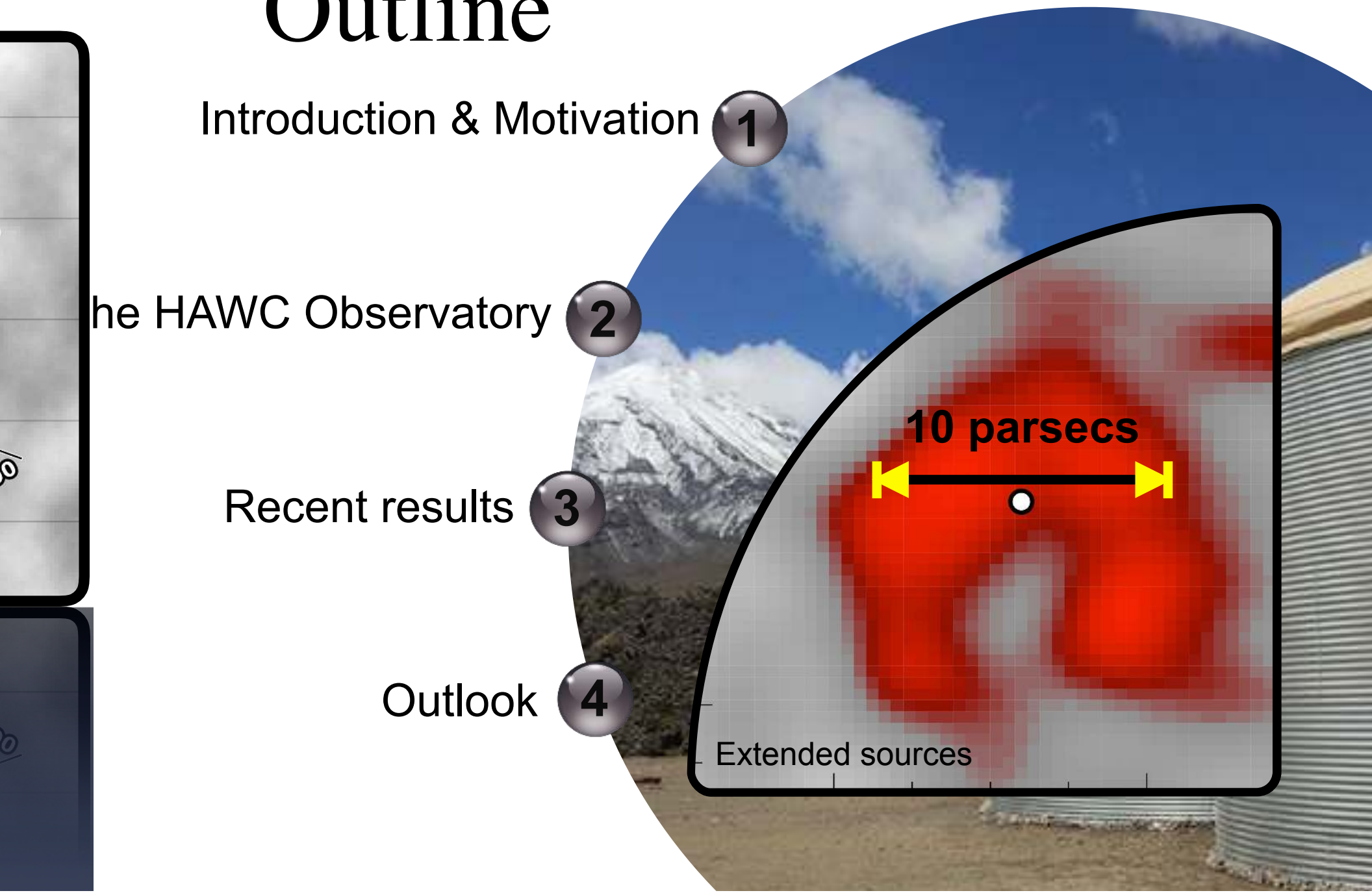
Isapp School - March 3, 2019

The High Altitude Water Cherenkov Observatory

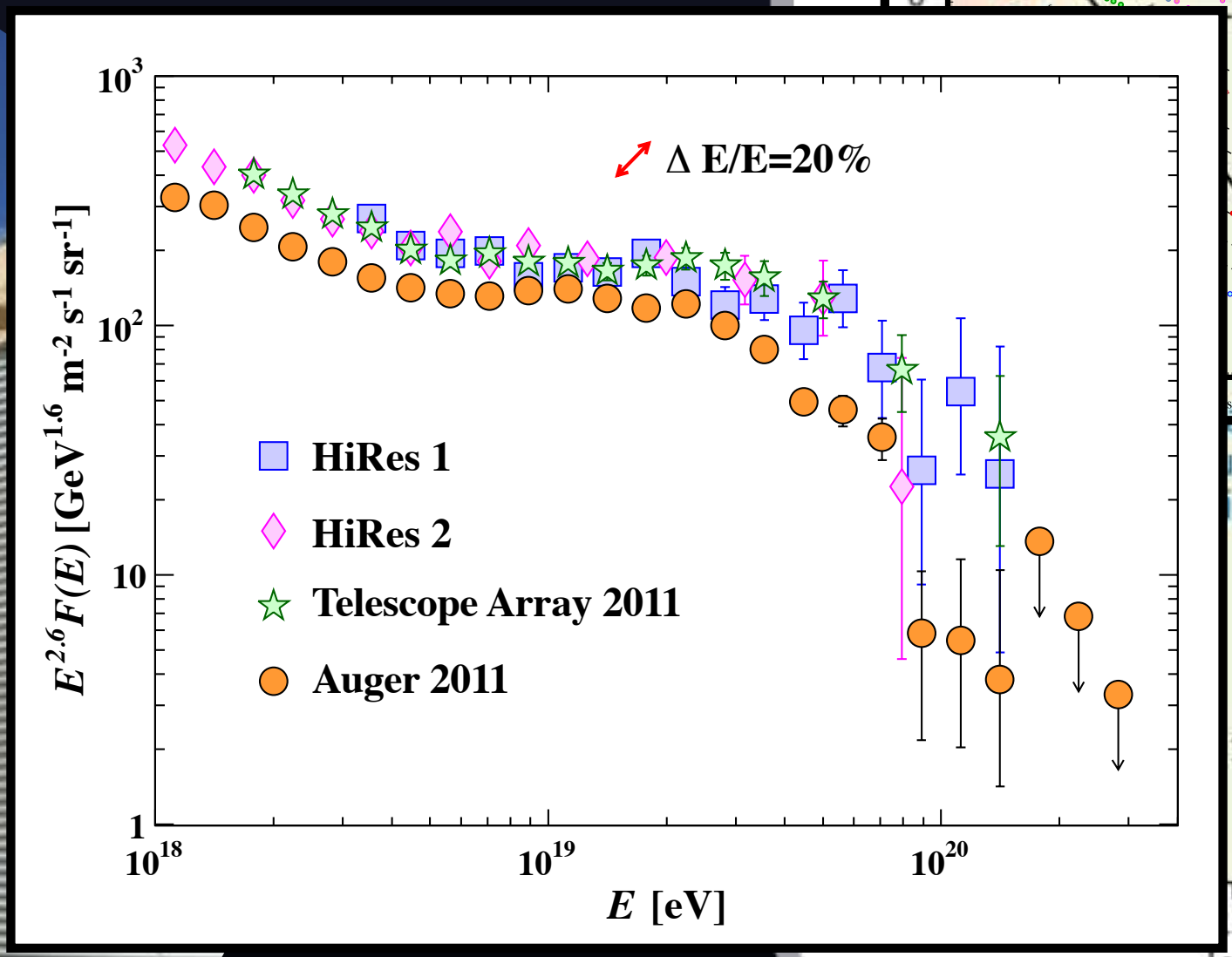
Outline

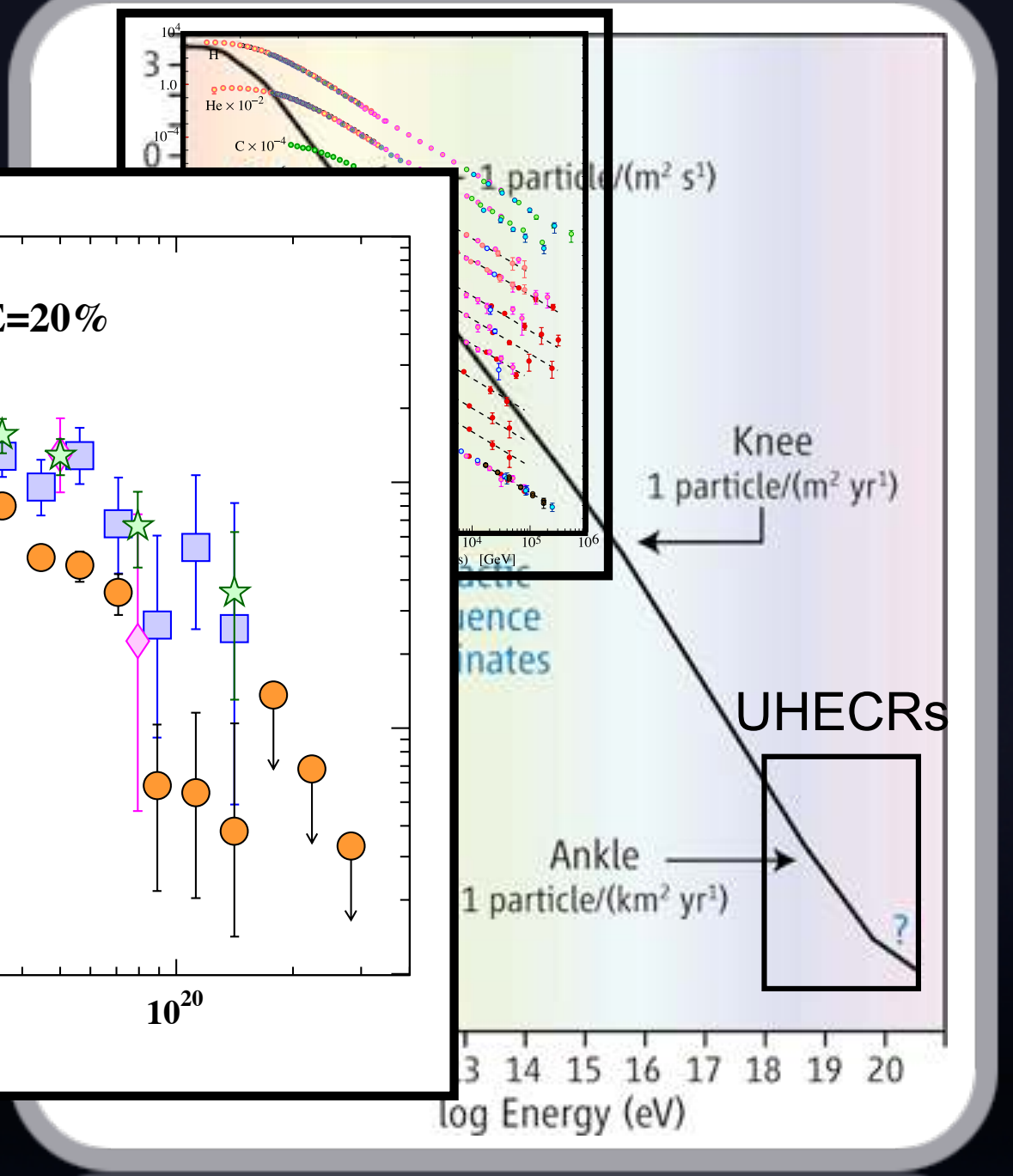
1. Introduction & Motivation
2. he HAWC Observatory
3. Recent results
4. Outlook



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

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

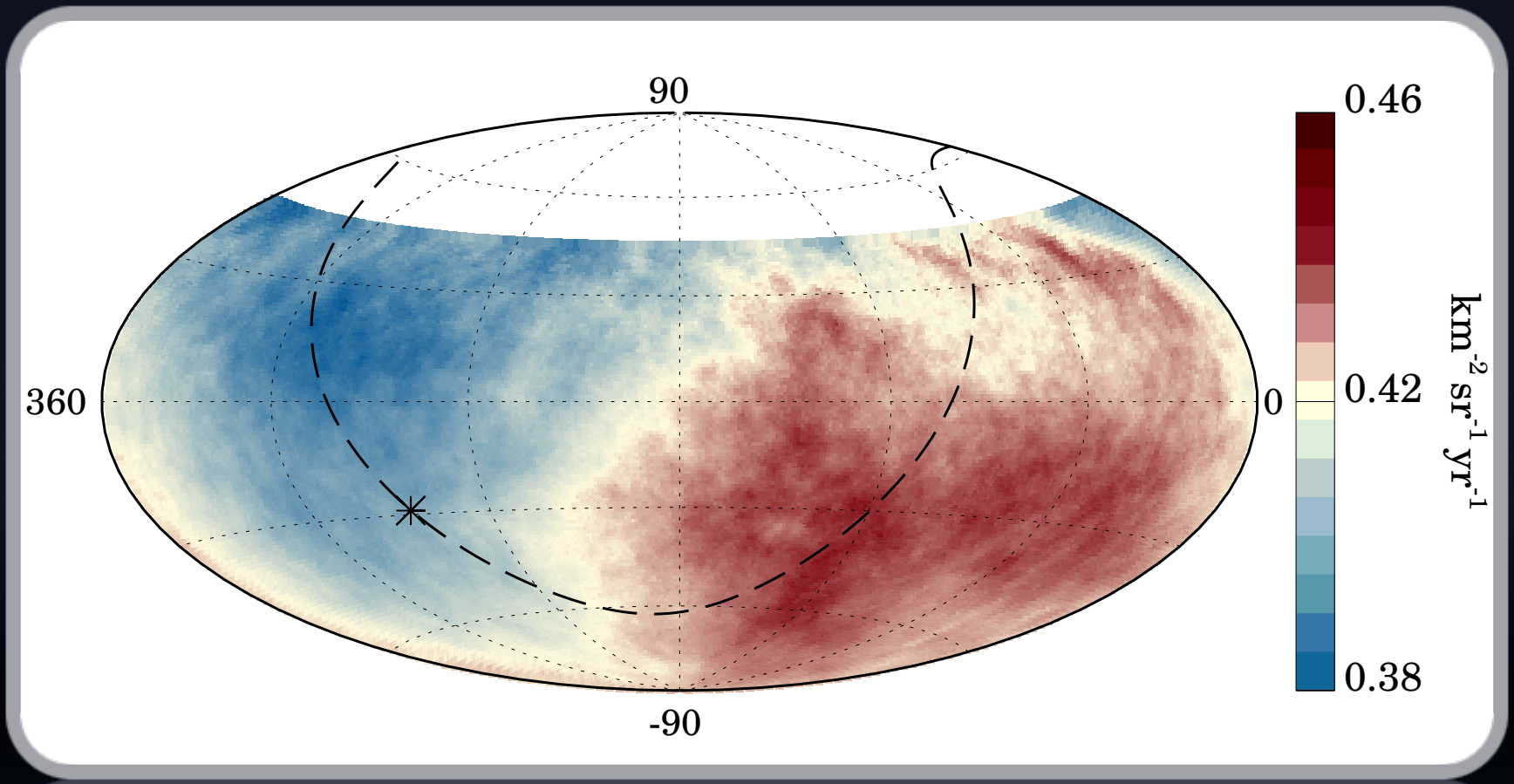




≡ 10^{18} eV

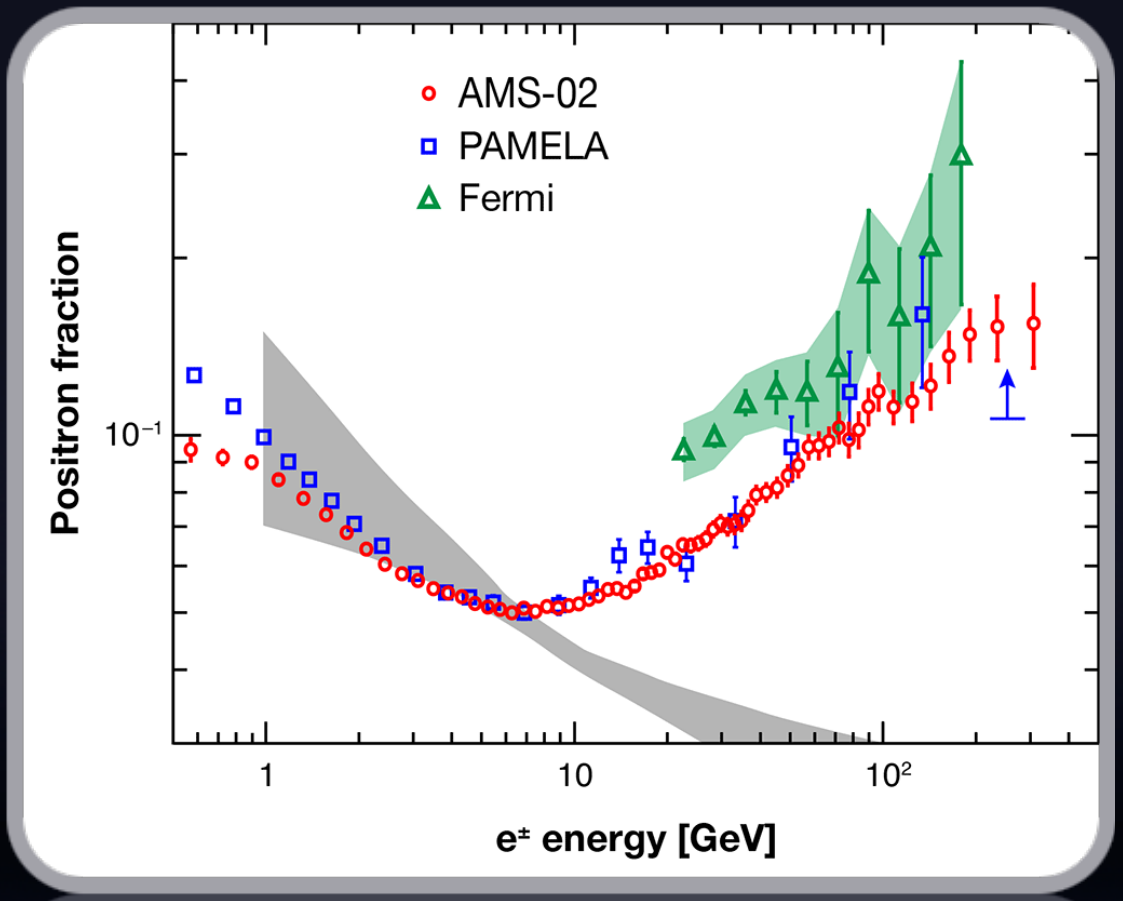
Auger Collaboration, Science **357** (2017) 1266-1270

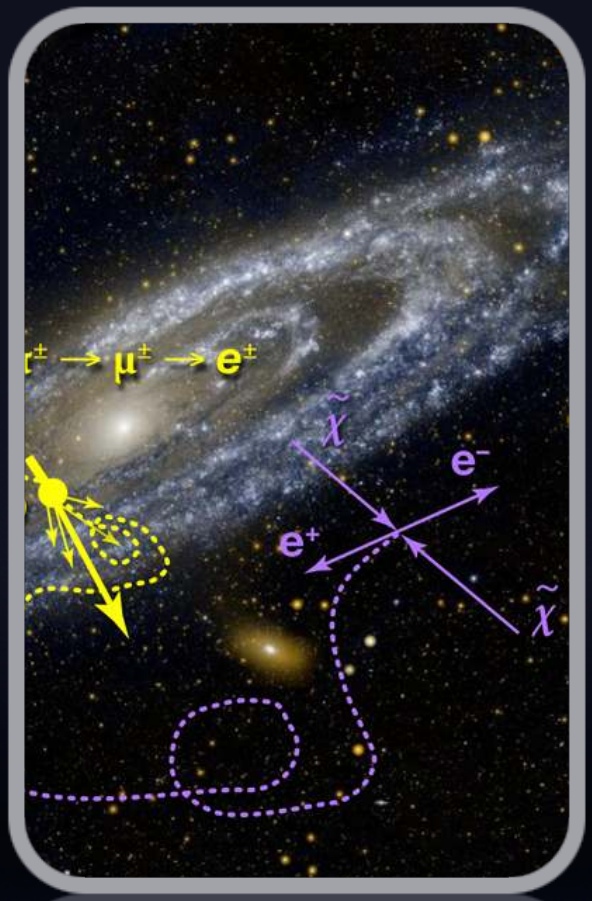
E > 8 EeV; 45° smoothing



UHECR sky map

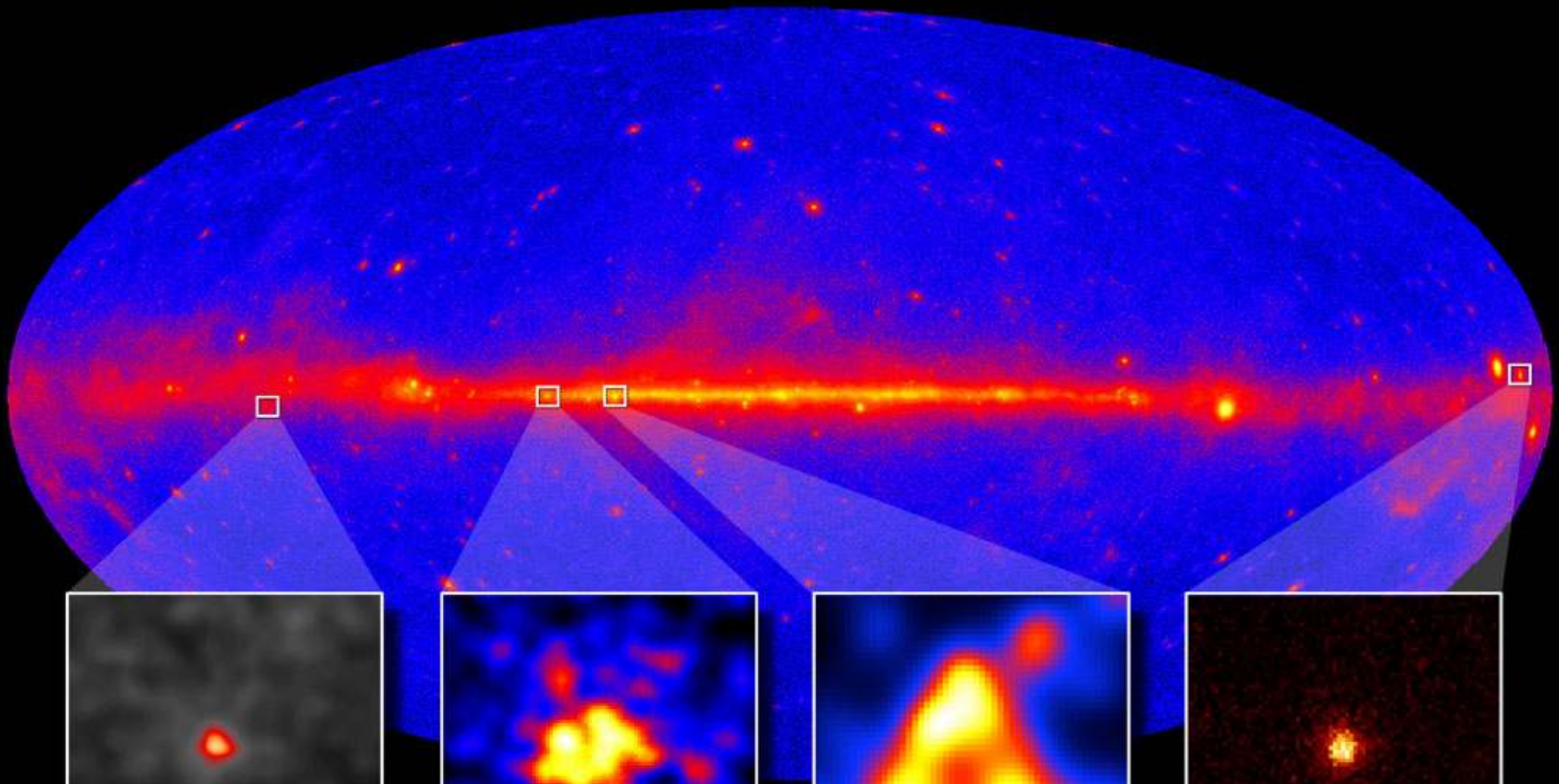
Positron Excess





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

NASA's Fermi telescope resolves supernova remnants at GeV energies



Cas A

W51C

W44

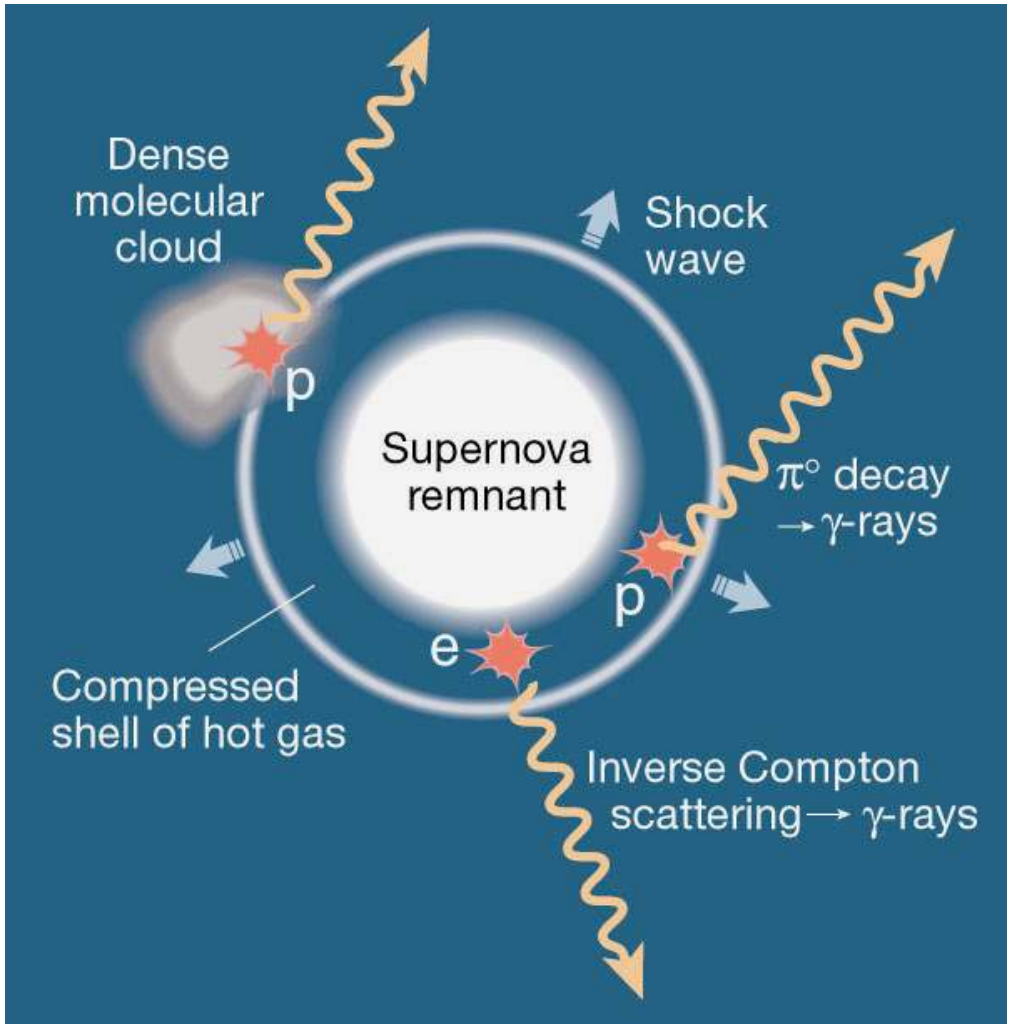
IC 443

Fermi Gamma-ray Space Telescope

Supernova Remnants

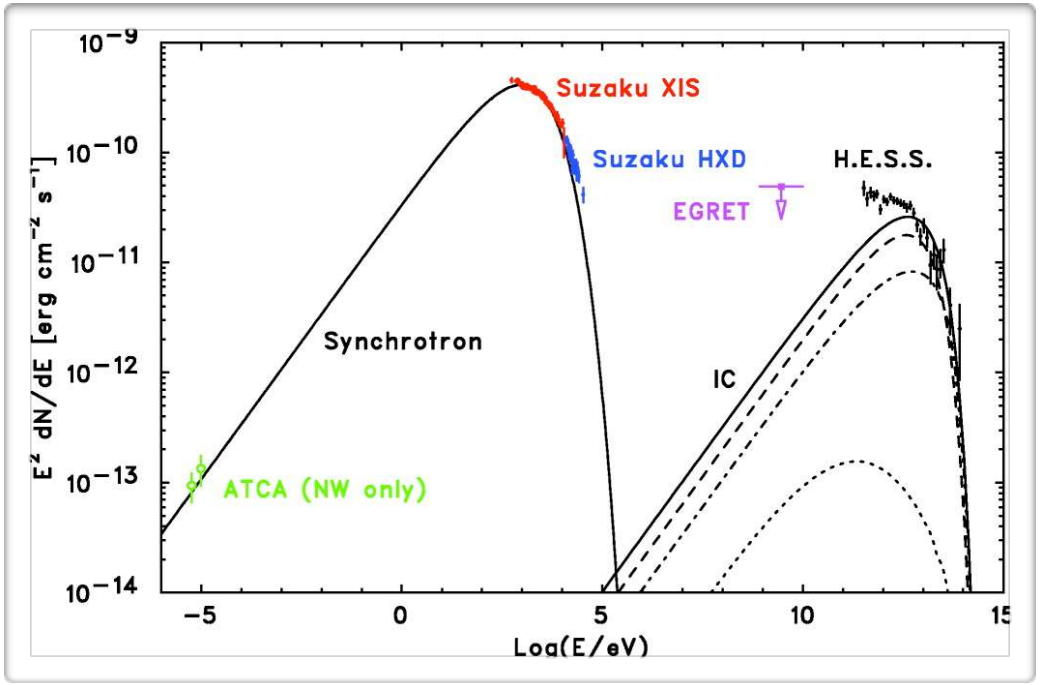
First resolved **TeV γ-ray** image of a Shell type SNR (Resolution ~10 arcmin)

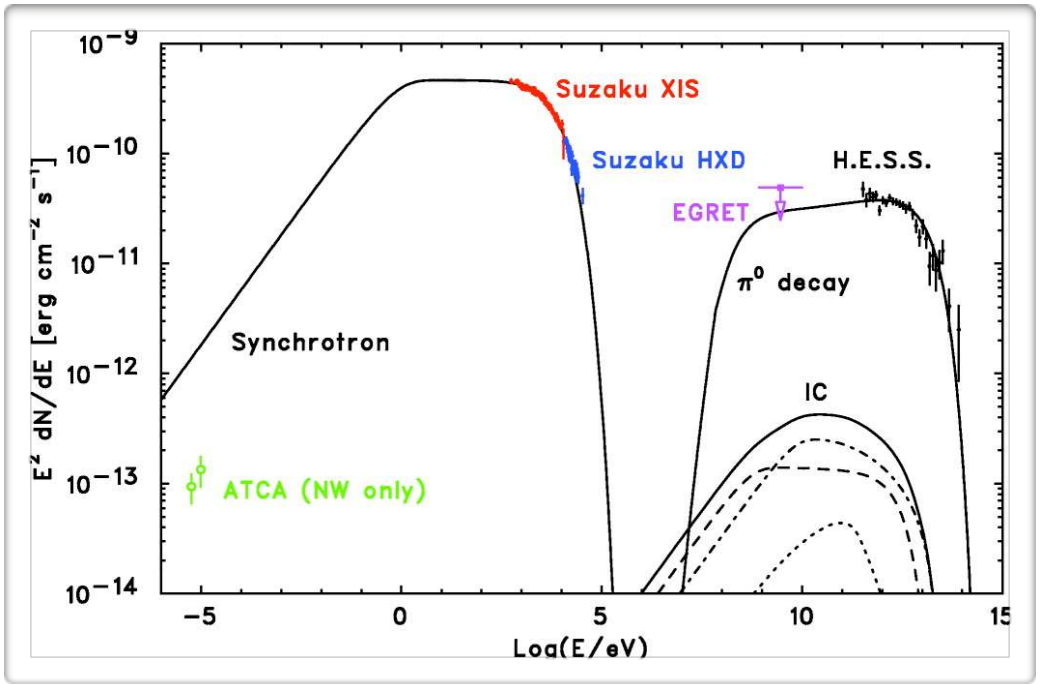
Acceleration source of cosmic rays, but is it evidence of protons?



Supernova Remnants

Tanaka et al., The Astrophysical Journal **685** (2008) 988





Leptonic *vs.* Hadronic

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

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

- - Small area

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

Gamma-Ray detectors

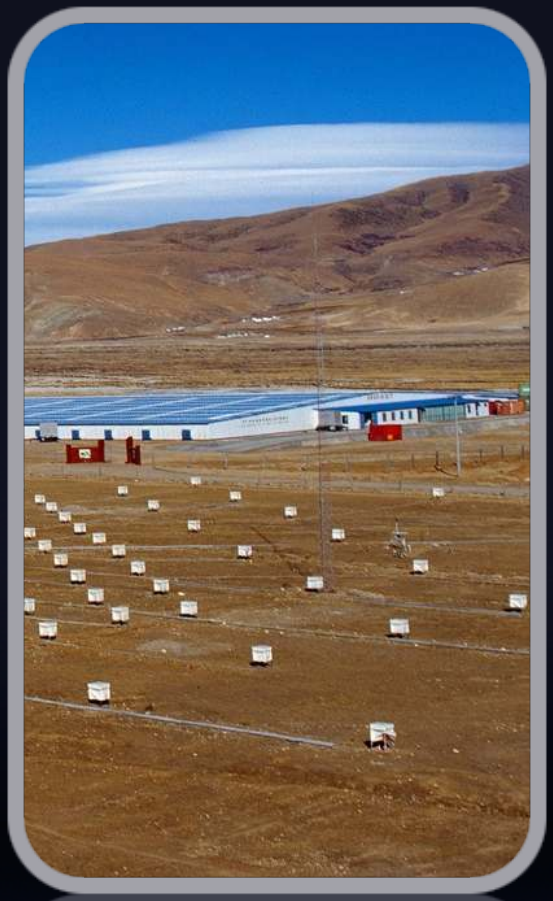
Experimental Techniques

- ✓ Large effective area
- ✓ Excellent background rejection

- - Small aperture
- - Low duty cycle (ground)

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

Experimental Techniques



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

- - Moderate area om the ground

- **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

HAWC

- 2nd generation water Cherenkov
- Wide instantaneous field of view (2 sr)
- High duty cycle (> 90%)
- Large area (22,000 m²)

A second generation wide-field γ-ray detector

Main Features

- Most bright Galactic GeV sources **extend to TeV**
- Best instrument for **hard spectrum** and **extended sources**

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

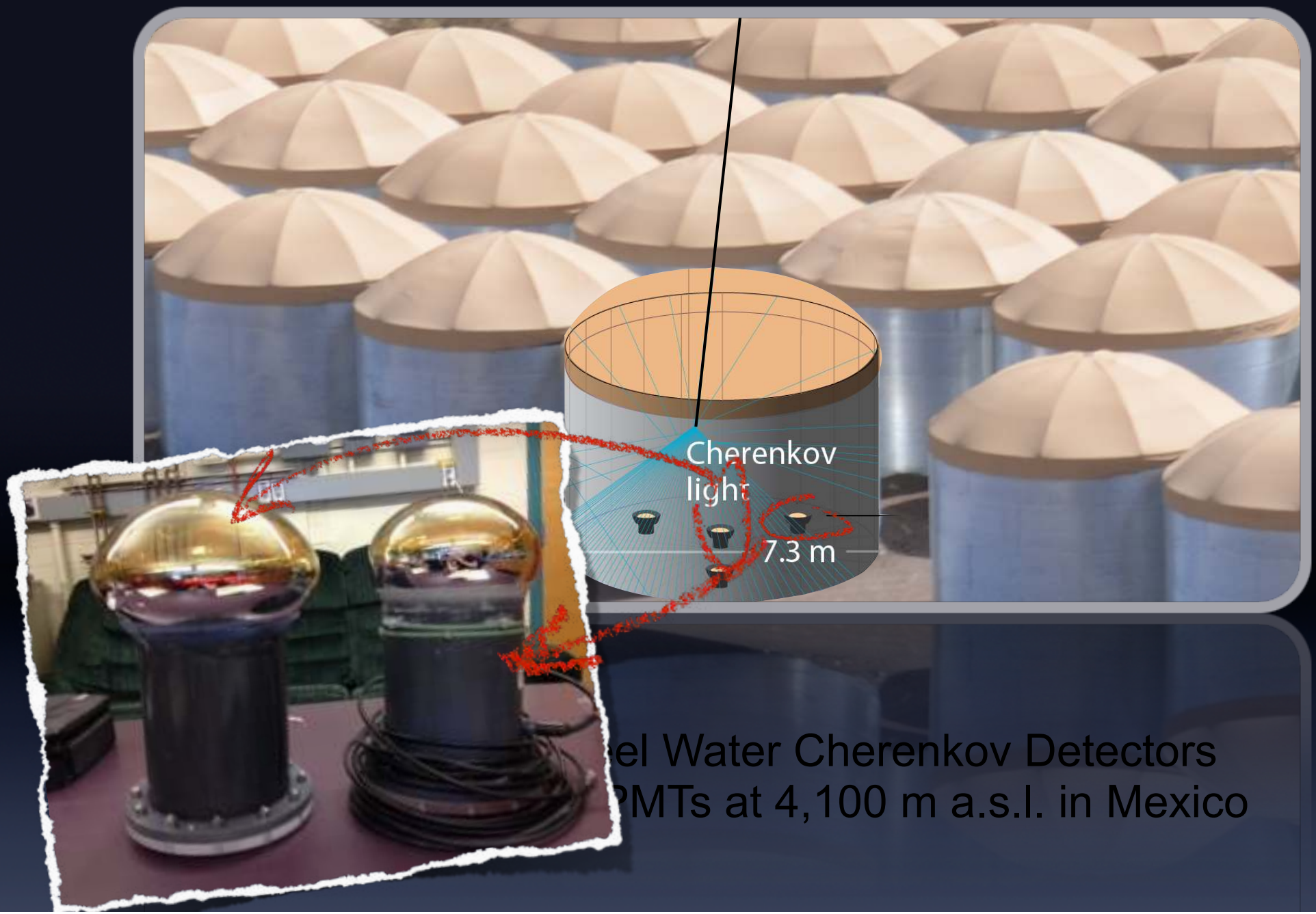
Water Cherenkov Detectors

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

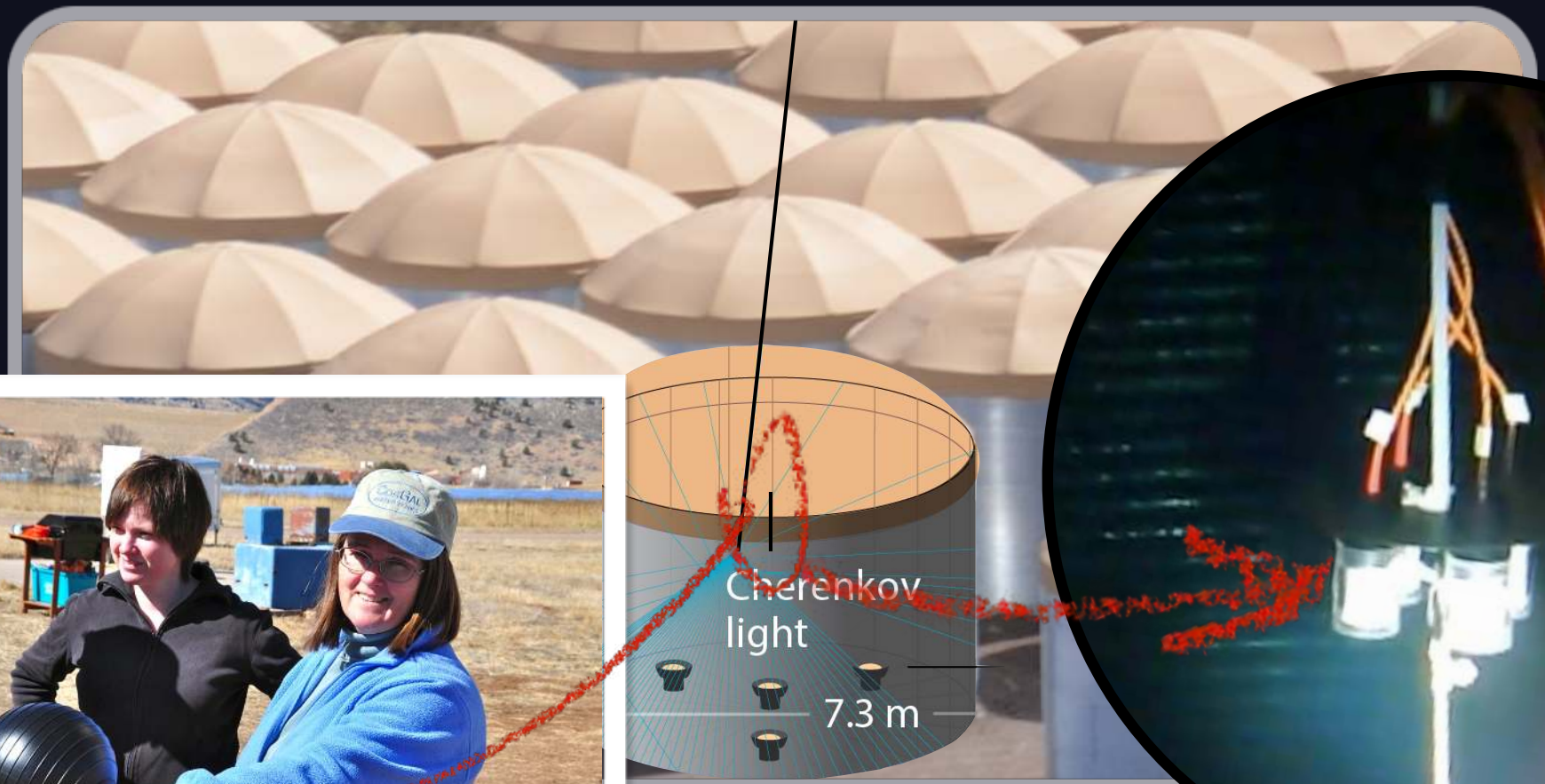
300 - 7 m x 5 m steel Water Cherenkov Detectors (a.k.a. tanks) with 4 PMTs at 4,100 m a.s.l. in Mexico

Water Cherenkov Detectors



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

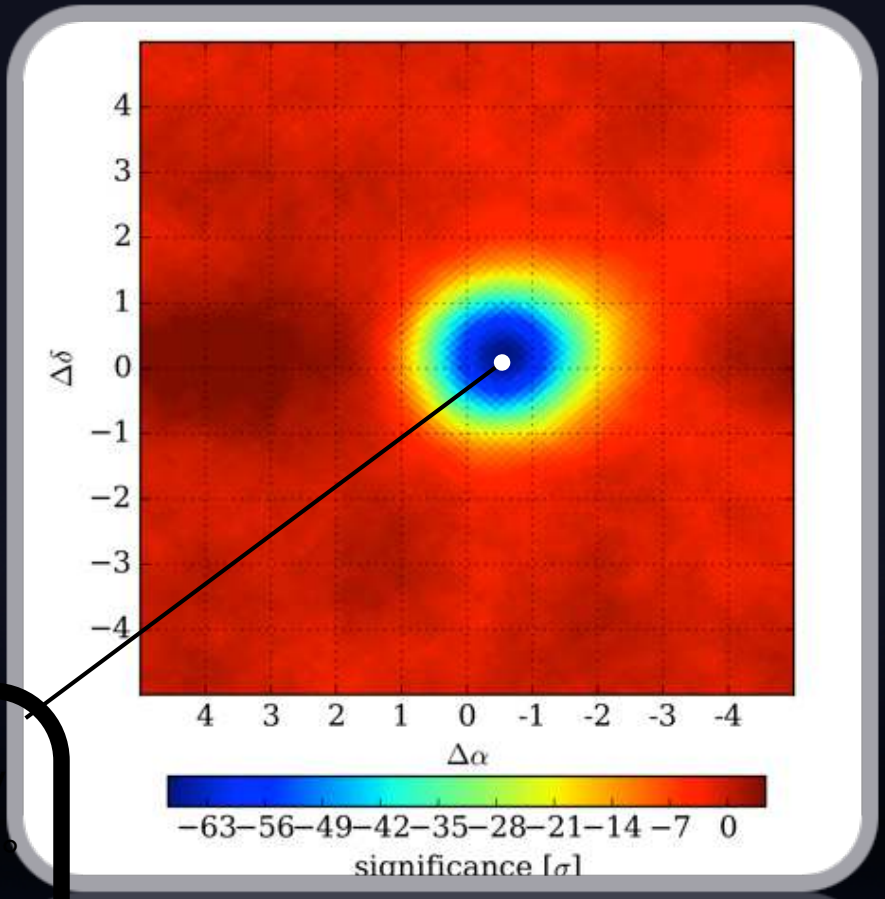
Water Cherenkov Detectors



tion system

Water Cherenkov Detectors

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



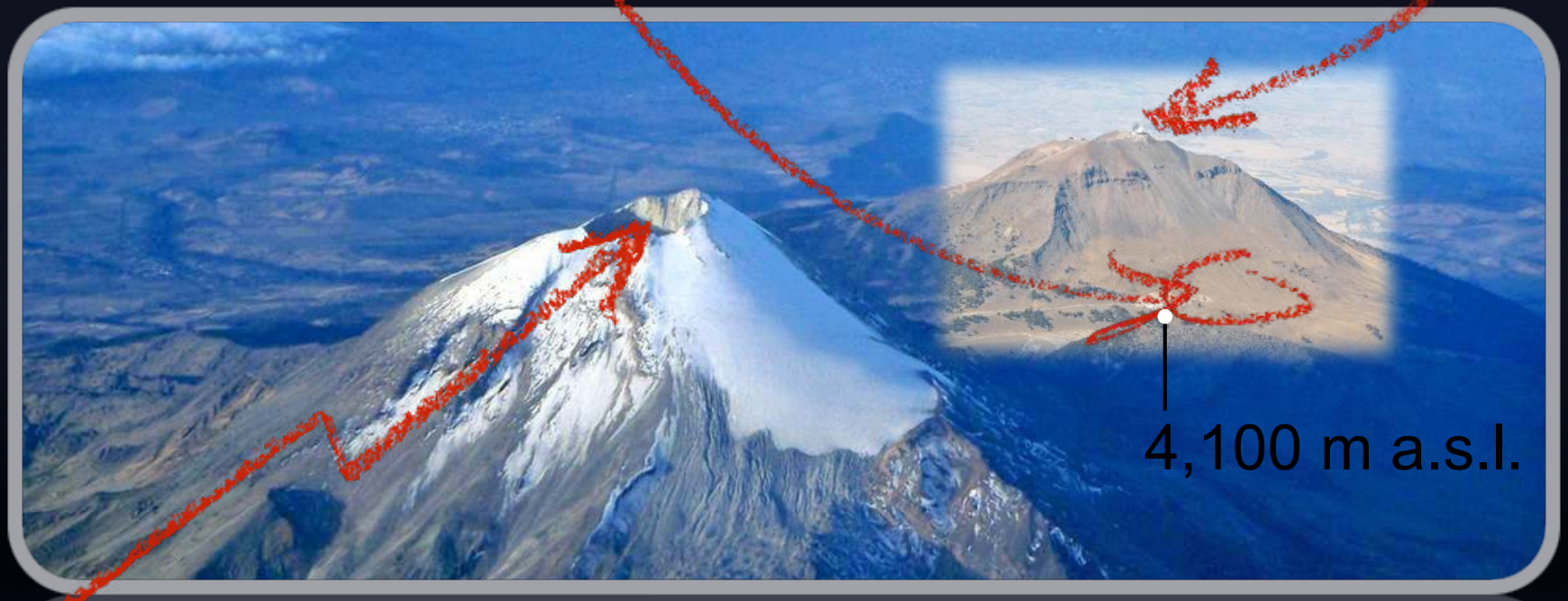
- deflection matches 2 TeV median energy
- angular resolution < shadow width of 1.2°
- position verifies pointing

Dedicated laser calibration system

HAWC site


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

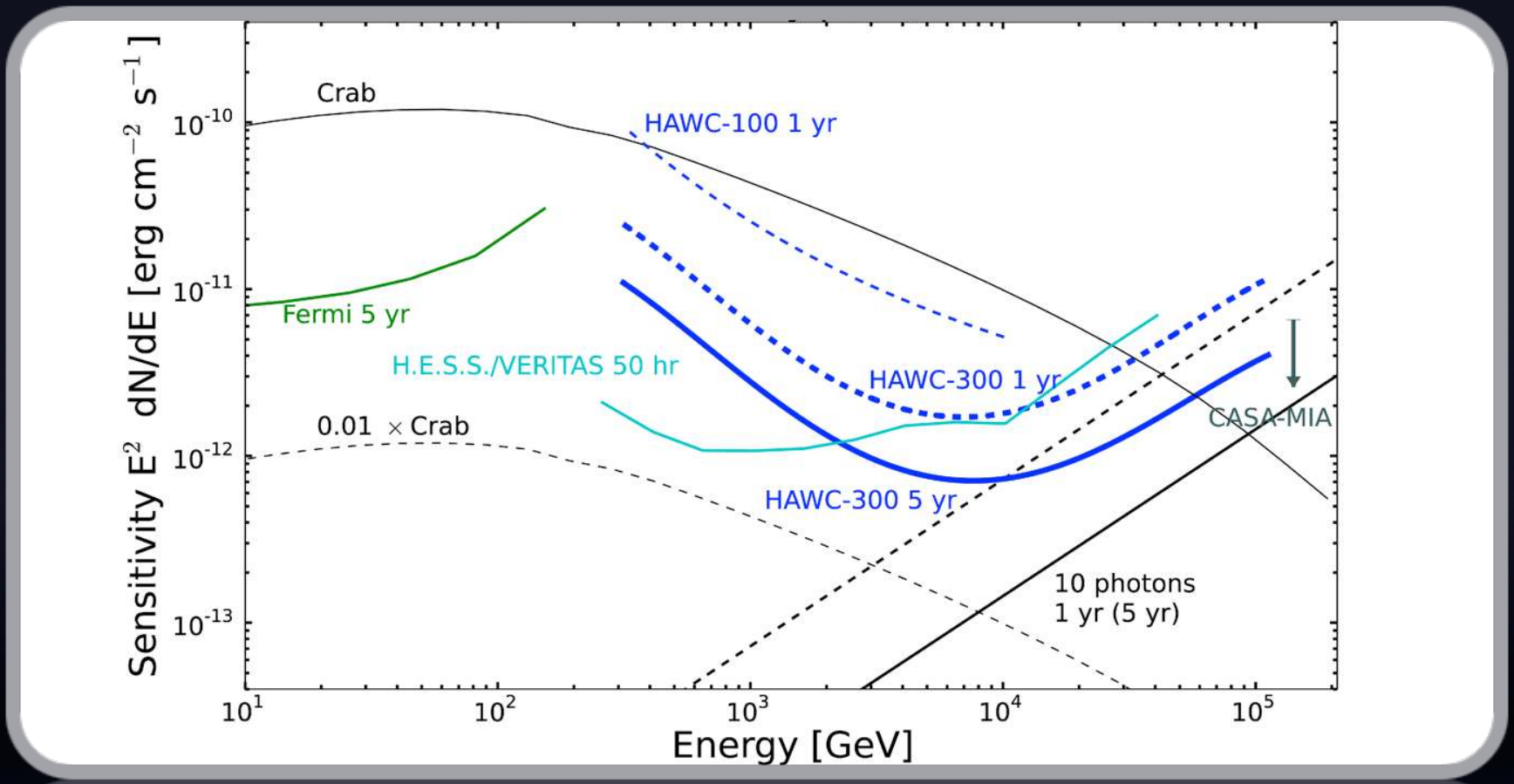
HAWC site



Deployment status

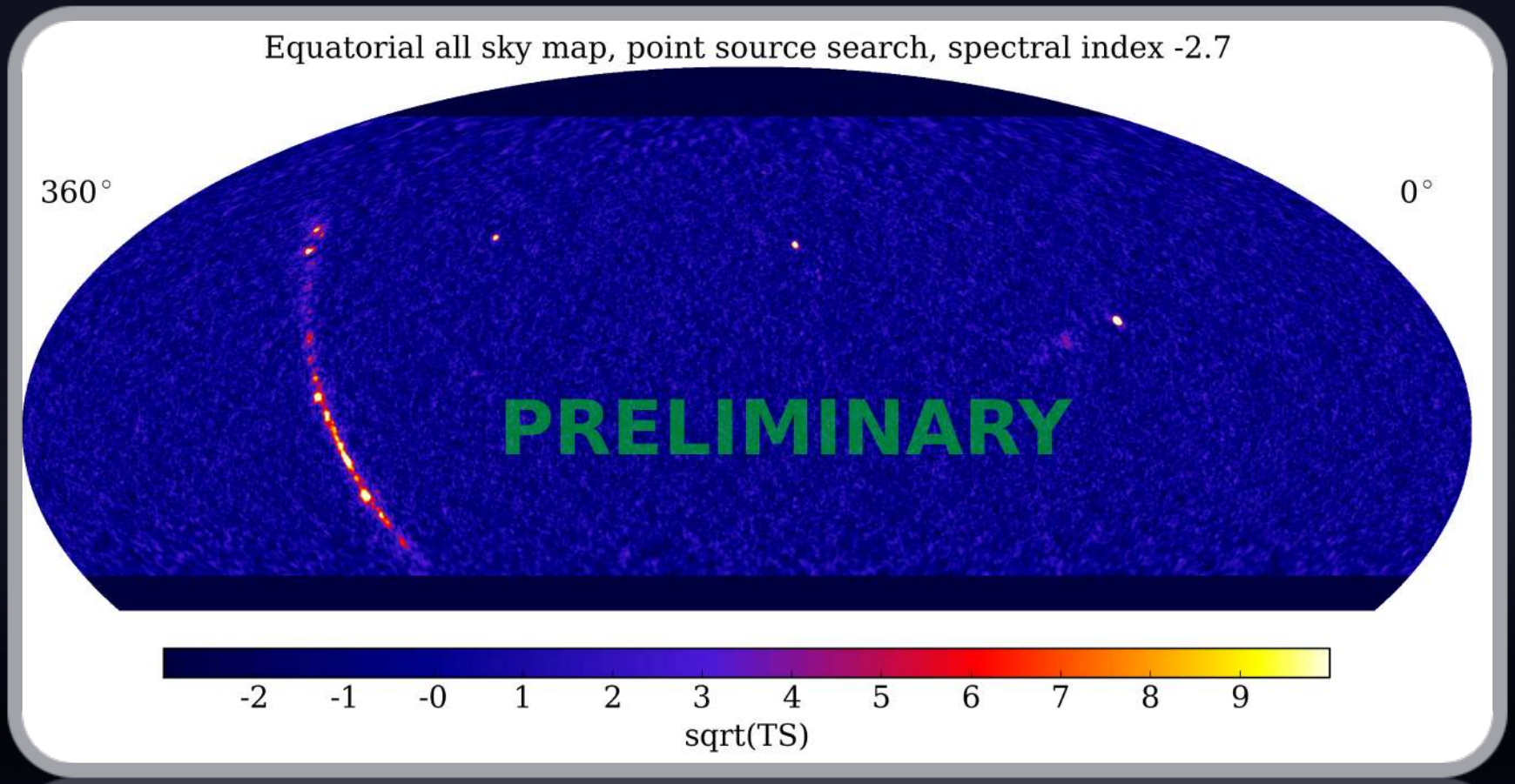
From 2011 to 2015

Design improvements



x15 more sensitive than Milagro

Design improvements

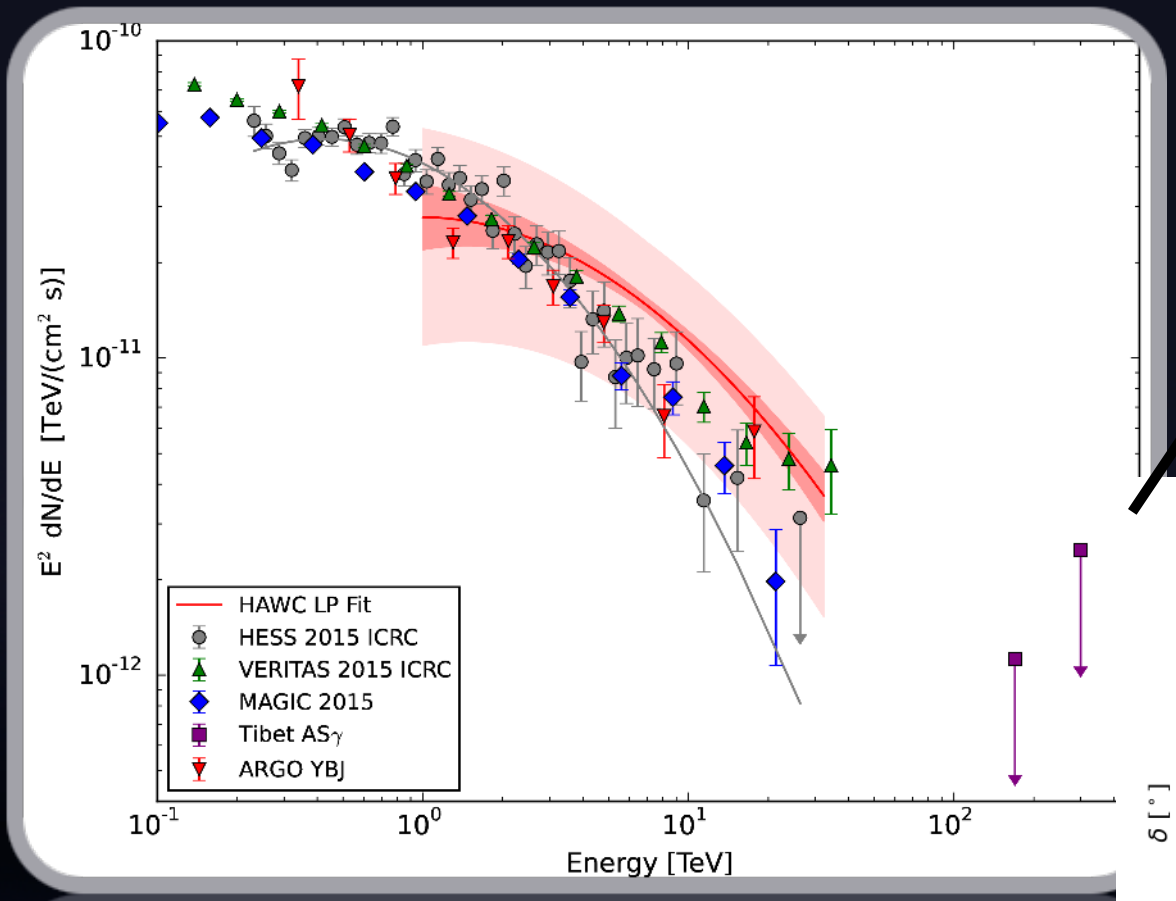


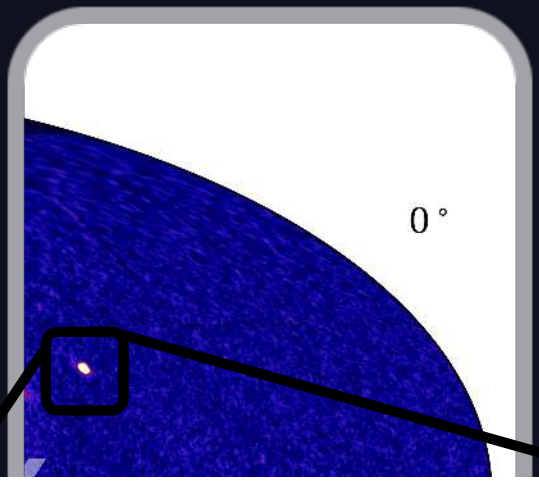
Fermi-LAT sky smoothed map
E > 50 GeV (Pass 8 - 6 years of data)
(courtesy of M. Ajello)

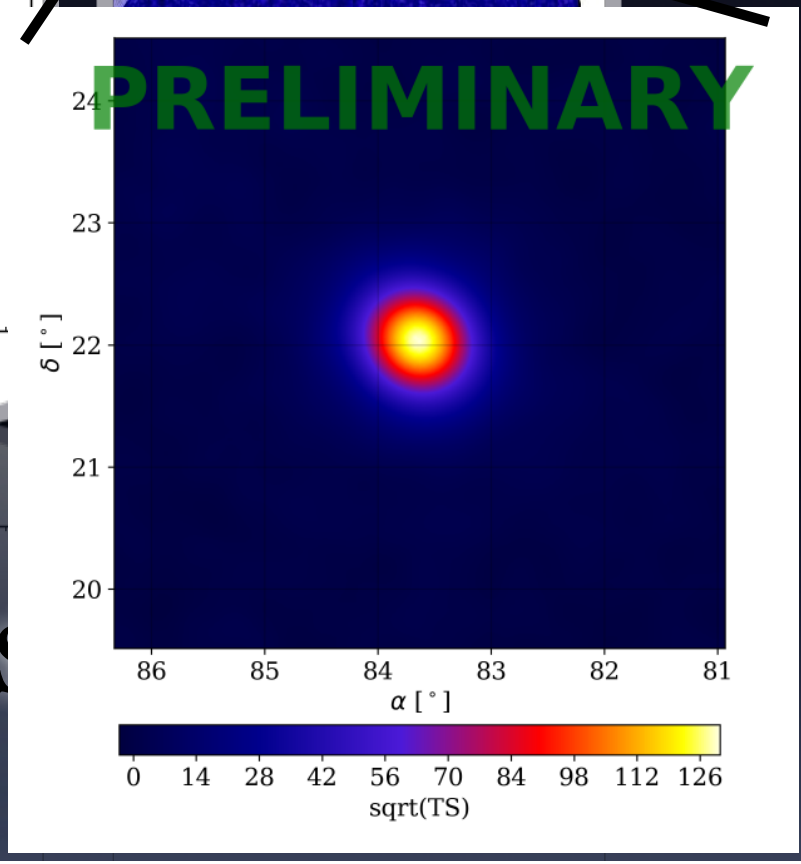
Preliminary HAWC smoothed map
E > 500 GeV (~1 year of data)
Full array

Abeysekara *et al* [HAWC] ApJ **843** (2017) 39

The Crab



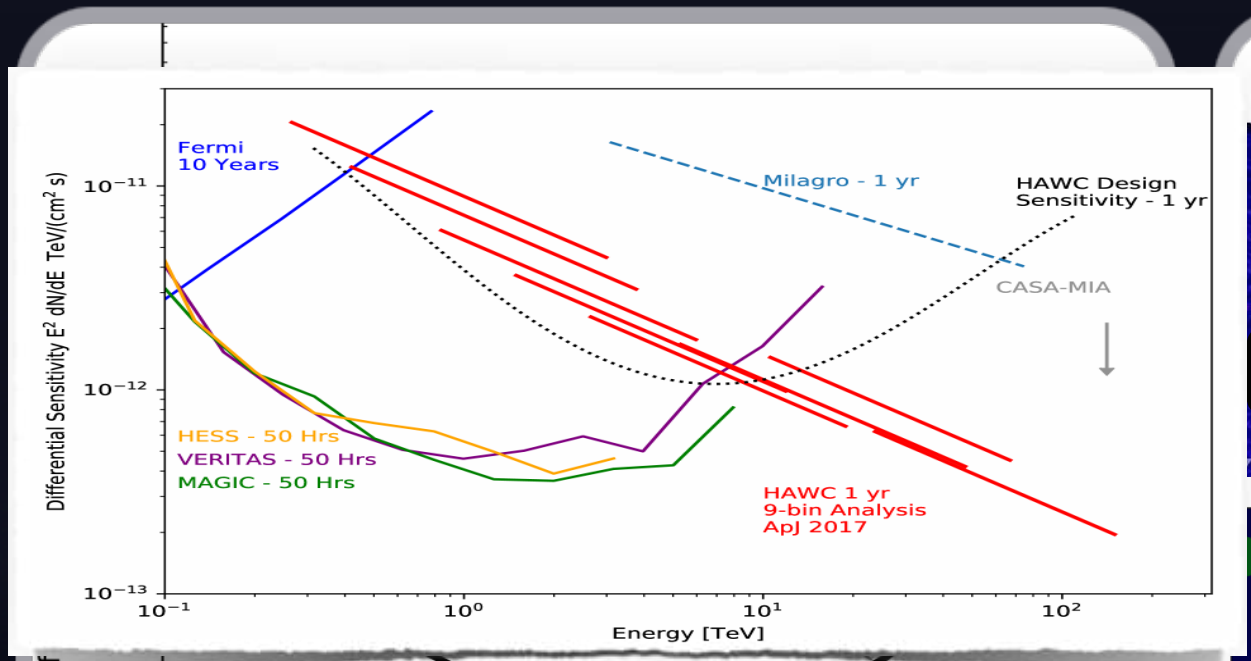


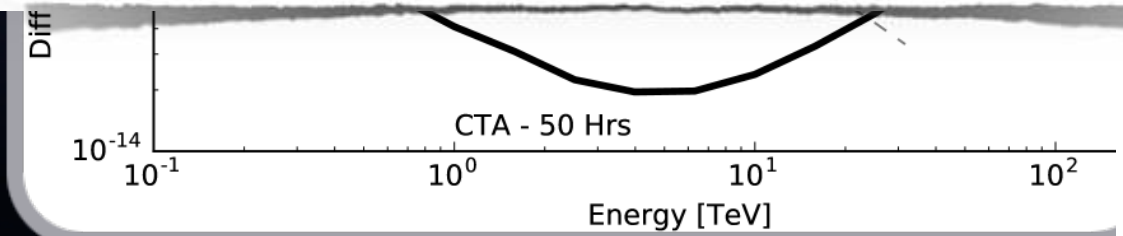


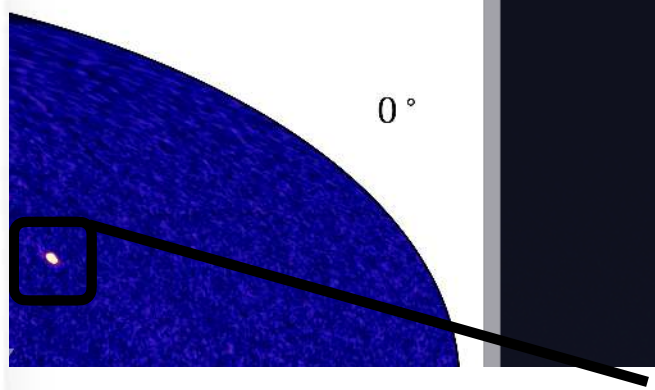
Multi-TeV

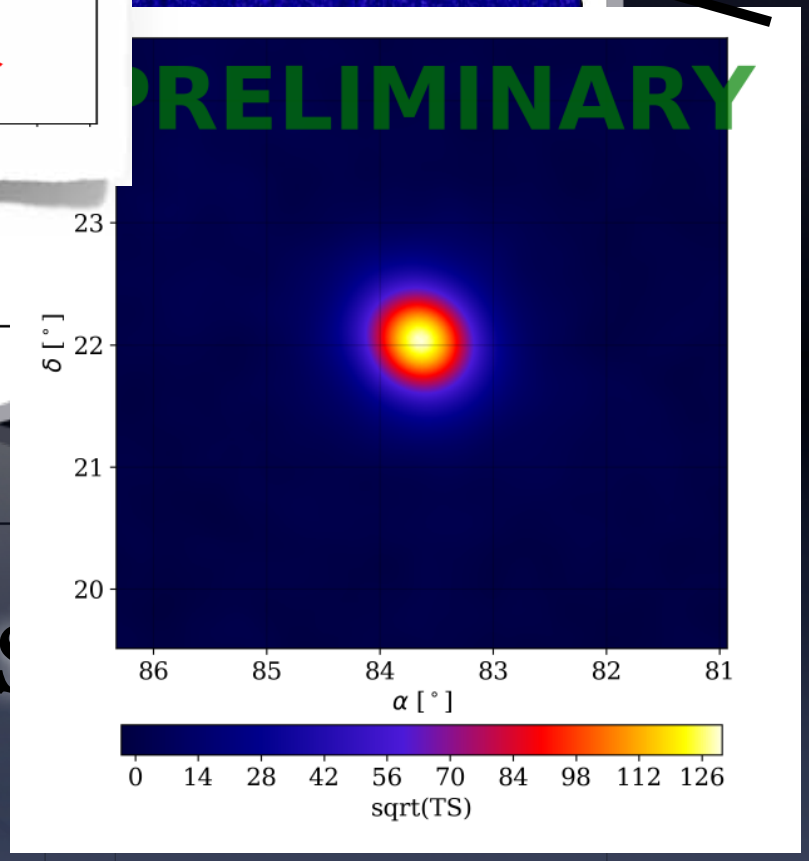
Abeysekara *et al* [HAWC] ApJ **843** (2017) 39

The Crab





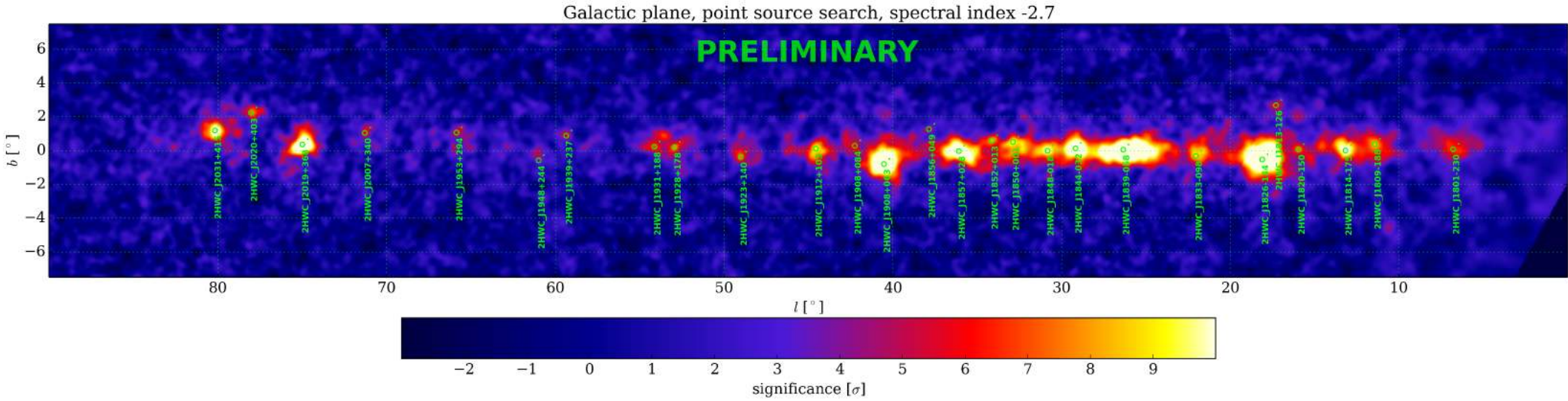




Multi-TeV s

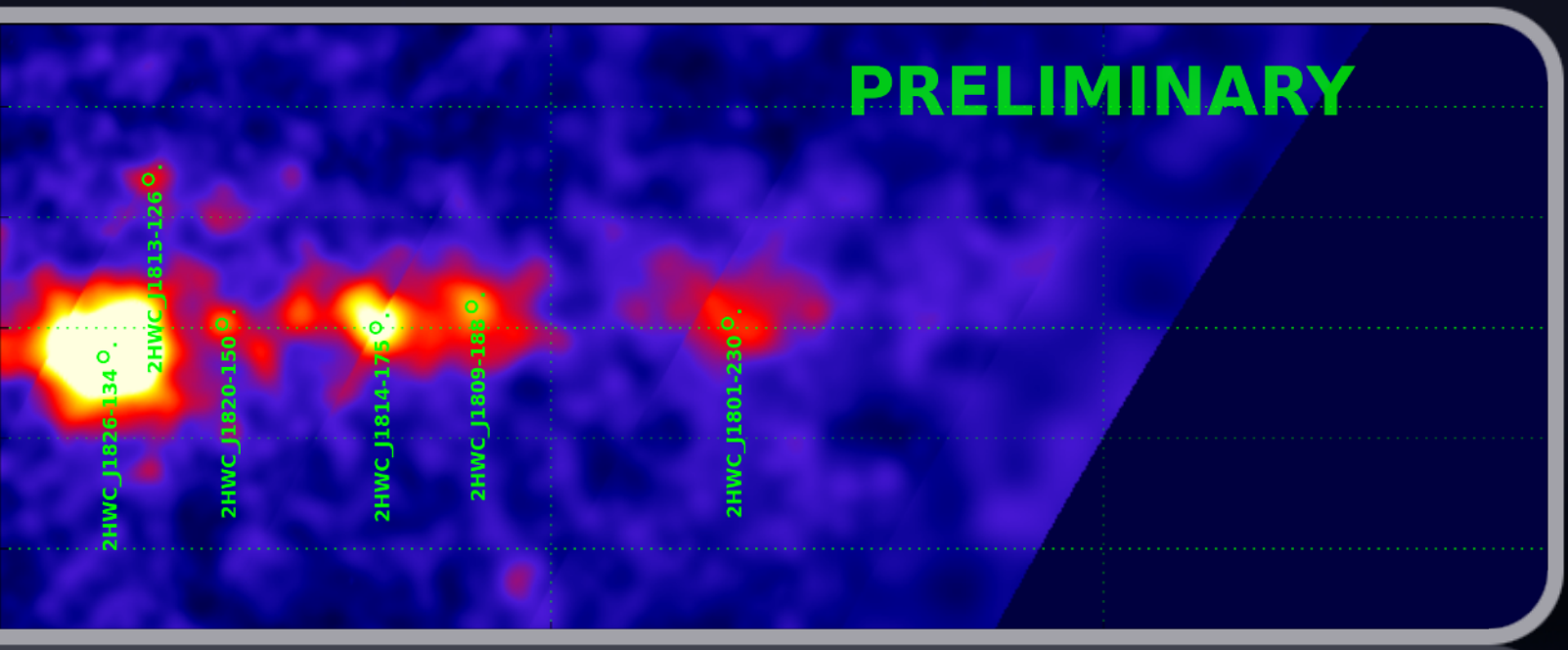
Abeysekara *et al* [HAWC] ApJ **843** (2017) 40

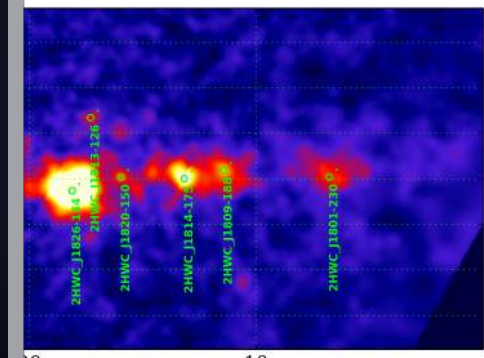
first HAWC catalog



Abeysekara *et al* [HAWC] ApJ **843** (2017) 40

first HAWC catalog





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

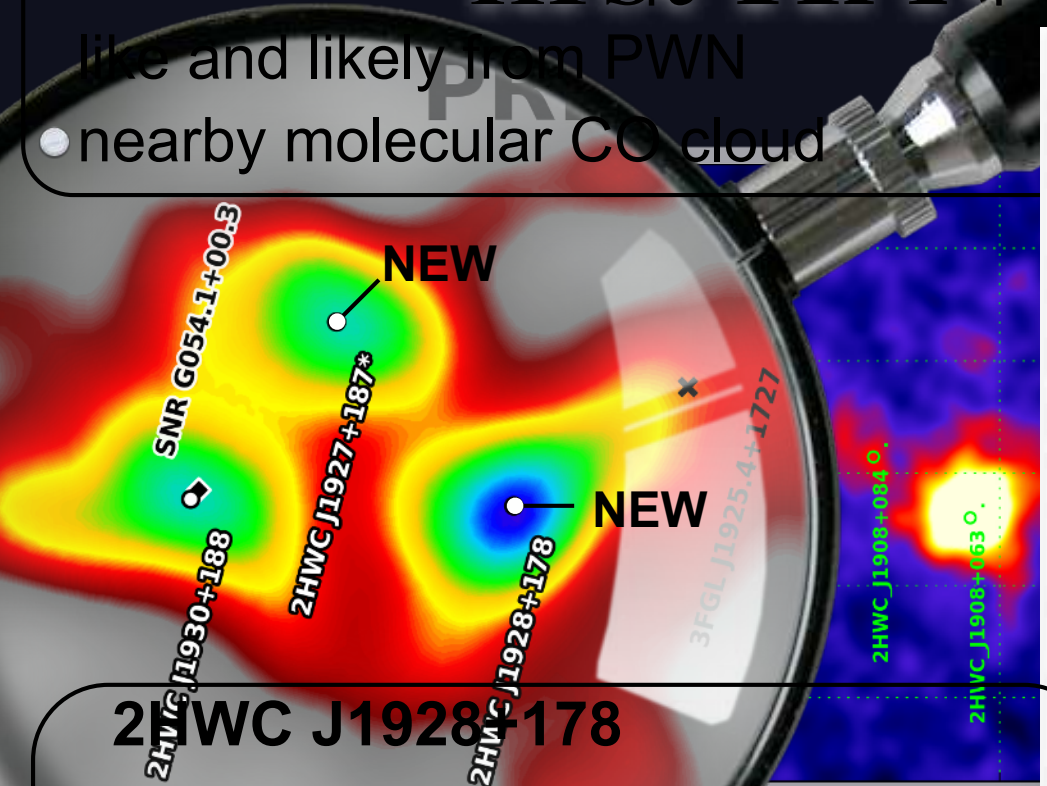
2HWC J1928+178

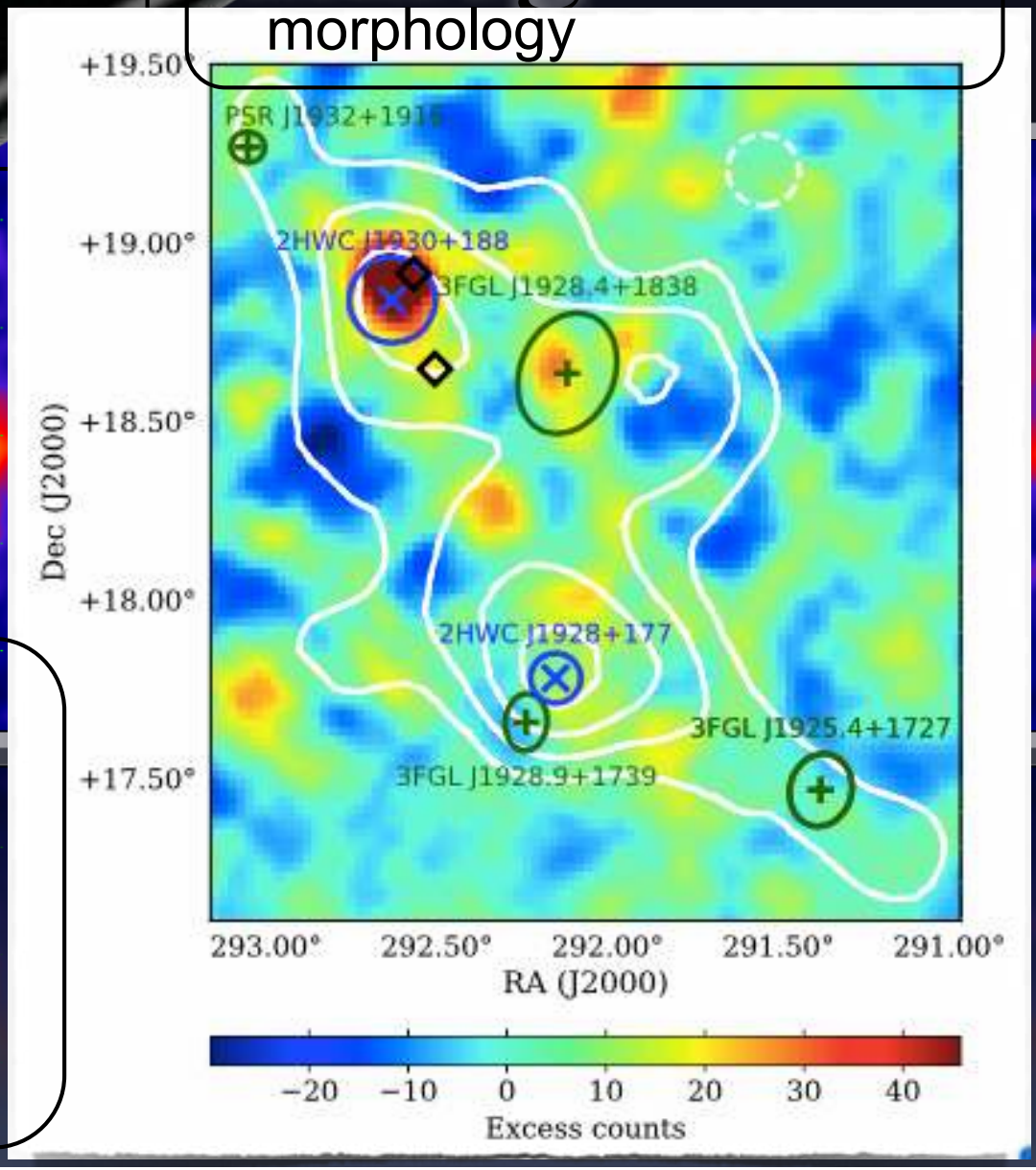
- coincident with **PSR J1928+1746**
- tail towards unidentified source **3FGL J1925.4+1727**
- VERITAS pt-src upper limit ~1.4% of Crab

2HWC J1927+187*

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

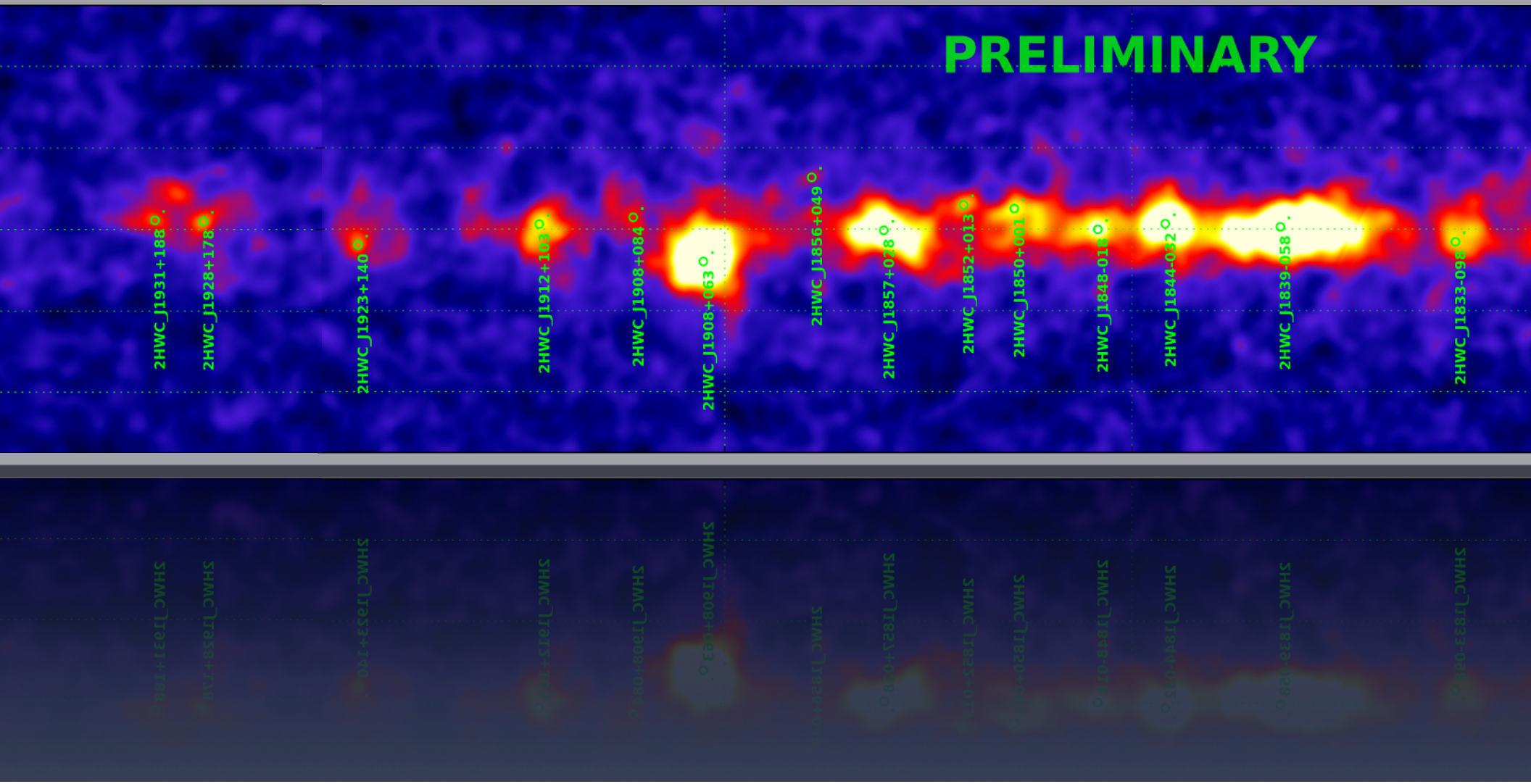
first HAWC catalog



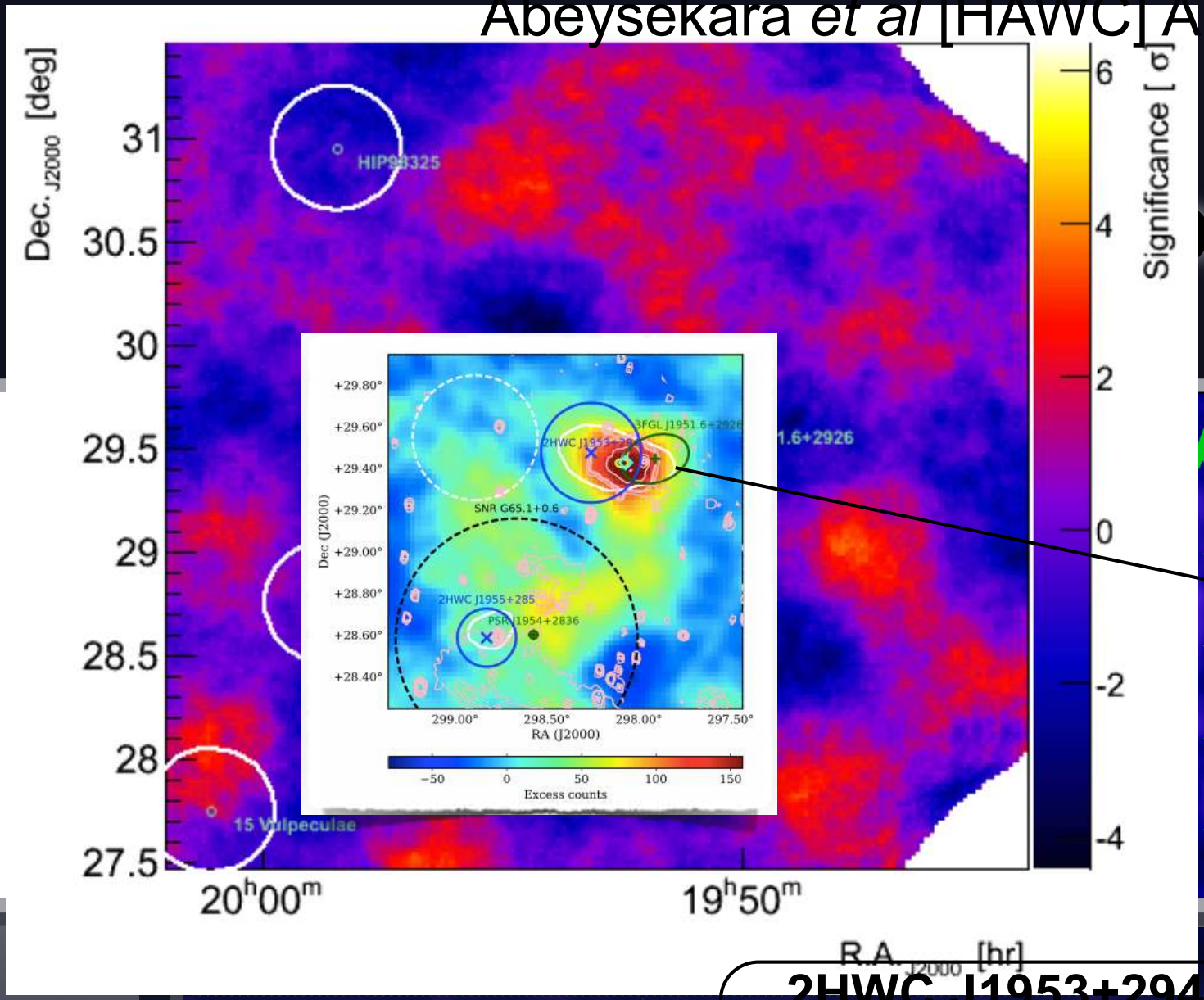


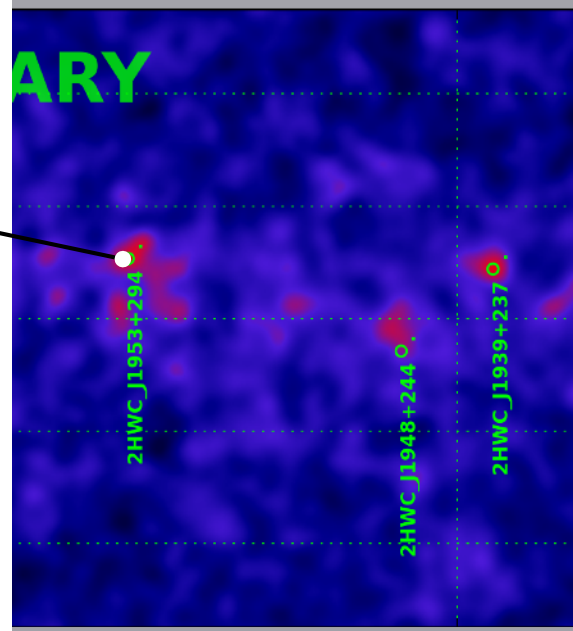
Abeysekara *et al* [HAWC] ApJ **843** (2017) 40

first HAWC catalog



Abeysekara *et al* [HAWC] ApJ **843** (2017) 40





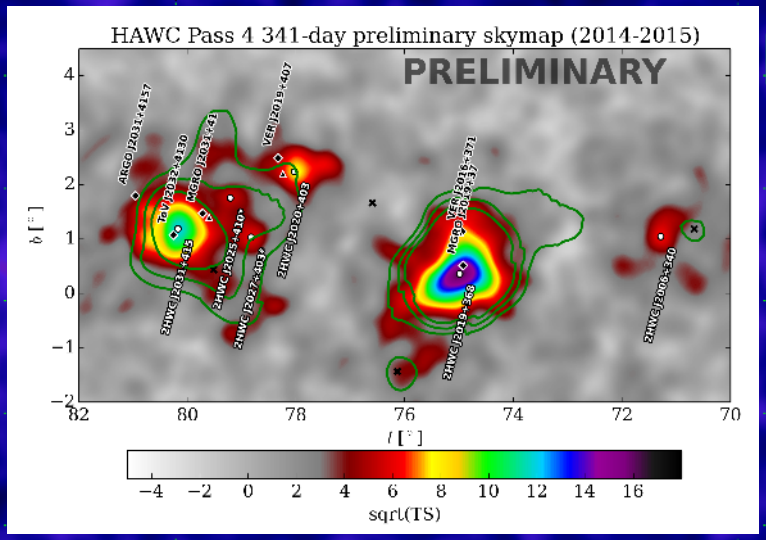
2HWC J1953+294

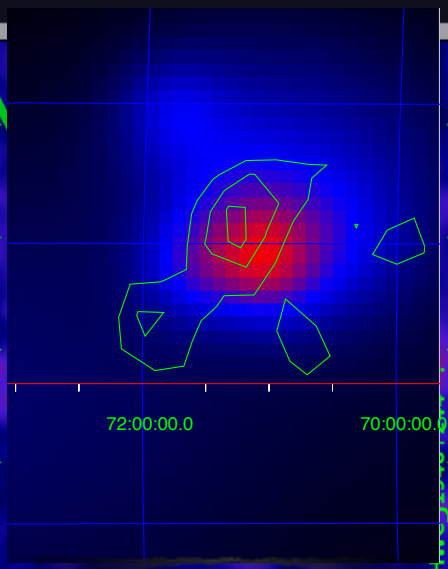
- VERITAS confirms **HAWC detection**
- nearby PWN likely counterpart

[VERITAS+Fermi-LAT+HAWC!] ApJ **866** (2018) 24

Abeysekara *et al* [HAWC] ApJ **843** (2017) 40

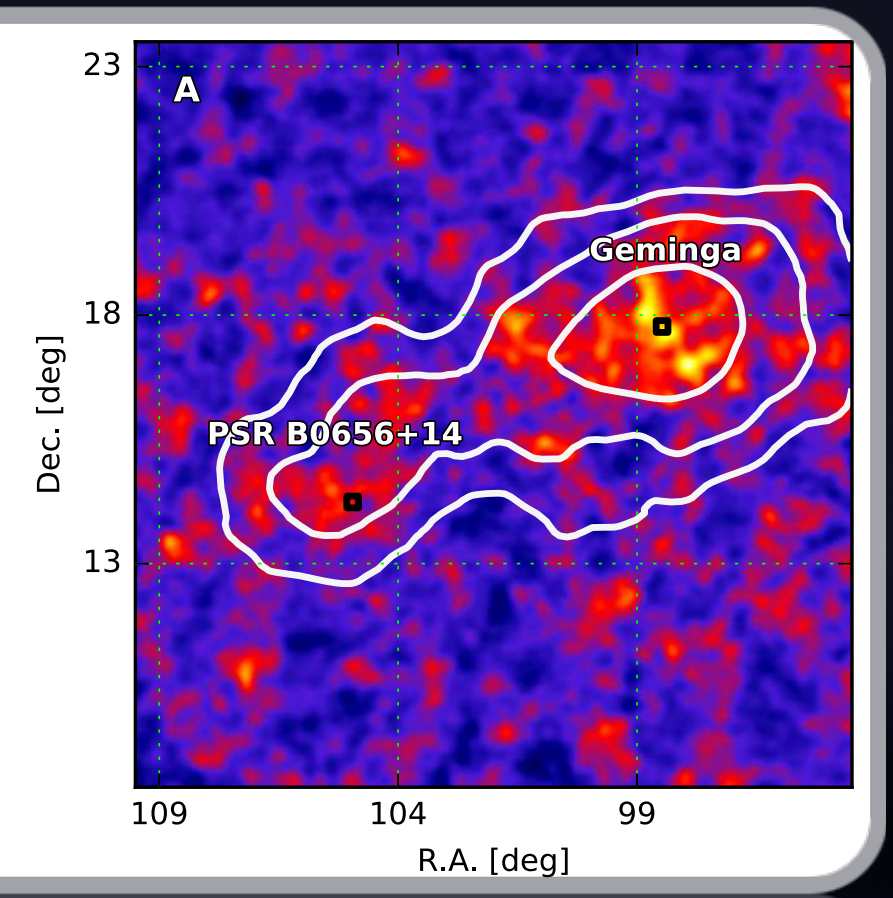
first HAWC catalog

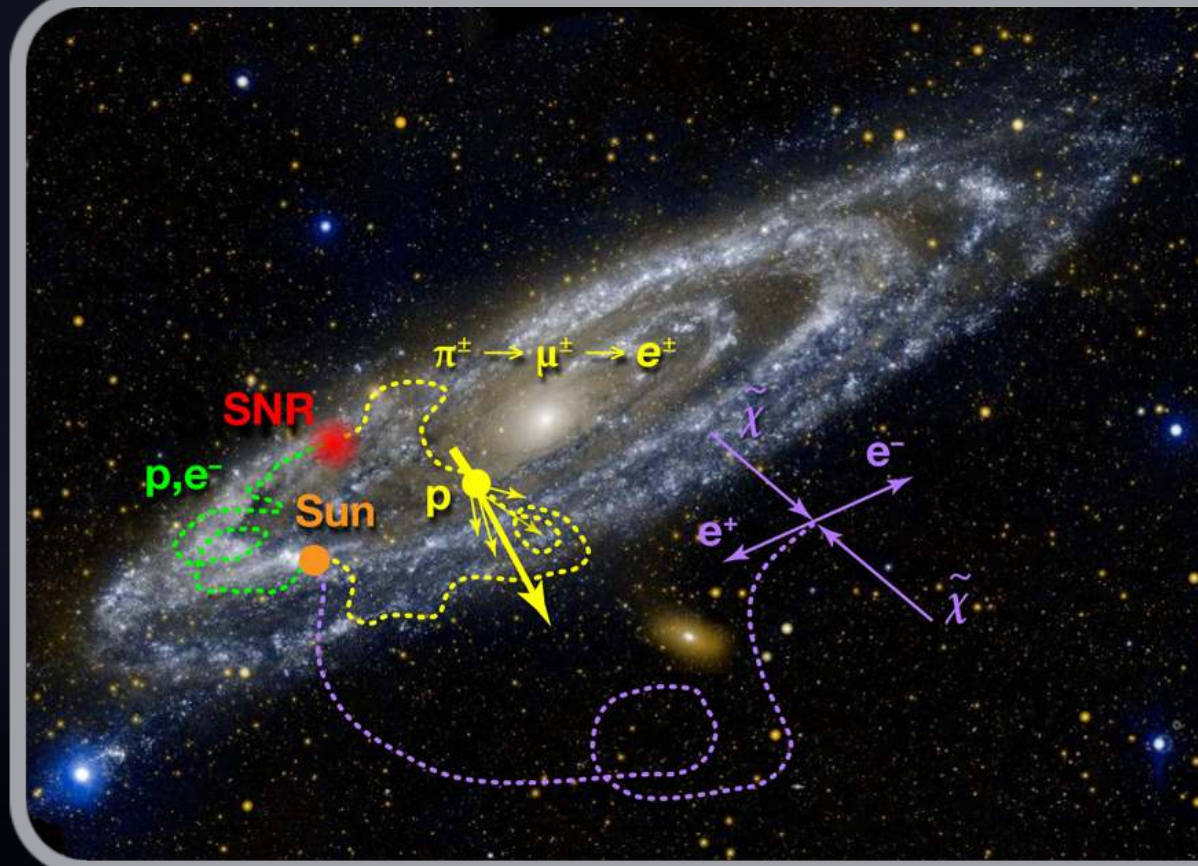




Abeysekara *et al* [HAWC] Science **6365** (2017) 911-914

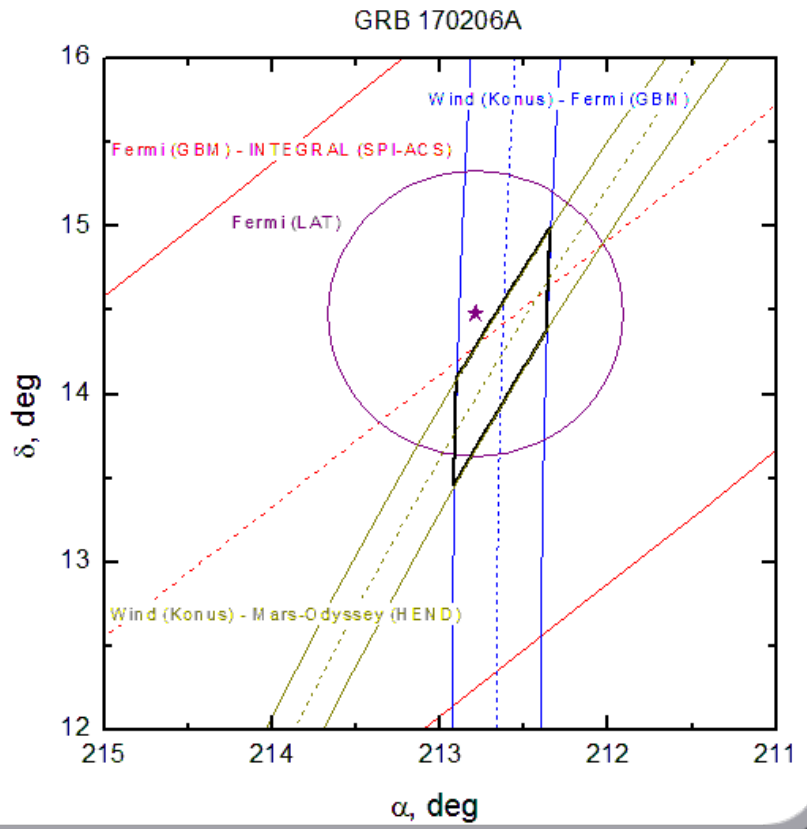
Positron excess from nearby pulsars?



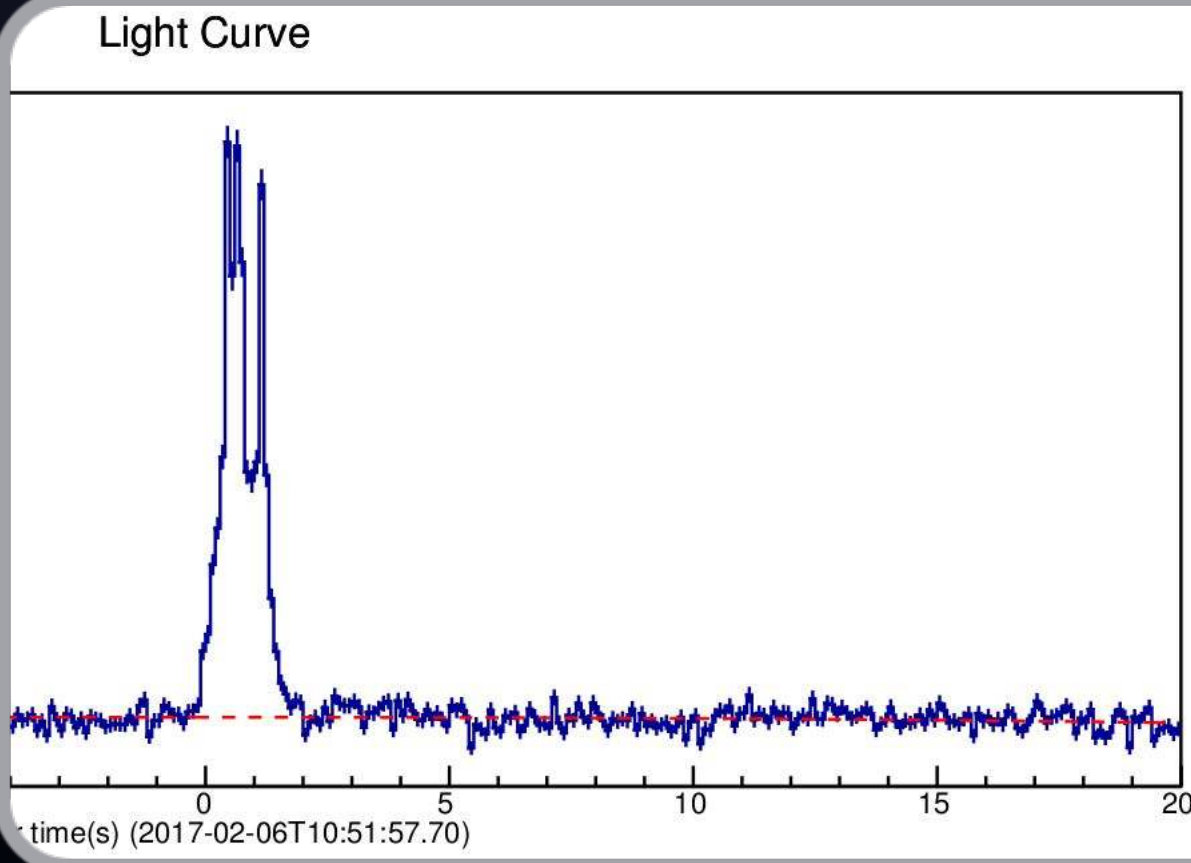


Extended emission

IPN triangulation map



GBM light curve



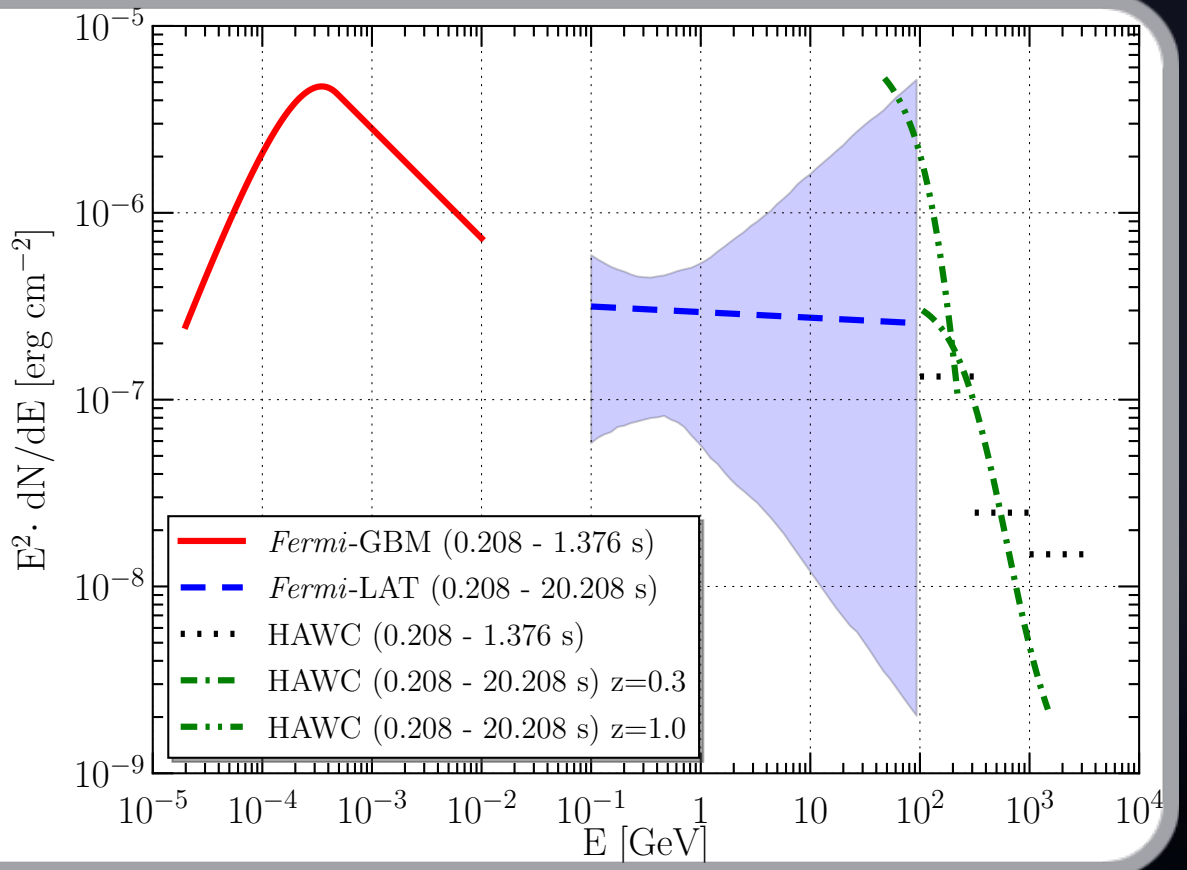
GRB 170206A

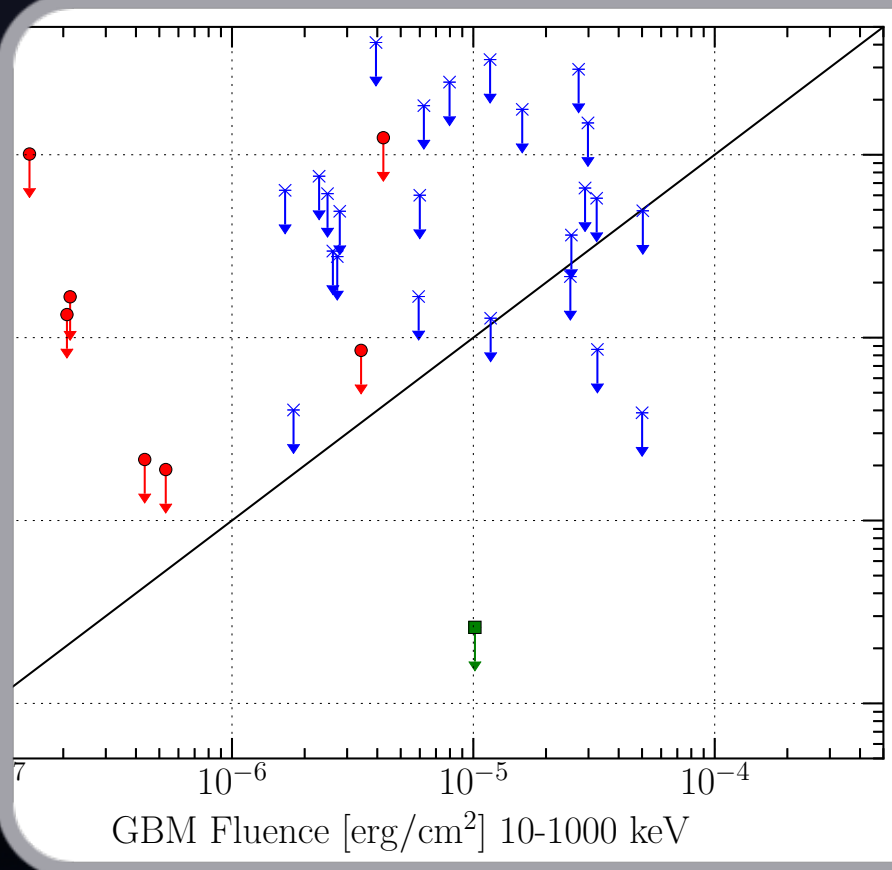
Alfaro *et al* [HAWC] ApJ **843** (2017) 88

HAWC limits

HAWC *vs.* GBM fluence

GBM light curve

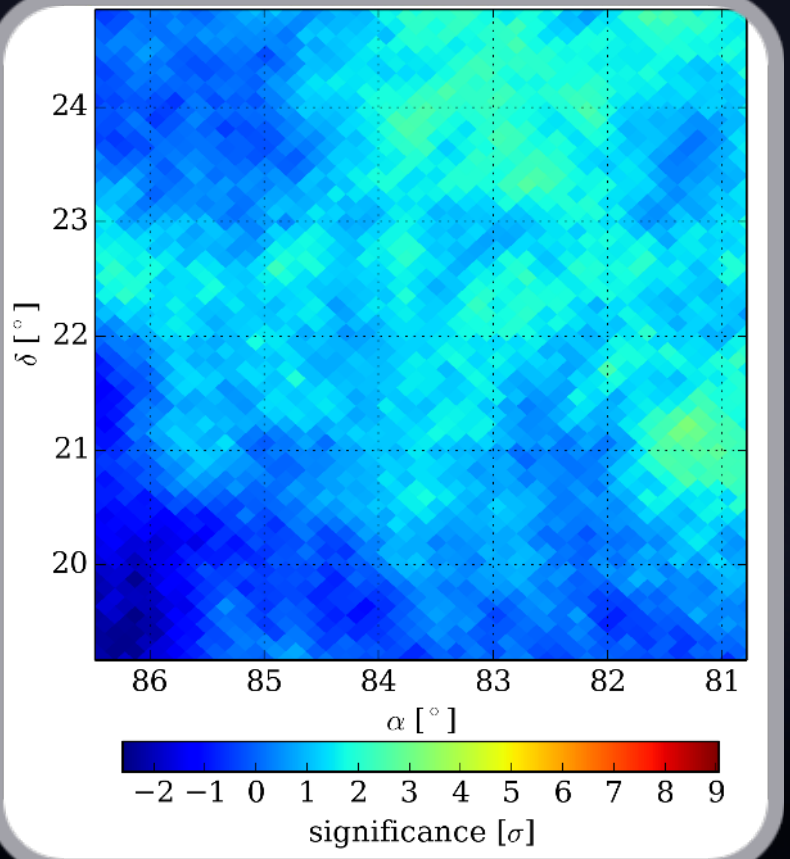




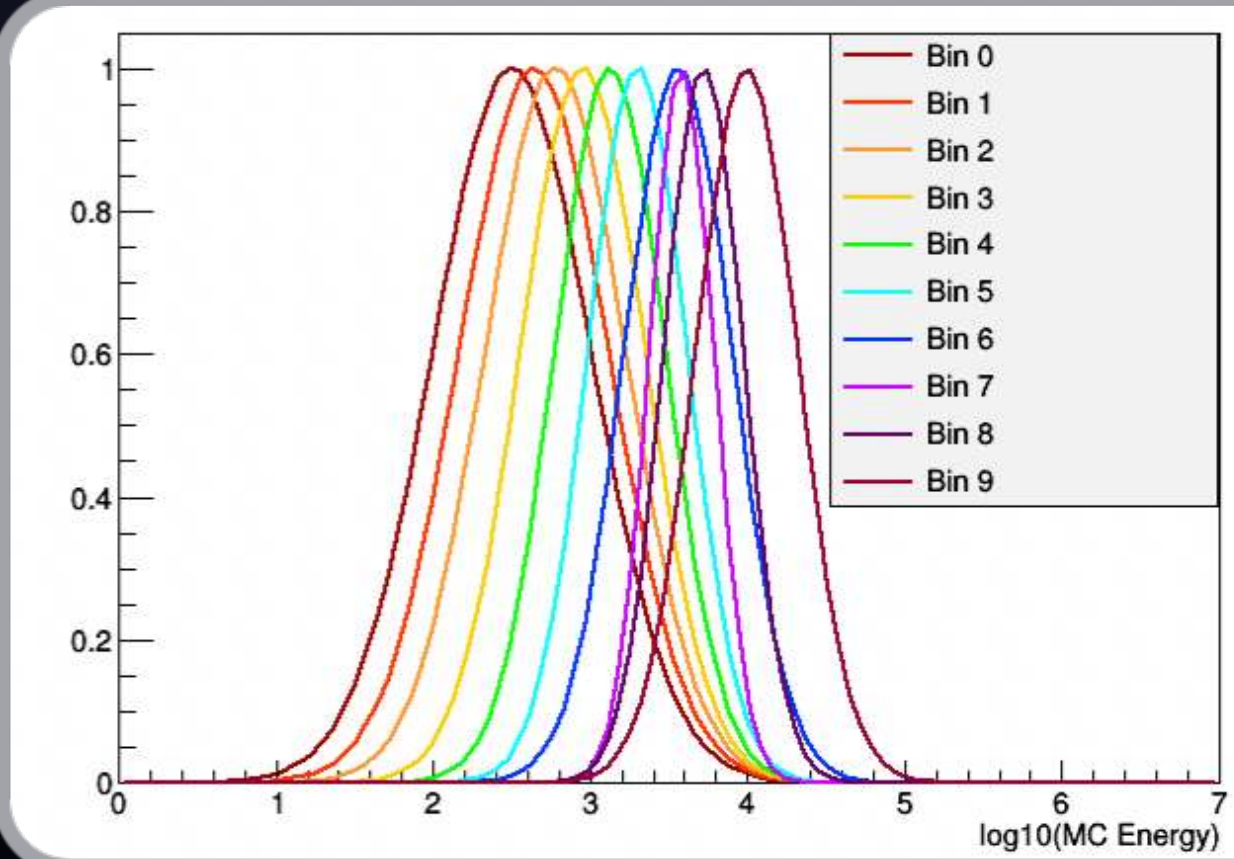
GRB 170206A

Very very preliminary; i.e., work in progress

Crab in bin 0



"Size" bins

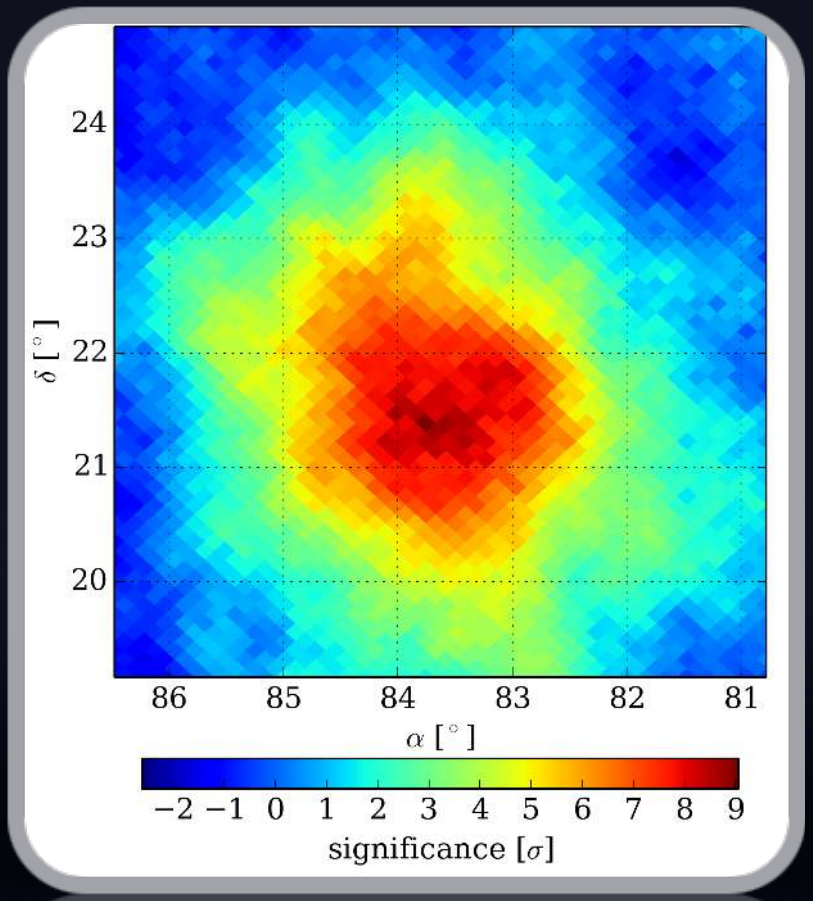


before

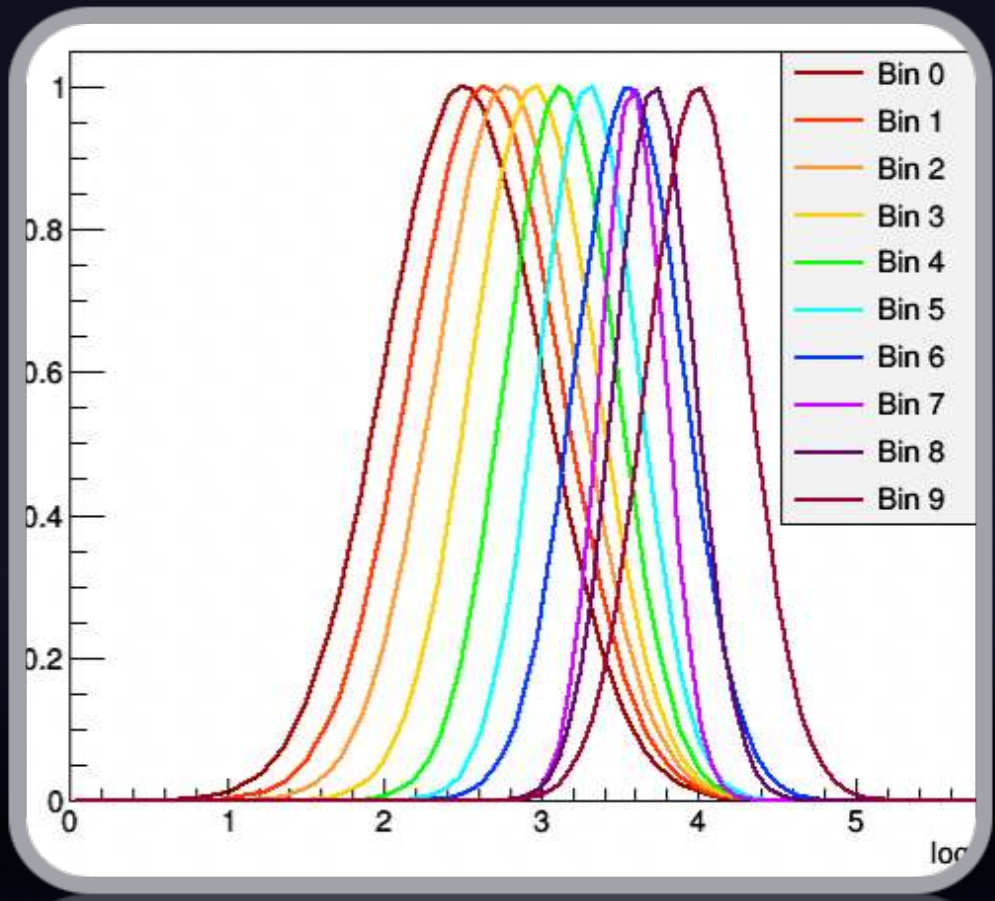
sub-TeV data

Very preliminary; i.e., work in p

Crab in bin 0



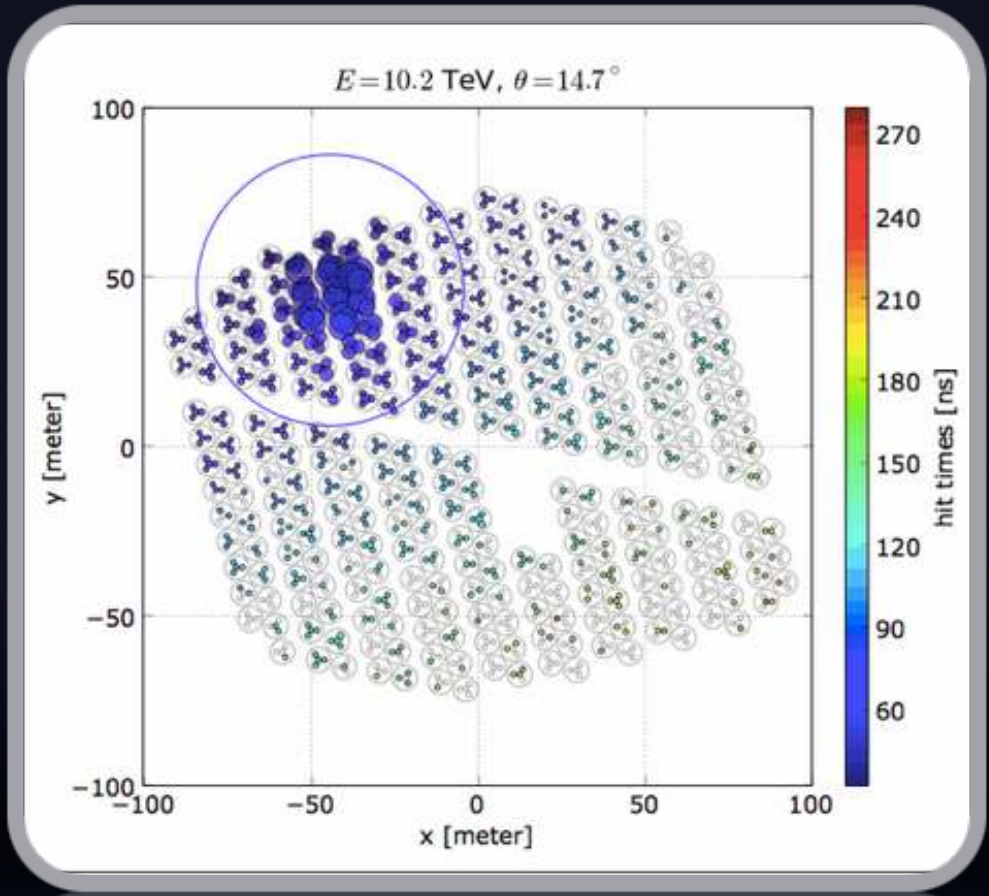
“Size” bins



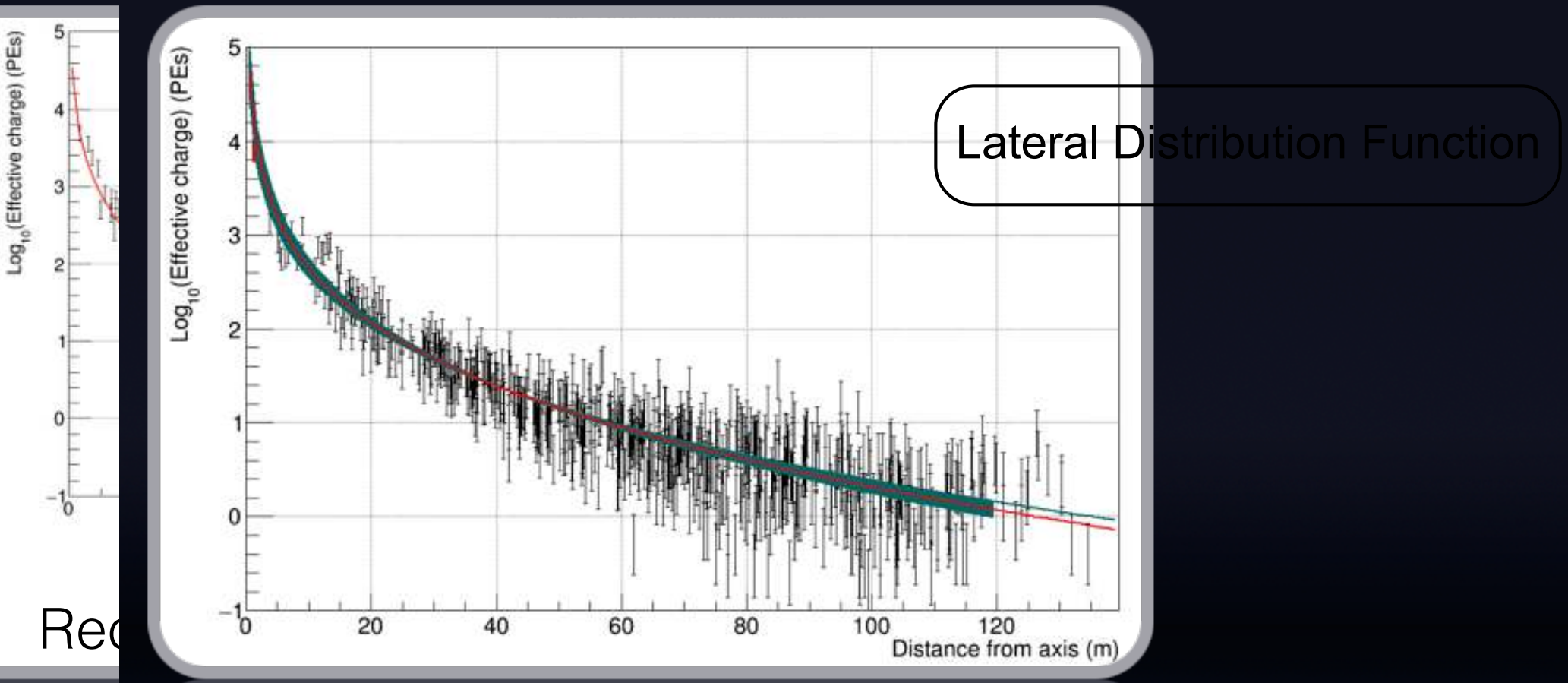
after

sub-TeV data

Number of triggered PMTs is the energy proxy

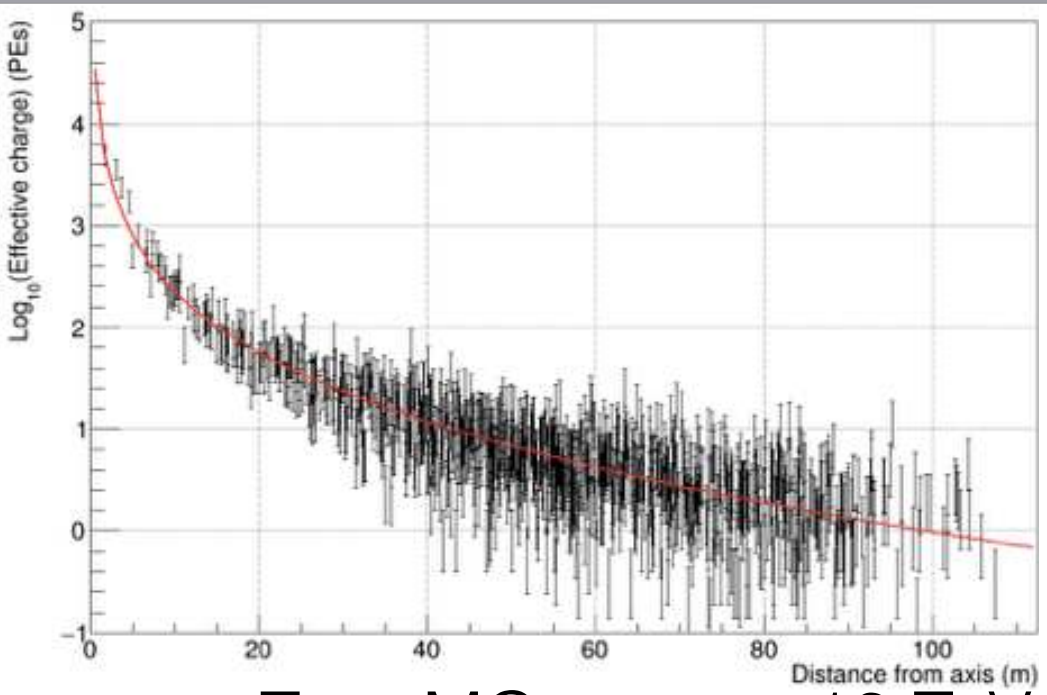


Energy measurement

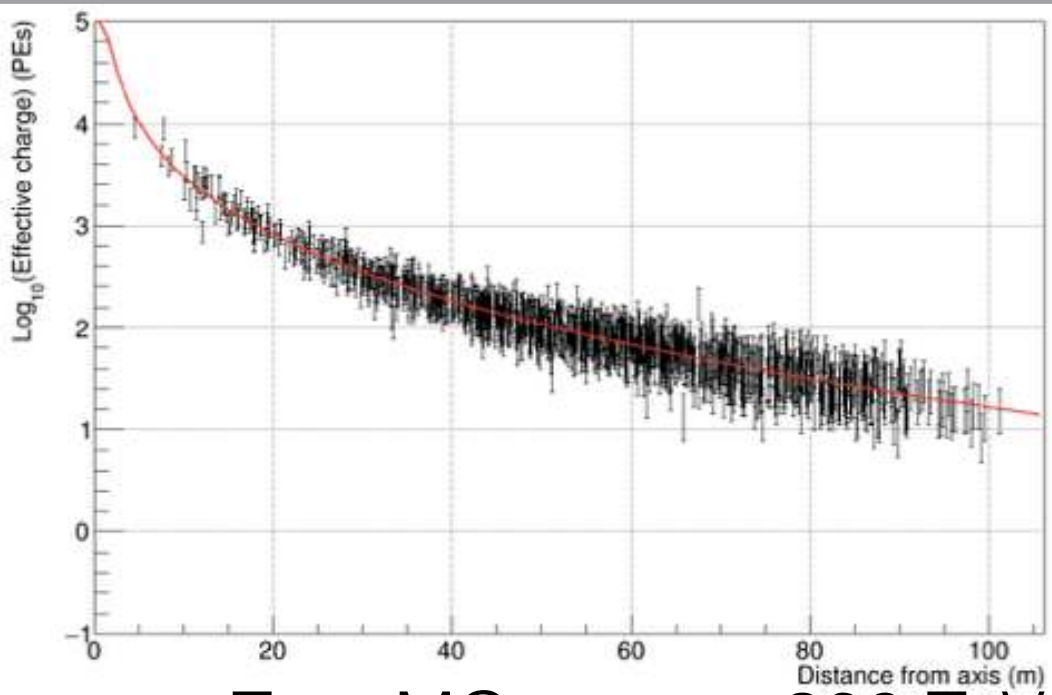


Lateral Distribution Function

Energy measurement



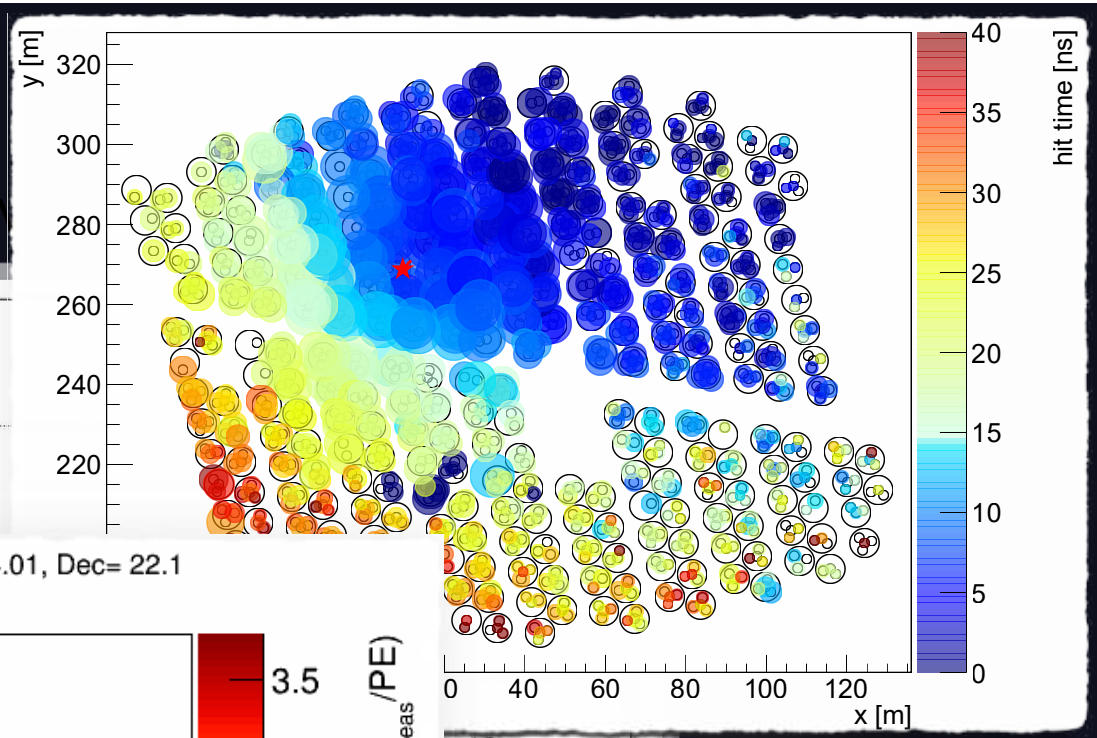
True MC energy 18 TeV
Reconstructed energy 17 TeV

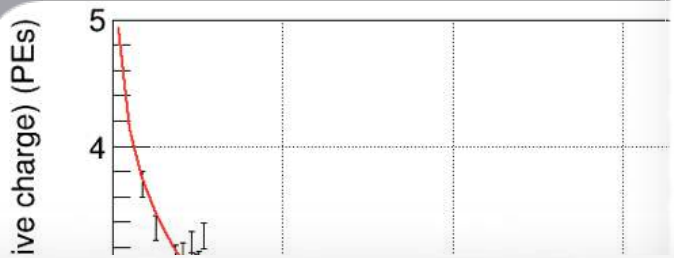


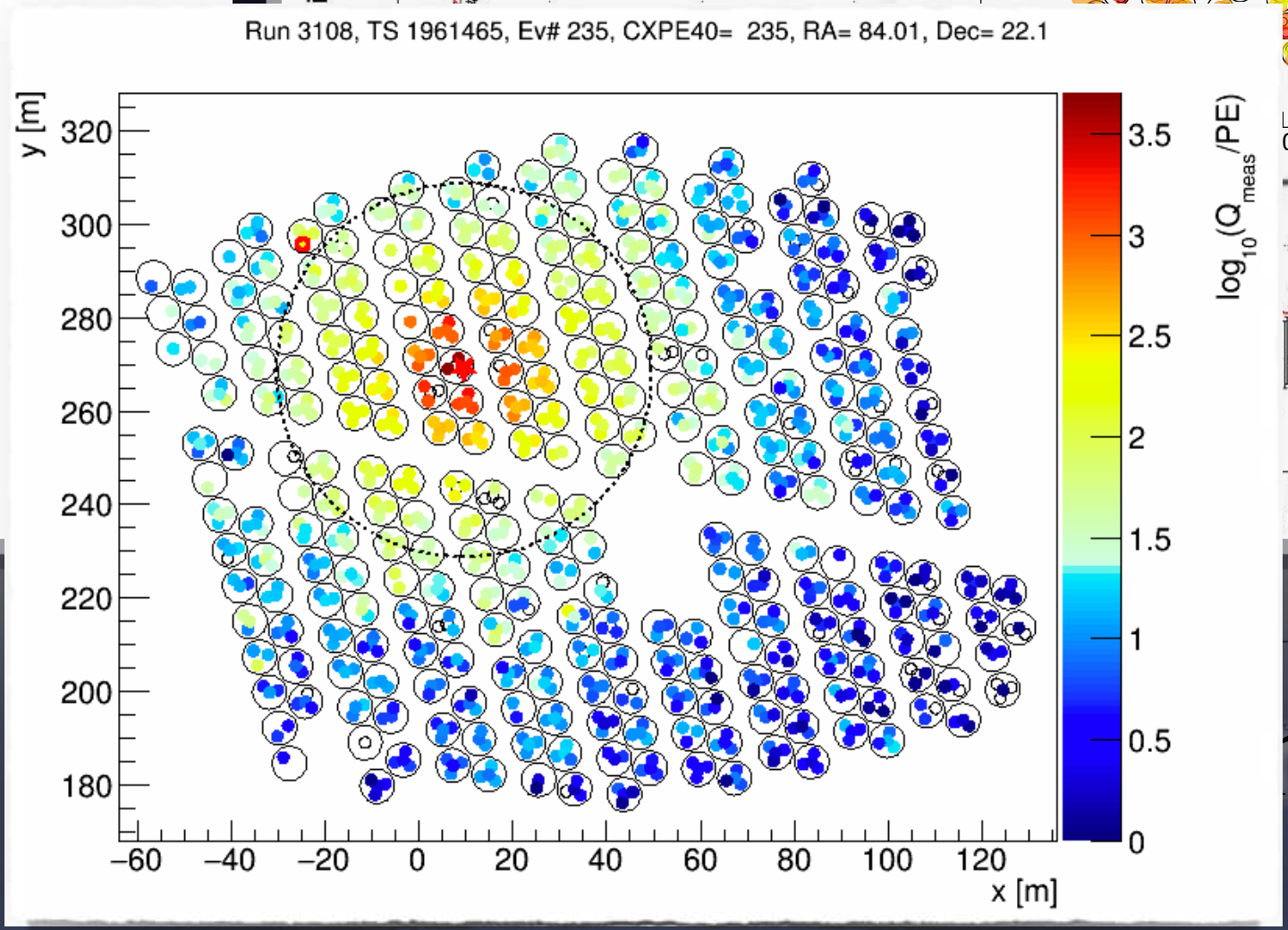
True MC energy 380 TeV
Reconstructed energy 350 TeV

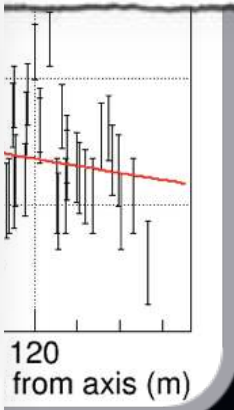
Energy measurement

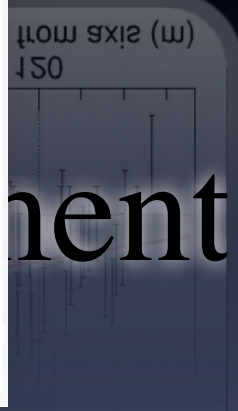
High energy ev





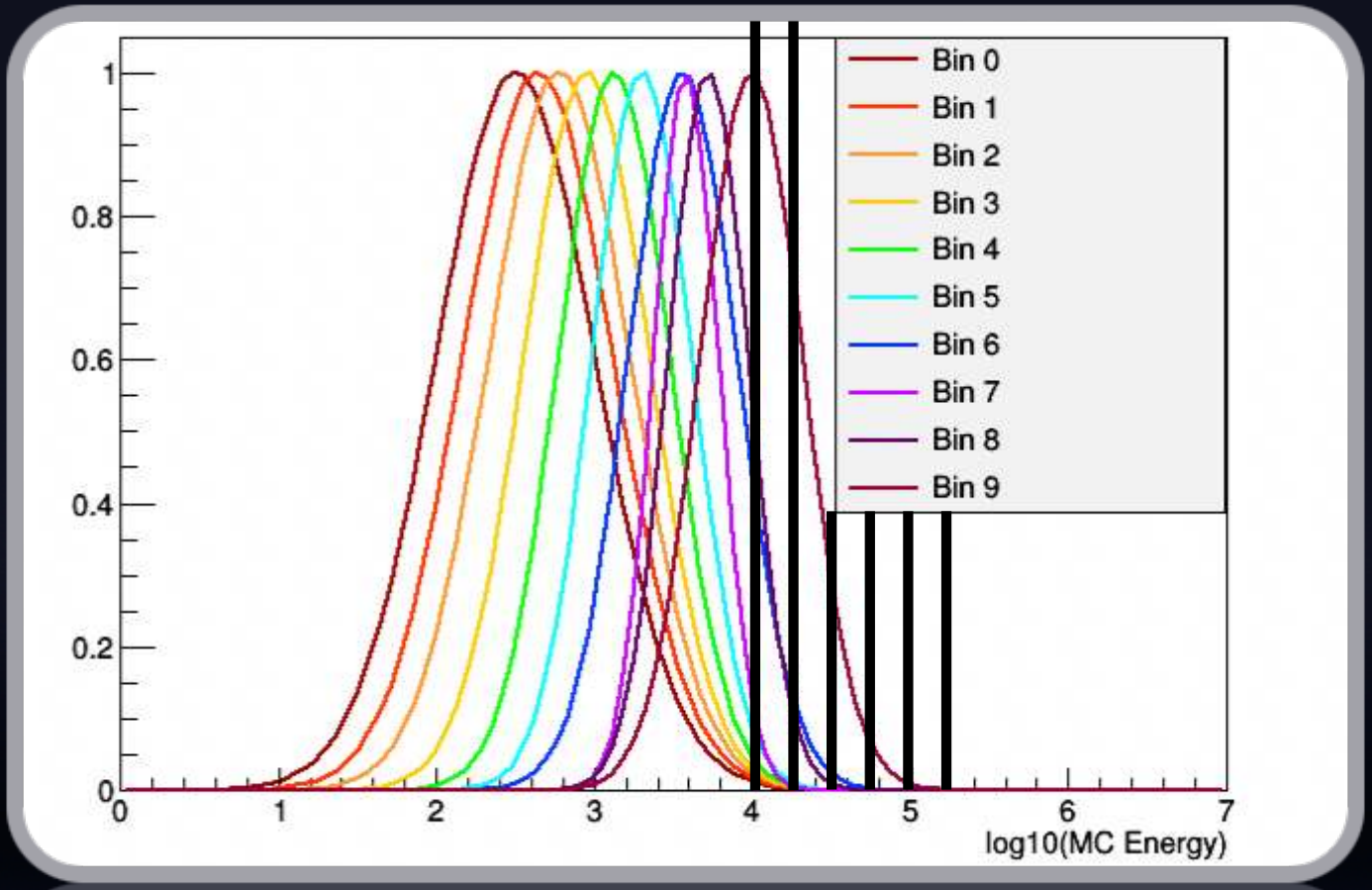




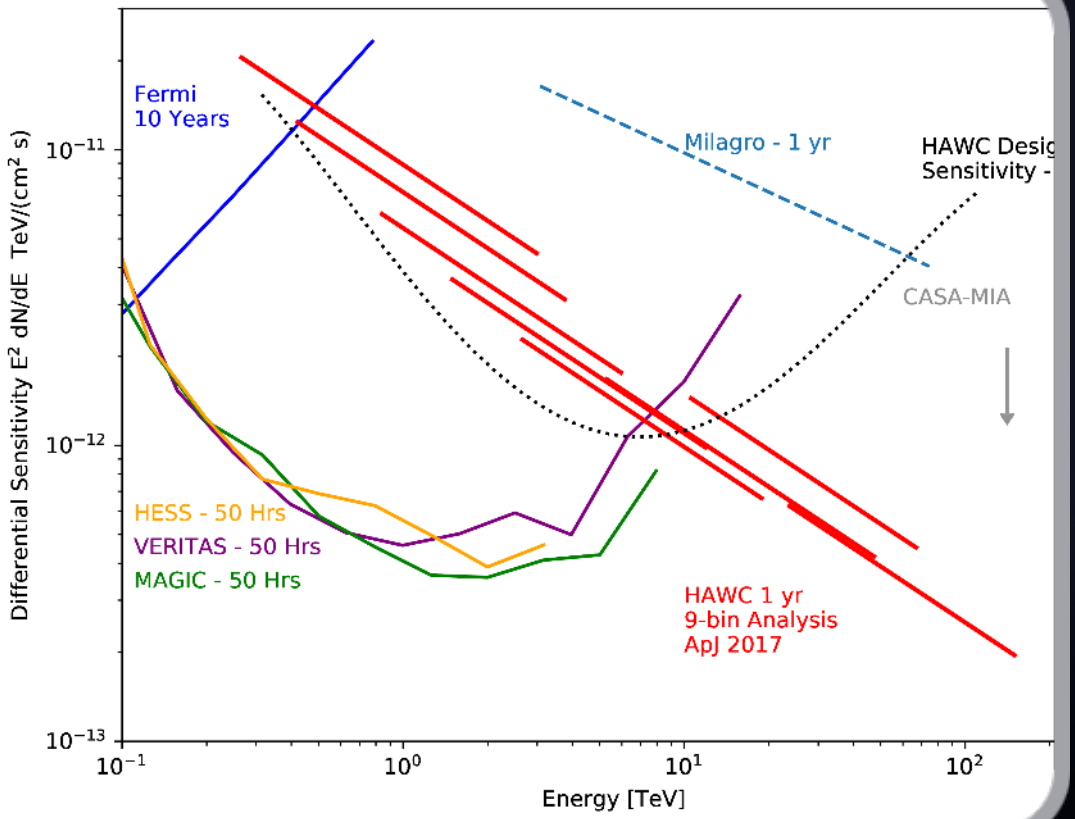


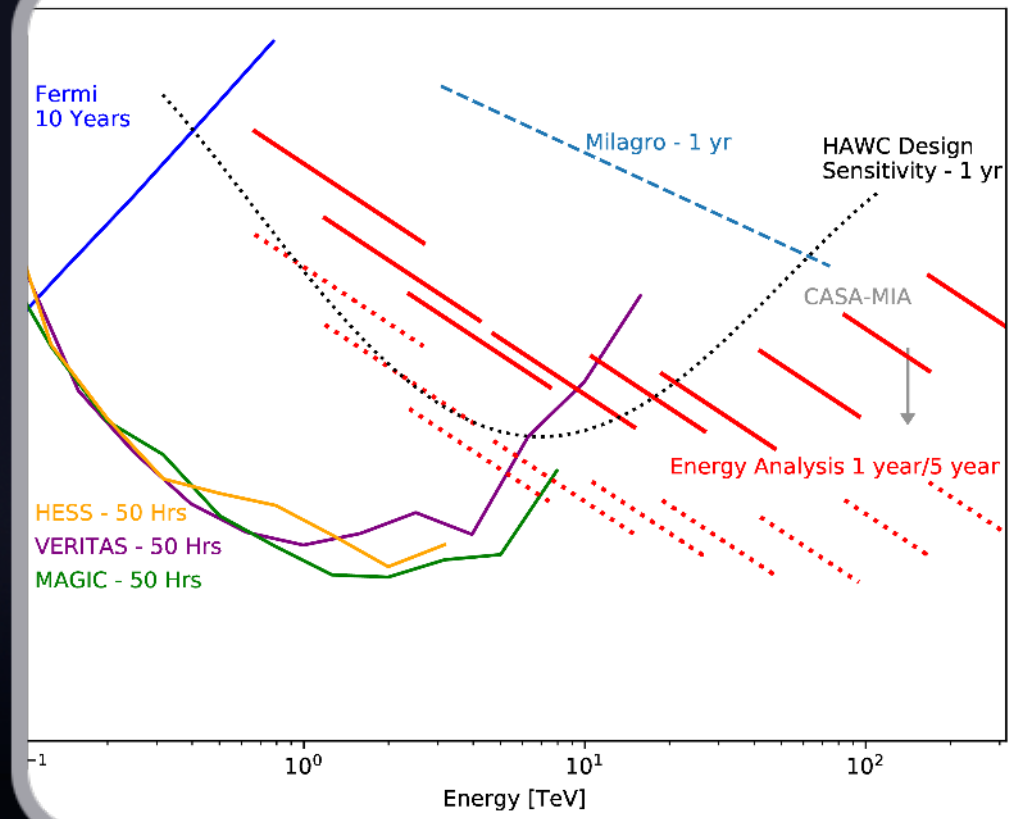
nent

“Size” bins



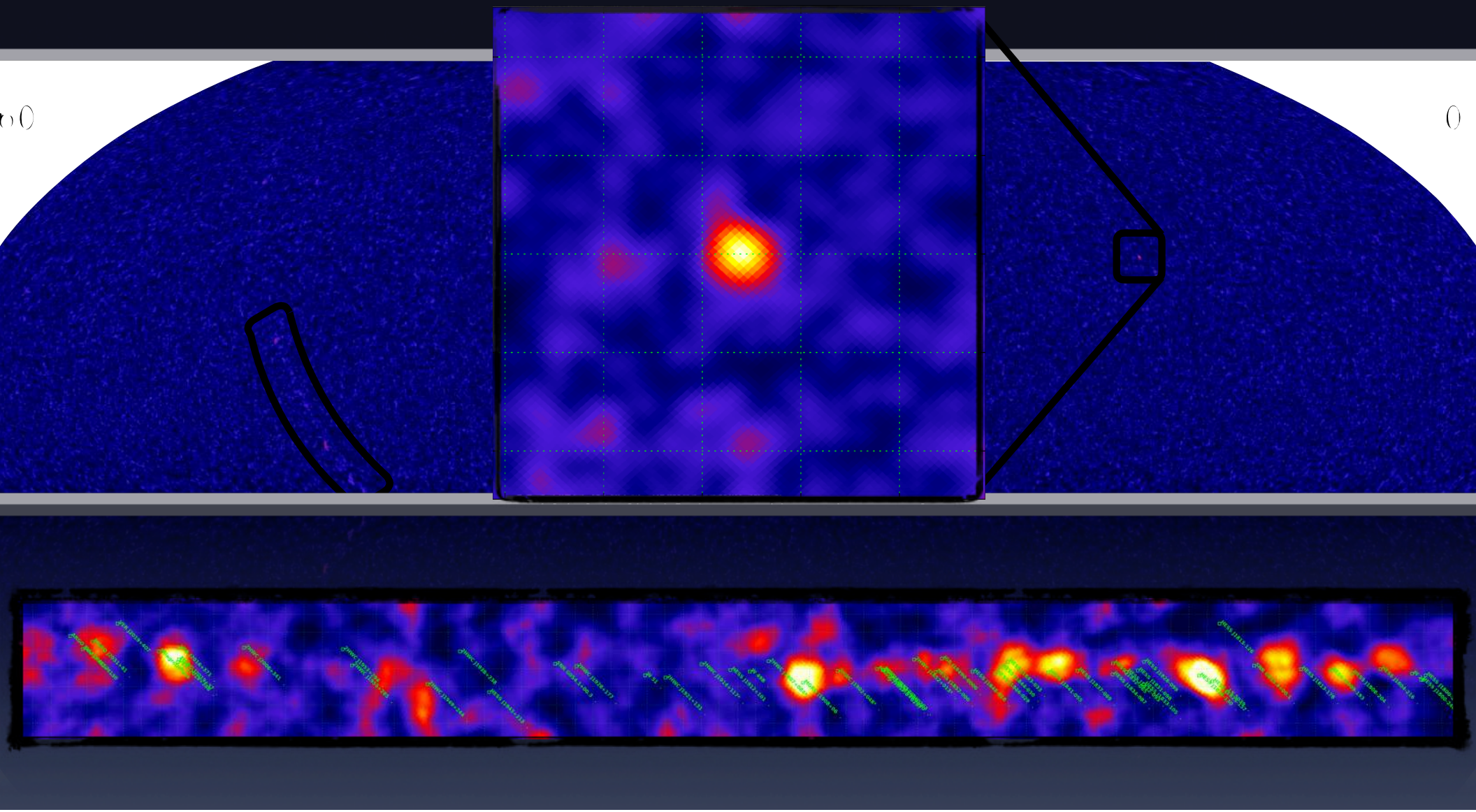
Energy measurement



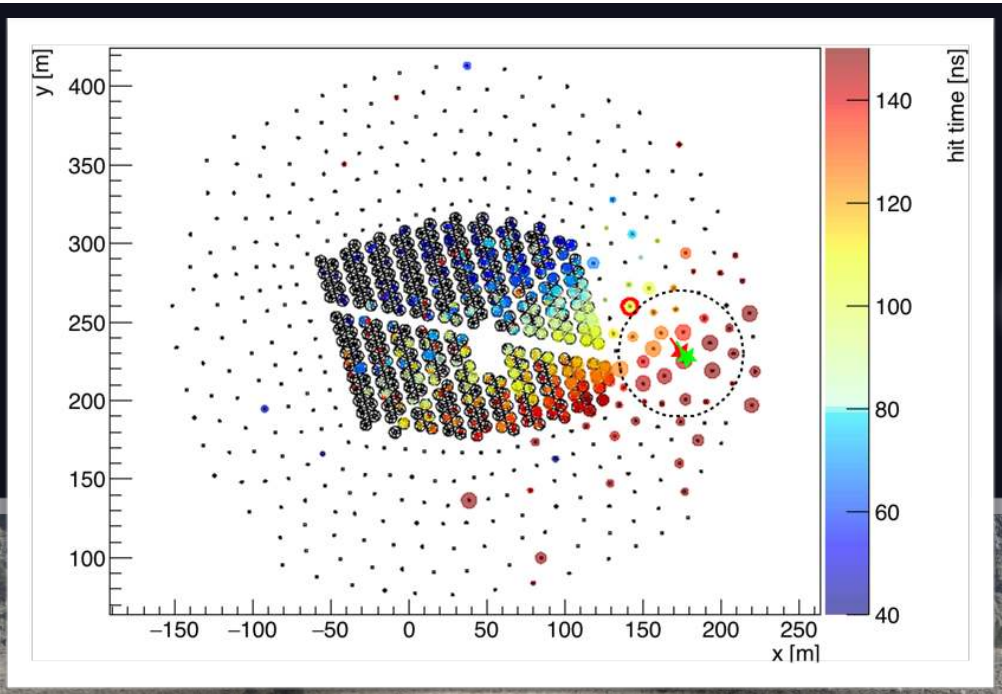


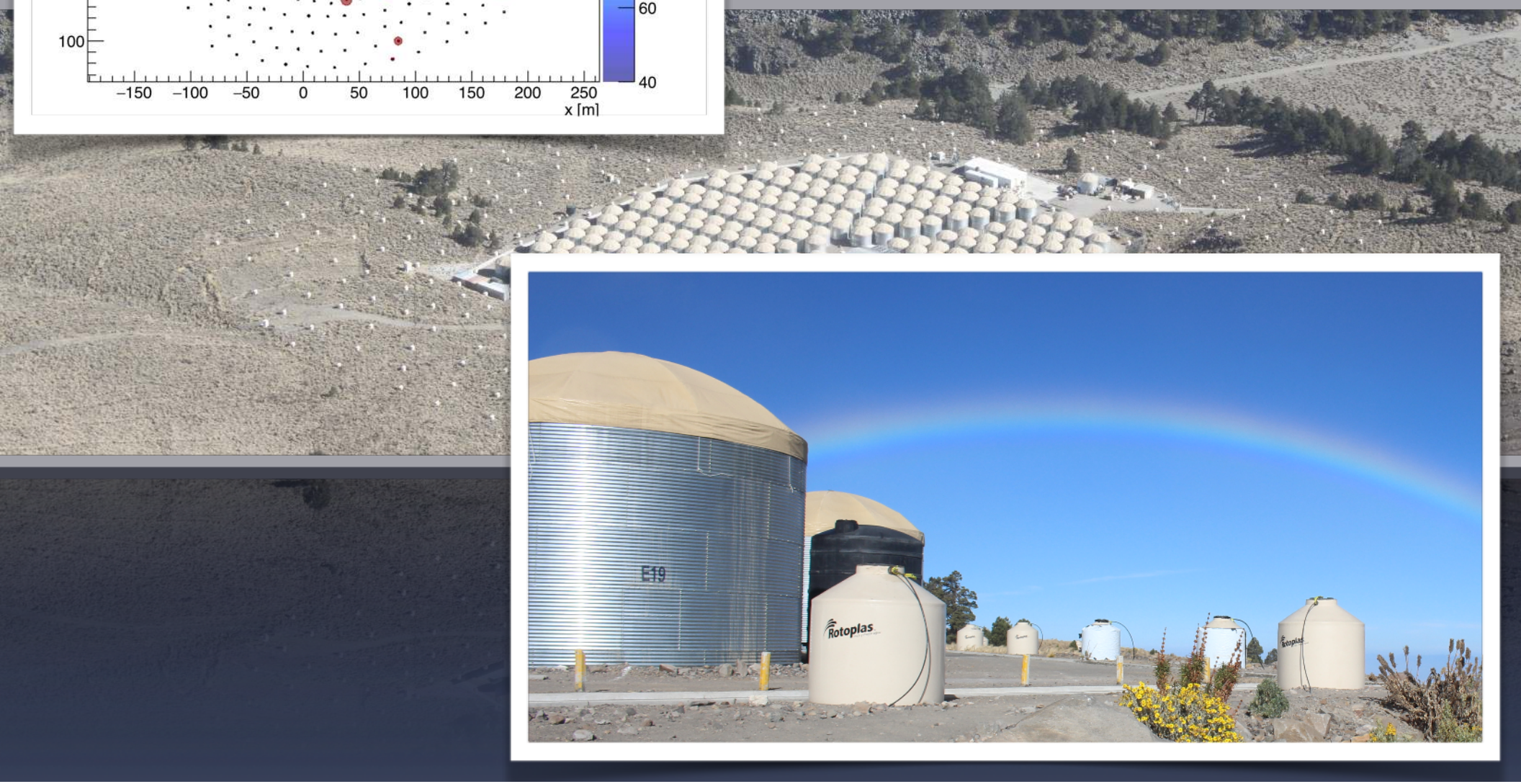
Energy measurement

γ-ray sky above 56 TeV



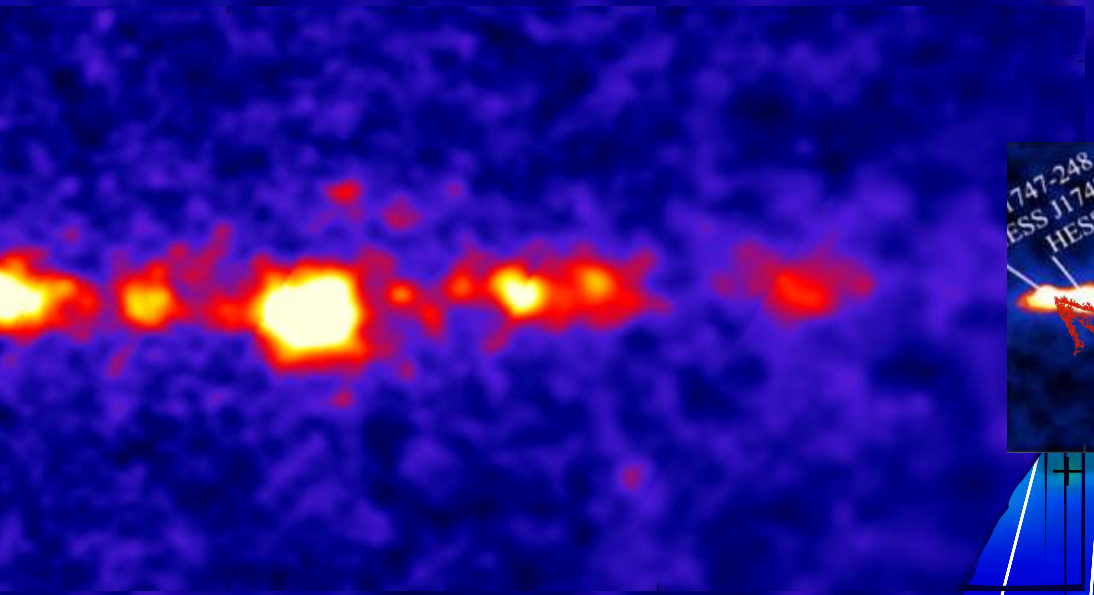
Outriggers

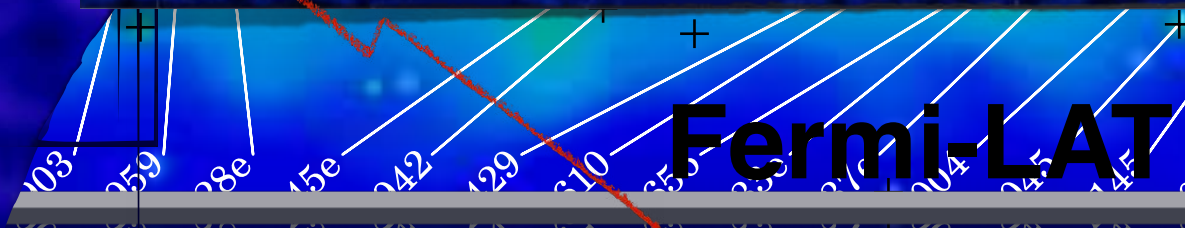

y [m]
400
350
300
250
200
150
100
−150
−100
−50
0
50
100
150
200
250
x [m]
hit time [ns]
140
120
100
80
60
40



E19
Rotoplas

Outlook: HAWC South



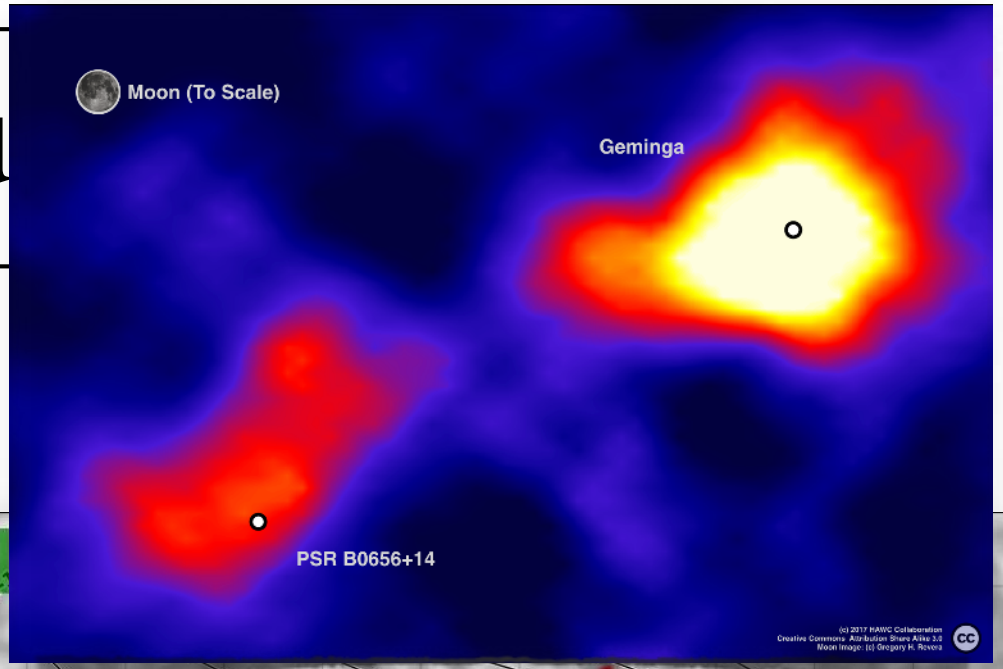


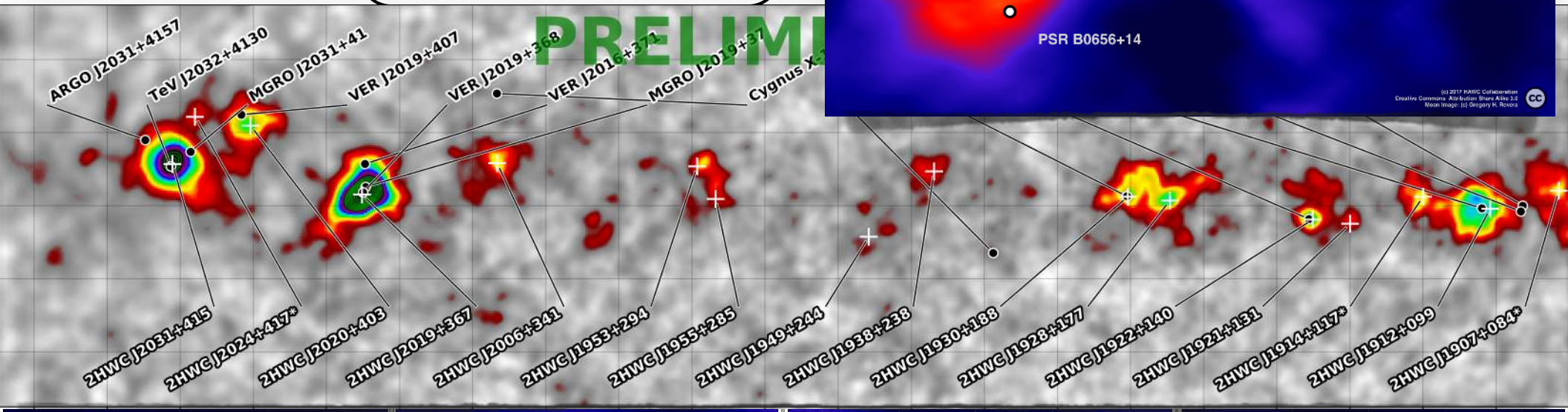
HAWC

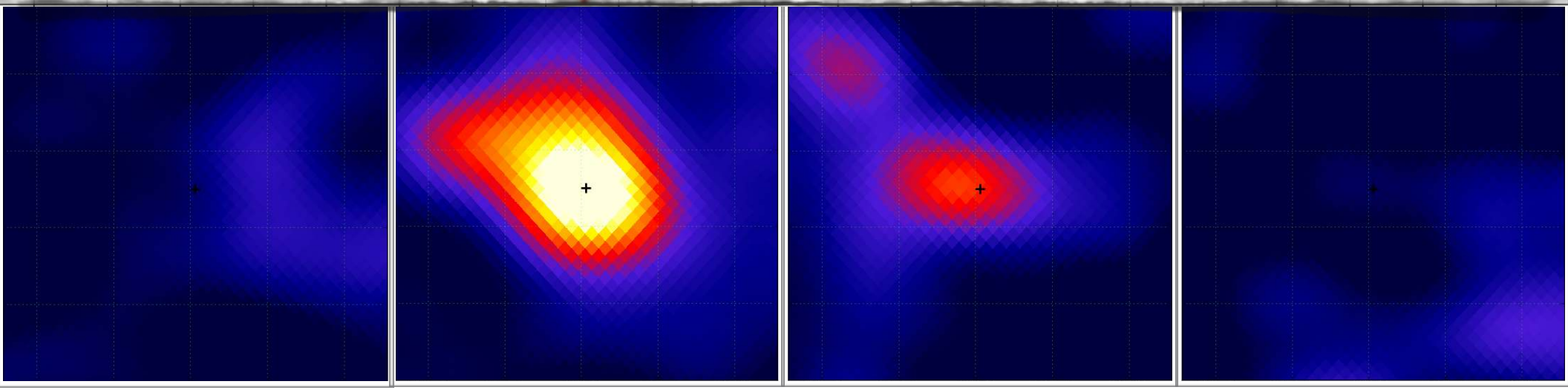
Conclu

Main results

- Extended regions, transient events, highest energies







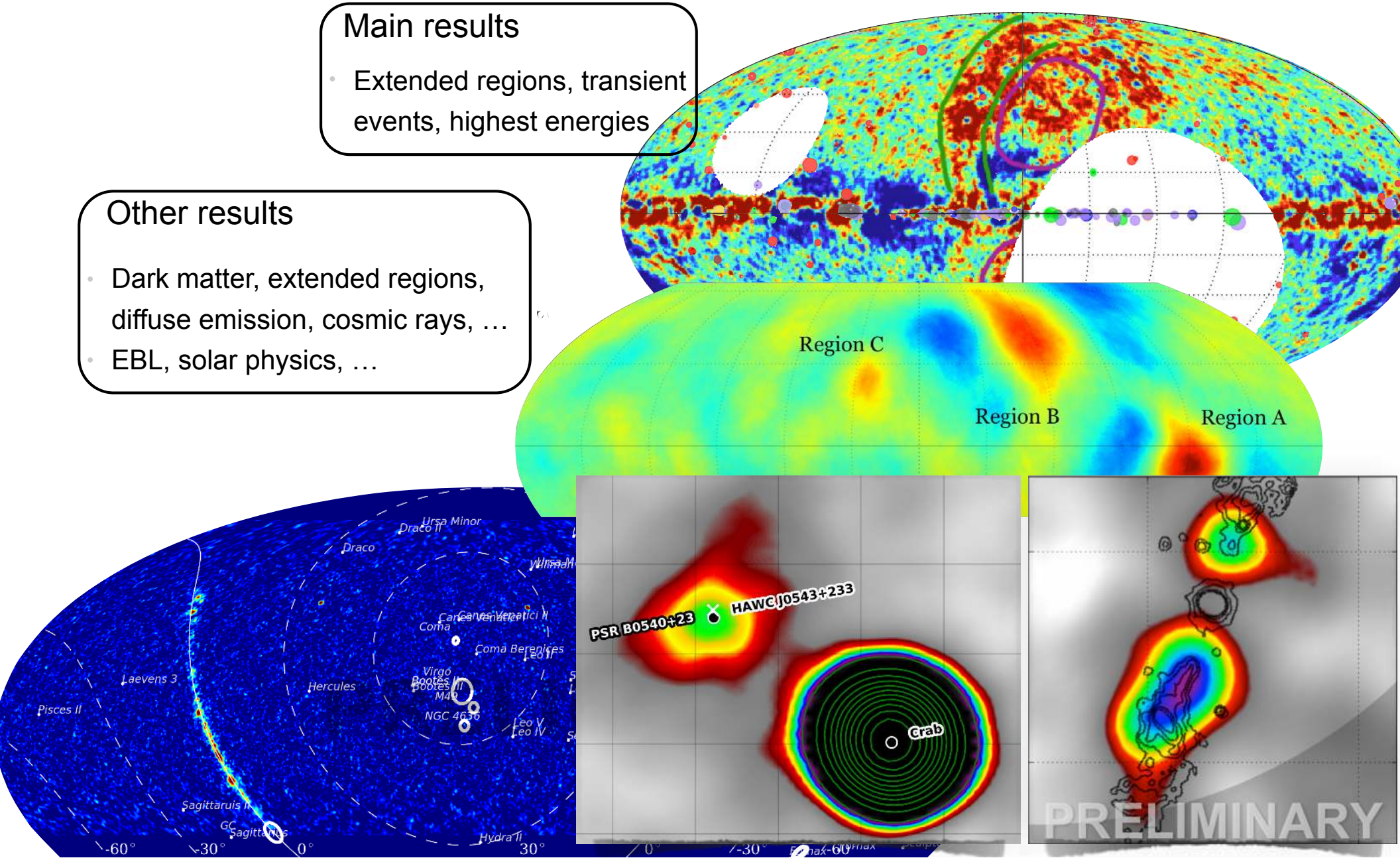
Conclusions

Main results

- Extended regions, transient events, highest energies

Other results

- Dark matter, extended regions, diffuse emission, cosmic rays, …
- EBL, solar physics, …



Conclusions

Main results

- Extended regions, transient events, highest energies

Other results

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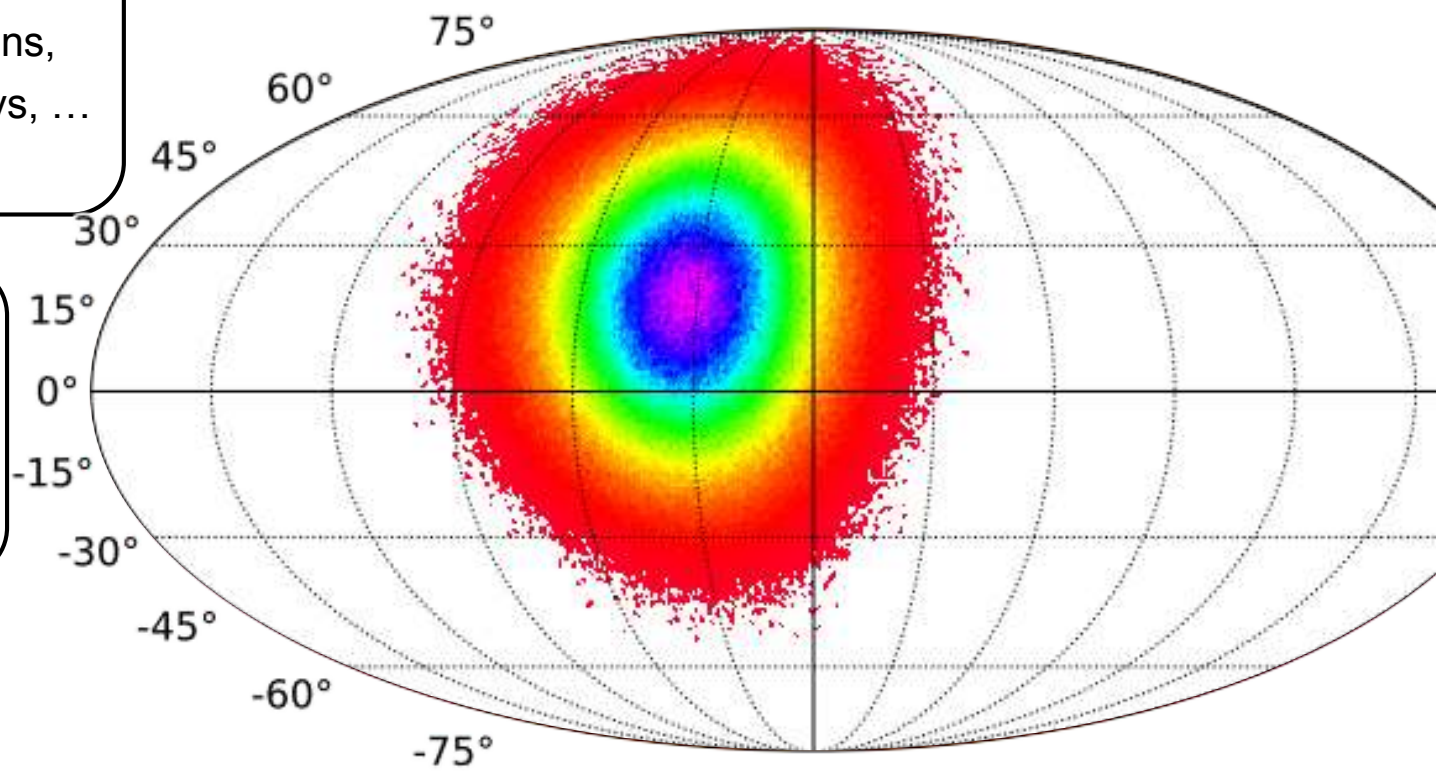
Multi-wavelength physics

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



Conclusions

Main results

- Extended regions, transient events, highest energies

Other results

- Dark matter, extended regions, diffuse emission, cosmic rays, …
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Multi-wavelength physics

- MoUs with IceCube, IACTs, etc
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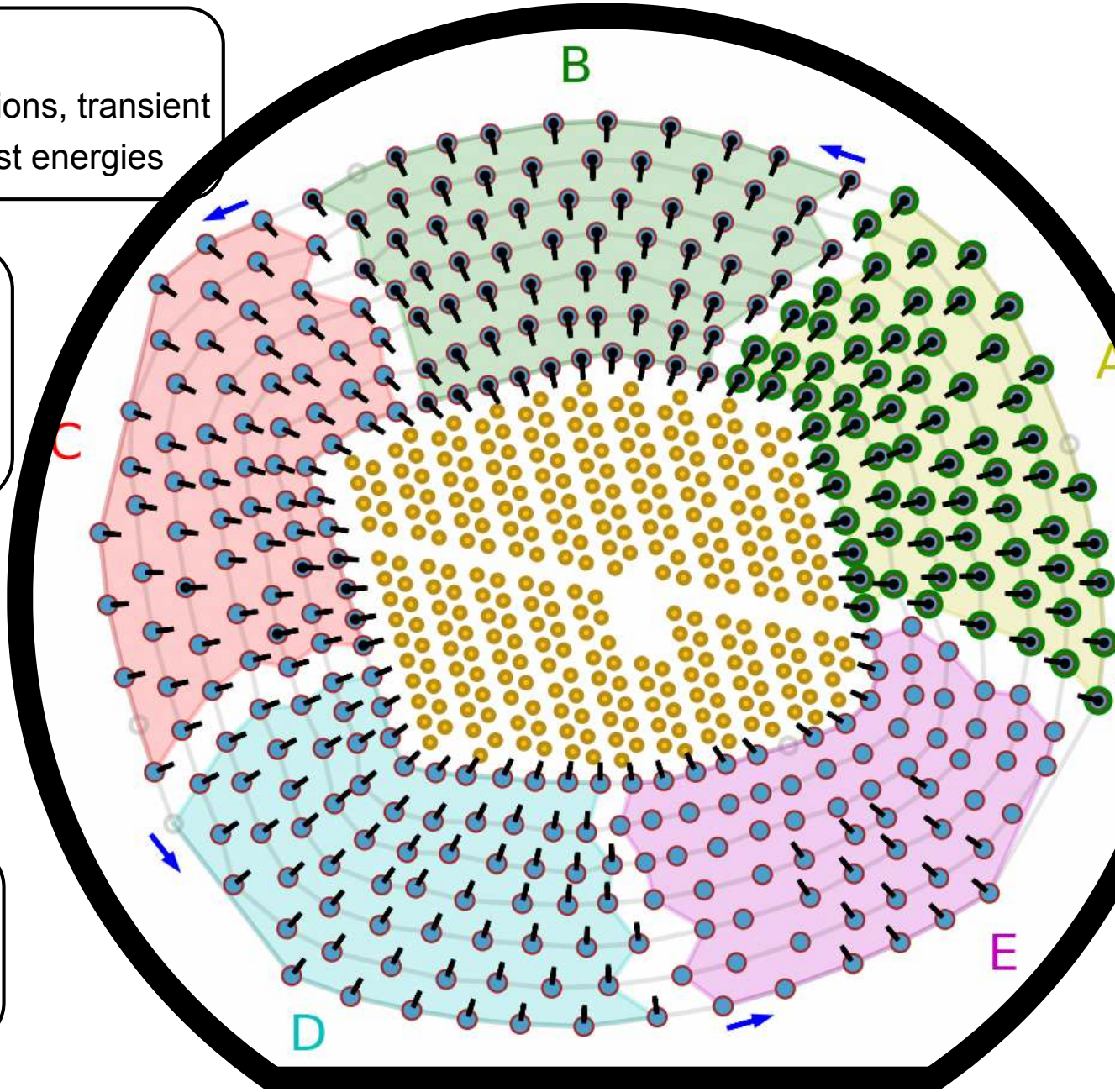
- HAWC alerts

Outlook

- Array of Outriggers
- Southern Observatory




Thank you very much!
The HAWC Collaboration

Recent HAWC publications

"Very-high-energy particle acceleration powered by the jets of the microquasar SS 433," **Nature** 562, 82-85 (2018)

"Constraints on spin-dependent dark matter scattering with long-lived mediators from TeV observations of the Sun with HAWC," Physical Review D 98, 123012 (2018)

"First HAWC observations of the Sun constrain steady TeV gamma-ray emission," Physical Review D 98, 123011 (2018)

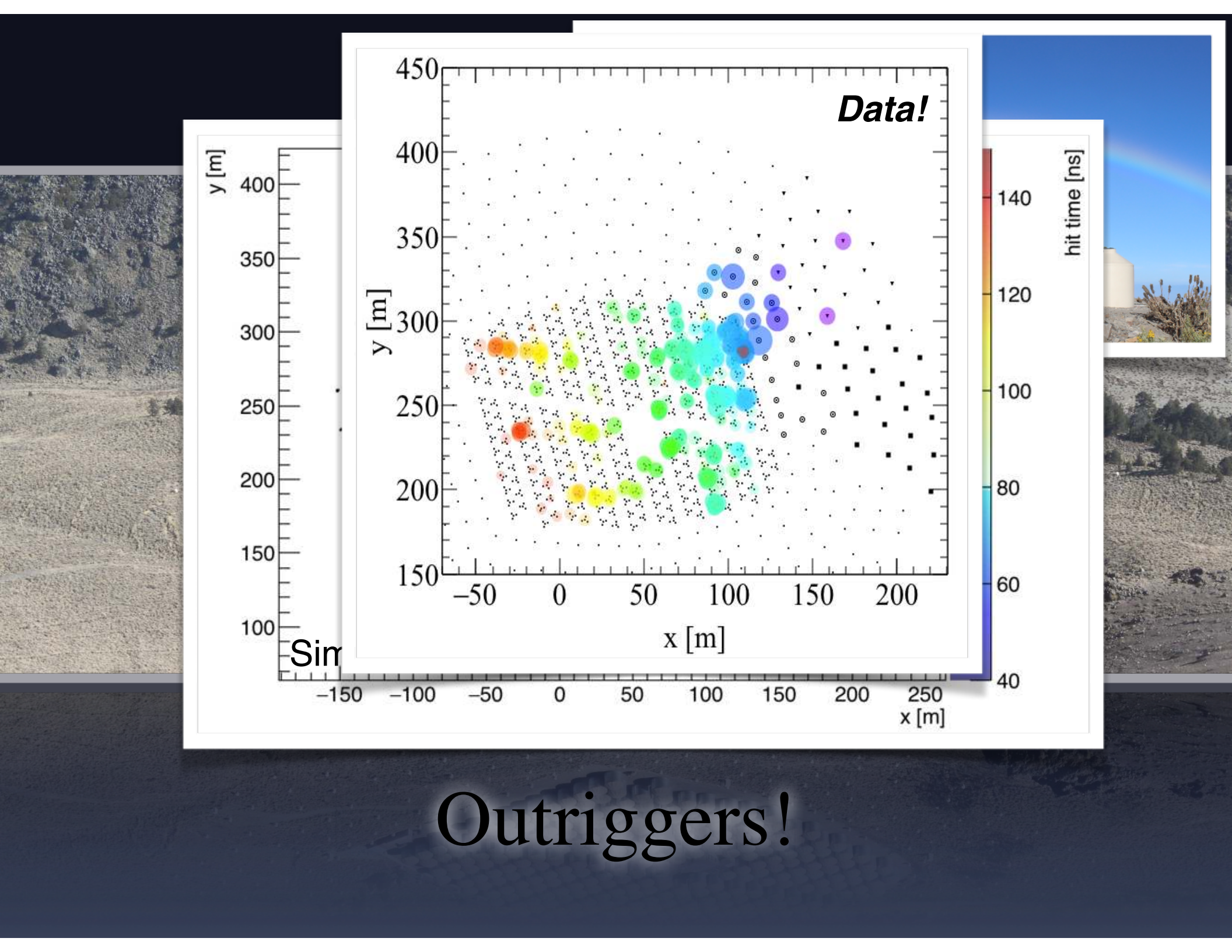
"Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A," **Science** 361 (13 Jul 2018) 6398

"Observation of Anisotropy of TeV Cosmic Rays with Two Years of HAWC," The Astrophysical Journal 865 (2018) 57

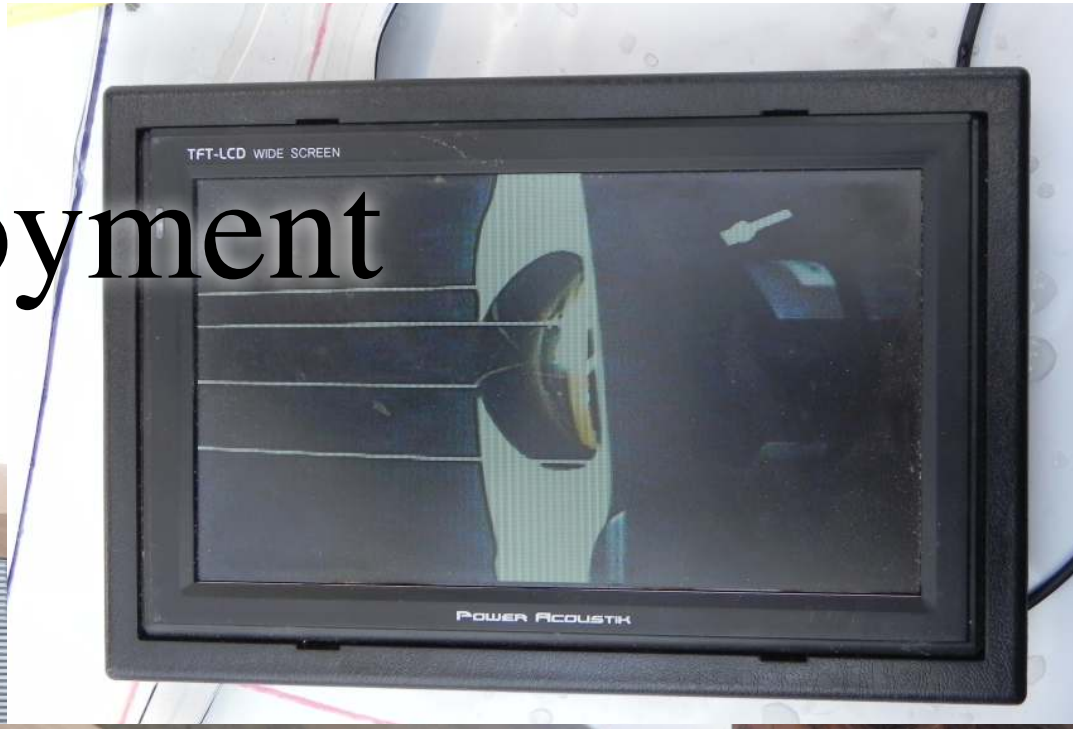
"Search for dark matter gamma-ray emission from the Andromeda Galaxy with the High-Altitude Water Cherenkov Observatory," Journal of Cosmology and Astroparticle Physics 06 (2018) 043

"Constraining the p-bar/p Ratio in TeV Cosmic Rays with Observations of the Moon Shadow by HAWC," Physical Review D 97, 102005 (2018)

Mixed bag of backup slides


Data!
y [m]
x [m]
hit time [ns]
Sim
Outriggers!

Deployment



Water Cherenkov Detectors

bladders
PMT mounts
detector prototype

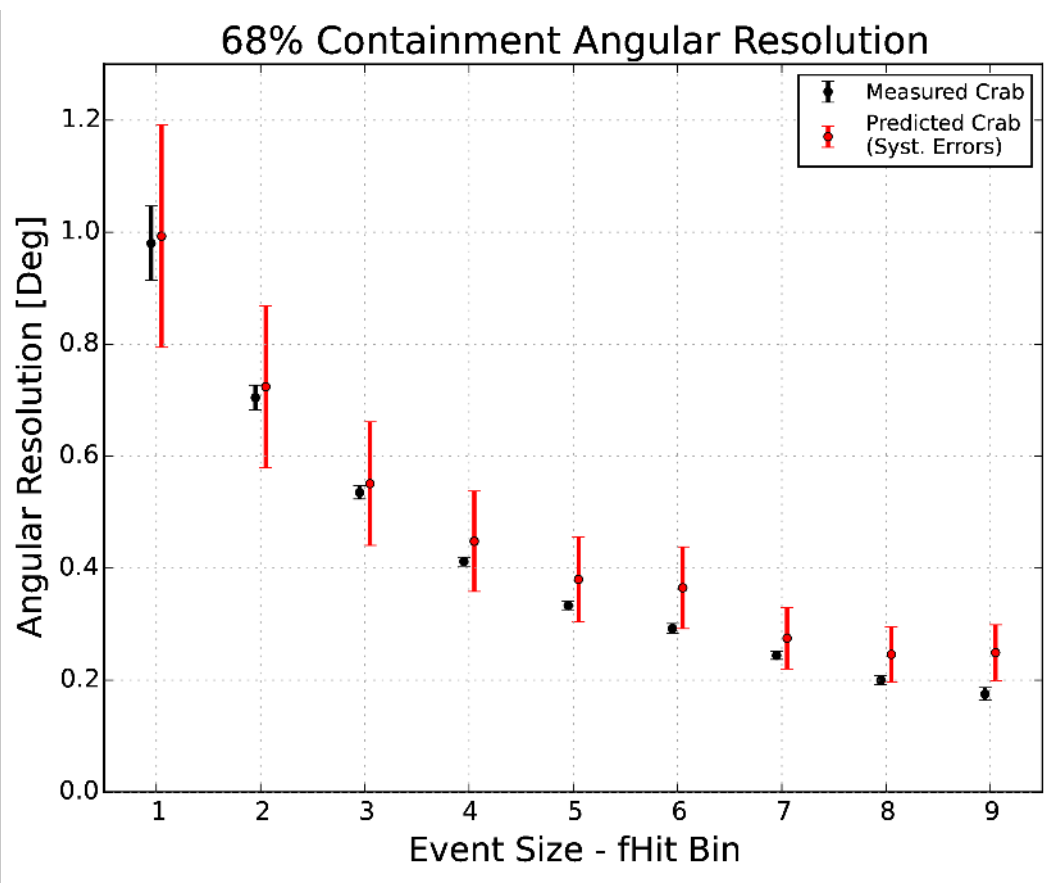
Water Cherenkov Detectors

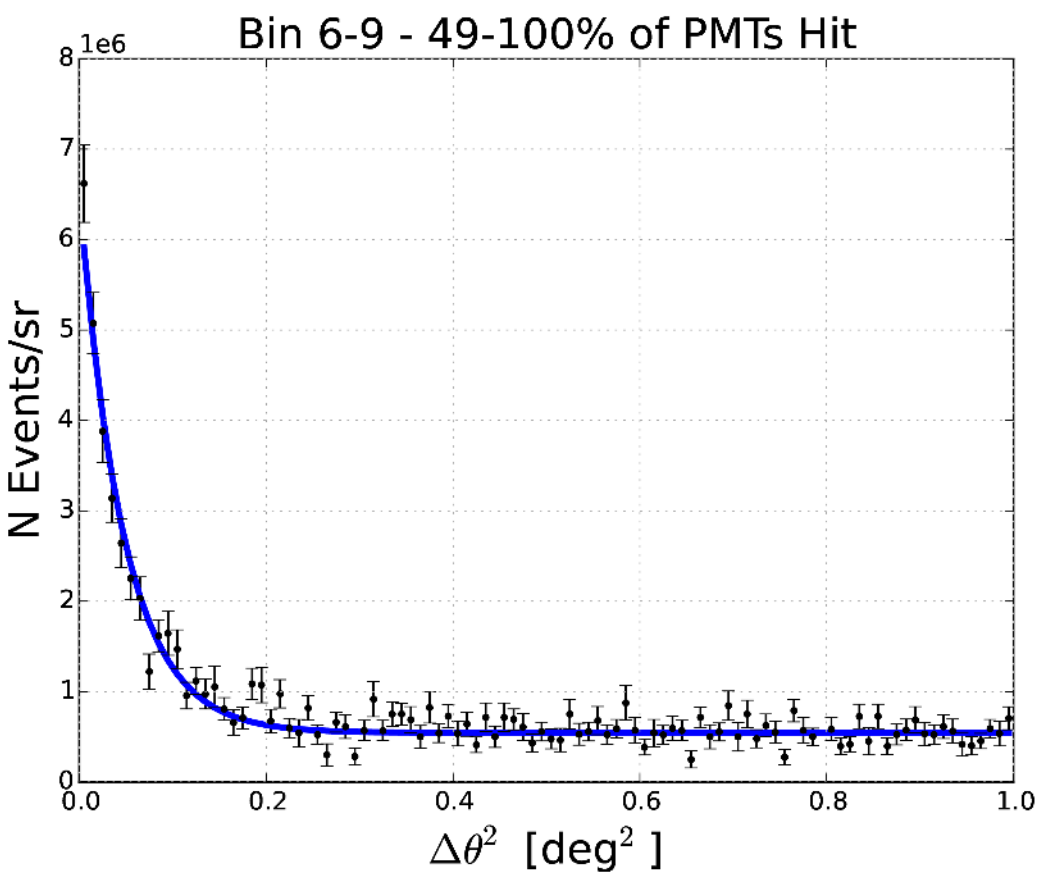
bladders
PMT mounts
detector prototype

Water Cherenkov Detectors

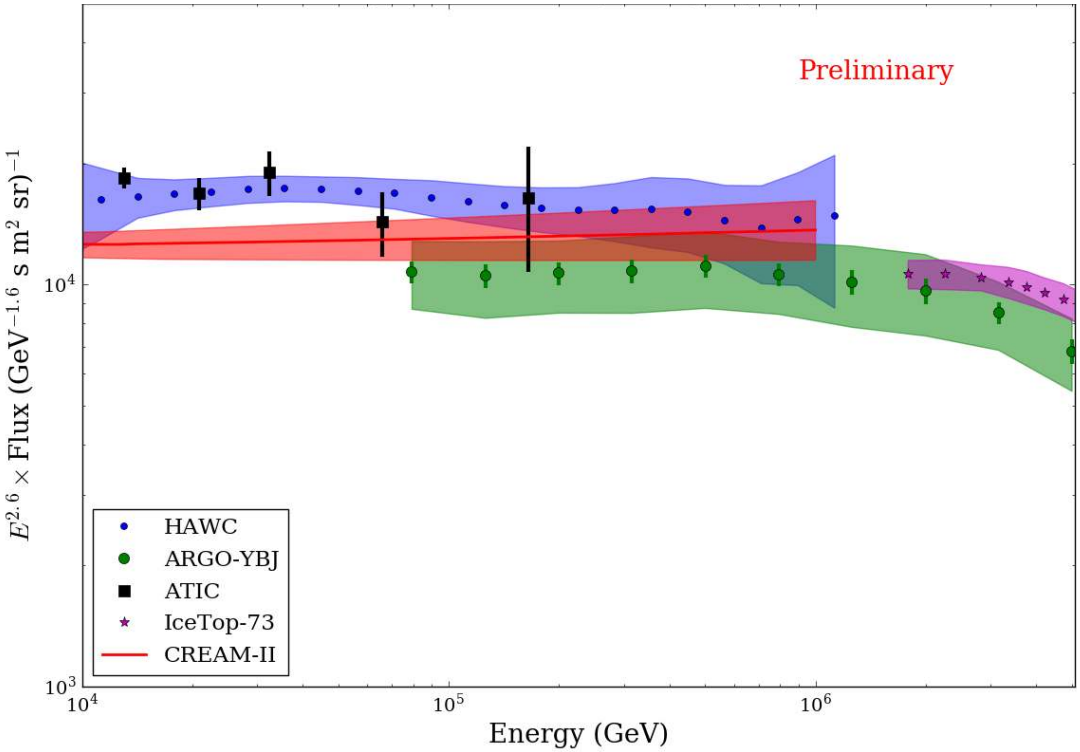
bladders
PMT mounts
detector prototype

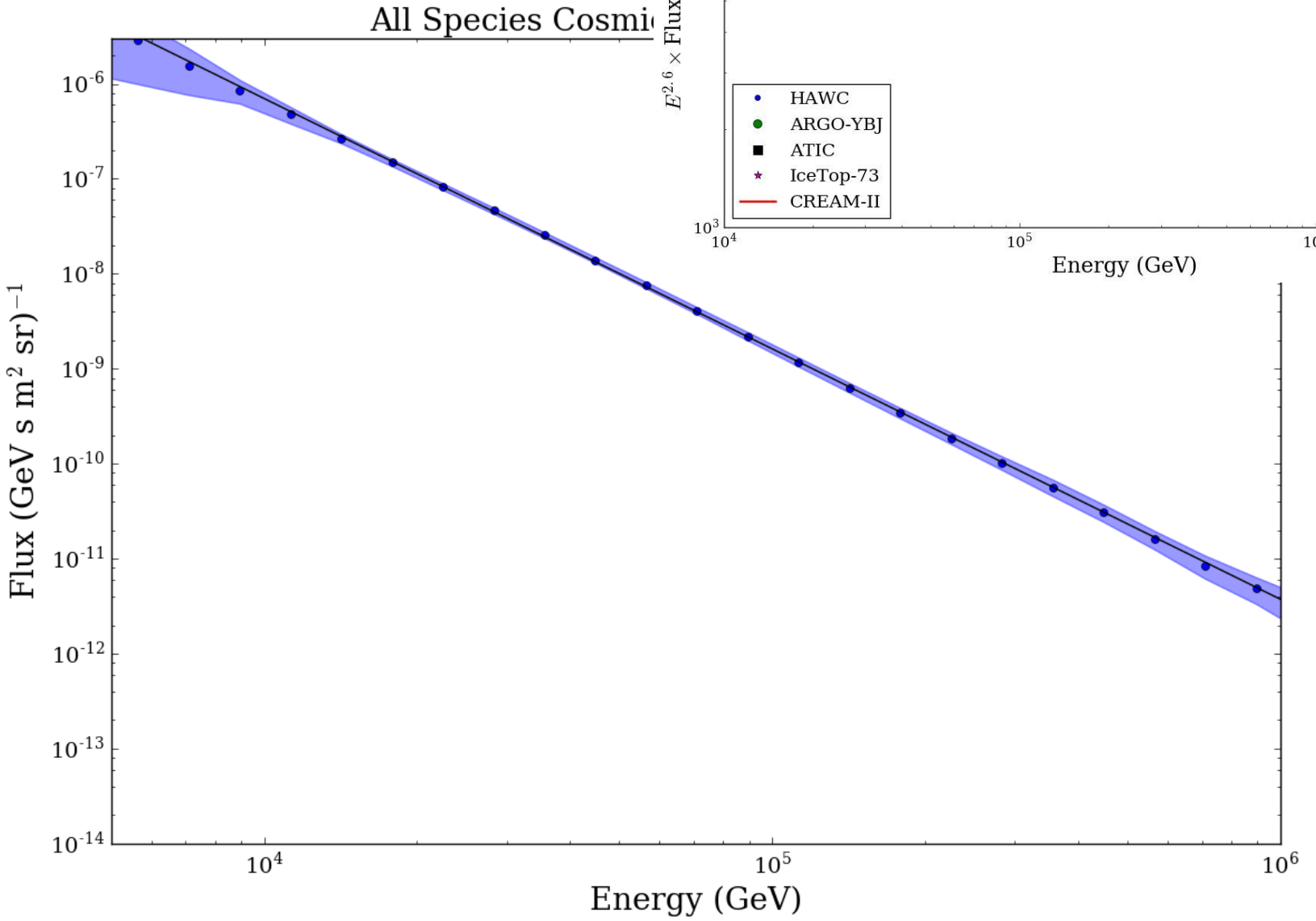
angular resolution

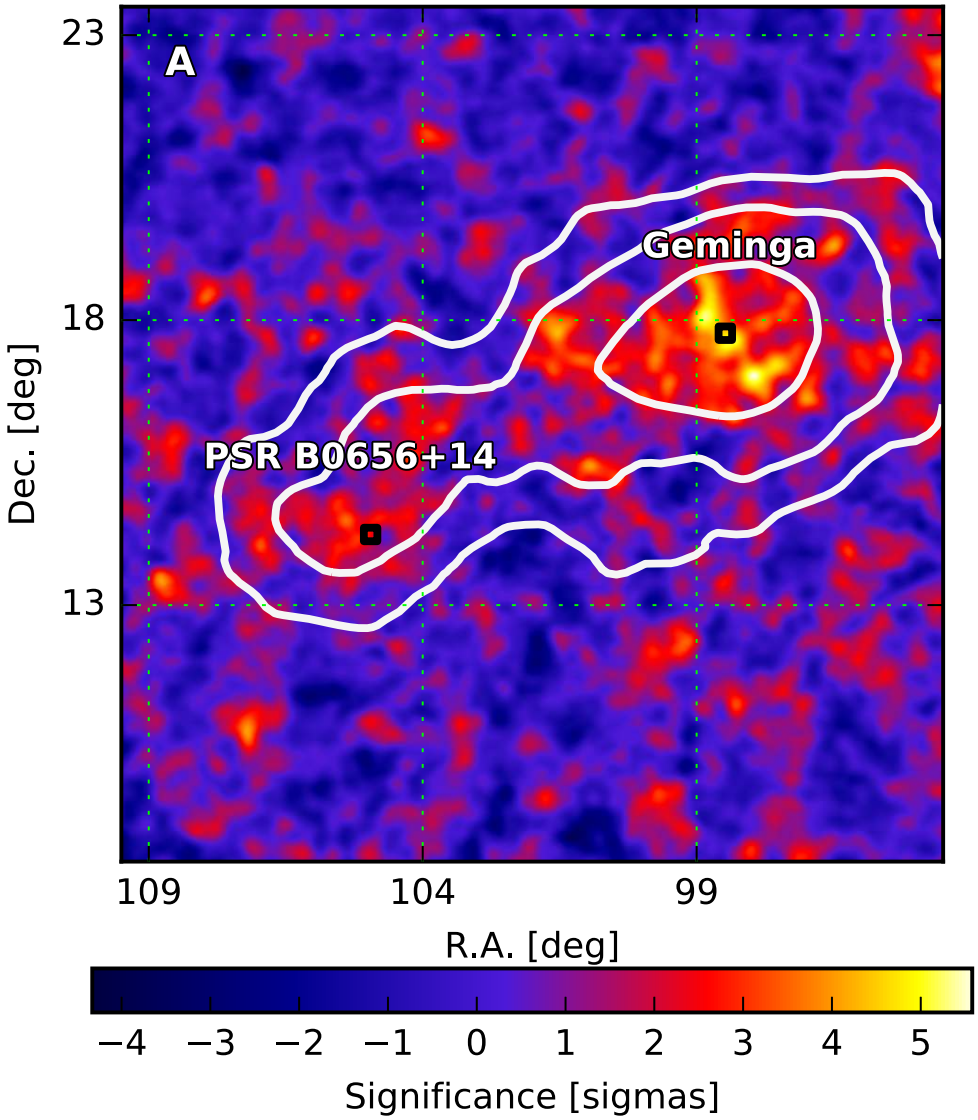


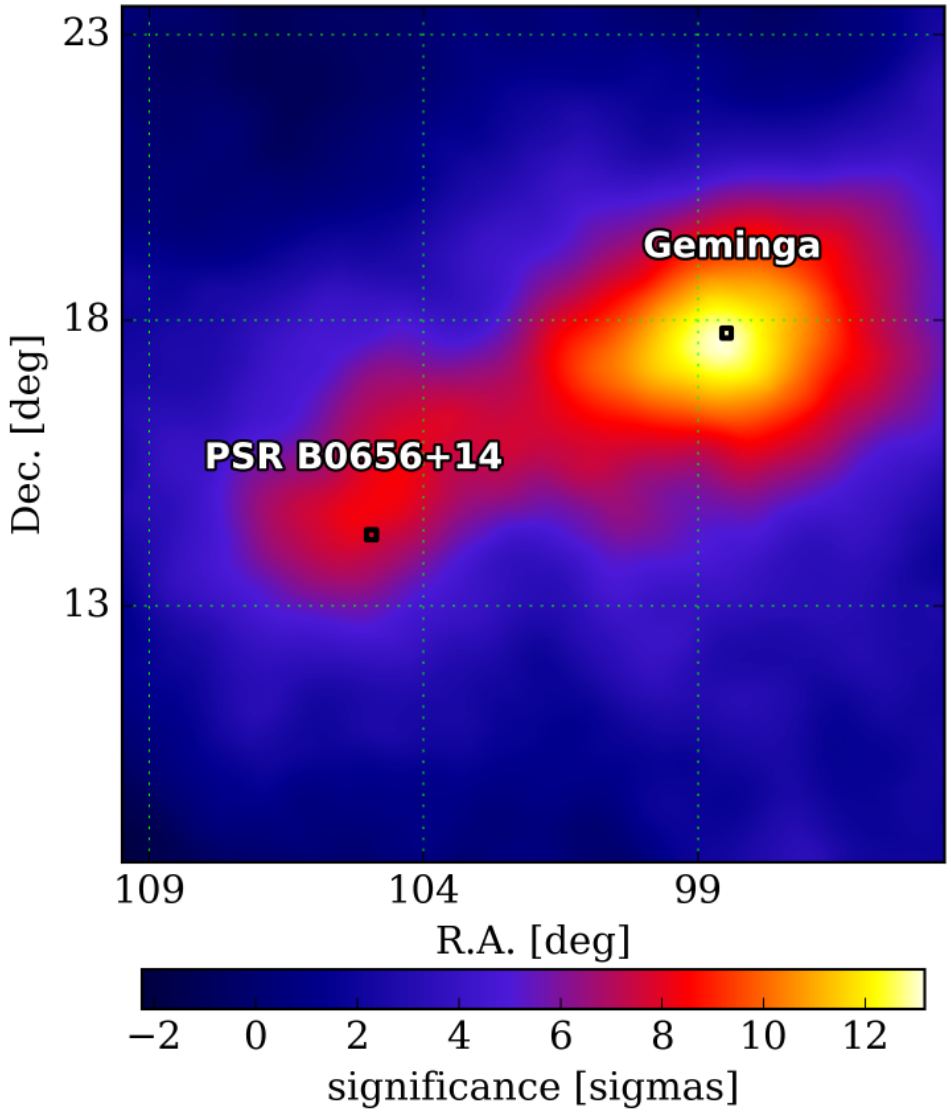


CR spectrum


Preliminary
$E^{2.6} \times$ Flux (GeV$^{-1.6}$ s m^2 sr)$^{-1}$
10^4
10^3
10^4
10^5
10^6
Energy (GeV)
HAWC
ARGO-YBJ
ATIC
IceTop-73
CREAM-II


All Species Cosmi
Flux (GeV s m^2 sr)$^{-1}$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^4
10^5
10^6
Energy (GeV)

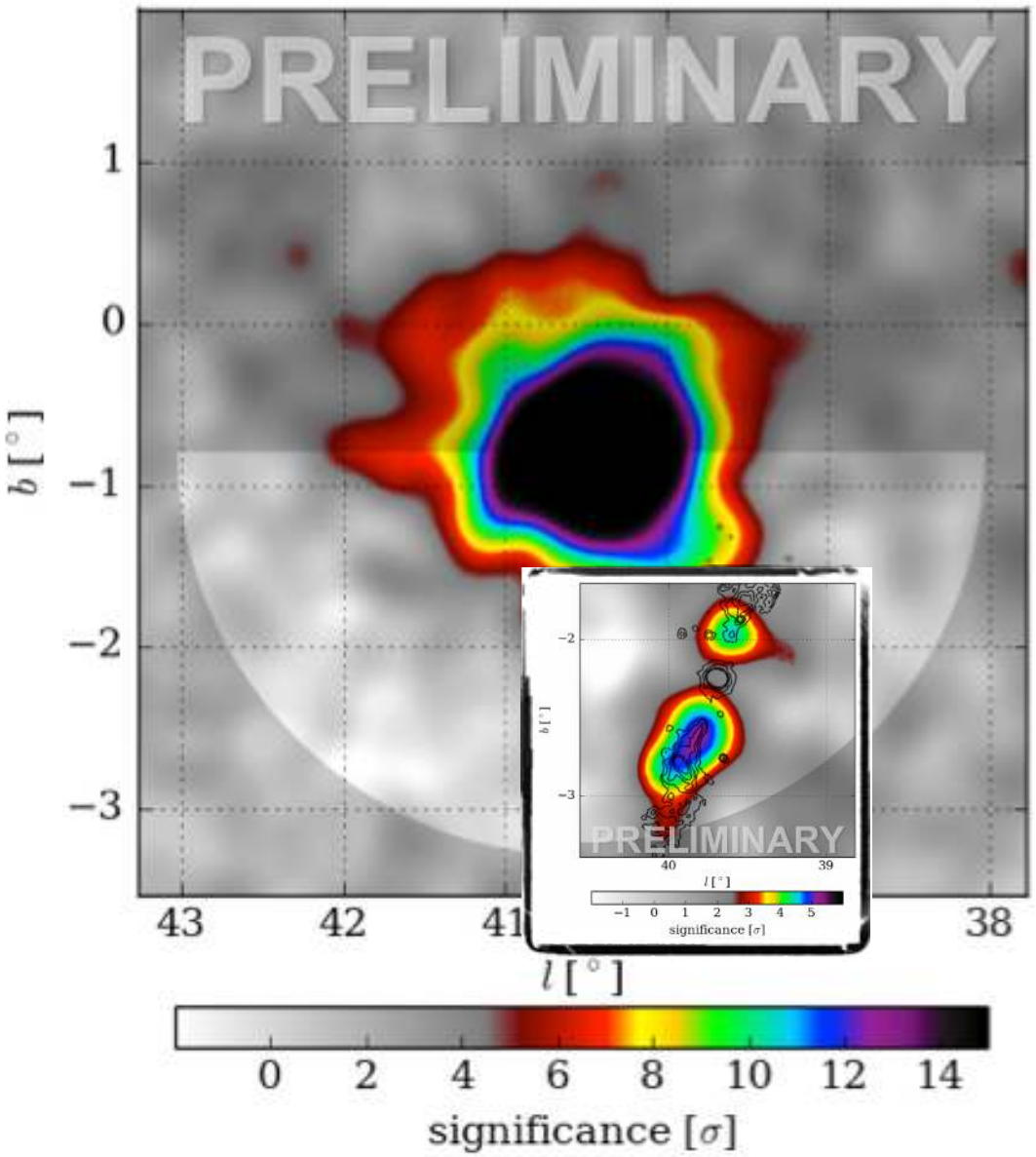

A
Geminga
PSR B0656+14
23
18
13
Dec. [deg]
109
104
99
R.A. [deg]
−4 −3 −2 −1 0 1 2 3 4 5
Significance [sigmas]

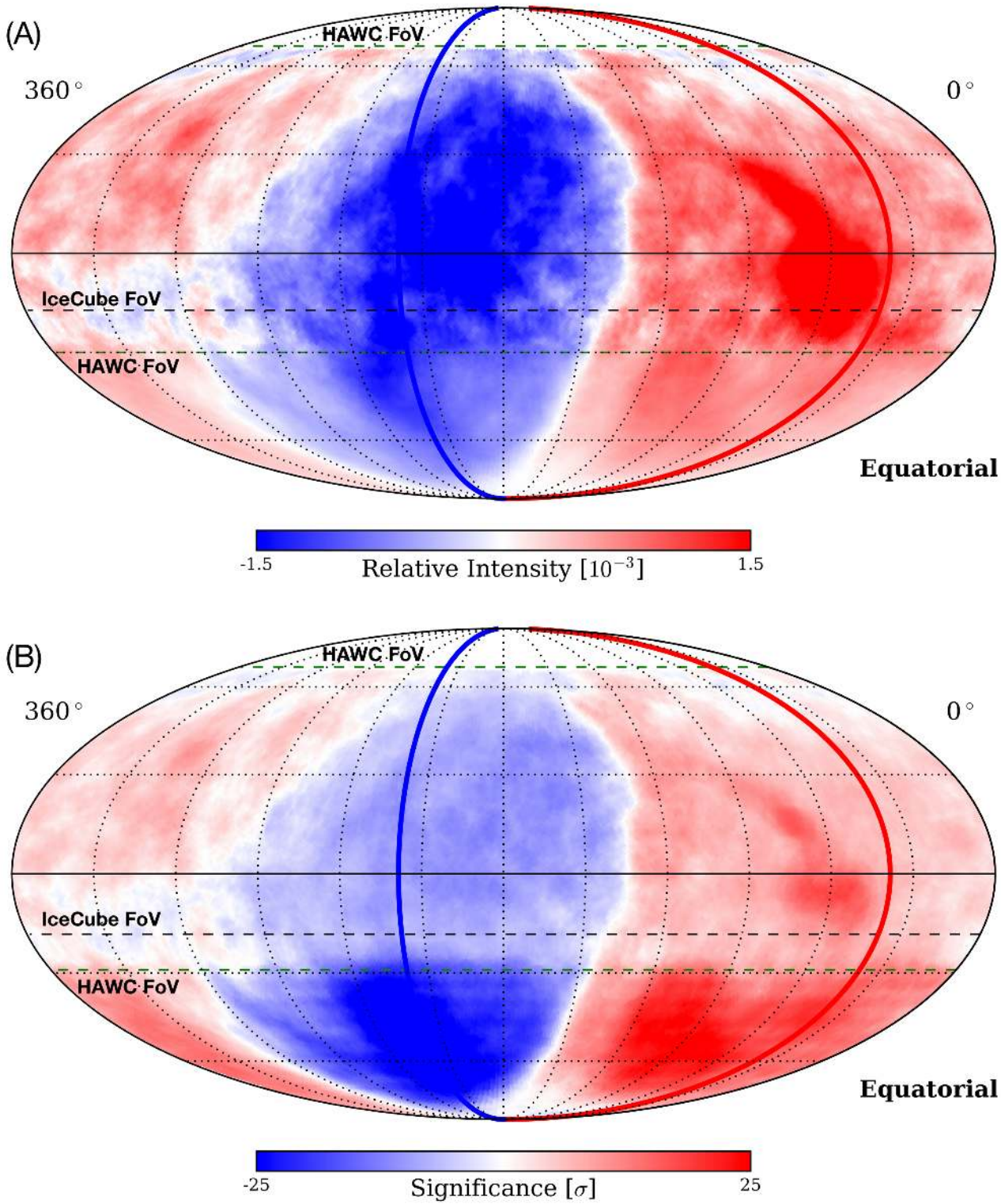

Geminga
PSR B0656+14
23
18
13
Dec. [deg]
109
104
99
R.A. [deg]
−2 0 2 4 6 8 10 12
significance [sigmas]

Abeysekara *et al* [HAWC] Nature **562** (2018), 82-85

VHE emission from the jets of a microquasar

SS 443

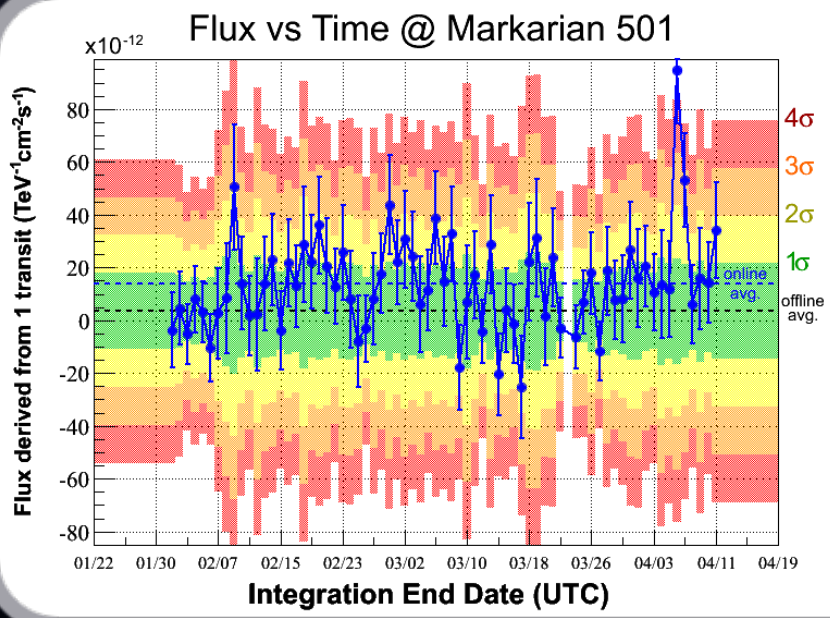



(A)
HAWC FoV
360°
0°
IceCube FoV
HAWC FoV
Equatorial
-1.5
Relative Intensity [10^{-3}]
1.5
(B)
HAWC FoV
360°
0°
IceCube FoV
HAWC FoV
Equatorial
-25
Significance [σ]
25


158007
51

AGN flares with HAWC

Markarian 501



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).

April 6, 2016

First TeV flare alert from HAWC!