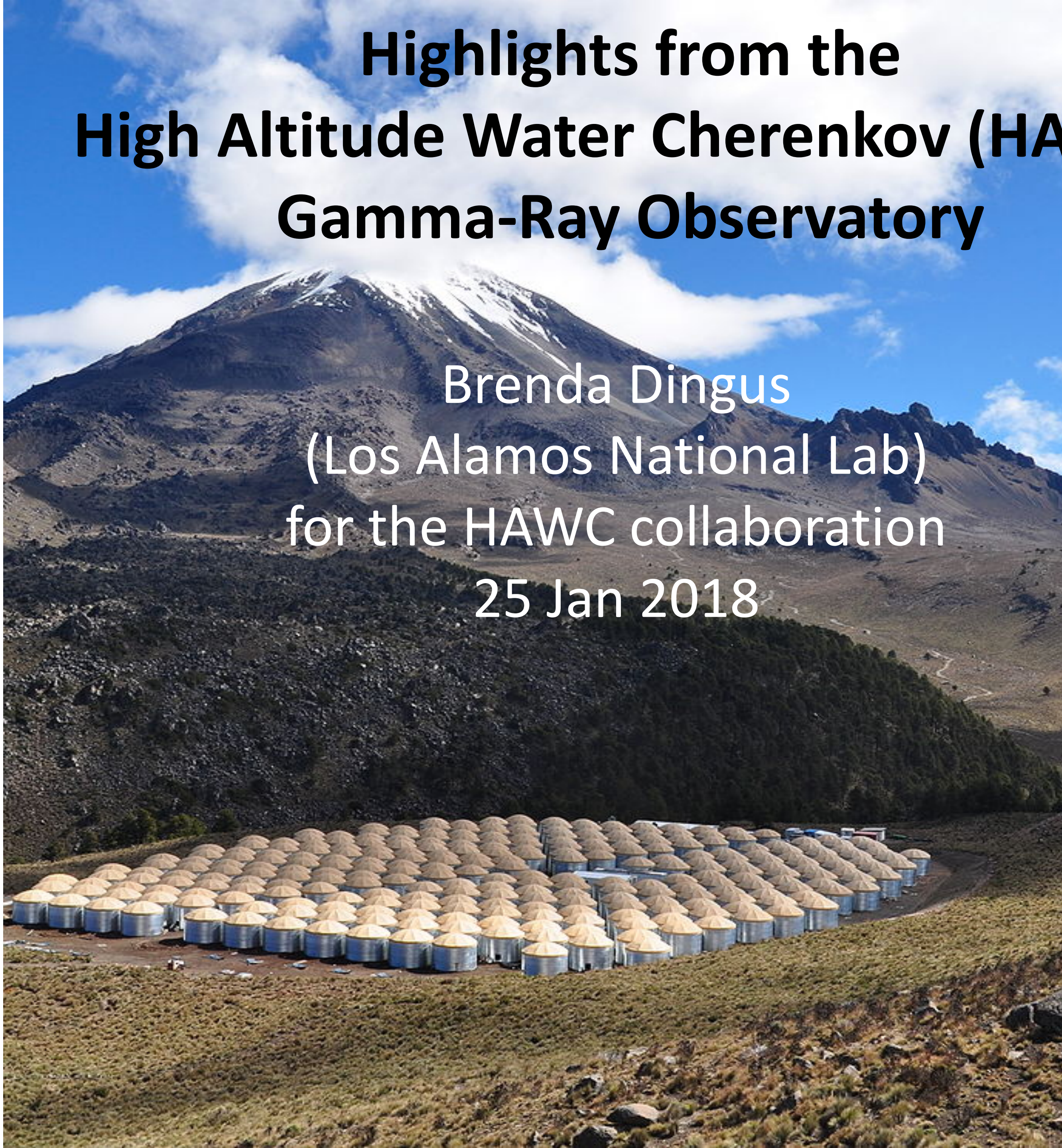
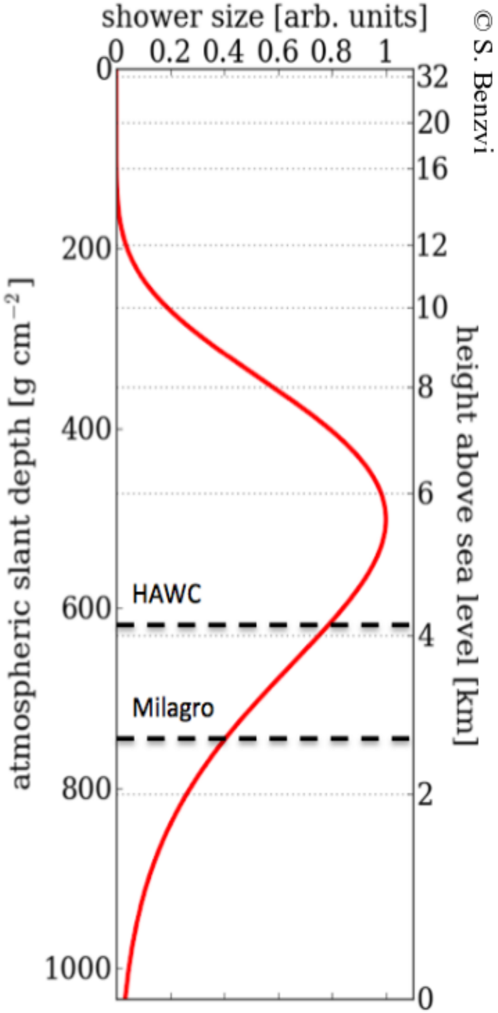
Highlights from the High Altitude Water Cherenkov (HAWC) Gamma-Ray Observatory

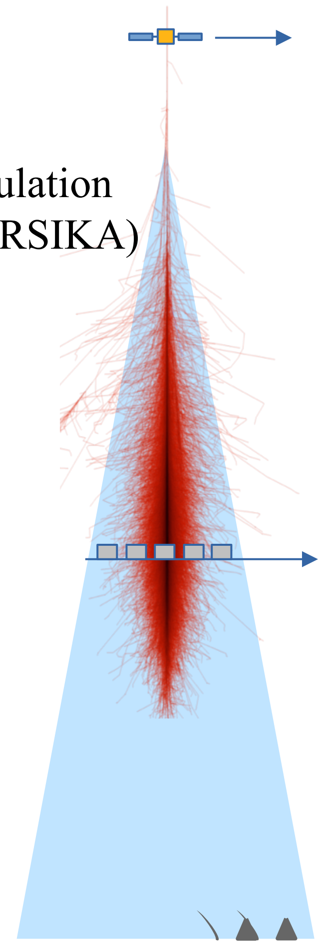


Brenda Dingus
(Los Alamos National Lab)
for the HAWC collaboration
25 Jan 2018

High Energy Gamma-Ray Detectors



Simulation
(CORSIKA)



Wide Field of View, Continuous Operations

Satellite Detector

Extensive Air Shower (EAS) Detector

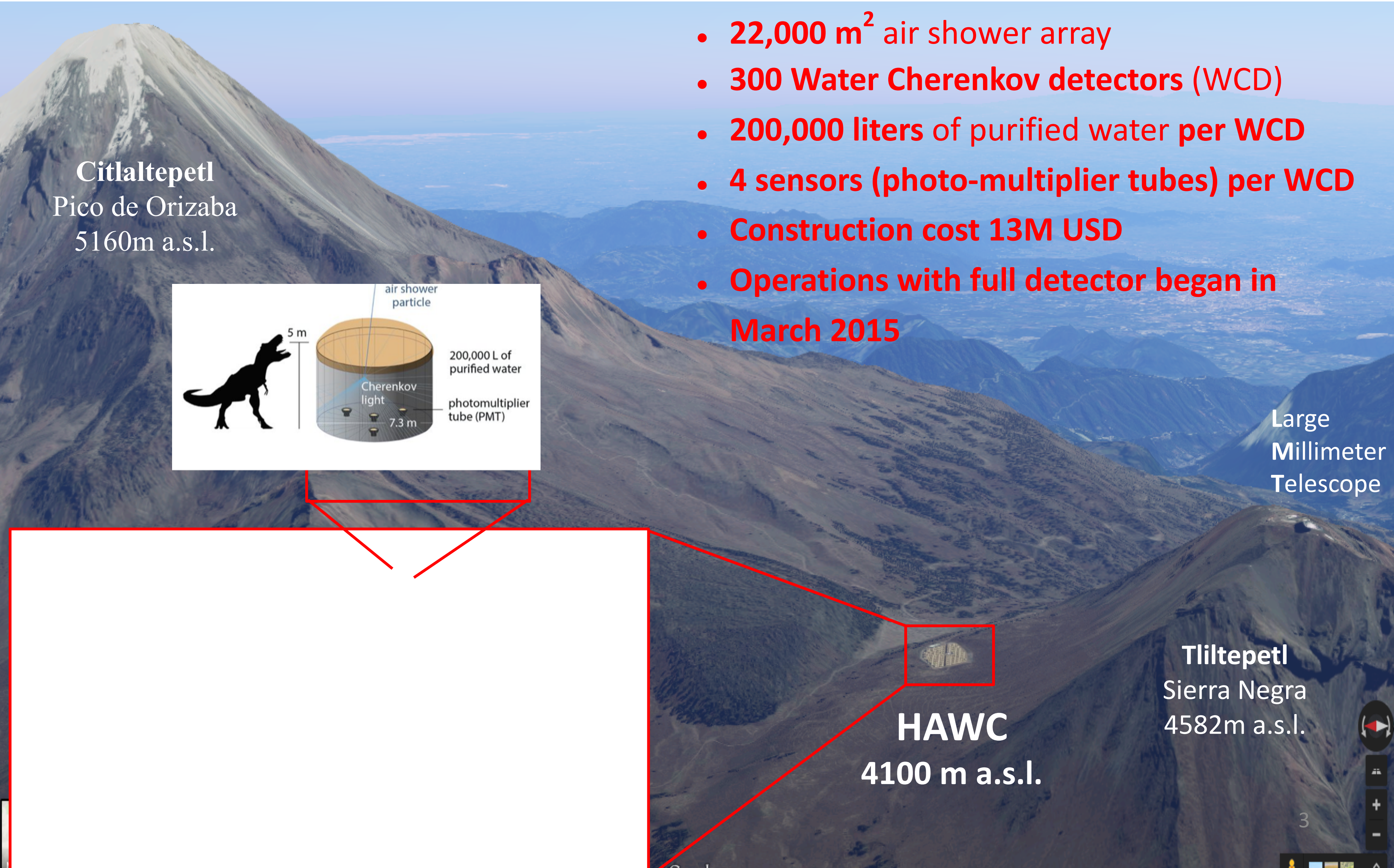
TeV Sensitivity

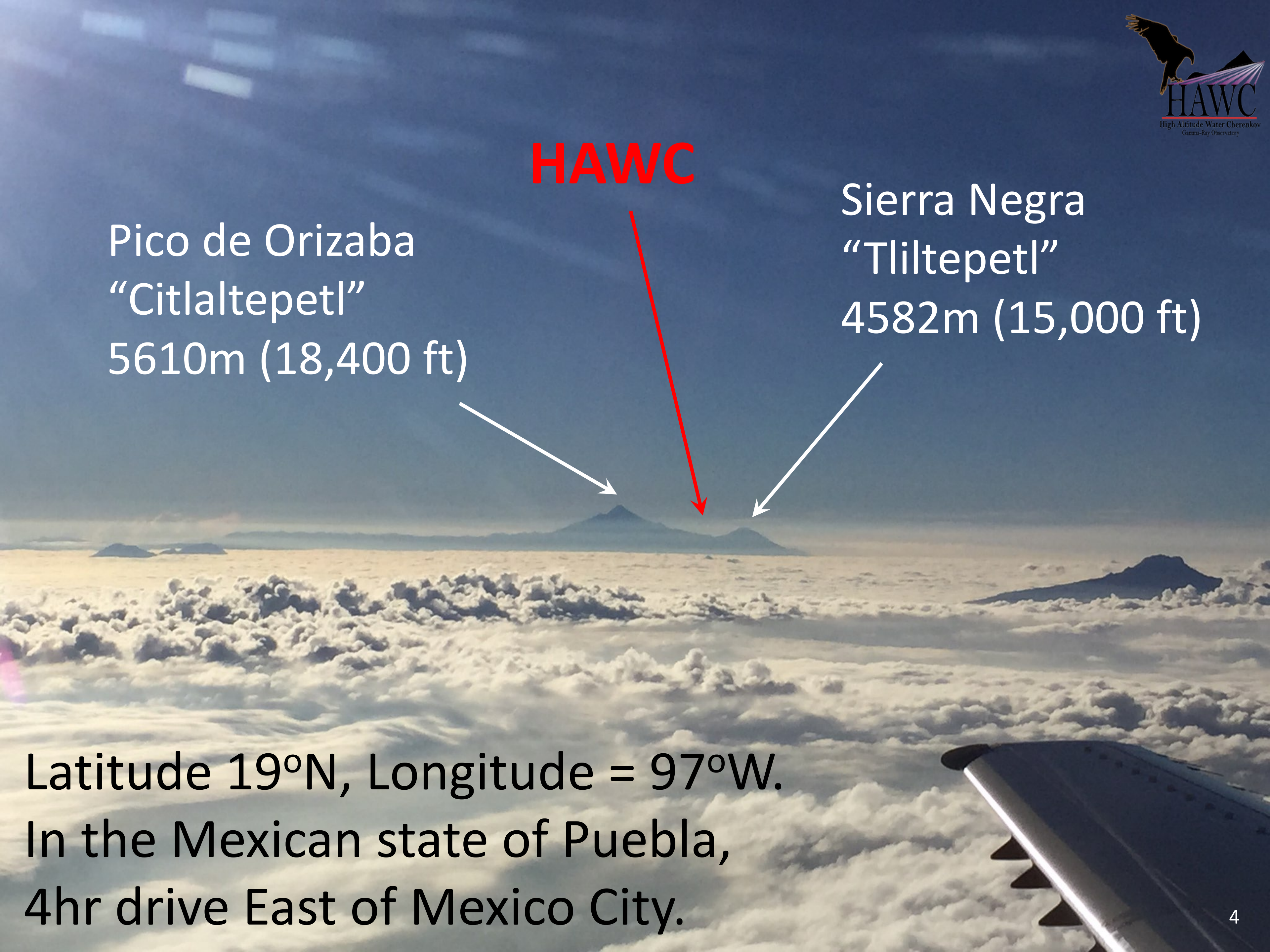
AS

Imaging Atmospheric Cherenkov Telescope (IACT)

High Altitude Water Cherenkov (HAWC) Extensive Air Shower Detector

- **22,000 m^2** air shower array
- **300 Water Cherenkov detectors** (WCD)
- **200,000 liters** of purified water **per WCD**
- **4 sensors (photo-multiplier tubes) per WCD**
- **Construction cost 13M USD**
- **Operations with full detector began in March 2015**

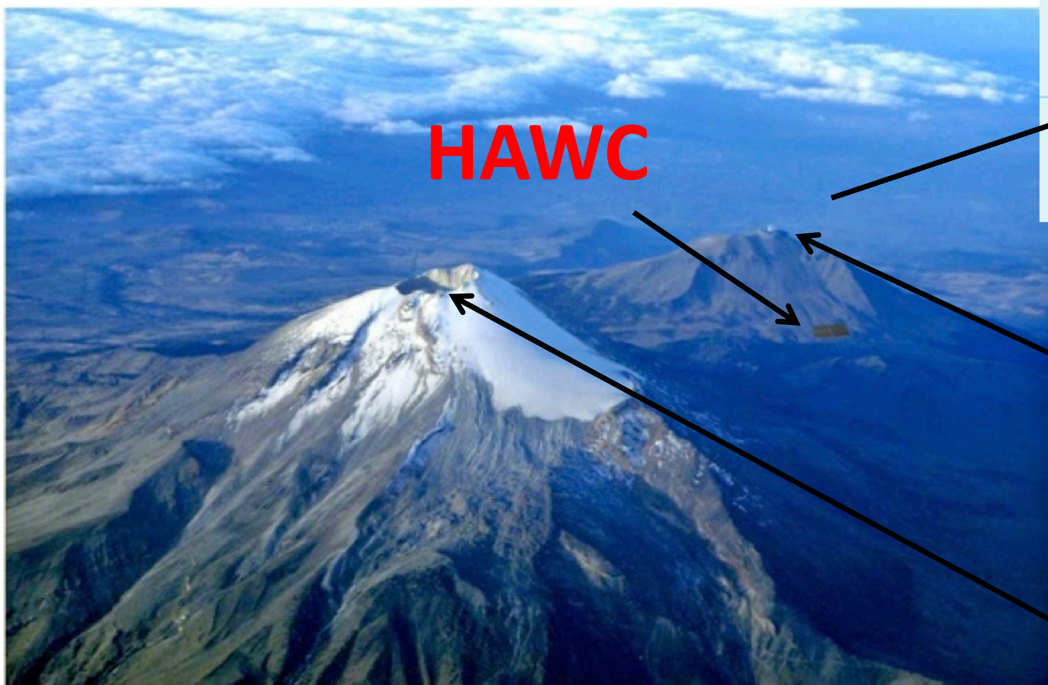




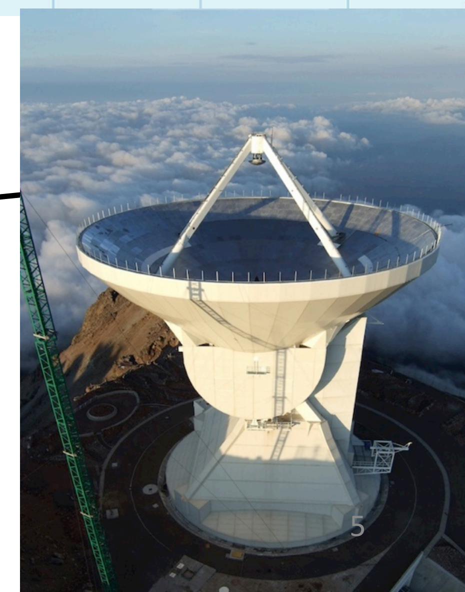
Latitude 19°N, Longitude = 97°W.
In the Mexican state of Puebla,
4hr drive East of Mexico City.

HAWC Site in Mexico

- High Altitude Site of 4100 m
- Temperate climate
- Existing infrastructure of electricity and internet within 1 km at LMT
- Latitude of 19 deg N



Gran Telescopio Milimétrico Alfonso Serrano (50m dia dish)



Pico de Orizaba 5600 m (18,500’)

The HAWC Collaboration

- **Los Alamos National Laboratory**
- **Univ. of Maryland**
- **Michigan State Univ.**
- **University of Wisconsin**
- **Pennsylvania State Univ.**
- **Univ. of Utah**
- **University of New Mexico**
- **Michigan Technological University**
- **NASA/Goddard Space Flight Center**
- **Georgia Institute of Technology**
- **Univ. California Santa Cruz**
- **Instituto Nacional de Astrofísica Óptica y Electrónica**

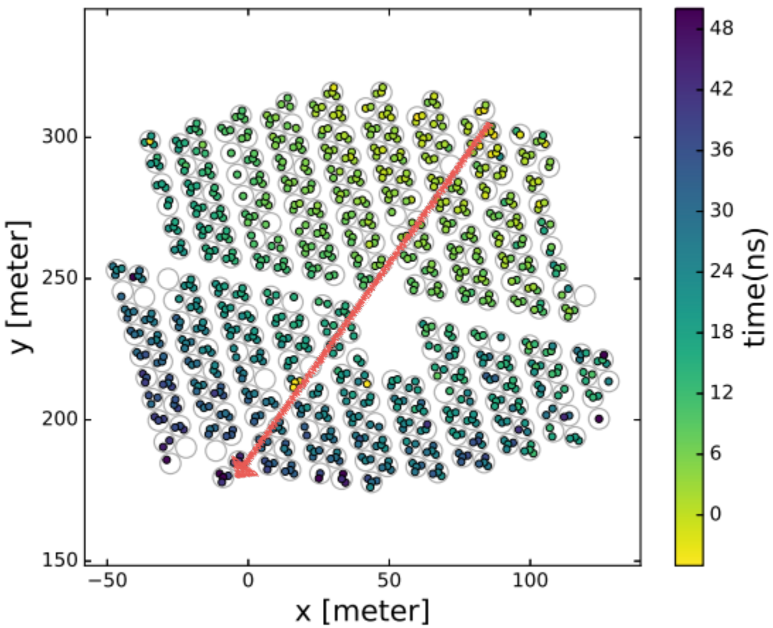
- **Universidad Nacional Autónoma de México**
  - **Instituto de Física**
  - **Instituto de Astronomía**
  - **Instituto de Geofisica**
  - **Instituto de Ciencias Nucleares**
- **Benemérita Universidad Autónoma de Puebla**
- **Universidad Autónoma de Chiapas**
- **Universidad Autónoma del Estado de Hidalgo**
- **Universidad de Guadalajara**
- **Universidad Michoacana de San Nicolás de Hidalgo**
- **Centro de Investigacion y de Estudios Avanzados**
- **Universidad de Guanajuato**

USA

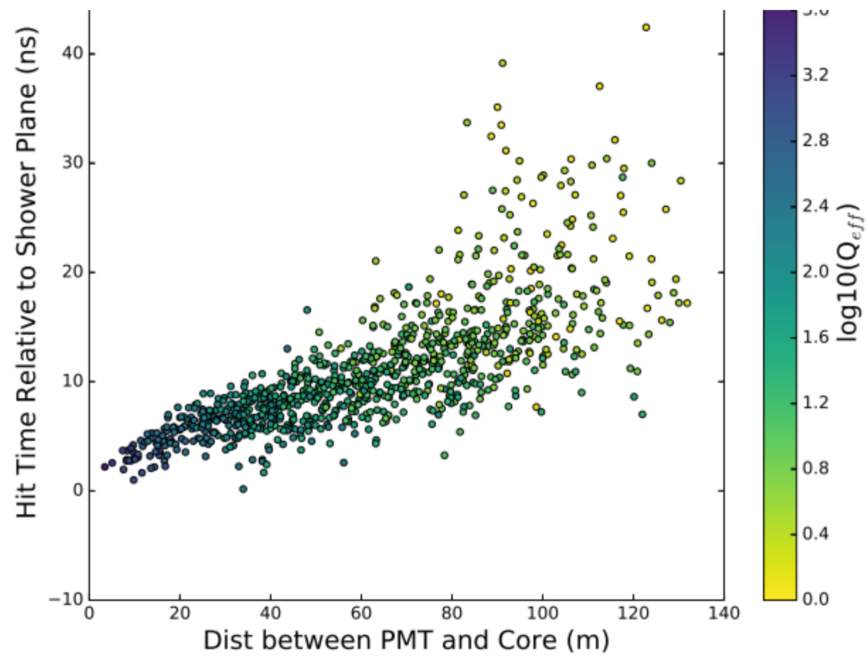
Mexico

During operations we've now added MPI Heidelberg, Krakow IFJ, & Costa Rica

Timing information



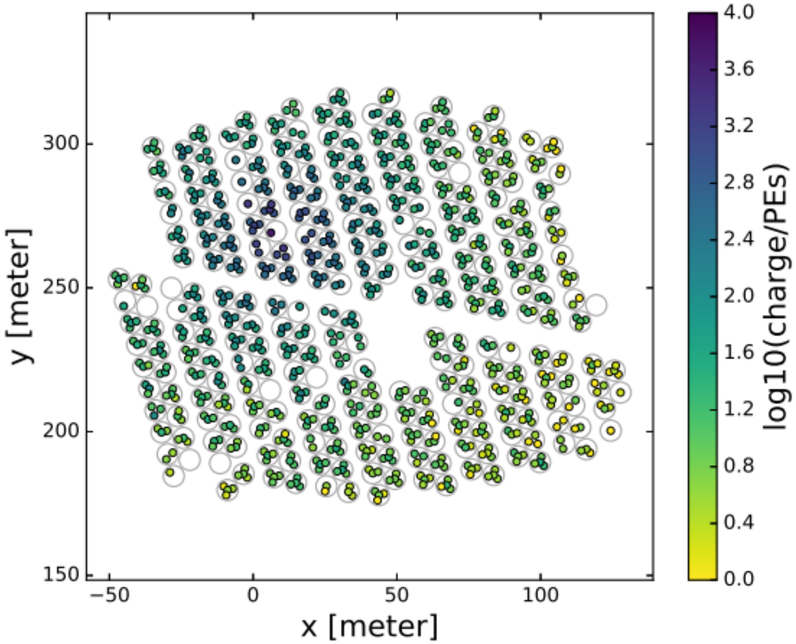
(c) Recorded Time



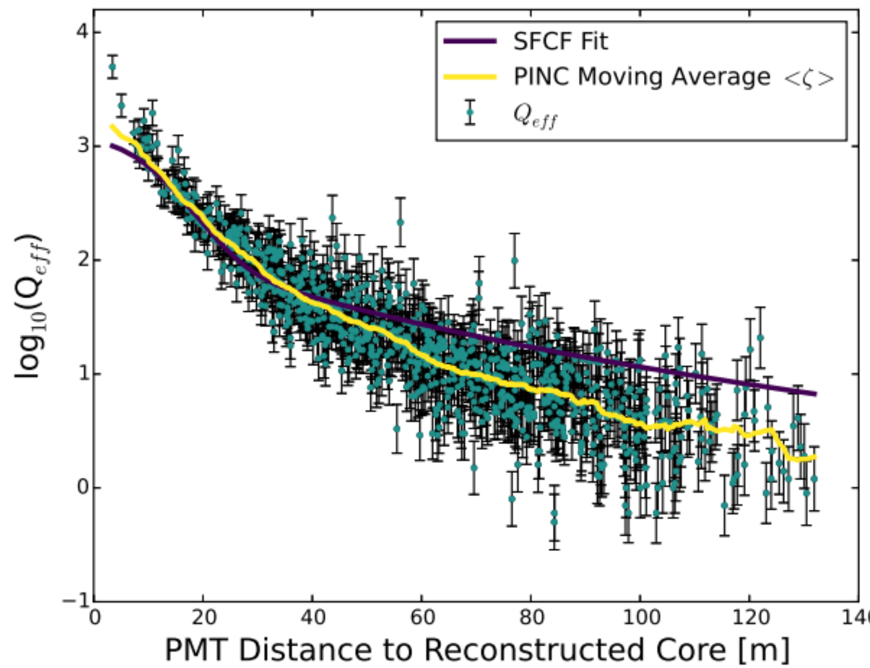
(d) Shower Curvature/Sampling

- Relative timing of PMT signals allows to determine the arrival direction of primary particles.
- Tank spacing is~ 25 to 50 light-ns.
- Arrival times are fitted to a curved plane with sub-ns timing residuals.

Energy deposition



(a) Recorded Effective Charge



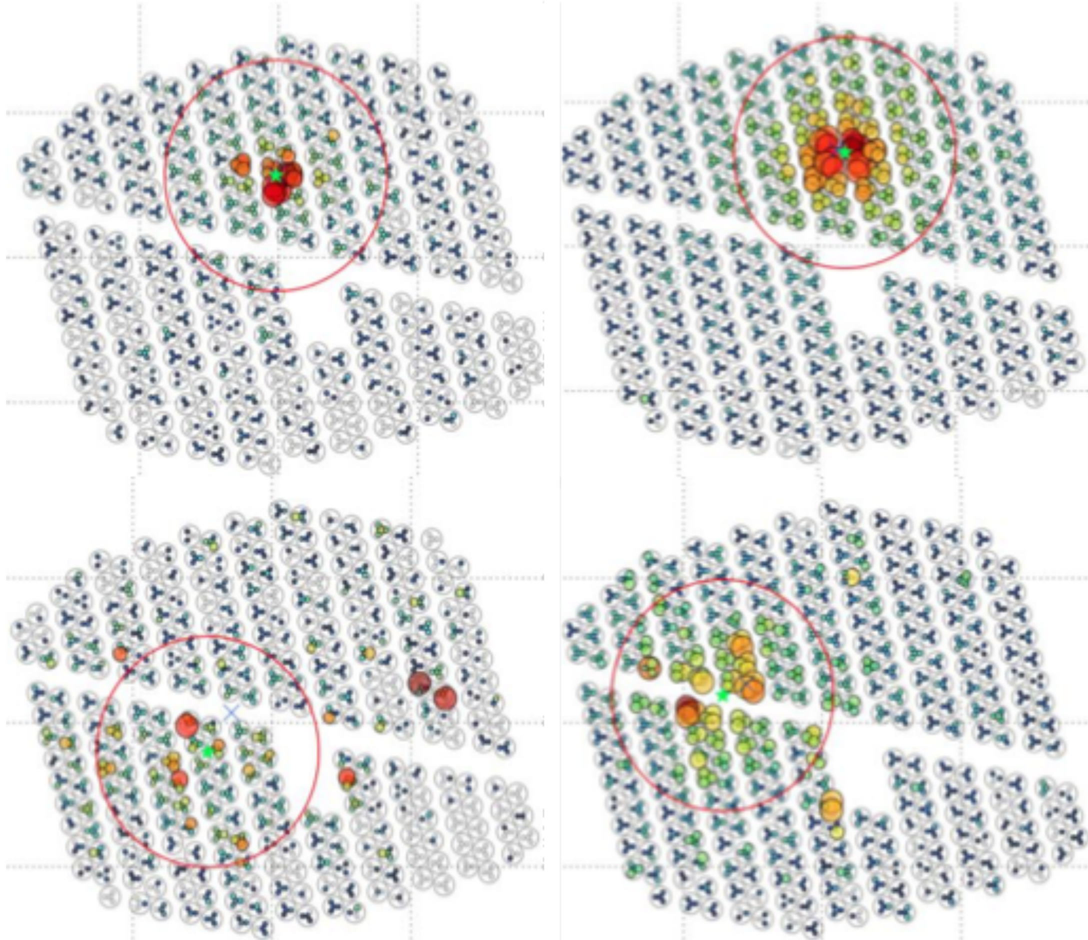
(b) Lateral Distribution Function

- PMTs measure individual pulses of light.
- Energy estimation and γ/hadron discrimination.
- Core location and model energy deposits: fit to standard shower models (NKG) and simulations of the HAWC detector response.

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)

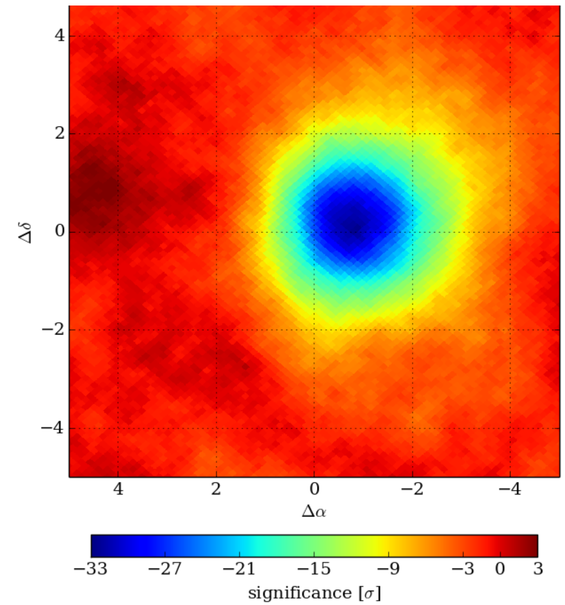
Cosmic-ray Moon shadow proves HAWC's E scale

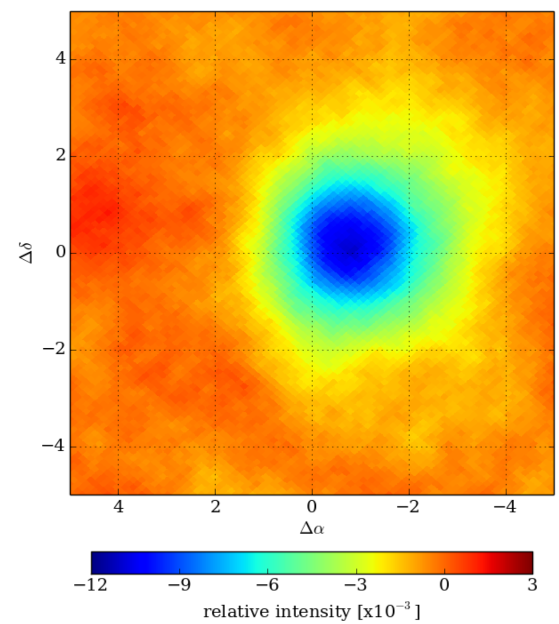
- Median energy of 2 TeV derived from deflection of -0.91°±0.04° due to Earth's magnetic field is consistent with Monte Carlo prediction for cosmic rays

- See HAWC small scale cosmic-ray anisotropy paper 2014 ApJ (or talk to Zig Hampel-Arias)

- -32.5σ deficit in 52 transits.

- Coming soon constraints on helium, antiproton, $e^{\pm}$ shadows

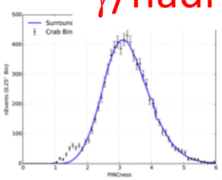




Crab with HAWC

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

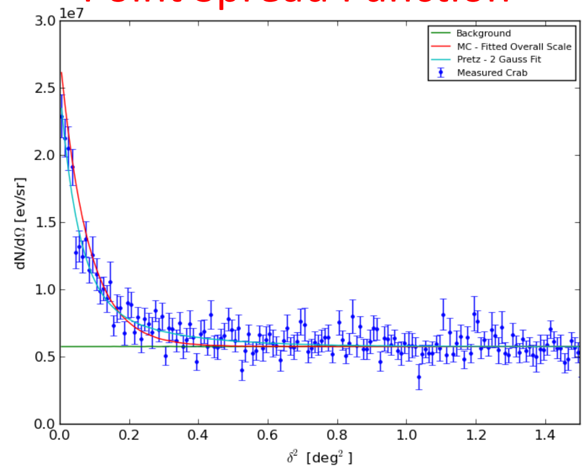
γ/hadron discrimination

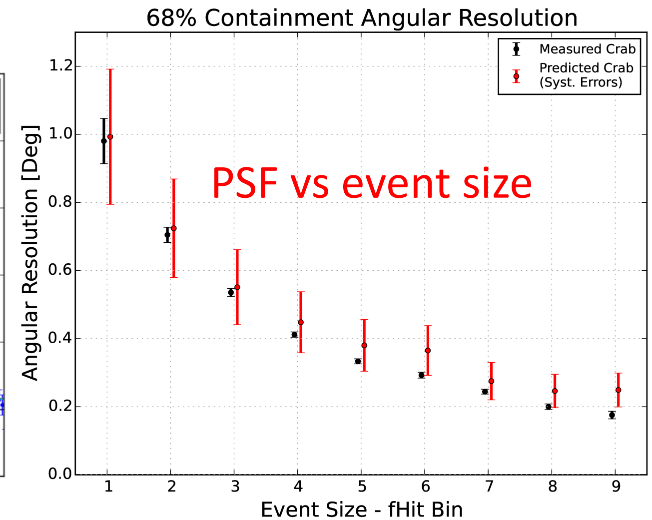


hadrons

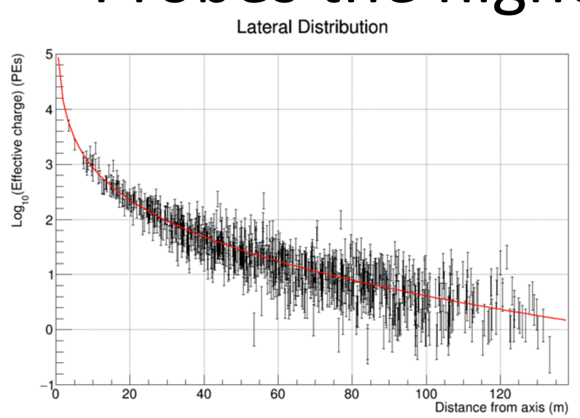
γ

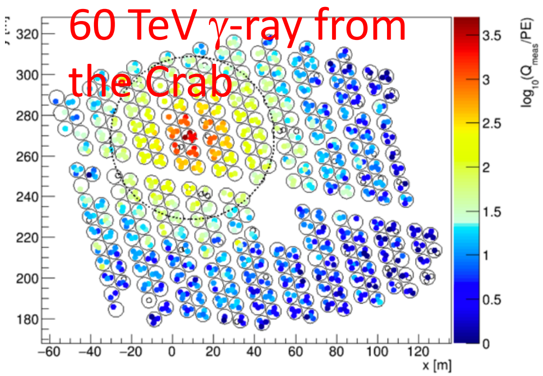
Point Spread Function

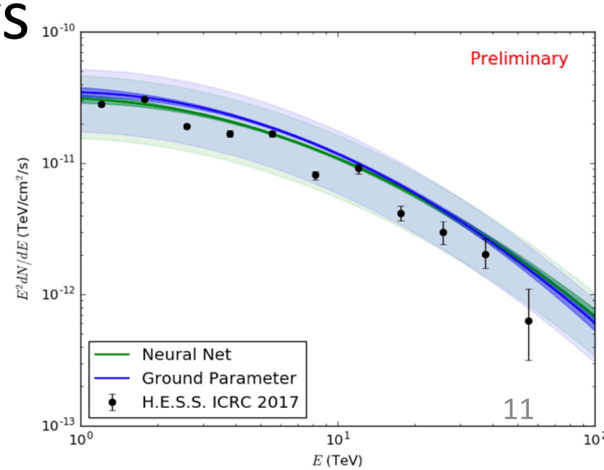




- Probes the highest energy gamma-rays

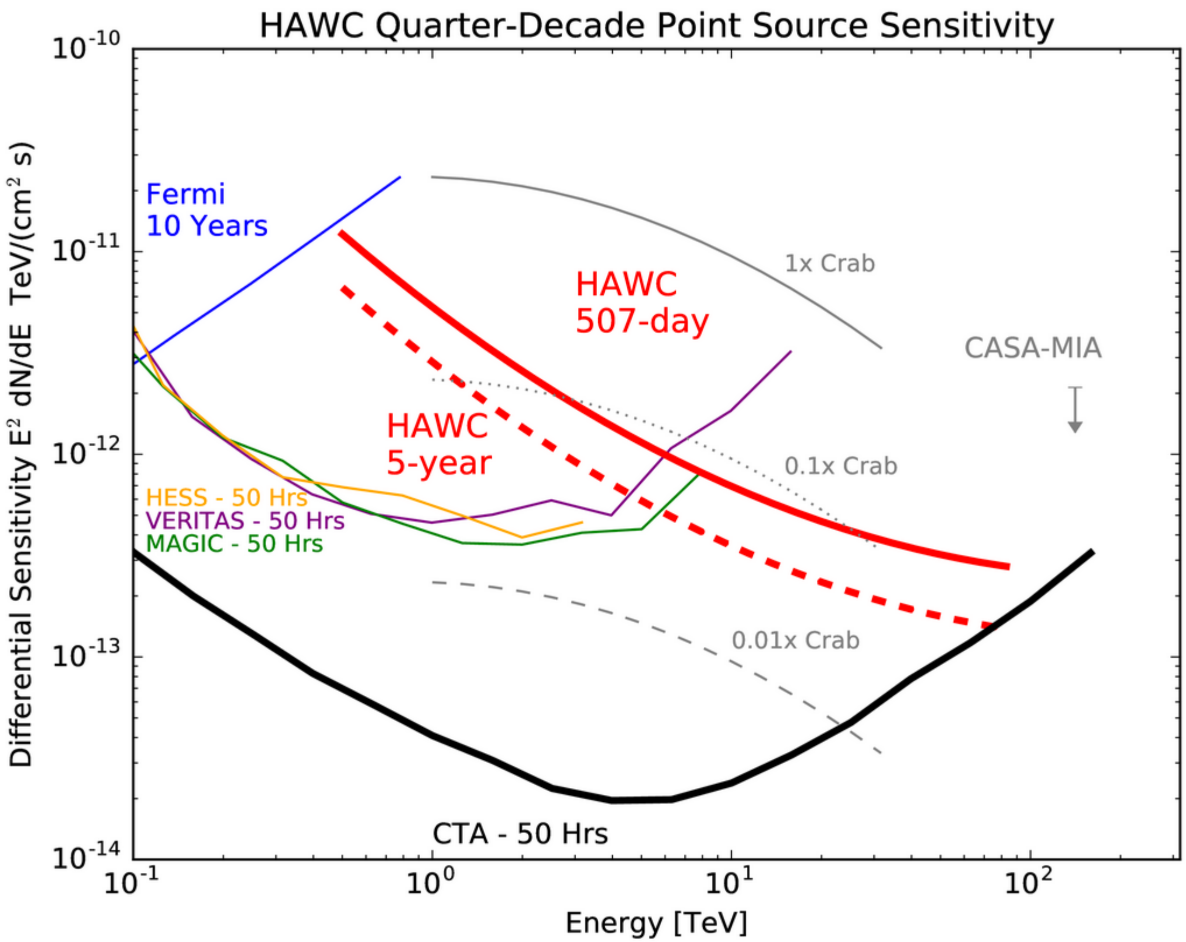




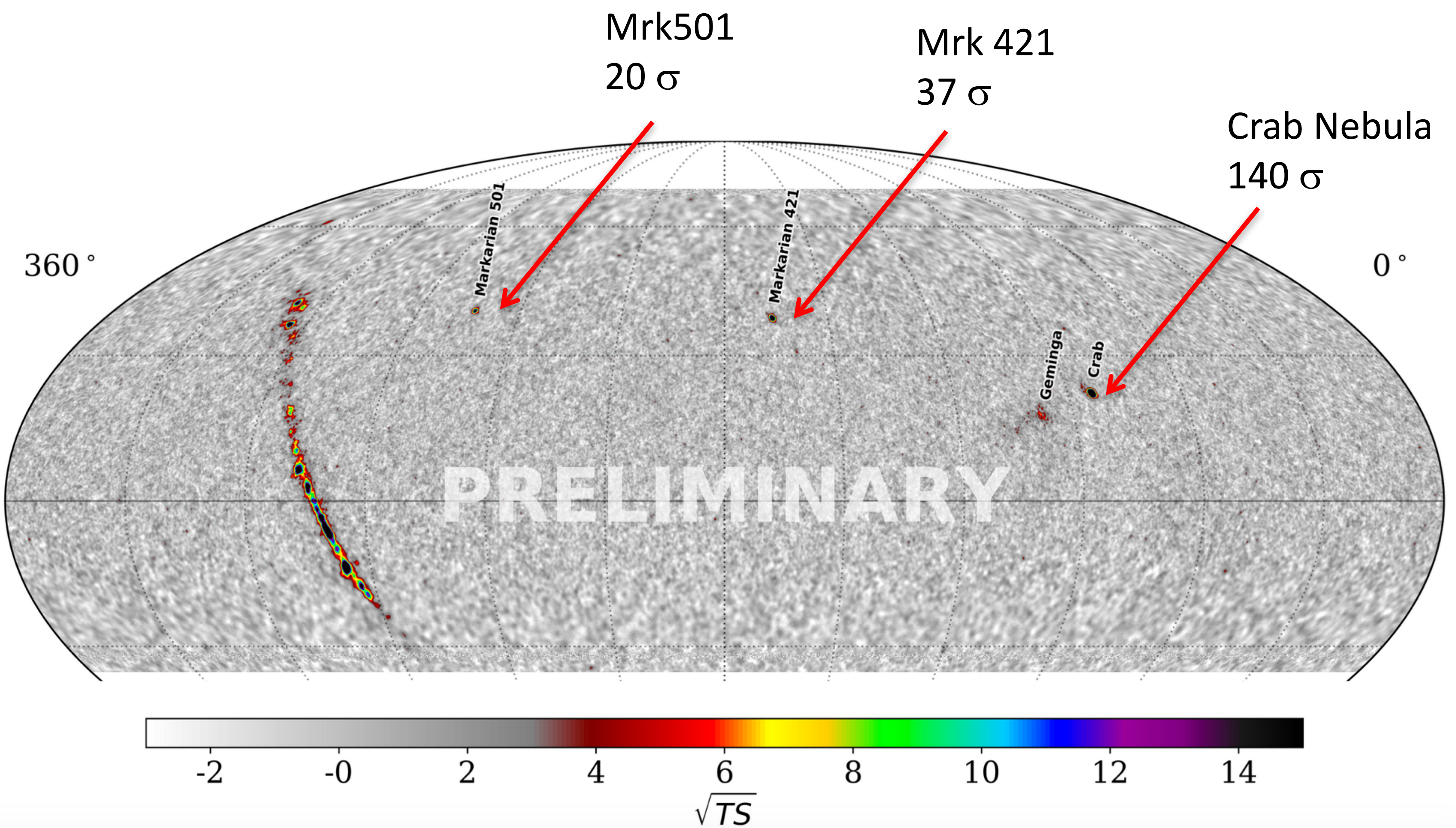


High Energy Gamma-Ray Sensitivity

- Fermi and HAWC have instantaneous field of view of ~2 sr and have similar angular resolution
- IACT observations are for a single source of 50 hours which is "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



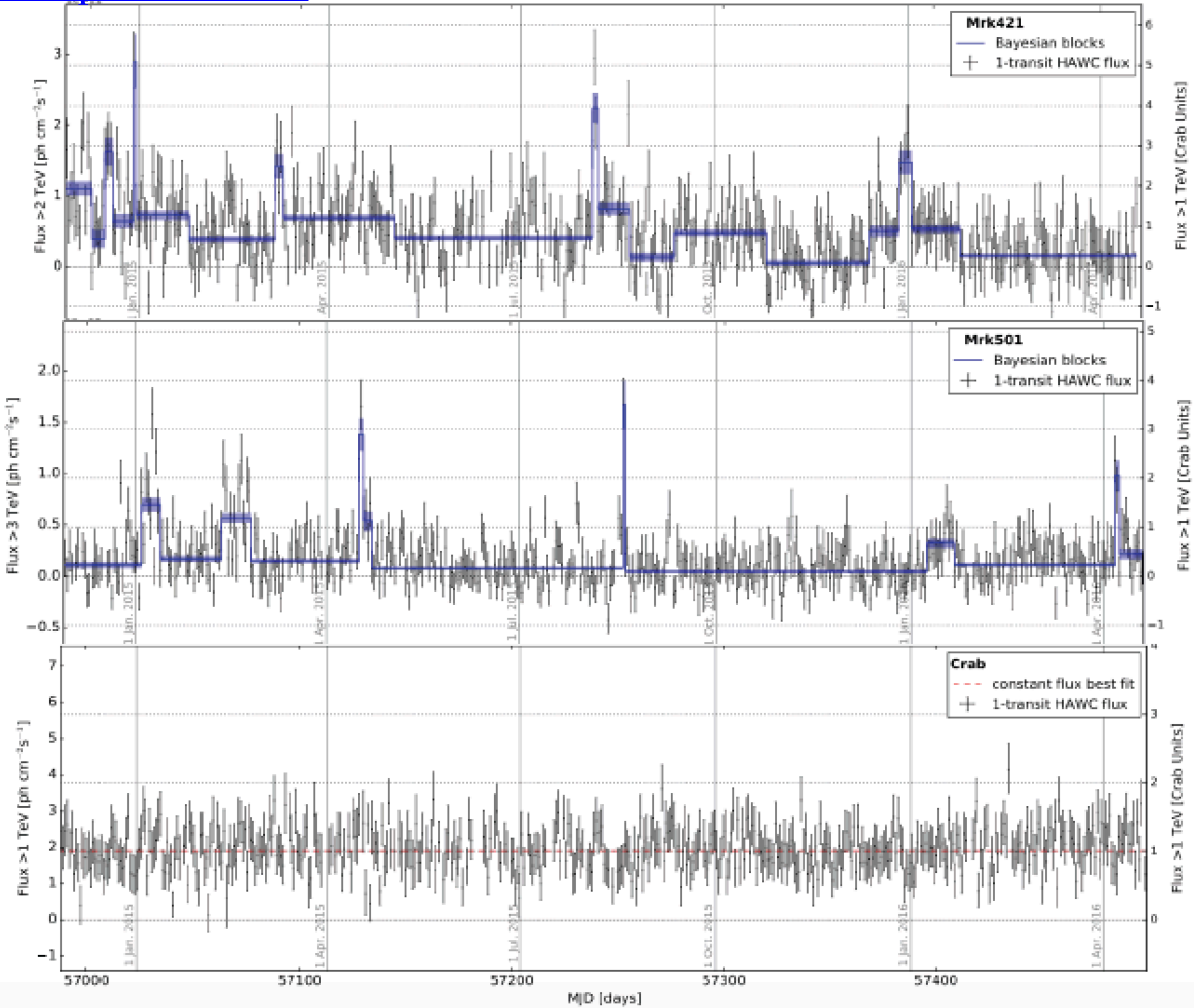
HAWC's 2.5 year Sky Map



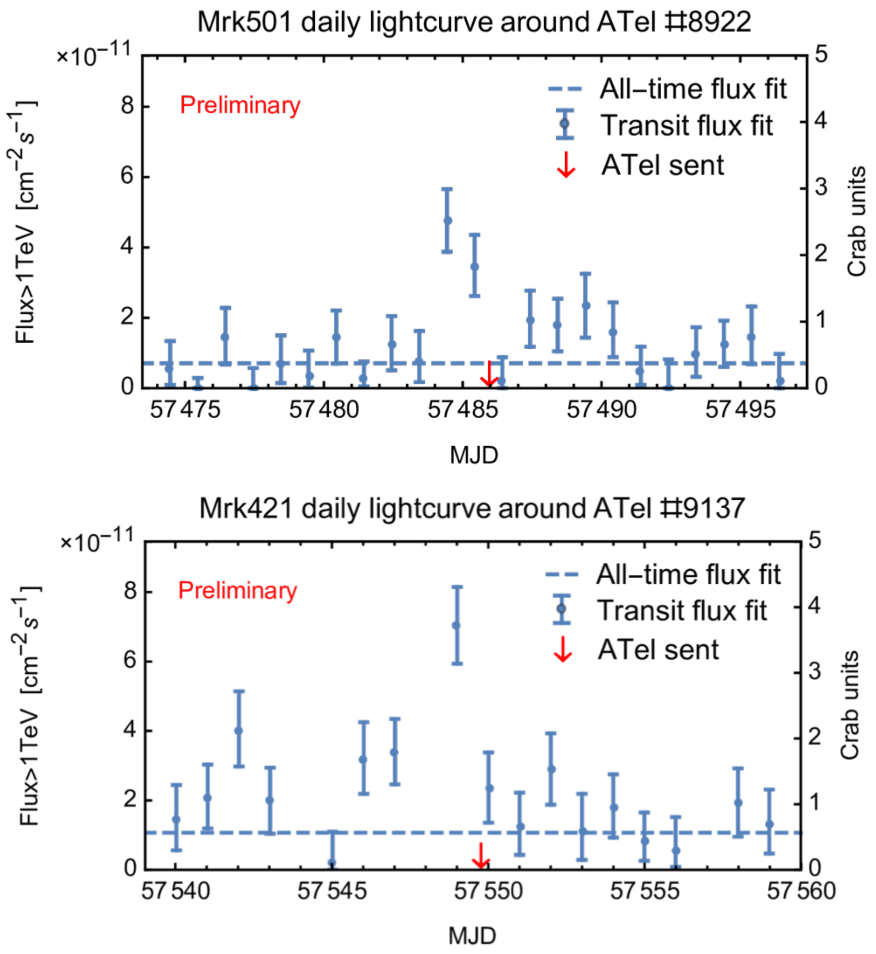
2HWC catalog ApJ 2017, arXiv:1702.02992, was 507 days and contained 39 sources of which 10 were new

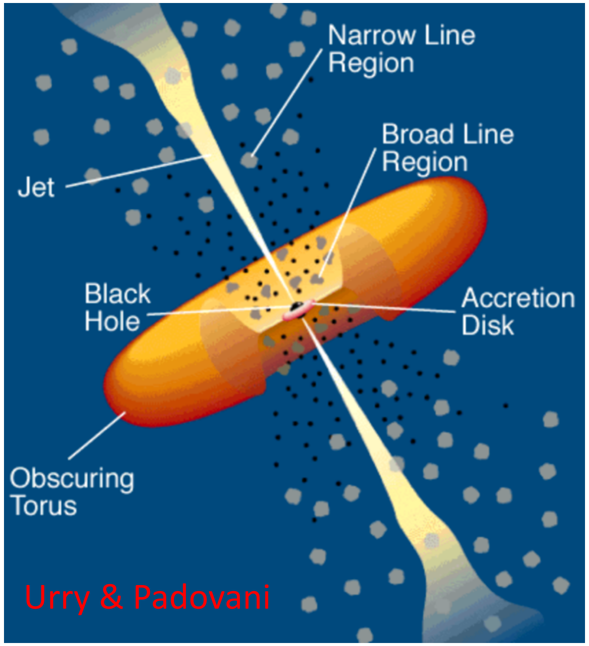
Daily Monitoring of Mrk421, Mrk501, Crab

2017ApJ...841..100A



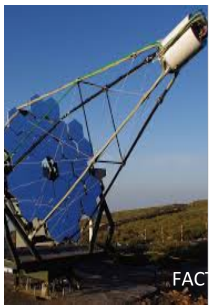
HAWC Monitors Active Galactic Nuclei for Flaring Daily

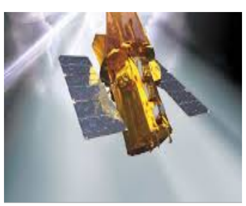


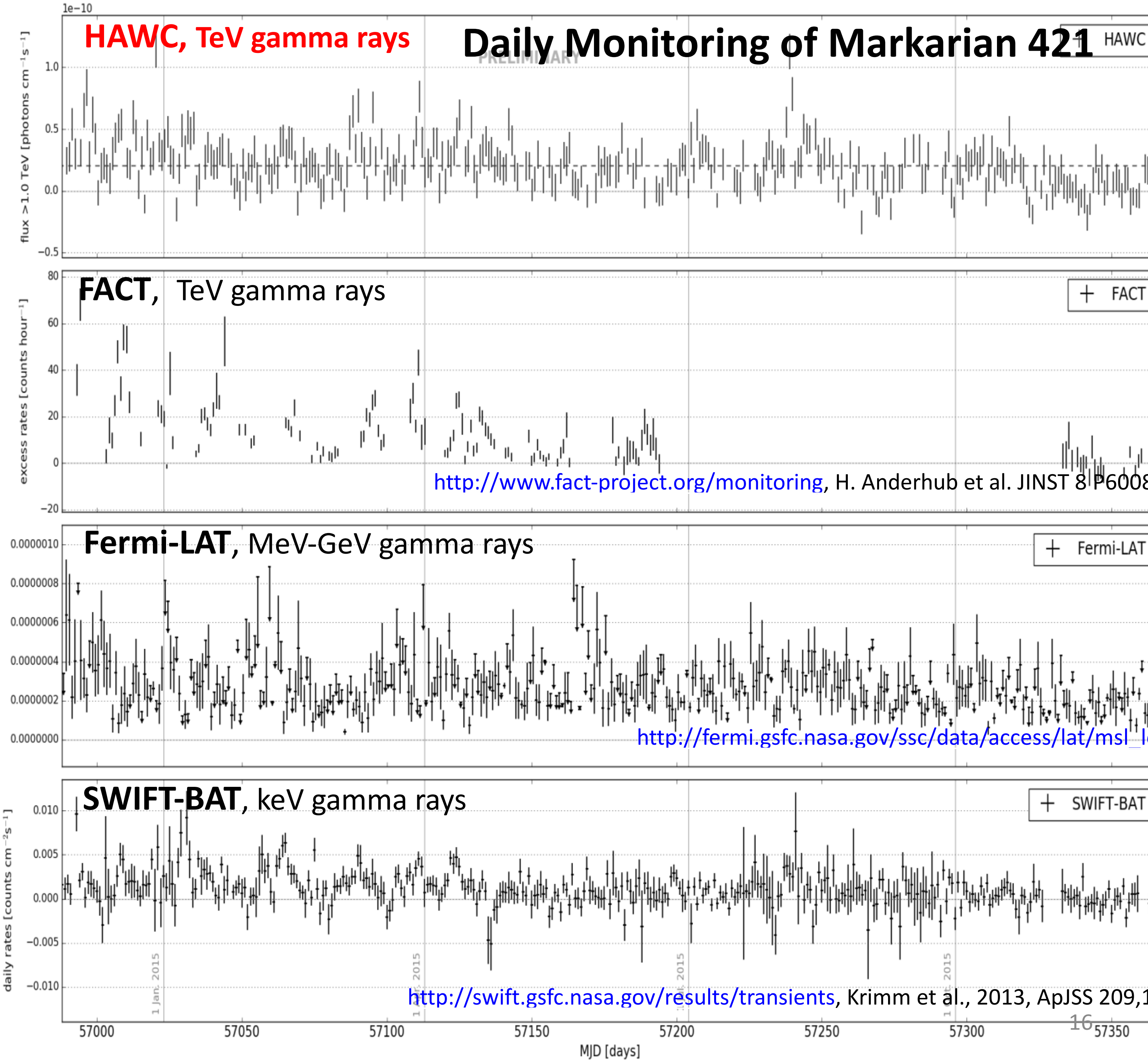


Most recent IAU Atel "HAWC observation of Mrk421 reaching peak TeV flux in month-long enhanced activity" last week. Plus many notifications to atmospheric Cherenkov telescopes via MOU in preceding days.

Daily Monitoring of Markarian 421



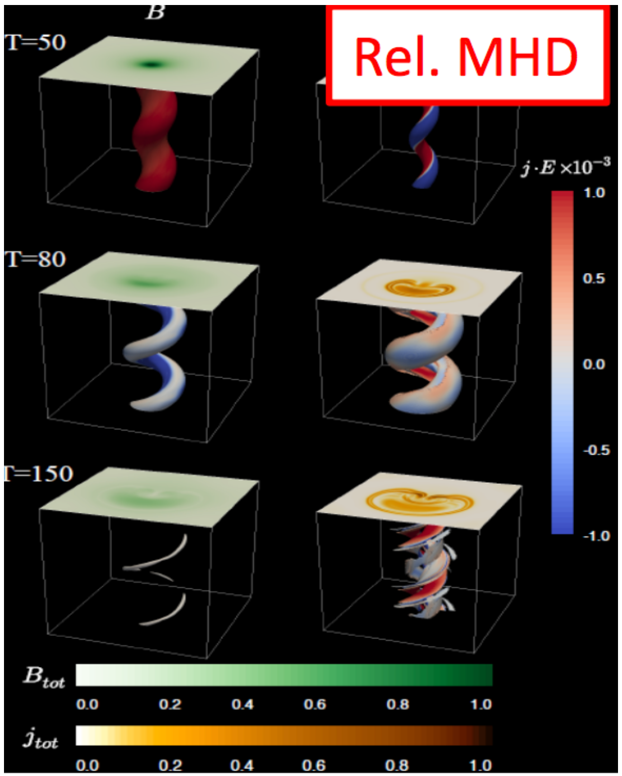


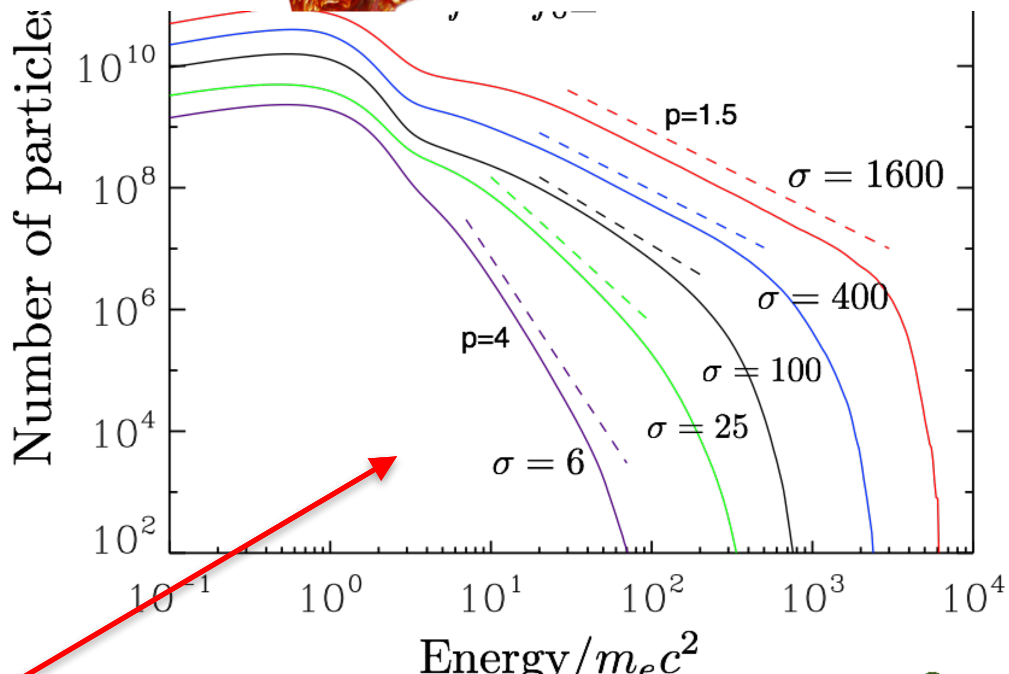


Magnetic Reconnection Efficiently Accelerates Particles

- Gives Fast Rise AND Fast Decay Flares
- Predicts Rapid Changes in Optical Polarization

Zhang, Li, Guo, Taylor ApJ 2017

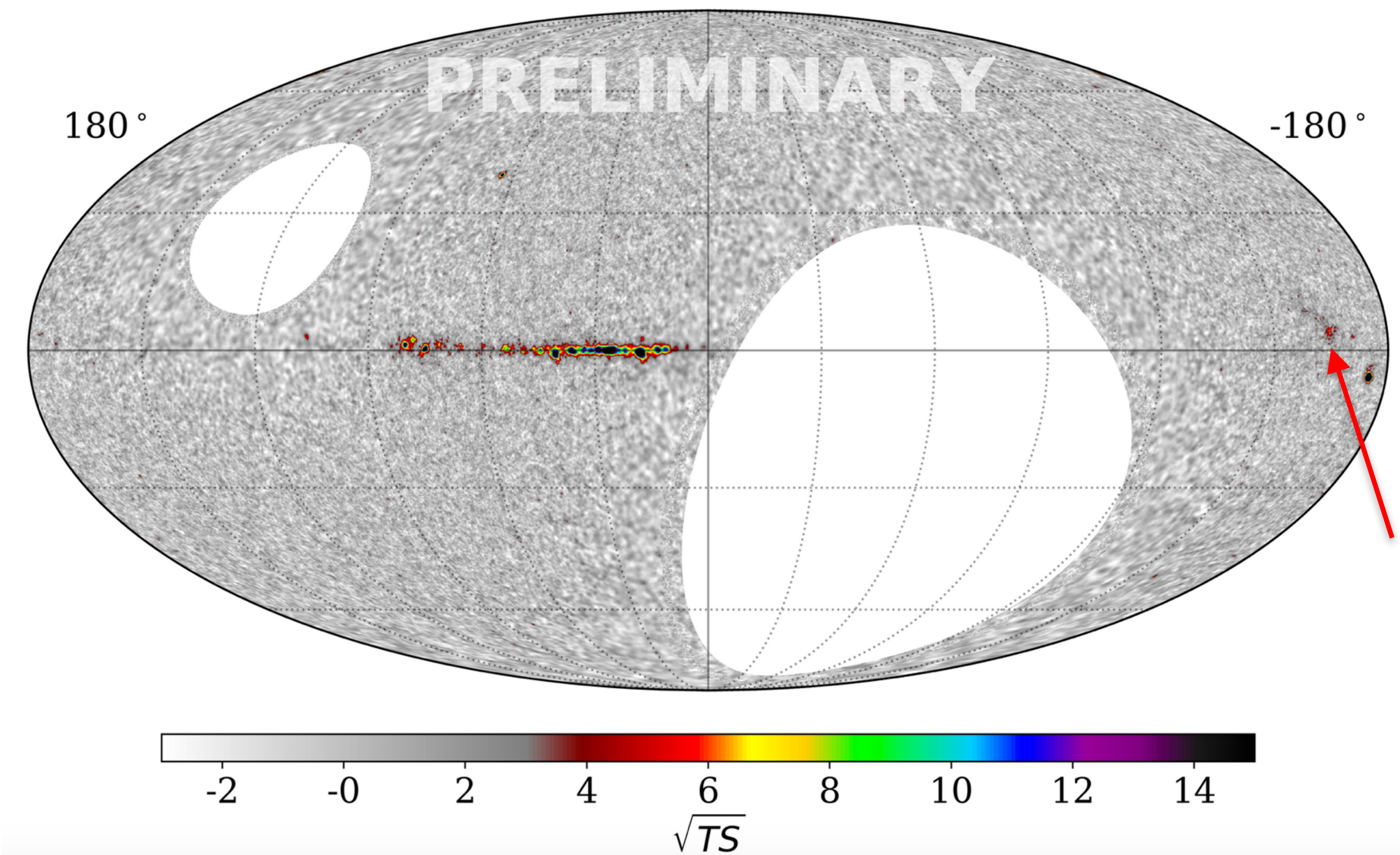




Guo et al. in prep.

σ is proportional to B^2
The larger B, the more high energy particles are accelerated.

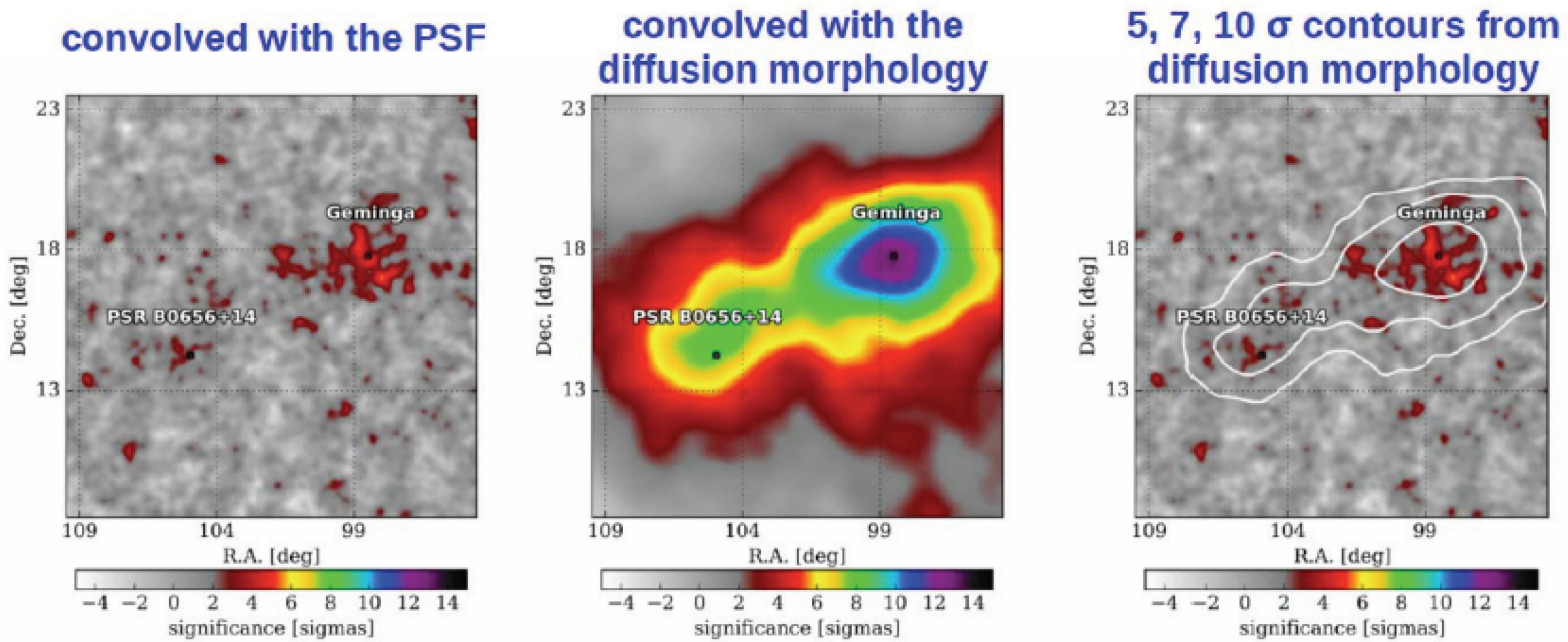
HAWC's 2.5 year Sky Map In Galactic Coordinates



Nearby TeV PWN are Very Extended

ergs/sec at distance ~250(288) pc and moderate velocity

- Postulated sources of PAMELA and AMS positron excess are the ~ 5 nearest pulsars of which these are two

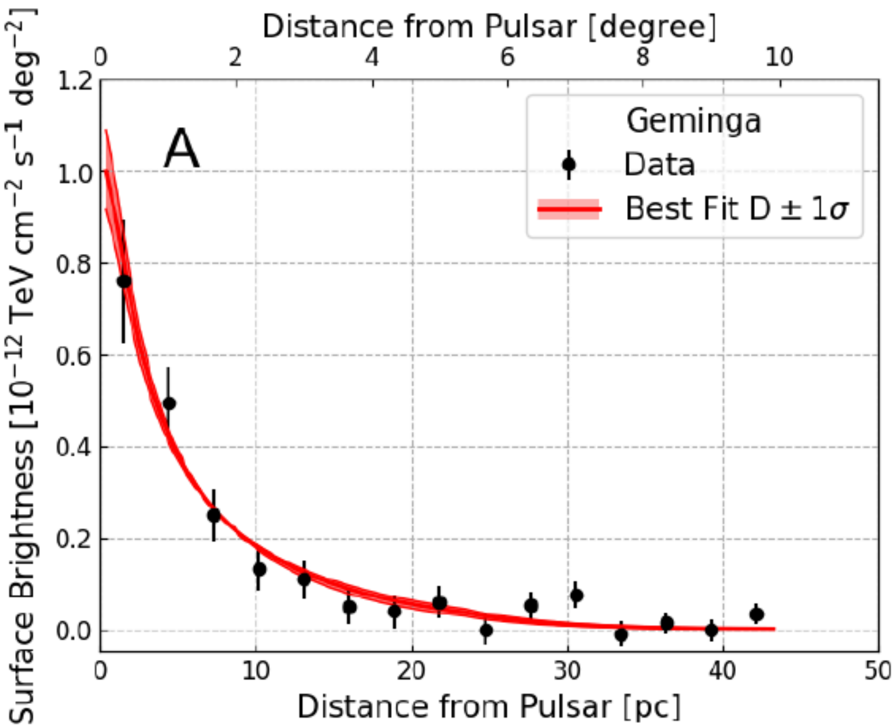


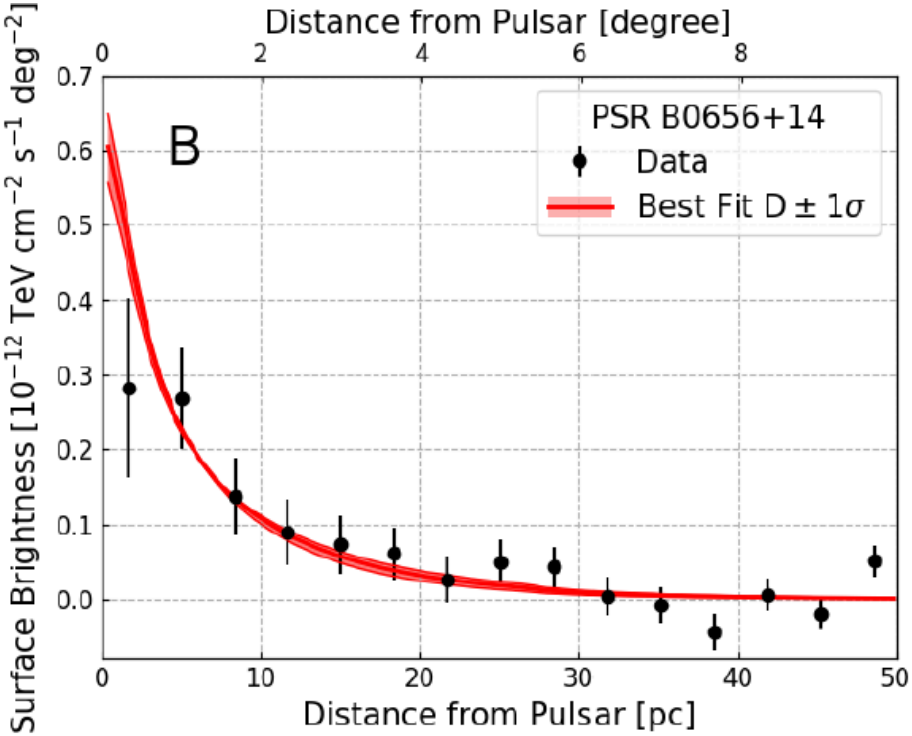
Science 17 November 2017

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

- HAWC observations prove that these sources are accelerating electrons and positrons to multi-TeV energies.
  - These are the oldest and nearest PWN observed at TeV energies and have the lowest spin down luminosity.
  - Geminga (Monogem) is 3×10^5 (1×10^5) years old as determined from period and period derivative.
- HAWC observations measure the total energy released in electrons and positrons.
  - The efficiency at converting spin-down energy to accelerated electrons is high -- 40% (7%) for Geminga (Monogem).
- HAWC observations of the angular extent of these TeV nebula measures the diffusion coefficient of their propagation in the interstellar medium.

HAWC Measures the Diffusion Coefficient

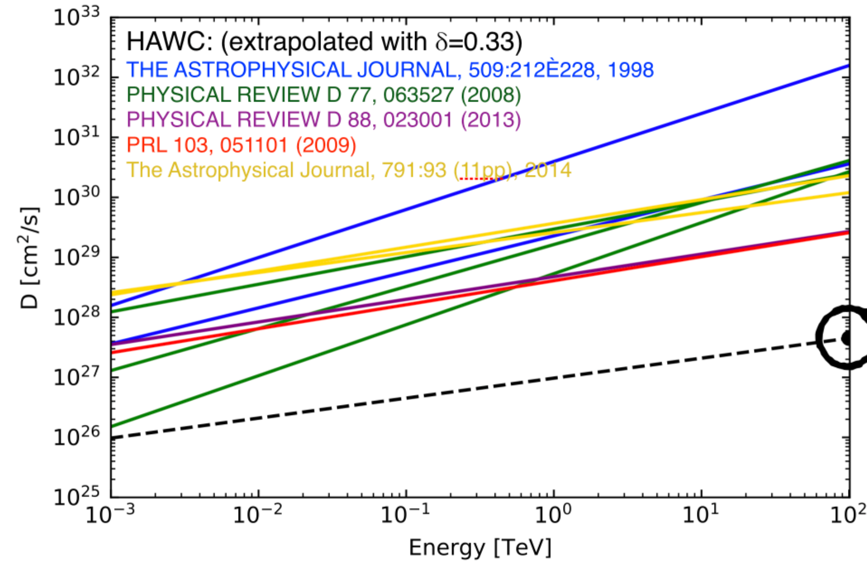


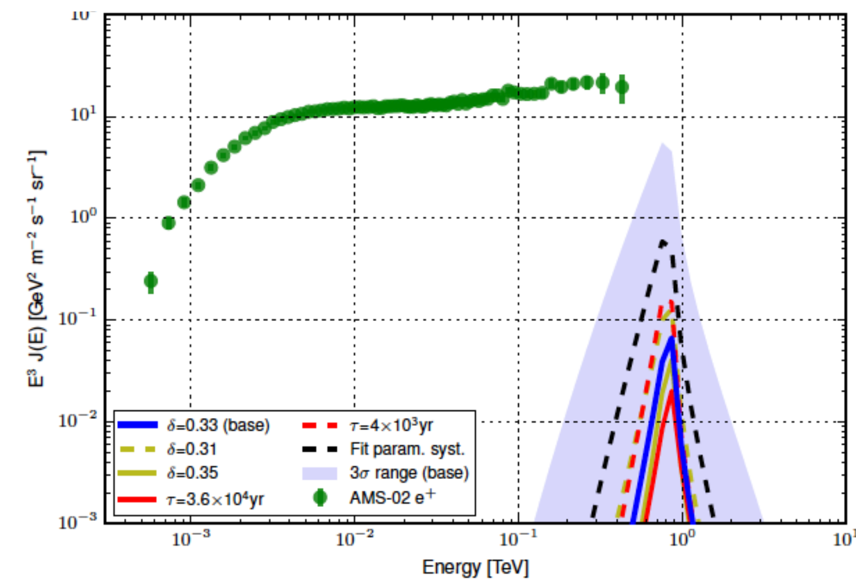


Electrons and Positrons Diffuse Away from the pulsar and produce gamma rays when they scatter the cosmic microwave background (CMB) radiation.

Diffusion is SLOW

- 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.





Diffusion & Cooling

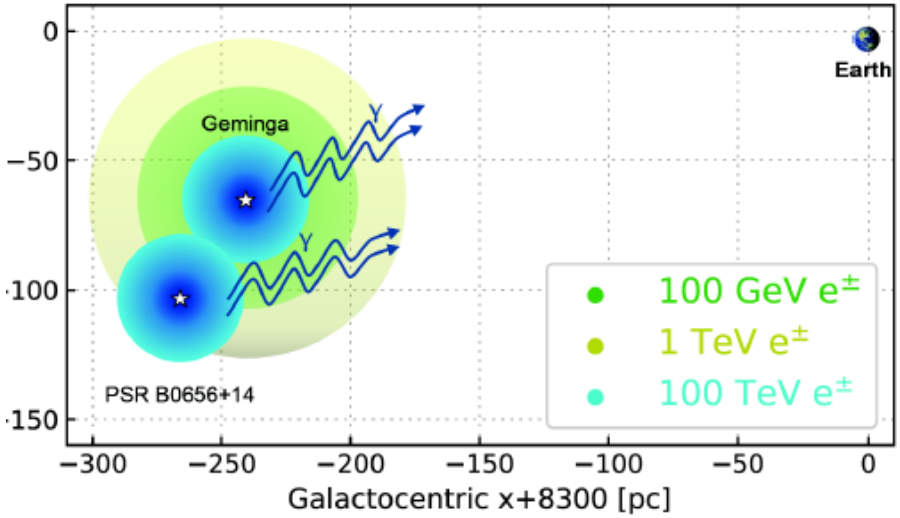
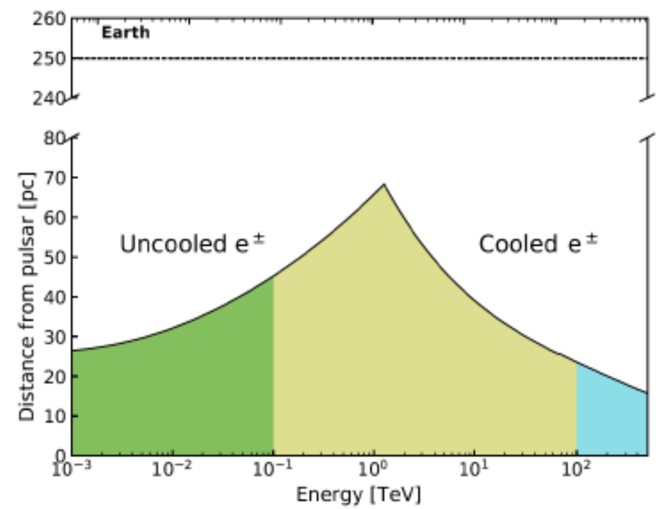


Illustration of the face-on view of the observed region and the Earth. The color circles correspond to the diffusion distance of leptons of three different energies from Geminga (for readability only the highest energy is shown for PSR B0656+14).



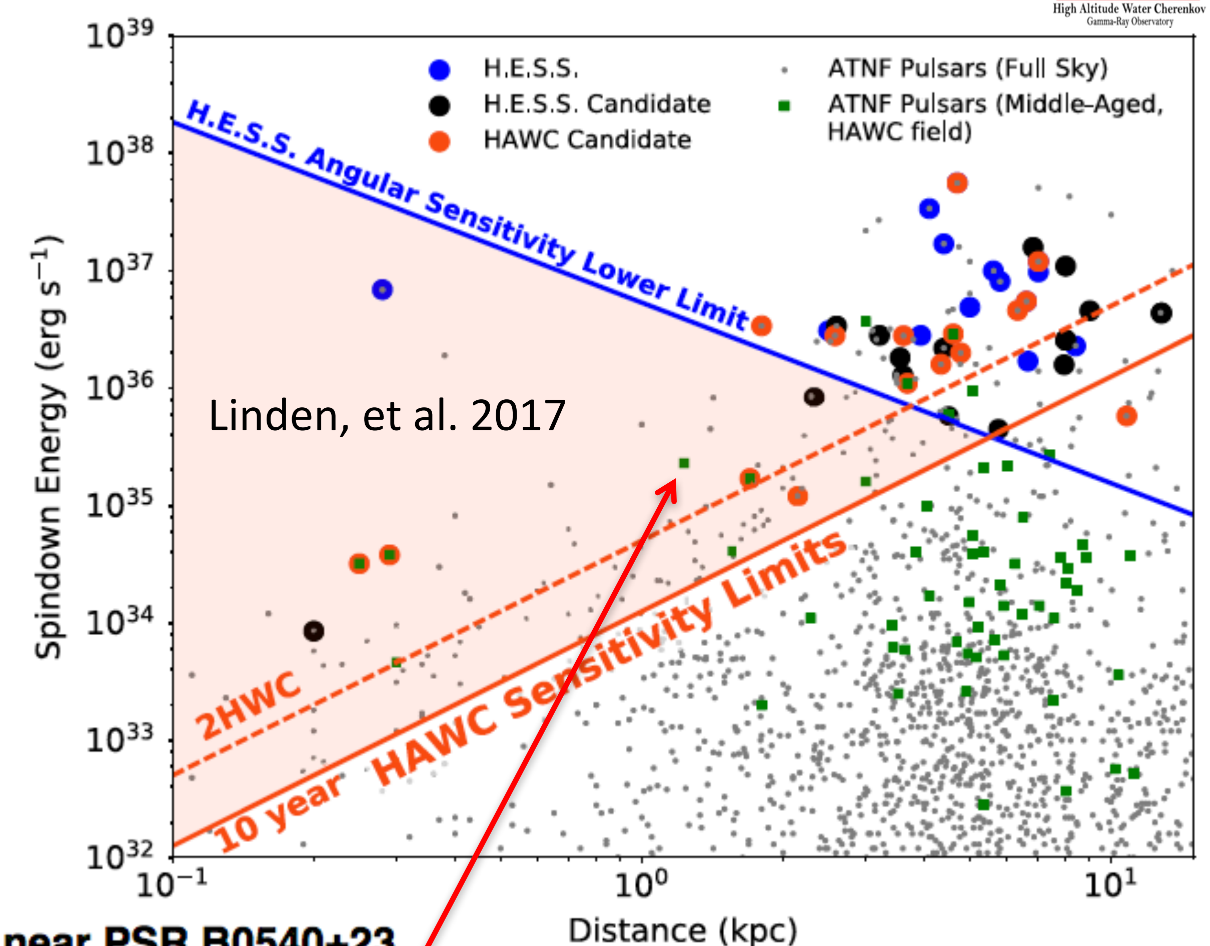
Particles diffuse farther with higher energy until cooling effects dominate, as a result TeV particles diffuse the farthest.

$$r_d = 2\sqrt{D(E_e)t_E} \qquad D(E_e) = D_0(E_e/10\,GeV)^{\delta}$$

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

Other Sources of the Positrons

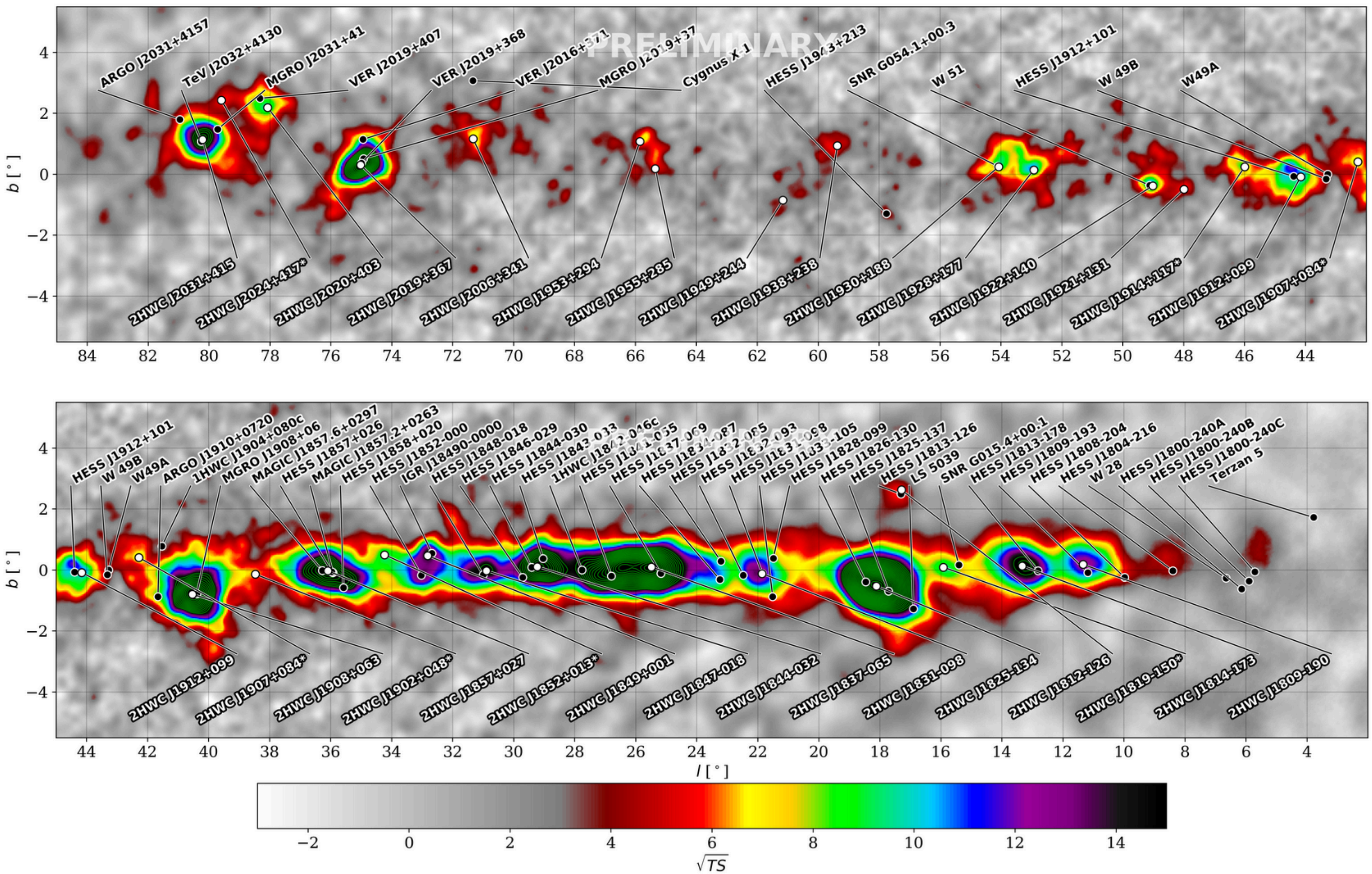
- Annihilation or Decay of Dark matter into Standard Model Particles
- Other Nearby PWN (perhaps as yet undiscovered)
- Nearby Supernova Remnant Shocks
- Nearby X-ray Binaries
- New Theories about Secondaries Produced by Cosmic Ray Propagation



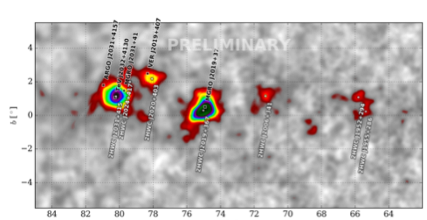
HAWC detection of TeV emission near PSR B0540+23

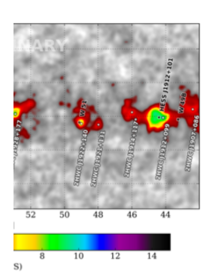
ATel #10941; *Colas Riviere (University of Maryland), Henrike Fleischhack (Michigan Technological University), Andres Sandoval (Universidad Nacional Autonoma de Mexico) on behalf of the HAWC collaboration*
on 9 Nov 2017; 23:11 UT
Credential Certification: Colas Riviere (riviere@umd.edu)

HAWC's Galactic Plane with 2.5 years of data

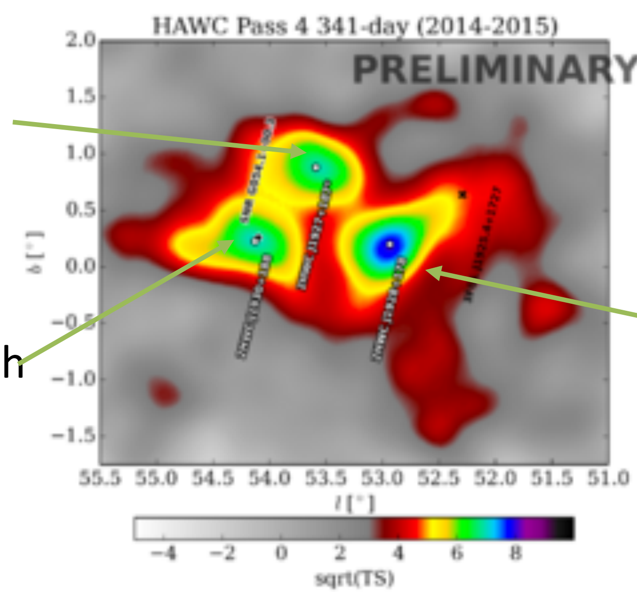


39 Sources in 2HWC catalog (ApJ 2017) of 1.5 years with 10 New TeV sources





Association unclear



Known TeV source with Supernova remnant AND energetic pulsar

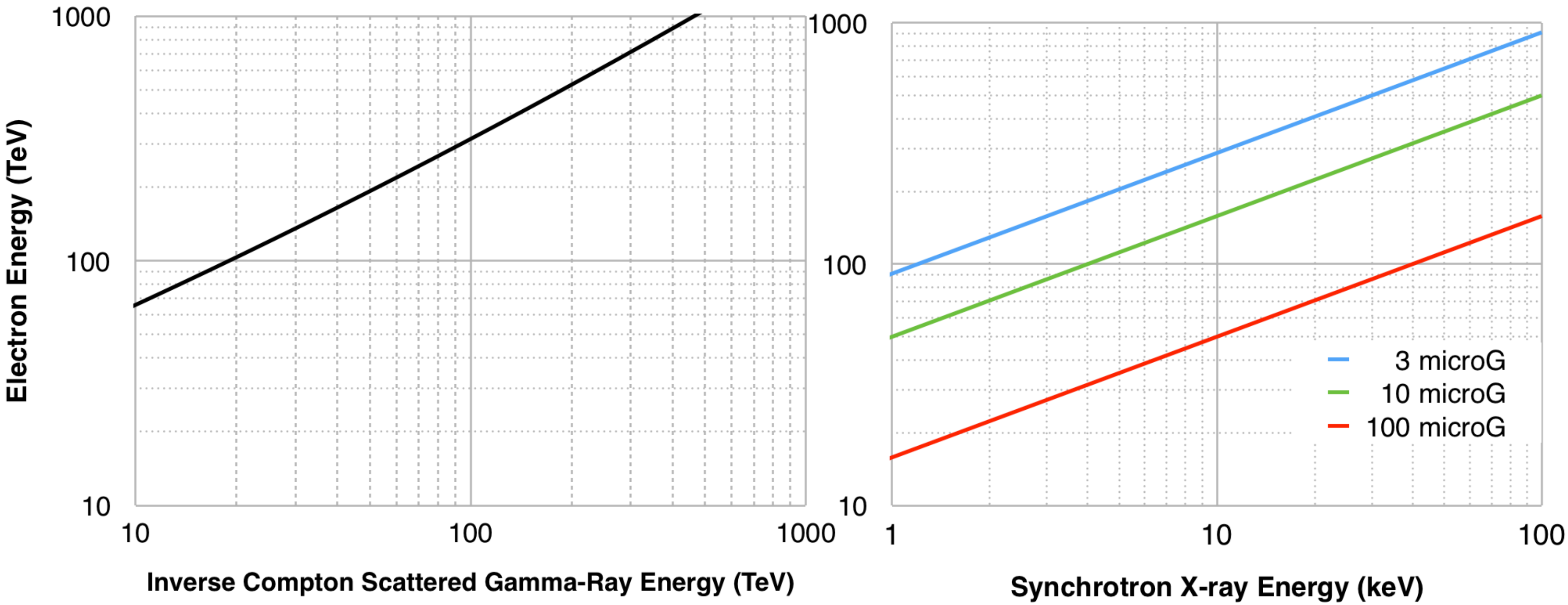
Pulsar ~8kpc (26,000 ly) away, but no PWN detected by NuSTAR

Electrons emit TeV gamma-rays and keV x-rays

$F_{x\text{-}ray} = F_{synchrotron} \quad \alpha\ n_e{}^{*}\ B^2$

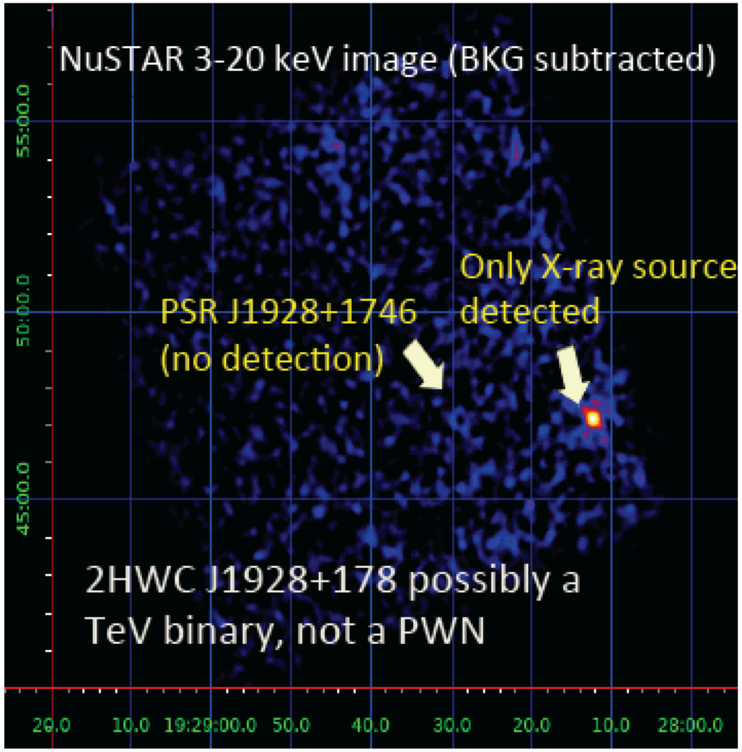
$F_{>10TeV} = F_{inverse\ Compton} \quad \alpha\ n_e{}^{*}\ n_{CMB}$

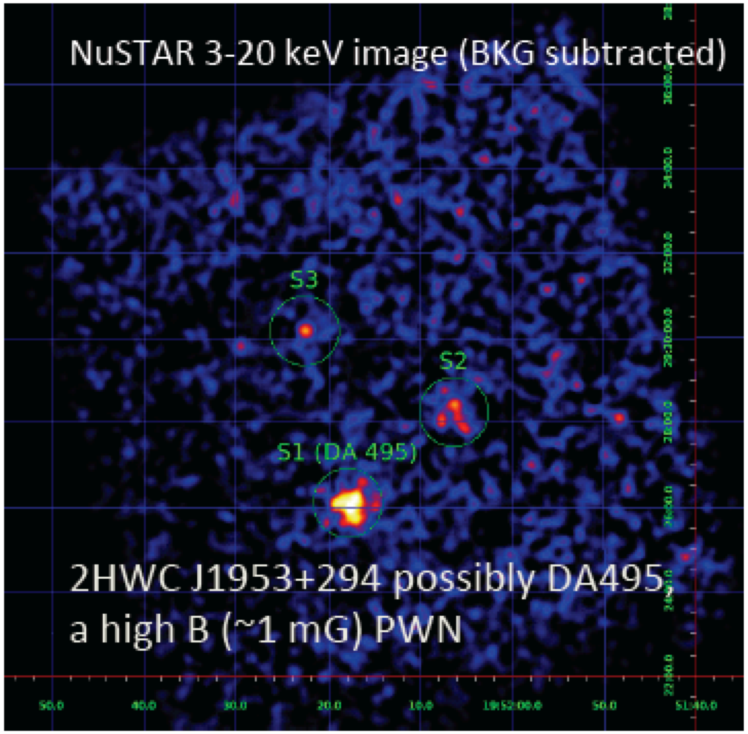
So $F_{x\text{-}ray}$ / F_{TeV} => magnetic field



NuSTAR-VERITAS-HAWC Legacy Project

- First 2 NuSTAR observations are very interesting
  - 2HWC 1928+178: A potential TeV binary of which there are only 6 known
  - 2HWC 1953+294: A high B field Pulsar Wind Nebula with no pulsar detected





Interesting PWN: DA 495

- 2HWC 1953+294 is one of the 10 new sources in 2HWC catalog.
- VERITAS confirmed TeV emission and better localized the source.
- Based on HAWC and VERITAS detections, we obtained NuSTAR observations. Ruled out other sources and measured hard x-ray spectrum.
- Source is a PWN with a Fermi discovered pulsar. Radio implies high magnetic field of ~1mG over a region of ~15 pc.
- Lots of energy, plus electrons cool quickly. Hadrons?

AAS Poster by Anna Coerver (NuSTAR student at Columbia University)

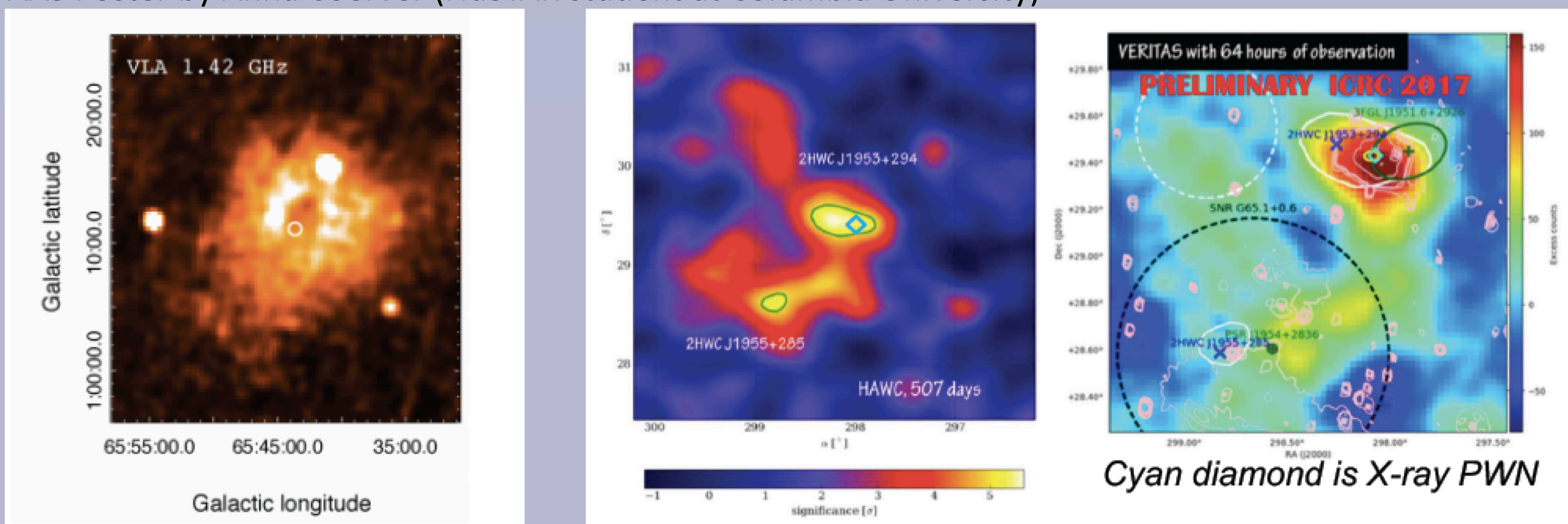
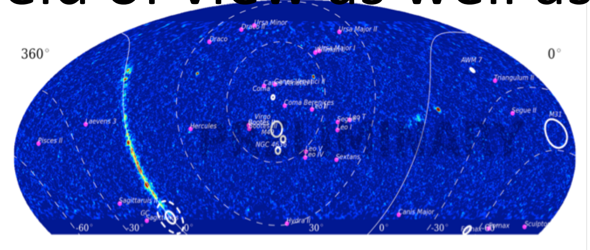


Fig 2. Radio emission (left, white circle is X-ray extent)[3] and Gamma-ray count maps[5] (right)

HAWC Searches for Sources Not (yet) Detected

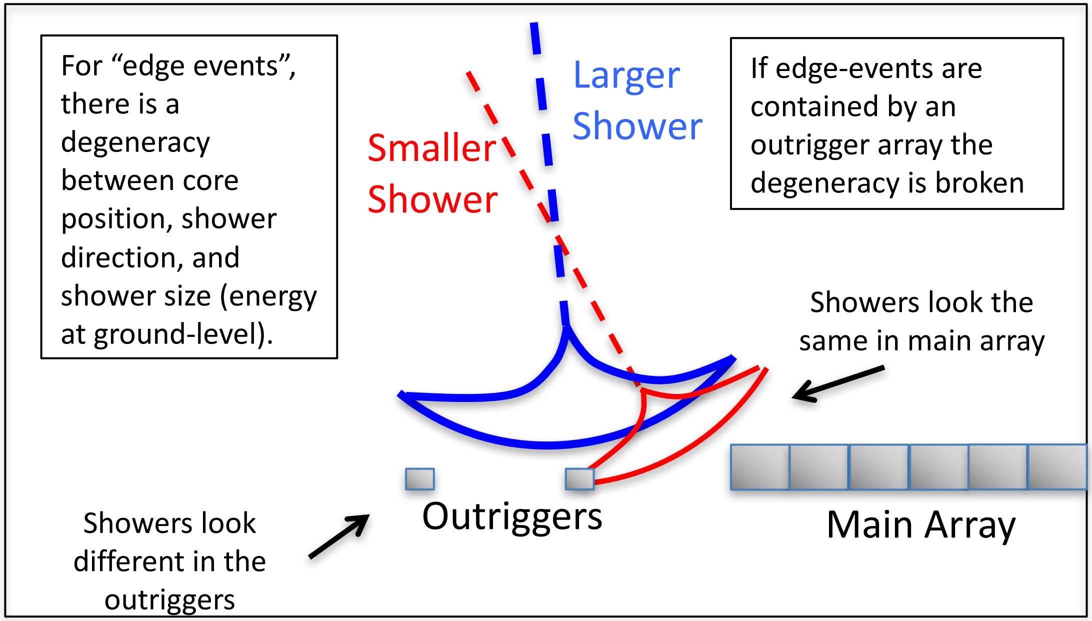
HAWC searches of 2 sr instantaneous field of view as well as 8 sr observed daily



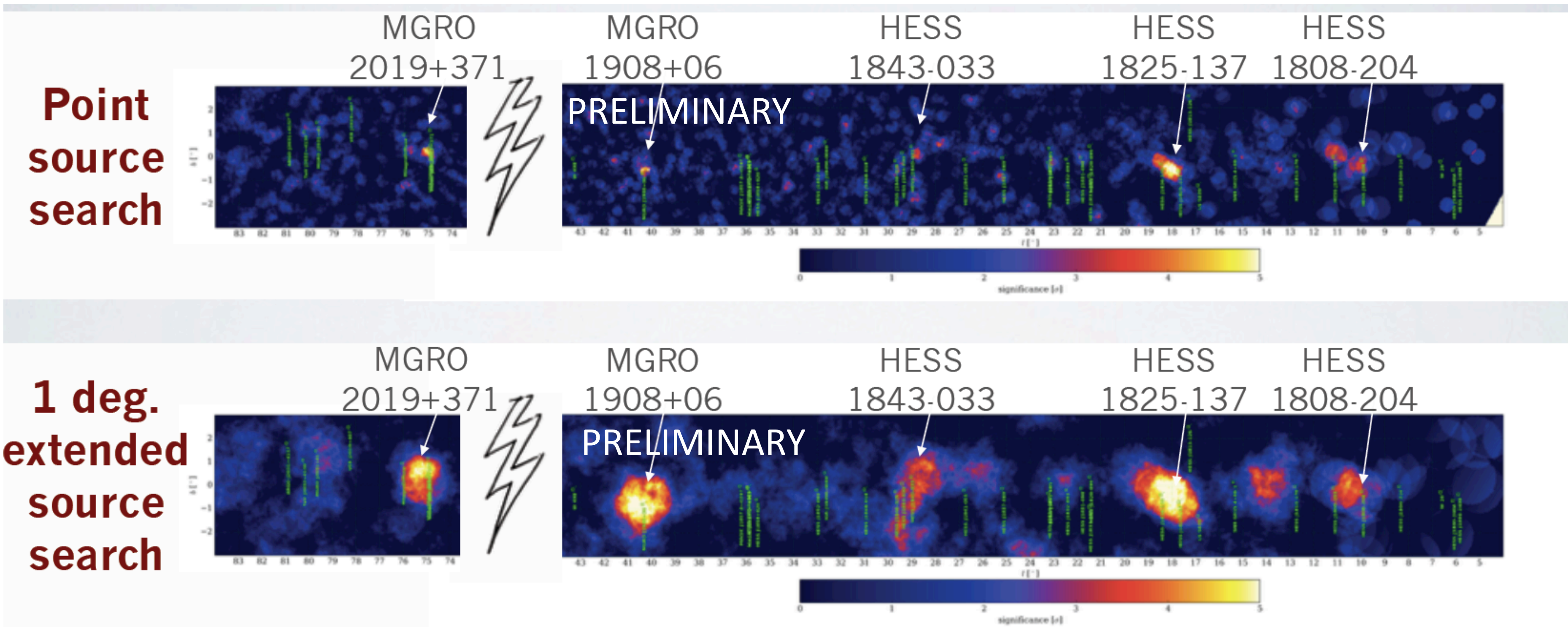
- VHE γ-rays from Dark Matter Annihilation or Decay
  - Best limits on decay lifetime and annihilation cross section for DM mass > 3-10 TeV for 15 dwarf spheroidal galaxies
- VHE γ-rays from the northern Fermi Bubble
- VHE γ-rays from same sources as IceCube PeV ν
- VHE γ-rays from gravitational wave sources
- VHE γ-rays from satellite-detected GRBs
- VHE γ-ray transients self-triggered by HAWC with time scales of 0.2 sec to 1 day

Outriggers for HAWC

- Increase sensitivity at highest energies
- Funded by LANL, MPI, and CONACyT
- 350 smaller tanks in sparse array covering 3x area of HAWC
- All tanks are deployed,
  60% are cabled, and
  20% are taking data
- 100% taking data in next few months



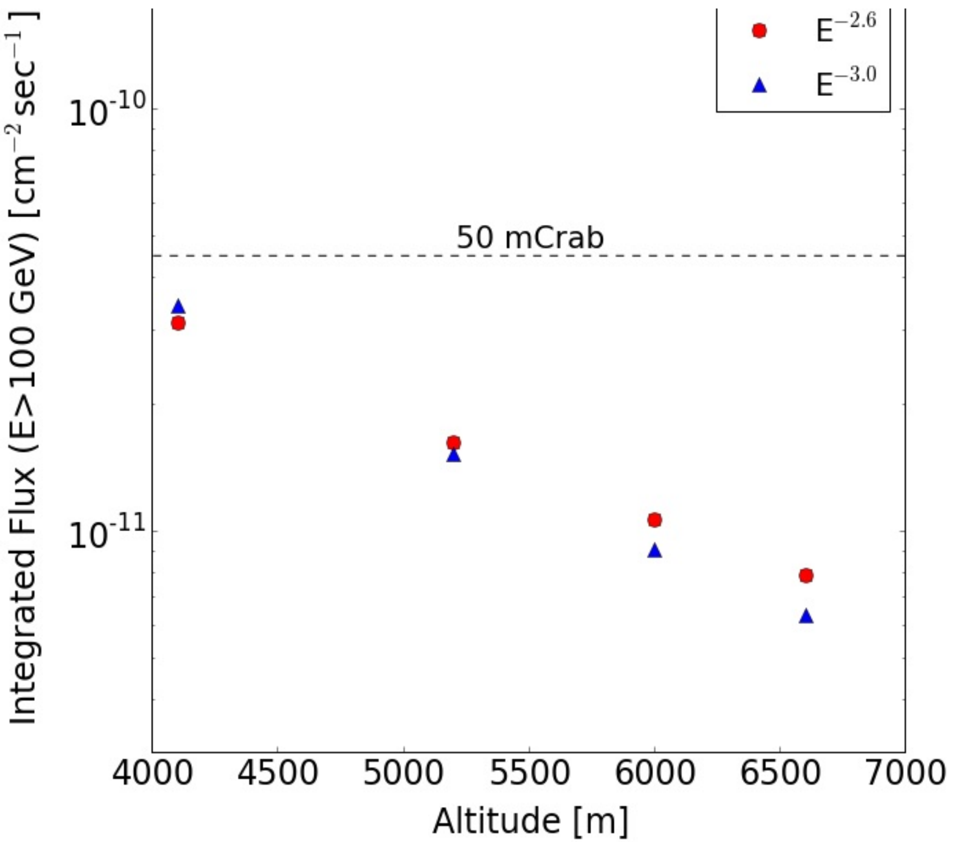
HAWC already detect sources > 50 TeV, so outriggers will detect even more



Beyond HAWC: Even Lower Energy

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

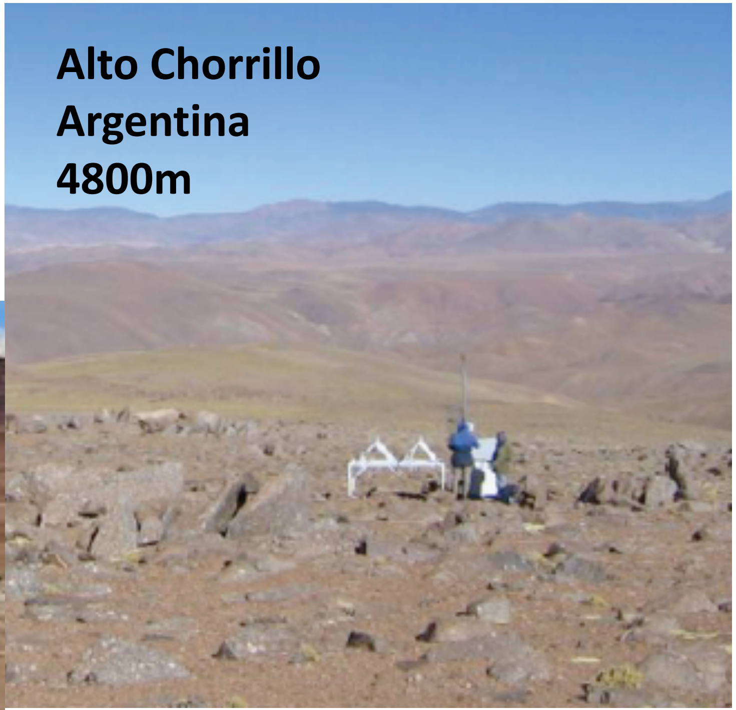
– Factor of 4 increase in sensitivity between ALMA (5000 m a.s.l.) and HAWC (4100m a.s.l.) altitude



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

Beyond HAWC: Southern Site

- 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

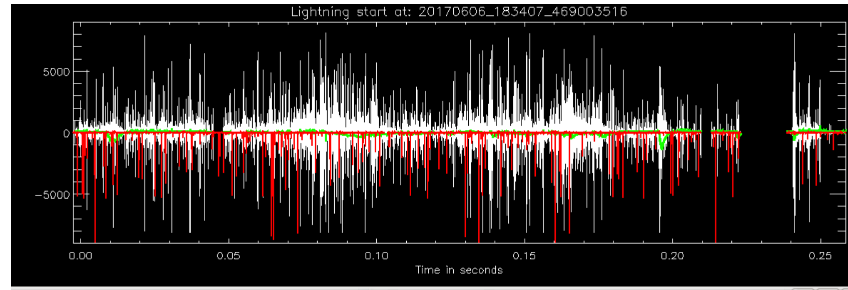


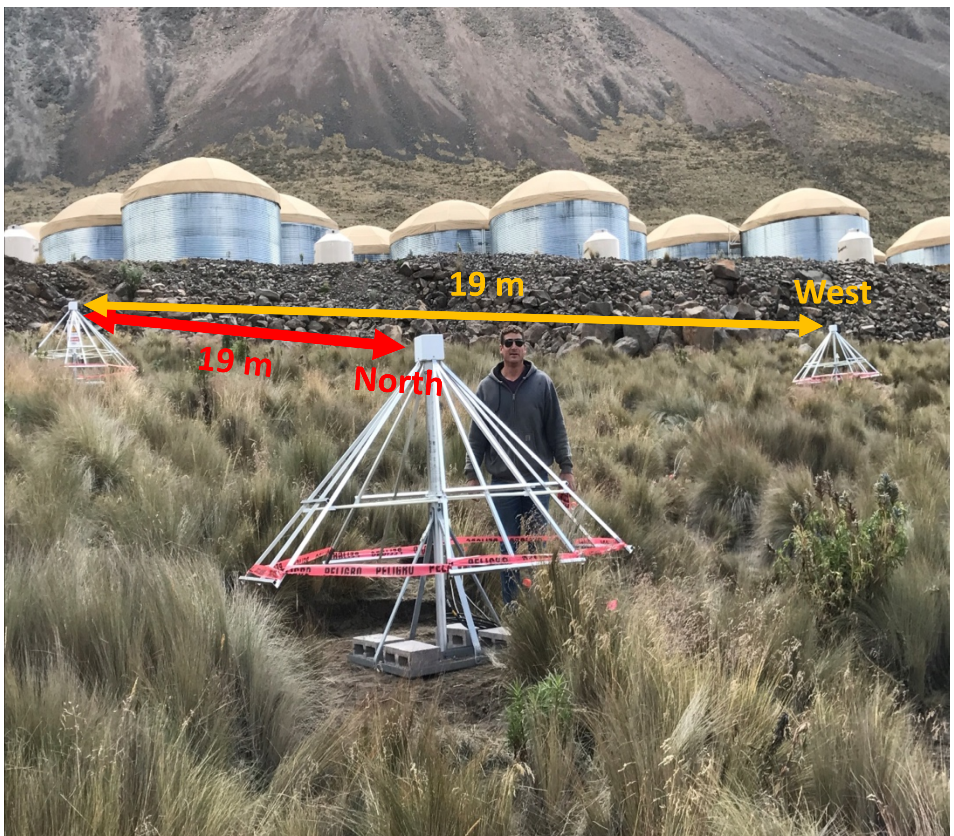
Outlook

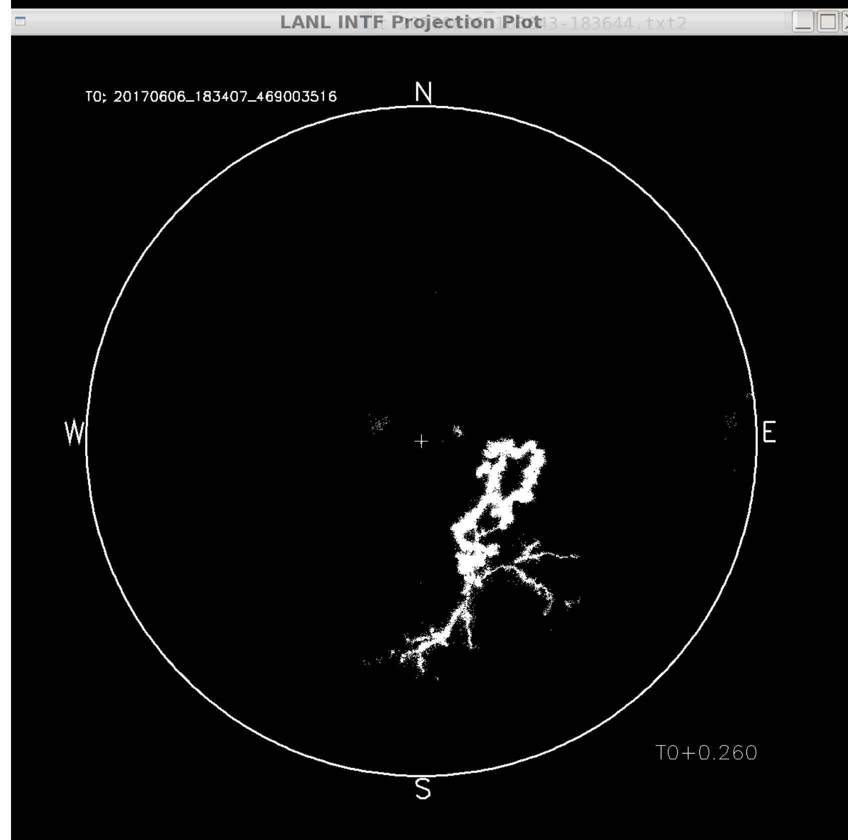
- HAWC is detecting new and interesting sources
- Algorithm improvements underway
  - Improve sensitivity at lowest and highest energies
  - New energy parameters using lateral distribution
- Outriggers completed in next few months
- More data coming
  - NSF proposal for operations until 2023 under review
- Southern Gamma-ray Survey Observatory (SGSO) being planned

RF (Lightning) Detectors at HAWC

- Terrestrial Gamma Ray Flashes from cloud to ground lightning?
- Lightning & Air Shower Correlation?



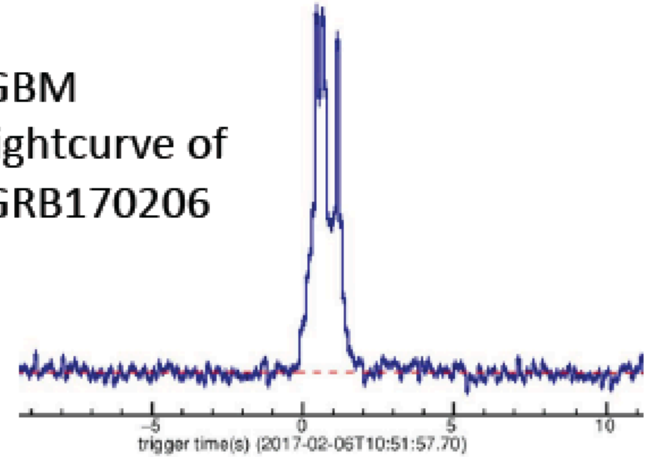


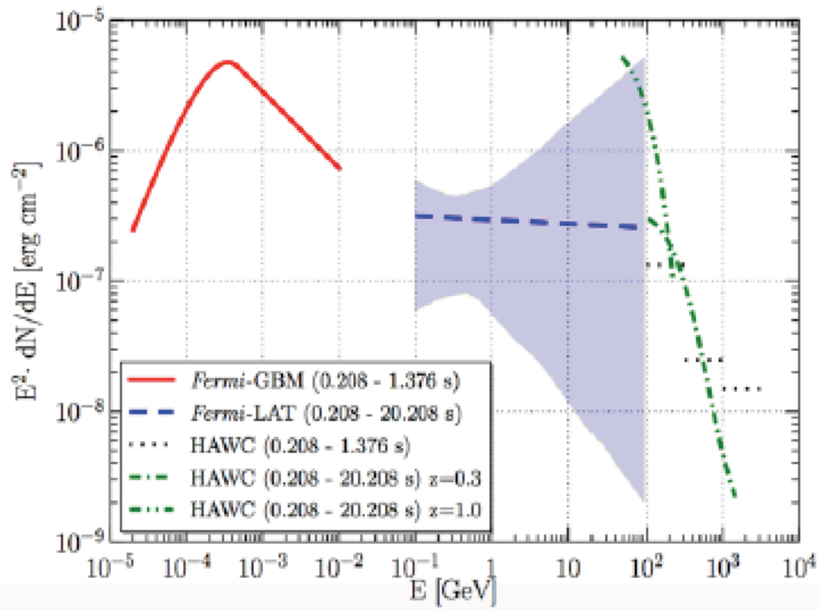


Search for TeV Counterparts to Gamma Ray Bursts

- HAWC effective area ~100m² at 100GeV
- Fermi with ~1m² 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

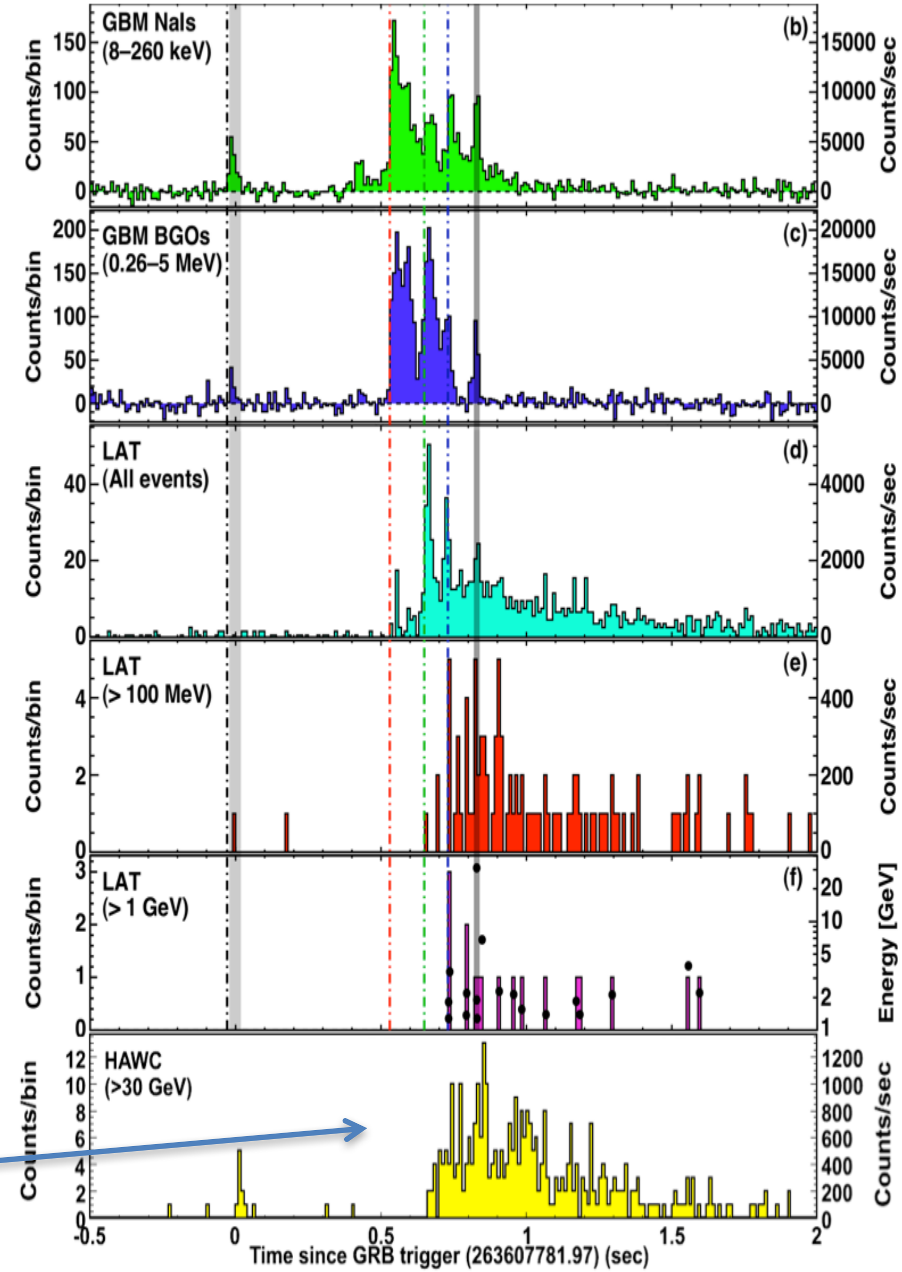
GBM lightcurve of GRB170206





Fermi has observed Gamma Ray Bursts that HAWC could detect

- HAWC effective area ~100m^2 at 100GeV and grows rapidly with energy
- Fermi has ~1m^2 area at 100GeV.

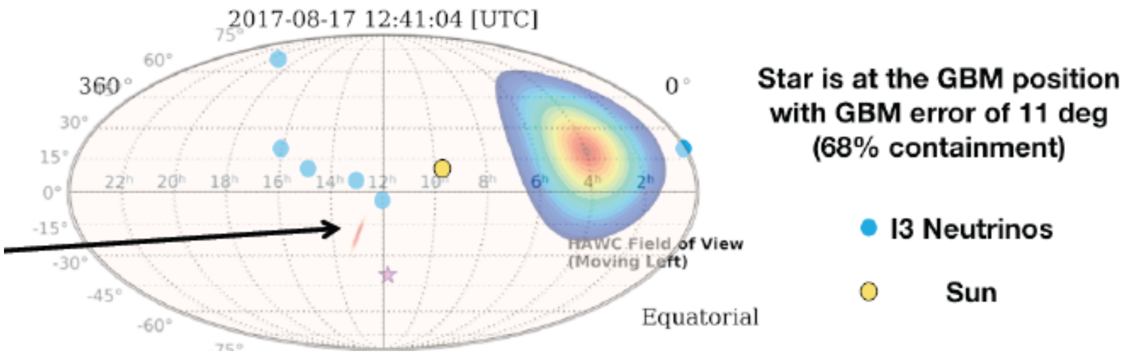


HAWC Simulated lightcurve for Fermi GRB 090510

Search for HAWC Counterparts to Gravitational Wave Detections

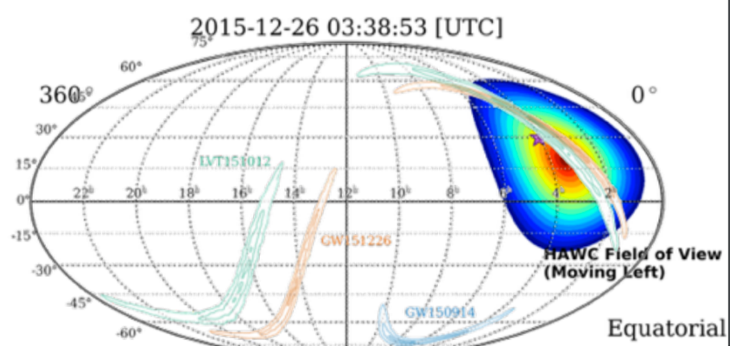
GW170817

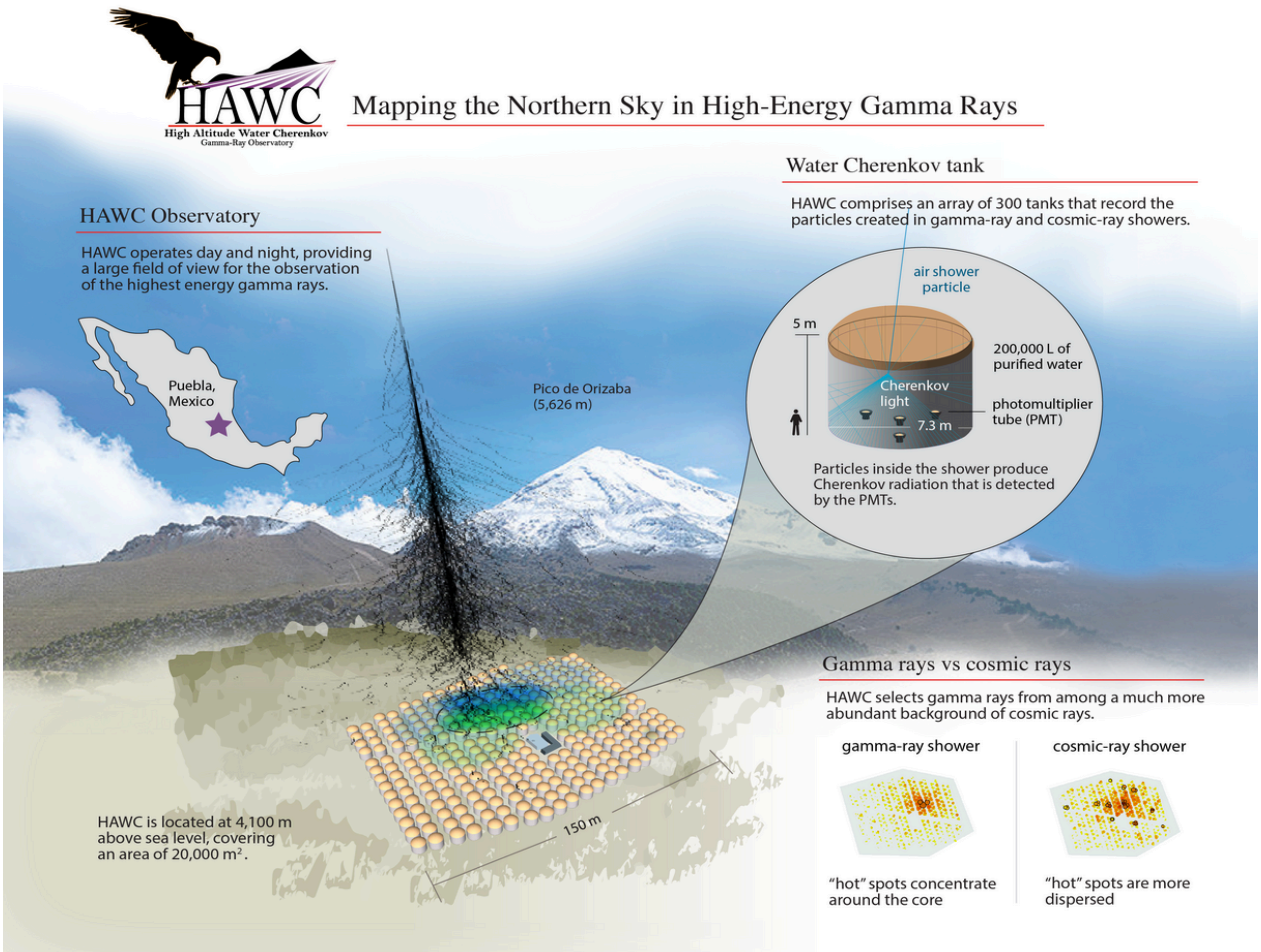
- Neutron Star Merger with electromagnetic counterpart
- Not in HAWC's field of view at the time, but TeV upper limit was placed 9 hours later (ApJ Lett 848, L12, 20 Oct 2017)



GW151226

- 2015 Dec 26 03:38:53.6 UTC
- >5 sigma
- 14.2M⊙ + 7.5M⊙ ➡ 21.8M⊙
- z=0.09 +0.03 -0.04




HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory
Mapping the Northern Sky in High-Energy Gamma Rays
HAWC Observatory
HAWC operates day and night, providing a large field of view for the observation of the highest energy gamma rays.
Puebla, Mexico
Pico de Orizaba (5,626 m)
HAWC is located at 4,100 m above sea level, covering an area of 20,000 m².
150 m
Water Cherenkov tank
HAWC comprises an array of 300 tanks that record the particles created in gamma-ray and cosmic-ray showers.
air shower particle
5 m
200,000 L of purified water
Cherenkov light
photomultiplier tube (PMT)
7.3 m
Particles inside the shower produce Cherenkov radiation that is detected by the PMTs.
Gamma rays vs cosmic rays
HAWC selects gamma rays from among a much more abundant background of cosmic rays.
gamma-ray shower
cosmic-ray shower
"hot" spots concentrate around the core
"hot" spots are more dispersed