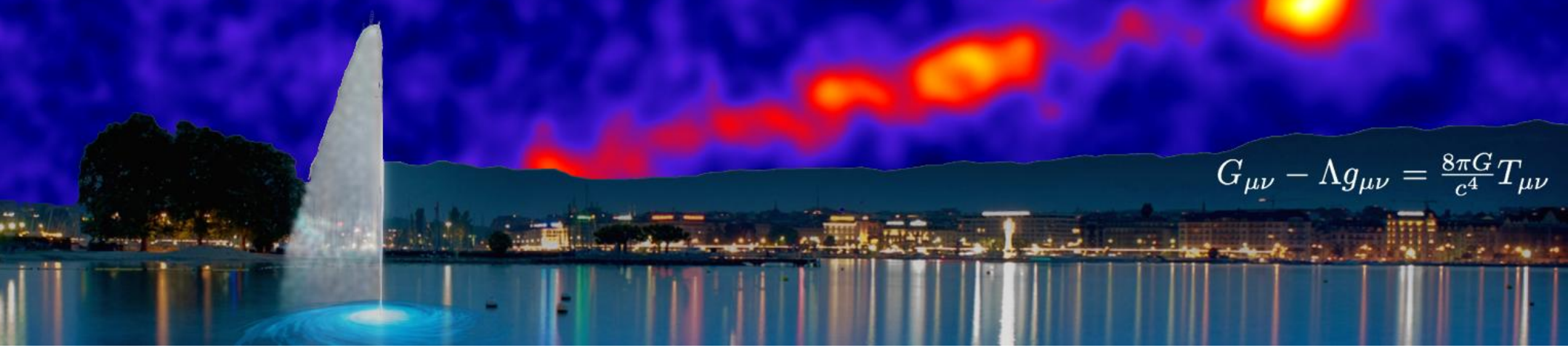


Exploring the TeV Universe with HAWC

Robert J. Lauer

THE UNIVERSITY of NEW MEXICO

28th Texas Symposium
on Relativistic Astrophysics

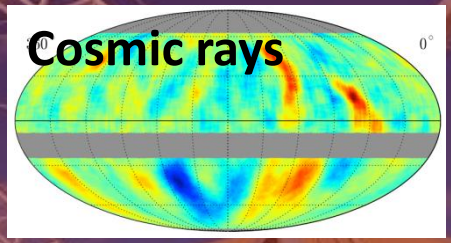
Geneva, Switzerland
December 16, 2015

The HAWC collaboration

HAWC science

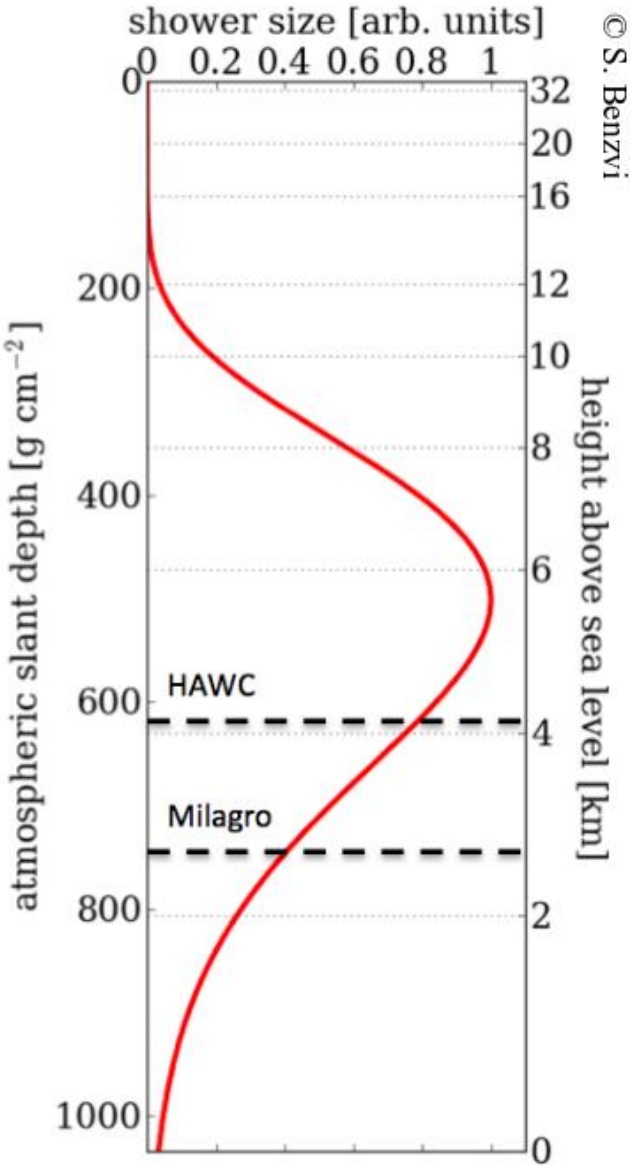
Cosmology
- extra-galactic background light
- inter-galactic magnetic fields
- diffuse emission
- ...

Fundamental physics
- dark matter
- photon propagation:
  axion-like particles, Lorentz invariance
- exotic particles:
  Primordial black holes, Q-balls,...

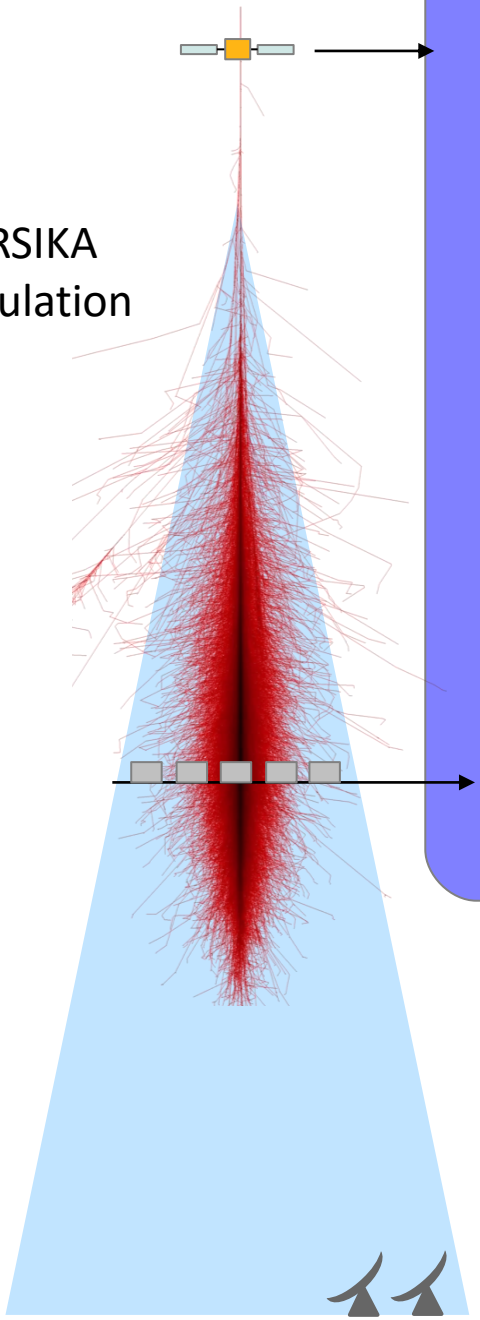


TeV astrophysics

Gamma-ray air showers



CORSIKA simulation



Direct γ-detection

Wide Field of View, Continuous Operations

Shower particle interception

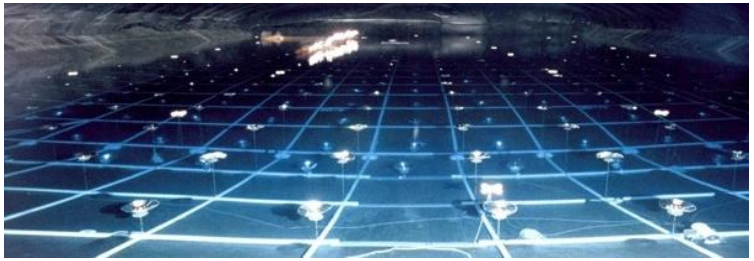
Shower imaging

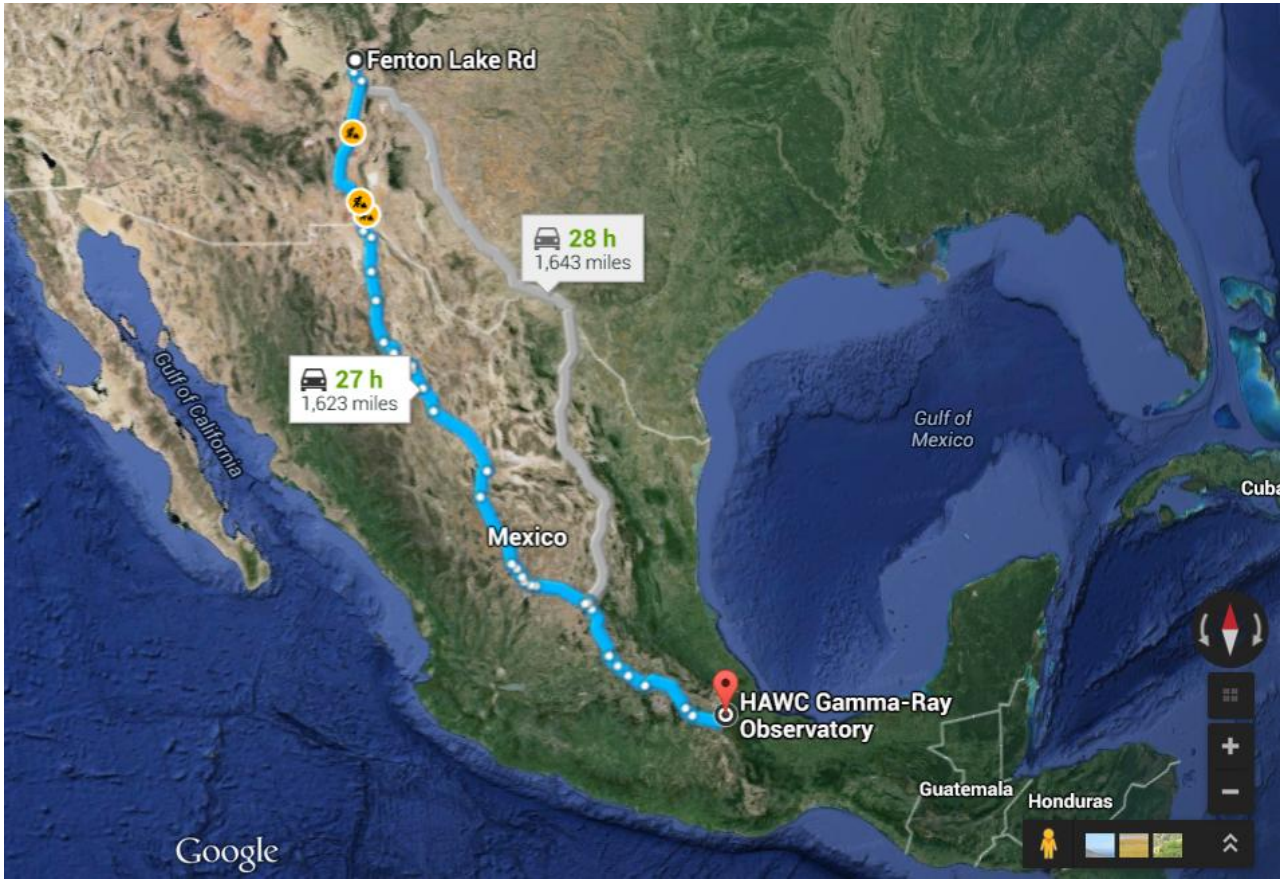
TeV Sensitivity

From MILAGRO to HAWC

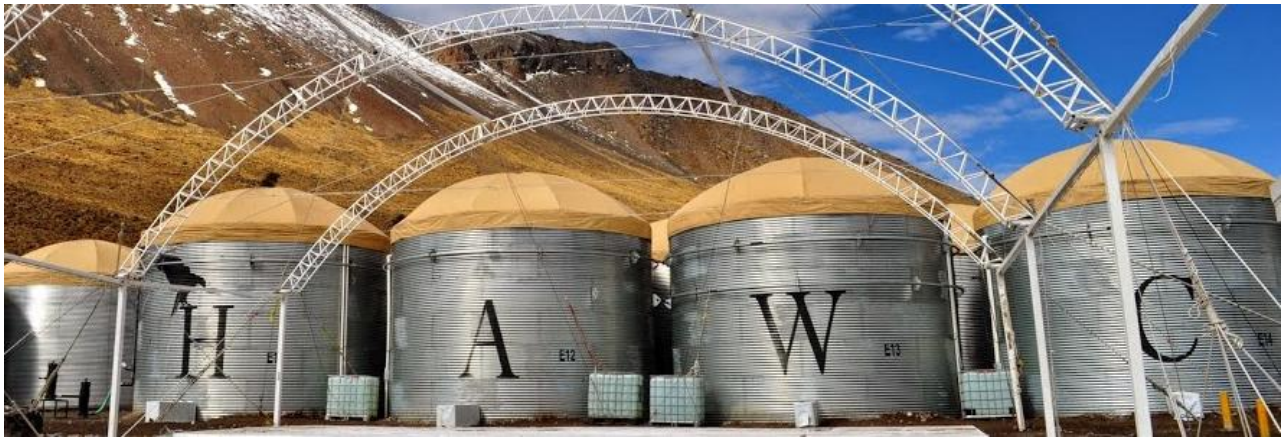
MILAGRO

- Jemez Mountains, NM
- **2350 m** above sea level
- operated from 2000 to 2008





High
Altitude
Water
Cherenkov
Observatory



HAWC Site

- State of Puebla, Mexico
- **4100 m** above sea level
- Temperate climate
- Existing infrastructure from LMT

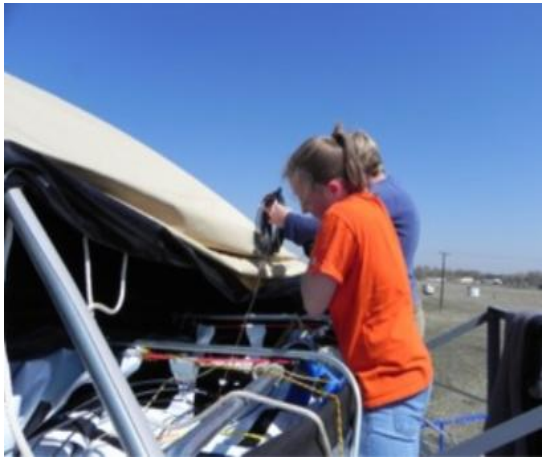
HAWC construction

Commercial steel tanks constructed at the site.

Custom-made, light-proof bladders shipped to the site.

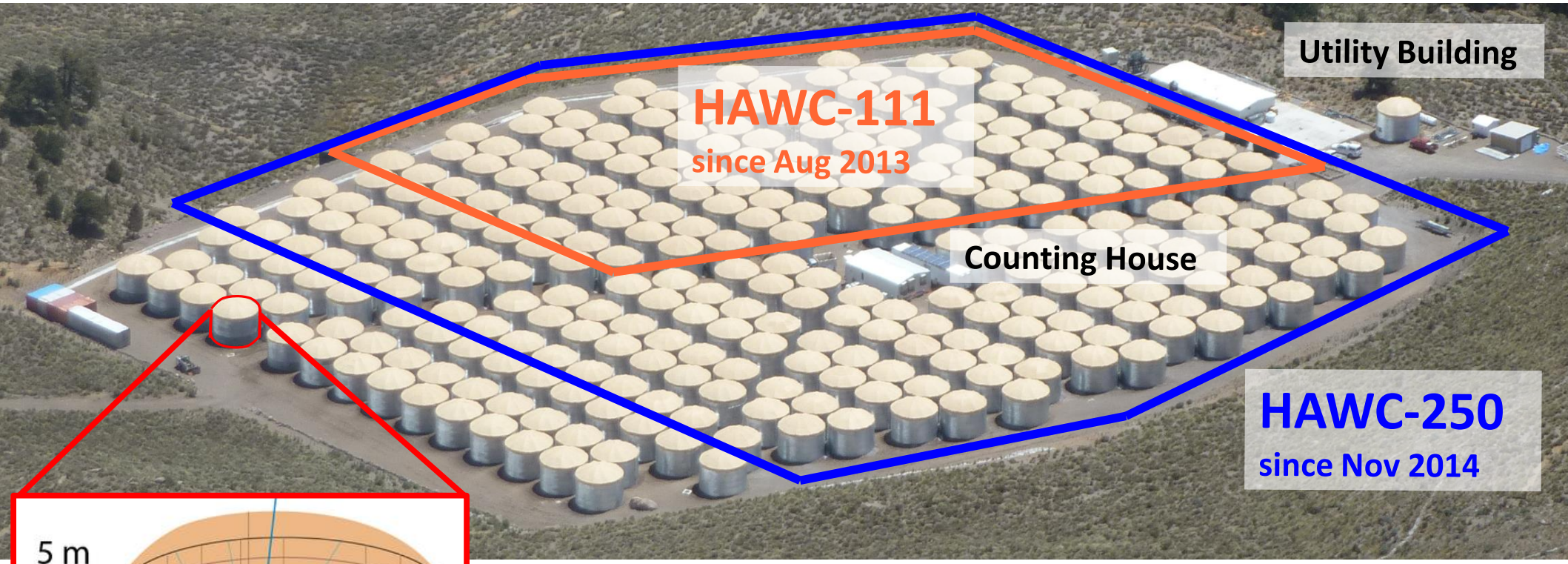
~3900 truck loads of water transported up the mountain

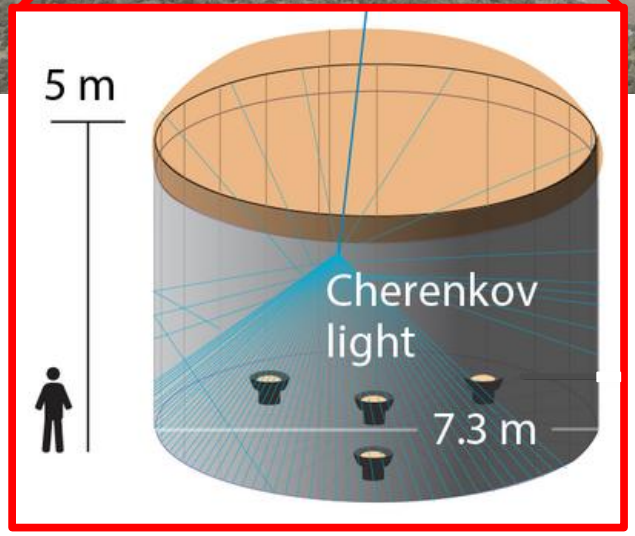
Water transported to the site and purified there.



PMTs deployed into water and connected to central Counting Hause.

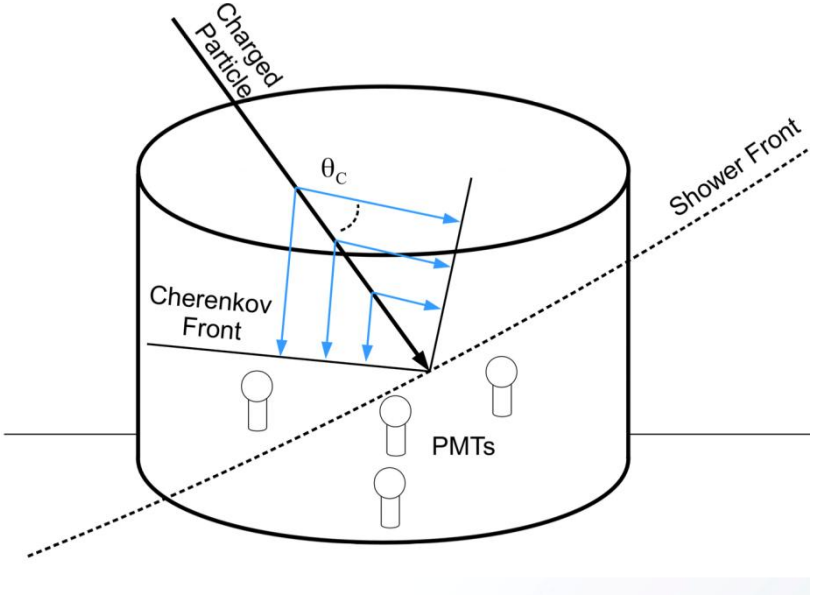
The HAWC array

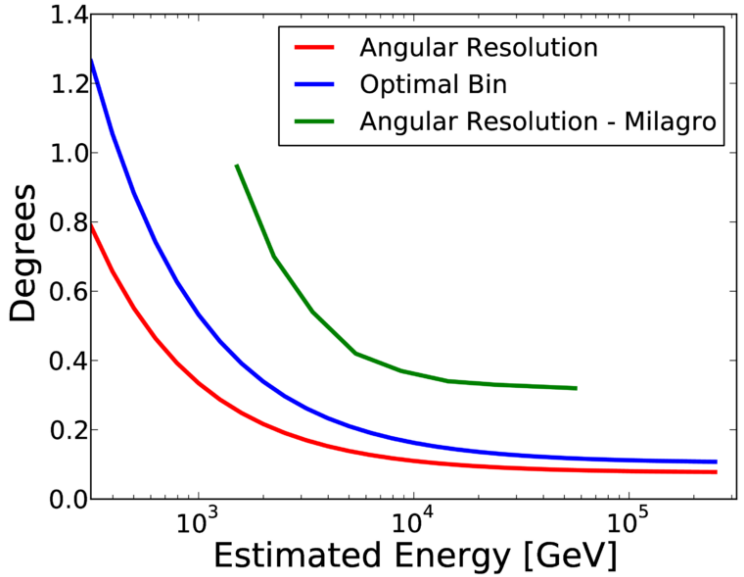


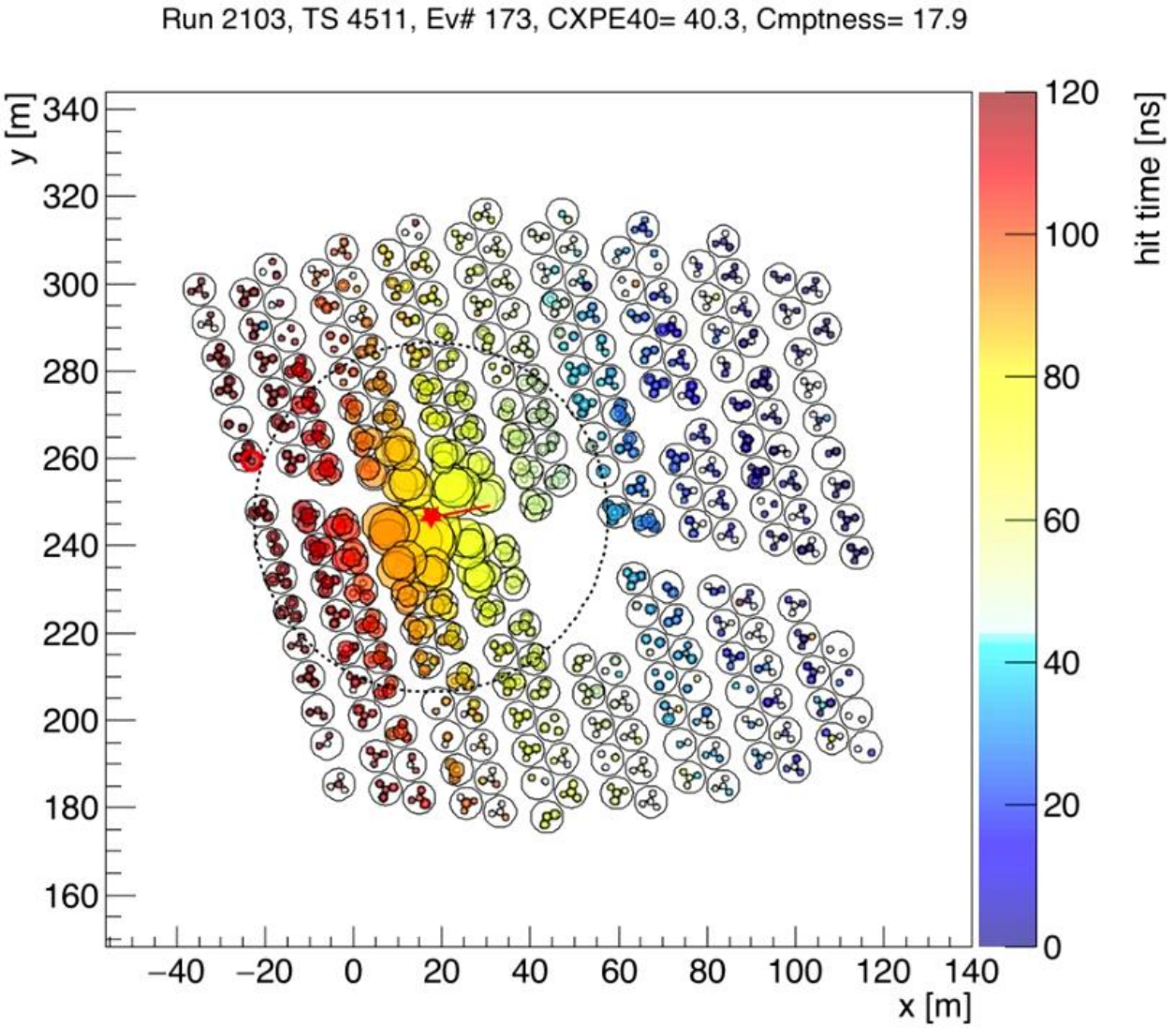


- **22,000 m^2** water Cherenkov detector (WCD) array
- **300 WCDs** at completion (March 2015)
- **188,000 liters** of purified water **per WCD**
- **4 PMTs per WCD** (3x 8" from Milagro + one high QE)
- Ongoing **data taking during construction**
- **March 2015: Completion** and inauguration

Air shower reconstruction



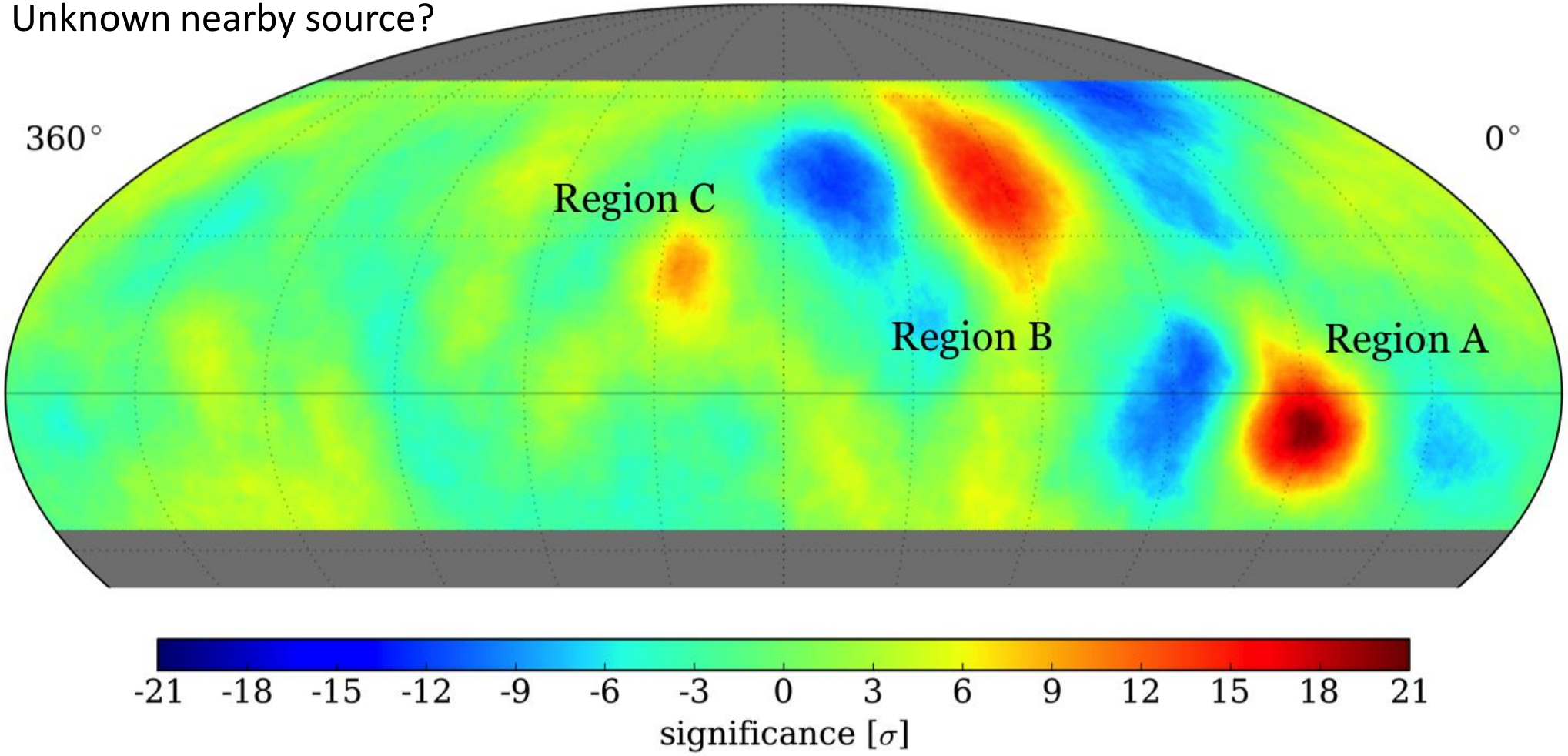




Cosmic ray anisotropy

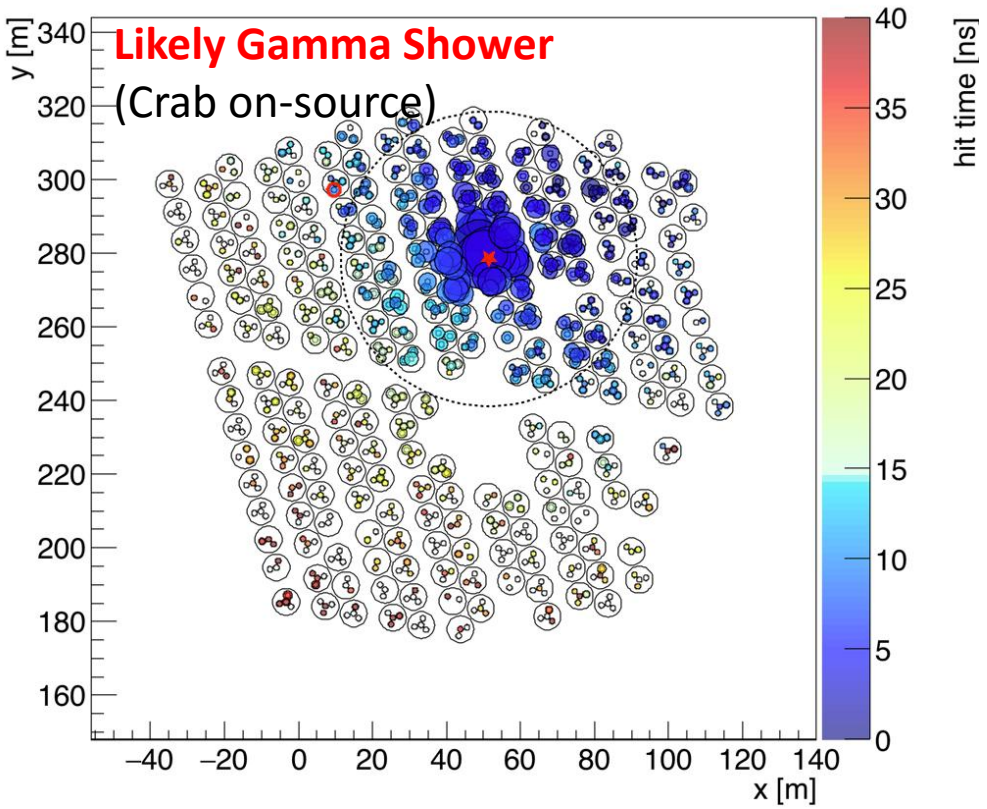
Abeysekara et al.
2014 Astrophys. J. **796** 108

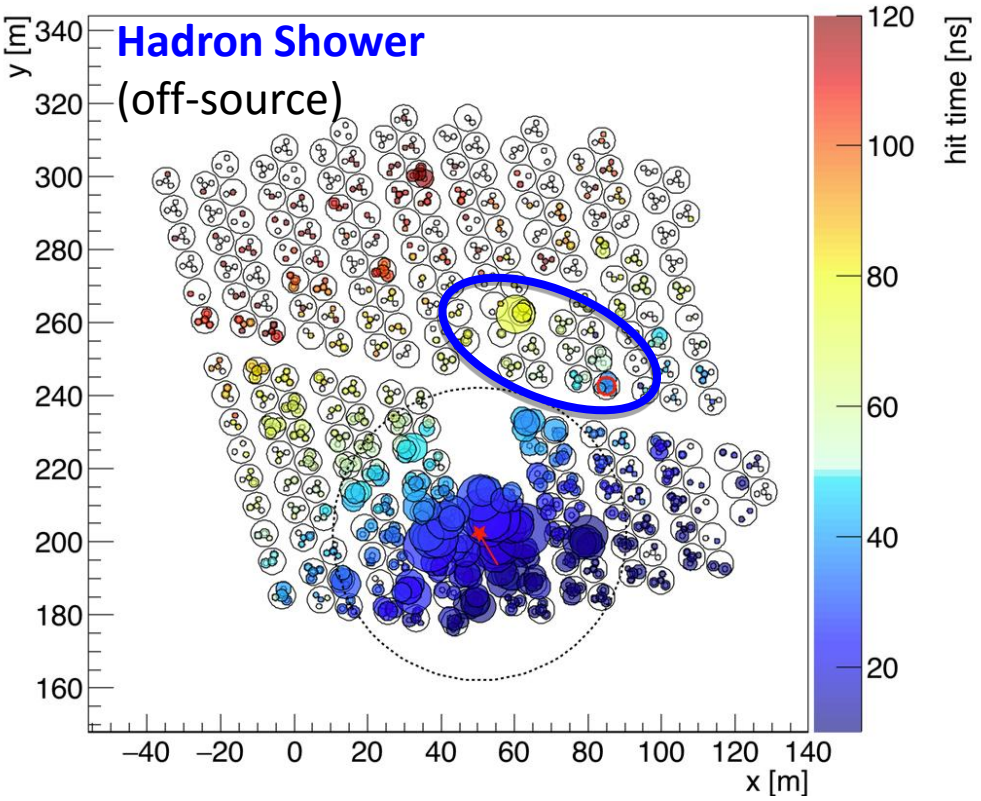
Propagation effect?
Unknown nearby source?



86 billion events, collected over **181 sidereal days** with ~1/3 of the array
Large scale (>60°) removed (dipole,quadrupole,octupole)
10° radial smearing and multipole subtraction of large scale anisotropy

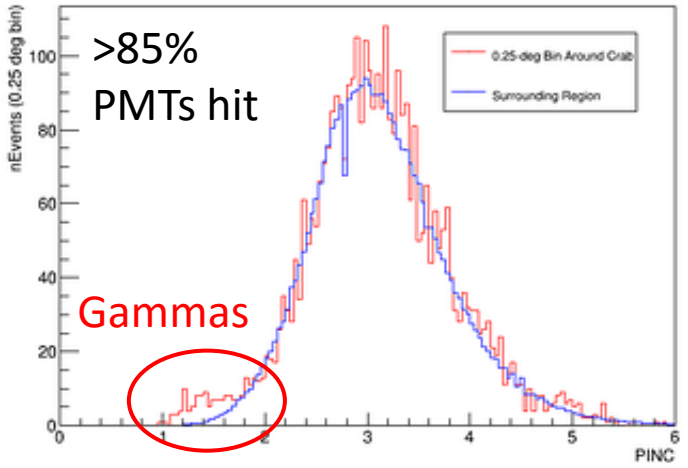
Discrimination of gamma rays



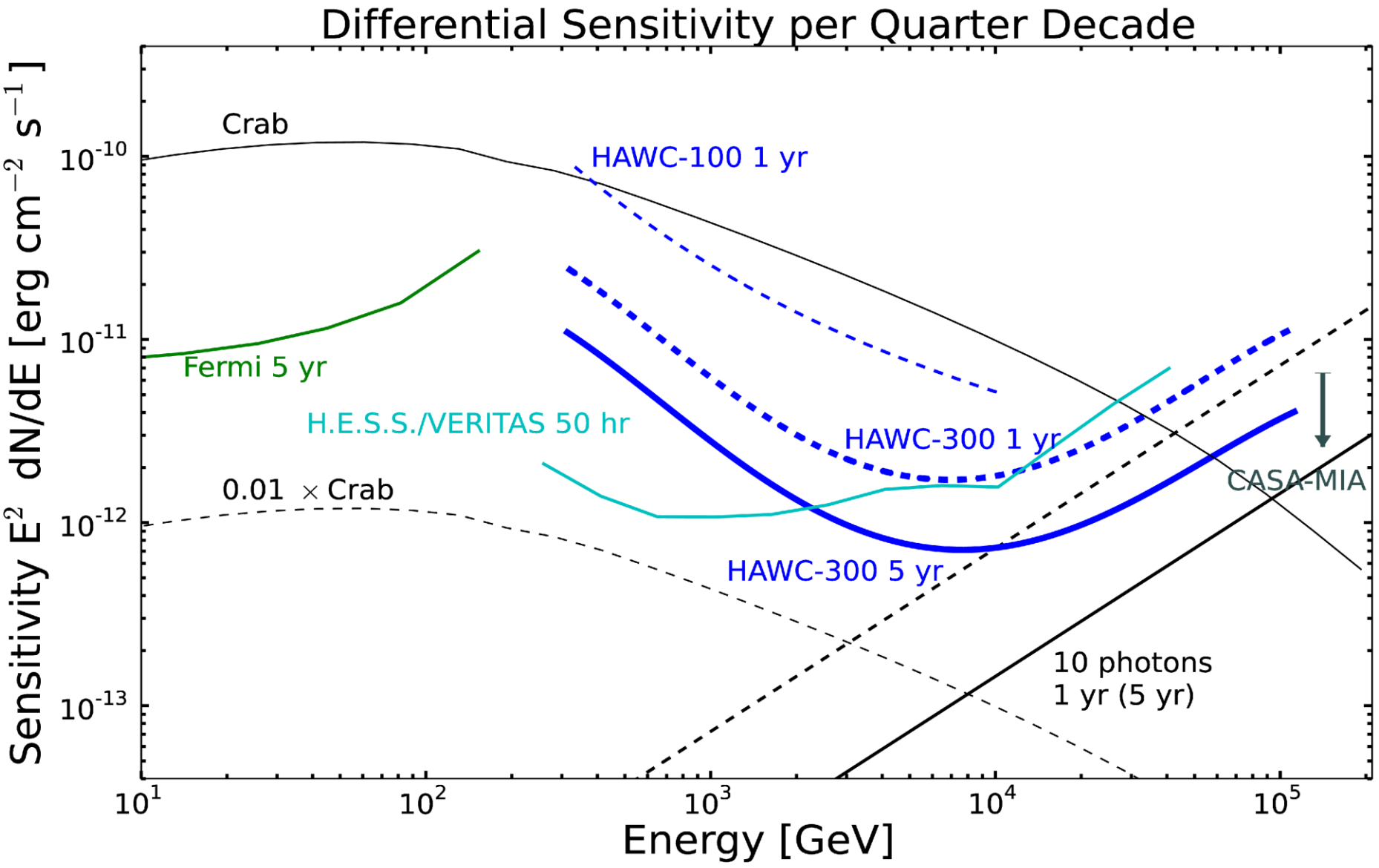


1. Reconstruct air showers based on **PMT hit times and charges**

2. Reject **hadronic primaries via bright hits outside the shower core**



HAWC sensitivity

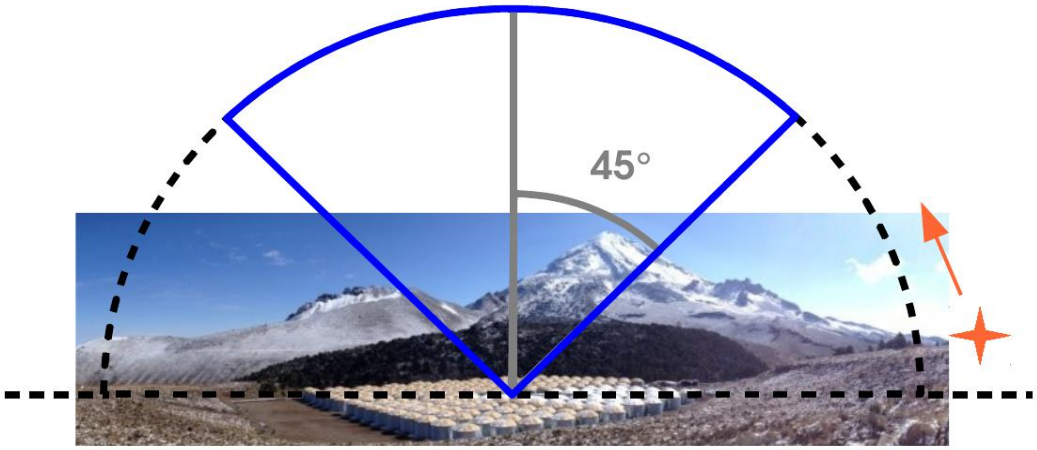


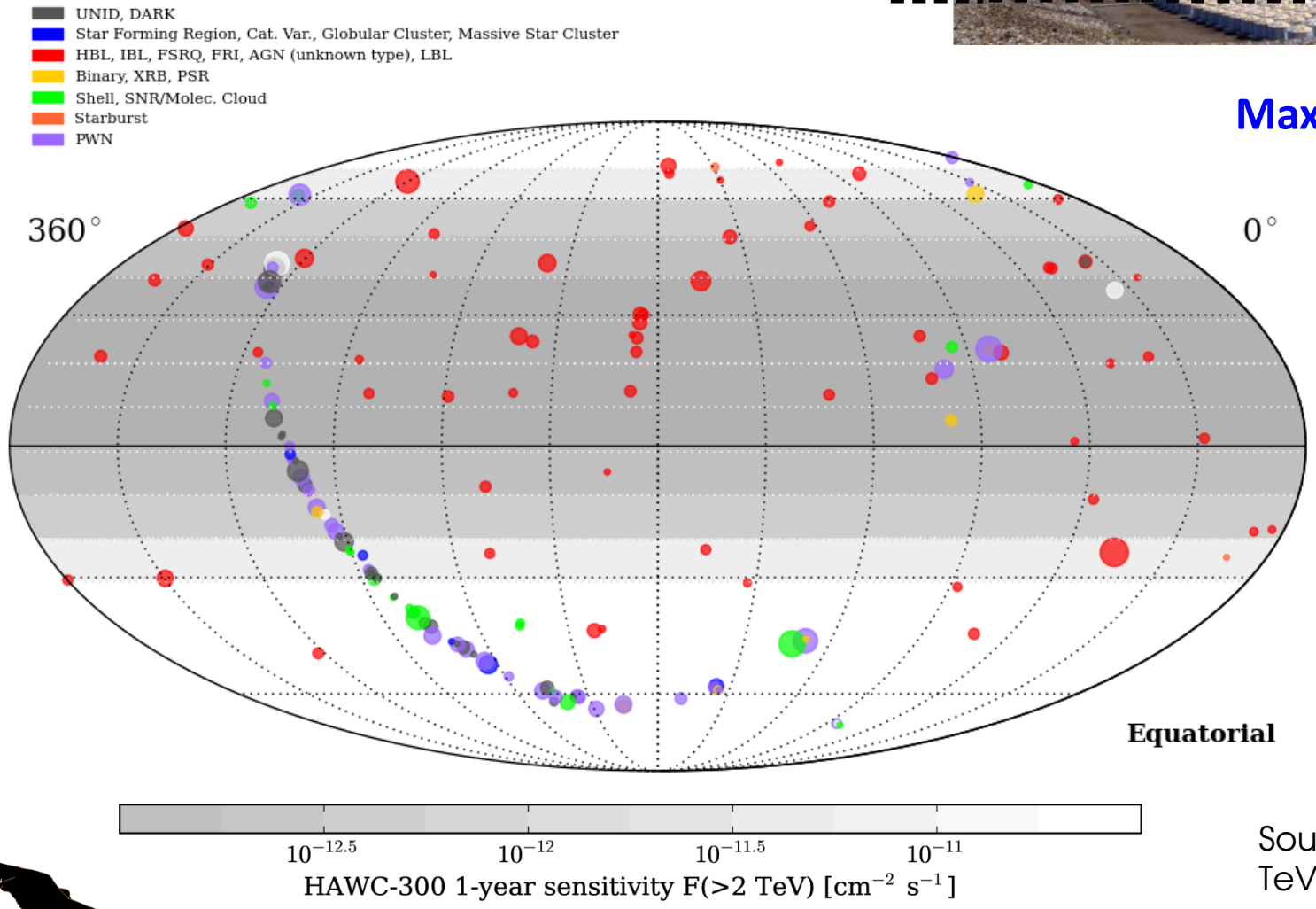
Abeysekara et al. (HAWC Collab.)
Astropart. Phys., **50-52** (2013)

HAWC Field of view

2 sr instantaneous FoV

2/3 of the sky each day



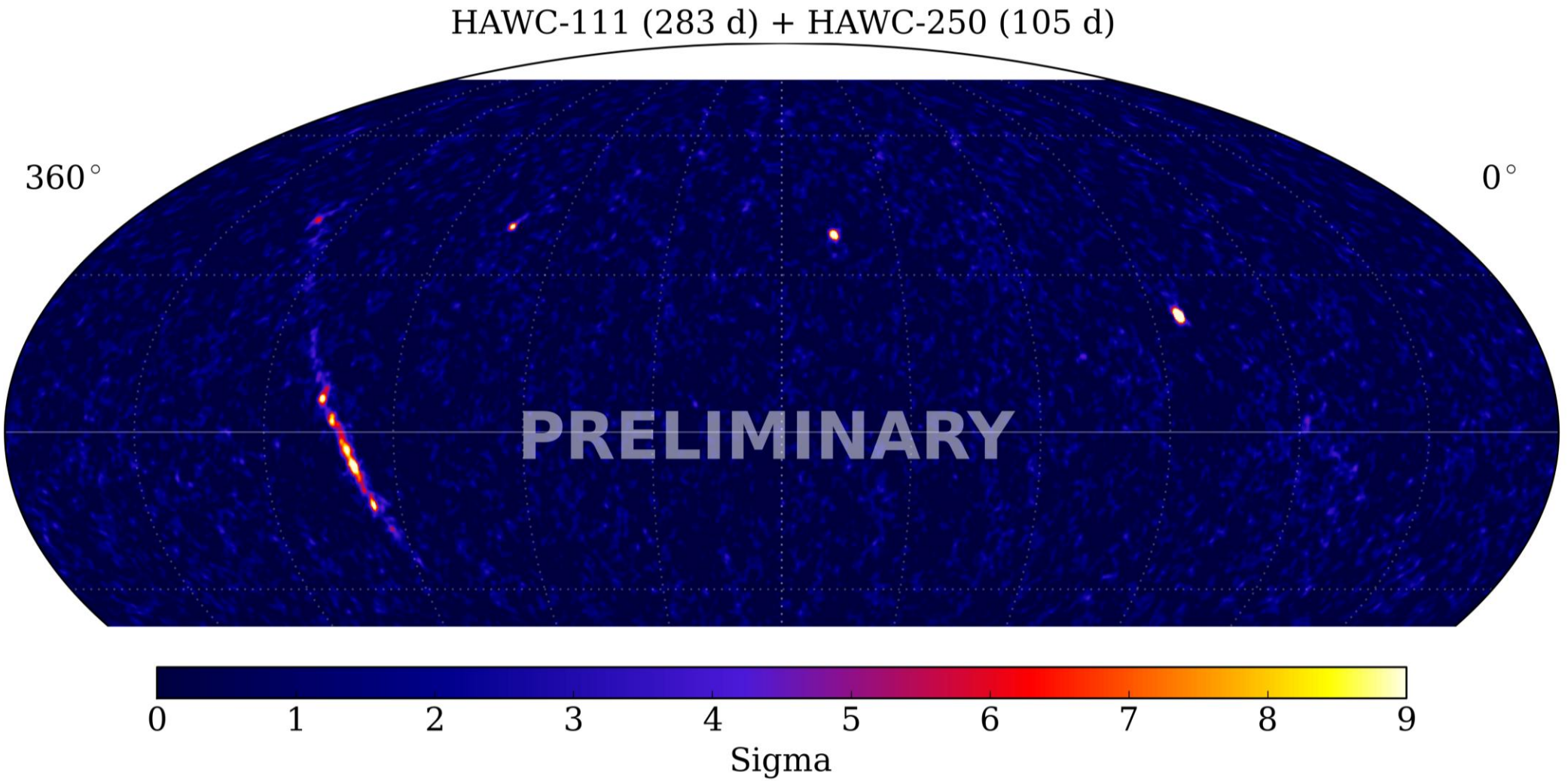


Maximum transit time: ~6 h for sources with peak elevation near zenith (e.g. the Crab)

HAWC can **monitor most of the ~60 known TeV-emitting Active Galactic Nuclei** (AGN)

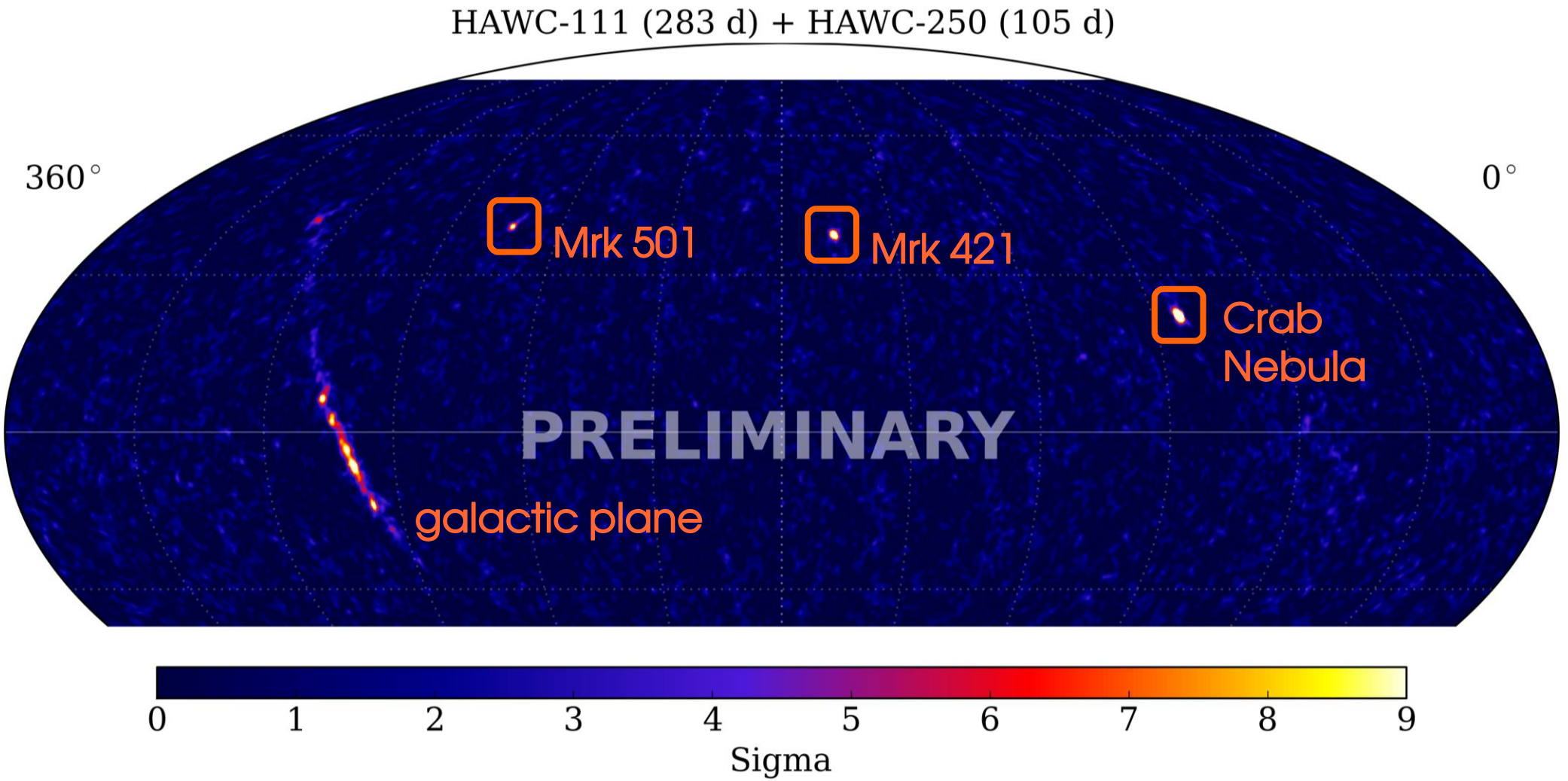
Sources from TeVCAT.uchicago.edu

HAWC gamma-ray sky map



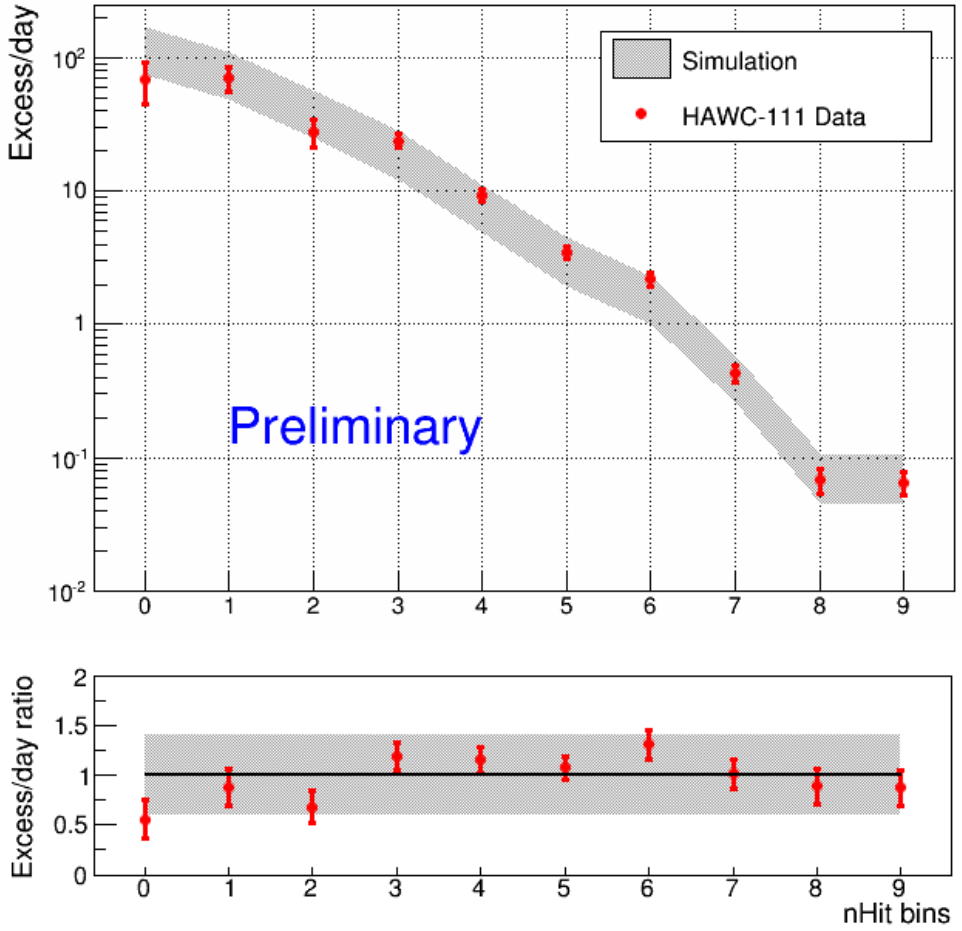
Significance sky map from operation during construction of the HAWC array, growing between June 2013 and March 2015 from 106 to 300 WCDs

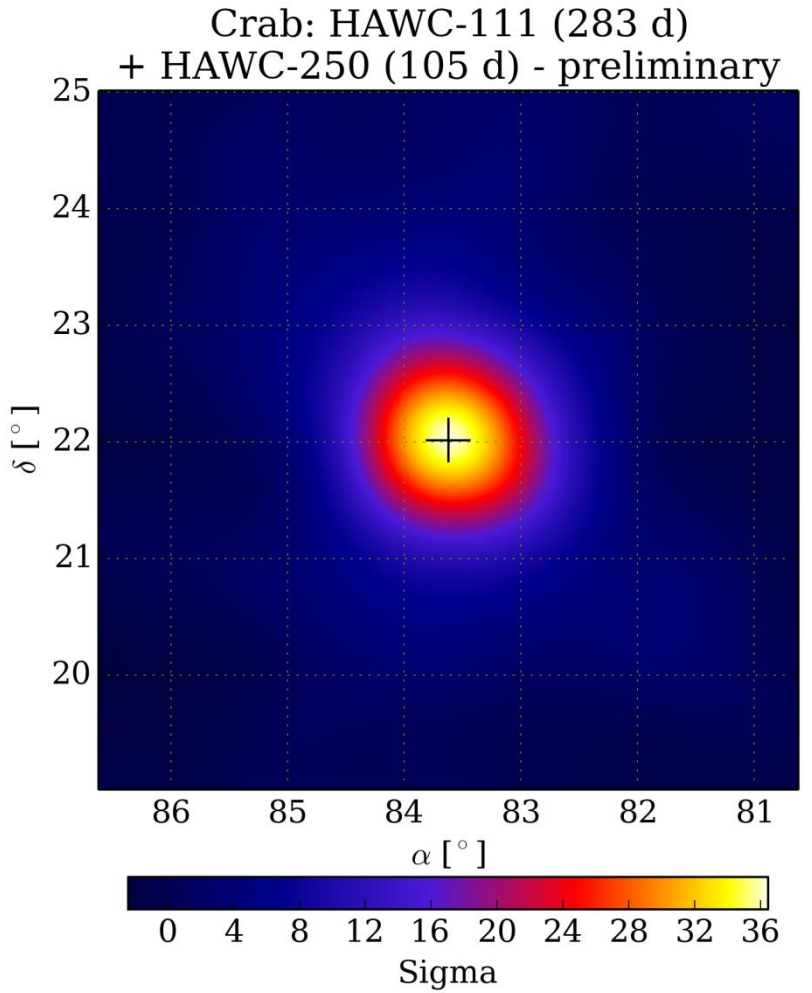
HAWC gamma-ray sky map



Significance sky map from operation during construction of the HAWC array, growing between June 2013 and March 2015 from 106 to 300 WCDs

The Crab nebula in early HAWC data





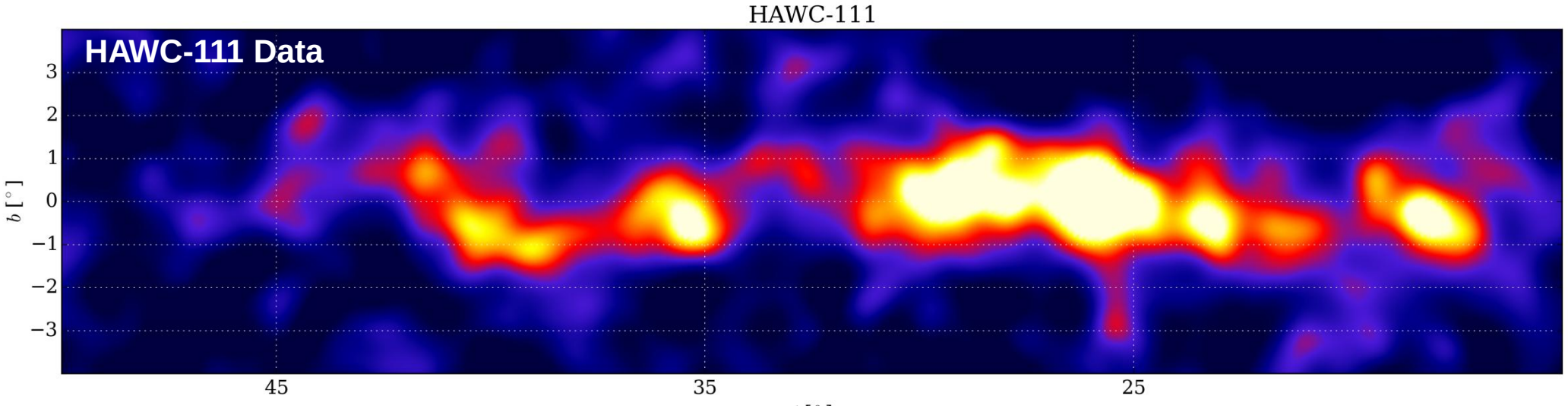
10 energy-proxy analysis bins (based on fraction of PMTs hit)

→ Verification of simulations: Gamma excesses for **Crab Nebula match predictions**

Data + simulation = input for a maximum likelihood analysis

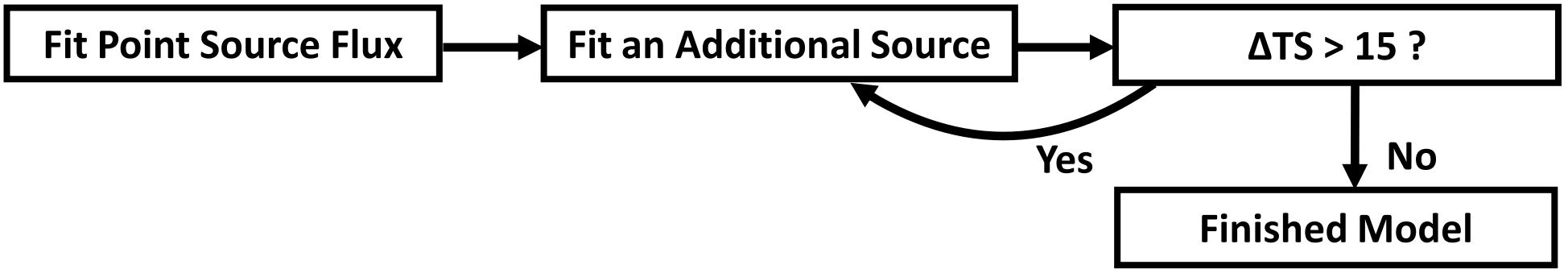
→ fit fluxes and spectral parameters for arbitrary sources

Galactic Plane Source Deconvolution



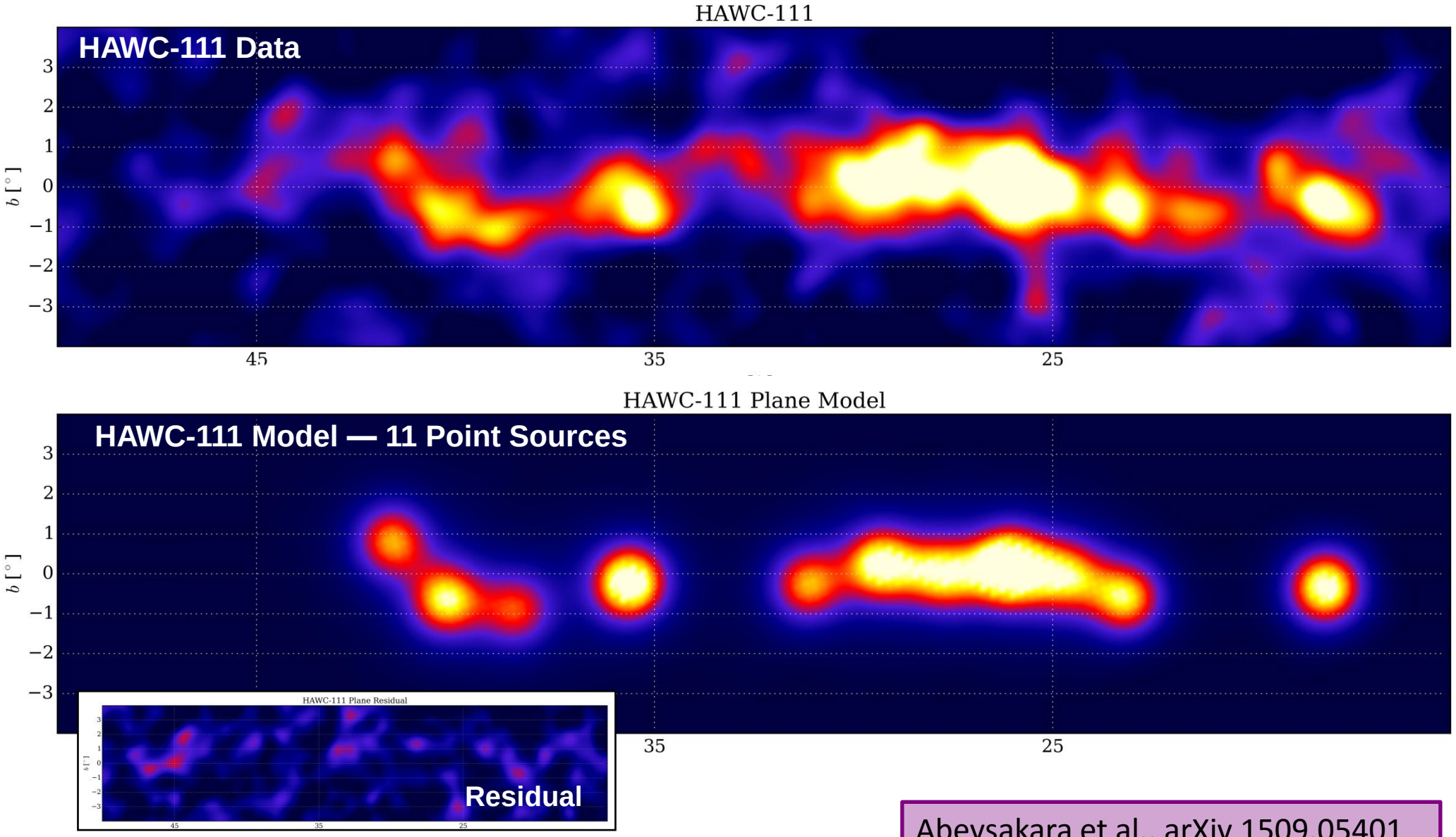
Maximum Likelihood Method

Poisson-Likelihood calculation, summed over all pixels and analysis bins



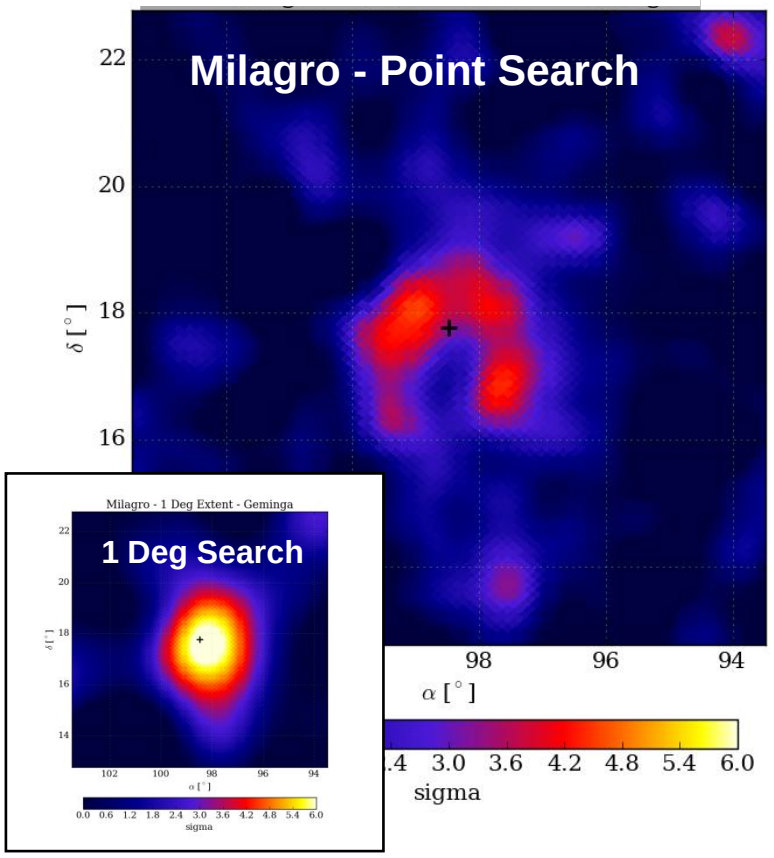
Abeysakara et al., arXiv 1509.05401
accepted for publication in **ApJ**

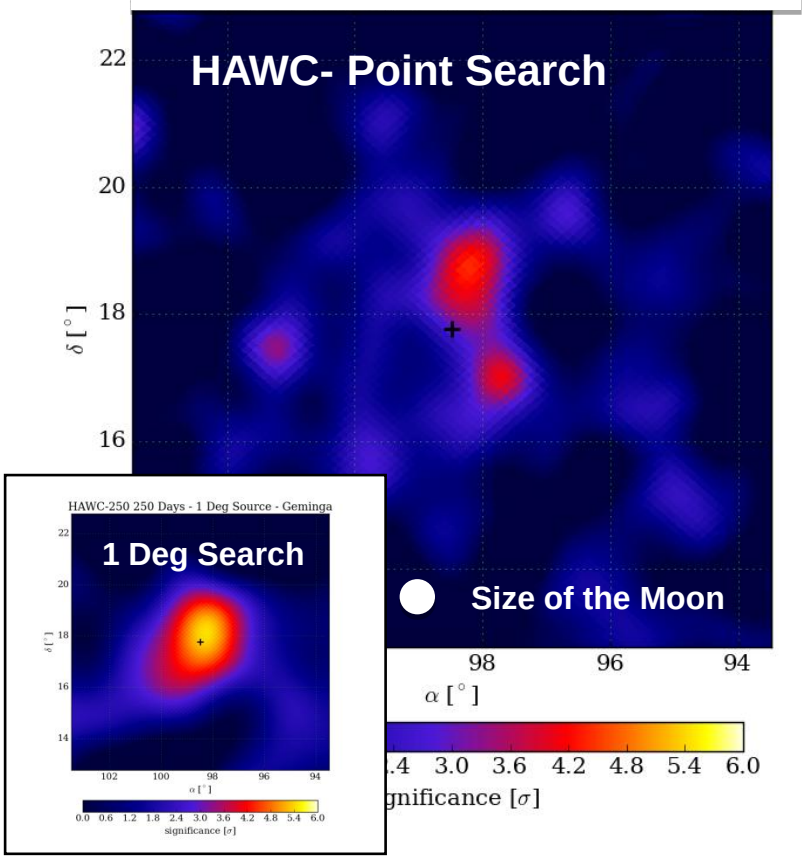
Galactic Plane Source Deconvolution



Abeysakara et al., arXiv 1509.05401
accepted for publication in **ApJ**

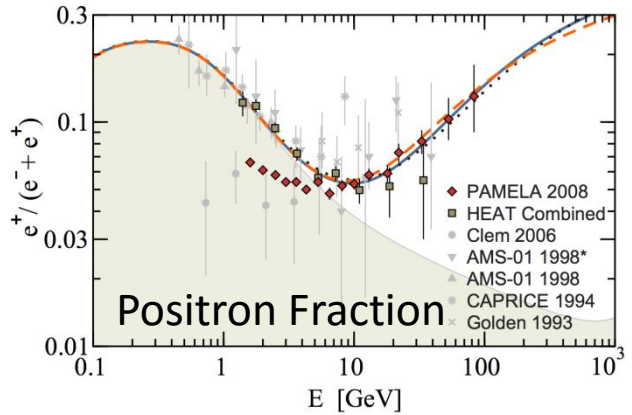
Geminga: A nearby particle accelerator

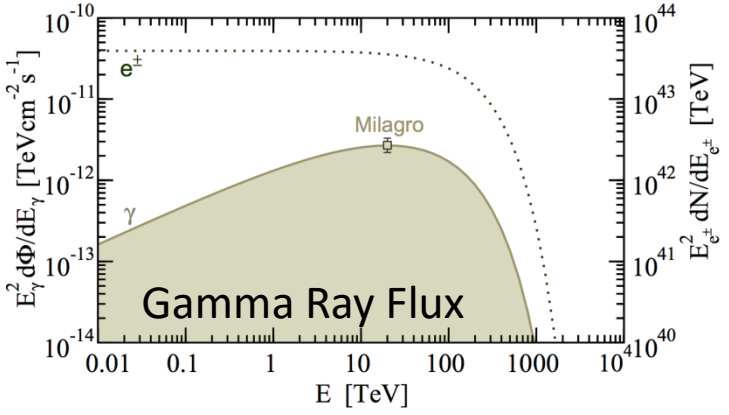




Preliminary
Top-hat smoothed significance map

Likelihood analysis of extended morphology under development

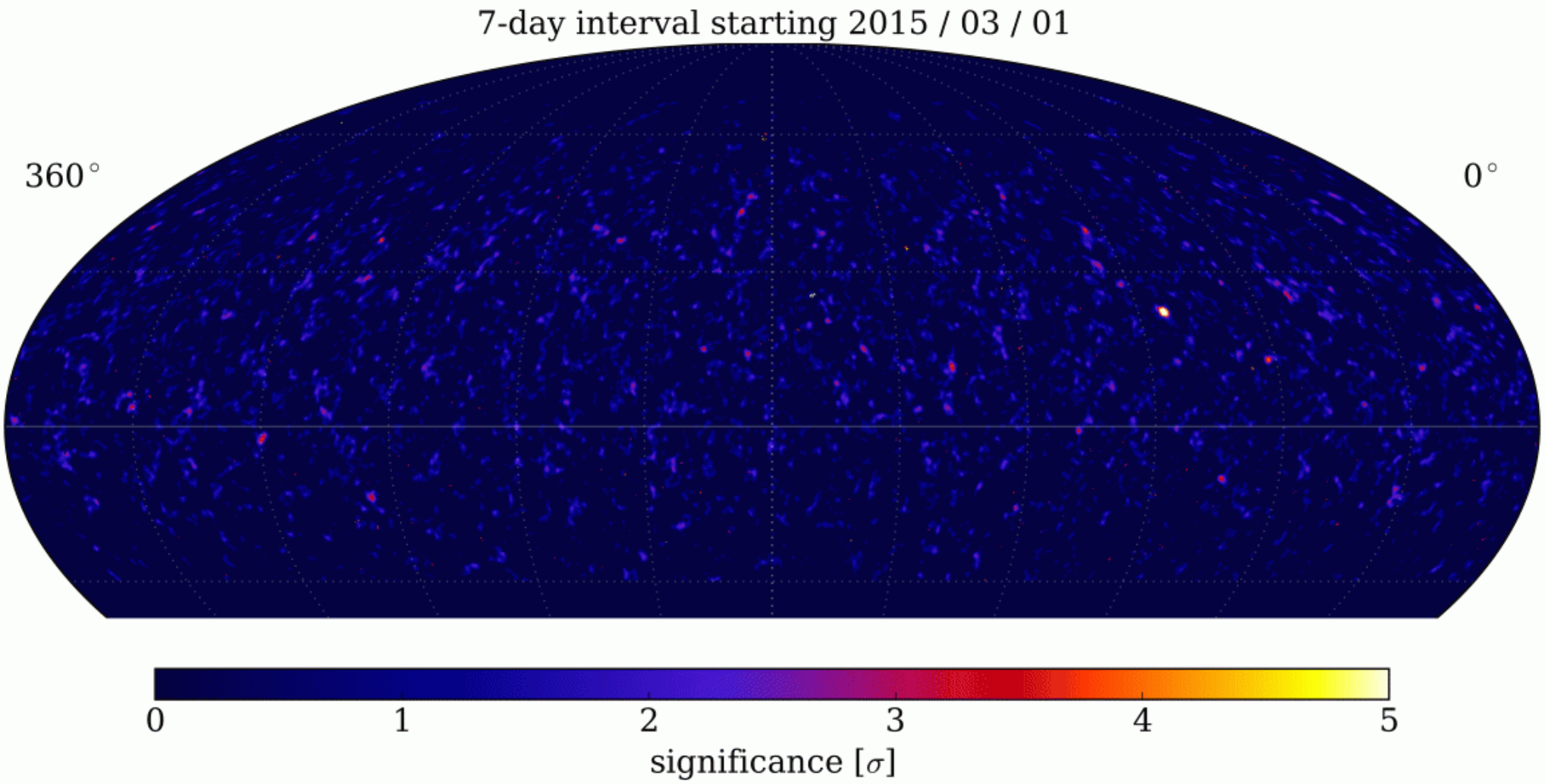




Contributor to the Positron Excess?

Yuksel, Kistler & Stanev, PRL. (2009)

Weekly sky maps from March 2015

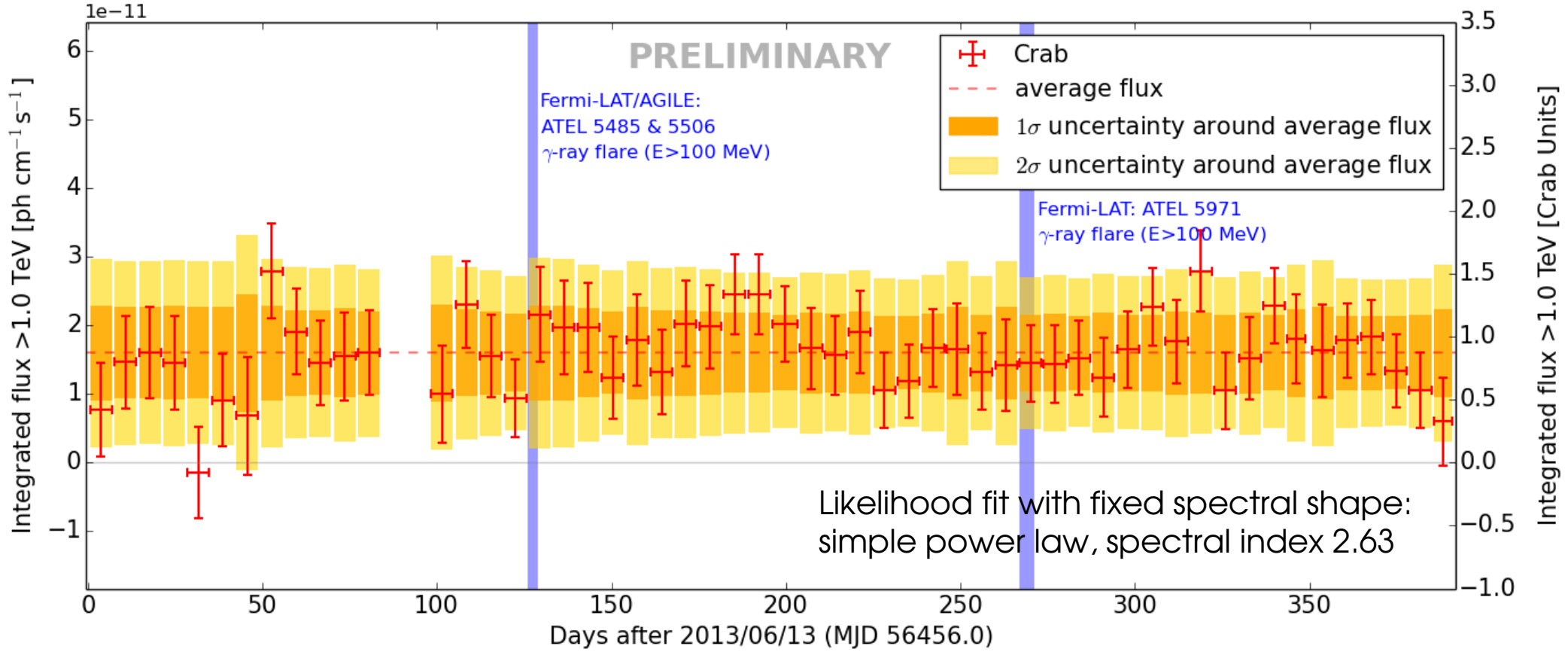


HAWC significance map for March 2015, 7-days per frame, shifted by 1 day

HAWC is monitoring over 2/3 of the sky for up to 6 hours per day

Crab Nebula light curve

HAWC-111 data from **June 13, 2013 to July 9, 2014**, binned in 7-day intervals.



Likelihood variability method (similar to 2FGL) with constant flux hypothesis:
p-value for steady source model: 0.5 → consistent with being a steady source

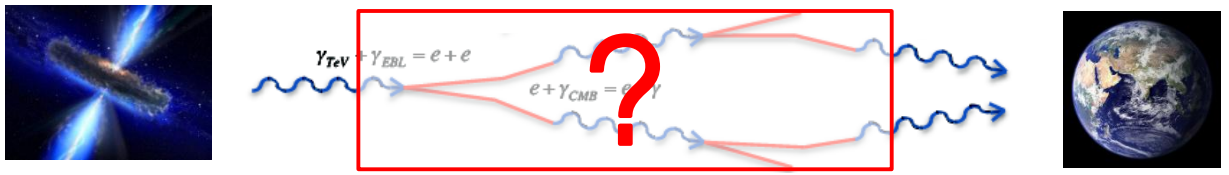
Flux normalization also consistent with TeV fluxes measured by IACTs.

Monitoring Active Galactic Nuclei (AGN)

AGN studies with unbiased flare data:

- **Flaring duty cycle** → acceleration mechanism
- **Orphan flare search** → decoupled second peak from hadronic acceleration
- **Flare alerts** → trigger multi-wavelength follow-ups

Cosmological features illuminated by bright flare emission:



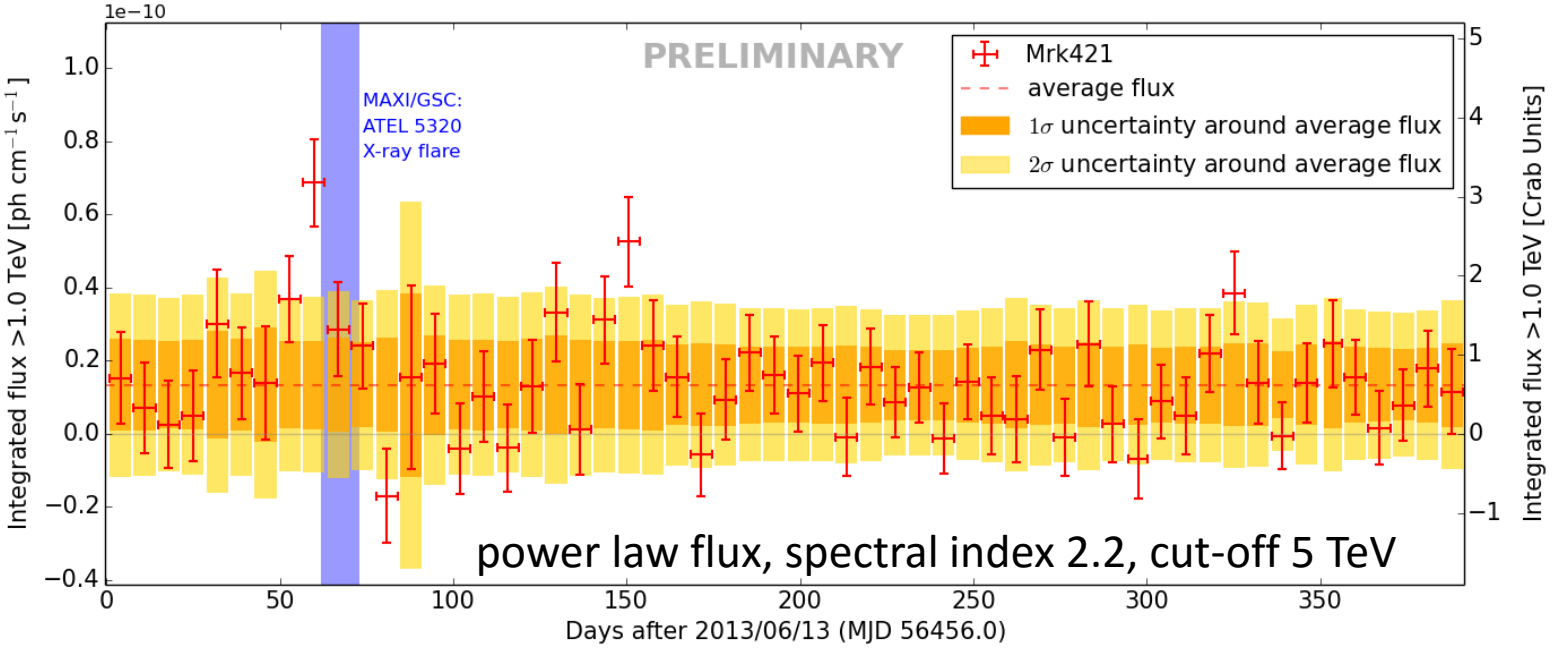
- **Extra-galactic background light** (EBL) studies:
  TeV cut-off due to absorption, probing evolution of infrared light emission
- **Axion-like dark matter** searches:
  reduced photon absorption due to conversion to/from axion-like particles
- **Inter-galactic magnetic field** searches:
  delayed/diffused lower energy emission pair production and deflection
- **Lorentz invariance violation** tests:
  delayed photons at lower energies due to energy-dependent speed

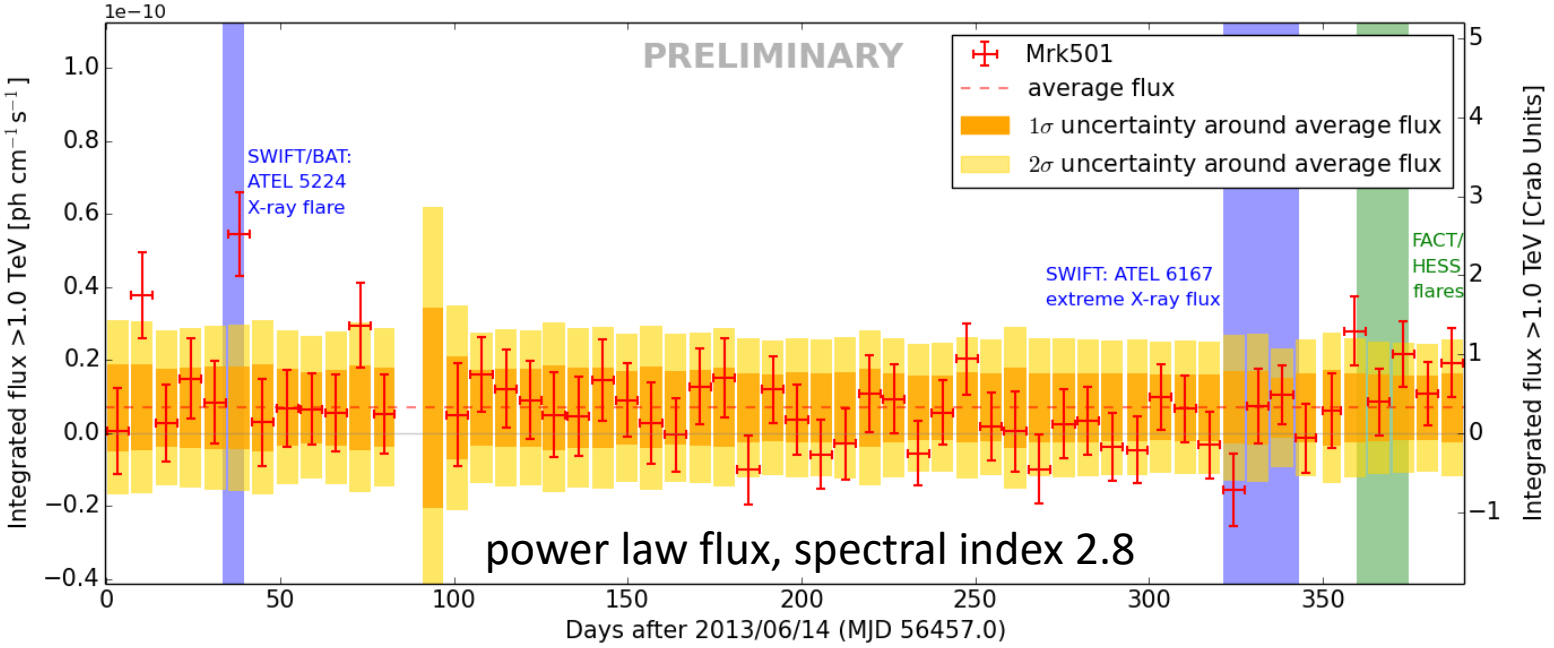
Mrk 421 and Mrk 501 flux light curves

HAWC-111 data
June 13, 2013
to July 9, 2014

Mrk 421:
Constant flux hypothesis
p-value: 0.0031
→ **excluded at 99% C.L.**

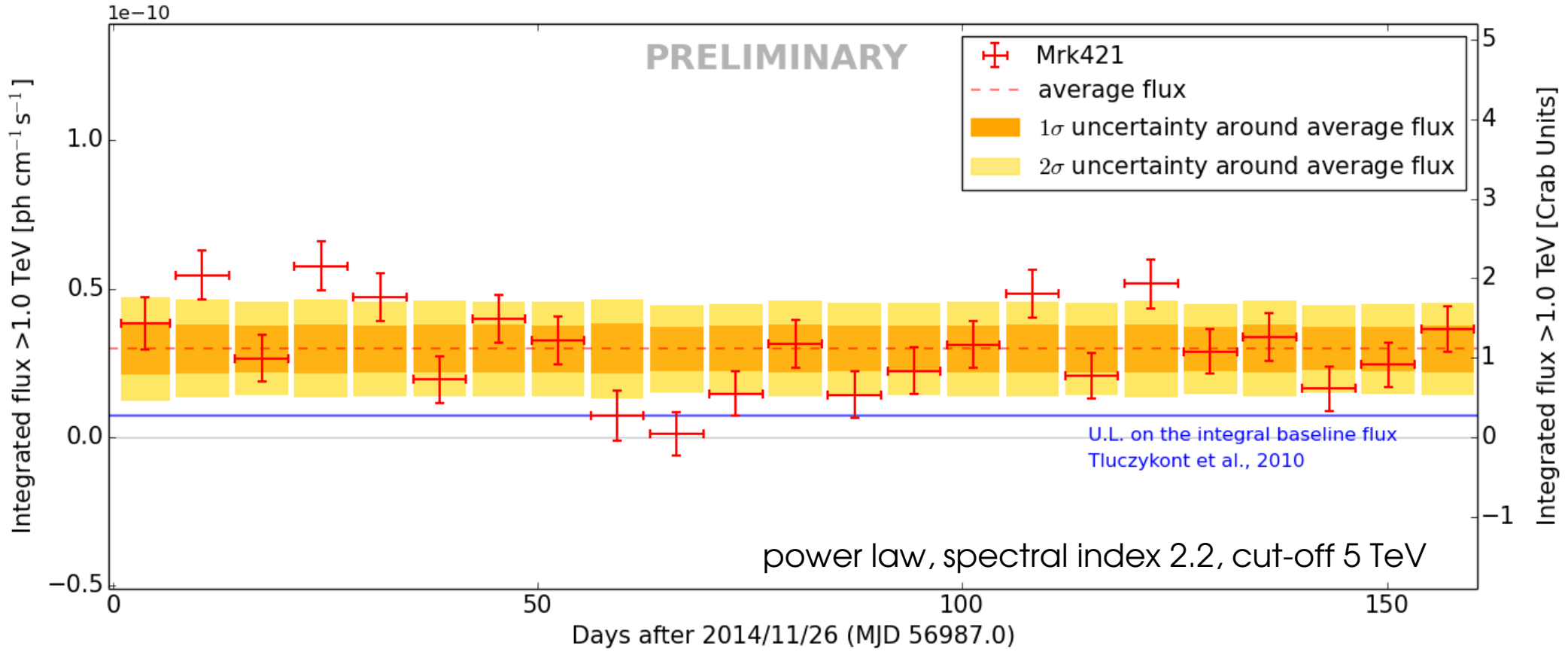
Mrk 501:
Constant flux hypothesis
P-value: 0.0299
→ **disfavored at 97% C.L.**





Latest Mrk 421 flux light curve

HAWC data from **Nov. 26, 2014 to May 6, 2015**, binned in 7-day intervals.



Constant flux hypothesis p-value: 1.6 *10 (5.6σ)

Average flux larger than 1 Crab Unit. Very high flux states observed in December 2014, analysis in progress.

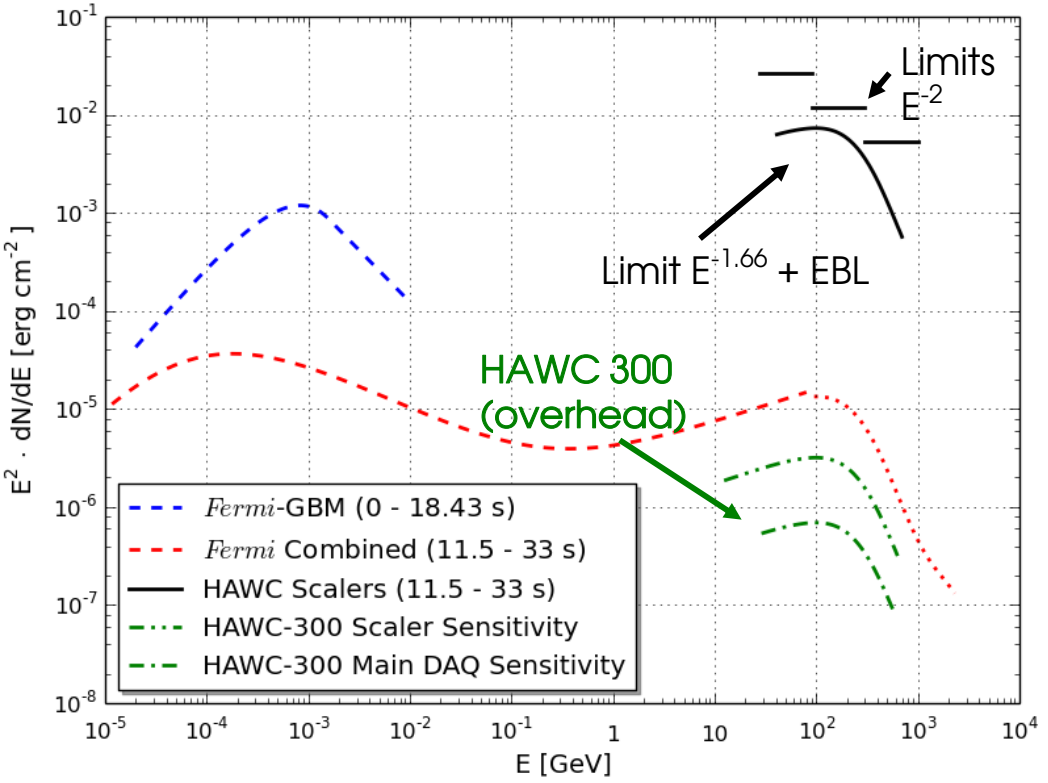
GRB and Flare Monitoring

Earliest HAWC (30 WCDs) GRB limit
(on "naked eye" **GRB 130427A**)

Abeysekara et al., 2014 ApJ 800, 70

Expect 1-2 Per year in HAWC
(extrapolating from Fermi)

Gilmore & Taboada, NIM A 2013



On-site automated searches:

- **Follow-up on SWIFT GRB alerts**
- **Untriggered all-sky GRB search**
  (designed to send out alerts,
  ~4 sec. reconstruction latency)
- **Light curve flare monitor** for selected
  extra-/galactic sources
  (ideal for very bright AGN flares)

Multi-wavelength analyses:

- HAWC can **significantly increase simultaneous TeV coverage** for transients
- We are working on **tools to perform joint analyses of multi-instrument data**: https://threeml.stanford.edu

Follow-up on IceCube neutrinos

Recent IceCube release (ATel: #7856):

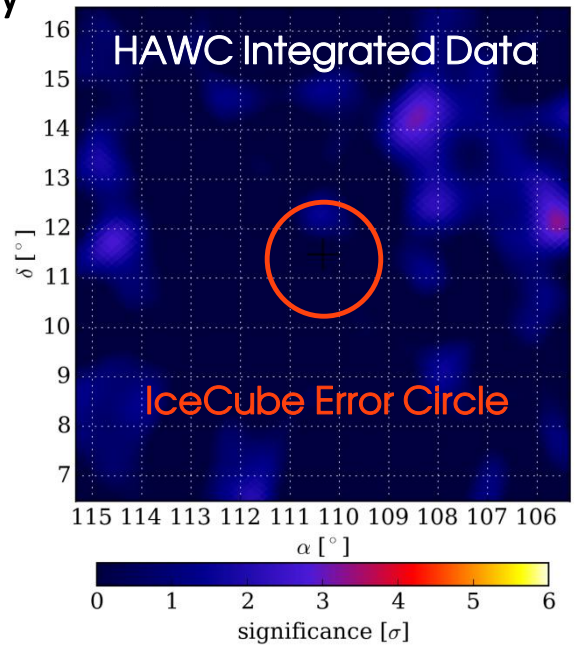
- **Muon Neutrino** with **E > 2.6 PeV**
- June 11, 2014, 4:54 UTC

If **neutrinos stem from $\pi^{+/-}$-decay**, we also expect **gamma rays from π^0-decay**

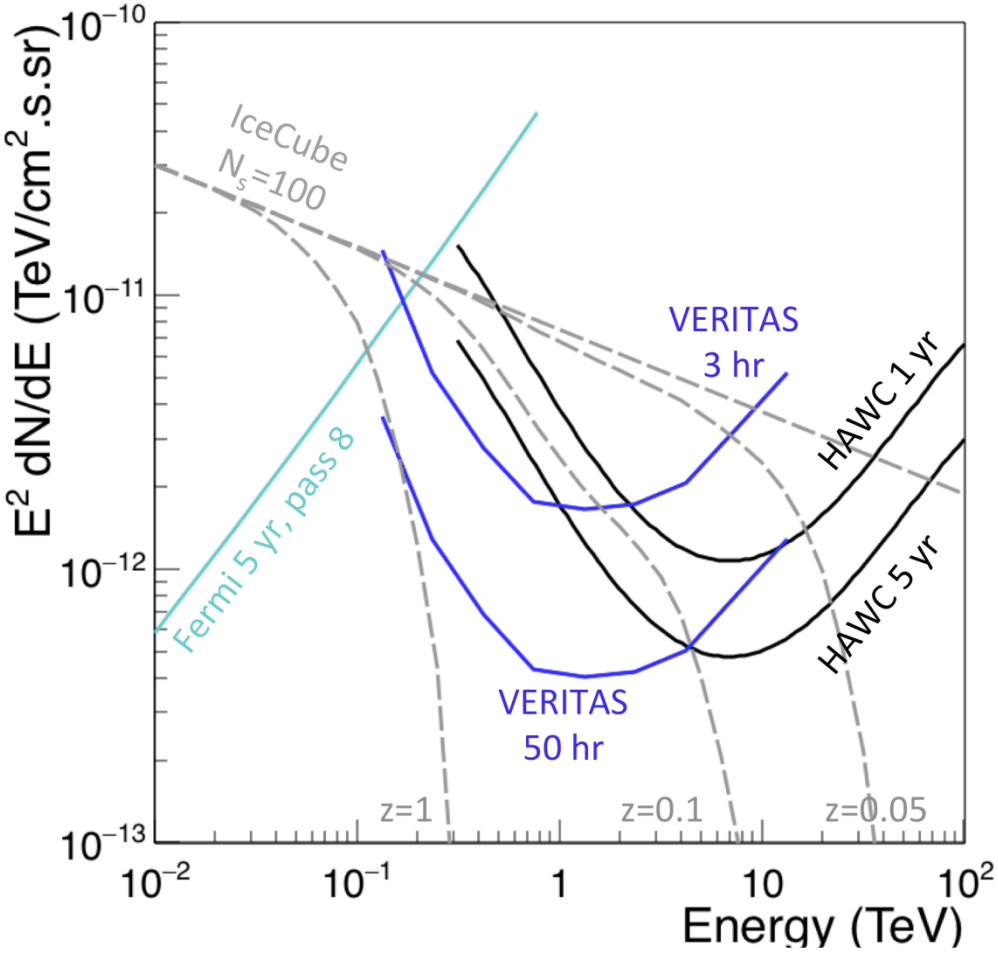
HAWC searches:

at event time, location not in HAWC FoV

- Integrated map for steady source
- Next day / prior day
- ±2 and ±5 days



All HAWC searches consistent with only background:
HAWC ATel: #7868



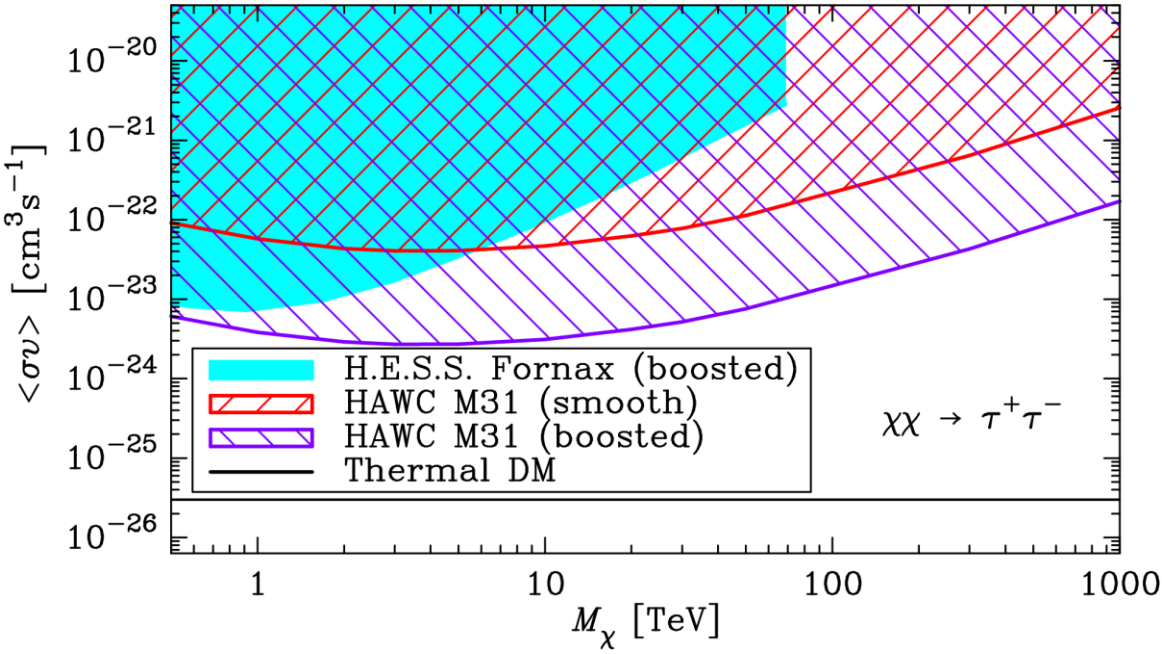
Assuming IceCube **neutrino flux is steady and originating from N_s point sources** (IceCube, PRL 2014):

$$E^2\Phi_\nu(E) = \frac{4\pi}{N_s} 1.5 \times 10^{-11} \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-0.3} \mathrm{TeV/cm^2\ s}$$

Dark matter annihilation...

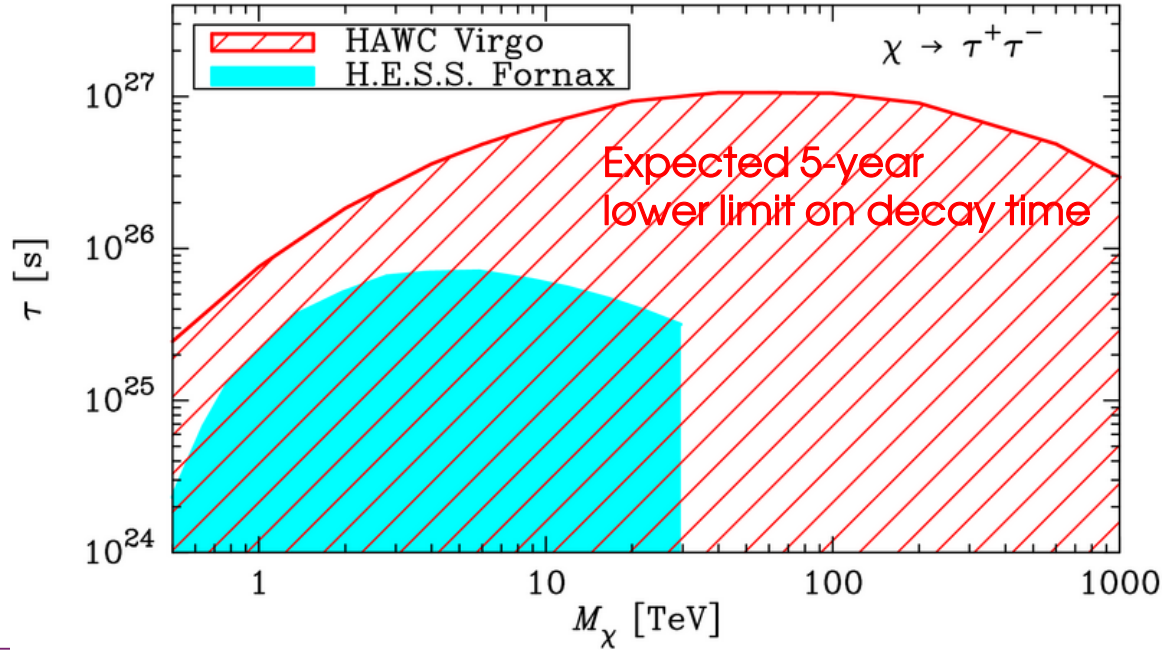
Abeysekara et al.
2014 Phys. Rev. D **90**, 122002

- Search for gamma rays emitted in **dark matter annihilation**, e.g. from $b\bar{b}$ or $\tau^+\tau^-$ chain
- Best targets: high-mass objects with low astrophysical backgrounds: **M31(Andromeda)**, Virgo cluster, **dwarf galaxies**

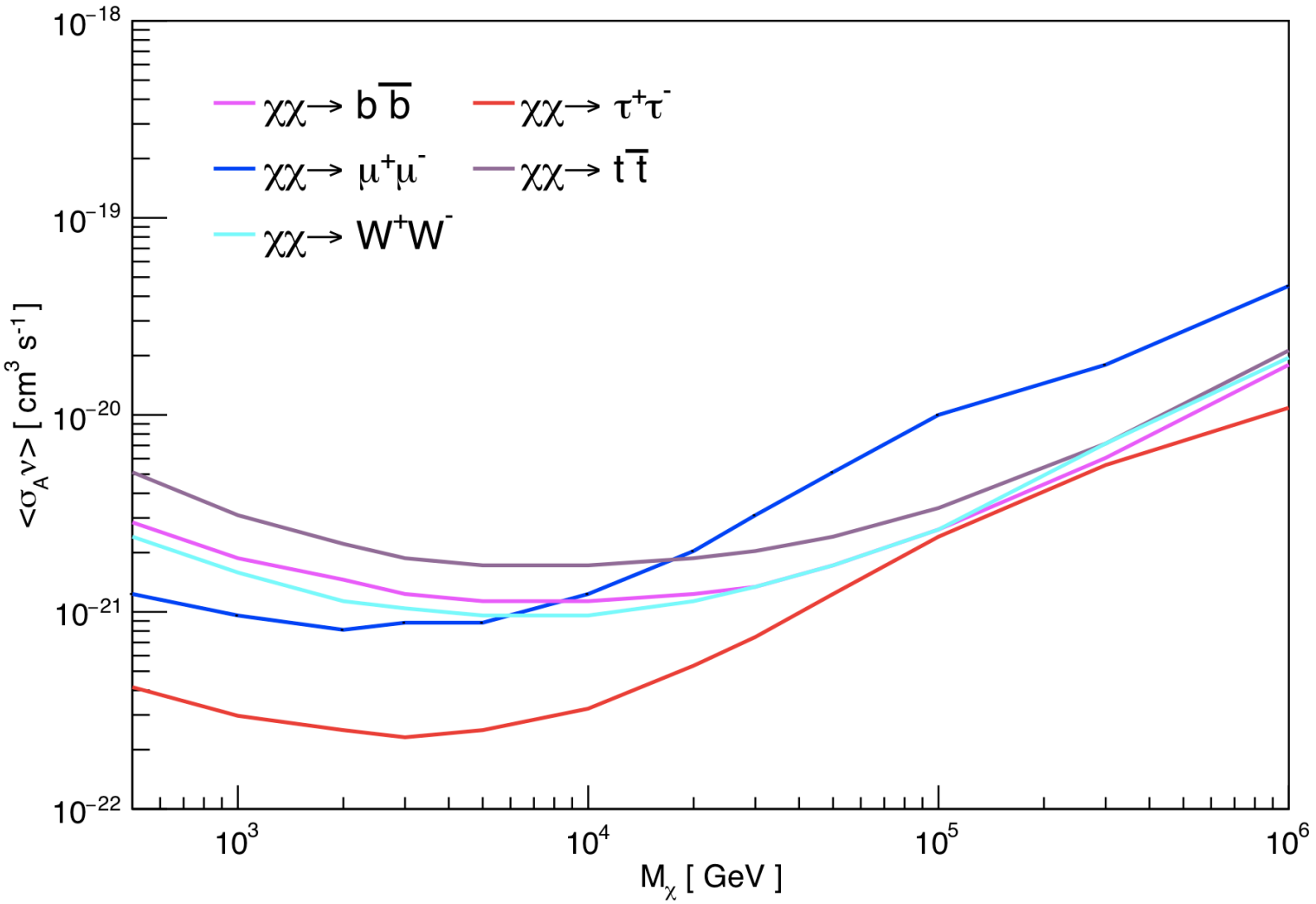


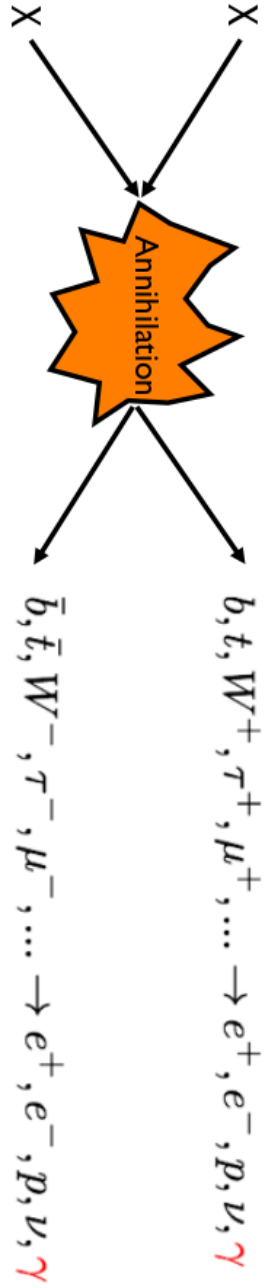
... and decay

- Search for gamma rays emitted from **decaying dark matter**
- Scales linearly with DM density: best targets are largest structures, e.g. **Virgo galaxy cluster**, M31



HAWC-111 dark matter annihilation limits



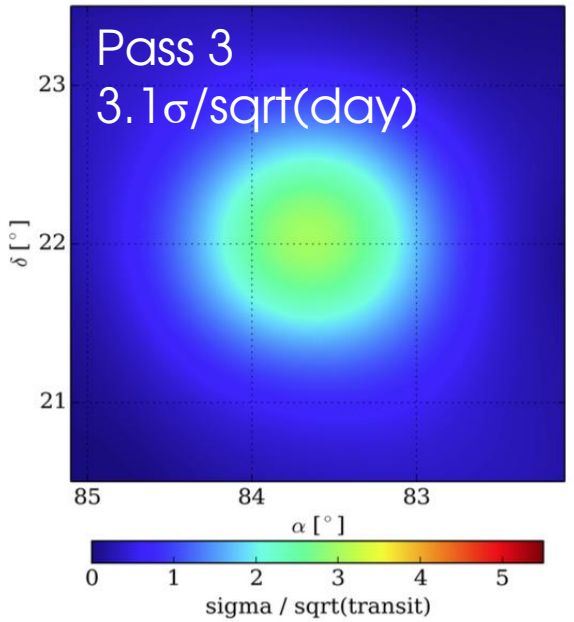


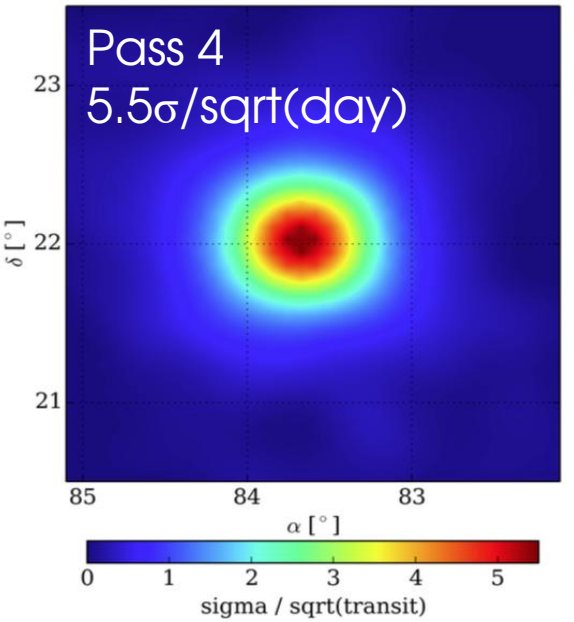
Limits on the **dark matter annihilation cross section for 5 different decay channels,** based on non-observation of gamma rays from **14 dwarf spheroidal galaxies**

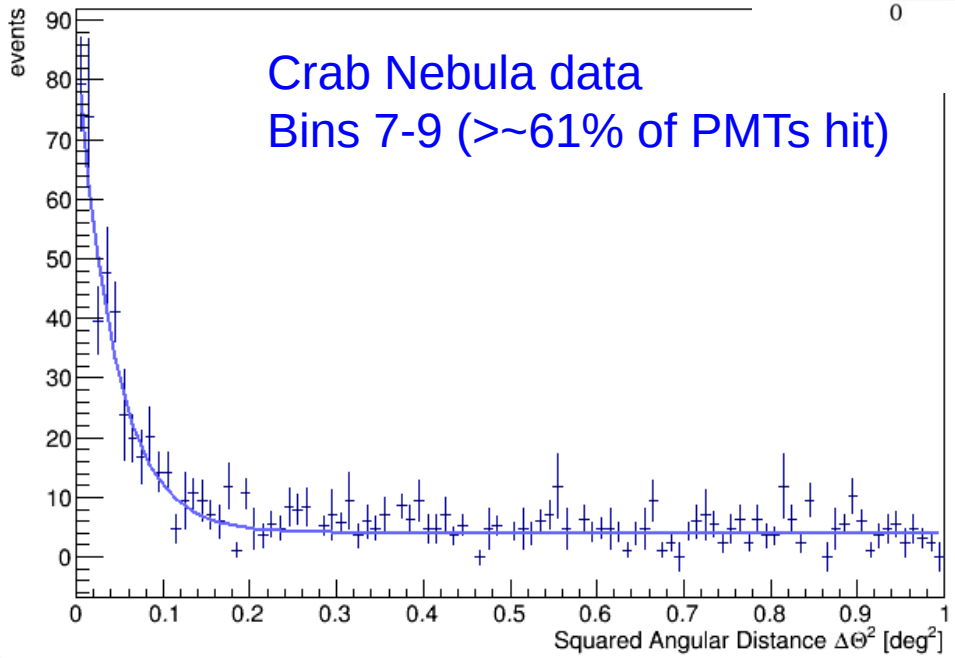
Outlook: Improved Reconstruction

Significantly improved reconstruction algorithms

- Reprocessing of all existing HAWC data in progress
- New algorithms already used in on-site reconstruction



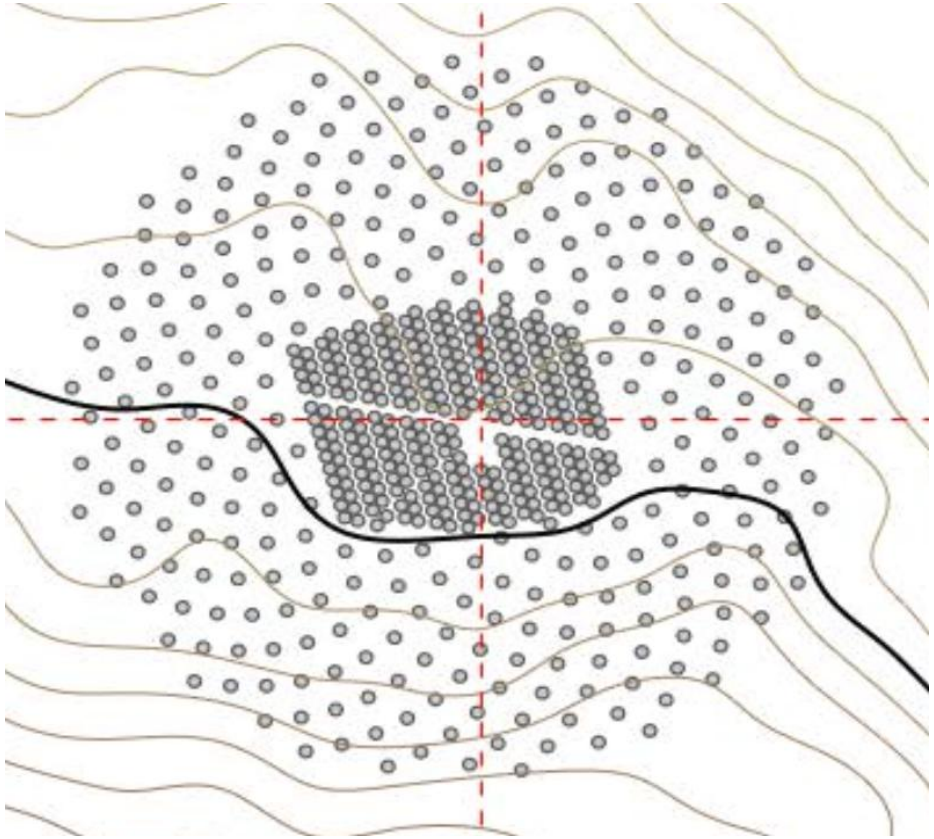


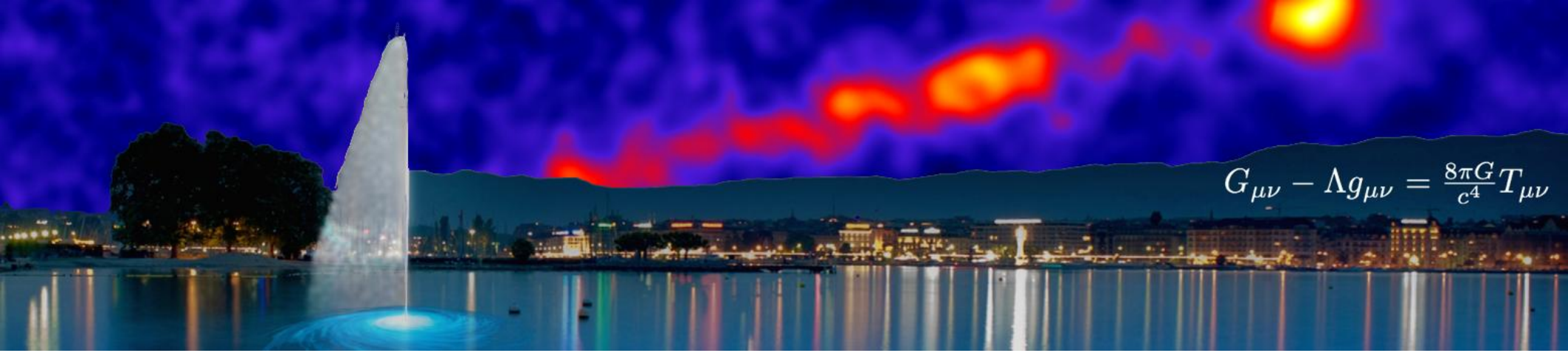


Angular resolution for large events:
Gaussian "sigma" ~ 0.15°
68% containment: 0.24°
Achieving design resolution

Outlook: Outrigger Extension

- **HAWC Sparse Outrigger Array**: Enhanced Sensitivity above 10 TeV
- Accurately determine **core position for showers off the main array**
- Increase effective area **above 10 TeV by 3-4x**
- Funded by Los Alamos National Laboratory / Mexico
- 2500 liter WCDs: 1/80th size of HAWC WCDs





Summary

- **HAWC is scanning TeV phenomena over 2/3 of the sky every day.**

- **HAWC is a unique TeV instrument for:**
  - **studying extended sources**
  - **surveying wide regions**
  - **monitoring transients**

- **Stay tuned for results from the first year of operating the full array.**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Thank you!