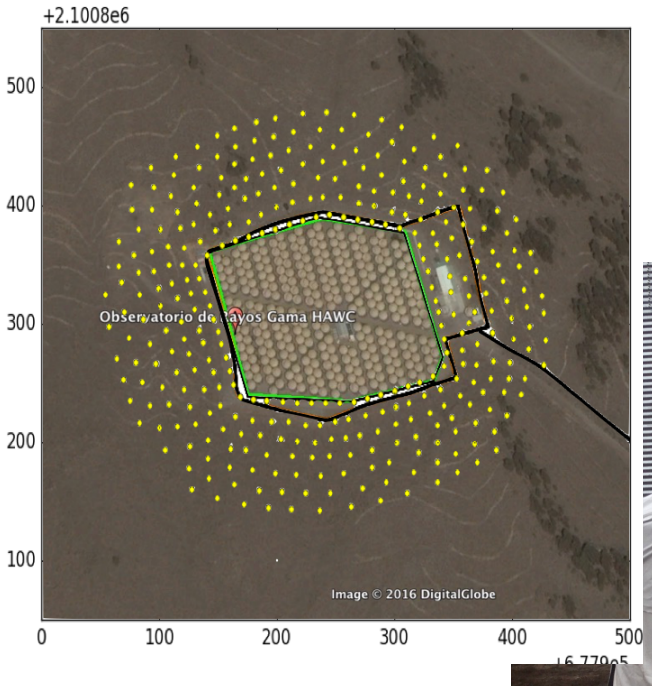
Gamma-Like Event of ~60TeV



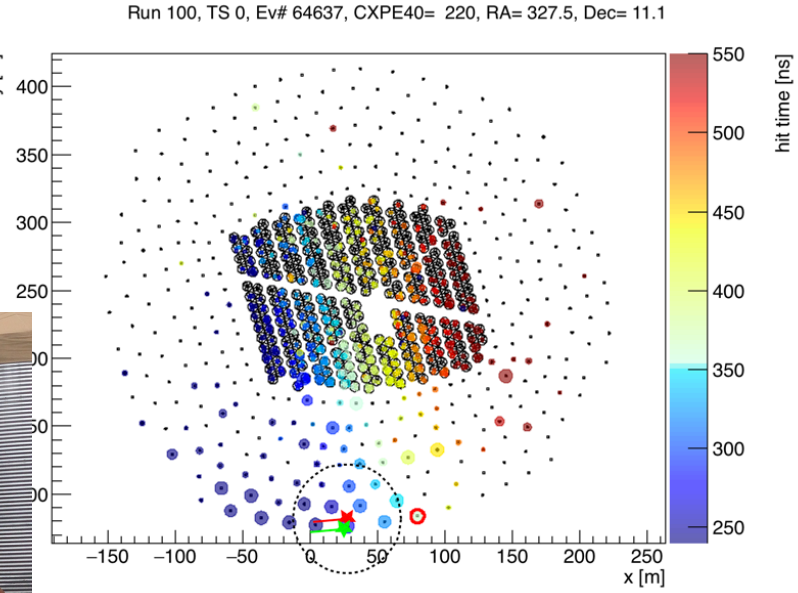
HAWC is getting better with "Outrigger" extension project

We can increase the sensitivity to the highest energy events by determining the core position for showers that fall off the array.

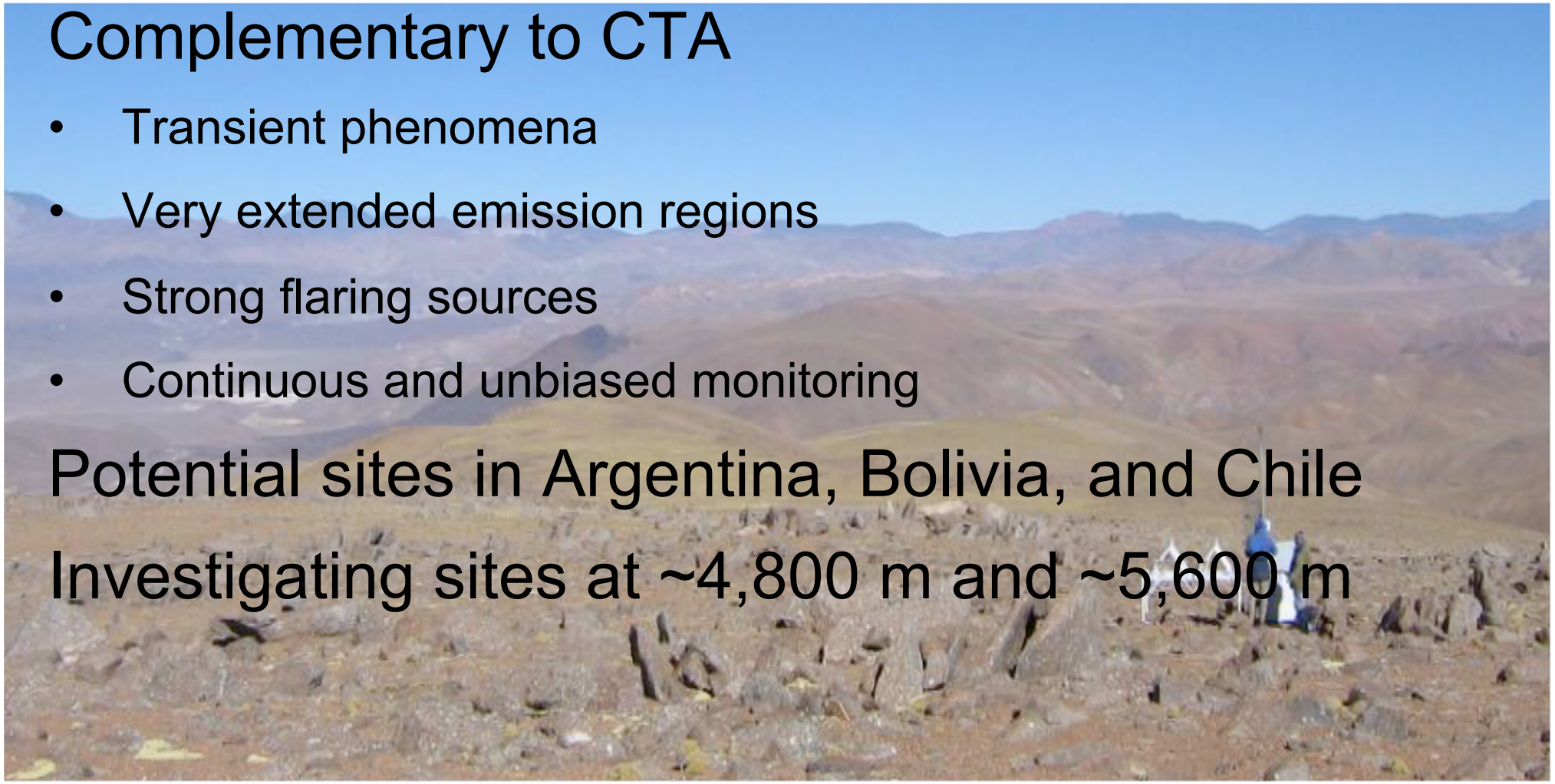
The 350 small WCD outrigger detectors cover an area 4x HAWC and will increase by 3-4x the sensitivity at 50 TeV.



Funded and in progress



Large Water Cherenkov Survey instrument in CTA Era



Complementary to CTA

- Transient phenomena
- Very extended emission regions
- Strong flaring sources
- Continuous and unbiased monitoring

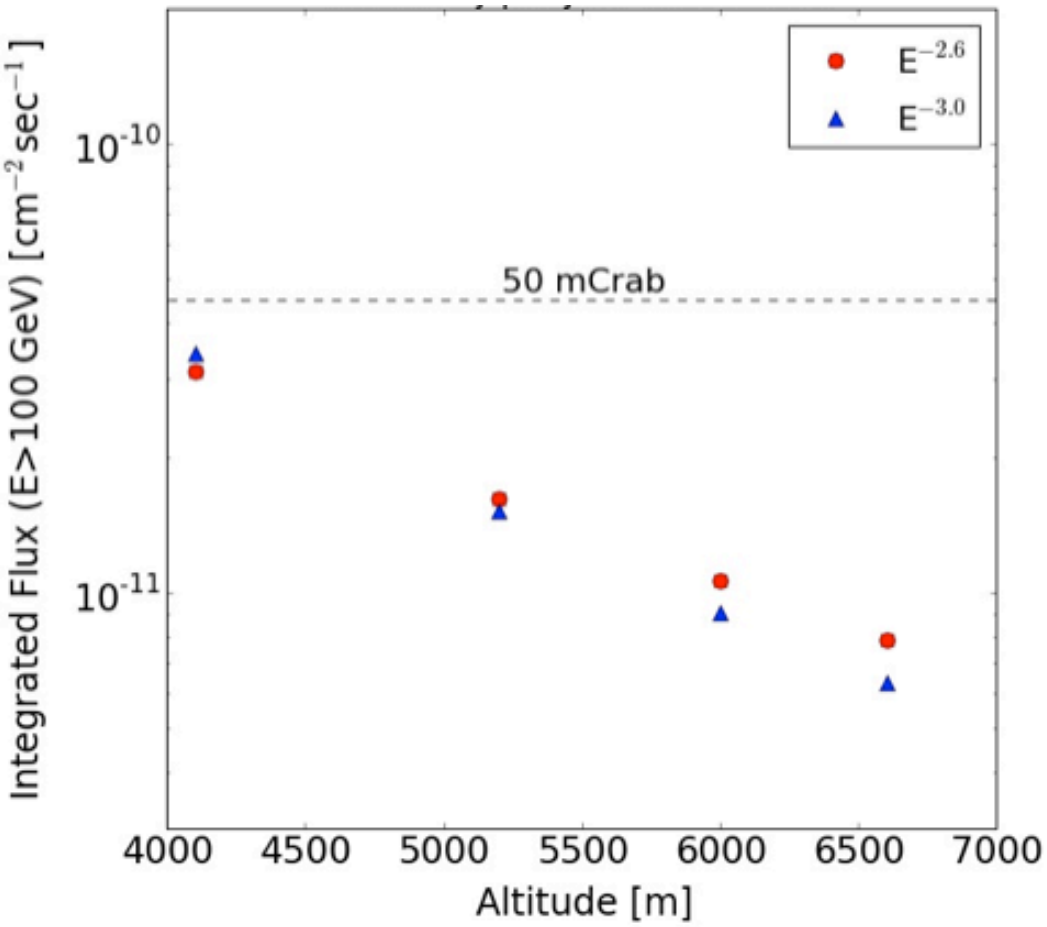
Potential sites in Argentina, Bolivia, and Chile

Investigating sites at ~4,800 m and ~5,600 m

Beyond HAWC: Even Lower Energy

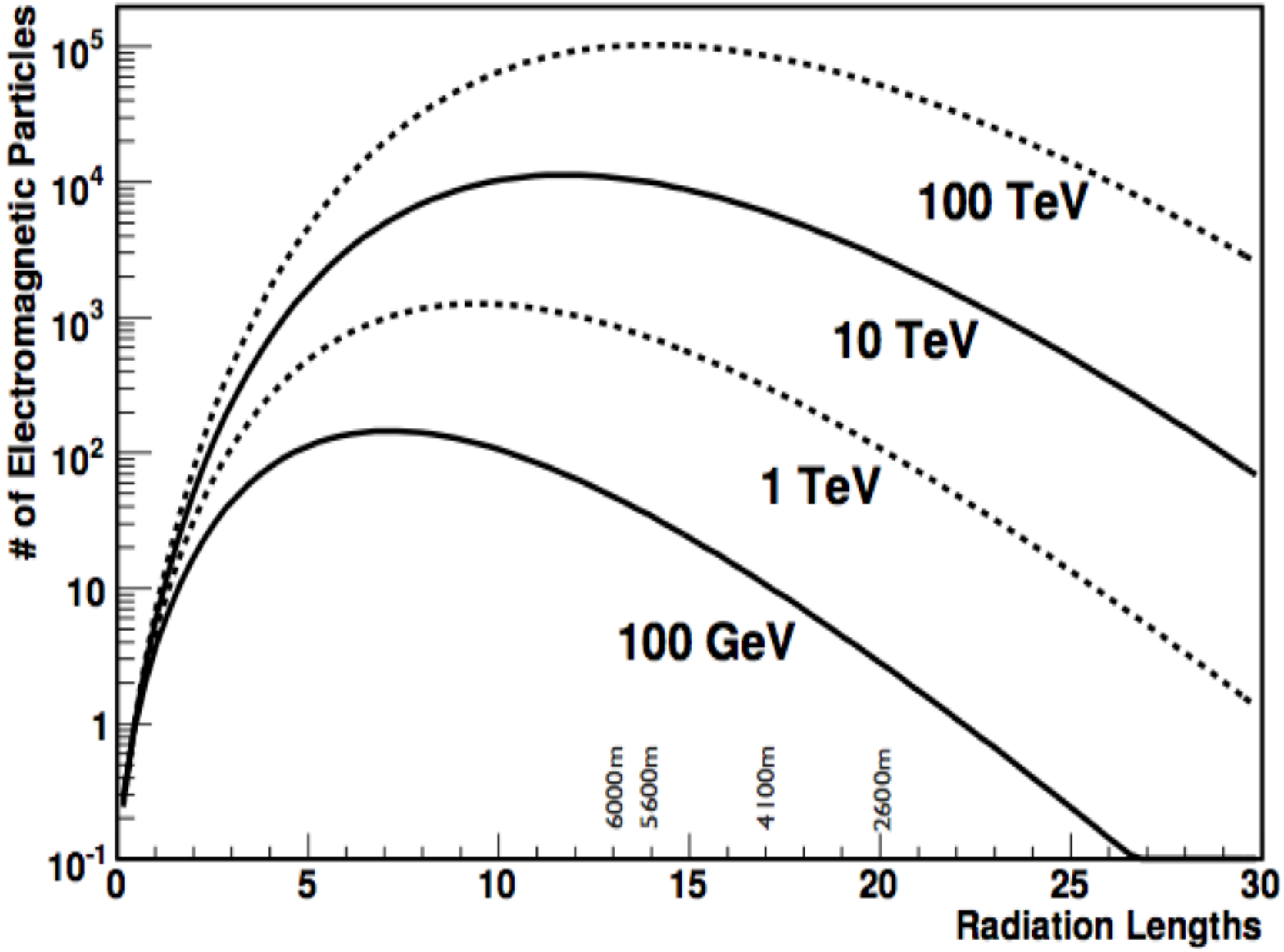
Same detector at a higher altitude has increased sensitivity especially at lower energies

Factor of 4 increase in sensitivity between ALMA and HAWC altitude



Sensitivity for one year of observation of an array of 900 tanks with 900 PMTs at different altitudes

High altitude -> low threshold



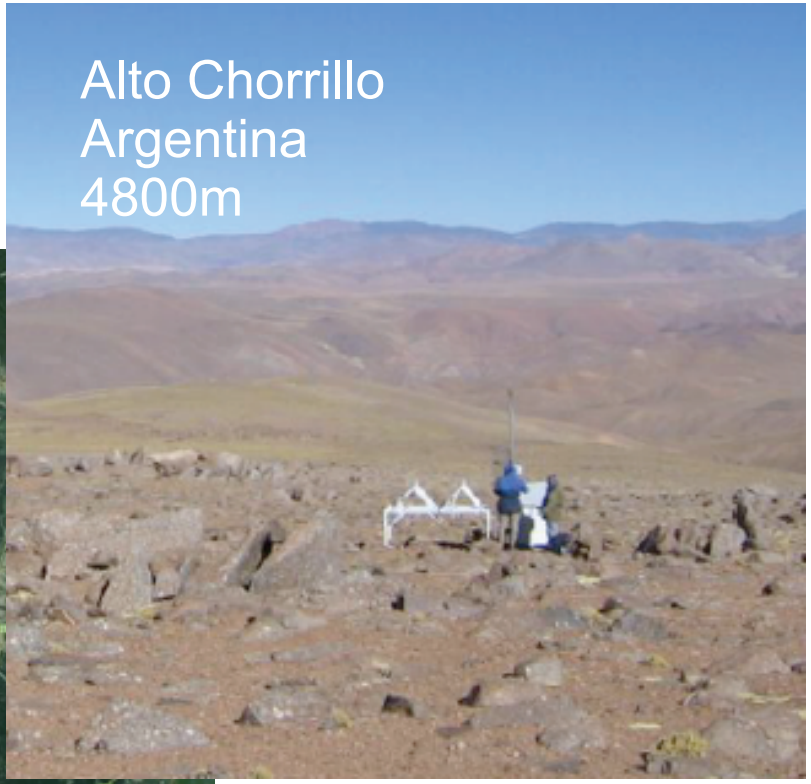
Beyond HAWC: Southern Site

Discovering rare transient events requires full sky coverage

- GRB finder for Advanced LIGO, which will detect all neutron binary coalescence with z<0.5
- AGN flares & GRBs as distant probes of high energy physics (e.g. Lorentz invariance and axions)

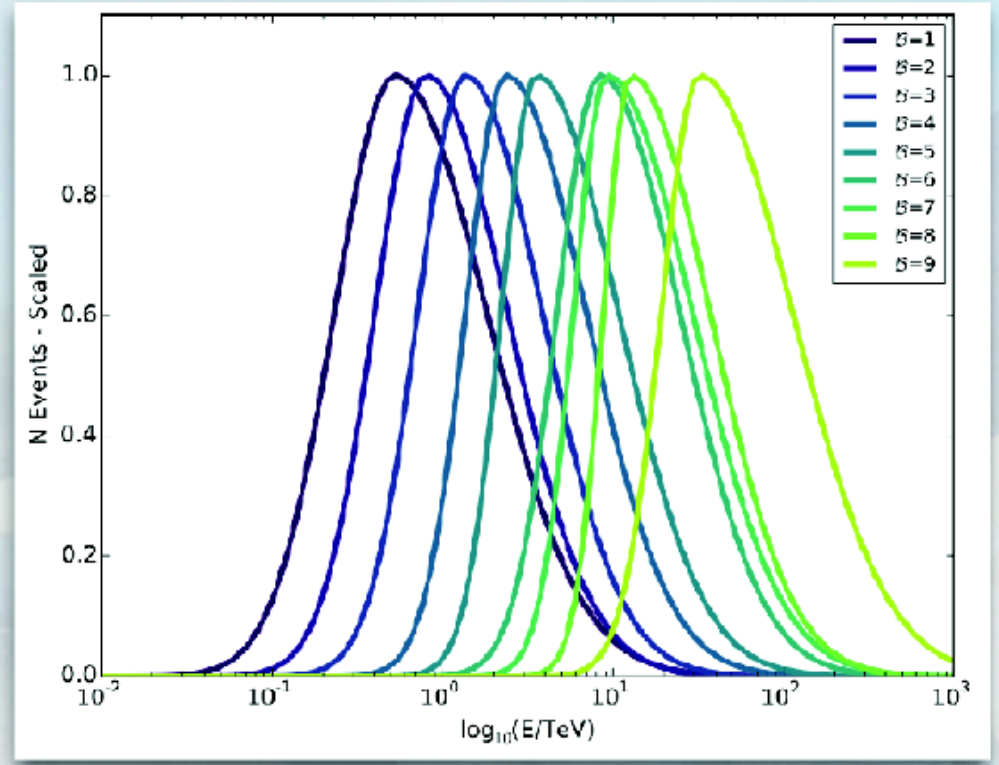
Galactic Center

TeV Source finder for CTA south

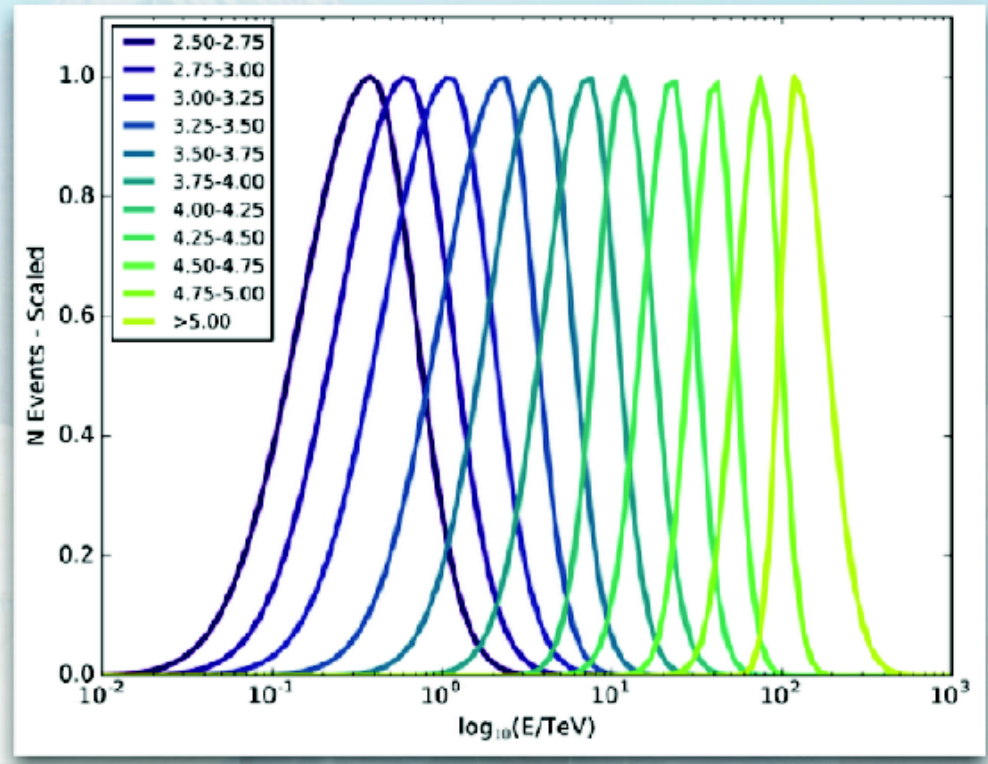


Backup slides

Bin Energy (current vs EE)

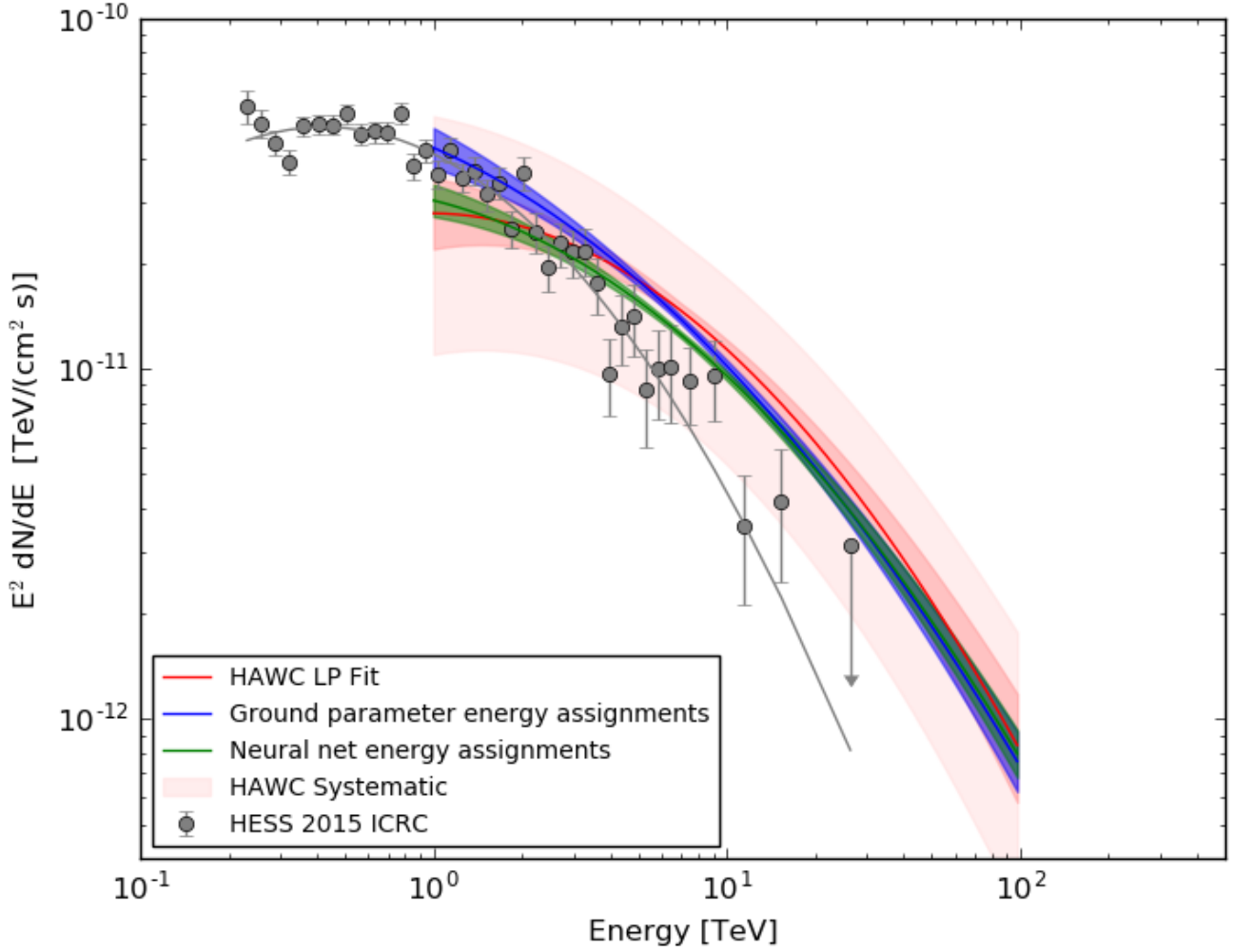


Old method arXiv: 1701.01778v1

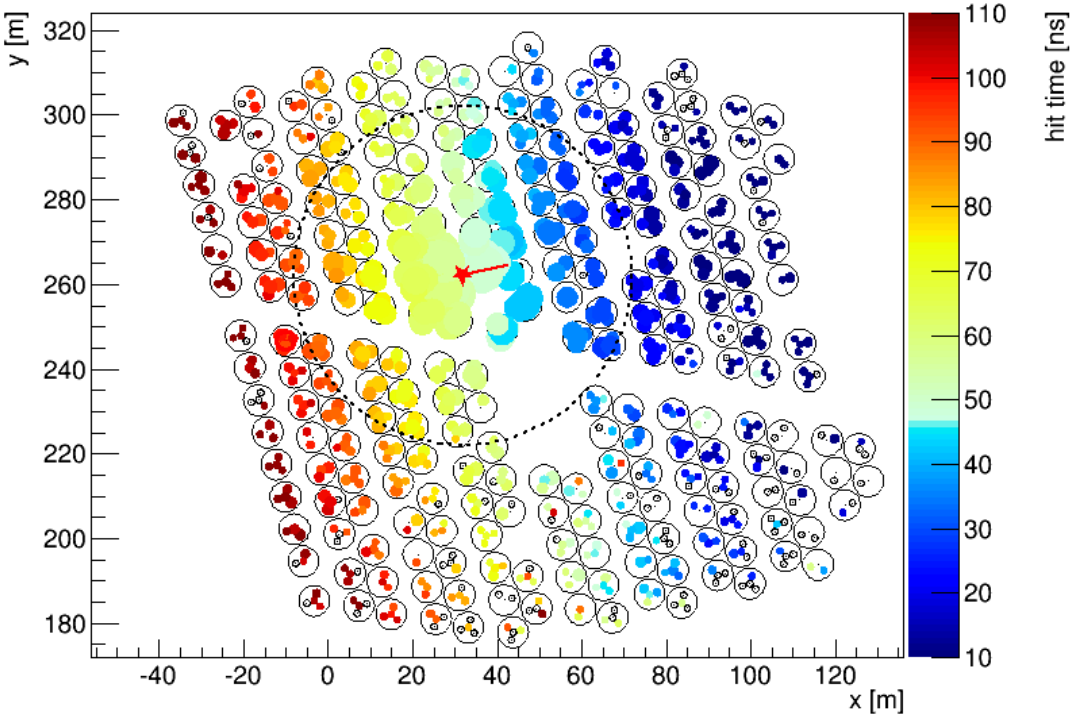


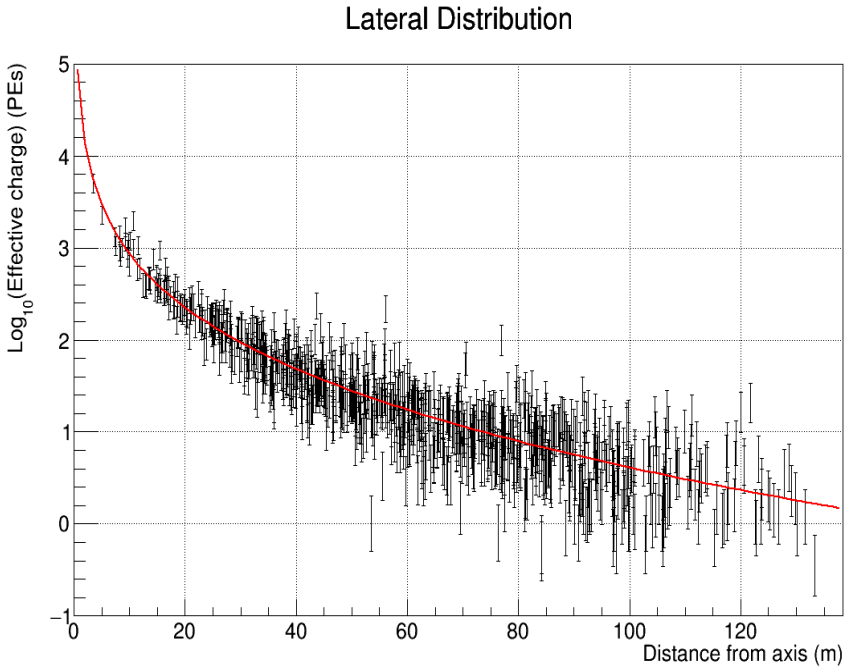
New method

Crab Nebula spectrum (EE)



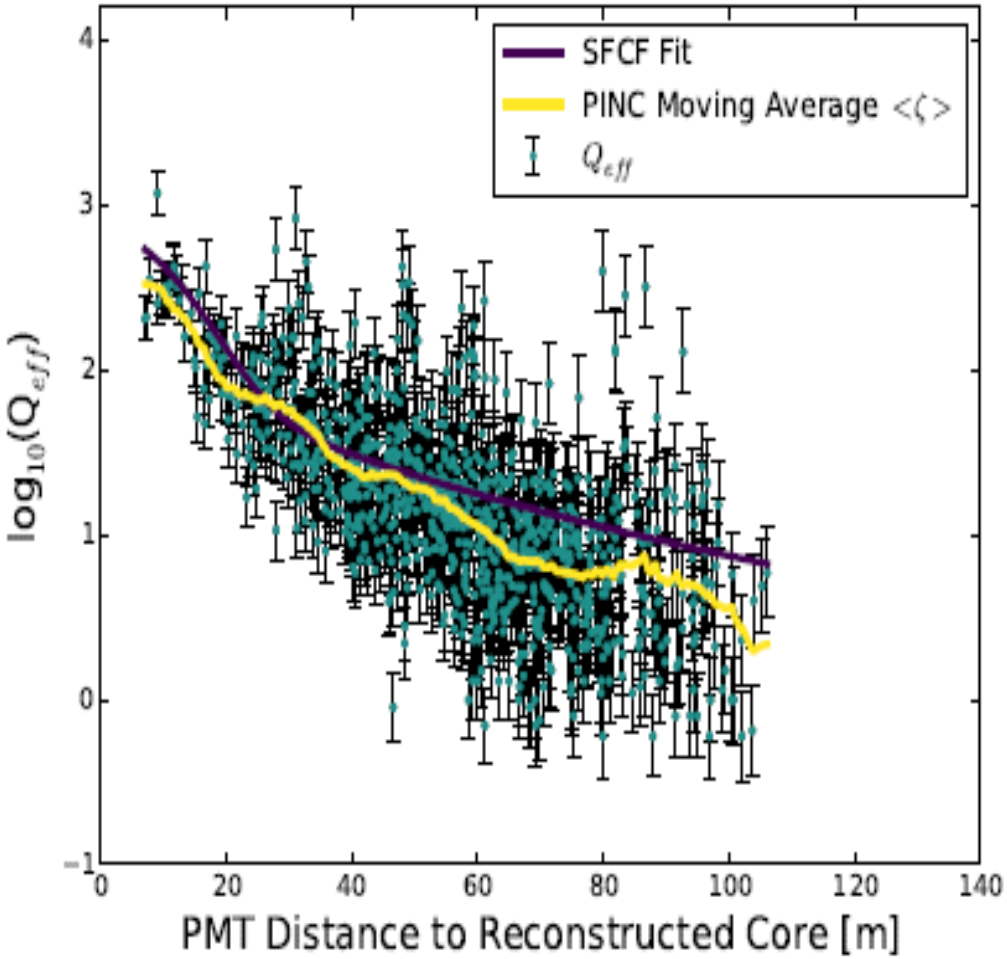
Crab gamma-ray candidate

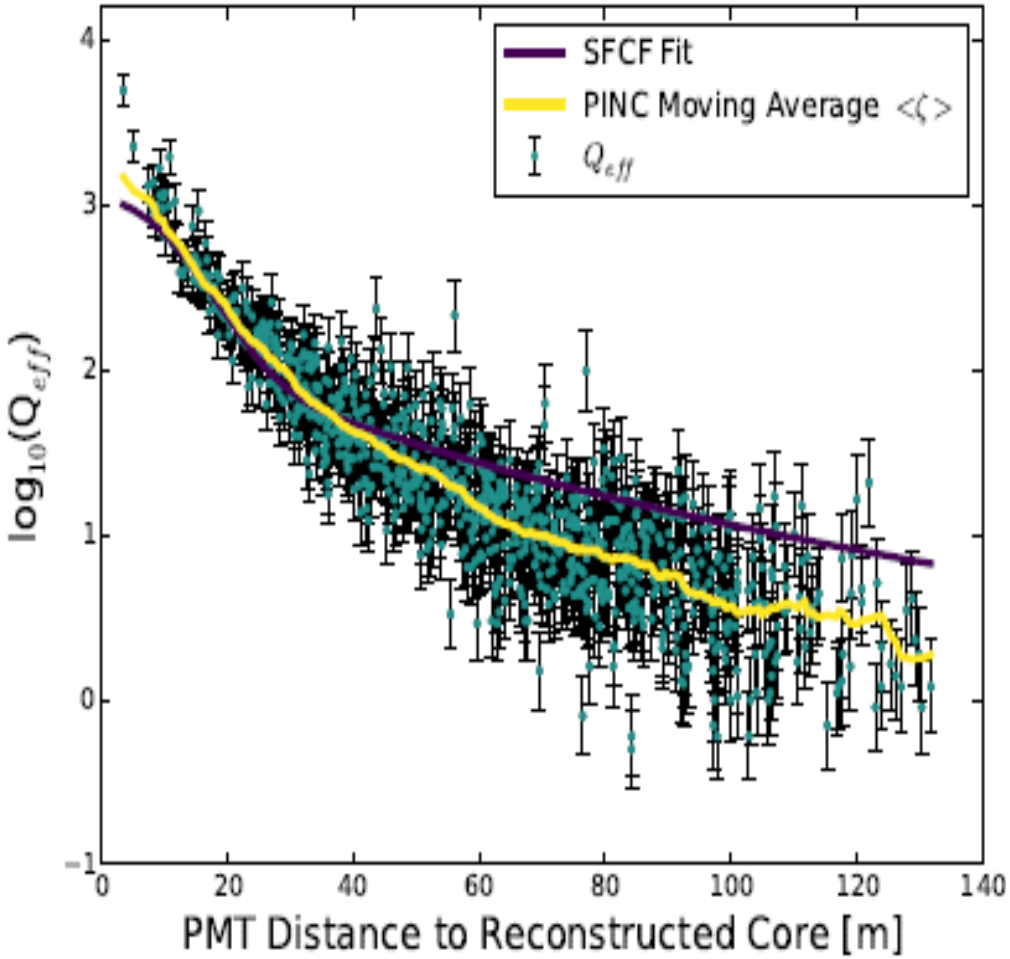




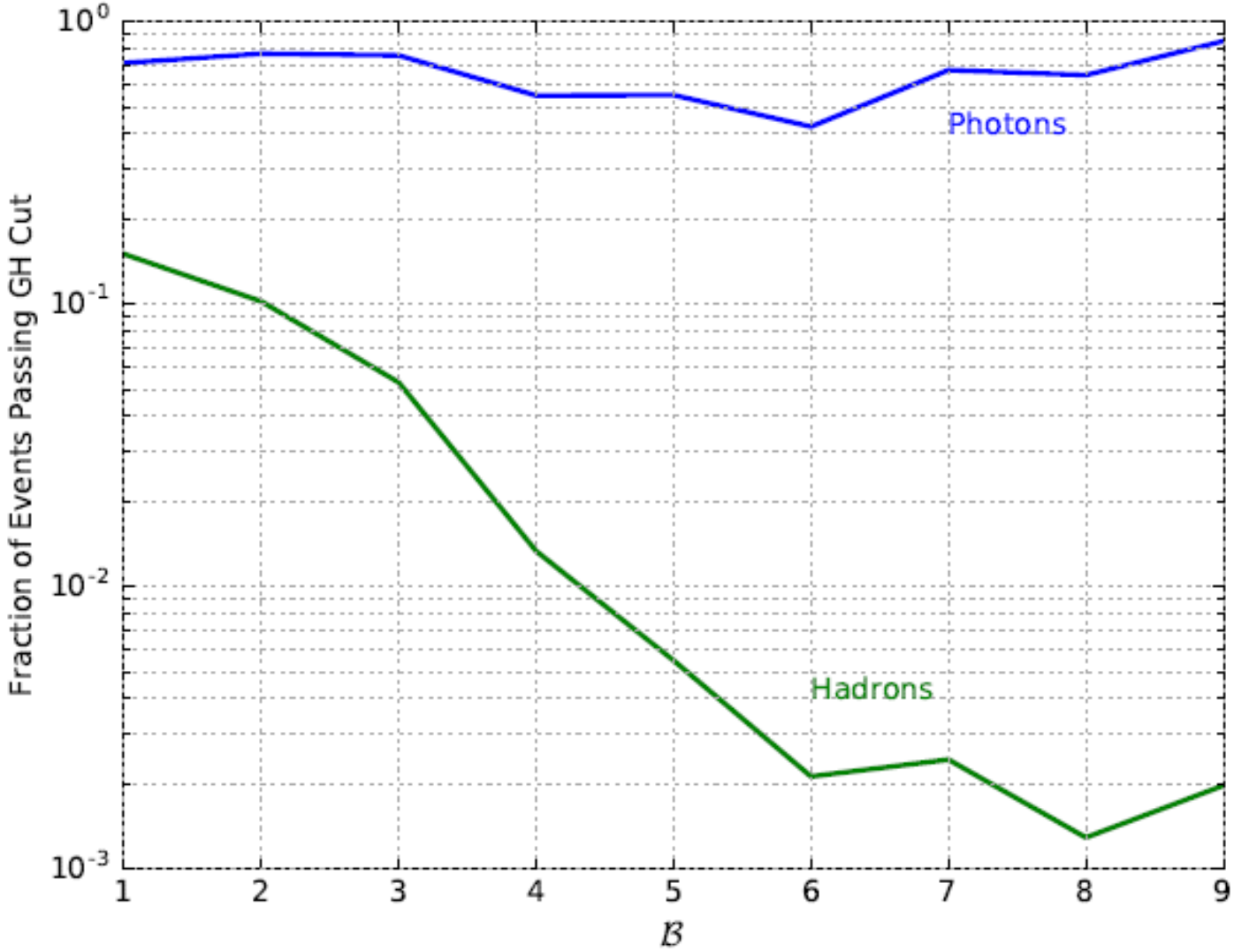
- Event reconstructed within 0.4° of the Crab Nebula.

γ/h separation

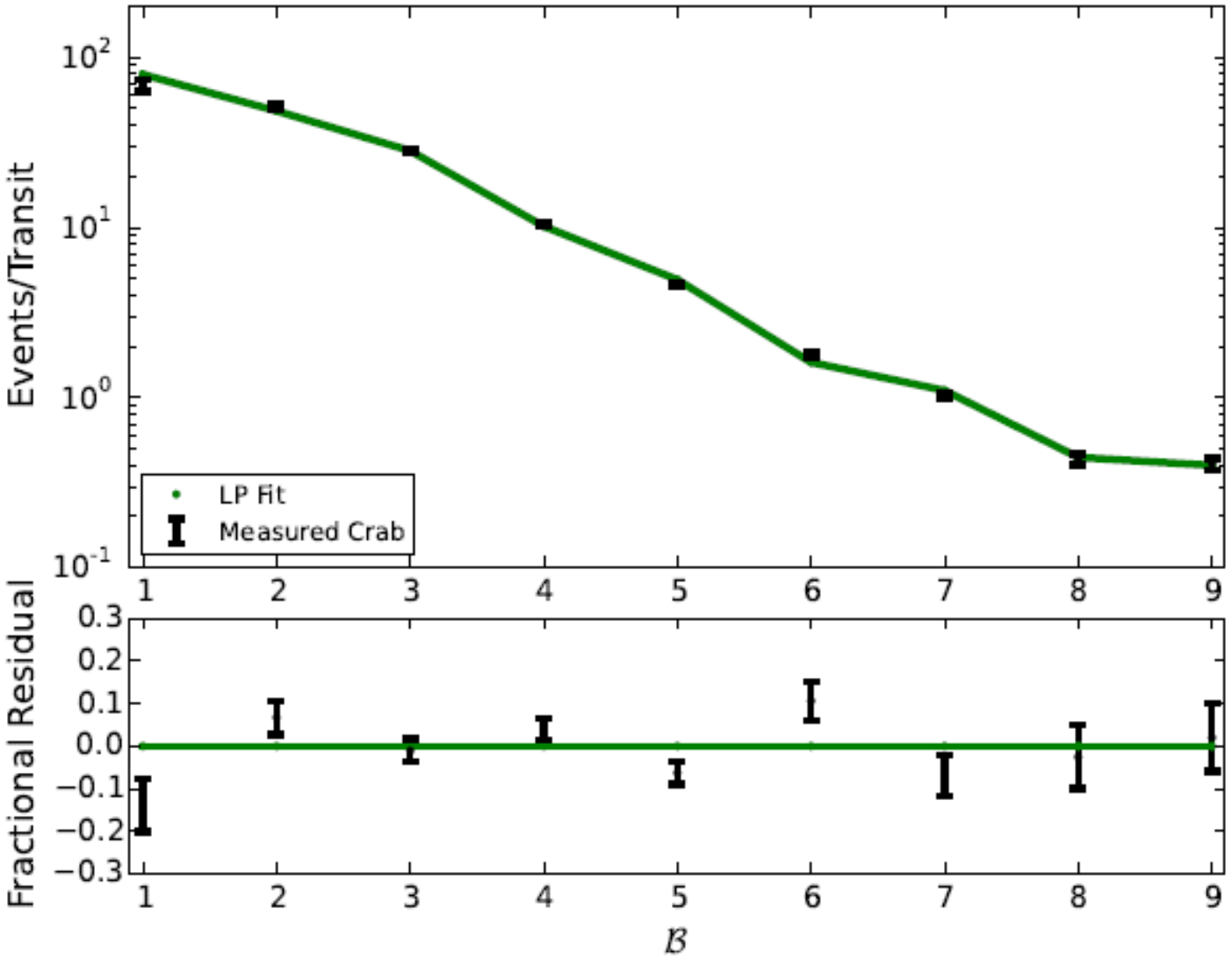




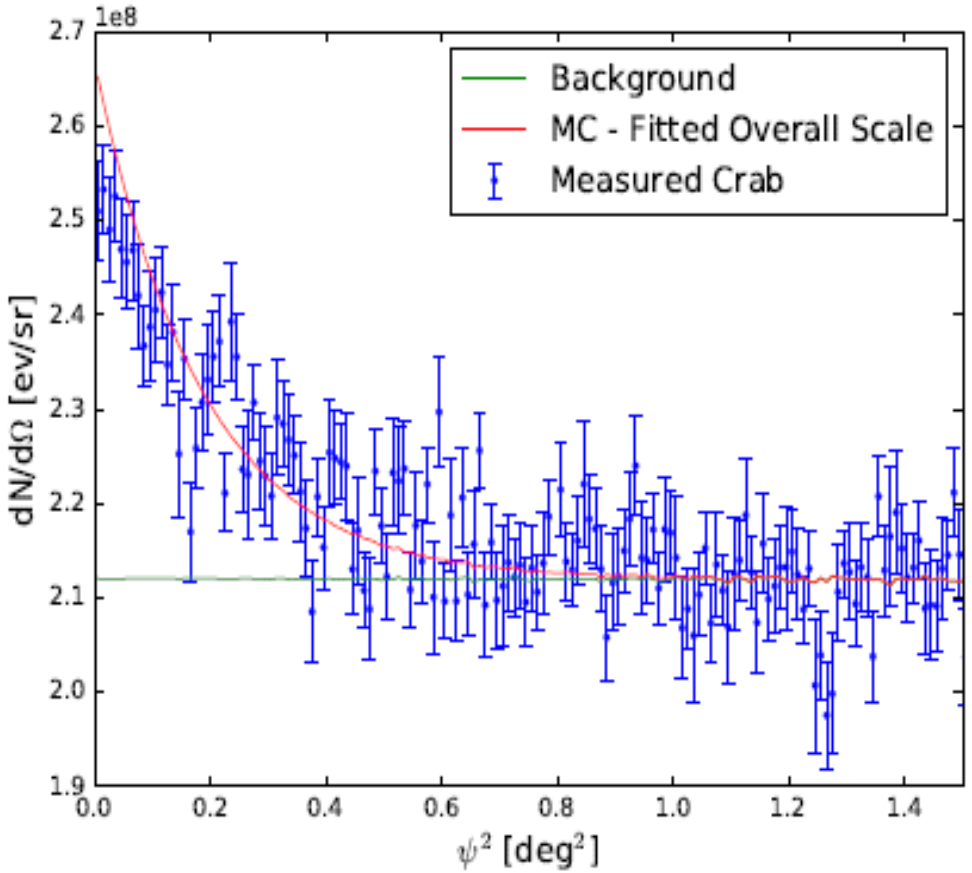
Cut Efficiency



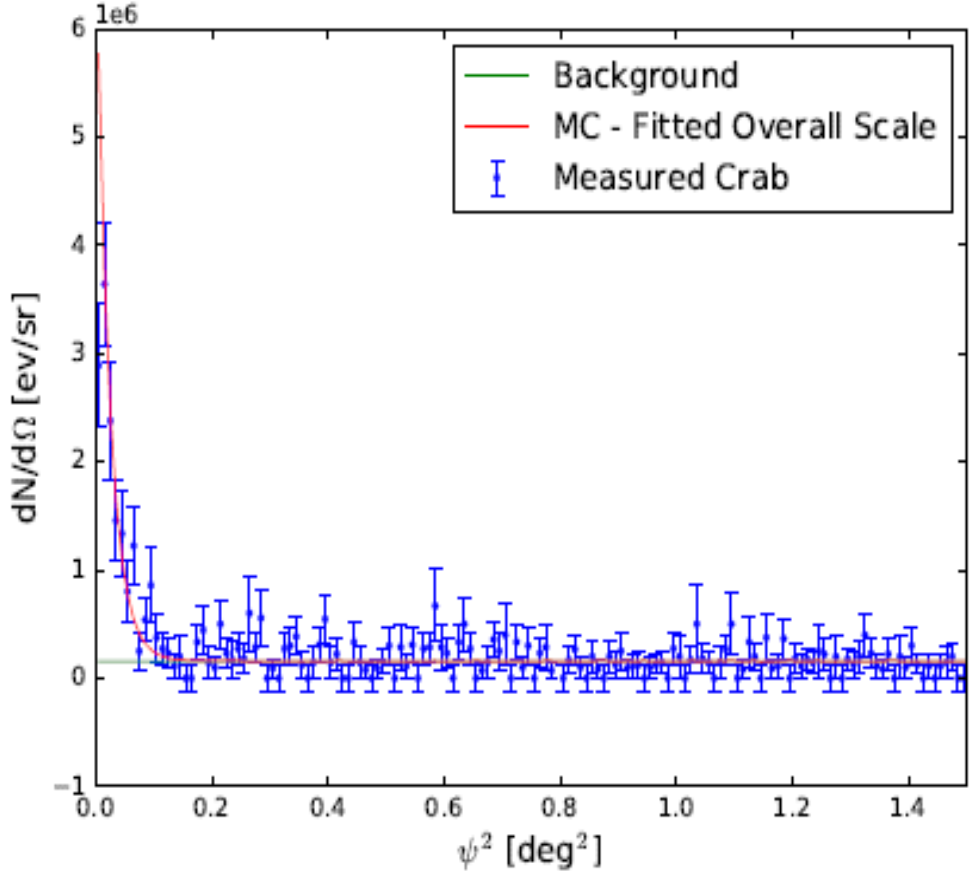
Crab Excess


Events/Transit
10^2
10^1
10^0
10^{-1}
LP Fit
Measured Crab
1
2
3
4
5
6
7
8
9
Fractional Residual
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
$\mathcal{B}$

Angular Resolution

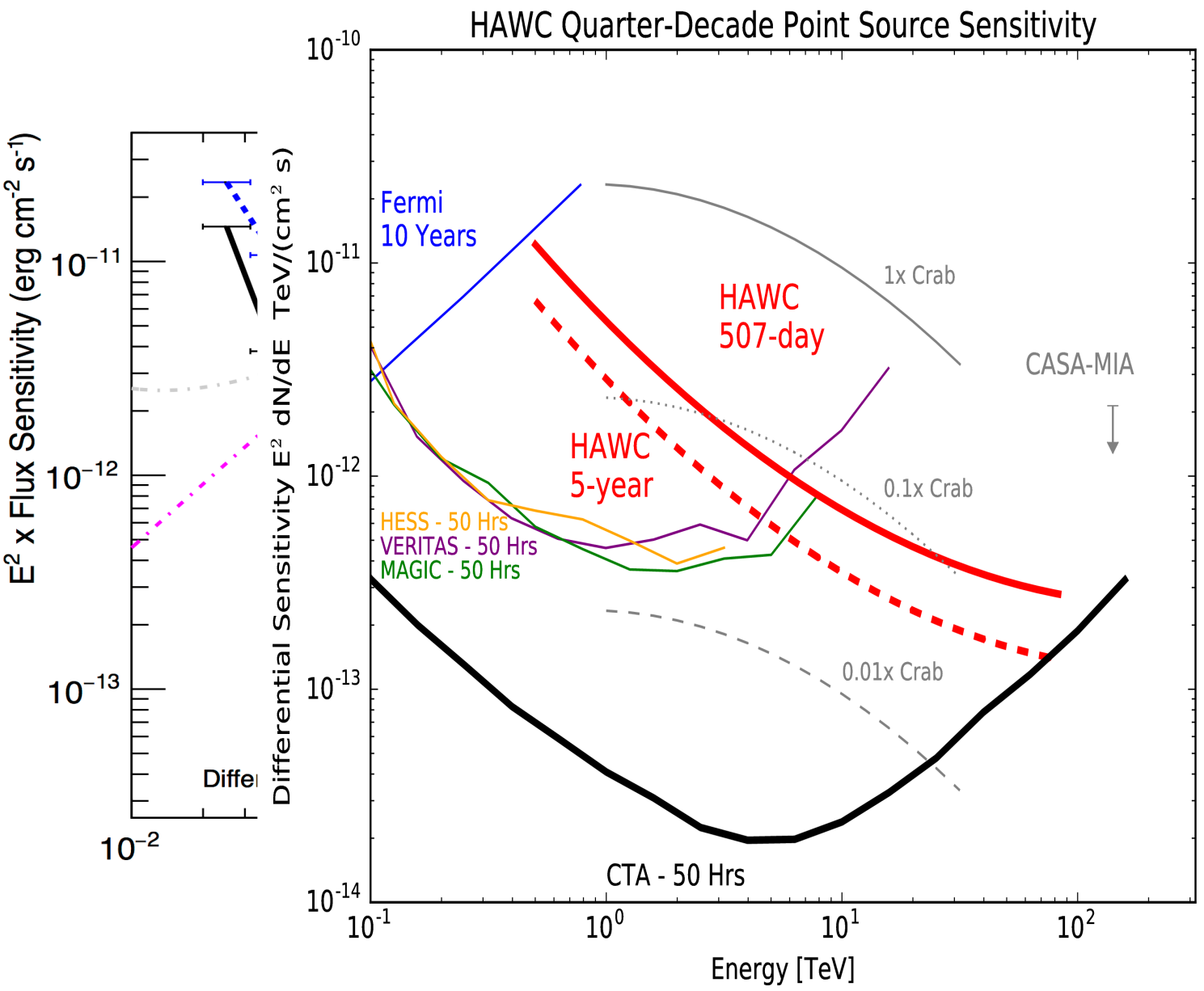


(c) $\mathcal{B} = 3$ Angular Profile

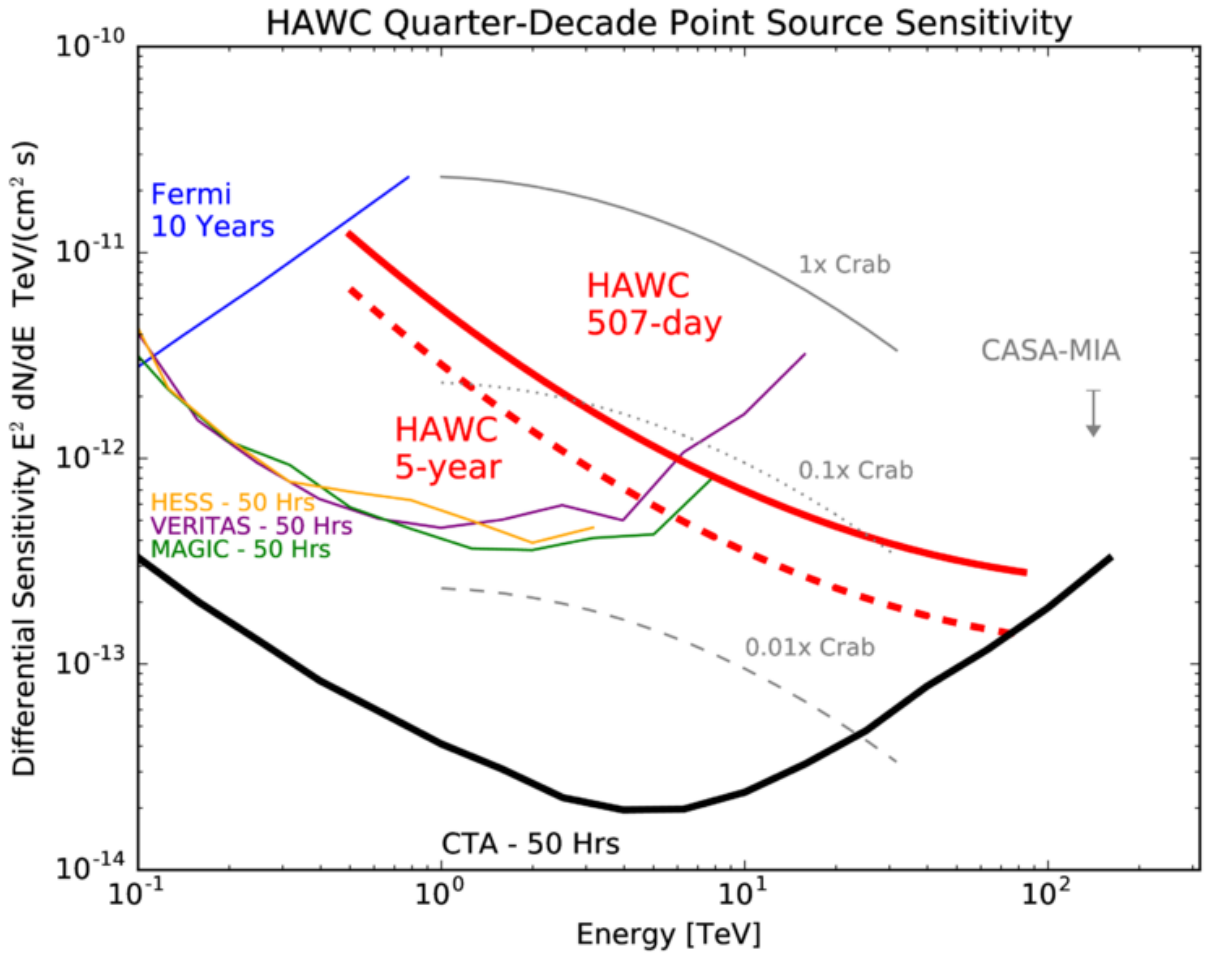


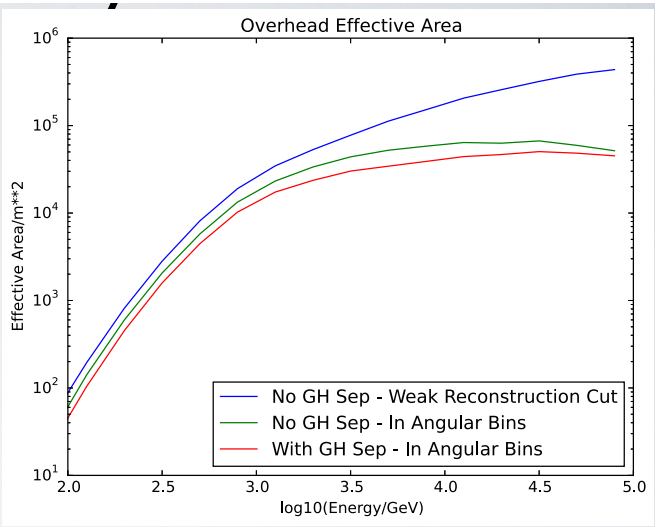
(d) $\mathcal{B} = 8$ Angular Profile

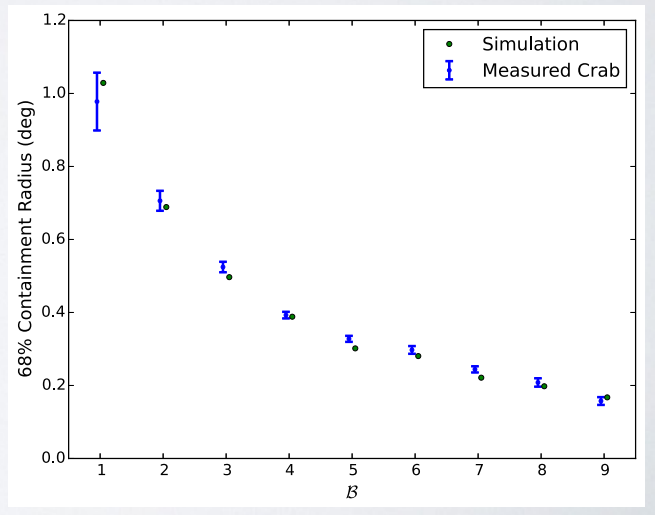
sensitivity



HAWC Sensitivity

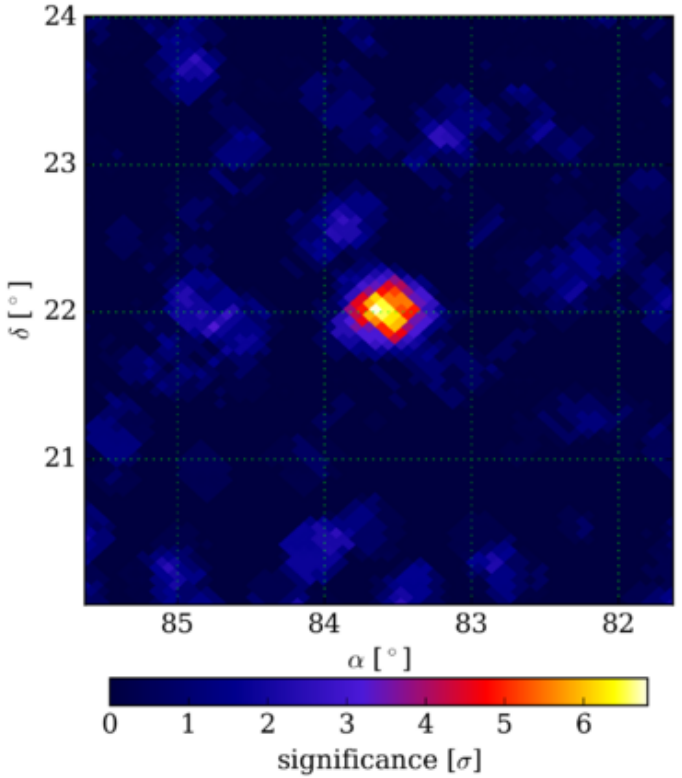






HAWC Collaboration+17

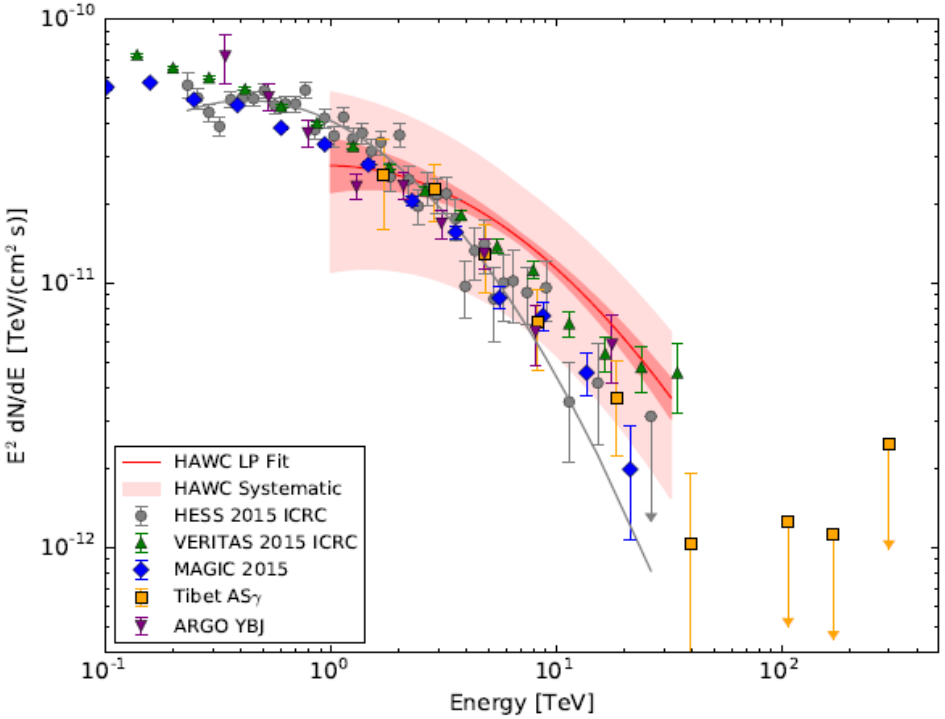
Crab Nebula above 56 TeV

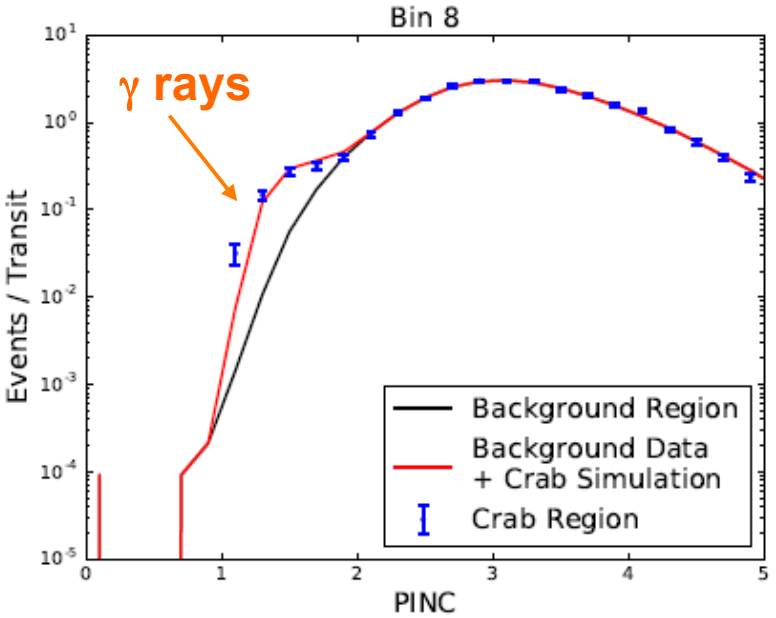


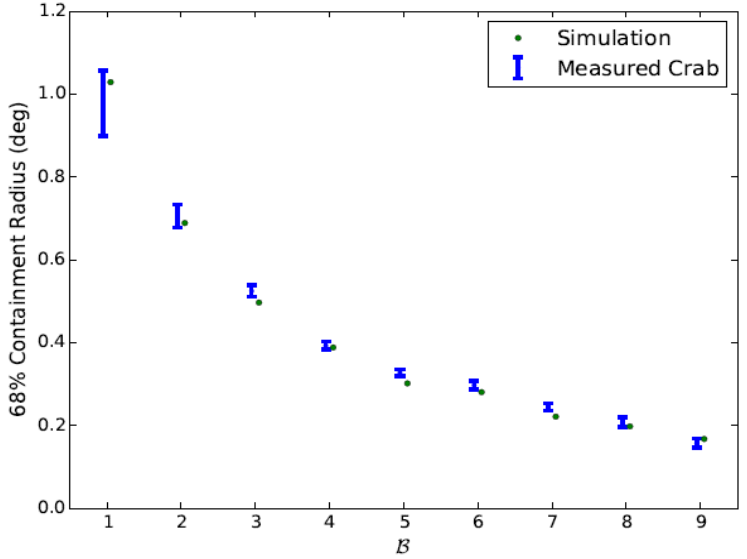
Pointlike Search :
Crab Nebula (>56TeV)

The Crab Nebula

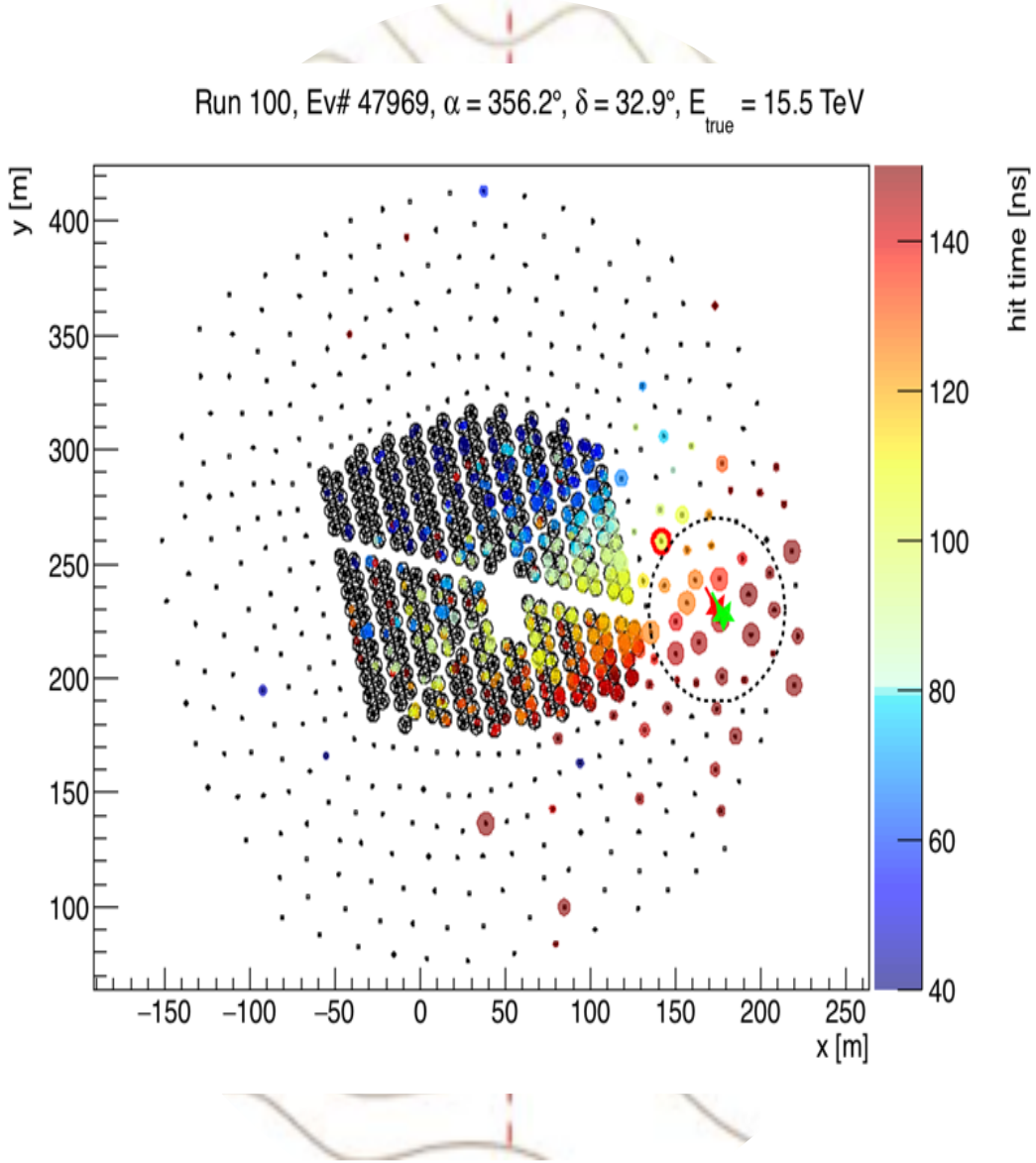
- Crab Nebula detected with high significance ~100σ.
- It was used to test our angular resolution and g/h cuts.
- The AR (68% containment) is 0.25° for events with more that hit more than 50% PMTs hit.
- Signal to background ratio ~10:1 for large events (>75% PMTs hit) while keeping >60% of the gamma-





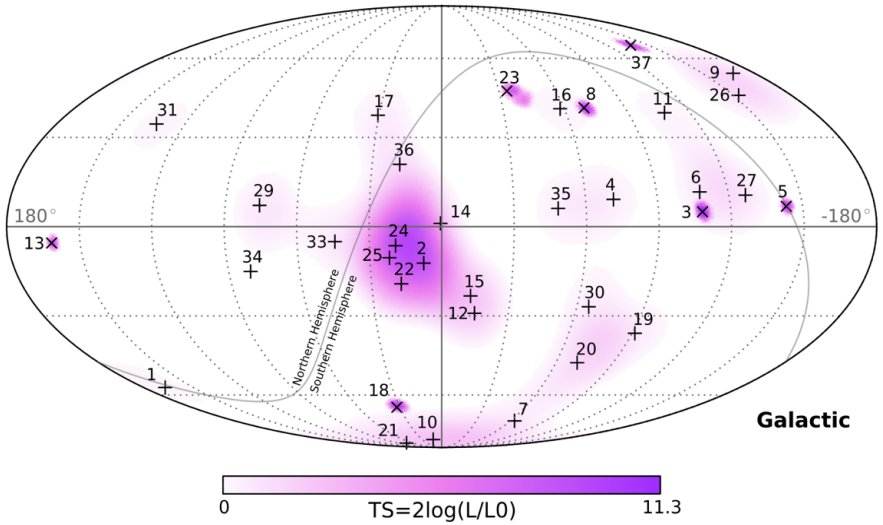


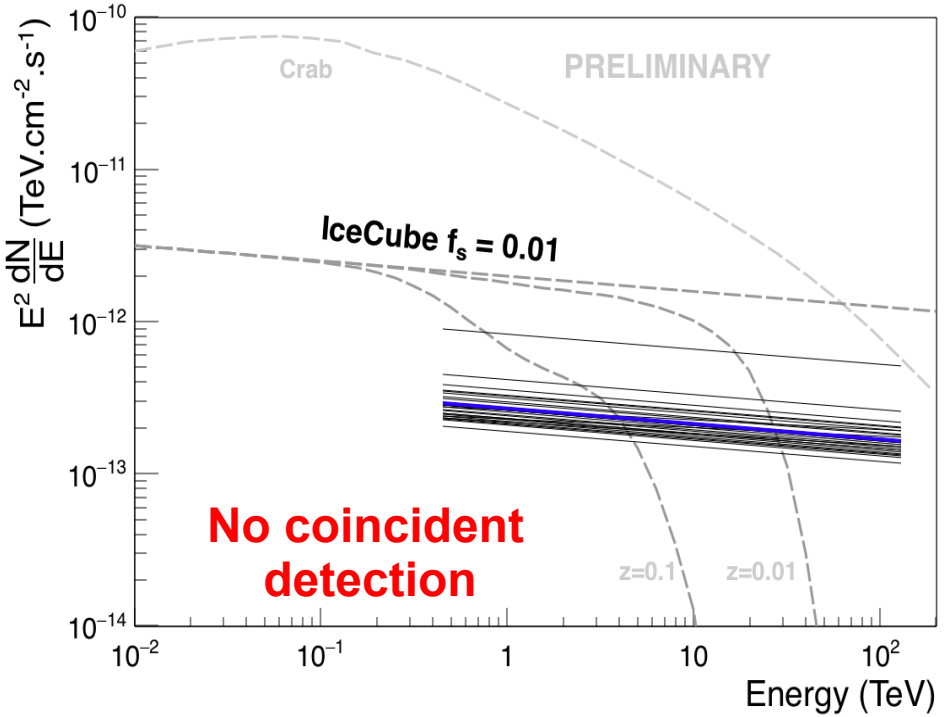
understanding larger area



HAWC Multi-Messenger: IceCube

IceCube Collab. Science, 2013; PRL, 2014; Phy.s Rev. D, 2015





Neutrino / Photon Connection: Pions

$$\pi^0 \rightarrow \gamma\gamma$$
$$\pi^{\pm} \rightarrow \mu\ \nu_\mu \rightarrow \nu_\mu\ \nu_\mu\ \nu_e$$
$$\frac{dN_\nu}{dE} \sim \frac{dN_\gamma}{dE}$$

HAWC's Strengths for IceCube Followup

- Wide FOV: Search for cascade coincidences.
- Continuous observation.
- Can search archival data.
- HAWC Sensitive up to 100 TeV

- Some interpretations. Sources may:
  - Be more than expected, weaker flux.
  - Be opaque to gamma- and cosmic-rays.
  - Have high redshift.
  - Be transient.

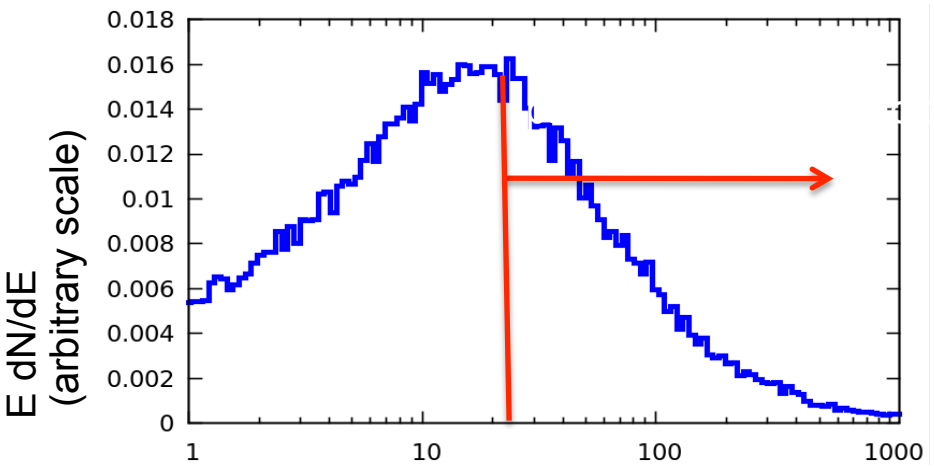
Beyond HAWC: Increase Sensitivity

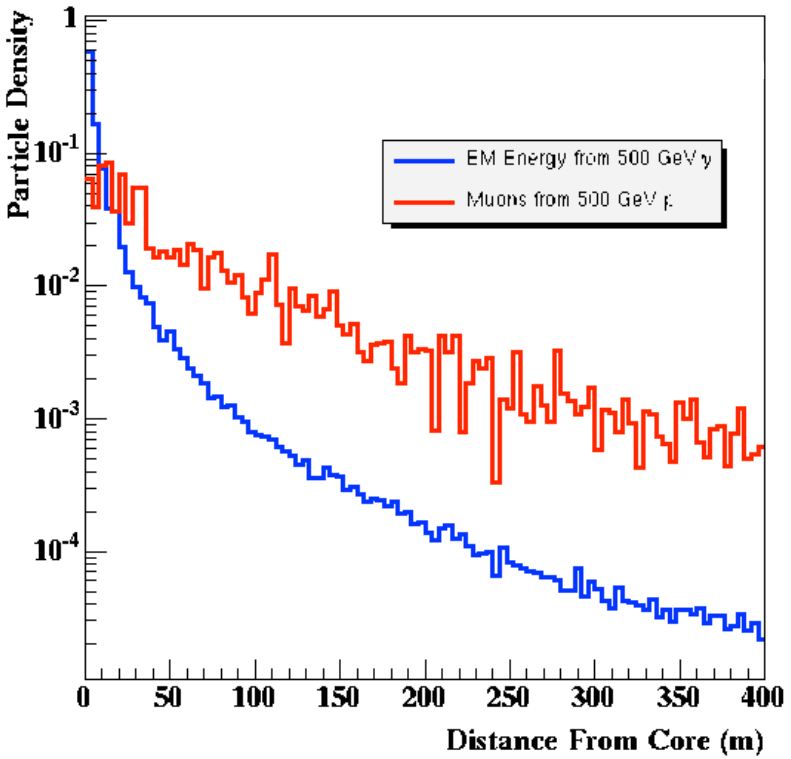
Increase photodetection efficiency for lower energies

- Winston Cones
- Large Area Photodetectors
- Liquid Scintillator

Larger Area Array

- Sensitivity proportional to Area, NOT sqrt(Area) due to background rejection





	HAWC 150m x 150m	HAWC(100k m^2) 300m x 300m
Deep Survey Sensitivity (4 years)	20mCrab	4-5mCrab
Instantaneous sensitivity ($\sigma/\sqrt{hr}$) ~	~3	12-15