Cosmic ray sidereal time variation of galactic origin provides valuable information concerning the origin of cosmic rays and their propagation and modulation in space.

K. NAGASHIMA

WISCONSIN ICECUBE PARTICLE ASTROPHYSICS CENTER

Cosmic ray (anisotropy) observations as probes into their propagation in interstellar medium

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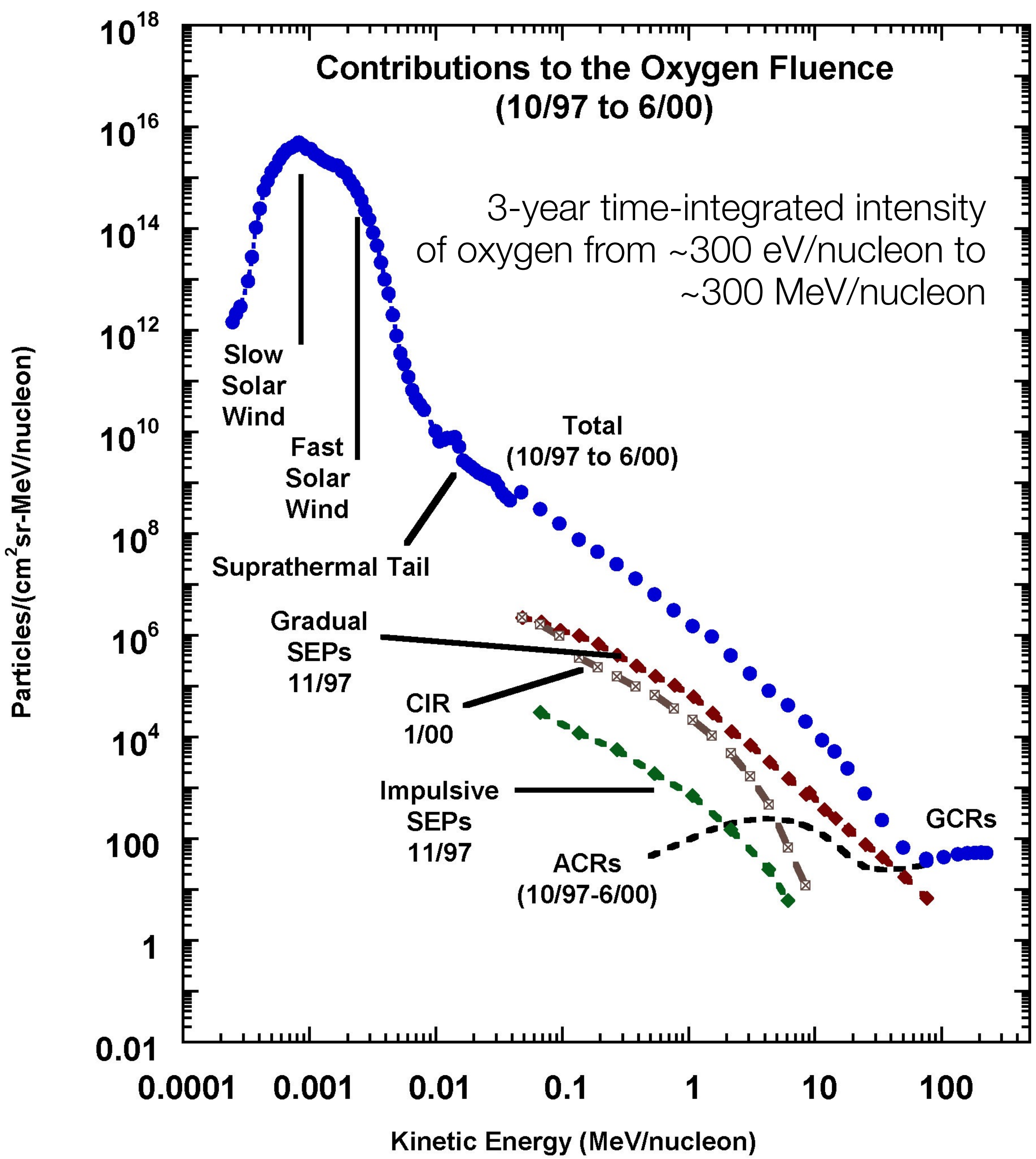
RAPP Center

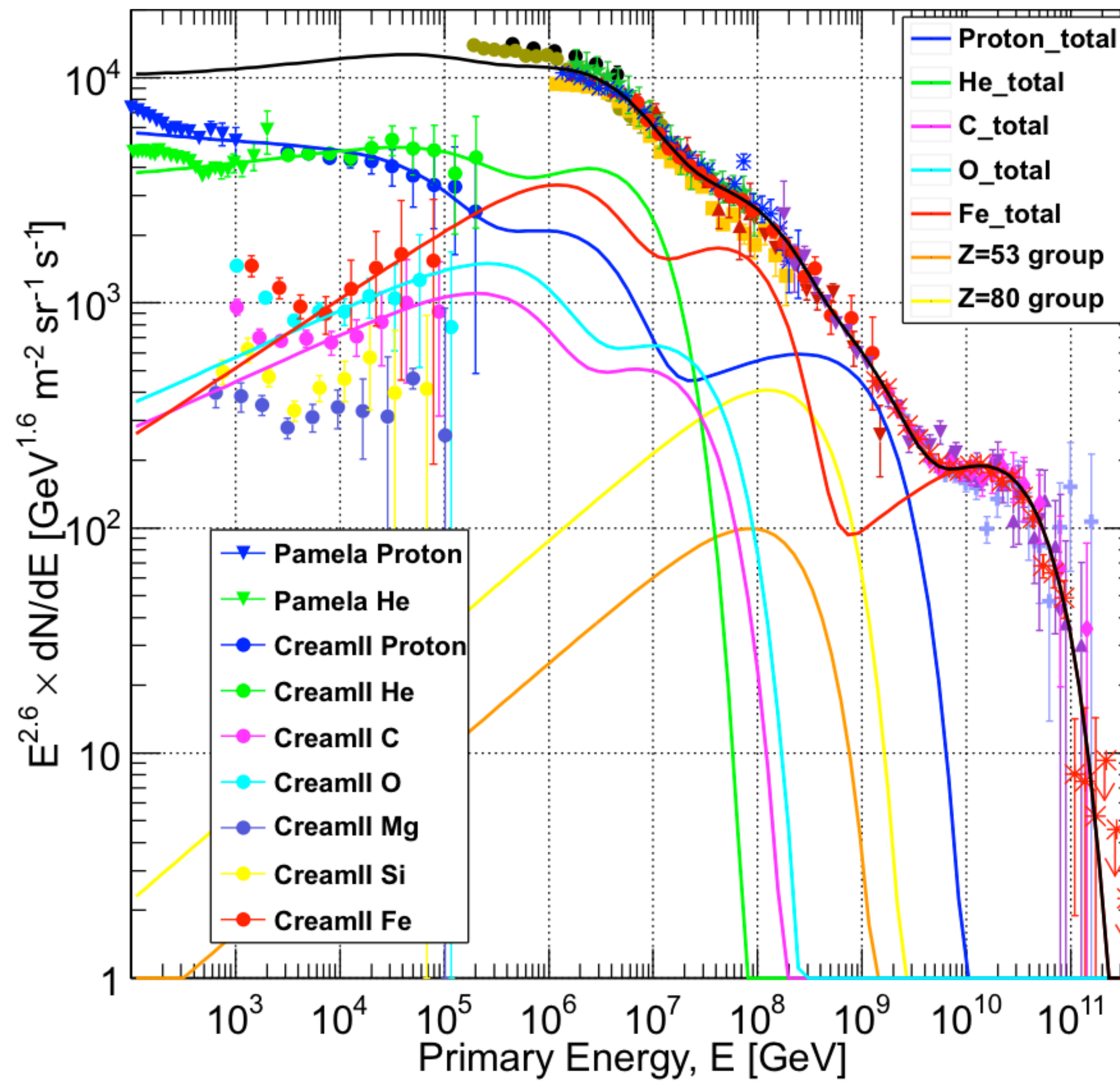
RAPP Center - Inauguration Workshop
Ruhr Universität Bochum - September 21-22, 2016

cosmic ray observations

spectral shape and their history

Richard Mewaldt (Caltech)
George Gloeckler & Glenn Mason (University of Maryland)





THE
PHYSICAL REVIEW
A Journal of Experimental and Theoretical Physics
VOL. 47, No. 11 JUNE 1, 1935 SECOND SERIES

An Apparent Effect of Galactic Rotation on the Intensity of Cosmic Rays

ARTHUR H. COMPTON, *University of Chicago and Oxford University* AND IVAN A. GETTING, *Oxford University*

(Received April 12, 1935)

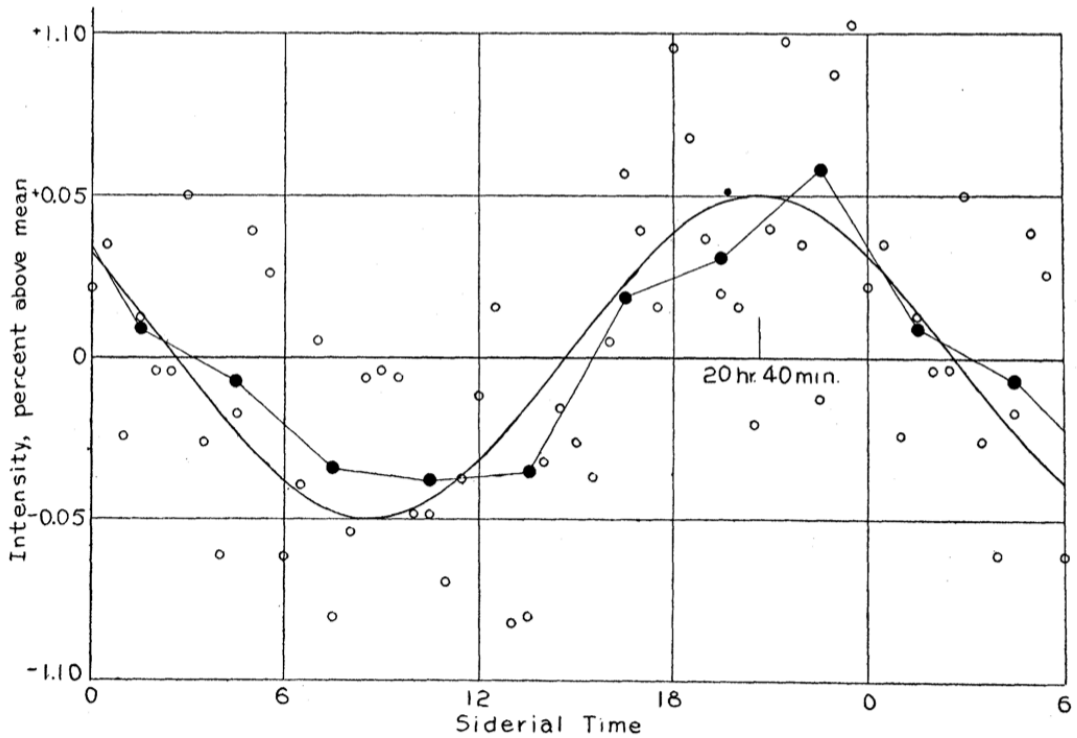
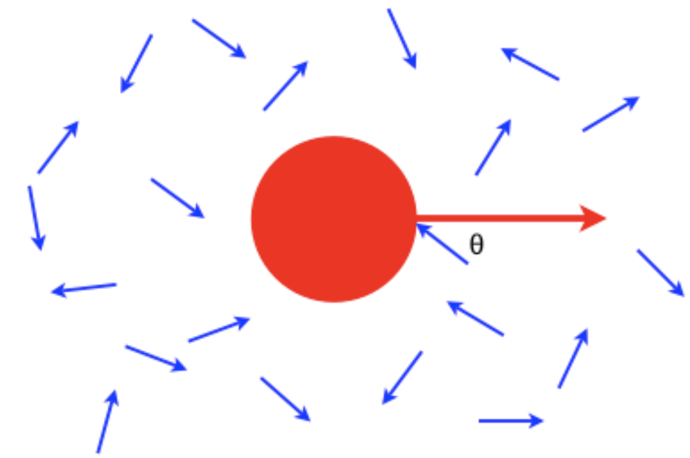


FIG. 2. Percentage variation in intensity of the cosmic rays with sidereal time. Curve, predicted effect due to galactic rotation. Data, Hess and Steinmaurer; open circles, half-hour means; solid circle, 3-hour means.

Its existence would imply that an important part of the cosmic rays originates outside of our galaxy. If its magnitude is found to be as great as we have predicted, it will imply that practically all the cosmic radiation has an extragalactic origin.

Compton-Getting Effect



$$\frac{\Delta I}{I} = (\gamma + 2)\frac{v}{c}\cos\theta$$

convective effect to produce a **dipole** anisotropy (**sidereal diurnal** anisotropy)

Compton & Getting, Phys. Rev. 47, 817 (1935)
Gleeson, & Axford, Ap&SS, 2, 43 (1968)

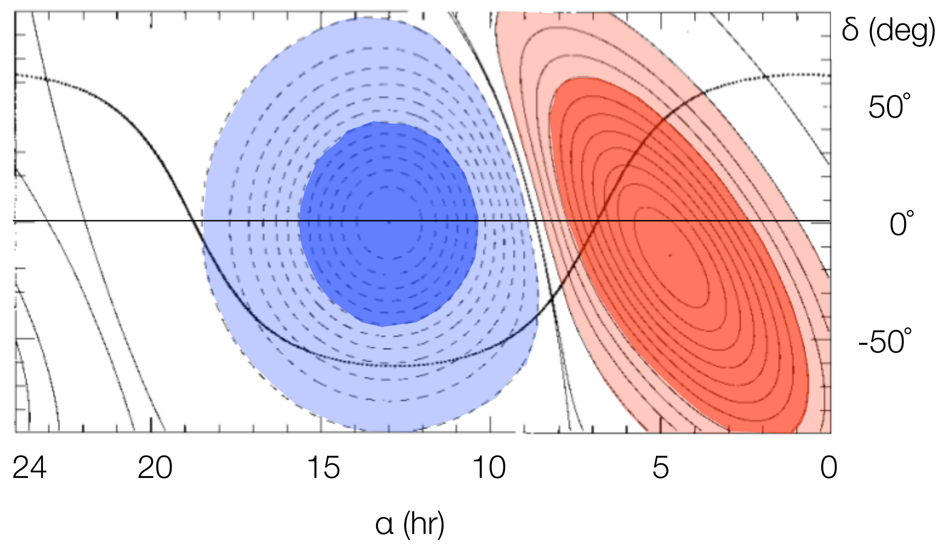
high energy cosmic rays

sidereal anisotropy

$\sim 10^{-3}$

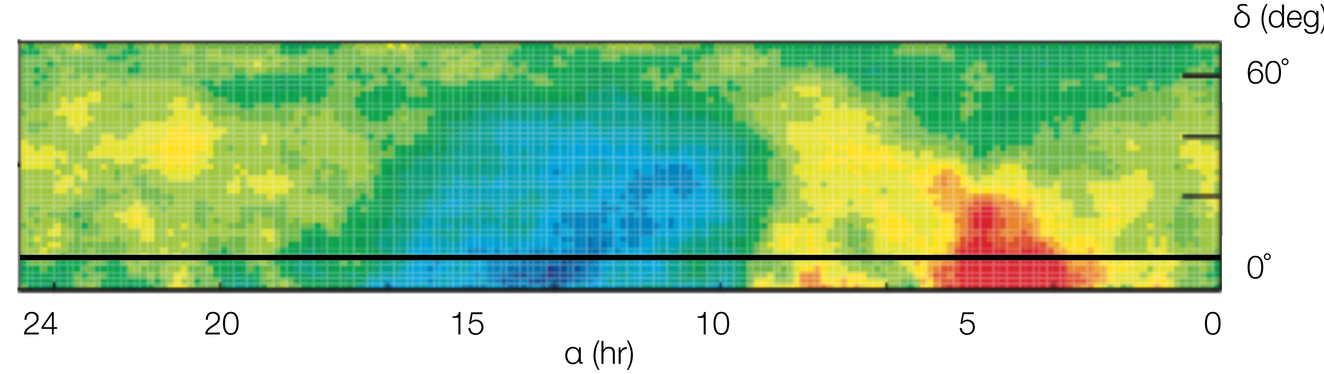
< 1 TeV

Nagashima et al. (1998)
Hall et al. (1999)

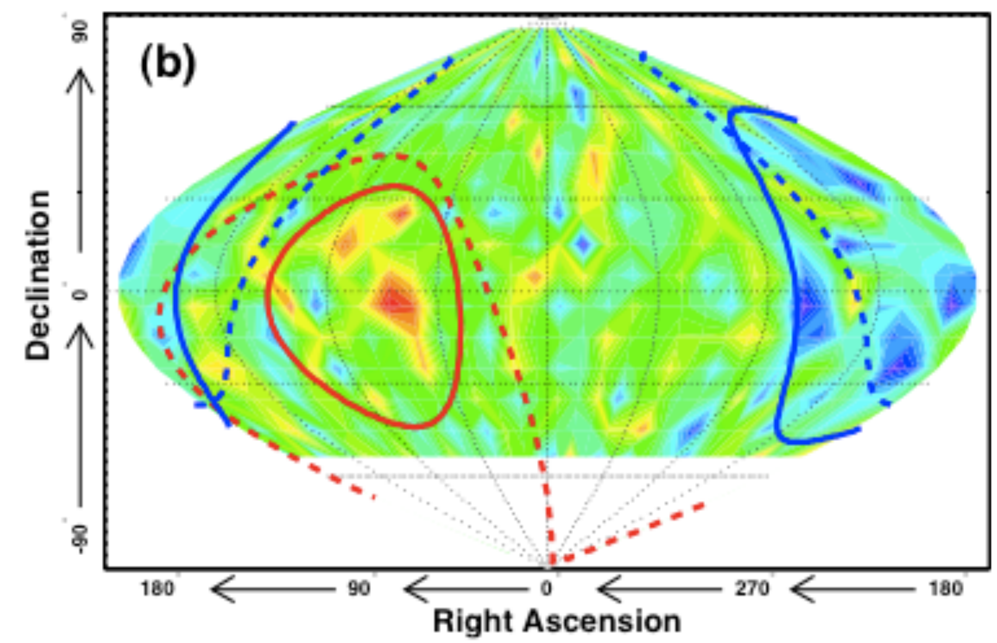


4 TeV

Tibet ASγ
Amenomori et al. (2006)



10 TeV

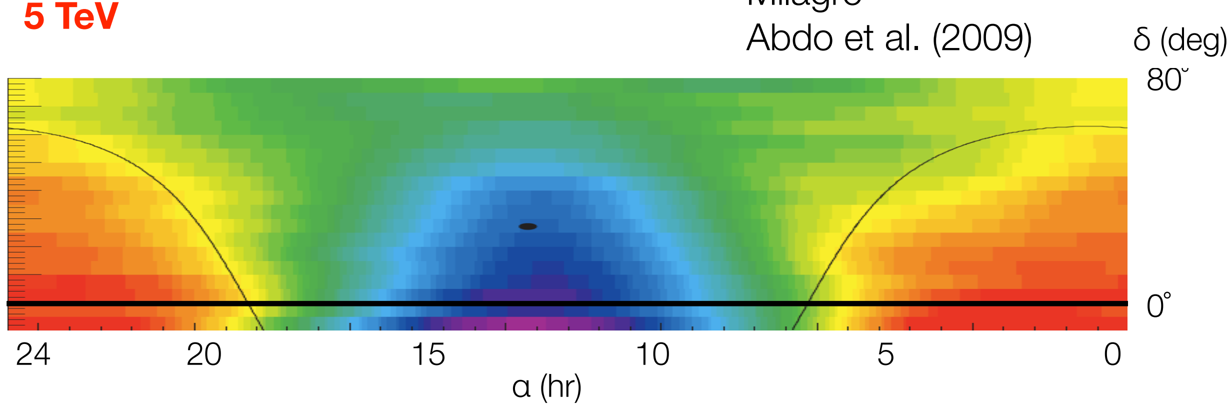


Super Kamiokande
Guillian et al. (2007)

equatorial coordinates

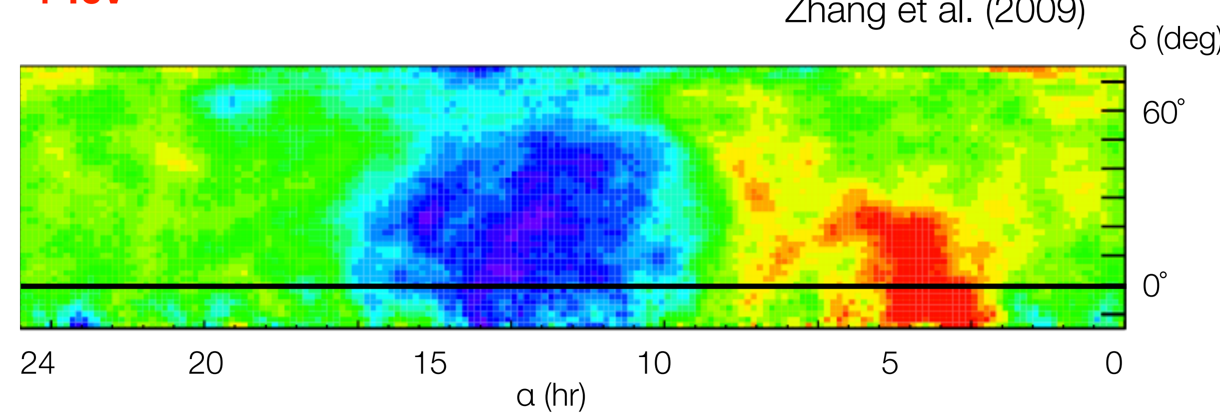
5 TeV

Milagro
Abdo et al. (2009)



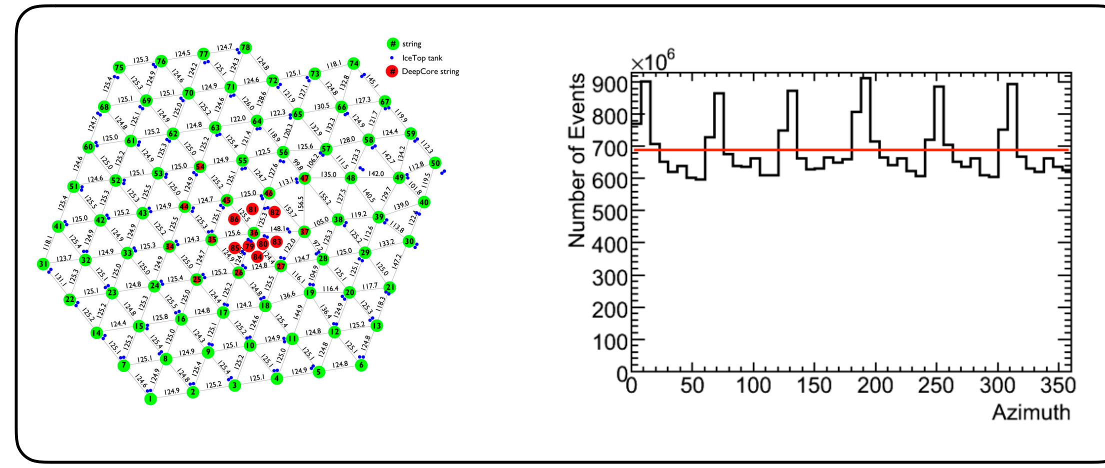
4 TeV

ARGO-YBJ
Zhang et al. (2009)



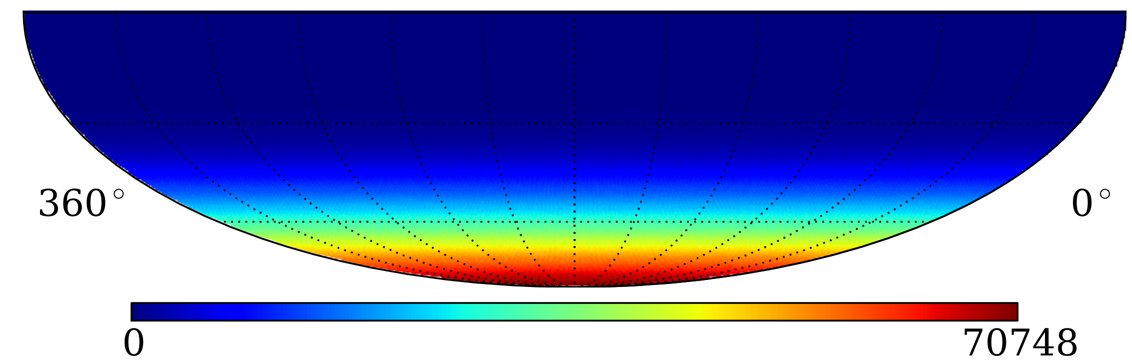
cosmic rays anisotropy

arrival direction distribution



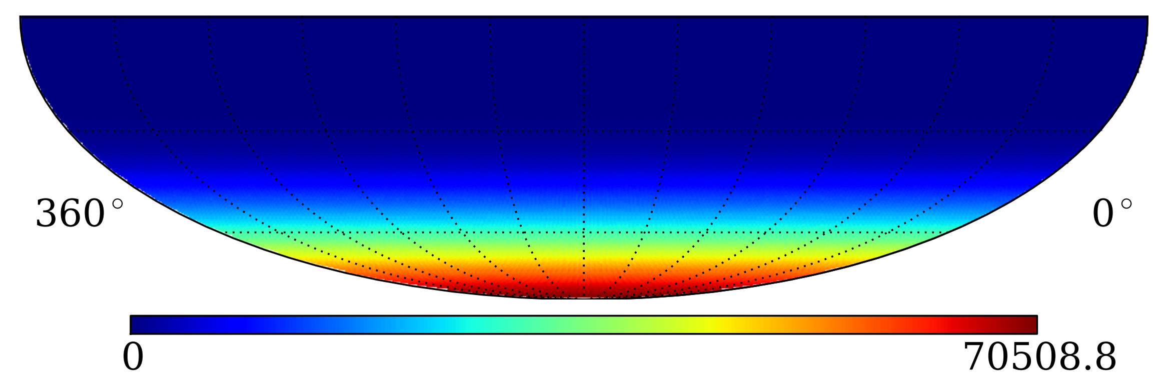
raw map of events in equatorial coordinates $(\alpha,\delta)_i$

1 month of data



reference map from events scrambled over 24hr in α (or time)

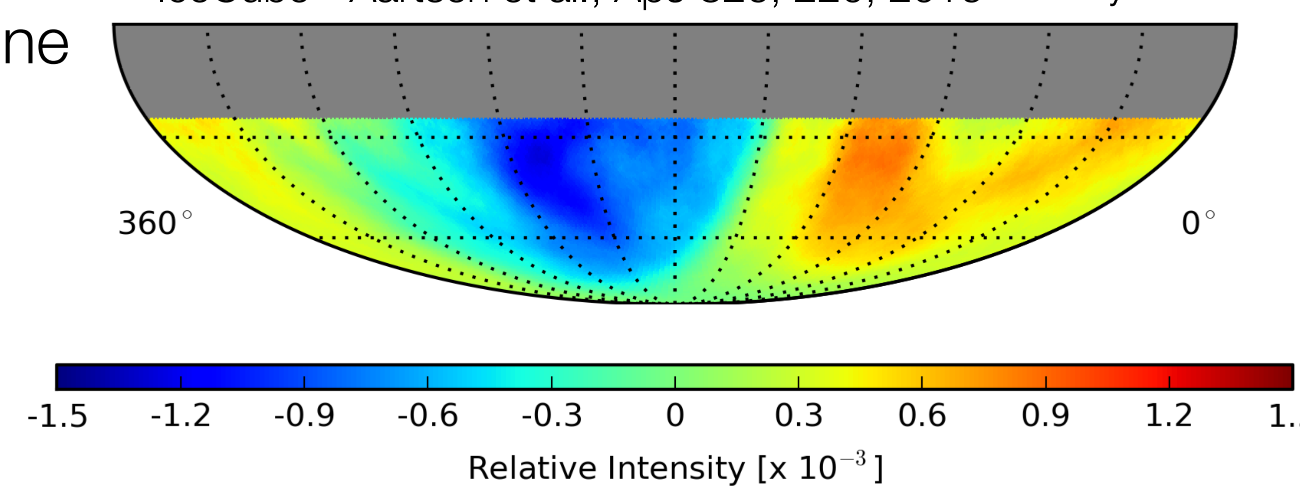
1 month of data



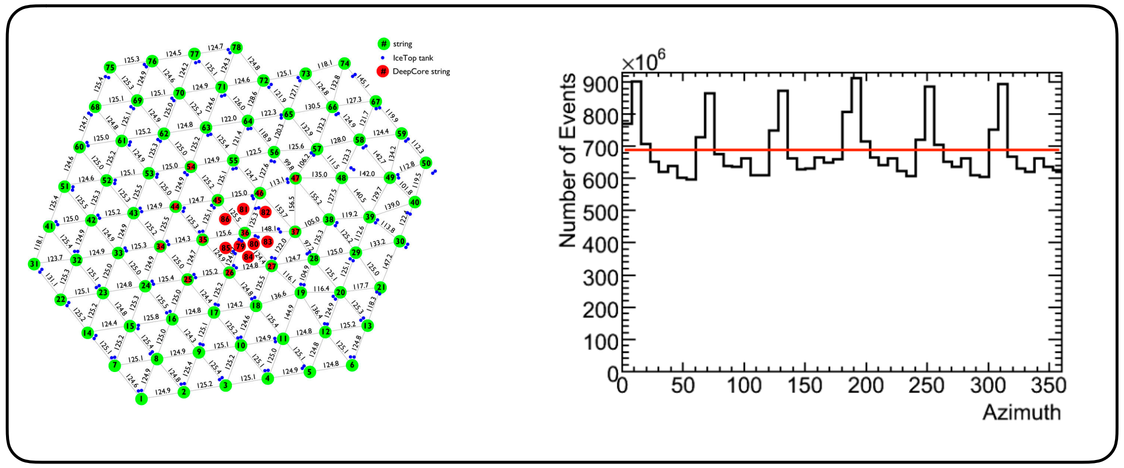
subtract reference map from raw map to determine the residual *relative intensity* map

$$\frac{\Delta I}{\langle I\rangle} \equiv \frac{N_i - \langle N\rangle}{\langle N\rangle}$$

IceCube - Aartsen et al., ApJ 826, 220, 2016 6 years of data



cosmic rays anisotropy
arrival direction distribution



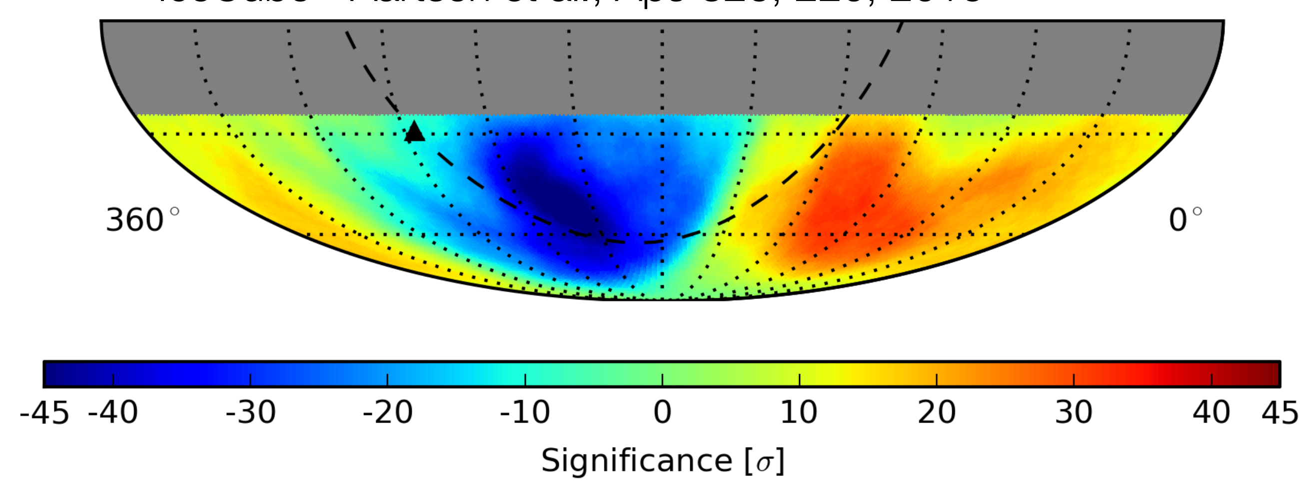
$$s = \sqrt{2}\left\{N_{\rm on}\ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\rm on}}{N_{\rm on}+N_{\rm off}}\right)\right]+N_{\rm off}\ln\left[(1+\alpha)\left(\frac{N_{\rm off}}{N_{\rm on}+N_{\rm off}}\right)\right]\right\}^{1/2}$$

$$\alpha = 1/20$$

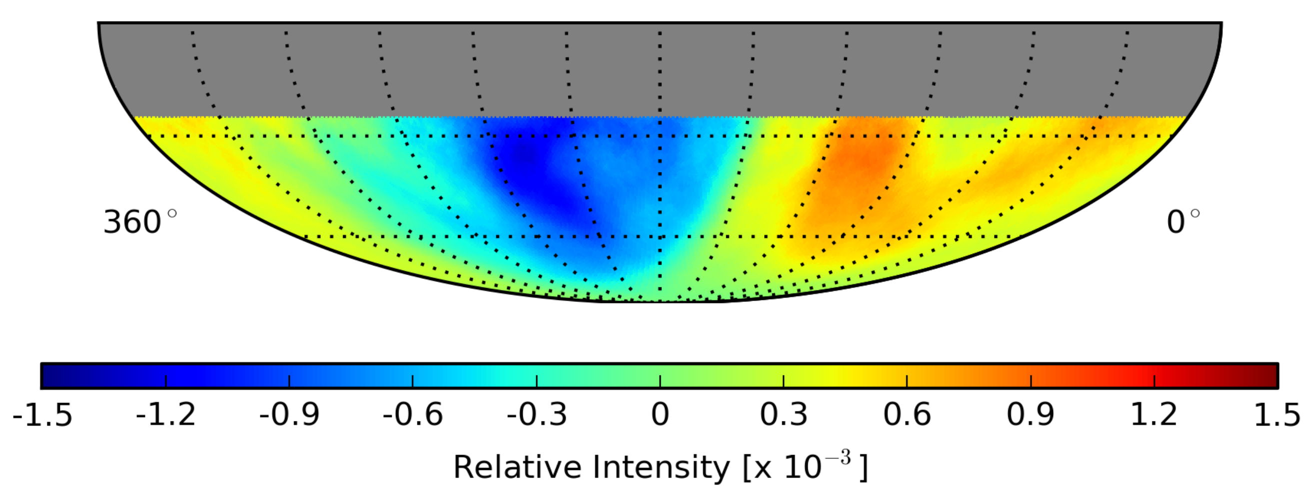
Li, T., & Ma, Y. 1983, ApJ, 272, 317

IceCube - Aartsen et al., ApJ 826, 220, 2016

statistical significance



relative intensity

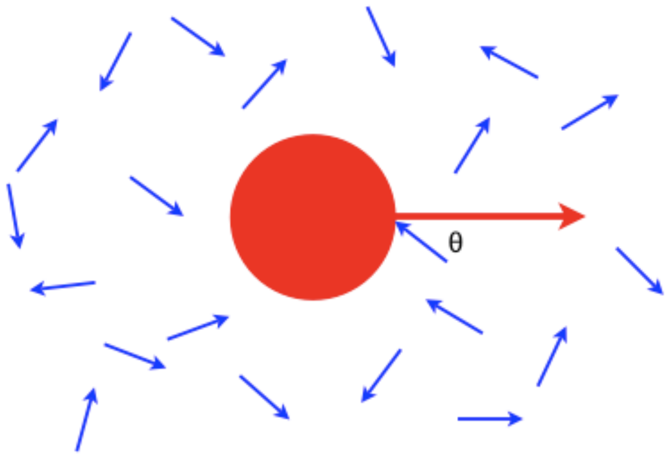


$$\frac{\Delta I}{\langle I\rangle} \equiv \frac{N_i - \langle N\rangle}{\langle N\rangle}$$

a known anisotropy

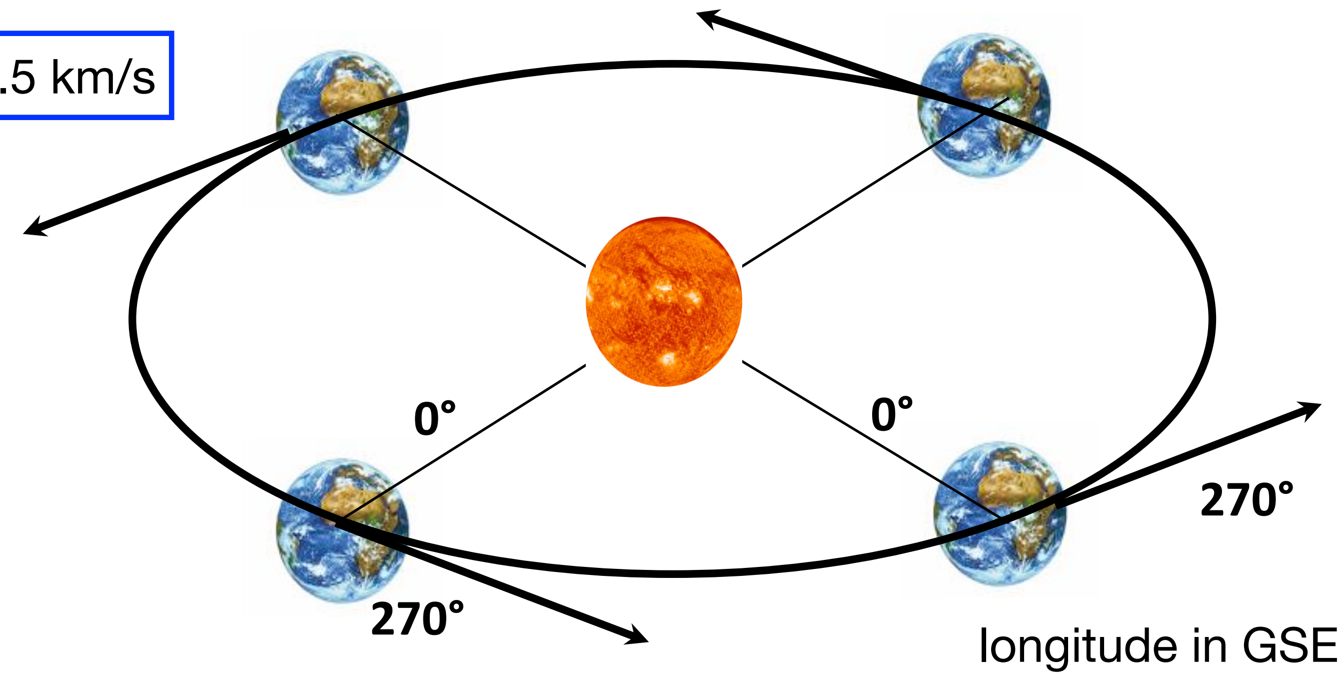
Earth's motion around the Sun

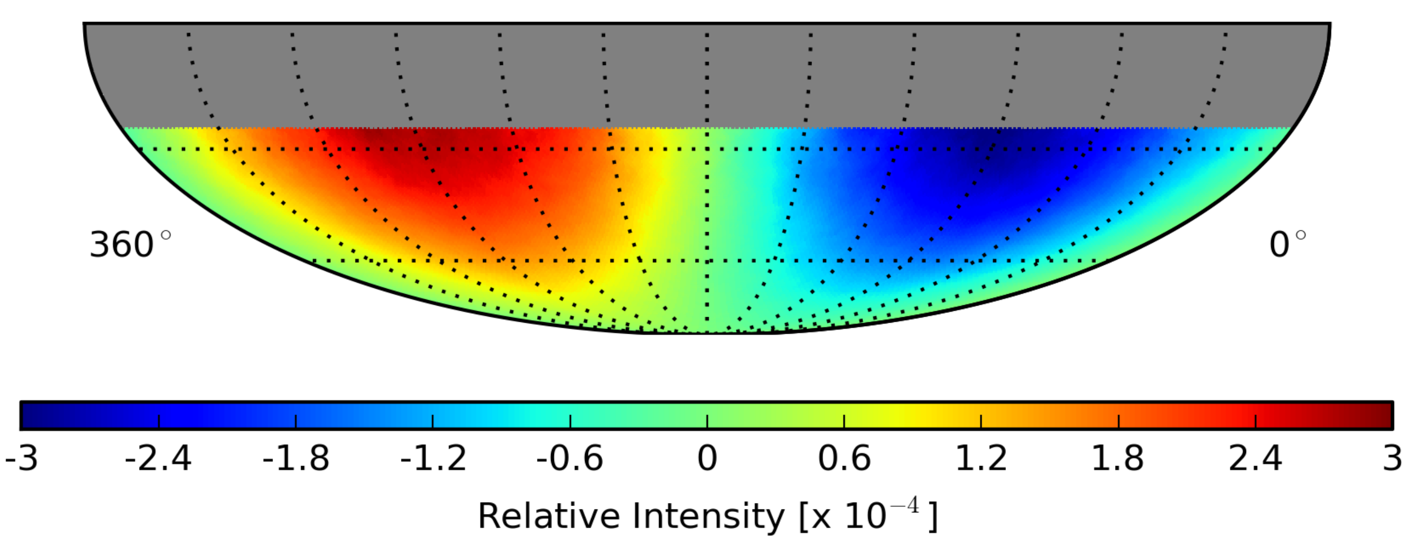
Compton & Getting, Phys. Rev. 47, 817 (1935)
Gleeson, & Axford, Ap&SS, 2, 43 (1968)

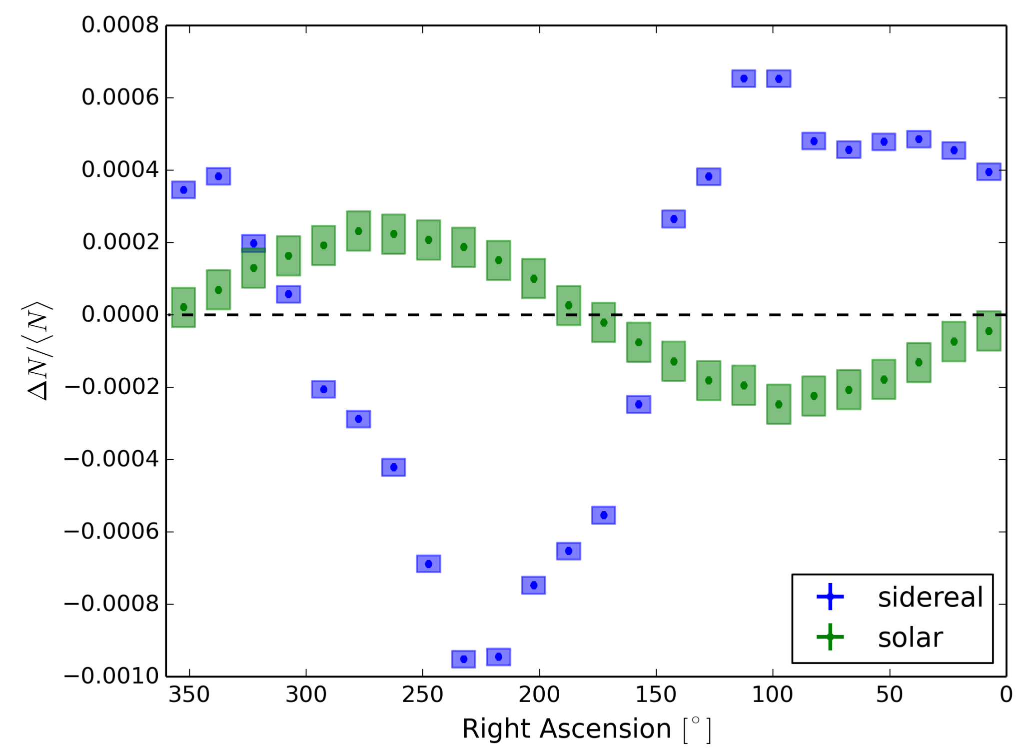


v = 29.8 ± 0.5 km/s

$$\frac{\Delta I}{I} = (\gamma + 2)\frac{v}{c}\cos\theta$$





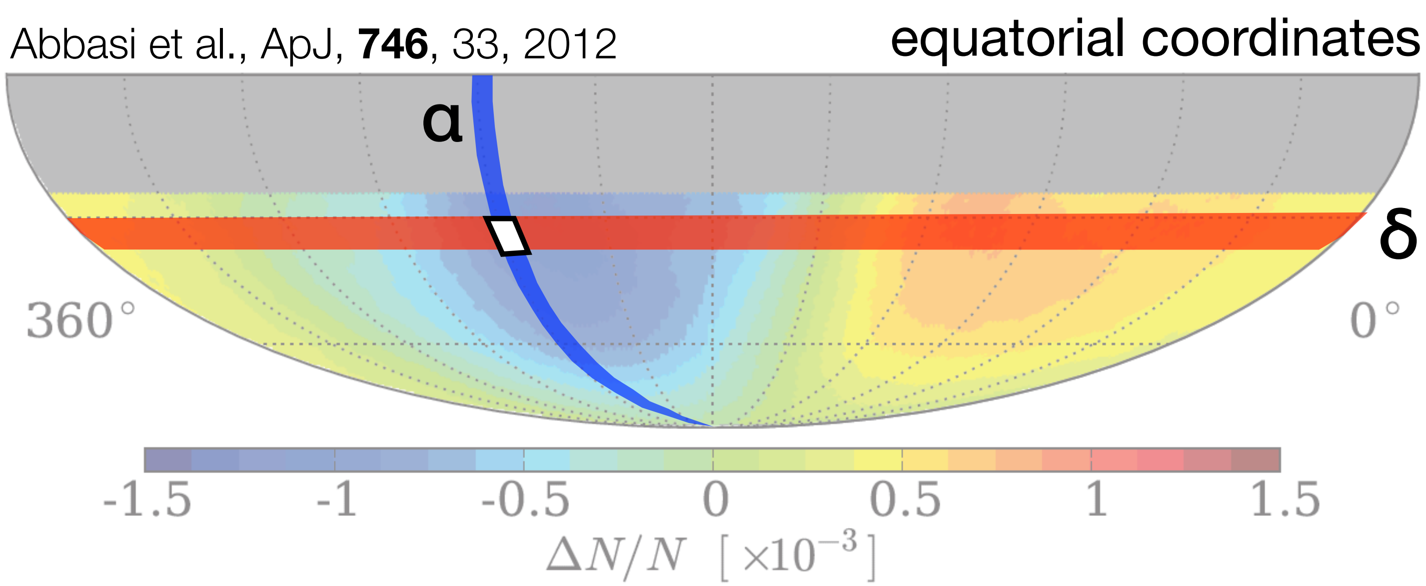


IceCube - Aartsen et al., ApJ 826, 220, 2016

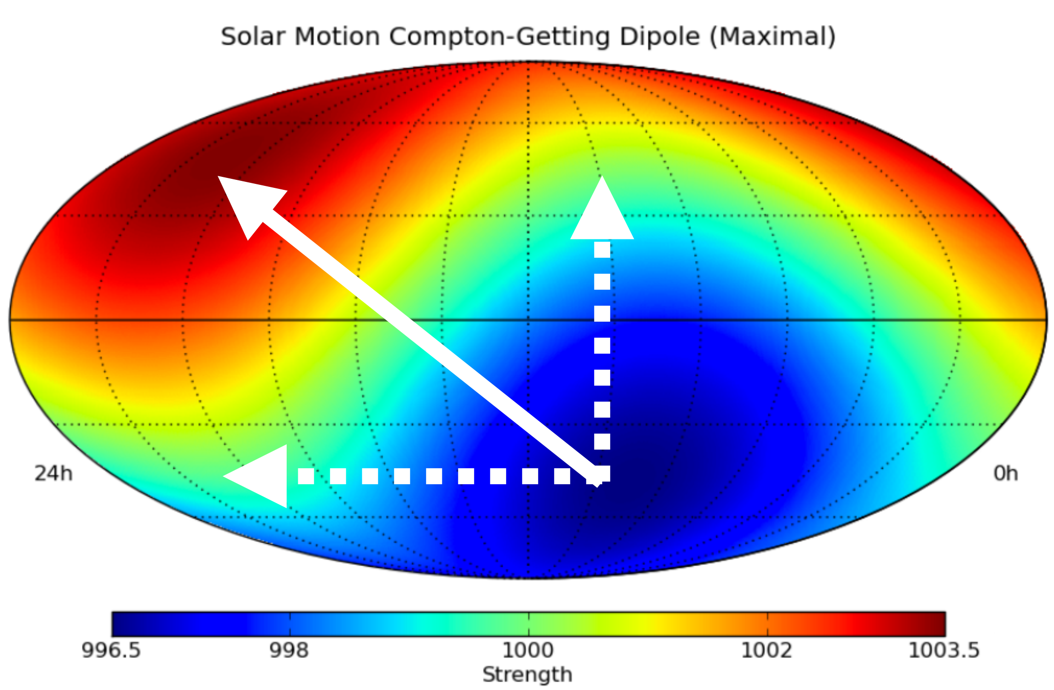
measuring cosmic ray anisotropy

projection biases

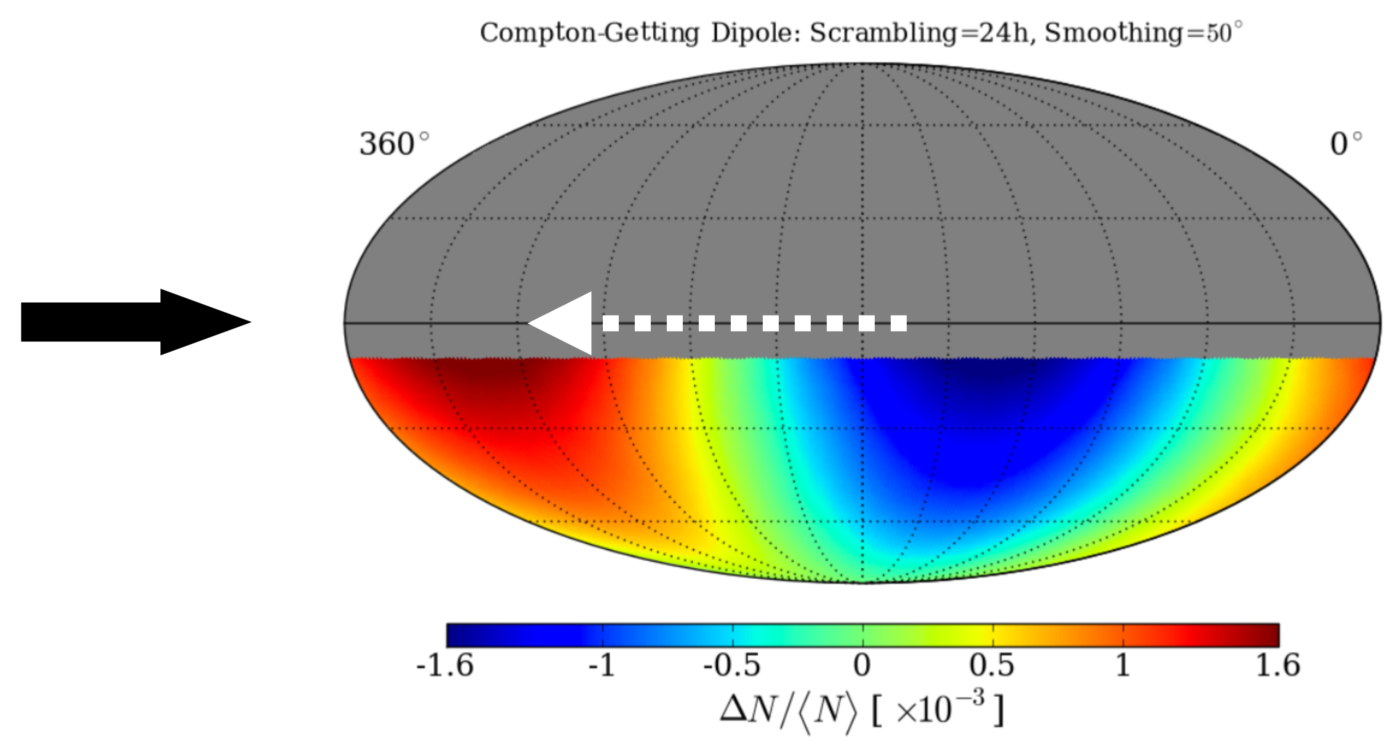
Abbasi et al., ApJ, **746**, 33, 2012



$$\frac{\Delta N_i}{\langle N \rangle_i} = \frac{N_i(\alpha,\delta) - \langle N_i(\alpha,\delta)\rangle}{\langle N_i(\alpha,\delta)\rangle}$$



$\Delta N/\langle N\rangle = 7\times10^{-3}$

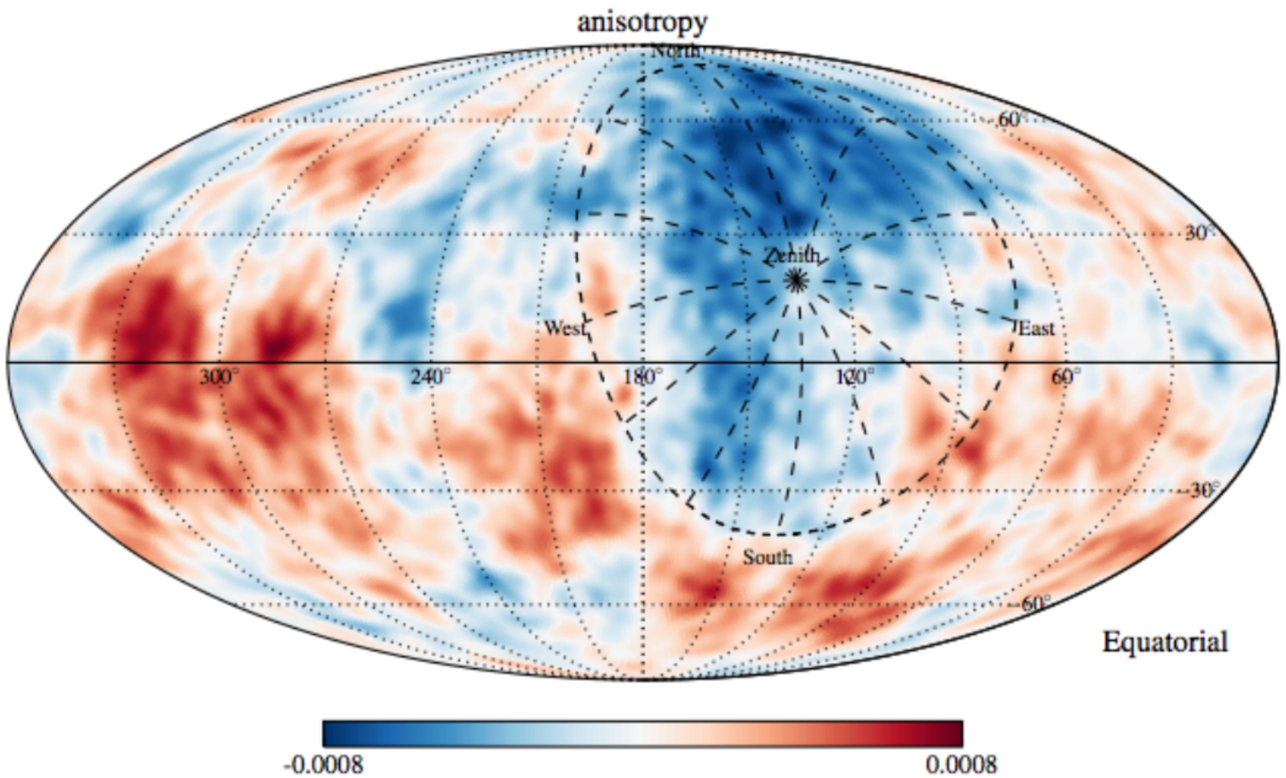


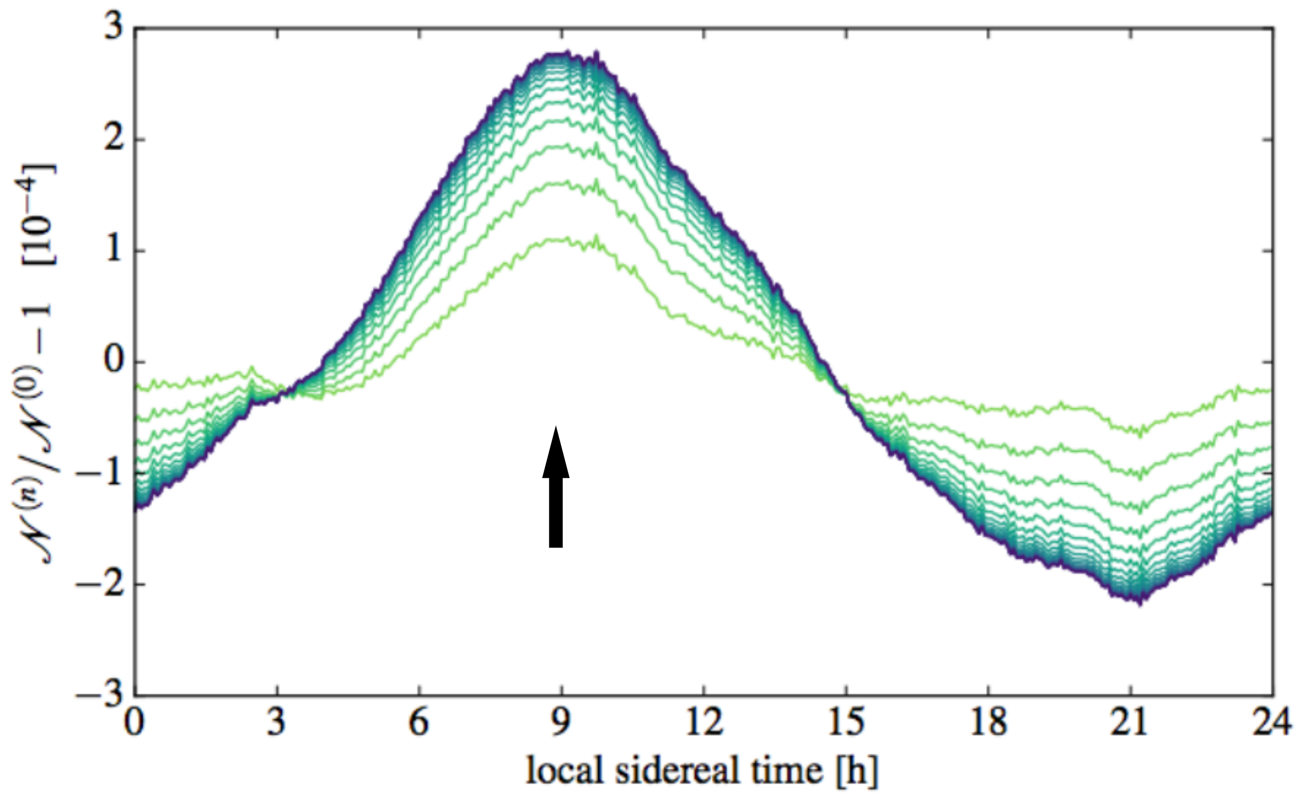
sky maps show **ONLY** modulations projected on **equatorial plane**

measuring cosmic ray anisotropy

field of view biases

Ahlers, BenZvi, PD, Díaz Vélez, Fiorino, Westerhoff
ApJ 823, 10 (2016) - arXiv:1601.07877





for experiments in a generic location on Earth

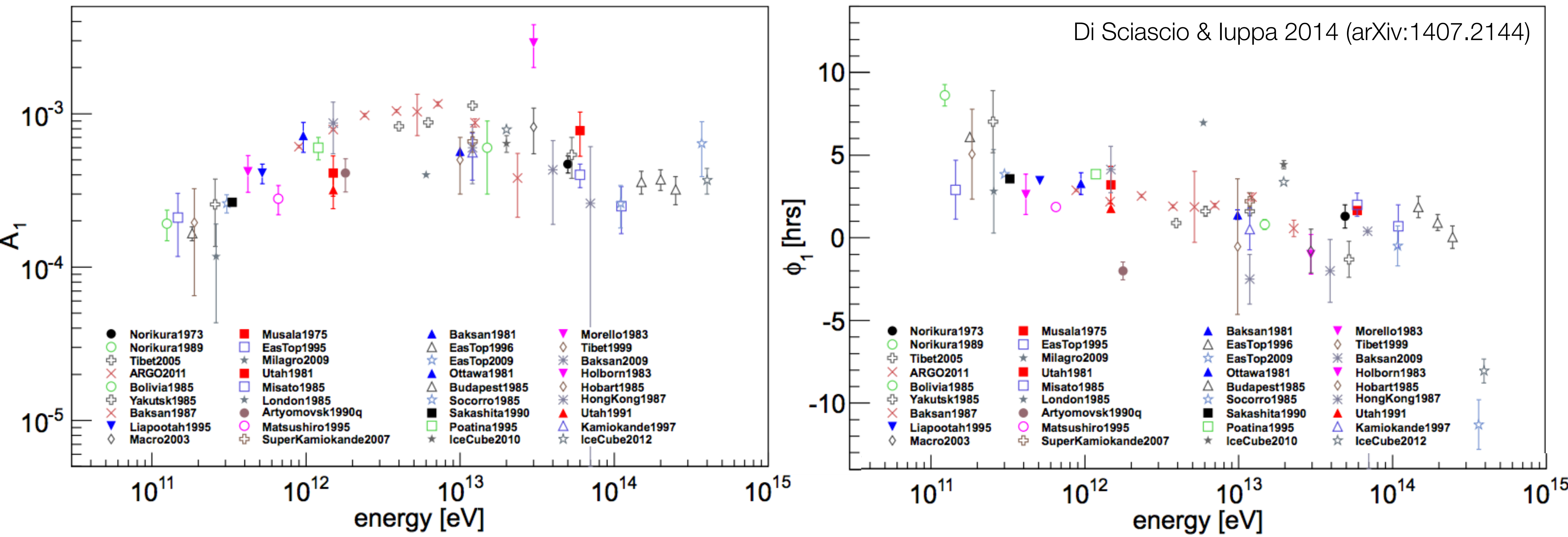
reduced anisotropy amplitude

wrong background estimation to be recovered with

iterative methods

measuring cosmic ray anisotropy

dipole component & interpretation

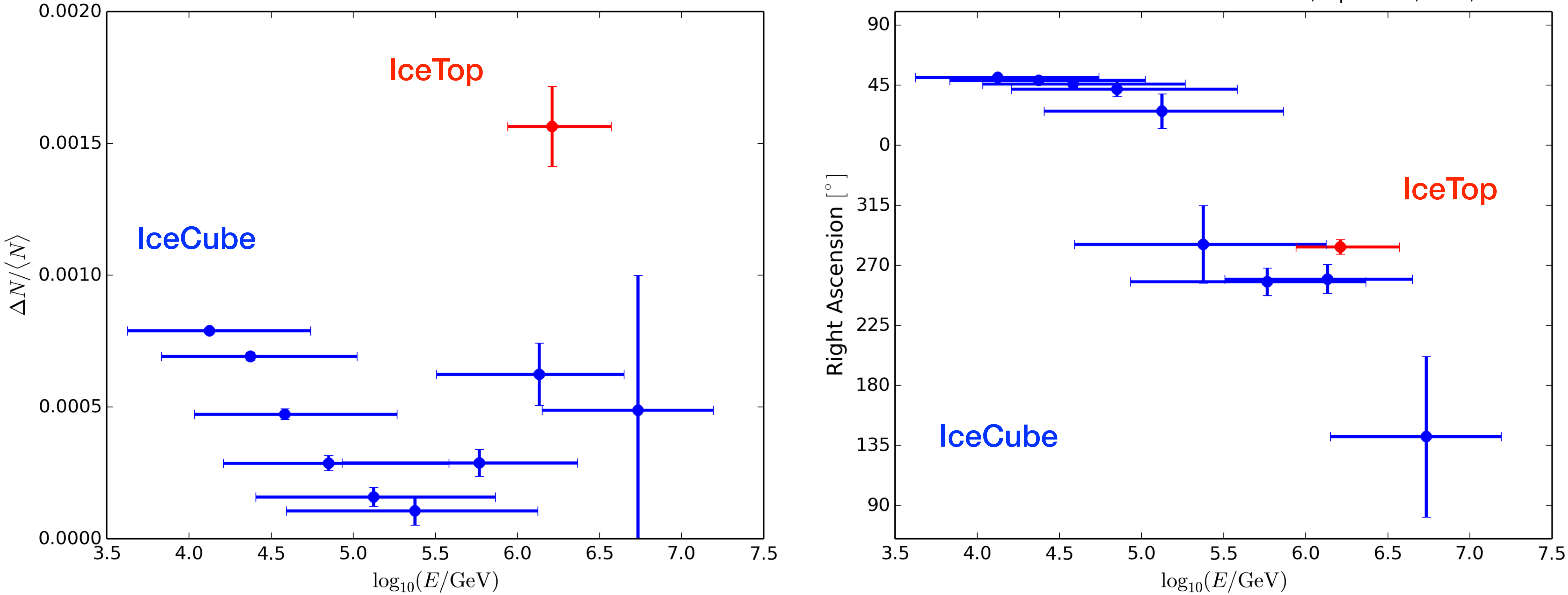


- some experimental methods might not sufficiently compensate for the limited FoV
- effect of missing vertical component on amplitude & phase variation
- anisotropy more structured than a simple dipole

measuring cosmic ray anisotropy

dipole component & interpretation

IceCube - Aartsen et al., ApJ 826, 220, 2016



- some experimental methods might not sufficiently compensate the limited FoV
- effect of missing vertical component on amplitude & phase variation
- anisotropy more structured than a simple dipole

measuring cosmic ray anisotropy

standard diffusion from local sources

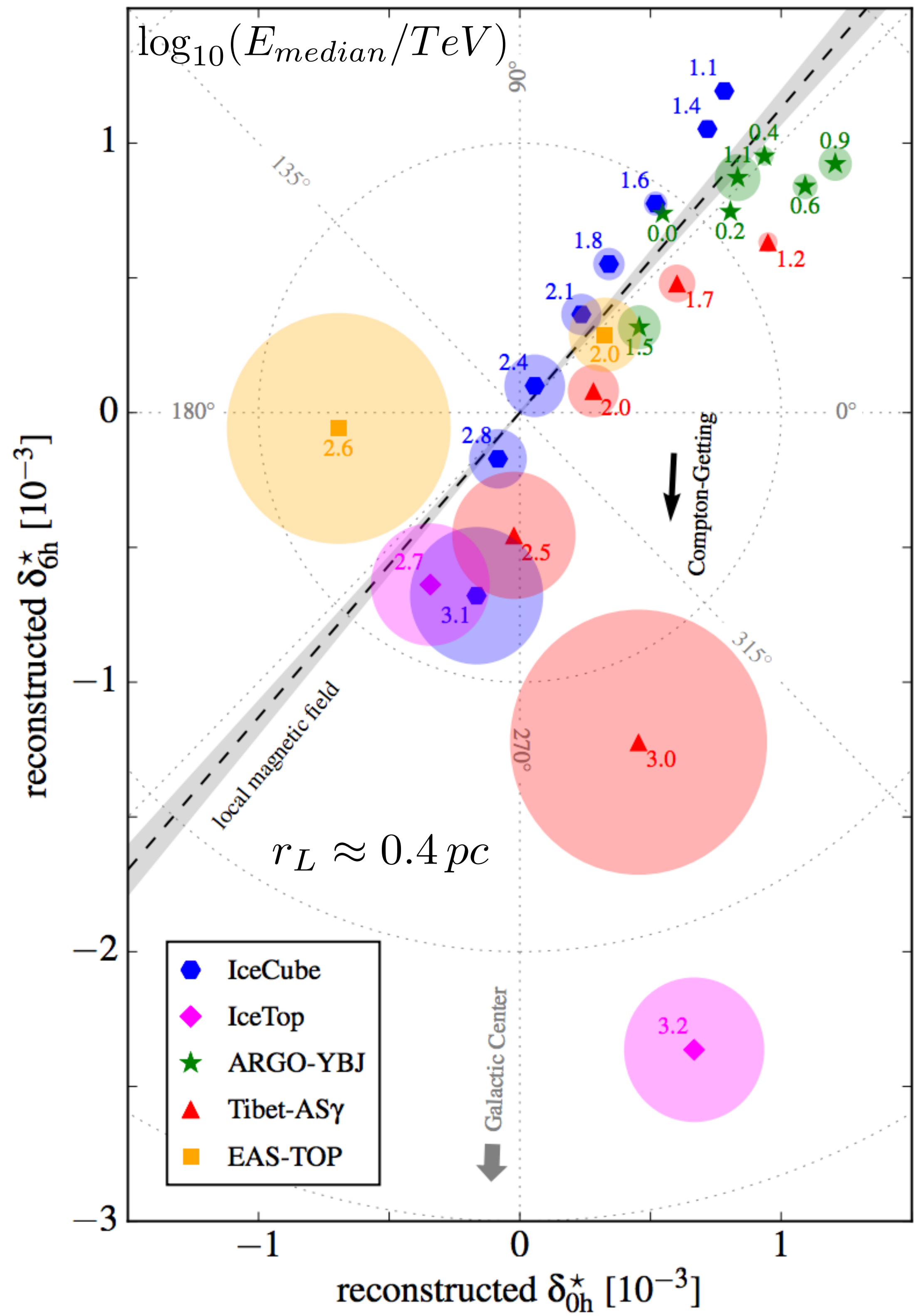
- dipole component on **equatorial plane**
- Compton-Getting corrected (wrt LSR)
- cross-talk between multipoles from limited FoV
- compare to IBEX LIMF direction

➡ dipole ordered by LIMF Schwadron, Adams, Christian, PD, Frisch, Funsten,Jokipii, McComas, Moebius, Zank Science 343, 988 (2014)

diffusion is **anisotropic** and aligned to LIMF

possible contribution from **Vela SNR**

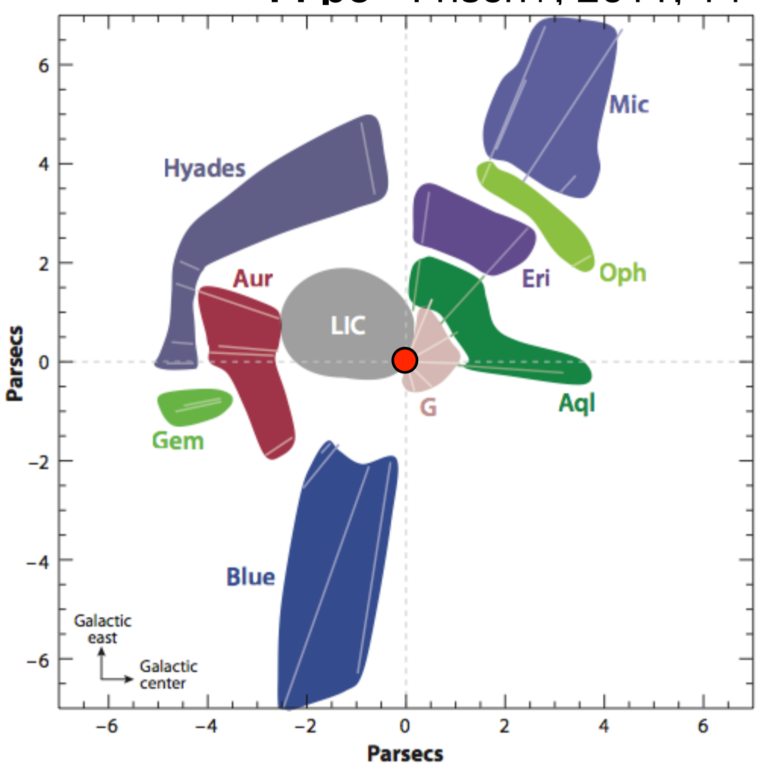
Ahlers 2016 - arXiv:1605.06446



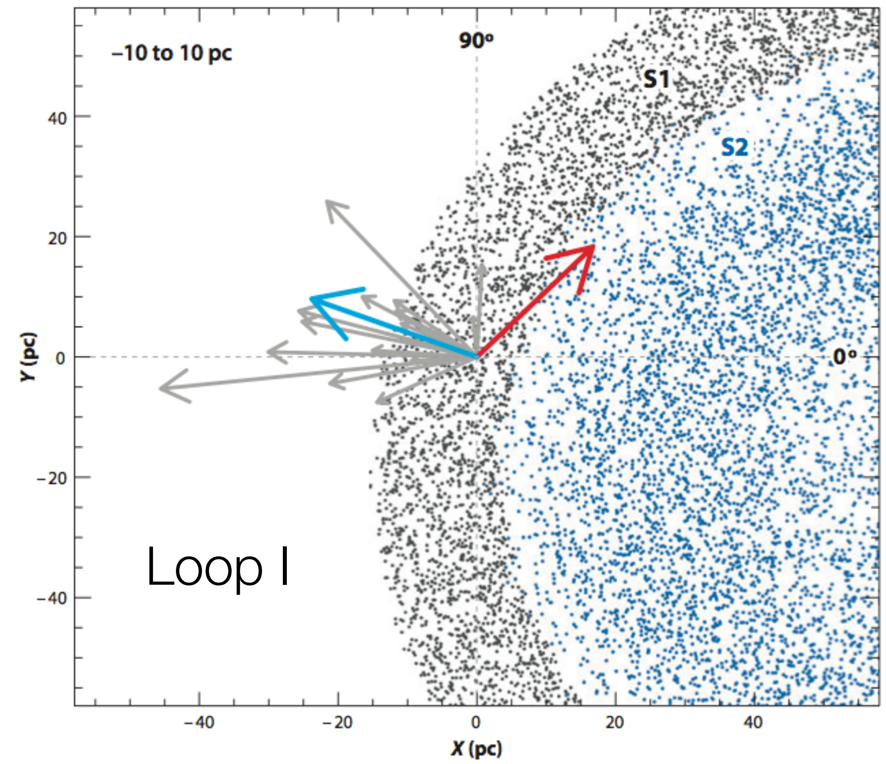
cosmic ray anisotropy

local interstellar medium

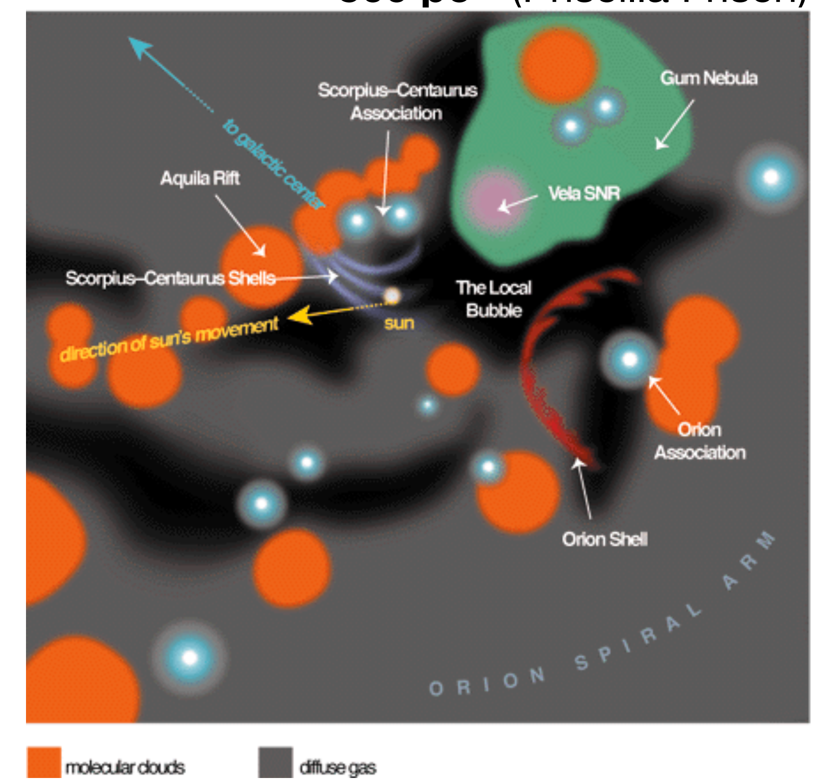
14 pc - Frisch+, 2011, 14



100 pc - Wolleben, 2007



500 pc - (Priscilla Frisch)



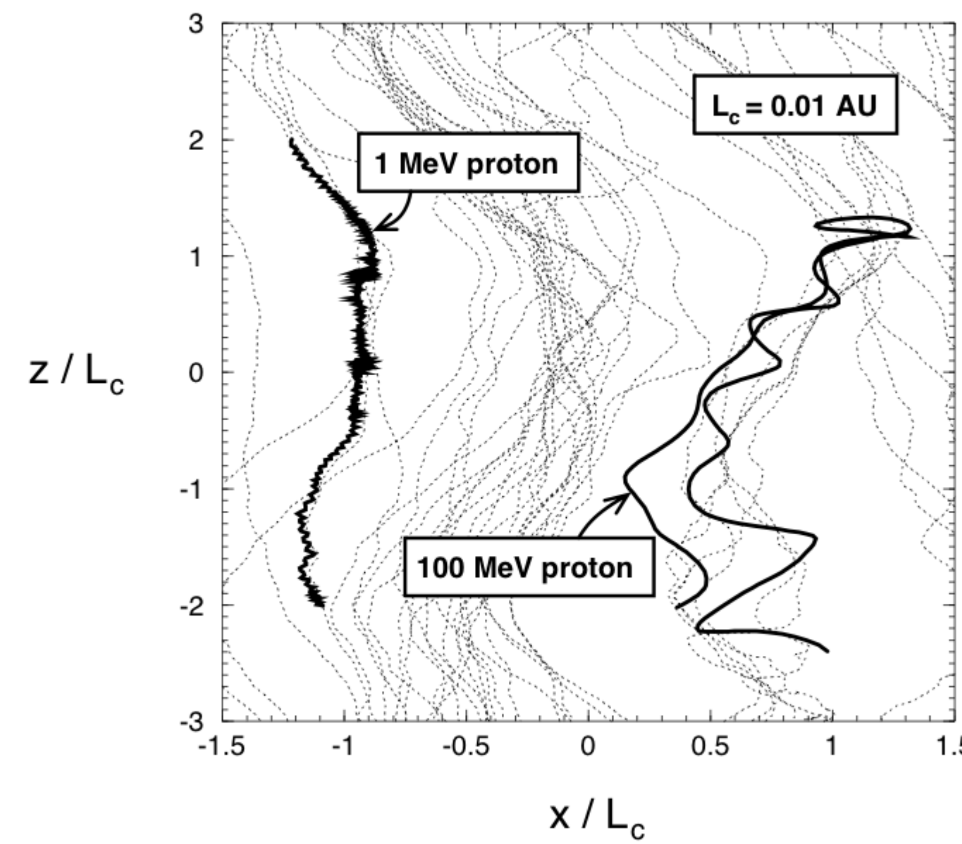
- interstellar magnetic field affected by inhomogeneities — Redfield & Linsky, 2008; Frisch+, 2011
- local ISMF relatively uniform over spacial scales of about 40-60 pc (**inter-arm**) — Frisch+, 2012,14, 15
- magnetic turbulence affects propagation and diffusion properties — Giacalone & Jokipii, 1994, 99; Yan, Lazarian, 2002,04,08
- non-diffusive processes from non-homogeneous magnetic fields — Harding+, 2016
- effects of *magnetic sinks* (astro-spheres) on CR arrival directions — Scherer+, 2016

transport across field lines

- if particles **tied** to magnetic field lines, $D_\perp$ limited by **FLRW** diffusion × $v_{particle}$
- parallel scattering reduces perpendicular diffusion below FLRW level
- **drift** due to large scale structure **too small**

$$\boxed{v_D \sim v_{particle}\,\frac{r_L}{L_{scale}}}$$

- **scattering** by small (~r_L) fluctuations, responsible of $D_\parallel$ also produces $D_\perp$



large scale geometry significantly enhances particle cross-field line diffusion

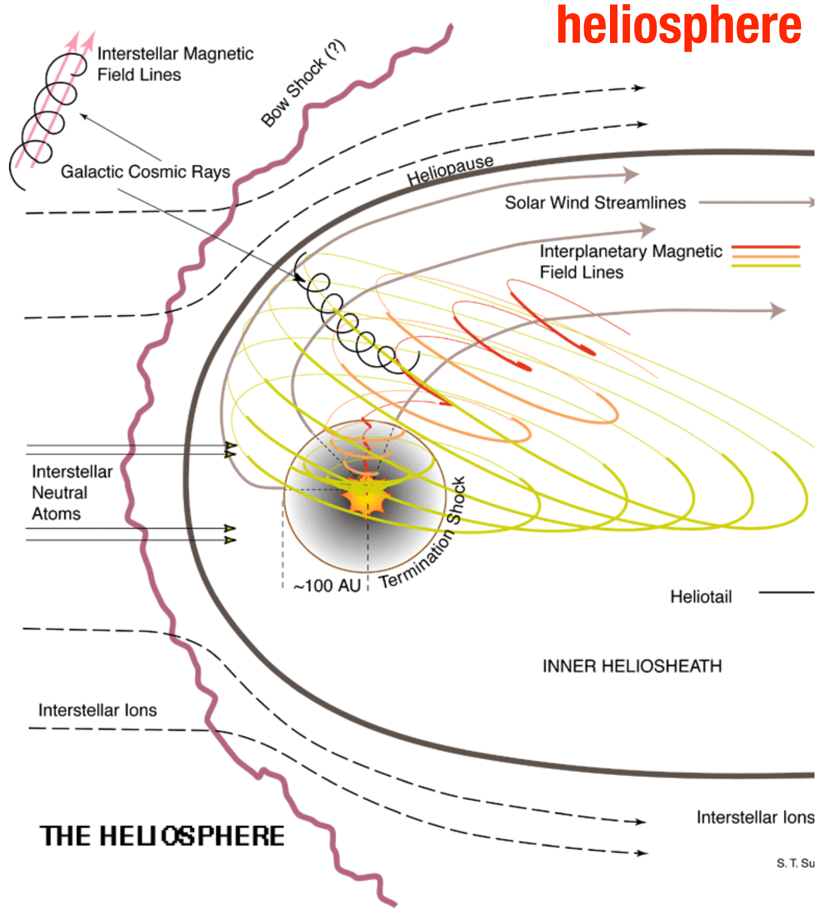
(PD, Zweibel ApJ 701, 51, 2014
PD, Zweibel, Sebald, in prep.)

cosmic ray anisotropy

heliosphere

$$r_L \approx \frac{200}{Z}\,\frac{E(TeV)}{B(\mu G)}\,AU$$

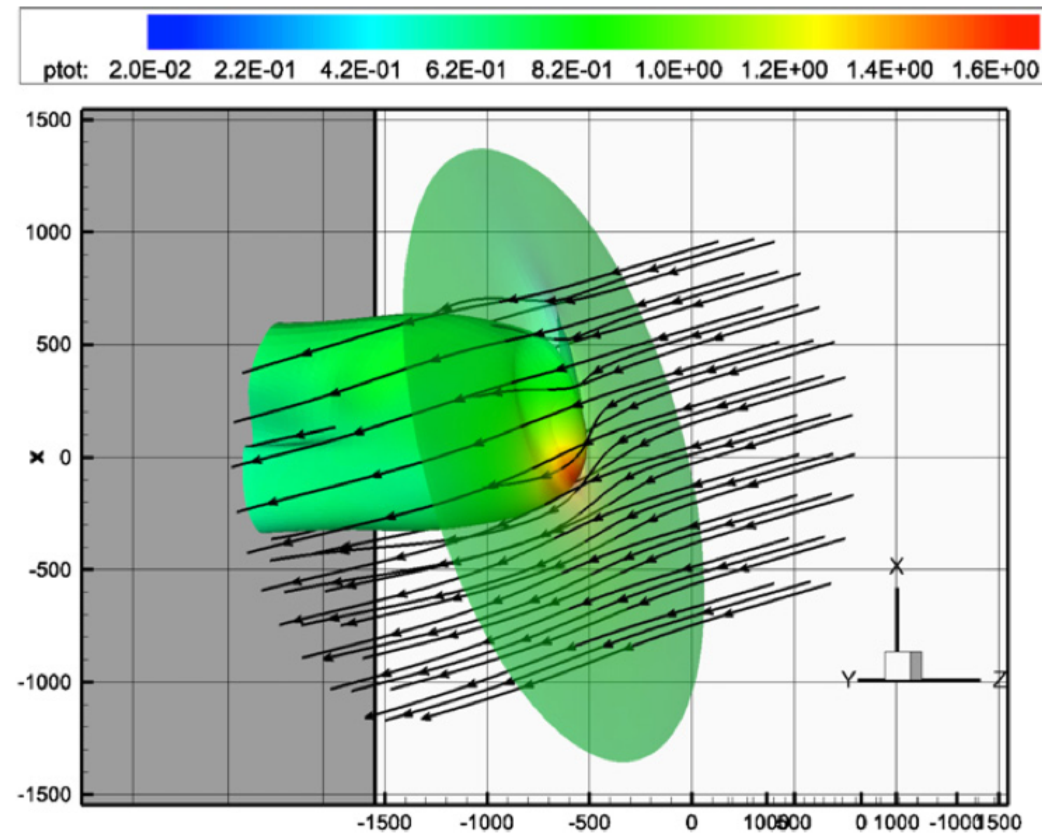
heliosphere



heliotail

local ISMF
draping around
heliosphere

Pogorelov+ 2011



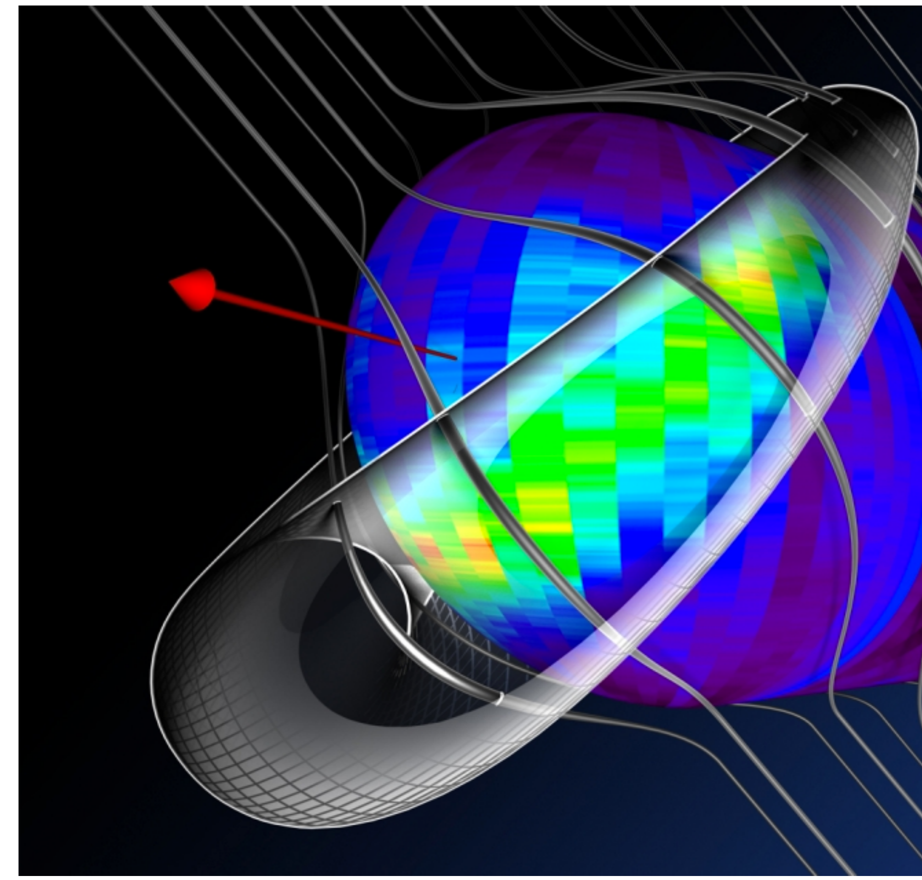
- heliosphere as O(100-1000) AU **magnetic perturbation of local ISMF** PD & Lazarian, 2013
- influence on ≲ 10 TeV protons (R_L ≲ 600 AU)
- cosmic rays >100's TeV influenced by interstellar magnetic field (**change of anisotropy**)

anisotropy and local galactic environment

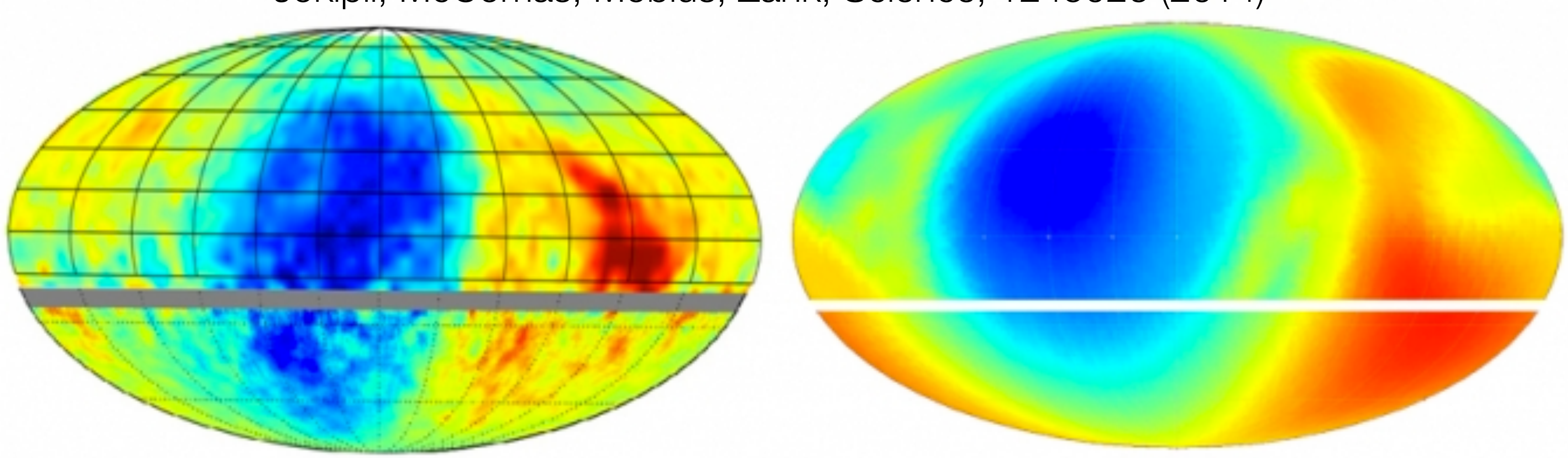
low to high energy connection

- IBEX observations of keV Energetic Neutral Atoms
- determination of interstellar flow direction
- determination of interstellar magnetic field direction

- large scale heliosphere to induce **perturbations** in arrival direction of TeV cosmic rays ordered by LIMF



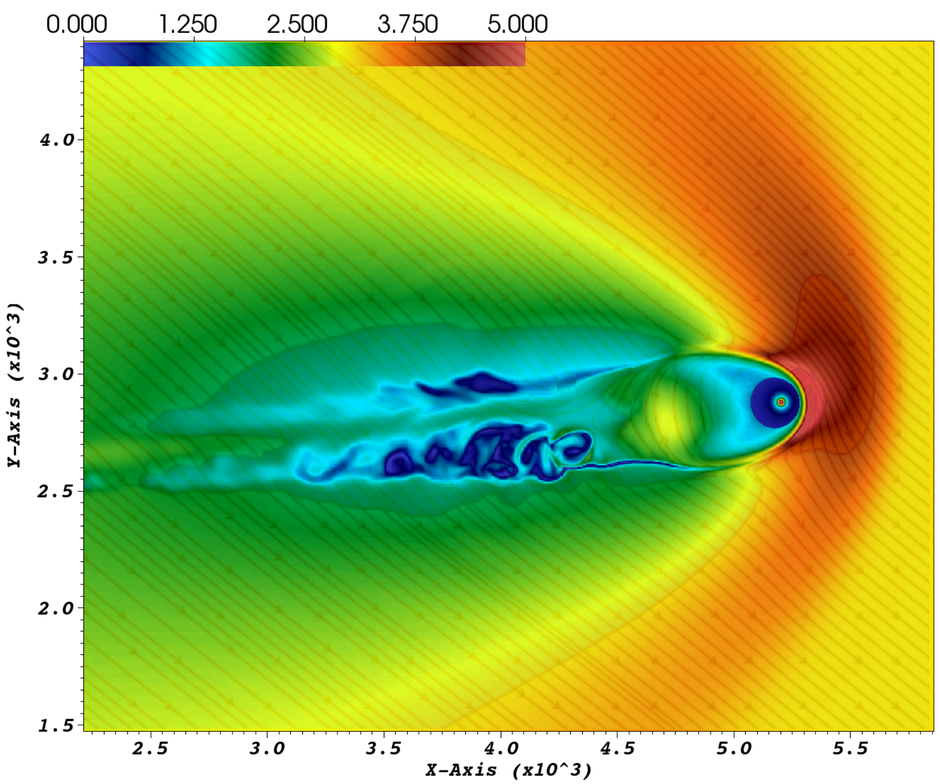
Schwadron, Adams, Christian, PD, Frisch, Funsten, Jokipii, McComas, Möbius, Zank, Science, 1245026 (2014)



Zhang Ming talk today

Zhang, Zuo & Pogorelov ApJ 790, 5 (2014)

cosmic ray anisotropy
probing heliospheric magnetic structure



Borovikov, Heerikhuisen, Pogorelov

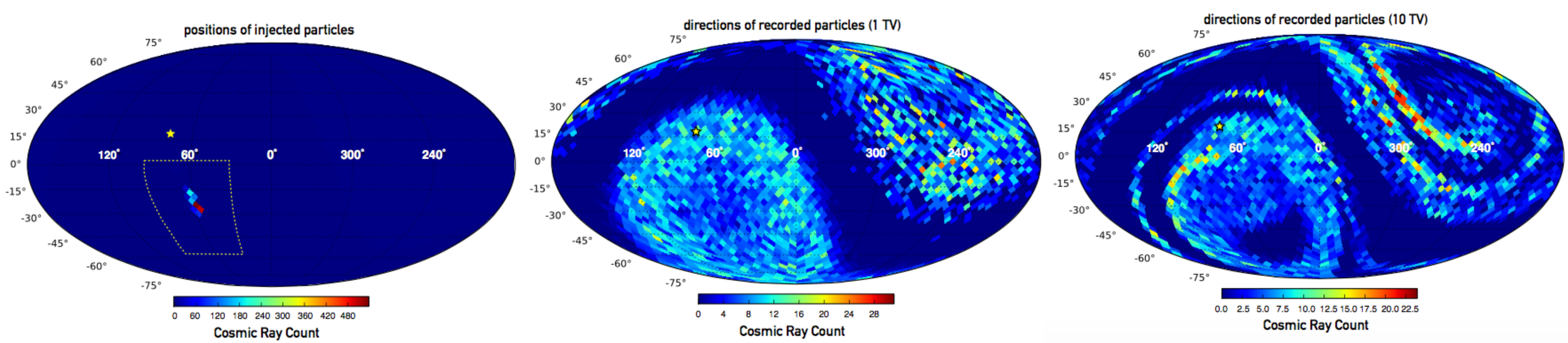
downstream instabilities on the flanks of heliotail

strong scattering

PD & Lazarian 2013

López-Barquero, Xu, PD, Lazarian, et al.

to be SUBMITTED



forward propagation

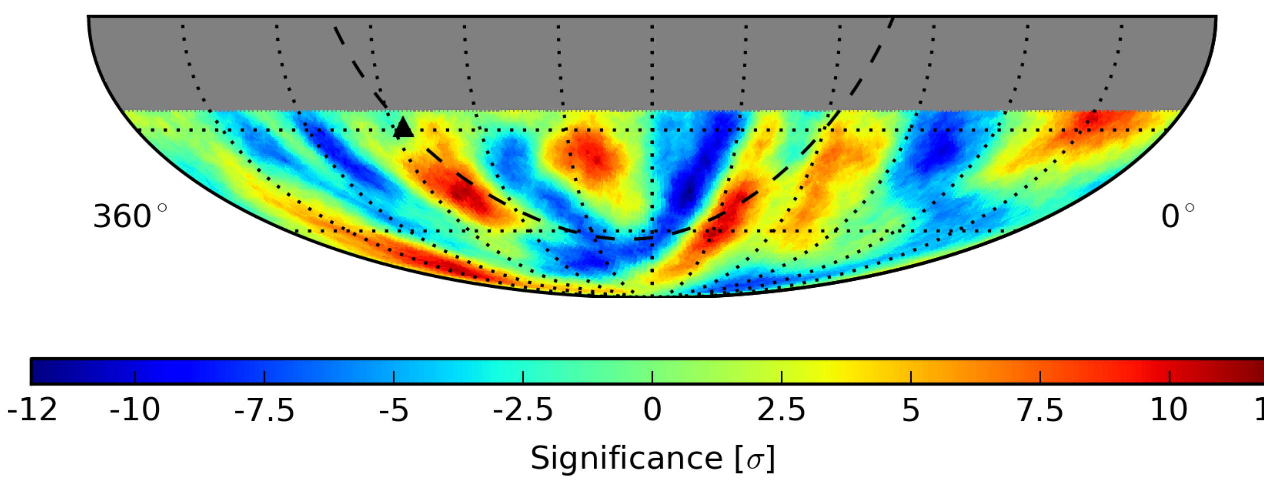
injection sphere 6000 AU - target sphere 200 AU

cosmic rays anisotropy
large and small angular scale

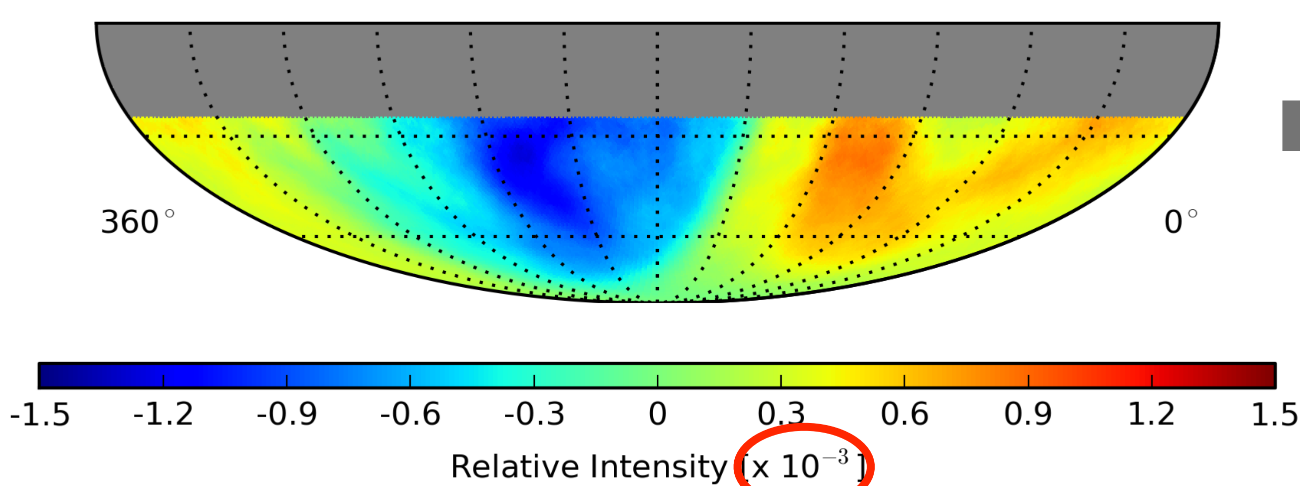
- fit 3D dipole + quadrupole and subtract from data

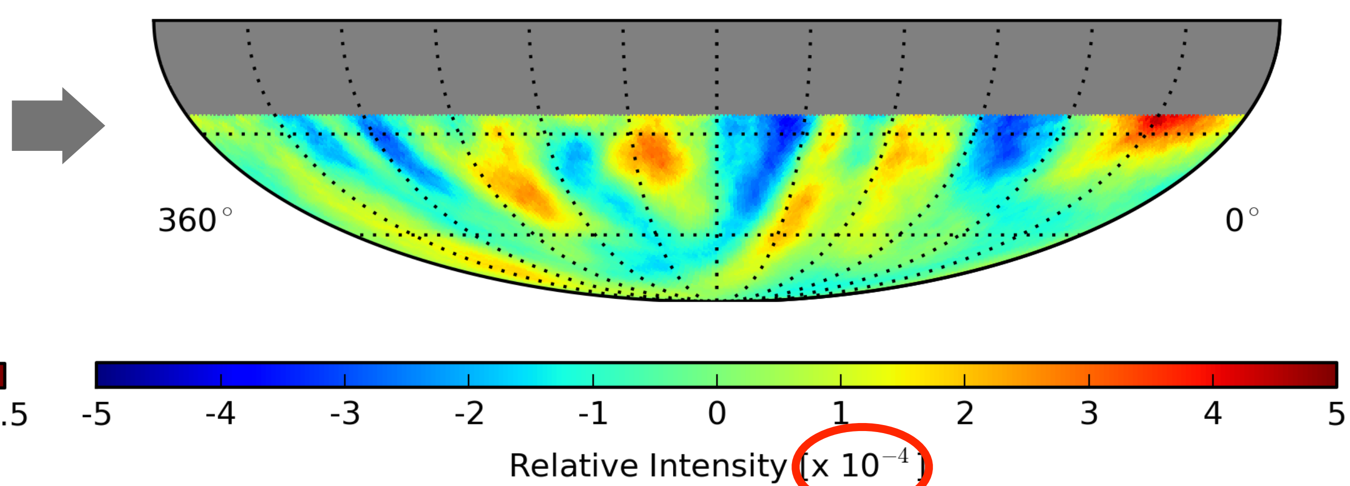
$$s=\sqrt{2}\left\{N_{\rm on}\ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\rm on}}{N_{\rm on}+N_{\rm off}}\right)\right]+N_{\rm off}\ln\left[(1+\alpha)\left(\frac{N_{\rm off}}{N_{\rm on}+N_{\rm off}}\right)\right]\right\}^{1/2} \qquad \alpha=1/20$$

Li, T., & Ma, Y. 1983, ApJ, 272, 317

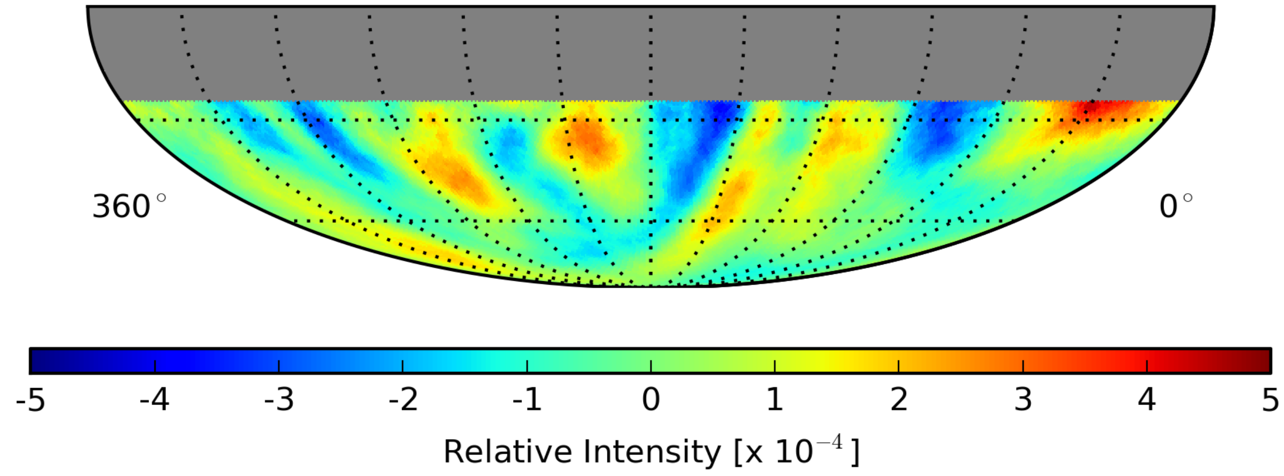


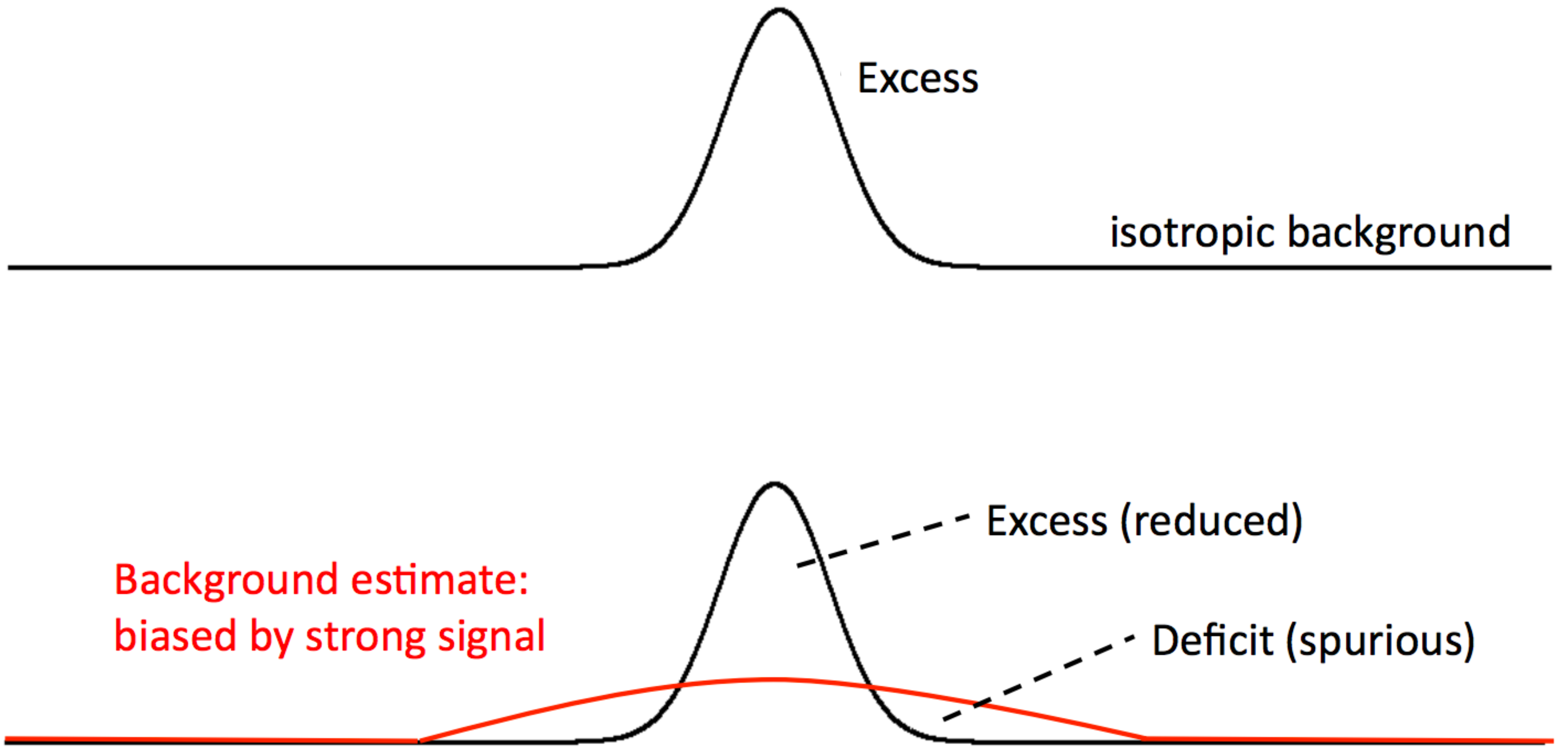
IceCube - Aartsen et al., ApJ 826, 220, 2016





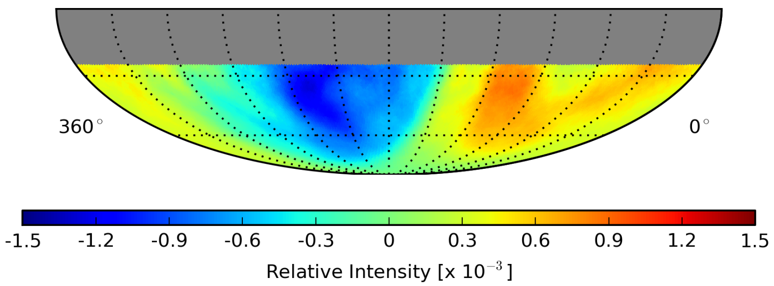
small scale anisotropy
localization artifacts

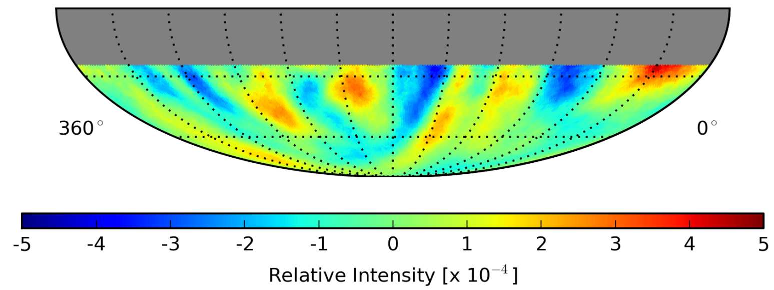


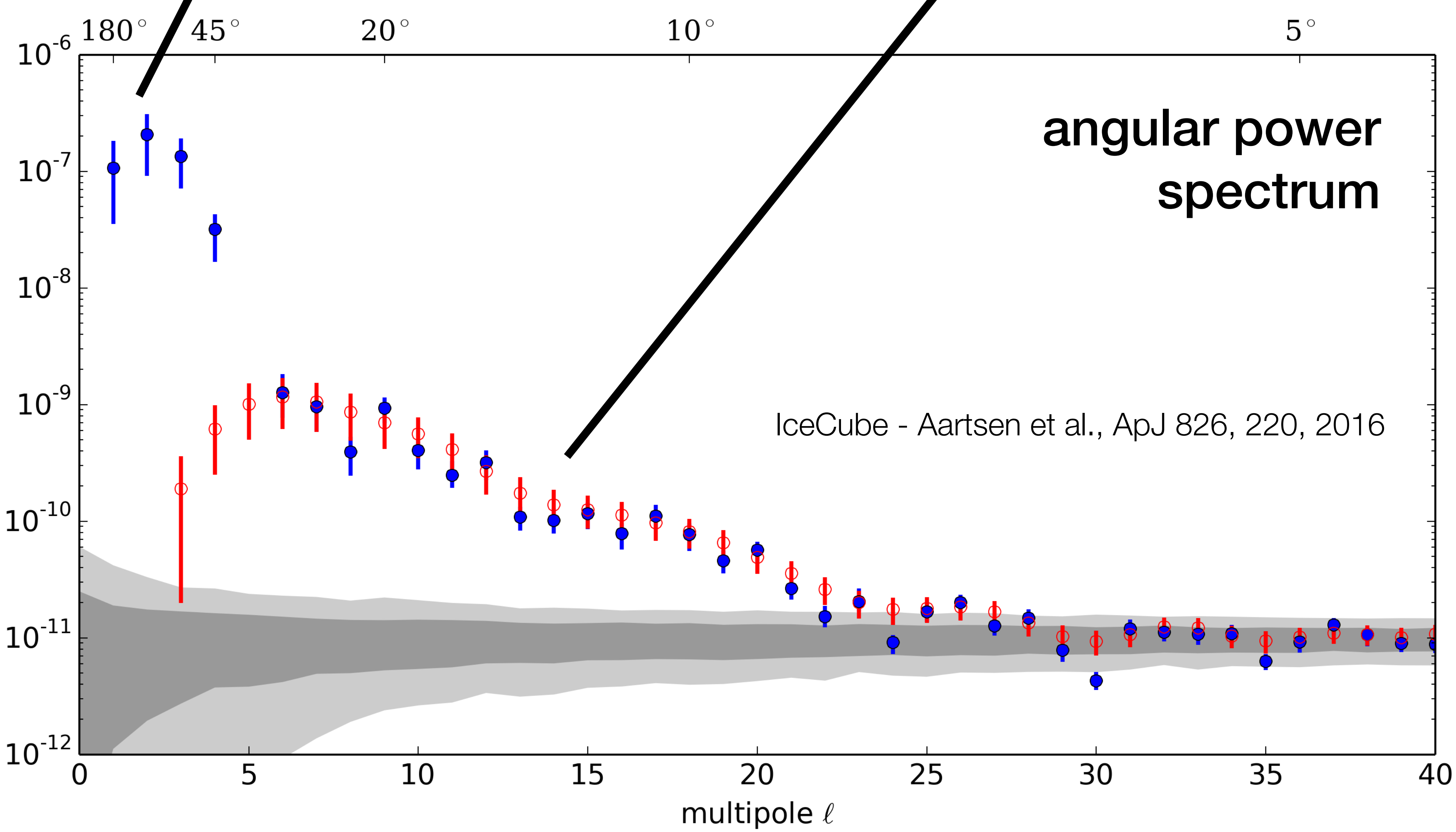


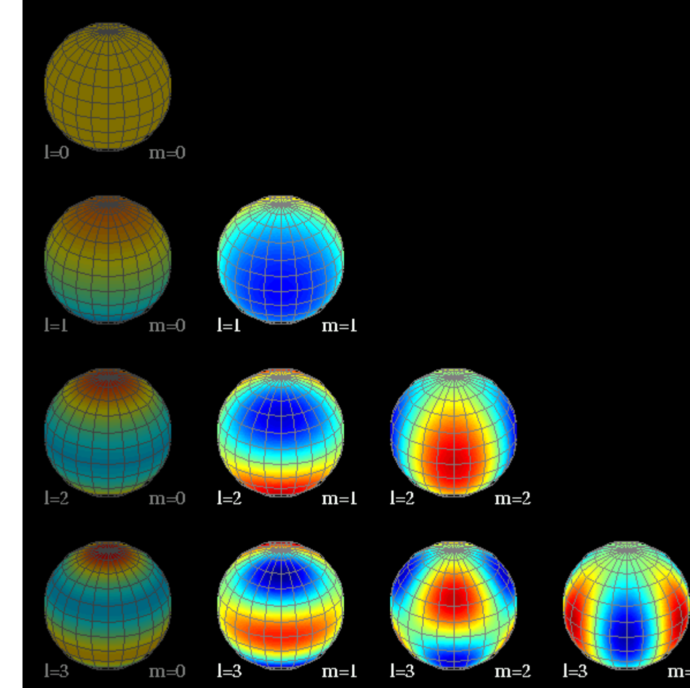
cosmic rays anisotropy

large and small angular scale







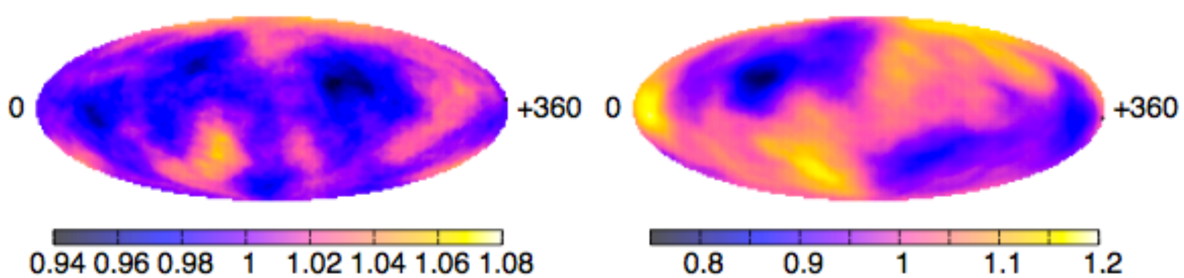


missing *vertical* component (m = 0)

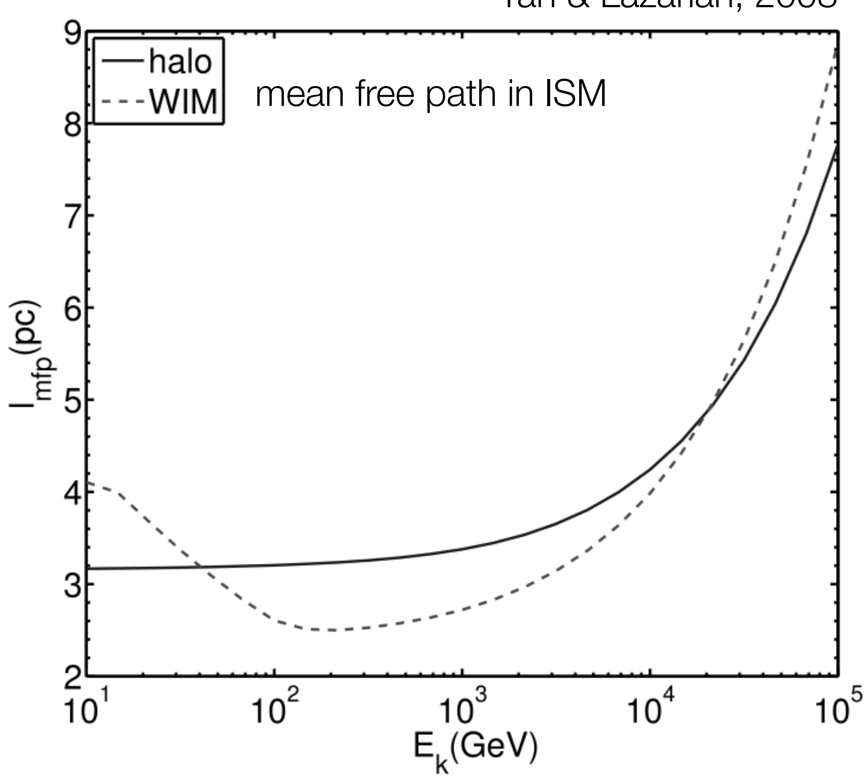
cosmic ray anisotropy
probing magnetic field turbulence ?

- propagation effect from turbulent realization of interstellar magnetic field within scattering mean free path

Giacinti & Sigl, 2012
Biermann+, 2012

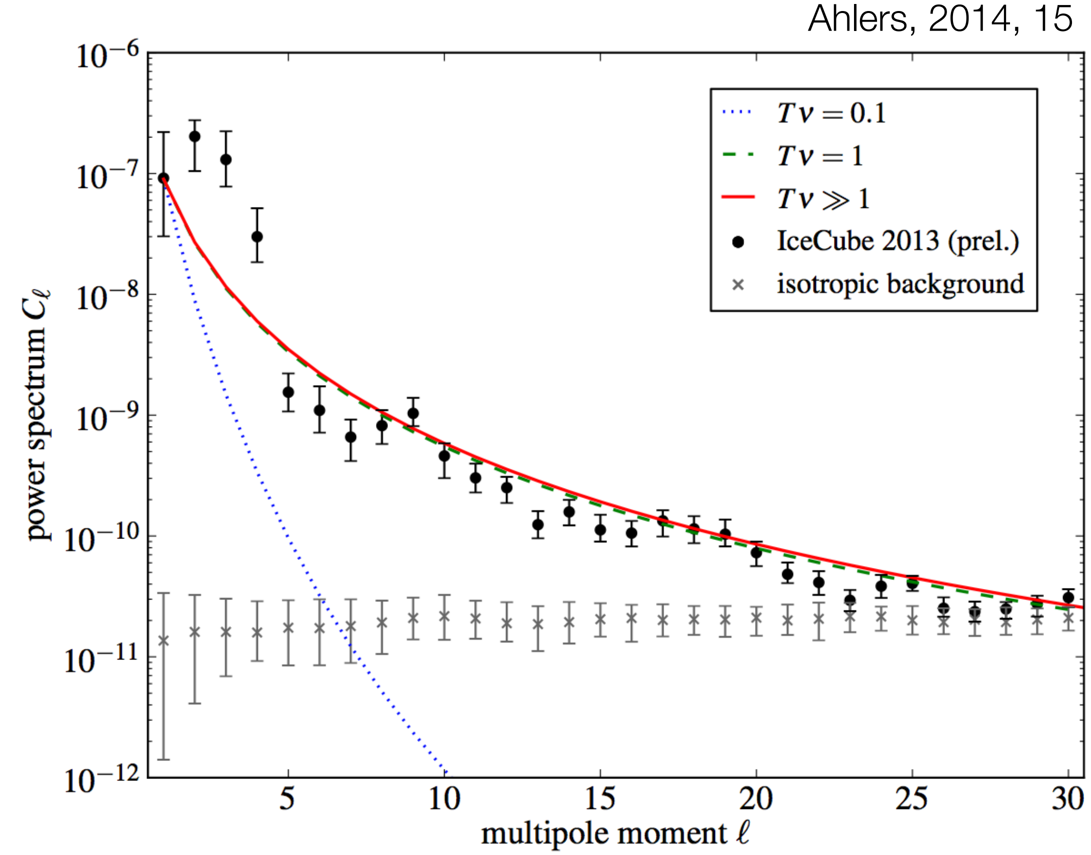


Yan & Lazarian, 2008



- angular structure of anisotropy spontaneously generated from a global dipole anisotropy as a consequence of Liouville Theorem in the presence of a local turbulent magnetic field (sum of multipoles is conserved)

Ahlers, 2014, 15

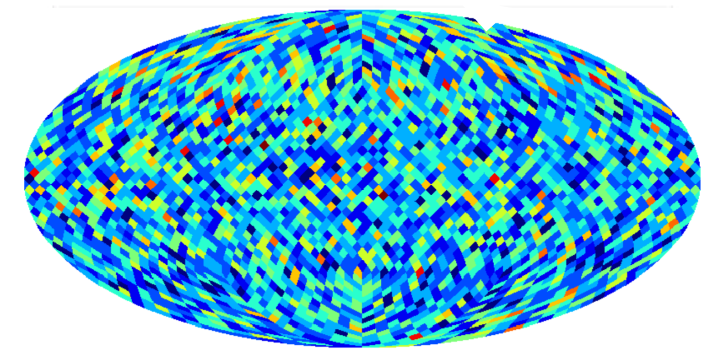


cosmic ray anisotropy

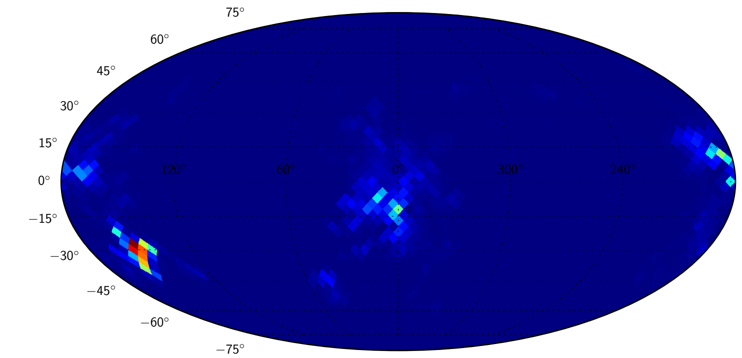
probing magnetic field turbulence ?

- compressible MHD turbulence (Cho & Lazarian, 2002)
- angular structures by scattering on turbulence within mean free path
- dipole oriented along average fields within mean free path (different from *regular field*)
- small angular structure depends on actual realization. But its fingerprint is power spectrum

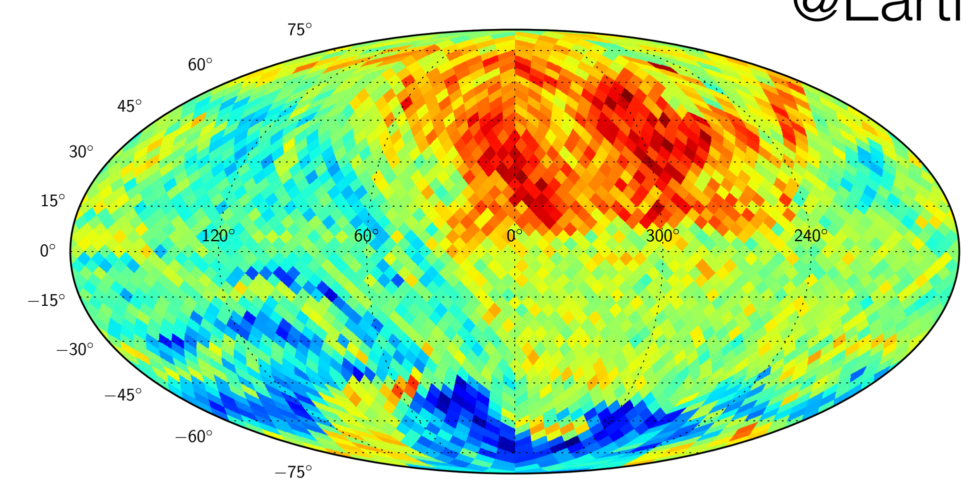
López-Barquero, Farber, Xu, PD, Lazarian - **to appear on ApJ**
arXiv:1509.00892



positions

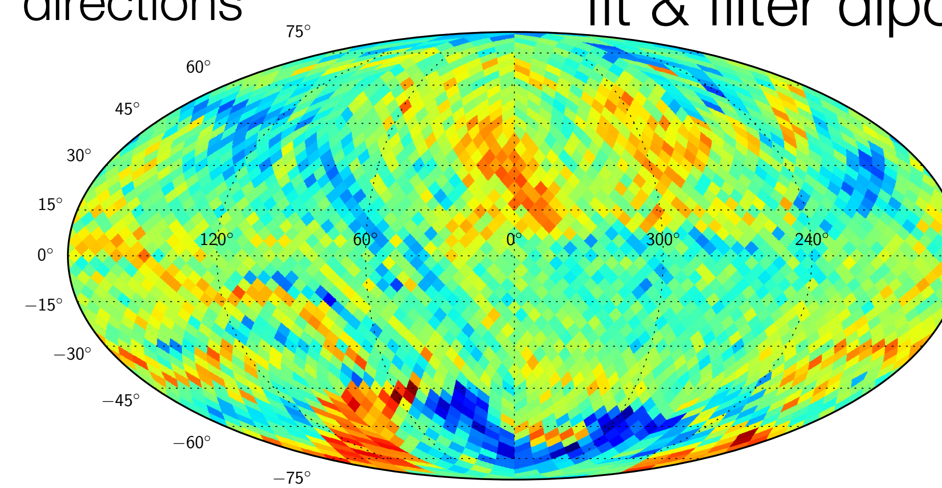


@Earth



directions

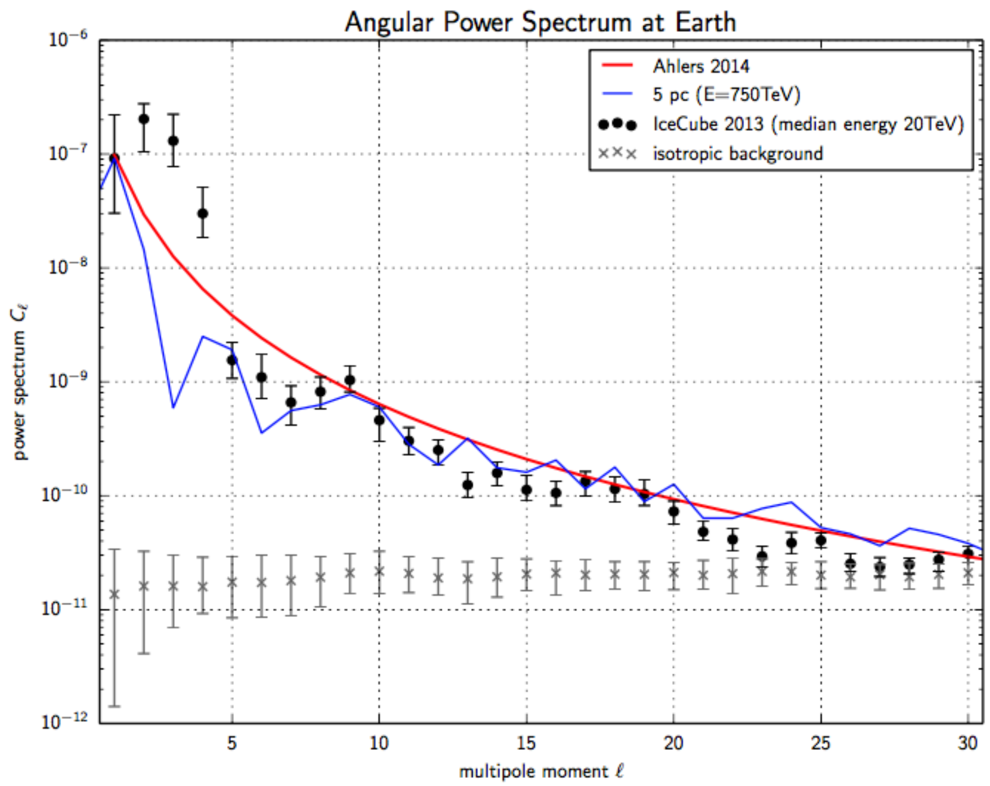
fit & filter dipole

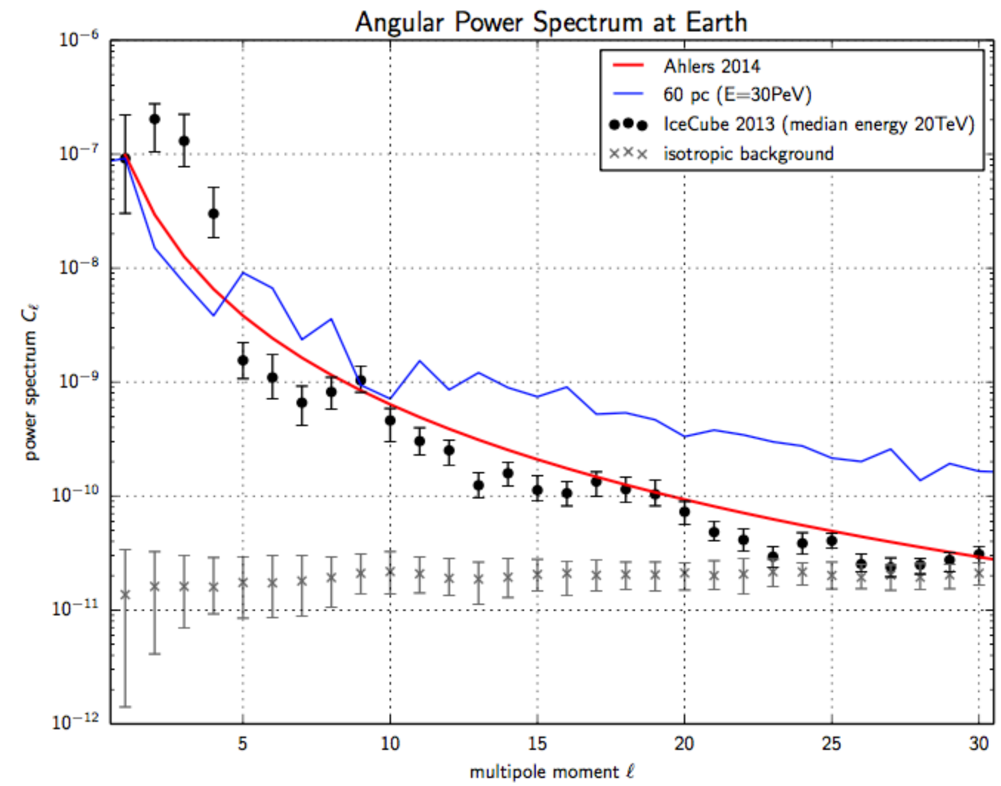


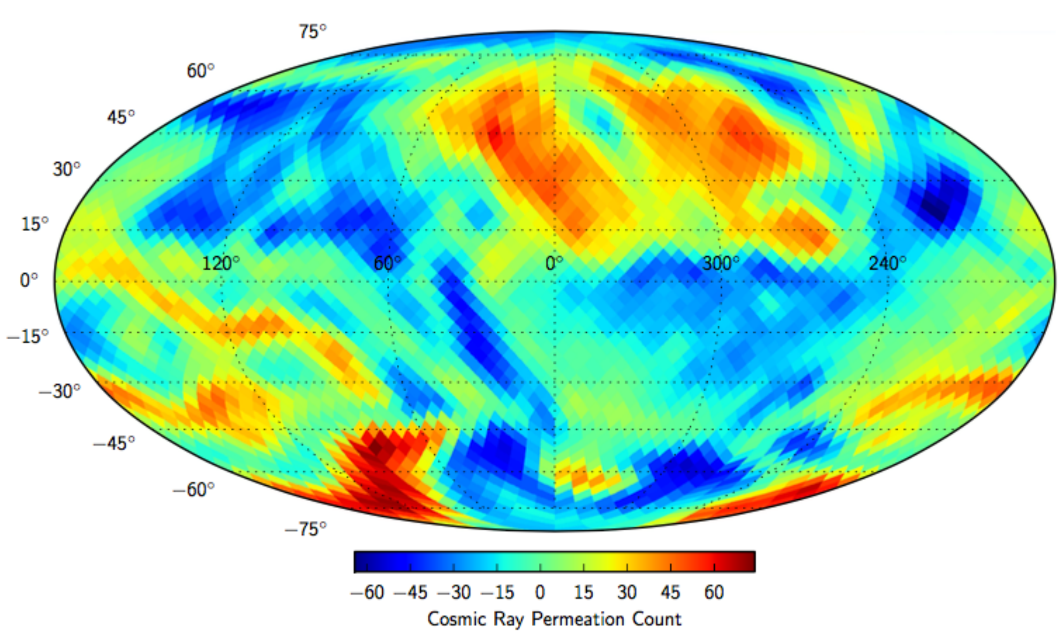
López-Barquero, Farber, Xu, PD, Lazarian in print on ApJ
arXiv:1509.00892

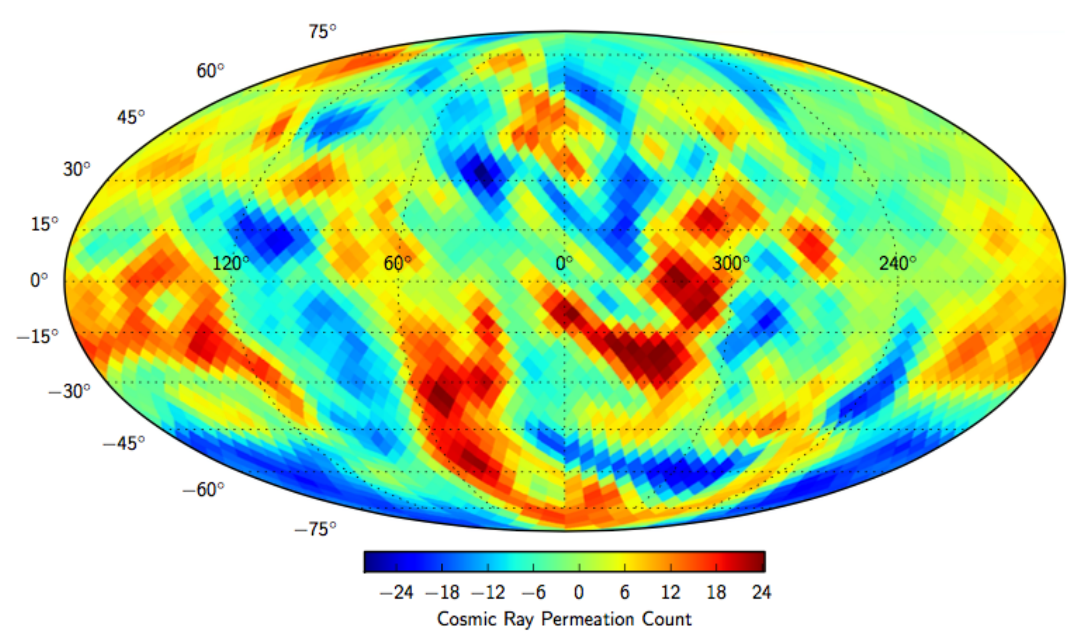
cosmic ray anisotropy

probing magnetic field turbulence ?

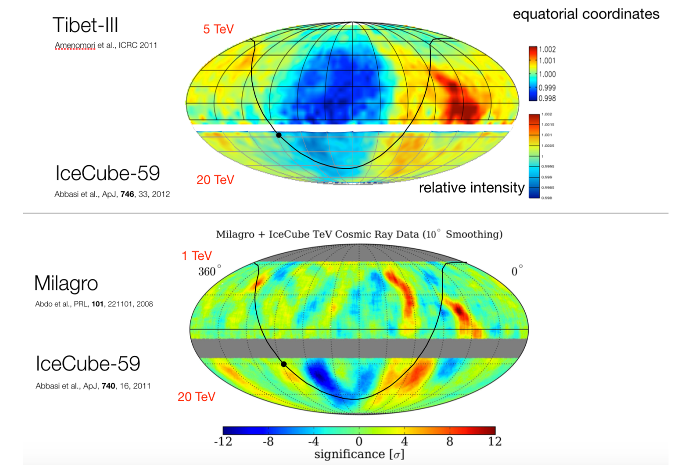








conclusions



- cosmic ray spectrum to provide hints about sources without pointing (like γ rays & ν but with pointing) **and** propagation effects

- cosmic ray anisotropy from standard diffusion at *large-scale* (dipole, sources) & non-diffusive processes (angular structure)

- probe into propagation properties, Local Bubble, LIMF, heliosphere, …

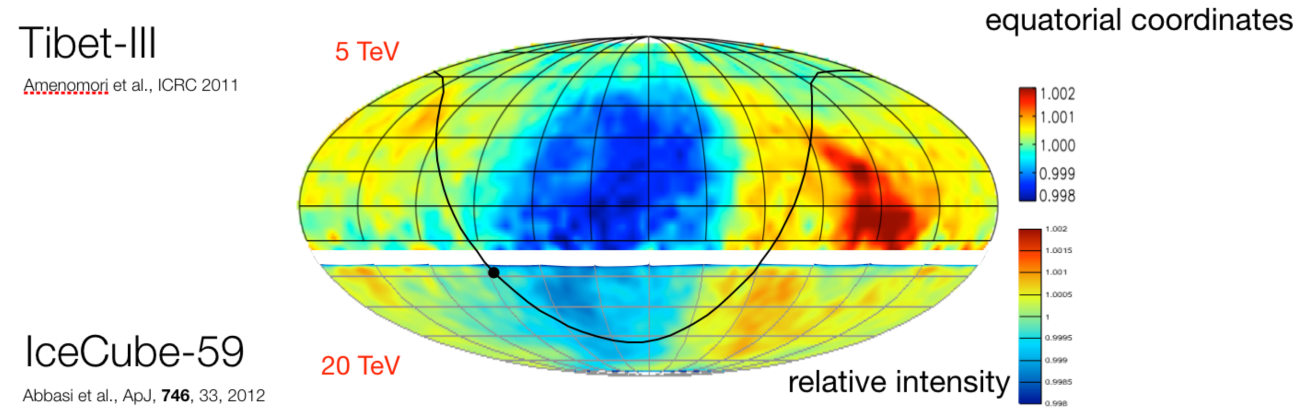
- what is the origin of *interstellar anisotropy* ?

- **improve experimental observations for phenomenological interpretation**

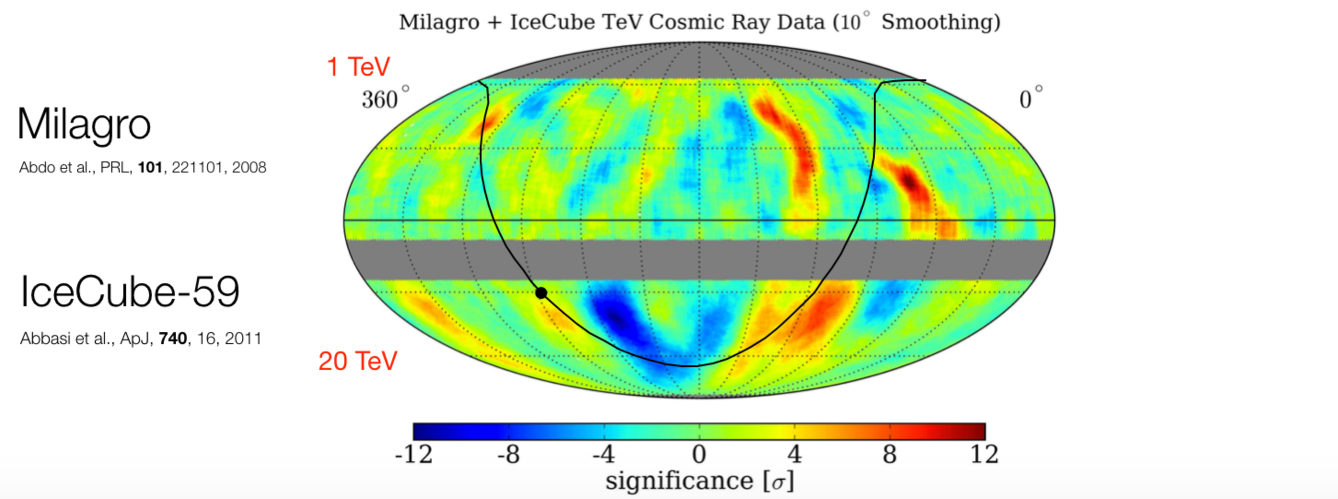
  - **anisotropy & angular scale structure vs. primary energy and mass**

  - **combined north-south & unbiased full-sky observations**

THANK YOU



Tibet-III
Amenomori et al., ICRC 2011
5 TeV
equatorial coordinates
1.002
1.001
1.000
0.999
0.998
IceCube-59
Abbasi et al., ApJ, 746, 33, 2012
20 TeV
relative intensity



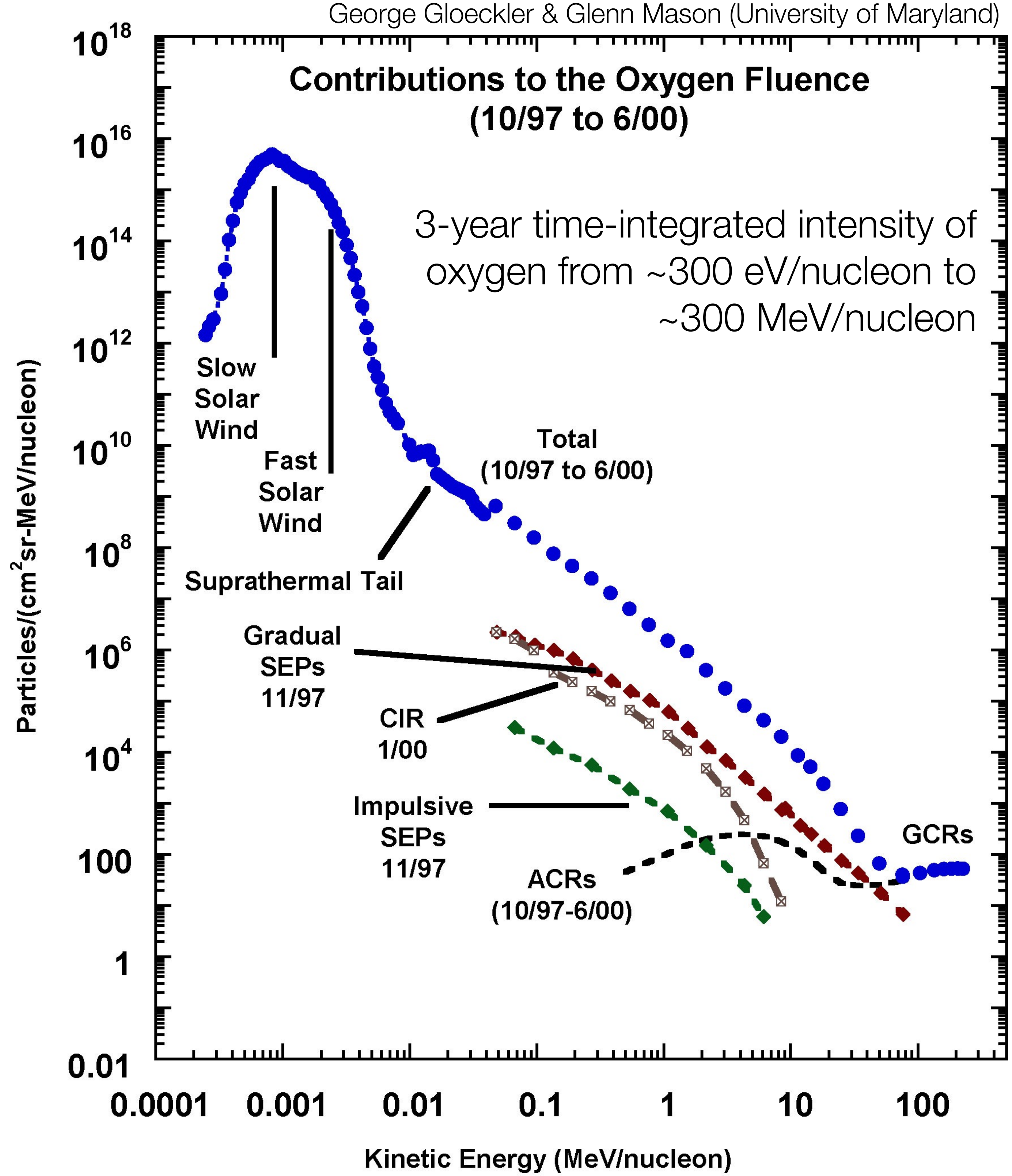
Milagro + IceCube TeV Cosmic Ray Data (10° Smoothing)
1 TeV
360°
0°
Milagro
Abdo et al., PRL, 101, 221101, 2008
IceCube-59
Abbasi et al., ApJ, 740, 16, 2011
20 TeV
-12
-8
-4
0
4
8
12
significance [σ]

backup slides

cosmic ray observations
spectral shape and their history

- energetic particles in heliosphere from **separate** *sources, acceleration & propagation processes*
- each feature in energy spectrum is a fingerprint of the **specific process**
- **time-dependence** and **arrival distribution** add further information about the processes involved

Richard Mewaldt (Caltech)
George Gloeckler & Glenn Mason (University of Maryland)

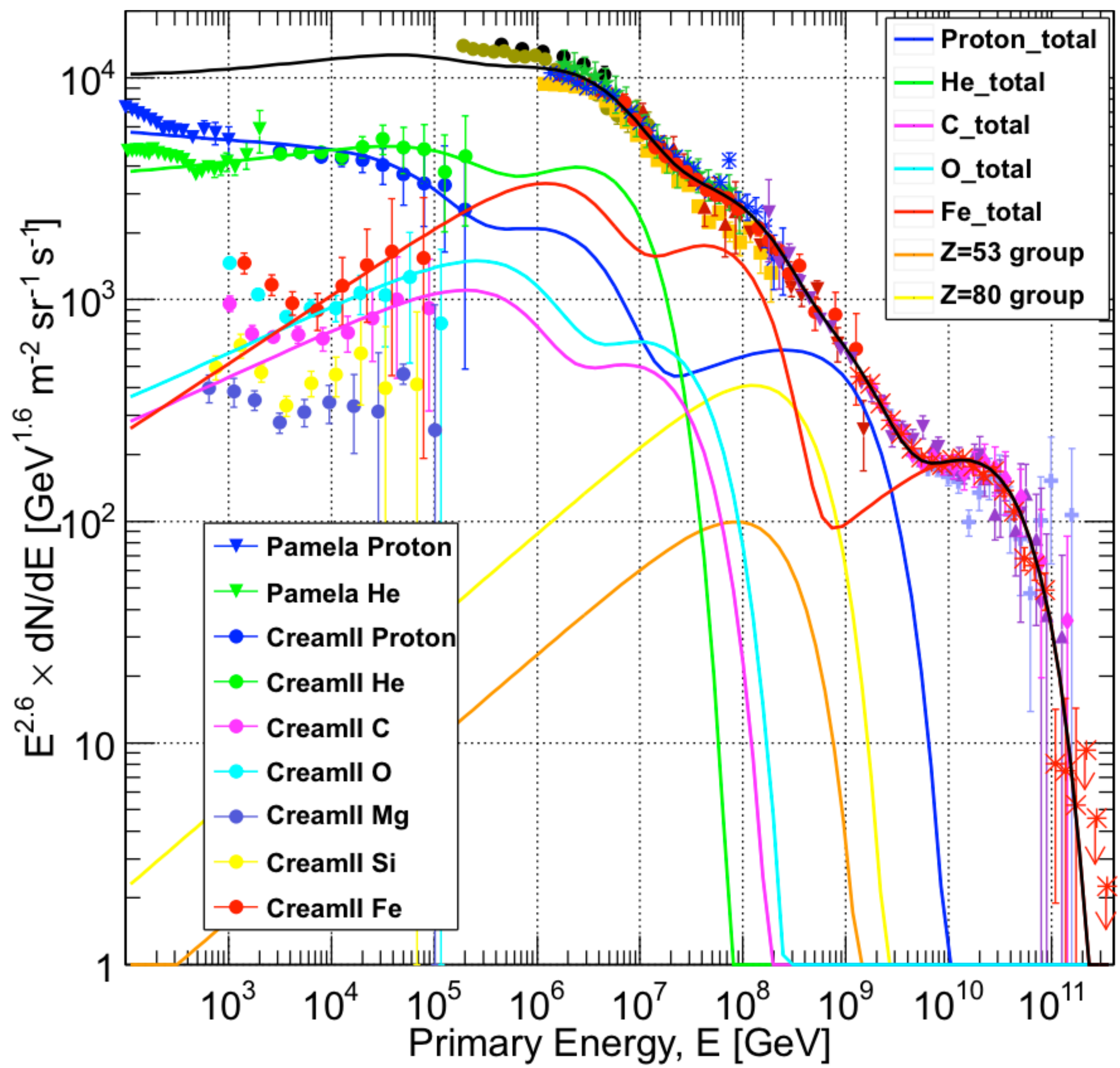


cosmic ray observations

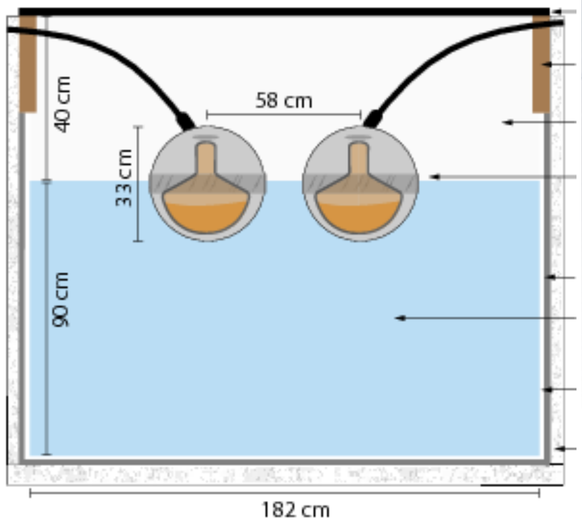
spectral shape and their history

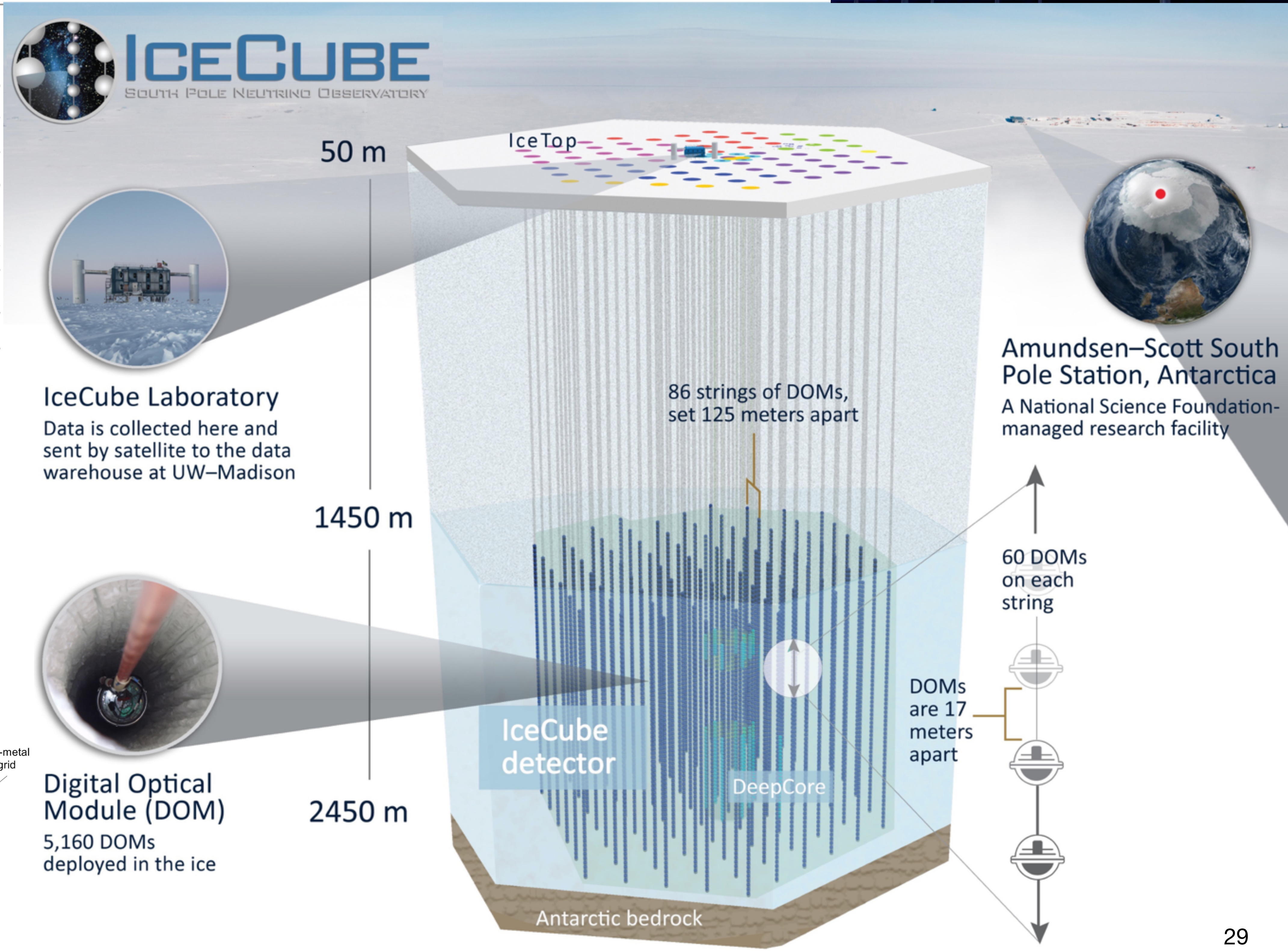
- **galactic** cosmic rays produced below 10^8-10^9 GeV
- **spectral features** from <u>acceleration</u> mechanisms & <u>propagation</u> effects
- **property & distribution of sources** in Galaxy and our neighborhood
- **magnetic field** configurations in local interstellar medium: turbulence & escape
- **anisotropy**

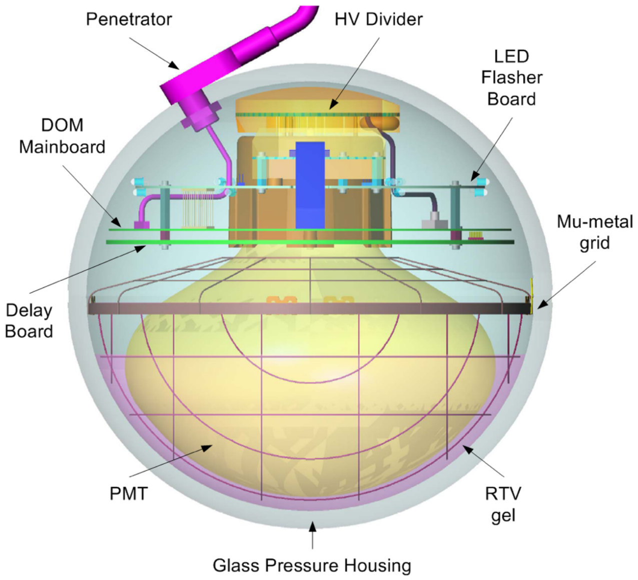
Gaisser, Stanev, Tilav, 2013 - arXiv:1303.3565



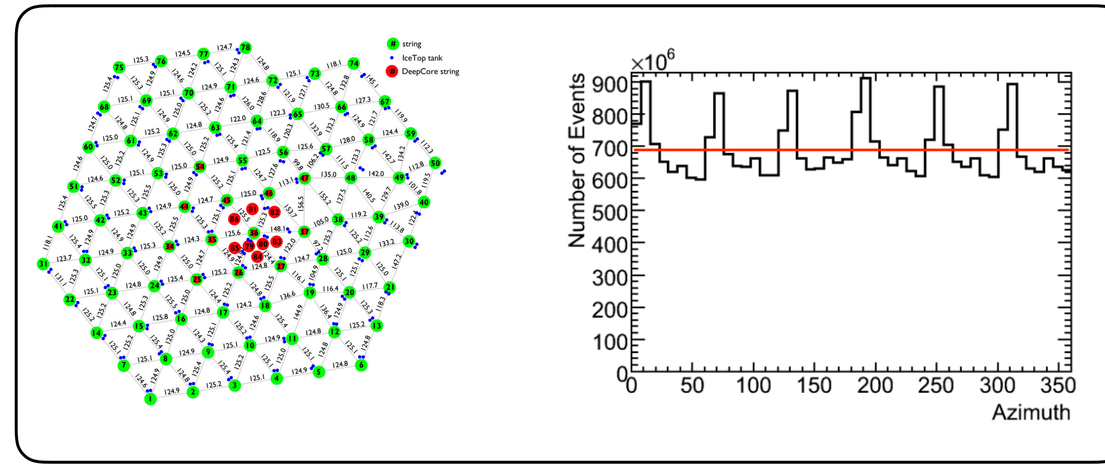
IceCube Observatory
the instrumentation



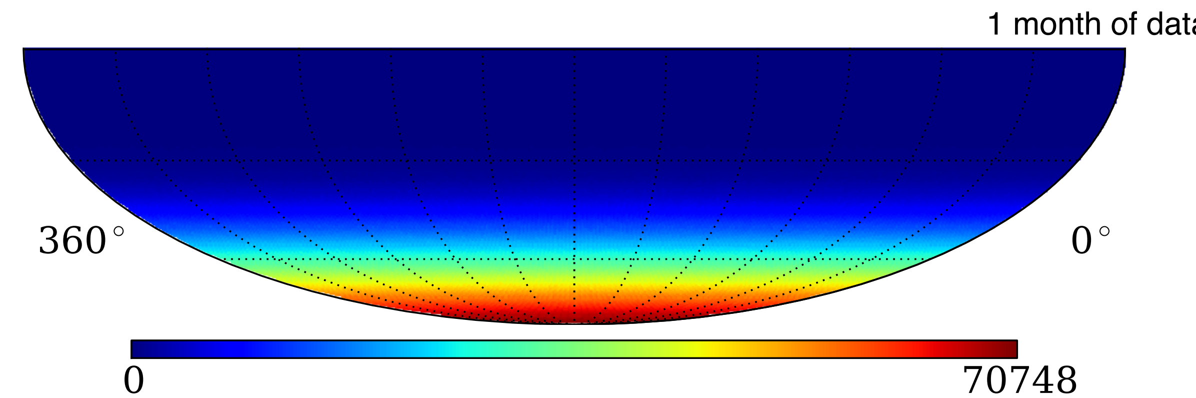




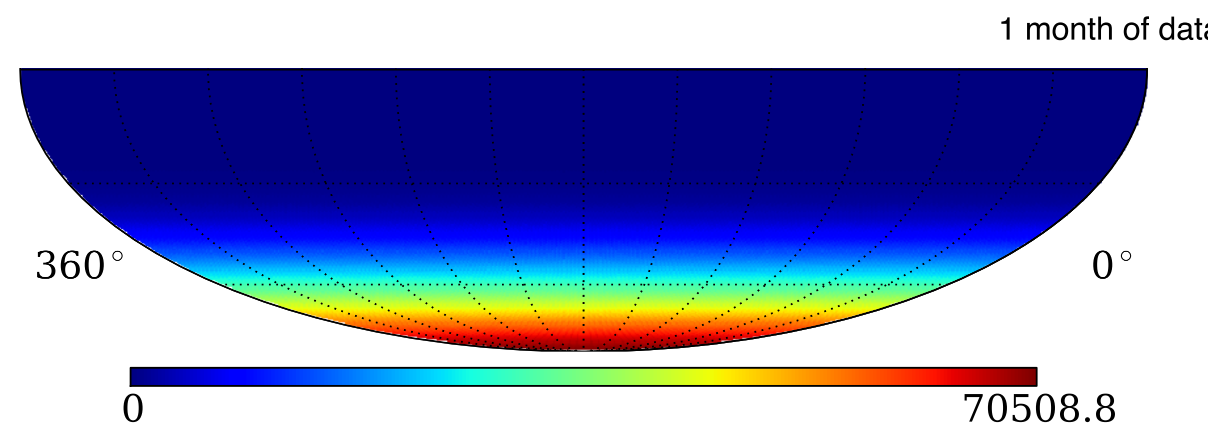
cosmic rays anisotropy
arrival direction distribution



raw map of events in equatorial coordinates $(\alpha,\delta)_i$

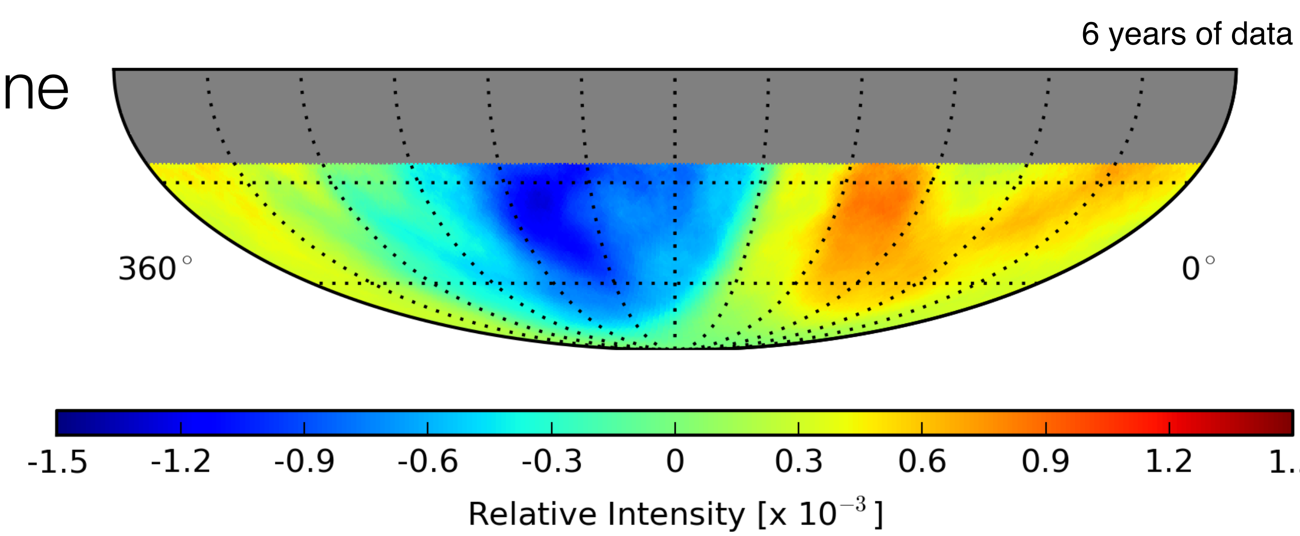


reference map from events scrambled over 24hr in α (or time)



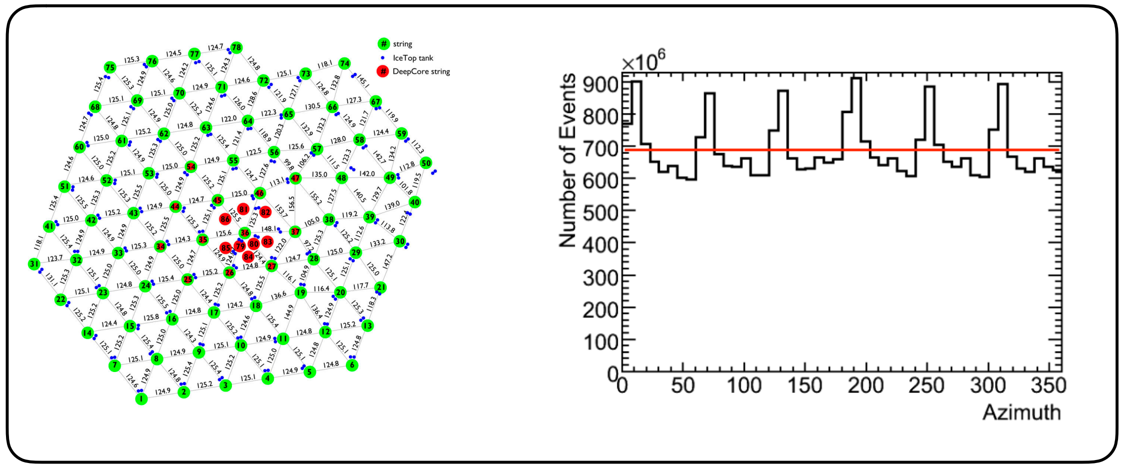
subtract reference map from raw map to determine the residual *relative intensity* map

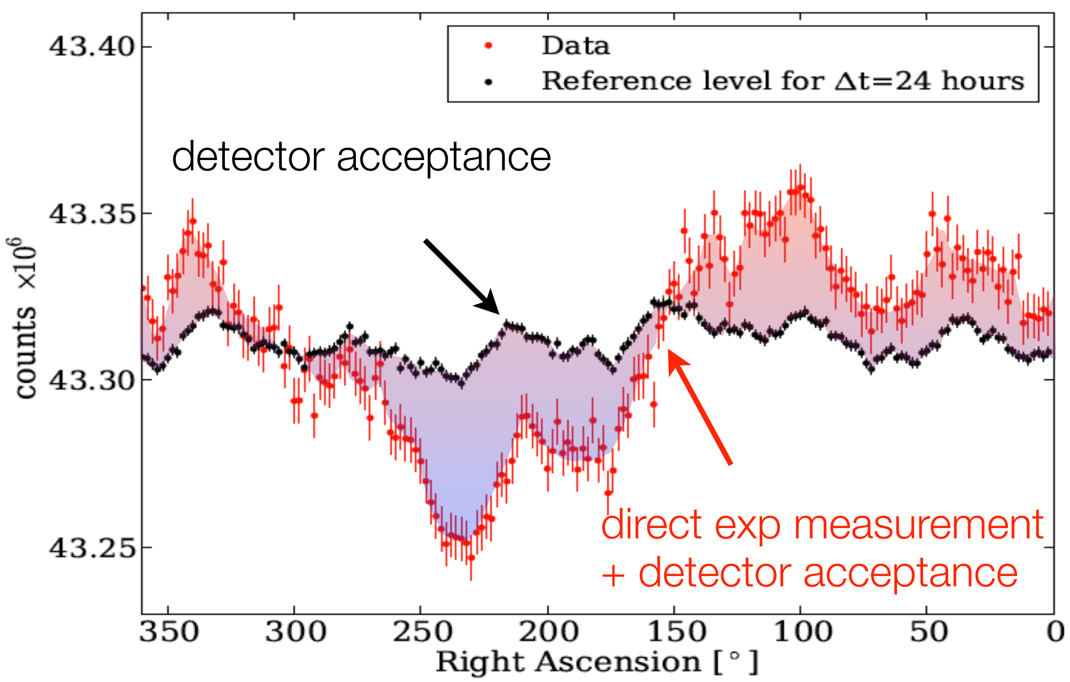
$$\frac{\Delta I}{\langle I \rangle} \equiv \frac{N_i - \langle N \rangle}{\langle N \rangle}$$

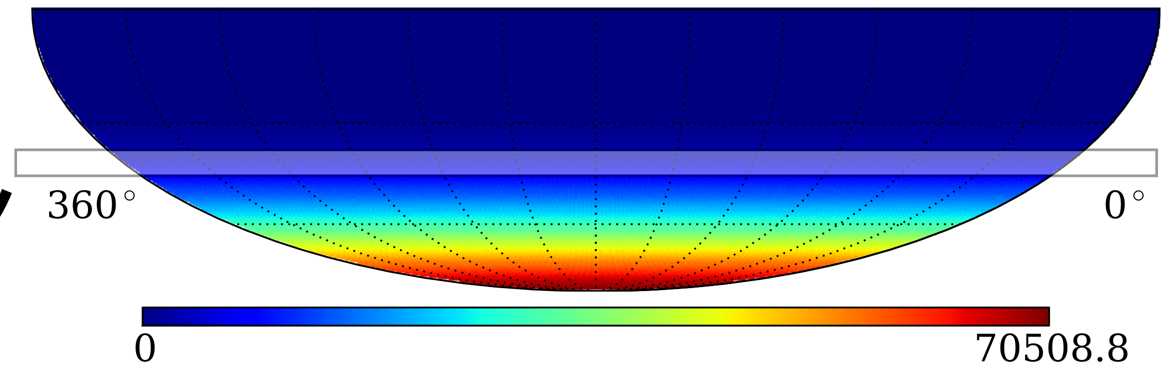


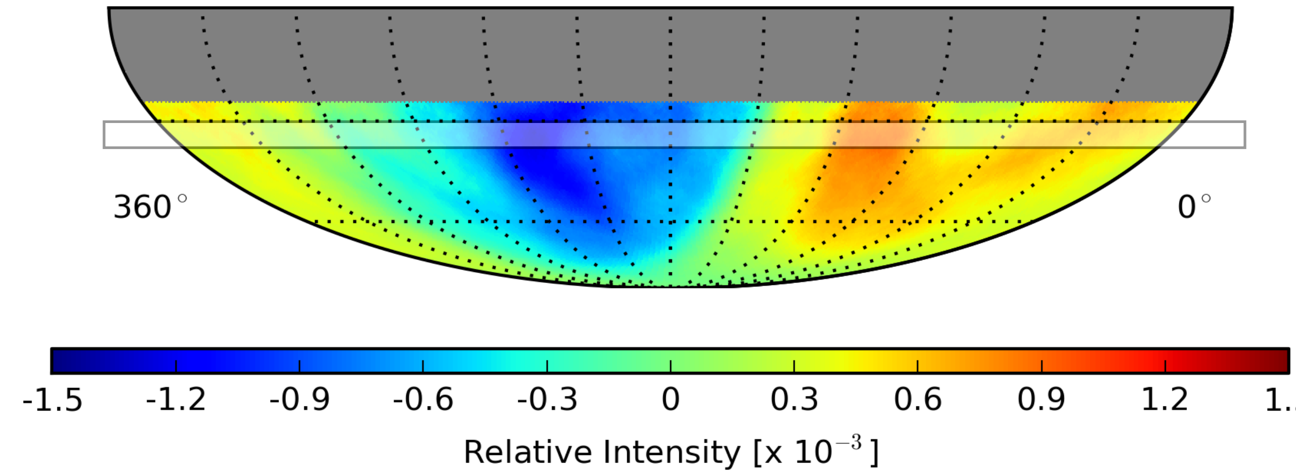
cosmic rays anisotropy

arrival direction distribution



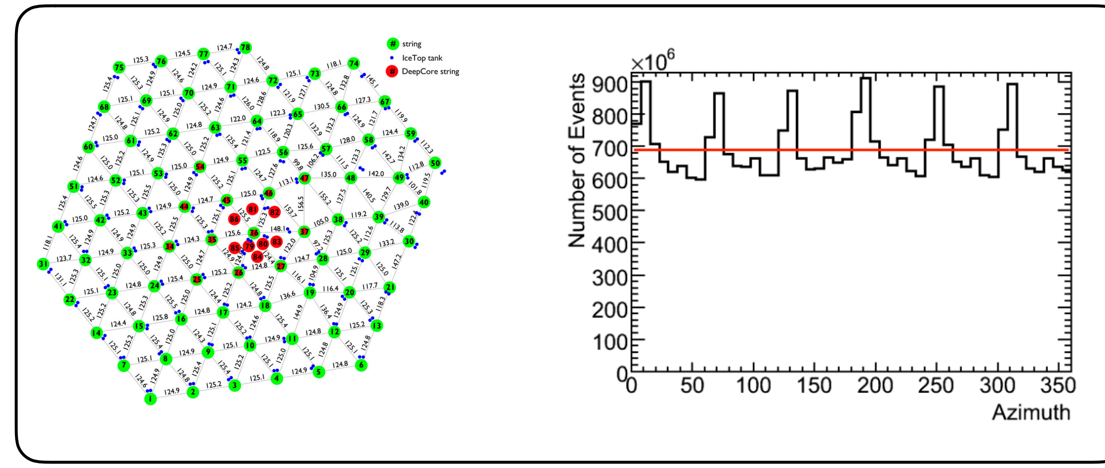






$$\frac{\Delta I}{\langle I \rangle} \equiv \frac{N_i - \langle N \rangle}{\langle N \rangle}$$

cosmic rays anisotropy
arrival direction distribution

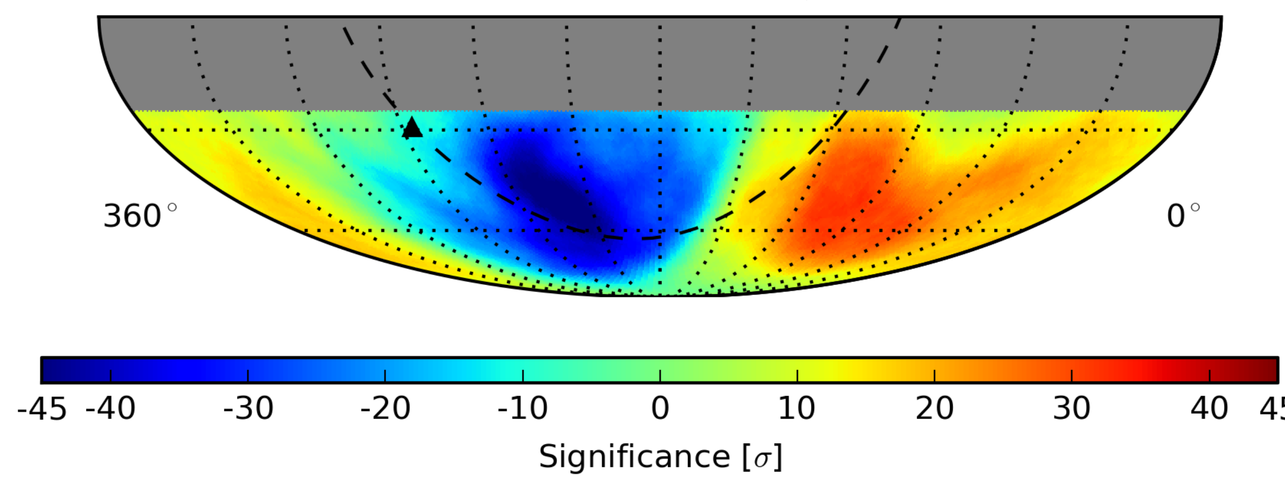


$$s = \sqrt{2}\left\{ N_{\mathrm{on}} \ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\mathrm{on}}}{N_{\mathrm{on}}+N_{\mathrm{off}}}\right)\right] + N_{\mathrm{off}} \ln\left[(1+\alpha)\left(\frac{N_{\mathrm{off}}}{N_{\mathrm{on}}+N_{\mathrm{off}}}\right)\right]\right\}^{1/2} \qquad \alpha = 1/20$$

Li, T., & Ma, Y. 1983, ApJ, 272, 317

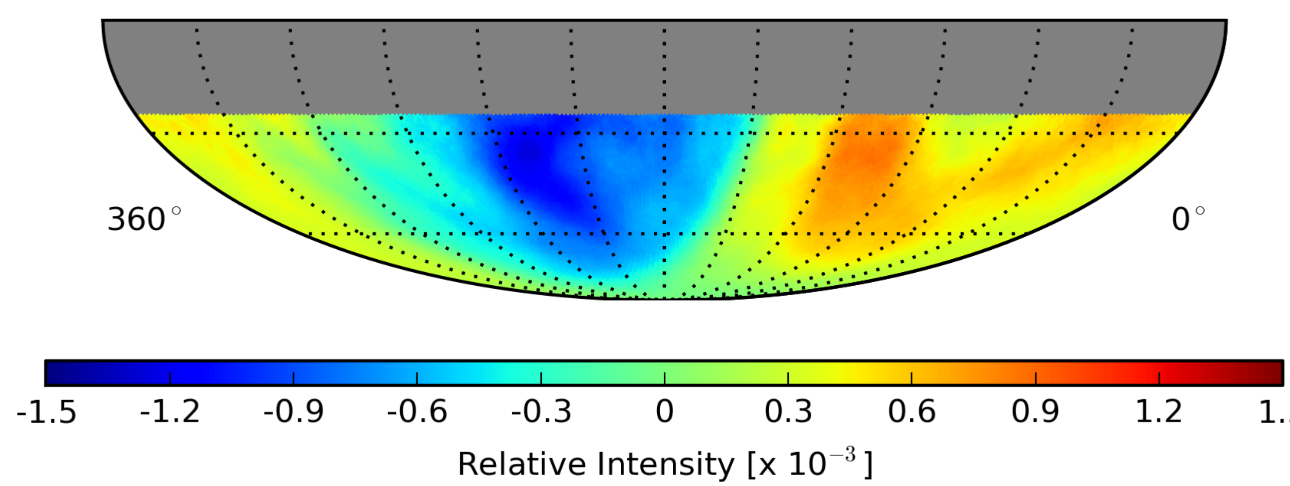
IceCube - Aartsen et al., 2016

statistical significance



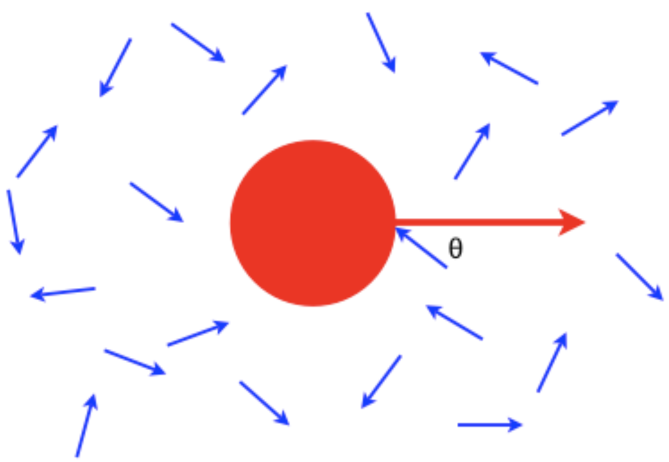
relative intensity

$$\frac{\Delta I}{\langle I \rangle} \equiv \frac{N_i - \langle N \rangle}{\langle N \rangle}$$



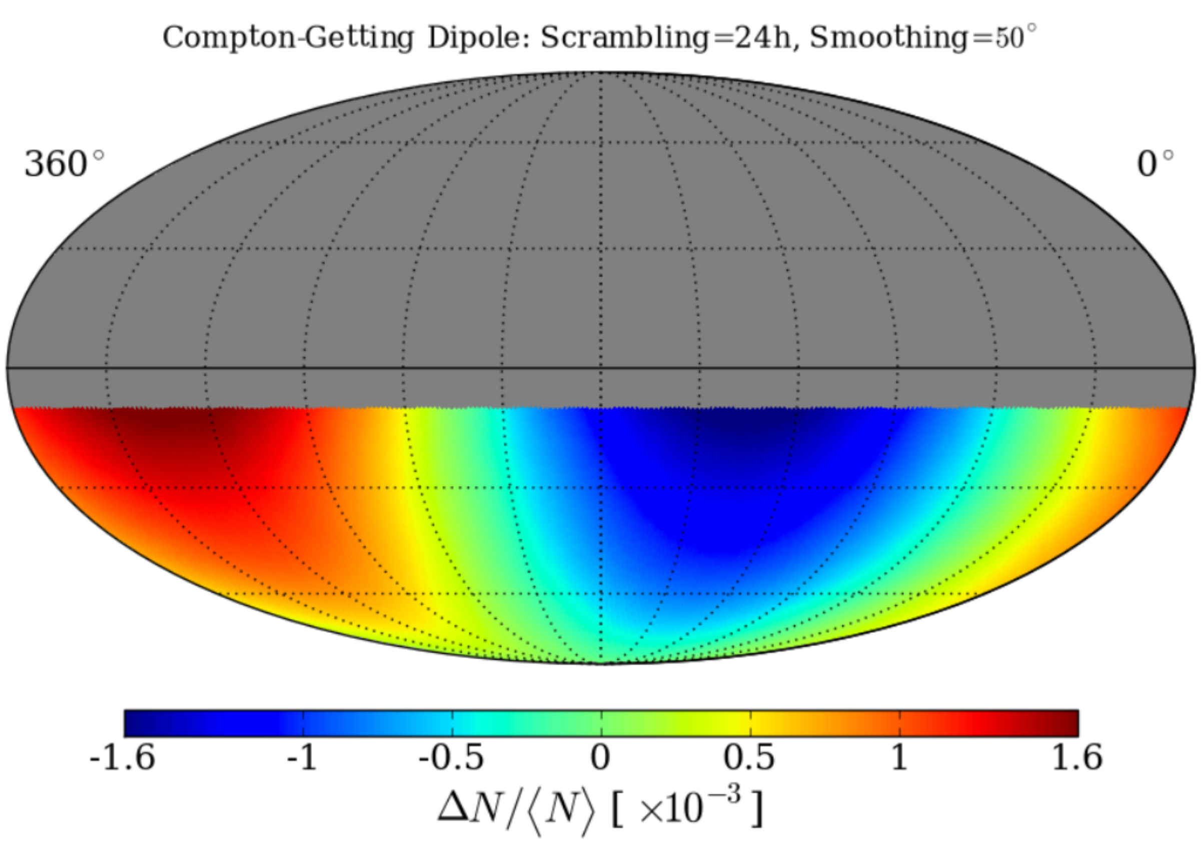
origin of large scale anisotropy
Compton-Getting Effect ?

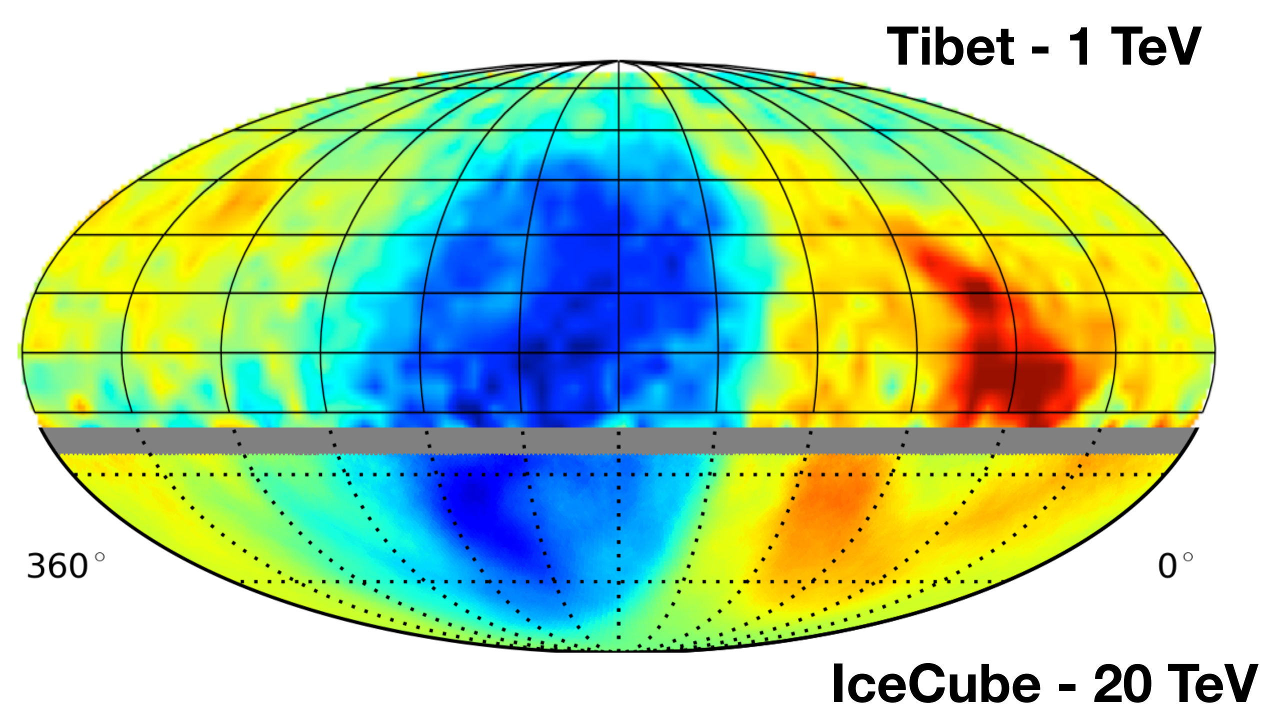
Compton & Getting, Phys. Rev. 47, 817 (1935)
Gleeson, & Axford, Ap&SS, 2, 43 (1968)



- motion of solar system around galactic center ~ 220 km/s
- reference system of cosmic rays is **unknown**
  - at most one dipole component of the observation

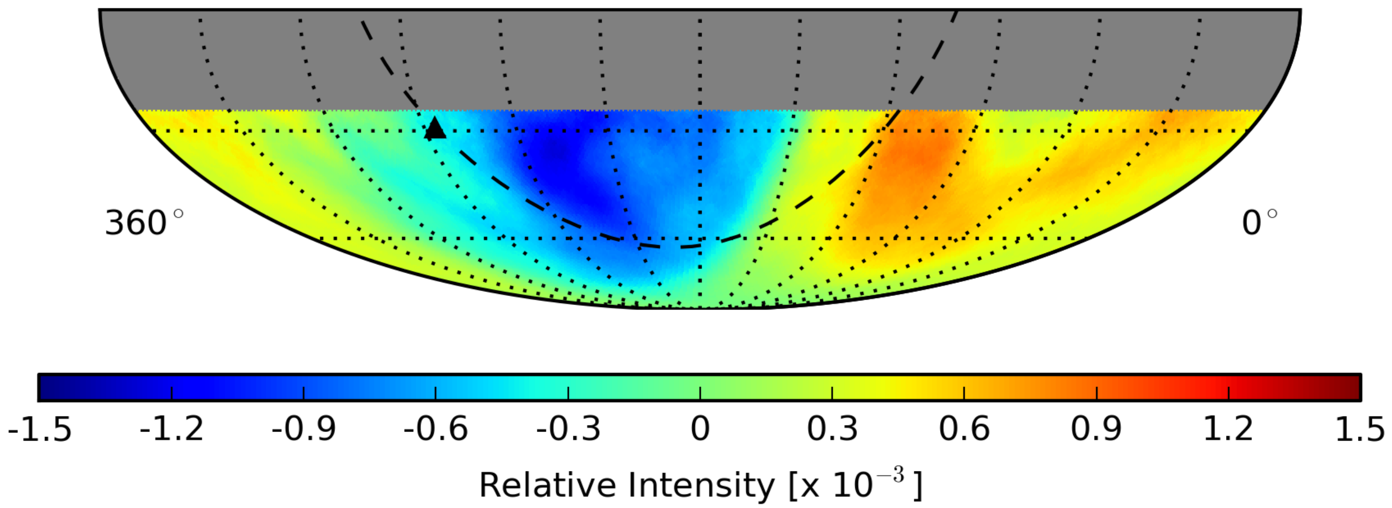
$$\frac{\Delta I}{I} = (\gamma + 2)\frac{v}{c}\cos\theta$$

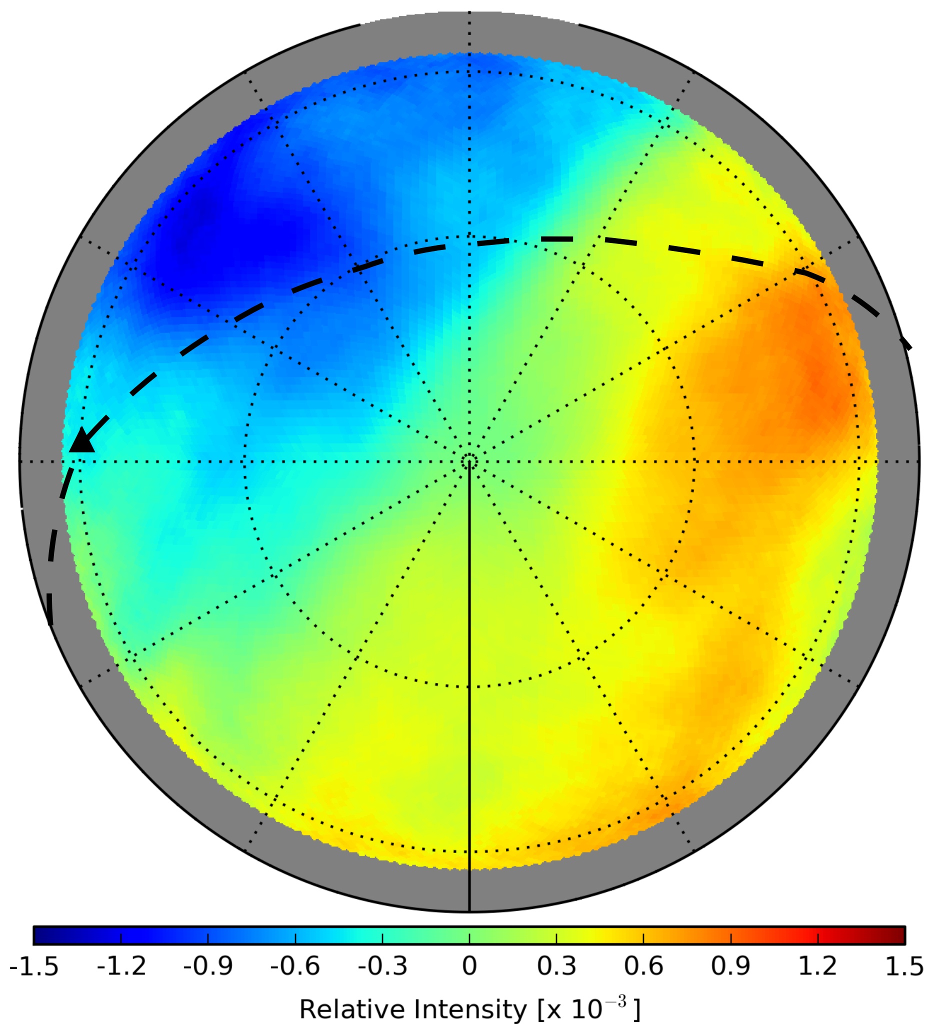




cosmic rays anisotropy
arrival direction distribution

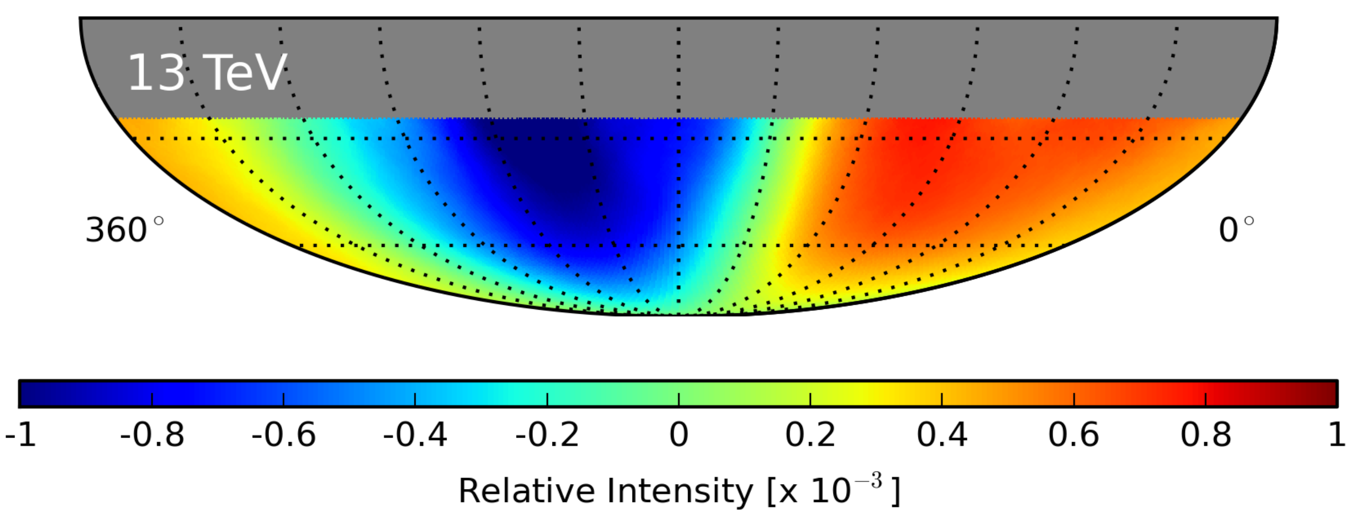
to be submitted to ApJ

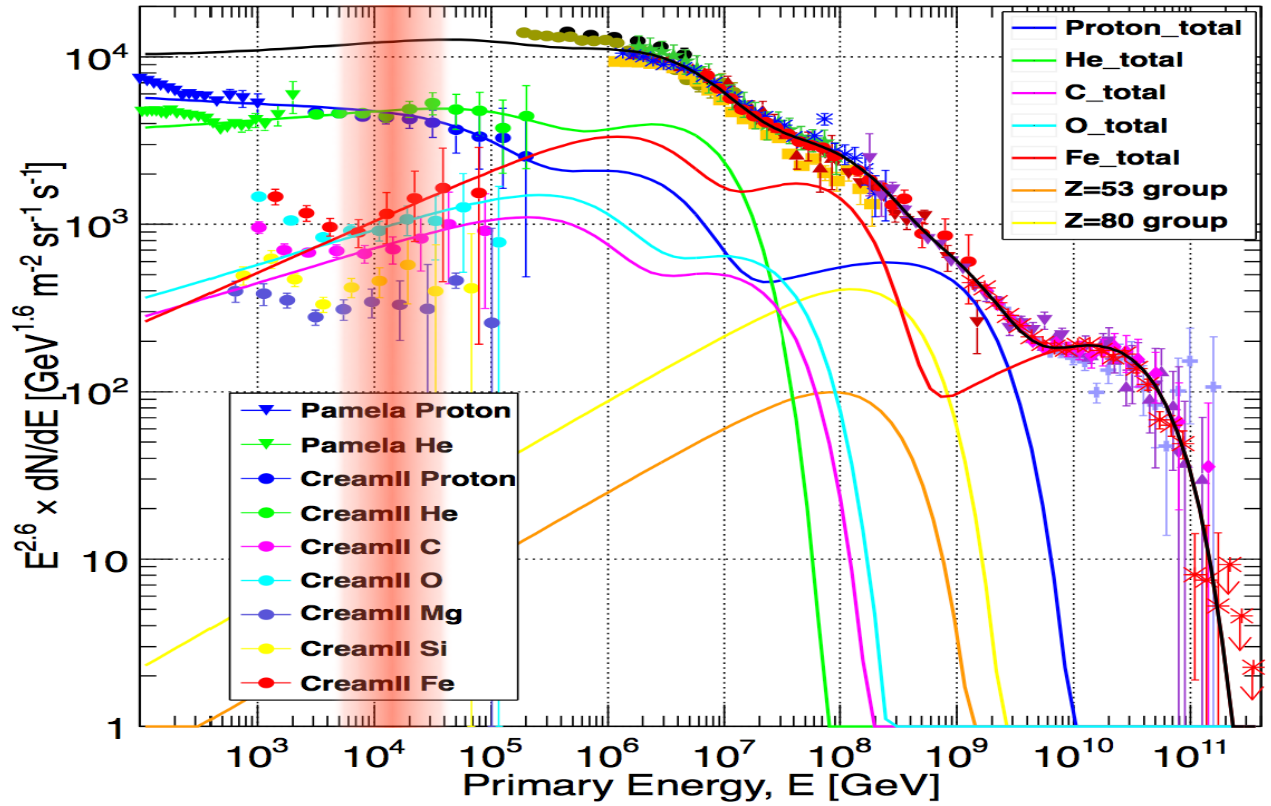


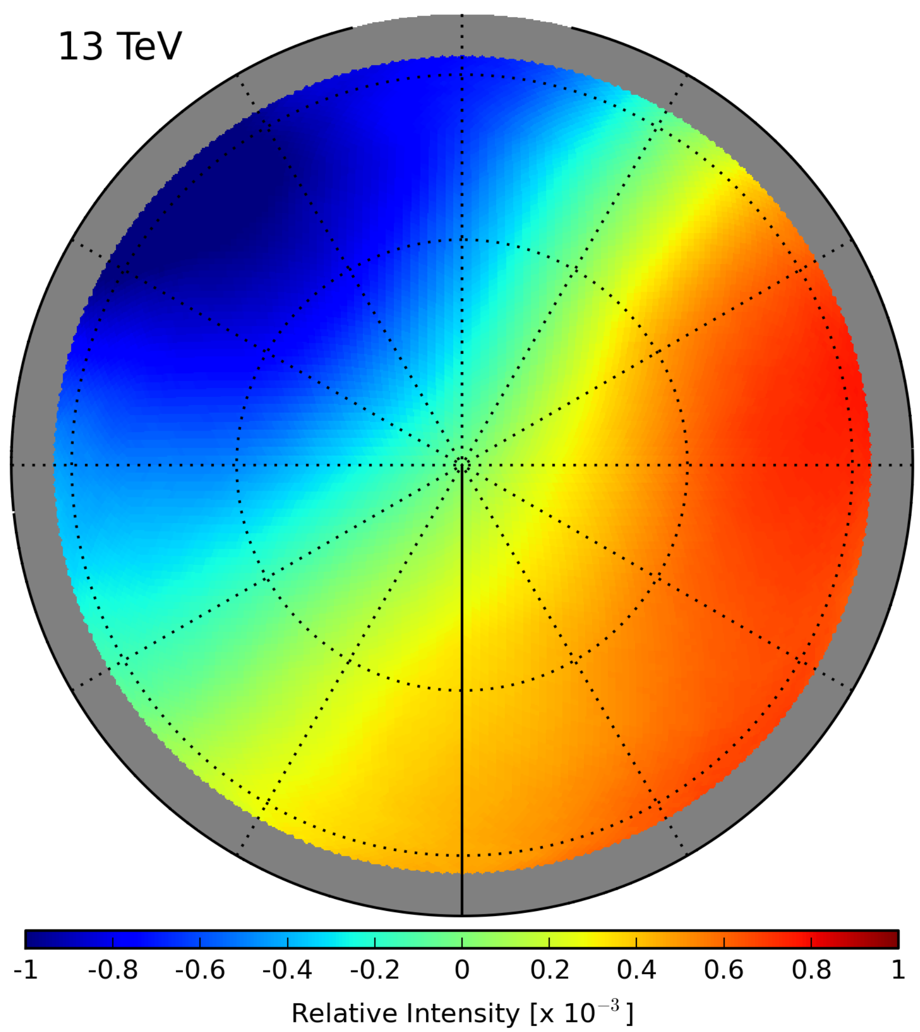


- 6 years of IceCube
- 300 billion events
- anisotropy on the level of 10^{-3}
- median cosmic ray energy **20 TeV**
- trace sources ? Magnetic fields ?

cosmic rays anisotropy
arrival direction distribution



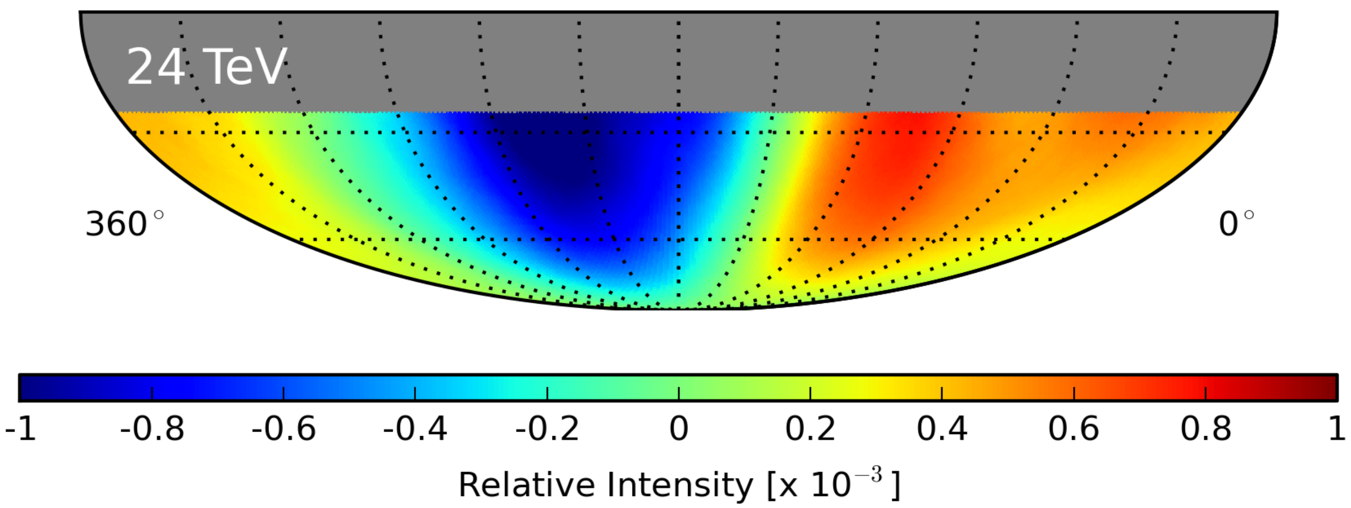


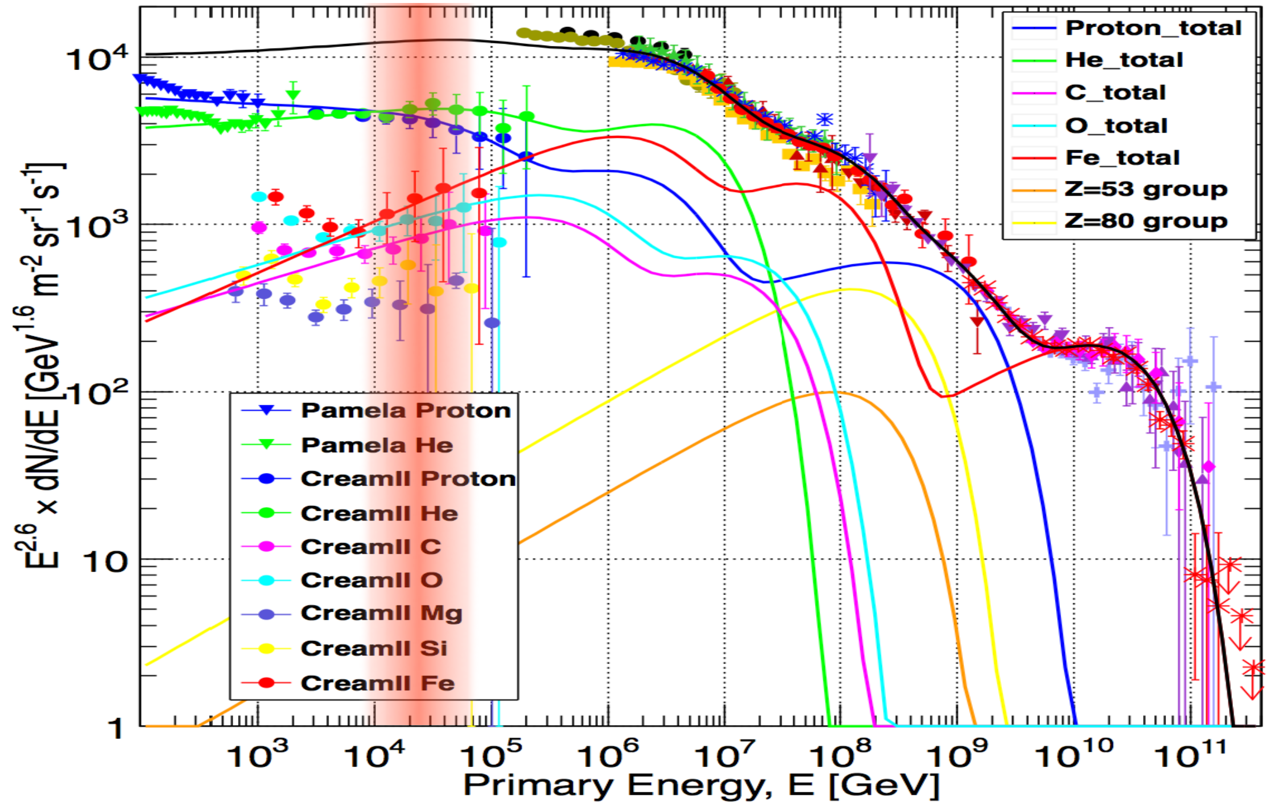


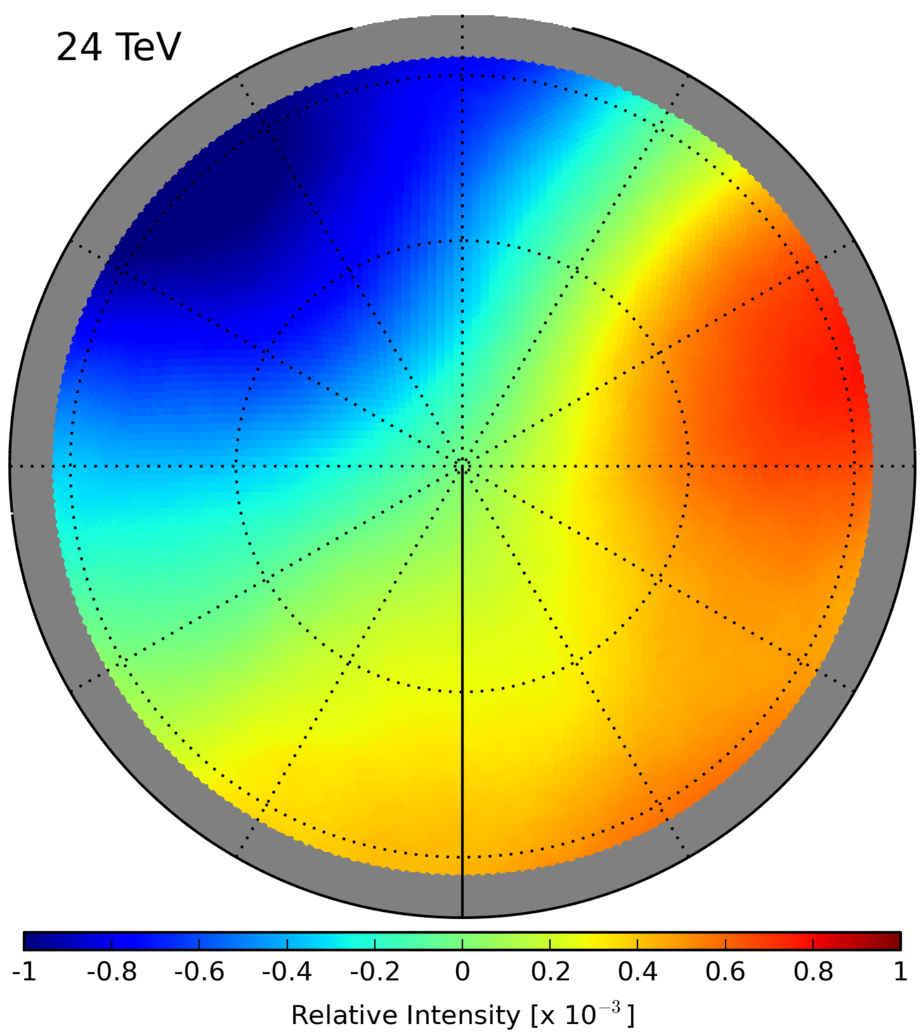
13 TeV **IceCube**

- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

cosmic rays anisotropy
arrival direction distribution





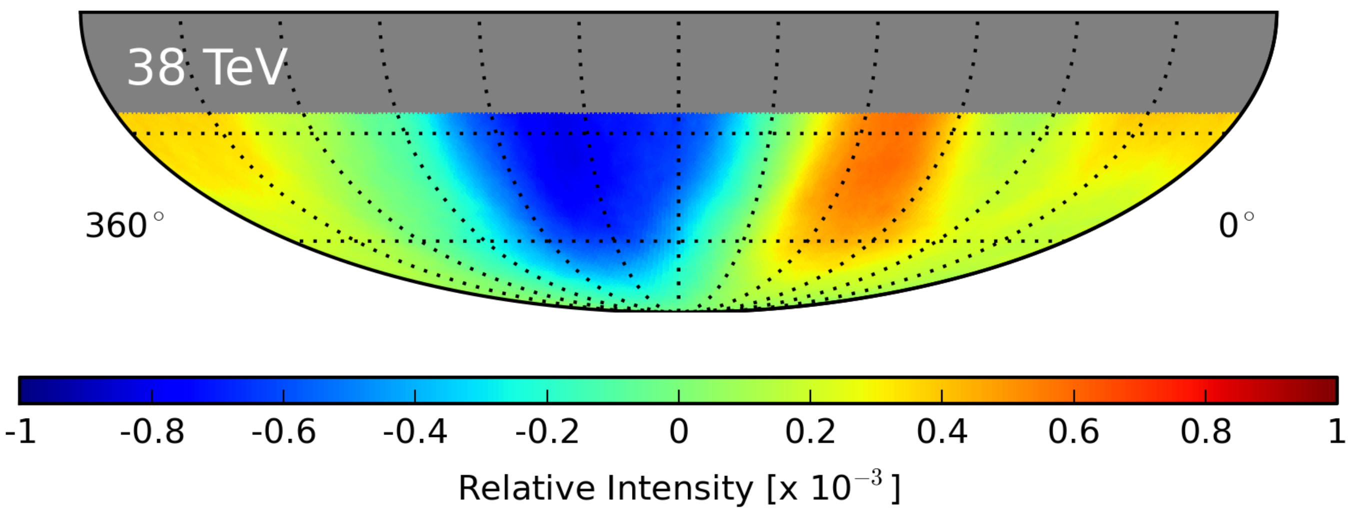


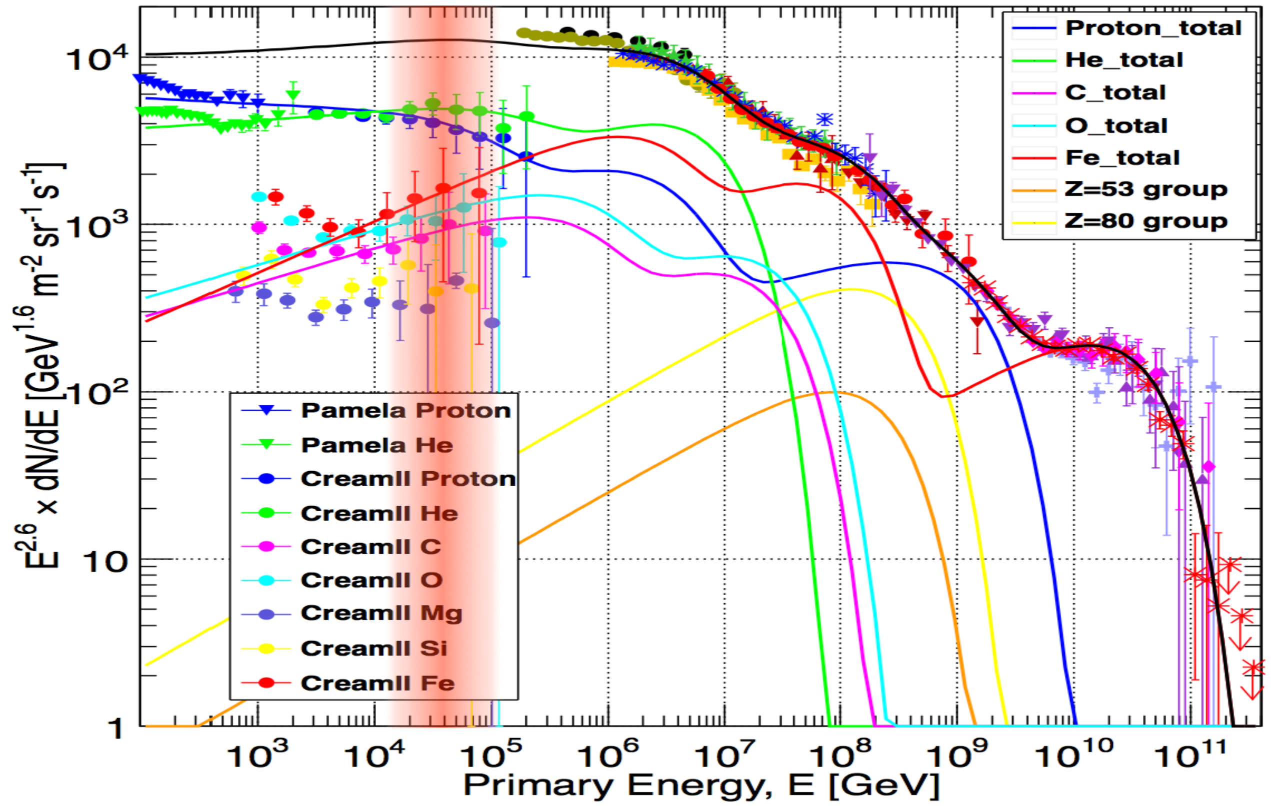
24 TeV **IceCube**

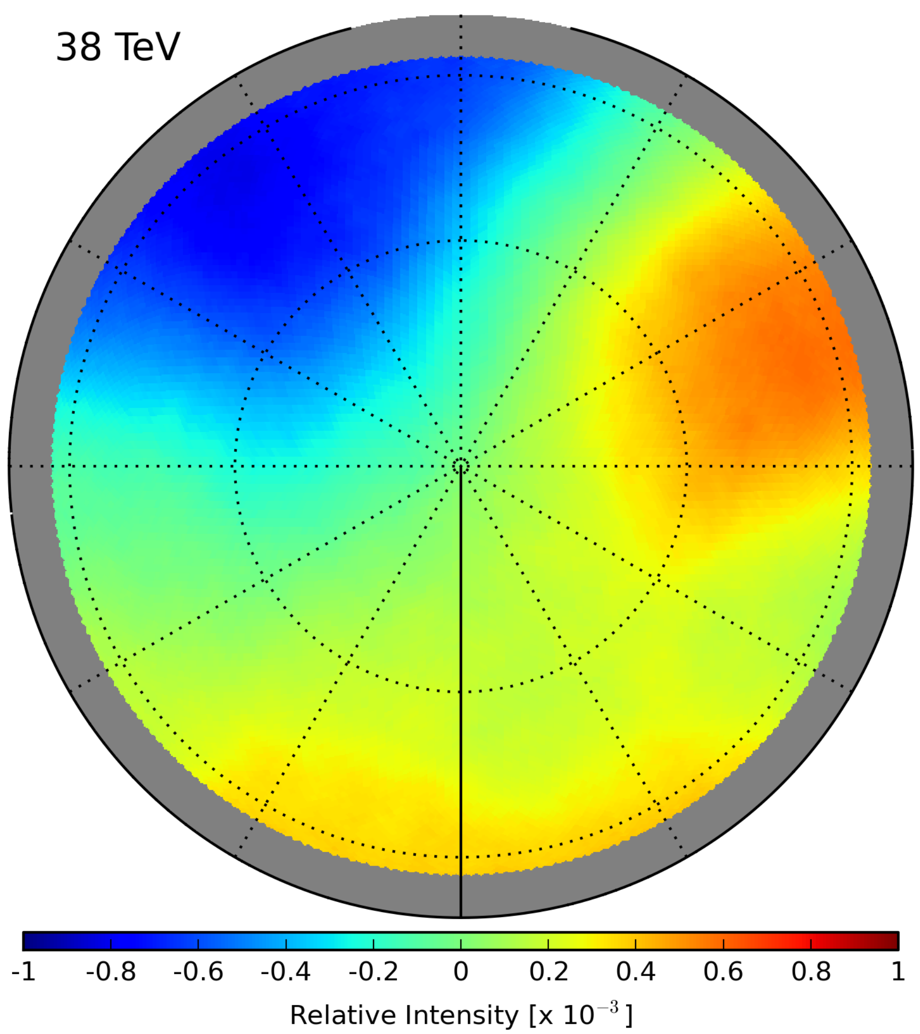
- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

cosmic rays anisotropy

arrival direction distribution





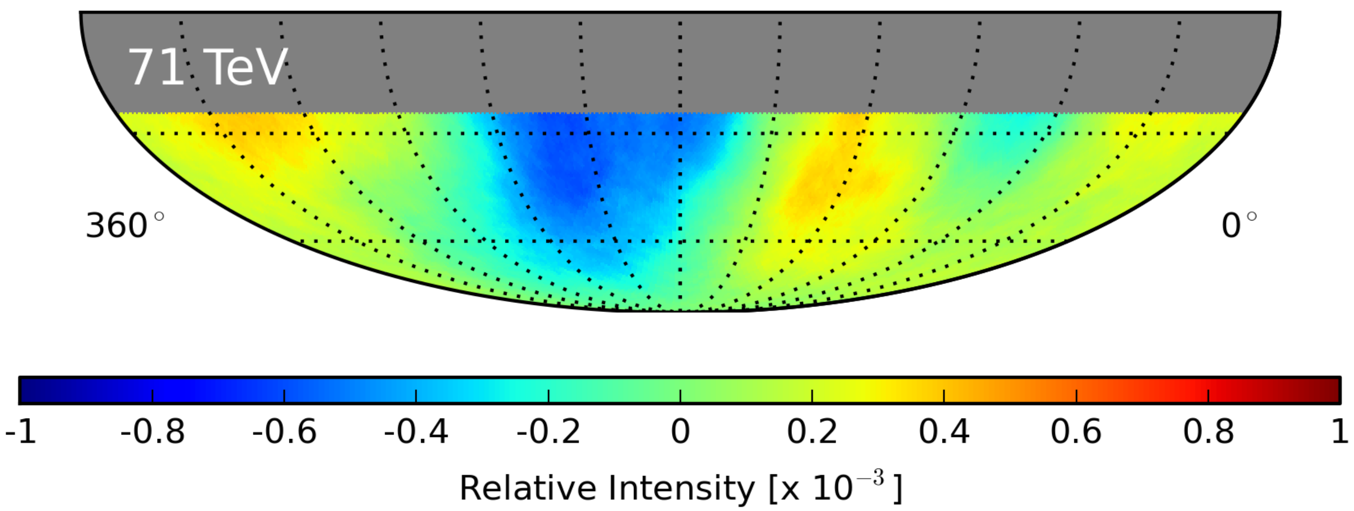


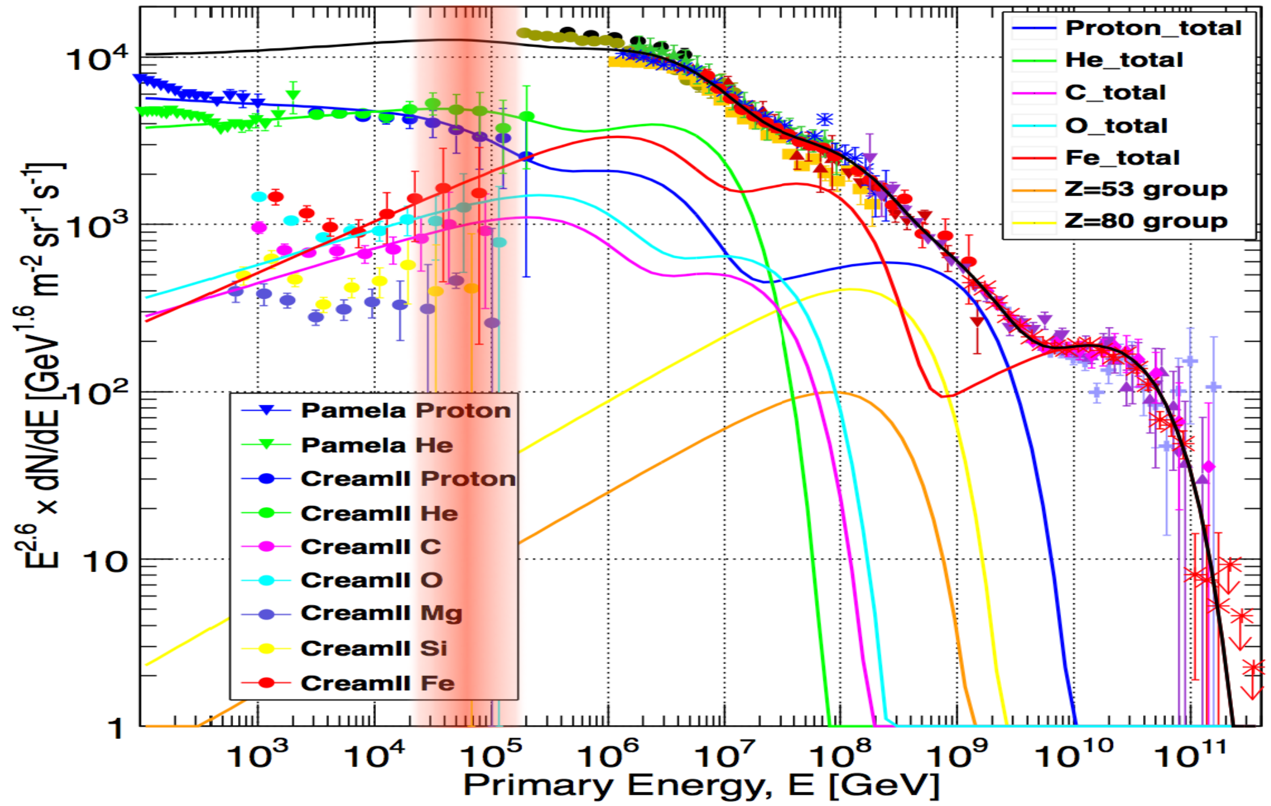
38 TeV **IceCube**

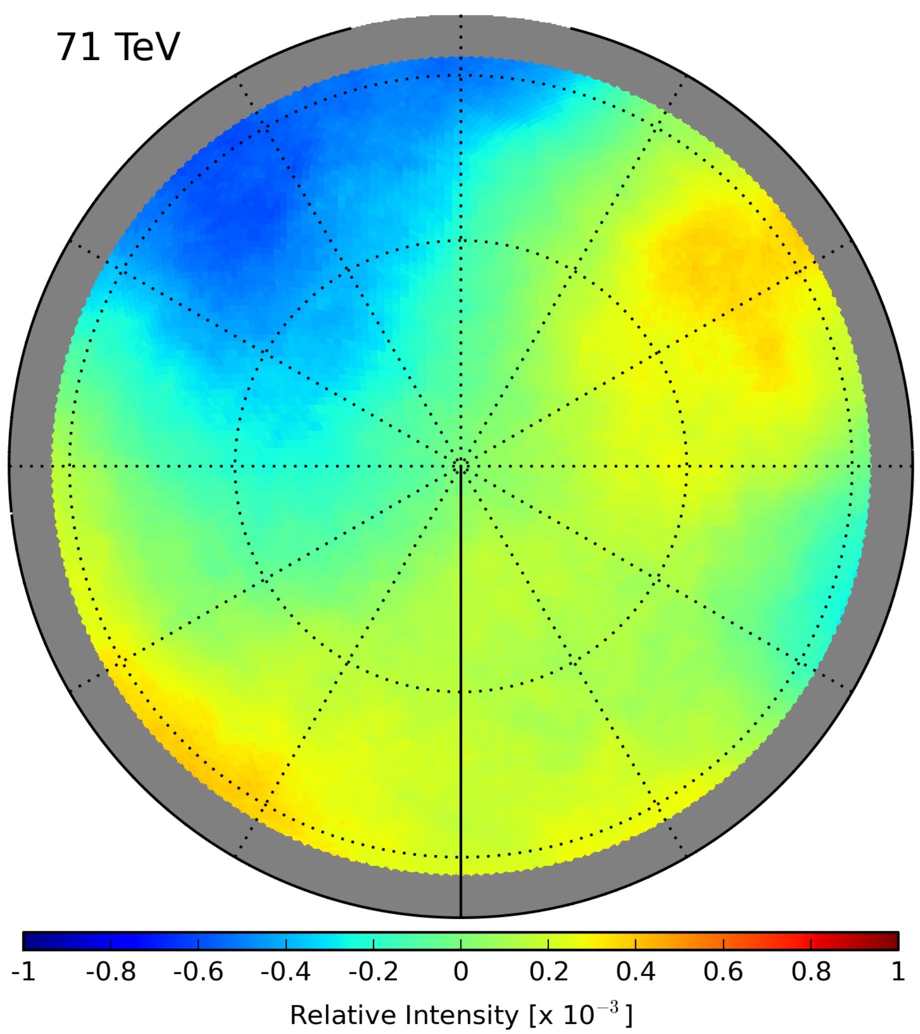
- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

cosmic rays anisotropy

arrival direction distribution





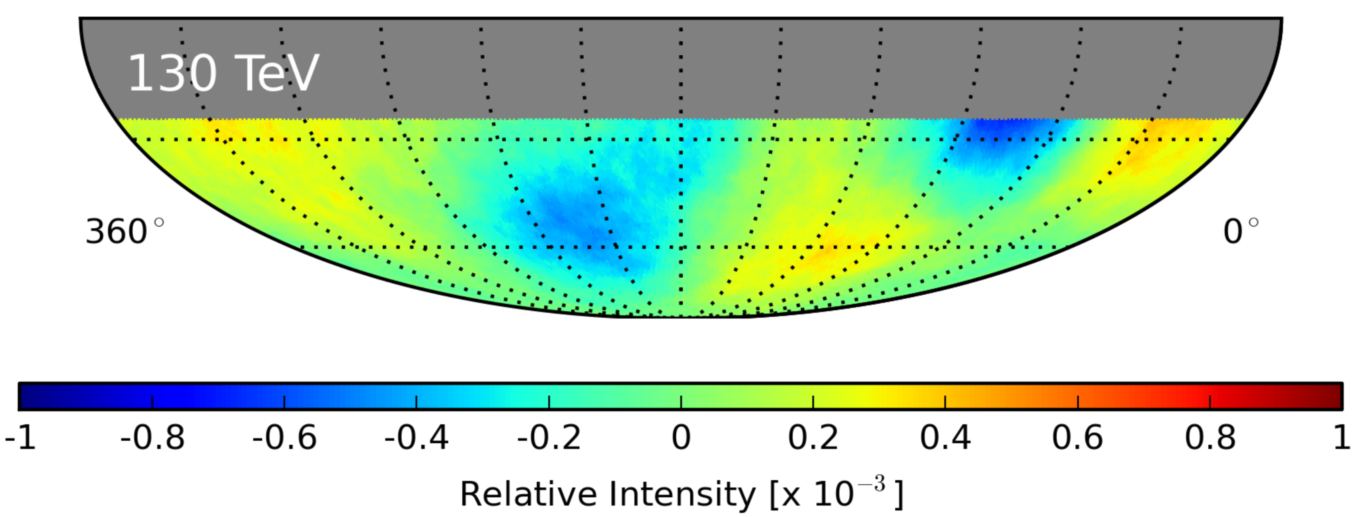


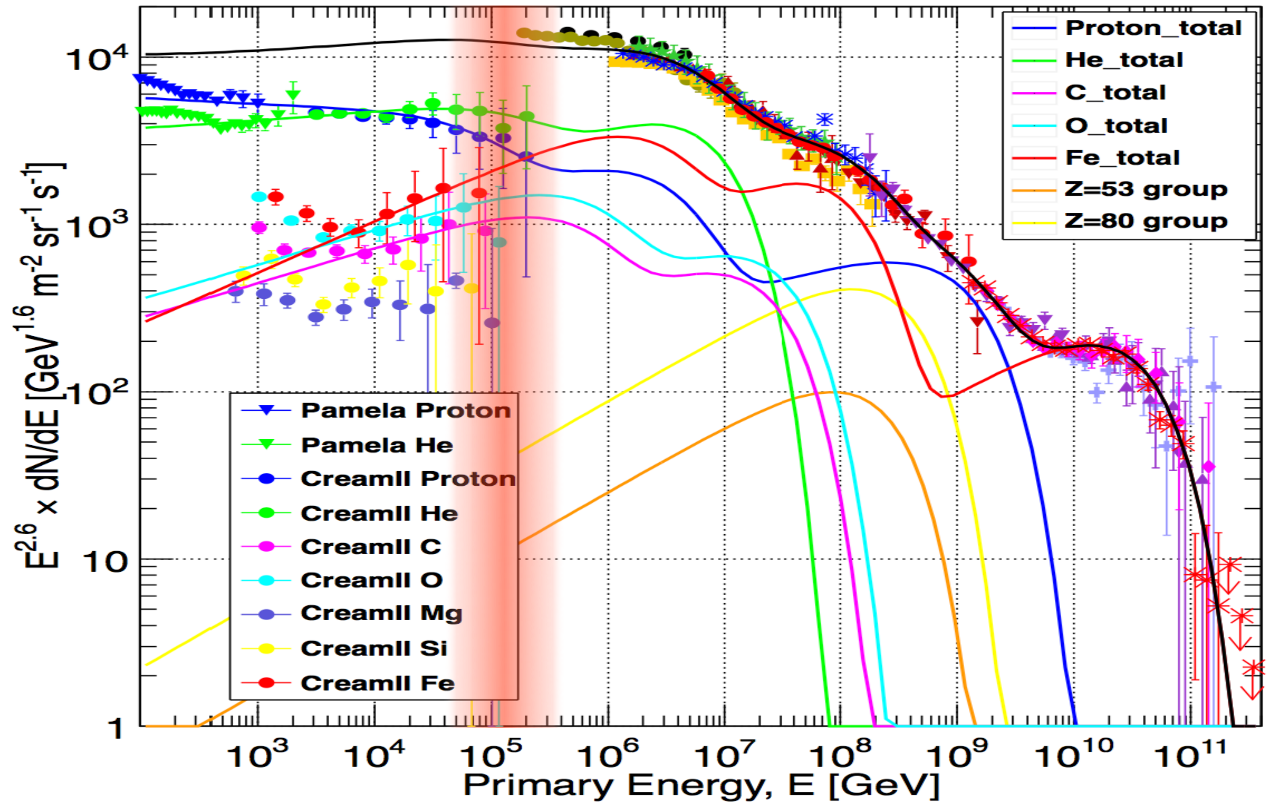
71 TeV **IceCube**

- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

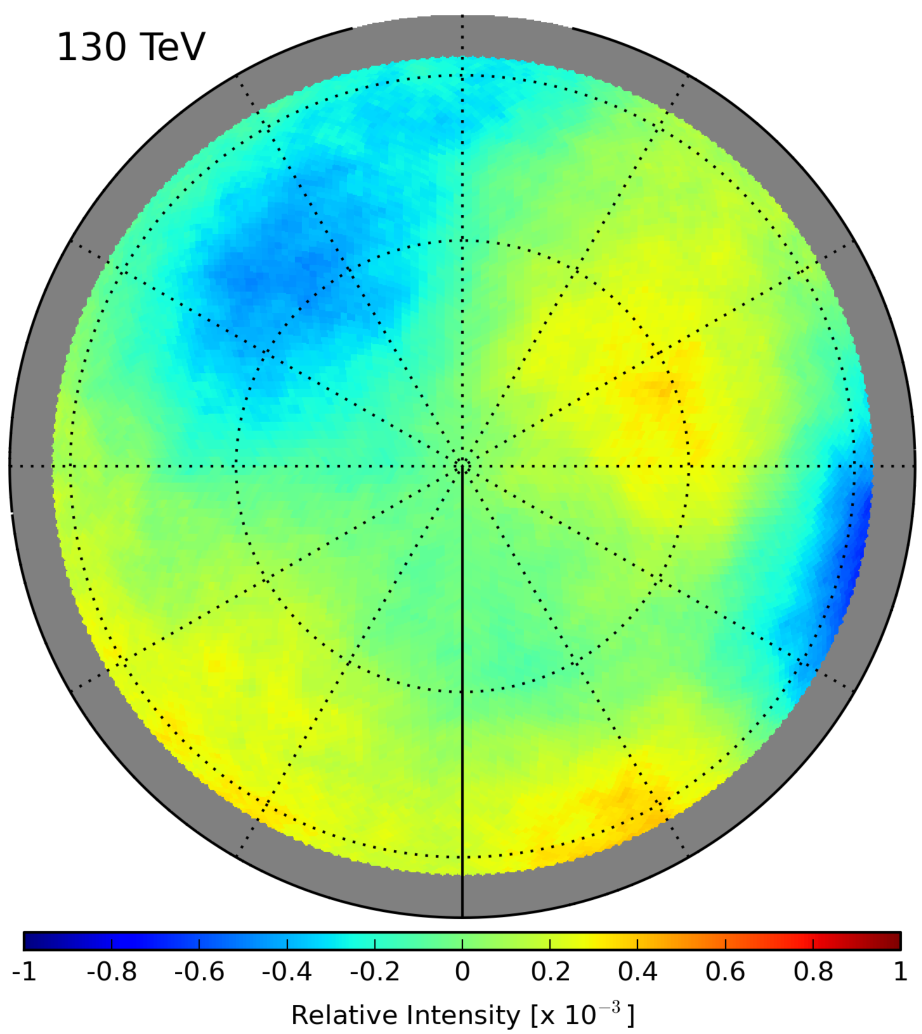
cosmic rays anisotropy

arrival direction distribution





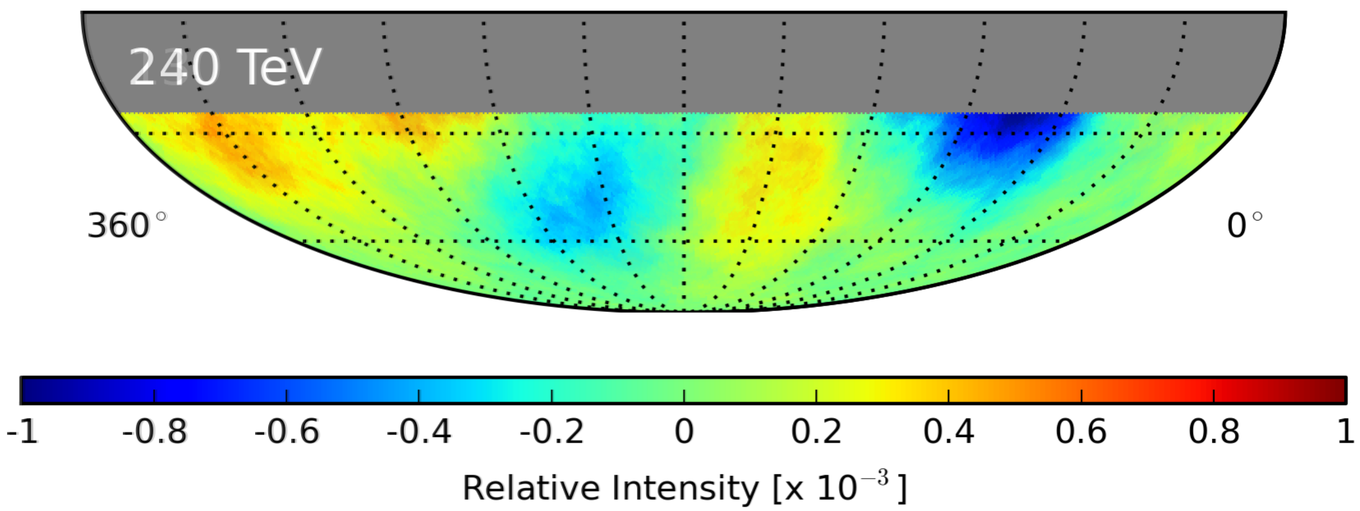
130 TeV **IceCube**

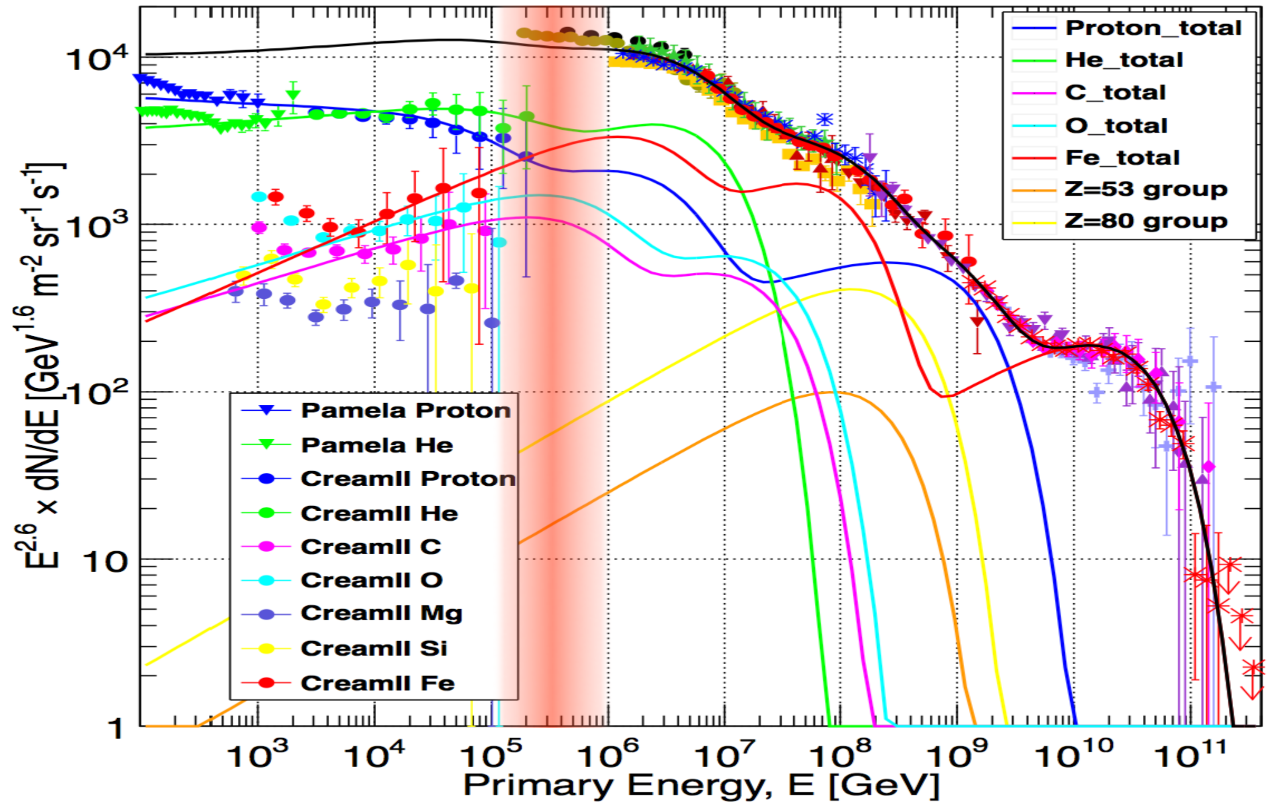


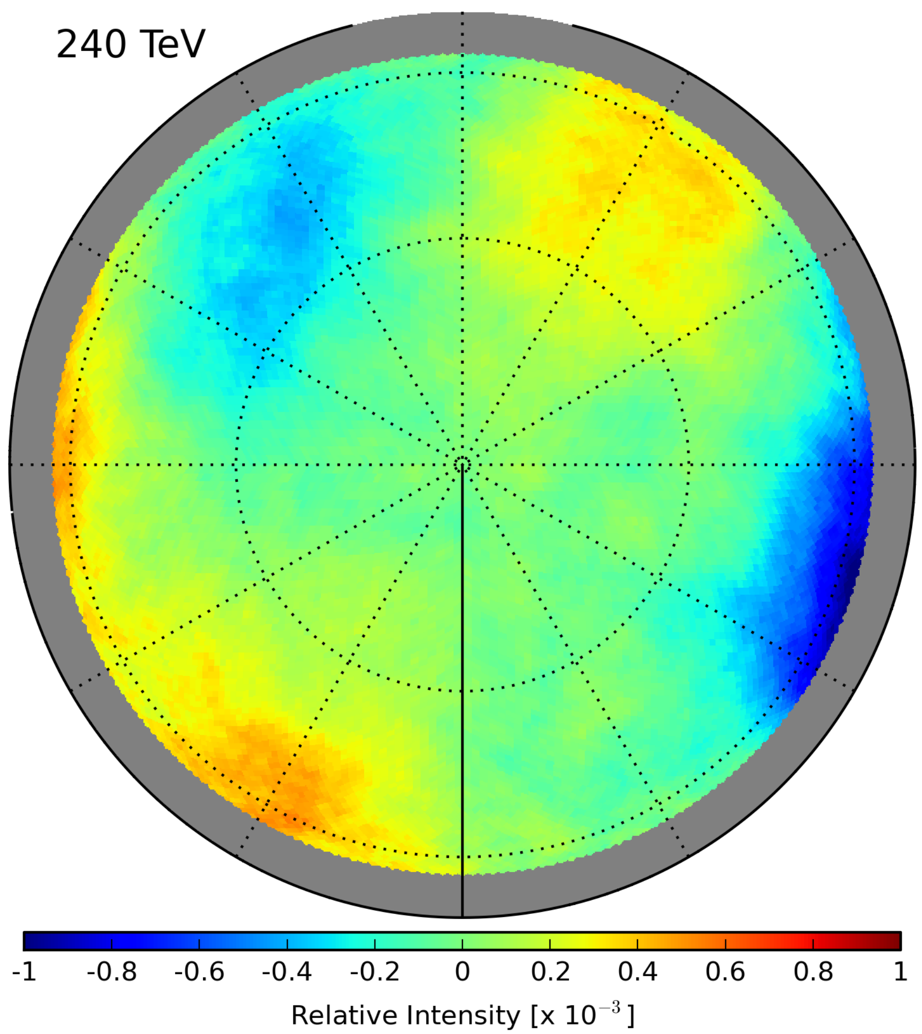
- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

cosmic rays anisotropy

arrival direction distribution





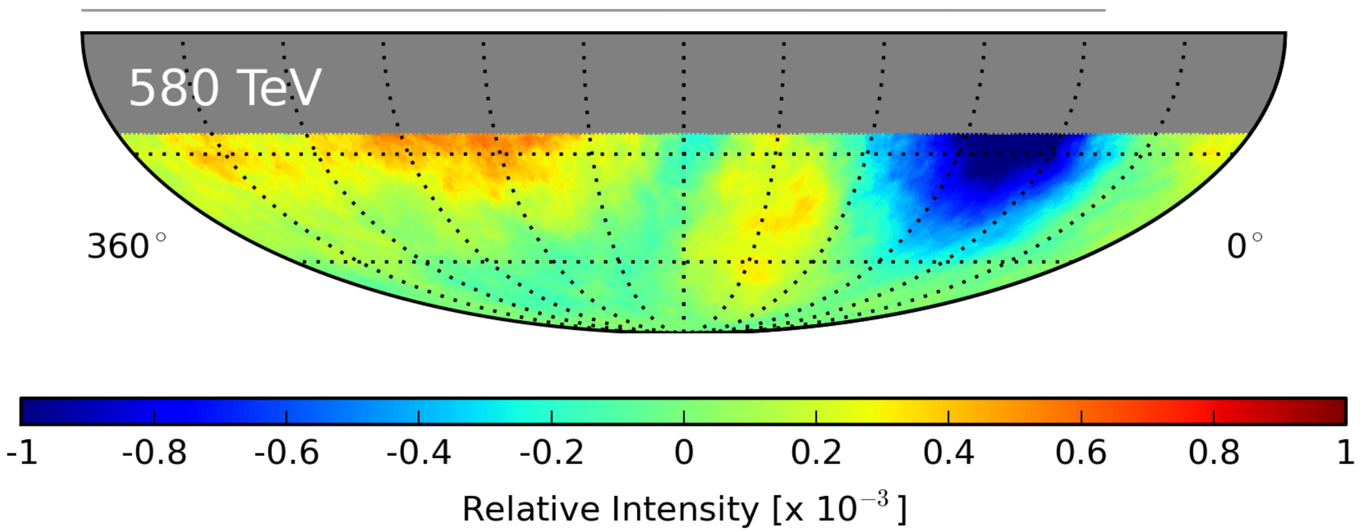


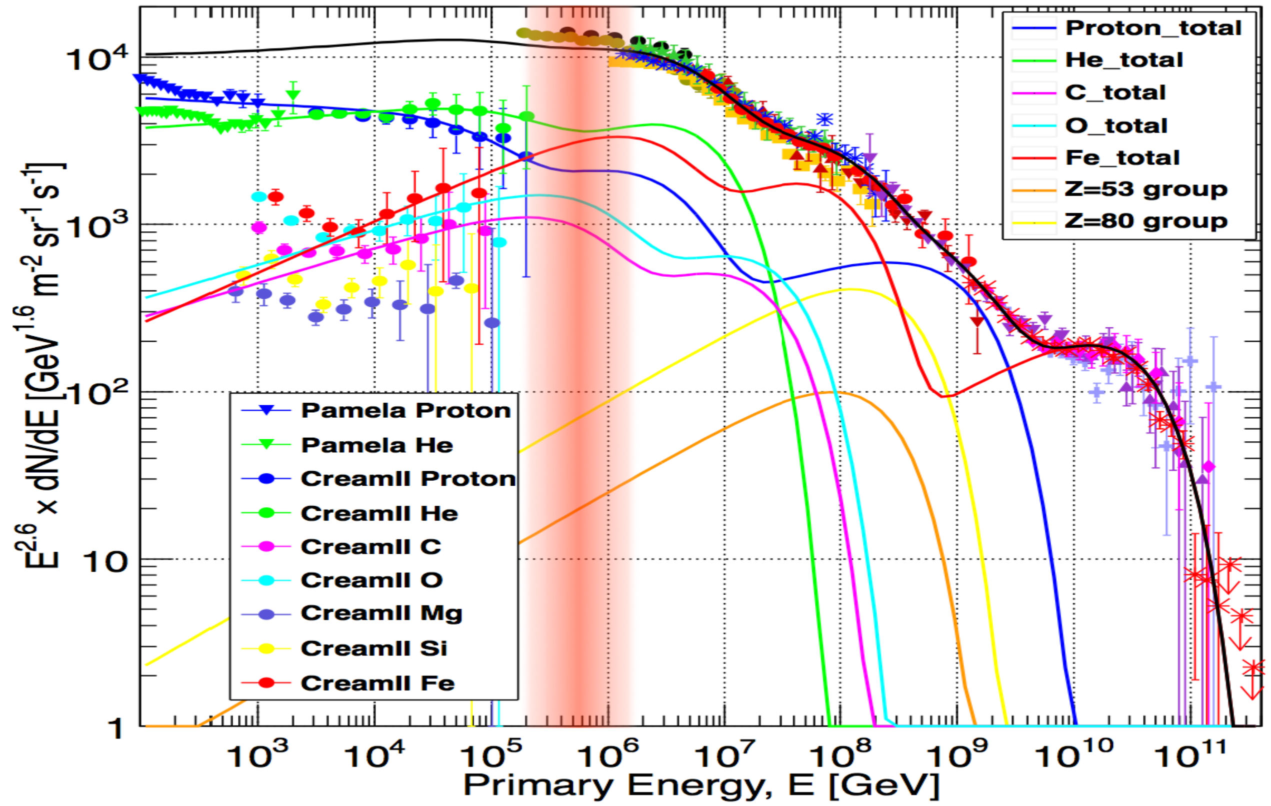
240 TeV **IceCube**

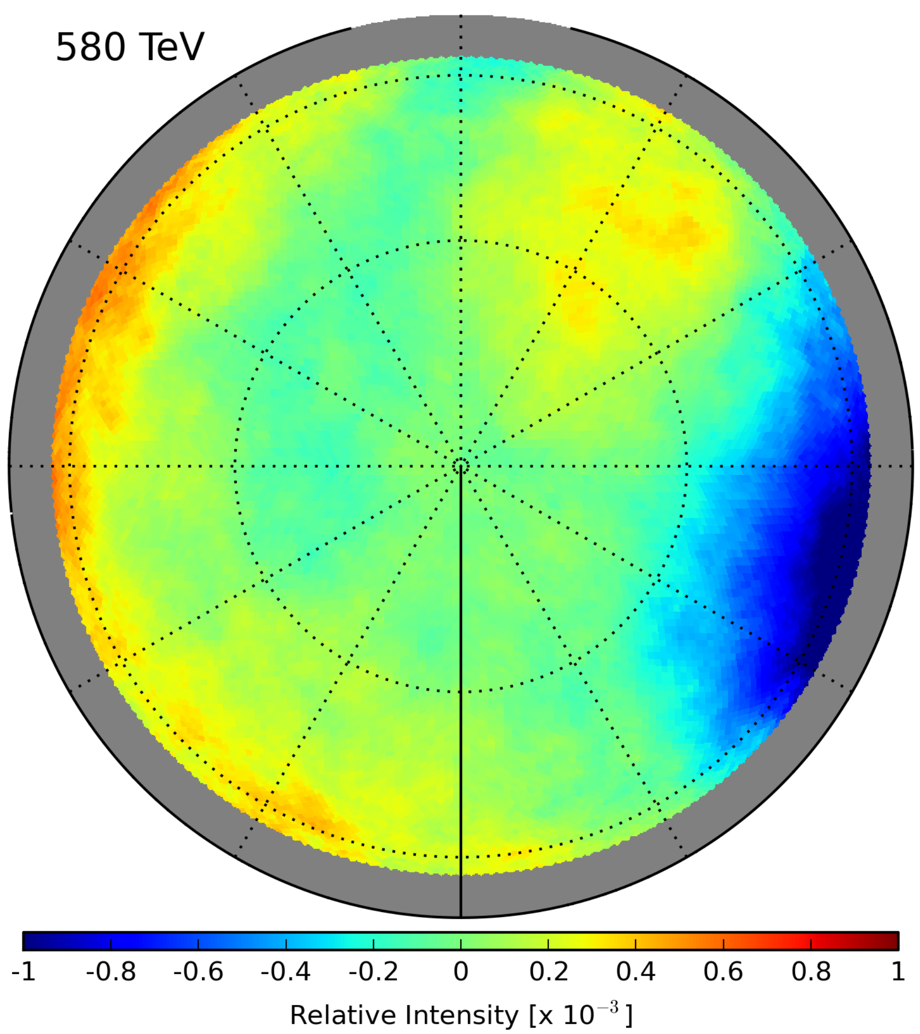
- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

cosmic rays anisotropy

arrival direction distribution





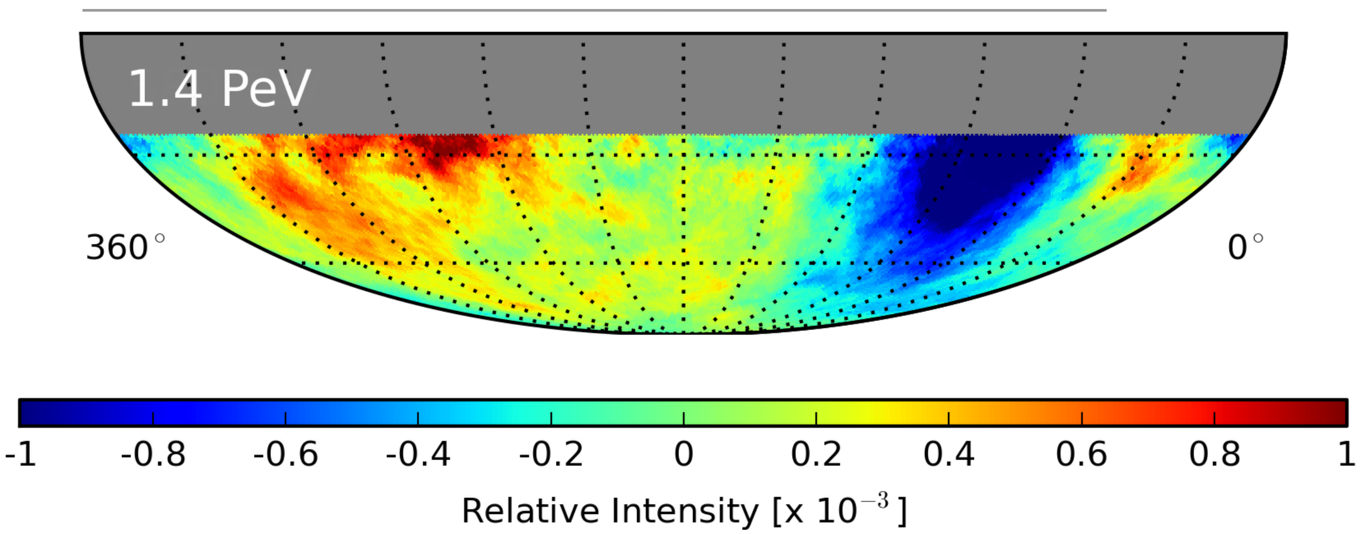


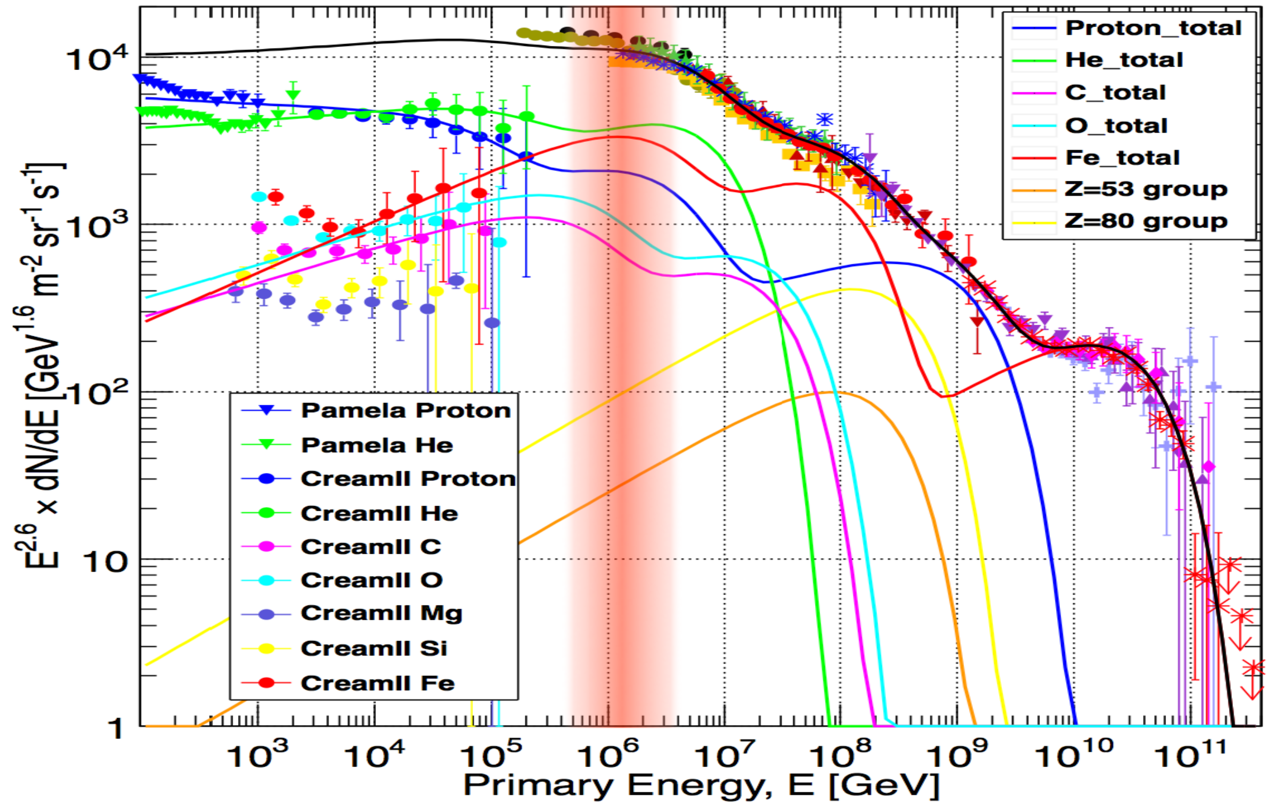
580 TeV **IceCube**

- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

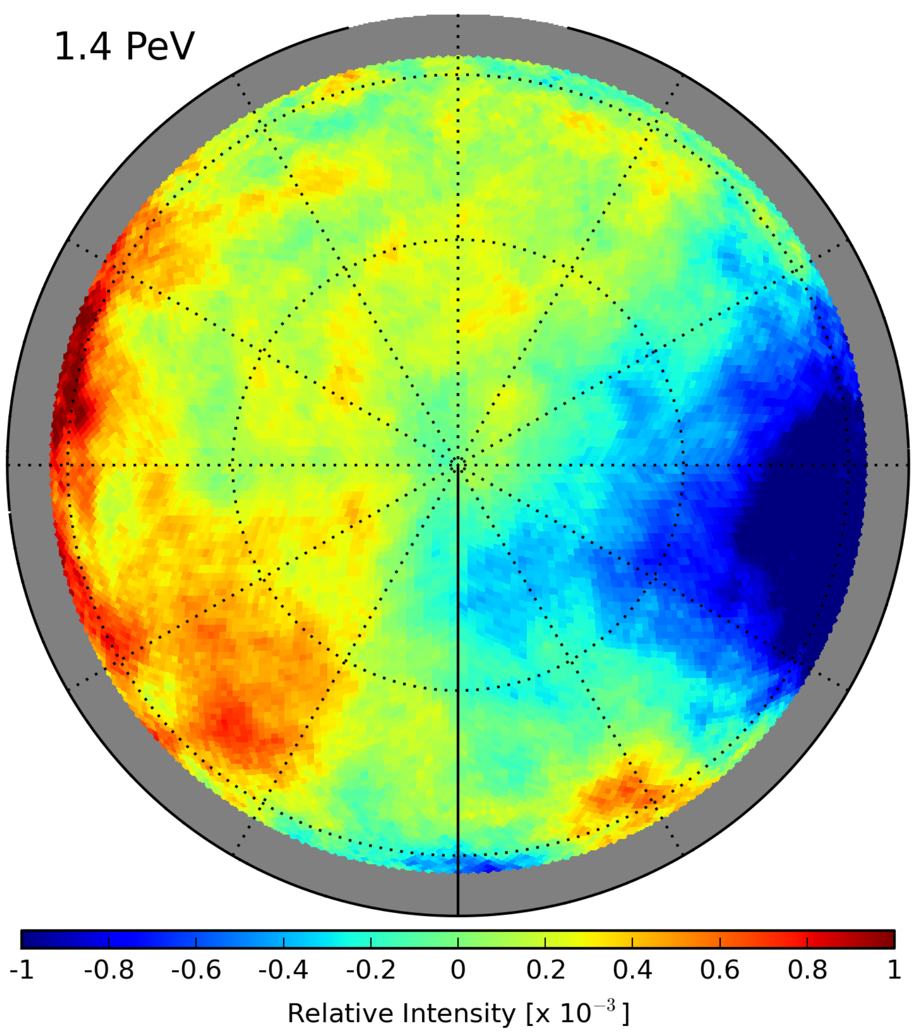
cosmic rays anisotropy

arrival direction distribution





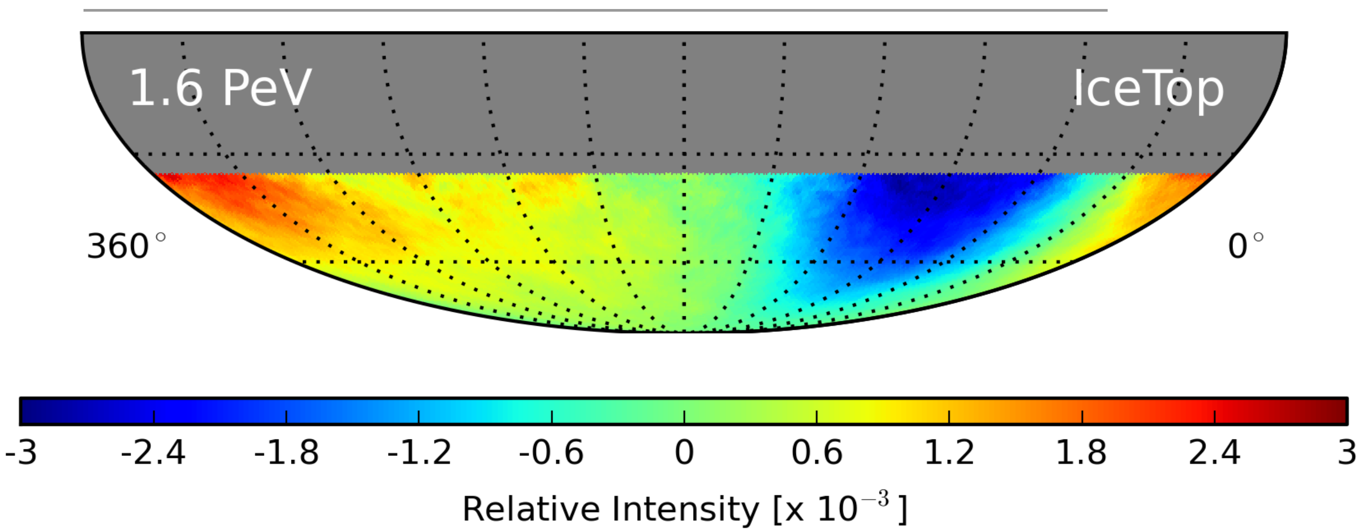
1.4 PeV **IceCube**

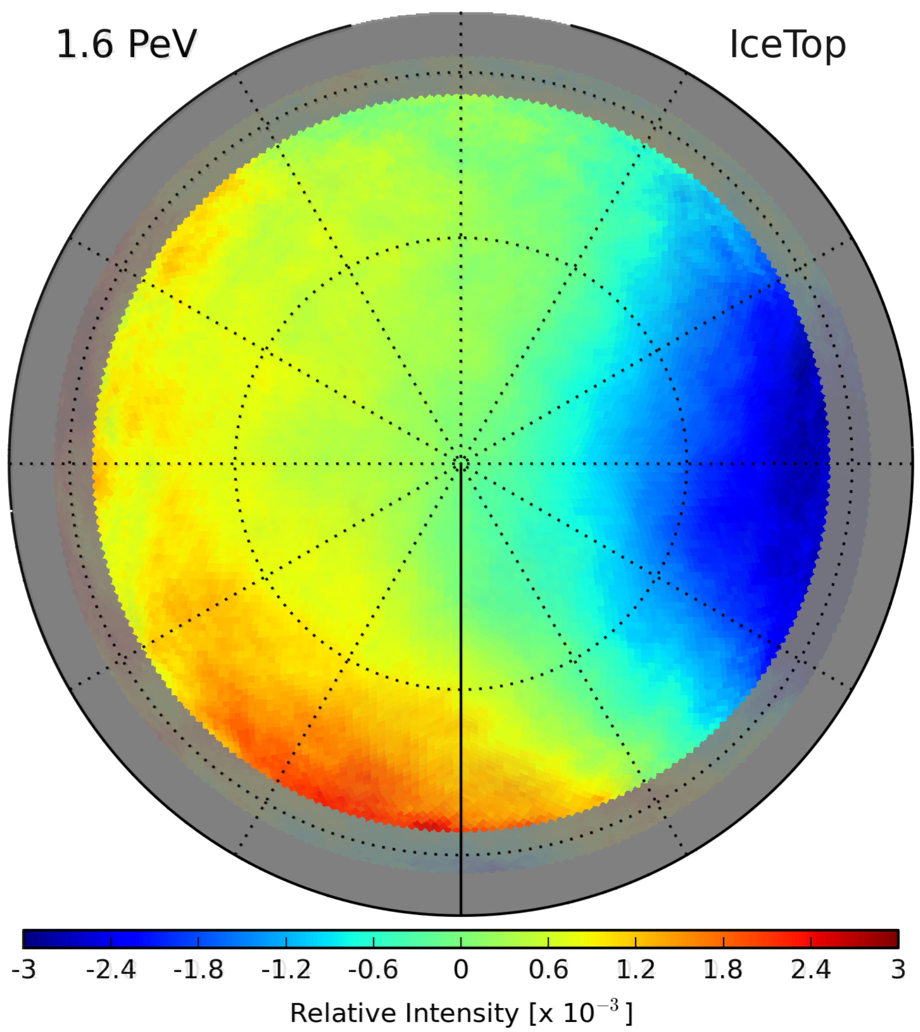


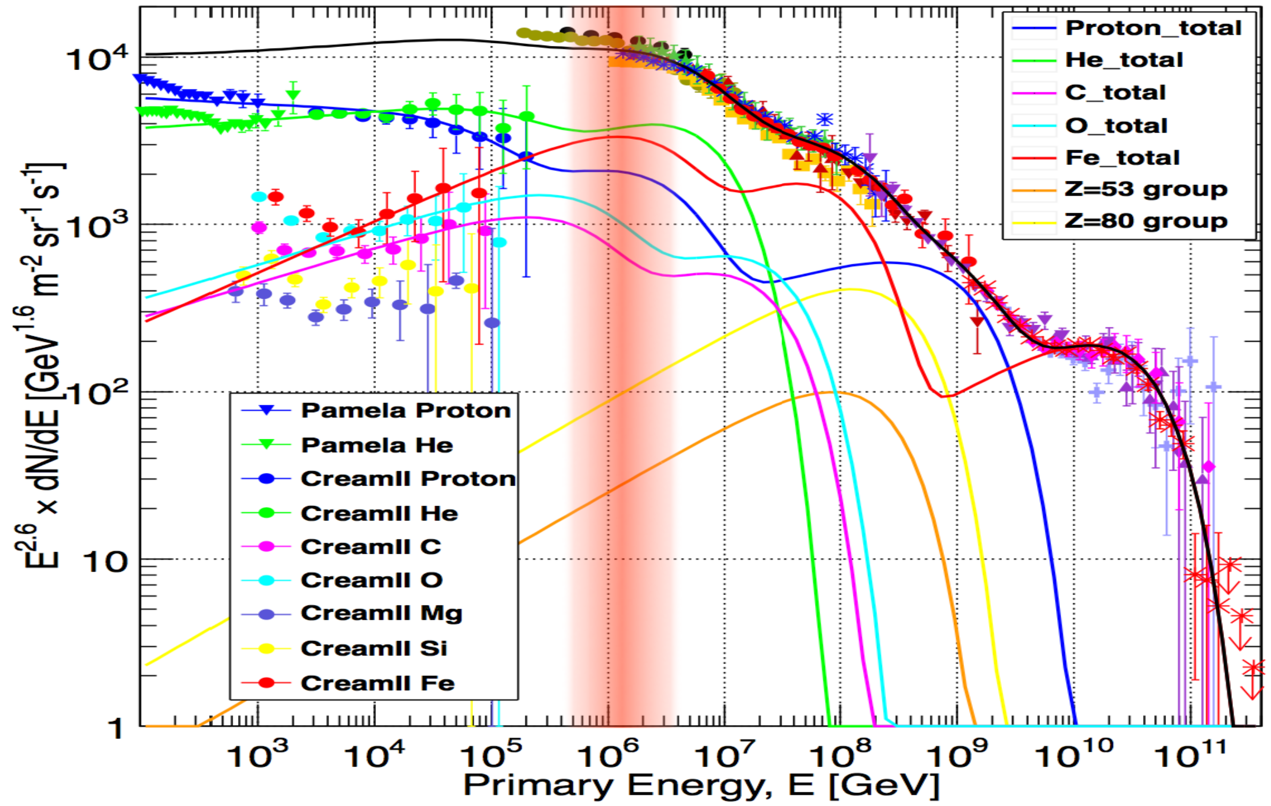
- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

cosmic rays anisotropy

arrival direction distribution





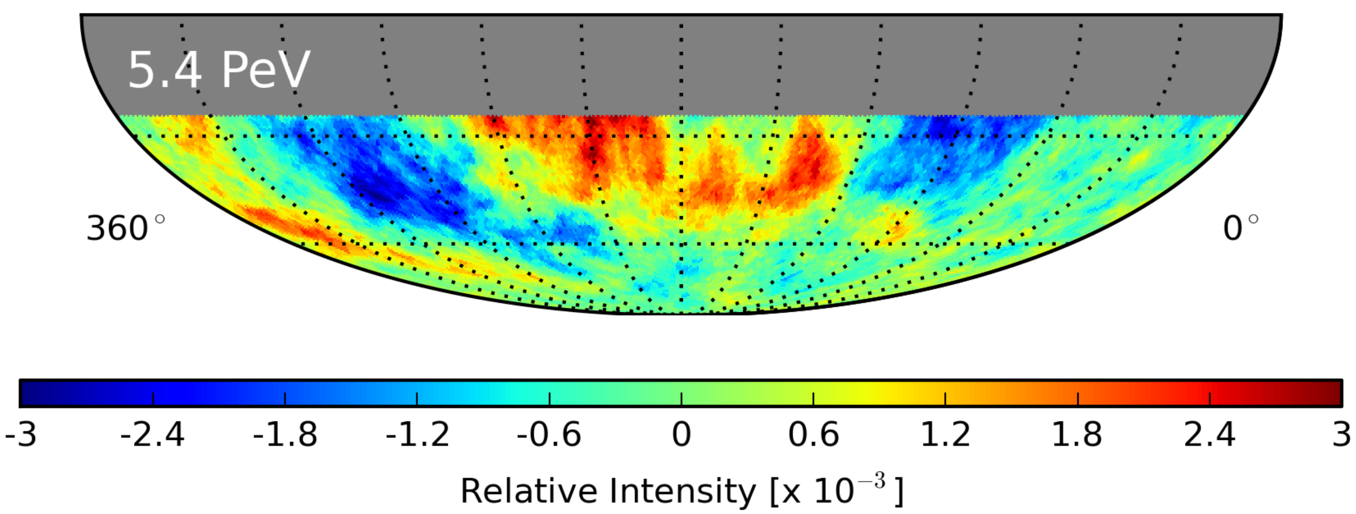


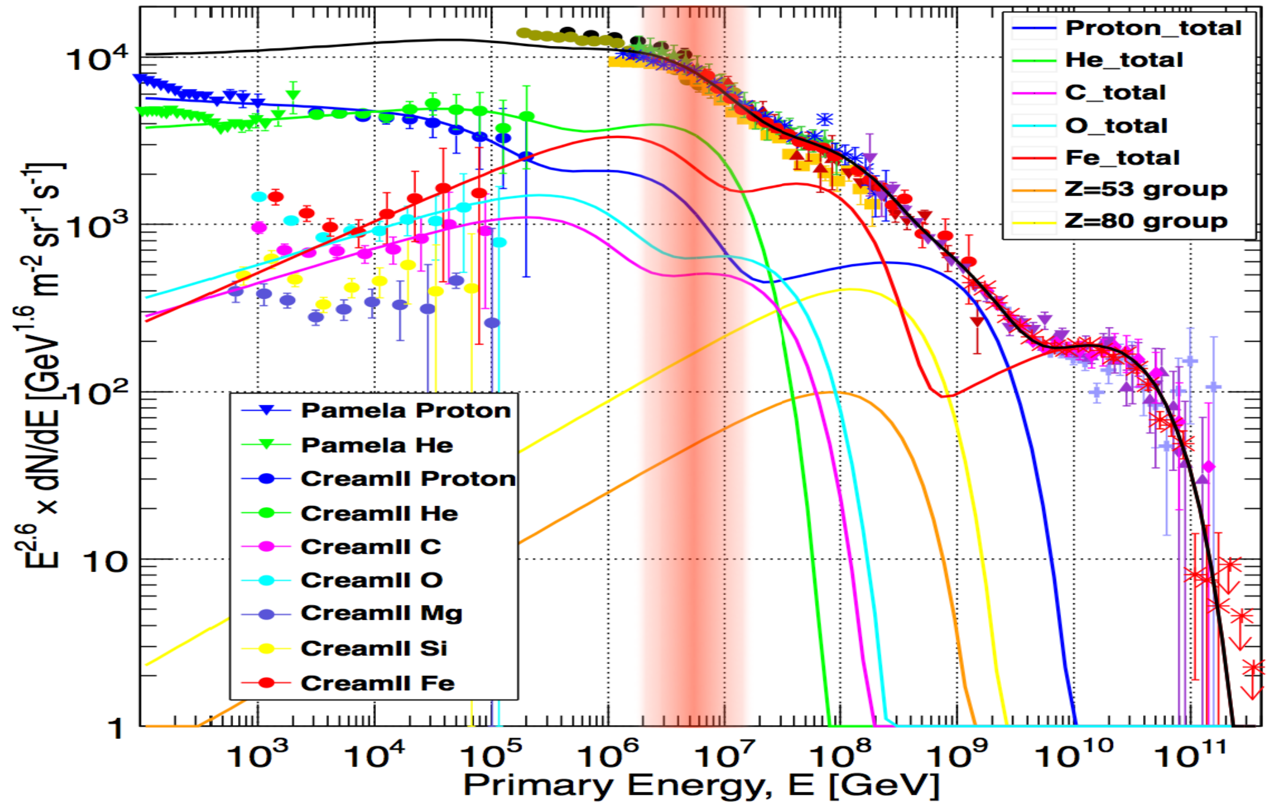
1.6 PeV **IceTop**

- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

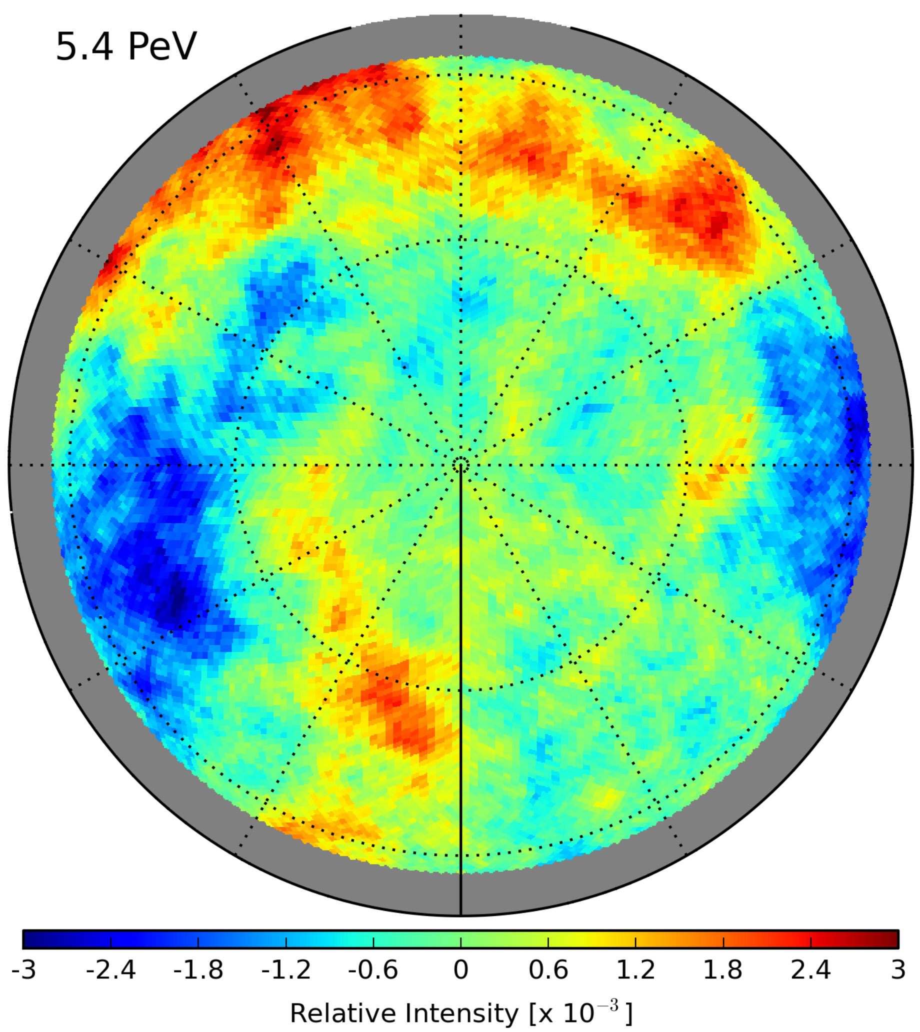
cosmic rays anisotropy

arrival direction distribution





5.4 PeV **IceCube**

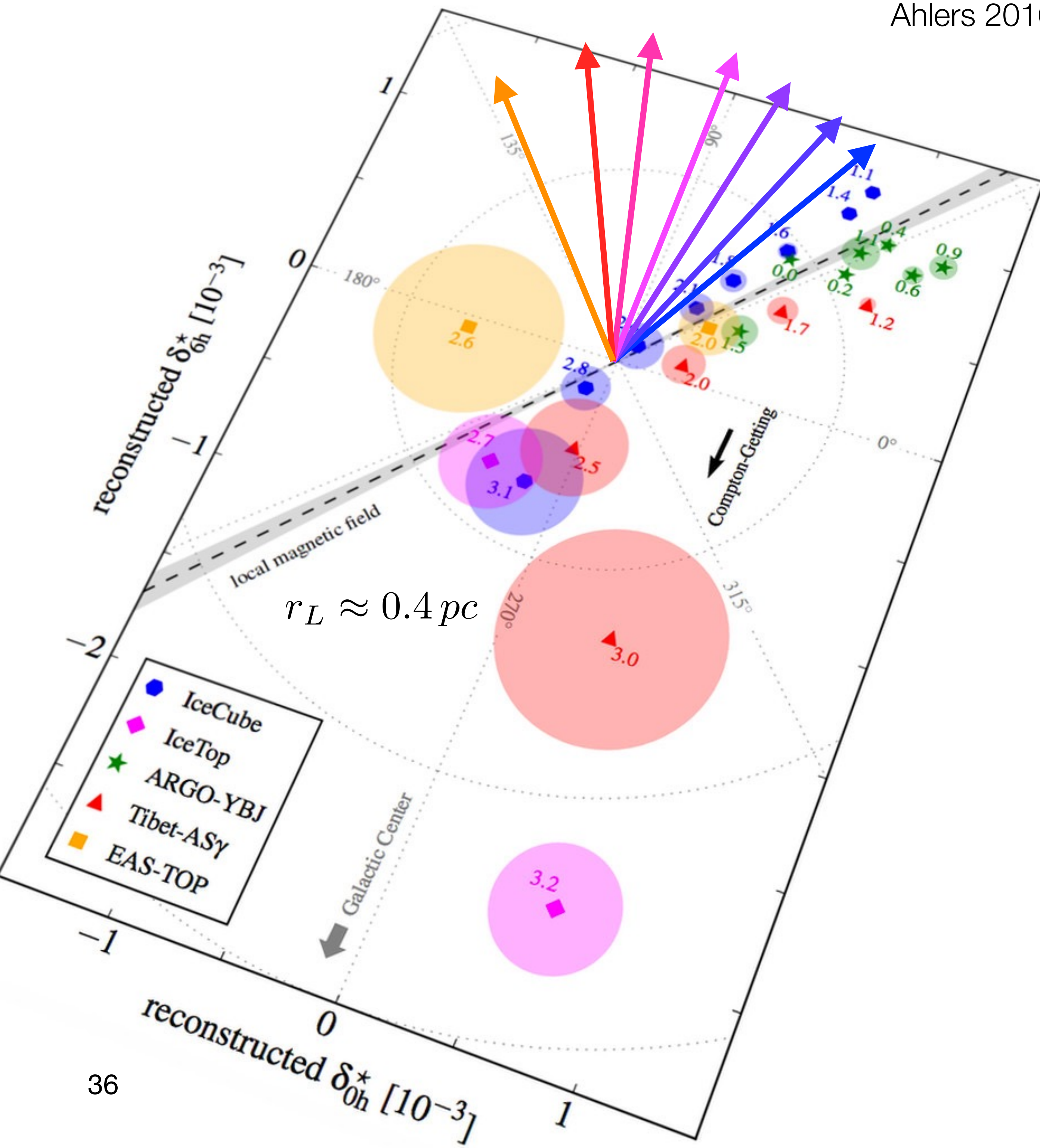


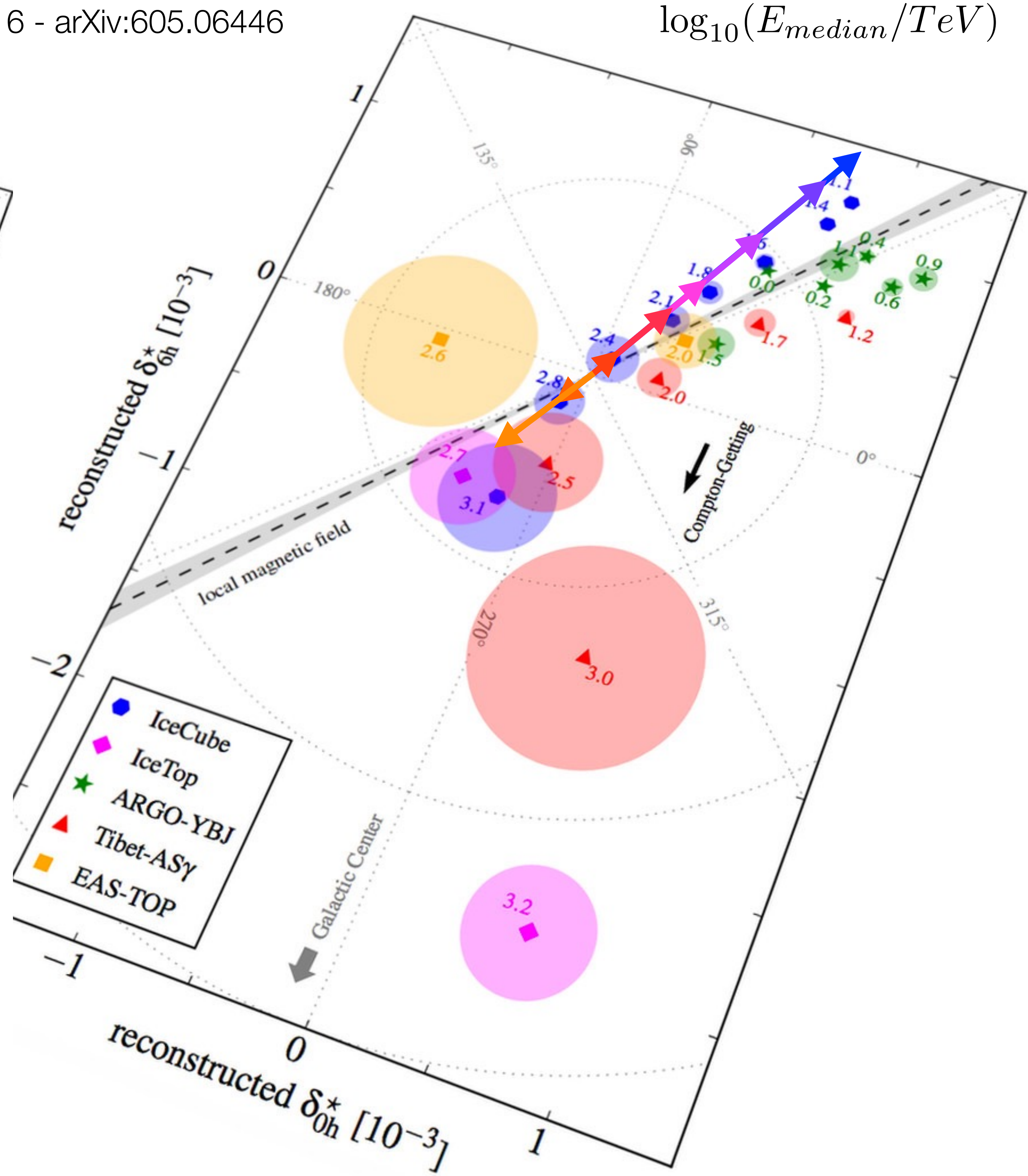
- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

measuring cosmic ray anisotropy

what is the missing information ?

Ahlers 2016 - arXiv:605.06446



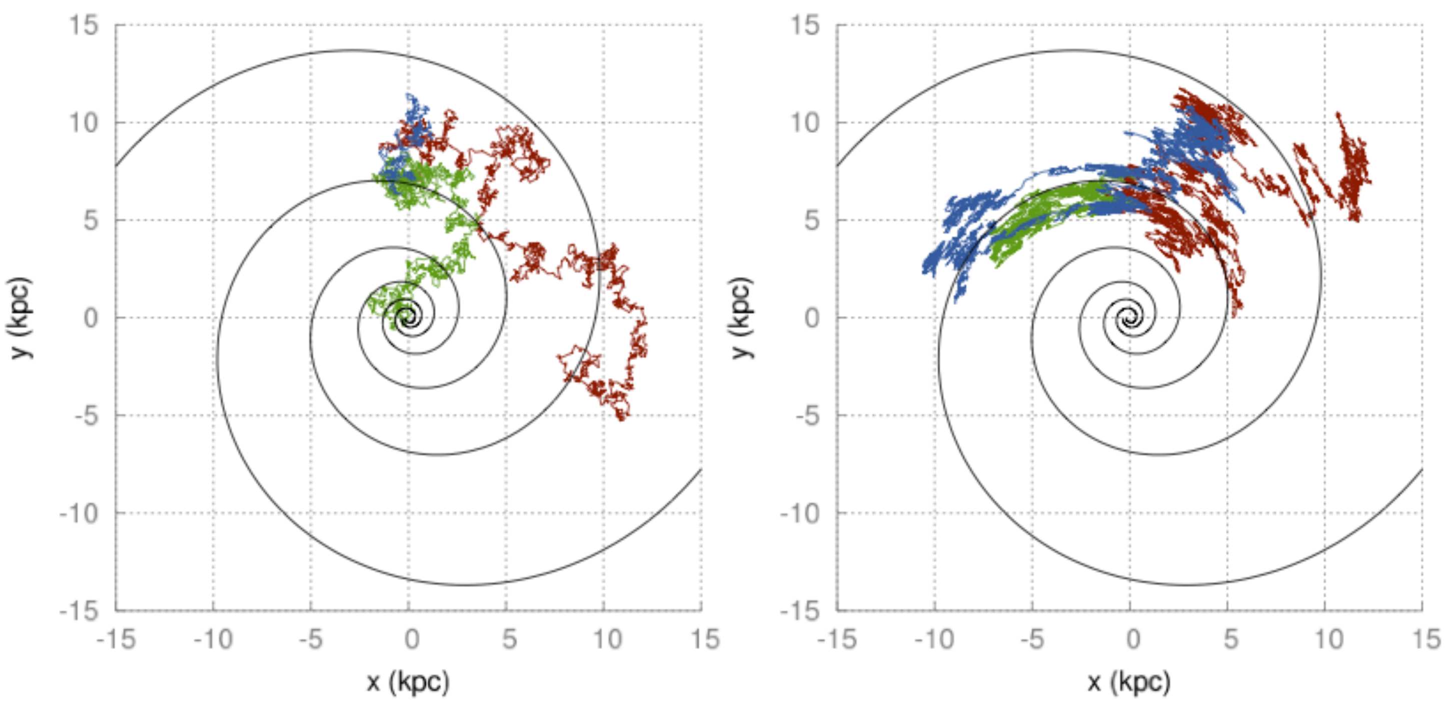


cosmic ray anisotropy

probing diffusion properties

anisotropic diffusion

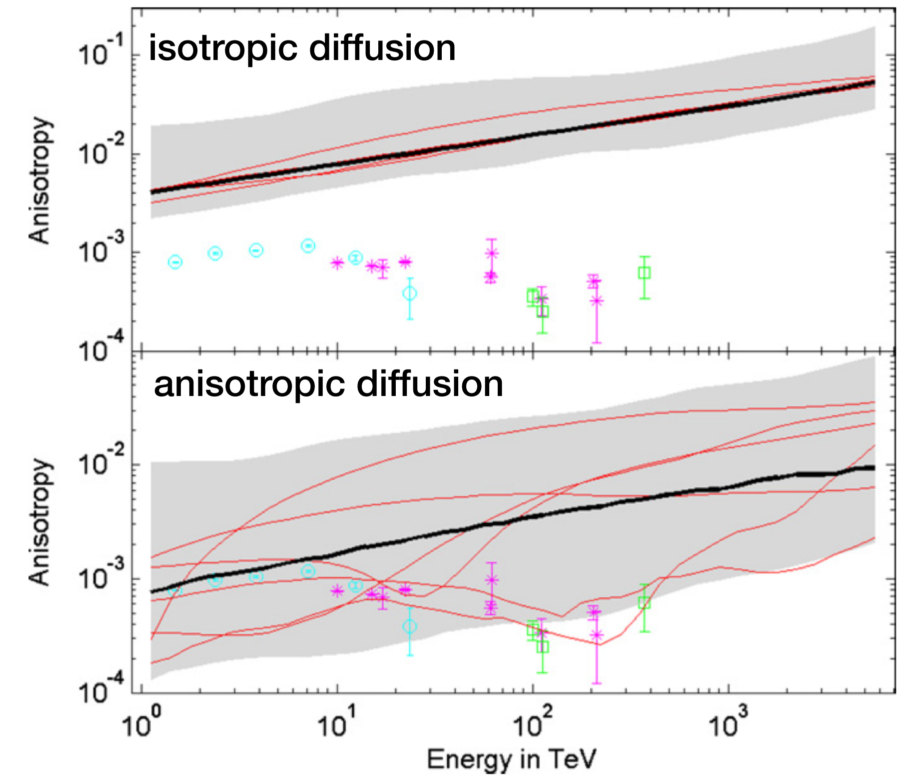
Effenberger+, 2012



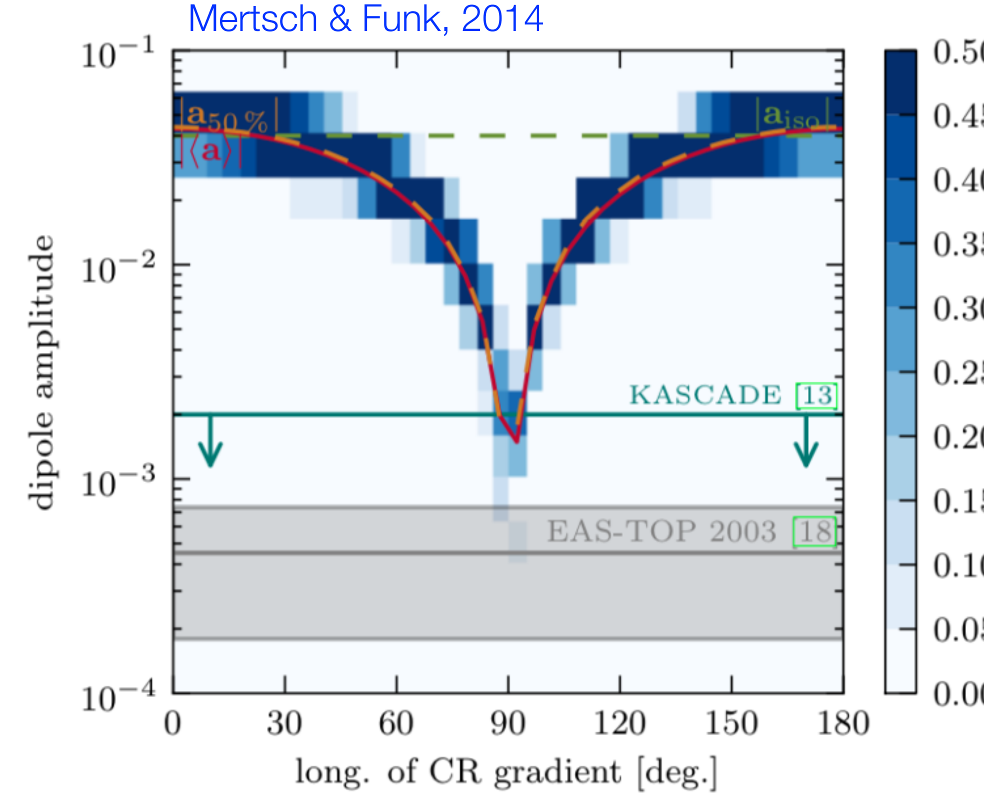
- **D⊥/D∥ << 1** - parallel projection of anisotropy
- cosmic ray **sources concealed** by propagation effects

diffusion coefficient hardly a single power law, homogeneous and isotropic

Kumar & Eichler, 2014



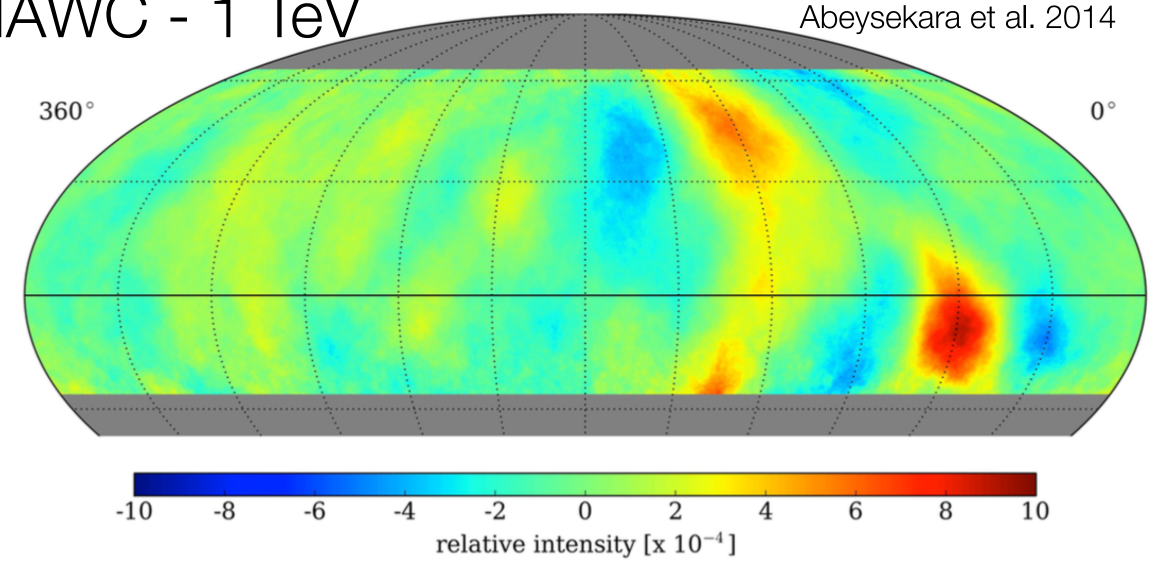
Mertsch & Funk, 2014

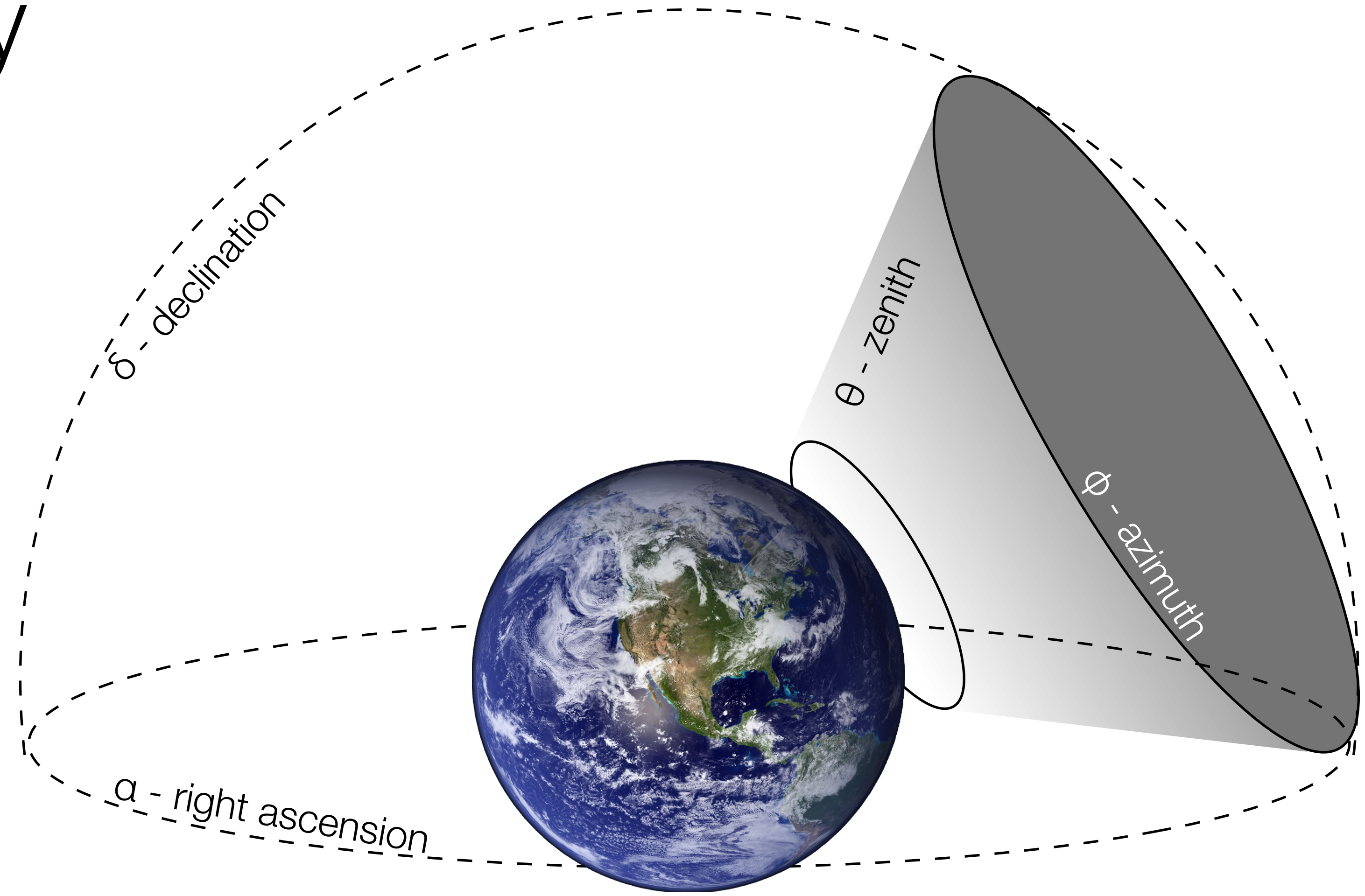


cosmic rays anisotropy
full-sky coverage

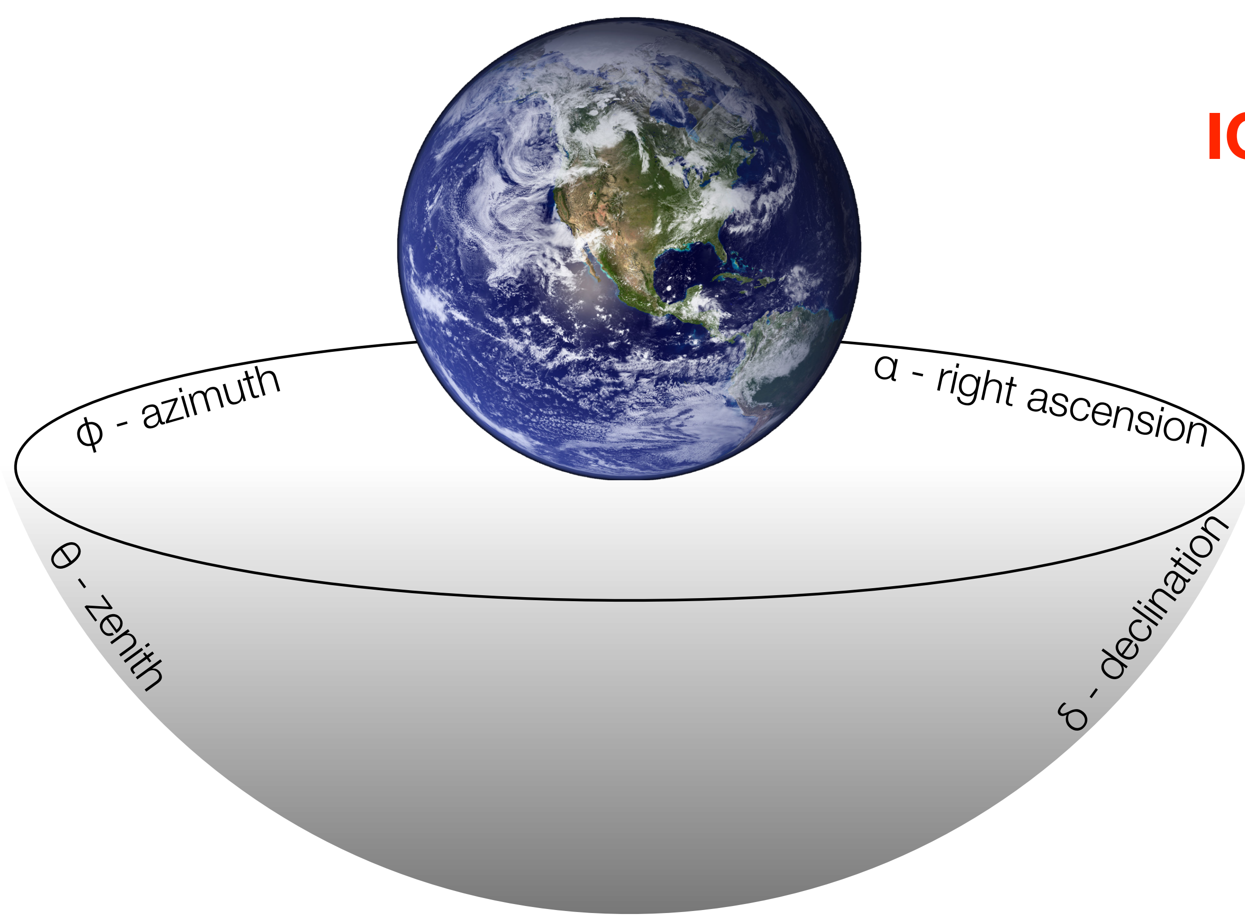
HAWC - 1 TeV

small scale anisotropy
Abeysekara et al. 2014



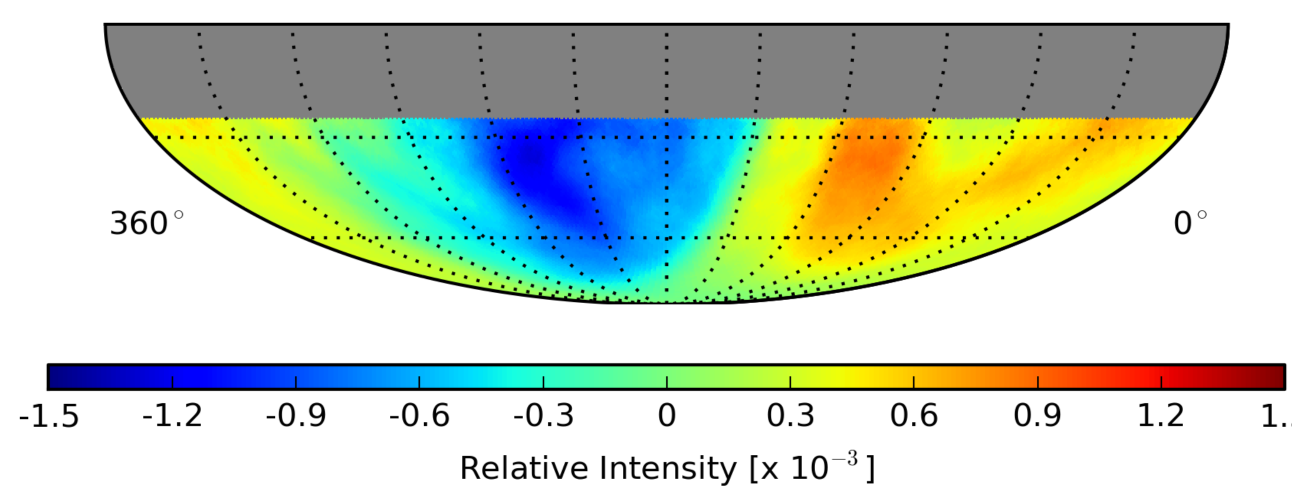


ICRC 2015



IceCube - 20 TeV

Abbasi et al. 2010, 11,12
Aartsen et al. 2013



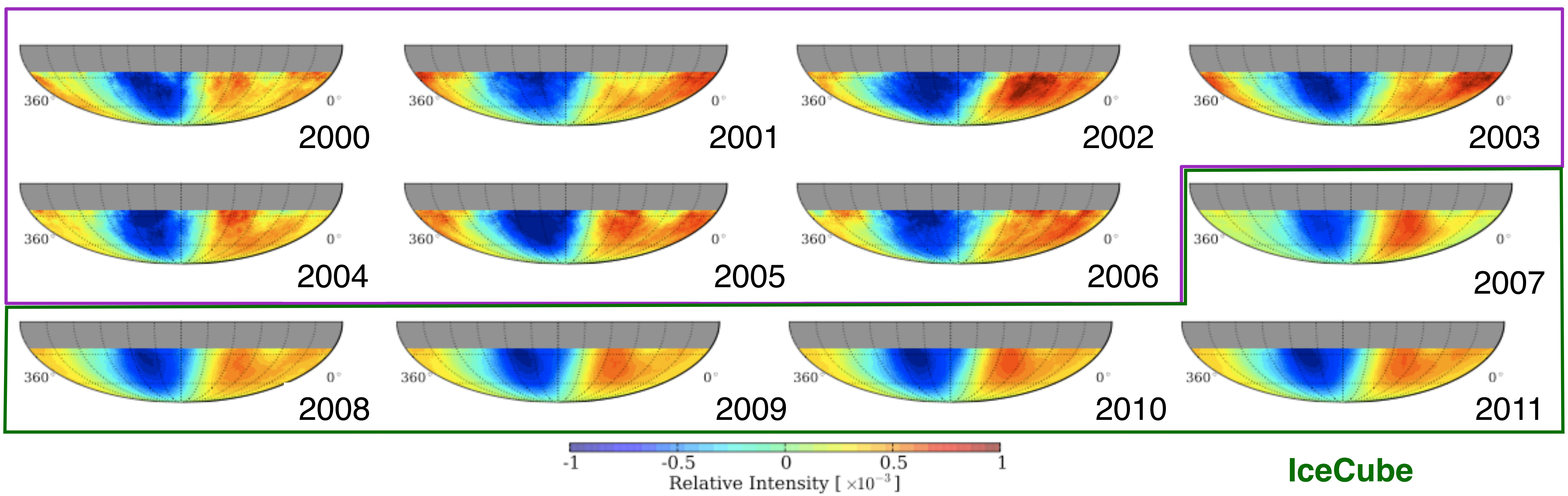
cosmic ray anisotropy

AMANDA-IceCube 2000-2011

ICRC 2013

20 TeV

relative intensity equatorial coordinates



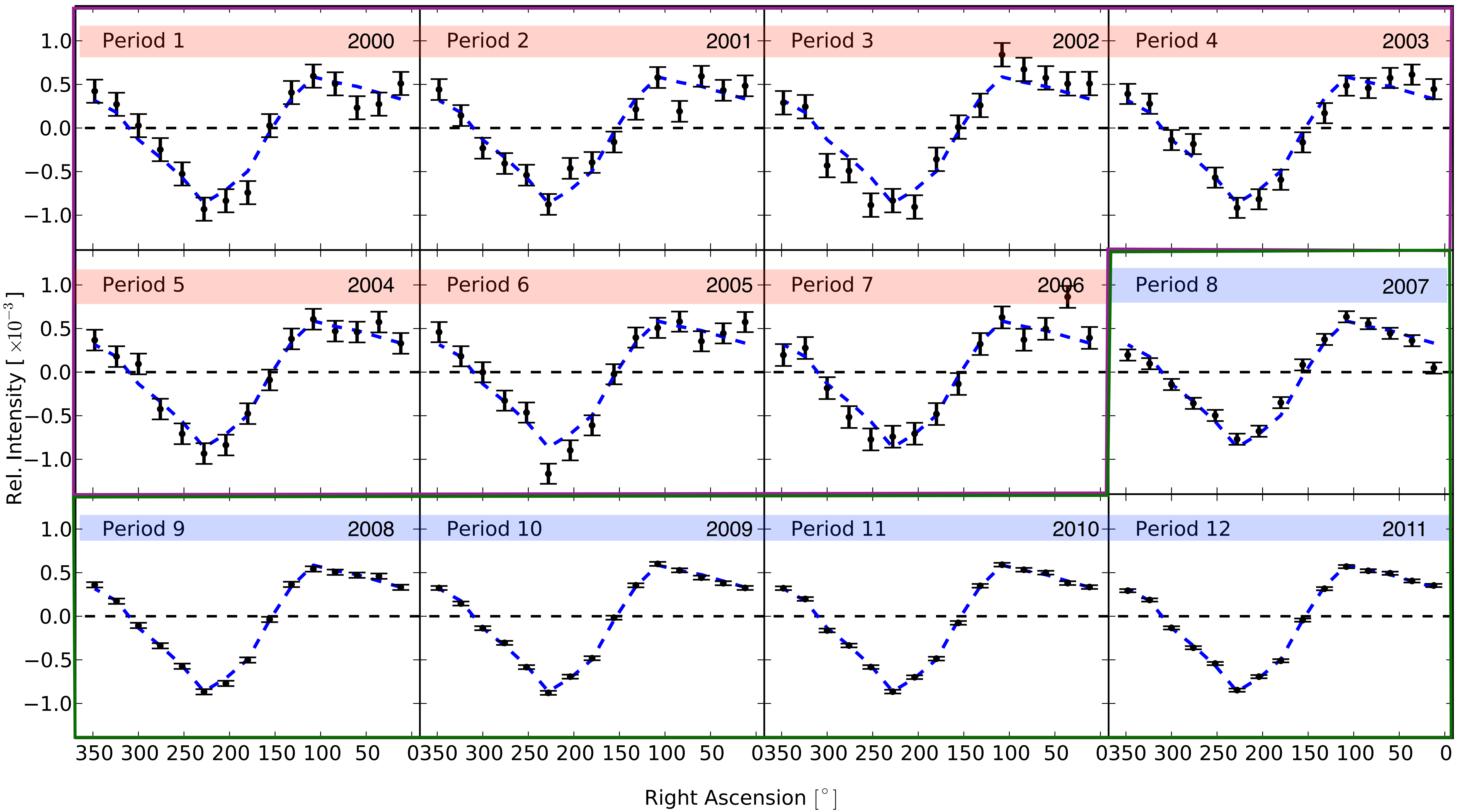
- AMANDA and IceCube yearly data show long **time-scale stability** of global anisotropy within statistical uncertainties
  - no apparent effect correlated to solar cycles

cosmic ray anisotropy stability

AMANDA-IceCube 2000-2011

ICRC 2013

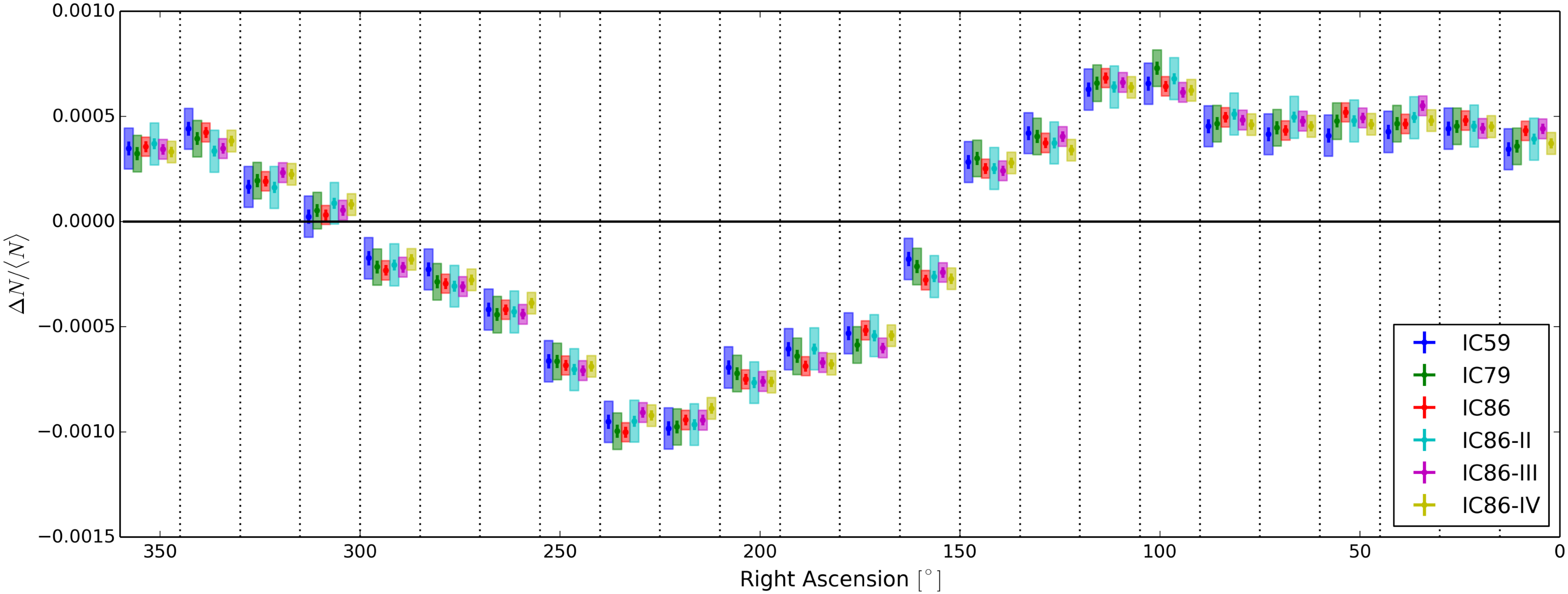
20 TeV



Paolo Desiati

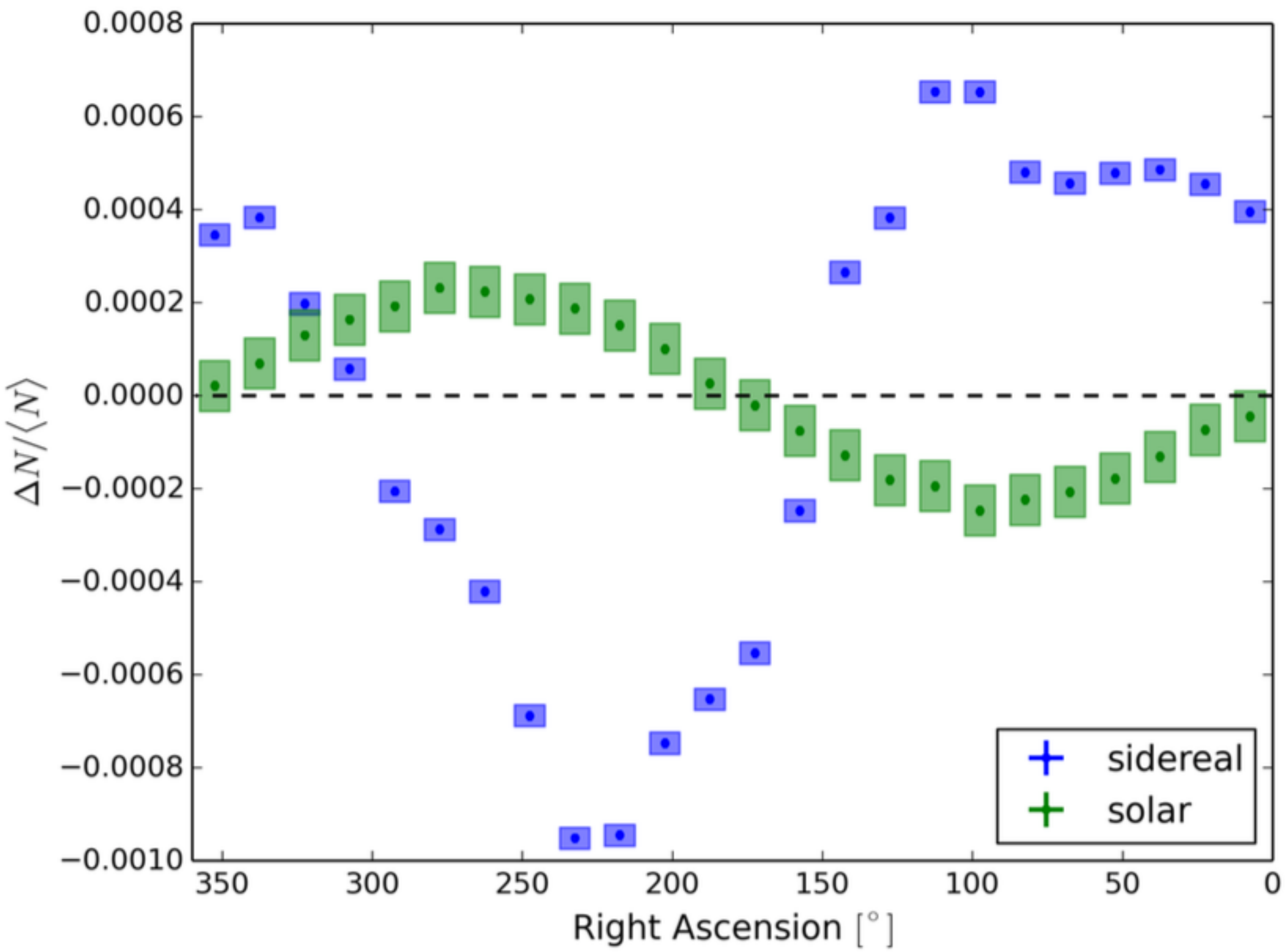
cosmic rays anisotropy stability

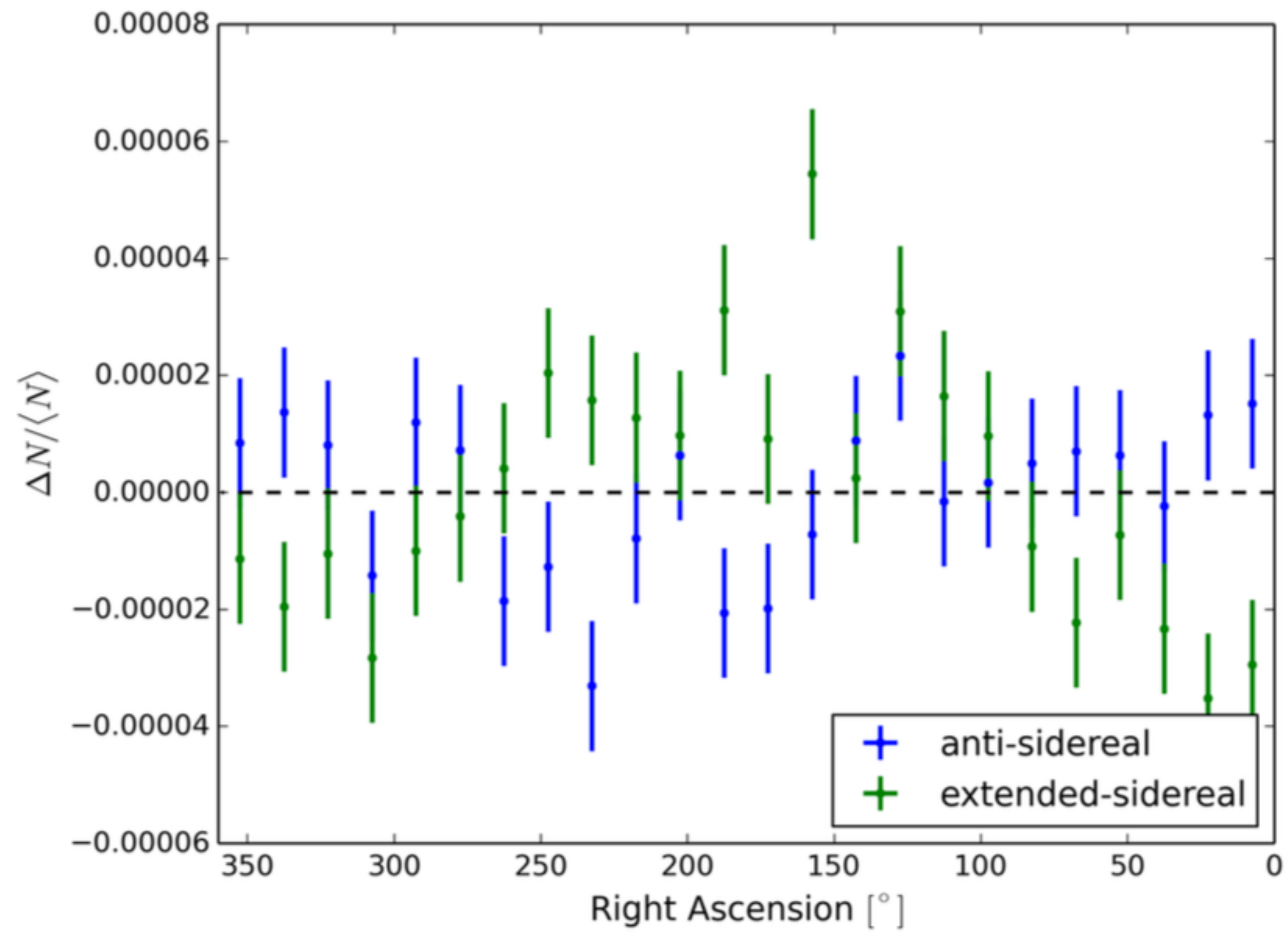
IceCube 2009-2014



systematics studies

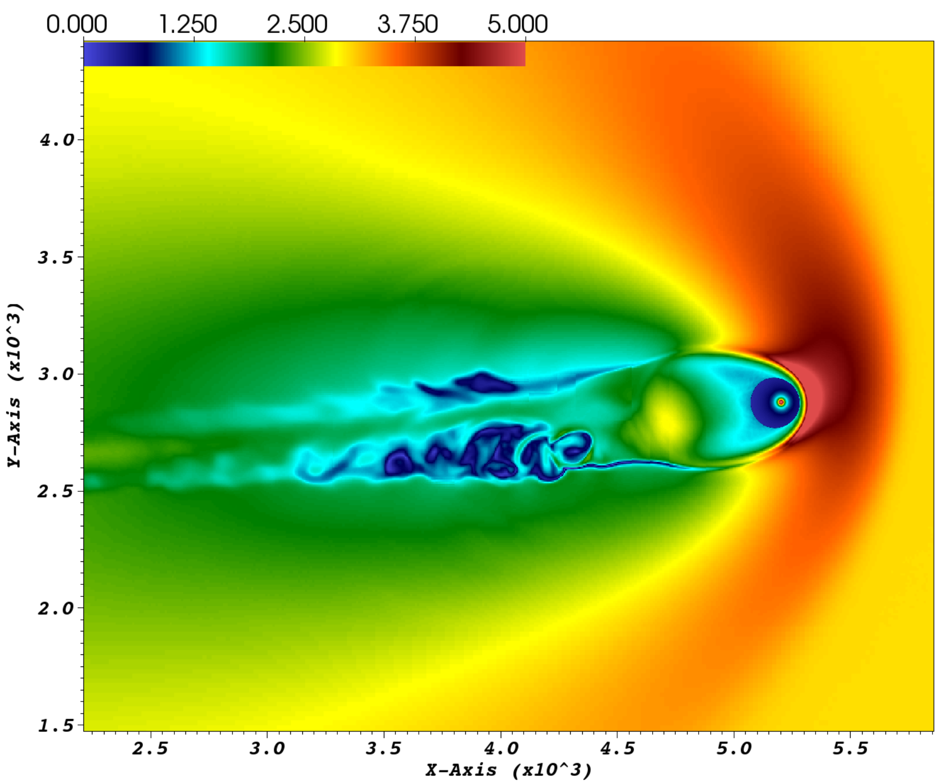
anti-/extended-sidereal time references





cosmic ray anisotropy

probing heliospheric magnetic structure



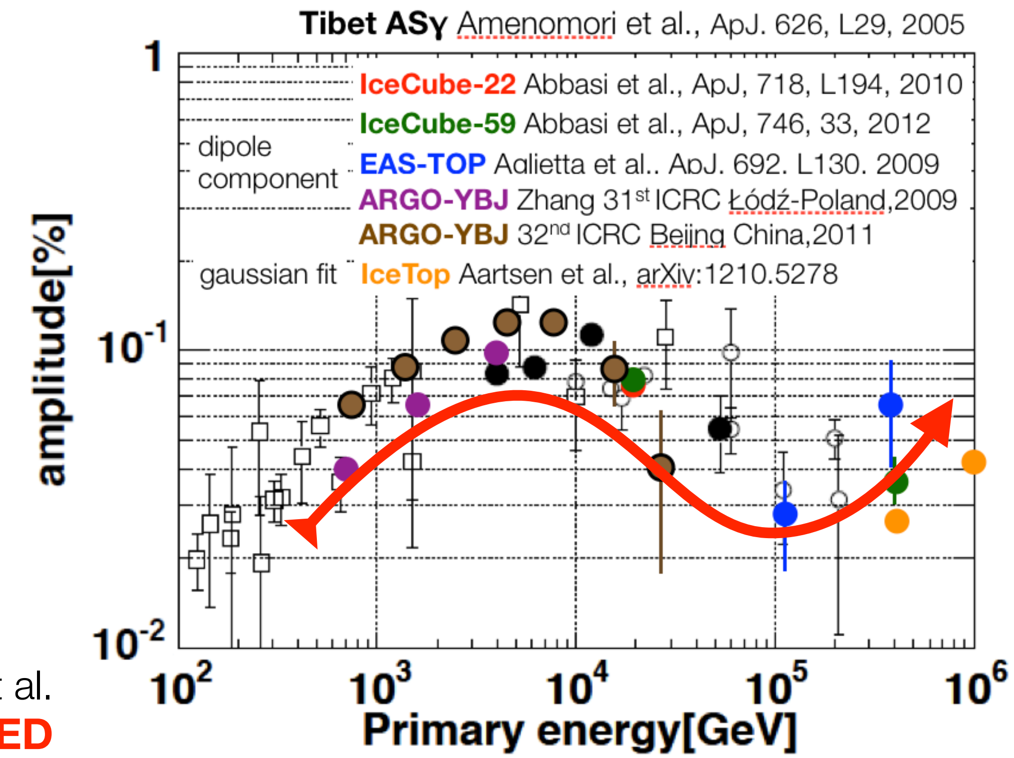
Borovikov, Heerikhuisen, Pogorelov

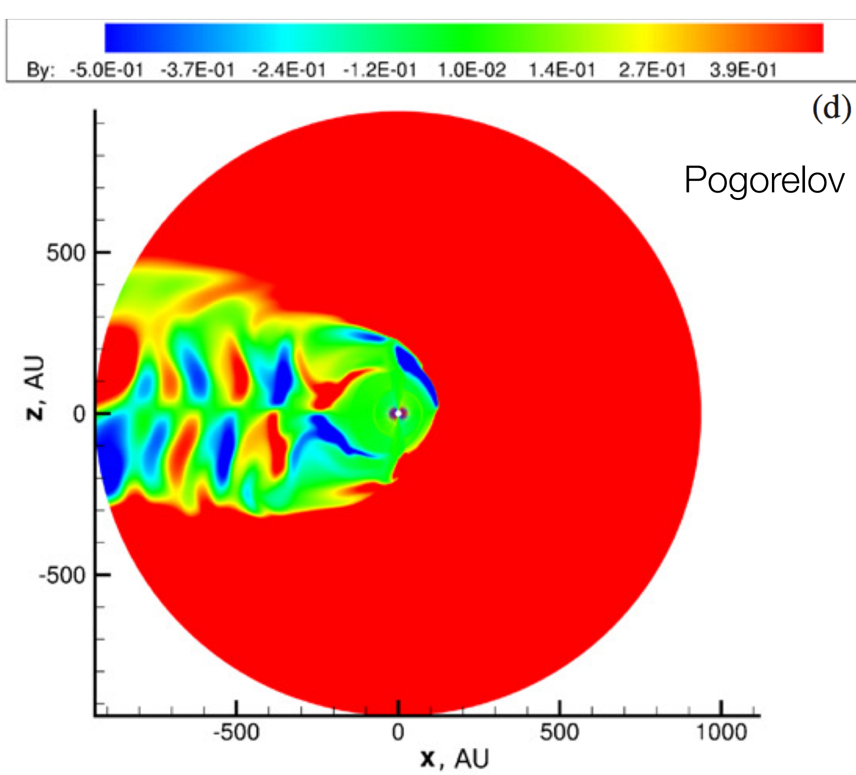
downstream instabilities on the flanks of heliotail

strong scattering

PD & Lazarian 2013

López-Barquero, Xu, PD, Lazarian, et al. **to be SUBMITTED**





Pogorelov et al., 2009

effects of magnetic polarity reversals from solar cycles

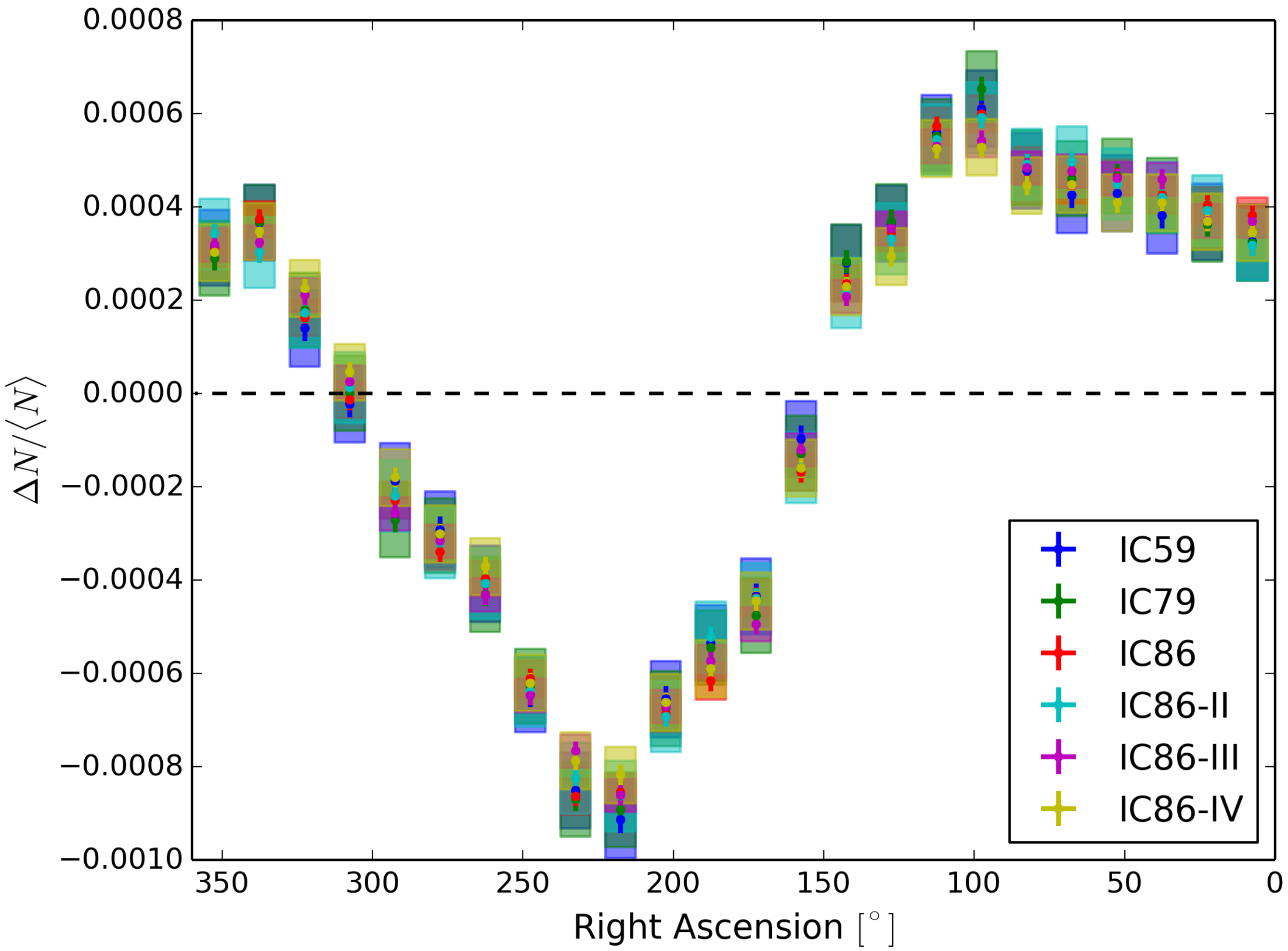
explain spectral anomaly @heliotail ?

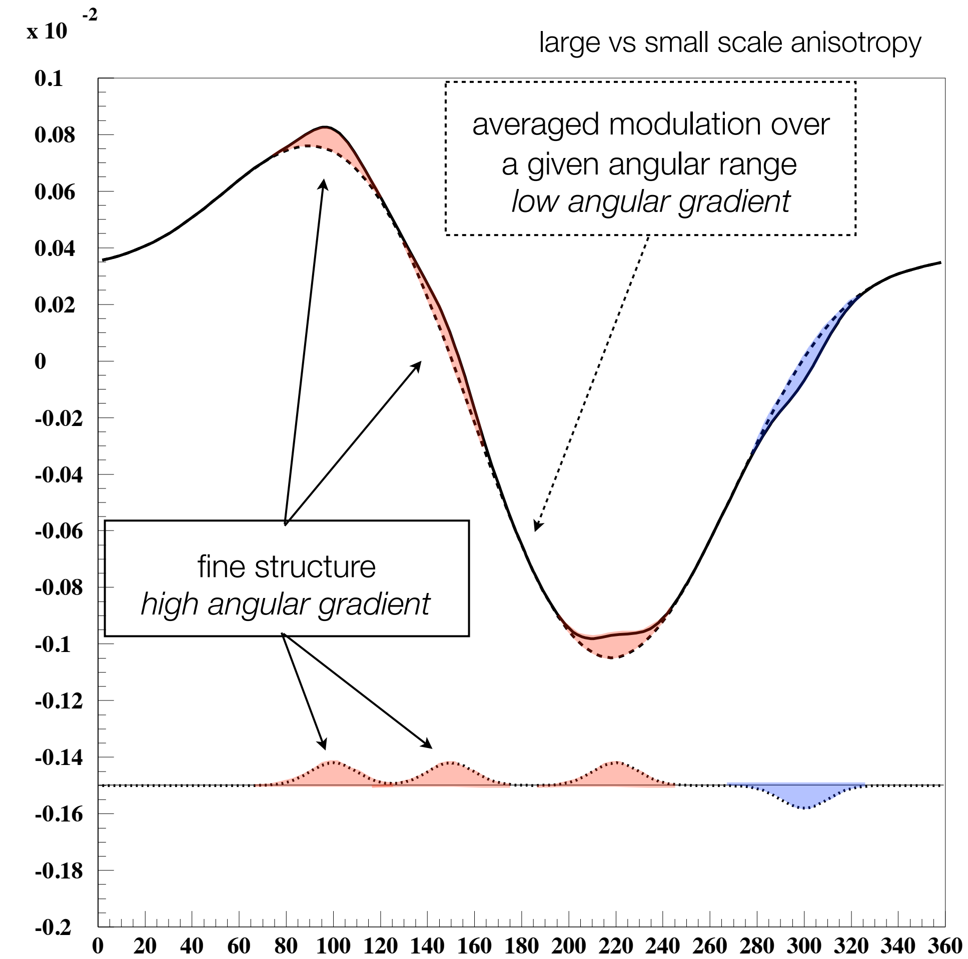
magnetic reconnection (?)

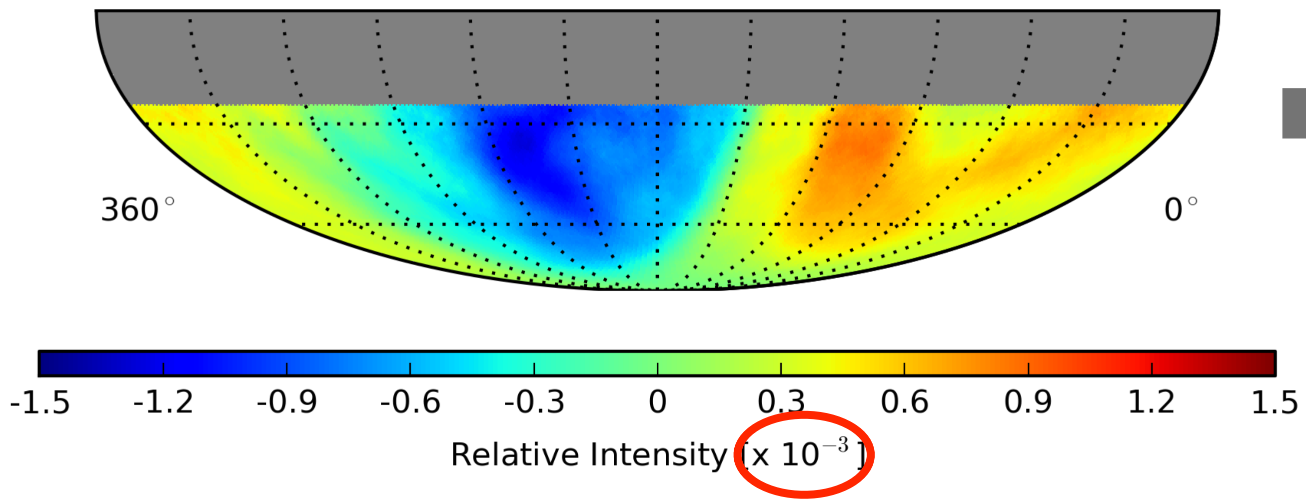
Lazarian & PD 2010
PD & Lazarian 2012

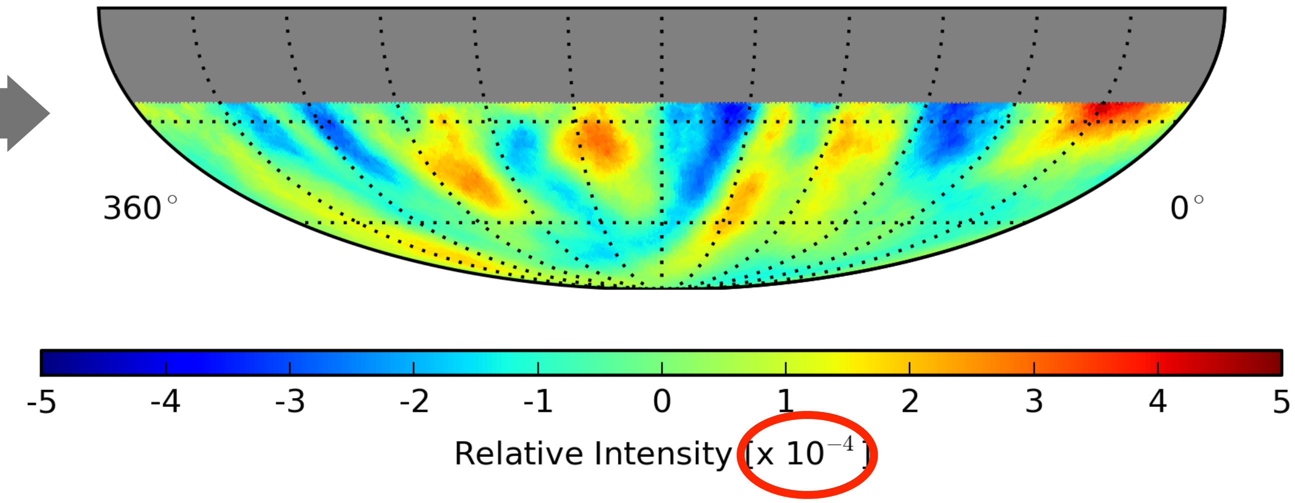
cosmic rays anisotropy

large and small angular scale







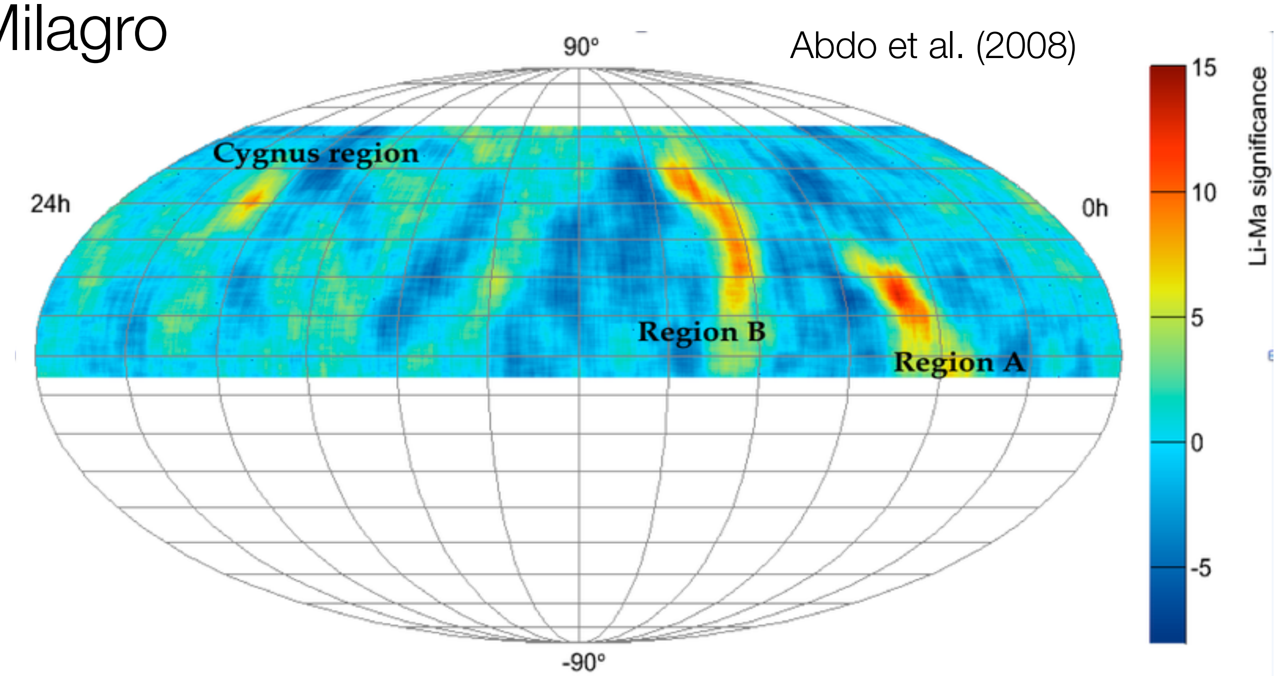


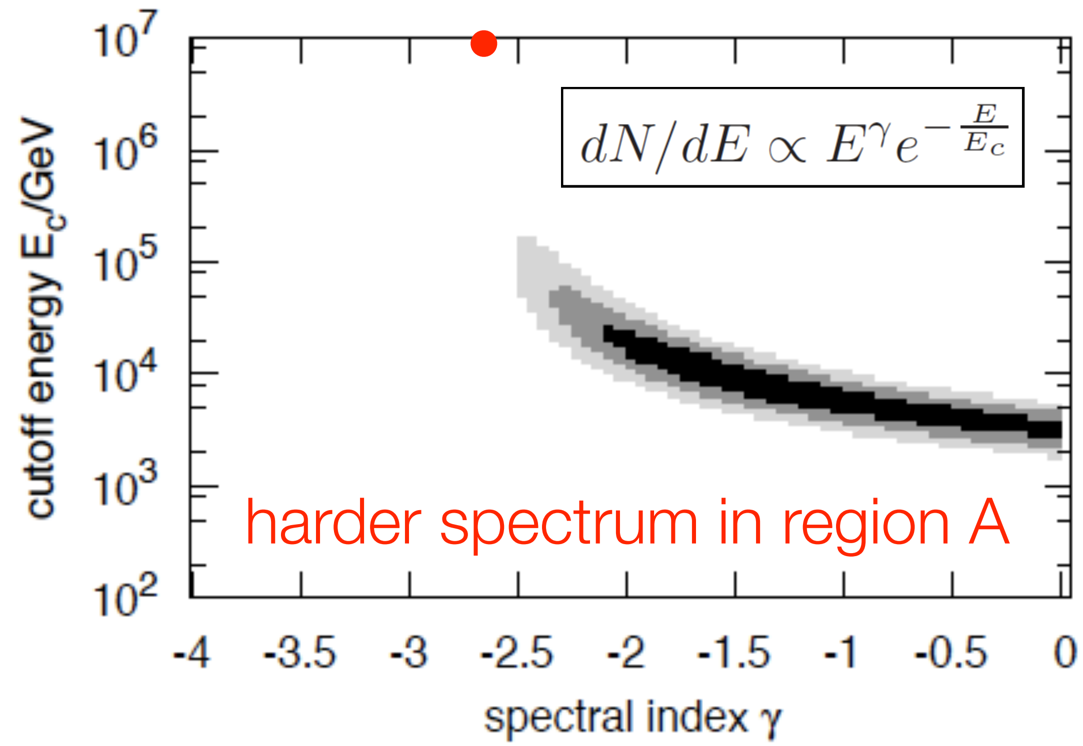
high energy cosmic rays
anisotropy & energy spectrum

HAWC results by S. BenZvi

Milagro

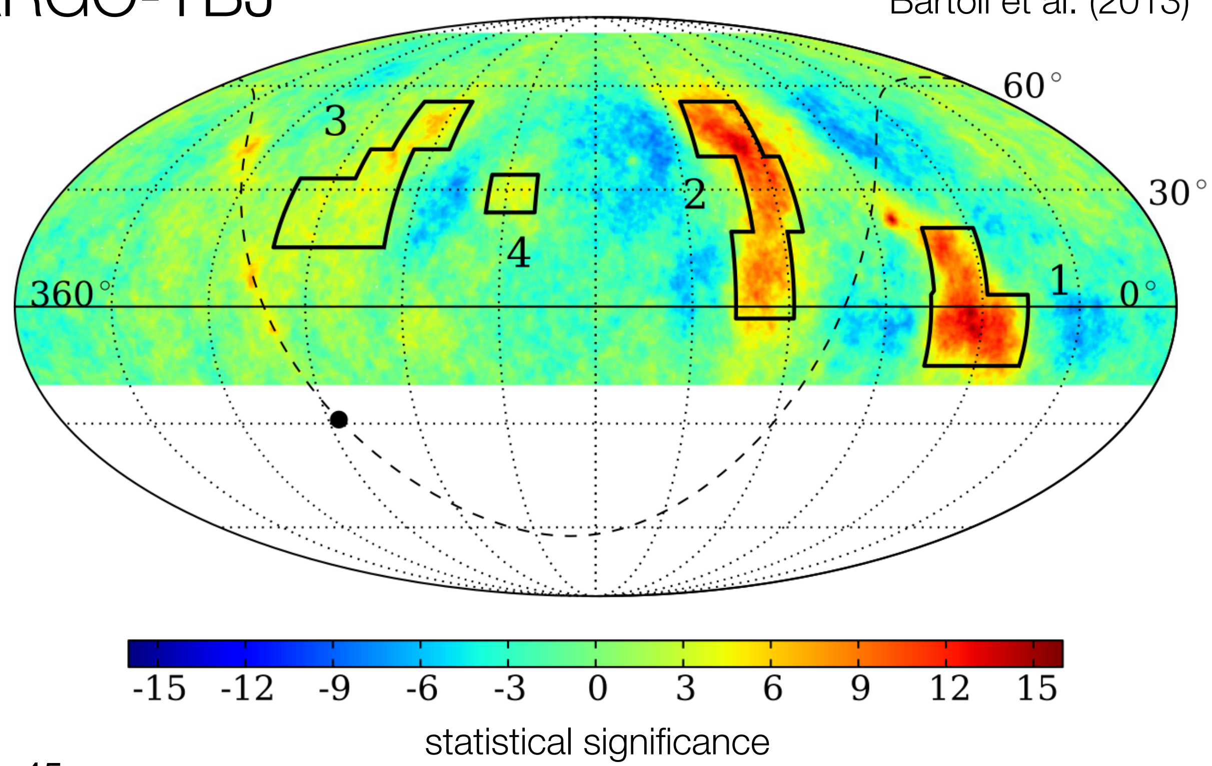
Abdo et al. (2008)

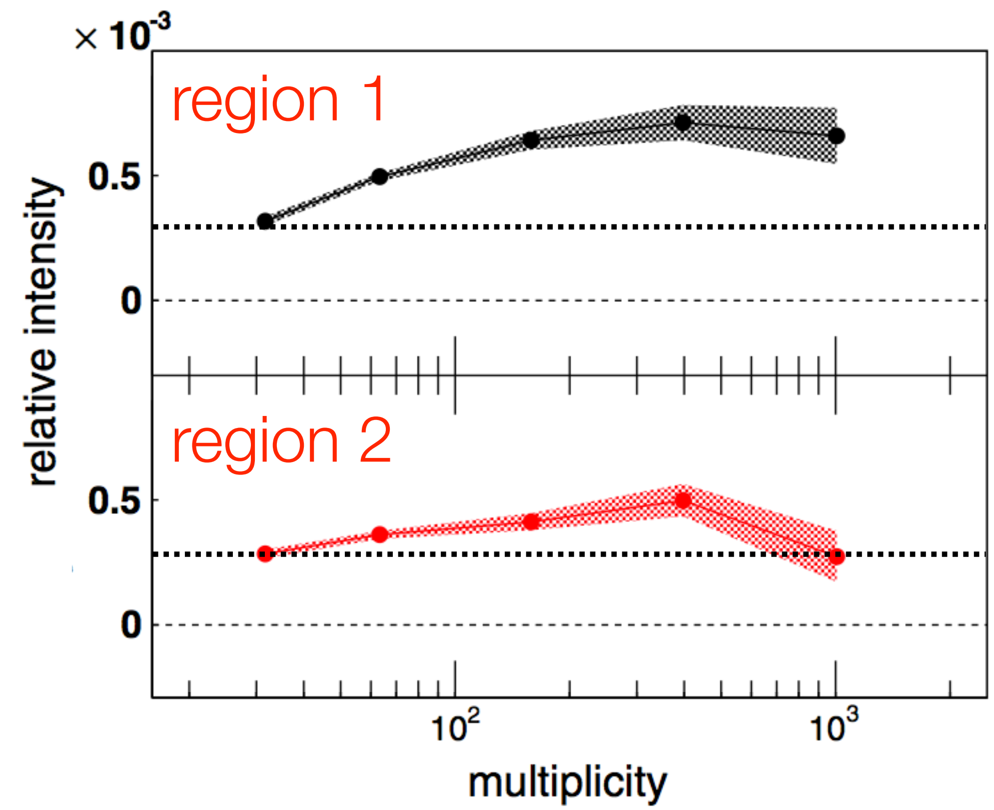




ARGO-YBJ

Bartoli et al. (2013)



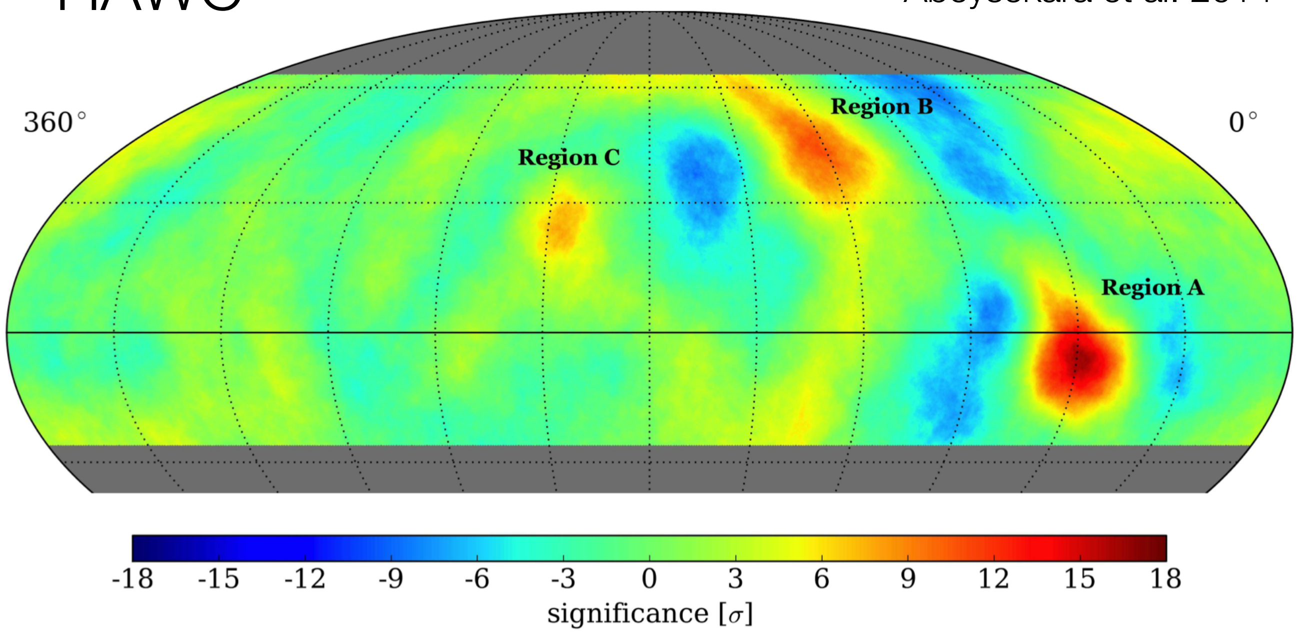


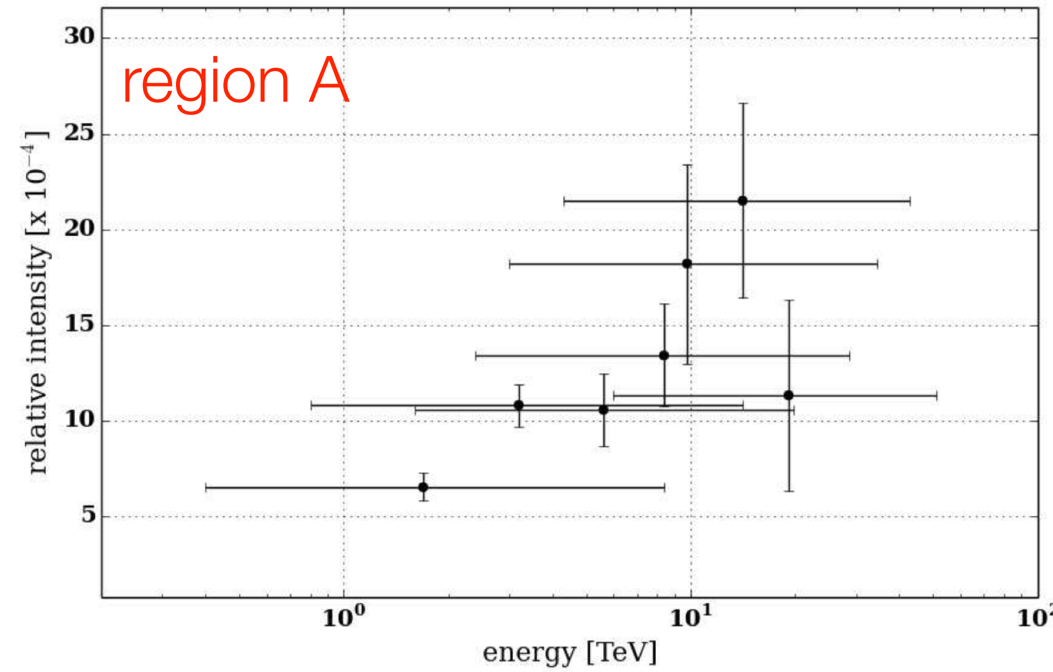
high energy cosmic rays

anisotropy & energy spectrum

HAWC

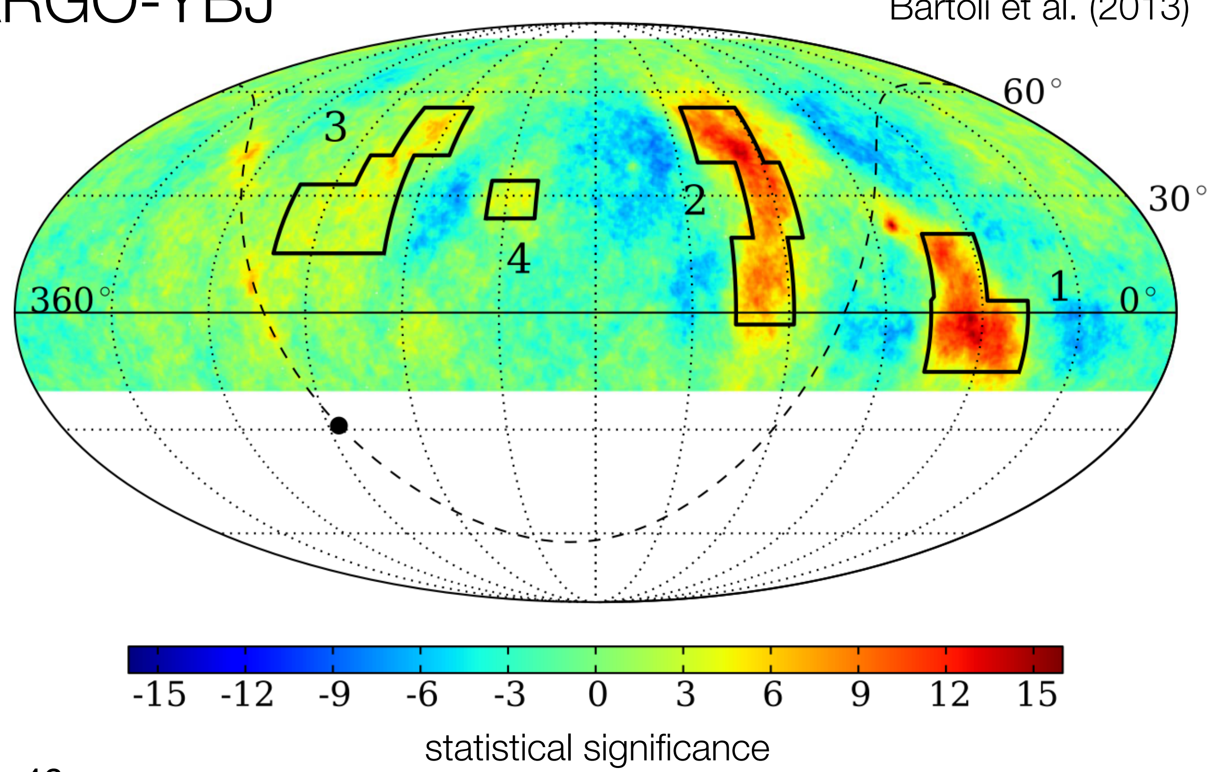
Abeysekara et al. 2014

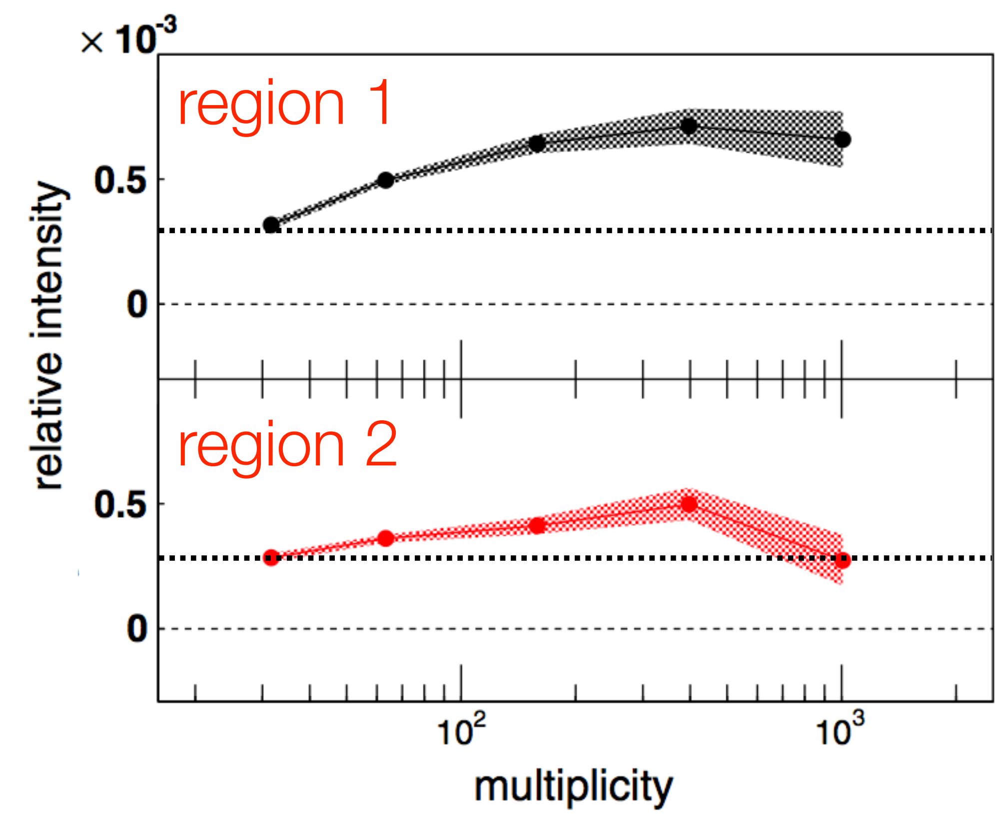




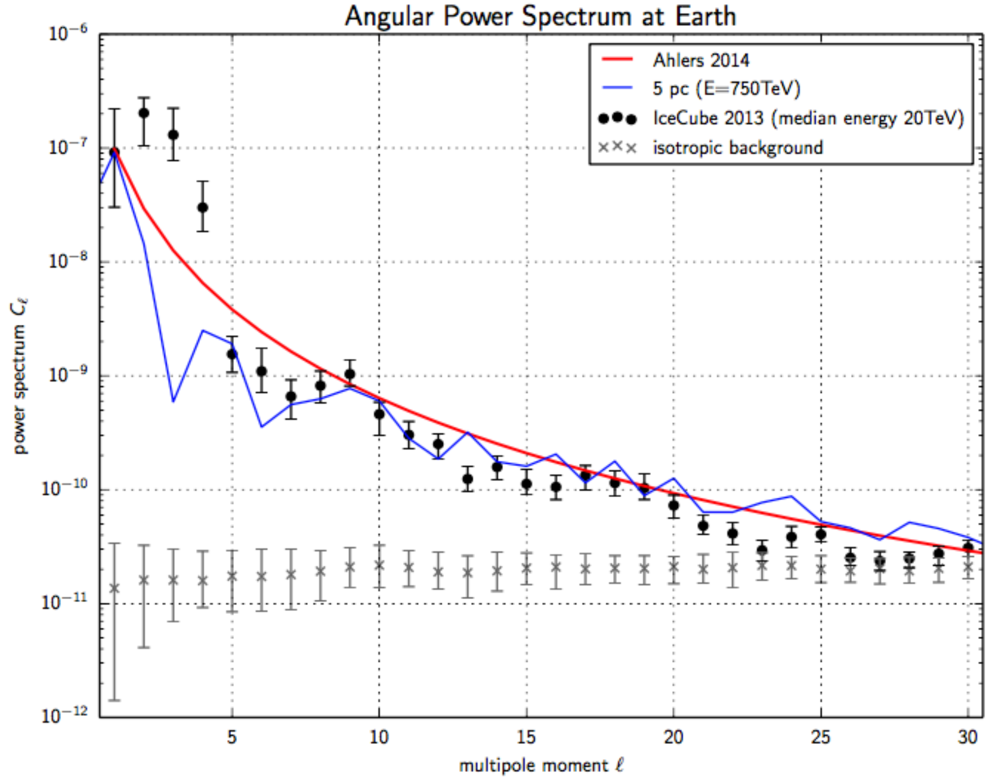
ARGO-YBJ

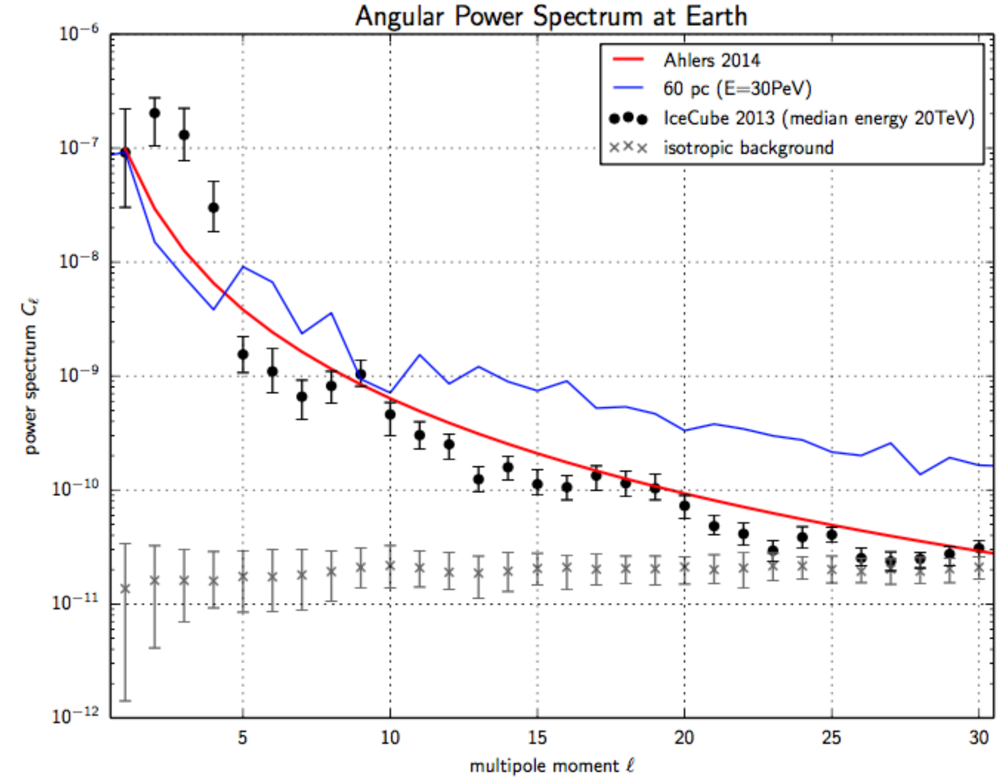
Bartoli et al. (2013)

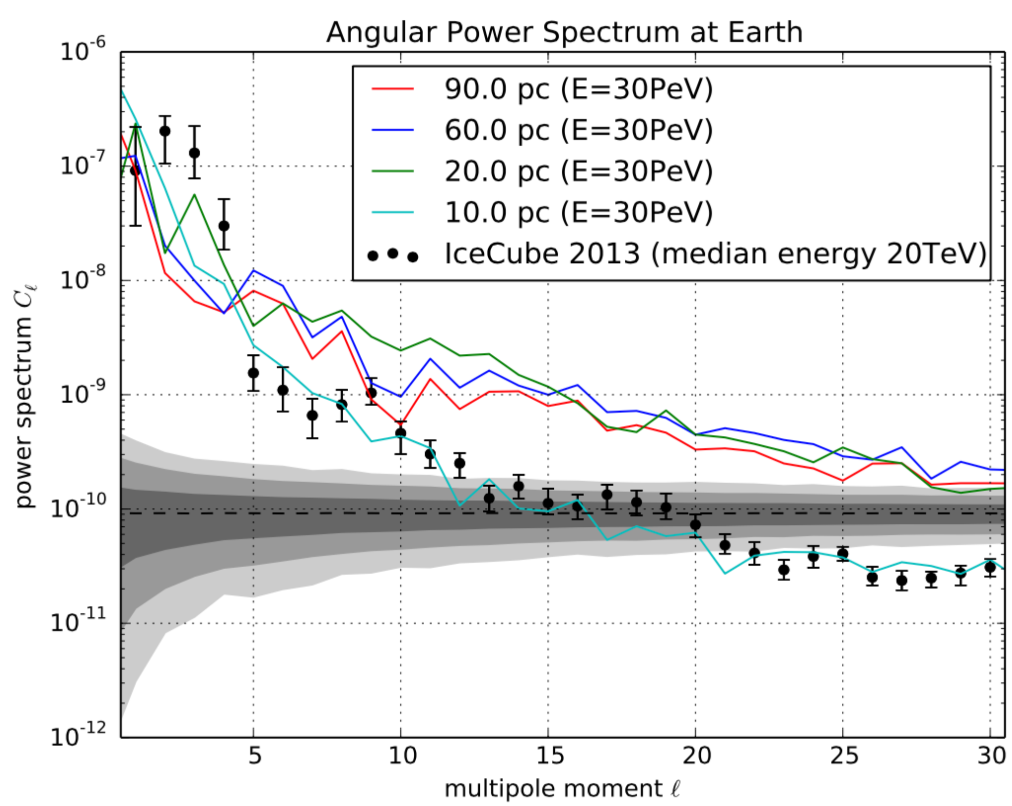




cosmic ray anisotropy
probing magnetic field turbulence ?



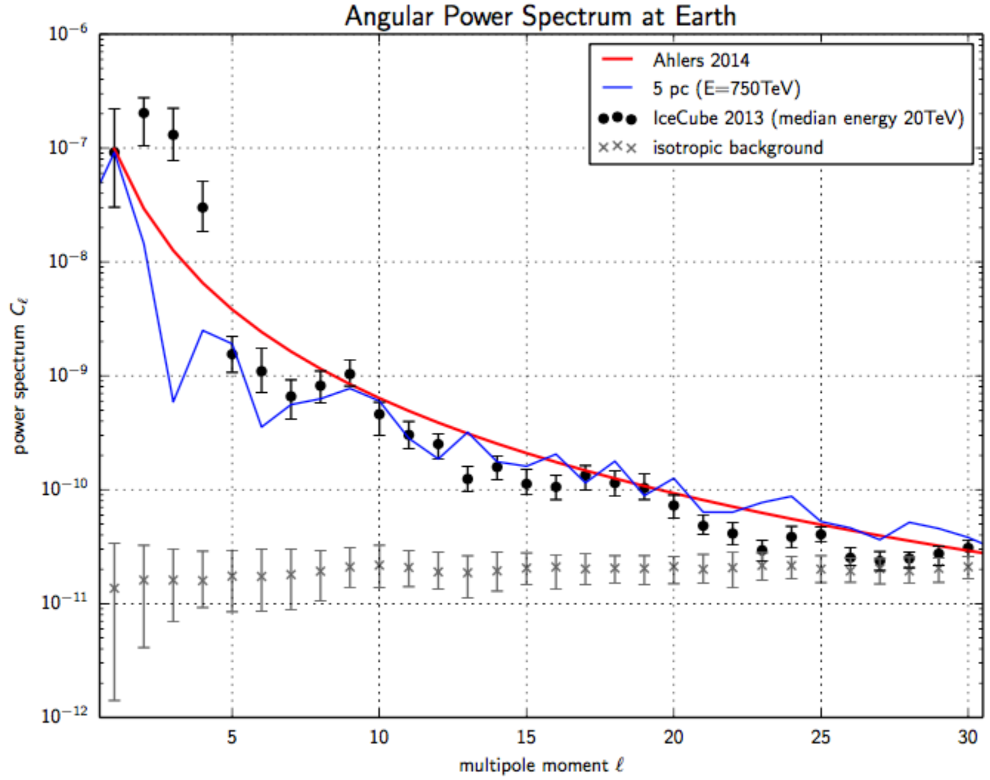


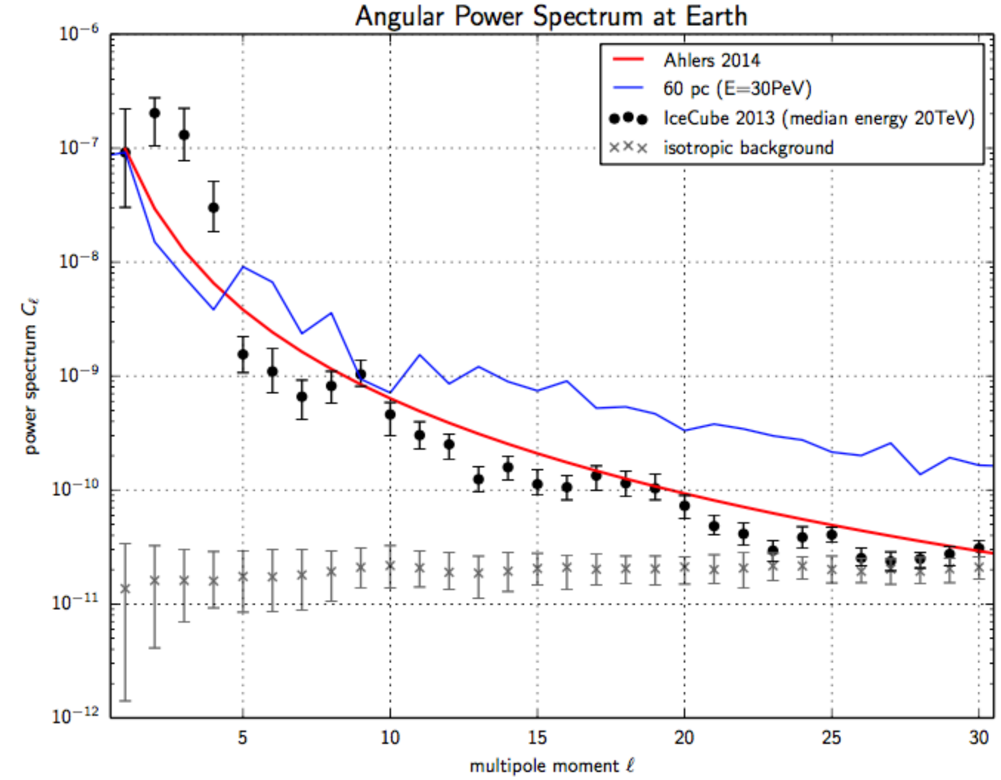


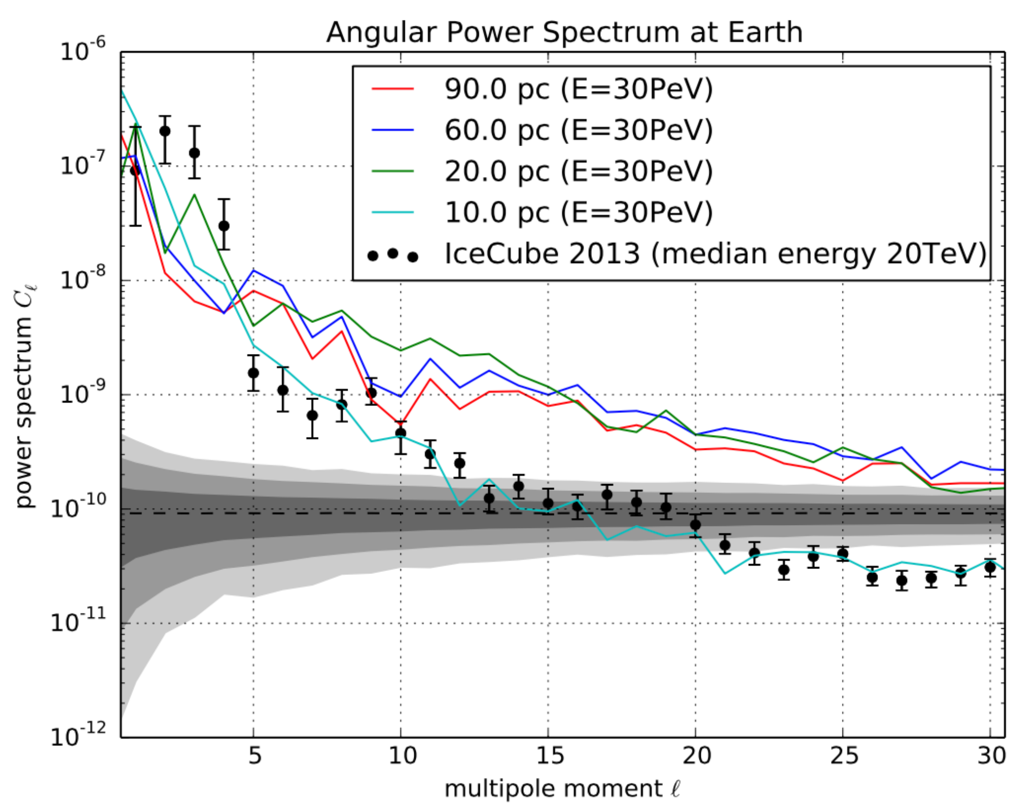
López-Barquero, Farber, Xu, PD, Lazarian in print on ApJ
arXiv:1509.00892

cosmic ray anisotropy

probing magnetic field turbulence ?







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