

# Cosmic Ray anisotropy with HAWC



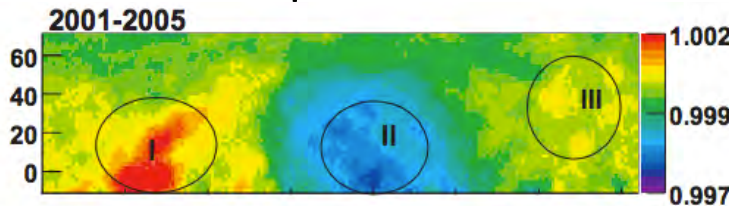
Ignacio Taboada  
Georgia Institute of Technology



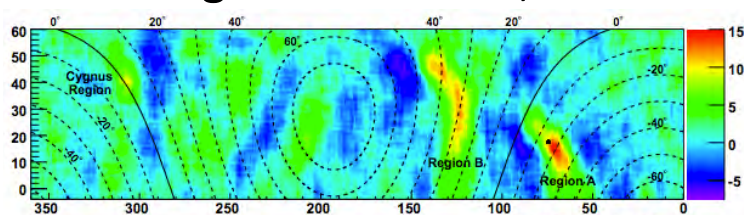
# Motivation

## Observations

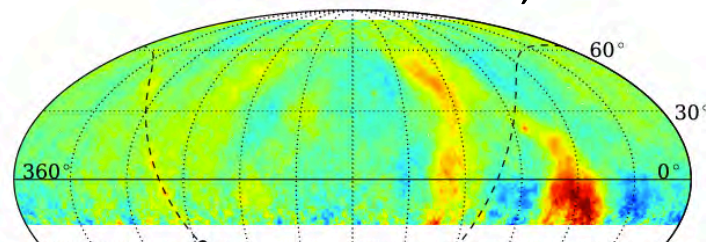
1 – Tibet-Asy 2005 (large only)



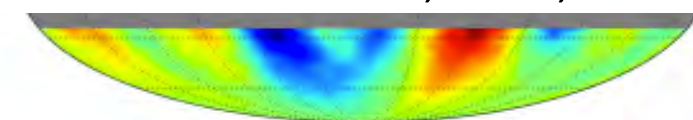
2 – Milagro 2008, 2009



3 – ARGO-YBJ 2009, 2013



4 – IceCube 2010, 2011, 2012



## Theory

Diffusive propagation of cosmic rays from supernova remnants in the Galactic environment

Anomalous Anisotropies of Cosmic Rays from Turbulent Magnetic Fields

WIPAC & D...

The pro...  
scribed as...  
isotropic...  
relative b...

Understanding TeV-band cosmic-ray anisotropy

Martin Pohl<sup>1,2</sup>, David Eichler<sup>3</sup>

The Milagro anticenter hot spots: cosmic rays from the Geminga supernova?

Local Magnetic Turbulence and TeV-PeV Cosmic Ray Anisotropies

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In the energy range from  $\sim 10^{12}$  eV to  $\sim 10^{15}$  eV, the Galactic cosmic ray flux has anisotropies of 0.1%, and on scales between  $\approx 10^\circ$  and  $\approx 100^\circ$ . With a diffusion coefficient inferred from an approximation predicts a dipolar anisotropy on the scale of the ring length. We show how such anisotropies arise from the local concrete realization of the ring length. We show how such anisotropies arise from the local concrete realization of the ring length. We show how such anisotropies arise from the local concrete realization of the ring length.

The problem of small angular scale structure in the cosmic ray anisotropy data

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Global Anisotropies in TeV Cosmic Rays Related to the Sun's Local Galactic Environment from IBEX

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D. J. McComas<sup>2,9</sup>, F. Moebius<sup>3</sup>, G. P. Zank<sup>10</sup>

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<sup>7</sup>Science and

<sup>8</sup>Engines, Tucson

<sup>9</sup>of Alabama

<sup>10</sup>Univ. of

Cosmic Ray Anisotropy as Signature for the Transition from Galactic to Extragalactic Cosmic Rays

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ANISOTROPY OF TEV COSMIC RAYS AND THE OUTER HELIOSPHERIC BOUNDARIES

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Draft version October 30, 2012

ABSTRACT

Cosmic-ray diffusion in collisionless plasmas including pressure anisotropy

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Abstract  
Using a hybrid kinetic magnetohydrodynamic formalism incorporating the effects of pressure anisotropy, we simulate the evolution of a turbulent collisionless plasma in six different models covering the sub/super-sonic and sub/super-Alfvénic regimes. Based on the power spectrum of the simulated magnetic field, we compute the particle diffusion coefficients for protons with kinetic energy in the 50 – 500 MeV range, and compare them to those obtained within standard magnetohydrodynamics. Our results show that the differences in the statistical properties of the magnetic field, generated by pressure anisotropy and its associated kinetic instabilities, have an appreciable impact on the diffusion coefficients of energetic protons. Moreover, the values of the diffusion coefficients that we obtain within each of the six models considered vary significantly.

Keywords: cosmic rays; diffusion; collisionless space plasma; pressure anisotropy

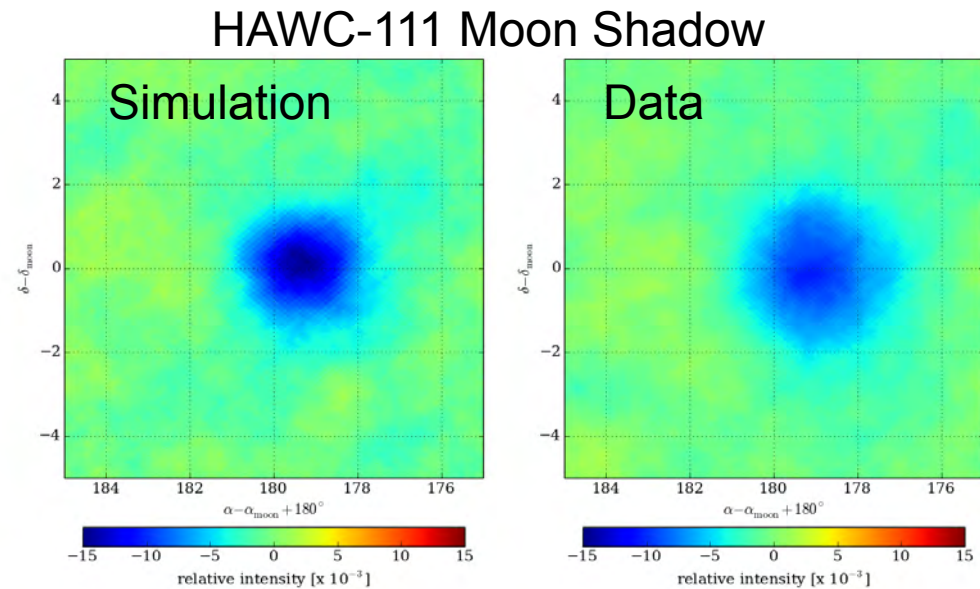
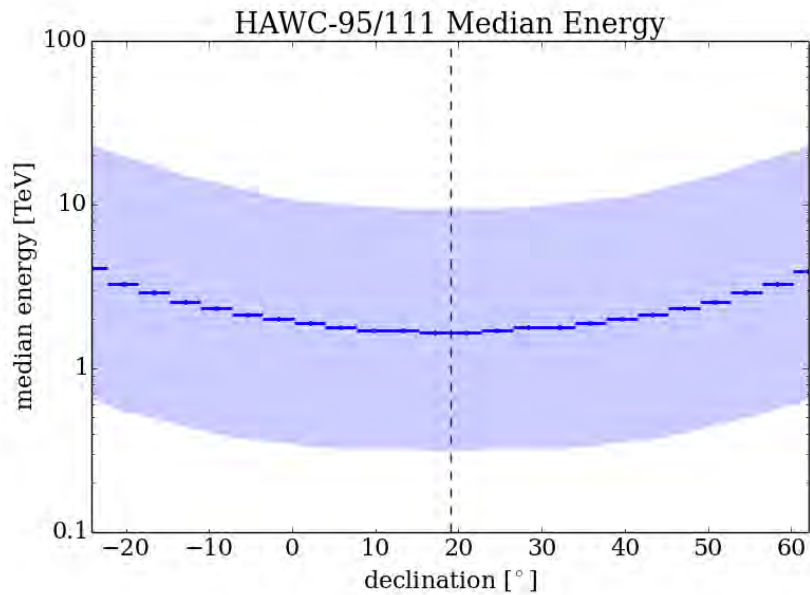
# Data Set

Using HAWC-95 and HAWC-111

June 2013 – February 2014

114 full sidereal days

50 billion events,  
1.2° median ang. res.,  
1.8 TeV median energy



# Analysis Technique

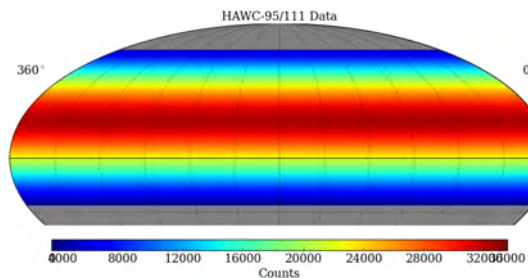
**HEALpix** (K.M. Gorski et al., *Astrophys. J.*, 2005, 622, 759)  
Equal-area binning of the sphere



**“Direct Integration”** (R. Atkins et al., *Astrophys. J.*, 2003, 595, 803.)  
Method to estimate background using the data themselves

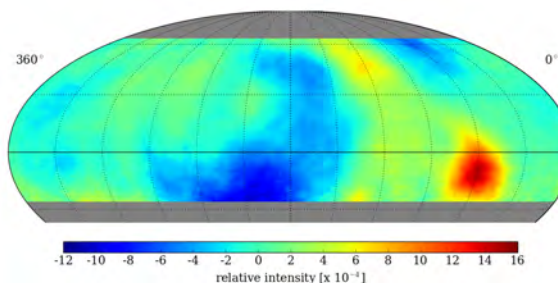
**PolSpice** (I. Szapudi et al. 2001, *Astrophys. J.*, 548, L115)  
Software to compute power spectrum with partial sky coverage

HEALpix



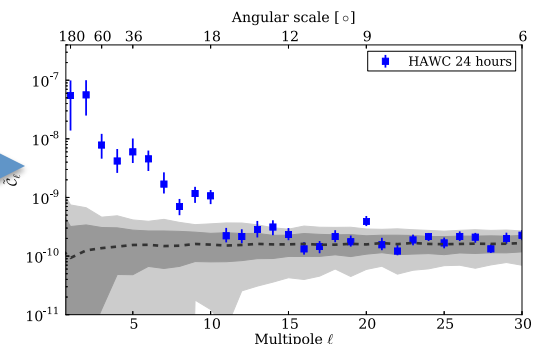
Binned data

“Direct integration”



Data & reference map  
→ relative intensity

PolSpice



Power Spectrum

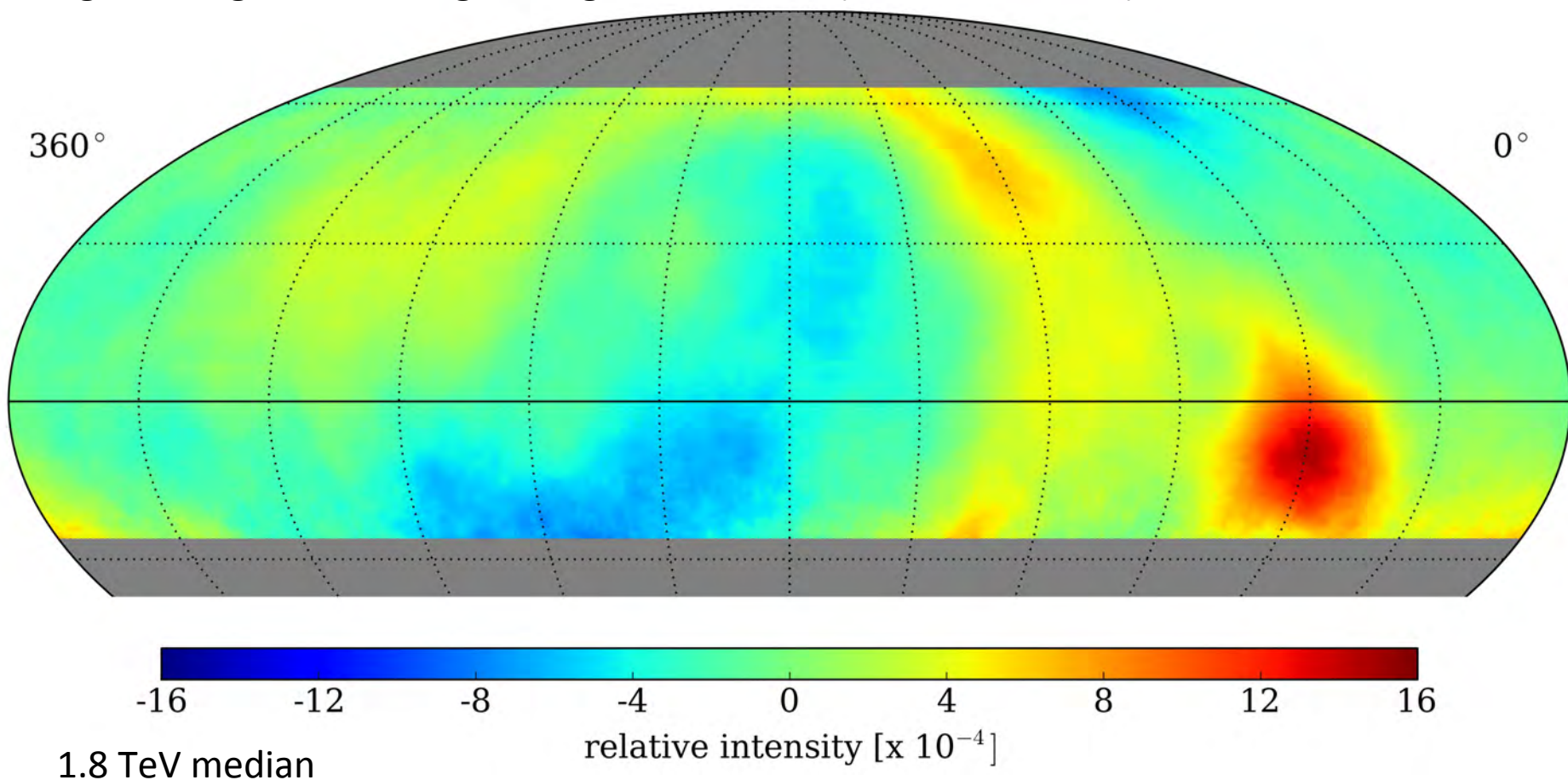
# Large Scale Anisotropy

Shows largest accessible features (24 hr background estimation)

Smoothed  $10^\circ$

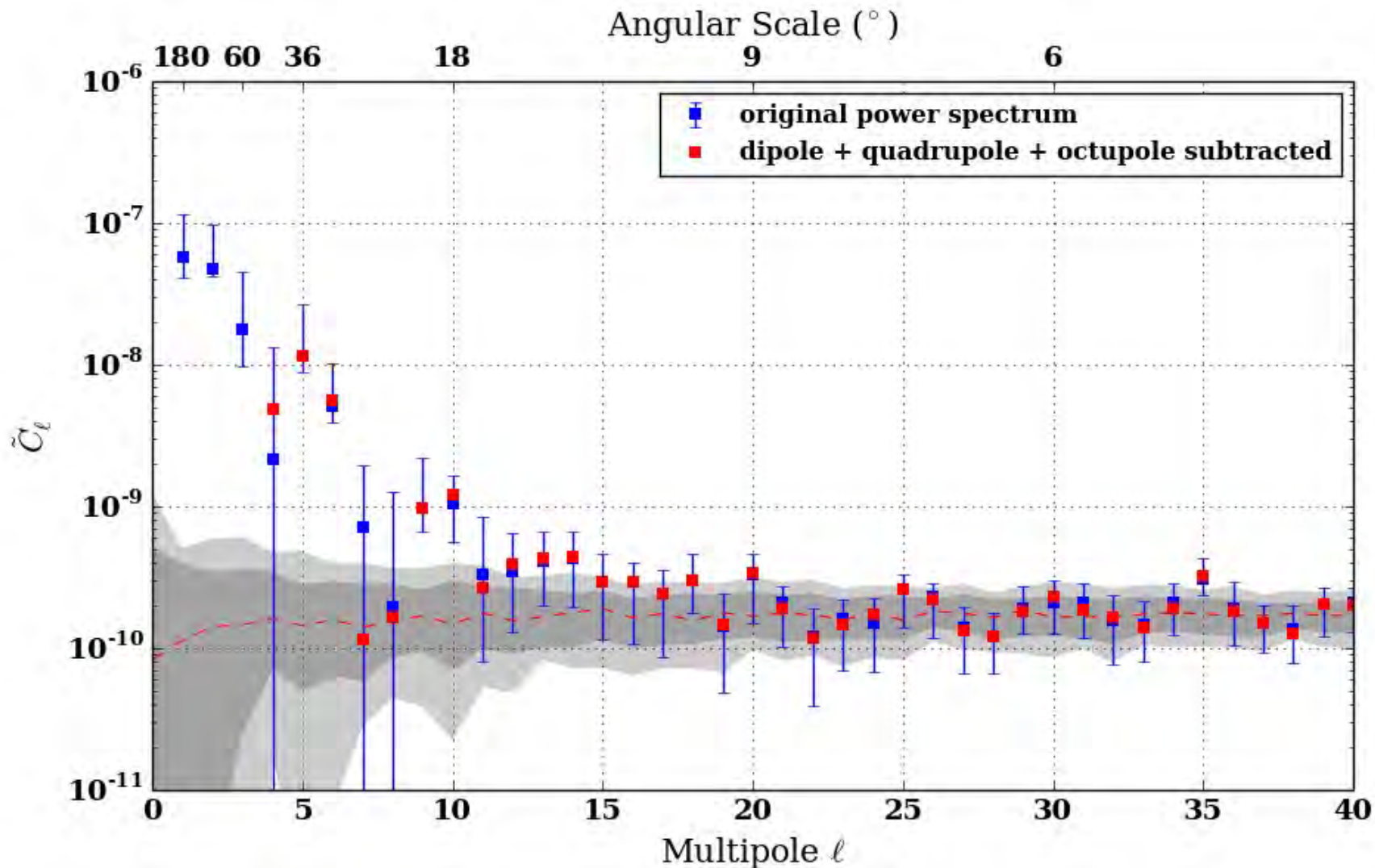
Dipole deficit is consistent with previous observations (  $1 \times 10^{-3}$  @  $ra=200^\circ$ ,  $dec$ )

Brightest region sits in region of general excess ( $ra=60^\circ$ ,  $dec=-10^\circ$ )



# Power Spectrum

Power spectrum of Large-Scale (24h bkg est). Strong dipole + quadrupole



# Power Spectrum

## Local Magnetic Turbulence and PeV-TeV Cosmic-Ray Anisotropies

*G. Giacinti and G. Sigl, Phys. Rev. Lett. 109, 071101 (2012) [arXiv:1111.2536](https://arxiv.org/abs/1111.2536)*

## Anomalous Anisotropies of Cosmic Rays from Turbulent Magnetic Fields

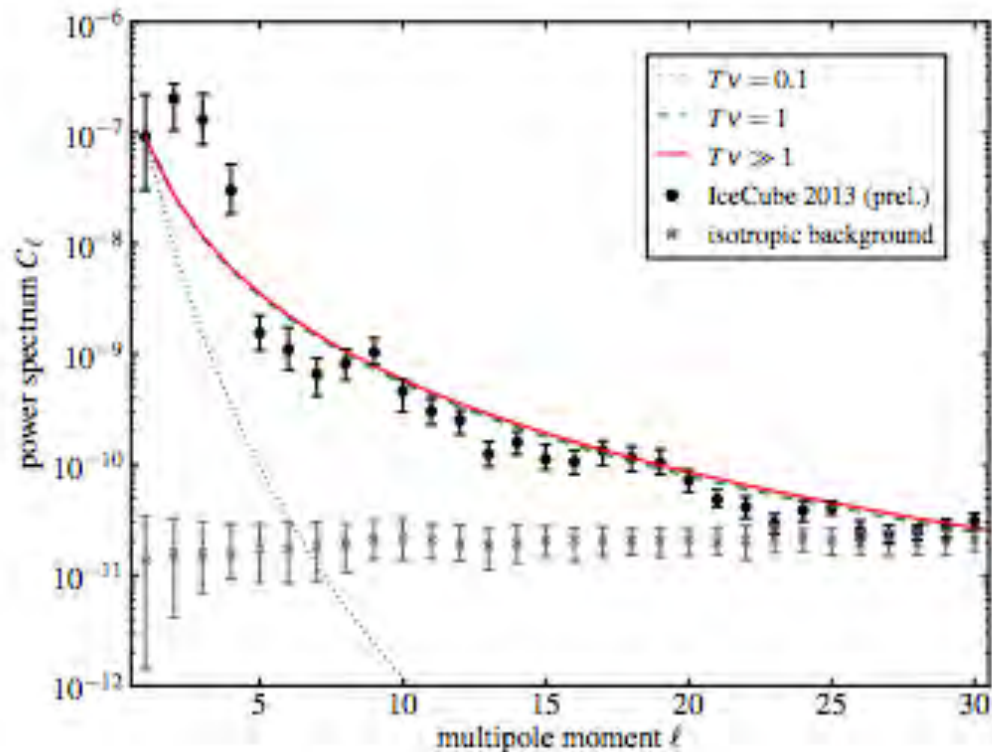
*M. Ahlers, Phys. Rev. Lett 112, 021101 (2014) [arXiv:1310.5712](https://arxiv.org/abs/1310.5712)*

Energy-dependent  
small-scale

Calculation is best tied  
to strength of dipole

HAWC  $\neq$  1 full year

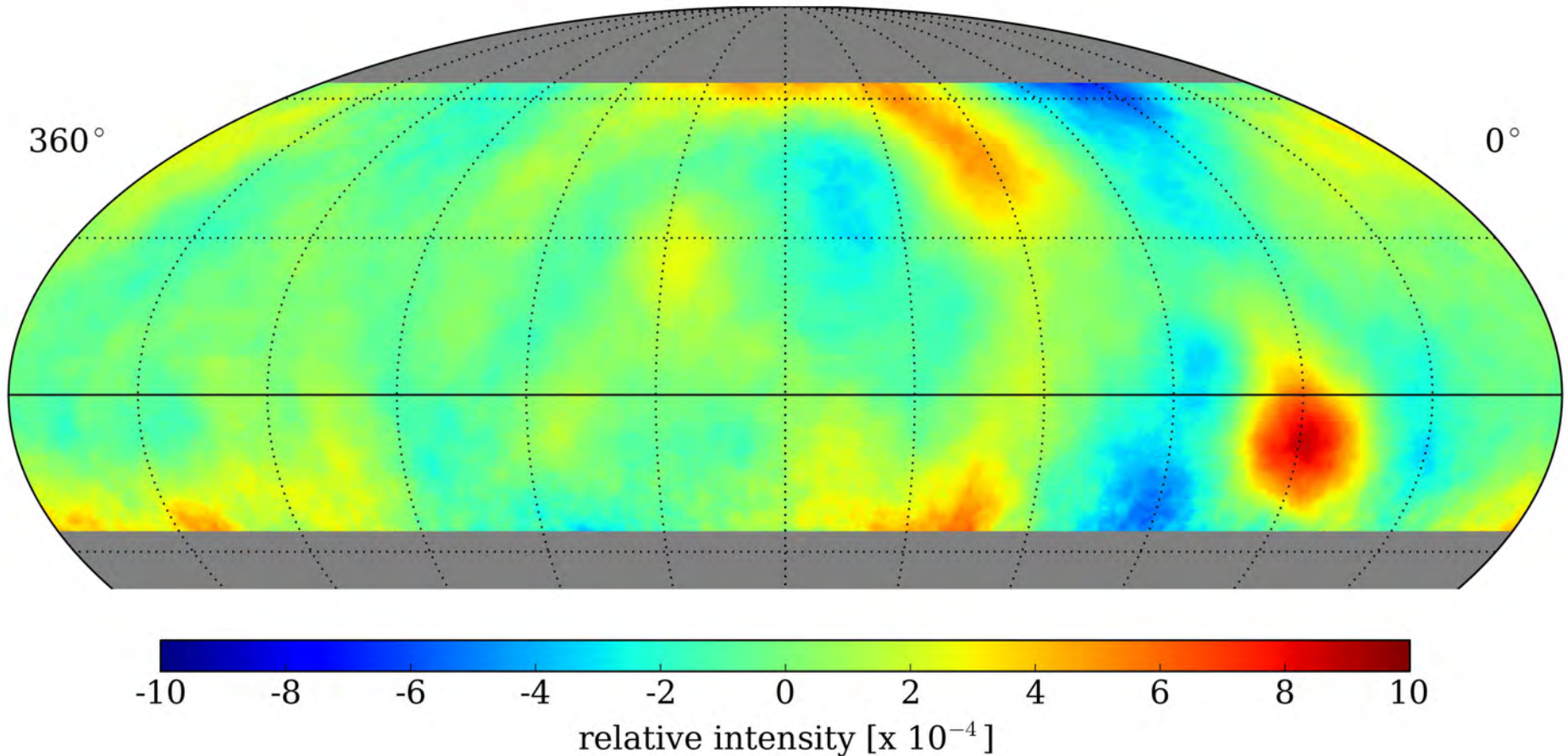
Solar dipole  
contamination



# Small Scale Anisotropy

Fit dipole+quadrupole to map for 24-hr background estimation

Subtracted fit relative intensity from 24-hr map

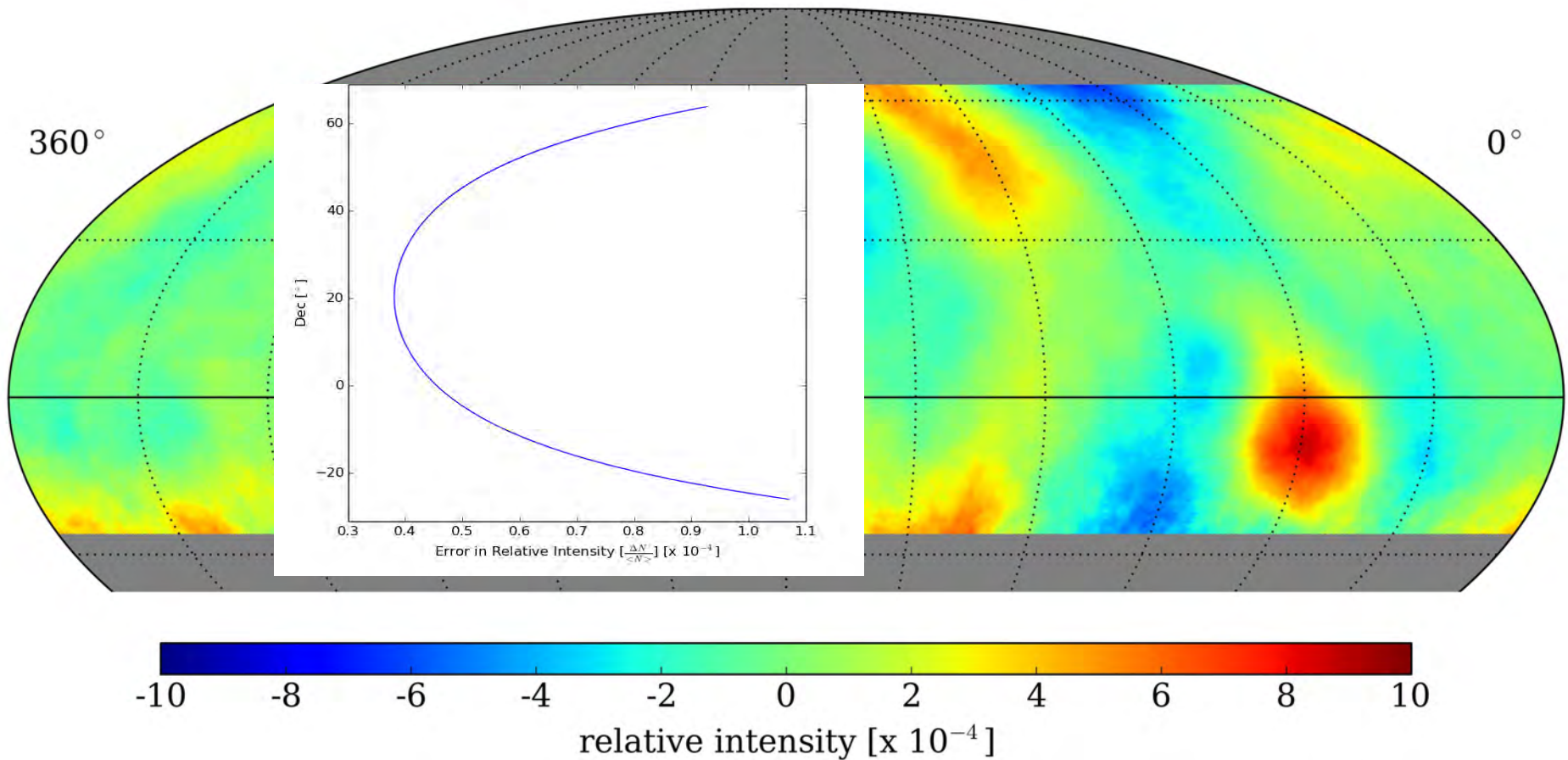




# Small Scale Anisotropy

Fit dipole+quadrupole to map for 24-hr background estimation

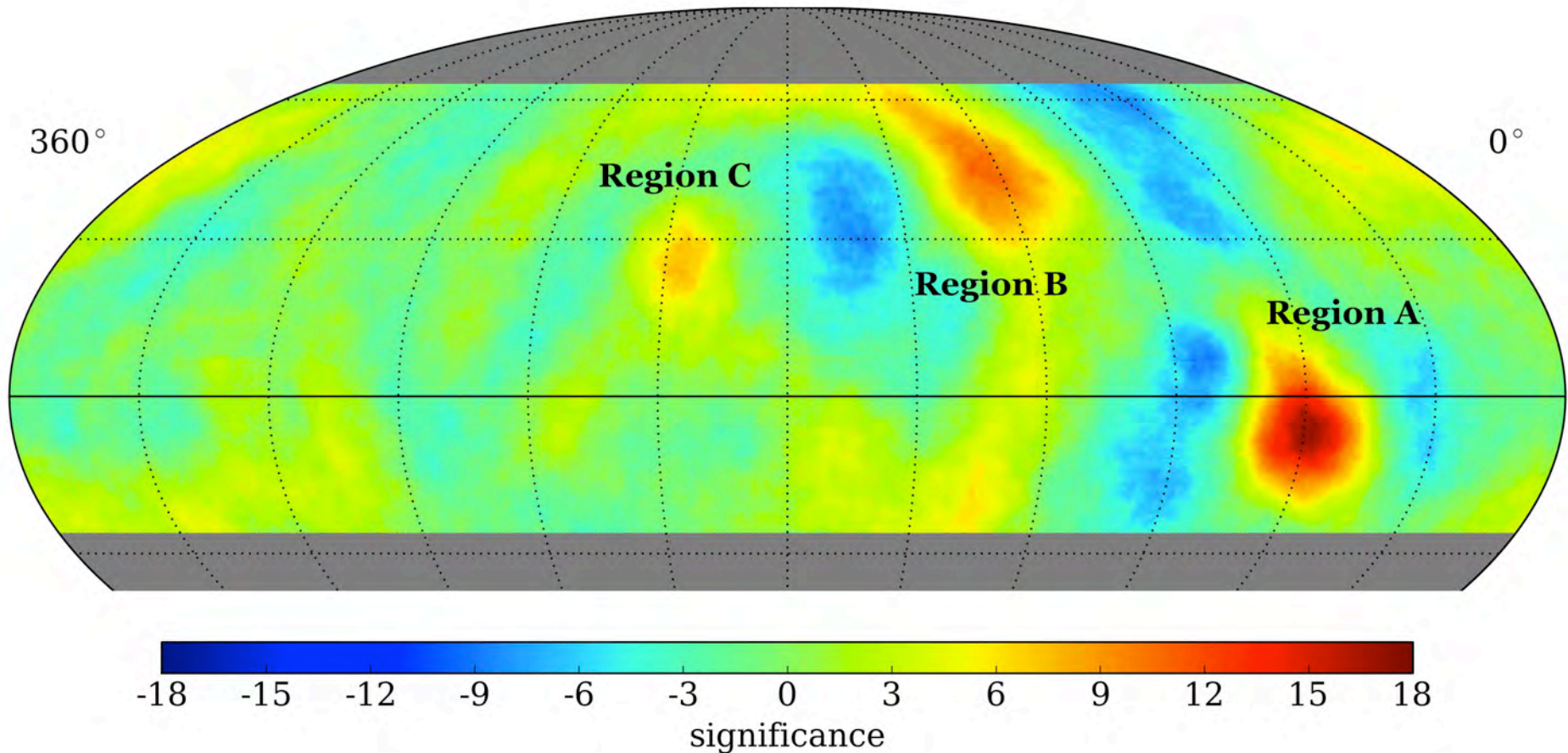
Subtracted fit relative intensity from 24-hr map



# Small Scale Anisotropy

Fit dipole+quadrupole to map for 24-hr background estimation

Subtracted fit relative intensity from 24-hr map

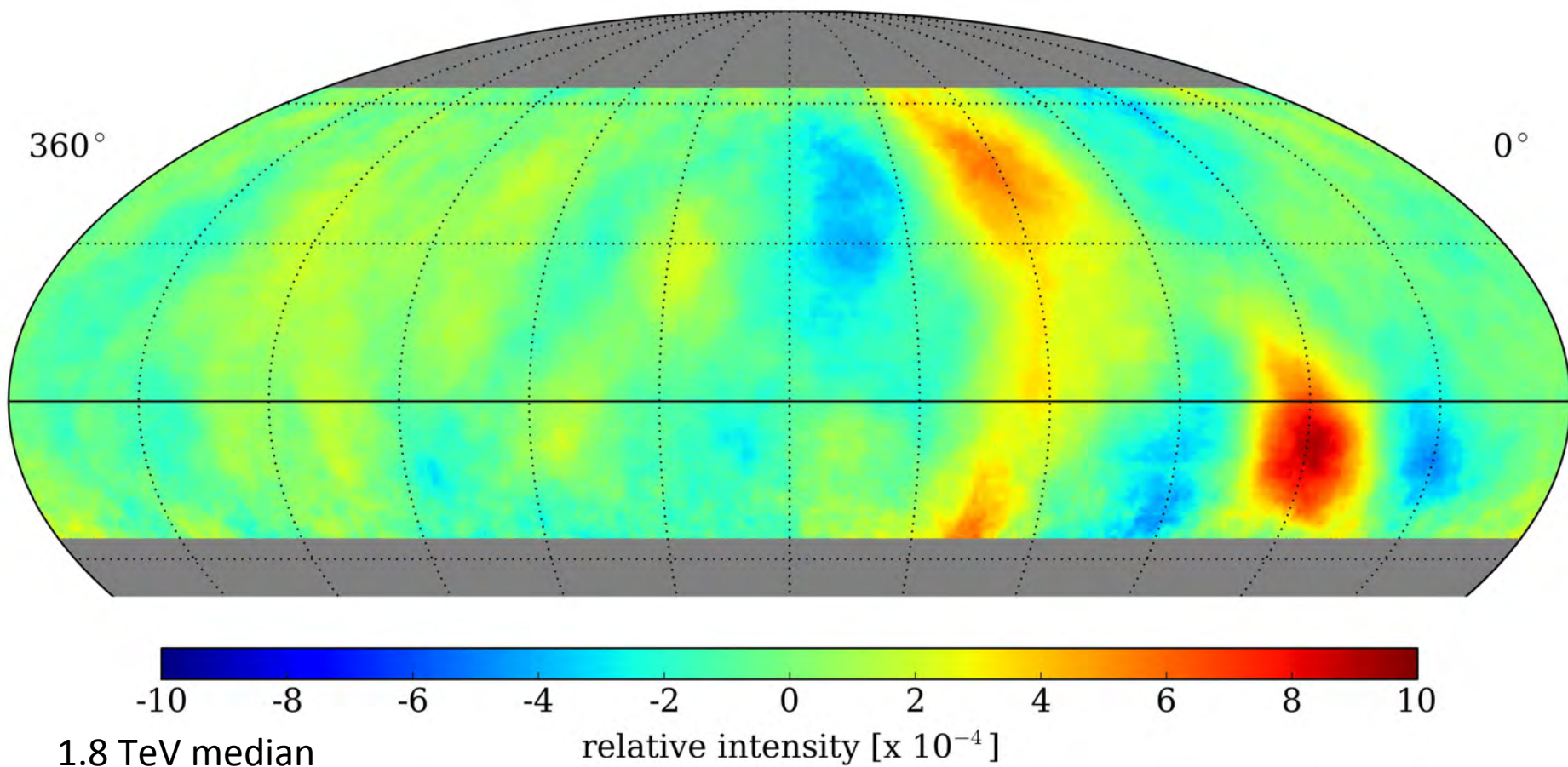


# Small Scale Anisotropy

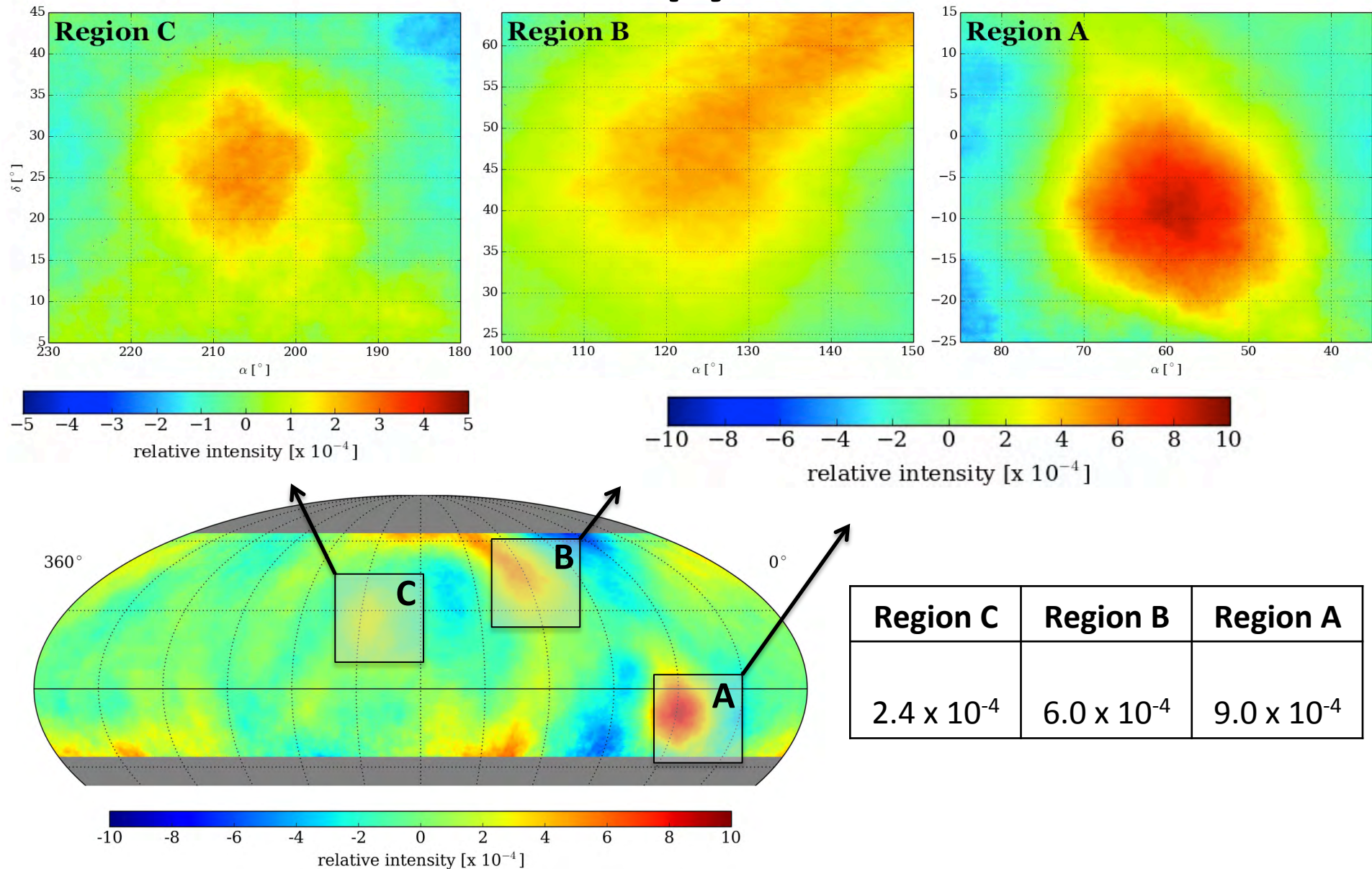
4 hr background estimation

Shows features  $\sim 60^\circ$ . Background fits to any features larger than that

Regions A, B and C are the only statistically significant excesses ( $>5\sigma$  post-trials)

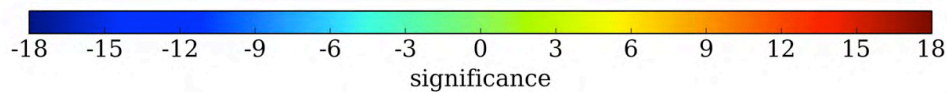
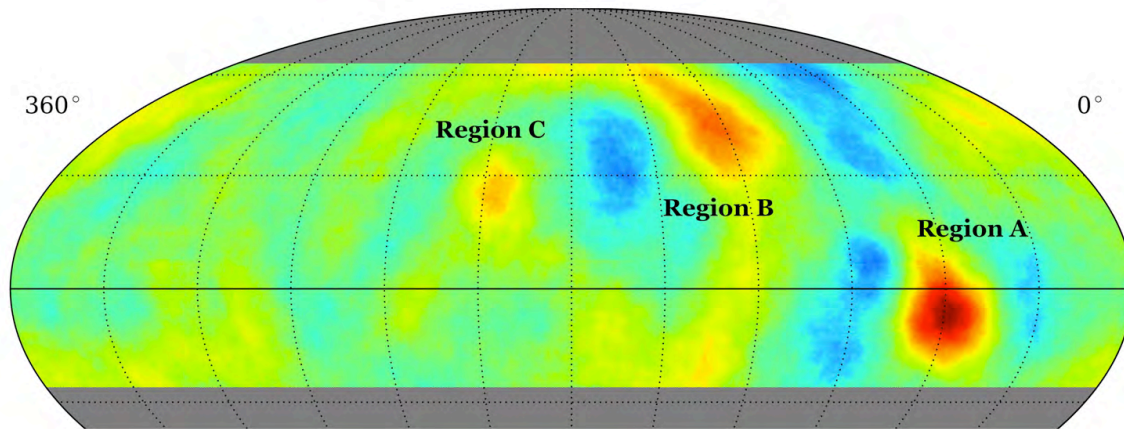
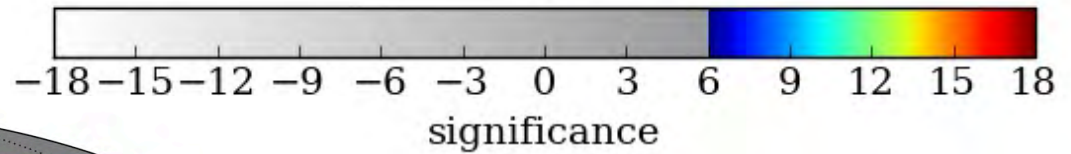
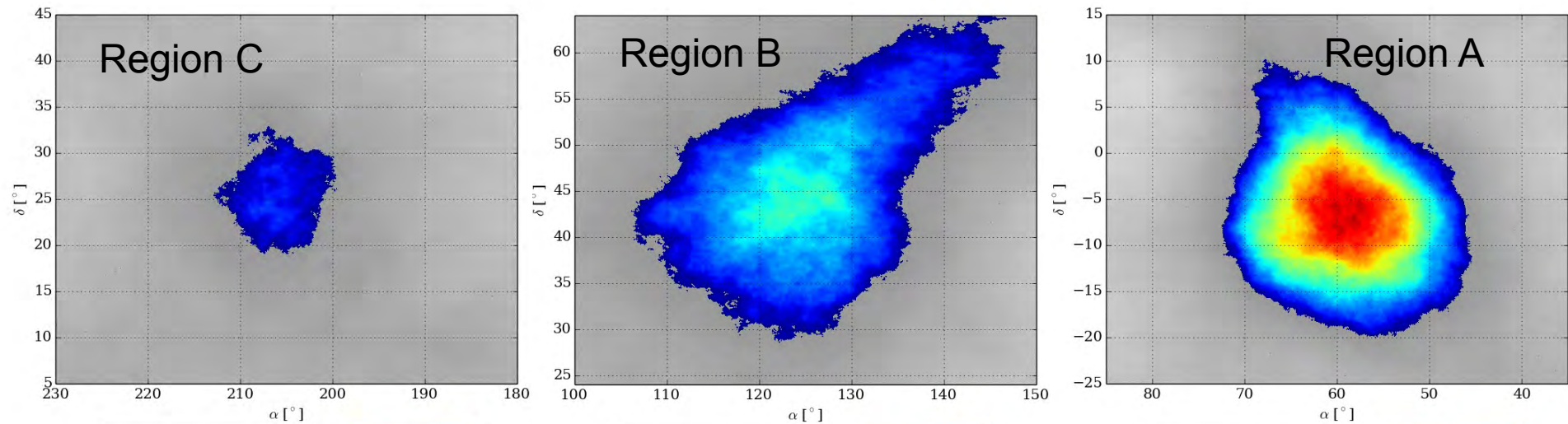


# Small Scale Anisotropy



Region C	Region B	Region A
$2.4 \times 10^{-4}$	$6.0 \times 10^{-4}$	$9.0 \times 10^{-4}$

# Small Scale Anisotropy



Region C	Region B	Region A
7.9 $\sigma$	11.5 $\sigma$	17.5 $\sigma$

# Region A

## Explanations for localized excess?

Local interstellar magnetic fields

M. Amenomori et al., *Astrophys. Space Sci. Trans.* 6, 49 (2010).

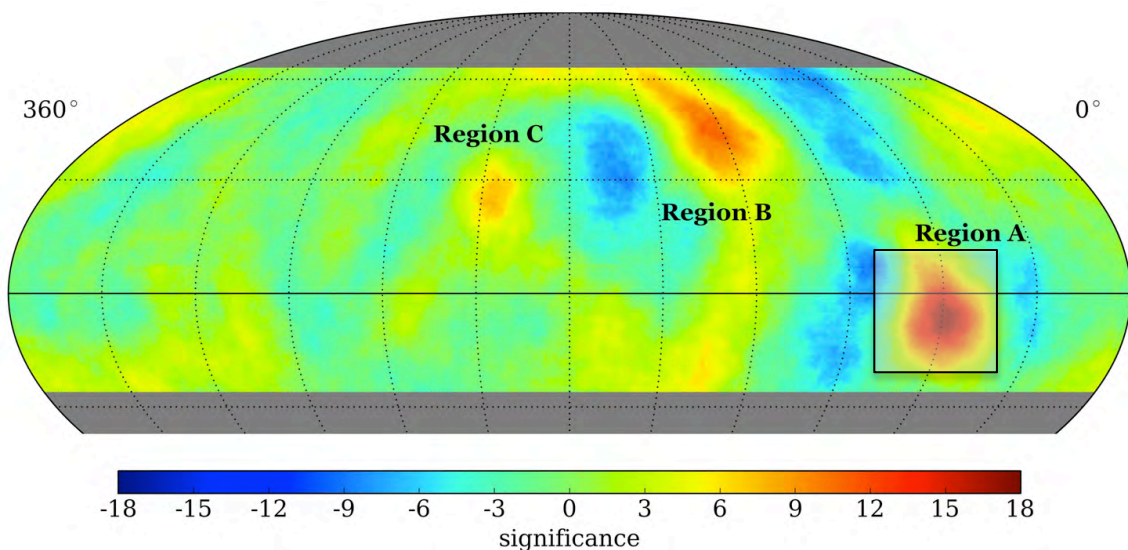
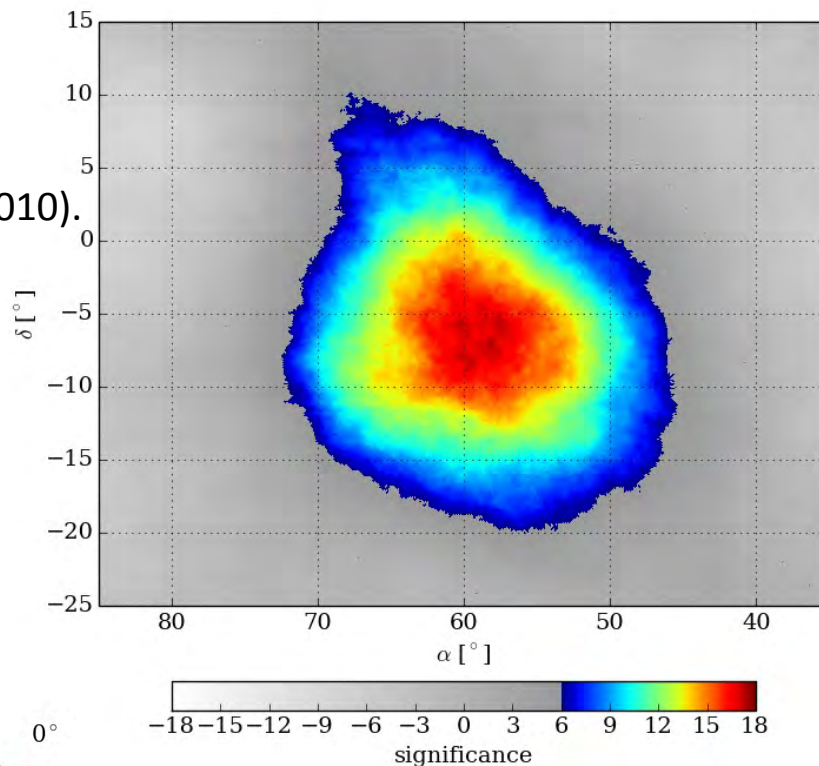
A. Lazarian and P. Desiati, *Astrophys. J.* 722, 188 (2010).

Magnetic bottle

L. Drury and F. Aharonian, *Astropart. Phys.* 29, 420(2008).

Dark Matter interpretation

J. Harding arXiv:1307.6537

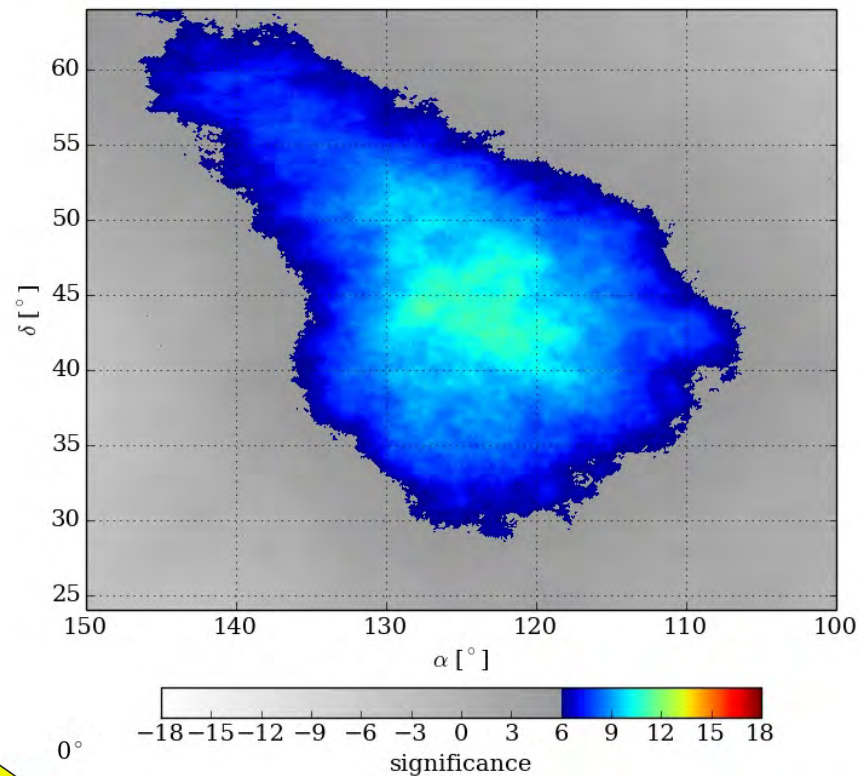
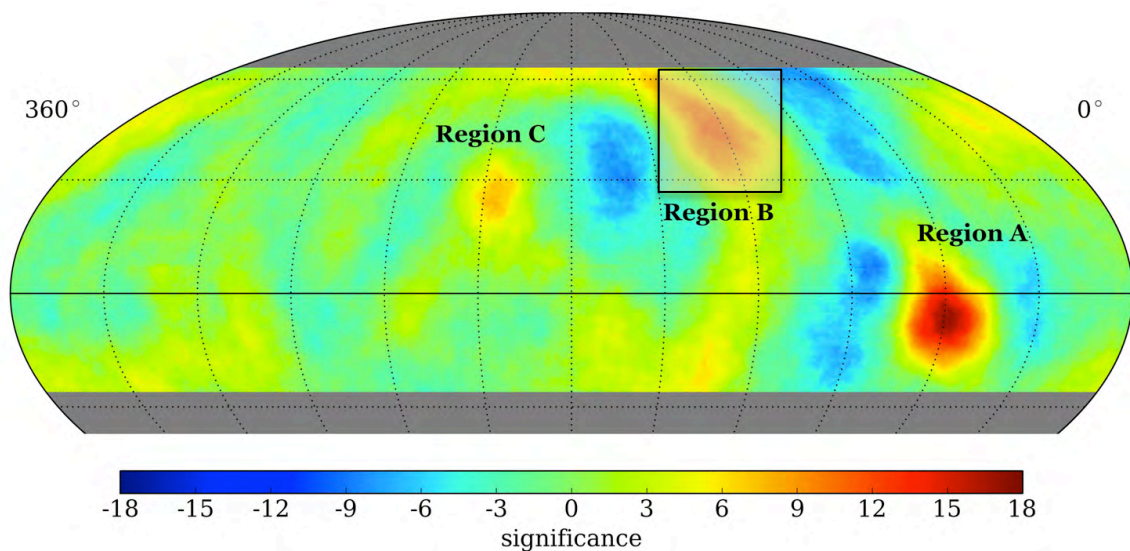


Far south for Milagro and ARGO  
(35°N and 30°N latitude)  
Sits on large-scale maximum

$(8.9 \pm 0.6) \times 10^{-4}$  excess

Milagro saw cutoff at  $\sim 4 - 20$  TeV

# Region B

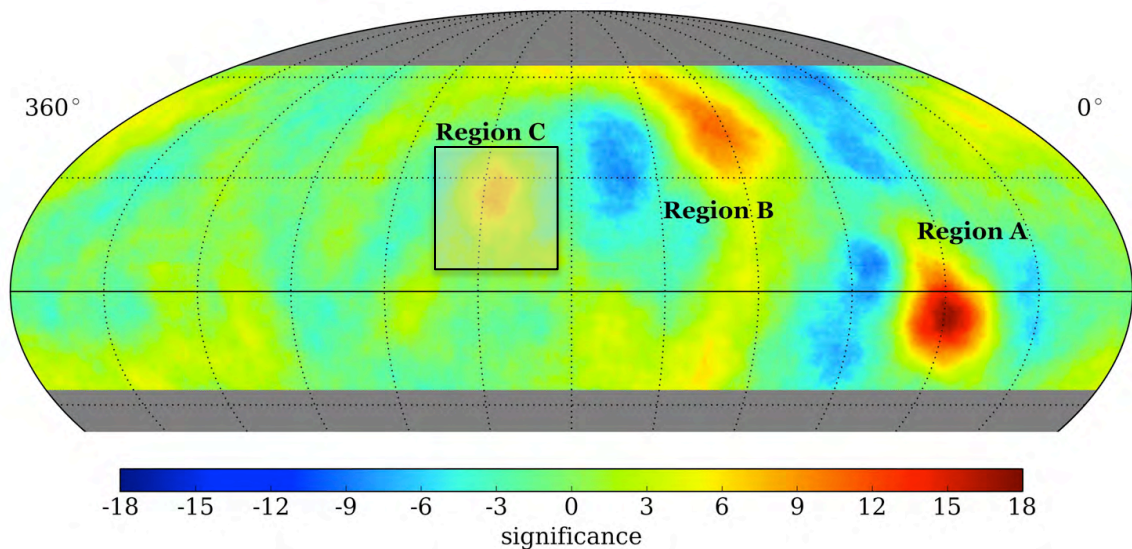
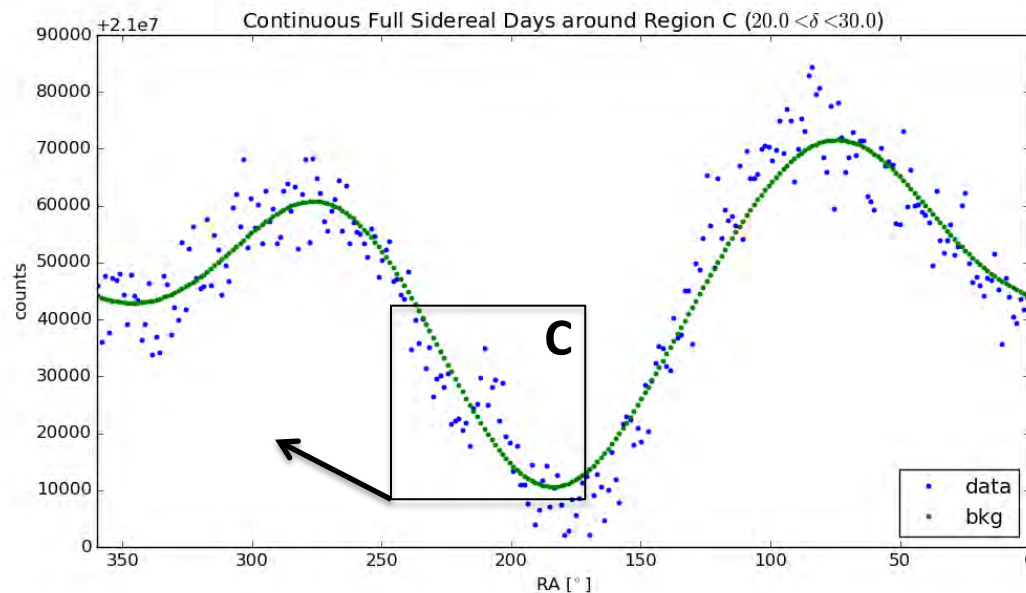
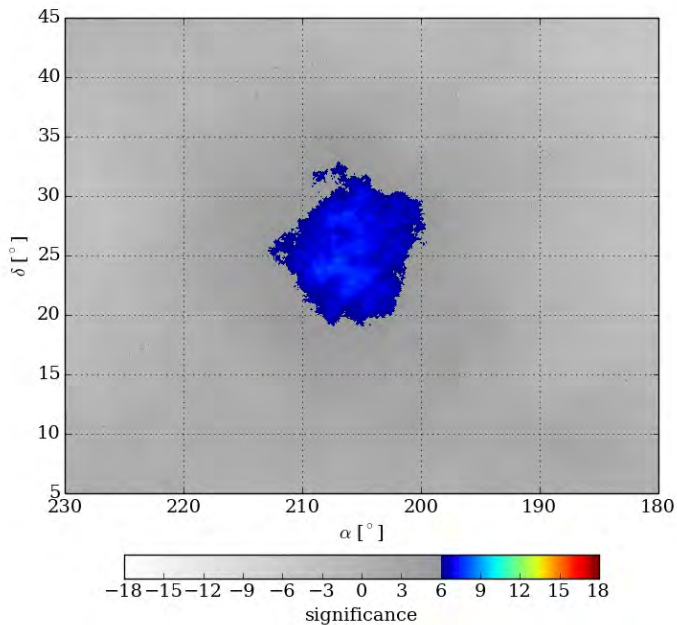


Extends full FOV in declination  
Sits at edge of large-scale maximum

$(5.3 \pm 0.6) \times 10^{-4}$  excess

Milagro: same spectrum as bkg

# Region C



Consistent with excess seen in ARGO  
Not present in Milagro

Sits in large-scale minimum

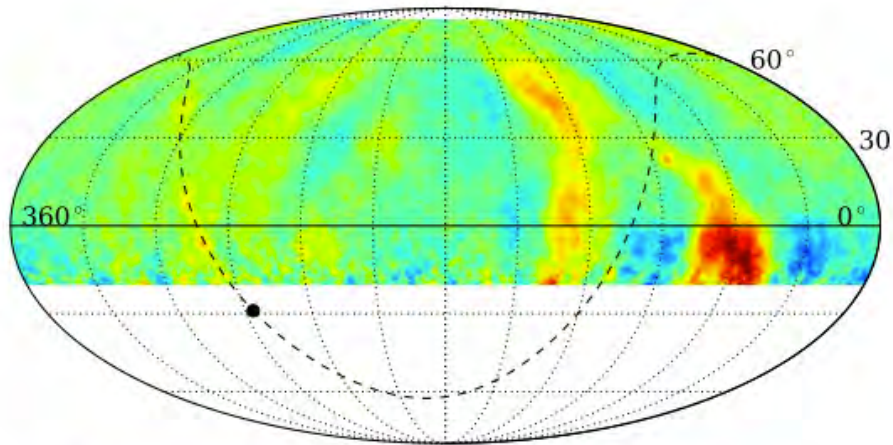
$(2.8 \pm 0.4) \times 10^{-4}$  rel. int.

$7.9\sigma$  pre-trials ( $> 5\sigma$  post-trials)

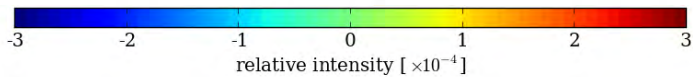
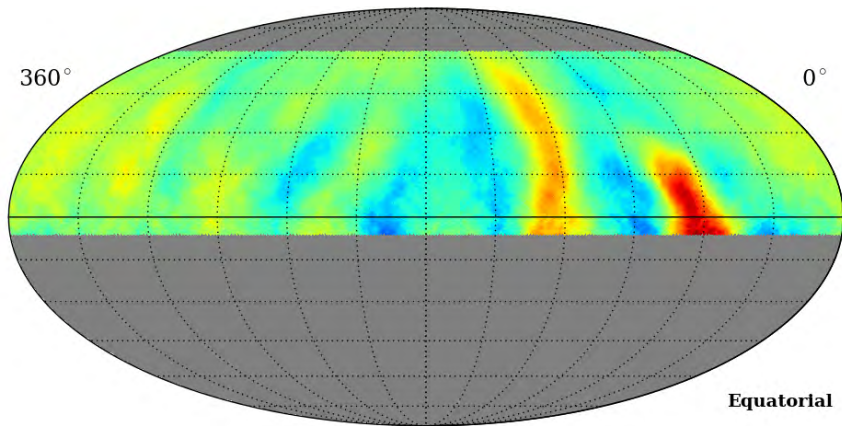


# Comparisons

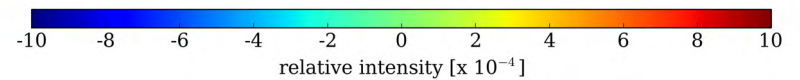
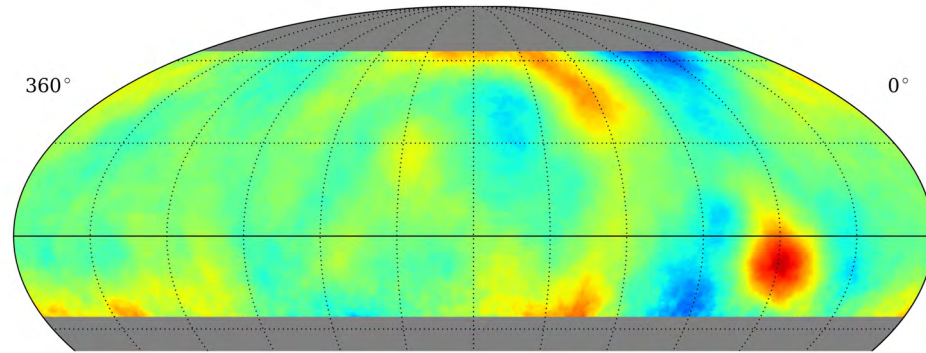
ARGO



Milagro

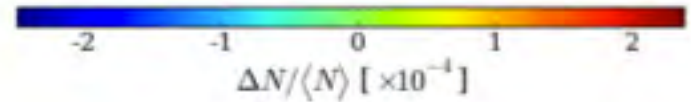
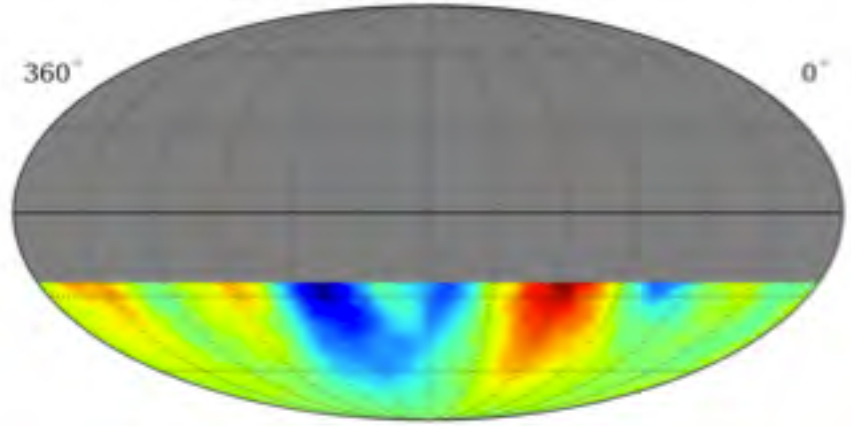


HAWC



IceCube

IC59 Data:  $\Delta t = 4$  hr, Smoothing =  $20^\circ$



# Conclusions



HAWC detected 3 regions of cosmic-ray excess

- 2 previously discovered (Region A & B)
- 1 newly discovered (Region C)

Consistency with ARGO observations

Energy-dependent study is promising and getting better