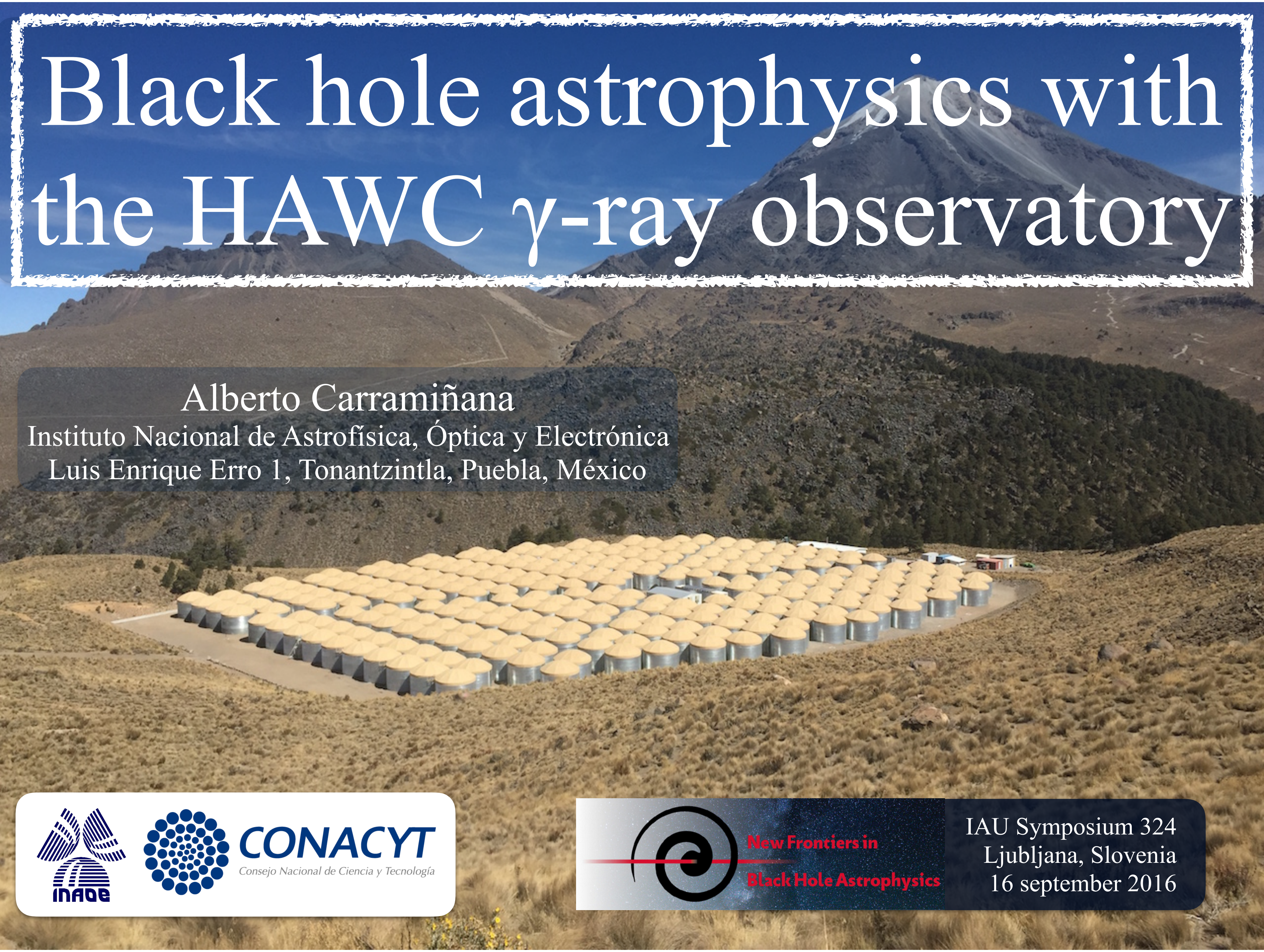


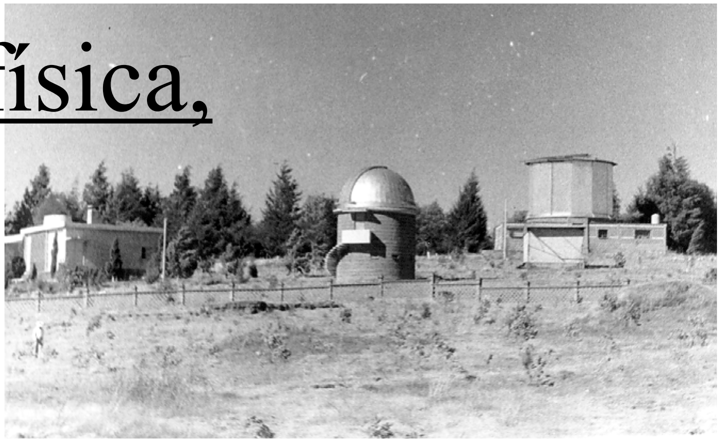
Black hole astrophysics with the HAWC γ-ray observatory

Alberto Carramiñana
Instituto Nacional de Astrofísica, Óptica y Electrónica
Luis Enrique Erro 1, Tonantzintla, Puebla, México

CONACYT
Consejo Nacional de Ciencia y Tecnología

New Frontiers in Black Hole Astrophysics
IAU Symposium 324
Ljubljana, Slovenia
16 september 2016

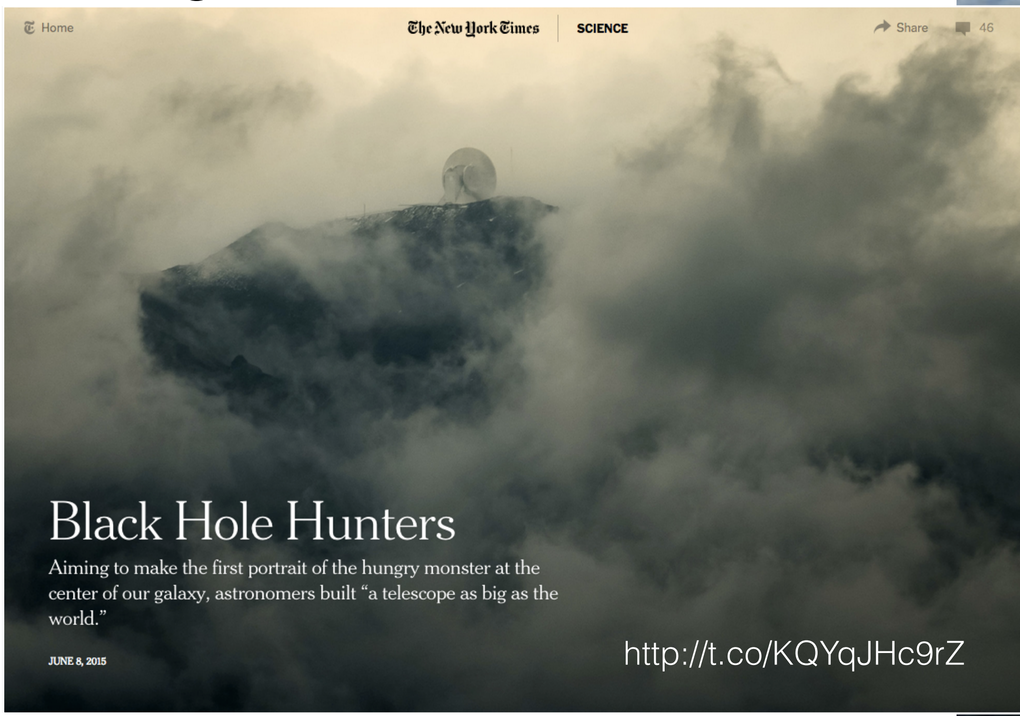
Instituto Nacional de Astrofísica, Óptica y Electrónica

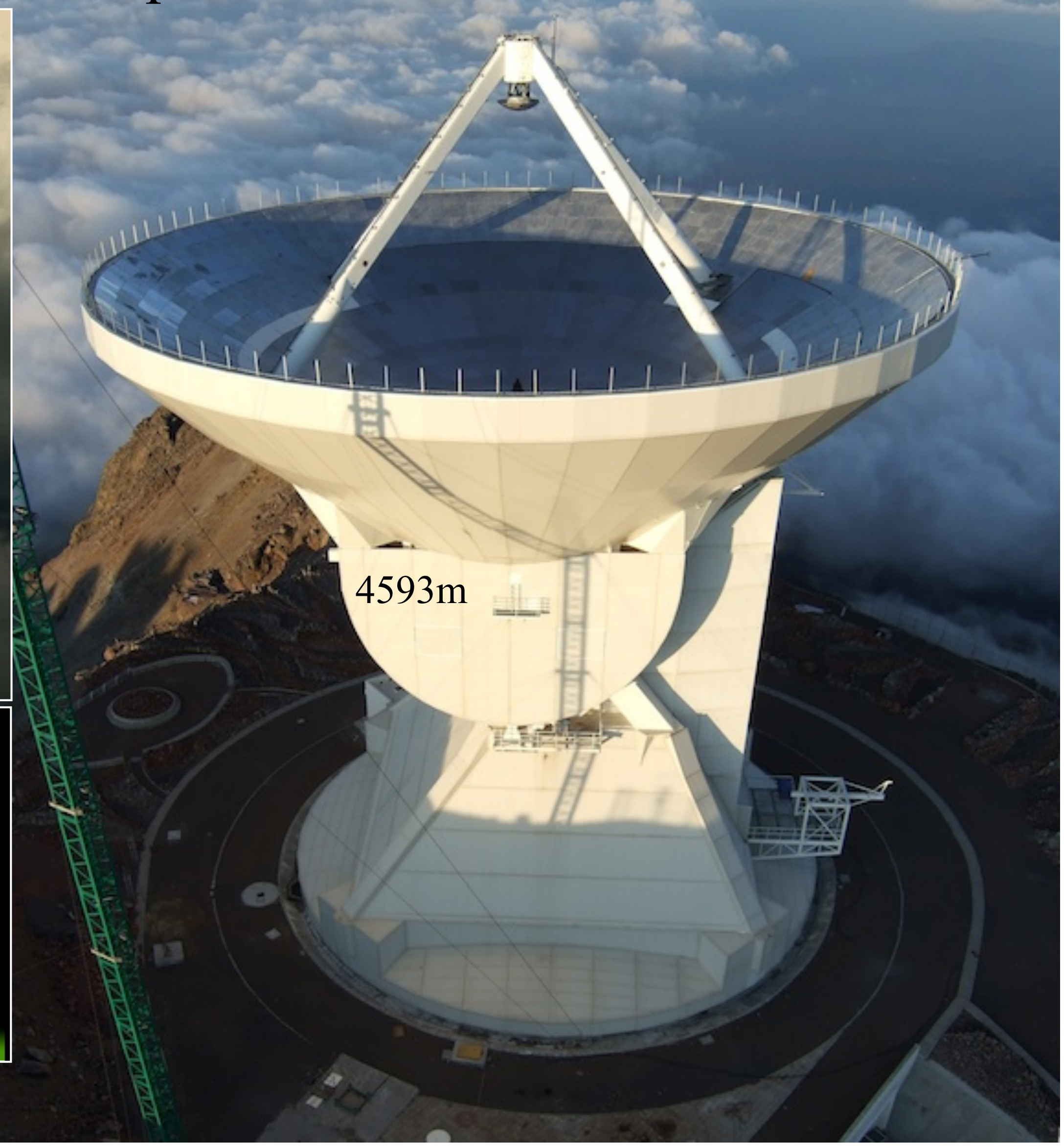


- INAOE is in the grounds of the Observatorio Astrofísico Nacional de Tonantzintla (OAN-Ton), Puebla, founded in 1942 by Luis Enrique Erro.
- OAN Tonantzintla is the site of the discovery of HH objects (& Ton blue galaxies, flare stars…).
- In 1971 Guillermo Haro transformed the OAN-Ton into INAOE, with the project of the Cananea observatory - today Observatorio Astrofísico Guillermo Haro, operational since 1988.
- Since 1994, INAOE is leading the Large Millimeter Telescope Alfonso Serrano, in partnership with the University of Massachusetts, Amherst.

Gran Telescopio Milimétrico Alfonso Serrano

The largest dish of the Event Horizon Telescope!

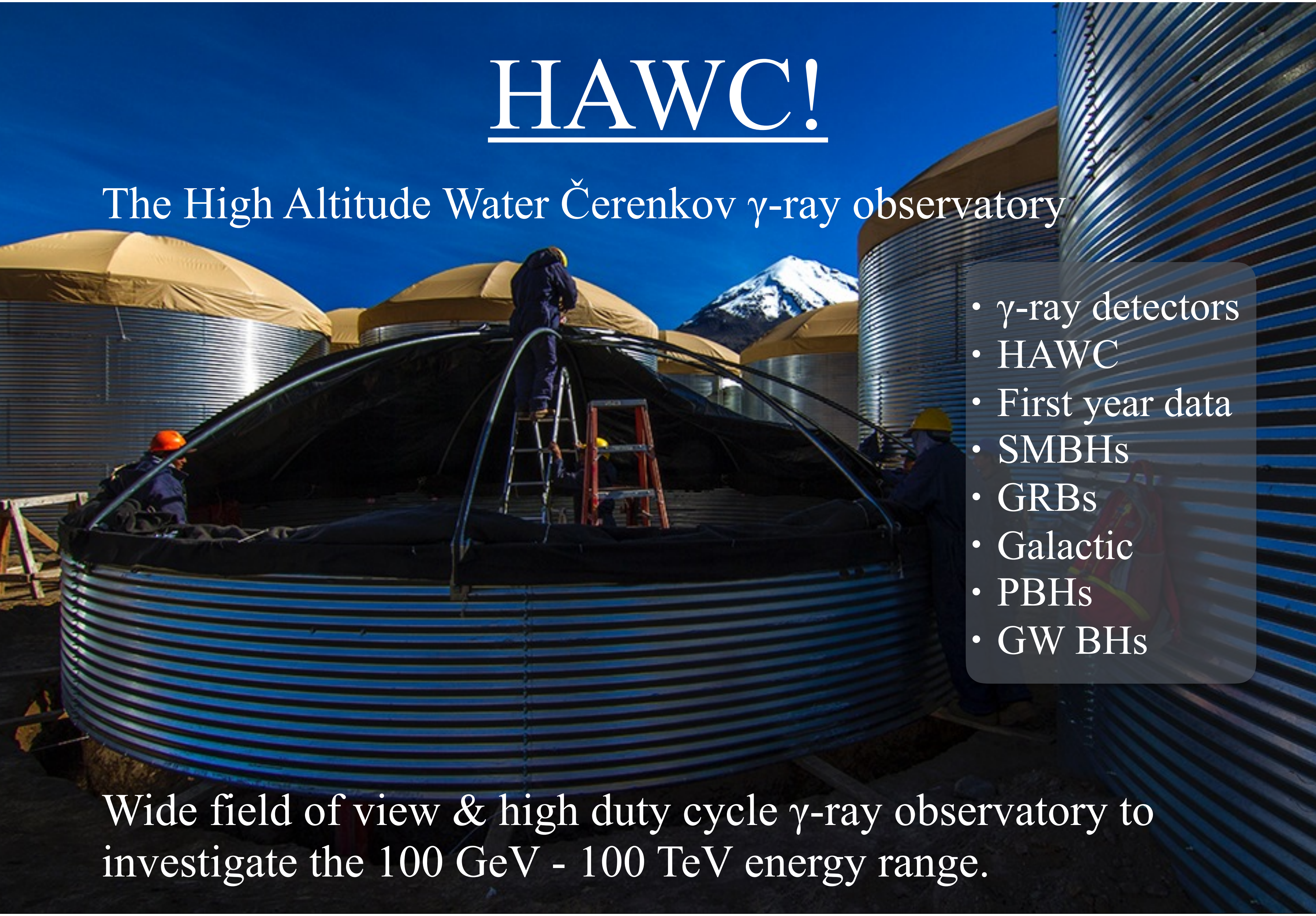




Redshift searches in BL Lacs.

HAWC!

The High Altitude Water Čerenkov γ-ray observatory



- γ-ray detectors
- HAWC
- First year data
- SMBHs
- GRBs
- Galactic
- PBHs
- GW BHs

Wide field of view & high duty cycle γ-ray observatory to investigate the 100 GeV - 100 TeV energy range.

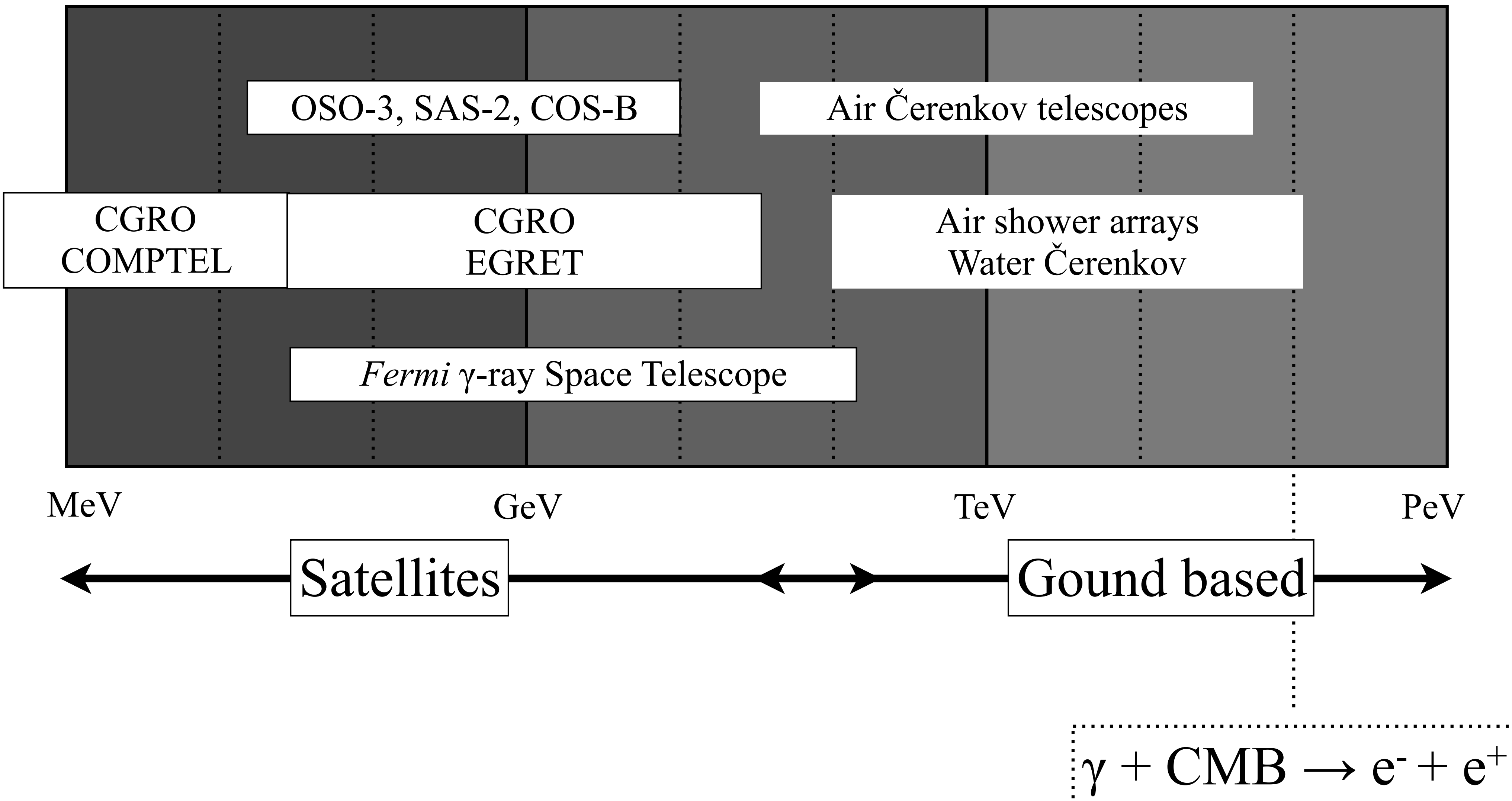
The HAWC Collaboration

High Altitude Water Cherenkov Gamma-Ray Observatory

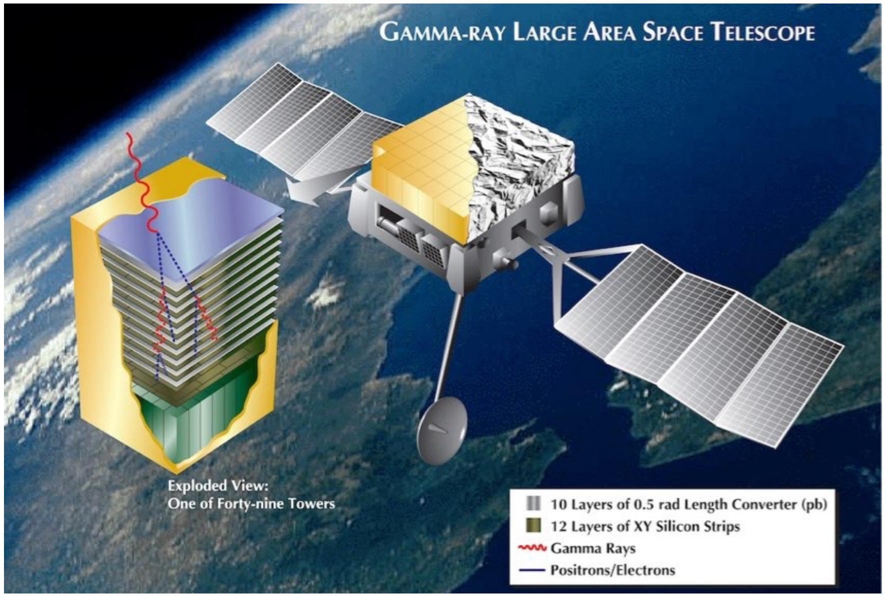
Mexico		**United States**	
Instituto Nacional de Astrofísica, Óptica y Electrónica	(INAOE)	University of Maryland	(UMD)
Universidad Nacional Autónoma de México		Los Alamos National Laboratory	(LANL)
Instituto de Astronomía UNAM	(IA-UNAM)	Colorado State University	(CSU)
Instituto de Ciencias Nucleares UNAM	(ICN-UNAM)	George Mason University	(GMU)
Instituto de Física UNAM	(IF-UNAM)	Georgia Institute of Technology	(GATECH)
Instituto de Geofísica UNAM	(IG-UNAM)	Michigan State University	(MSU)
Benemérita Universidad Autónoma de Puebla	(BUAP)	Michigan Technological University	(MTU)
Instituto Politécnico Nacional		Pennsylvania State University	(PSU)
Centro de Investigación y Estudios Avanzados	(CINVESTAV)	NASA GSFC	
Centro de Investigación en Cómputo - IPN	(CIC-IPN)	University of California Santa Cruz	(UCSC)
Universidad Autónoma de Chiapas	(UNACH)	University of California Irvine	(UCI)
Universidad Autónoma del Estado de Hidalgo	(UAEH)	University of New Hampshire	(UNH)
Universidad de Guadalajara	(UdG)	University of New Mexico	(UNM)
Universidad Michoacana de San Nicolás de Hidalgo	(UMSNH)	University of Rochester	(UR)
Universidad Politécnica de Pachuca	(UPP)	University of Utah	(UU)
		University of Wisconsin	(UW)

MPI-HD, Univ. Costa Rica and Krakow now also in HAWC

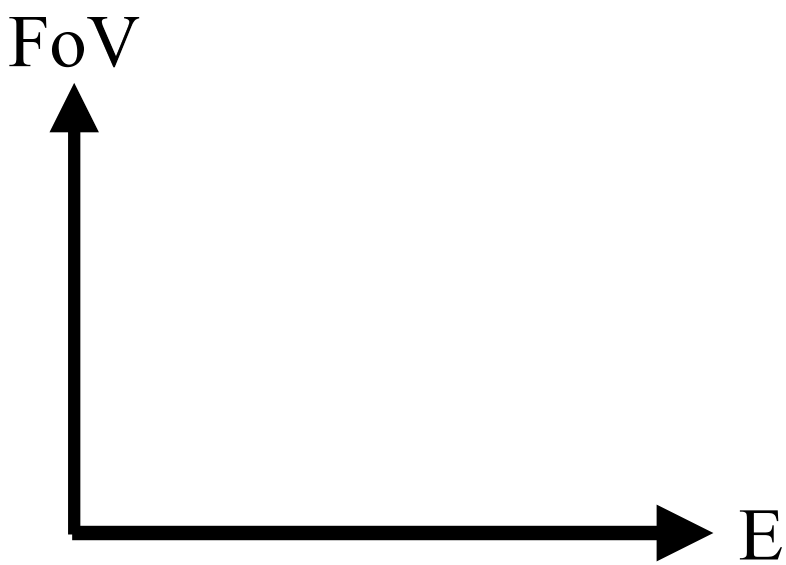
The γ-ray band

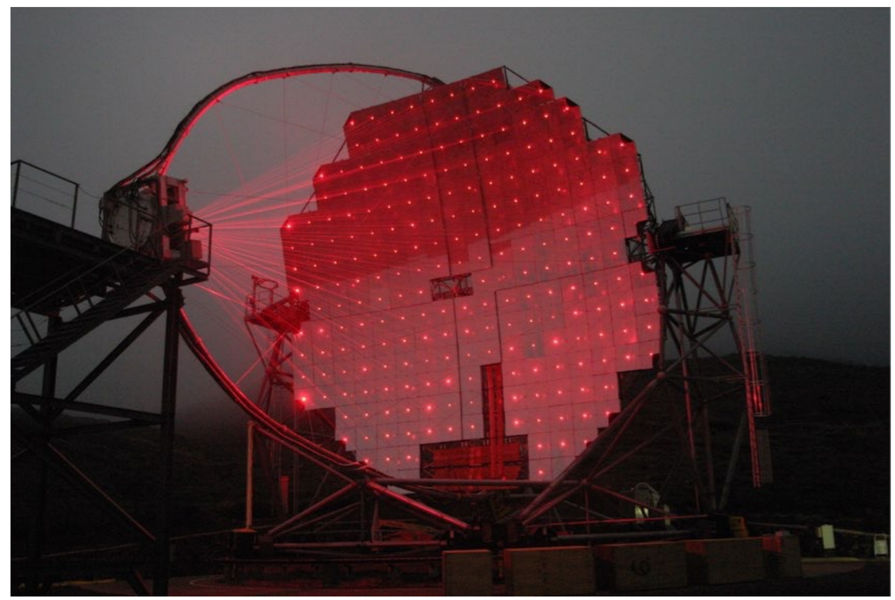


Sr



Deg





GeV

TeV

Sr

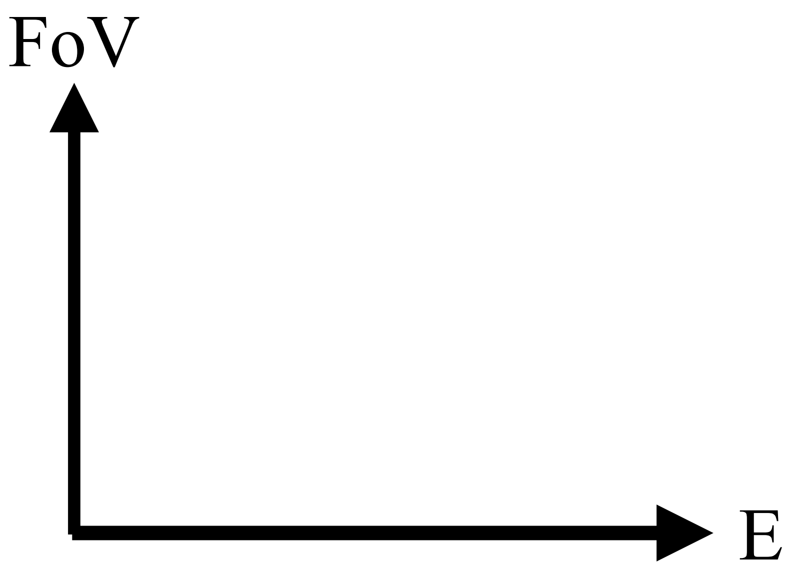
Pair production telescopes
0.1 - 100 GeV
Space based: small effective area
Background free
Large f.o.v. and high duty cycle

All sky survey & monitoring
Transients (AGN, GRB)
Diffuse emission

Extensive air-shower arrays
100 GeV - 100 TeV
Good background rejection
Large f.o.v. and high duty cycle

Partial sky survey & monitoring
Extended sources
Transients (AGN, GRB)
Highest energies

Deg

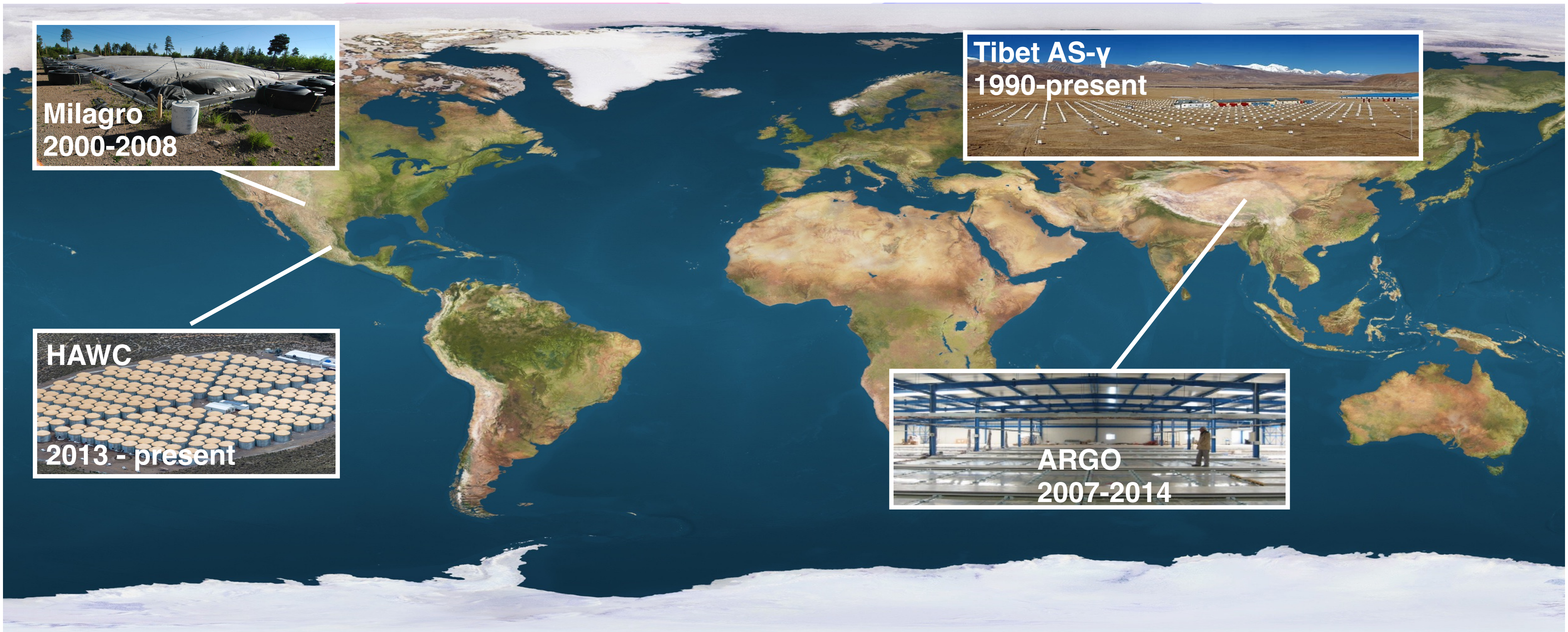


Atmospheric Cherenkov Telescopes
50 GeV - 100 TeV
Large effective area
Excellent background rejection
Small f.o.v. and low duty cycle

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

GeV TeV

Extensive Air Shower Arrays γ-ray observatories



EAS with γ-ray capabilities benefit of high altitude sites.
Ideal for monitoring large portions of the sky: unbiased surveys.

The HAWC detector

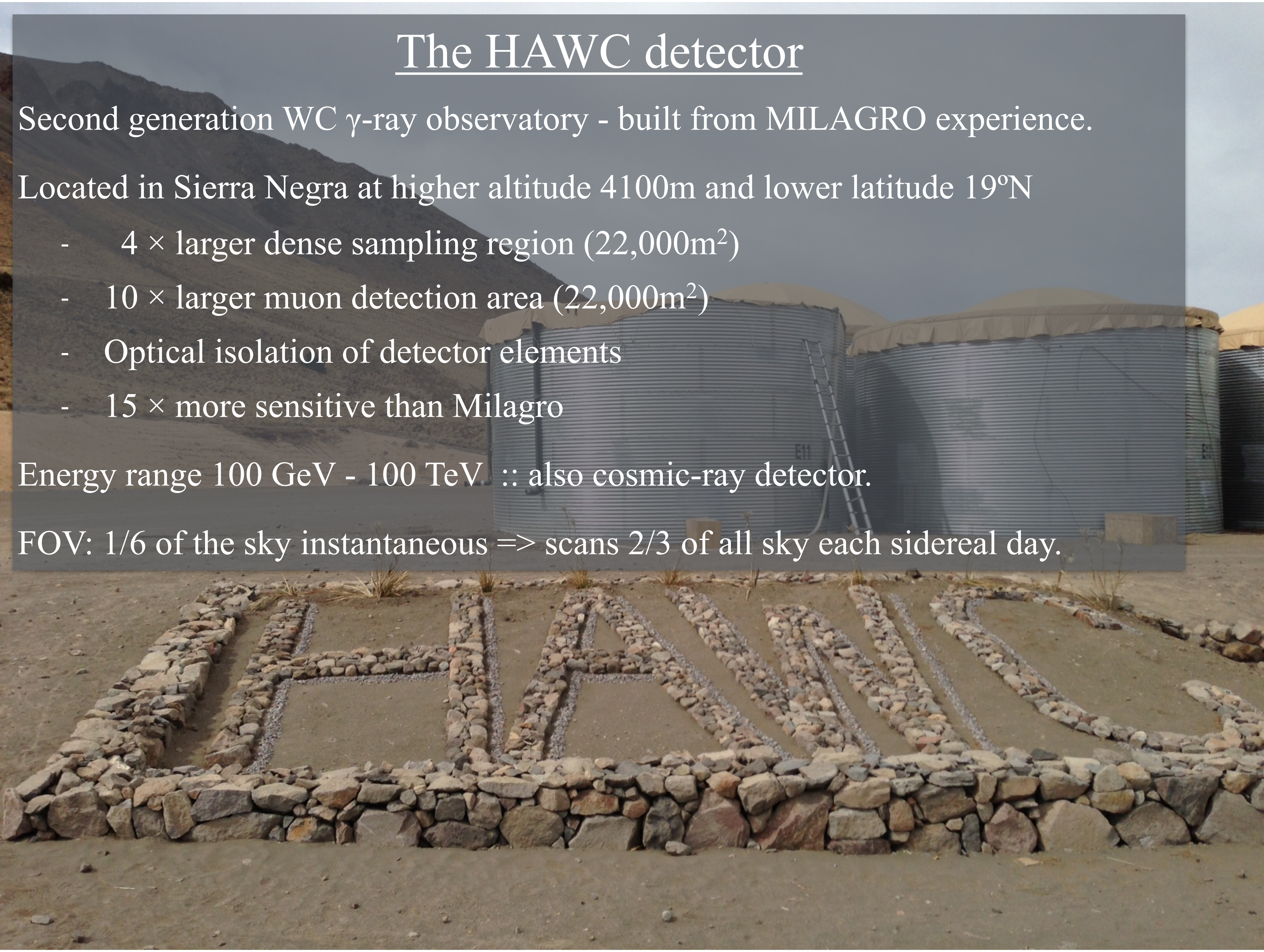
Second generation WC γ-ray observatory - built from MILAGRO experience.

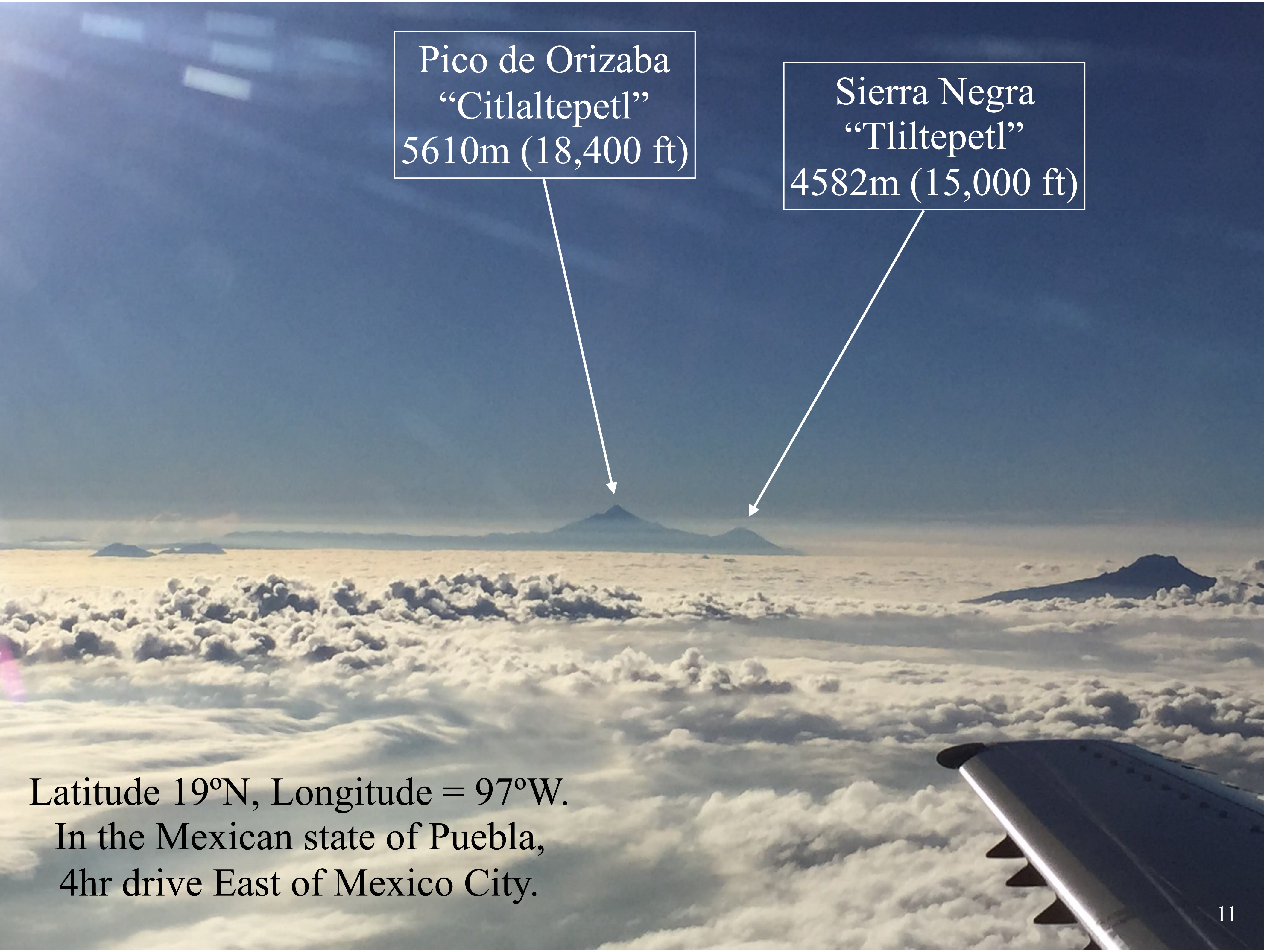
Located in Sierra Negra at higher altitude 4100m and lower latitude 19ºN

- 4 × larger dense sampling region (22,000m^2)
- 10 × larger muon detection area (22,000m^2)
- Optical isolation of detector elements
- 15 × more sensitive than Milagro

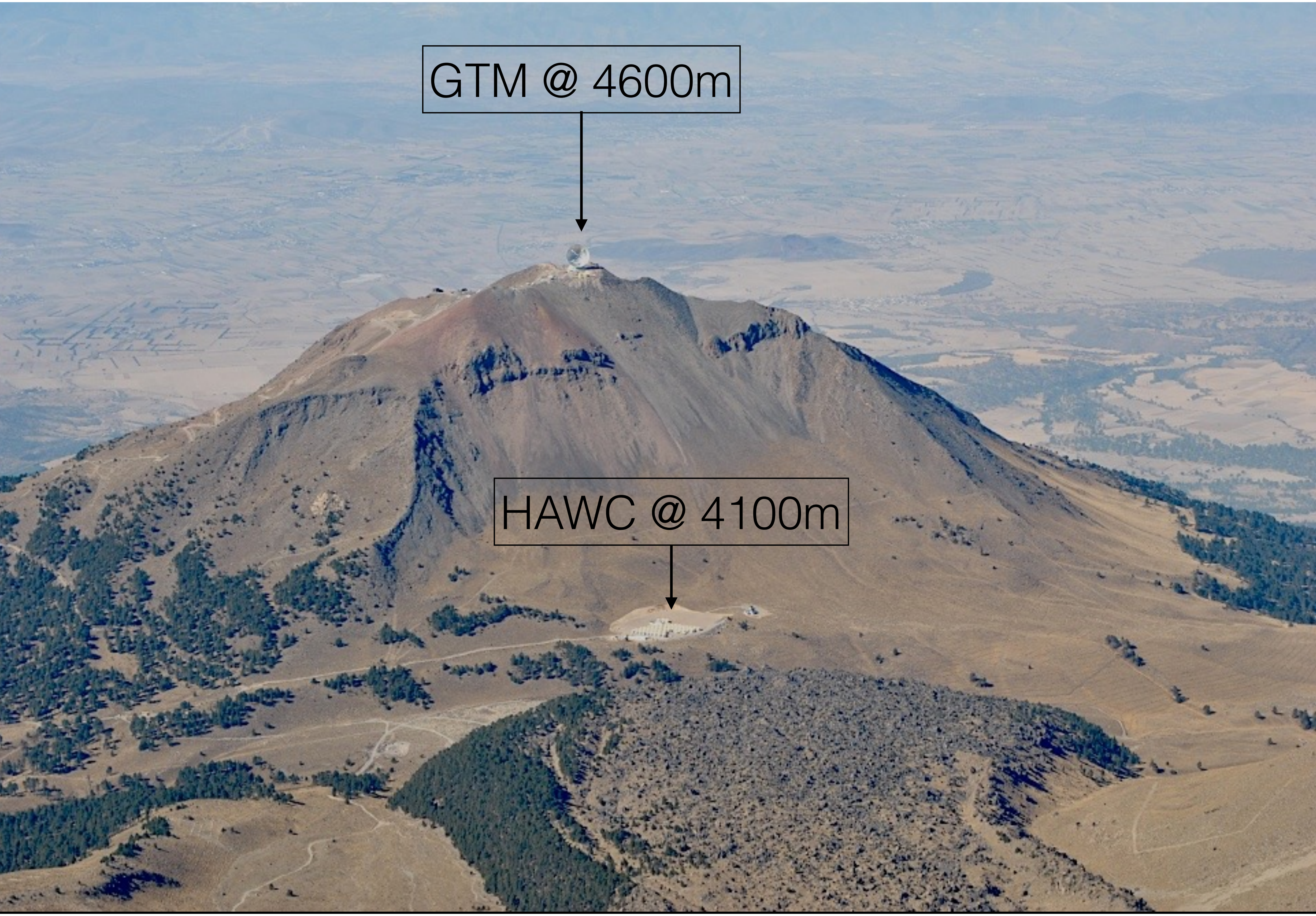
Energy range 100 GeV - 100 TeV :: also cosmic-ray detector.

FOV: 1/6 of the sky instantaneous => scans 2/3 of all sky each sidereal day.





Pico de Orizaba
"Citlaltepetl"
5610m (18,400 ft)
Sierra Negra
"Tliltepetl"
4582m (15,000 ft)
Latitude 19ºN, Longitude = 97ºW.
In the Mexican state of Puebla,
4hr drive East of Mexico City.


GTM @ 4600m
HAWC @ 4100m

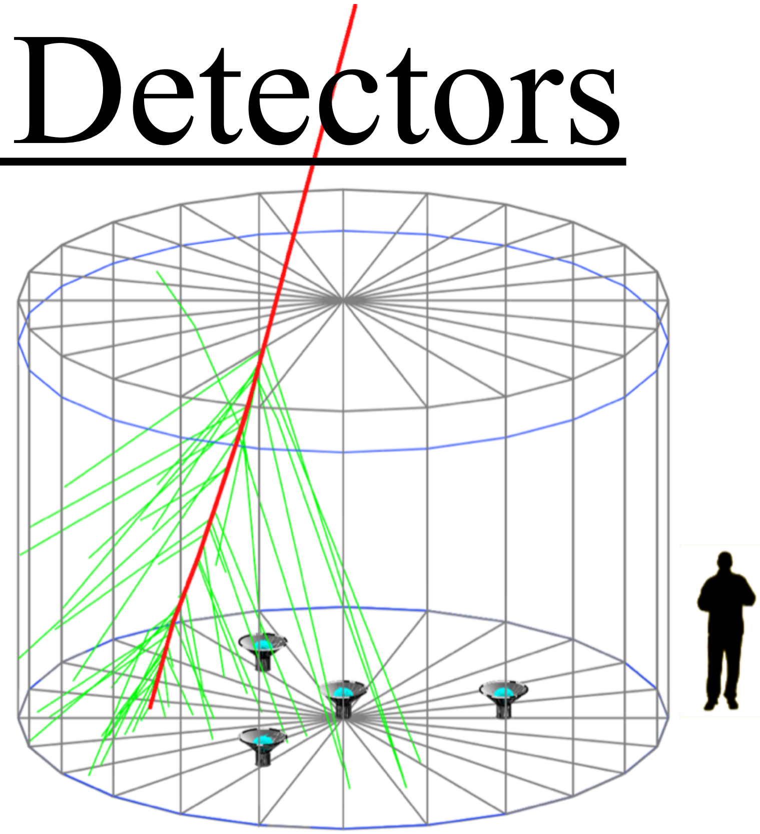

May 2011


Jan 2012


Dec 2014


Mar 2015
HAWC
HAWC 300
Full operations
DATE: 03/20/2015
TIME: 12:26:30

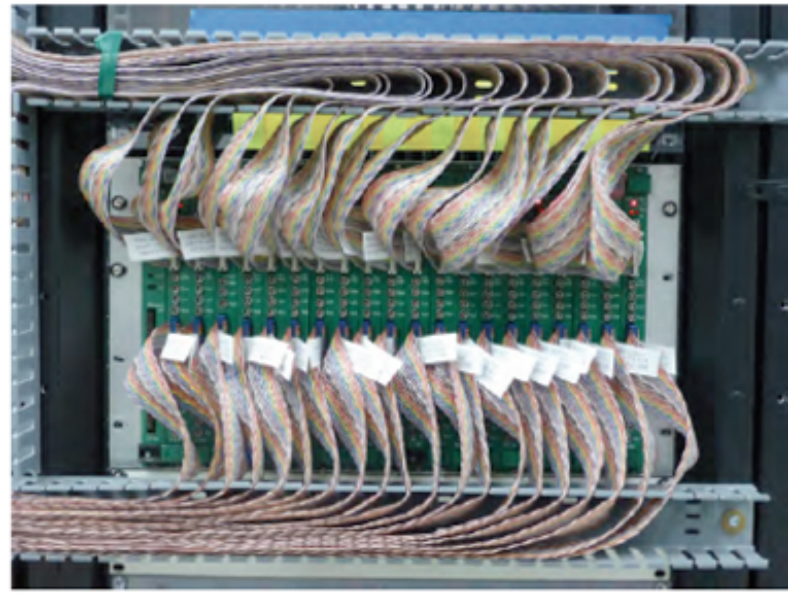
Water Cherenkov Detectors

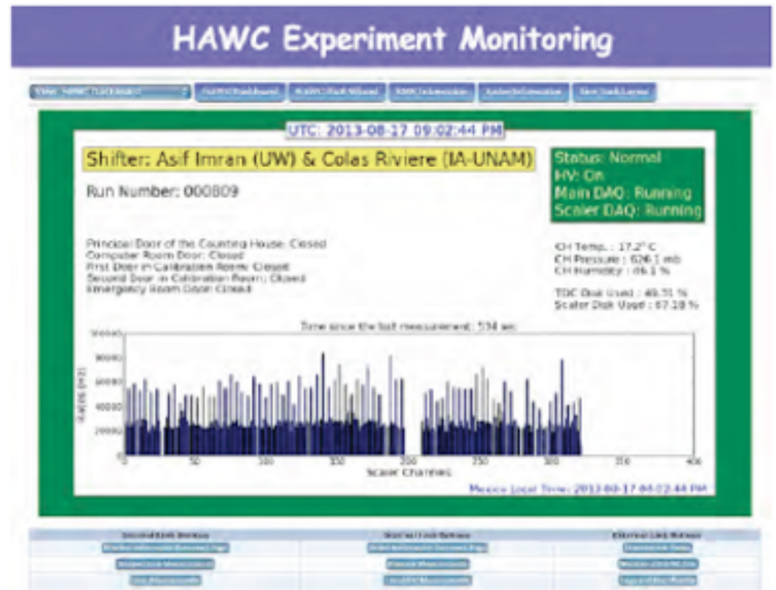


- Each WCD contains 180,000 liters of water treated for transparency.
- Each WCD has 3(8”) + 1(10”) PMTs: fast response and high QE to Cherenkov light.
- Optical fibre system for calibration.
- Each WCD is connected to the central counting house: 180 km of cabling!

Counting house
- Data acquisitions
- Laser calibration system

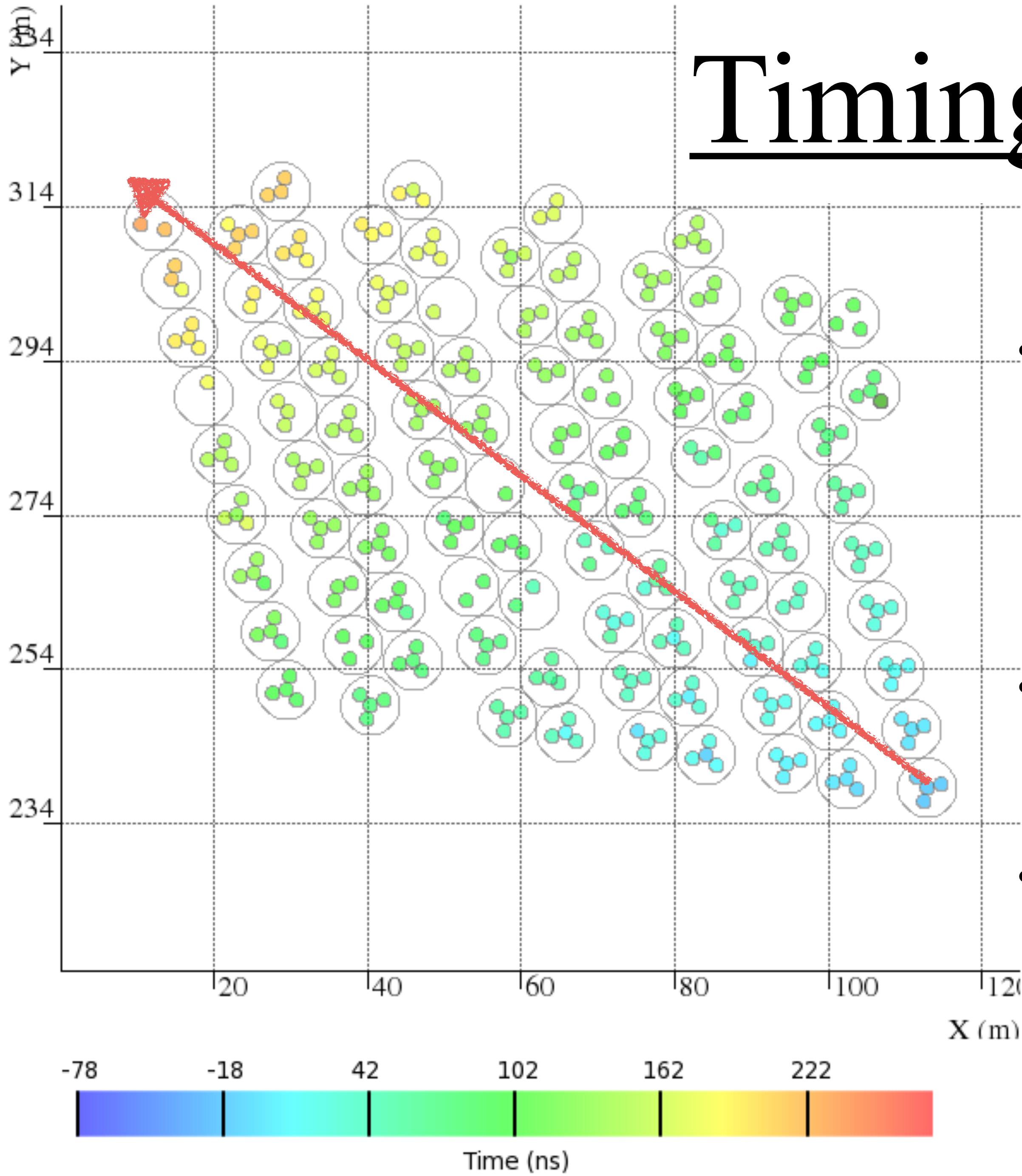
HAWC Utility Building
- Water filtration
- Bladder tests





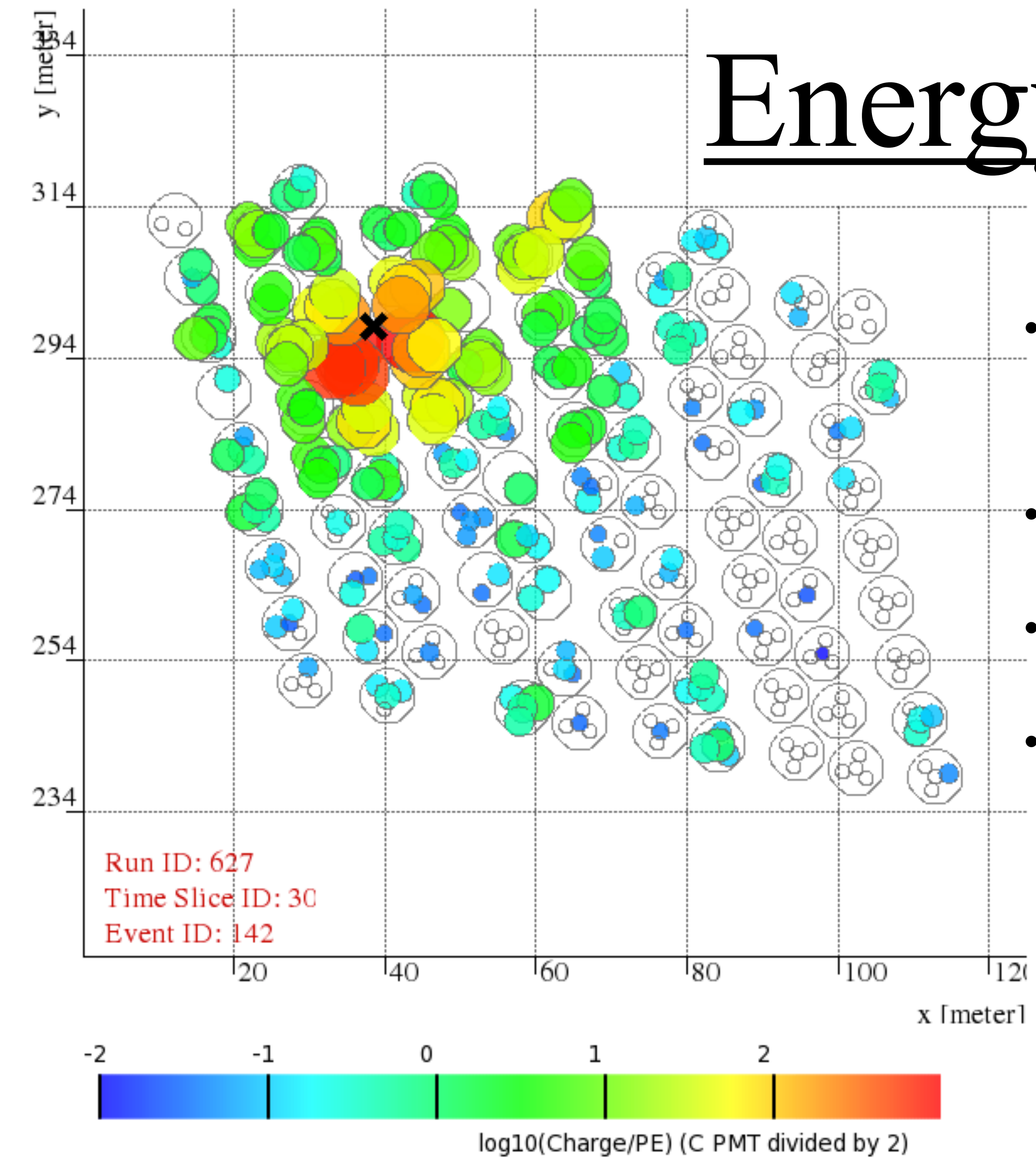
HAWC registers 20,000 cosmic rays per second
& generates 2 Terabytes per day - every day.

Timing information



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

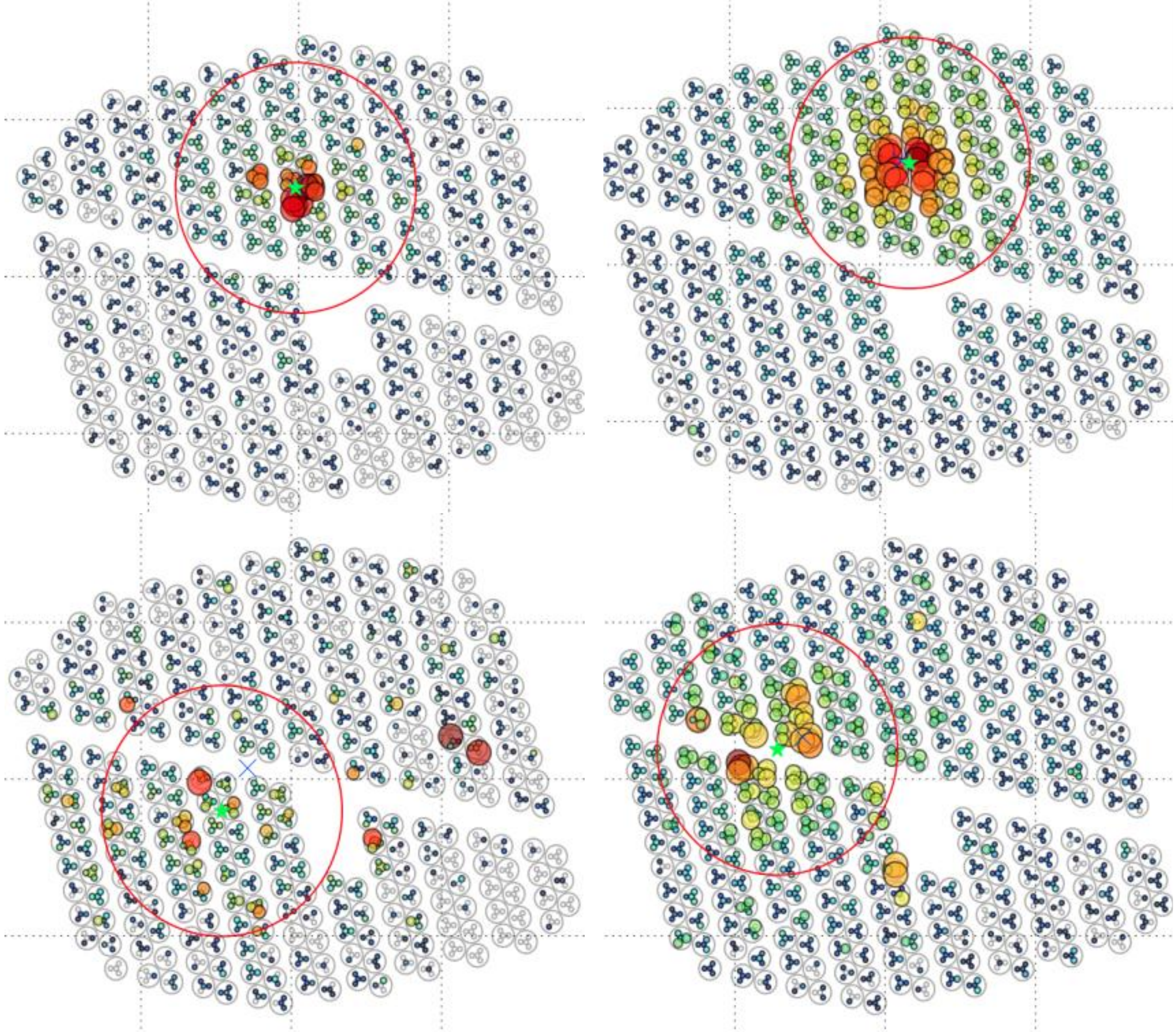
Energy deposition



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

γ ray

Hadron



E

Sensitivity & Field of View

Transit instrument

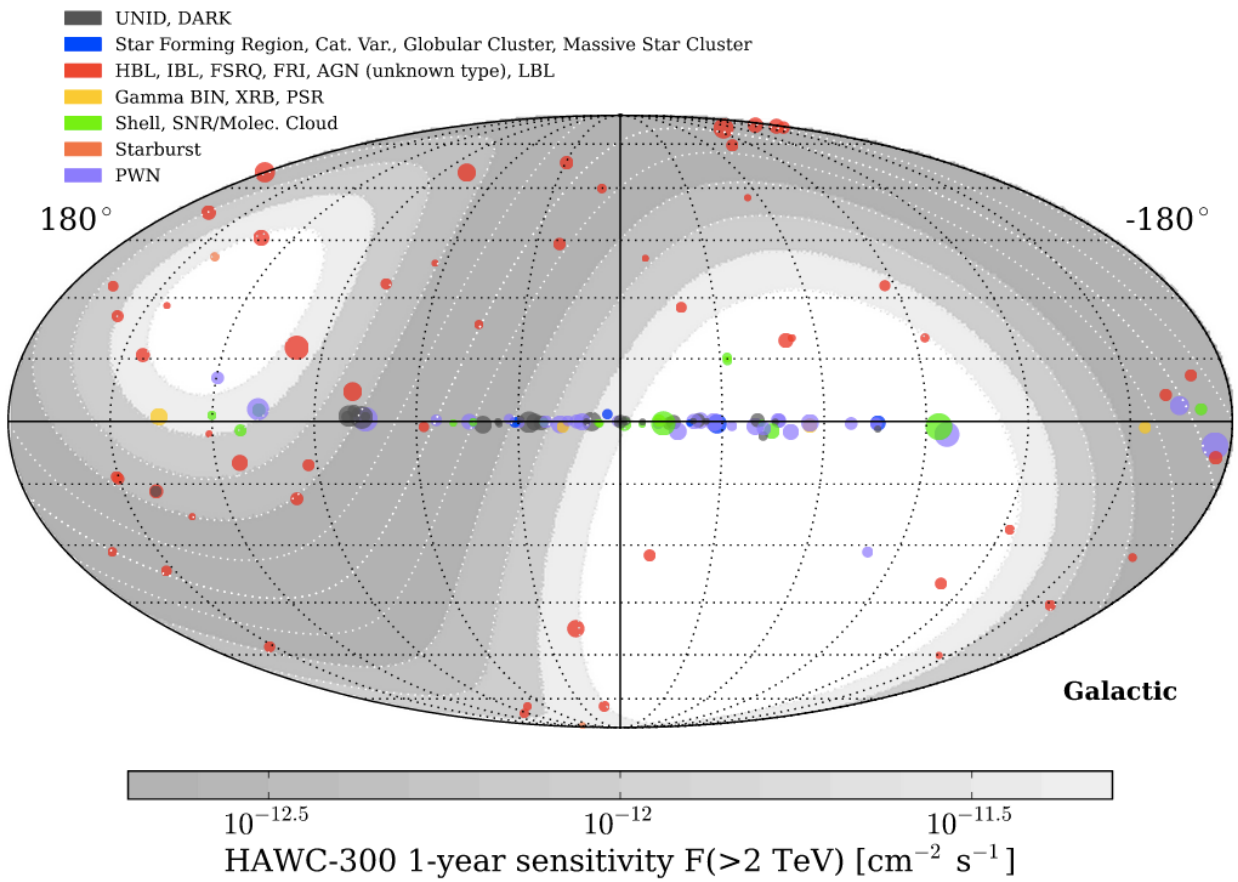
FOV = 1.8 Sr

HAWC scans 2/3 of the celestial sphere every sidereal day to a depth of 1 Crab @ 5σ:

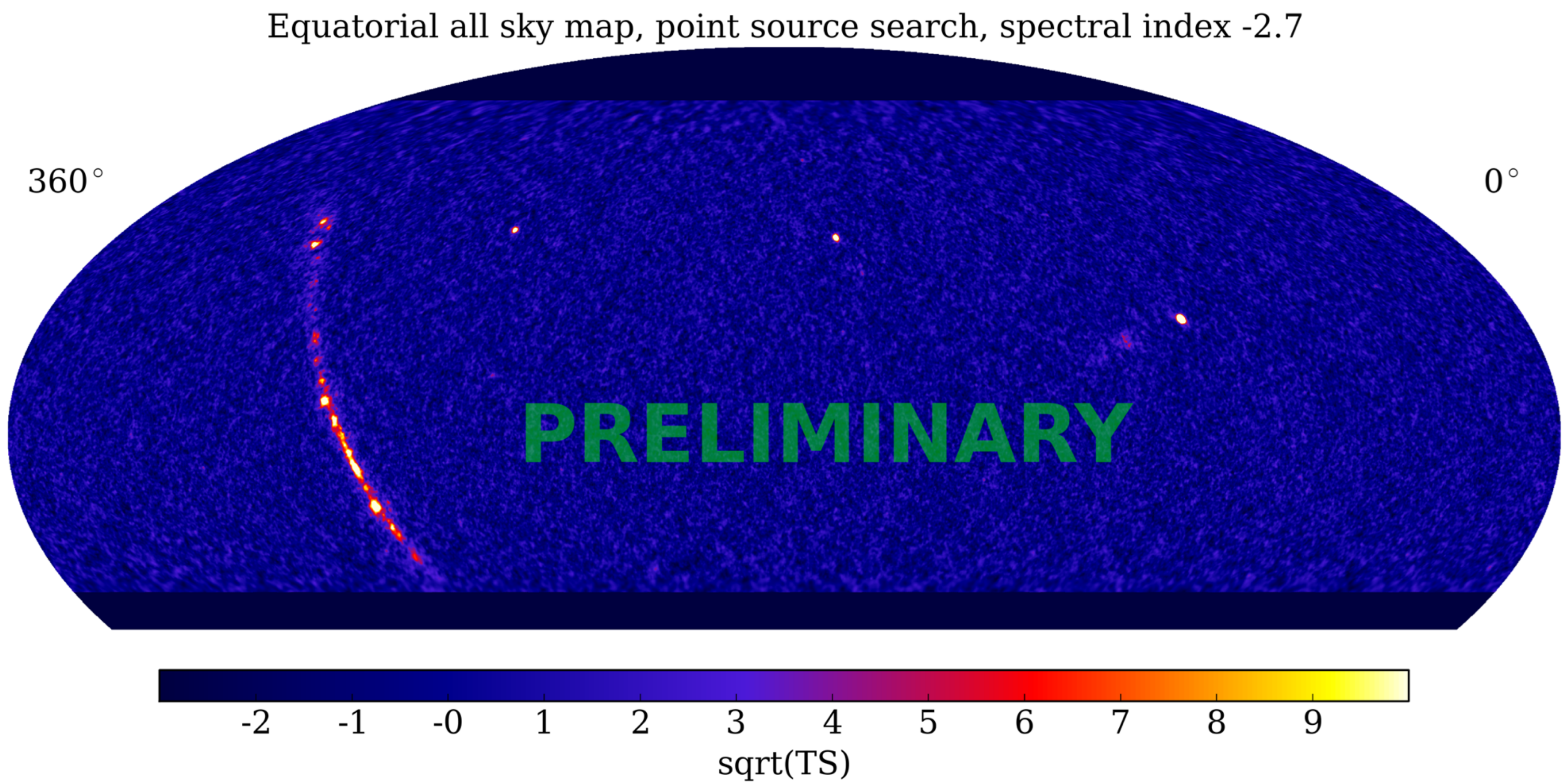
➡ transient events

➡ extended diffuse sources

➡ 60 mCrab / sqrt(year)

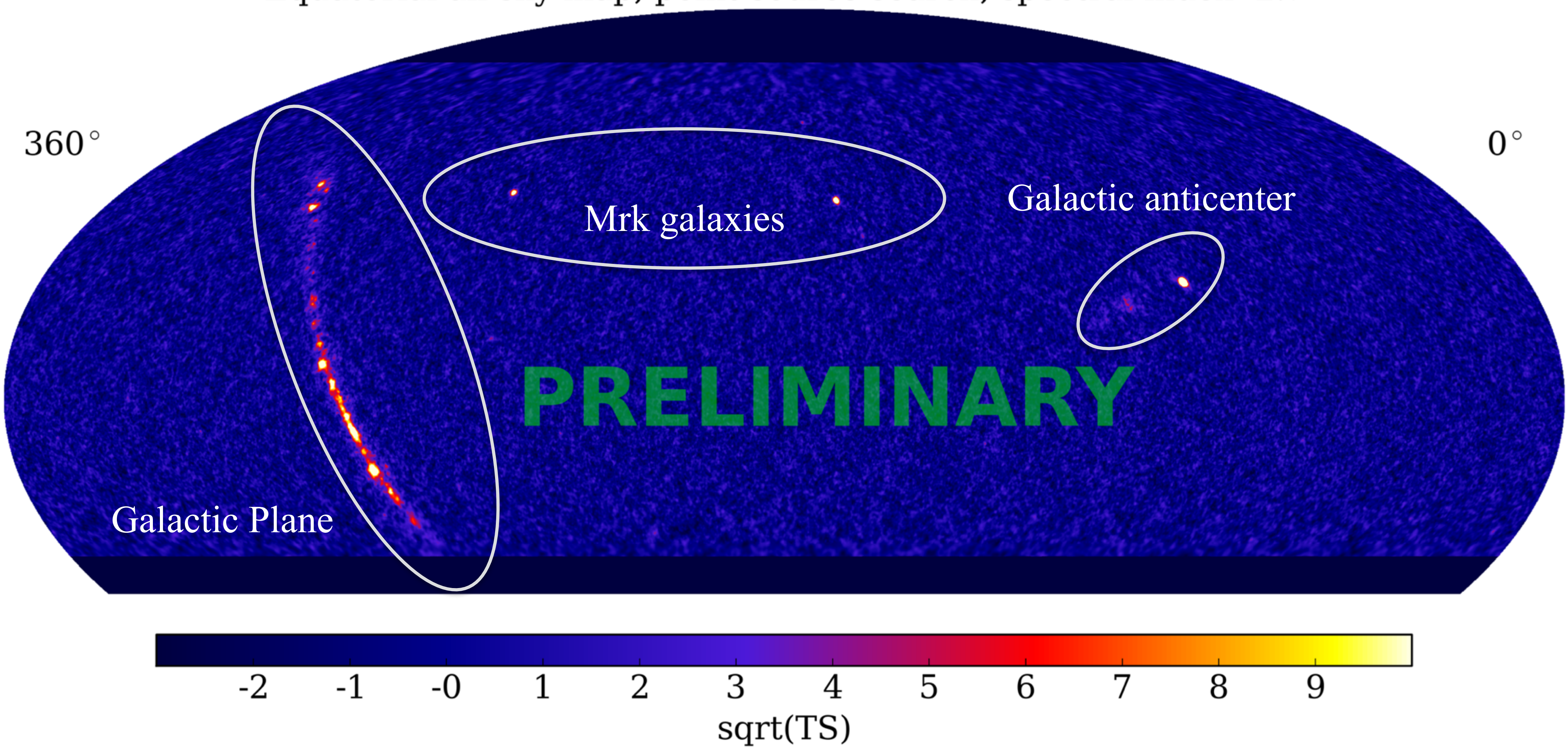


First year of HAWC data

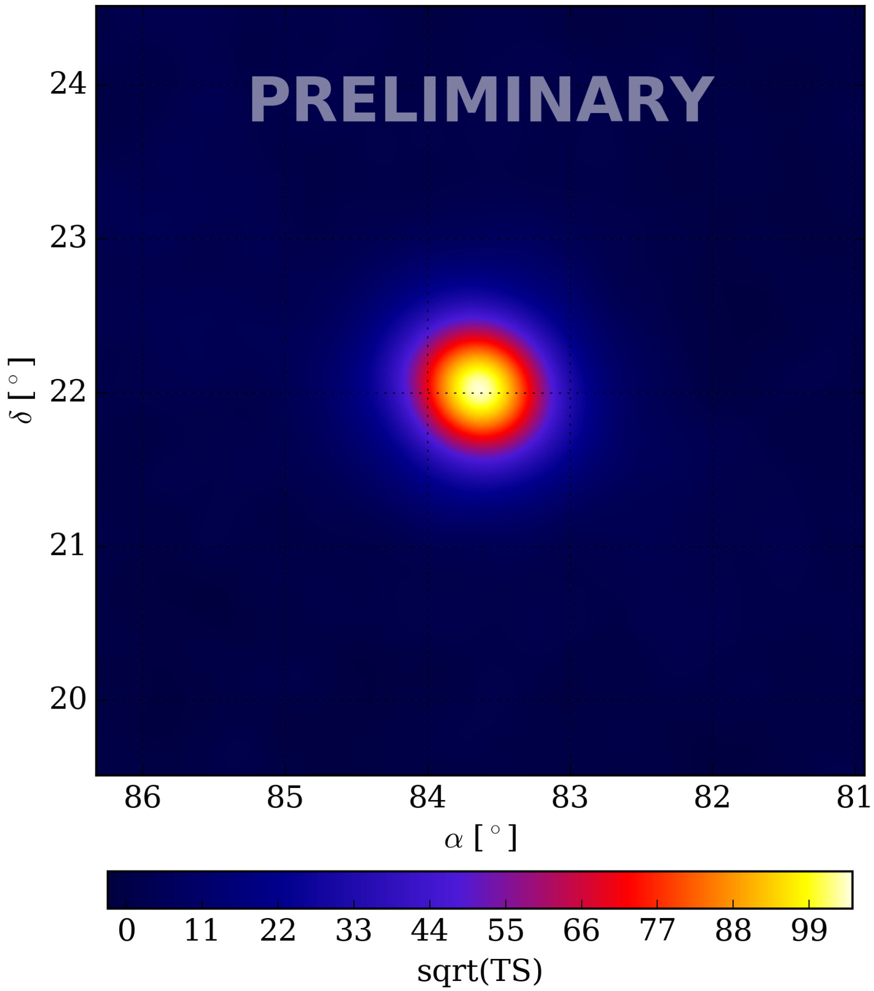


¡17 months of HAWC data!

Equatorial all sky map, point source search, spectral index -2.7

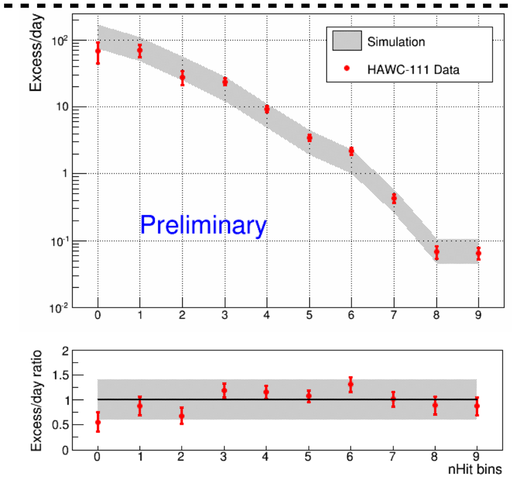


The Crab

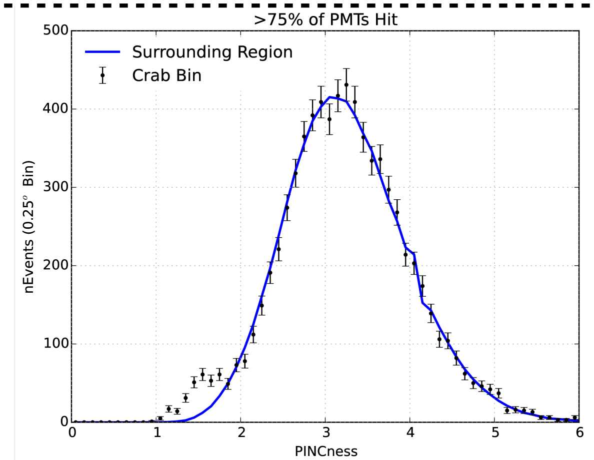


Now detected at ~100σ
Analysis optimized on the Crab.

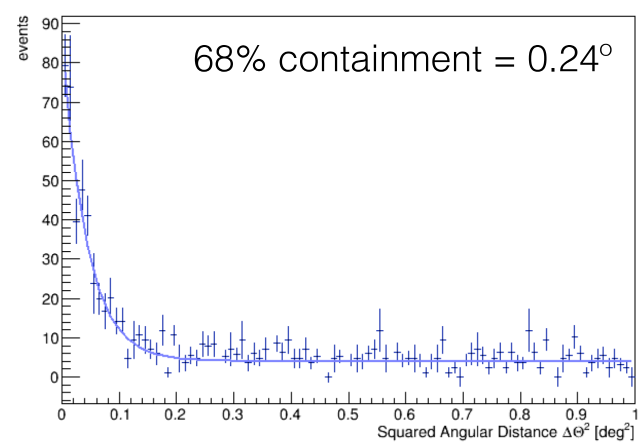
Validation of Montecarlo simulations



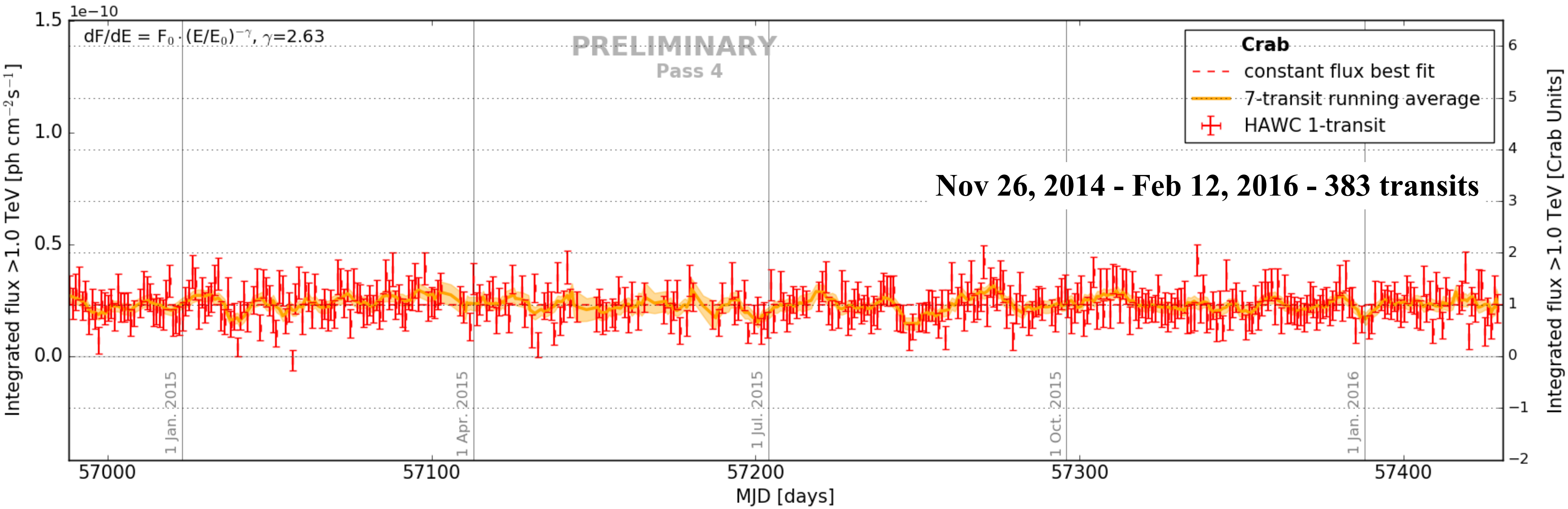
Improve on hadron rejection algorithms



Evaluate detector response



Crab Nebula: daily flux



- Light curve consistent with constant flux.
- The Crab Nebula has show flares at lower (~MeV) energies, but none was observed by Fermi-LAT during the period shown here.
- Daily signal at 5.5σ ⇒ slightly better than design

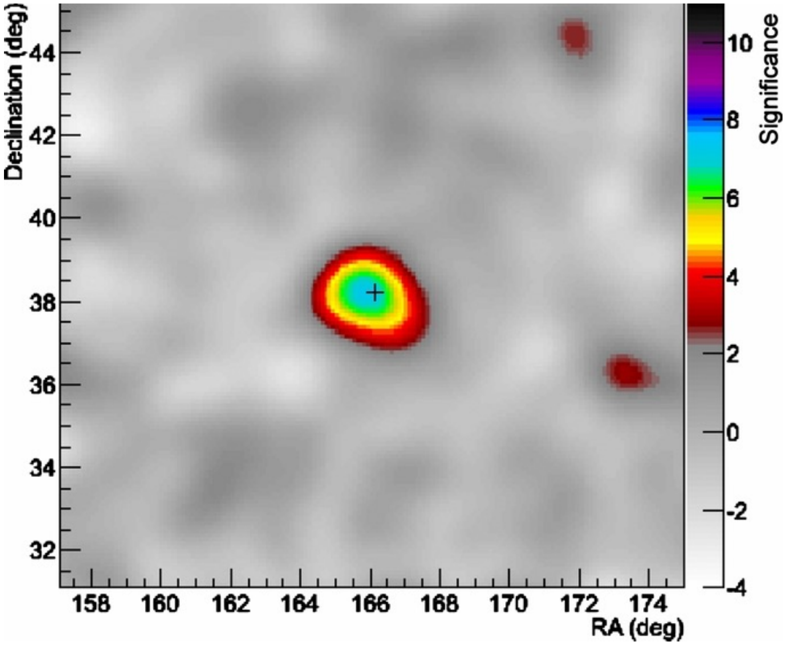
HAWC Crab paper in preparation

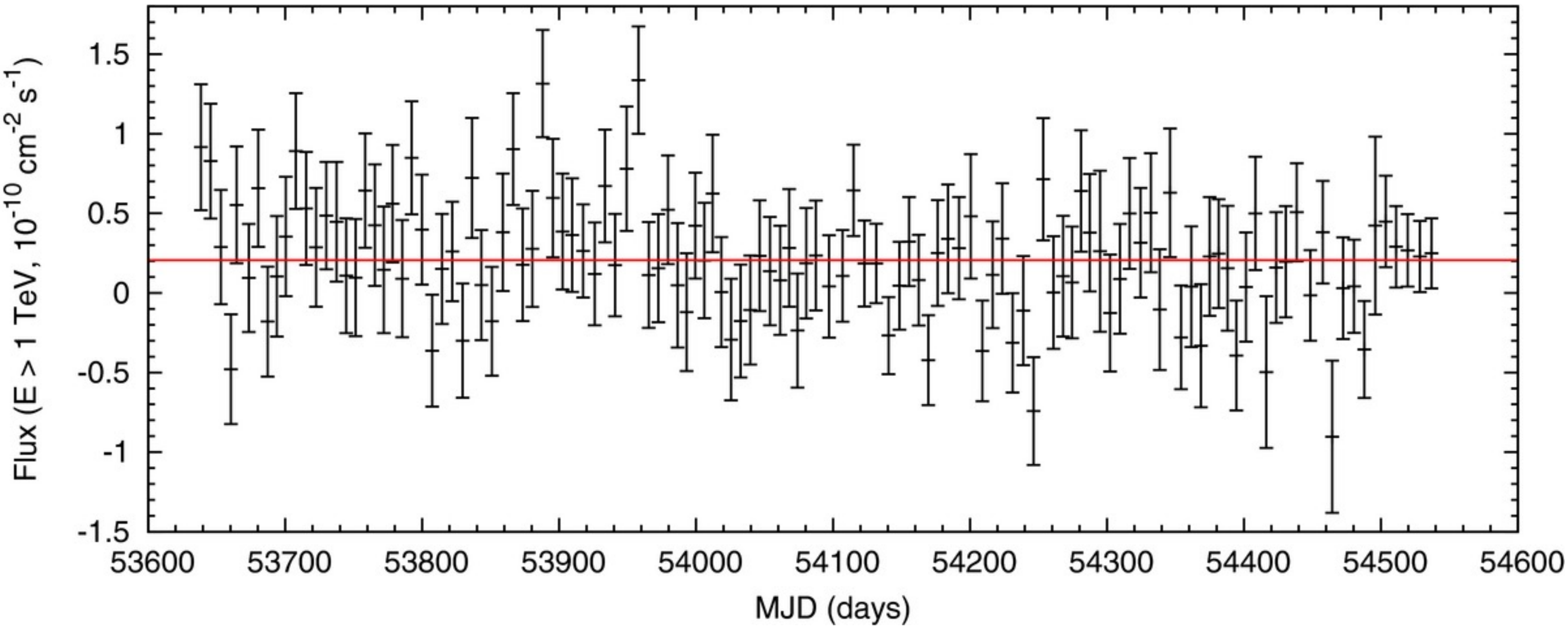
Mrk 421

- BL Lac AGN detected all across the EM spectrum.
- Nearby z=0.031 (d_L = 134 Mpc) - spectroscopically.
- Detected early-on by *CGRO*-EGRET in GeV energies (Fichtel et al. 1994).
- First AGN found in TeV energies (Punch et al. 1992).
- Detected with MILAGRO (Abdo et al. 2014).
- In the 2FHL catalog, up to the 0.585 - 2 TeV band (Ackermann et al. 2016).

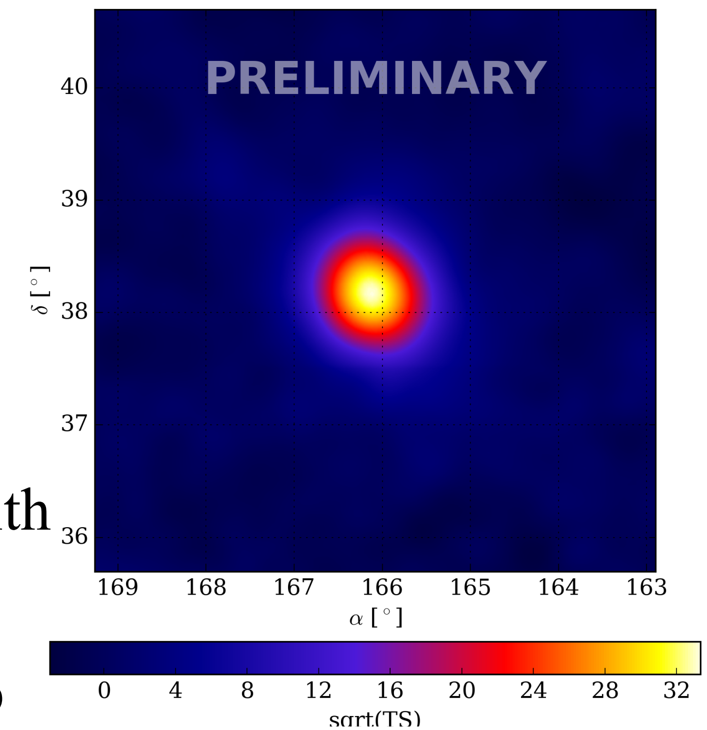
Mrk 421 - MILAGRO

- MILAGRO detection at 7.1σ between Sept 2005 and March 2008.
- Median photon energy = 1.7 TeV.

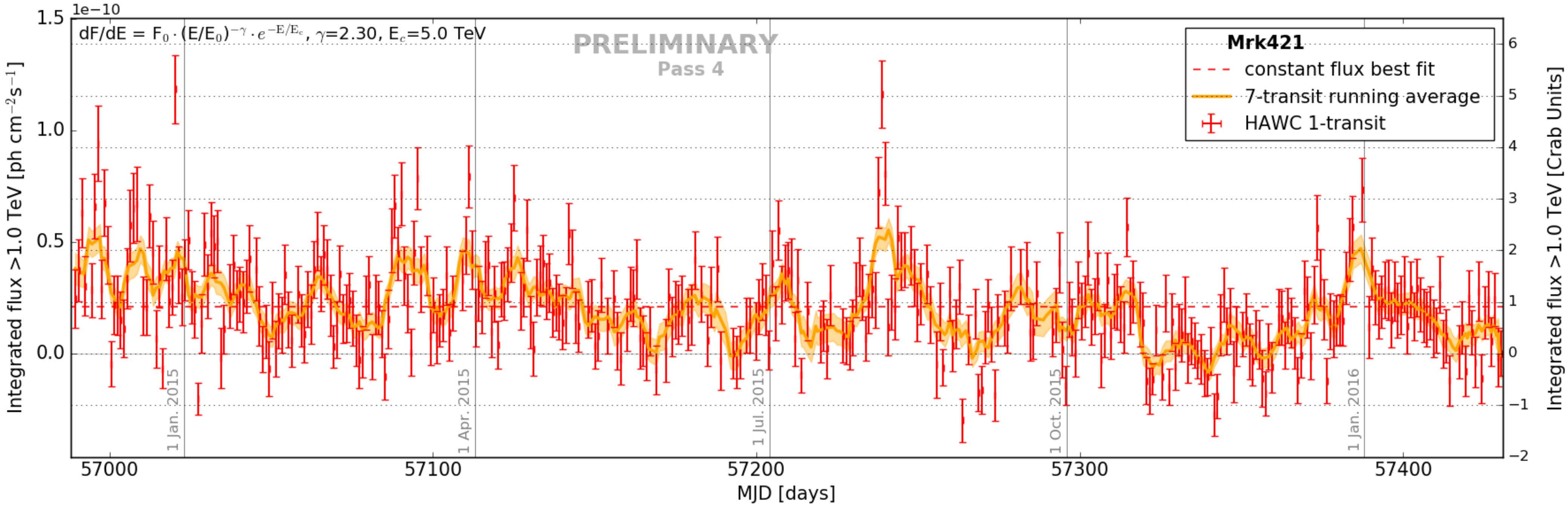




Mrk 421 - HAWC



- Detected at 33σ between Nov 2014 and Feb 2016.
- Observed up to ≳ 10 TeV.
- Daily light curve from 387 transits: inconsistent with constant flux @ $p<10^{-10}$.
- Frequent high states early 2015: Mean Flux ~ Crab

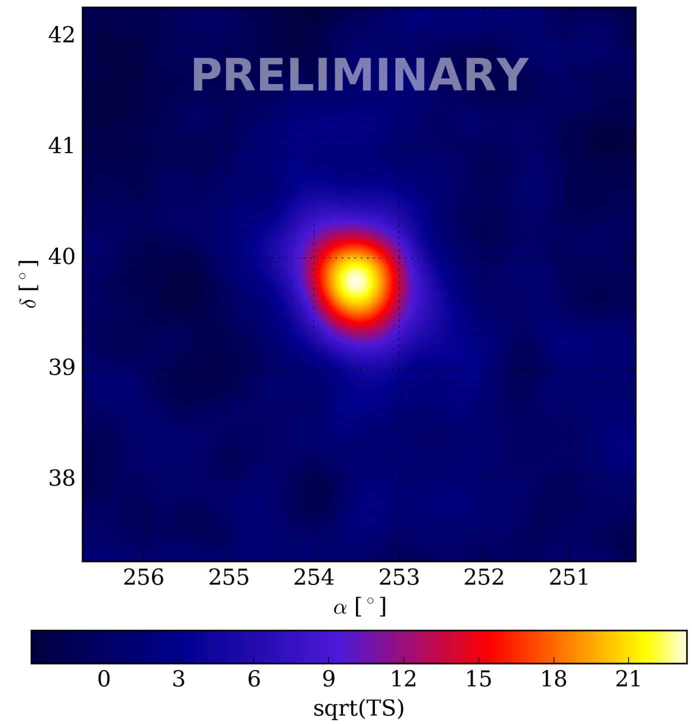


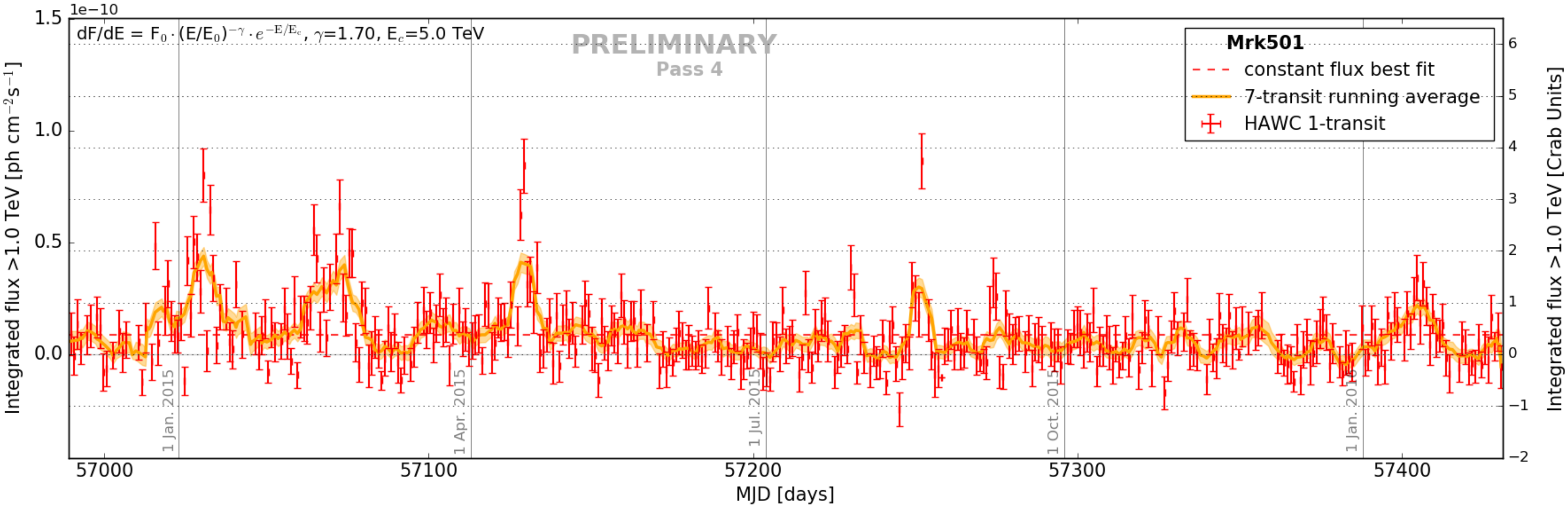
Mrk 501

- BL Lac AGN detected all across the EM spectrum.
- Nearby z=0.033 (d_L = 143 Mpc) - spectroscopically.
- Undetected by *CGRO*-EGRET!
- Found in TeV energies (Quinn et al. 1996).
- In the 2FHL catalog, up to the 0.585 - 2 TeV band (Ackermann et al. 2016).
- Nearby probe of pair-pair absorption of TeV γ rays by the extragalactic background light, together with Mrk 421.

Mrk 501 - HAWC

- Detected at 23σ between Nov 2014 and Feb 2016.
- Observed up to ≳ 10 TeV.
- Daily light curve from 390 transits: inconsistent with constant flux @ $p<10^{-10}$.
- Five transits with Flux > 4σ above mean Flux.

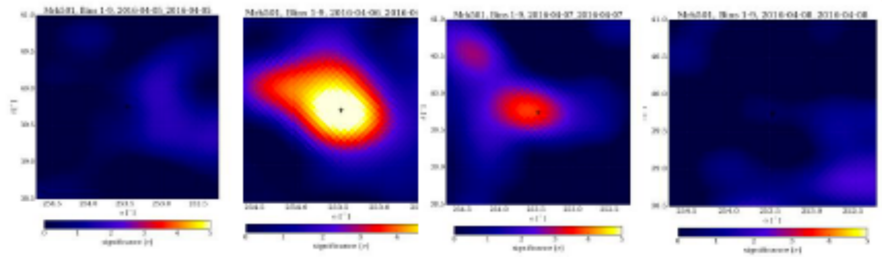




Alerts from AGN monitoring

Recent HAWC-triggered transient alerts:

First HAWC-triggered blazar flare alert:



~2 Crab units, elevated flux for ~2 days

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

First joint FACT-HAWC-SWIFT ATEL:

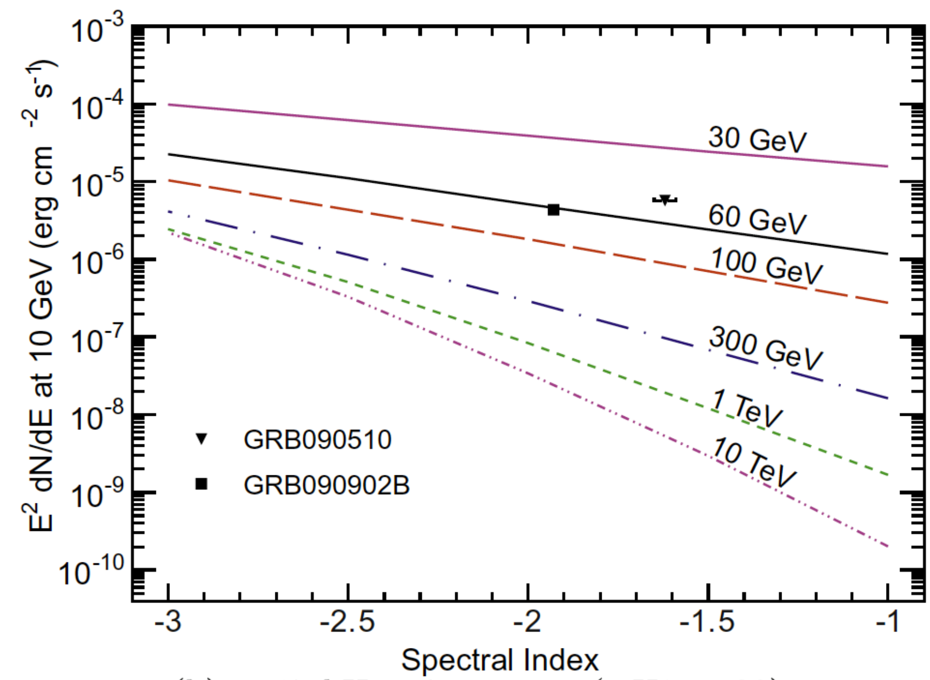
Enhanced and increasing activity in gamma rays and X-rays from the HBL Mrk421

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."*

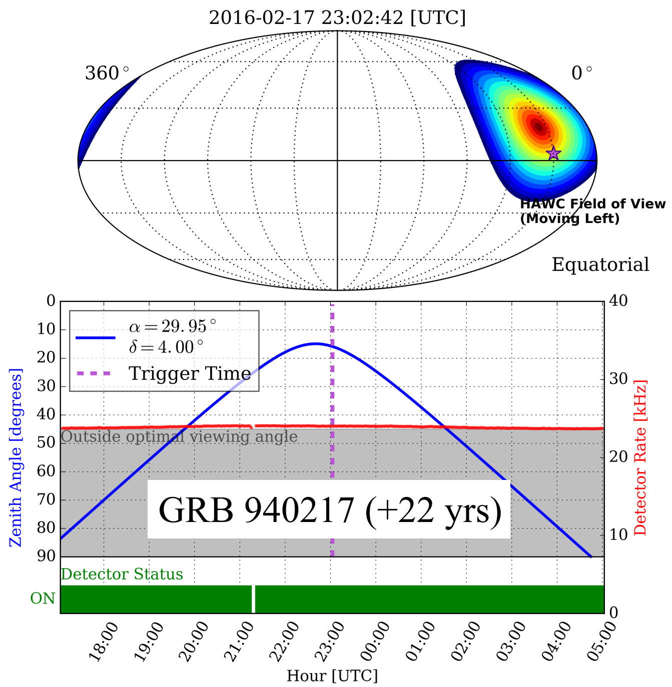
Gamma Ray Bursts

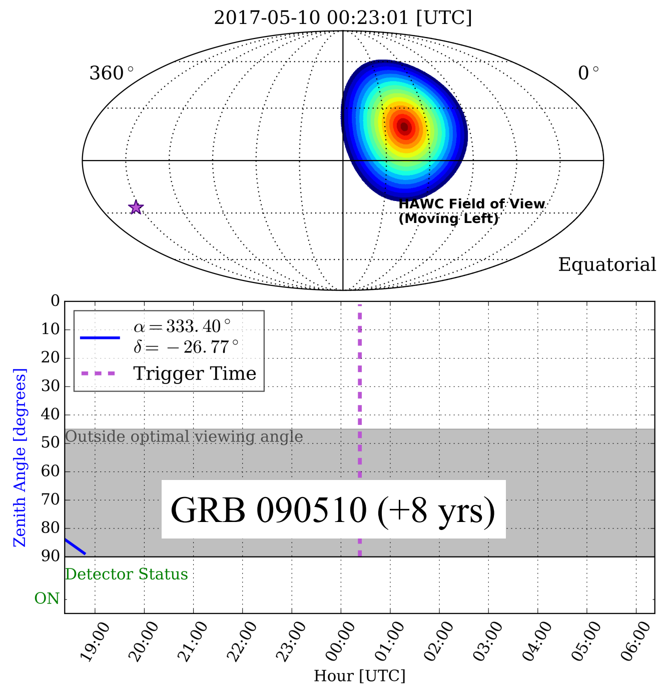
- Capability to observe TeV emission from GRBs:
  - If they do emit TeV photons;
  - Long, short, any… Just a good one and some better luck!
- Main DAQ and Scaler systems.
- HAWC performs triggered or untriggered GRB searches.

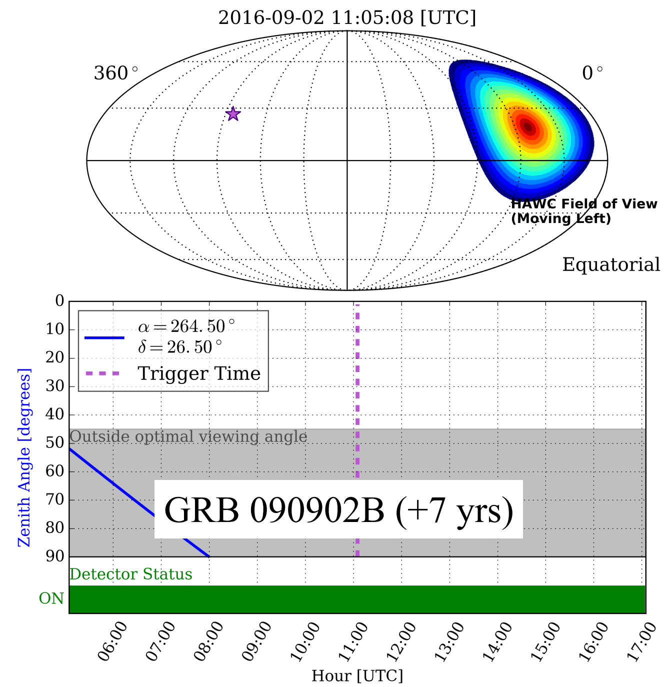


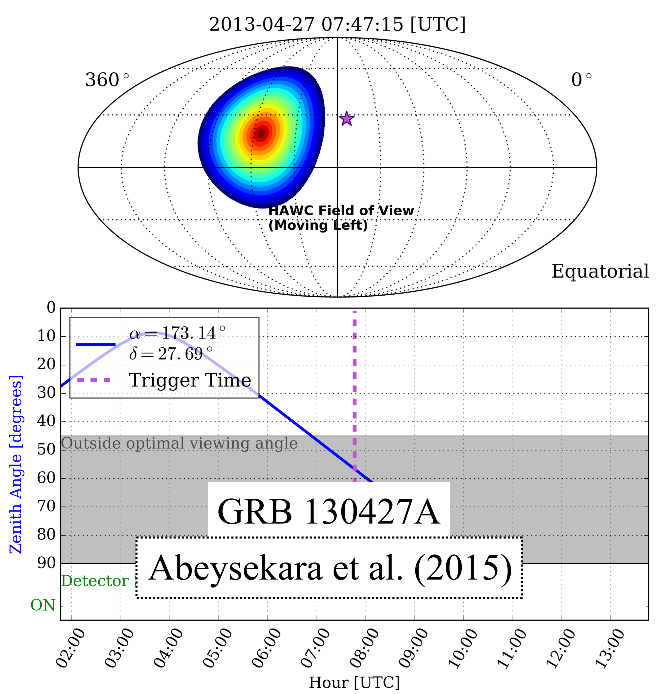
(b) $\approx$ 17 kHz trigger rate ($nHit > 30$)

DAQ trigger for spectral index & cut-off GRB models - GRB @ 20º zenith (Abeysekara et al. 2012)



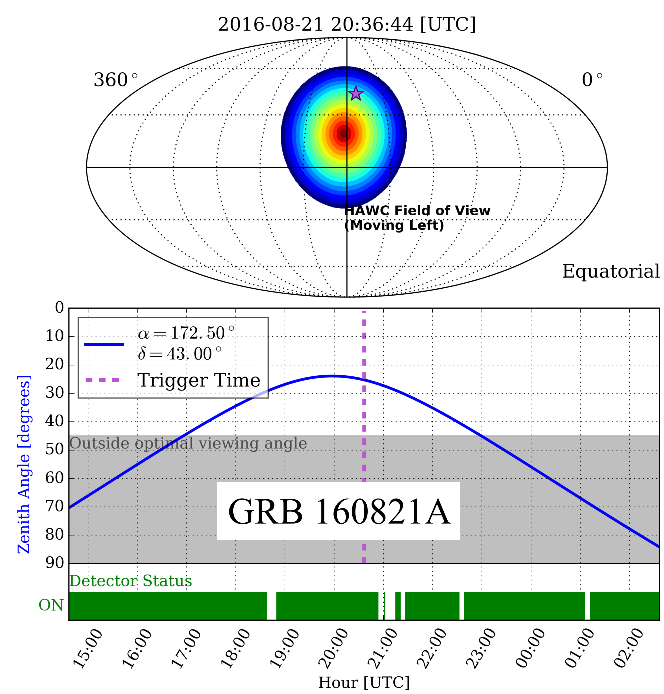




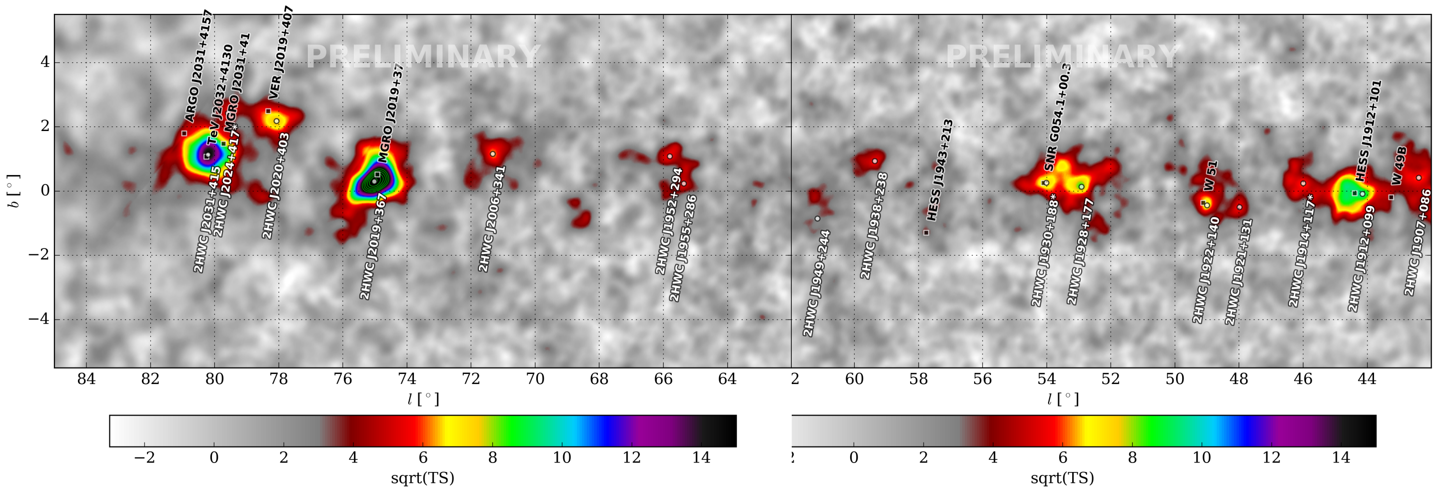


Some LAT (& EGRET) GRBs *versus* HAWC field of view

HAWC covers ~15% of the sky with a ~98% duty cycle.

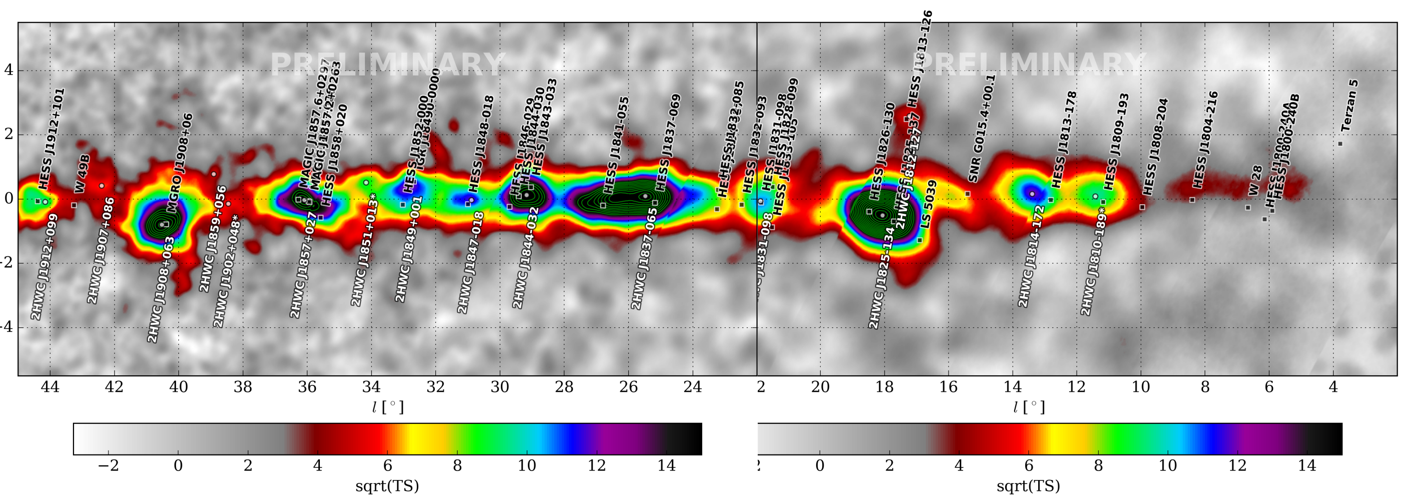


Galactic Plane & BHs

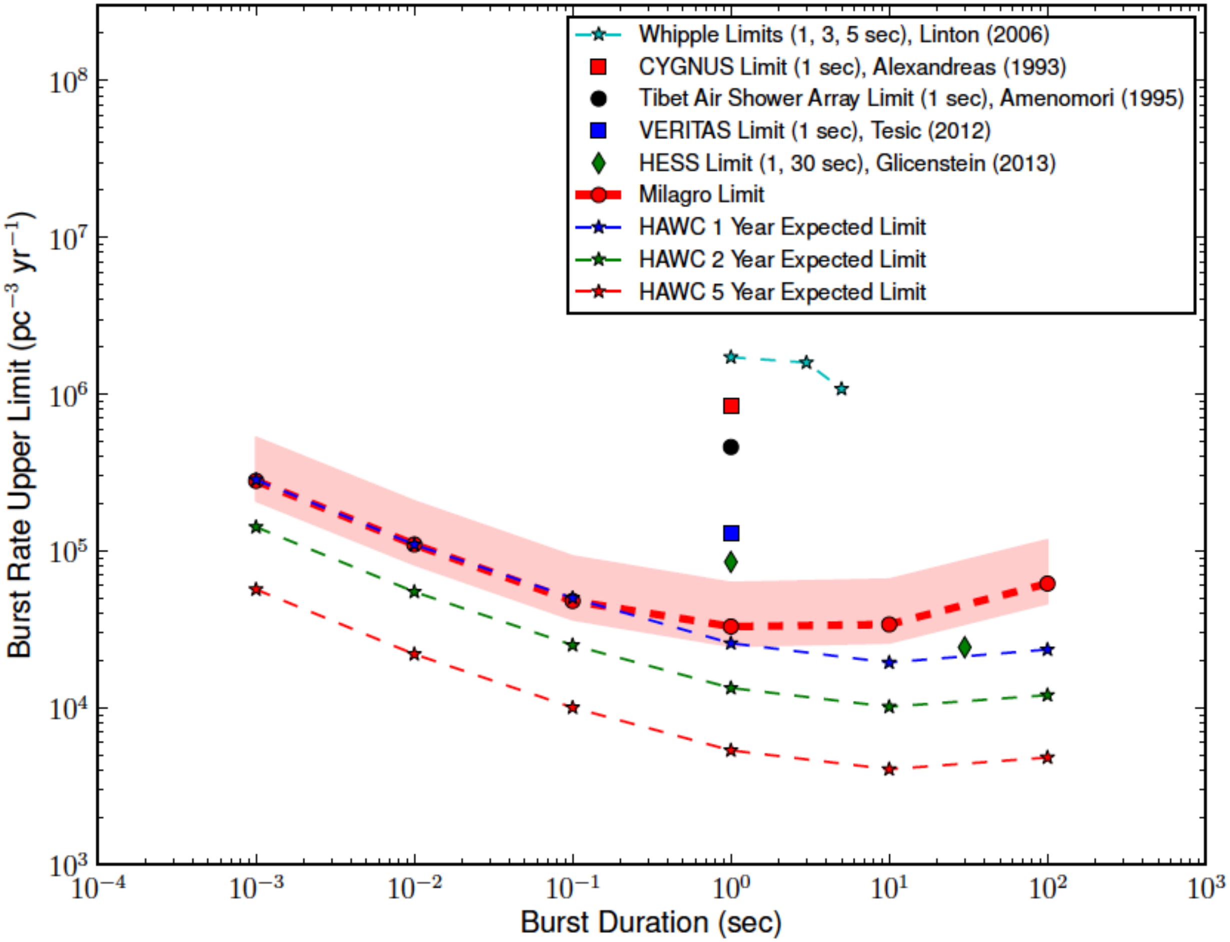


HAWC Galactic Plane data in good match with HESS GP survey and VERITAS; ¡Plus 25% new sources!

Search for emission and monitoring of Galactic BH systems in process.



Primordial Black Holes



BH should radiate thermally with a temperature (Hawking 1974):

$$T_{\rm BH} = \frac{\hbar\, c^3}{8\pi\, G\, M\, k_{\rm B}} \sim 10^{-7} \left(\frac{M}{M_\odot}\right)^{-1} \mathrm{K},$$

Evaporation occurs in time scale:

$$\tau(M) \sim \frac{G^2\, M^3}{\hbar\, c^4} \sim 10^{64} \left(\frac{M}{M_\odot}\right)^3 \mathrm{yr}\,.$$

PBHs smaller than 10^{15}g should have evaporated by now.

PBH evaporation limits on multiple time scales set with Milagro (Abdo et al. 2015).

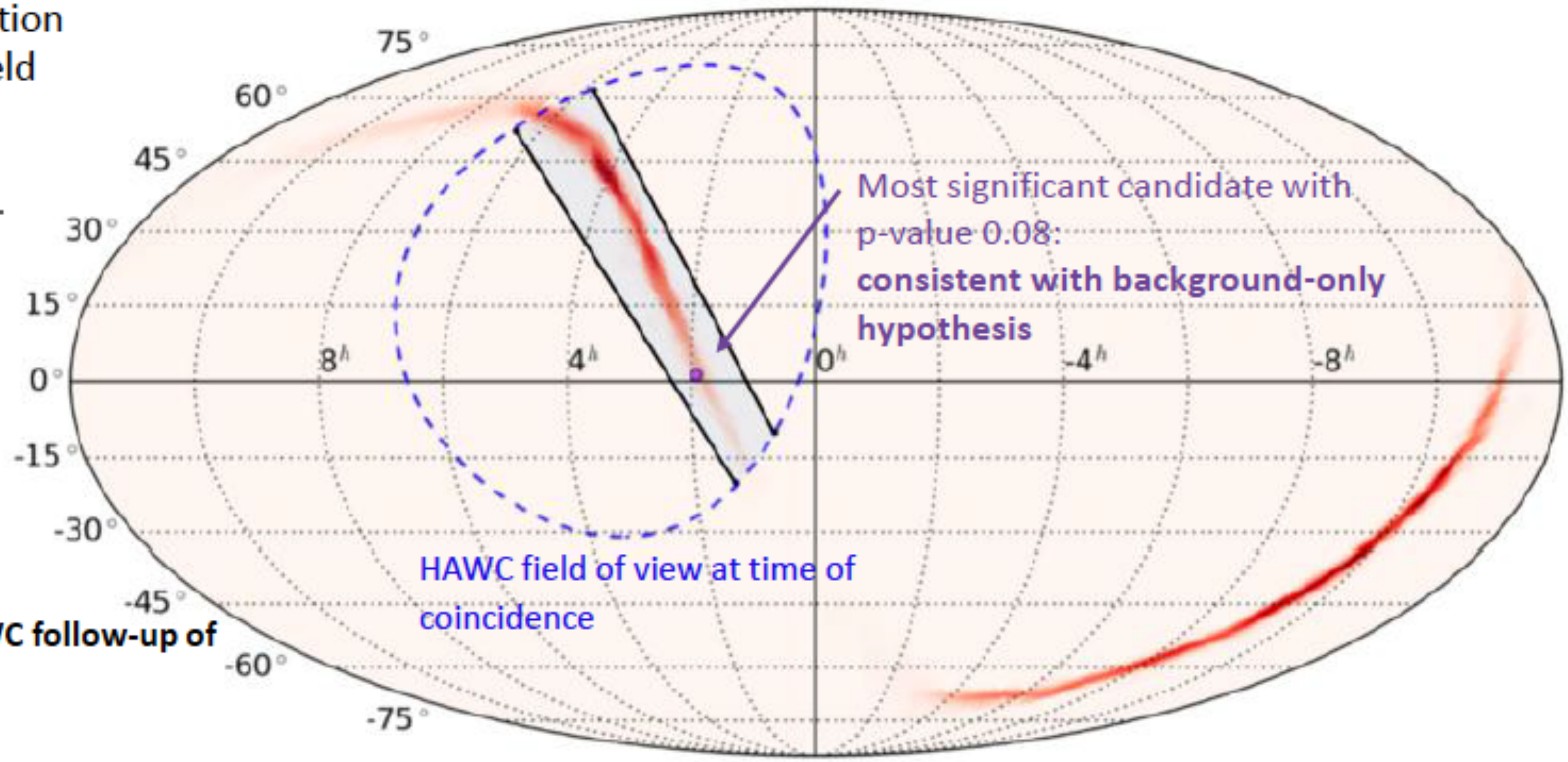
HAWC will set the most stringent upper limits for burst lasting 1ms - 100s and emitting in the TeV range.

Follow-up on 2nd Gravitational Wave Alert

GW BHs

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



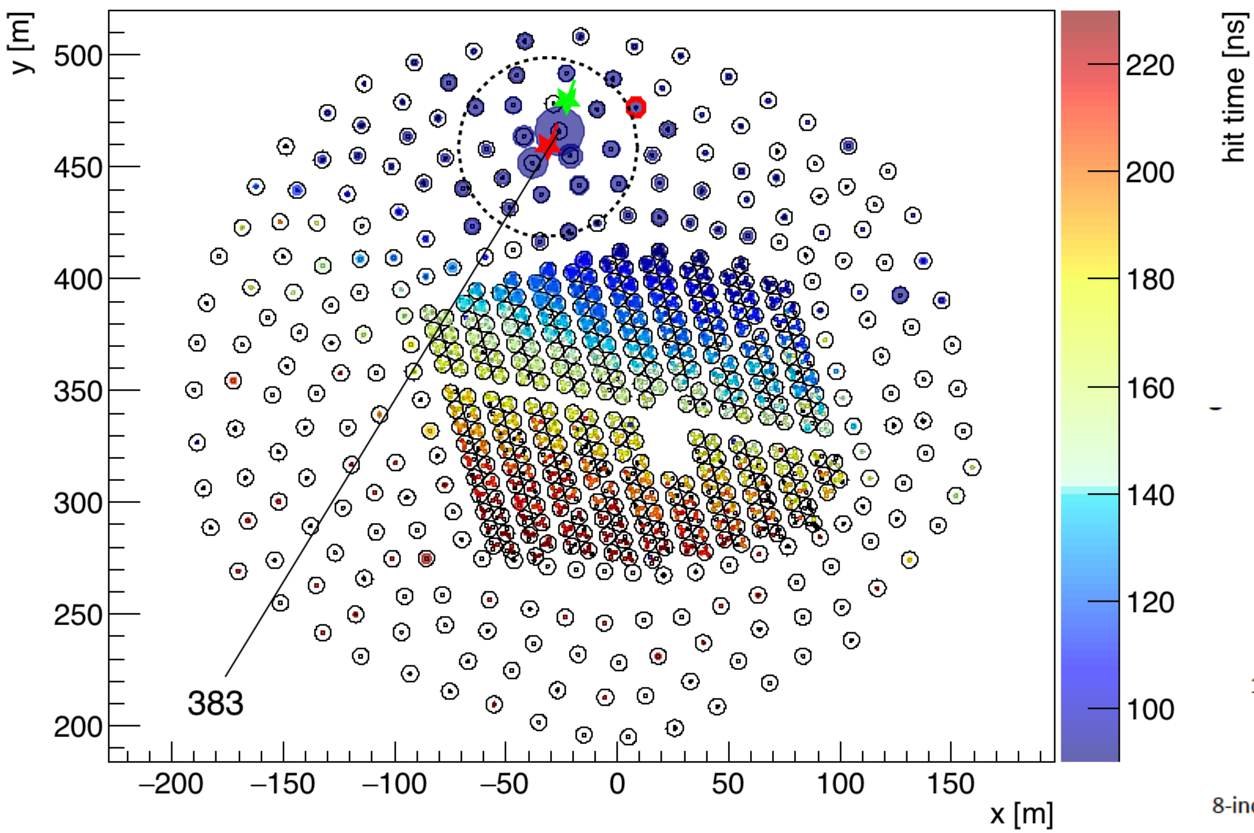
A GRB-optimized search within ±10 s shows no significant excesses, see:
GCN CIRCULAR #19156
LIGO/Virgo G211117: HAWC follow-up of northern sky

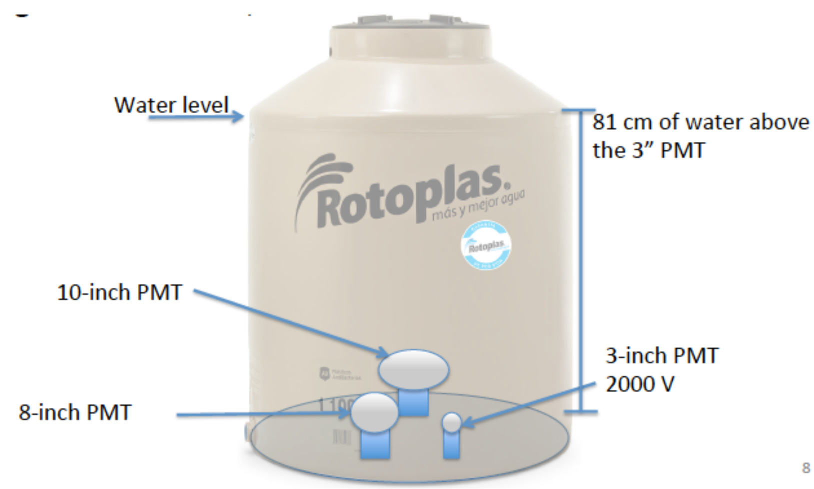
HAWC Robert Lauer — Monitoring the variable γ-ray sky with HAWC — 15

- Future follow-ups (e-boxes with VIRGO) would be direct can be complemented with alerts and revisiting previous data.

HAWC outrigger extension

- Low cost extension to improve HAWC sensitivity, in particular at E>10 TeV.
- Over 300 WCDs of 2500 liters each.
- Resources of LANL, Mexico and MPI-HD.





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Workshop on a wide field-of-view Southern Hemisphere TeV gamma ray observatory

10-12 November 2016 *Puebla, Mexico*
US/Central timezone

https://events.icecube.wisc.edu/conferenceDisplay.py?confId=81

- **Overview**
- Scientific Programme
- Registration
  - Registration Form
- Call for Abstracts
  - View my abstracts
  - Submit a new abstract
- Timetable
- Contribution List
- Author index
- Book of abstracts
- List of registrants
- Travel
- Venue & location information
- Accommodation

We wish to invite the broader gamma-ray community to a discussion of a future wide field-of-view TeV observatory for the Southern Hemisphere. The HAWC collaboration will host this meeting on the 10th and 11th of November followed by a visit to the high-altitude HAWC site a couple of hours from Puebla on the 12th. Transport up the mountain and lunch will be provided.

Our goal is to build up an international collaboration and a white paper on the science and technology of a southern TeV all-sky observatory on the time scale of the 2017 summer International Cosmic Ray Conference.

The meeting will be held in the beautiful colonial city of Puebla, Mexico, less than two hours by bus from Mexico City, and also served by an international airport.

- HAWC is a novel γ-ray survey detector in full operations since March 2015.
- HAWC ideally suited for BH astrophysics: GRBs, SMBHs, Gal-BH, GW-BH, PBHs.