Gamma-ray astronomy with the High Altitude Water Cherenkov observatory

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CPPM seminar
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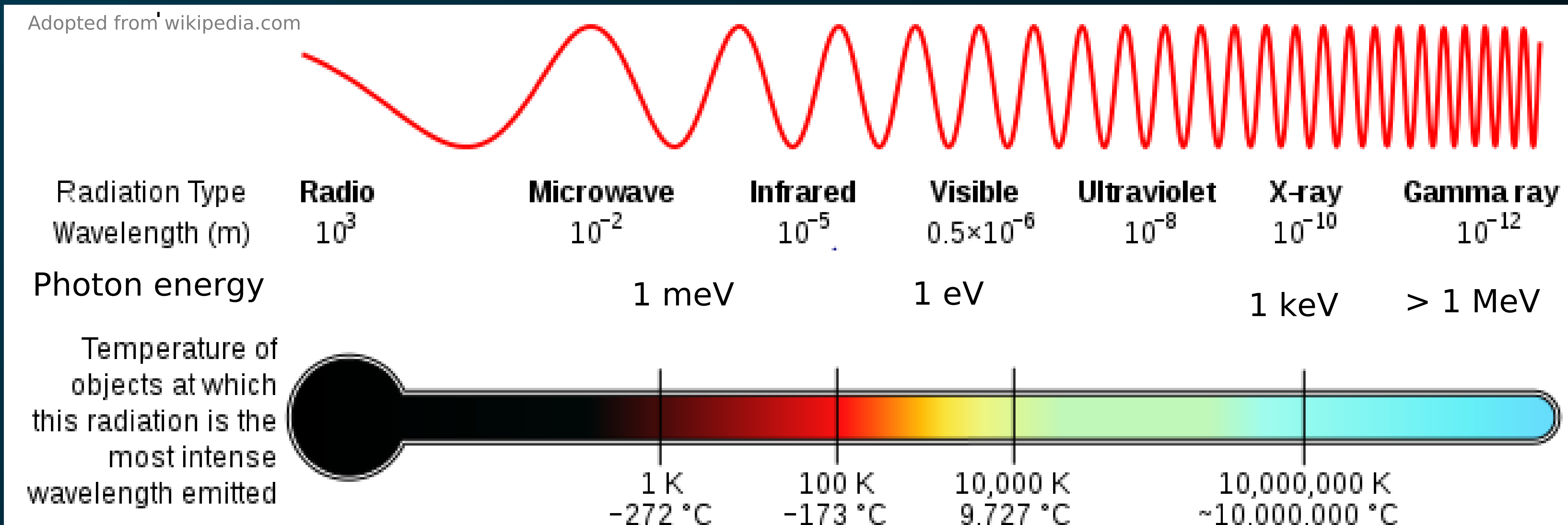
HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

Electromagnetic spectrum



Non-thermal processes (synchrotron radiation, ...)

CMB

Interstellar gas and dust

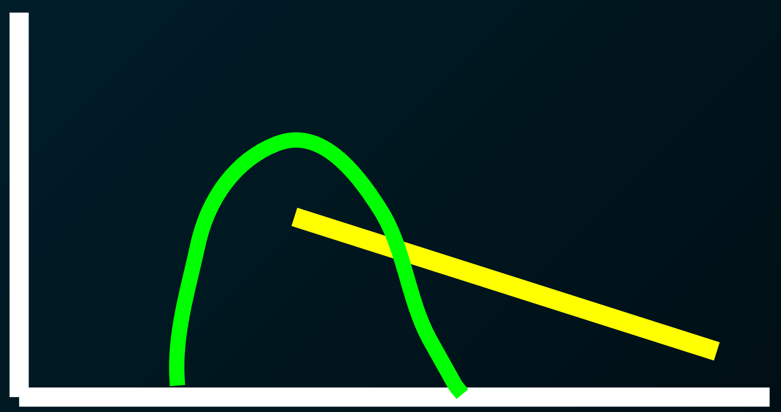
stars

Shock waves, black hole accretion, Cosmic Ray interactions, ...

Thermal vs non-thermal processes

Thermal radiation

- black body spectrum
- peak energy proportional to temperature
- astrophysical environments rarely exceed ~10 000 000 K (~1 keV)



Non-thermal radiation

- power-law spectrum
- particles boosted to higher energies by collective effects (diffusive shock acceleration)

> example - Cosmic Rays: E up to ~10^20 eV;
total energy density is comparable with energy density of star light, interstellar magnetic fields, and kinetic energy of interstellar gas

gamma-ray sky is dominated by non-thermal processes

Gamma-ray emission

Leptonic scenario

- electrons are accelerated in magnetic fields (*Fermi* acceleration due to multiple collisions with magnetic mirrors)
- synchrotron radiation of electrons in magnetic fields
- inverse compton scattering off photons of starlight, CMB, IR photons, synchrotron photons, etc

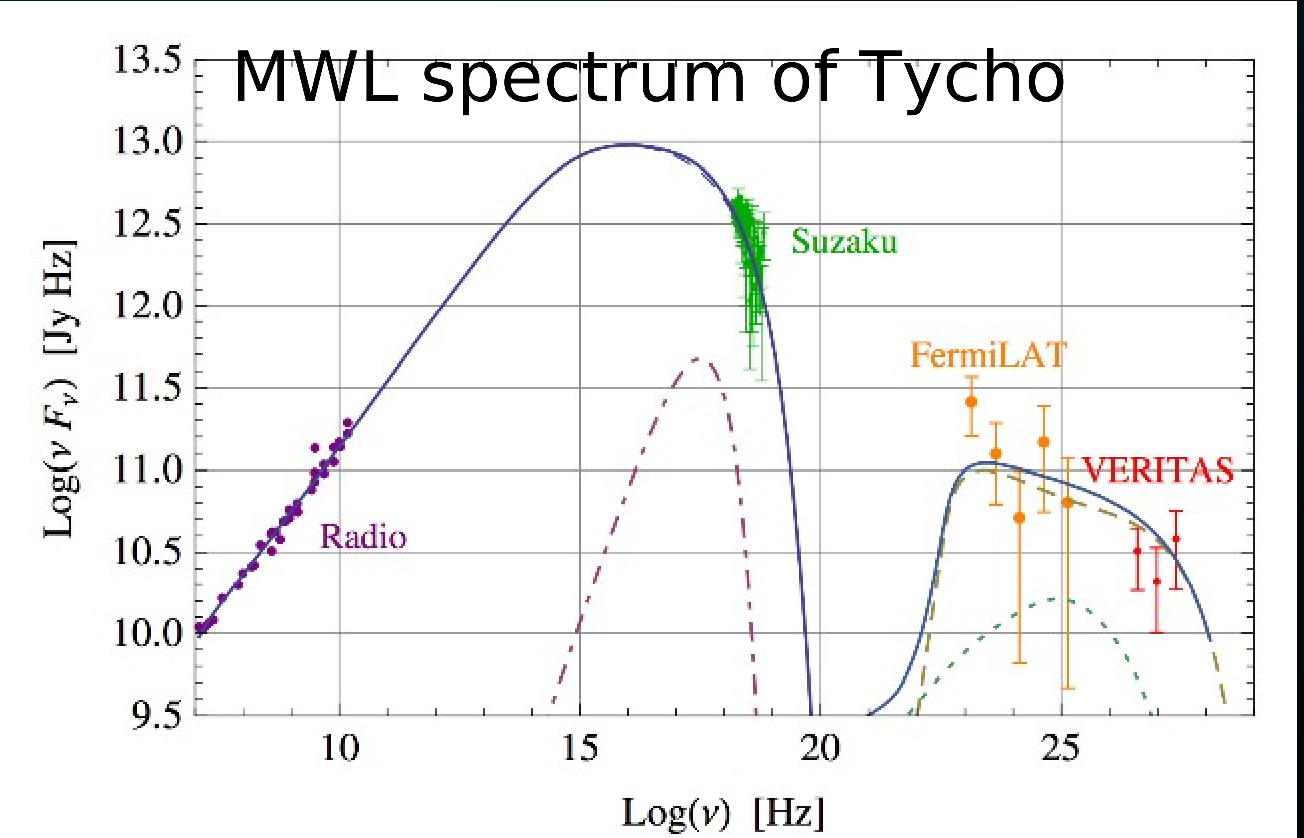
Hadronic scenario

- protons or heavier nuclei are accelerated
- interactions with ambient matter or photon fields produce pions
- π^0 decays produces photons

$p + p \Rightarrow \pi^+ \pi^- \pi^0 \ldots$

$\qquad\qquad\qquad\quad \rightarrow \gamma\gamma$

* Proton synchrotron also possible



(Morlino & Caprioli 2012)

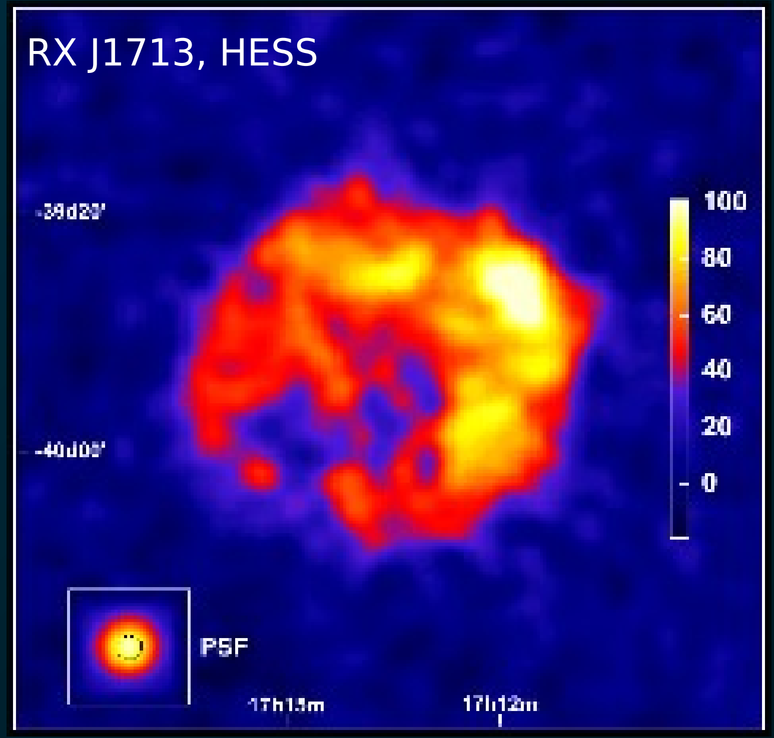
Multi-wavelength studies are essential to distinguish the different mechanisms and extract physics quantities (magnetic field strength, primary electron density, ...)

Natural Particle Accelerators

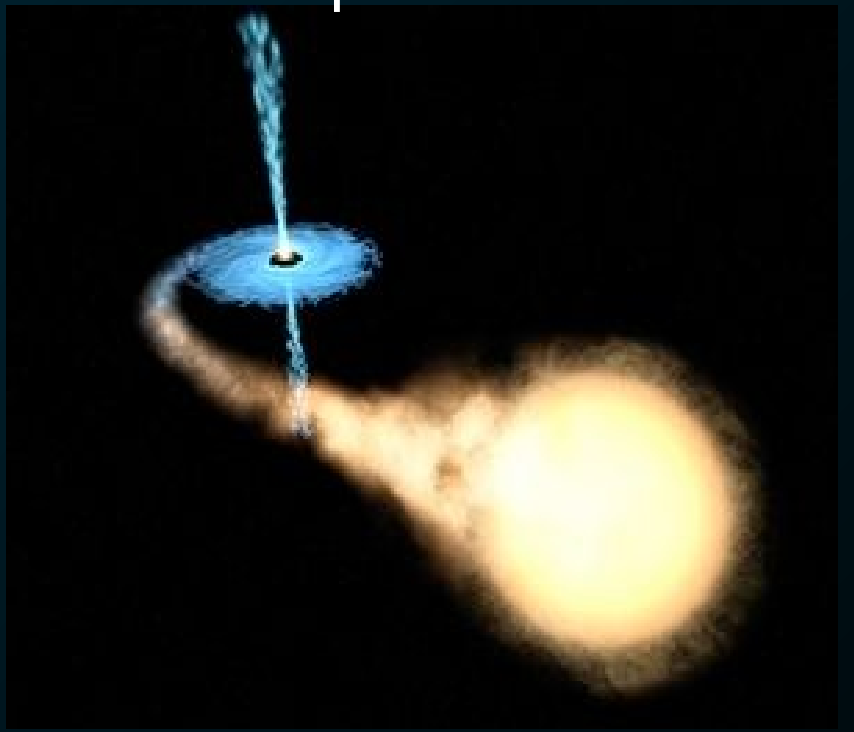
Pulsor Wind Nebulae

Crab, Chandra

Supernova Remnants



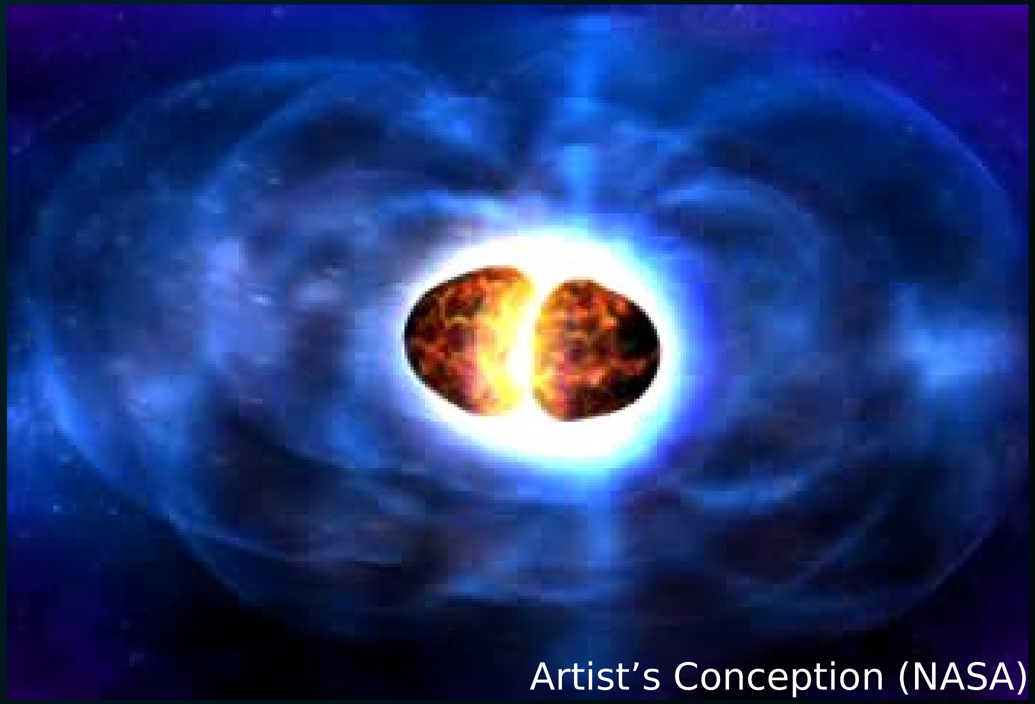
X-ray binaries / microquasars



Active Galactic Nuclei

M87, HST

Gamma-Ray Bursts



Artist’s Conception (NASA)

?

Gamma-ray astronomy

emission

Astrophysics
Particle physics
General relativity (black holes)

propagation

gas

γ

dust

Magnetic fields

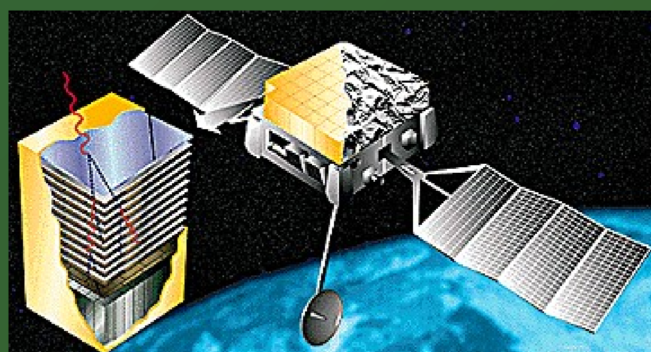
Astrophysics
Particle physics
(interactions with gas and dust, extragalactic background light, axions, ...)
Cosmology (redshift, ...)

detection

Particle physics
Astronomy

Gamma Ray Detectors

Wide field of view
Continuous operation



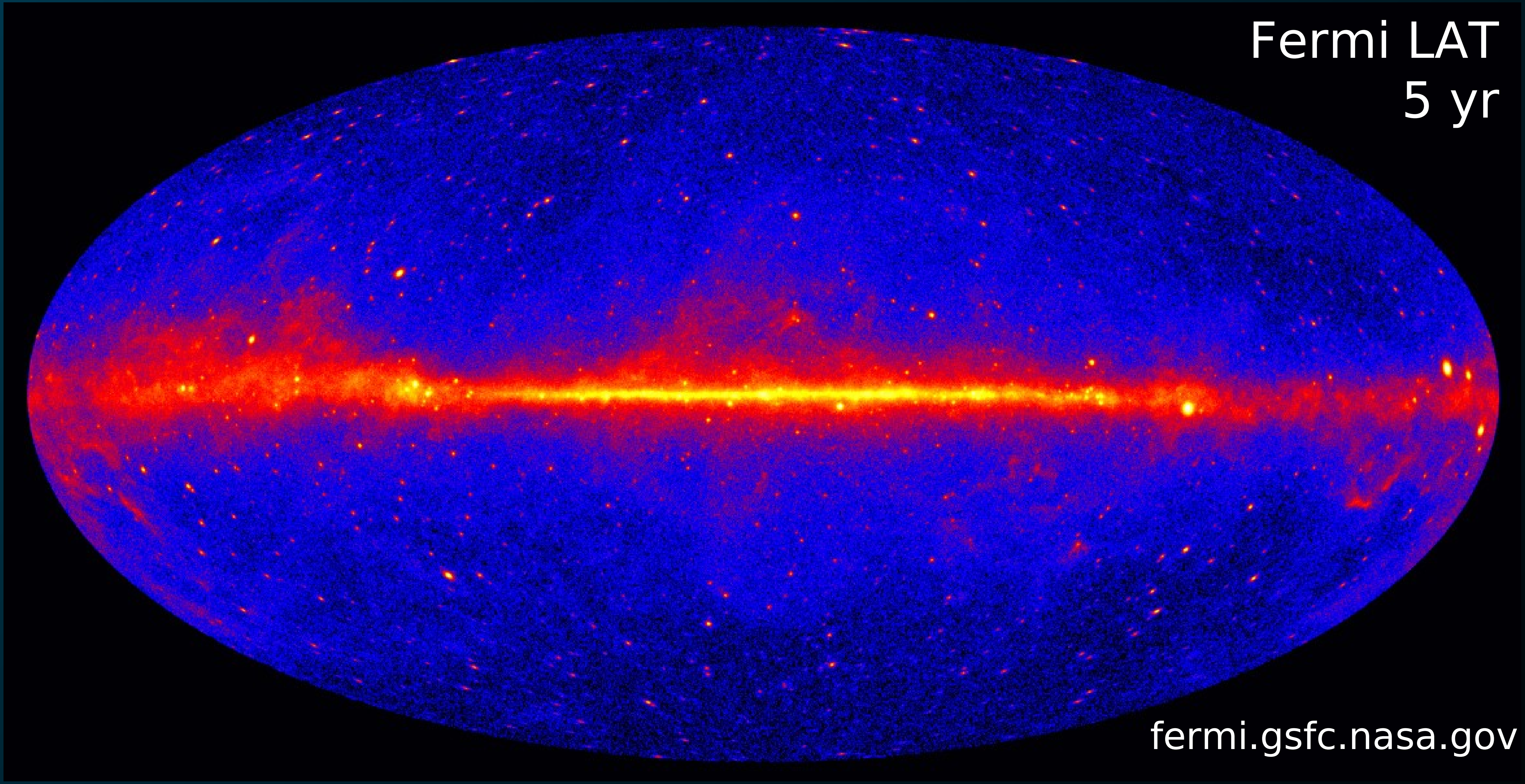
Fermi
AGILE
EGRET
(satellites)

HAWC
ARGO
Milagro
Tibet ASγ
(Air Shower Arrays)

TeV sensitivity

VERITAS
HESS
MAGIC
(Imaging Atmospheric Cherenkov Telescops)

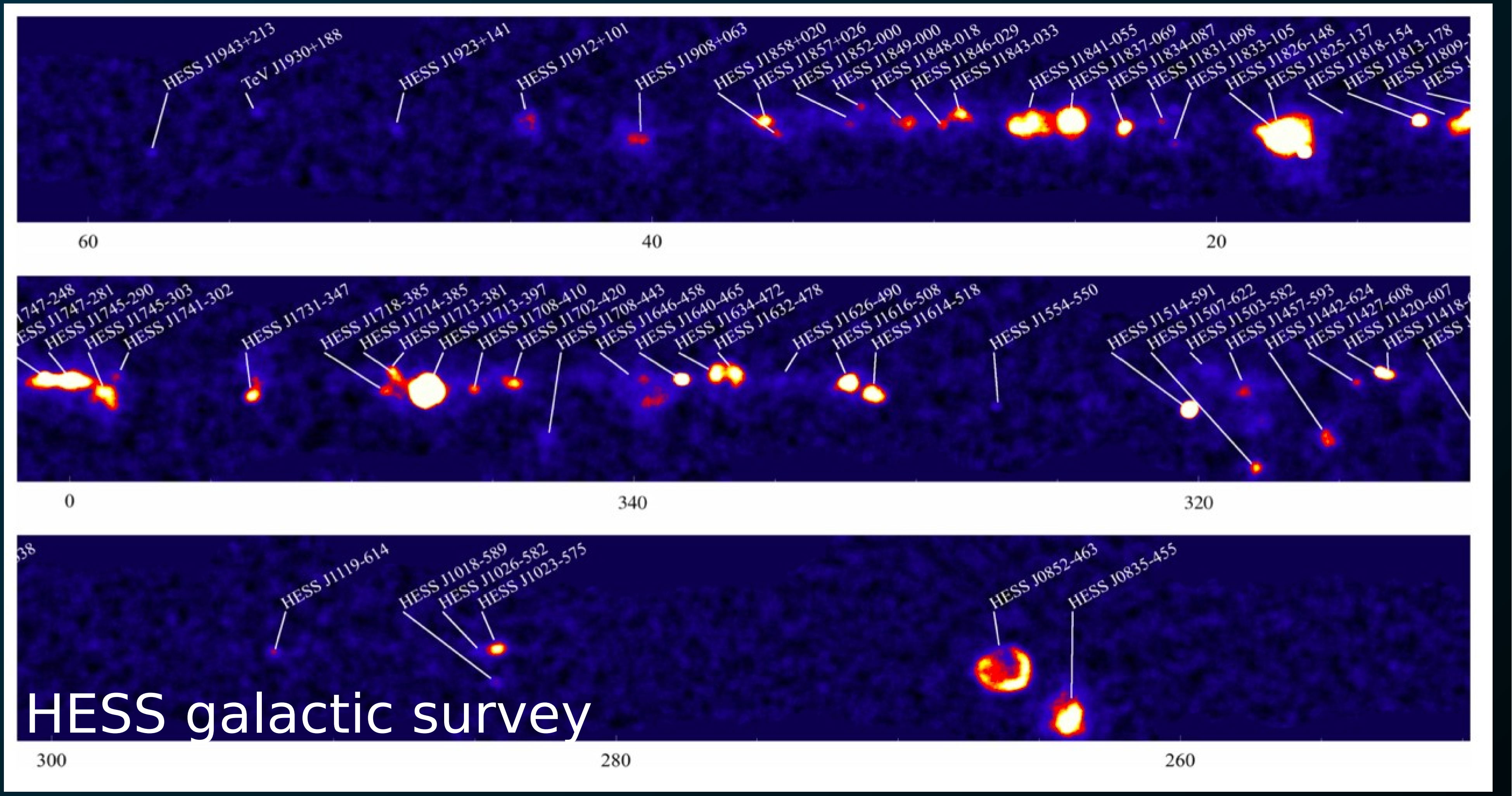
GeV sky



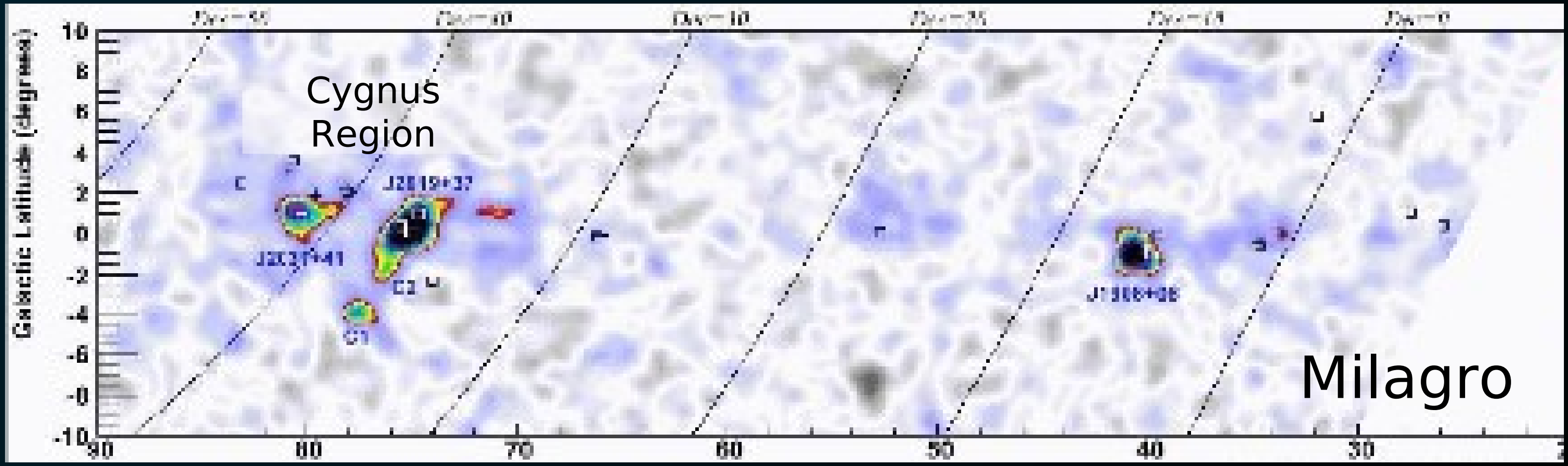
~2000 point sources
~30 GRBs
galactic diffuse emission (CR interactions)

TeV sky

Pointed onservations and surveys of galactic plane by IACTs (HESS, VERITAS and MAGIC, ...)



Wide-field surveys by Air Shower Arrays (Milaro, ARGO, Tibet, ...)



TeVCat now contains 148 sources - see http://tevcat.uchicago.edu/

HAWC - High Altitude Water Cherenkov Observatory

location: saddle point between Volcán Sierra Negra (also site of Large Millimeter Telescope) and Pico de Orizaba

N 18°59'48", W 97°18'34"

altitude: 4100 m

Pico de Orizaba

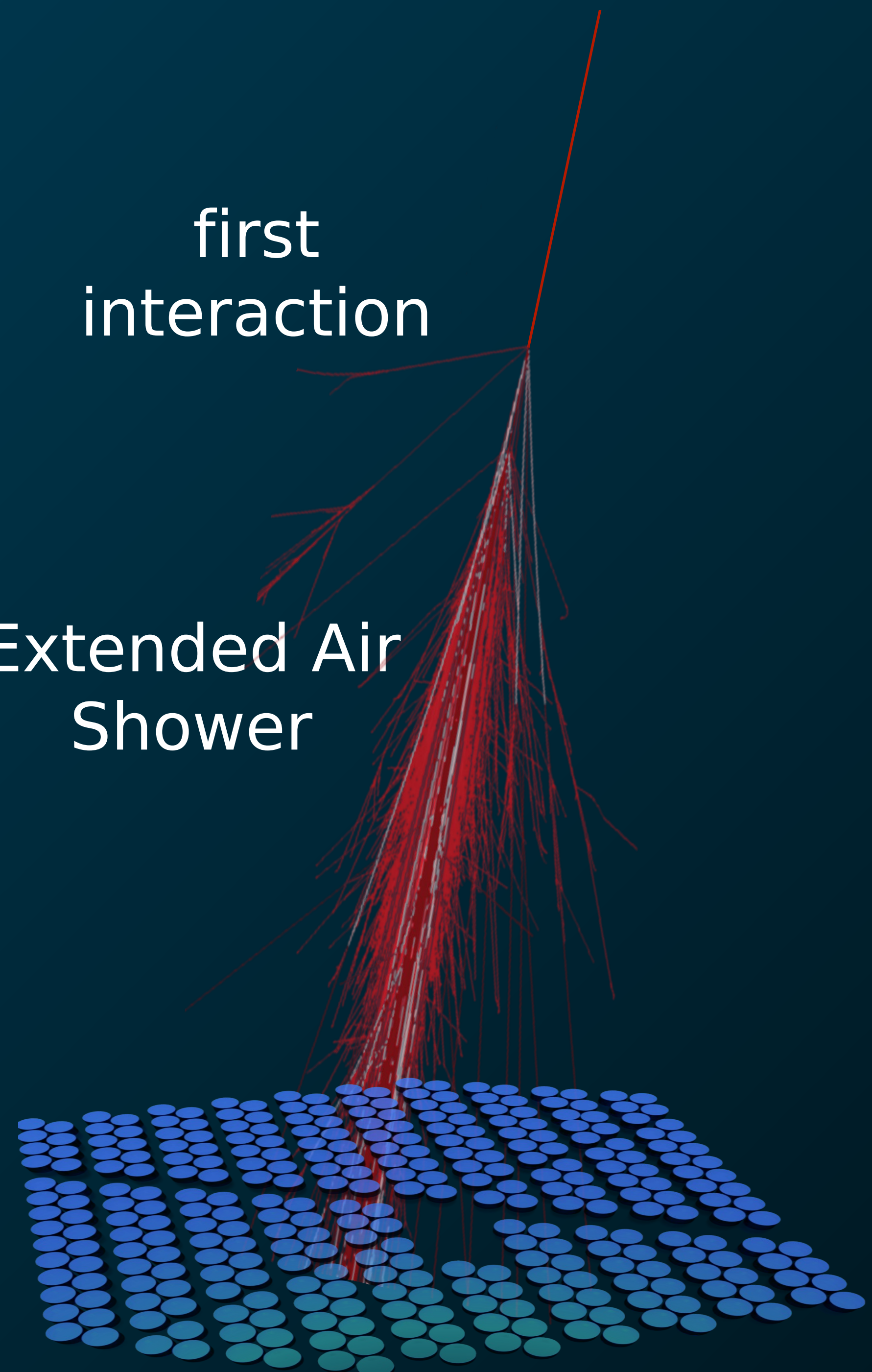
http://www.hawc-observatory.org/

Operation principle

gamma ray or cosmic ray

first interaction

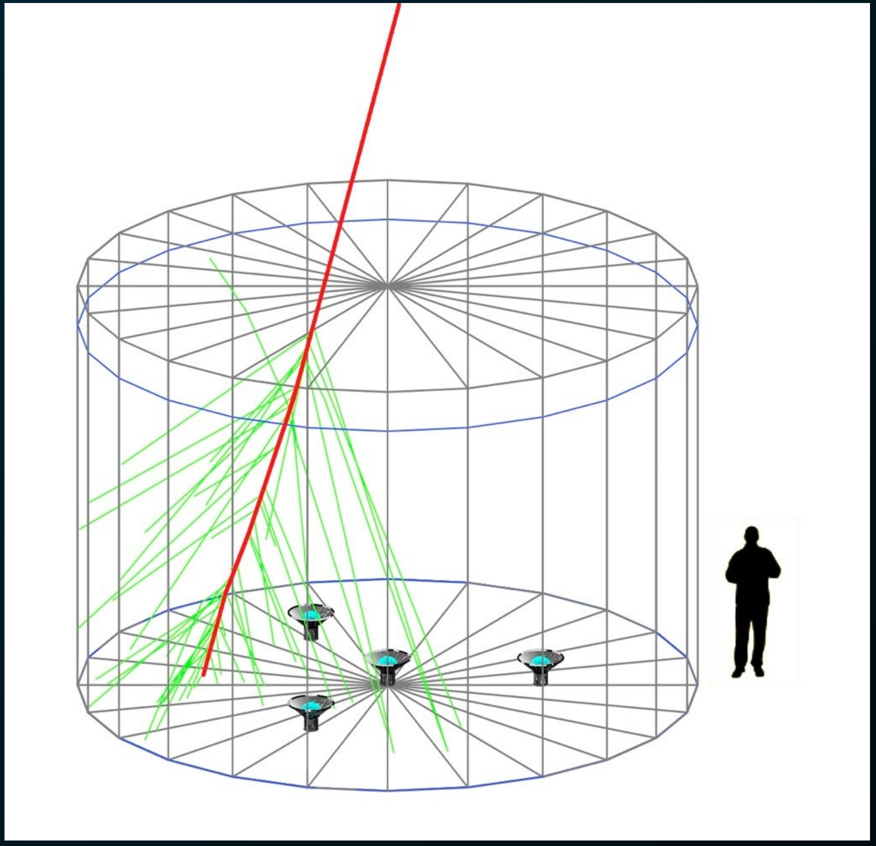
Extended Air Shower

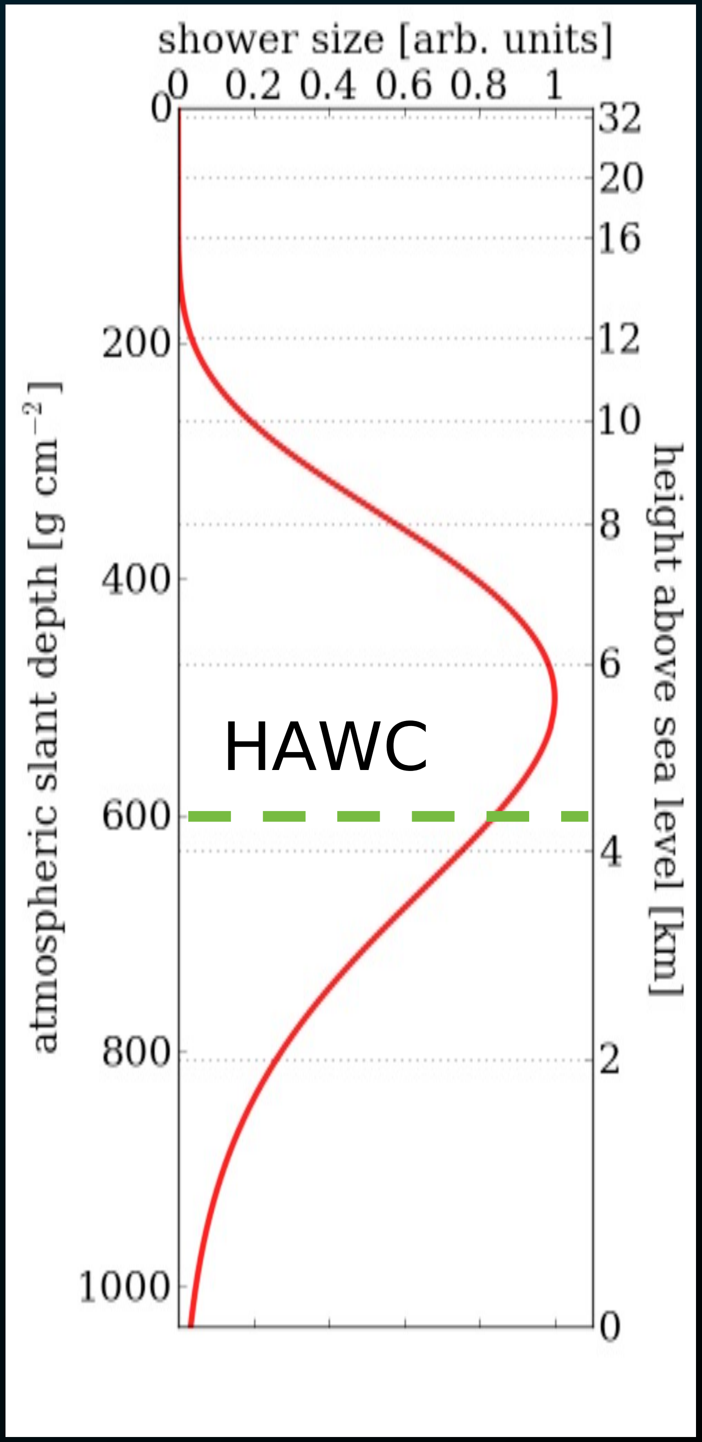


secondary particles reach ground level

charged particles produce Cherenkov light in HAWC tanks

light is detected by photomultiplier tubes (PMT)





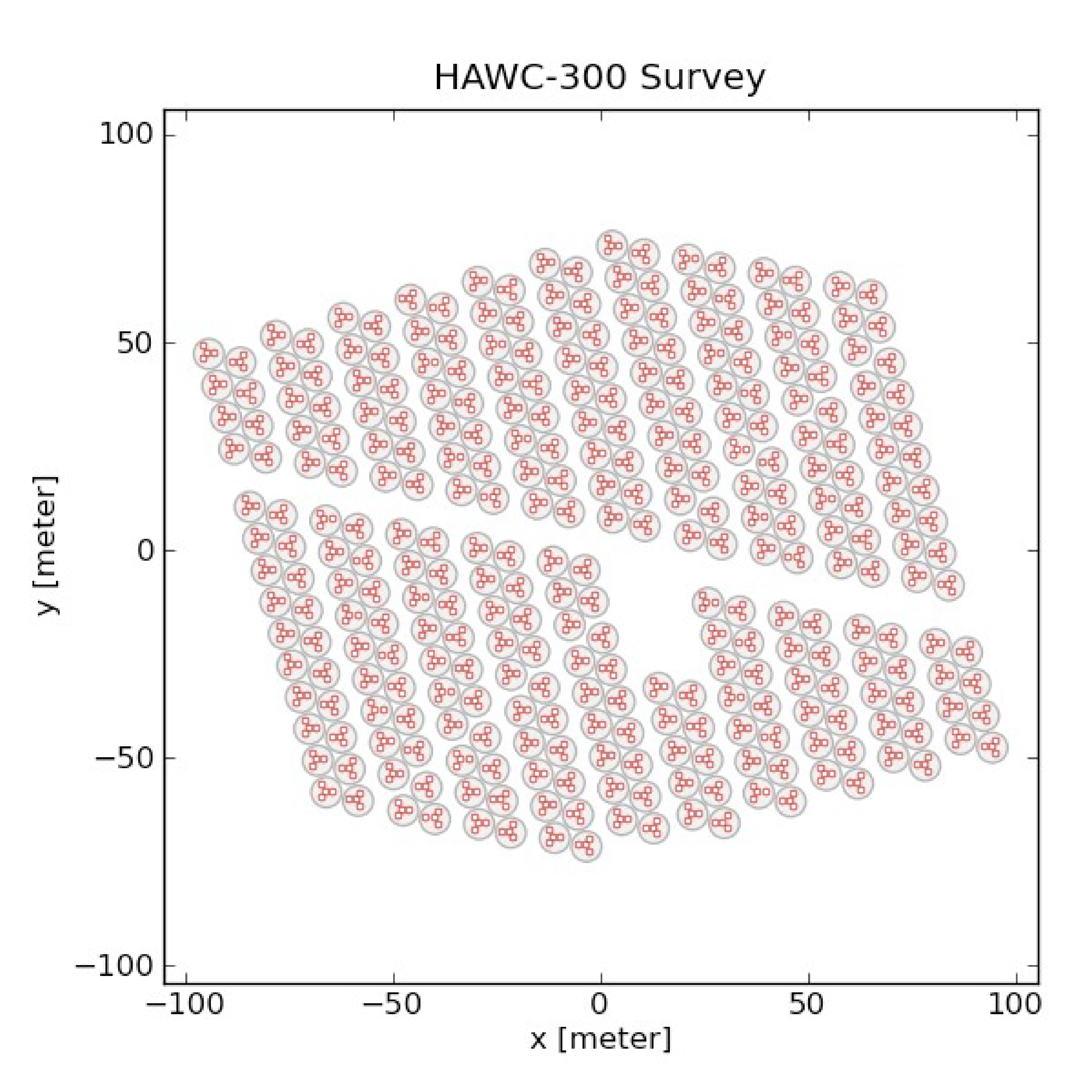
HAWC Collaboration

Collaboration of ~100 scientists from US & Mexico

HAWC's mission

- Perform an unbiased survey of the TeV sky (search for the unknown)
- Map the diffuse emission from the Galactic plane and extended sources
- Discover new transients (GRB, AGN flares, ...)
- Probe Extragalactic Background Light
- Search for Dark Matter (WIMPs) and other Physics Beyond the Standard Model (primordial black holes. Q-balls, Lorentz invariance violation, ...)
- Solar physics, cosmic ray anisotropy, and more

Detector layout



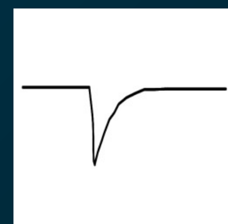
- 300 water Cherenkov detectors ("tanks")
- ~20,000 m^2 area
- >60% active Cherenkov volume

Water Cherenkov Detector (WCD)

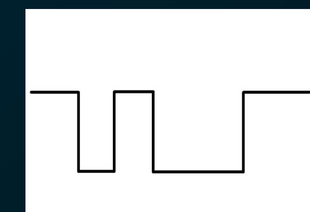
- Steel structure with a roof and a plastic bladder inside
- 7.3 m diameter x 4.5 m tall
- Bladders are custom-designed for HAWC and built at a facility in Colorado; weight < 300 lbs
- ~200,000 liters of purified water per tank
- 4 upward looking PMTs per tank: three 8” PMTs (Hamamatsu R5912, re-used from Milagro) and 1 high quantum efficiency 10” PMT in the center (Hamamatsu R7081-MOD)

Electronics

PMT



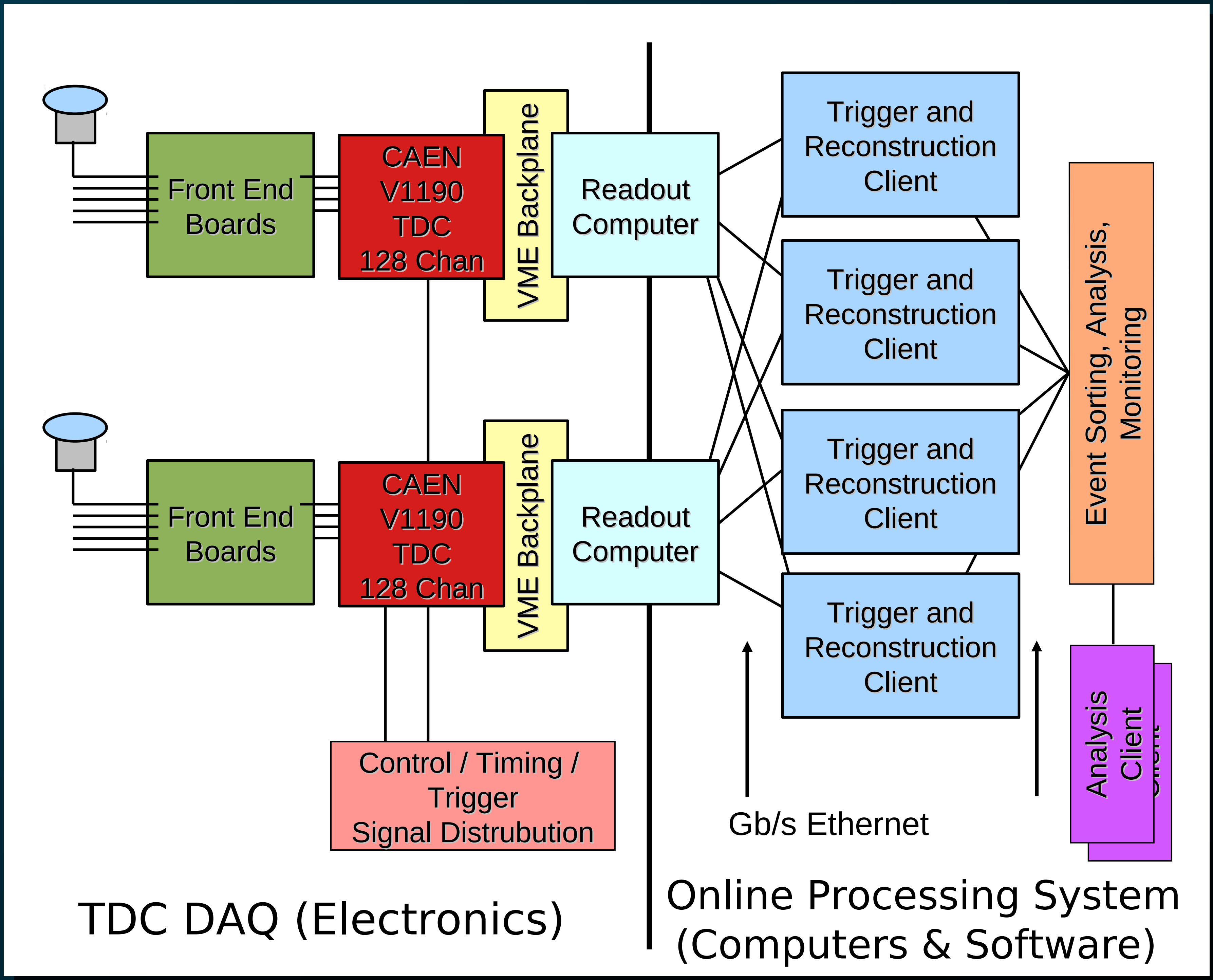
Front End Boards
(custom designed for Milagro)



CAEN TDC

- Re-used 8” Milagro PMTs and front-end electronics
- Front-end boards distribute high voltage and apply discriminators at ~0.3 photo-electrons and ~5 photo-electrons
- Time-over-threshold ∝ log(charge)
- Output logical pulses digitized by CAEN VME Vx1190 TDCs (128 channels)
- GPS timing signals sent to TDC every 10 µs
- TDCs synchronized by common 40 MHz clock
- A second DAQ - “scalers” - measures PMT rates

“Triggerless" DAQ



- Continuous acquisition with common trigger
- Each TDC is read out by a VME single-board computer (SBC)
- DAQ records ALL photoelectrons from ALL 1200 PMTs = 500 MB/sec
- Data transfered over Ethernet using ZeroMQ
- Complete events assembled by reconstruction clients
- Triggering is done entirely in software (reduces data to 20 MB/sec = 600 TB/yr)
- Events are reconstructed and analyzed in real time

the online processing system nominally includes 4 “big” servers (176 CPU cores in total)

Effective area and energy threshold

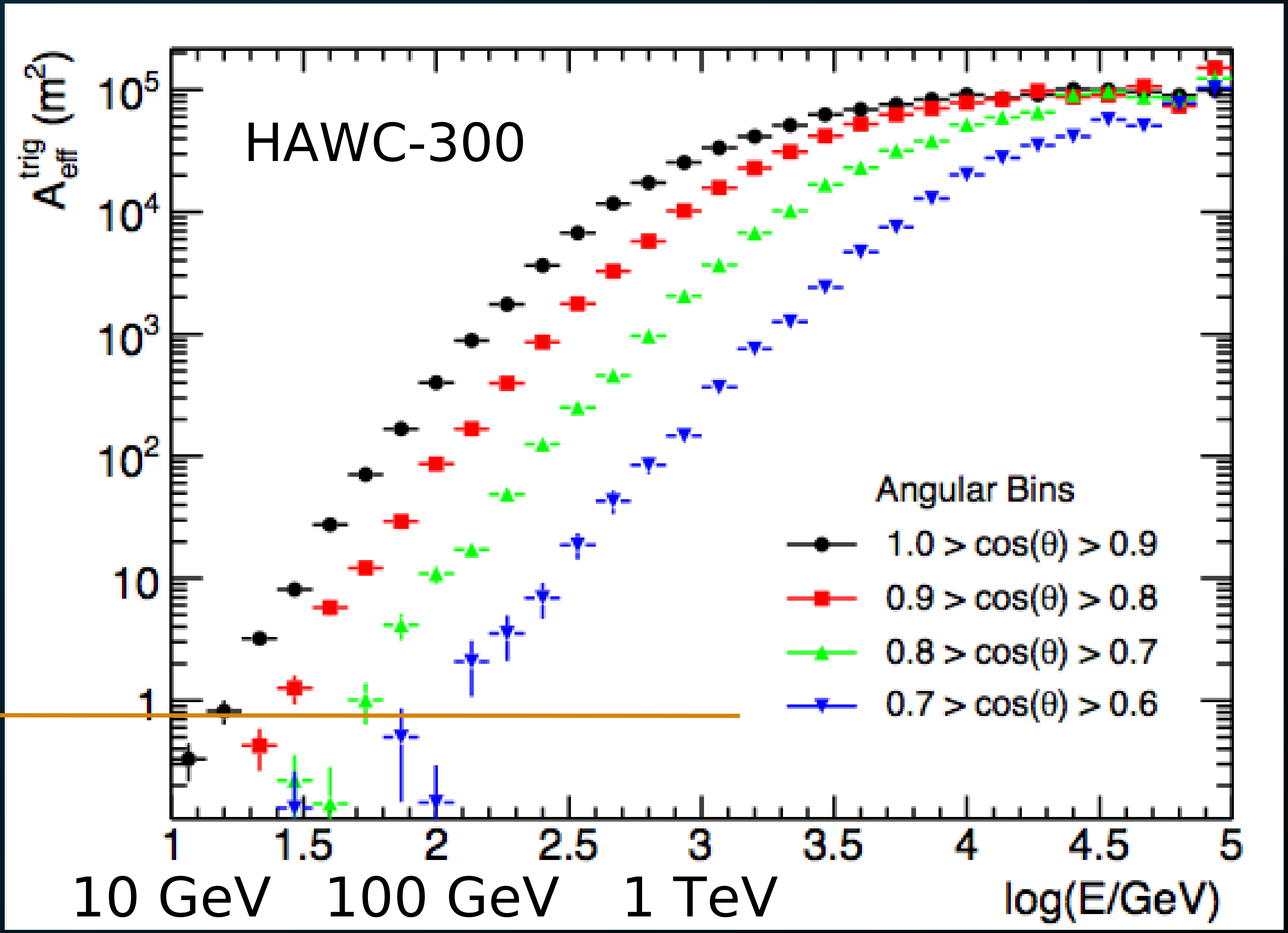
- Effective area up to ~10^5 m^2 in multi-TeV regime
- Energy threshold ~30 GeV, fully efficient at E > 3 TeV
- Still >100 m^2 at E = 100 GeV

Soft cuts:

Nhit > 30

Angular error < 1.1°

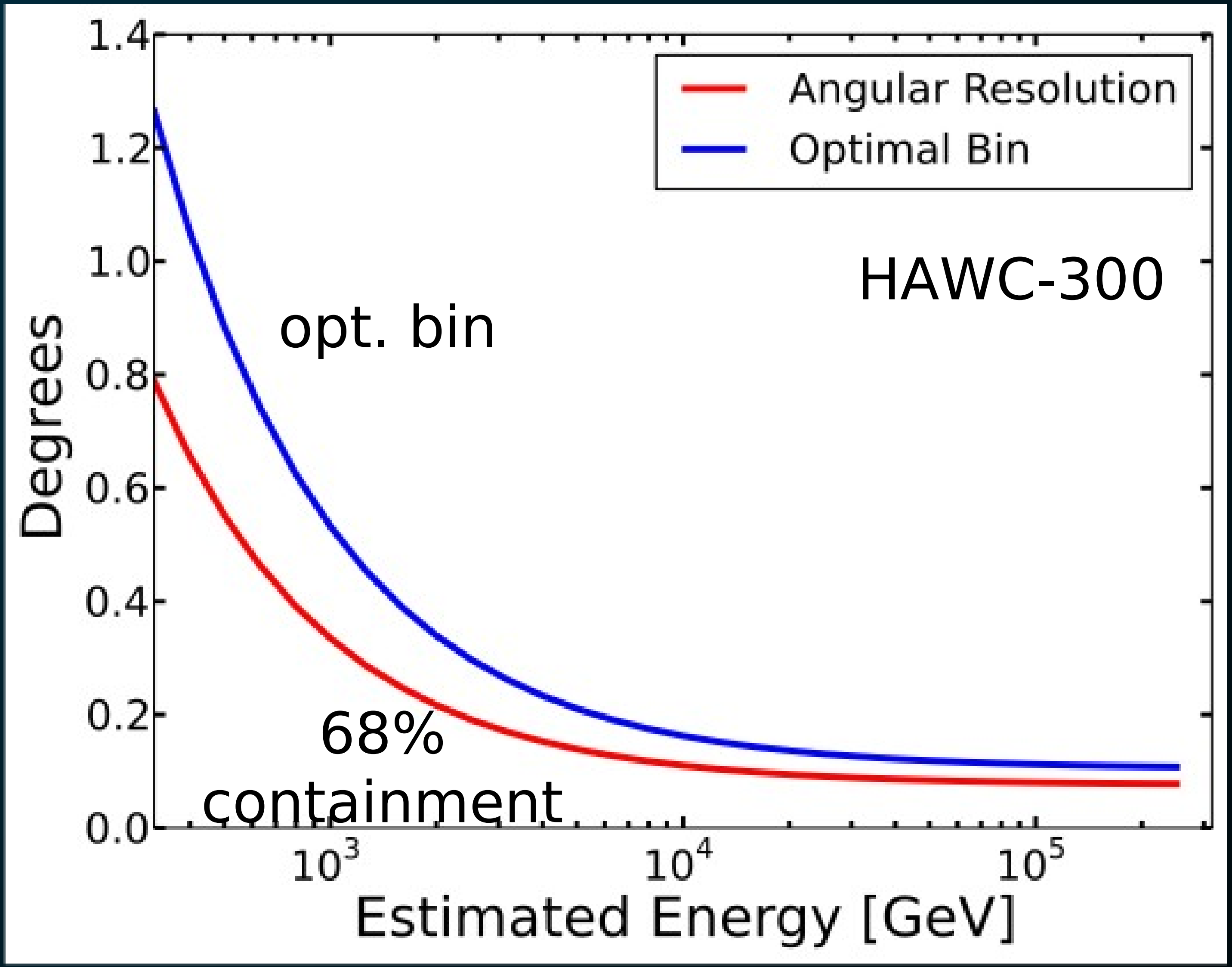
No hadron rejection cut applied (!)



Fermi LAT ($0.8\ m^2$)

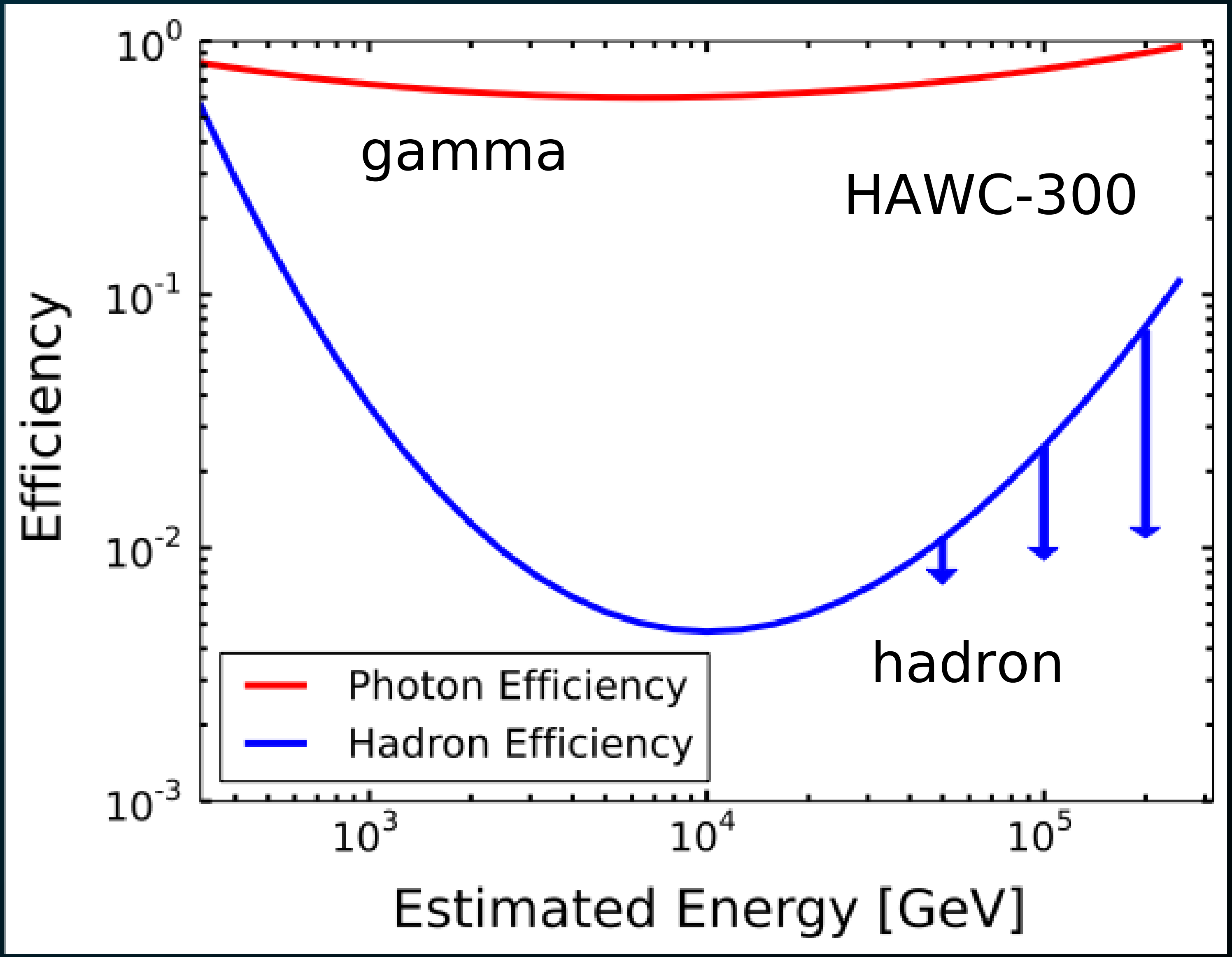
Angular resolution

- Shower front is generally perpendicular to the primary gamma ray direction
- Shower plane fit uses hit timing information
- Angular resolution up to 0.1 degree at TeV energies



Gamma-hadron separation: expected performance

• Gamma-hadron separation is based on shower lateral size, clumpiness, and high amplitude pulses produced by muons (typically confined within a single tank)
• “Compactness” parameter C = nHit / CxPE
•where CxPE = largest hit amplitude (in p.e.) outside of a 40 m radius from reconstructed shower core
• > 100-fold hadron rejection while retaining >50% of photon-induced events

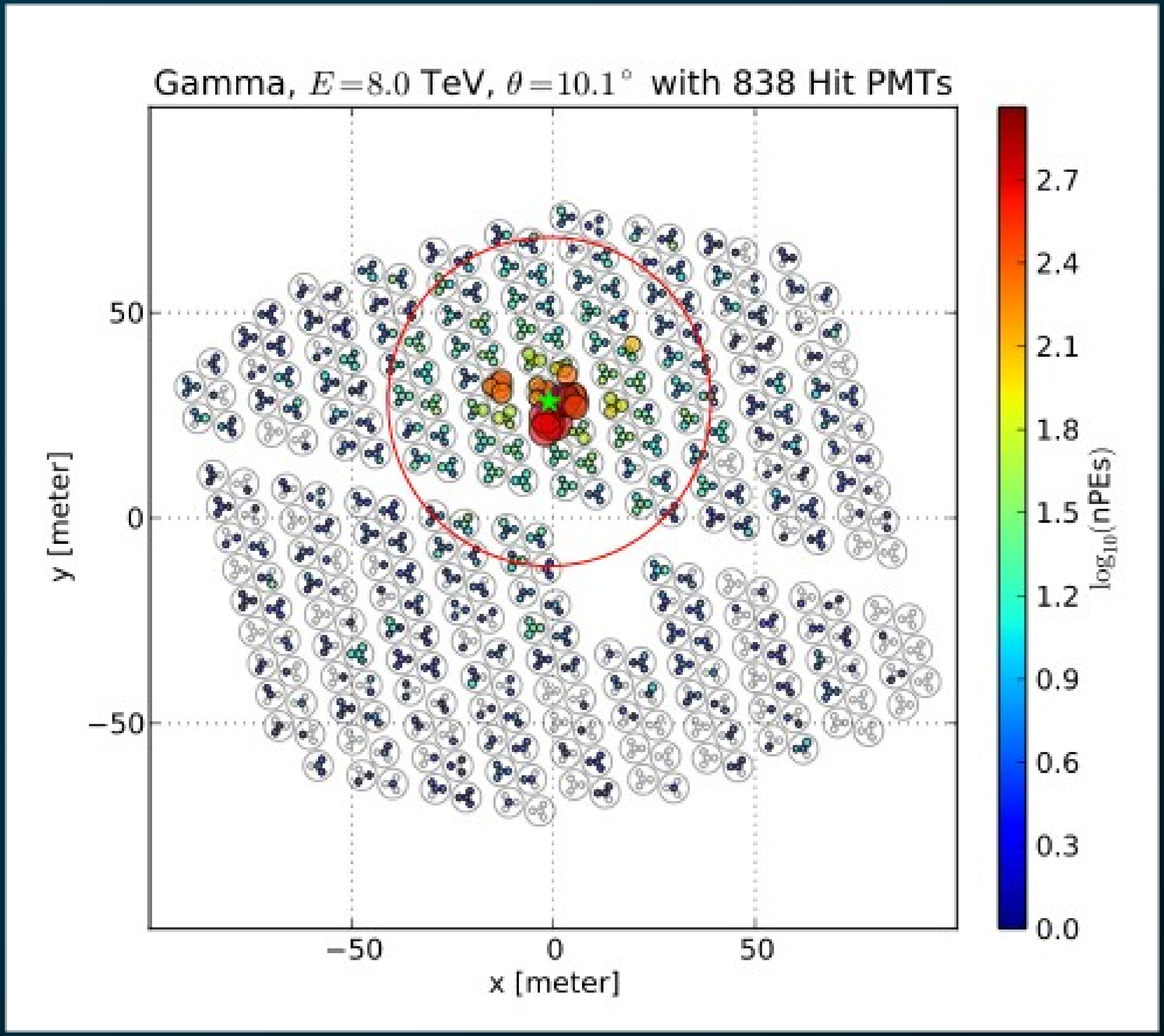


g-h separator behavior at high energy depends on the choice of energy estimator and desired quality (purity) of the event sample

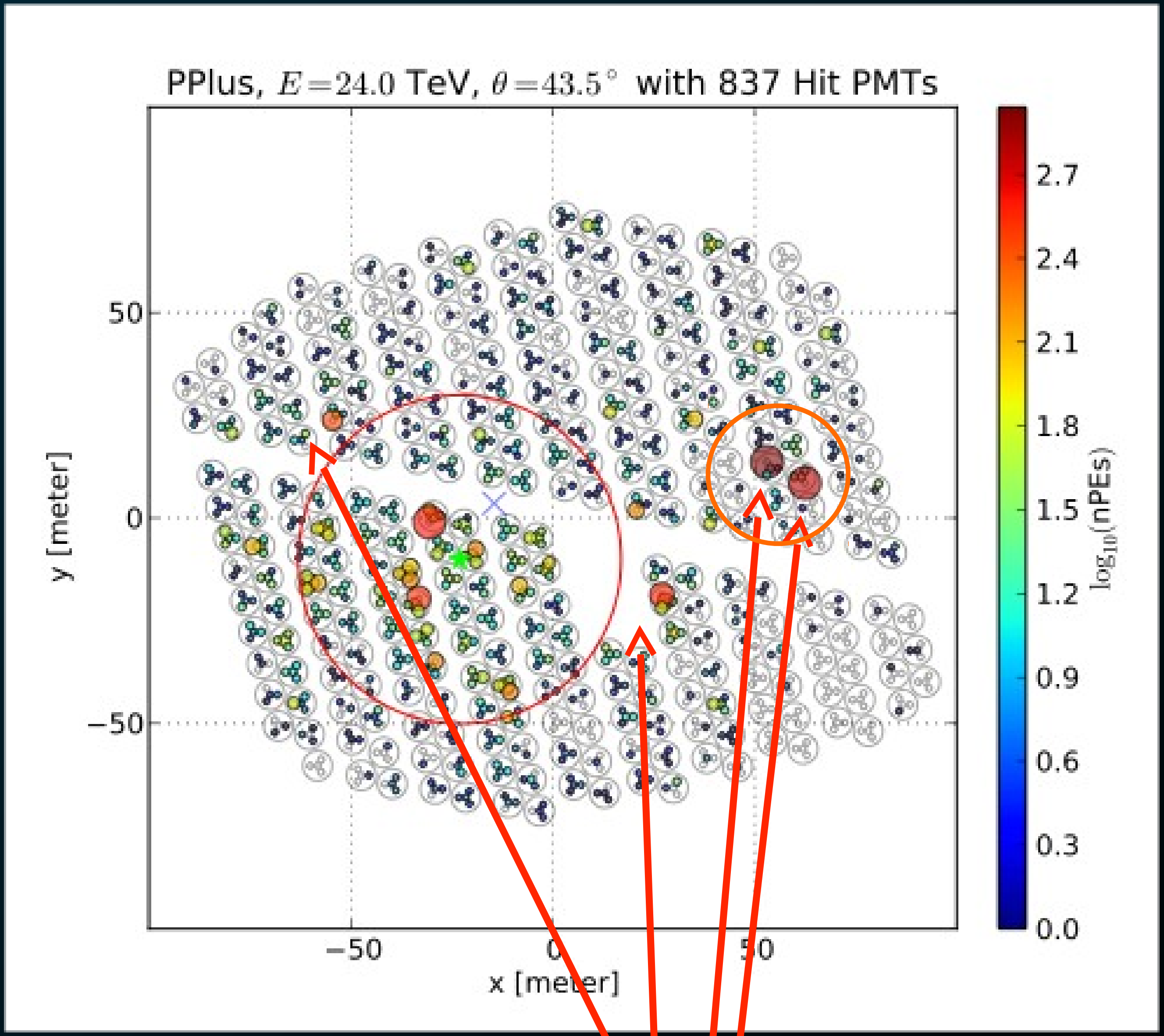
Gamma-hadron separation

vast majority of detected events are hadronic cosmic rays

γ - ray shower



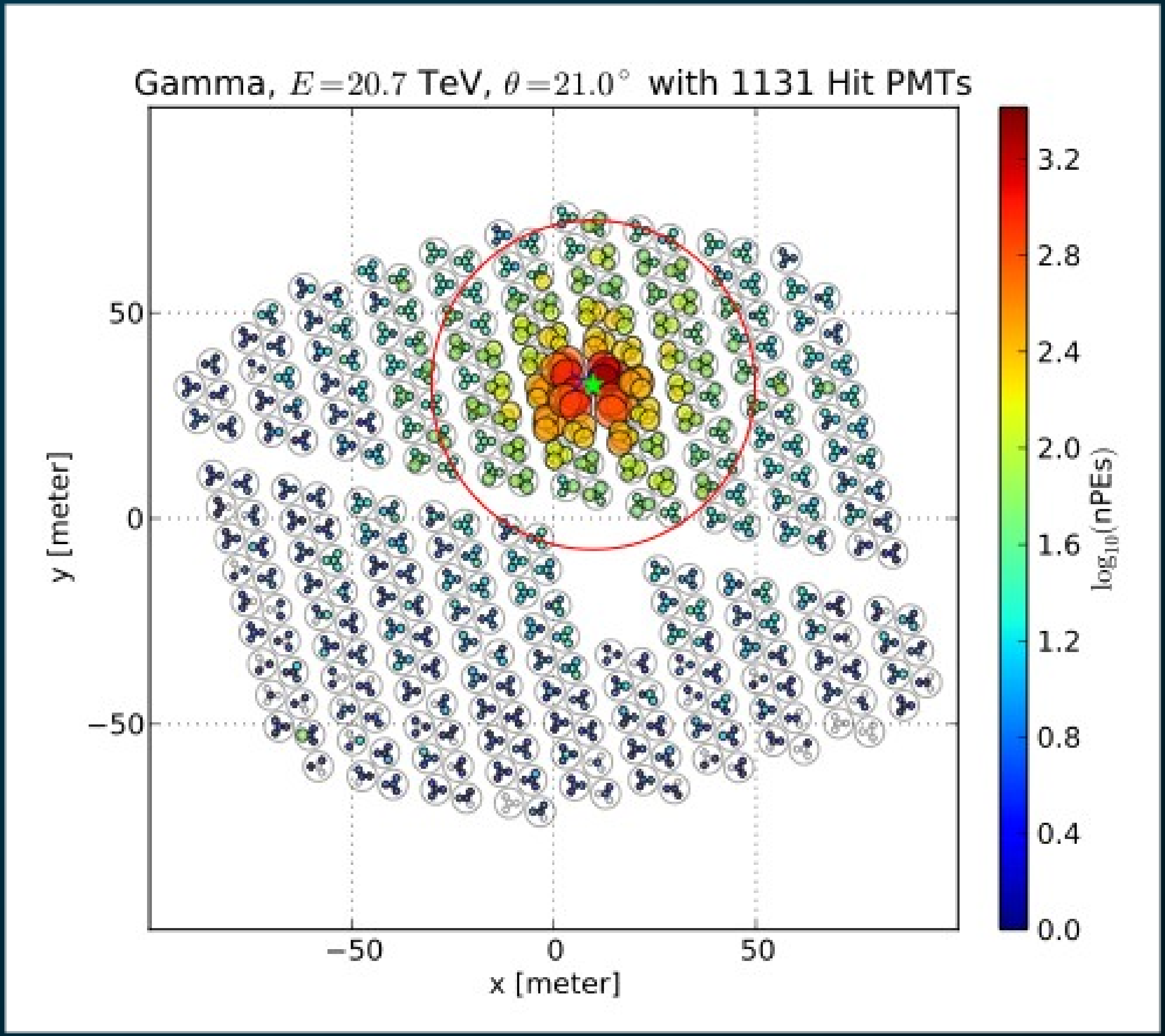
Cosmic Ray shower



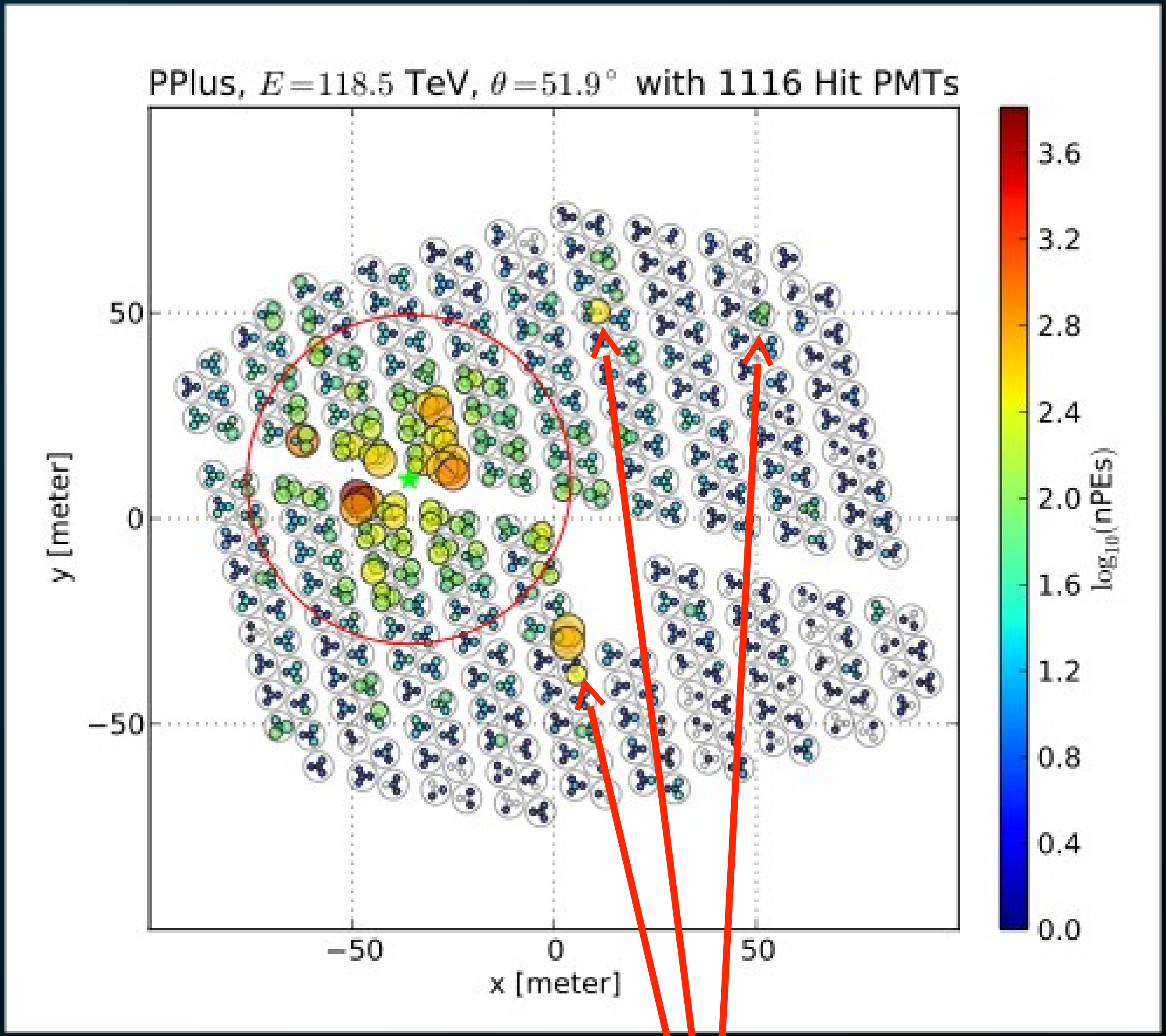
Pictures show amount of light detected at each position
Cosmic rays have large localized spots of light far from the center of the event

Gamma-hadron separation (more examples)

γ - ray shower



Cosmic Ray shower



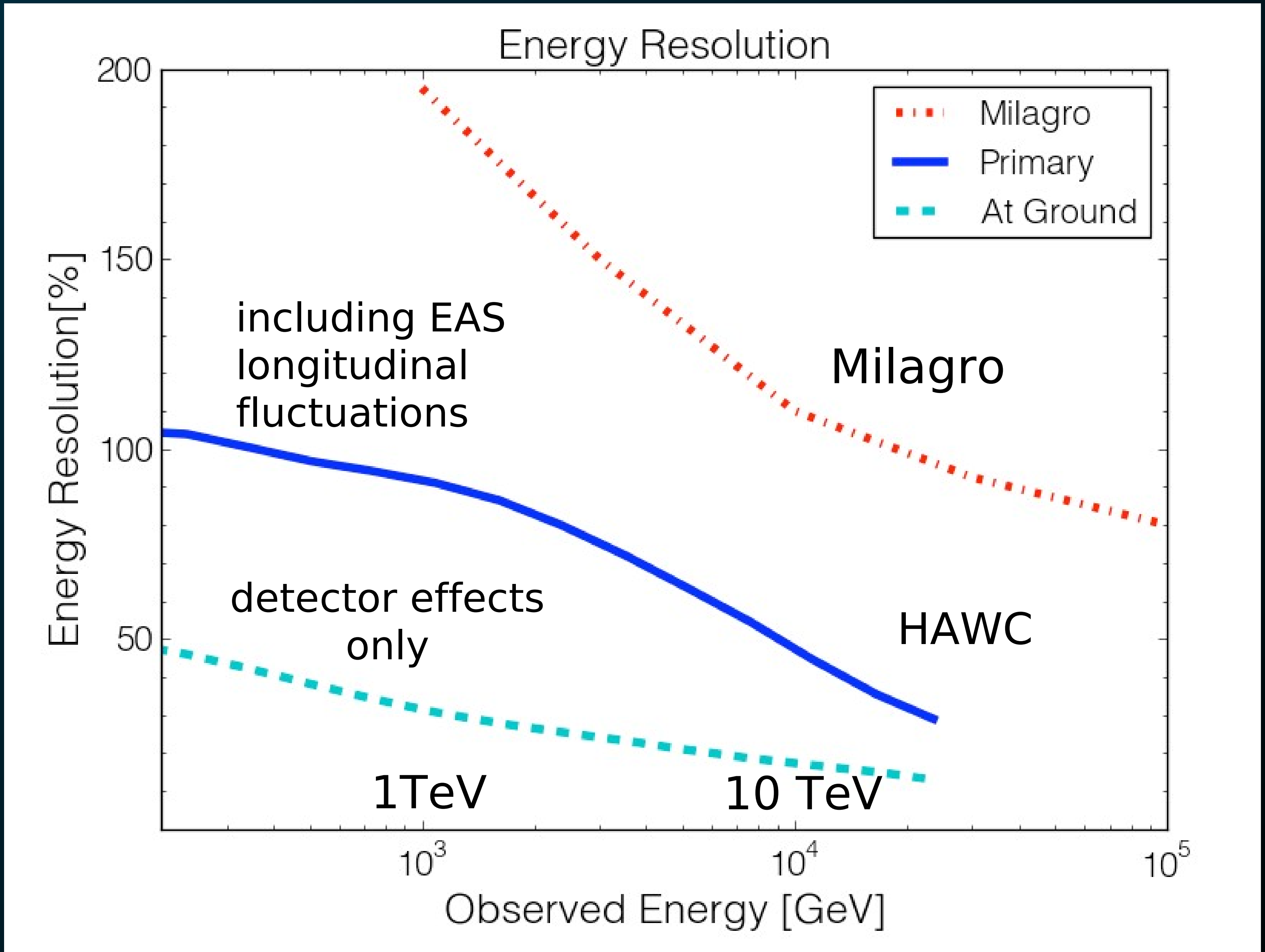
hot spots

Try HAWC gamma-hadron separation game !

http://www.hawc-observatory.org/observatory/ghsep.php

Energy resolution

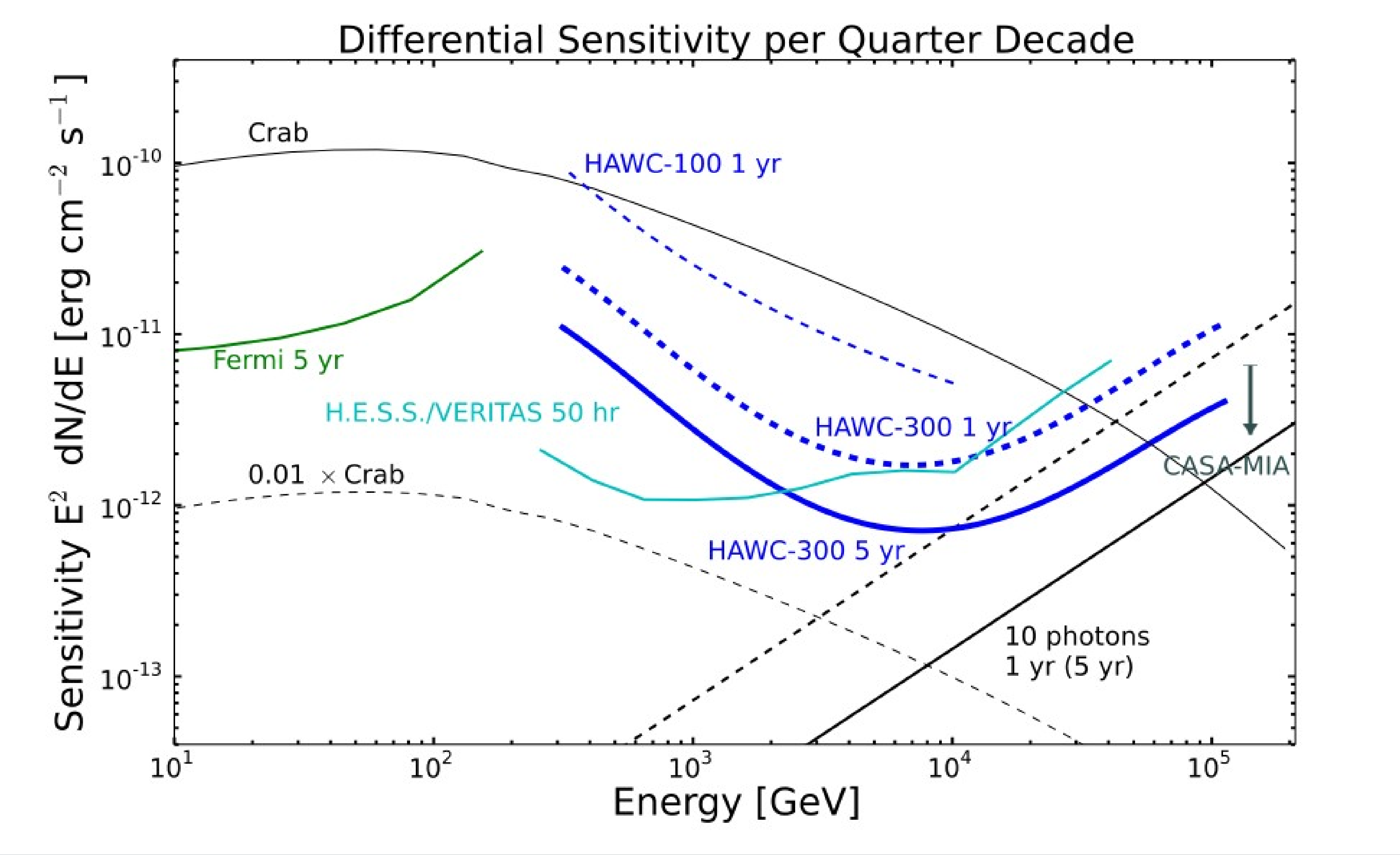
- Uncertainty from two sources:
  - Measurement of energy deposited at ground level
  - Fluctuations in shower development in atmosphere (naturally log-normal)
- Higher elevation means HAWC has a big advantage over Milagro



Resolutions are log-normal:
50% resolution indicates 1σ range [.67,1.5] times measured value

Sensitivity to Crab-like point sources

- Long integration times lead to excellent sensitivity at highest energies (> few TeV)
- 5σ sensitivity to:
  10 Crab in 3 min
  1 Crab in 1 transit
  0.1 Crab in 1/3 year



- 15x Milagro sensitivity
  - Lower energy threshold
  - Better angular resolution
  - Better rejection of cosmic rays

HAWC source transit 15° off zenith (?)

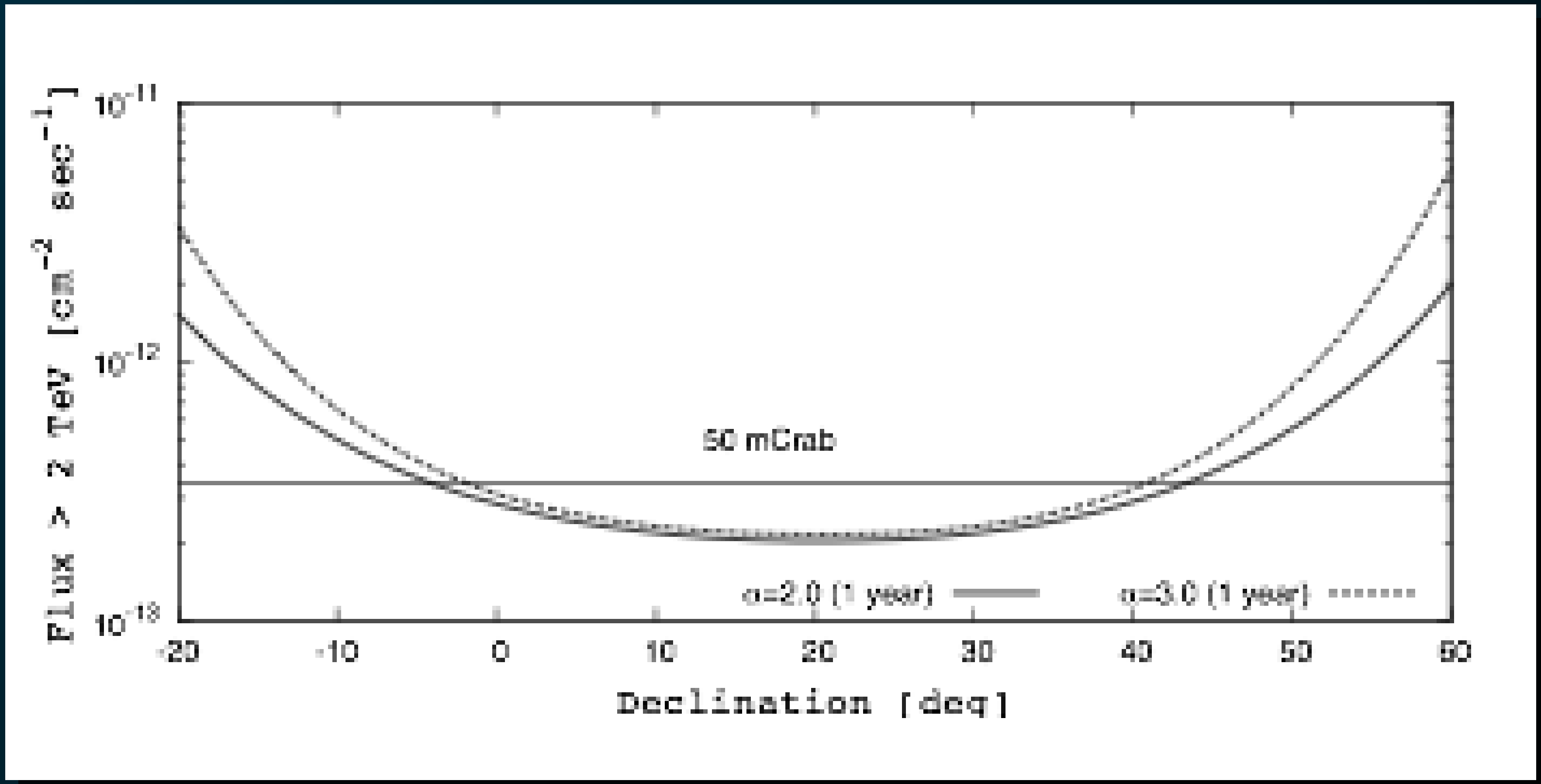
IACT: 50 hr on-source ==> ~ 15 sources / yr

Observable sky

Wide field of view
limited by atmospheric
depth (~45º from zenith)

instantaneous filed
of view ~ 2 sr

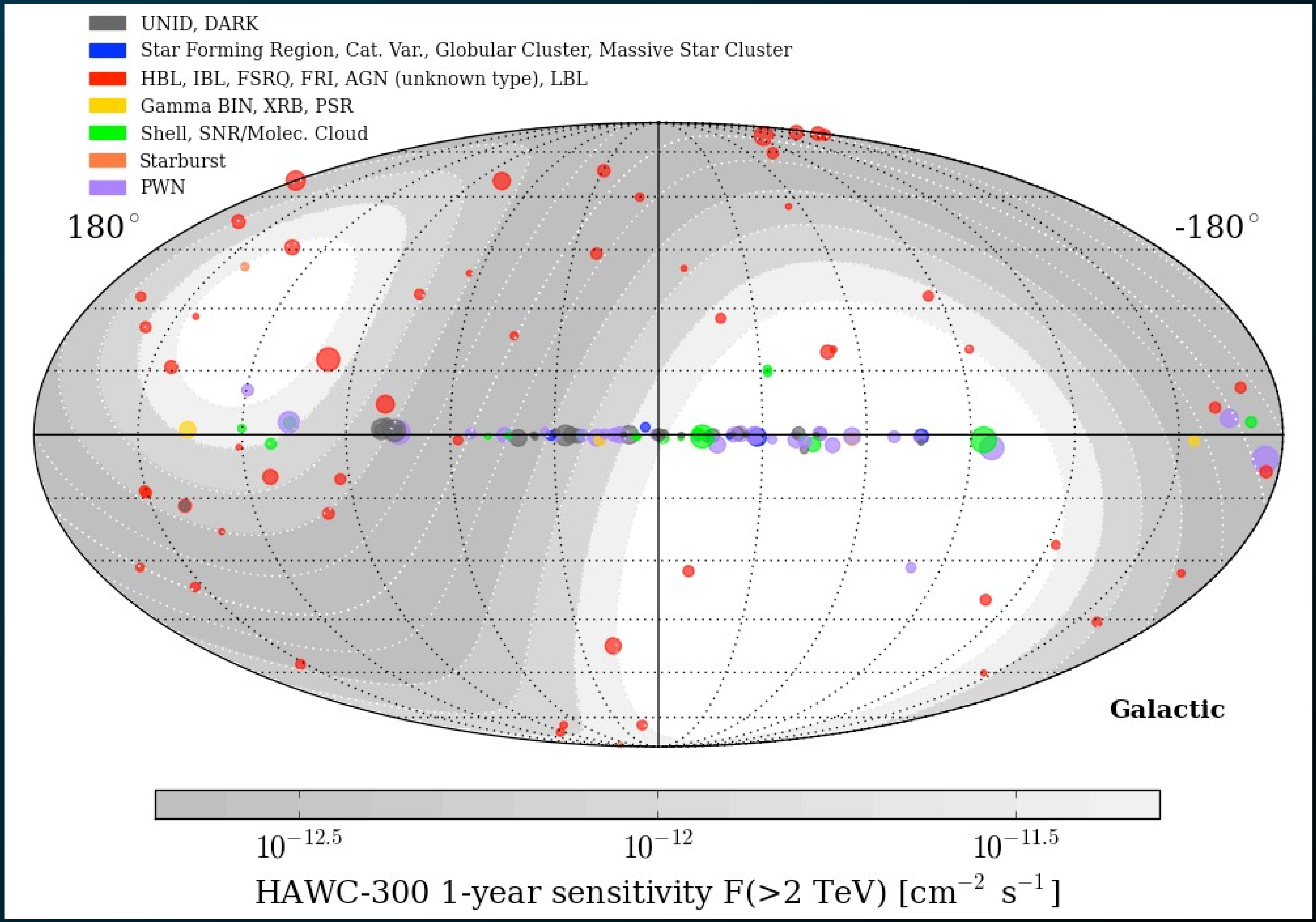
Daily observation of ~8 sr
50 mCrab survey in 1 yr



Wide field of view provides several advantages:

- Survey of a large fraction of the sky (look for the unknown)
- Measure the highest energy emission (where long exposure is essential)
- Observe larger objects (nearby supernova remnants & pulsar wind nebulae, Galactic disk)
- Observe transient events (gamma-ray bursts, flares from active galactic nuclei)

Observable sky / TeVCat sources



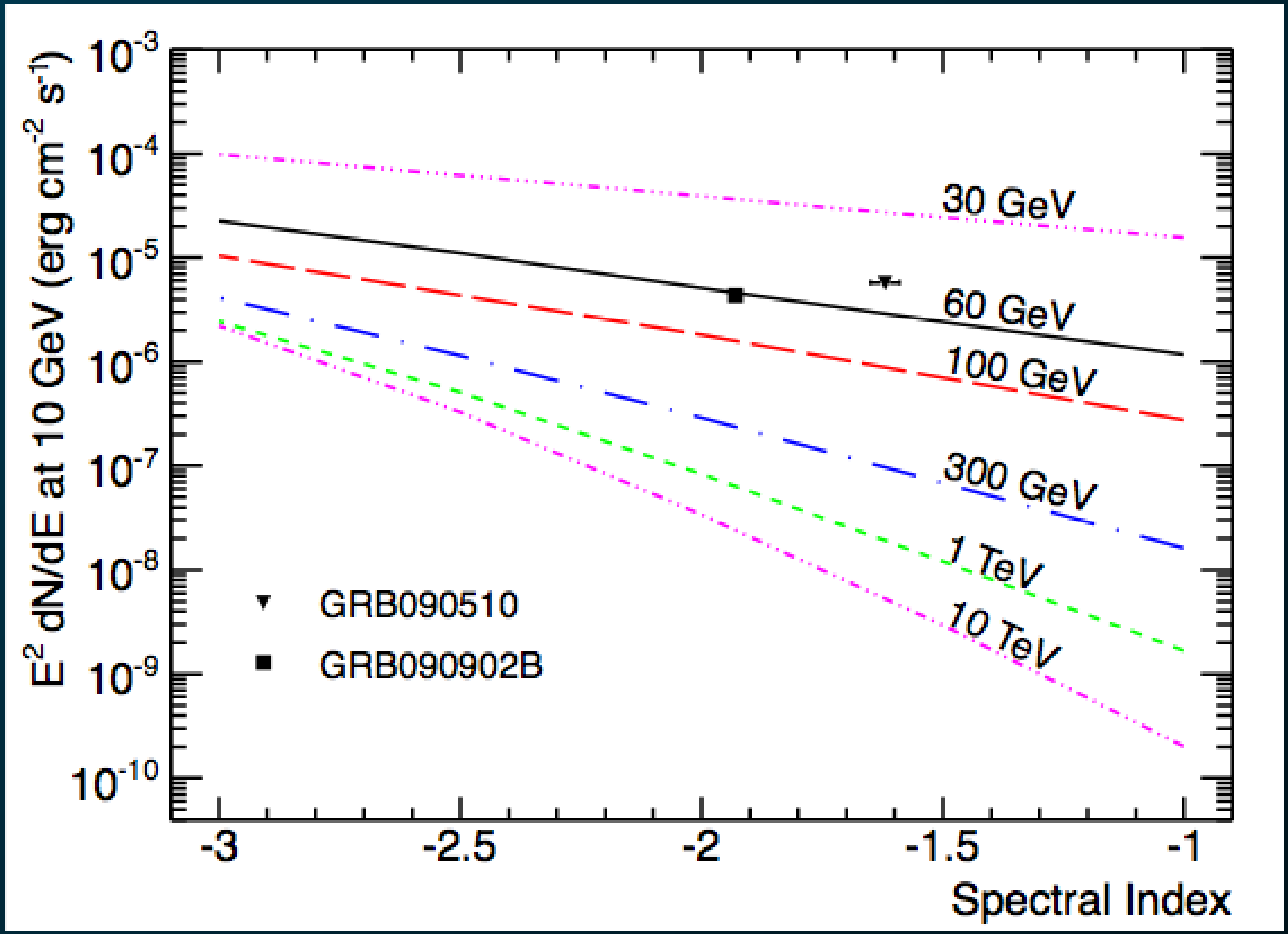
sensitivity contours are for E^-2 spectrum

Expected significance for a selection of known TeV sources

Name	RA (deg)	Dec (deg)	α	E_{cut} (TeV)	Flux (> 2 TeV) $1\text{x}10^{13}$ photon/(cm^2 s)	Significance (1 yr)
Crab (Milagro)	83.6	22.0	3.1	∞	91.1	229.9
Crab (Milagro)			2.6	31	79.2	163.1
Crab (Reference)			2.63	∞	68.5	147.8
MGRO J2019+37	206.1	18.4	2.8	∞	40.5	66.8
MGRO J1908+06	287.1	6.18	2.1	∞	17.6	36.6
MGRO J2031+41	308.0	41.6	3.2	∞	33.8	53.0
MRK 421 (very low)	166.1	38.2	2.29	1.59	18.4	31.5
MRK 421 (mid)			2.28	4.36	131.5	178.0
MRK 421 (very high)			1.87	2.74	462.9	567.9
M87	187.7	12.2	2.31	∞	2.3	4.7
IC443 (hard)	94.2	22.5	2.61	∞	2.6	5.6
IC443 (measured)			2.99	∞	1.1	2.5
IC443 (soft)			3.37	∞	0.4	1.3

Adapted from table 2 of *Sensitivity of the High Altitude Water Cherenkov Detector to Sources of Multi-TeV Gamma Rays, Astropart. Phys. Vol 50-52, pp 26-32.*

Sensitivity to transients (air shower analysis)



Simulated GRB:
T = 1 s
zenith = 20 deg

Power law spectrum with Heaviside cutoff

The cutoff is either intrinsic or EBL absorption cutoff

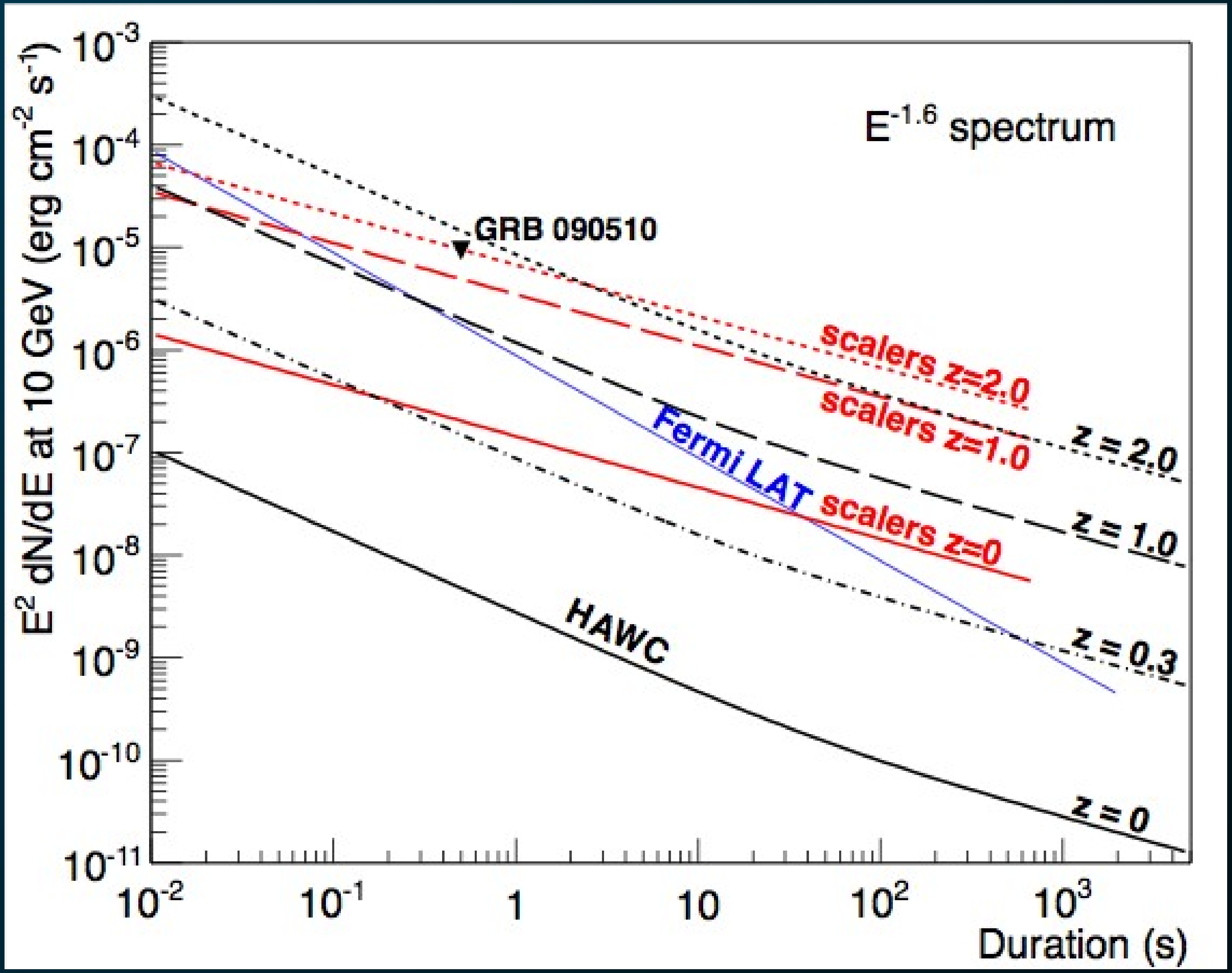
trigger: Nhit > 30

* Correlated noise from simultaneous hadronic showers not included in simulation

Brightest GRBs detected by Fermi should be observable with 5 sigma significance if cutoff is above ~50 GeV

For details see Astropart. Phys. 35 (2012) 641-650. Also arXiv:1108.6034 [astro-ph.HE]

Sensitivity vs. duration



Redshift is modeled according to Gilmore et al.
No intrinsic spectral cutoff
Fermi LAT curve: 1 photon above 10 GeV

Fermi LAT is essentially "background free" (sensitivity ~ 1 / T)

HAWC scalers are background dominated (sensitivity ~ 1 / sqrt(T))

Above 10 GeV HAWC's sensitivity is comparable to Fermi LAT's

For details see Astropart. Phys. 35 (2012) 641-650. Also arXiv:1108.6034 [astro-ph.HE]

Prospects for GRB detection by HAWC

I.Taboada, R.C. Gilmore, Prospects for the detection of GRBs with HAWC, arXiv:1306.1127

cutoff	Short GRB / yr (standard main DAQ analysis)	Long GRB / yr
n/a	1.4	0.25
150 GeV	0.27	0.04

HAWC will primarily detect short GRBs (complementary to CTA)

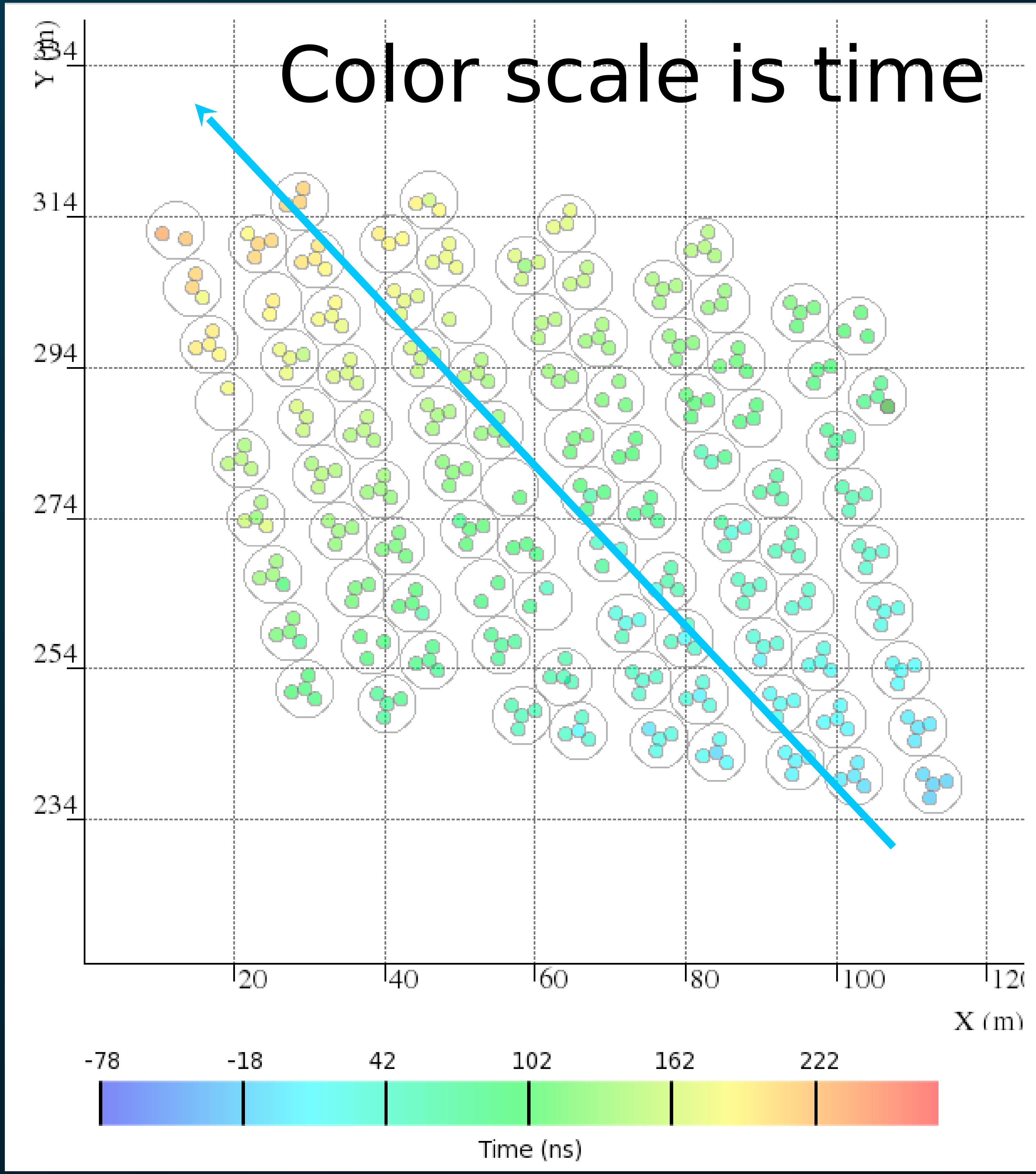
Compare: Fermi LAT above 10 GeV: 0.25 short GRB / yr

HAWC construction progress

December 2013

May 2014

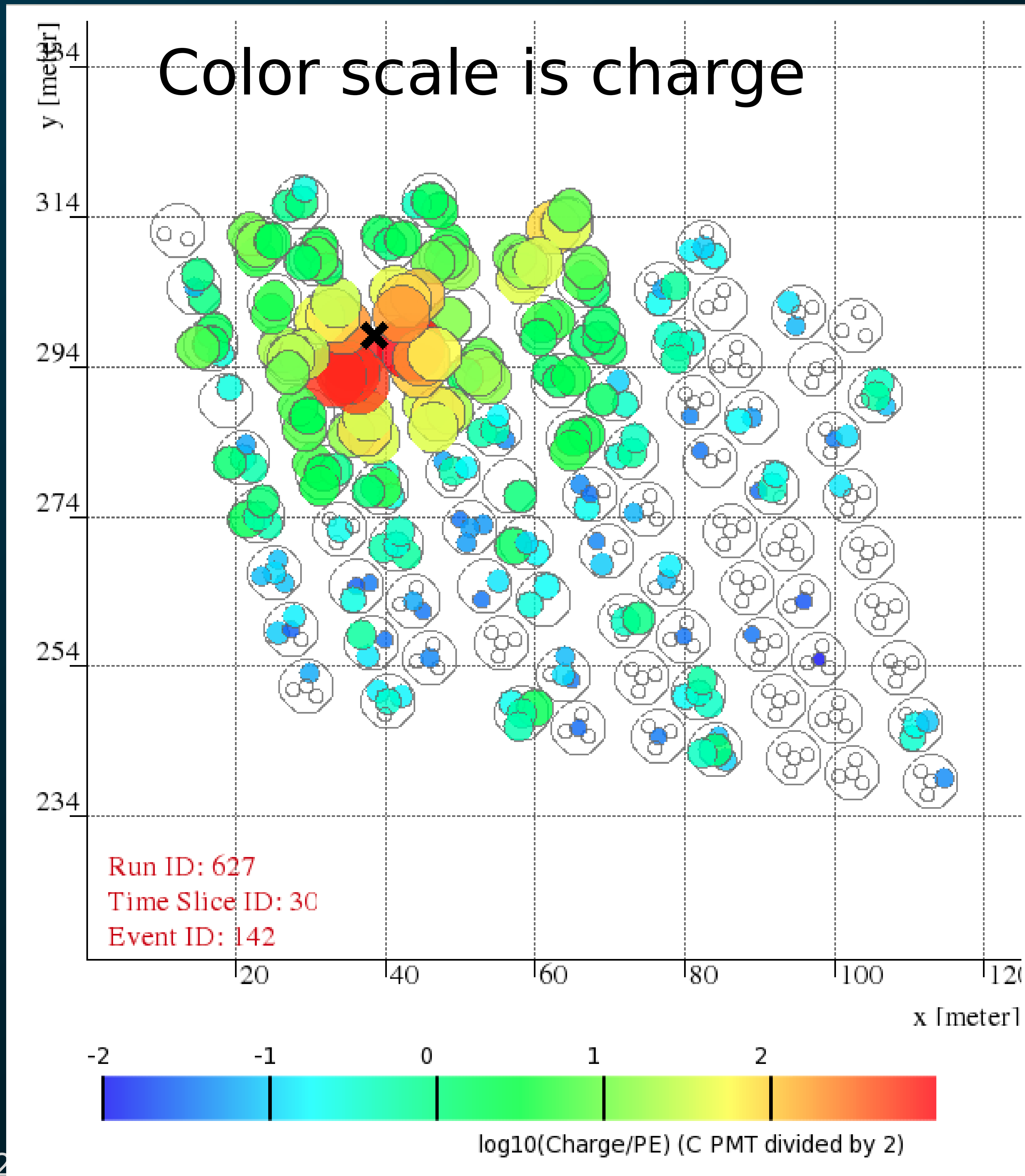
Event display example



- This event:
- Recorded on June 12
- 95 Tanks
- 341 PMTs

Time gradient is evident (inclined shower)

Another event display example



Core location is evident

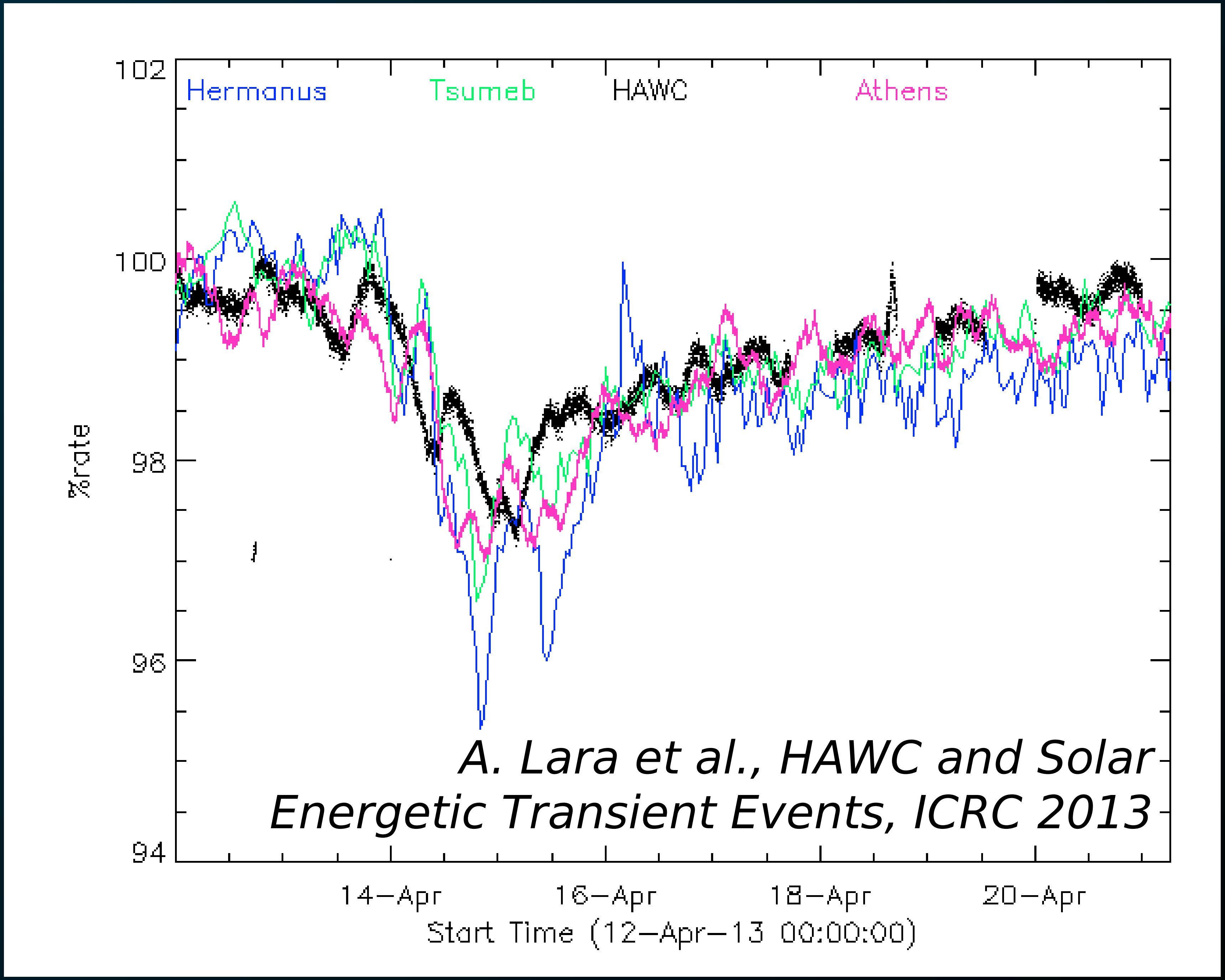
April 2013 Forbush decrease with HAWC-30

Forbush decrease is a modulation of the galactic cosmic ray flux by Solar activity (Coronal Mass Ejections)

HAWC data have been corrected for barometric pressure and temperature variations

cutoff rigidity for vertically incident protons at HAWC is 7.9 GV; Athens, Hermanus and Tsumeb sites have cutoofs at 8.5, 4.5 and 8.9 GV respectively

HAWC data clearly show the Forbush decrease and are in agreement with data from neutron monitors

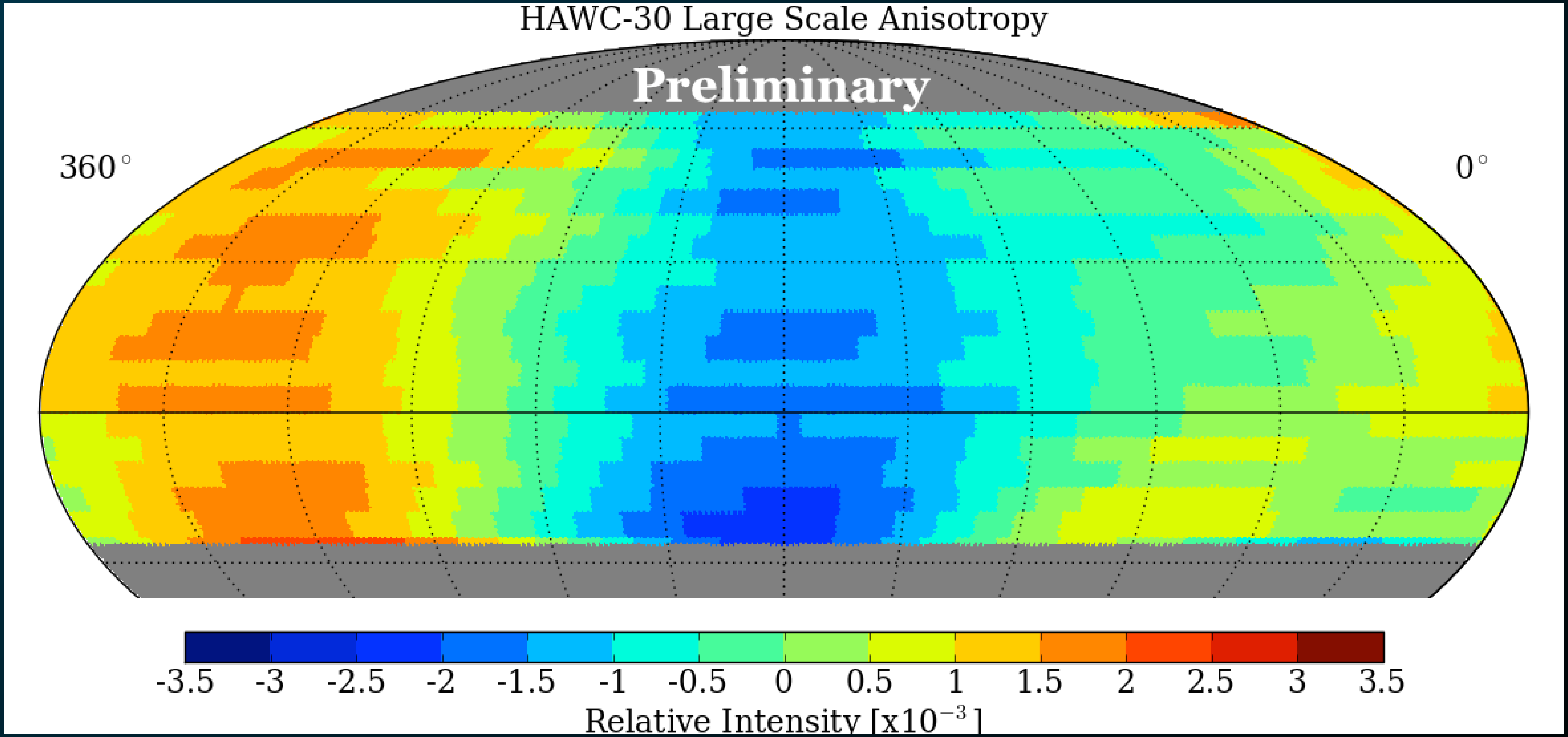


HAWC will also detect solar energetic particles known as Ground Level Enhancements (GLEs)

Large scale cosmic ray anisotropy

Note: this is not a sky map, but a series of 3-term harmonic fits within 18 declination bands

95 days (Jan 1 - Apr 15)
21 billion events
median energy 2 TeV



S. BenZvi et al., Observation of the Anisotropy of Cosmic Rays with HAWC, ICRC 2013

Uses the forward-backward technique (A.A. Abdo et al., Astrophys. J., 2009, 698: 2121)

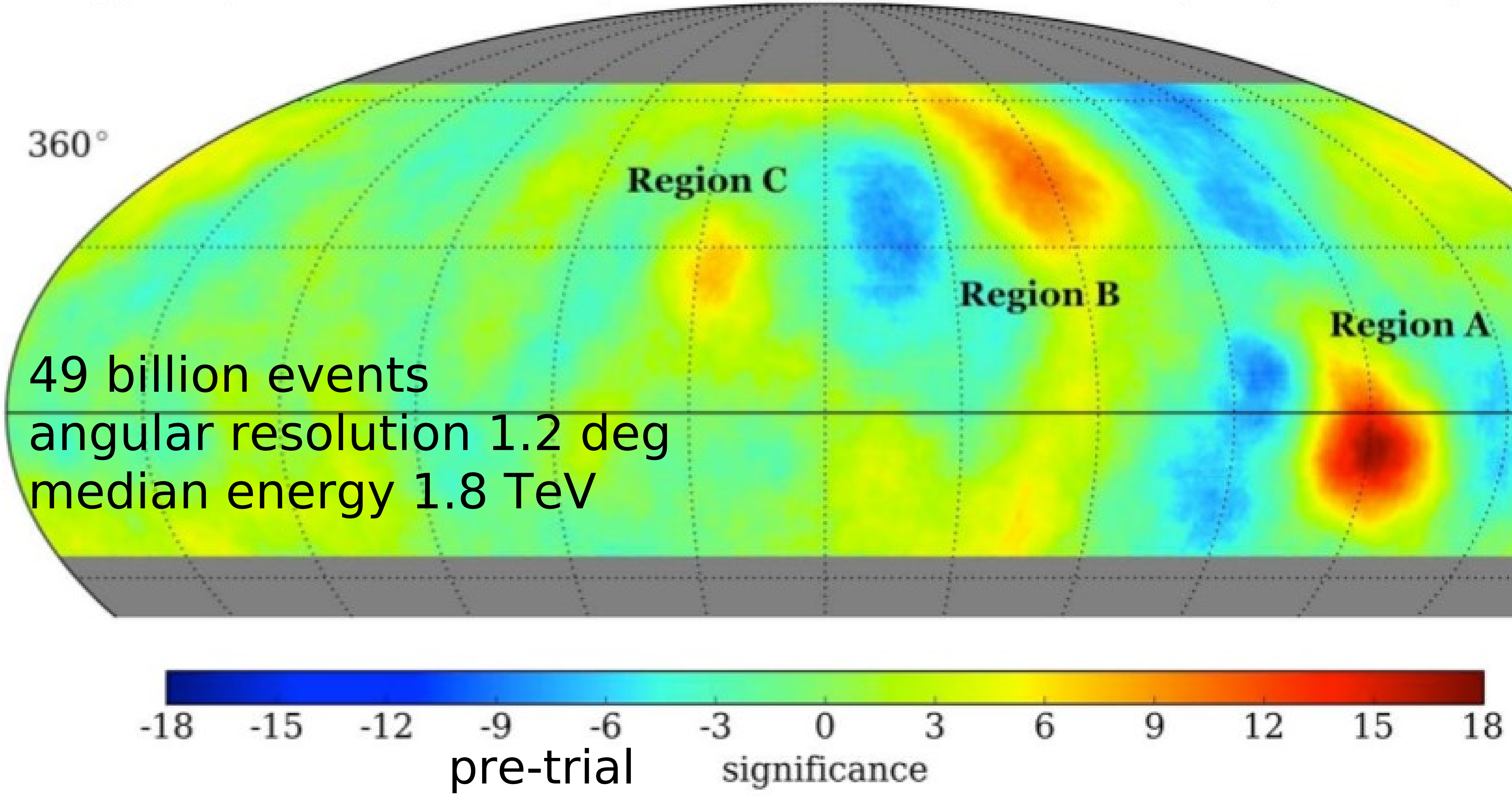
Small scale Cosmic Ray anisotropy

Jun 2013 – Feb 2014, 110 full siderial days, HAWC-95 and HAWC-111 combined

Fit dipole+quadrupole+octupole to map for 24-hr background estimation

Subtracted fit relative intensity from 24-hr map

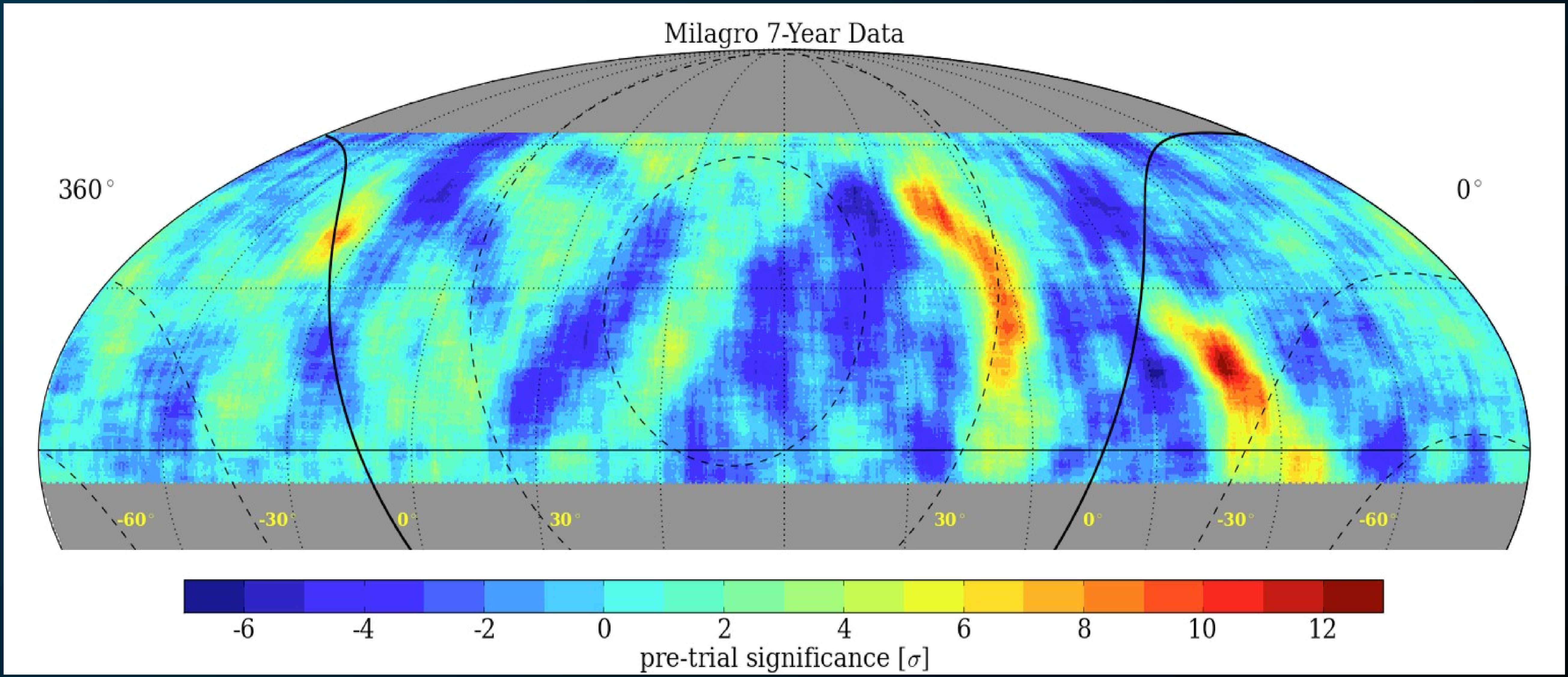
Regions A, B and C are the only statistically significant excesses (>5σ post-trials)



D. Fiorino, The Cosmic Ray Anysotropy as seen be HAWC, workshop on air shower detection at high altitude, Paris, May 2014

Compare to Milagro

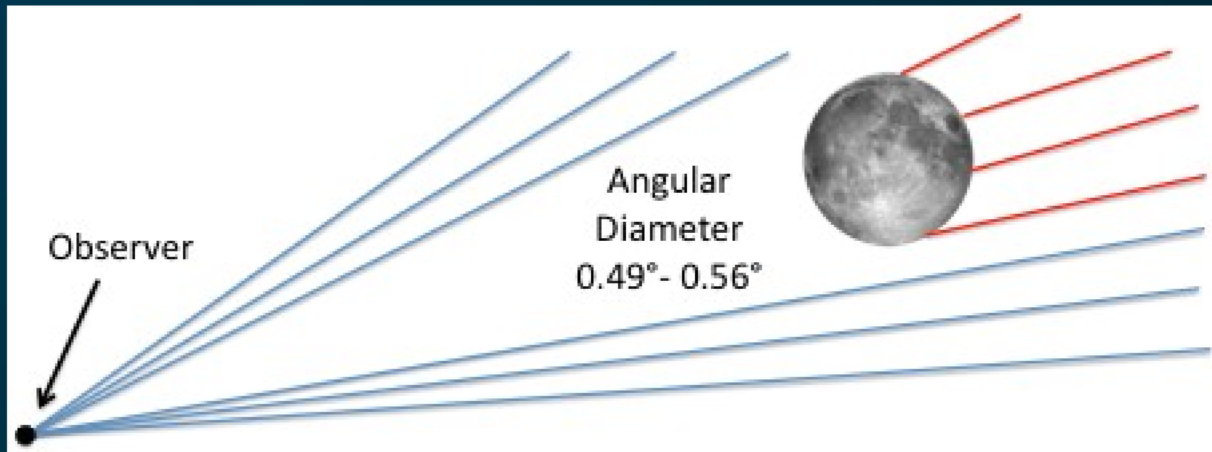
median energy ~ 10 TeV

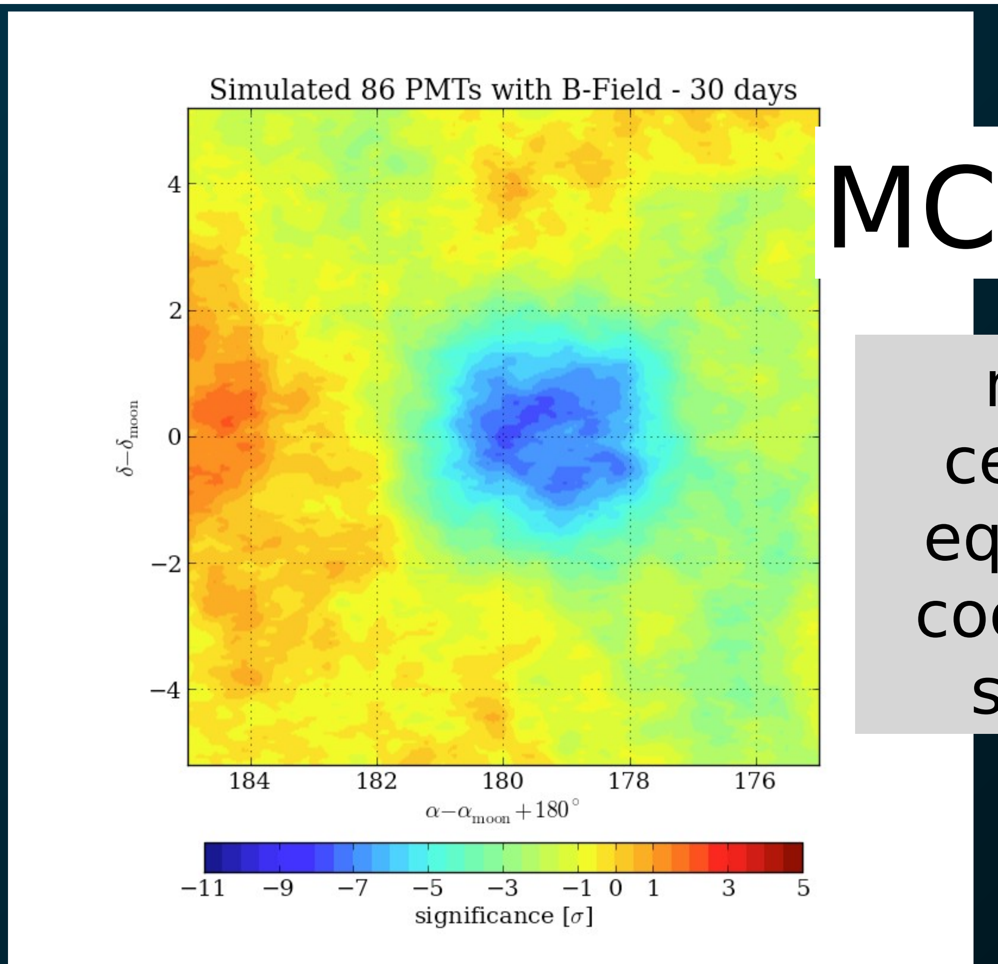


Milagro anisotropy: PRL 101:221101, 2008

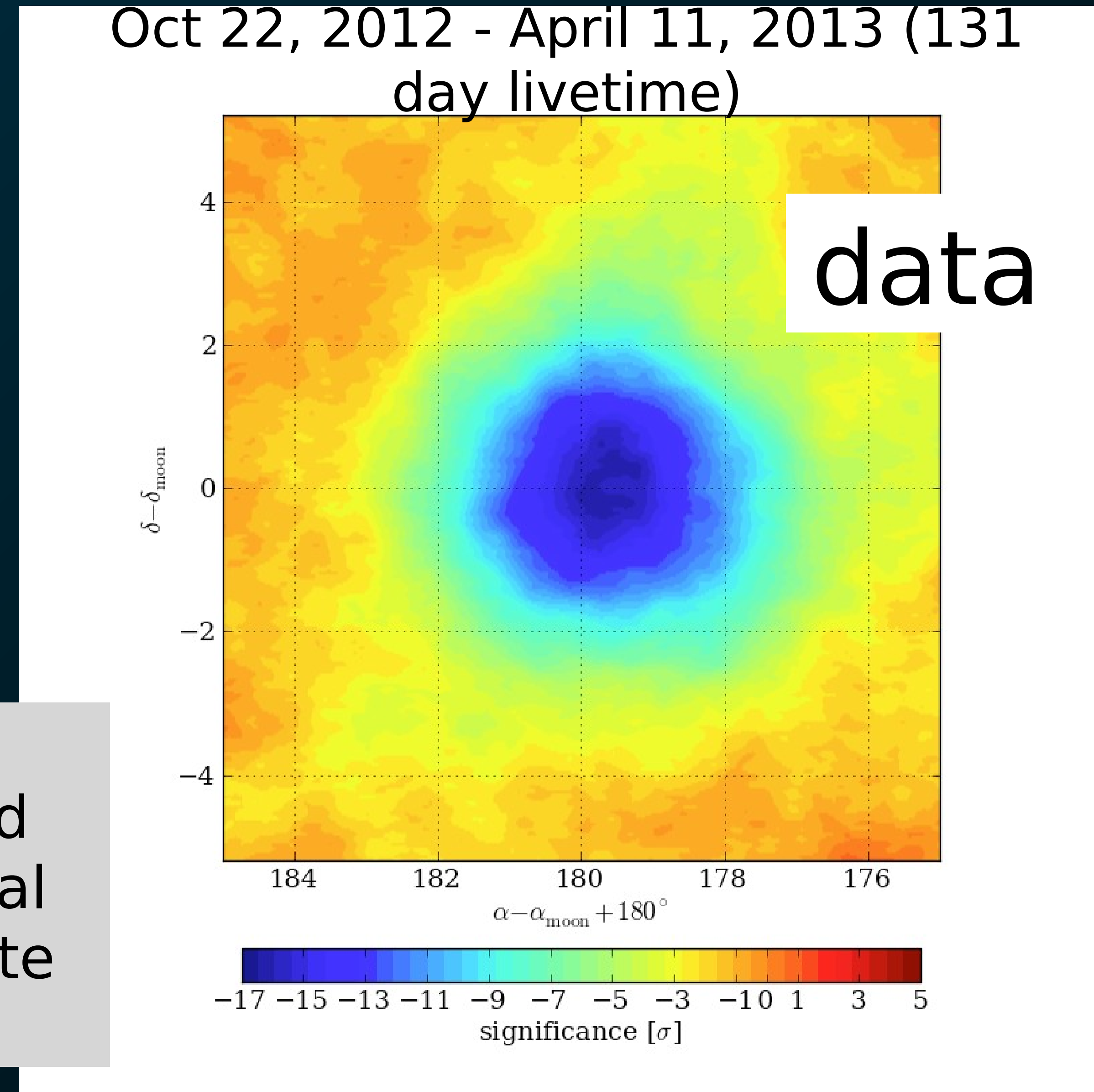
HAWC sees the same regions of excess (Milagro regions A and B)

Moon shadow





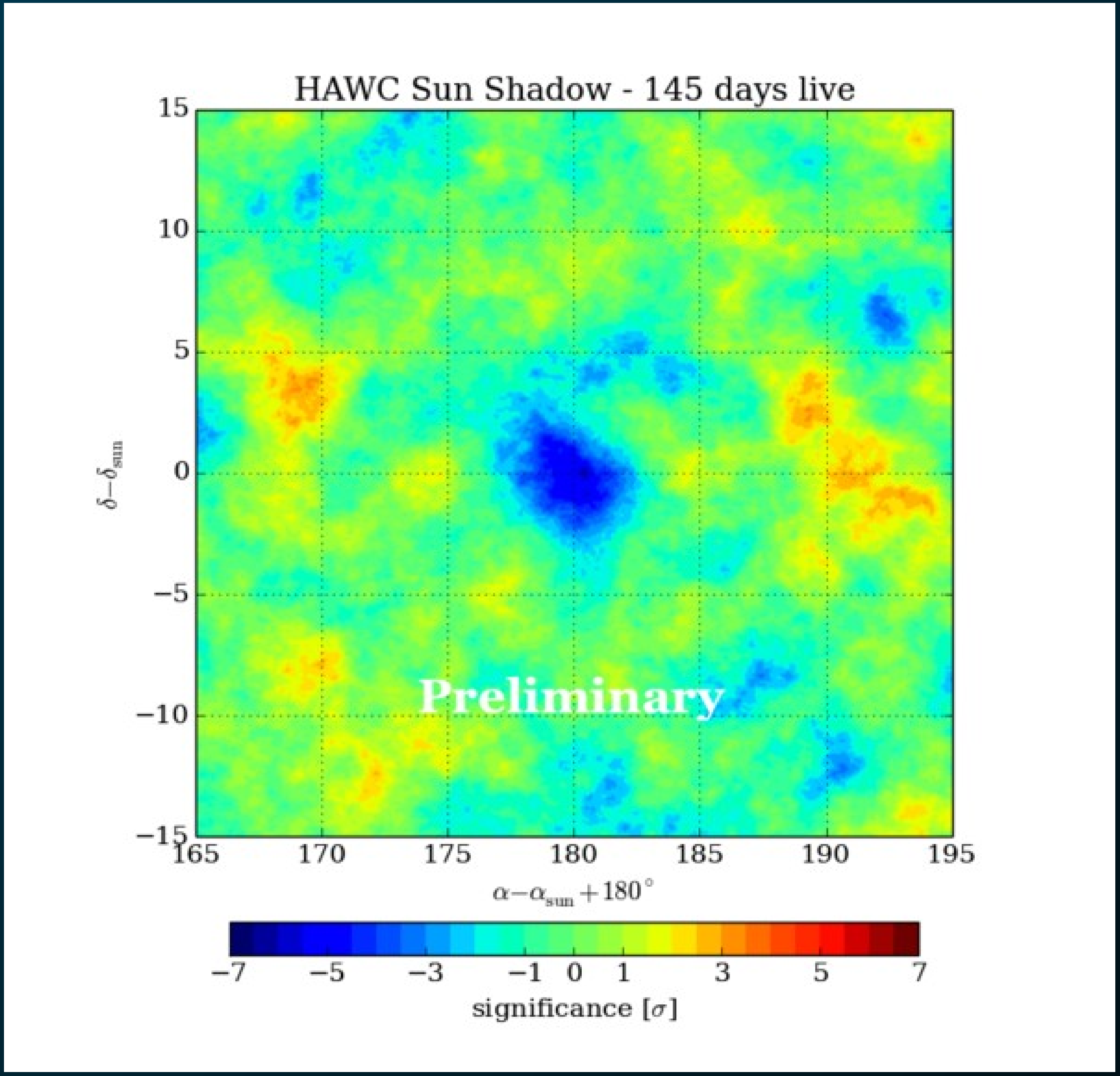
moon-centered equatorial coordinate system



Earth magnetic field model: IGRF 2011
HAWC-30 angular resolution is ~1.2 deg at 3 TeV
2 degree smoothing used

7 billion shower events (nCh > 31)
peak significance: -15.6 σ
centered at 179.6+/-0.1, 0.0+/-0.1 deg
Observed width σ = 1.6 +/- 0.1 deg, consistent with expectation
blocked flux in a 5 deg radius circle is 0.255% (0.25 % expected)

Sun shadow



Shadow location:
179.7° ± 0.4°, -0.1° ± 0.5°

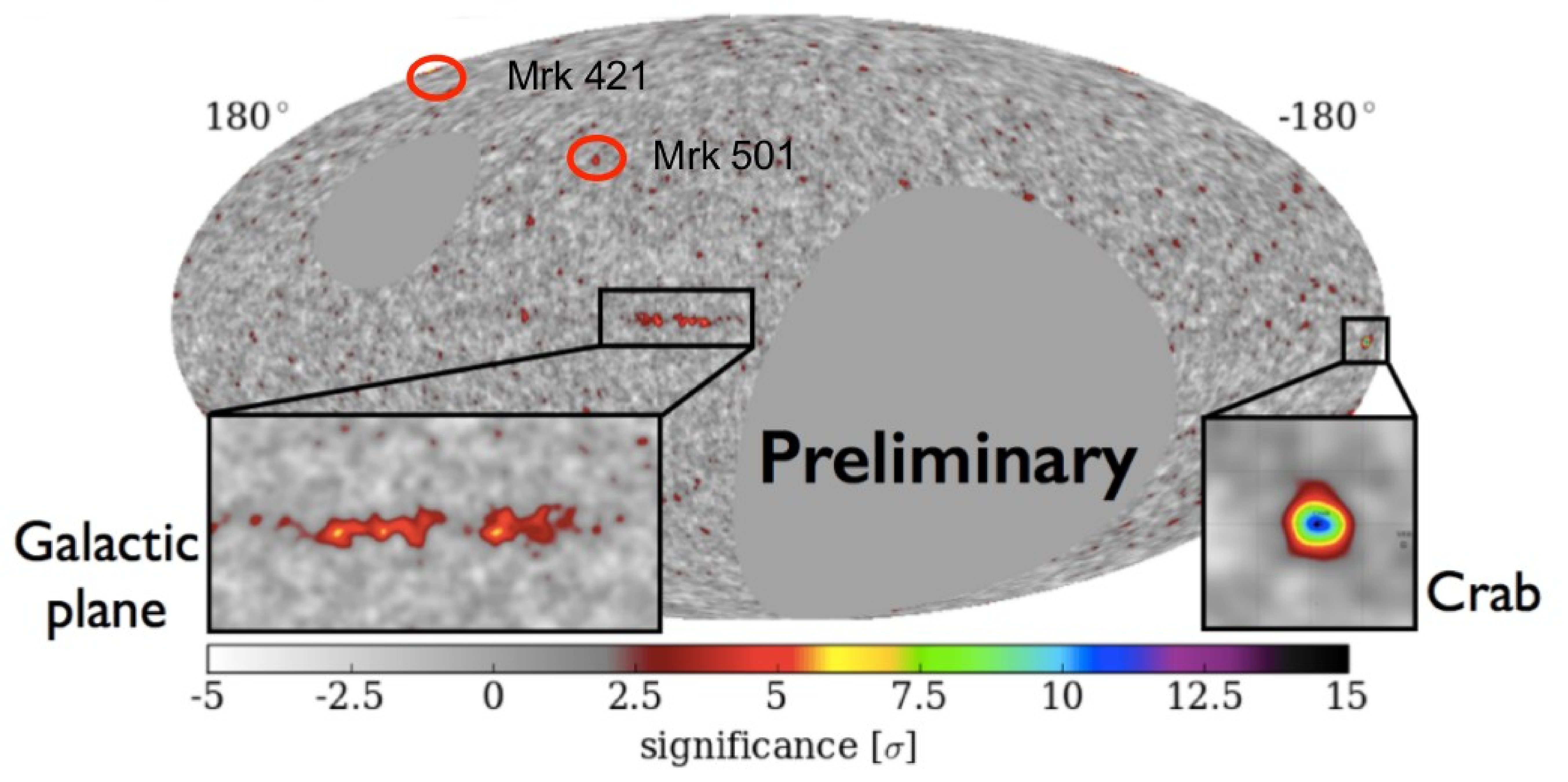
Shadow significance:
-6.4 sigma

Shadow strength depends on Solar activity (due to magnetic fields)

Detailed analysis in progress

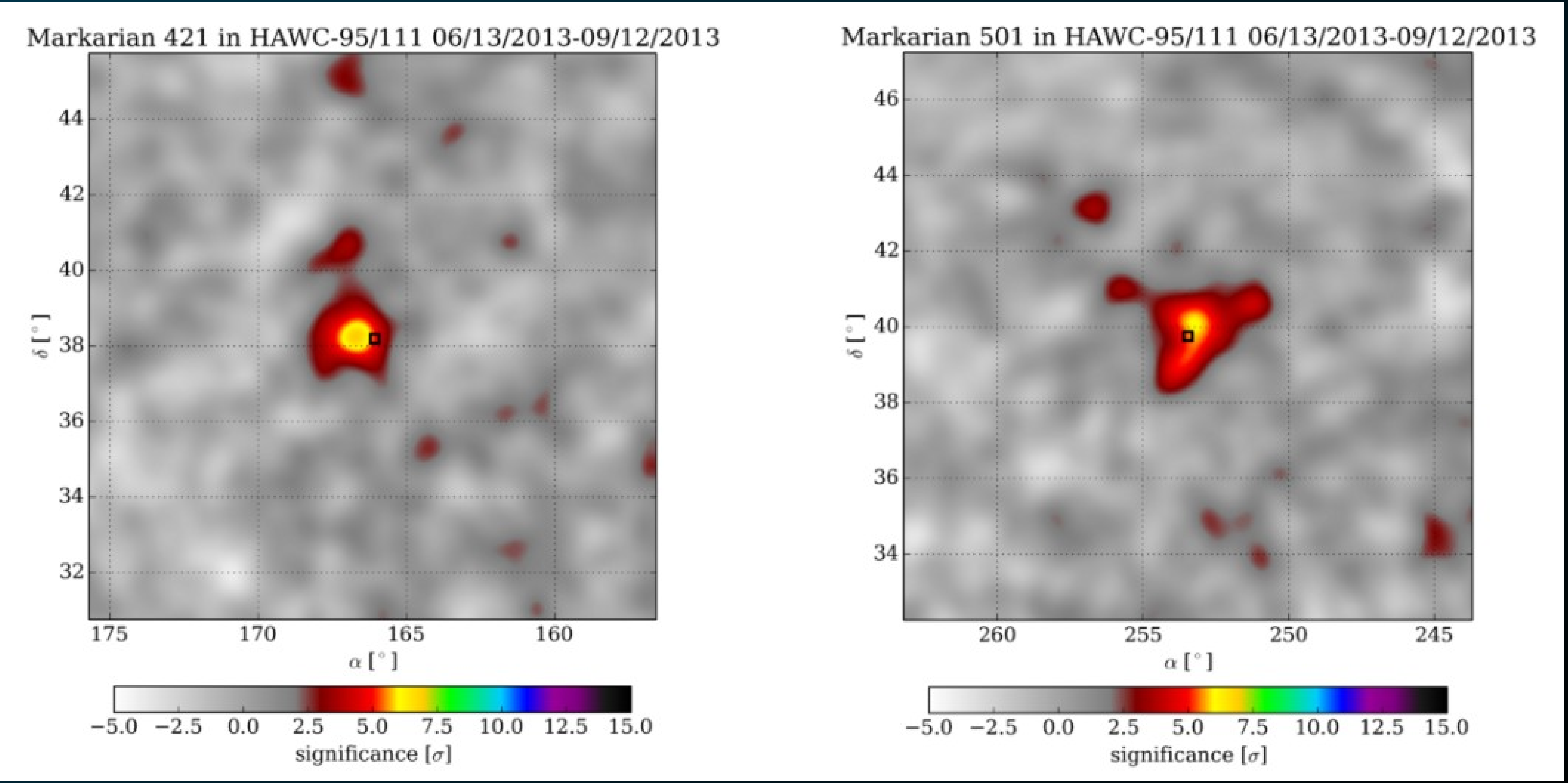
All sky gamma ray map

Using data from HAWC-111

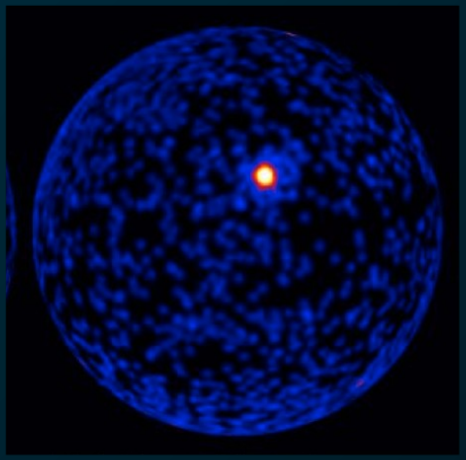


Mrk 421 and Mrk 501

(Zoom of the map on previous slide)



GRB 130427A

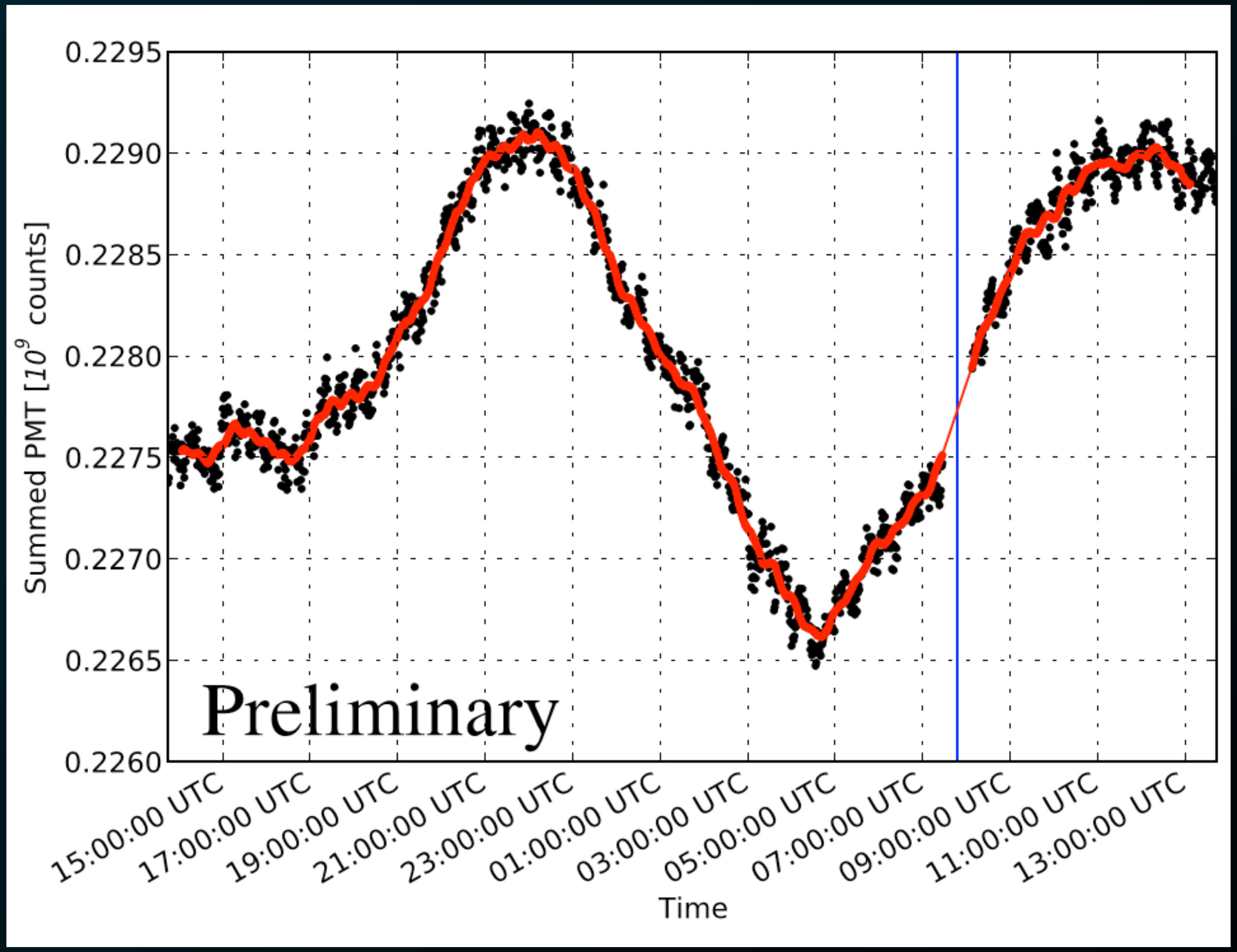


- Brightest GRB detected in 30 years (2×10^{-3} ergs/cm^2)
- Highest energy photon ever recorded from a GRB - 94 GeV
- low redshift (0.34)
- zenith angle at HAWC = 57 deg and setting
- HAWC main DAQ was off, but PMT rates were recorded by the scalers DAQ

6 different time windows examined, **no excess found**

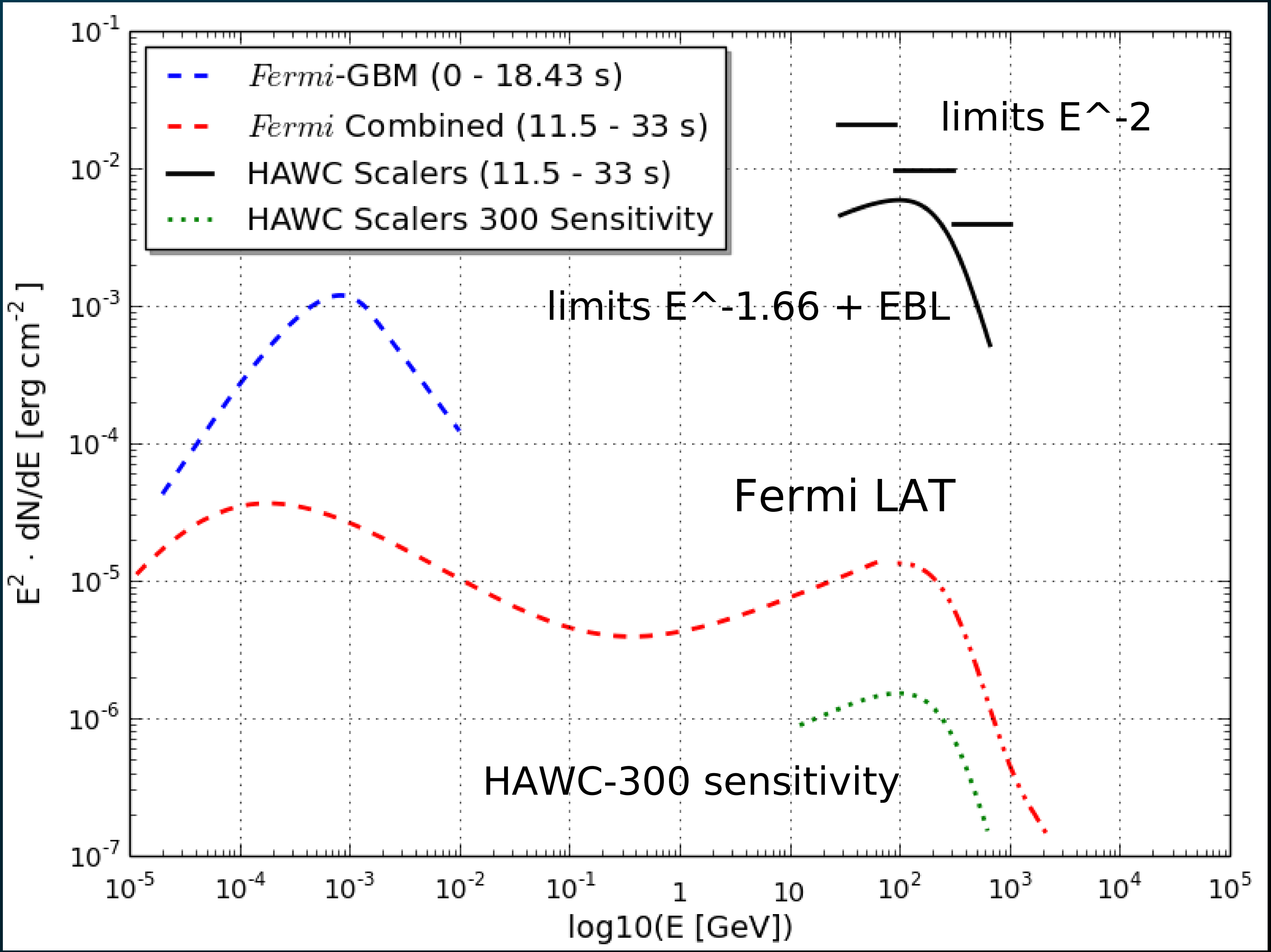
First HAWC GCN circular

summed PMT rate and moving average

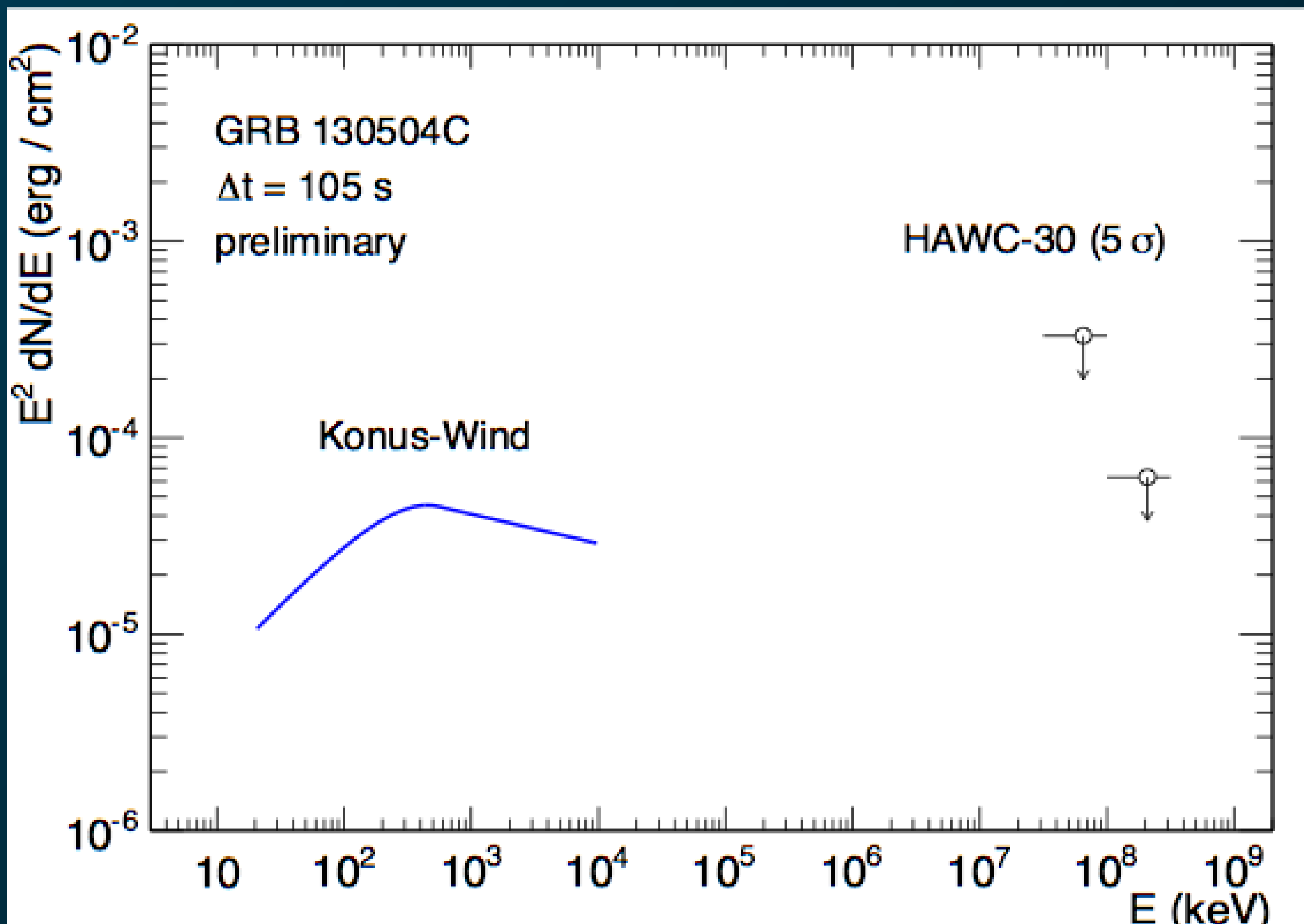


D. Lennarz et al., Sensitivity of the HAWC Observatory to Gamma-ray Bursts Using the Scaler System, ICRC 2013

Limit on GRB 130427A



GRB 130504C

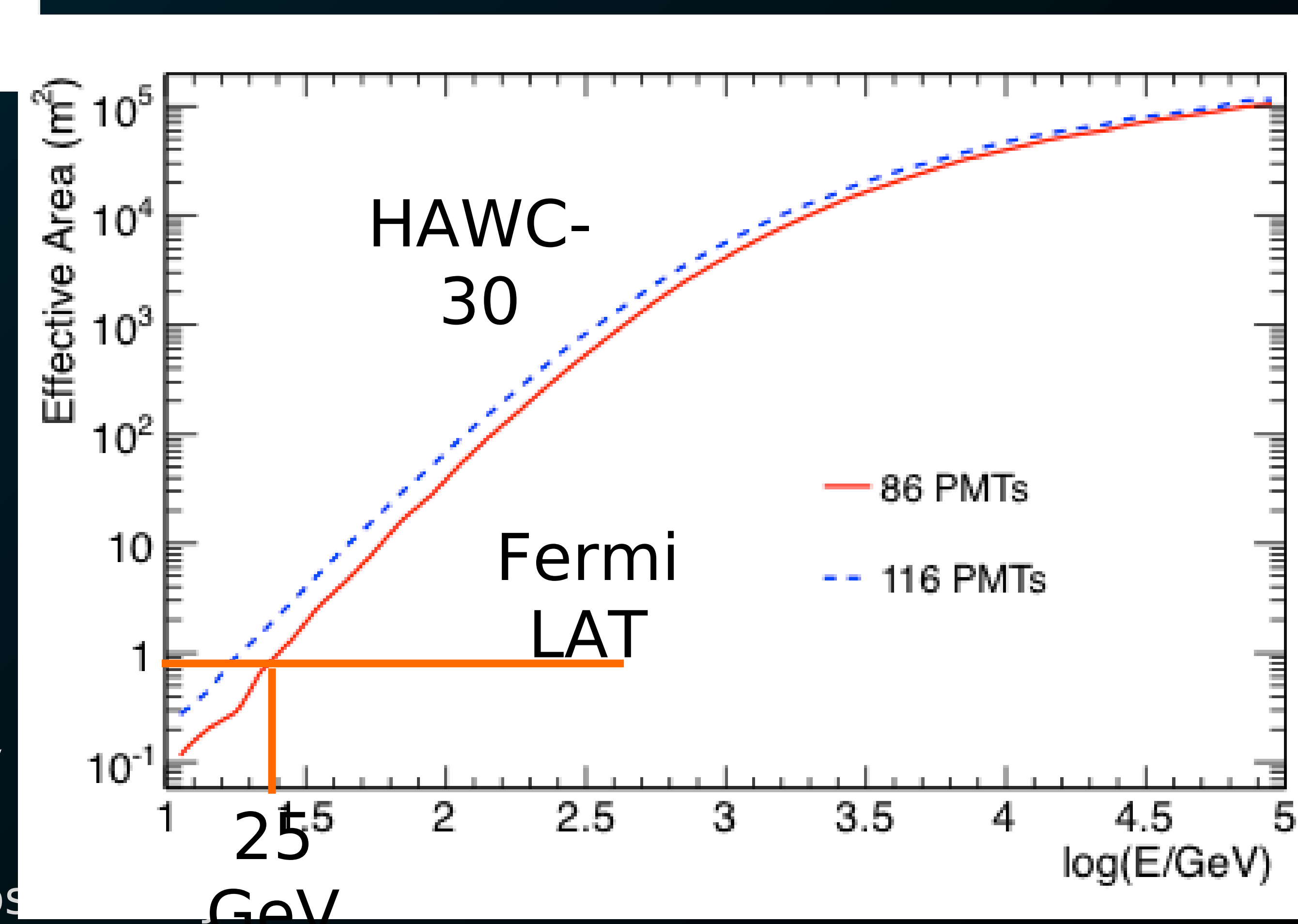


- A high fluence GRB detected by Fermi LAT (also by Fermi GBM and Swift XRT)
- LAT detected > 70 photons above 100 MeV (GCN circular 14574)
- highest energy LAT photon ~ 5 GeV
- Zenith angle at HAWC: 30 deg
- HAWC was taking data with 28 tanks
- No excess observed in HAWC

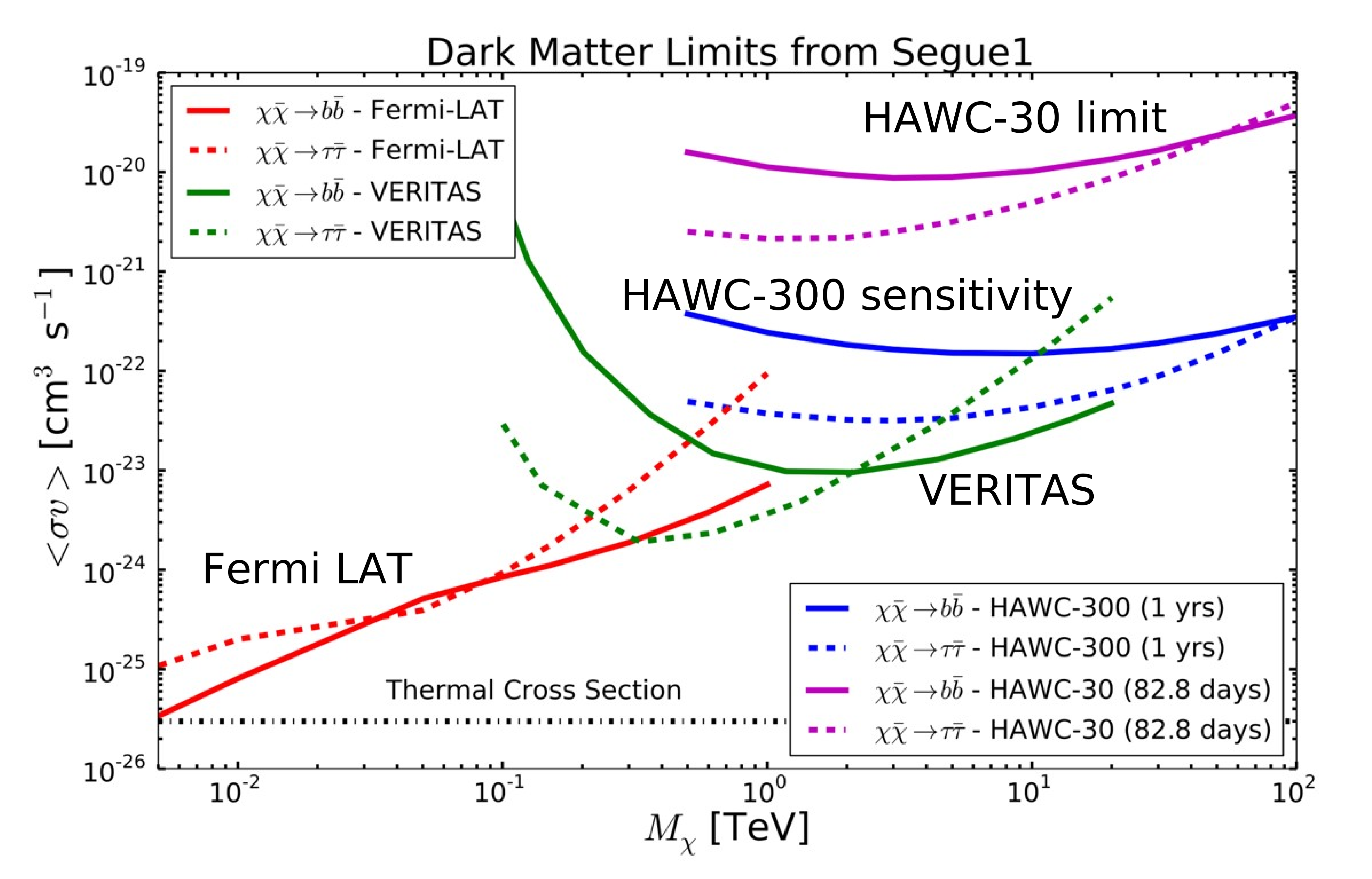
* HAWC limit shows the flux level corresponding to a 50% probability of 5 sigma detection

* Fermi LLE (LAT low energy) spectral analysis was not available at this time

HAWC-30 effective area exceeds Fermi LAT's above 25 GeV



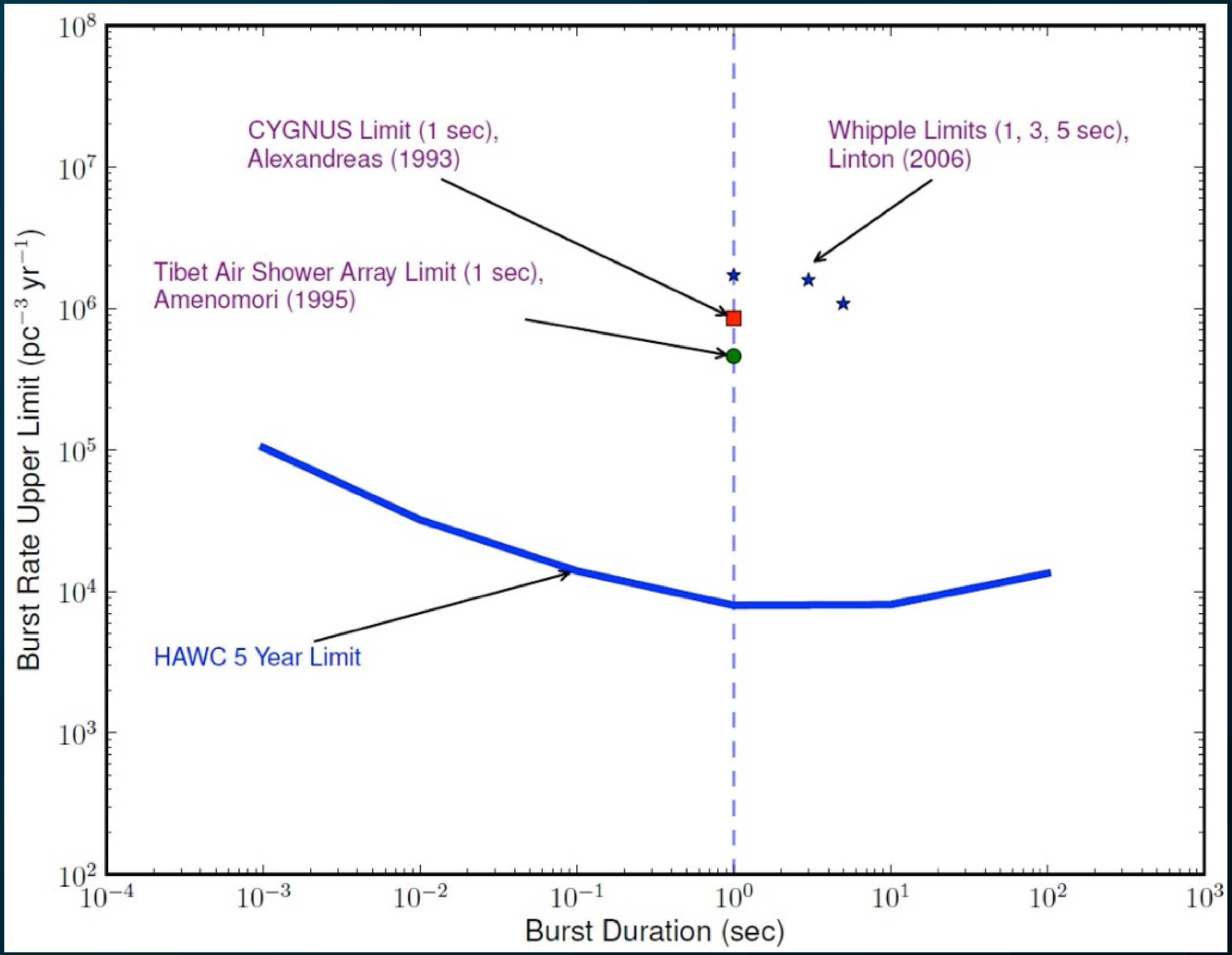
Limits on Segue I Dark Matter



HAWC-30 provides best limits available above 20 TeV

B. Baughman et al., Limits on Indirect Detection of WIMPs with the HAWC Observatory, ICRC 2013

Primordial Black Holes

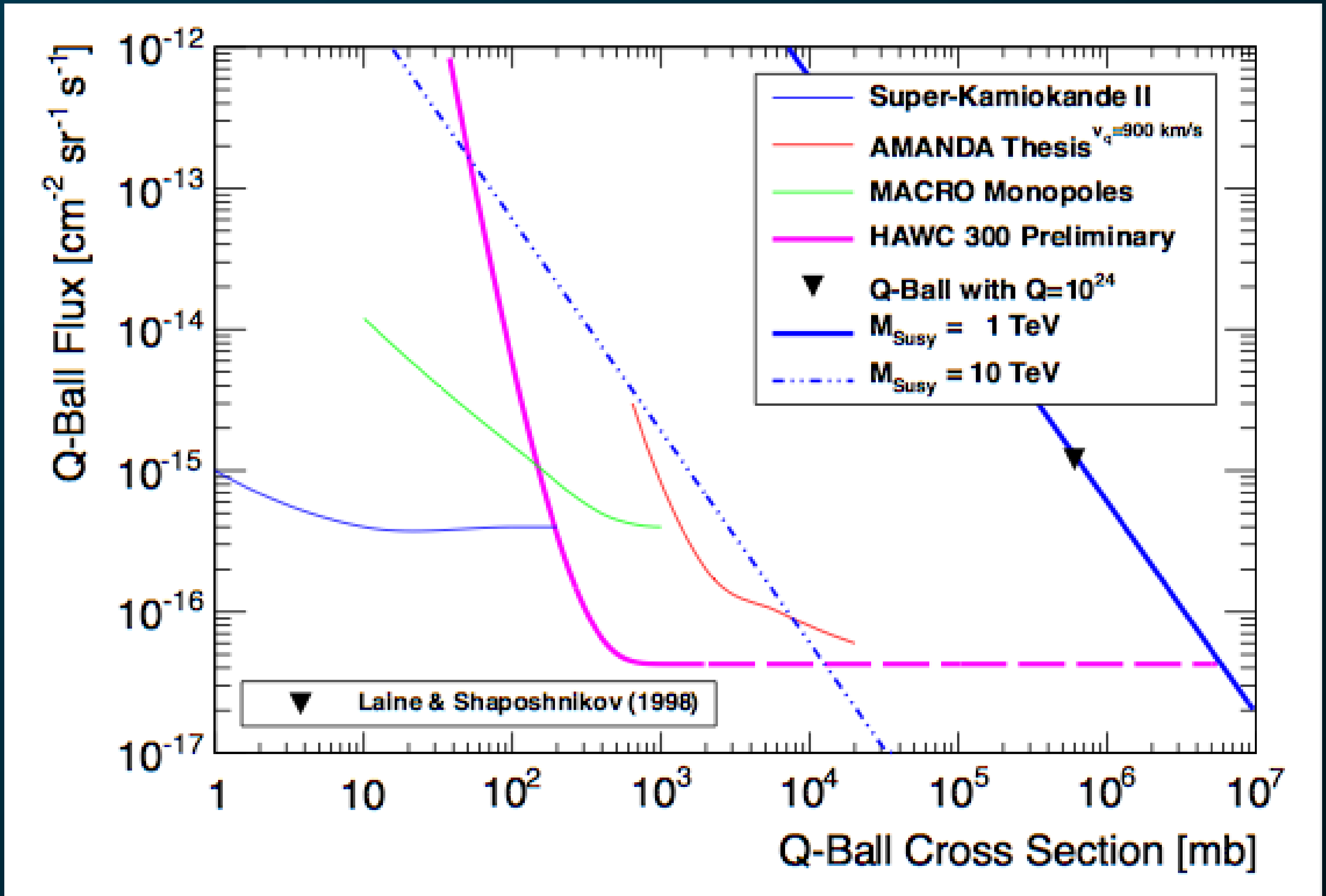


- PBH could be (were?) created from density fluctuations in the early Universe
- Masses ~ 10^{15} g should be expiring now ("standard model" black hole)
- Black hole evaporation produces a burst of particles including gamma-rays
- Analysis similar to GRB searches

Expecting ~200x improvement over current direct limits

T. Ukwatta et al, HAWC sensitivity for the Rate-Density of evaporating Primordial Black Holes, ICRC 2013

Sensitivity to Q-balls (very preliminary)



- Hypothetical particle - massive condensate of scalar fields formed at end of inflationary period - predicted in supersymmetric theories
- Enormous baryon number ($Q>10^{16}$)
- signal in HAWC: subrelativistic (~220 km/s) particle that dissociate nuclei, producing a series of localized energy deposition (~16 GeV / per interaction)
- 30 microsecond burst of light

Aiming at world-best sensitivity at 1000 mb

Q-ball track direction can be reconstructed if multiple interactions are detected ==> directional dark matter detector

A dedicated Q-ball trigger is already part of the online system

P. Karn et al., Searching for Q-balls with the High Altitude Water Cherenkov Observatory, ICRC 2013

Summary

- HAWC is a new generation wide-field-of-view gamma -ray telescope that starts operations in Mexico
- With a >10000 m^2 effective area, HAWC will provide an unbiased high-resolution (~0.1°) survey of the observable TeV sky, including regions of diffuse emission
- High duty cycle, long exposure and advanced gamma-hadron separation will lead to a world-largest sample of >10 TeV gamma rays
- HAWC is on watch for gamma-ray transients such as GRB and AGN flares and will send alerts to the community
- HAWC science also includes Dark Matter searches and various fundamental physics topics
- HAWC will also study Solar transient events - Forbush decreases and Ground Level Enhancements

Thank you for your attention!

(backup slides follow)