The HAWC very high energy γ-ray observatory

High Altitude Water Cherenkov
Gamma-Ray Observatory

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GH 2018 workshop, Tonantzintla
7 September 2018

INAOE

CONACYT
Consejo Nacional de Ciencia y Tecnología

The HAWC Collaboration

High Altitude Water Cherenkov Gamma-Ray Observatory

México	
Instituto Nacional de Astrofísica, Óptica y Electrónica	(INAOE)
Asociado: Universidad de Costa Rica	
Universidad Nacional Autónoma de México	
Instituto de Astronomía UNAM	(IA-UNAM)
Instituto de Ciencias Nucleares UNAM	(ICN-UNAM)
Instituto de Física UNAM	(IF-UNAM)
Instituto de Geofísica UNAM	(IG-UNAM)
Benemérita Universidad Autónoma de Puebla	(BUAP)
Instituto Politécnico Nacional	
Centro de Investigación y Estudios Avanzados	(CINVESTAV)
Centro de Investigación en Cómputo - IPN	(CIC-IPN)
Universidad Autónoma de Chiapas	(UNACH)
Universidad Autónoma del Estado de Hidalgo	(UAEH)
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Universidad Politécnica de Pachuca	(UPP)

United States	
University of Maryland	(UMD)
Los Alamos National Laboratory	(LANL)
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Georgia Institute of Technology	(GATECH)
Michigan State University	(MSU)
Michigan Technological University	(MTU)
Pennsylvania State University	(PSU)
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University of California Santa Cruz	(UCSC)
University of California Irvine	(UCI)
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University of Utah	(UU)
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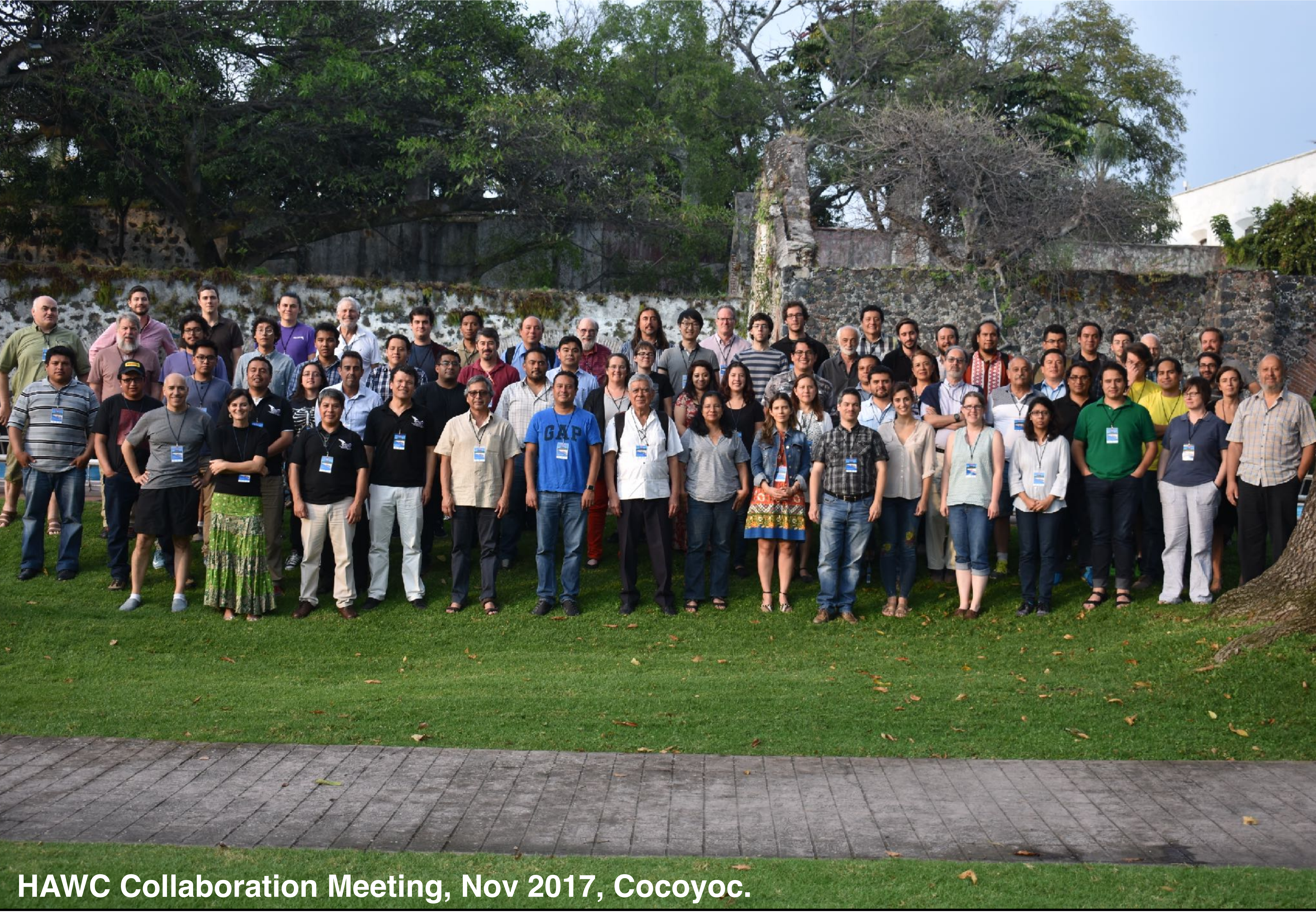
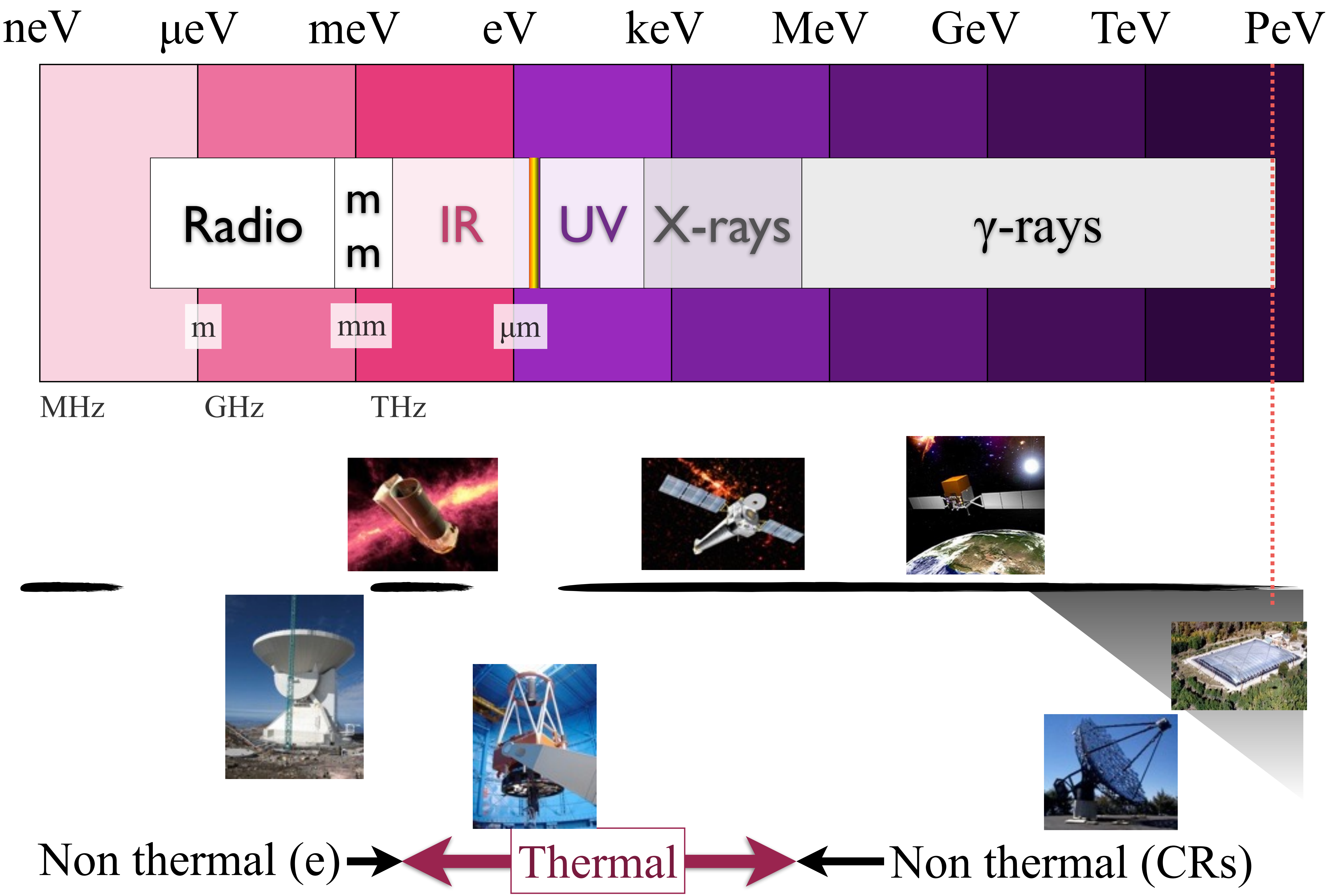
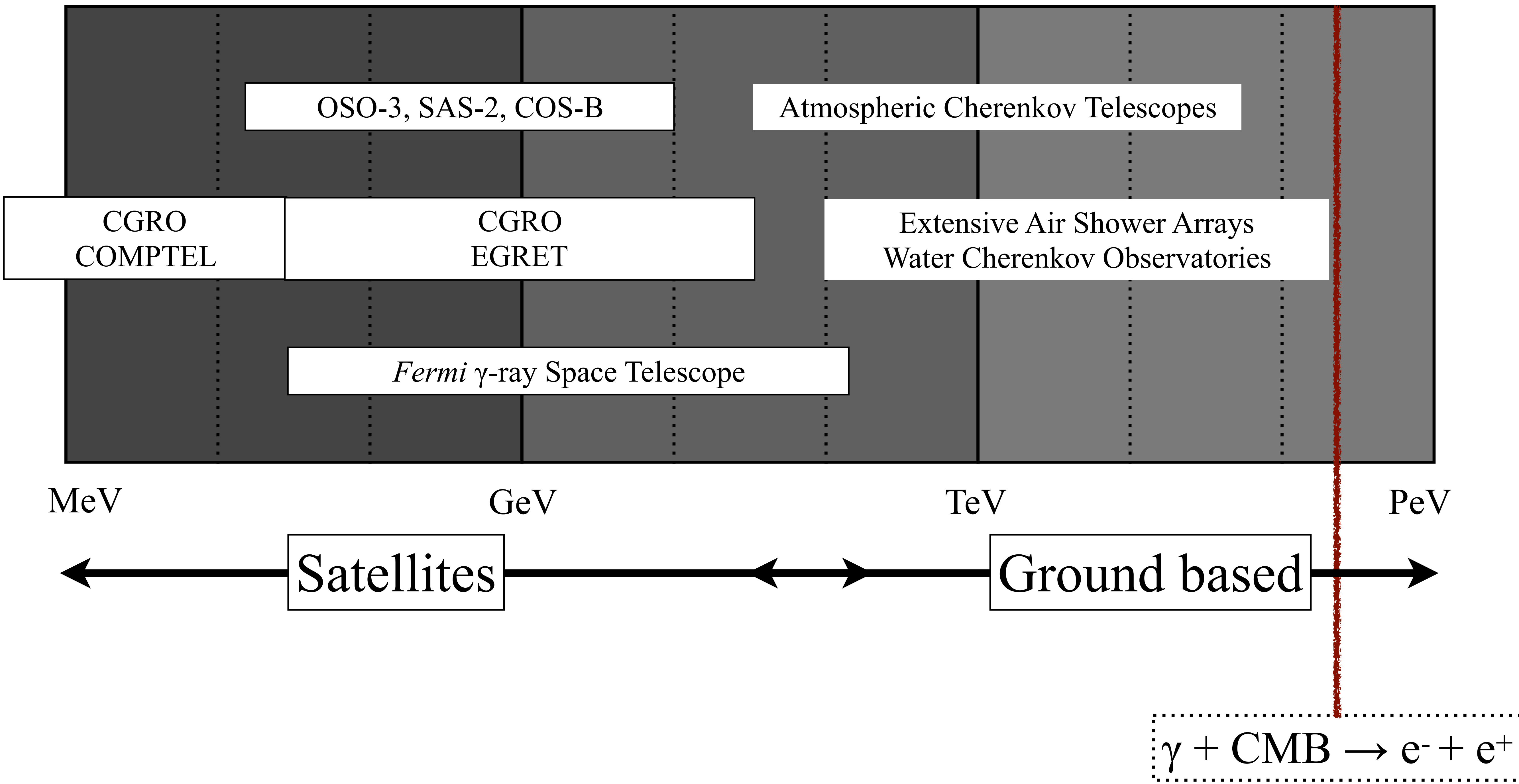
Europe	
Max Planck Institut für Kernphysik, Heidelberg	(MPI-HD)
Institute of Nuclear Physics, Krakow	(IFJ-PL)



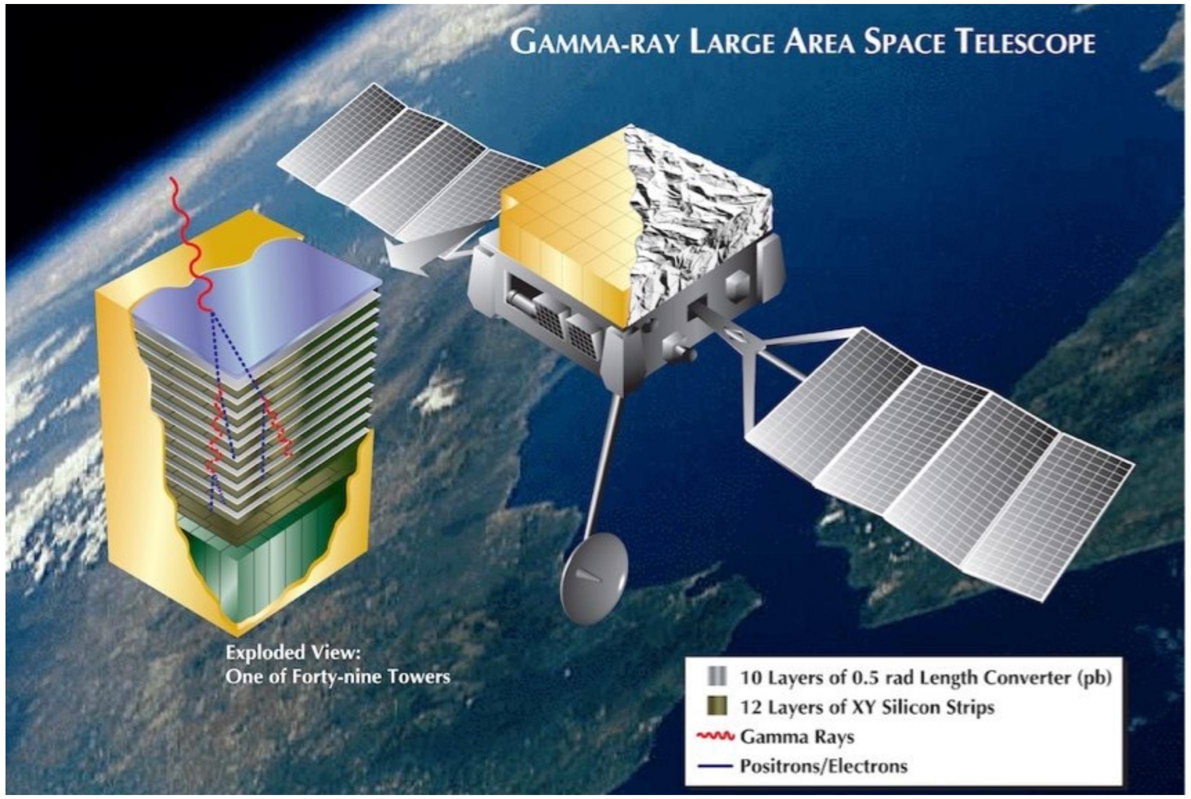
HAWC Collaboration Meeting, Nov 2017, Cocoyoc.


neV
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
Radio
m m
IR
UV
X-rays
γ-rays
m
mm
μm
MHz
GHz
THz
Non thermal (e)
Thermal
Non thermal (CRs)

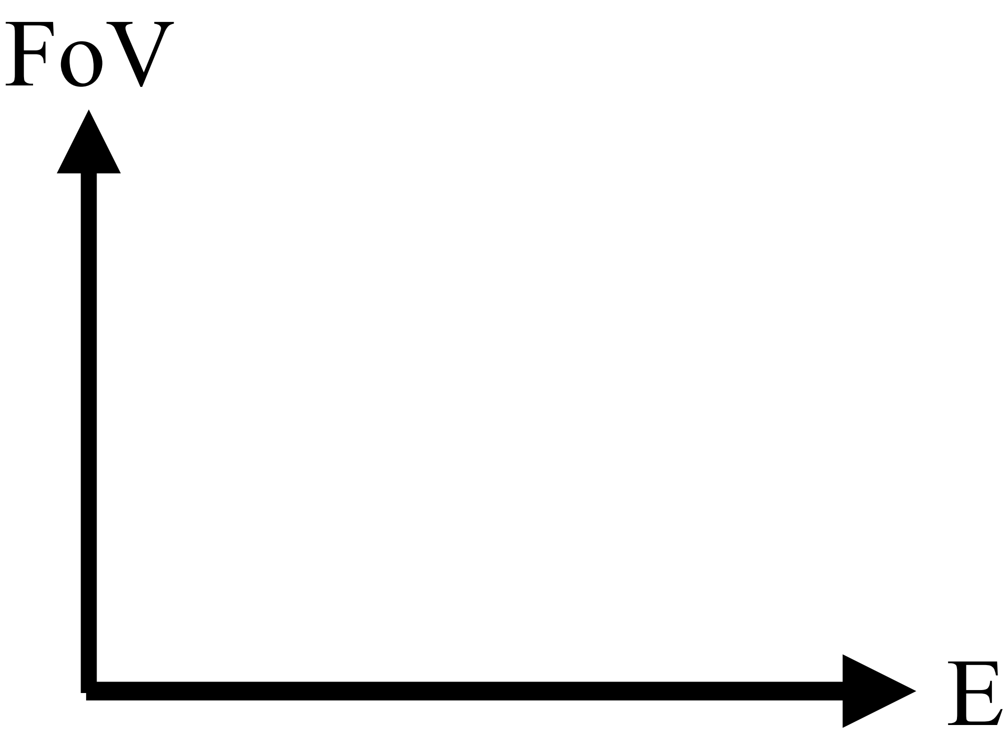
The γ-ray spectrum

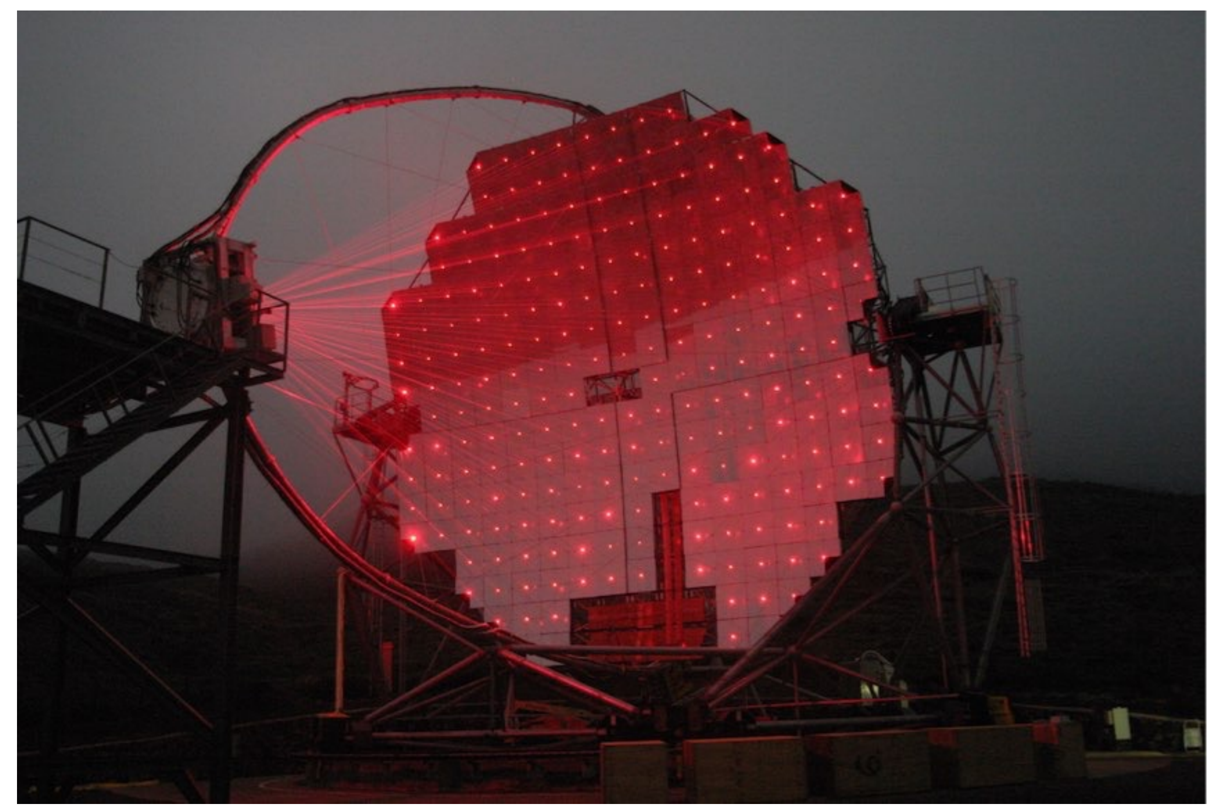


Sr



Deg





GeV

TeV

Sr

Pair production telescopes

0.1 - 100 GeV
Small effective area
Perfect CR background rejection
Large field of view & duty cycle

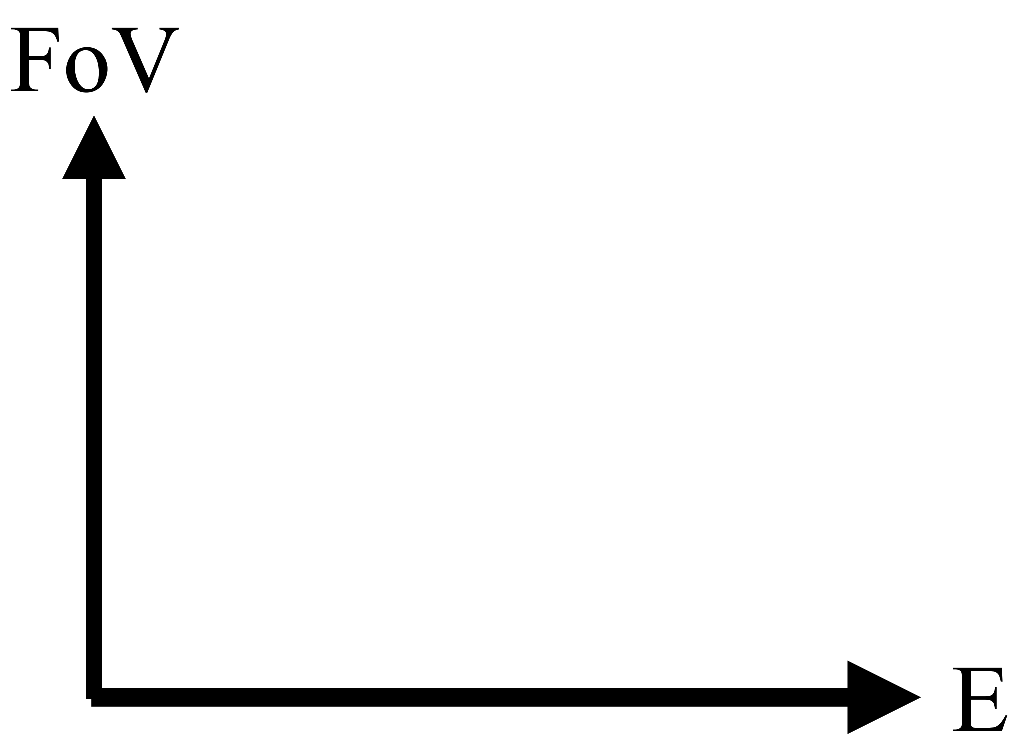
Sky surveys & monitoring
Transients (AGN, GRB)
Extended diffuse emission

Air shower arrays

100 GeV - 100 TeV
Large effective area
Good CR background rejection
Large field of view & duty cycle

Sky surveys & monitoring
Transients (AGN, GRB)
Extended sources
The highest energies

Deg



Atmospheric Cherenkov telescopes

30 GeV - 30 TeV
Large effective area
Excellent CR background rejection
Limited field of view & duty cycle
High sensitivity

Detailed studies of known sources
Deep surveys of limited regions
High resolution spectra

GeV TeV

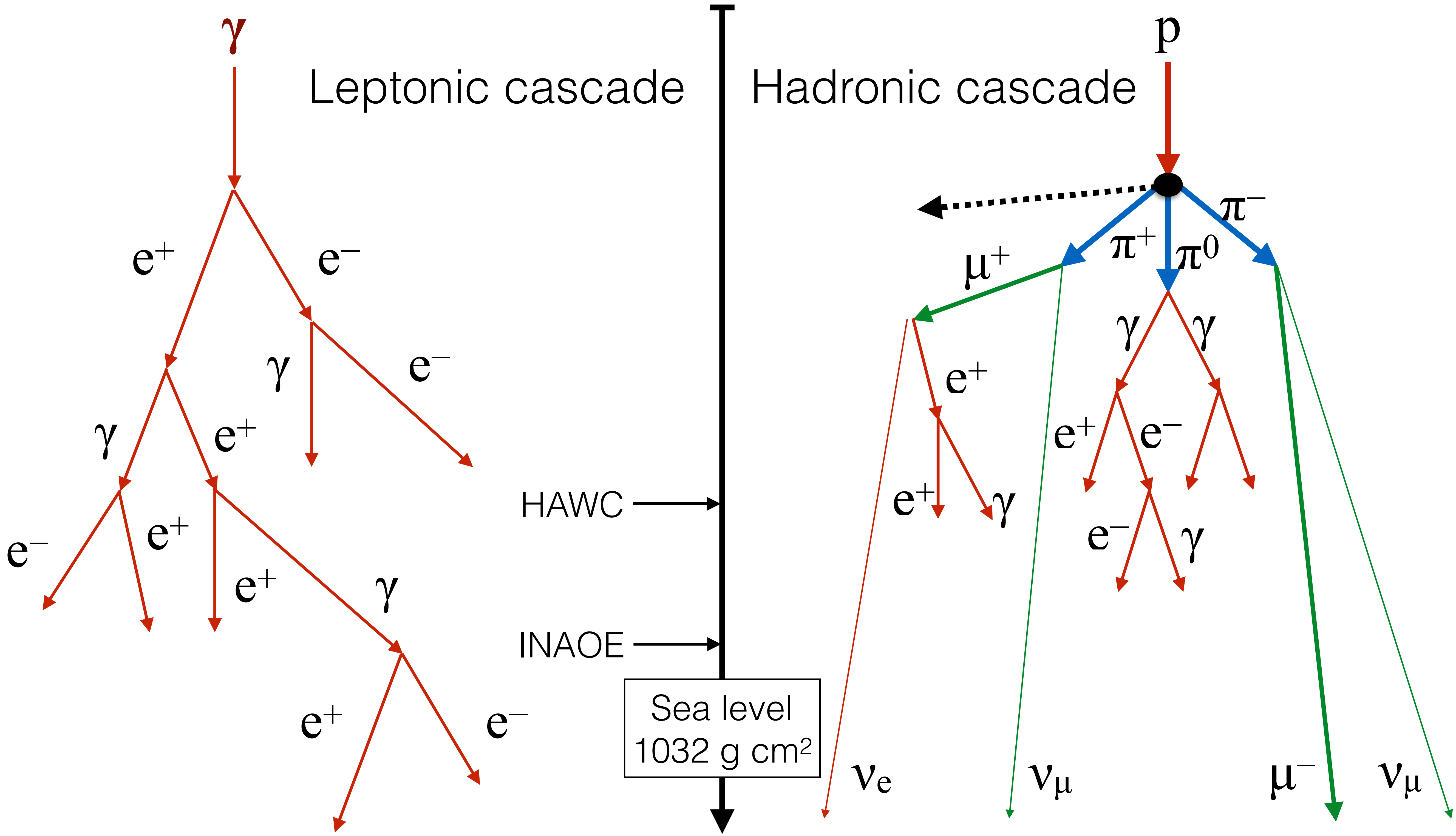
HAWC science

- Cosmic ray studies between 1 TeV and 1 PeV
- Sky survey at TeV energies
- Monitoring of TeV γ ray transients
- Study Galactic sources of γ rays (hence of cosmic rays)
- Study extragalactic sources of γ rays: blazars, GRBs
- Multiwavelength studies (Fermi, Swift, ….)
- Multimessenger follow ups: neutrinos and GW
- Searches: dark matter sources; primordial black holes

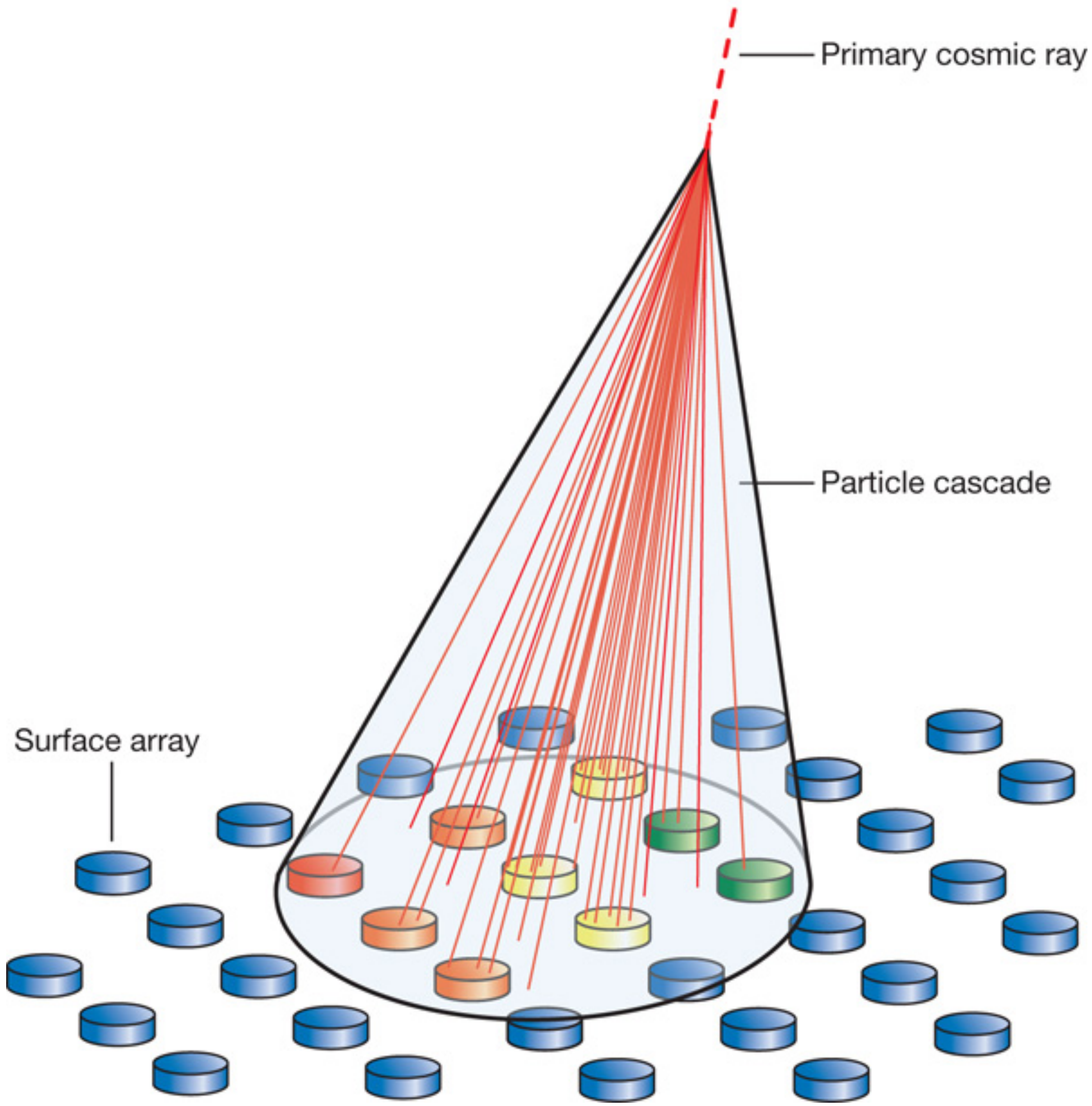
How HAWC works

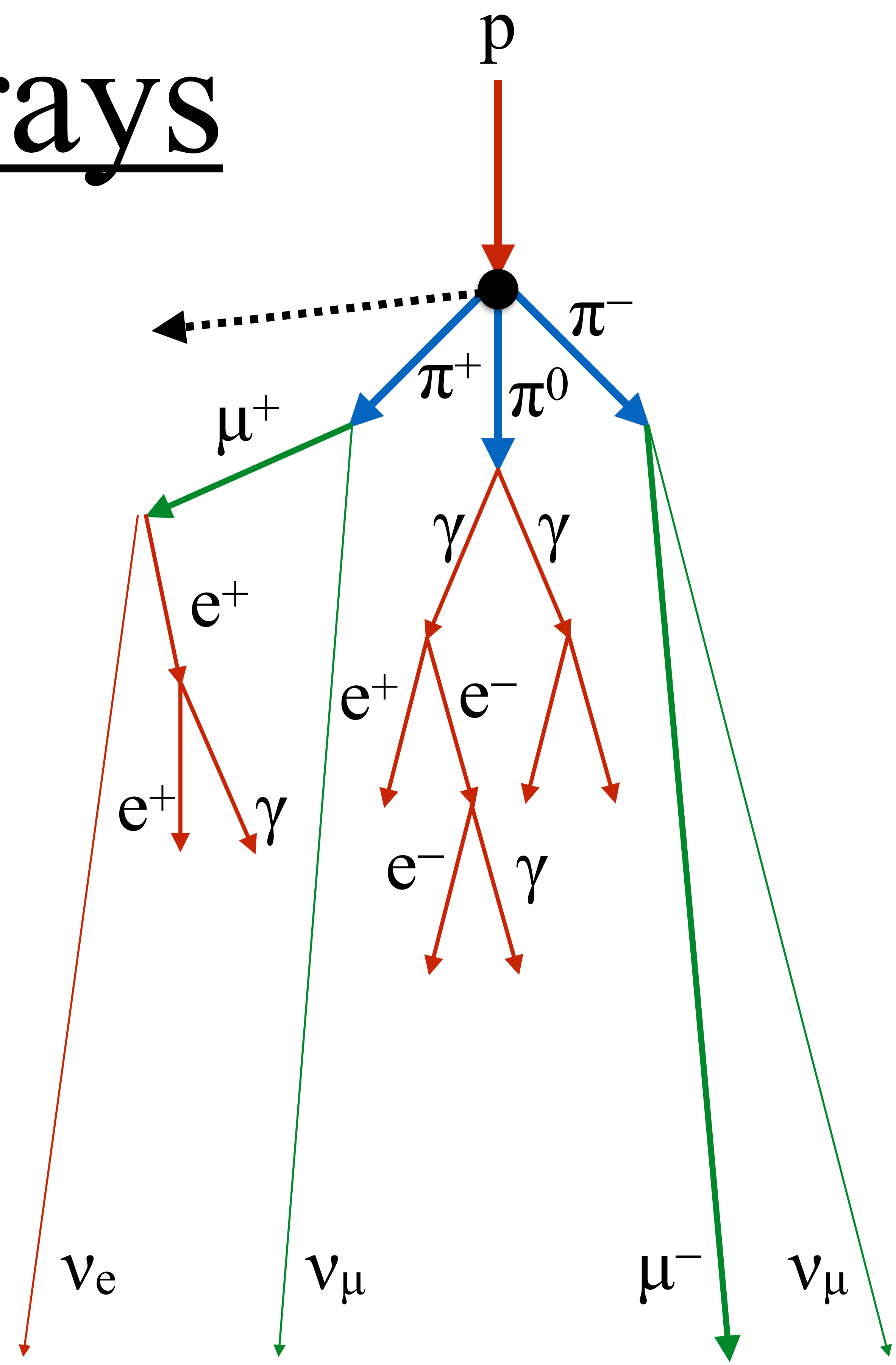
- The first layer of the HAWC detector is the atmosphere, where cosmic particles and photons of TeV energies produce showers of secondary particles.
- The HAWC size and compact detector design are optimized to study TeV photons at the atmospheric depth corresponding to an altitude of about 4000m.
- Water allows the detection of secondary particles through the production of Cherenkov light which is registered with PMTs.
- Simulations of these processes in the atmosphere and in the instrument are mandatory to predict and assess the performance of the experiment.

Atmospheric particle cascades

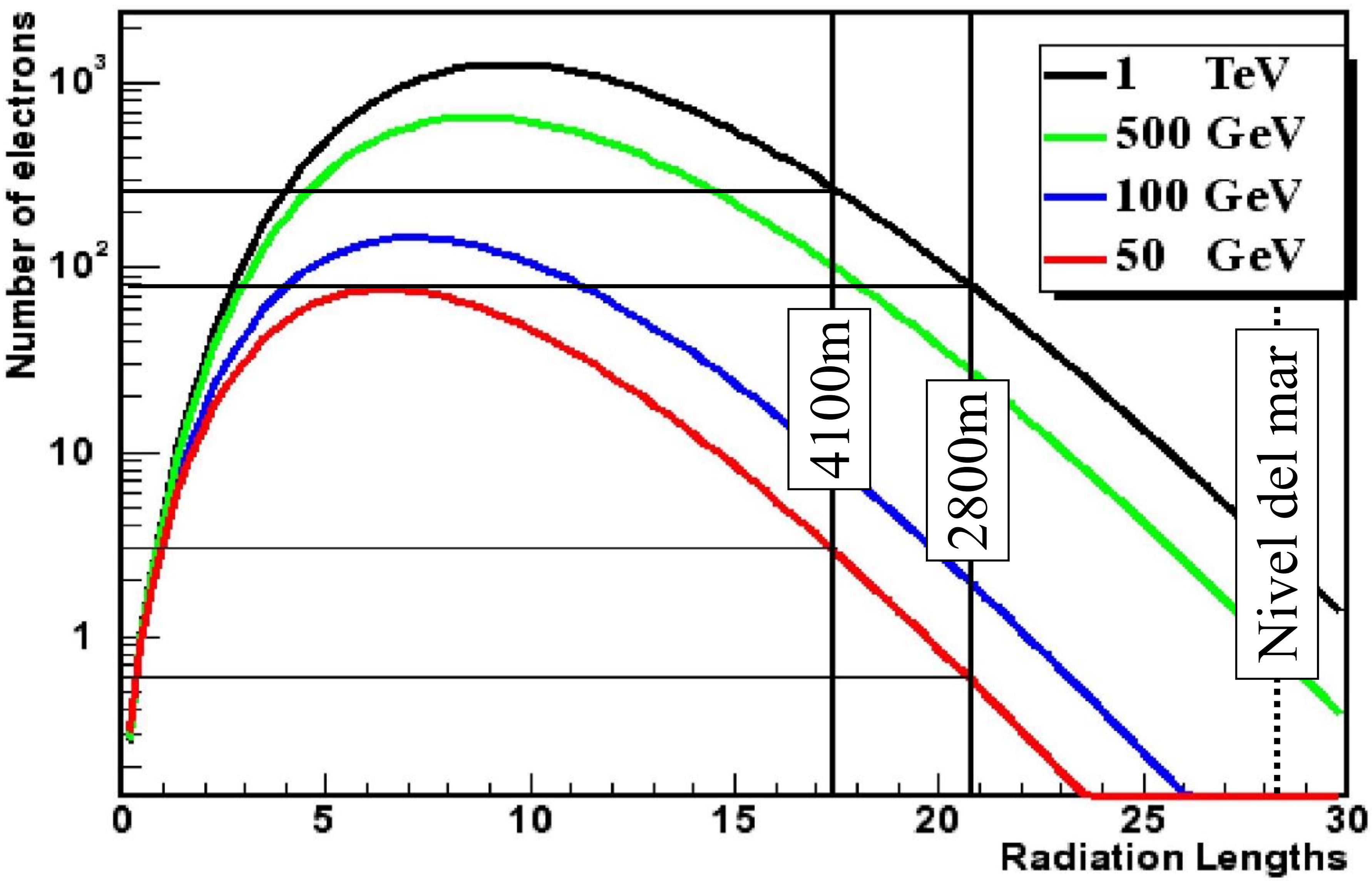


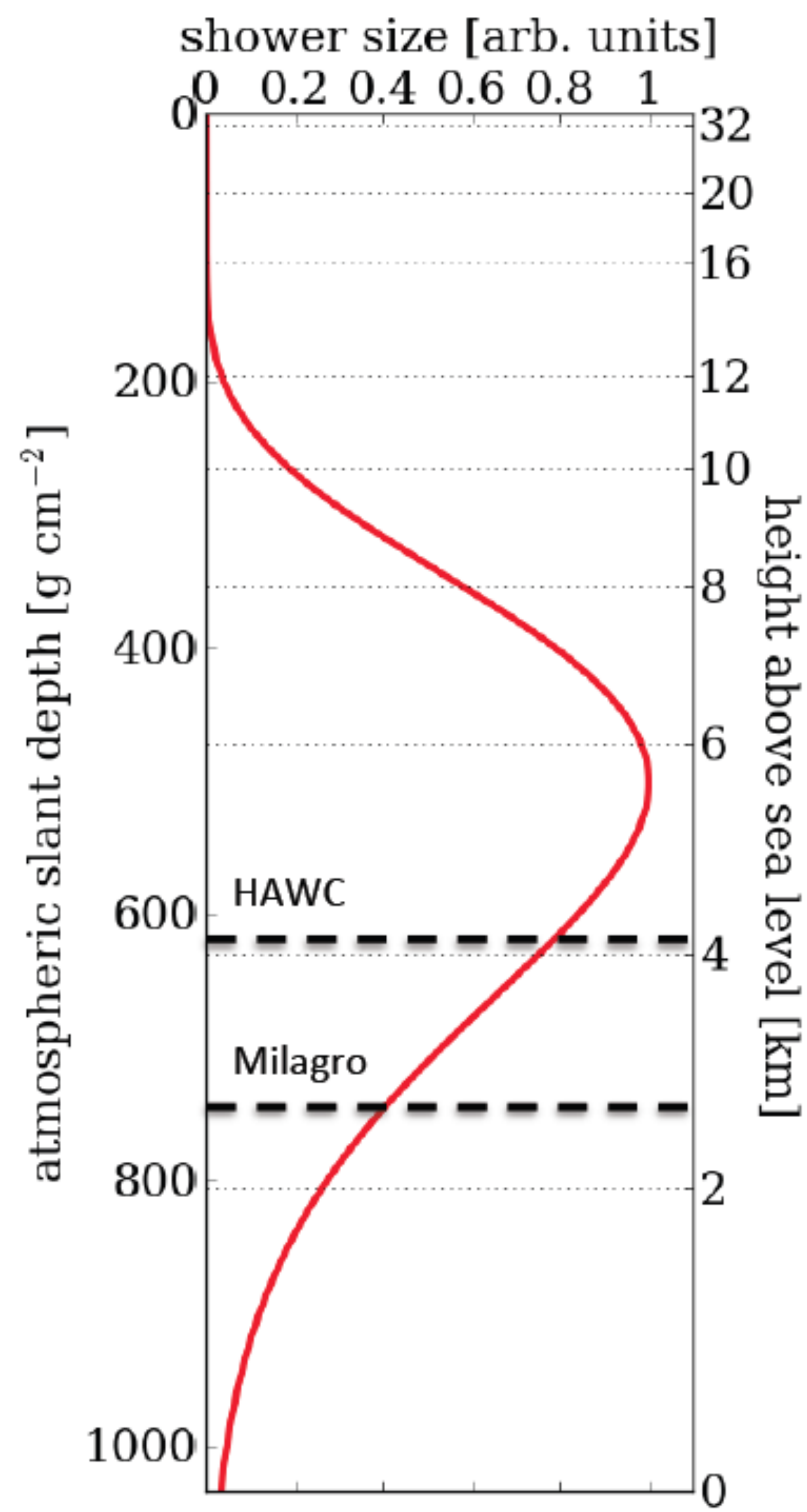
Air shower arrays



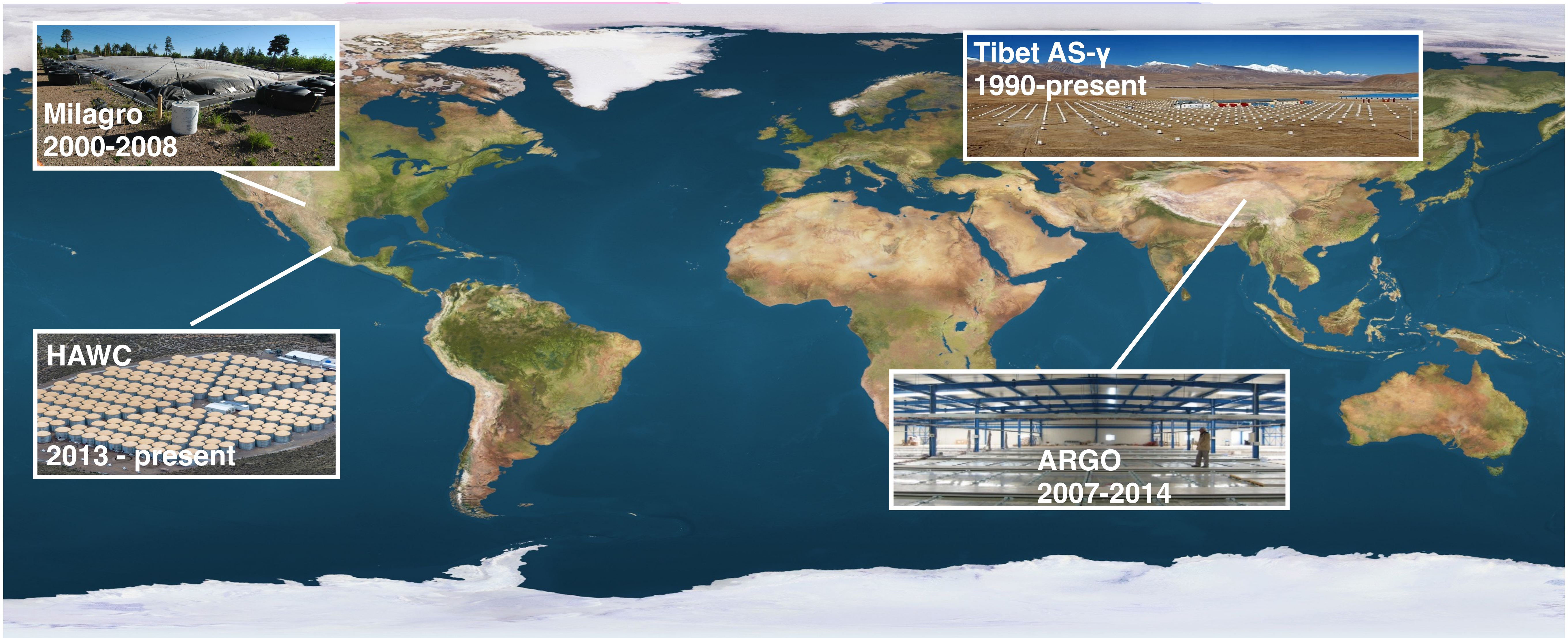


The atmosphere is part of the detector

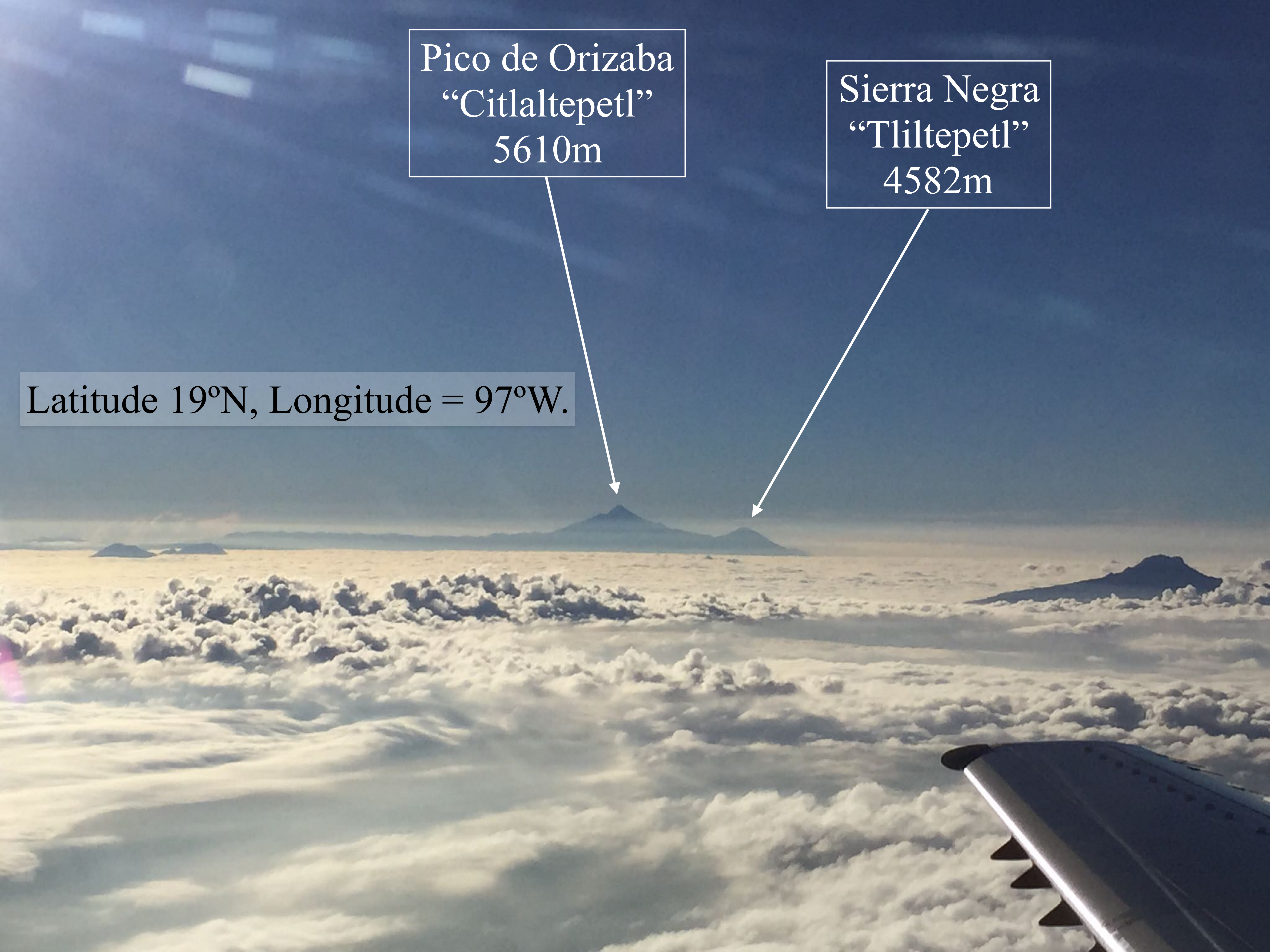


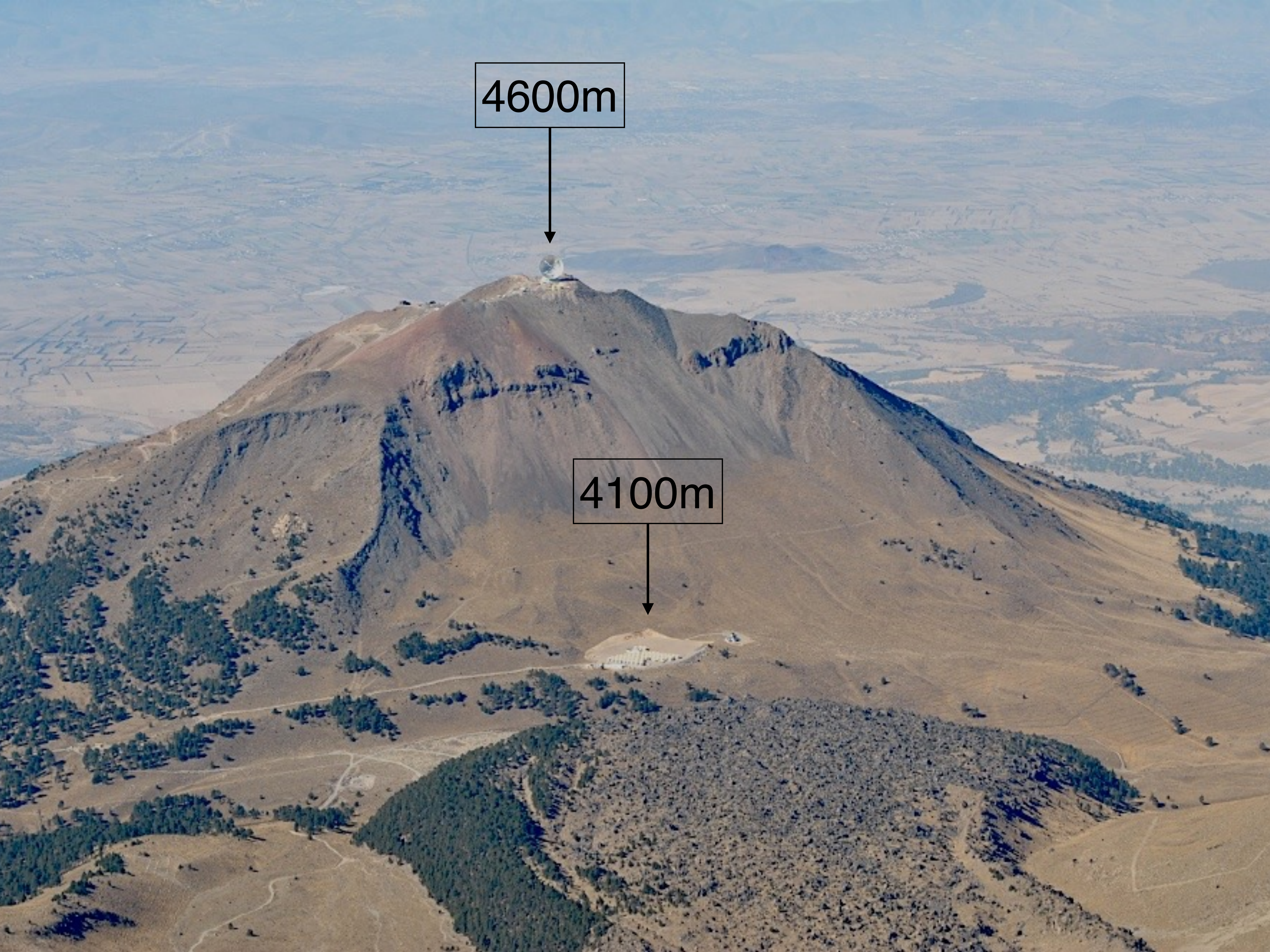


Air shower arrays as γ-ray observatories

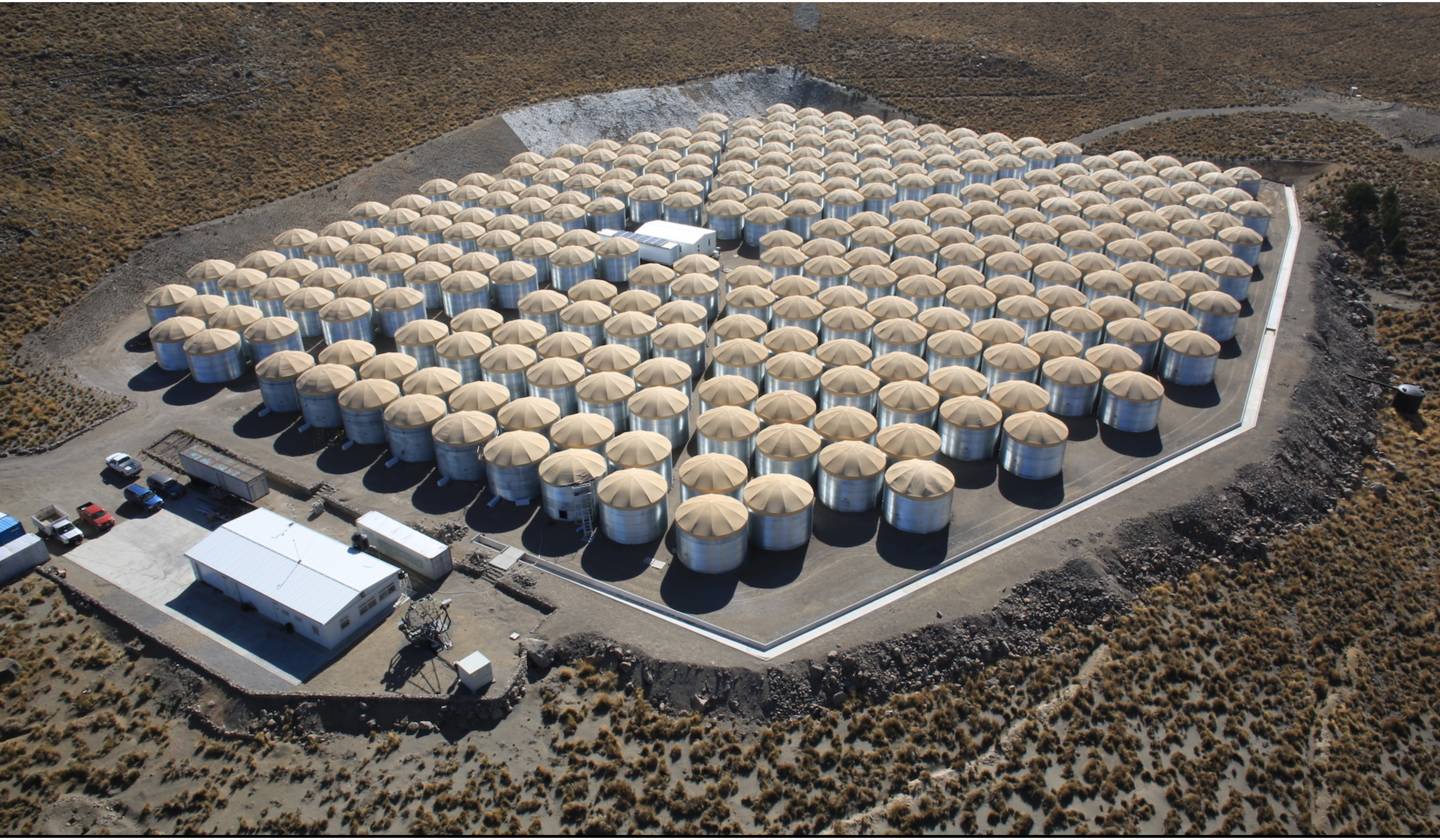


High altitude air shower arrays are well-suited to measure γ rays. They are ideal for surveying and monitoring large regions of the sky.


Pico de Orizaba
“Citlaltepetl”
5610m
Sierra Negra
“Tliltepetl”
4582m
Latitude 19ºN, Longitude = 97ºW.

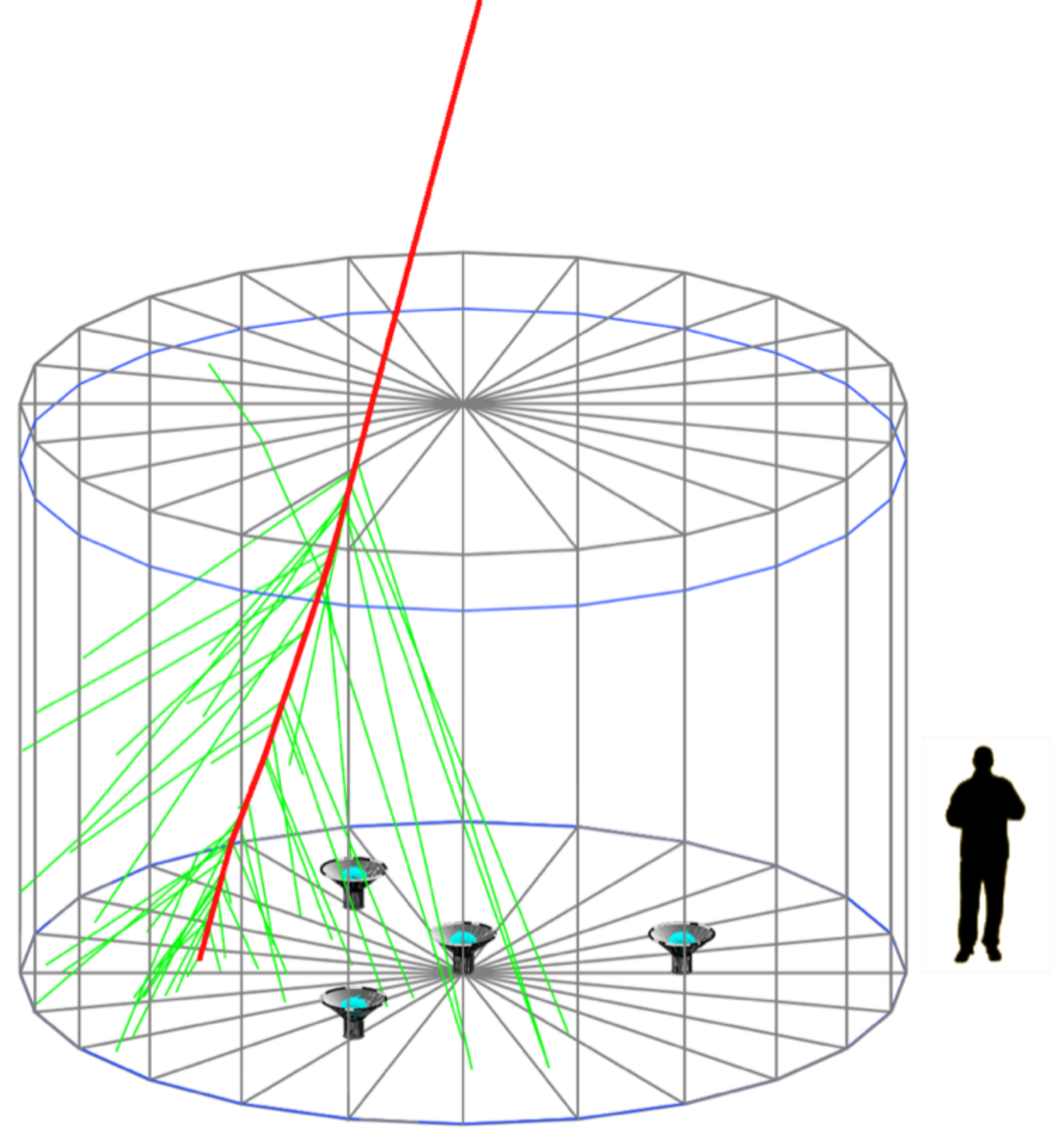

4600m
4100m

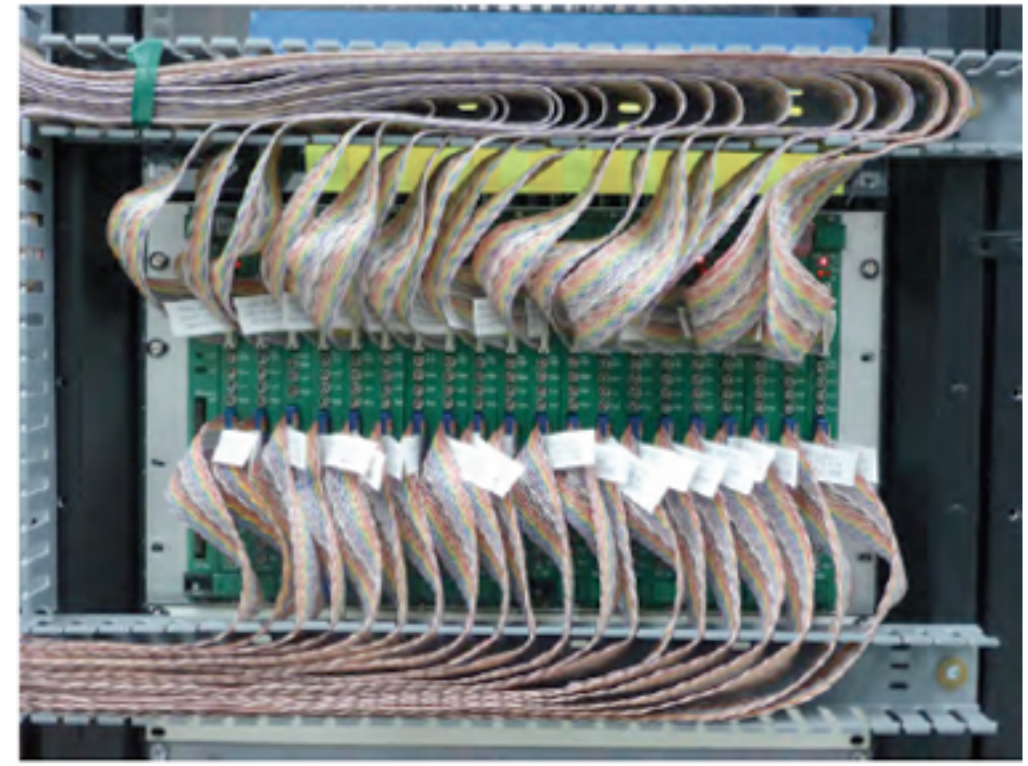
The HAWC γ-ray observatory

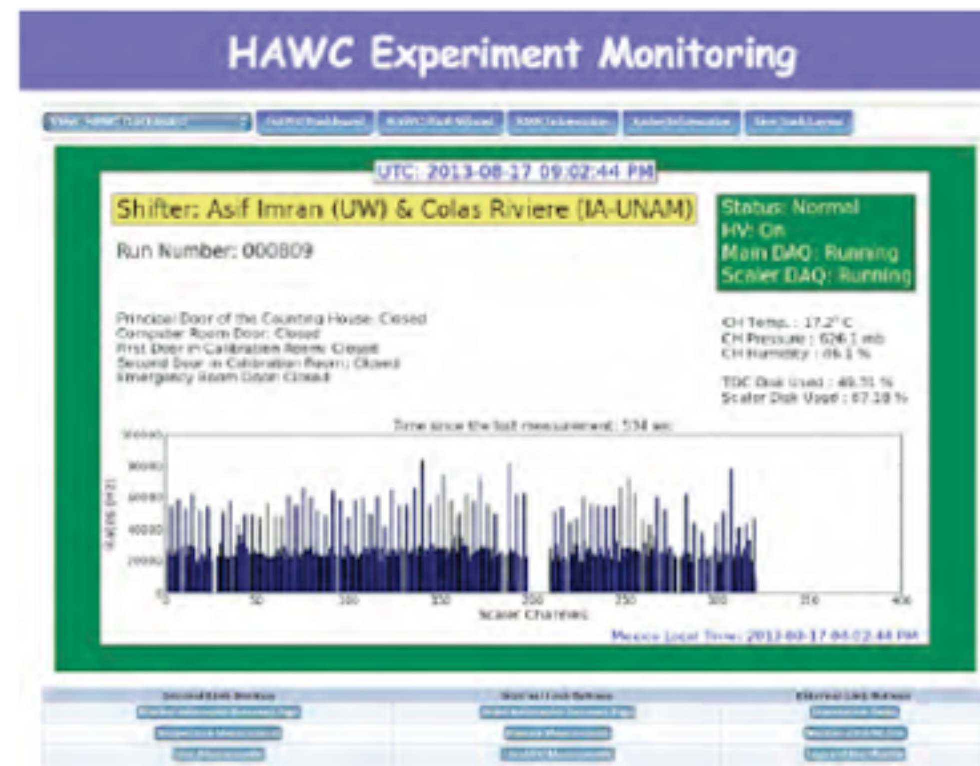


The WCDs

- HAWC is formed by 300 water Cherenkov detectors.
- Each WCD consists of a tank of 7.2m diameter and 4.5m height, containing 180,000 liters of water in deep darkness.
- Each detector has four PMTs to register Cherenkov light: three of 8" and one 10".
- Water is filtered for transparency and to avoid scattering.

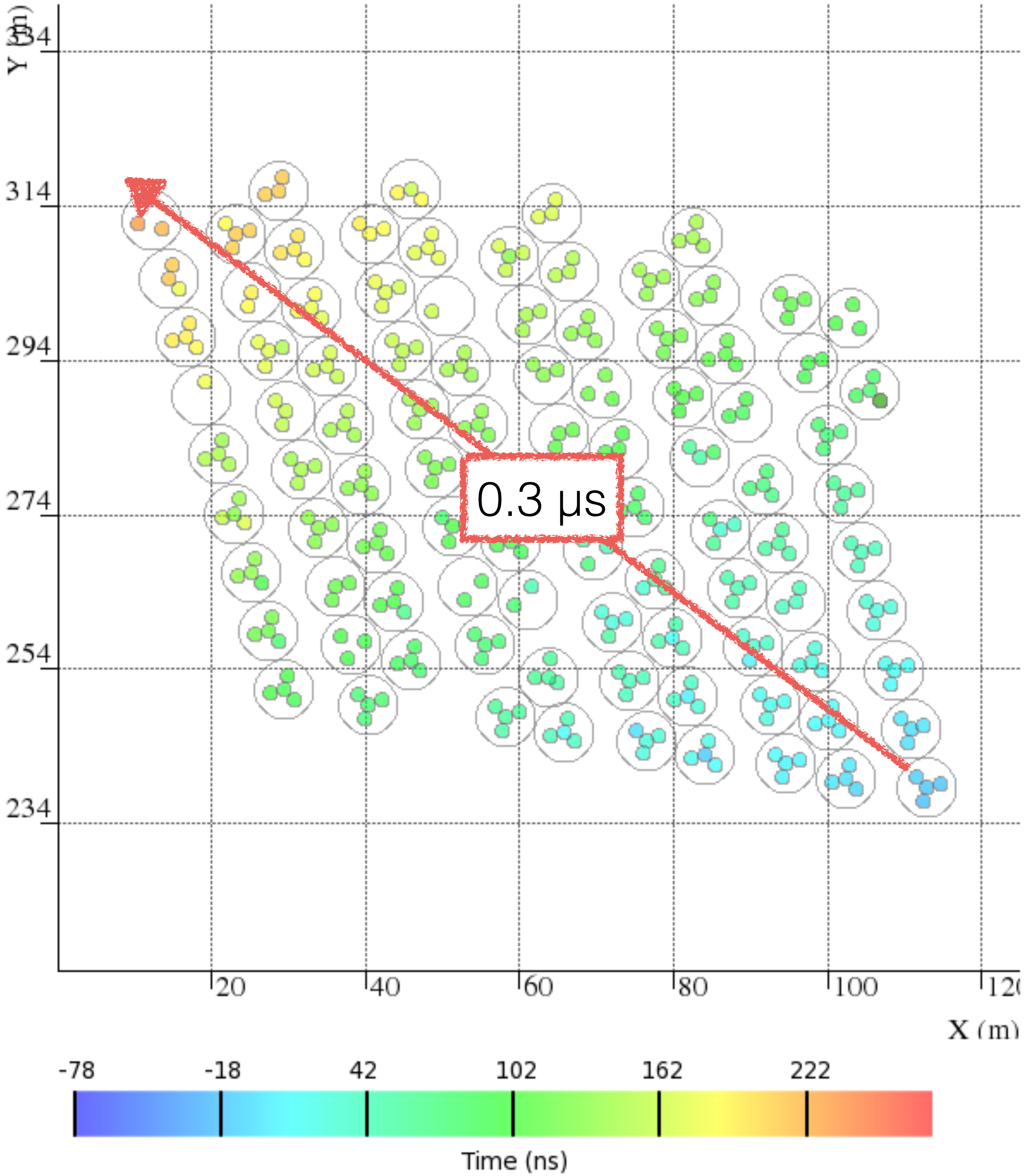






HAWC registers more than 20,000 cosmic rays per second, generating 2 Terabytes of data per day - every day.

Timing

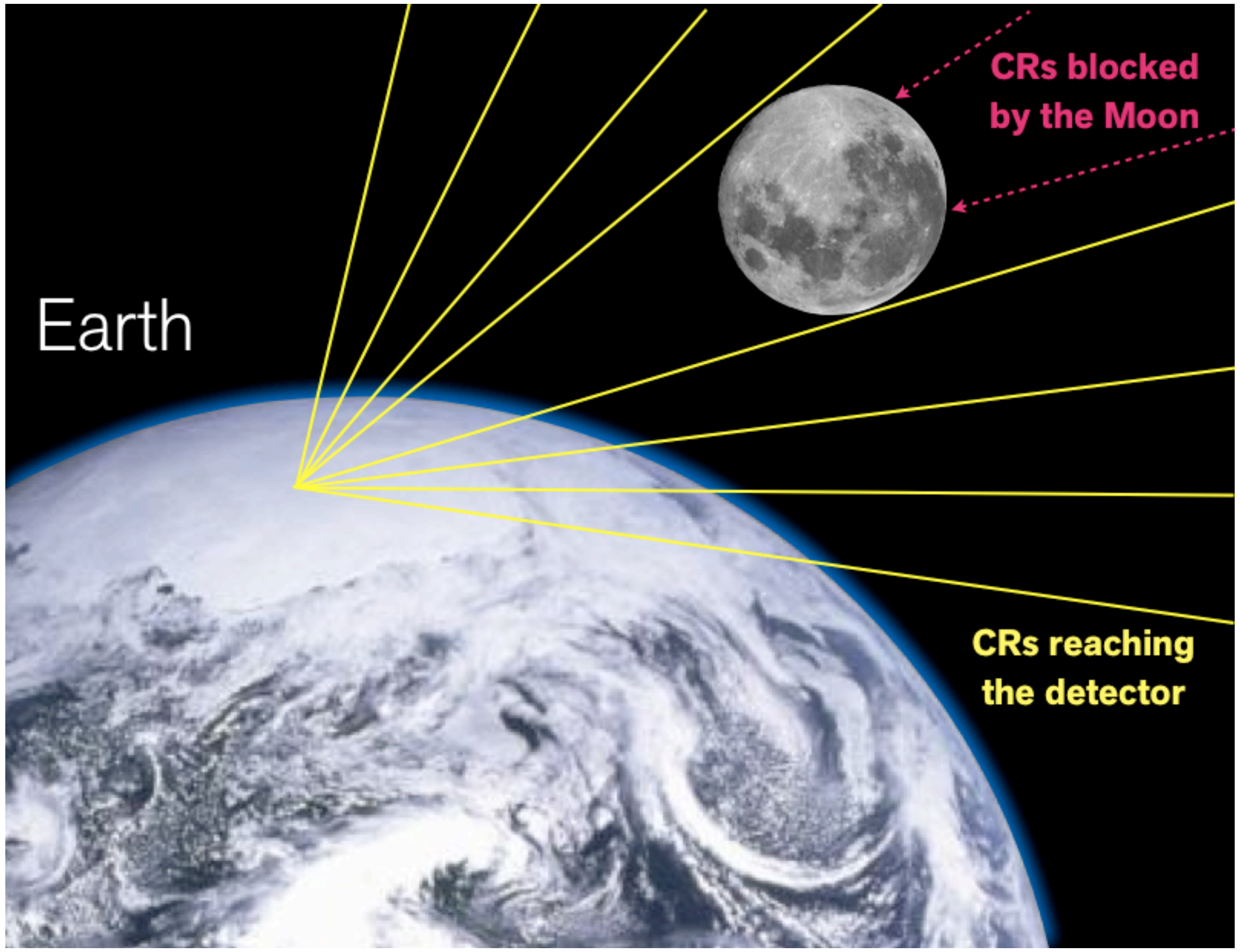


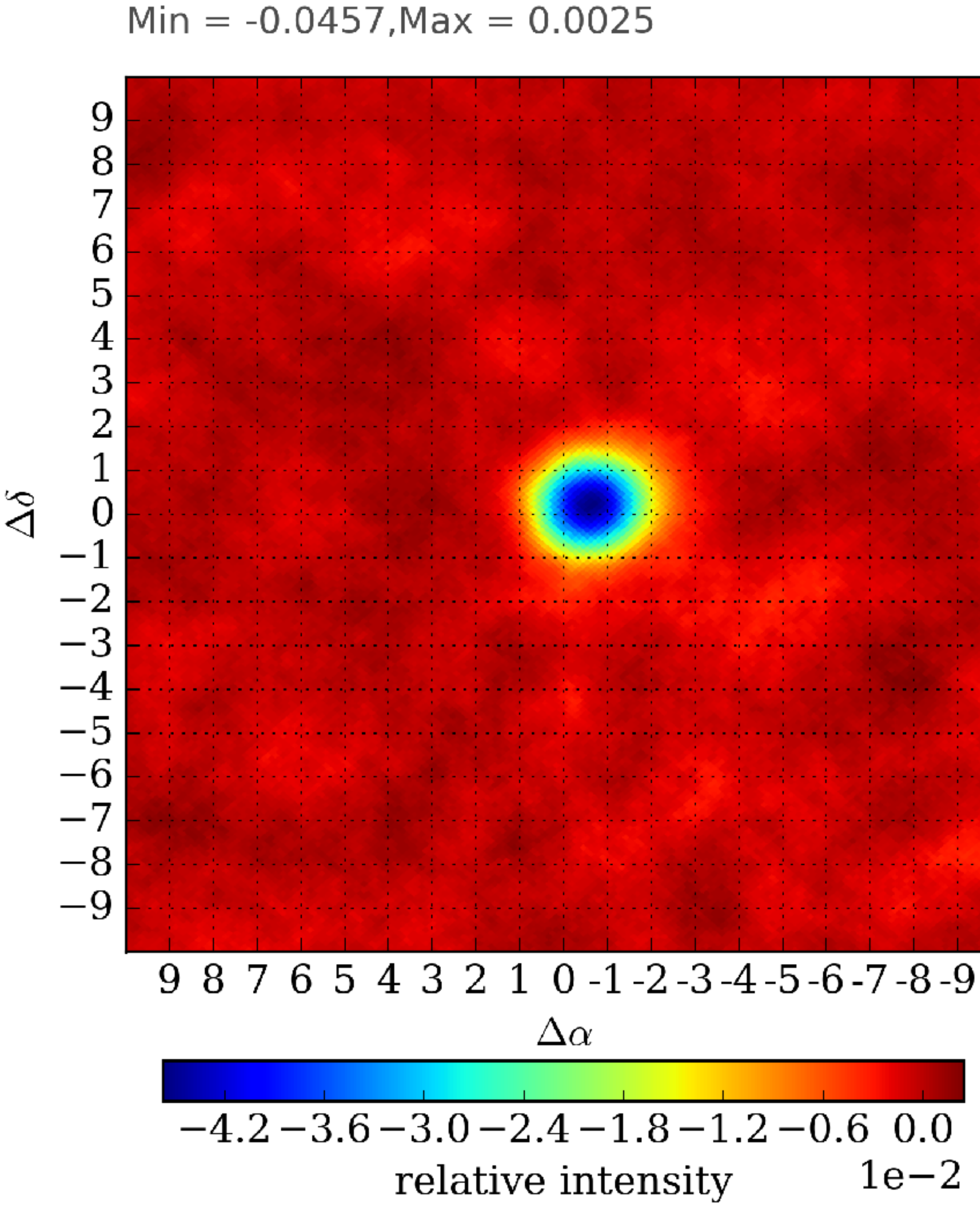
The front of particles takes about 20 *nano-seconds* to go from one tank to next.

Measuring the relative arrival times with precision allows determining the direction of the primary particle.

HAWC times showers with sub-ns residuals.

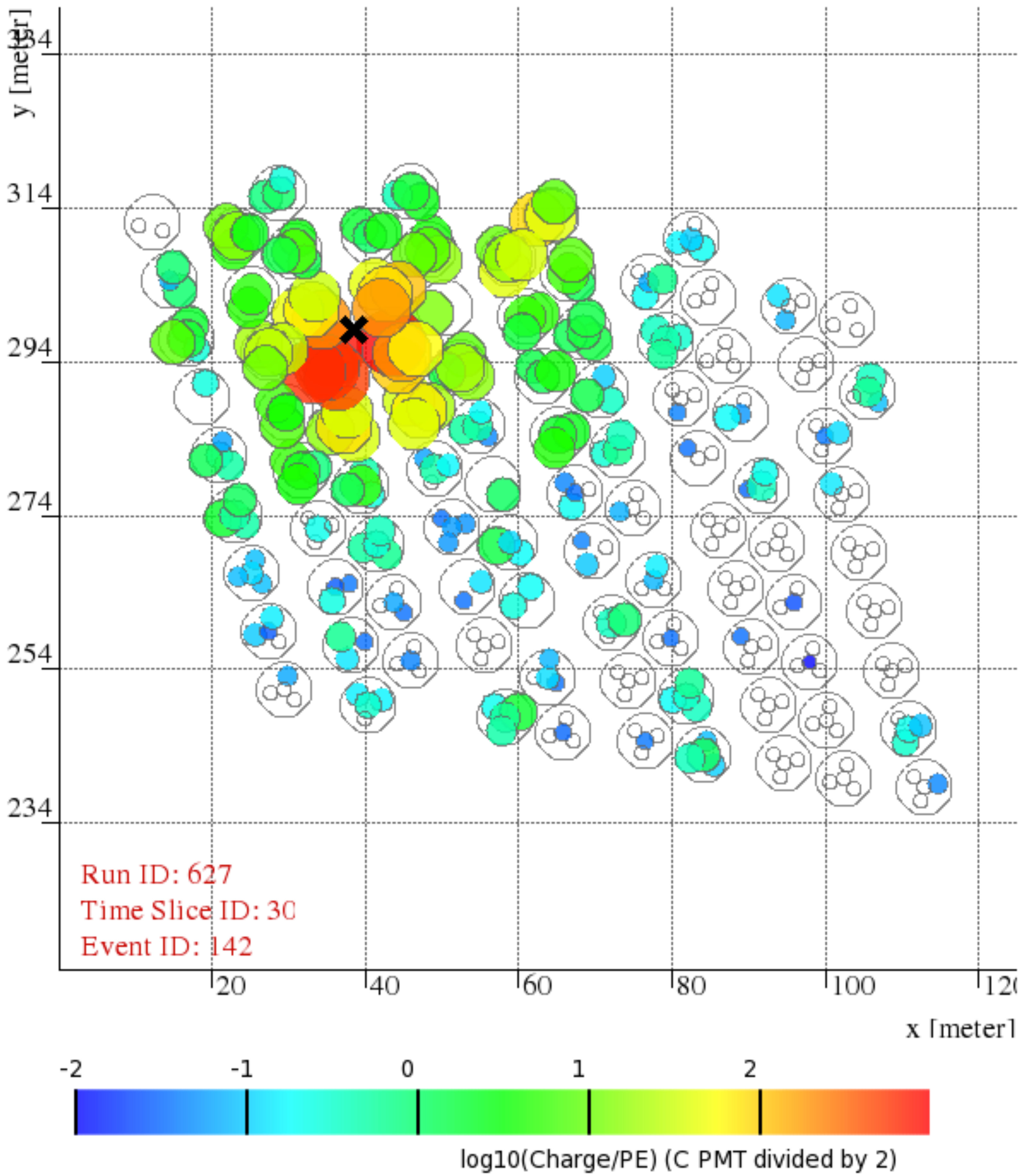
Cosmic rays: the Moon shadow





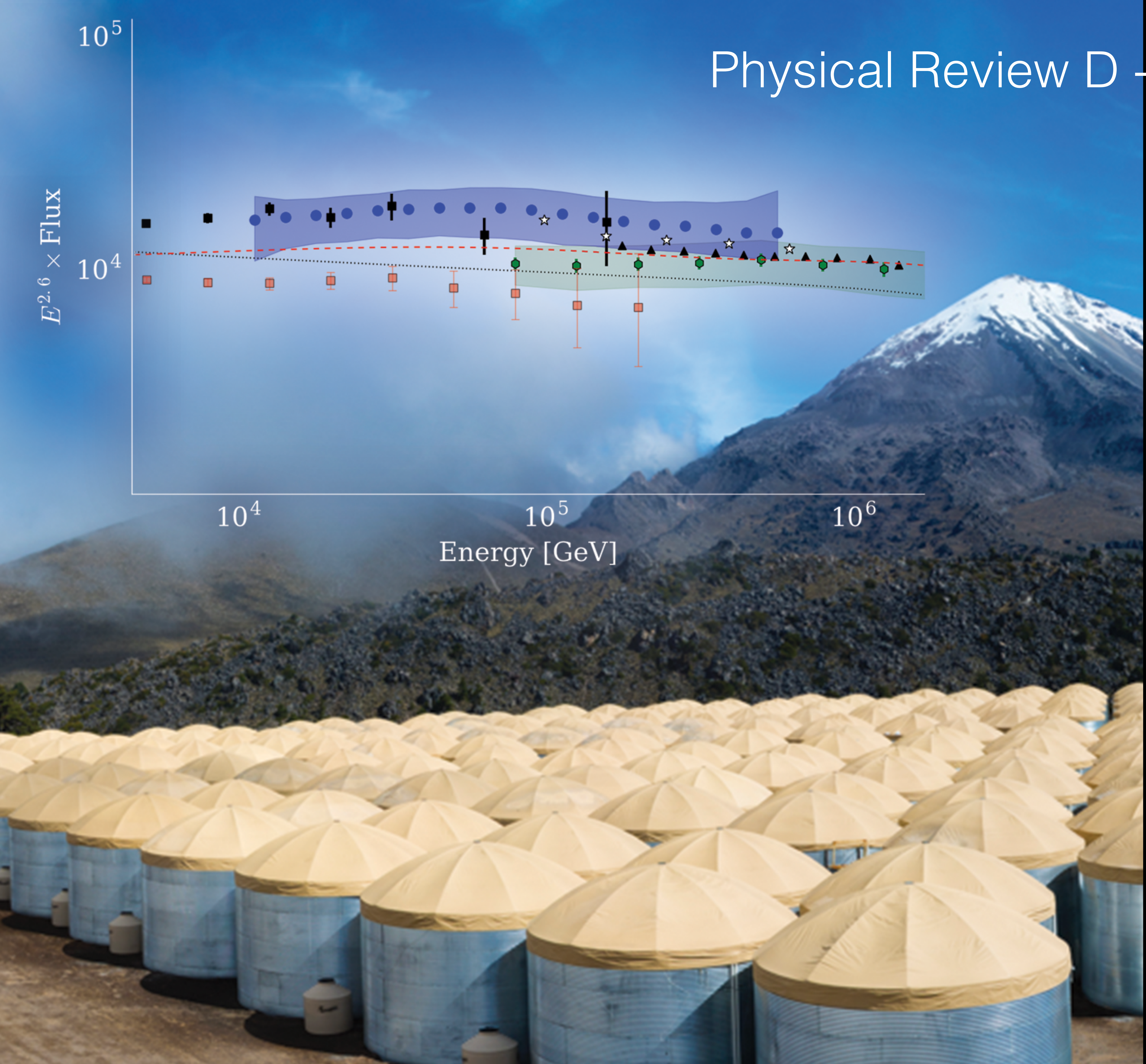
- Early pointing verification.
- Position and depth of the Moon depend on detector response and geomagnetic field.
- Search of antiprotons.

Abeysekara et al. (2018) Phys Rev D 97, 102005



Charge deposition

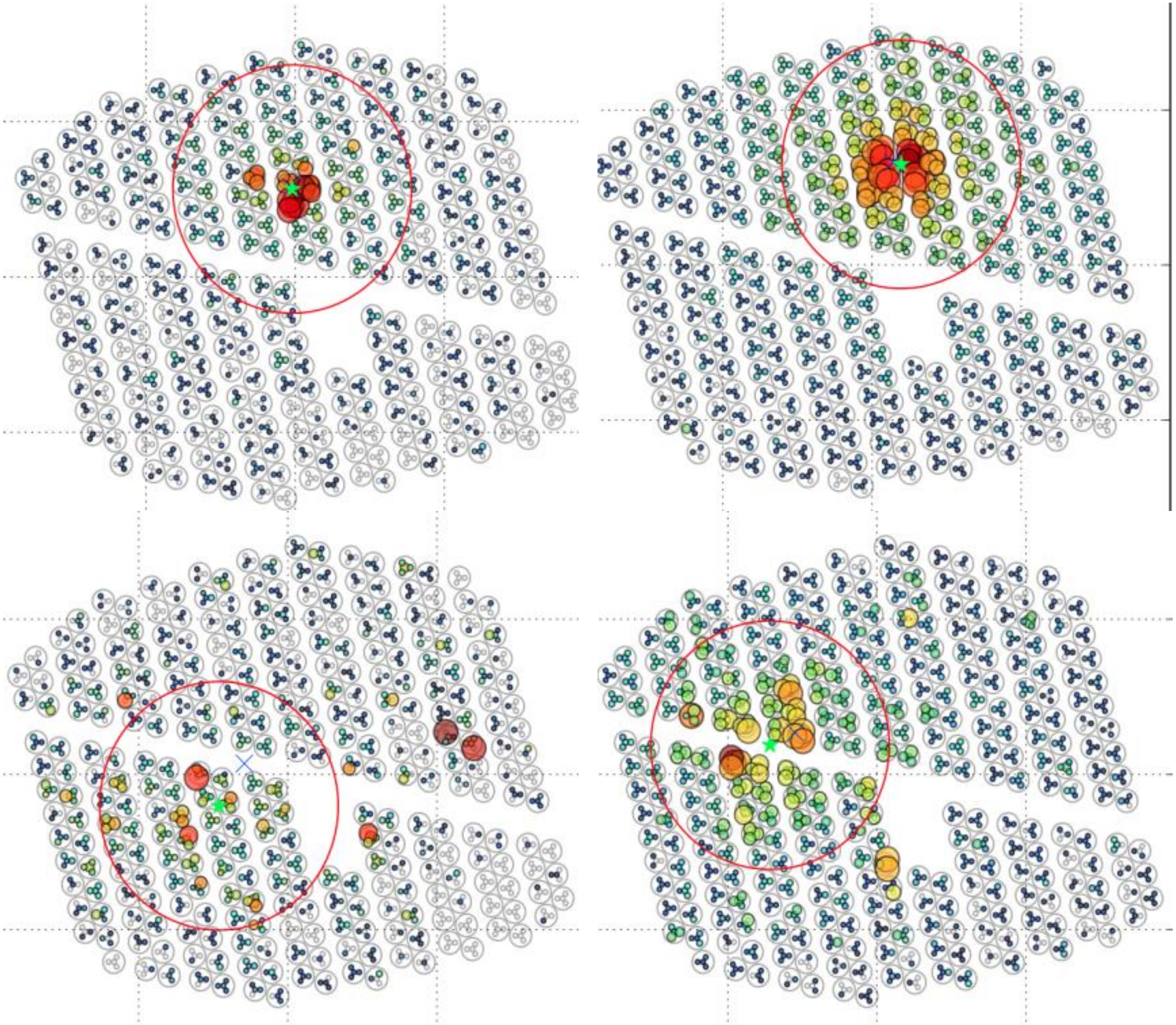
- Light pulses are recorded on each PMT, allowing for:
  - Energy estimation.
  - γ/hadron discrimination.
- Once the core of the shower is located, the radial distribution of particles is fitted with standard shower models (NKG) and Monte-carlo simulations of HAWC response.



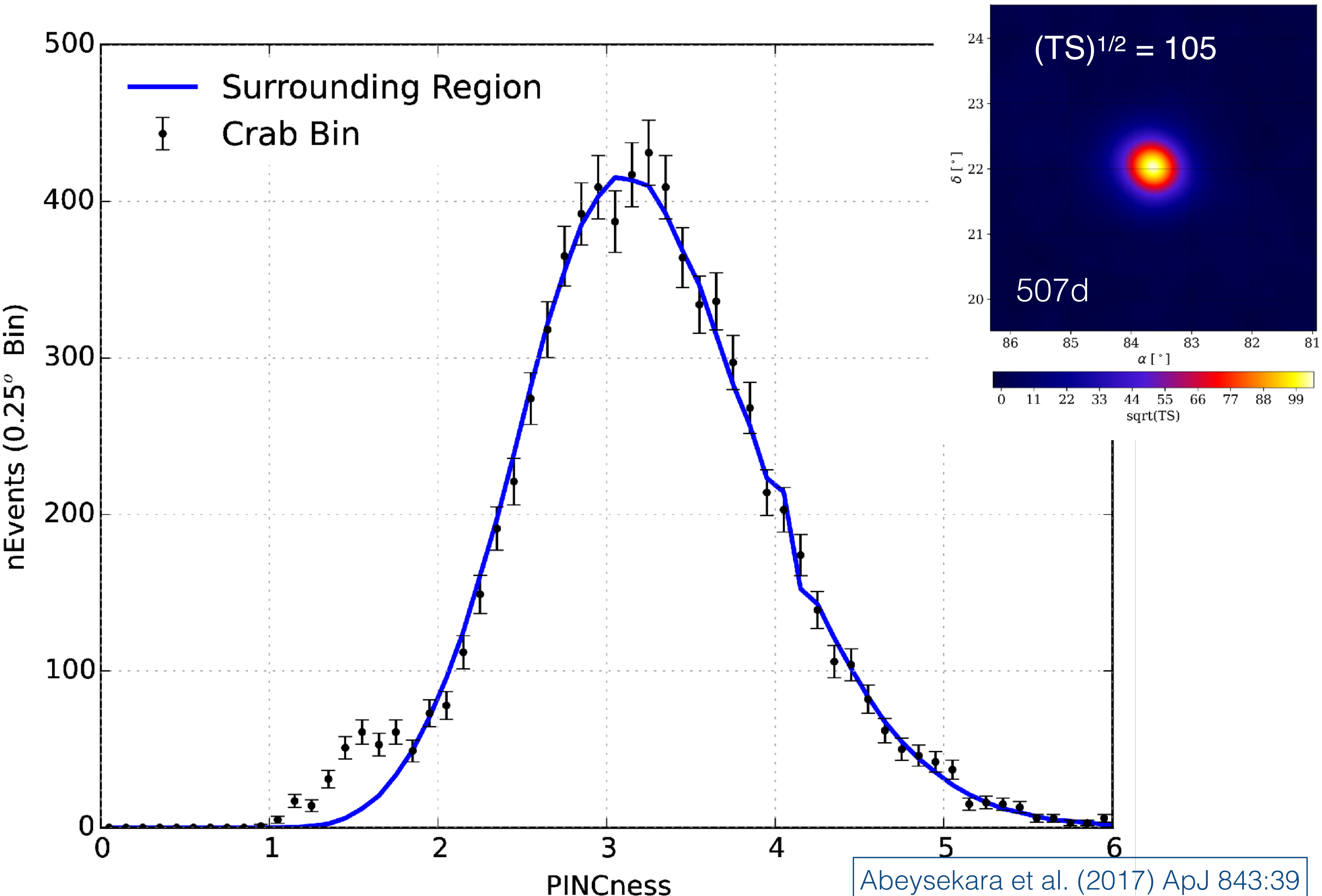
Physical Review D - Dec 2017

γ rays

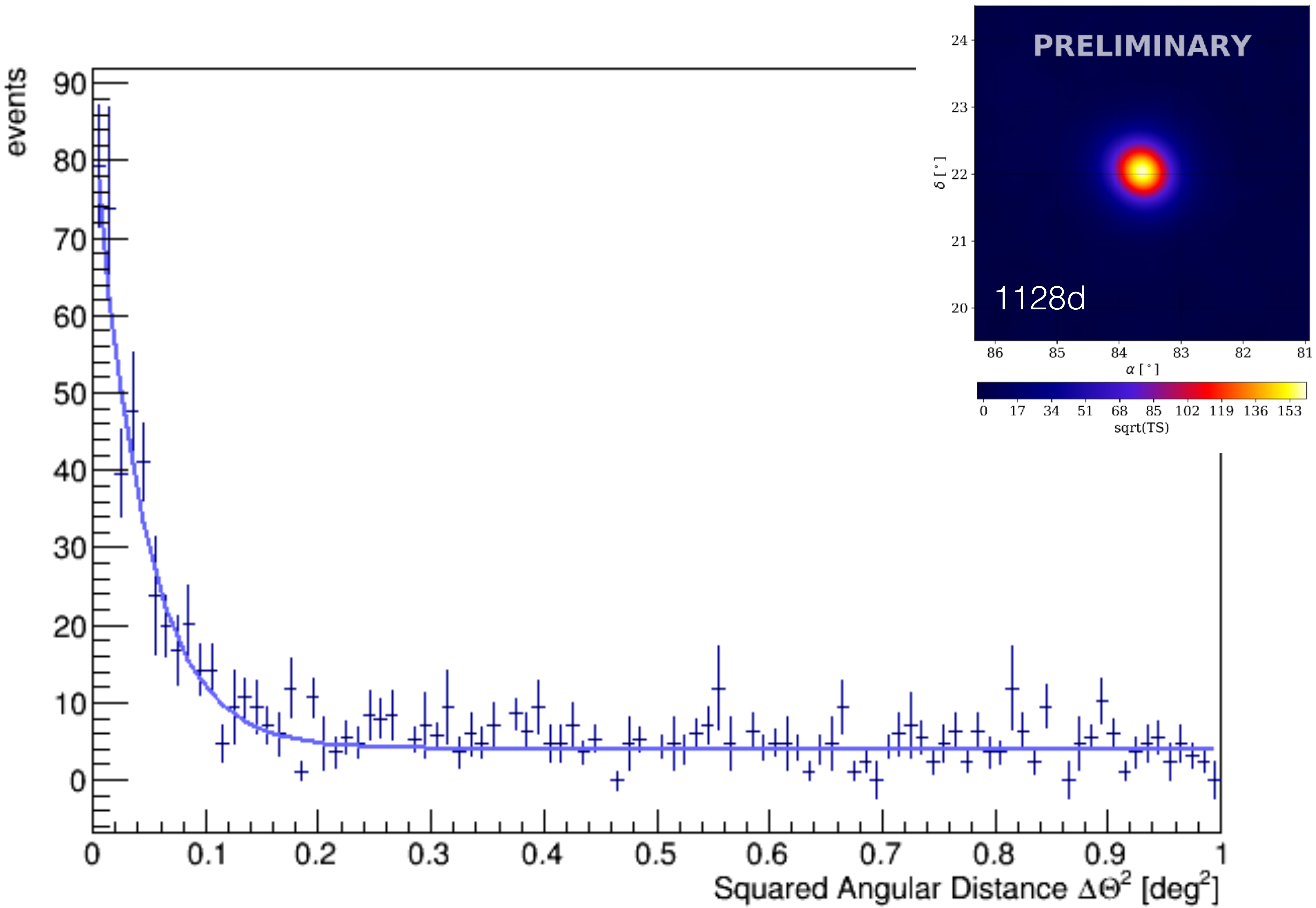
Hadrons



E

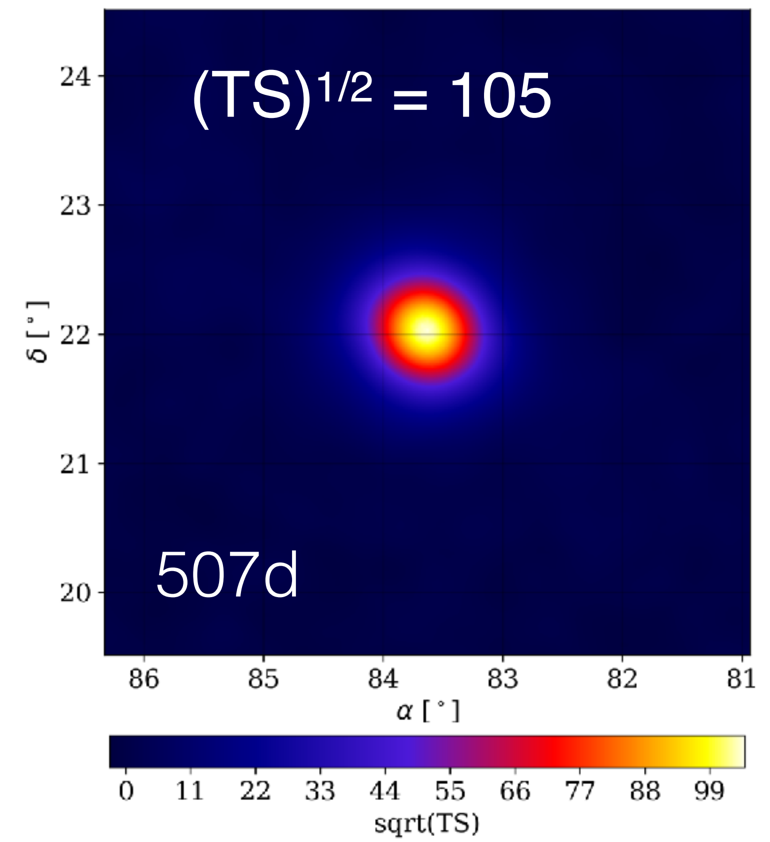


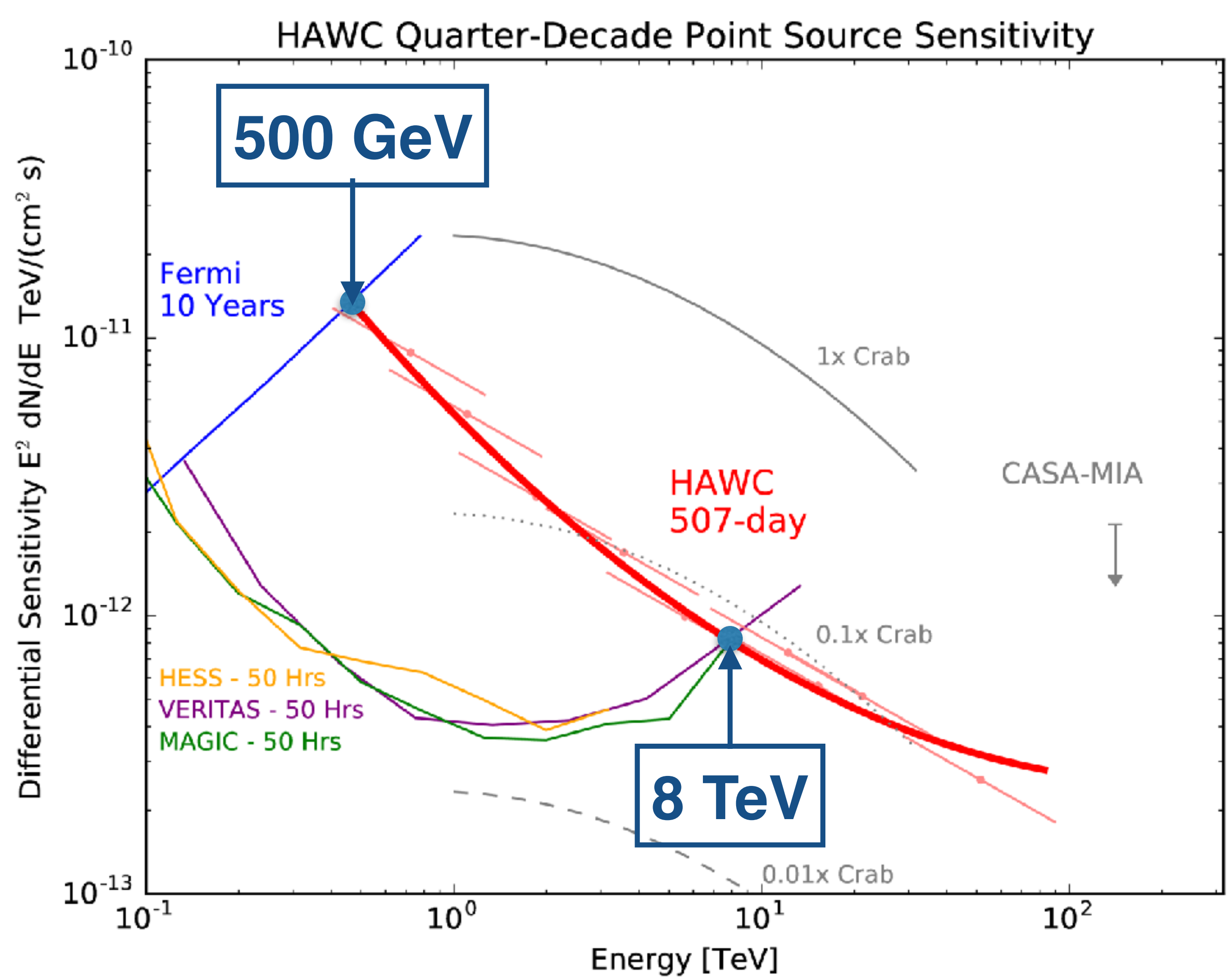
Abeysekara et al. (2017) ApJ 843:39

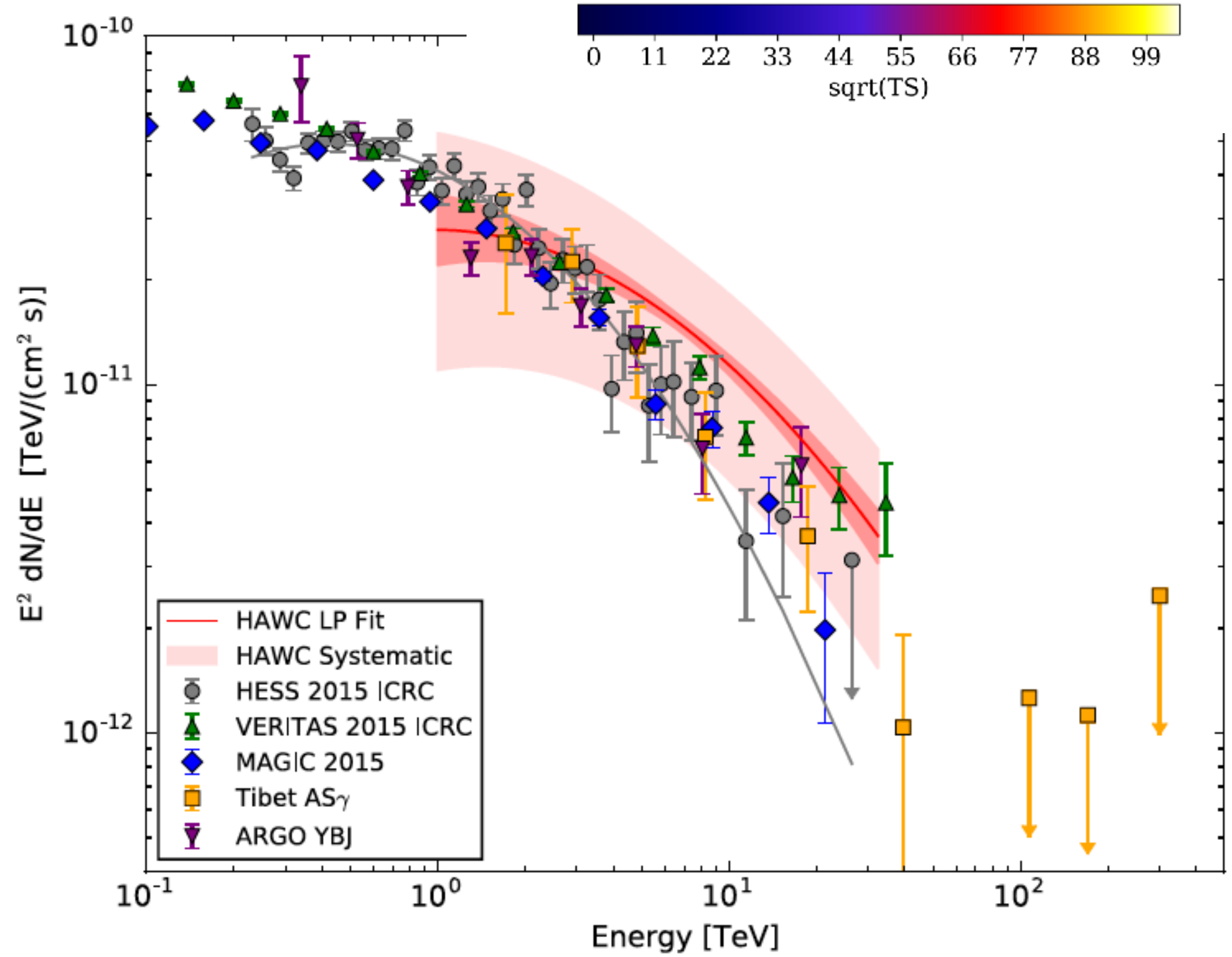

events
Squared Angular Distance ΔΘ² [deg²]
PRELIMINARY
1128d
δ [°]
α [°]
sqrt(TS)

The Crab Nebula

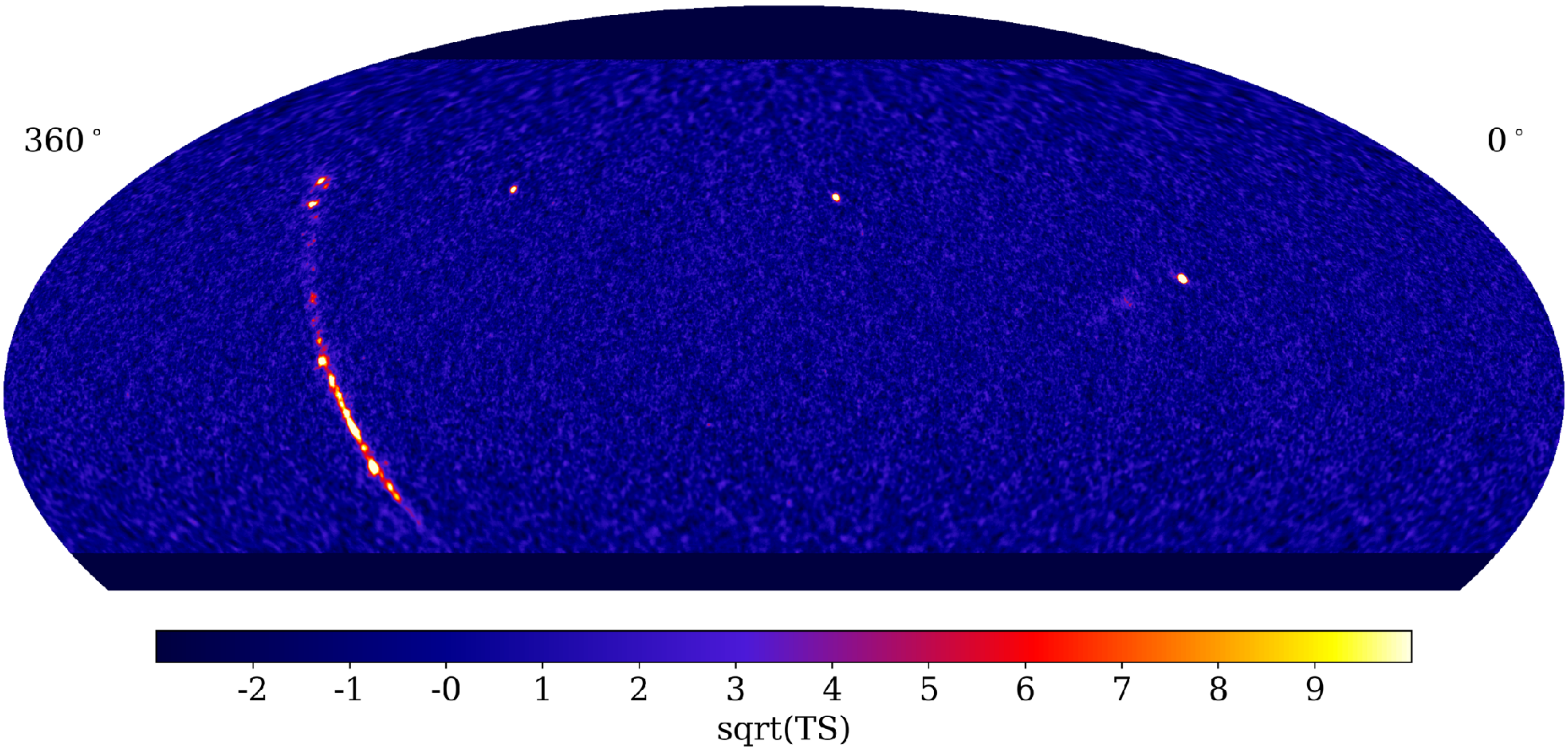
The 507 day data in Abeysekara et al. (2017)







The 2HWC catalog



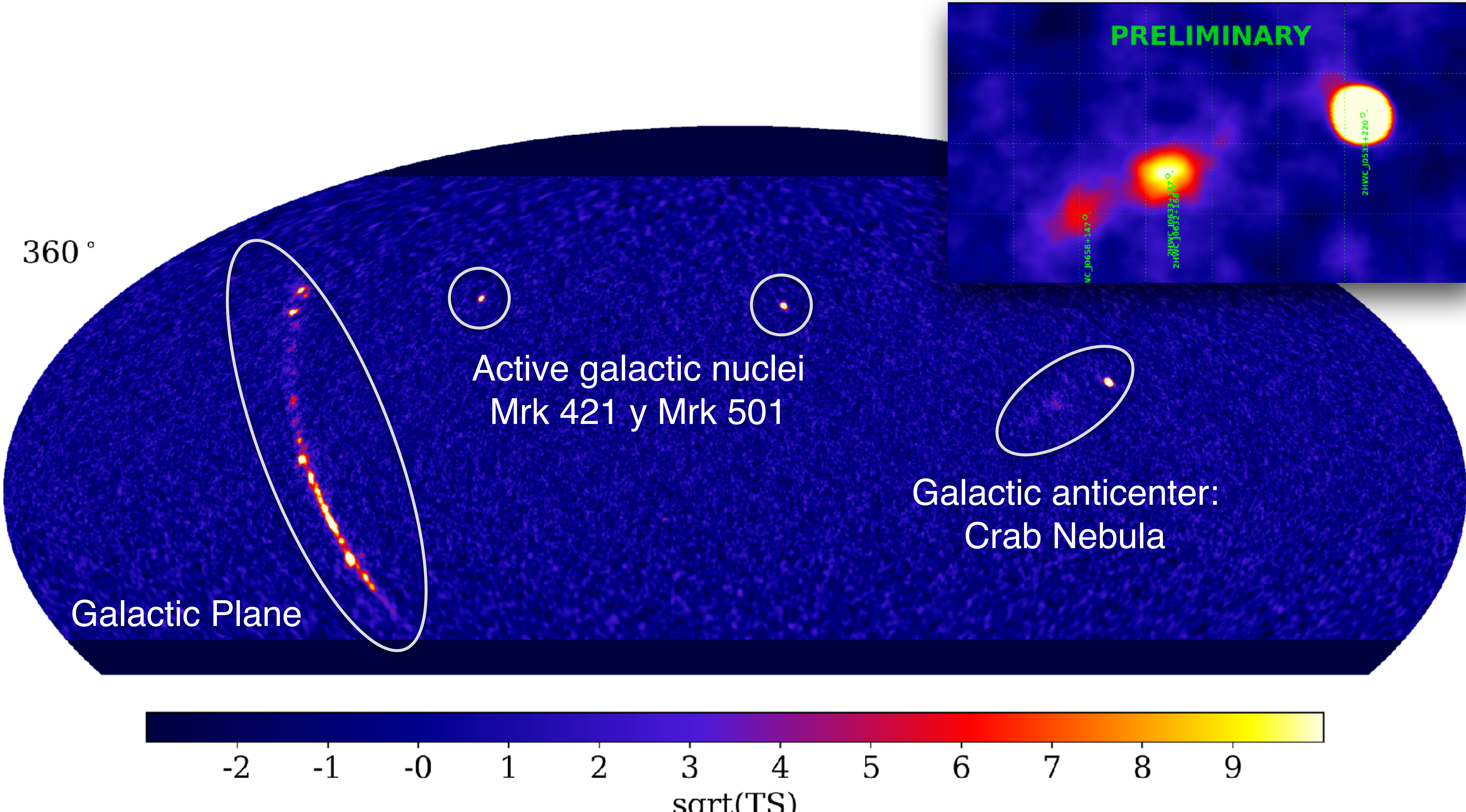
Abeysekara et al. (2017) ApJ 843:40

2HWC catalog

- 507 days of data, declination range −20º a +60º.
- Maximum likelihood analysis with fixed spectral model:
  - point source: $dN/dE = K\,(E/7\ \mathrm{TeV})^{-2.7}$
  - extended source: index= −2.0.
- The 2HWC catalog contains 39 sources, 19 of which were not previously reported at TeV energies.

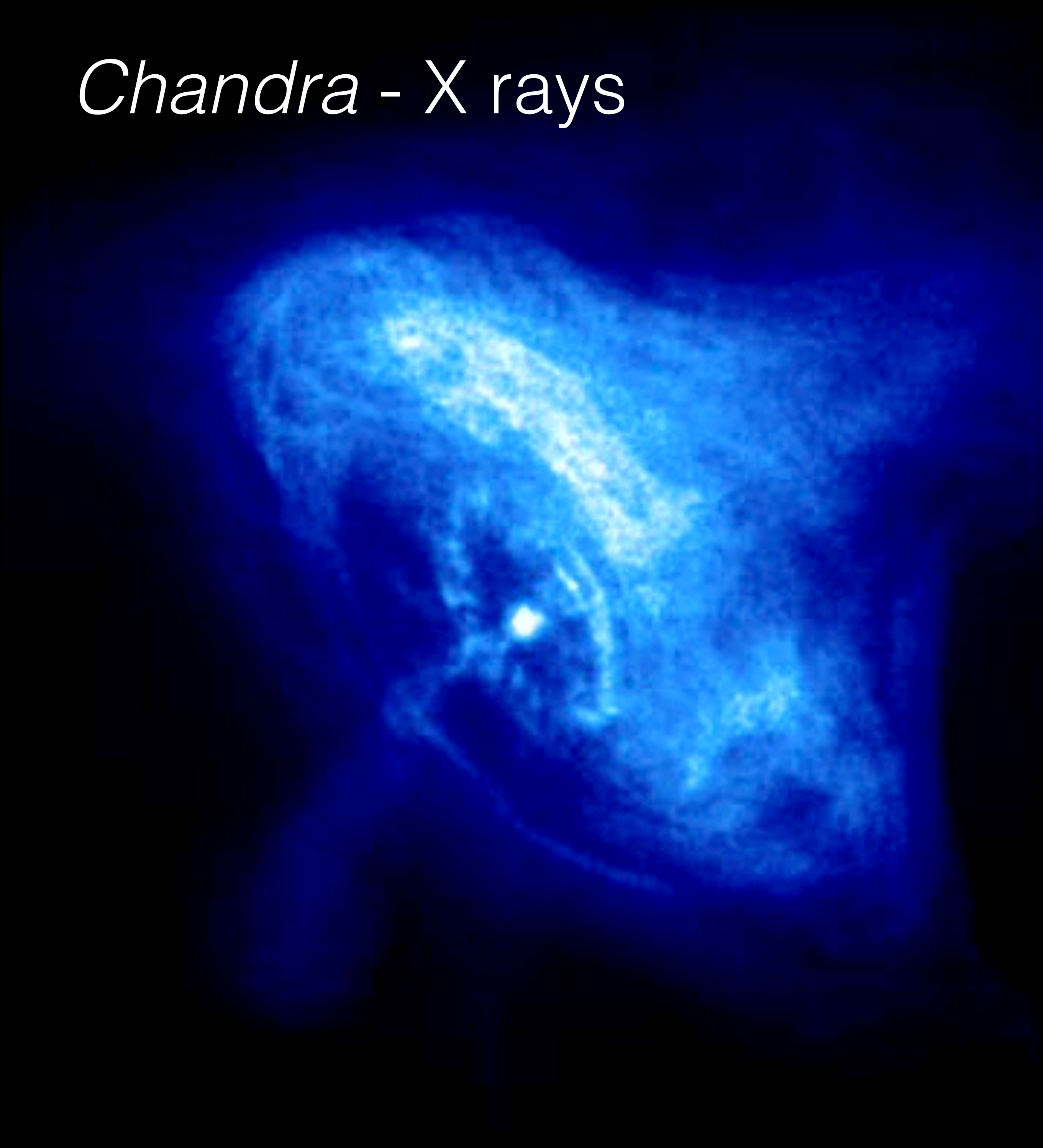
Abeysekara et al. (2017) ApJ 843:40

The sky at TeV photon energies

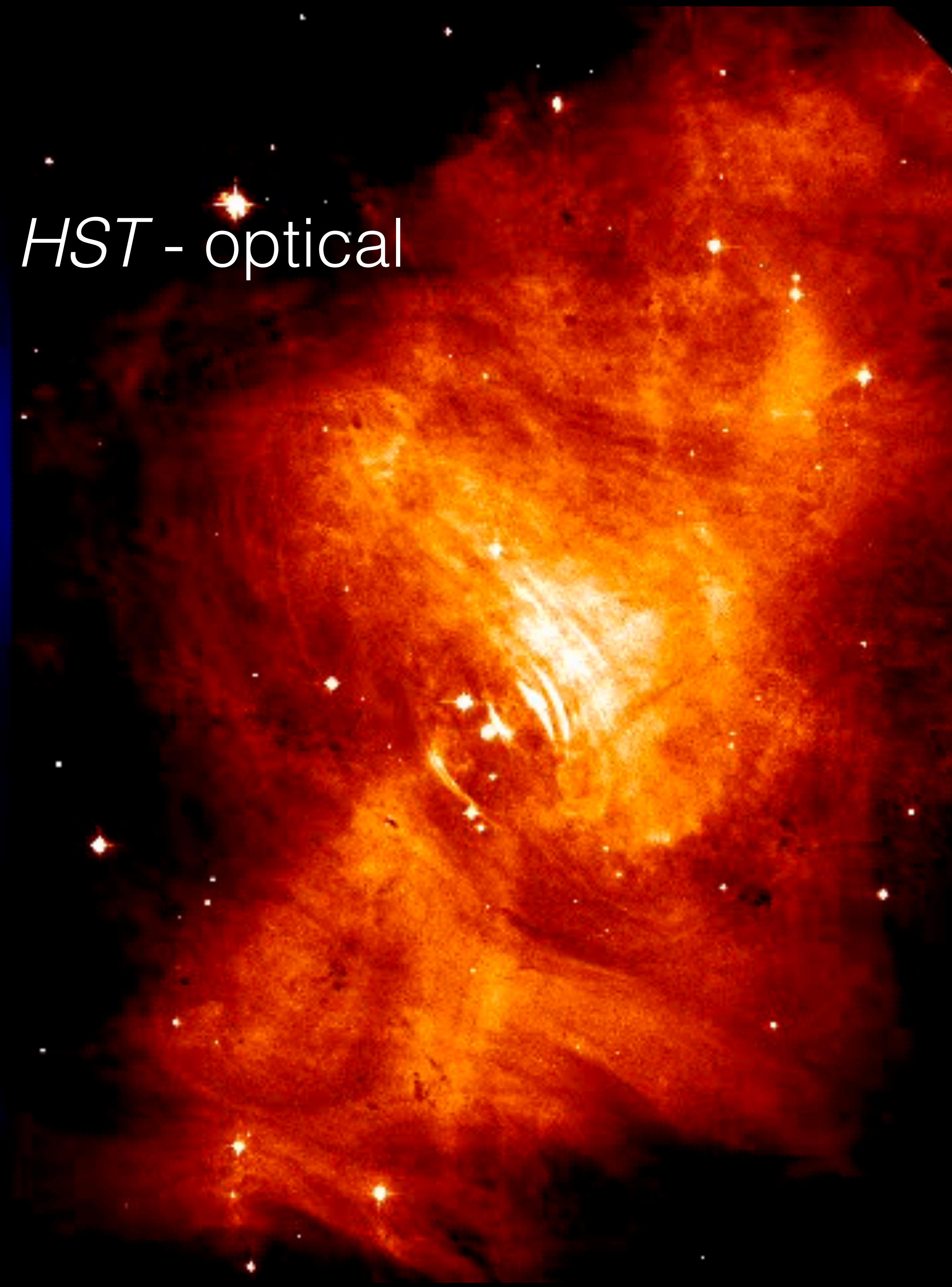


The Crab Nebula

Chandra - X rays

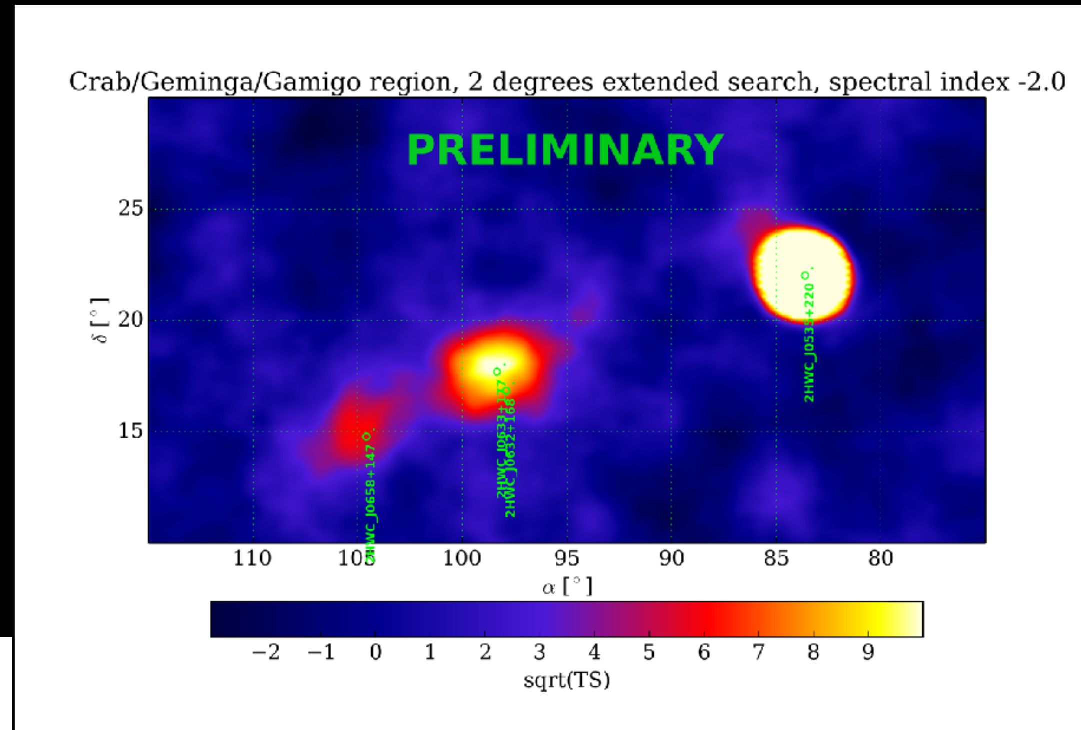


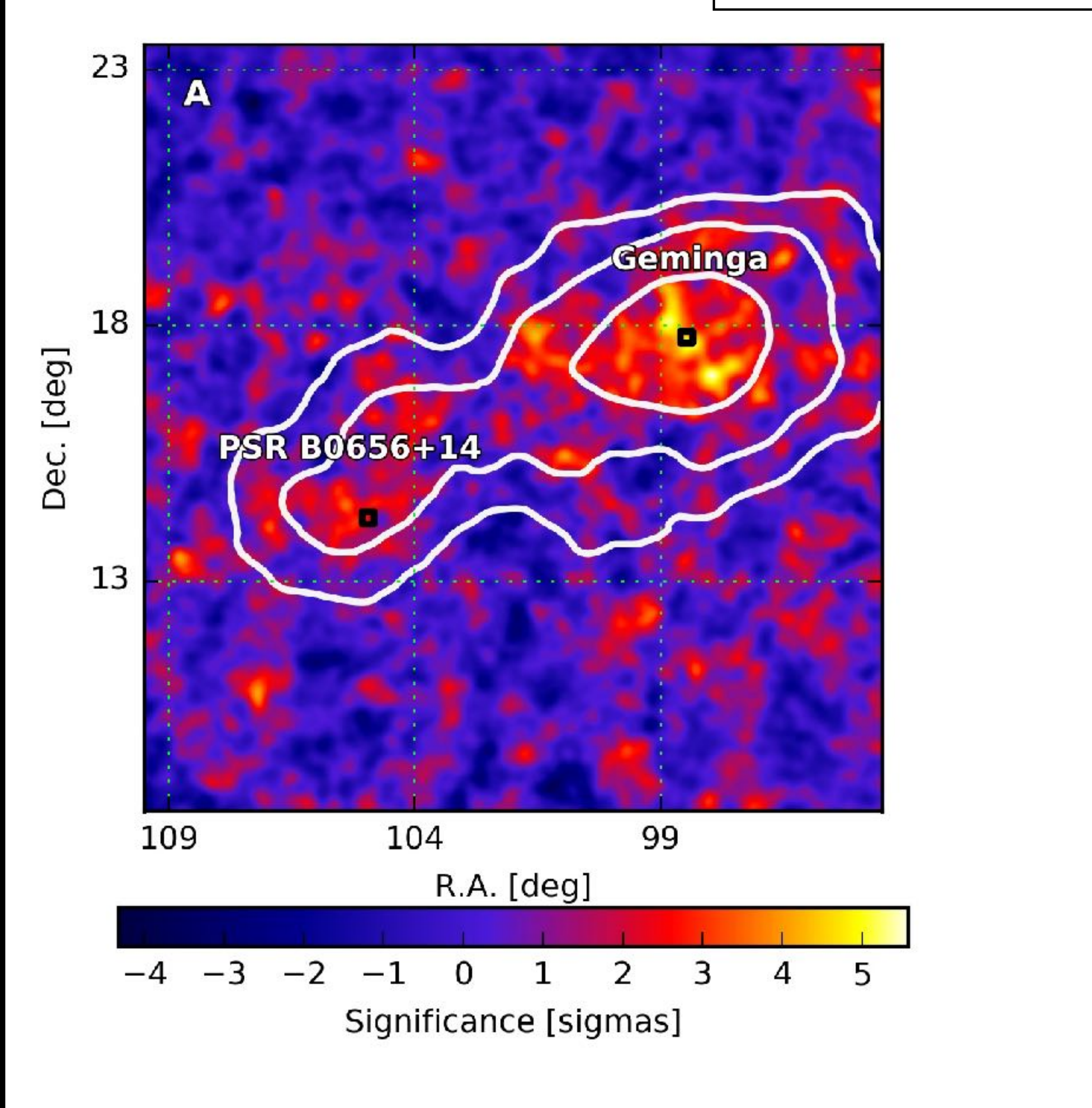
HST - optical

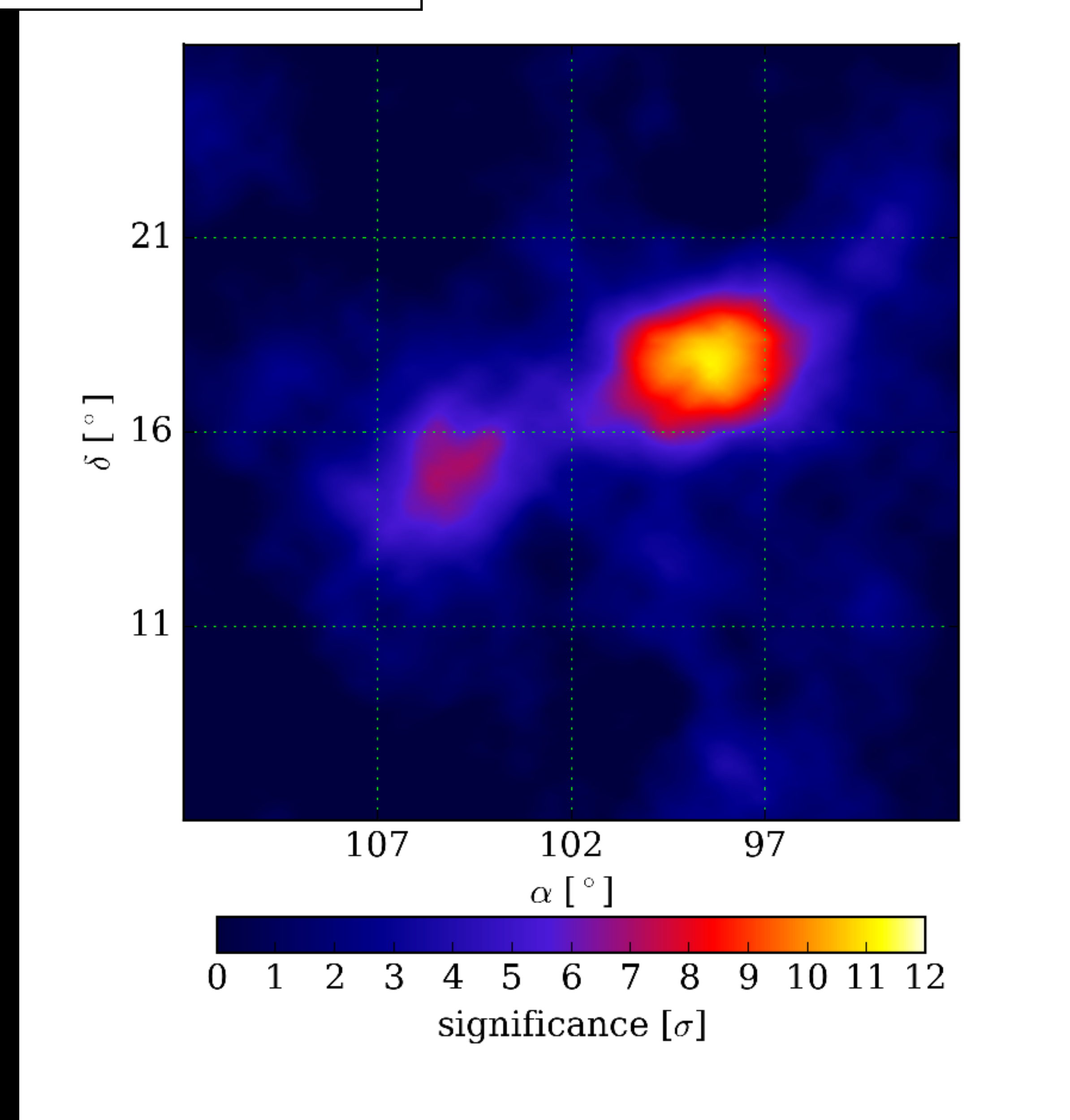


Hester et al. (1995)
Weisskopf et al. (2000)

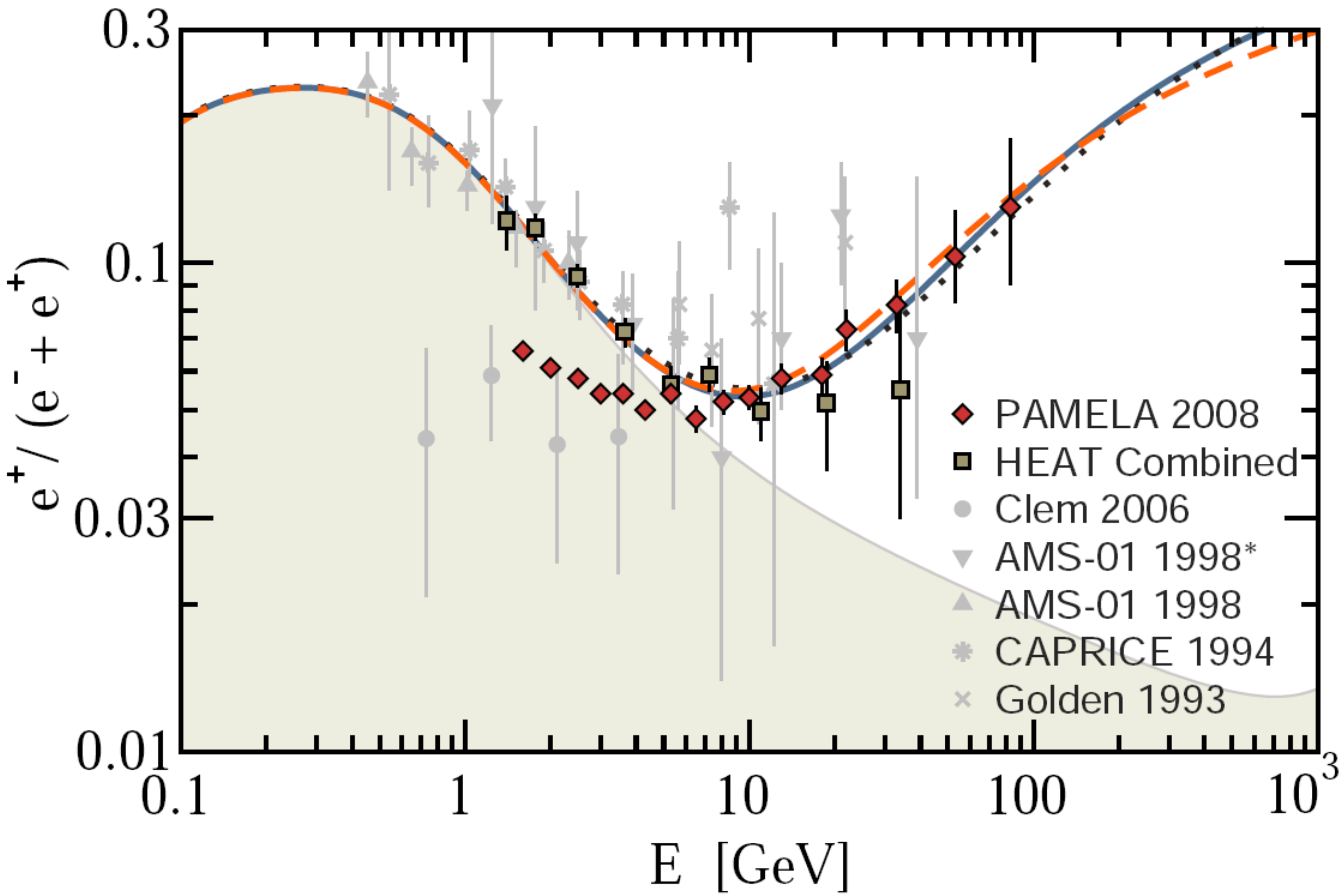
Pulsar Wind Nebulae







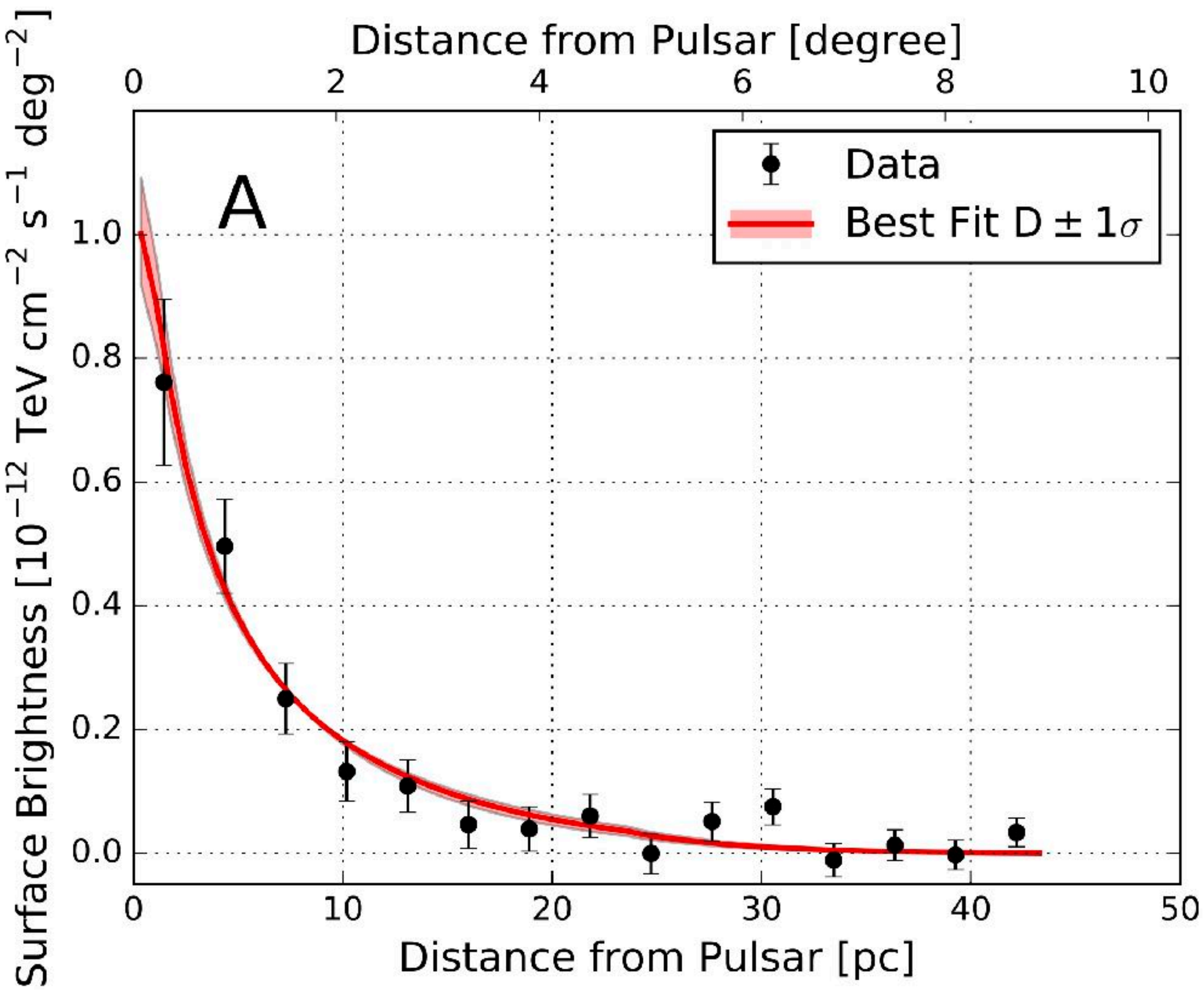
The positron CR excess



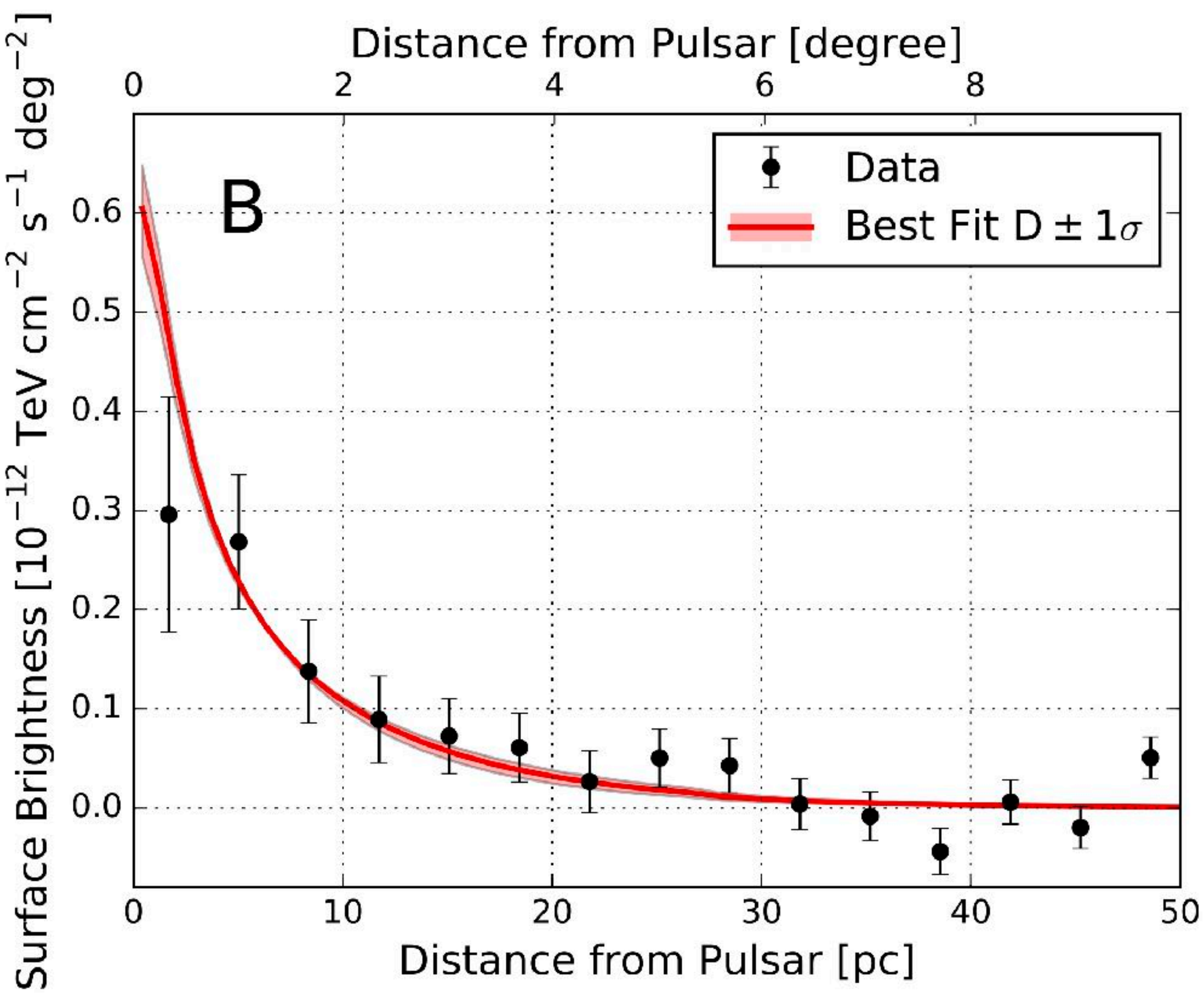
- Pulsars are efficient e^+e^- factories.
- But $e^\pm$ don't travel well….
- $e^\pm$ could also be produced by dark matter.

Yuksel, Klister, Stanev (2009)

Geminga

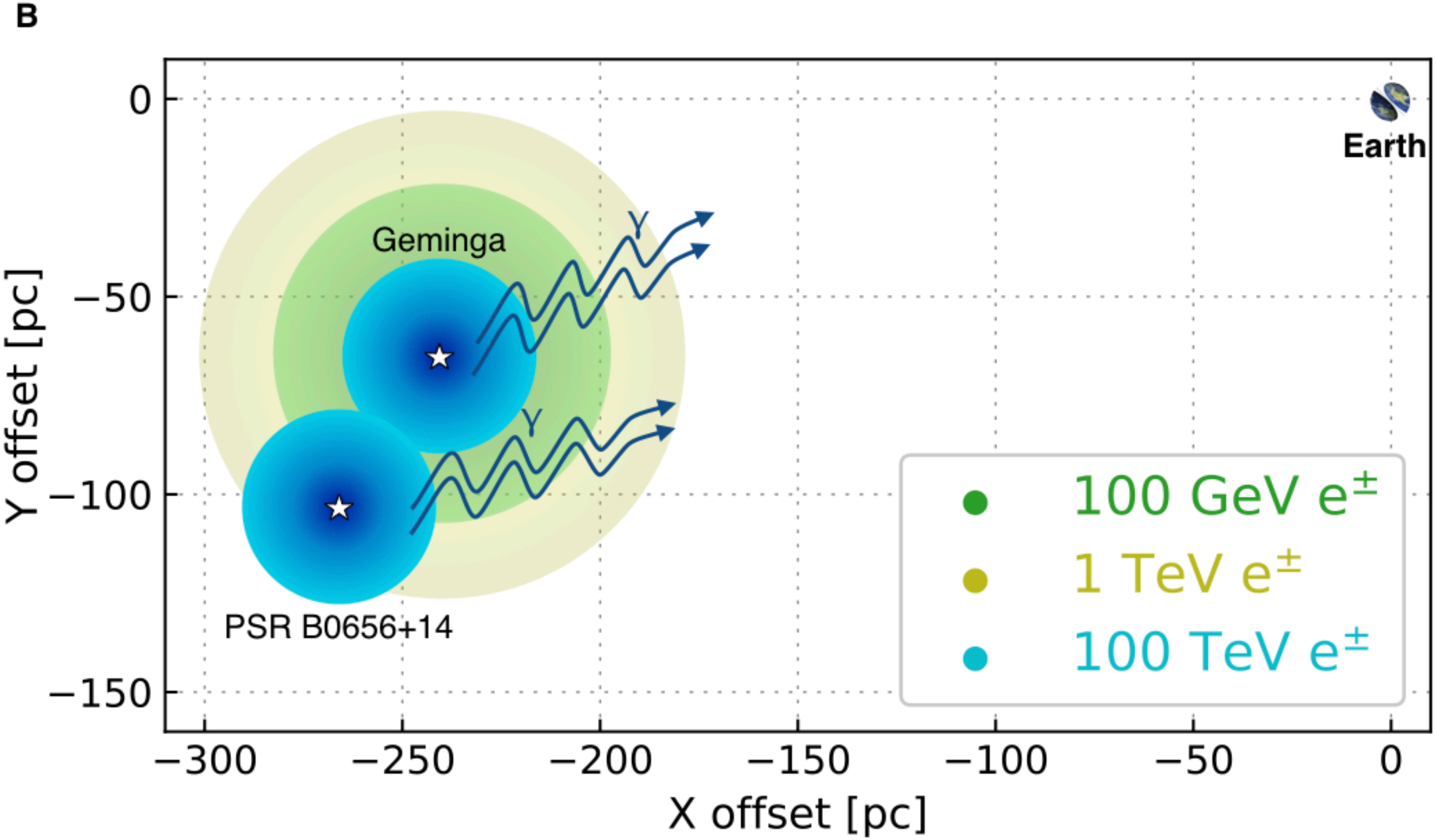


Monogem - B0656+14



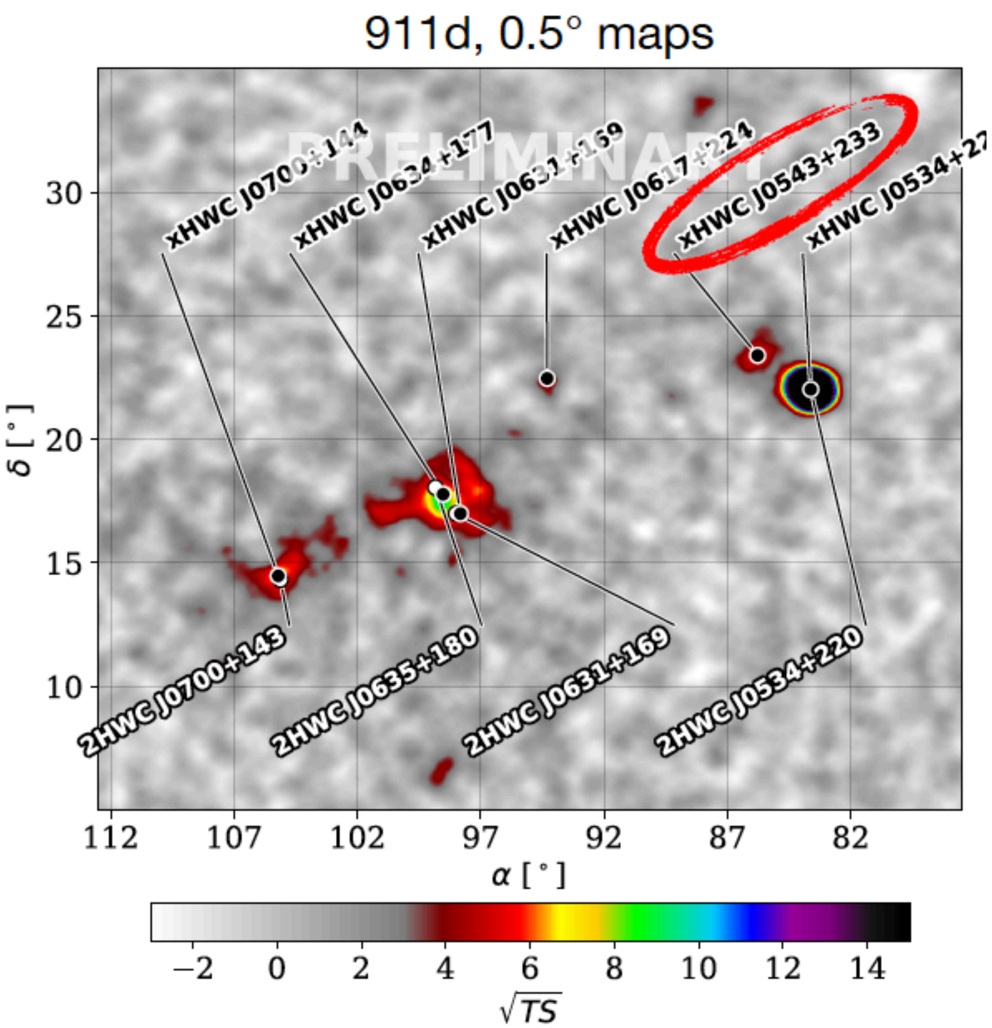
HAWC, Science 358, 911 (2017)

The positron excess cannot be explained with the most energetic nearby pulsars



Abeysekara et al. (2017), Science 358, 911.

And another one…!



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)

Subjects: Gamma Ray, TeV, VHE, Pulsar

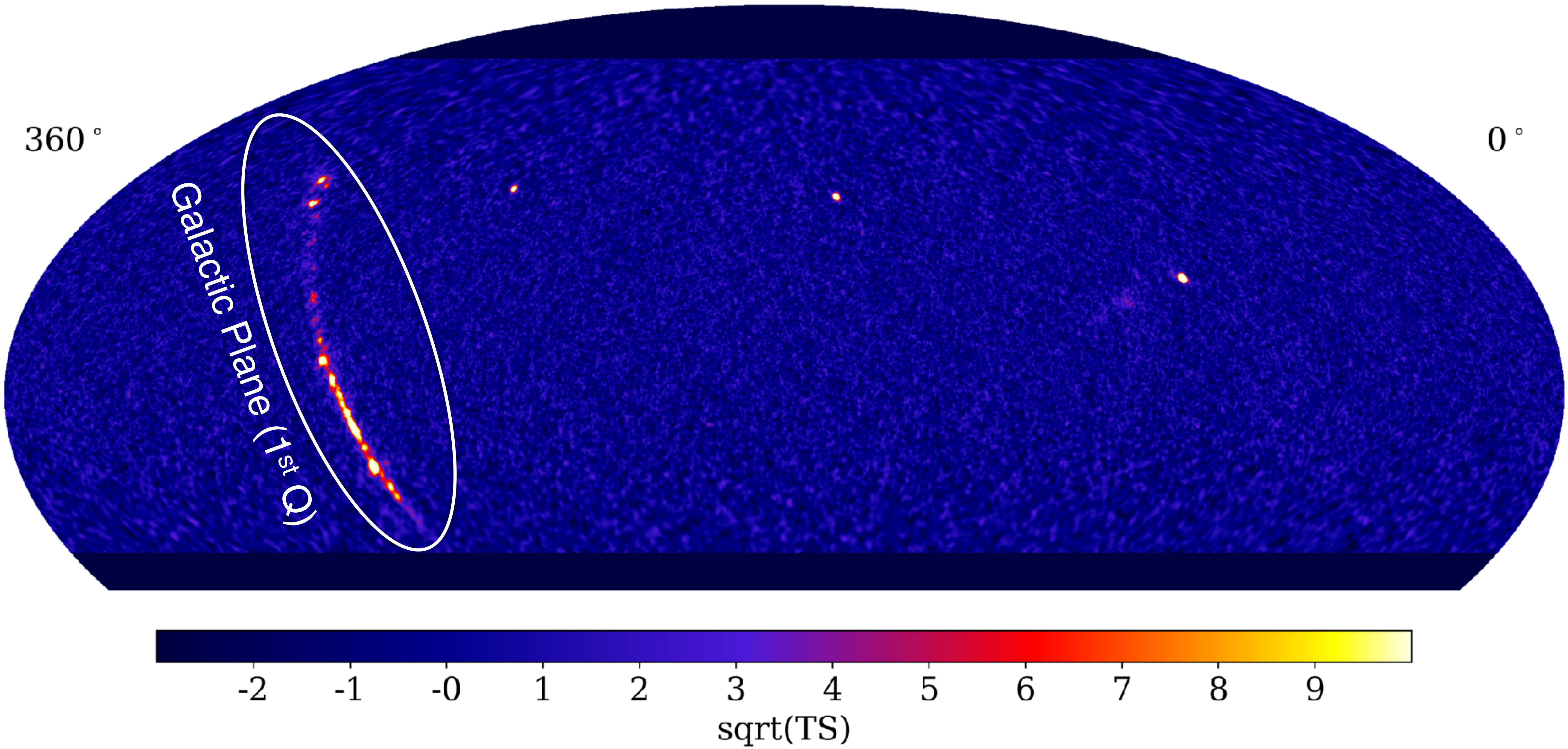
Tweet | Recommend 5

The High Altitude Water Cherenkov (HAWC) collaboration reports the discovery of a new TeV gamma-ray source HAWC J0543+233. It was discovered in a search for extended sources of radius 0.5° in a dataset of 911 days (ranging from November 2014 to August 2017) with a test statistic value of 36 (6σ pre-trials), following the method presented in Abeysekara et al. 2017, ApJ, 843, 40. The measured J2000.0 equatorial position is RA=85.78°, Dec=23.40° with a statistical uncertainty of 0.2°. HAWC J0543+233 was close to passing the selection criteria of the 2HWC catalog (Abeysekara et al. 2017, ApJ, 843, 40, see HAWC J0543+233 in 2HWC map), which it now fulfills with the additional data.

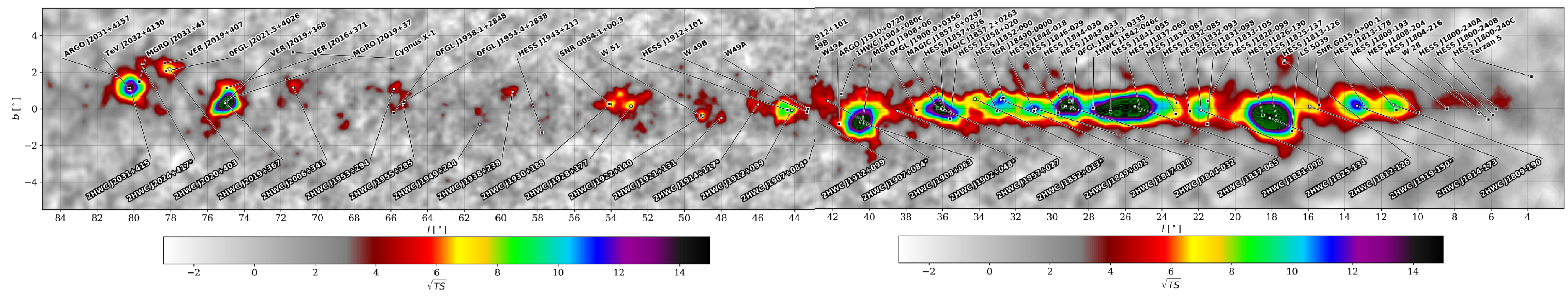
HAWC J0543+233 is positionally coincident with the pulsar PSR B0540+23 (Edot = 4.1e+34 erg s-1, dist = 1.56 kpc, age = 253 kyr). It is the third low Edot, middle-aged pulsar announced to be detected with a TeV halo, along with Geminga and B0656+14. It was predicted to be one of the next such detection by HAWC by Linden et al., 2017, arXiv:1703.09704.

Using a simple source model consisting of a disk of radius 0.5°, the measured spectral index is -2.3 ± 0.2 and the differential flux at 7 TeV is (7.9 ± 2.3) × 10^-15 TeV-1 cm-2 s-1. The errors are statistical only. Further morphological and spectral analysis as well as studies of the systematic uncertainty are ongoing.

The Galactic Plane



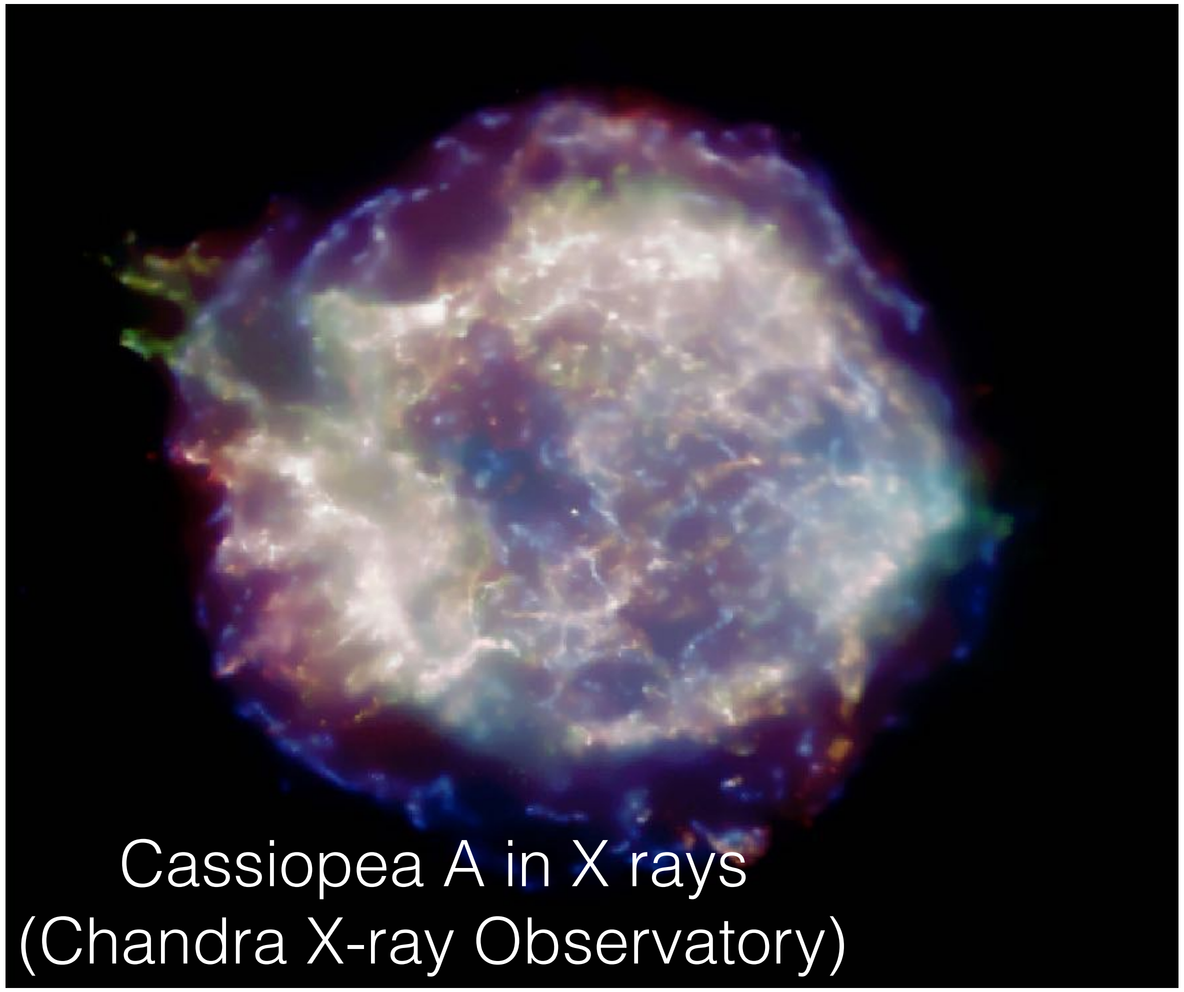
The Galactic Plane



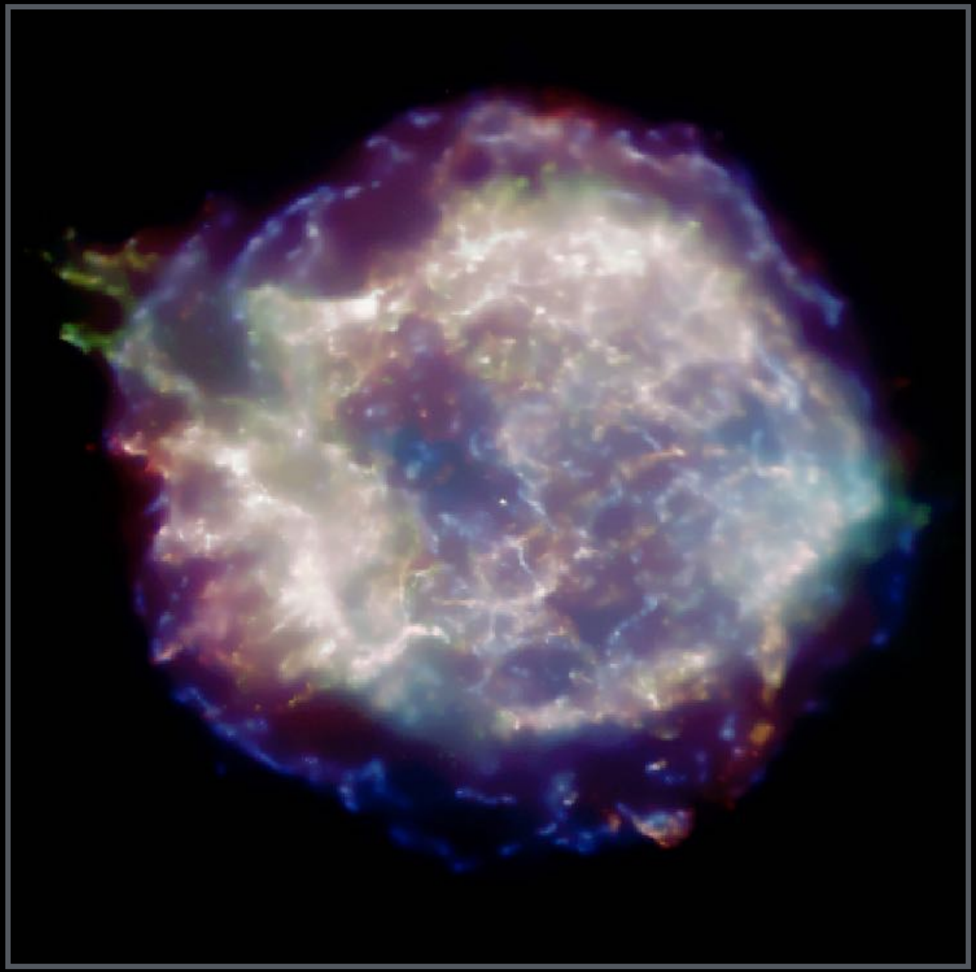
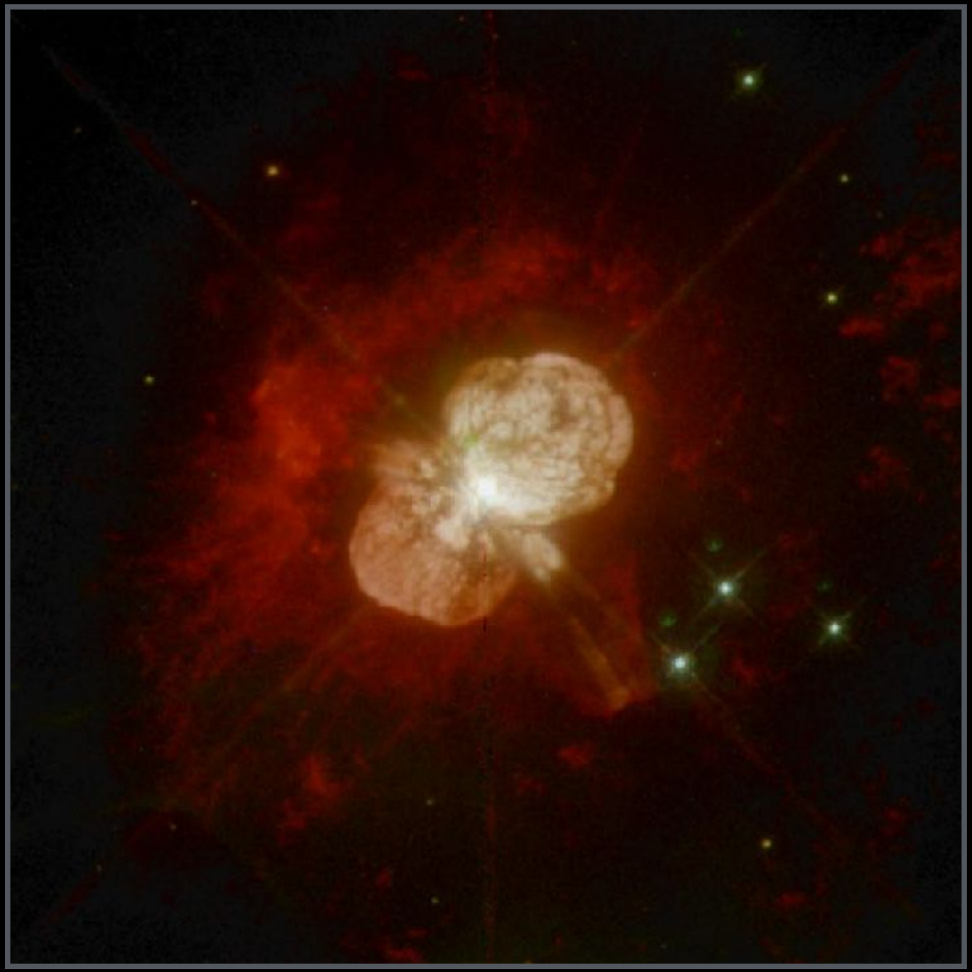
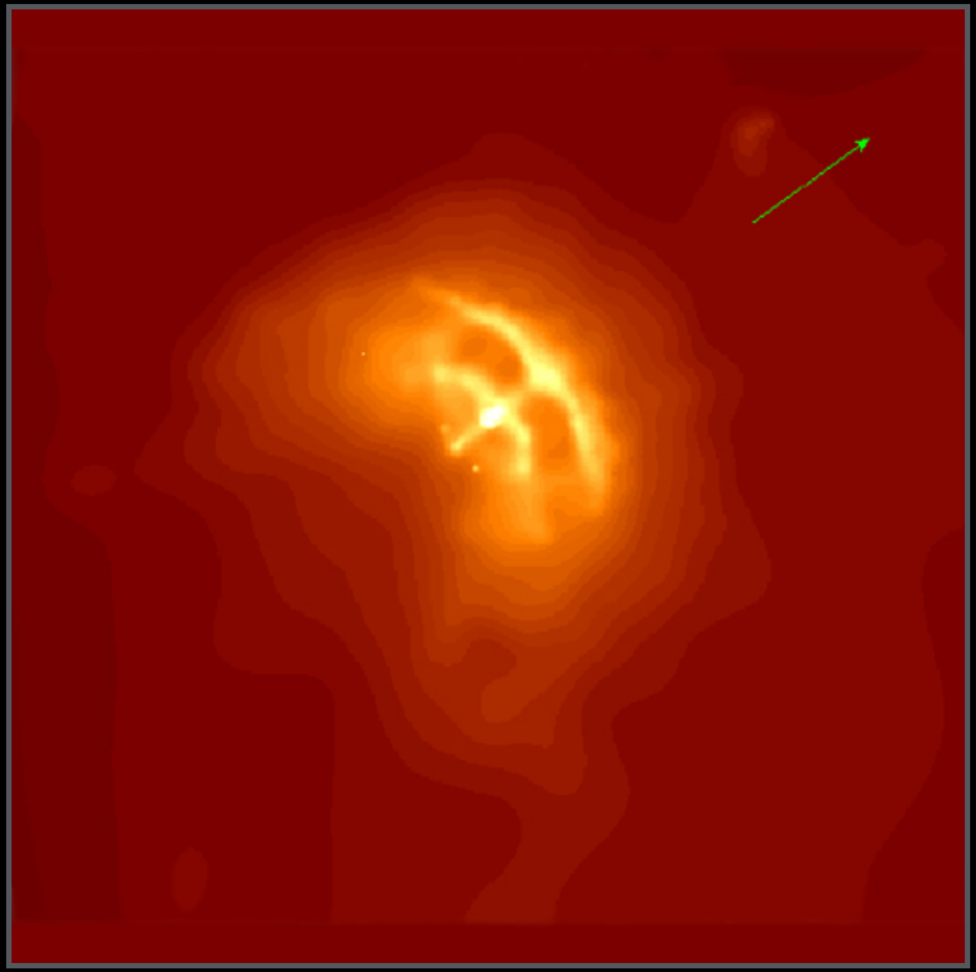
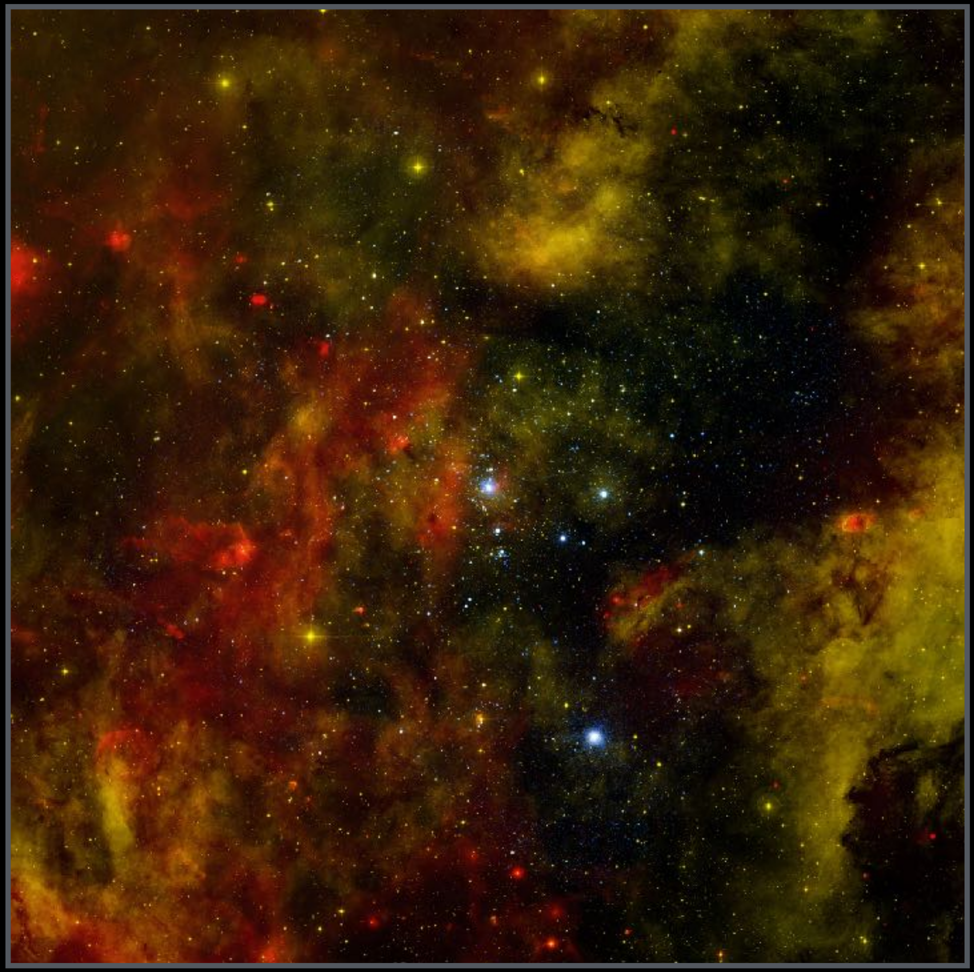
Supernovae remnants were proposed in the 1950s as the sources of Galactic cosmic rays by Enrico Fermi and others.

- ➡ shocks produce high energy particles with power law spectra

$$u_{cr} \approx 0.03 \left(\frac{E_{sn}/t_{sn}}{V_{gal}} \right) t_{esc}$$

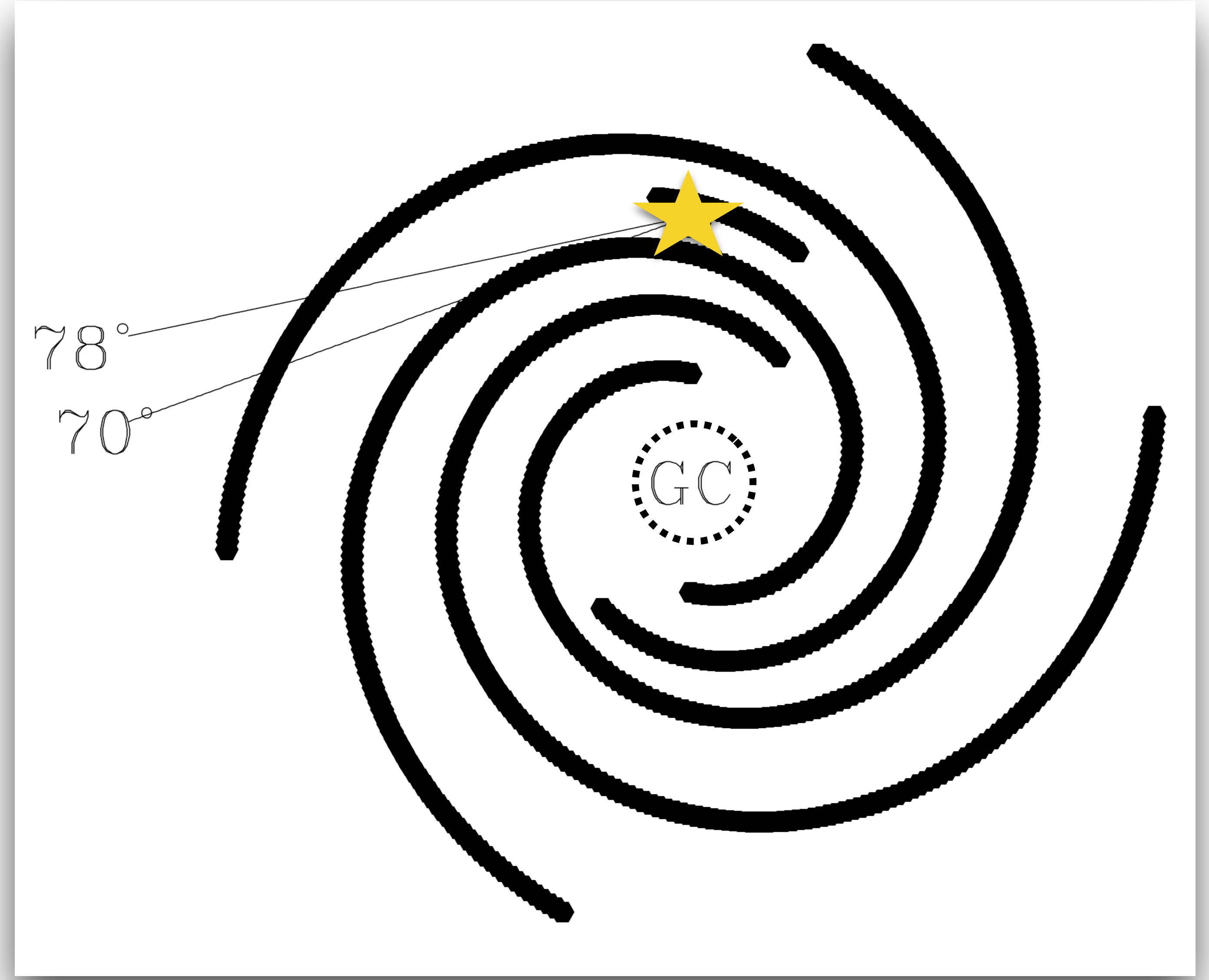


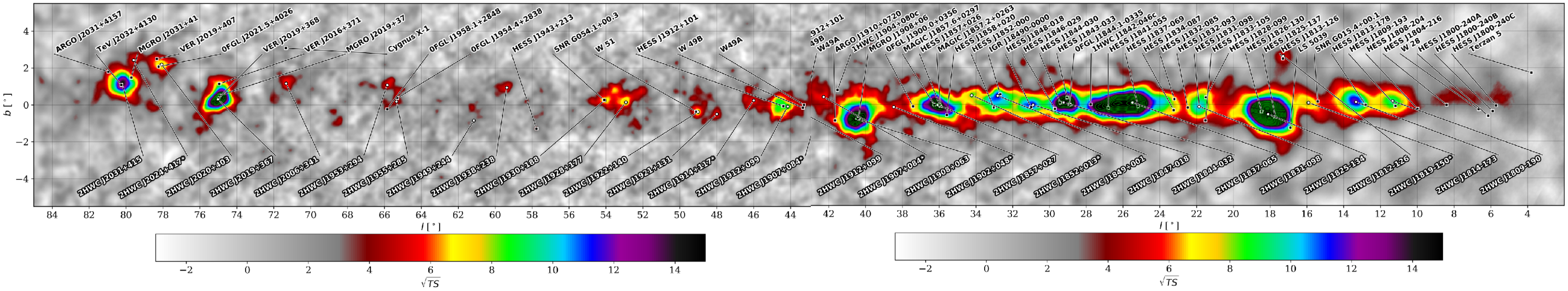
Cassiopea A in X rays
(Chandra X-ray Observatory)

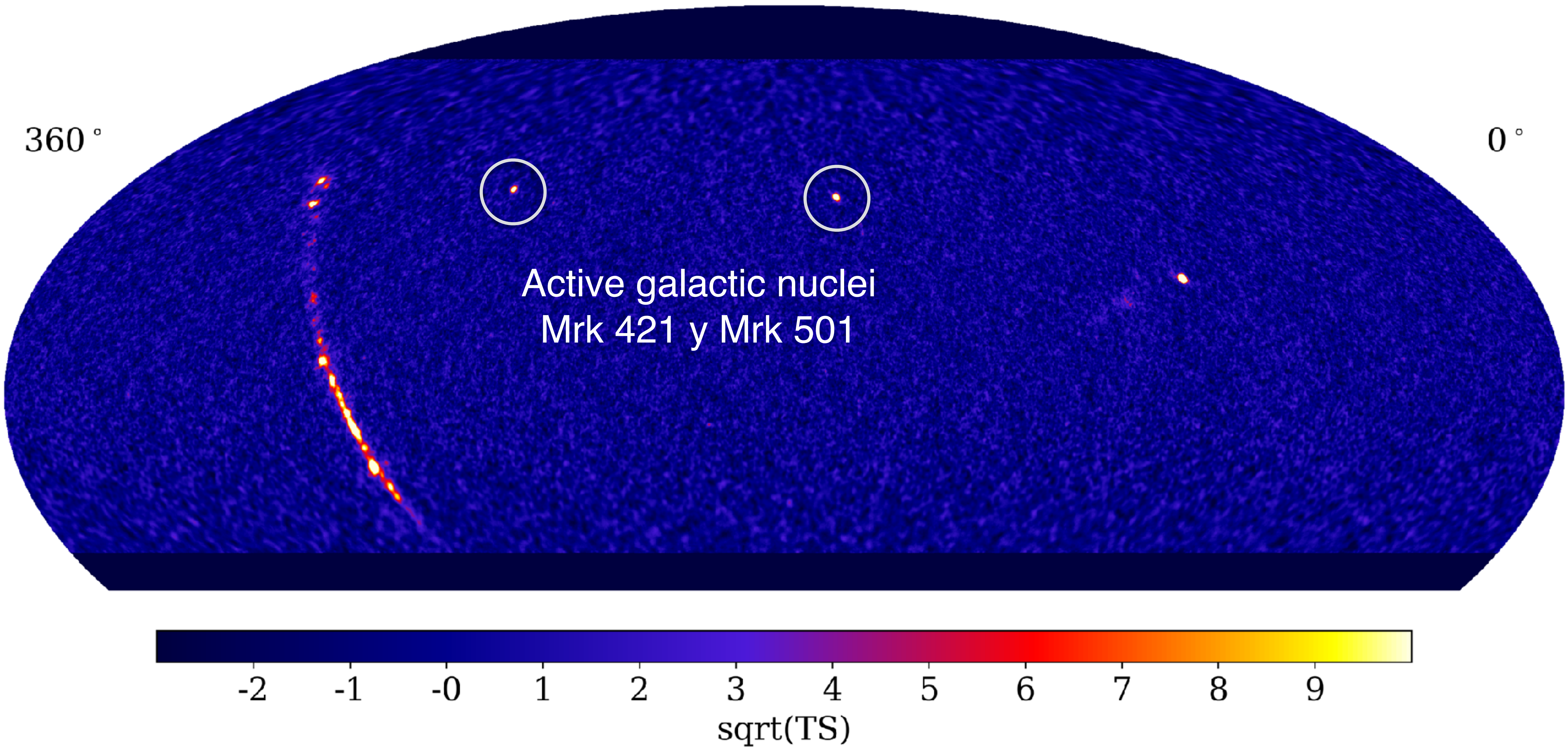
The spiral structure of the Galaxy

HAWC sees star formation occurs in the spiral arms; in particular high mass star formation.





Extragalactic sources



- Two bright BL Lac objects
- And the cosmic fog….

From the 2HWC

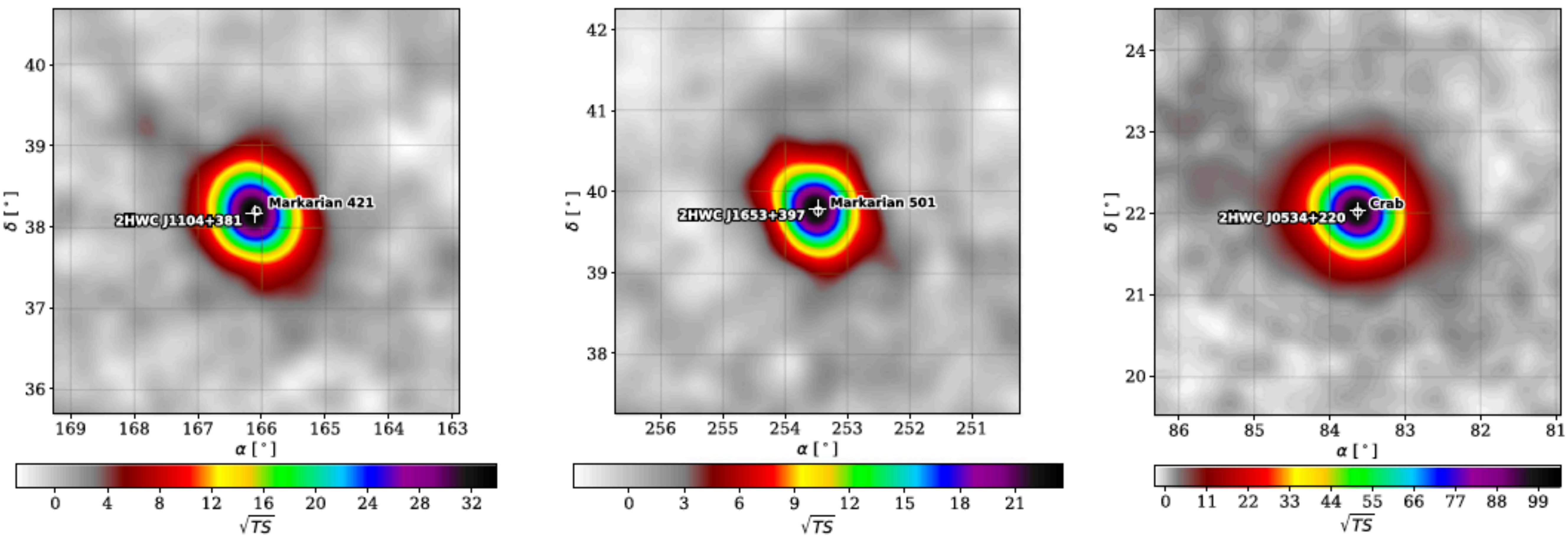
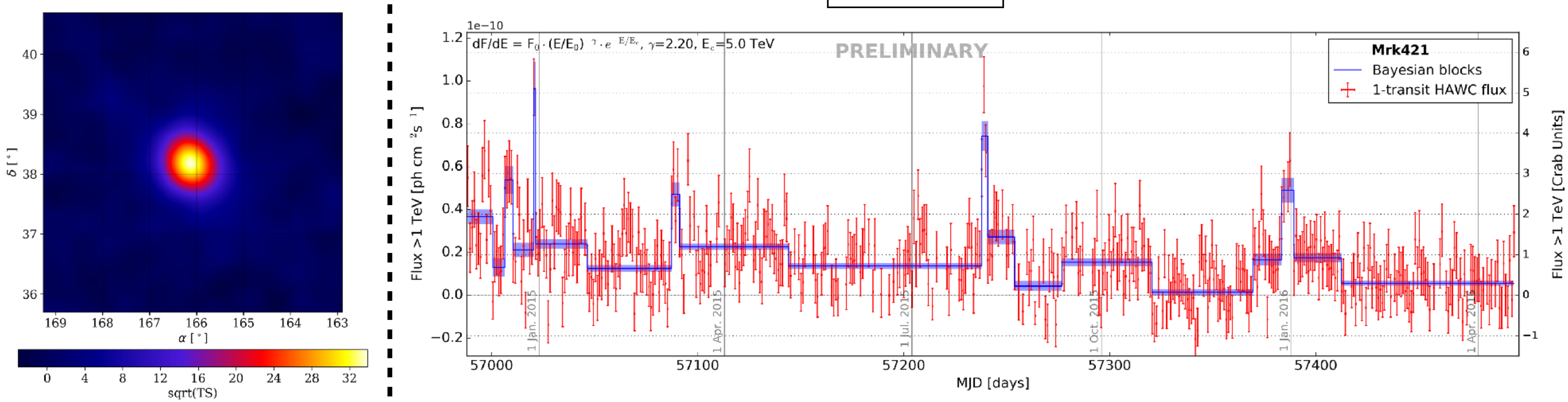
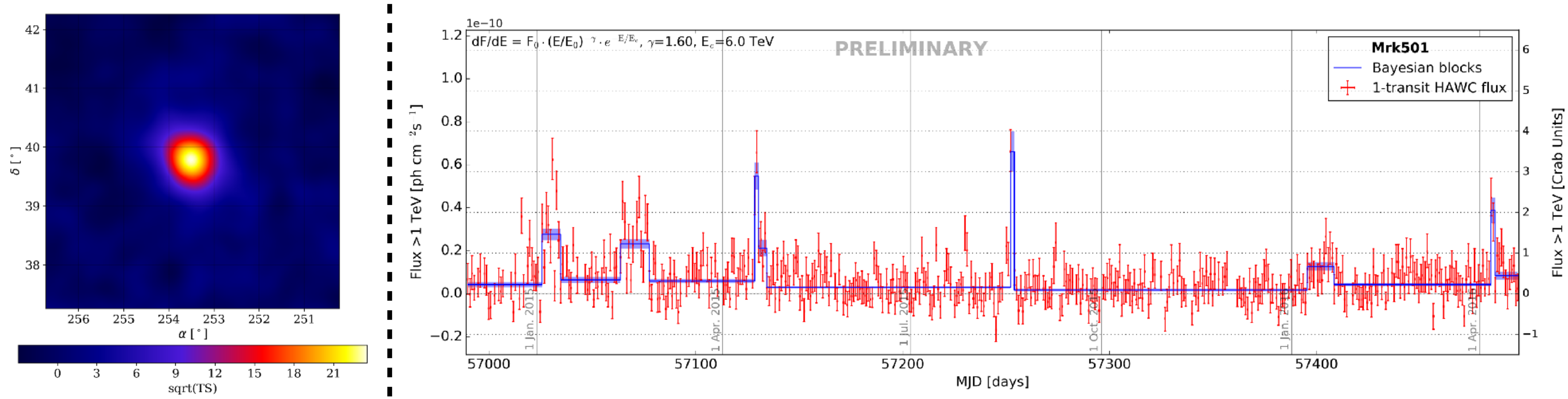


Figure 4. Regions around Markarian 421, Markarian 501, and the Crab Nebula: equatorial TS maps, for a point source hypothesis with a spectral index of −2.7. In this figure and the following, 2HWC sources are represented by white crosses and labels below them, whereas the sources listed in TeVCat are represented with black circles and labels above them.

Mrk 421 & Mrk 501

1 year

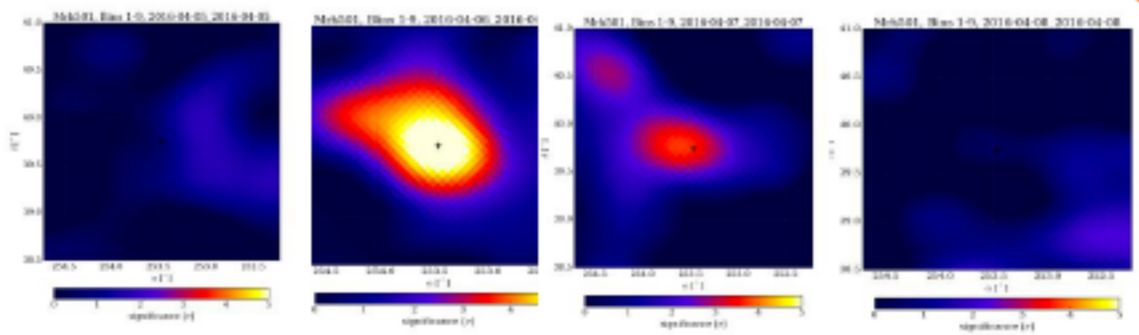




HAWC monitoring alerts

Recent HAWC-triggered transient alerts:

First HAWC-triggered blazar flare 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

~2 Crab units, elevated flux for ~2 days

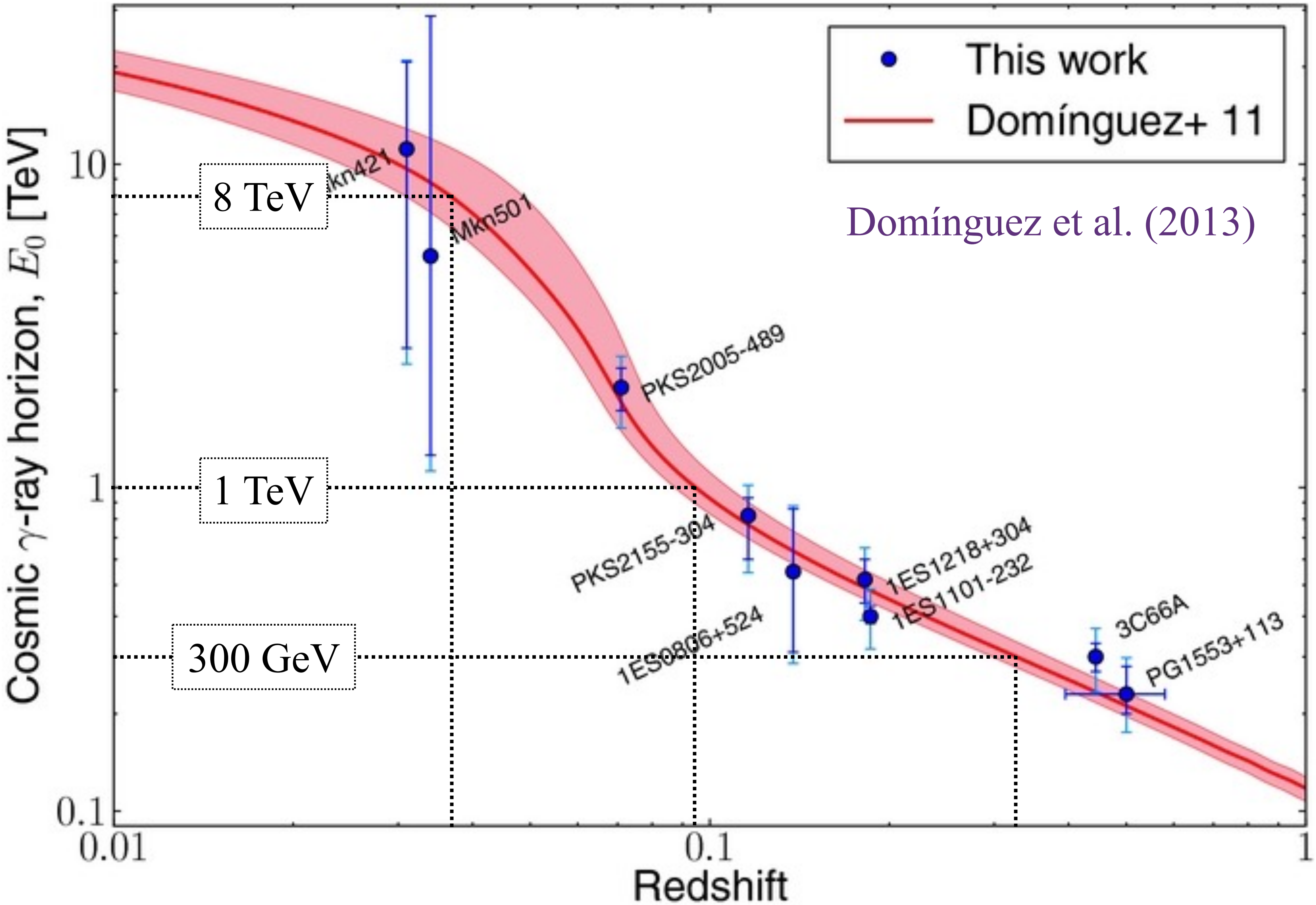
First joint FACT-HAWC-SWIFT ATEL:

Enhanced and increasing activity in gamma rays and X-rays from the HBL Mrk421

ATel #9137; *A. Biland (ETH Zurich) and D. Dorner (University of Wuerzburg, FAU Erlangen) for the FACT Collaboration, R. Lauer (University of New Mexico) and J. Wood (University of Maryland) for the HAWC Collaobration, B. Kapanadze (Abastumani Astrophysical Observatory, Ilia State University), A. Kreikenbohm (University of Wuerzburg)*
on 10 Jun 2016; 19:00 UT

- **FACT and HAWC with daily TeV coverage** and complementary observation times.
- HAWC, FACT and SWIFT all show **rising fluxes with highest values on June 9, 2016** (~3 x Crab flux).
- SWIFT observations at 0.3-10 keV:
  "Note that higher or comparable X-ray fluxes were observed only four times so far."

A limited γ-ray horizon!



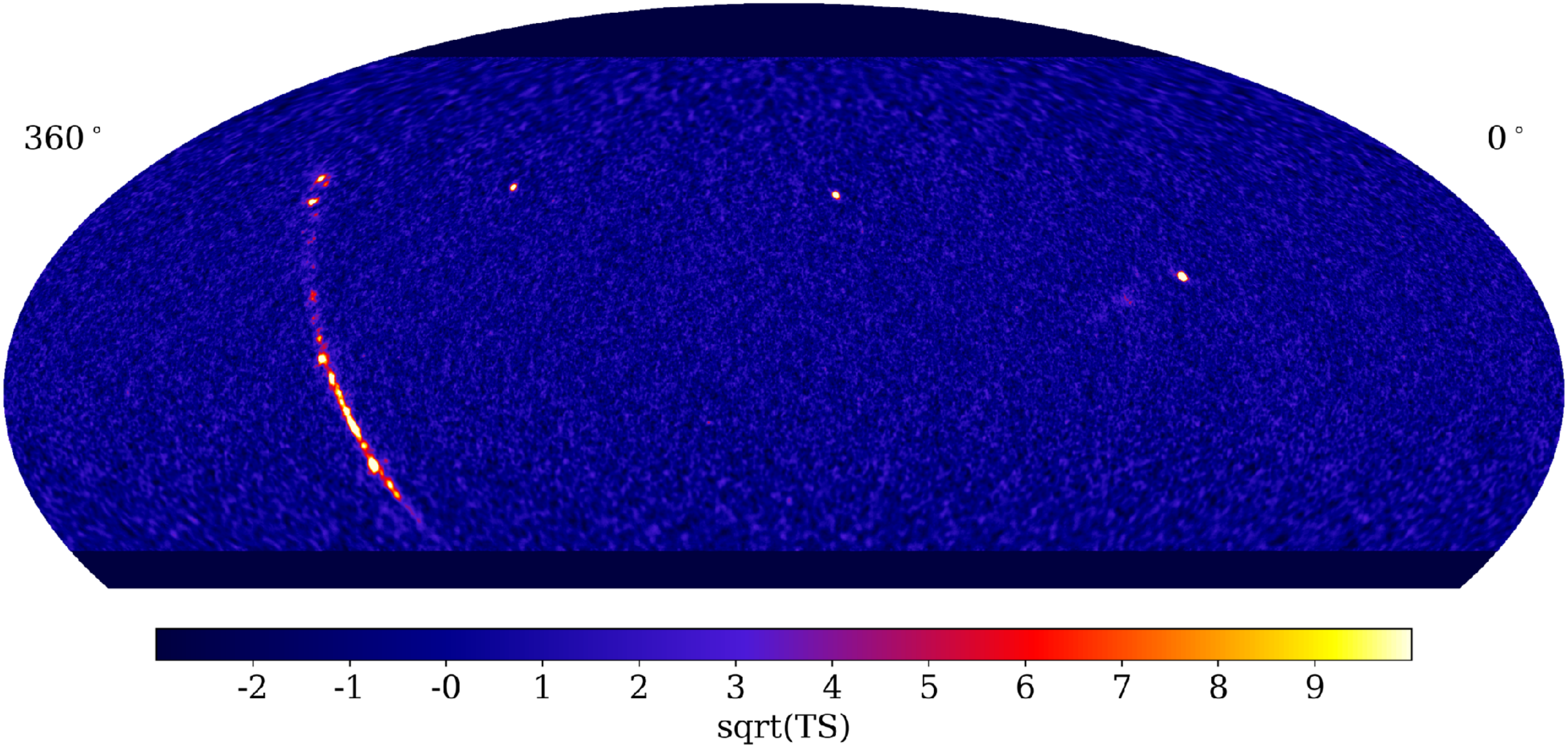
TeV γ rays suffer pair production with the extragalactic background light (EBL):

$\gamma\,\gamma \rightarrow e^{-}e^{+}$

$$E\ h\nu \simeq 0.35\ \mathrm{TeV\ eV}$$

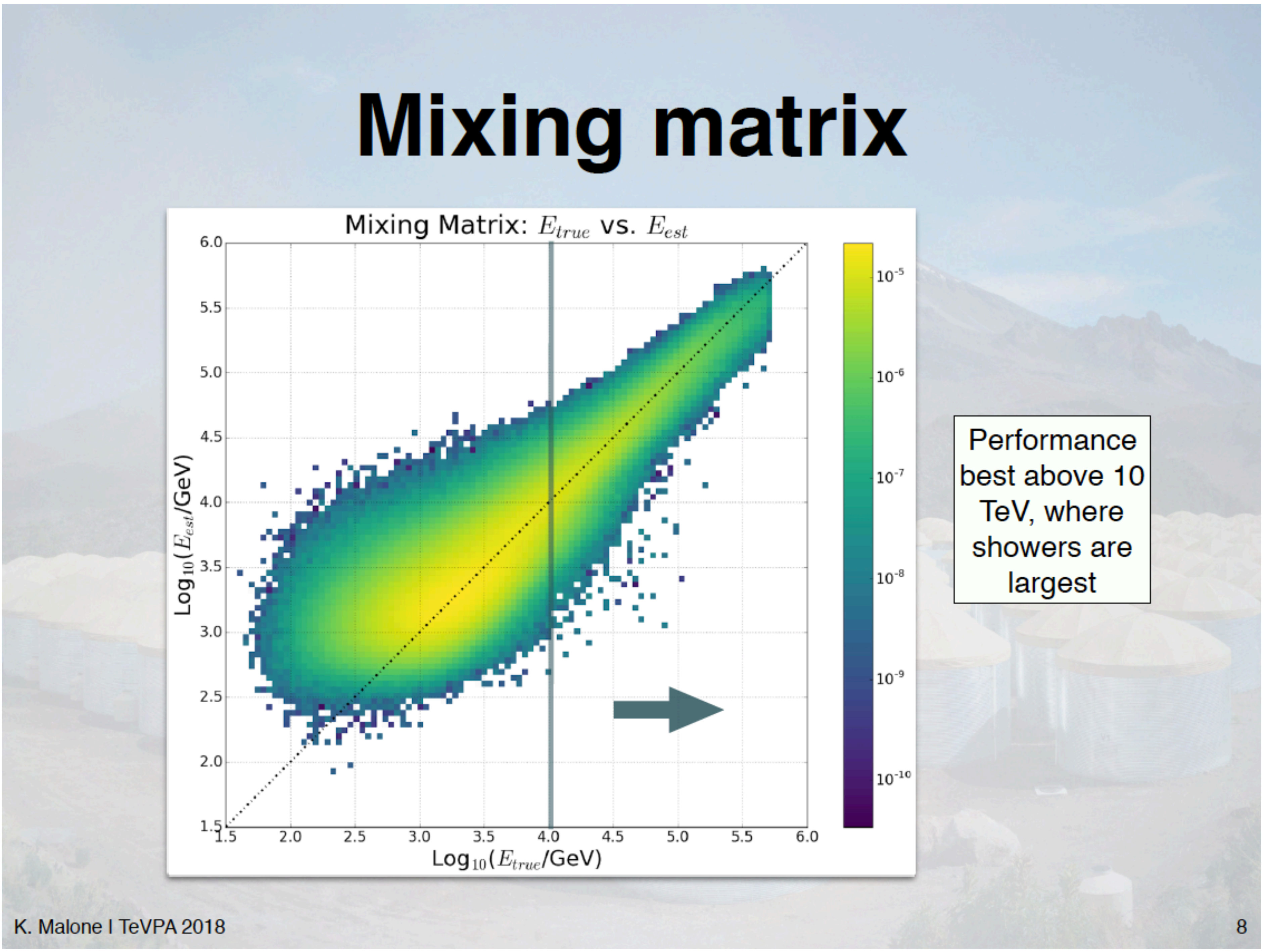
The mean free path at 1 TeV corresponds to *z ≲ 0.1*

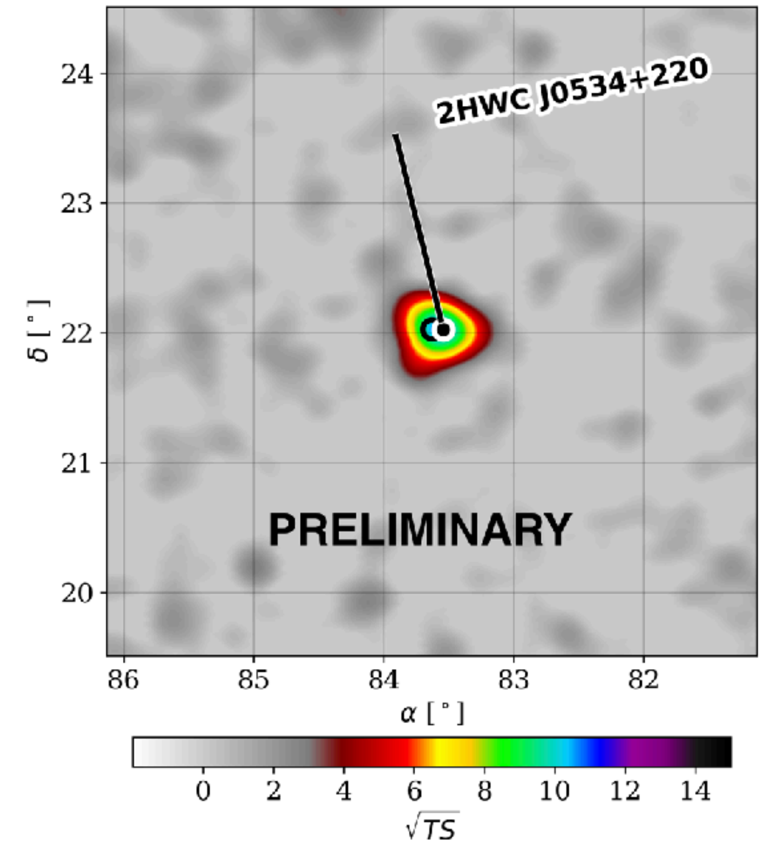
The γ-ray sky to the limit

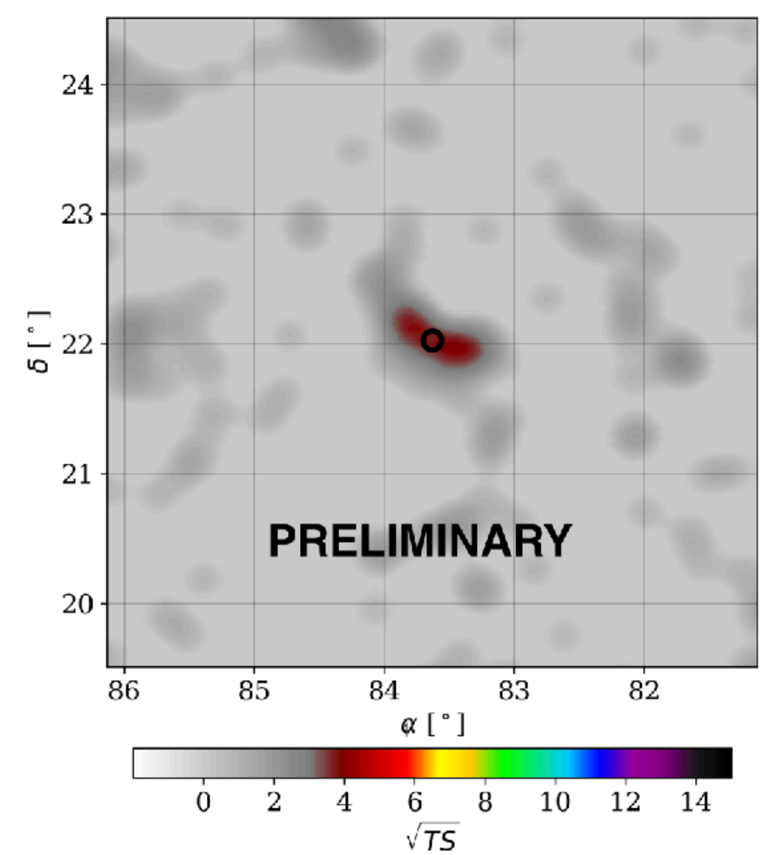


To 100 TeV and beyond!

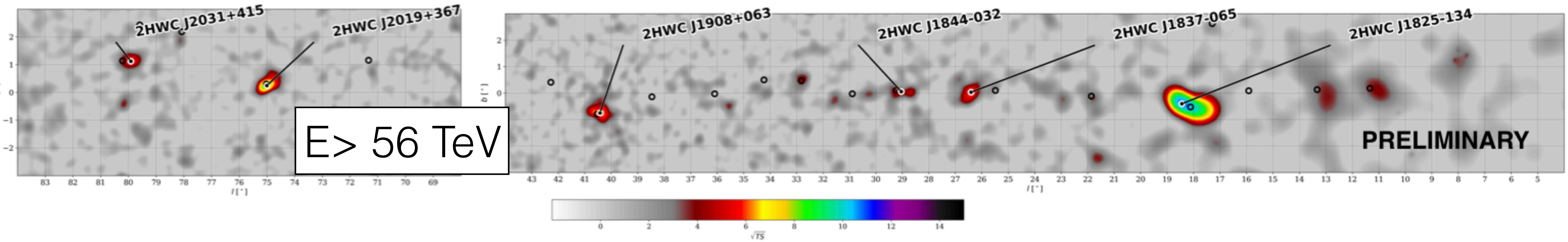
Work on event by event energy estimators







The Galactic Plane above 56 TeV

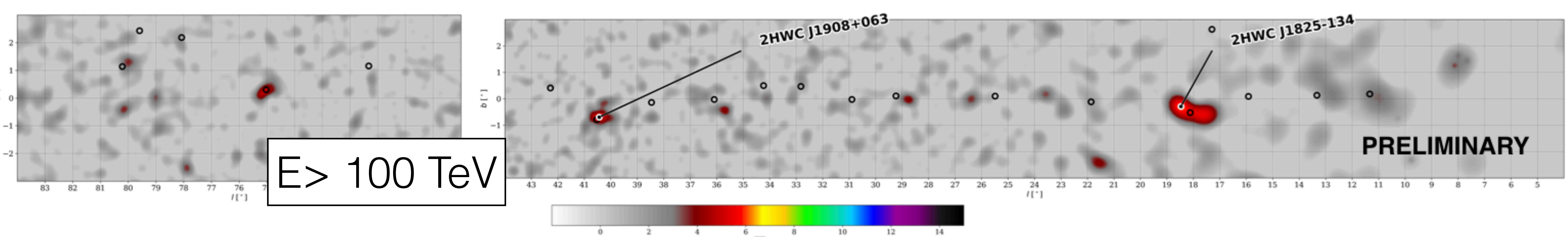


First maps of the Galactic Plane at these energies!

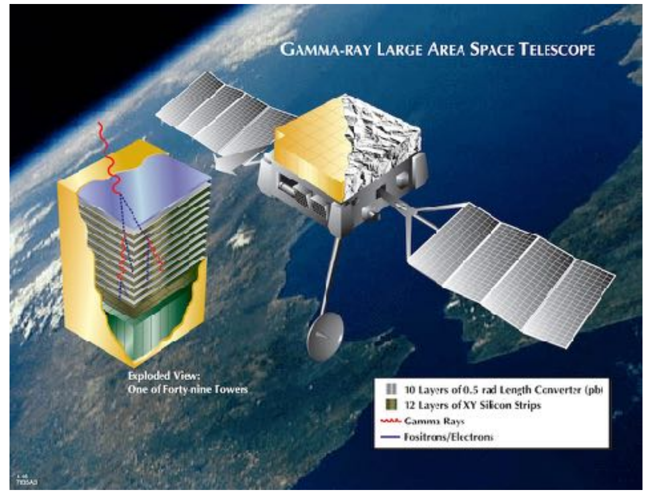
- Six sources in the E>56 TeV Galactic Plane.
- Two sources in the E>100 TeV Galactic Plane.

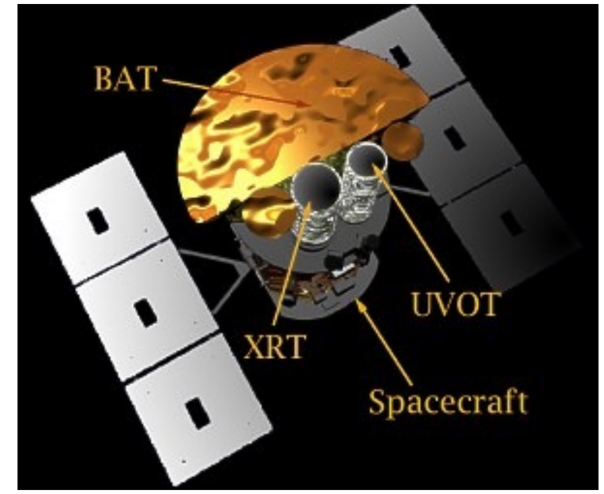
All six coincident with 2HWC Catalog sources (7 TeV).

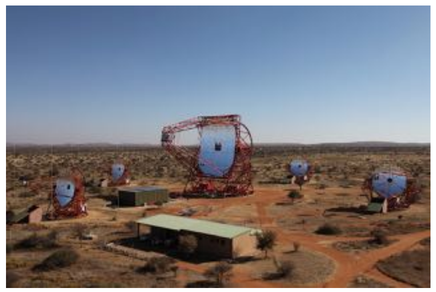
PeV hadronic accelerators would emit neutrinos (IceCube - Halzen et al. 2017).

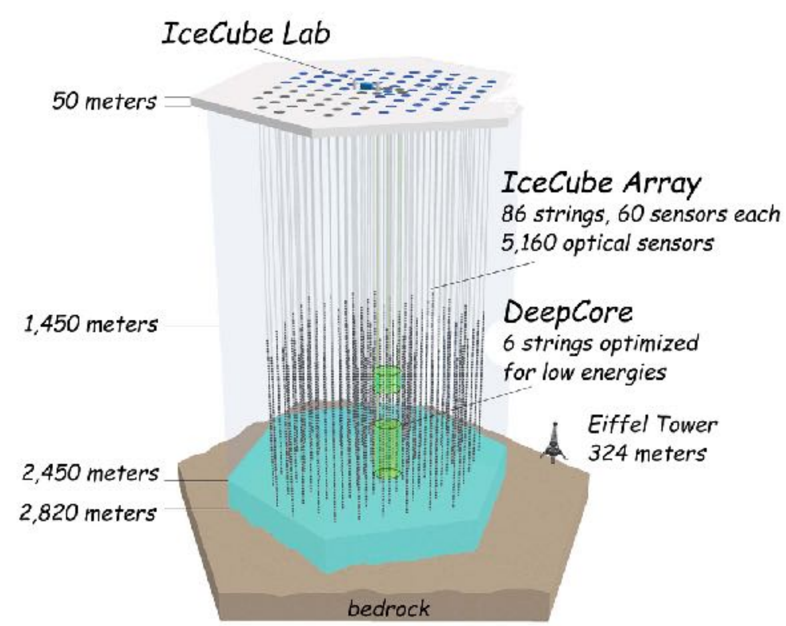


Multi-wavelength synergies









Multi-messenger synergies

HAWC follow-ups

TITLE: GCN CIRCULAR
NUMBER: 19423
SUBJECT: GRB 160509A: non-observation of VHE emission with HAWC
DATE: 16/05/11 17:27:37 GMT
FROM: Dirk Lennarz at HAWC <dirk.lennarz@gatech.edu>

D. Lennarz (Michigan State University), I. Taboada (Georgia Tech) report on behalf of the HAWC collaboration (http://www.hawc-observatory.org/collaboration/):

We used data from the HAWC detector to perform a search for VHE emission in temporal coincidence with GRB 160509A (F.Longo et al., GCN 19403). At the time of the LAT trigger, the elevation of the burst in HAWC's field of view was only 27.98 degrees (it was rising, but culminated at an elevation of 33 degrees). The sensitivity of HAWC at this elevation is more than 2 orders of magnitude poorer than near the zenith. Furthermore, the energy threshold towards the horizon is much higher. Combined with the moderate redshift of z=1.17 (N. R. Tanvir et al., GCN 19419) it makes a detection by HAWC unlikely.

We used four search windows with respect to the LAT trigger time: one in the range -5 s to 45 s, which covers the main GBM emission episode (O.J. Roberts et al., GCN 19411) and appears to be correlated with the >100 MeV soft emission observed by the LAT (F.Longo et al., GCN 19413), a window from -5 s to 375 s, which extends slightly beyond the T90 observed by GBM and a time window from 45 s to 375 s, where the LAT data is fit with a power-law of index -2.0 +/- 0.1. We also searched -20 s to 20 s around the time of the highest-energy LAT photon (52 GeV) 77 seconds after the GBM trigger. A 2 degree angular bin is defined around the position of the Swift-XRT afterglow position (J. A. Kennea et al., GCN 19408) and the number of background events is estimated using an ON/OFF method. We find the counts in the search bin to deviate by 1.9 / 0.9 / 0.2 / -1.4 sigma from the background expectation. Our observations are consistent with background only.

The search was conducted using the main data acquisition that
...on of showers. It uses data
...not applying gamma-hadron separation.
...ection with respect to the VHE fluence
...where.

GRB 160509A

HAWC is a very-high-energy gamma-ray observatory operating in Central Mexico at a latitude of 19 deg north. HAWC has an instantaneous field of view of 2 sr and surveys 2/3 of the sky every day. A detailed description of the sensitivity of HAWC to GRBs can be found in A.U. Abeysekara et al., Astroparticle Physics 35, 641-650 (2012).

[Previous | Next | ADS]

HAWC TeV gamma-ray follow-up observation of the sky region of IceCube's multi-PeV neutrino-induced event

ATel #7868; *Ignacio Taboada (GATECH) on behalf of the HAWC collaboration*
on 3 Aug 2015; 13:25 UT
Credential Certification: Alberto CarramiÃ±ana (alberto@inaoep.mx)

Subjects: Gamma Ray, VHE, Neutrinos, Transient

Tweet | Recommend | 40

We have studied HAWC TeV gamma-ray archival data in the sky region corresponding to the multi-PeV neutrino-induced event reported by IceCube (ATEL # 7856). Putative cosmic ray sources that produce neutrinos are also expected to produce gamma-rays with approximately the same spectrum. If the source is transient, the neutrino light-curve is expected to be very similar to the gamma-ray light-curve. An observation by HAWC is possible, if, the neutrino spectrum extends from the observed PeV scale to the TeV energy scale to which HAWC is sensitive, and if source is not distant enough that the gamma-rays are attenuated by extragalactic background light. For TeV scale gamma-rays, sources can be observed if they are closer than approximately redshift 0.1. HAWC is a gamma-ray observatory, operating in central Mexico. It has an instantaneous field of view of about 2 sr. It can operate continuously, day or night and in any weather conditions. Over the course of a day, HAWC observes over half the sky in TeV gamma rays. HAWC, began full operations on March 20, 2015, but operated in partial configurations previously. Though the declination of the event is ideal for observations by HAWC, at the time, this region of the sky was at the occulted by Earth. Therefore, we could not perform a search in strict temporal coincidence. We conducted the follow up search using 5 different time periods. None of these searches found a gamma-ray source. In all five studies a region of 2 degrees by 2 degrees centered at the location reported by IceCube was searched. This matches the 1 degree uncertainty reported by IceCube for 99% containment of the PSF. The time periods studied are: 1) August 2, 2013 to May 6, 2015: Time integrated search 2) June 10, 2014: Sidereal day before the neutrino 3) June 11, 2014: Sidereal day after the neutrino 4) June 10-13, 2014: Four sidereal days around the time of the neutrino 5) June 6-15, 2014: Ten sidereal days around the time of the neutrino For the time integrated search, we used data from the partially built HAWC (aka HAWC-111, or 37% of final detector size and 283 days effective live-time) from August 2nd, 2013 to July 7th, 2014 and data with a second partially built HAWC (aka HAWC_250, 83% of final size and 150 days effective live-time) from November 26, 2014 to May 6th, 2015. The date of the neutrino event, June 11th, 2014, corresponds to the end of operation of HAWC-111. The preliminary 5 sigma discovery potential for this first search is (E^2 flux) 1.9e-12 TeV/cm^2/s at 100TeV assuming a power law flux with index of -2.3. For the other time periods the preliminary one day discovery potential was 3.9e-11 TeV/cm^2/s at 100TeV with a power-law index of ... HAWC contact for this obs... ...bada@gatech.edu) and Mi...

IceCube et al., A&A 607, 115 (2017)

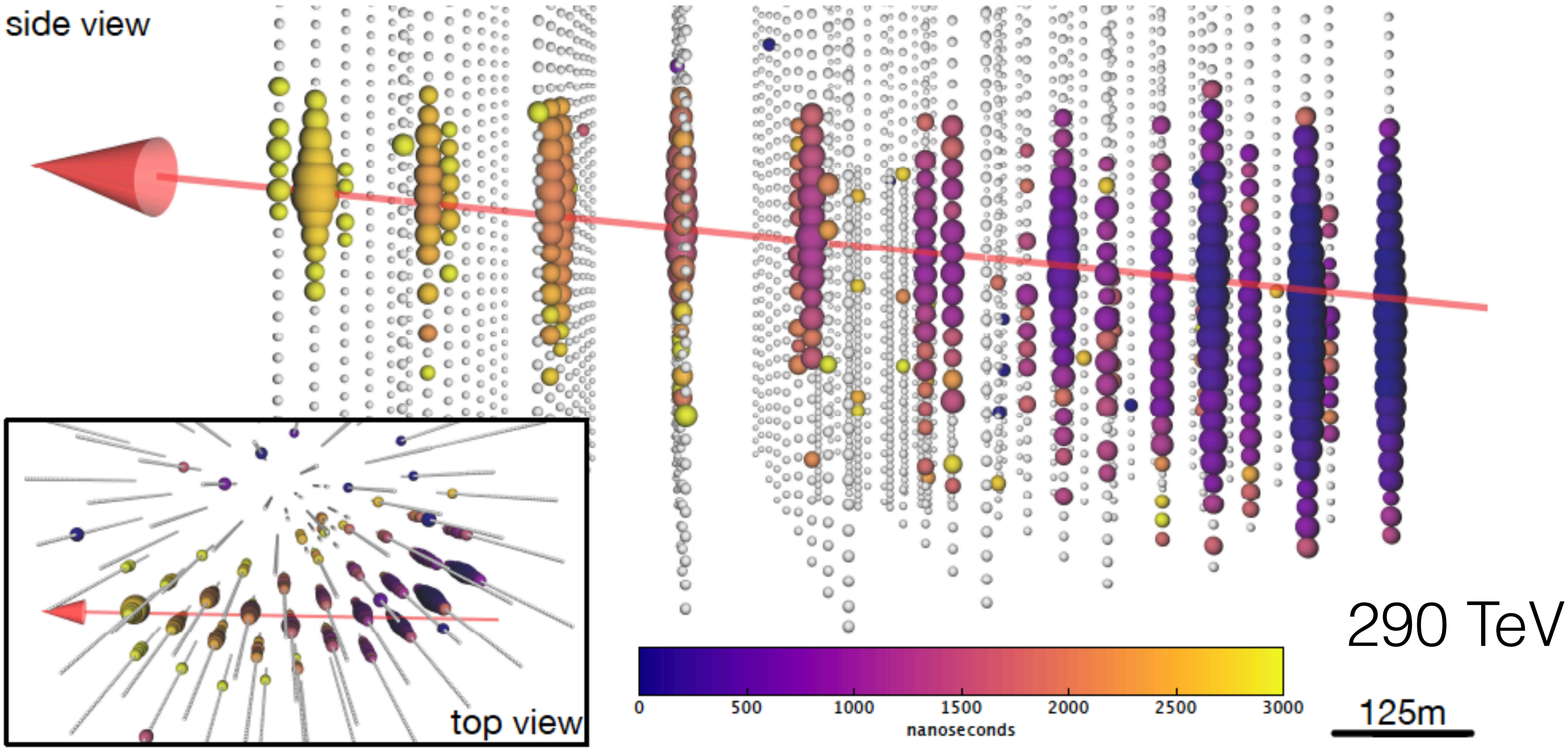
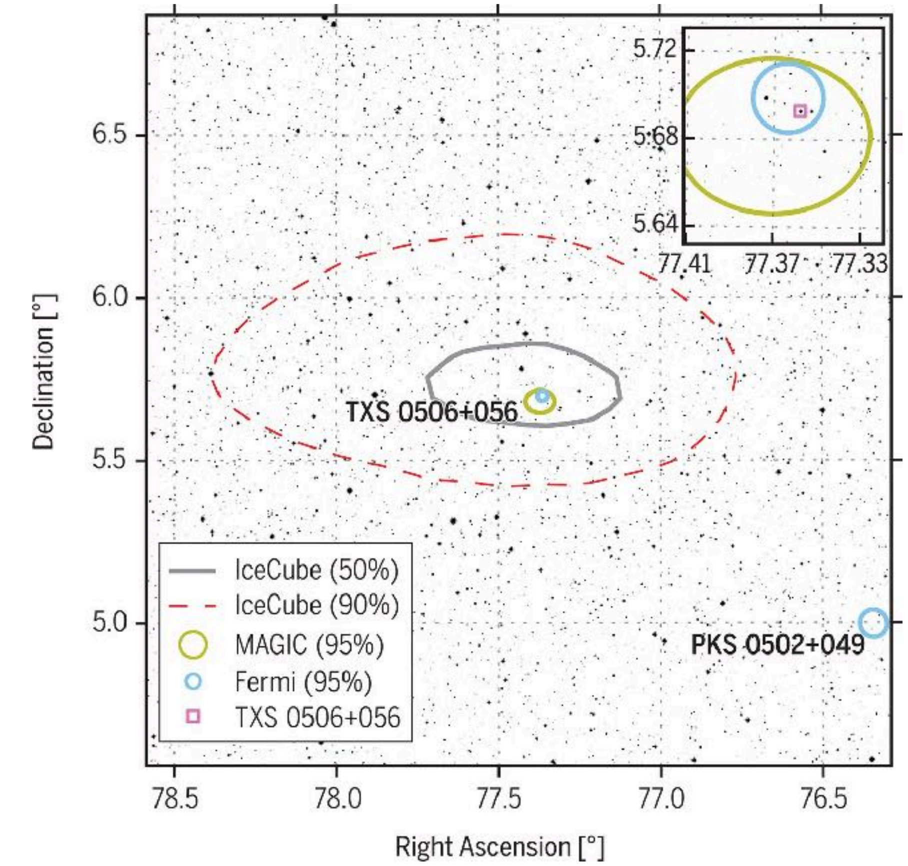


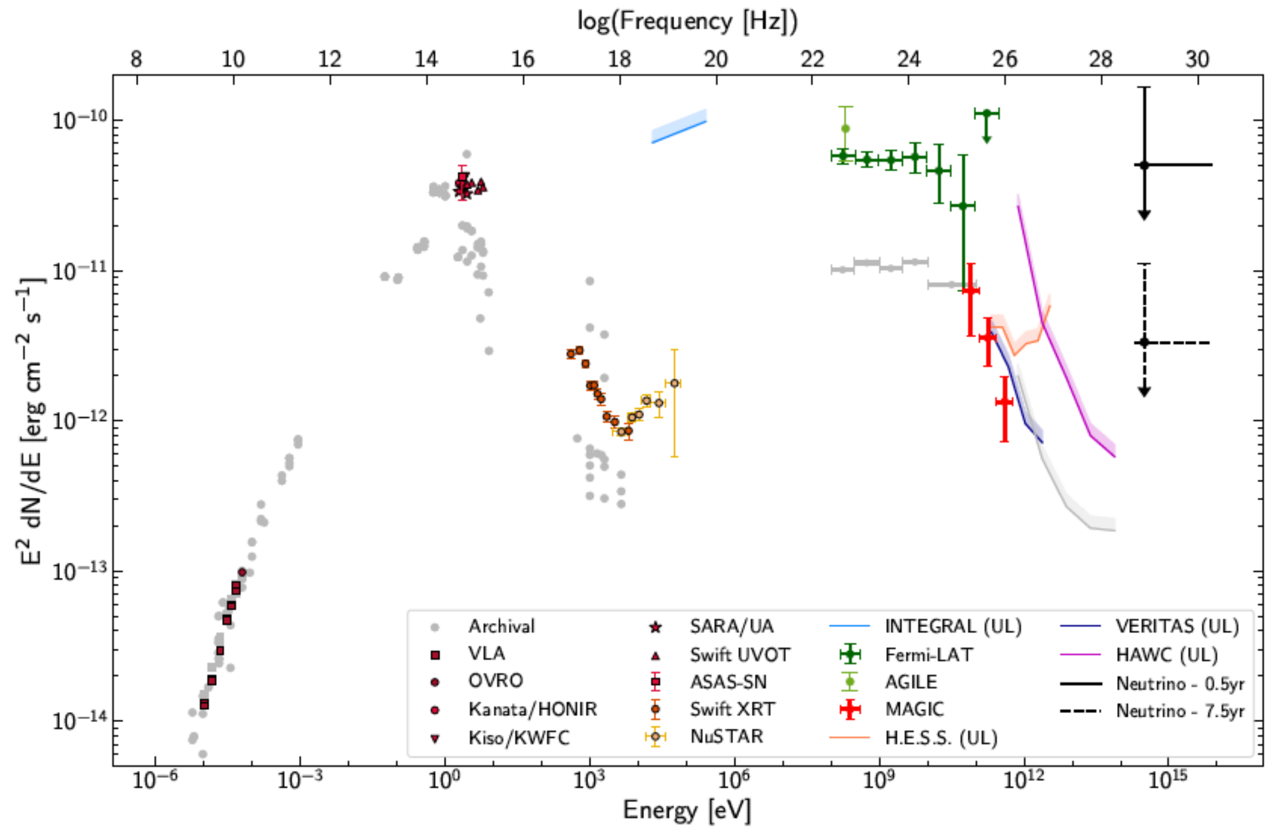
Figure 1: **Event display for neutrino event IceCube-170922A.** The time at which a DOM observed a signal is reflected in the color of the hit, dark blues for earliest hits and yellow for latest. Time shown are realtive to the first DOM hit according to the track reconstruction, and earlier and later times are shown with the same colors as the first and last times, respectively. The total time the event took to cross the detector is ~3000 ns. The size of a colored sphere is [...] amount of light observed at the DOM, with larger spheres

IceCube et al., Science 361, 1378 (2018)

IceCube 170922-A

- Position consistent with the Fermi (3FHL) BL Lac TXS 0506+056.
  - redshift z=0.3365 from GTC
- Not in HAWC FoV at the time of the ν-event; UL determined from prior and posterior transits.
- Analysis of archival HAWC and IceCube contemporaneous data coming out soon.





IceCube et al., Science 361, 1378 (2018)

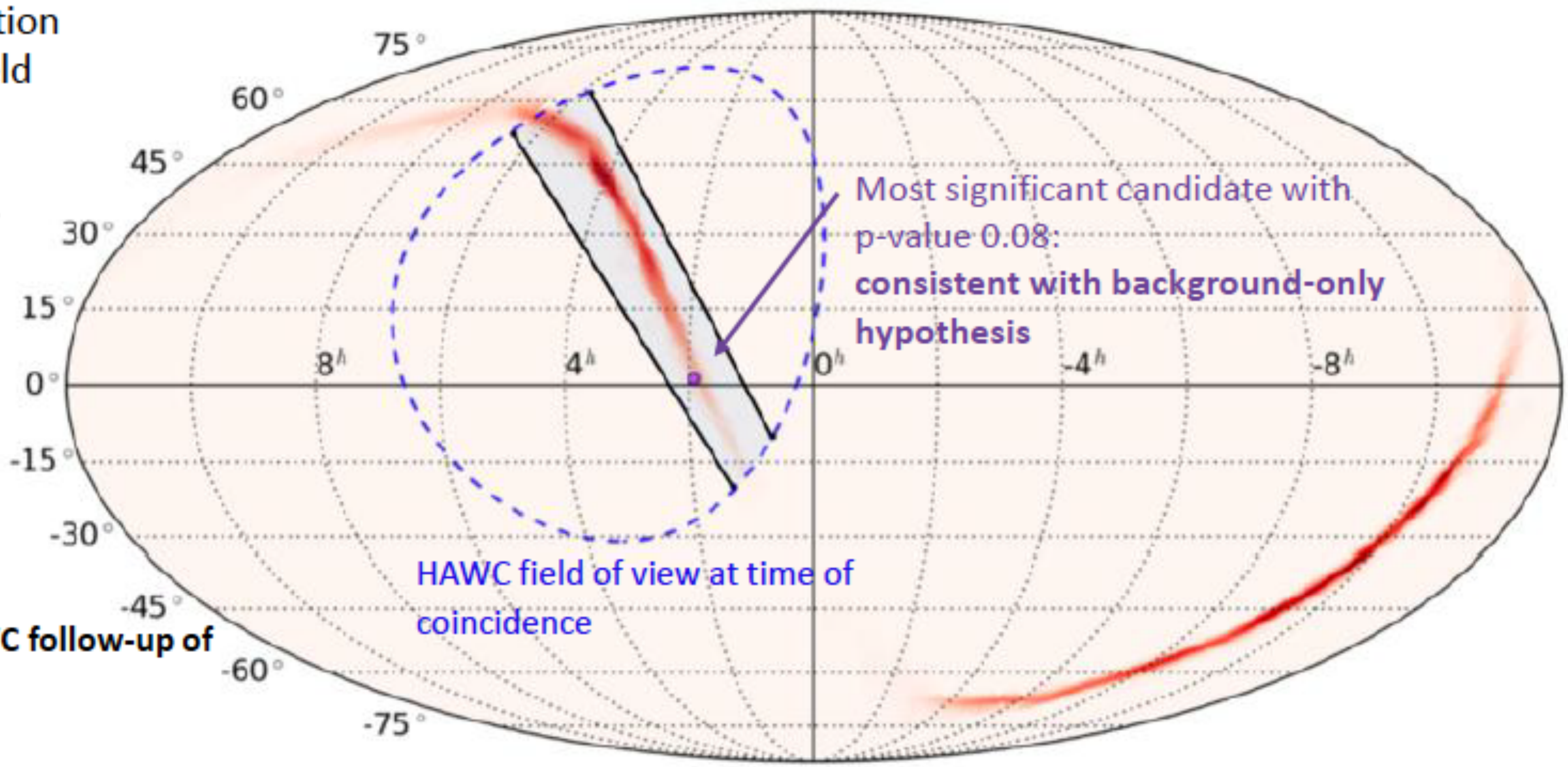
Figure 4: **Broadband spectral energy distribution for the blazar TXS 0506+056.** The SED is based on observations obtained within 14 days of the detection of the IceCube-170922A

GW follow ups

Follow-up on 2nd Gravitational Wave Alert

LIGO GW150914: Outside HAWC field of view

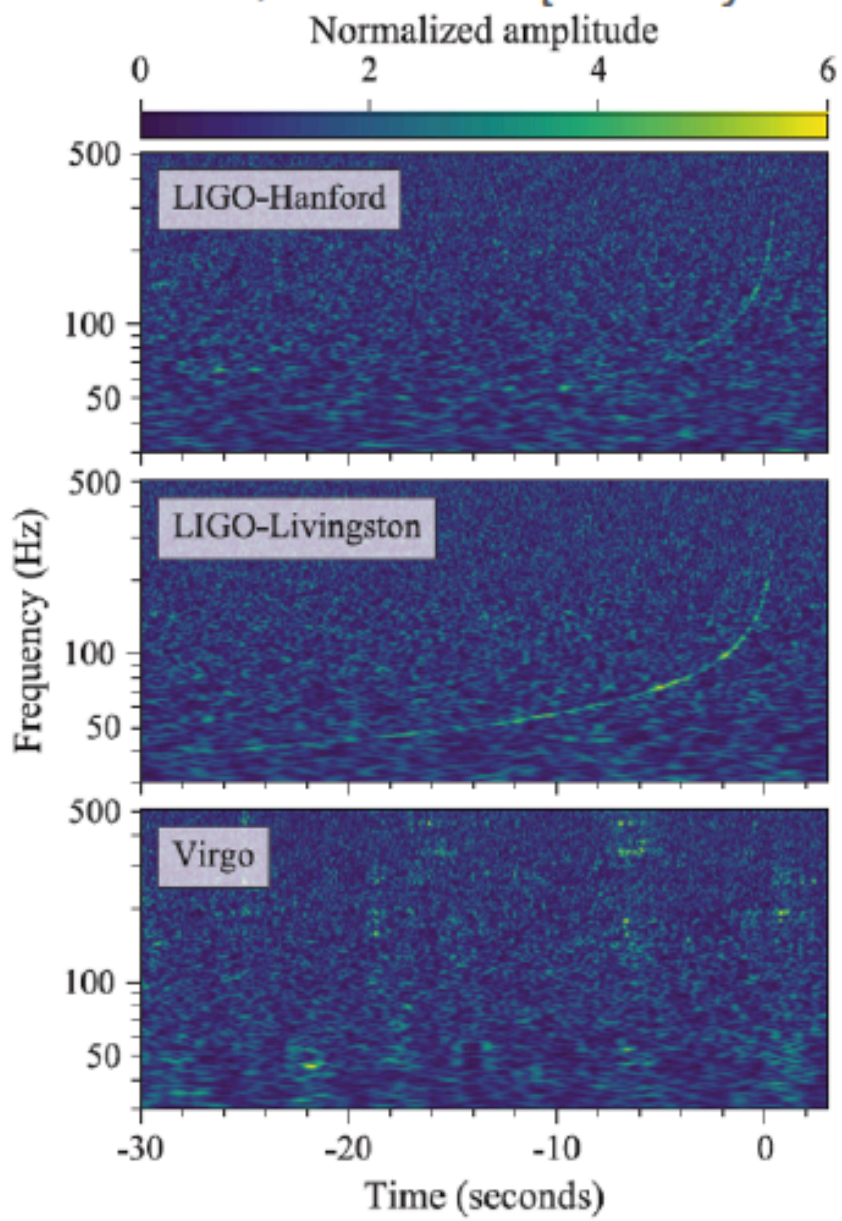
LIGO GW151226, 2015-12-26 03:38:53 UTC:
Large part of the localization Contour within HAWC field of view at time of coincidence

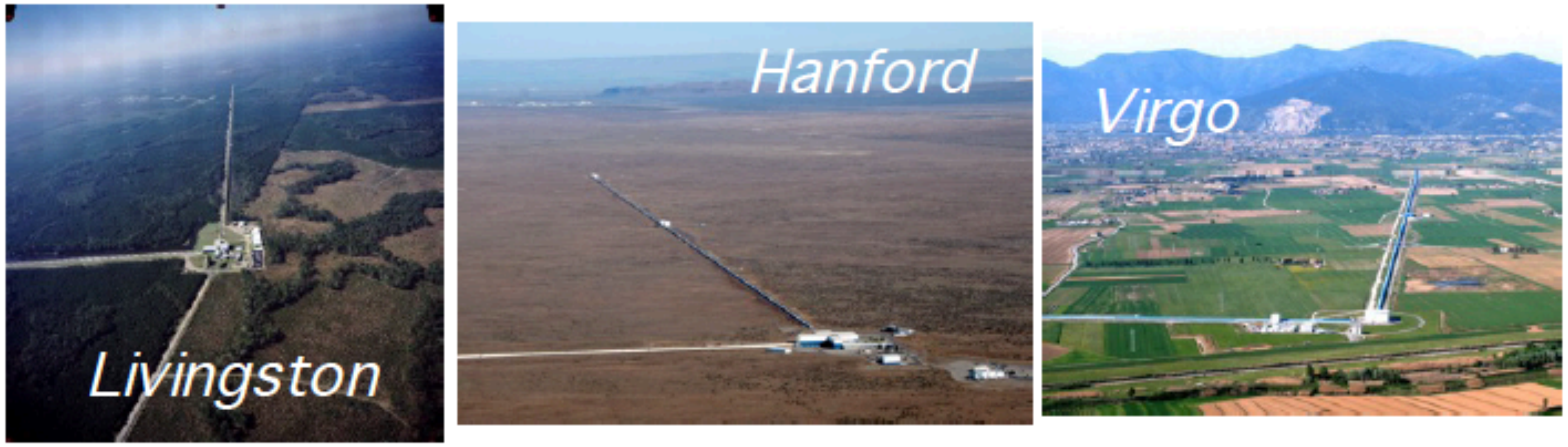


A GRB-optimized search within ±10 s shows no significant excesses, see:
GCN CIRCULAR #19156
LIGO/Virgo G211117: HAWC follow-up of northern sky

Binary neutron star merger

LIGO & Virgo Collaborations
PRL 119, 161101 (2017)



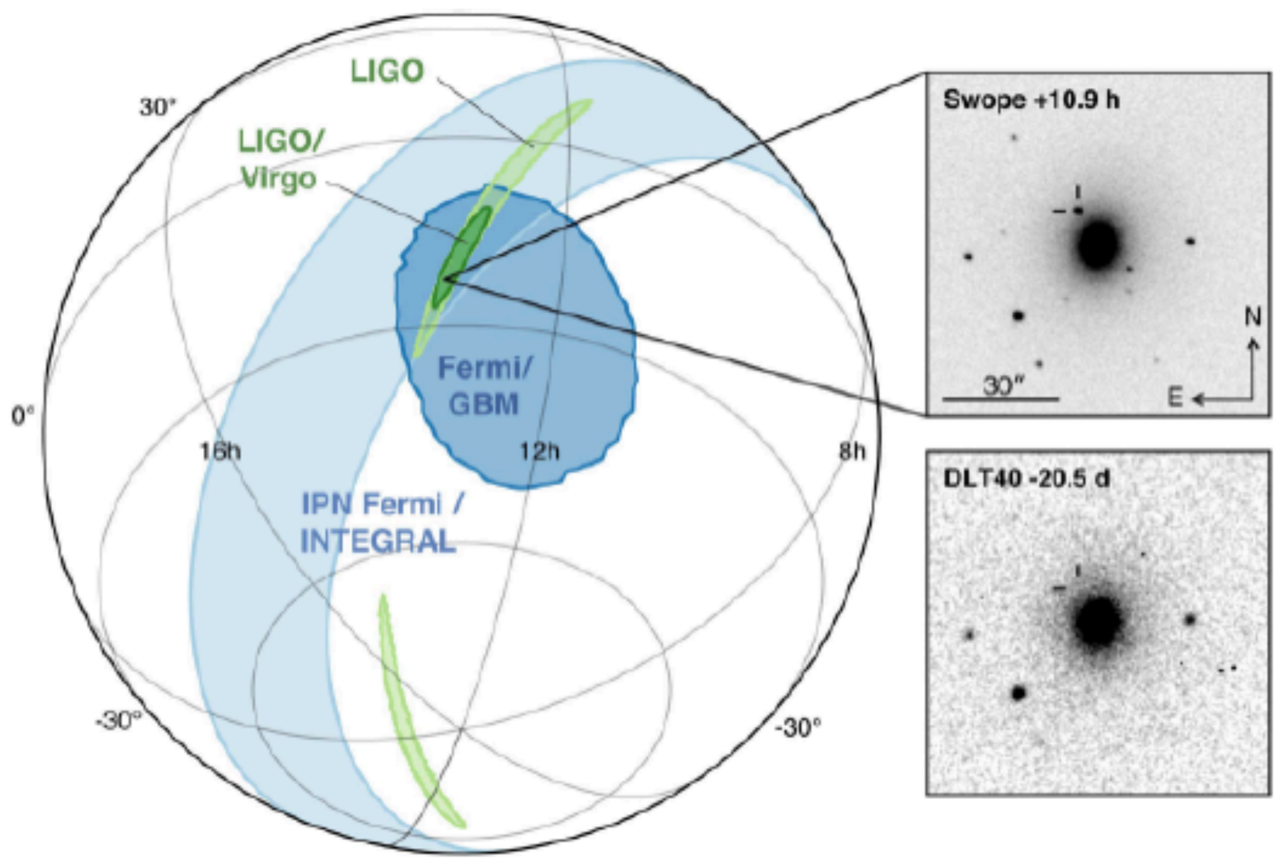


- First observation of a binary neutron star inspiral
- Associated with a gamma-ray burst detected by Fermi-GBM
- First direct evidence of a link between mergers and short gamma-ray bursts

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 a not favorable 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.

2HWC Catalog maps are public!

https://data.hawc-observatory.org/datasets/2hwc-survey/coordinate.php

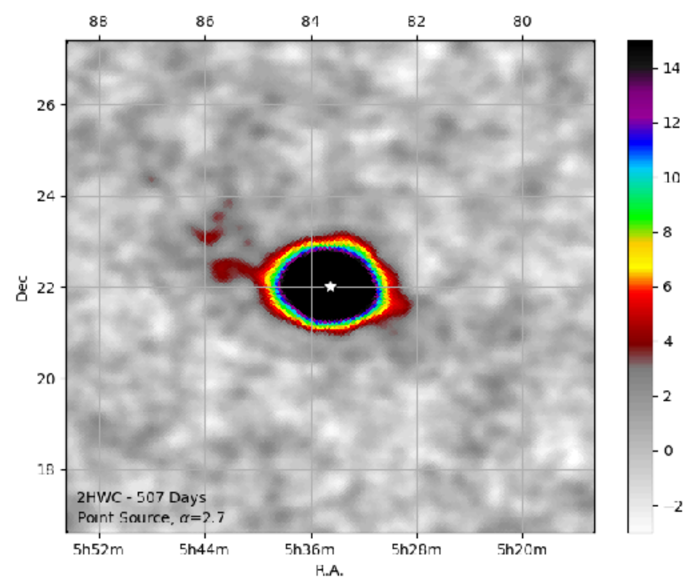
HAWC High Altitude Water Cherenkov

HAWC Observatory | Publications | **Public Datasets** | Resources

- Intro
- **2HWC Survey**
- Geminga Paper
- Lightcurves

2HWC Survey

Details | Catalog View | **Coordinate View**



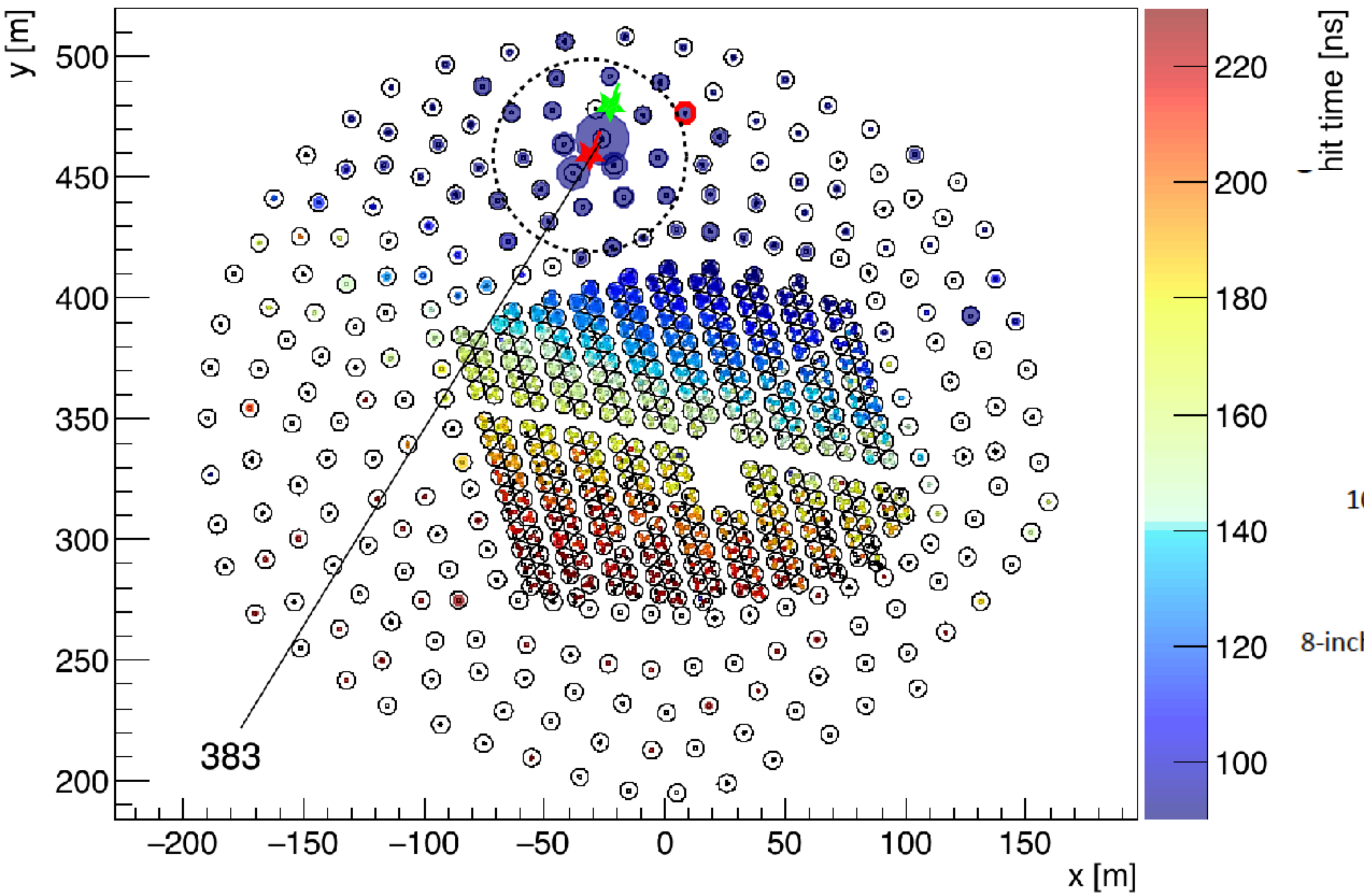
Point Source (2.7 Index)

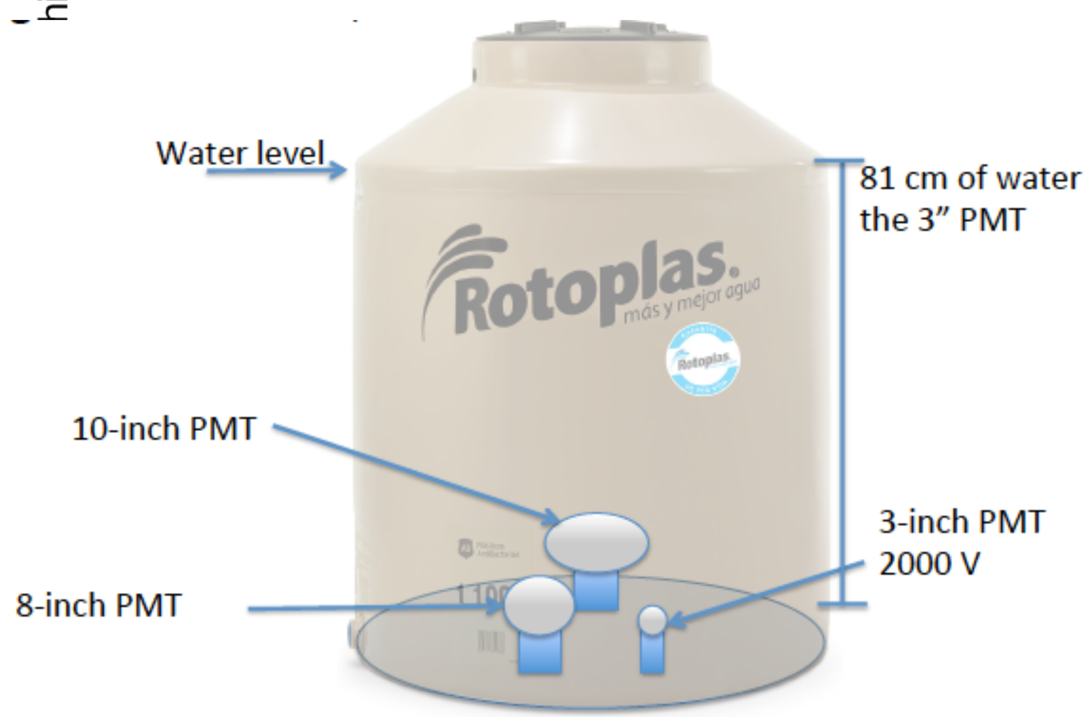
RA (J2000 – Decimal):	Dec (J2000 – Decimal):	Submit
83.63	22.01	
Significance	104.958443	[sqrt(TS)]
Flux	1.752774e-13	[cm^-2 s^-1 TeV^-1]
Flux Upper	1.796217e-13	[cm^-2 s^-1 TeV^-1]
Flux Lower	1.709344e-13	[cm^-2 s^-1 TeV^-1]

Read the Details Tab for explanation of these numbers.

Contact John Pretz with questions or comments

HAWC expansion





Sparse array of 350 small WCDs around HAWC **now** extending its effective area above 10 TeV to 100,000 m².


Rotoplas


NSF
DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA
CONACYT
UNIVERSITY OF
18
56
MARYLAND
INAOE
Los Alamos
NATIONAL LABORATORY
EST.1943