Rencontres du Vietnam
Quy Nhon, Vietnam
August 11-17, 2013

The High Altitude Water Cherenkov Observatory and its first results

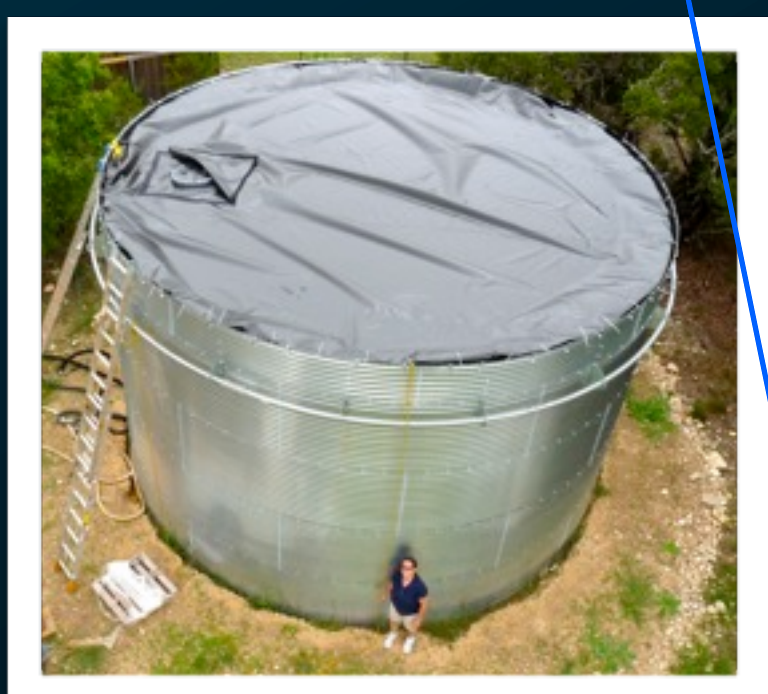
Dmitry Zaborov (Pennsylvania State University)
for the HAWC collaboration

- HAWC
- HAWC science
- First results

HAWC - High Altitude Water Cherenkov Observatory

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

Collaboration of ~100 scientists from US & Mexico



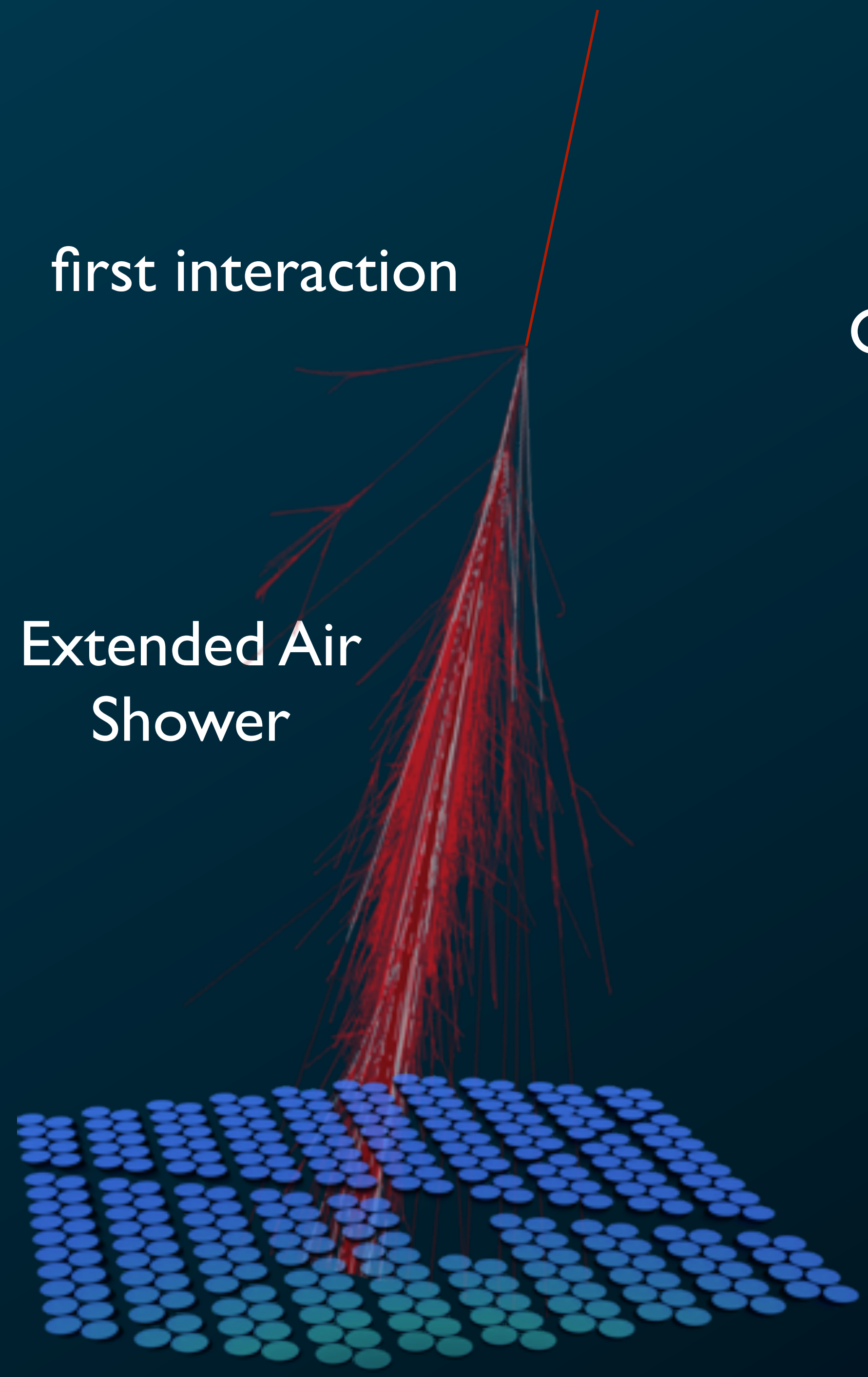
7.3 m dia x 4.5 m tall

Operation principle

gamma ray or cosmic ray

first interaction

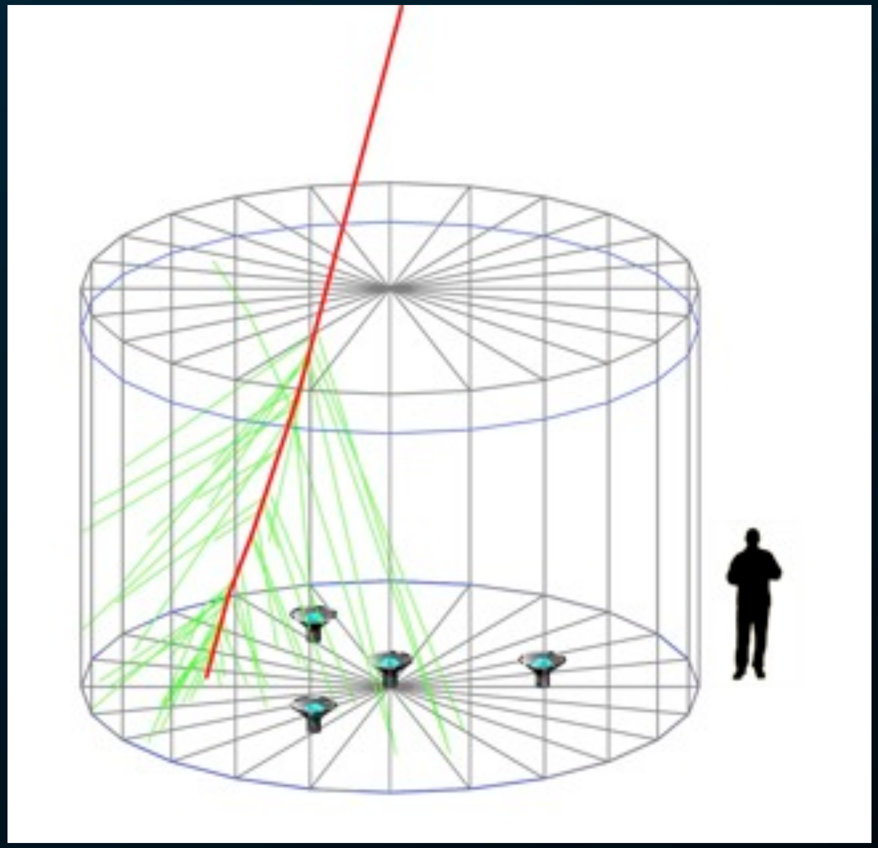
Extended Air Shower



secondary particles reach ground level

charged particles produce Cherenkov light in HAWC tanks

light is detected by photomultiplier tubes (PMT)



4 upward looking PMTs per tank: three 8” PMTs (Hamamatsu R5912, re-used from Milagro) and one high quantum efficiency 10” PMT in the center (Hamamatsu R7081-MOD)

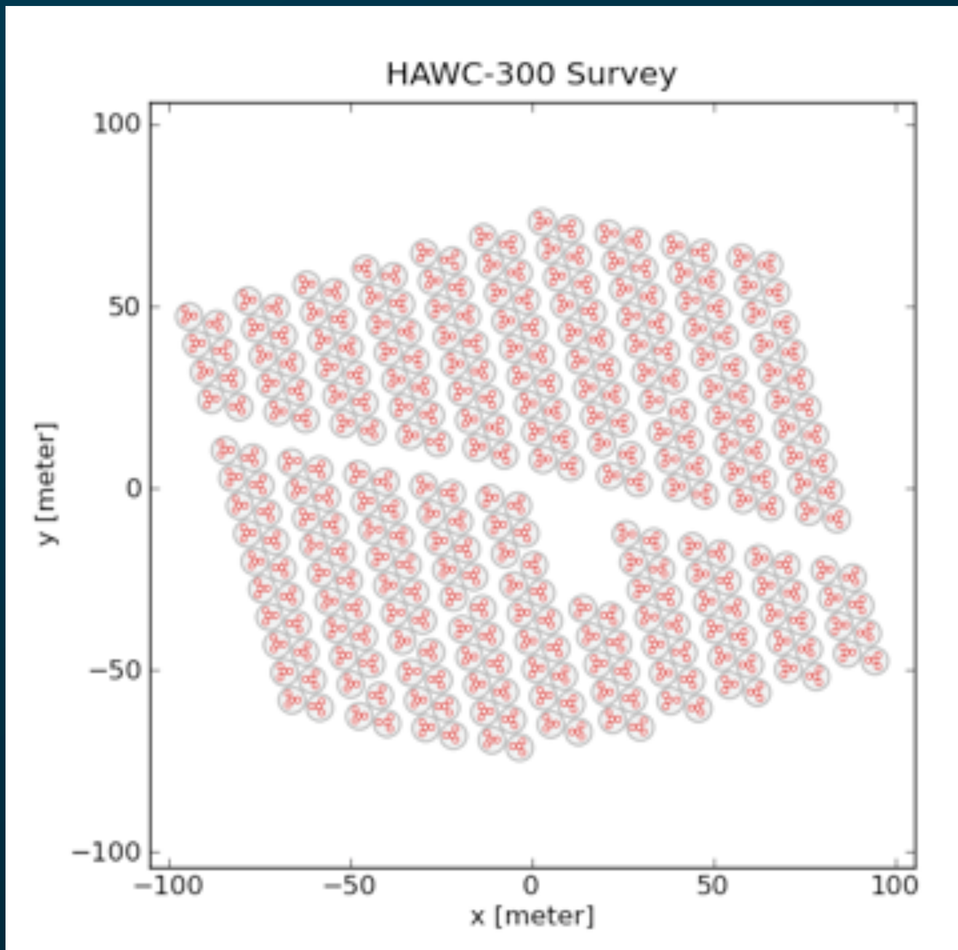
Physics goals

- Particle acceleration in astrophysical sources
  - What astrophysical sources accelerate particles?
  - How do astrophysical sources accelerate particles?
  - What new high energy physics can we learn from astrophysics?
- Solar and galactic cosmic rays
  - Forbush Decreases, Solar Energetic Particles
  - Cosmic Ray anisotropy
  - Diffuse emission from the Galactic plane and other extended sources
- Search for Dark Matter (WIMPs) and other Physics Beyond the Standard Model (Q-balls, primordial black holes, Lorentz invariance violation, ...)

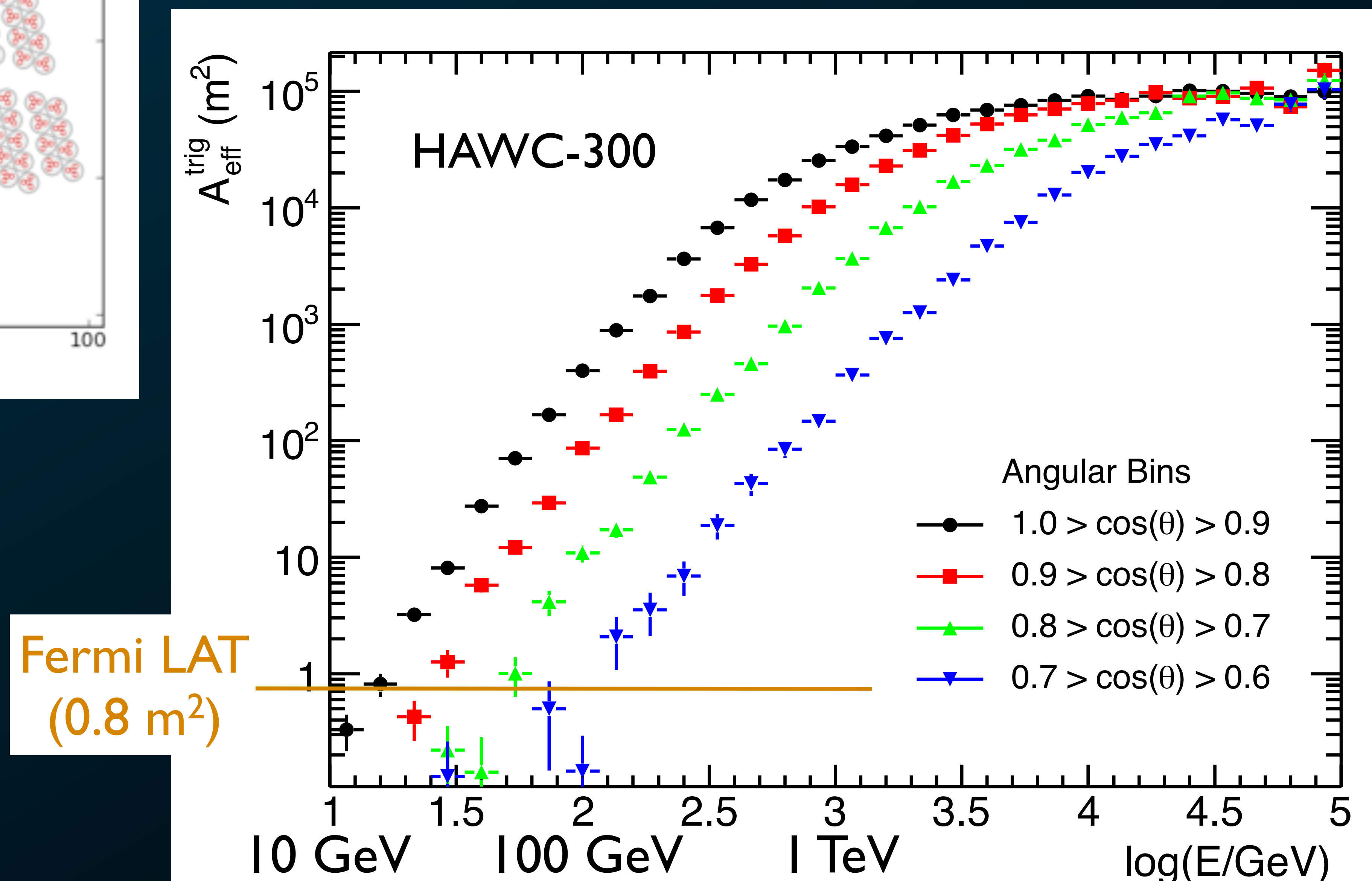

Crab, Chandra


Artist's Conception (NASA)

Detector layout and effective area



- 300 water Cherenkov detectors (“tanks”)
- ~20,000 m² area
- >60% active Cherenkov volume

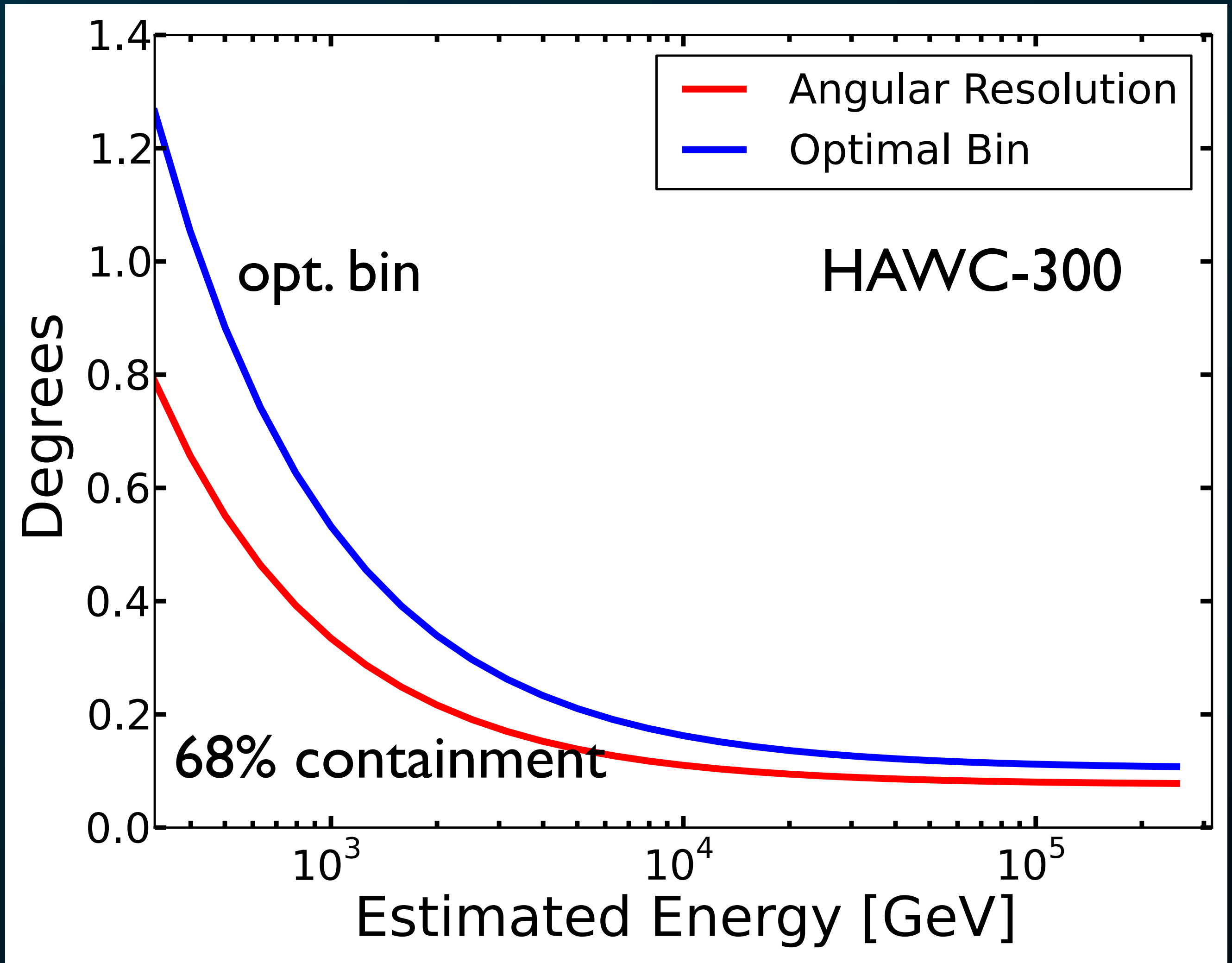


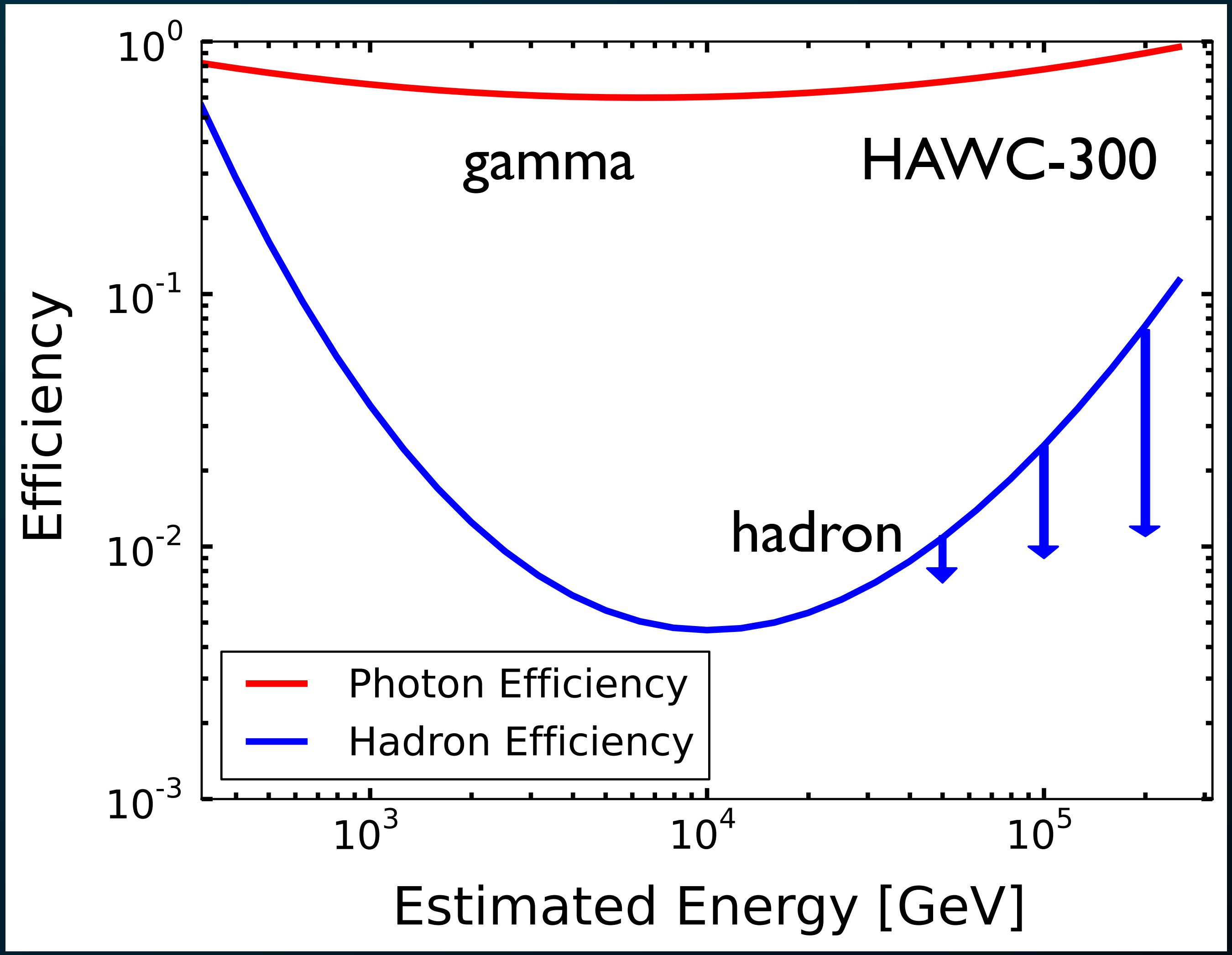
Nhit > 30; Angular error < 1.1°; No hadron rejection cut applied

- Effective area up to ~10^5 m² in multi-TeV regime
- Energy threshold ~30 GeV
- >100 m² at 100 GeV

Angular resolution and gamma-hadron separation

- Reconstruct shower core position from hit amplitudes and shower plane / direction from hit timing
- Angular resolution up to 0.1° at TeV energies

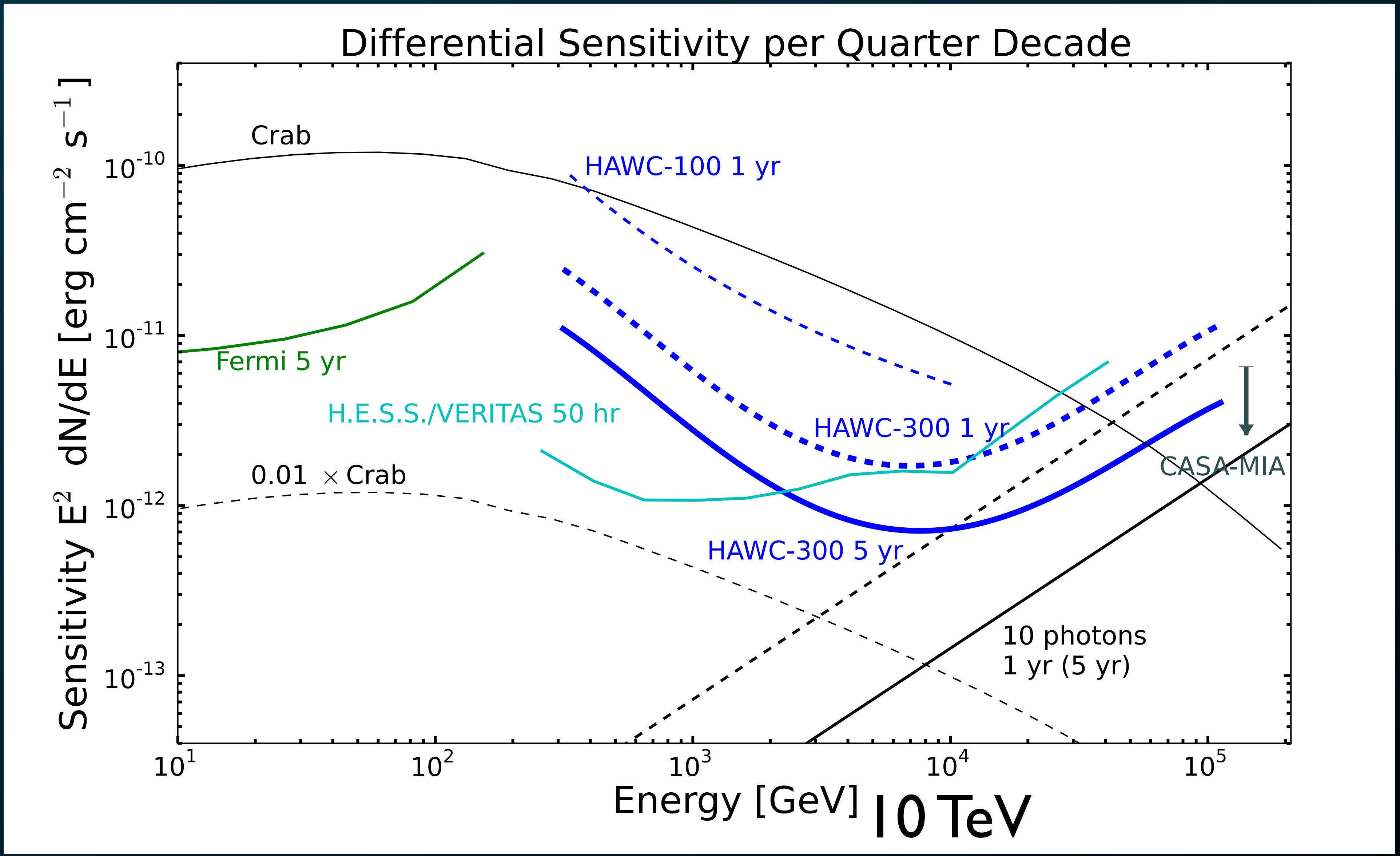




- Gamma-hadron separation is based on shower lateral size, clumpiness, and high amplitude pulses produced by muons
- > 100-fold hadron rejection while retaining >50% of photon-induced events

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



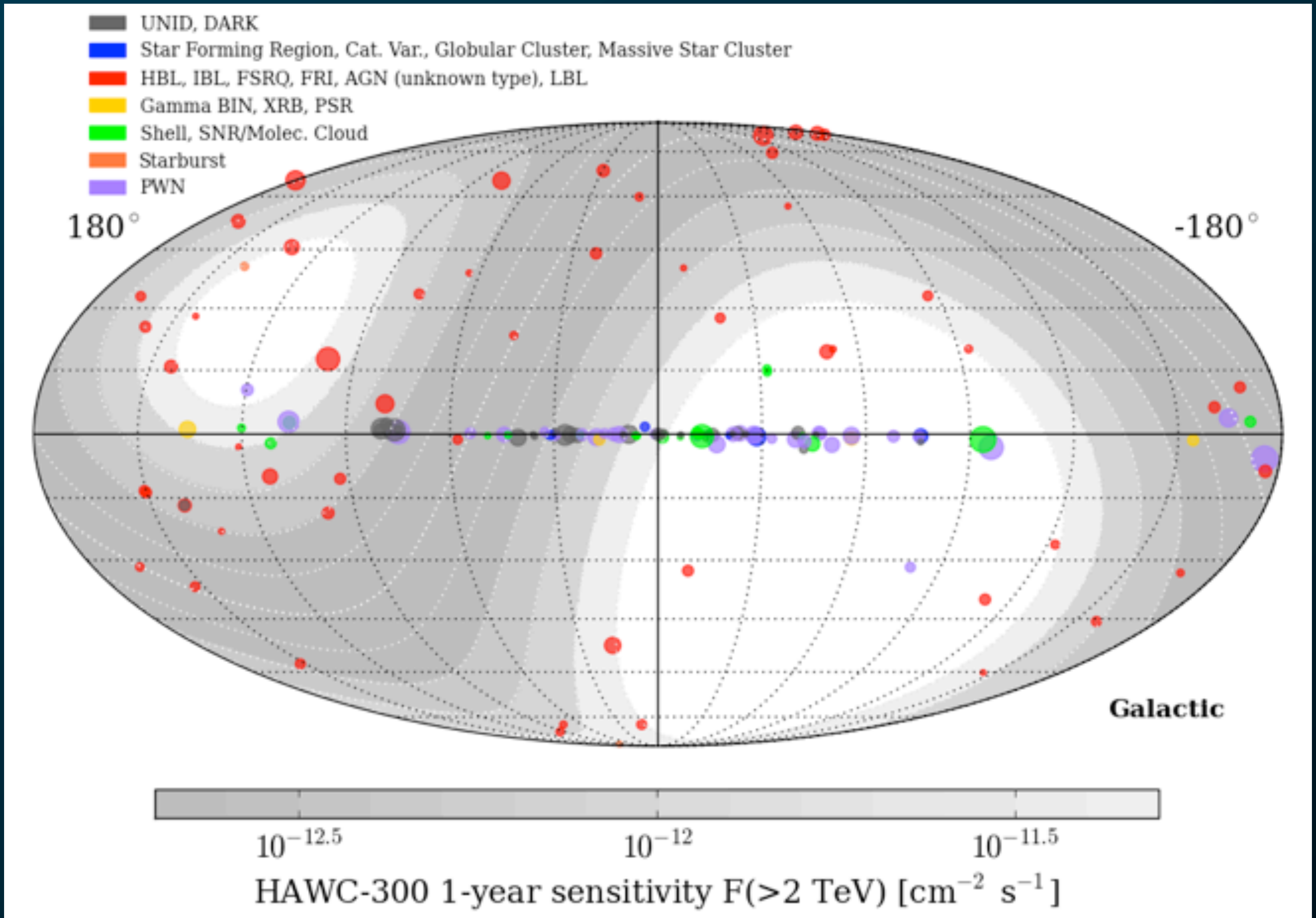
HAWC source transit 15° off zenith (?)

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

The world's most sensitive wide-field-of-view high energy gamma-ray instrument

Sensitivity of the High Altitude Water Cherenkov Detector to Sources of Multi-TeV Gamma Rays, by HAWC collaboration, Accepted to Astropart. Phys.

Observable sky



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

instantaneous filed of view ~ 2 sr

Daily observation of ~8 sr (2/3 of the sky)

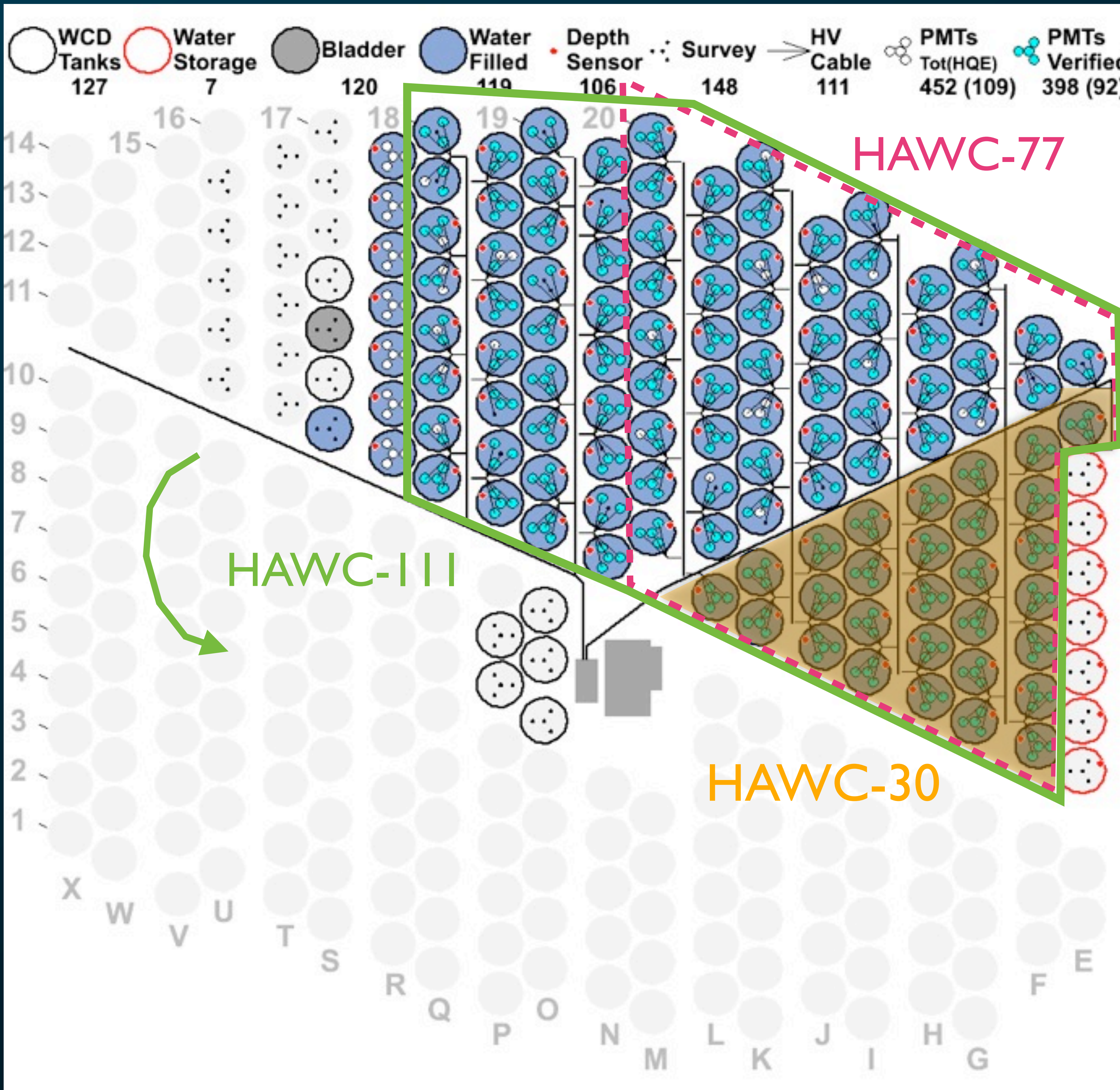
50 mCrab survey in 1 yr

* sensitivity contours are for E^{-2} spectrum

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)

HAWC construction progress



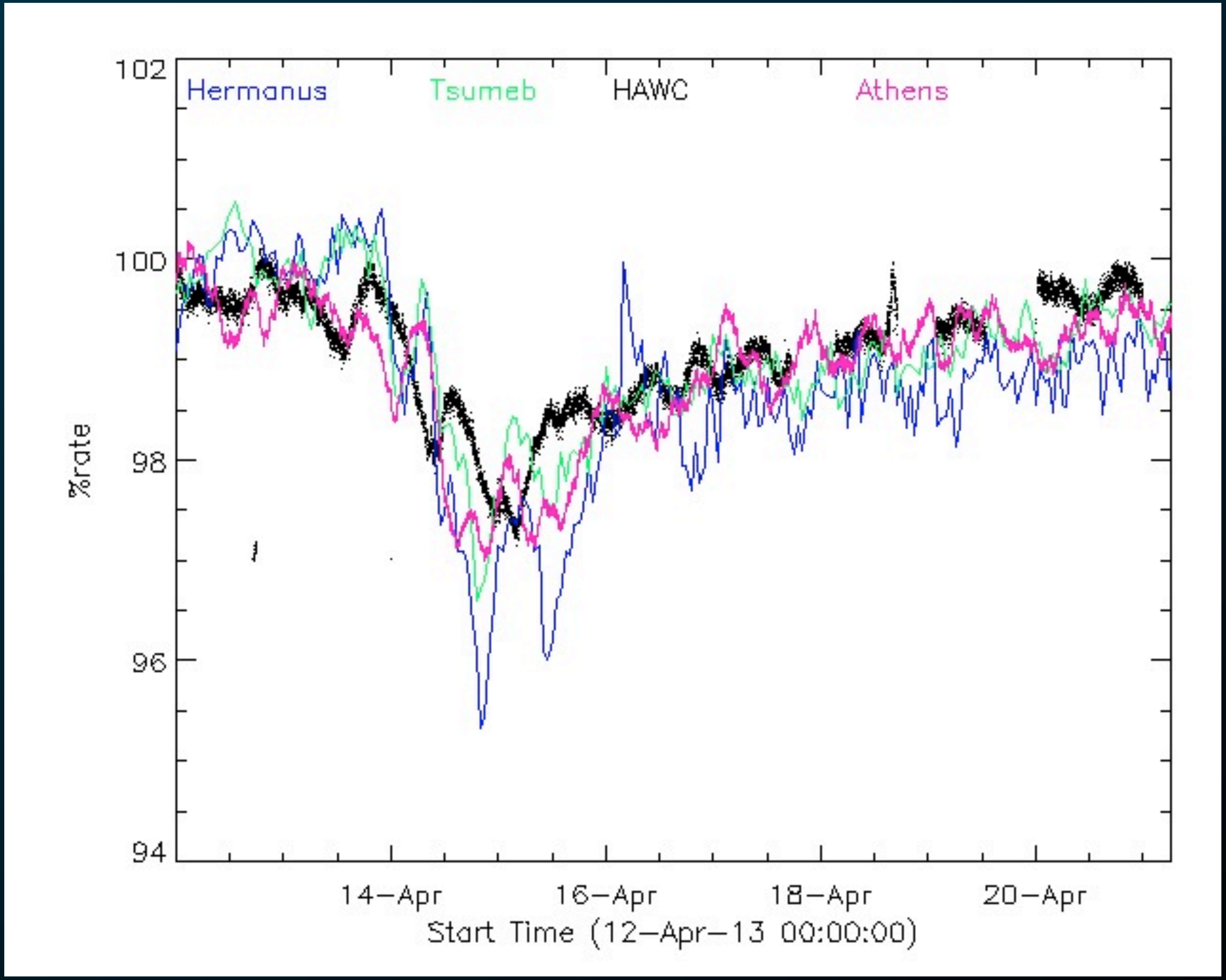
- Sep 2012: first 29 tanks completed; regular data taking begins
- January-March 2013: high QE PMTs added
- mid-May: 77 tanks operational
- June: >90% uptime reached (automatic running)
- Now: operating with 111 tanks / 400 PMTs
- summer 2014: expect complete detector

April 2013 Forbush decrease

HAWC will routinely observe Forbush Decreases (the effect of Coronal Mass Ejections on galactic cosmic rays)

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

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

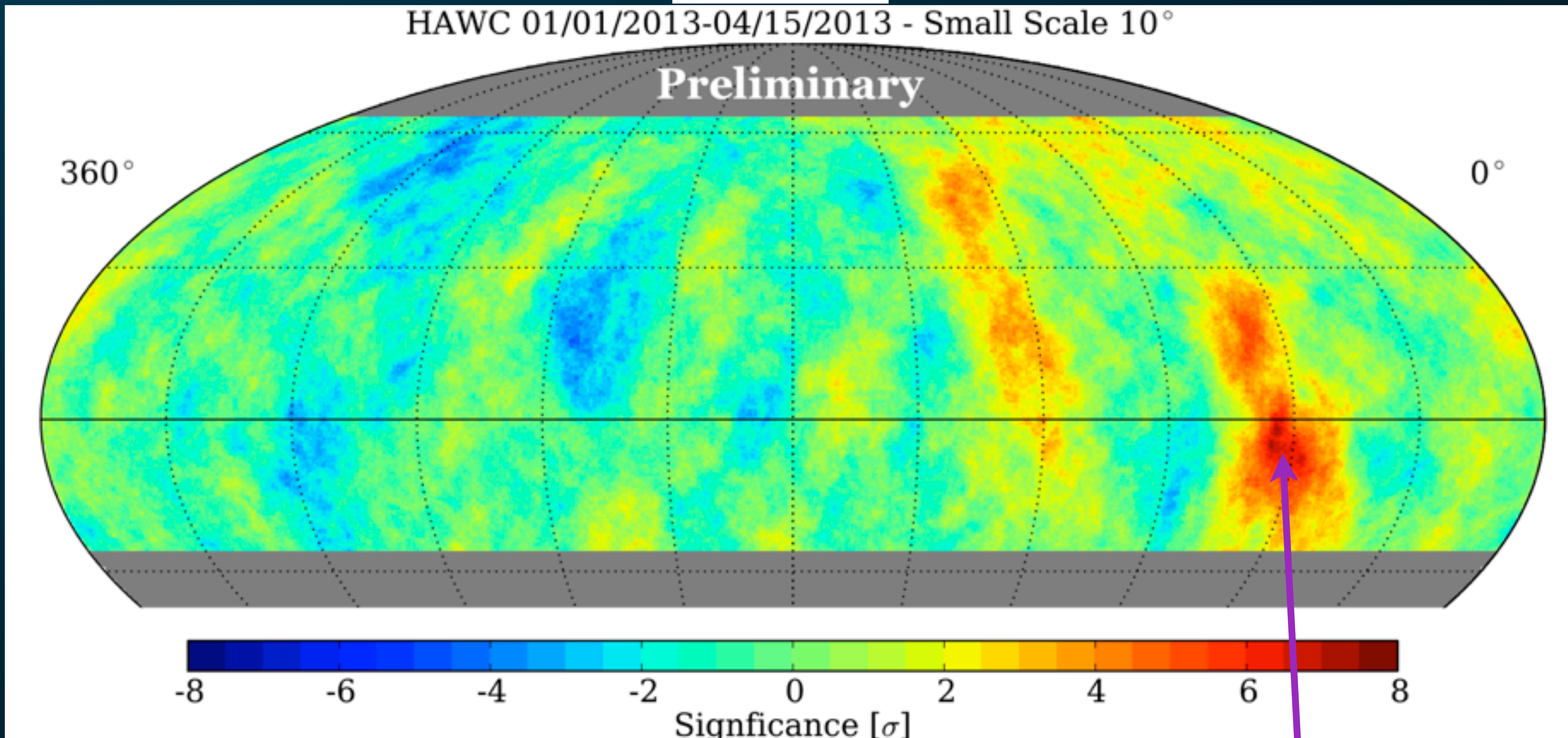


each channel was corrected for barometric pressure and temperature variations

A. Lara et al., HAWC and Solar Energetic Transient Events, ICRC 2013

Small scale Cosmic Ray anisotropy

95 days live



> 5 sigma excess region

2 hr integration window, 10 deg smoothing applied
median energy the event sample ~ 2 TeV

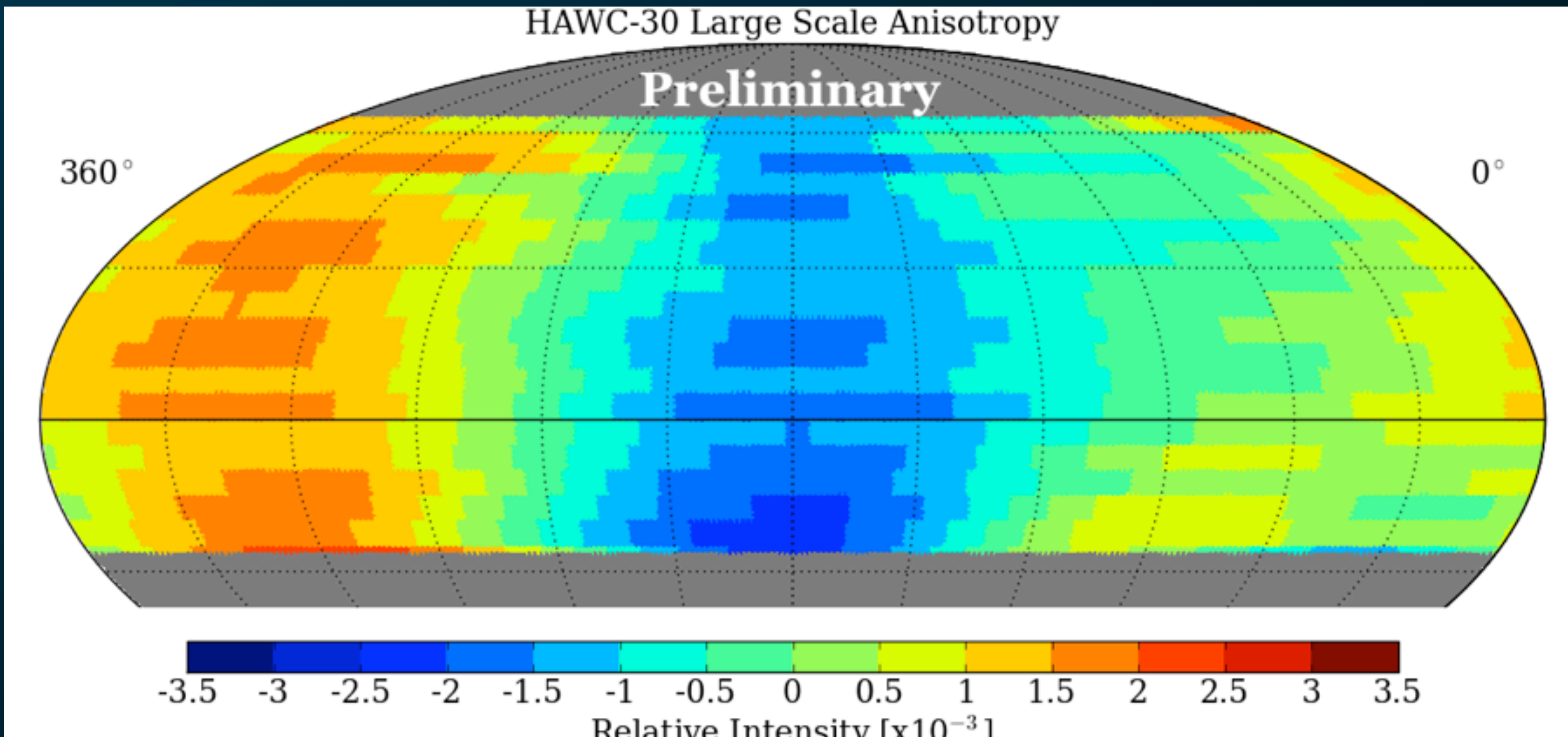
A confirmation of CR anisotropy regions discovered by Milagro
(PRL 101:221101, 2008)

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

Large scale cosmic ray anisotropy

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

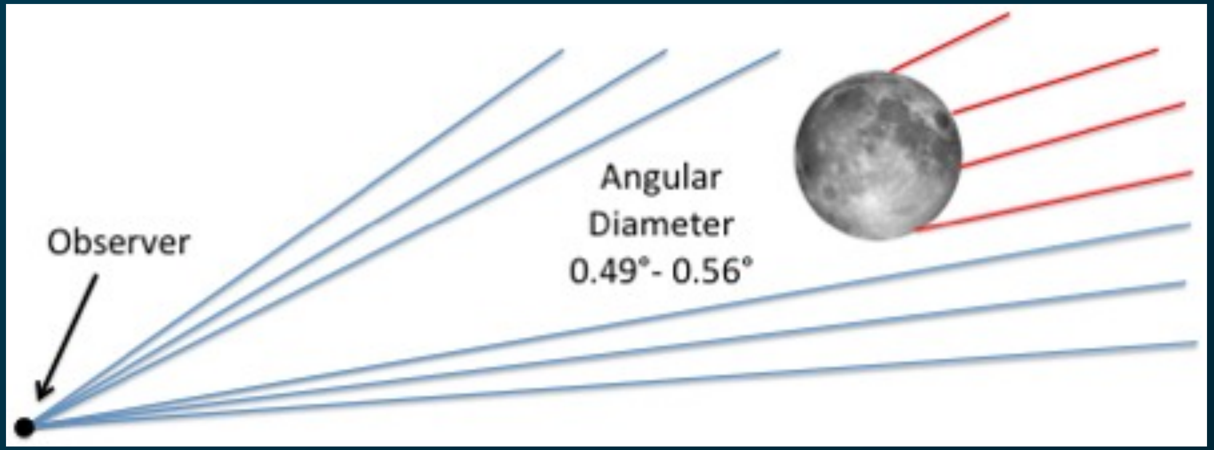
Note: not a sky map, but a series of 3-term harmonic fits within 18 declination bands



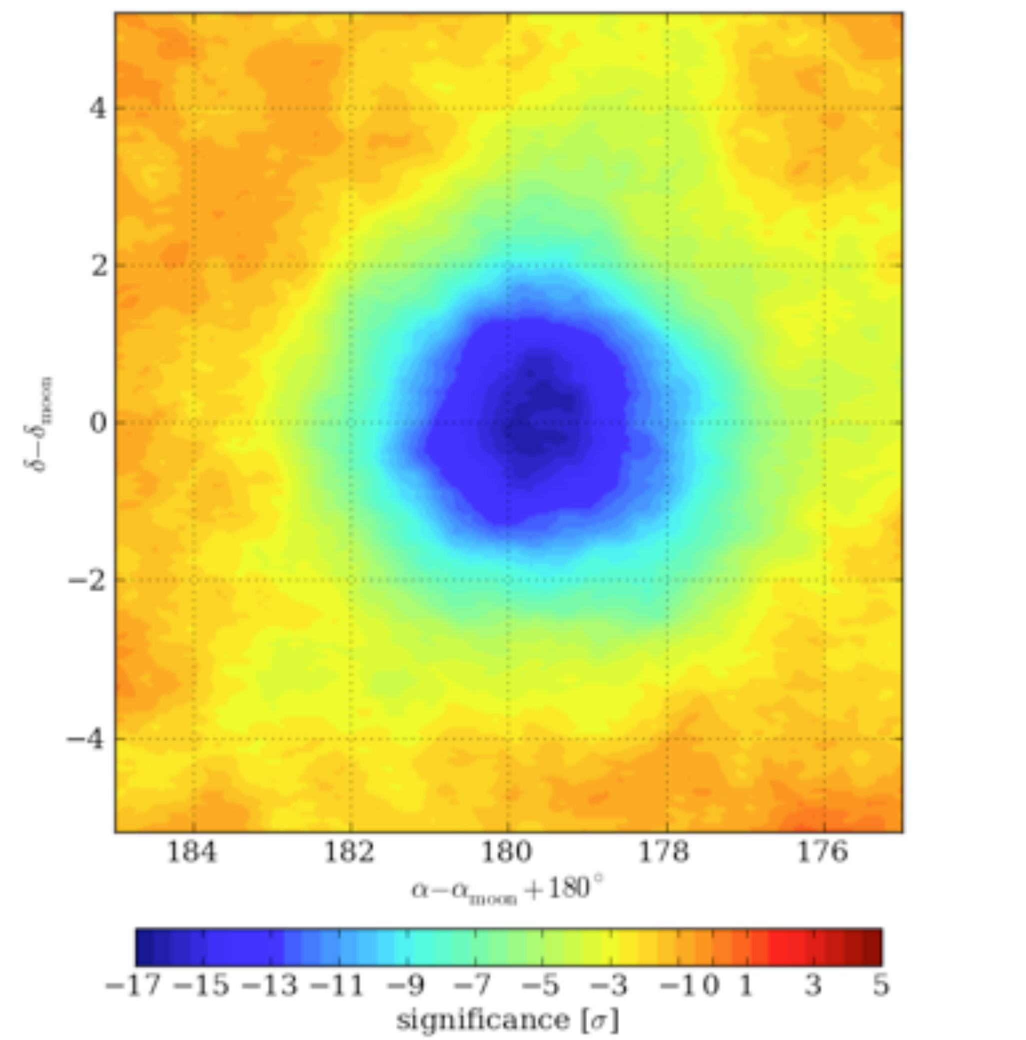
Using the forward-backward technique (A.A. Abdo et al., Astrophys. J., 2009, 698: 2121)

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

Moon shadow



Oct 22, 2012 - April 11, 2013 (131 day live)



7 billion shower events (cut at > 31 PMTs hit)

2 degree smoothing used (HAWC-30 angular resolution is ~1.2 deg at 3 TeV)

observed peak significance: -15.6 σ

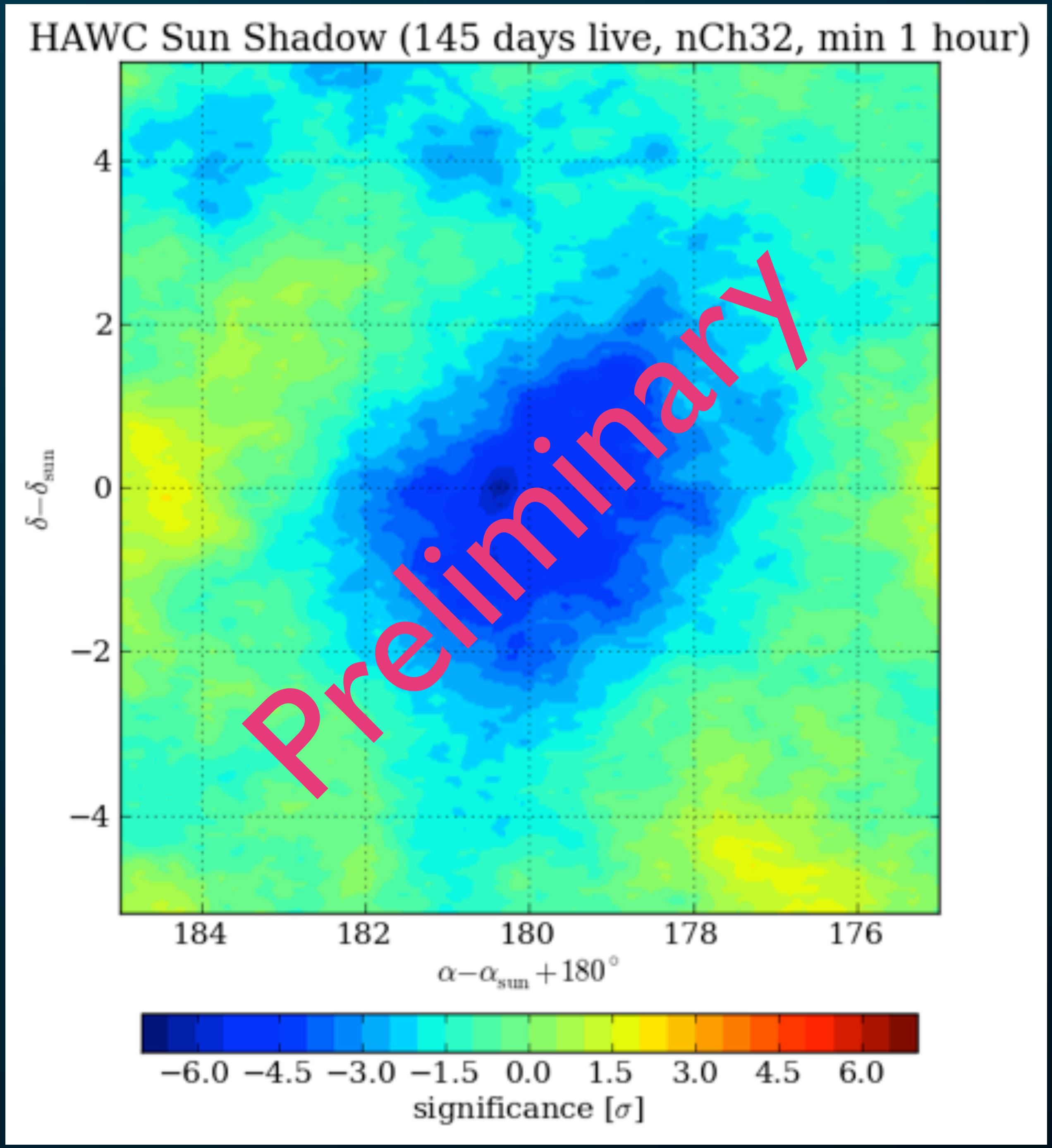
centered at 179.6 ± 0.1, 0.0 ± 0.1 deg (moon-centered equatorial coordinate system)

blocked flux in a 5 degree radius circle is 0.255% (0.25 % expected)

Shadow RMS width is 1.6 ± 0.1 deg (consistent with expectation)

D. Fiorino, et al., Observation of the Moon Shadow and Characterization of the Point Response of HAWC-30, ICRC 2013

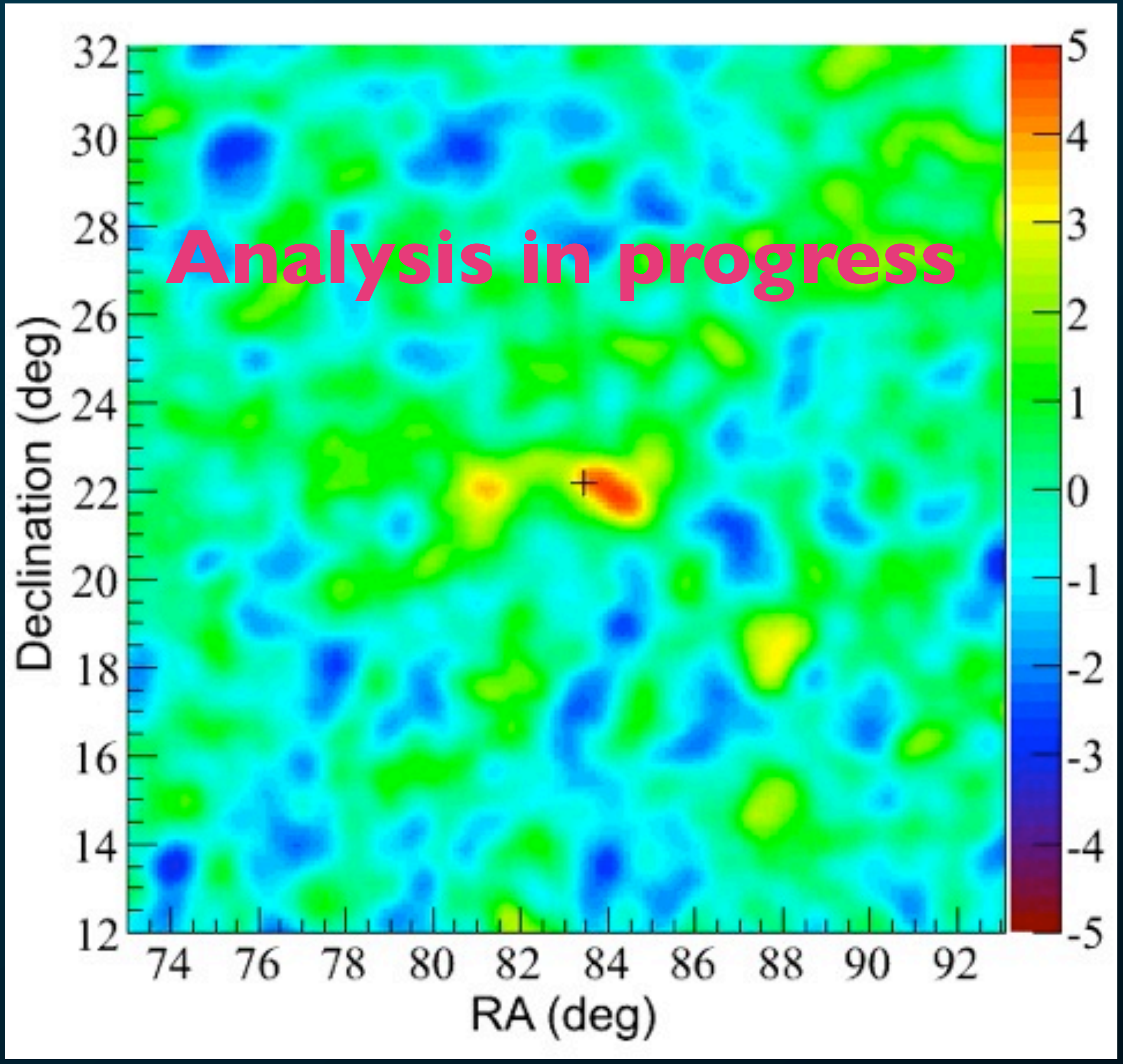
Sun shadow



- Analysis in progress (similar to the moon shadow analysis)
- 8.5 billion events
- Observed significance: -6.4 σ
- Consistent with expectations for near the Solar maximum

Work by D. Fiorino and Segev BenZvi (UW-Madison)

First look at the Crab



Crab (Dec +22 deg) transits near zenith and is observed 5-6 hr per day

A subset of data from HAWC-95 shown (online reconstruction using 95 tanks)

4.8 σ in the vicinity of the Crab position

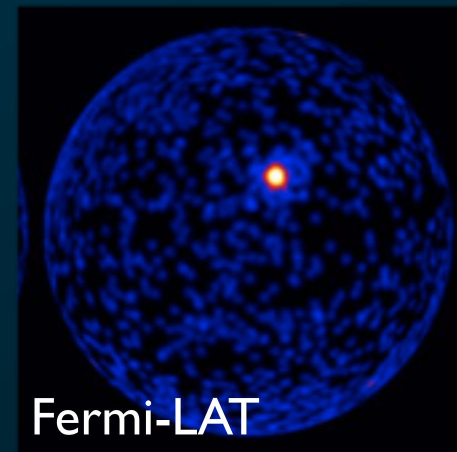
Full calibrations are still to be incorporated

Data show evidence of gamma rays. Further analysis in progress

For analysis details see J. Braun, B. Baughman et al., HAWC Observations of the Crab Nebula, ICRC 2013

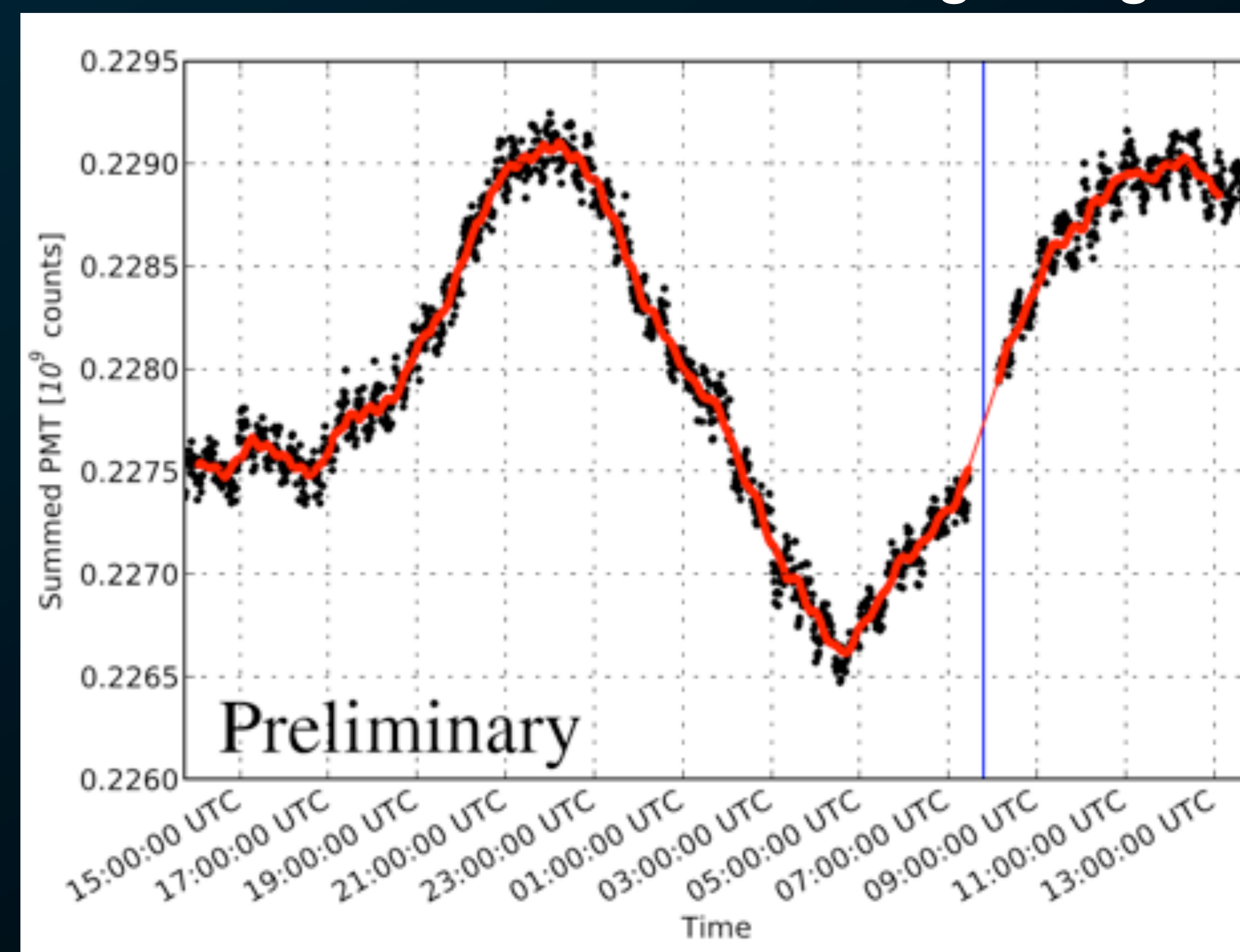
GRB 130427A

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



?

summed PMT rate and moving average

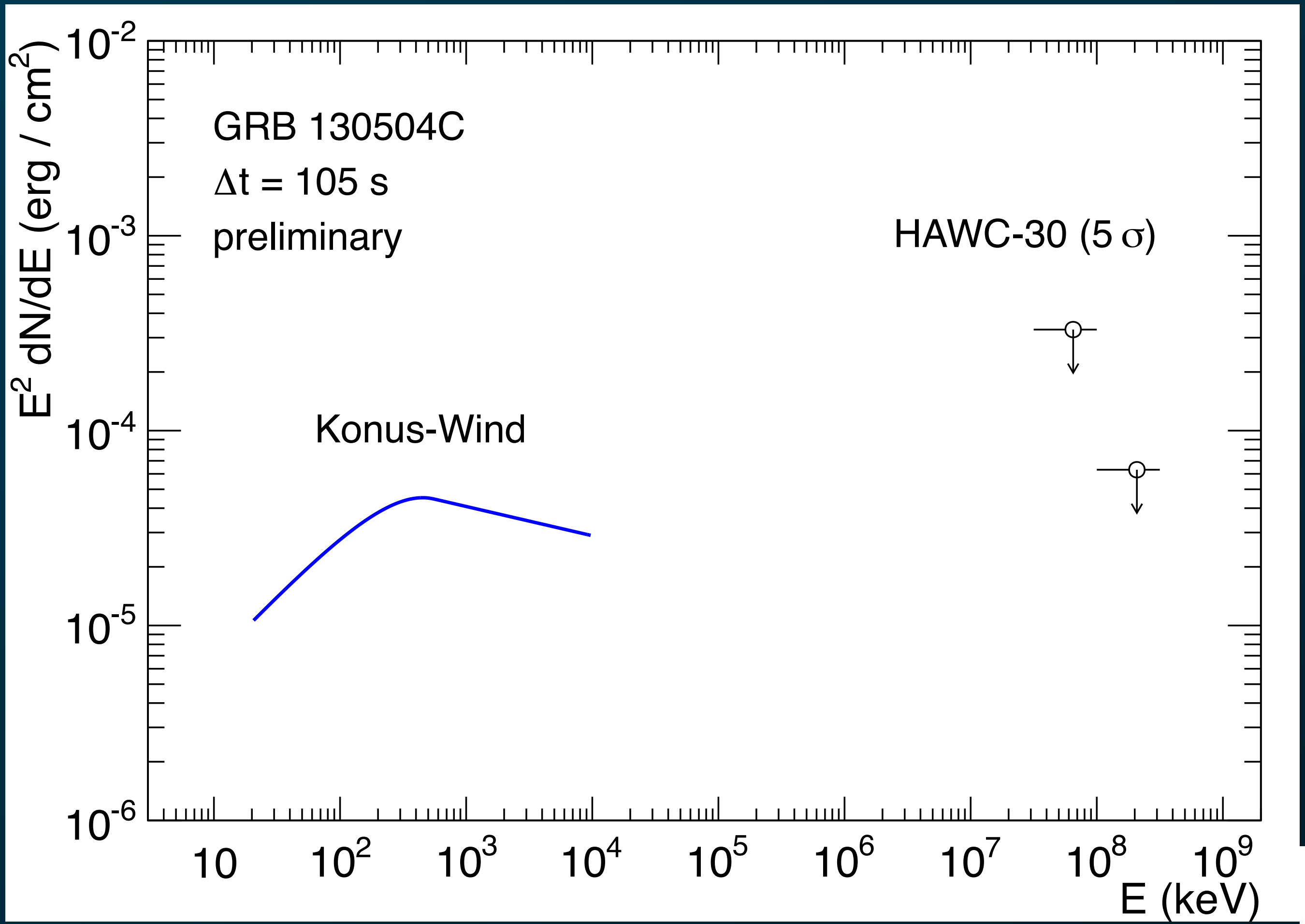


6 different time windows examined, no excess found (GCN circular 14549)

would be seen at ~5σ if it happened near zenith

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

GRB 130504C

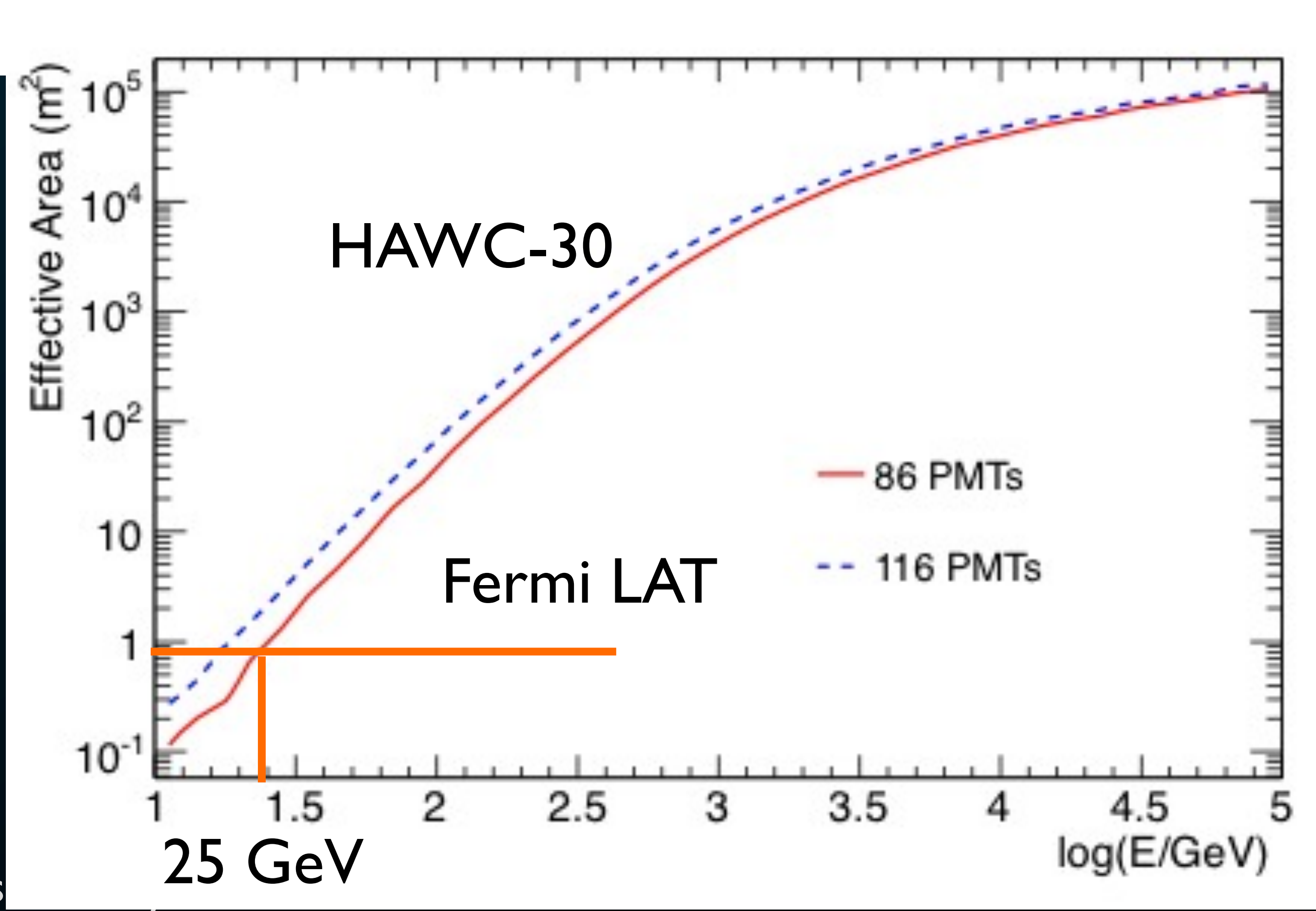


- A high fluence GRB detected by Fermi LAT (also by Fermi GBM and Swift XRT)
- LAT detected > 70 photons above 100 MeV (GCN circular 14574)
- highest energy LAT photon ~ 5 GeV
- Zenith angle at HAWC: 30°
- HAWC was taking data with 28 tanks
- No excess observed in HAWC

* HAWC limit shows the flux level corresponding to 50% probability of 5 σ 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

K. Sparks et al., Search for high energy emission from GRBs with the HAWC Observatory, ICRC 2013
Also see Astropart. Phys. 35 (2012) 641-650.

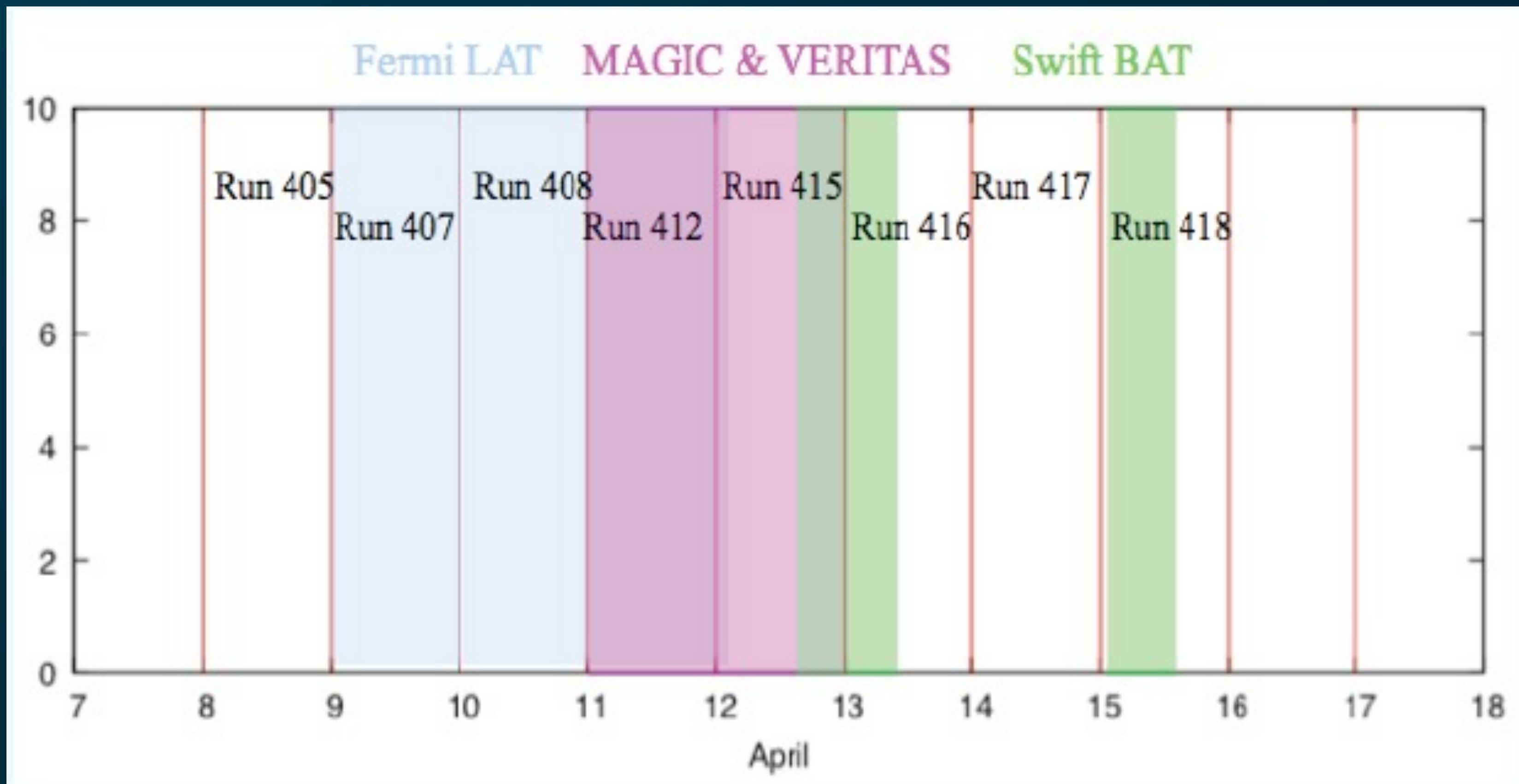


Summary

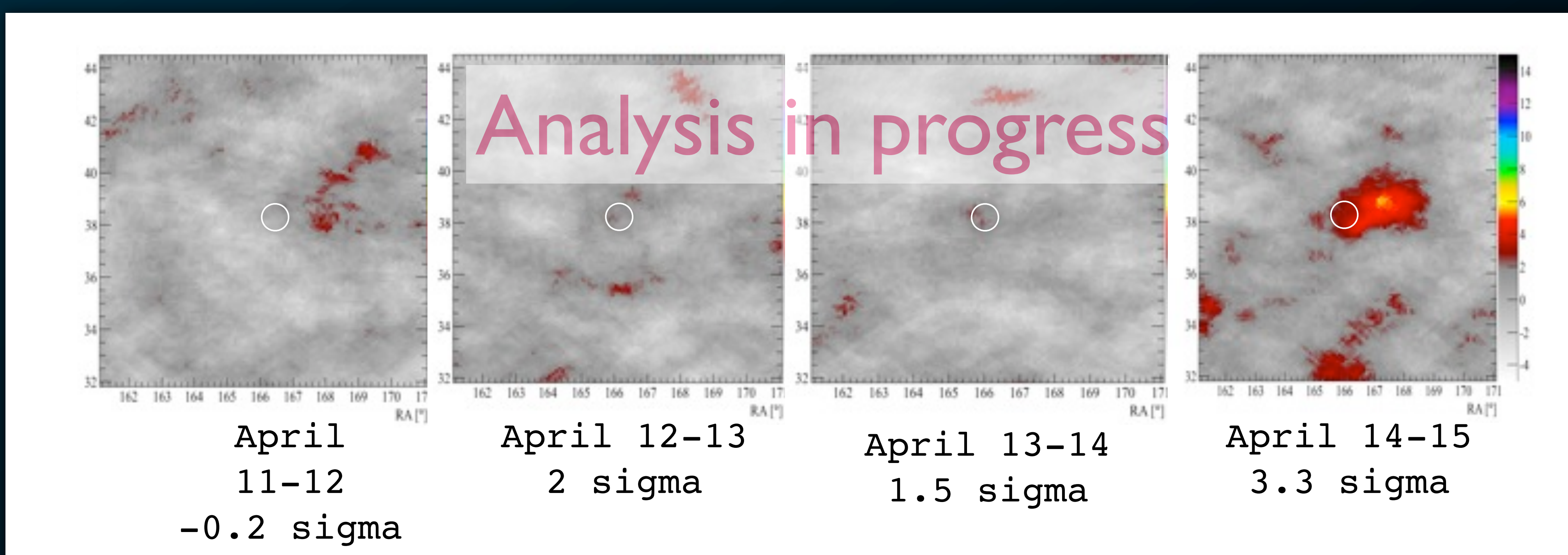
- HAWC is a new generation wide-field-of-view gamma -ray telescope
- With a >10000 m^2 effective area, HAWC will provide an unbiased high resolution (~0.1°) survey of ~2/3 of the TeV sky, including regions of diffuse emission and large extended sources
- High duty cycle, long exposure and advanced gamma-hadron 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 searches for Dark Matter, Q-balls, primordial black holes, Lorentz invariance violation and more
- HAWC will also study Solar transient events - Forbush decreases and ground level enhancements


Thank you for your attention!
(backup slides follow)

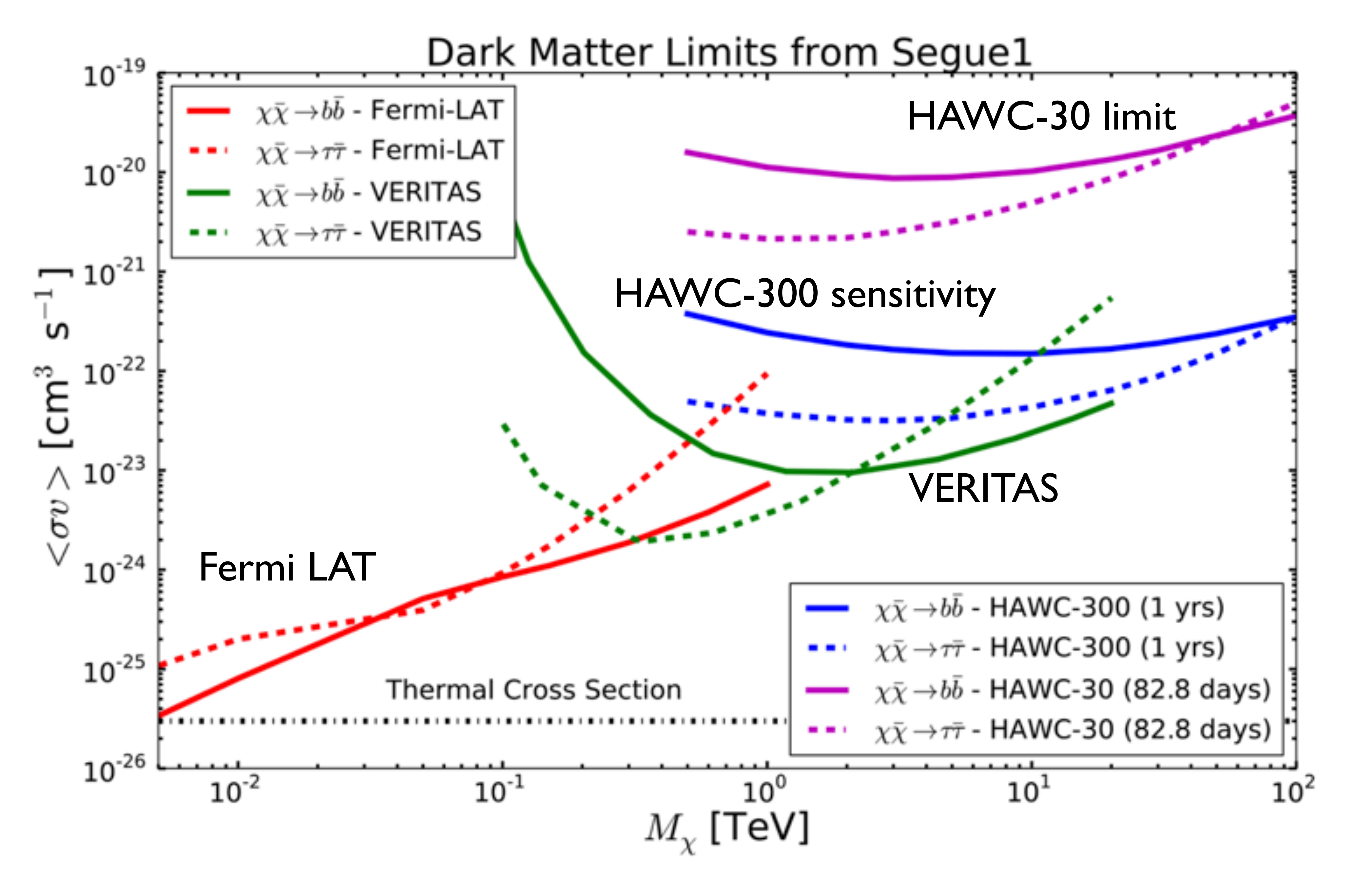
Mrk 421 flare - April 2013



- Brightest known flare from Mk 421
- up to 10 Crab
- Seen by NuSTAR, SWIFT, Fermi, VERITAS, MAGIC
- HAWC was taking data



Limits on Segue I Dark Matter

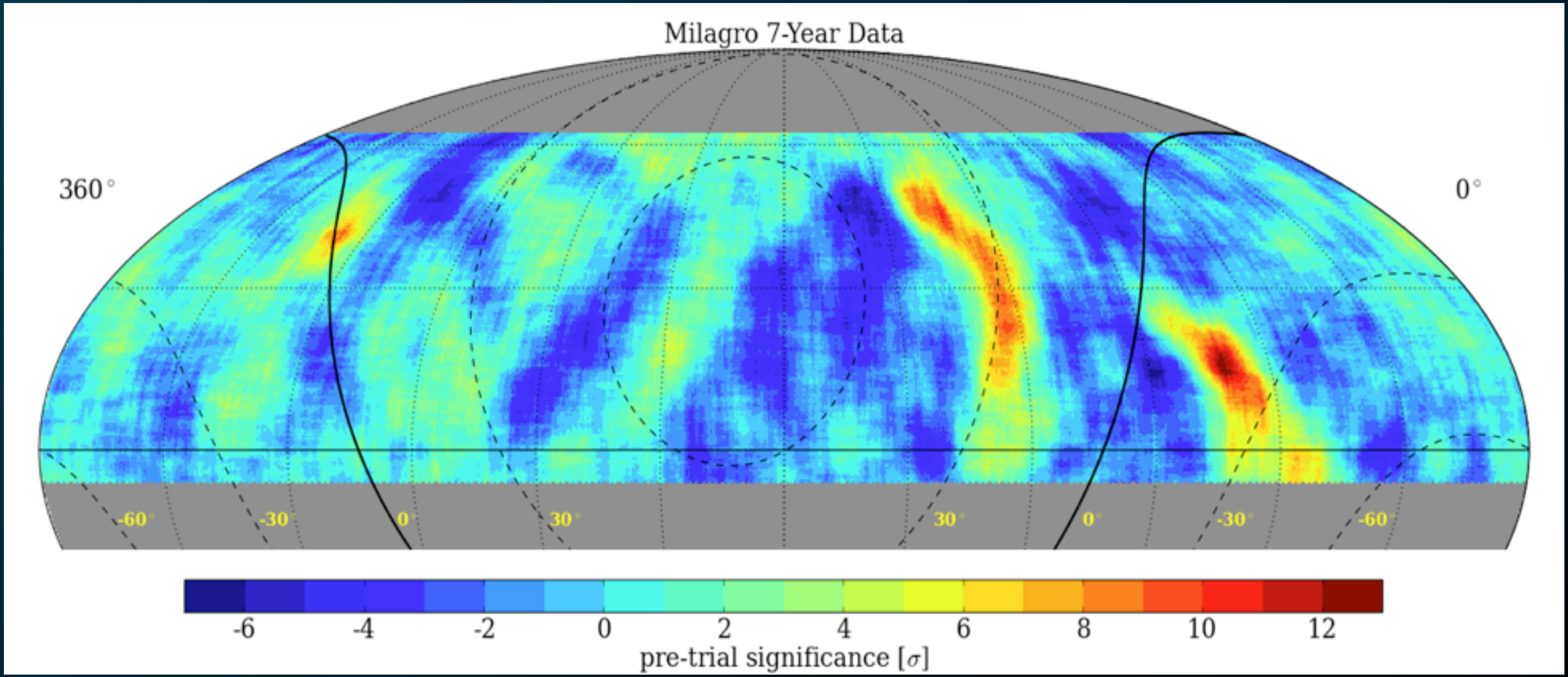


HAWC-30 provides best limits available above 20 TeV

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

Milagro CR anysitropy

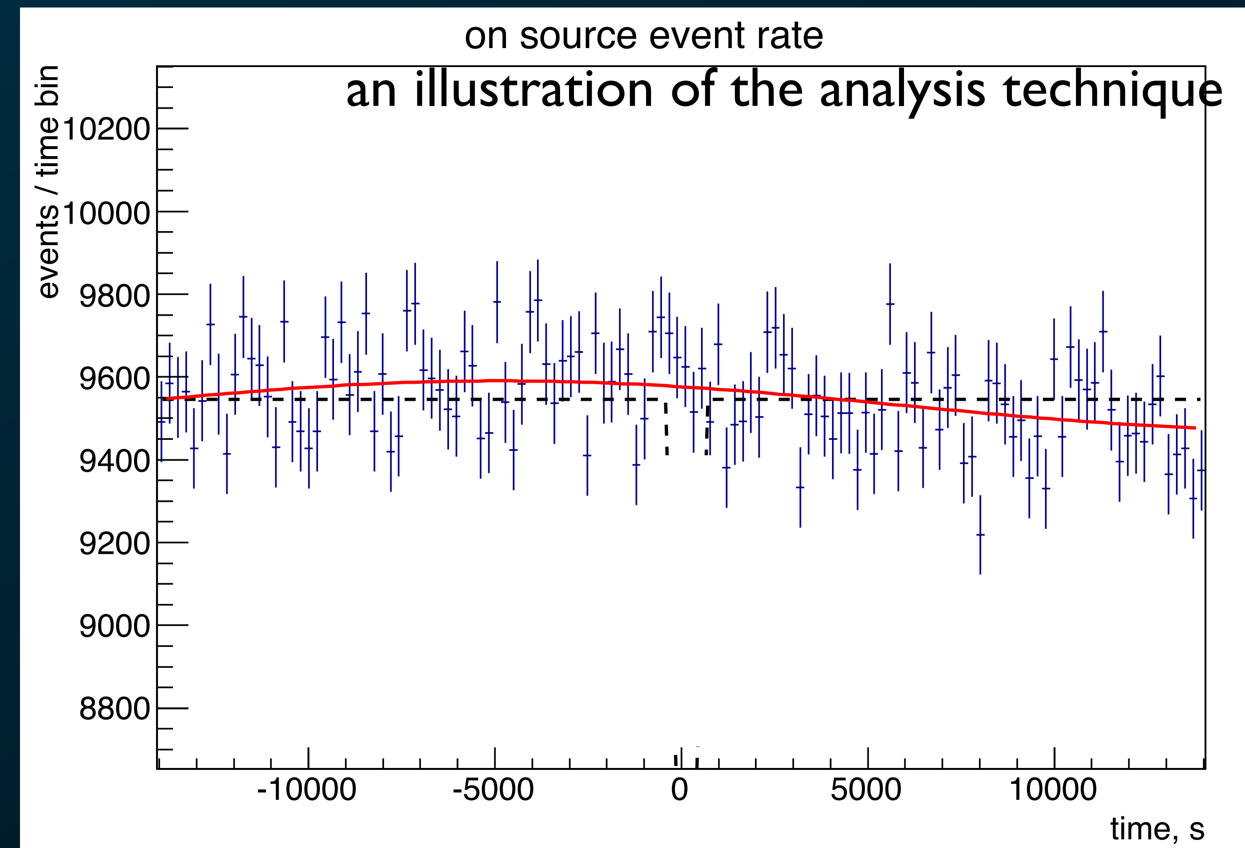
median energy ~ 10 TeV

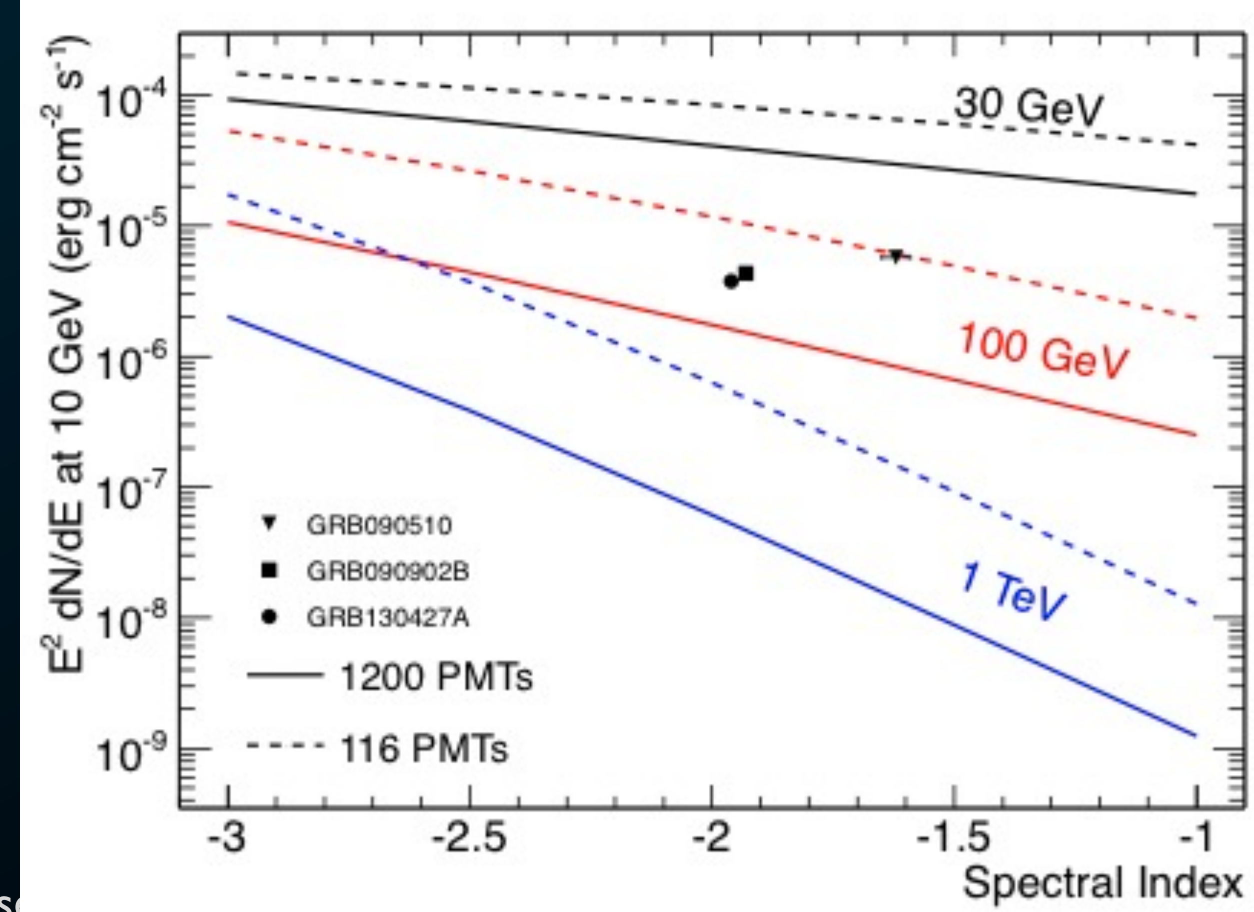


HAWC sees the same regions of excess (Milagro regions A and B)

GRB analysis using air shower data

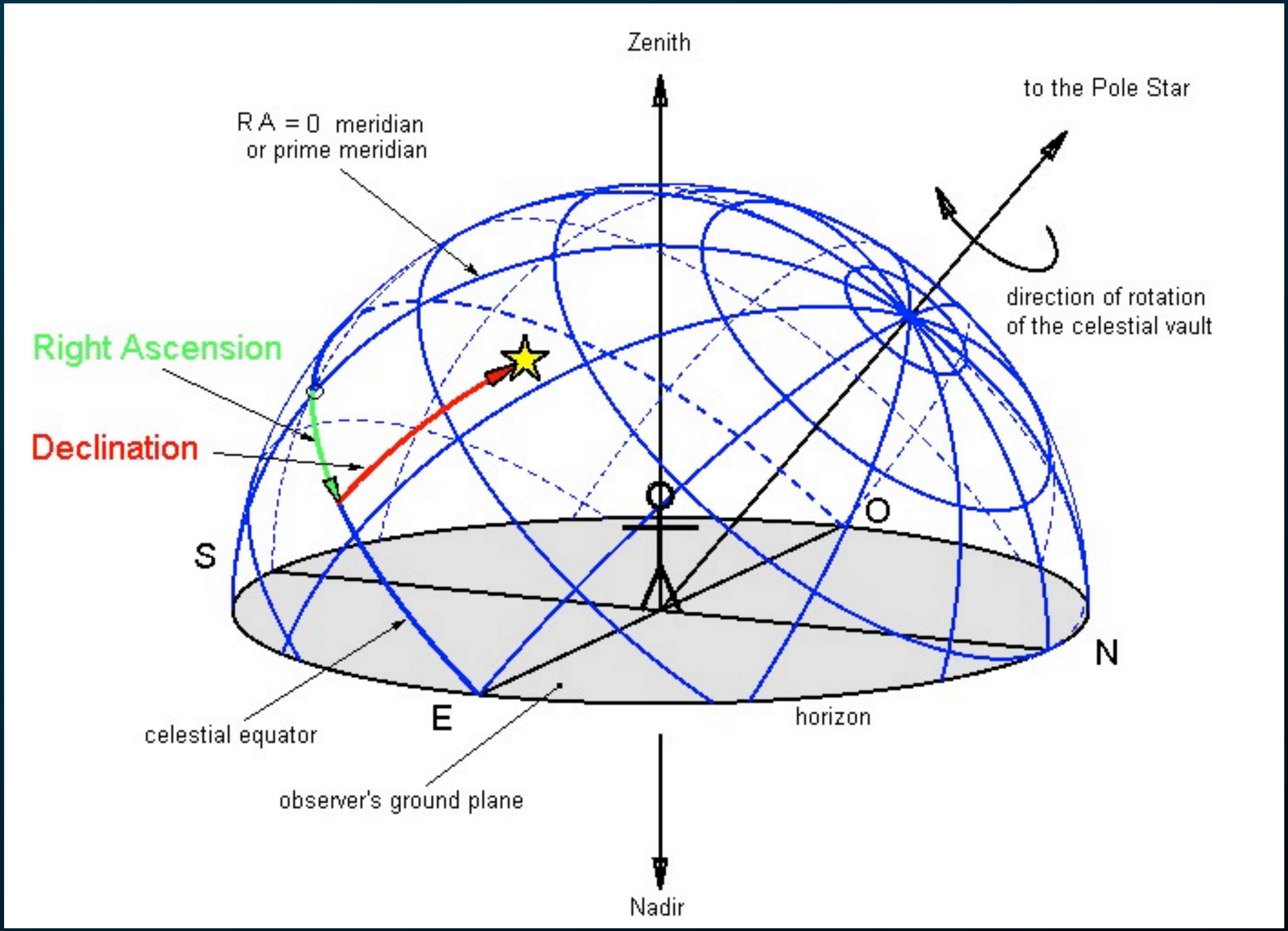
- Triggered search using Fermi GBM and Swift catalogs - 12 GRBs in HAWC FoV analyzed
- 4° angular bin radius
- Time windows: T90 and 3×T90
- no gamma-hadron separation
- Estimate background from off-time data
- Count events in search bin
- Keep blind if within 5 sigma from the background estimate
- a more sensitive likelihood analysis is being developed





HAWC-30 is ~10x less sensitive than HAWC-300

Background estimation



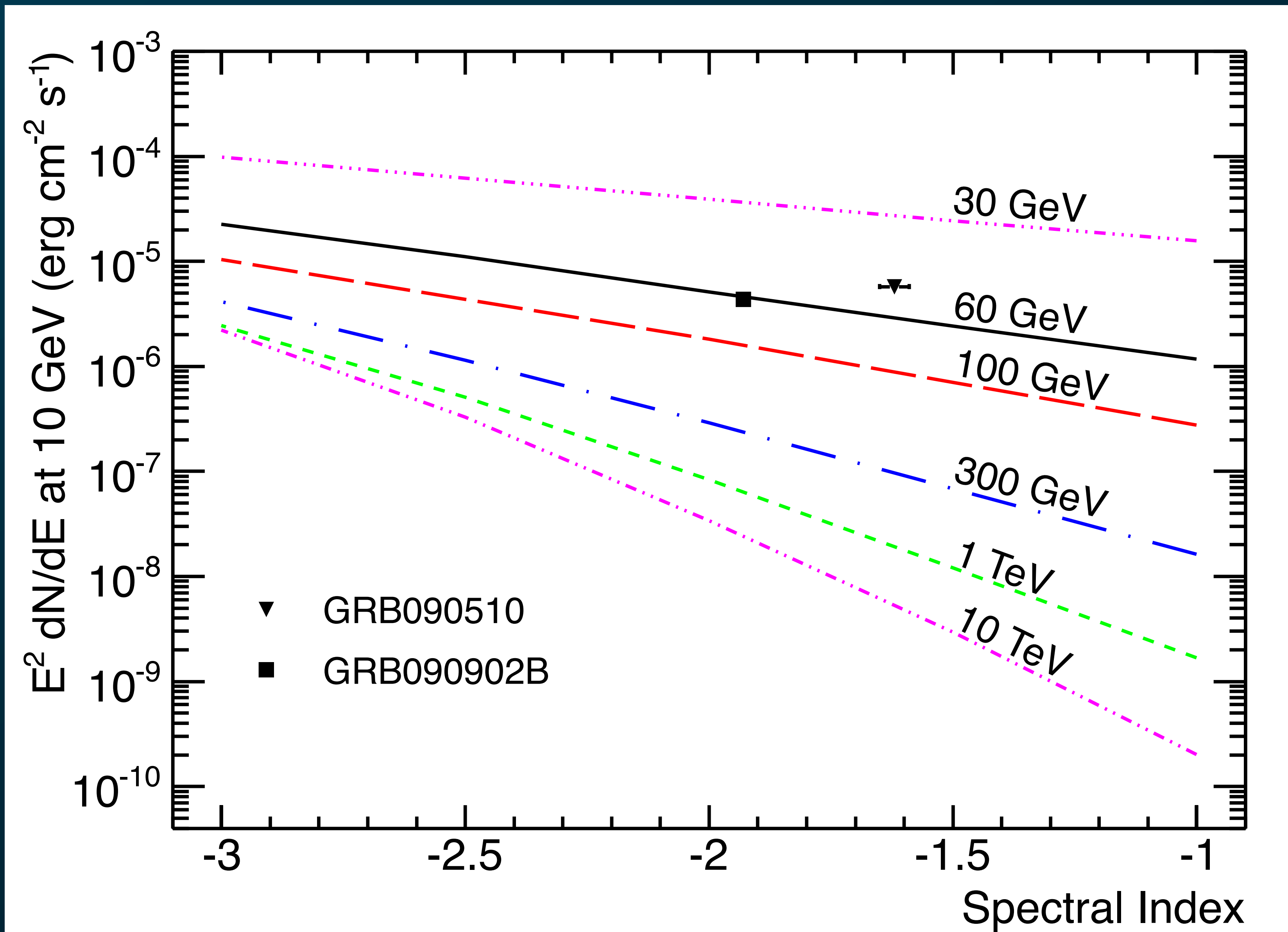
During time interval (0,T) follow the source at RA, Dec

During time interval (T, 2T) follow imaginary source at RA+T, Dec

Due to difference between solar day and

time interval of 60 s corresponds to 60 * 24 / 23.9344699 = 60.0164 angular seconds

Sensitivity to transients (air shower analysis)



Simulated GRB:
T = 1 s
zenith = 20 deg

Power law spectrum
with Heaviside cutoff

The cutoff is intended to mimic either an intrinsic or an EBL absorption cutoff

trigger: Nhit > 30

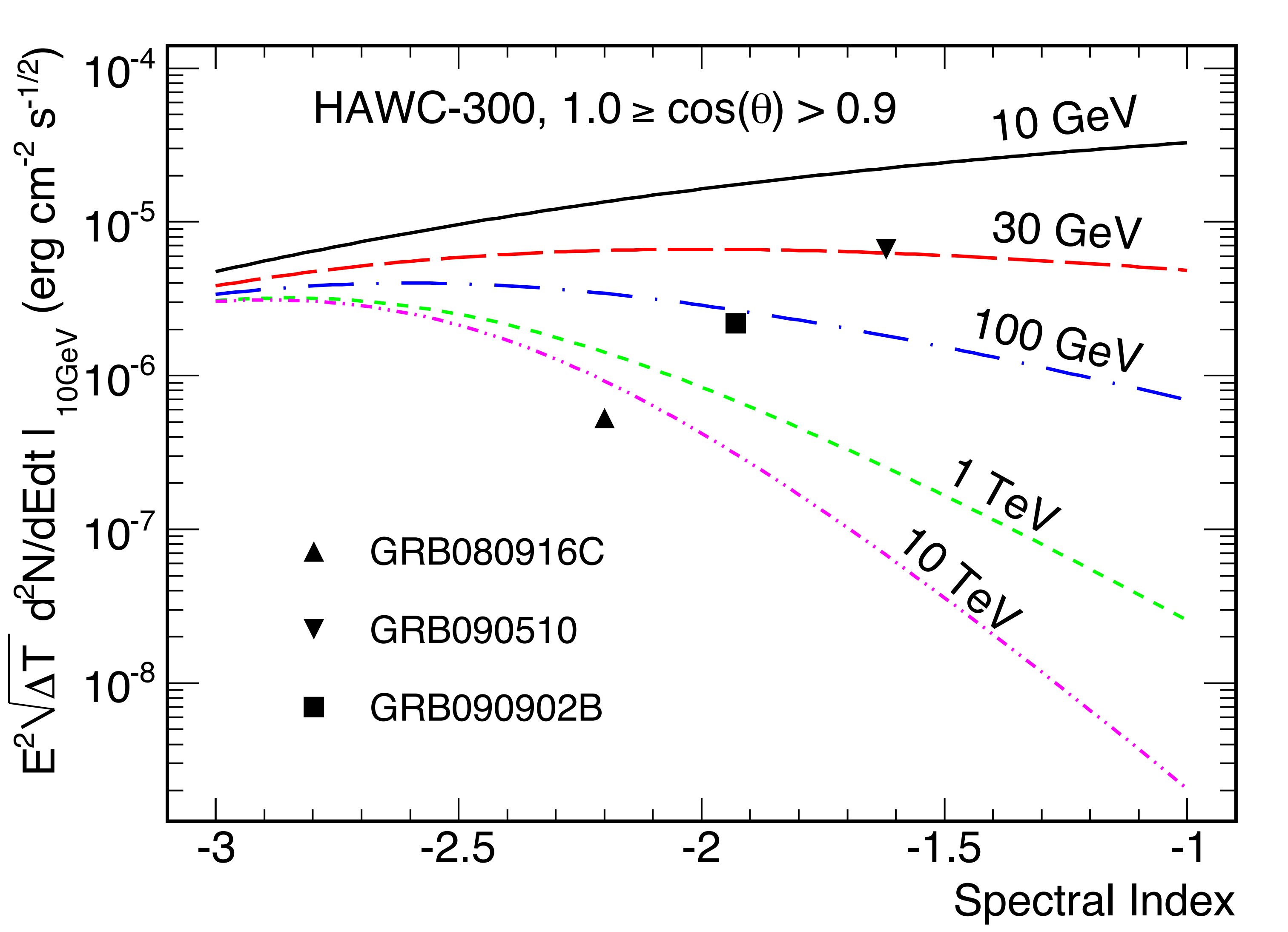
* Correlated noise from simultaneous hadronic showers not included in simulation

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.

Sensitivity to transients (Scaler DAQ)

- Scaler DAQ measures PMT rates
- GRB produces simultaneous increase of PMT counting rates
- Sudden increase in PMT counting rates may reveal a GRB

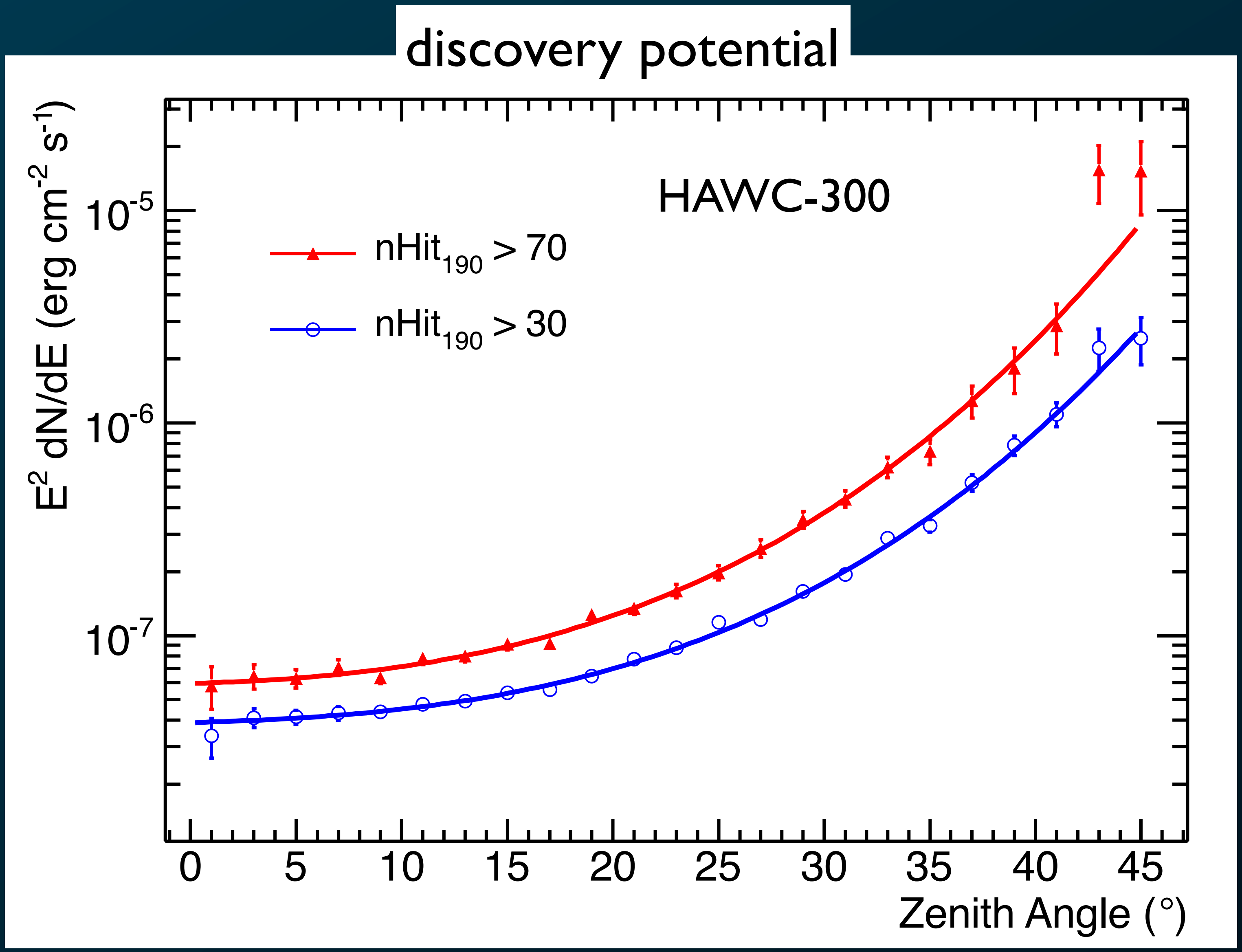


sensitivity down to a few GeV

For details see *On the sensitivity of the HAWC observatory to gamma-ray bursts, by HAWC Collaboration, Astropart.Phys. 35 (2012) 641-650. Also arXiv: 1108.6034 [astro-ph.HE].*

Scaler analysis complements the main DAQ analysis, covering short GRBs with soft spectra and cutoffs <100 GeV

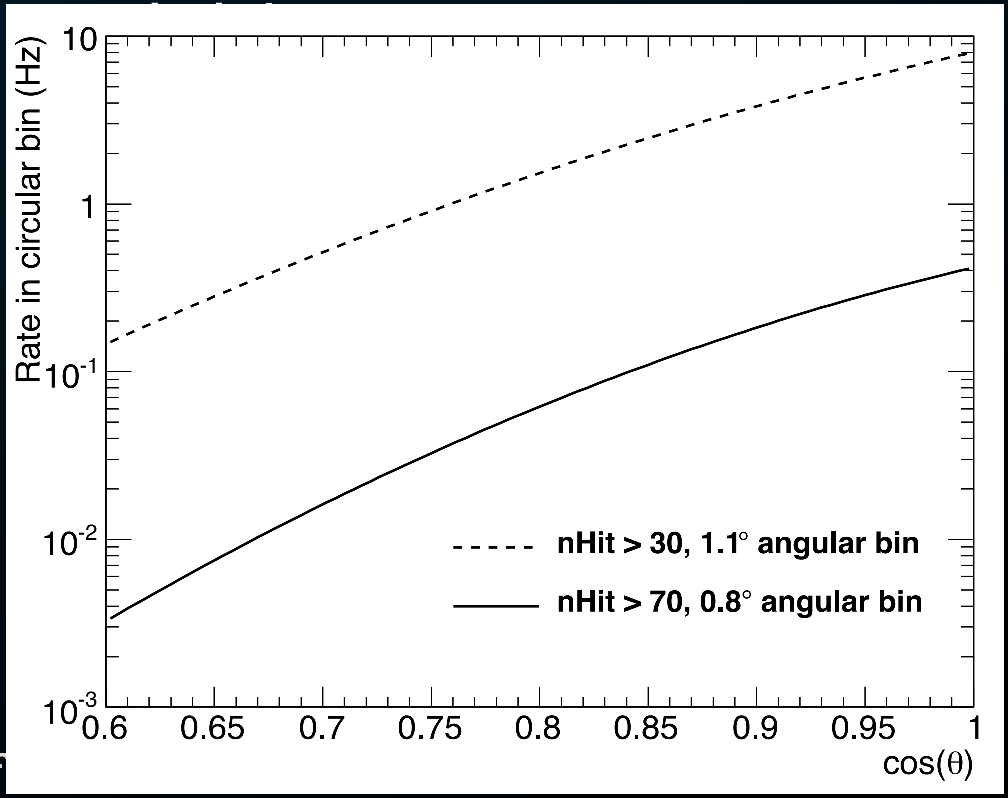
Sensitivity vs. zenith angle (main DAQ)



Simulated GRB:
duration = 20 seconds
spectral index = 2
redshift = 0.5 (EBL absorption following Gilmore et al.)

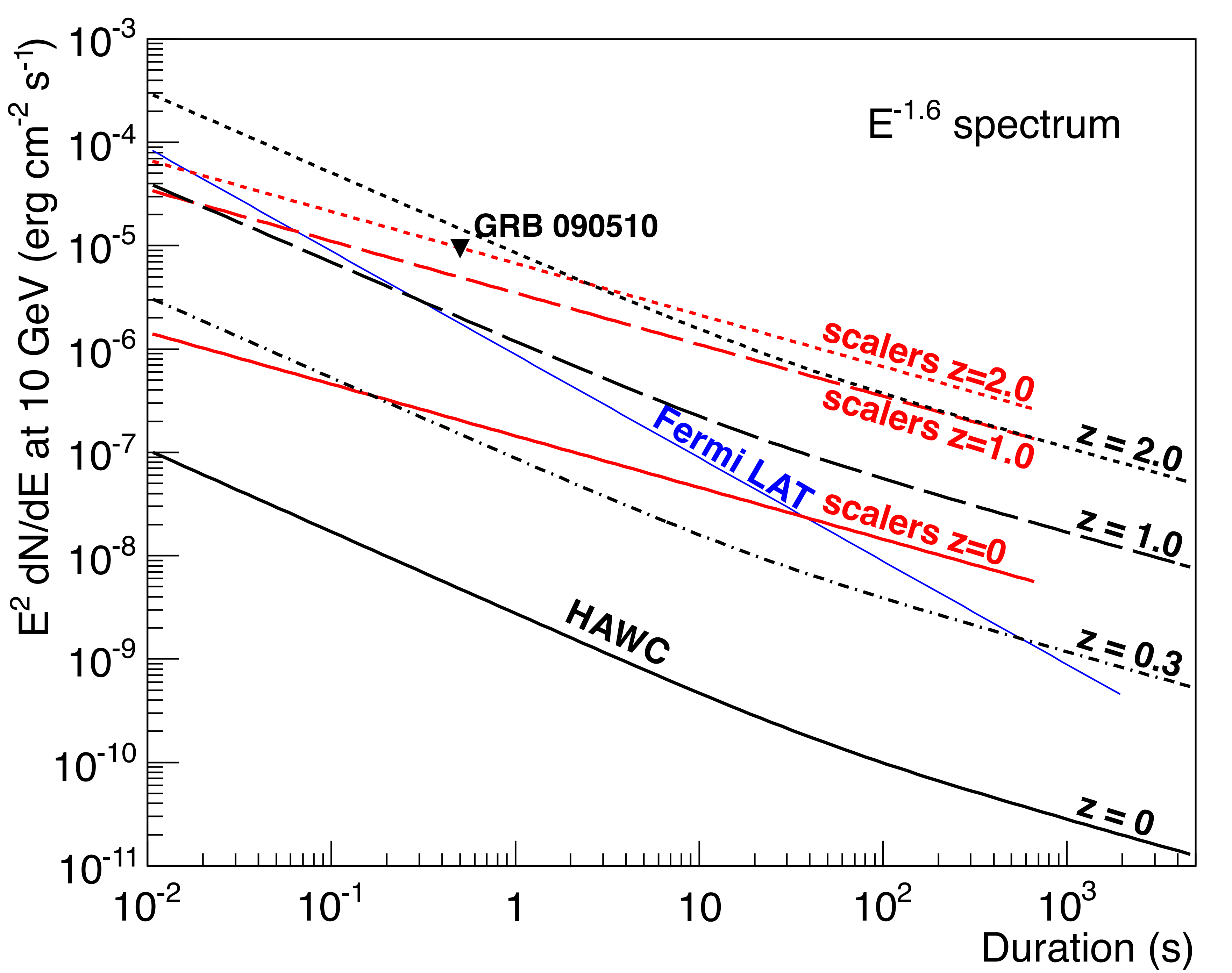
Number of events in the time window (20 s) is examined

Shown is the flux detectable at 5 sigma significance with 50%



Relatively background-free analysis due to narrow time window (duration of GRB)
--> Angular resolution and gamma-hadron separation performance not critical

Sensitivity vs. duration



Above 10 GeV HAWC's sensitivity will be comparable to Fermi LAT's

Redshift is modeled according to Gilmore et al.

No intrinsic spectral cutoff

Fermi LAT curve: 1 photon above 10 GeV

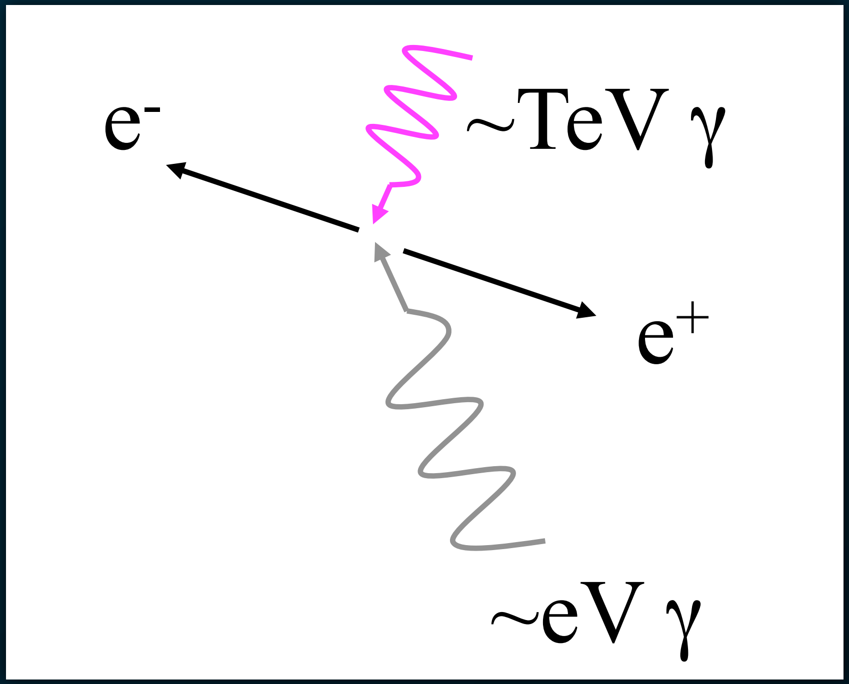
Fermi LAT is essentially "background free" (sensitivity ~ 1 / T)

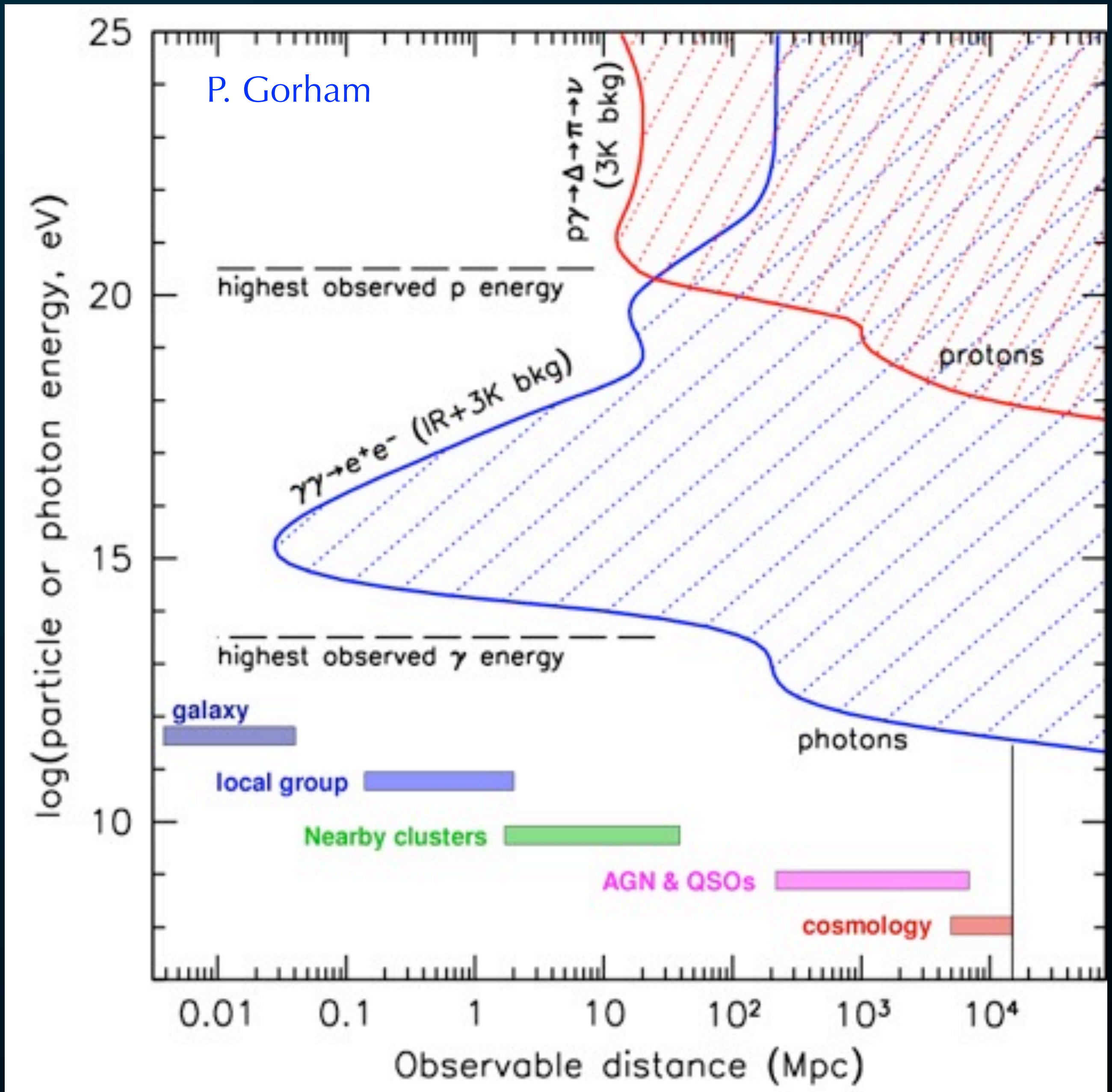
HAWC scalers are background dominated (sensitivity ~ 1 / sqrt(T))

high energy GRB detections would provide information on the acceleration mechanism of GRB or probe the extra-galactic background light

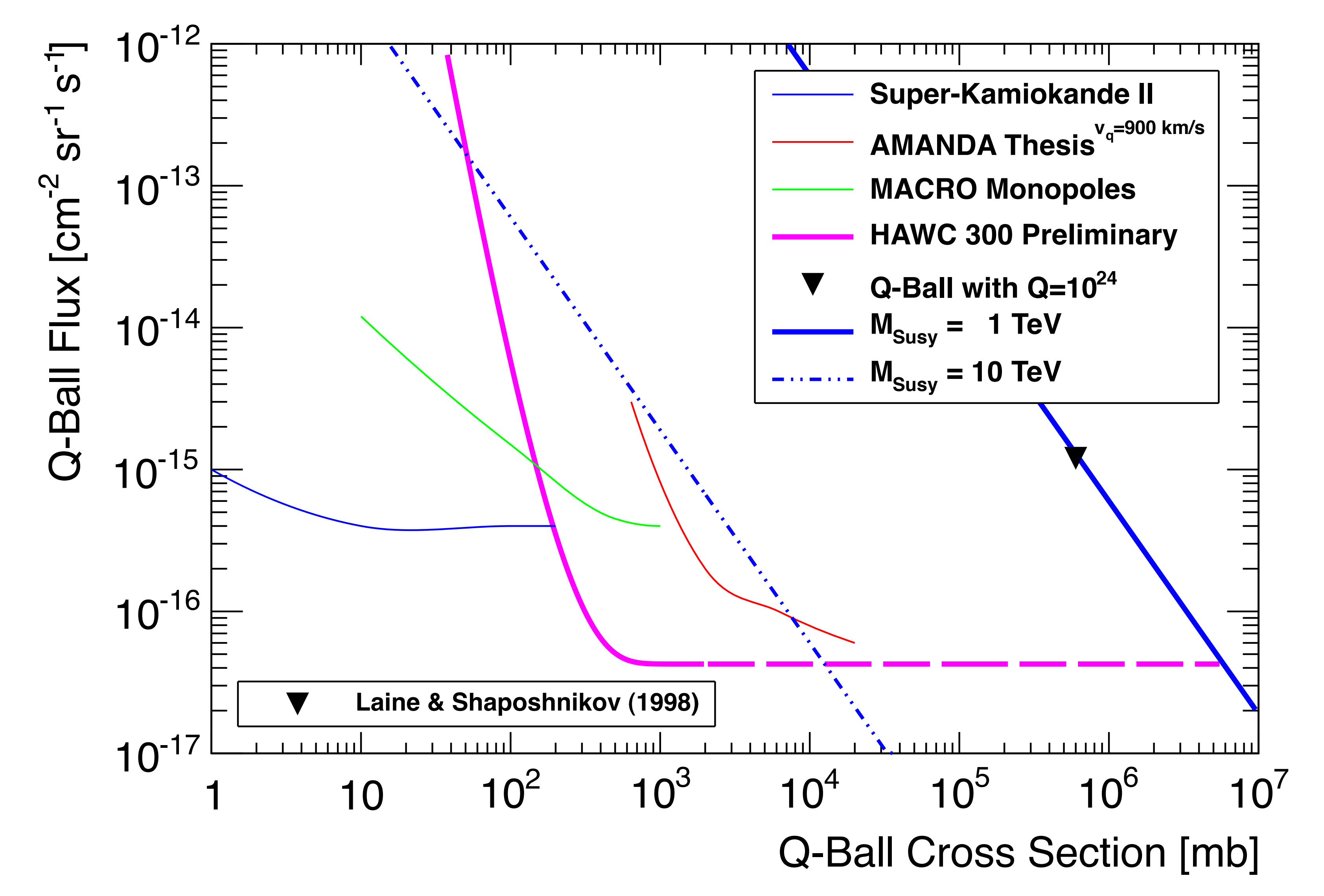
For details see Astropart. Phys. 35 (2012) 641-650. Also arXiv:1108.6034 [astro-ph.HE]

EBL absorption





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

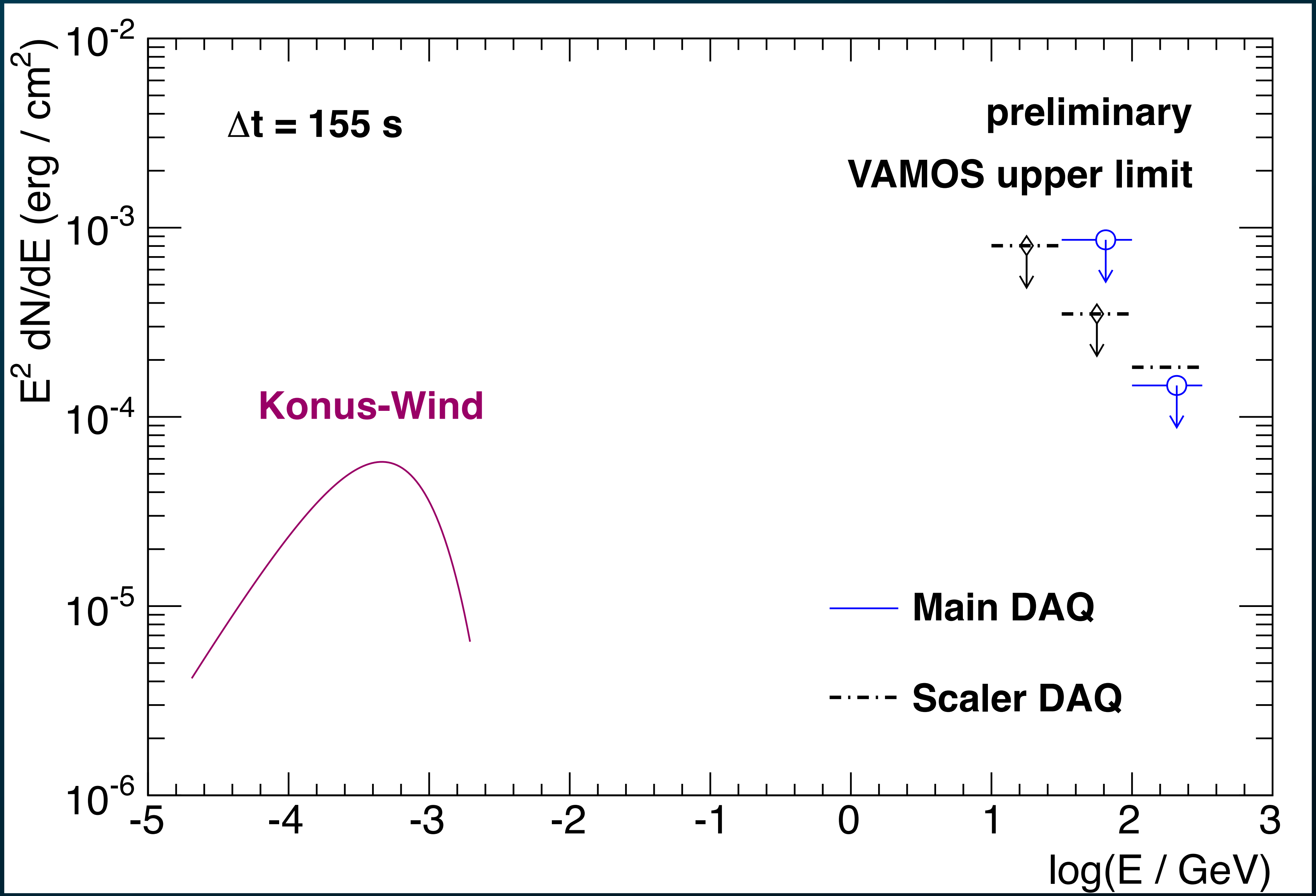
Aiming at world-best sensitivity at 1000 mb

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

Upper limits on GRB 111016B

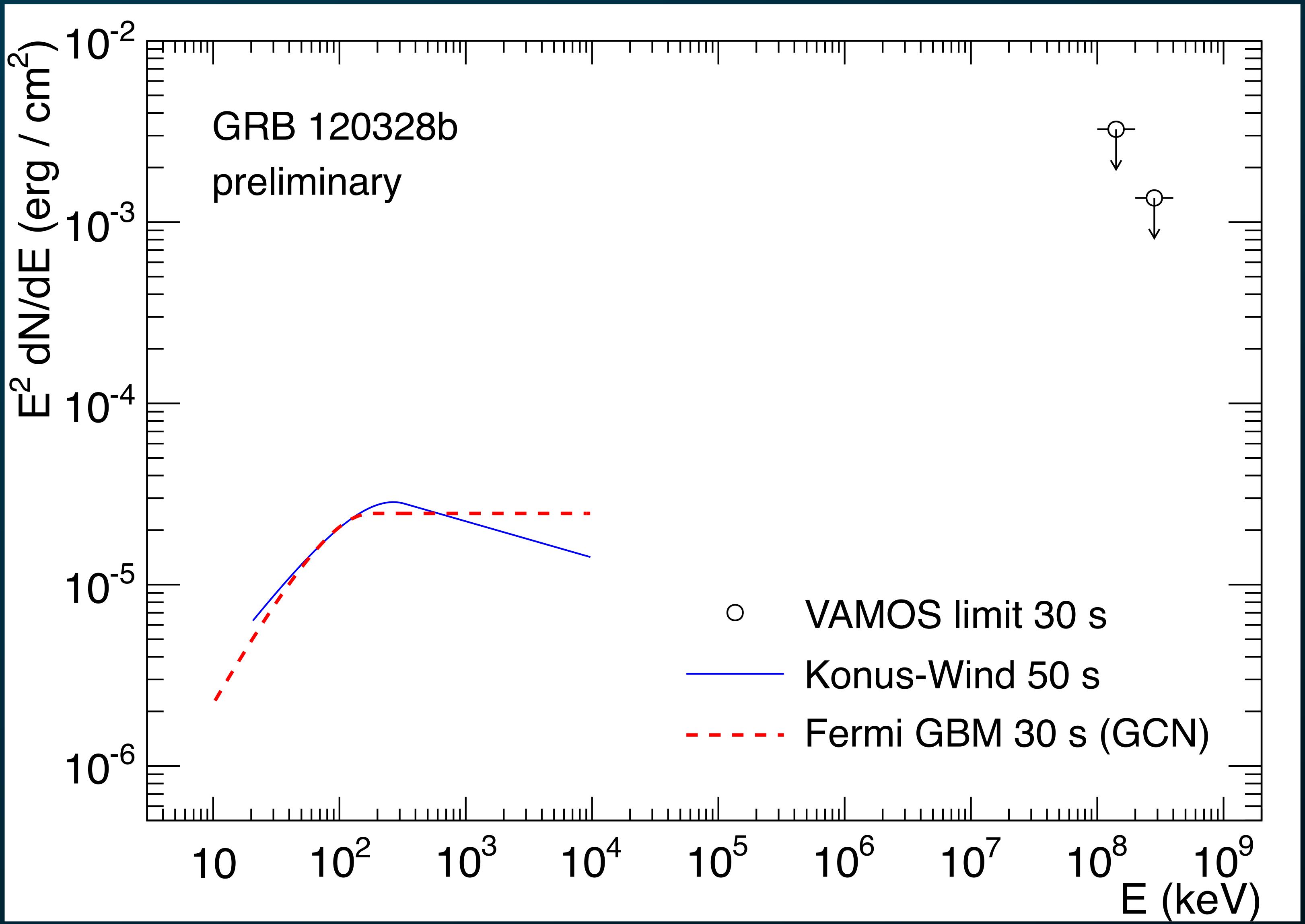


- A high fluence GRB discovered by IPN
- VAMOS zenith angle = 32 deg
- 3 time windows examined, no excess found
- Cuts used: number of hits >= 14; 6 degree radius circle around GRB position
- 90% C.L. limit in two energy bands are reported
- Results from scalers analysis are also shown (three energy bands)

First GRB limit from VAMOS!

D. Zaborov for the HAWC collaboration, The HAWC observatory as a GRB detector, proceedings of the 4th Fermi symposium, Monterey, CA, 28 Oct - 2 Nov 2012, arXiv:1303.1564 [astro-ph.HE]

Upper limits on GRB 120328B

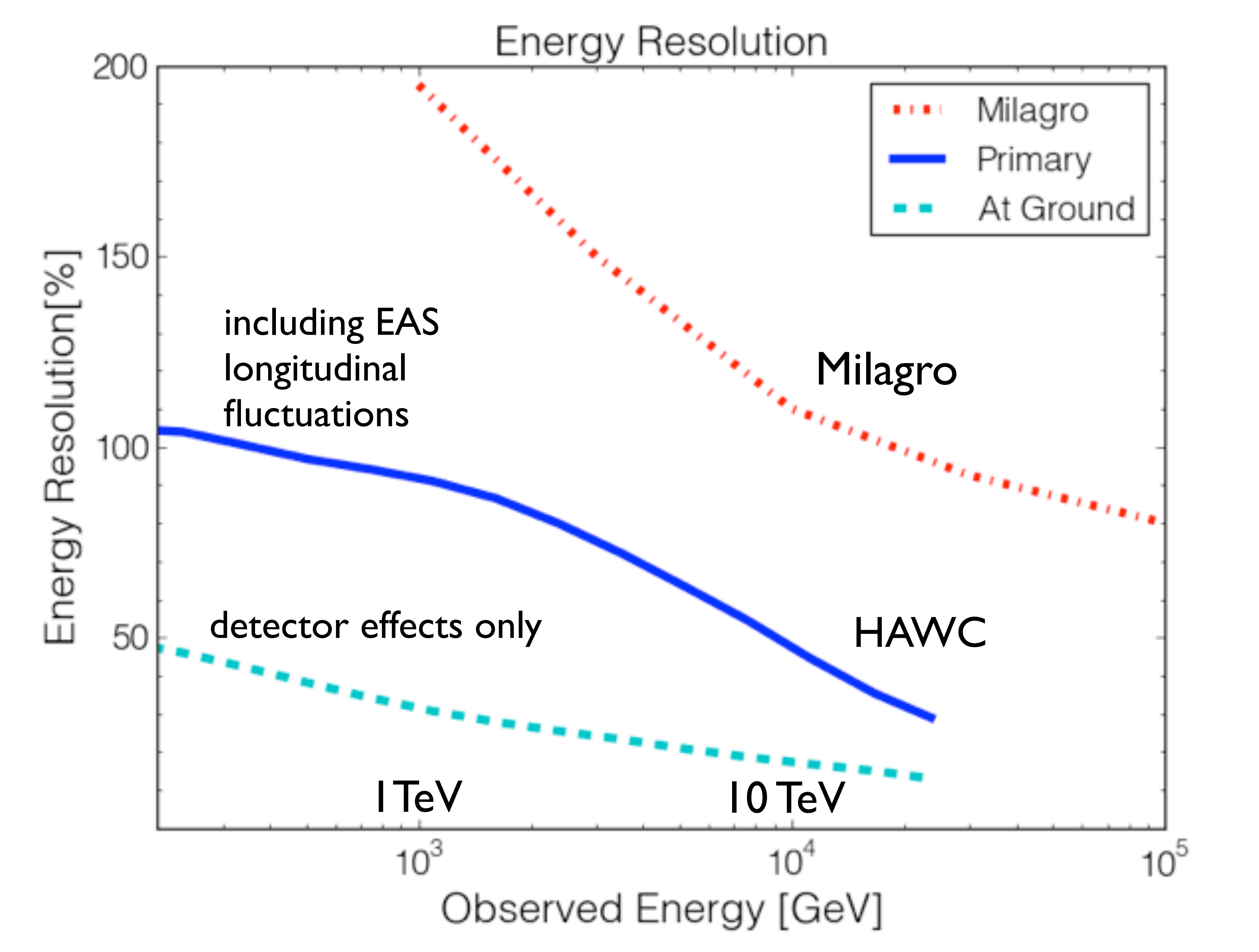


Weak limits due to unfavorable zenith angle (41 deg) and a positive fluctuation observed

- Very bright (1.2 x 10^{-4} erg/cm^2) GRB discovered by IPN
- Observed by Fermi, Konus-Wind, MESSENGER (GRNS), INTEGRAL (SPI-ACS), Swift-BAT (outside coded field of view) and AGILE (MCAL)
- Emission was seen up to ~8 MeV by Konus-Wind
- Fermi LAT reported 8 sigma excess using non-standard analysis (burst was 66 degrees off axis and zenith angle was 105 deg meaning high Earth limb background)
- VAMOS zenith angle 41 deg
- 7 time windows examined, no significant excess found

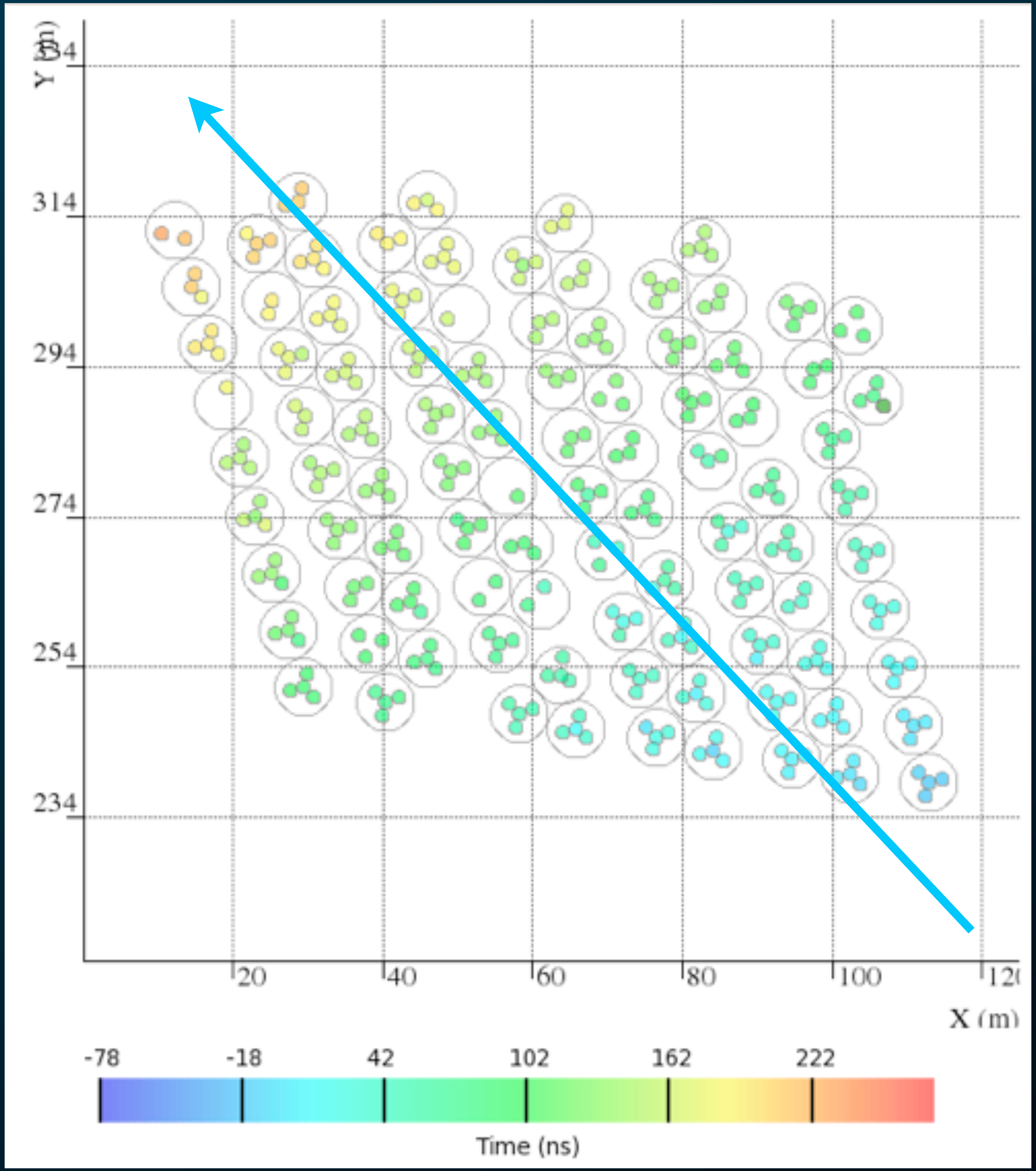
Energy resolution

- 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

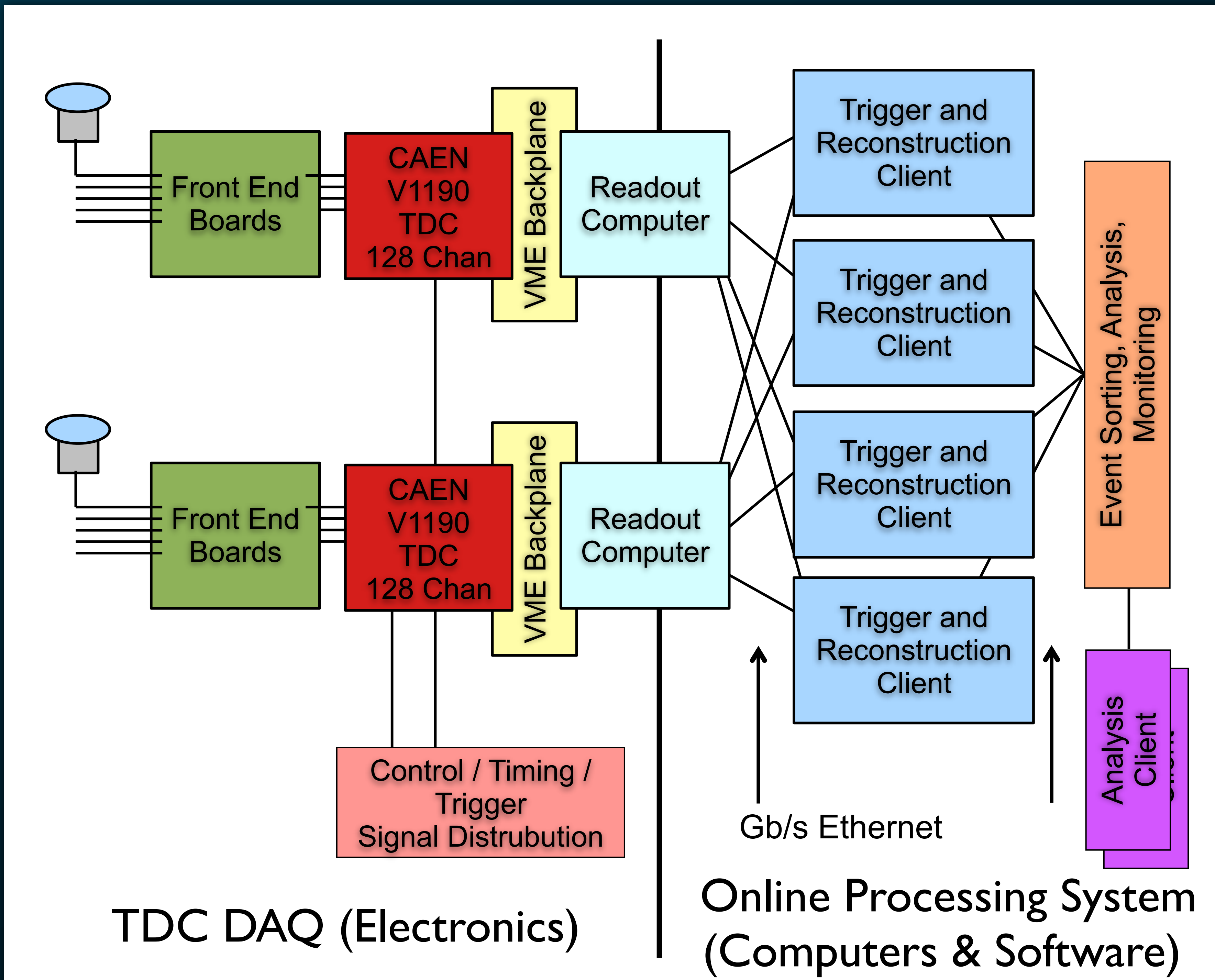
HAWC data



- This event:
- Recorded on June 12
- 95 Tanks
- 341 PMTs
- Color scale indicates timing

All distributions are in fair agreement with Monte Carlo expectations

"Triggerless" DAQ



- TDCs synchronized by common 40 MHz clock
- Continuous acquisition with common 40 kHz trigger (25 µs data blocks)
- Each TDC is read out by a VME single-board computer (SBC)
- DAQ records ALL photoelectrons from ALL 1200 PMTs = 500 MB/sec
- Sets of 1000 data blocks pushed to processing clients over Ethernet and merged with those from other TDCs
- Triggering is done entirely in software (requires ~10% of ~200 CPU cores on-site)
- Software Trigger reduces data to 20 MB/sec (600 TB/yr)
- A second DAQ - "scalers" - measures PMT rates

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