Recent Results from the HAWC Observatory

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

SciNeGHE – Pisa Oct 18th 2016

Francisco Salesa Greus
IFJ-PAN, Krakow

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

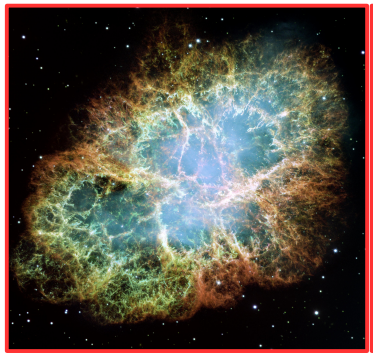
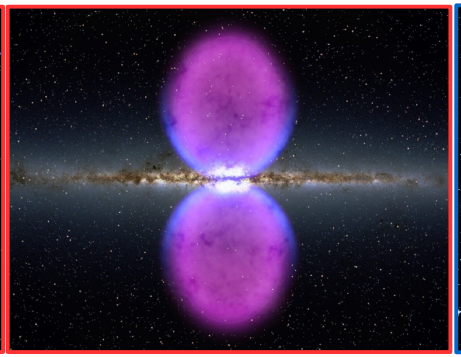
HAWC Science Goals

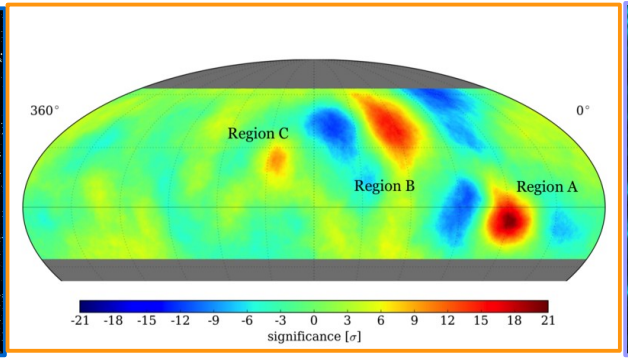
Galactic sources:

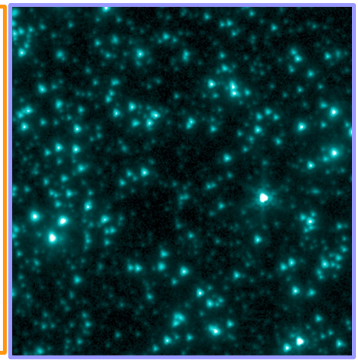
- Plane survey, sensitive at high-energies (>10TeV).
- Large extended sources: Geminga region, Fermi bubbles.
- Distinction of gamma-ray emission: hadronic/leptonic.

Extra-Galactic sources:

- Continuous AGN monitoring: flaring alerts, light curves [multi-wavelength follow-up], EBL and propagation studies.
- Transients phenomena: GRBs [blind and triggered].





Cosmic ray:

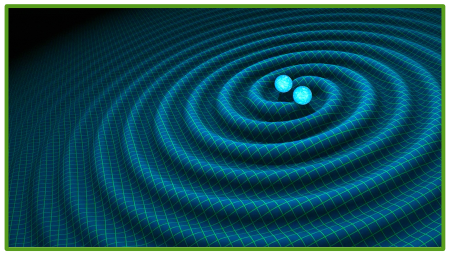
- Cosmic ray large and small scale anisotropy.
- Spectrum and composition.
- Solar physics

Fundamental physics:

- Dark matter.
- Primordial black holes.
- Lorentz invariance violation.

Multi-messenger program, MoU partners:

IACTs: VERITAS, MAGIC, H.E.S.S., FACT. Space telescopes: Swift, Fermi. Particle detectors: IceCube, ANTARES. Gravitational Waves: LIGO/VIRGO. Also in AMON network.



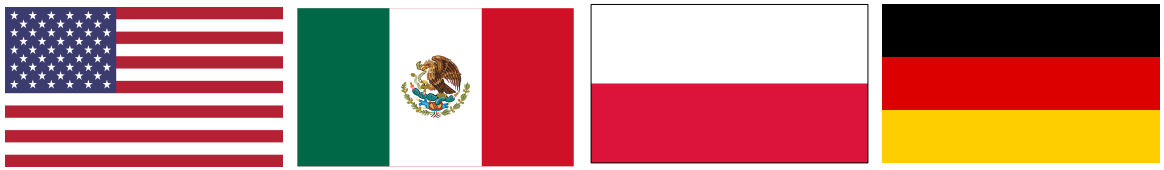
HAWC Collaboration

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, NASA/Goddard Space Flight Center, Georgia Institute of Technology, Colorado State University, Michigan State University, University of Rochester, University of California Santa Cruz, Standford University, George Mason University

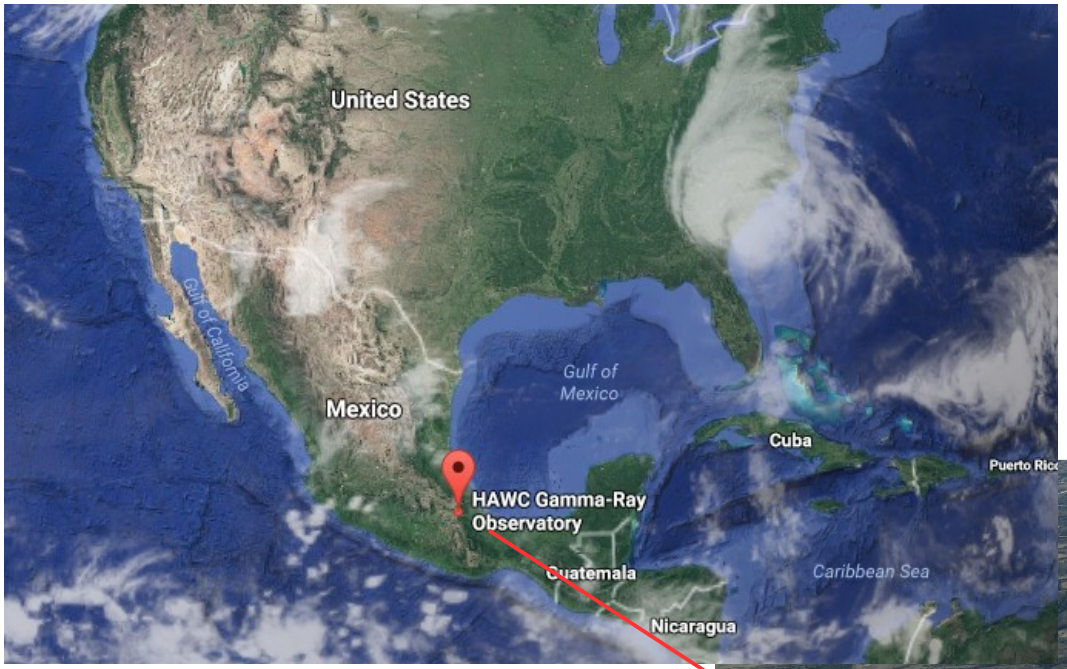
Mexico: Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE),Universidad Nacional Autónoma de México (UNAM): Instituto de Física, Instituto de Astronomía, Instituto de Geofísica, Instituto de Ciencias Nucleares, Universidad Politécnica de Pachuca, Benemérita Universidad Autónoma de Puebla, 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

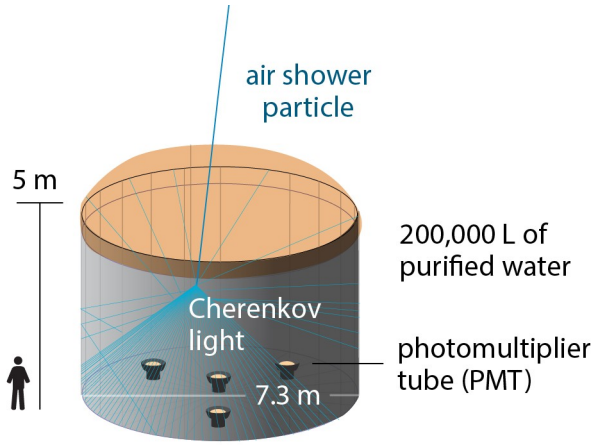
Germany: Max-Planck-Institut für Kernphysik



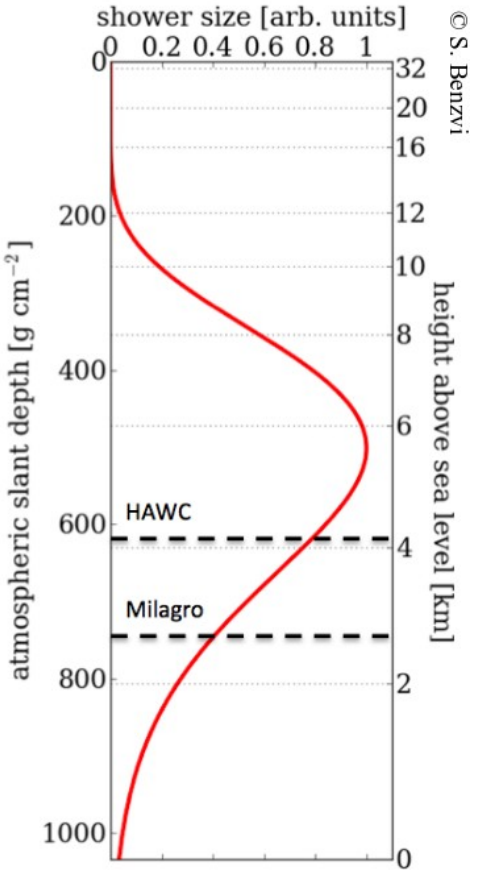
The HAWC Detector

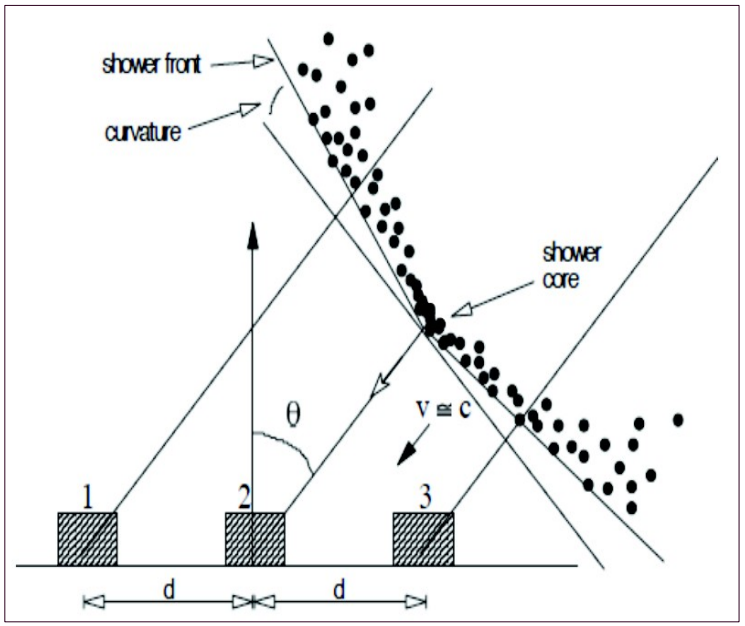


- Site: Sierra Negra, Mexico, 19°N, 4,100 m altitude.
- Instantaneous FOV 2sr. Daily 8sr (66% of the sky).
- Duty cycle >90%.
- 300 WCDs covering 22,000m^2 area.
- Inaugurated **March 2015**.



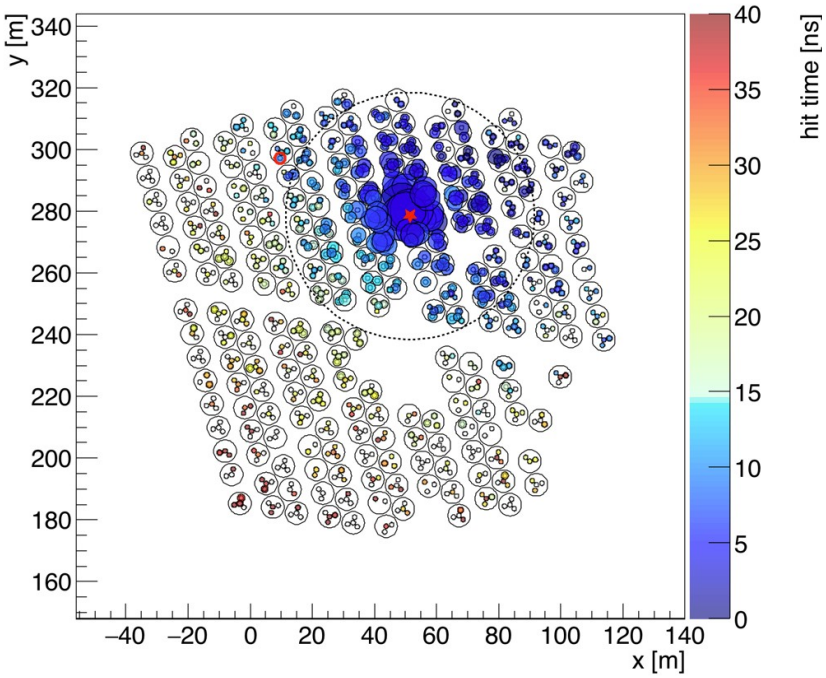
Detection Technique





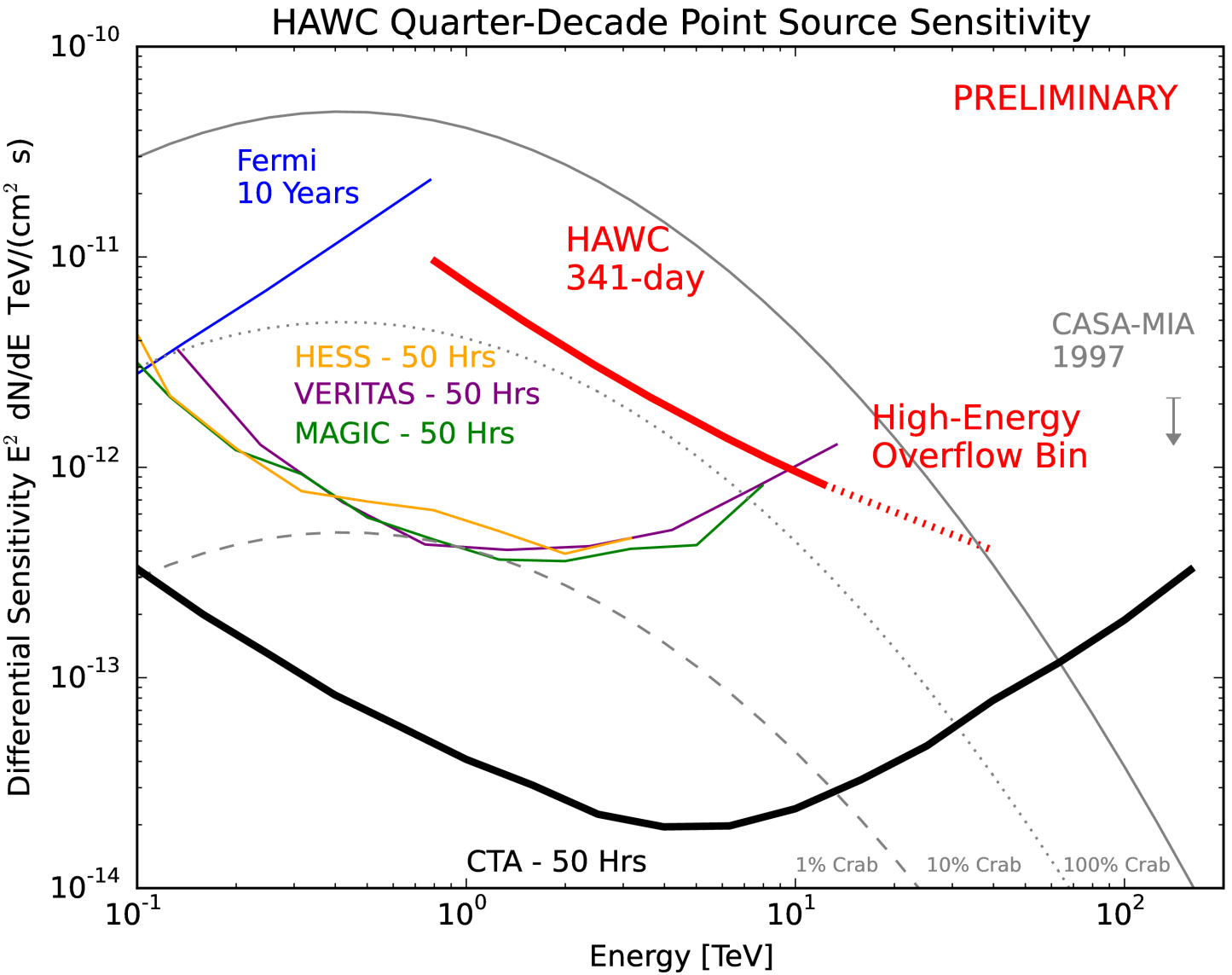
HAWC Data

Likely Gamma Ray



- In HAWC the particle detectors are 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: gamma-ray showers are more compact, cosmic rays showers tend to "break apart".

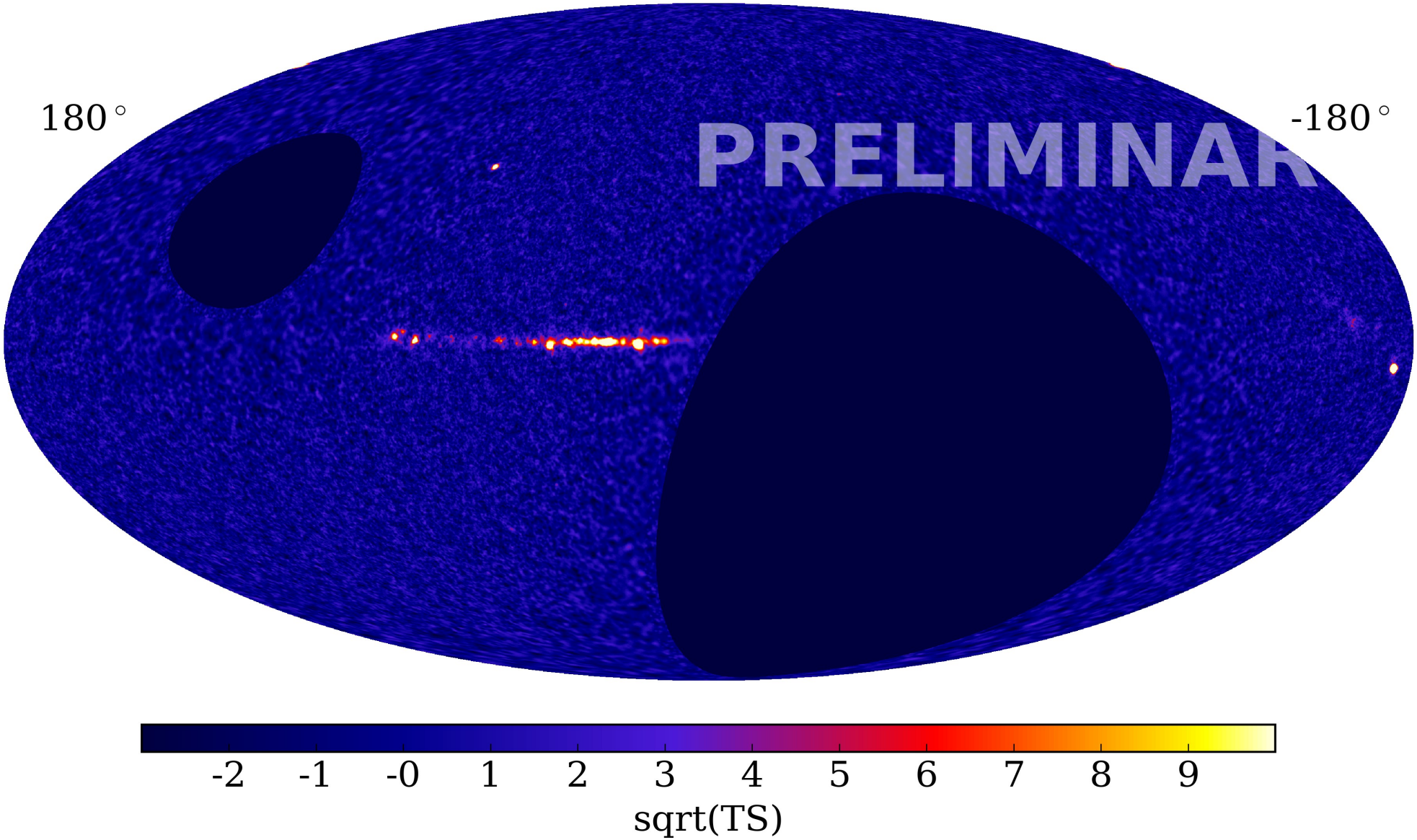
HAWC Sensitivity



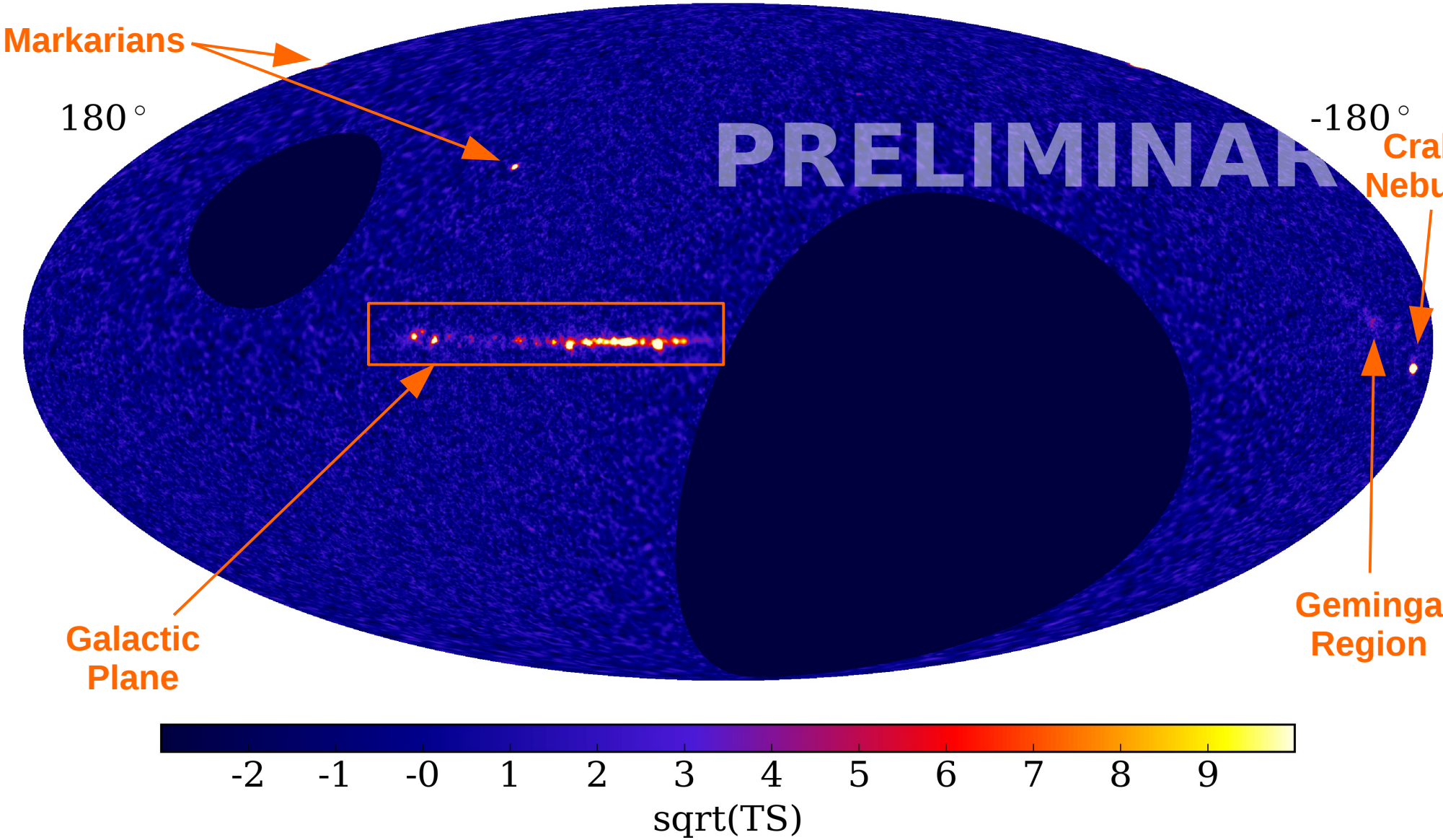
- Instantaneous sensitivity 15-20x less than IACTs.
- Exposure (sr/yr) is 2000-4000x higher than IACTs.
- Above 10 TeV HAWC 1-yr sensitivity is comparable to 50h observation by an IACT.
- Survey > half the sky to:
  40 mCrab [5σ] (1yr)
  <20 mCrab [5σ] (5yr)

Paper on Crab detection + Sensitivity in preparation!

HAWC SkyMap 17 Months

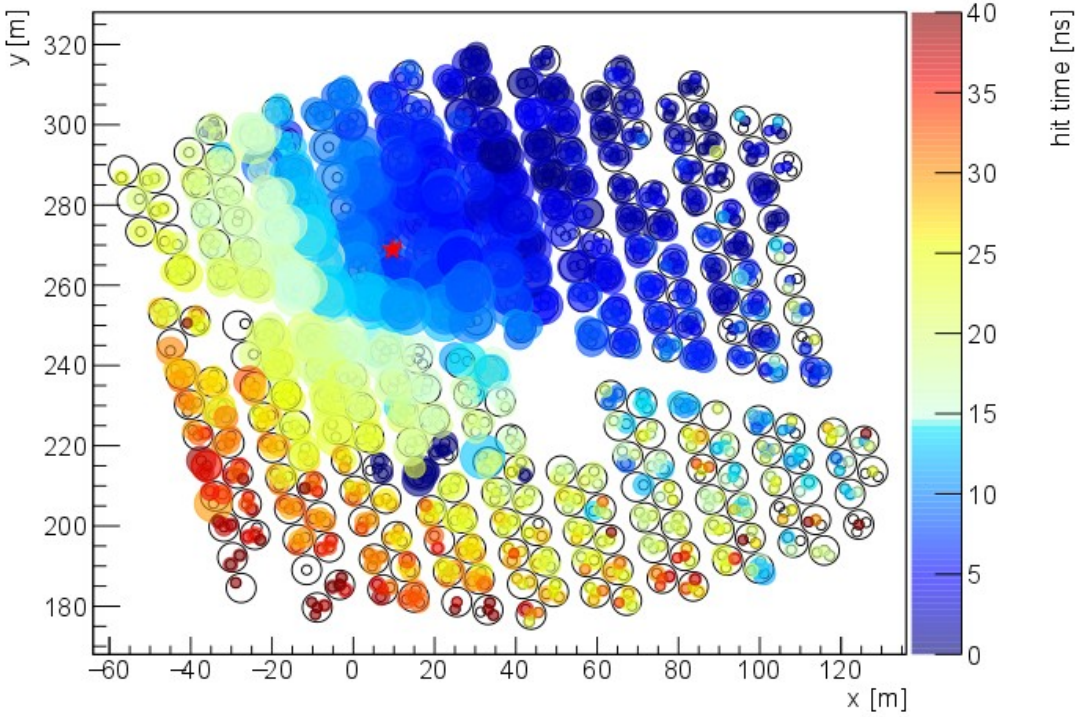


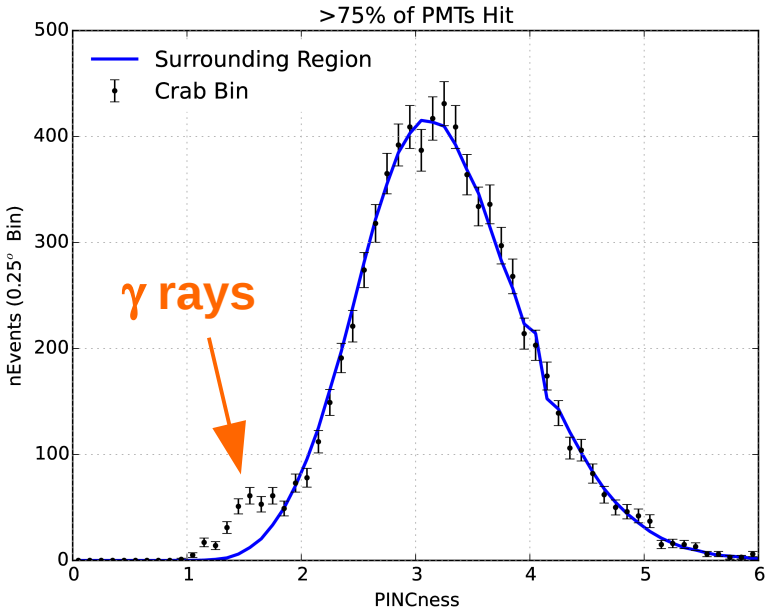
HAWC SkyMap 17 Months

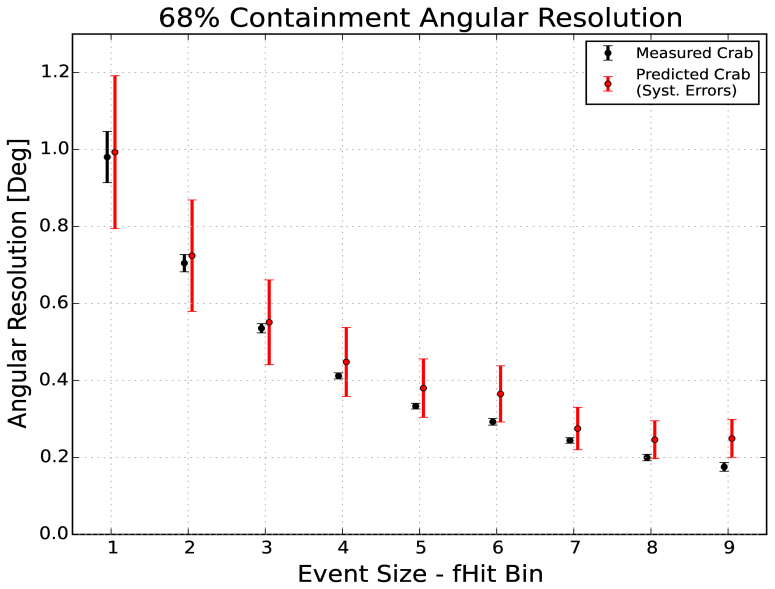


The Crab Nebula

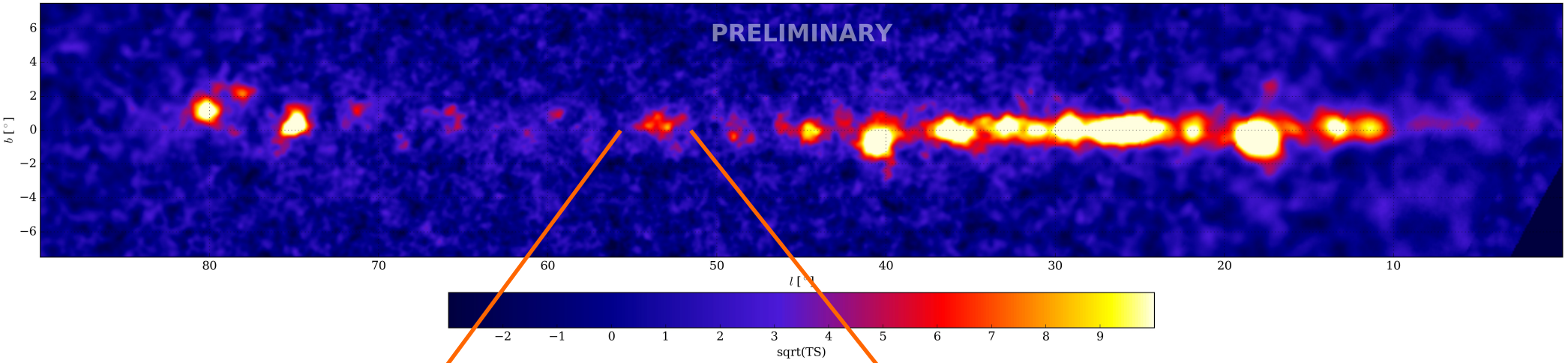
- Crab Nebula detected with high significance ~100σ.
- It was used to test our angular resolution and g/h cuts.
- The AR (68% containment) is 0.25° for events with more that hit more than 50% PMTs hit.
- Signal to background ratio ~10:1 for large events (>75% PMTs hit) and still keeping more than 60%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





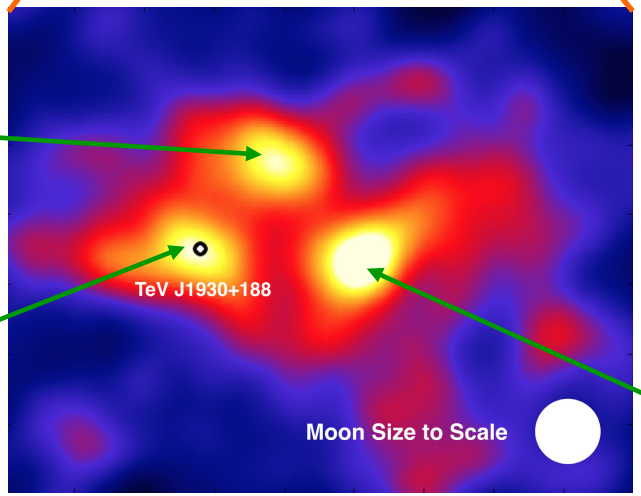


Galactic Plane Survey



New source:
Association unclear

Supernova remnant with very energetic pulsar

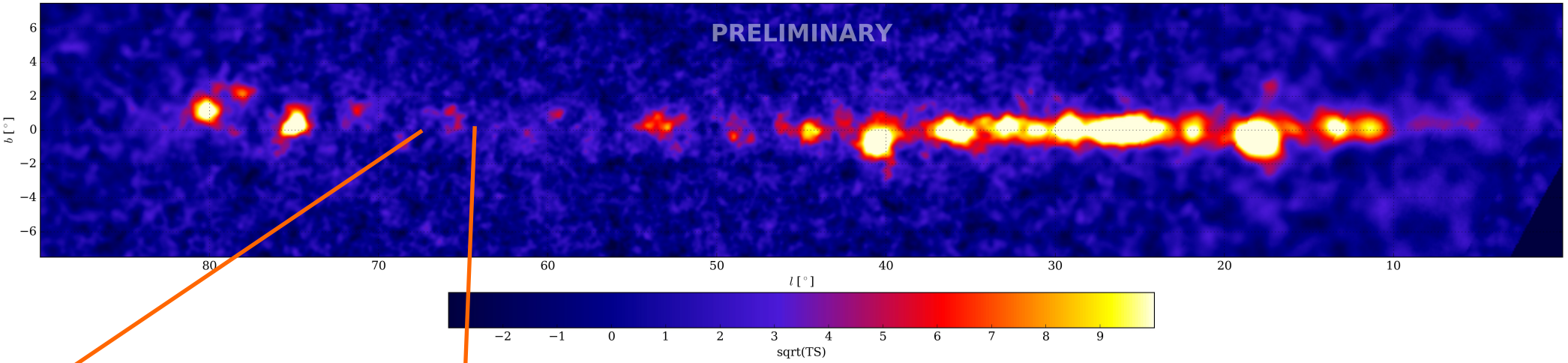


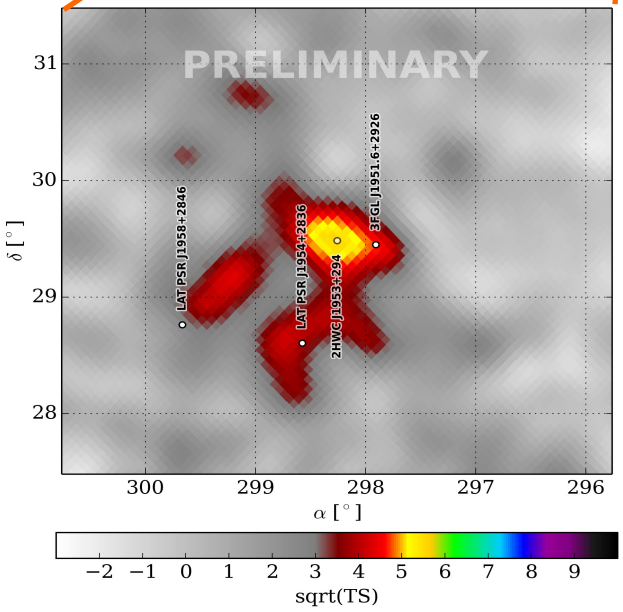
- Preliminary catalog shared with MoU partners.
- Various sources coincident with TeVCat.
- Several w/o counterpart.

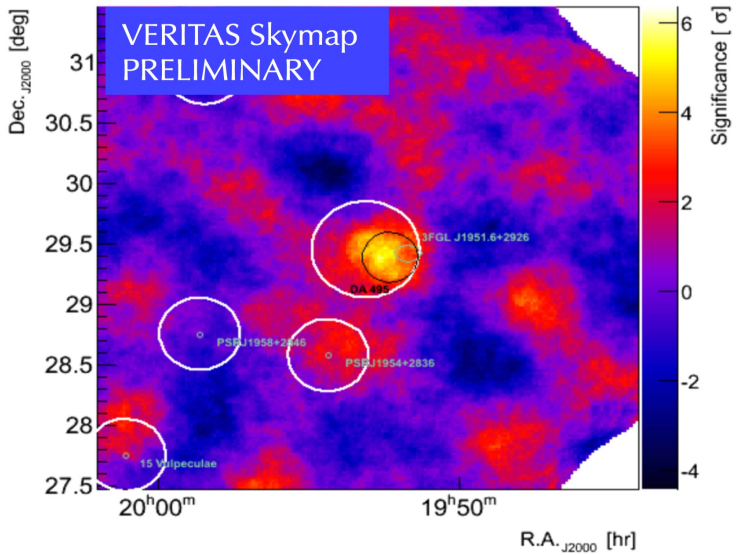
New source: Pulsar ~8kpc away

Paper in preparation!

New Source Confirmed

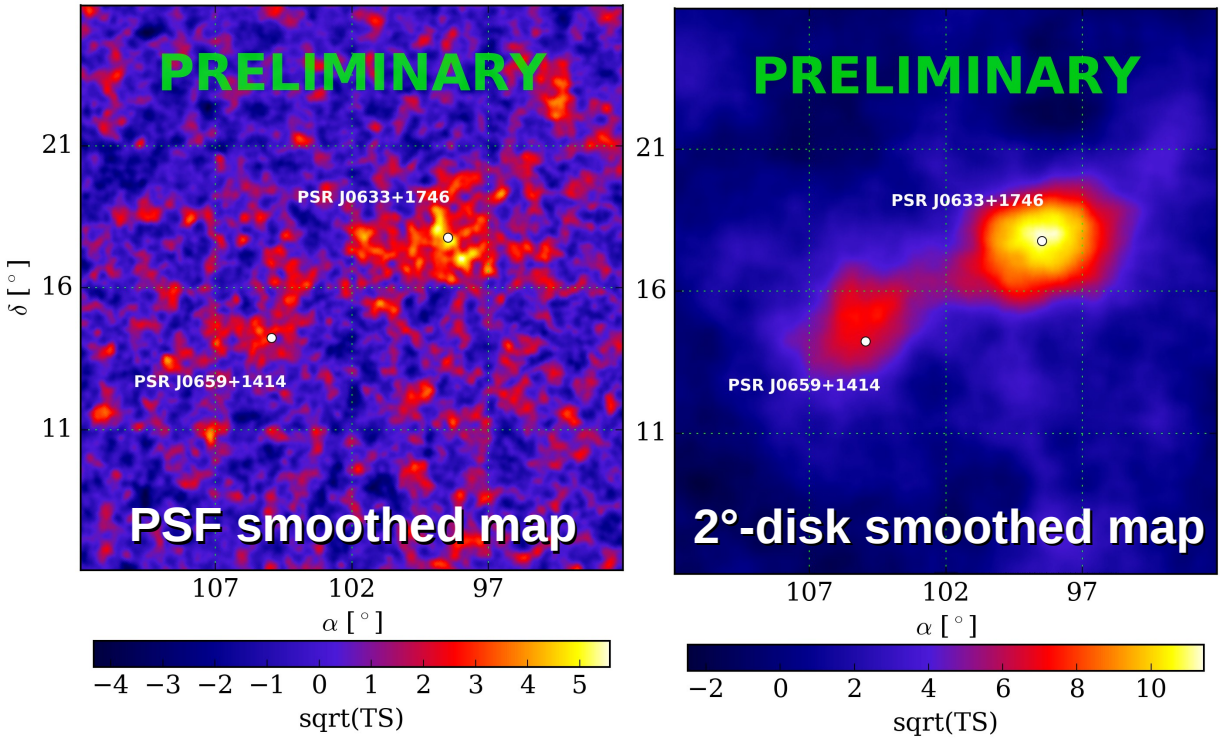


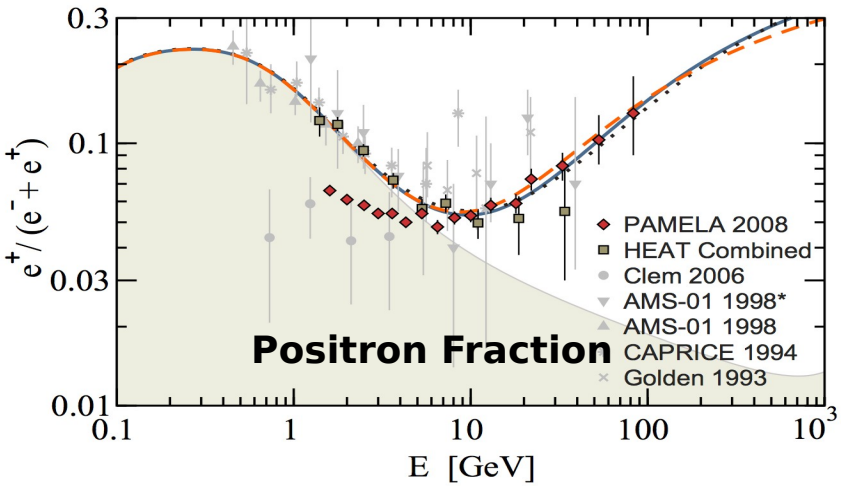




- No previously known TeV source.
- New analysis by VERITAS, archival plus new data, **source confirmed**.
- Tentative association 3FGL J1951.6+2926

Geminga Region





Yuksel, Kistler & Stanev. PRL. (2009)

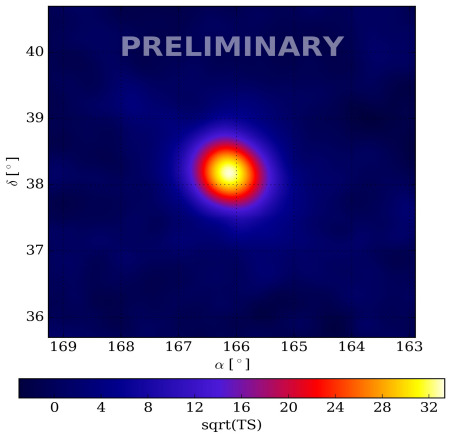
Paper in preparation!

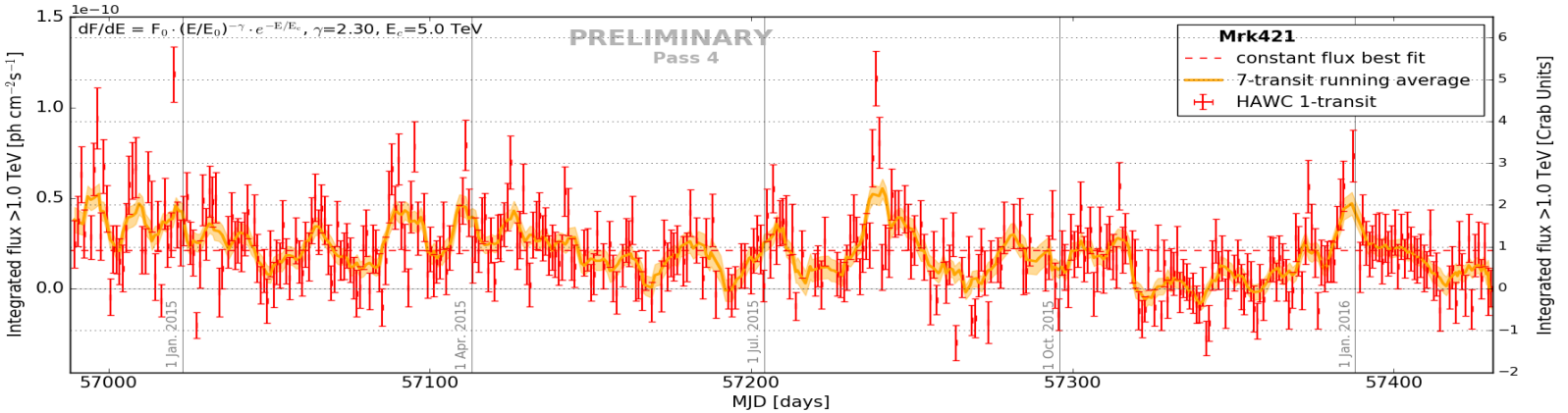
- Confirmation (~12σ pre-trial) of Geminga (PSR J0633+1746) by HAWC.
- Evidence (~7σ pre-trial) of a new extended source near PSR B0656+14.
- Both pulsars, similar in age and distance, were suggested as contributors of the positron fraction.

Markarian Galaxies

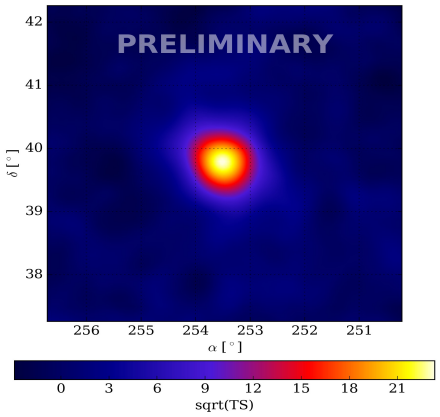
Paper in preparation!

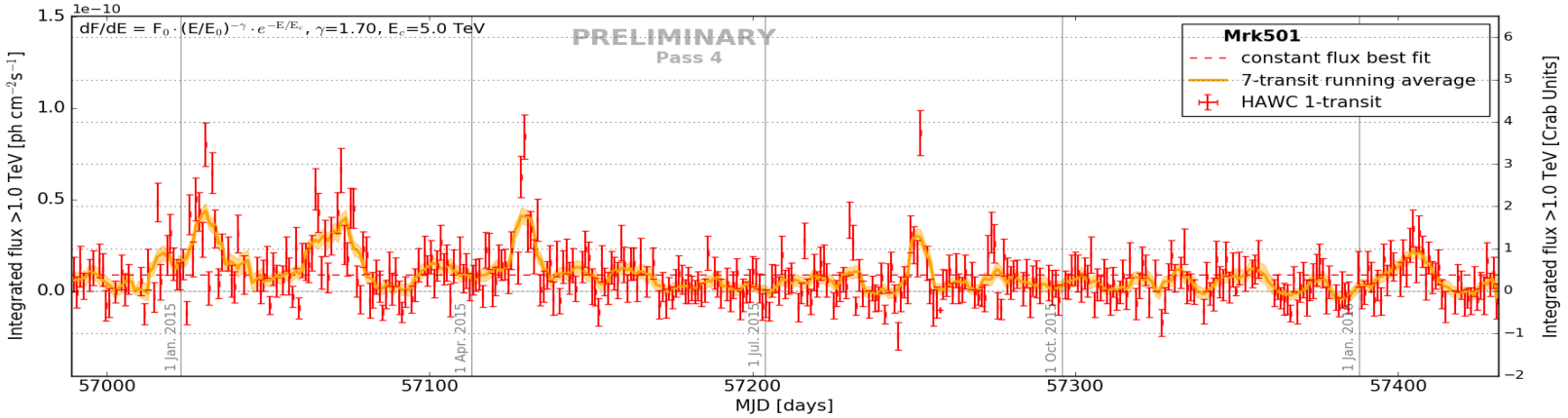
Mrk 421





Mrk 501

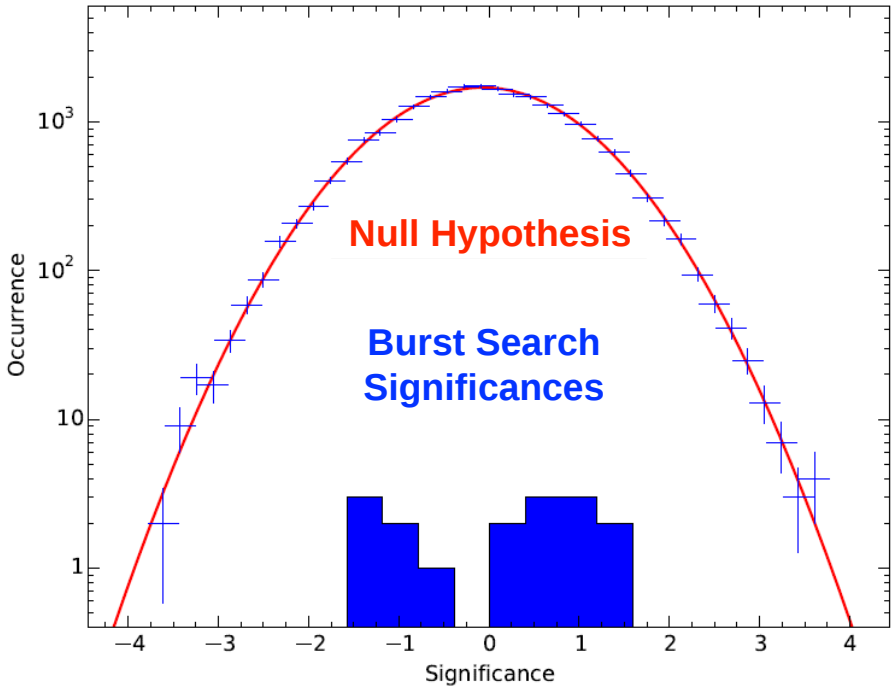


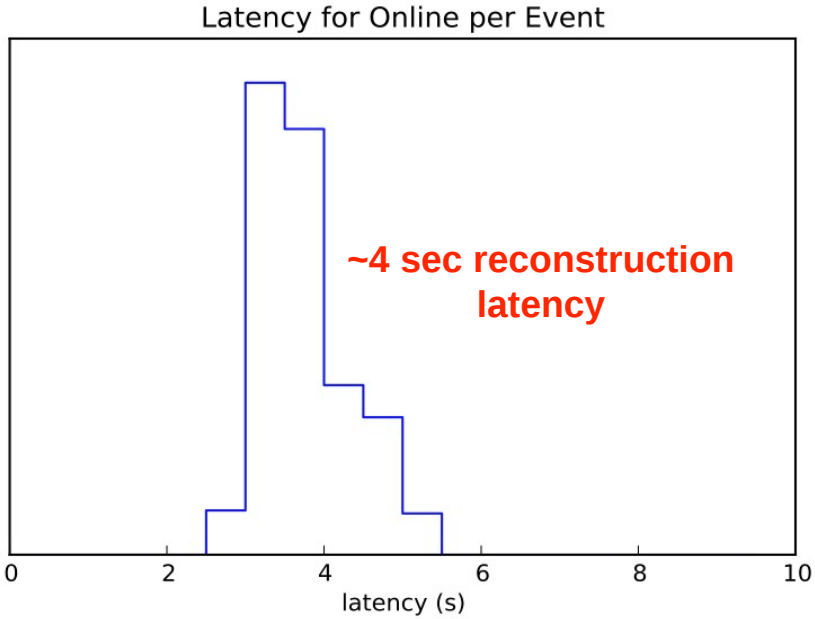


- Daily light curves show high variability in both sources (>6σ inconsistent with constant flux).
- Ongoing efforts to correlate HAWC observations with other instruments and wavelengths.

Gamma-Ray Bursts Search

- Currently 2 search methods:
  - Follow-up on alerts from satellites (Fermi-GBM, LAT, and Swift).
  - Online search for GRBs. **Transient alerts in near-real time.**
- Tested 16 GRBs from Swift in HAWC field of view. No detection yet.
- Expected 1-2 GRBs per year in HAWC. **NIMA 742, 2014, 276-277**.





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

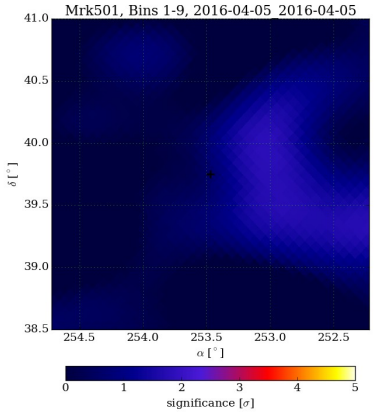
First HAWC Alert

HAWC detection of increased TeV flux state for Markarian 501

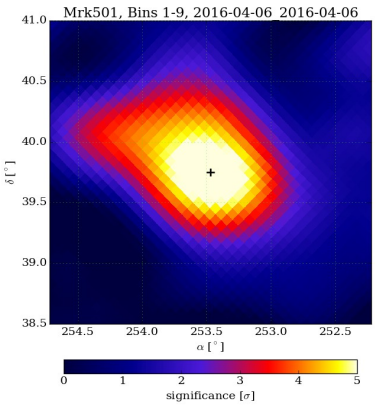
ATel #8922; *Andrés Sandoval (IF-UNAM), Robert Lauer (UNM), Joshua Wood (UMD) on behalf of the HAWC collaboration*
on 7 Apr 2016; 23:38 UT
Credential Certification: C. Michelle Hui (c.m.hui@nasa.gov)

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

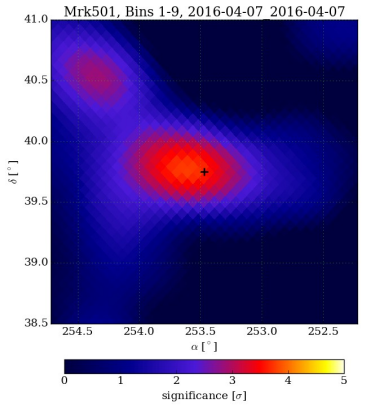
Paper on online flare monitoring in preparation!



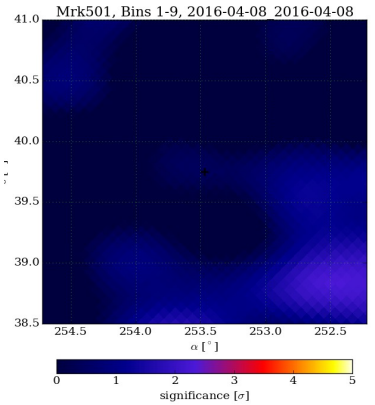
April 5, 2016



April 6, 2016



April 7, 2016



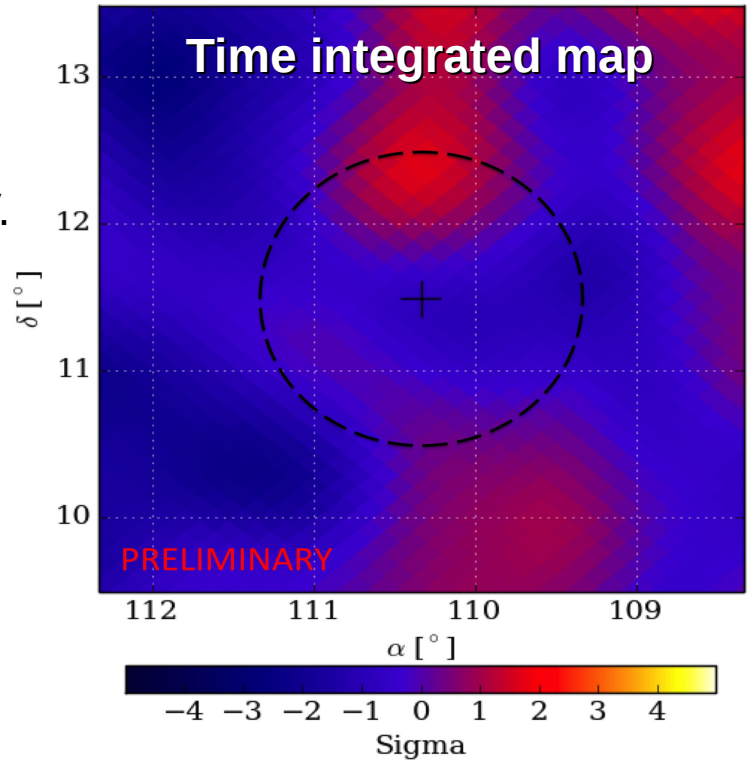
April 8, 2016

- 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.

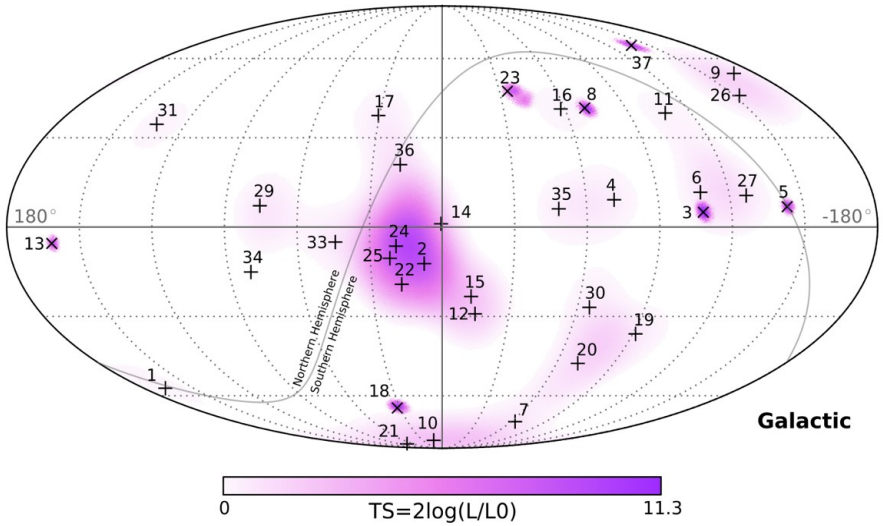


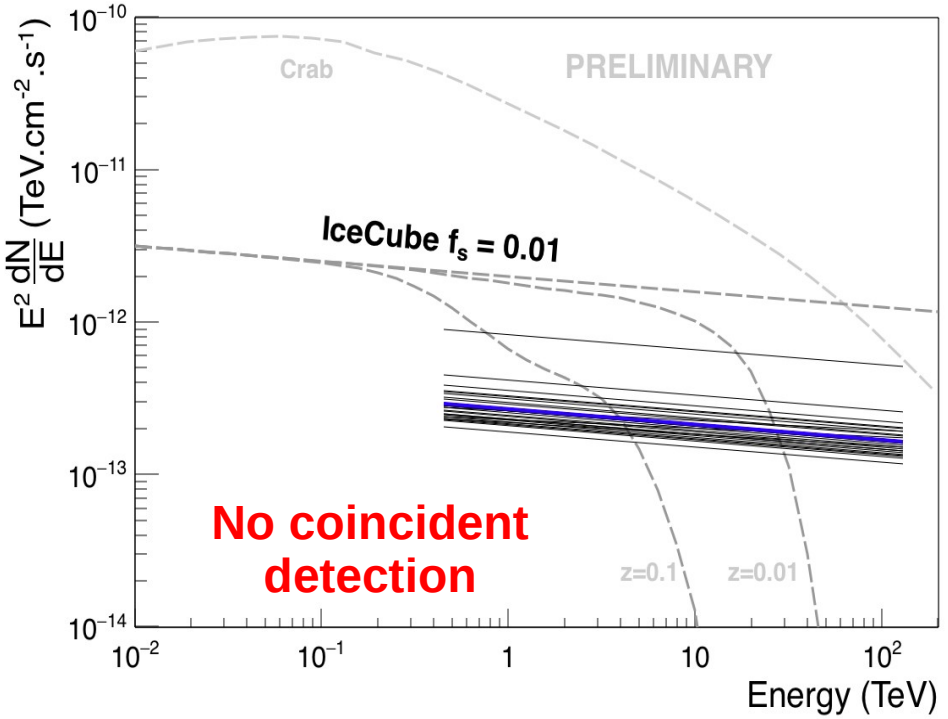
The steady neutrino flux, assuming it is evenly divided among N_s sources (IceCube, PRL 2014), should be detectable in HAWC in a year if photons are not attenuated.
We can set constraining limits on every IceCube event in the HAWC FOV.

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

HAWC Multi-Messenger: IceCube

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





Neutrino / Photon Connection: Pions

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

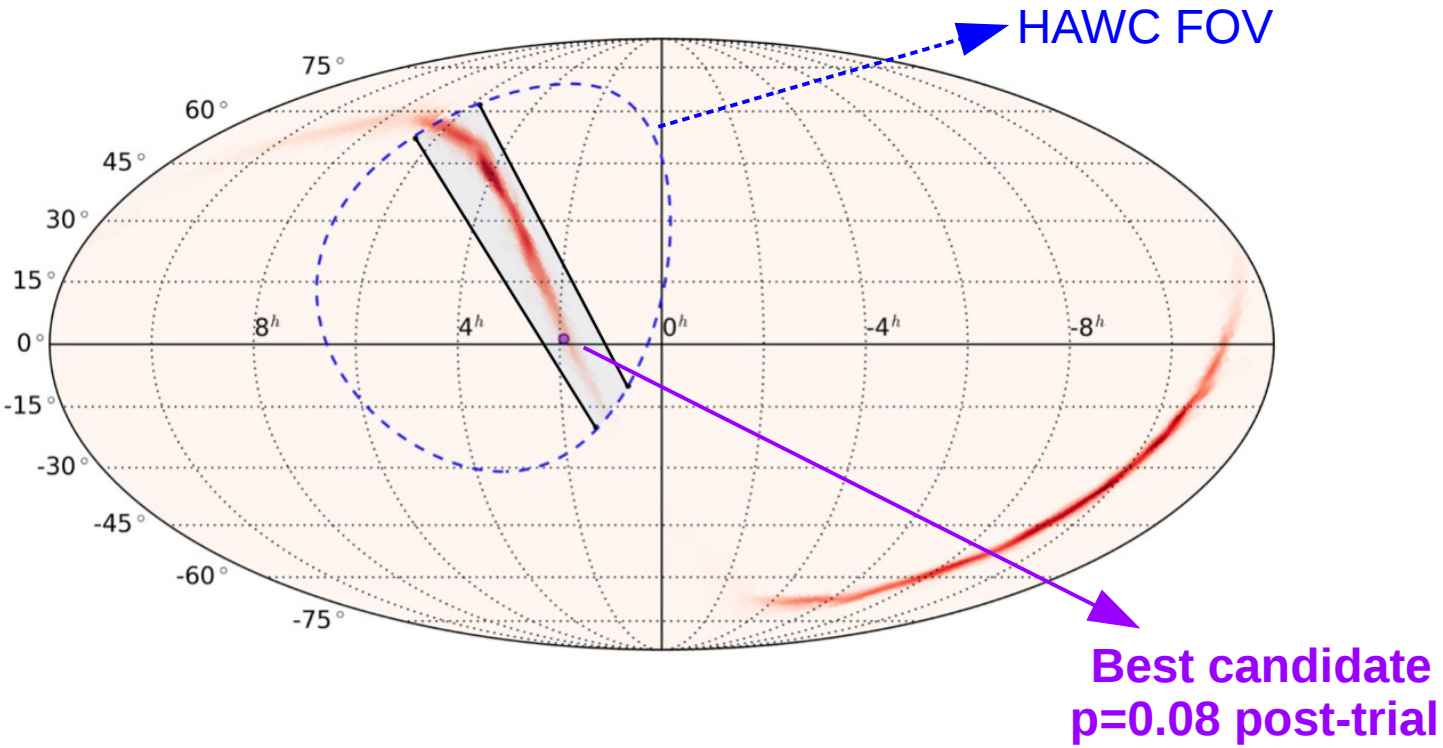
HAWC's Strengths for IceCube Followup

- 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.

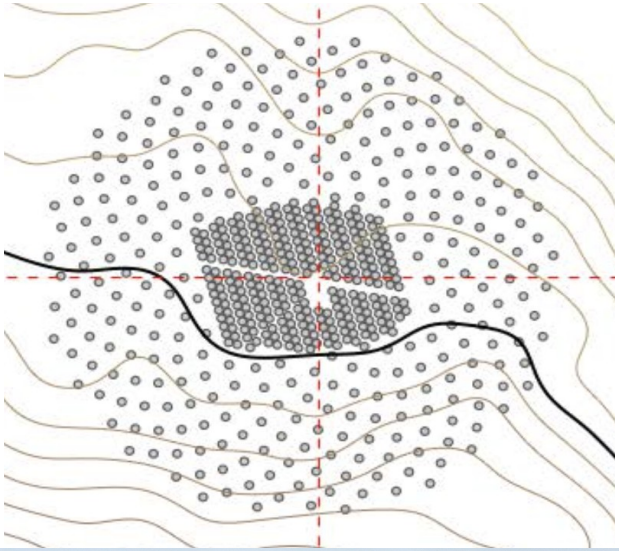
HAWC Multi-Messenger: LIGO Gravitational Waves

- Analysis under MoU with LIGO:
  - The first GW detection **GW150914**, 20150914 09:50:45 UTC, not in the FOV.
  - Second detection **GW151226**, 20151226 03:38:53 UTC, HAWC field of view covered a large part of the localization contour at time of coincidence. No significant detection.
    GCN circular: http://gcn.gsfc.nasa.gov/gcn3/19156.gcn3



- Applied **GRB all-sky search** with three time sliding windows of 1s, 10s, and 100s during a time interval ±15m from the LIGO trigger.
- The best candidate, occurred 9.98s after the GW trigger.
- Compatible with background fluctuations.

The Future of HAWC



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.

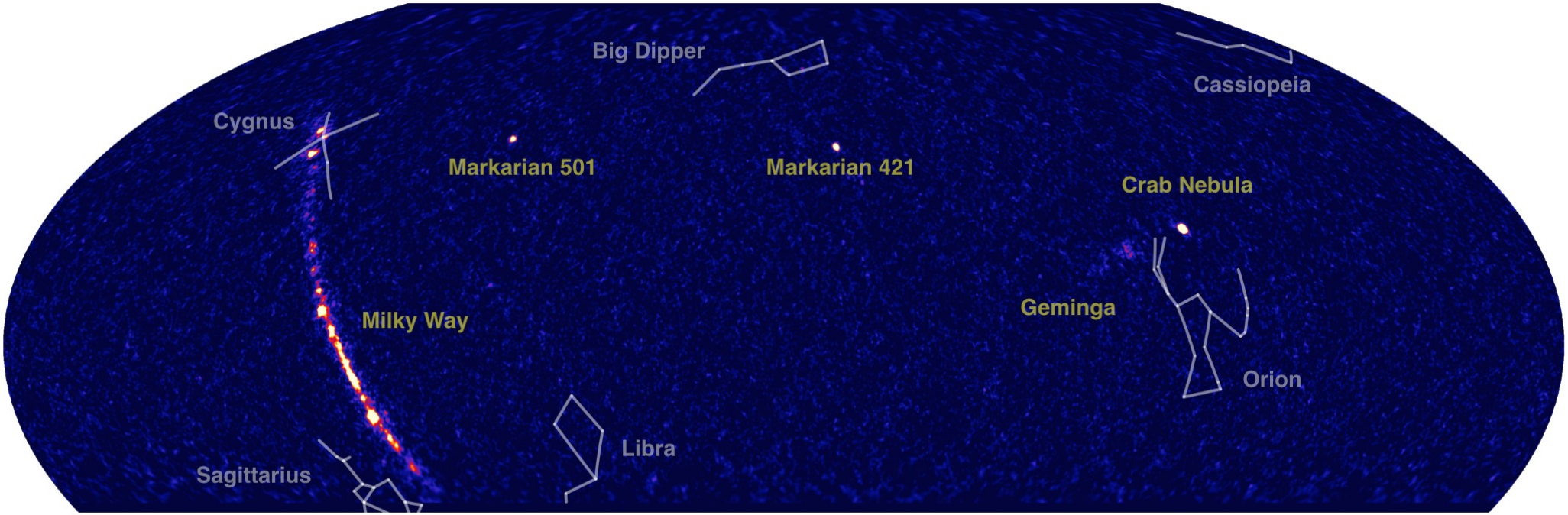
Future:

- HAWC South: Southern complement for CTA.
- Expected improvements: higher altitude, larger area, better hadronic rejection, better shower sensitivity.

Summary

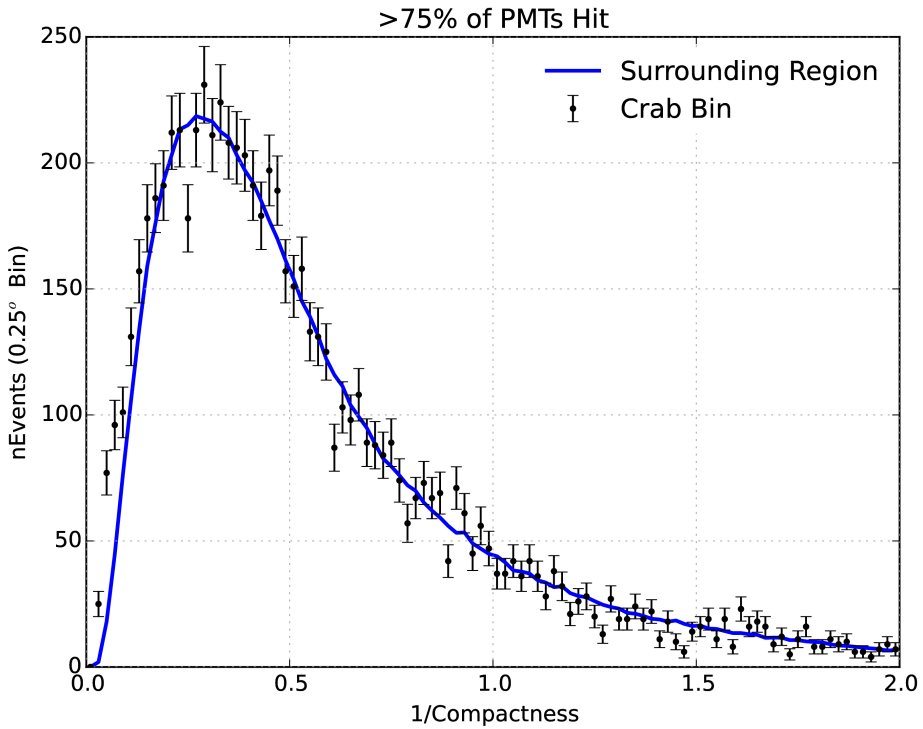
- HAWC fully operational for more than a year monitoring 66% of the sky daily with >90% duty cycle.
- Results being released (several papers in preparation).
- New sources discovered (some already confirmed).
- Alerts system running, first alerts delivered.
- Multi-messenger and multi-wavelength program with different analysis ongoing, e.g., Gravitational Waves.
- Future: HAWC outriggers being build and HAWC South being discussed.

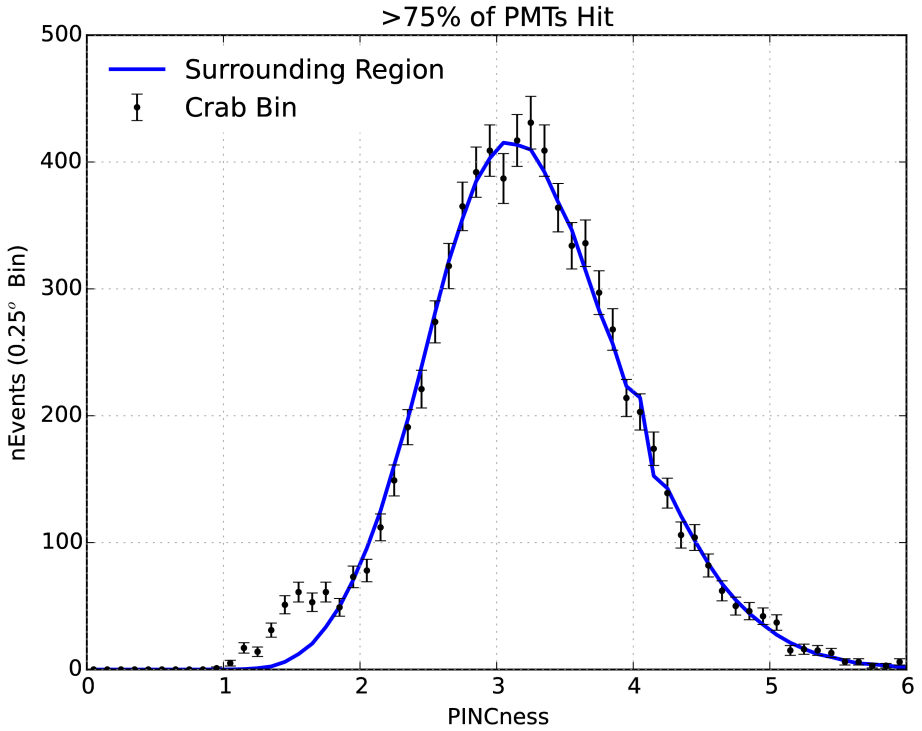
Thanks for your attention!



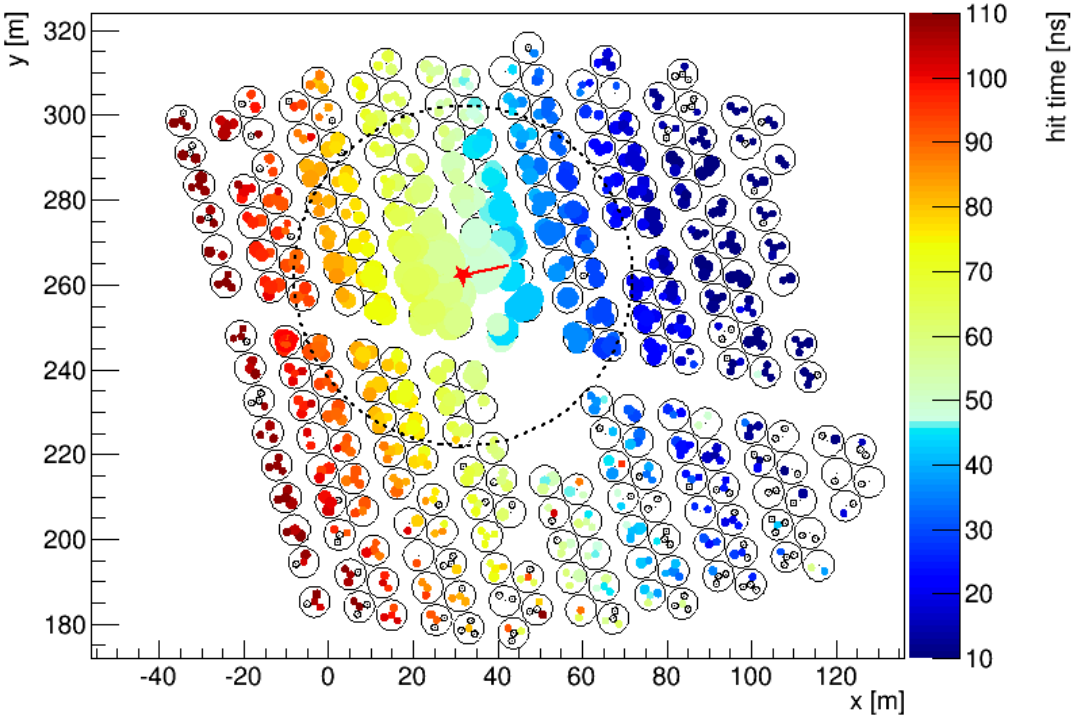
Back-up slides

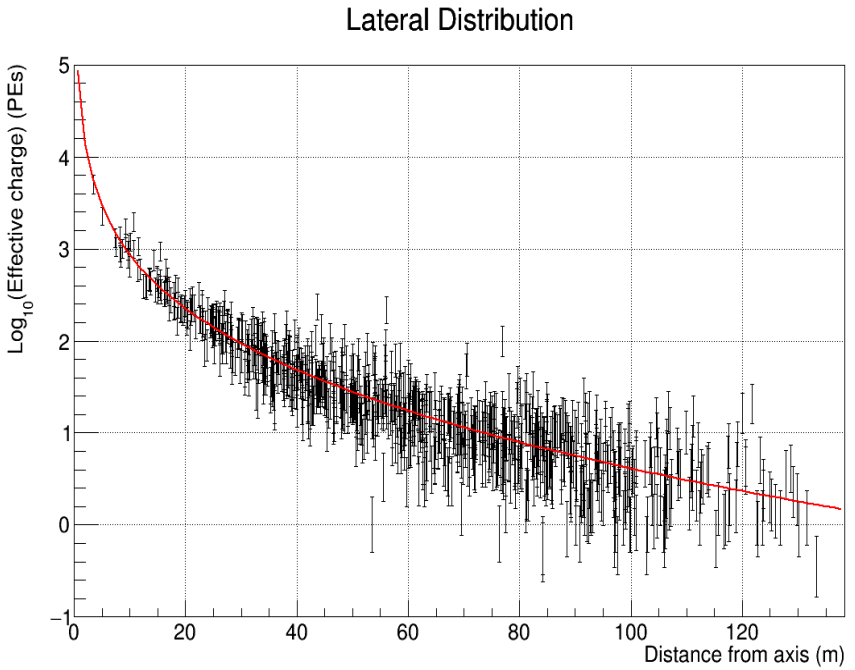
γ/h separation





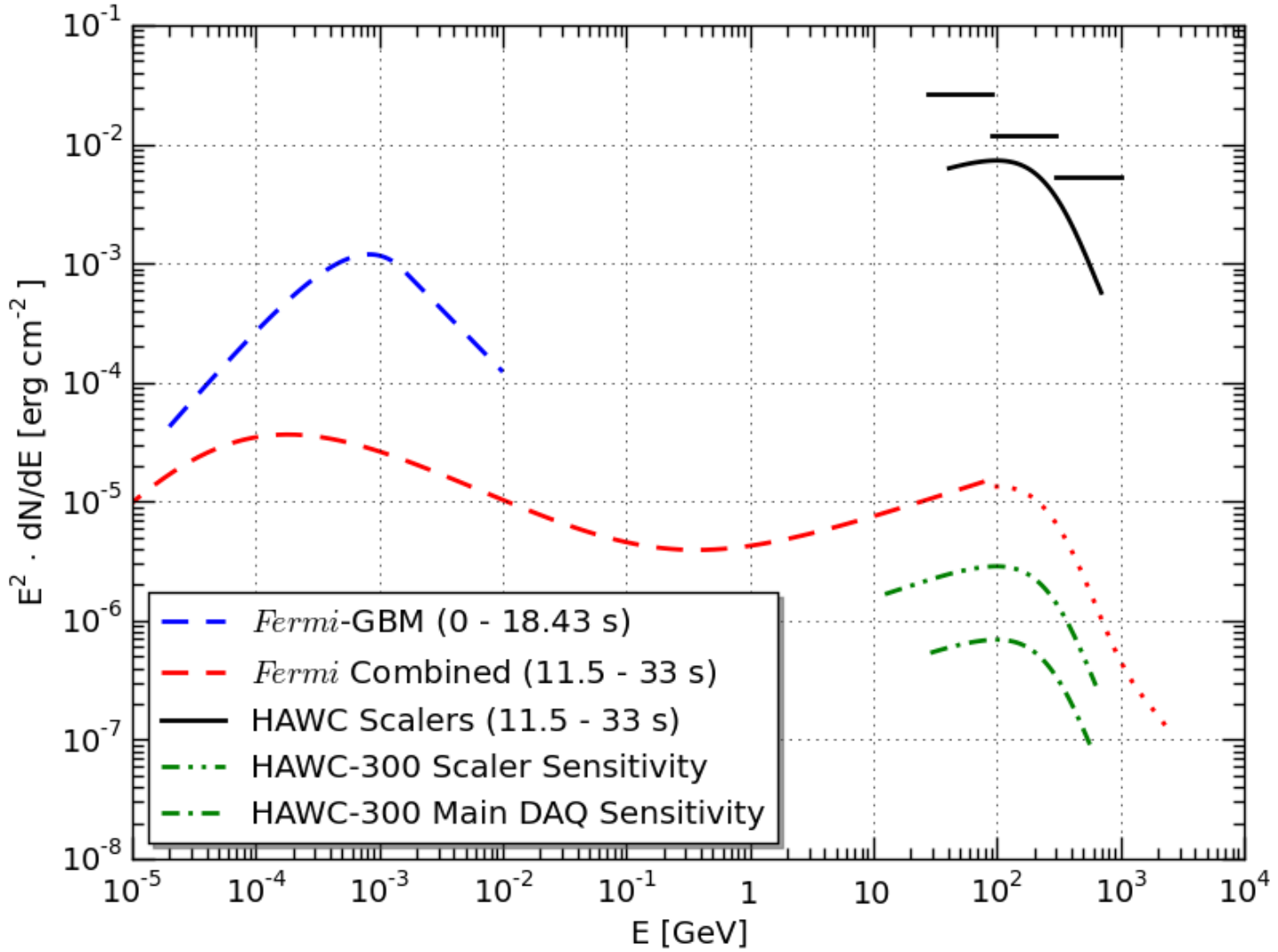
Crab gamma-ray candidate





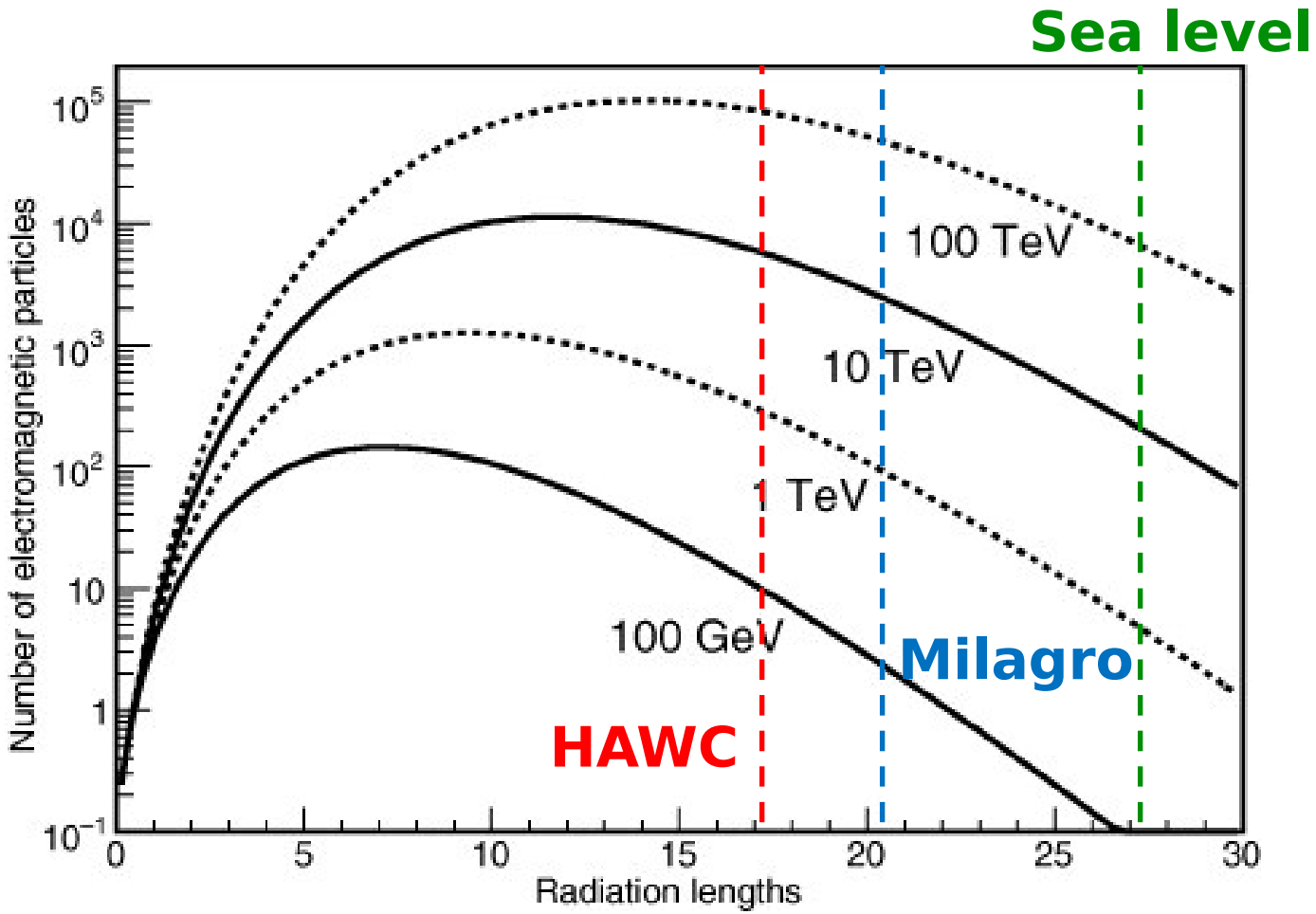
- Event reconstructed within 0.4° of the Crab Nebula.

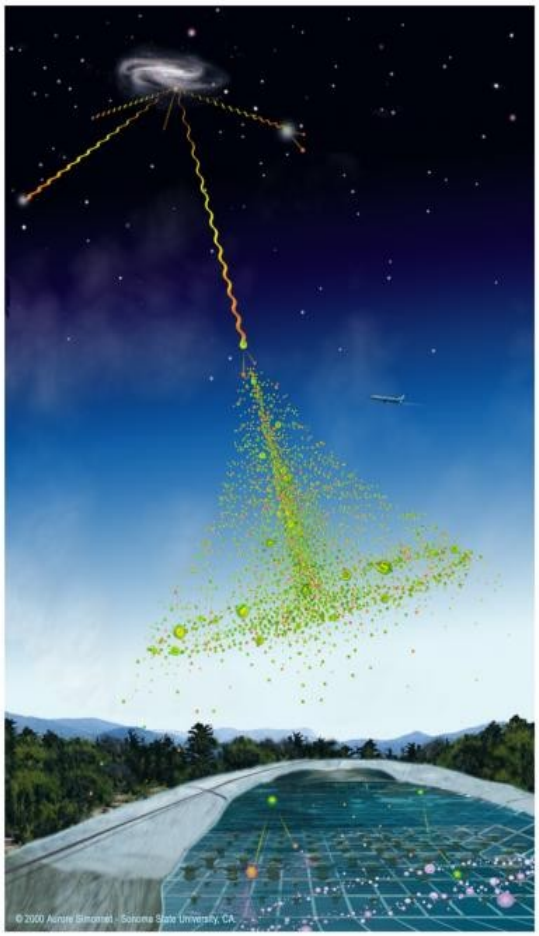
GRB 130427A limits



From Milagro to HAWC

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





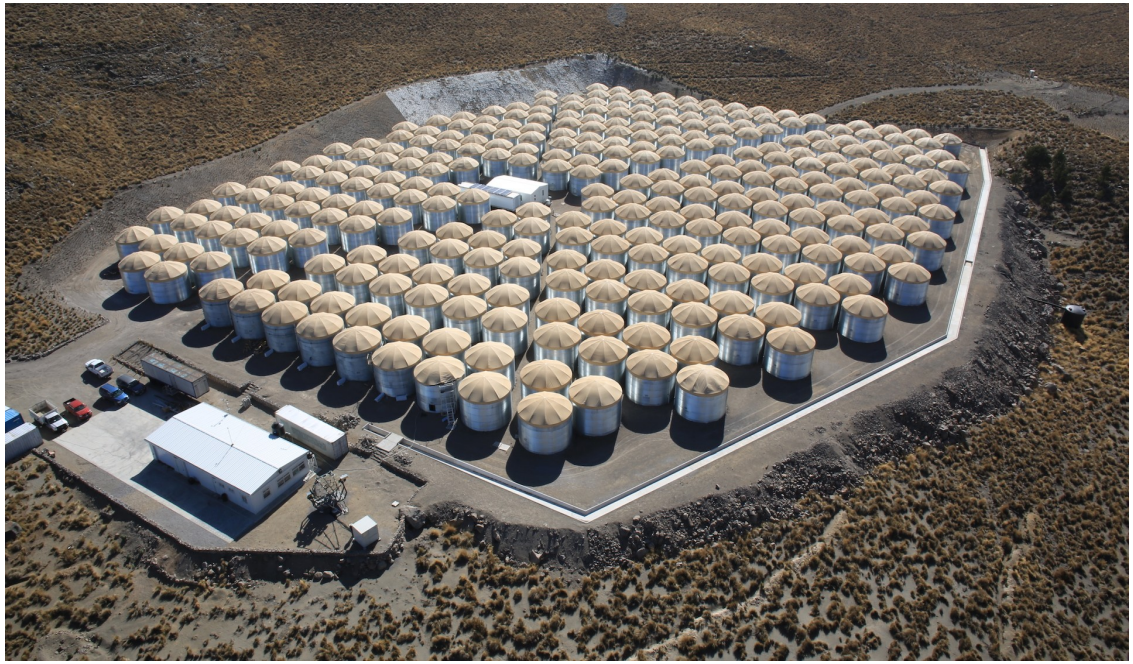
From Milagro to HAWC

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

Milagro

~60 m x 80 m

HAWC

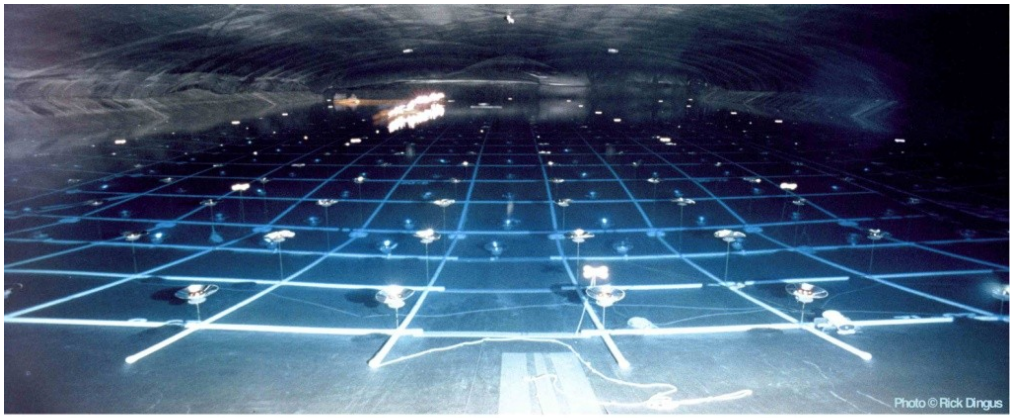


~150 m x 150 m

From Milagro to HAWC

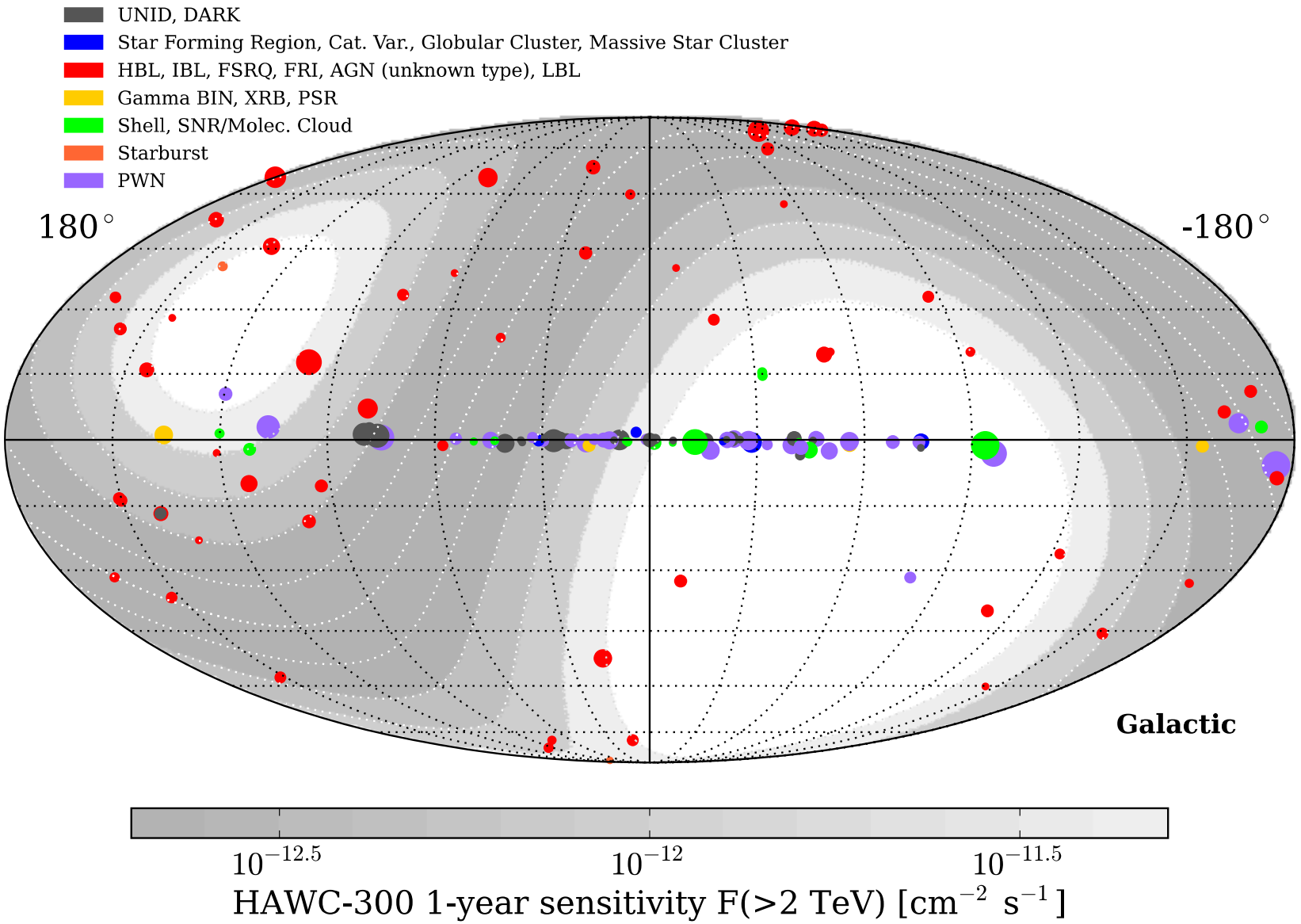
- Improve optical separation:
  one big pond -> individual water Cherenkov detectors (a.k.a. tanks)
- Taking data even during construction.

Milagro



HAWC

HAWC FOV


UNID, DARK
Star Forming Region, Cat. Var., Globular Cluster, Massive Star Cluster
HBL, IBL, FSRQ, FRI, AGN (unknown type), LBL
Gamma BIN, XRB, PSR
Shell, SNR/Molec. Cloud
Starburst
PWN
180°
-180°
Galactic
$10^{-12.5}$
10^{-12}
$10^{-11.5}$
HAWC-300 1-year sensitivity F(>2 TeV) [cm^{-2} s^{-1}]