



# Cosmic ray anisotropy with the IceCube Observatory

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Guadalajara, Jalisco, México



# cosmic ray observations



**galactic** origin below  $\sim 10^8$ - $10^9$  GeV

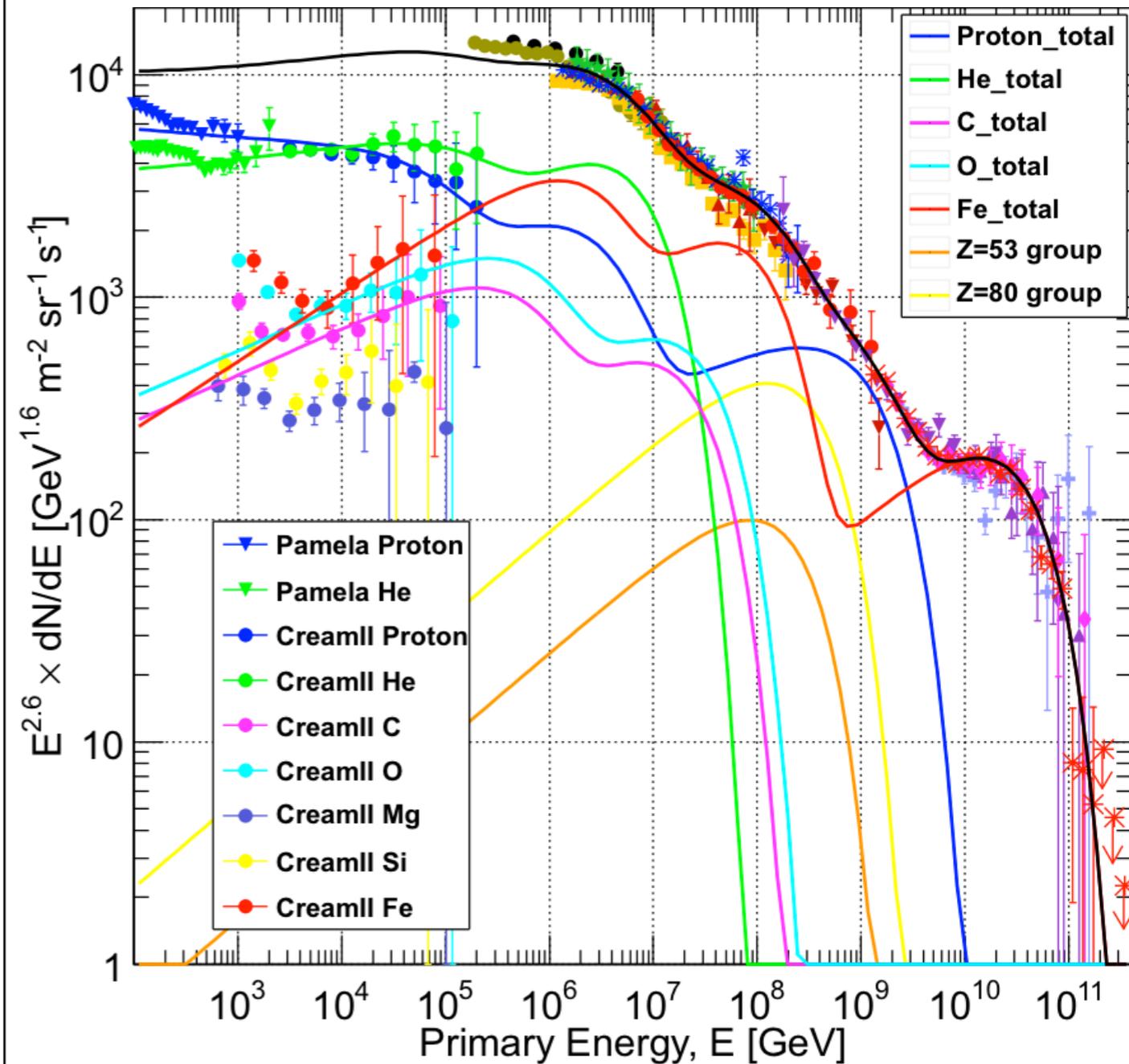
**spectral features** from acceleration mechanisms & propagation effects

**source distribution** in the Milky Way and our neighborhood

**magnetic field** properties in galactic and local interstellar medium

**anisotropy**

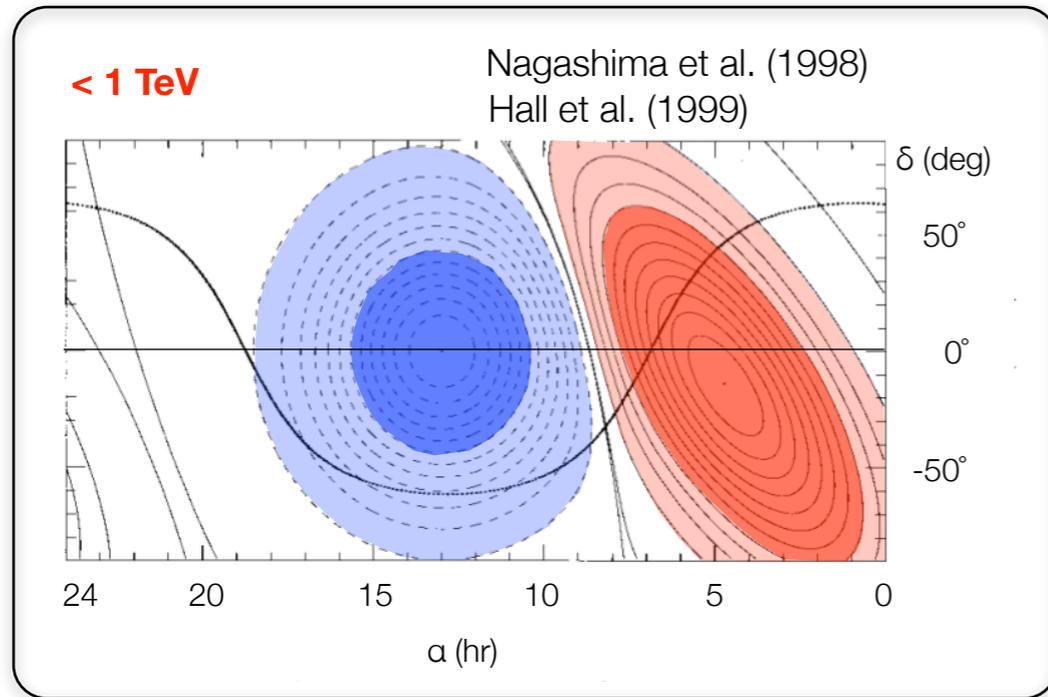
Gaisser, Stanev, Tilav, 2013 - arXiv:1303.3565



# high energy cosmic rays

## sidereal anisotropy

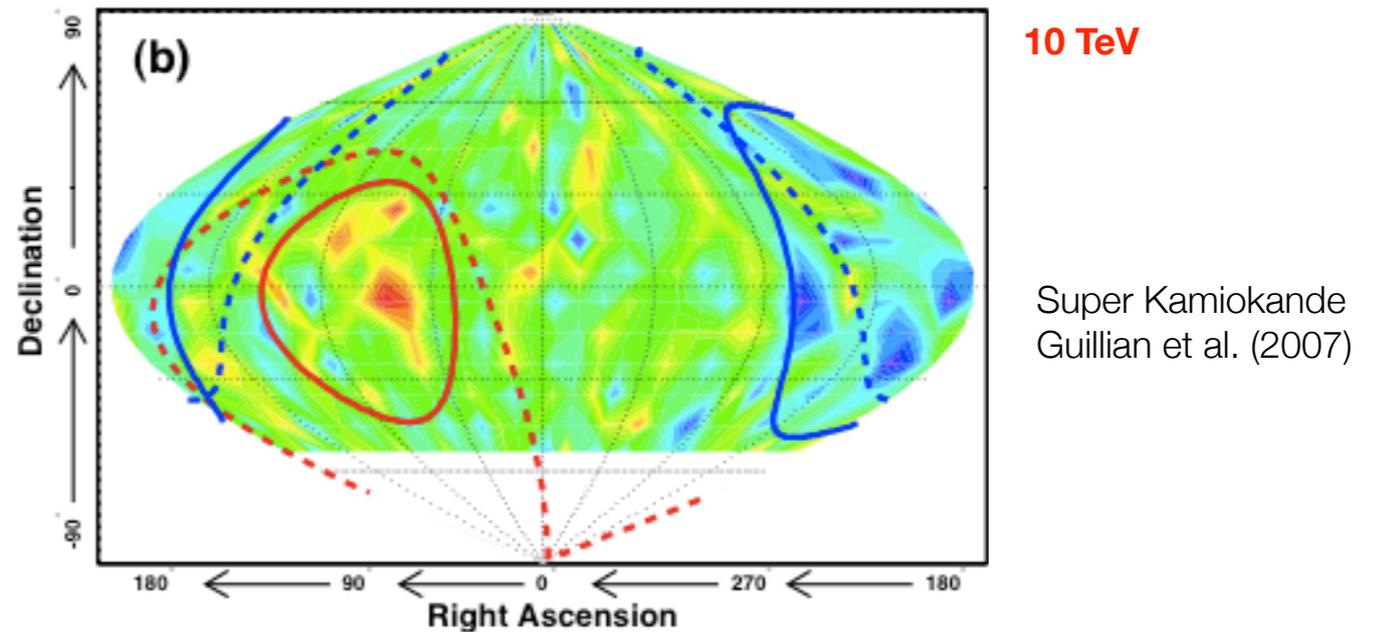
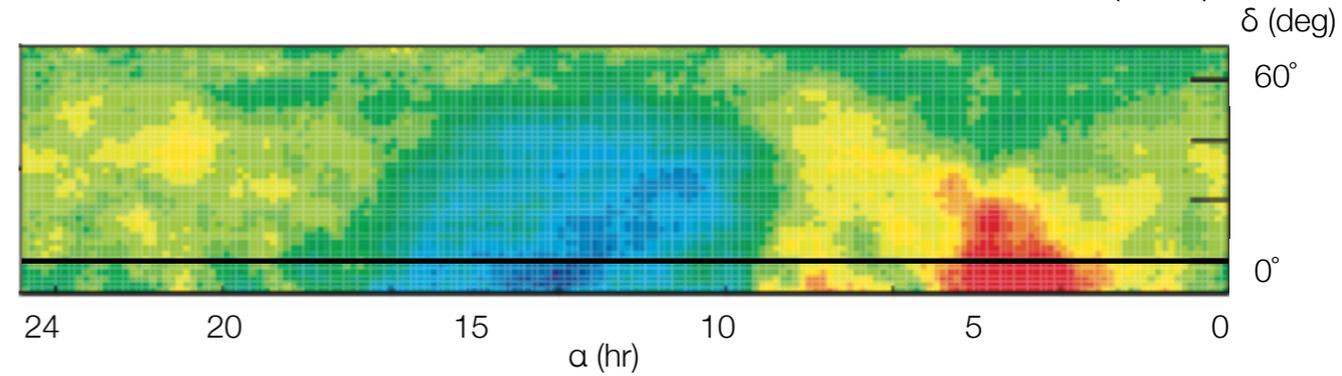
$\sim 10^{-3}$



equatorial coordinates

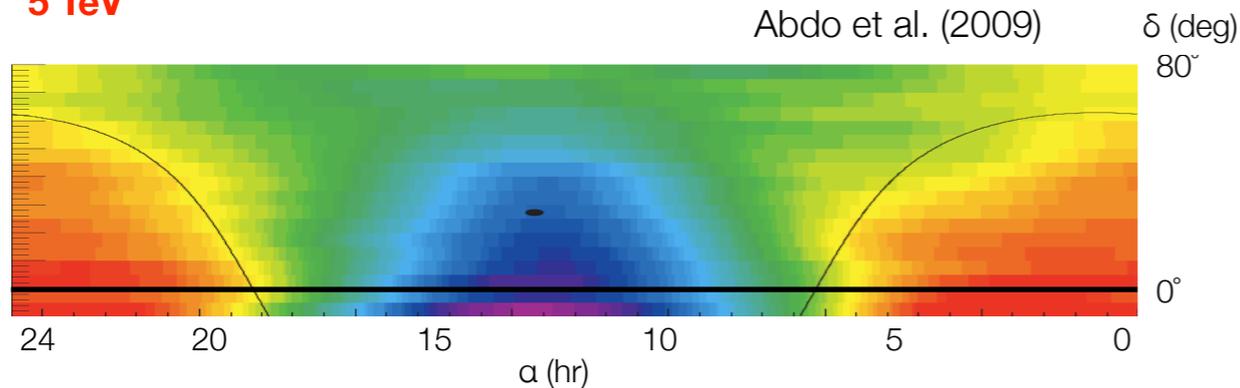
**4 TeV**

Tibet ASy  
Amenomori et al. (2006)



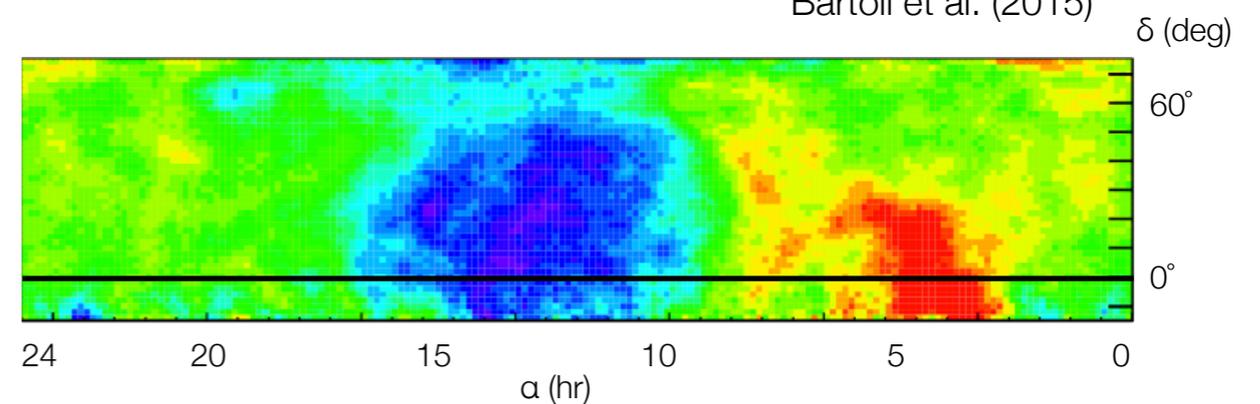
**5 TeV**

Milagro  
Abdo et al. (2009)



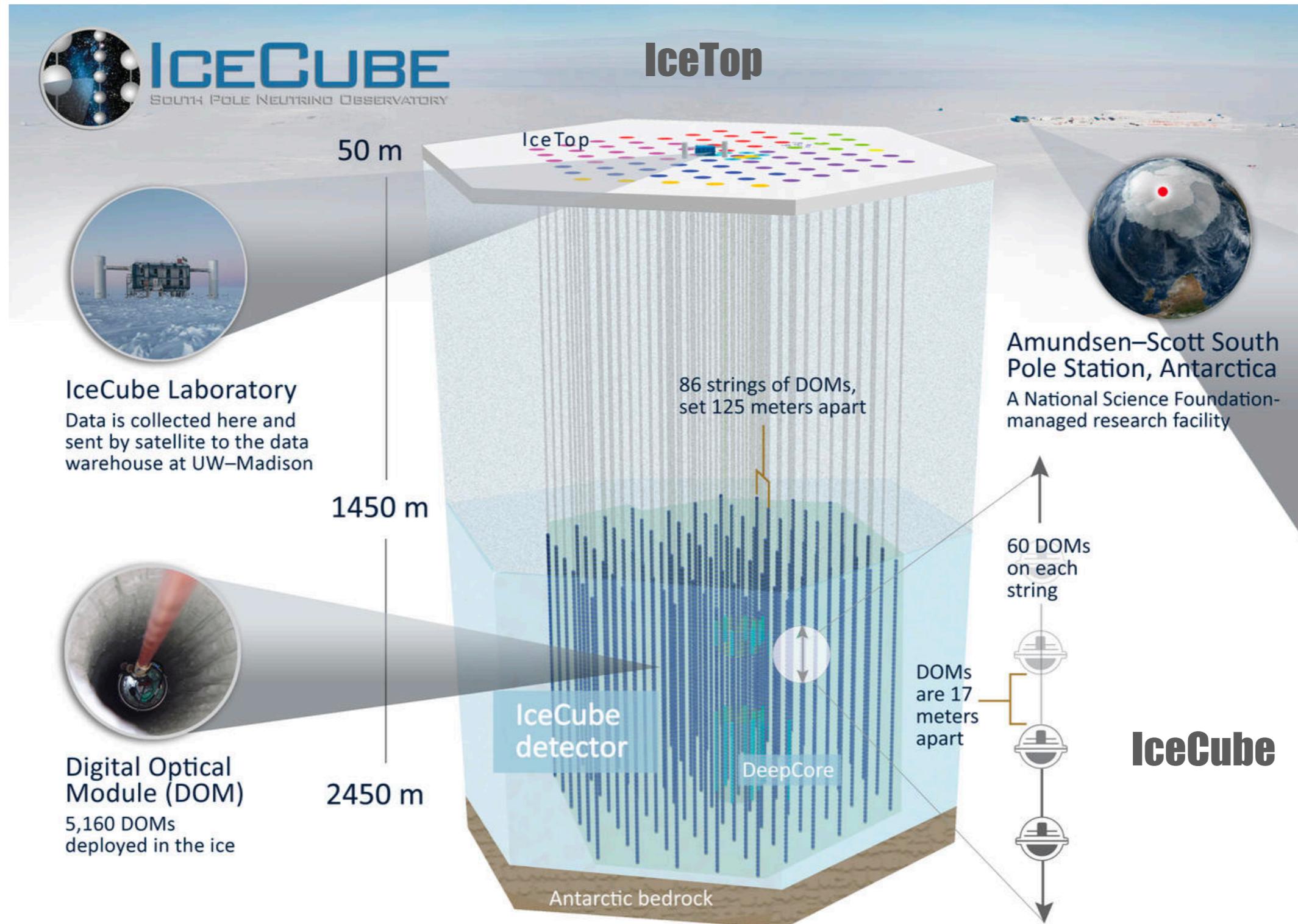
**4 TeV**

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



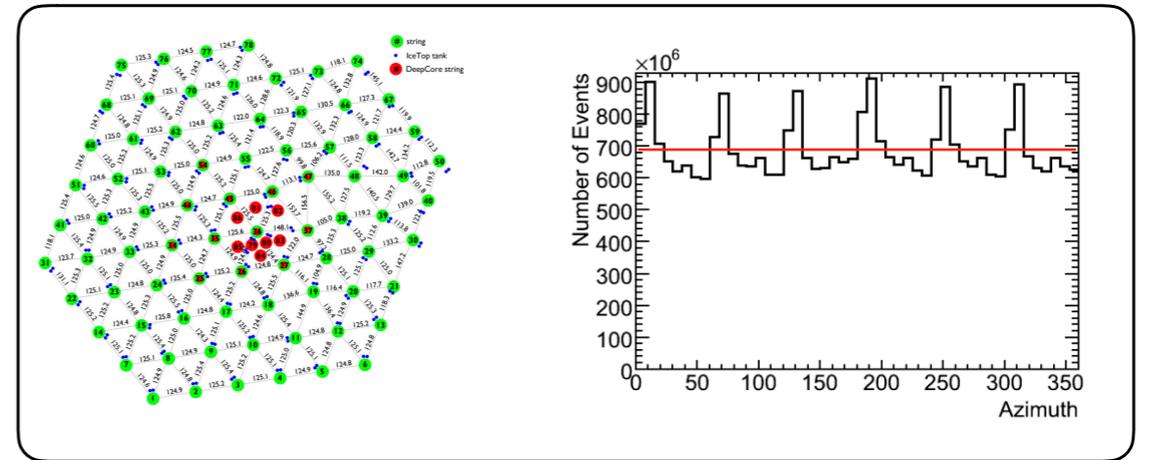
# IceCube & IceTop

observing neutrinos and cosmic rays at South Pole

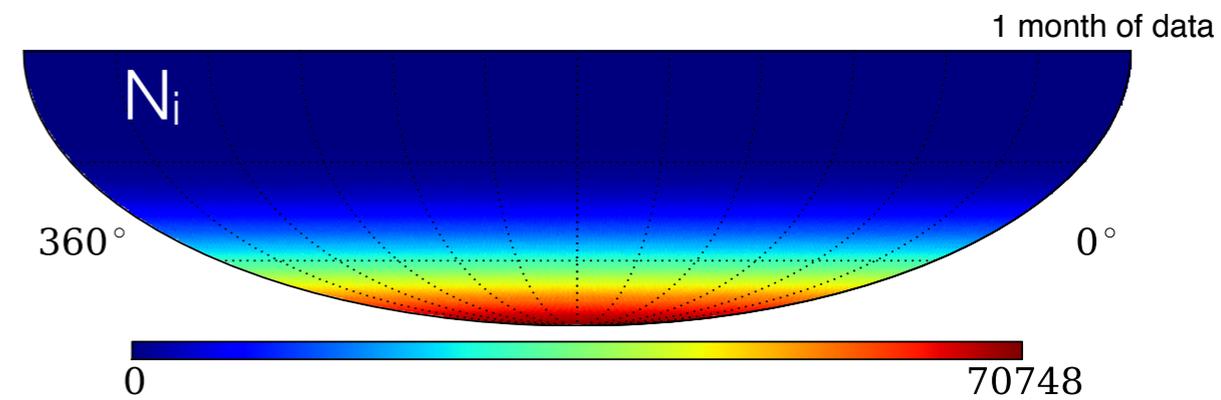


# determination of anisotropy arrival direction distribution

## IceCube local coordinates



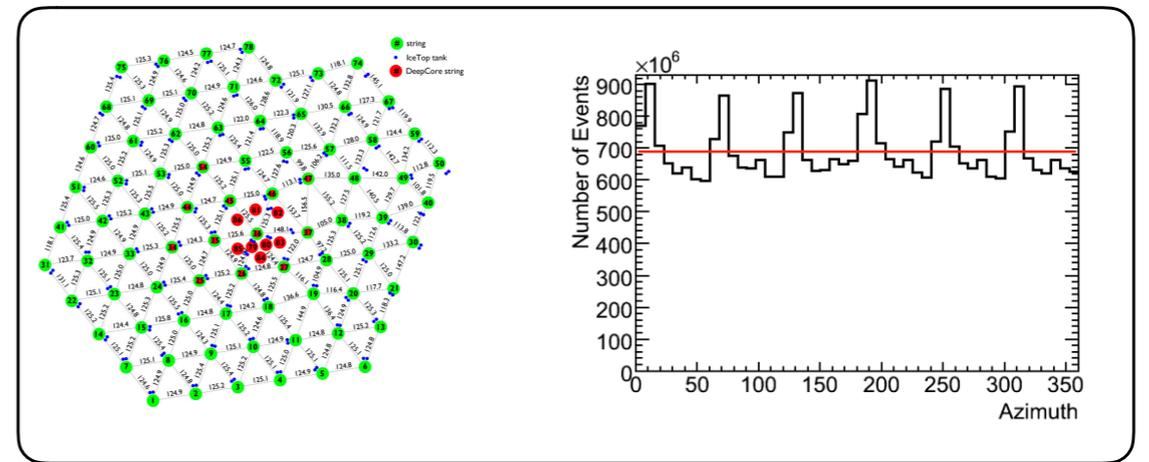
**raw map** of events in equatorial coordinates  $(\alpha, \delta)_i$



# determination of anisotropy

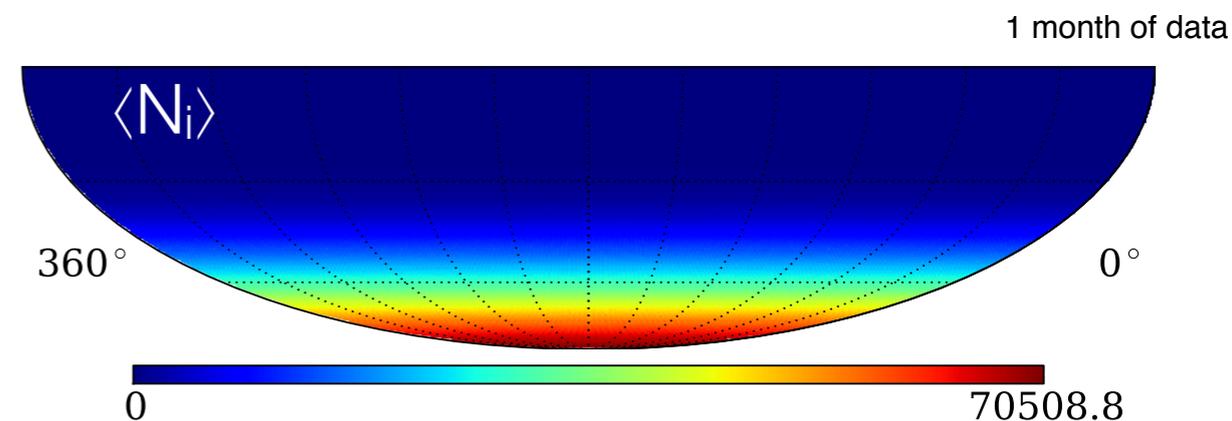
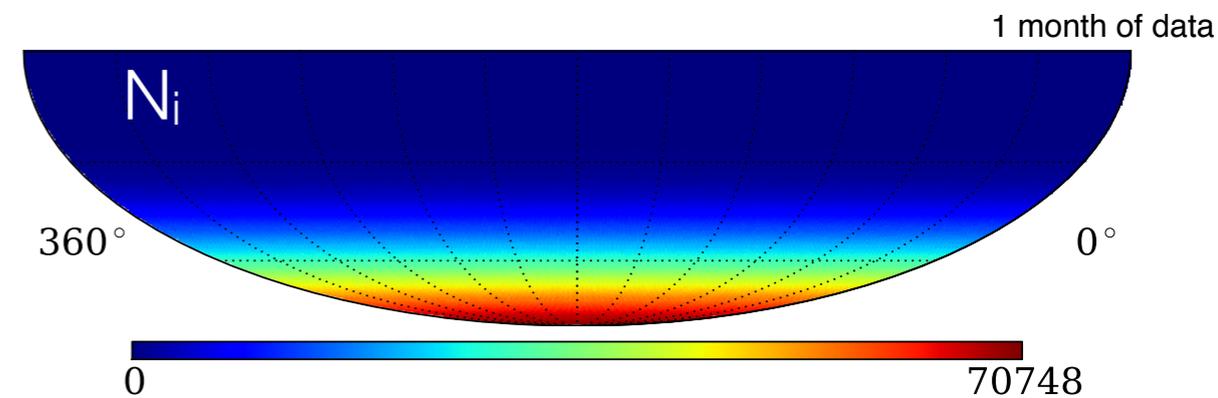
## arrival direction distribution

### IceCube local coordinates



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

**reference map** of events *scrambled* over 24hr in  $\alpha$  (or time) within same  $\delta$  band  
→ **response map to isotropic flux**



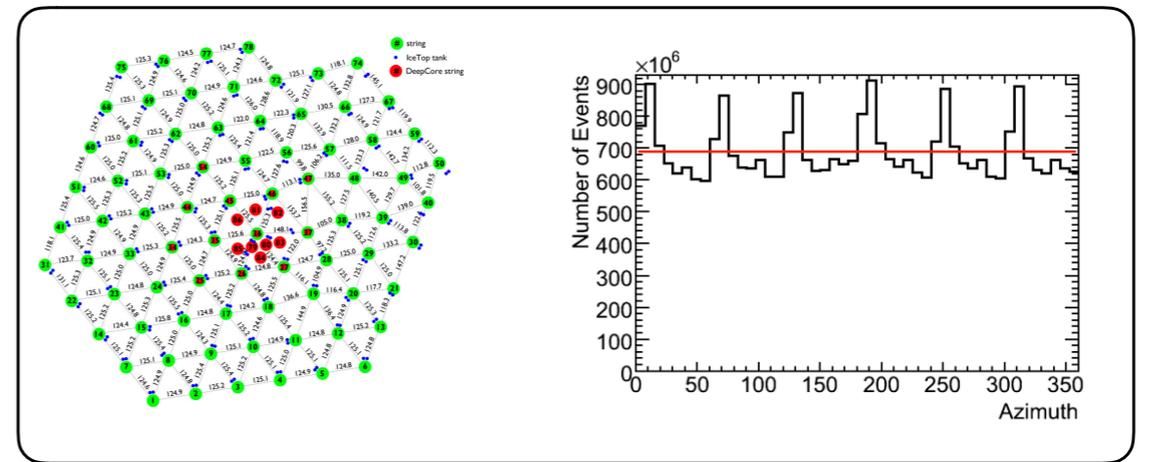
Time Scrambling (Alexandreas et al., NIM A 328 (1993) 570)

Direct Integration (Atkins et al., ApJ 595 (2003) 803)

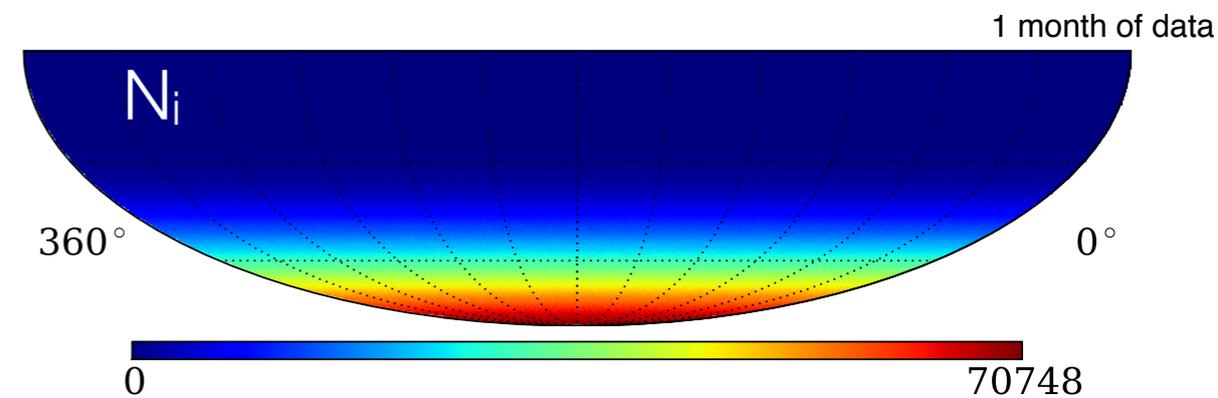
# determination of anisotropy

## arrival direction distribution

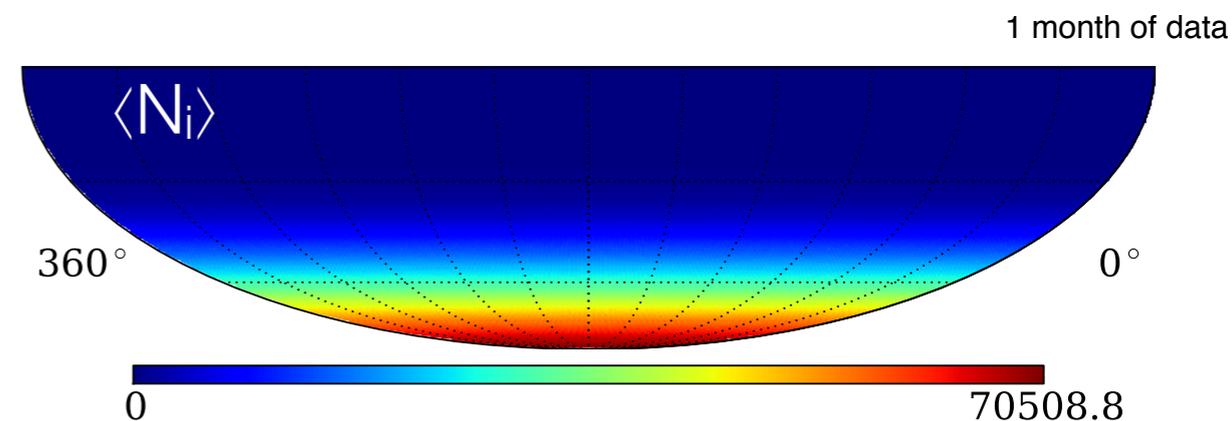
### IceCube local coordinates



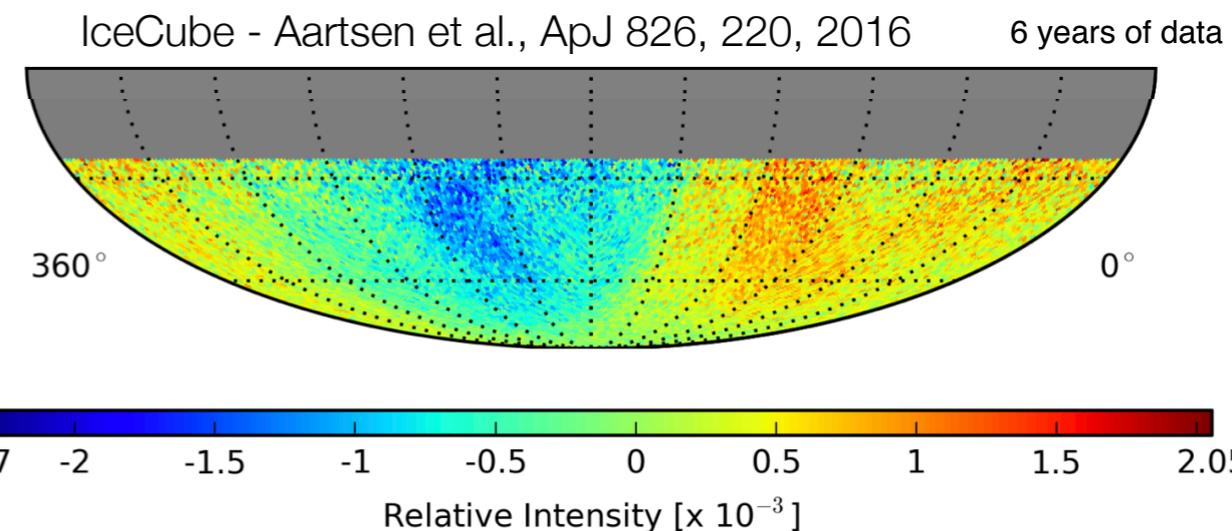
**raw map** of events in equatorial coordinates  $(\alpha, \delta)_i$



**reference map** of events *scrambled* over 24hr in  $\alpha$  (or time) within same  $\delta$  band  
 → **response map to isotropic flux**



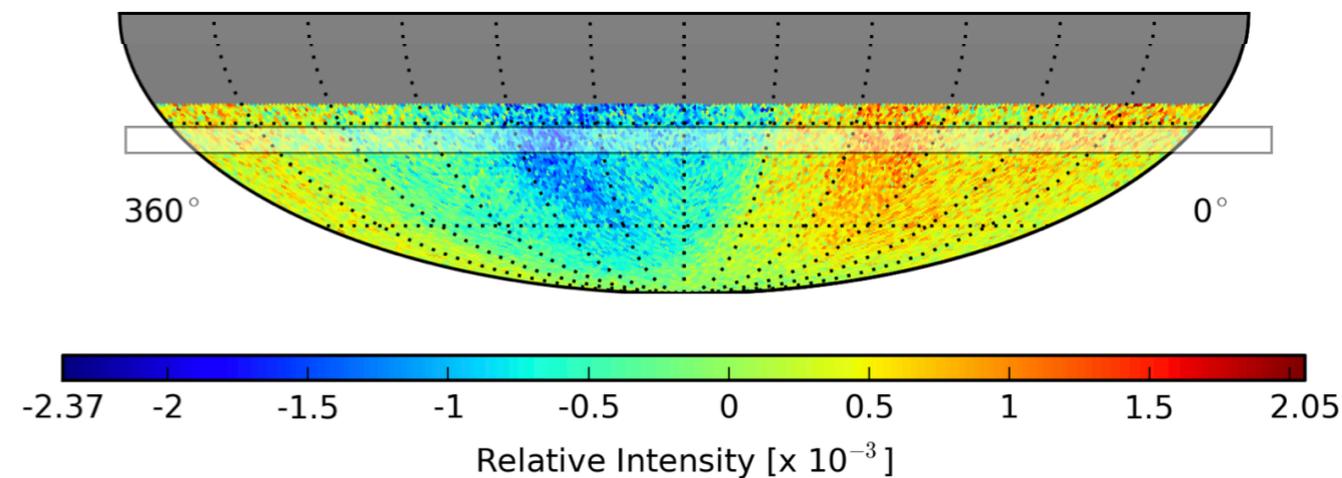
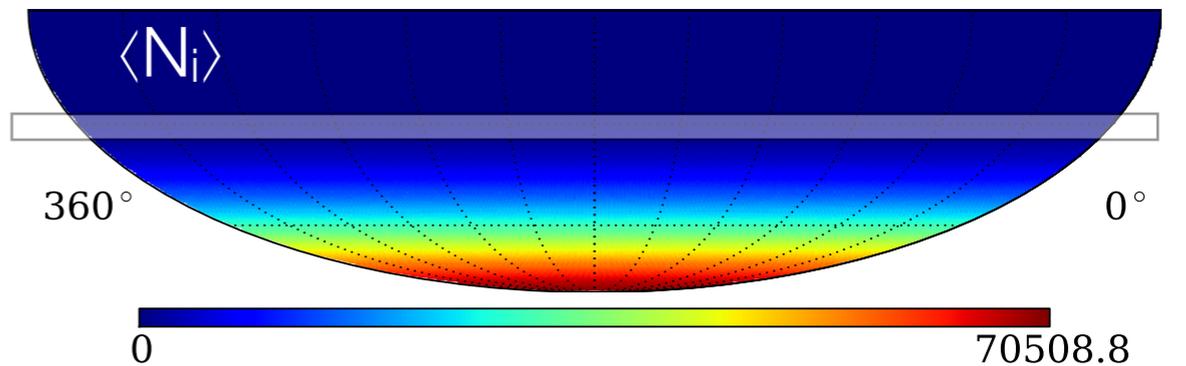
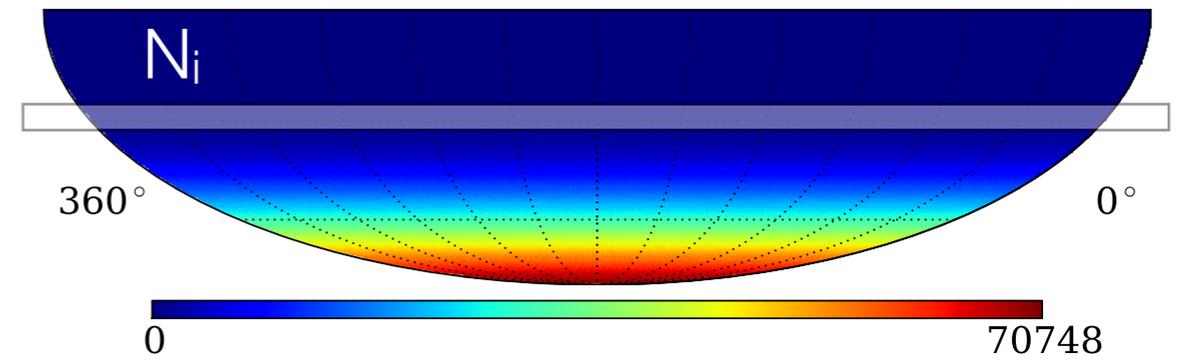
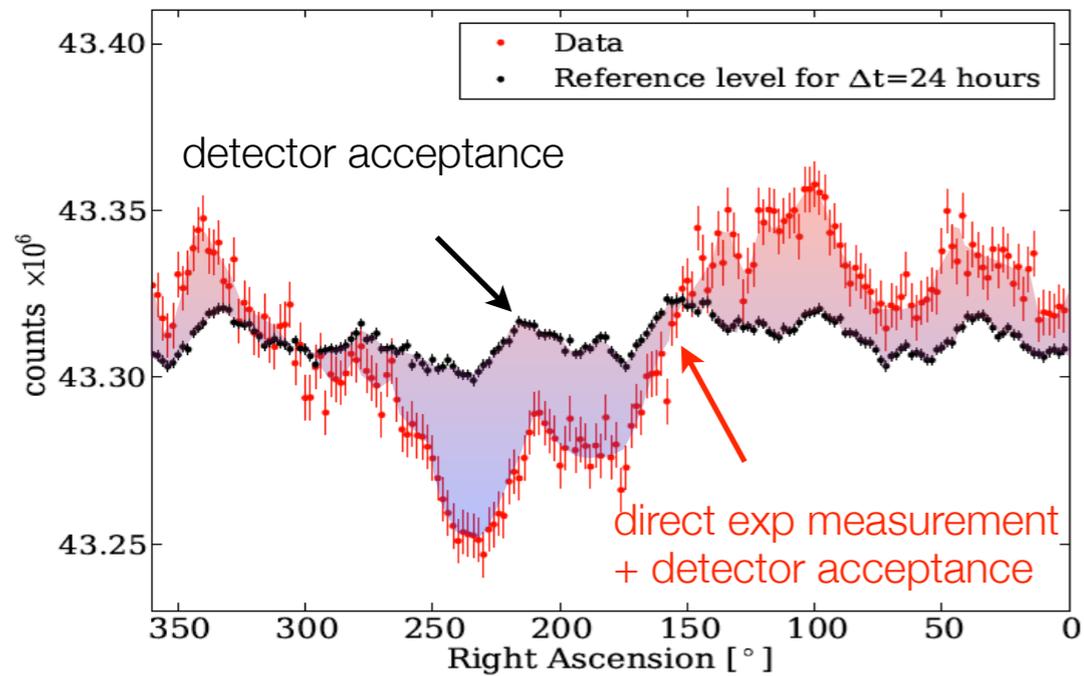
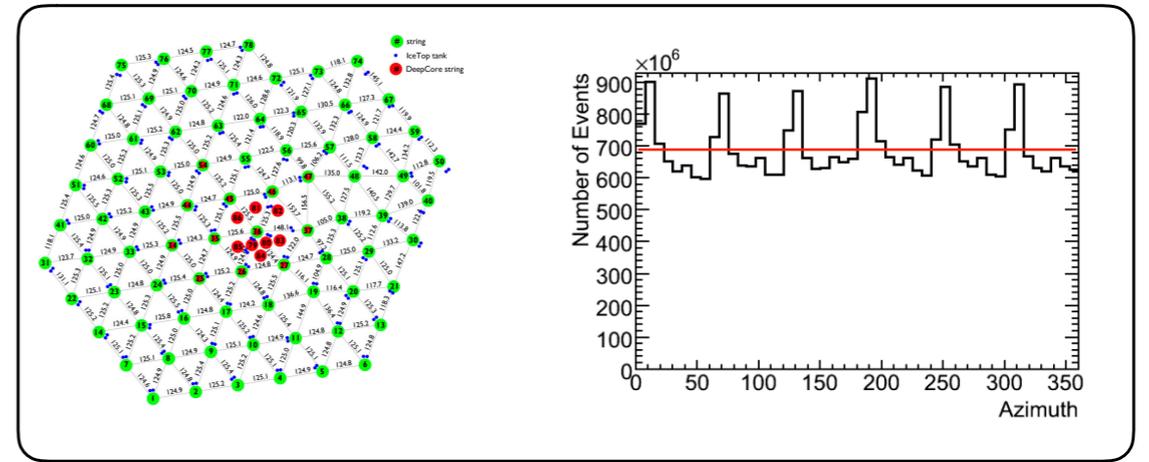
**residual map** as relative intensity normalized in each  $\delta$  band: equal deficit/excess.  
 → **equal deficit/excess contribution**



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

# determination of anisotropy arrival direction distribution

IceCube local coordinates

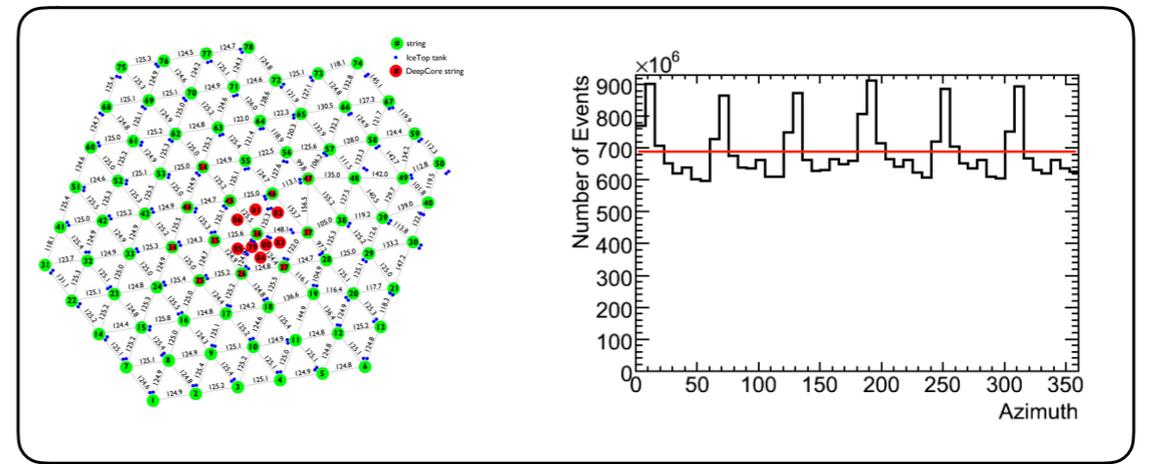


$$\frac{\Delta I}{\langle I \rangle} \equiv \frac{N_i - \langle N \rangle}{\langle N \rangle}$$

# determination of anisotropy

## arrival direction distribution

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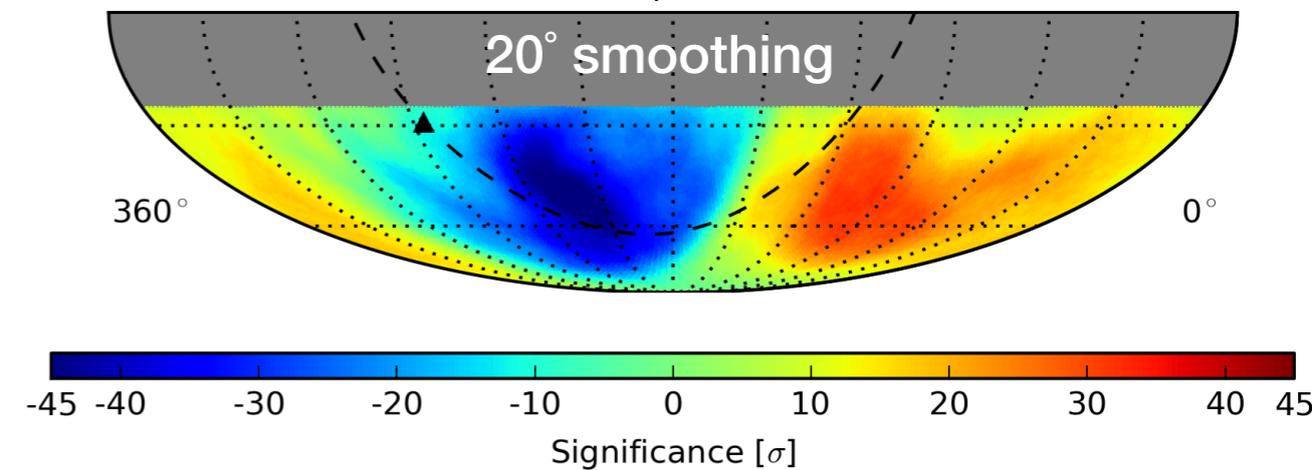


$$s = \sqrt{2} \left\{ N_{\text{on}} \ln \left[ \frac{1 + \alpha}{\alpha} \left( \frac{N_{\text{on}}}{N_{\text{on}} + N_{\text{off}}} \right) \right] + N_{\text{off}} \ln \left[ (1 + \alpha) \left( \frac{N_{\text{off}}}{N_{\text{on}} + N_{\text{off}}} \right) \right] \right\}^{1/2} \quad \alpha = 1/20$$

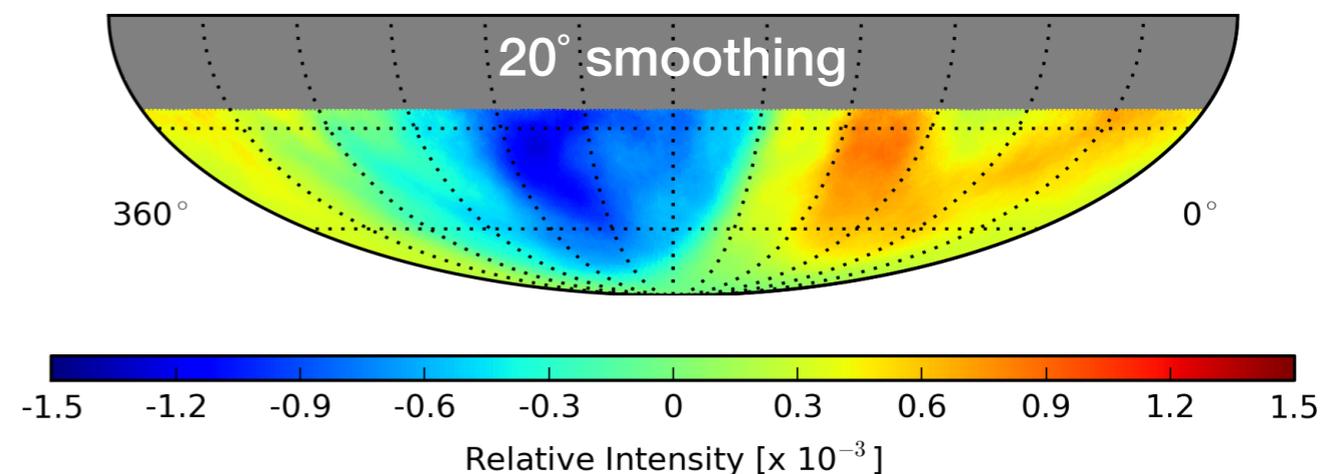
Li, T., & Ma, Y. 1983, *ApJ*, 272, 317

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

statistical significance



relative intensity



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

# observing TeV cosmic ray anisotropy

high statistics but small effects



understanding **experimental biases** and compensate , when possible



determine anisotropy at **different energies**



determine anisotropy at **different angular scales**



determine anisotropy **variations in time**



determine anisotropy at **different primary masses**



determine anisotropy with **full sky observations**

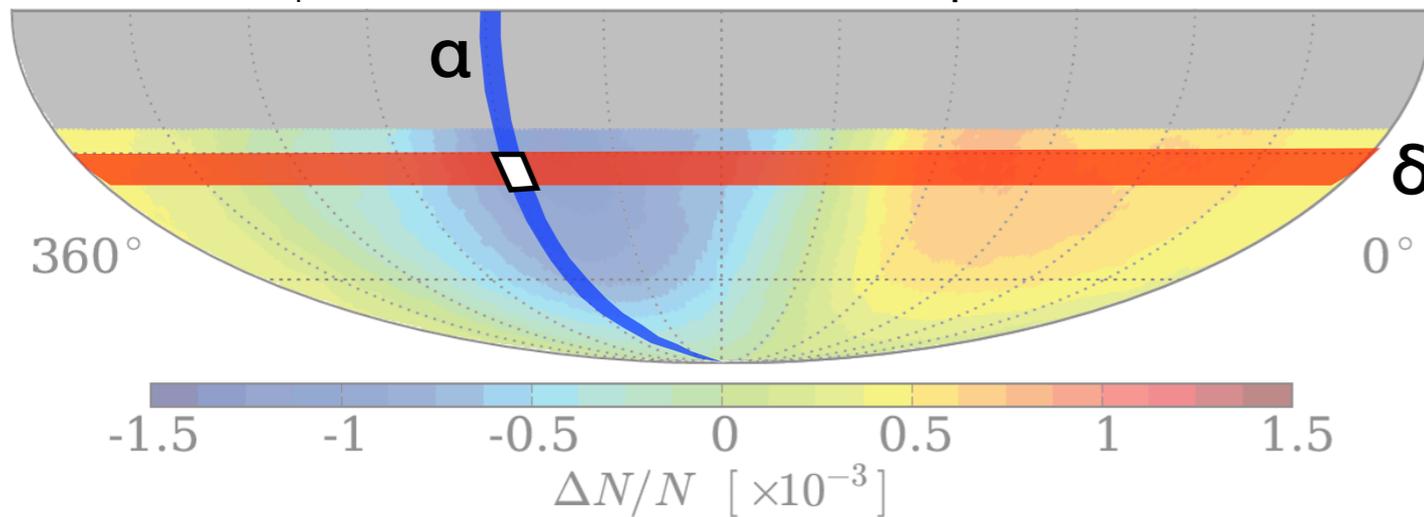
# observing cosmic ray anisotropy

## projection biases



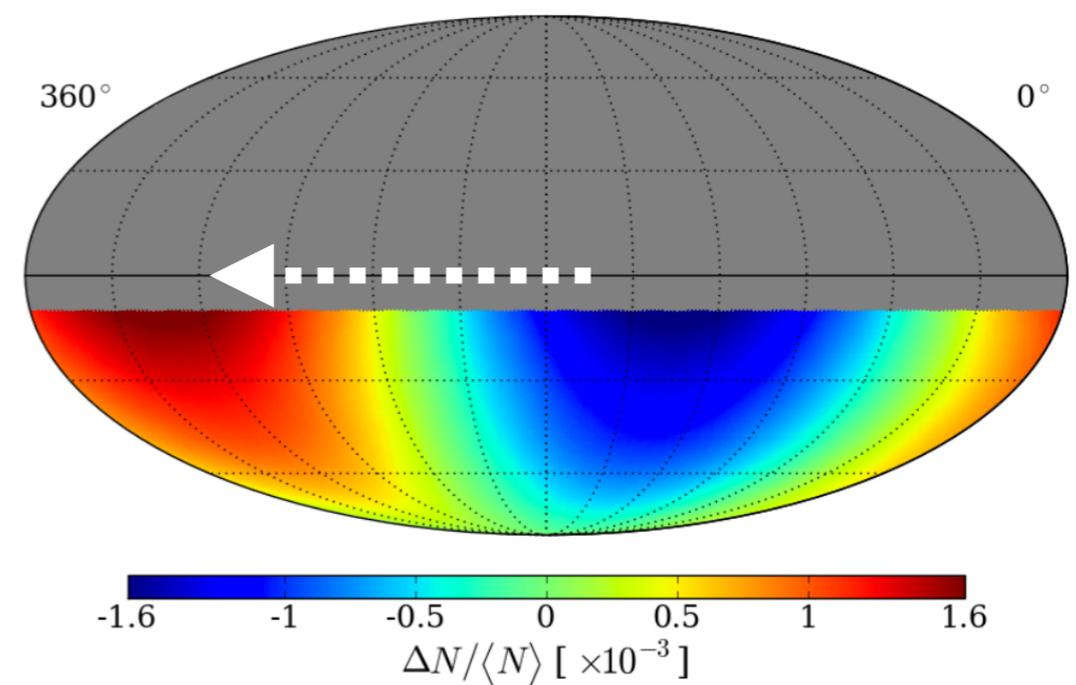
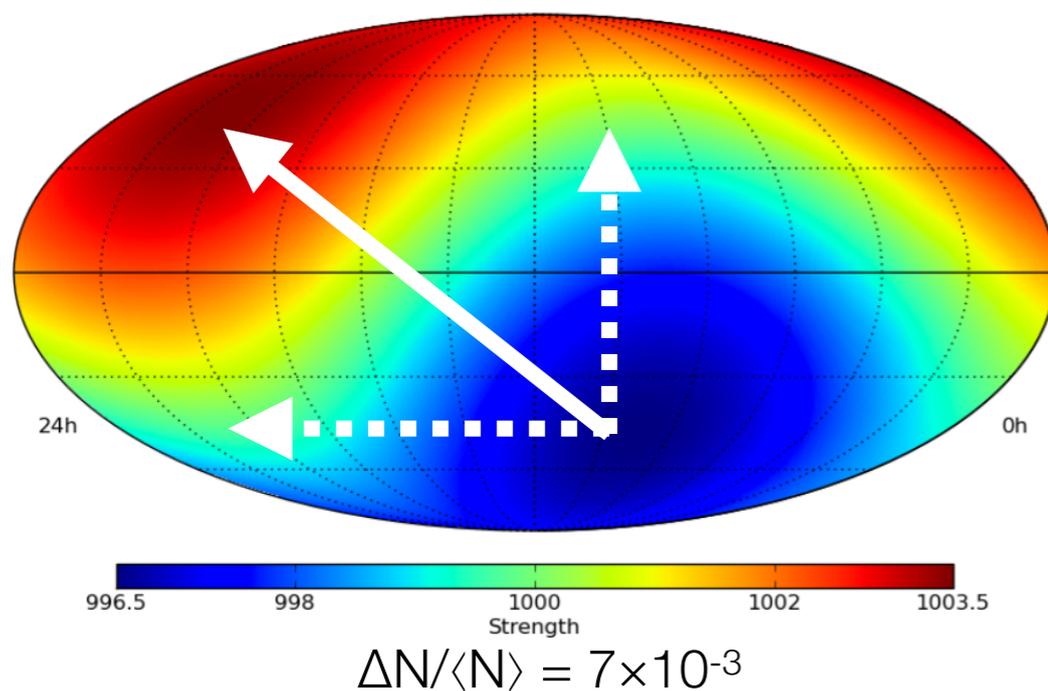
Abbasi et al., ApJ, **746**, 33, 2012

equatorial coordinates



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

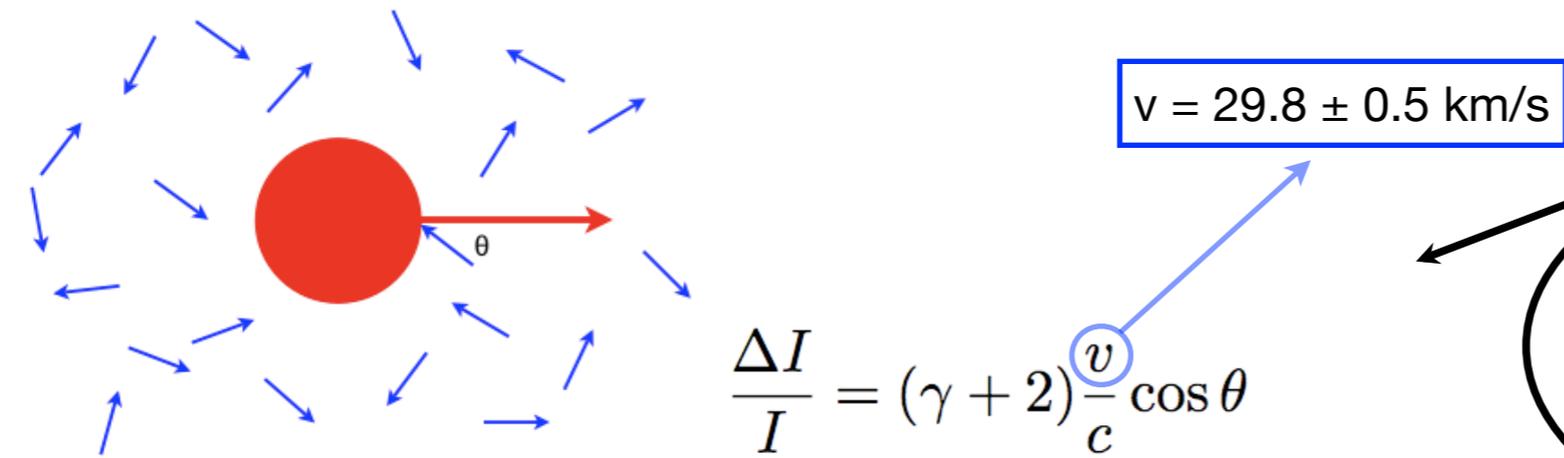
declination bands  
independently normalized



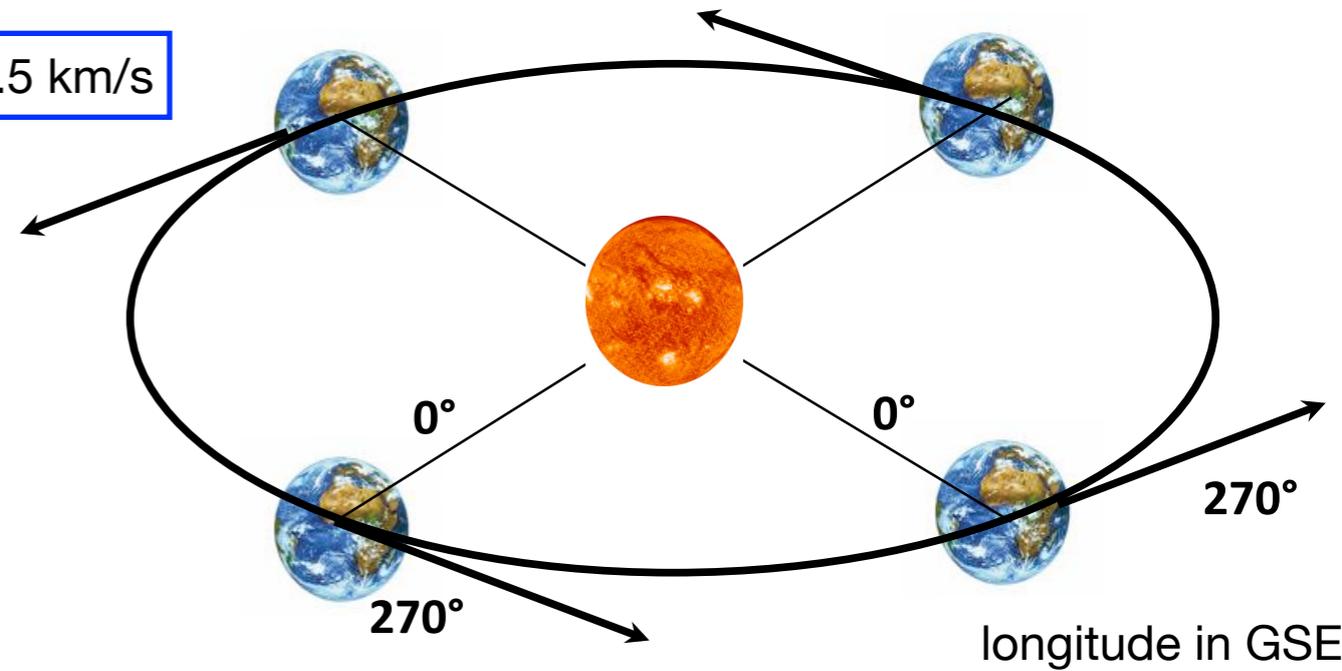
sky maps show **ONLY** modulations projected on **equatorial plane**

# a known anisotropy

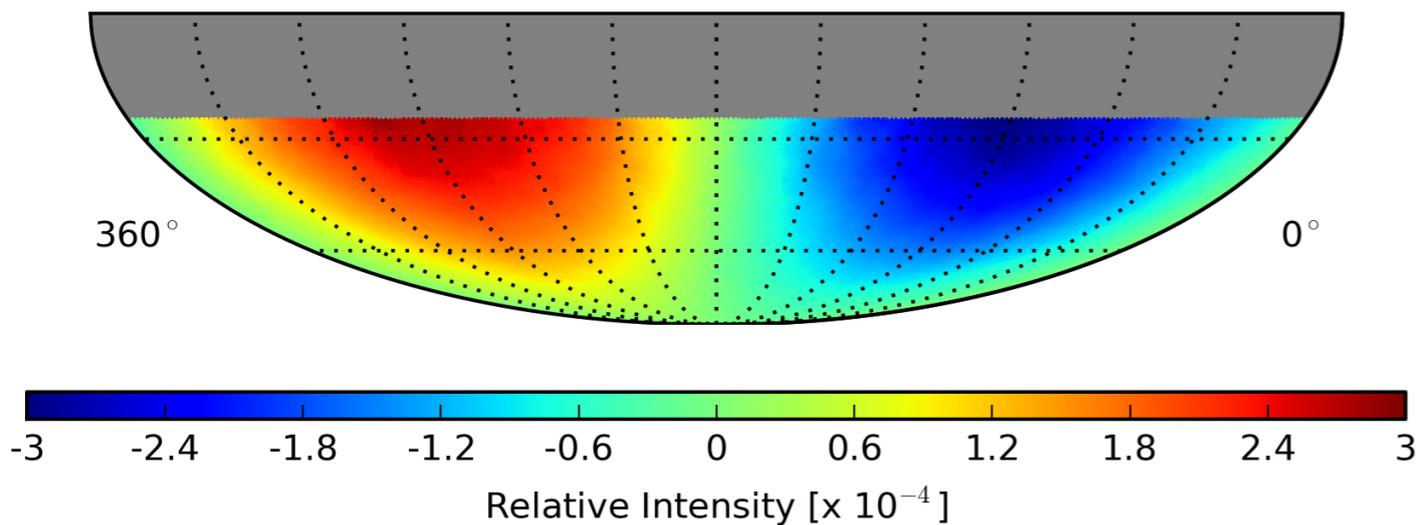
## Earth's revolution around the Sun



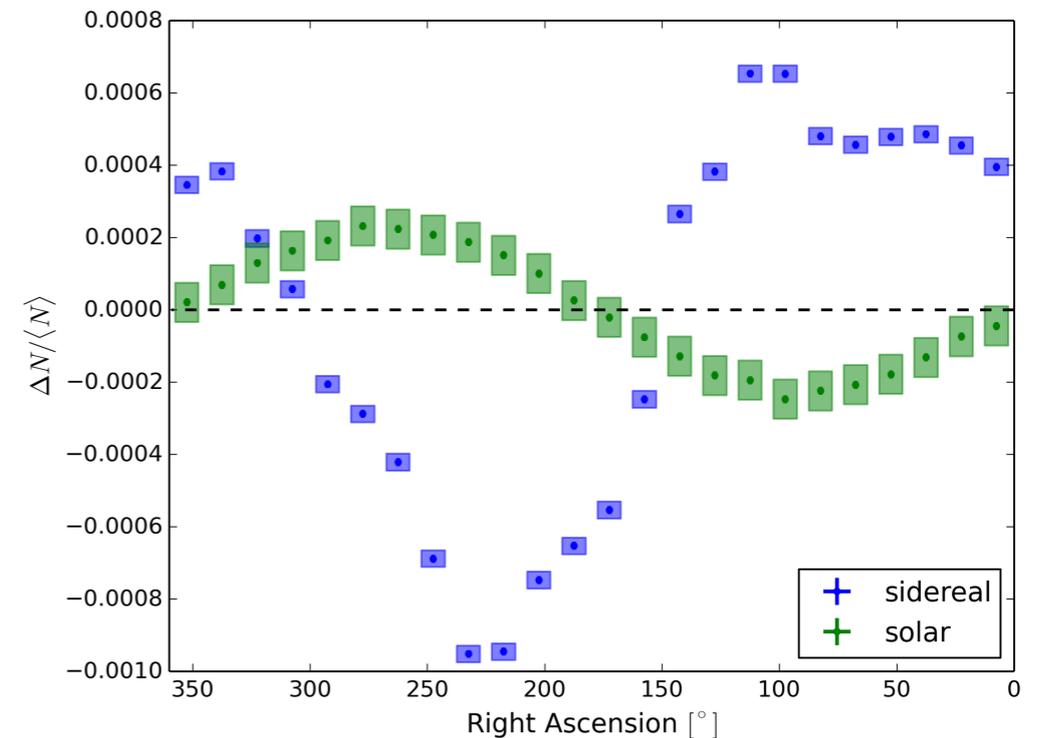
$$\frac{\Delta I}{I} = (\gamma + 2) \frac{v}{c} \cos \theta$$



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

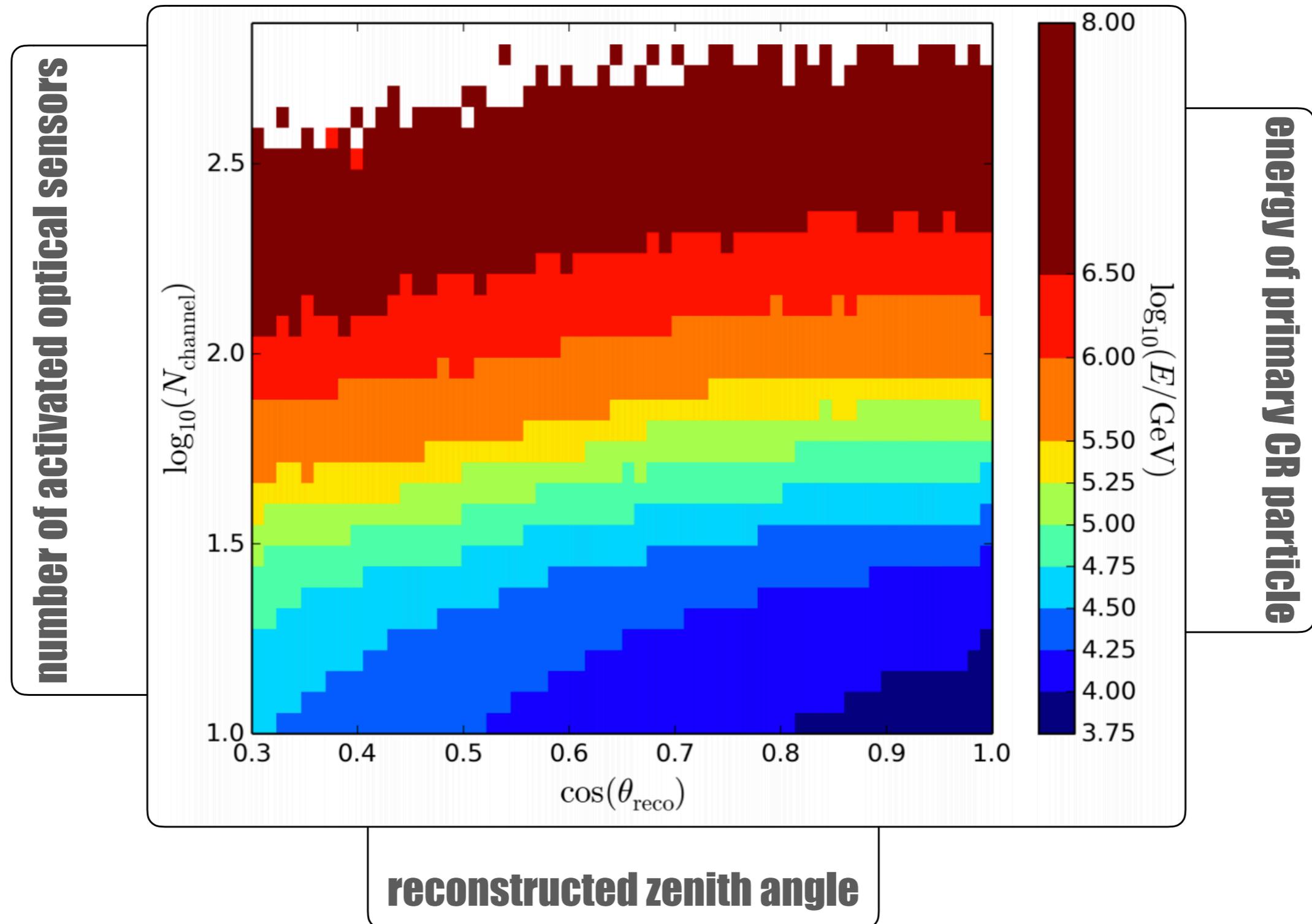


IceCube - Aartsen et al., ApJ 826, 220, 2016



# observing cosmic ray anisotropy

energy dependency

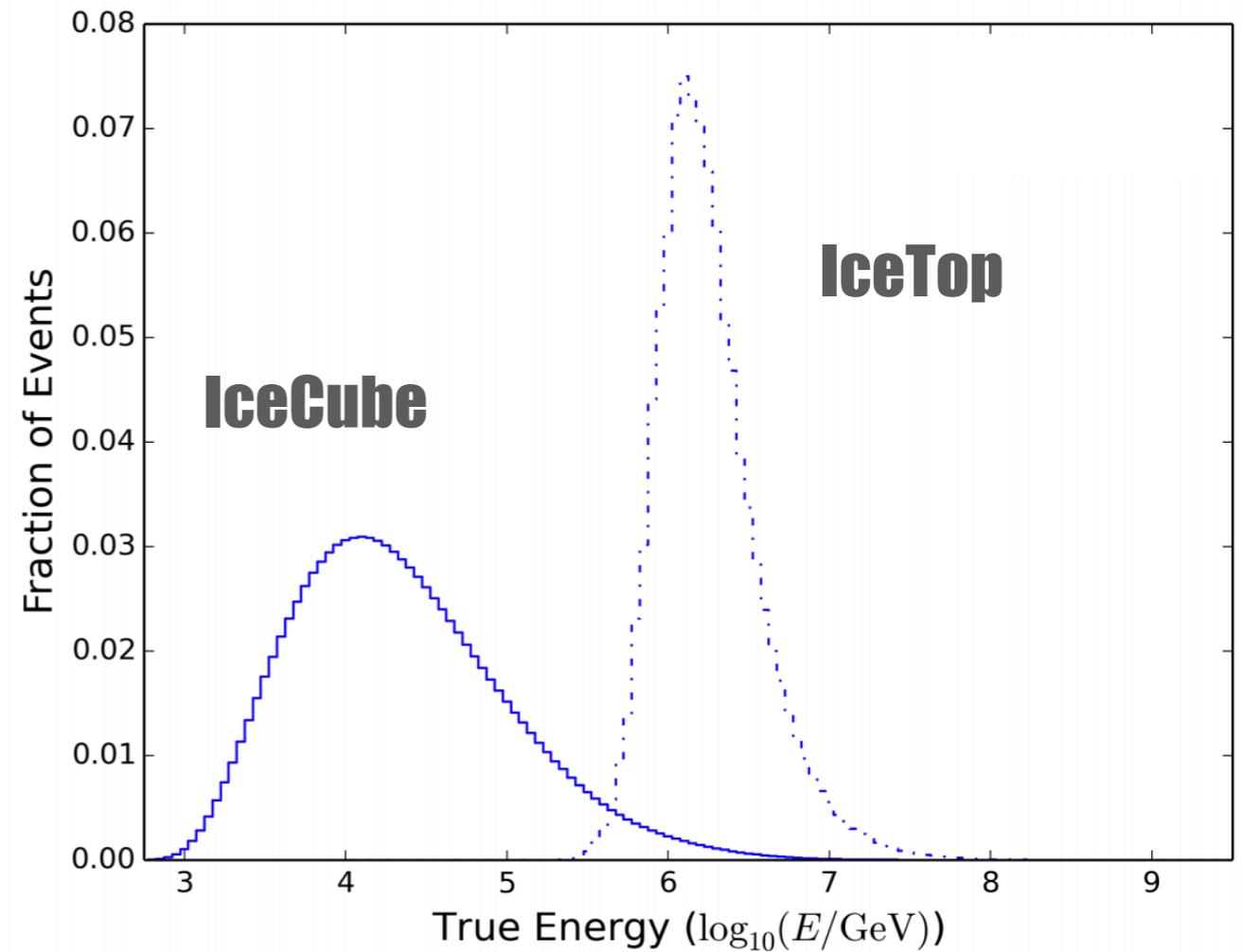
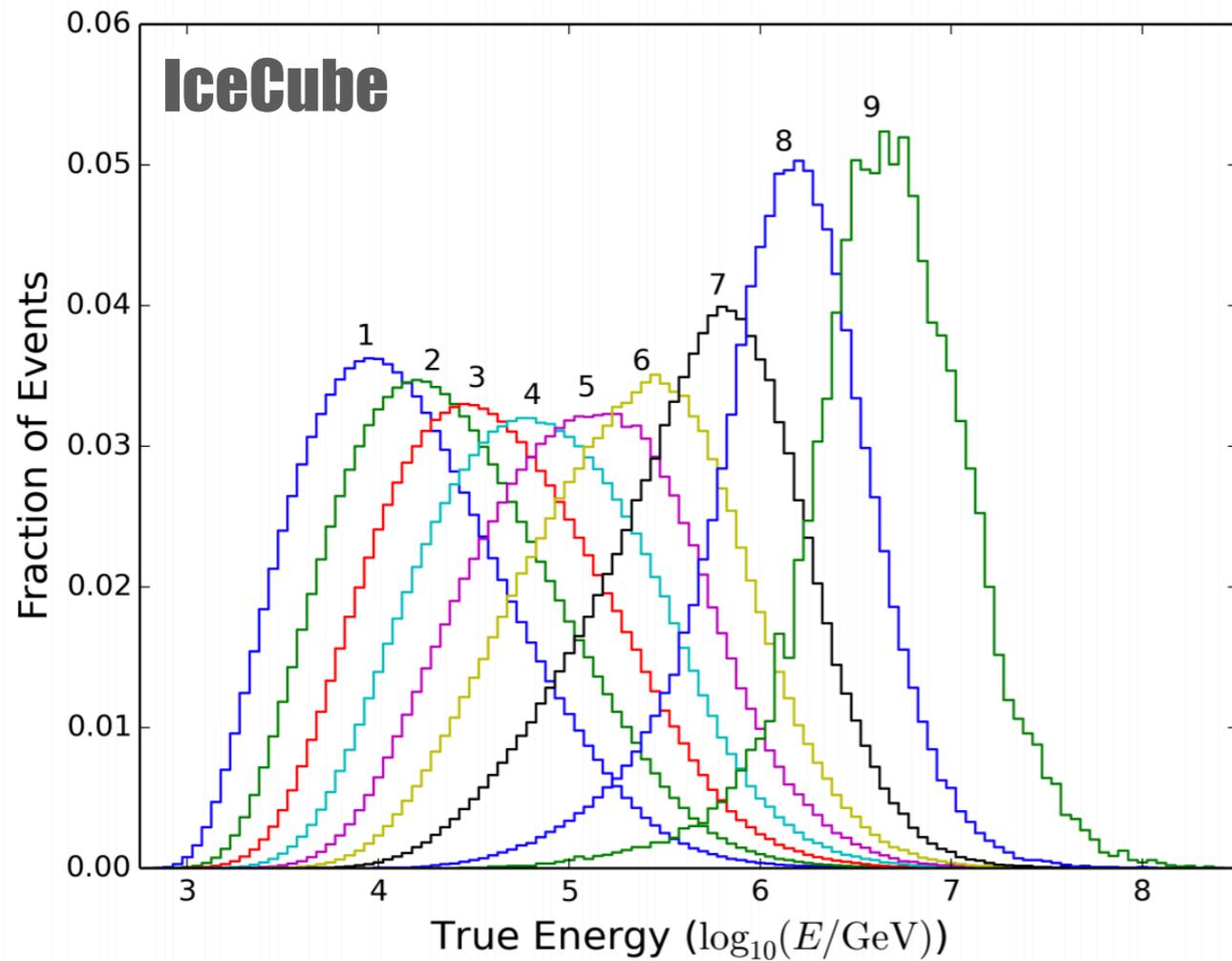


# observing cosmic ray anisotropy

energy dependency



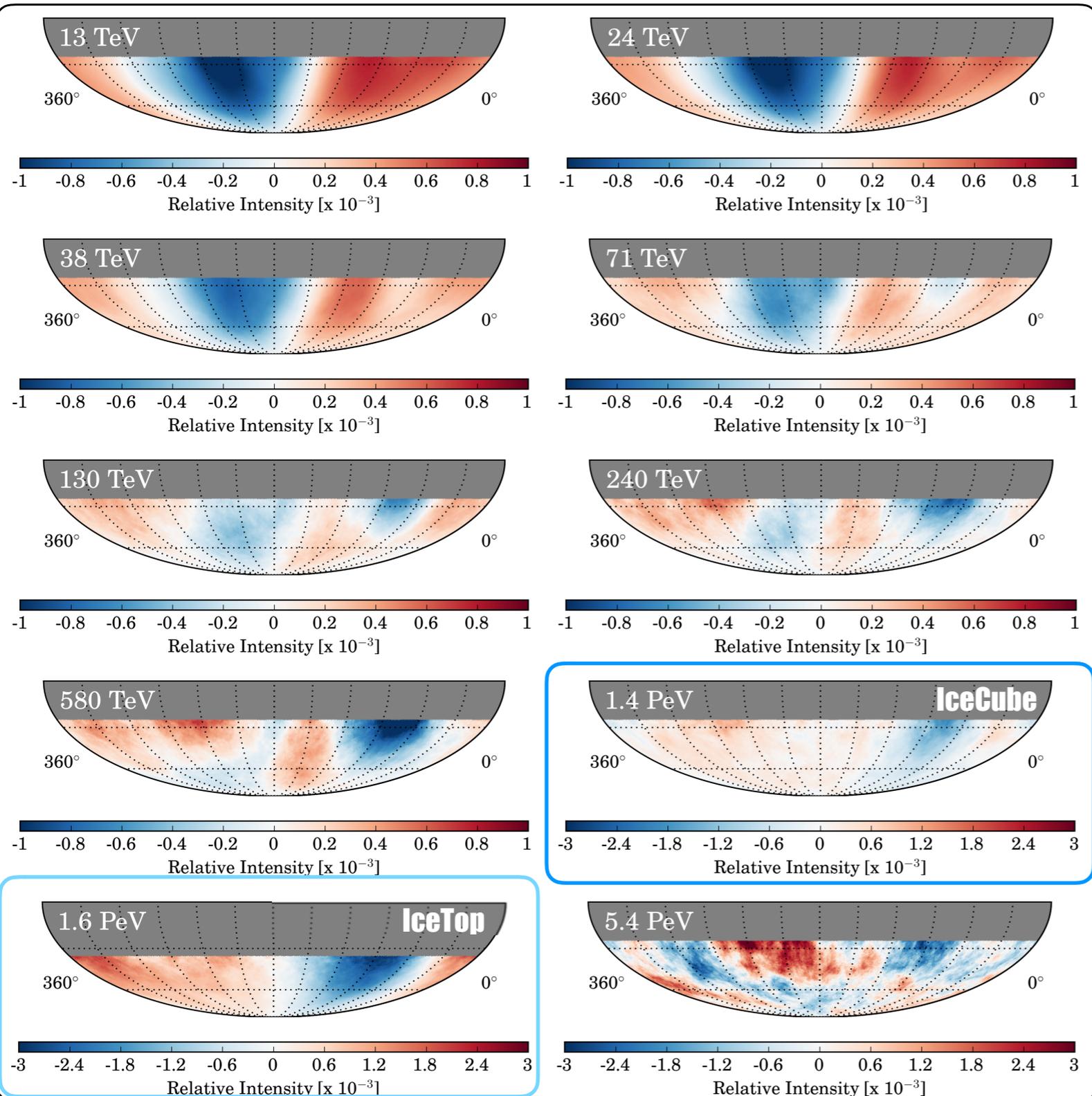
**energy response**



**energy of primary CR particle**

# observing cosmic ray anisotropy

## energy dependency



cosmic ray anisotropy depends on primary energy

large scale changes structure above 100 TeV

*imaging* magnetic effects at larger distances with increasing energy

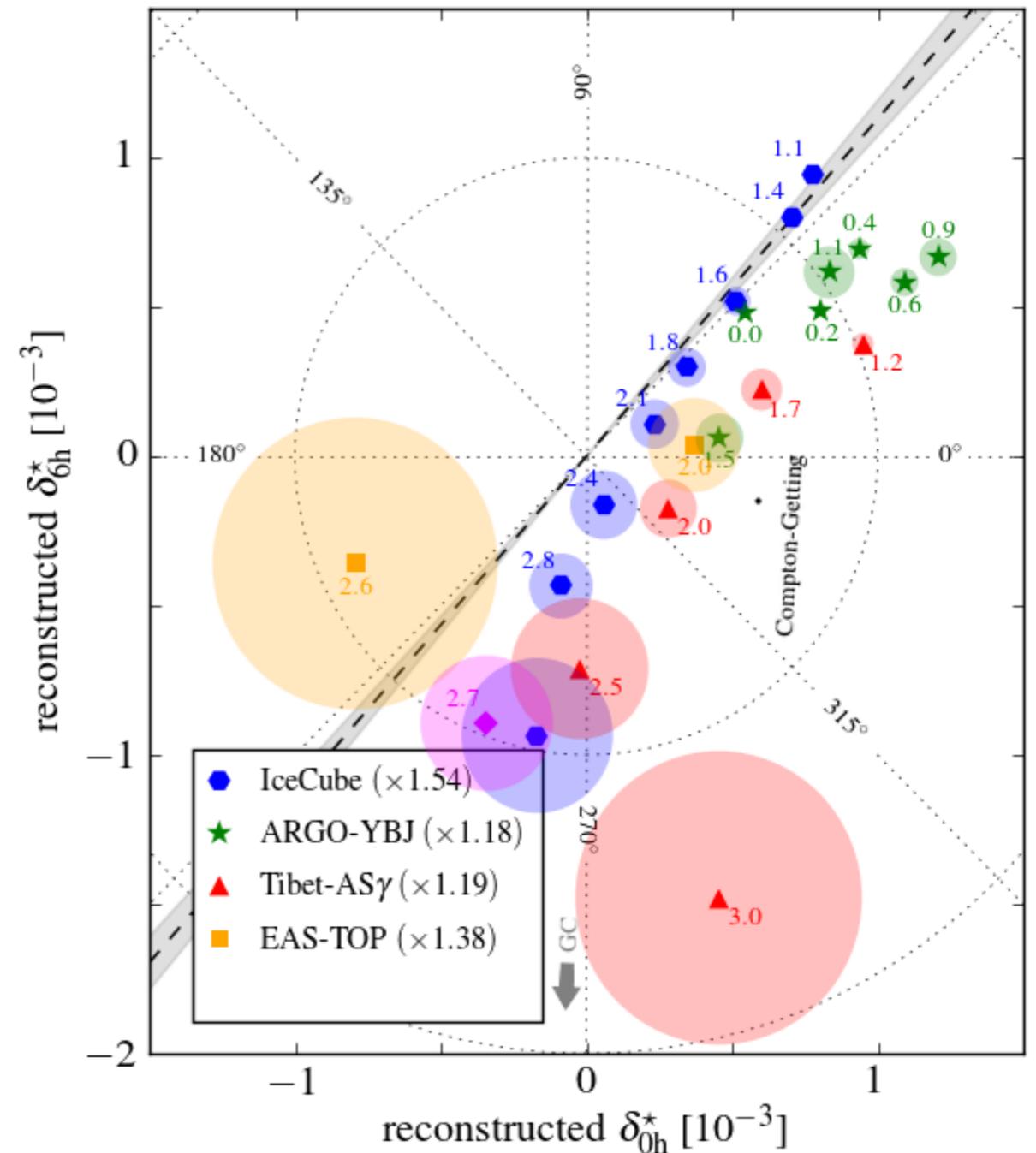
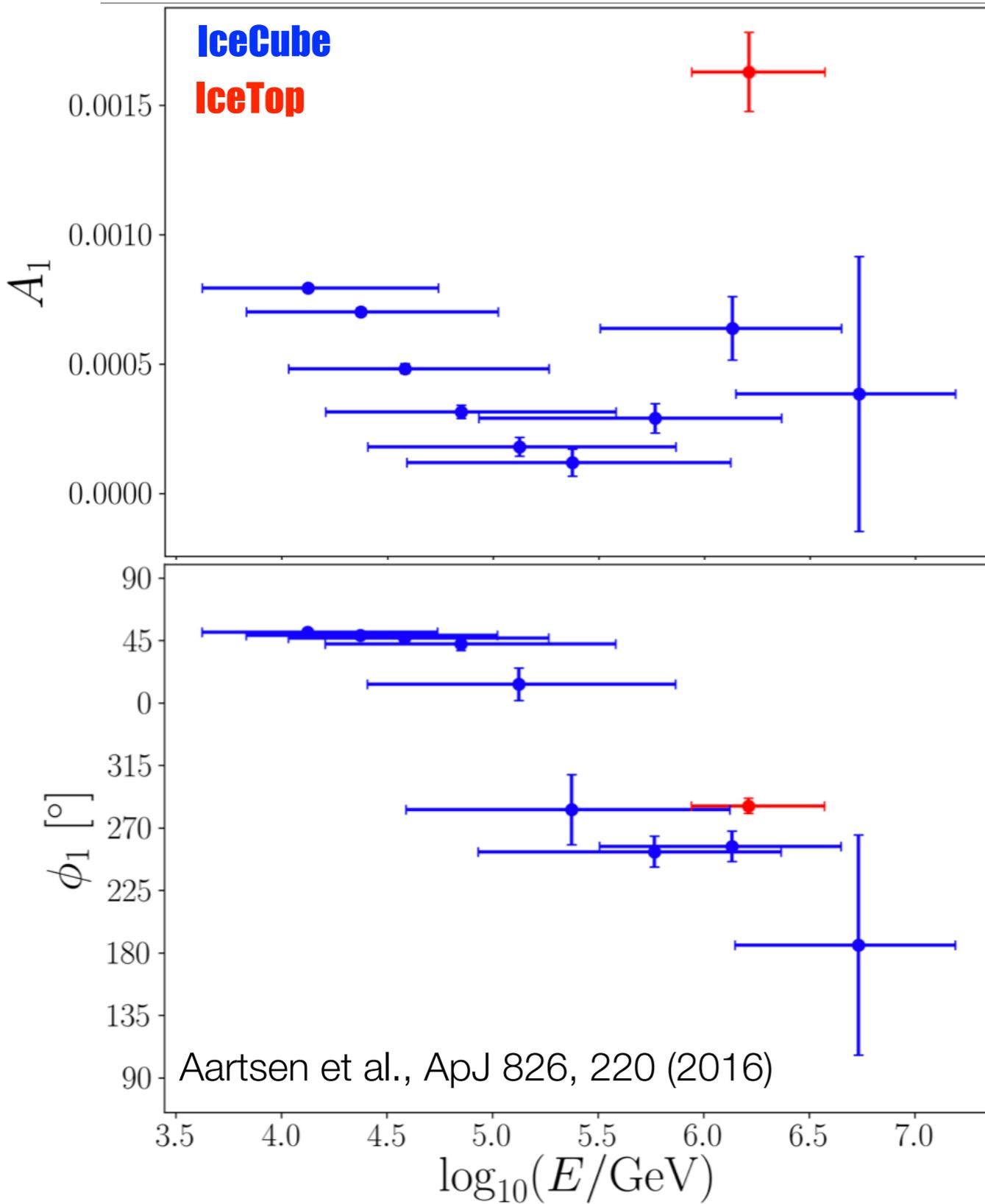
**Note:** cosmic ray composition changes as well vs. energy

# observing cosmic ray anisotropy

dipole component (diffusion?)

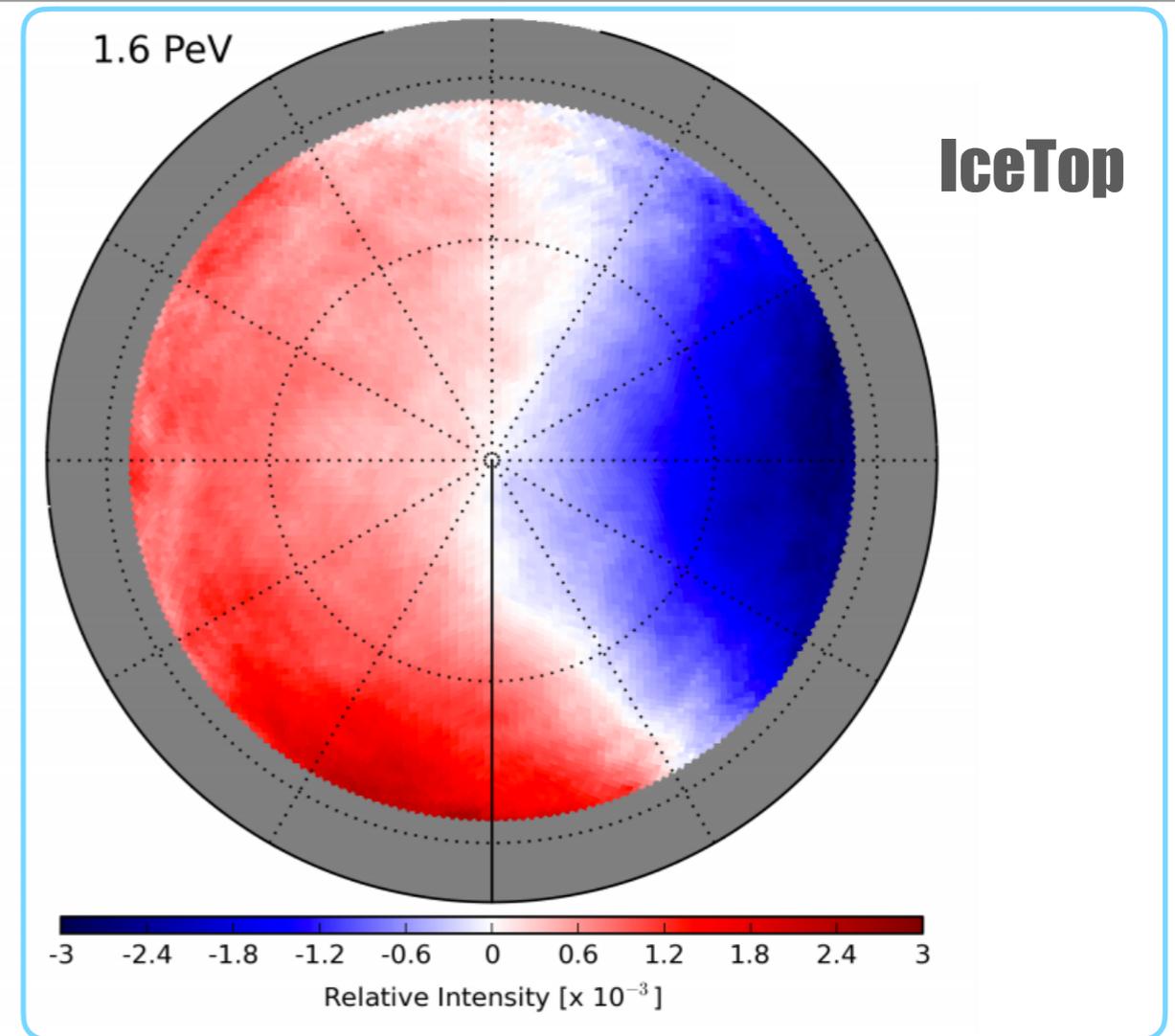
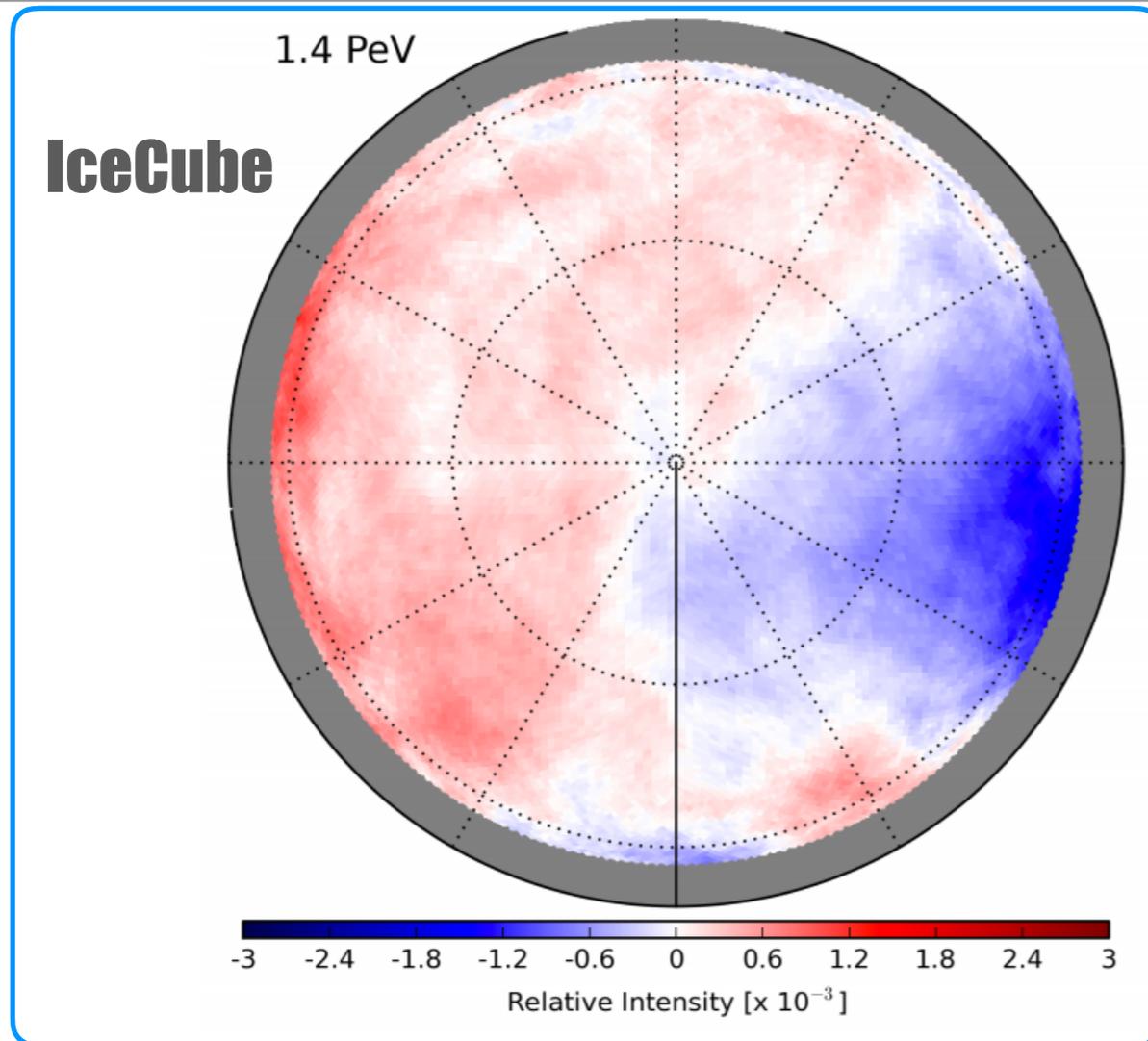


Ahlers arXiv:1605.06446

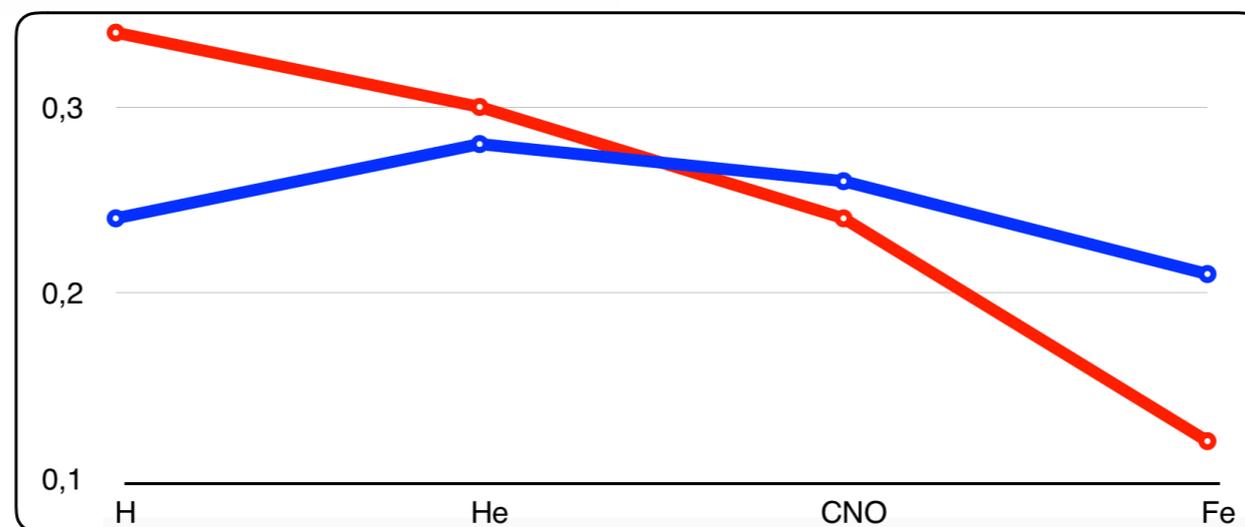


# observing cosmic ray anisotropy

CR mass dependency ?



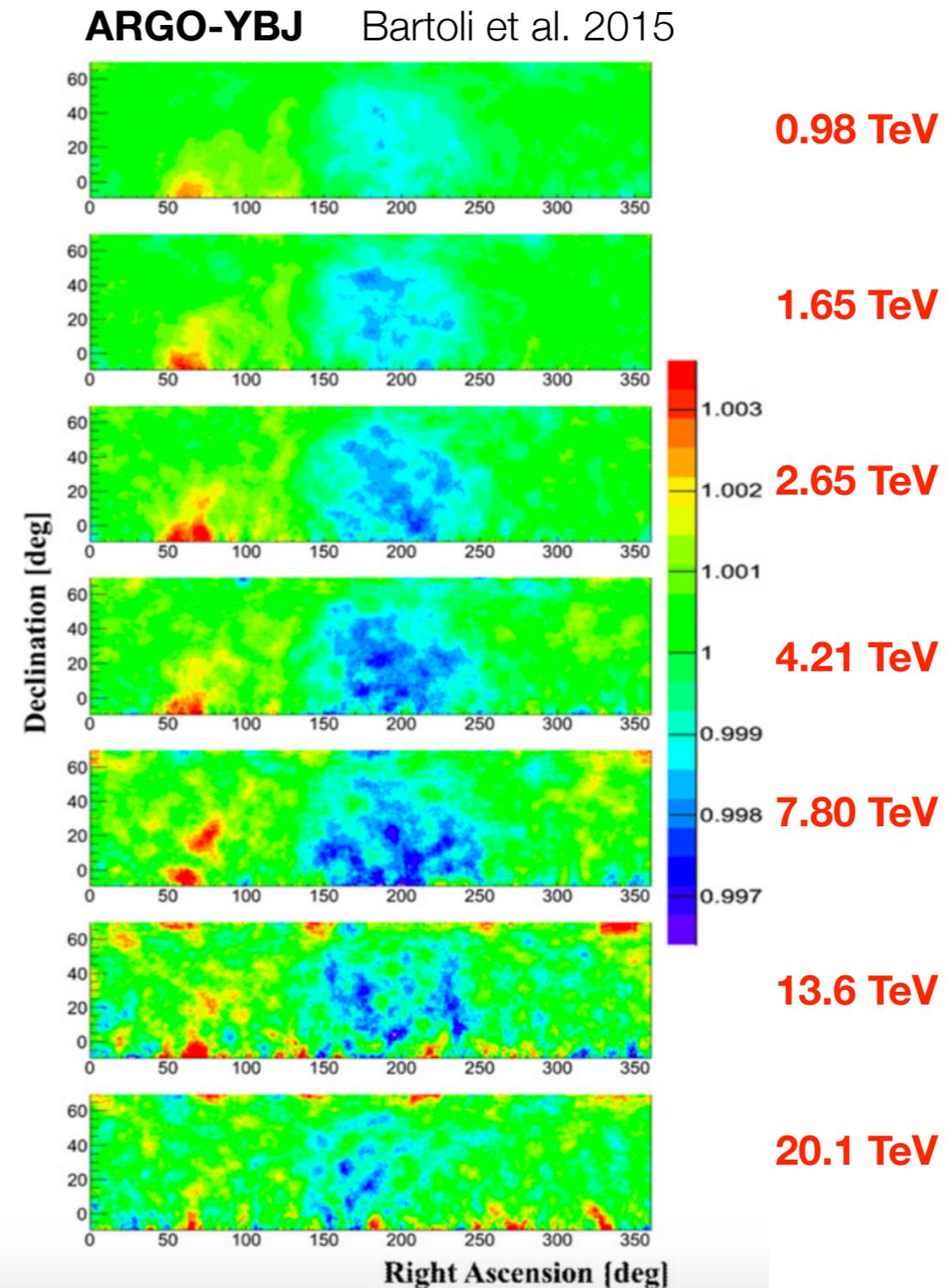
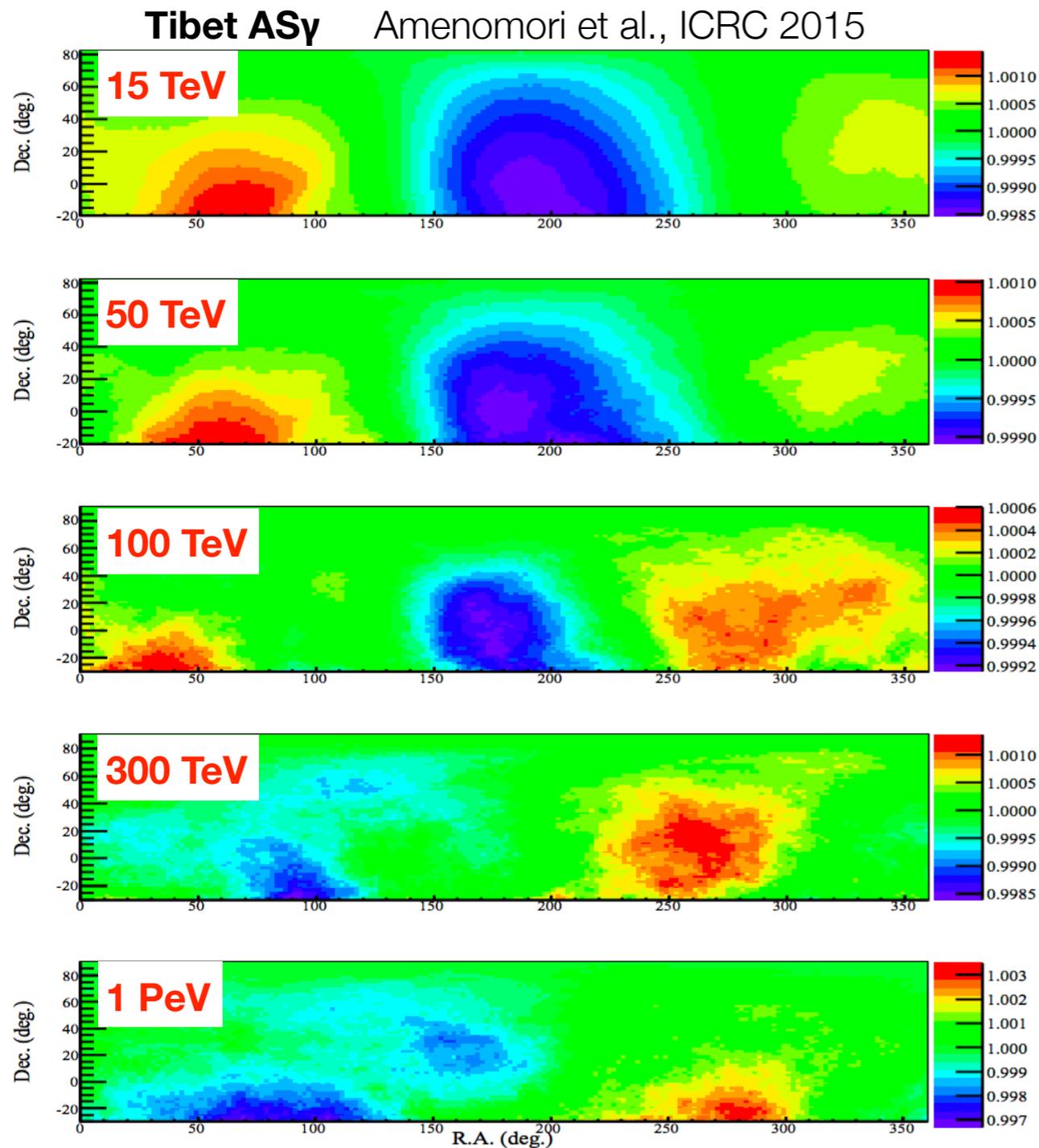
**IceCube**



**IceTop**

# cosmic ray anisotropy

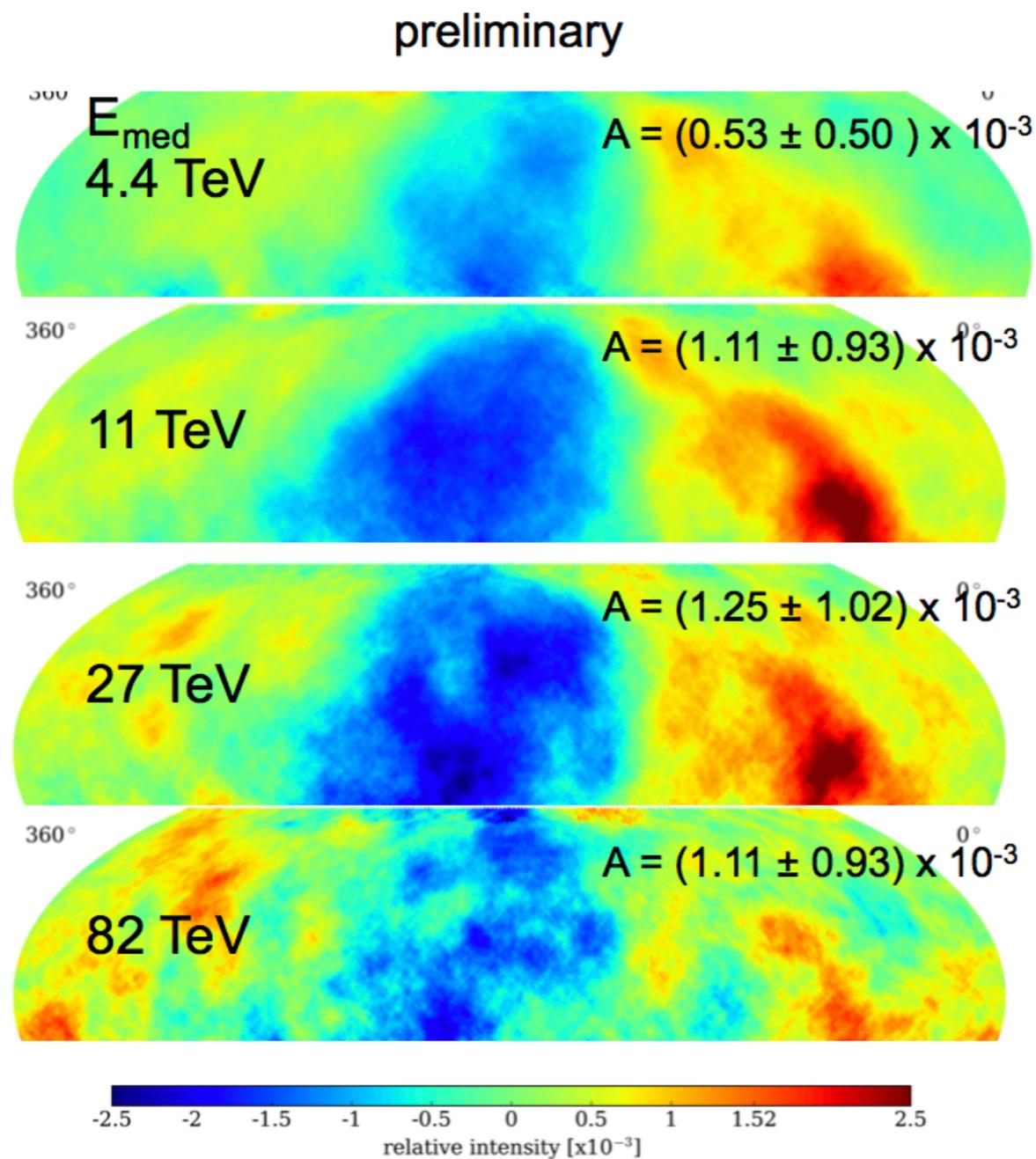
## energy dependence



# cosmic ray anisotropy

## energy dependence

**HAWC-300** D. Fiorino (from S. Westerhoff)

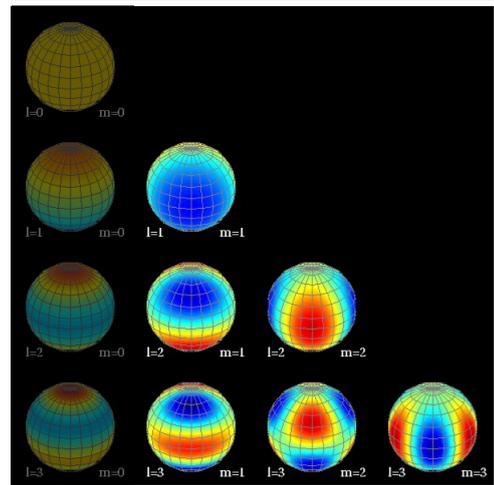
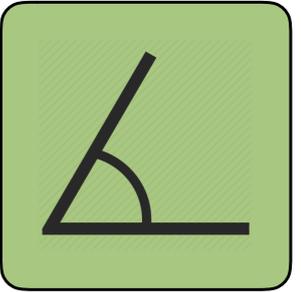


**HAWC-300**  
D. Fiorino

- 241 days of HAWC, 19 billion events.
- Sky maps shown after  $10^\circ$  top-hat smoothing.
- The amplitudes are the dipole moment of a full multipole fit (note large error bars).
- Fluctuations take over at  $E_{\text{med}} = 82$  TeV.

# observing cosmic ray anisotropy

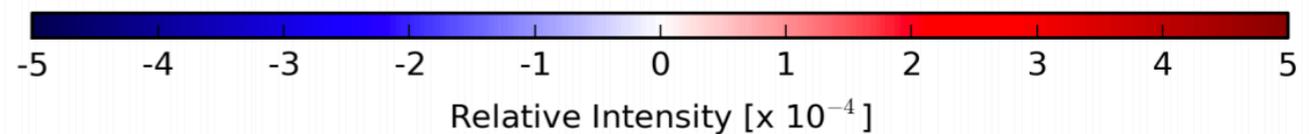
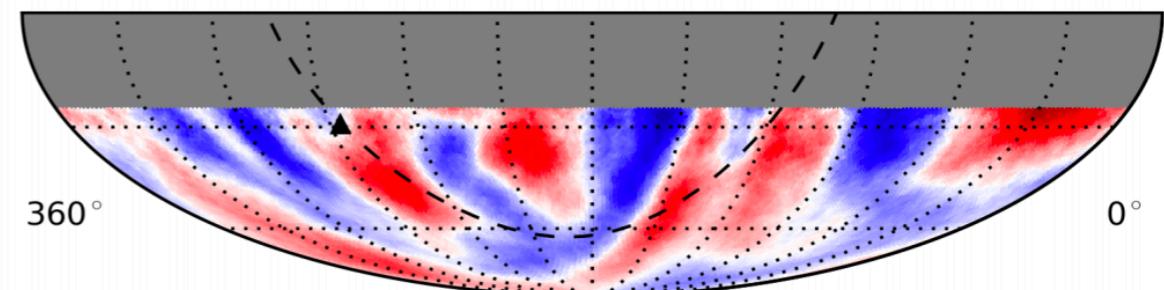
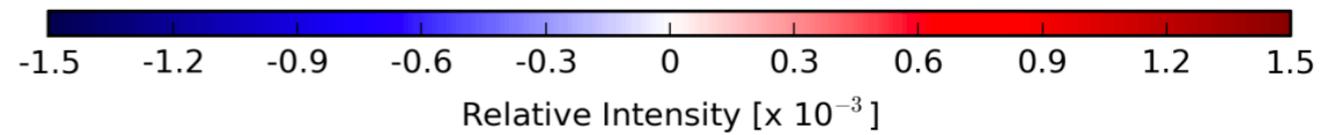
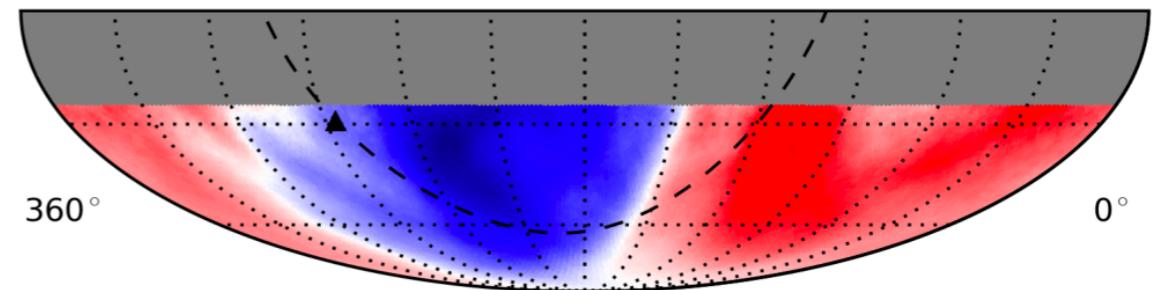
## angular structure decomposition



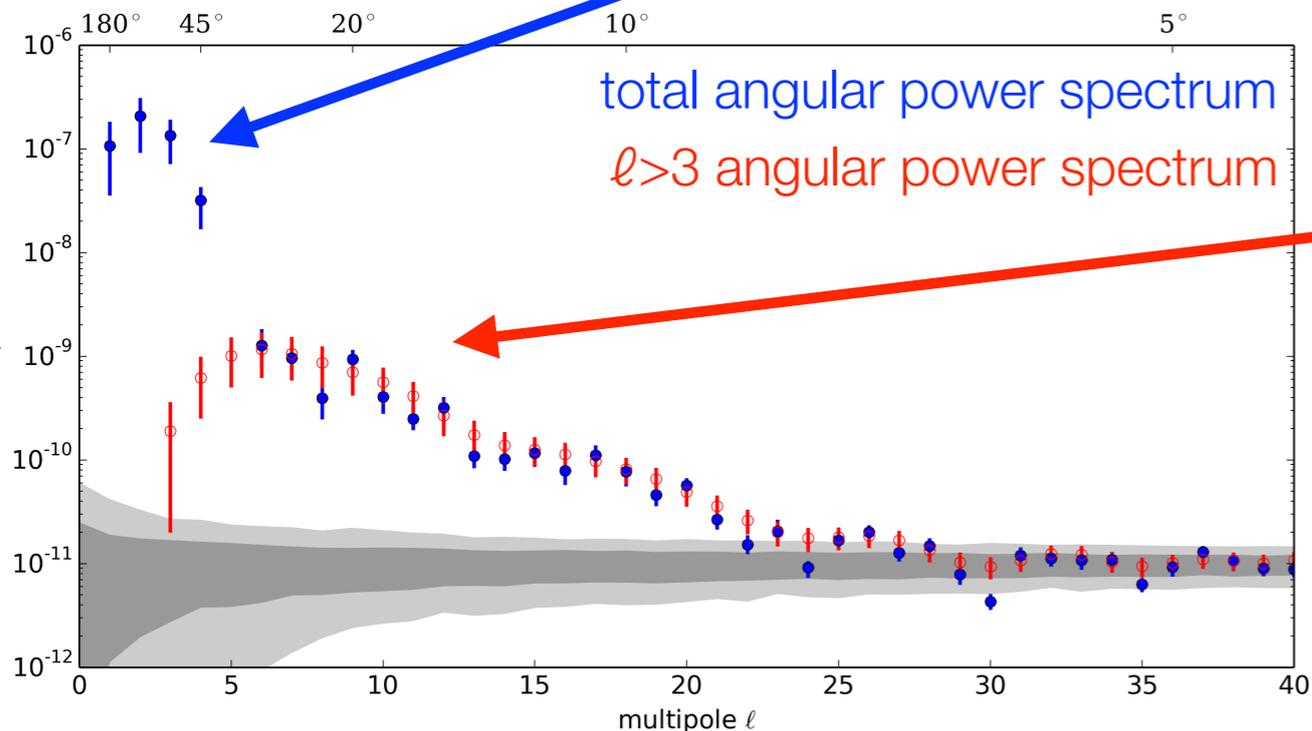
spherical harmonic analysis

missing  
*vertical*  
component  
( $m = 0$ )

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



**median energy 20 TeV**



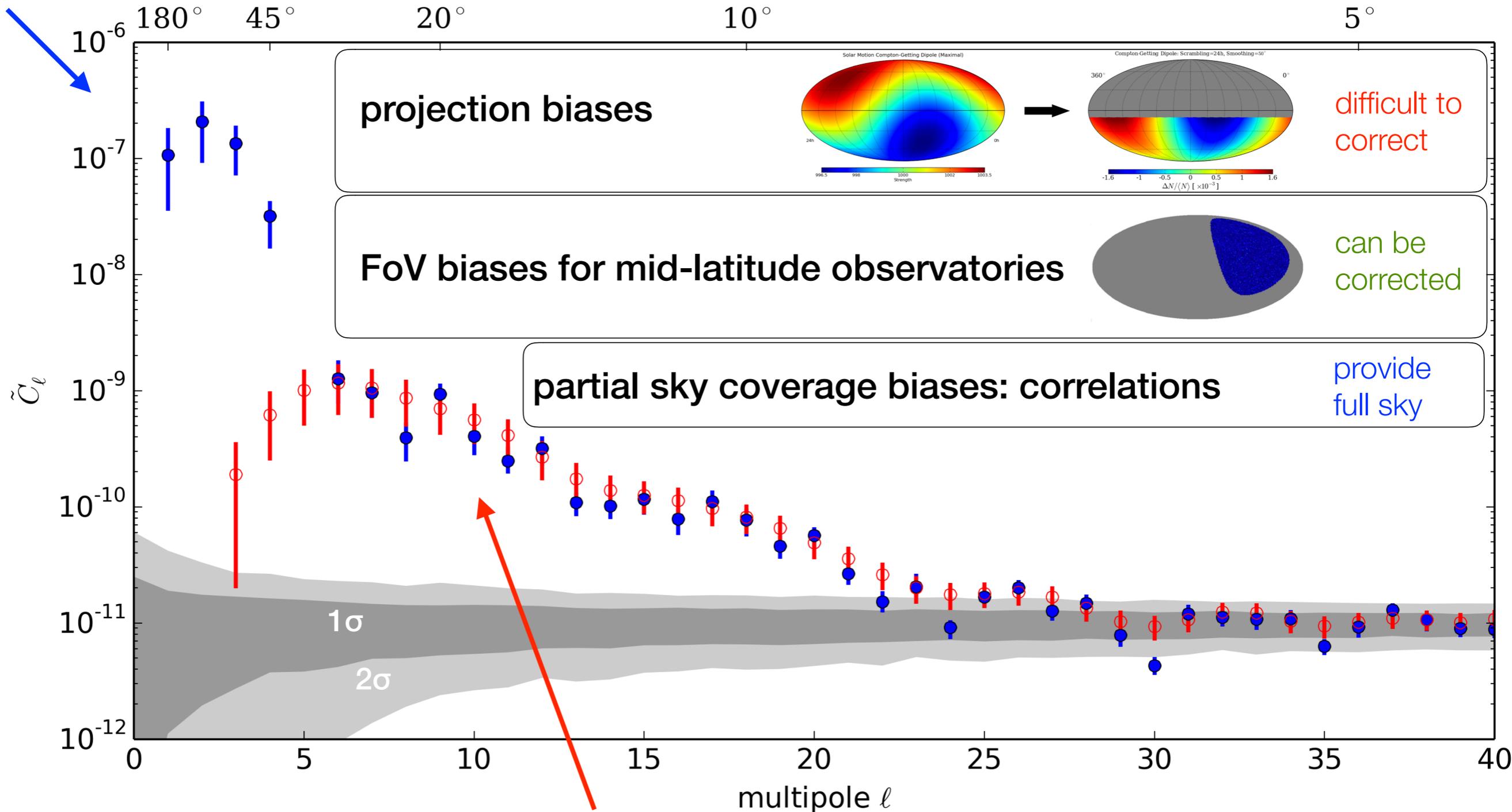
southern hemisphere

# angular power spectrum

phenomenological fingerprint: physics + biases



density gradient / homogeneous diffusion?



effects of magnetic instabilities / turbulence?

# high energy cosmic rays

small scale anisotropy & spectral anomalies

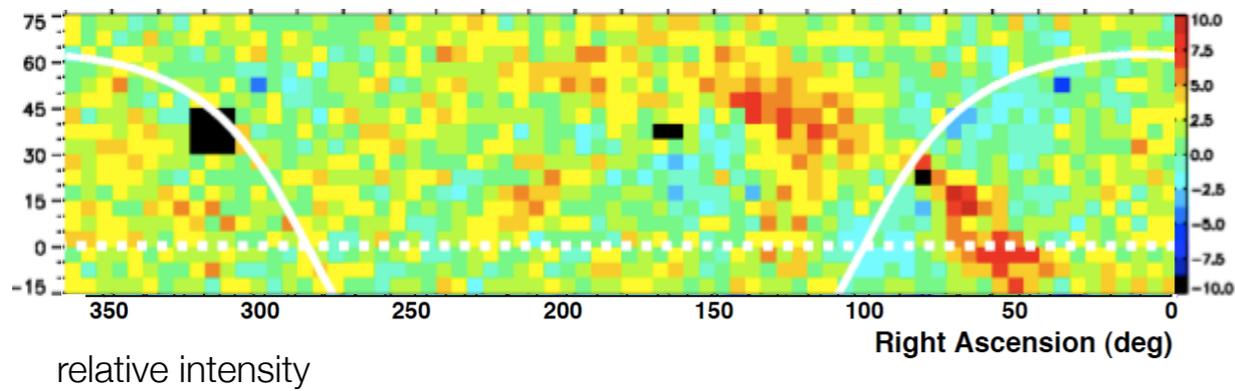
1-5 TeV

$\sim 10^{-4}$

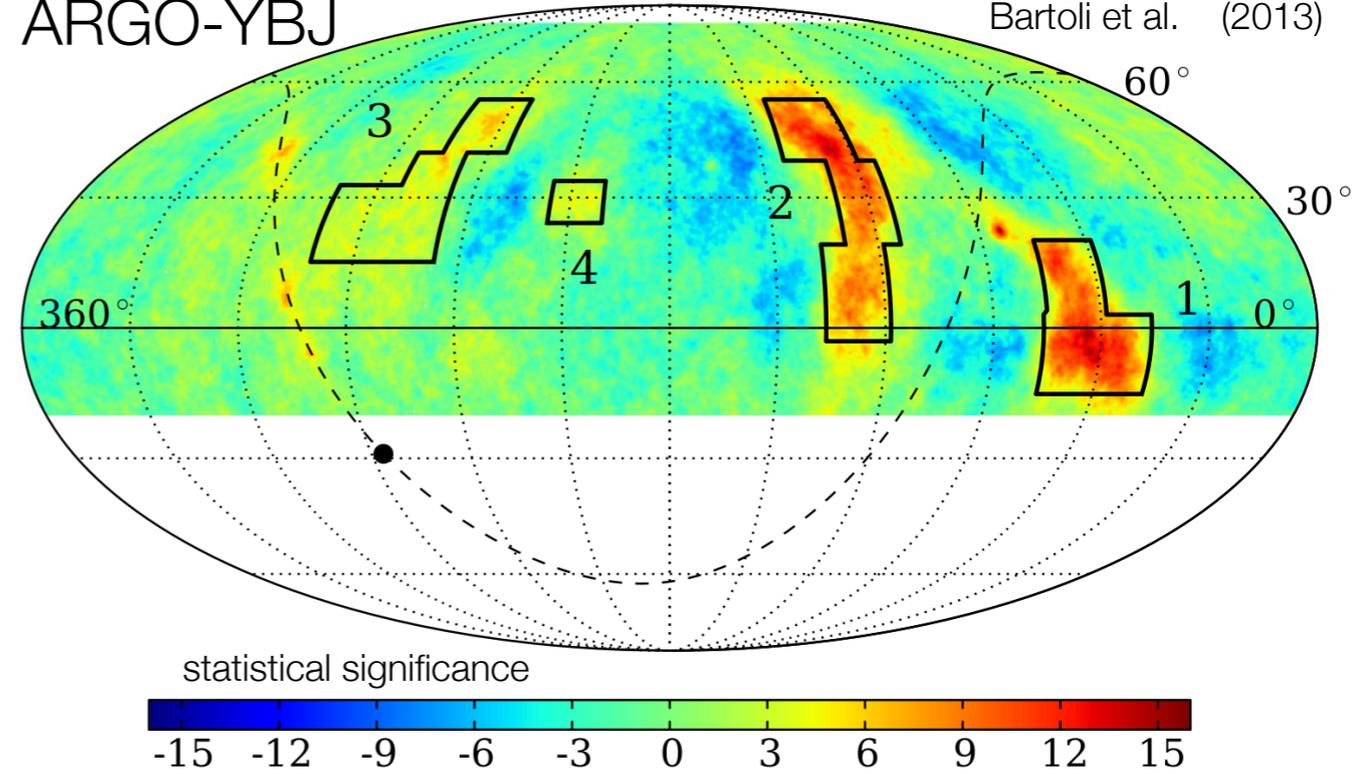
Vernetto et al. (2009)  
Iuppa et al. (2011)  
Bartoli et al. (2013)

Tibet-III

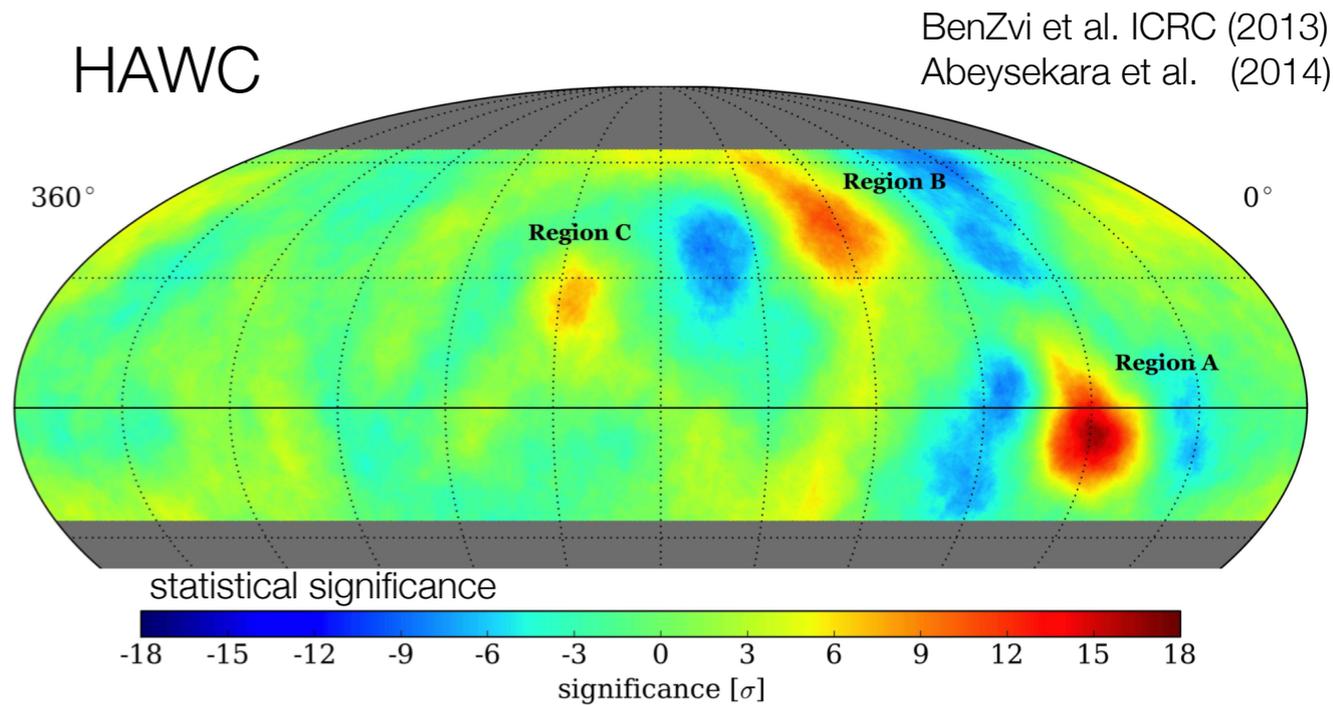
Amenomori et al. ICRC (2007)



ARGO-YBJ

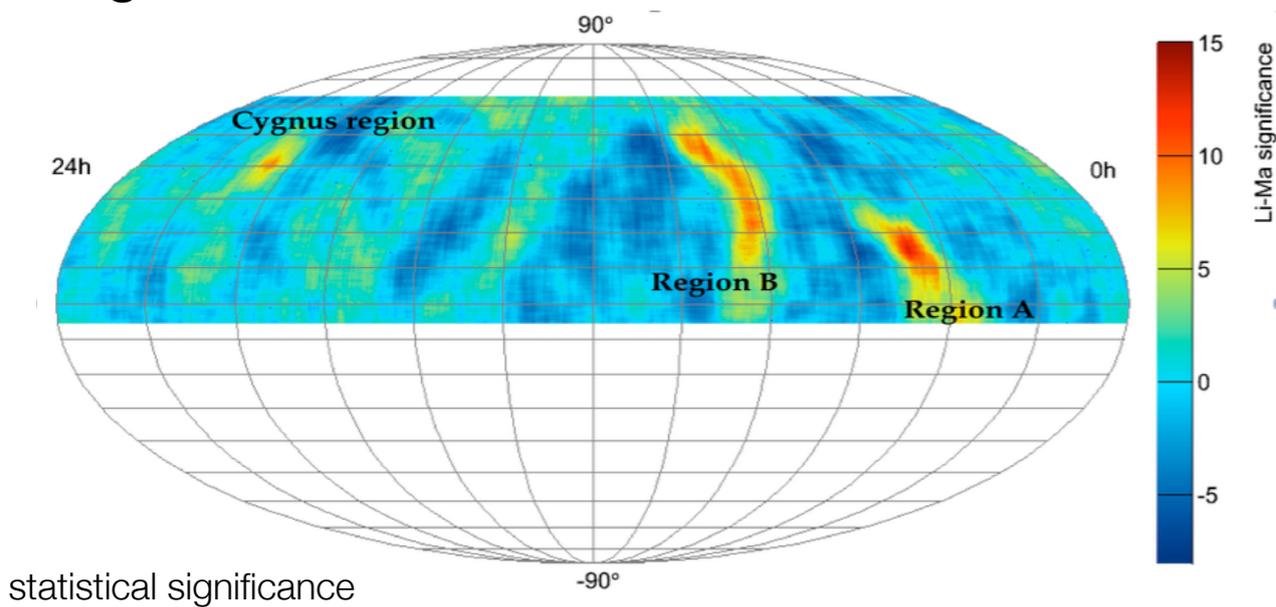


HAWC



Milagro

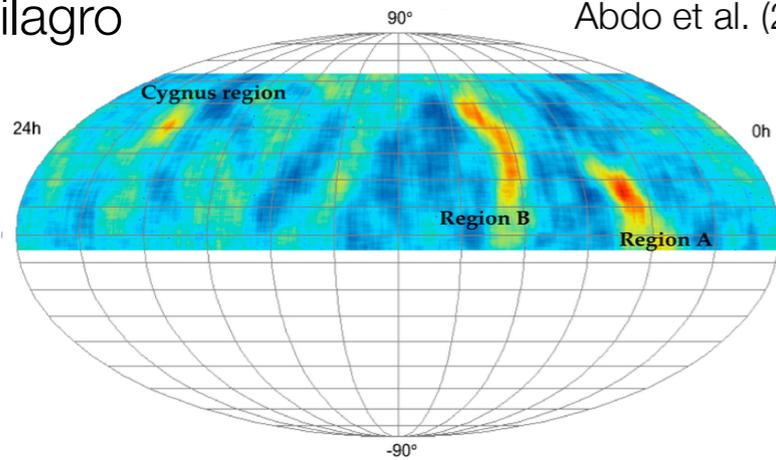
Abdo et al. (2008)



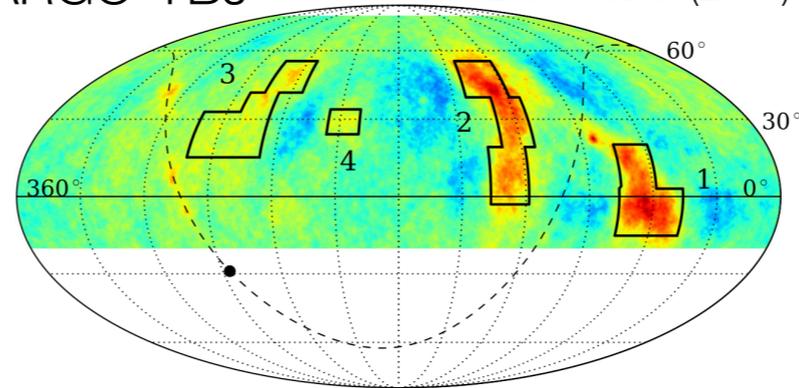
# high energy cosmic rays

## small scale anisotropy & spectral anomalies

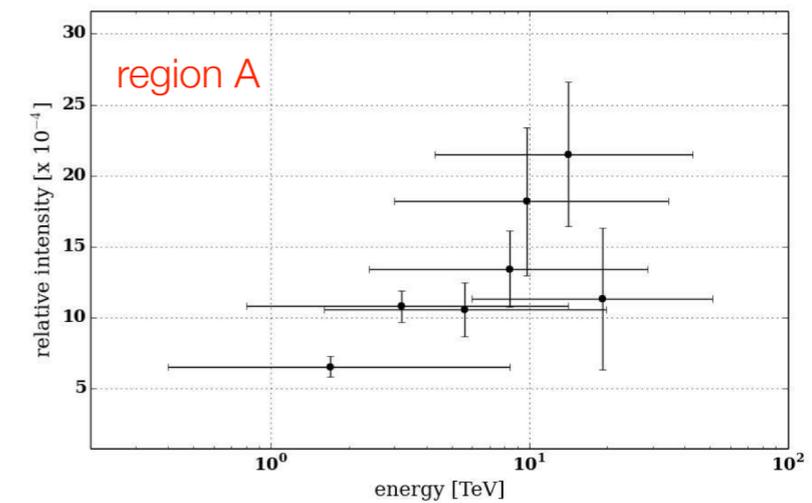
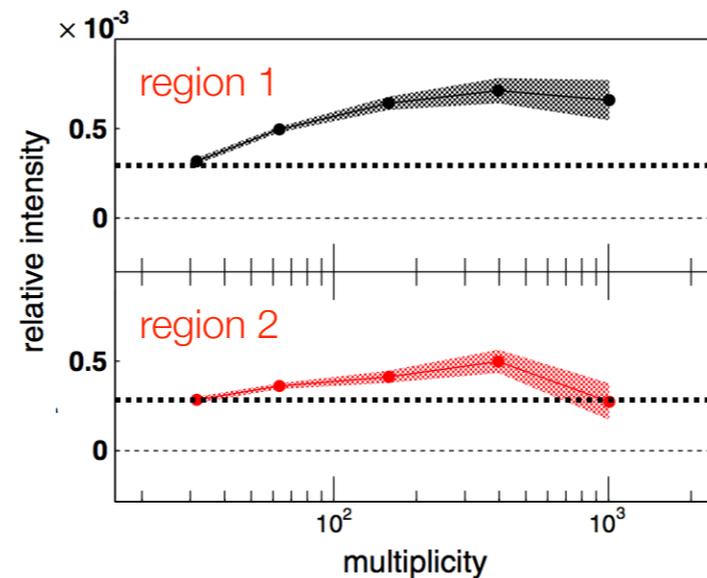
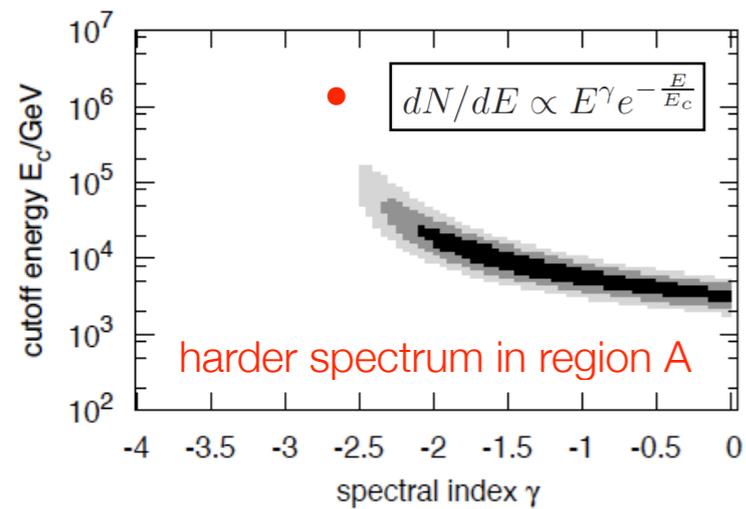
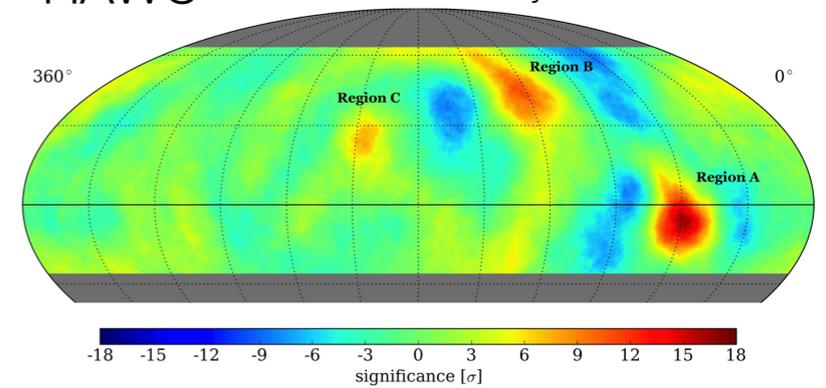
Milagro Abdo et al. (2008)



ARGO-YBJ Bartoli et al. (2013)

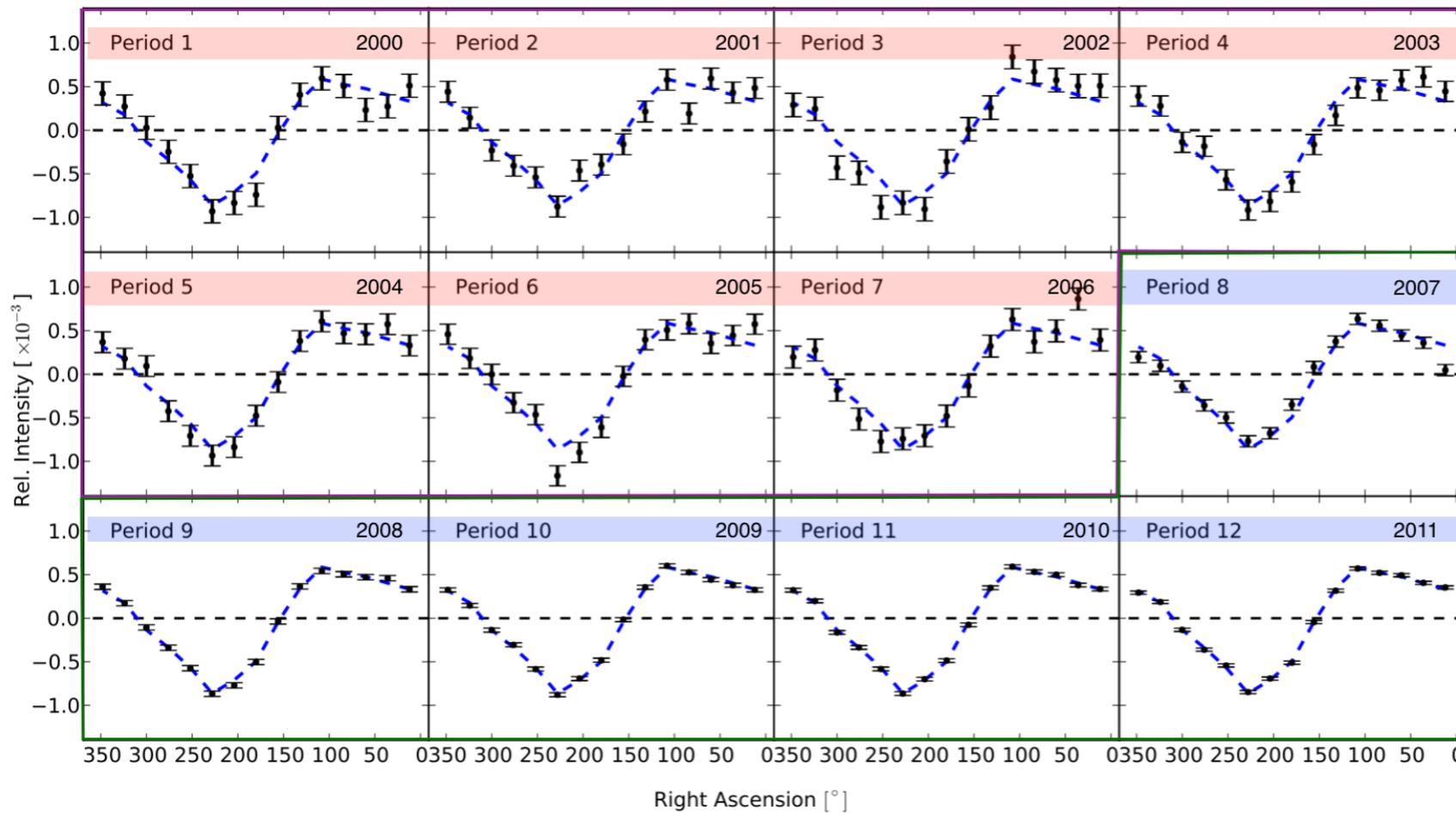
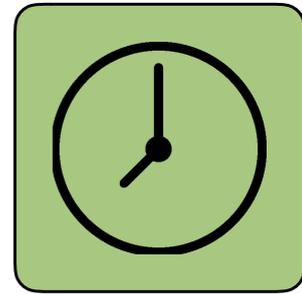


HAWC Abeysekara et al. 2014



# cosmic rays anisotropy stability

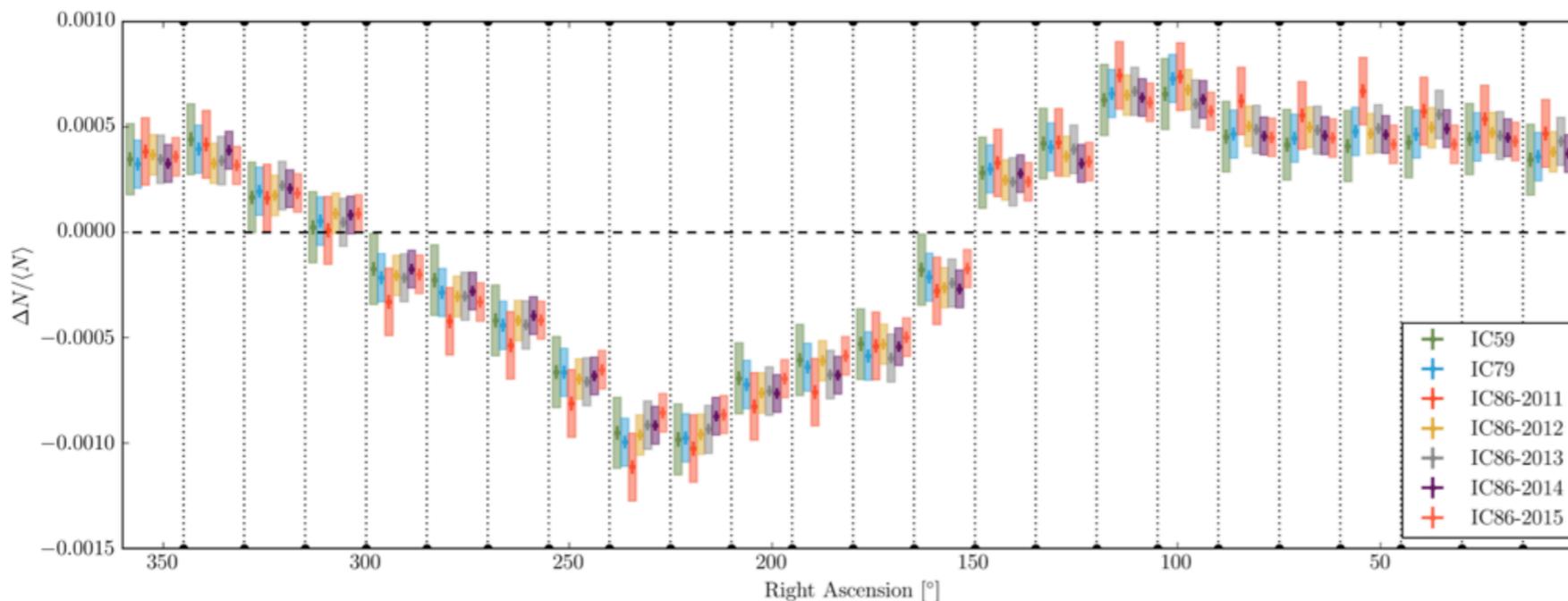
AMANDA-IceCube 2000-2015



ICRC 2013

IceCube - Aartsen et al., ApJ 826, 220, 2016  
- ICRC 2017

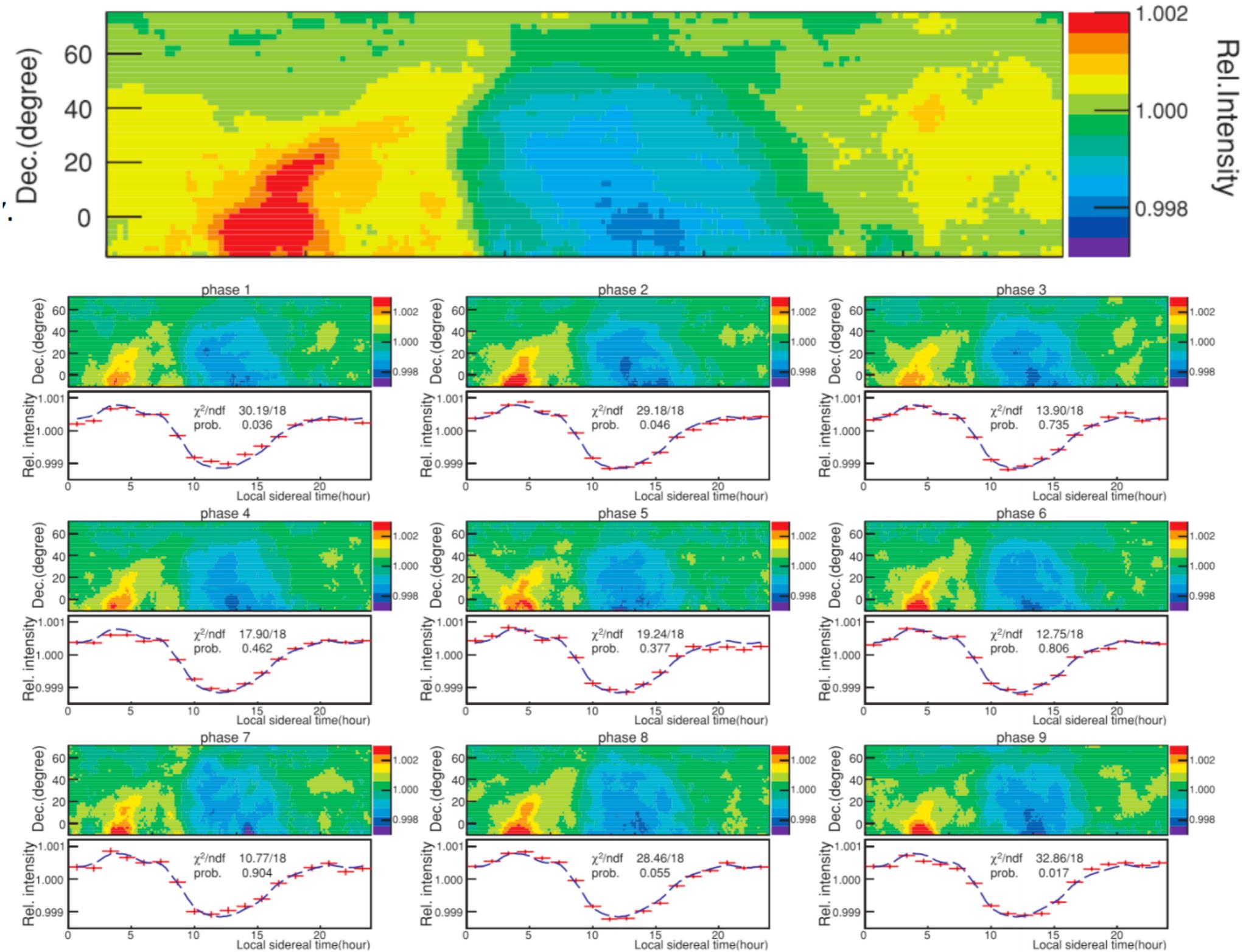
median energy ~ 20 TeV



# cosmic rays anisotropy stability

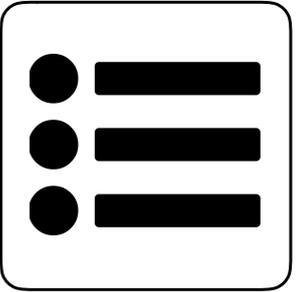
## Tibet Array

Tibet Array 2005



# conclusions

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CR anisotropy as fingerprint on **origin** and **propagation**

CR anisotropy from **standard diffusion** at *large-scale* (global) & **non-diffusive processes** (angular structure)

**probe** into local environment properties (Local Bubble, LIMF, heliosphere, ...) and into interstellar turbulence properties

likely many overlapping phenomena: anisotropy vs. **energy, angular structure, time, primary particle mass**

overcome experimental limitations

compensate for limited FoV

full-sky observations: **surface IceCube-HAWC & satellite observations**

discussion topics...

# TeV cosmic ray anisotropy

## discussion topics

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Full sky angular spectrum has two features

- diffusive (low harmonic components)
- non-diffusive (high harmonic components)
- probe into the propagation properties in local magnetic fields?

Sky map shows correlations with heliospheric features ( $<100$  TV rigidity)

- probe into the properties of heliosphere at the boundary and tail?
- is heliosphere's boundary turbulent or dynamically unstable?
- TeV CR trajectories become stochastic fast in heliosphere (strong scattering)?

Global anisotropy telling us about the turbulence properties of ISM?

Global anisotropy telling us something about direction of LIMF?

Global anisotropy telling us about the nearest and most recent CR source?

Small angular scale telling us about magnetic turbulence, heliospheric boundary instabilities?