Surveying the TeV Sky with HAWC

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UNAM, Mexico

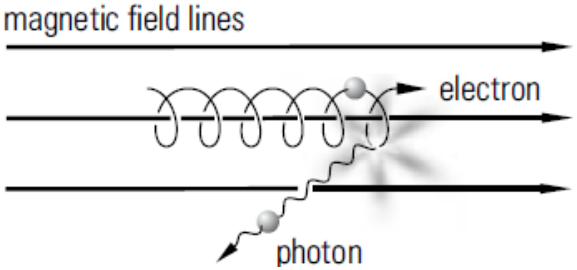
7th International Conference on High Energy Physics – Valparaiso 12/01/2018

TeV gamma rays

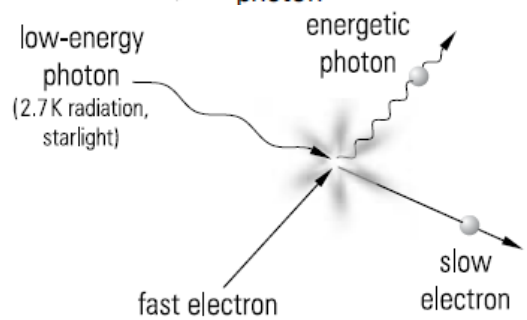
- They are of non thermal origin
- photons can not be accelerated
- therefore they have to be created by higher energy charged particle interactions or by decay or annihilation of higher mass dark matter particles

How are TeV gamma-rays produced?

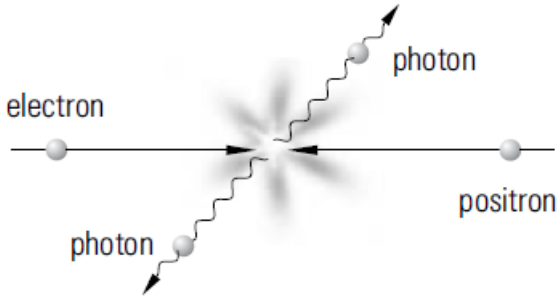
- Synchrotron radiation

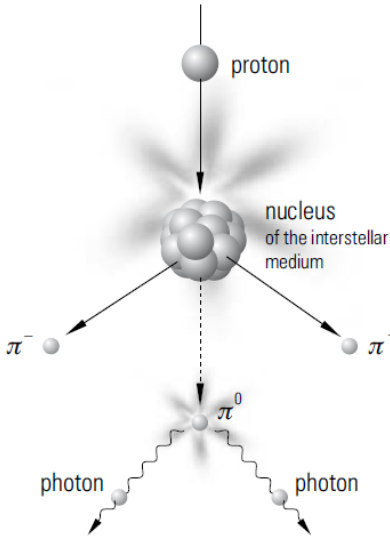


- Inverse Compton production



- Hadronic pions from cosmic ray interactions





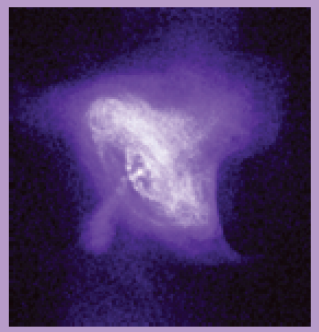
- Dark matter annihilation or decay

$$\chi + \chi \to \gamma, W^{\pm}, q\bar{q}, \tau^{\pm} \qquad \chi \to q\bar{q}, \tau^{\pm}$$

Gamma Ray Astrophysics

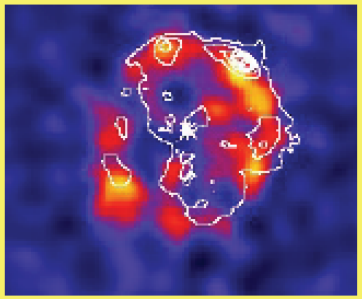
Galactic

Pulsars Wind Nebula

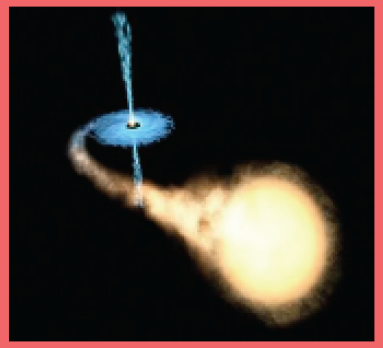


Pulsars

Supernova Remnant

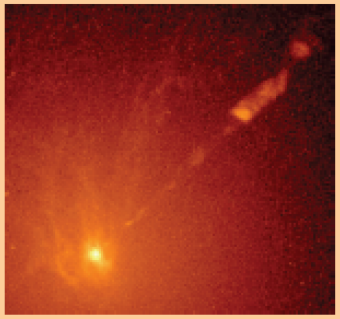


X-ray Binaries



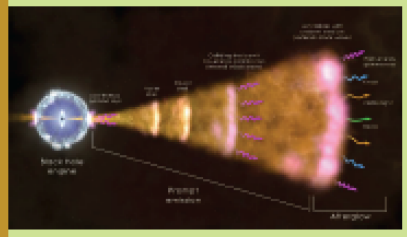
Extragalactic

Active Galactic Nuclei

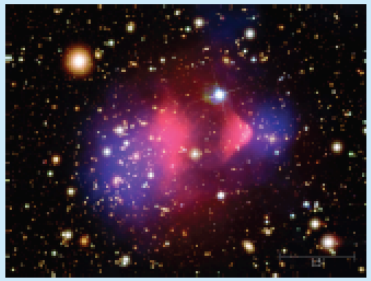


Starburst Galaxies

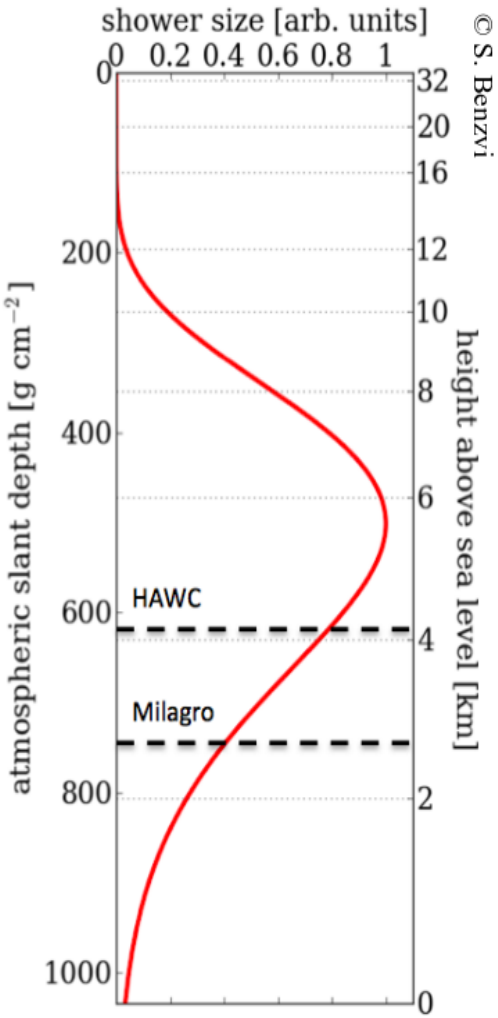
Gamma-Ray Burst



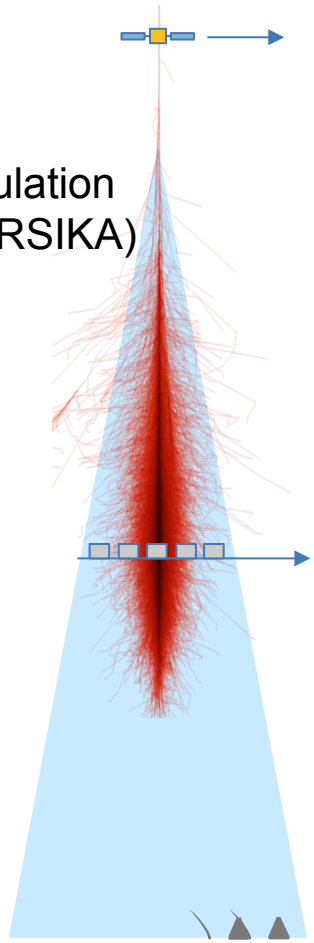
Indirect Dark Matter



High Energy Gamma-Ray Detectors



Simulation (CORSIKA)



Wide Field of View, Continuous Operations

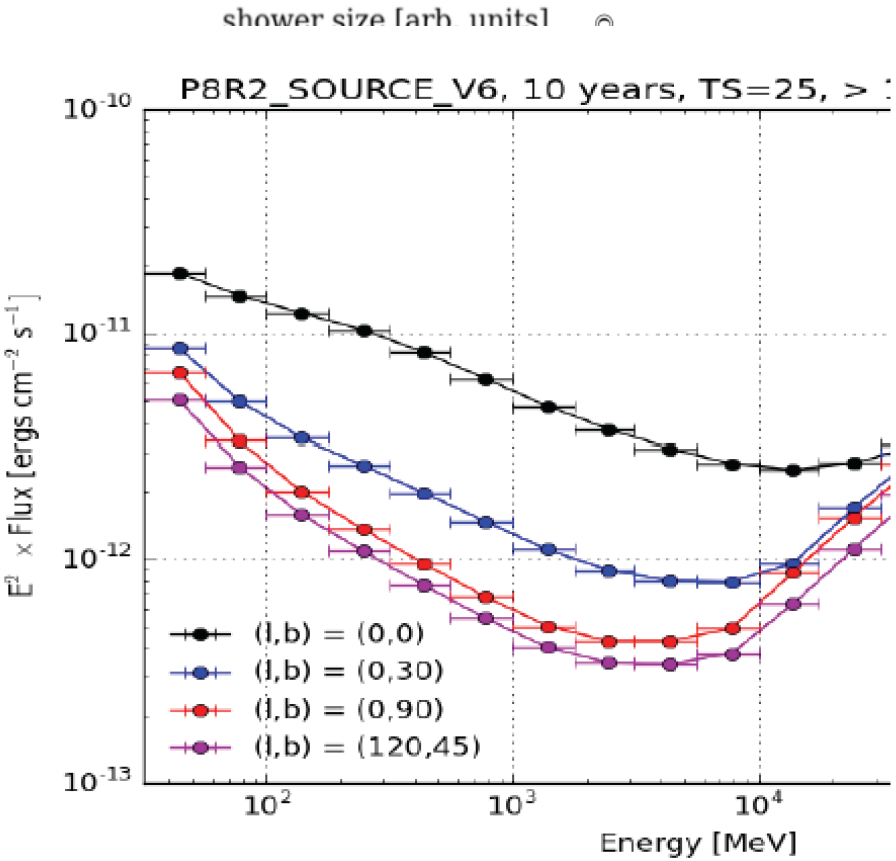
Satellite Detector

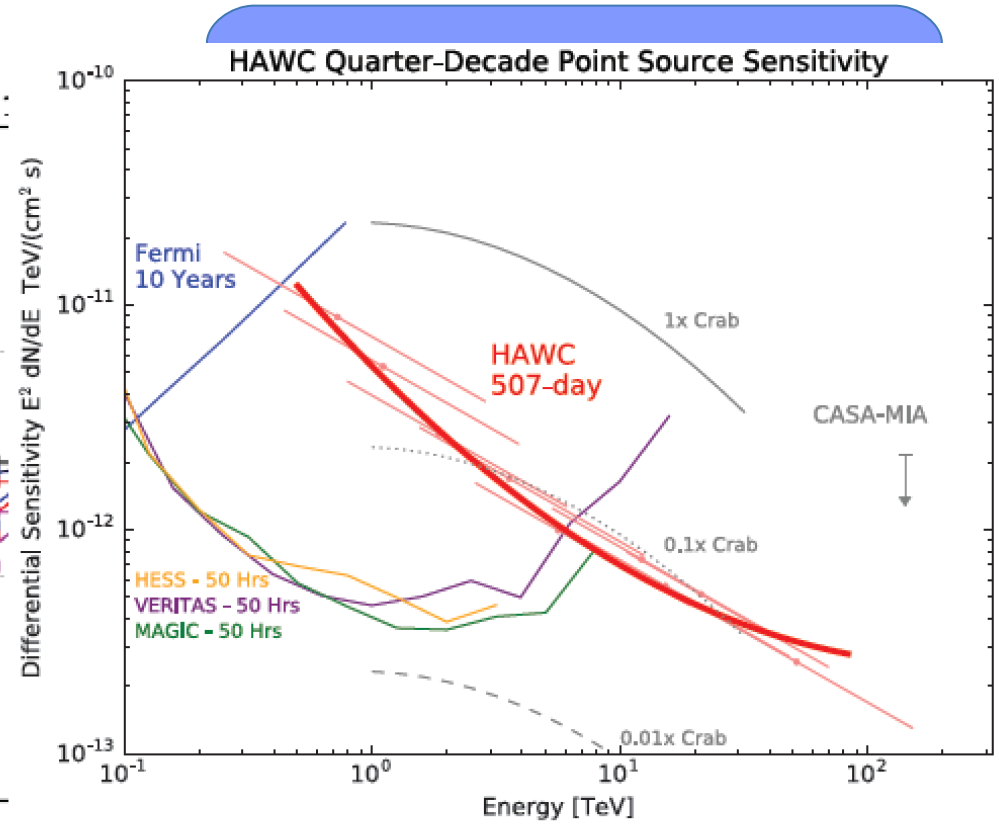
Extensive Air Shower (EAS) Detector

TeV Sensitivity

Imaging Atmospheric Cherenkov Telescope (IACT)

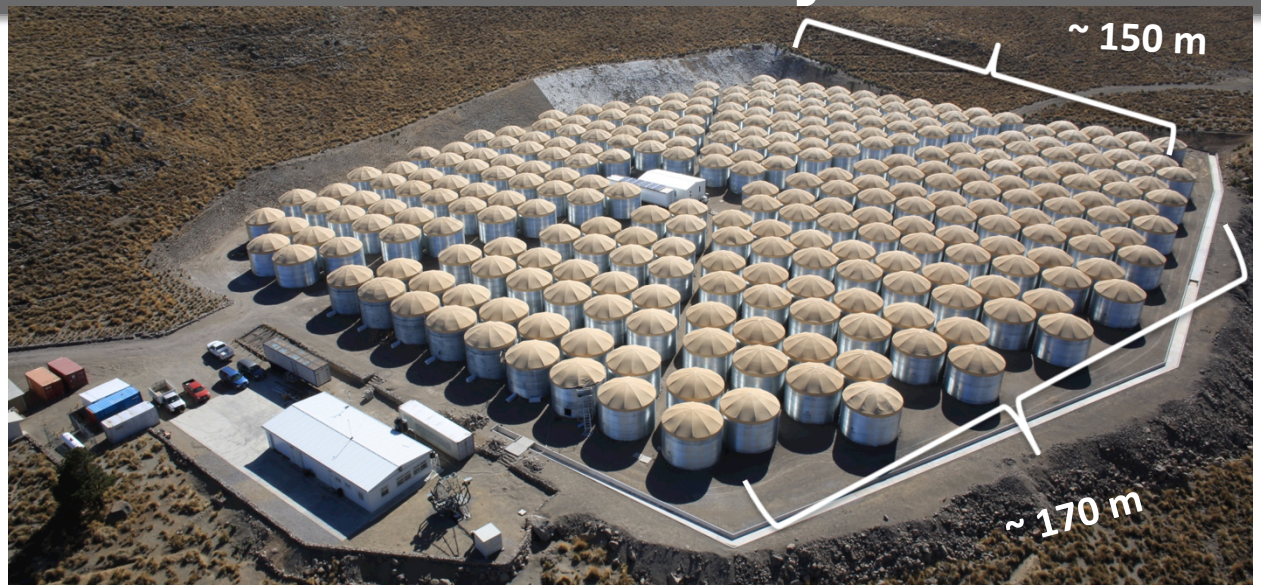
High Energy Gamma-Ray Detectors





Imaging Atmospheric Cherenkov Telescope (IACT)

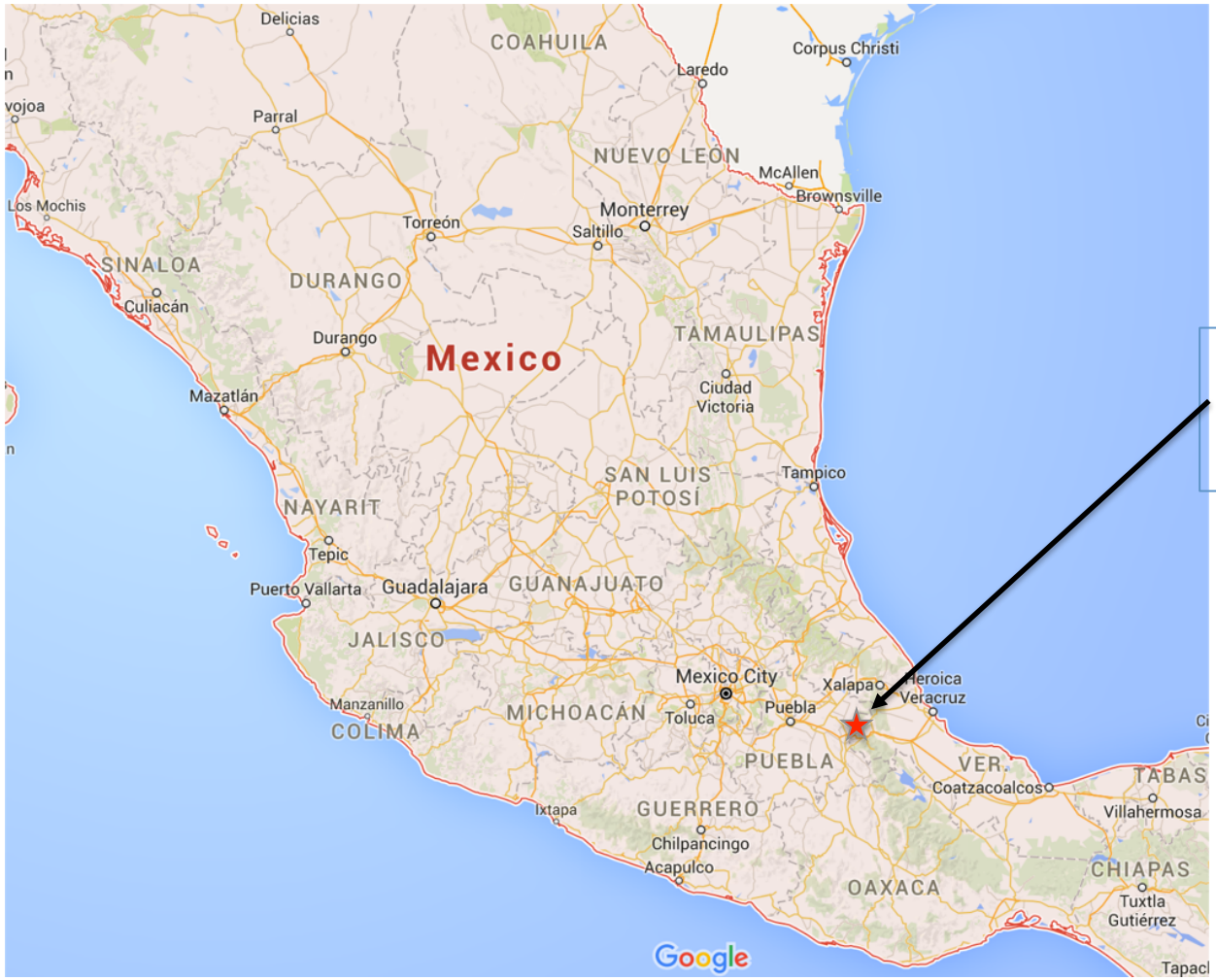
High Altitude Water Cherenkov Observatory HAWC



HAWC "2nd Generation" of water Cherenkov gamma-ray detector

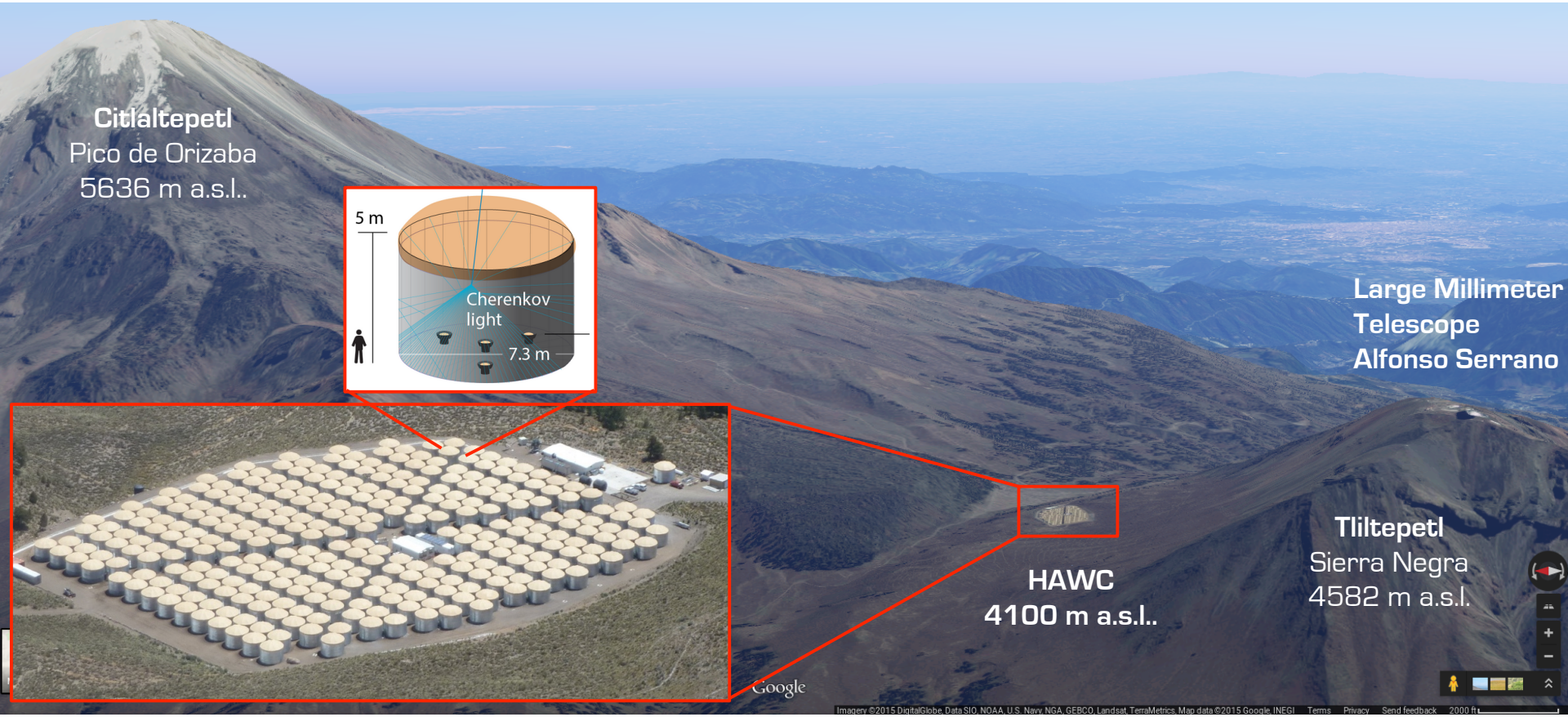
- Large aperture and continuously operating covers 2/3 of the sky every day
- Elevation of 4100 m a.s.l in central Mexico
- 300 tanks of 200,000 *liters* covering an area of ~22,000 m^2
- Construction 2011-2015
- Records 25 kHz of high energy air showers, mostly from cosmic rays

Location of the observatory



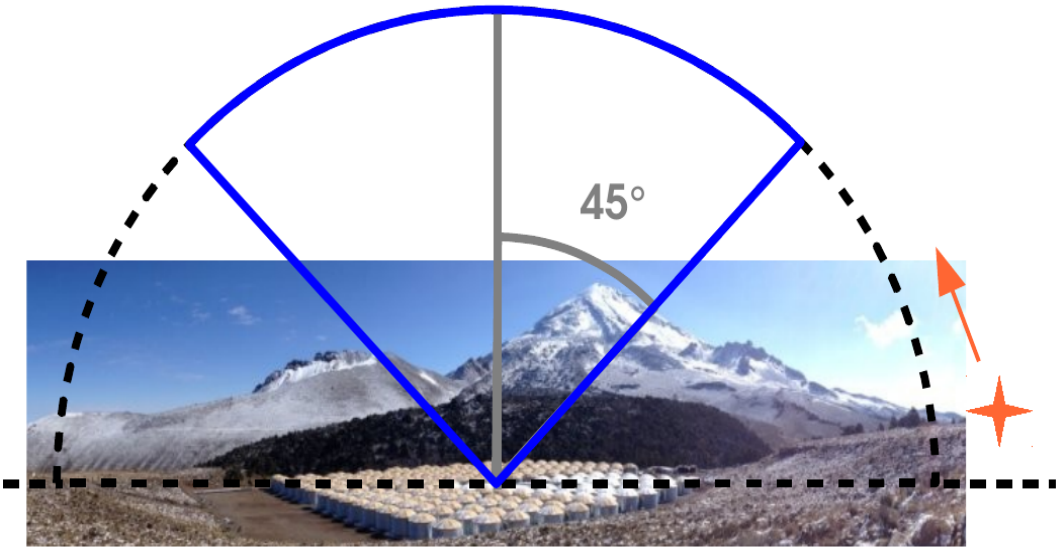
Latitude: 18°59.7' N
Longitude: 97°18.6' W

Location of the observatory



HAWC's field of view and duty cycle

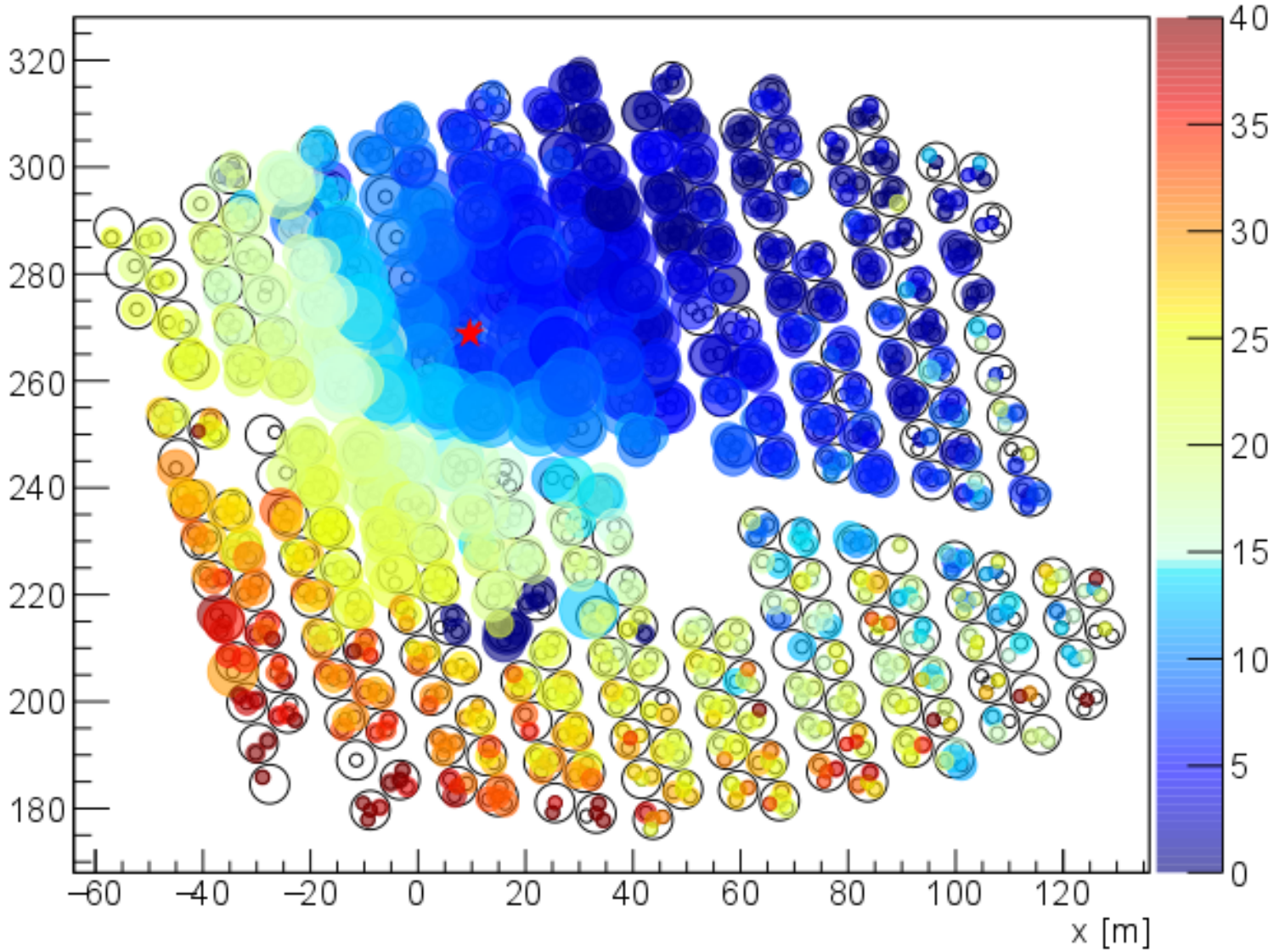
Field of view down up to ~45° from zenith
Due to Earth's rotation, HAWC is able to scan 2/3 of the sky each day



A source is visible for HAWC up to 6 hours each day

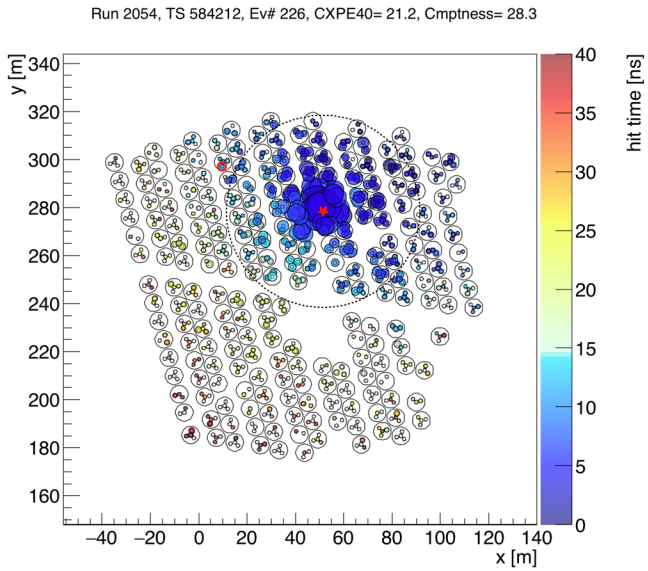
The shower plane is reconstructed from the arrival times of the signals in each tank; the perpendicular to it gives the direction of the originating particle: cosmic- or gamma-ray

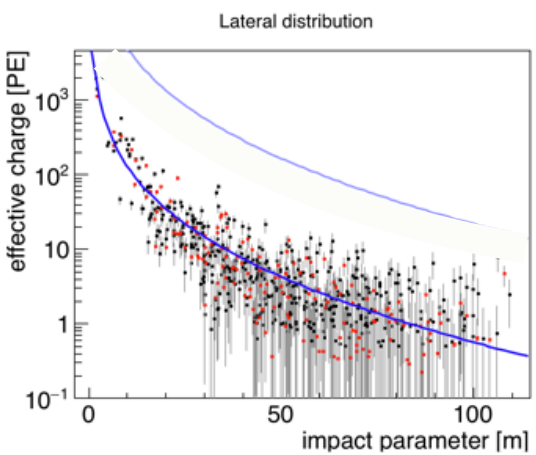
Air shower propagation through the HAWC PMTs



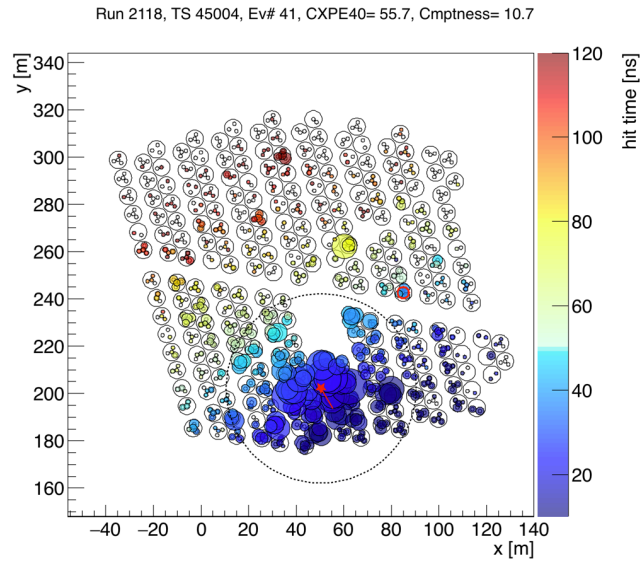
Gamma/hadron discrimination in HAWC

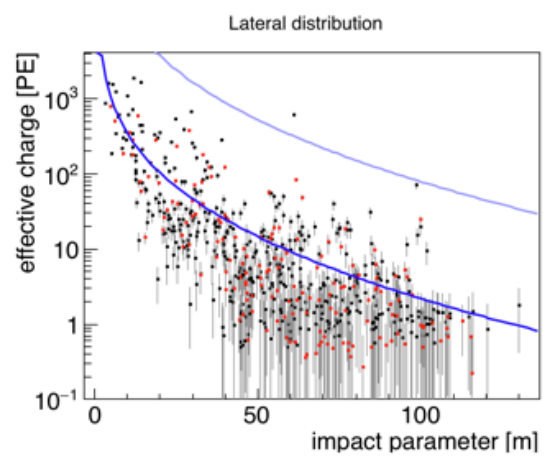
Air shower consistent with a gamma-ray produced at the Crab Nebula



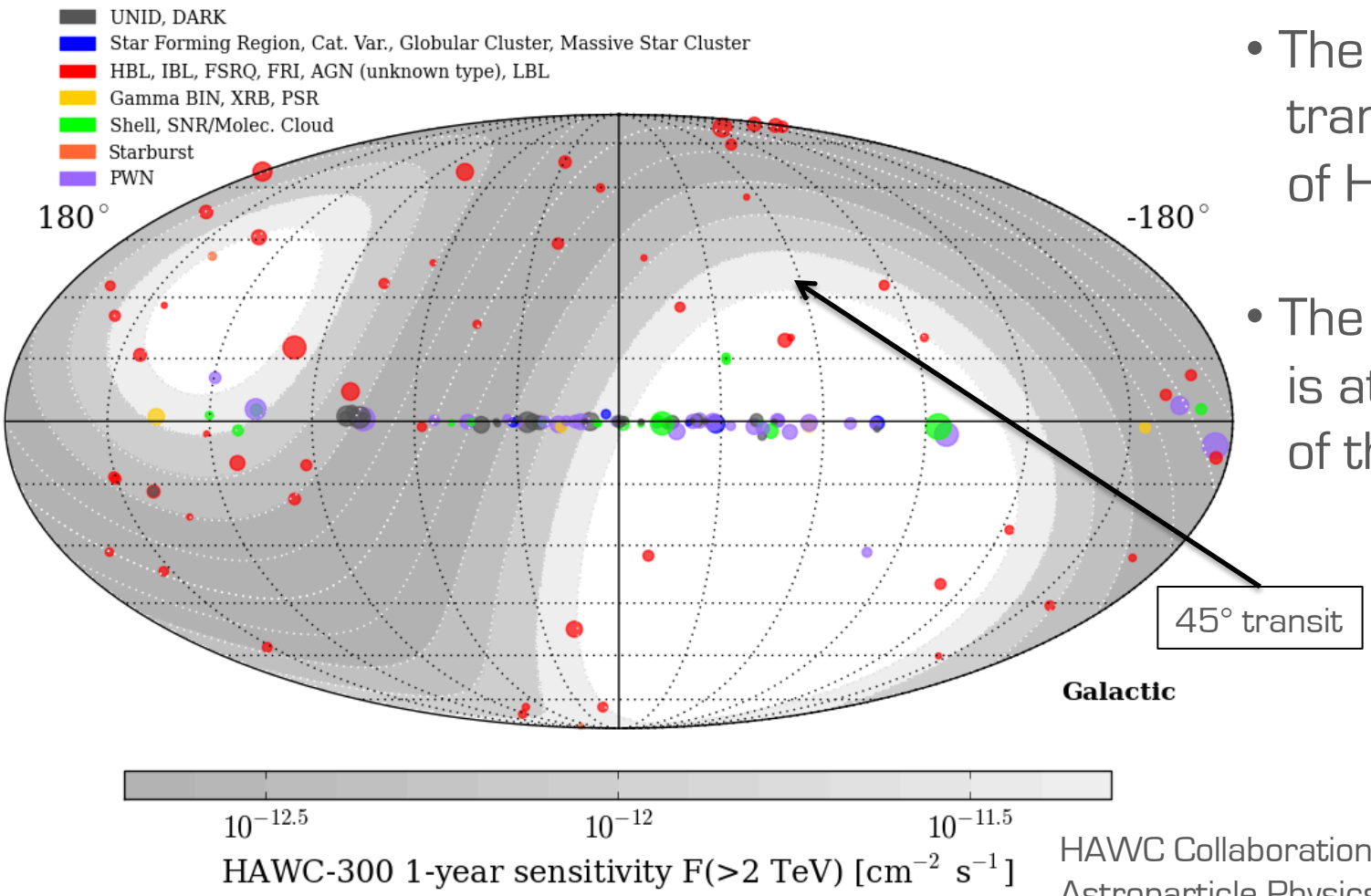


Hadronic shower





HAWC's sky coverage



- The Crab nebula transits overhead of HAWC
- The galactic center is at the boundary of the field of view

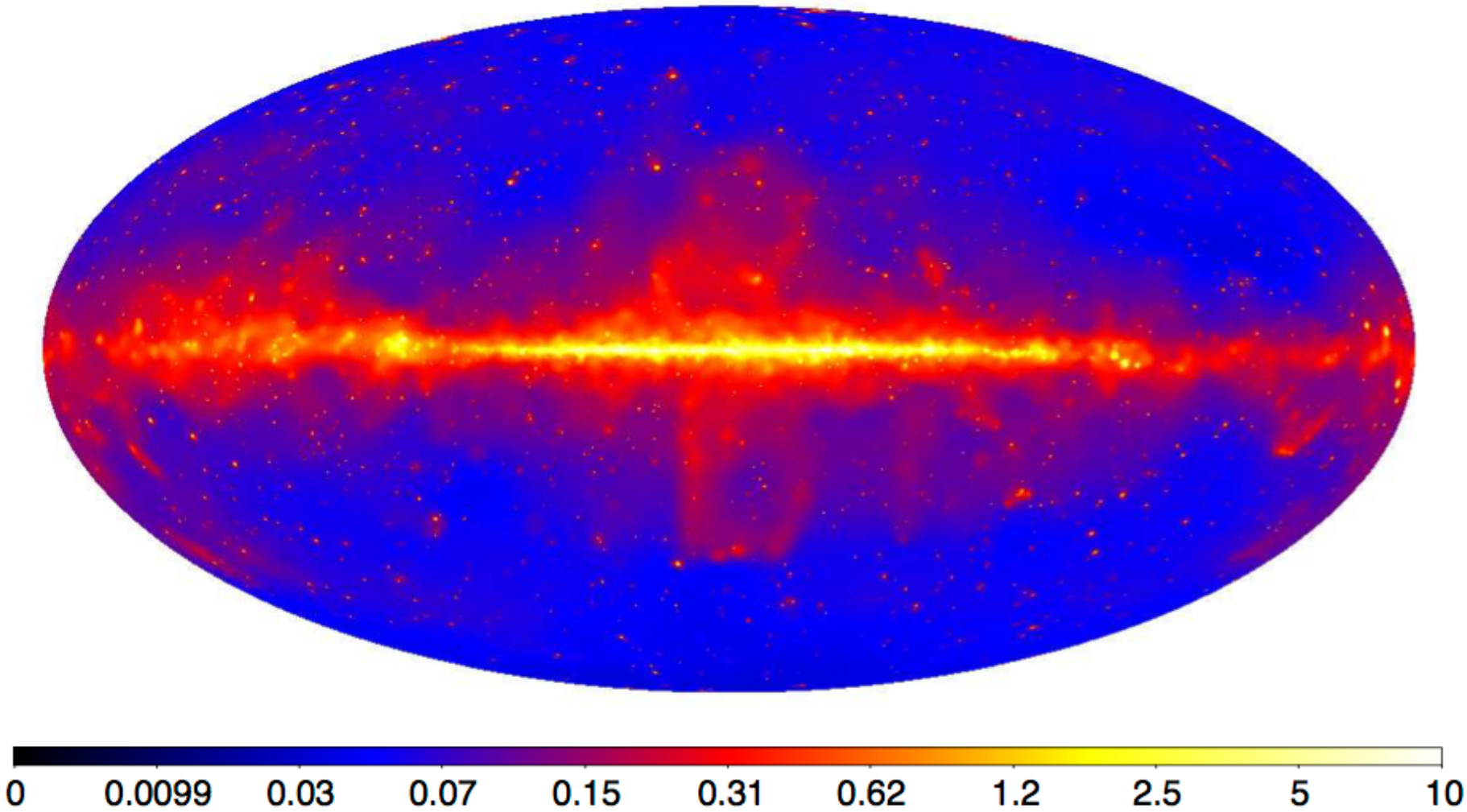
HAWC Collaboration
Astroparticle Physics 50-52 (2013)

There are 205 known gamma-ray sources (Oct 2017)

Scientific targets of HAWC

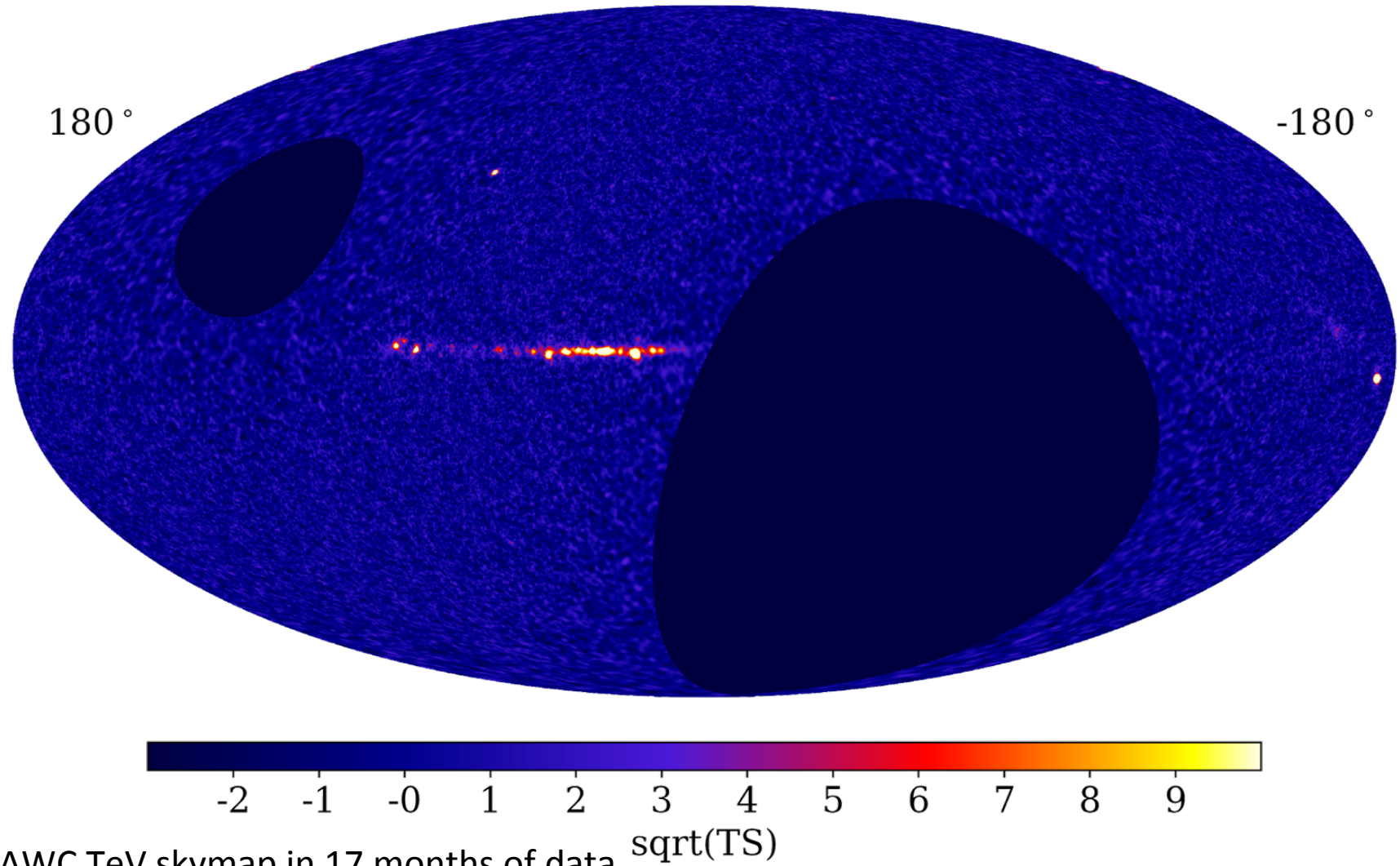
- Monitor 2/3 of the sky continuously, searching for very high energy gamma-ray emission
- Measure the spectrum and temporal variations of gamma-ray sources (for both known and recently discovered) up to the highest energies
- Look for very high energy gamma-ray emission from Gamma-Ray Bursts (GRBs)
- Study fundamental physics topics such as: dark matter, primordial black holes, Lorentz invariance, supersymmetric particles such as Q-Balls ...
- Study in detail the cosmic-ray anisotropy discovered by Milagro
- Solar physics

FERMI low energy γ ray sky



Fermi-LAT count map 10 GeV — 2 TeV with >1500 objects in 84 months of data.

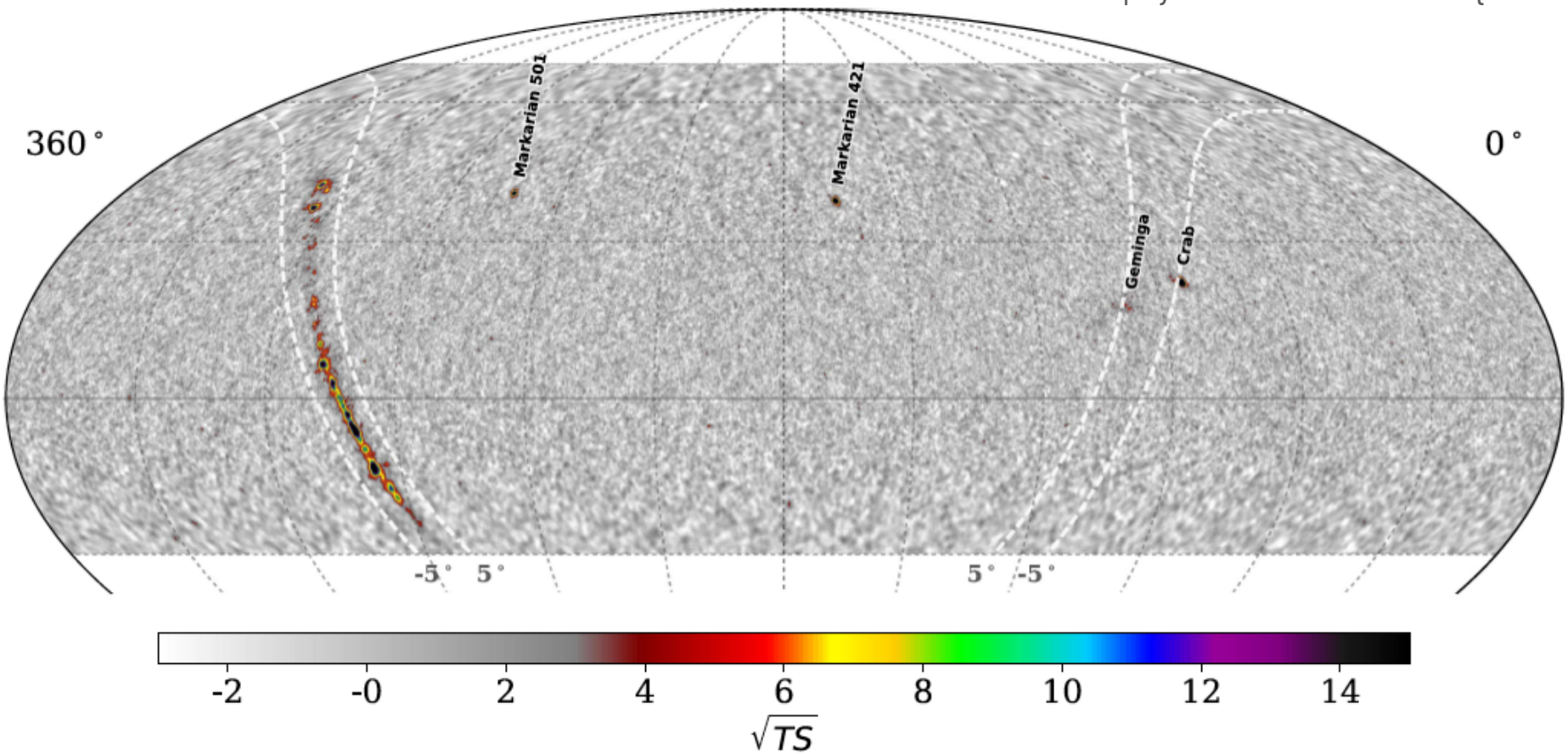
HAWC high energy γ ray sky



- HAWC TeV skymap in 17 months of data.
- 39 2HWC sources: 2 blazars, 5 UID off the Galactic plane, 19 are unassociated with any known TeV source.

Second Gamma-Ray Catalog

HAWC Collaboration
The Astrophysical Journal 843:40 (2017)



Skymap from 507 days of data: Most sensitive TeV survey up to now
Point source analysis assuming power-law index of 2.7

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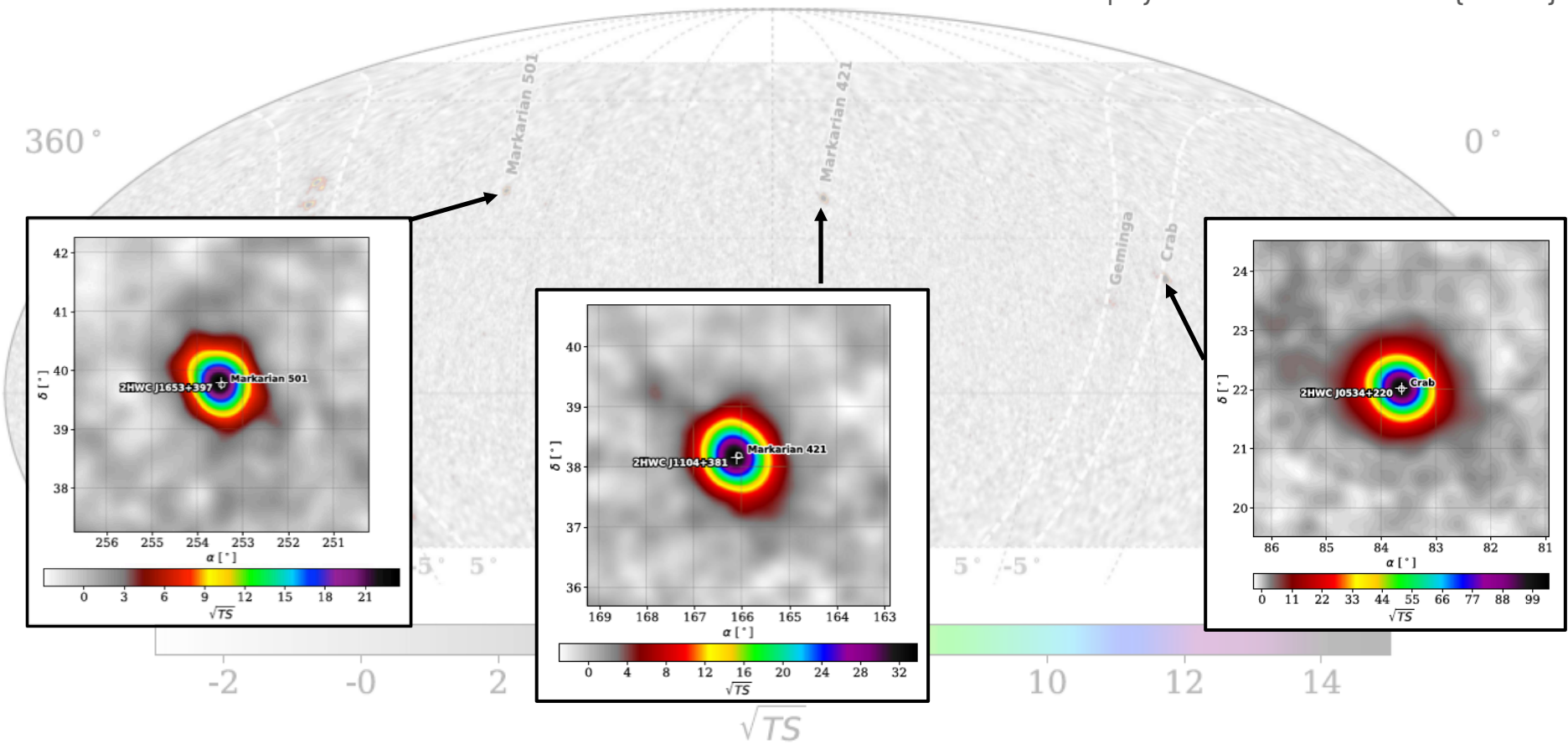
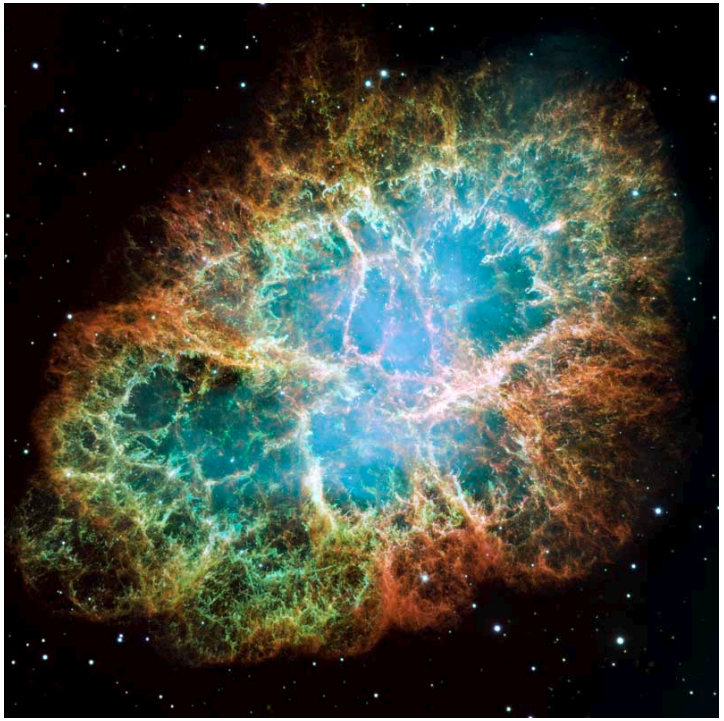


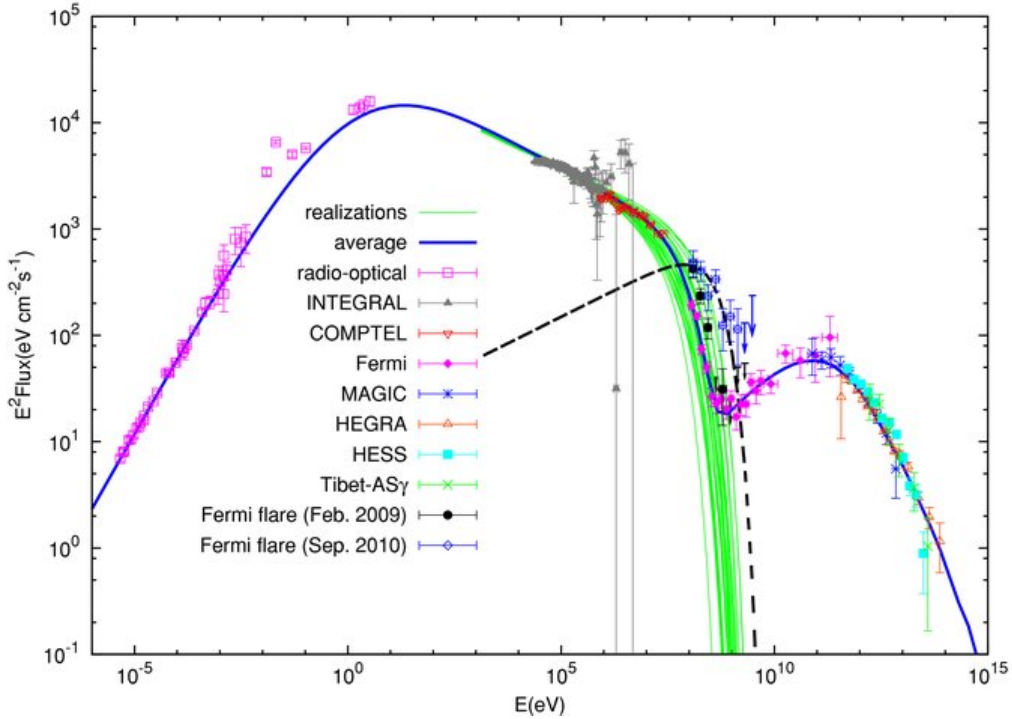
Skymap from 507 days of data: Most sensitive TeV survey up to now
Point source analysis assuming power-law index of 2.7

The Crab Nebula

- At approximately 6500 light years from the Earth
- Diameter of approximately 11 light years, expanding at 0.005 c



NASA



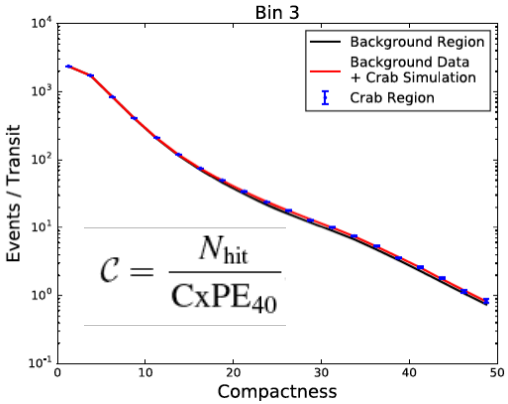
Qiang Yuan et al. ApJ 730 L15, 2011

The Crab Nebula seen by HAWC

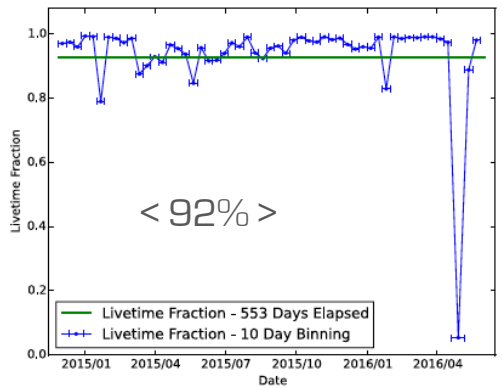
The standard candle of TeV gamma-rays sources: First high confidence TeV detection

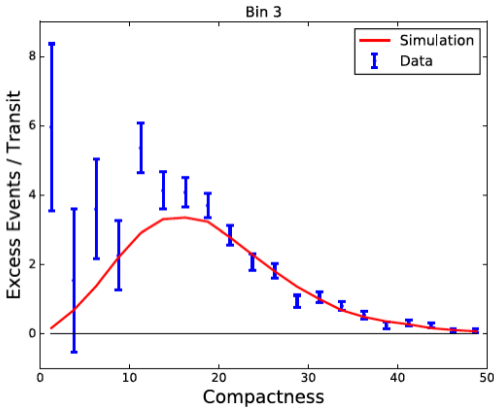
Brightest steady source in the northern sky above 1 TeV

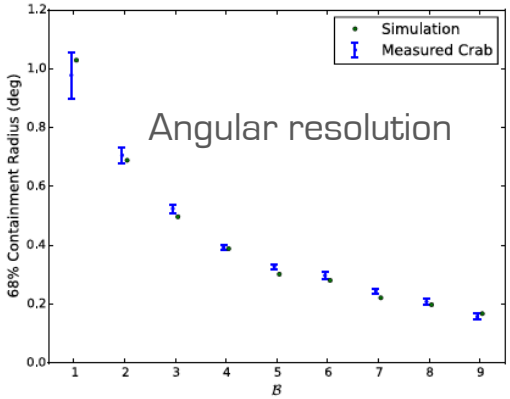
γ/hadron discrimination



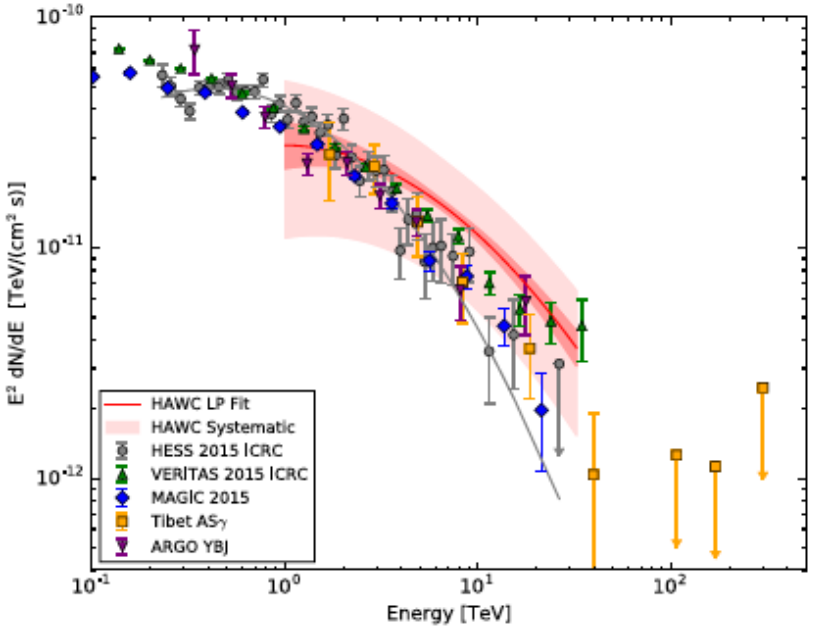
Detector livetime







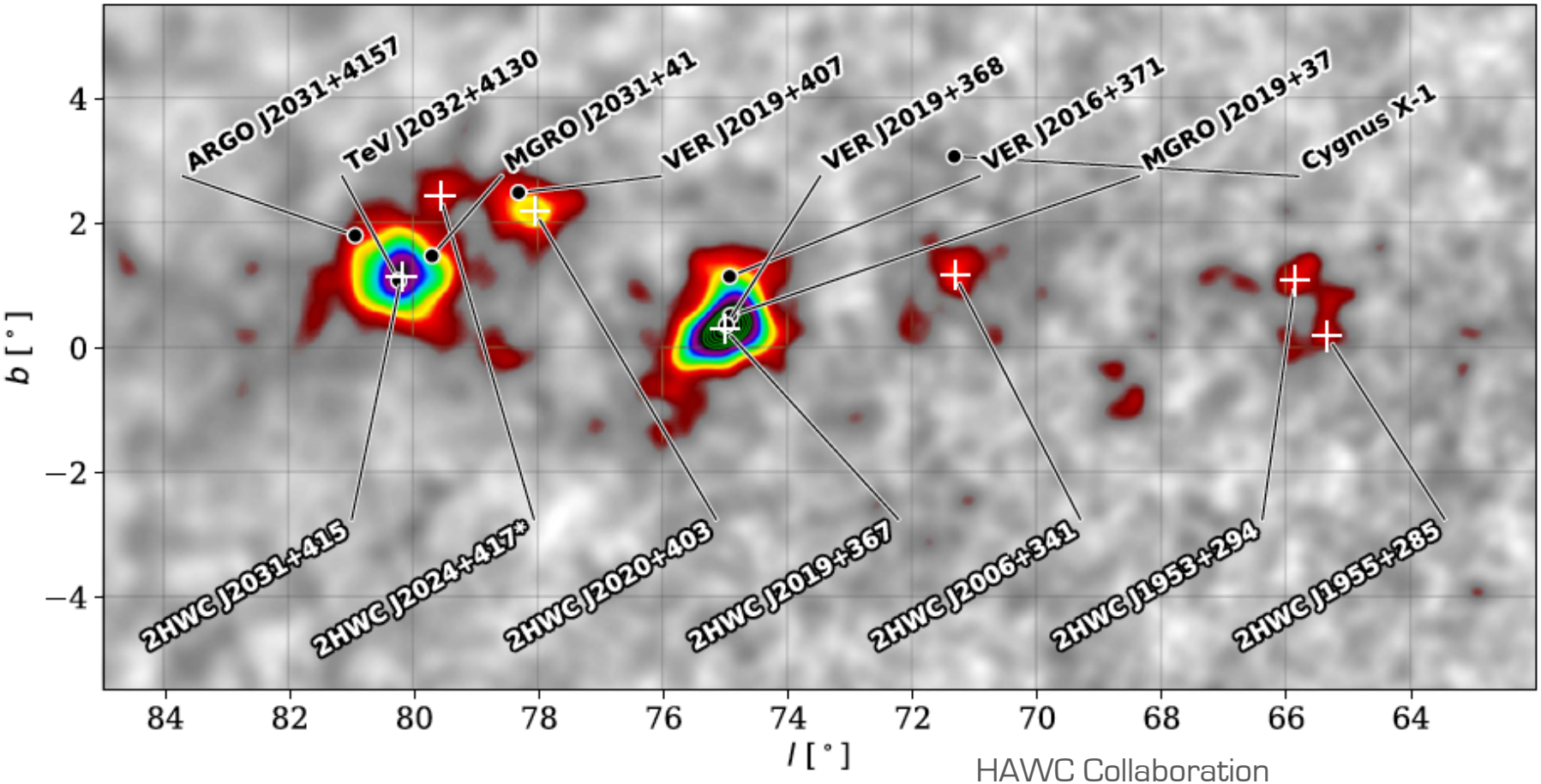
Energy spectrum



HAWC Collaboration
The Astrophysical Journal 843:39 (2017)

- Used to refine analysis and validate simulations

Galactic Plane (an example section of it)



HAWC Collaboration
The Astrophysical Journal 843:40 (2017)

39 sources detected, **19 are new** (not associated with know TeV sources)

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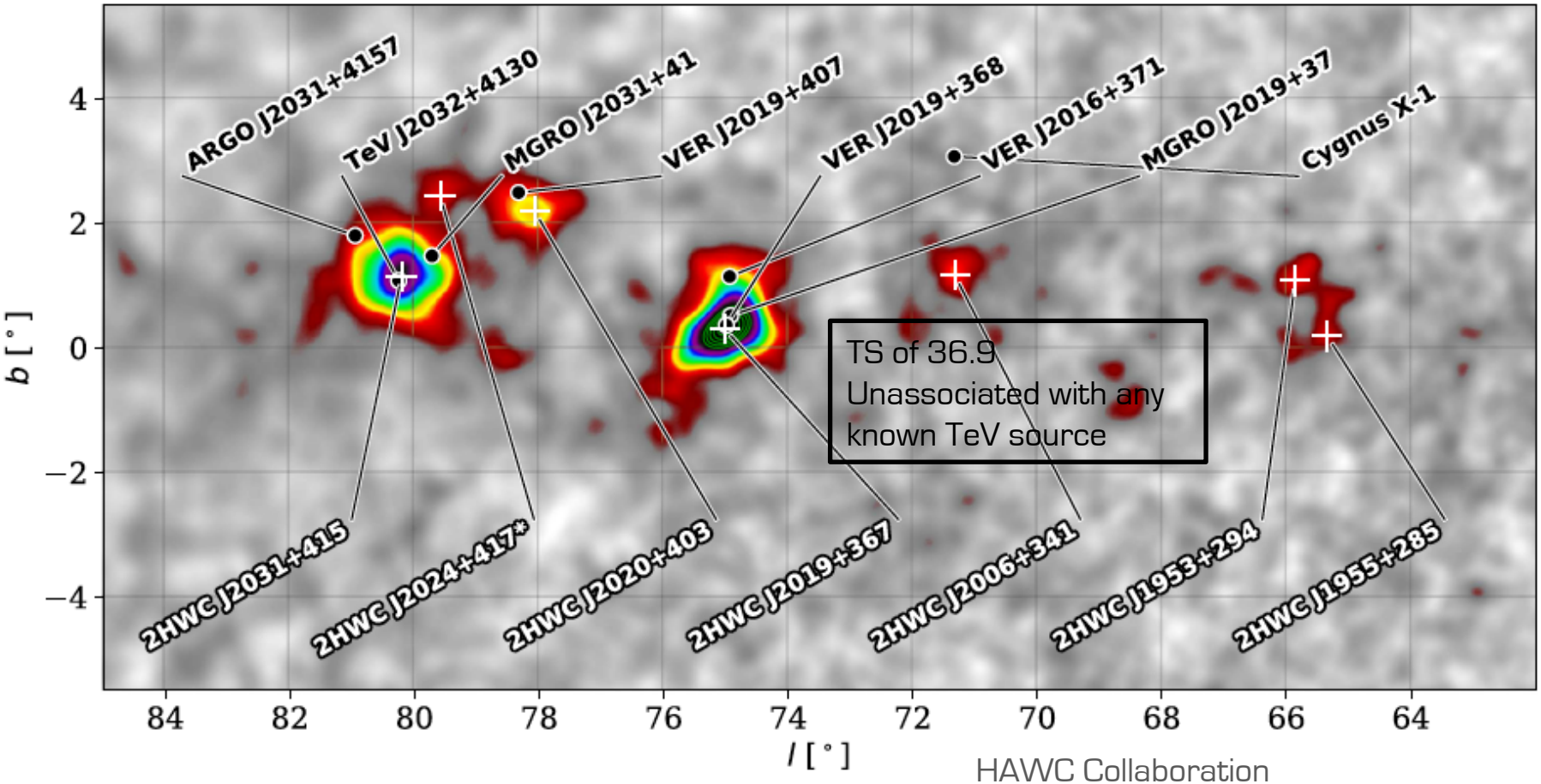

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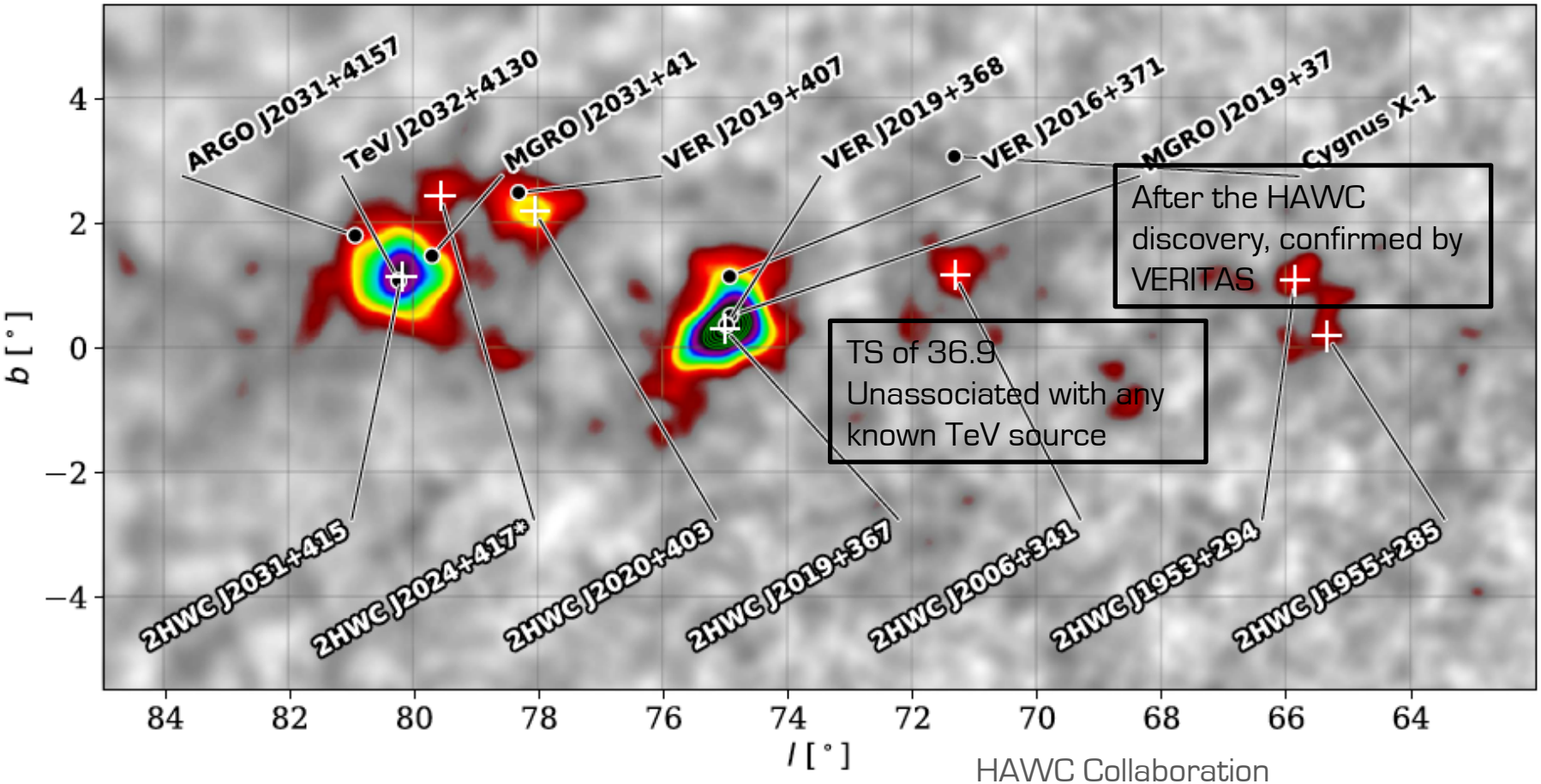

HAWC Collaboration
The Astrophysical Journal 843:40 (2017)

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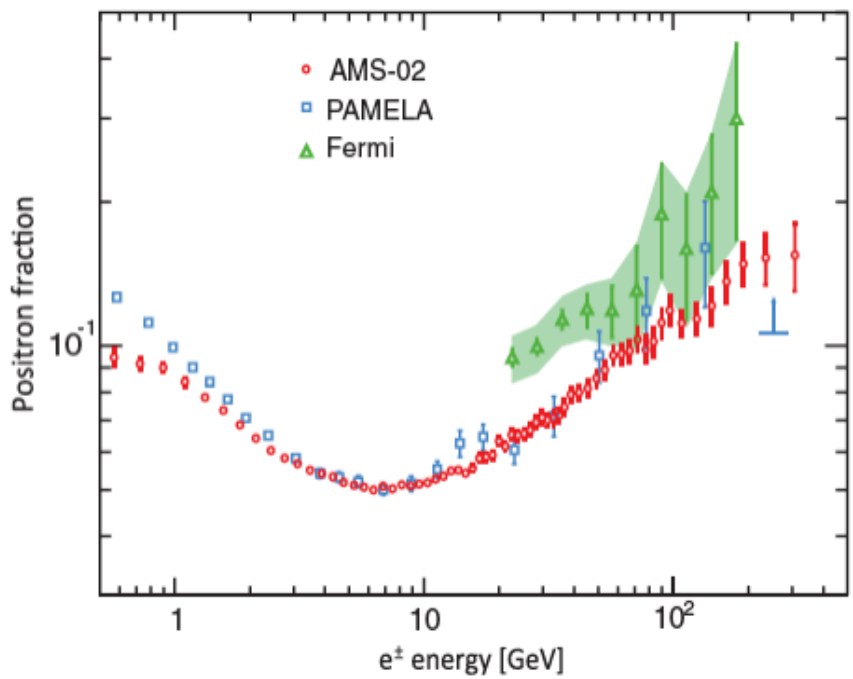
The positron excess and extended sources

- With HAWC's study of the galactic plane we found point and extended sources, some of them not previously reported



AMS Collaboration
PRL 110, 141102 (2013)

PAMELA and AMS have measured a positron excess at energies > 10 GeV

Could this excess be due to a nearby pulsar instead of a product of dark matter annihilation?

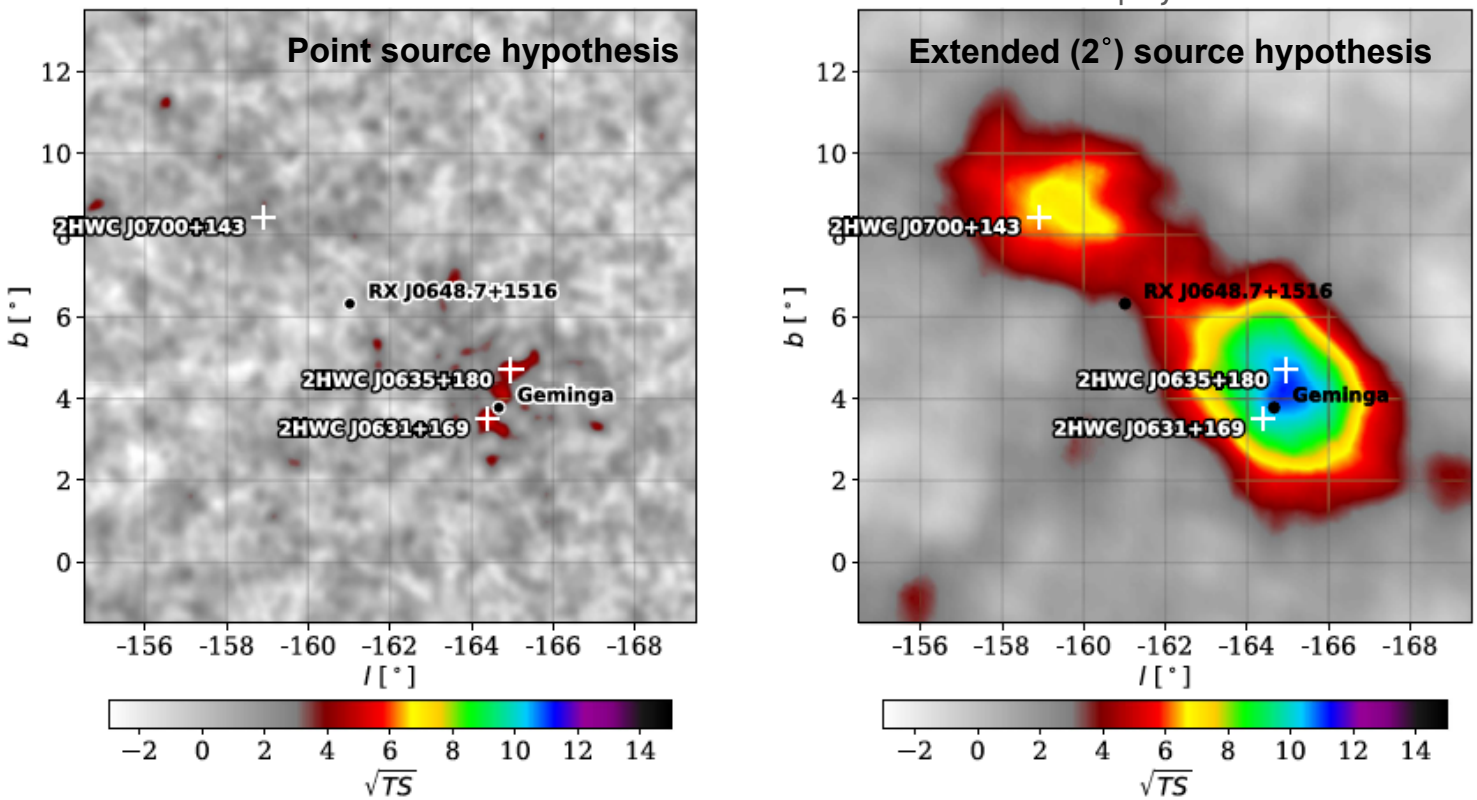
Requirements for the pulsar hypothesis:

- Old enough so we can be receiving its wind of e^+e^-
- Young enough so it is still emitting this wind
- Close enough so the e^+e^- can reach us

Discovery of very extended TeV halos

Geminga (3 x 10^5 y old, 250 pc away) and PSR B056+14 (1 x 10^5 y old, 288 pc away) are candidates to be the source of this positron excess. HAWC is the only instrument able to characterize these extended sources

HAWC Collaboration
The Astrophysical Journal 843:40 (2017)



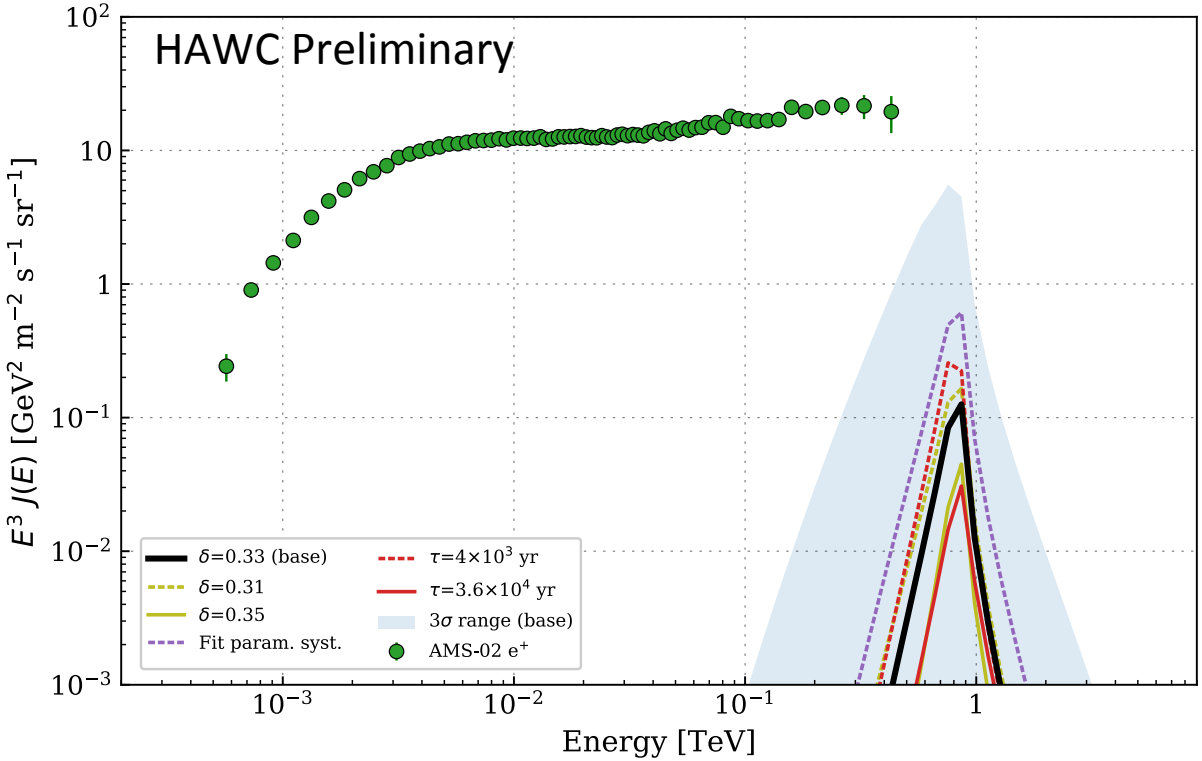
Before HAWC, Milagro was the only TeV instrument to detect Geminga, 2HWC J0700+143 is a new source discovered by HAWC with a pulsar similar to Geminga

The positron excess and extended sources

The measured gamma ray emission is produced by the leptons diffusing into the ISM and IC scattering from the CMB

Using the properties measured by HAWC of these sources, we can infer the propagation of the $e^{\pm}$ to Earth

Contribution of Geminga, the other source is negligible



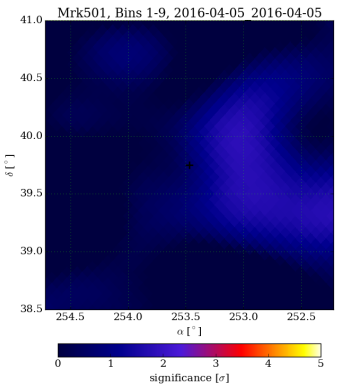
The measured positron flux cannot be explained by the contributions from Geminga and 2HWC J0700+143

Variability of sources: Detection of increased TeV flux from the active galaxy Markarian 501

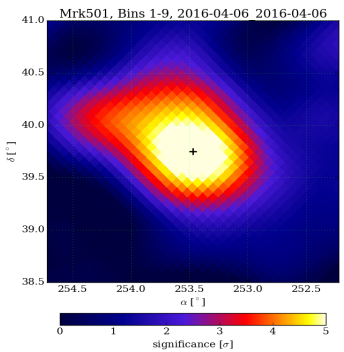
HAWC detection of increased TeV flux state for Markarian 501

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

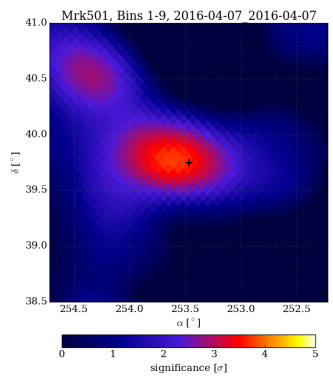
An Astronomer's Telegram was immediately sent to alert the community about this observation.



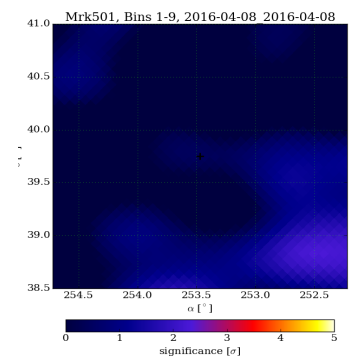
April 5, 2016



April 6, 2016



April 7, 2016



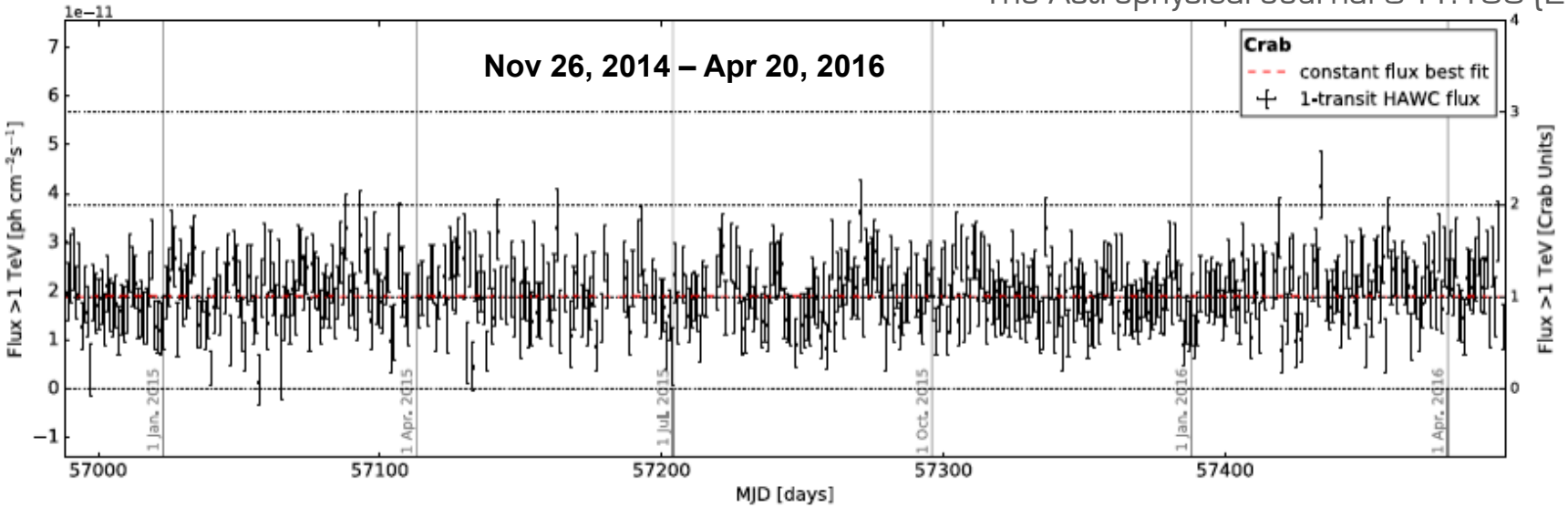
April 8, 2016

- Studies of the variability can provide insights into the acceleration mechanisms
- HAWC monitors continuously multiple gamma-ray sources every day in an unbiased way

Crab Nebula monitoring

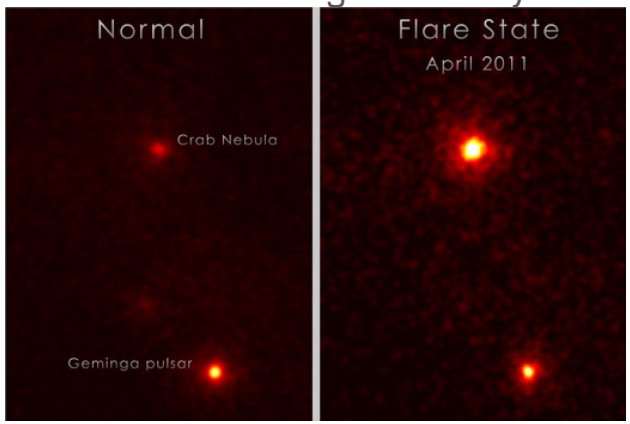
Daily flux light curve

HAWC Collaboration
The Astrophysical Journal 841:100 (2017)



- Observations with Fermi-LAT reported a flare at lower gamma-ray energies (>100 MeV), approximately 1.7 times the average flux
- Crab flares, continue up to TeV?
- A likelihood test shows that the data is consistent with a constant flux

MeV-GeV gamma ray



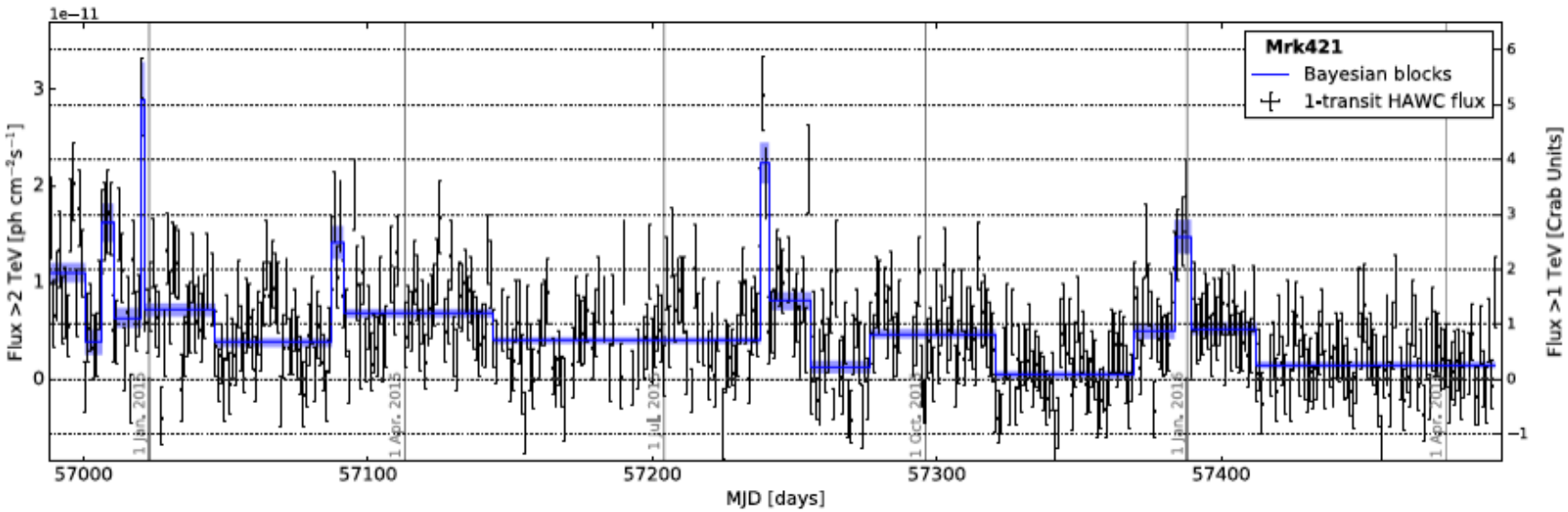
NASA/DOE/Fermi LAT/R. Buehler

Active galaxy Markarian 421

Daily flux light curve

HAWC Collaboration
The Astrophysical Journal 841:100 (2017)

Nov 26, 2014 – Apr 20, 2016

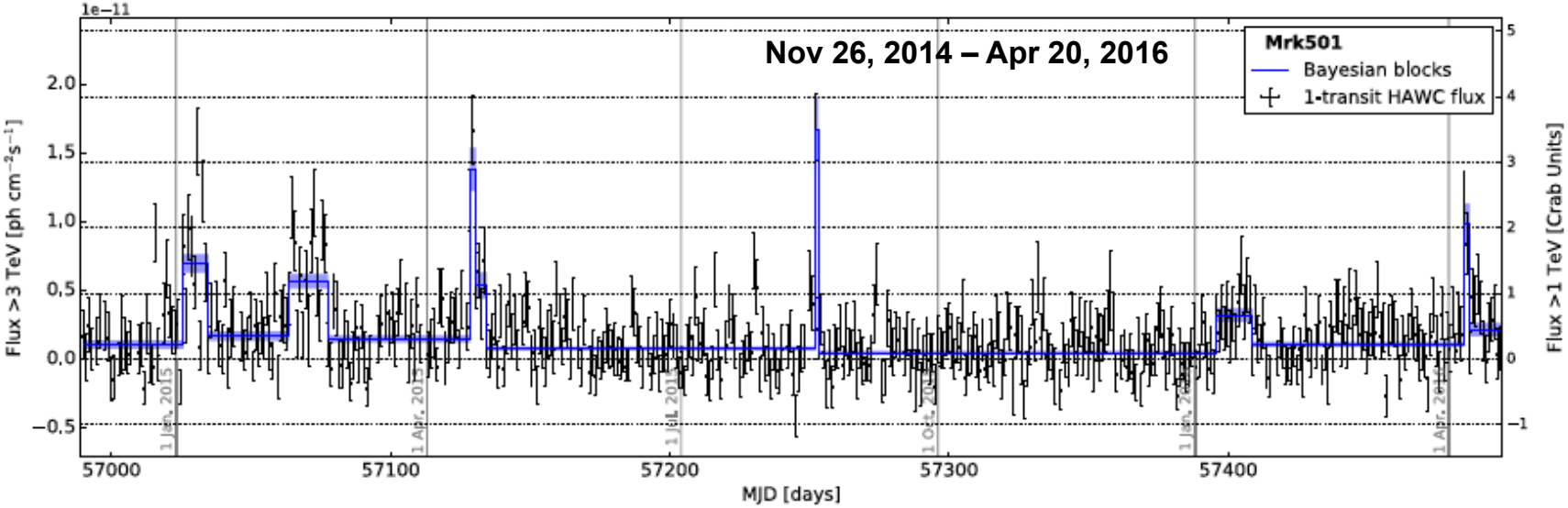


- First extragalactic object discovered in the TeV band, is a galaxy with an active nucleus whose jet points in Earth's direction
- Variability in timescales of hours or less
- A Bayesian block analysis (to find regions of constant flux) is used to identify 19 distinct flux states
- The highest per-transit fluxes exceed the Crab Nebula flux by a factor of approximately 5

Active galaxy Markarian 501

Daily flux light curve

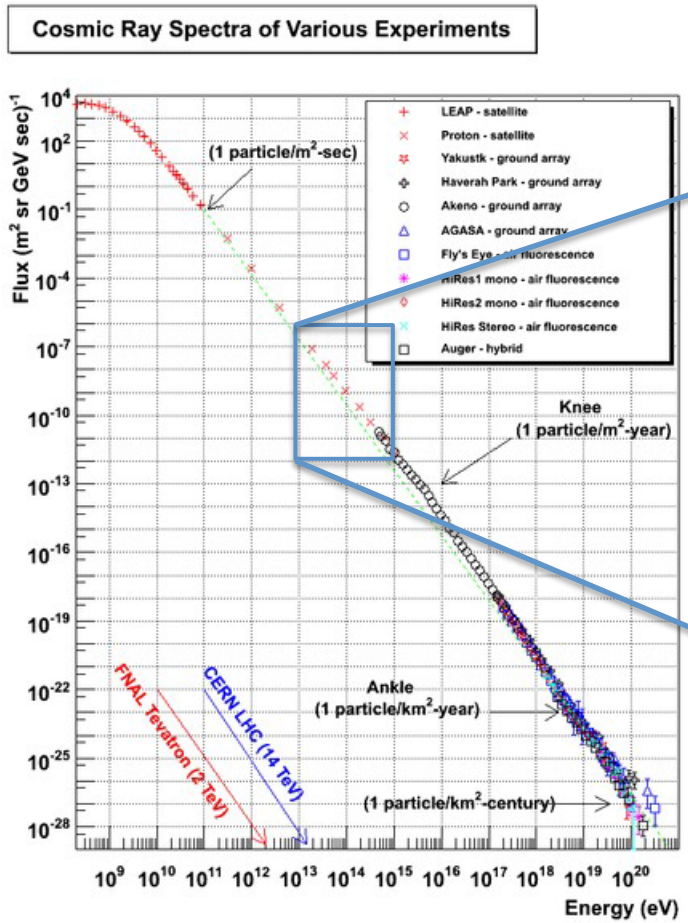
HAWC Collaboration
The Astrophysical Journal 841:100 (2017)



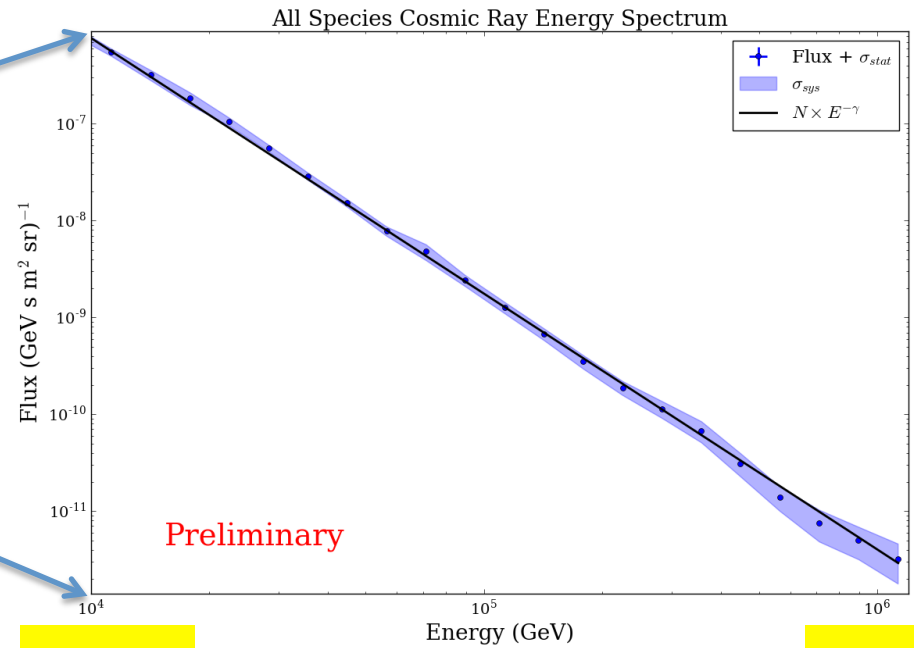
- Also a BL Lacertae type blazar
- Second of such objects discovered at TeV energies
- The highest per-transit fluxes exceed the Crab Nebula flux by a factor of approximately 3
- 14 distinct flux states in this period of time

Cosmic Ray Spectrum

359 days of data



HAWC

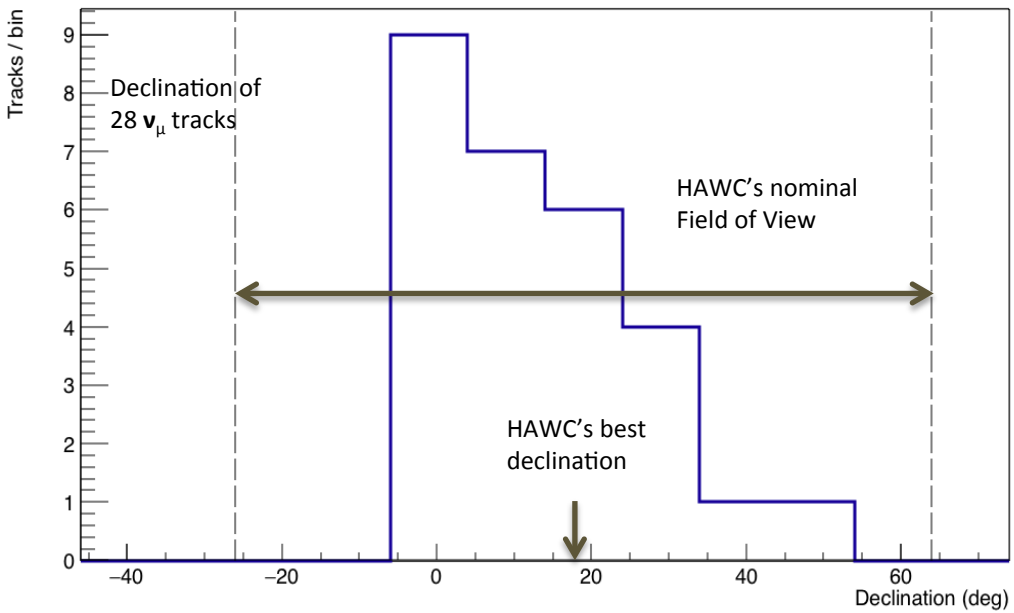


10 TeV

1 PeV

Search of TeV gamma-ray counterparts to IceCube neutrinos

Looked for gamma-ray sources in the direction from where the 28 highest energy neutrinos arrived.



No detections so far

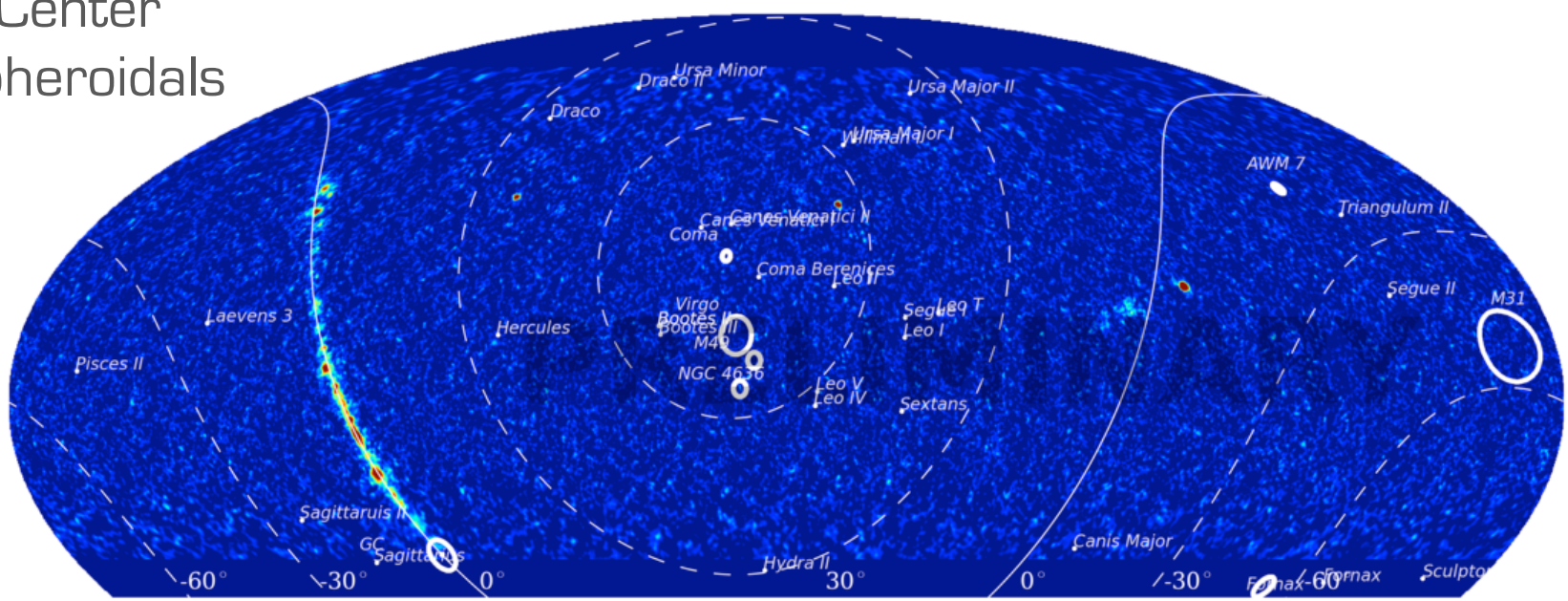
- sources opaque to gamma-rays?
- sources too far away ?
- too many sources?

Performing searches in real time in order to look for transients

Dark Matter targets

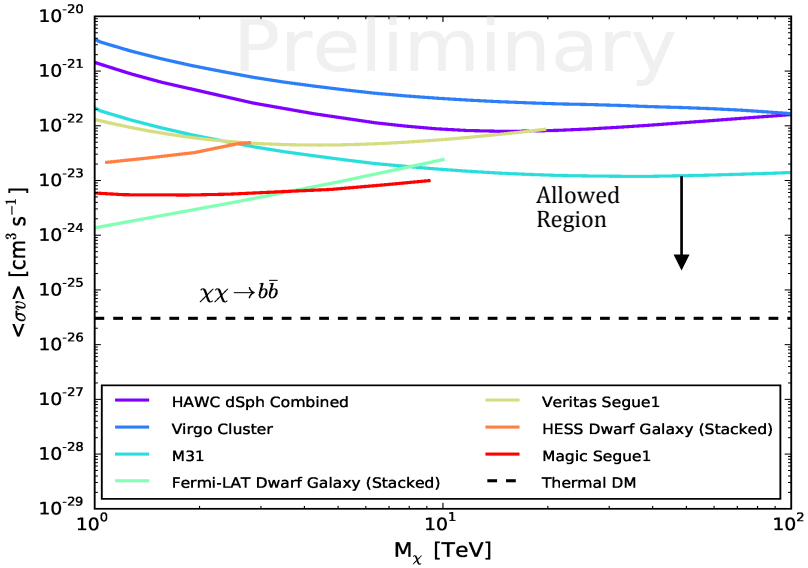
- Decay or annihilation of DM particles in the regions of enhanced DM density to SM particles eventually leads to gamma-rays. If m_{DM} is 1 TeV-100 TeV HAWC could detect it indirectly.

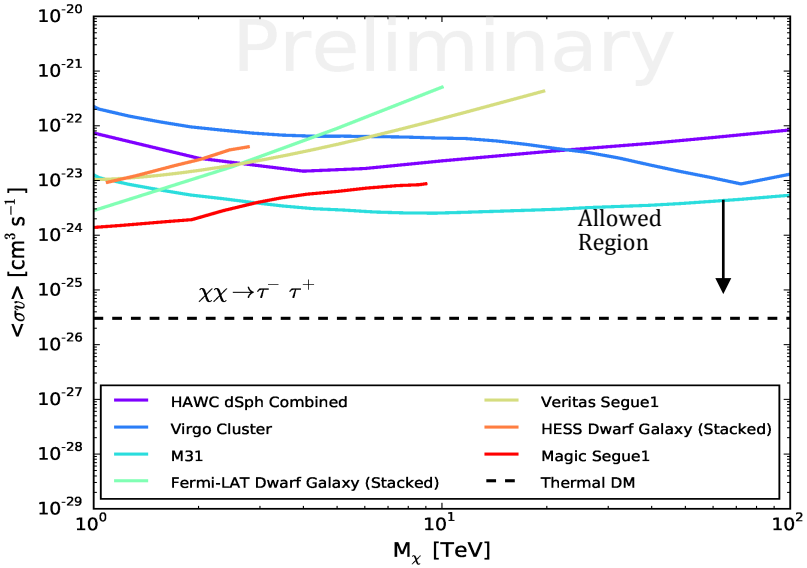
Virgo Cluster
M31
Galactic Center
Dwarf spheroidals



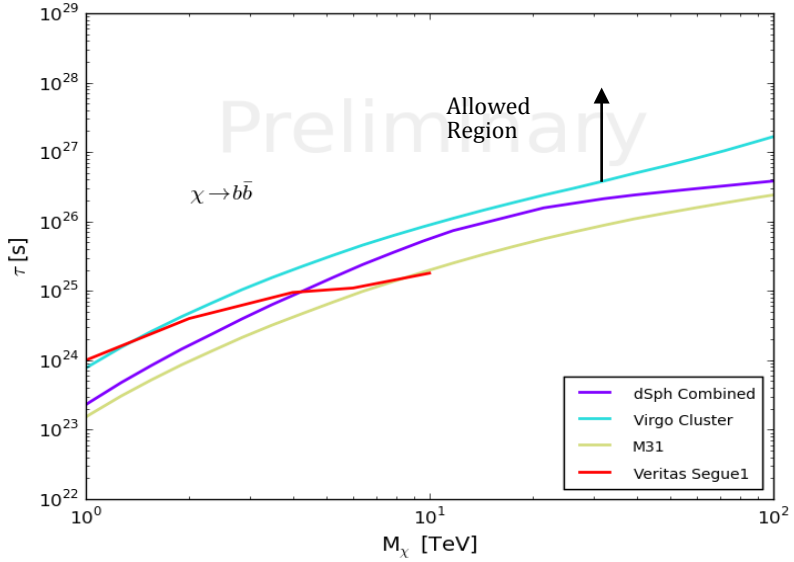
Constrains on Multi-TeV Mass DM

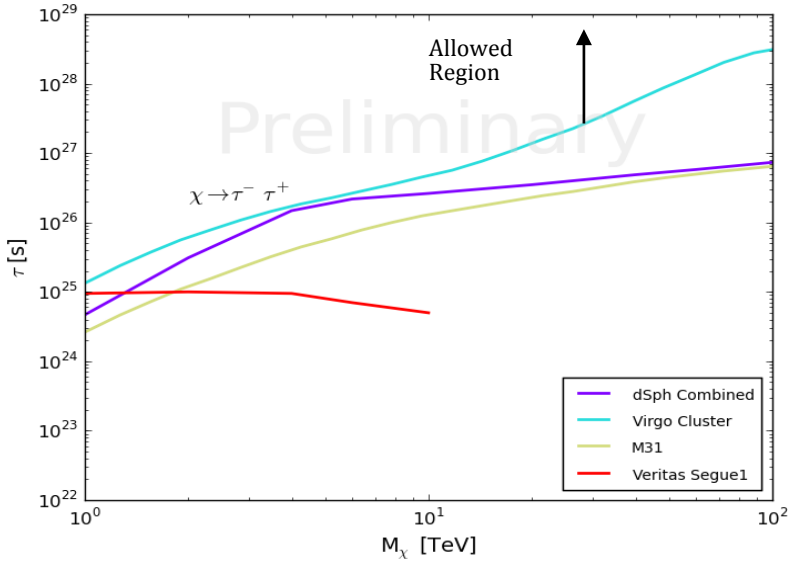
Annihilation





Decay





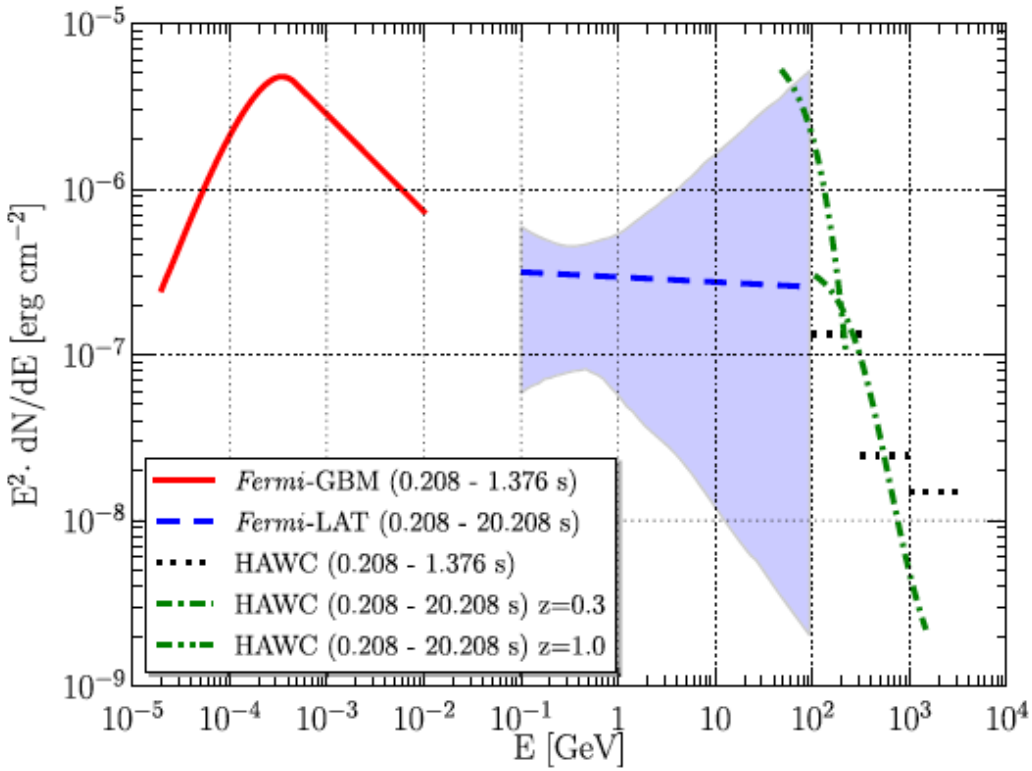
TeV counterparts to GRBs

HAWC effective area is of ≈ 100 m^2 at 100 GeV

Fermi with an effective area of ≈ 1 m^2 has detected ≈ 100 GeV gamma-rays from GRBs

No detections so far, but HAWC has set limits from 64 GRBs detected by Swift and Fermi

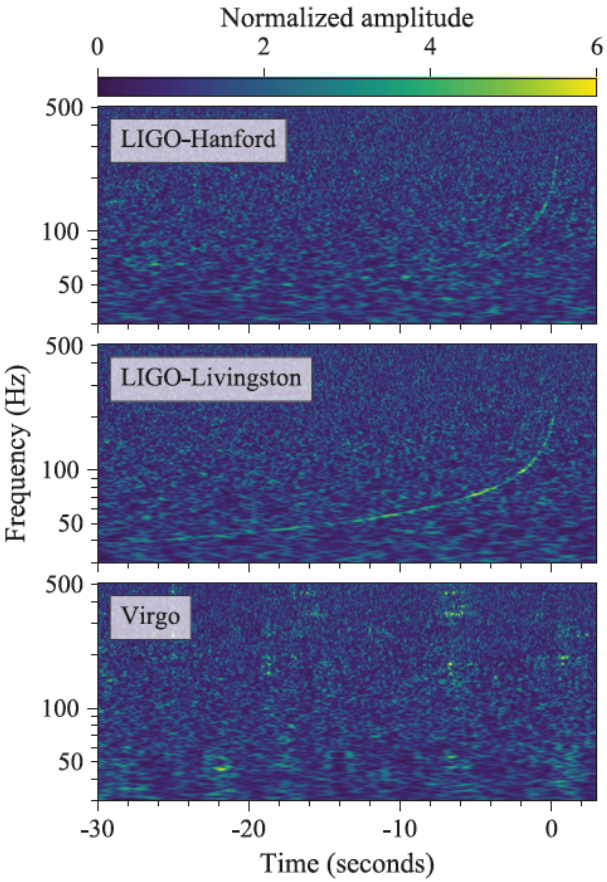
GRB 170206
Third brightest short GRB detected by Fermi-GBM

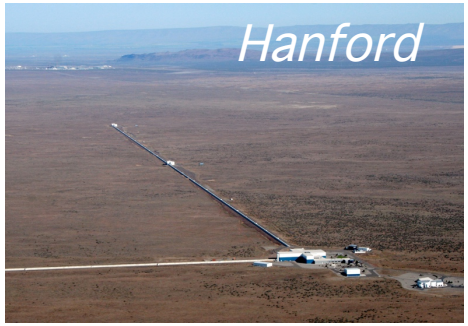


HAWC Collaboration
APJ 843:88 (2017)

Binary neutron star merger

LIGO & Virgo Collaborations
PRL 119, 161101 (2017)



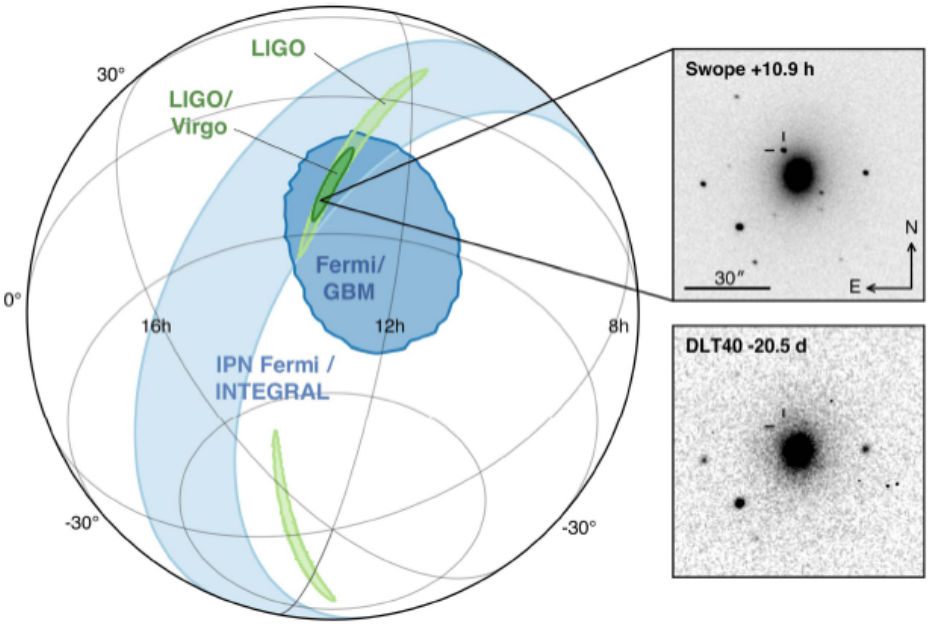


- First observation of a binary neutron star inspiral
- Associated with a gamma-ray burst detected by Fermi-GBM
- First direct evidence of a link between mergers and short gamma-ray bursts

August 17, 2017
12:41:04 UTC

Multi-messenger observations of the merger

Follow up observations from 60 collaborations around the world, including HAWC

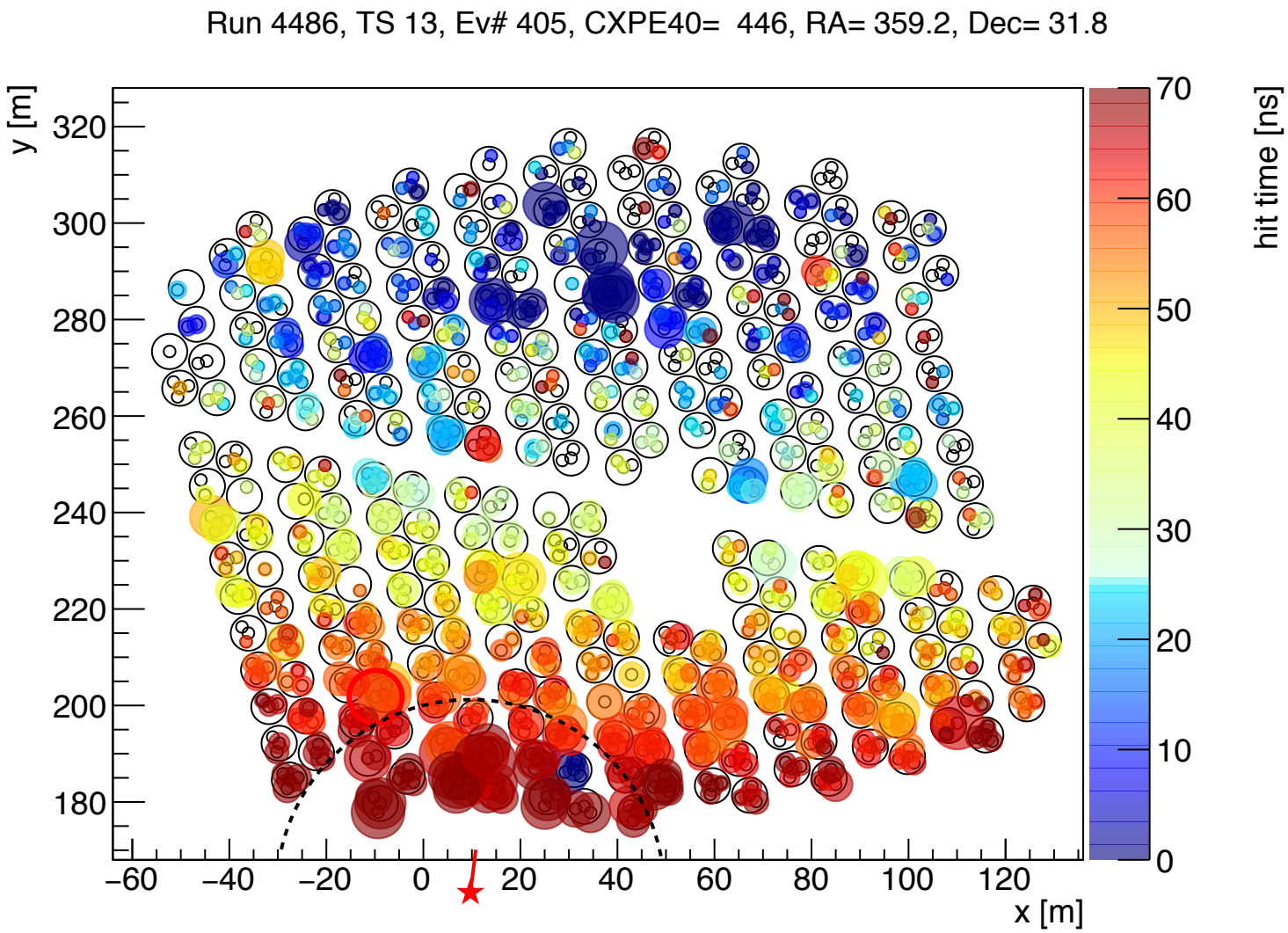


APJ Letters 848:L12 (2017)

- The region where the event happened was not in the field of view of HAWC
- Transited through 9 hrs after at an unfavorable zenith angle for HAWC (42°)
- Upper limits from HAWC for energies > 40 TeV assuming an $E^{-2.5}$ spectrum were reported in a GCN (Gamma-ray Coordinates Network) circular.

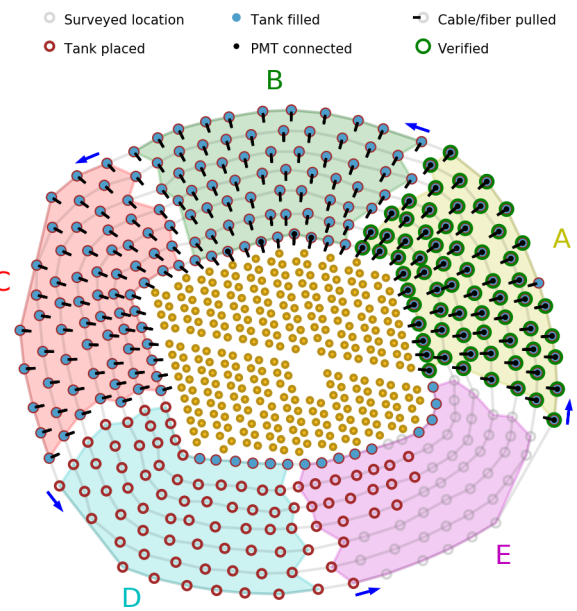
First upgrade: Outriggers

Air shower with a core far from the array



First upgrade: Outriggers

- HAWC Sparse Outrigger Array:
  - Increase the sensitivity for air showers with energies > 10 TeV
  - Precise location of the shower core, for showers that occur at the edges of the array
  - Increase of the effective area for energies > 10 TeV by 3-4x
- Funding from LANL/Mexico/MPI Heidelberg.
- Composed of tanks of 2500 liters: 1/80 of the volume of the current WCDs



Conclusions

- The HAWC observatory began full-scale operation in March 20, 2015
- The 2HWC catalog of gamma ray sources contains 39 sources, including 19 new sources
- HAWC produced the first TeV light curves with daily binning from the Crab Nebula, Markarian 421 and 501. HAWC can study the variability of any TeV source within its field of view and provide alerts to other observatories
- The measurements of HAWC from Geminga and 2HWC J0700+143 show that the associated pulsars are not the main contributors to the detected positron excess
- HAWC is performing follow-up observations triggered by partner observatories like IceCube and LIGO-Virgo
- Lots of interesting scientific results coming up!