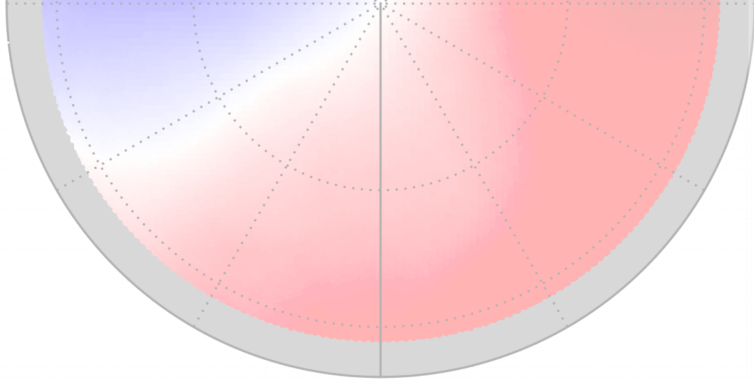
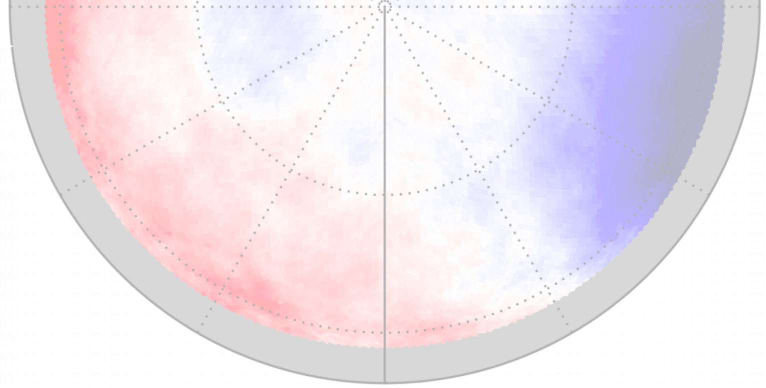

Cosmic Ray Anisotropy
at TeV to PeV scale

(IceCube biased)

Paolo Desiati

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Wisconsin IceCube Particle Astrophysics Center (WIPAC)
University of Wisconsin - Madison

Vulcano Workshop 2018 - Frontier Objects in Astrophysics and Particle Physics

20-26 May 2018 *Vulcano Island, Sicily, Italy*

cosmic ray observations

galactic origin below ~10^8-10^9 GeV

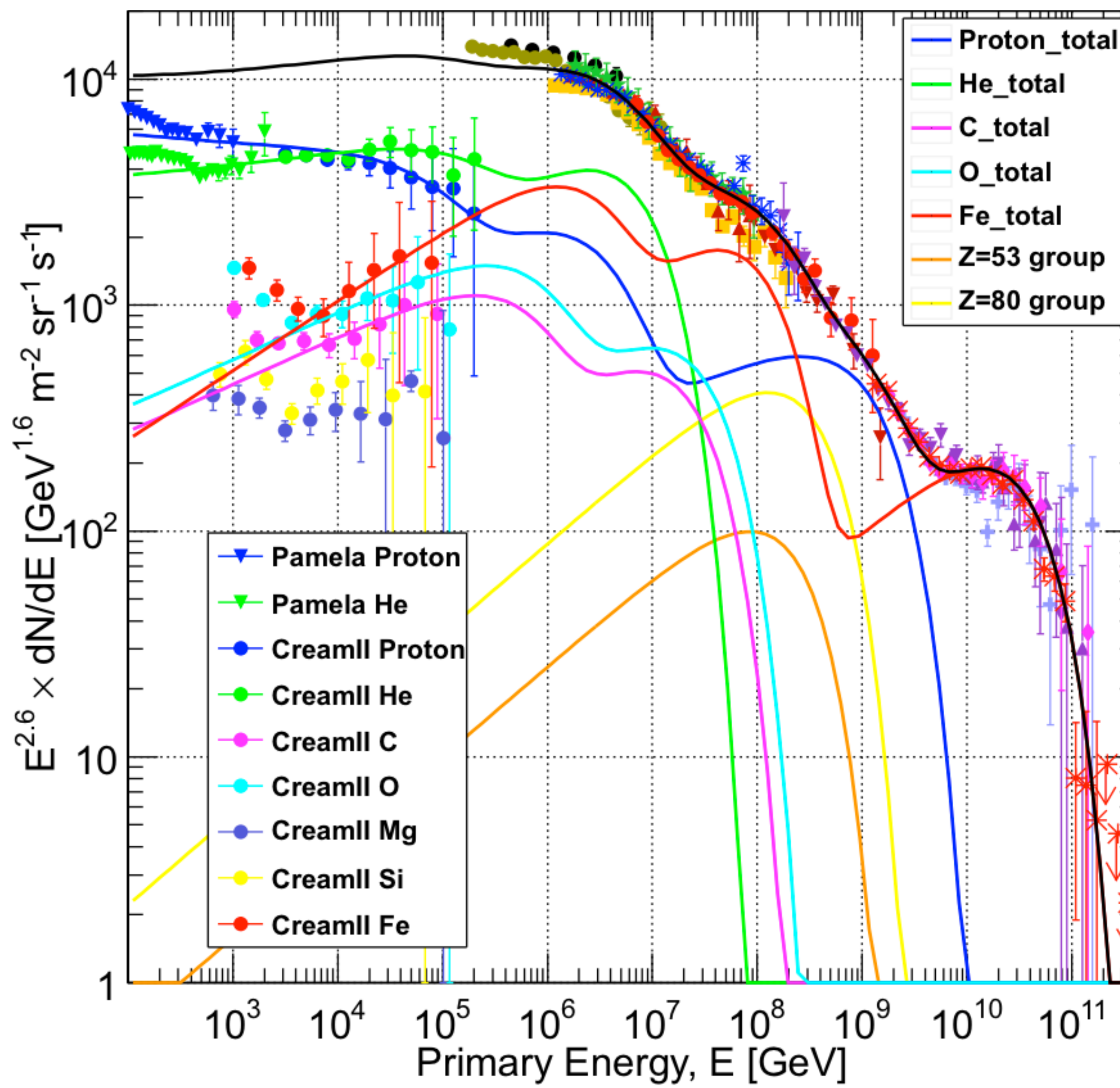
spectral features from acceleration mechanisms & propagation effects

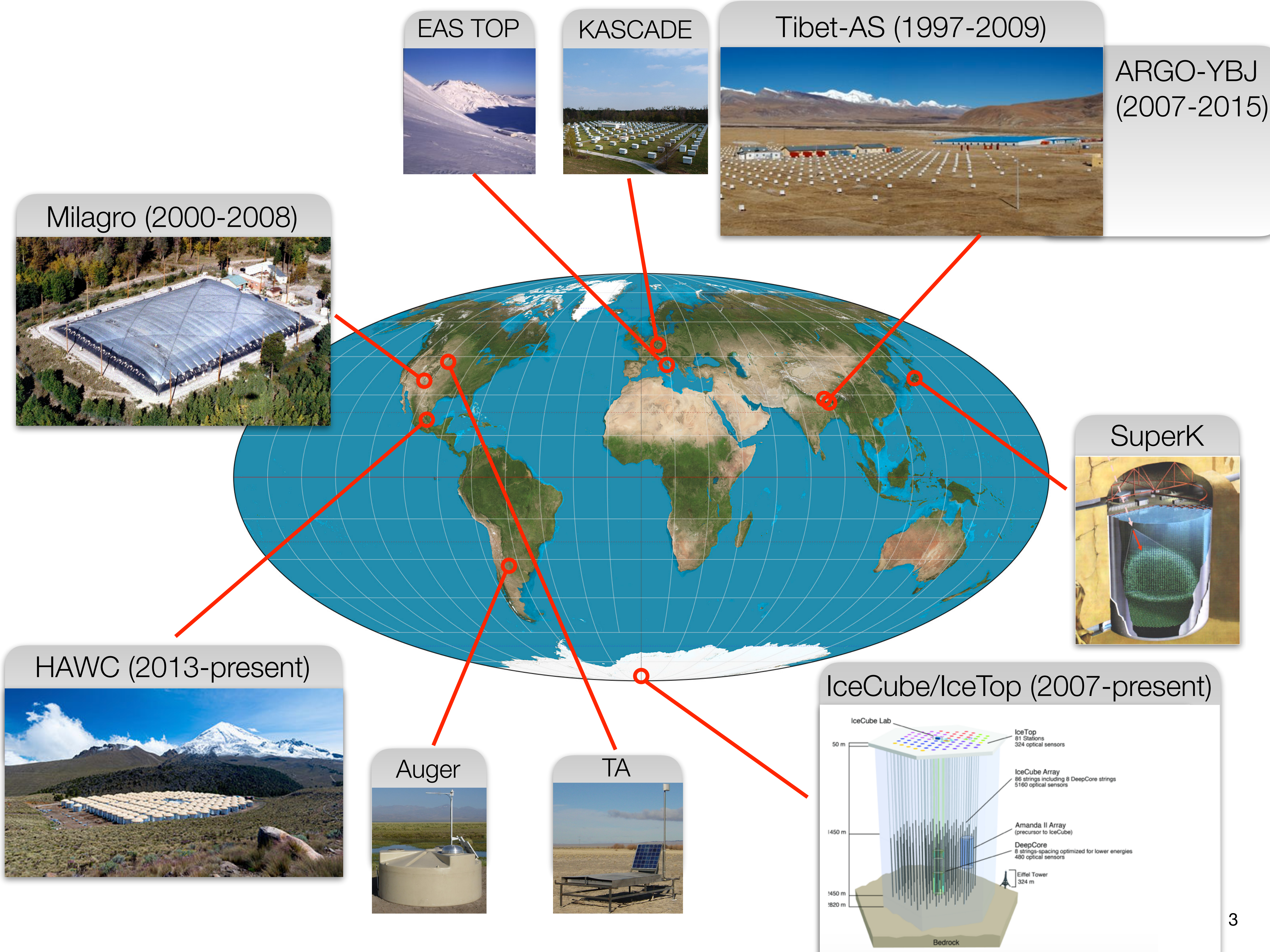
source distribution in the Milky Way and our neighborhood

magnetic field properties in galactic and local interstellar medium

anisotropy

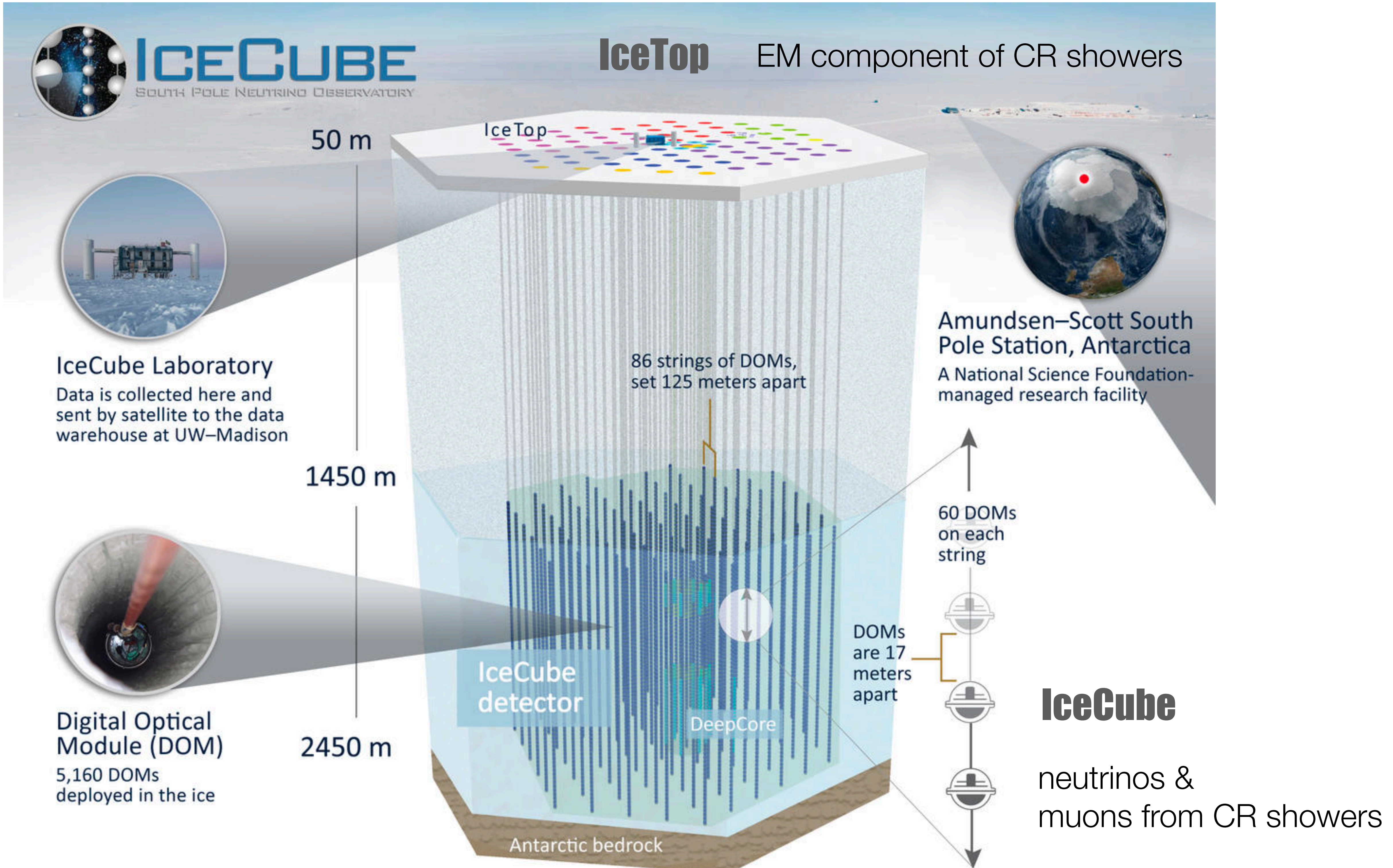
Gaisser, Stanev, Tilav, 2013 - arXiv:1303.3565




EAS TOP
KASCADE
Tibet-AS (1997-2009)
ARGO-YBJ (2007-2015)
Milagro (2000-2008)
SuperK
HAWC (2013-present)
Auger
TA
IceCube/IceTop (2007-present)
IceCube Lab
IceTop
81 Stations
324 optical sensors
50 m
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
Amanda II Array
(precursor to IceCube)
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
Bedrock

IceCube & IceTop

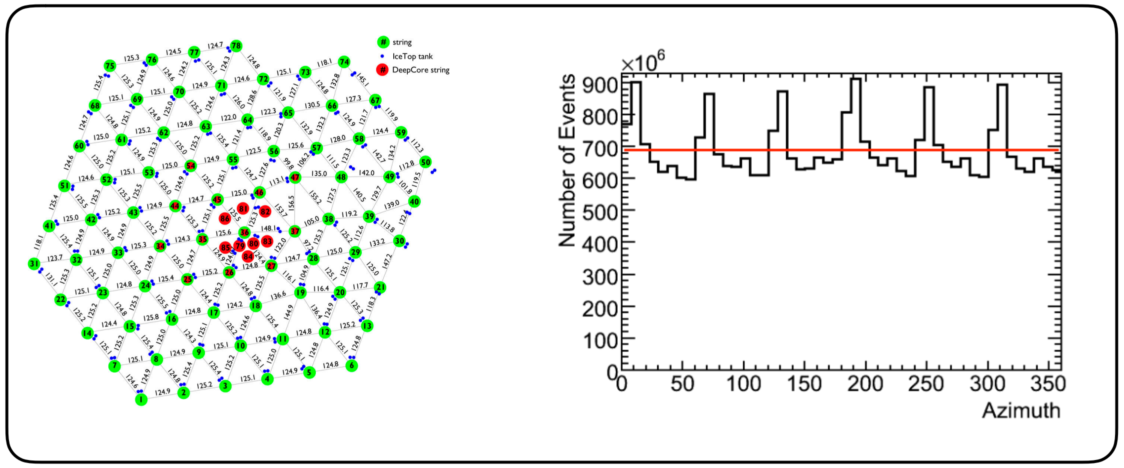
observing neutrinos and cosmic rays at South Pole



determination of anisotropy

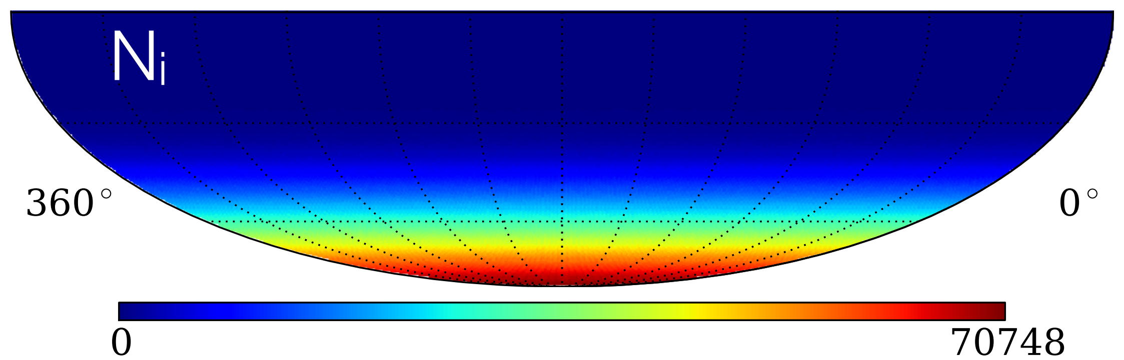
arrival direction distribution

IceCube local coordinates



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

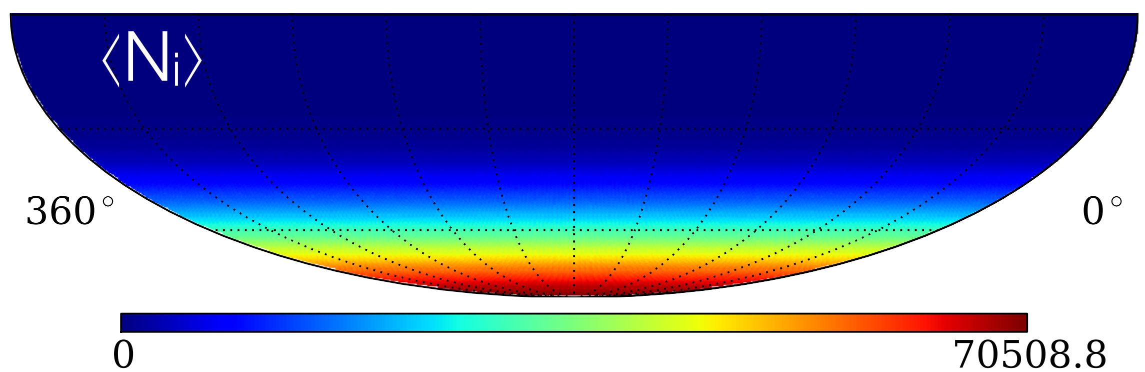
1 month of data



reference map of events *scrambled* over 24hr in α (or time) within same δ band

→ **response map to isotropic flux**

1 month of data



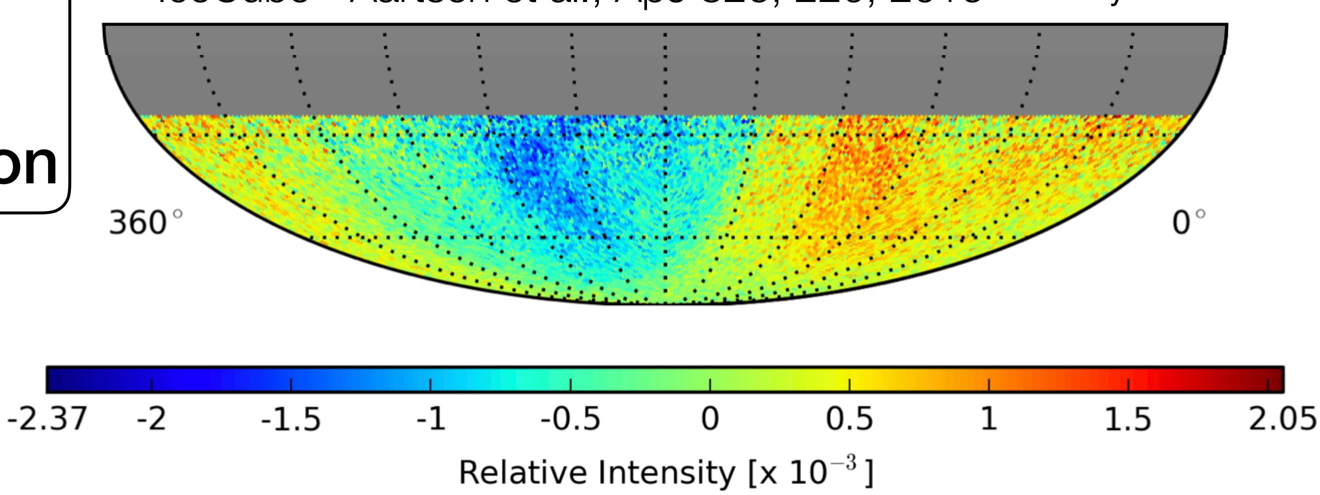
residual map as relative intensity normalized in each δ band: equal deficit/excess.

→ **equal deficit/excess contribution**

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

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

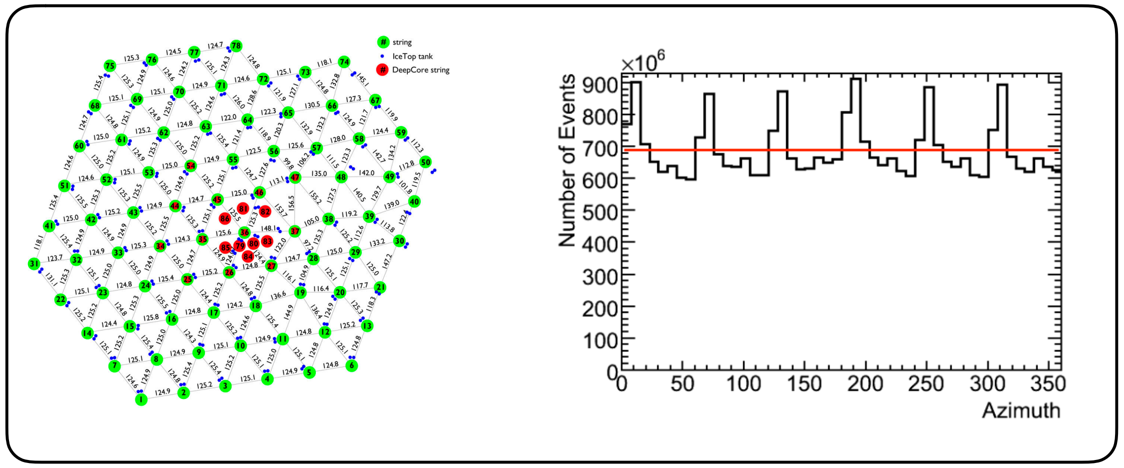
6 years of data

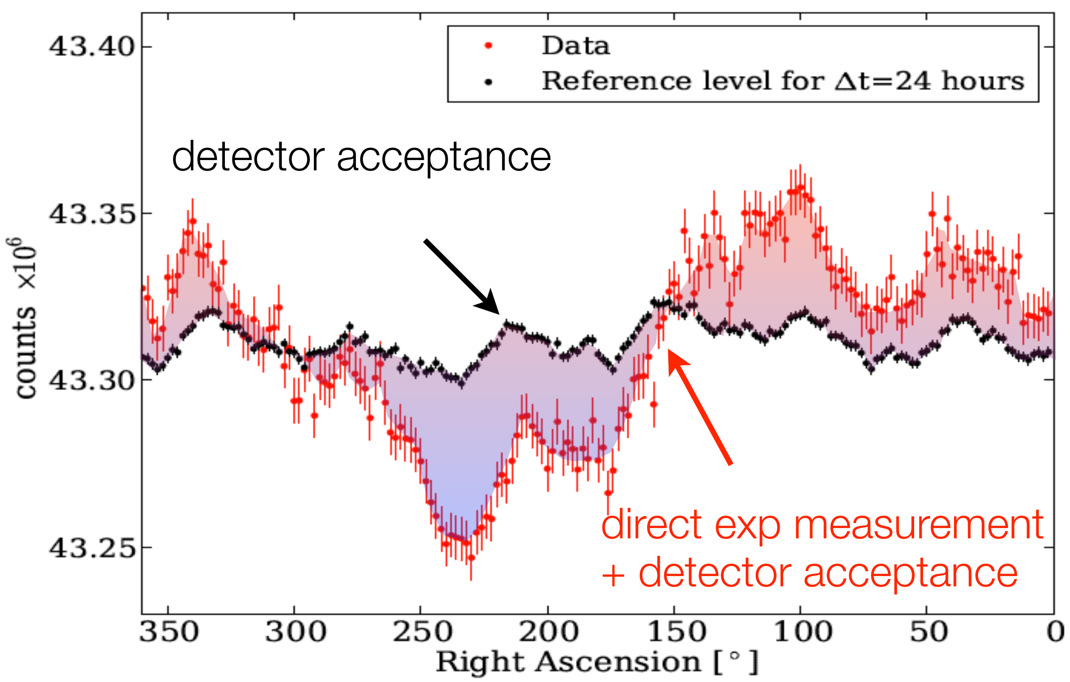


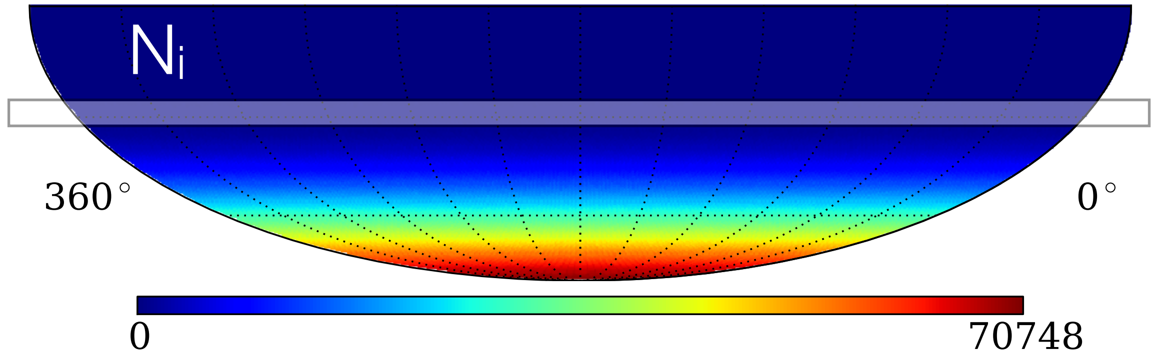
determination of anisotropy

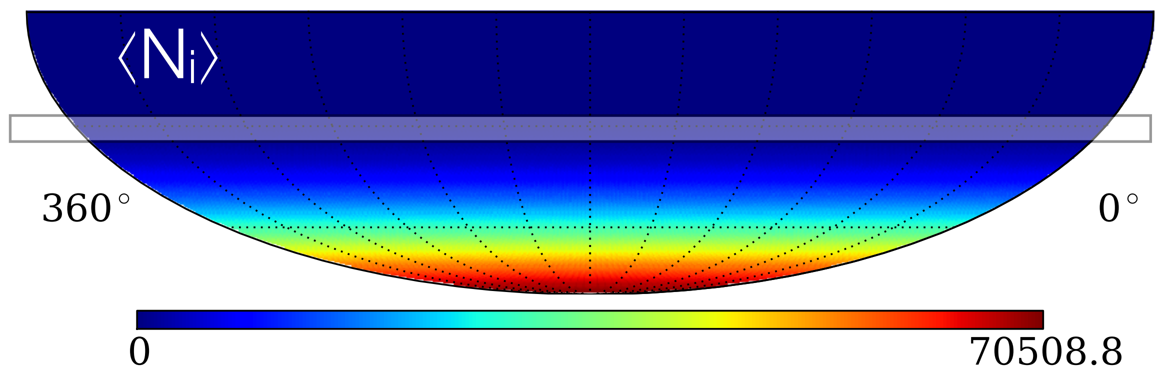
arrival direction distribution

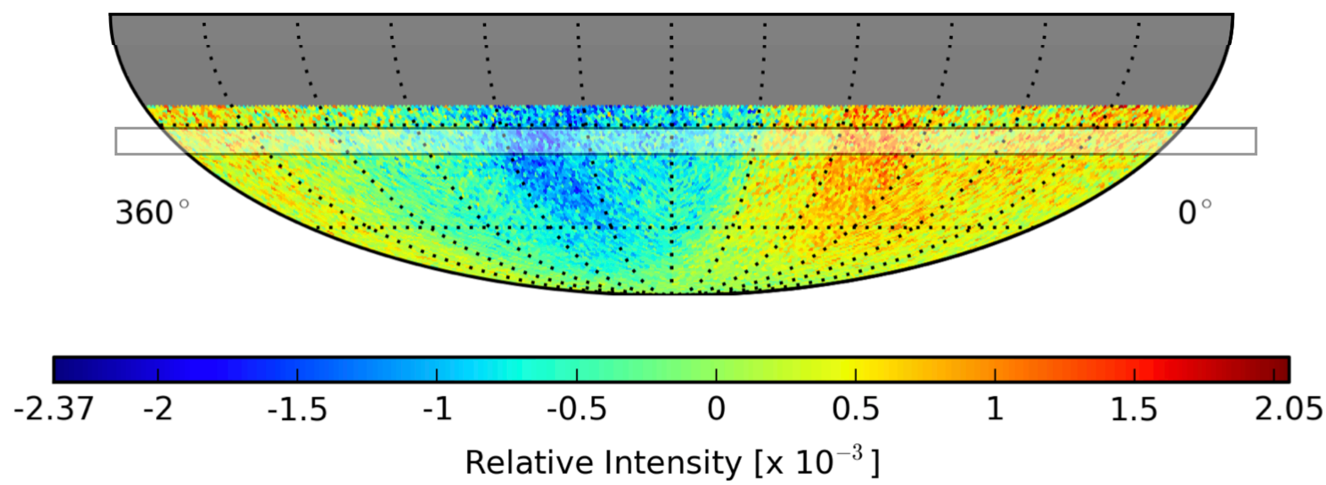
IceCube local coordinates









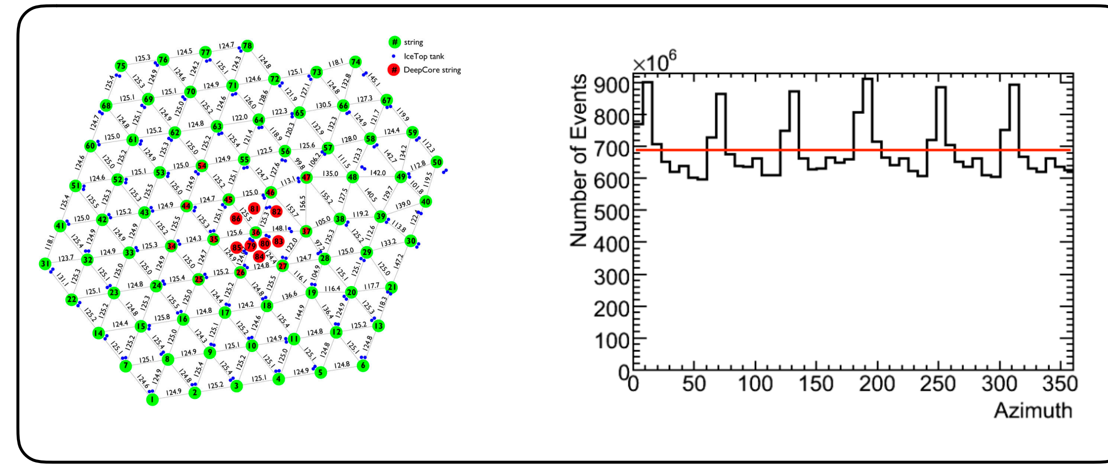


$$\boxed{\frac{\Delta I}{\langle I \rangle} = \frac{N_i - \langle N \rangle}{\langle N \rangle}}$$

determination of anisotropy

arrival direction distribution

IceCube local coordinates

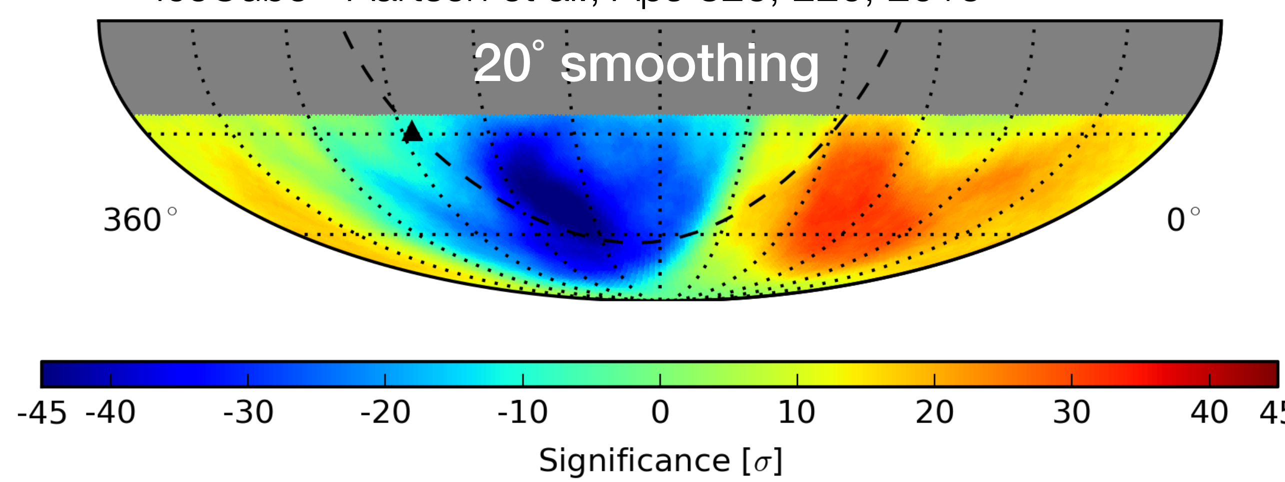


$$s=\sqrt{2}\left\{N_{\rm on}\ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\rm on}}{N_{\rm on}+N_{\rm off}}\right)\right]+N_{\rm off}\ln\left[(1+\alpha)\left(\frac{N_{\rm off}}{N_{\rm on}+N_{\rm off}}\right)\right]\right\}^{1/2}\qquad \alpha=1/20$$

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

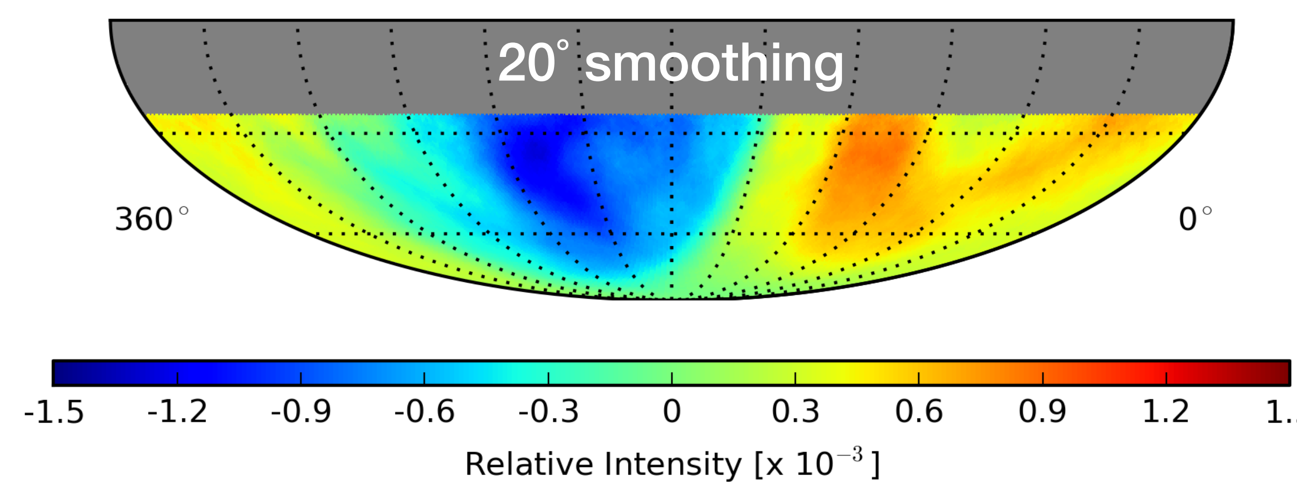
statistical significance

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



relative intensity

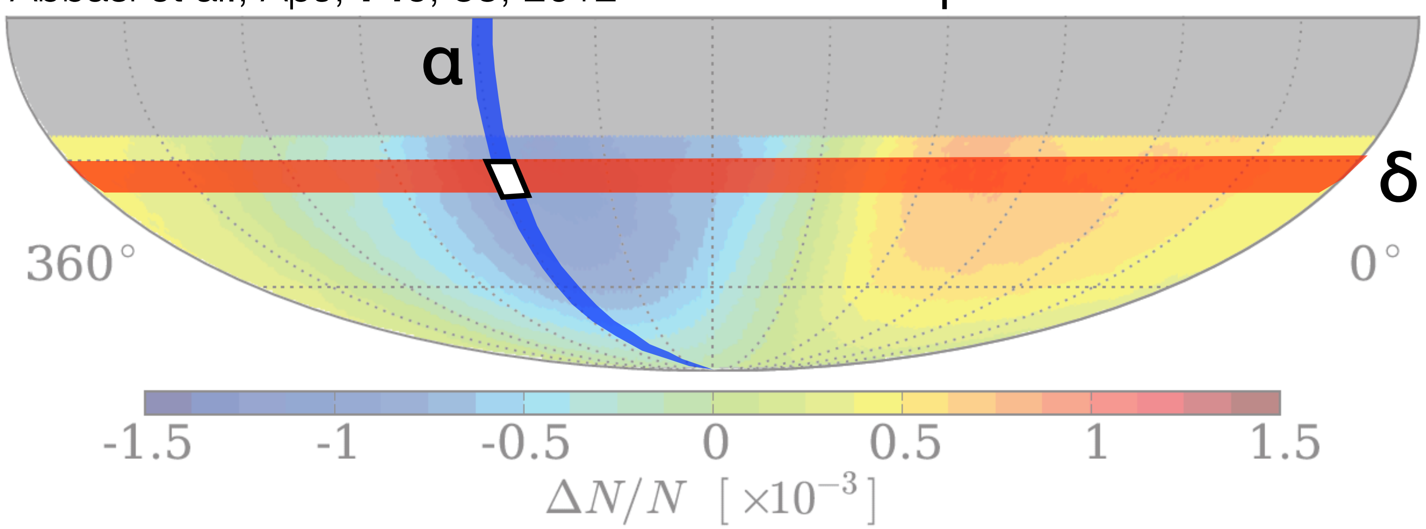
$$\boxed{\frac{\Delta I}{\langle I\rangle}\equiv\frac{N_i-\langle N\rangle}{\langle N\rangle}}$$



observing cosmic ray anisotropy
projection blindness

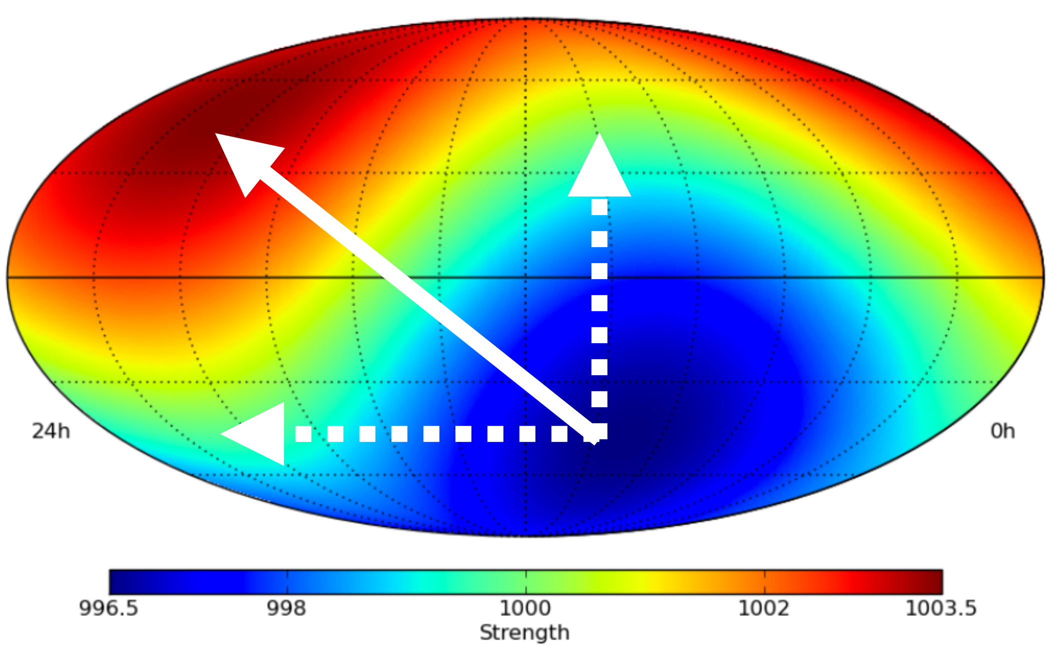
Abbasi et al., ApJ, **746**, 33, 2012

equatorial coordinates

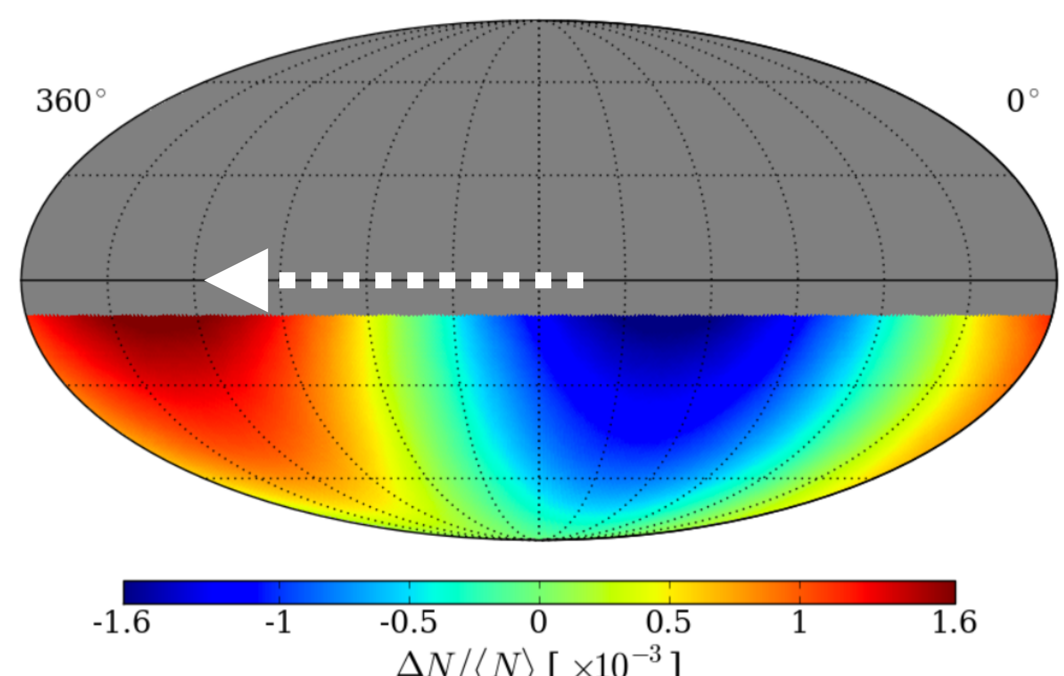


$$\frac{\Delta N_i}{\langle N \rangle_i} = \frac{N_i(\alpha,\delta) - \langle N_i(\alpha,\delta)\rangle}{\langle N_i(\alpha,\delta)\rangle}$$

declination bands
independently normalized



$\Delta N/\langle N\rangle = 7\times 10^{-3}$

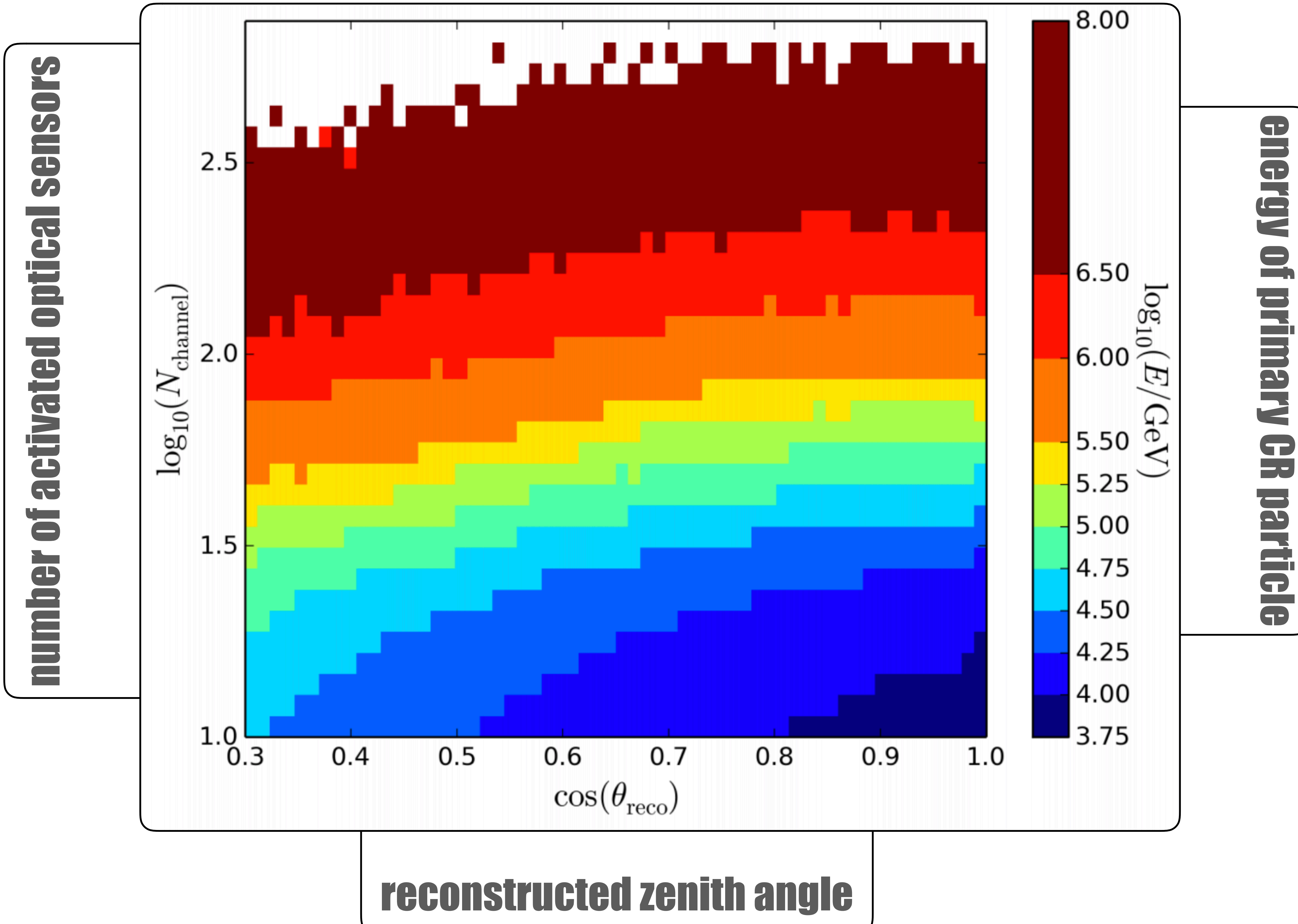


sky maps show **ONLY** modulations projected on **equatorial plane**

observing cosmic ray anisotropy

energy dependency

IceCube

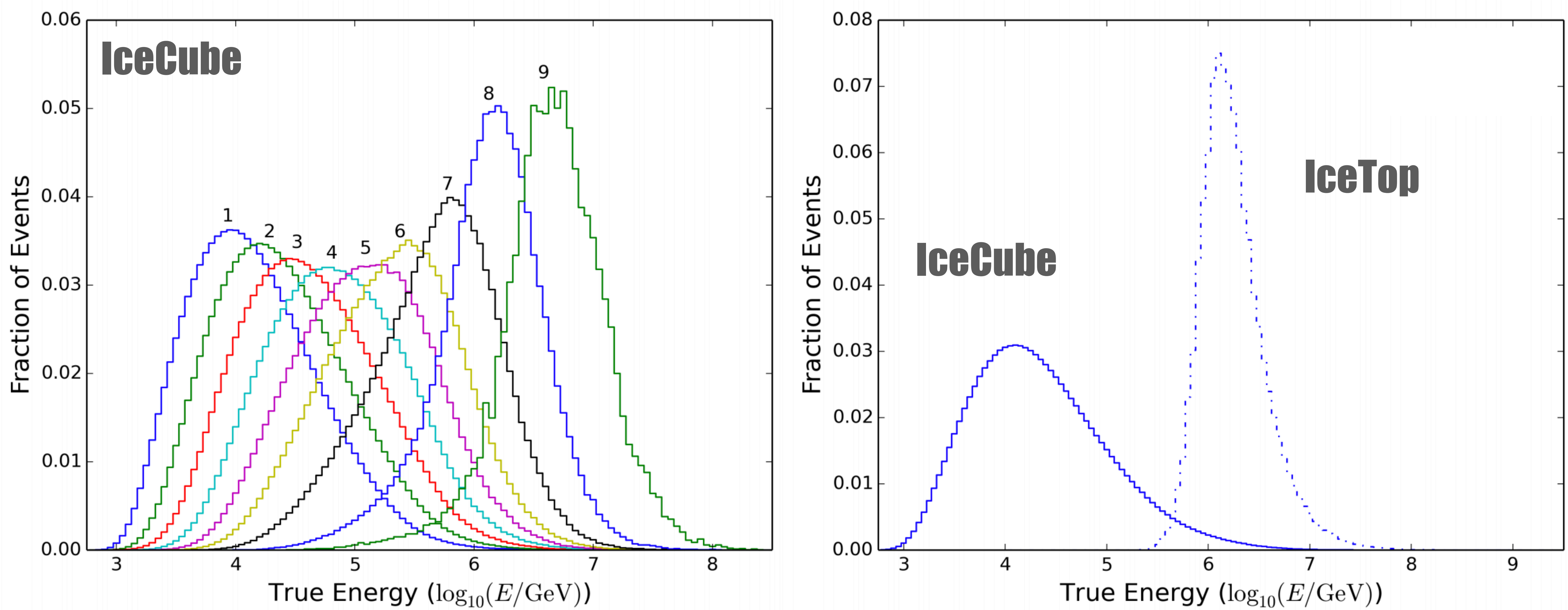


Aartsen et al., ApJ 826, 220 (2016)

observing cosmic ray anisotropy

energy dependency

energy response



energy of primary CR particle

Aartsen et al., ApJ 826, 220 (2016)

observing cosmic ray anisotropy

energy dependency (< knee)

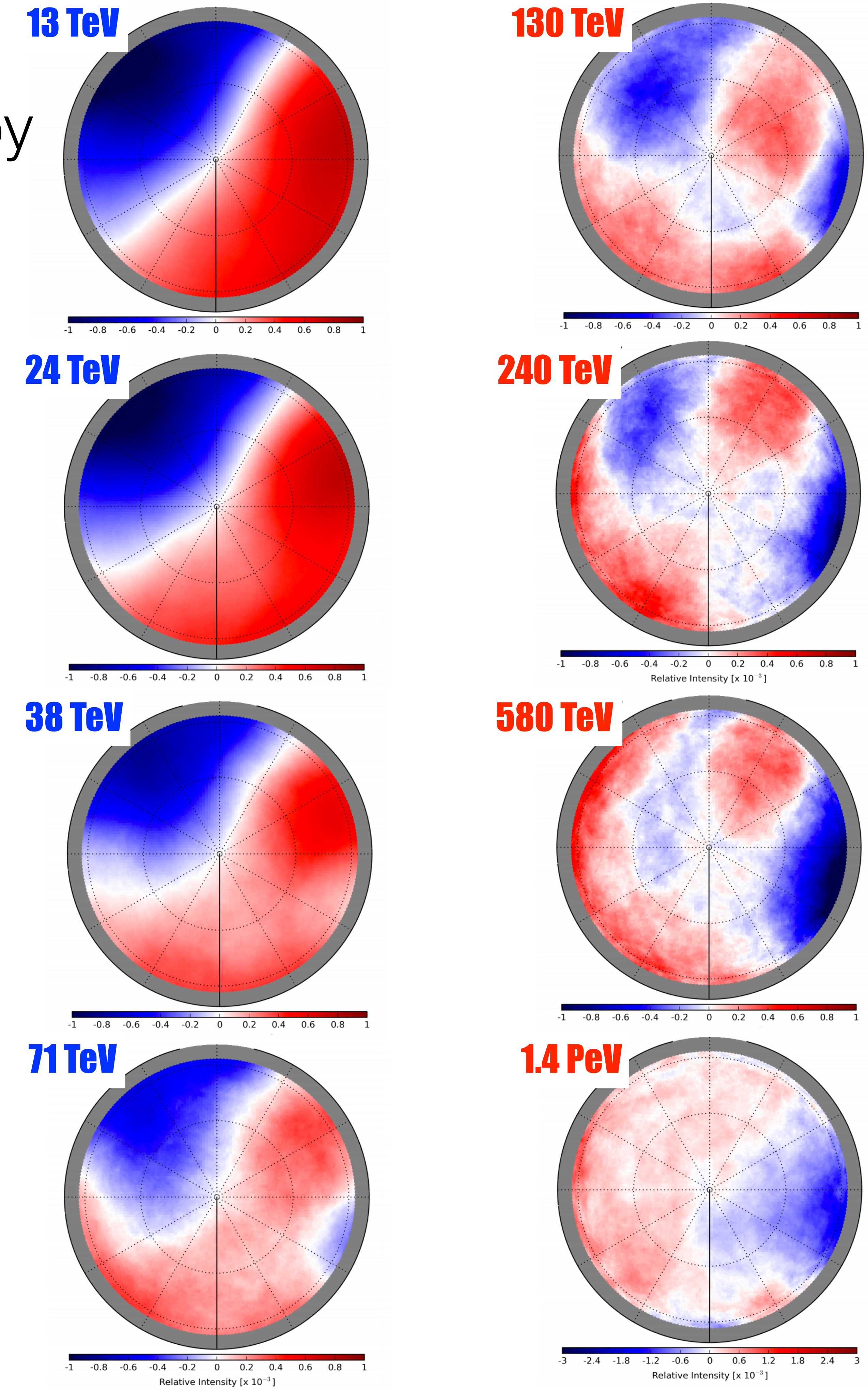
IceCube Aartsen et al., ApJ 826, 220, 2016

cosmic ray anisotropy depends on primary energy

large scale changes structure **>100 TeV**

imaging magnetic effects at larger distances with increasing energy

Note: cosmic ray composition changes as well vs. energy

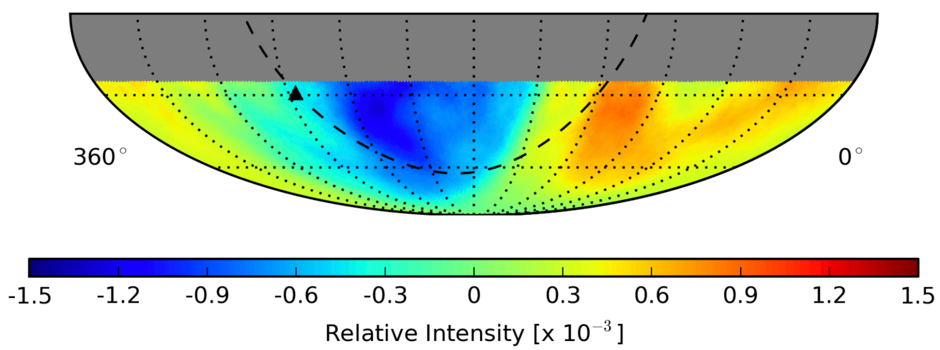


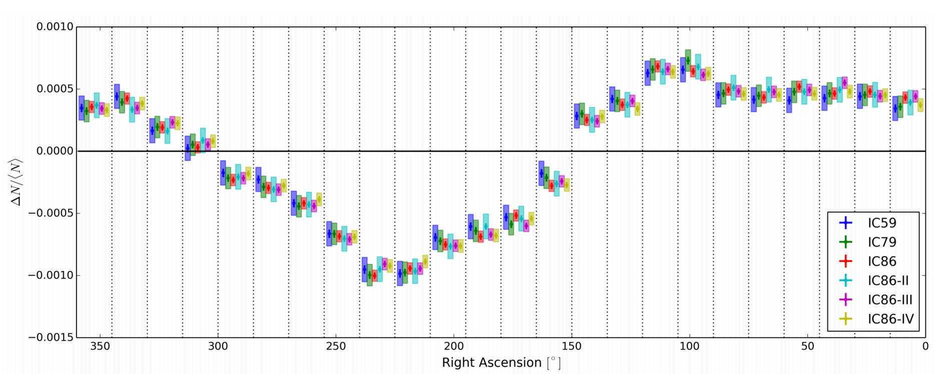
observing cosmic ray anisotropy

energy dependency (< knee)

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

~20 TeV

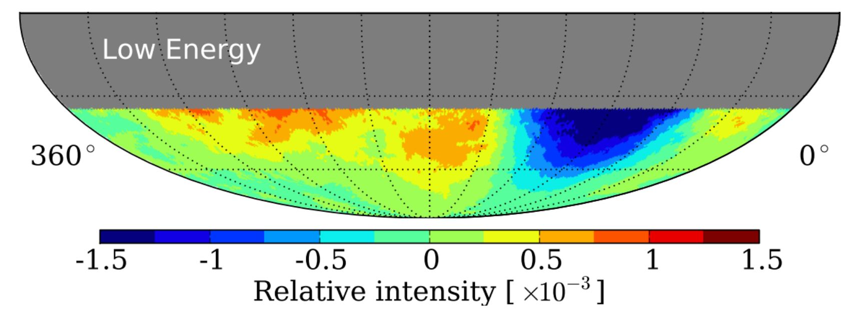




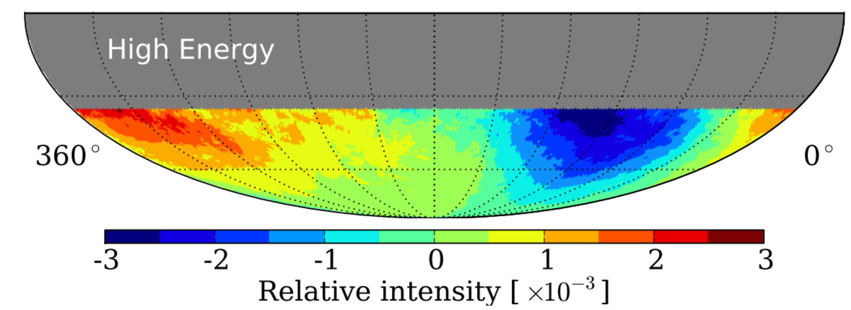
not a dipole distribution

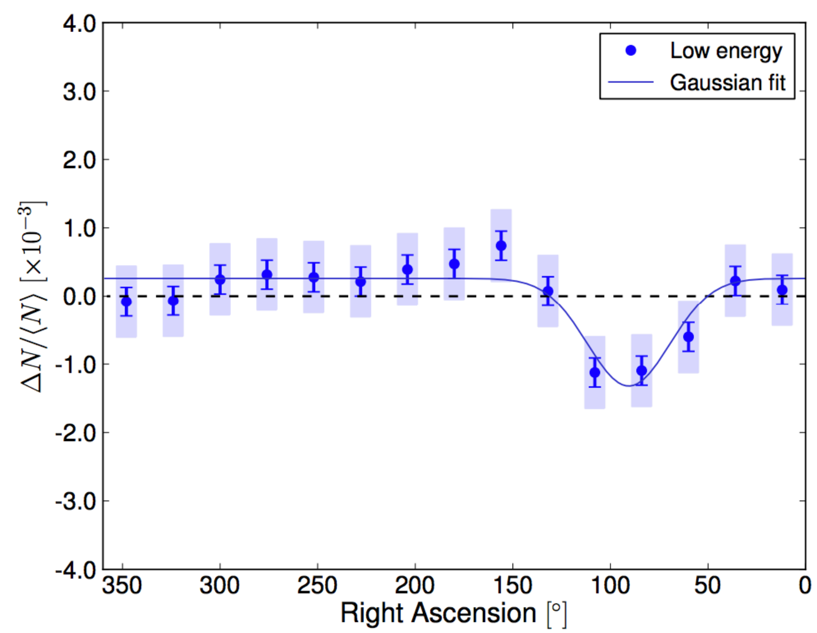
IceTop Aartsen et al., ApJ 765, 55, 2013

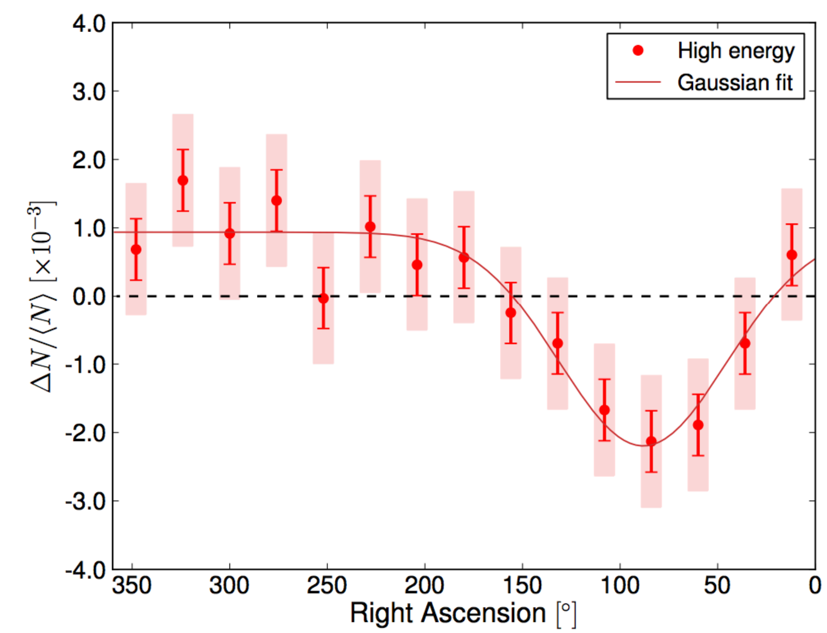
~400 TeV



~2 PeV







hardly a dipole distribution

observing cosmic ray anisotropy
horizontal dipole component

IceCube

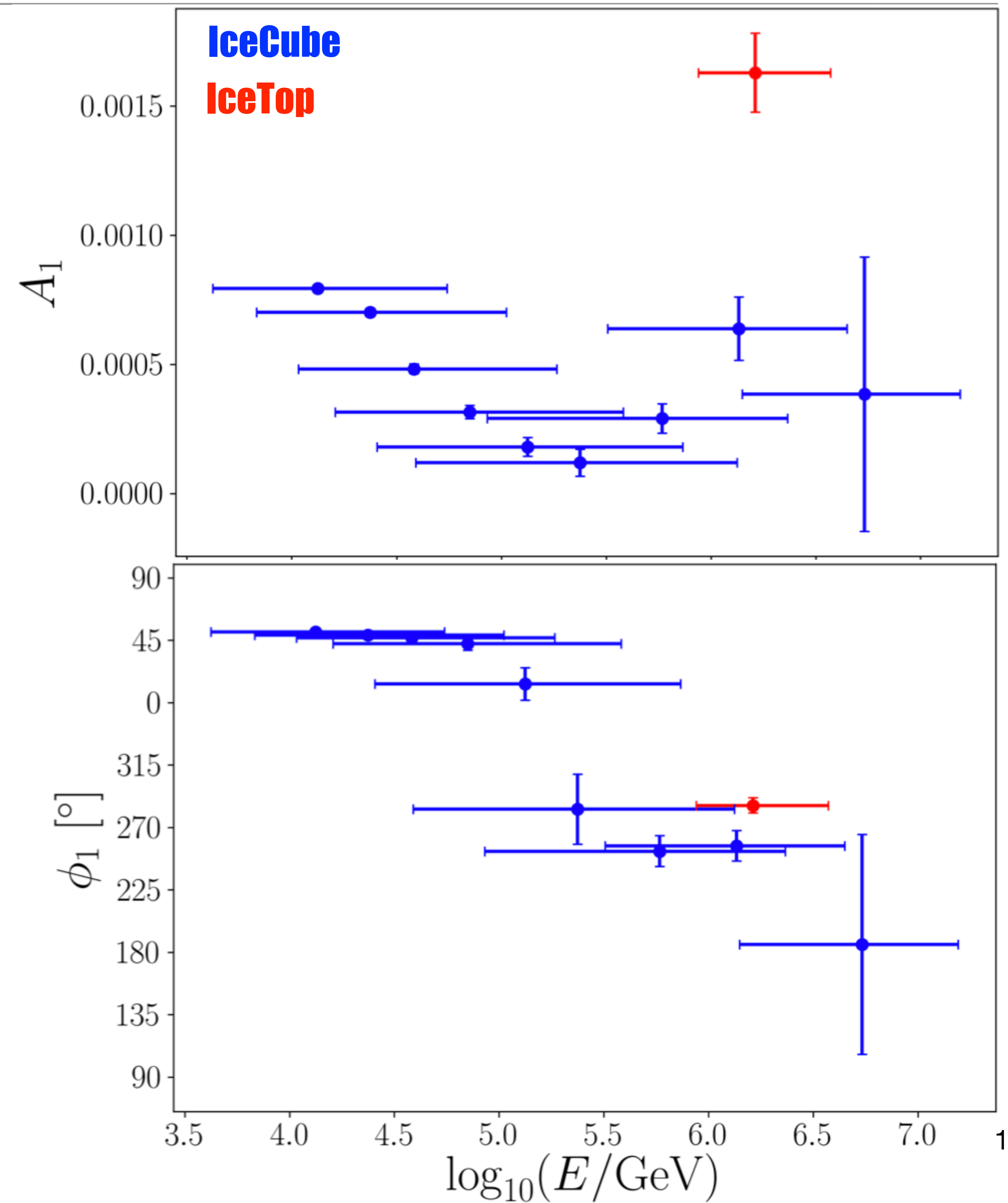
Aartsen et al., ApJ 826, 220, 2016

anisotropy has complex **angular structure**

dipole component thought to be related to **diffusion** in interstellar magnetic fields

as if two dipole components **transition** from one to another

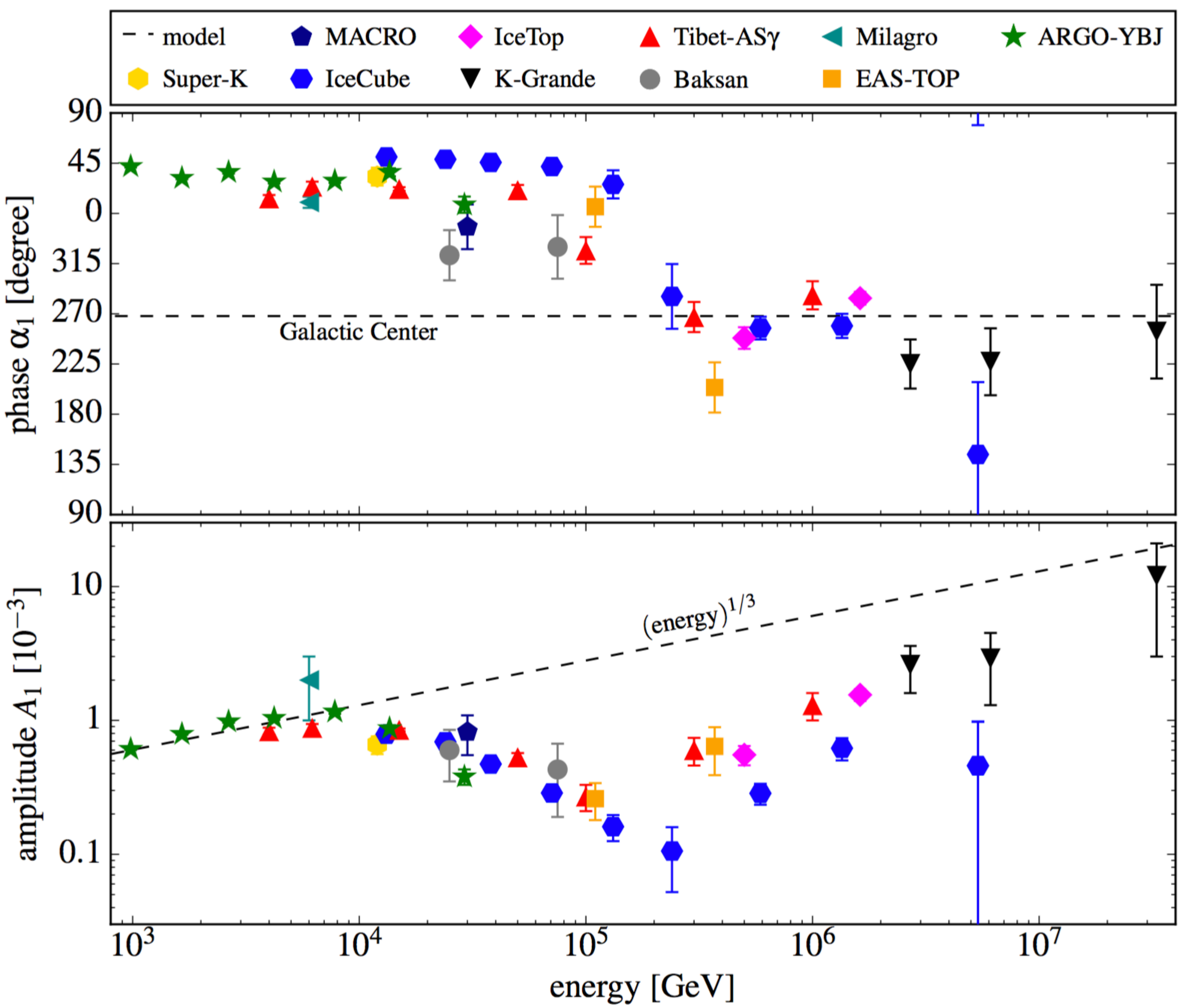
dependence on **mass composition**?



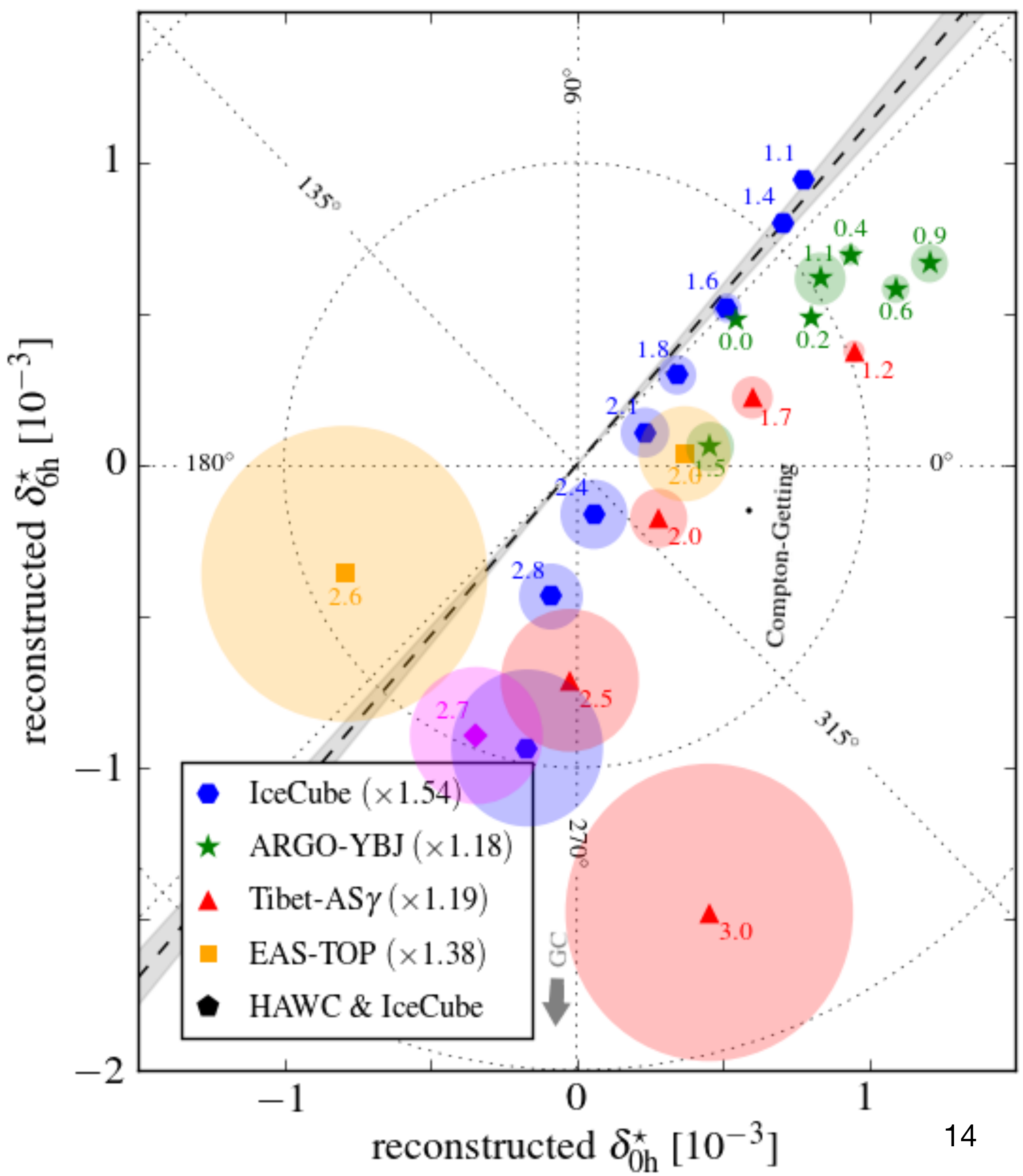
observing cosmic ray anisotropy

horizontal dipole component

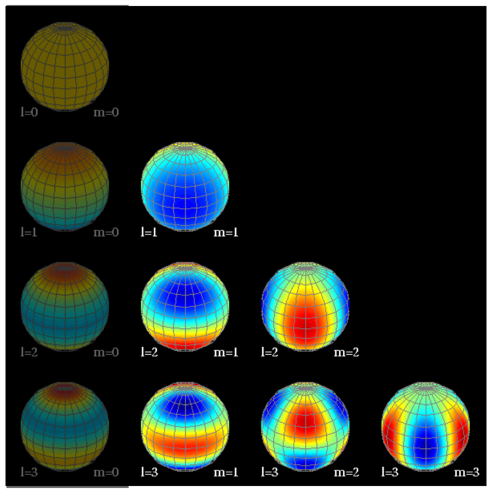
Review: Ahlers & Mertsch, 2016



Ahlers, PRL 117, 151103 (2016)



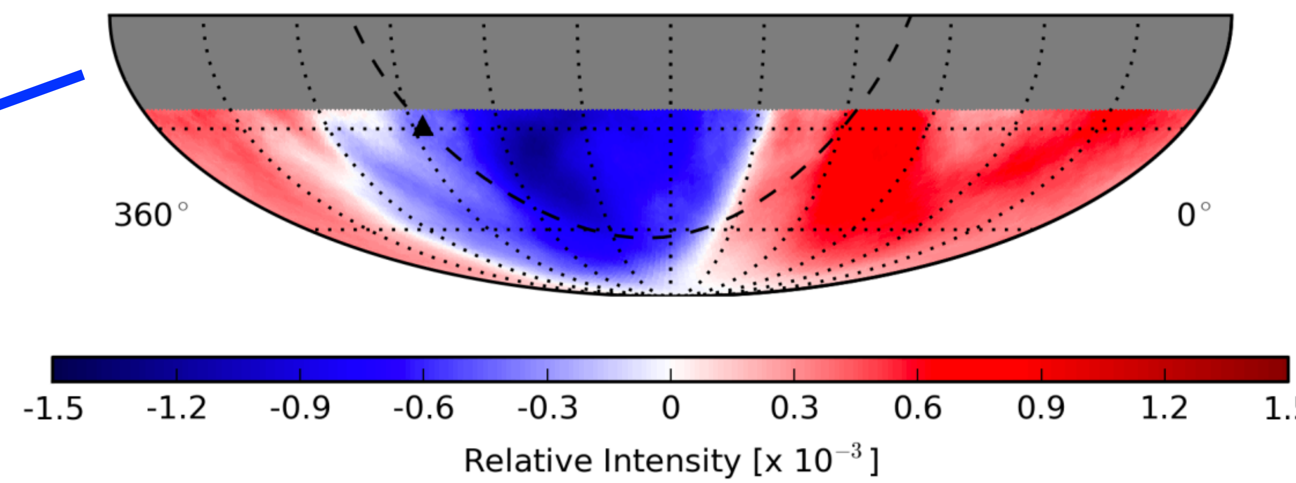
observing cosmic ray anisotropy
angular structure decomposition

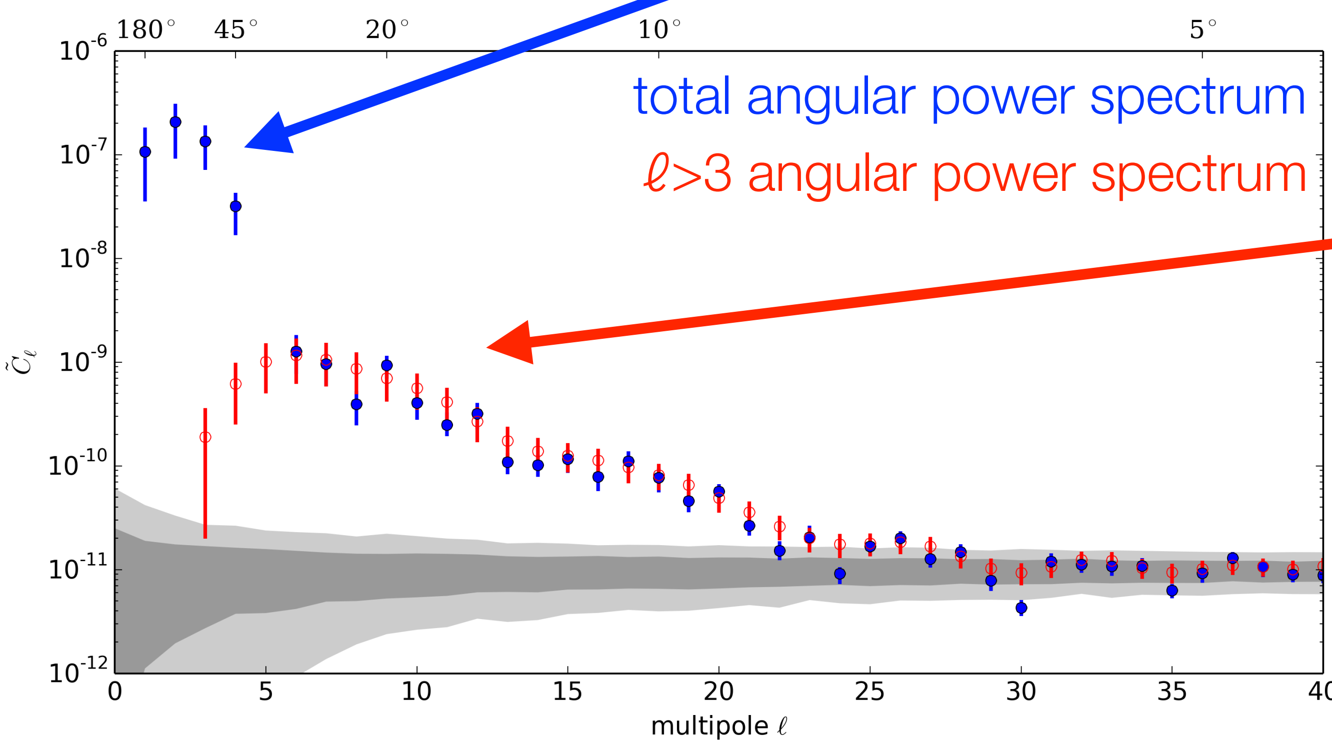


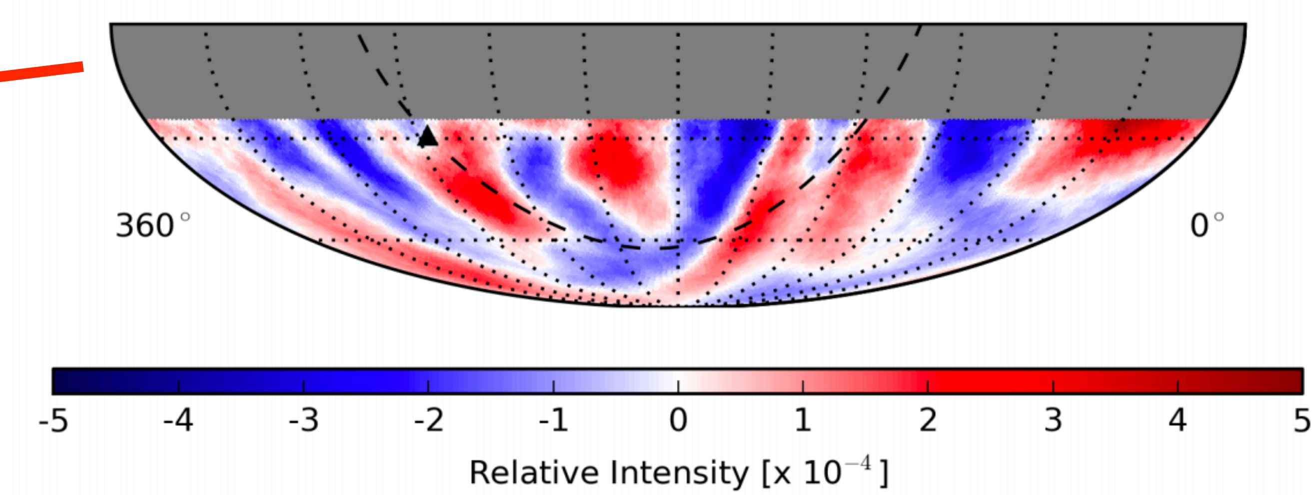
spherical harmonic analysis

missing
vertical
component
(m = 0)

Aartsen et al., ApJ 826, 220 (2016)







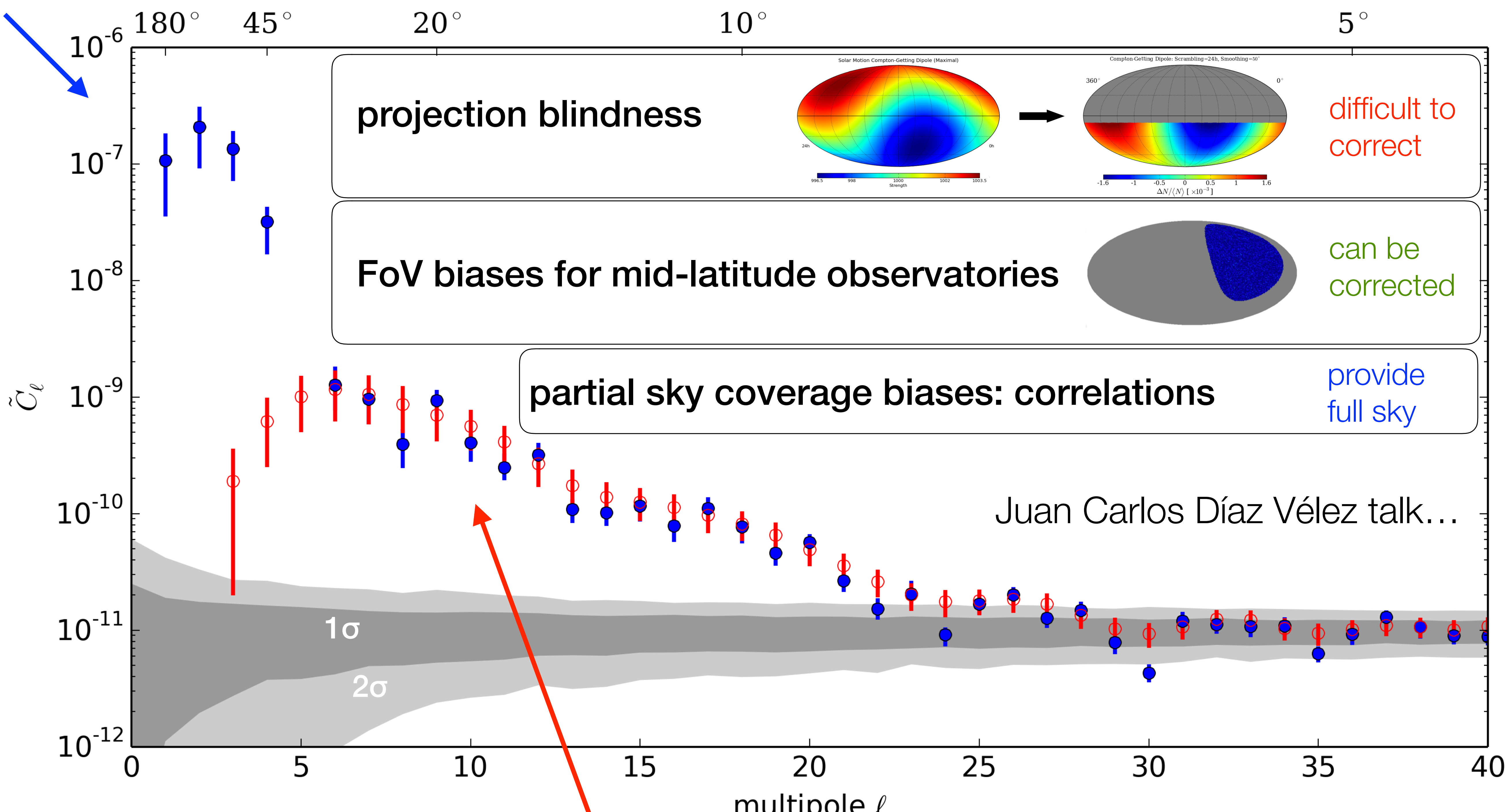
southern hemisphere

median energy 20 TeV

angular power spectrum

phenomenological fingerprint: physics + biases

density gradient / diffusion?



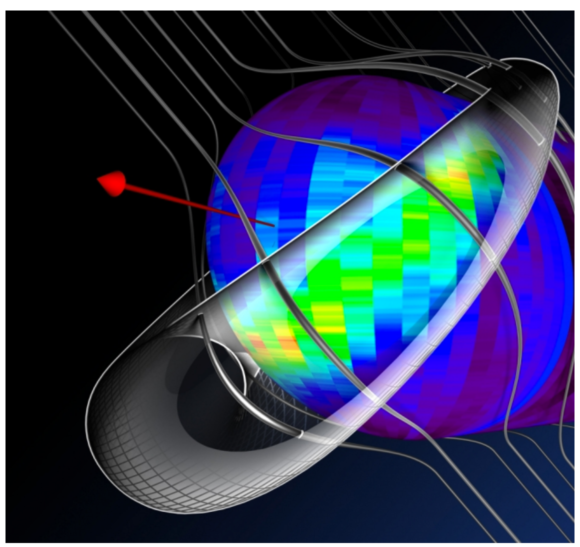
effects of magnetic instabilities / turbulence?

anisotropy and local magnetic environment
probing heliospheric magnetic structure

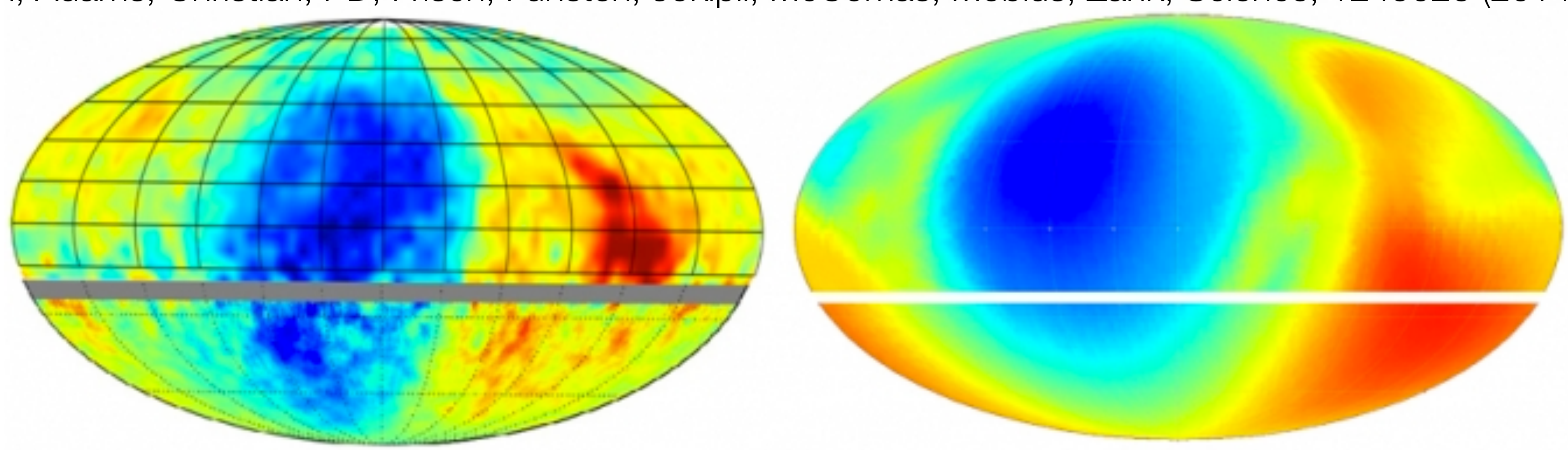
PD & Lazarian 2013
López-Barquero, Xu, PD, Lazarian, Pogorelov, Yan
ApJ 842,54 2017

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)



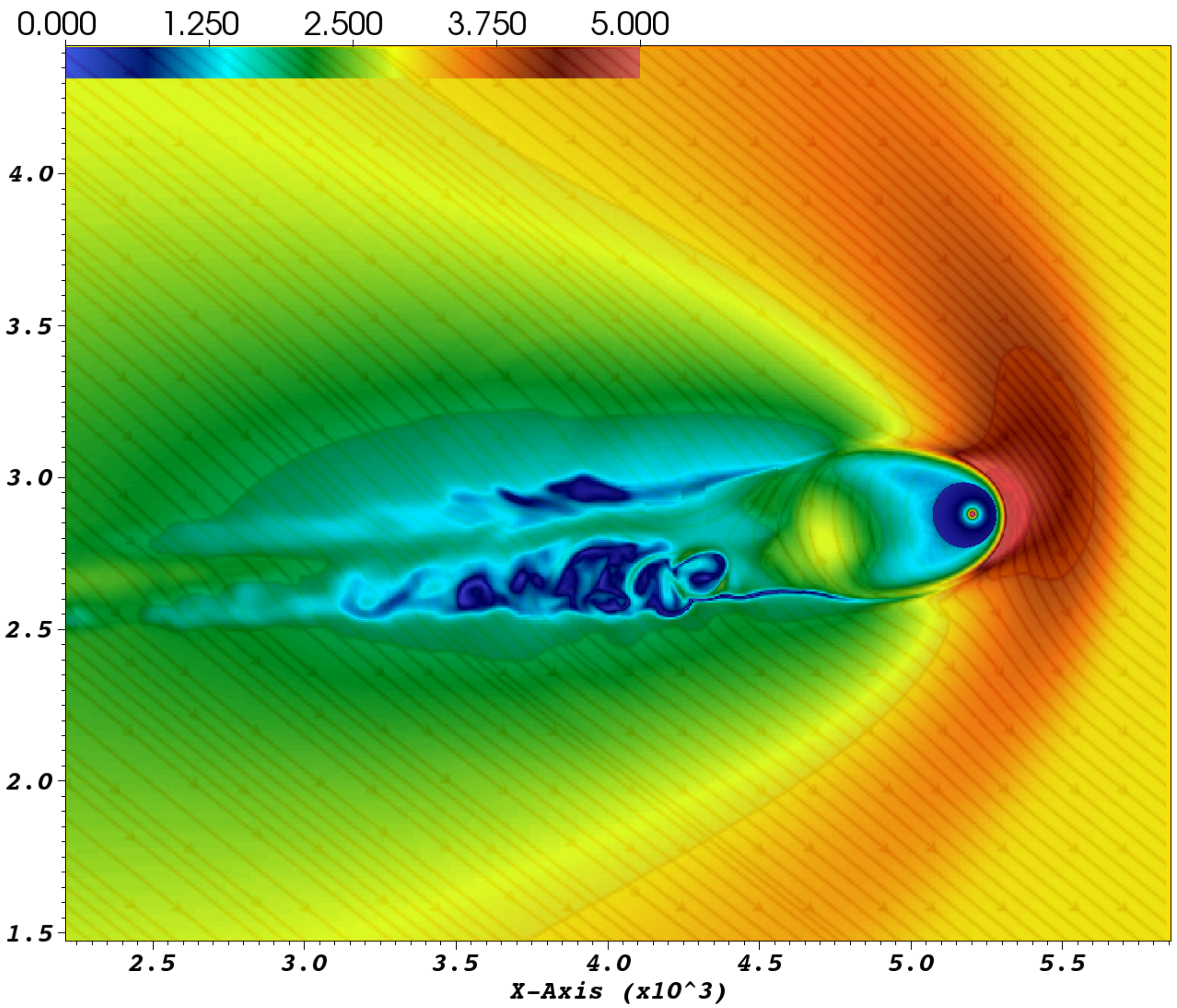
CR density gradient ordered by LIMF - heliosphere perturbs **TeV CR** arrival directions

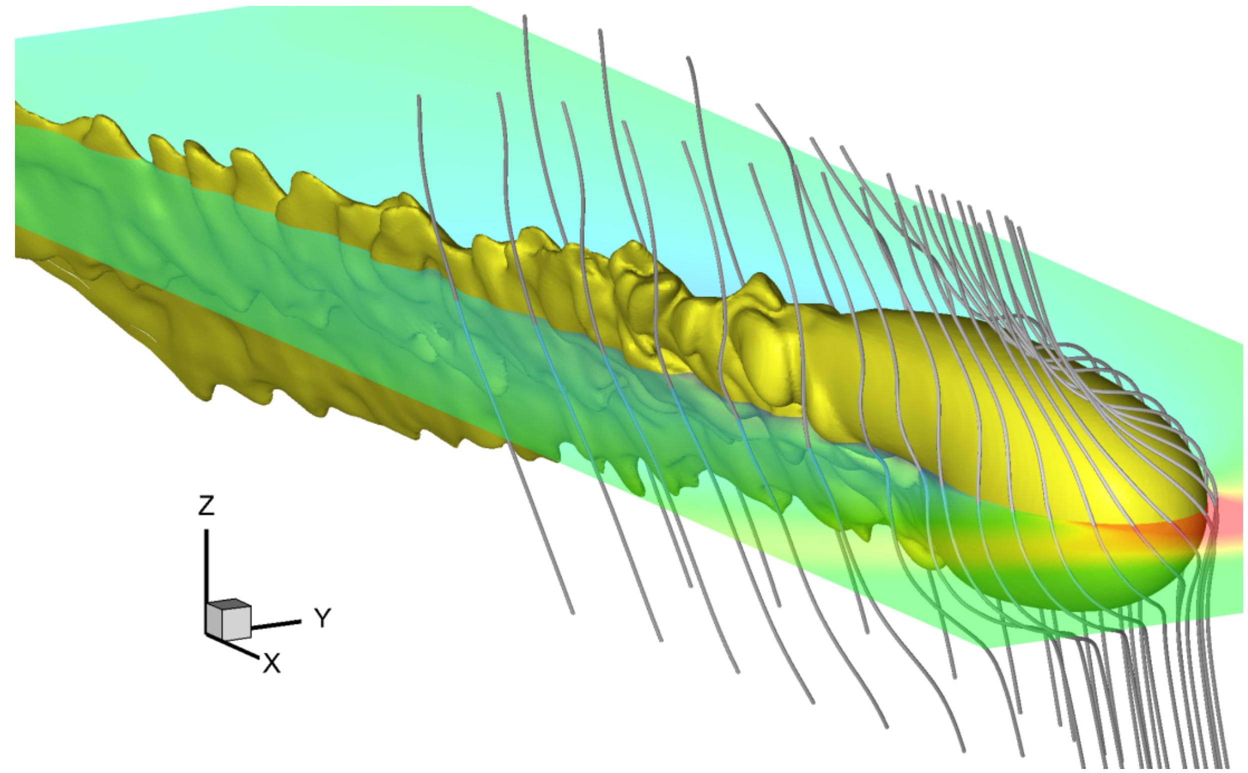
accounting for complex heliospheric magnetic field
unfold interstellar arrival directions
standard diffusion

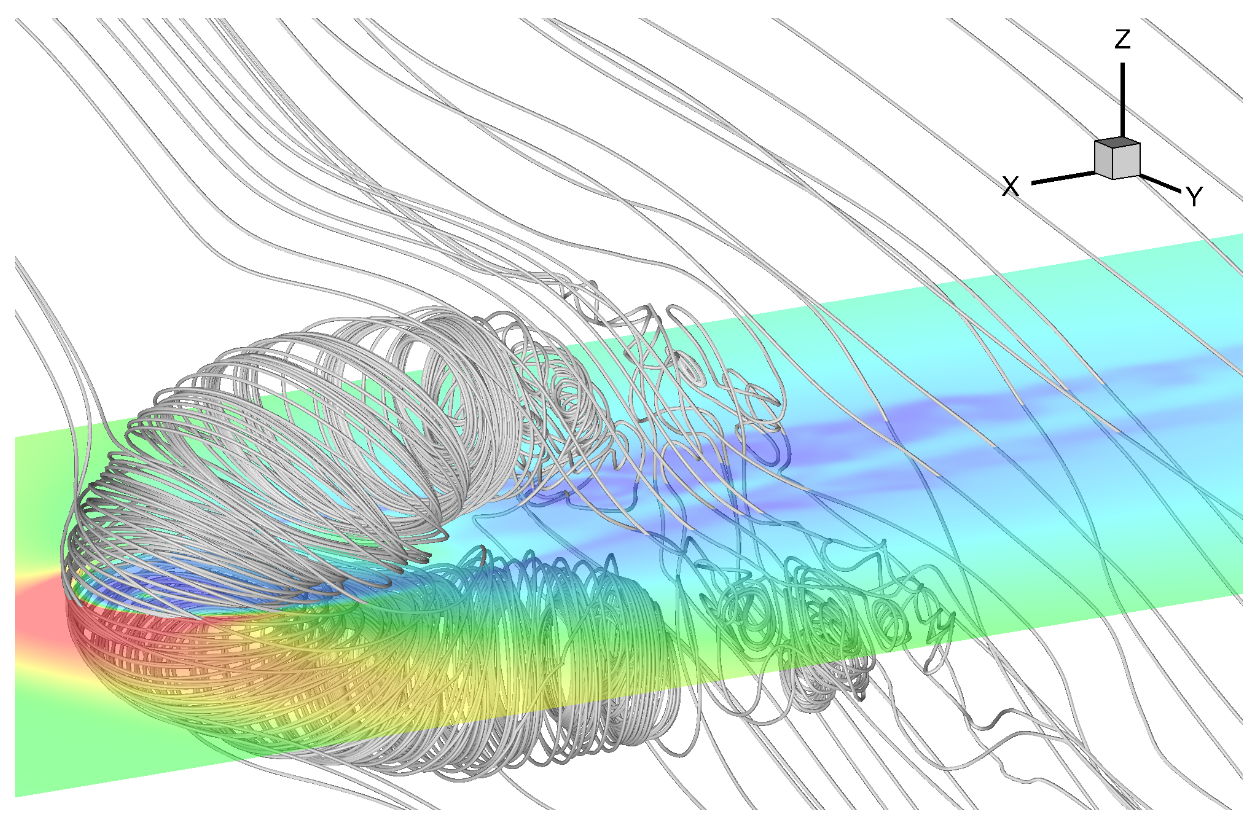
Zhang, Zuo & Pogorelov ApJ 790, 5 (2014)
Zhang & Pogorelov, JPCS 767, 012027 (2016)

cosmic ray anisotropy

heliosphere







Heliospheric model by
Borovikov, Heerikhuisen, Pogorelov, 2015

cosmic ray anisotropy
heliosphere

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

draping of interstellar magnetic field

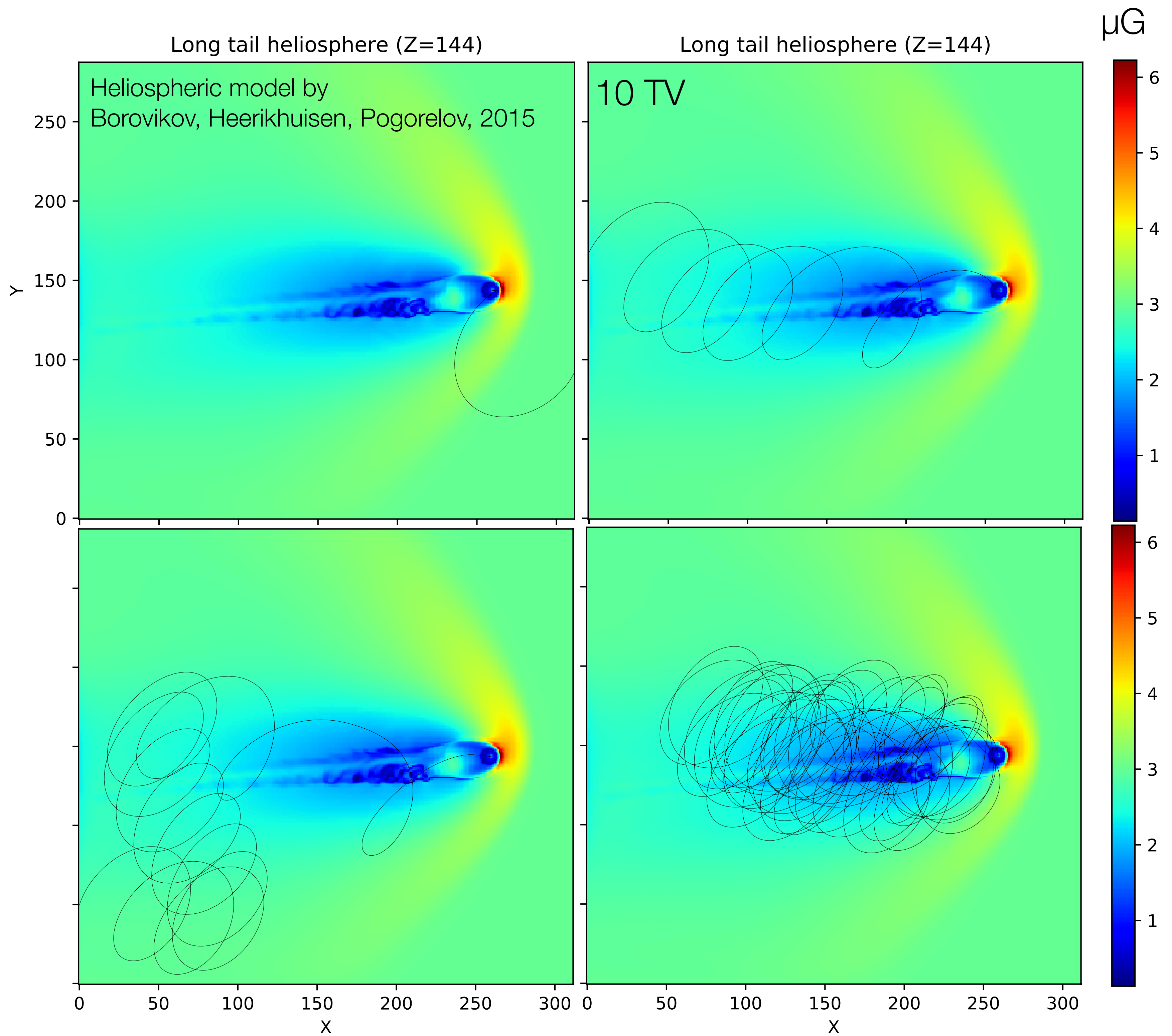
magnetic mirror

10 TV particles can be trapped

residence time can reach ~20 years

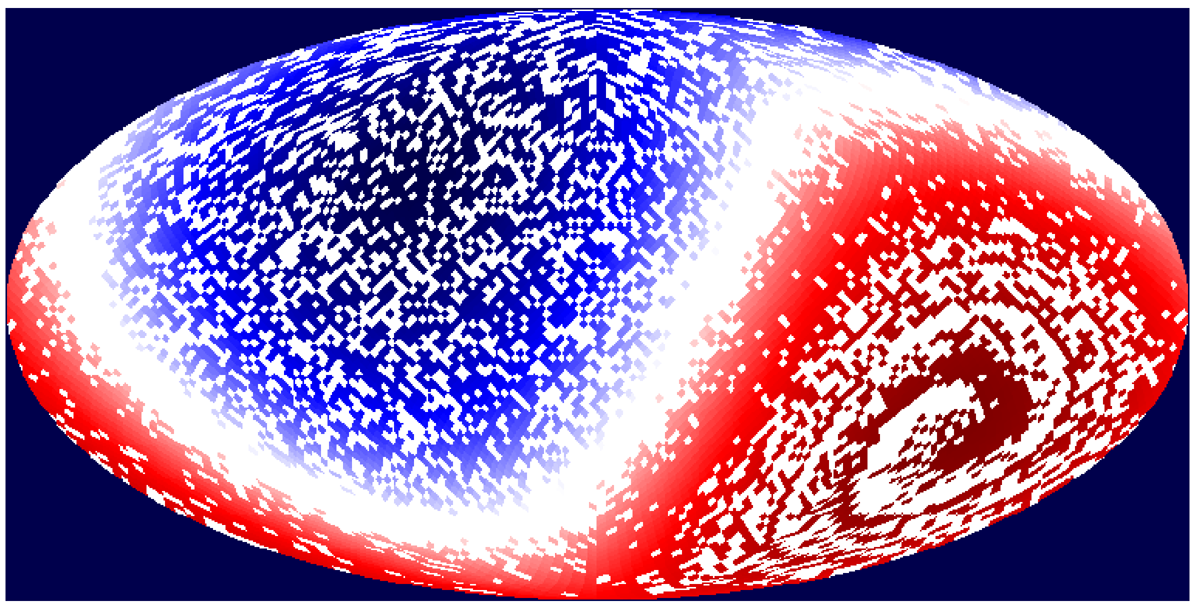
strong heliospheric influence

cosmic rays ISM distribution re-shaped



anisotropy and local magnetic environment
probing heliospheric magnetic structure

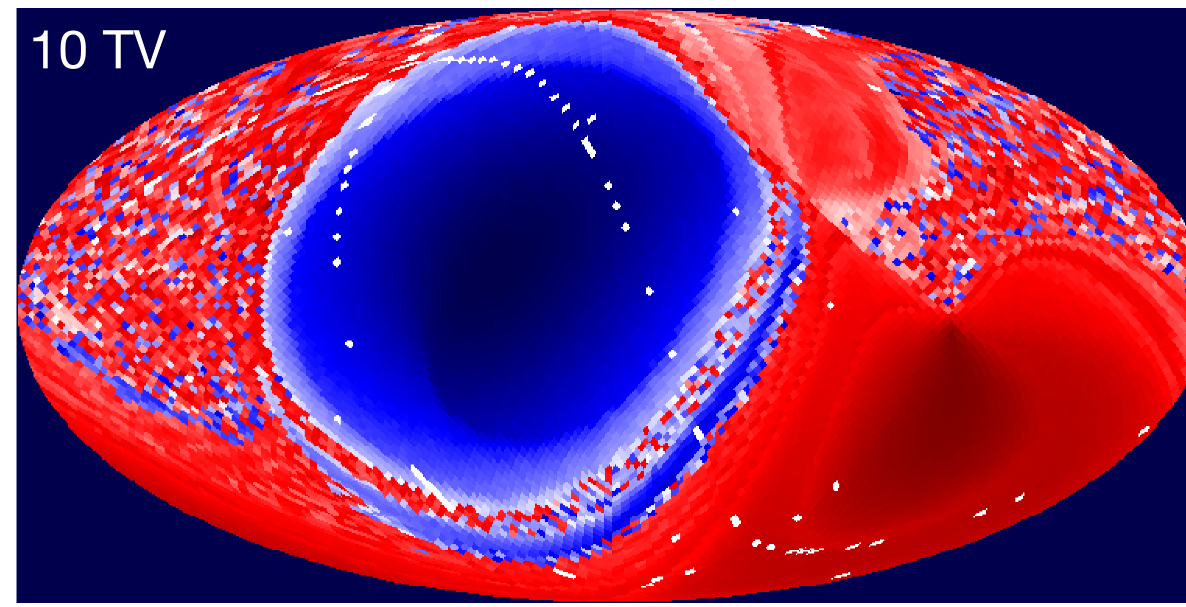
Juan Carlos Díaz Vélez & PD

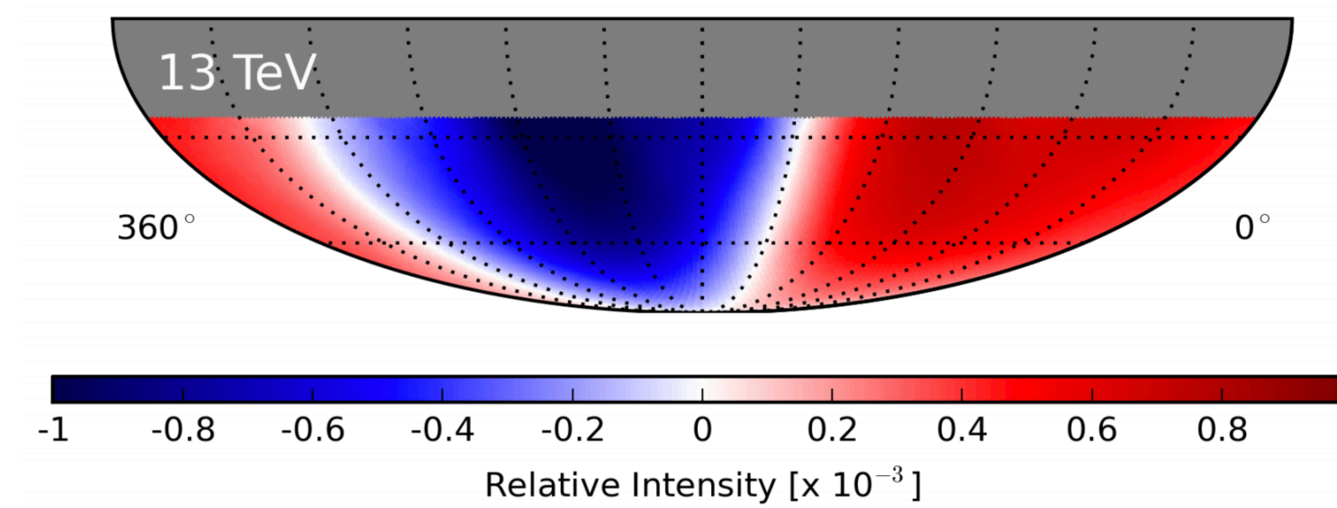


backward propagation
assume dipole pitch-angle distribution in the ISM
(isotropic diffusion)

strong heliospheric influence

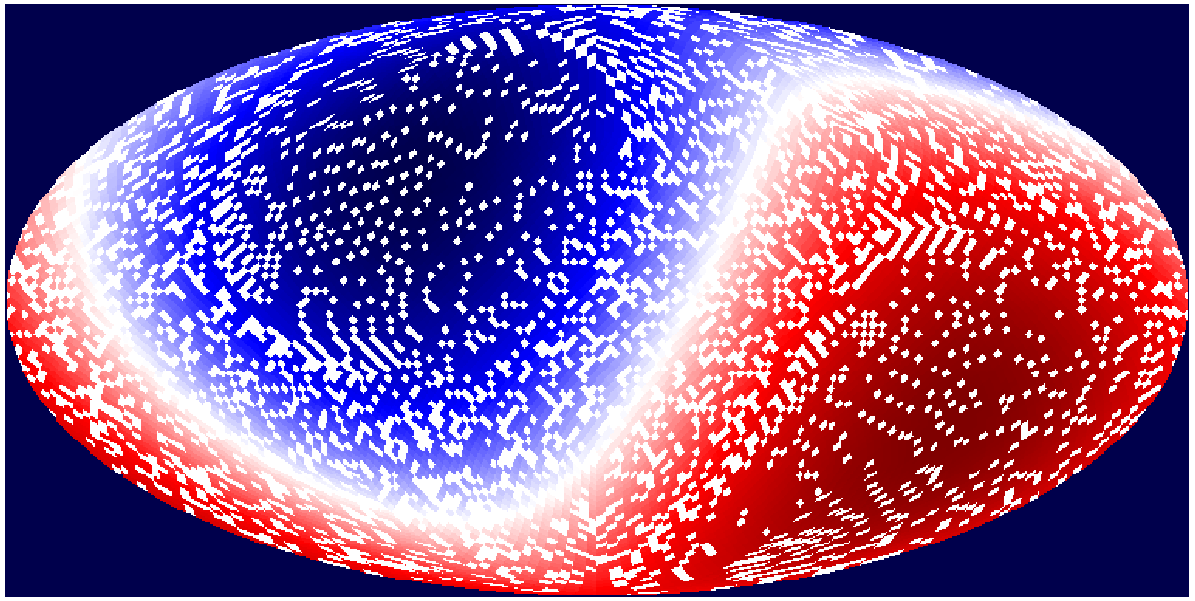
- \+ energy response distribution
- \+ cosmic ray mass composition
- \+ experimental sky map reconstruction

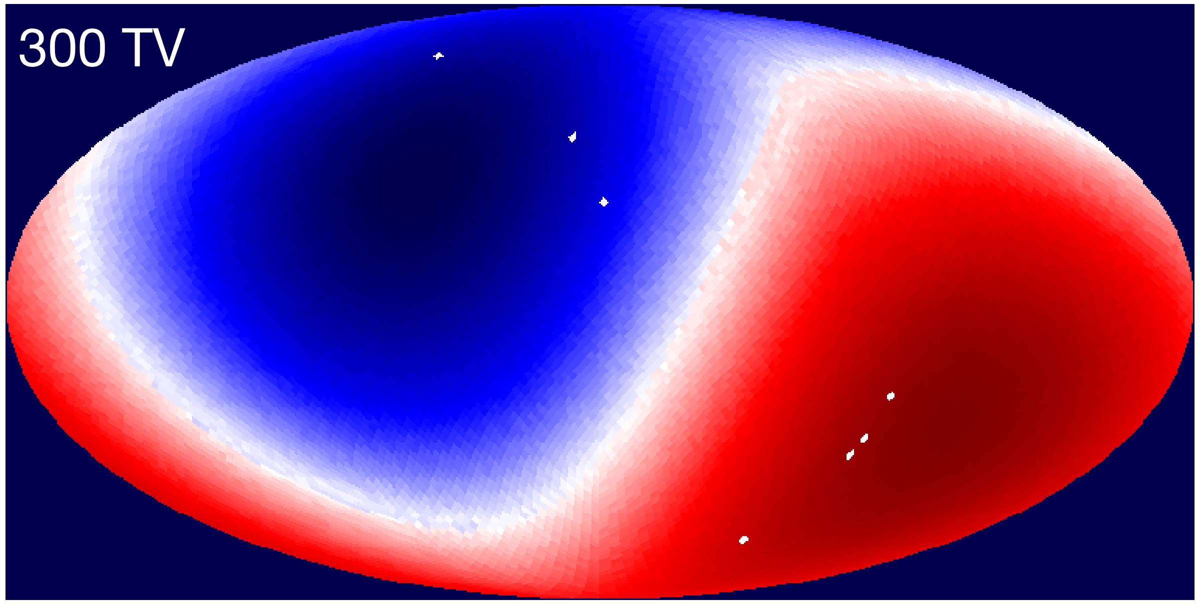


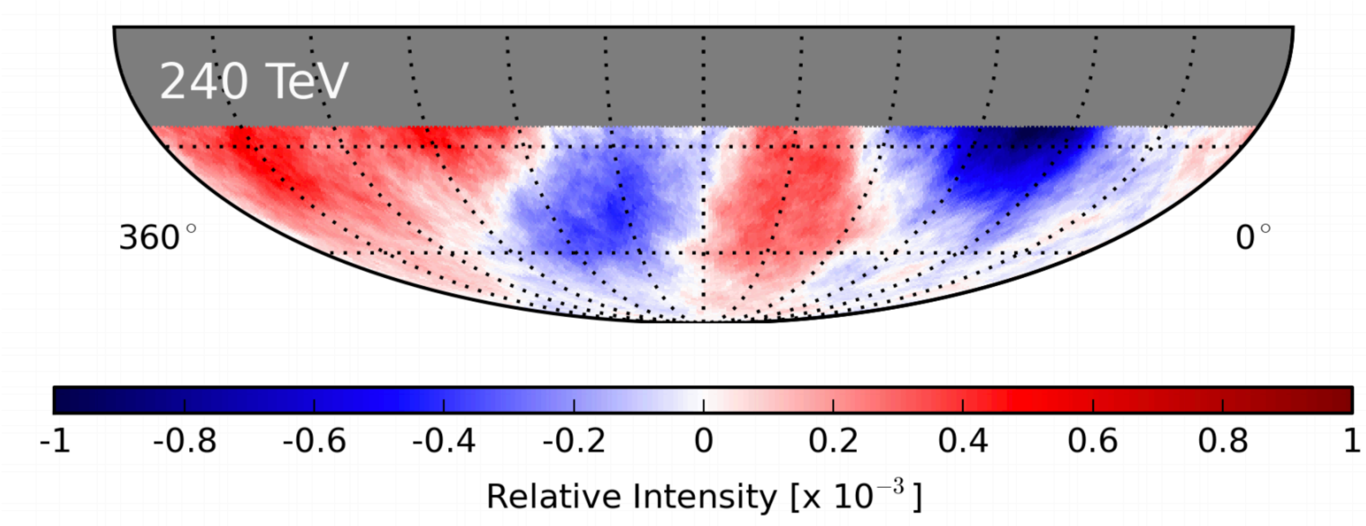


anisotropy and local magnetic environment
probing heliospheric magnetic structure

Juan Carlos Díaz Vélez & PD







backward propagation
assume dipole pitch-angle distribution in the ISM (isotropic diffusion)

no heliospheric influence

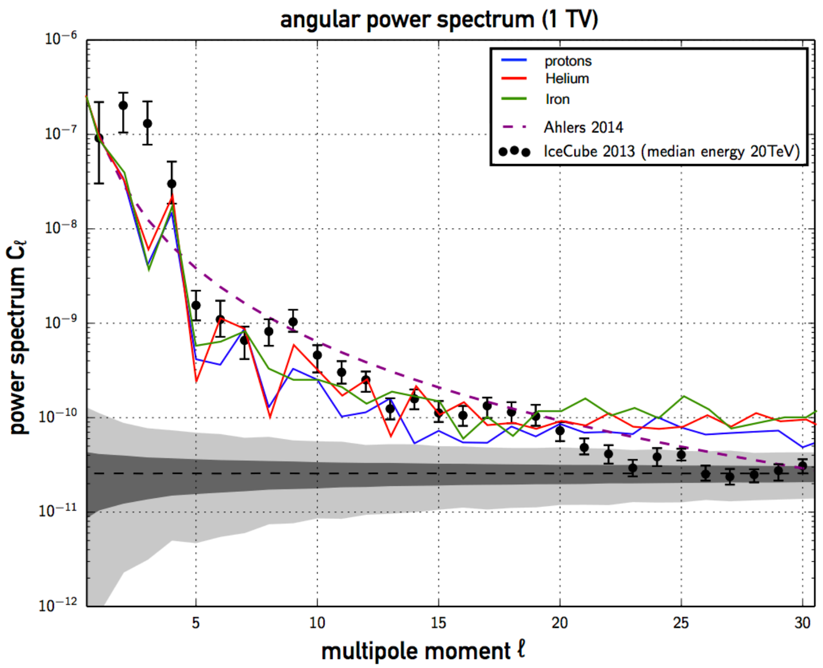
pitch-angle distribution in the ISM cannot be the same as that at 10 TV

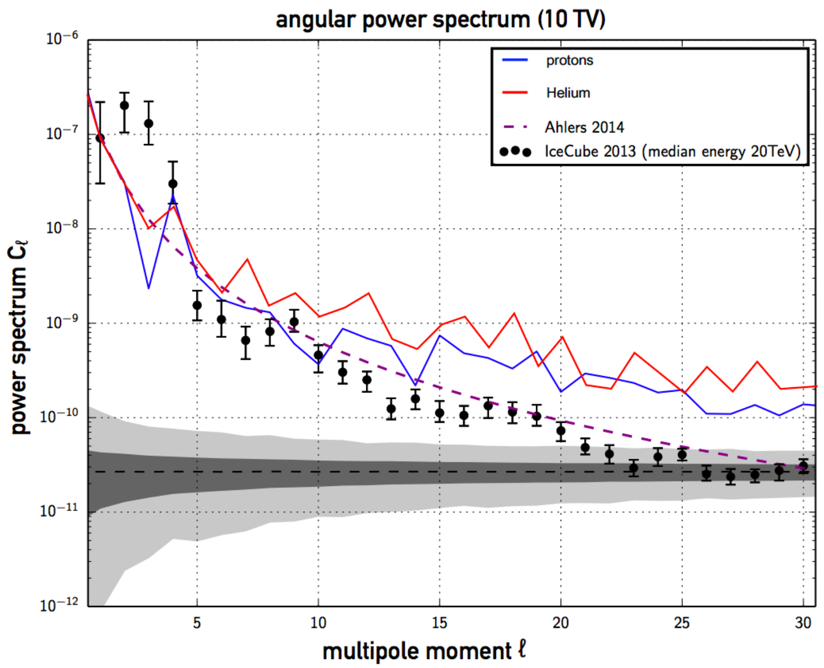
anisotropy and local magnetic environment
probing heliospheric magnetic structure

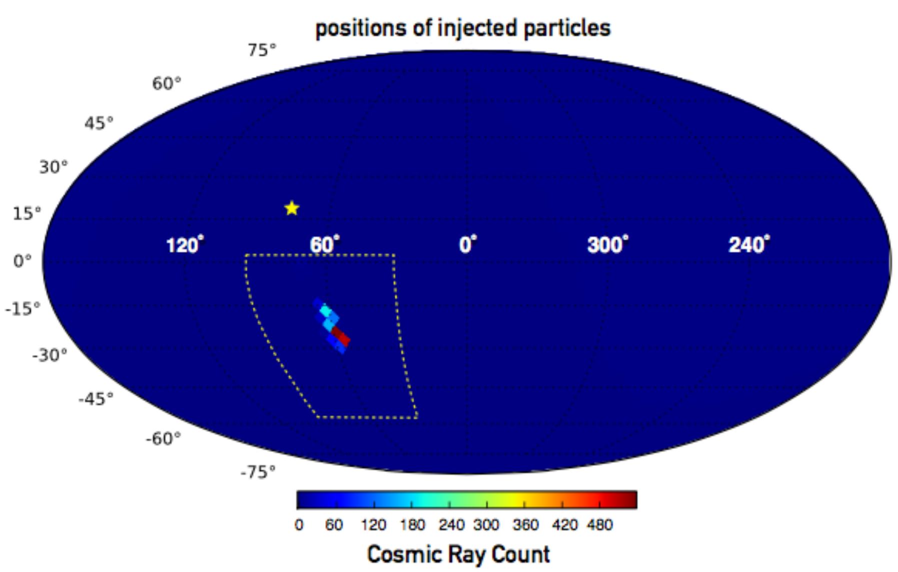
forward propagation
injection @ 6000 AU - target @ 200 AU

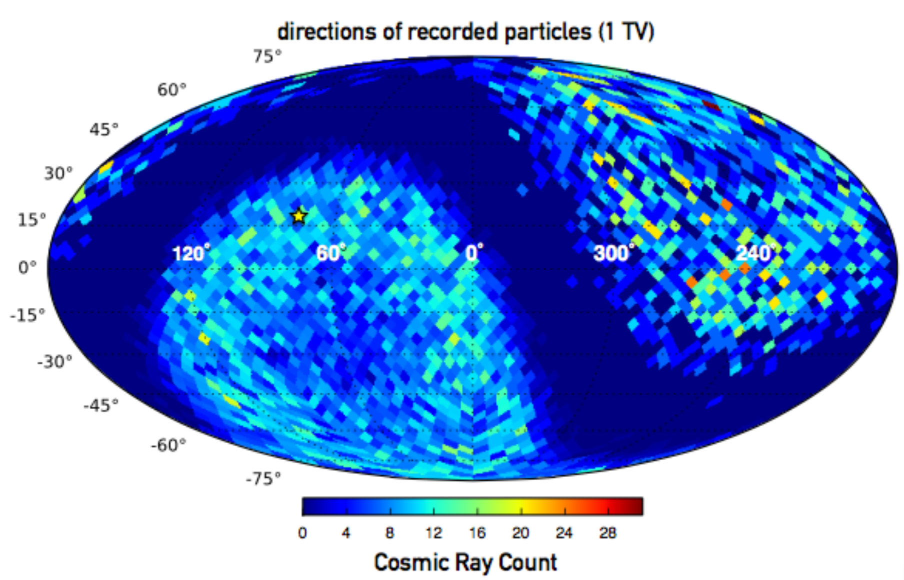
strong heliospheric influence

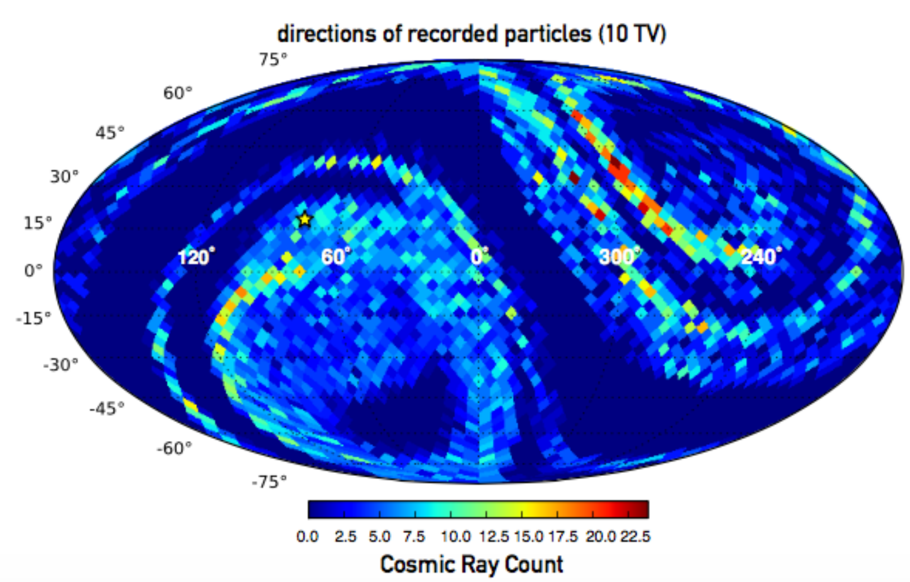
uniform pitch-angle distribution
decomposed into angular components











López-Barquero, Xu, PD, Lazarian, Pogorelov, Yan
ApJ 842,54 (2017) - arXiv:1610.03097

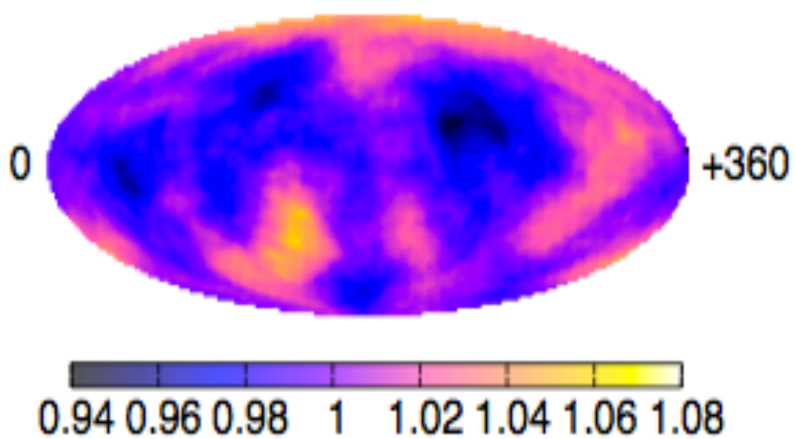
backward propagation
assume dipole pitch-angle distribution in the ISM
(isotropic diffusion)

cosmic rays anisotropy

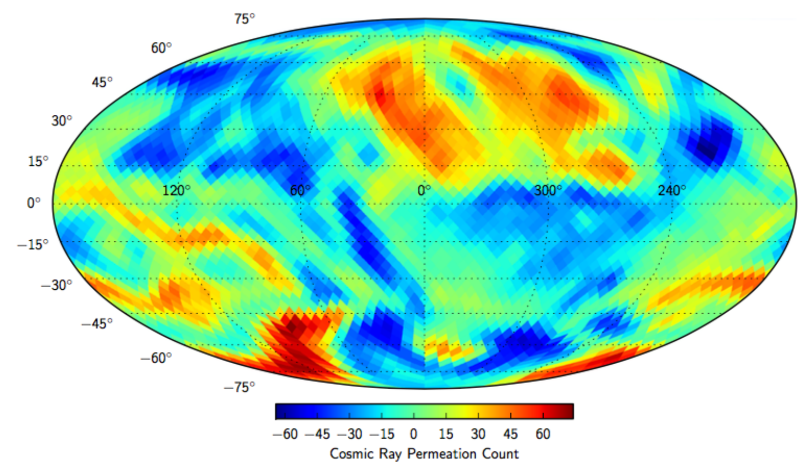
probing magnetic turbulence in the ISM

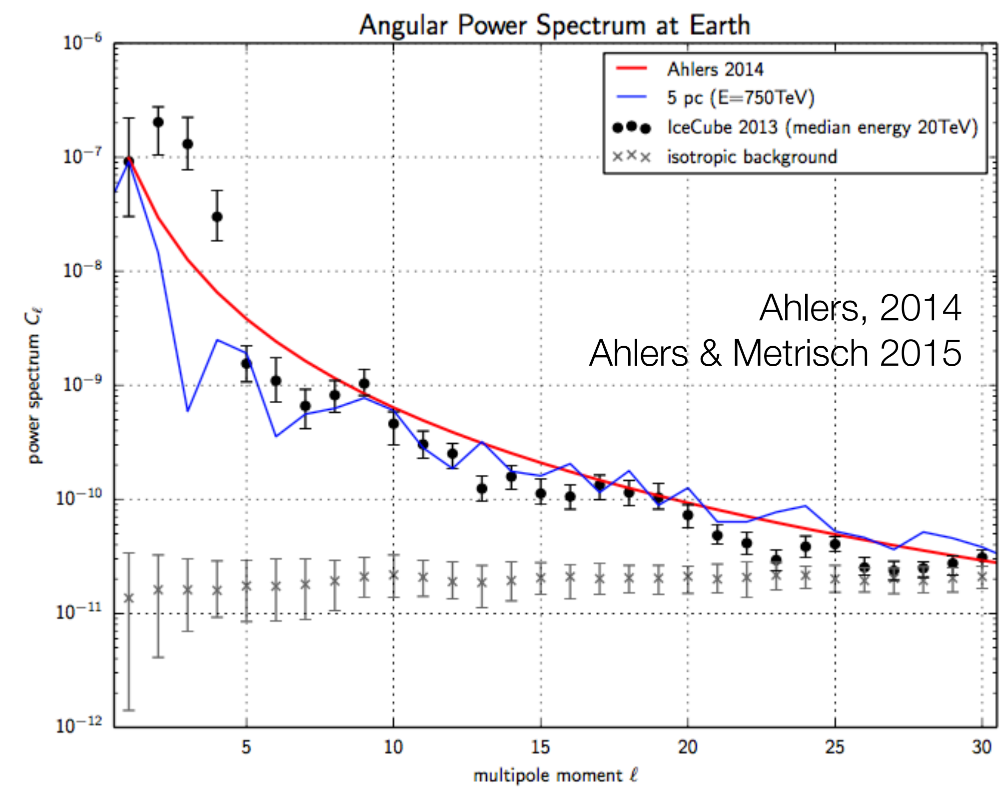
compressible MHD turbulence
(Cho & Lazarian, 2002)

10 PV



750 TV



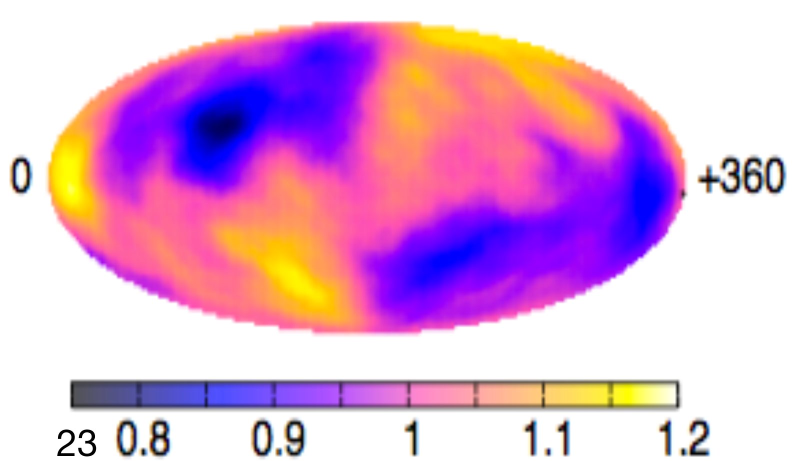


Ahlers, 2014
Ahlers & Metrisch 2015

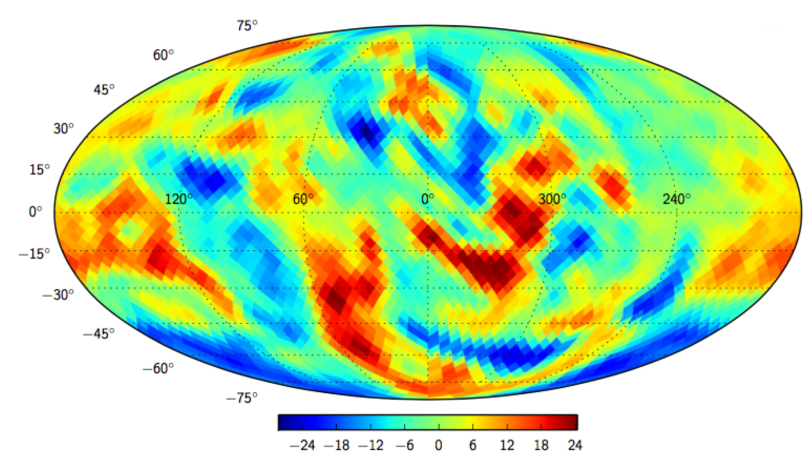
Giacinti & Sigl, 2012

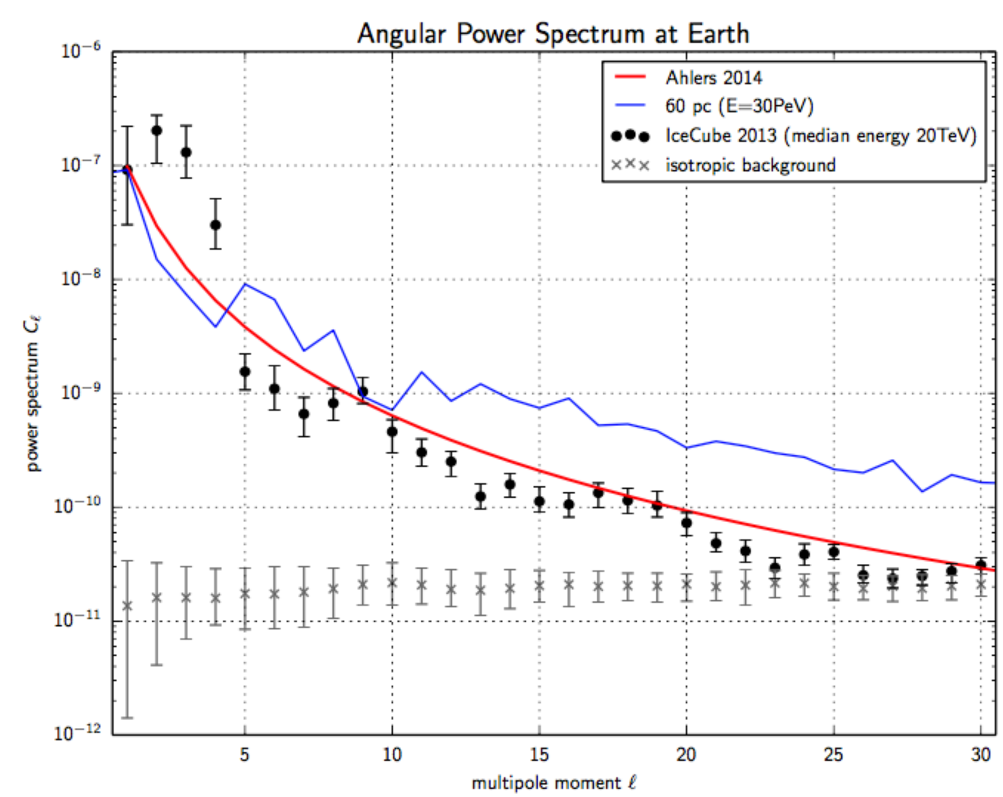
López-Barquero, Farber, Xu, PD, Lazarian
ApJ 830 19 (2016) - arXiv:1509.00892

50 PV



30 PV





cosmic rays anisotropy
probing magnetic turbulence in the ISM

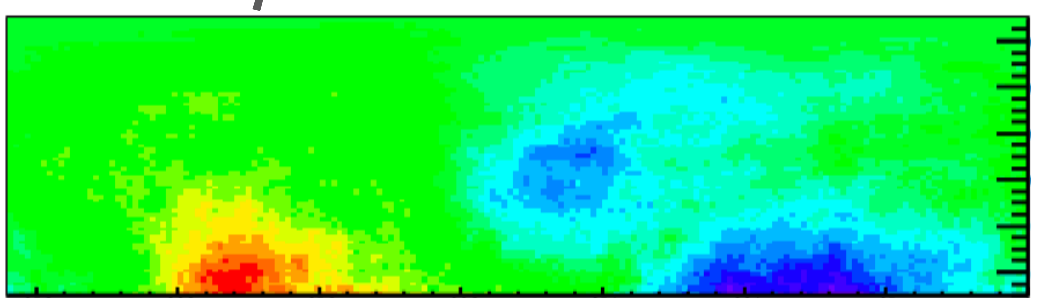
PeV-scale

Giacinti & Kirk, ApJ 835, 258 (2017)

pitch angle scattering on *incompressible* & *compressible* magnetic turbulence

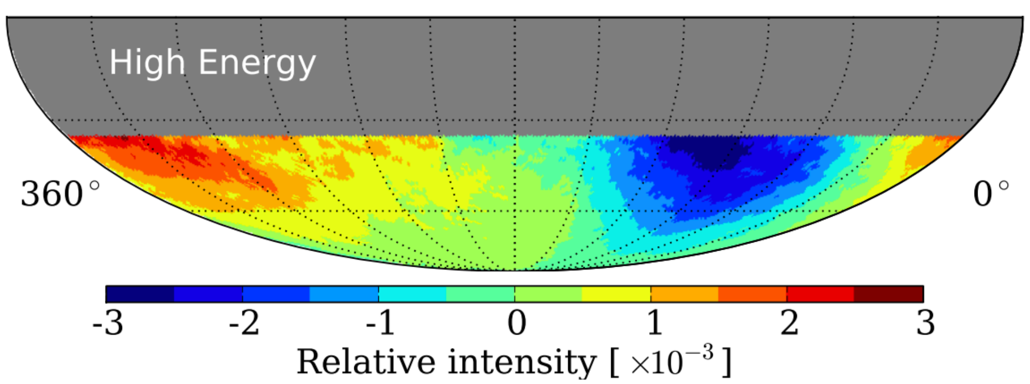
Tibet ASγ

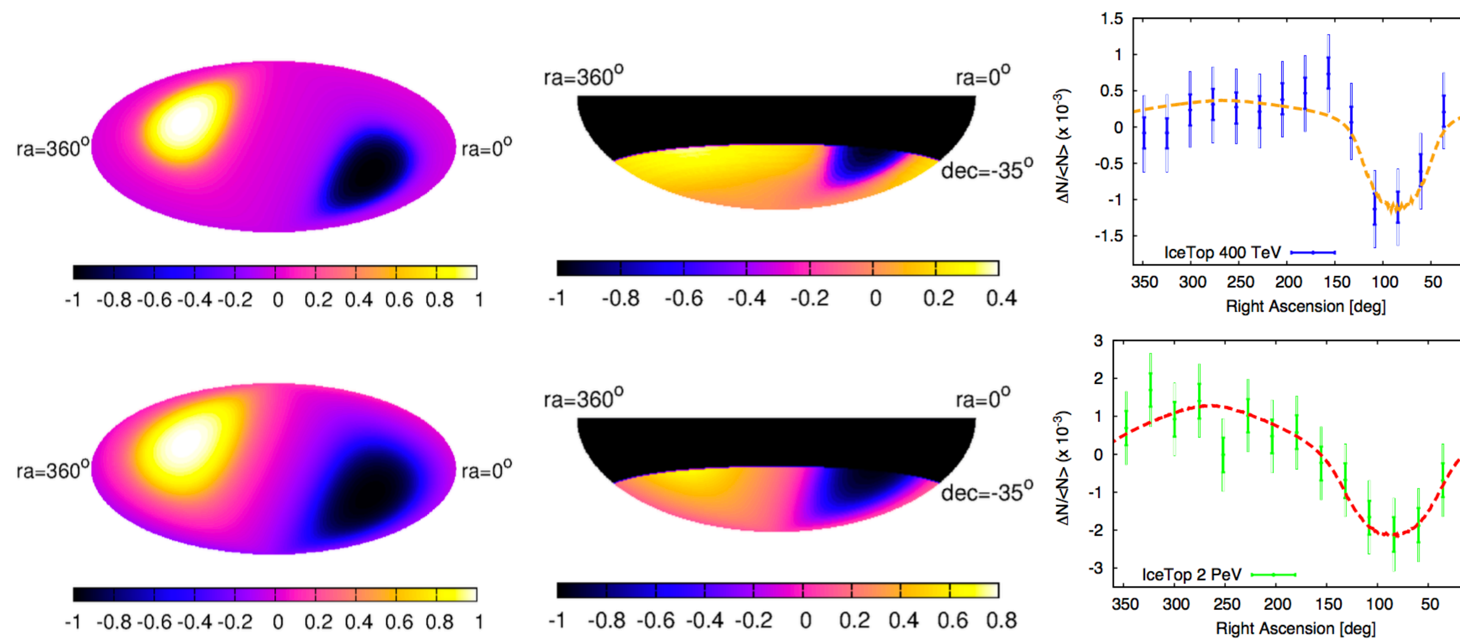
Amenomori et al. 2017



IceTop

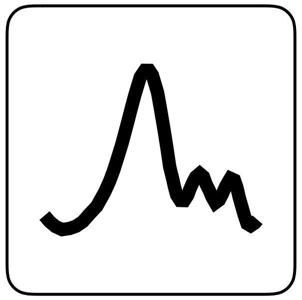
Aartsen et al., ApJ 765, 55, 2013





non-dipolar distribution aligned to LIMF

cosmic ray anisotropy
as a probe into…



propagation through interstellar medium

- diffusion in non-homogeneous turbulent plasmas — **large scale anisotropy**
- scattering with magnetic turbulence within mean free path — **small scale anisotropy**
- interstellar influence on rigidities ≳100 TV — **$r_L \gtrsim$ 7000 AU in 3 μG**

propagation through the heliosphere

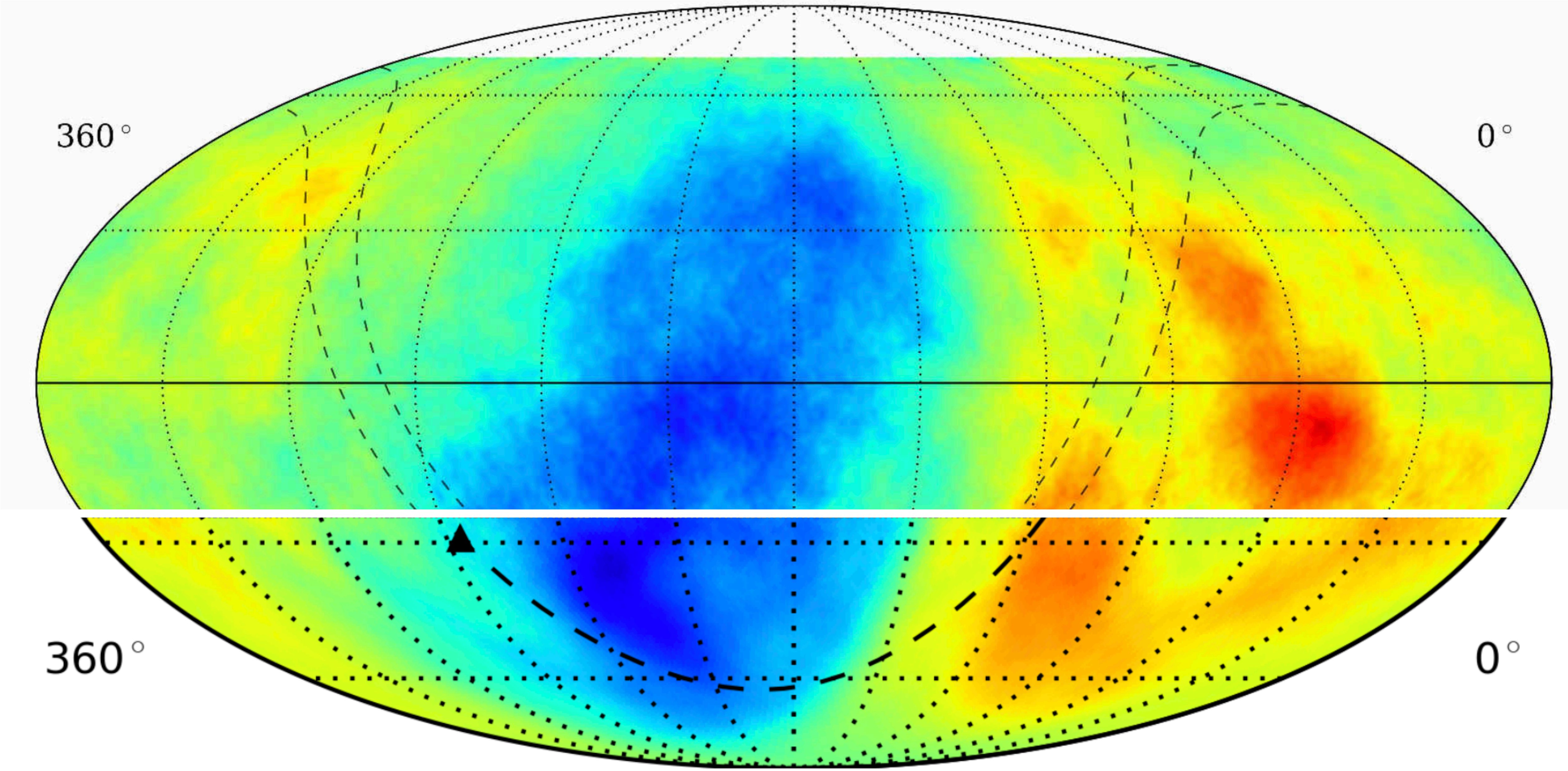
- heliospheric influence on rigidities ≲10 TV — **$r_L \lesssim$ 700 AU in 3 μG**
- redistribution of cosmic rays by heliospheric magnetic fields
- heliospheric modeling unfolding of interstellar properties

angular power spectrum as the **fingerprint** of the propagation history of cosmic rays

provide unbiased observations, if possible, to use anisotropy as a probe

provide anisotropy observations vs. CR particle rigidity

HAWC



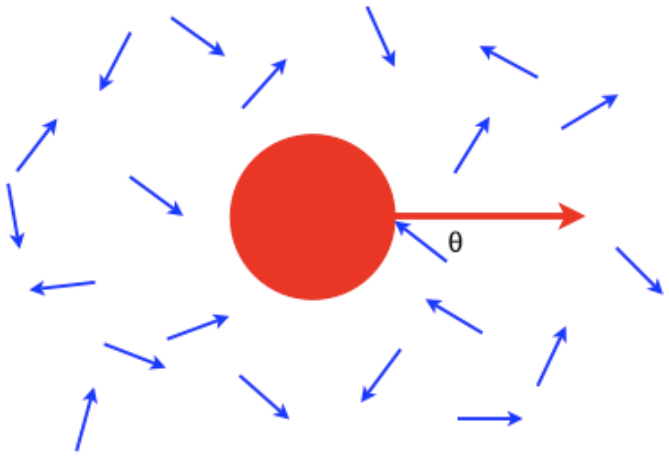
IceCube

talk by Juan Carlos Díaz Vélez later…

Backup

a known anisotropy

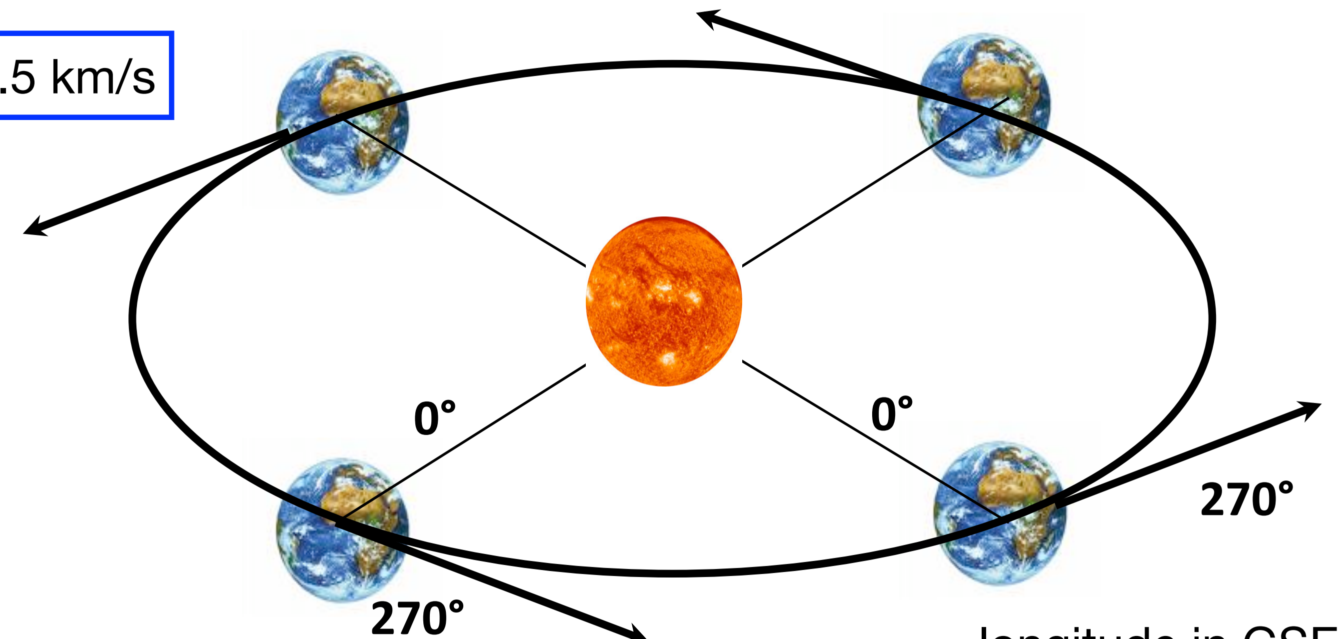
Earth's revolution around the Sun

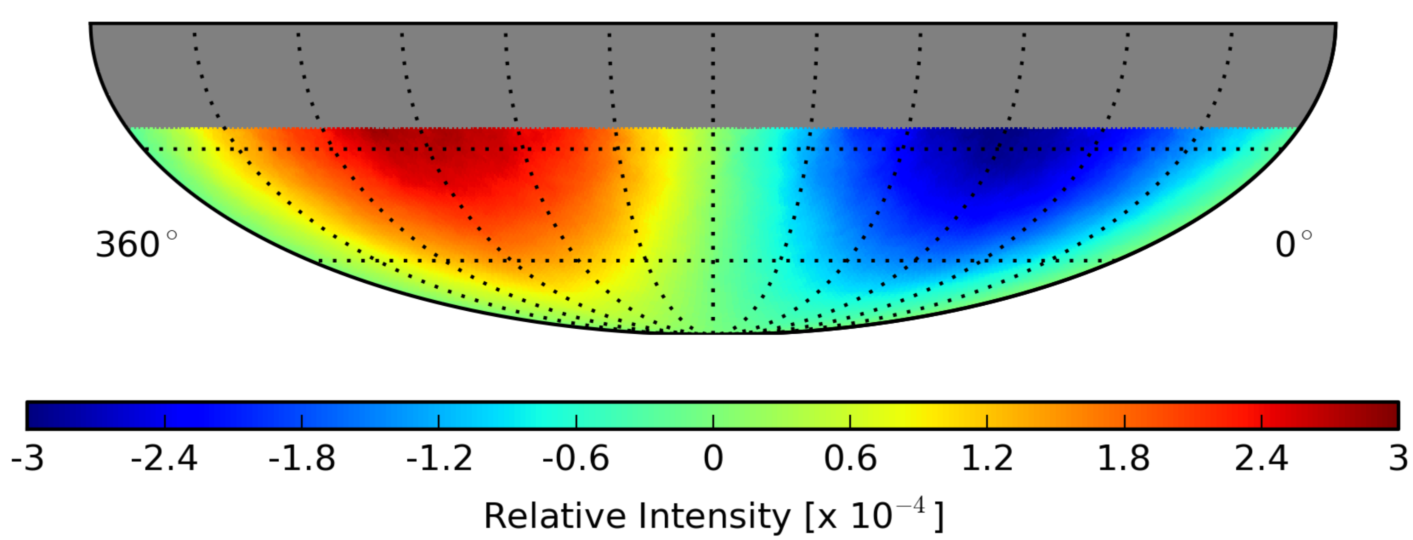


v = 29.8 ± 0.5 km/s

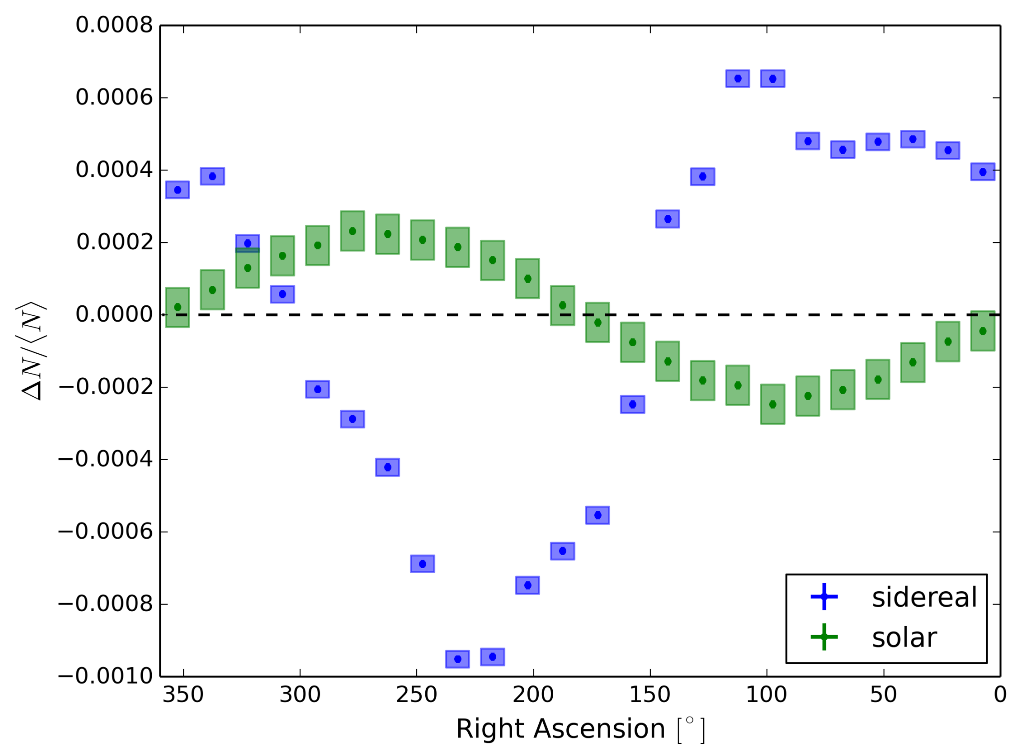
$$\frac{\Delta I}{I} = (\gamma + 2)\frac{v}{c}\cos\theta$$

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



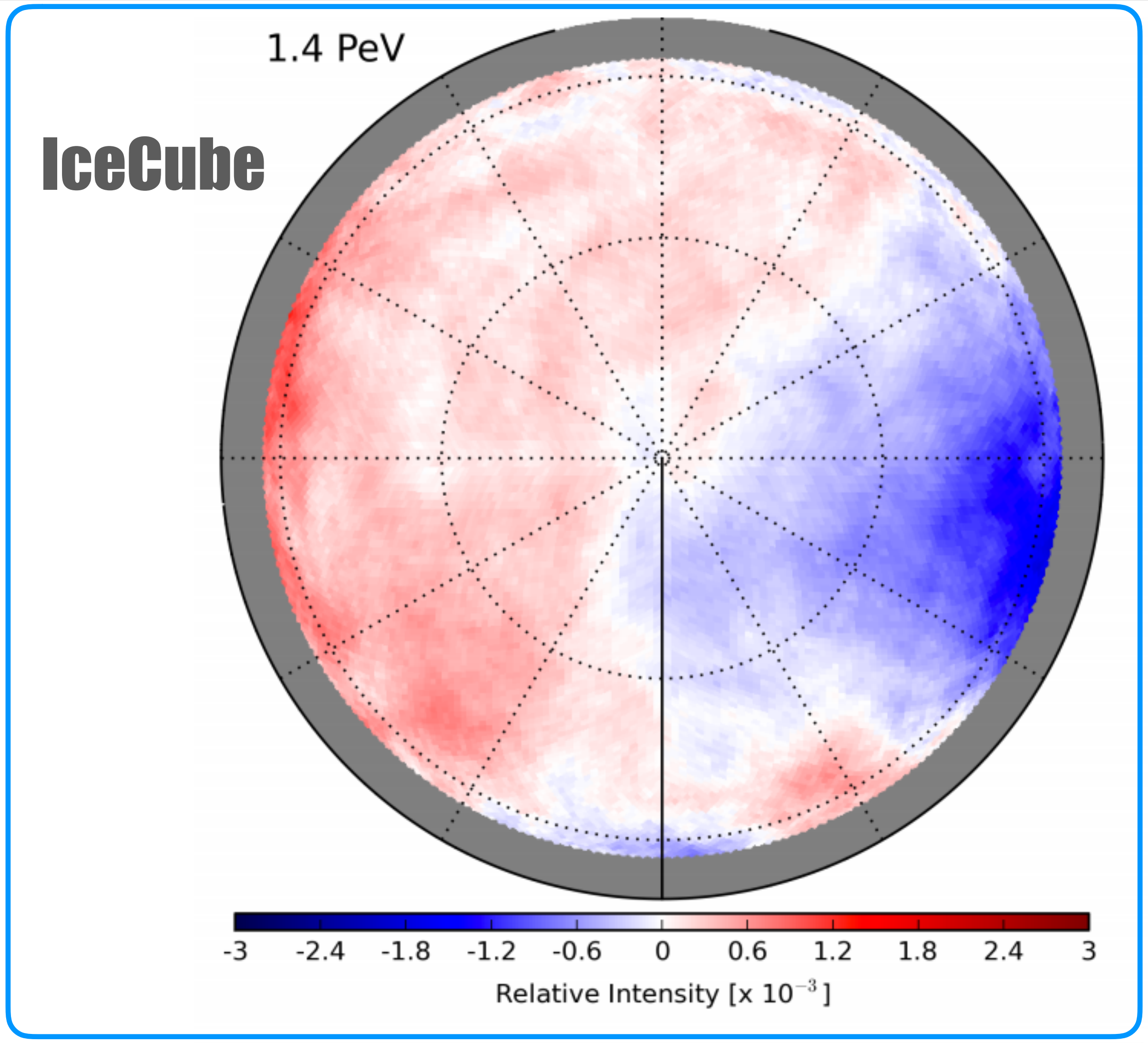


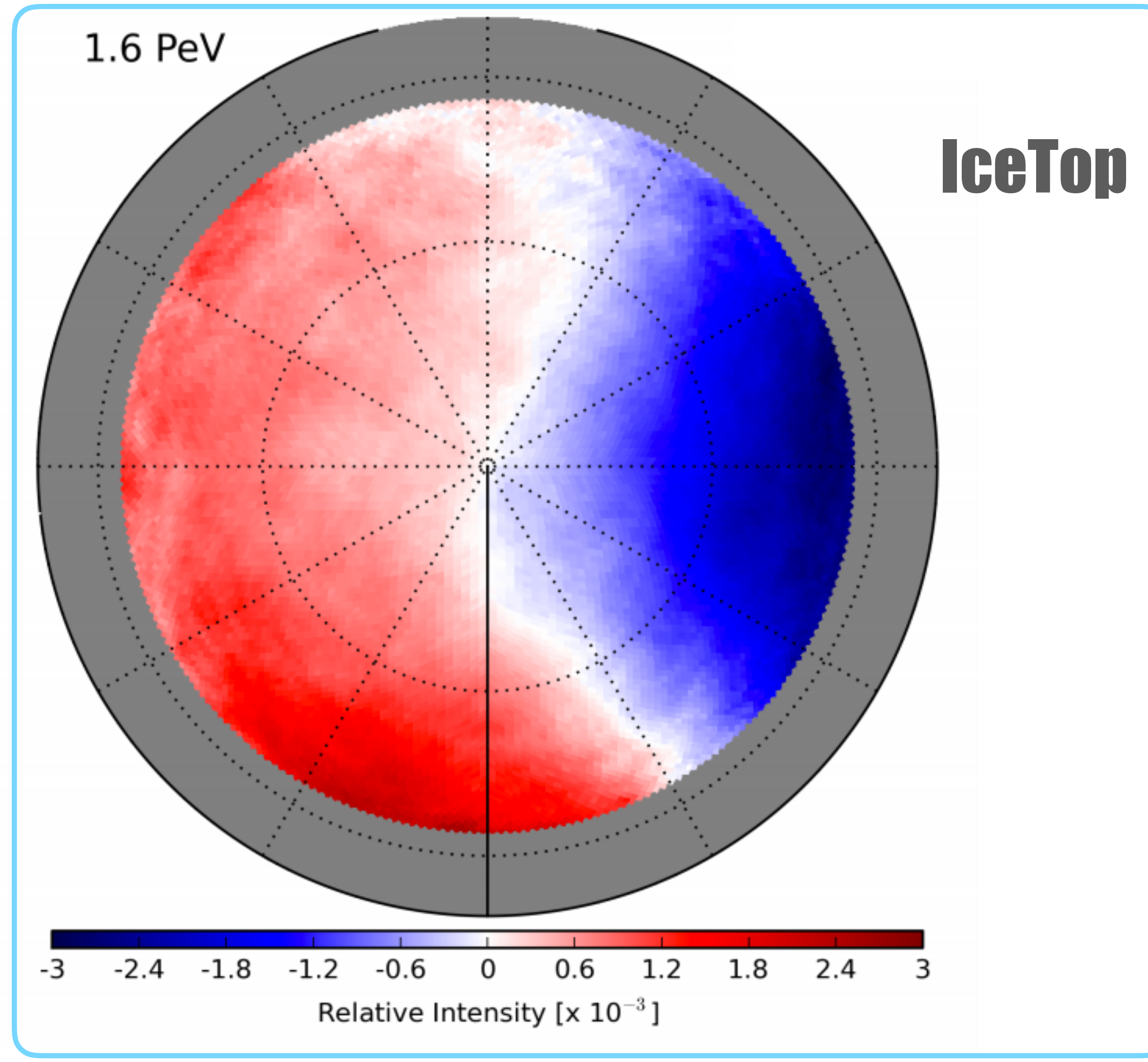
IceCube - Aartsen et al., ApJ 826, 220, 2016



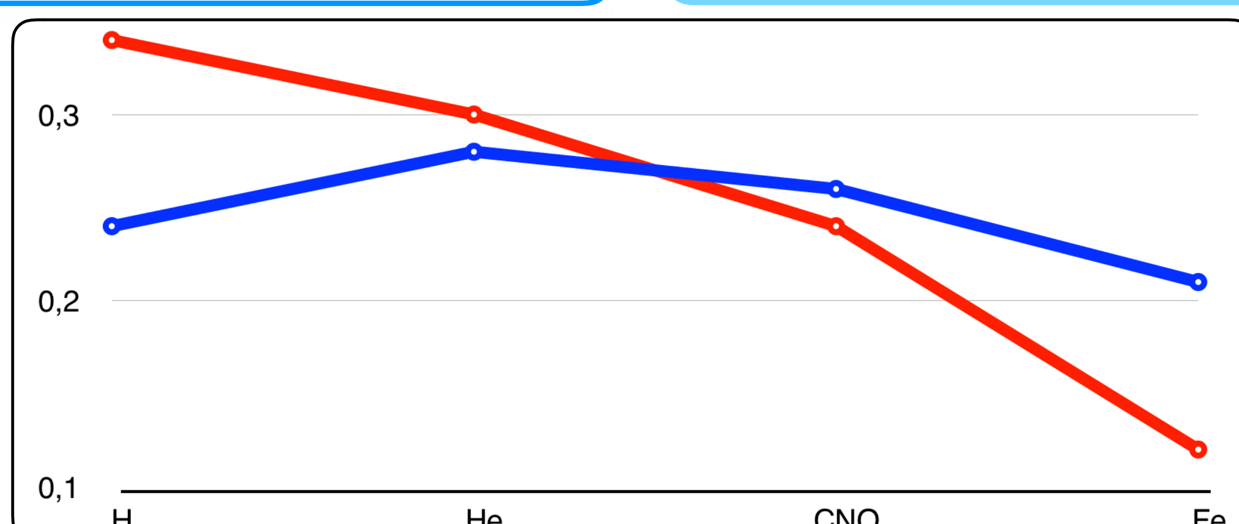
observing cosmic ray anisotropy

CR mass dependency ? Muons vs. EM showers?





IceCube



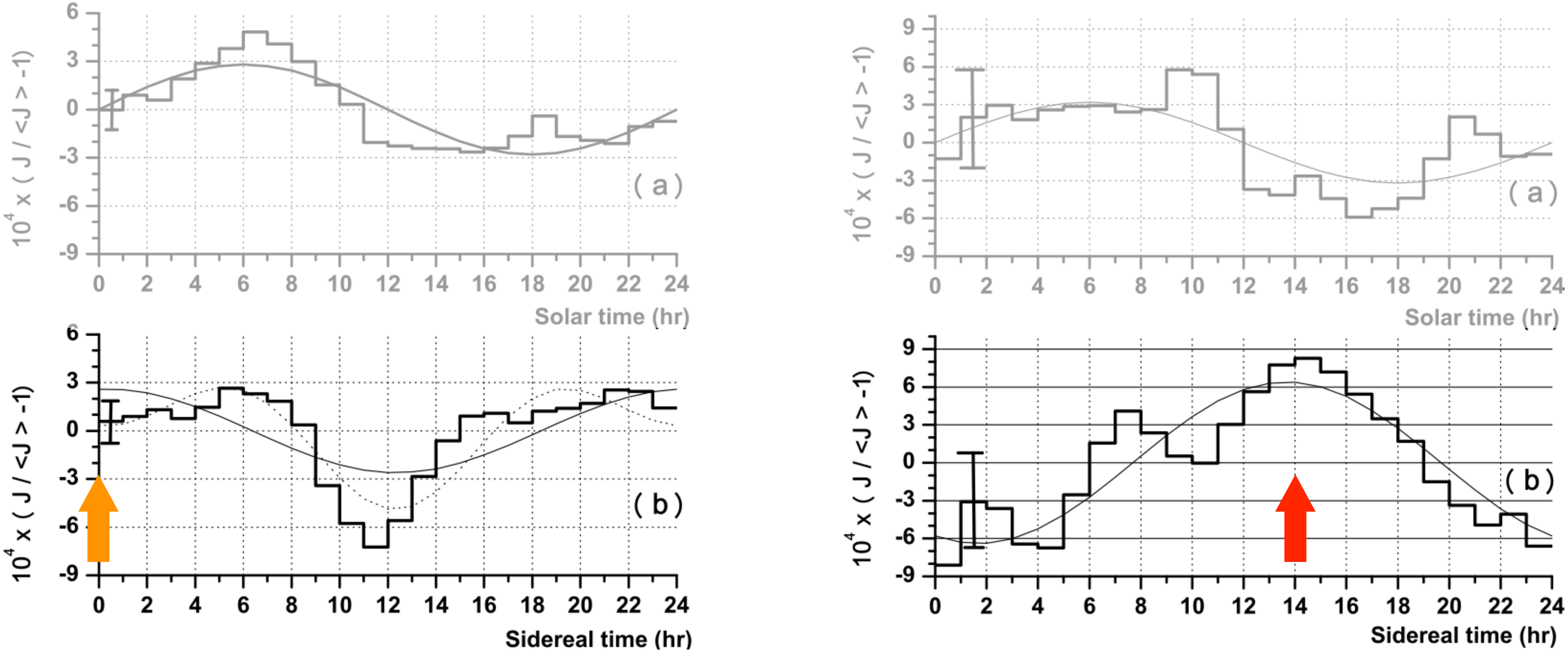
IceTop

large scale anisotropy
energy dependence

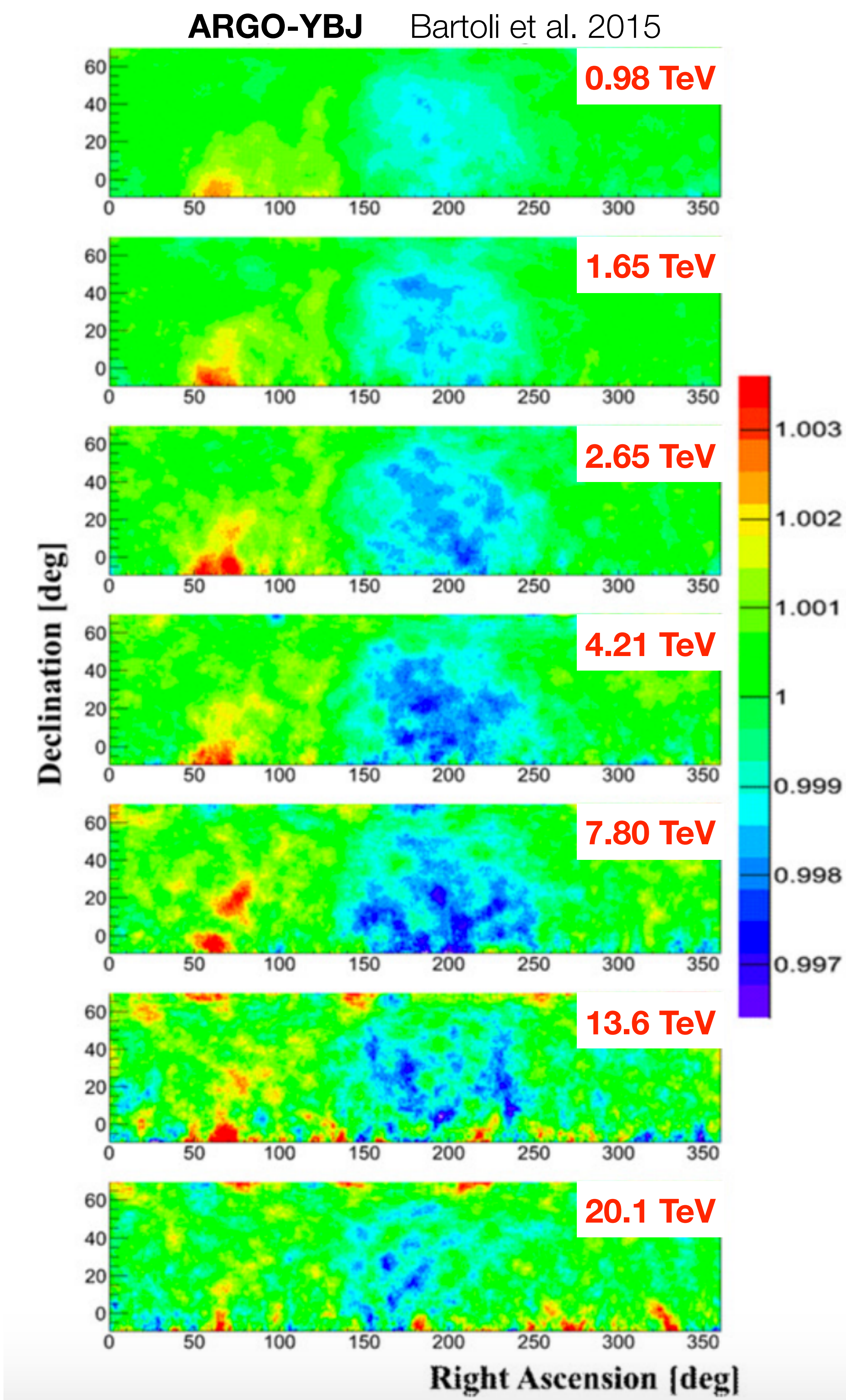
anisotropy changes with energy

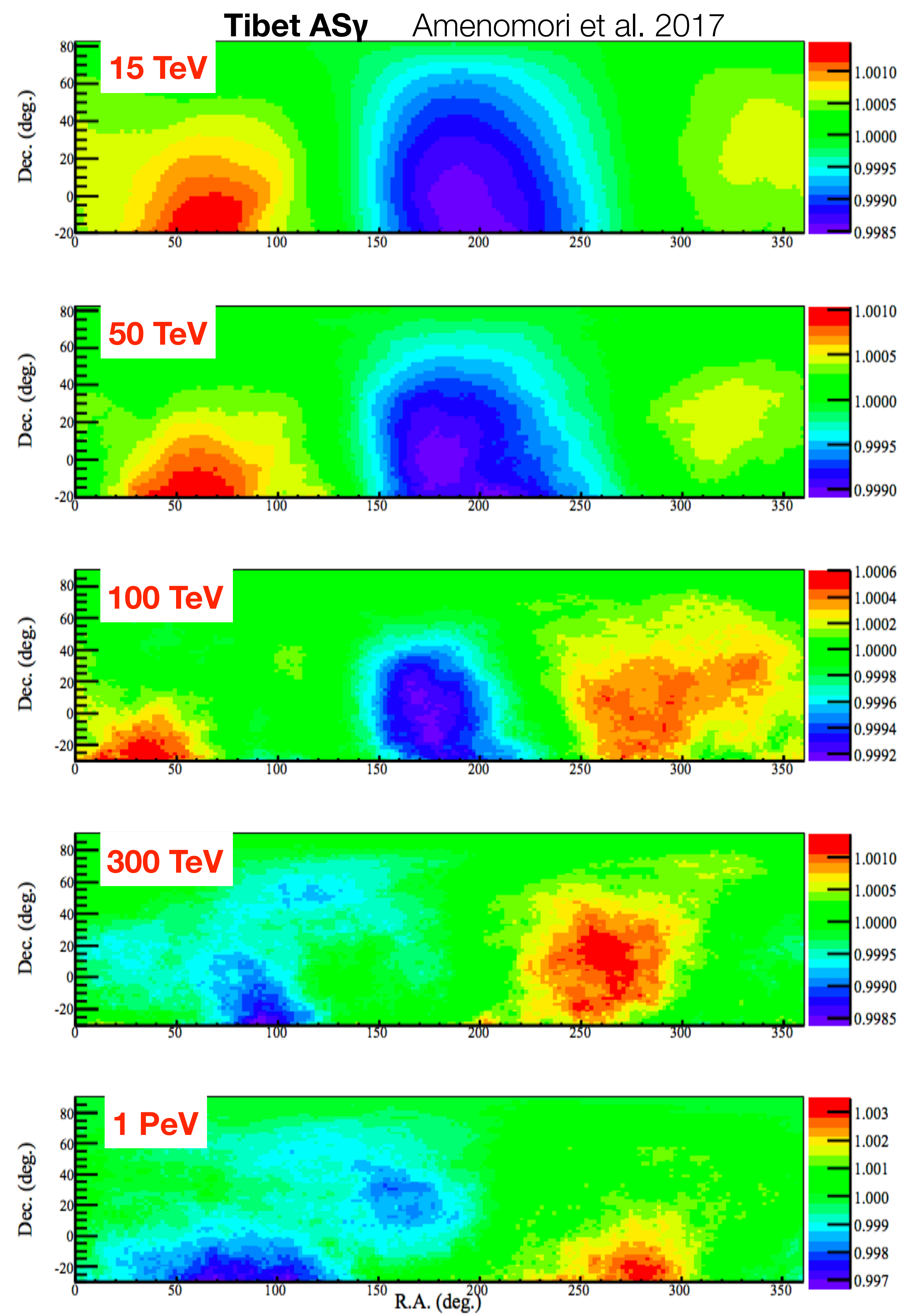
EAS TOP Aglietta et al., 2009

110 TeV **370 TeV**



anisotropy ***flips direction*** between 100 TeV and 400 TeV

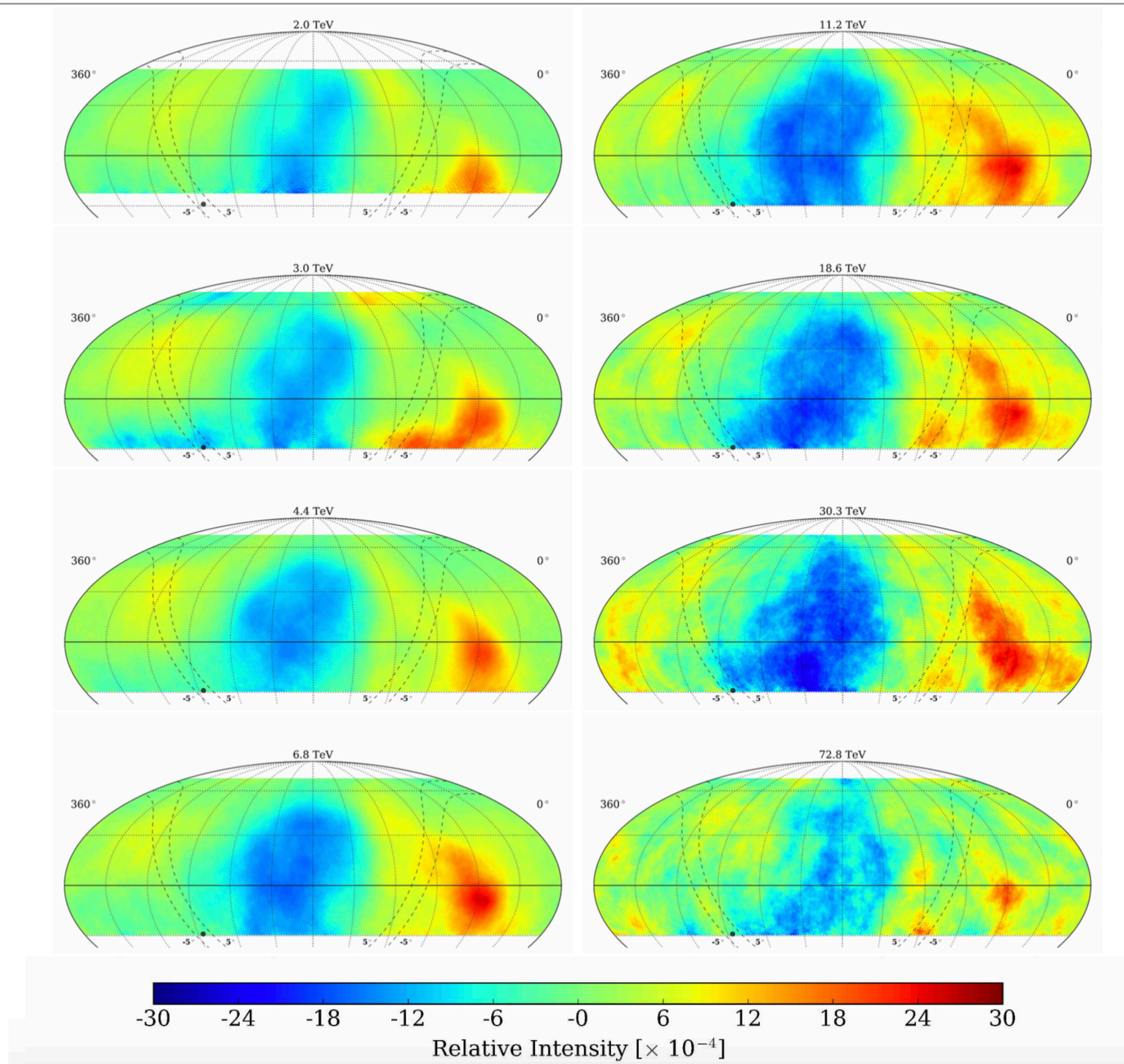

ARGO-YBJ
Bartoli et al. 2015
0.98 TeV
1.65 TeV
2.65 TeV
4.21 TeV
7.80 TeV
13.6 TeV
20.1 TeV
Declination [deg]
Right Ascension [deg]
1.003
1.002
1.001
1
0.999
0.998
0.997


Tibet ASγ
Amenomori et al. 2017
15 TeV
50 TeV
100 TeV
300 TeV
1 PeV
Dec. (deg.)
R.A. (deg.)

cosmic ray anisotropy
energy dependence

HAWC

Abeysekara et al. 2018



2 TeV

11.2 TeV

3 TeV

18.6 TeV

4.4 TeV

30.3 TeV

6.8 TeV

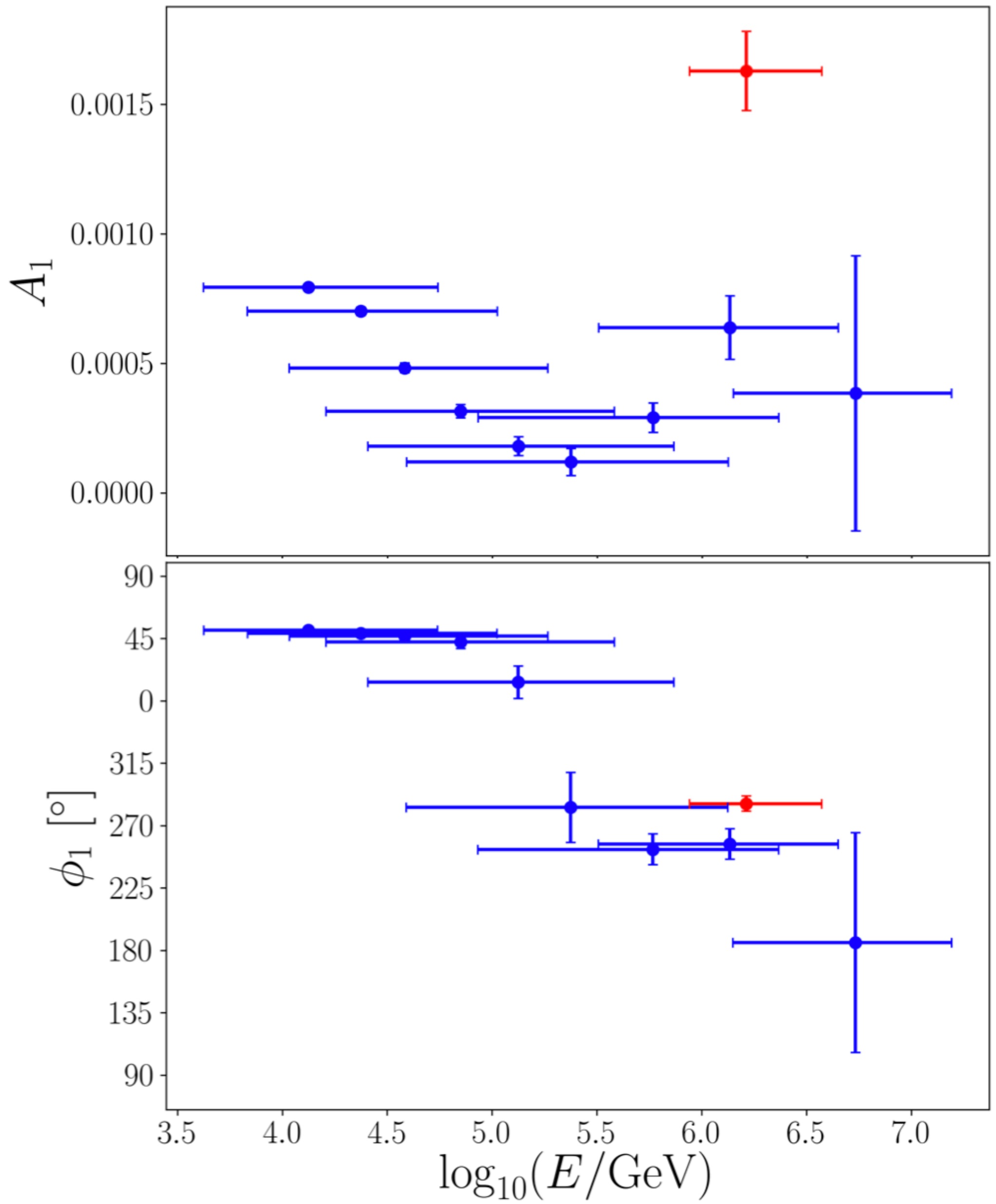
72.8 TeV

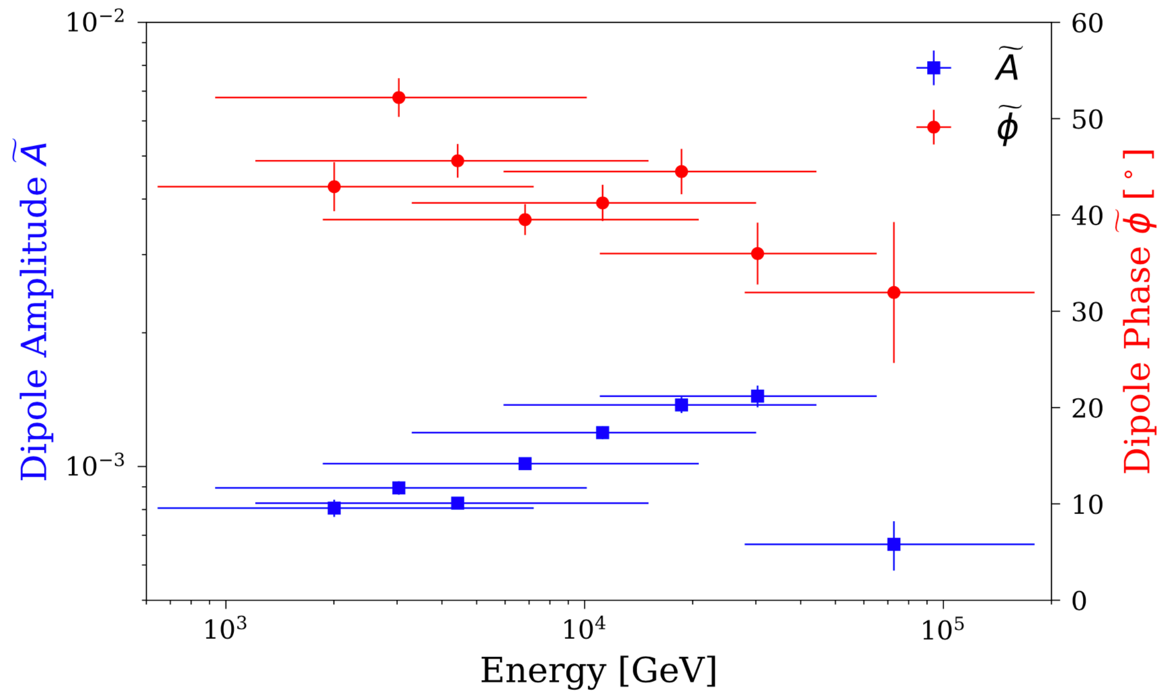
cosmic ray anisotropy

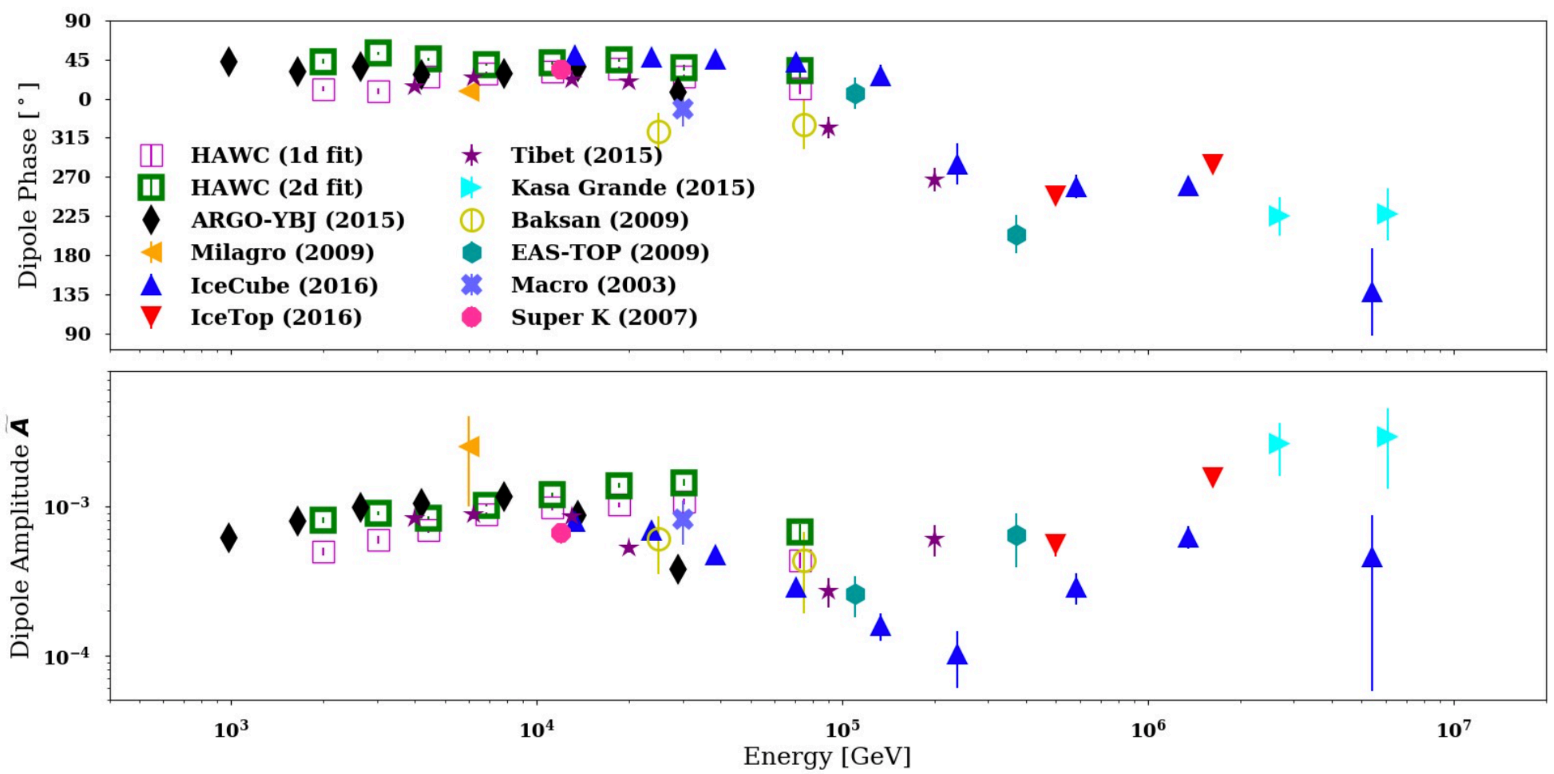
energy dependence

HAWC Abeysekara et al. 2018

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







high energy cosmic rays

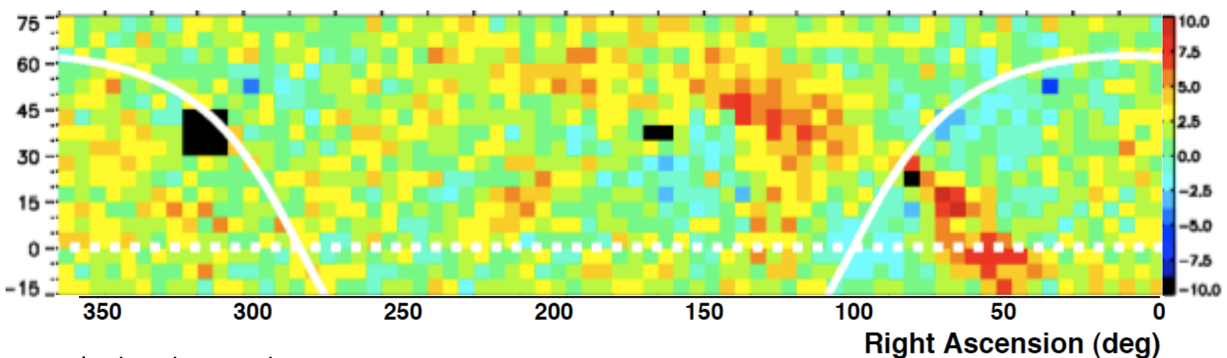
small scale anisotropy & spectral anomalies

1-5 TeV

$\sim 10^{-4}$

Tibet-III

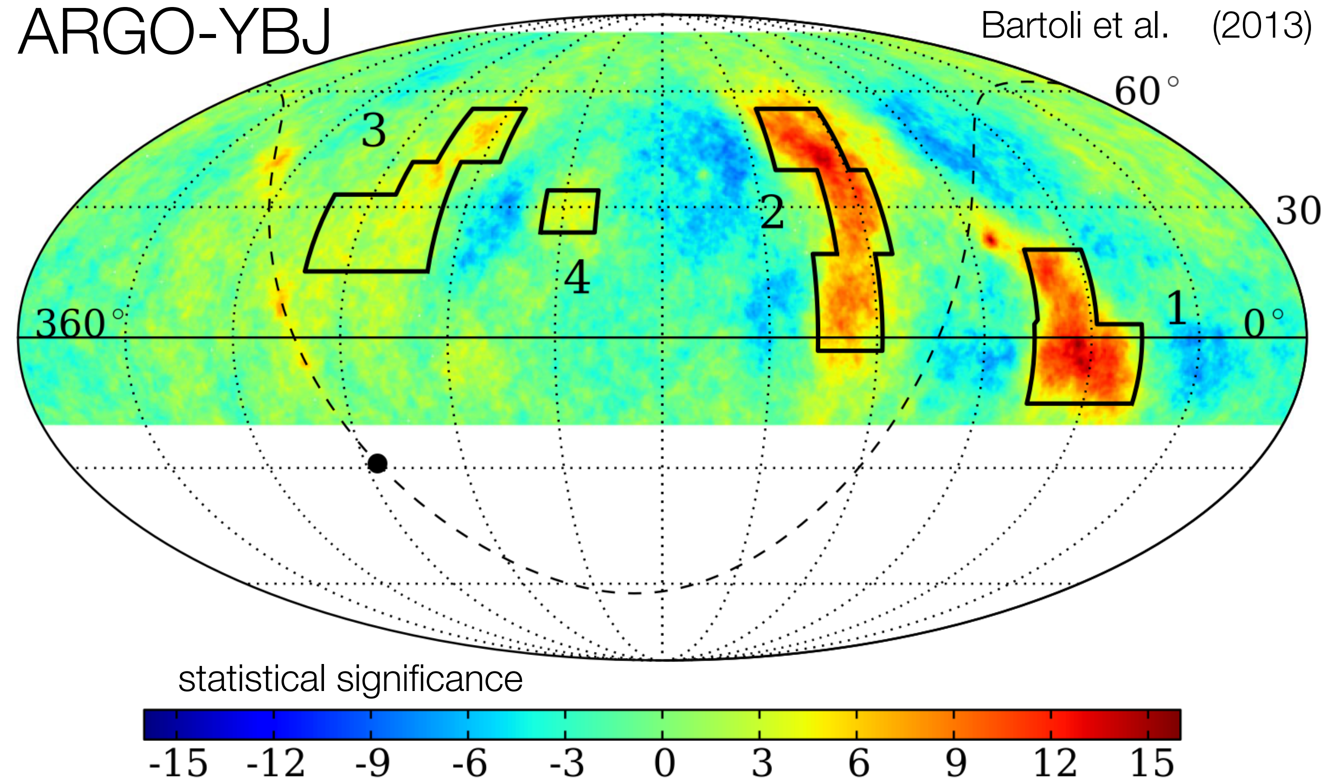
Amenomori et al. ICRC (2007)



relative intensity

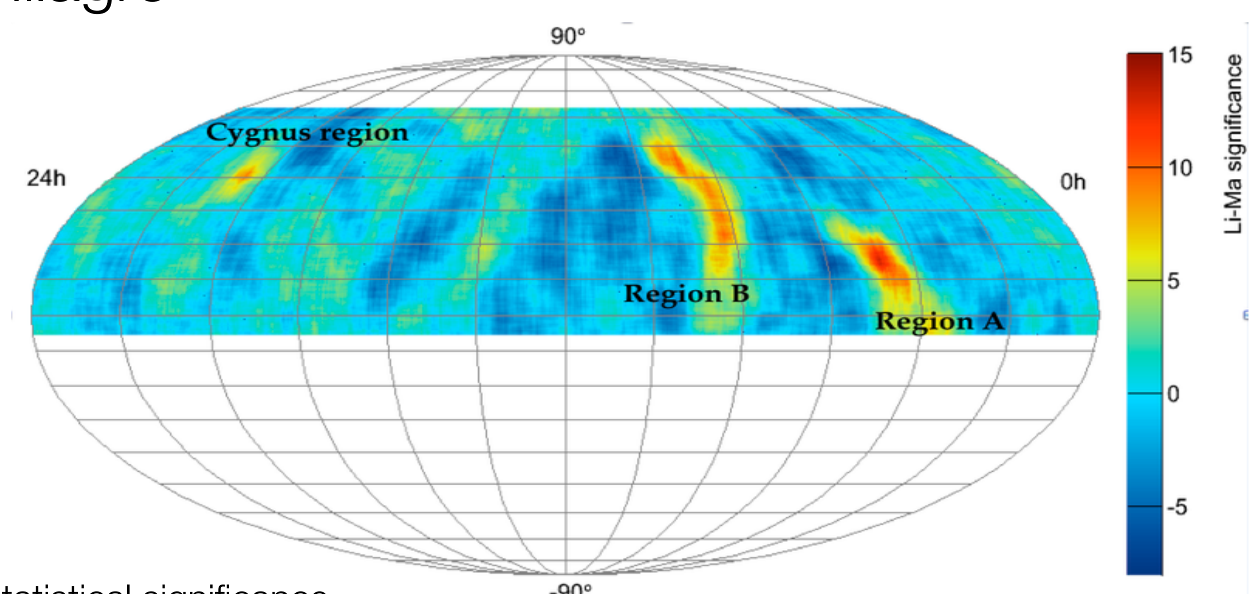
ARGO-YBJ

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



Milagro

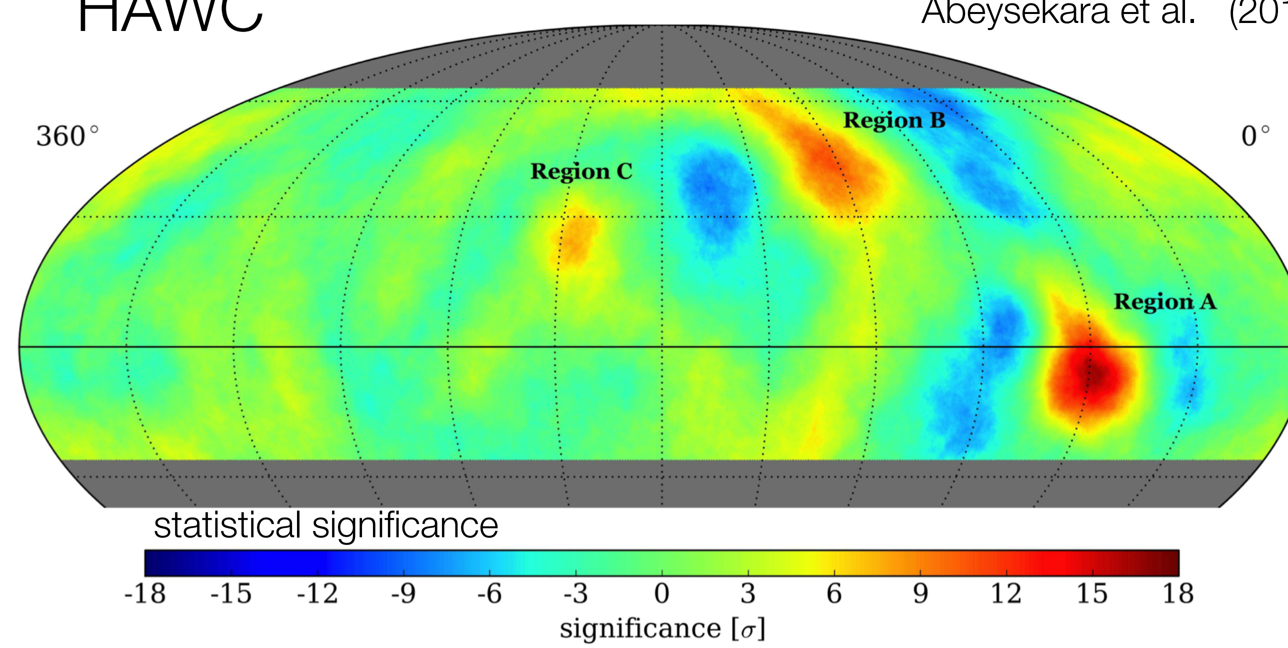
Abdo et al. (2008)



statistical significance

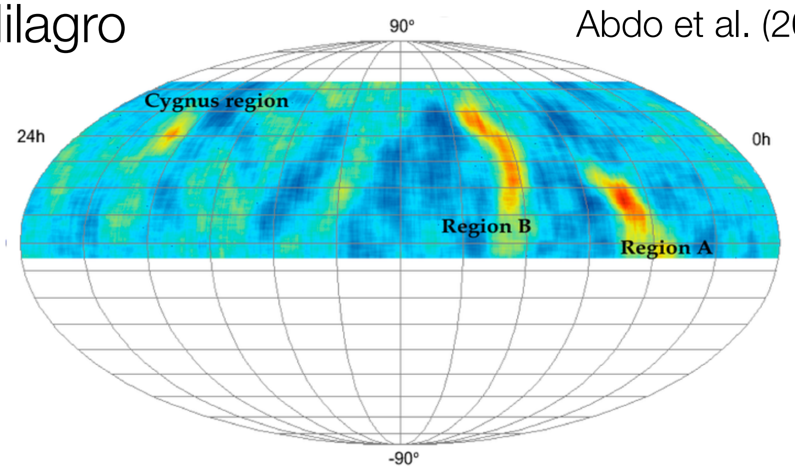
HAWC

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

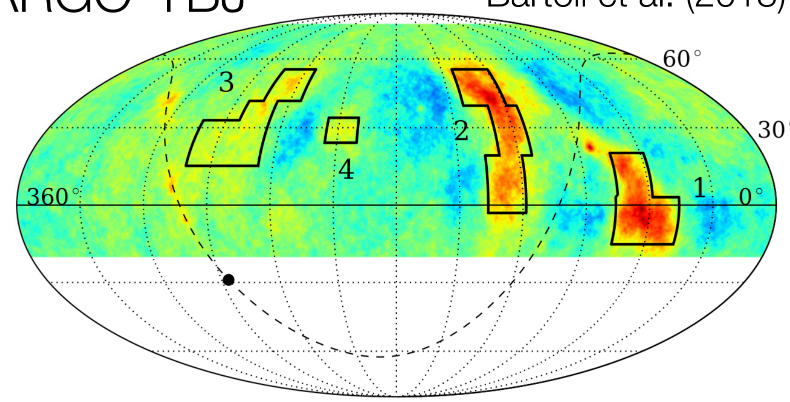


high energy cosmic rays
small scale anisotropy & spectral anomalies

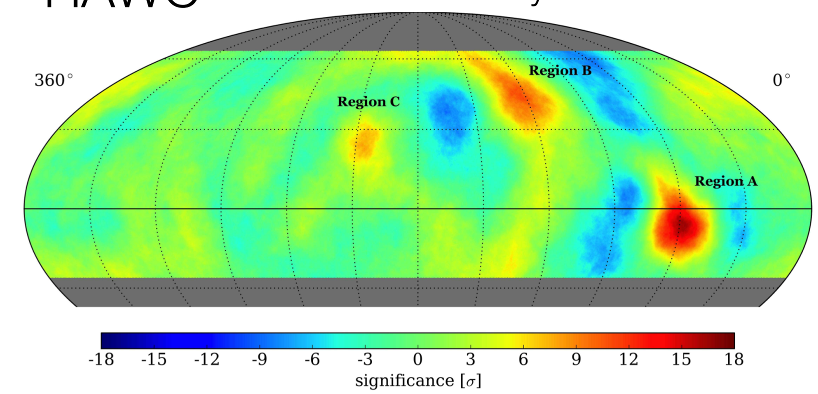
Milagro Abdo et al. (2008)

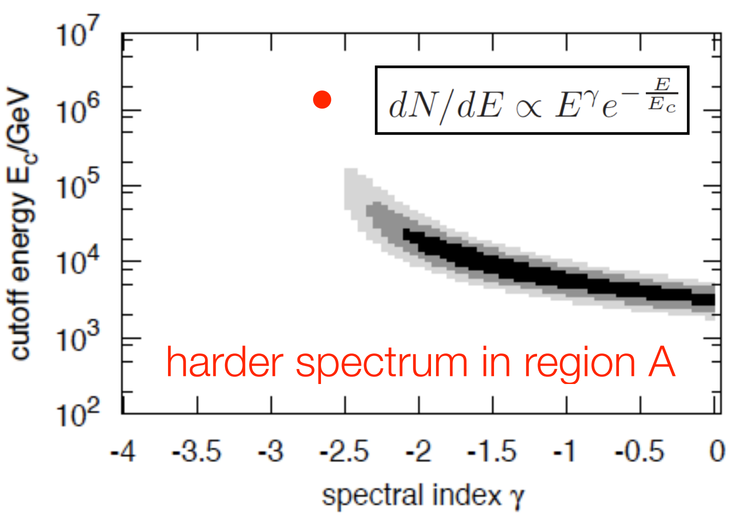


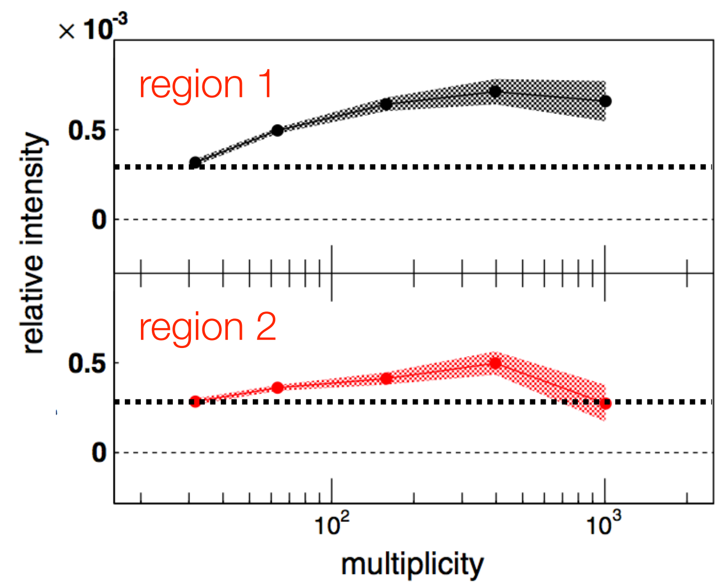
ARGO-YBJ Bartoli et al. (2013)

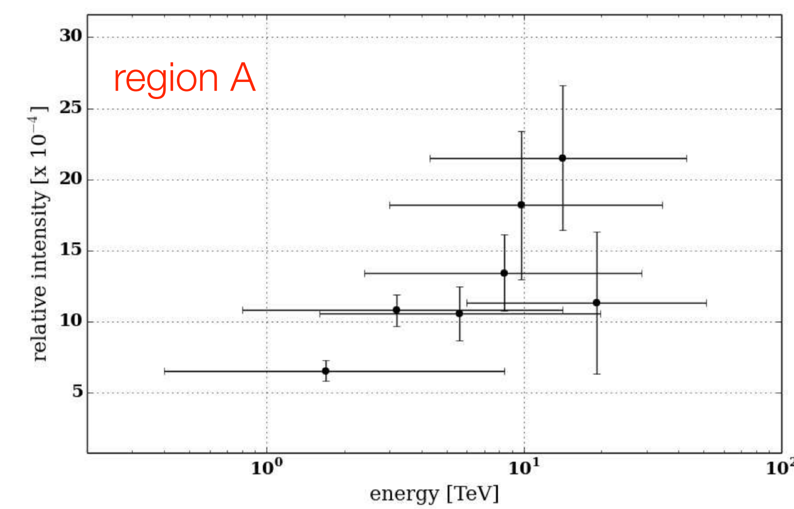


HAWC Abeysekara et al. 2014





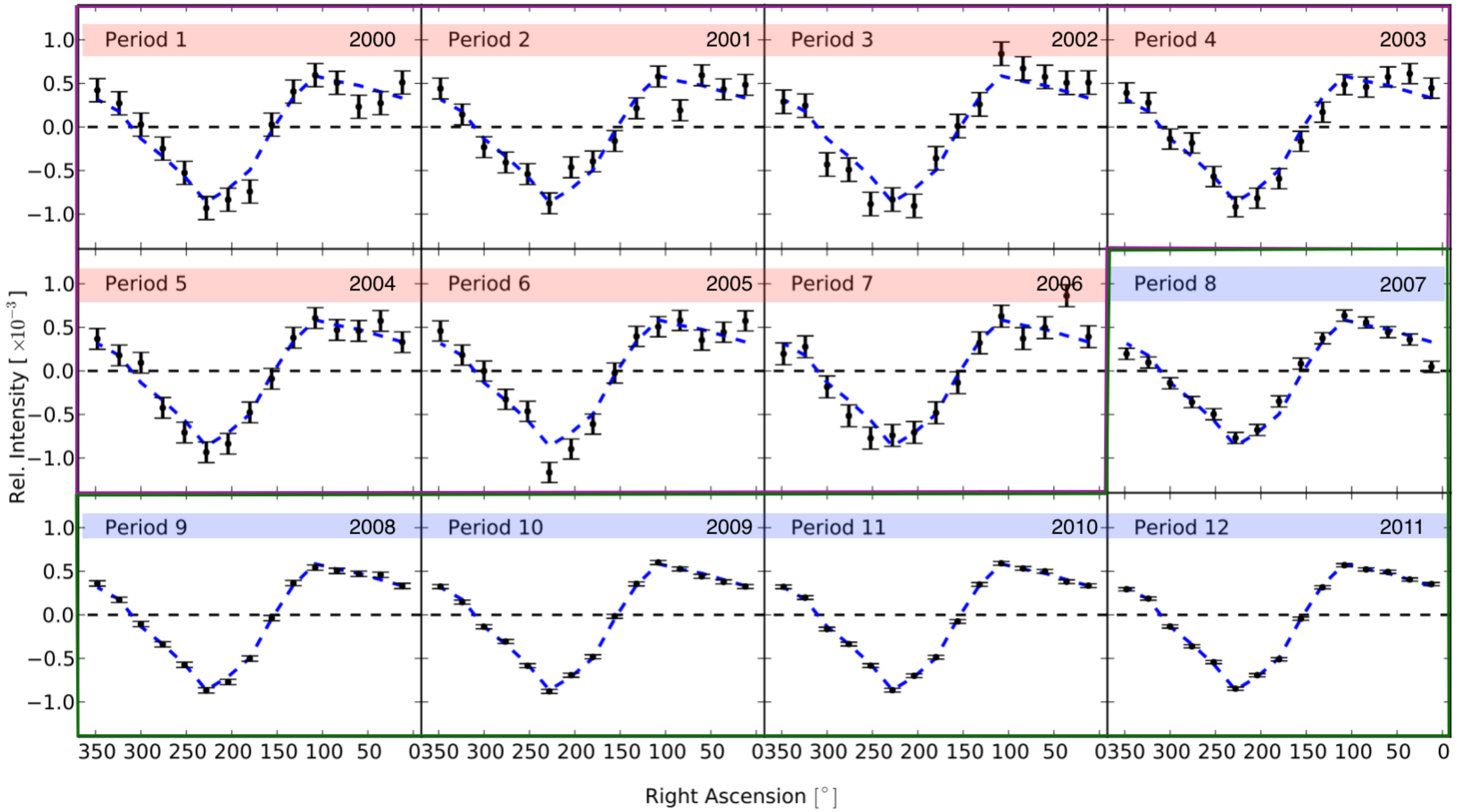




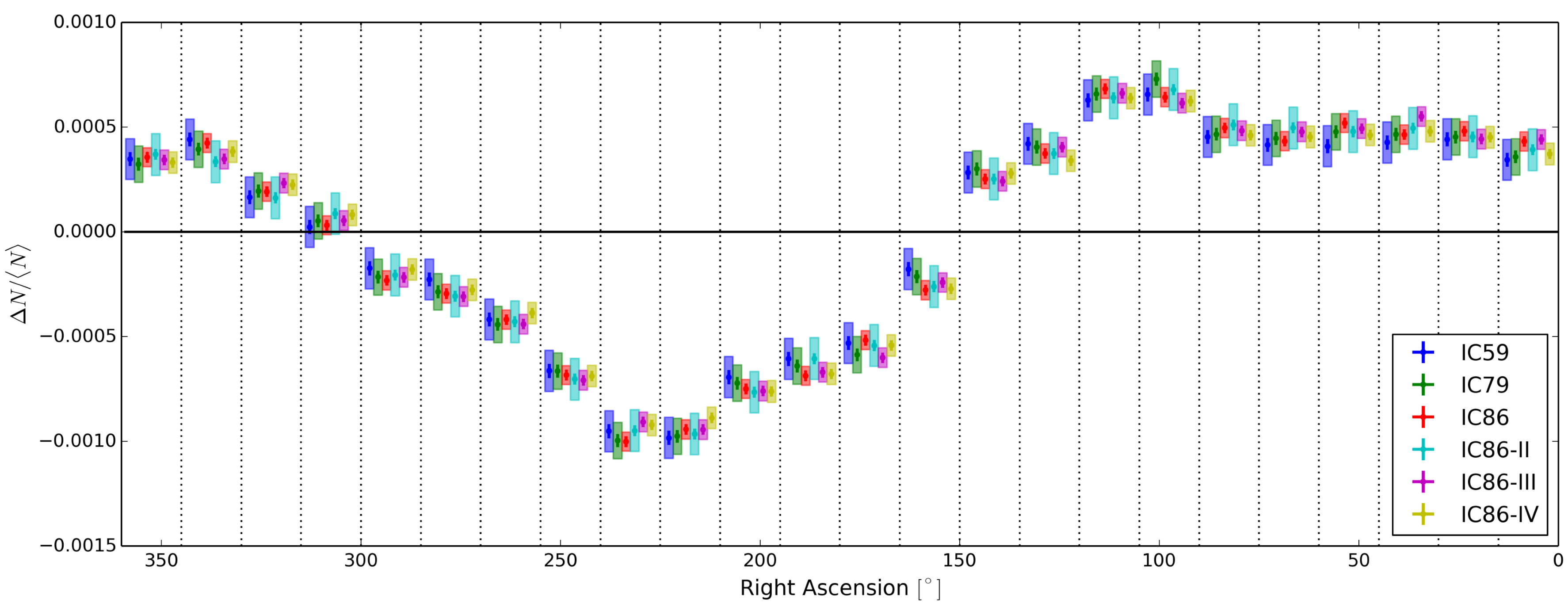
re-acceleration by magnetic reconnection in the heliotail
Lazarian & PD 2010
PD& Lazarian 2012

cosmic rays anisotropy stability

AMANDA-IceCube 2000-2014



Marcos Santander ICRC 2013



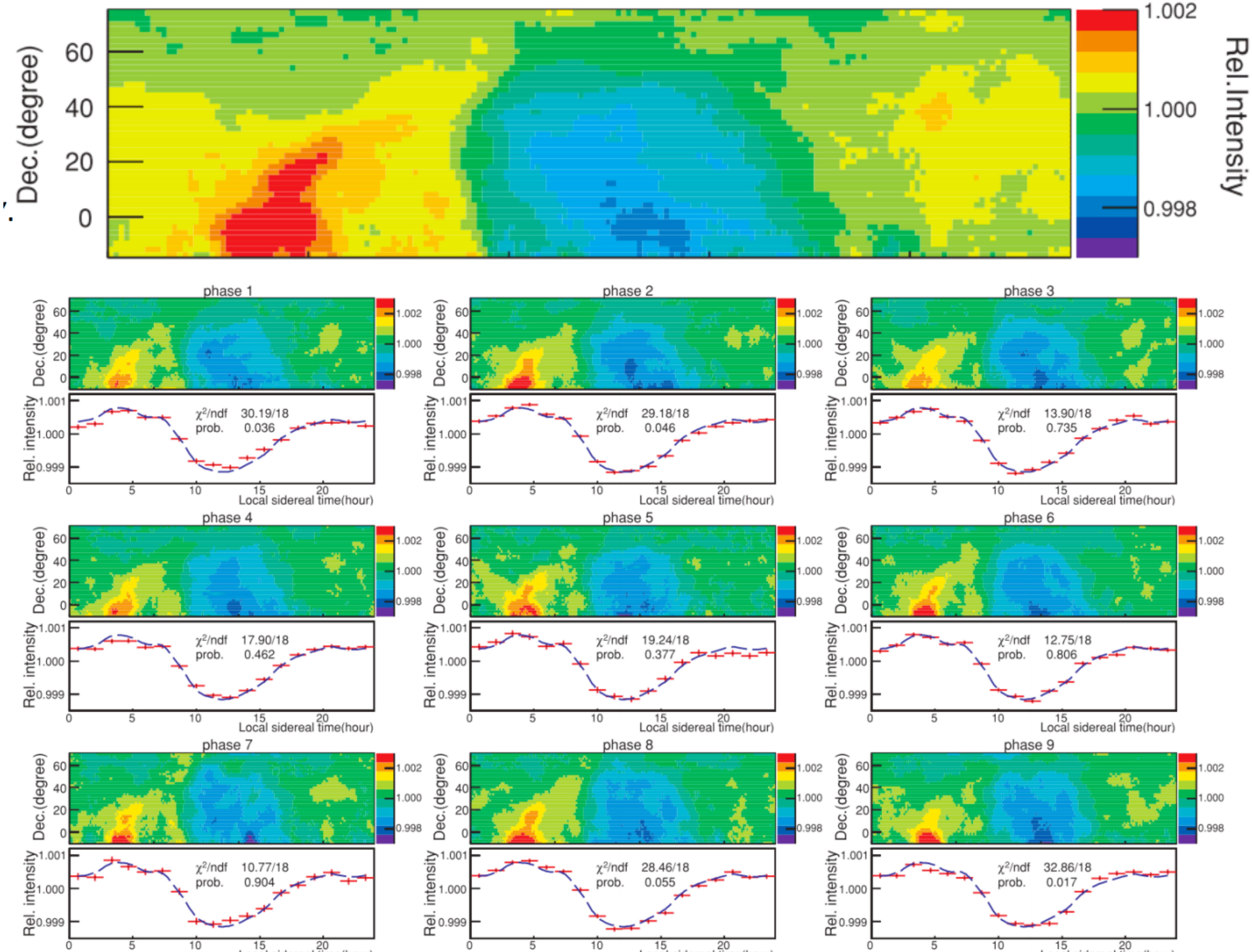
IceCube - Aartsen et al., ApJ 826, 220, 2016

median energy ~ 20 TeV

cosmic rays anisotropy stability

Tibet Array

Tibet Array 2005



observing cosmic ray anisotropy

horizontal dipole component

IceCube

Aartsen et al., ApJ 826, 220, 2016

Auger

J. Phys. Conf. Series, 409, 012108, 2013