

Recent results from the High Altitude Water Cherenkov (HAWC) Gamma-Ray Observatory



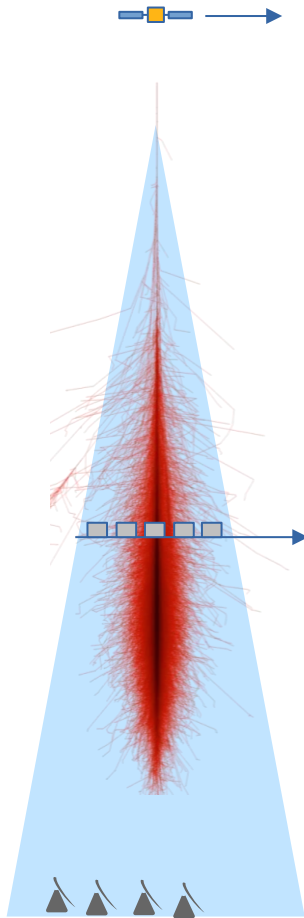
Brenda Dingus
for the HAWC collaboration

Los Alamos National Lab

18 May 2018



High Energy Gamma-Ray Detectors



**Wide Field of View,
Continuous
Operations**

Fermi LAT

**Satellite Detectors
(Fermi, AGILE, EGRET)**



HAWC

**Extensive Air Shower (EAS)
Detector (HAWC, ARGO, Milagro)**



VERITAS

**TeV
Sensitivity**

**Imaging Atmospheric Cherenkov
Telescope (VERITAS, HESS,
MAGIC)**

High Altitude Water Cherenkov (HAWC) Extensive Air Shower Detector



Citlaltepetl
Pico de Orizaba
5160m a.s.l.



- 22,000 m² air shower array
- 300 Water Cherenkov detectors (WCD)
- 200,000 liters of purified water per WCD
- 4 sensors (photo-multiplier tubes) per WCD
- Completed March 2015

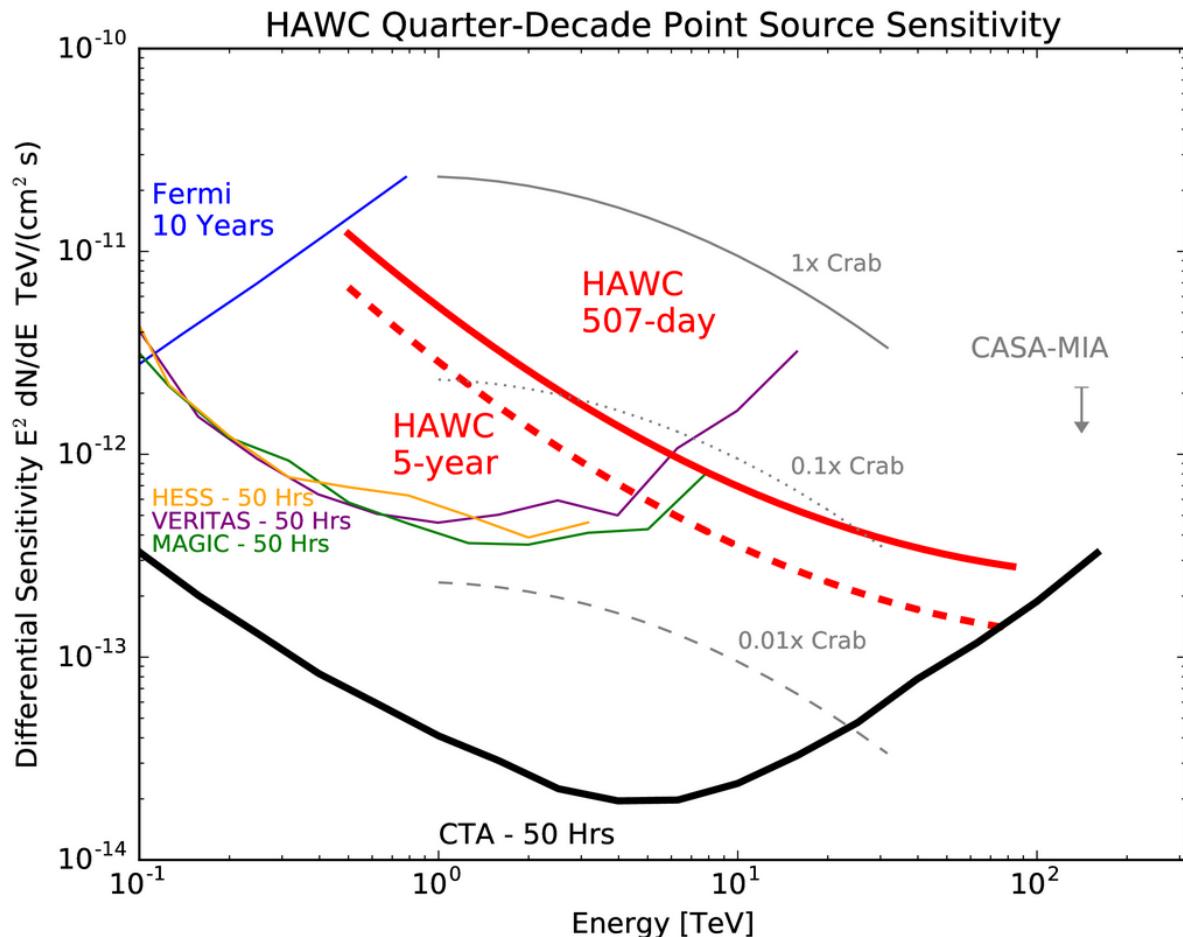
Large
Millimeter
Telescope

HAWC
4100 m a.s.l.

Tliltepetl
Sierra Negra
4582m a.s.l.

High Energy Gamma-Ray Sensitivity

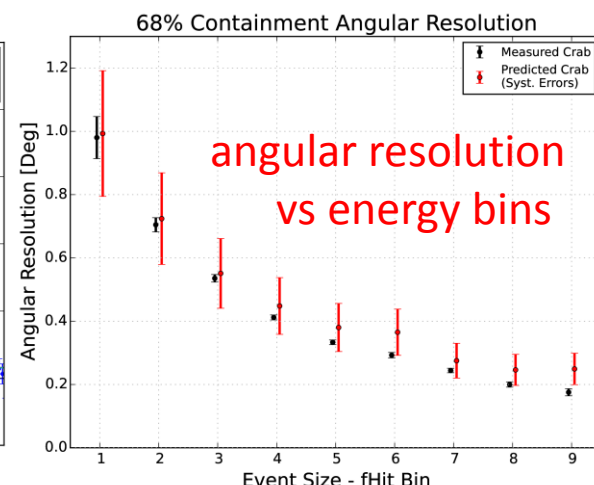
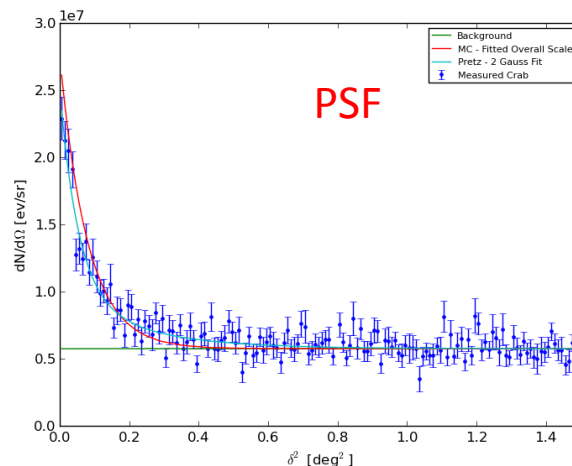
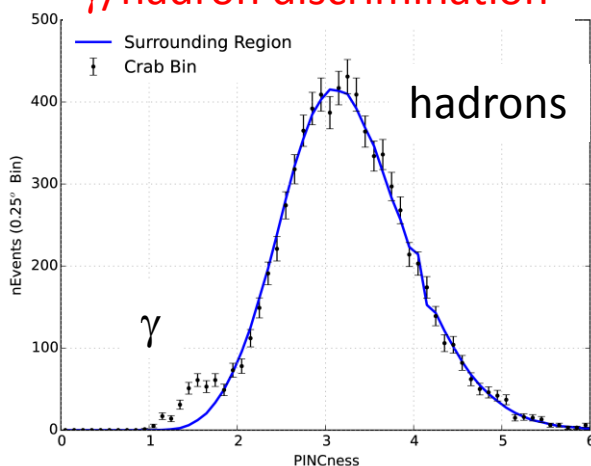
- Fermi and HAWC have instantaneous field of view of ~ 2 sr
- IACT observations of 50 hours are typical after a few years of operation
- HAWC observes 8 sr (i.e. 2/3) of the sky each day
- HAWC has the best sensitivity > 10 TeV of currently operating observatories (CTA is planned for mid 2020s)



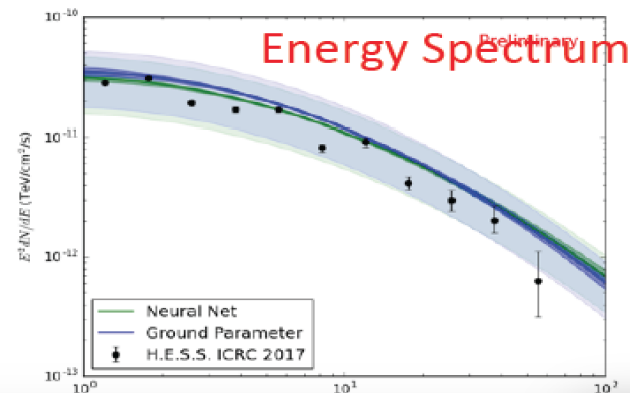
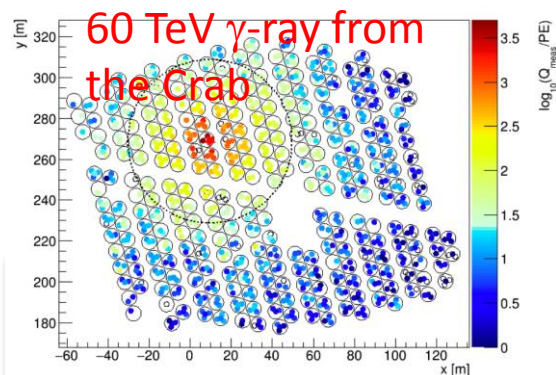
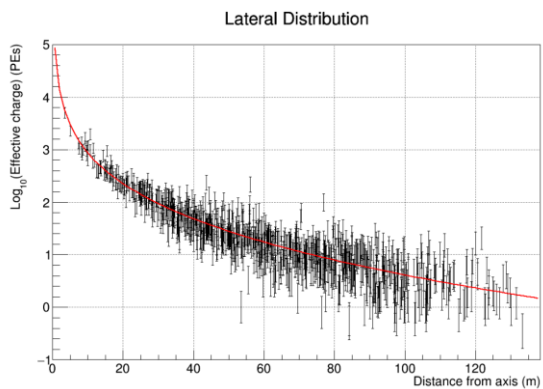
Crab with HAWC

- The Crab is $> 100 \sigma$.
- Validates our sensitivity (Abeysekara, ApJ, 843, 39, 2017)

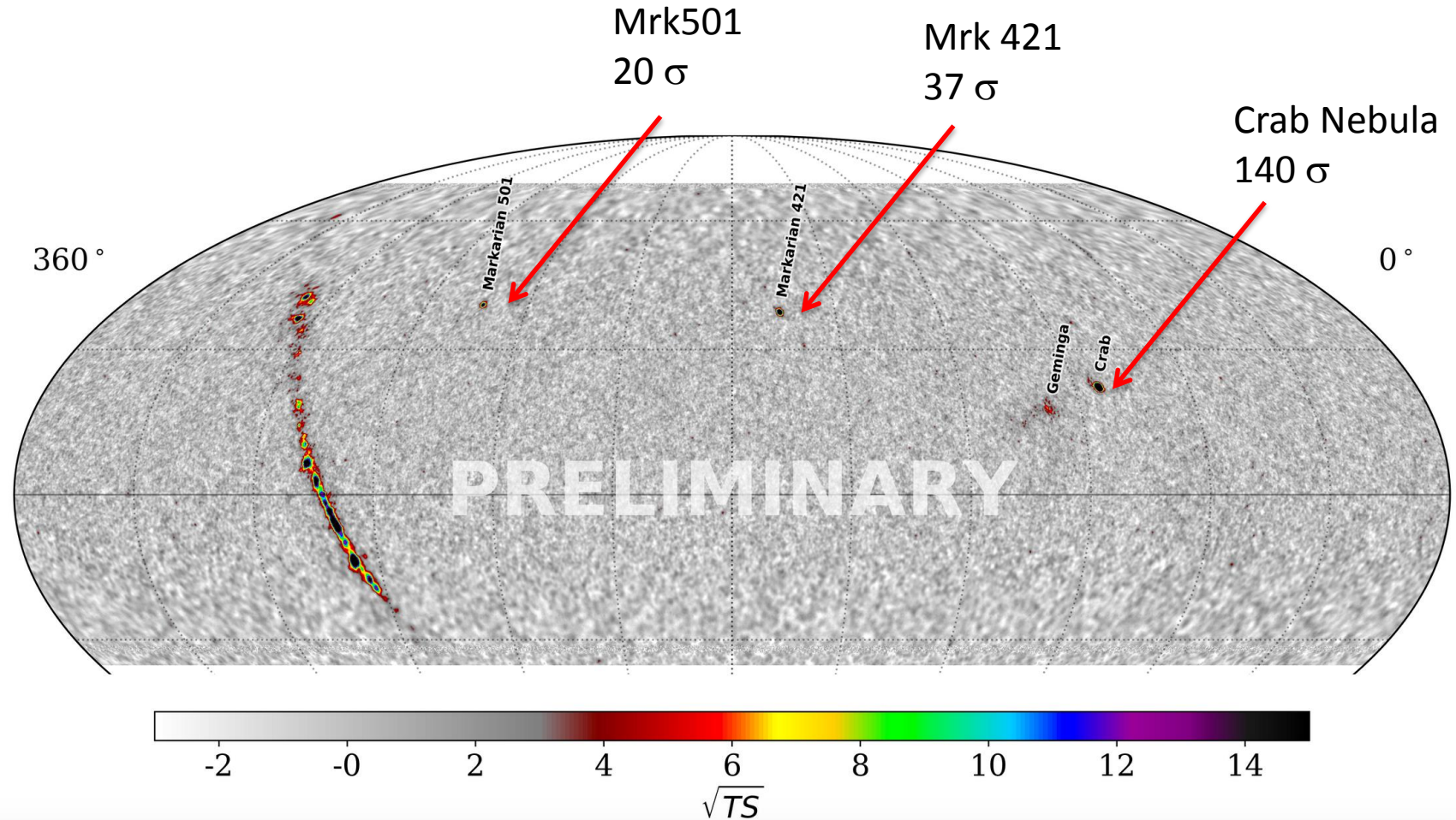
γ /hadron discrimination



- Probes the highest energy gamma-rays

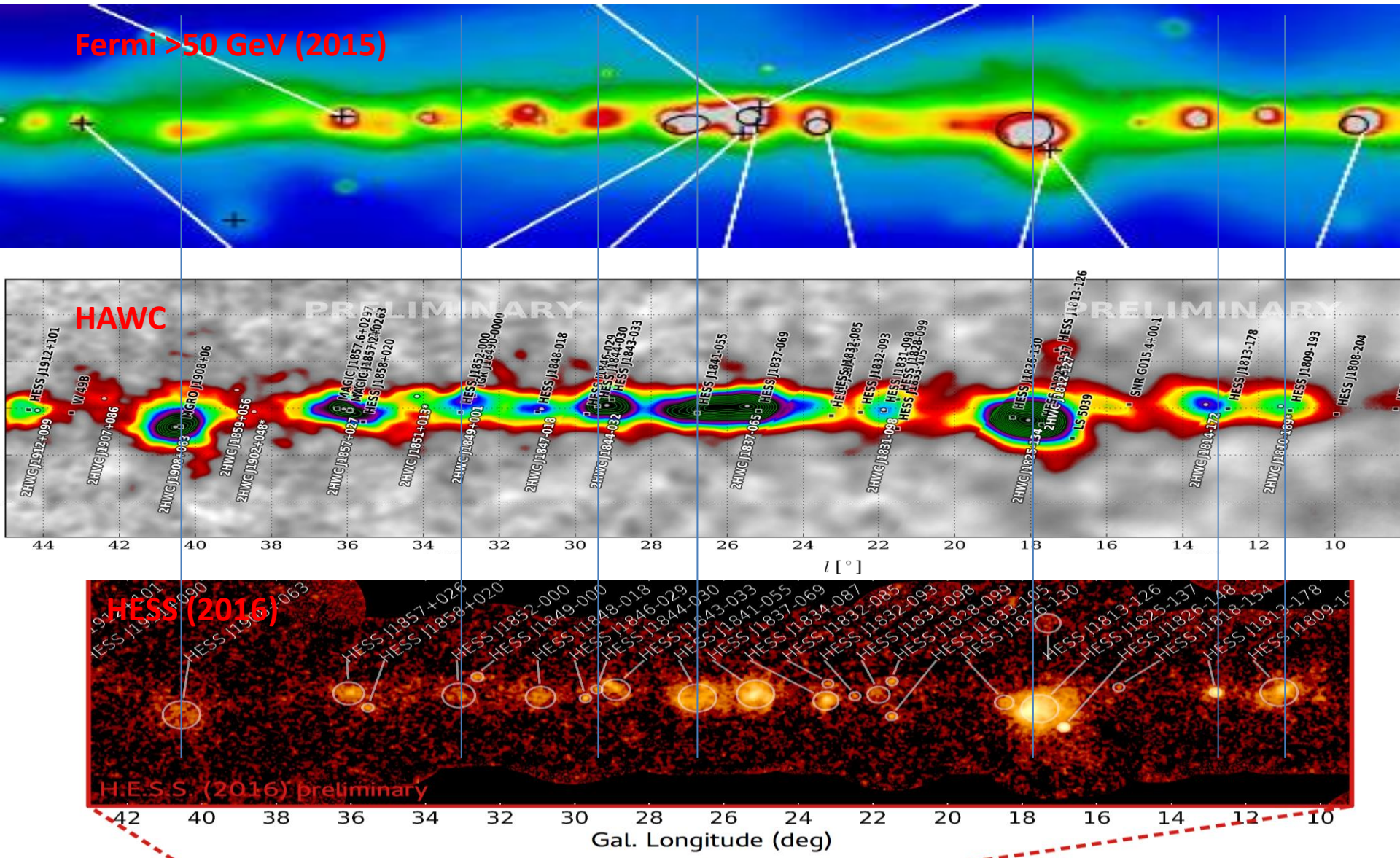


HAWC's 2.5 year Sky Map

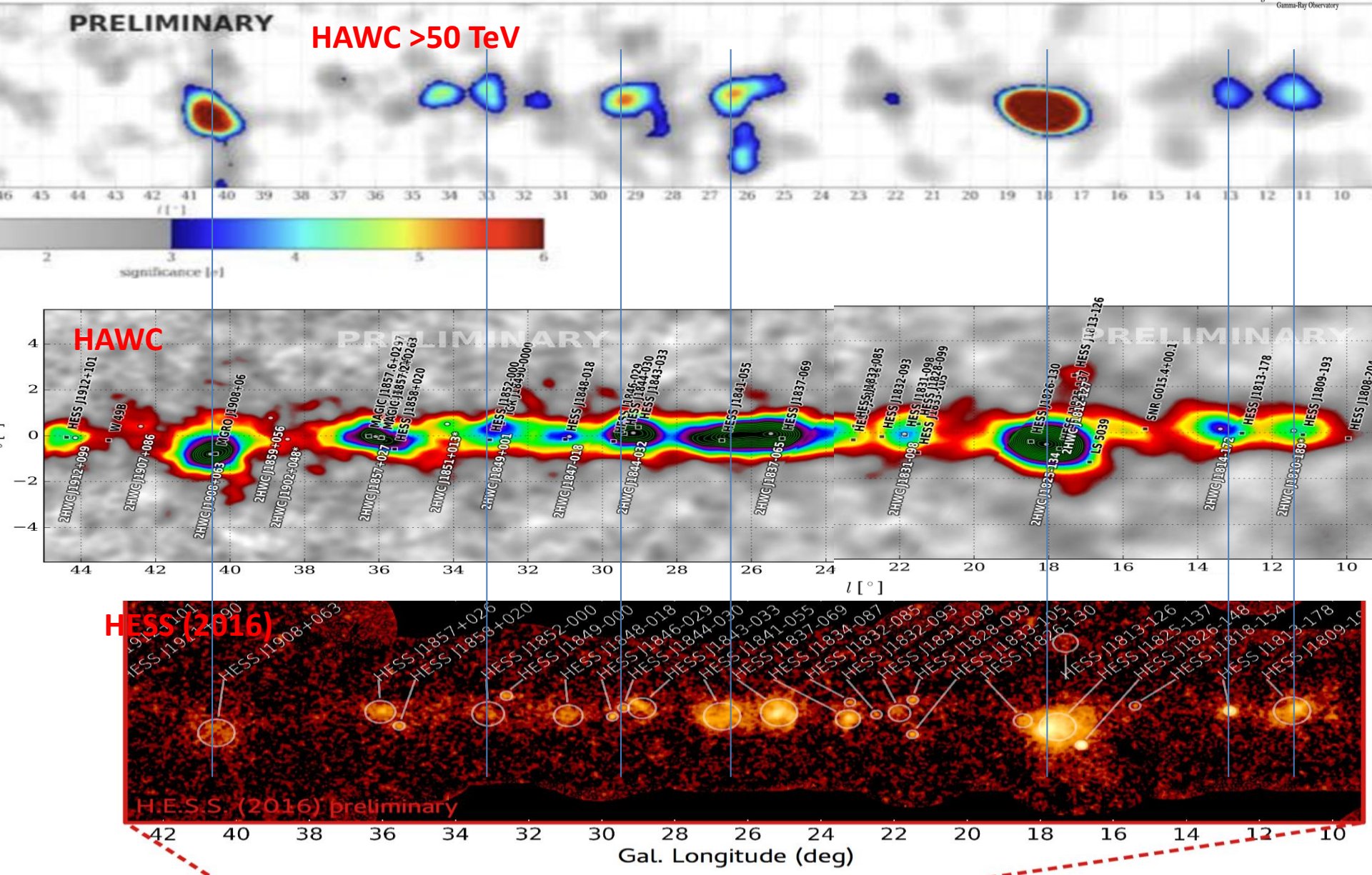


2HWC catalog ApJ 2017, arXiv:1702.02992, was 507 days
and contained 39 sources of which 10 were new

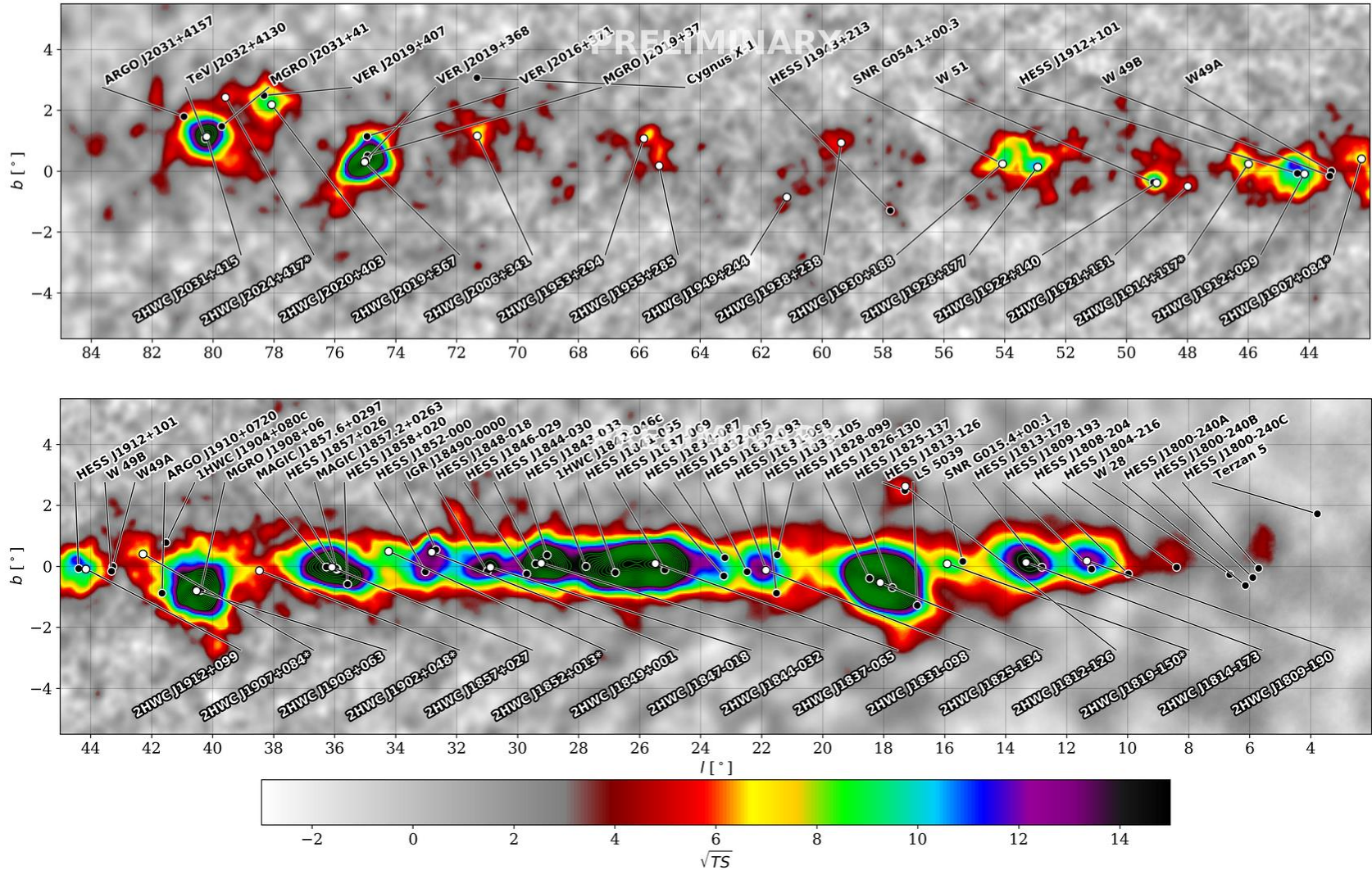
Fermi, HAWC, and HESS



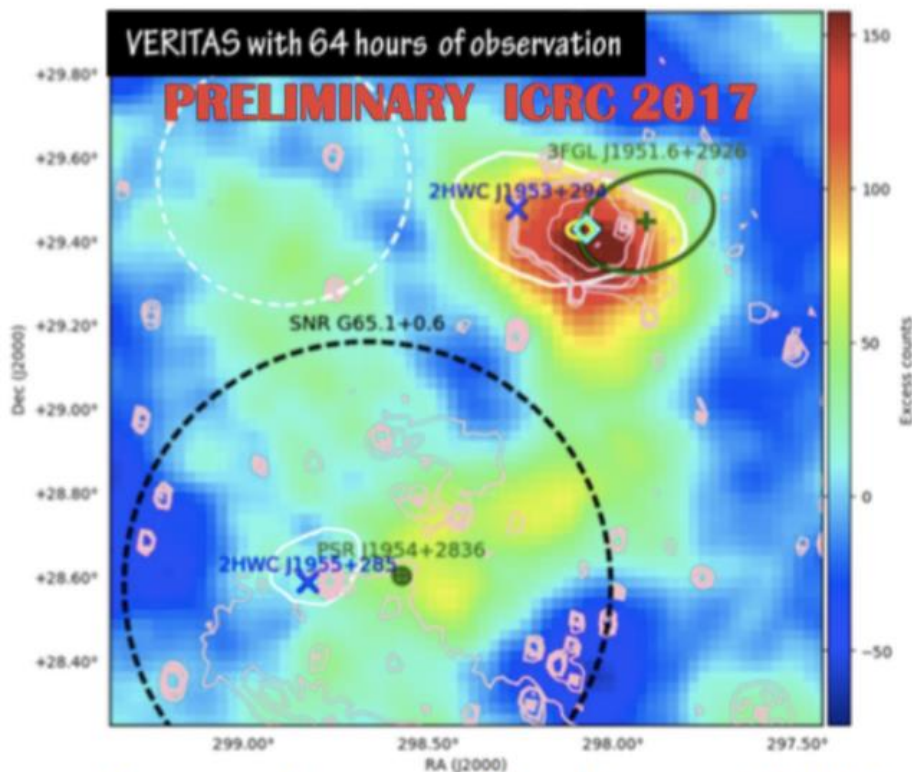
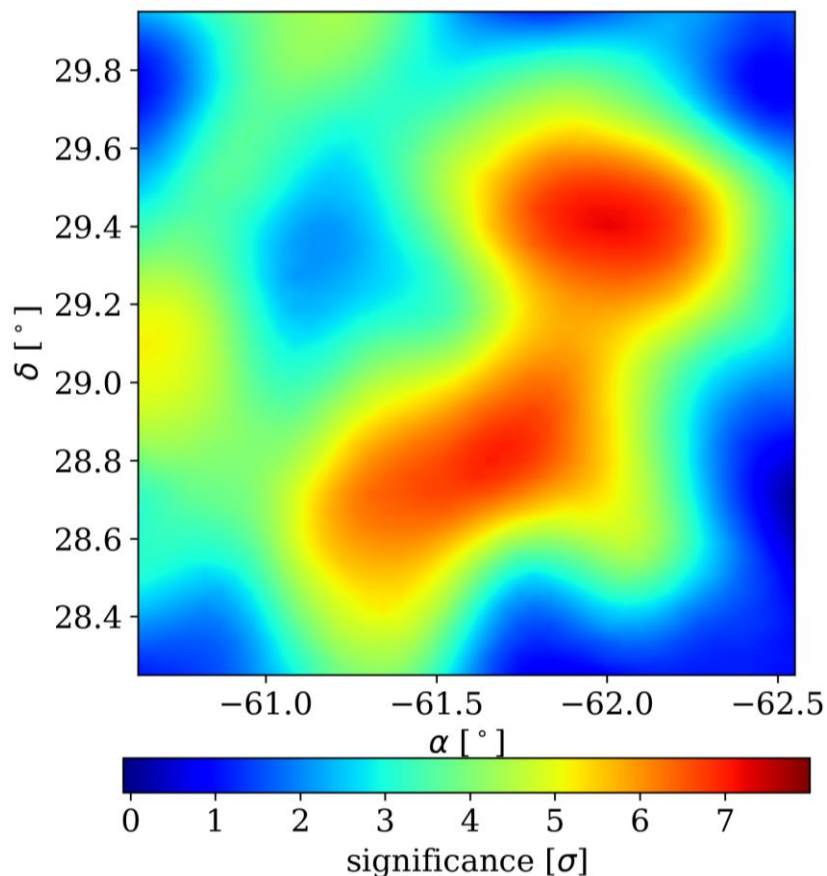
HAWC >50 TeV, HAWC, and HESS



HAWC's Galactic Plane with 2.5 years of data



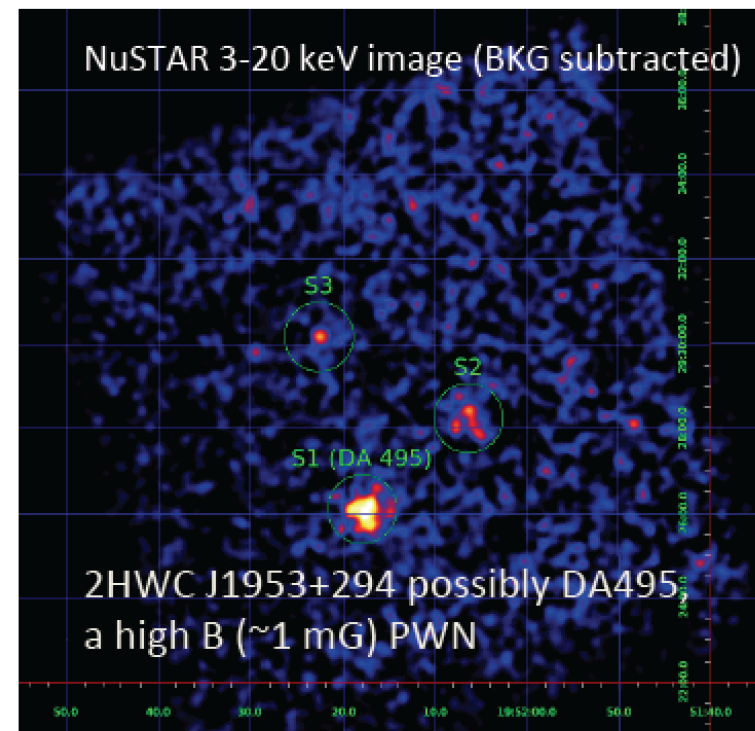
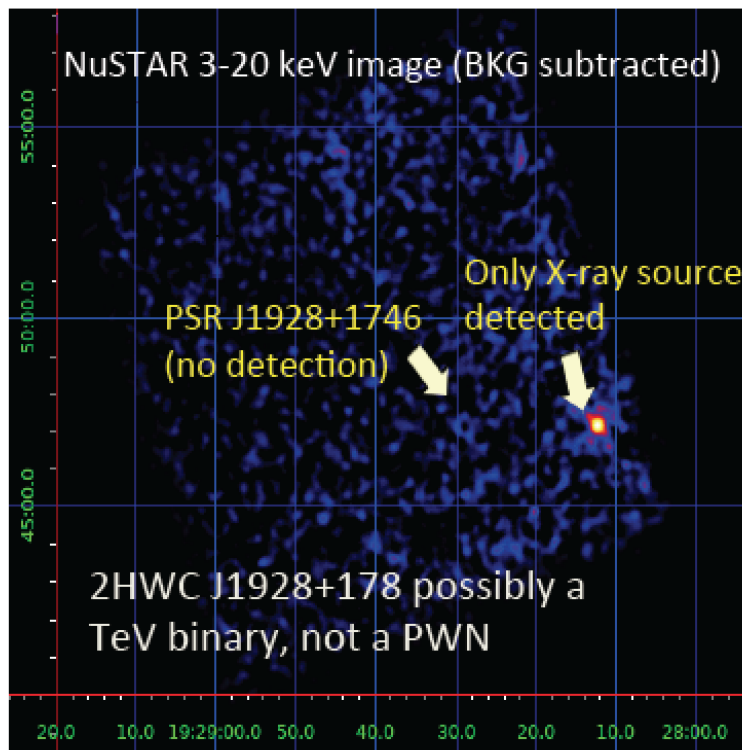
VERITAS Confirms HAWC detection



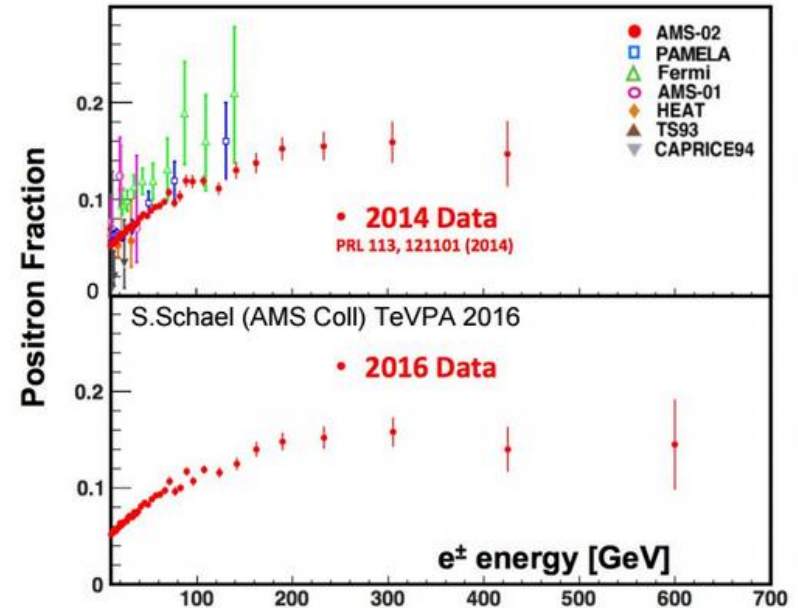
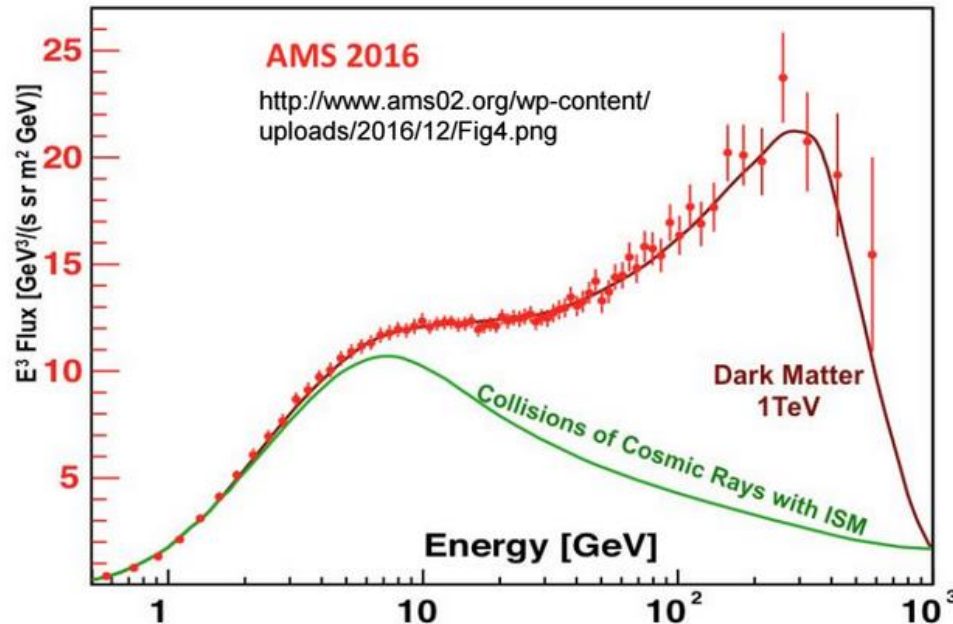
Cyan diamond is X-ray PWN

NuSTAR-VERITAS-HAWC Legacy Project

- First 2 NuSTAR observations are very interesting: a potential TeV binary of which there are only 6 known, and a high B field Pulsar Wind Nebula with no pulsar detected
- Joint project involves Columbia scientists on VERITAS (Brian Humensky and Reshmi Mukherjee) and on NuSTAR (Kaya Mori and Chuck Hailey)



Local Cosmic Positrons

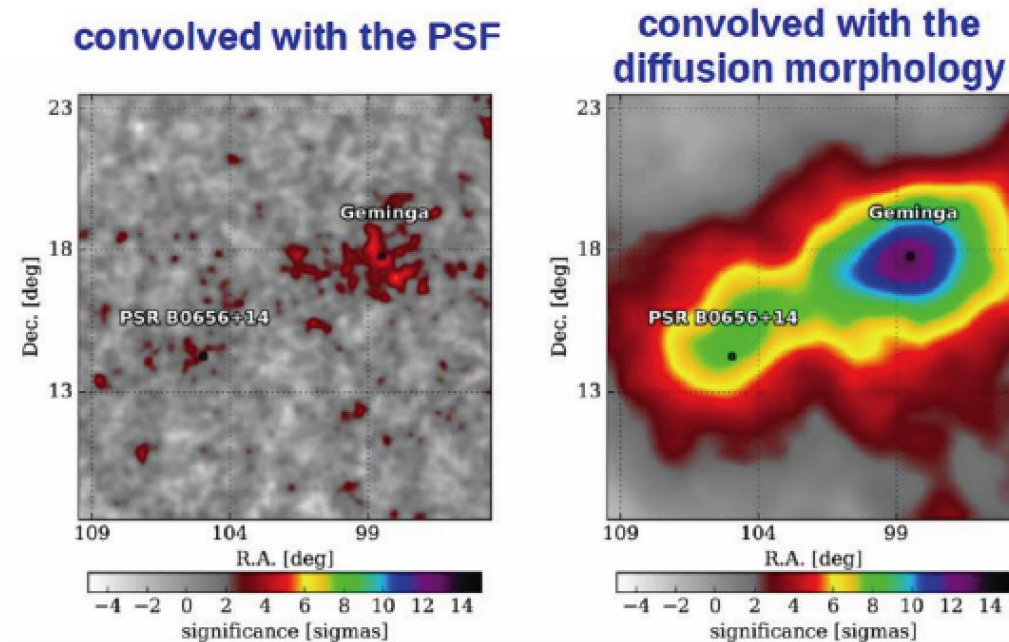


- AMS-02 on board the International Space Station observes local cosmic rays since 2011
 - excellent charge resolution and particle species discrimination
- TeV e^-e^+ lose energy quickly and therefore must be produced locally ($d < \sim 100$ pc)
 - secondaries produced by cosmic ray interactions with ISM (spallation)
 - primaries produced by local source
 - local cosmic accelerator (e.g. Geminga)? local dark matter interactions?
- Larger positron flux observed above ~ 10 GeV than expected from secondaries
 - First observed by Pamela in 2009, since confirmed by Fermi LAT and AMS-02
 - Are they from a local cosmic accelerator or dark matter?
 - If they are from dark matter, other annihilation products should be produced



AMS Positrons from Pulsars?

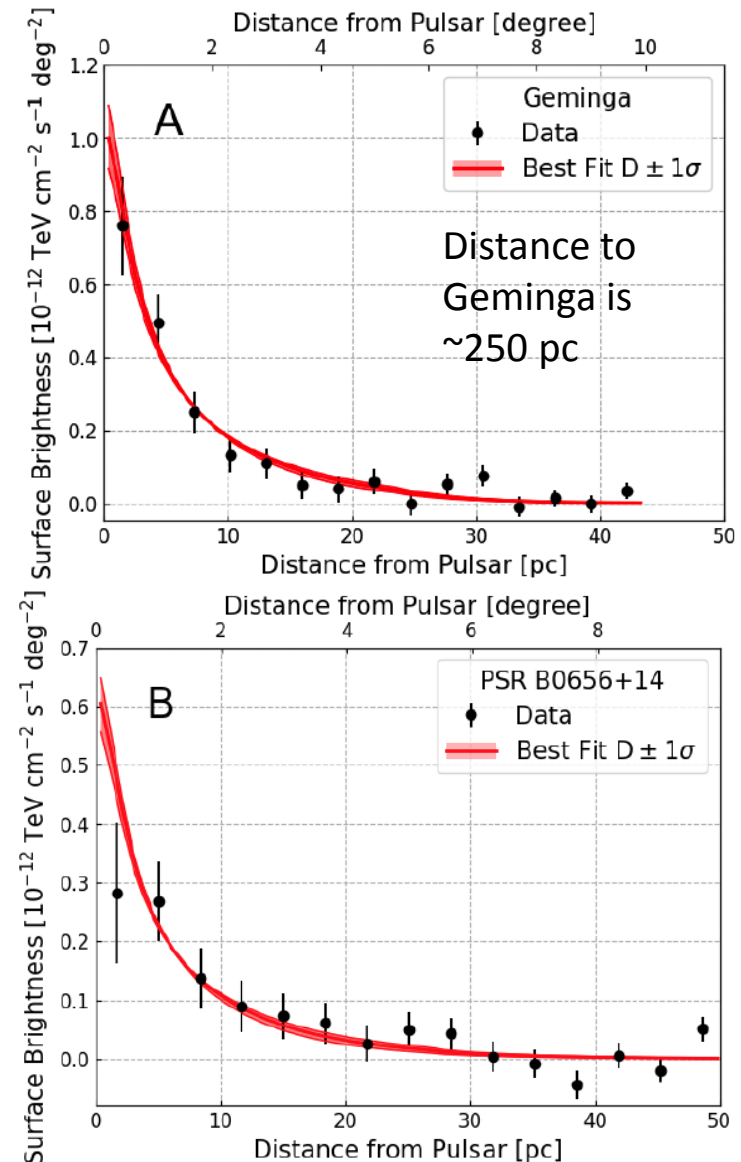
- Postulated sources of AMS positron excess are nearby, old pulsars
- Geminga and Monogem are the best candidates
- HAWC detects both as very extended TeV gamma-ray sources



Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth

by the HAWC collaboration

- HAWC observations prove that these sources are indeed accelerating electrons and positrons to multi-TeV energies.
- HAWC observations measure the total energy released in electrons and positrons which is much of their measured spin down energy.
- HAWC observations of the angular extent of these TeV nebula measures the diffusion coefficient of their propagation in the interstellar medium.

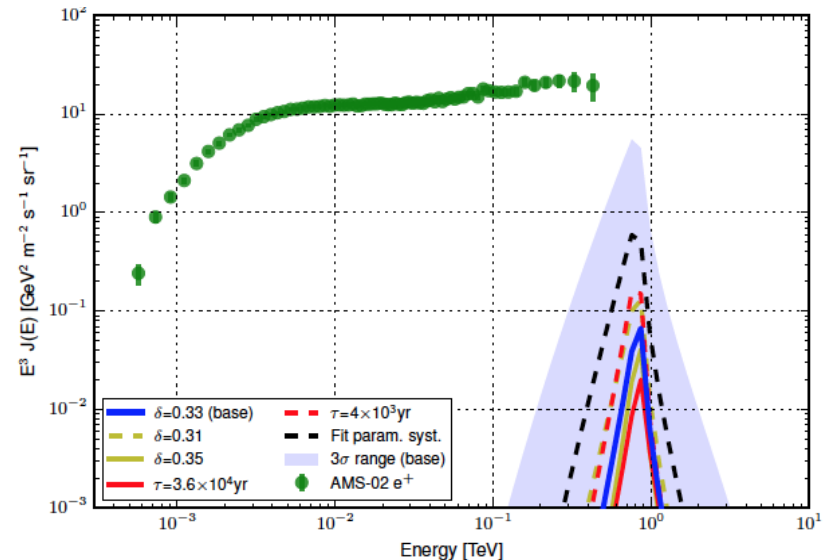
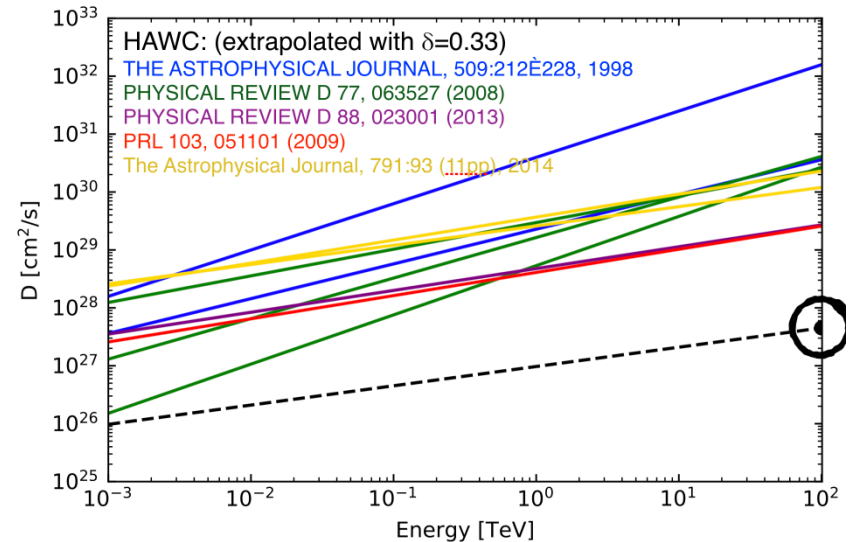


HAWC Diffusion vs. Cosmic Ray

Secondary Derived Diffusion

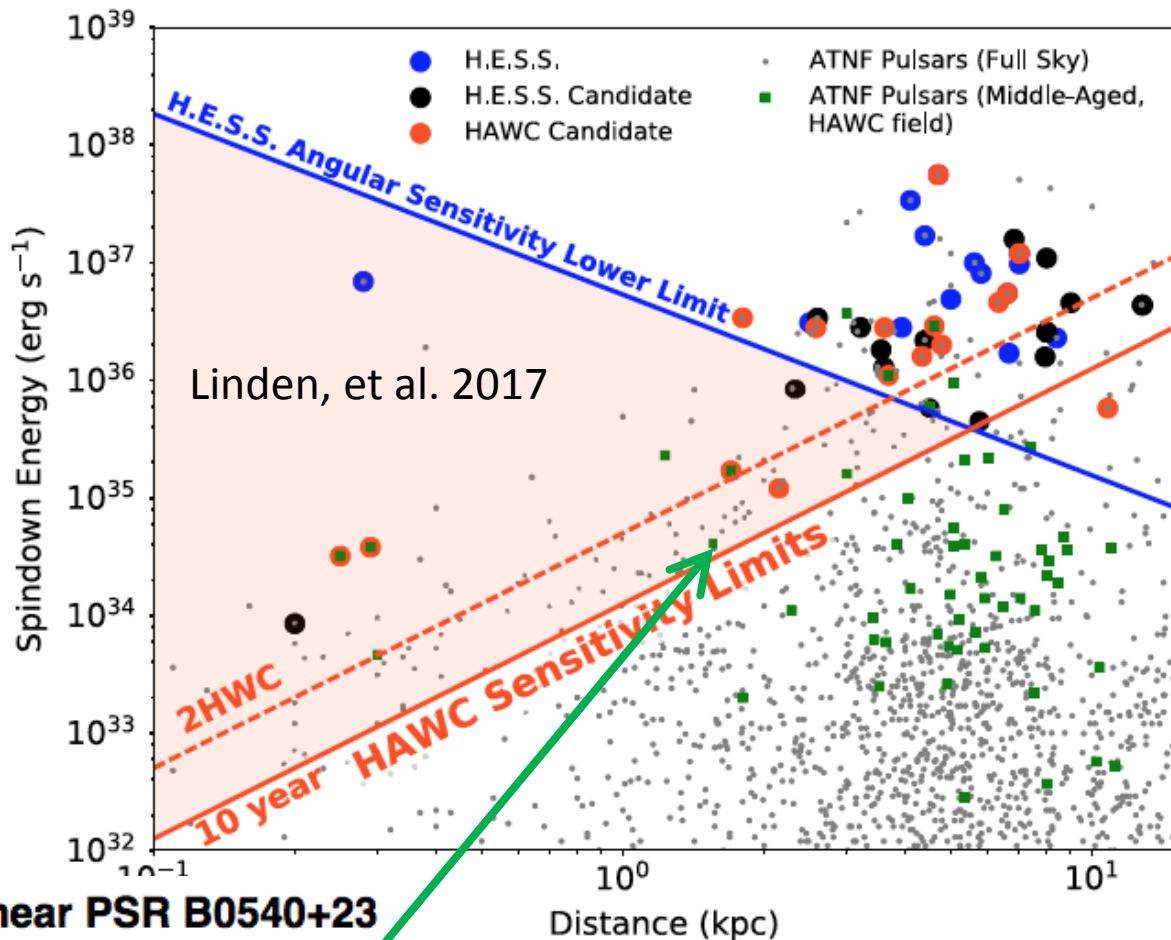


- Diffusion Coefficient, D , Measured by HAWC is much lower than that derived from cosmic ray secondaries
 - The ratio of Boron to Carbon is used to determine D averaged over the ~ 10 million year lifetime of cosmic rays. However, cosmic rays spend much of their lifetime in the halo of the galaxy where diffusion is probably faster.
- Assuming the HAWC measured D , the positrons from Geminga or Monogem **contribute negligibly to the positron flux** measured by satellite detectors like AMS-02.
- Hooper & Linden, 2017 argue that the highest energy electrons imply that D cannot be so low.



Other Sources of the Positrons

- Annihilation or Decay of Dark matter into Standard Model Particles
- Other Nearby PWN (perhaps as yet undiscovered) →
- Nearby Supernova Remnant Shocks
- Nearby X-ray Binaries
- New Theories about Secondaries Produced by Cosmic Ray Propagation



HAWC detection of TeV emission near PSR B0540+23

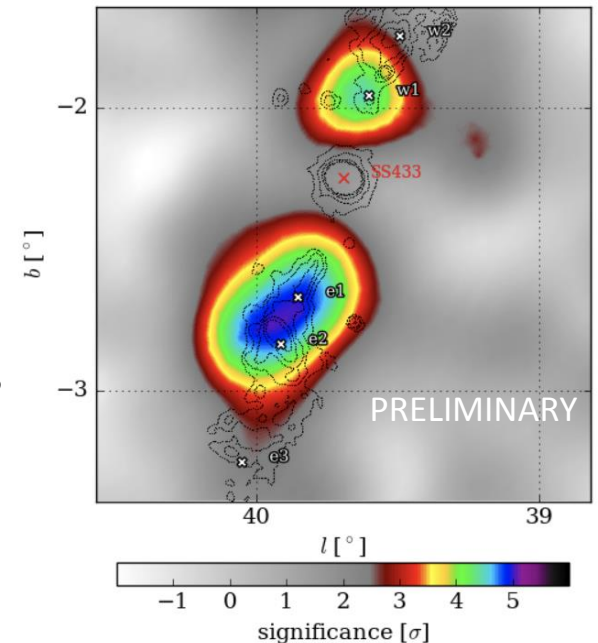
ATel #10941; *Colas Riviere (University of Maryland), Henrike Fleischhack (Michigan Technological University), Andres Sandoval (Universidad Nacional Autonoma de Mexico) on behalf of the HAWC collaboration*

on 9 Nov 2017; 23:11 UT

Credential Certification: Colas Riviere (riviere@umd.edu)

SS433: Galactic Black Hole in a Binary inside a Supernova Remnant

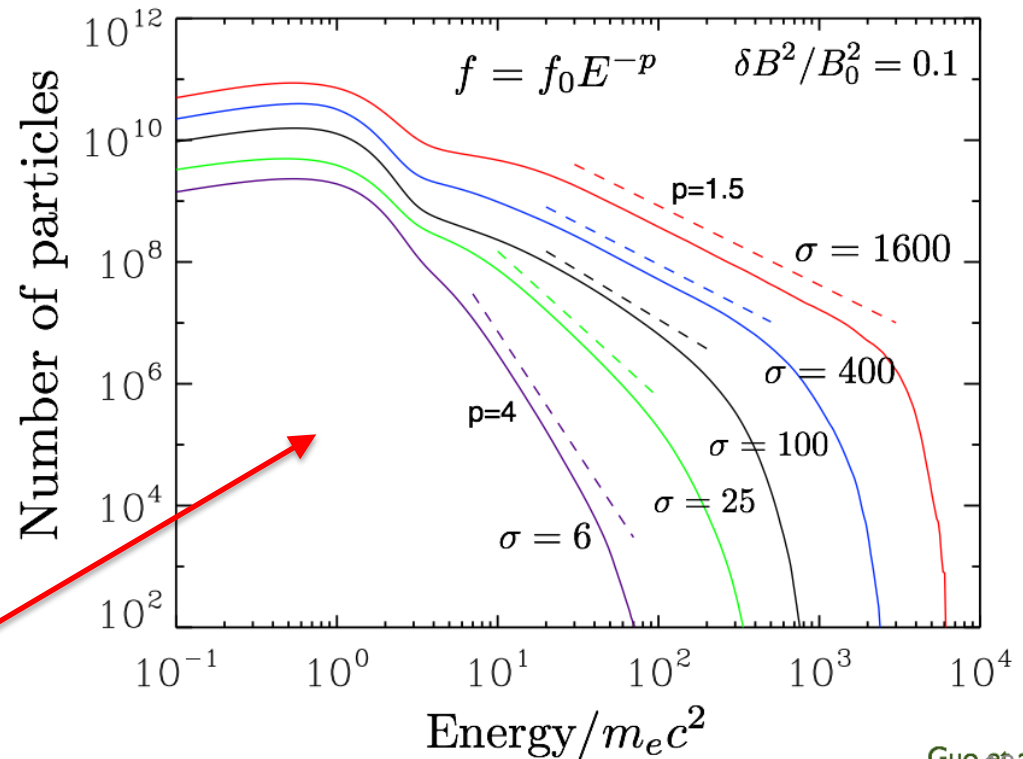
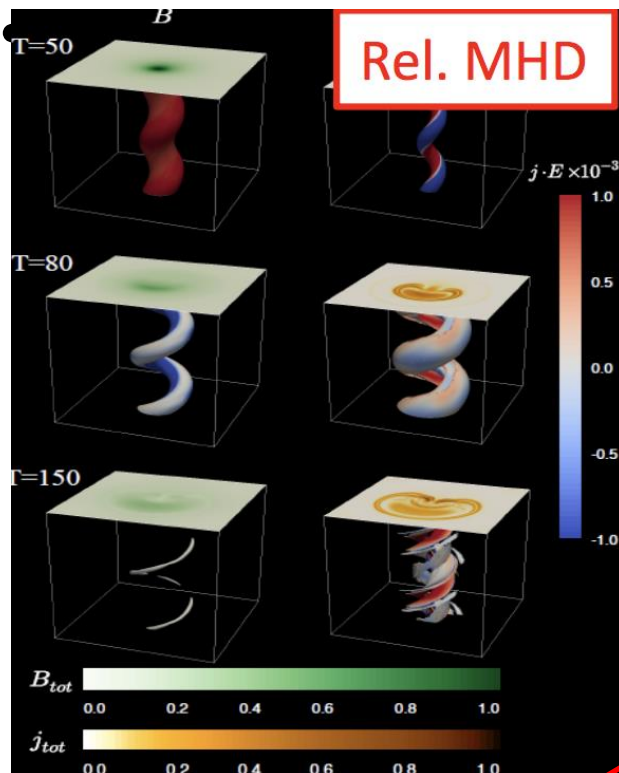
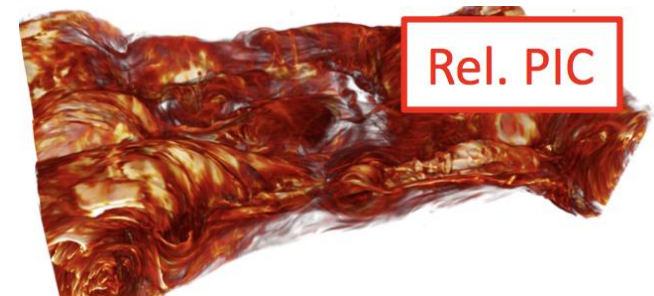
- Jets are postulated to accelerate particles in many gamma-ray sources and probably in the UHECR sources
 - Acceleration could be due to shocks when the jet slows due to interaction with the external medium or due to magnetic reconnection within the intense fields of the jet
- HAWC observation of SS433 is the direct proof that electrons (not hadrons) are accelerated to $>100\text{TeV}$ in jets
 - Jets are observed edge-on so the gamma rays are not Doppler boosted to higher energies or higher luminosities
 - Magnetic field is constrained by the x-ray synchrotron emission now that HAWC determined the electron energy
 - Acceleration does not happen at the black hole because the cooling time of the electrons is too short to make the observed gamma-rays



HAWC significance with the overlay of x-ray contours. The HAWC detection is correlated with the jet lobes and not the black hole.

New Paradigm in Particle Acceleration

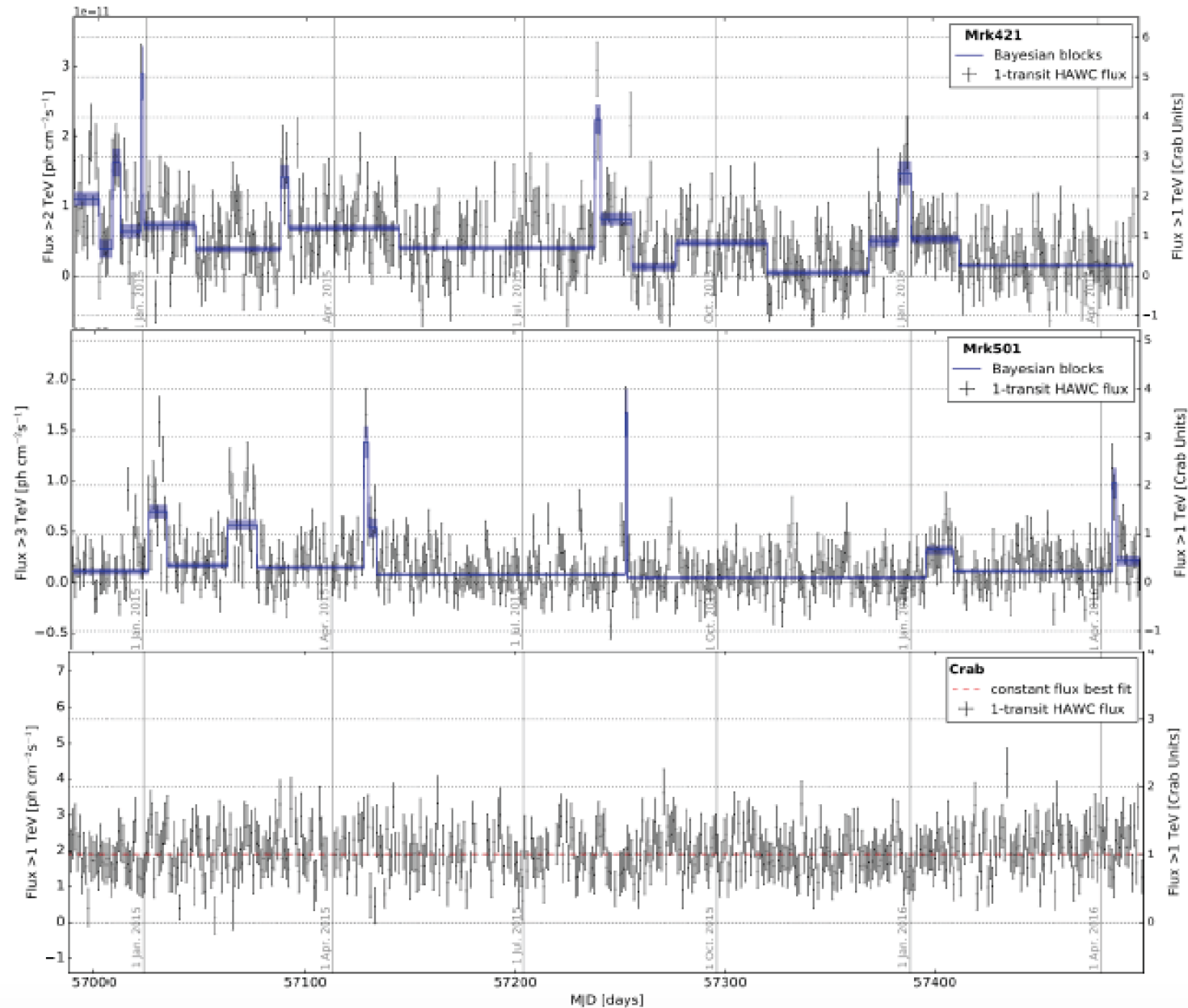
- Regions of magnetically dominated plasma accelerate particles efficiently giving hard power law spectra with fast rise AND decay flares
- Predicts Rapid Changes in Optical Polarization (Zhang, Li, Guo, Taylor ApJ 2017)



σ is proportional to B^2

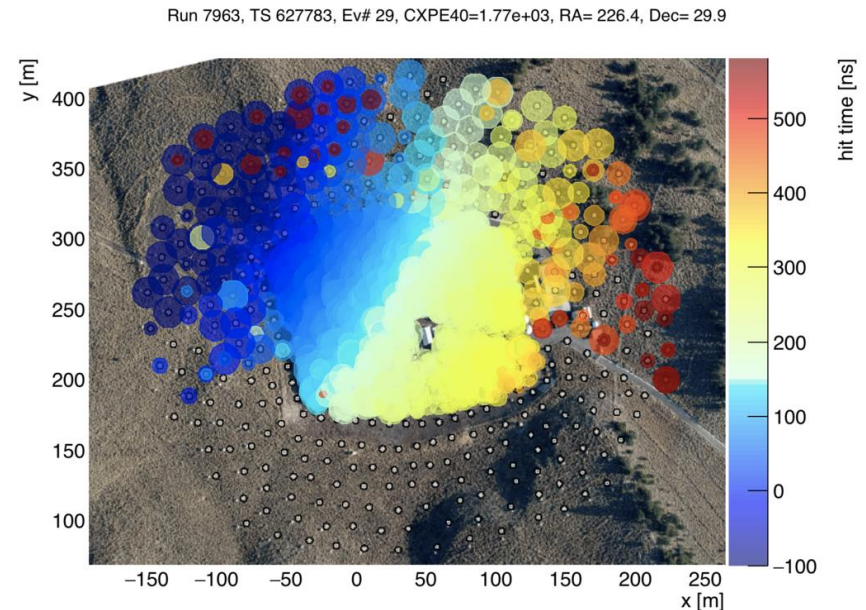
The larger B, the more high energy particles are accelerated.

Daily Monitoring of Mrk421, Mrk501, Crab



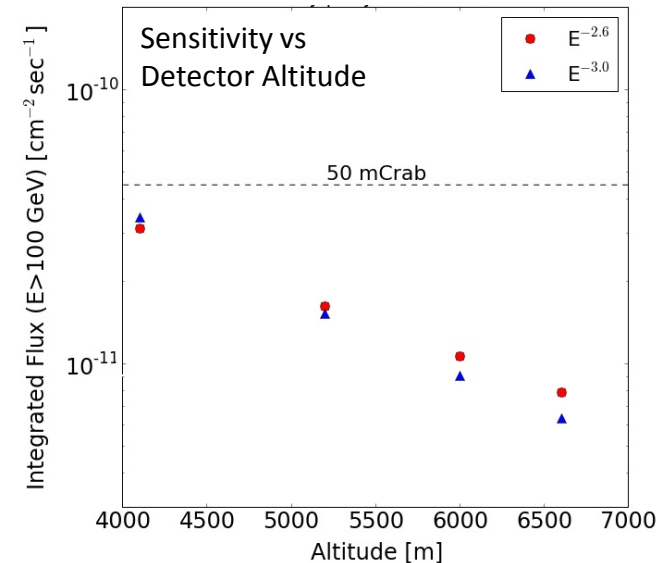
Conclusion

- HAWC is surveying the TeV sky.
 - Multiple papers recently appeared or are in progress
 - “Crab”, “2HWC Catalog”, “Mrk421 & Mrk501”, “Geminga & 0656+14”, “Cosmic-ray Anisotropy”, “FERMI Bubble”, GRB Search”, “Dark Matter Search”, “Antiproton Limit”, “GW Search”, “IceCube Neutrino Search”
- More exciting results to come
- Outrigger array upgrade nearly complete which increases HAWC’s effective area x 4 for gamma-rays > ~20 TeV



Beyond HAWC

- Higher Altitude than HAWC increases low energy sensitivity and larger than HAWC detector also increases high energy sensitivity
- Developing international collaboration for a southern hemisphere, HAWC-like observatory
- Interested US, European, Mexican, and South American collaborators have had several meetings
 - Visited potential sites in Argentina and Chile
 - Formed Southern Gamma-Ray Survey Observatory (SGSO) Alliance
 - Preparing White Paper for Astronomy and Astrophysics Decadal Survey 2020
- Science Objectives are many
 - Discovering rare transient events requires full sky coverage (e.g. Gamma Ray Bursts & Gravitational Wave Sources)
 - Galactic Center Region
 - TeV Source finder for CTA south



SGSO Alliance (Please Join!)

<https://www.sgso-alliance.org/SGSOWiki/doku.php>

- Current Focus is writing of white paper on science objectives
- Next face-to-face meeting In Heidelberg Oct 2018

The Southern Gamma-ray Survey Observatory Alliance

The SGSO Alliance mission statement

The Southern Gamma-ray Survey Observatory Alliance is a collection of scientists interested in the science and engineering of an extensive air shower detector located at a high-altitude site in the mountains of South America. SGSO will be sensitive to astrophysical gamma rays and cosmic rays in the energy range between 100 GeV and 100 TeV. The purpose of the alliance is the advancement of such a detector.

The member scientists intend to elucidate the expected scientific discoveries of SGSO and the design parameters required to obtain these discoveries; to prototype and test various elements of the detectors; to explore and prototype several detector designs options; to evaluate the suitability of possible sites; to simulate and optimize the sensitivity of different detector designs; and to investigate and make measurements at potential sites. We will work together to communicate our findings among ourselves and the international scientific community.

The alliance will work toward the completion of whitepapers on the scientific capabilities of the detector, pursue funding and promote SGSO for long term planning within the astrophysics community.

Members of SGSO are entitled to access shared documents and participate in workshops and scientific meetings. Membership is informal and carries no obligation or commitment.

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- ♦ SGSO Internal
- ♦ Science Case
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- ♦ Related Experiments

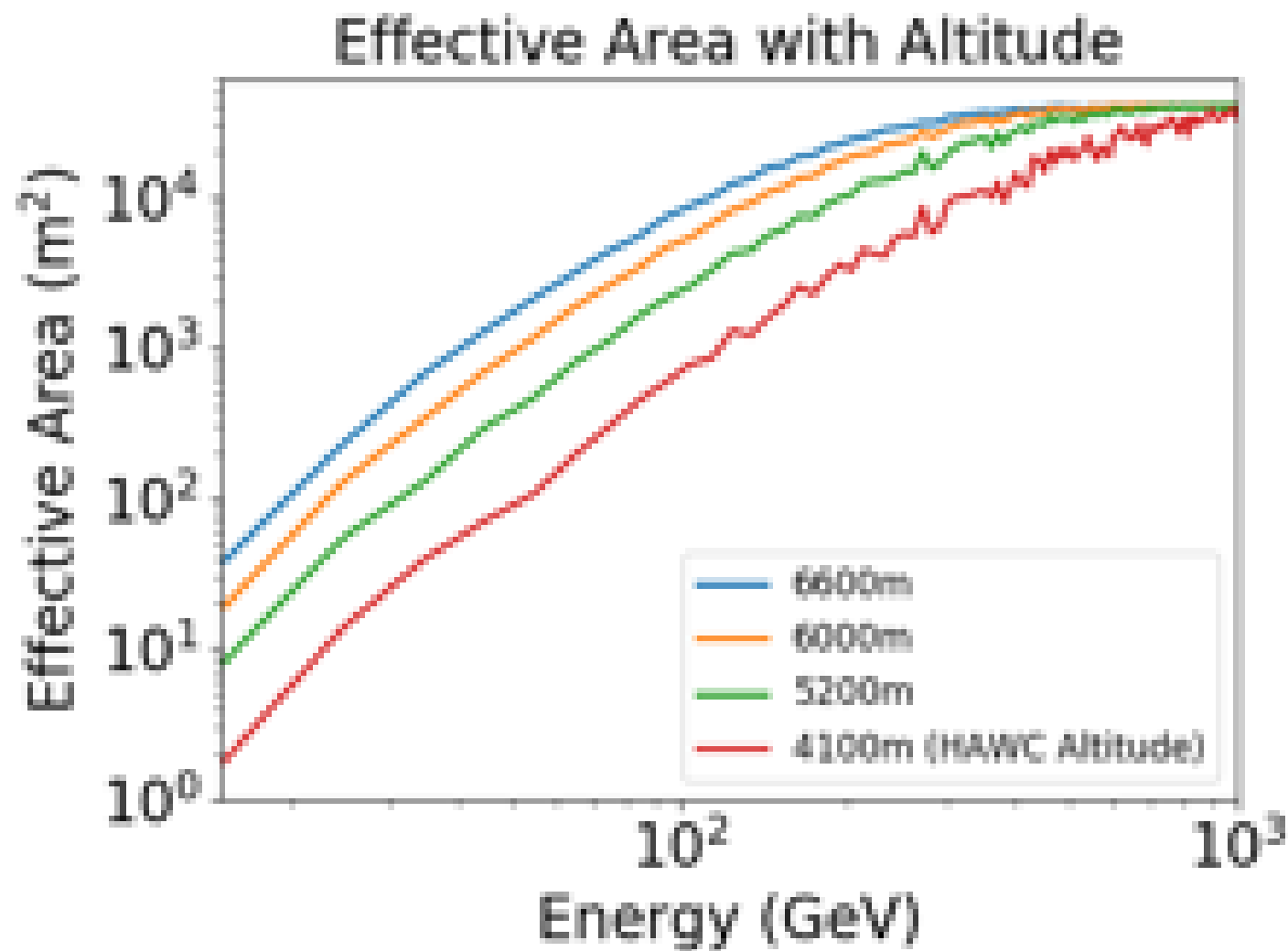


Figure 1: The effects of increasing altitude on the effective area of air shower detectors. Below 1 TeV, SGSO can gain an order of magnitude over HAWC by building at higher altitude.

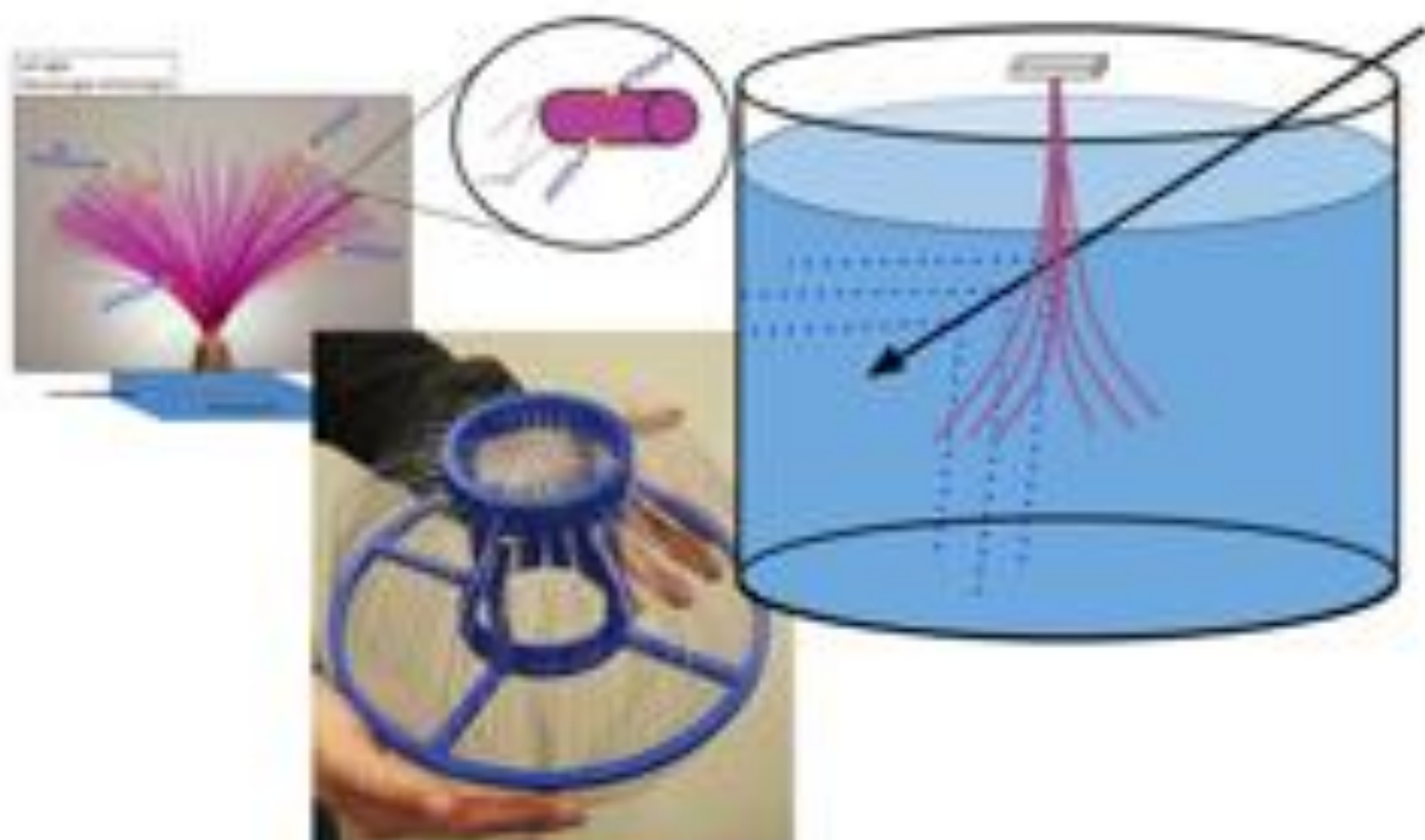
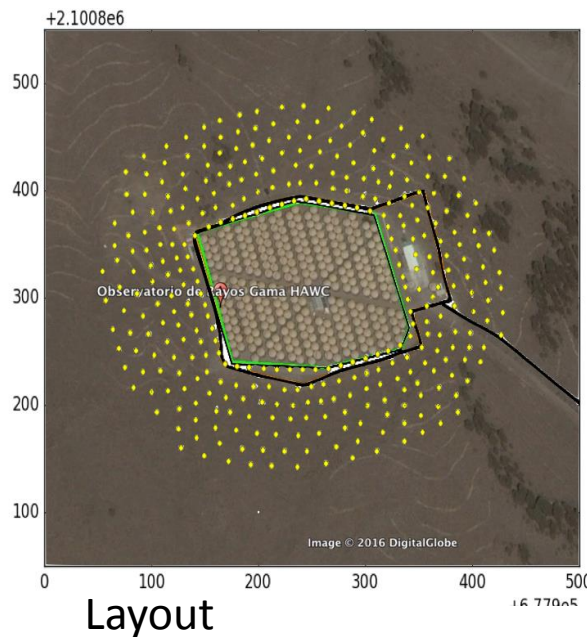


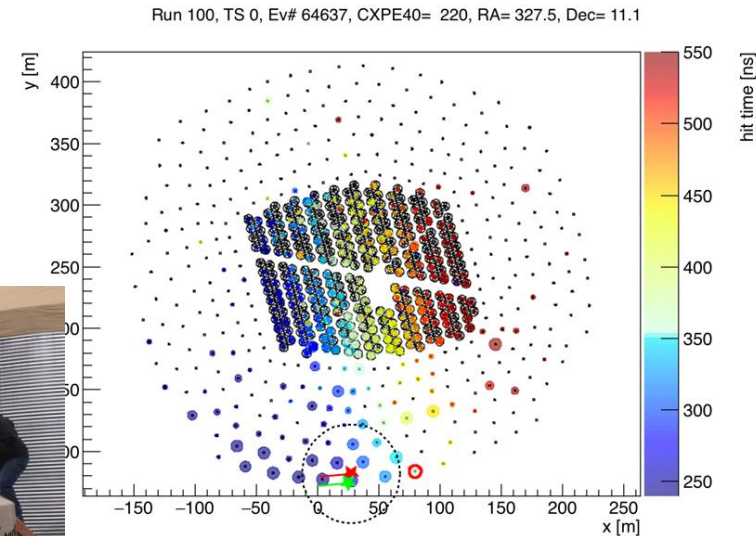
Figure 1: Optical concentrators built from wavelength-shifting scintillating fiber [21] can increase the effective volume of a PMT by over an order of magnitude by collecting light from a large volume of water. These designs may allow SGSO to use $\frac{1}{4}$ of the PMTs and electronics of HAWC for the same detector area.

“Outrigger” extension project

- We will 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.
- LANL funded with additional contributions from Mexico and Germany Max Planck Institute



Funded and
Soon complete



Simulated event

Diffusion & Cooling

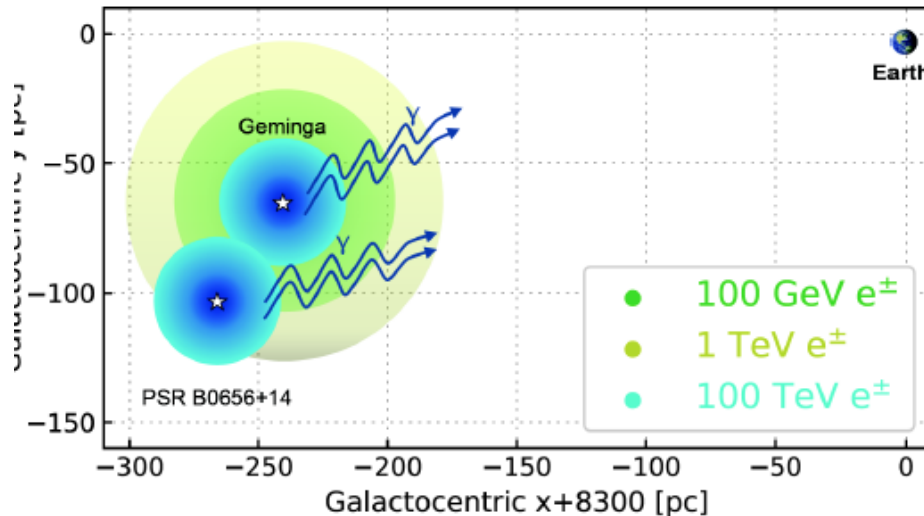
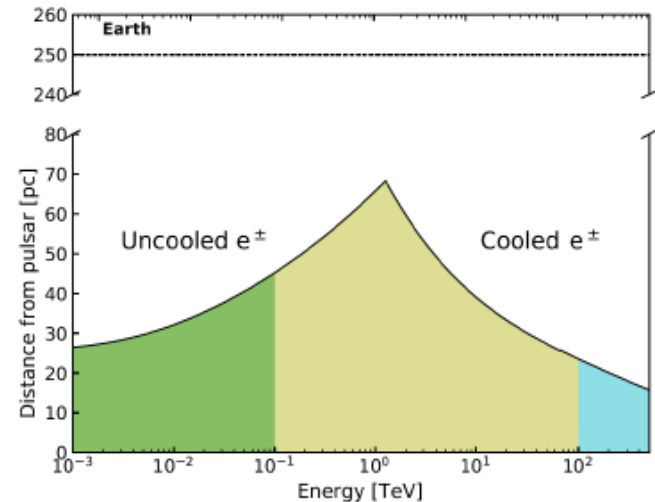


Illustration of the face-on view of the observed region and the Earth. The color circles correspond to the diffusion distance of leptons of three different energies from Geminga (for readability only the highest energy is shown for PSR B0656+14).

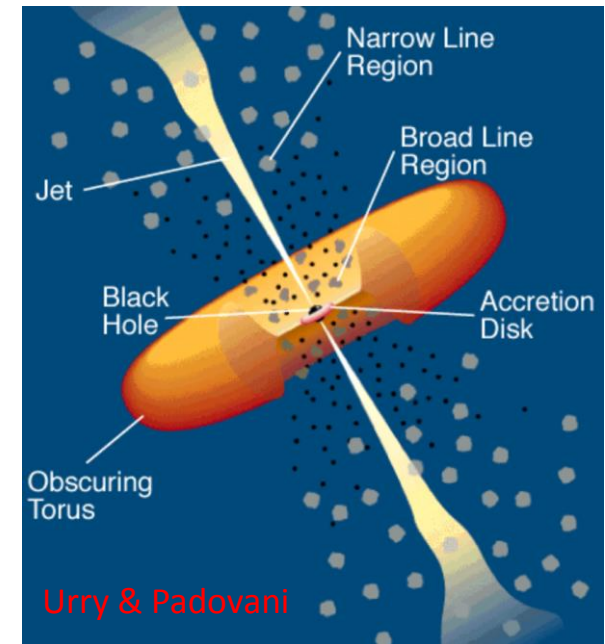
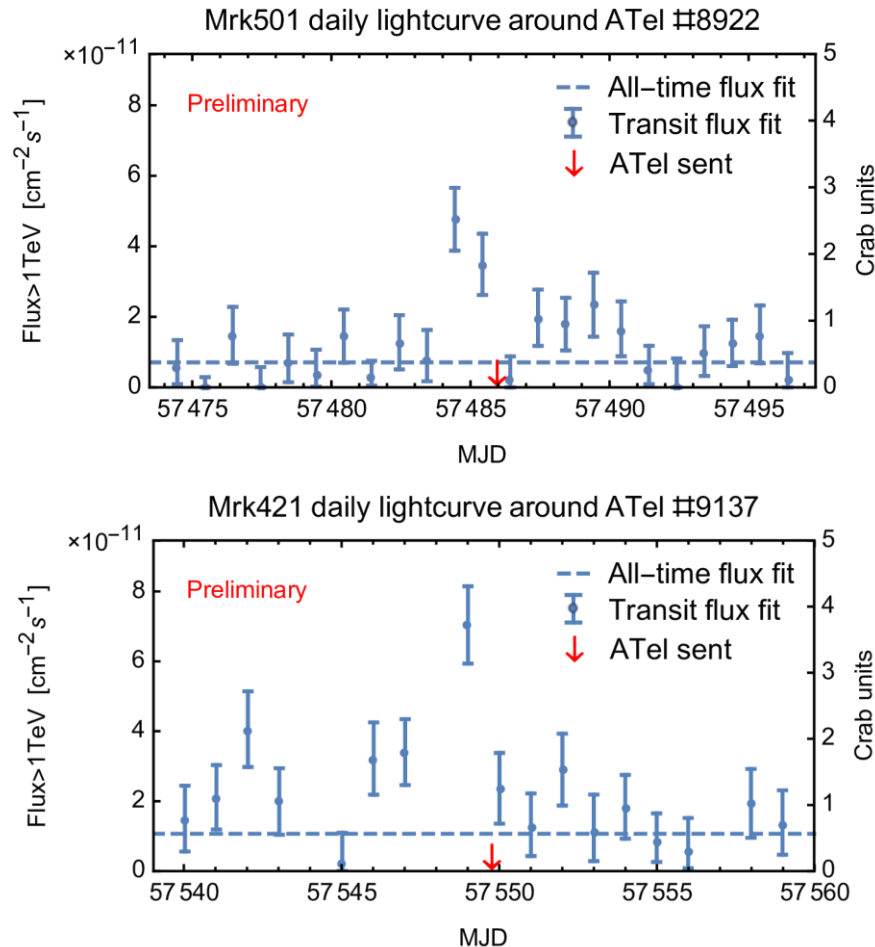


Particles diffuse farther with higher energy until cooling effects dominate, as a result TeV particles diffuse the farthest.

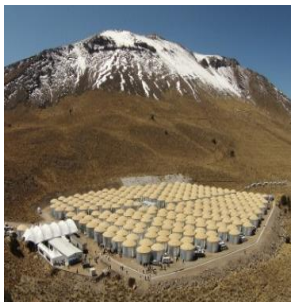
$$r_d = 2\sqrt{D(E_e)t_E} \quad D(E_e) = D_0(E_e/10 \text{ GeV})^{\alpha}$$

t_E is the smaller of the cooling time (depends on E) and the injection time (pulsar age).

HAWC Monitors Active Galactic Nuclei for Flaring Daily



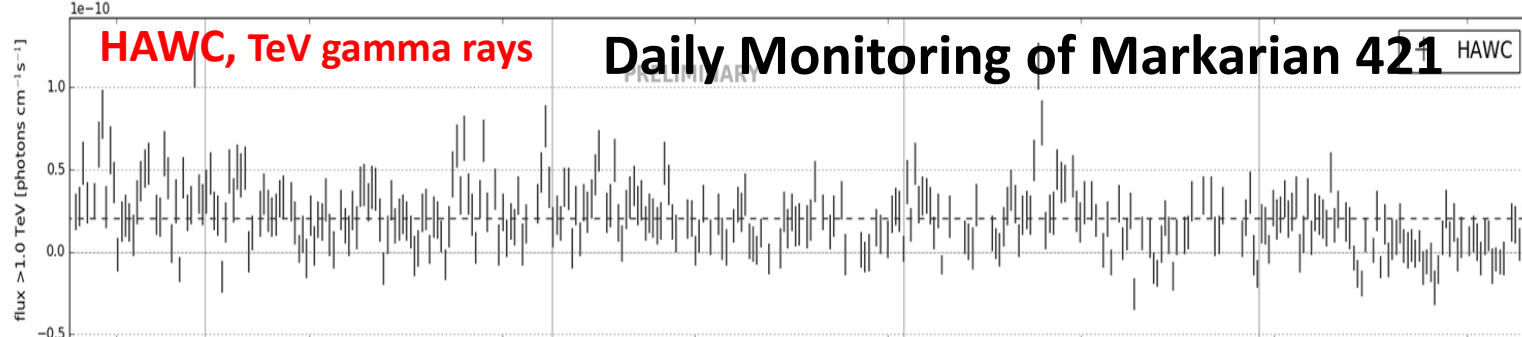
Most recent IAU Atel “HAWC observation of Mrk421 reaching peak TeV flux in month-long enhanced activity” last week. Plus many notifications to atmospheric Cherenkov telescopes via MOU in preceding days.



HAWC, TeV gamma rays

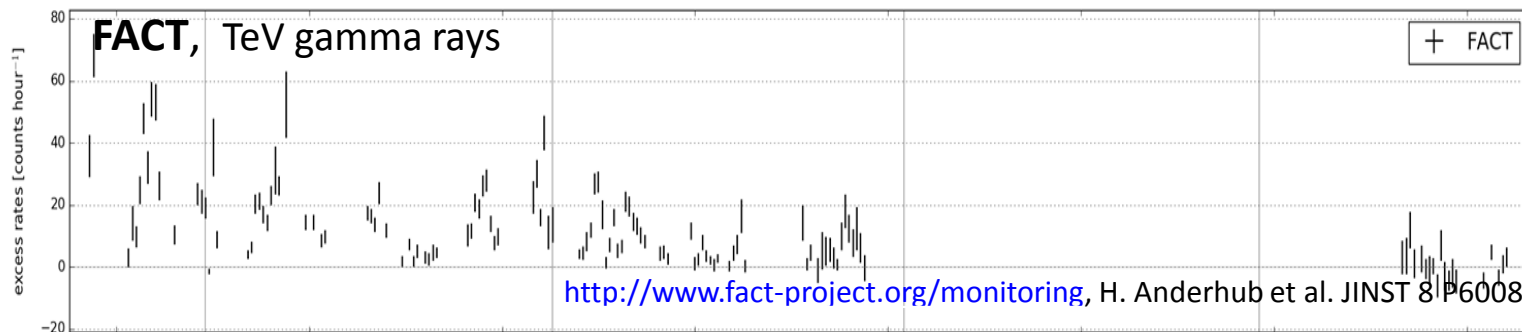
Daily Monitoring of Markarian 421

HAWC



FACT, TeV gamma rays

+ FACT

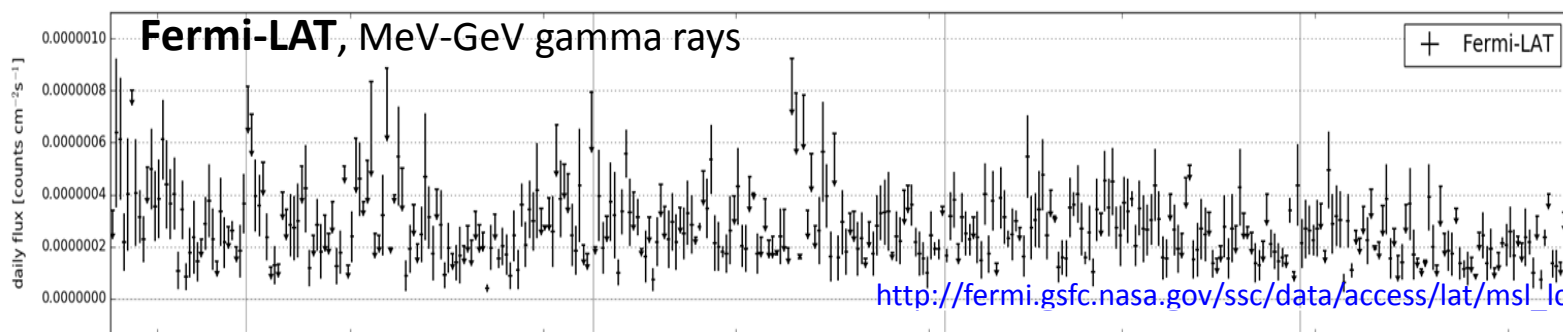


<http://www.fact-project.org/monitoring>, H. Anderhub et al. JINST 8 P6008



Fermi-LAT, MeV-GeV gamma rays

+ Fermi-LAT

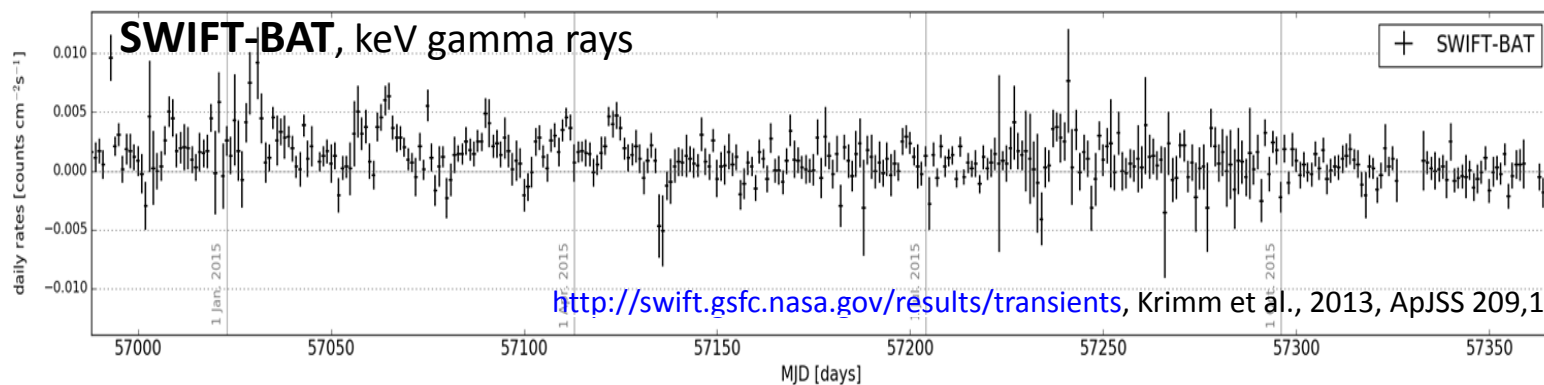


http://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc



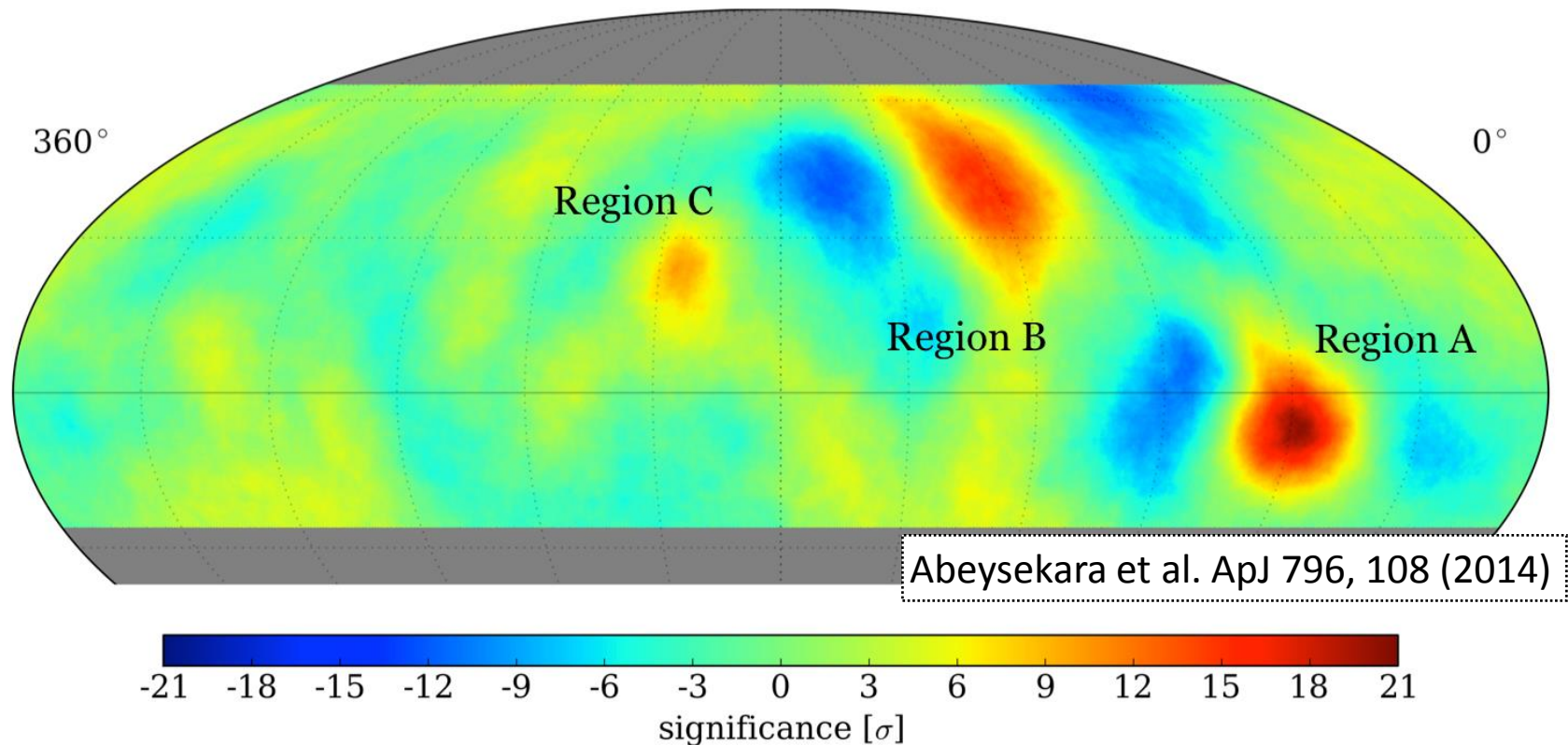
SWIFT-BAT, keV gamma rays

+ SWIFT-BAT



<http://swift.gsfc.nasa.gov/results/transients>, Krimm et al., 2013, ApJSS 209,1

CR: small scale anisotropy

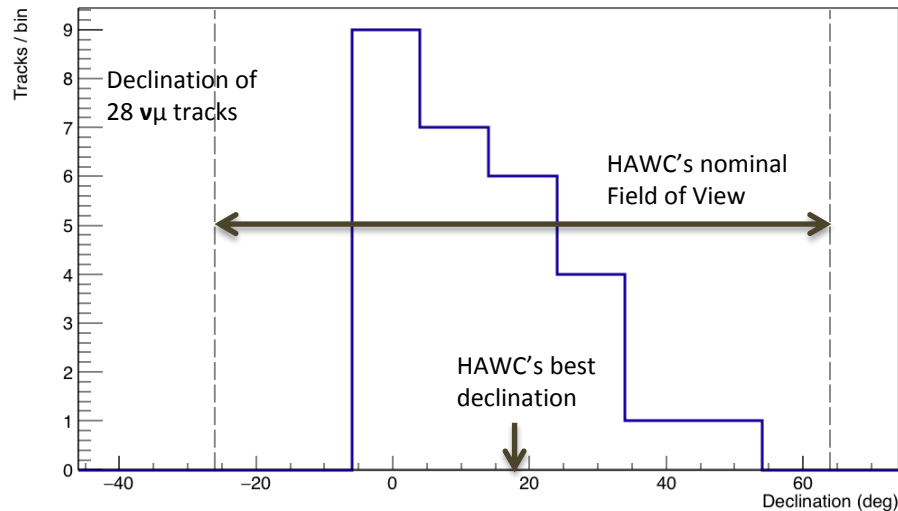


- 86×10^9 events in 181 transits with large scale anisotropy removed (\geq octupole): scales below 60° .
- Median E of 2 TeV has gyroradius in 3 microG field of < 0.001 pc = 200 AU.
- What can focus cosmic rays at that distance?

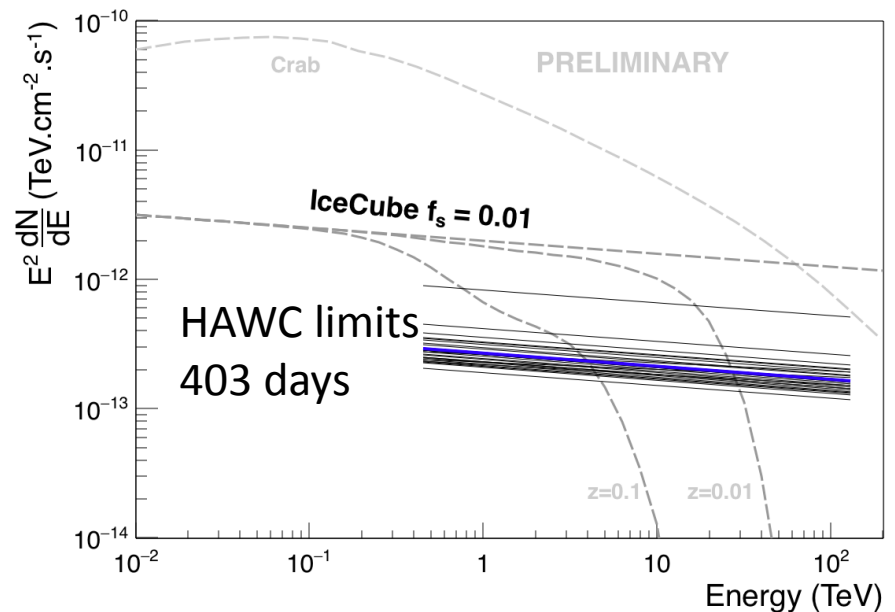
Search for HAWC Counterparts to IceCube astrophysical ν



- We have looked for γ sources in the direction from where the 28 highest energy ν_μ arrived.



- No sources detected
 - sources opaque to γ ?
 - sources too far away ?
 - too many sources?

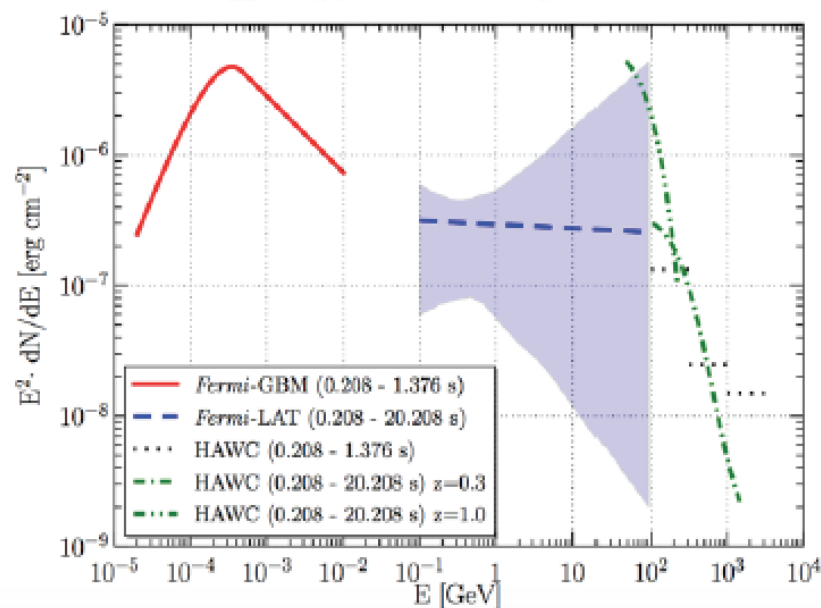
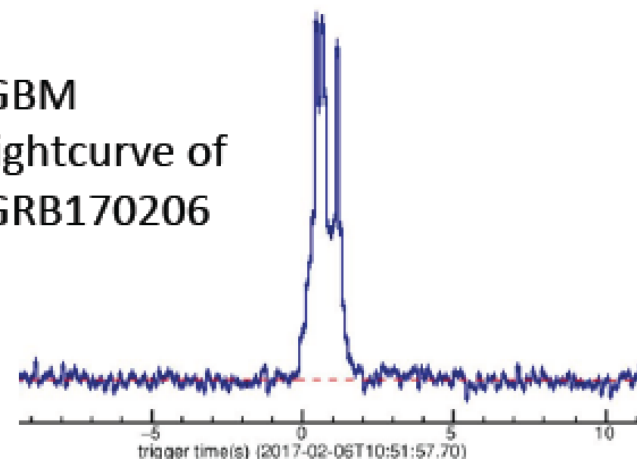


Also searching in real time
in case they are transient

Search for TeV Counterparts to Gamma Ray Bursts

- HAWC effective area $\sim 100\text{m}^2$ at 100GeV
- Fermi with $\sim 1\text{m}^2$ has detected ~ 100 GeV γ -rays from GRBs
- Still waiting for a big one!
 - HAWC Upper Limits from 64 GRBs in ApJ 2017
 - HAWC observation of GRB 170206 is most constraining

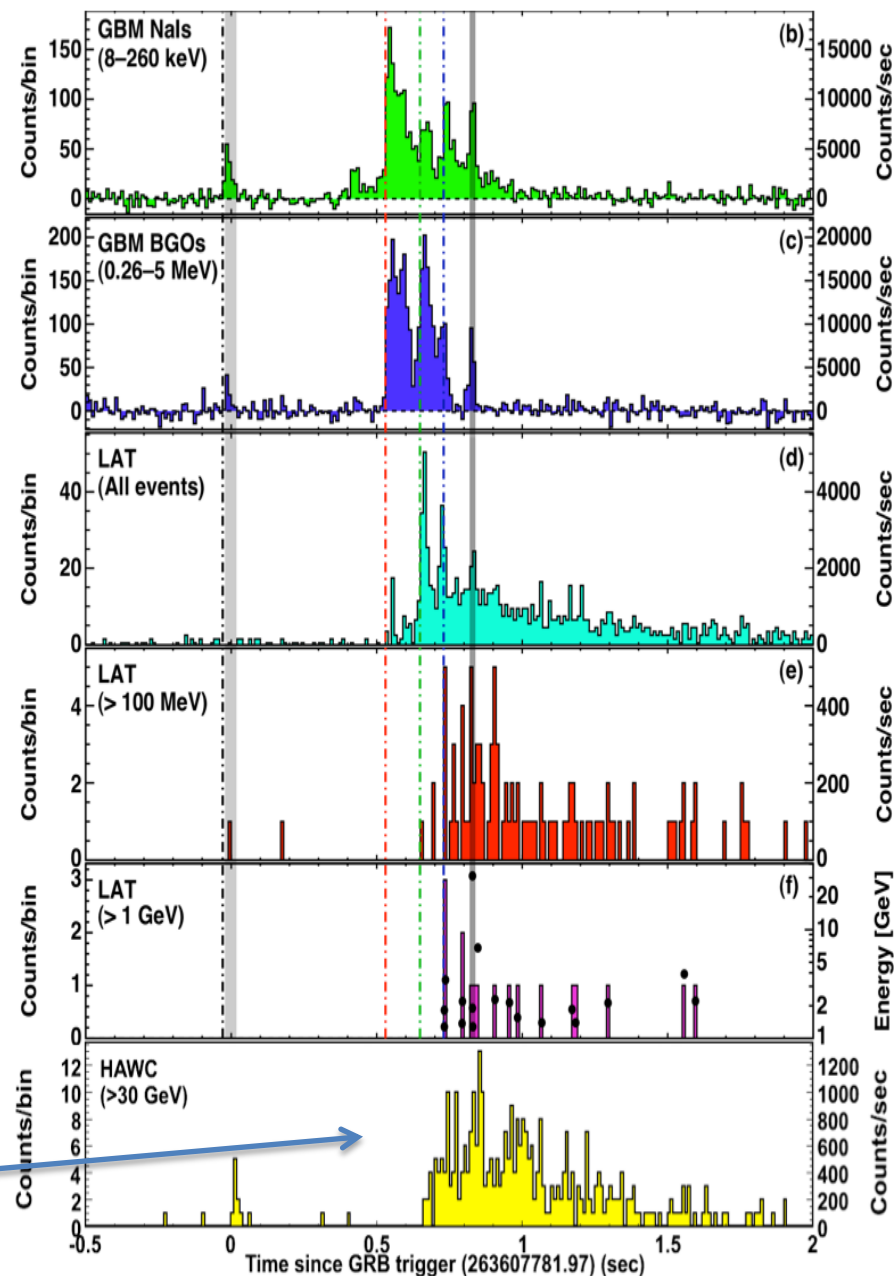
GBM
lightcurve of
GRB170206



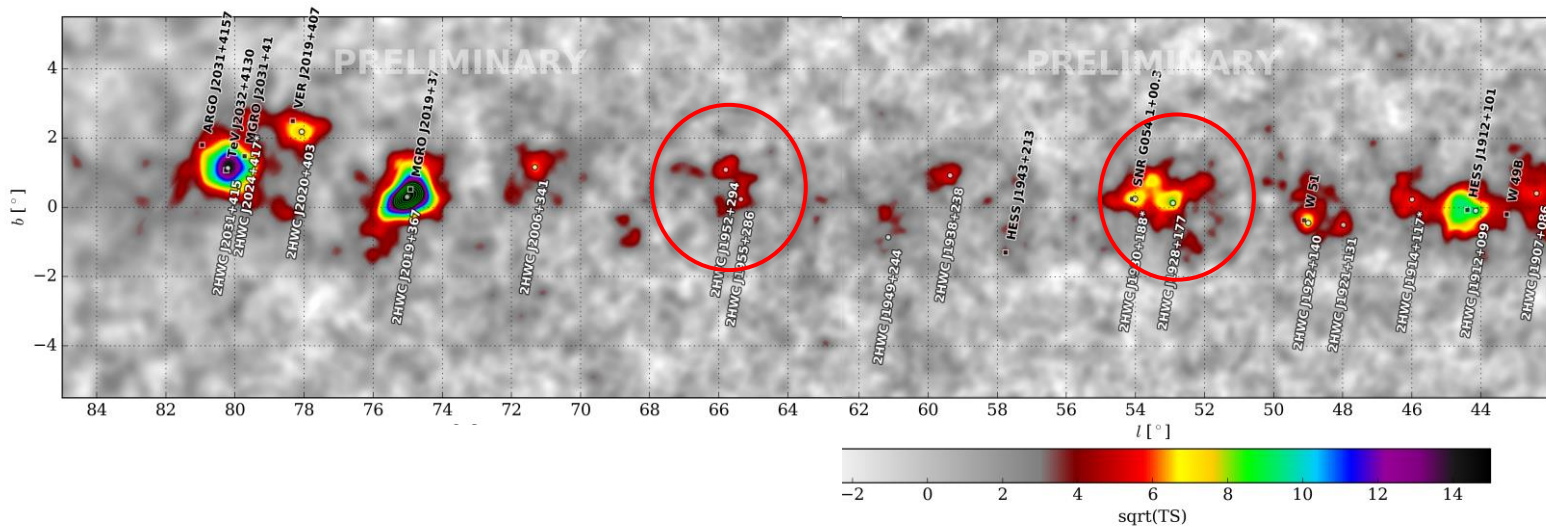
Fermi has observed Gamma Ray Bursts that HAWC could detect

- HAWC effective area
~100m² at 100GeV and
grows rapidly with energy
- Fermi has ~1m² area at
100GeV.

HAWC Simulated
lightcurve for Fermi
GRB 090510

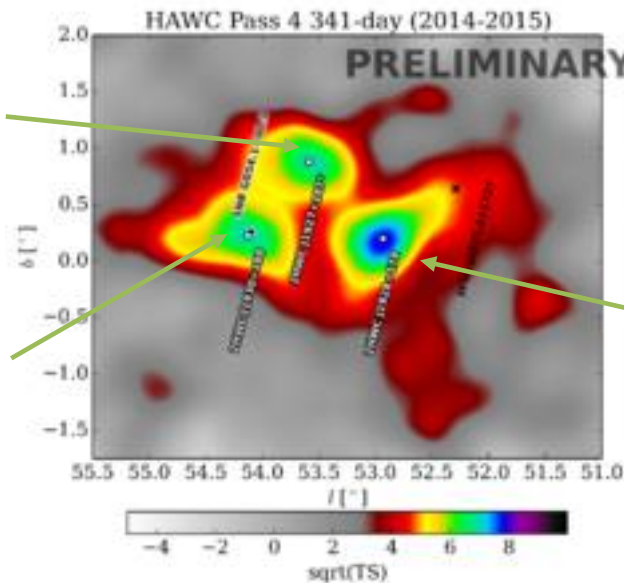


Known TeV Sources AND New TeV sources



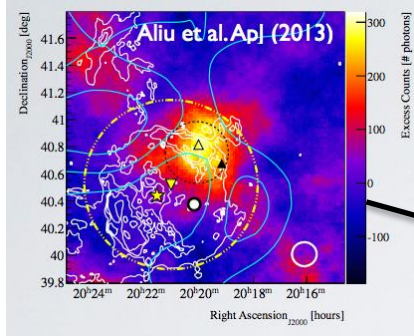
Association unclear

Supernova remnant
with very energetic
pulsar



Pulsar $\sim 8\text{kpc}$ (26,000 ly) away, but
no PWN detected by NuSTAR

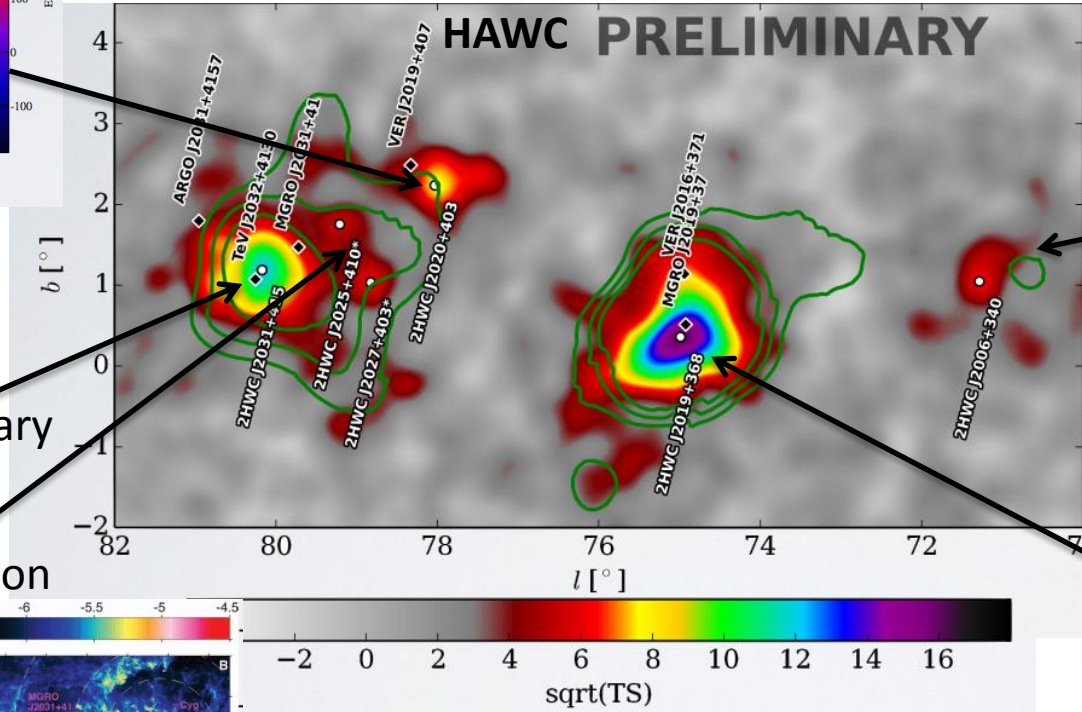
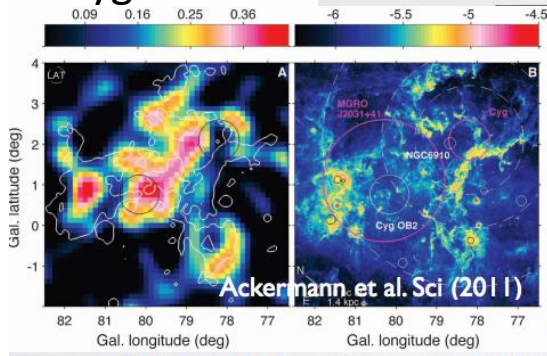
Complex Cygnus Region



VERITAS source

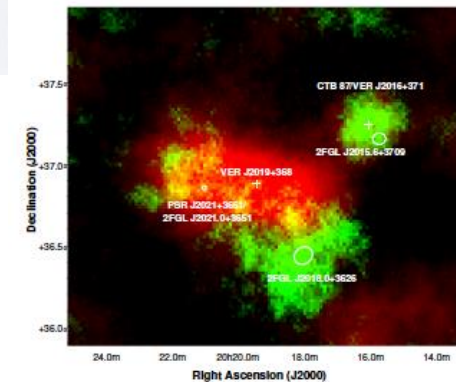
HEGRA Source
PWN in x-ray binary

Fermi's
Cygnus Cocoon



New TeV Source

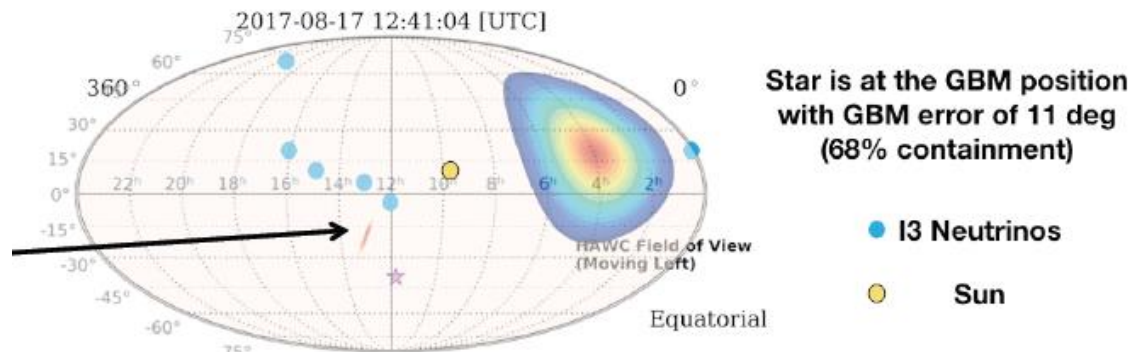
Multiple VERITAS
sources



Search for HAWC Counterparts to Gravitational Wave Detections

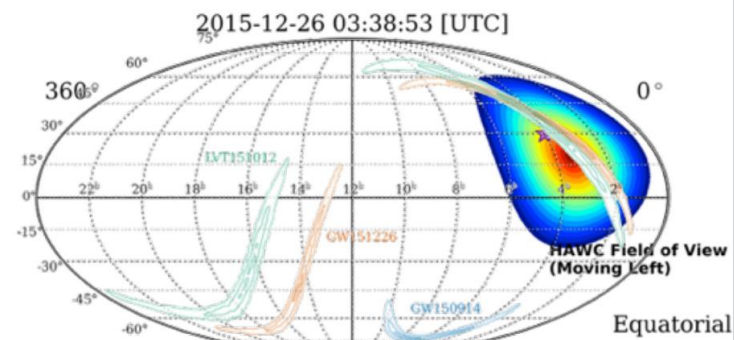
GW170817

- Neutron Star Merger with electromagnetic counterpart
- Not in HAWC's field of view at the time, but TeV upper limit was placed 9 hours later (ApJ Lett 848, L12, 20 Oct 2017)



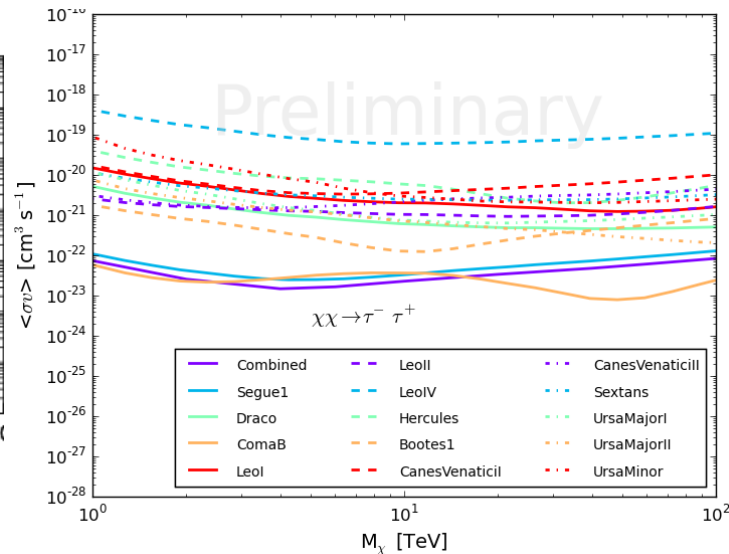
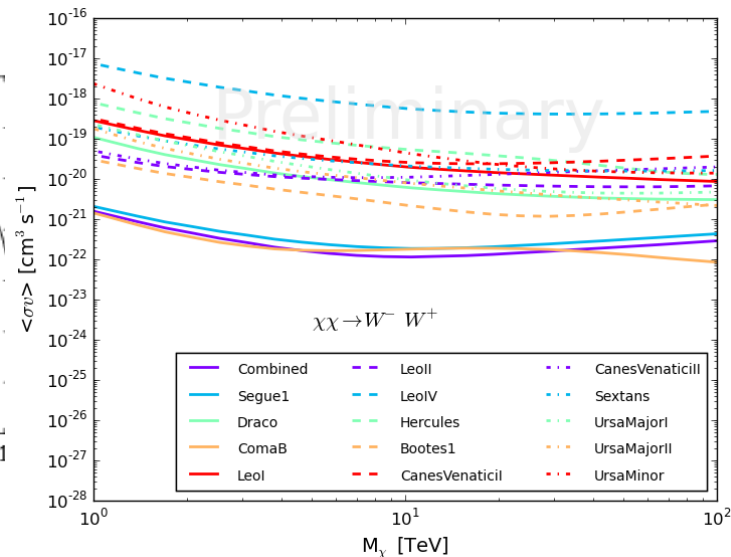
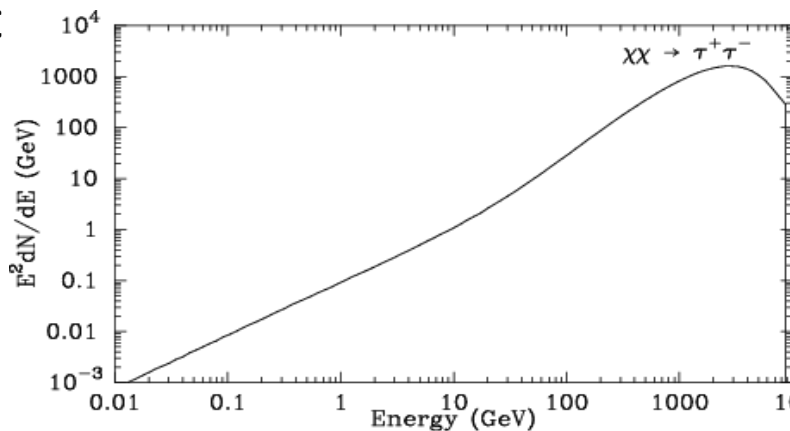
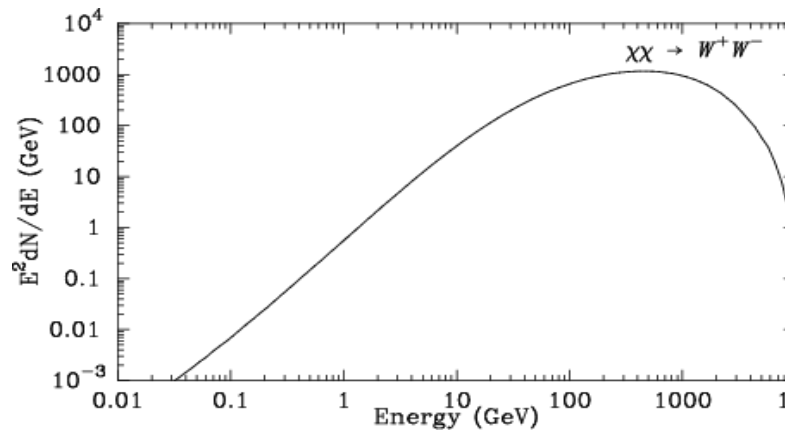
GW151226

- 2015 Dec 26 03:38:53.6 UTC
- >5 sigma
- $14.2M_{\odot} + 7.5M_{\odot} \Rightarrow 21.8M_{\odot}$
- $z=0.09 \pm 0.03 \pm 0.04$



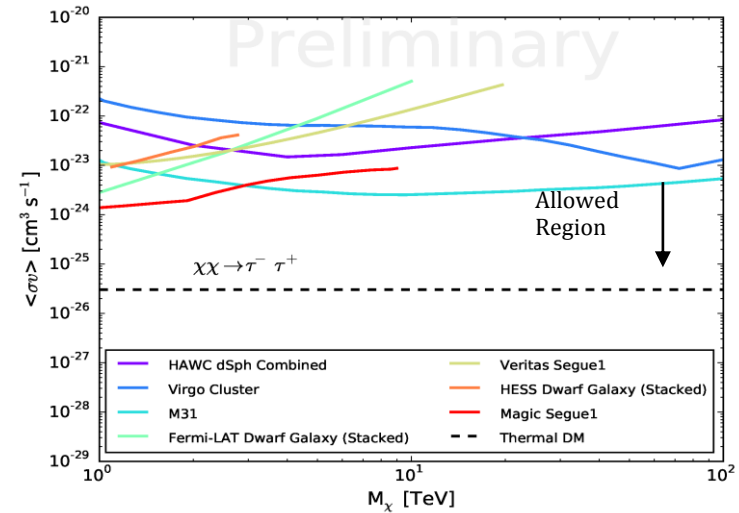
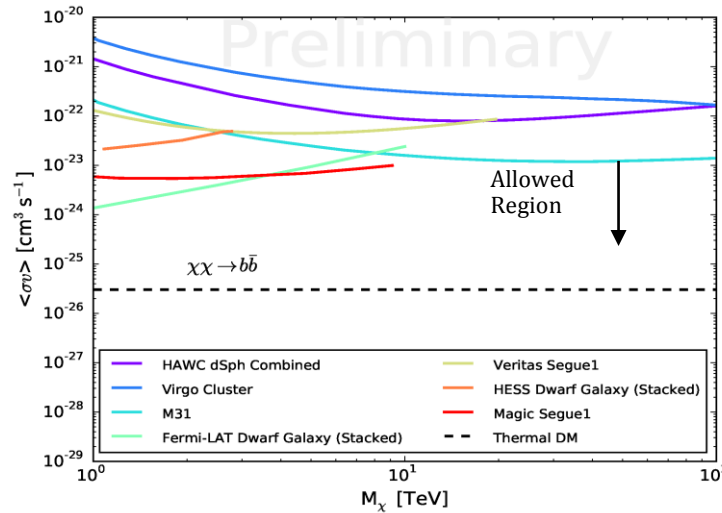
HAWC's Limits on Annihilating DM in 14 Dwarf Spheroidal Galaxies

Calculate spectra for different DM mass and annihilation channels with Pythia 8, then determine counts upper limit from HAWC maps vs # of hit PMTs, then use Corsika & GEANT4 to convert to limit on $\langle\sigma v\rangle$.

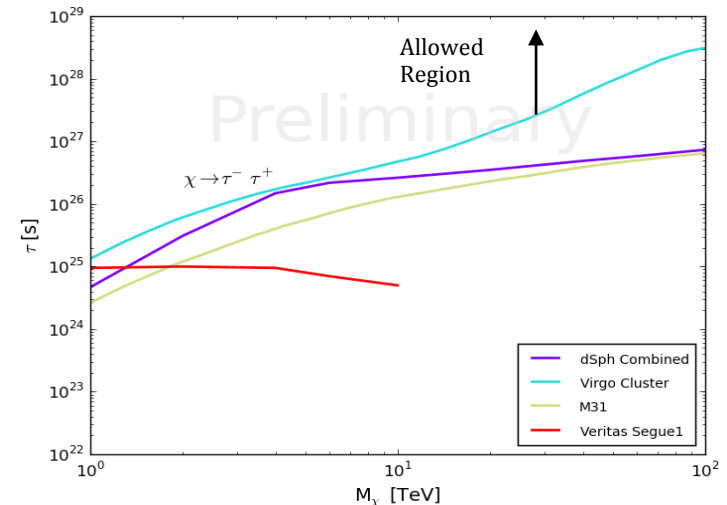
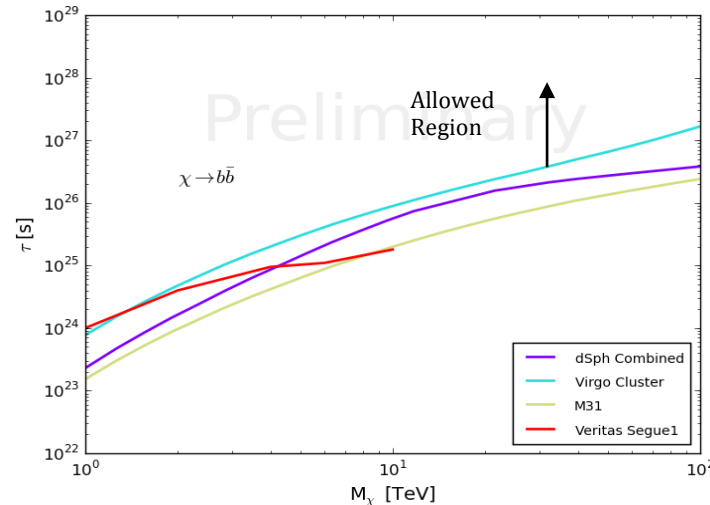


HAWC's DM Limits Are Better than other Gamma-Ray Observatories above a few TeV

Annihilation



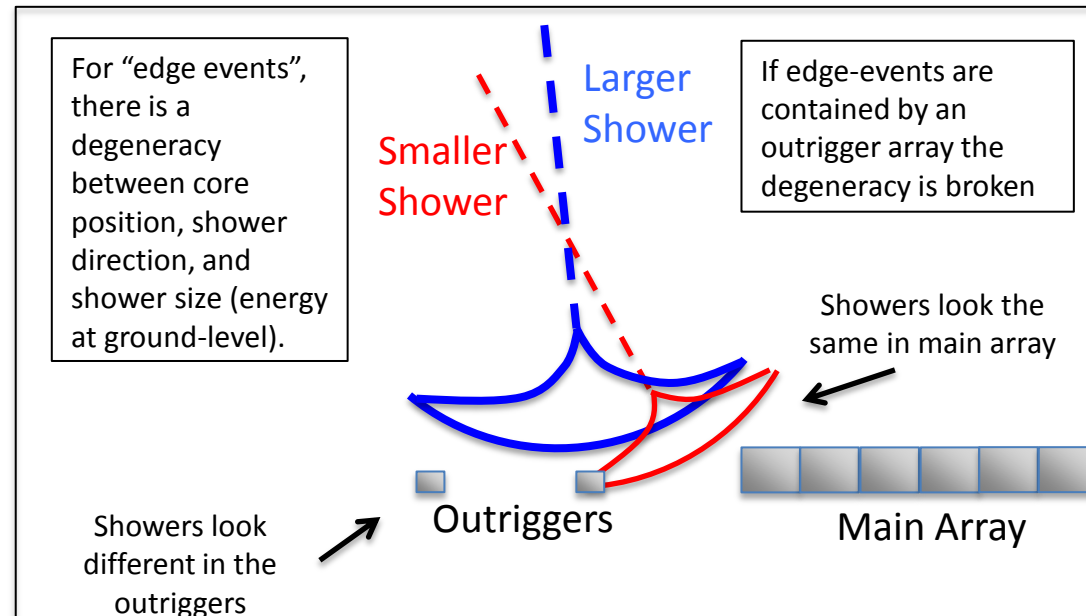
Decay



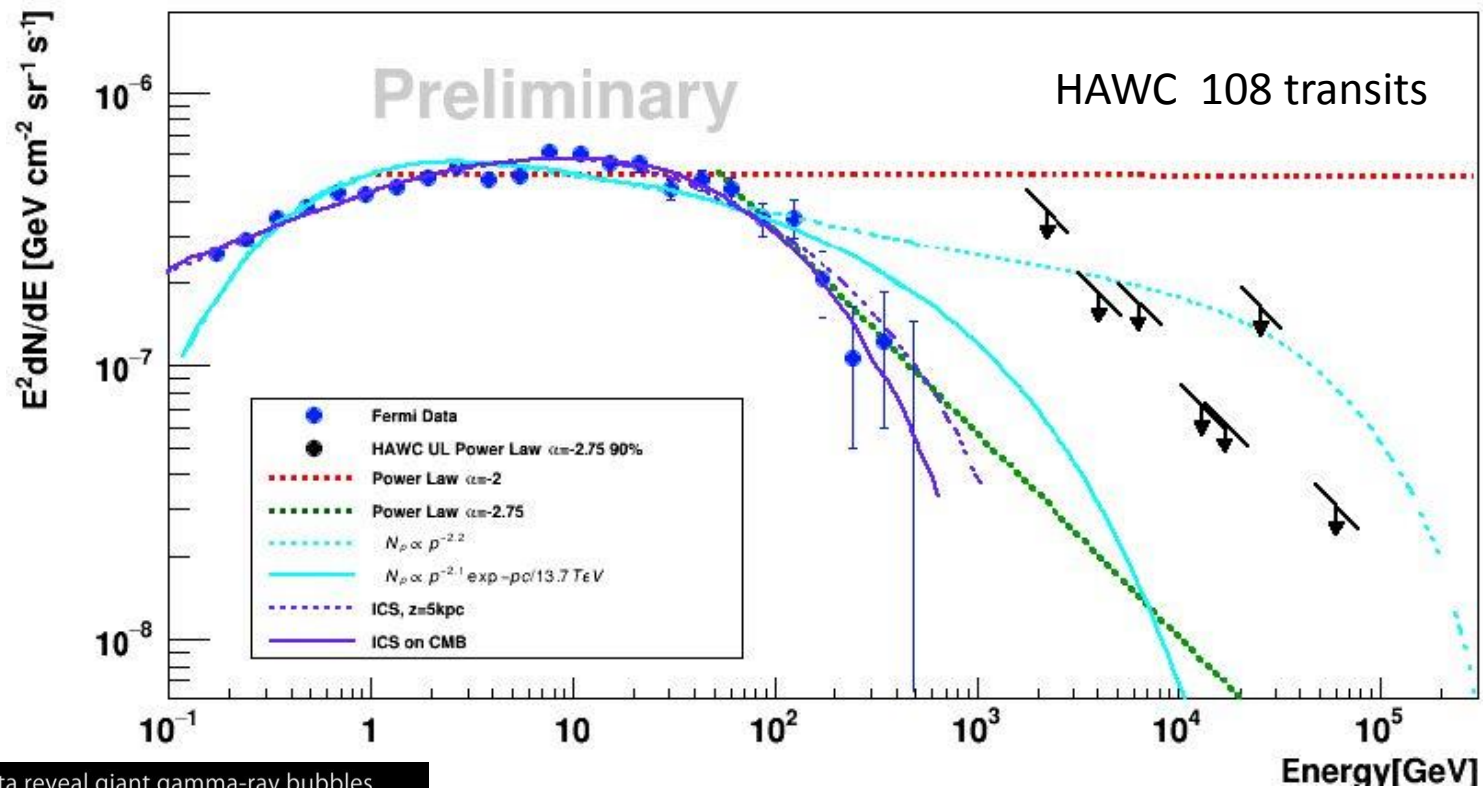
Note that HESS Galactic Center limits are better than HAWC's if the dark matter distribution is known to not be cored.

Outriggers for HAWC

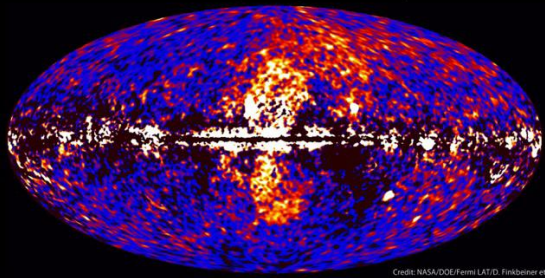
- Increases sensitivity at highest energies
- Shower cores can be located when they hit off the main array, so that direction and energy can be measured
- 350 outriggers funded by LANL, MPIK Heidelberg, and CONACyT (Mexico)



Search for North FERMI Bubble

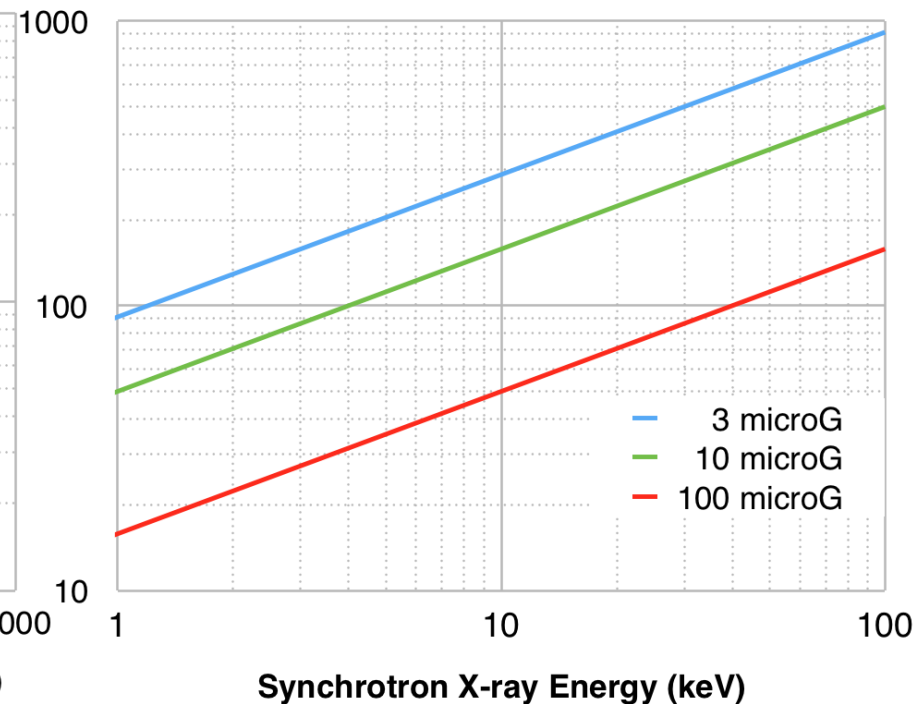
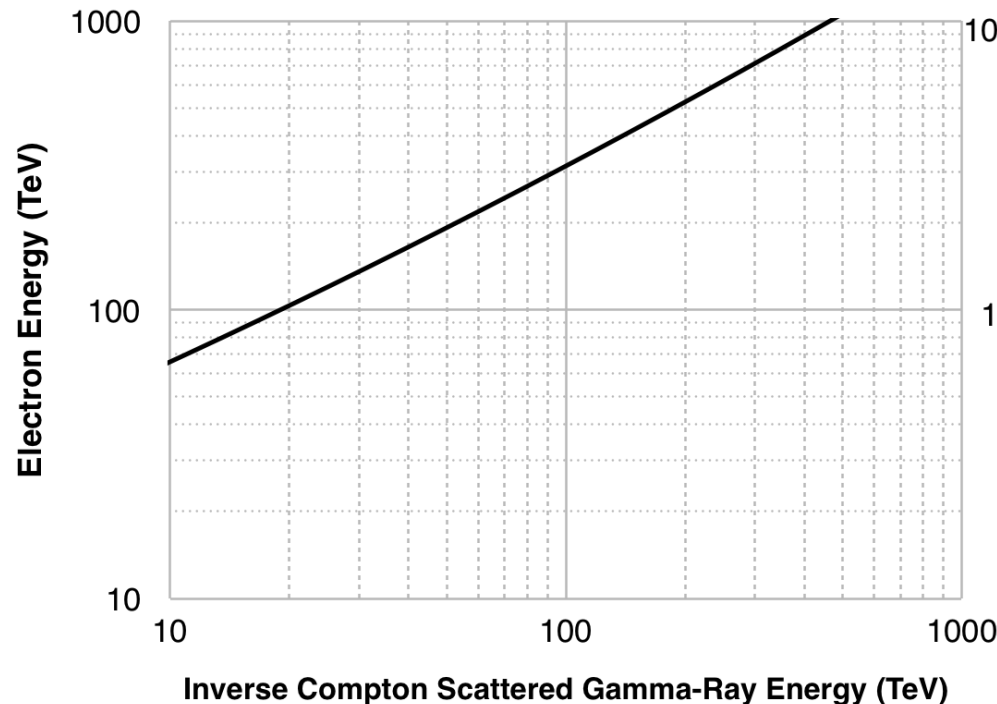


Fermi data reveal giant gamma-ray bubbles



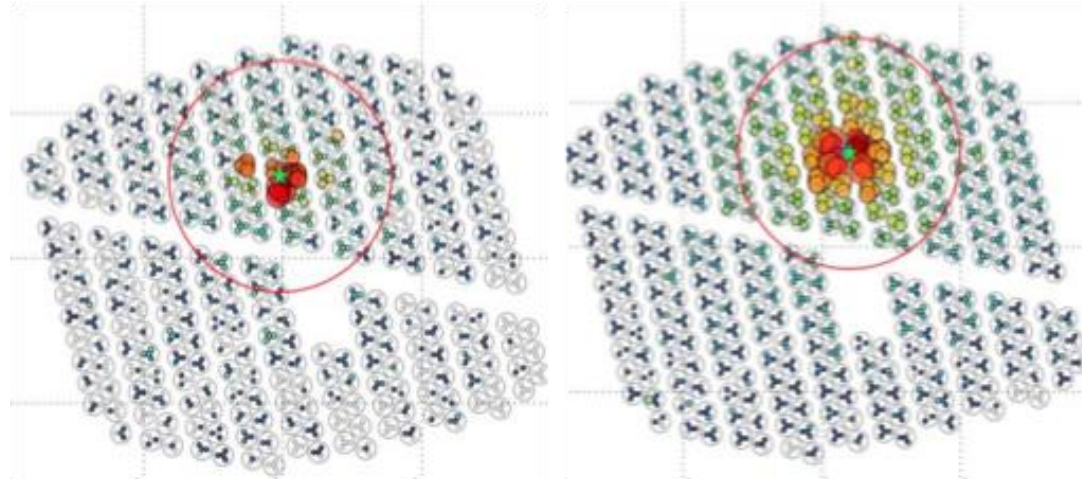
Electrons emit TeV gamma-rays and keV x-rays

X-ray energy depends on the magnetic field, so with TeV observations to constrain the electron energy, the magnetic field can be measured!

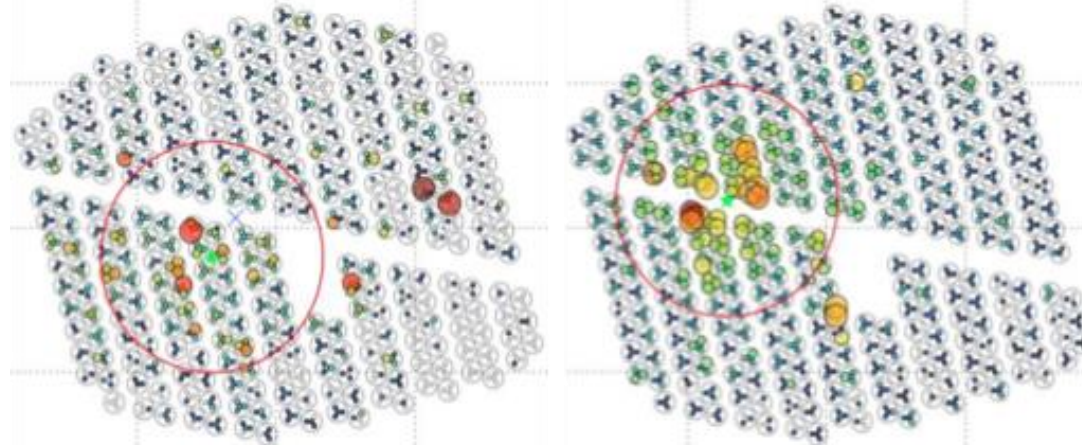


HAWC Rejects Background Cosmic Rays

γ ray



hadron



HAWC detects a few thousand γ rays per day and 20,000 hadronic cosmic rays per second (~ 2 billion/day)