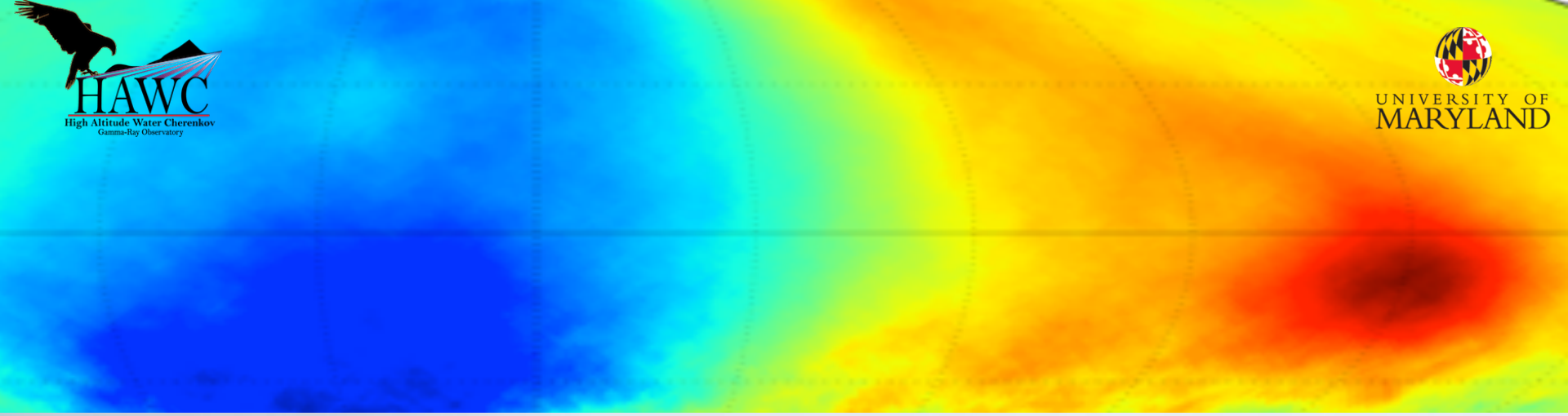


Measurements of Cosmic-Ray Anisotropy with the HAWC Observatory

Daniel Fiorino
Univ. Maryland – College Park
The HAWC Observatory

TeVPA 2016 – Geneva

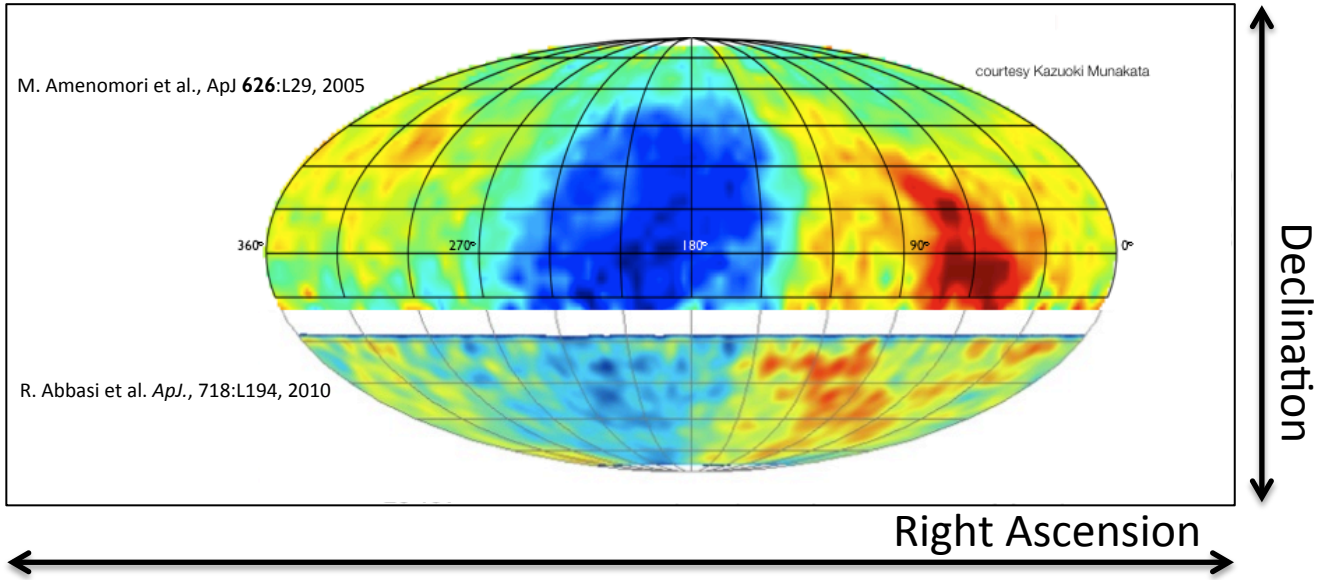
Outline

- <u>Introduction to TeV-PeV CR Anisotropy</u>
- Explanation of Detection Methods
- Experimental Results

Cosmic-Ray Anisotropy

- Cosmic rays < 10 PV are well confined within our Galaxy by ~ μG magnetic fields.

- A sidereal anisotropy at the 10^{-3} – 10^{-4} level has been observed by ground-based air shower detectors from 1 TeV to 1 PeV (reconstructed energy).



Anisotropy measure:

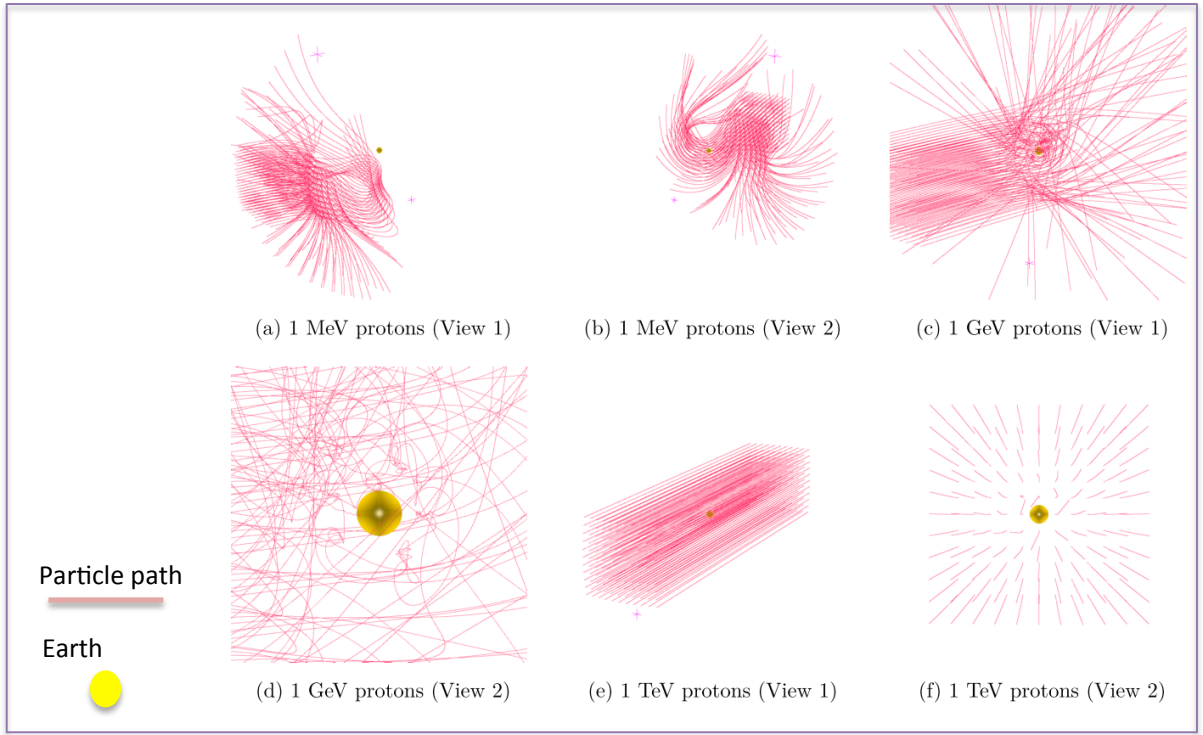
Relative intensity =
flux observed /
flux expected from isotropy

Differential relative intensity =
Relative intensity – 1

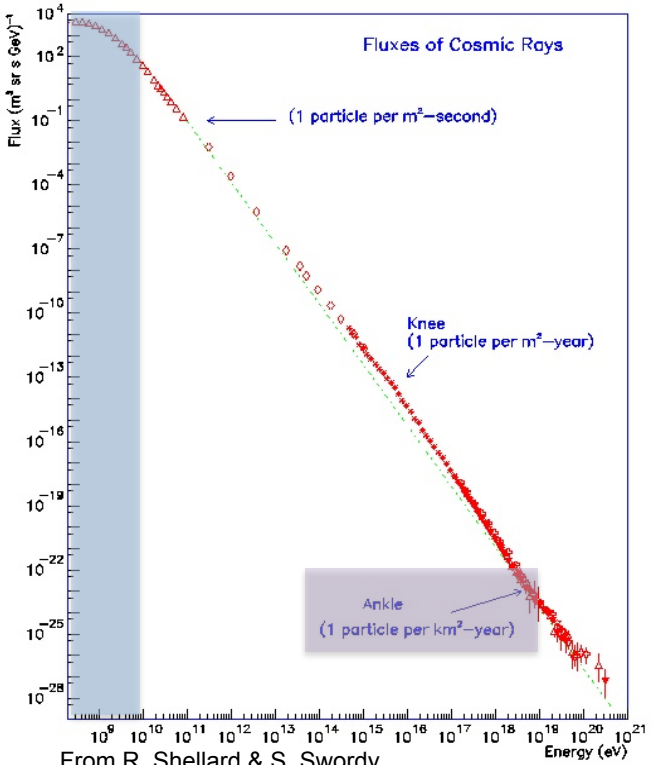
Why only at TeV-PeV?

< 10 GeV : Solar modulation of flux, Geomagnetic cutoff, Local and time-dependent

> 1 PeV : Particle flux ≈ 1 per m^2 per year, Extragalactic? Evidence, no discovery



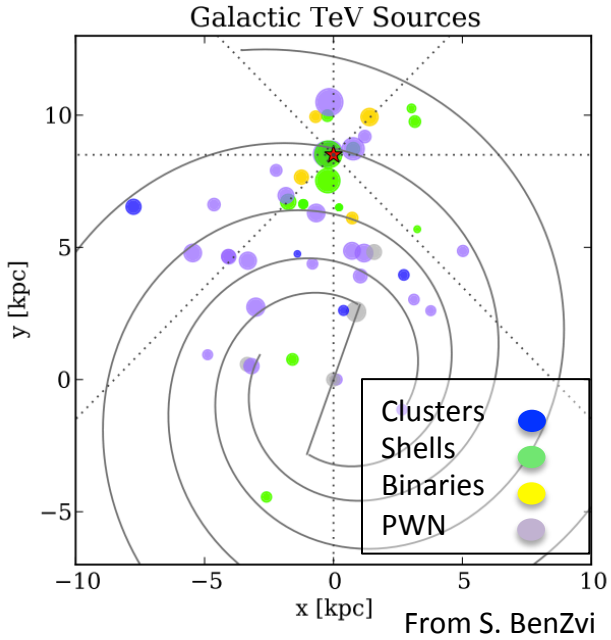
From J.M. Santander (2013 thesis)



From R. Shellard & S. Swordy

Producing Anisotropy

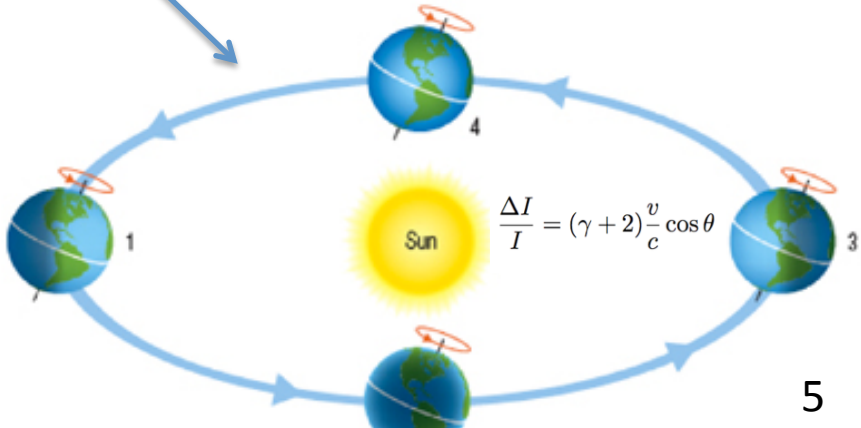
- Simple cosmic-ray gradient
  - inhomogeneous source distribution in our Galaxy and local magnetic fields.



From S. BenZvi

- Compton and Getting (1935)

  Motion through inertial frame of cosmic-ray gradient.
  - Maximum in direction of motion (pure dipole)
    - Cosmic rays are swept up by motion
    - Doppler shift pushes cosmic rays above/below E_{thresh}
  - Solar System around Galaxy
    - RA=315°, Dec 49°
    - Amplitude of 0.35%. NOT OBSERVED
  - Earth around Sun
    - Theta = 270° in Solar frame
    - Amplitude of 0.02%. OBSERVED



Outline

- Introduction to TeV-PeV CR Anisotropy
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Ground-based Mid-Latitude Air-shower Observatories

Path to anisotropy measurement:

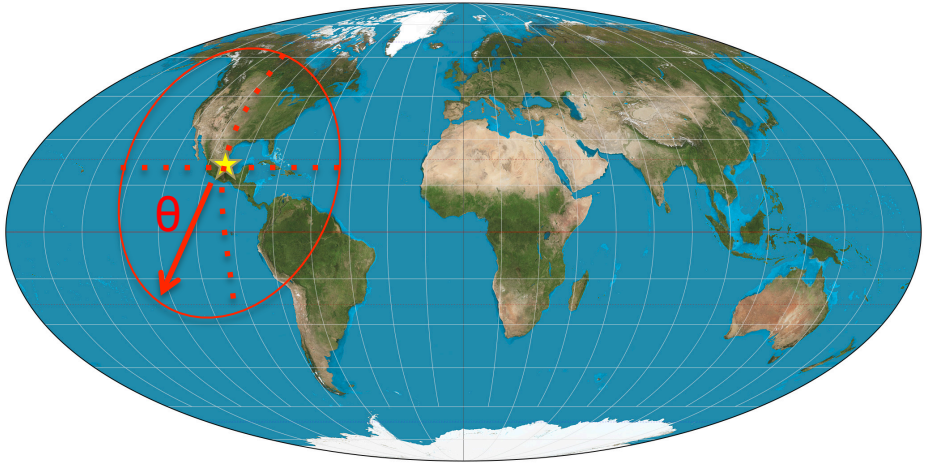
1 - Estimate detector response to isotropic flux
- Changing rate
- Changing signal contamination (constant in sidereal sky)
- Use 24-hour observing periods (for 10^{-4} precision)

2 - Interpret partial sky measurement

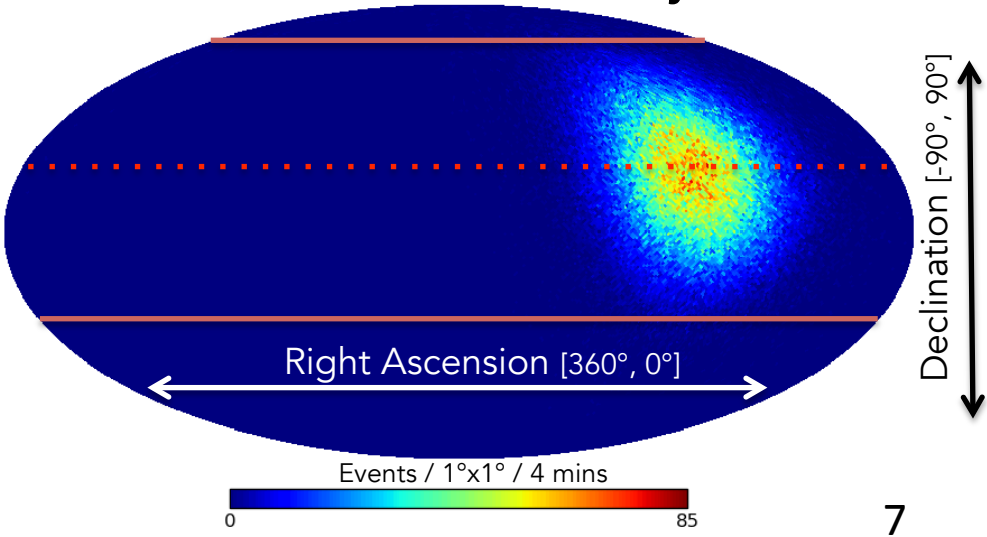
3 - Interpret partial signal sensitivity

- Sensitive to $\theta < 50°$ due to atmospheric attenuation & falling CR spectrum
- Scan the sky in Right Ascension along the line Declination = Latitude

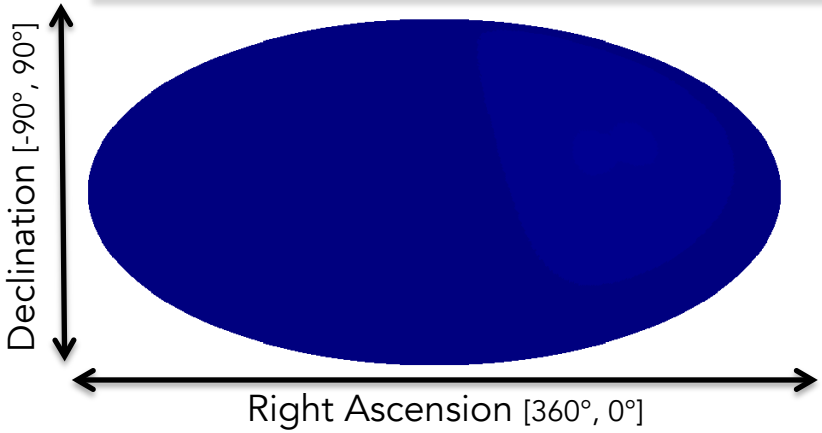
HAWC Local Sky



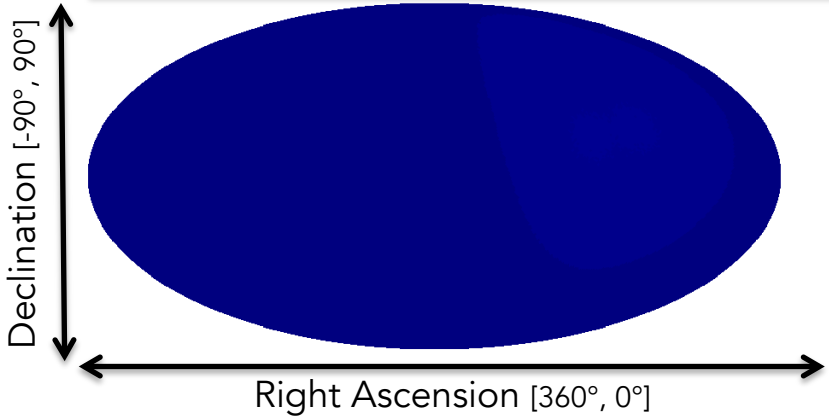
HAWC Sidereal Sky



Count map (in equatorial coordinates)



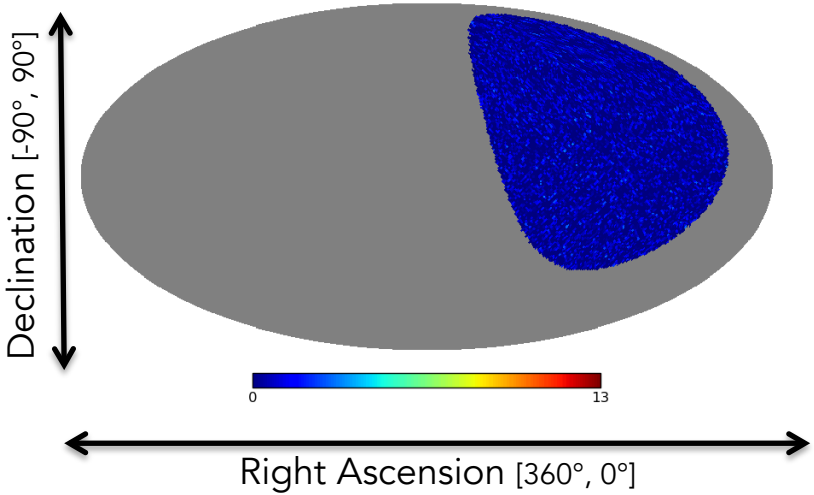
Expected count map (in equatorial coordinates)



Example:

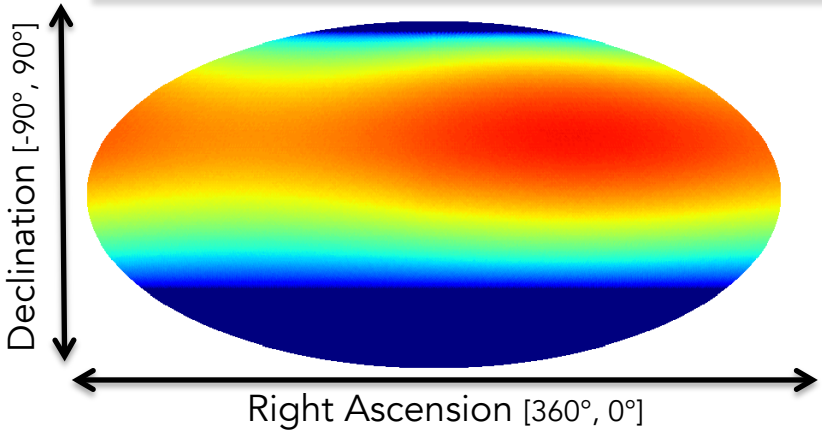
Right-Ascension Averaging
(Direct Integration)

Significance of the Excess (in equatorial coordinates)

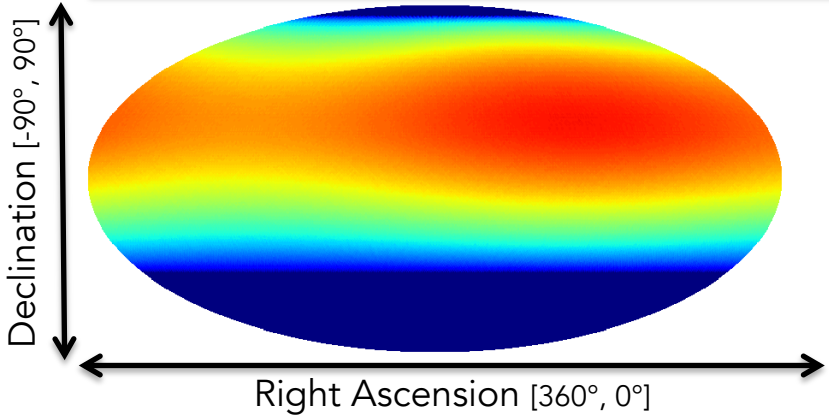


*For demonstration purposes only. Background found using a simplified, low resolution algorithm

Count map (in equatorial coordinates)



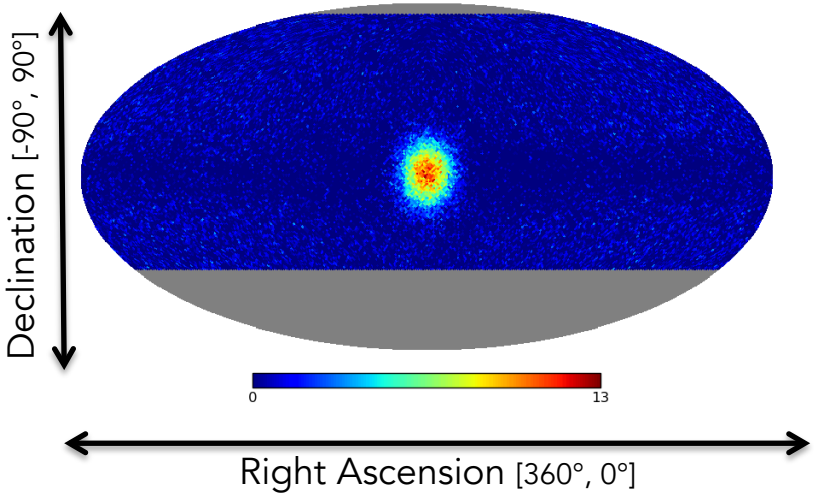
Expected count map (in equatorial coordinates)



Example:

Right-Ascension Averaging
(Direct Integration)

Significance of the Excess (in equatorial coordinates)

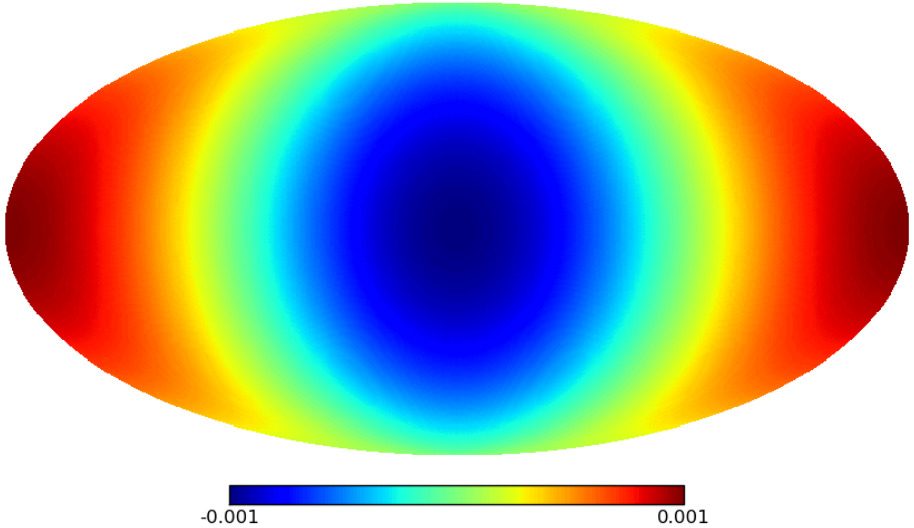


*For demonstration purposes only. Background found using a simplified, low resolution algorithm

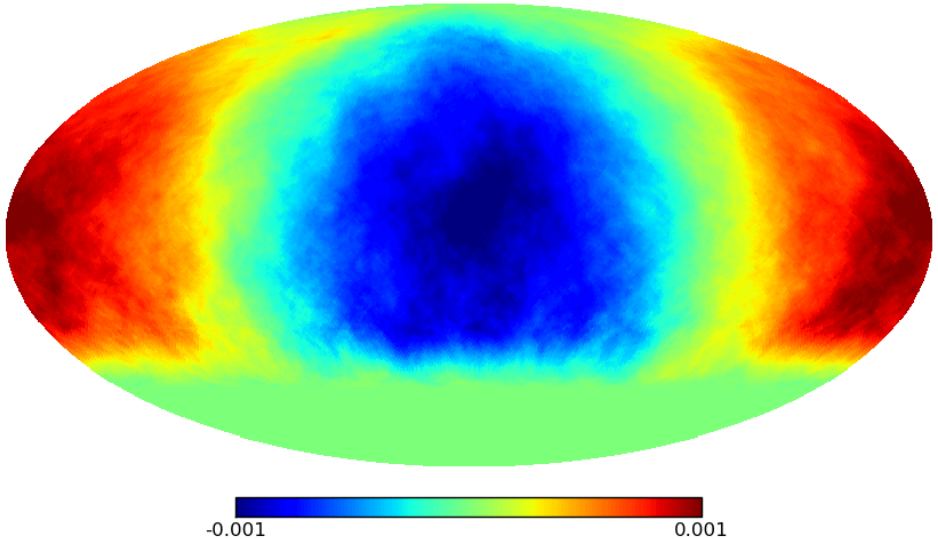
RA Projection effect

Right-Ascension Averaging is only sensitive to anisotropies along RA.
This affects all signals which extend in RA.

True injected signal



Observed signal

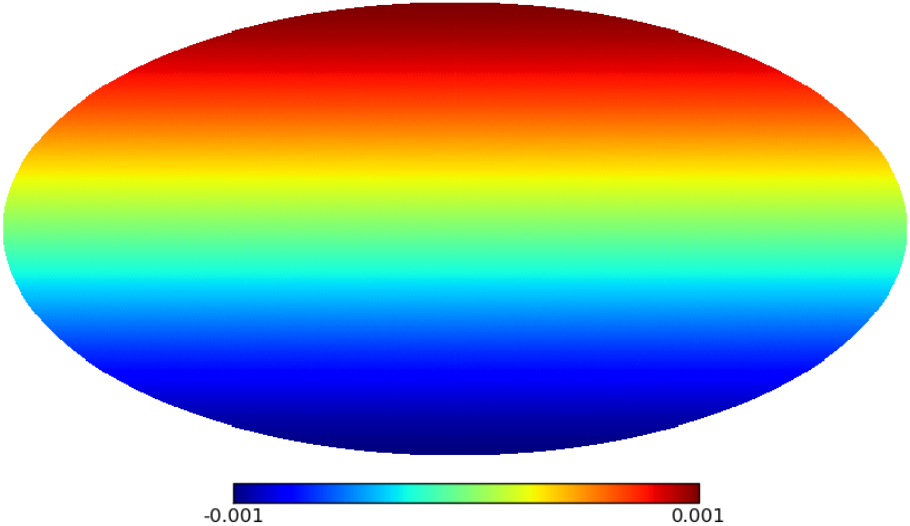


Differential Relative Intensity

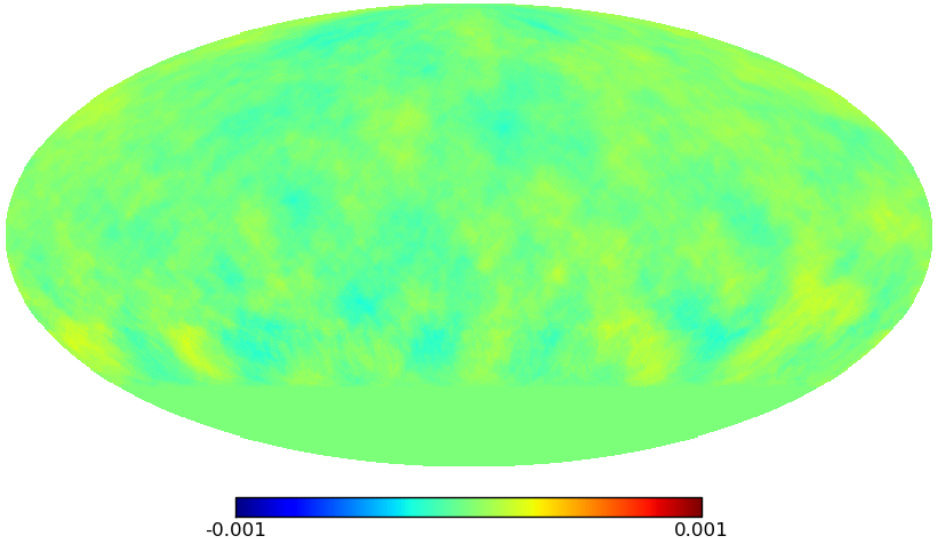
RA Projection effect

Right-Ascension Averaging is only sensitive to anisotropies along RA.
This affects all signals which extend in RA.

True injected signal



Observed signal



Differential Relative Intensity

Outline

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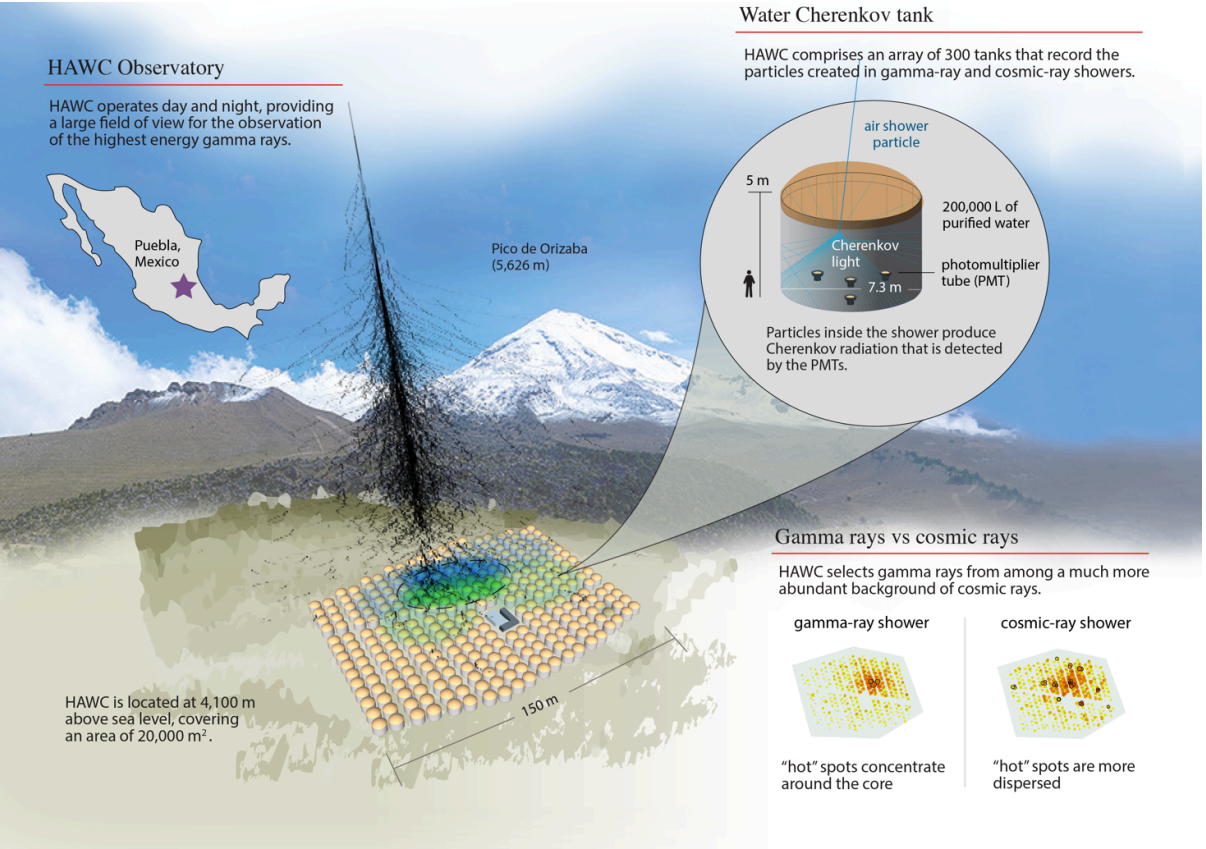
- Explanation of Detection Methods
- <u>Experimental Results</u>

The High Altitude Water Cherenkov Observatory



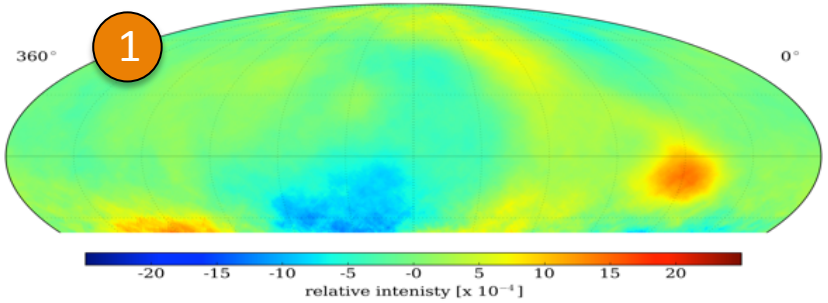
- Array of 300 large water-Cherenkov detectors (WCDs) at high altitude observing extensive cosmic-ray air showers

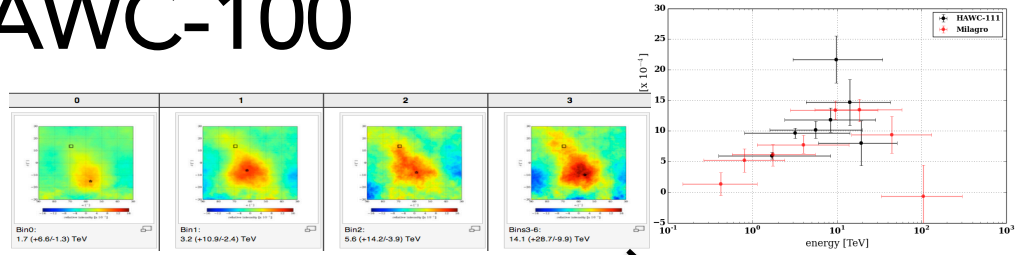
- Partial operation
  2012 to 2013, 30 WCDs
  2013 to 2015, 100 WCDs

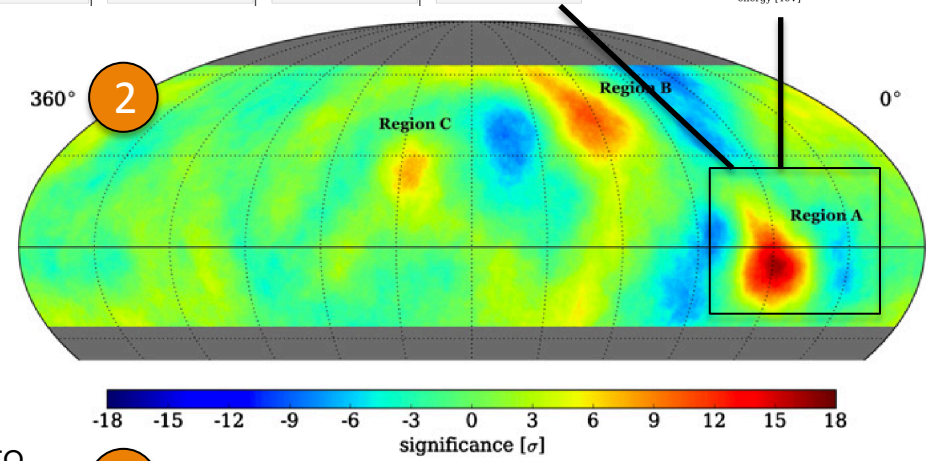
- Full operation
  since March 2015
  1 trillion event triggers

For gamma-ray summary
See T.Weisgarber talk

Previous Results – HAWC-100





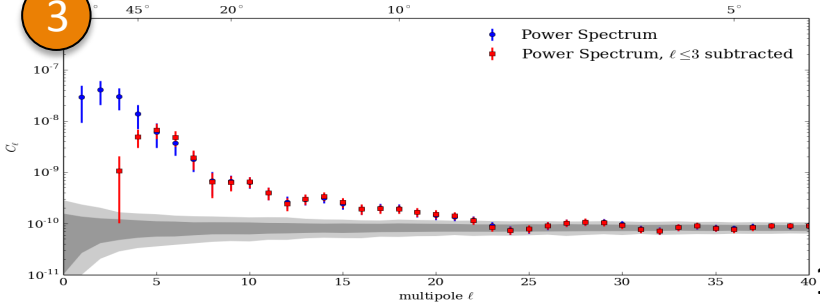


HAWC-100 anisotropy paper (ApJ) reported only small-scale (≤ 60°) features. arXiv:1408.4805

1. Started with map sensitive to features ≤ HAWC Field-of-view.

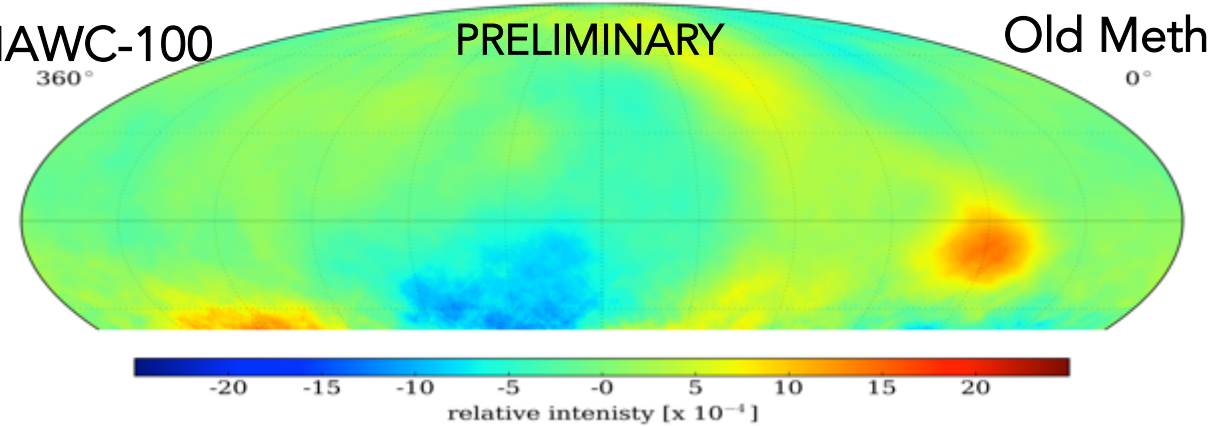
2. Subtracted dipole/octupole/quadrupole moments to remove any angular power from large-scale (≤ 60°) anisotropy.

3. Observed 3 significant excesses.
   Region A: Harder than background
   Energy-dependent morphology



Improvement to Large-scale Sensitivity

HAWC-100



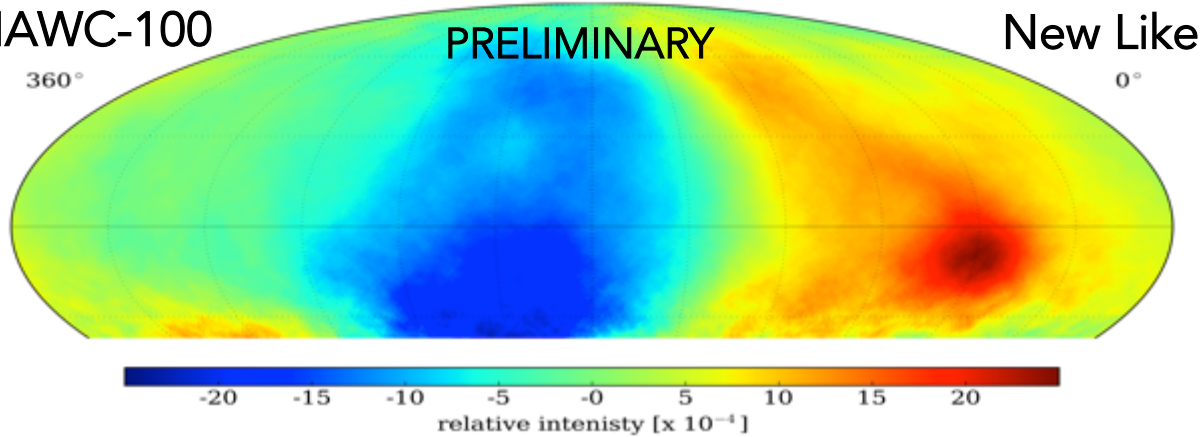
Old Method : Direct Integration

Standard method for HAWC

Sensitive only to features ≤ HAWC FOV
SNRs and AGN are OK

Ahlers, DF, et al. (2015) – arXiv:1601.07877
Improved upon this algorithm by iteratively correcting the all-sky rate for the influence of the large signals

HAWC-100



New Likelihood-based Method

Large-scale features are enhanced by over a factor of 2.

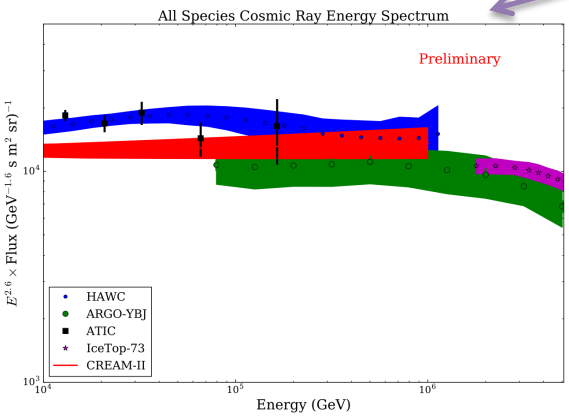
Low-moments become stronger because of correction to all-sky exposure as a function of sidereal time.

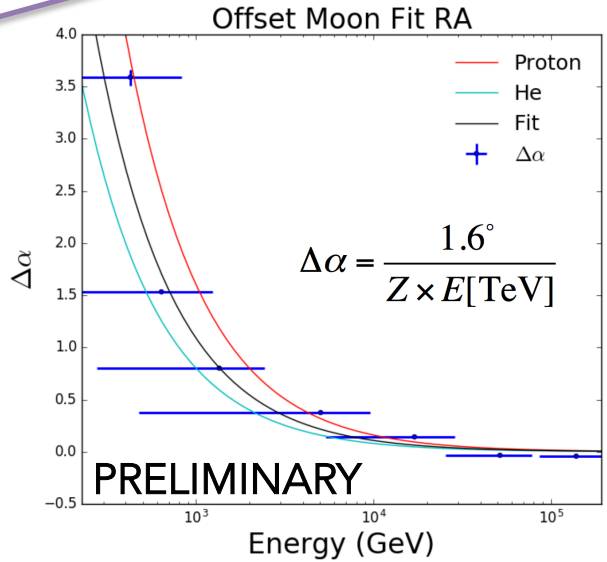
Improvement to CR Energy Estimation

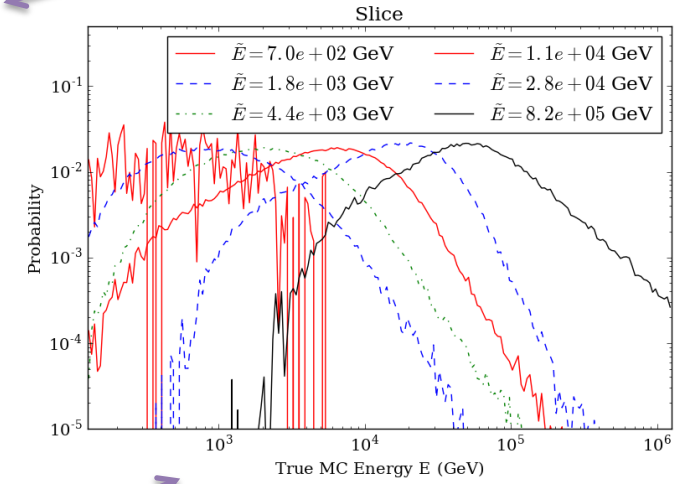
Z. Hampel (Wisconsin)

Simulation-based likelihood function of detector observables and Bayesian unfolding

Verified by the cosmic-ray all-particle energy spectrum and Moon shadow deflection





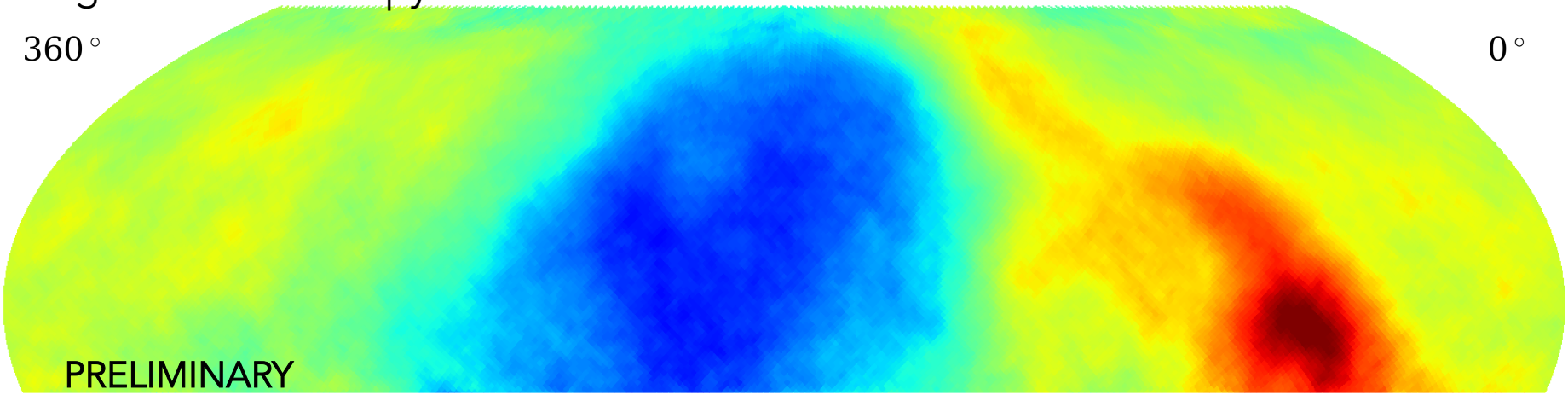


Used to create energy bins for cosmic-ray maps

HAWC

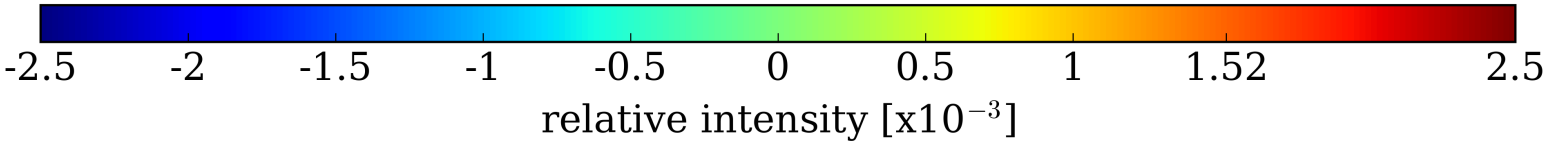
241 stable sidereal days, E_{med} = 6.7 TeV
Restrictive cuts for energy estimation (19×10^9 events)
Uneven coverage throughout the year (sys. err.)

Large-scale anisotropy



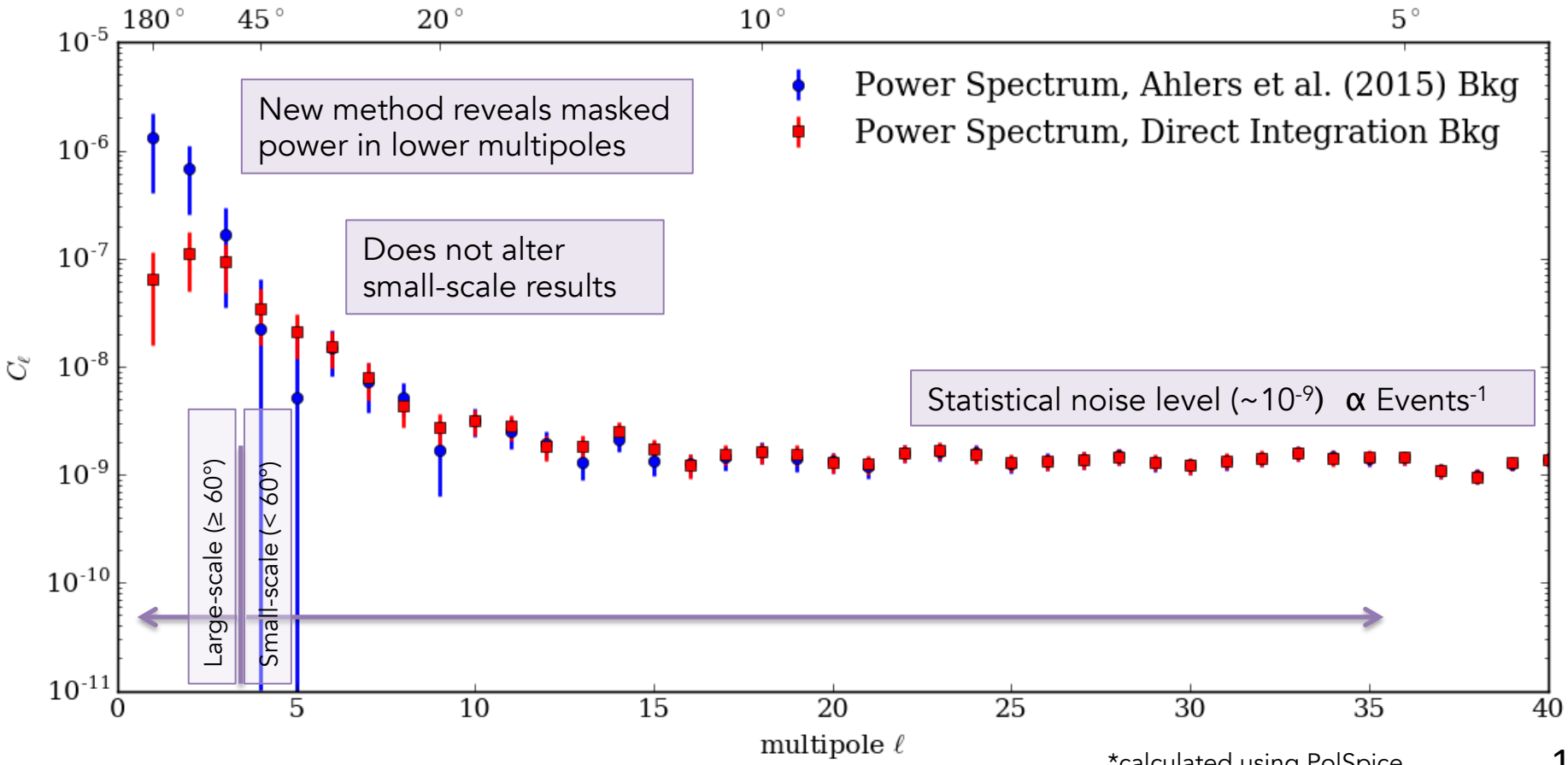
$A = (1.14 \pm 0.94) \times 10^{-3}$

Amplitude from dipole moment as part of multipole fit (large errorbars). Dipole-only usually reported.

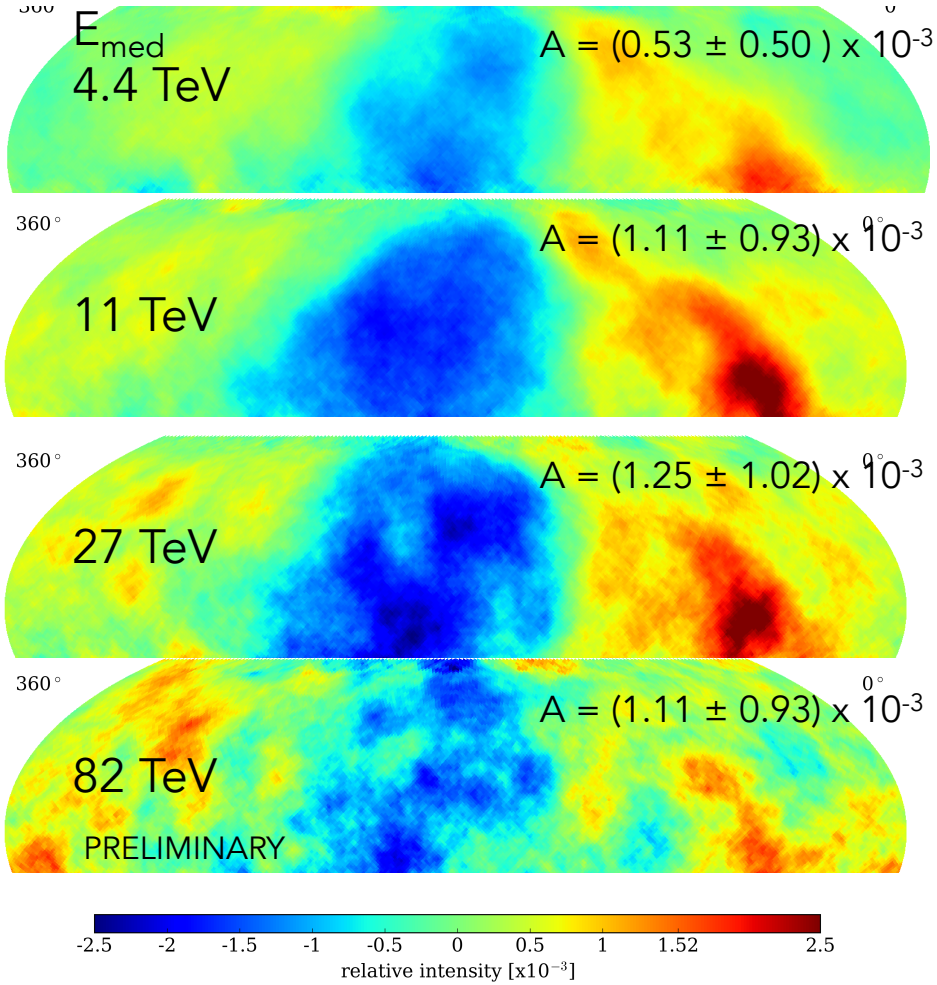


HAWC

Angular power spectrum with / without improved method



*calculated using PolSpice

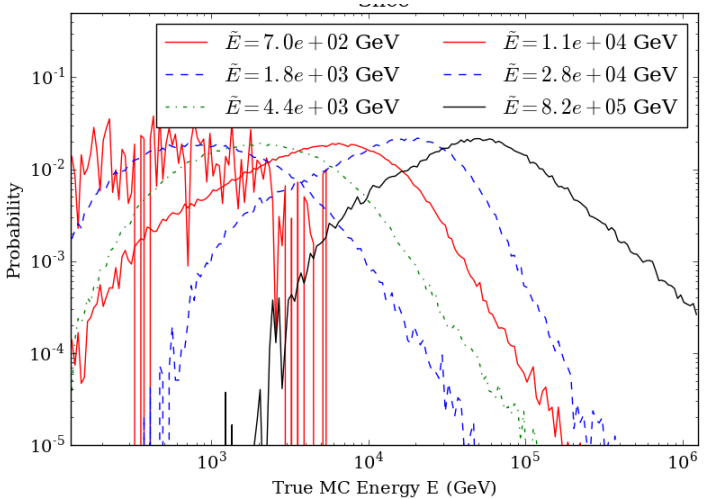


241 days of HAWC, 19 billion events
10° smoothing shown

Amplitudes from dipole moment as part of multipole fit (large errorbars). Dipole-only usually reported.

Solar/Geomagnetic effects E_{med}= 4 TeV

Fluctuations take over at E_{med} = 82 TeV



HAWC

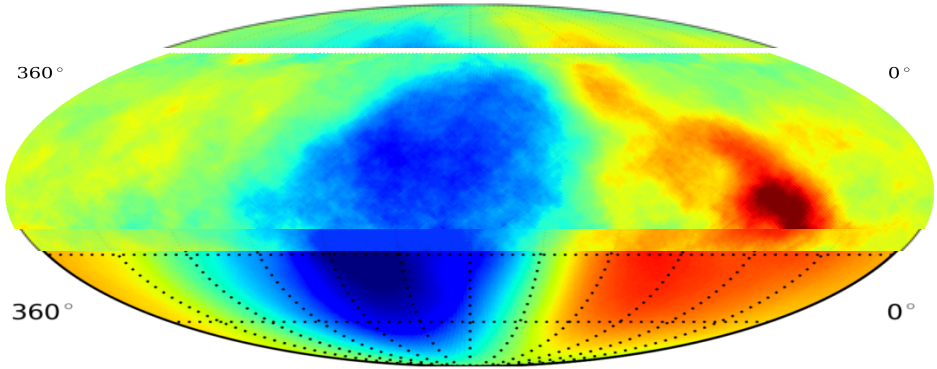
Consistent with previous experiments.

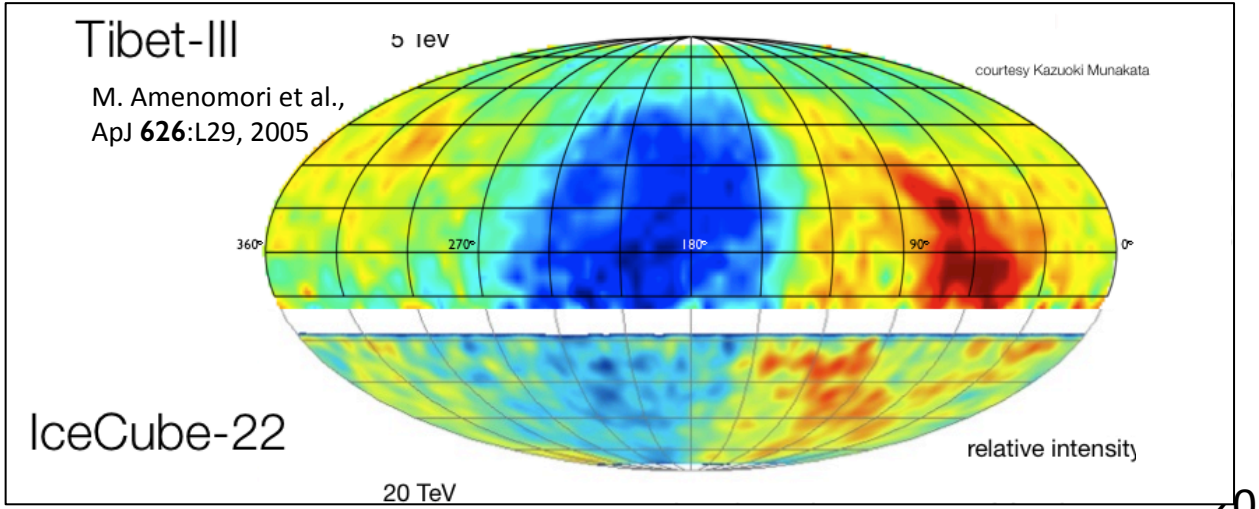
Small offset in HAWC data likely due to unaccounted seasonal effect from partial year coverage & Solar Compton-Getting anisotropy.

This will be corrected in future work.

HAWC
~ 11 TeV

IceCube
~13 TeV





- Observational biases affect interpretation of excess/deficit
    - RA projection effect
        Dipole orientation is not fully constrained
    - Partial sky causes degeneracy in large-scale moments
    - Partial years of data have Solar C-G effect
    - E ≤ 1 TeV: Amp. is affected by Solar activity

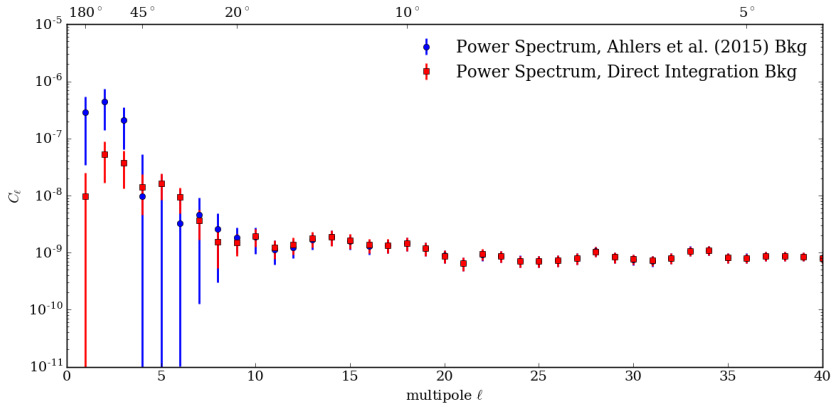
- HAWC has a large & still growing data set (1 billion day^{-1})
    - A new reconstruction method (Ahlers et al.)
    - A new cosmic-ray energy estimation method
    - Preliminary results agree well with previous

Ongoing work includes
- Joint studies of Northern/Southern – arXiv:1510.04134
    - Matching energy/rigidity responses
    - Tests agreement of small-scale anisotropy

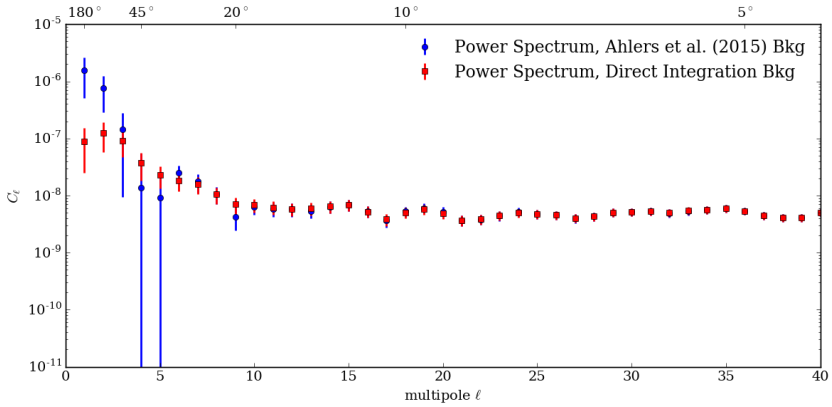
- Leptonic anisotropy search &
- Gamma-ray diffuse study
    - Both require understanding CR anisotropy

- Extending measurement to E ~ 100 TeV

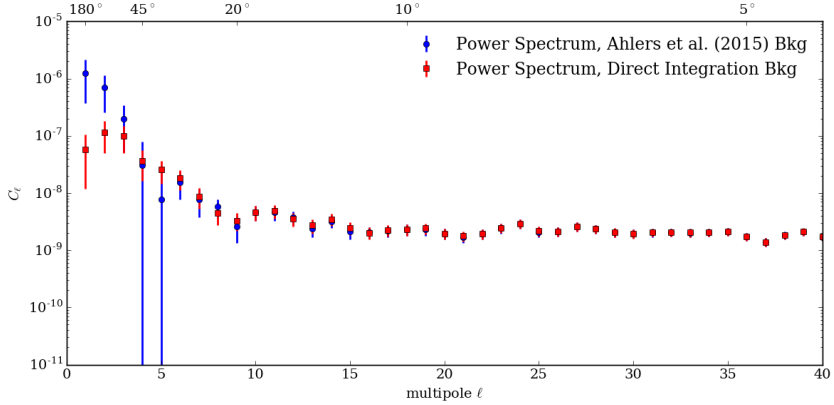
Bin 2



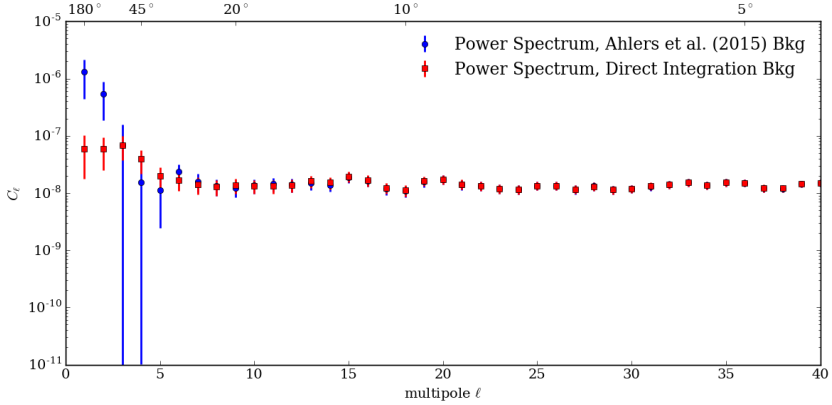
Bin 4



Bin 3

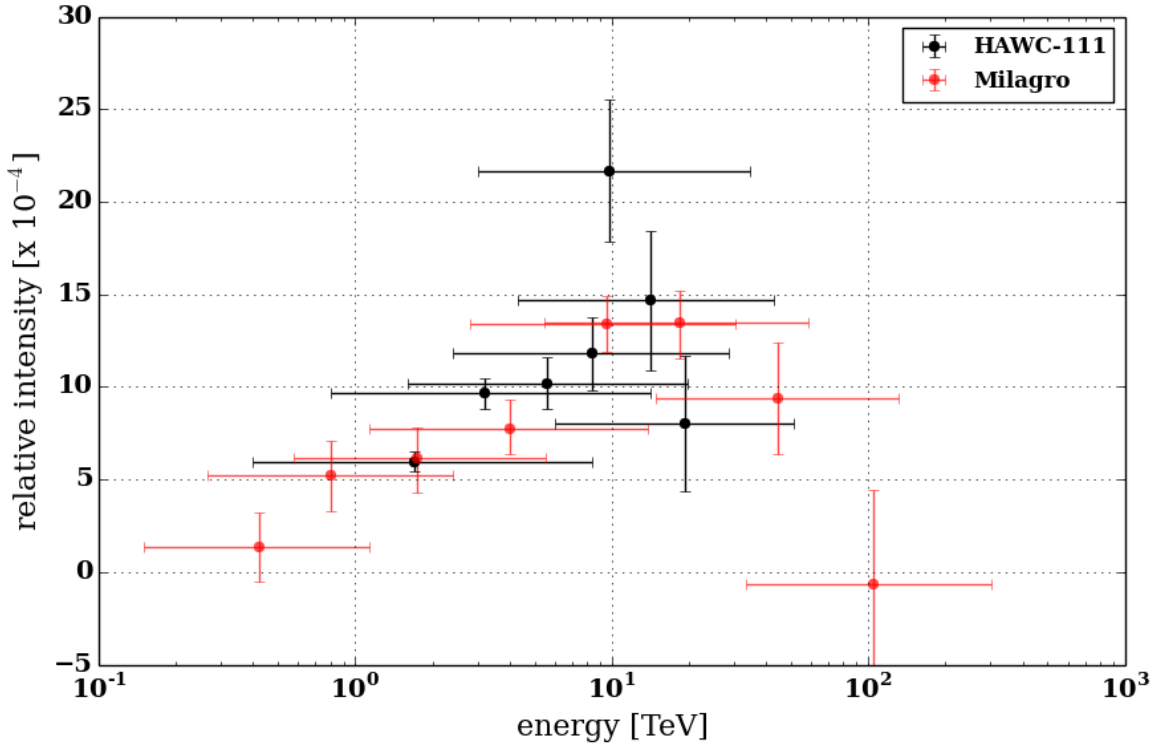


Bin 5



HAWC - Region A

- Relative intensity in 10° circle for 7 energy proxy bins
- Hard spectrum in Region A, compared to off-source regions:

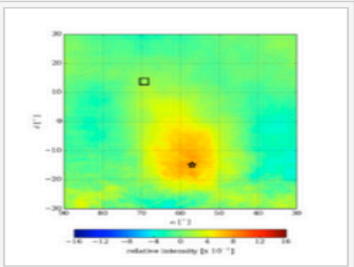
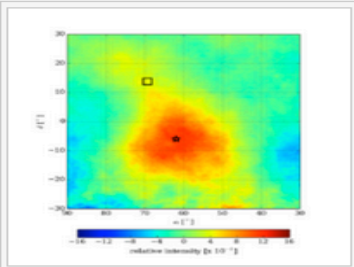
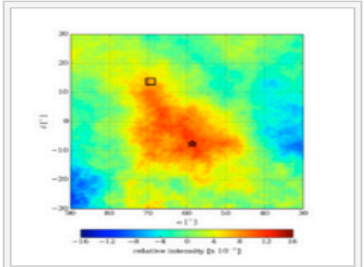
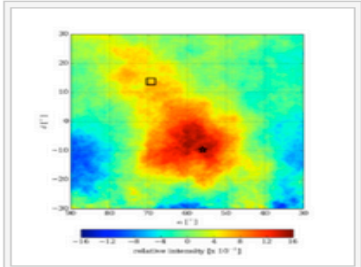
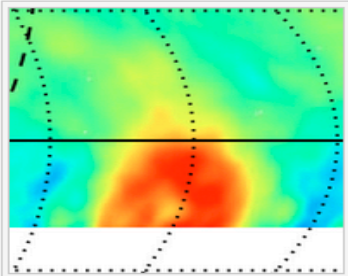
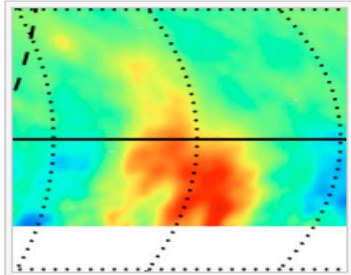
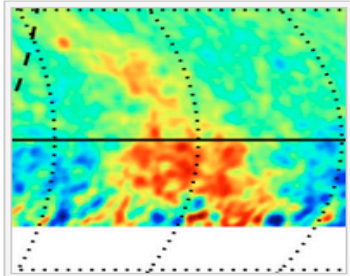
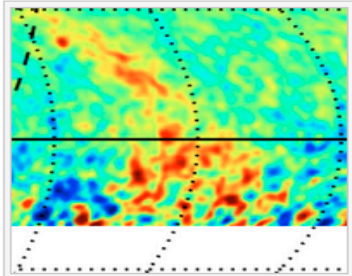


4.3 σ effect

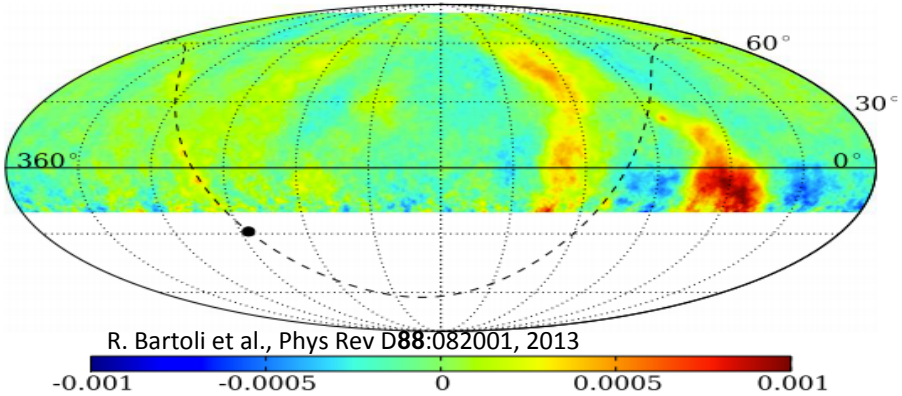
Proxy Bin	Median Energy (TeV)
1	1.7
2	3.2
3	5.6
4	8.4
5	9.8
6	14.1
7	19.2

Region A : Energy Dependence

HAWC–ARGO Comparison

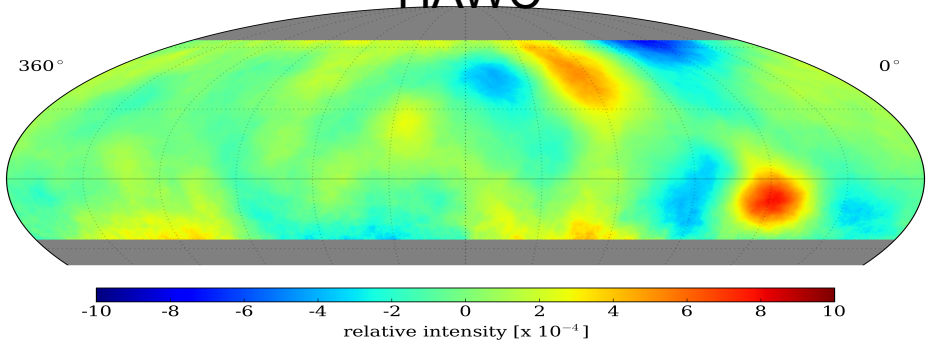
	0	1	2	3
HAWC	 Bin0: 1.7 (+6.6/-1.3) TeV Milagro Hotspot (square) HAWC Hotspot (star)	 Bin1: 3.2 (+10.9/-2.4) TeV Milagro Hotspot (square) HAWC Hotspot (star)	 Bin2: 5.6 (+14.2/-3.9) TeV Milagro Hotspot (square) HAWC Hotspot (star)	 Bins3-6: 14.1 (+28.7/-9.9) TeV Milagro Hotspot (square) HAWC Hotspot (star)
ARGO	 Bin0: 25-39 hits ≈ 0.66 TeV	 Bin1: 40-99 hits ≈ 1.4 TeV	 Bin2: 100-249 hits ≈ 3.5 TeV	 Bin3: 250-629 hits ≈ 7.3 TeV

ARGO

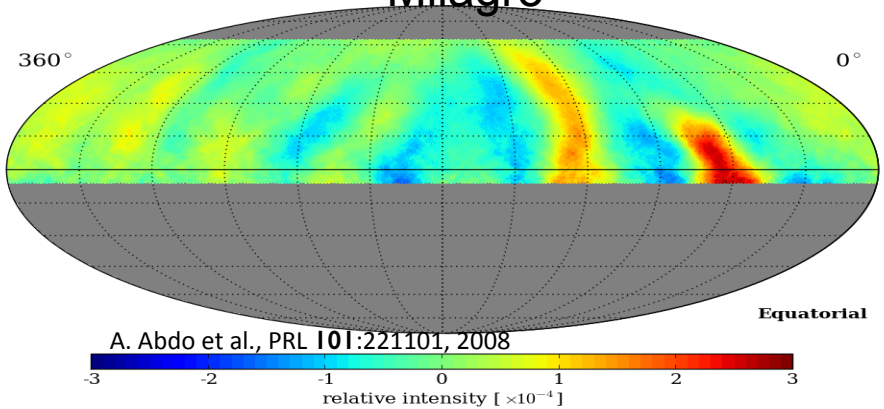


R. Bartoli et al., Phys Rev D**88**:082001, 2013

HAWC

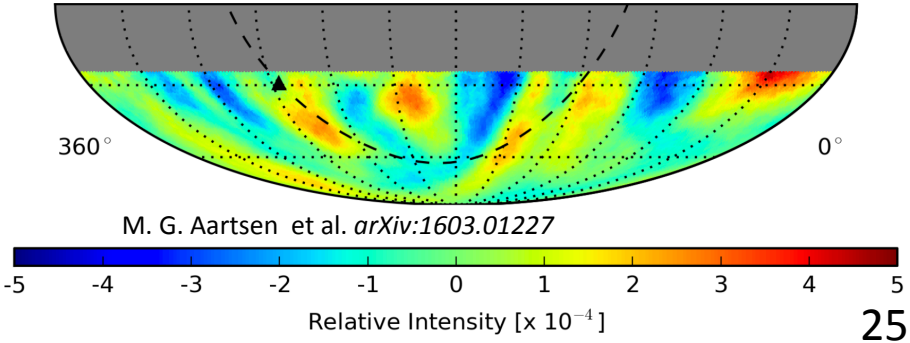


Milagro



A. Abdo et al., PRL **101**:221101, 2008

IceCube

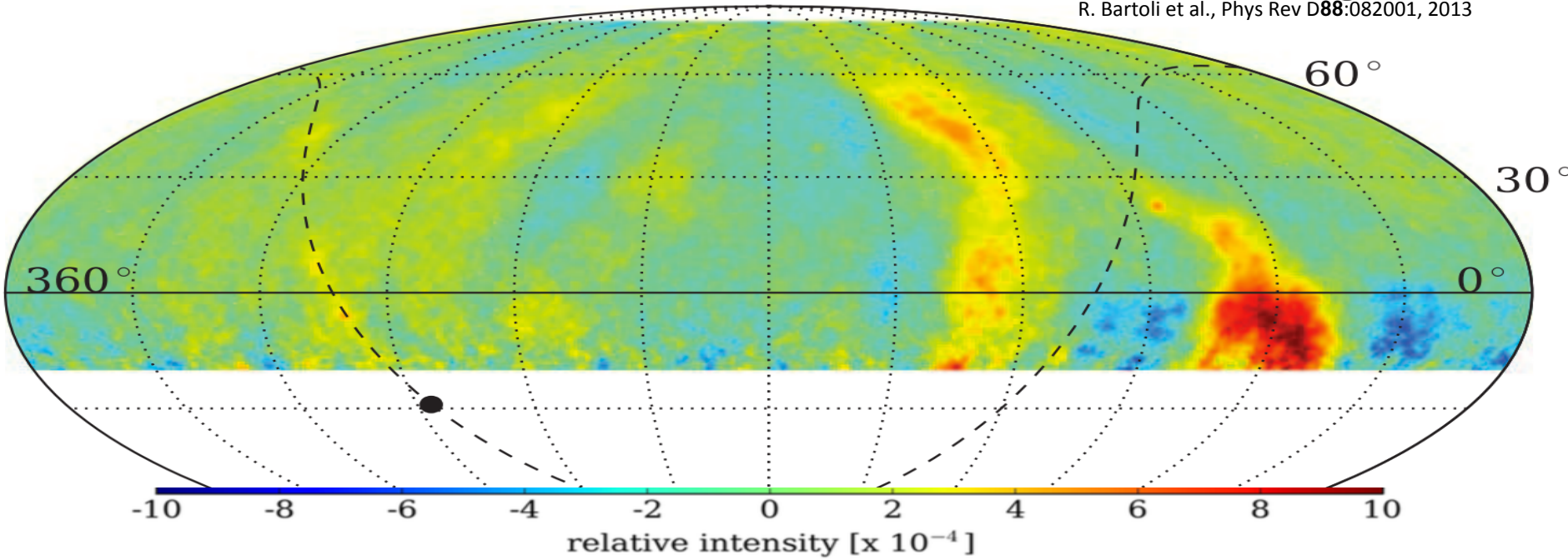


M. G. Aartsen et al. *arXiv:1603.01227*

Comparing Previous Results

ARGO-YBJ to HAWC (same smoothing)

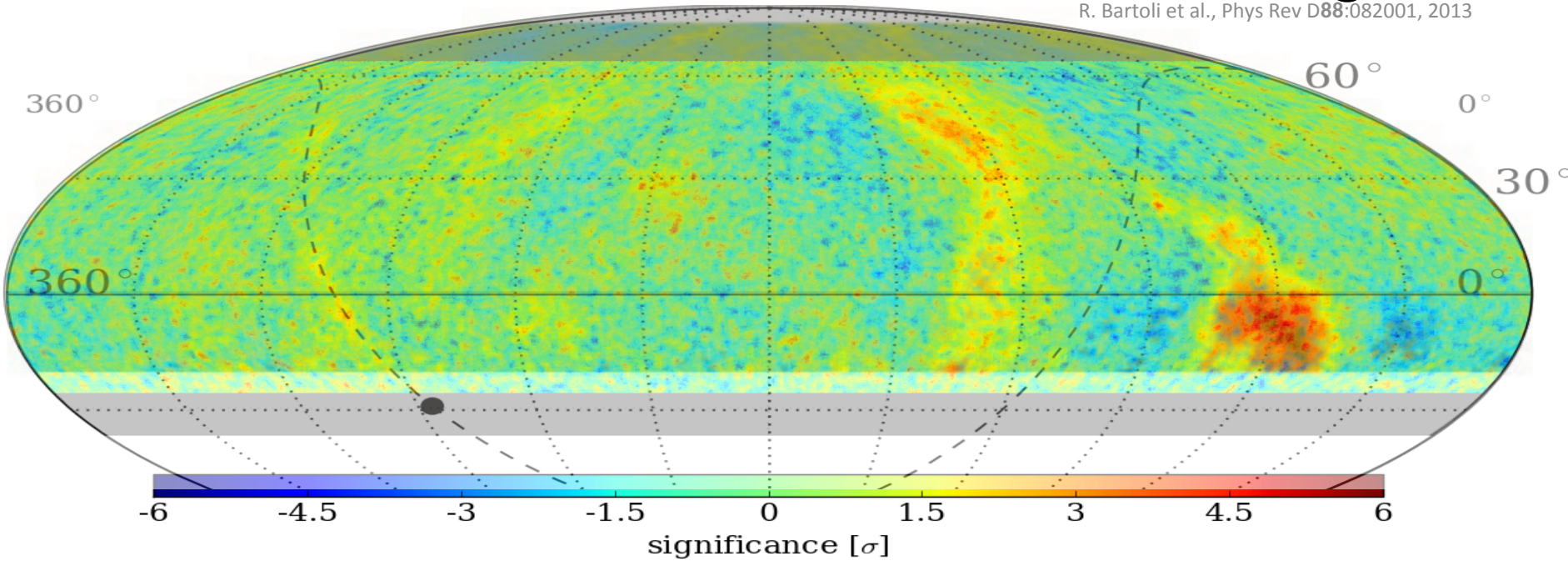
R. Bartoli et al., Phys Rev D**88**:082001, 2013



Comparing Previous Results

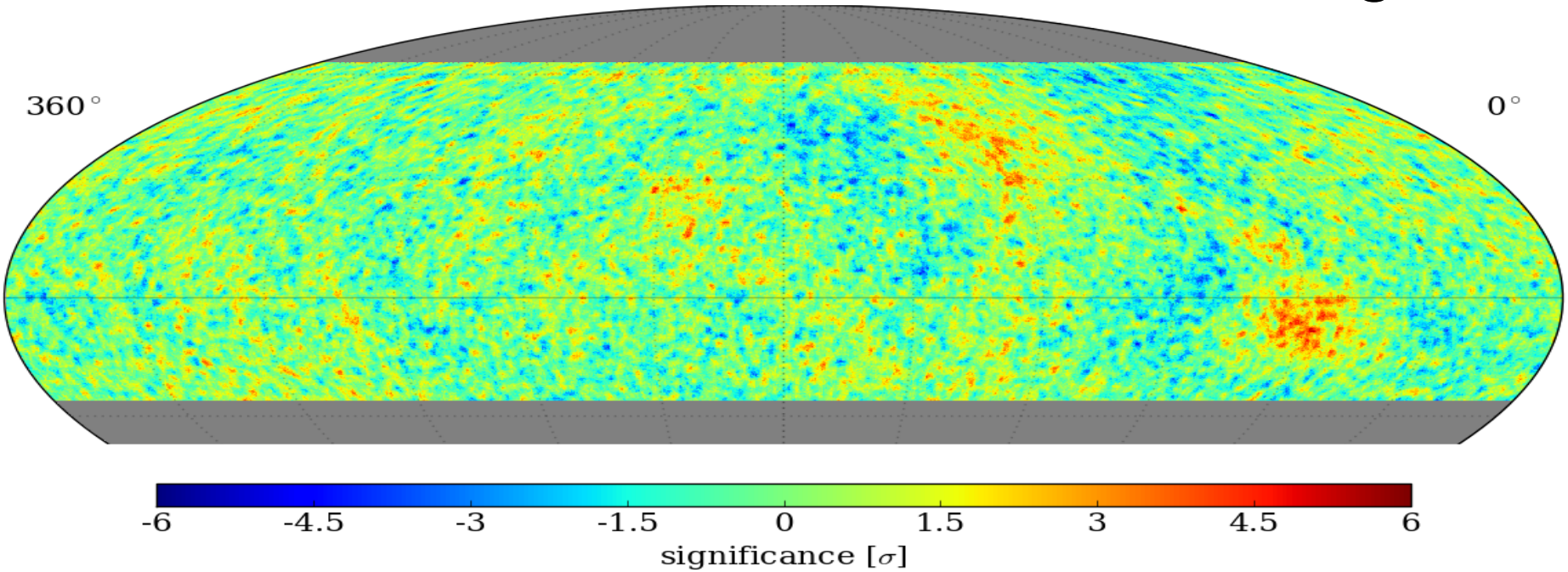
ARGO-YBJ to HAWC (same smoothing)

R. Bartoli et al., Phys Rev D88:082001, 2013

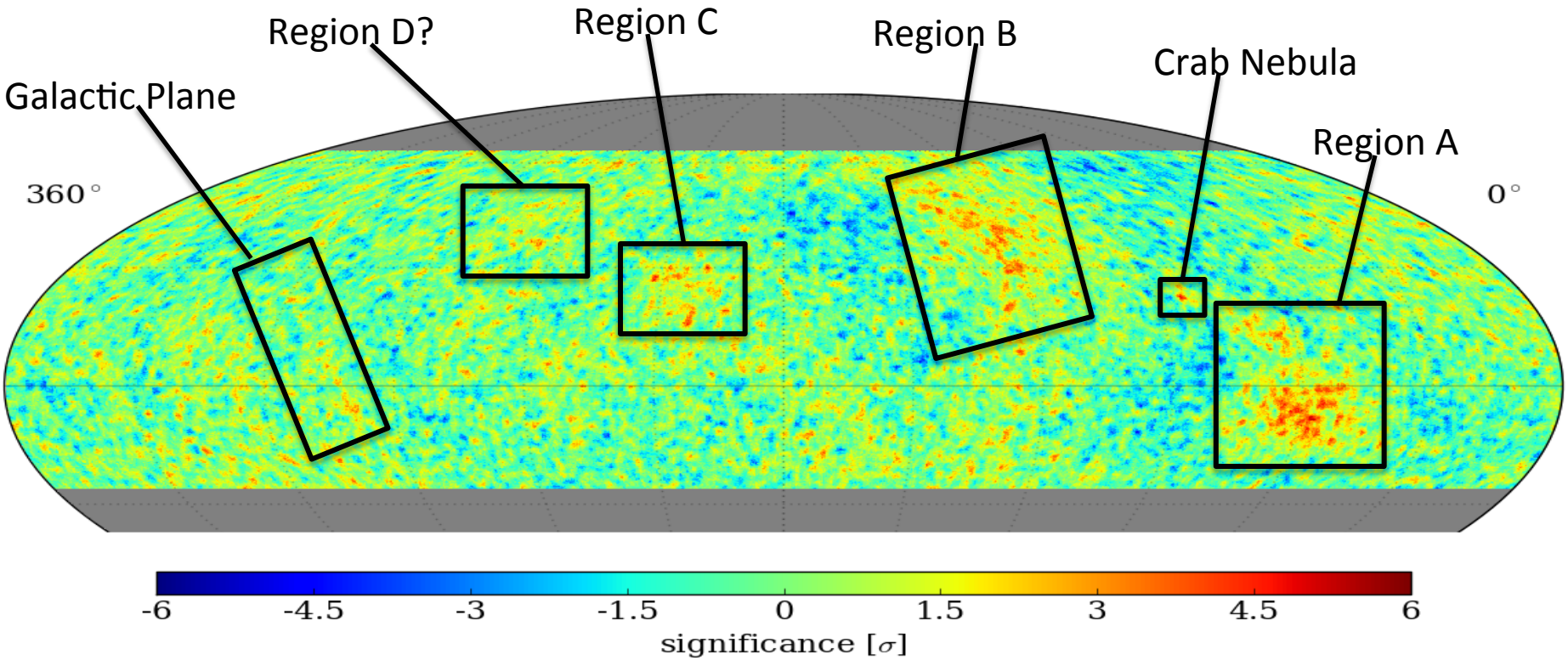


Comparing Previous Results

ARGO-YBJ to HAWC (same smoothing)



HAWC Smoothed by PSF



Comparing Small-scale Regions

Experiment	Region A	Region B	Region C (Region 4)	Region D (Region 3)
ARGO-YBJ	(57°, -10°) 10×10^{-4} 16σ	(125°, 45°) 5×10^{-4} 15σ	(208°, 29°) 1.6×10^{-4} 6σ	(240°, 45°) 2.3×10^{-4} 7σ
HAWC	(59°, -9°) 8.8×10^{-4} 21σ (pre)	(125°, 46°) 5.3×10^{-4} 16σ (pre)	(206°, 24°) 2.6×10^{-4} 11σ (pre)	
Milagro	(69°, 14°) 6×10^{-4} 15σ (pre)	(136°, 45°) 4×10^{-4} 13σ (pre)		