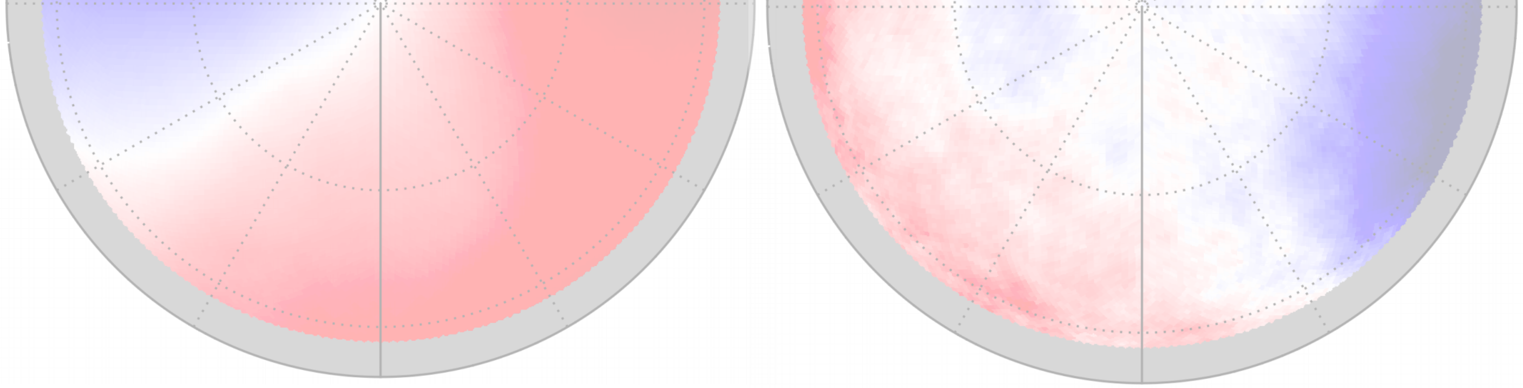

Galactic Cosmic Ray Anisotropy with the IceCube Observatory

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for

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University of Wisconsin - Madison

Wisconsin IceCube Particle Astrophysics Center

International Solvay Institutes Brussels

Solvay workshop on SuGAR 2018

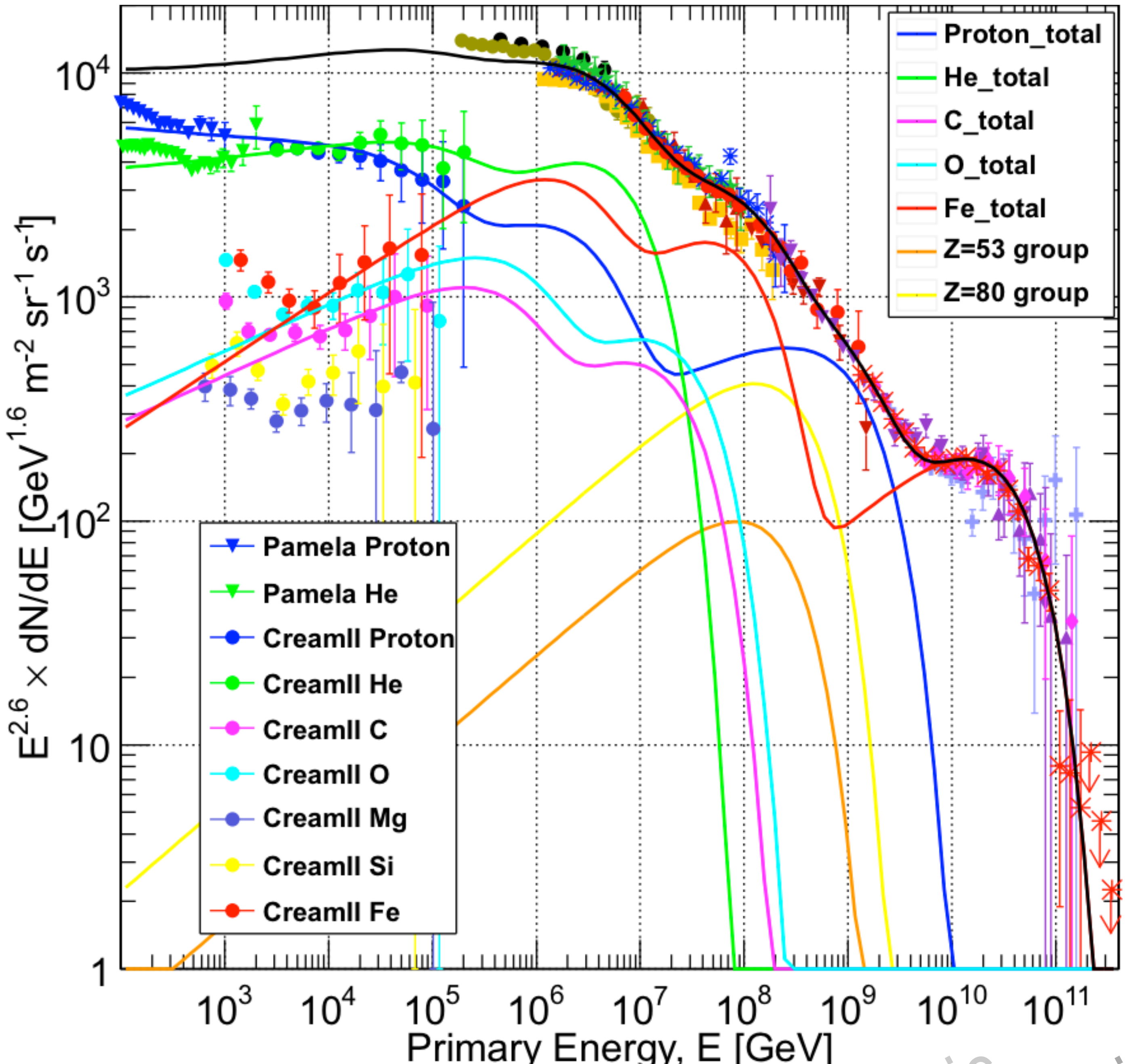
Brussels, 23-26 January

cosmic ray observations

energy spectrum & composition

Gaisser, Stanev, Tilav, 2013 - arXiv:1303.3565

direct measurements

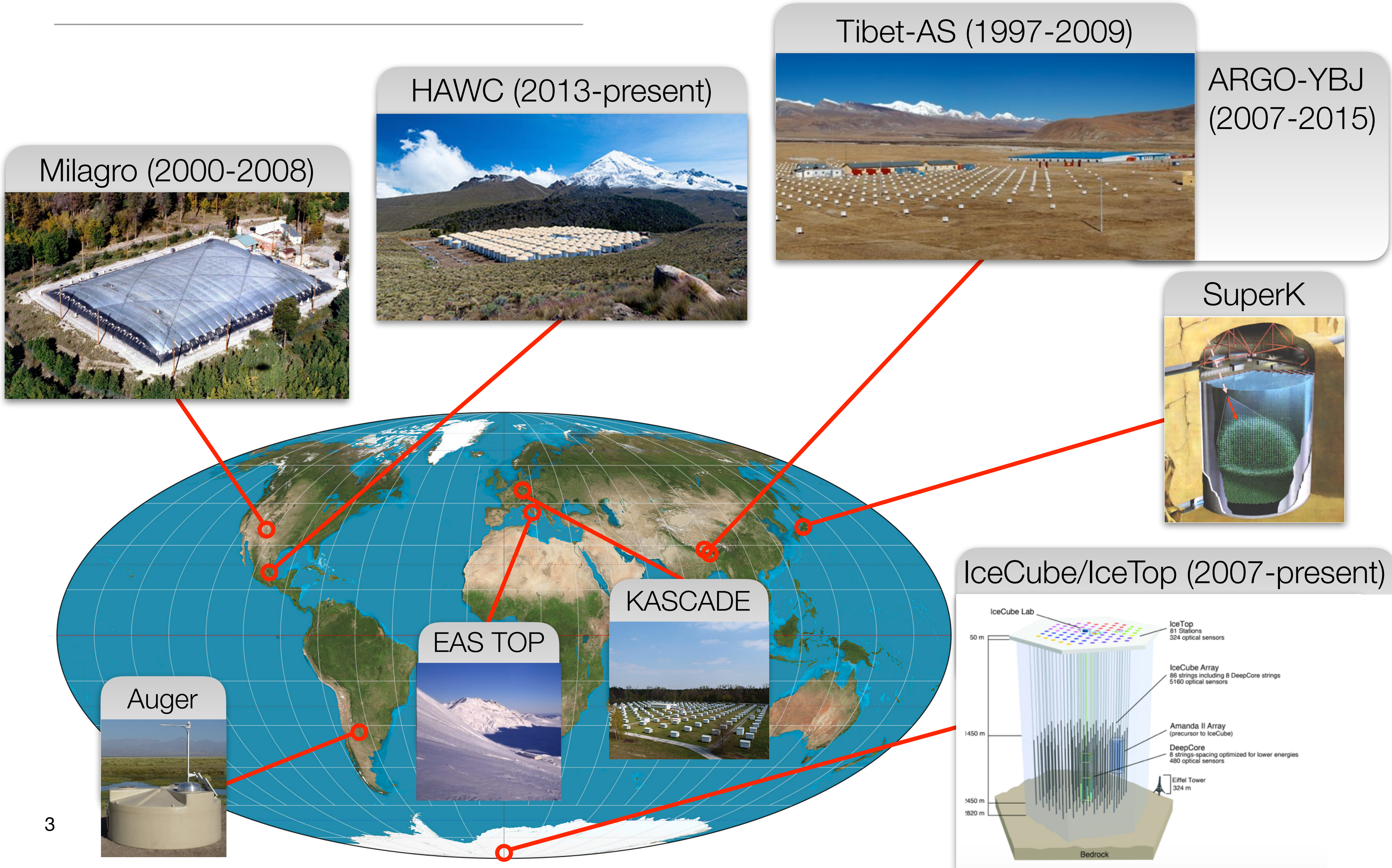


indirect measurements

galactic galactic galactic extra-galactic extra-galactic extra-galactic

cosmic ray observations

the age of air shower experiments

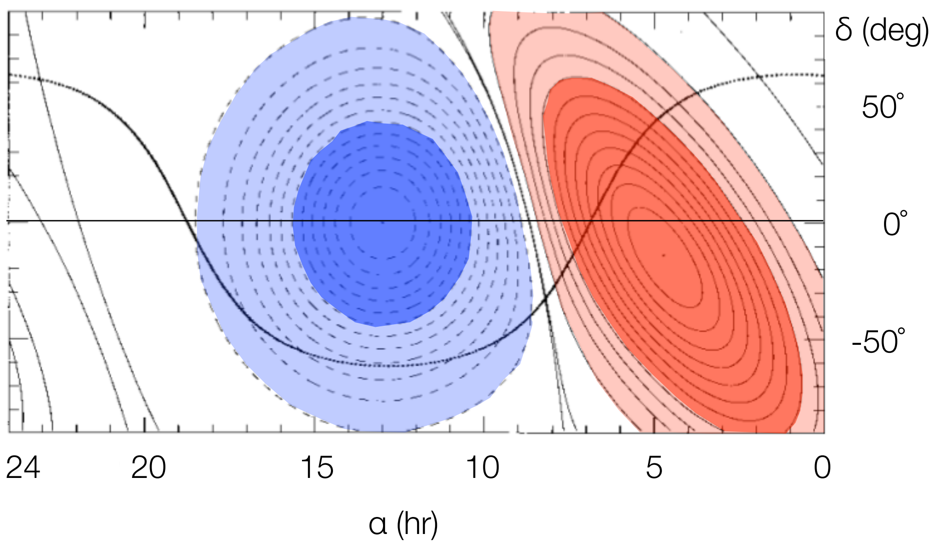


high energy cosmic rays
sidereal anisotropy

$\sim 10^{-3}$

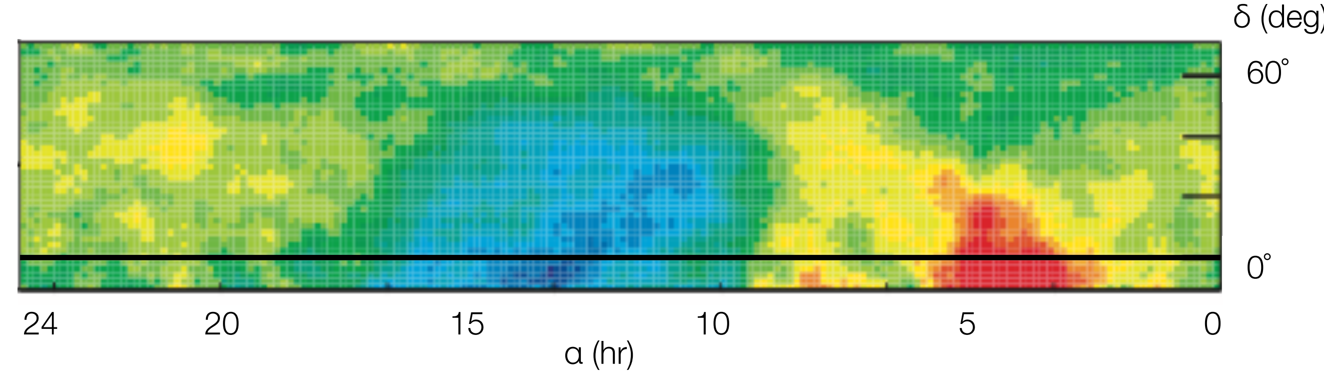
< 1 TeV

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

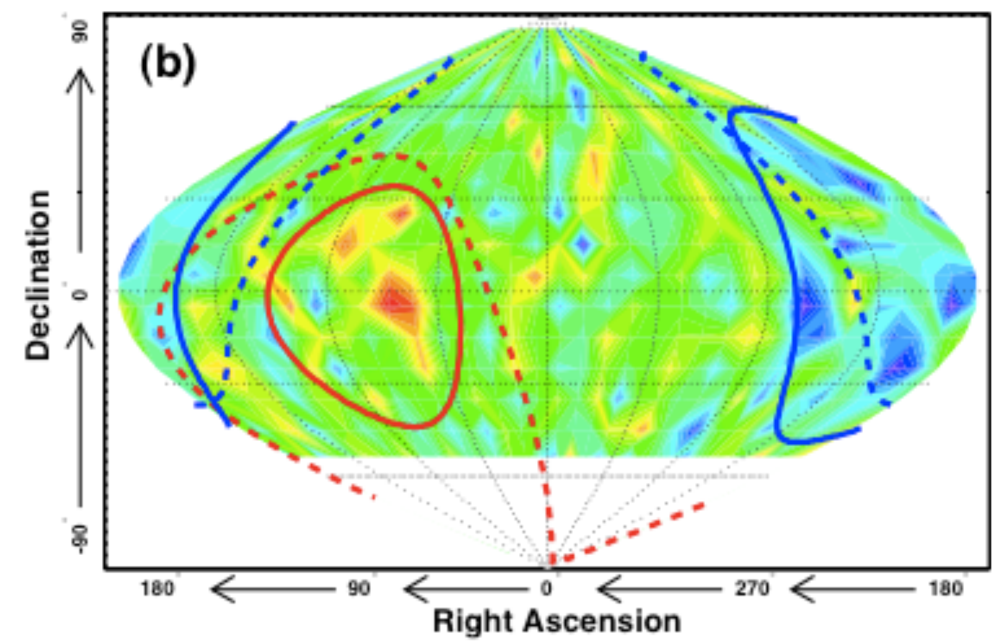


4 TeV

Tibet ASγ
Amenomori et al. (2006)



10 TeV

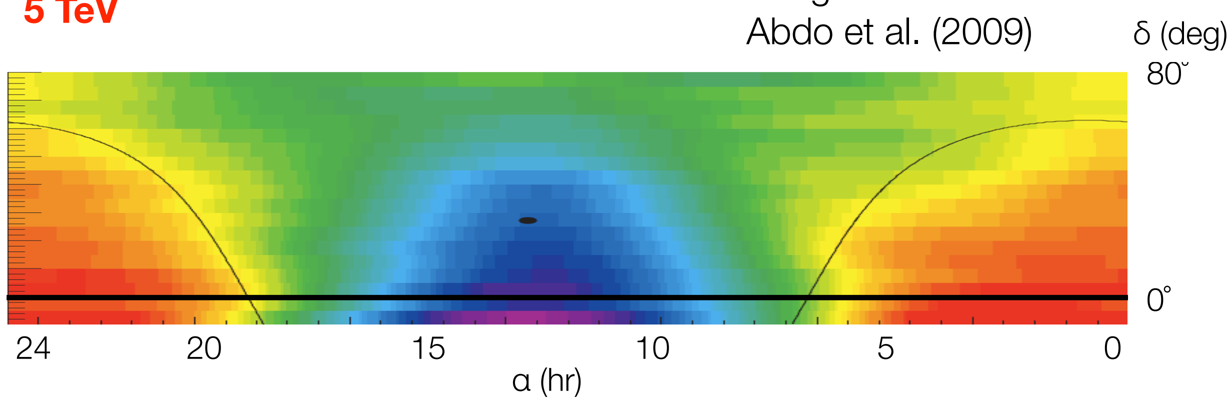


Super Kamiokande
Guillian et al. (2007)

equatorial coordinates

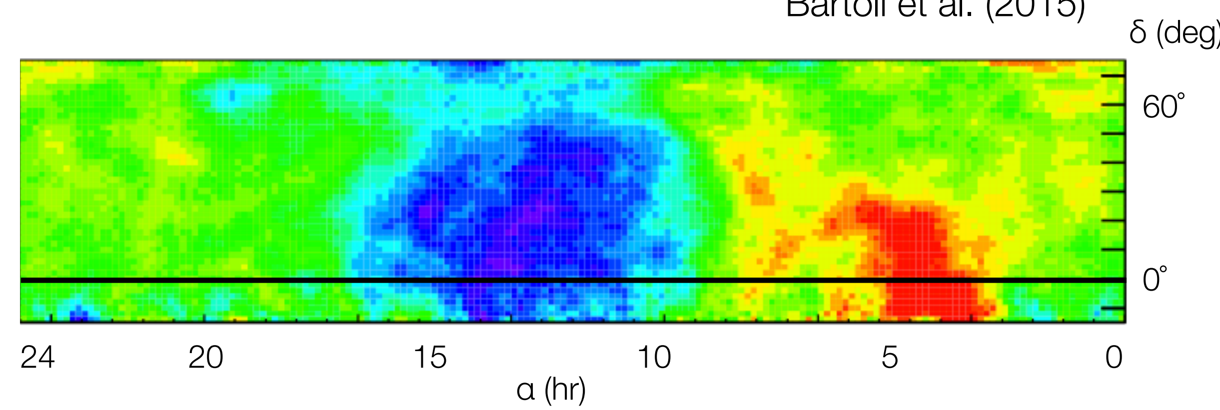
5 TeV

Milagro
Abdo et al. (2009)



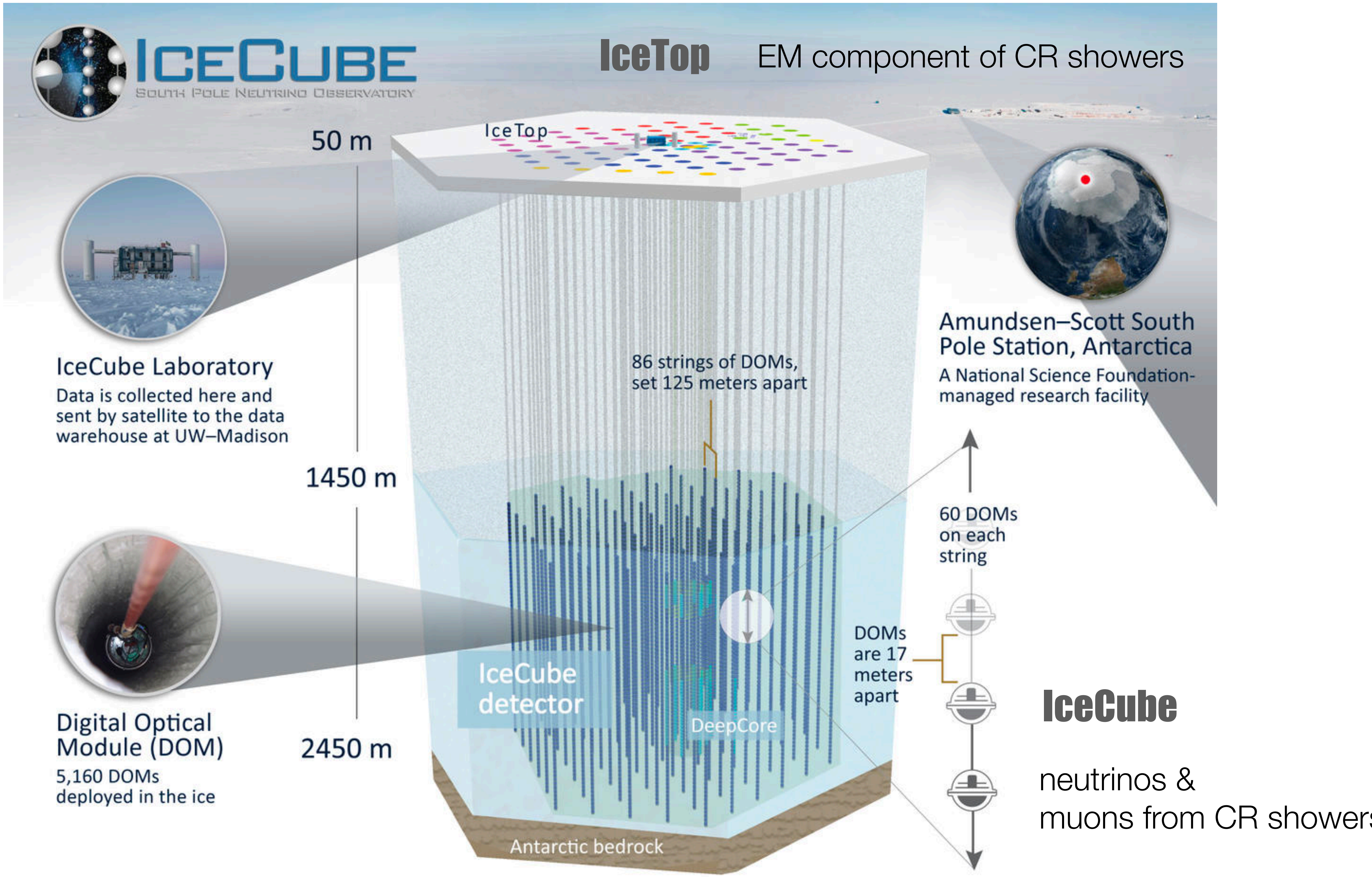
4 TeV

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

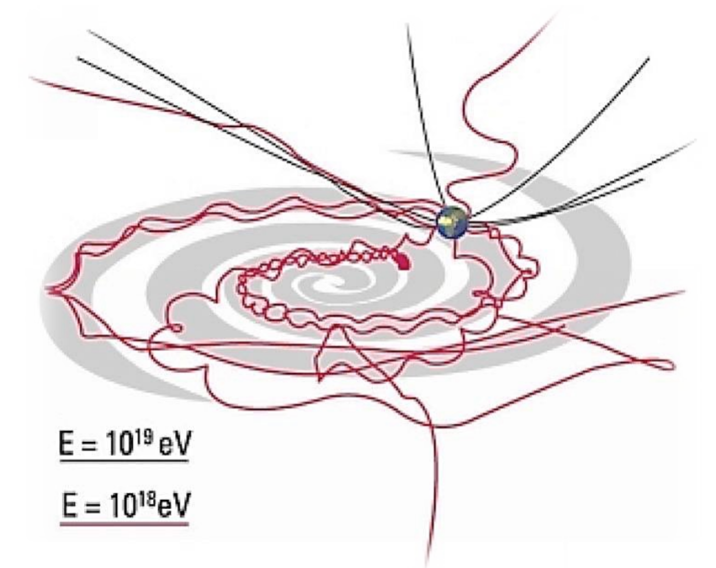


IceCube & IceTop

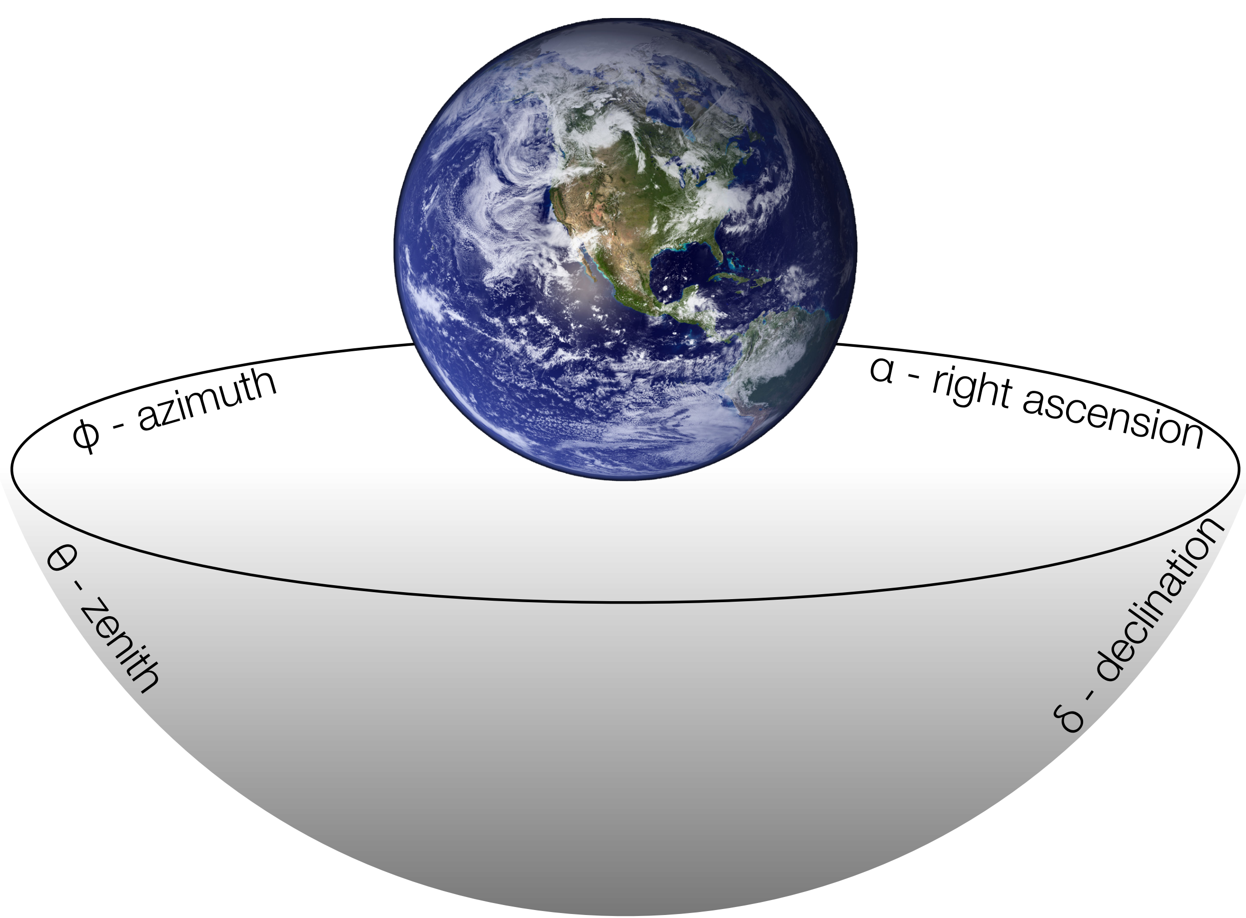
observing neutrinos and cosmic rays at South Pole

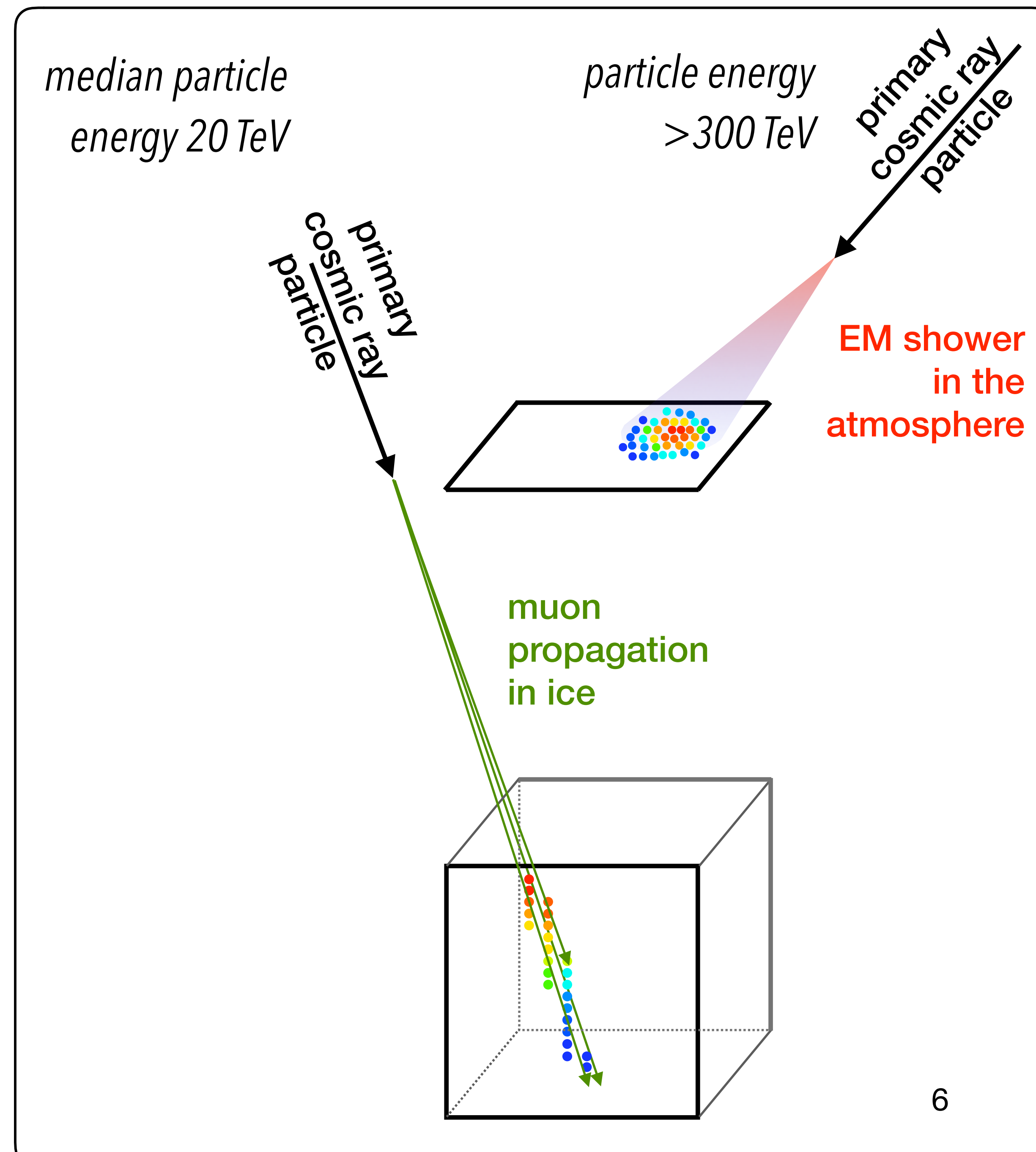


cosmic rays anisotropy
arrival direction distribution



- cosmic rays expected to be ***almost*** isotropic
- ***scrambled*** by galactic magnetic field
- what does ***isotropy*** look like in IceCube ?





determination of anisotropy

arrival direction distribution

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

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

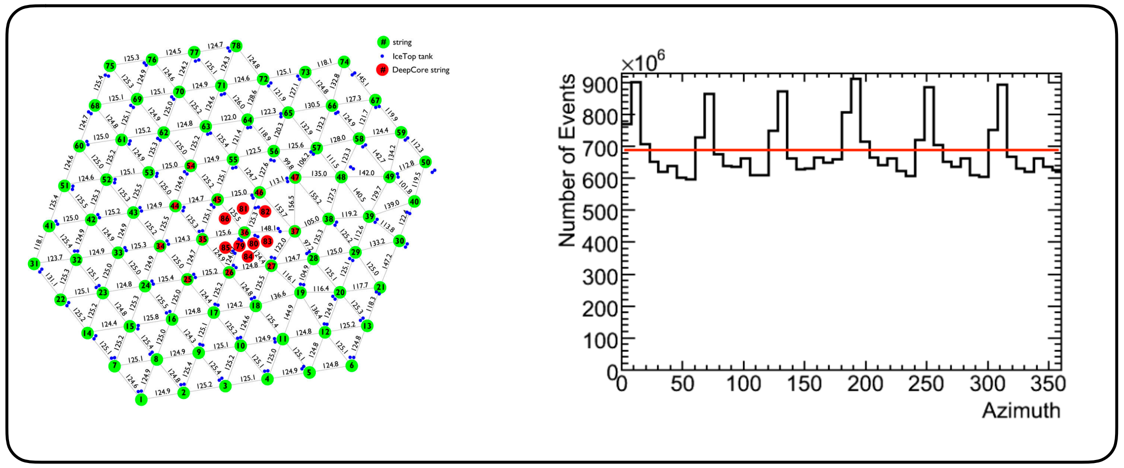
→ **response map to isotropic flux**

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

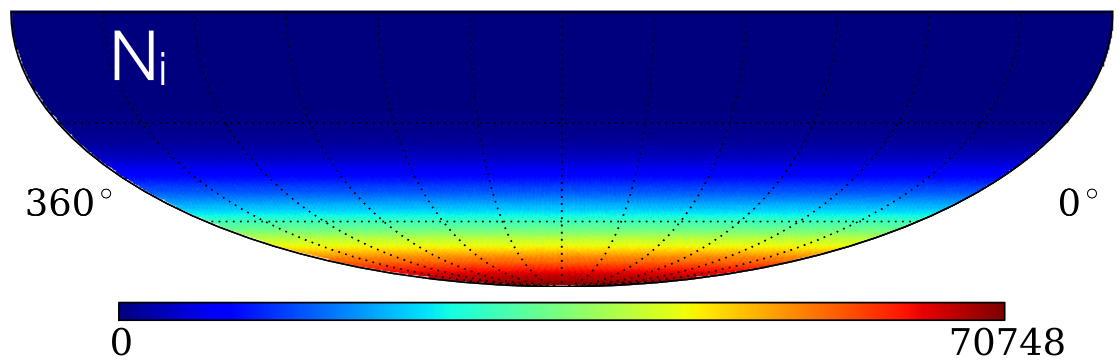
→ **equal deficit/excess contribution**

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

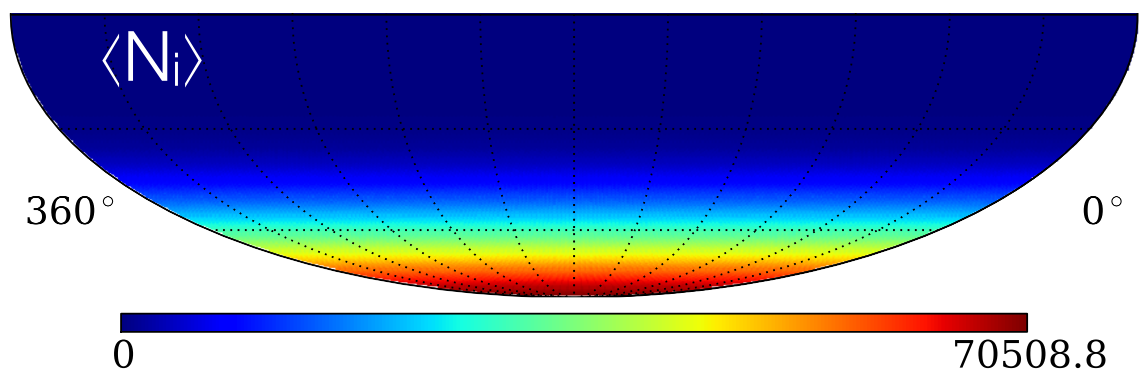
IceCube local coordinates



1 month of data

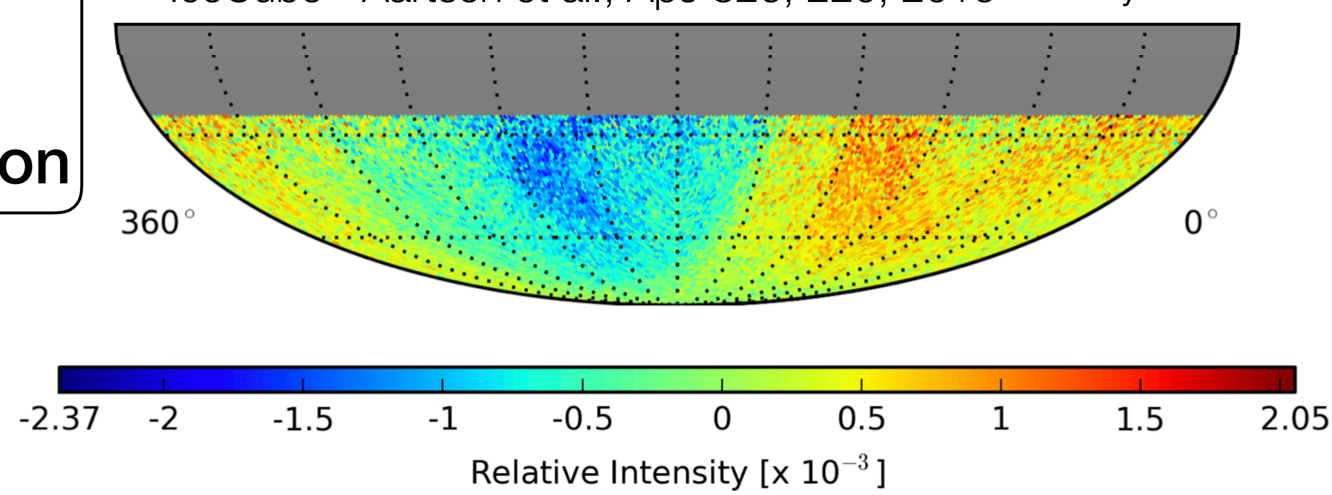


1 month of data



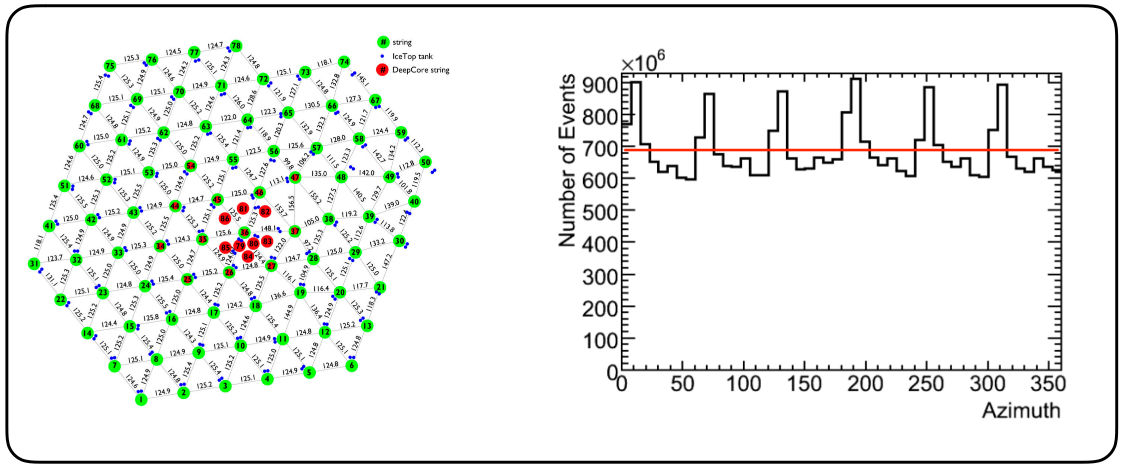
IceCube - Aartsen et al., ApJ 826, 220, 2016

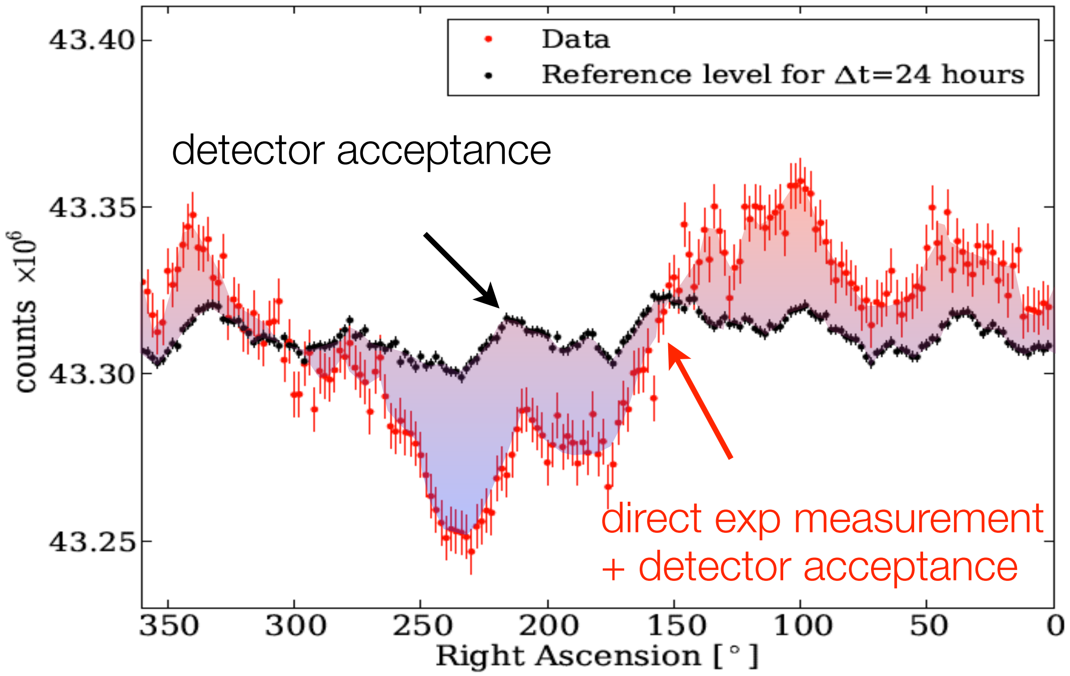
6 years of data

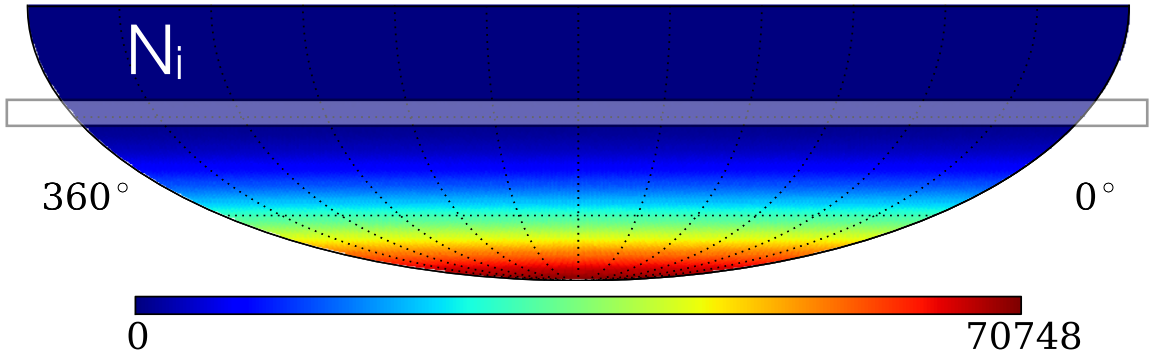


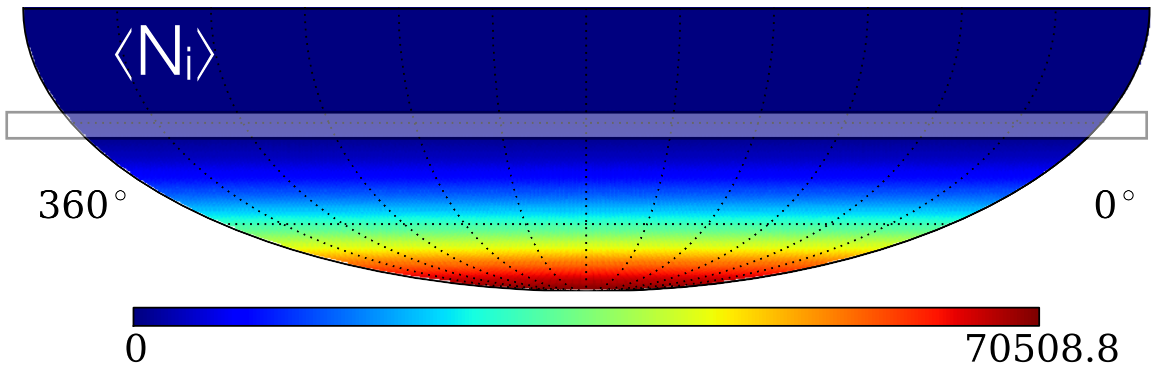
determination of anisotropy
arrival direction distribution

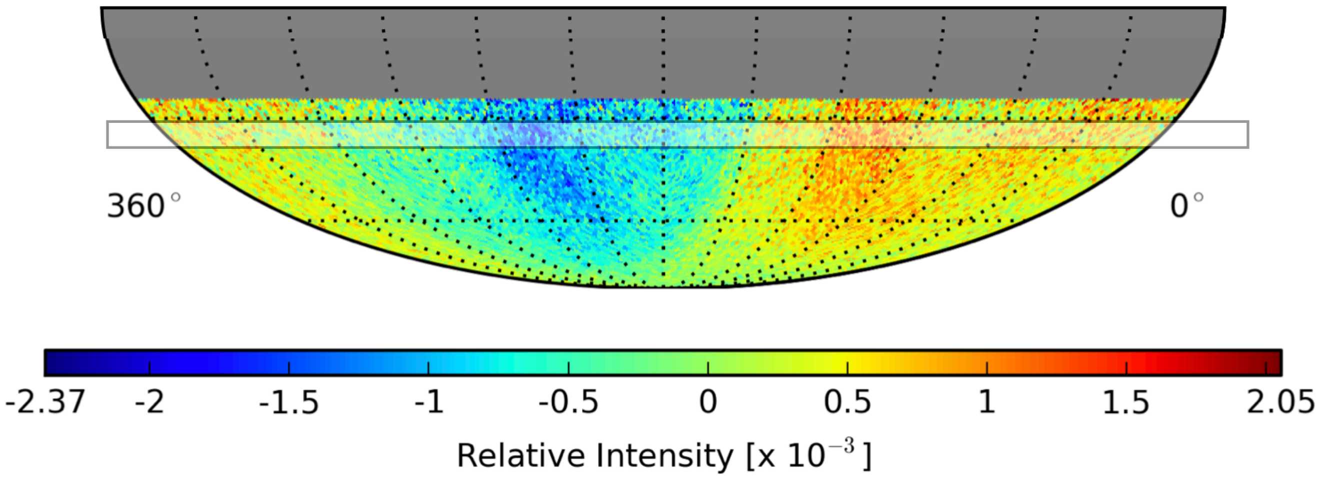
IceCube local coordinates









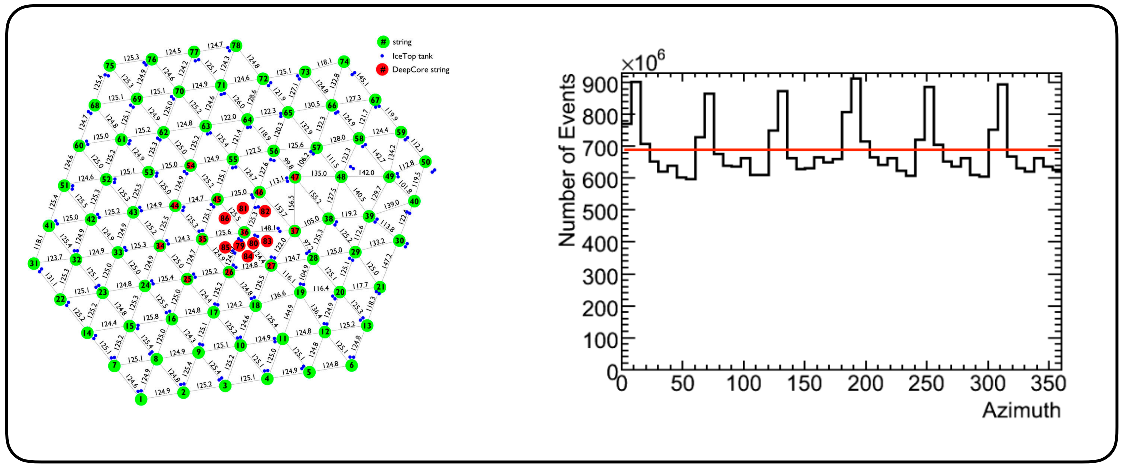


$$\frac{\Delta I}{\langle I \rangle} = \frac{N_i - \langle N \rangle}{\langle N \rangle}$$

determination of anisotropy

arrival direction distribution

local coordinates

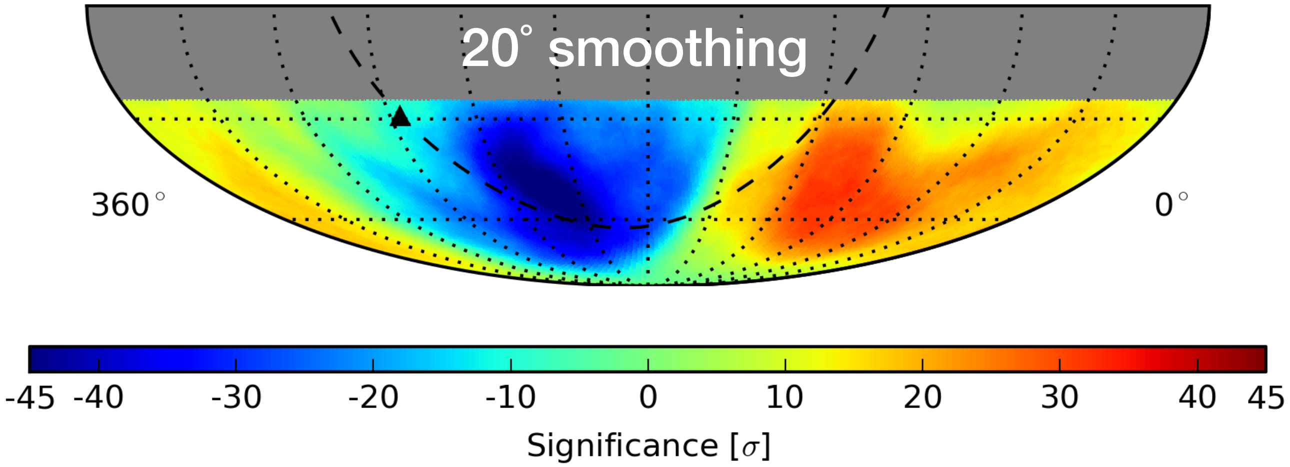


$$s = \sqrt{2}\left\{ N_{\rm on} \ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\rm on}}{N_{\rm on}+N_{\rm off}}\right)\right] + N_{\rm off} \ln\left[(1+\alpha)\left(\frac{N_{\rm off}}{N_{\rm on}+N_{\rm off}}\right)\right]\right\}^{1/2} \qquad \alpha = 1/20$$

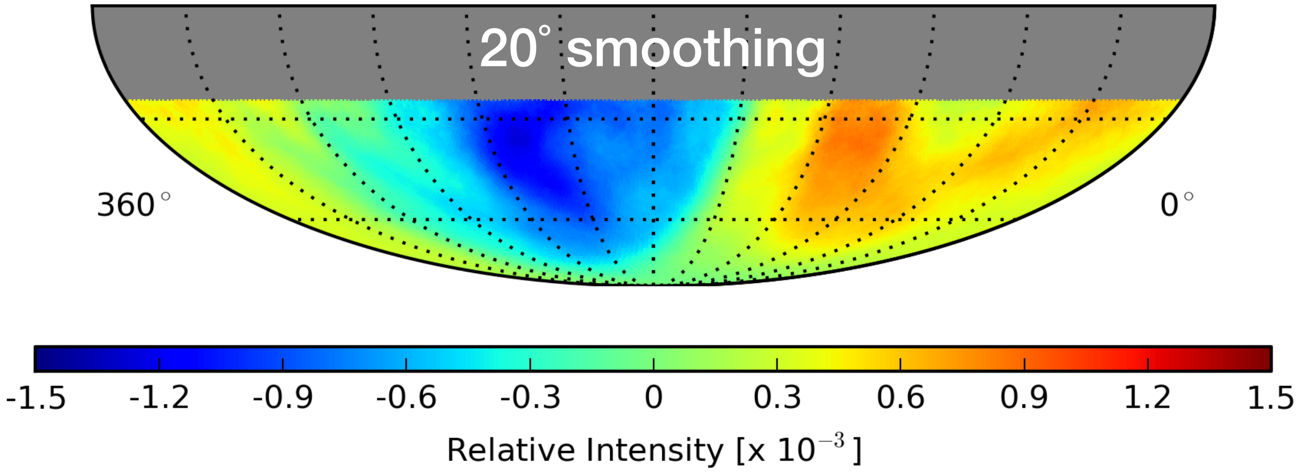
Li, T., & Ma, Y. 1983, ApJ, 272, 317

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

statistical significance



relative intensity



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

observing TeV-PeV cosmic ray anisotropy

high statistics but small effects

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

determine anisotropy at **different energies**

determine anisotropy at **different angular scales**

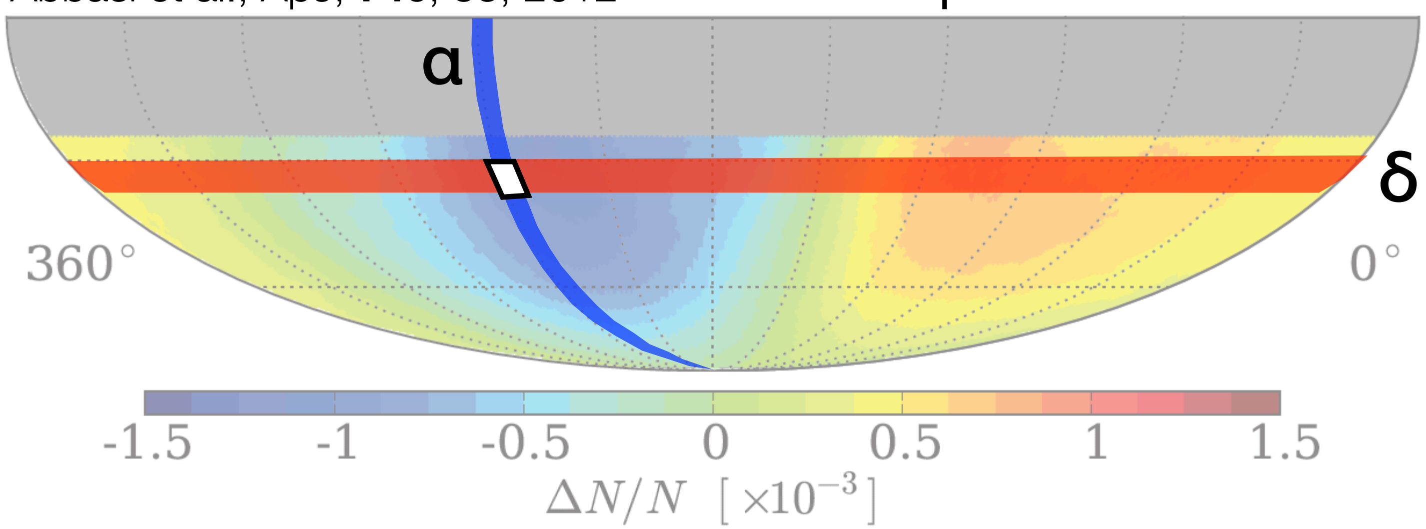
determine anisotropy **variations in time**

determine anisotropy at **different primary masses**

determine anisotropy with **full sky observations**

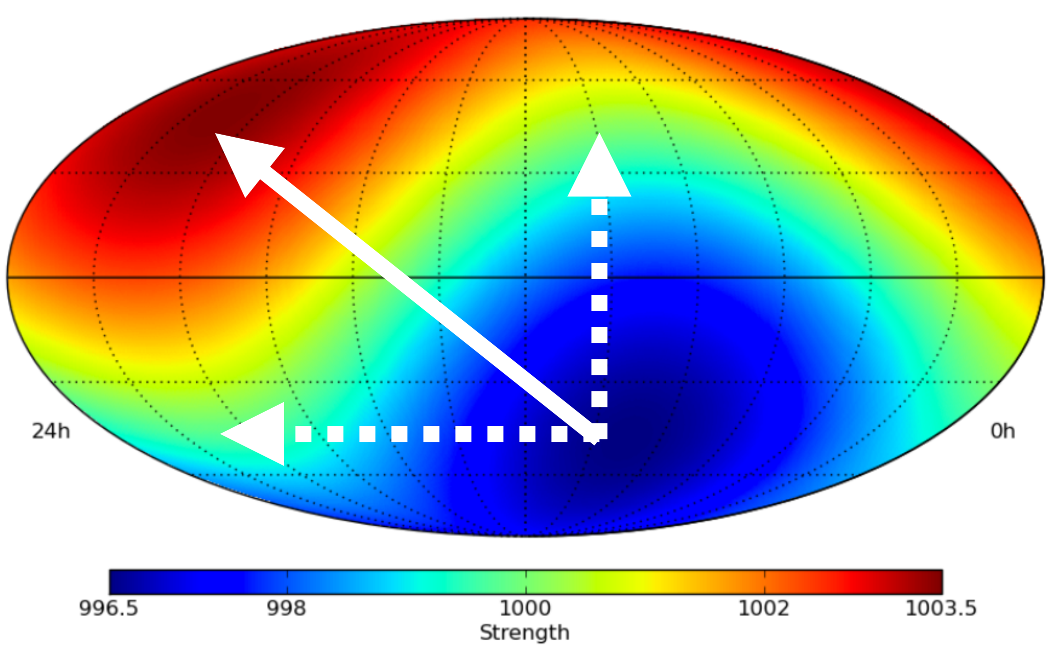
observing cosmic ray anisotropy

projection blindness

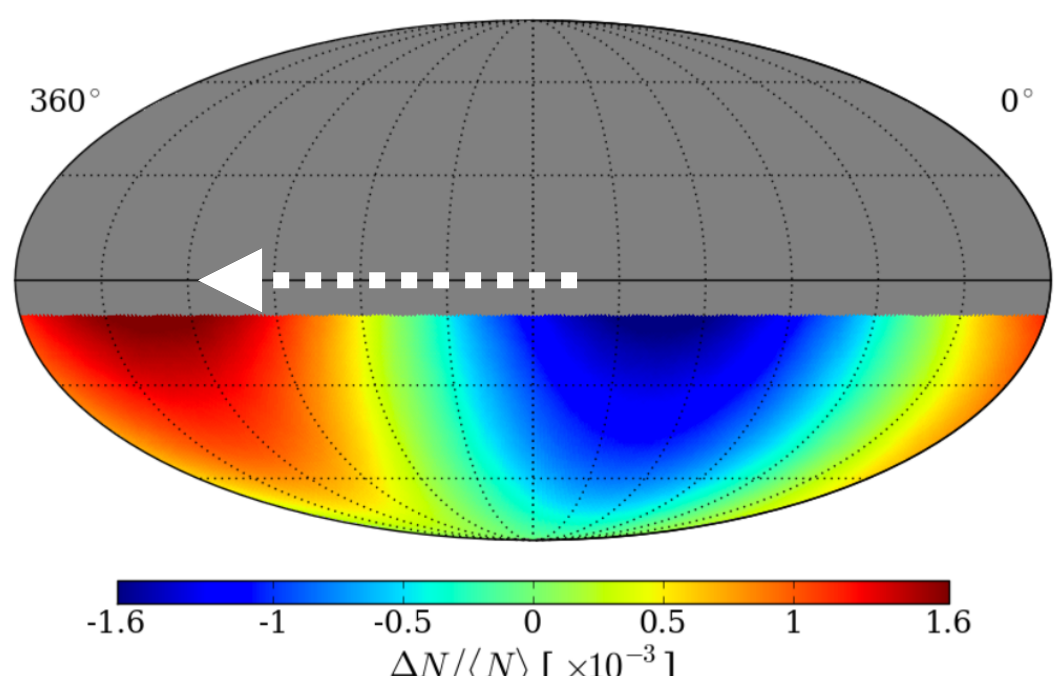


$$\frac{\Delta N_i}{\langle N \rangle_i} = \frac{N_i(\alpha,\delta) - \langle N_i(\alpha,\delta)\rangle}{\langle N_i(\alpha,\delta)\rangle}$$

declination bands independently normalized



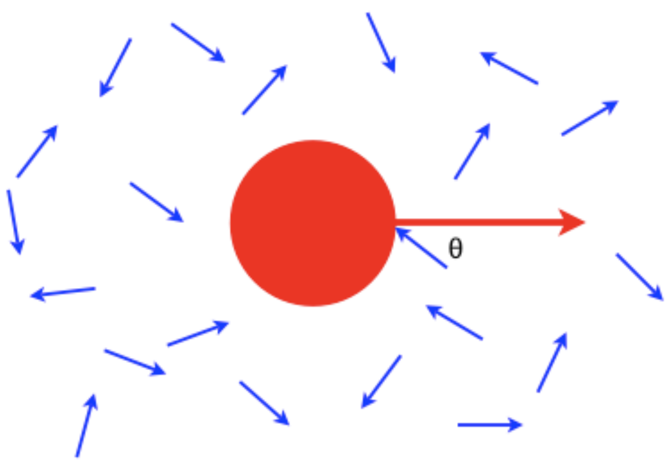
$\Delta N/\langle N\rangle = 7\times10^{-3}$



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

a known anisotropy

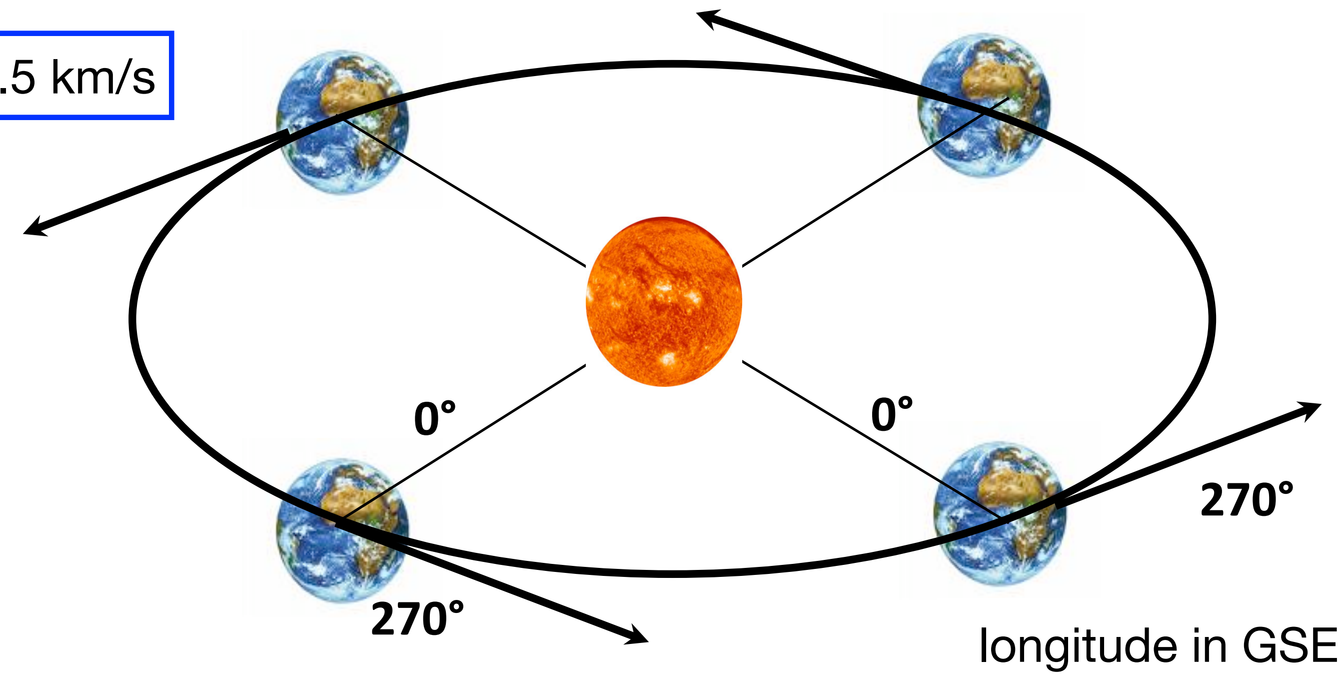
Earth's revolution around the Sun

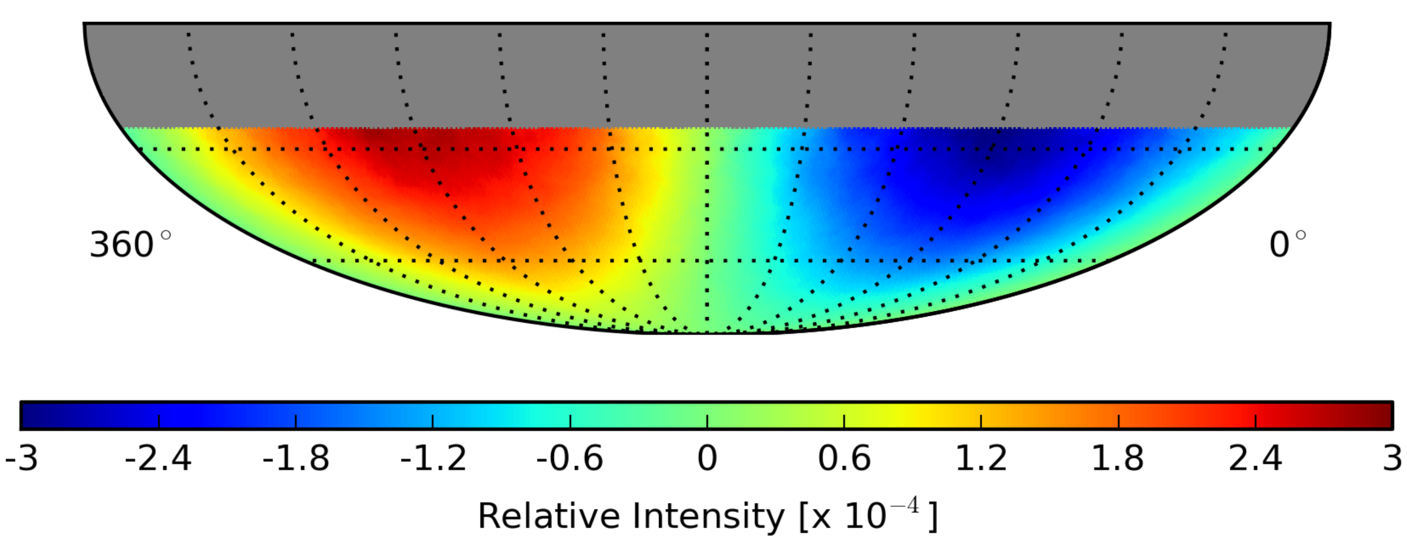


v = 29.8 ± 0.5 km/s

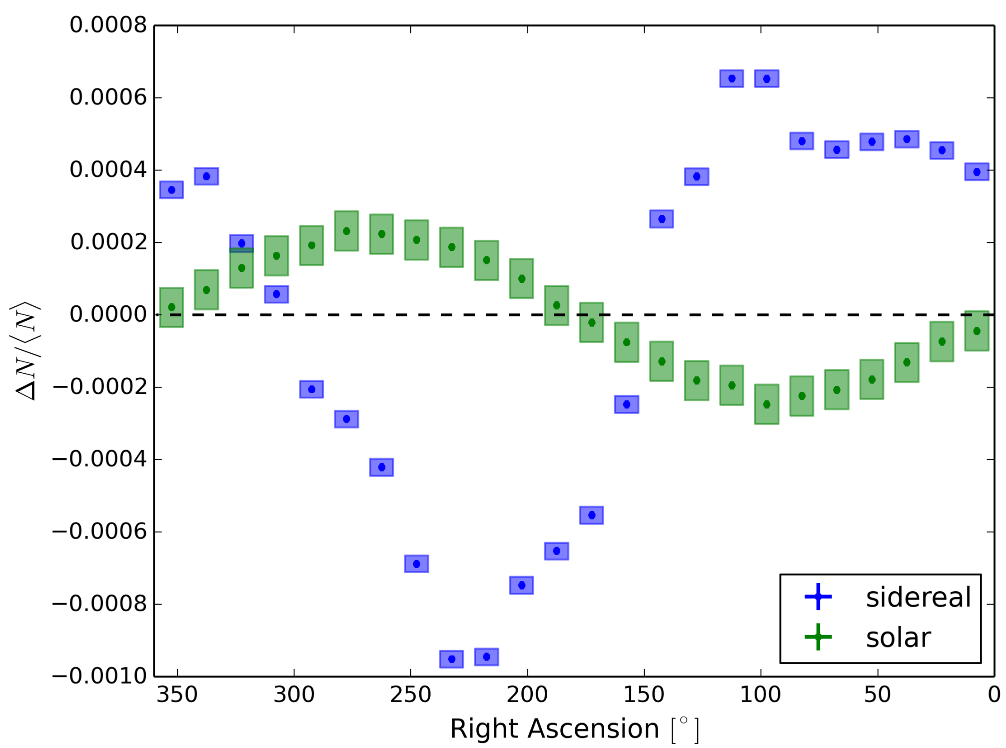
$$\frac{\Delta I}{I} = (\gamma + 2)\frac{v}{c}\cos\theta$$

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



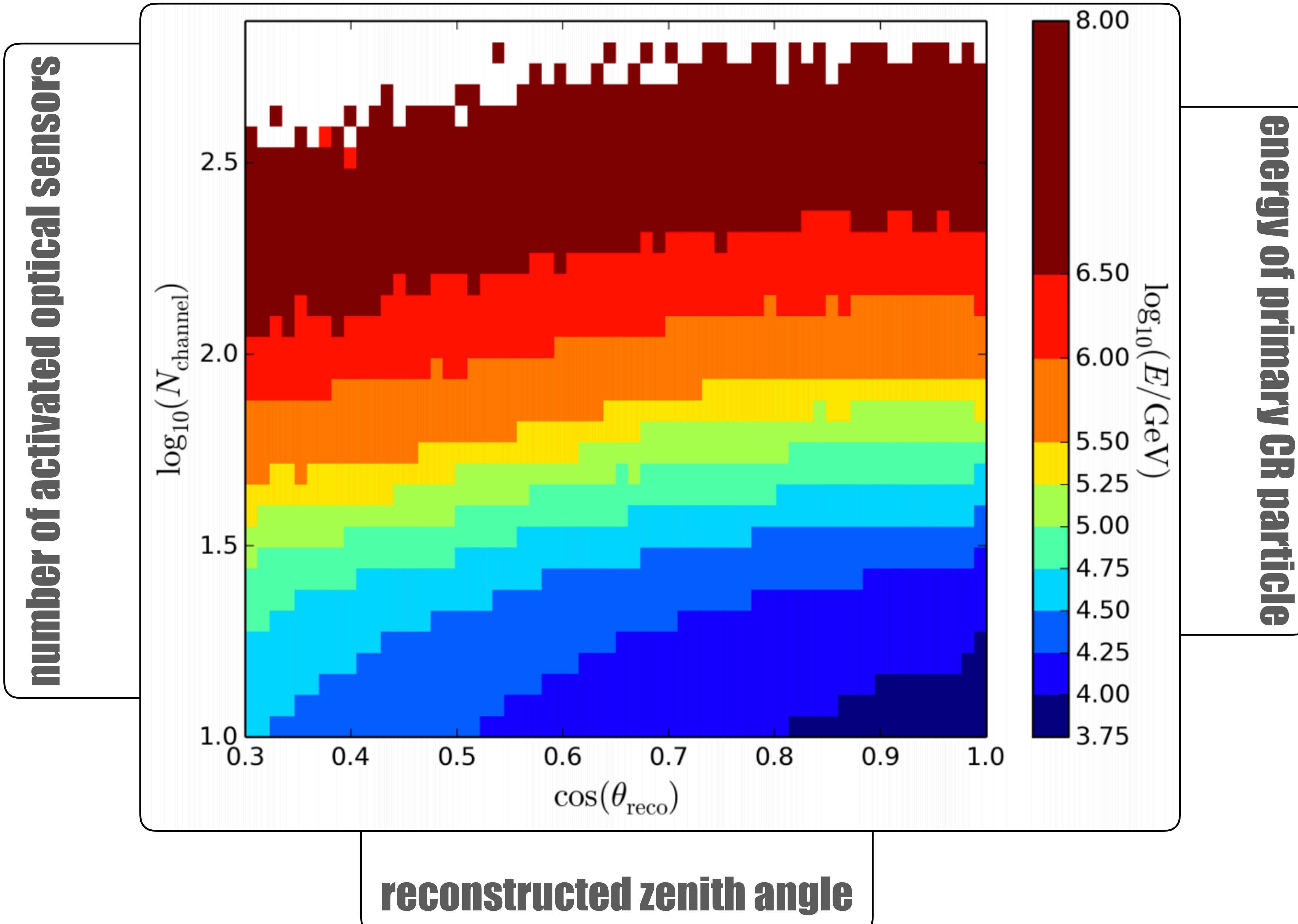


IceCube - Aartsen et al., ApJ 826, 220, 2016



observing cosmic ray anisotropy

energy dependency

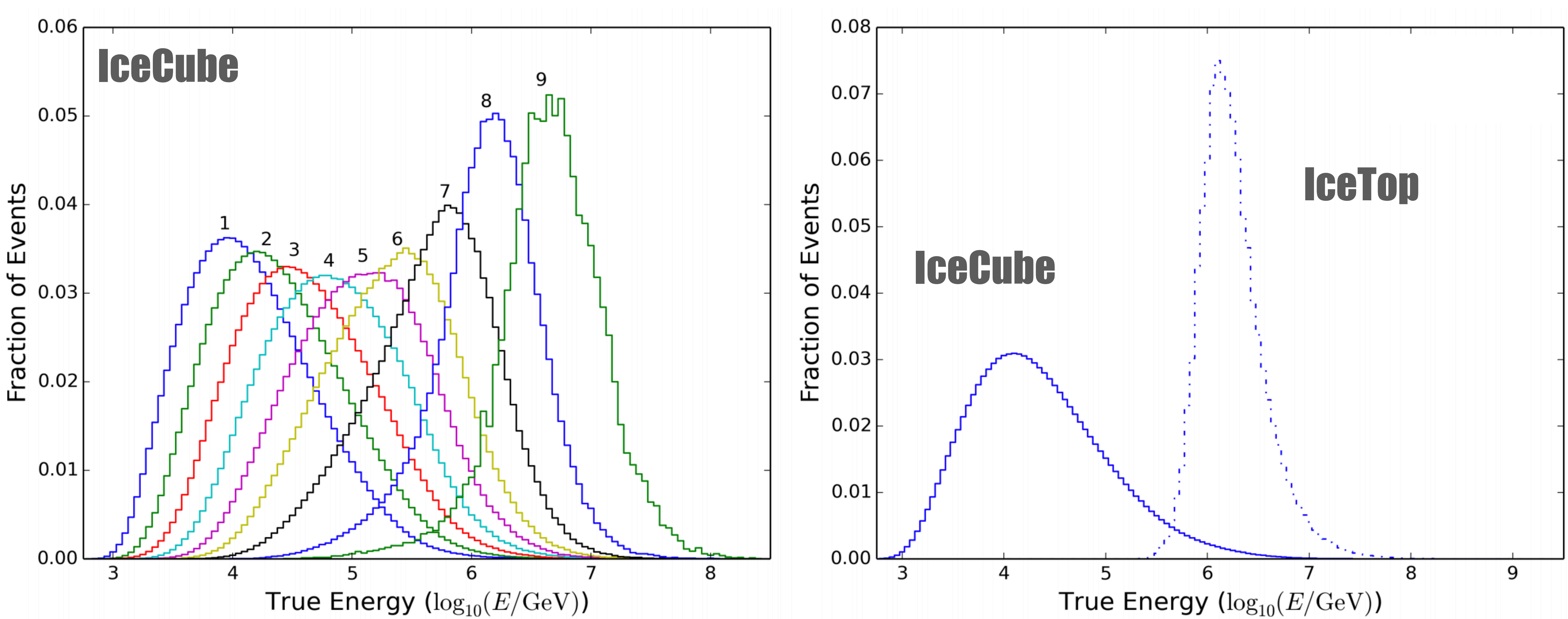


Aartsen et al., ApJ 826, 220 (2016)

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)

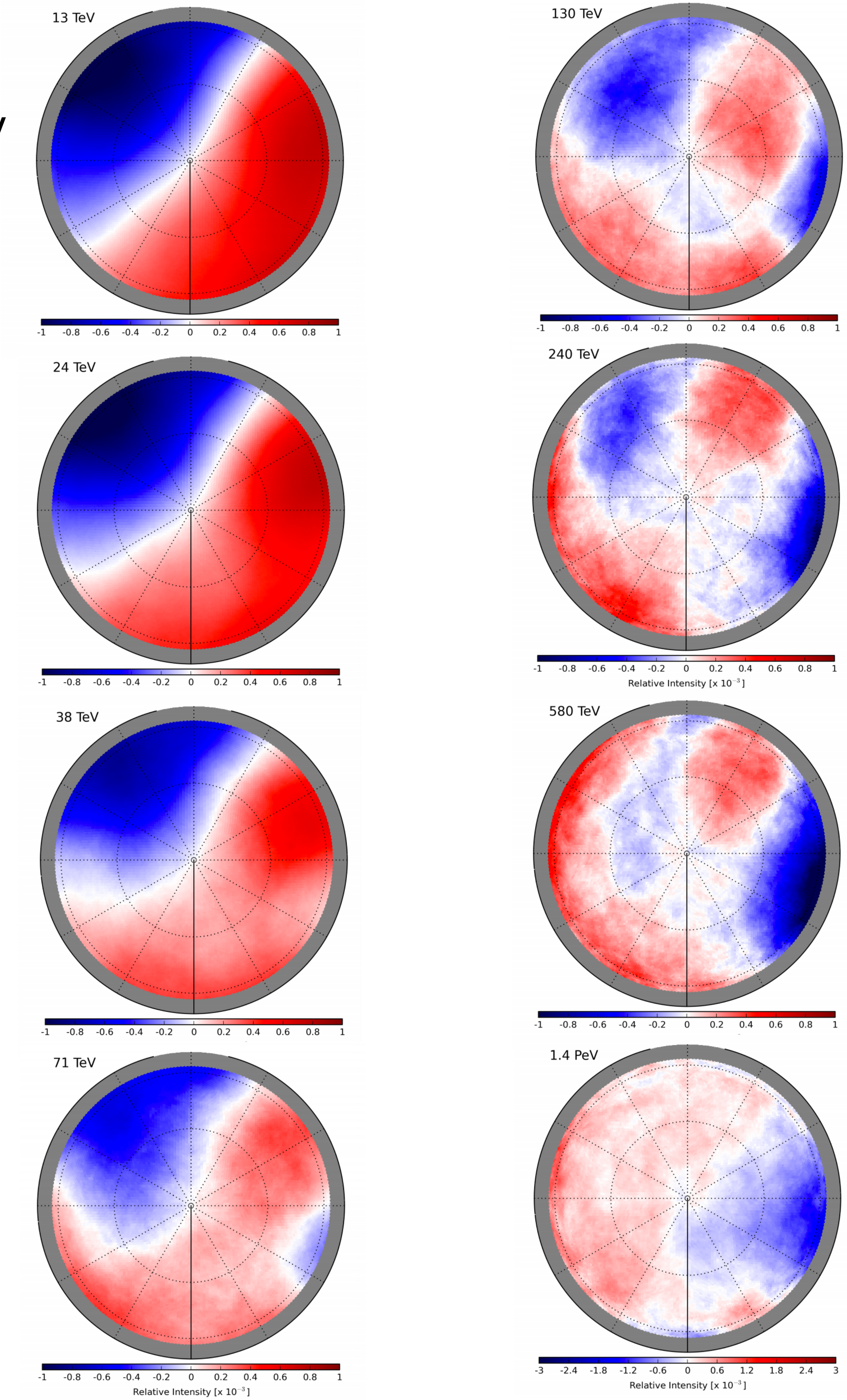
IceCube Aartsen et al., ApJ 826, 220, 2016

cosmic ray anisotropy depends on primary energy

large scale changes structure above 100 TeV

imaging magnetic effects at larger distances with increasing energy

Note: cosmic ray composition changes as well vs. energy

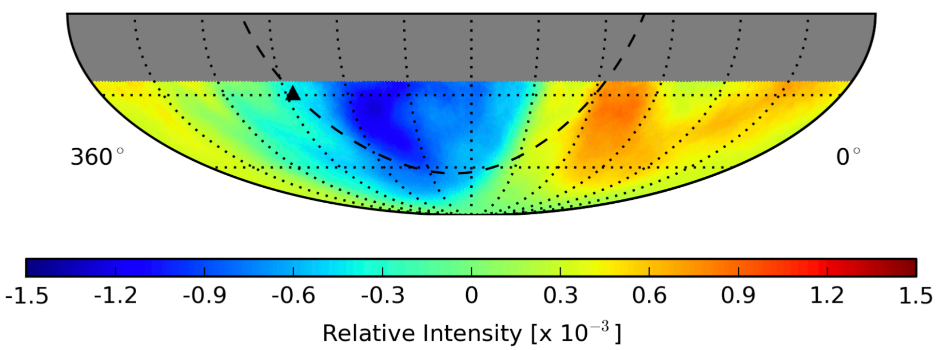


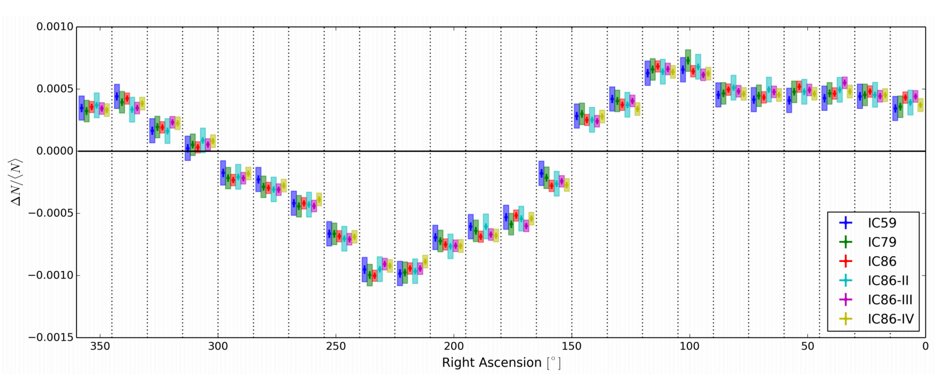
observing cosmic ray anisotropy

energy dependency (< knee)

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

~20 TeV

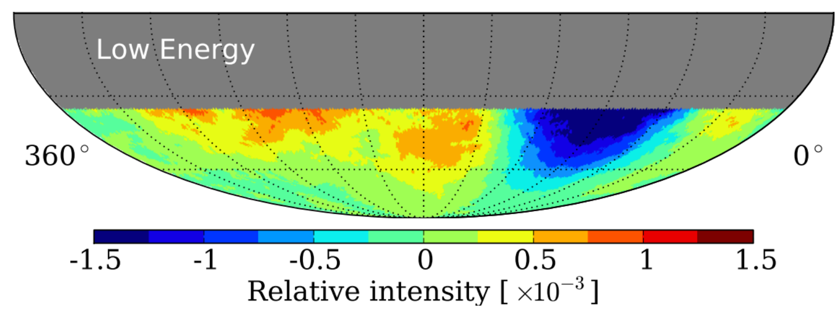




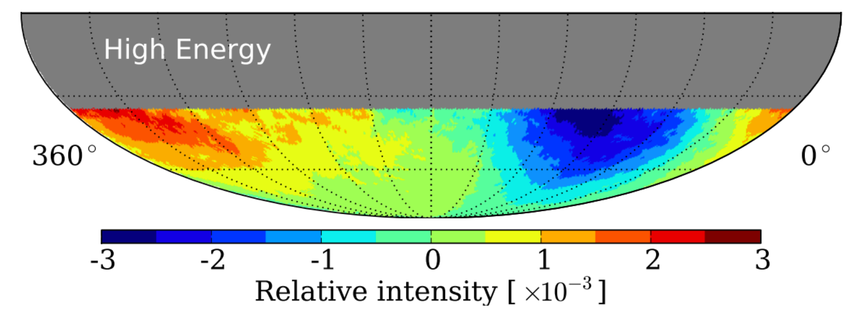
not a dipole distribution

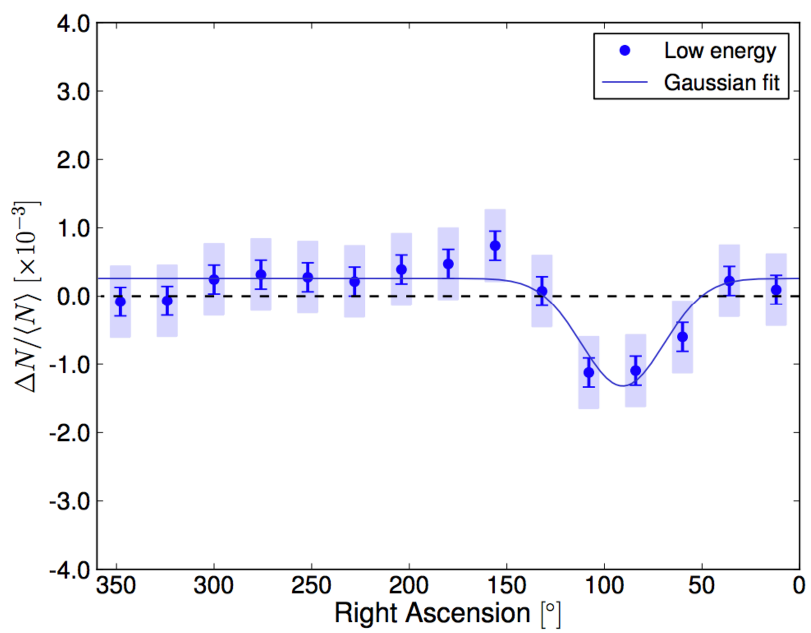
IceTop Aartsen et al., ApJ 765, 55, 2013

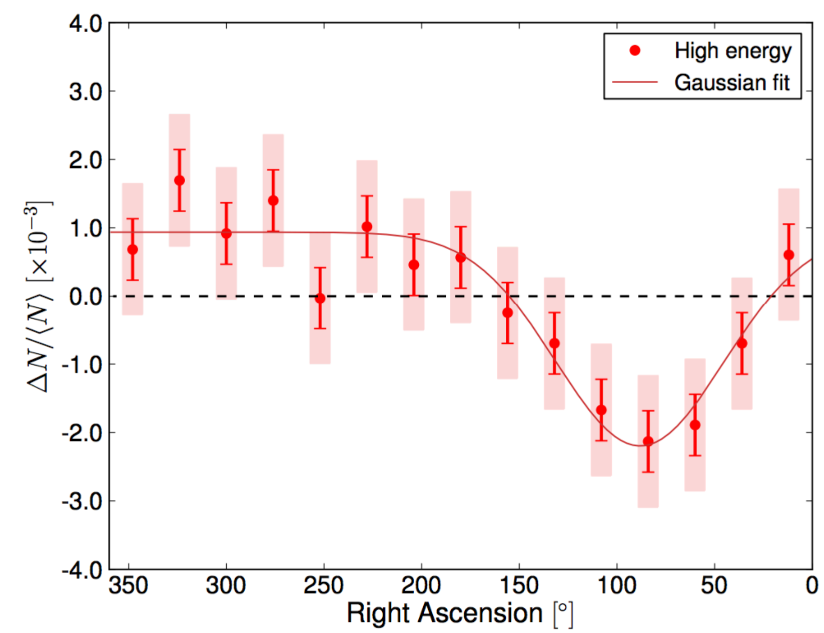
~400 TeV



~2 PeV







hardly a dipole distribution

observing cosmic ray anisotropy
dipole component

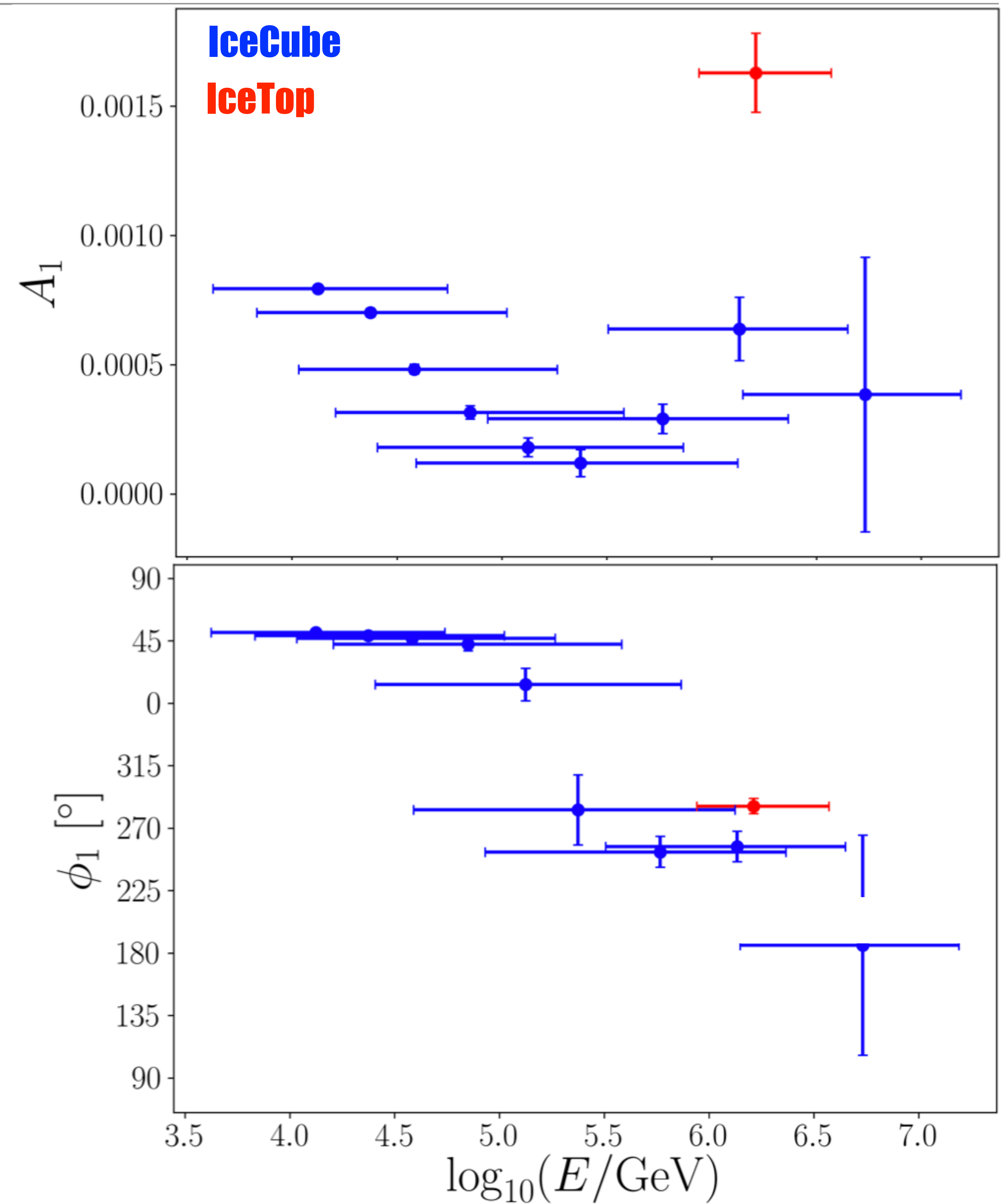
IceCube

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



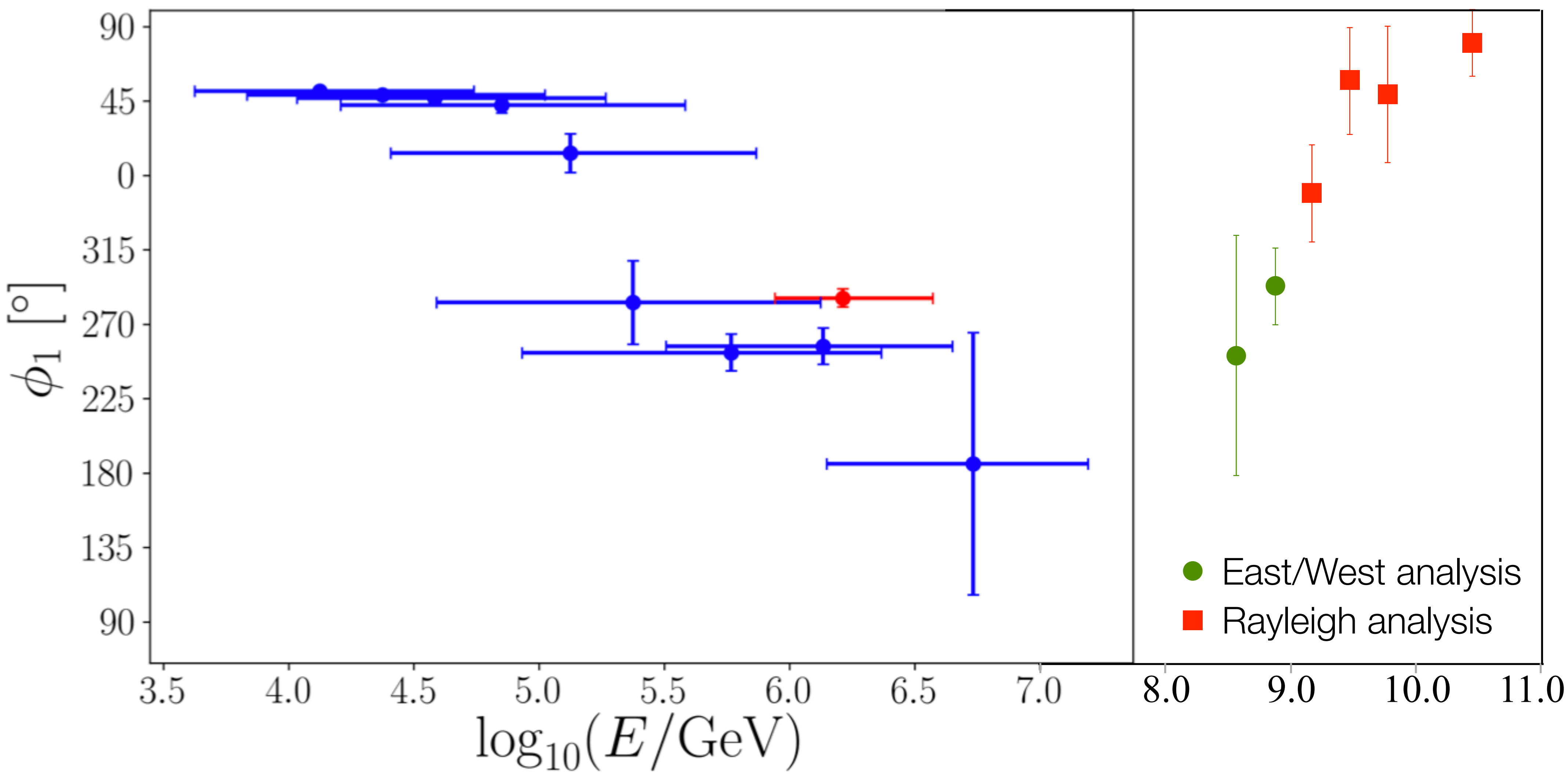
observing cosmic ray anisotropy
dipole component

IceCube

Aartsen et al., ApJ 826, 220, 2016

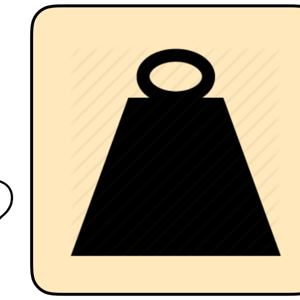
Auger

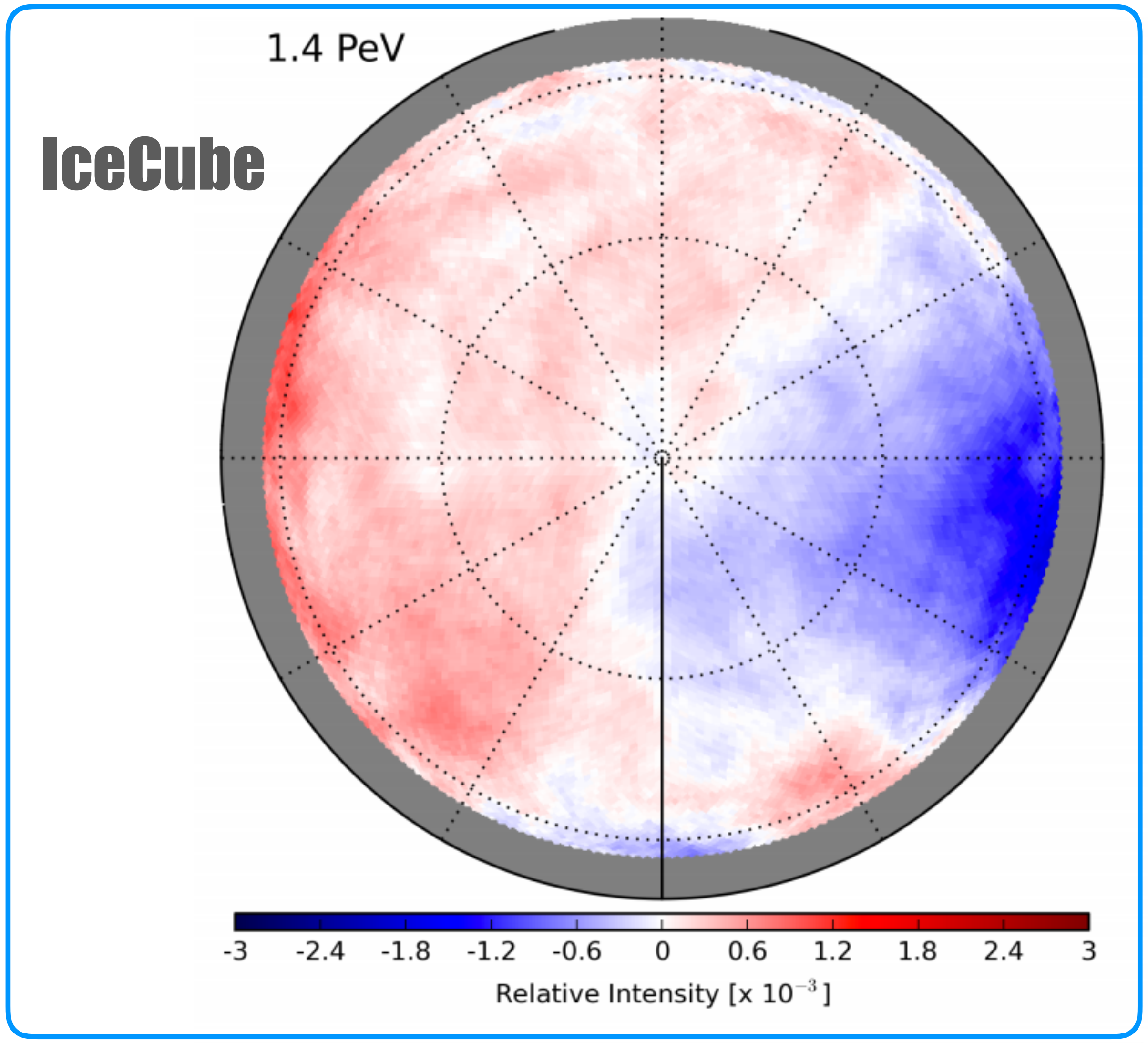
J. Phys. Conf. Series, 409, 012108, 2013

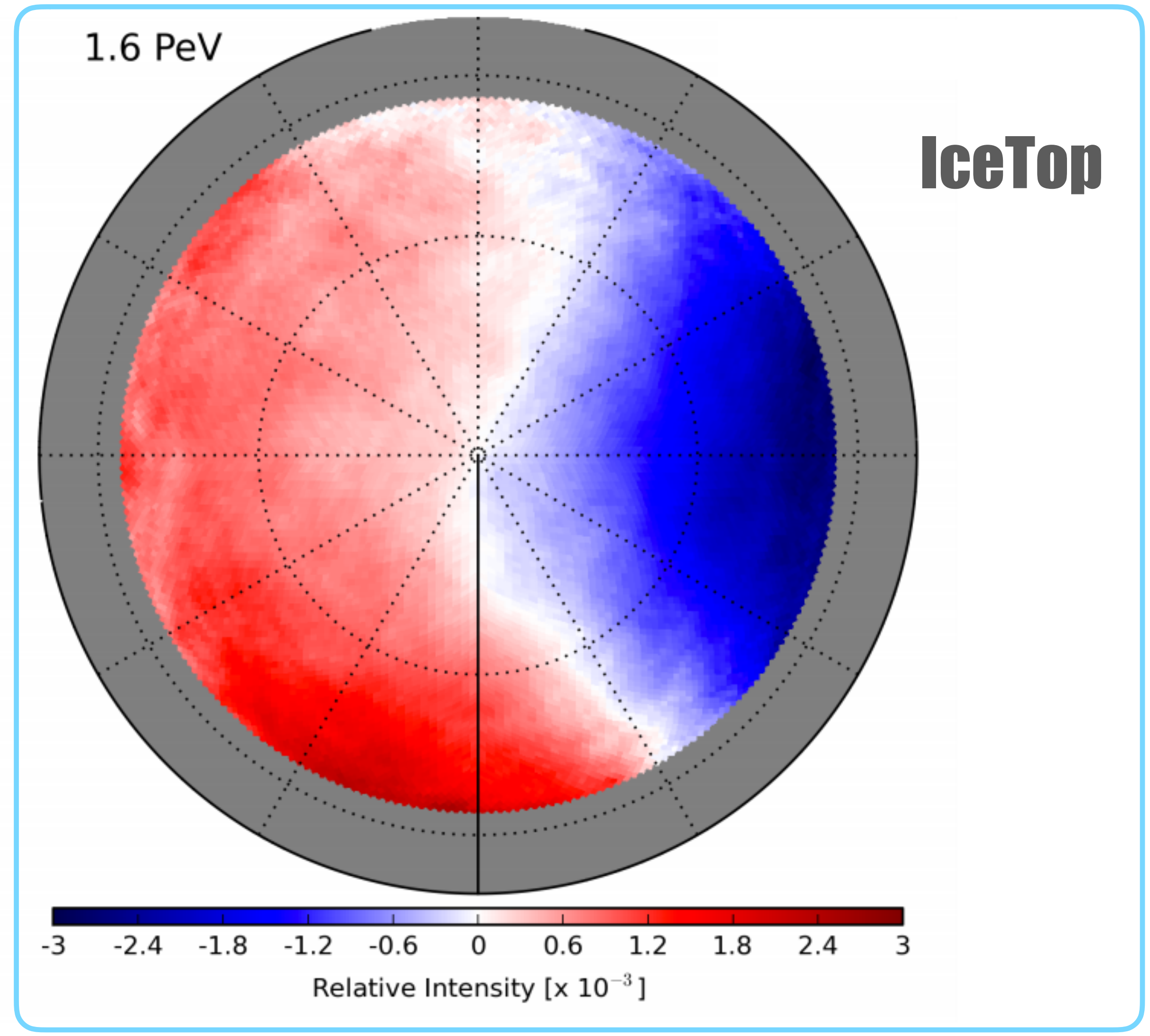


observing cosmic ray anisotropy

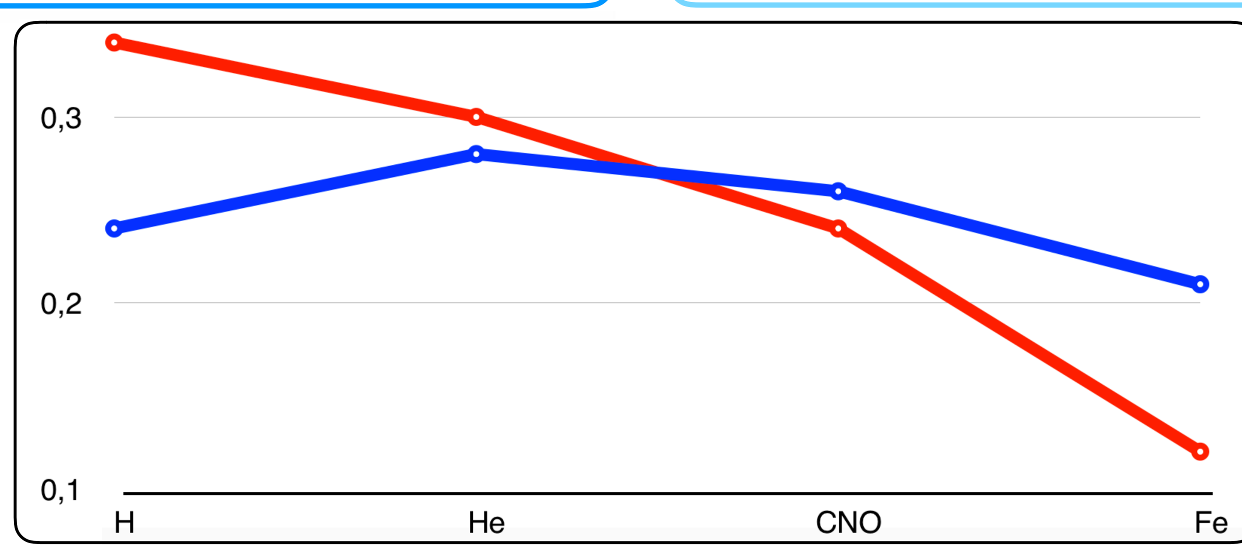
CR mass dependency ? Muons vs. EM showers?







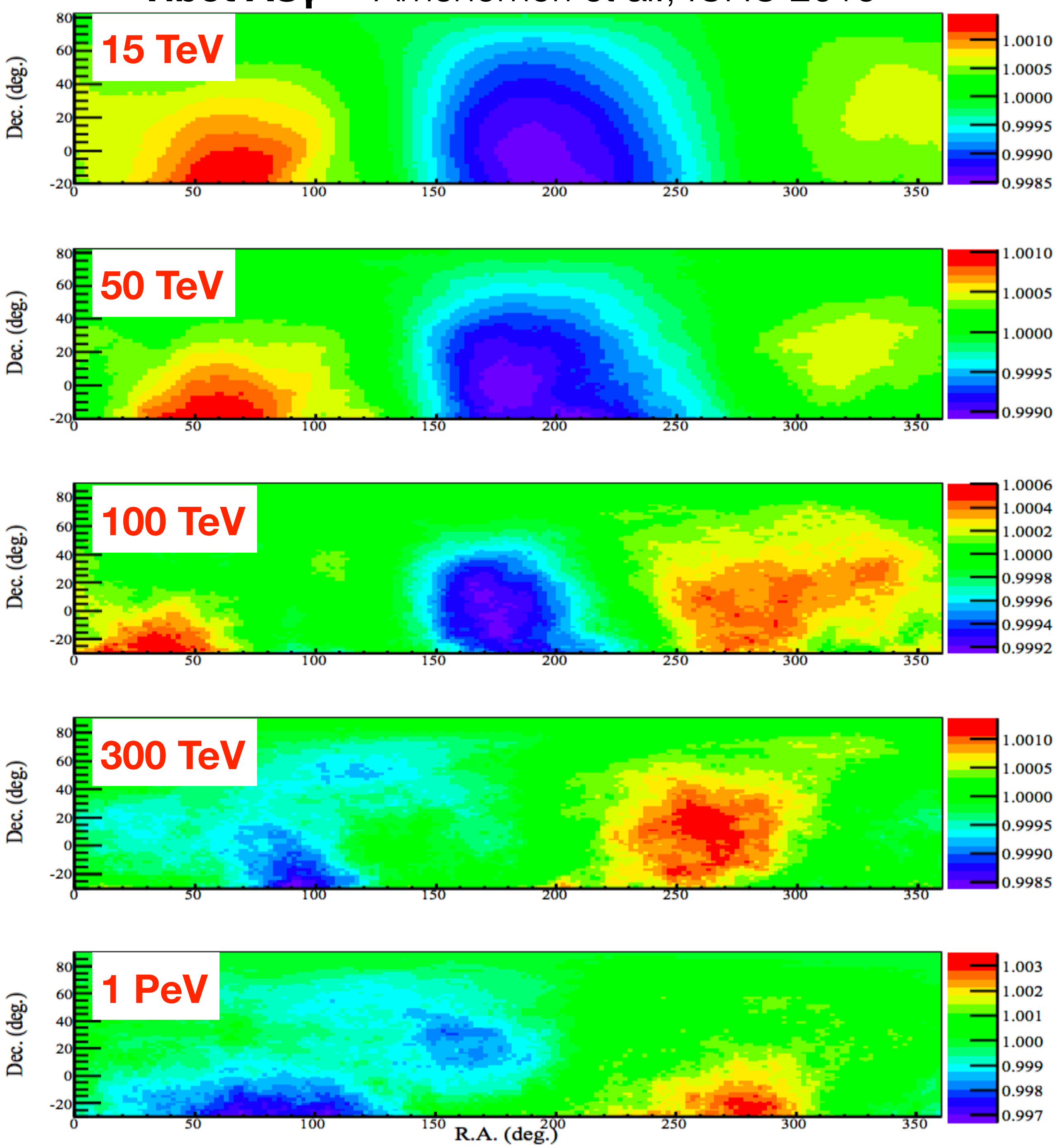
IceCube



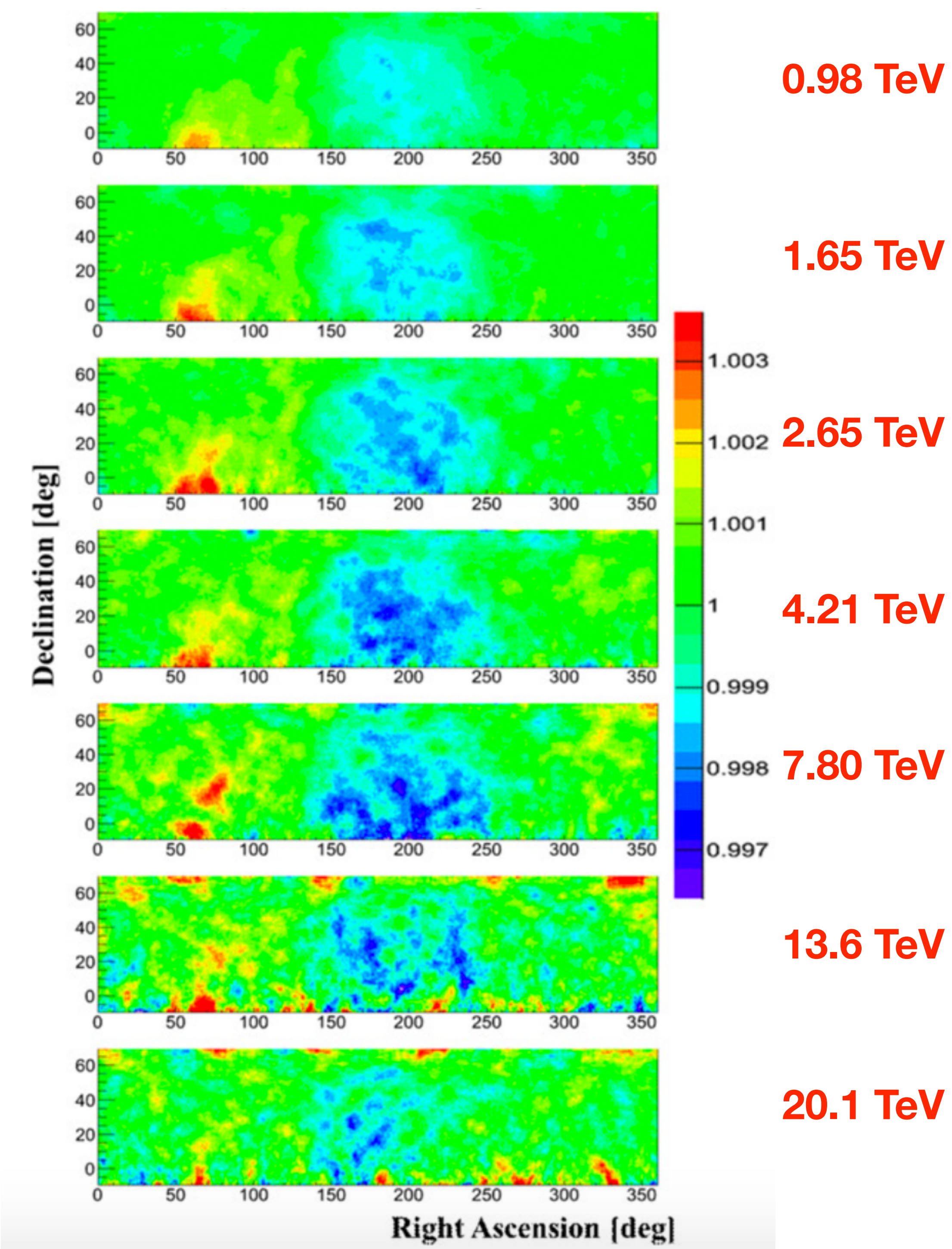
IceTop

cosmic ray anisotropy
energy dependence

Tibet ASγ Amenomori et al., ICRC 2015

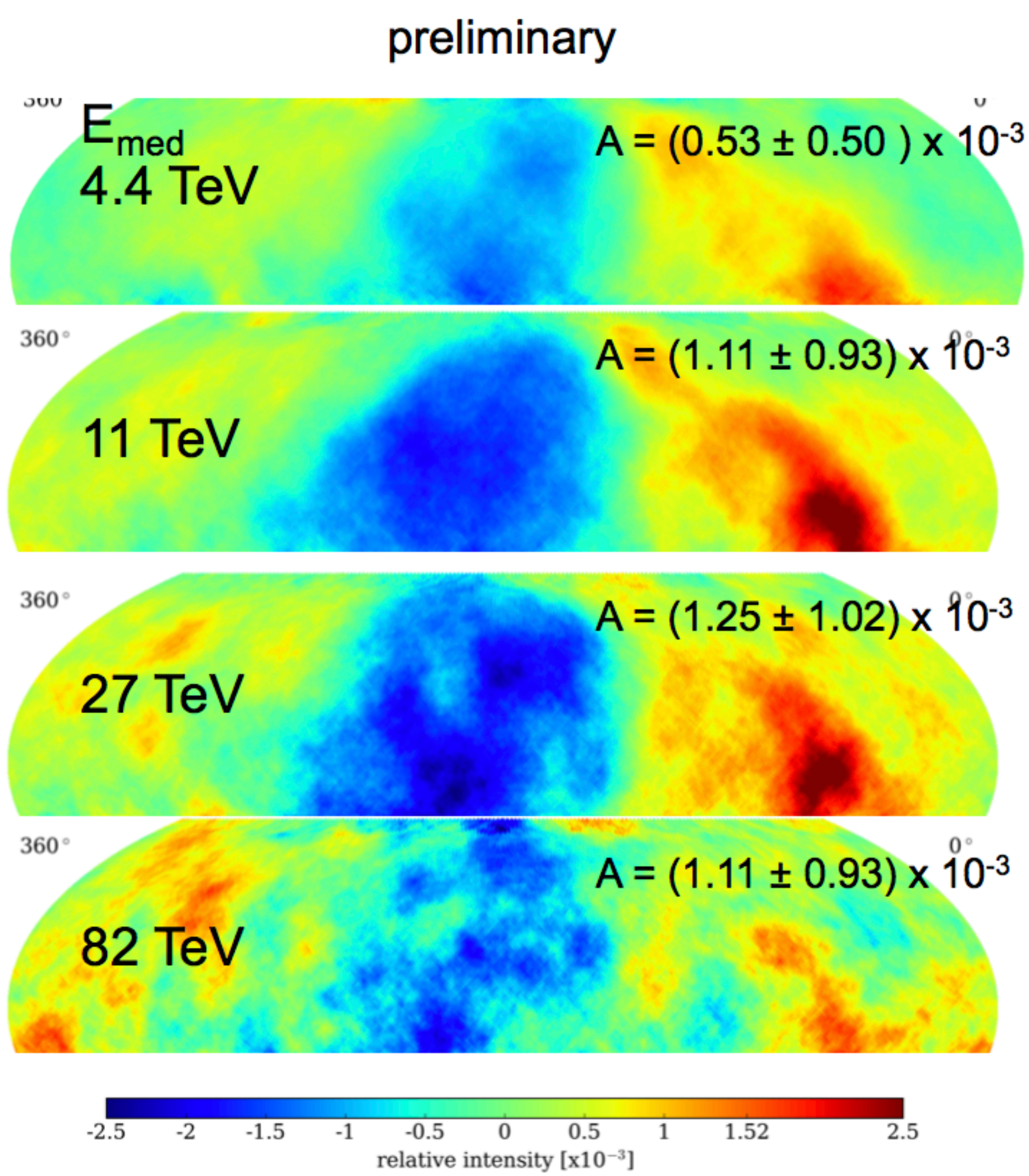


ARGO-YBJ Bartoli et al. 2015



cosmic ray anisotropy
energy dependence

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

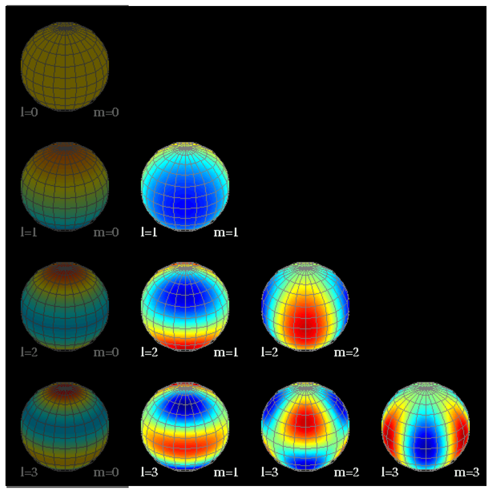


HAWC-300
D. Fiorino

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

observing cosmic ray anisotropy

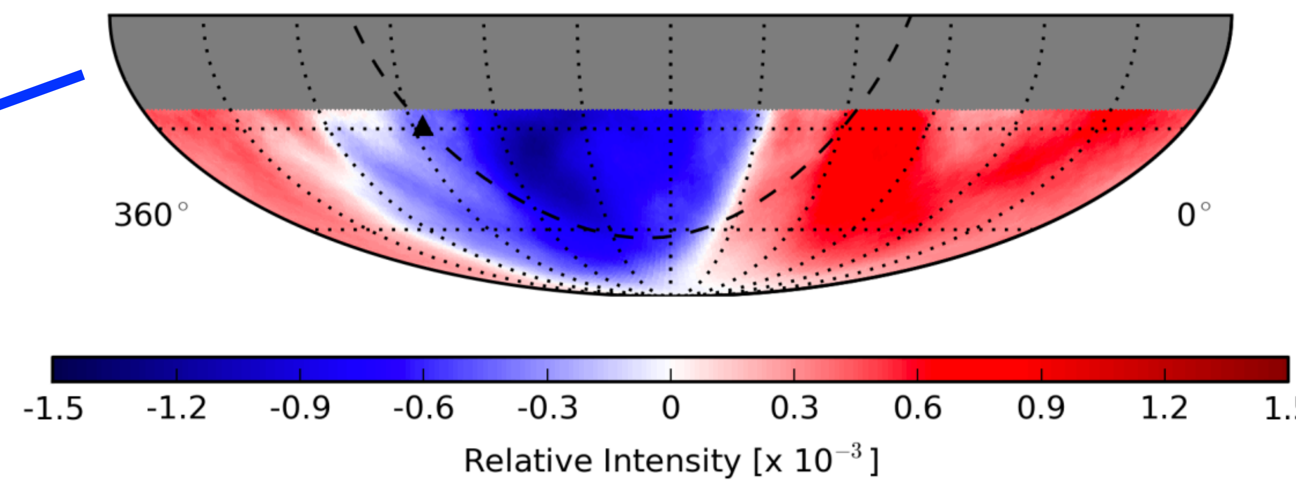
angular structure decomposition

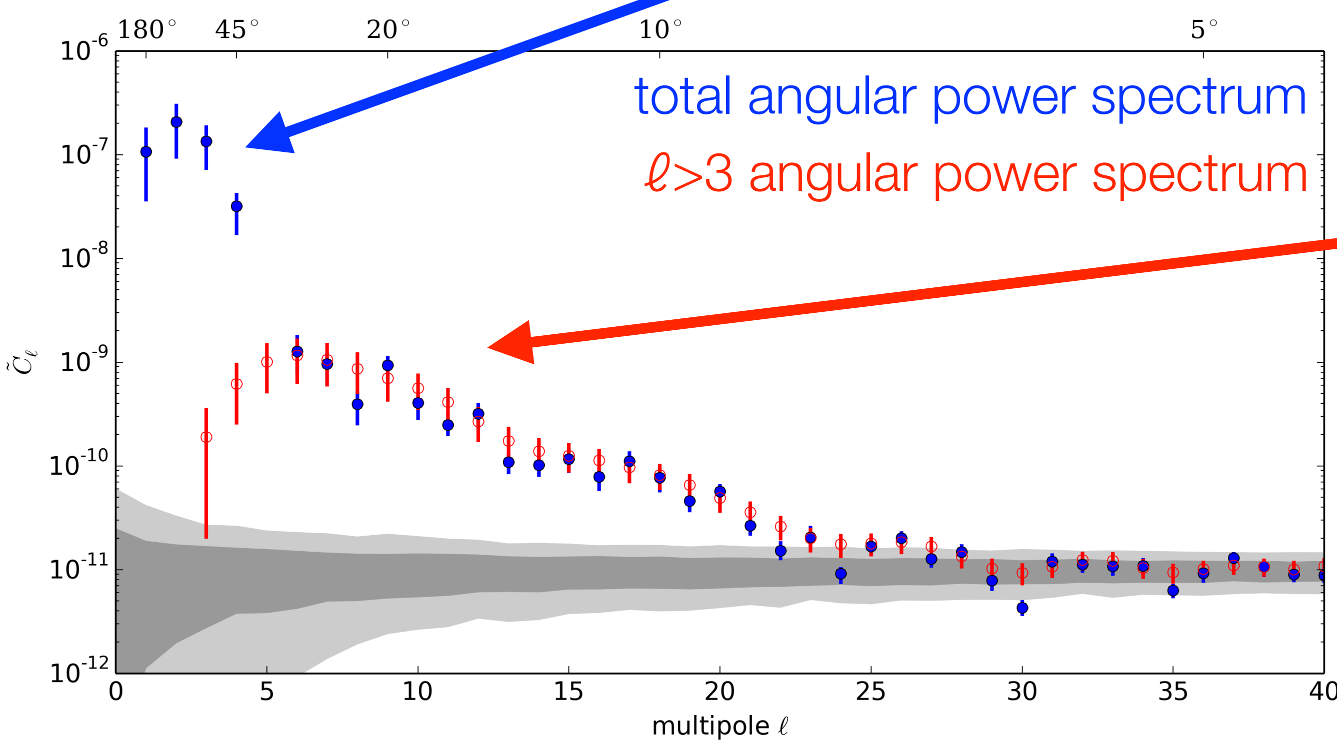


spherical harmonic analysis

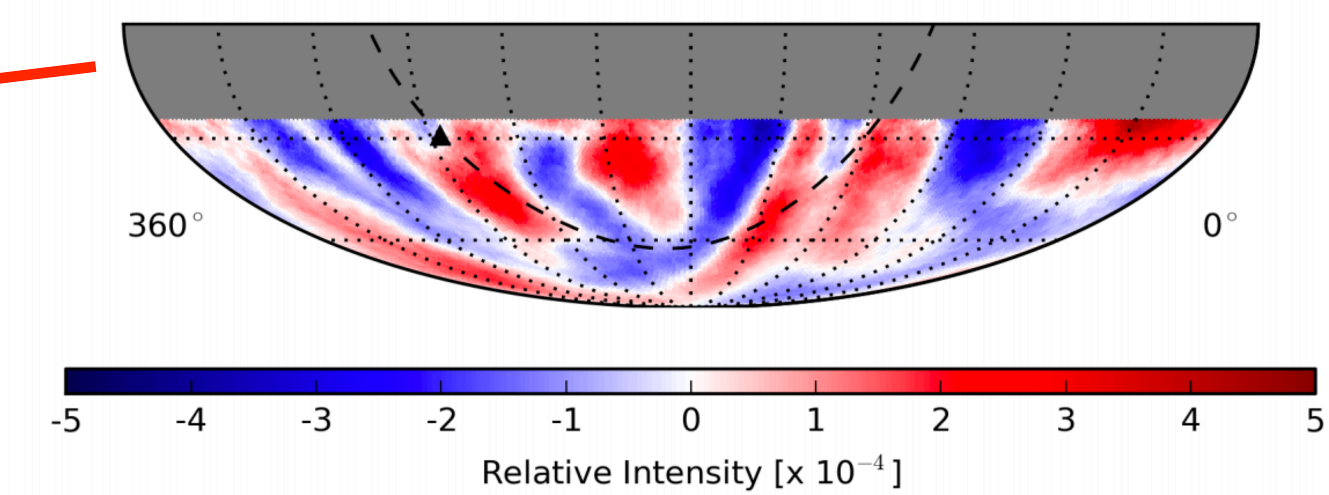
missing
vertical
component
(m = 0)

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





southern hemisphere

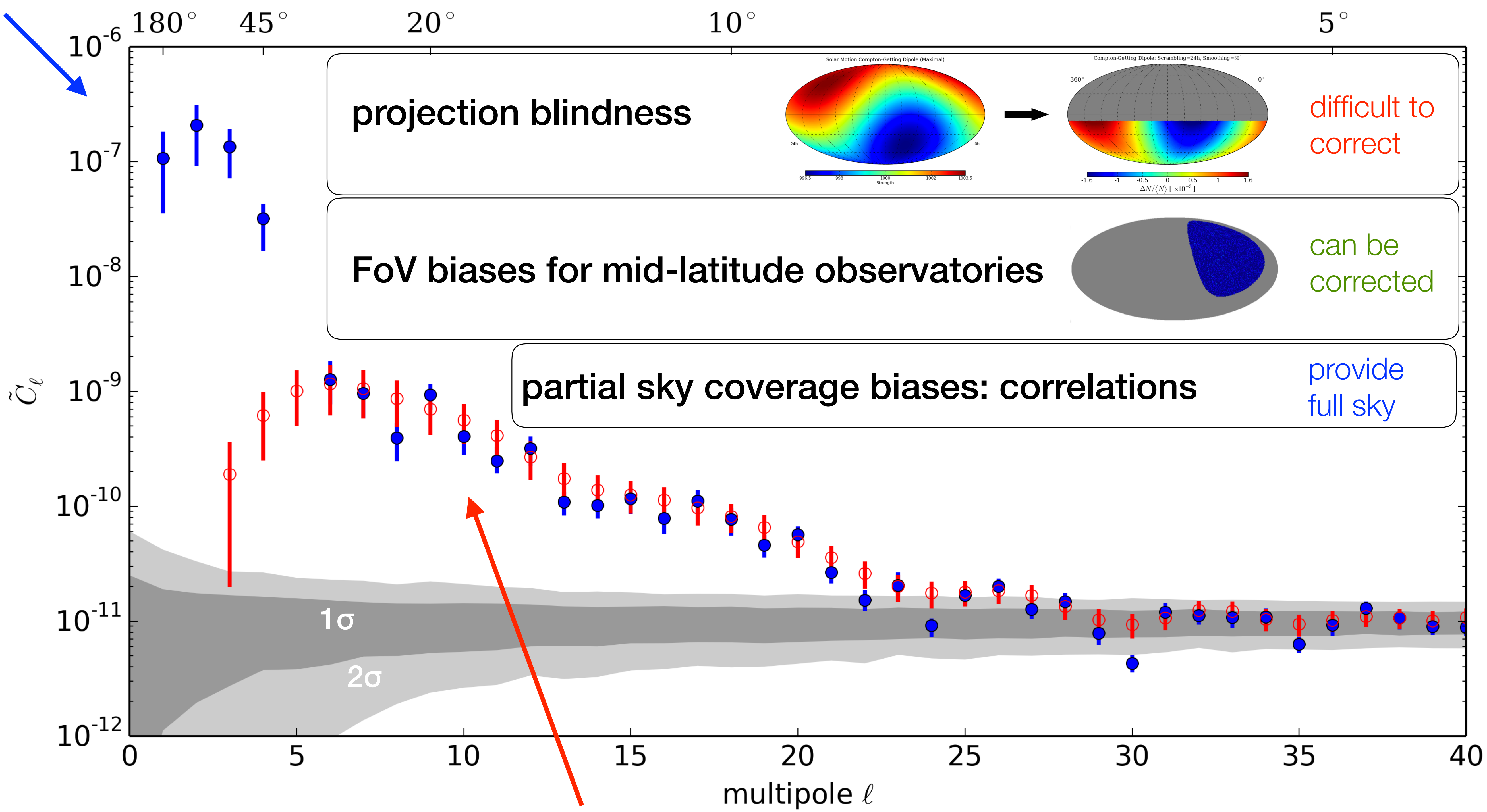


median energy 20 TeV

angular power spectrum

phenomenological fingerprint: physics + biases

density gradient / diffusion?



effects of magnetic instabilities / turbulence?

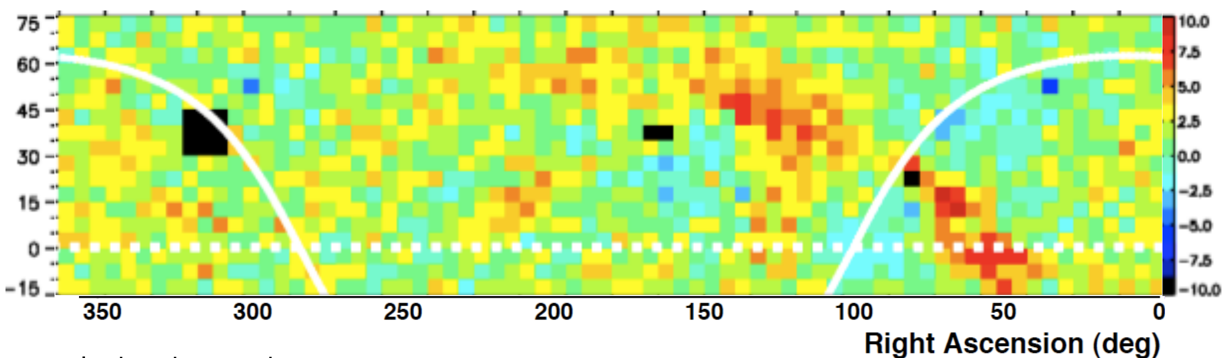
high energy cosmic rays

small scale anisotropy & spectral anomalies

1-5 TeV ~10^{-4}

Tibet-III

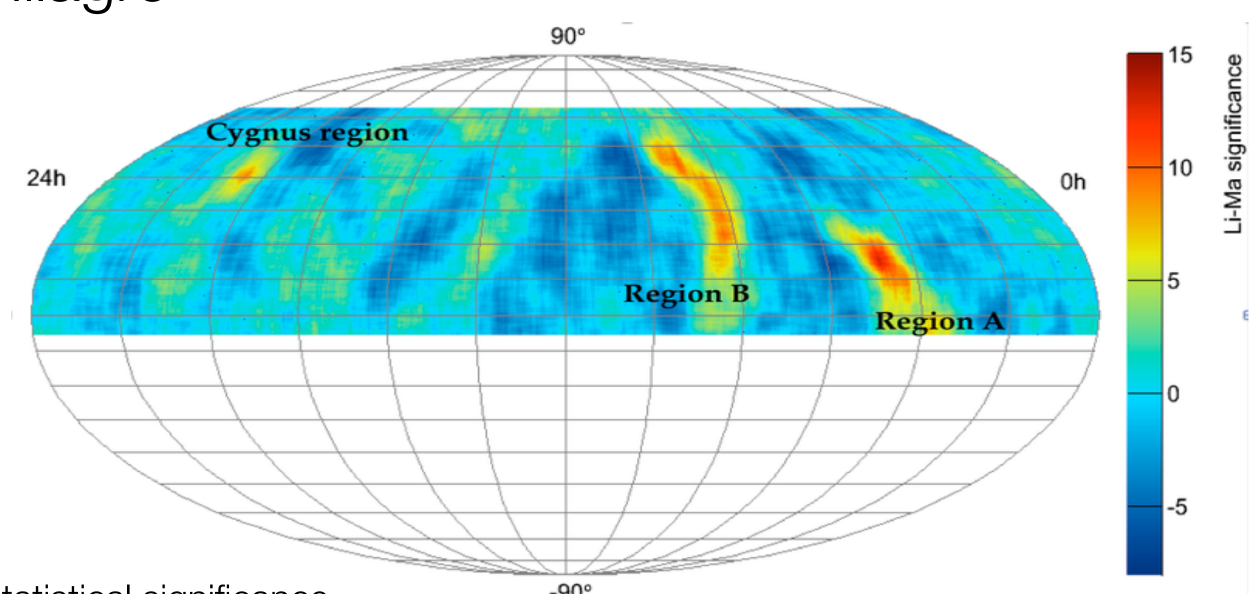
Amenomori et al. ICRC (2007)



relative intensity

Milagro

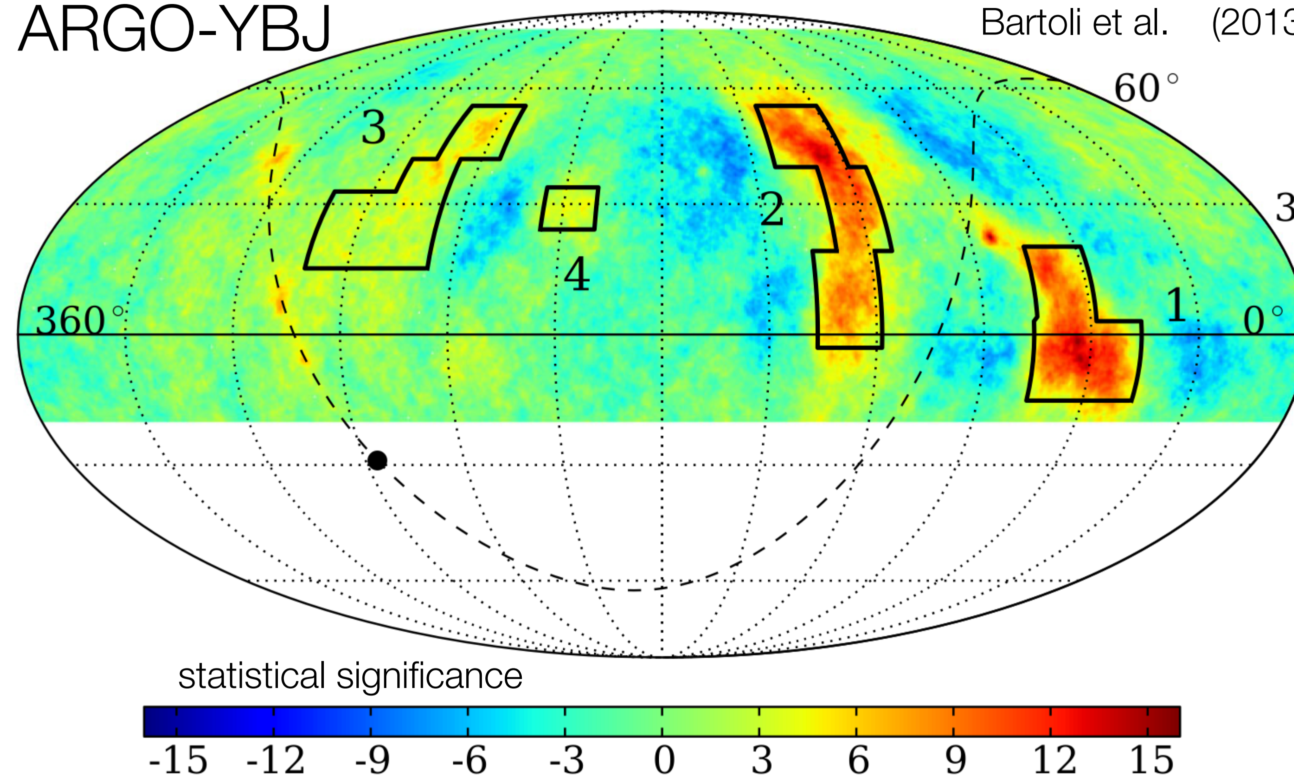
Abdo et al. (2008)



statistical significance

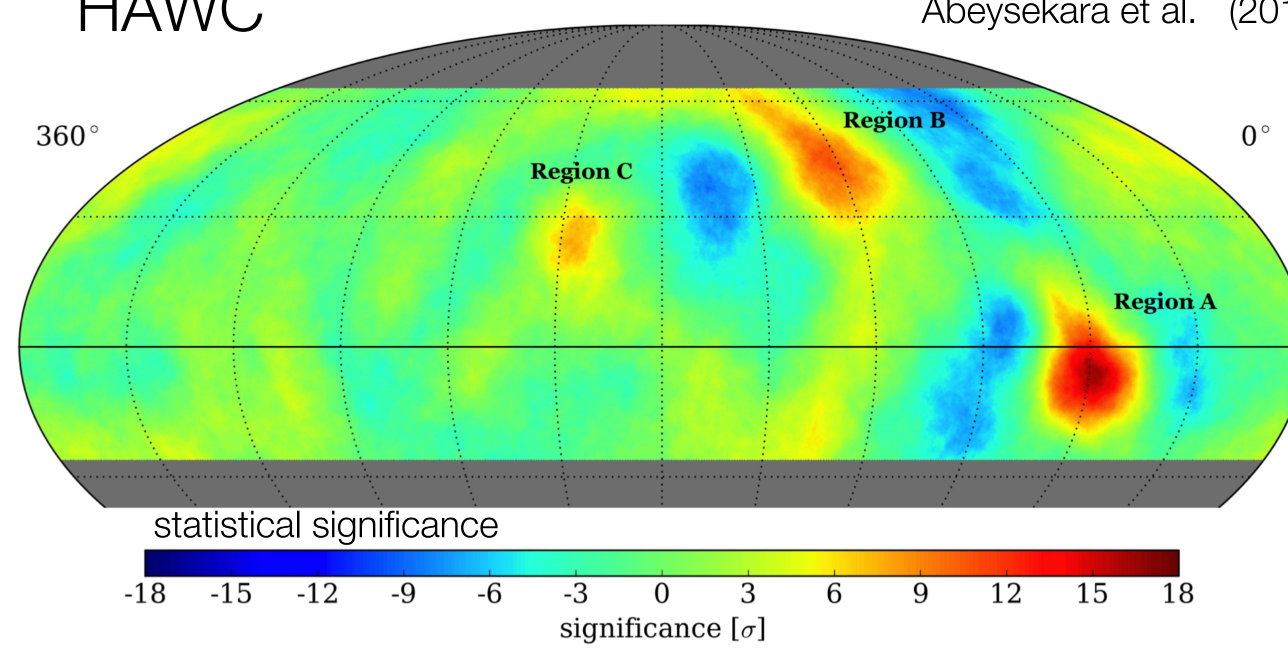
ARGO-YBJ

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



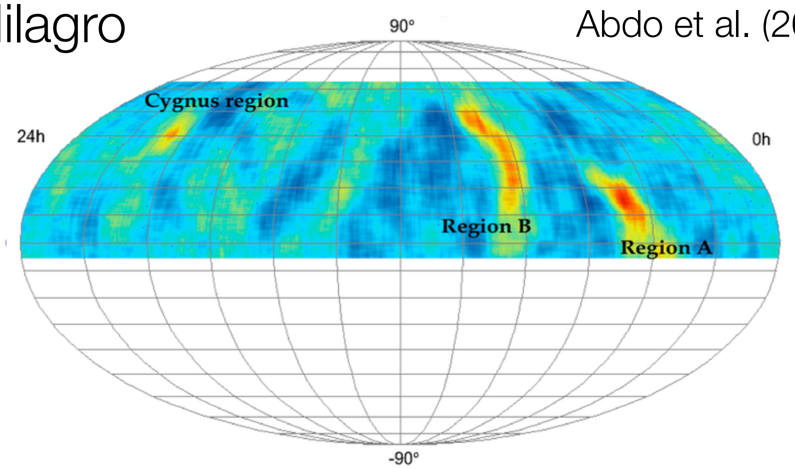
HAWC

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

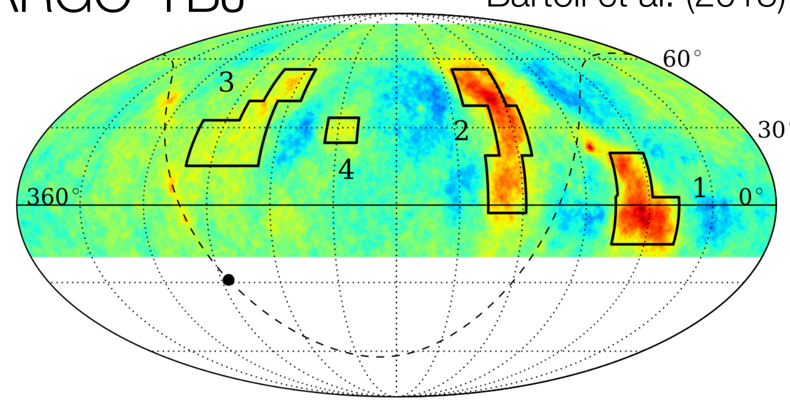


high energy cosmic rays
small scale anisotropy & spectral anomalies

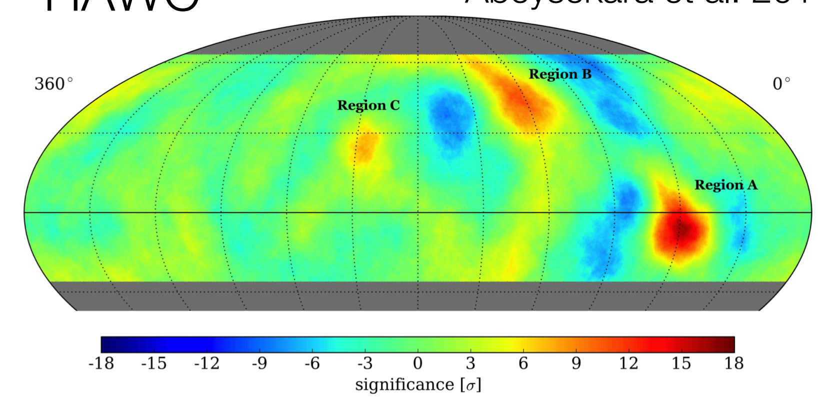
Milagro Abdo et al. (2008)

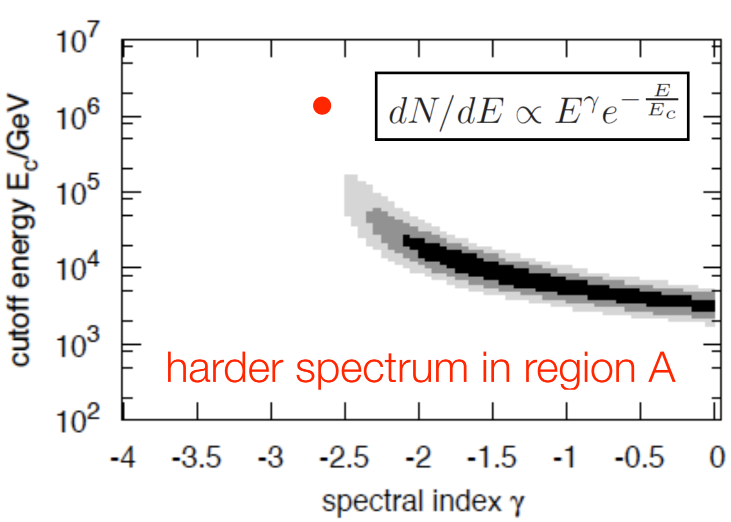


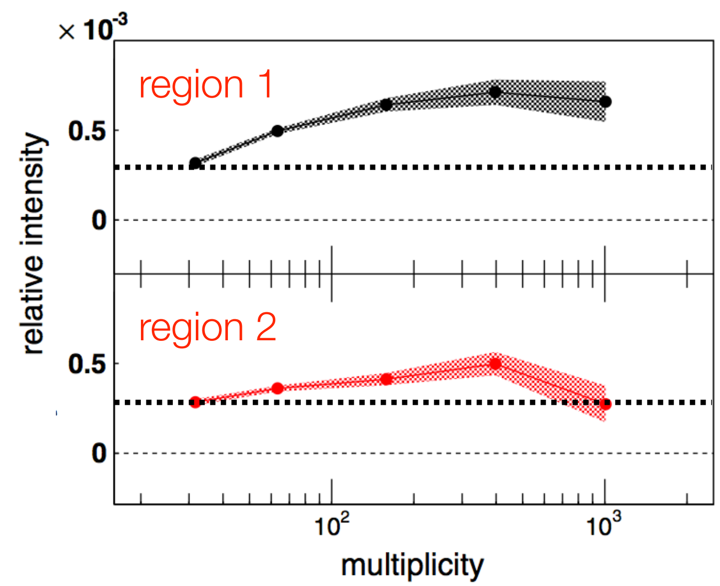
ARGO-YBJ Bartoli et al. (2013)

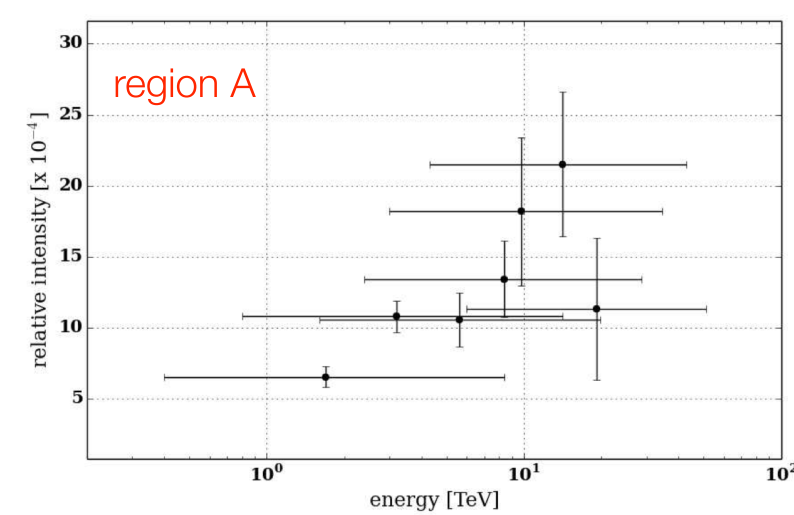


HAWC Abeysekara et al. 2014

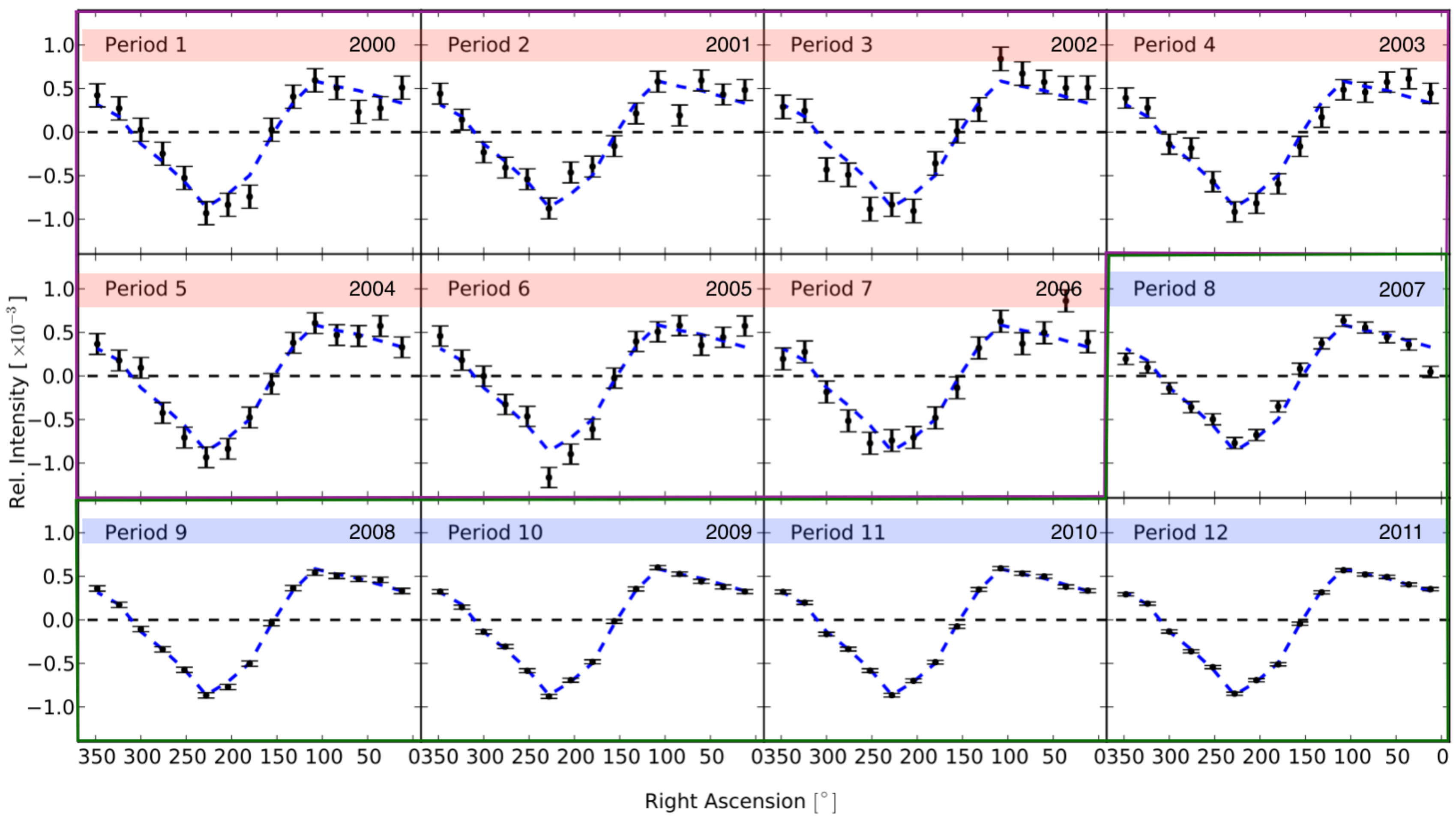




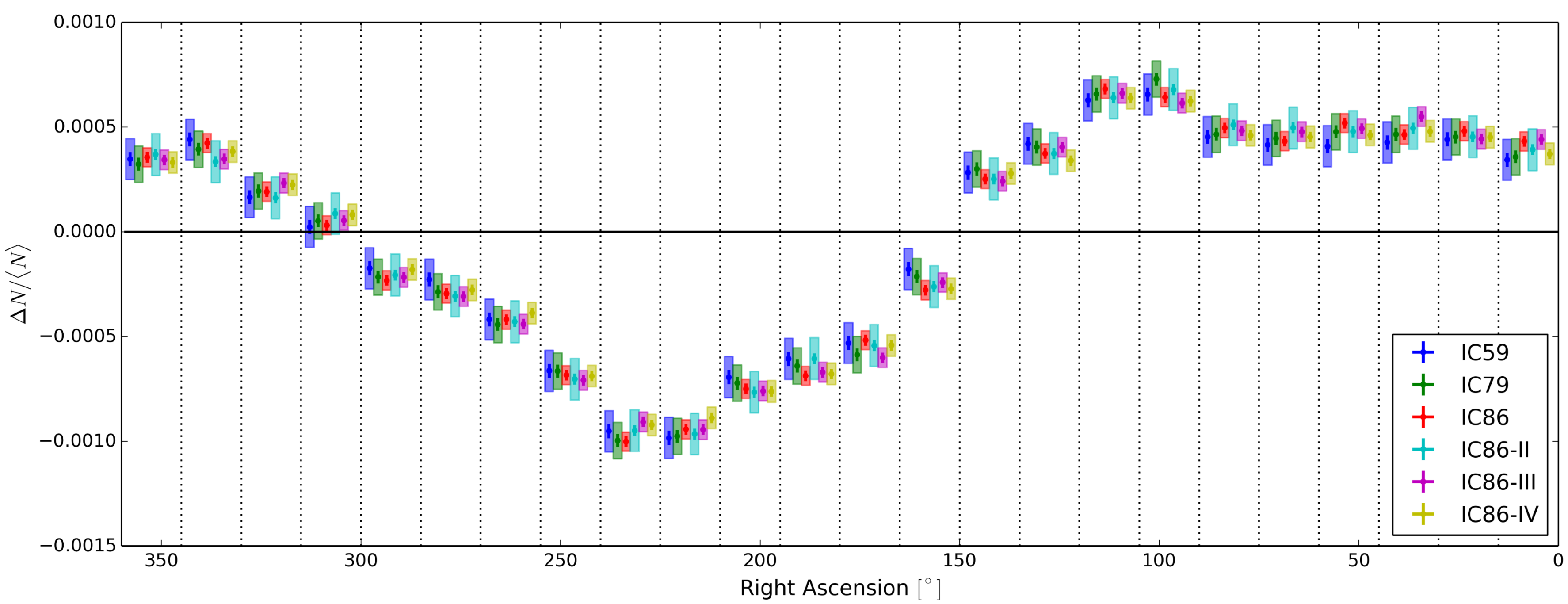




cosmic rays anisotropy stability
AMANDA-IceCube 2000-2014



Marcos Santander ICRC 2013



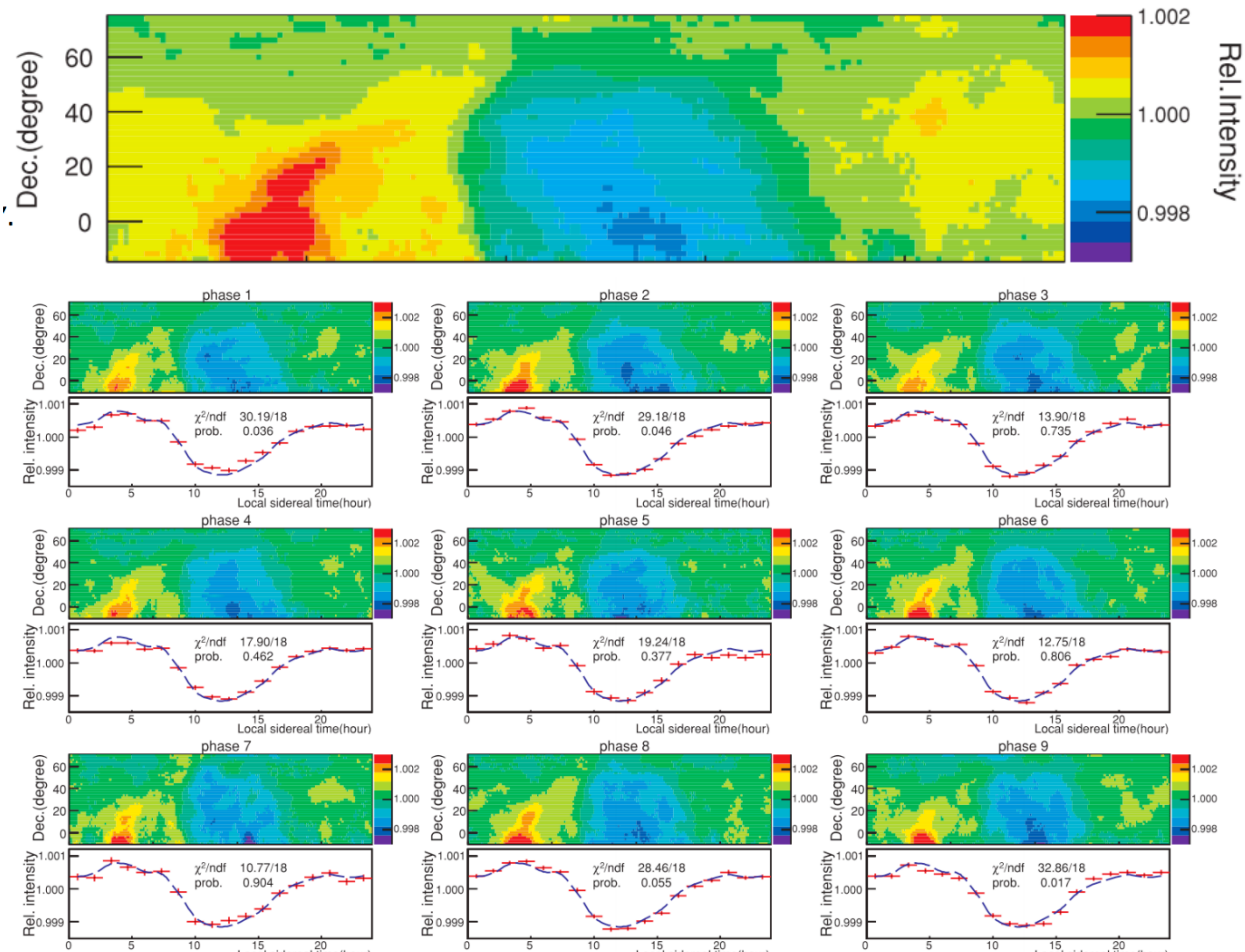
IceCube - Aartsen et al., ApJ 826, 220, 2016

median energy ~ 20 TeV

cosmic rays anisotropy stability

Tibet Array

Tibet Array 2005



outlook

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**

- determine anisotropy vs. rigidity (i.e. for different CR particle masses)
- overcome experimental limitations, such as limited FoV
- full-sky observations: **surface IceCube-HAWC & satellite observations**

Solvay workshop on

SUGAR 2018

Brussels, 23-26 January

INTERNATIONAL SOLVAY INSTITUTES BRUSSELS

Thank you…