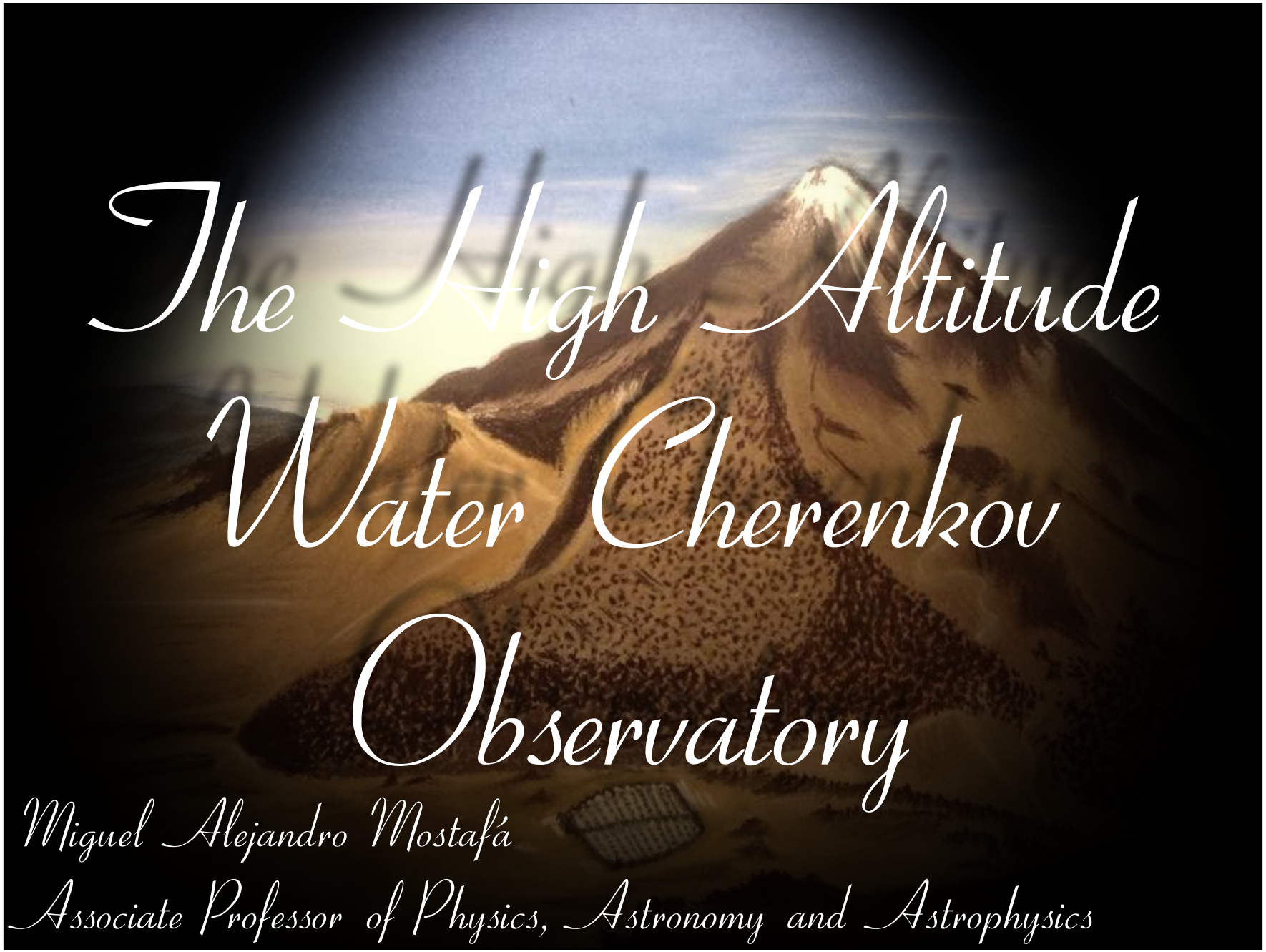


The High Altitude Water Cherenkov Observatory

Miguel Alejandro Mostafá

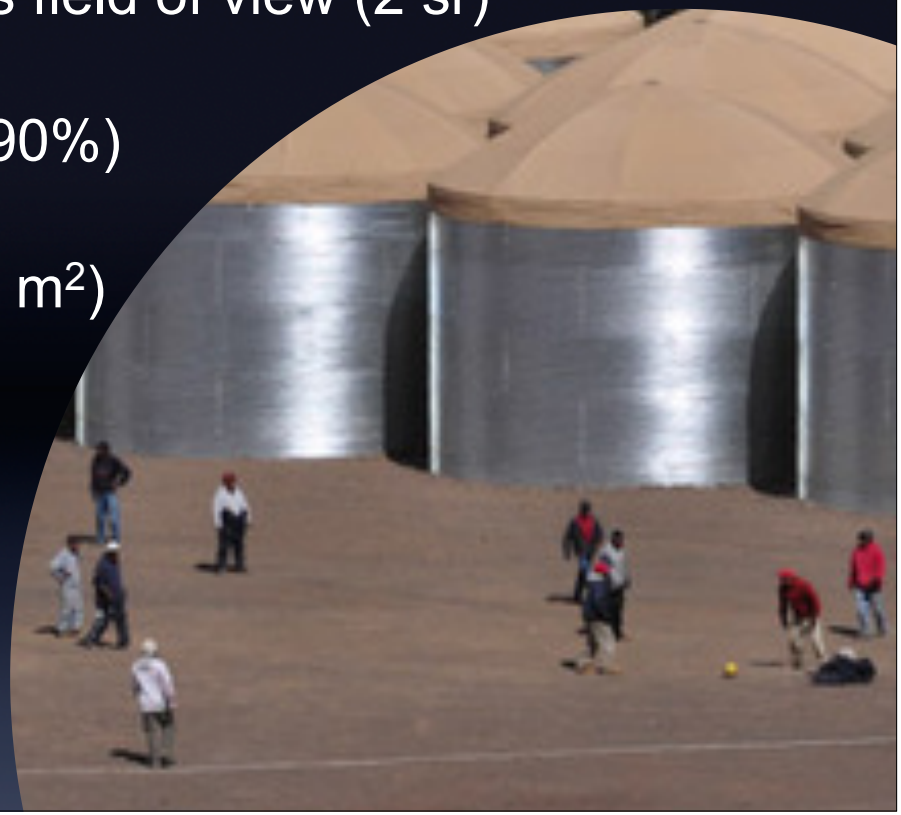
Associate Professor of Physics, Astronomy and Astrophysics

Outline

1. Motivation for VHE γ rays
2. The HAWC Observatory
3. Preliminary first results
4. Outlook

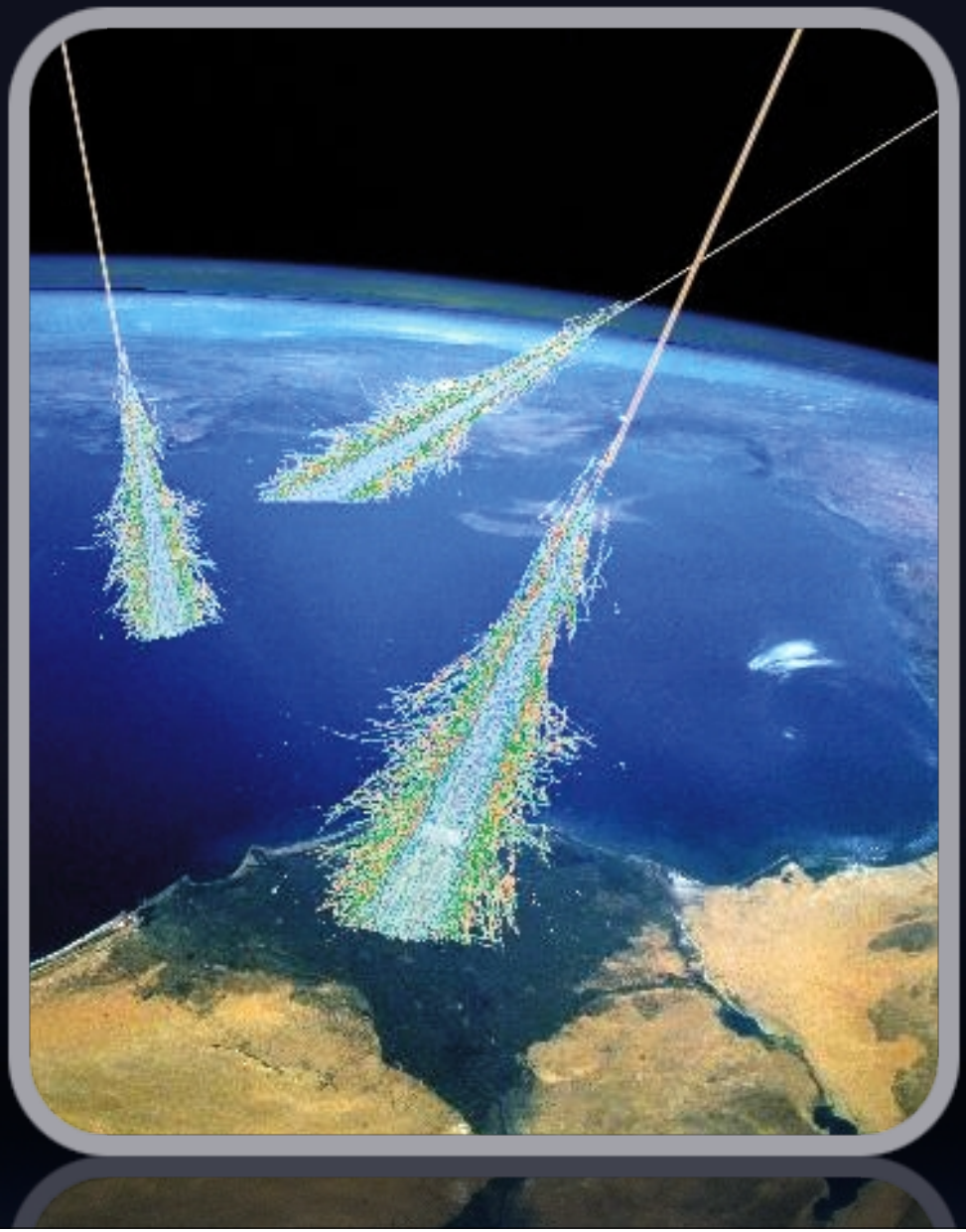
Introduction

- 2nd generation water Cherenkov
- Wide instantaneous field of view (2 sr)
- High duty cycle (> 90%)
- Large area (22,000 m^2)



Cosmic Rays

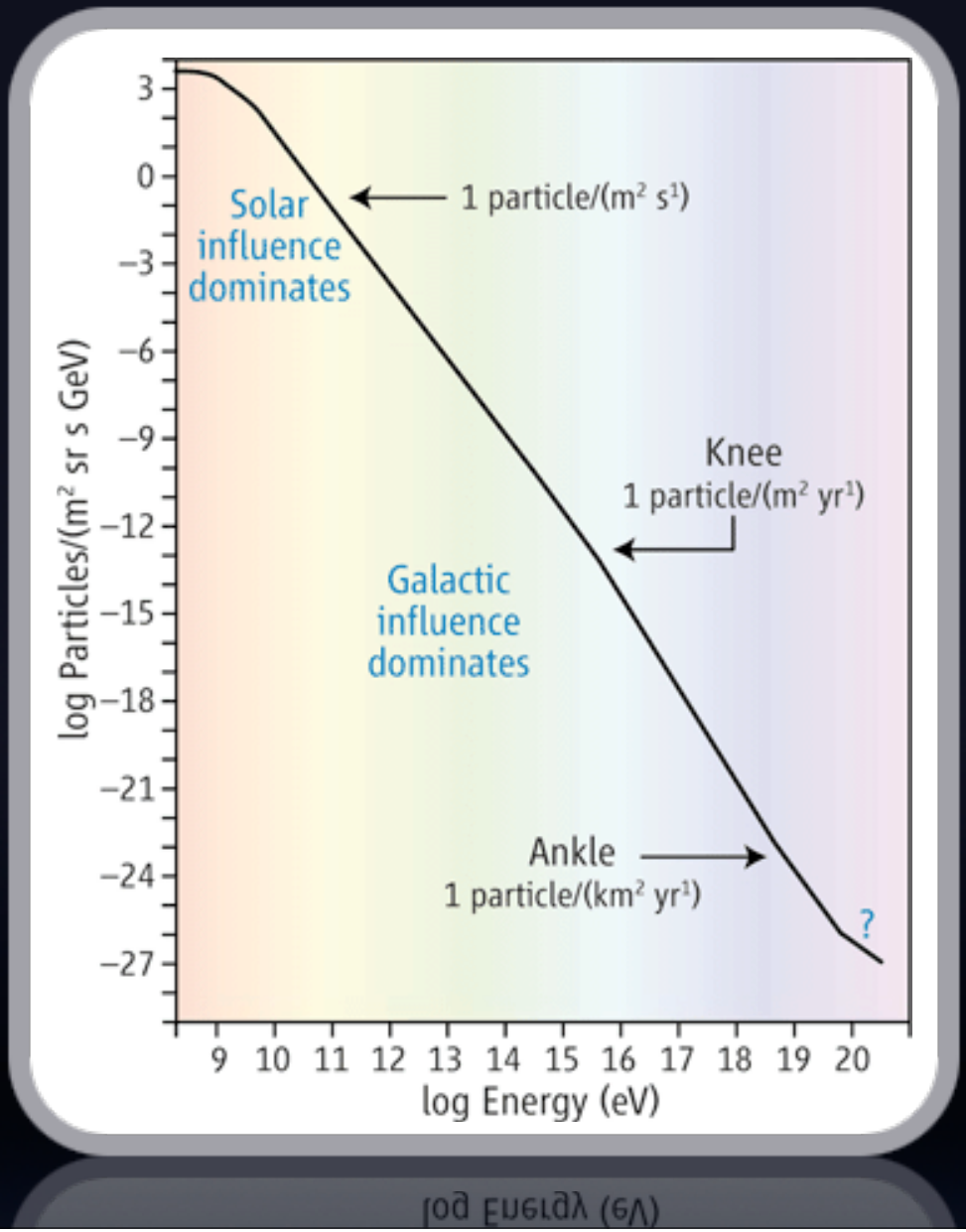
- *All the time*
  you are being hit by a **flux of high energy particles** from above!



Cosmic Ray Flux

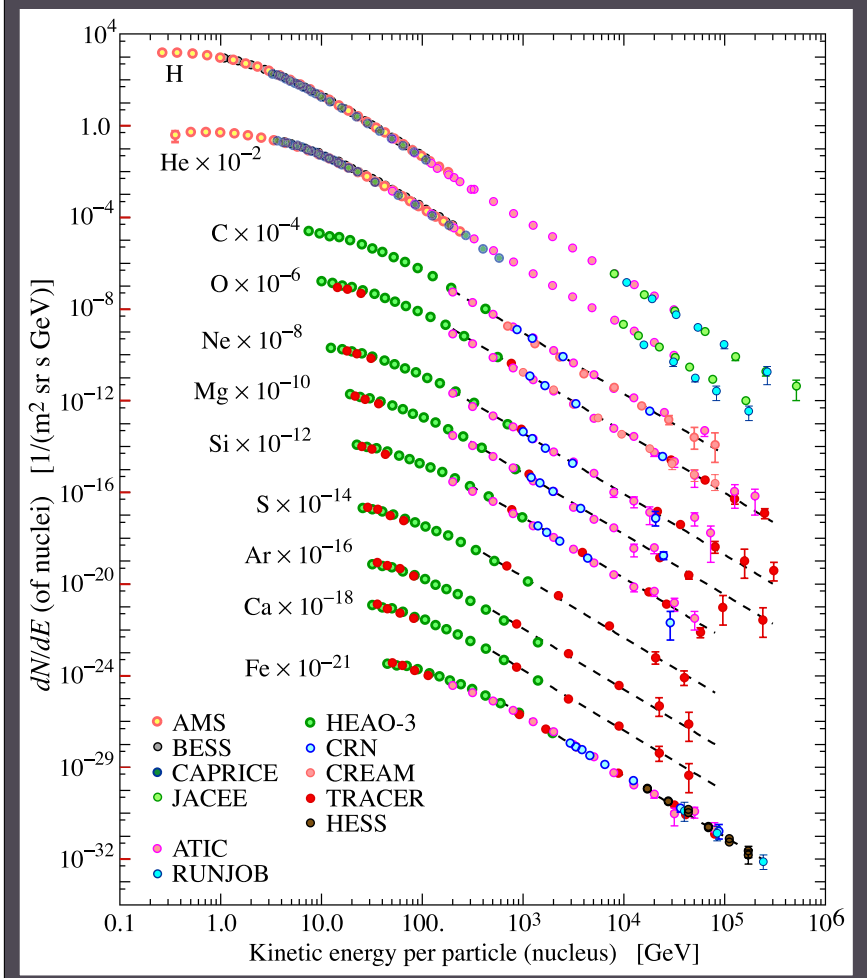
- At low E, solar magnetic fields strongly influence CR propagation
- At high E, the minimally deflected CRs are far less intense and thus much harder to detect.

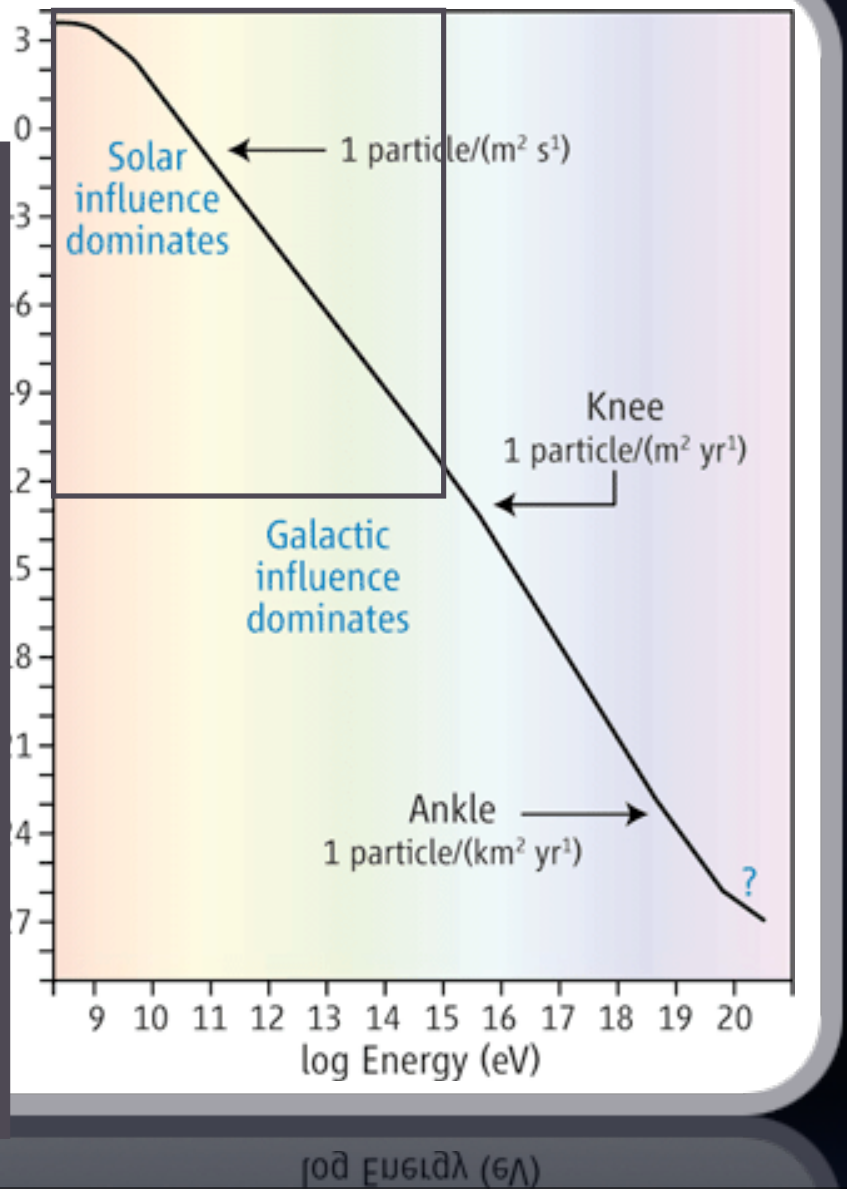
Duldig, Science **314** (2006) 429-430



Duldig, Science **314** (2006) 429-430

J. Beringer et al. (Particle Data Group)
Phys. Rev. **D86**, 010001 (2012)





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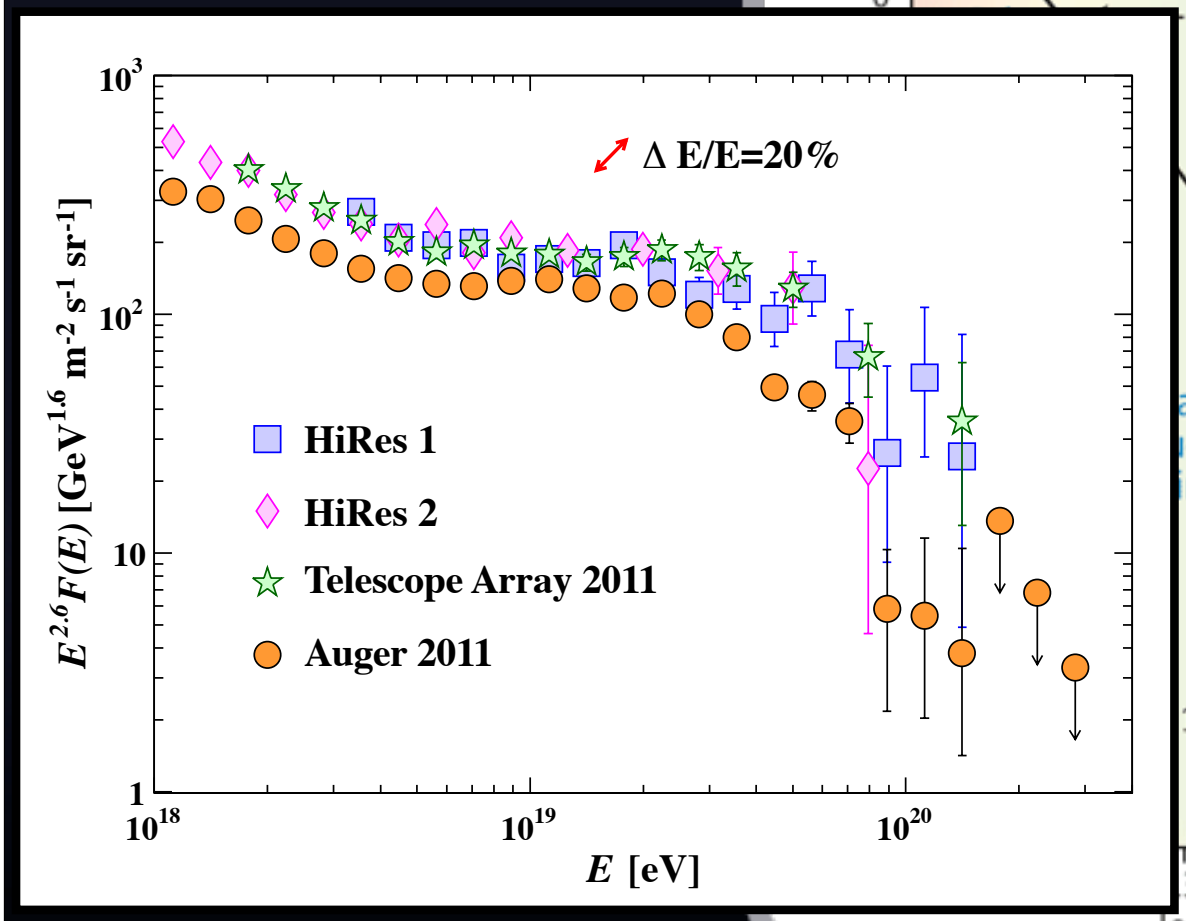
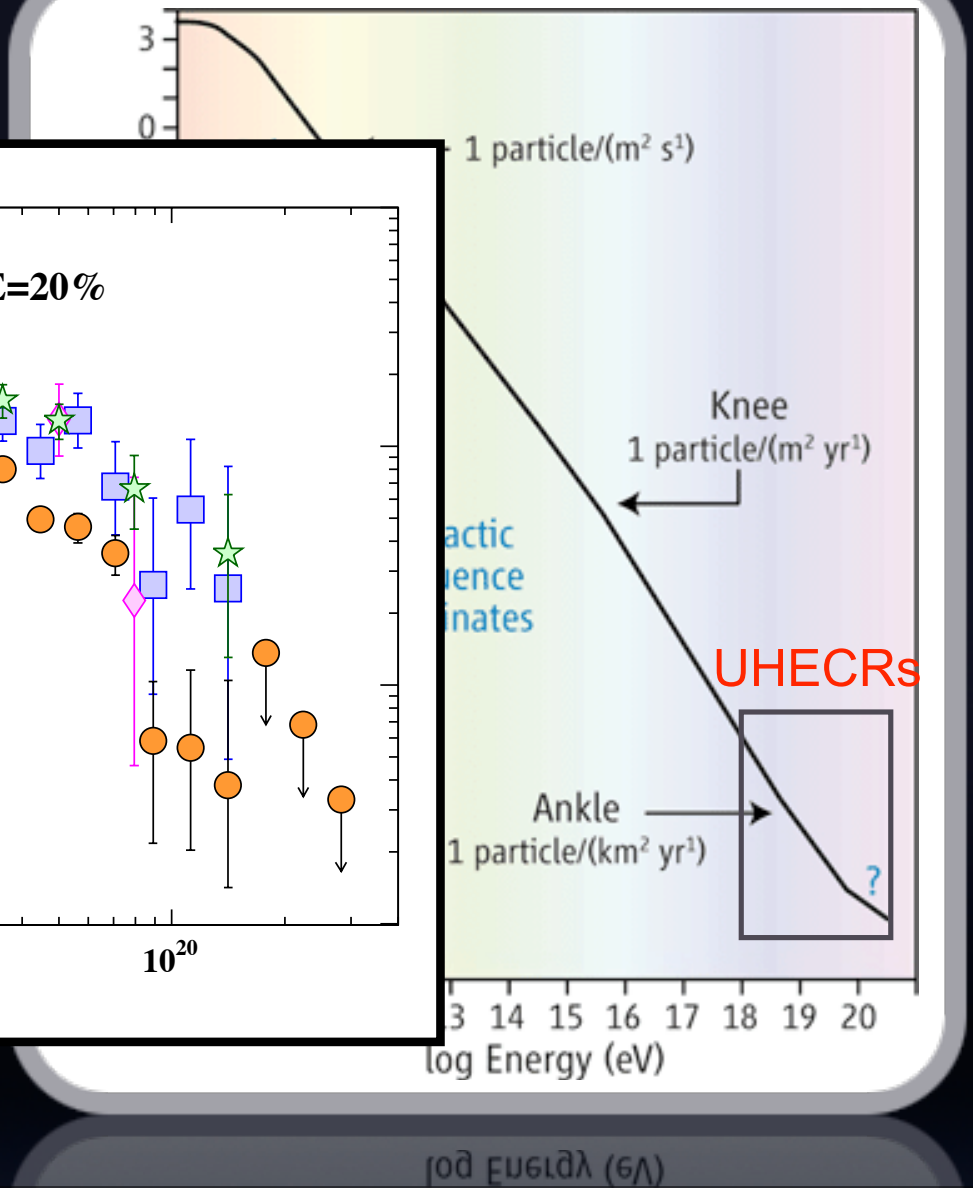
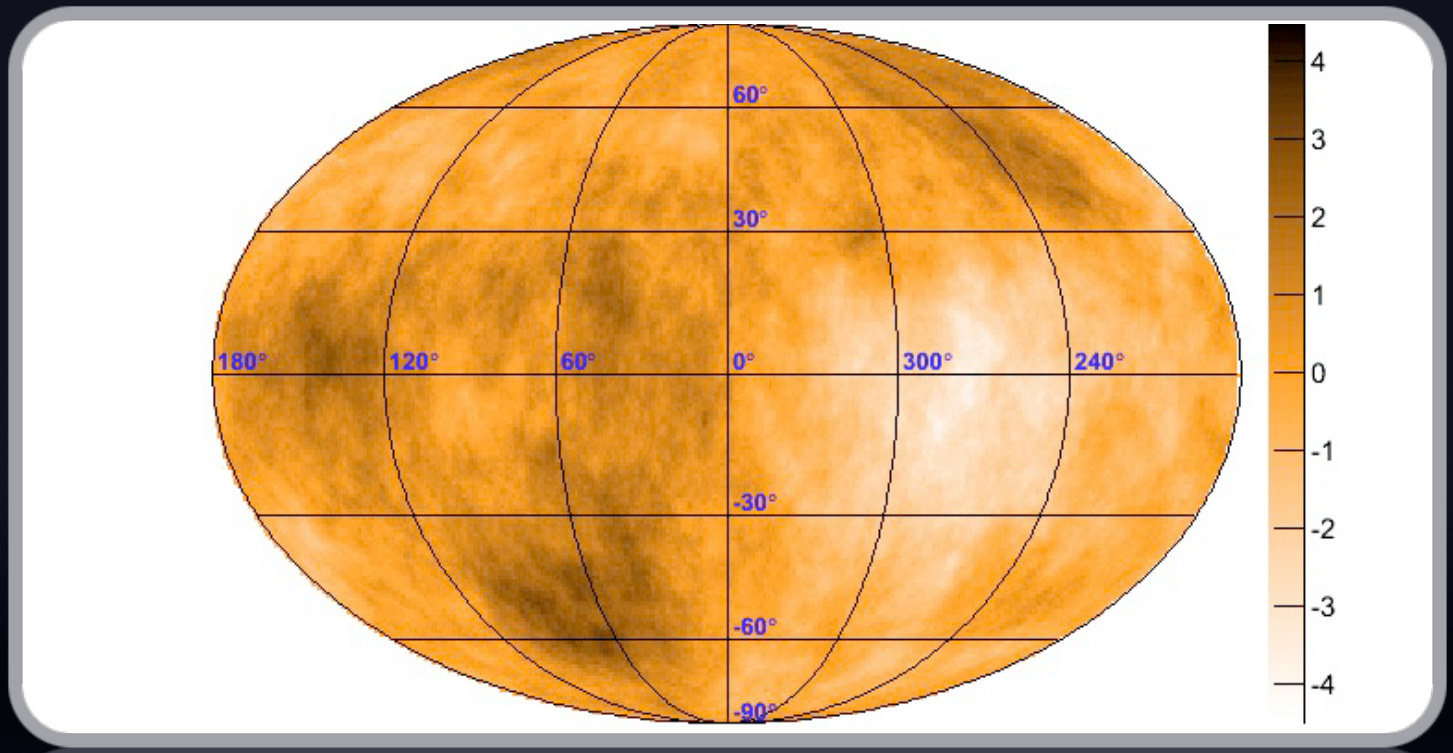
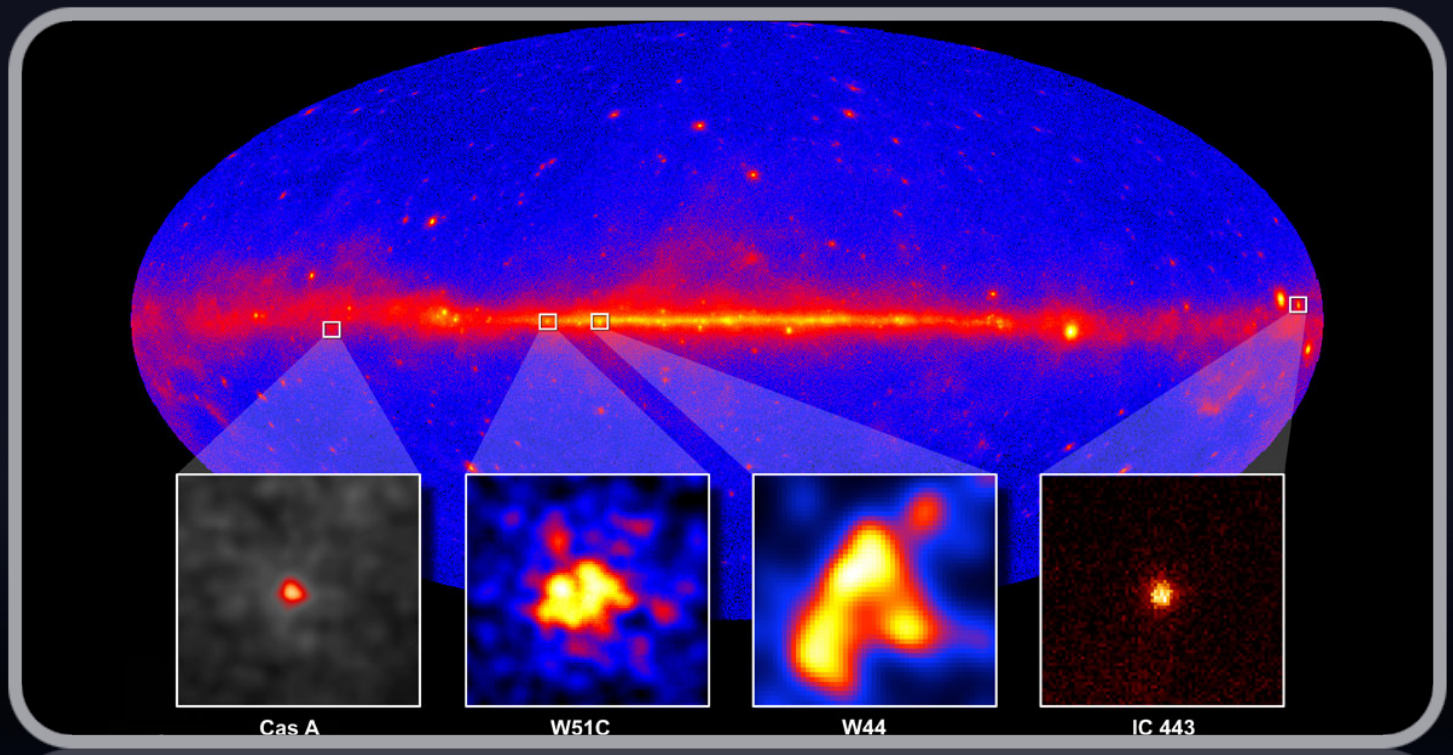




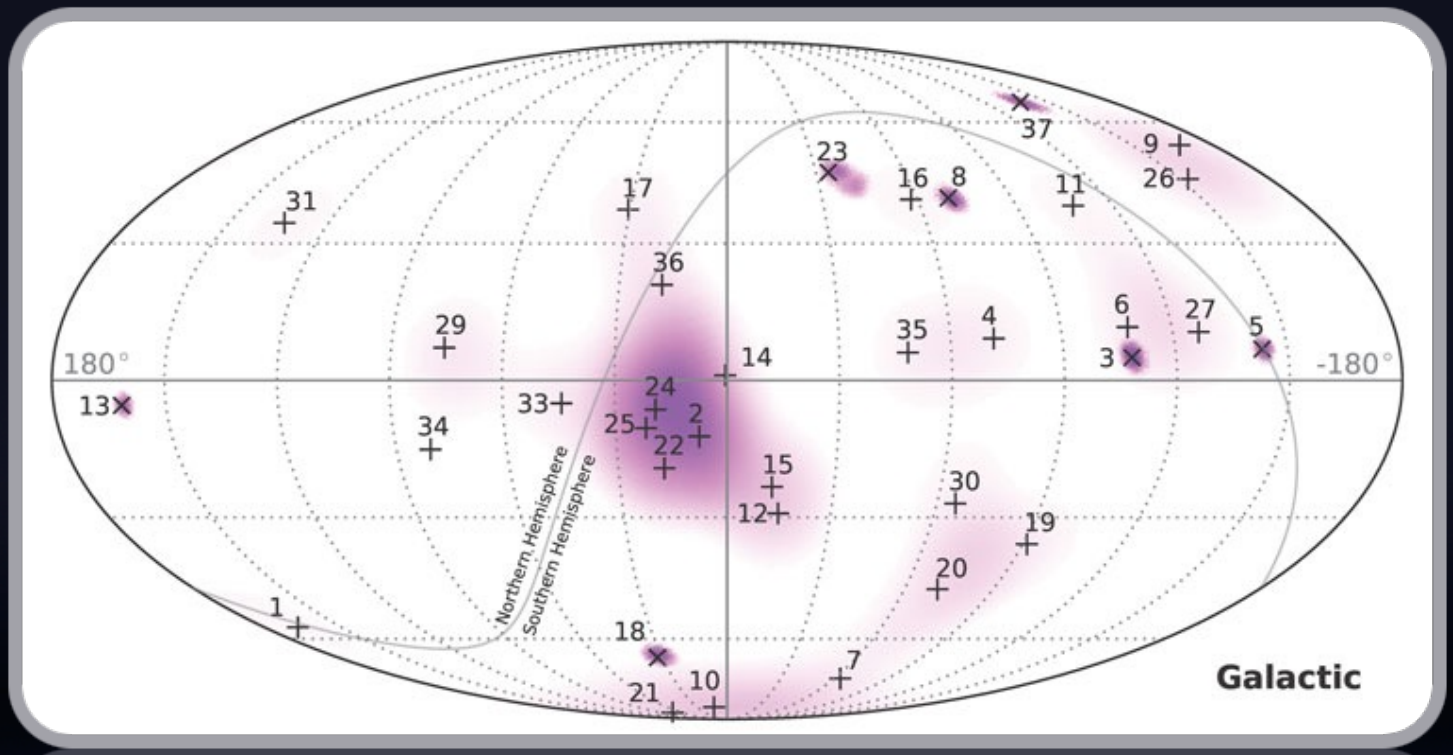
E > 10 EeV; 30° smoothing



UHECR sky map

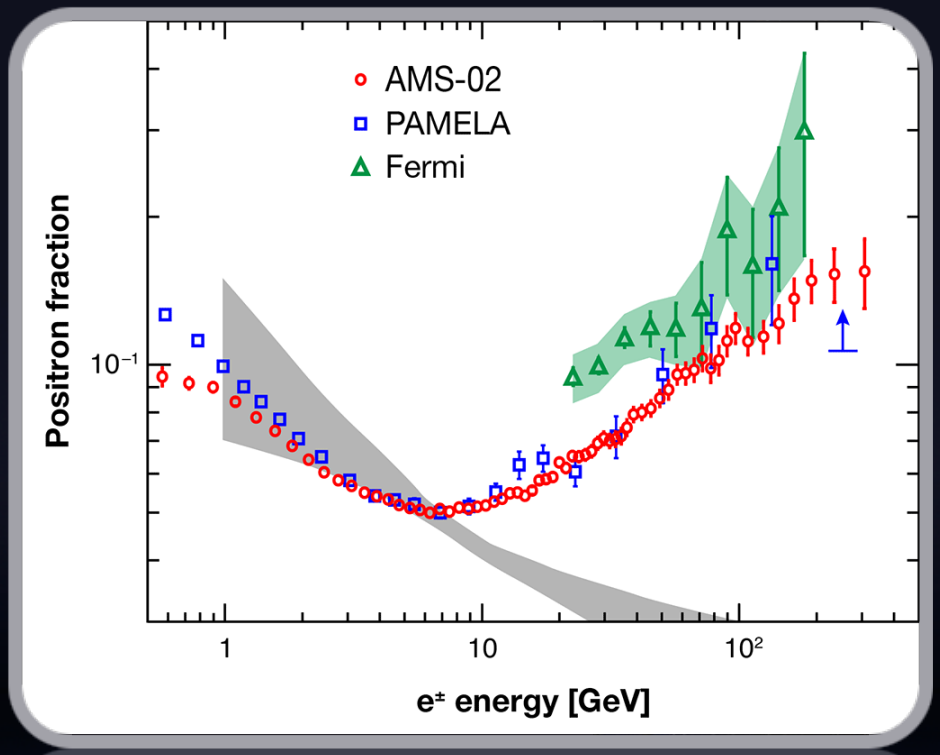


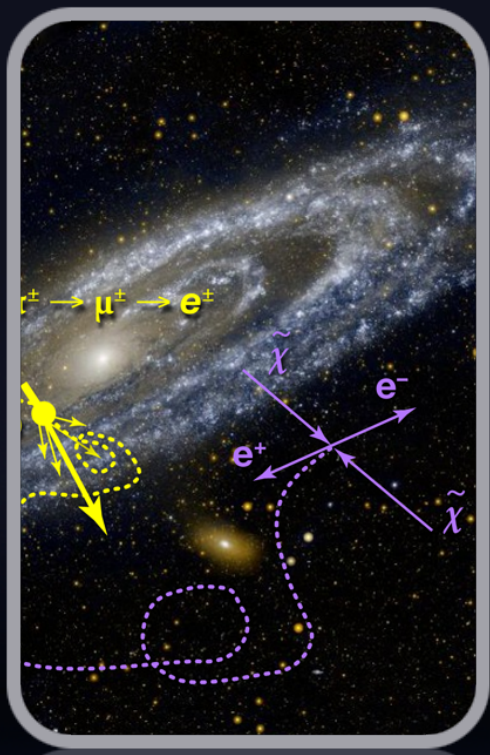
GeV γ-ray sky map



Astrophysical ν sky map

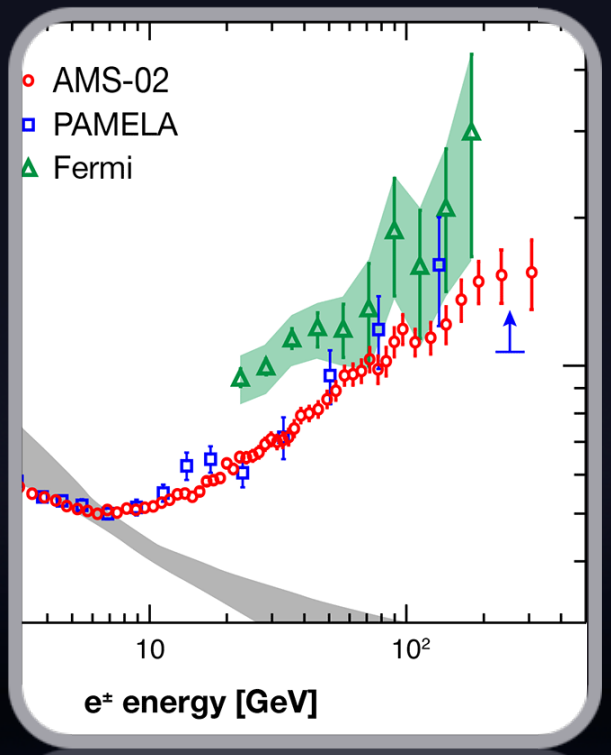
Positron Excess

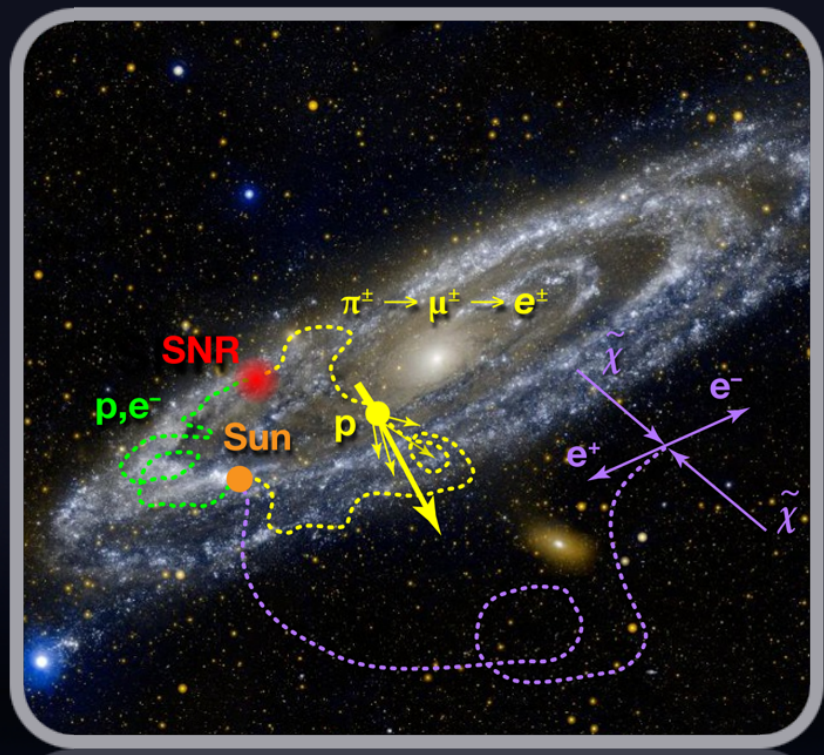




Credit: Plot: M. Aguilar et al. [AMS Collaboration] Phys. Rev. Lett. 110, 141102 (2013); Grey region: Astrophys. J. 254, 391 (1982); Astrophys. J. 493, 693 (1998); Astron. Astrophys. 524, A51 (2010)

Positron Excess



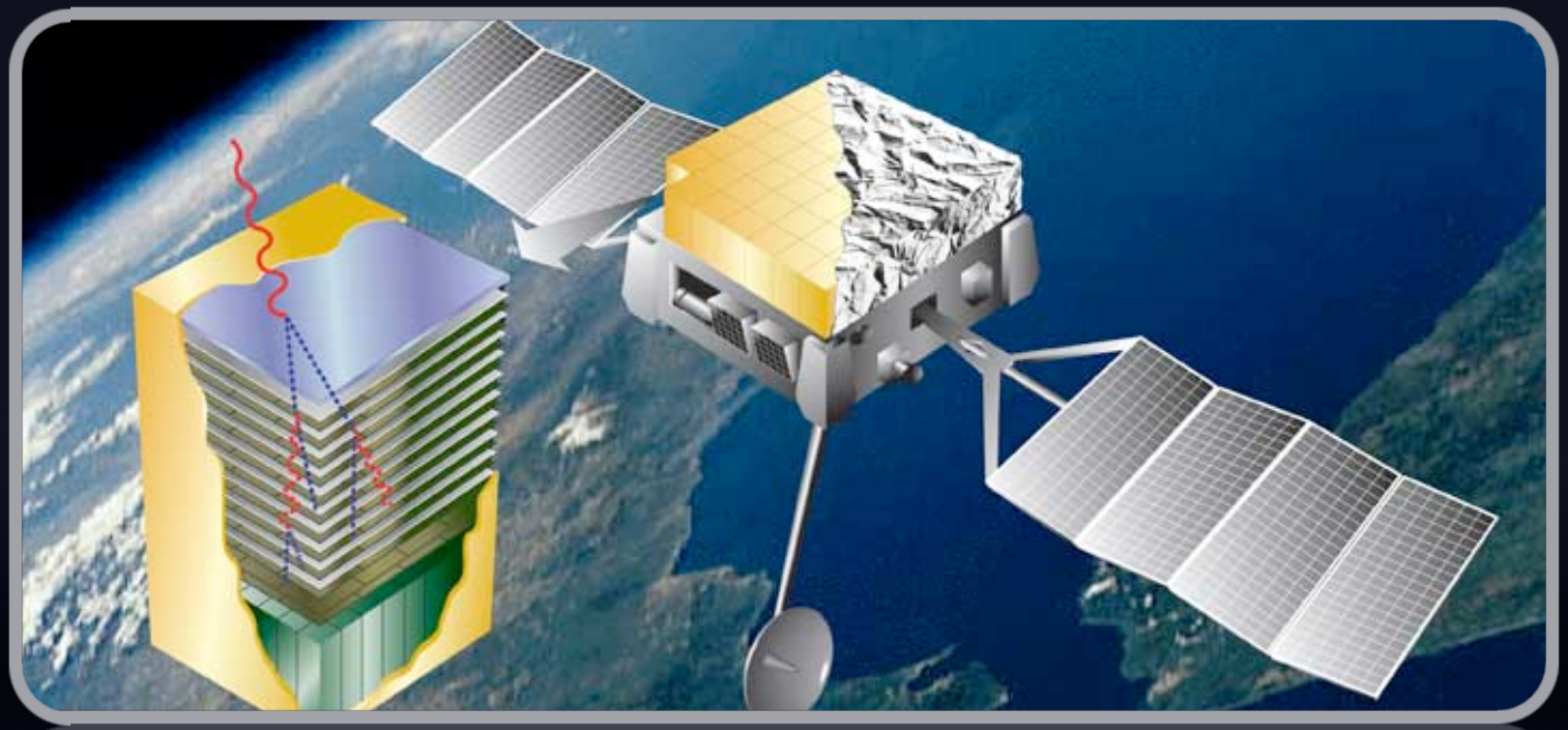


Credit: Image: GALEX, JPL-Caltech, NASA;
Drawing: APS/**Alan Stonebraker**

Scientific Motivation

- Constrain the **origin of cosmic rays** by measuring gamma-ray **spectra to 100 TeV**.
- Probe **particle acceleration** in astrophysical jets with **wide field of view, high duty factor** observations.
- Explore **new physics** with an **unbiased survey** of the **TeV sky**.

Experimental Techniques



- **Space-based detectors**
  - Low energy threshold
  - EGRET, Fermi-LAT

Experimental Techniques

- ✓ Background free
- ✓ Large duty cycle
- ✓ Large aperture

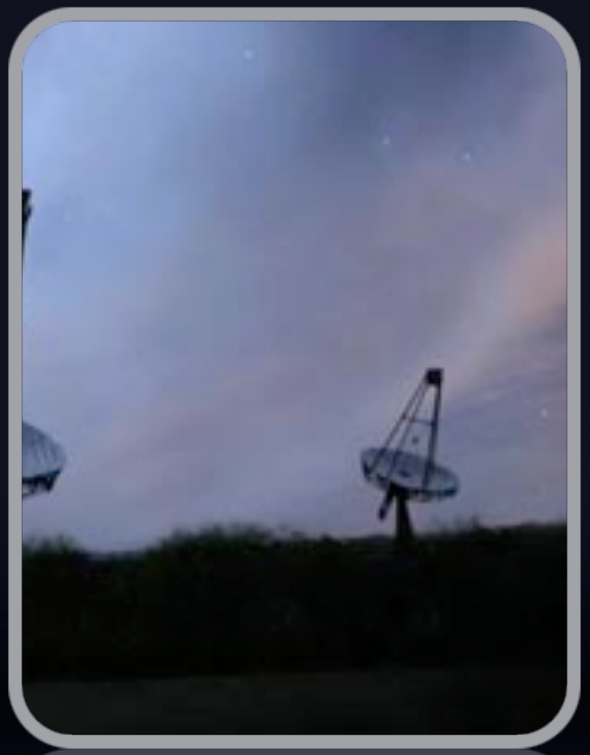
- \- Small area

- **Space-based detectors**
  - Low energy threshold
  - EGRET, Fermi-LAT

Experimental Techniques

- **Imaging Atmospheric Cherenkov Telescopes**
  - High sensitivity
  - HESS, MAGIC, VERITAS

Experimental Techniques



- ✓ Large effective area
- ✓ Excellent background rejection

- - Small aperture
- - Low duty cycle

- **Imaging Atmospheric Cherenkov Telescopes**
  - High sensitivity
  - HESS, MAGIC, VERITAS

Experimental Techniques

- **Ground array of air-shower particle detectors**
  - Large aperture + High duty cycle
  - Milagro, Tibet, ARGO, HAWC

Experimental Techniques

- ✓ Large aperture
- ✓ Excellent background rejection
- ✓ Large duty cycle

- - Moderate area

- **Ground array of air-shower particle detectors**
  - Large aperture + High duty cycle
  - Milagro, Tibet, ARGO, HAWC

Experimental Techniques

- **Ground array of air-shower particle detectors**
  - Large aperture + High duty cycle
  - Milagro, Tibet, ARGO, HAWC

The HAWC Collaboration

- ~100 scientists from the U.S. and Mexico
- 2 new European groups

The HAWC Observatory

300 - 7 m x 5 m steel Water Cherenkov Detectors
(a.k.a. tanks) with 4 PMTs at 4,100 m a.s.l. in Mexico

Water Cherenkov Detectors

300 - 7 m x 5 m steel Water Cherenkov Detectors
(a.k.a. tanks) with 4 PMTs at 4,100 m a.s.l. in Mexico

Water Cherenkov Detectors

300 - 7 m x 5 m steel Water Cherenkov Detectors
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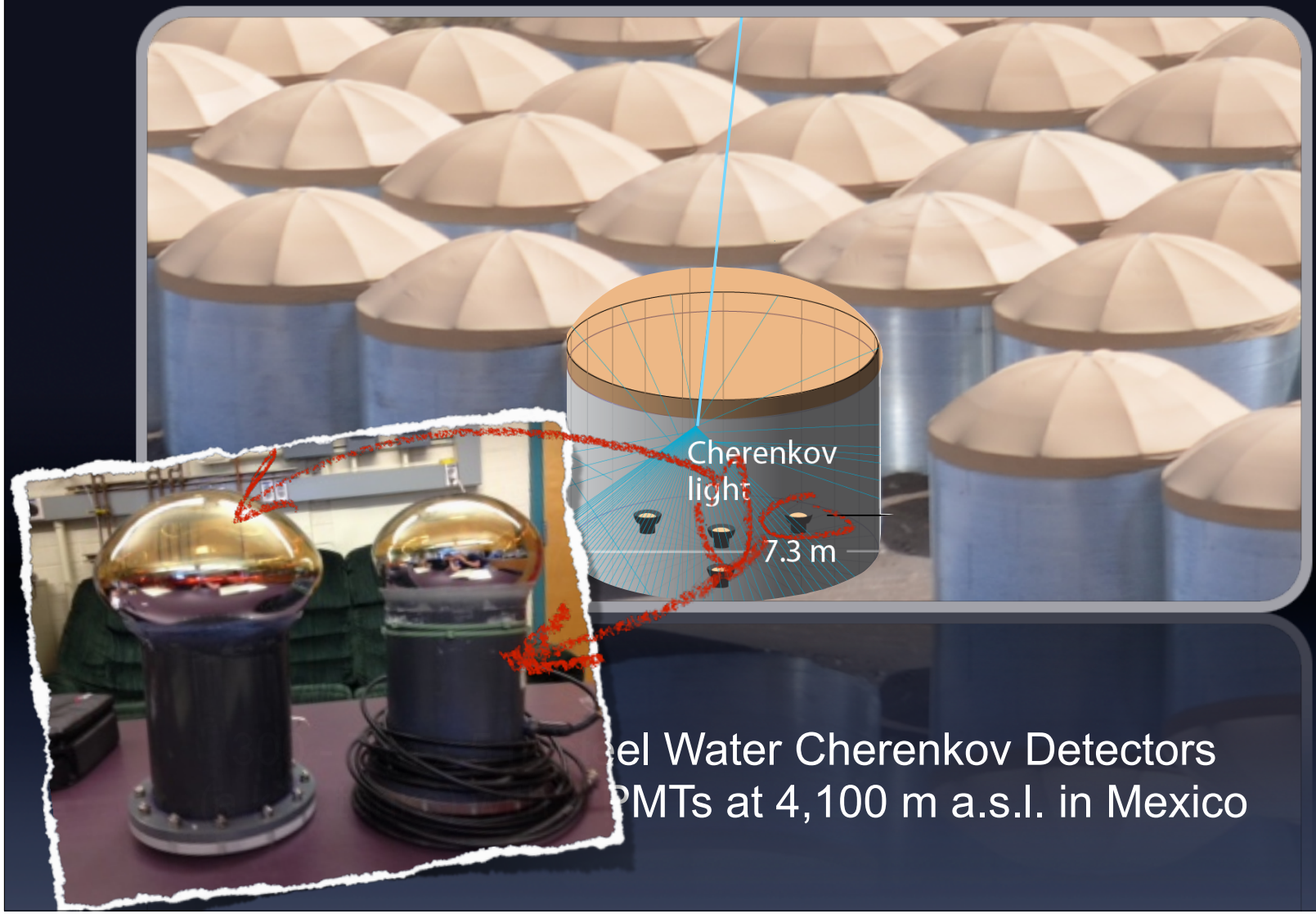
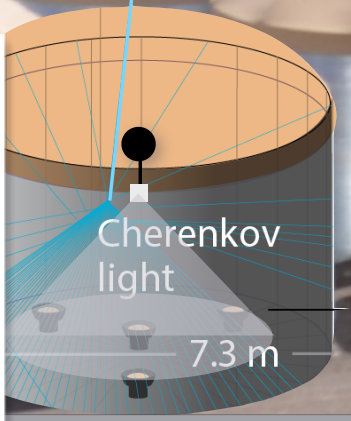
Water Cherenkov Detectors



el Water Cherenkov Detectors
MTs at 4,100 m a.s.l. in Mexico

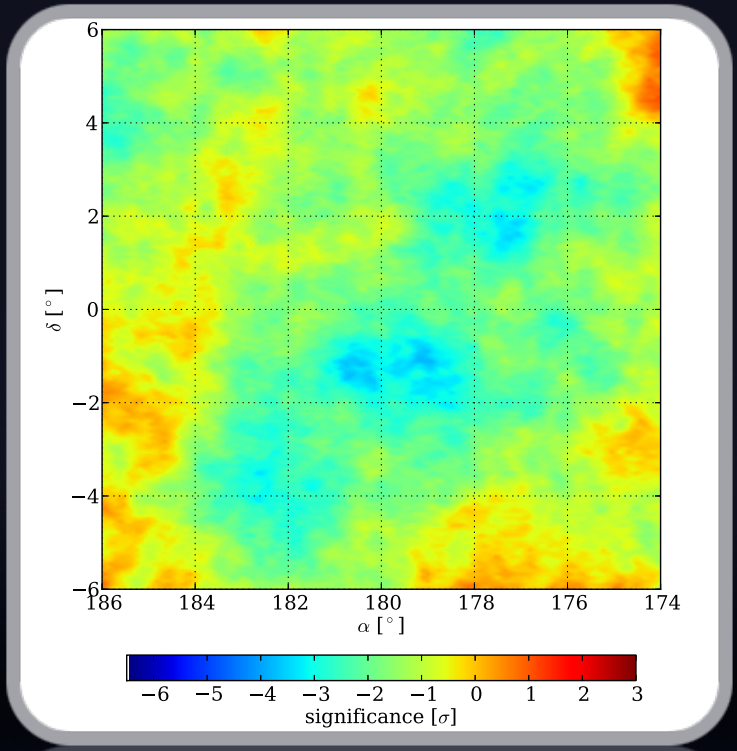
Water Cherenkov Detectors



tion system

Water Cherenkov Detectors

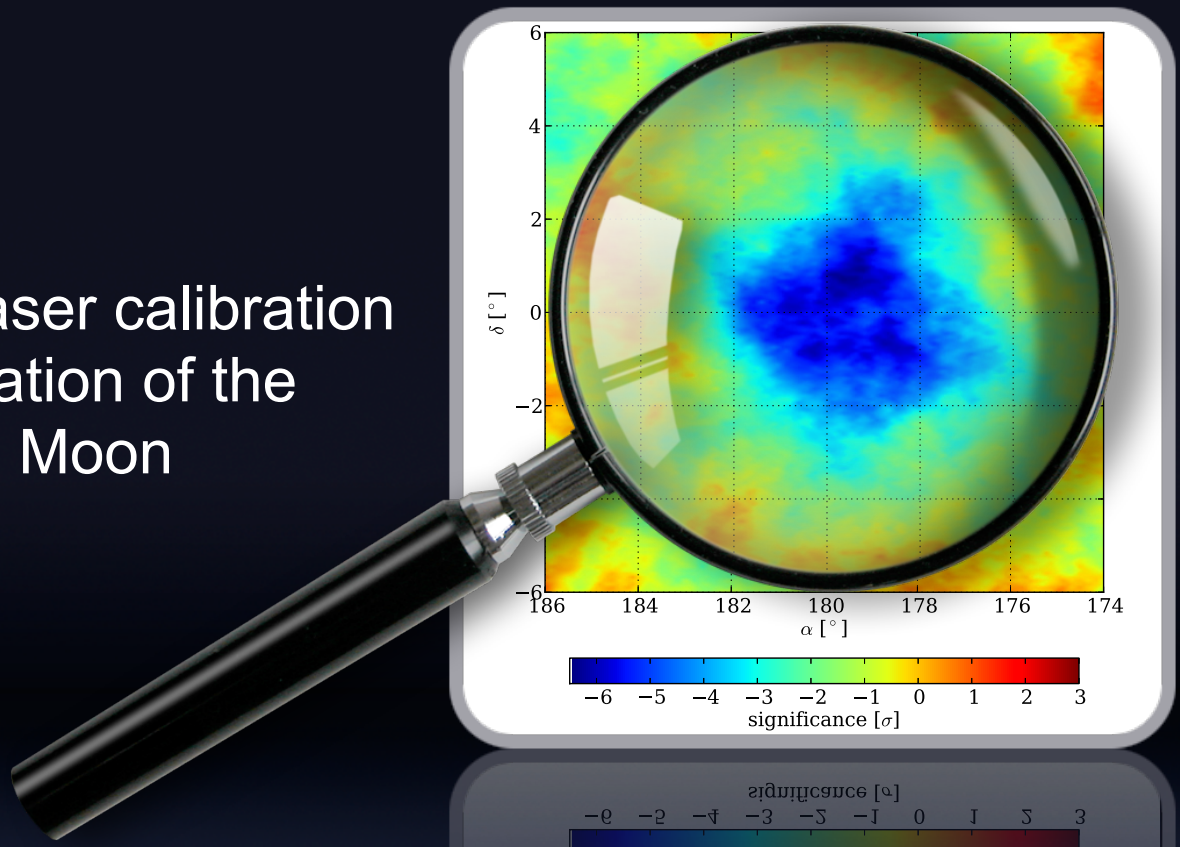
Effect of the laser calibration on the observation of the shadow of the Moon



Dedicated laser calibration system

Water Cherenkov Detectors

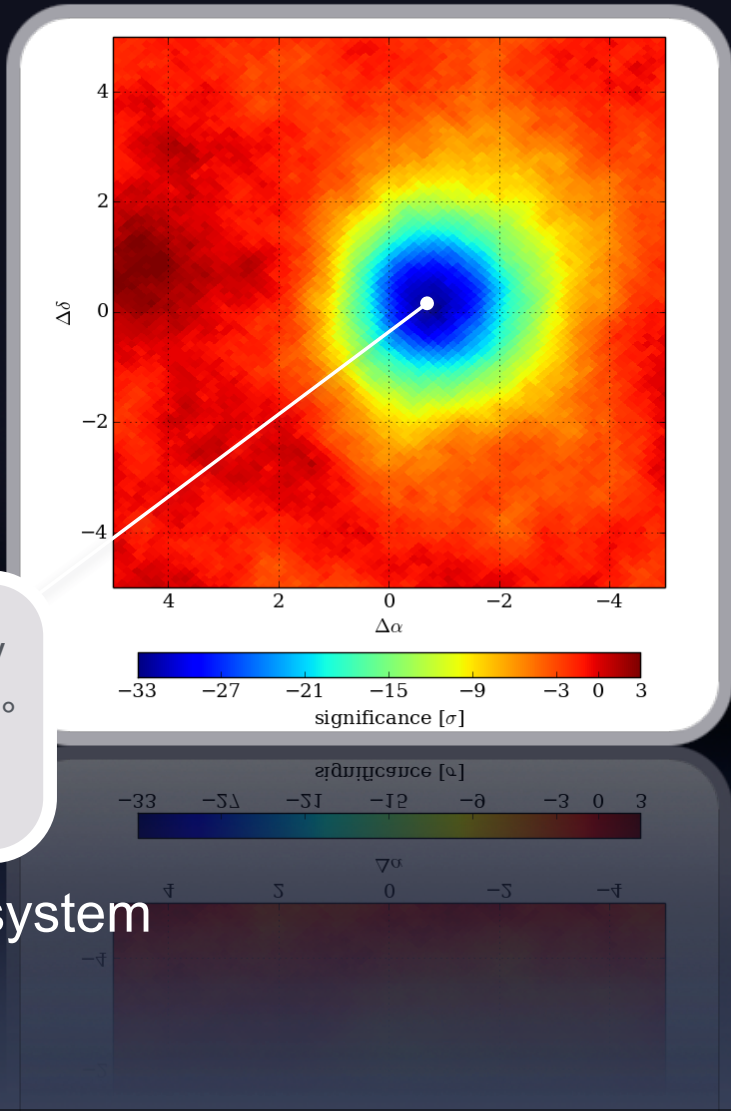
Effect of the laser calibration on the observation of the shadow of the Moon



Dedicated laser calibration system

Water Cherenkov Detectors

Effect of the laser calibration on the observation of the shadow of the Moon



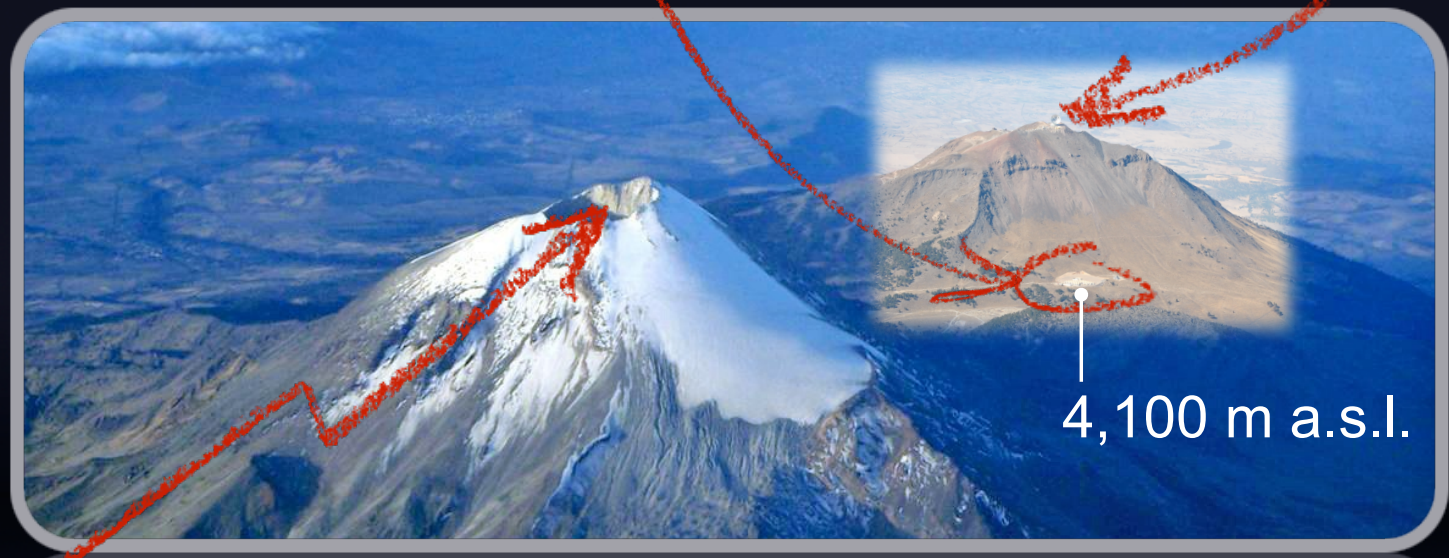
- deflection matches 2 TeV median energy
- angular resolution < shadow width of 1.2°
- position verifies pointing

Dedicated laser calibration system

HAWC site


Jalapa
Veracruz
Veracruz
Tlaxcala
Tlaxcala
(Mexico City)
Distrito Federal
HAWC Site
Puebla, PU, Mexico
Puebla
Cuernavaca

HAWC site



working at the HAWC site

Design improvements

Go higher (altitude a.s.l.)

Milagro

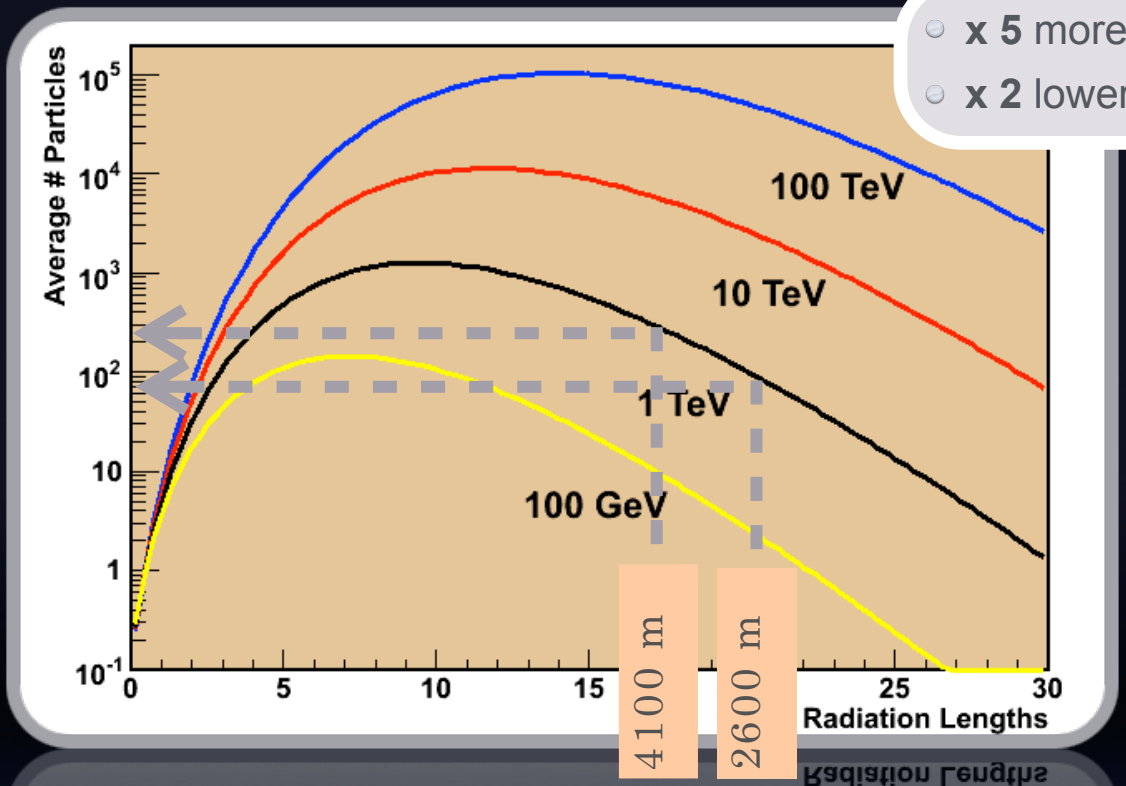
2,650 m a.s.l.

HAWC

4,100 m a.s.l.

Design improvements

- **x 5** more particles
- **x 2** lower energy threshold



Milagro

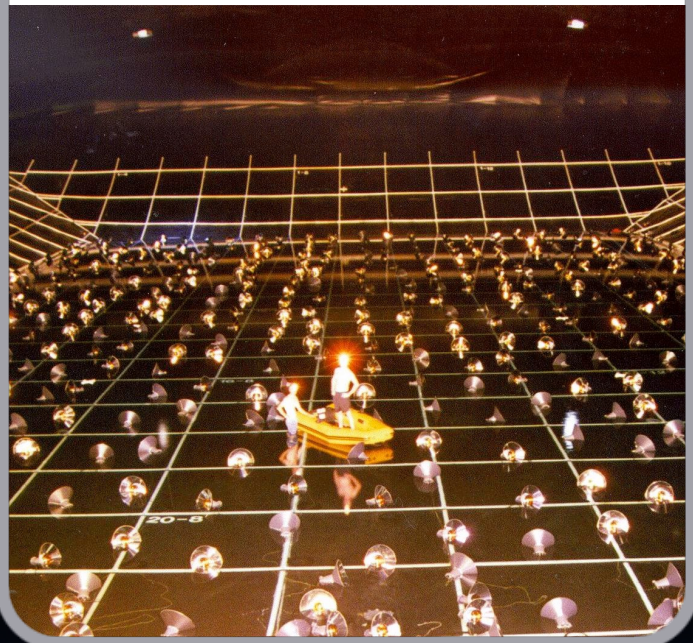
2,650 m a.s.l.

HAWC

4,100 m a.s.l.

Design improvements

Optical isolation



Milagro

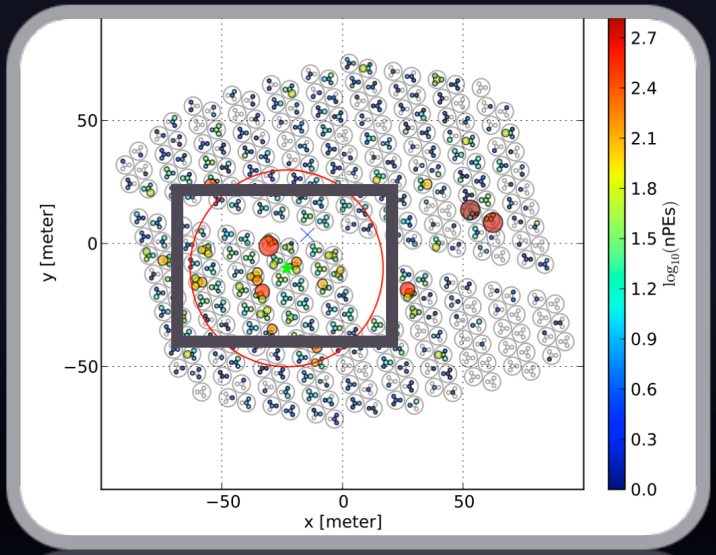
large pond

HAWC

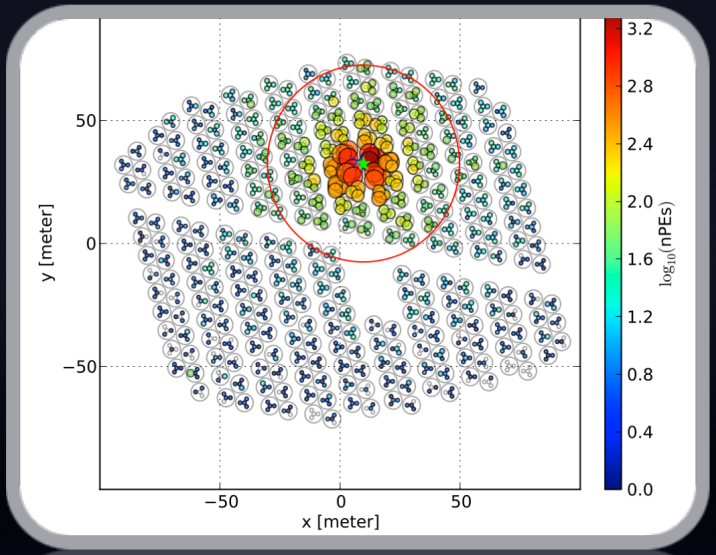
individual tanks

Design improvements

proton-shower; 24 TeV; 43°



gamma-shower; 20 TeV; 21°



Milagro

large pond

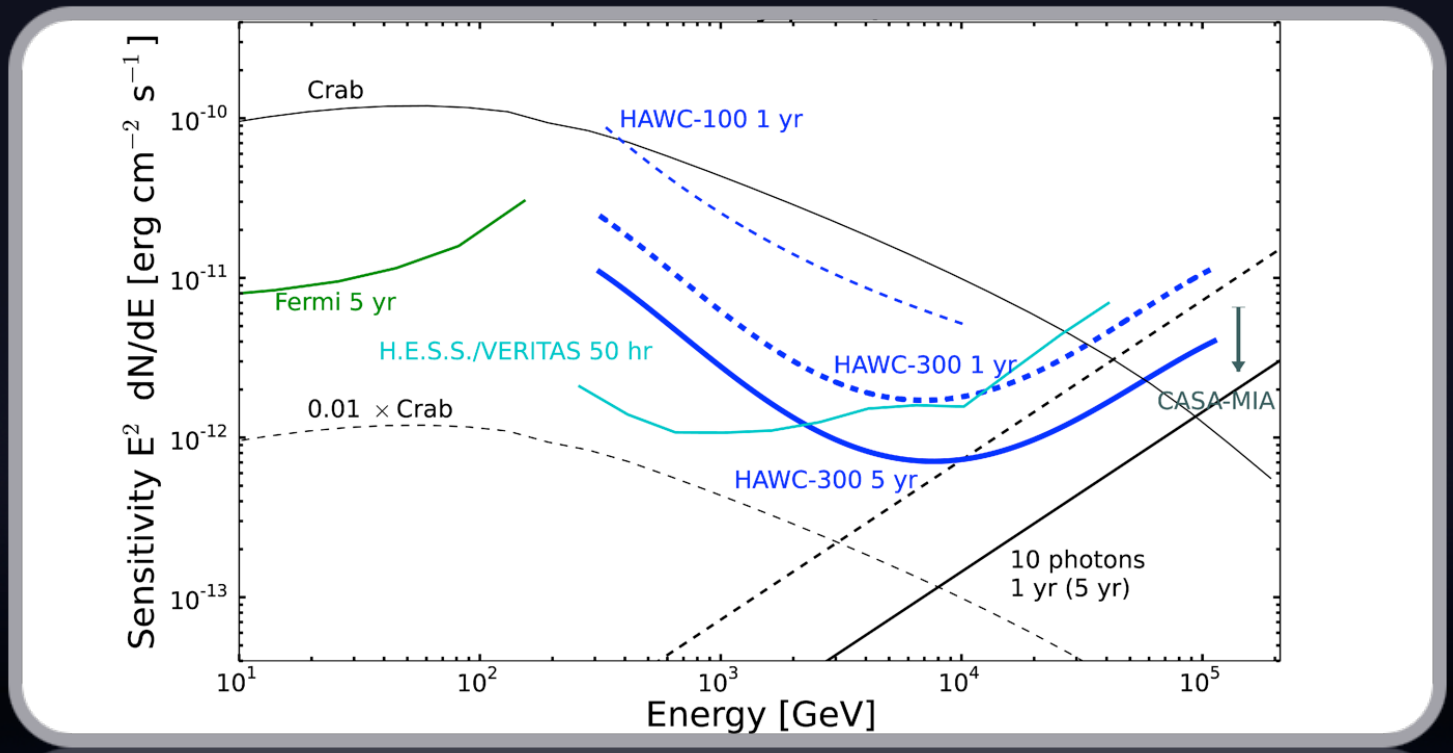
HAWC

individual tanks

Design improvements

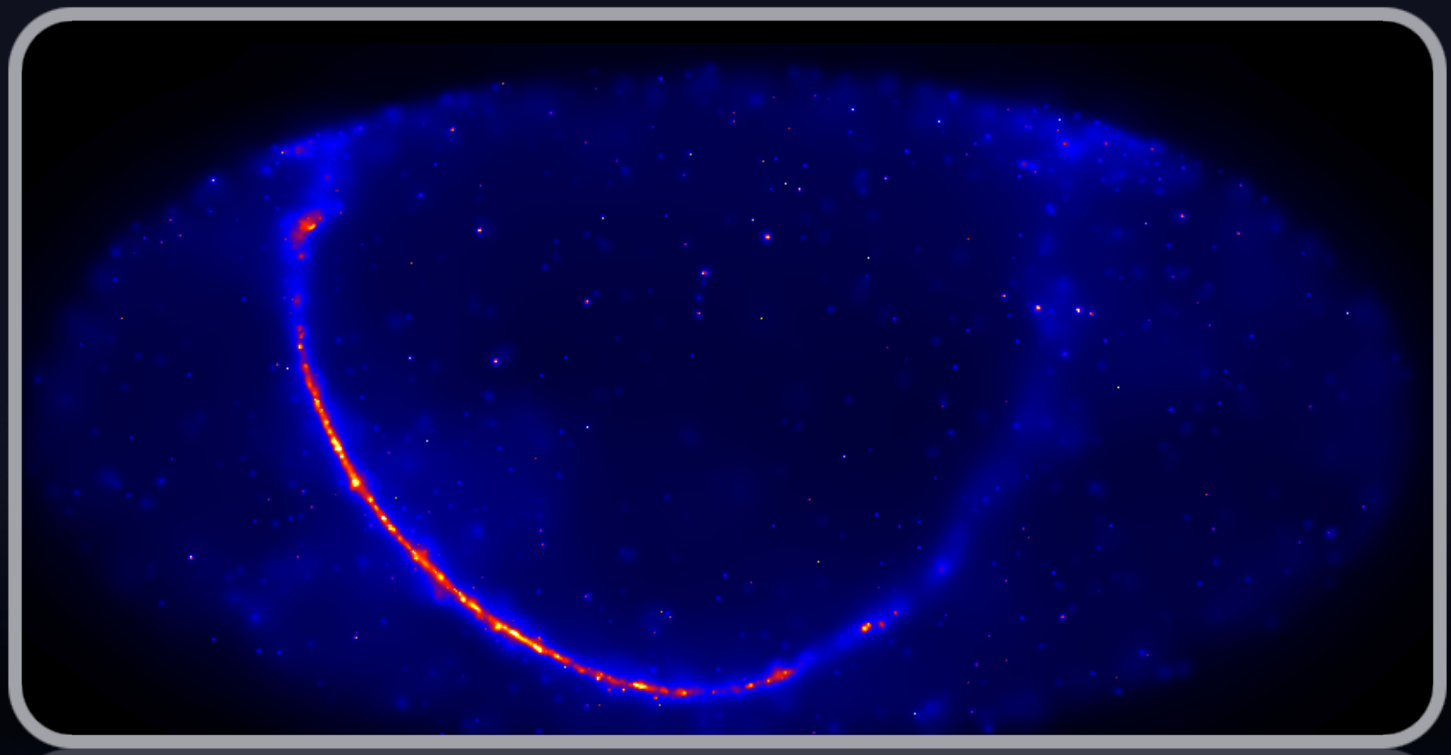
Milagro	HAWC
4,000 m^2	**22,000 m^2**

Design improvements



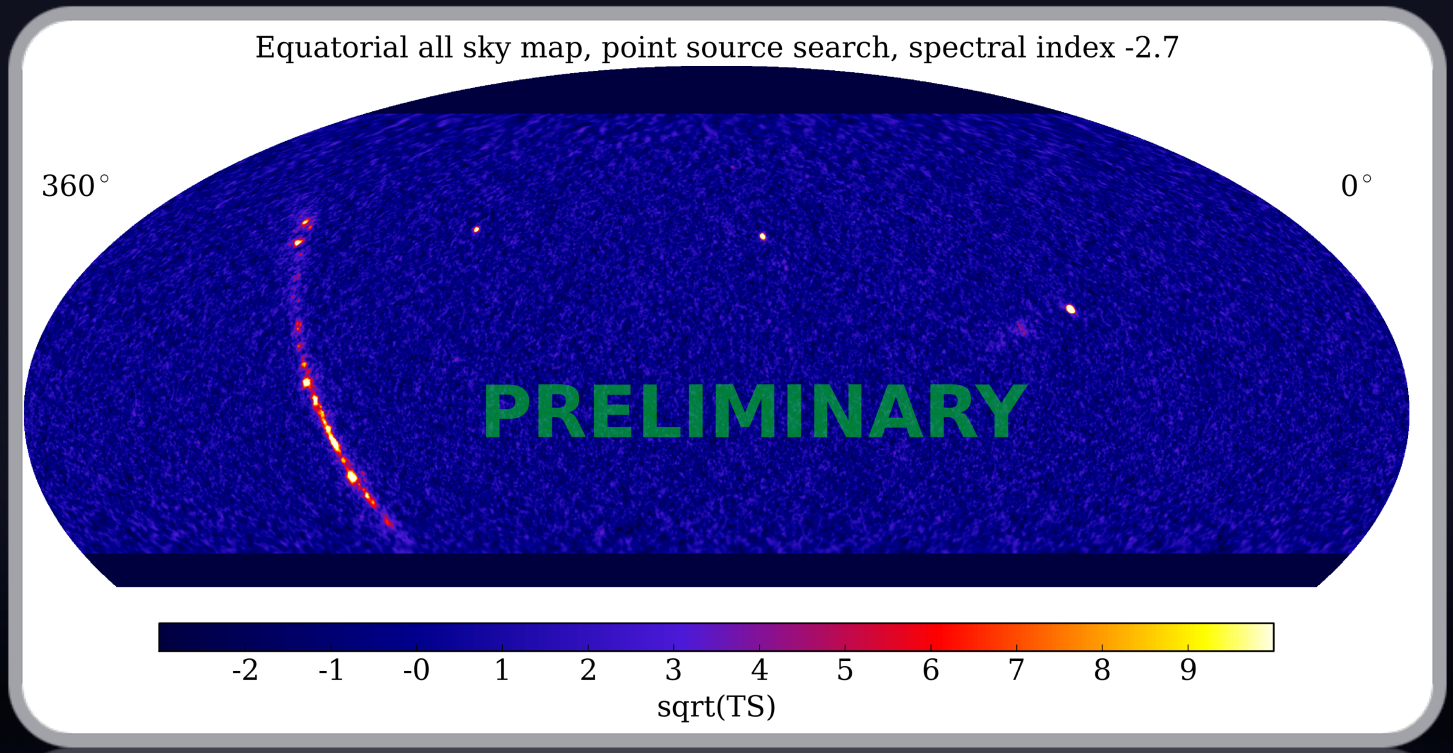
x15 more sensitive than Milagro

Design improvements



Fermi-LAT sky smoothed map
E > 50 GeV (Pass 8 - 6 years of data)
(courtesy of M. Ajello)

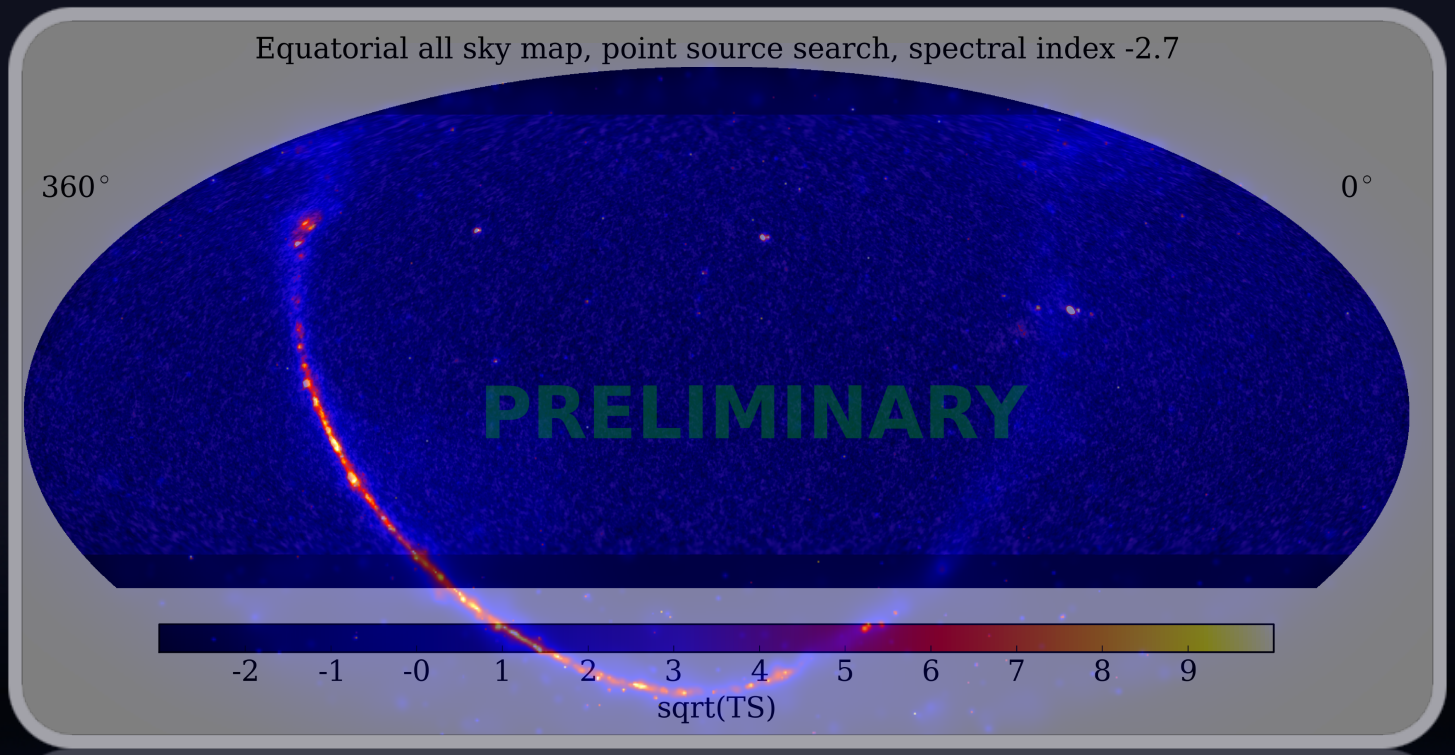
Design improvements



Fermi-LAT sky smoothed map
E > 50 GeV (Pass 8 - 6 years of data)
(courtesy of M. Ajello)

Preliminary HAWC smoothed map
E > 300 GeV (~1 year of data)
Full array

Design improvements



Fermi-LAT sky smoothed map
E > 50 GeV (Pass 8 - 6 years of data)
(courtesy of M. Ajello)

Preliminary HAWC smoothed map
E > 300 GeV (~1 year of data)
Full array

Deployment status

February 2011

Deployment status

February 2012 — VAMOS

Deployment status

September 2012 — HAWC-30

Deployment status

May 2013 — HAWC-111

Deployment status

May 2014 — HAWC-250

Deployment status

May 2014 — HAWC-250

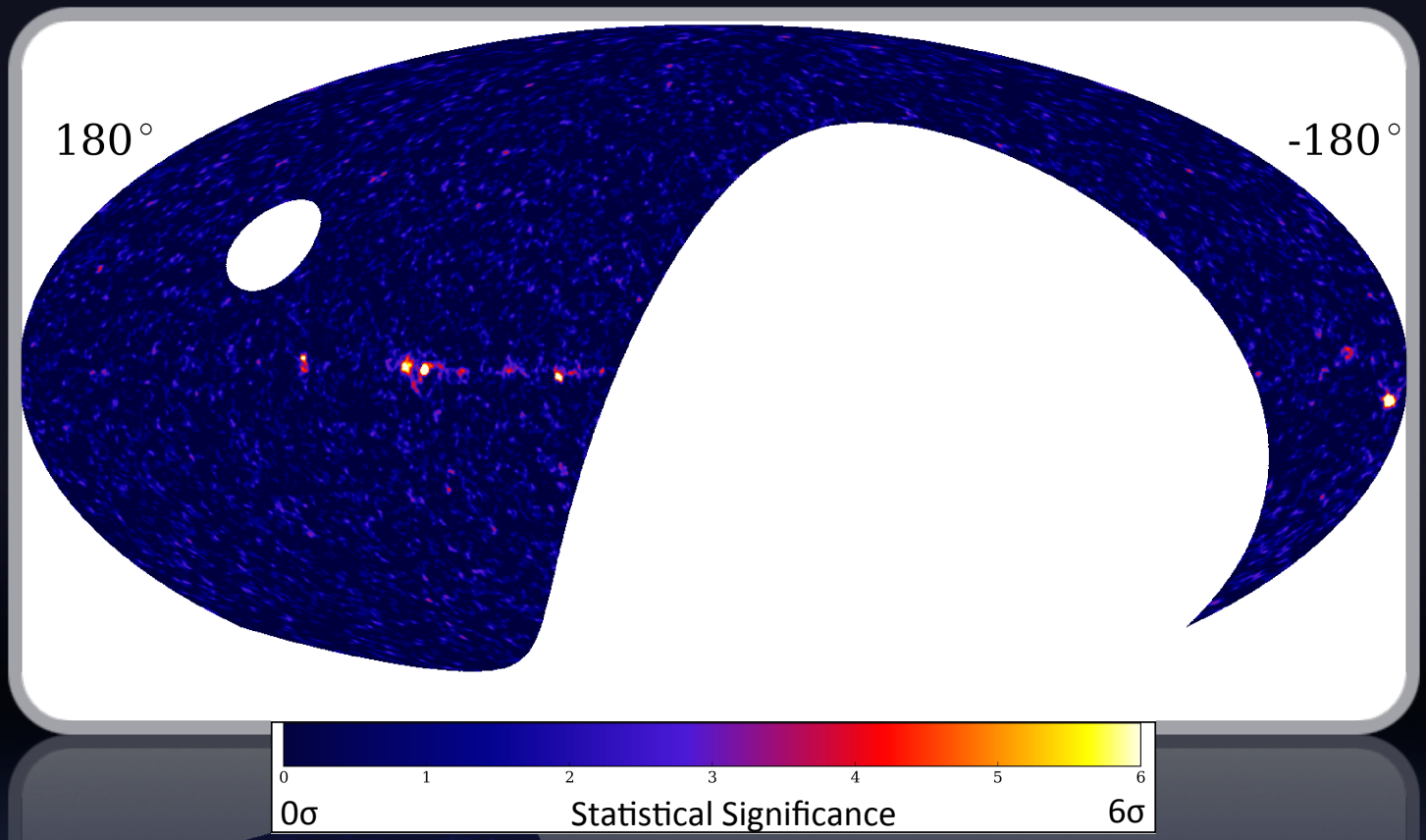
Deployment status

December 2014 — HAWC

First Results

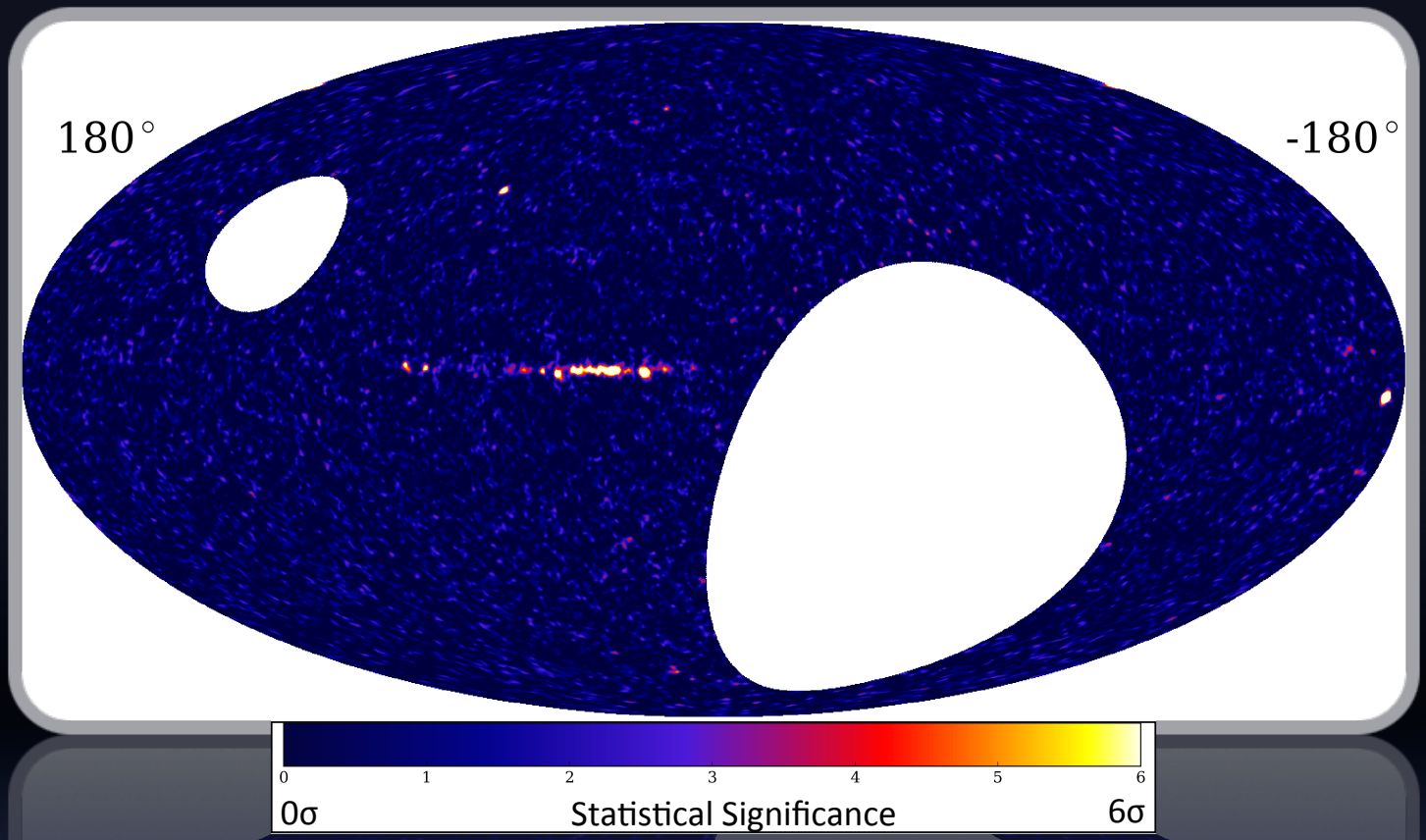

First Results
Penn State group in Hidalgo, Mexico (2014)

Milagro — 8-year TeV sky survey (17σ Crab)



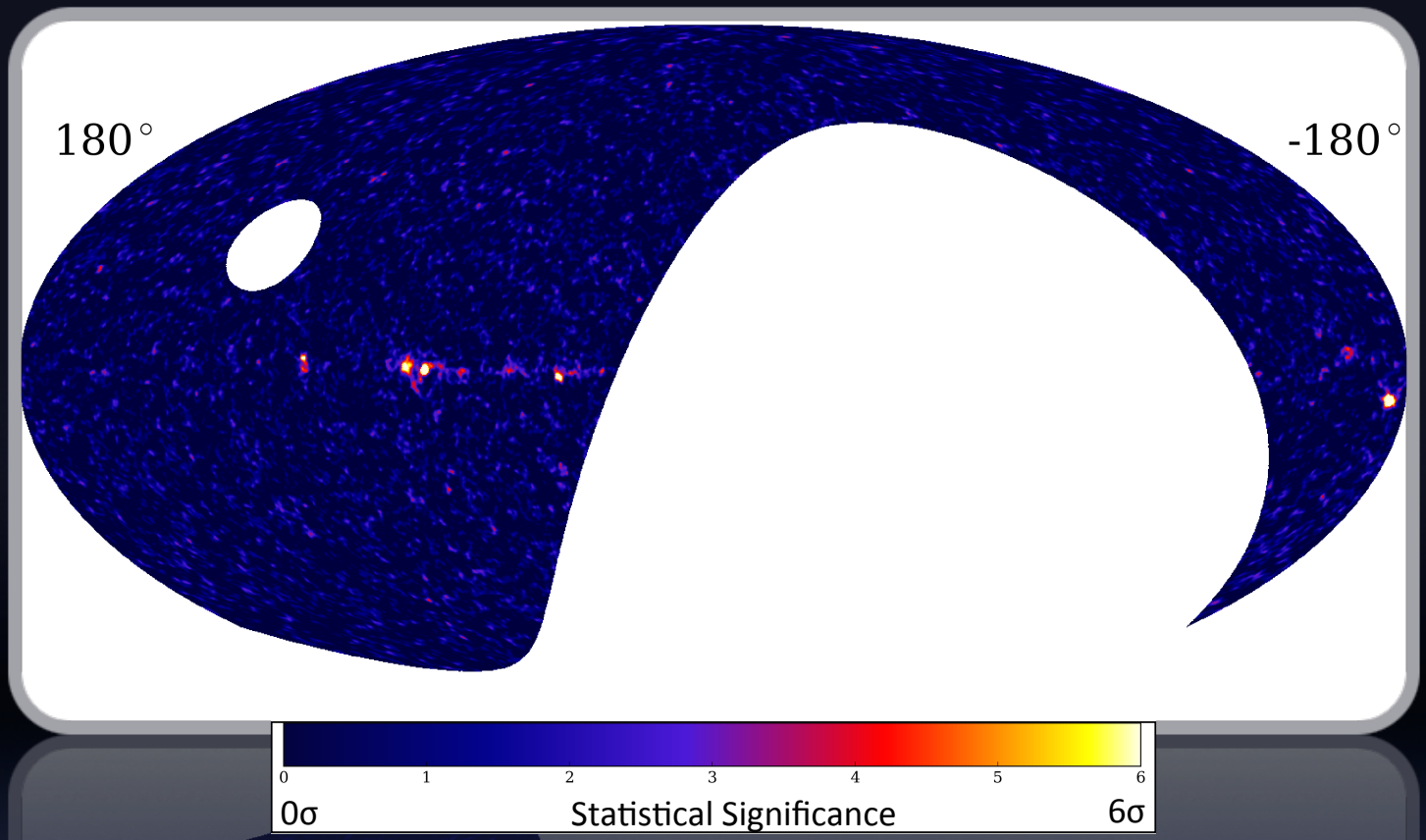
Multi-TeV sky

HAWC-250 — 150-day TeV sky survey (38σ Crab)



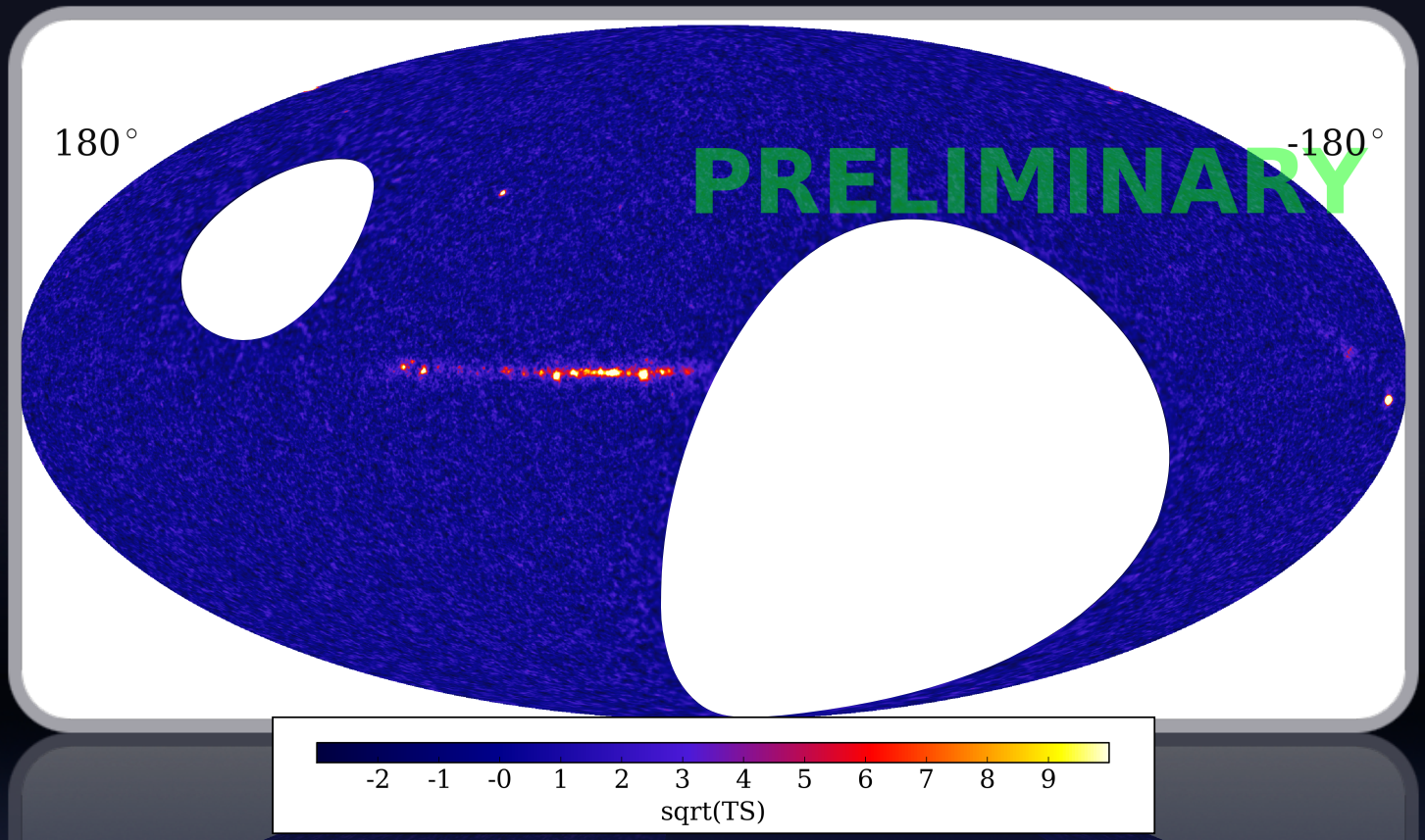
Multi-TeV sky

Milagro — 8-year TeV sky survey (17σ Crab)



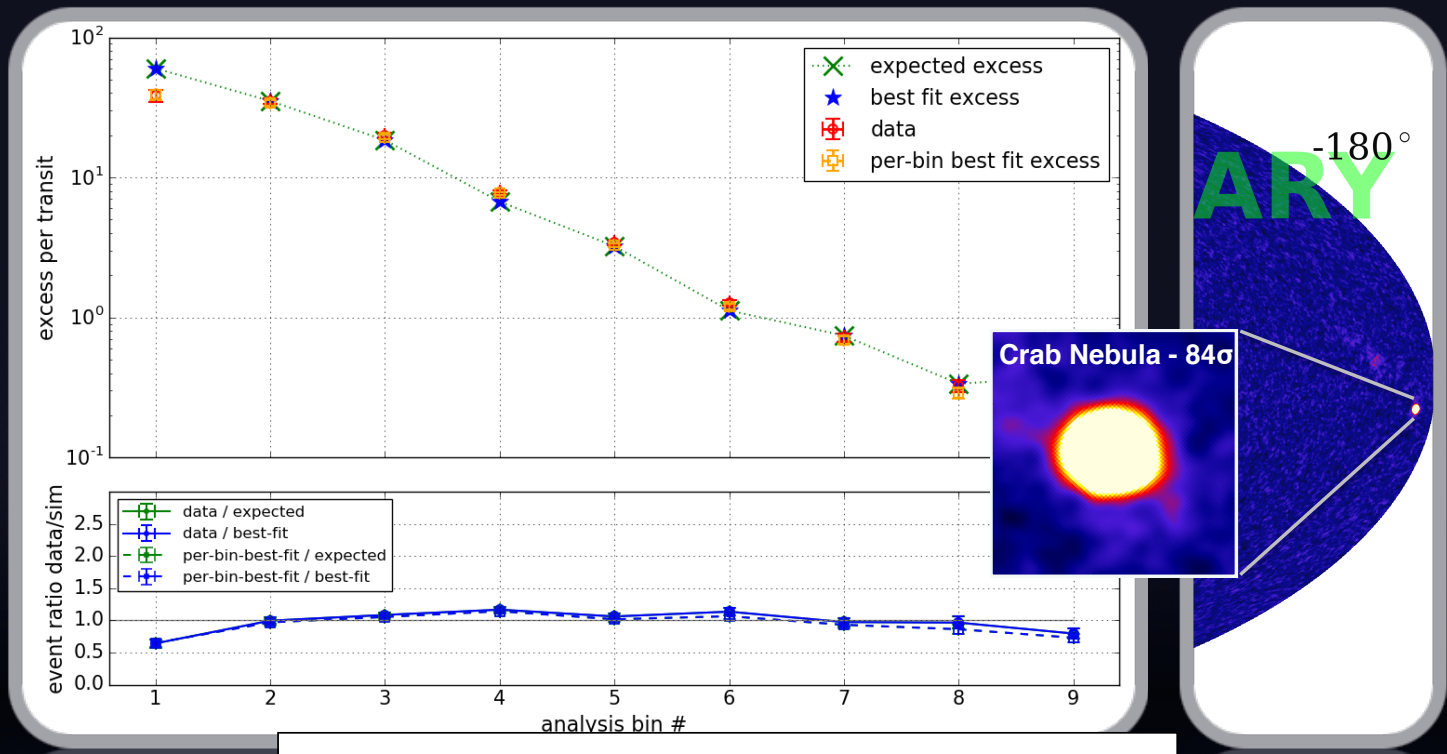
Multi-TeV sky

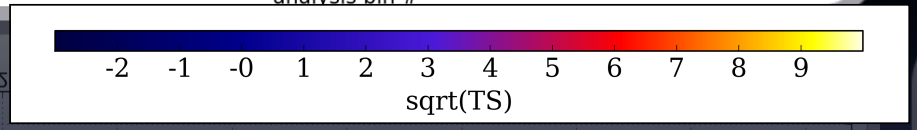
HAWC — 340-day TeV sky survey (>80σ Crab)



Multi-TeV sky

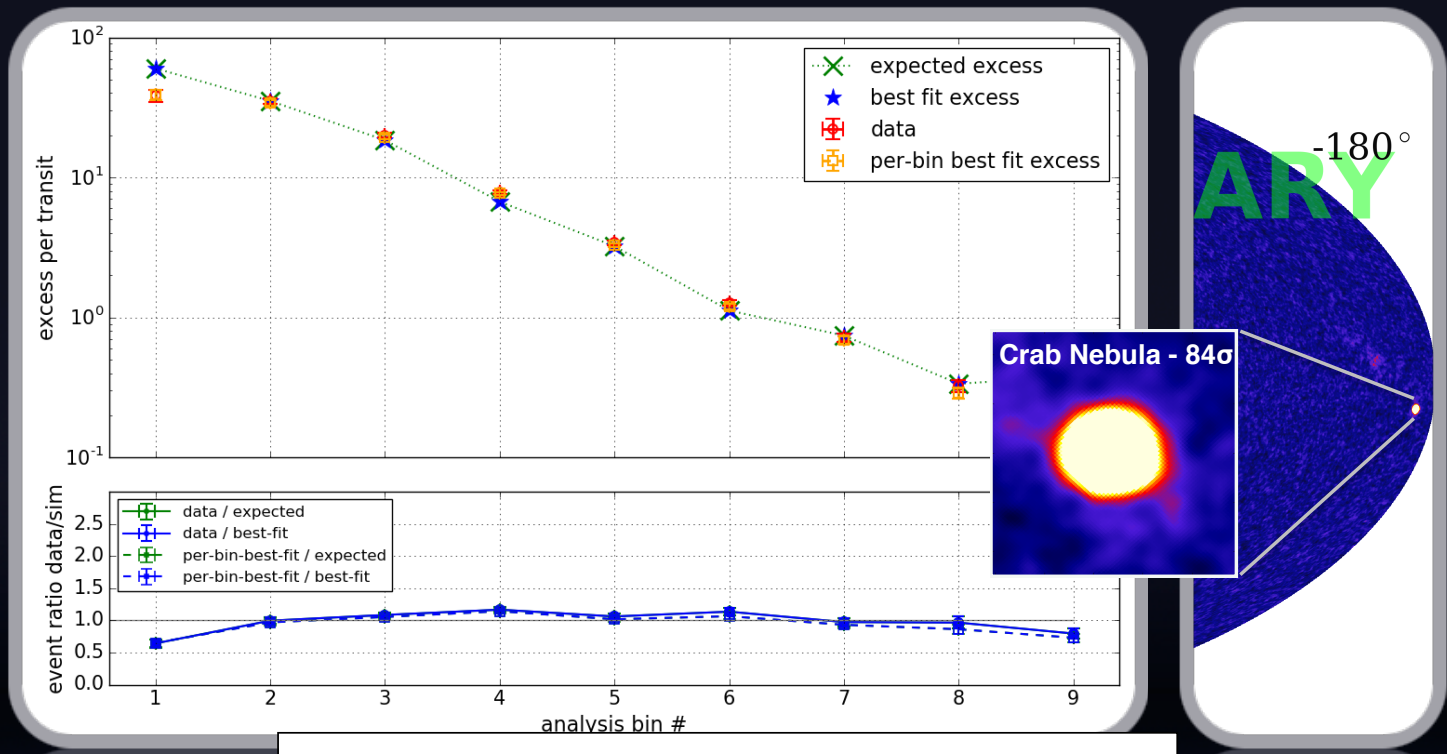
HAWC — 340-day TeV sky survey (>80σ Crab)

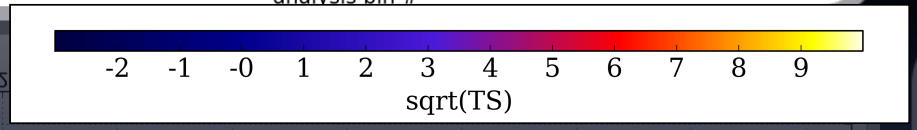




Multi-TeV sky

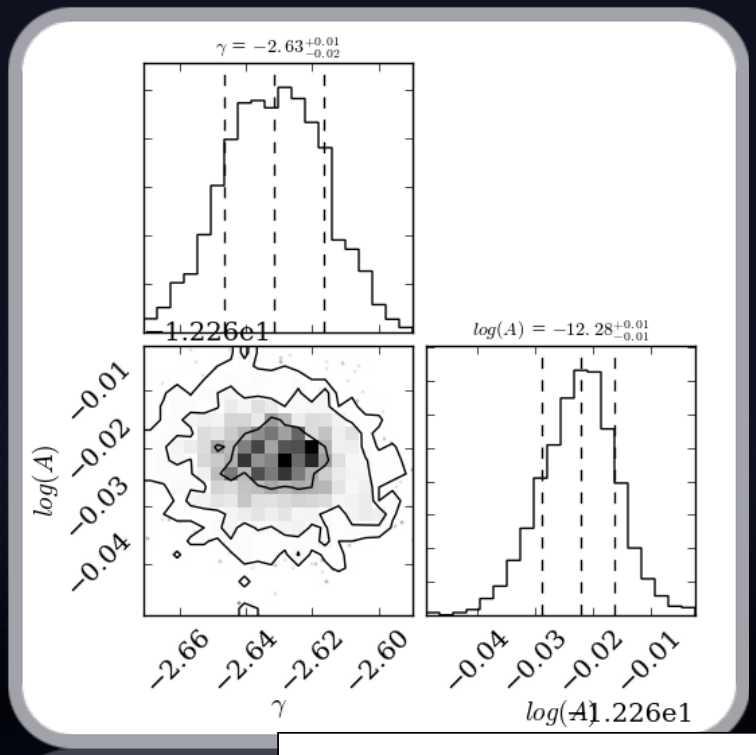
HAWC — 340-day TeV sky survey (>80σ Crab)

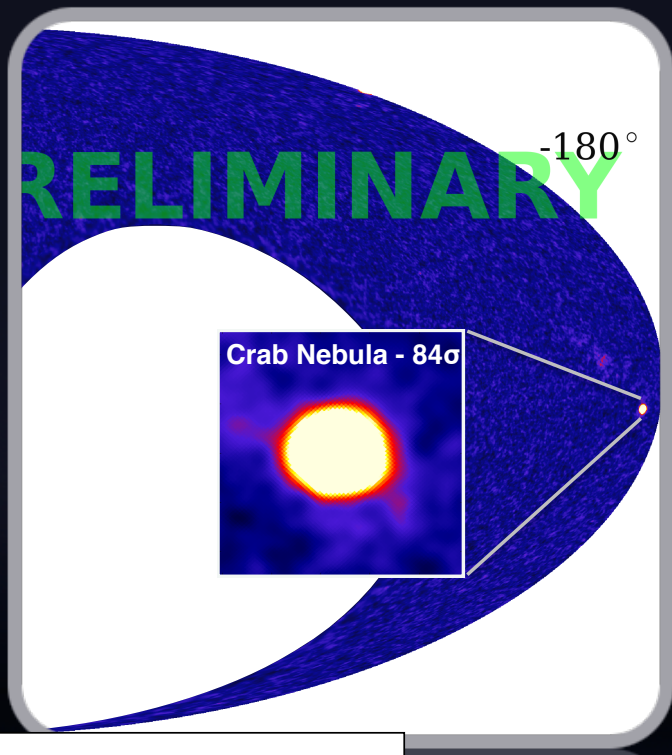


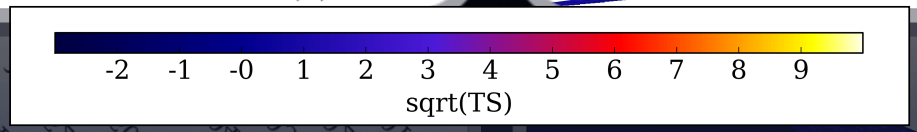


Multi-TeV sky

HAWC — 340-day TeV sky survey (>80σ Crab)

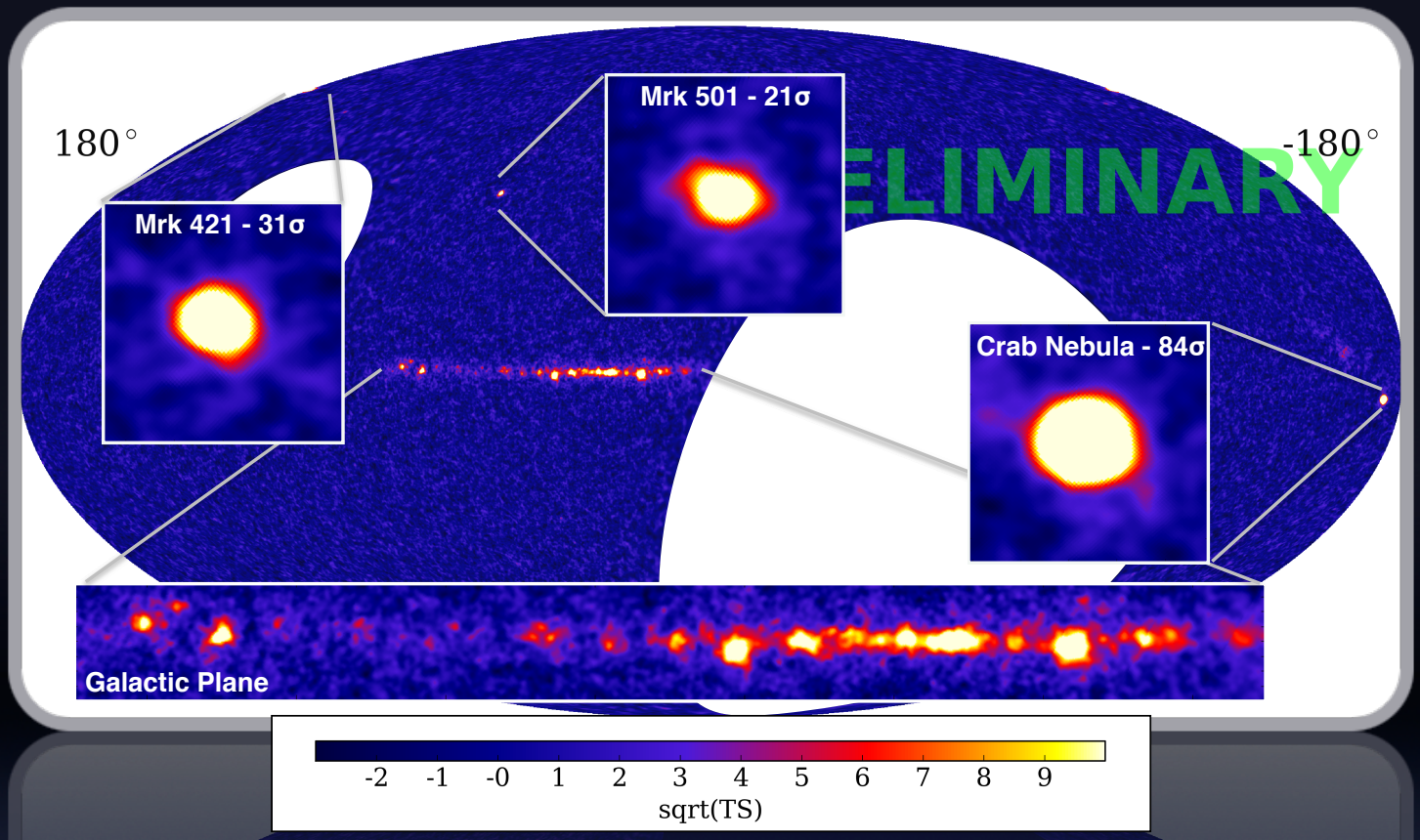






Multi-TeV sky

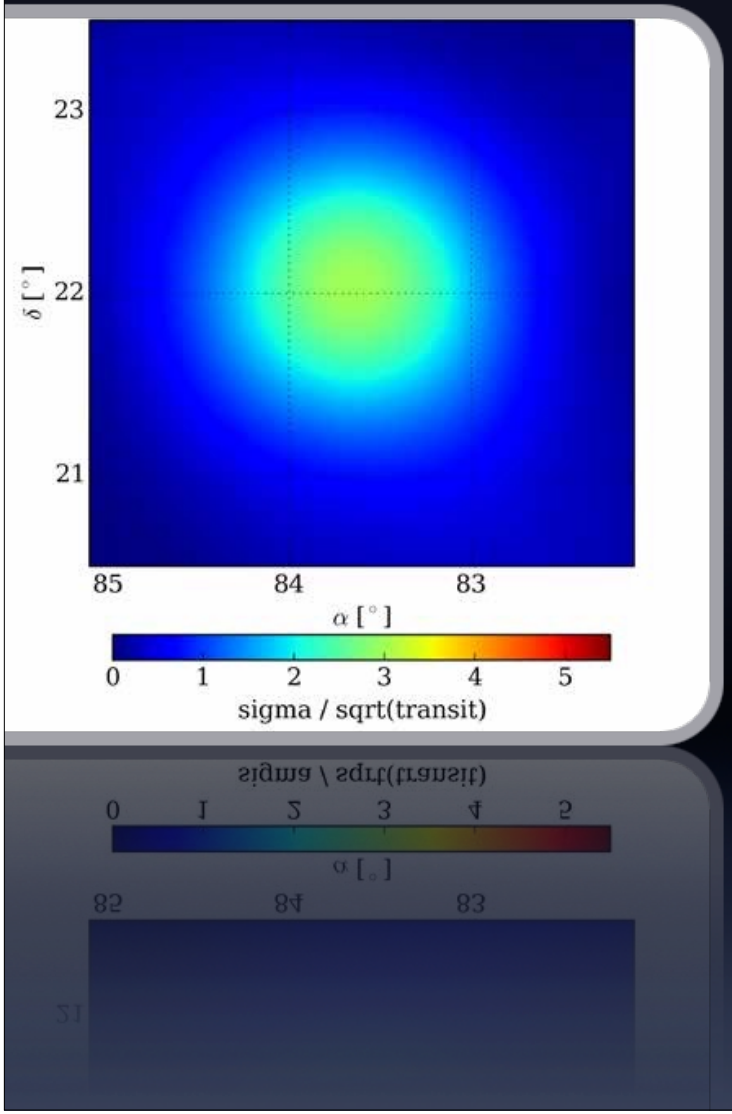
HAWC — 340-day TeV sky survey (>80σ Crab)



Multi-TeV sky

reconstruction improvements

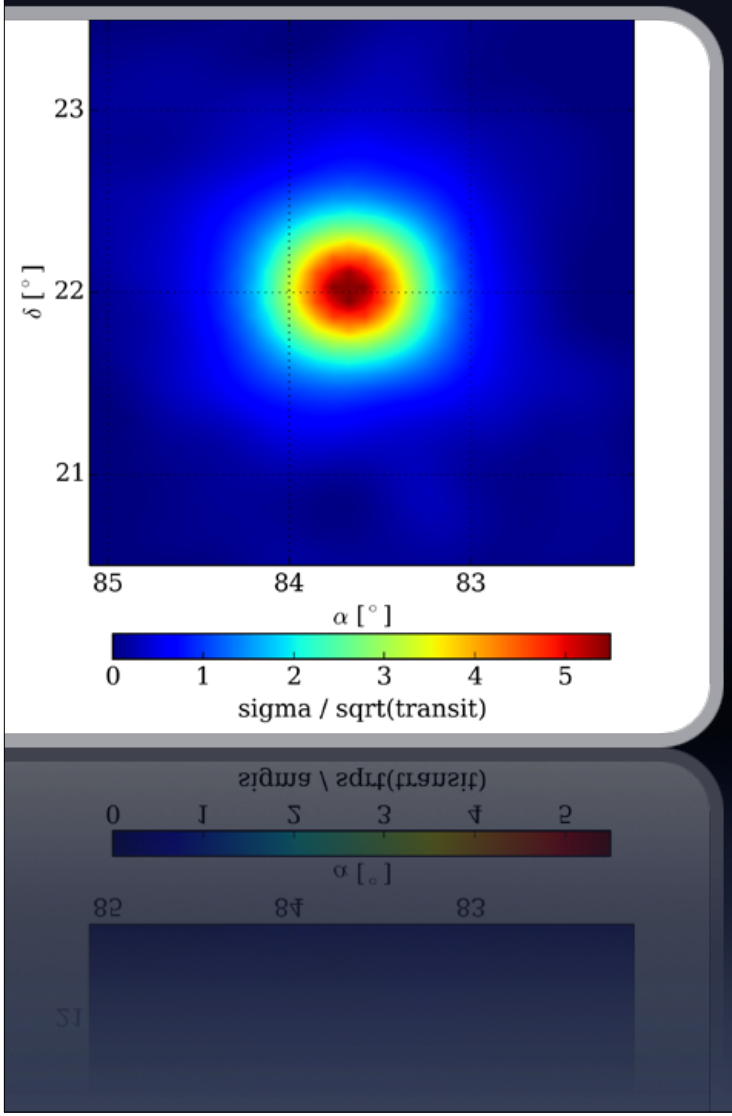
Crab Nebula



- A factor of 2 over previous “pass”
- New shower front curvature

reconstruction improvements

Crab Nebula

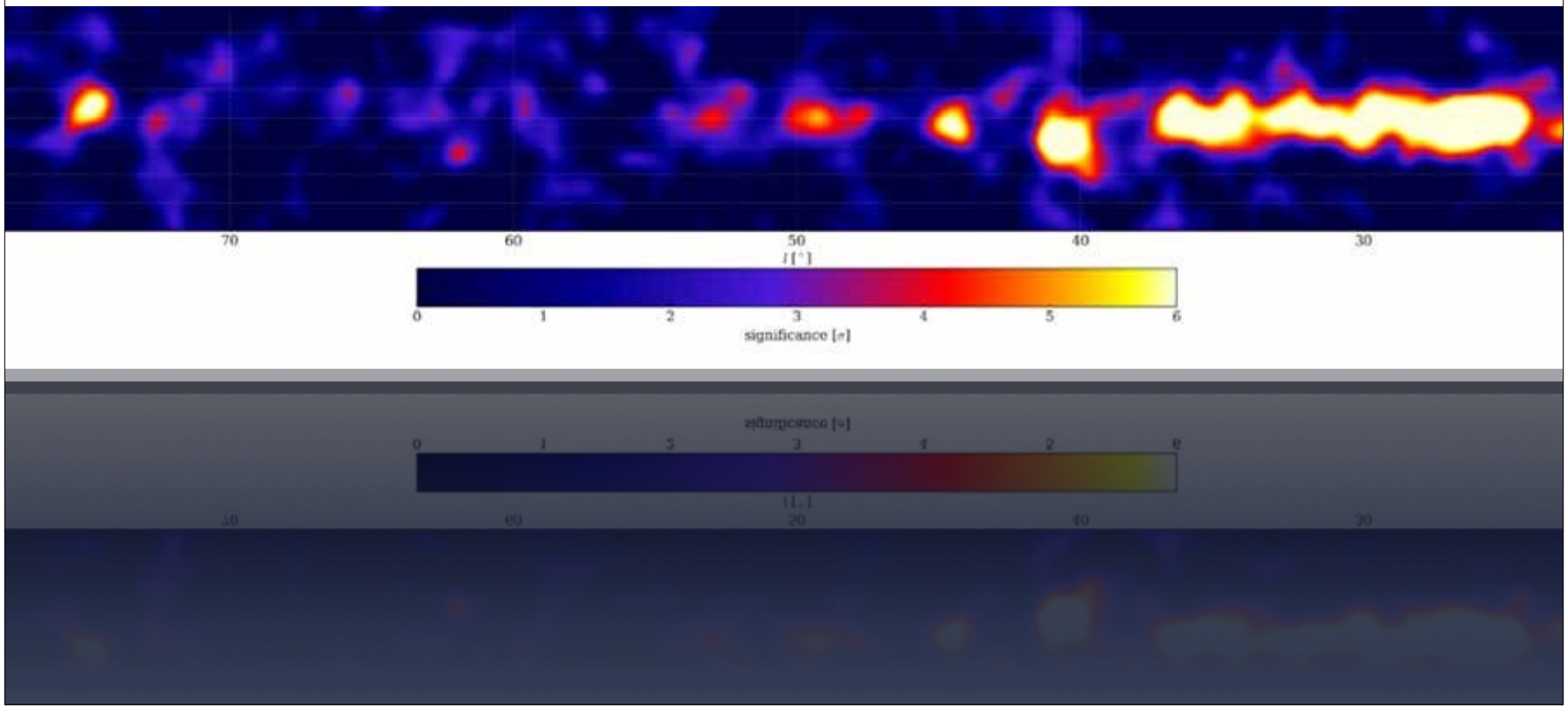


- A factor of 2 over previous “pass”
- New shower front curvature

reconstruction improvements

Preliminary results…

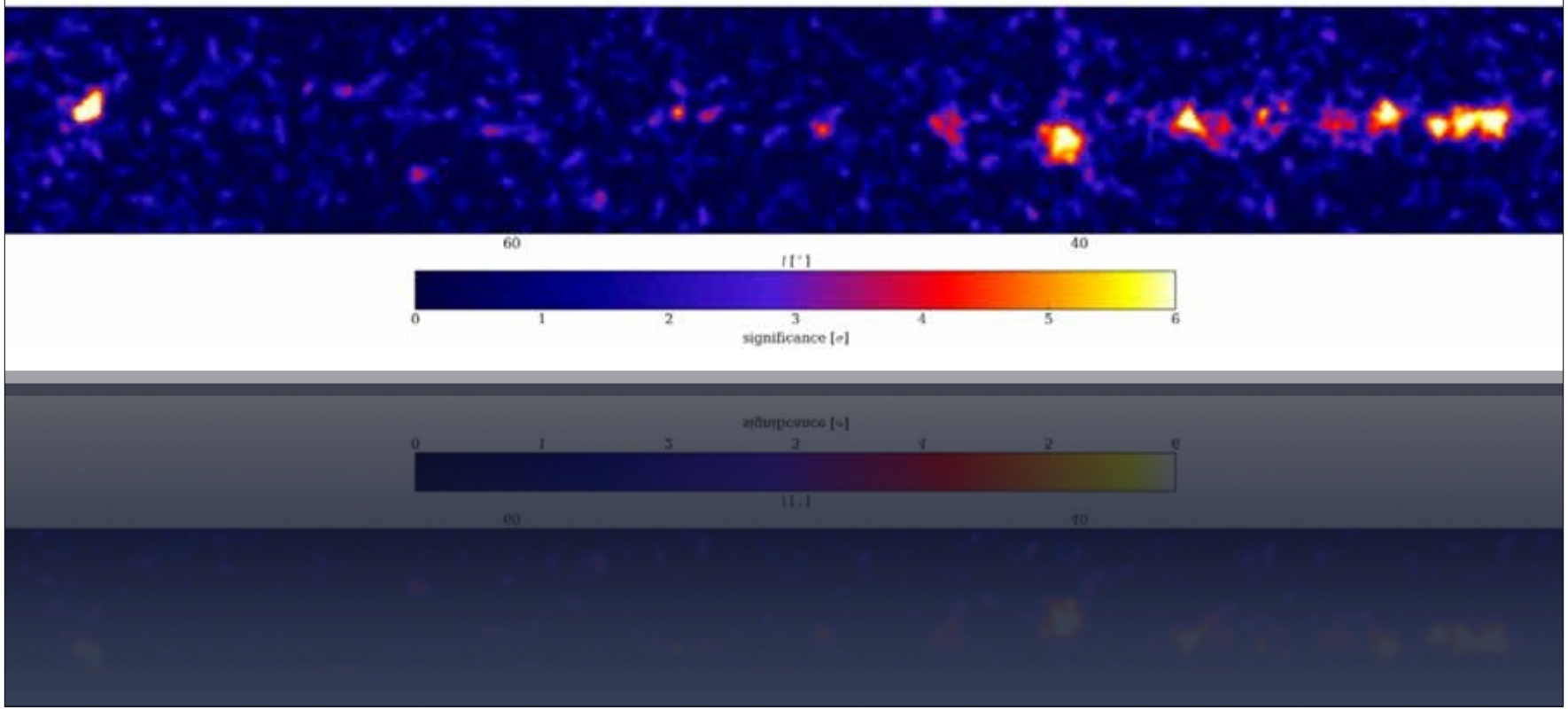
Galactic Plane



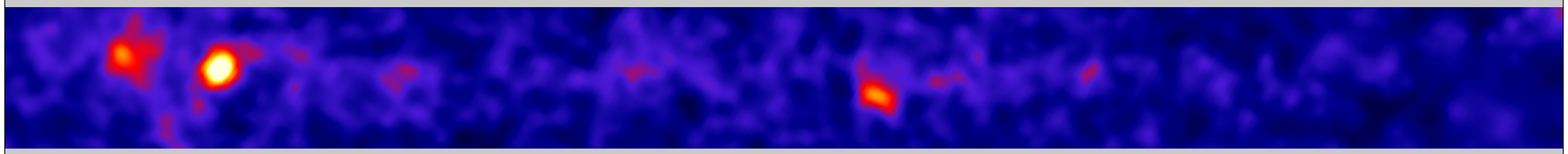
reconstruction improvements

Preliminary results…

Galactic Plane

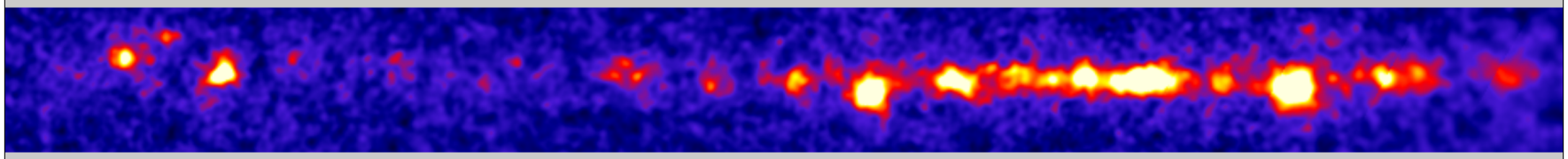


from Milagro to HAWC



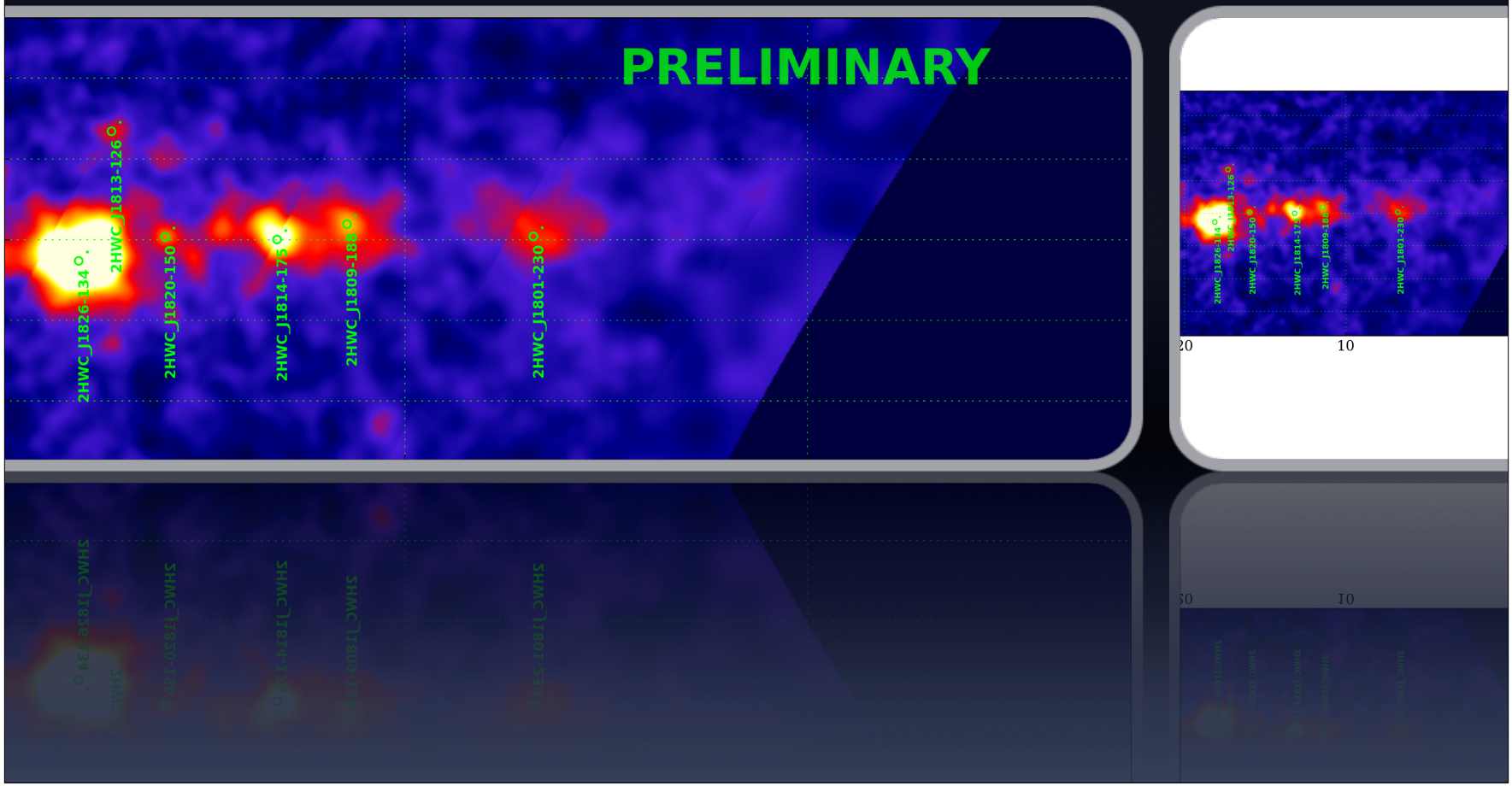
- Inner Galaxy: Milagro (8 years) vs. 1st year of HAWC

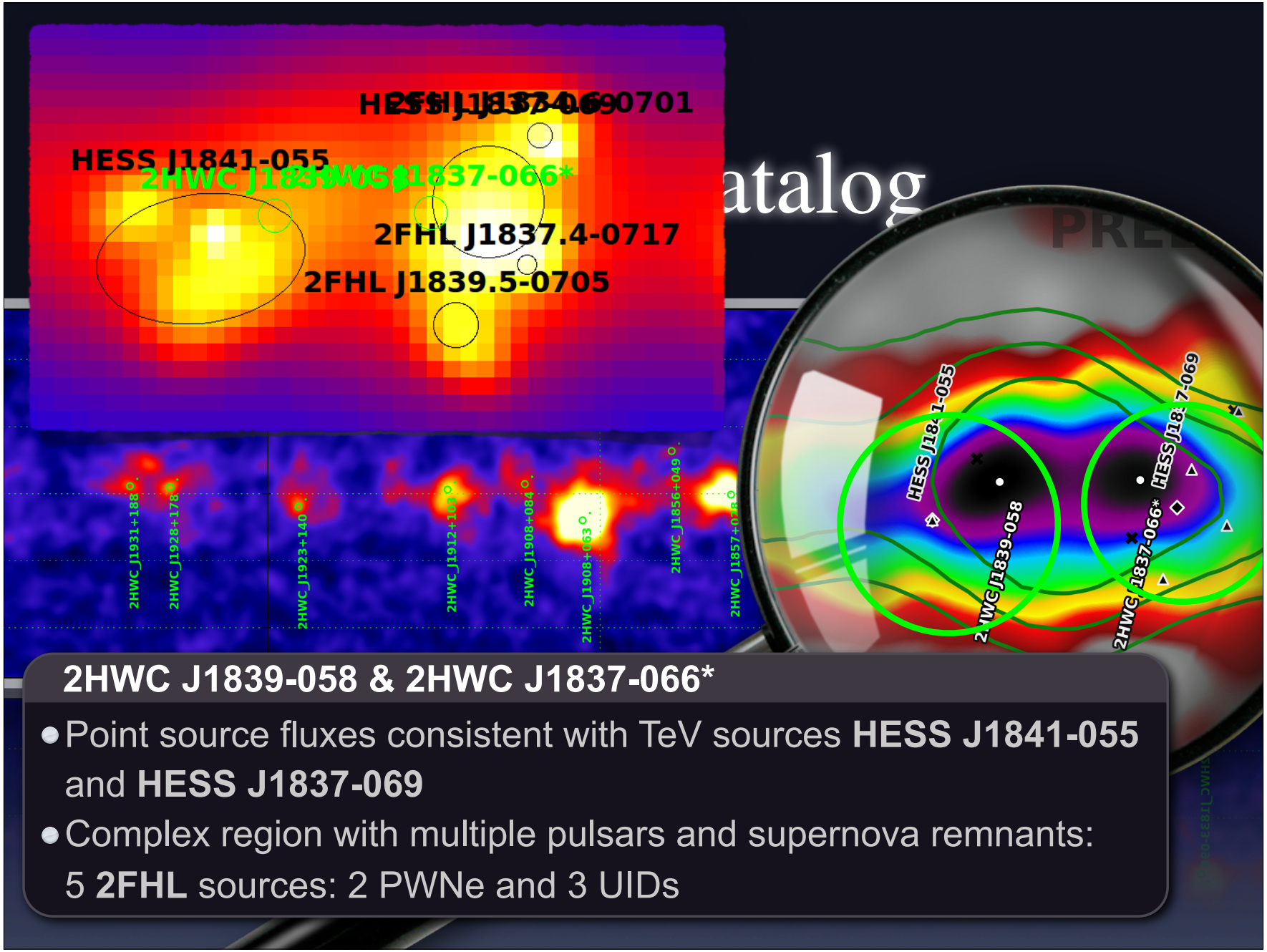
from Milagro to HAWC



- Inner Galaxy: Milagro (8 years) vs. 1st year of HAWC

first year catalog





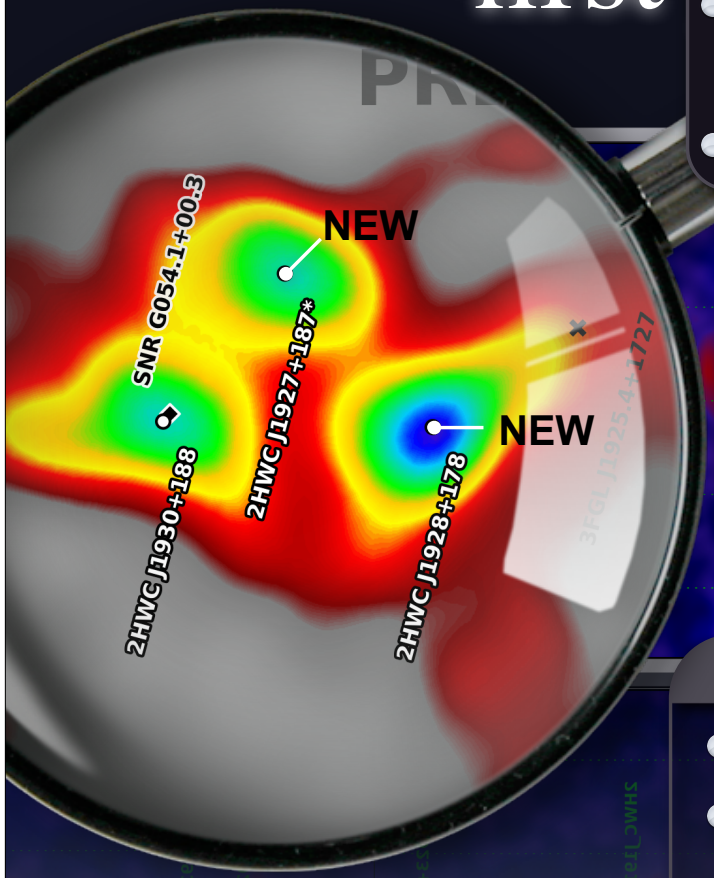
atalog

PRE

2HWC J1839-058 & 2HWC J1837-066*

- Point source fluxes consistent with TeV sources **HESS J1841-055** and **HESS J1837-069**
- Complex region with multiple pulsars and supernova remnants: 5 **2FHL** sources: 2 PWNe and 3 UIDs

first



2HWC J1930+188

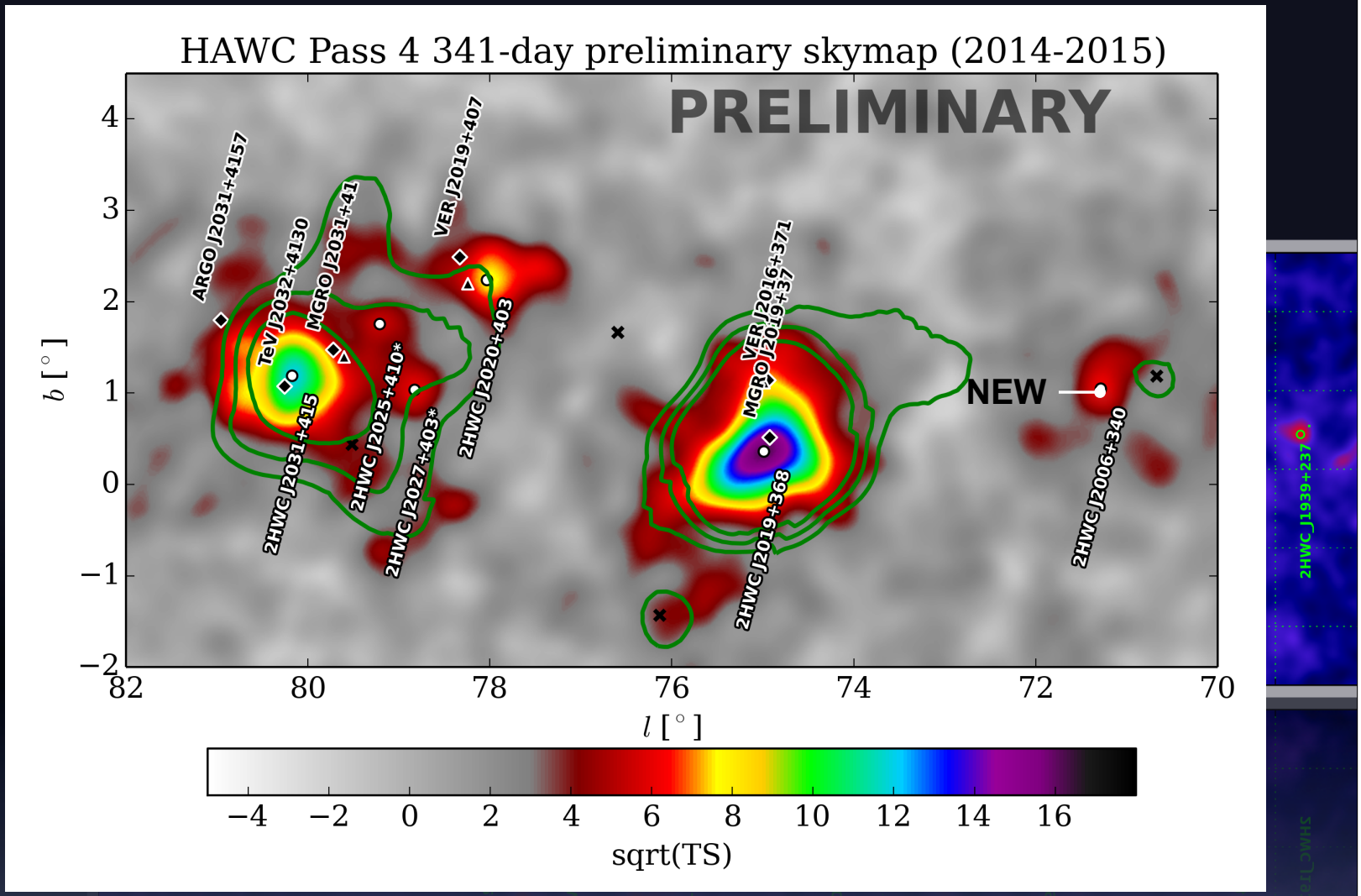
- coincident with **VER J1930+188**
  SNR G54.1+00.3 — PSR J1930+1852
- TeV emission was reported to be point-like and likely from PWN
- nearby molecular CO cloud

2HWC J1927+187*

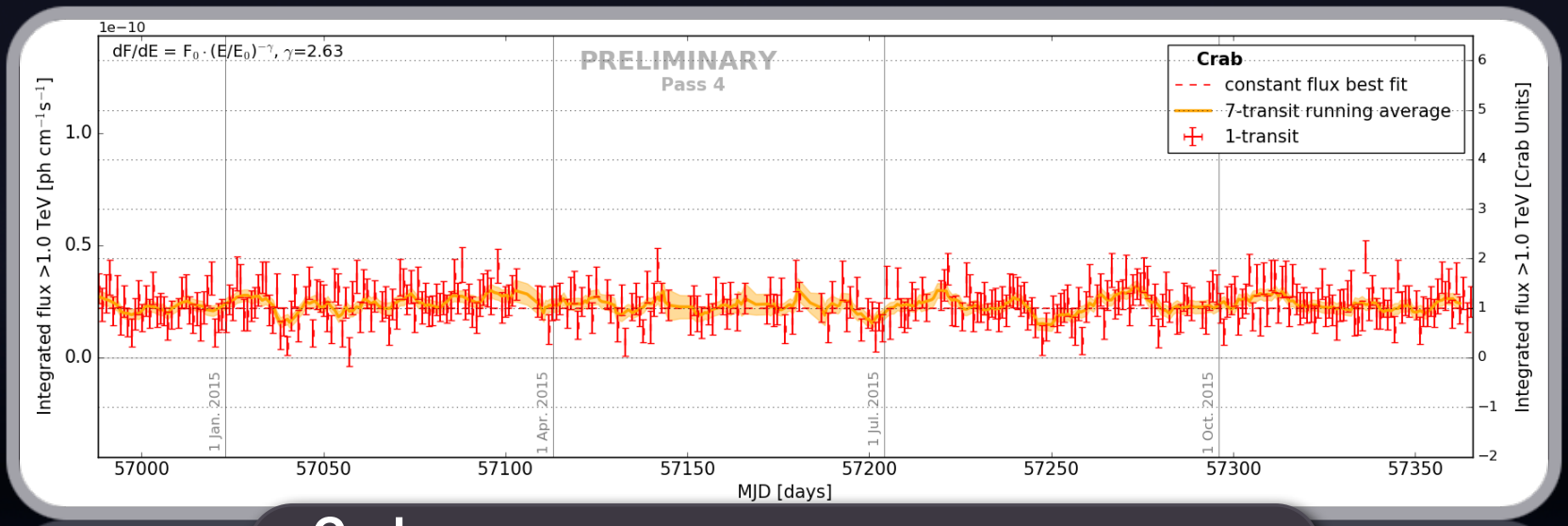
- associated with **2HWC J1930+188**?
- ongoing analysis on spatial morphology

2HWC J1928+178

- coincident with **PSR J1928+1746**
- tail towards unidentified source **3FGL J1925.4+1727**
- VERITAS pt-src upper limit ~1.4% of Crab


HAWC Pass 4 341-day preliminary skymap (2014-2015)
PRELIMINARY
ARGO J2031+4157
TeV J2032+4130
MGRO J2031+41
VER J2019+407
2HWC J2020+403
2HWC J2025+410*
2HWC J2031+415
2HWC J2027+403*
VER J2016+371
MGRO J2019+37
NEW
2HWC J2006+340
2HWC J2019+368
2HWC J1939+237*
b [°]
l [°]
sqrt(TS)

transient searches

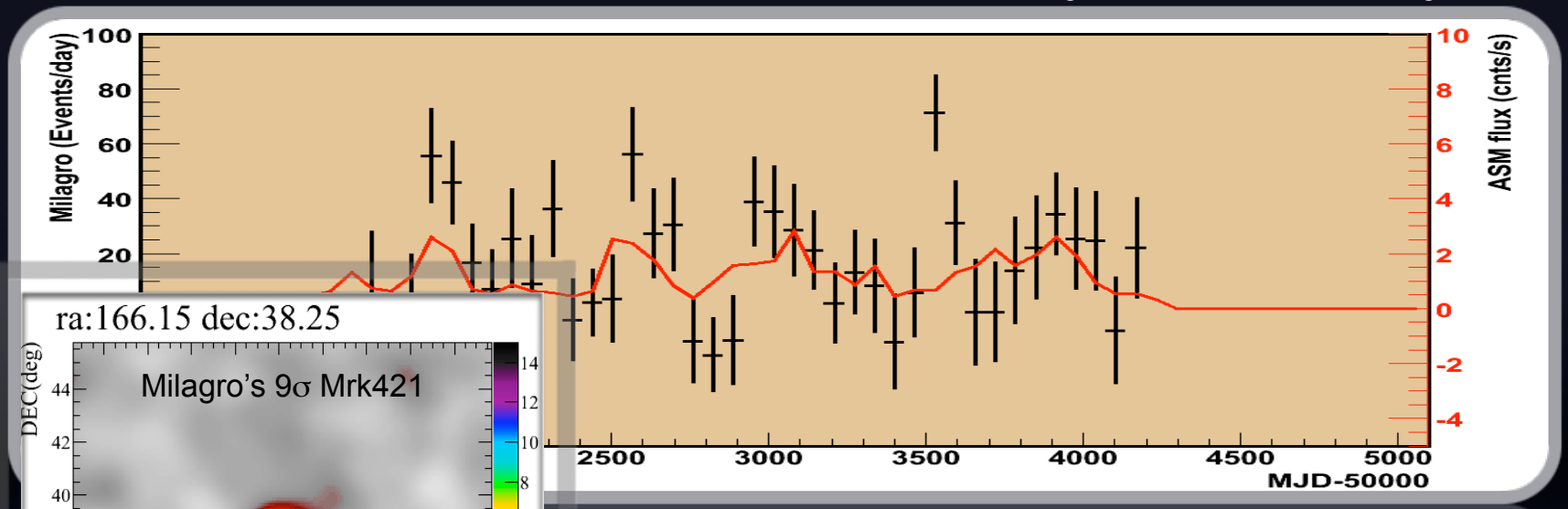


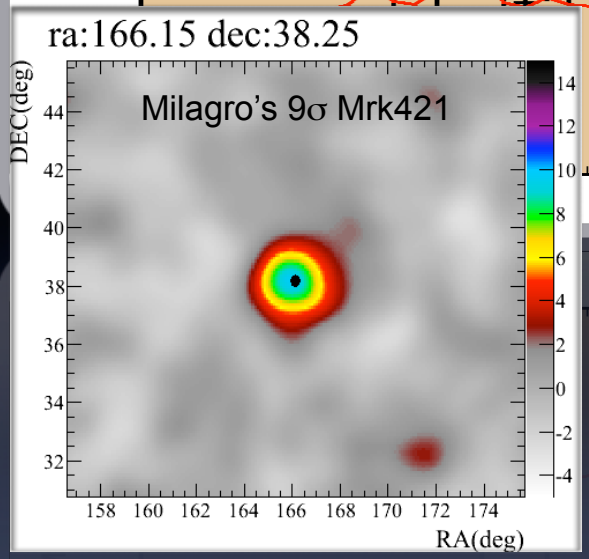
Crab

- Pass 4 data from 26 Nov 2014 to 9 Dec 2015
- >80σ in 315 transits
- lightcurve binned in sidereal day
- consistent with constant flux

AGN flares with Milagro

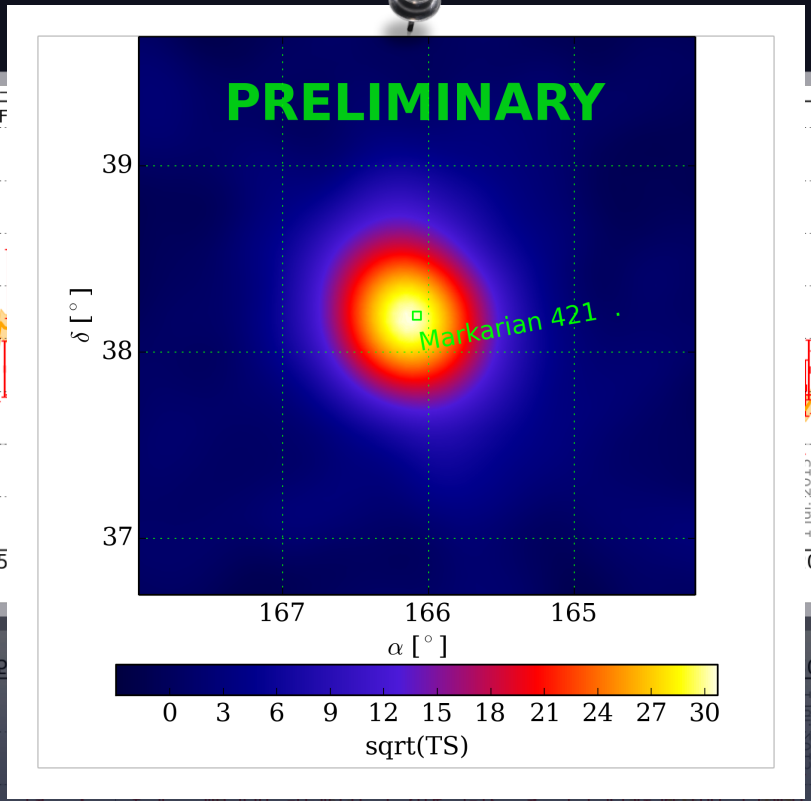
Milagro Collaboration, Proceedings ICRC'07





- continuously monitor flares
- notify multi-wavelengths observers
- discover orphan TeV flares

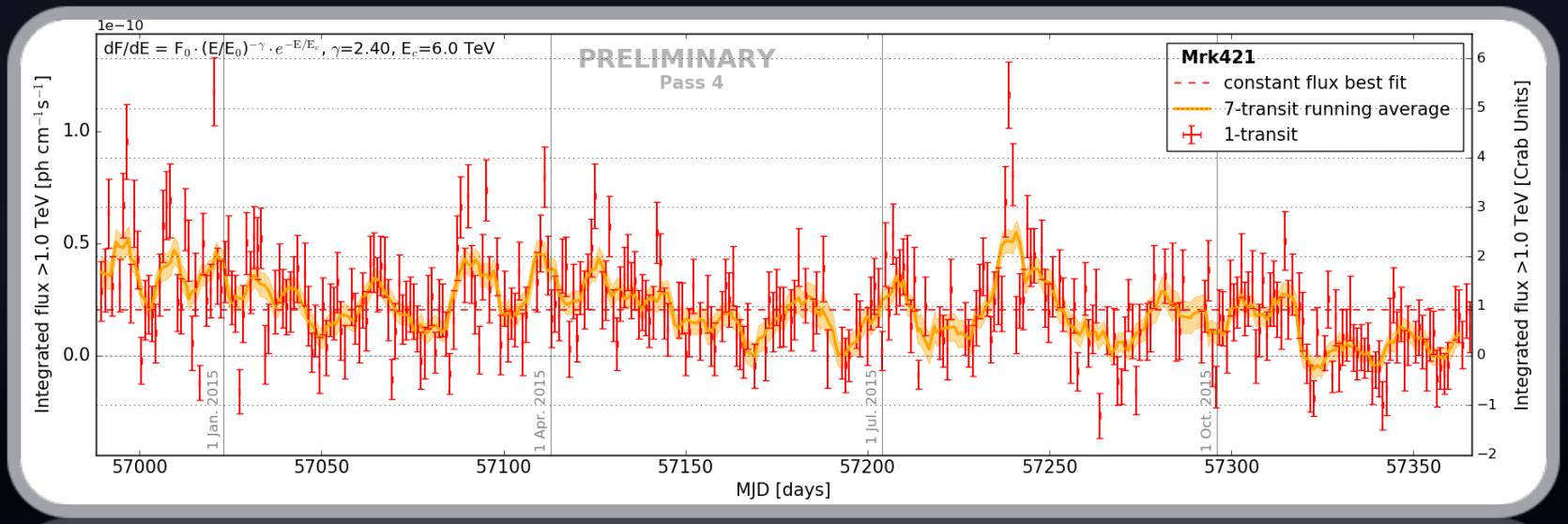
AGN flares with HAWC



Nov 26, 2014 – Dec 9, 2015

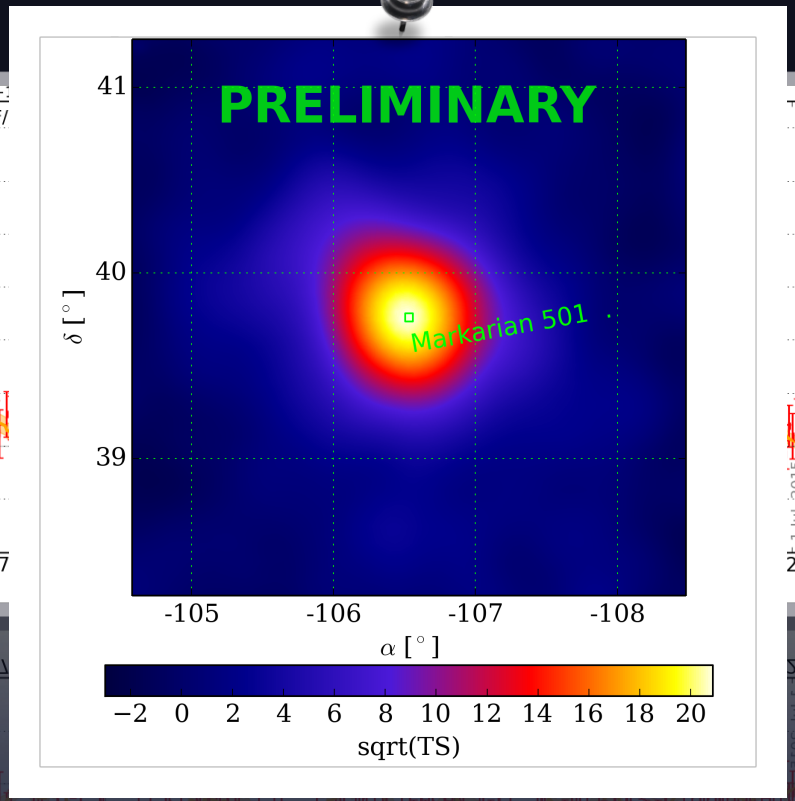
AGN flares with HAWC

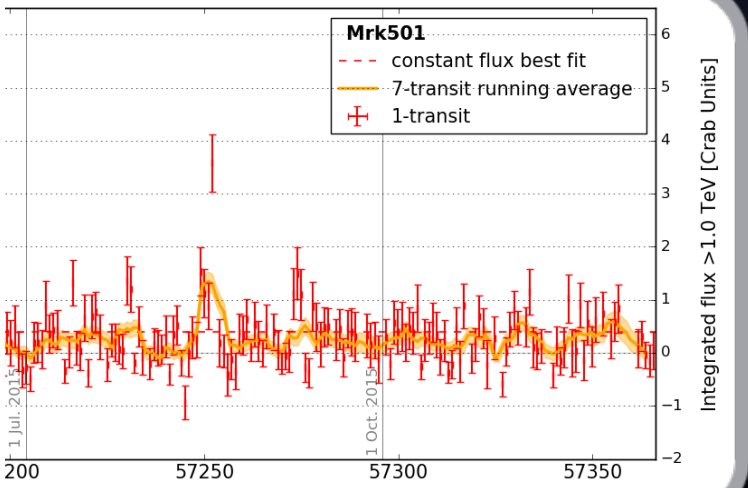
Nov 26, 2014 – Dec 9, 2015



AGN flares with HAWC

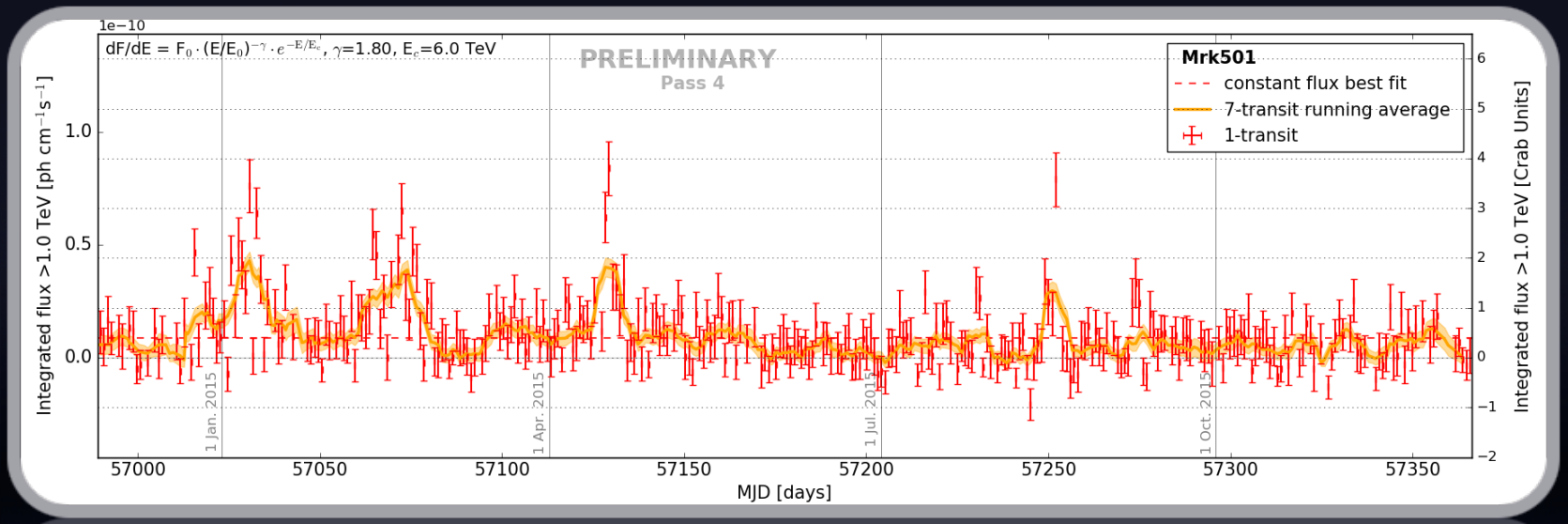
Nov 26, 2014 – Dec 9, 2015



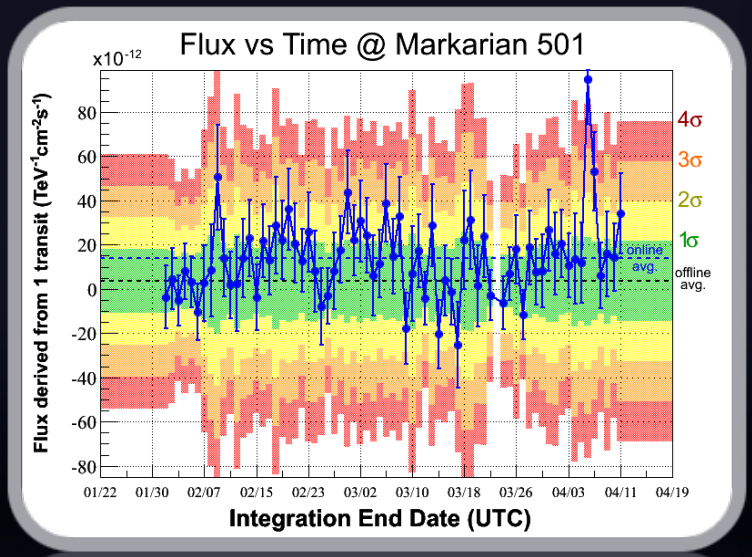


AGN flares with HAWC

Nov 26, 2014 – Dec 9, 2015



AGN flares with HAWC



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
Credential Certification: C. Michelle Hui (c.m.hui@nasa.gov)

Subjects: Gamma Ray, TeV, VHE, Request for Observations, AGN, Blazar

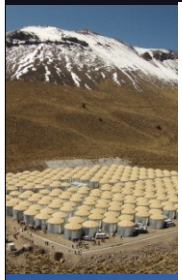
Tweet Recommend 15

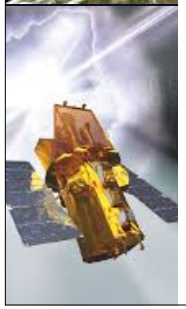
The HAWC Observatory measured an increased gamma-ray flux from the direction of the BL Lac Markarian 501 (z=0.033) at the level of (4.88 +/- 1.05) x 10e-11 photons cm^-2 s^-1 above 1 TeV when averaged during the 6 hour transit over HAWC on April 6, 2016 (MJD 57484.31 - 57484.56) which is 2.2 times the average Crab flux observed by HAWC. For the following transit on April 7, 2016 (MJD 57485.30 - 57485.55), a decreased but still above-average flux of (2.78 +/- 0.09) x 10e-11 photons cm^-2 s^-1 was observed, 1.3 times the Crab flux seen by HAWC. The flux on April 6 lies 4 sigma above the average flux of 0.89 x 10e-11 photons cm^-2 s^-1 that was measured for this source by HAWC during the previous year. The flux level on April 7 is 2 sigma above this average and seems to indicate a declining but on-going high flux state. All flux values are obtained from a maximum likelihood fit under the assumption of a fixed spectral shape with power law index of 1.8 and exponential cut-off at 6 TeV. These spectral parameters are the best fit results for HAWC data from Markarian 501 collected between November 2014 and December 2015. HAWC is a TeV gamma ray water Cherenkov array located in the state of Puebla, Mexico that monitors 2/3 of the sky every day with an instantaneous field of view of ~2 sr. The HAWC contact people for this analysis are Robert Lauer (University of New Mexico, rjlauer@unm.edu) and Michelle Hui (Marshall Space Flight Center, c.m.hui@nasa.gov).

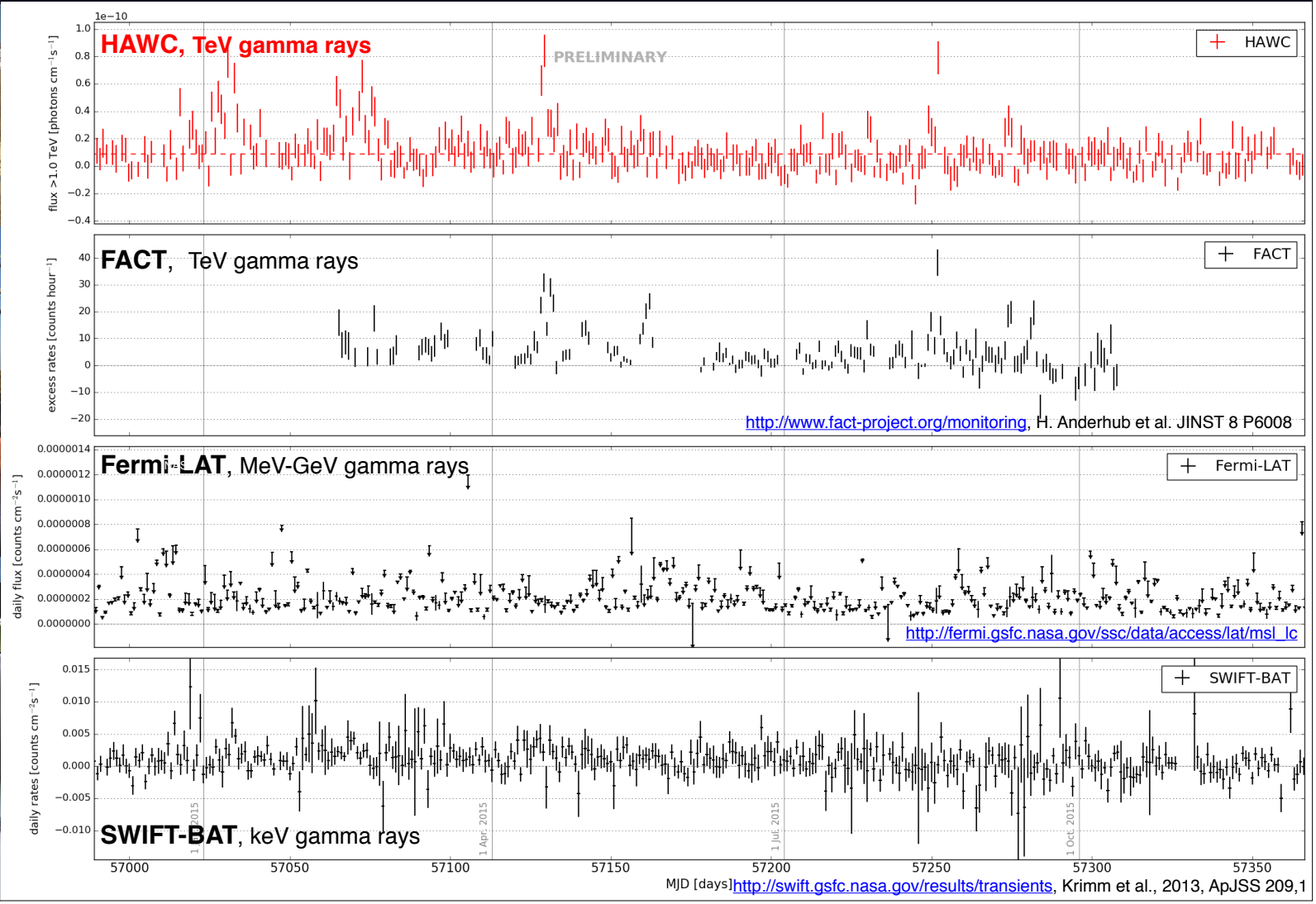
First TeV flare alert from HAWC!

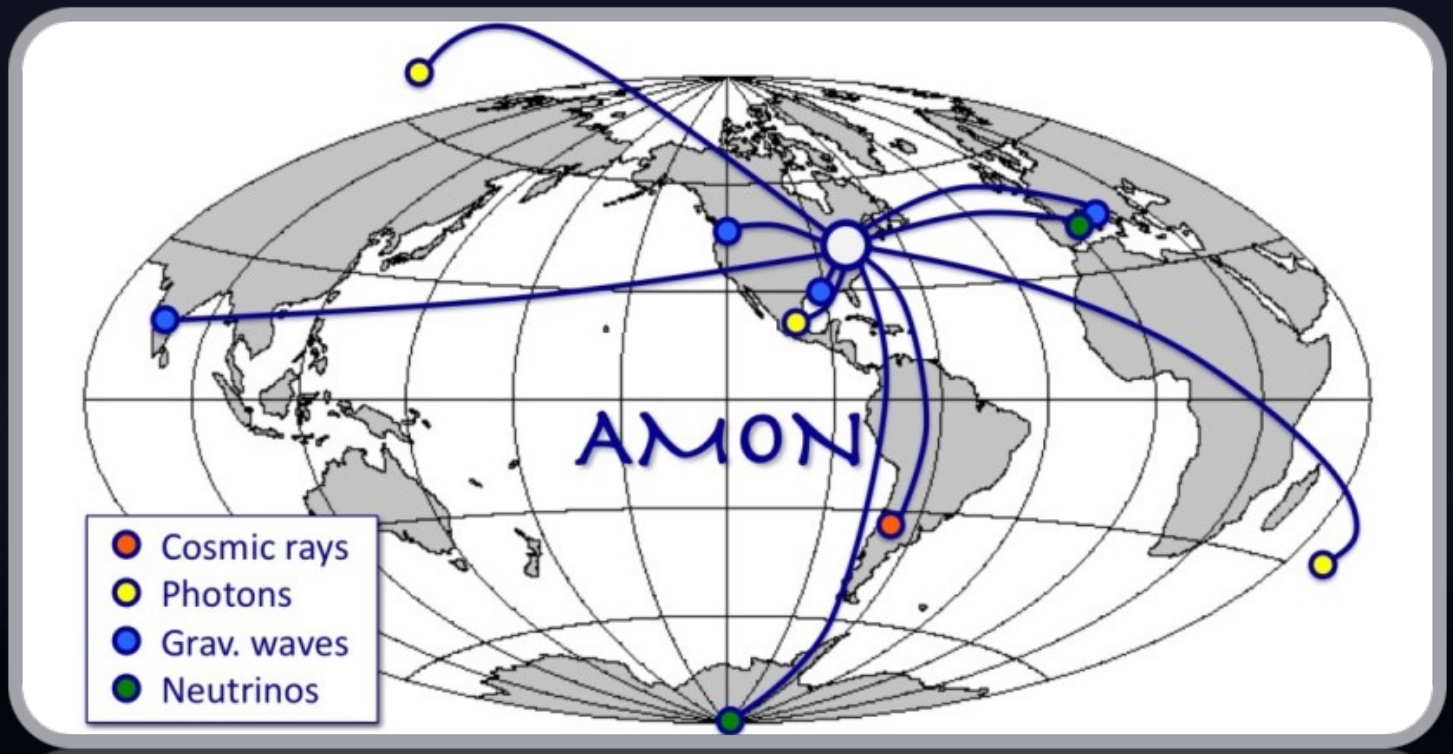
multi-wavelength studies

Daily Monitoring of Markarian 501



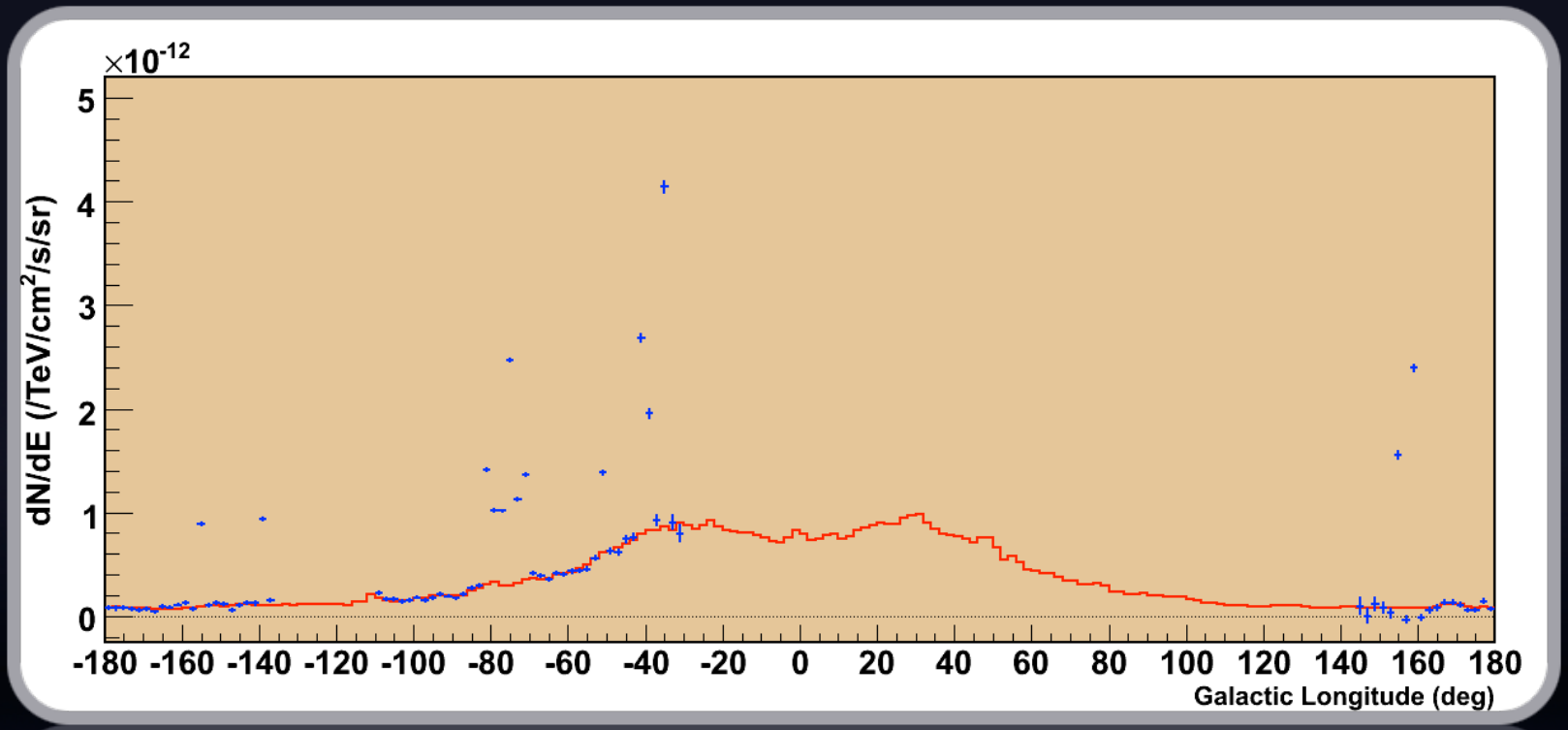






Multi-Messenger Studies

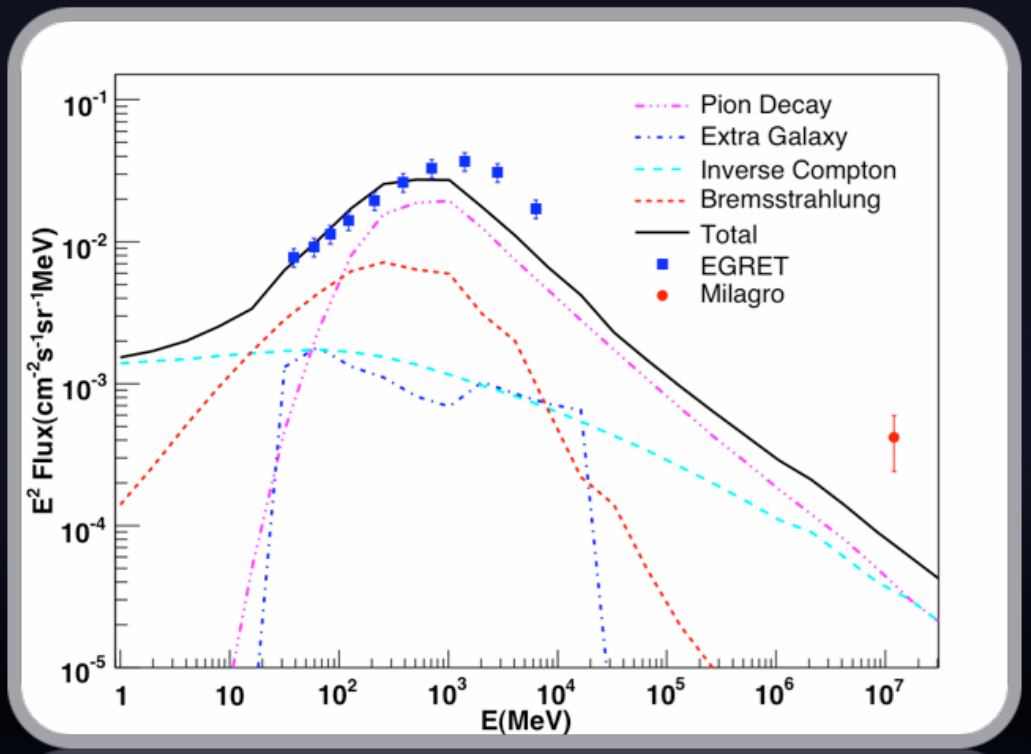
TeV diffuse emission



HAWC can map TeV diffuse emission with **2º** longitude resolution.

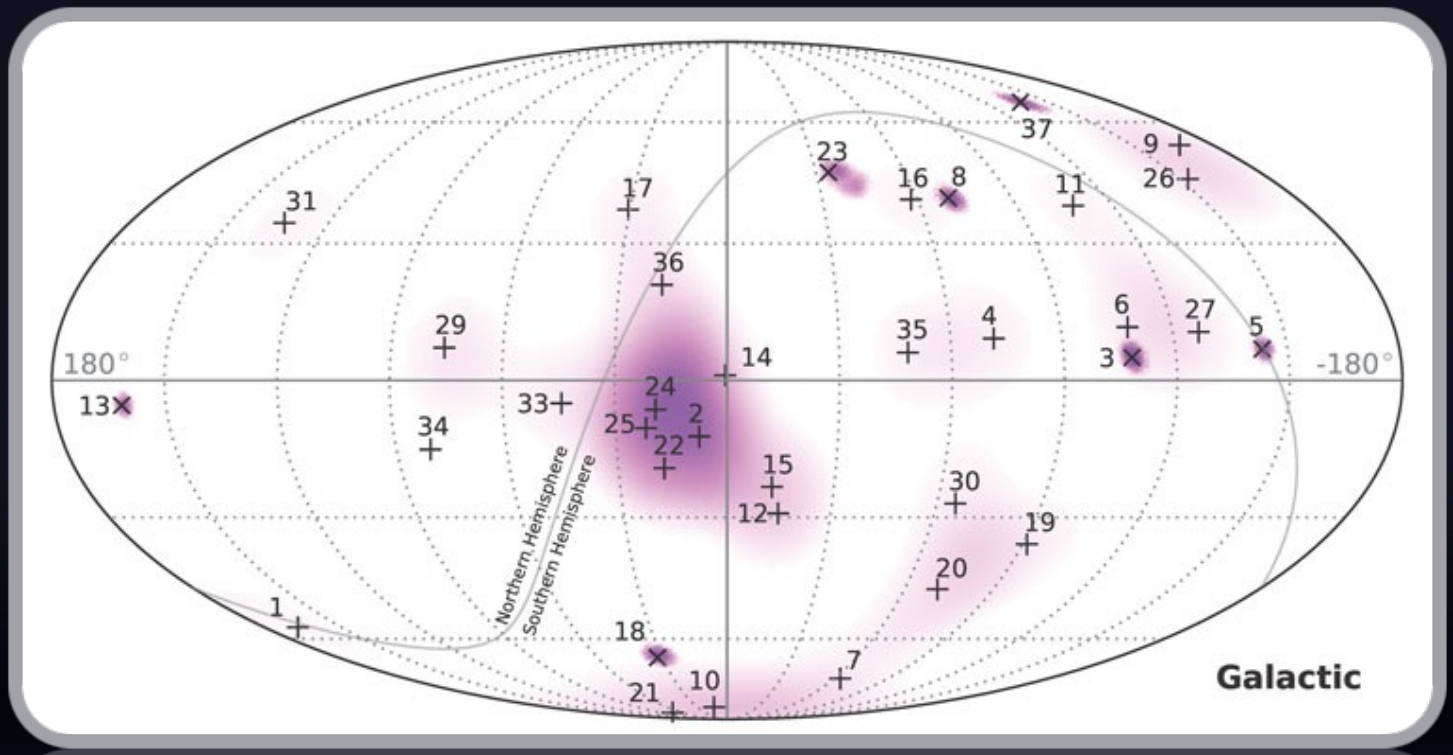
TeV diffuse emission

Whether or not there is a GeV excess, Milagro sees a **TeV excess**.



HAWC can map TeV diffuse emission with **2º** longitude resolution.

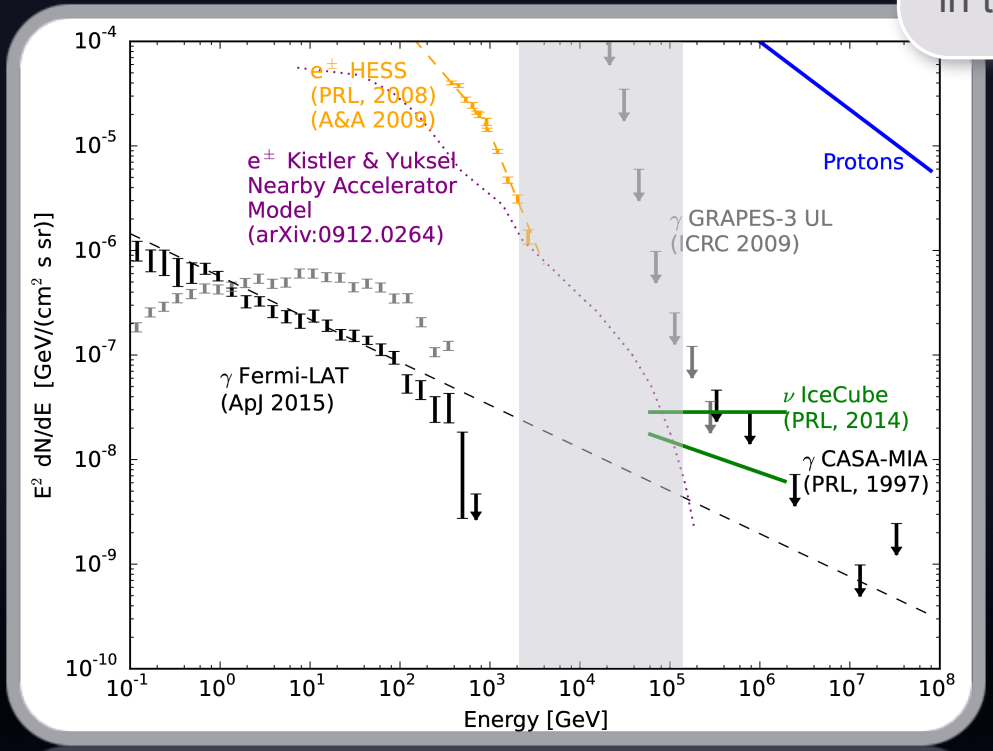
Milagro Collaboration, The Astrophysical Journal **688** (2008) 1078-1083


180°
-180°
Northern Hemisphere
Southern Hemisphere
Galactic
37
9
26
23
16
8
11
17
31
36
29
35
4
6
27
5
3
14
13
24
33
2
25
22
34
15
30
12
19
20
1
18
7
21
10

IceCube

Isotropic Diffuse Emission

Neither measurements nor limits in the **10-100 TeV** range



connecting HAWC with IC

Isotropic Diffuse Emission

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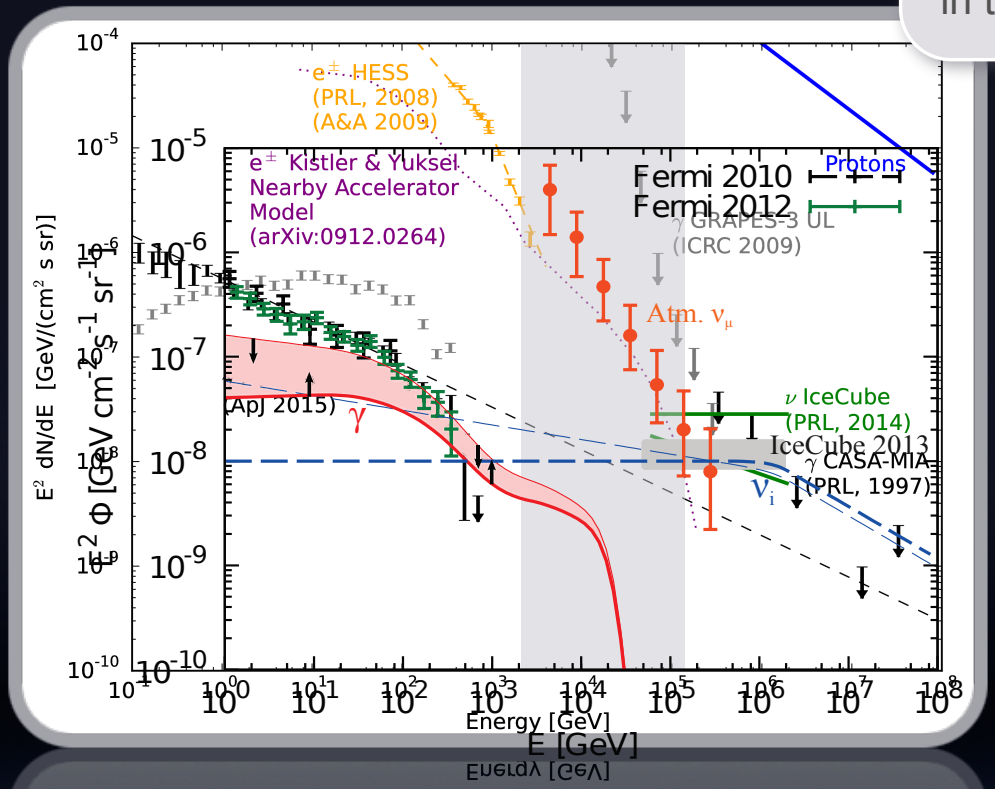

Kohta Murase, M. Ahlers, B.C. Lacki, Phys. Rev. D 88 (2013) 121301

connecting HAWC with IC

Isotropic Diffuse Emission

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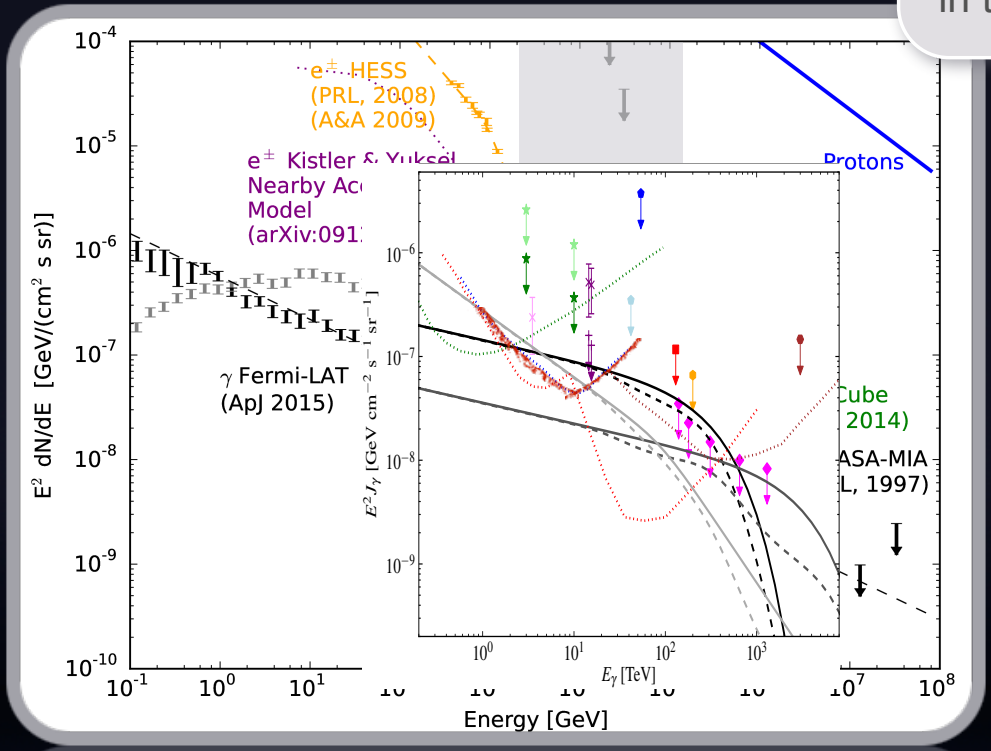
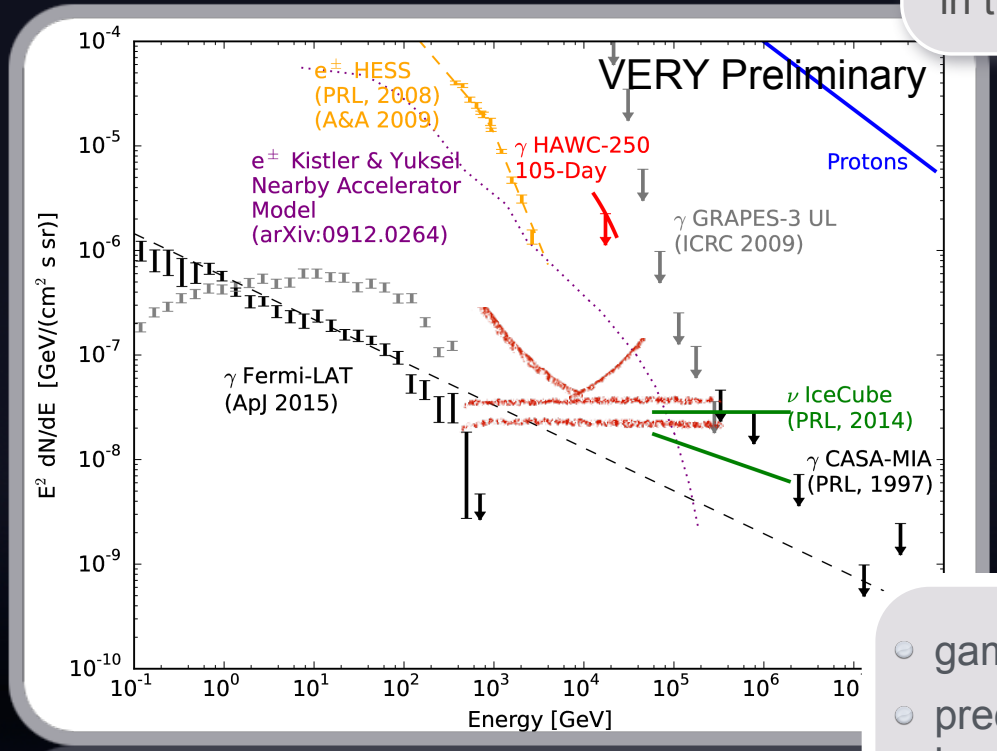


M. Ahlers, Kohta Murase,
Phys. Rev. D 90 (2014) 023010

connecting HAWC with IC

Isotropic Diffuse Emission

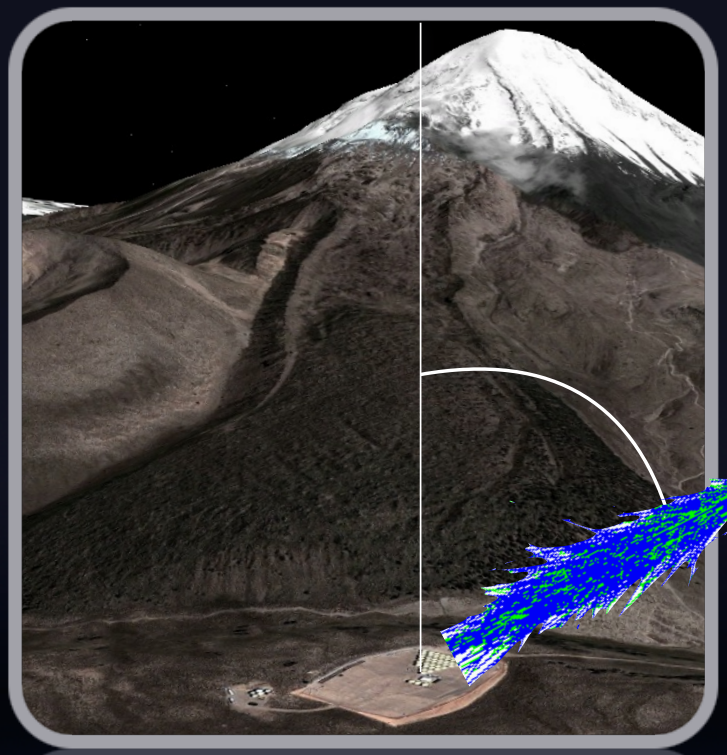
Neither measurements nor limits in the **10-100 TeV** range

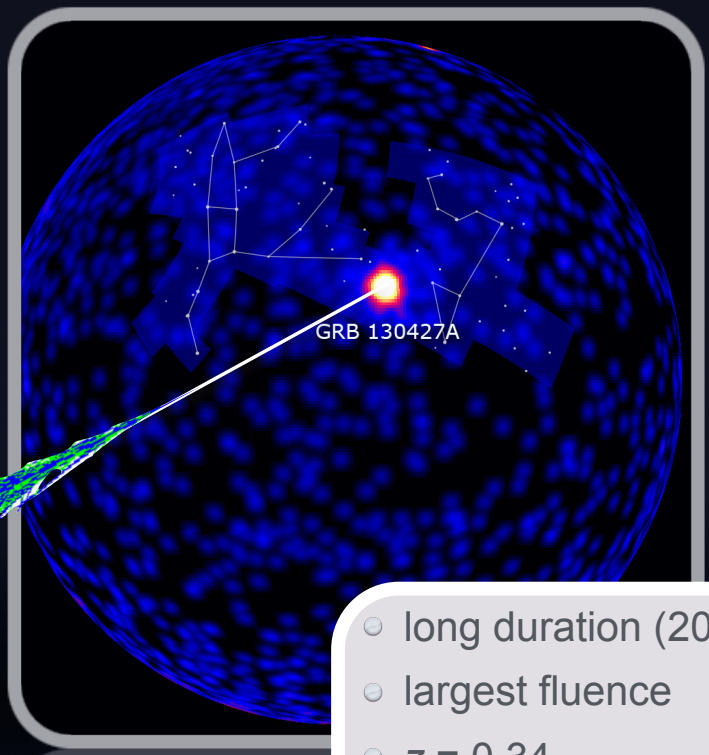


- gamma/hadron separation
- precise understanding of background efficiency

connecting HAWC with IC

GRB 130427A

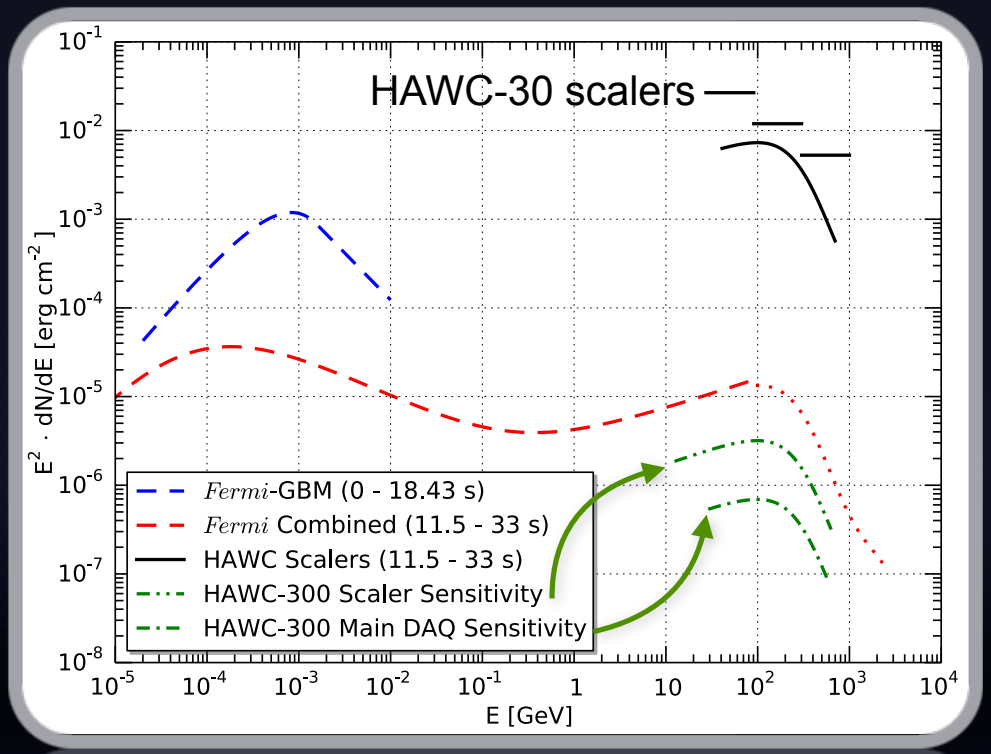


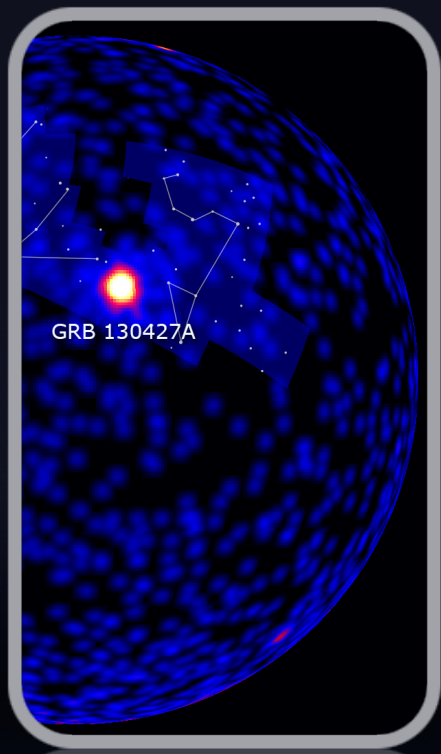


- HAWC-30
- θ = 57°
- only scalers DAQ up

- long duration (20 h)
- largest fluence
- z = 0.34
- highest energy photon (95 GeV)

GRB 130427A





- HAWC-30
- θ = 57°
- only scalers DAQ up

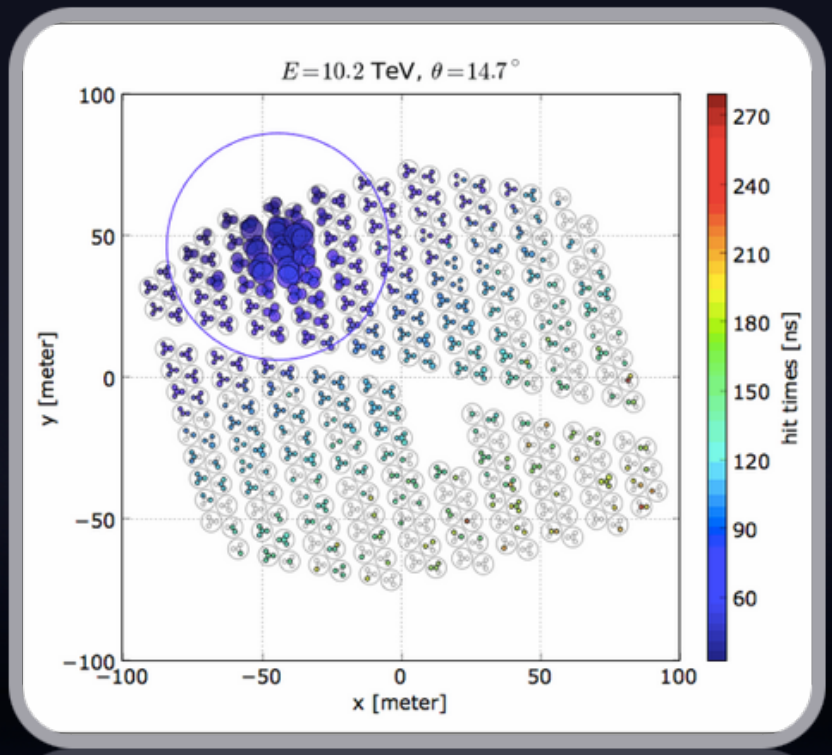
"Search for gamma-rays from the unusually bright GRB 130427A with the HAWC Gamma-ray Observatory," *The Astrophysical Journal,* Volume 800 (2015) Number 2, p78

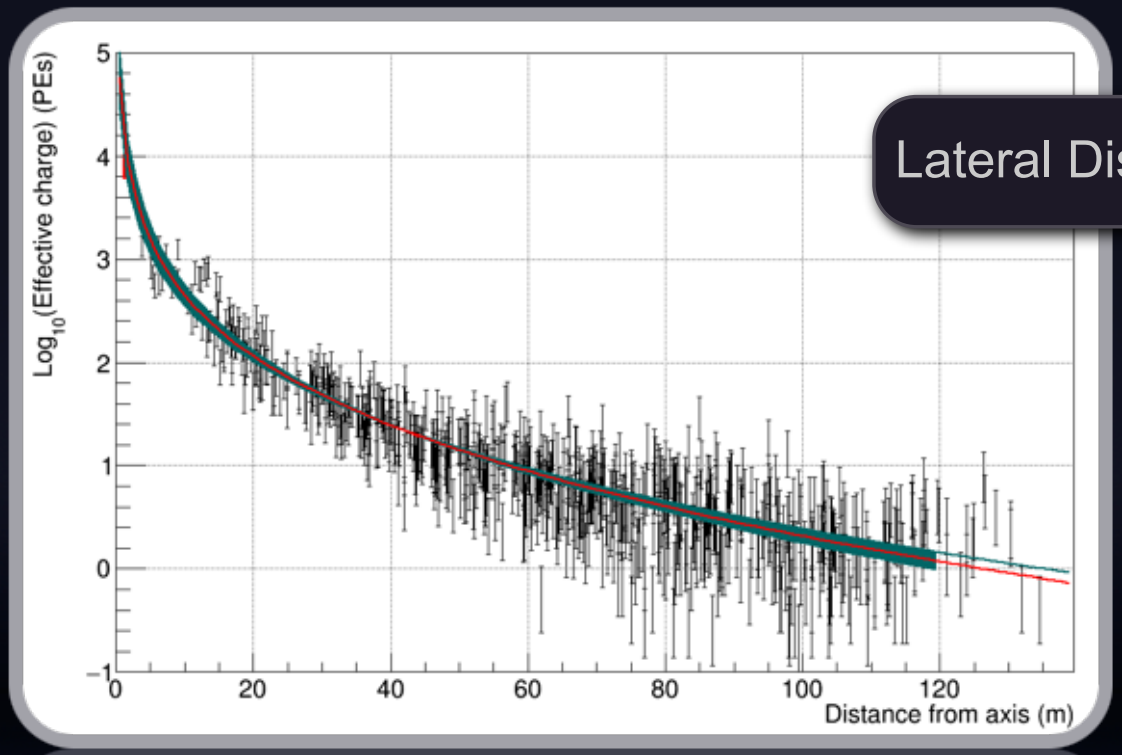
Improvements...

HAWC group at Penn State (2015)

Energy measurement

Number of triggered PMTs is the energy proxy



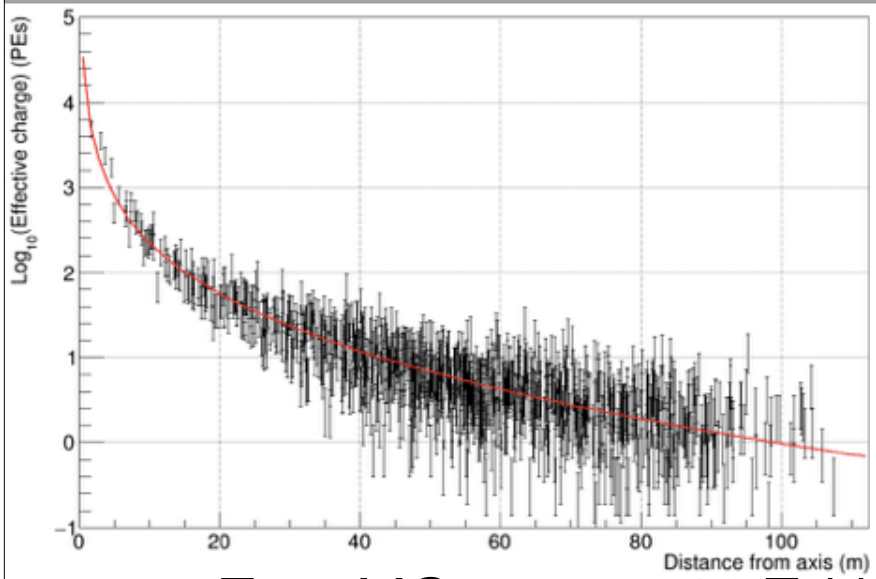


Lateral Distribution Function

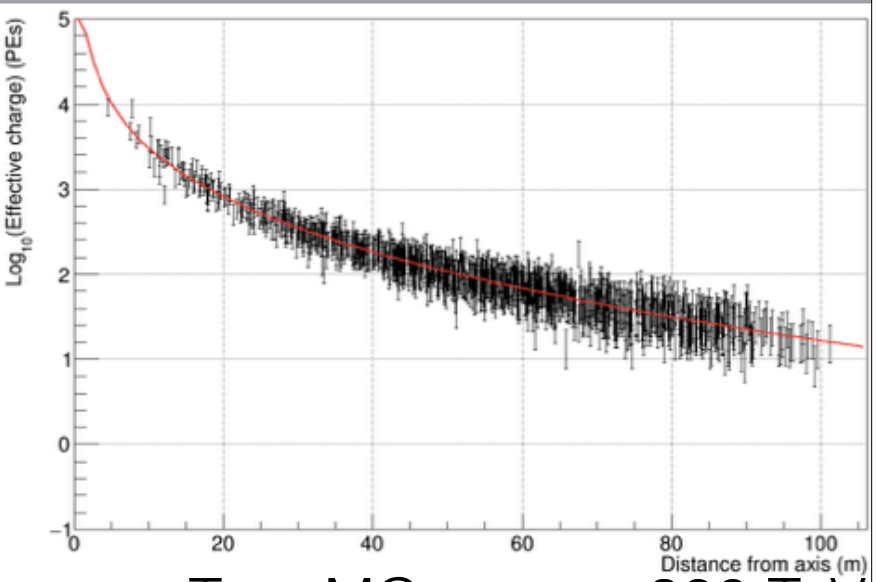
Energy measurement

Energy measurement

Preliminary results!

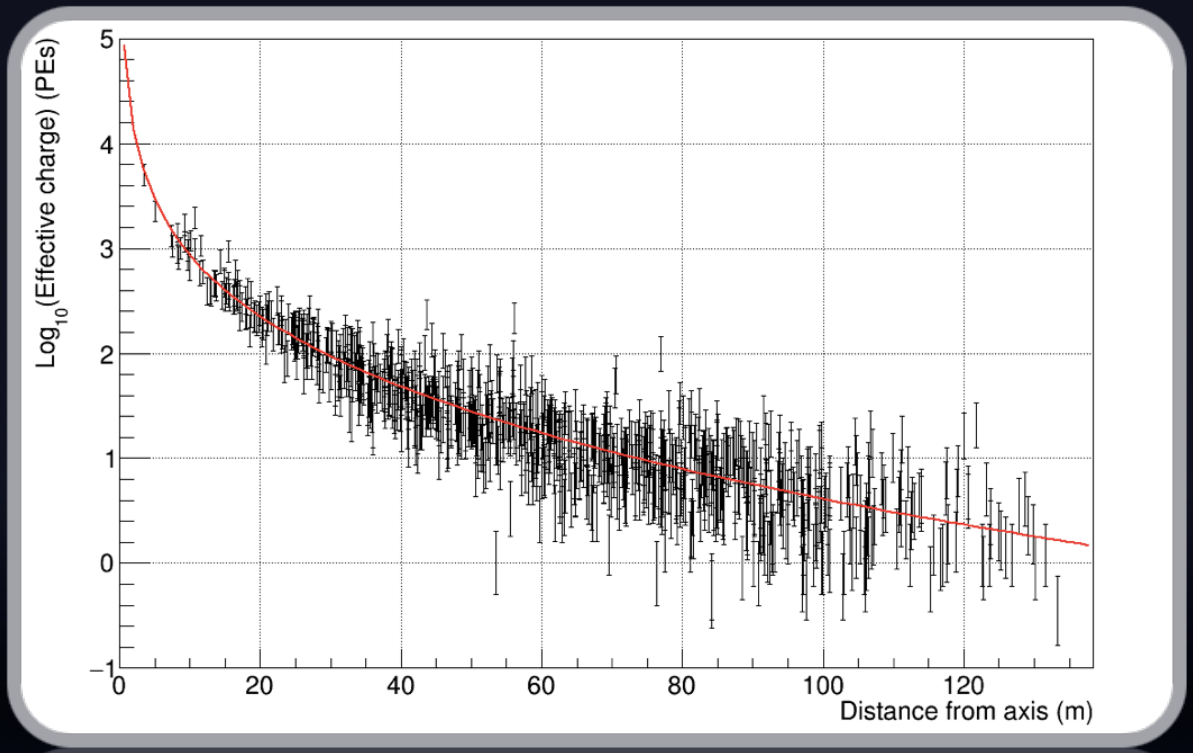


True MC energy 18 TeV
Reconstructed energy 17 TeV

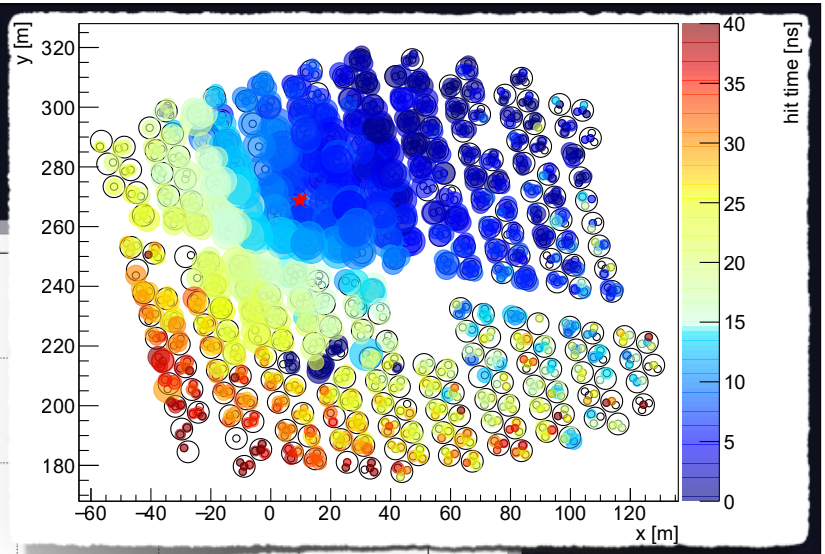


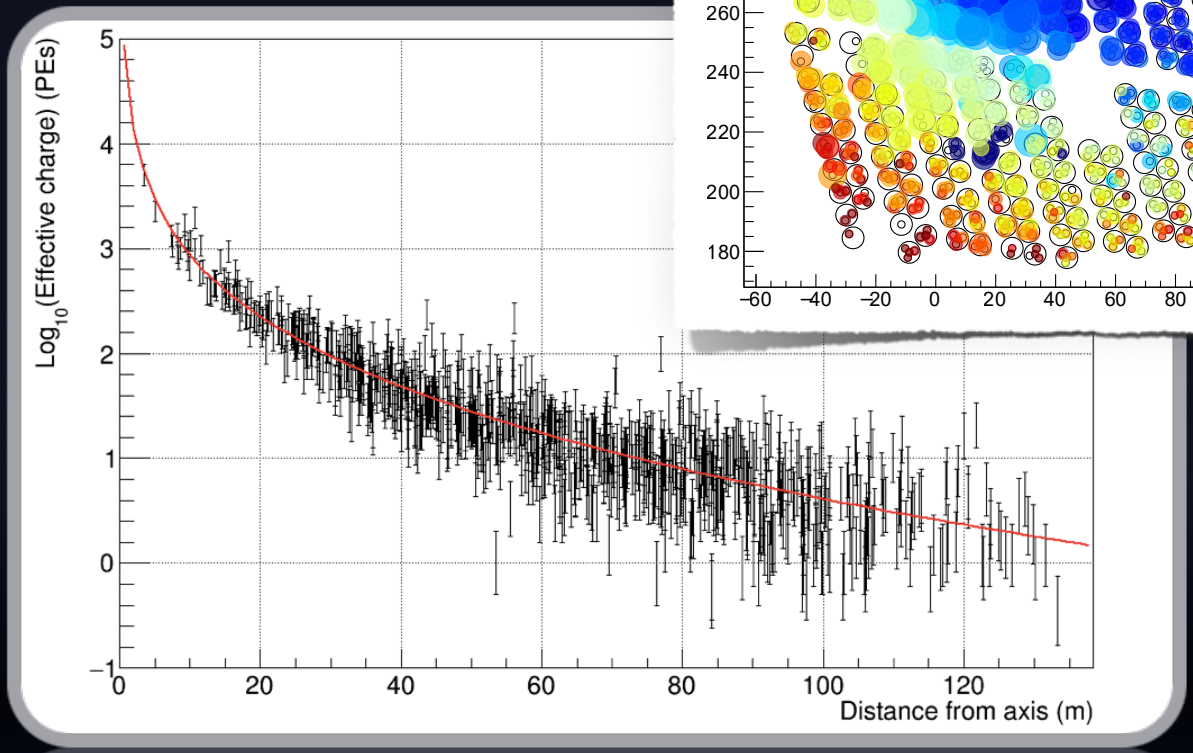
True MC energy 380 TeV
Reconstructed energy 350 TeV

Preliminary results!



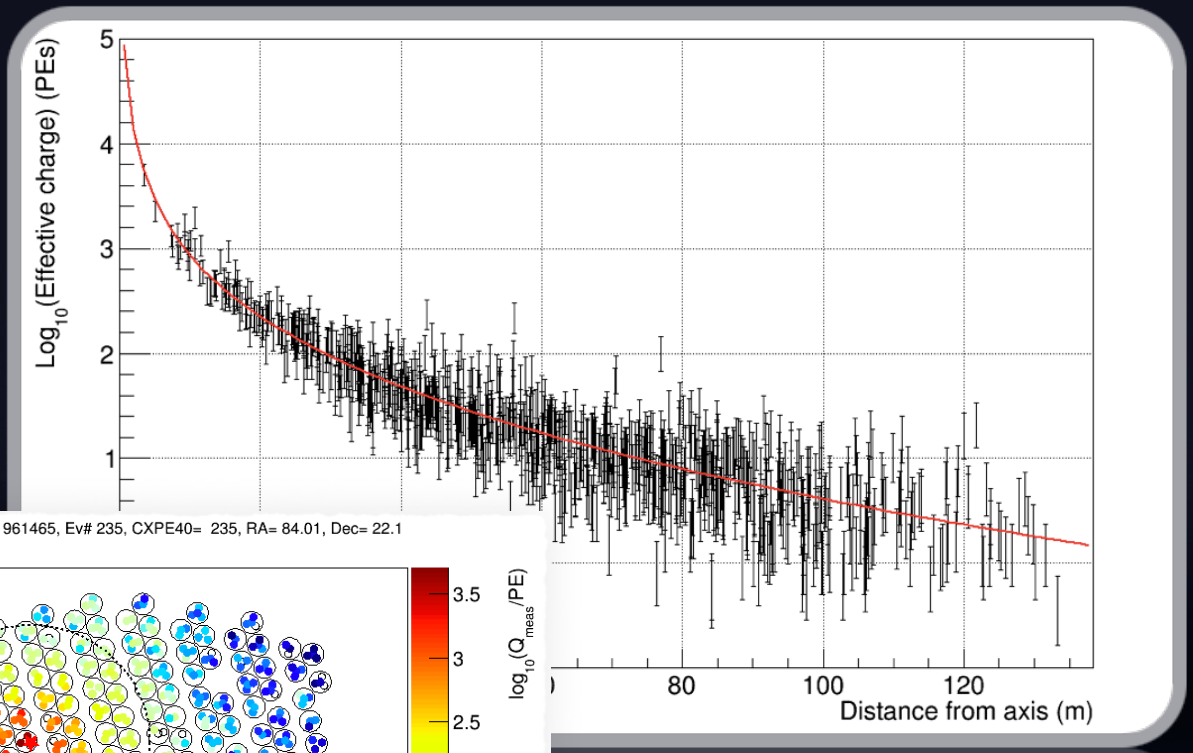
Energy measurement

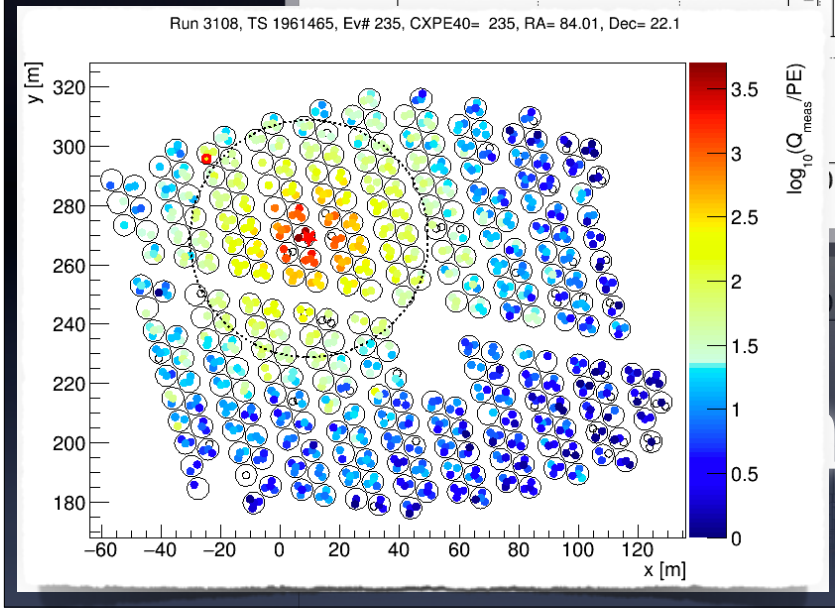




Energy measurement

Preliminary results!



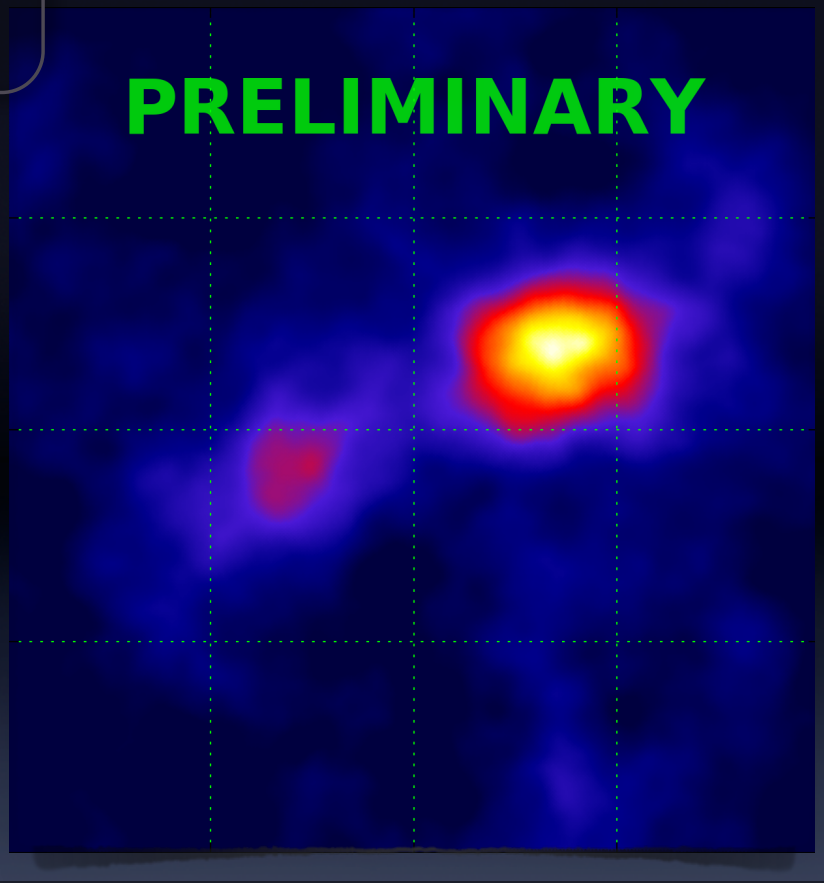


easurement

Outlook

Other results

- Dark matter, extended regions, Cosmic rays, …
- EBL, solar physics, …



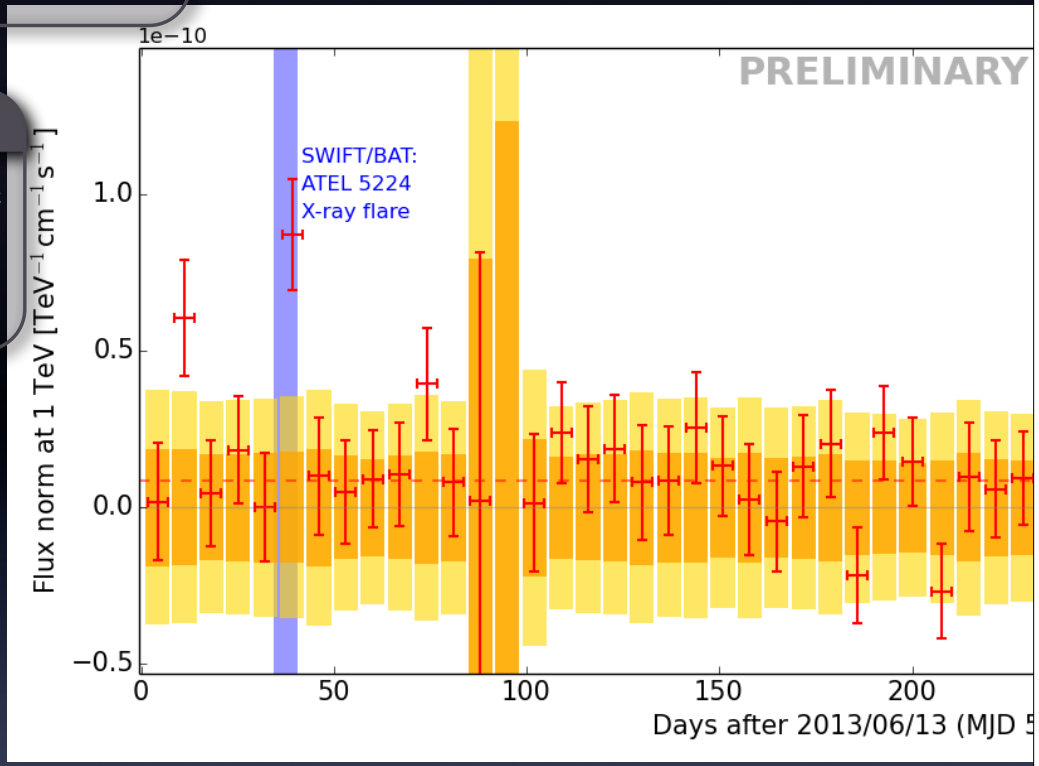
Outlook

Other results

- Dark matter, extended regions, Cosmic rays, …
- EBL, solar physics, …

Multi-wavelength physics

- MoUs with IceCube, IACTs, etc
- AMON
- HAWC alerts



Outlo

Other results

- Dark matter, extended regions, Cosmic rays, …
- EBL, solar physics, …

Multi-wavelength physics

- MoUs with IceCube, IACTs, etc
- AMON
- HAWC alerts

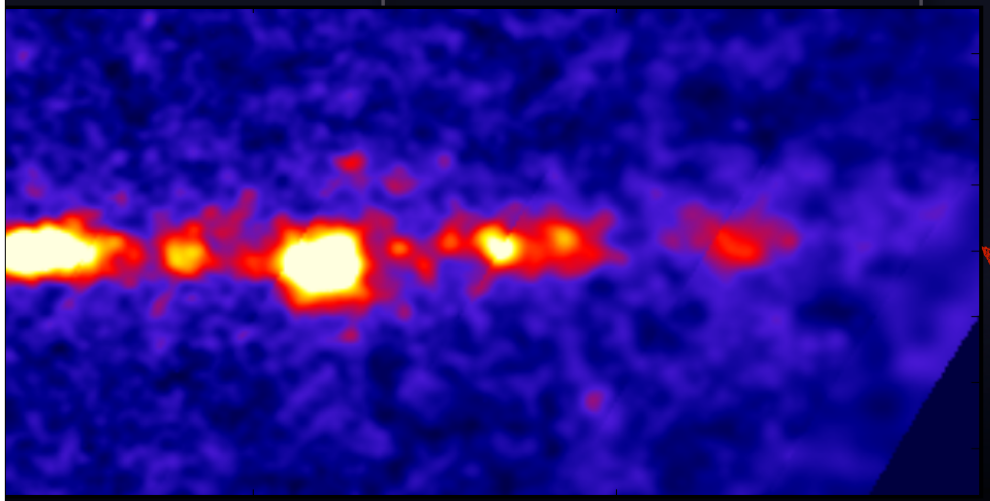
Enhancements

- Array of Outriggers

Outlook

Other results

- Dark matter, extended regions,



Galactic Center

Enhancements

- Array of Outriggers

Future Experiment

- Southern Observatory


Thank you very much