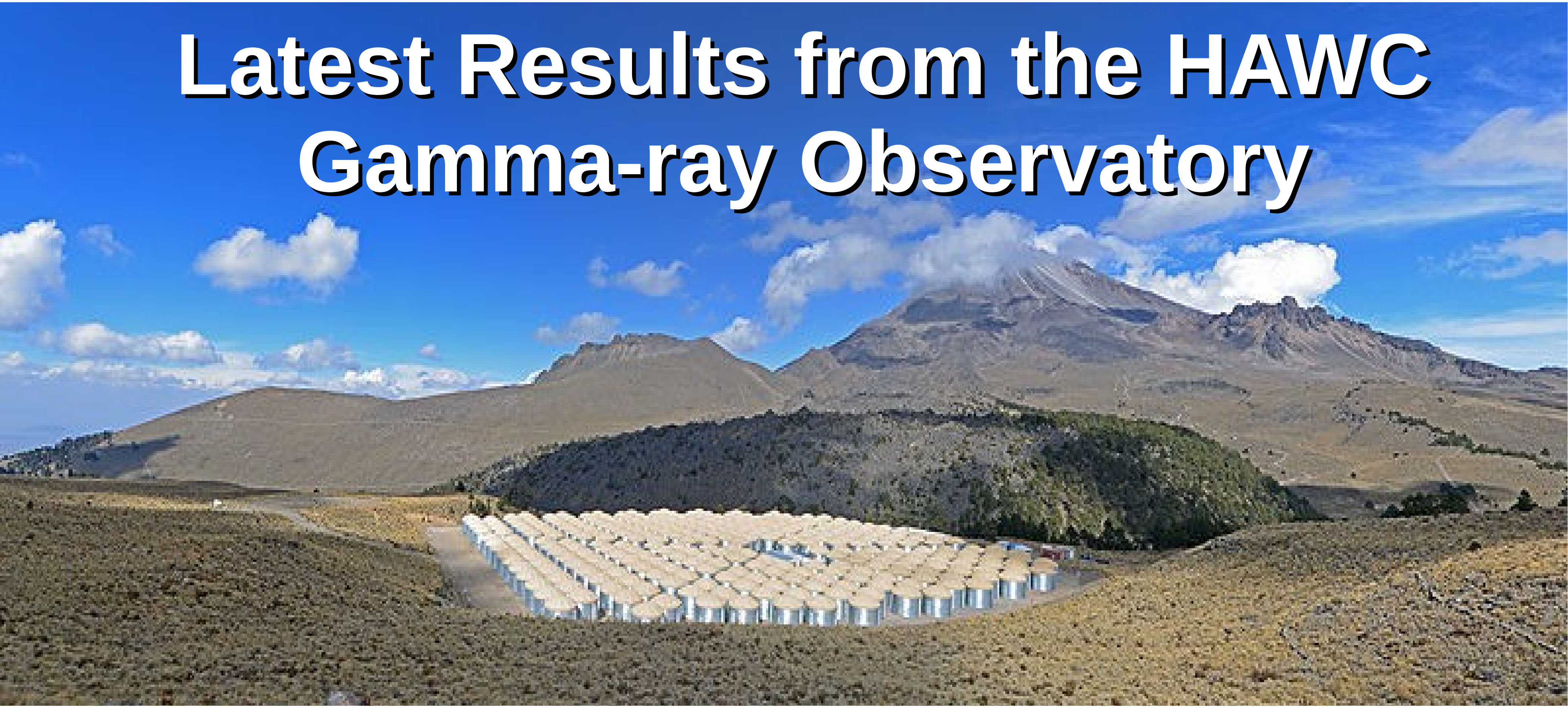
CPPM

Dec 7th Marseilles, France

Latest Results from the HAWC Gamma-ray Observatory

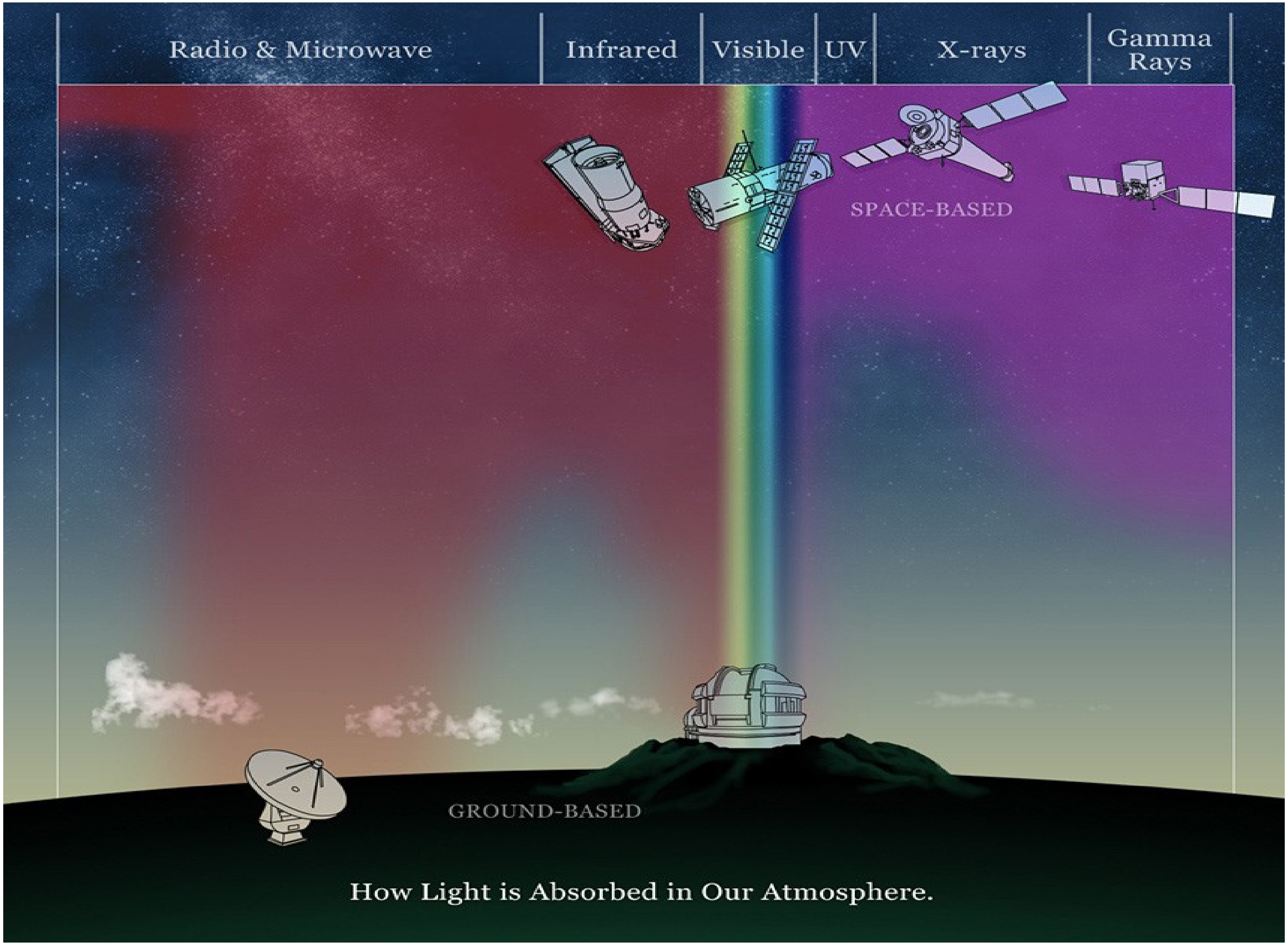


HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

Francisco Salesa Greus
IFJ-PAN, Krakow, Poland

ifj

Astronomy with Photons



Gamma-Ray Observatories

Wide FOV continuous operation

TeV sensitivity

Satellites

AGILE
EGRET
Fermi-LAT

EAS

Milagro
Tibet ASγ
ARGO-YBJ
HAWC

IACT

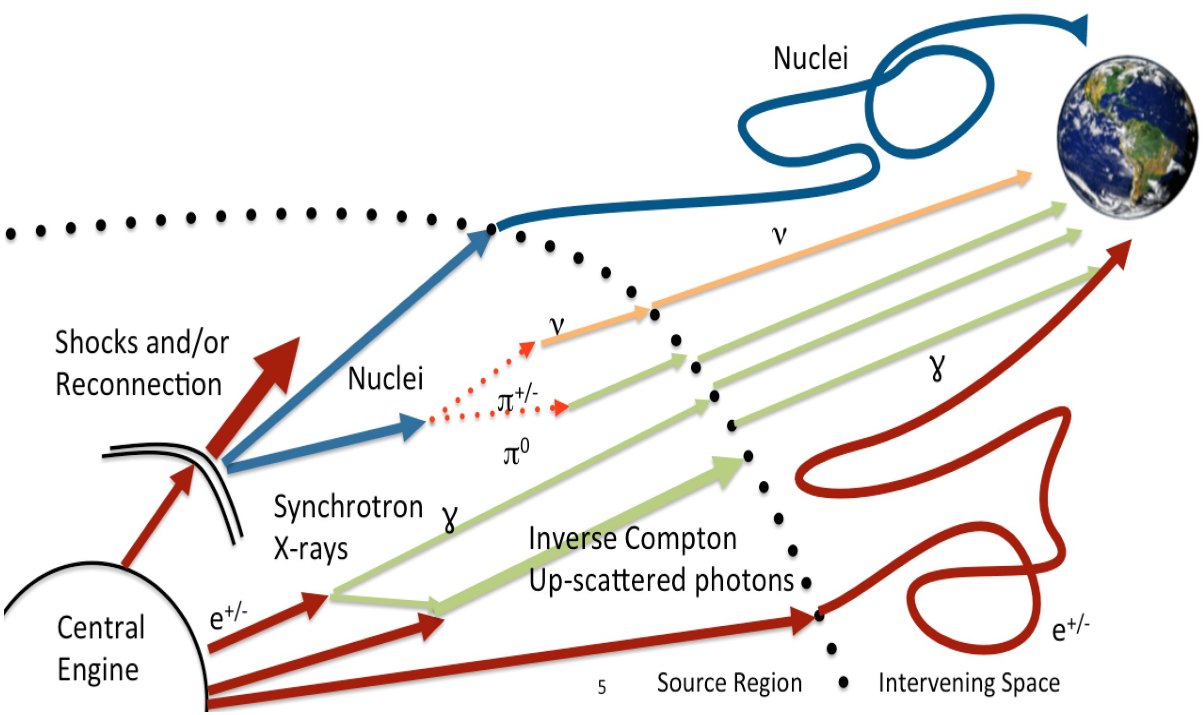
H.E.S.S.
MAGIC
VERITAS
CTA

Space-based

Ground-based

Extensive Air Shower Arrays: Scientific Motivation

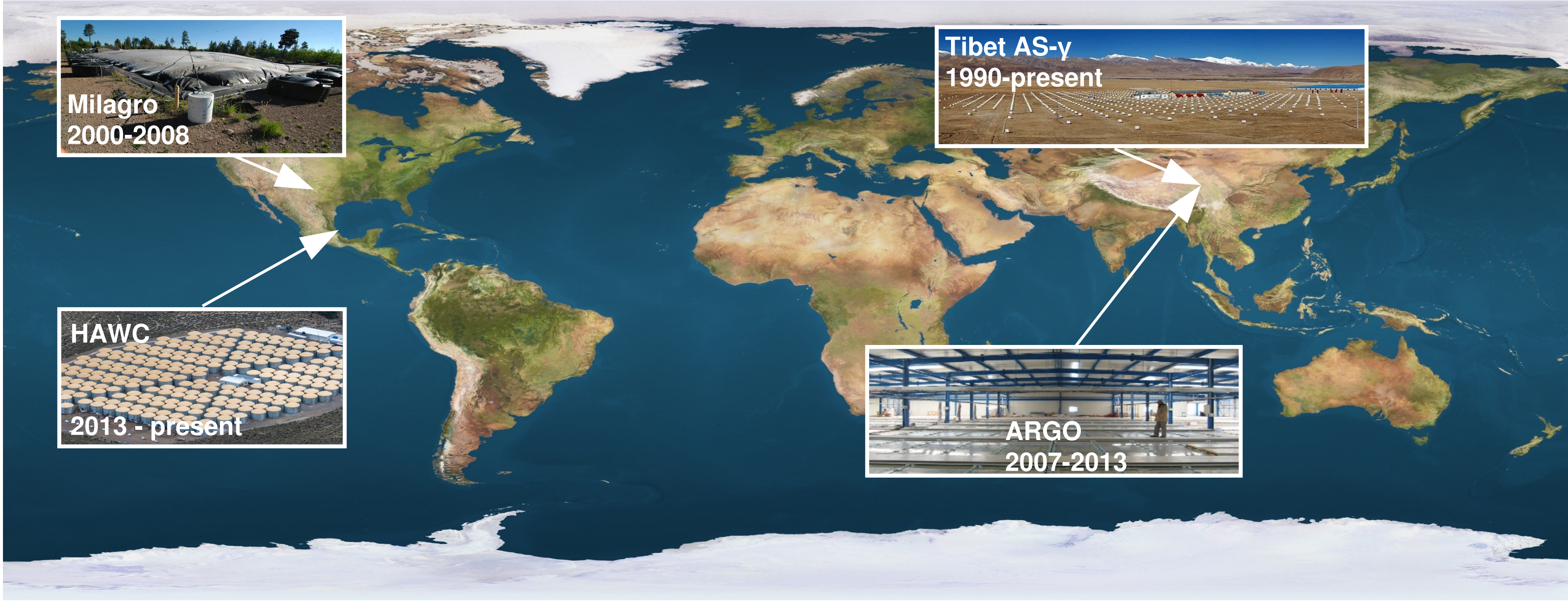
- Main features:
  - Large active area >10^4 m^2.
  - High duty cycle >90%.
  - Large FOV (~2sr).



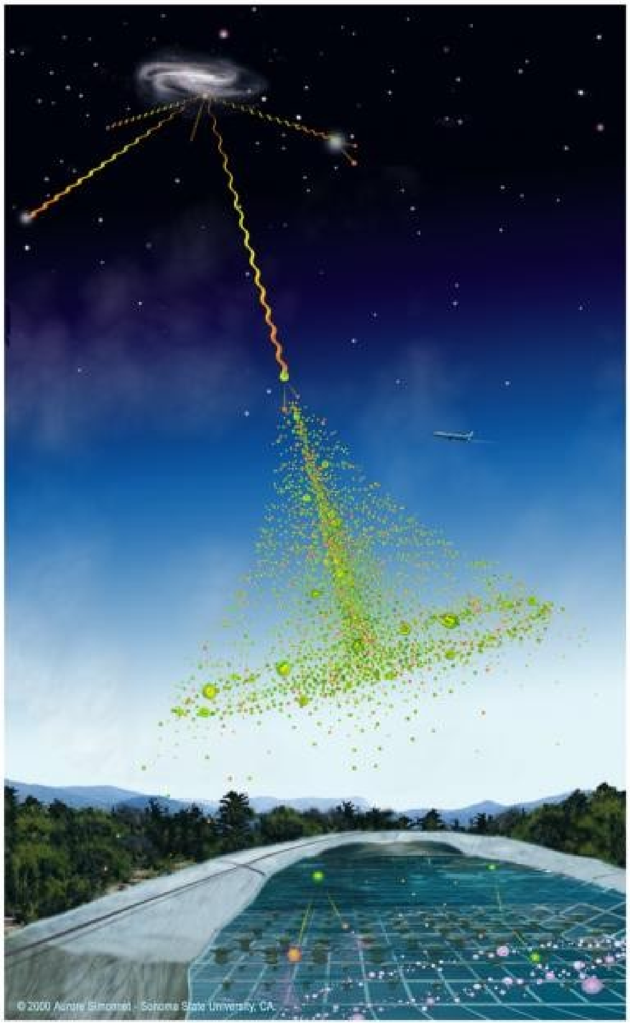
- Some scientific topics:
  - Study the highest energy gamma-rays (>10 TeV). Distinguish the gamma-ray emission: hadronic or leptonic.
  - Continuous observation: Transient phenomena and flaring sources (e.g. GRBs, AGNs).
    Long duration light curves and multi-wavelength follow-up.
  - Large gamma-ray structures: extended sources, Galactic Plane emission, Fermi bubbles.
  - Cosmic ray physics.

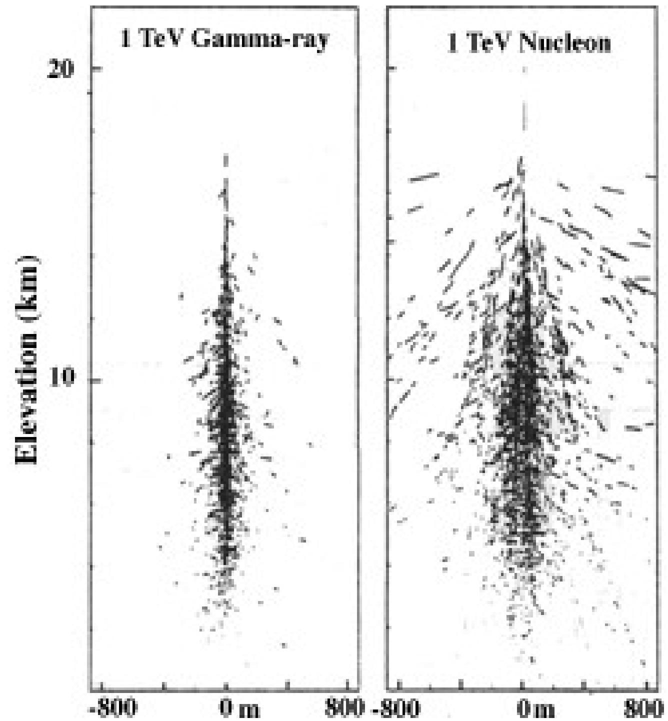
EAS Detectors

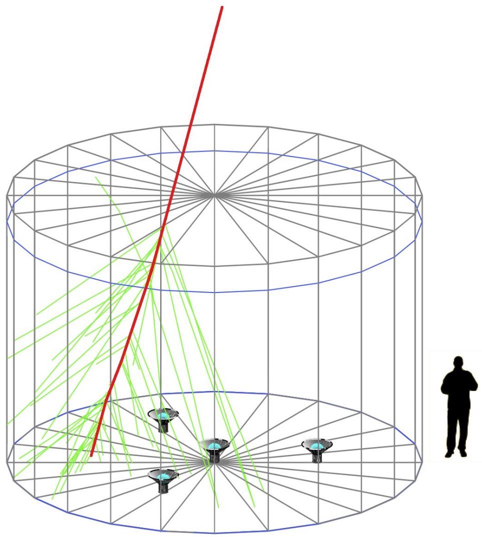
- Several EAS arrays have been operational using different detection techniques.
- It is time for second generation experiments like HAWC.



Detection Technique of the EAS Arrays



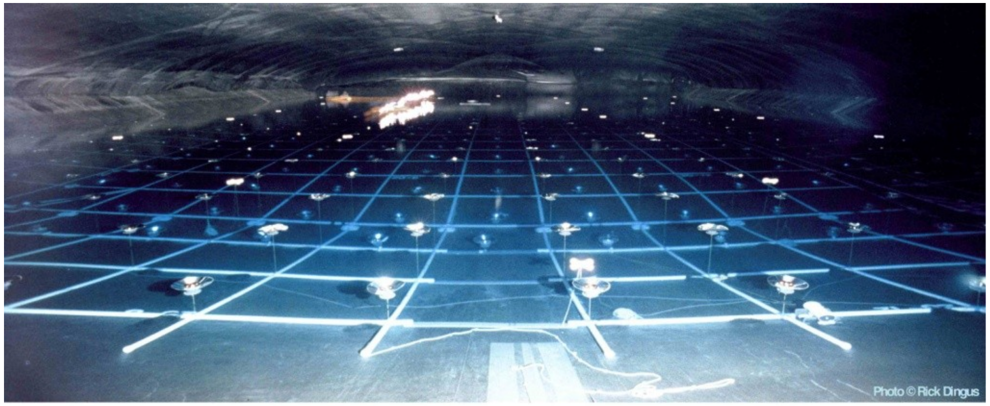


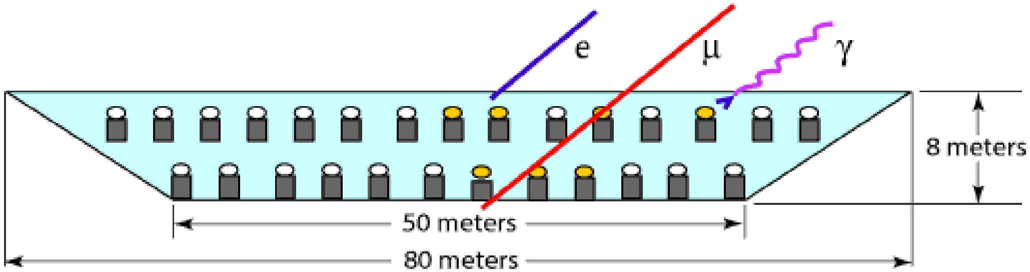


- The particle detectors can be tanks full of water. Particles from the shower pass through the water and induce Cherenkov light detected by PMTs.
- Gamma/hadron can be discriminated based on the event footprint on the detector. Although is one of the challenges of this kind of detectors.

Milagro Gamma-Ray Observatory

- Milagro (2000-2008) was the HAWC predecessor.
- First generation of EAS, proof of the concept.
- It had 450+273 PMTs installed in a water pond at LANL (NM, USA) at 2630m a.s.l.
- Energy threshold ~300 GeV.

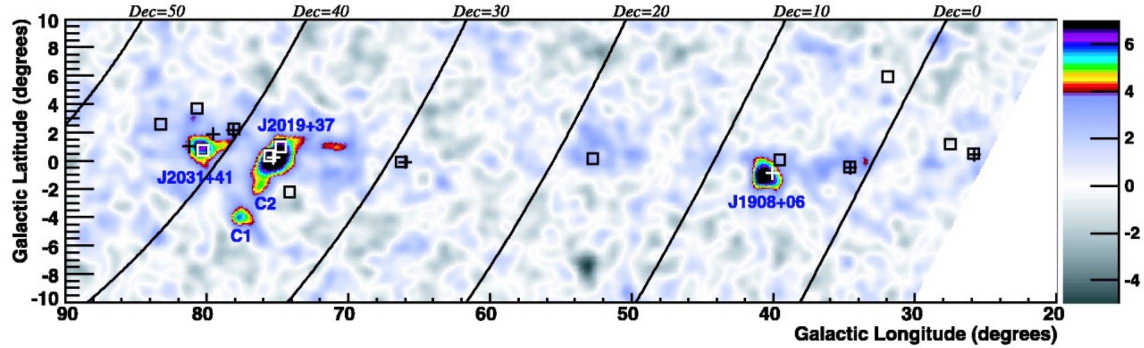


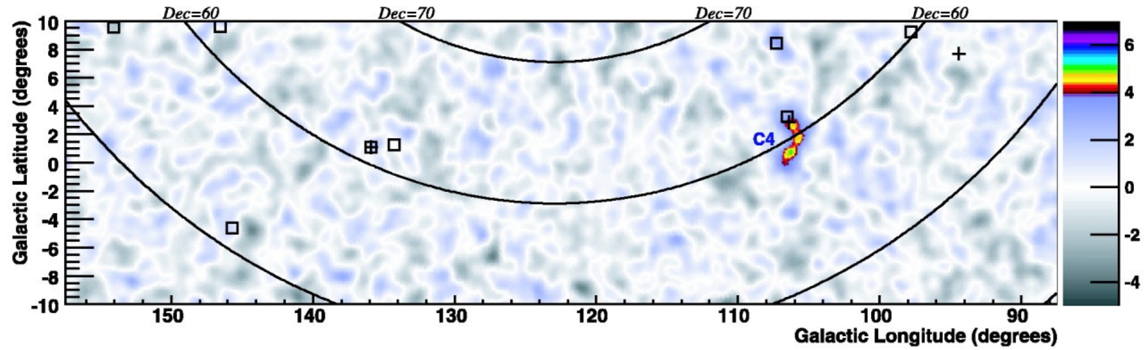


Milagro Highlight Results (I)

- Deepest survey of sources in the Galactic Plane at 20 TeV energy:
  - 8 sources with >4.5σ pre-trial (4 of them >4σ post-trial).
  - Discovery of 2 new sources: Cygnus region (C2) reported later by Fermi as PSR, and Geminga (C3).

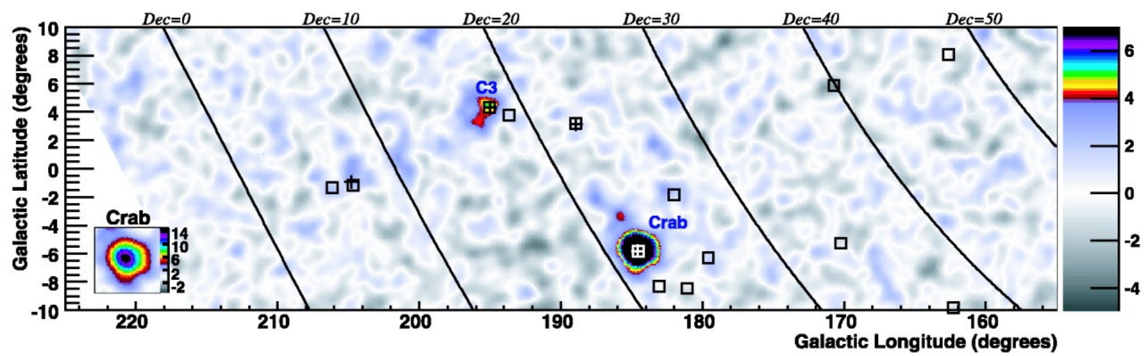
  ApJ **664 (2007) L91–L94**.





- Multi-TeV emision detection (>3σ) of 14 out of a list of 34 Fermi GeV bright sources.

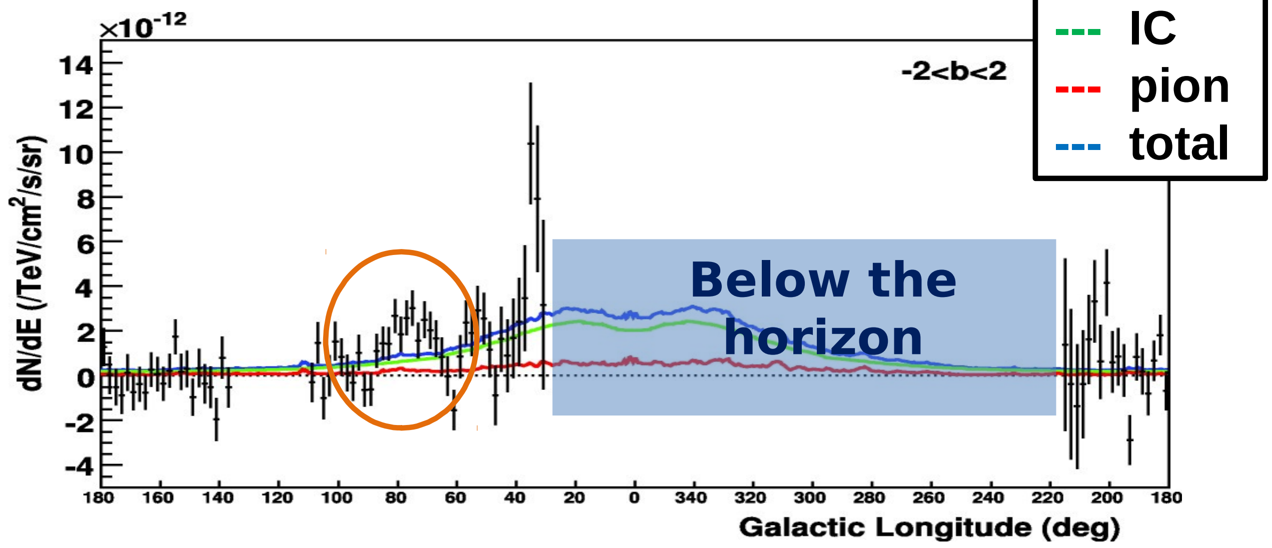
  ApJ **700 (2009) L127–L131**.

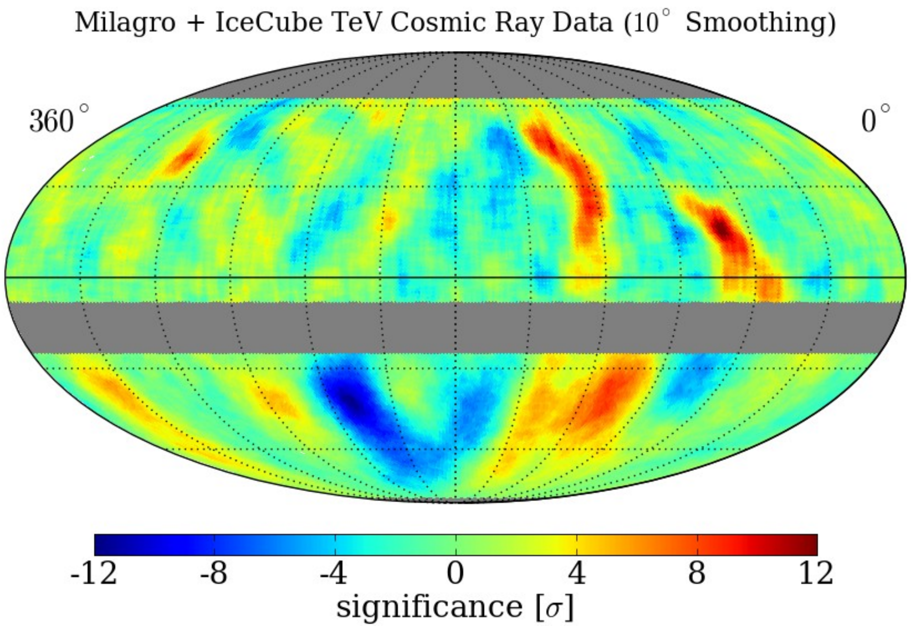


Milagro Highlight Results (II)

- Diffuse TeV emission from the Galactic Plane (sources subtracted).

ApJ **688 (2008) 1078-1083**.





- Unexpected anisotropy on the arrival of the cosmic rays. Confirmed later by other experiments like IceCube.

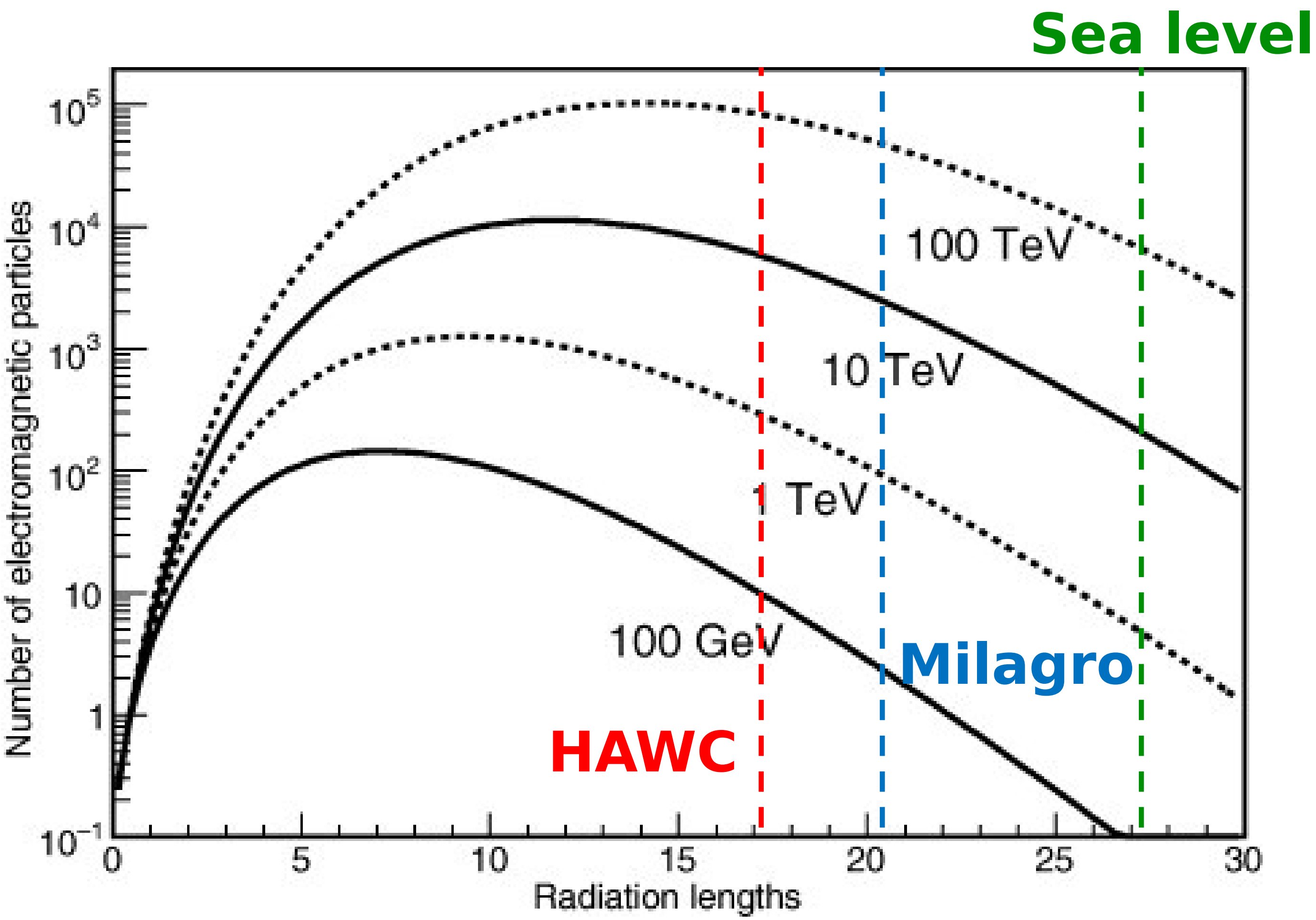
Milagro: **Abdo, et al. PRL, 2009**
IceCube: **R. Abbasi, et al., ApJ 2011**

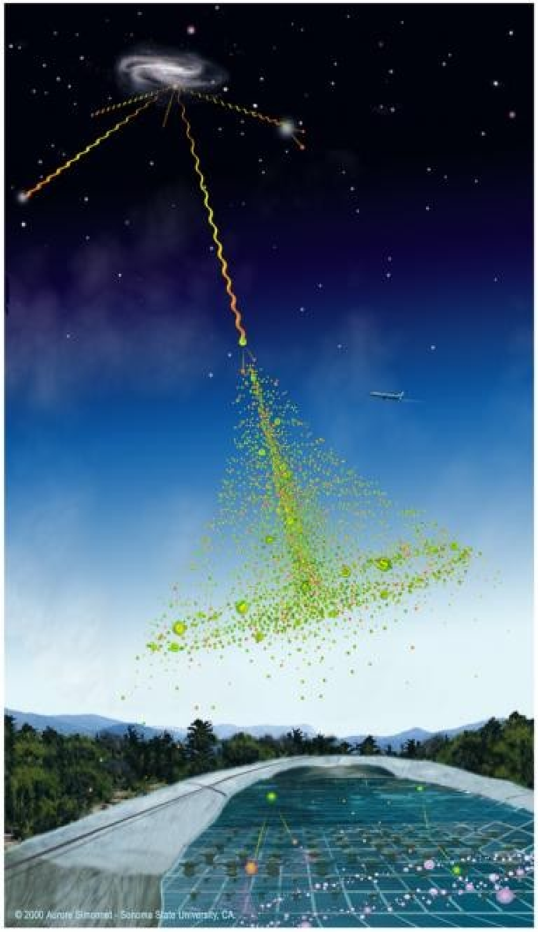
From Milagro to HAWC

- Milagro was the proof of concept.
- A second generation EAS detector is needed to complement the (more sensitive) IACT observations.
- How do you make a better detector?

From Milagro to HAWC

- Higher altitude: 2630 m a.s.l. -> 4100 m a.s.l.
- Closer to the shower maximum.





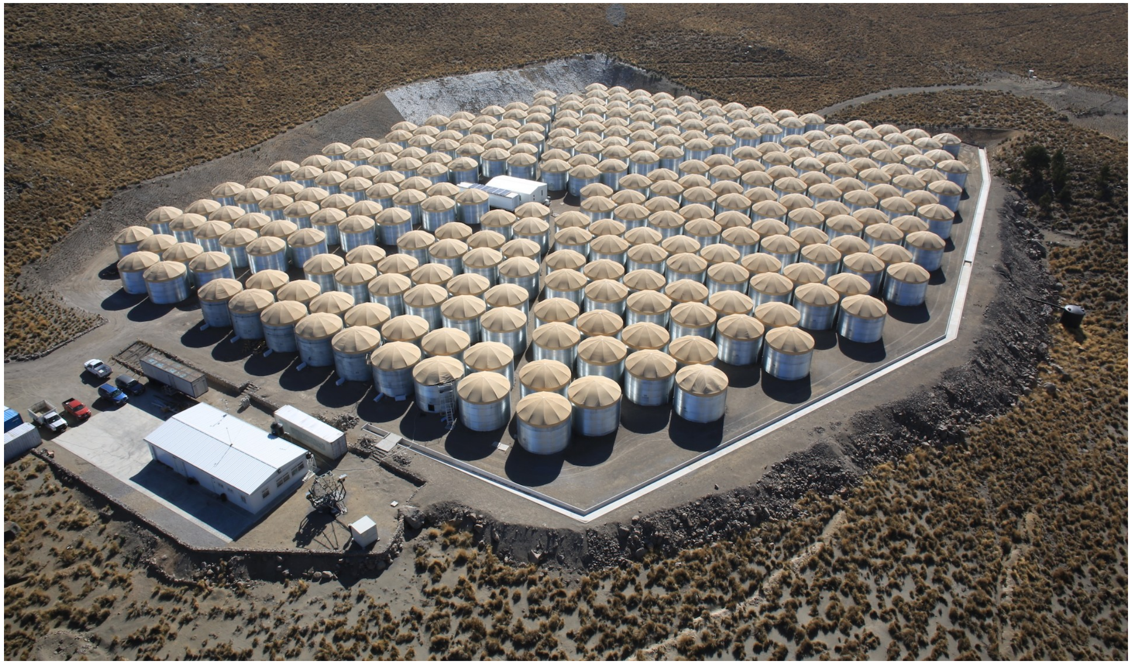
From Milagro to HAWC

- Bigger detector: 4000 m^2 -> 22000 m^2.

Milagro

~60 m x 80 m

HAWC

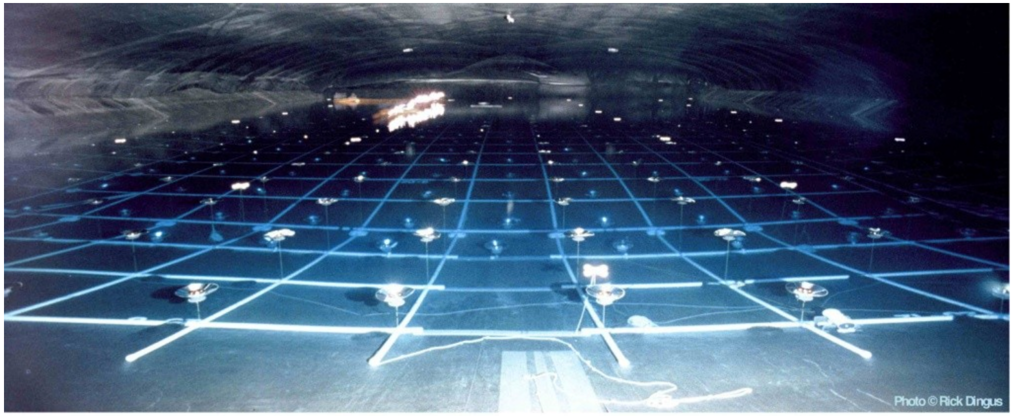


~150 m x 150 m

From Milagro to HAWC

- Improve optical separation:
  one big pond -> individual water Cherenkov detectors (a.k.a. tanks)
- Taking data even during construction.

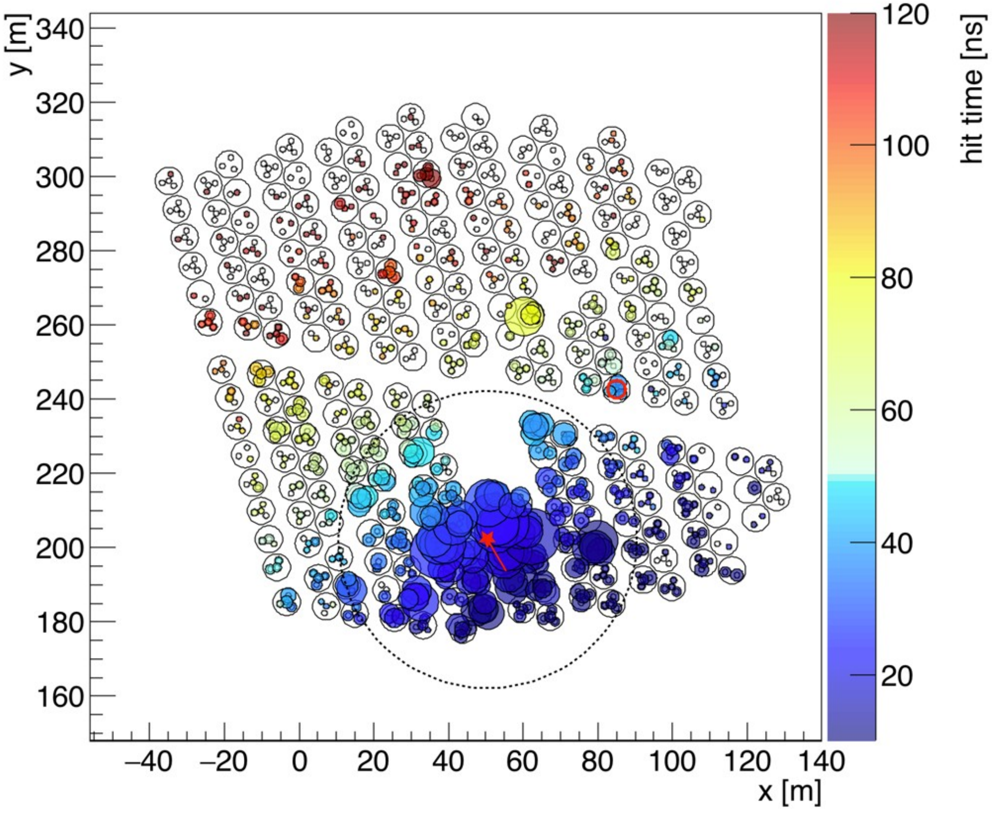
Milagro



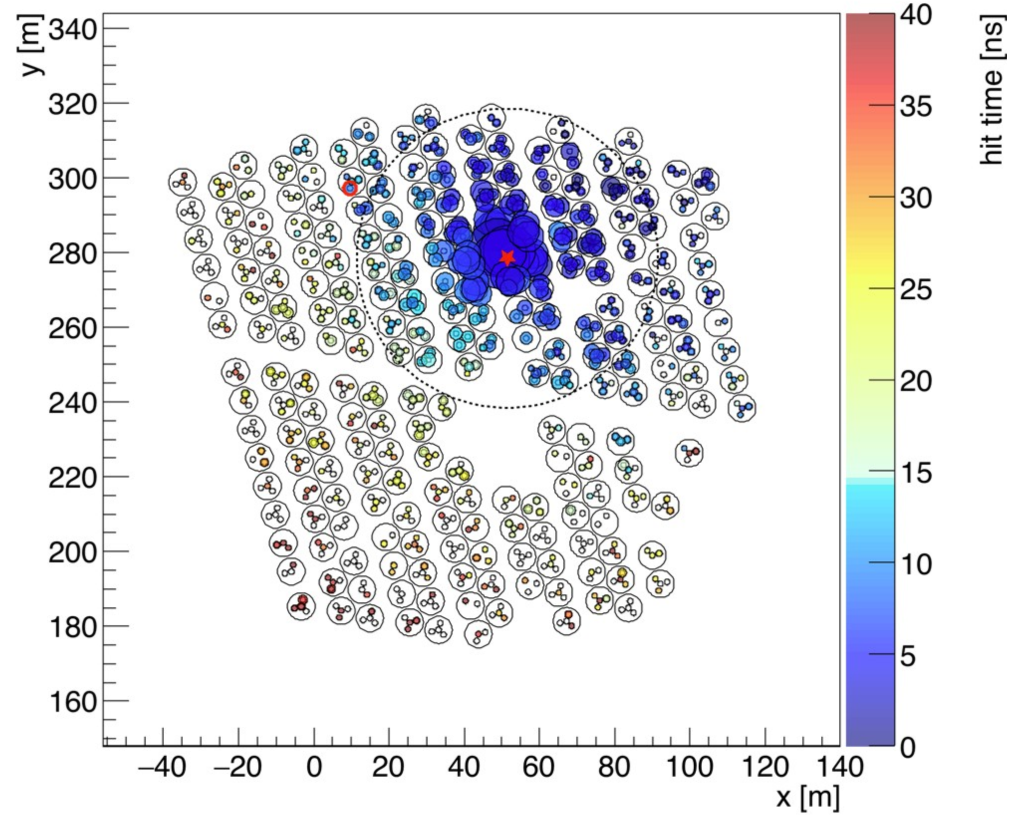
Gamma/Hadron Separation

- Main background is hadronic CR, e.g. 400 γ/day from the Crab vs 15k CR/s.
- In gamma-ray showers, most of the signal at ground level is located near the shower axis.
- In charged cosmic rays tend to "break apart”, much messier signals at ground level.

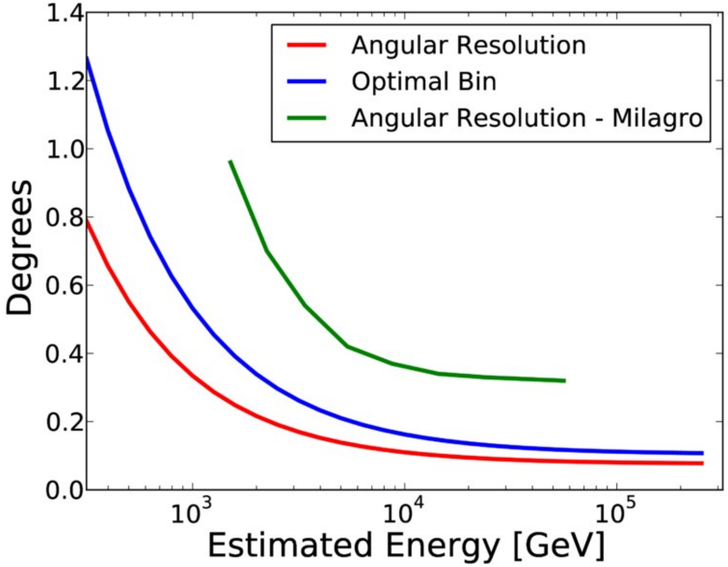
HAWC Data – Hadron Shower



HAWC Data – Likely Gamma Ray

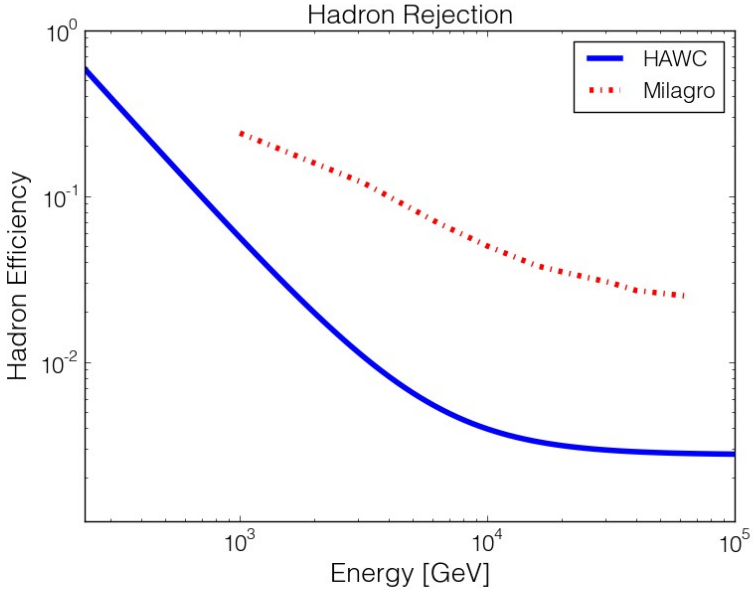


HAWC Performance

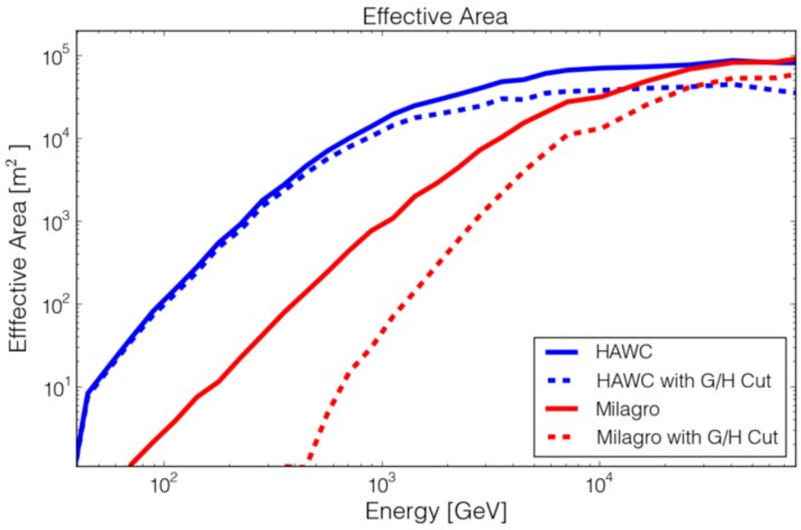


Much Better Angular Resolution

Much Better Background Rejection

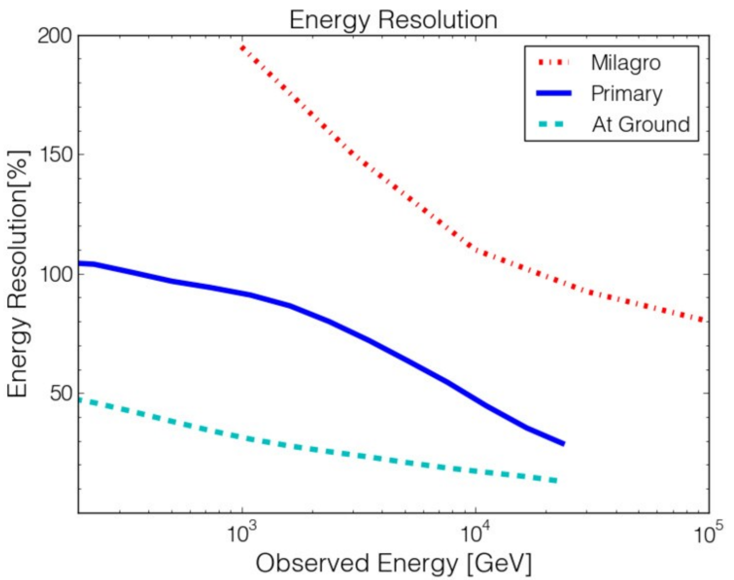


Overall x15 Milagro sensitivity



Much Better Low Energy Response

Better Energy Resolution



HAWC Collaboration

USA:
Pennsylvania State University
University of Maryland
Los Alamos National Laboratory
University of Wisconsin
University of Utah
Univ. of California, Irvine
University of New Hampshire
University of New Mexico
Michigan Technological University
NASA/Goddard Space Flight Center
Georgia Institute of Technology
Colorado State University
Michigan State University
University of Rochester
University of California Santa Cruz

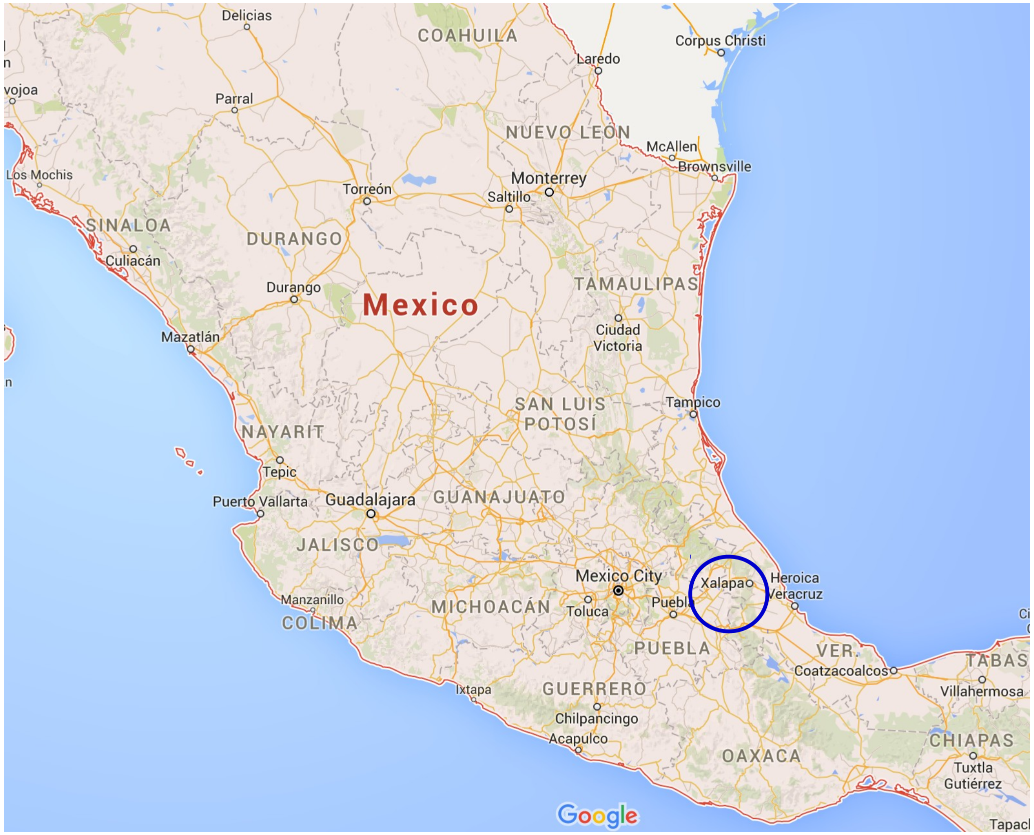
Mexico:
Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE)
Universidad Nacional Autónoma de México (UNAM)
    Instituto de Física
    Instituto de Astronomía
    Instituto de Geofísica
    Instituto de Ciencias Nucleares
Universidad Politécnica de Pachuca
Benemérita Universidad Autónoma de Puebla
Universidad Autónoma de Chiapas
Universidad Autónoma del Estado de Hidalgo
Universidad de Guadalajara
Universidad Michoacana de San Nicolás de Hidalgo
Centro de Investigación y de Estudios Avanzados
Instituto Politécnico Nacional
Centro de Investigación en Computación - IPN

Poland:
Instytut Fizyki Jądrowej im. Henryka Niewodniczańskiego - Polskiej Akademii Nauk

Germany:
Max-Planck-Institut für Kernphysik

HAWC Site

- At the slope of volcano Sierra Negra in the state of Puebla, Mexico.
- High altitude site at 4100 m.
- Latitude of 18°59.7'N, longitude 97°18.6'W.



HAWC Construction

- Feb 2011: beginning of the construction.

HAWC Construction

- Summer 2011: VAMOS engineering array.

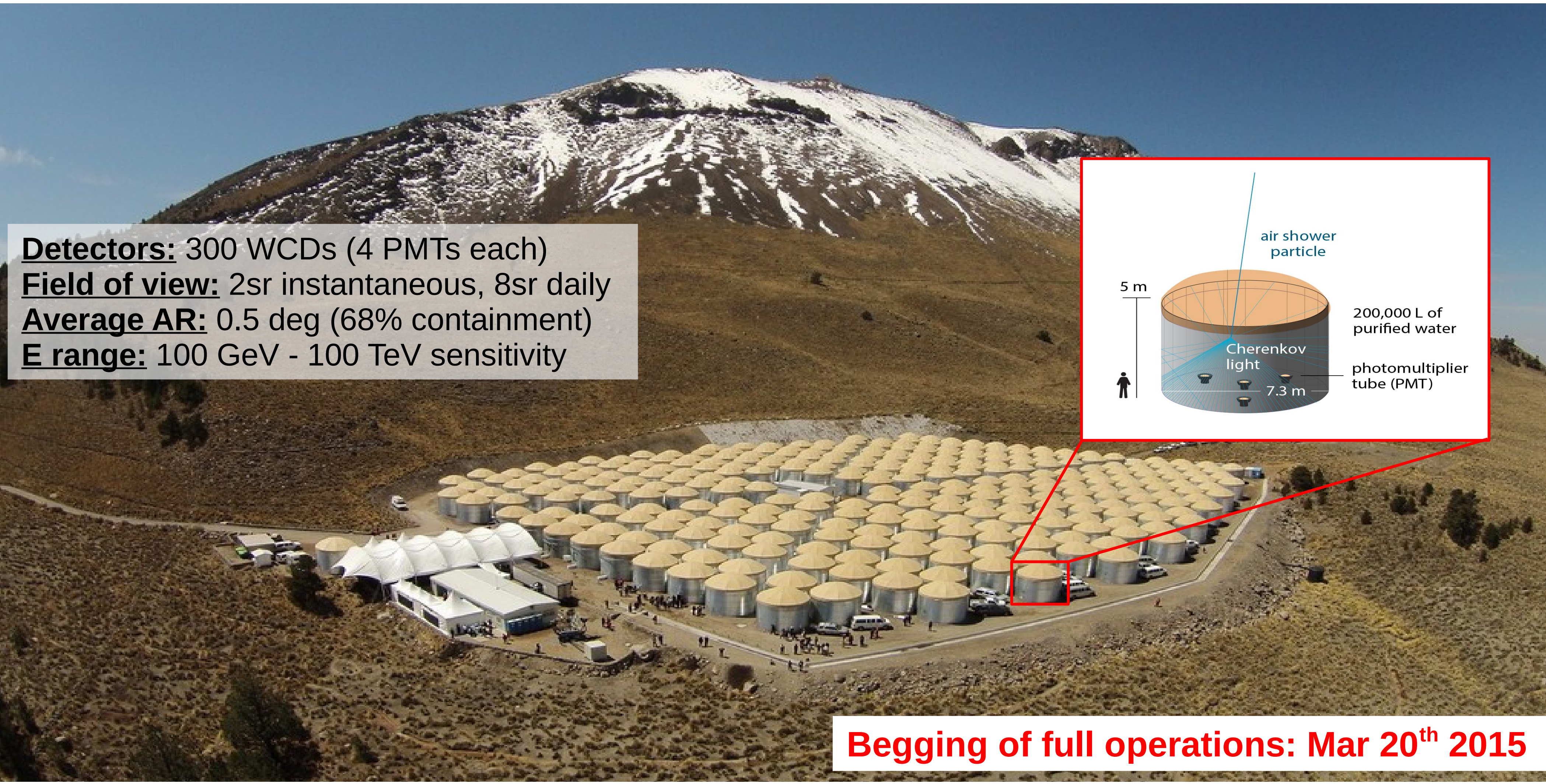
HAWC Construction

- October 2012: 30 WCDs.

HAWC Construction

- August 2013: beginning of science operations.

HAWC Inauguration



Detectors: 300 WCDs (4 PMTs each)
Field of view: 2sr instantaneous, 8sr daily
Average AR: 0.5 deg (68% containment)
E range: 100 GeV - 100 TeV sensitivity

Begging of full operations: Mar 20th 2015

HAWC Water Cherenkov Detector

- 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

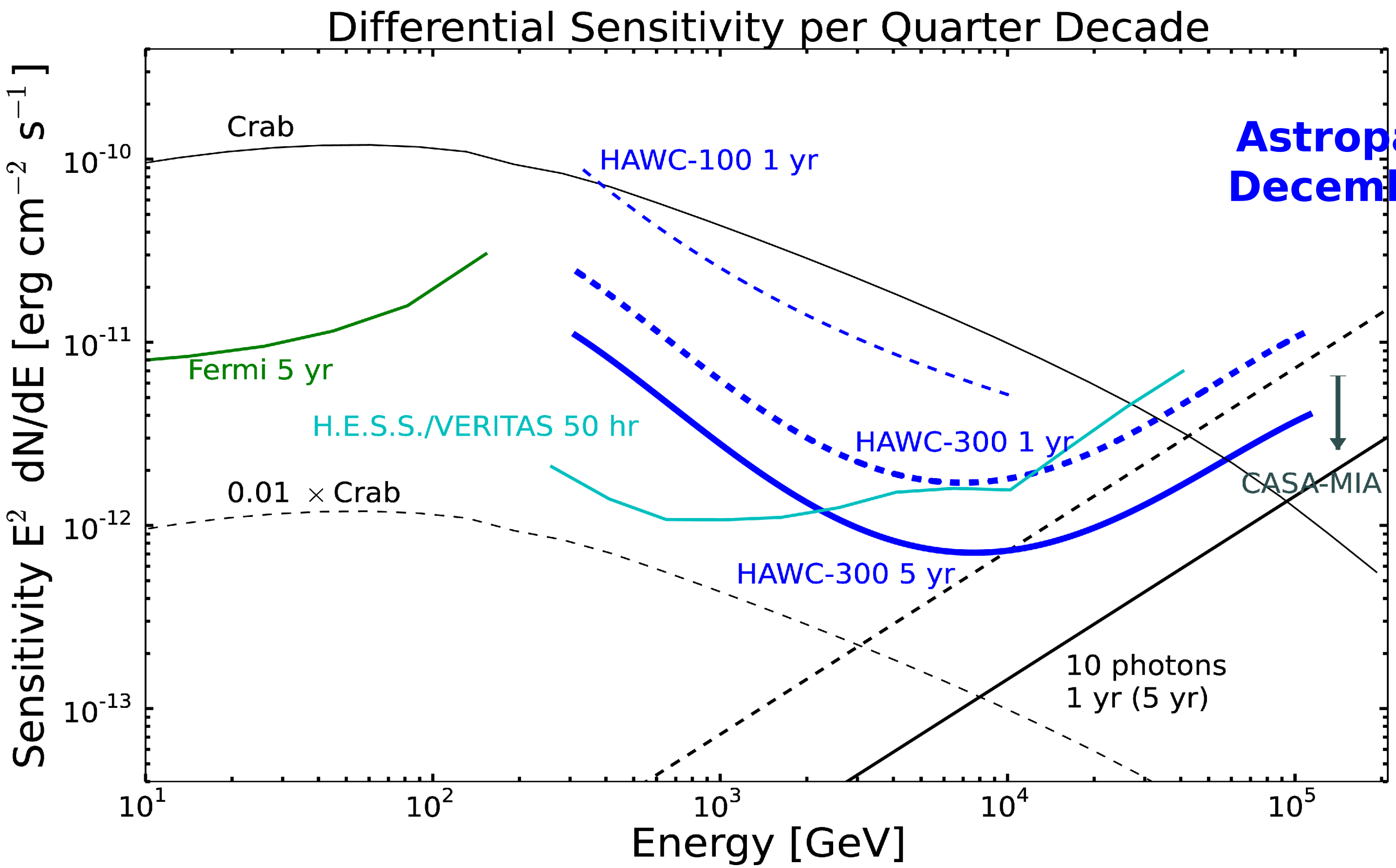
Water trucks filling the tanks

8-inch
10-inch
PMTs

HAWC Designed Sensitivity

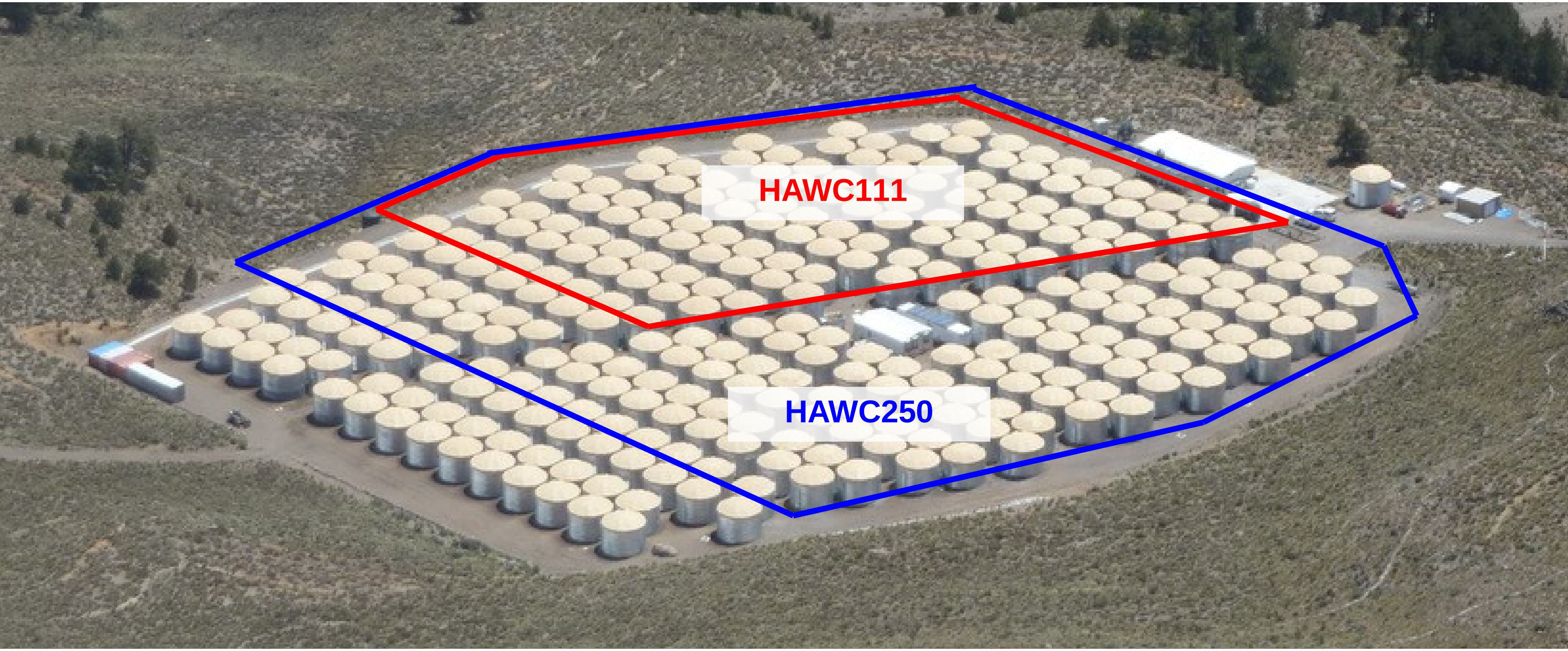
- Instantaneous sensitivity 15-20x less than IACTs.
- Exposure (sr/yr) is 2000-4000x higher than IACTs.

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



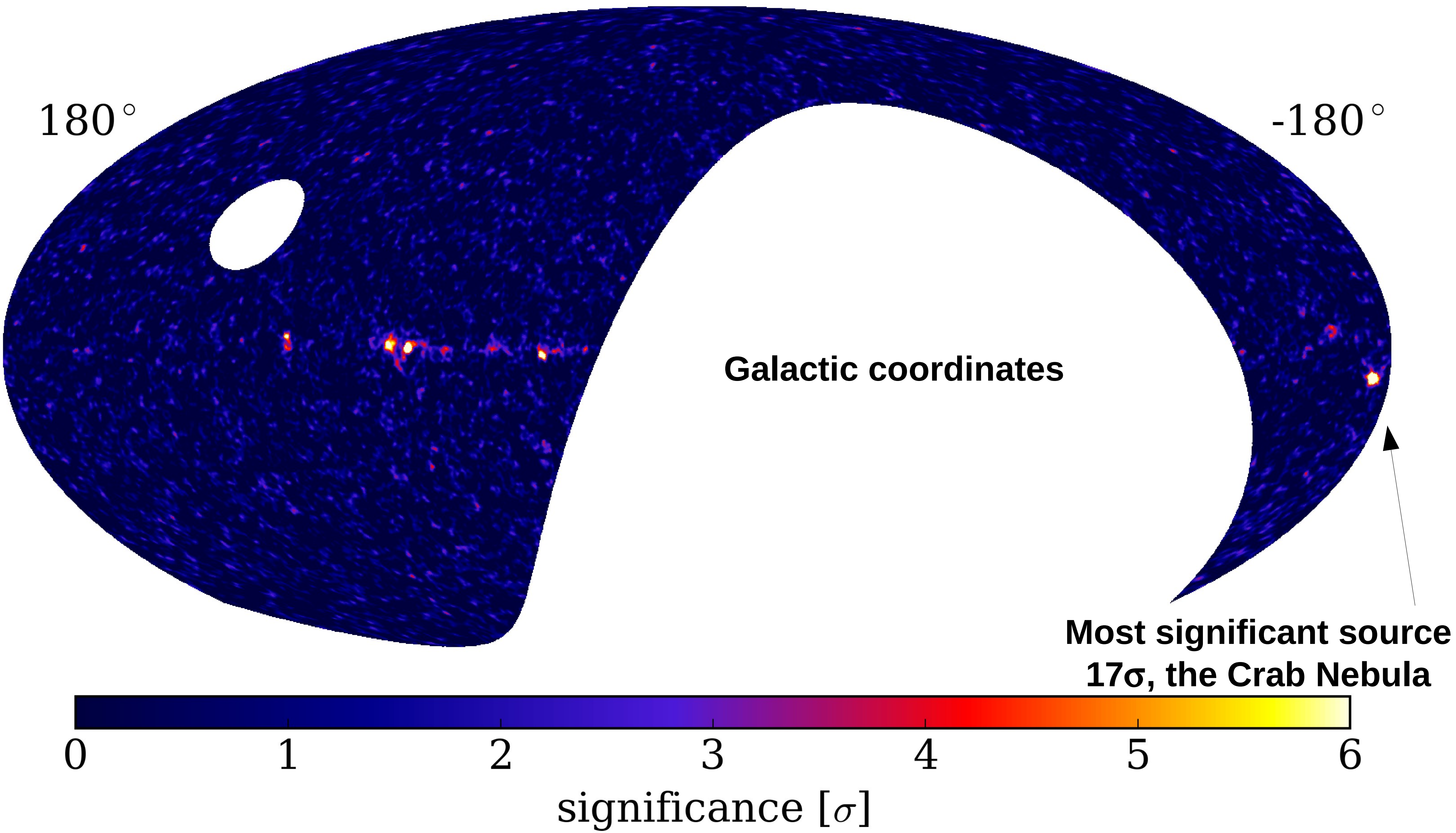
Astropart Phys 50-52, December 2013, 26-32

HAWC Data

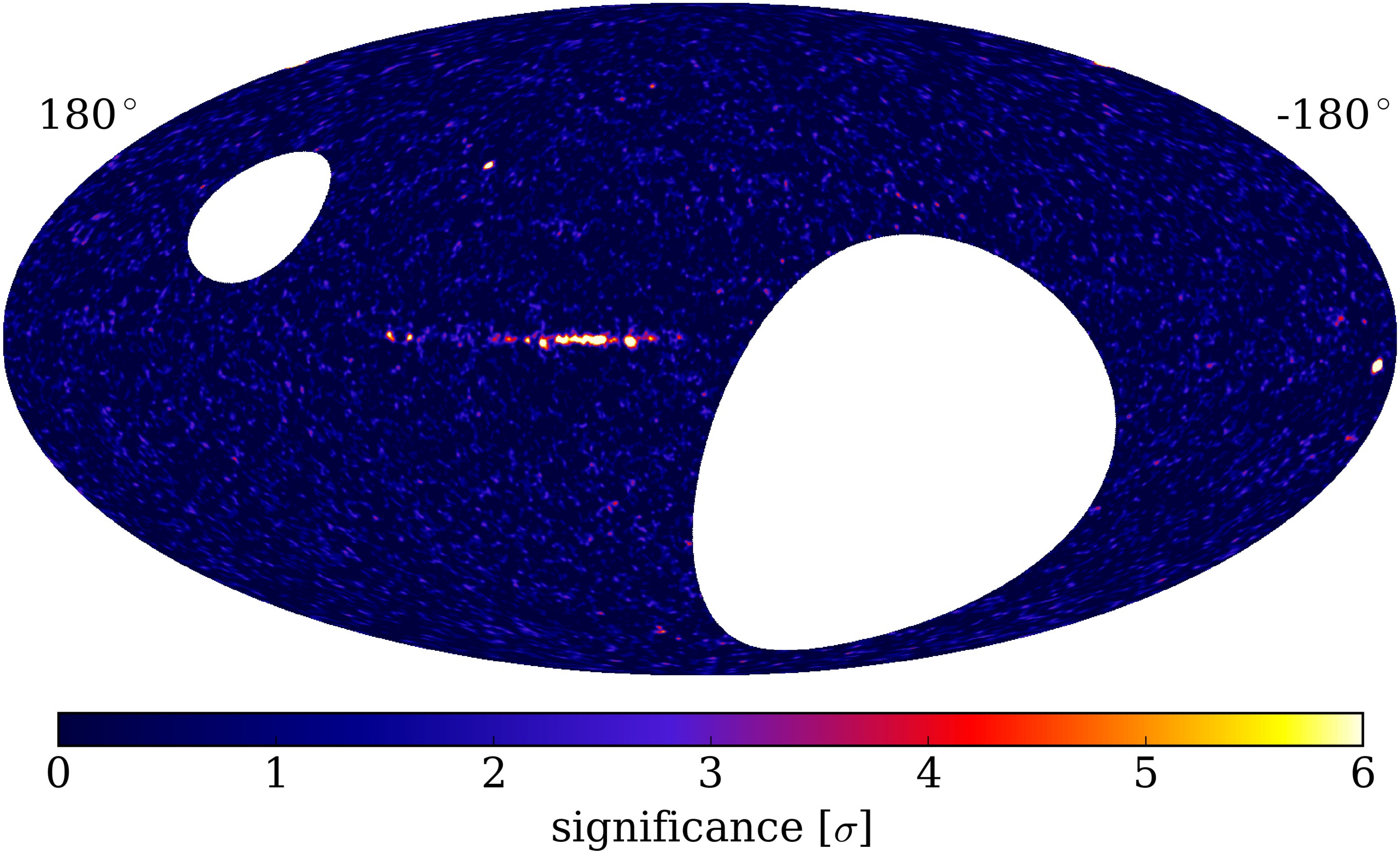


Pass 1: **HAWC111:** Aug 2013 – Jul 2014 (106 - 133 WCDs), 283 days
Pass 3: **HAWC250:** Nov 2014 – Summer 2015 (247 - 293 WCDs), 150 days
Pass 4: coming next winter, >1 year.

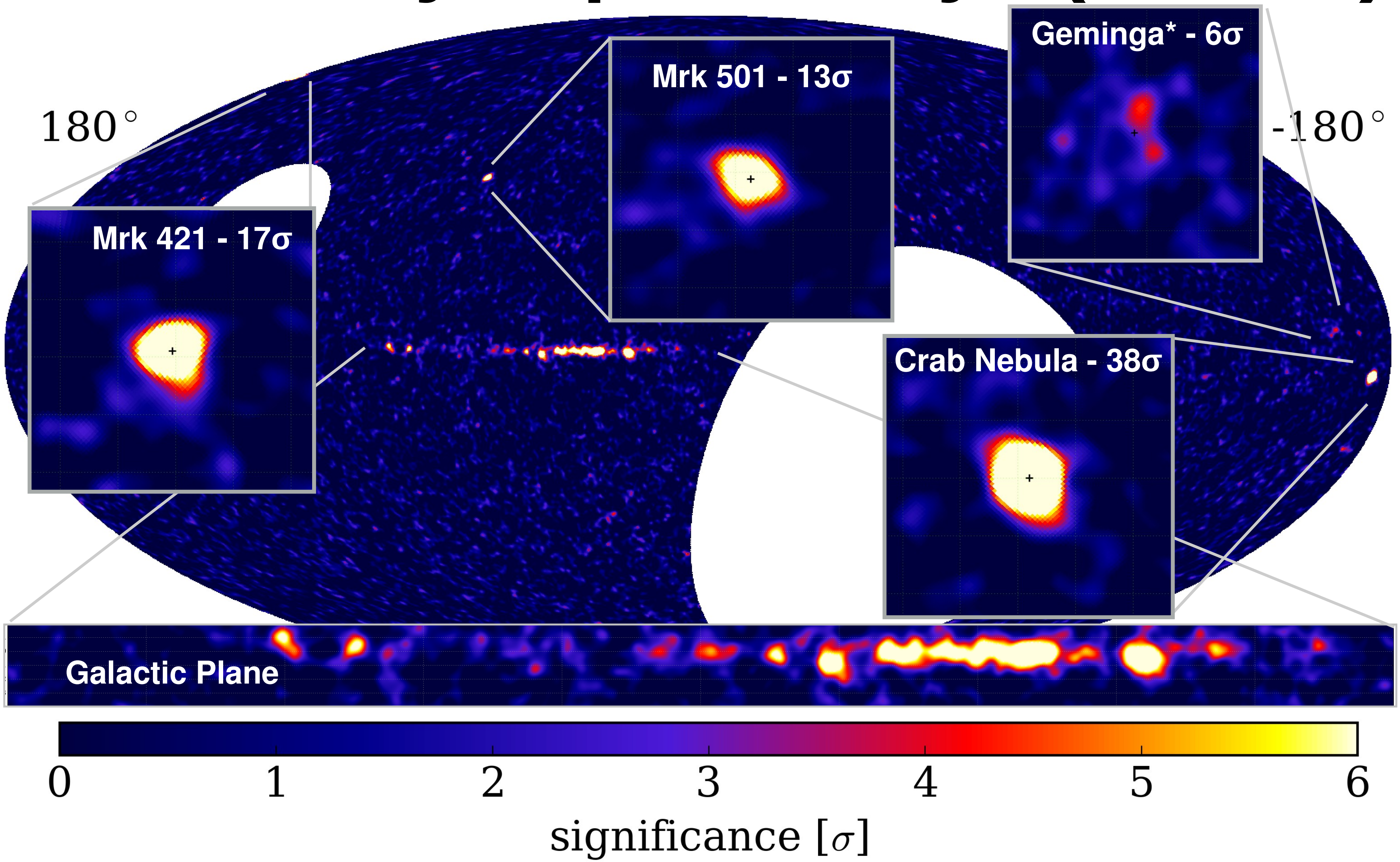
Milagro 8-Year TeV Sky Survey



HAWC SkyMap 150 Days (Pass 3)

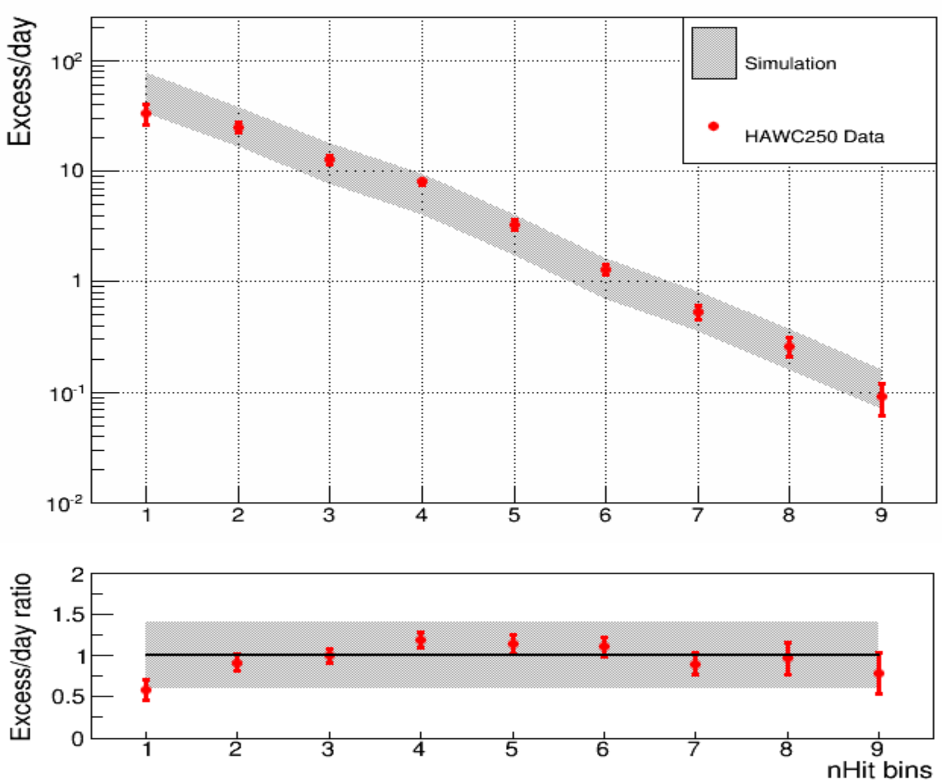


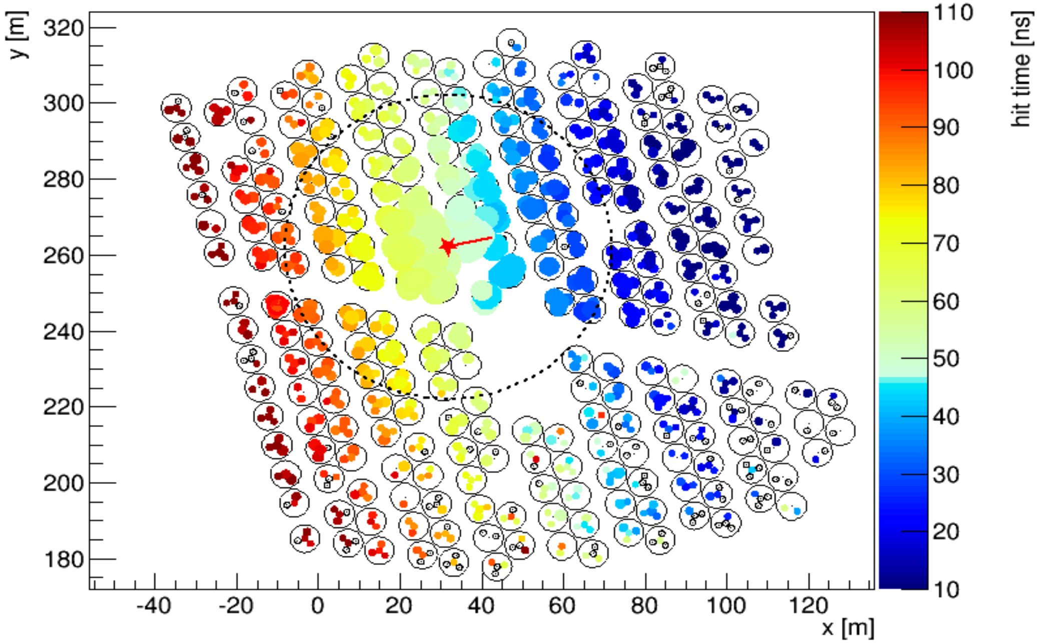
HAWC SkyMap 150 Days (Pass 3)



The Crab Nebula

- Crab Nebula detected with high significance ~38σ in 150 days (Pass 3).
- Data/MC agreement within uncertainties.
- Signal:background ratio of almost 10:1 in the last analysis bin.

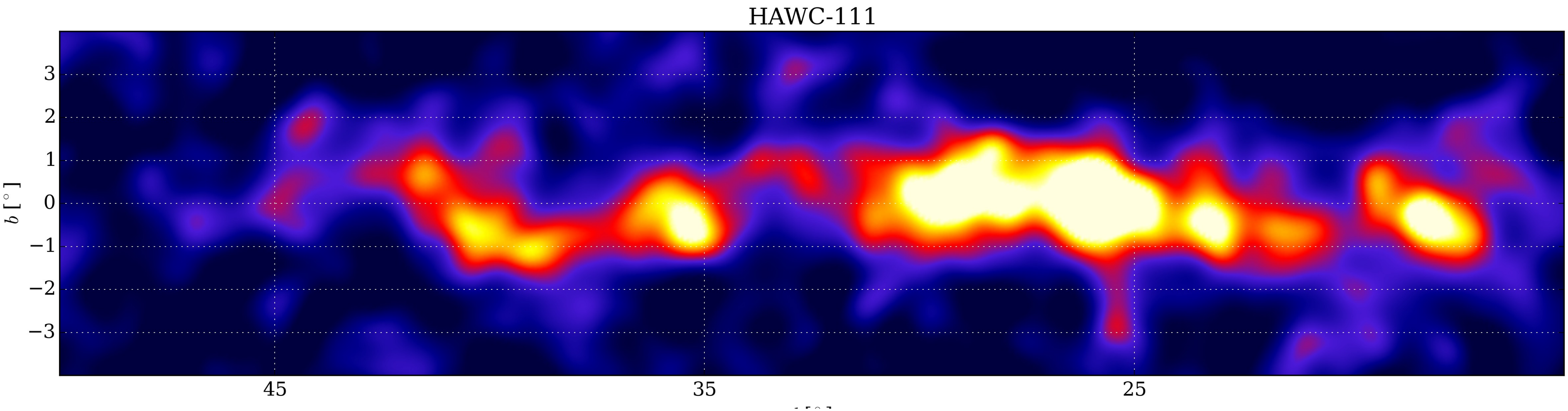




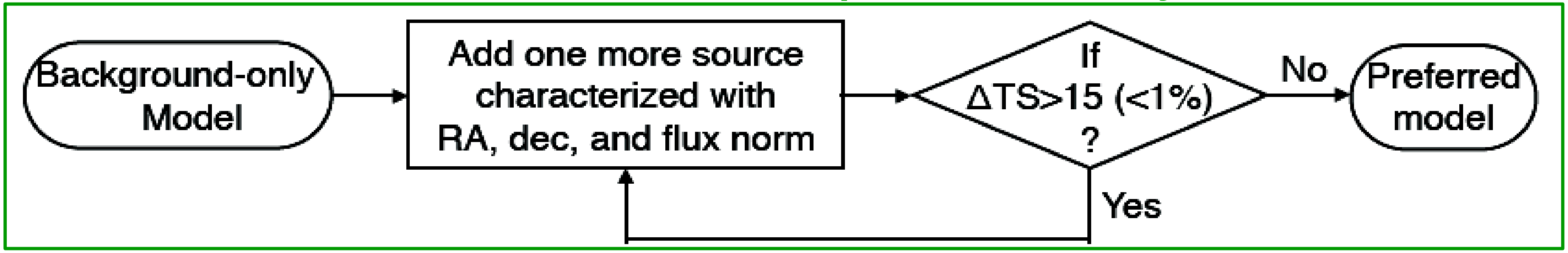
Bin	frac. NHit	angular bin radius (deg)	E (TeV)	excess	back	signif
1	0.07-0.10	1.33	0.60	4900	9.6×10^5	4.8
2	0.10-0.16	0.93	0.94	3700	1.53×10^5	9.2
3	0.16-0.25	0.83	1.4	1900	2.5×10^4	11.6
4	0.25-0.36	0.7	2.3	1200	7200	13.5
5	0.36-0.48	0.73	3.8	490	1550	11.6
6	0.48-0.62	0.65	6.0	191	180	12.1
7	0.62-0.74	0.55	9.8	79	32	10.6
8	0.74-0.84	0.45	14	39	10.4	8.4
9	0.84-1.00	0.4	24	13.5	1.53	6.2

HAWC GP Survey

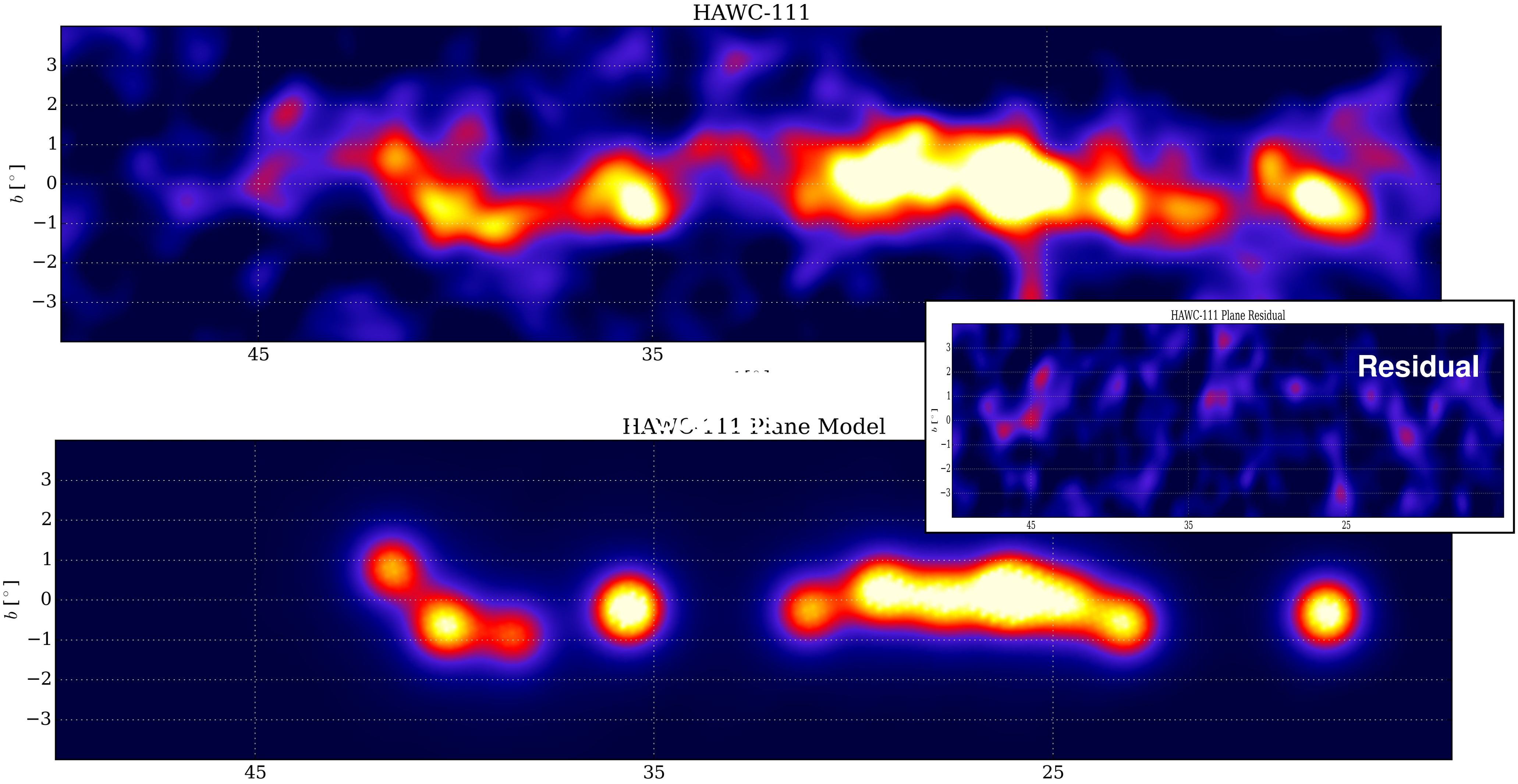
- First GP survey with 1/3 of the detector for 283 days (**Pass1:** Crab >20σ in this data set).
- Five ROI analyzed in the region: l in [+15º,+50º], b in [-4º,+4º].



Likelihood method used to perform the analysis



HAWC GP Survey



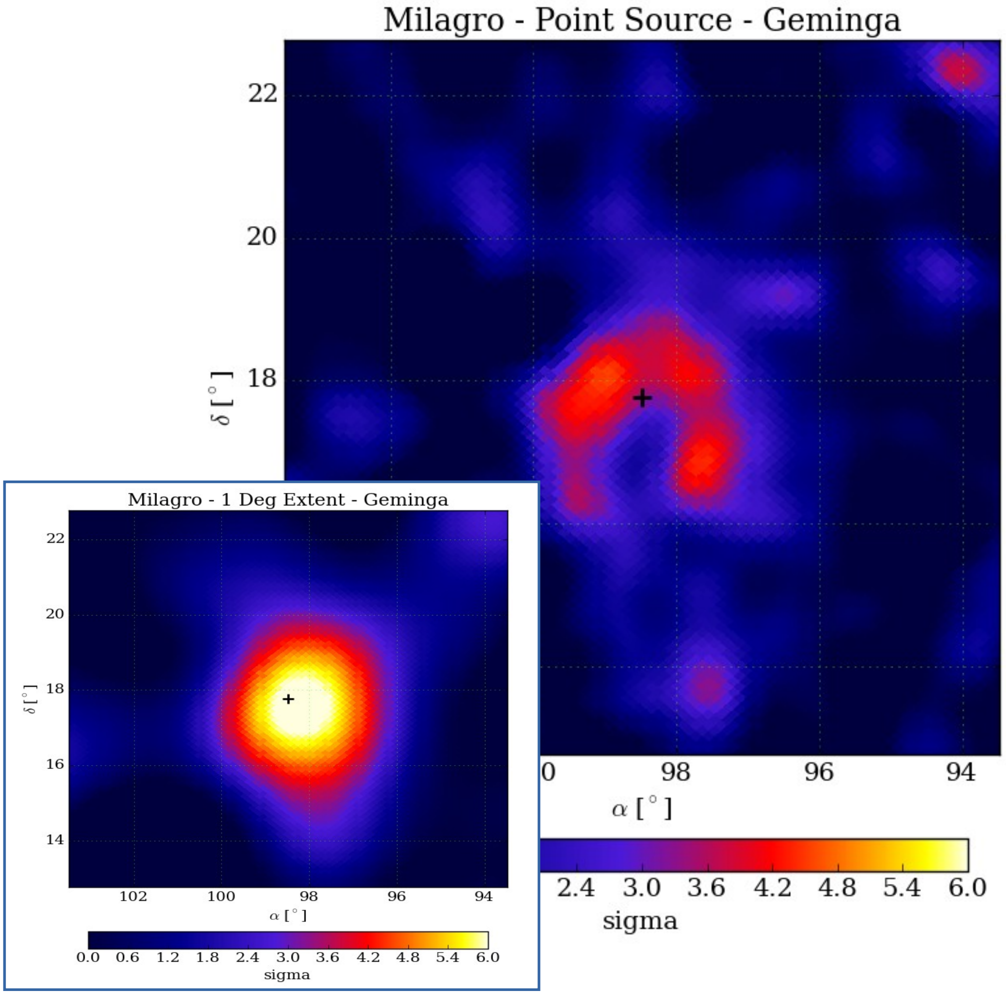
- 10 sources/candidates are >3σ post-trial: 3 firm detections (>5σ) and 7 candidates (<5σ).

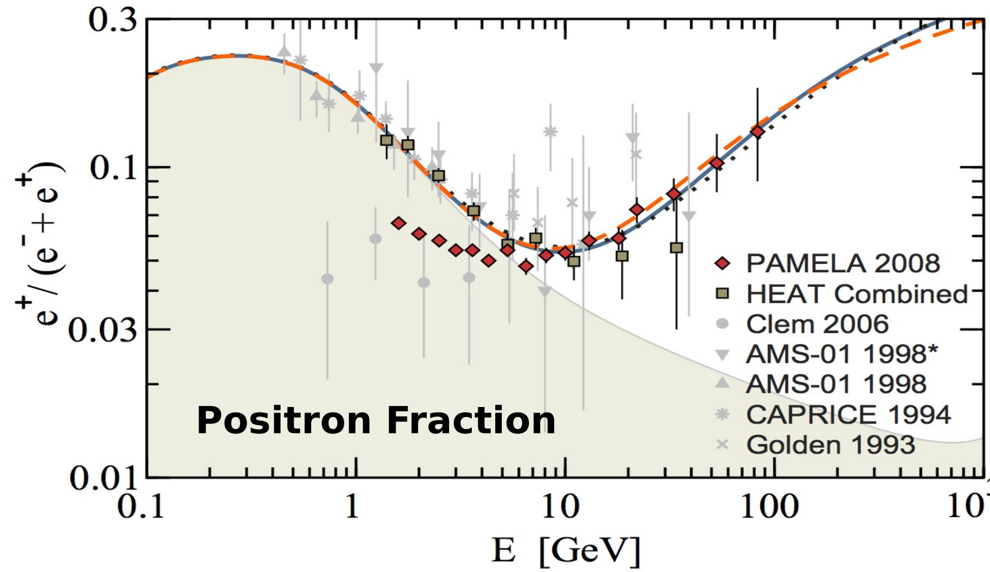
HAWC GP Survey

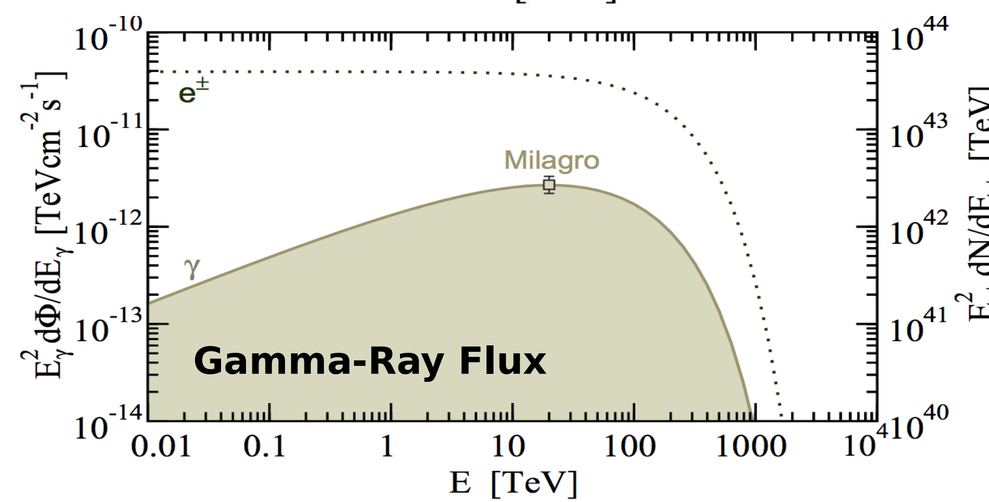
- Paper accepted in ApJ. **arXiv:1509.05401**

Region	Source[a]	ΔTS[b]	RA (°)[c]	Dec (°)[c]	l (°)[c]	b (°)	Differential Flux (Pivot Energy) (10^{-14}TeV^{-1}cm^{-2}s^{-1})	TS[c]	Post-trials Significance
1	1HWC J1907+062c	40.9	286.8±0.2	6.2±0.2	40.2±0.2	-0.7±0.2	22.0±4.6 (4 TeV)	32.8	4.6 σ
	1HWC J1904+080c	26.8	286.1±0.2	8.0±0.2	41.5±0.2	0.8±0.2	19.0±4.4 (4 TeV)	26.5	3.9 σ
	–	16.2	286.2±0.4	4.5±0.3	38.5±0.4	-0.9±0.4	N/A	17.2	2.5 σ
2	1HWC J1857+023	52.1	284.3±0.2	2.3±0.2	35.6±0.2	-0.2±0.2	18.0±3.0 (5 TeV)	50.2	6.2 σ
3	1HWC J1838-060	74.7	279.6±0.3	-6.0±0.2	26.1±0.3	0.2±0.3	11.3±1.2 (7 TeV)	48.9	6.1 σ
	1HWC J1844-031c	47.4	281.0±0.2	-3.1±0.2	29.3±0.2	0.2±0.2	11.8±2.4 (6 TeV)	33.7	4.7 σ
	1HWC J1849-017c	25.2	282.3±0.3	-1.7±0.2	31.2±0.3	-0.3±0.3	9.1±2.2 (6 TeV)	24.9	3.7 σ
	1HWC J1842-046c	23.7	280.5±0.3	-4.6±0.3	27.8±0.3	0.0±0.3	7.0±1.6 (7 TeV)	23.2	3.4 σ
4	–	70.7	279.7±0.2	-6.1±0.3	26.1±0.3	0.0±0.3	11.3±1.2 (7 TeV)	48.9	same source as J1838-060
	1HWC J1836-090c	33.6	278.9±0.3	-9.0±0.2	23.1±0.3	-0.6±0.3	5.8±1.3 (8 TeV)	26.6	3.9 σ
	1HWC J1836-074c	18.4	279.1±0.3	-7.4±0.3	24.6±0.3	0.0±0.3	6.9±1.4 (7 TeV)	22.0	3.2 σ
5	1HWC J1825-133	40.8	276.3±0.1	-13.3±0.2	18.1±0.2	-0.3±0.2	7.3±1.4 (9 TeV)	40.6	5.4 σ

Geminga



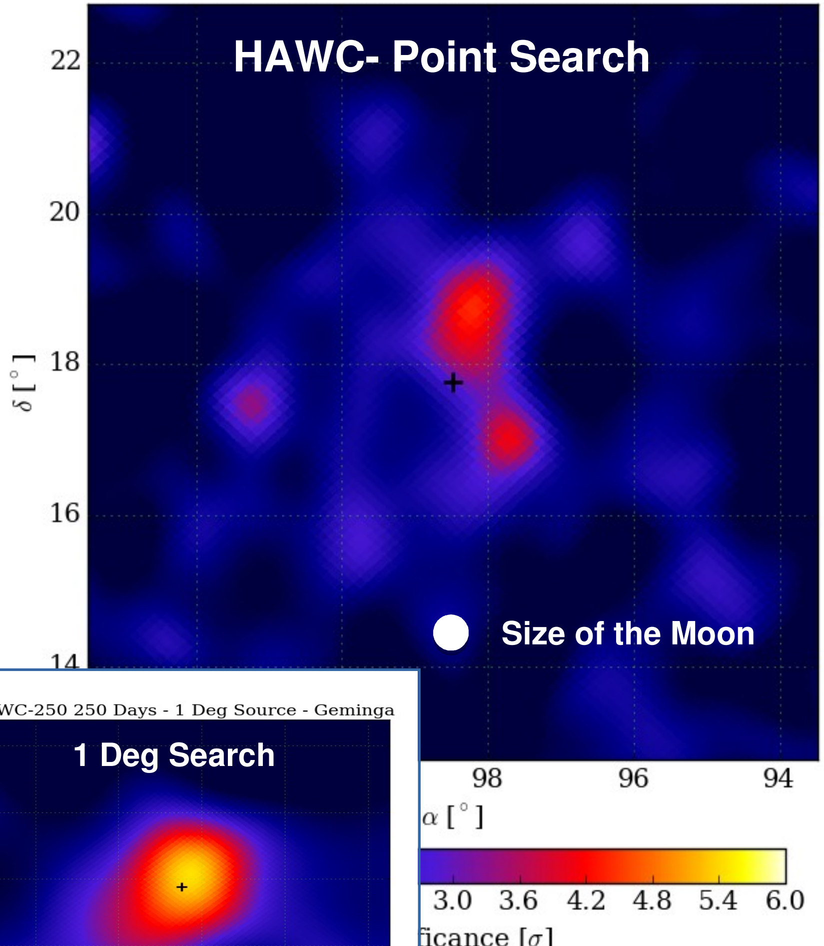


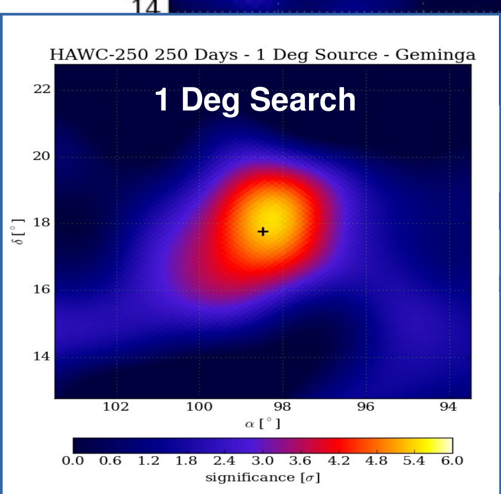


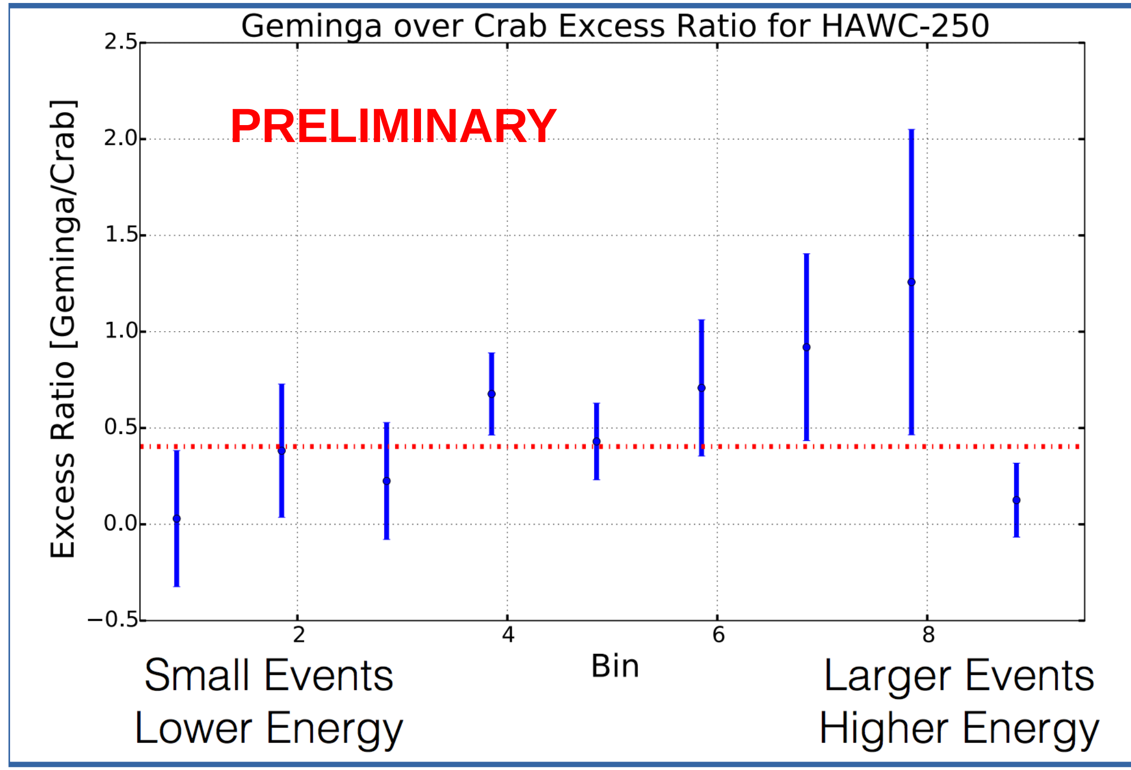
- Extended TeV emission discovered by Milagro.
- Contributor to positron excess?

Yuksel, Kistler & Stanev. PRL. (2009)

Geminga





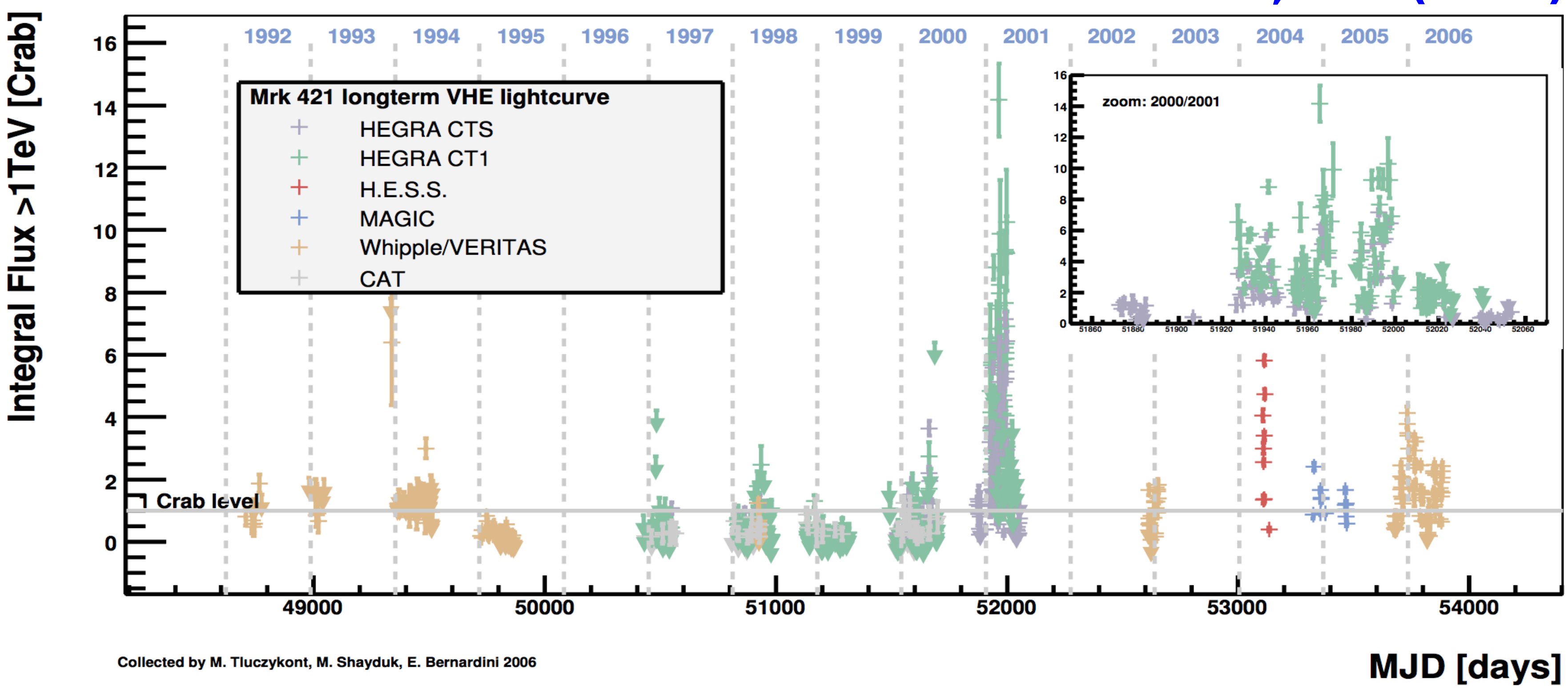


- Detected in HAWC (Pass 3) at ~6σ using a 3 deg search.
- Looks harder than the Crab.
- Analysis in progress.

Transients

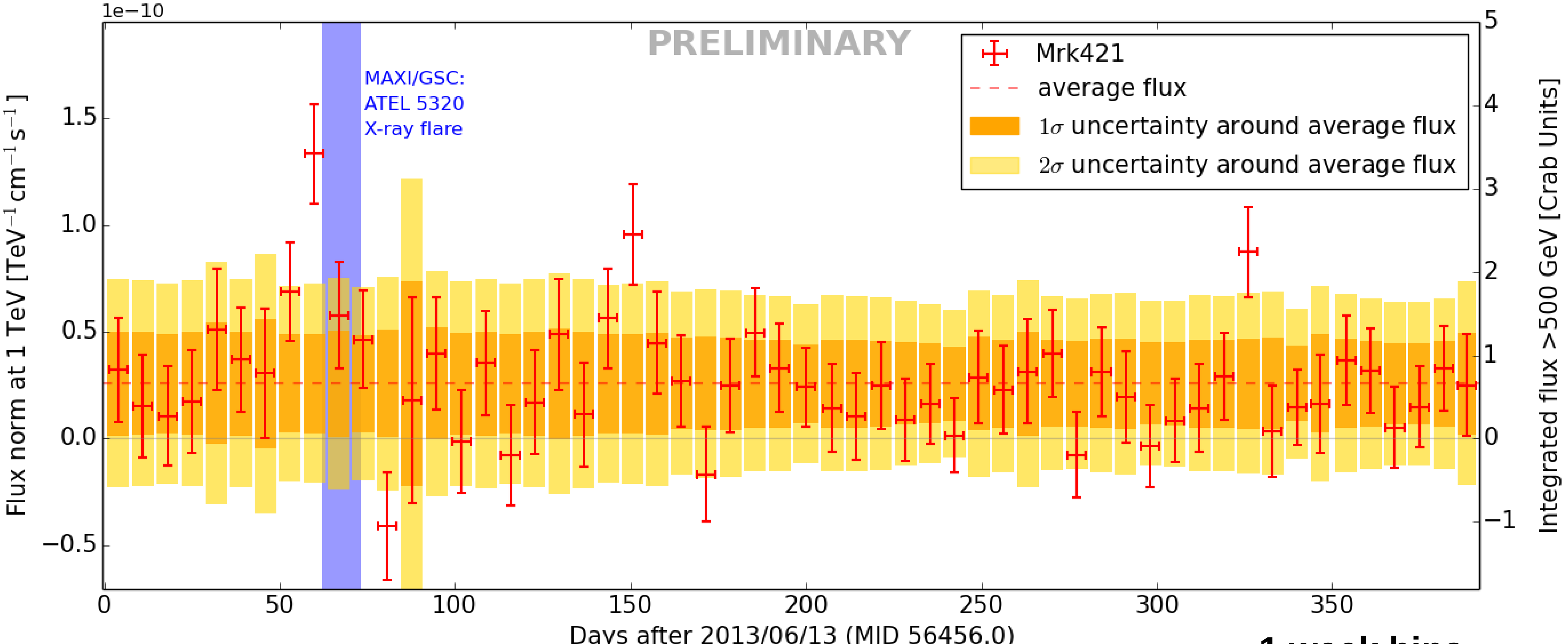
- Around 60 known TeV Active Galactic Nuclei (AGN), yet most of the extragalactic sky has not been surveyed.
- HAWC's 5σ sensitivity is (10, 1, 0.1) Crab in (3 min, 5 hrs, 1/3 yr).
- HAWC will provide prompt notification of flaring activity.

A&A 524, A48 (2010)



Mrk 421

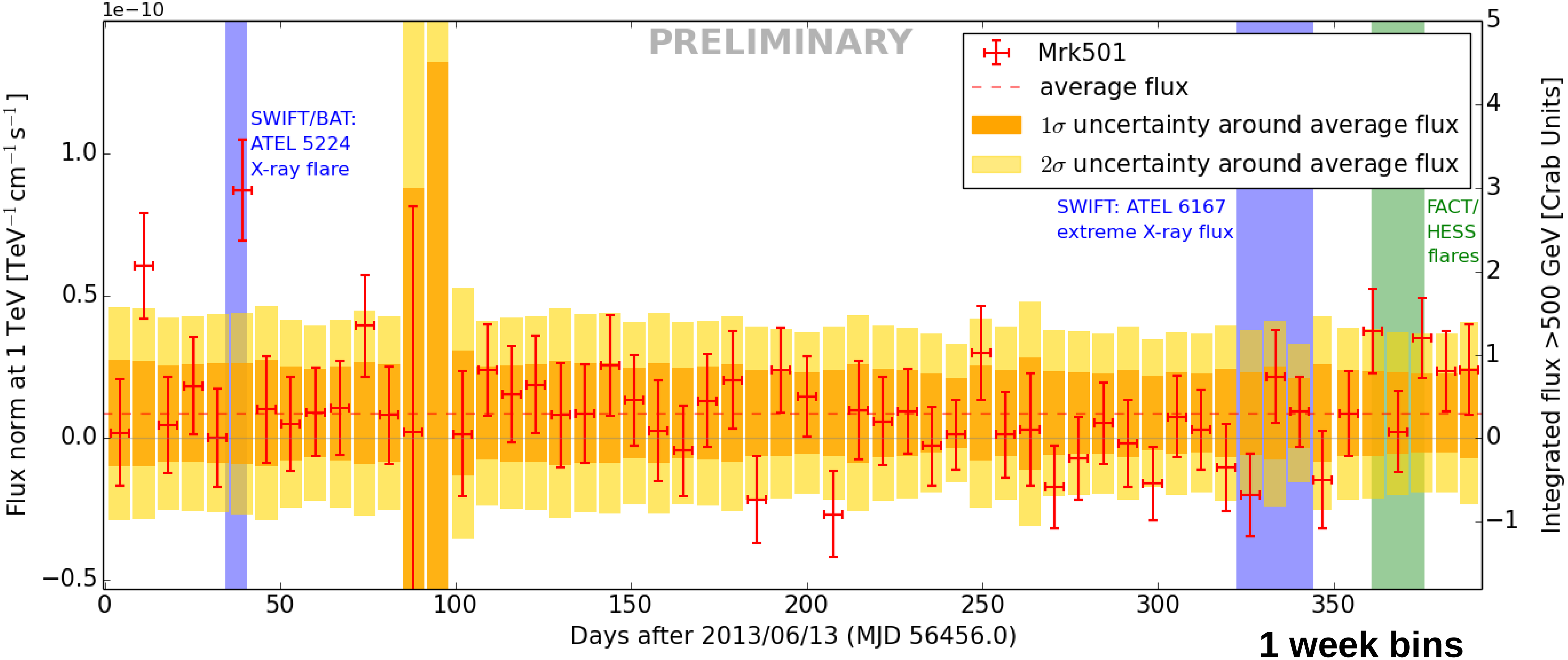
- Data from 2013/06/13 to 2014/07/09 in Pass 1.
- HAWC coincident with the onset of a X-ray flare (ATEL 5320).
- Mrk 421 shows variability also in Pass 3 data (analysis in progress).



1 week bins

Mrk 501

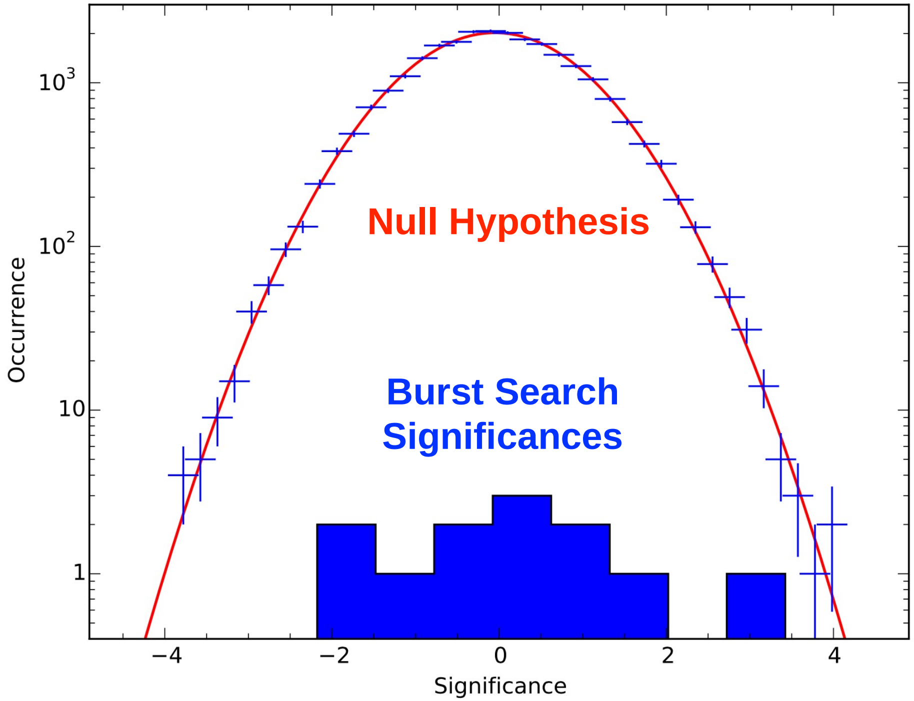
- Mrk 501 also variable: highest flux is coincident with a X-ray flare.
- No significant observation of other flares.
- No variability observed in the Crab Nebula data.

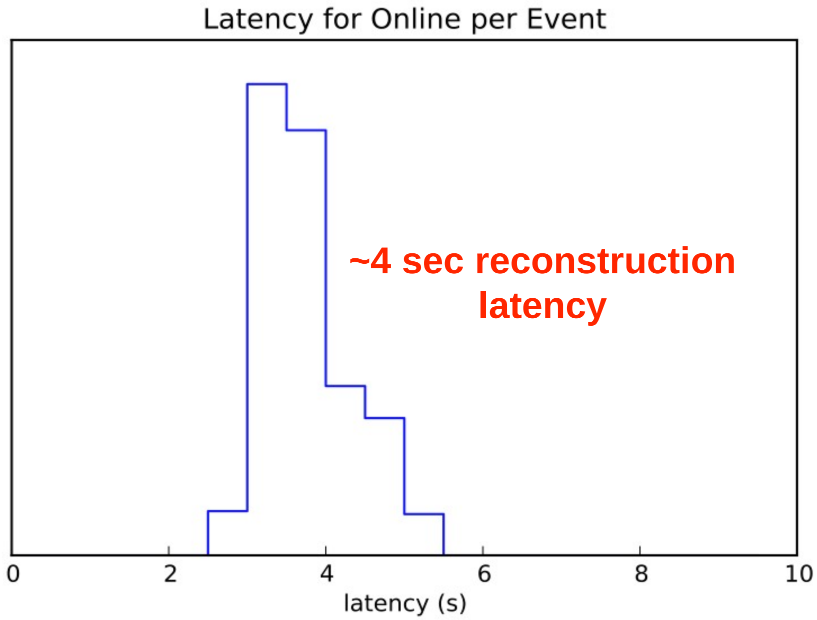


1 week bins

Gamma-Ray Burst

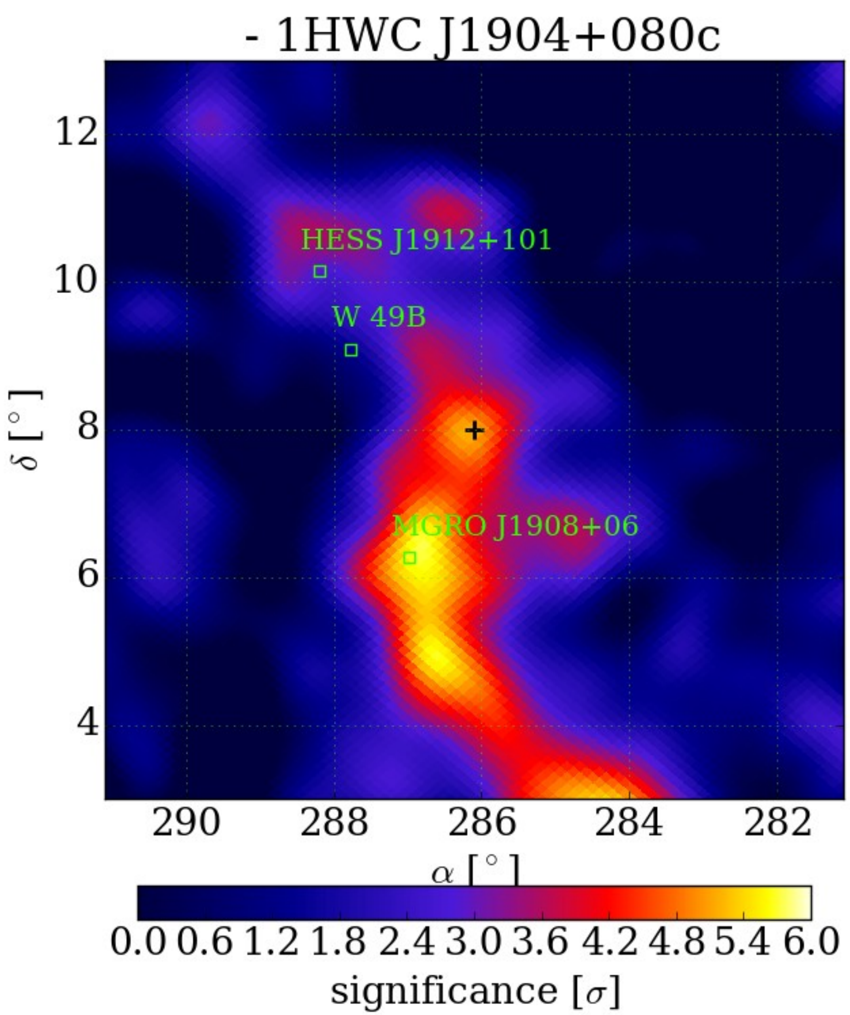
- Currently 2 search methods:
  - Follow-up on alerts from satellites (mostly Fermi-GBM).
  - Online search for GRBs. The plan is to deliver transient alerts in near-real time.
- Tested 18 GRBs from Swift. No detection yet.
- Expect 1-2 GRBs per year in HAWC (extrapolating from Fermi) **NIMA 742, 2014, 276-277**.





Reconstruct and analyze data in real time, within a few seconds of trigger. ~200 cores.

Multi-Wavelength Response and Follow-up



Two MOU Paradigms

HAWC-Triggered
1HWC J1904+08c seen at 3.9σ post-trials in HAWC-111. MOU partners notified.

VERITAS observed (moon and dark observations) and set a point source upper limit.

AMON Integration

Externally Triggered
IceCube notified HAWC of a high-confidence neutrino for HAWC followup (see next slides).

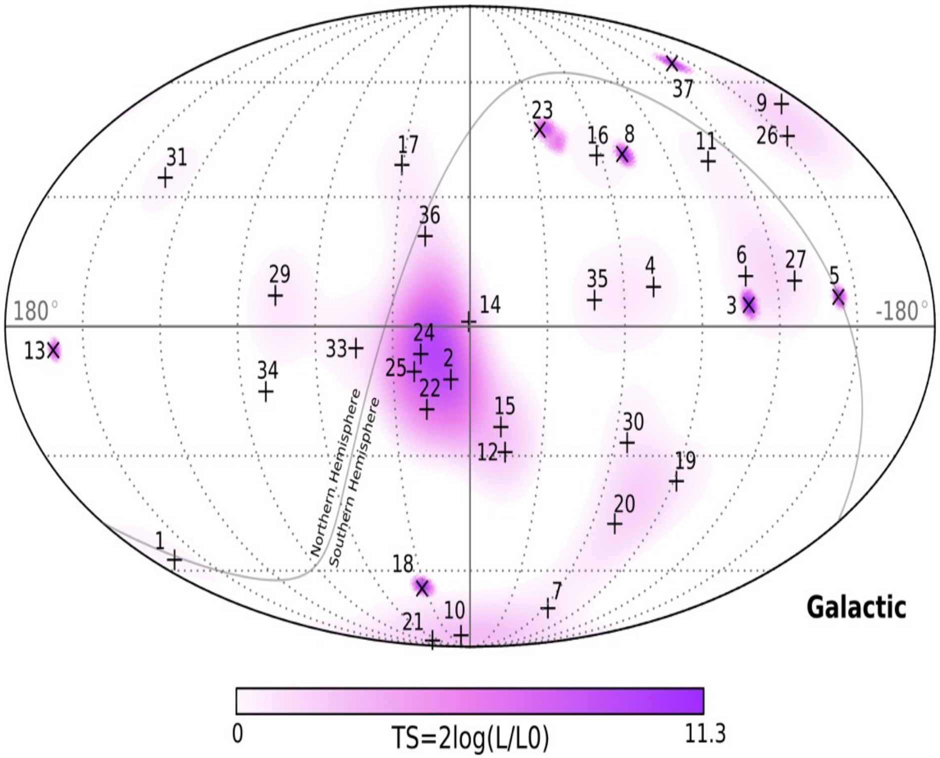
Fermi-LAT team asked about TeV emission from several points.

ANTARES notified an interesting neutrino event. No significant in pass 3 integrated data. The analysis will be completed with pass 4.

HAWC and Neutrino Telescopes Multi-Messenger Complementarity

Neutrino / Photon Connection: Pions

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



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

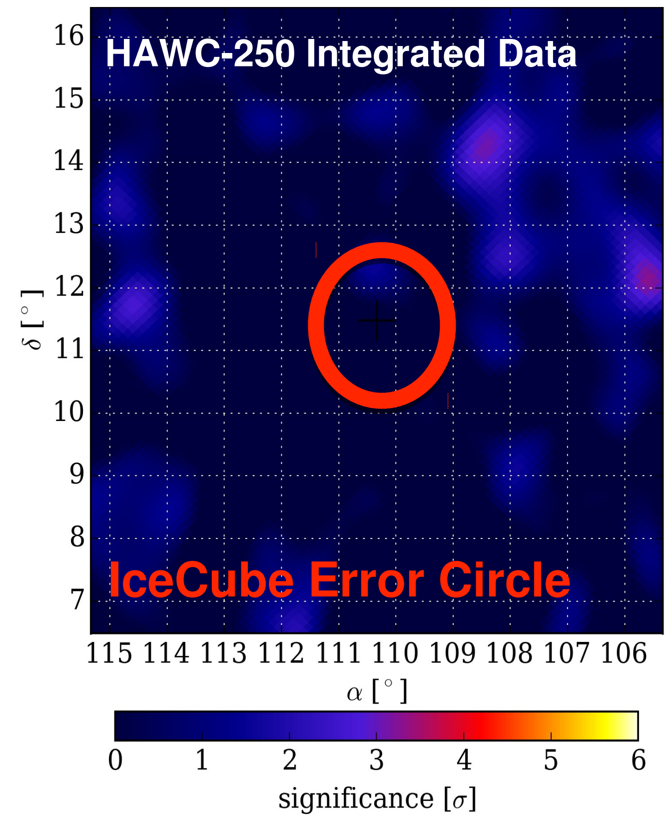
HAWC's Strengths for IceCube Followup

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

HAWC Follow-up on 2.6 PeV IceCube Neutrino

IceCube Event

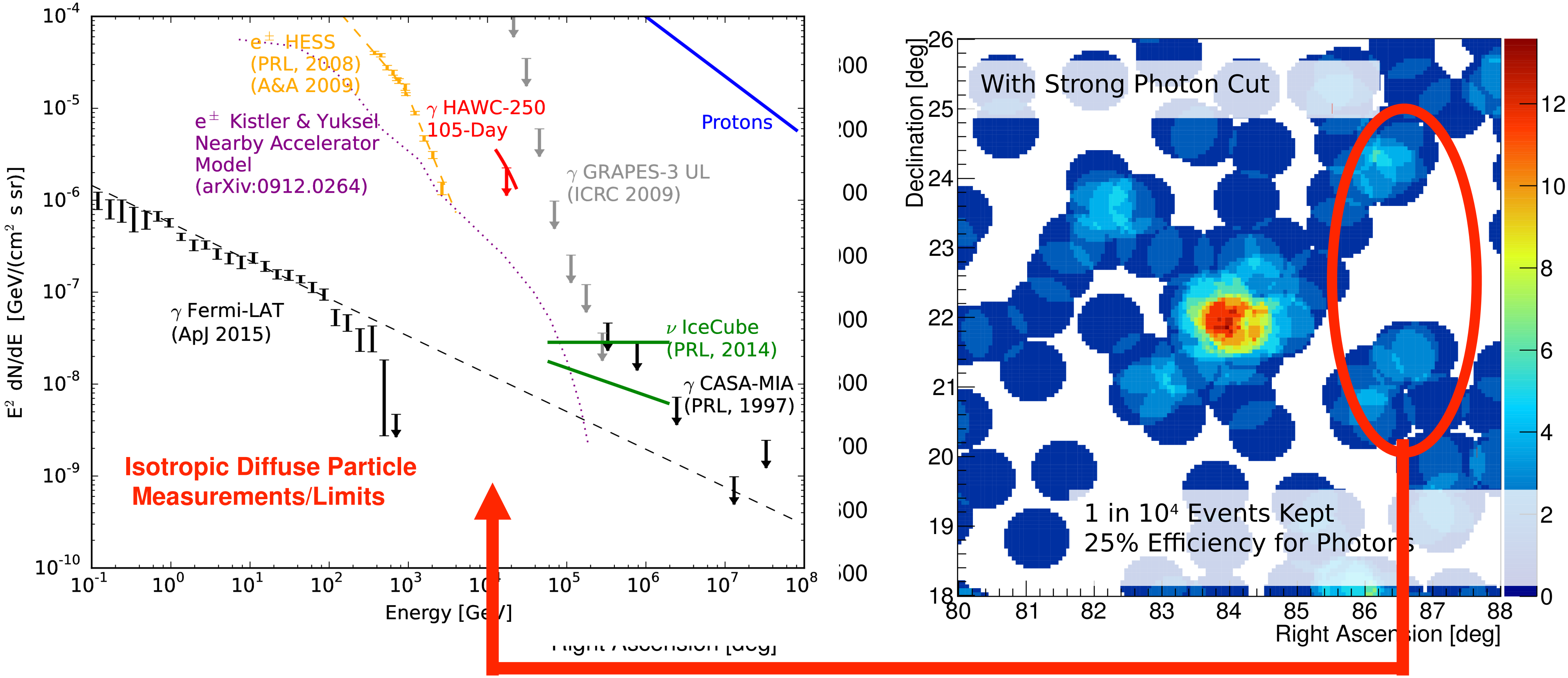
- Highest energy pointed astrophysical track-like event
- June 11, 2014, 4:54 UTC. (RA,Dec) = (110.3, 11.5)
- HAWC-111 live (pass1). Several hours out of HAWC’s FOV.
- Searches:
  - Integrated dataset (Steady, Aug 2013-May 2015)
  - Next Day / Prior Day
  - ±2 and ±5 days around the event.
  - All searches 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 Photon Rich Dataset above 10 TeV



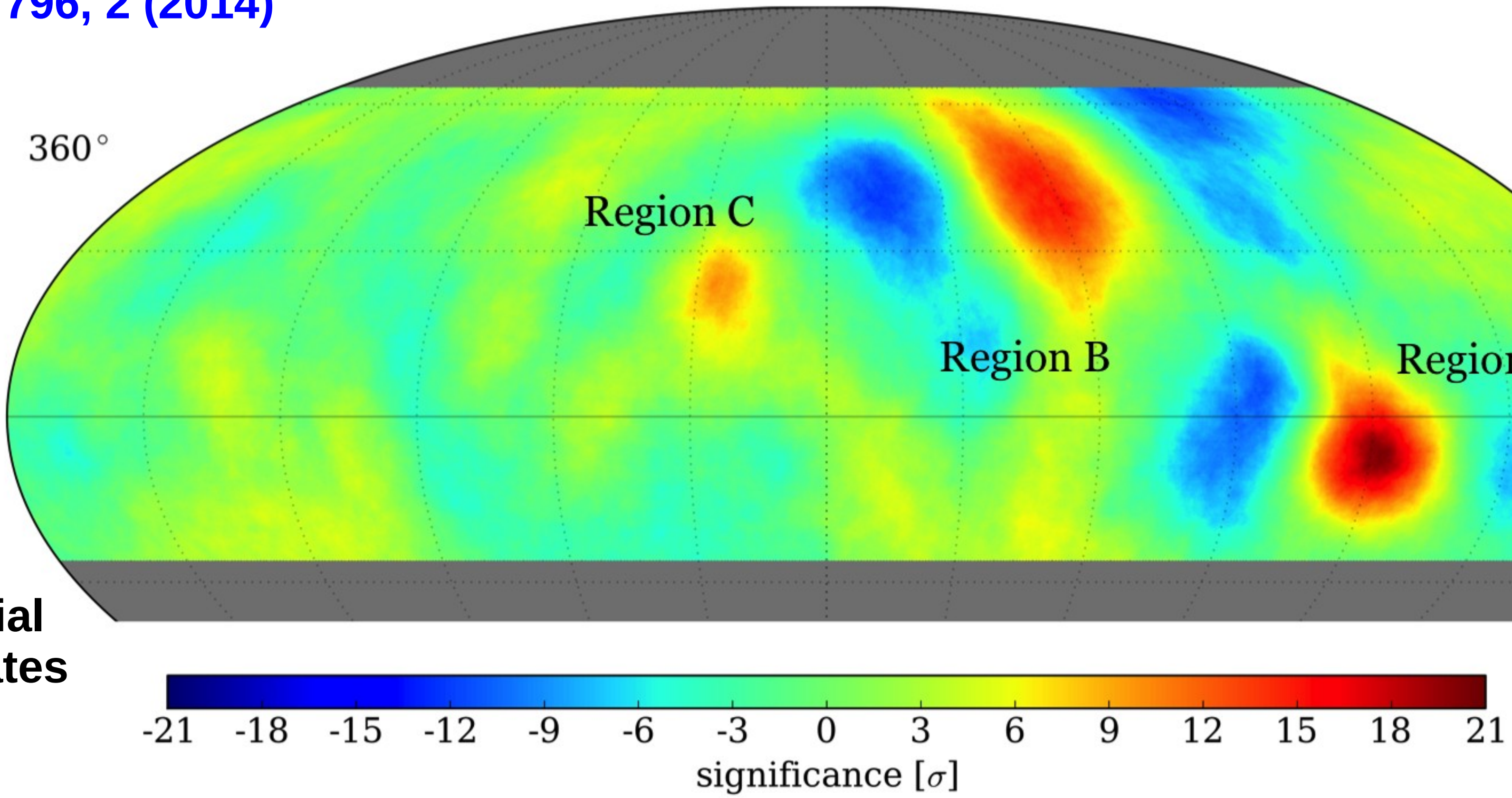
Isotropic Gamma-Rays @ 11-23 TeV Cannot Exceed Off-Crab Observations

Cosmic Ray Anisotropy

- Small-scale (<60º). Large scale removed (dipole, quadrupole, +octupole).
- 10º smoothing applied.
- 8.6×10^{10} events over 181 days.

ApJ 796, 2 (2014)

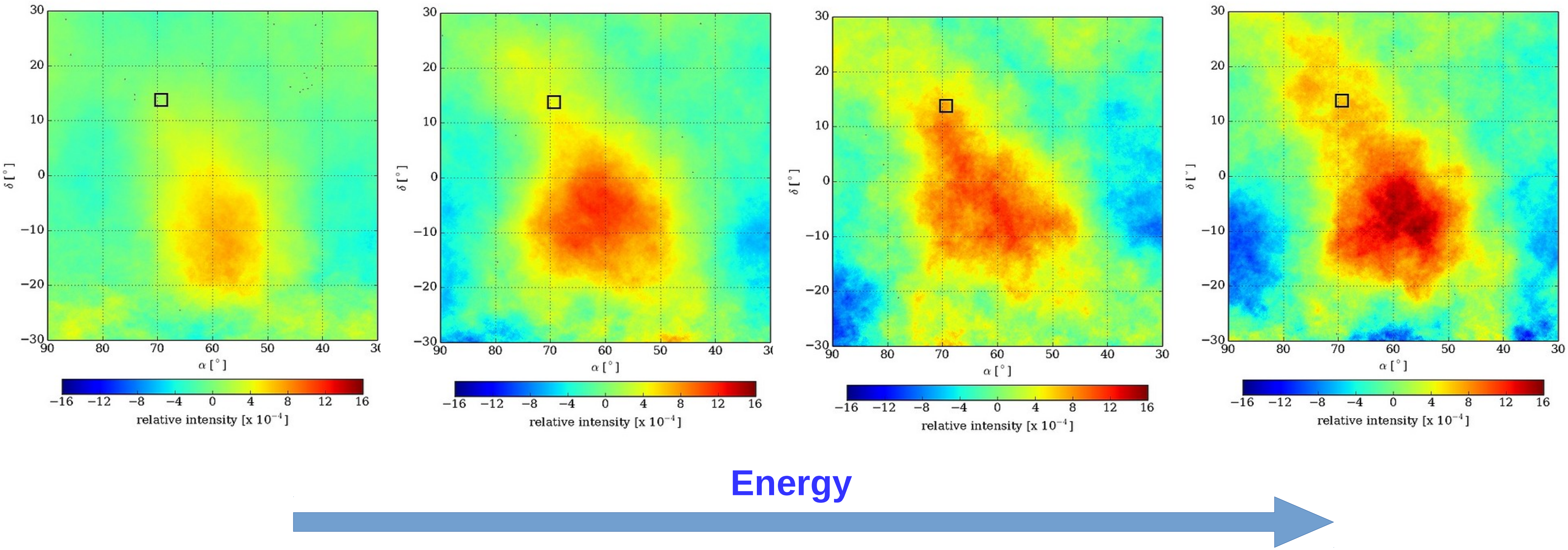
- Three significant excess:
  - Region A: strongest. Harder spectrum than the background at 10TeV, consistent with Milagro.
  - Region B most extended.
  - Region C,confirms ARGO-YBJ observations.



Equatorial coordinates

Cosmic Ray Anisotropy

- Region A has a spectrum harder than the cosmic-ray background.



More Results

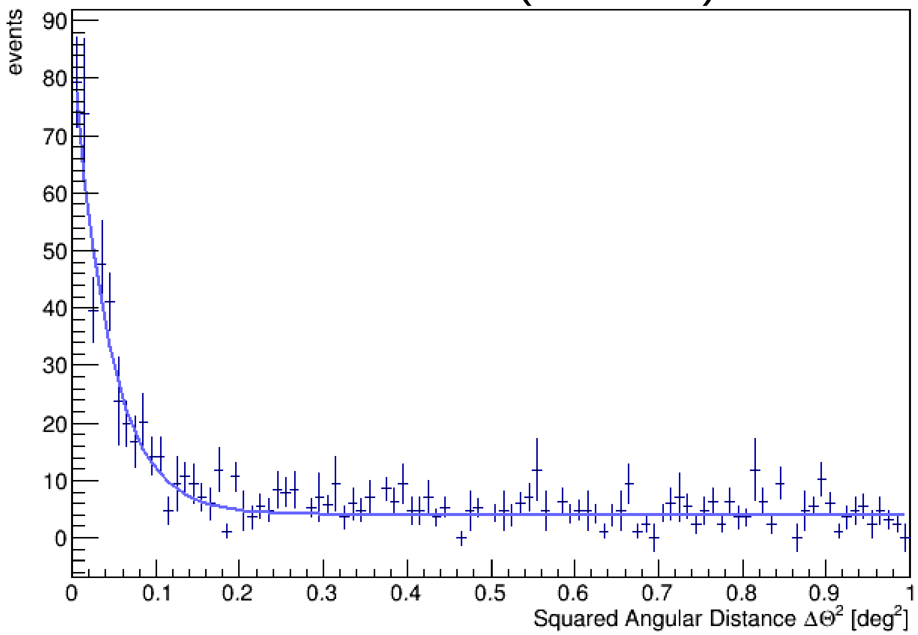
- HAWC contributions to the ICRC 2105 (**arXiv:1508.03327**) include:
  - Dark matter searches.
  - Fermi bubbles with HAWC.
  - Sensitivity to PBH.
  - Observation of the Moon and Sun shadow.
  - Solar physics.
  - Etc.

Pass 4 Preview: Crab Data

- Reconstruction and calibration improvements.

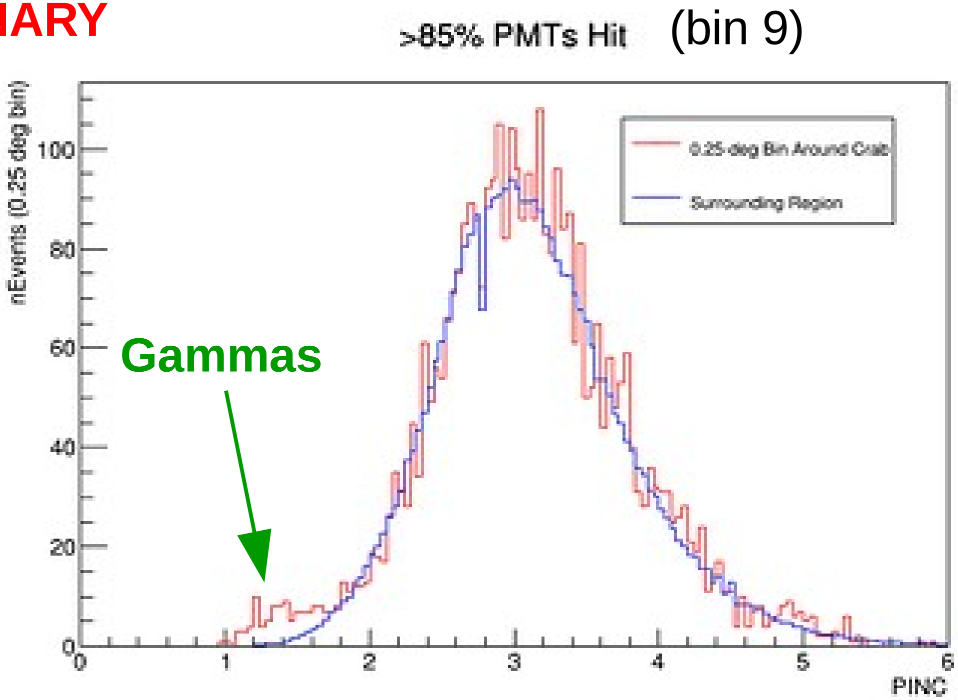
PRELIMINARY

> 62% PMTs hit (bins 7-9)



Angular resolution (68% containment): 0.24° for large event, achieving proposed resolution.

(bin 9)

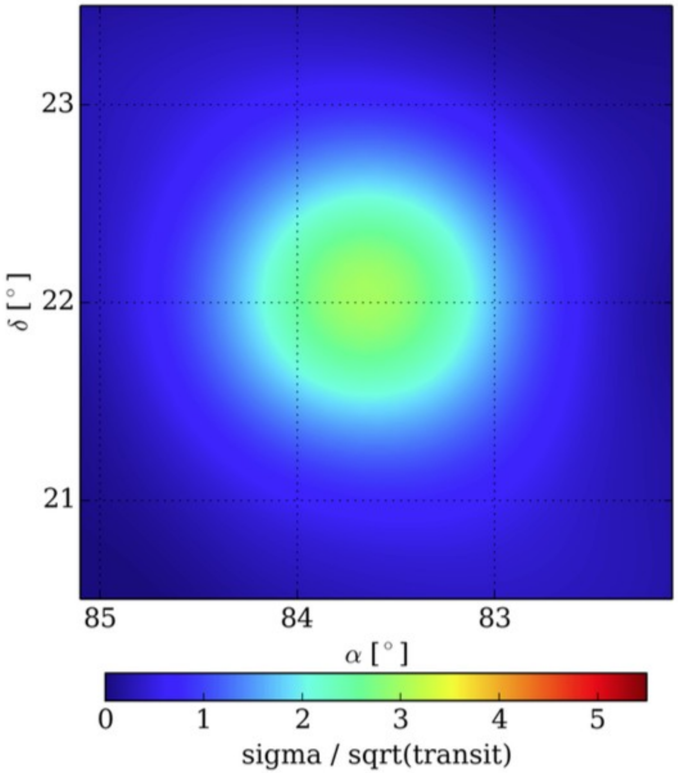


Gamma/Hadron separation:
Reject >99.9% of hadronic background for large events while retaining >50% of gamma rays.

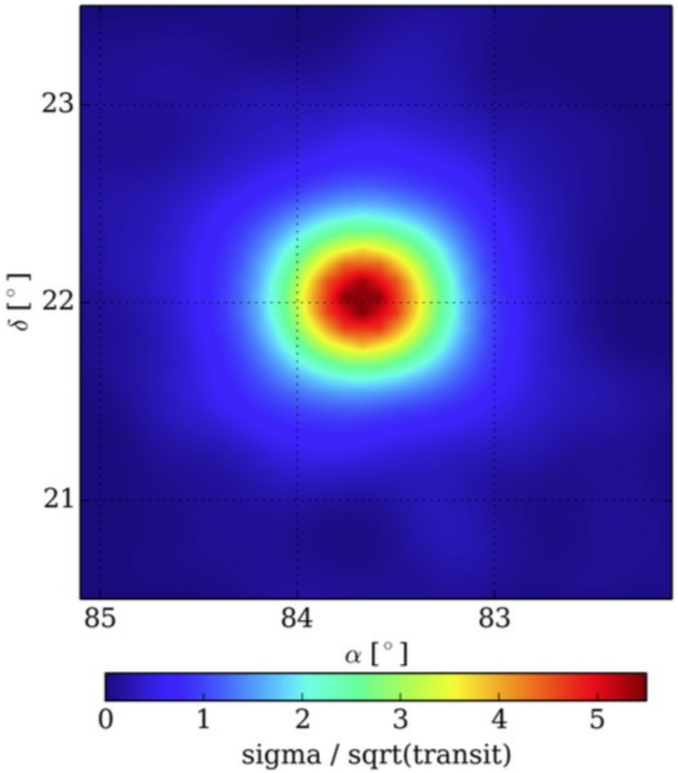
Pass 4 Preview: Crab Data

- Recovers the designed sensitivity.
- Already running online: presently getting >5σ per day on the Crab.

PRELIMINARY

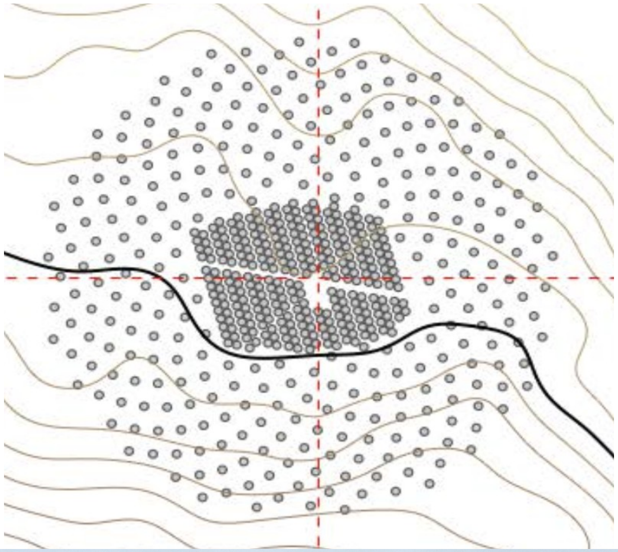


Pass 3
3.1σ/sqrt(day)



Pass 4
5.5σ/sqrt(day)

The Future of HAWC



Near future:

- HAWC will add 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. Firsts tests ongoing.

Future:

- HAWC South: Southern complement for CTA.
- Needs to be better: higher altitude, larger area, improved hadronic rejection, imroved shower sensitivity.

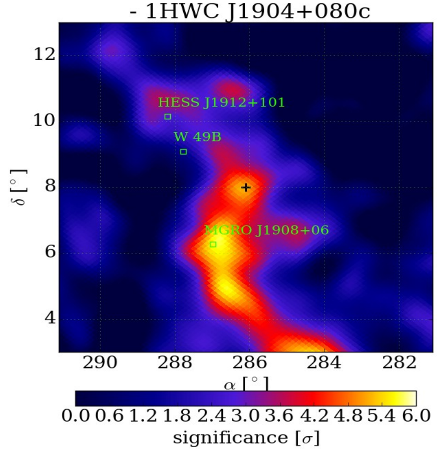
Summary

Detector:

- HAWC is a second generation of EAS which started full operations in March 2015.
- HAWC is about 1 order of magnitude more sensitive than the predecessors EAS . It will survey more than half of the sky for at least 5yr, reaching 20mCrab sensitivity.

Firts Results:

- Galactic Plane survey.
- Flaring blazars observations.
- Geminga detection, etc.

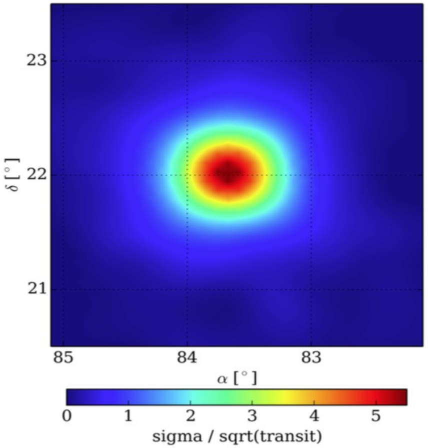


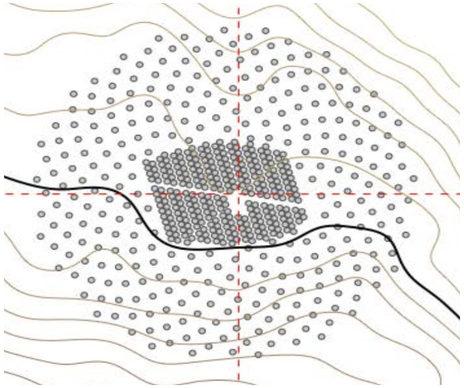
Status:

- More than one year of data.
- New production in less than 1 month.

Future:

- Public transient alerts and data release.
- Outriggers.
- HAWC South.





Thanks for your attention!