

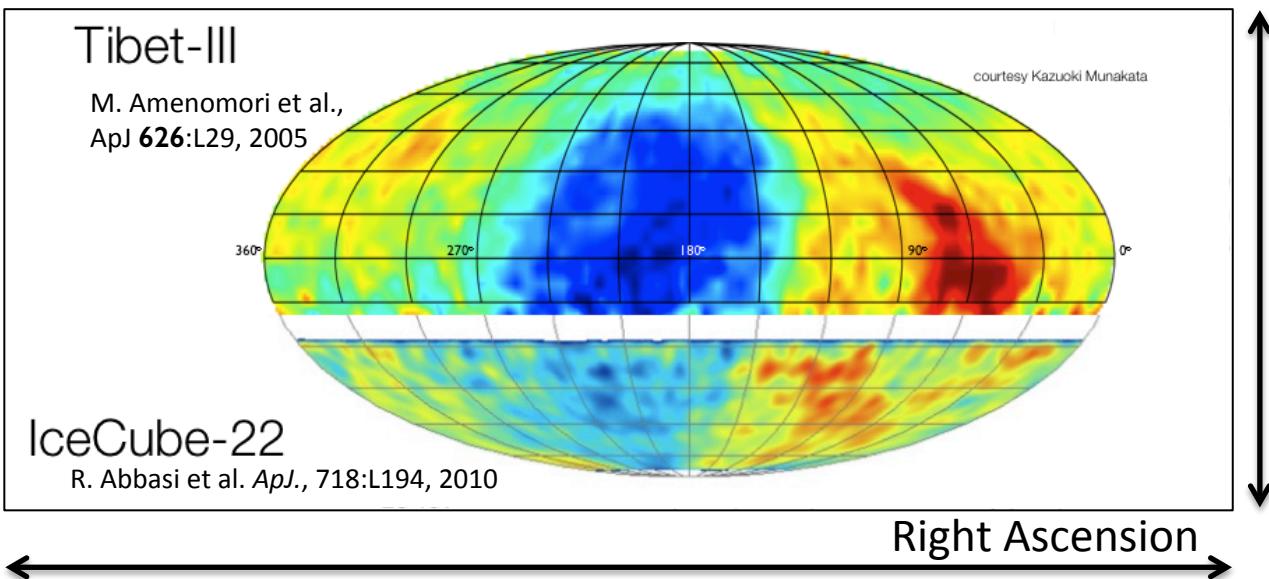
Cosmic-Ray Anisotropy with the HAWC Observatory

Daniel Fiorino for the HAWC Collaboration
University of Wisconsin--Madison
ICRC-2015



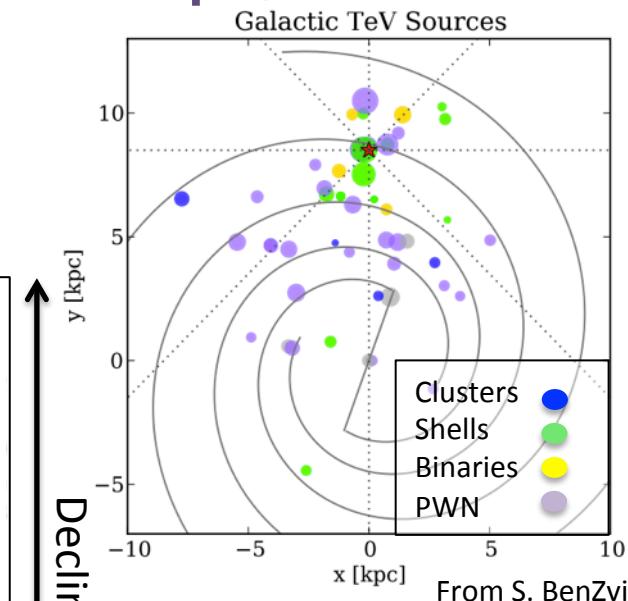
Cosmic-Ray Anisotropy

- Cosmic rays < 10 PV are **well confined** within our Galaxy by $\sim \mu\text{G}$ magnetic fields. They scatter many times before reaching Earth.
- The cause likely involves the **inhomogeneous source distribution** in our Galaxy and local magnetic fields.



2015, July

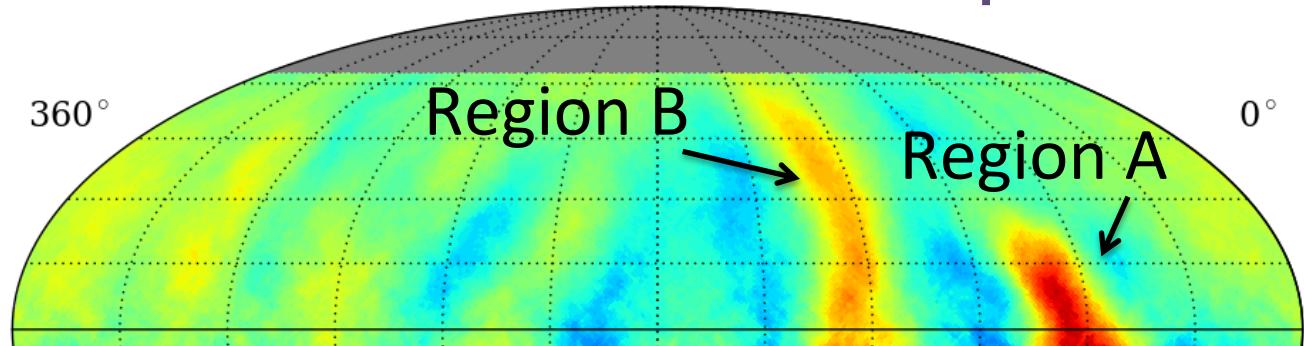
Daniel Fiorino



Cosmic-Ray Anisotropy

Milagro

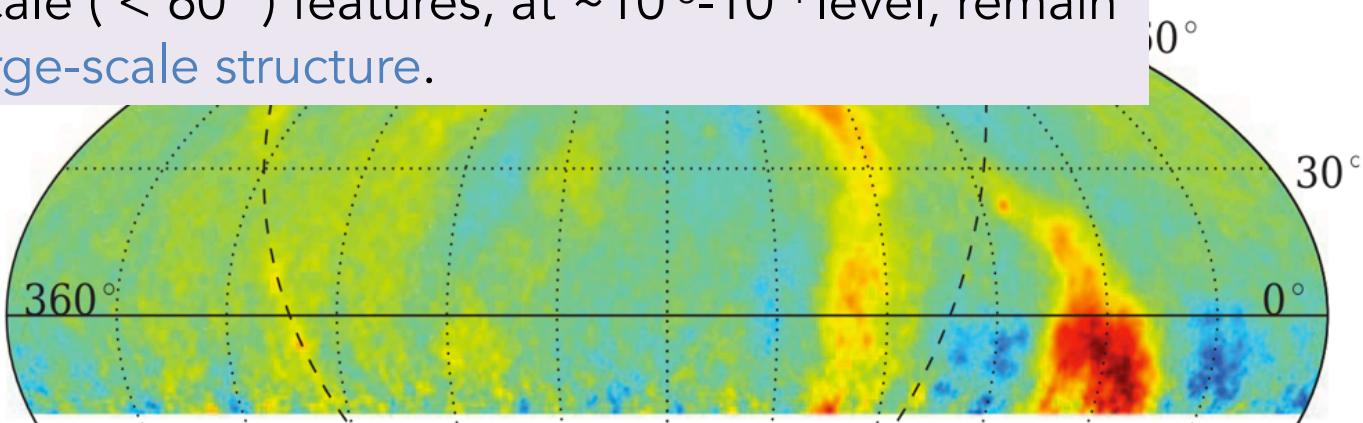
A. Abdo et al., PRL
101:221101, 2008



Significant small-scale ($< 60^\circ$) features, at $\sim 10^{-3}$ - 10^{-4} level, remain after removal of large-scale structure.

ARGO-YBJ

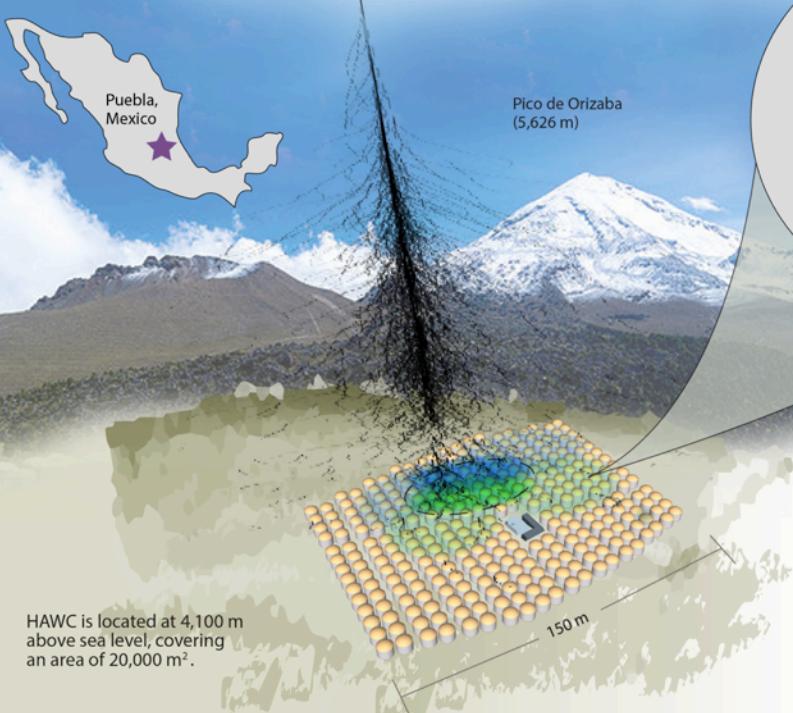
R. Bartoli et al.,
Phys Rev D88:082001, 2013



High-Altitude Water Cherenkov

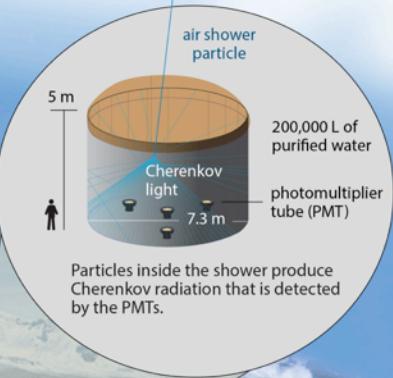
HAWC Observatory

HAWC operates day and night, providing a large field of view for the observation of the highest energy gamma rays.



Water Cherenkov tank

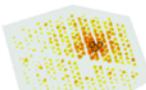
HAWC comprises an array of 300 tanks that record the particles created in gamma-ray and cosmic-ray showers.



Gamma rays vs cosmic rays

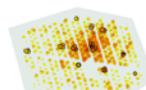
HAWC selects gamma rays from among a much more abundant background of cosmic rays.

gamma-ray shower



"hot" spots concentrate around the core

cosmic-ray shower



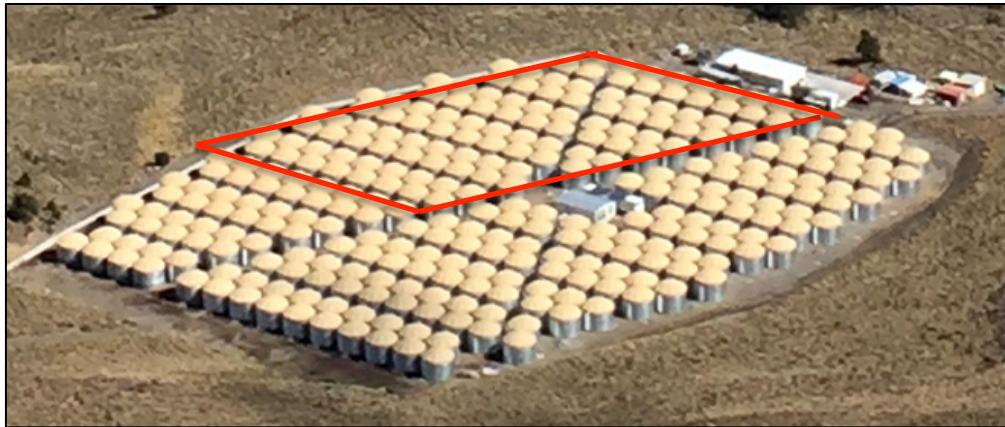
"hot" spots are more dispersed

2015 July

Daniel Fiorino

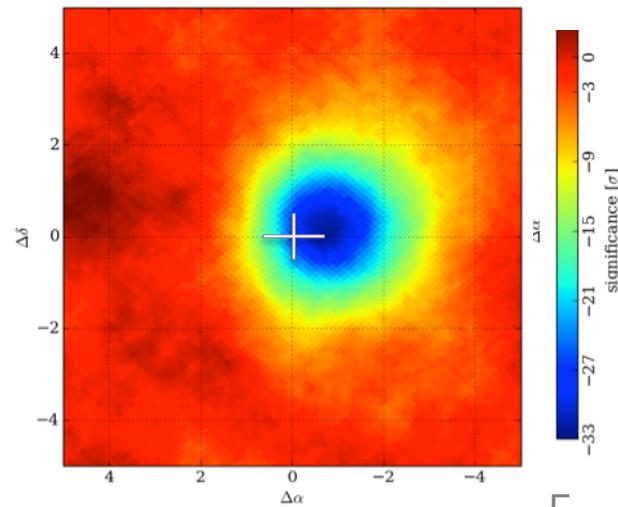


HAWC-111 Data Set



- Moon Shadow confirms simulated values:
 - 2 TeV median energy (0.9° offset)
 - $\delta\theta \simeq 1.6^\circ \cdot Z \left(\frac{E}{\text{TeV}} \right)^{-1}$
 - 1.2° angular resolution (1.2° width)

- Construction phase
- June 2013 to July 2014
- 181 days (4332.1 hr)
- 85.6 billion events



HAWC Small-scale Anisotropy

Large-scale removed

Small-scale features ($< 60^\circ$) remain

Smoothing applied (10°)

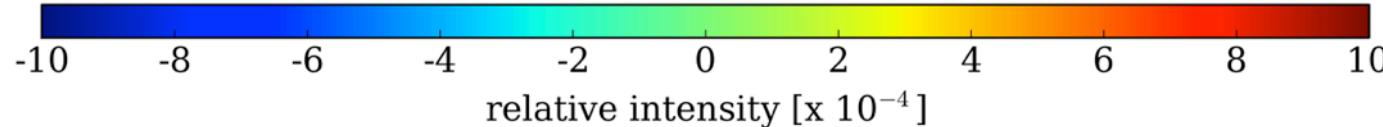
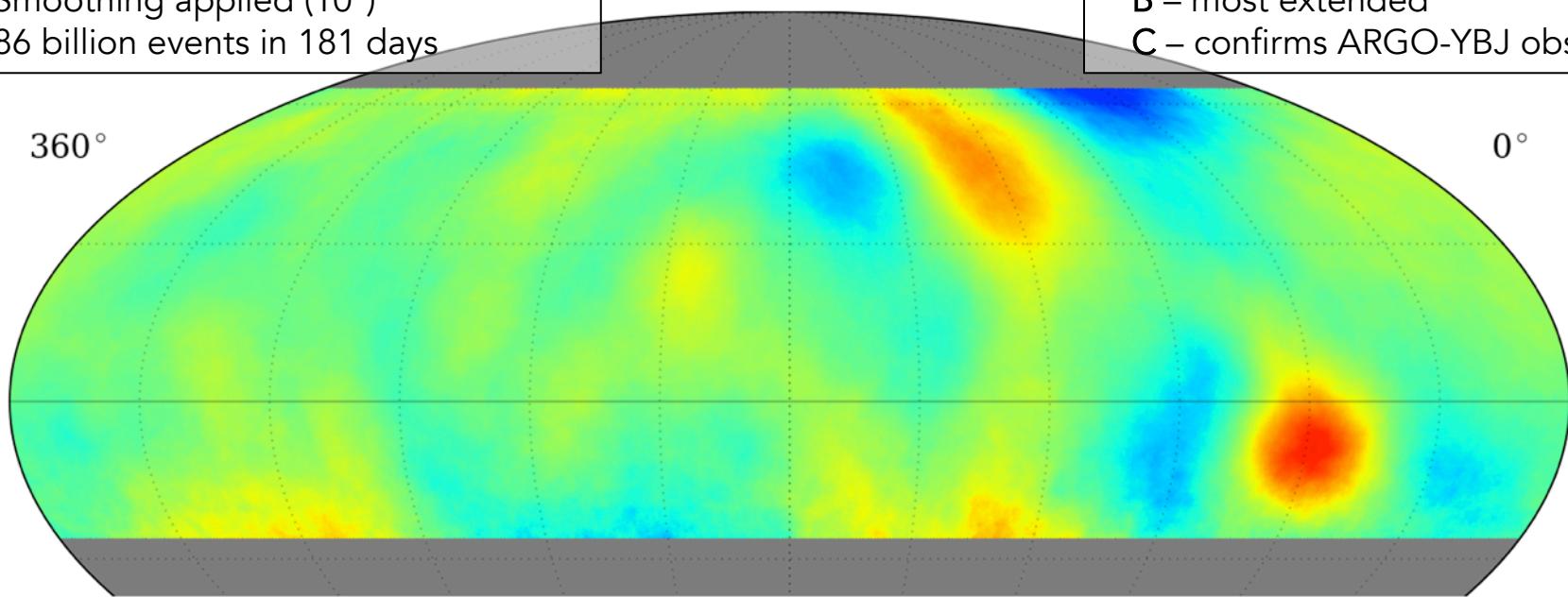
86 billion events in 181 days

3 significant excesses

A – strongest, harder than bkg

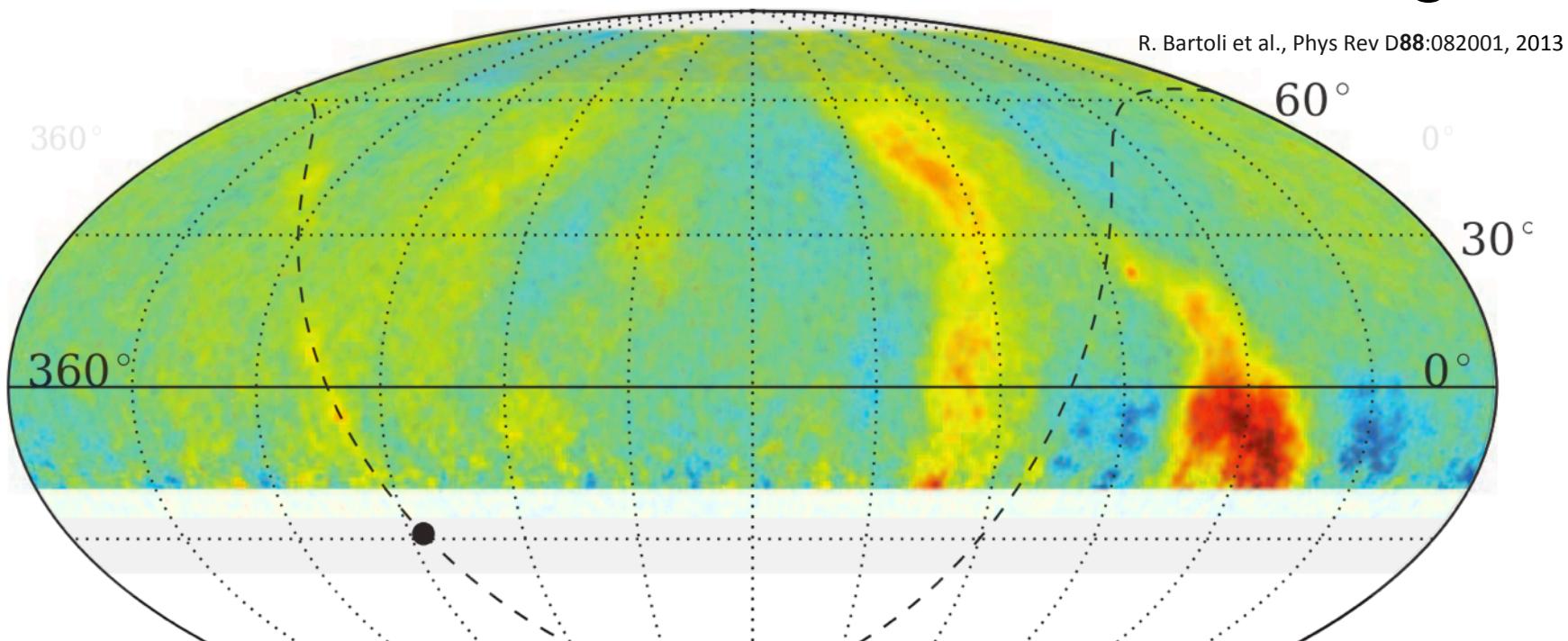
B – most extended

C – confirms ARGO-YBJ observation



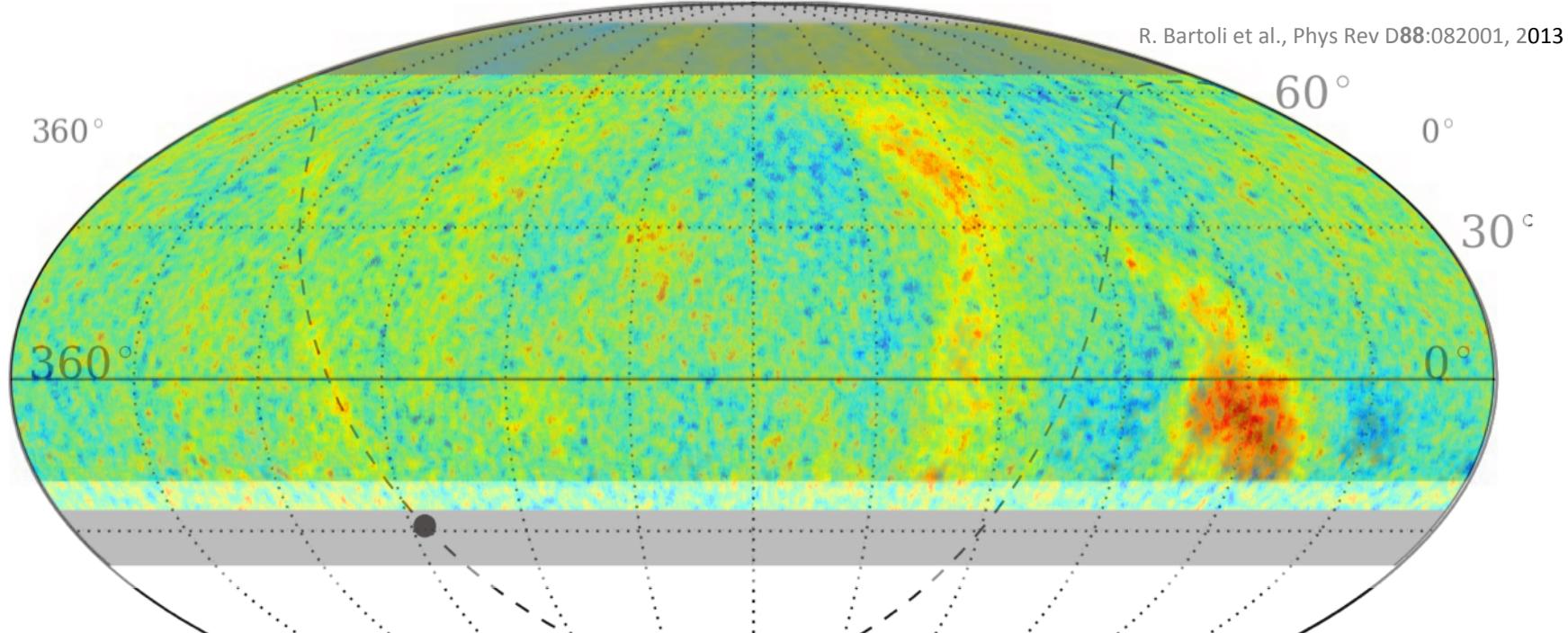
Comparing Previous Results

ARGO-YBJ to HAWC (same smoothing)



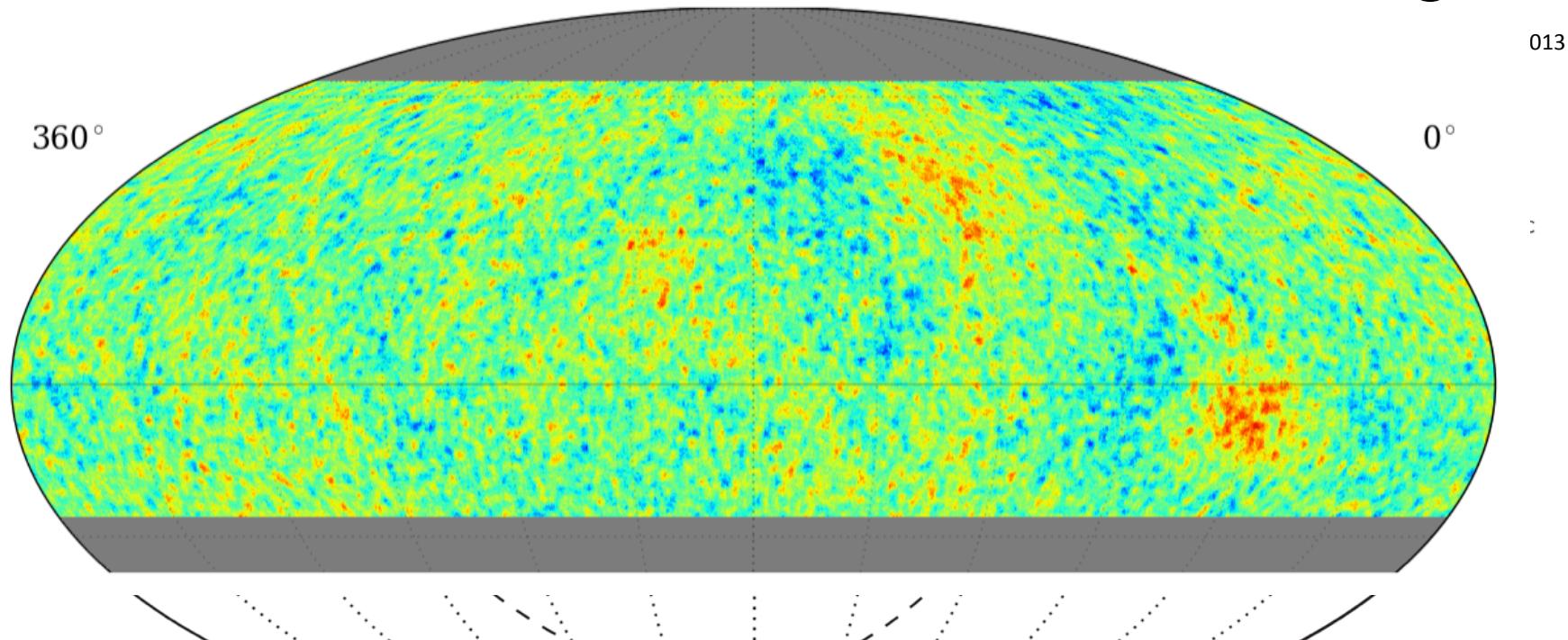
Comparing Previous Results

ARGO-YBJ to HAWC (same smoothing)

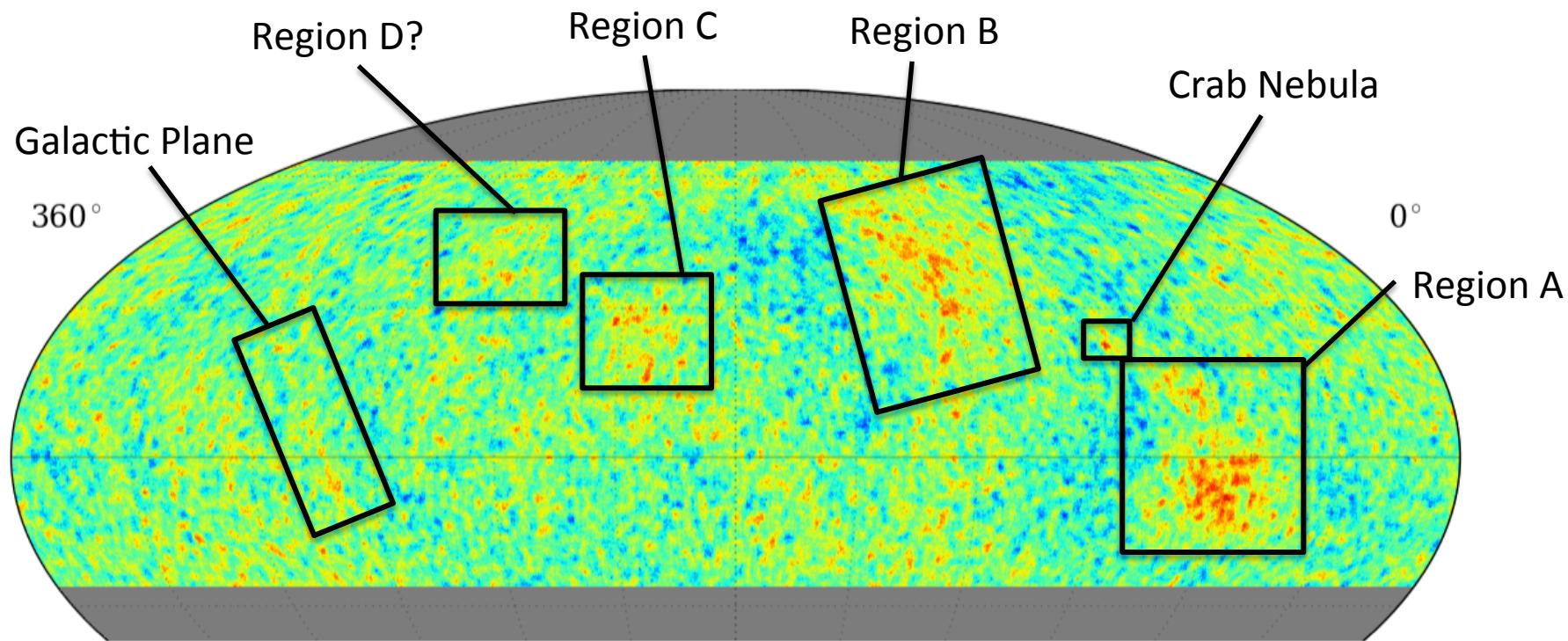


Comparing Previous Results

ARGO-YBJ to HAWC (same smoothing)

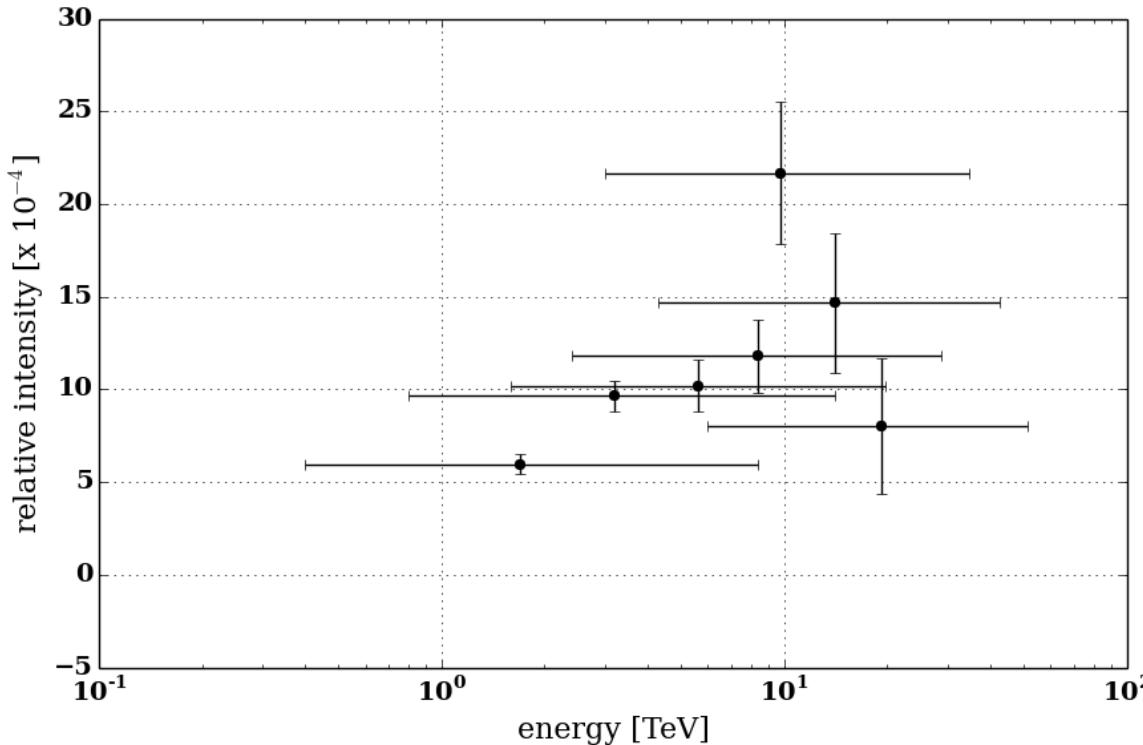


HAWC Smoothed by PSF



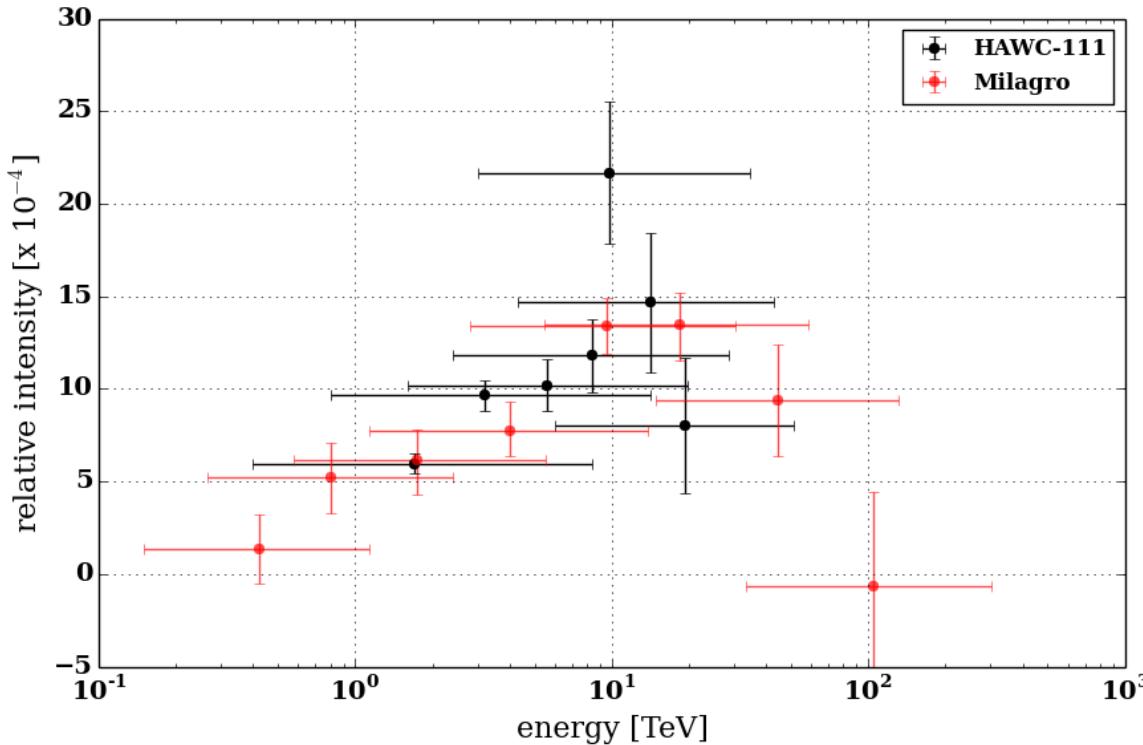
HAWC - Region A

- Relative intensity in 10° circle for 7 "energy" bins
- "Hardening" of spectrum in Region A, compared to off-source regions:
4.3 σ effect



HAWC - Region A

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

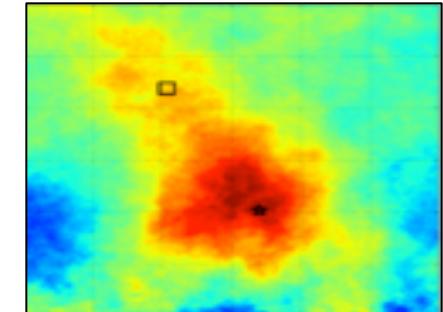
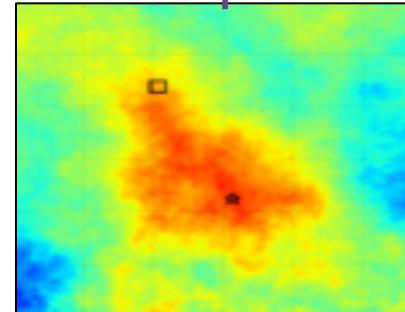
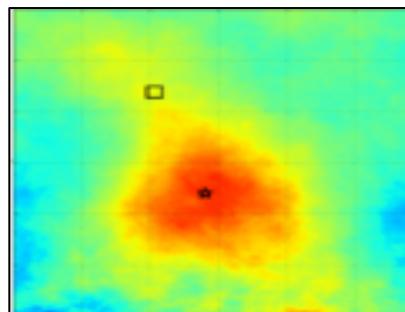
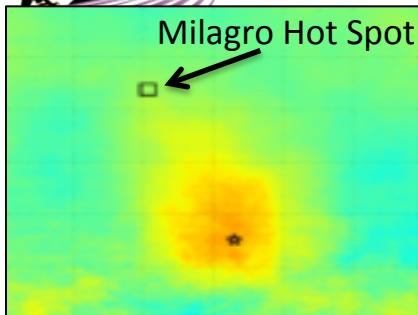


4.3 σ effect

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



1.7 +6.6/-1.3 TeV

3.2 +10.9/-2.4 TeV

5.6 +14.2/-3.9 TeV

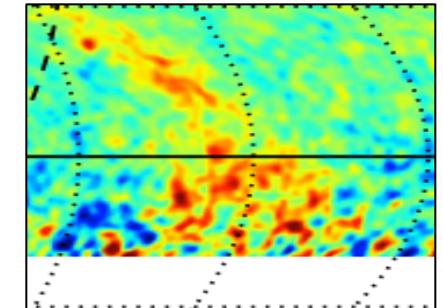
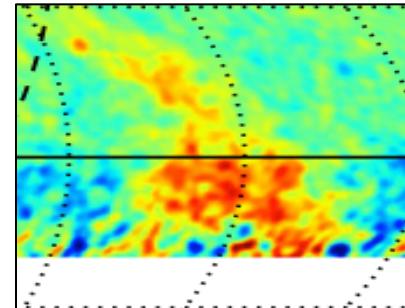
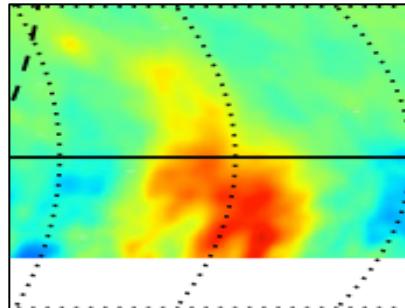
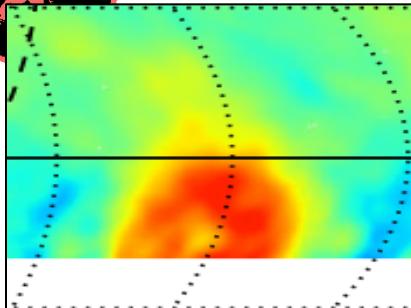
14.1 +28.7/-9.9 TeV

0.66 TeV

1.4 TeV

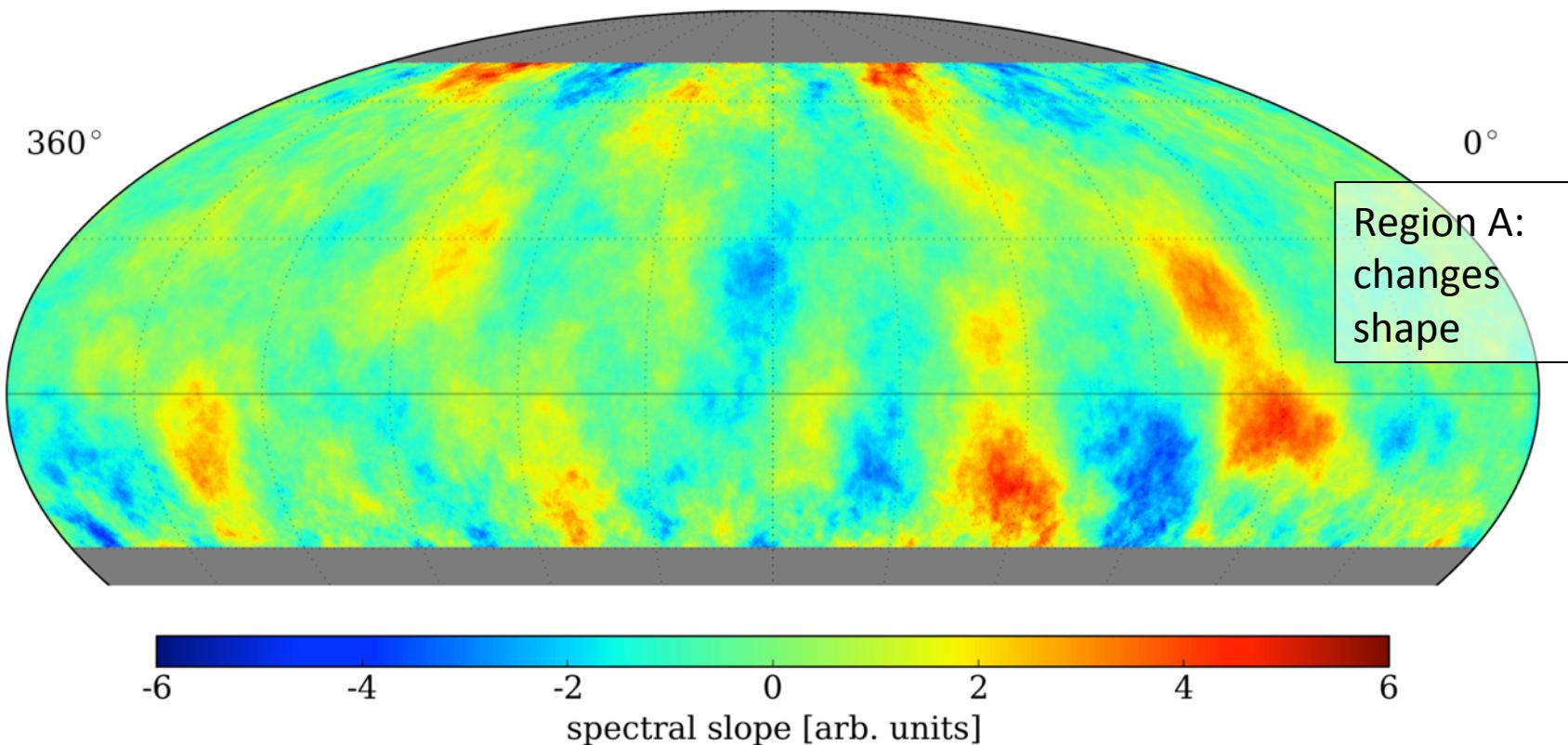
3.5 TeV

7.3 TeV



Energy Dependence of Whole Sky

Perform spectral fit on each pixel in sky. **Red** : Harder spectrum than background.
Only Region A is significantly harder. (Error not shown.)



Conclusions

- Cosmic-ray anisotropy is a [Galactic probe](#) and an unexplained phenomena.
- Full HAWC detector turned on in March, amassing a [large data set](#) of TeV cosmic rays.
- We understand the energy and angular response of the HAWC detector to cosmic rays.
- The entire field is beginning to understand the [energy](#) & [composition](#) response of the cosmic-ray anisotropy to constrain possible causes.

HAWC Publication

A. Abeysekara et al., ApJ **796**:108, 2014

HAWC Highlights

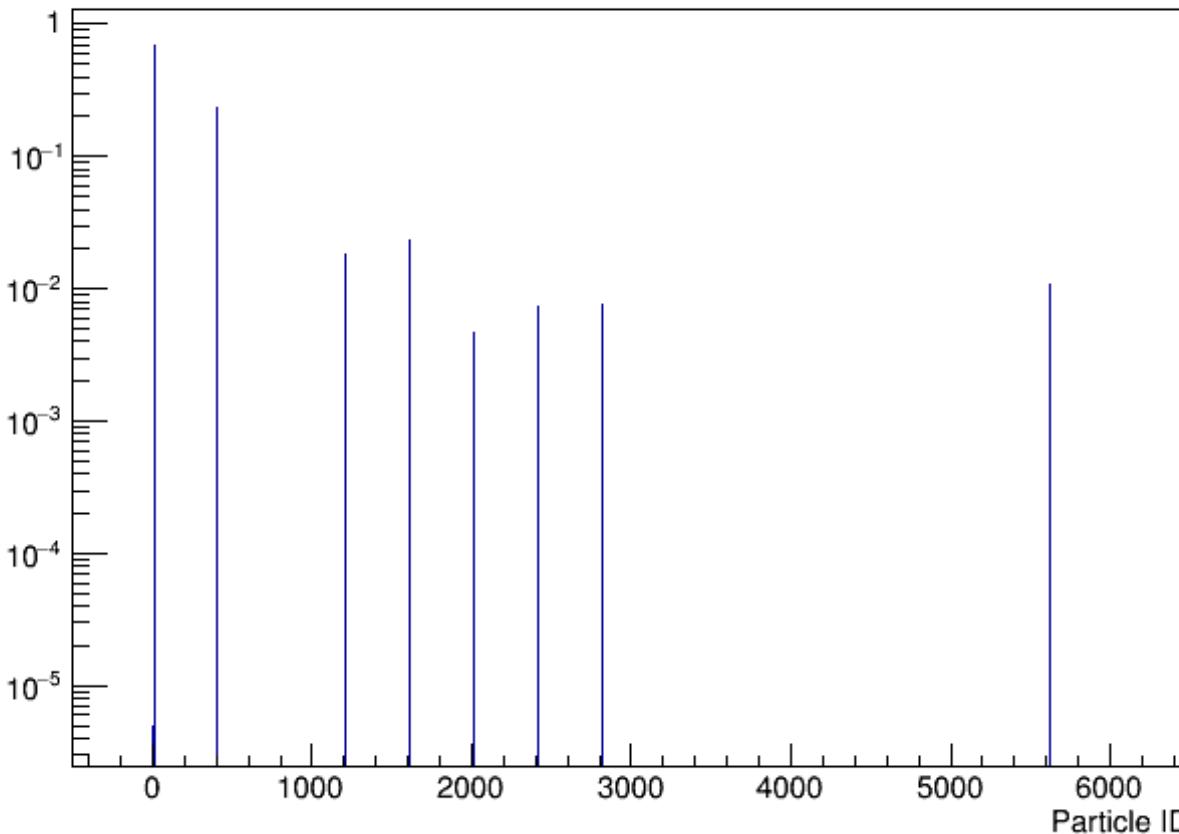
Blazars	J. Pretz
Crab Nebula	R. Lauer
Dark Matter Limits	P. Salesa
Fermi Bubbles	M. Longo-Proper
Galactic Plane	H. Ayala
Geminga	H. Zhou
GRBs	J. Wood
SNRs & PWN	D. Lennarz
	M. Hui

All-sky GRB search

Blazar Alerts	J. Wood
Dark Matter	T. Weisgarber
e+/e- Study	P. Harding
Gamma/Hadron Sep.	S. BenZvi
HAWC Design/Ops	Z. Hampel, T. Capistran
Lorentz Invariance	A. Smith, M. Duvernois, A. Sandoval
PBHs	L. Nellen
Pulsed VHE	T. Ukwatta
Solar Physics	C. Alvarez
	O. Enriquez/A. Lara

HAWC – Chemical Abundances

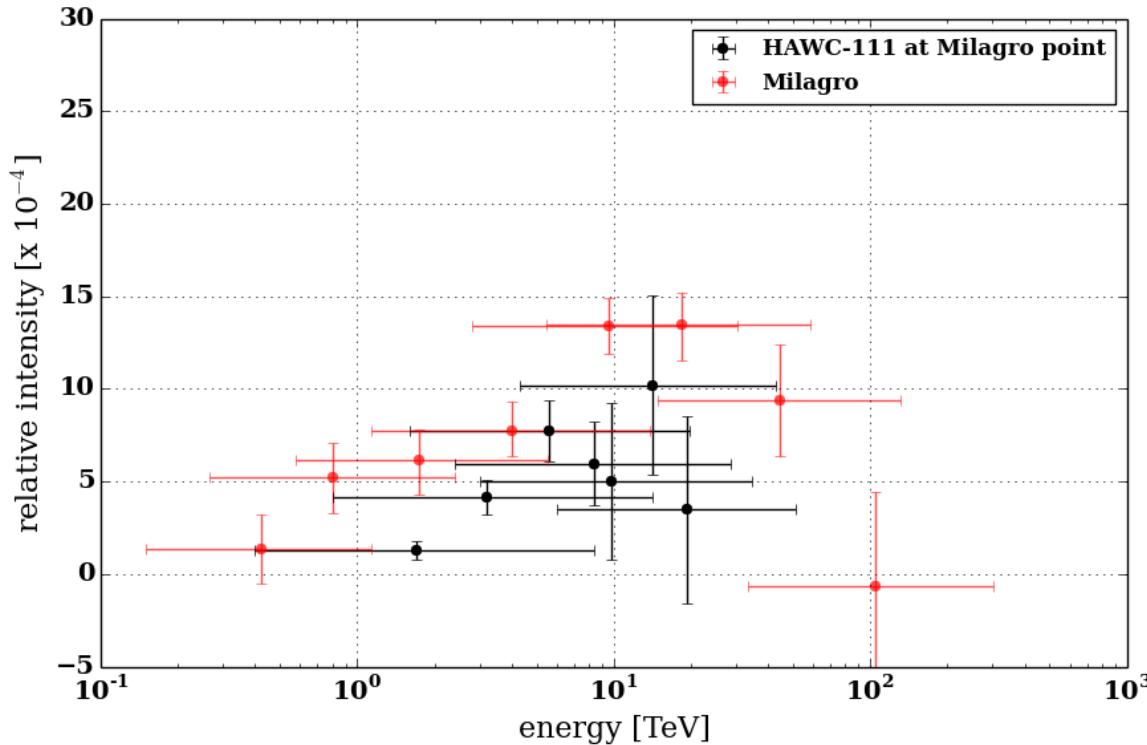
Relative Abundances



- Weighted by CREAM spectrum
- Gamma, H, He, C, O, Ne, Mg, Si, Fe
- Incident on HAWC detector

HAWC - Region A

- Relative intensity in 10° circle for 7 energy proxy bins
- “Hardening” of 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

HAWC Small-scale Anisotropy

Region C

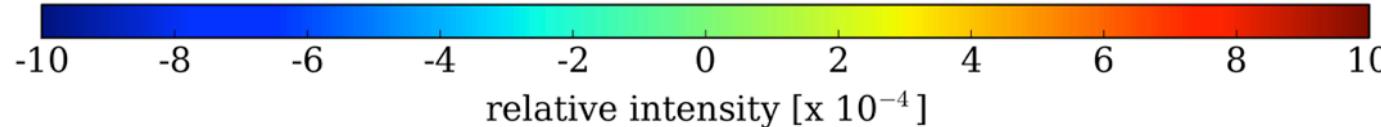
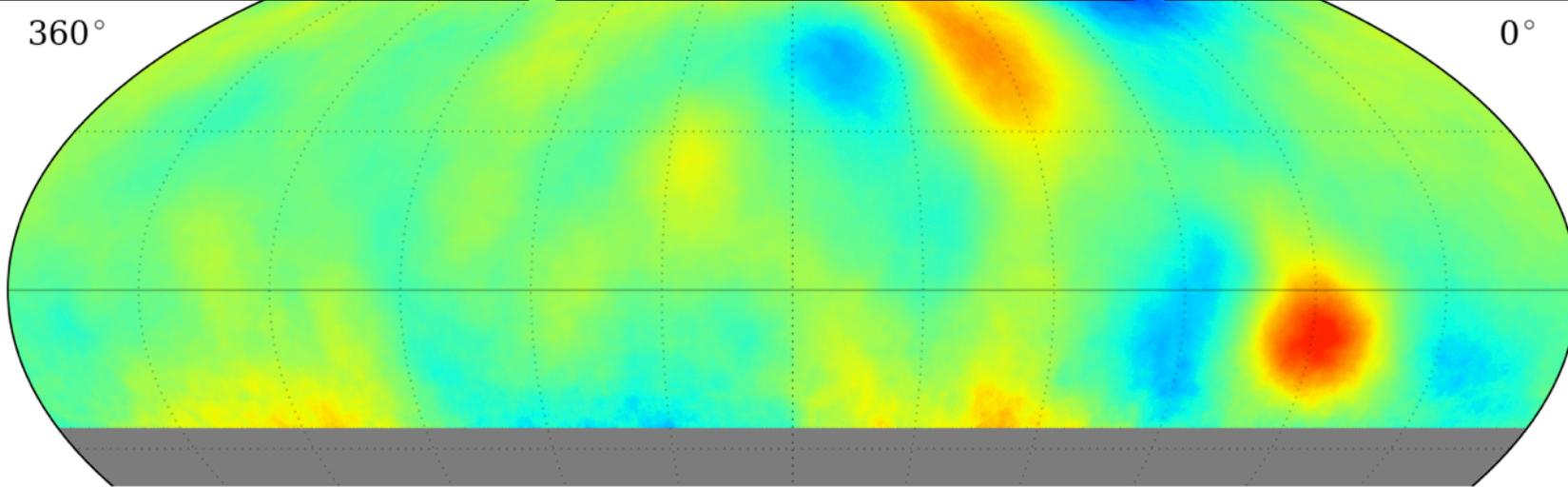
$(\alpha_0, \delta_0) = (206^\circ, 24^\circ)$
pre-trial significance 10.5σ
 $\Delta N / \langle N \rangle = 2.8 \times 10^{-4}$

Region B

$(\alpha_0, \delta_0) = (125^\circ, 46^\circ)$
pre-trial significance 15.6σ
 $\Delta N / \langle N \rangle = 5.3 \times 10^{-4}$

Region A

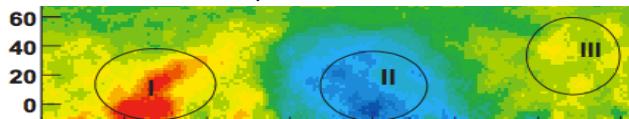
$(\alpha_0, \delta_0) = (58^\circ, -9^\circ)$
pre-trial significance 20.6σ
 $\Delta N / \langle N \rangle = 7.9 \times 10^{-4}$



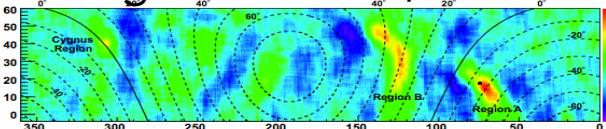
Experiment

1 sky map / year

1 – Tibet-AS γ 2005

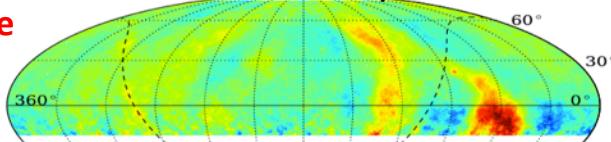


2 – Milagro 2008, 2009



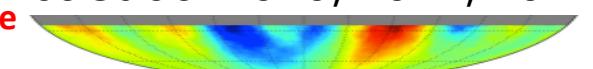
3 – ARGO-YBJ 2009, 2013

active



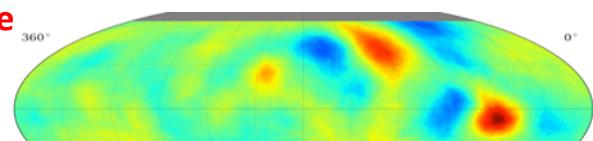
4 – IceCube 2010, 2011, 2012

active



5 – HAWC 2014

active



Theory

2 papers / month

Diffusive propagation of cosmic rays

Anomalous Anisotropies of Cosmic Rays from Turbulent Magnetic Fields

Understanding TeV band cosmic ray anisotropy

Martin Pohl

The Milagro anticenter hot spots: cosmic rays from the Geminga supernova ? (Research Note)

M. Salvat and P. Sacco²

Local Magnetic Turbulence

We study the effect of magnetic field anisotropy with local magnetic turbulence on the propagation of particles with low energy.

Gwenaelle Drury¹,
Dublin Institute for Advanced Studies
School of Cosmic Physics
31 Fitzwilliam Place,
Dublin 2, Ireland
ld@cp.dias.ie

In the energy range from $\sim 10^{12}$ eV both on large scales, with an amplitude $\approx 30^\circ$, and with amplitudes smaller by a factor of 10, the dipole moment is advected into anisotropic regions.

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

L. O'C. DRURY¹,
Dublin Institute for Advanced Studies
School of Cosmic Physics
31 Fitzwilliam Place,
Dublin 2, Ireland
ld@cp.dias.ie

ANISOTROPY OF TEV COSMIC RAYS AND THE OUTER HELIOSPHERIC BOUNDARIES

P. DESIATI¹,
Wisconsin IceCube Particle Astrophysics Center (WIPAC)
Department of Astronomy, University of Wisconsin, Madison, WI 53706
pdesiat@wisc.edu

LAZARIAN
Astronomy Department, University of Wisconsin, Madison, WI 53706
azarian@astro.wisc.edu

October 20, 2012

ABSTRACT

Cosmic-ray diffusion in collisionless plasmas including pressure anisotropy

M. S. Nakawka¹

Depto de Astronomía y Física del Espacio (IAFE)-CONICET, Ciudad Universitaria, Buenos Aires 1428, Argentina.

J. Pérez-Hernández²

Depto de Física, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires and IAFE-CONICET, Ciudad Universitaria, Buenos Aires 1428, Argentina

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

N. A. Schwadron^{1,2,*}, F. C. Adams³, E. R. Christian⁴, P. Desiati⁵, P. Frisch⁶, H. O. Funsten⁷, J. L. McComas^{2,8}, E. Moebius³, G.P. Zank^{1,9}

¹University of New Hampshire, Durham, NH 03824, USA
²Goddard Space Flight Center, Greenbelt, MD 20771, USA
³Astro-Particule and Cosmology (APC), Paris, France
⁴University of Texas at San Antonio, San Antonio, TX 78249, USA
⁵University of Texas at San Antonio, San Antonio, TX 78249, USA
⁶University of New Mexico, Albuquerque, NM 87545, USA
⁷University of New Mexico, Albuquerque, NM 87545, USA
⁸Corresponding author. E-mail: nash.schwadron@nasa.gov

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

G. Giacinti,^{a,b} M. Kachelrieß,^b D. V. Semikoz,^{c,d} G. Sigl^b

^aInstitut für Kybernetik, NTNU, Trondheim, Norway

^bII. Institut für Theoretische Physik, Universität Hamburg, Germany

^cAstro-Particle and Cosmology (APC), Paris, France

^dInstitute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia

Includes:

P. Mertsch and S. Funk, Phys. Rev. Lett., 114:021101 (2015)

L.G. Sveshnikova et al. Astropart Phys 50-52 (2013)

P. Desiati and A. Lazarian, Astrophys. J. 762, 44 (2013)

M. Pohl and D. Eichler, Astrophys. J. 766, 4 (2013)

G. Giacinti and G. Sigl, Phys. Rev. Lett. 109, 071101 (2012)

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