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

Cosmic ray anisotropy measurements

Paolo Desiati

WIPAC & Department of Astronomy
University of Wisconsin - Madison

<desiati@wipac.wisc.edu>

7th Workshop on Air Shower Detection at High Altitude
University and INFN - Torino - Nov 30 - Dic 2, 2016

cosmic ray observations

the age of air shower experiments

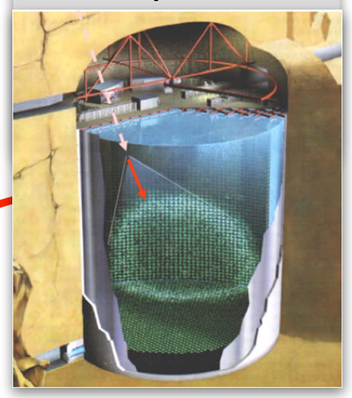
Milagro (2000-2008)

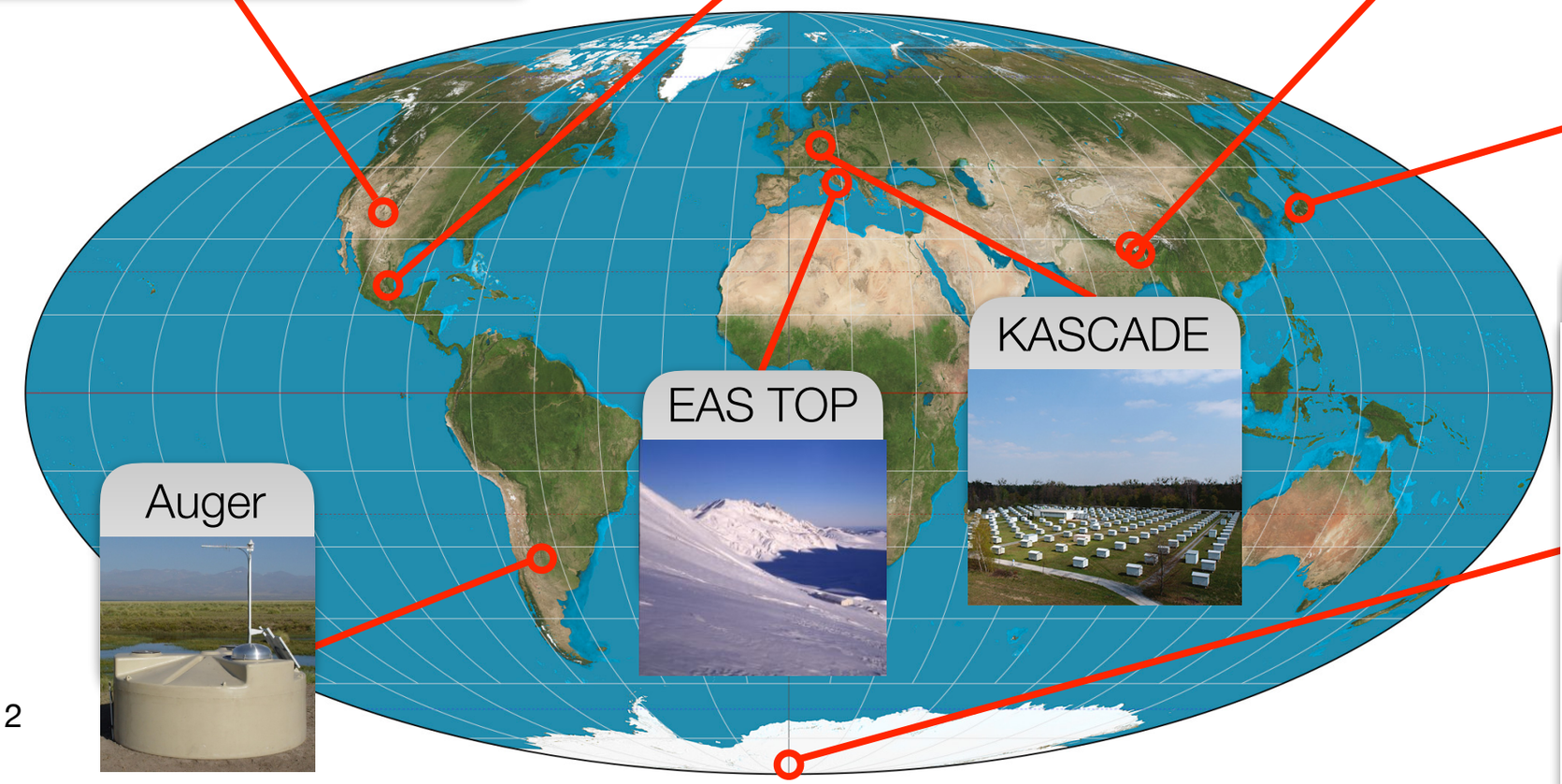
HAWC (2013-present)

Tibet-AS (1997-2009)

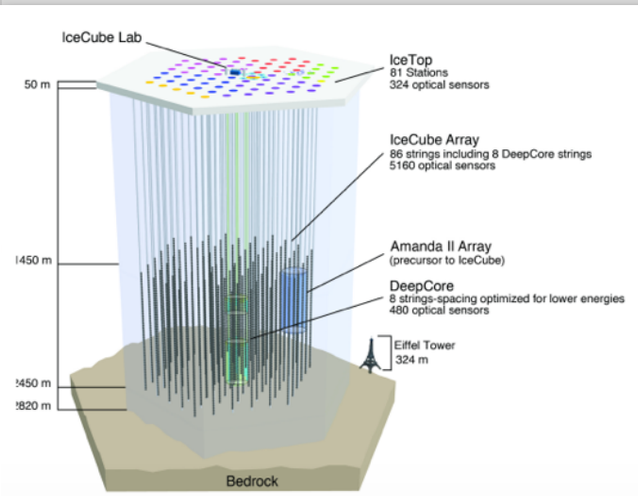
ARGO-YBJ
(2007-2015)

SuperK





IceCube/IceTop (2007-present)

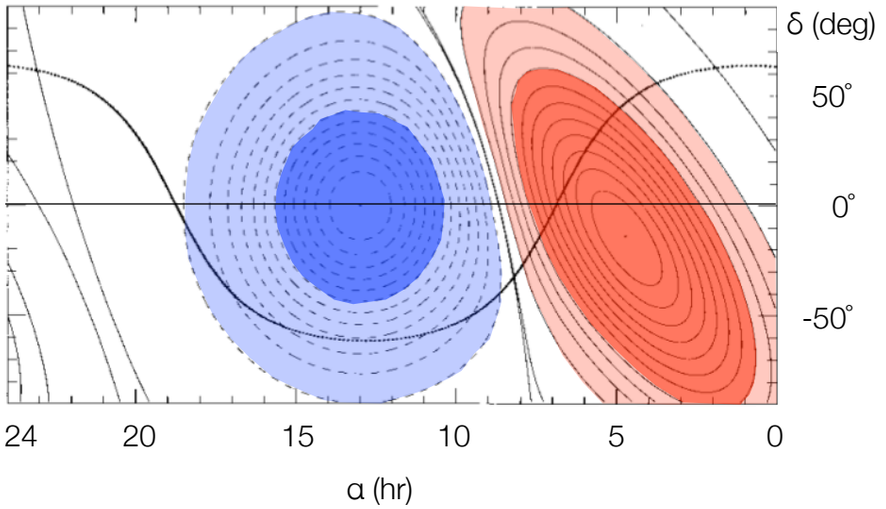


high energy cosmic rays
sidereal anisotropy

~10^{-3}

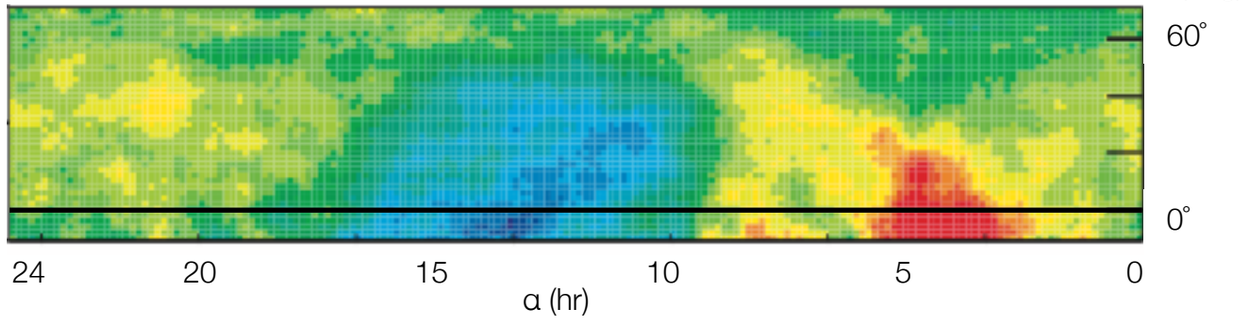
< 1 TeV

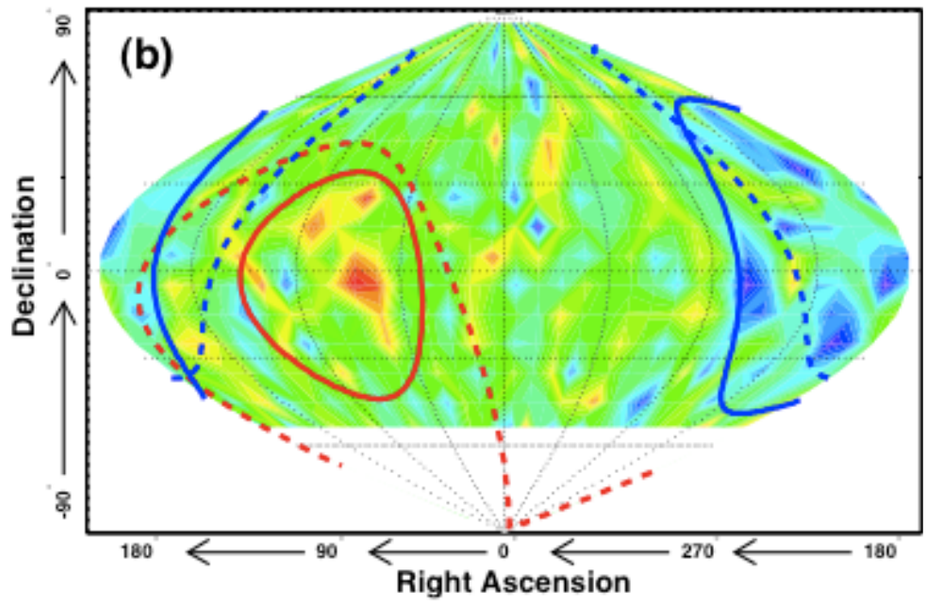
Nagashima et al. (1998)
Hall et al. (1999)



4 TeV

Tibet ASγ
Amenomori et al. (2006)





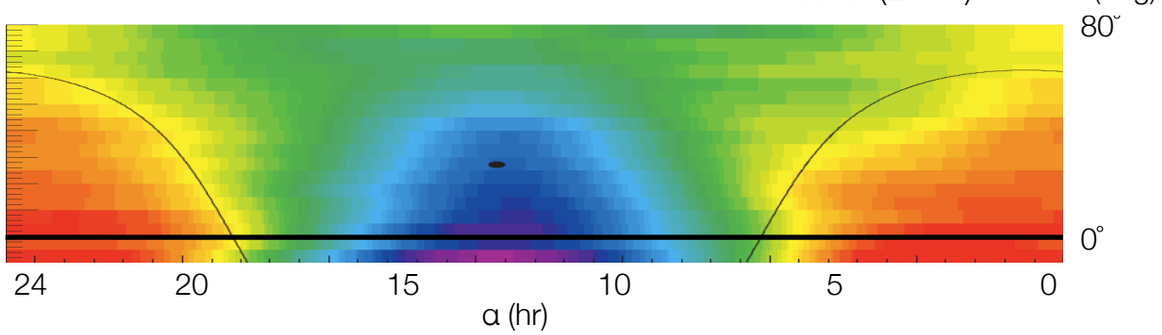
10 TeV

Super Kamiokande
Guillian et al. (2007)

equatorial coordinates

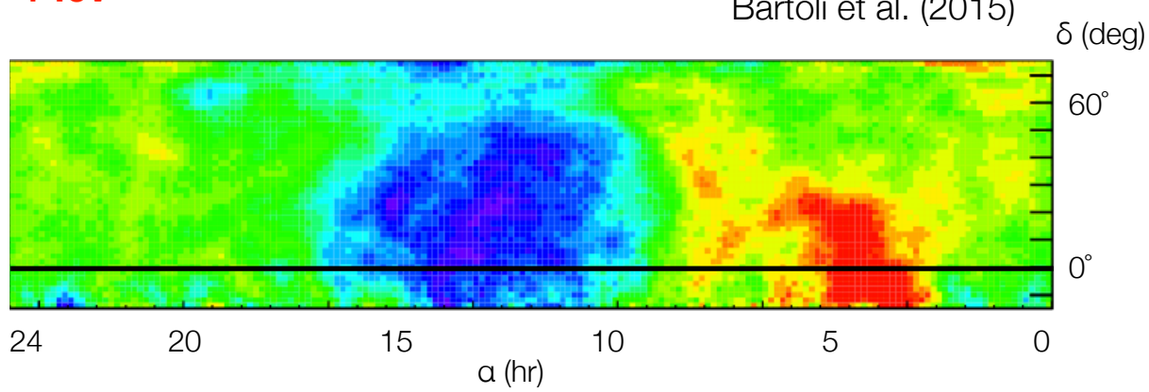
5 TeV

Milagro
Abdo et al. (2009)



4 TeV

ARGO-YBJ
Zhang et al. (2009)
Bartoli et al. (2015)



determination of anisotropy

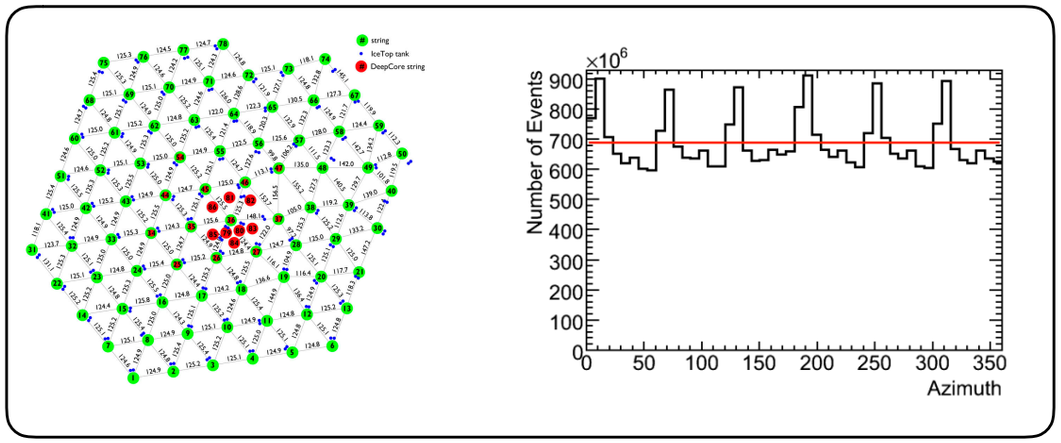
arrival direction distribution

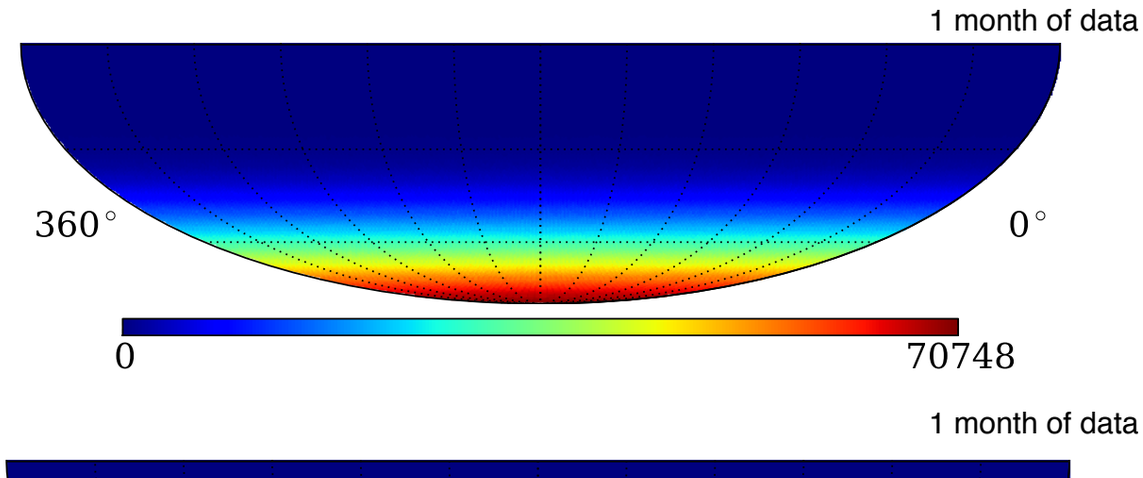
raw map of events in equatorial coordinates $(\alpha,\delta)_i$

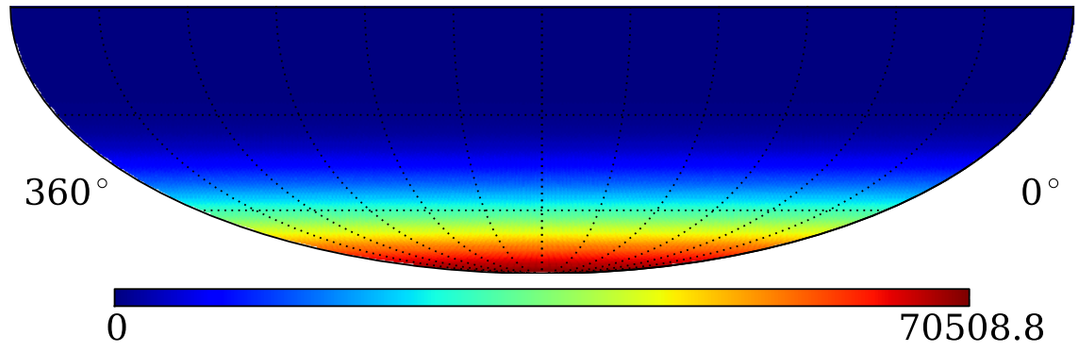
reference map from events scrambled over 24hr in α (or time)

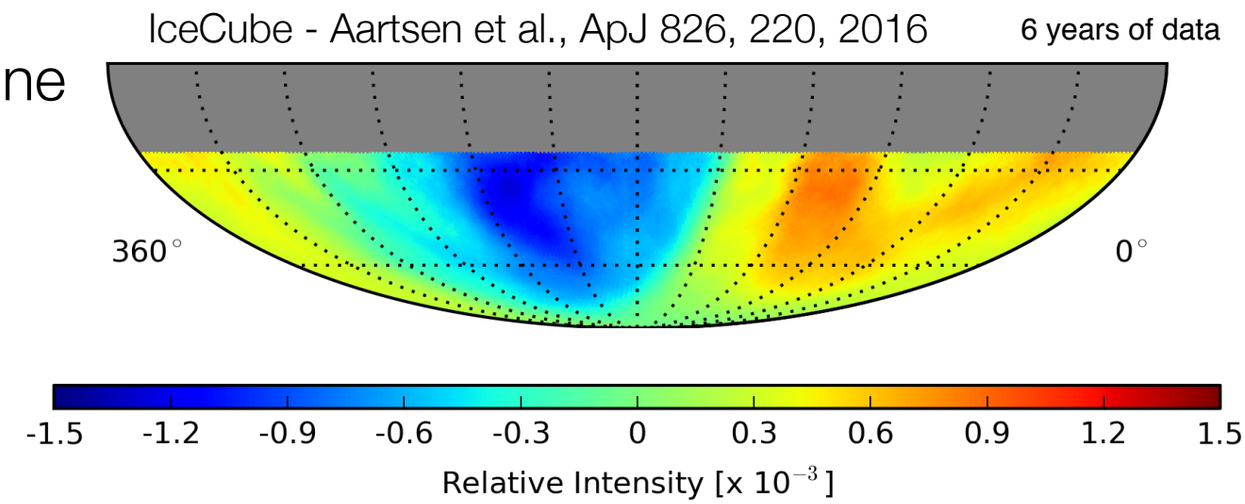
subtract reference map from raw map to determine the residual *relative intensity* map

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





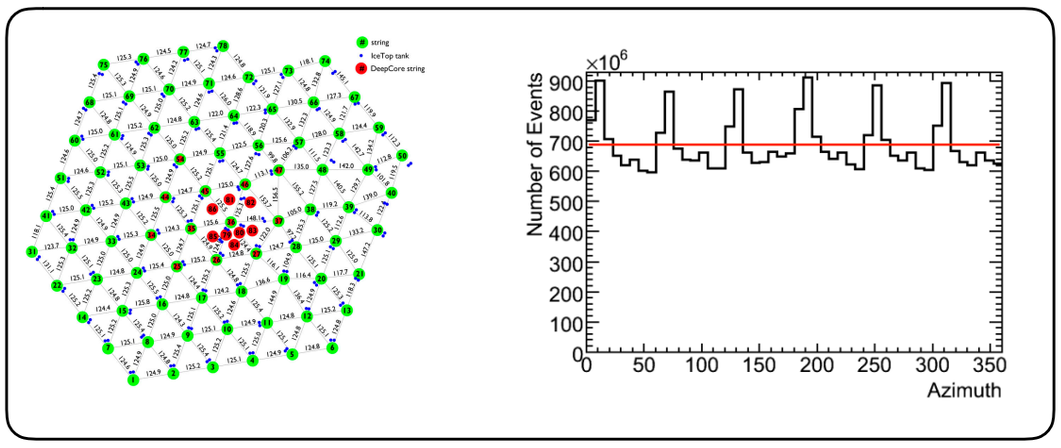




determination of anisotropy

arrival direction distribution

local coordinates

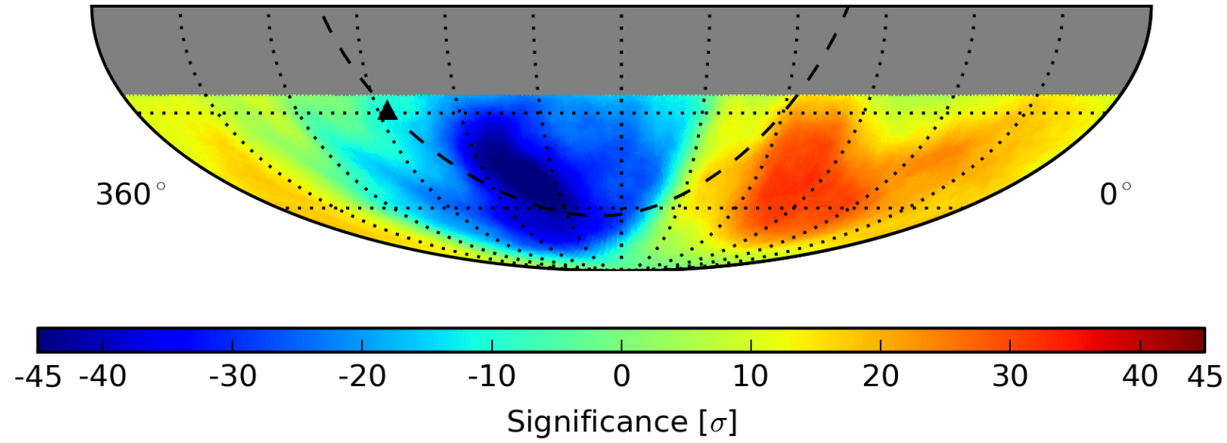


$$s = \sqrt{2}\left\{ N_{\mathrm{on}} \ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\mathrm{on}}}{N_{\mathrm{on}}+N_{\mathrm{off}}}\right)\right] + N_{\mathrm{off}} \ln\left[(1+\alpha)\left(\frac{N_{\mathrm{off}}}{N_{\mathrm{on}}+N_{\mathrm{off}}}\right)\right]\right\}^{1/2} \qquad \alpha = 1/20$$

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

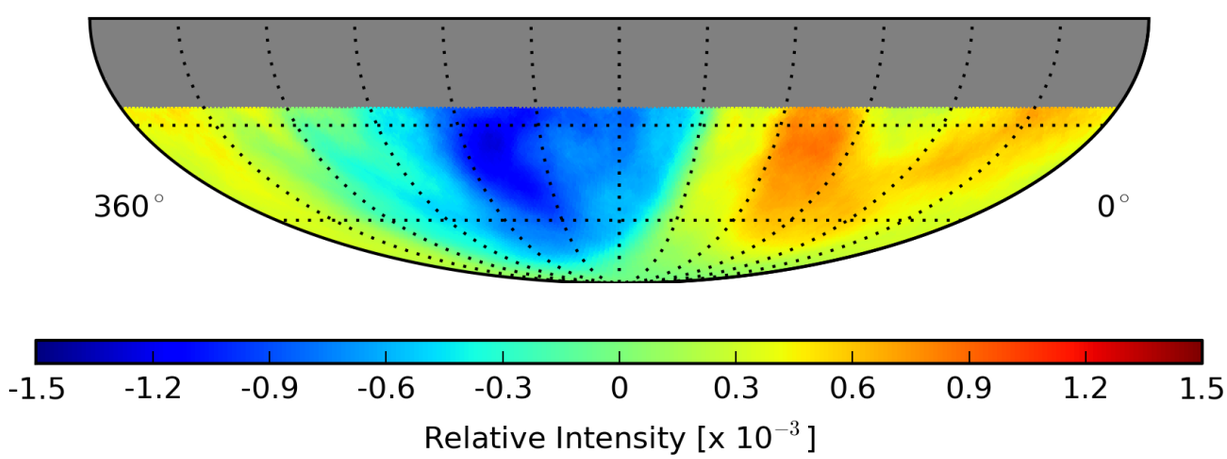
IceCube - Aartsen et al., ApJ 826, 220, 2016

statistical significance



relative intensity

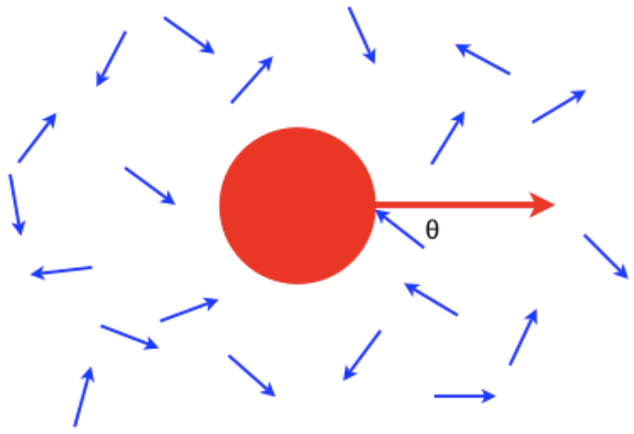
$$\boxed{\frac{\Delta I}{\langle I \rangle} \equiv \frac{N_i - \langle N \rangle}{\langle N \rangle}}$$



a known anisotropy

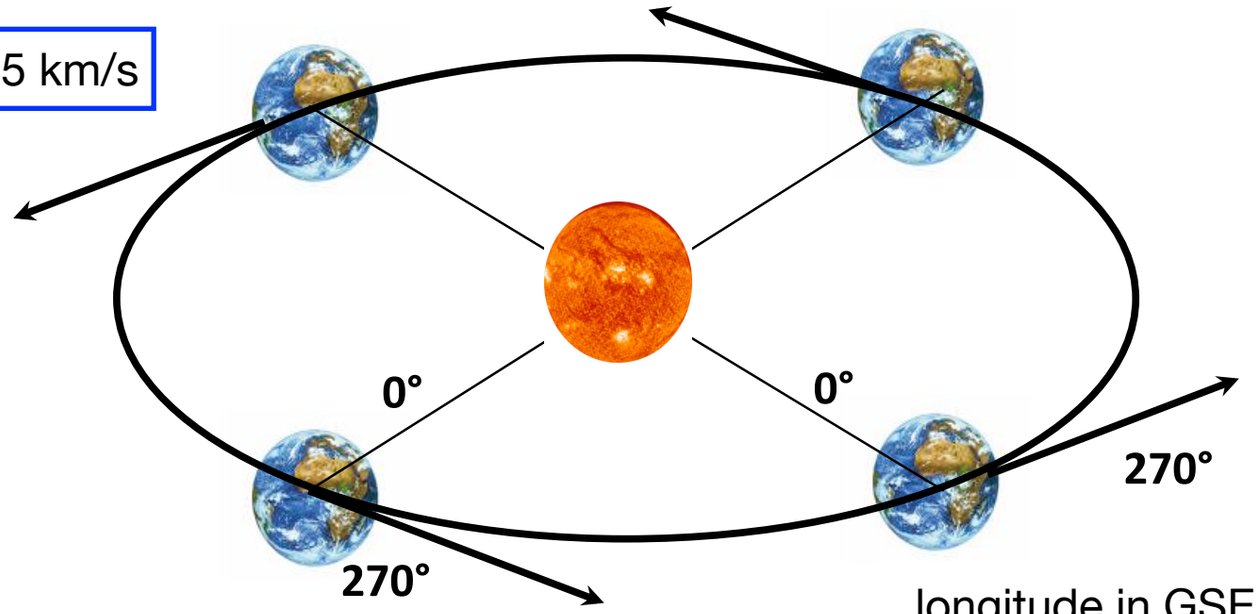
Earth's revolution around the Sun

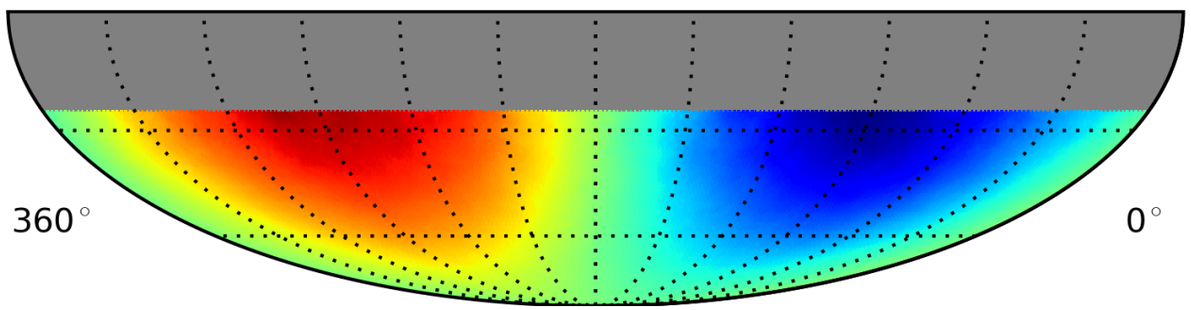
Compton & Getting, Phys. Rev. 47, 817 (1935)
Gleeson, & Axford, Ap&SS, 2, 43 (1968)

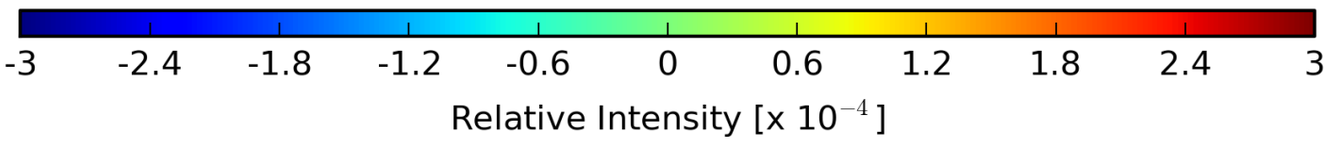


$$\frac{\Delta I}{I} = (\gamma + 2)\frac{v}{c}\cos\theta$$

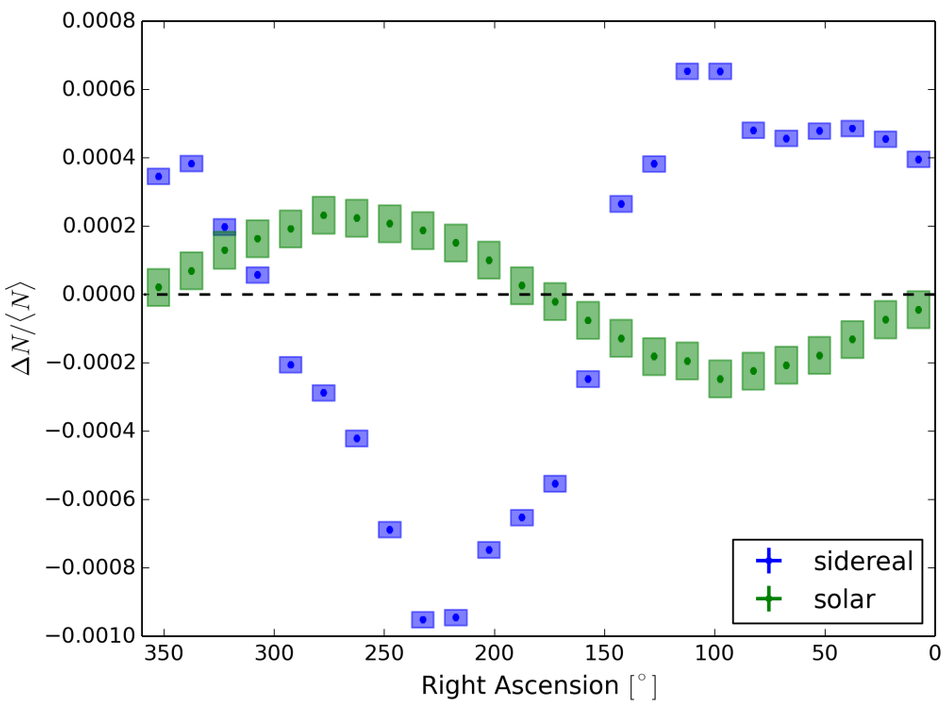
v = 29.8 ± 0.5 km/s





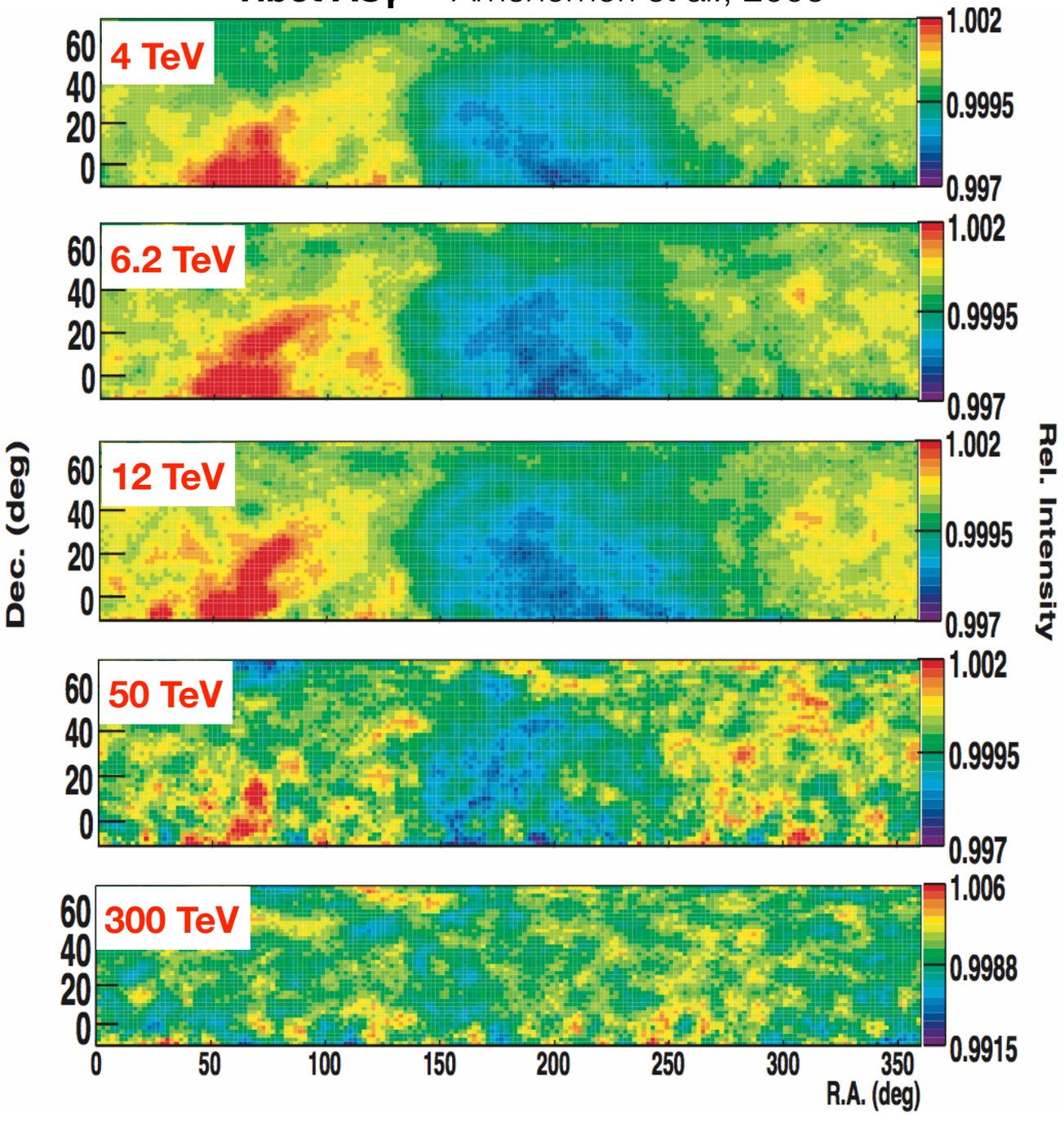


IceCube - Aartsen et al., ApJ 826, 220, 2016

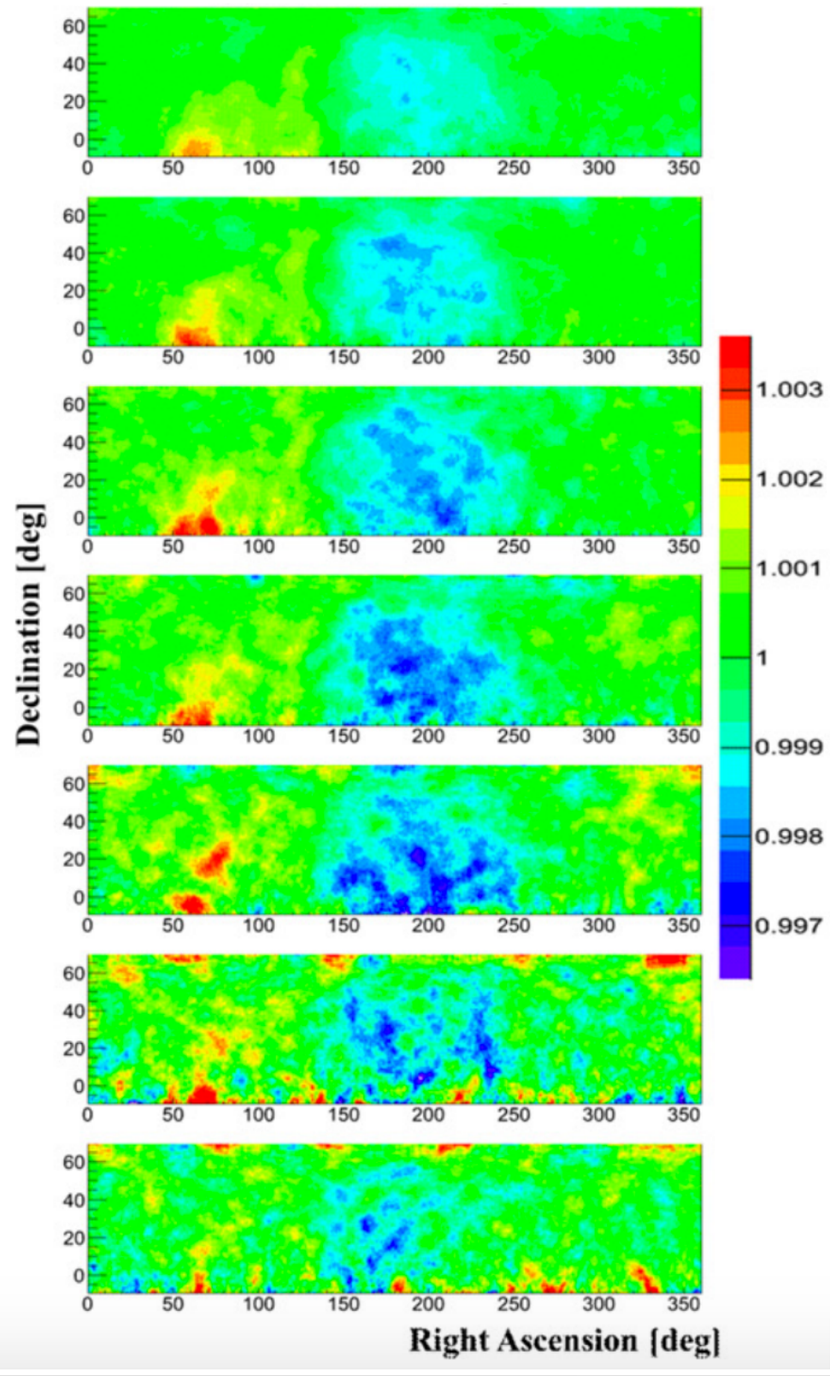


cosmic ray anisotropy
energy dependence

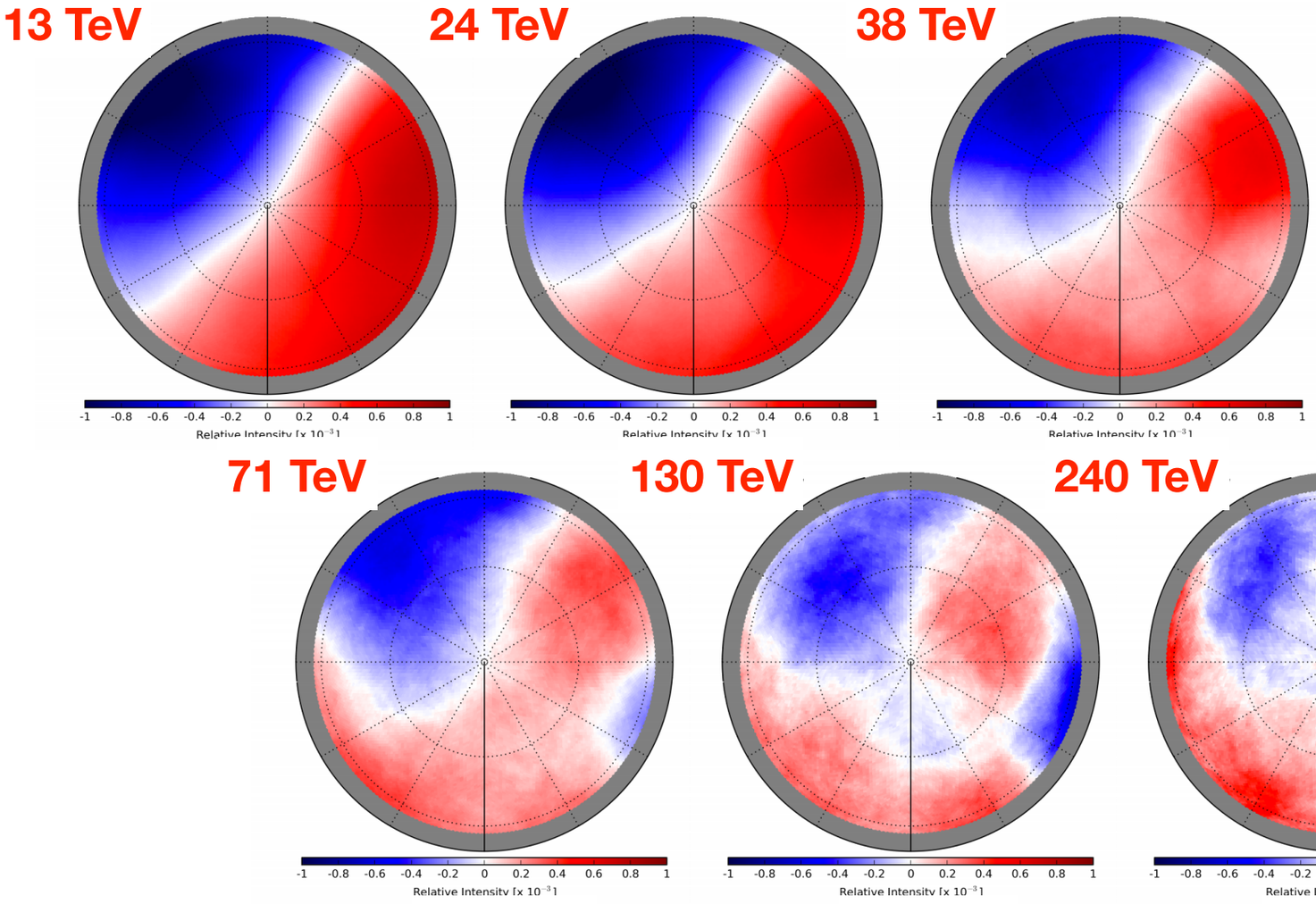
Tibet ASγ Amenomori et al., 2006



ARGO-YBJ Bartoli et al. 2015



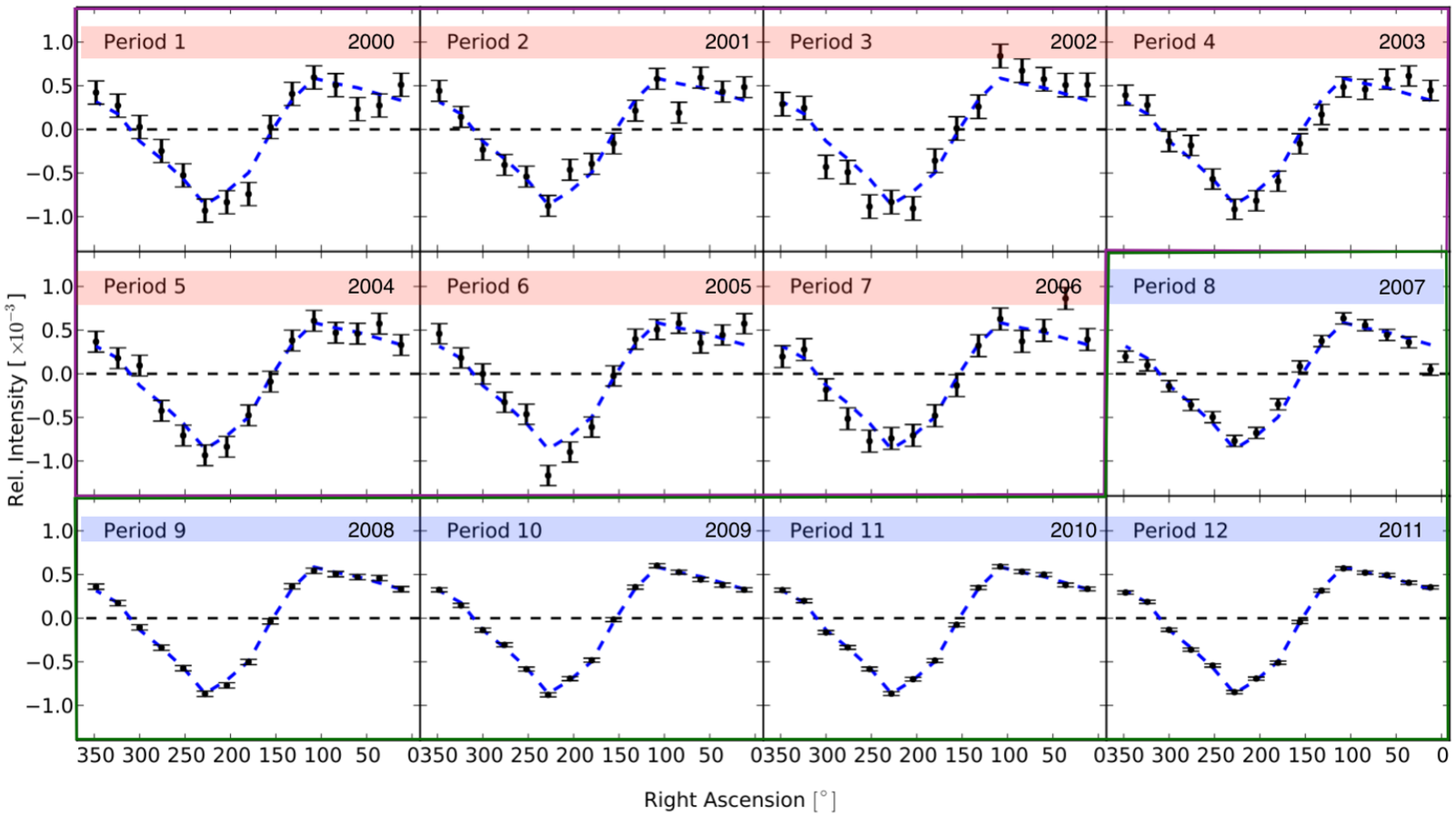
cosmic rays anisotropy
energy dependence



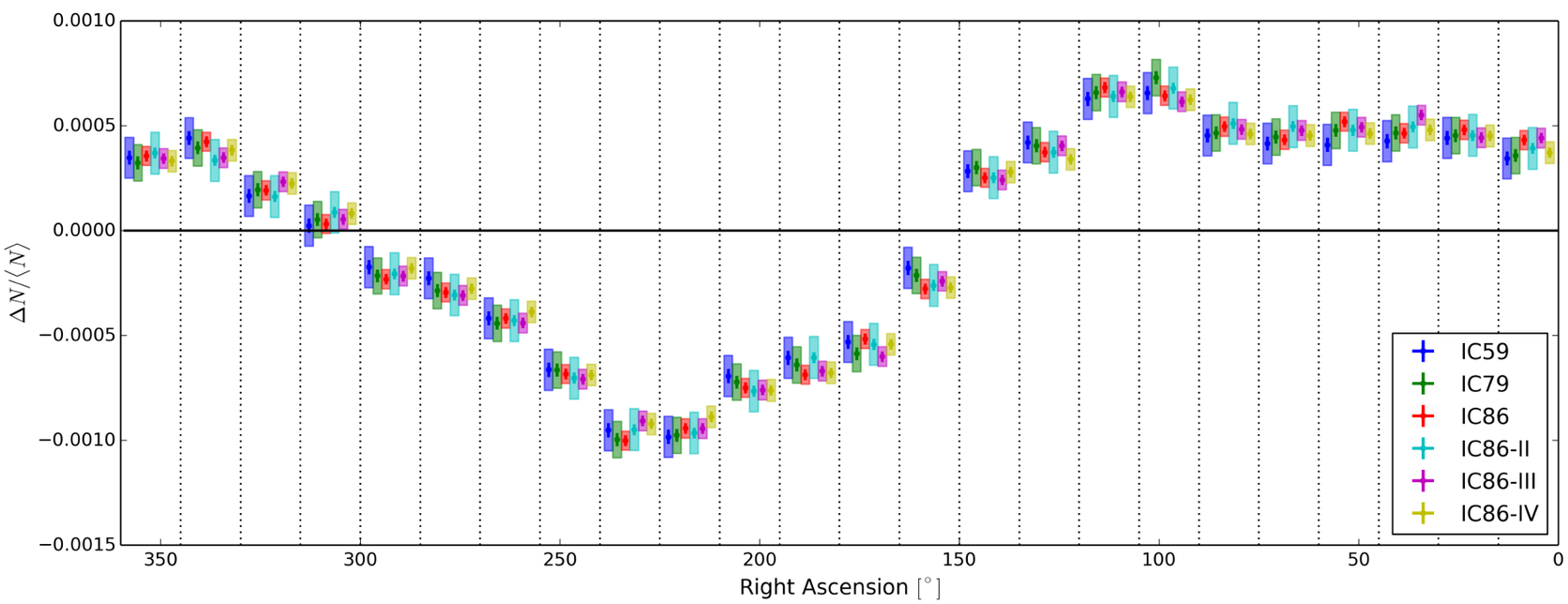
IceCube Aartsen et al., ApJ 826, 220, 2016

cosmic rays anisotropy stability

AMANDA-IceCube 2000-2014



ICRC 2013

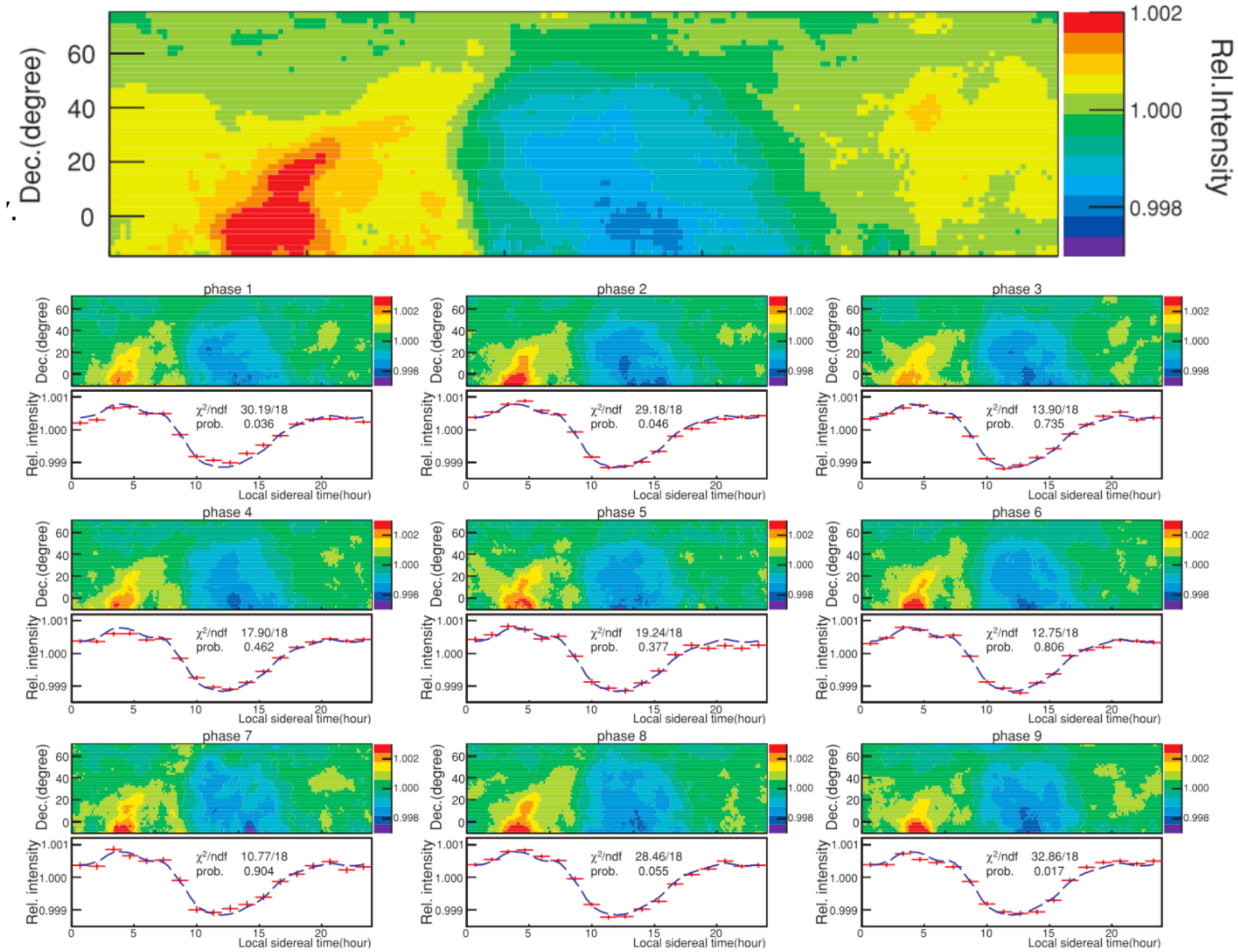


IceCube - Aartsen et al., ApJ 826, 220, 2016

cosmic rays anisotropy stability

Tibet Array

Tibet Array 2005



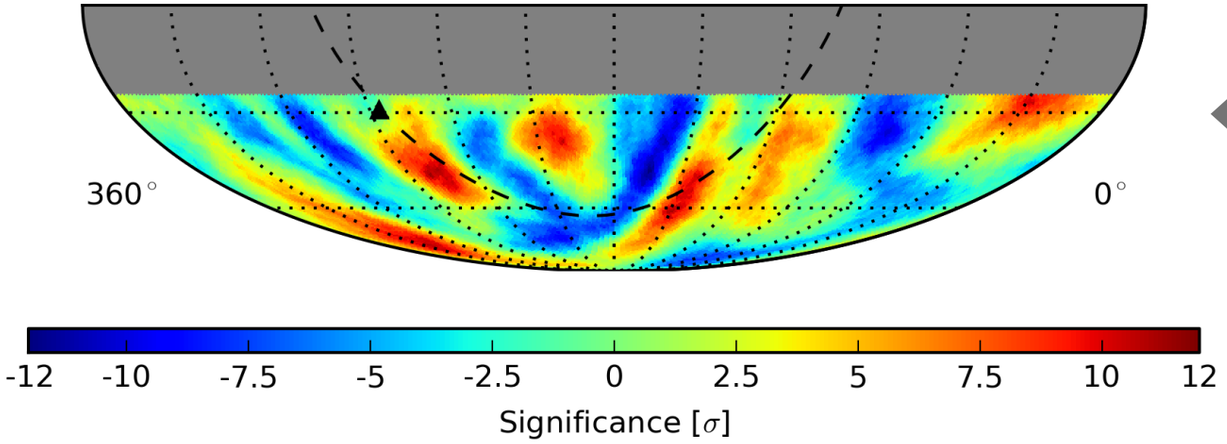
cosmic rays anisotropy
angular scale decomposition

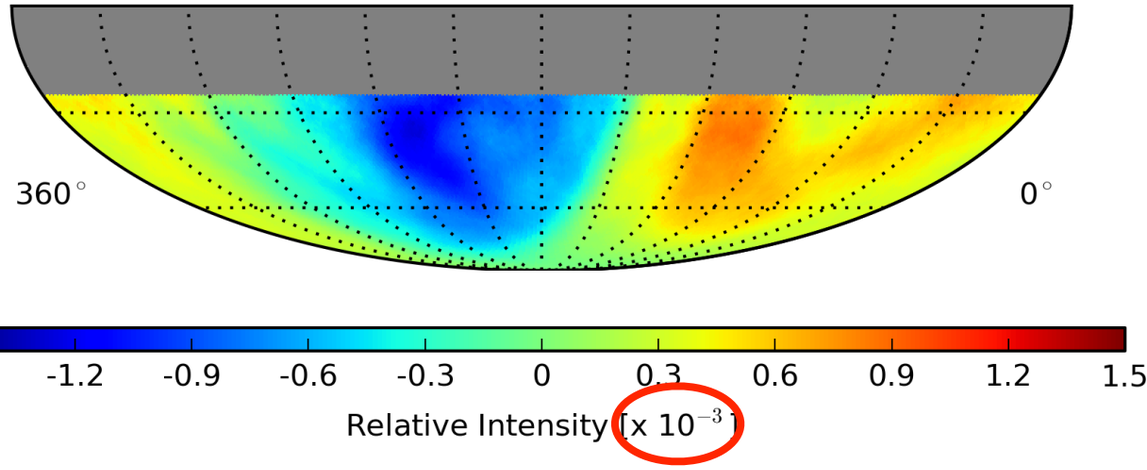
- fit 3D dipole + quadrupole and subtract from data

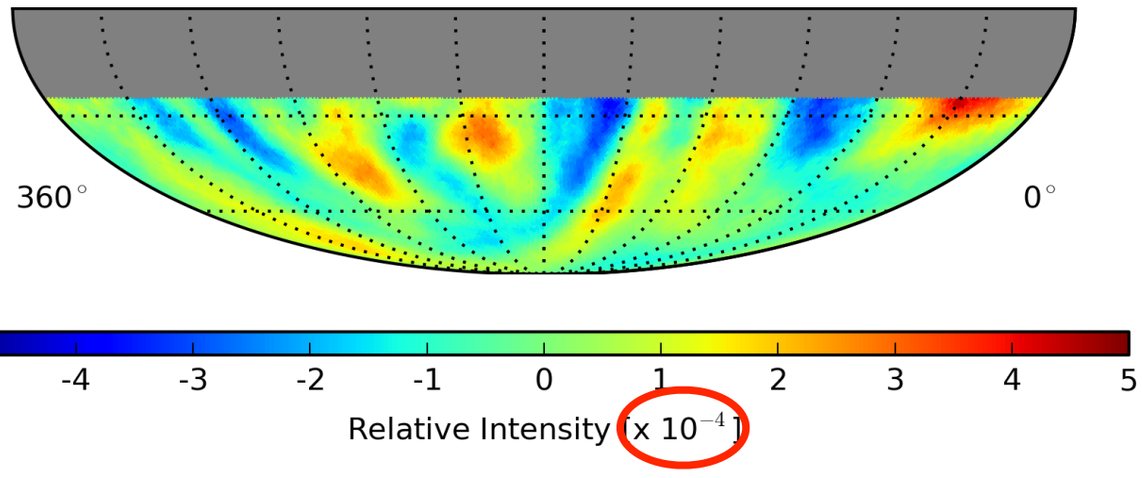
$$s = \sqrt{2}\left\{ N_{\mathrm{on}} \ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\mathrm{on}}}{N_{\mathrm{on}}+N_{\mathrm{off}}}\right)\right] + N_{\mathrm{off}} \ln\left[(1+\alpha)\left(\frac{N_{\mathrm{off}}}{N_{\mathrm{on}}+N_{\mathrm{off}}}\right)\right]\right\}^{1/2} \qquad \alpha = 1/20$$

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

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







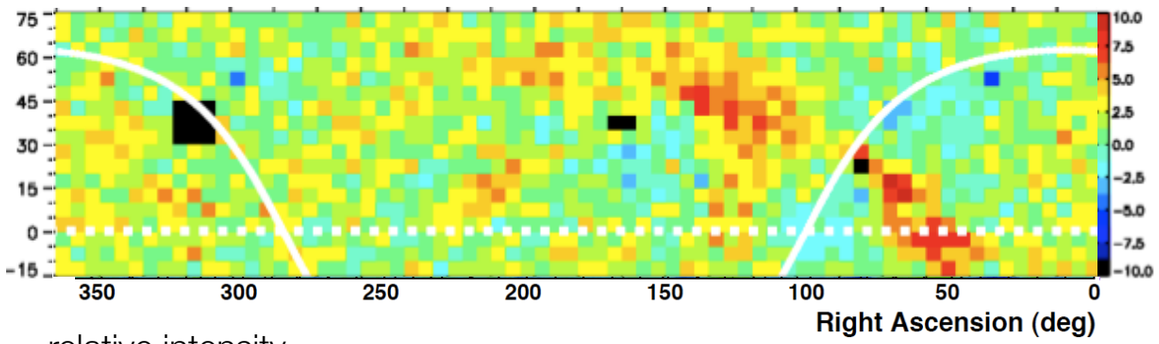
high energy cosmic rays
small scale anisotropy & spectral anomalies

1-5 TeV

$\sim 10^{-4}$

Tibet-III

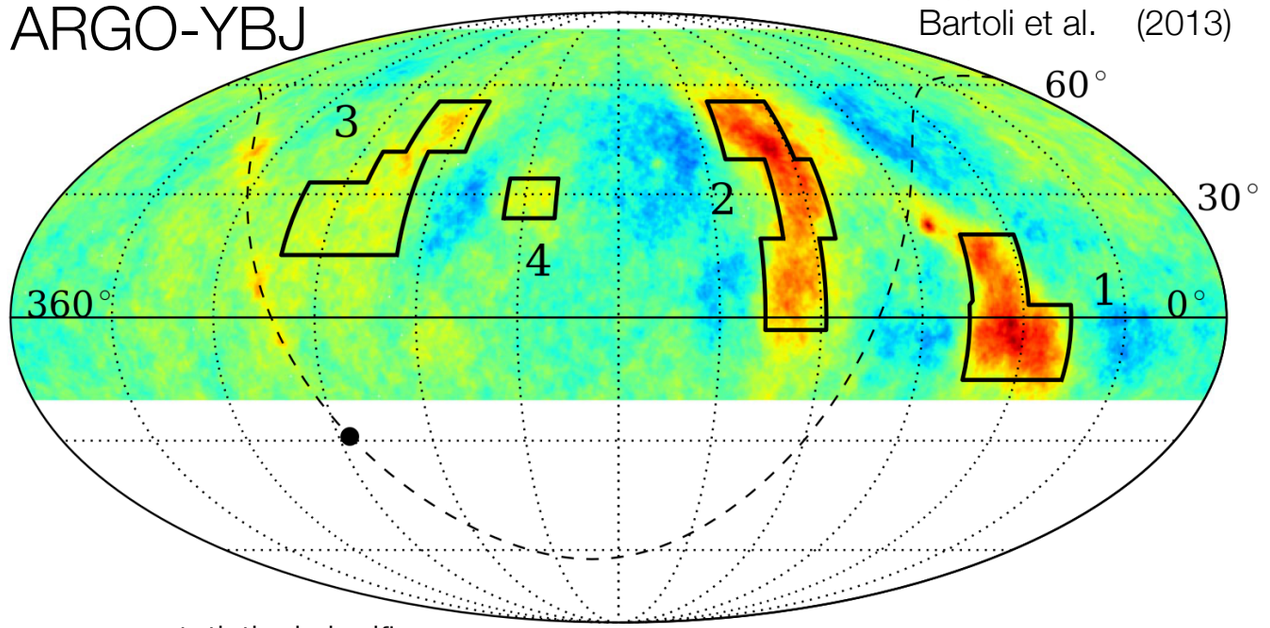
Amenomori et al. ICRC (2007)



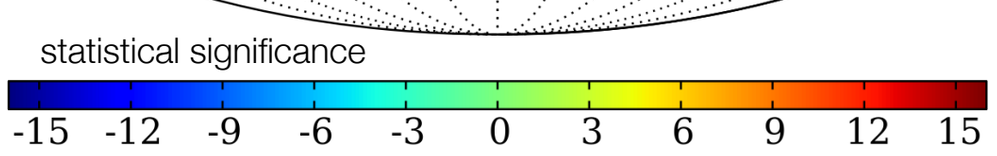
relative intensity

ARGO-YBJ

Vernetto et al. (2009)
Iuppa et al. (2011)
Bartoli et al. (2013)

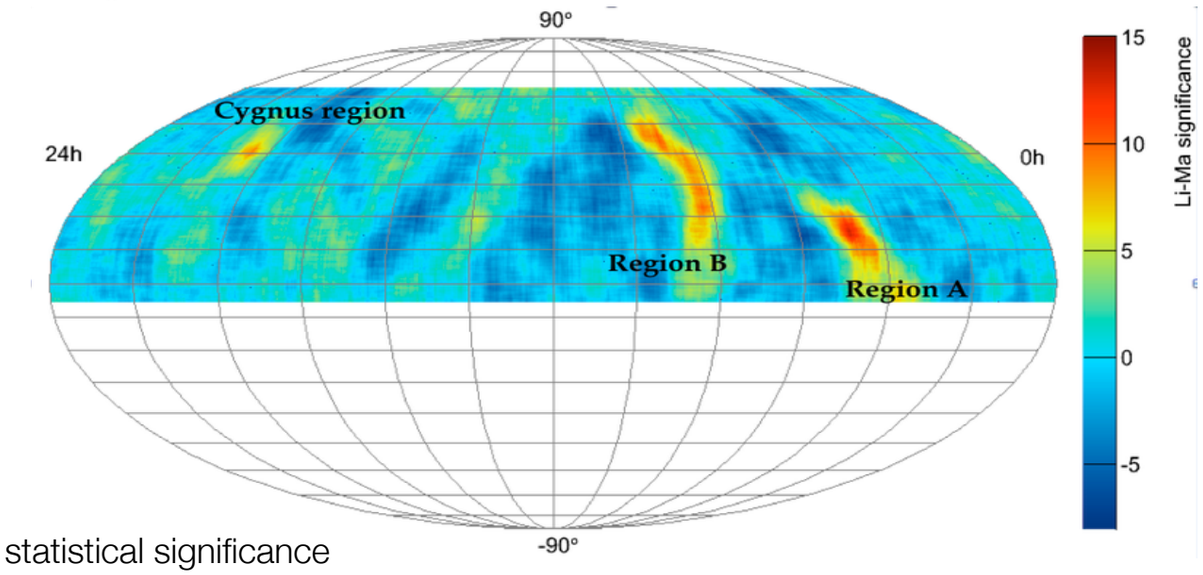


statistical significance



Milagro

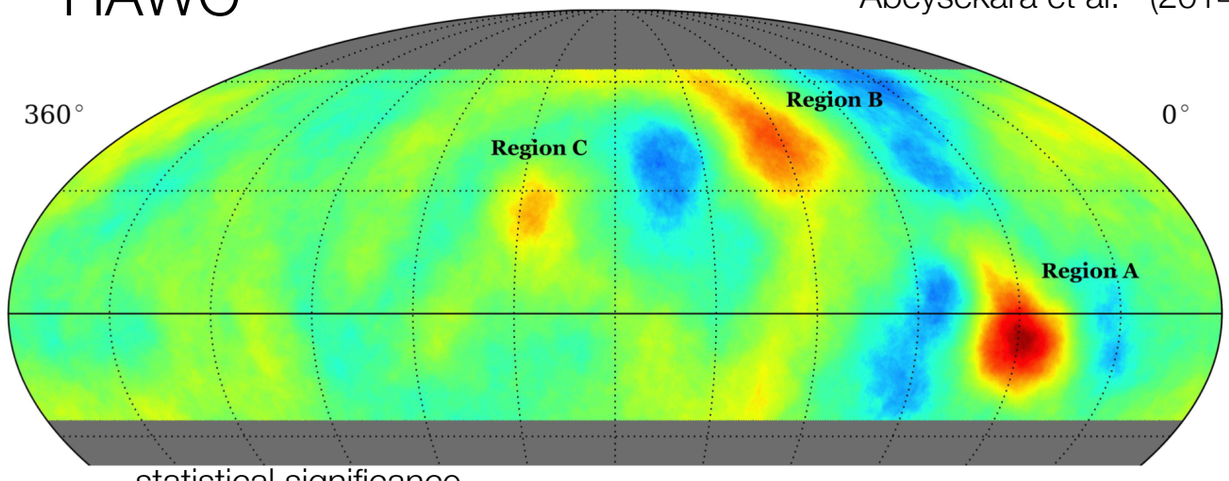
Abdo et al. (2008)



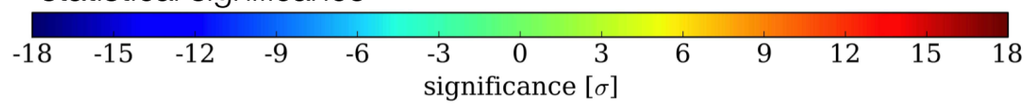
statistical significance

HAWC

BenZvi et al. ICRC (2013)
Abeysekara et al. (2014)

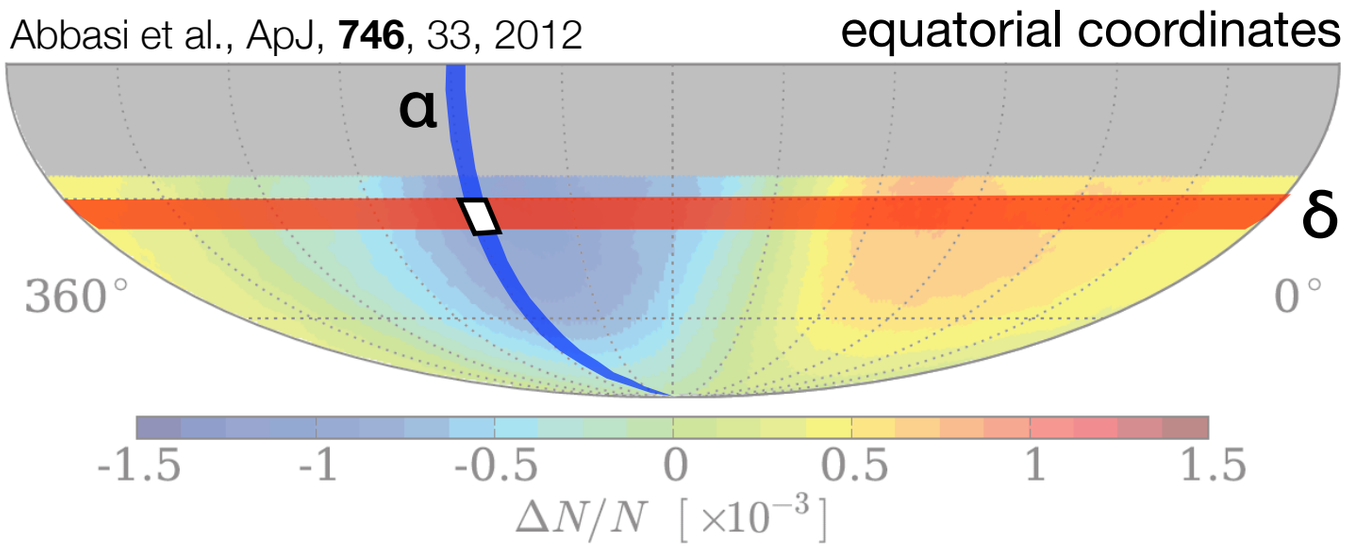


statistical significance

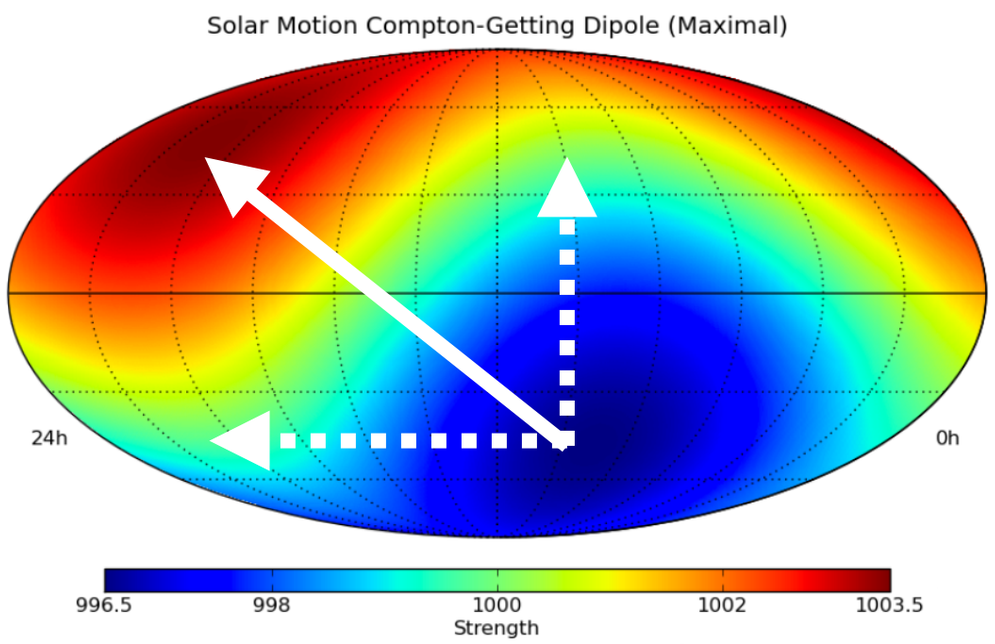


measuring cosmic ray anisotropy

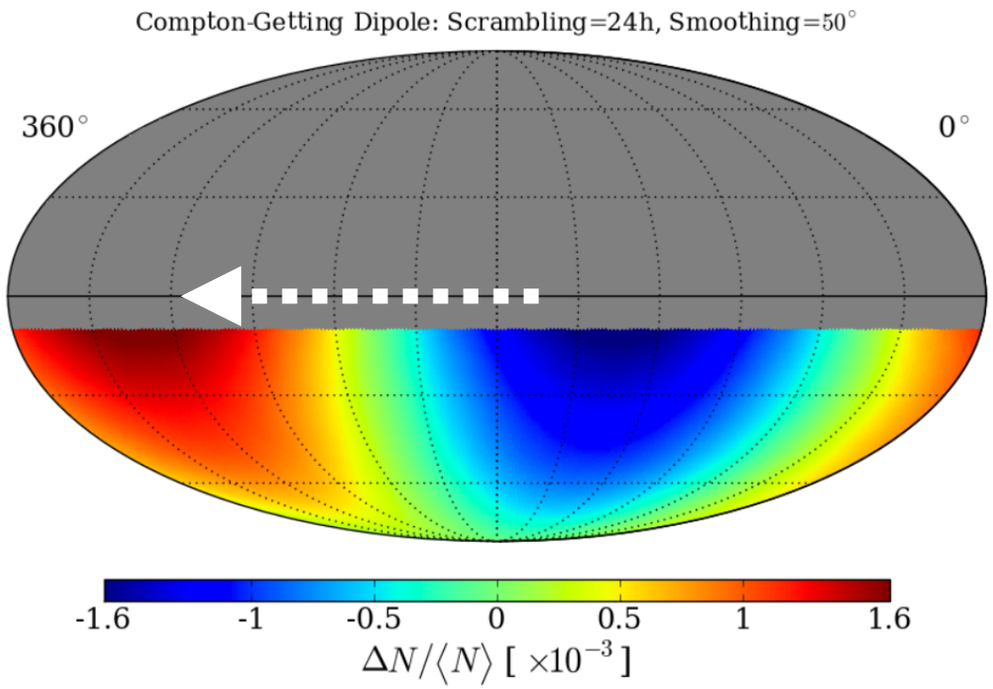
projection biases



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



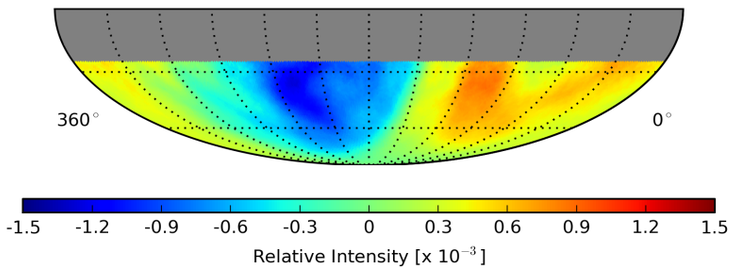
$\Delta N/\langle N \rangle = 7\times10^{-3}$

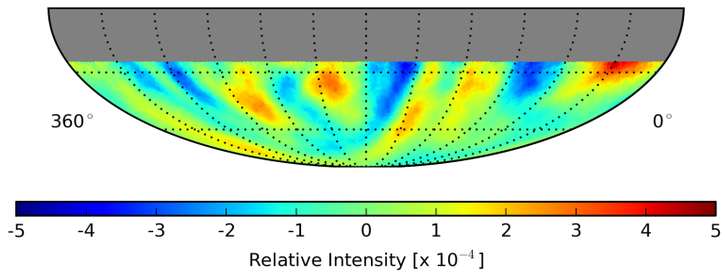


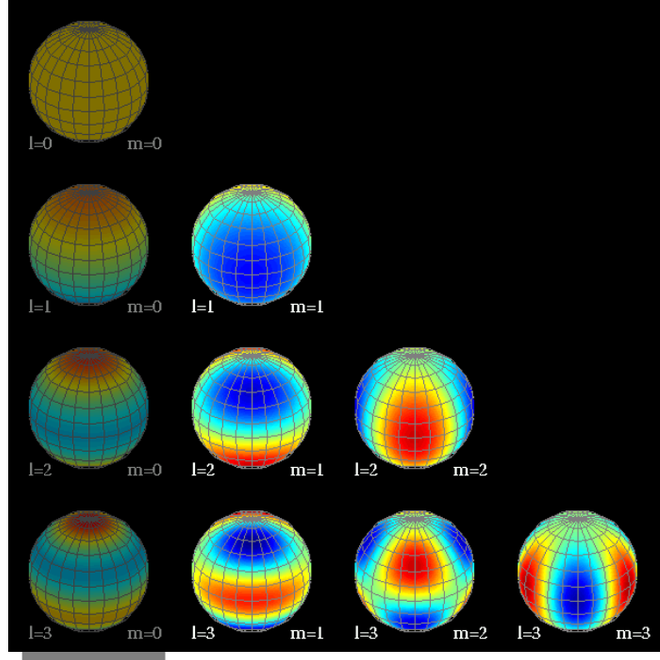
sky maps show **ONLY** modulations projected on **equatorial plane**

cosmic rays anisotropy

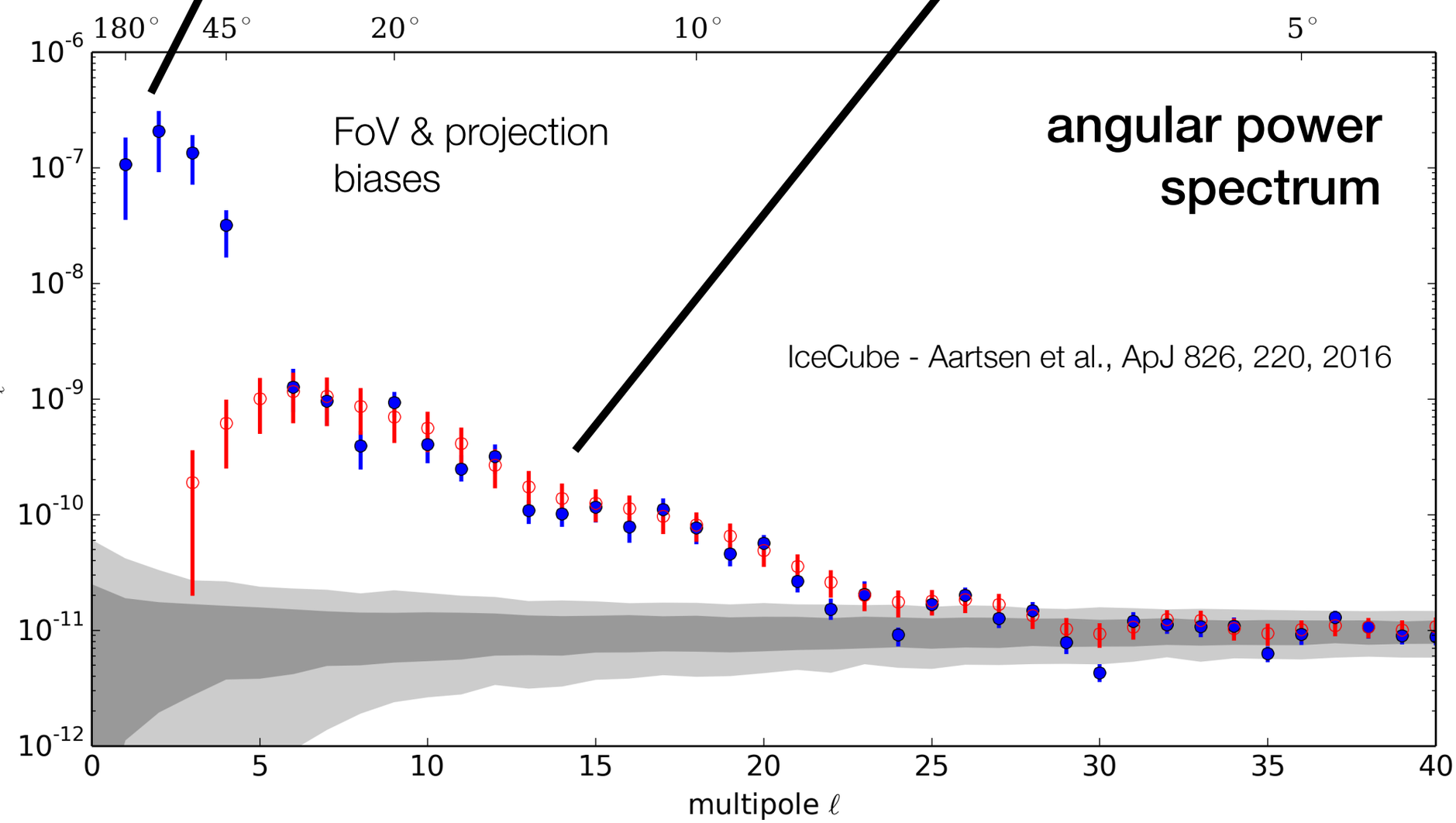
angular scale decomposition





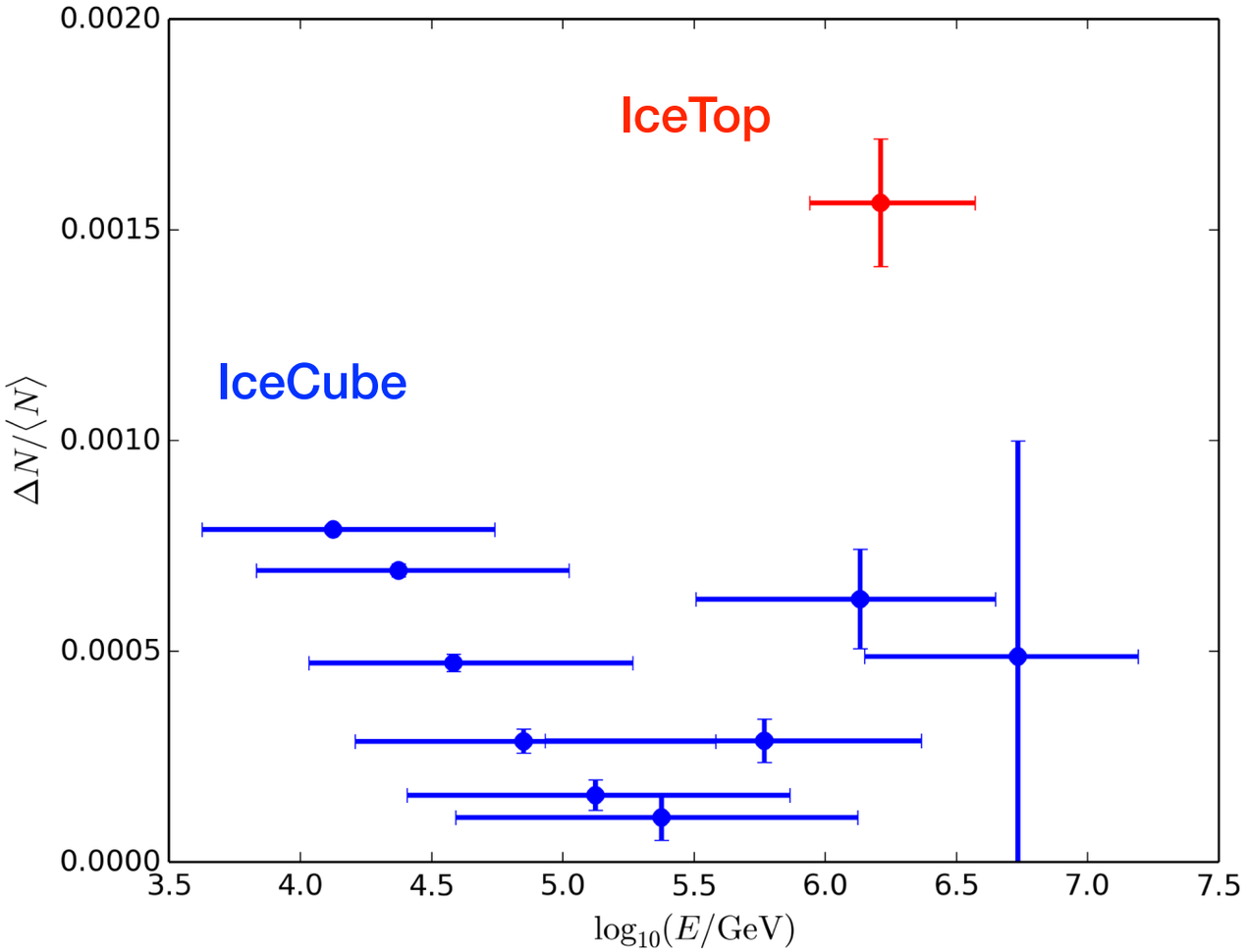


missing *vertical* component (m = 0)

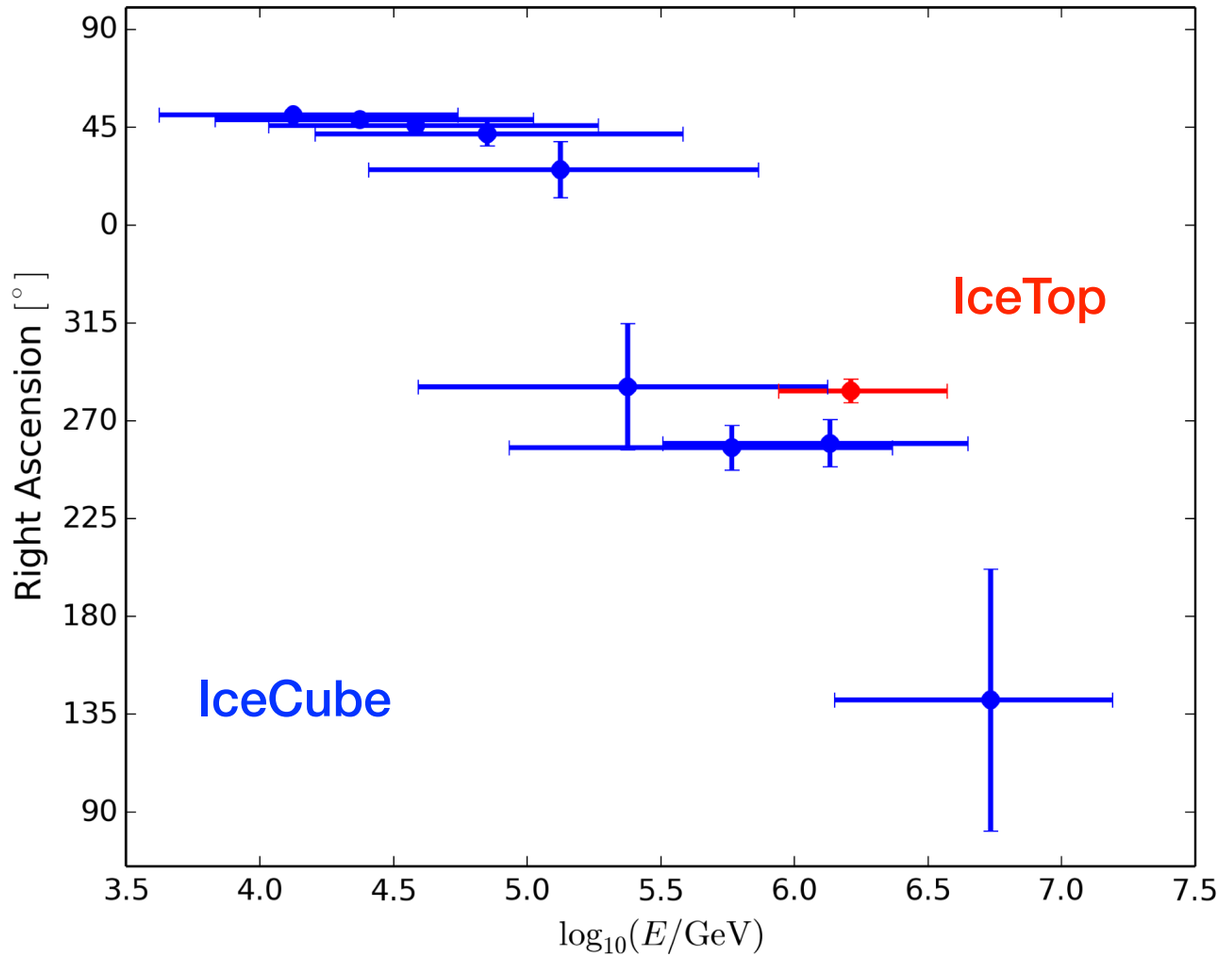


cosmic ray anisotropy

dipole component & galactic diffusion



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

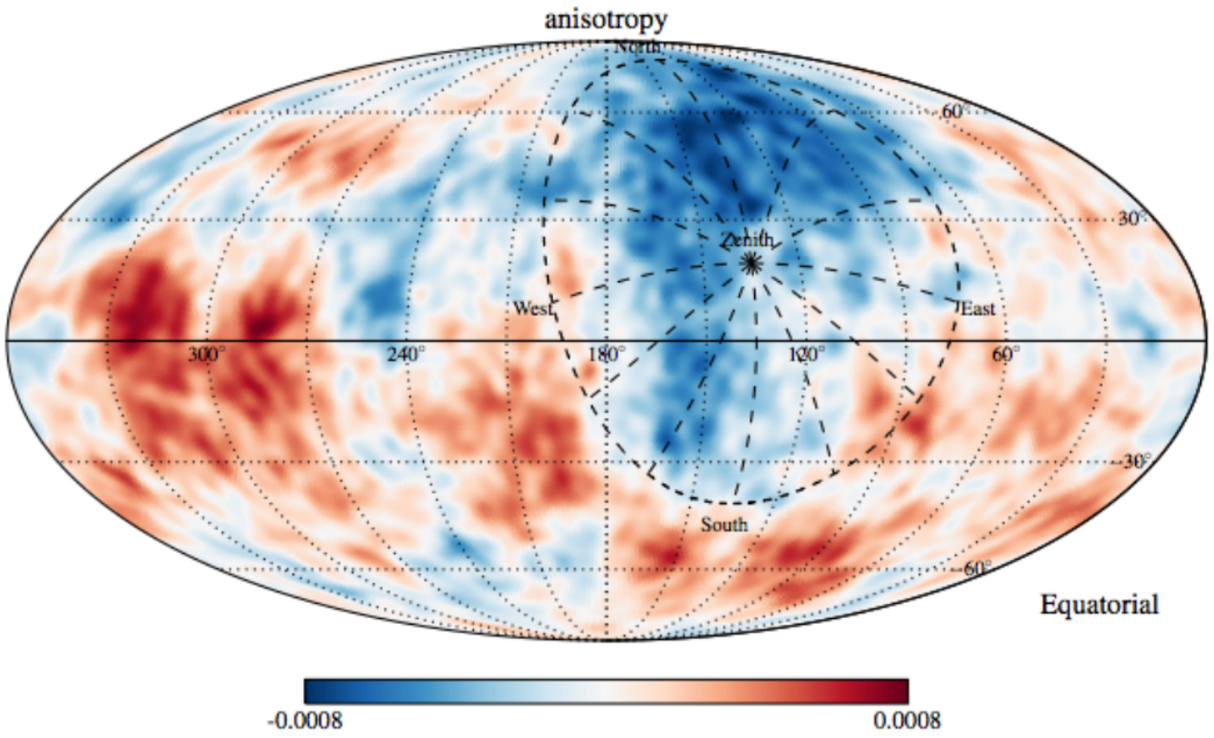


dipole component assumed to be originated by galactic standard diffusion

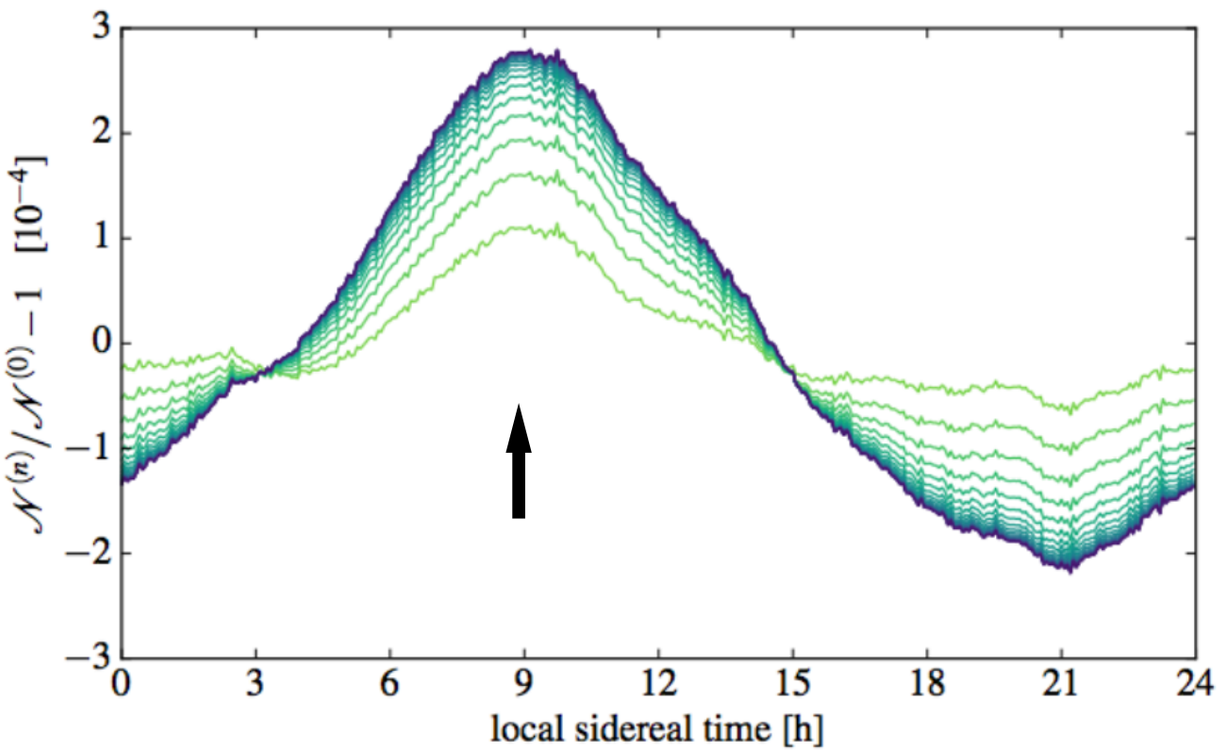
measure anisotropy as a function of primary particle mass / rigidity

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

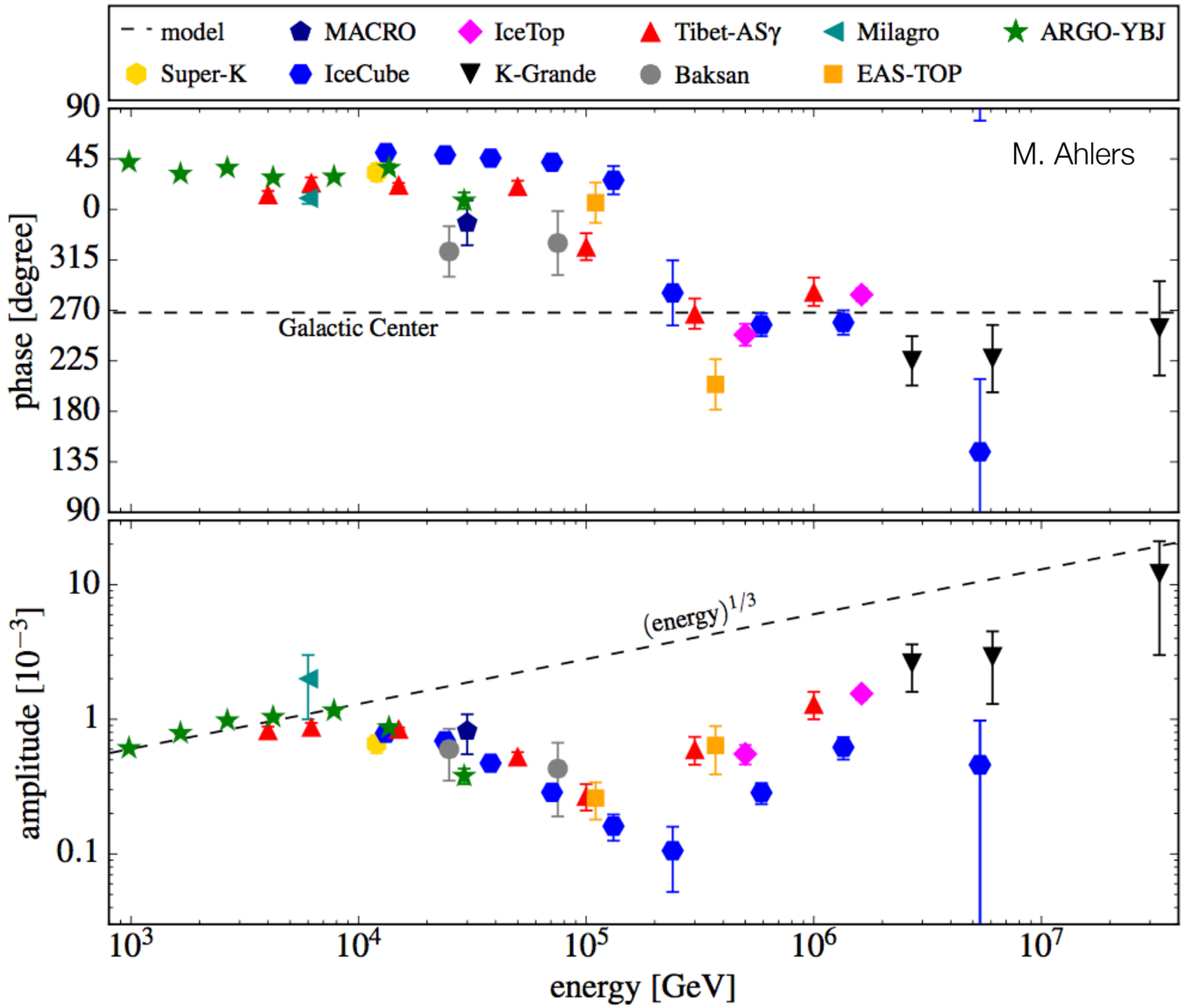
iterative methods

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

anisotropy more structured than a simple dipole



Di Sciascio & Iuppa 2014 (arXiv:1407.2144)

measuring cosmic ray anisotropy
standard diffusion from local sources

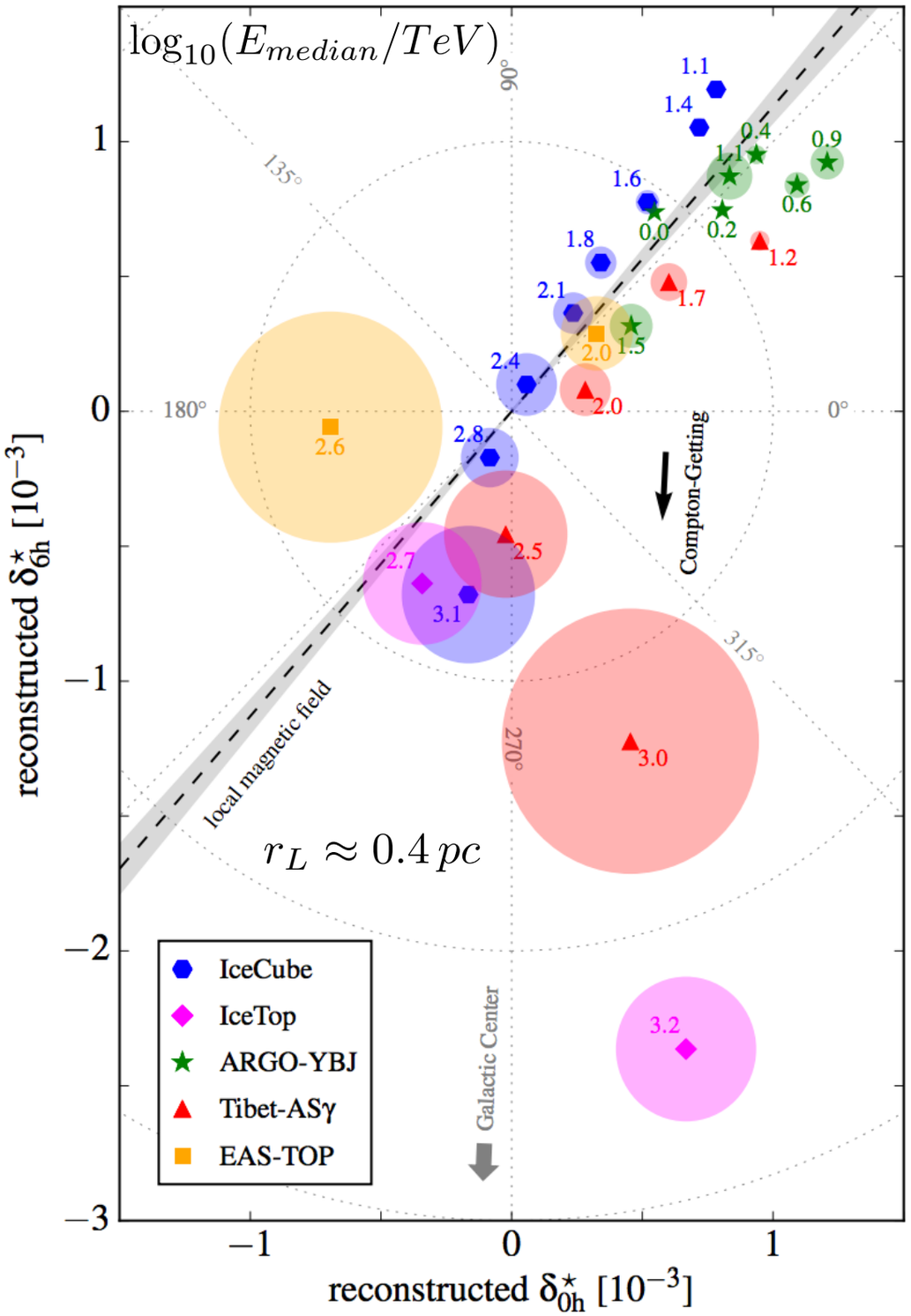
- dipole component on **equatorial plane**
- Compton-Getting corrected (wrt LSR)
- cross-talk between multipoles from limited FoV
- compare to IBEX LIMF direction

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

unknown **vertical** component & diffusion

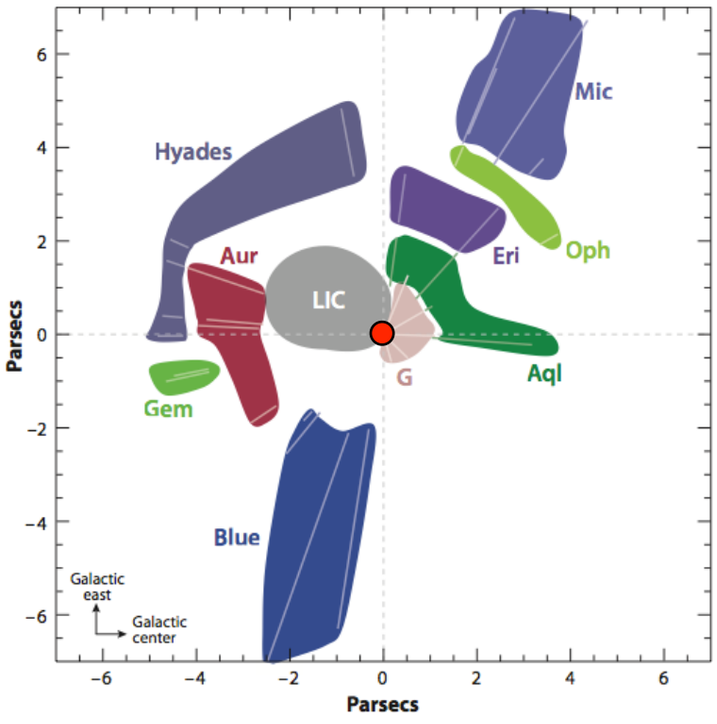
possible contribution from **Vela SNR**

Ahlers 2016 - arXiv:1605.06446

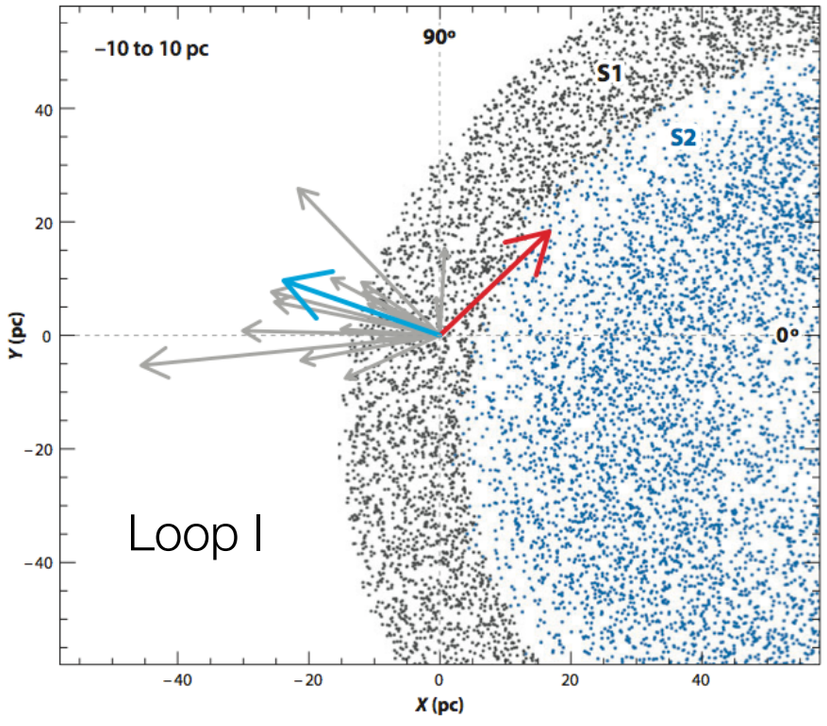


cosmic ray anisotropy
local interstellar medium

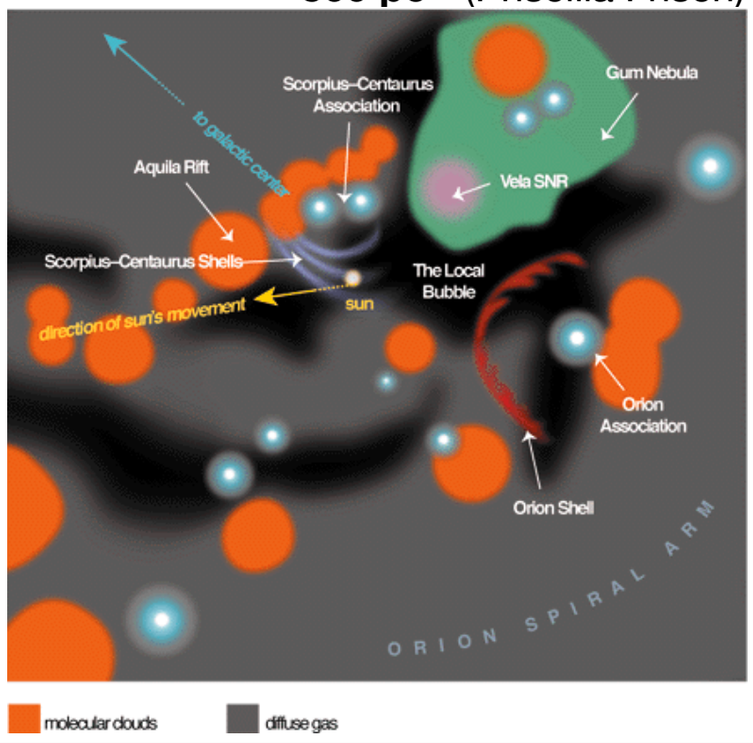
14 pc - Frisch+, 2011, 14



100 pc - Wolleben, 2007



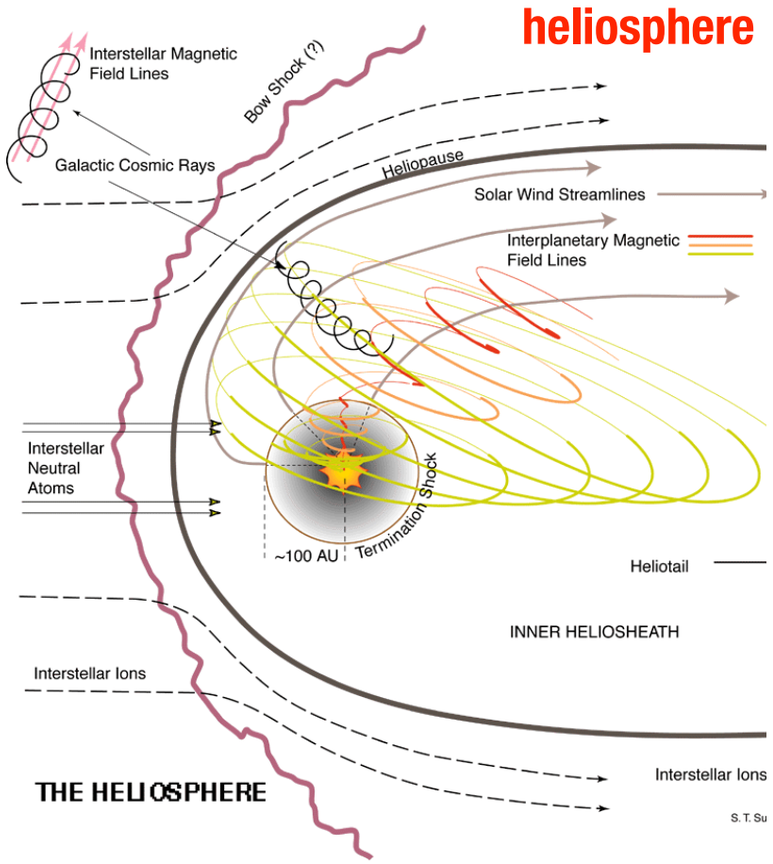
500 pc - (Priscilla Frisch)



- 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

cosmic ray anisotropy
heliosphere

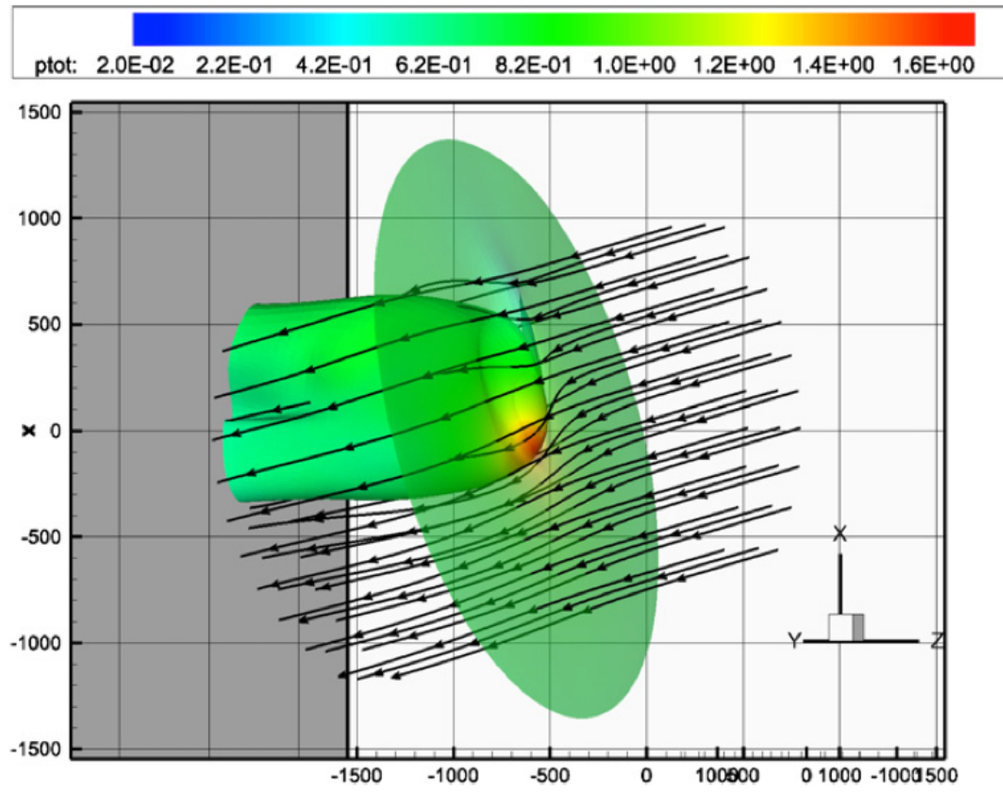
$$r_L \approx \frac{200}{Z} \frac{E(TeV)}{B(\mu G)} AU$$



heliotail

local ISMF draping around heliosphere

Pogorelov+ 2011



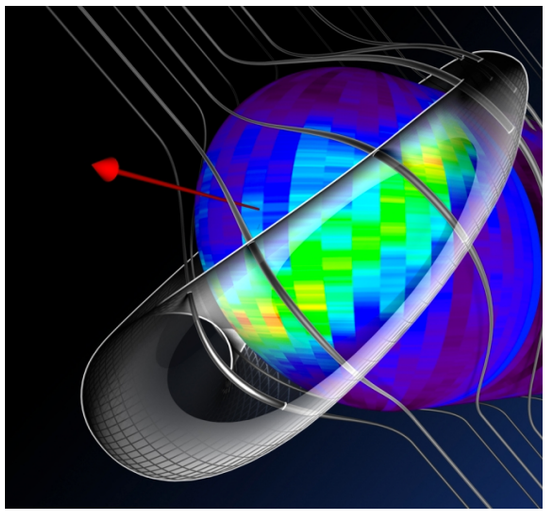
- heliosphere as O(100-1000) AU **magnetic perturbation of local ISMF** PD & Lazarian, 2013
- influence on ≲ 10 TeV protons (R_L ≲ 600 AU)
- cosmic rays >100's TeV influenced by interstellar magnetic field (**change of anisotropy**)

anisotropy and local magnetic environment
heliospheric effect

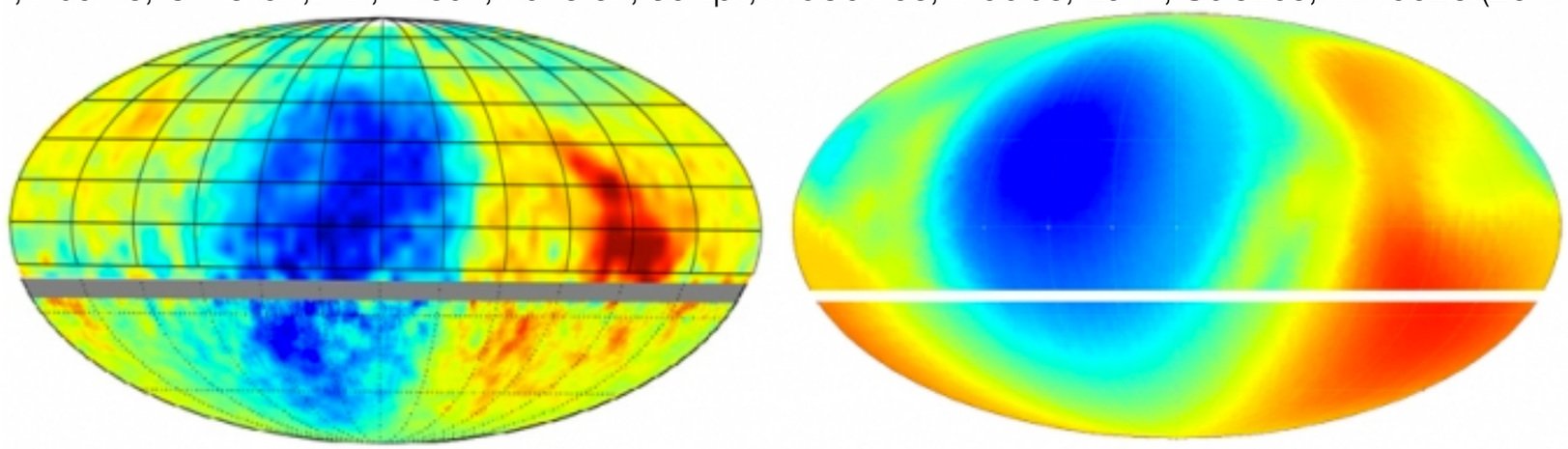
PD & Lazarian 2013
López-Barquero, Xu, PD, Lazarian, et al. submitted to ApJ

Lazarian & PD 2010
PD & Lazarian 2012

TeV CRs can be used to probe the far reaches of heliosphere (e.g. the heliotail)



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



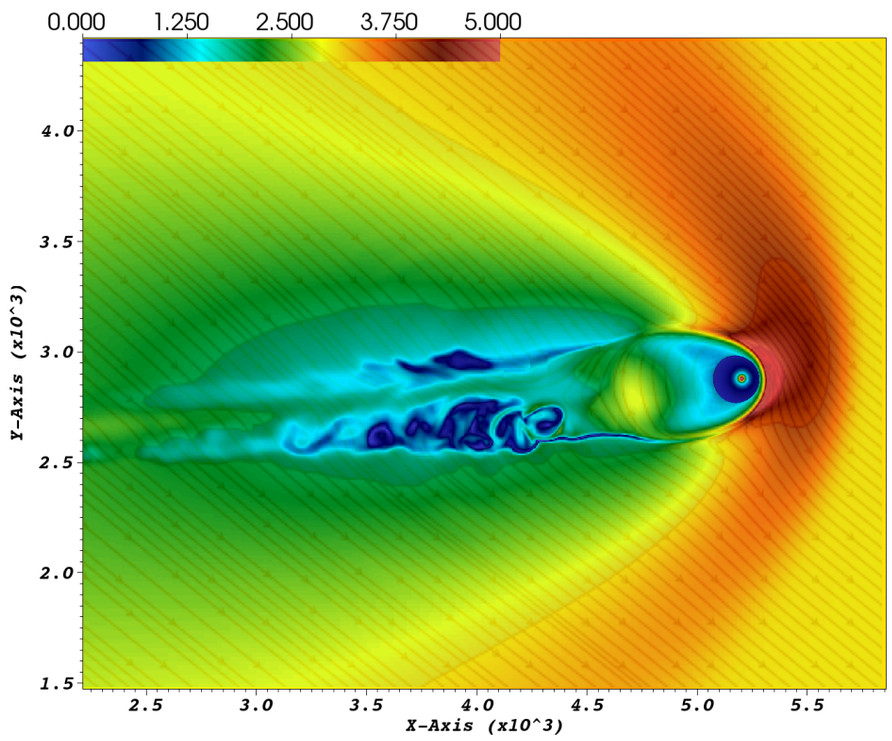
CR density gradient ordered by LIMF - heliosphere perturbs TeV CR arrival directions

accounting for complex heliospheric magnetic field - *unfold* interstellar arrival directions - standard diffusion

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

cosmic ray anisotropy

probing heliospheric magnetic structure

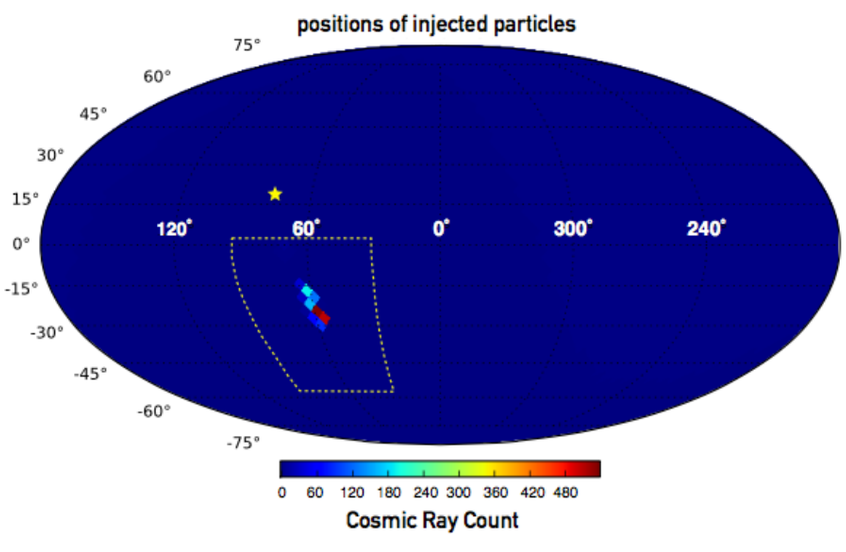


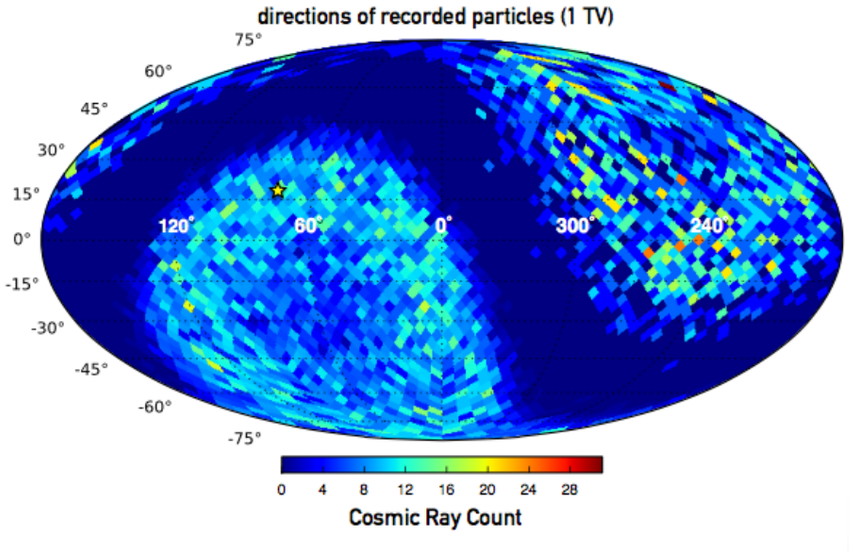
Borovikov, Heerikhuisen, Pogorelov

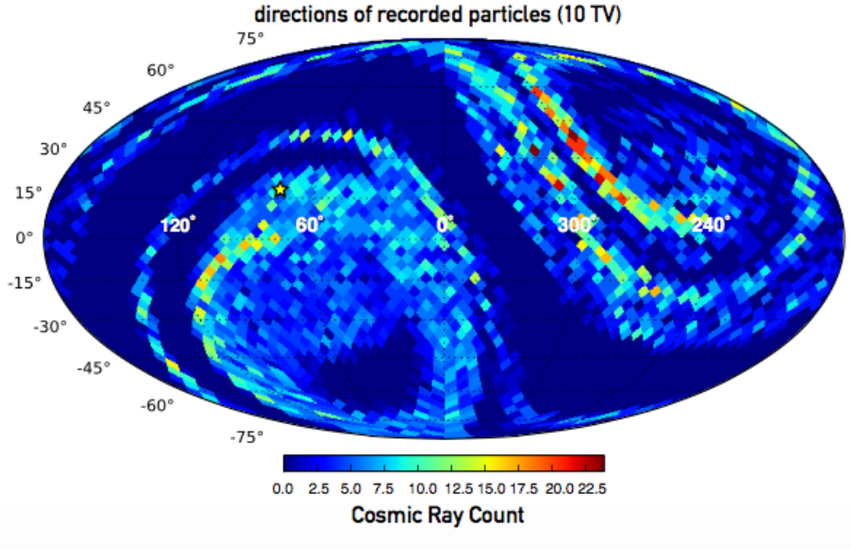
downstream instabilities on the flanks of heliotail

strong scattering

PD & Lazarian 2013
López-Barquero, Xu, PD, Lazarian, et al. submitted to ApJ







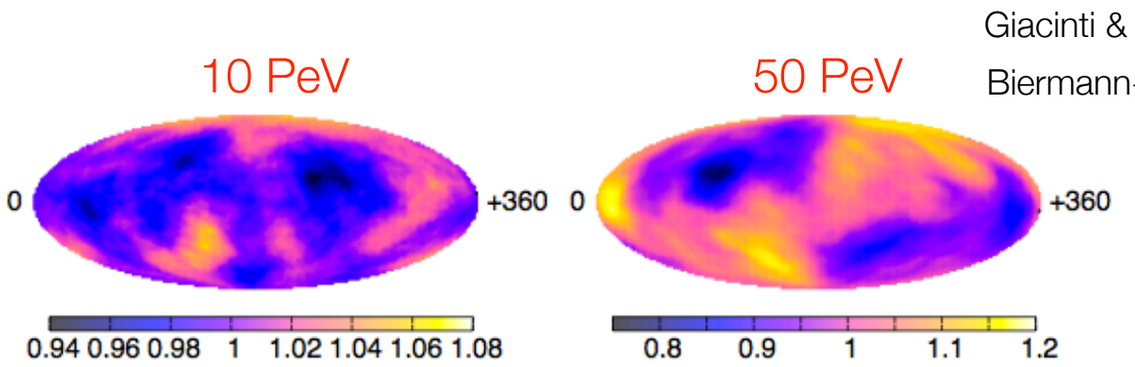
forward propagation

injection sphere 6000 AU - target sphere 200 AU

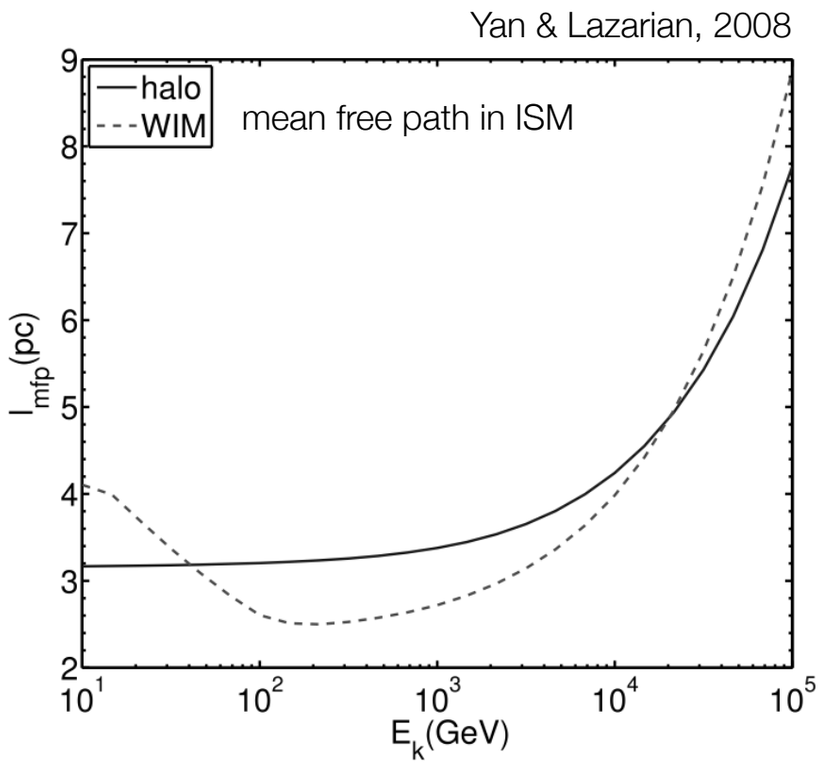
cosmic ray anisotropy
non-diffusive phenomena

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

Giacinti & Sigl, 2012
Biermann+, 2012

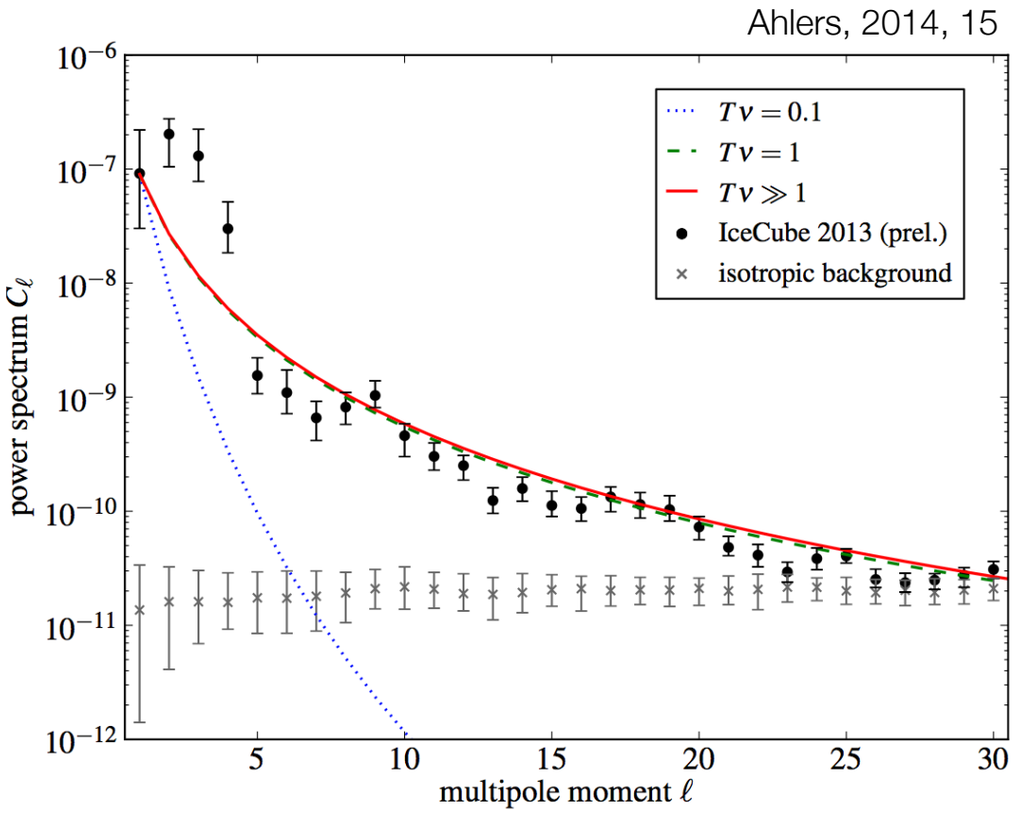


Yan & Lazarian, 2008



- 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 ?

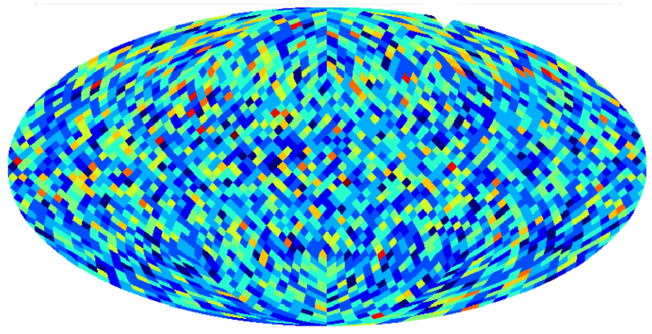
- compressible MHD turbulence (Cho & Lazarian, 2002)

- angular structures by scattering on turbulence within mean free path

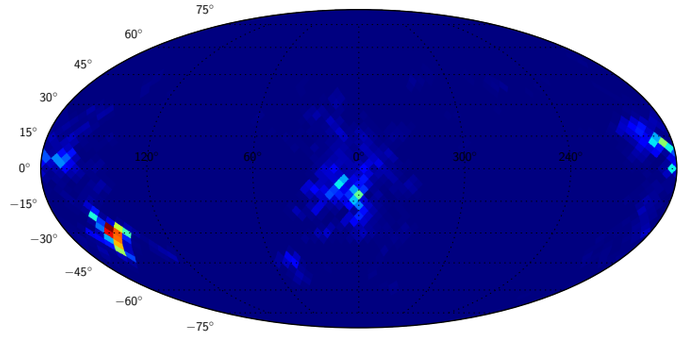
- dipole oriented along average fields within mean free path (different from *regular field*)

- small angular structure depends on actual realization. But its fingerprint is power spectrum

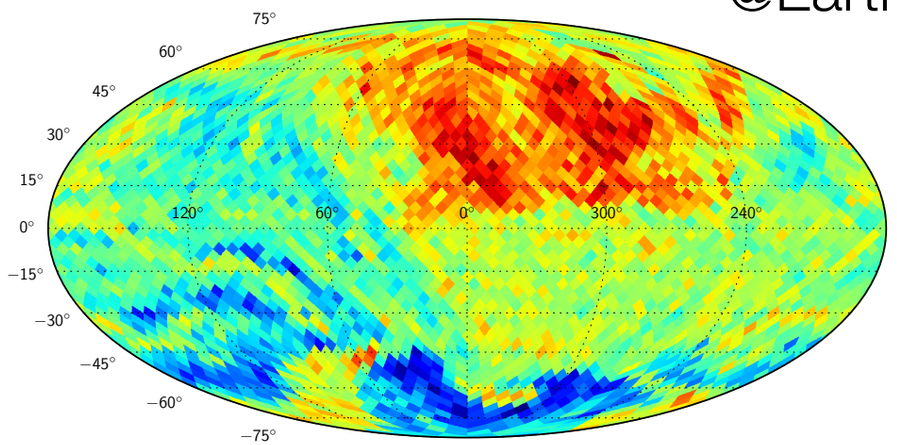
backward propagation



positions

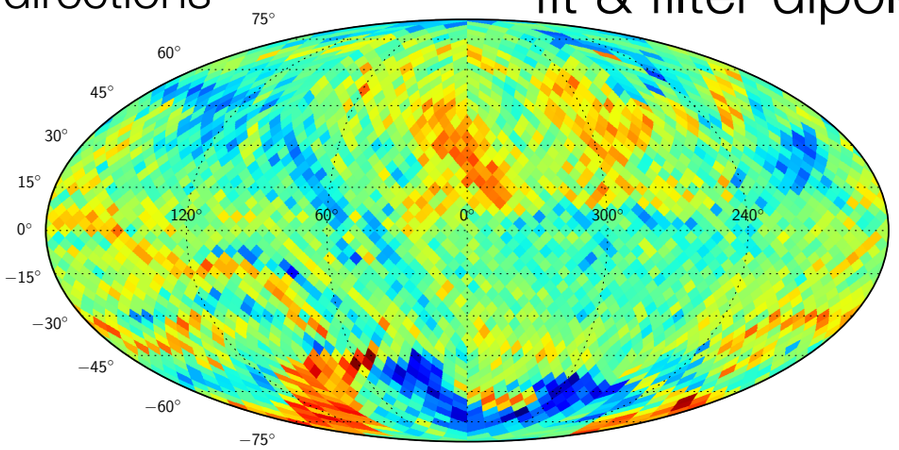


@Earth



directions

fit & filter dipole

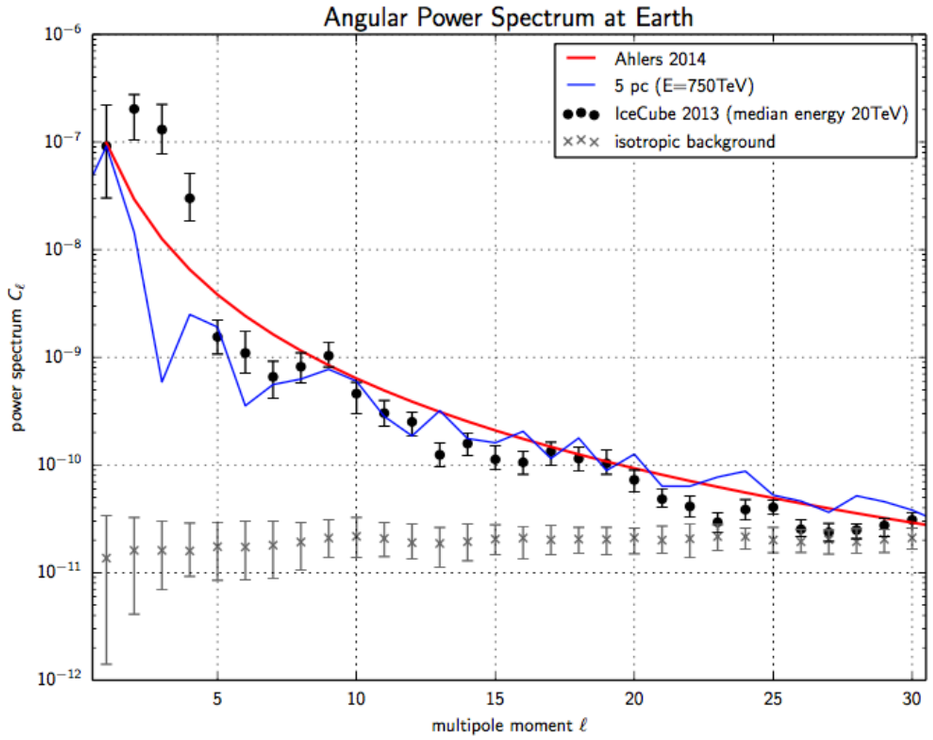


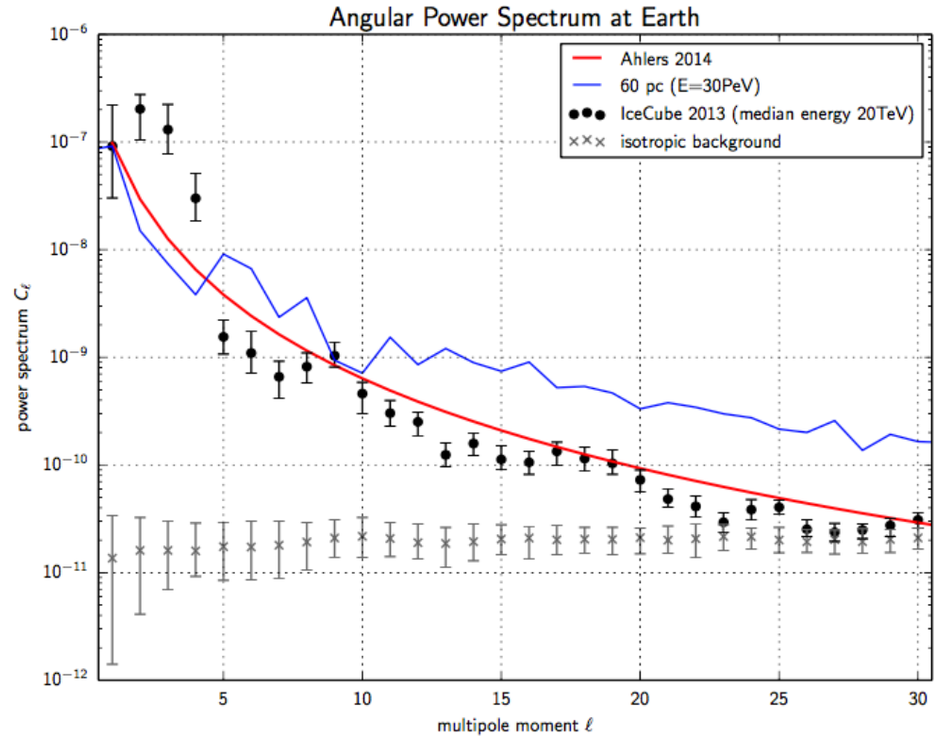
López-Barquero, Farber, Xu, PD, Lazarian, ApJ 830 19 (2016)
arXiv:1509.00892

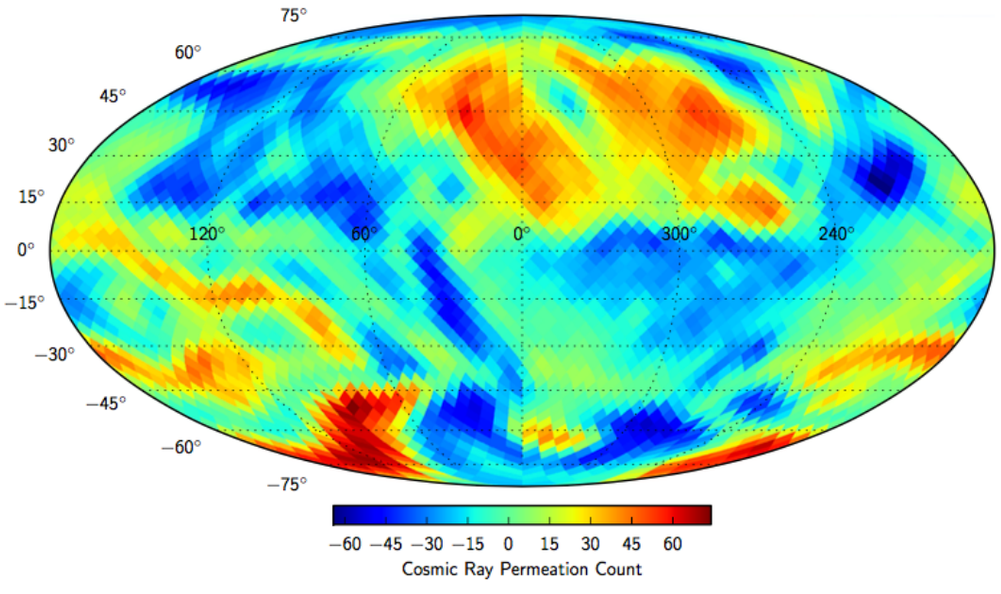
López-Barquero, Farber, Xu, PD, Lazarian, ApJ 830 19 (2016)
arXiv:1509.00892

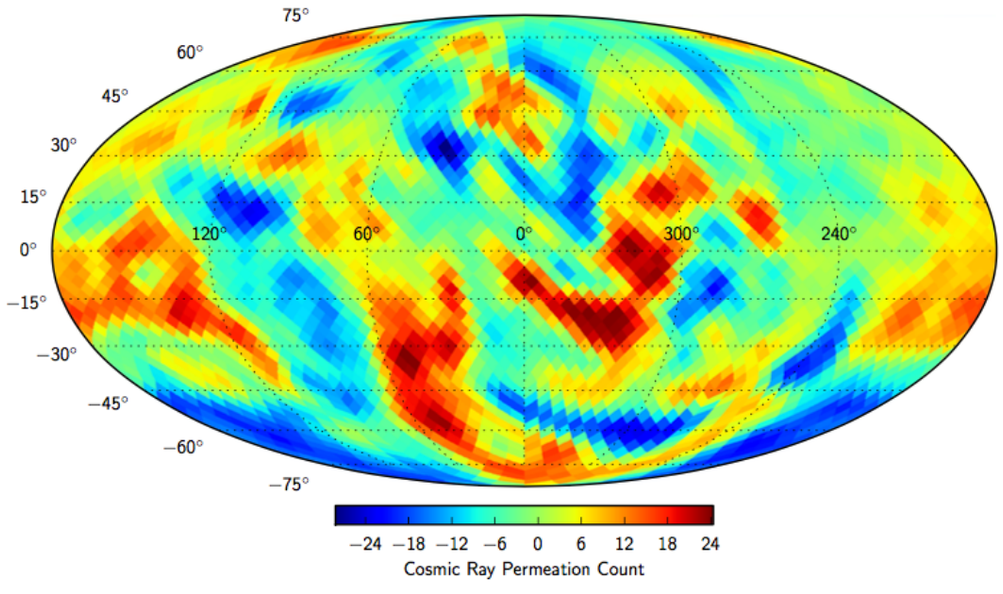
cosmic ray anisotropy

probing magnetic field turbulence ?

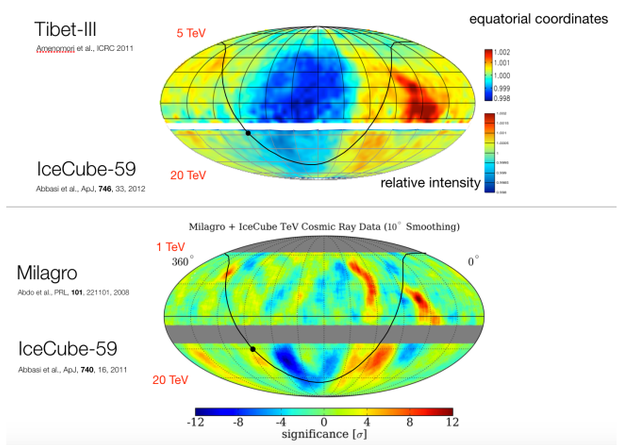








conclusions



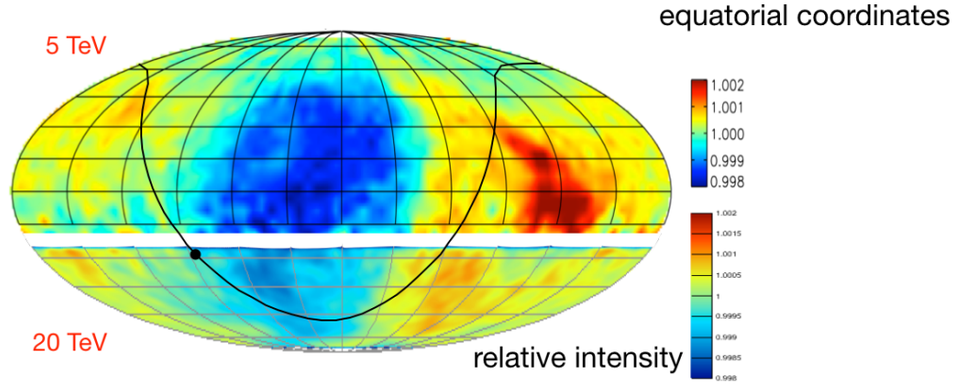
- cosmic ray anisotropy as fingerprint for their **origin** and **propagation**
- cosmic ray anisotropy from **standard diffusion** at *large-scale* (dipole, sources) & **non-diffusive processes** (angular structure)
- probe into propagation properties, Local Bubble, LIMF, heliosphere, …

- different overlapping phenomena to shape observations
  - anisotropy vs. **energy, angular structure, time, primary particle mass**
- overcome experimental limitations
  - full-sky observations: **on-Earth IceCube-HAWC & satellite observations**

THANK YOU

Tibet-III

Amenomori et al., ICRC 2011



IceCube-59

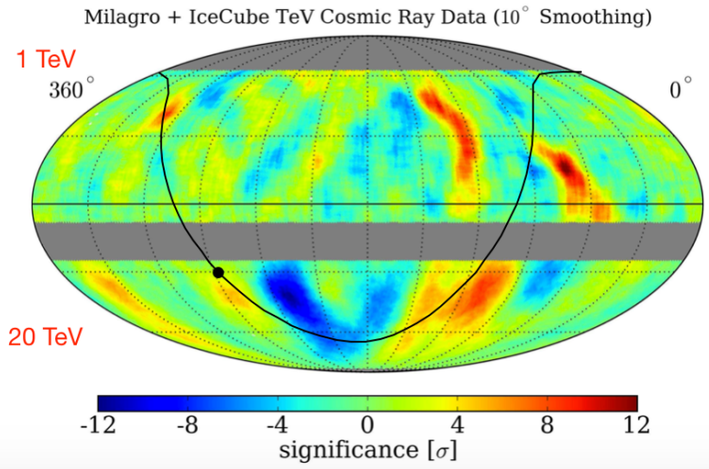
Abbasi et al., ApJ, **746**, 33, 2012

Milagro

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

IceCube-59

Abbasi et al., ApJ, **740**, 16, 2011



backup slides

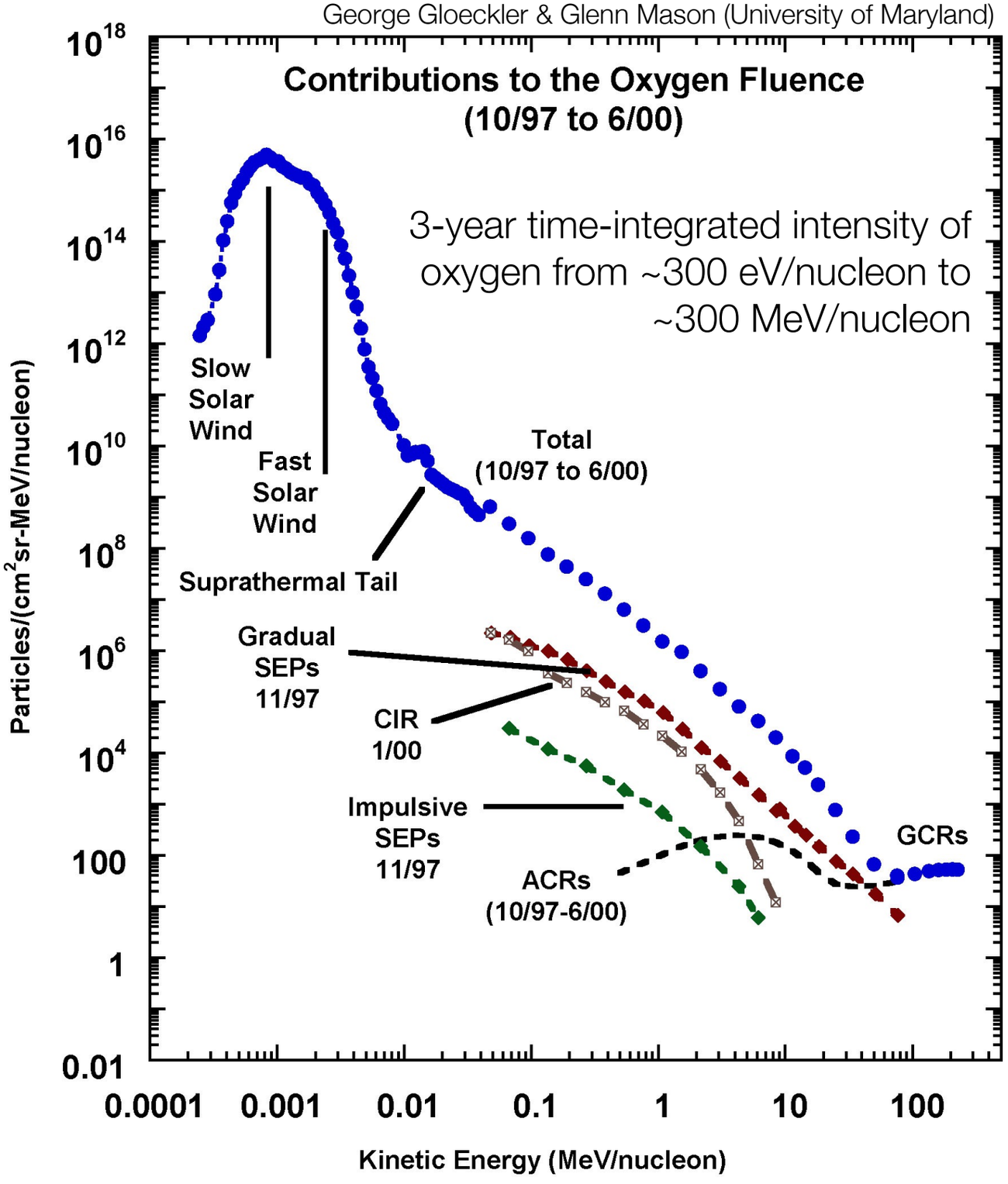
cosmic ray observations
spectral shape and their history

- 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

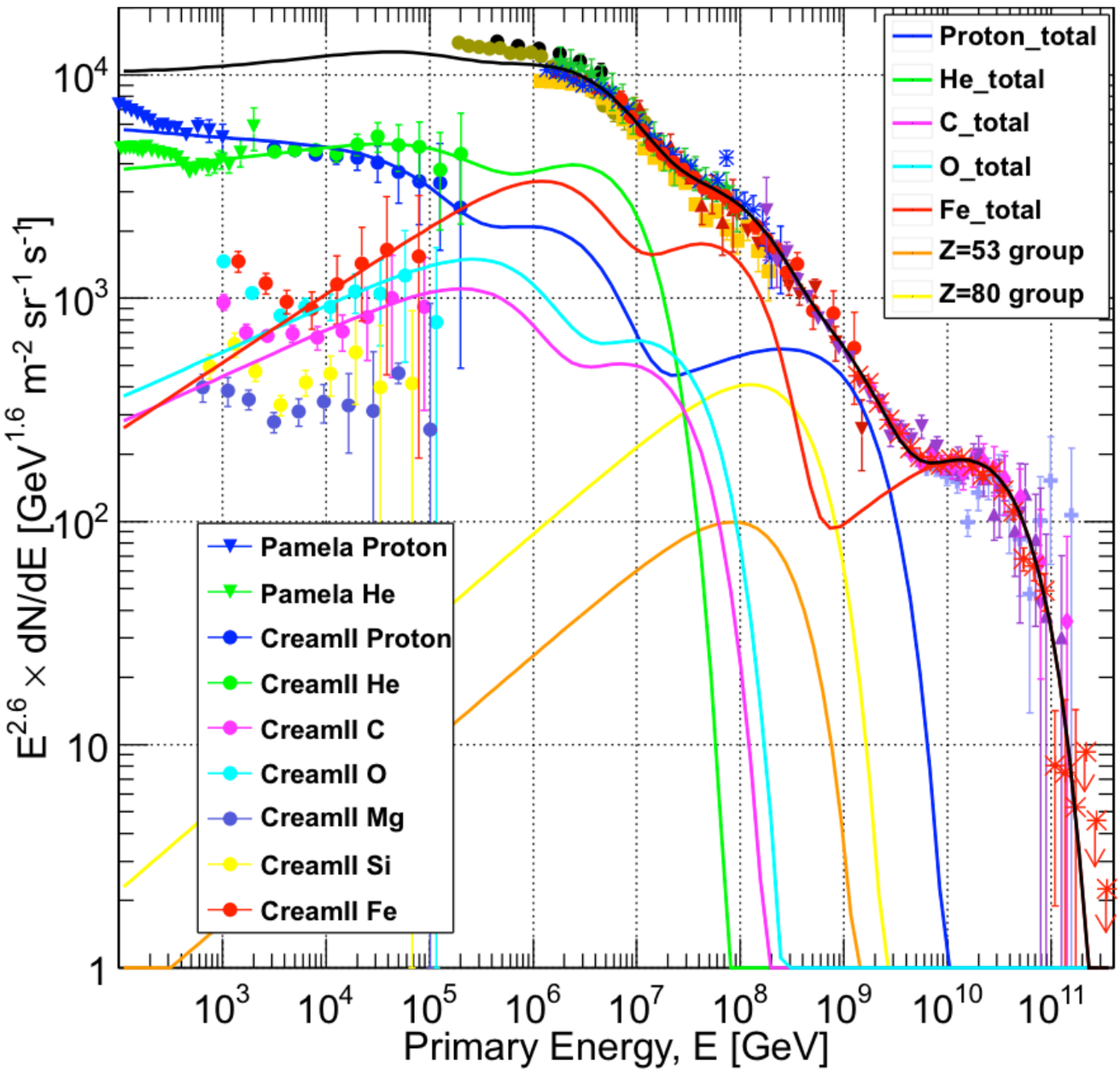
Richard Mewaldt (Caltech)
George Gloeckler & Glenn Mason (University of Maryland)



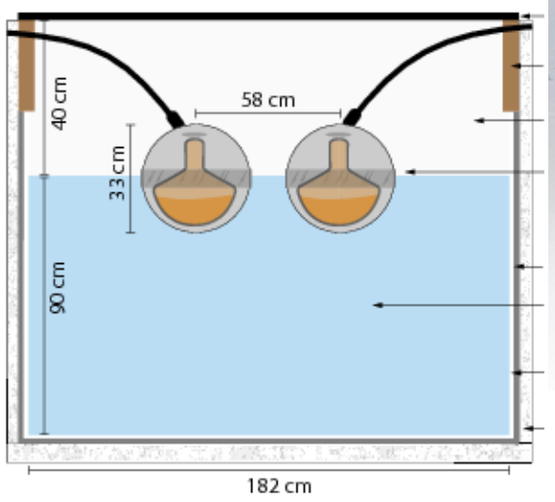
cosmic ray observations
spectral shape and their history

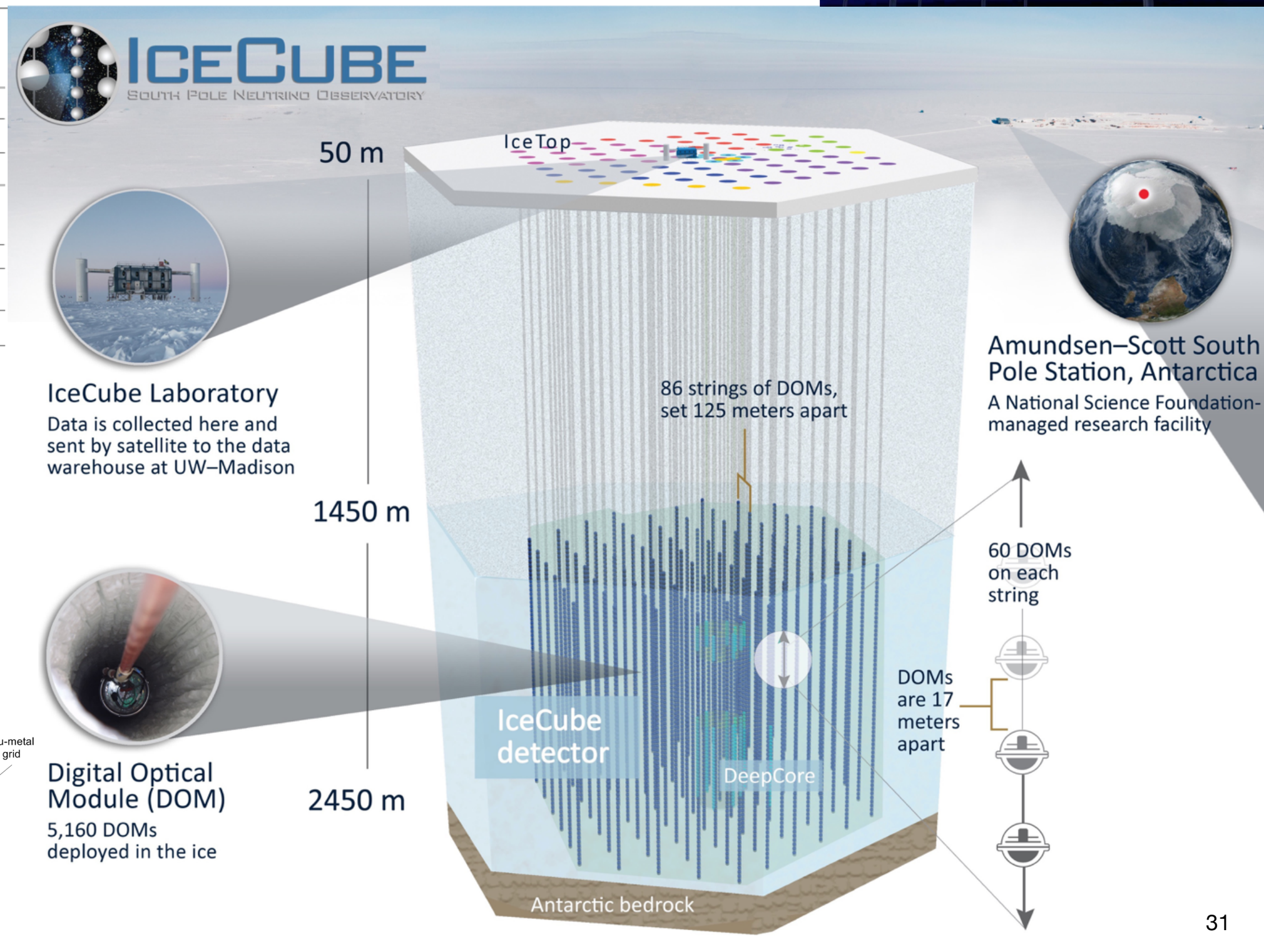
- **galactic** cosmic rays produced below 10^8-10^9 GeV
- **spectral features** from acceleration mechanisms & propagation effects
- **property & distribution of sources** in Galaxy and our neighborhood
- **magnetic field** configurations in local interstellar medium: turbulence & escape
- **anisotropy**

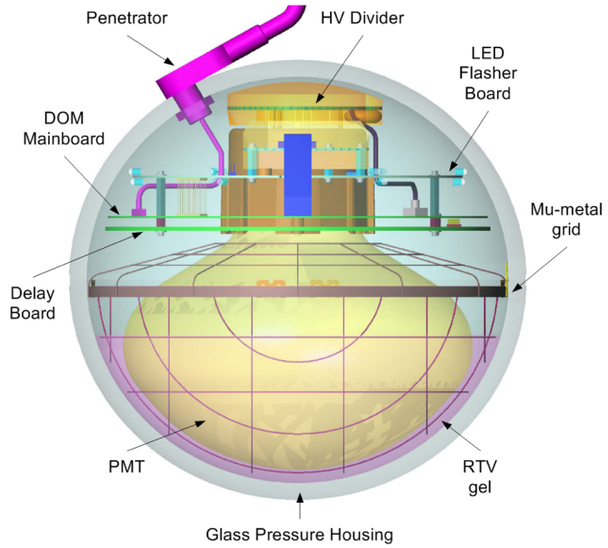
Gaisser, Stanev, Tilav, 2013 - arXiv:1303.3565



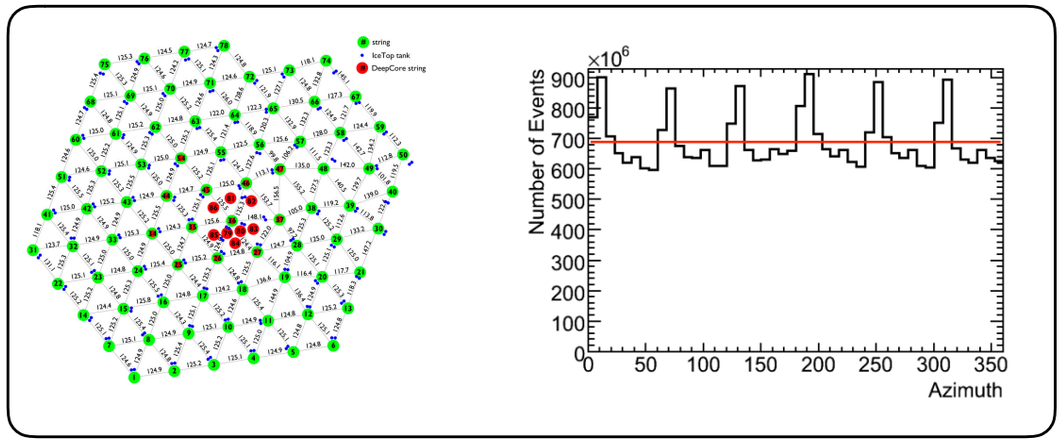
IceCube Observatory
the instrumentation



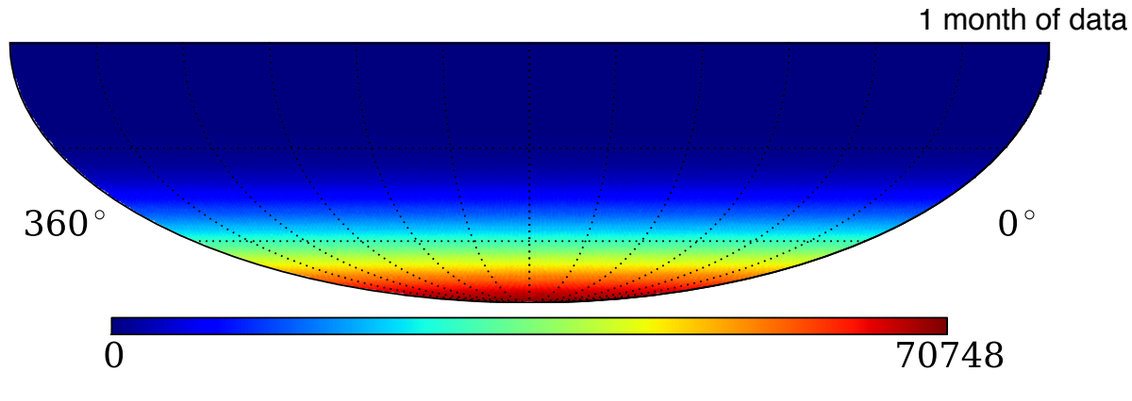




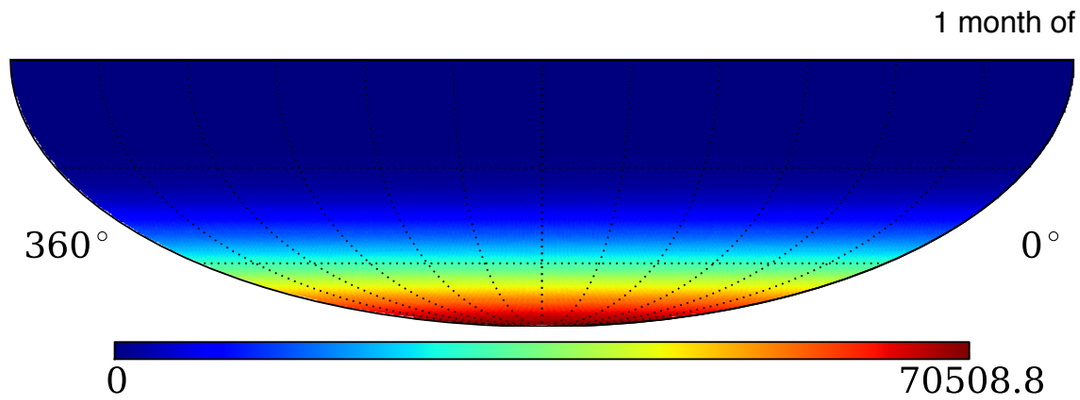
cosmic rays anisotropy
arrival direction distribution



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

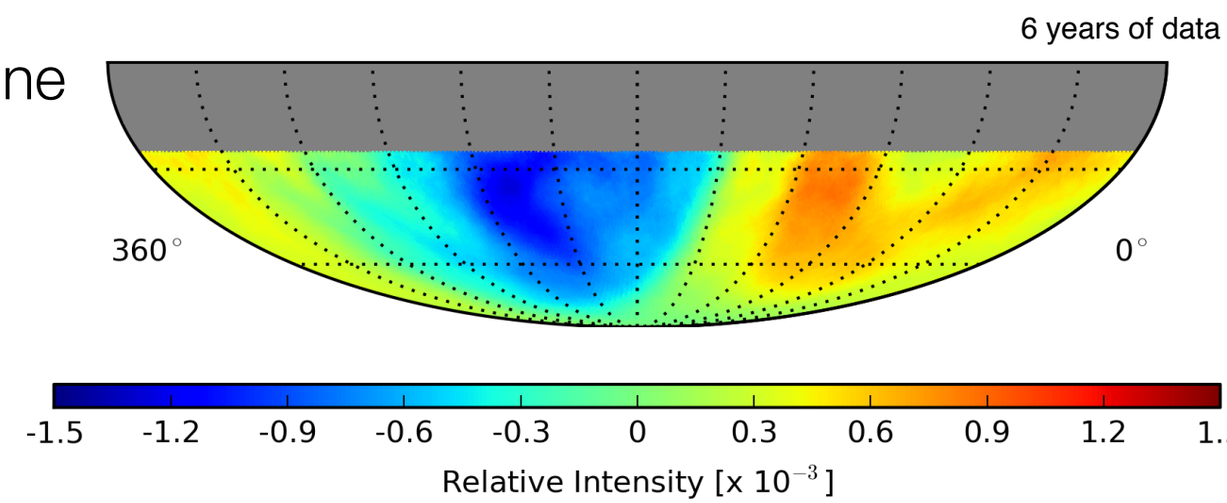


reference map from events scrambled over 24hr in α (or time)

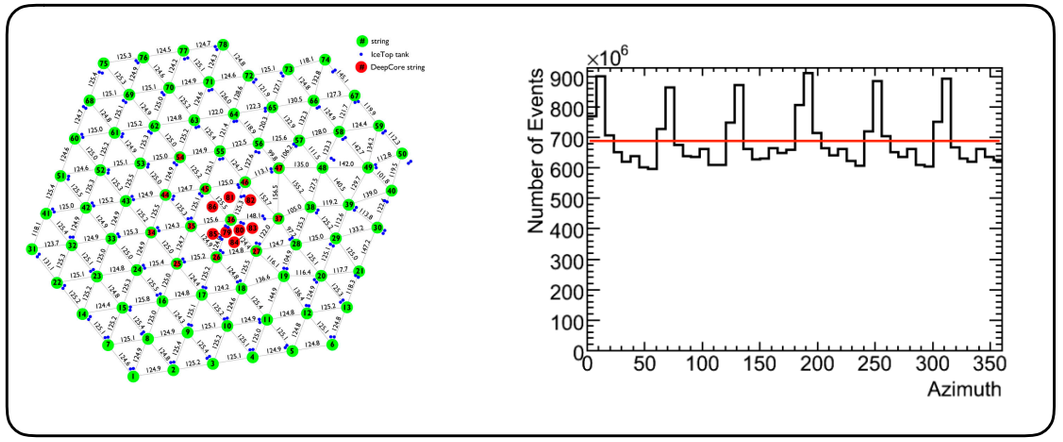


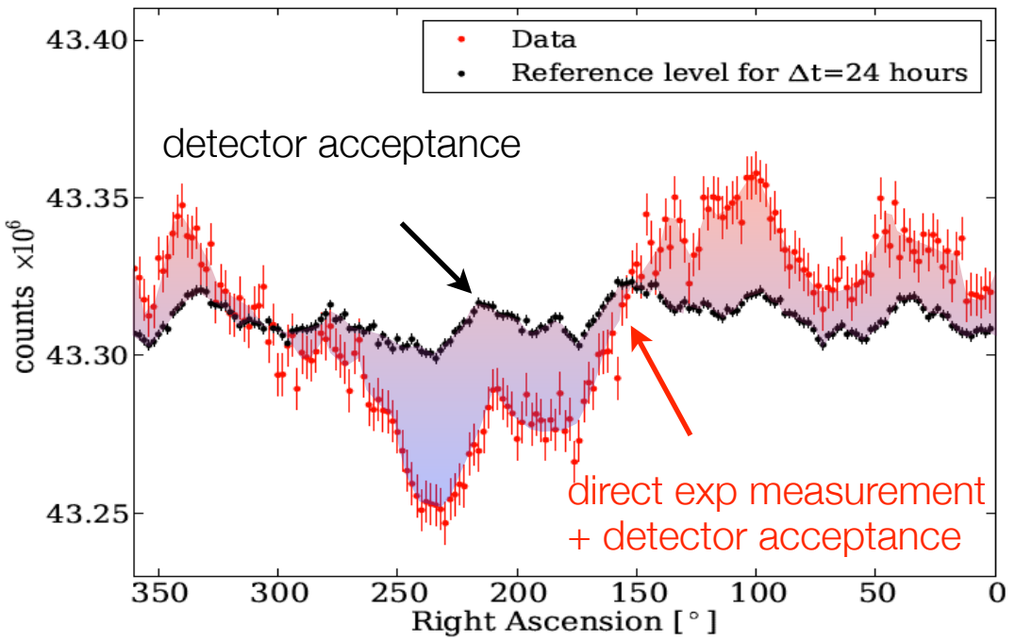
subtract reference map from raw map to determine the residual *relative intensity* map

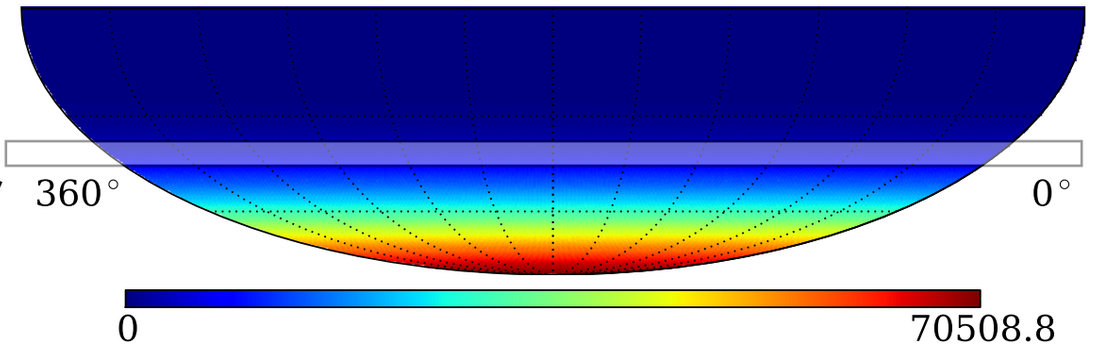
$$\frac{\Delta I}{\langle I \rangle} \equiv \frac{N_i - \langle N \rangle}{\langle N \rangle}$$



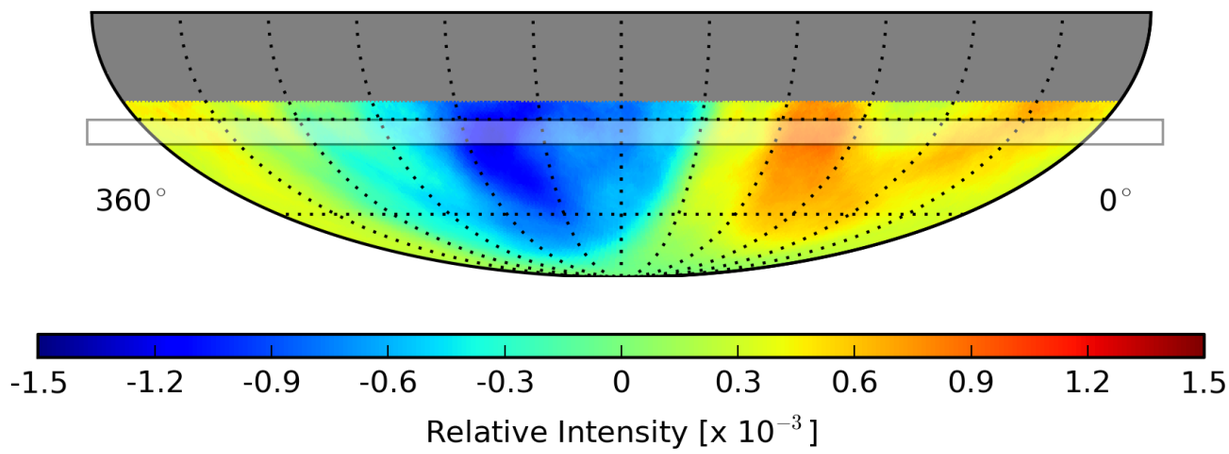
cosmic rays anisotropy
arrival direction distribution



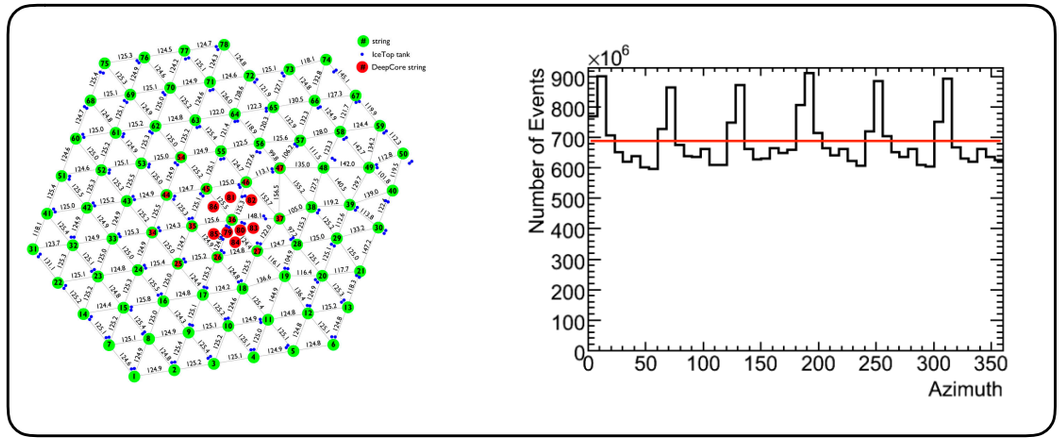




$$\frac{\Delta I}{\langle I \rangle} \equiv \frac{N_i - \langle N \rangle}{\langle N \rangle}$$



cosmic rays anisotropy
arrival direction distribution

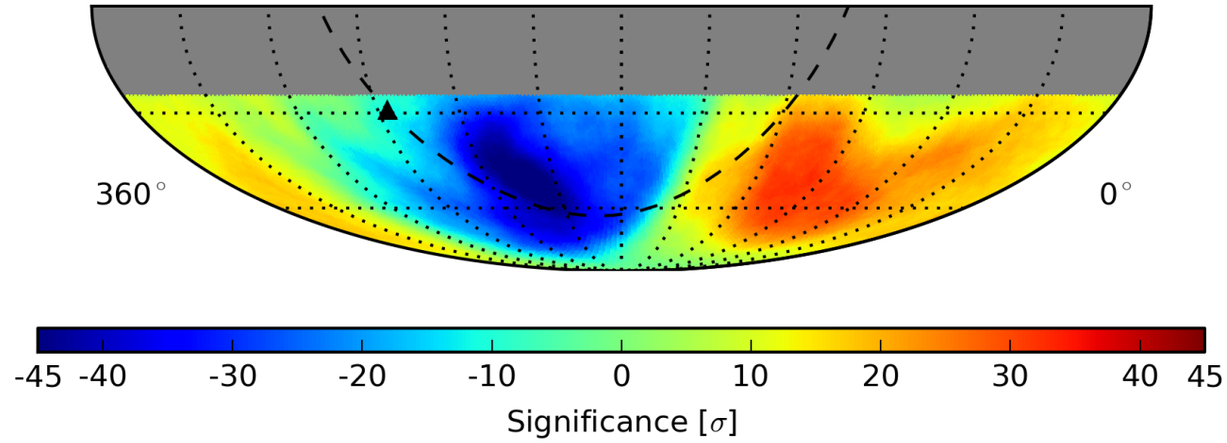


$$s = \sqrt{2}\left\{ N_{\mathrm{on}} \ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\mathrm{on}}}{N_{\mathrm{on}}+N_{\mathrm{off}}}\right)\right] + N_{\mathrm{off}} \ln\left[(1+\alpha)\left(\frac{N_{\mathrm{off}}}{N_{\mathrm{on}}+N_{\mathrm{off}}}\right)\right]\right\}^{1/2} \qquad \alpha = 1/20$$

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

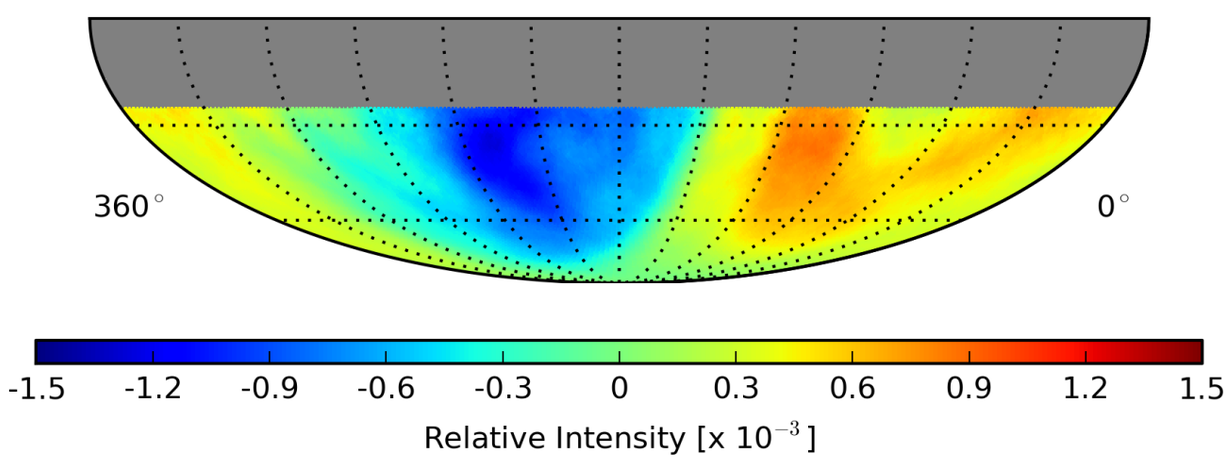
IceCube - Aartsen et al., 2016

statistical significance

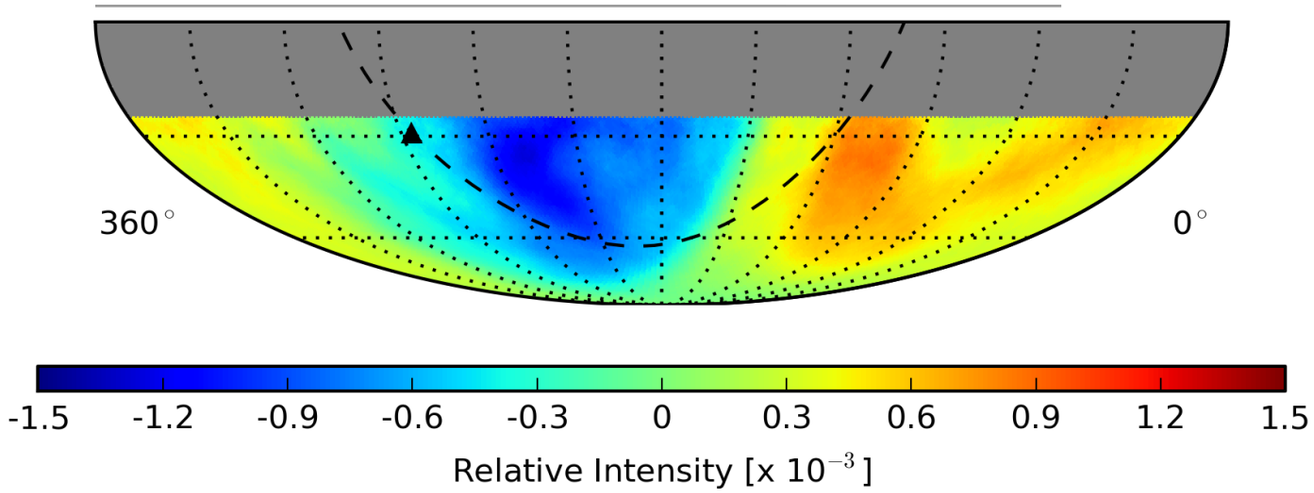


relative intensity

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

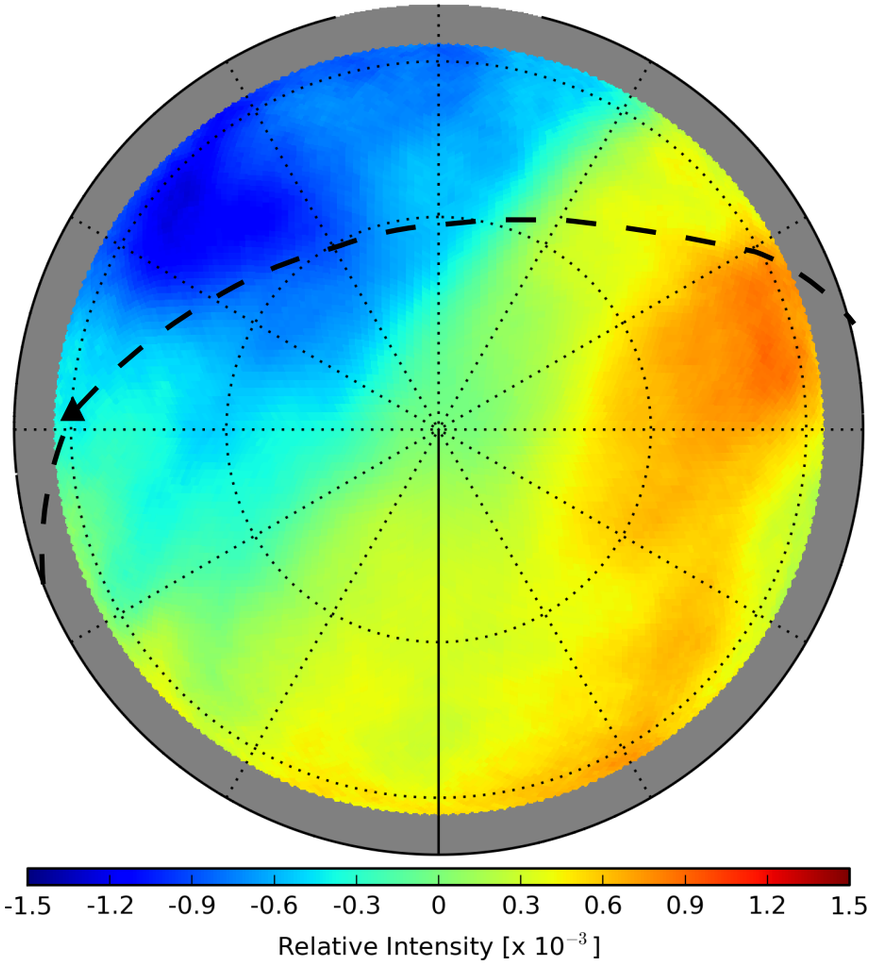


cosmic rays anisotropy
energy dependence



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

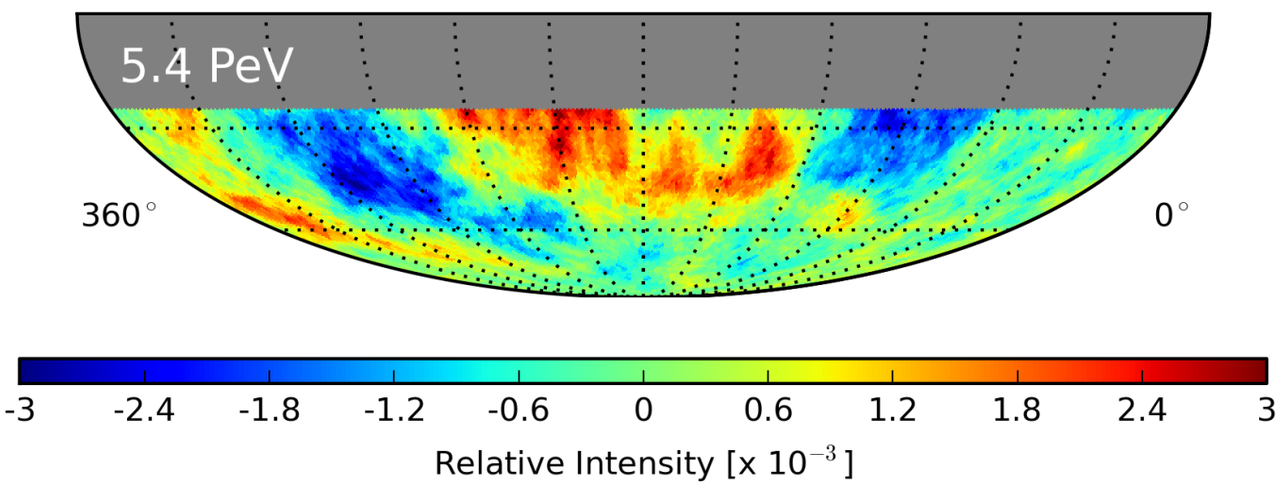
- 6 years of IceCube
- 300 billion events

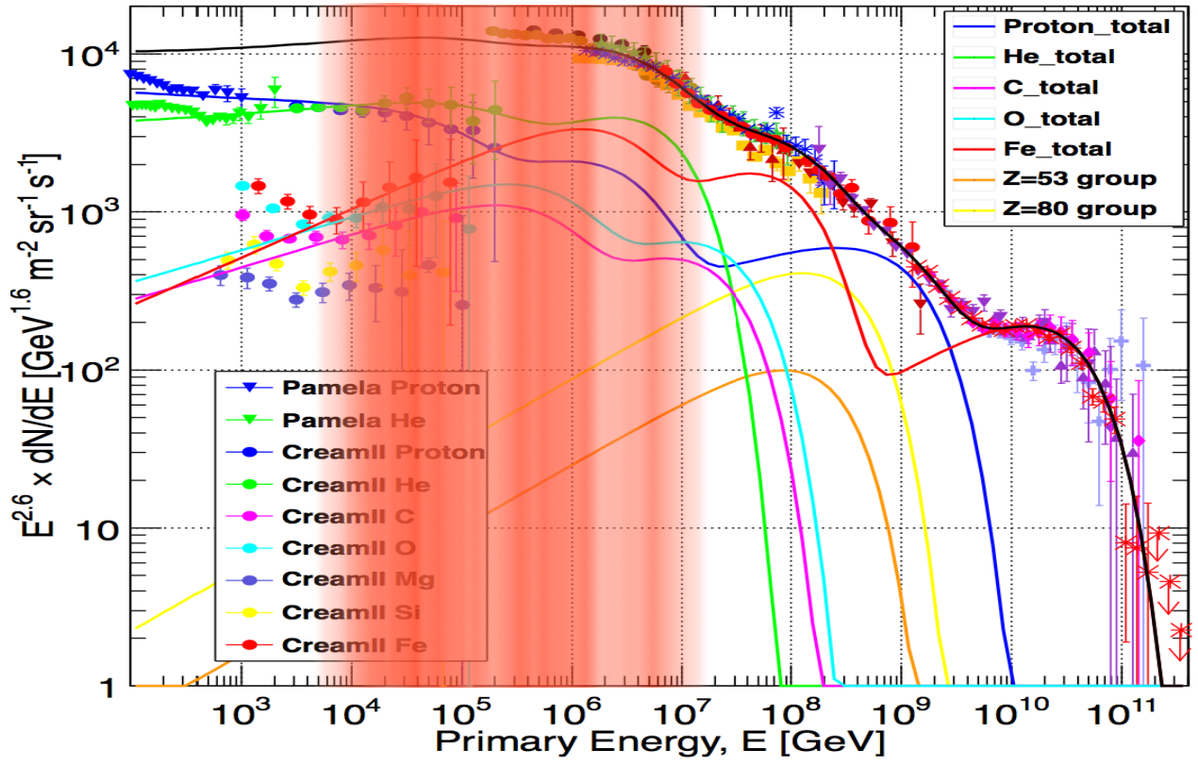


- anisotropy on the level of 10^{-3}
- median cosmic ray energy **20 TeV**
- trace sources ? Magnetic fields ?

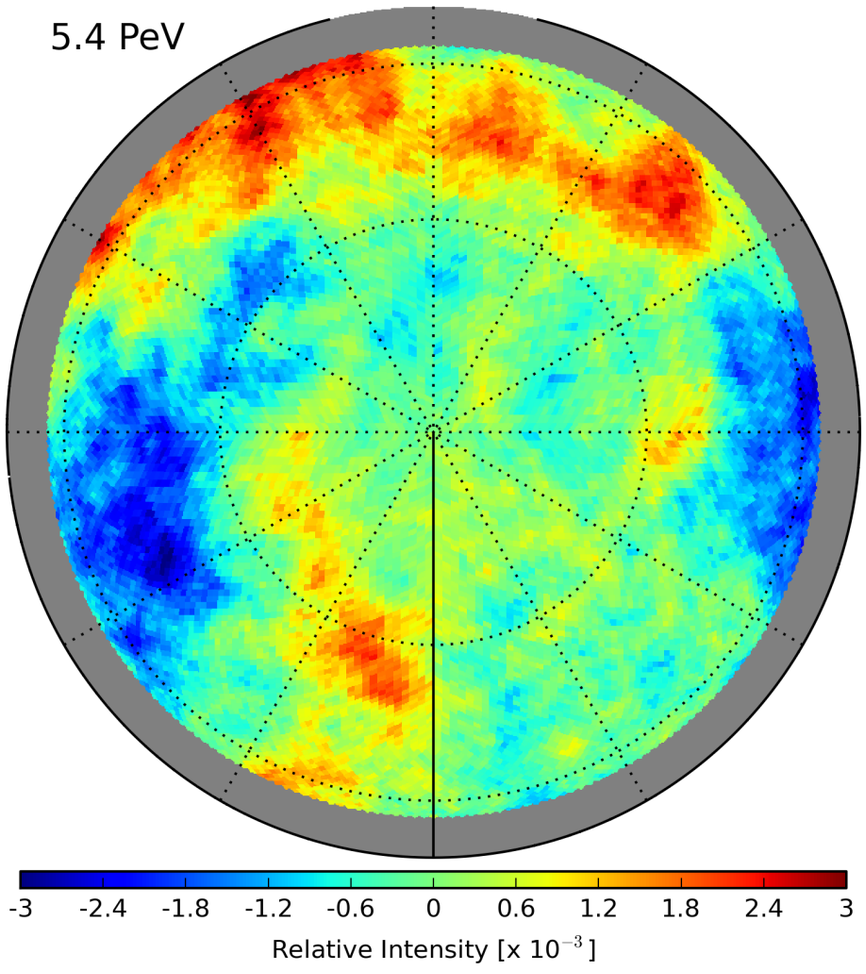
cosmic rays anisotropy

energy dependence





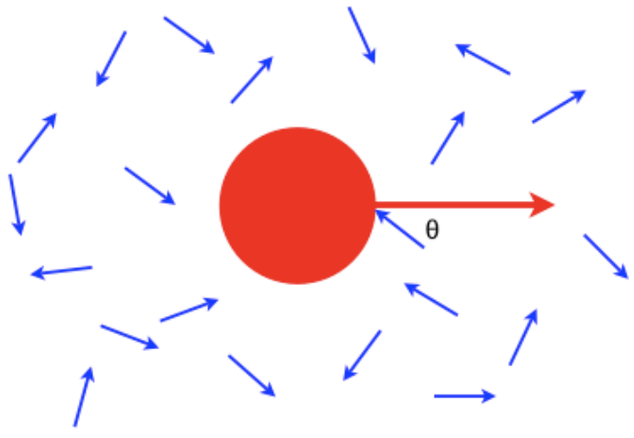
5.4 PeV **IceTop**



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

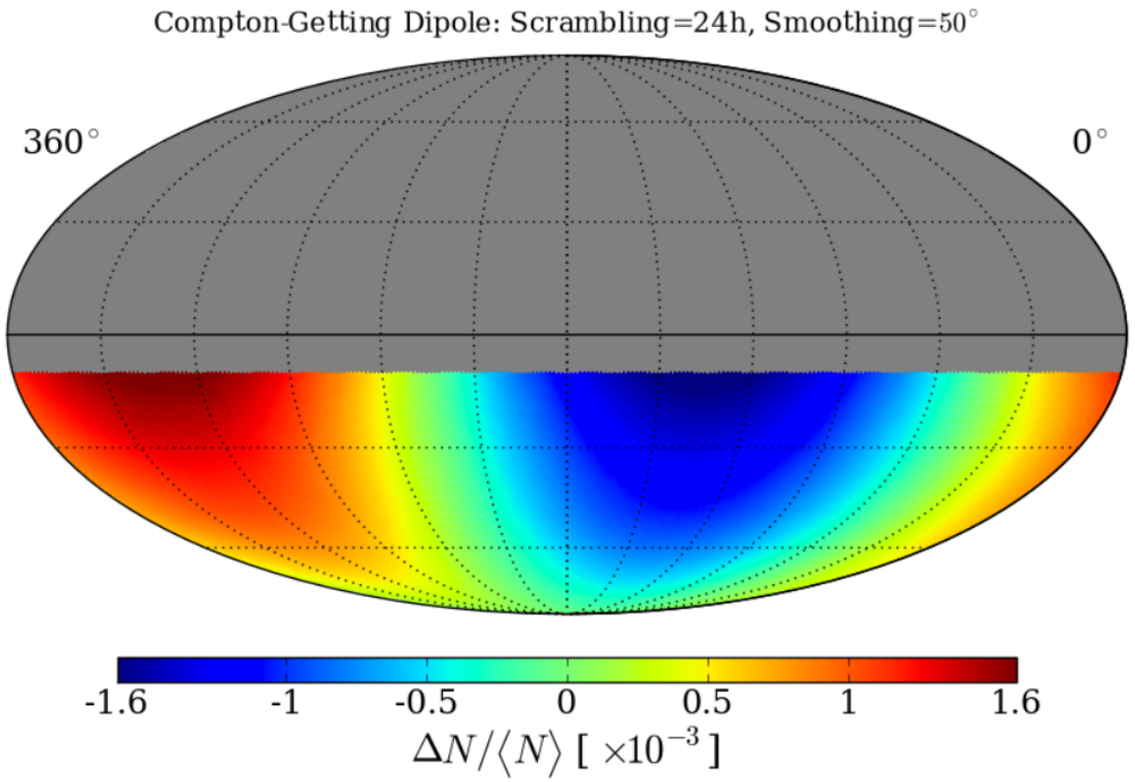
origin of large scale anisotropy
Compton-Getting Effect ?

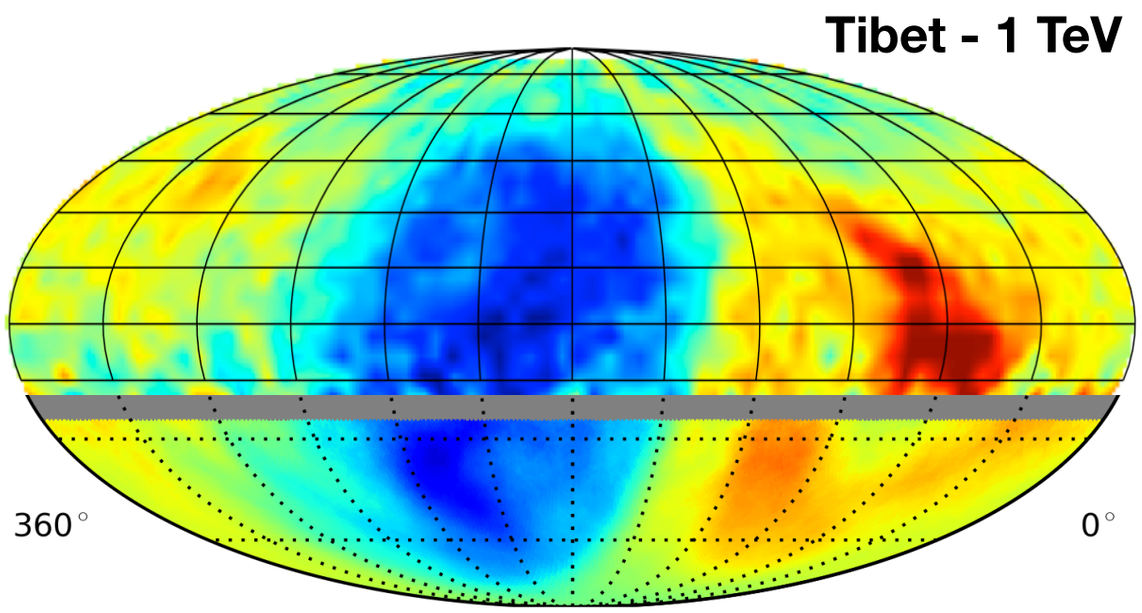
Compton & Getting, Phys. Rev. 47, 817 (1935)
Gleeson, & Axford, Ap&SS, 2, 43 (1968)



- 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

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

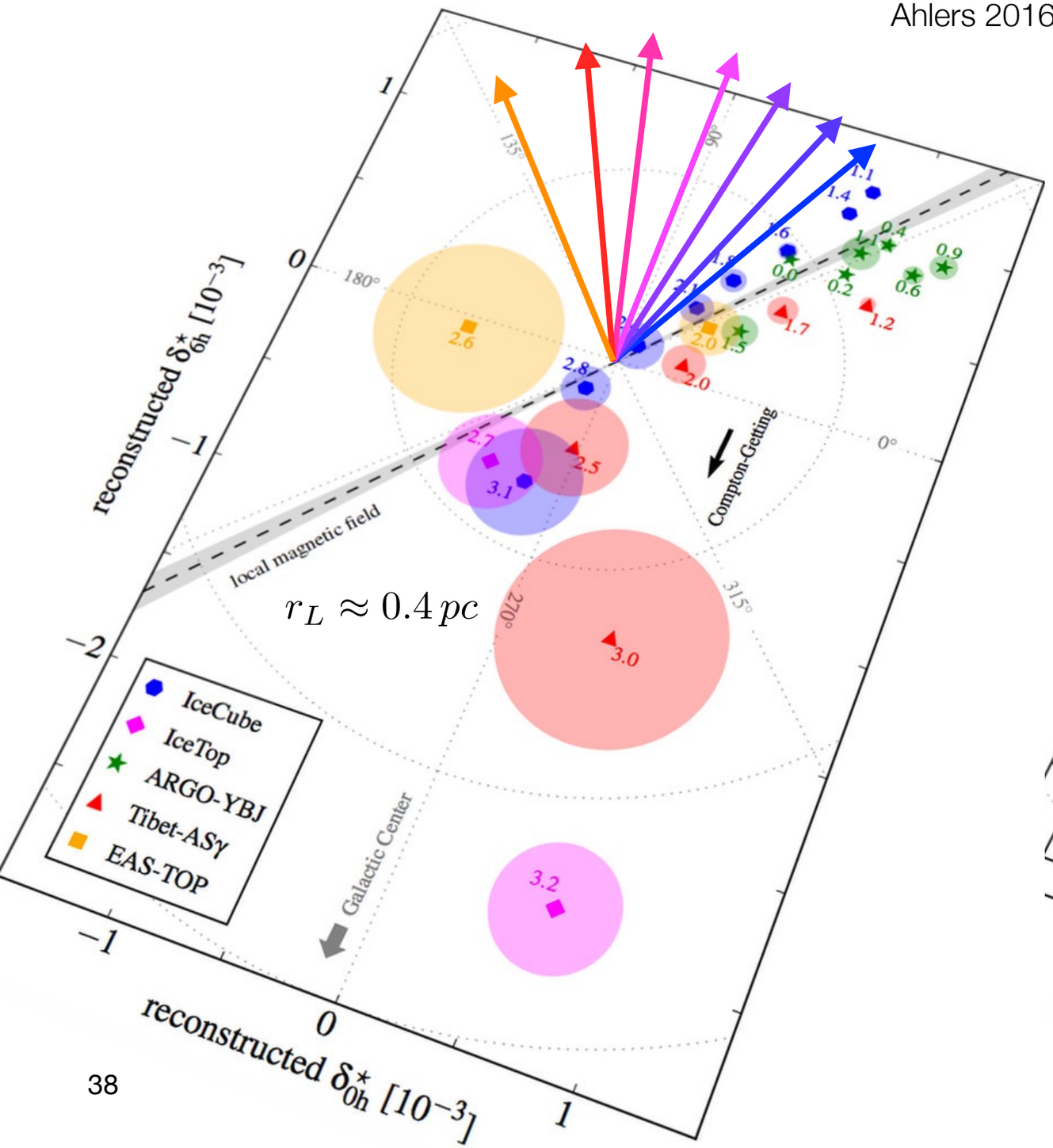


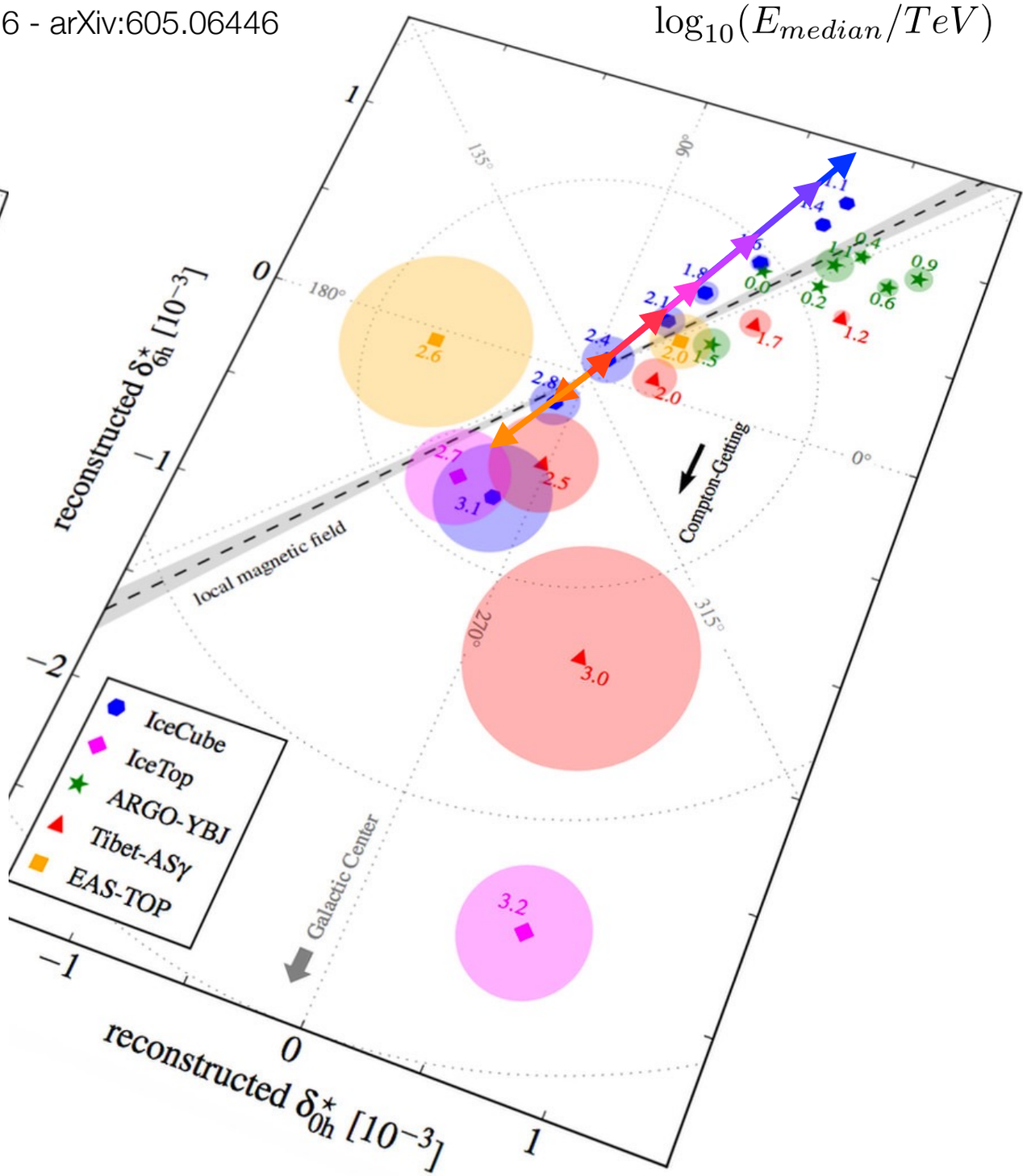


measuring cosmic ray anisotropy

what is the missing information ?

Ahlers 2016 - arXiv:605.06446

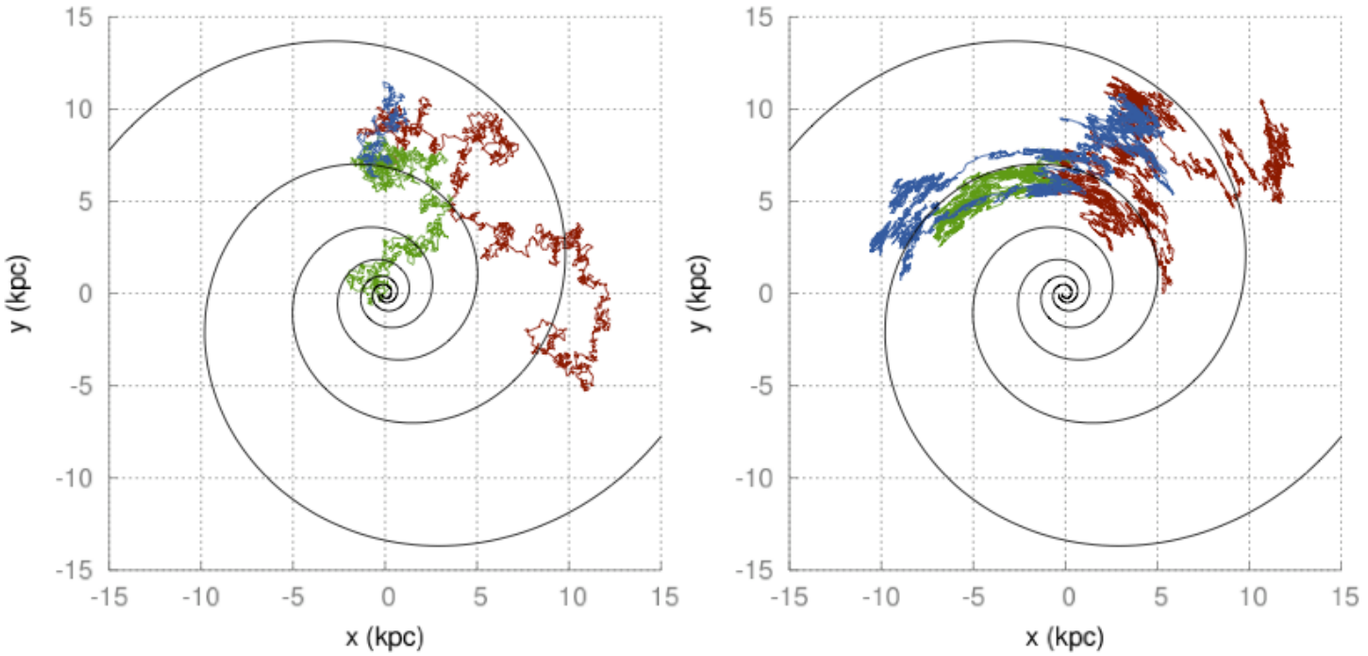




cosmic ray anisotropy
probing diffusion properties

anisotropic diffusion

Effenberger+, 2012

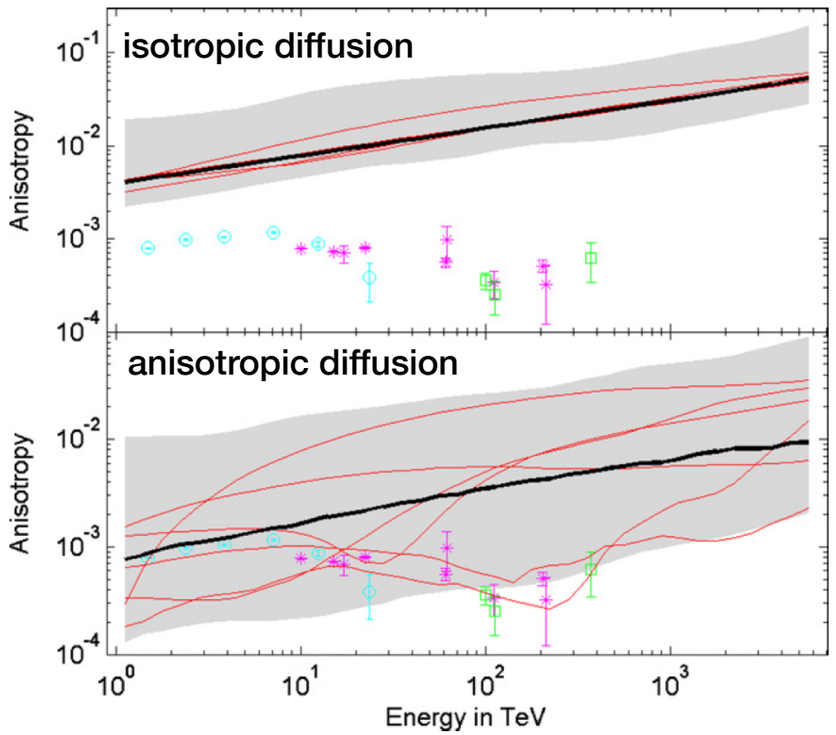


- $D_{\perp}/D_{\parallel} << 1$ - parallel projection of anisotropy

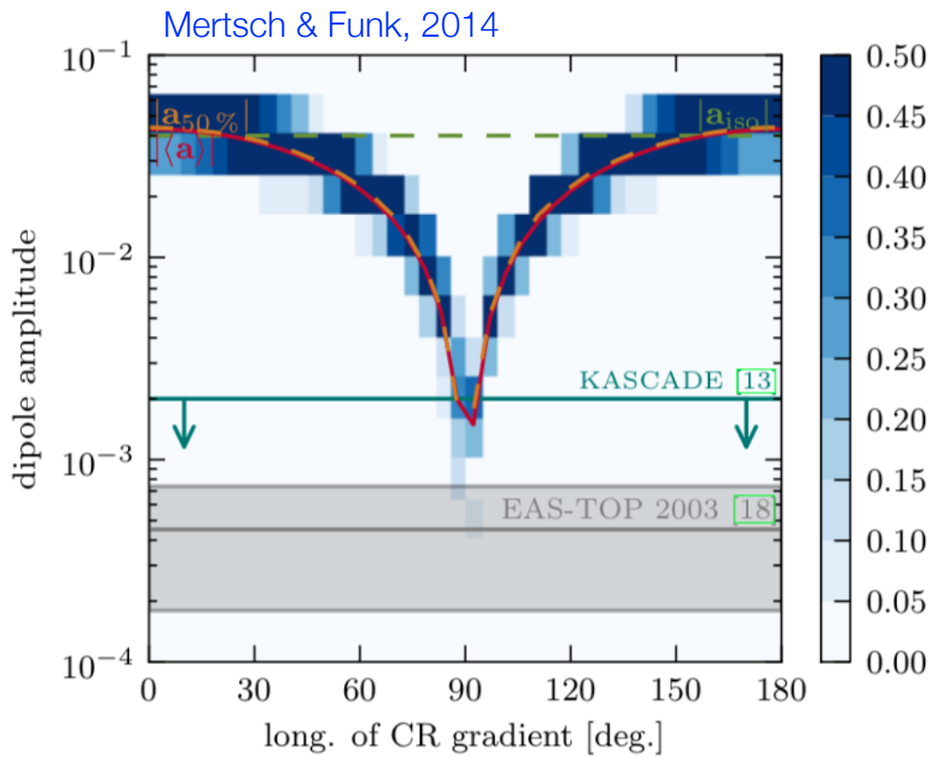
- cosmic ray **sources concealed** by propagation effects

diffusion coefficient hardly a single power law, homogeneous and isotropic

Kumar & Eichler, 2014



Mertsch & Funk, 2014

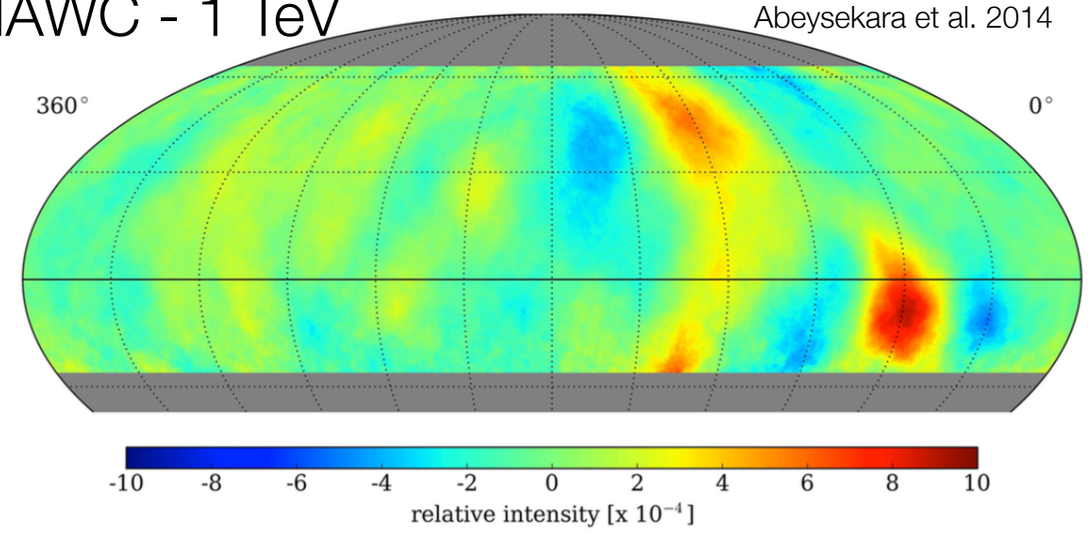


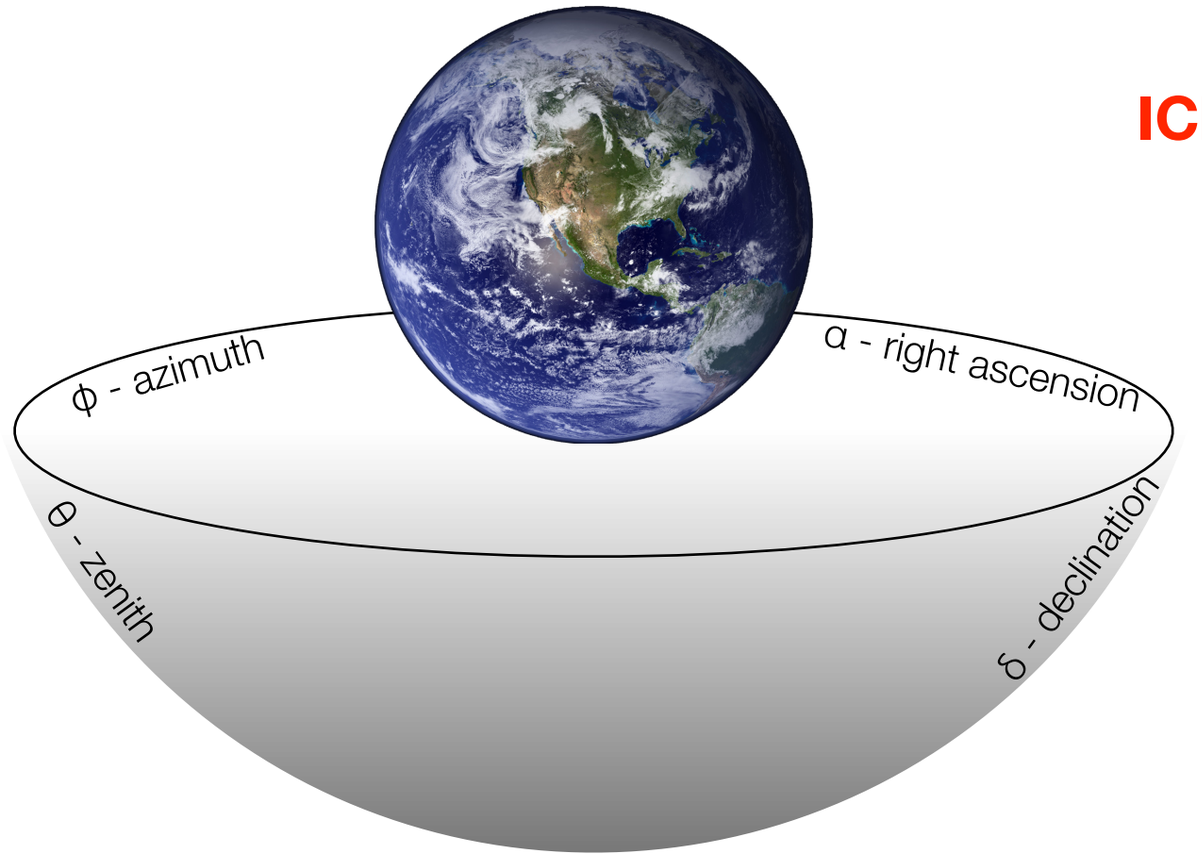
cosmic rays anisotropy

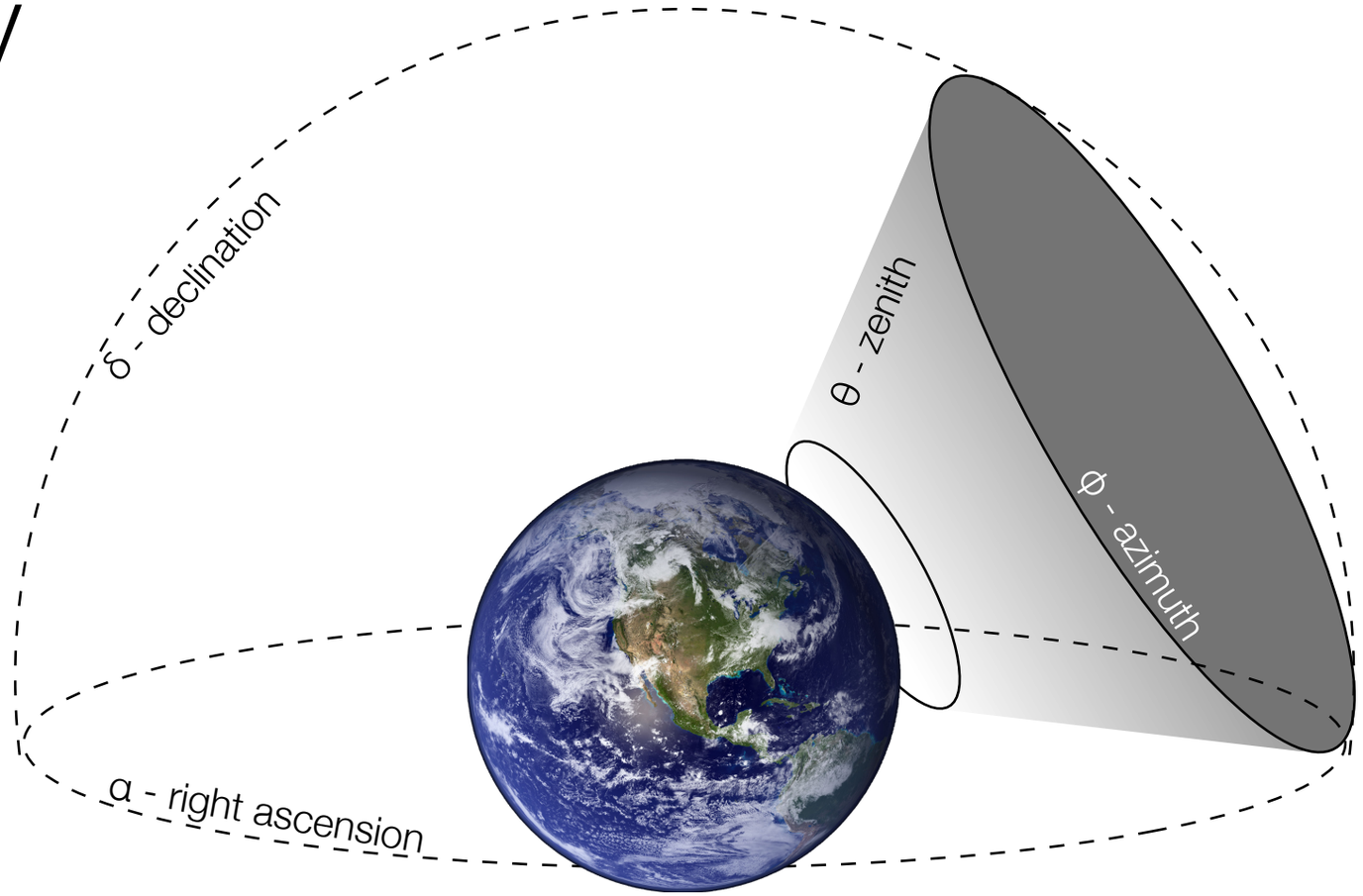
full-sky coverage

HAWC - 1 TeV

small scale anisotropy
Abeysekara et al. 2014



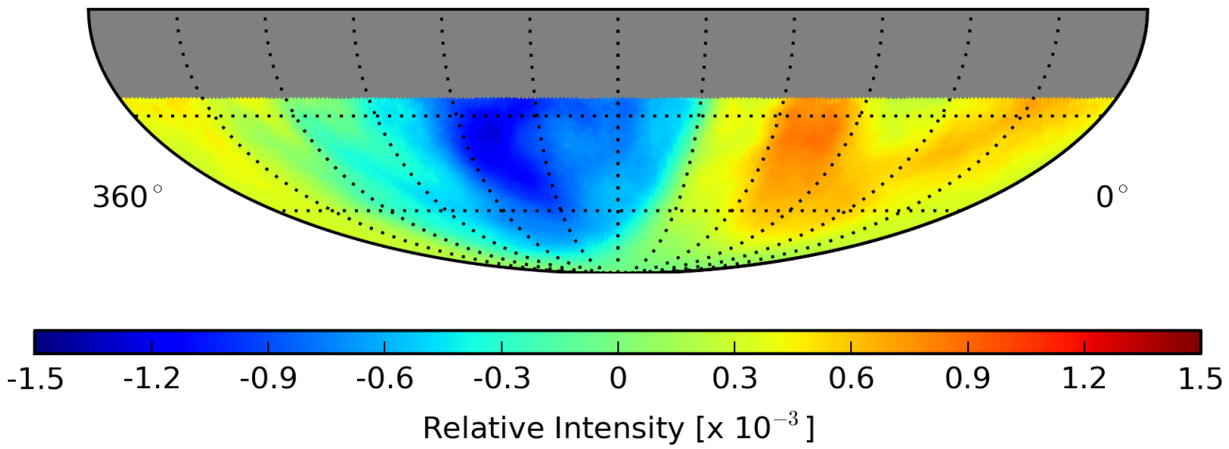




ICRC 2015

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

IceCube - 20 TeV



cosmic ray anisotropy

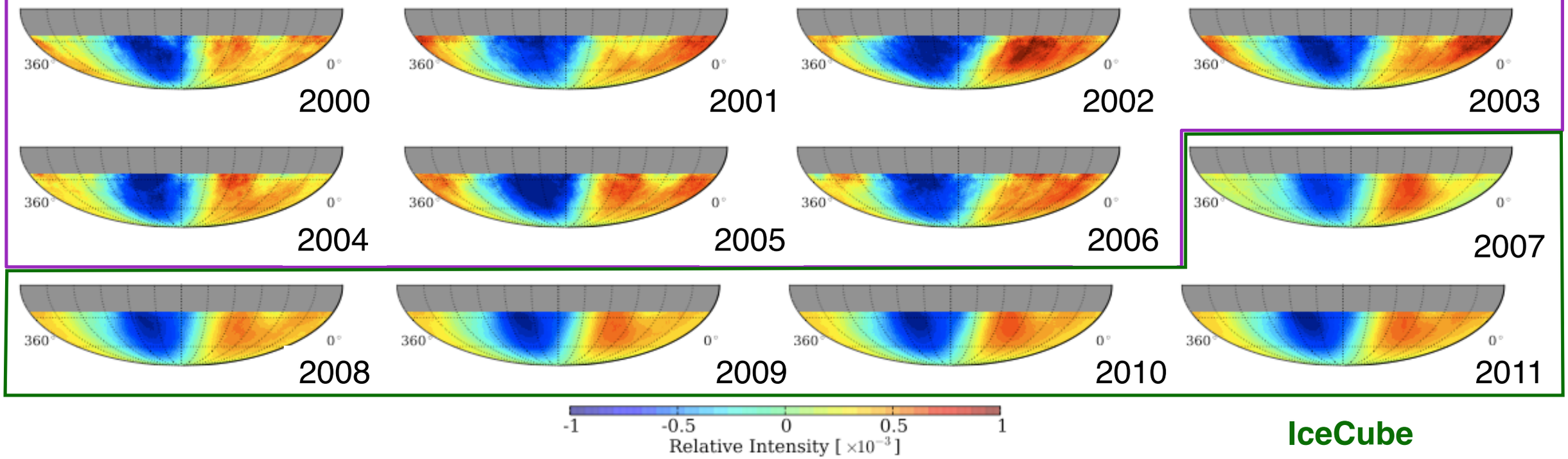
AMANDA-IceCube 2000-2011

ICRC 2013

20 TeV

relative intensity equatorial coordinates

AMANDA



IceCube

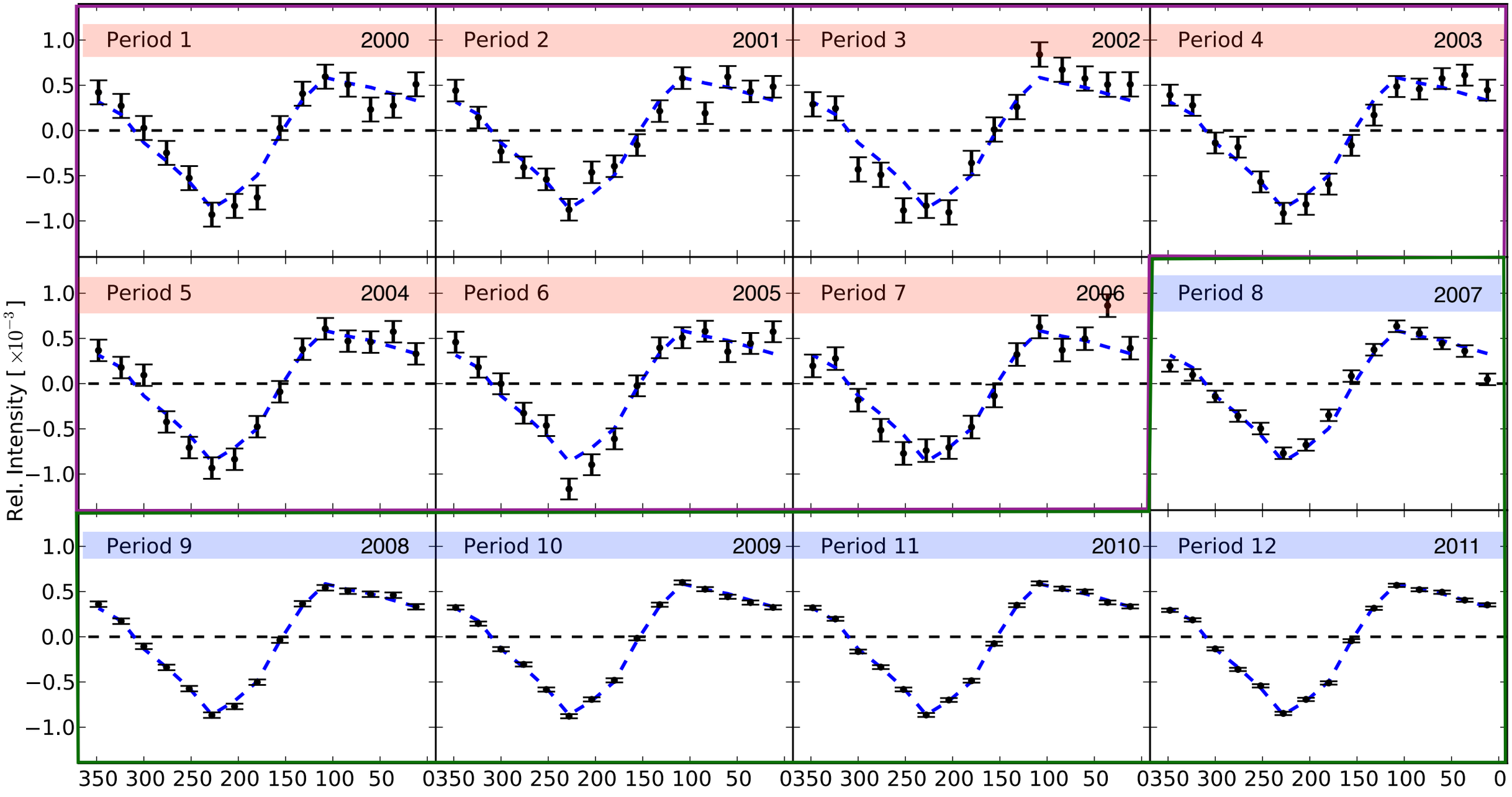
- AMANDA and IceCube yearly data show long **time-scale stability** of global anisotropy within statistical uncertainties
  - no apparent effect correlated to solar cycles

cosmic ray anisotropy stability

AMANDA-IceCube 2000-2011

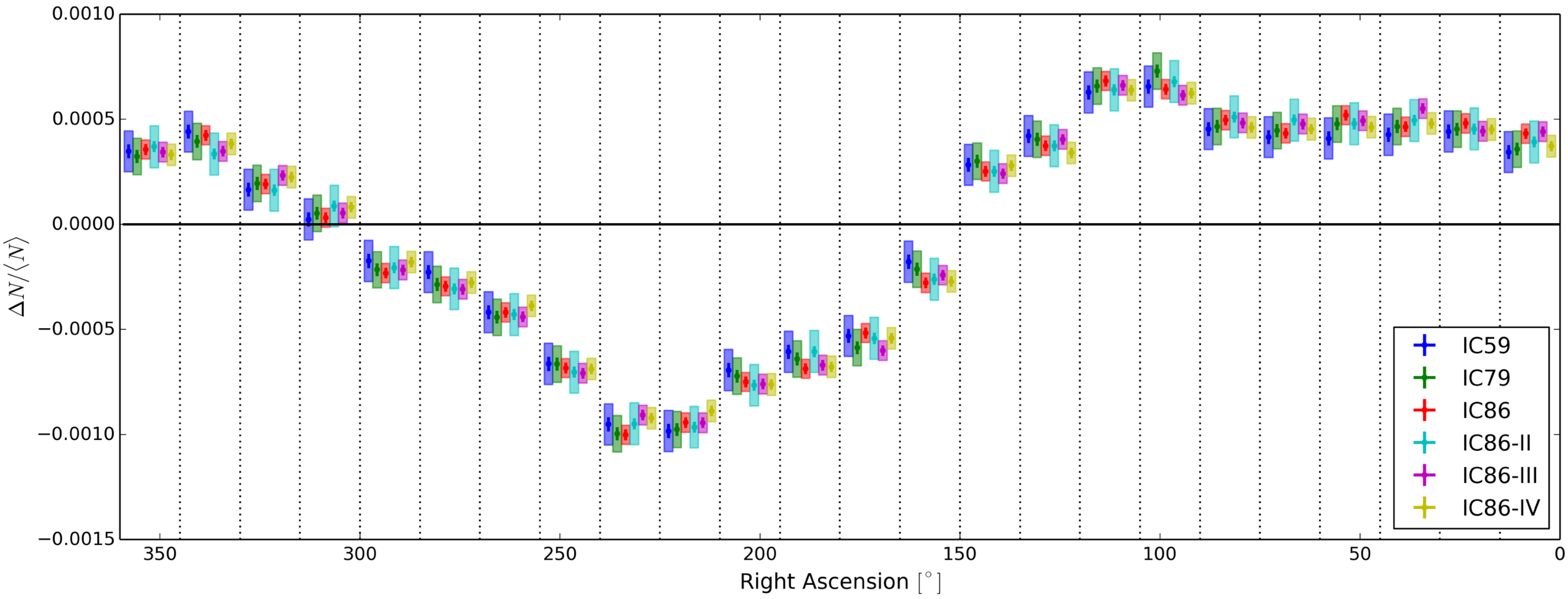
ICRC 2013

20 TeV



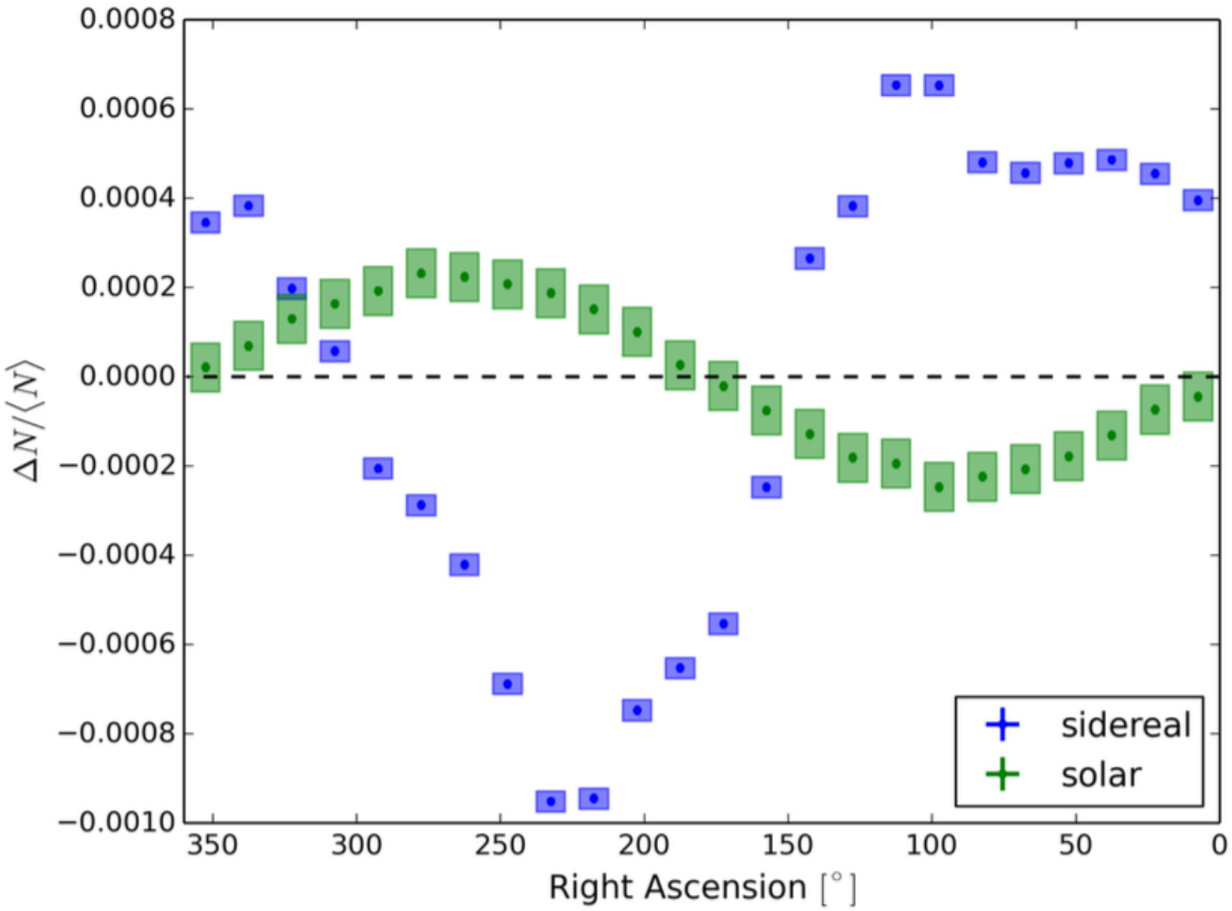
cosmic rays anisotropy stability

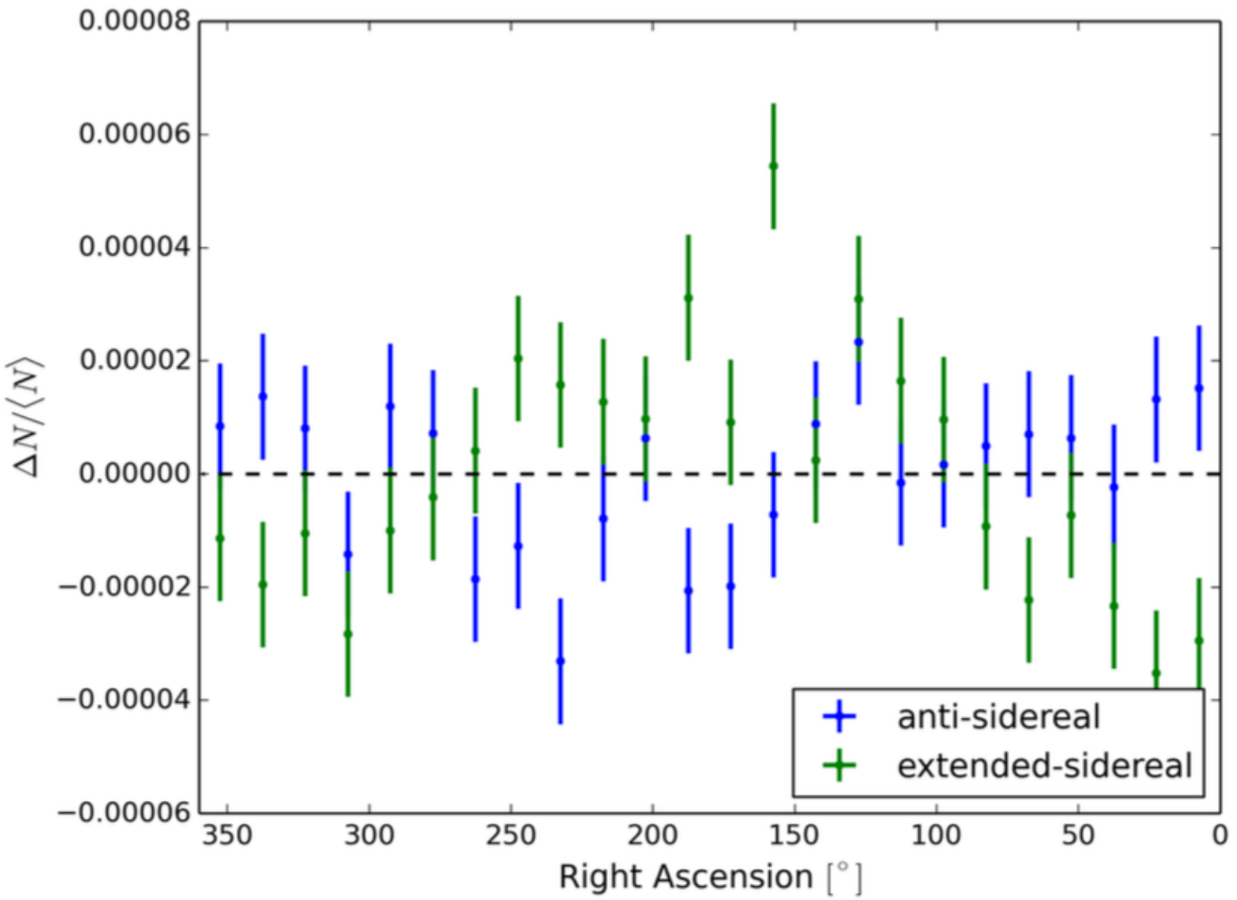
IceCube 2009-2014



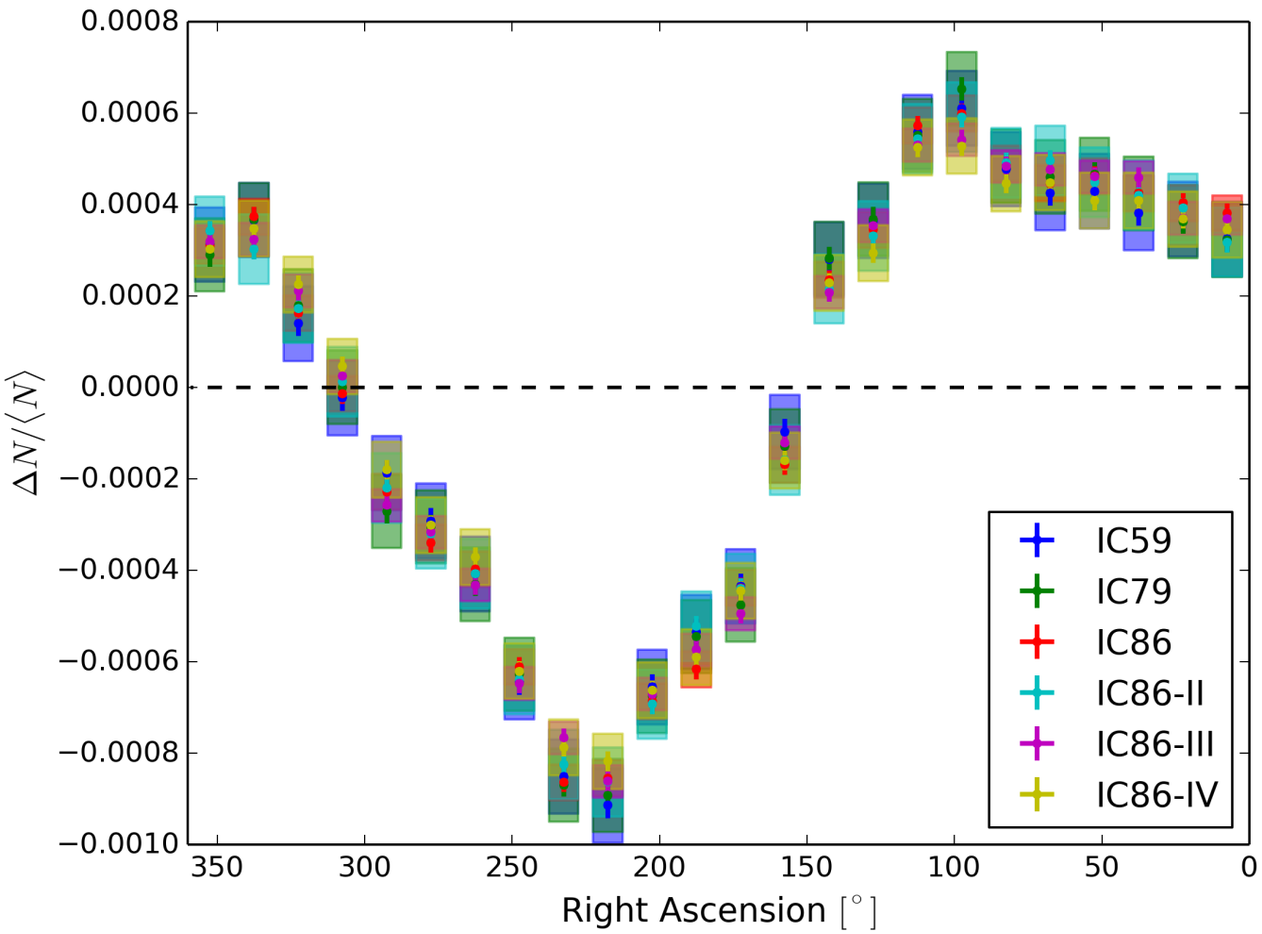
systematics studies

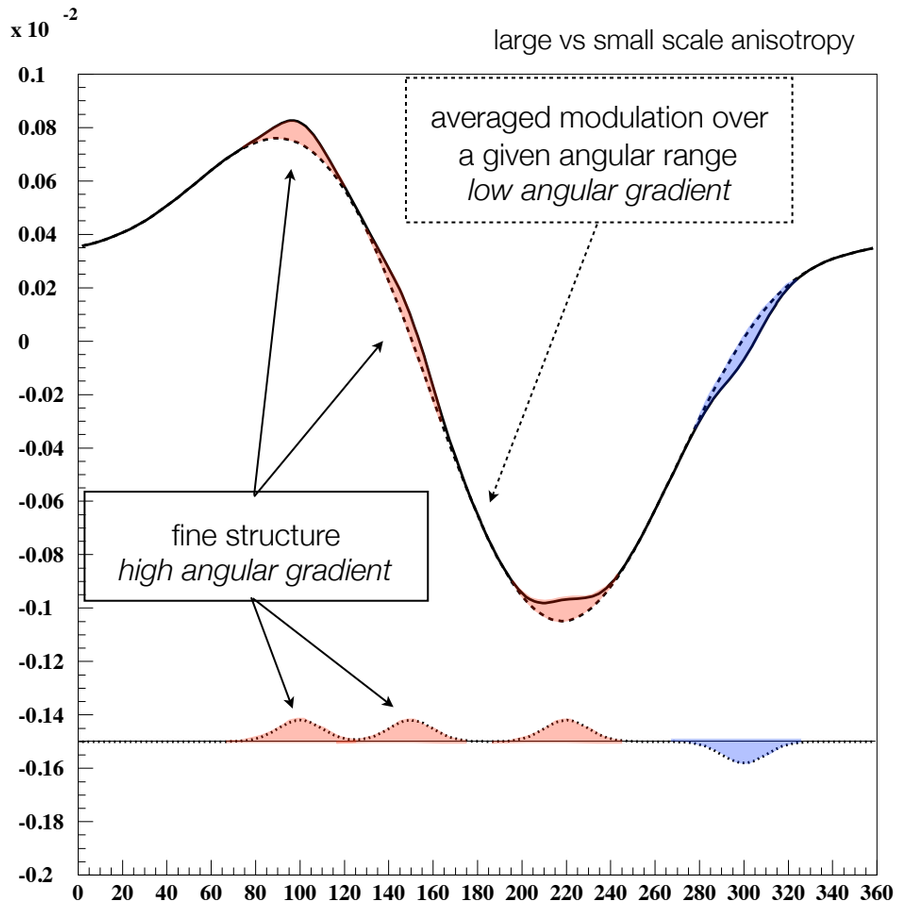
anti-/extended-sidereal time references

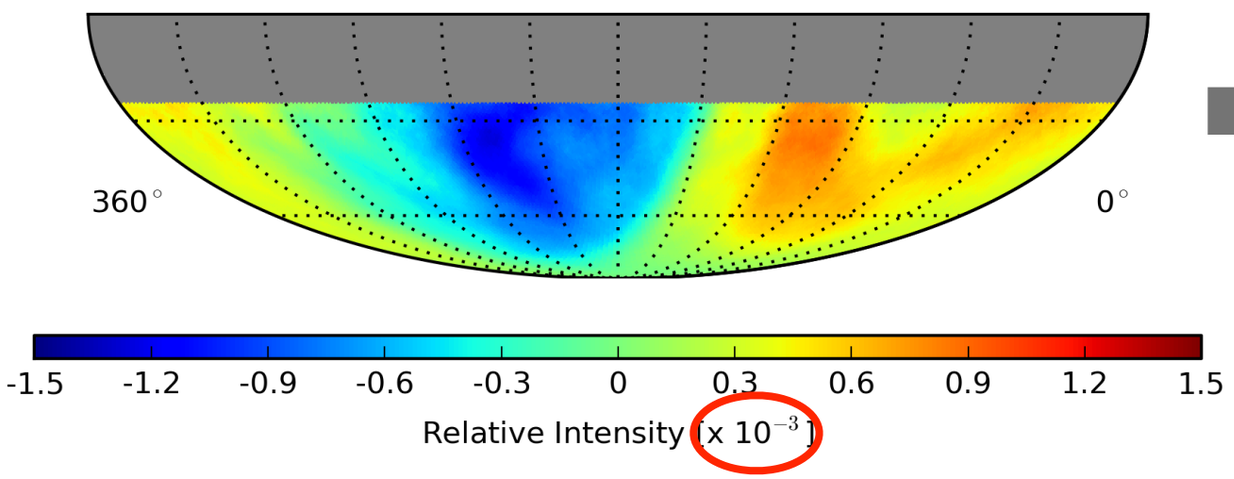


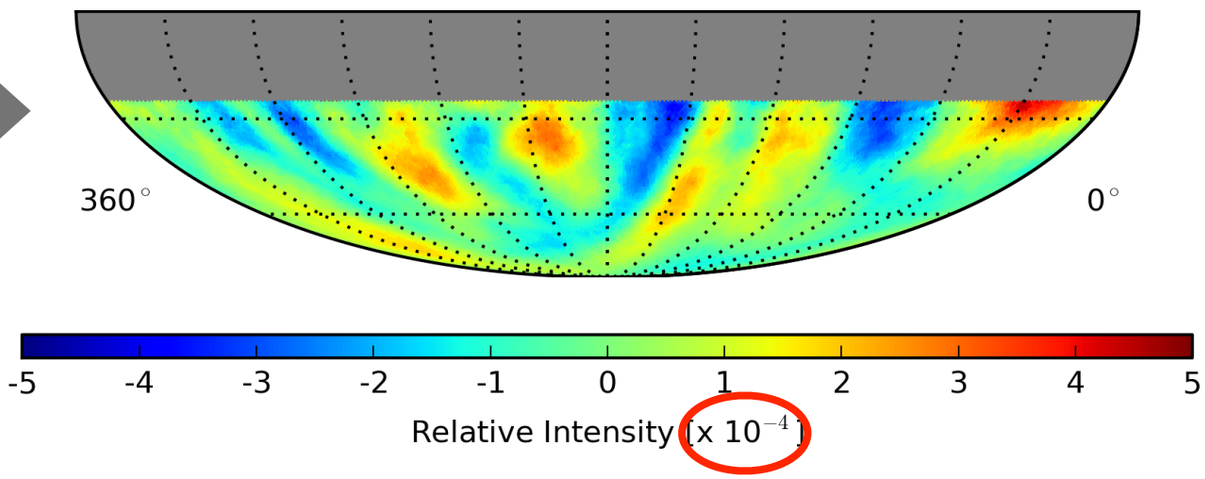


cosmic rays anisotropy
large and small angular scale





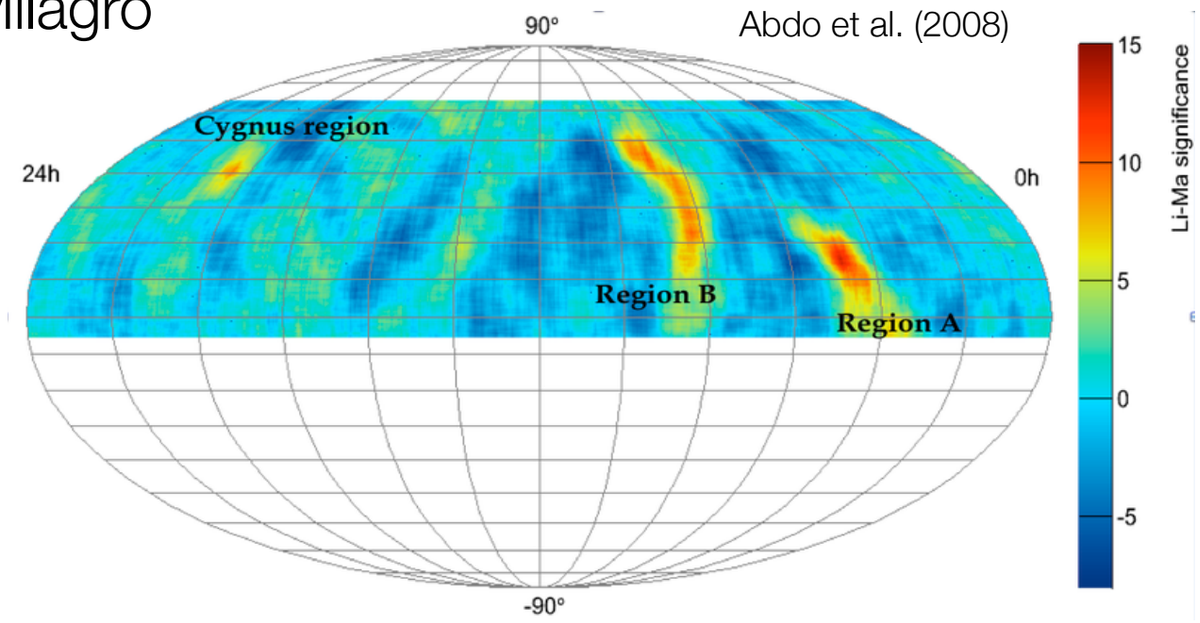




high energy cosmic rays
anisotropy & energy spectrum

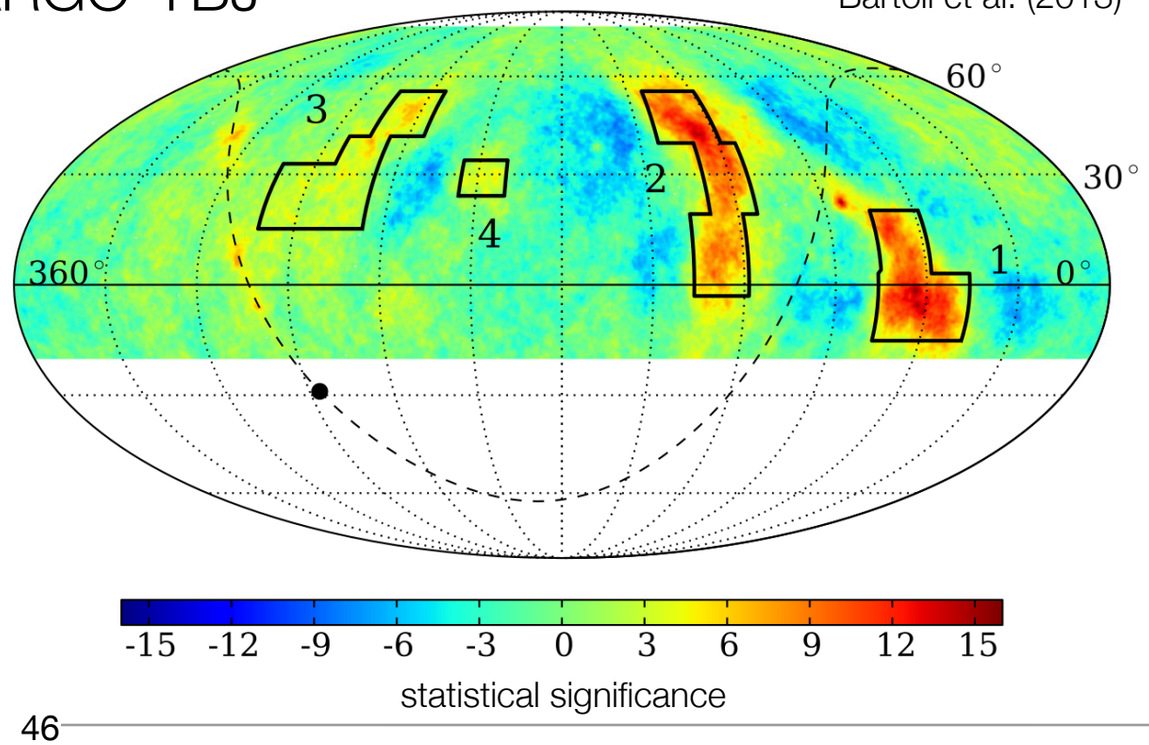
Milagro

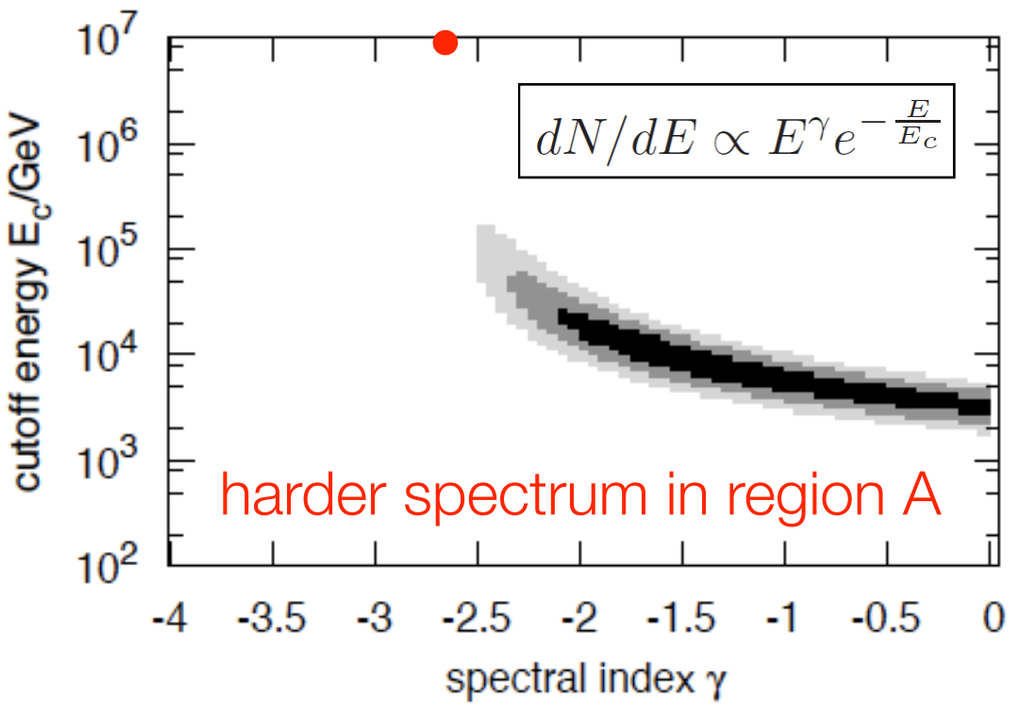
Abdo et al. (2008)

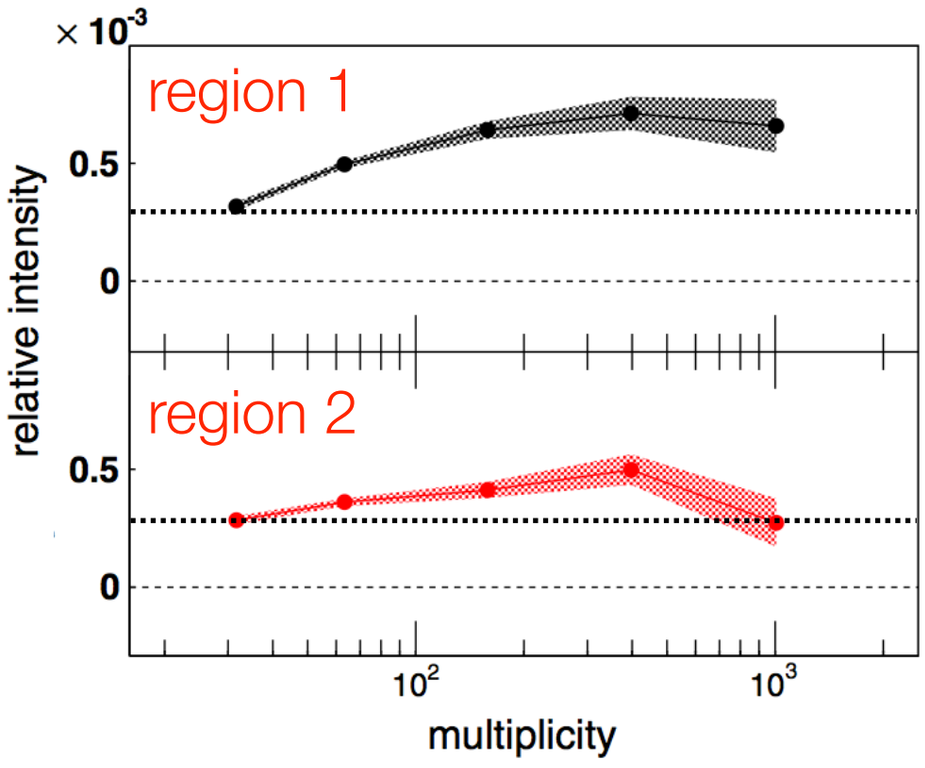


ARGO-YBJ

Bartoli et al. (2013)



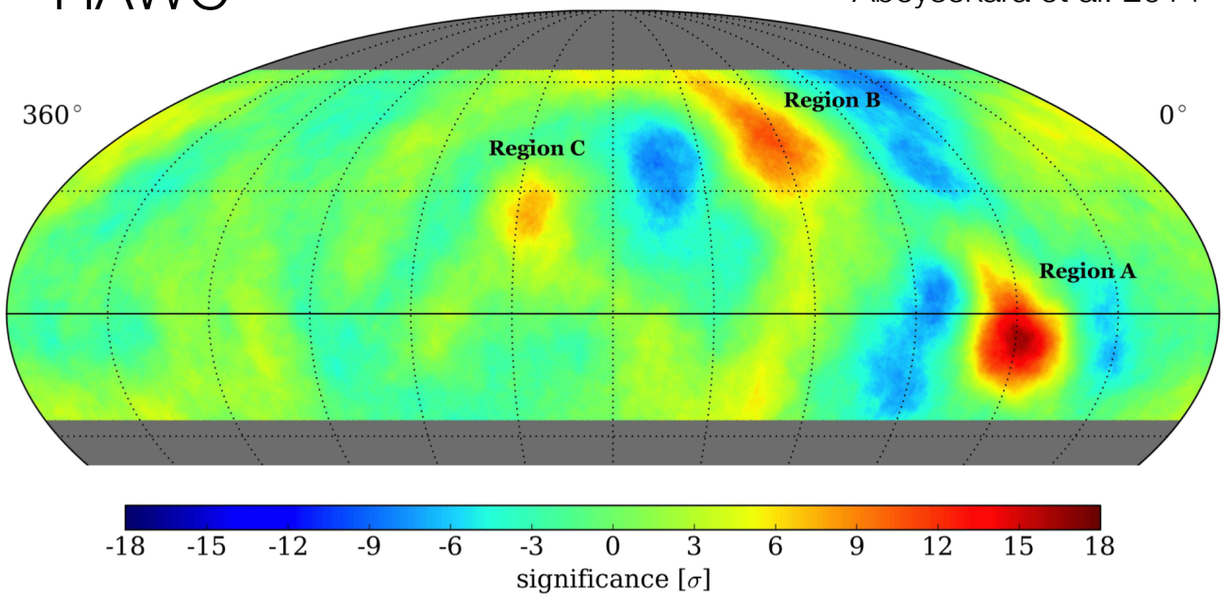




high energy cosmic rays
anisotropy & energy spectrum

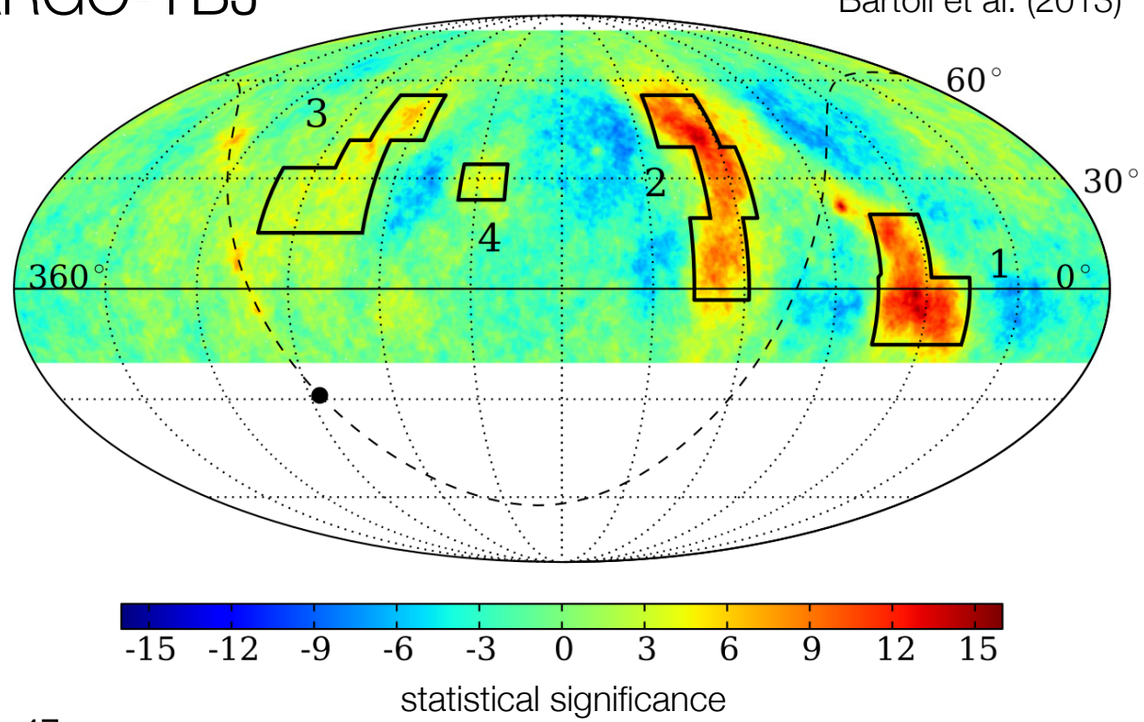
HAWC

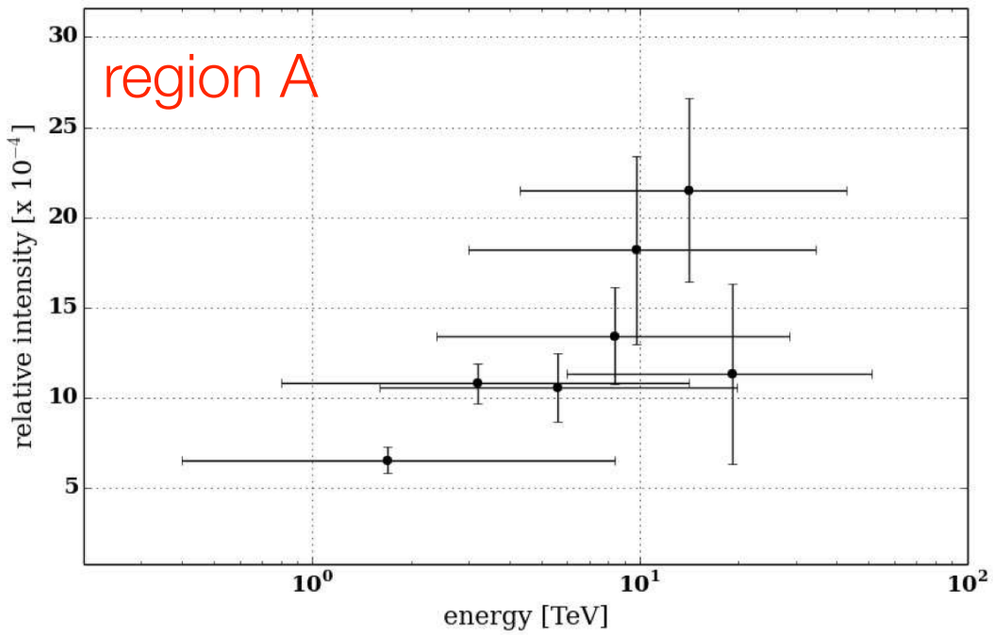
Abeysekara et al. 2014

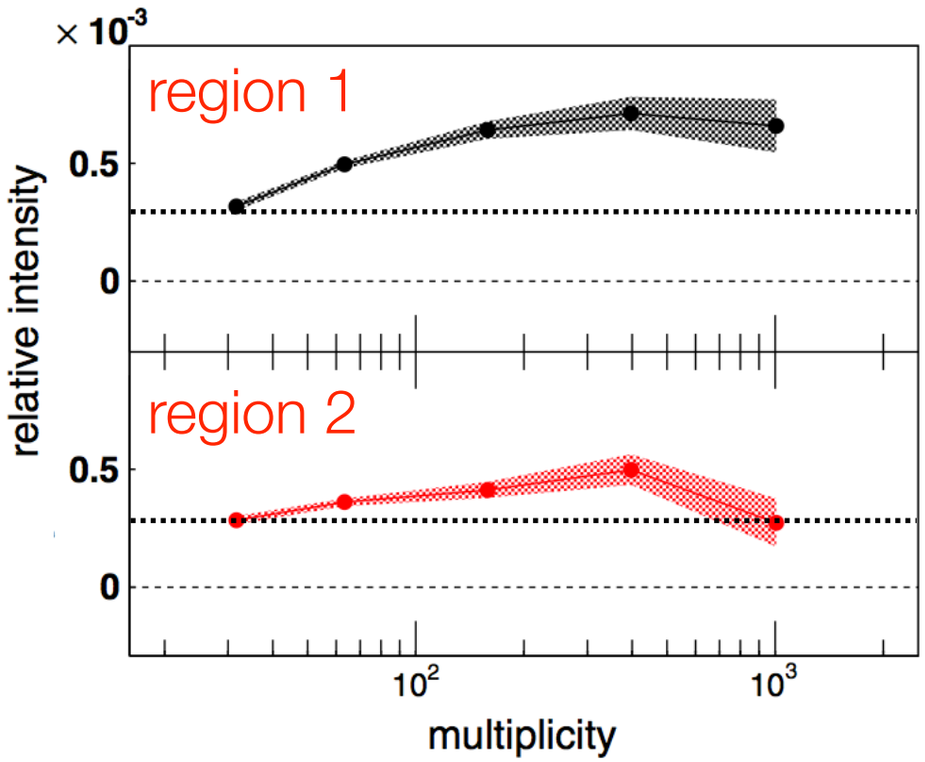


ARGO-YBJ

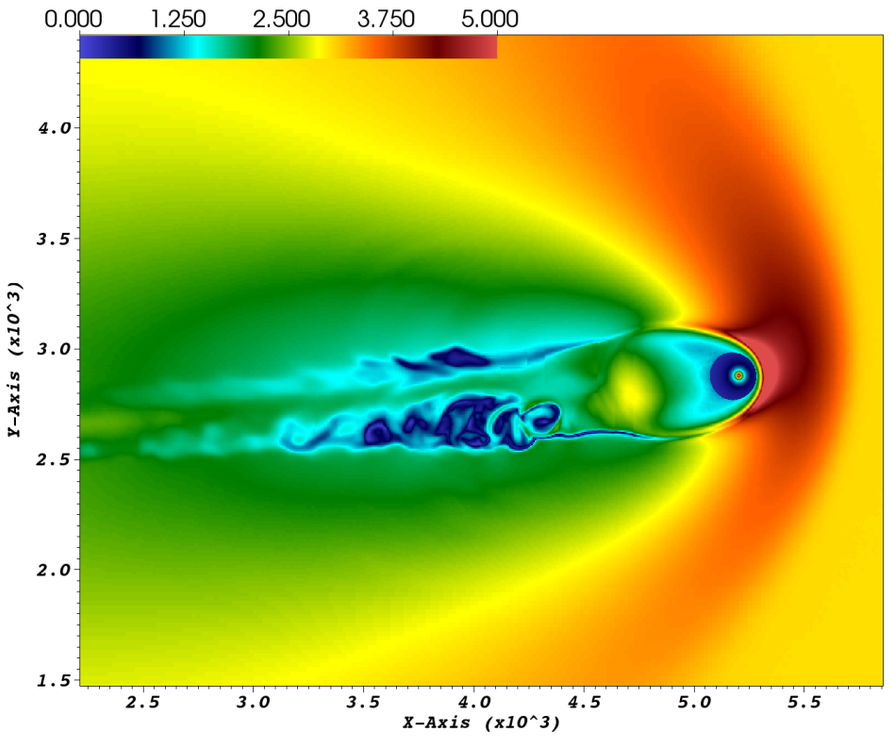
Bartoli et al. (2013)







cosmic ray anisotropy
probing heliospheric magnetic structure



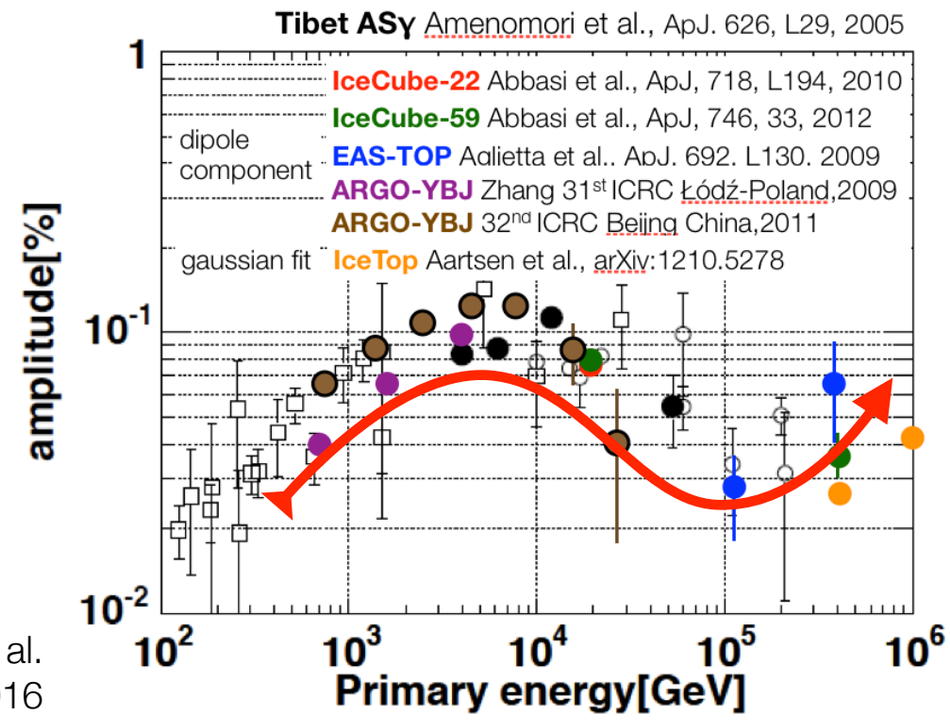
Borovikov, Heerikhuisen, Pogorelov

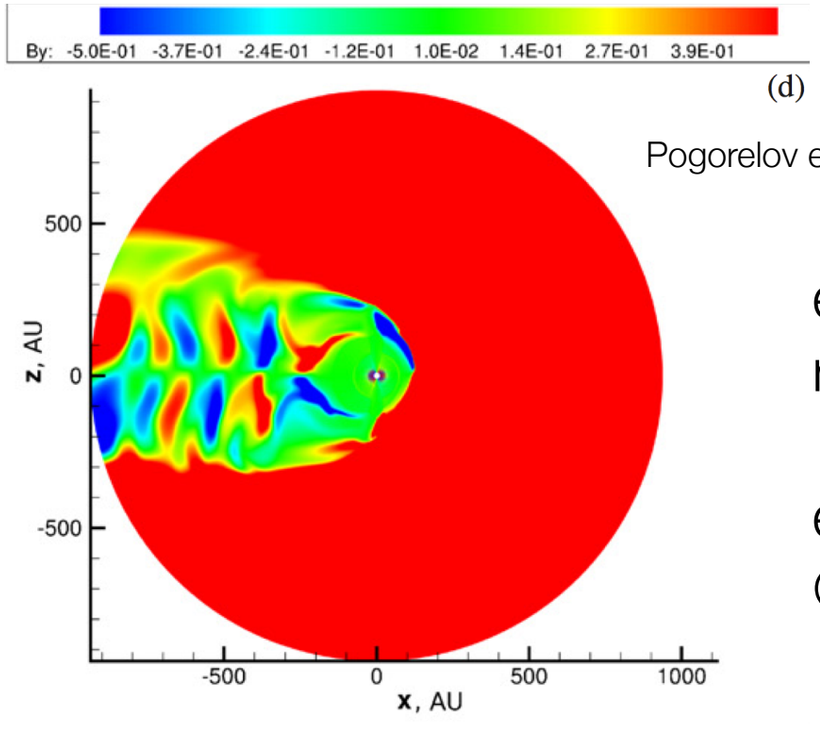
downstream instabilities on the flanks of heliotail

strong scattering

PD & Lazarian 2013

López-Barquero, Xu, PD, Lazarian, et al. 2016





Pogorelov et al., 2009

effects of magnetic polarity reversals from solar cycles

explain spectral anomaly @heliotail ?

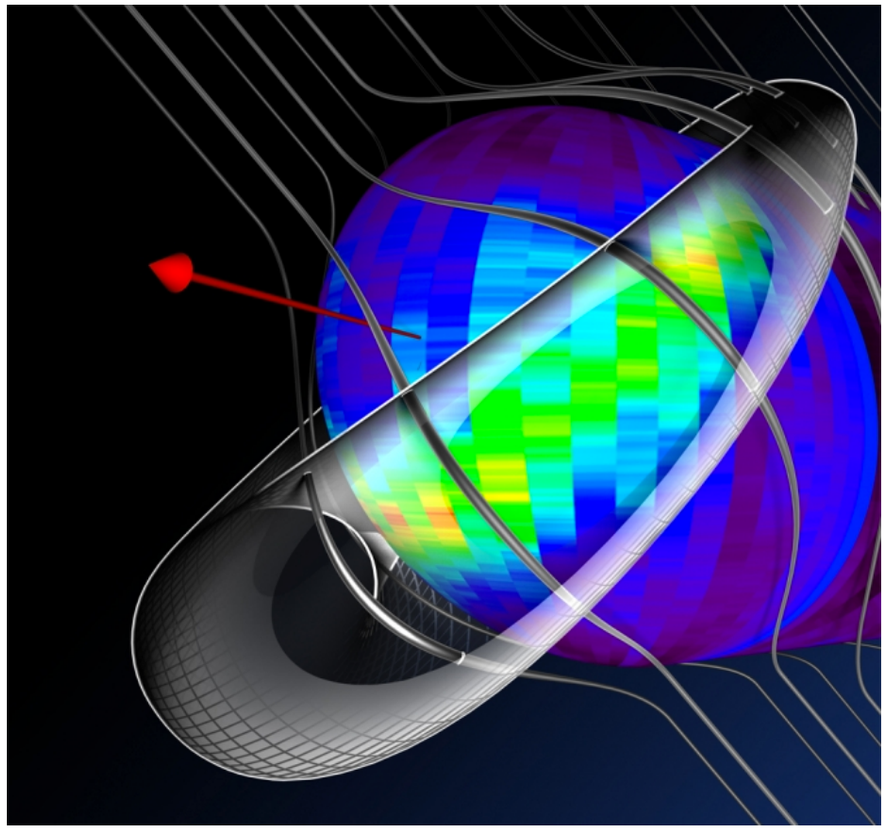
magnetic reconnection (?)

Lazarian & PD 2010
PD & Lazarian 2012

anisotropy and local galactic environment

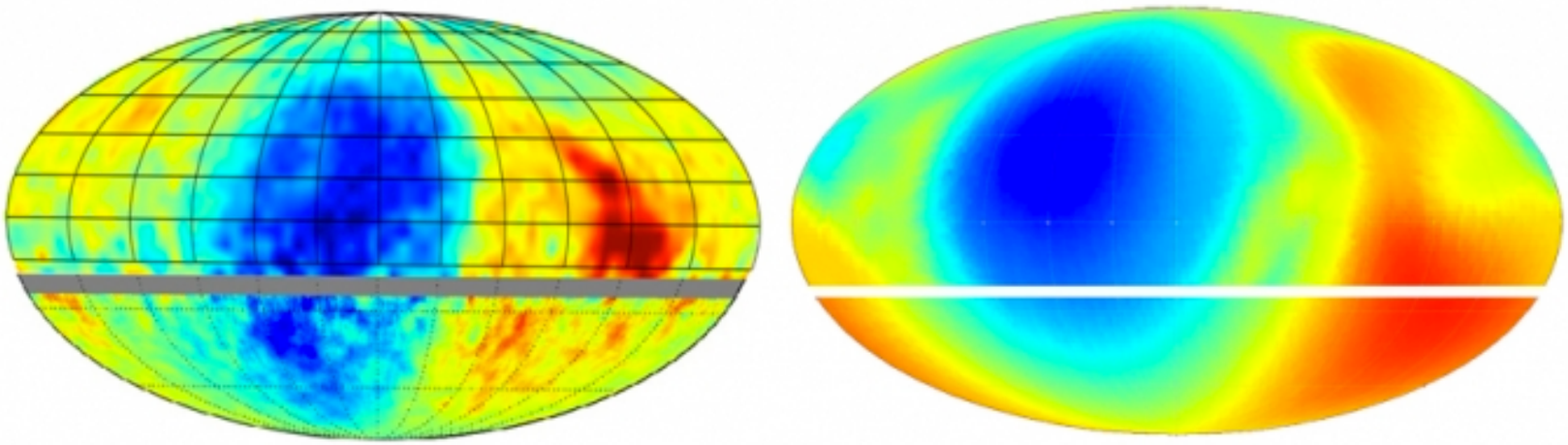
low to high energy connection

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

transport across field lines

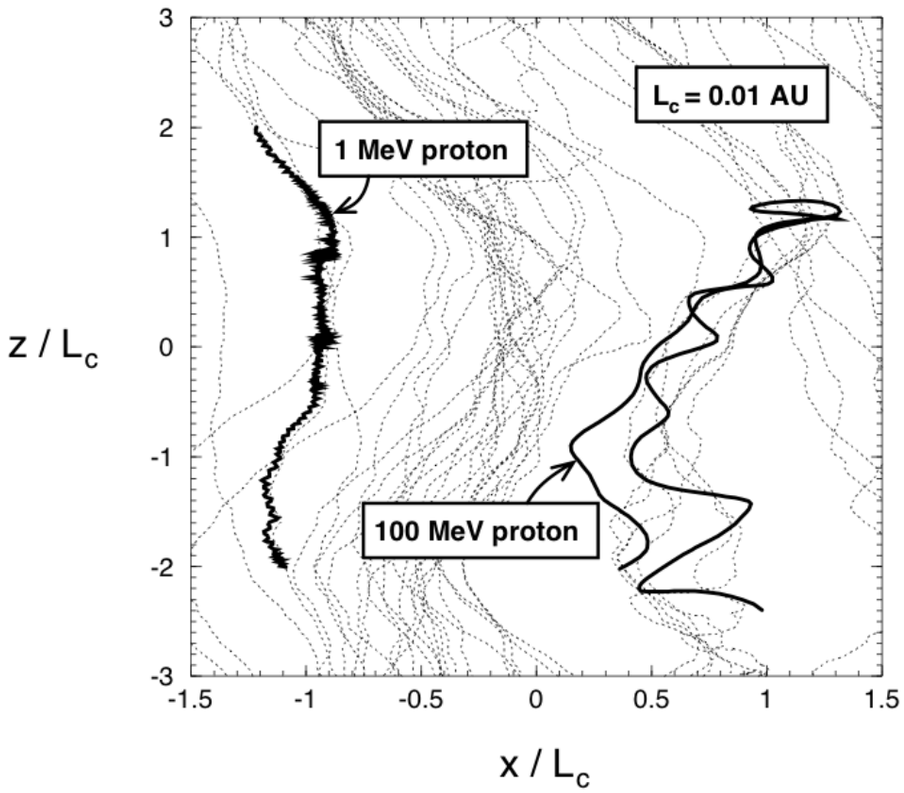
- if particles **tied** to magnetic field lines, $D_\perp$ limited by **FLRW** diffusion × $v_{particle}$

- 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 $D_\perp$

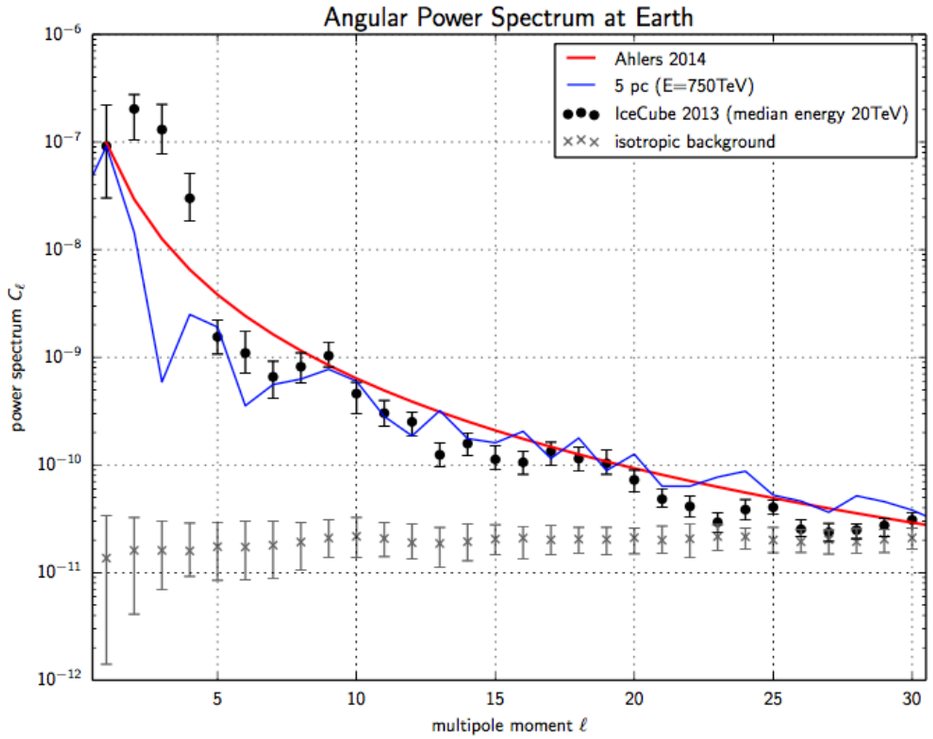


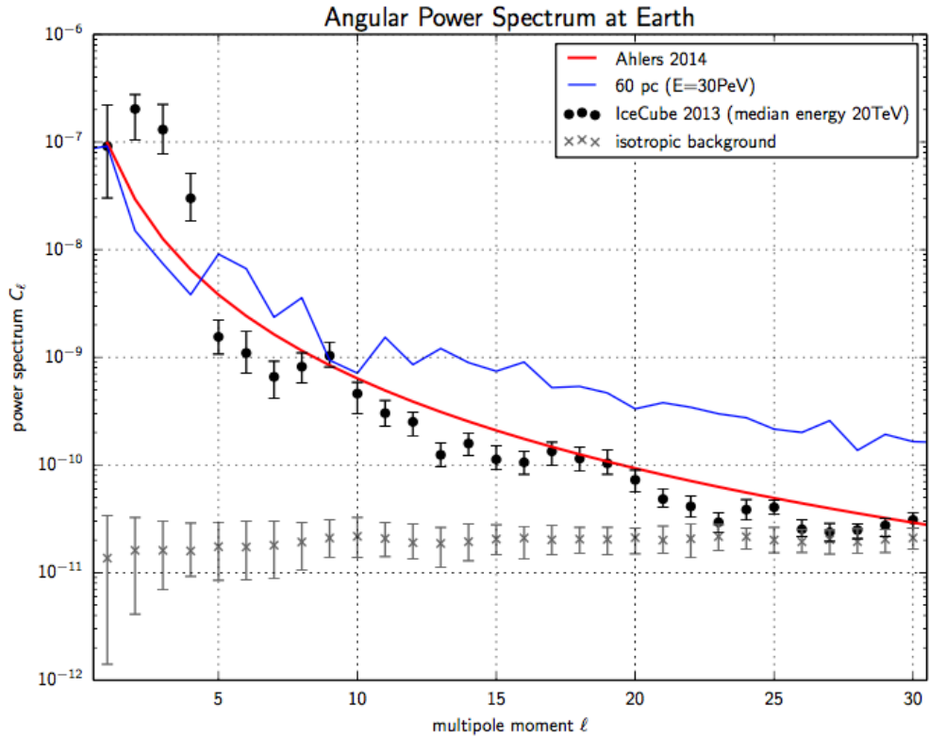
large scale geometry significantly enhances particle cross-field line diffusion

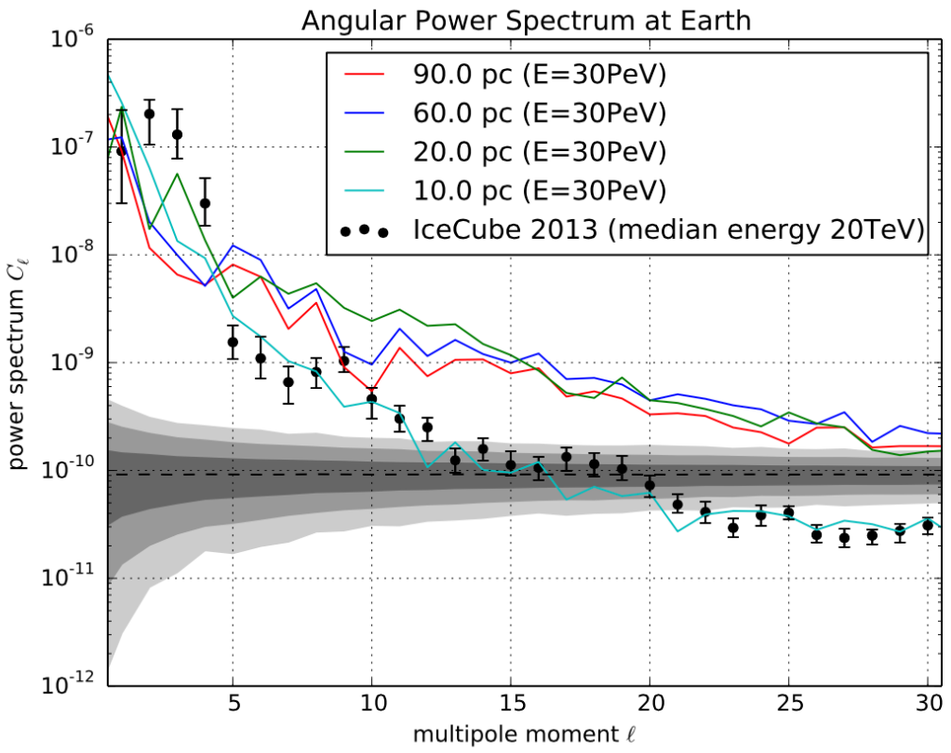
(PD, Zweibel ApJ 701, 51, 2014)

cosmic ray anisotropy

probing magnetic field turbulence ?







López-Barquero, Farber, Xu, PD, Lazarian, ApJ 830 19 (2016)
arXiv:1509.00892