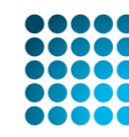
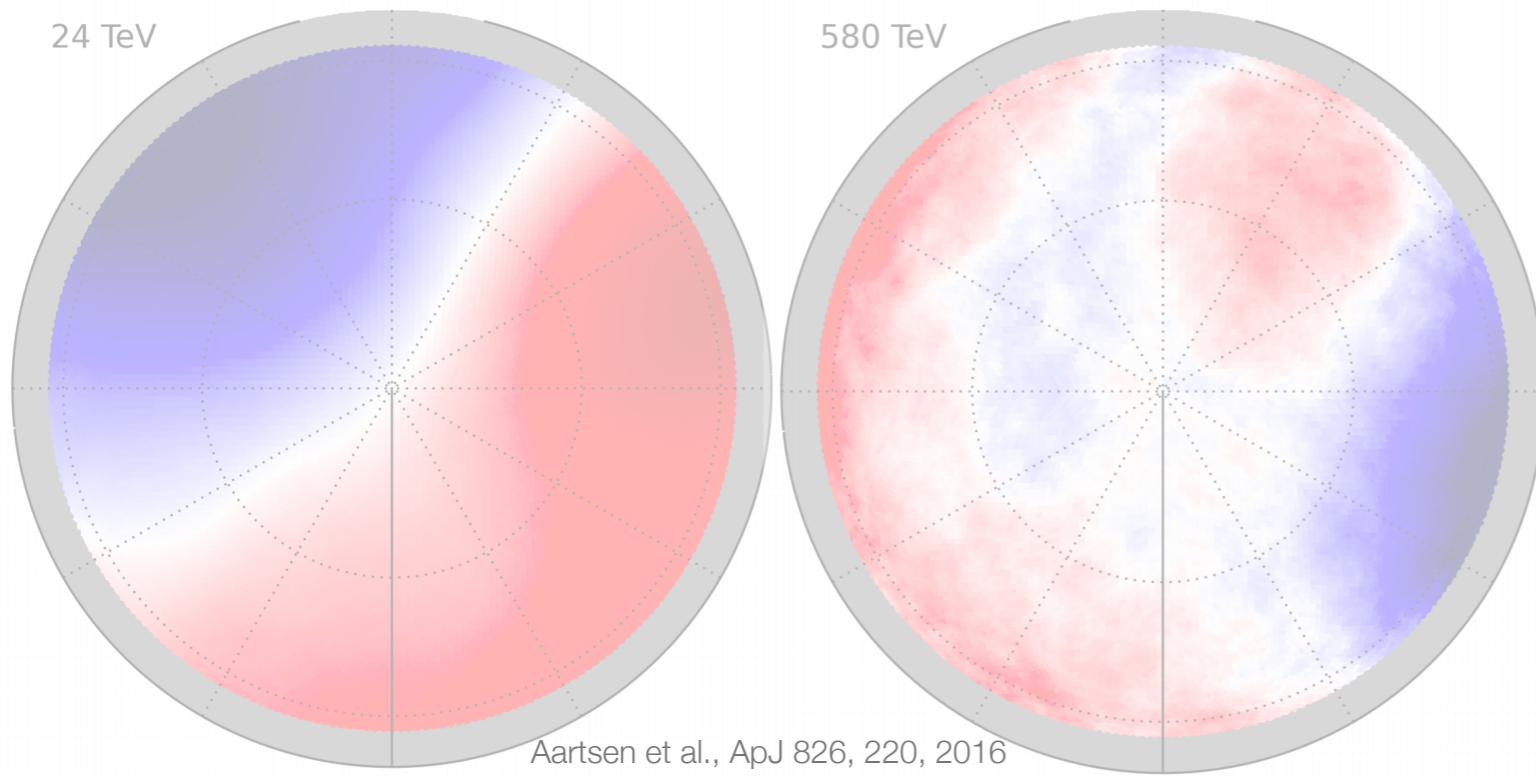


24 TeV

580 TeV



WISCONSIN ICECUBE  
PARTICLE ASTROPHYSICS CENTER



Aartsen et al., ApJ 826, 220, 2016

# anisotropy and propagation of cosmic rays

**Paolo Desiati**

desiati@wipac.wisc.edu



University of Wisconsin - Madison

**Midwest Magnetic Fields 2017 Workshop**

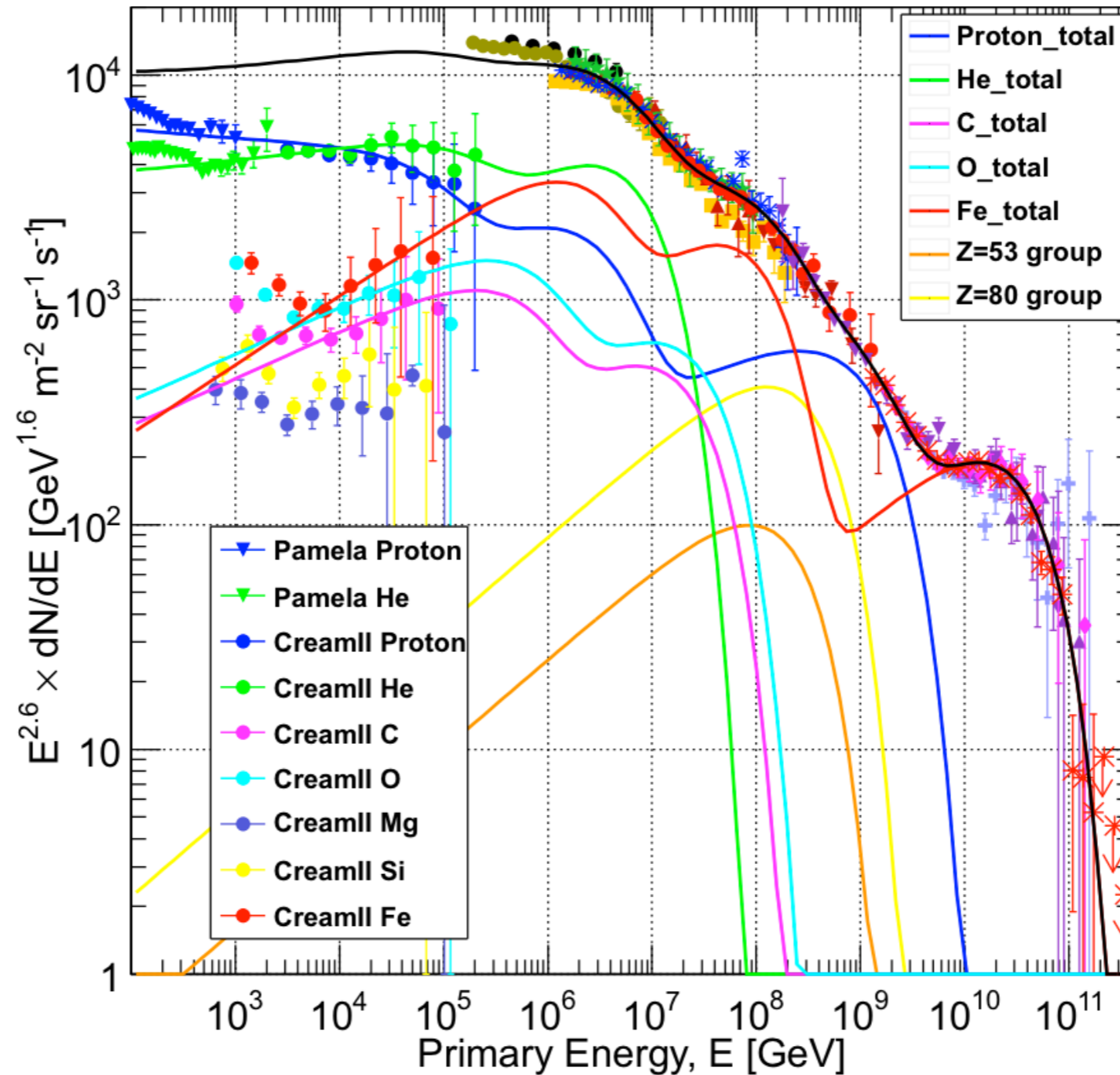
25-26 May, 2017

# understanding cosmic rays

## energy spectrum & composition

Gaisser, Stanev, Tilav, 2013 - arXiv:1303.3565

direct  
measurements

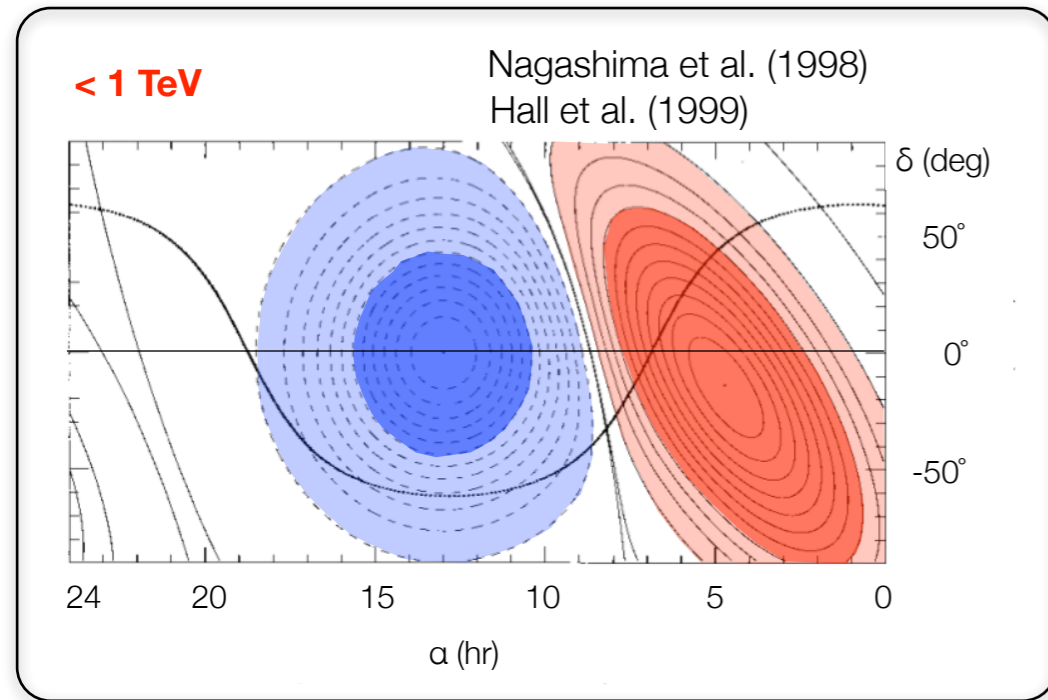


indirect  
measurements

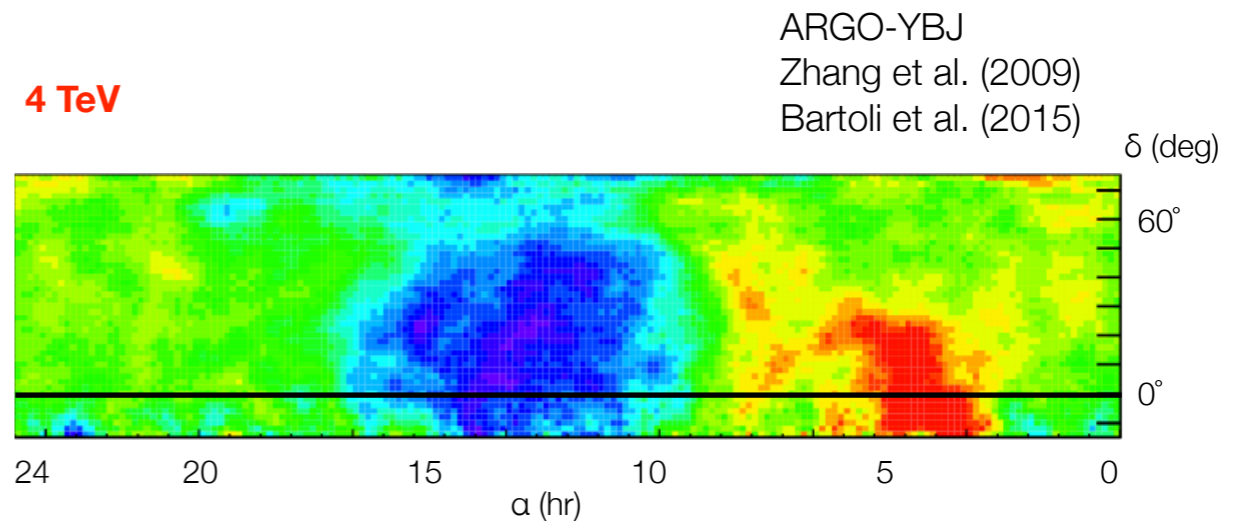
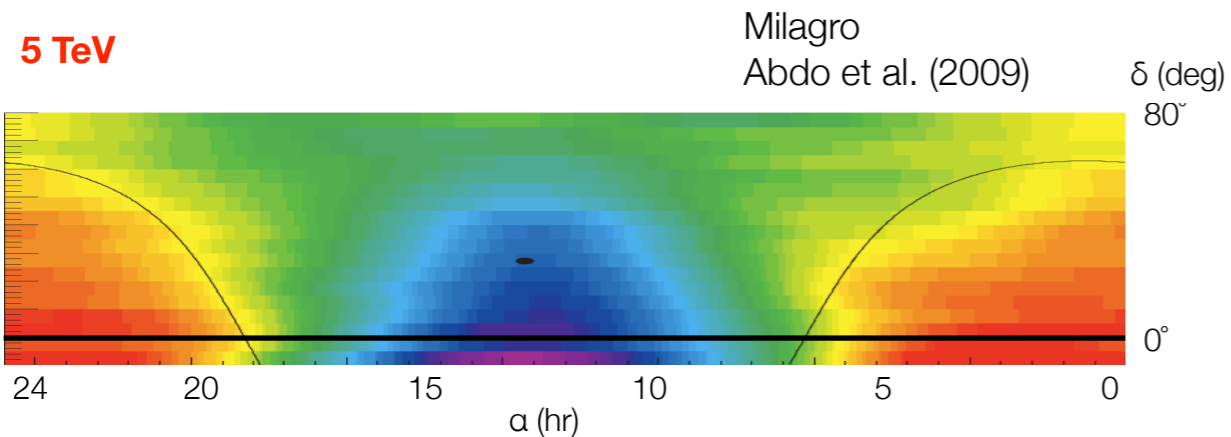
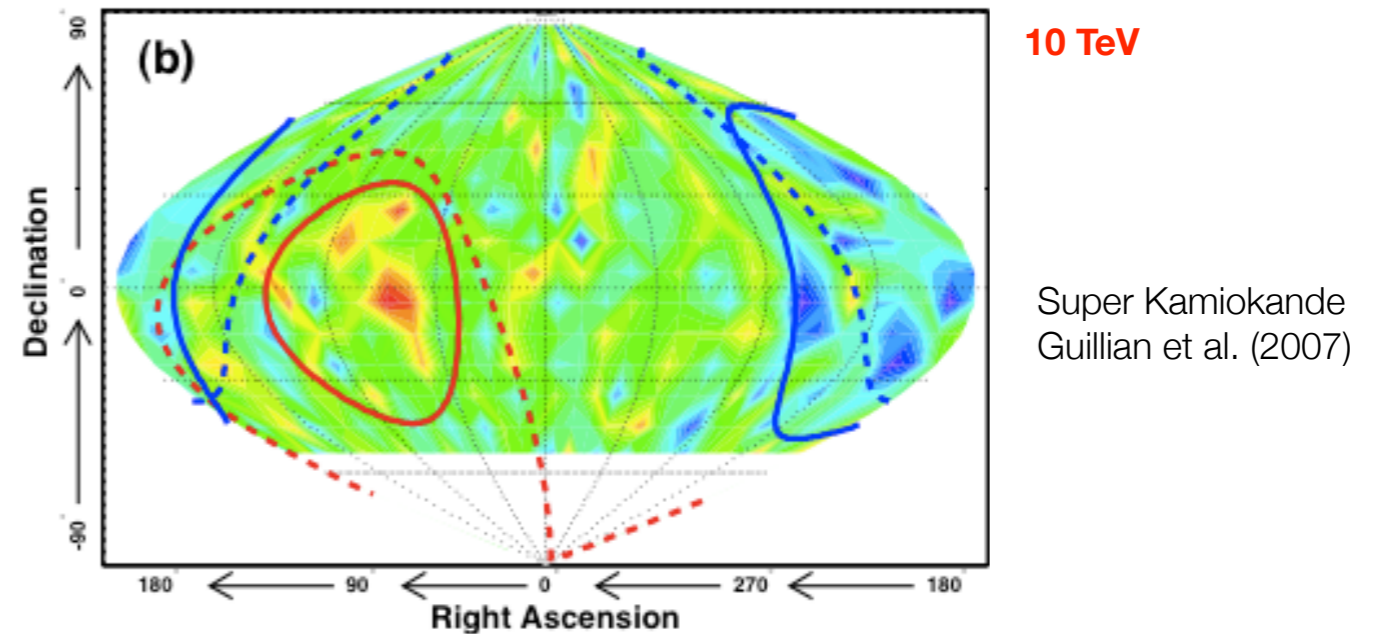
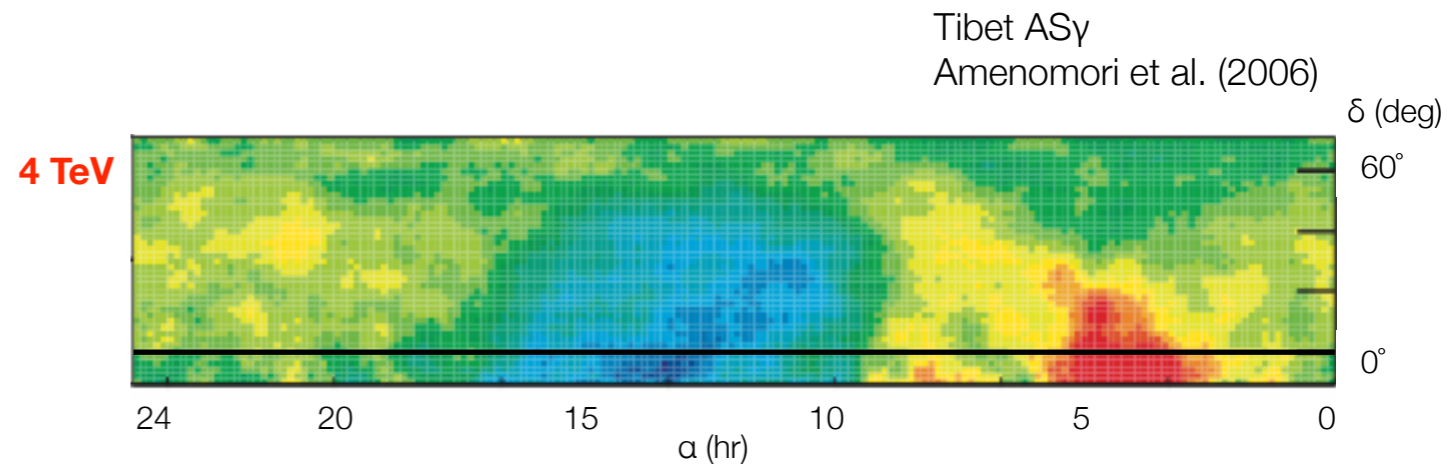
# understanding cosmic rays

## anisotropy

$\sim 10^{-3}$



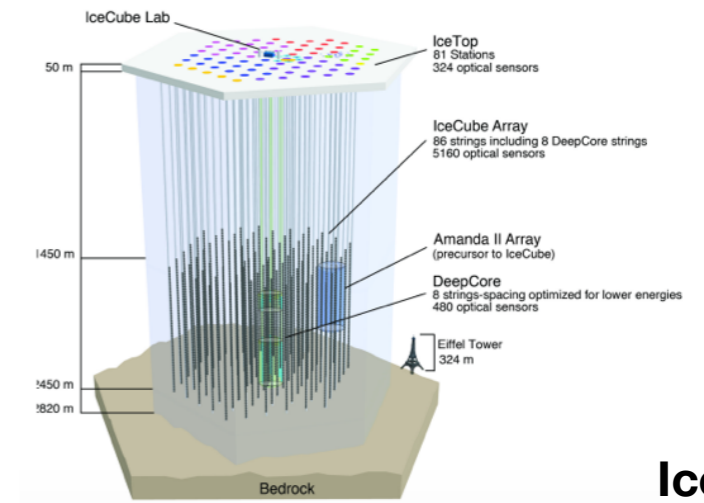
relative intensities in  
equatorial coordinates





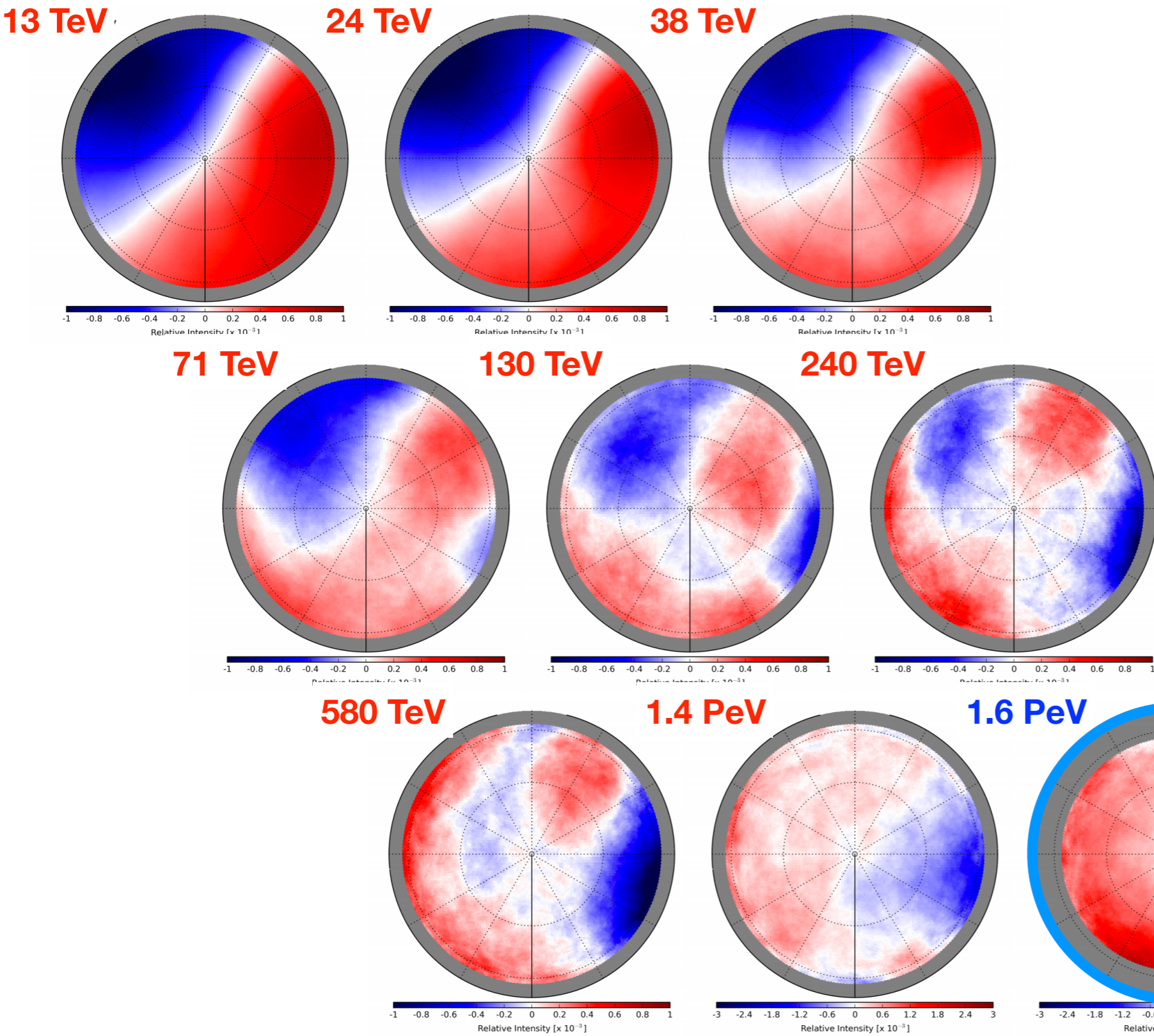
# cosmic rays anisotropy

## energy dependence



**IceCube**

Aartsen et al., ApJ 826, 220, 2016



relative intensity

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



# cosmic rays anisotropy

## energy dependence

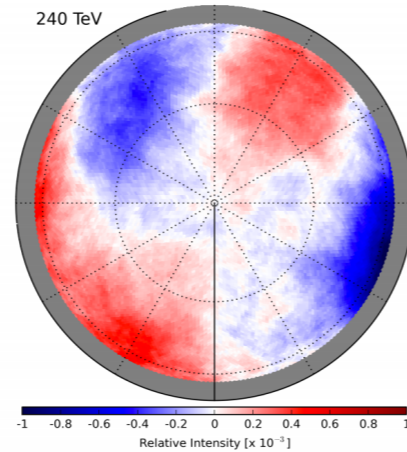
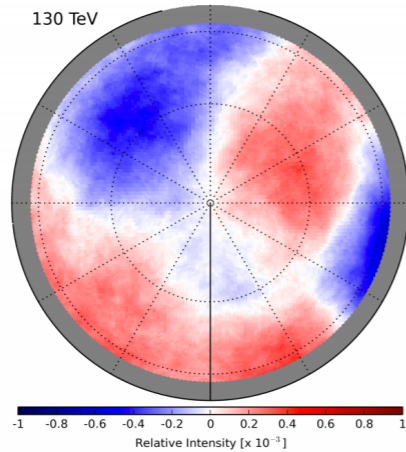
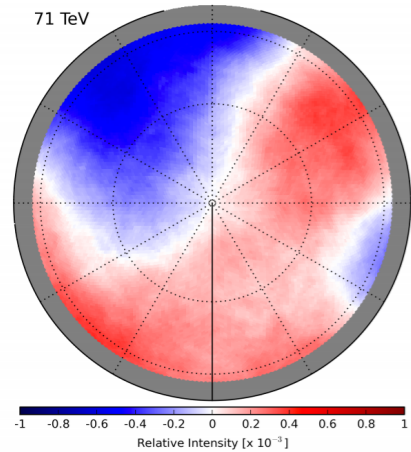
**IceCube** Aartsen et al., ApJ 826, 220, 2016

**Tibet ASy** Amenomori et al., ICRC 2015

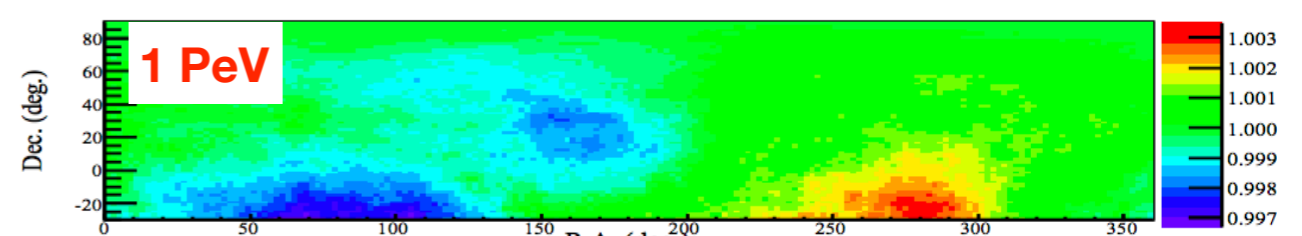
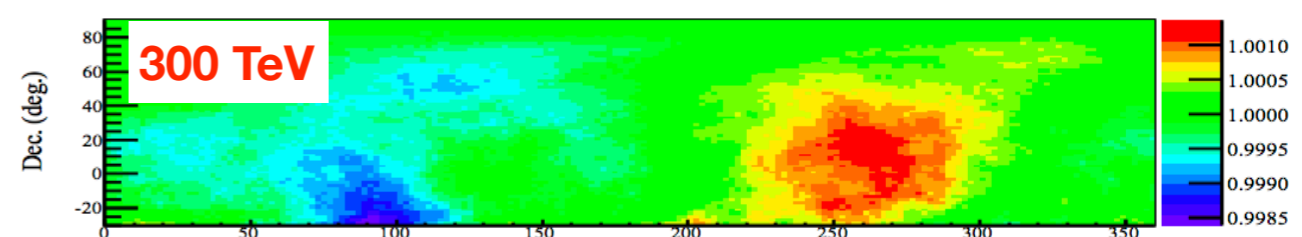
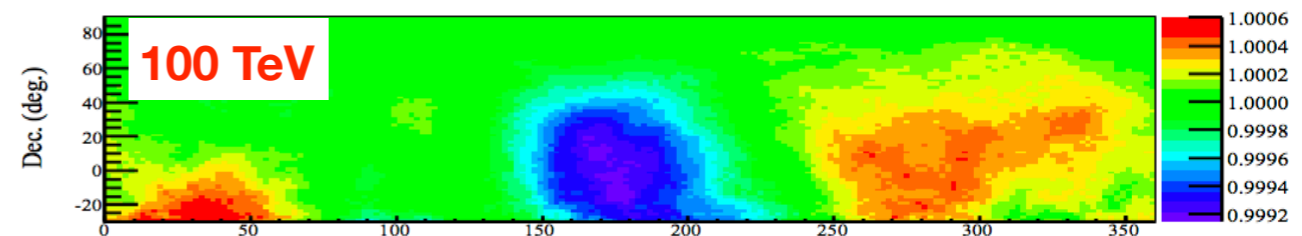
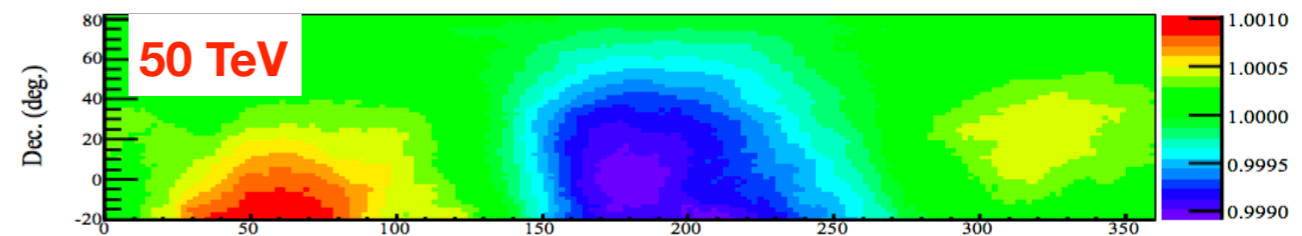
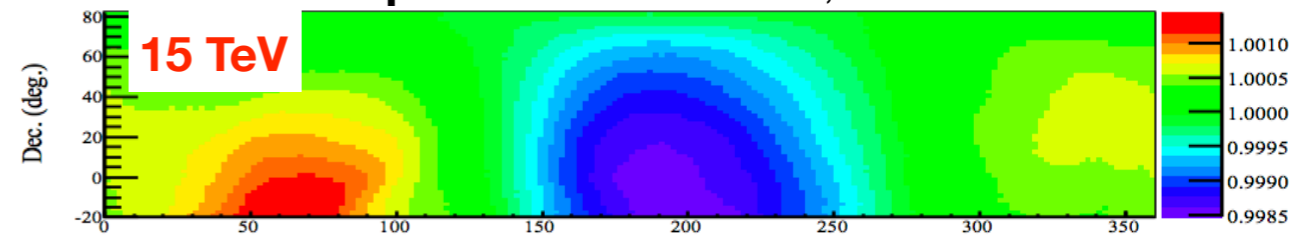
**71 TeV**

**130 TeV**

**240 TeV**



southern hemisphere



northern hemisphere

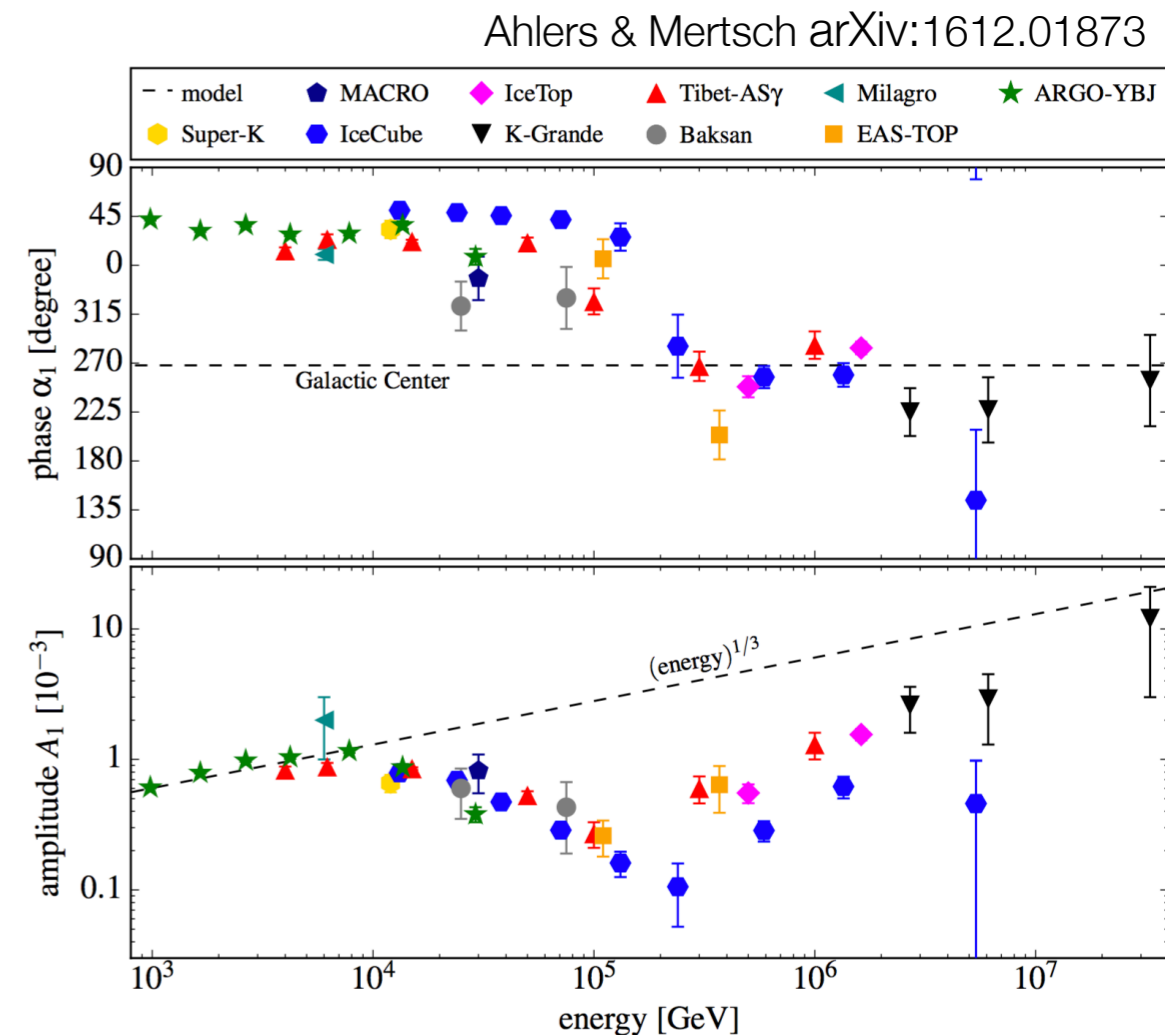
# anisotropy observations

## summary #1

---

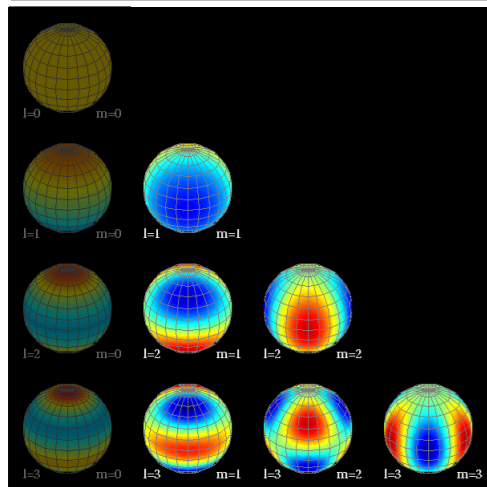
- ▶ cosmic ray anisotropy is **small** and **energy-dependent**
- ▶ anisotropy topology changes above  $\sim 100$  TeV
- ▶ **dipole** component of anisotropy typically associated to **diffusion**

dipole component  
of anisotropy

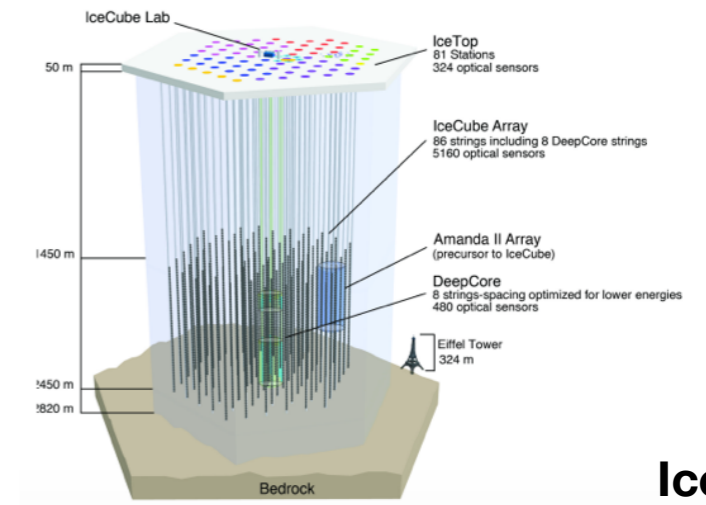


# cosmic rays anisotropy

## angular scale decomposition

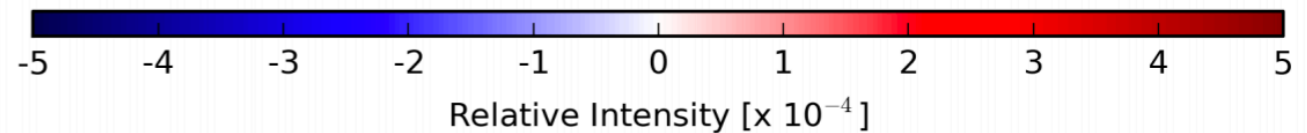
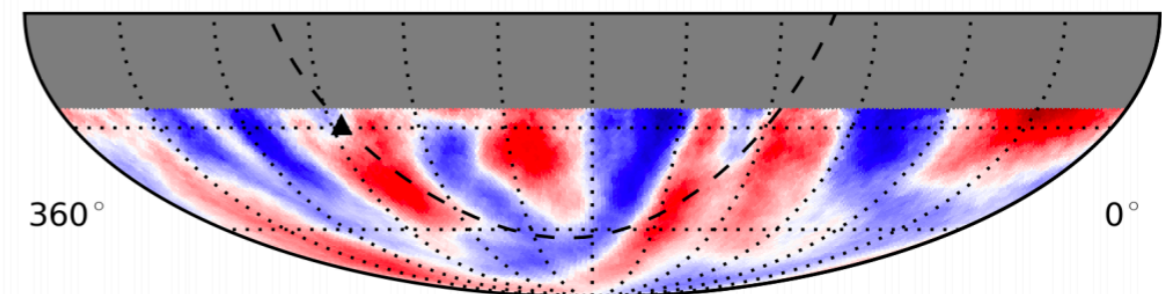
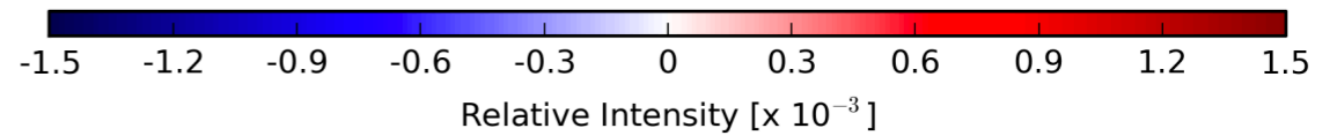
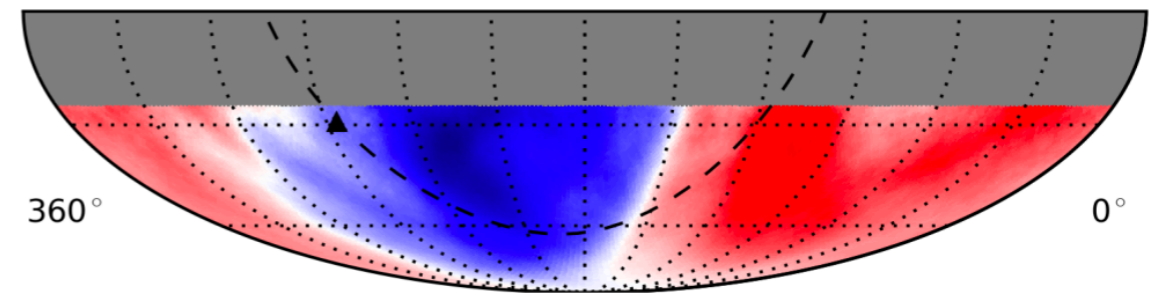


spherical harmonic analysis

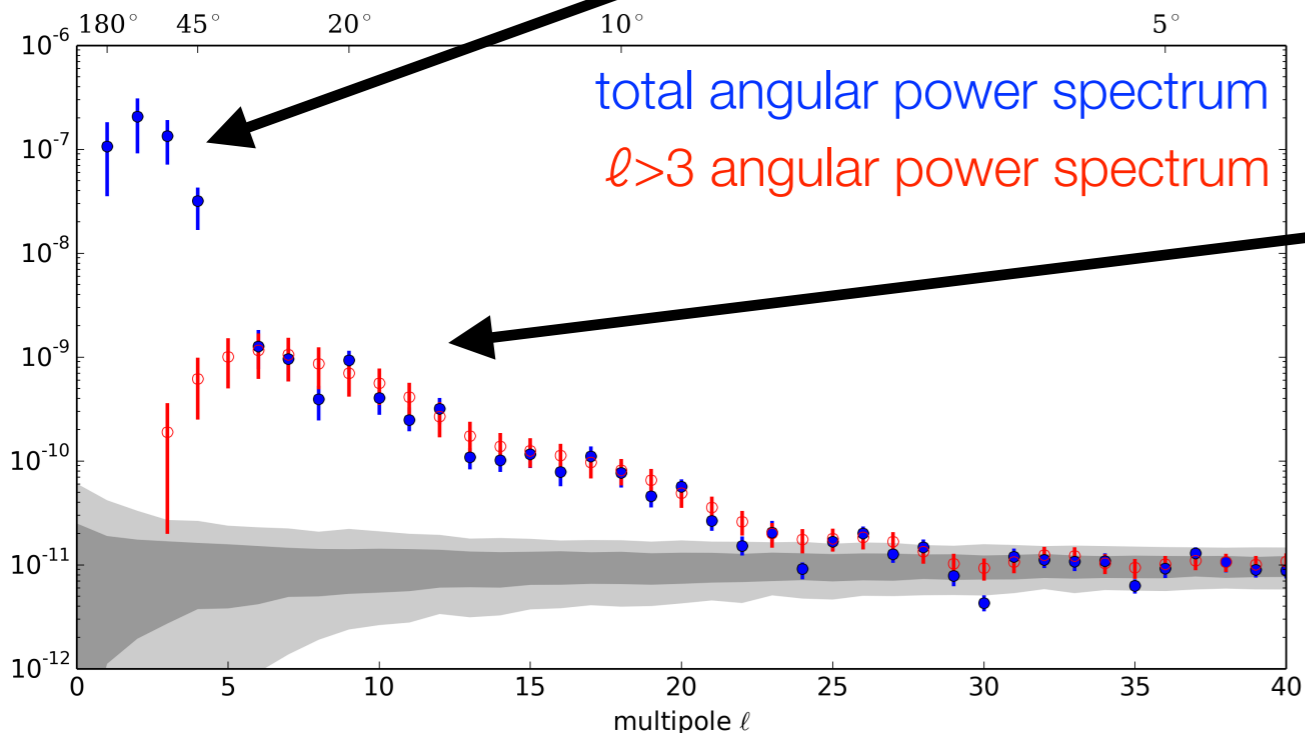


**IceCube**

Aartsen et al., ApJ 826, 220, 2016



**median energy 20 TeV**



southern hemisphere



# cosmic rays anisotropy

## medium/small scale structures

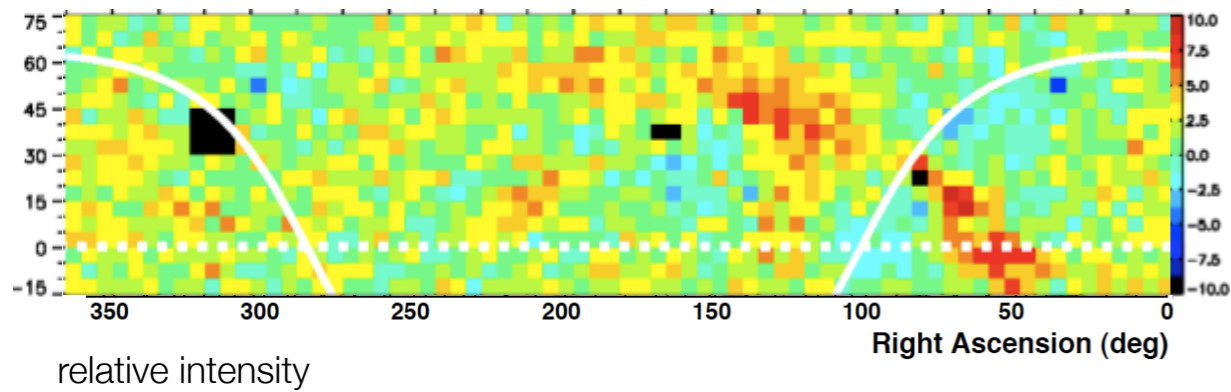
1-5 TeV

$\sim 10^{-4}$

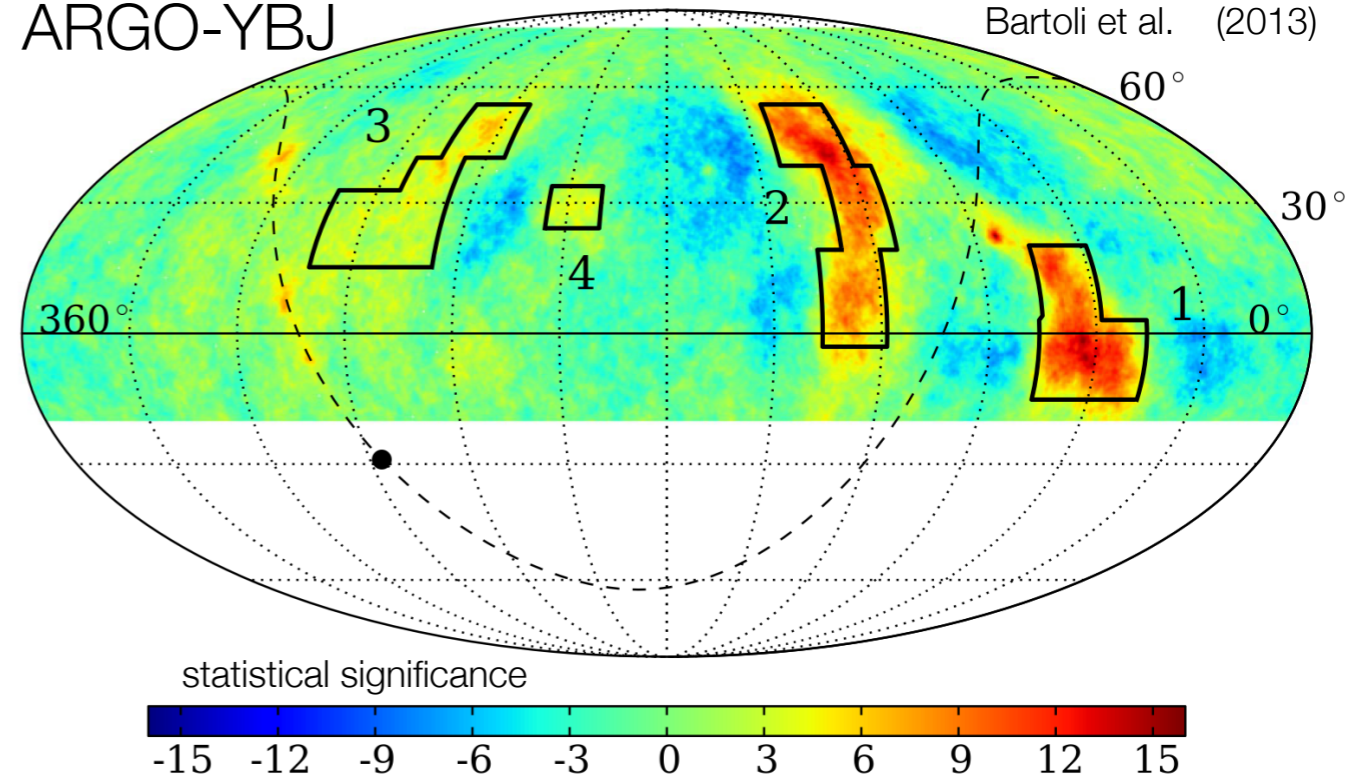
Vernetto et al. (2009)  
Iuppa et al. (2011)  
Bartoli et al. (2013)

Tibet-III

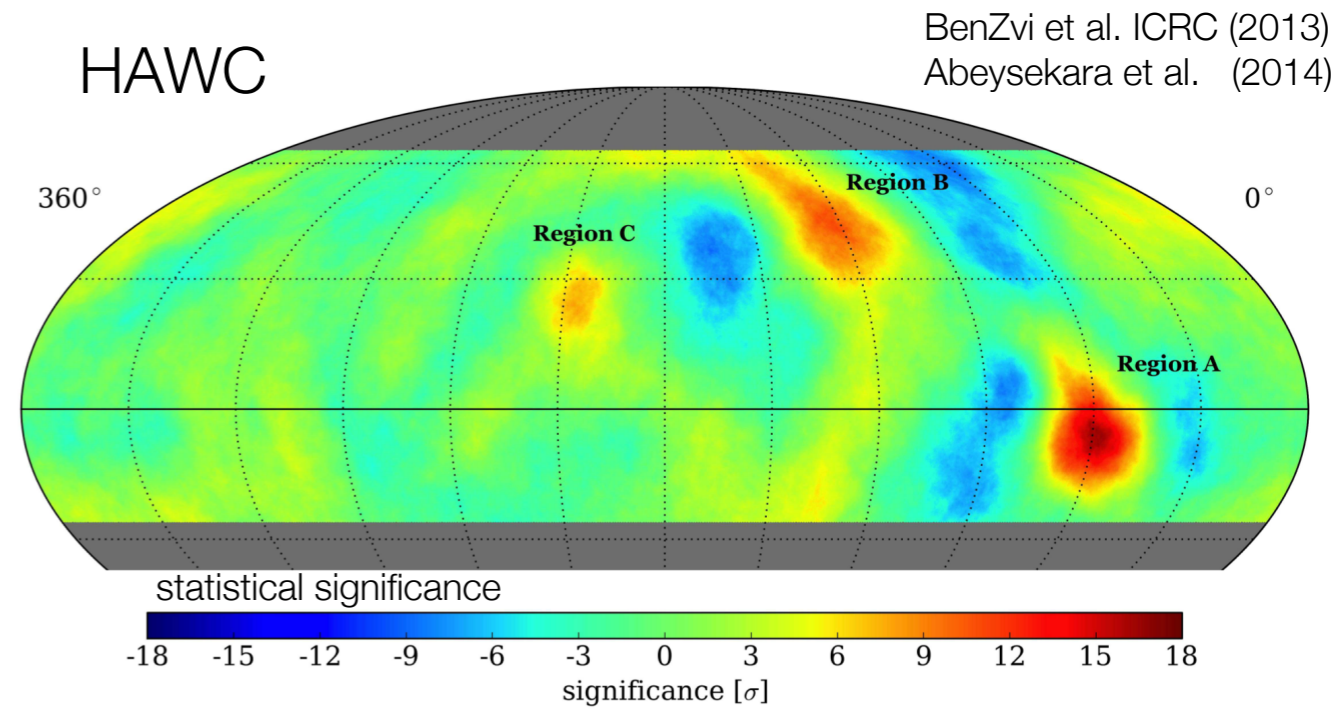
Amenomori et al. ICRC (2007)



ARGO-YBJ



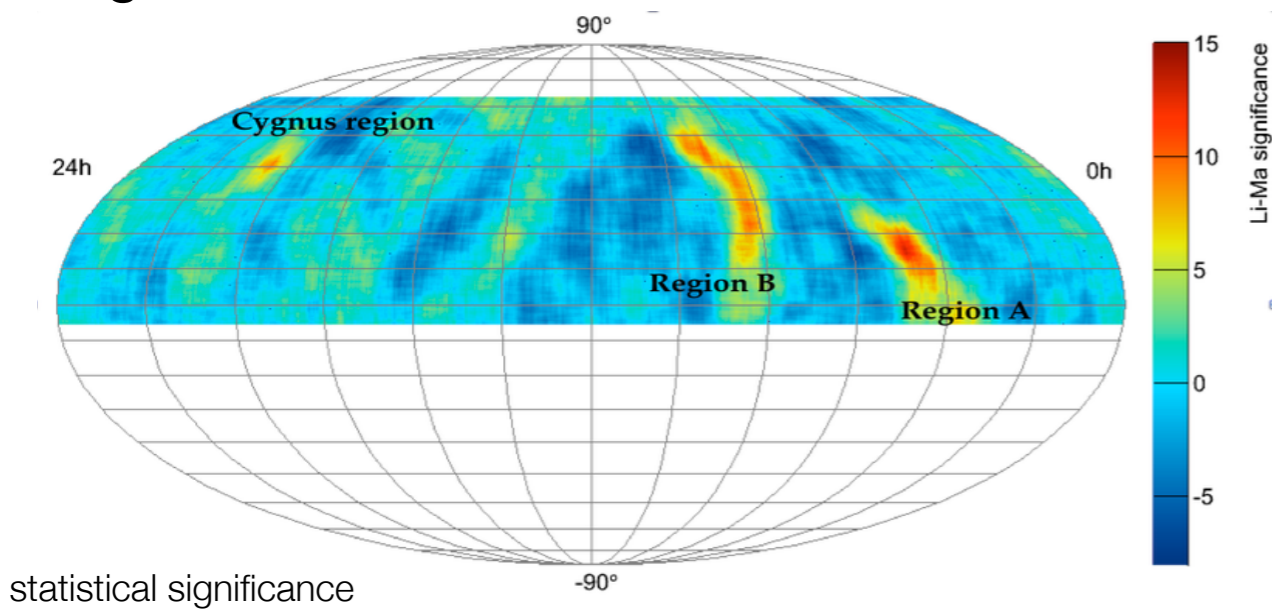
HAWC



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

Milagro

Abdo et al. (2008)



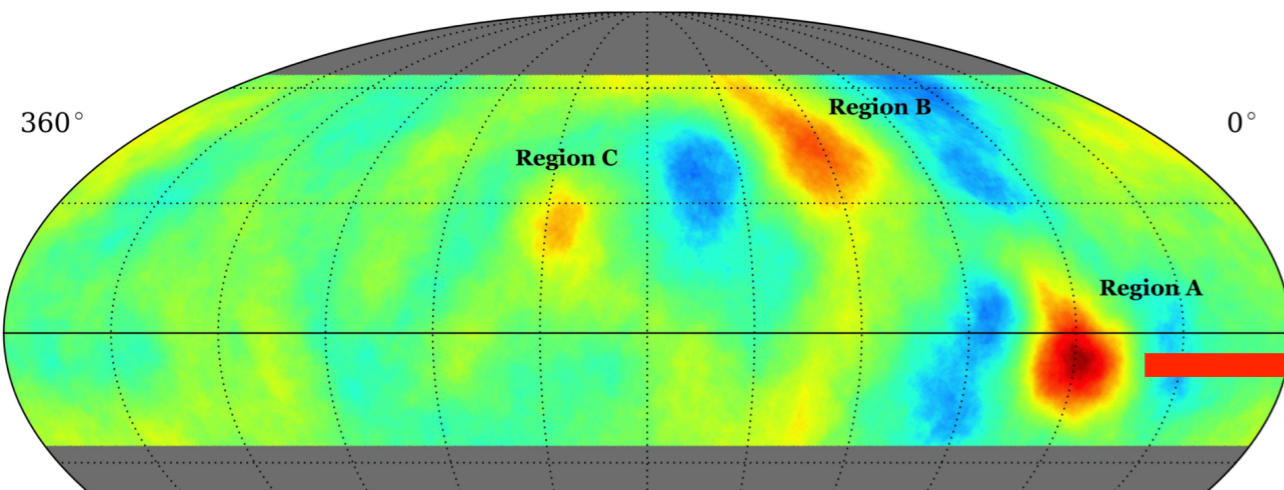
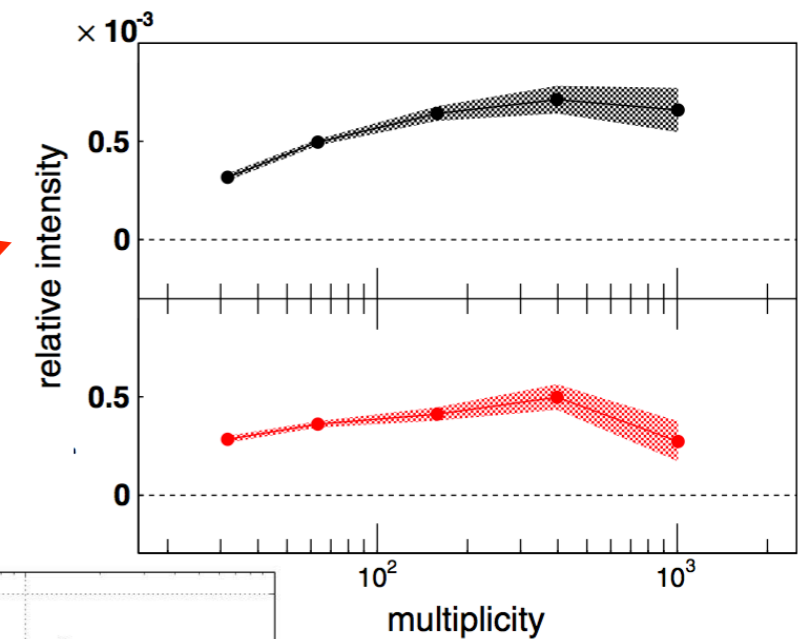
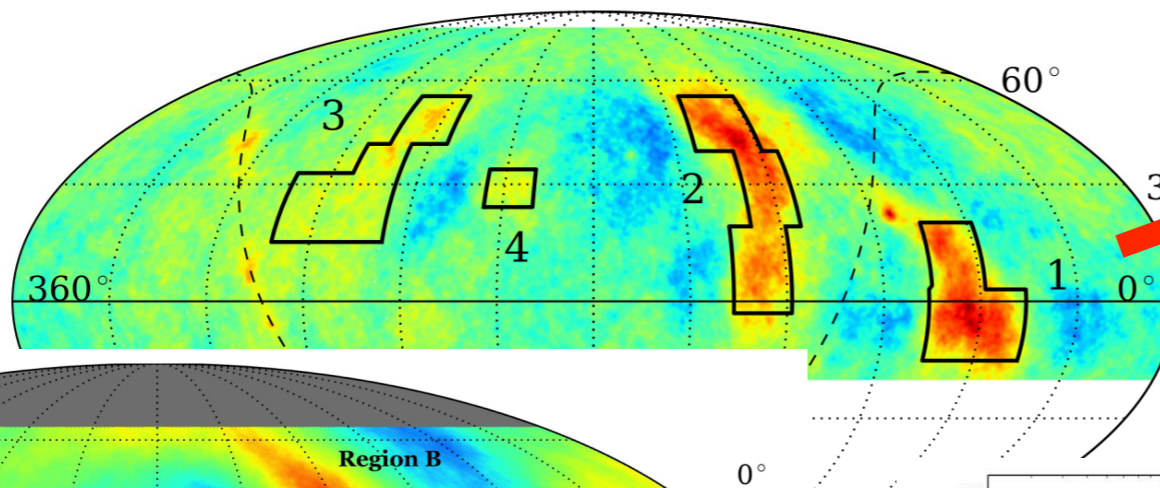
northern hemisphere

# anisotropy observations

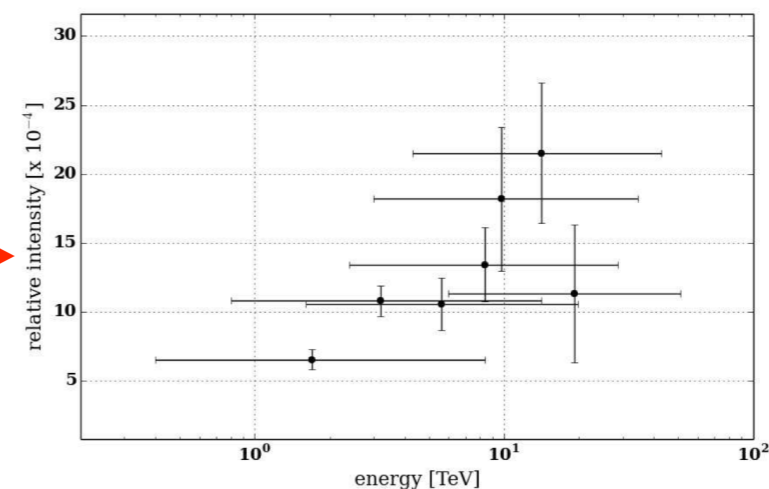
## summary #2

- ▶ cosmic ray anisotropy has **complex angular structure**
- ▶ from **stochastic scattering** on turbulence and/or on coherent structures
- ▶ with a few associated **spectral anomalies**

ARGO-YBJ  
Bartoli et al. (2013)



HAWC Abeysekara et al. 2014

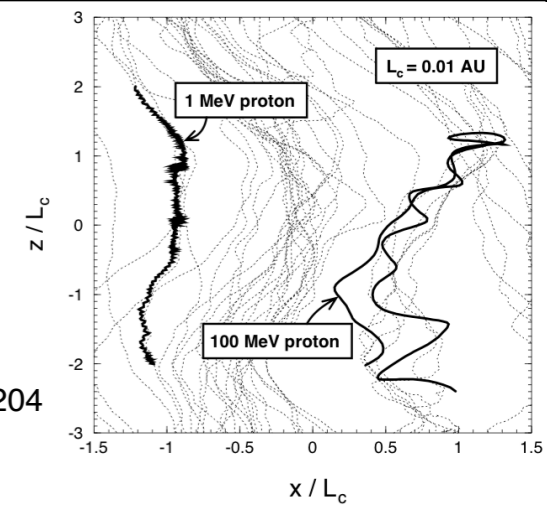




# cosmic rays anisotropy

## astrophysical probe

Giacalone & Jokipii 1999, ApJ, 520, 204



- ▶ stochastic effect of nearby & recent sources & temporal correlations

Erykin & Wolfendale, Astropart. 2006

Blasi & Amato, 2011

Ptuskin+, 2012

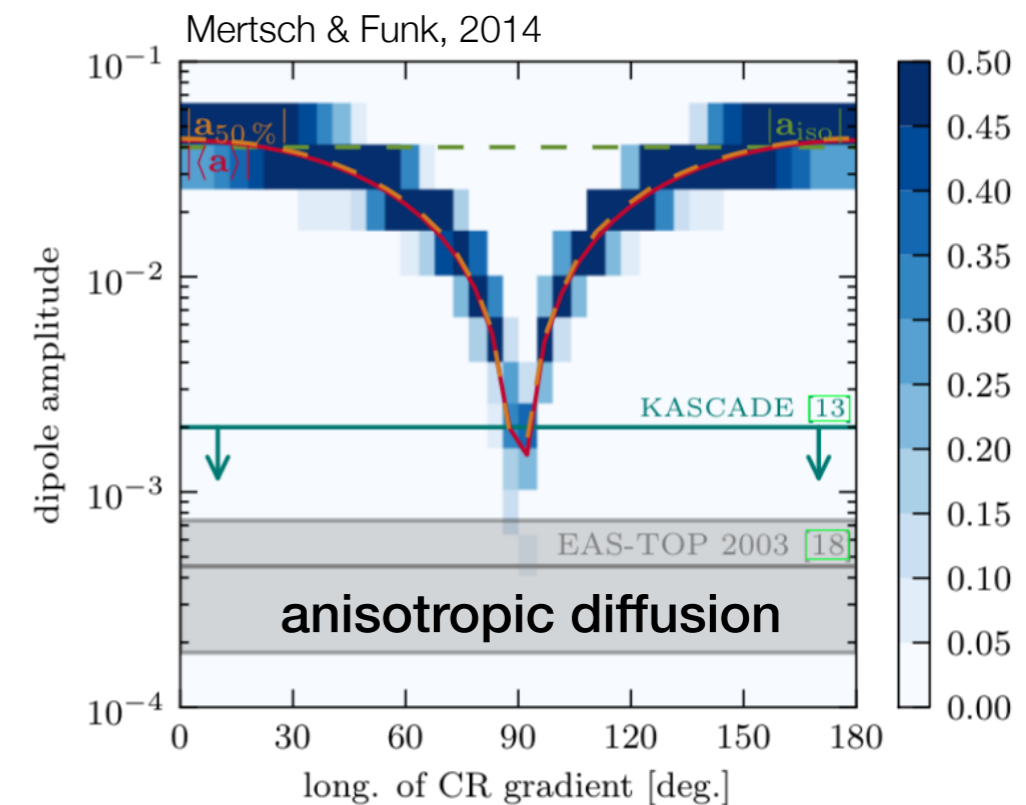
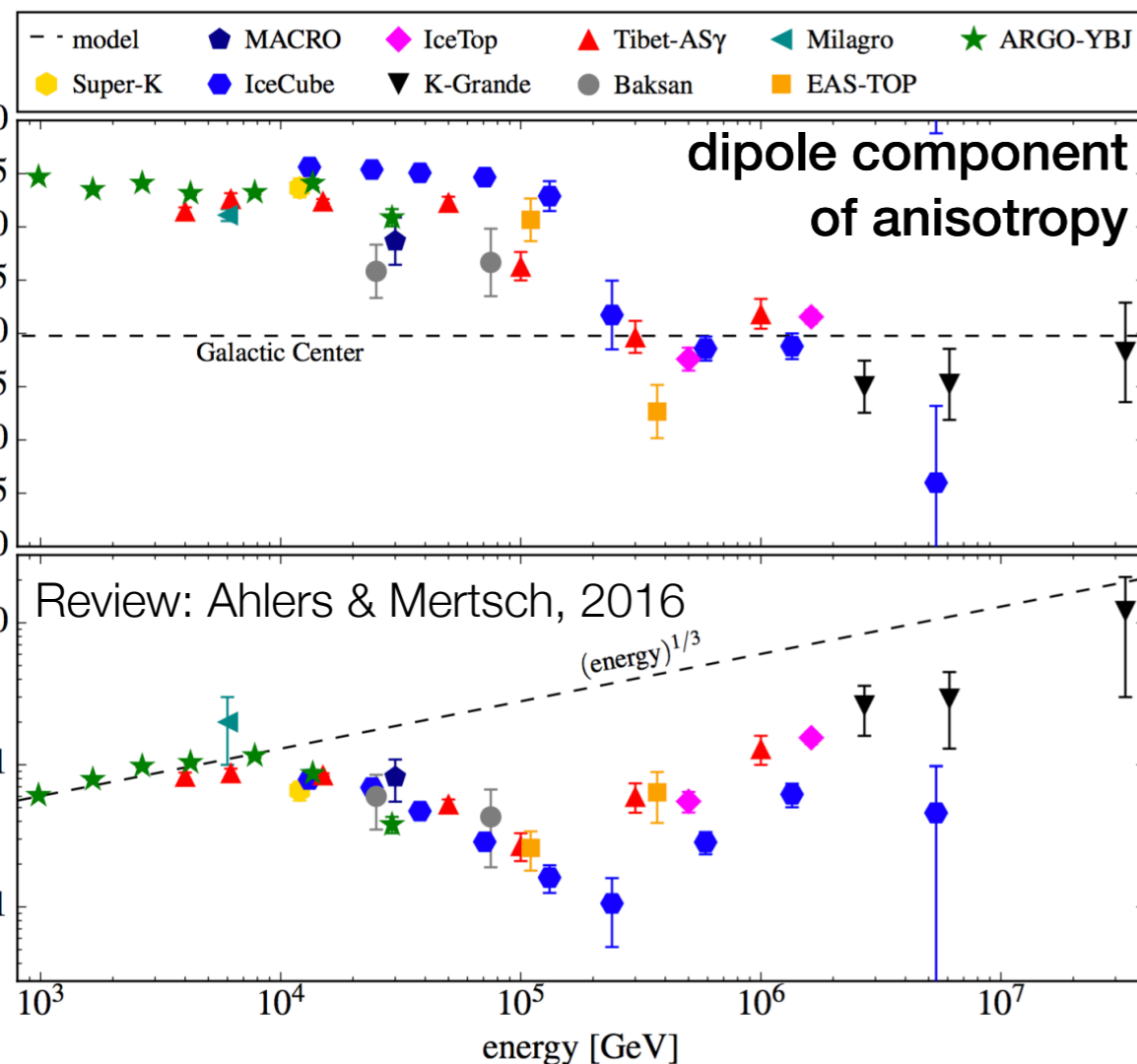
Pohl & Eichler, 2012

Effenberger+, 2012

Sveshnikova+, 2013

Kumar & Eichler, 2014

- ▶ dipole component **aligned** to local interstellar magnetic field





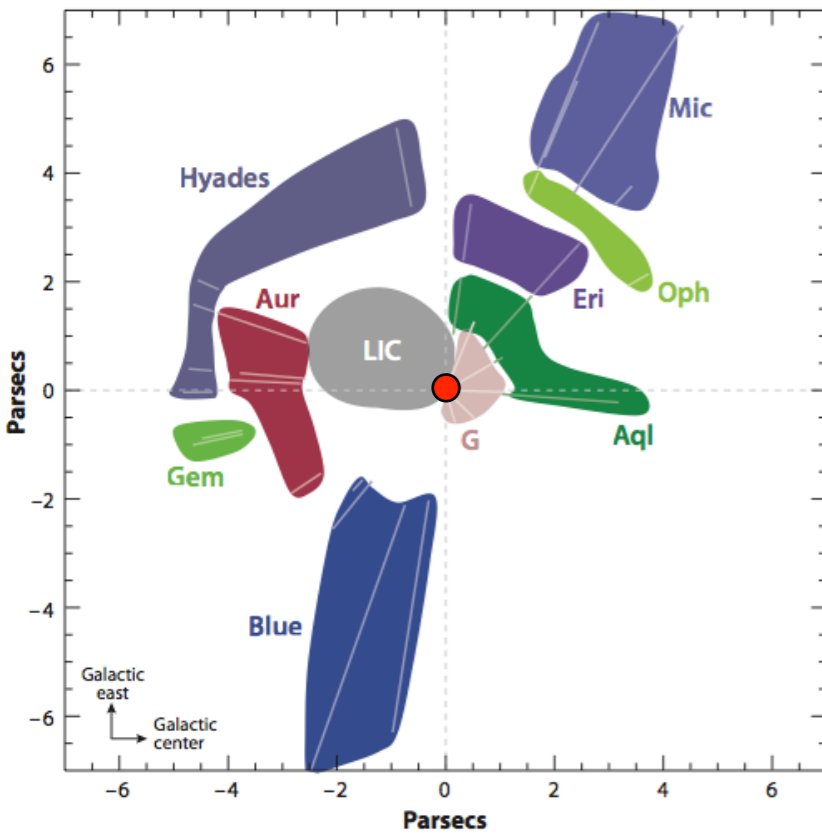
# cosmic rays anisotropy

## local interstellar medium

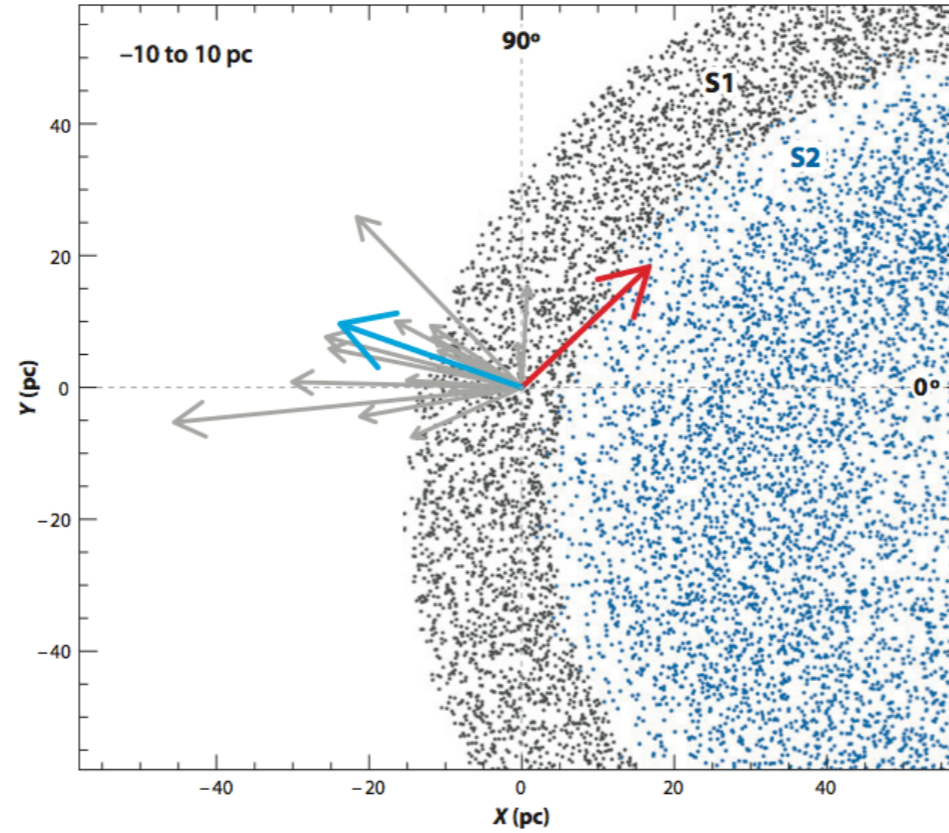
local ISMF shaped by LOOP I expansion  
sub-shell (with center ~60 pc away in  
Scorpius-Centaurus OB Association)

local cloudlets fragments of the  
shell moving at similar velocities

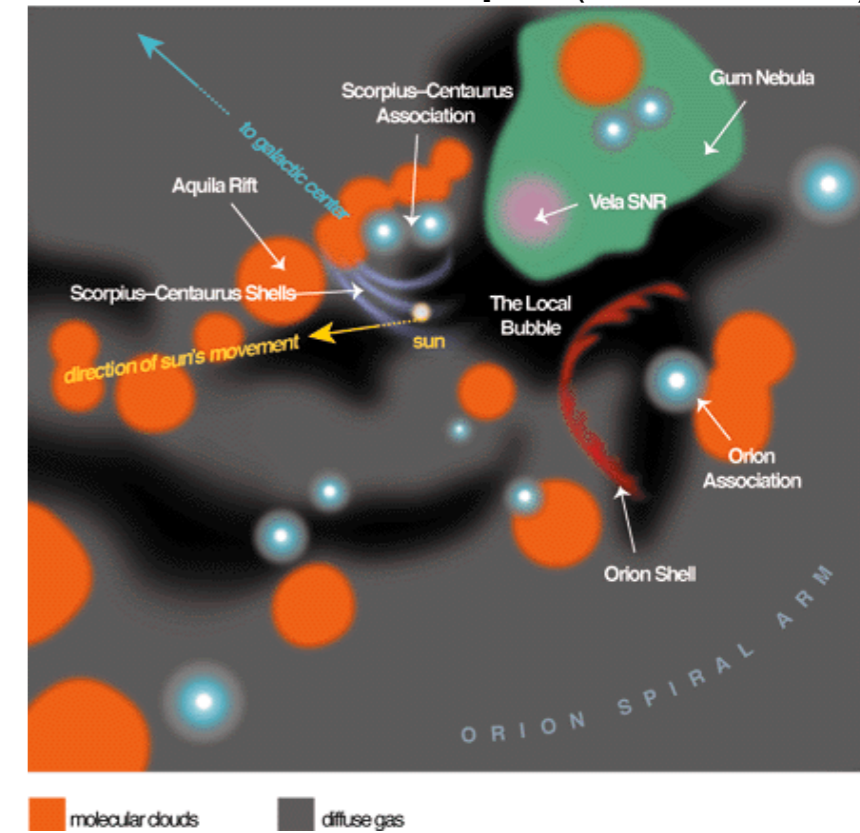
14 pc - Frisch+, 2011, 14



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 ~60 pc (inter-arm)

Frisch+, 2012,14

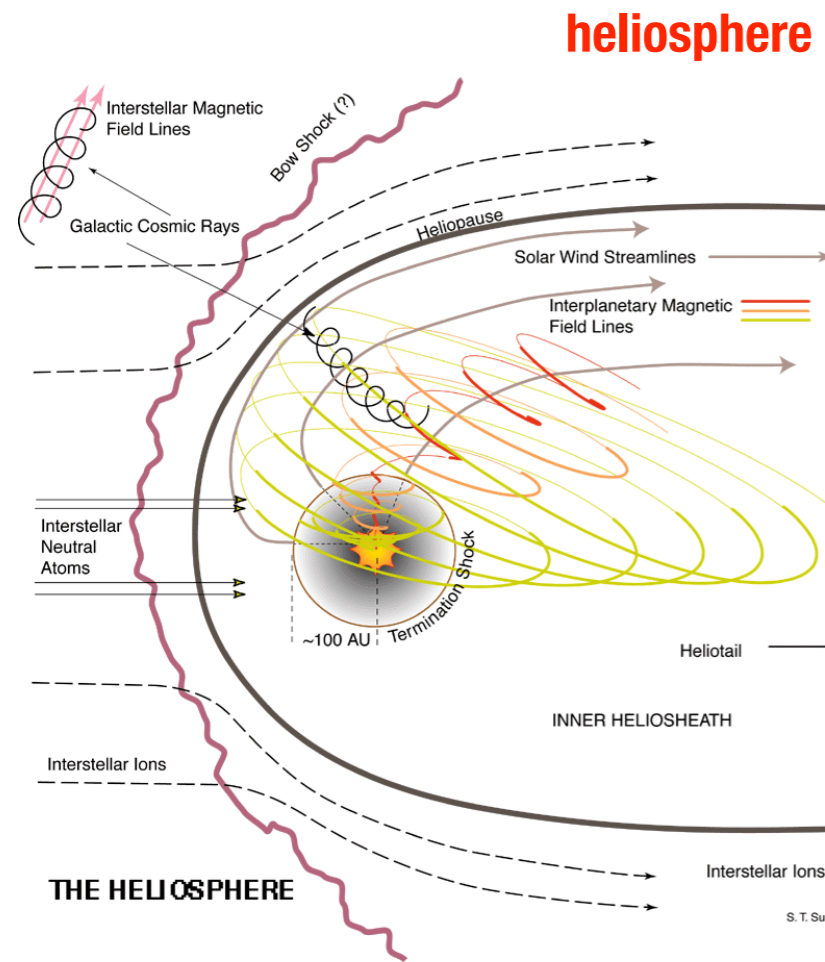
▶ magnetic turbulence affects propagation and diffusion properties

Giacalone & Jokipii, 1994, 99

Yan, Lazarian, 2002,04,08

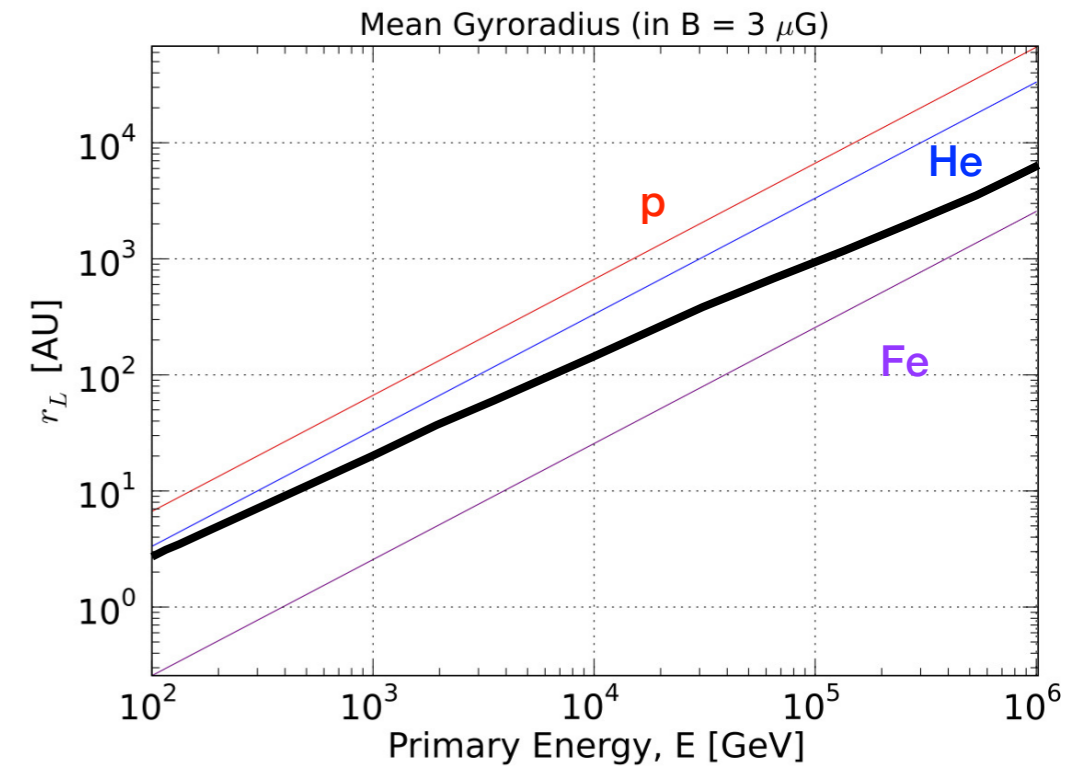
# cosmic ray anisotropy

## heliosphere

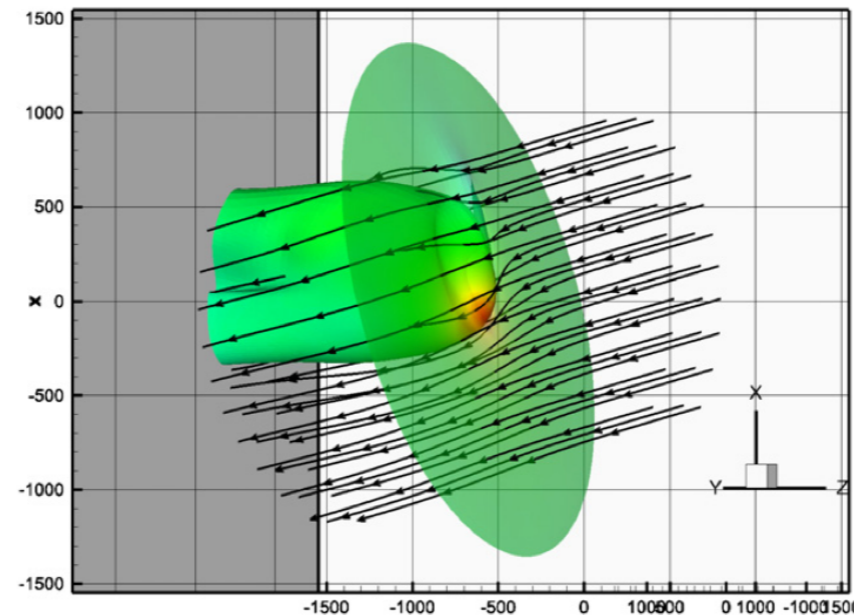


heliosphere

heliotail



Pogorelov+ 2011



local ISMF  
draping around  
heliosphere

▶ heliosphere as  $O(100-1000)$  AU magnetic perturbation of local ISMF

PD & Lazarian, 2013

▶ influence on  $\lesssim 10$  TeV protons ( $R_L \lesssim 600$  AU)

▶ cosmic rays  $>100$ 's TeV influenced by interstellar magnetic field (**change of anisotropy**)



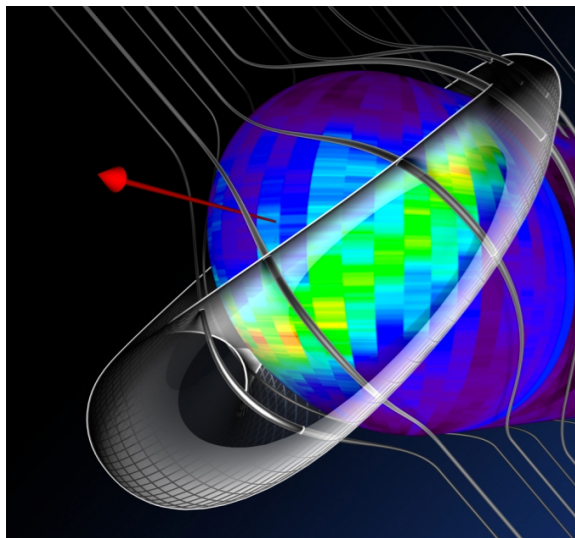
# anisotropy and local magnetic environment

## probing heliospheric magnetic structure

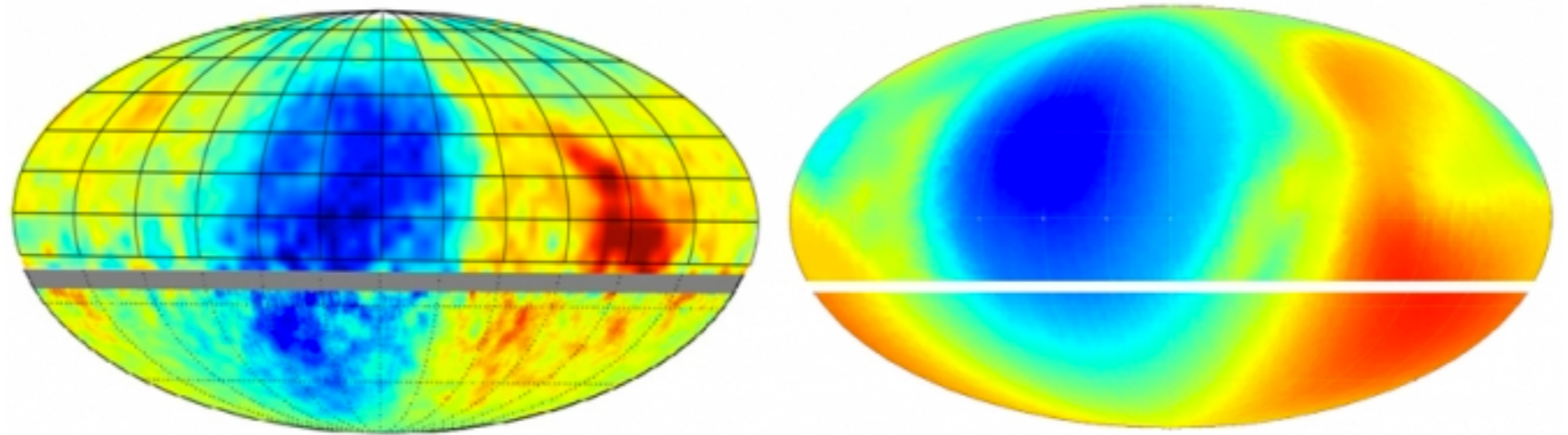
PD & Lazarian 2013  
López-Barquero, Xu, PD, Lazarian, Pogorelov, Yan  
ApJ in print - arXiv:1610.03097

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

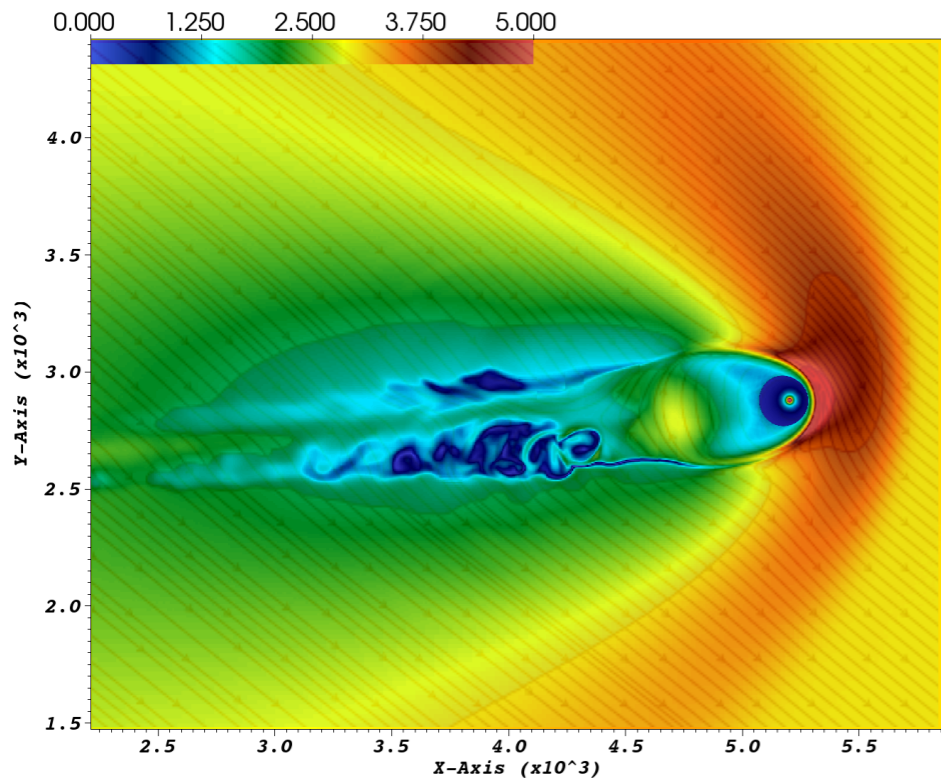
accounting for complex heliospheric magnetic field - *unfold* interstellar arrival directions - standard diffusion

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



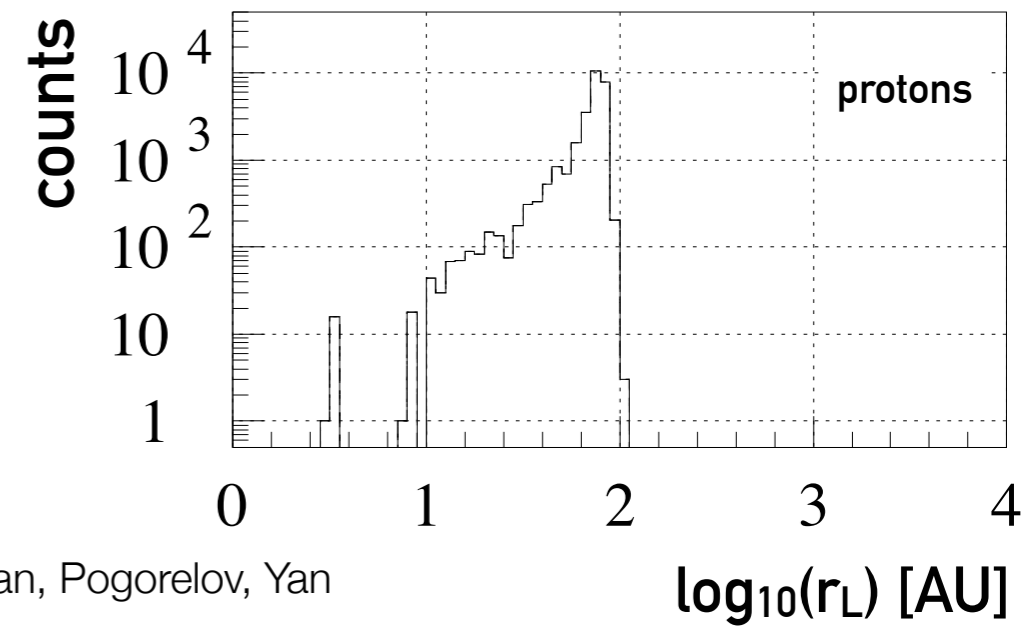
# anisotropy and local magnetic environment

## probing heliospheric magnetic structure



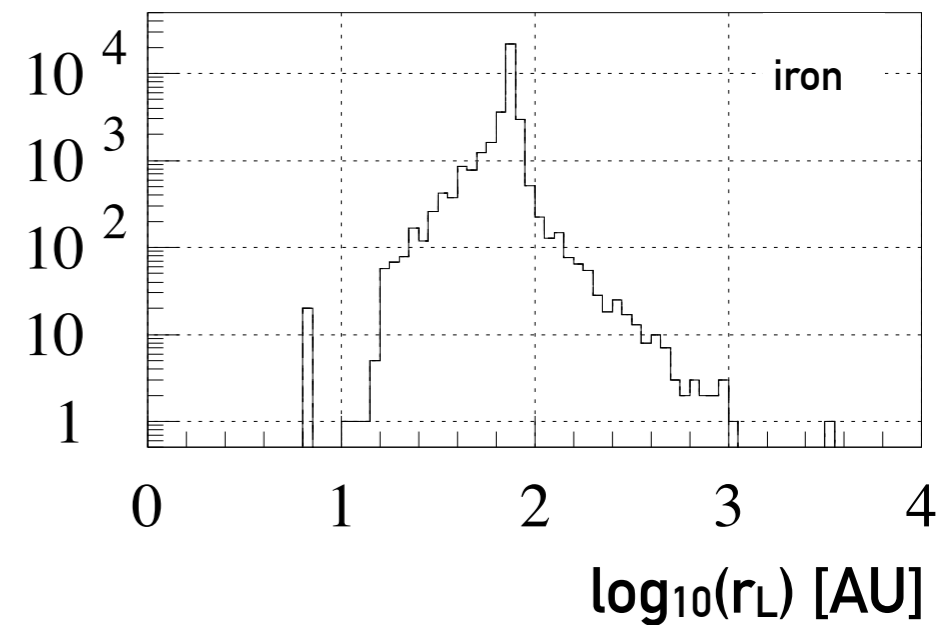
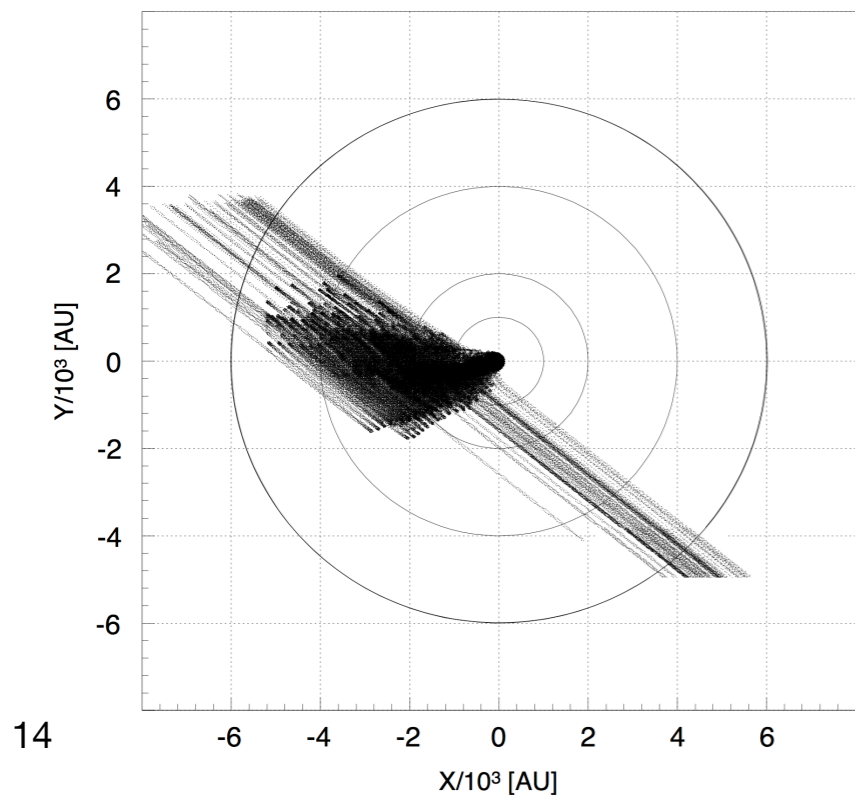
Borovikov, Heerikhuisen, Pogorelov

gyro-radius distributions  
**1 TV**



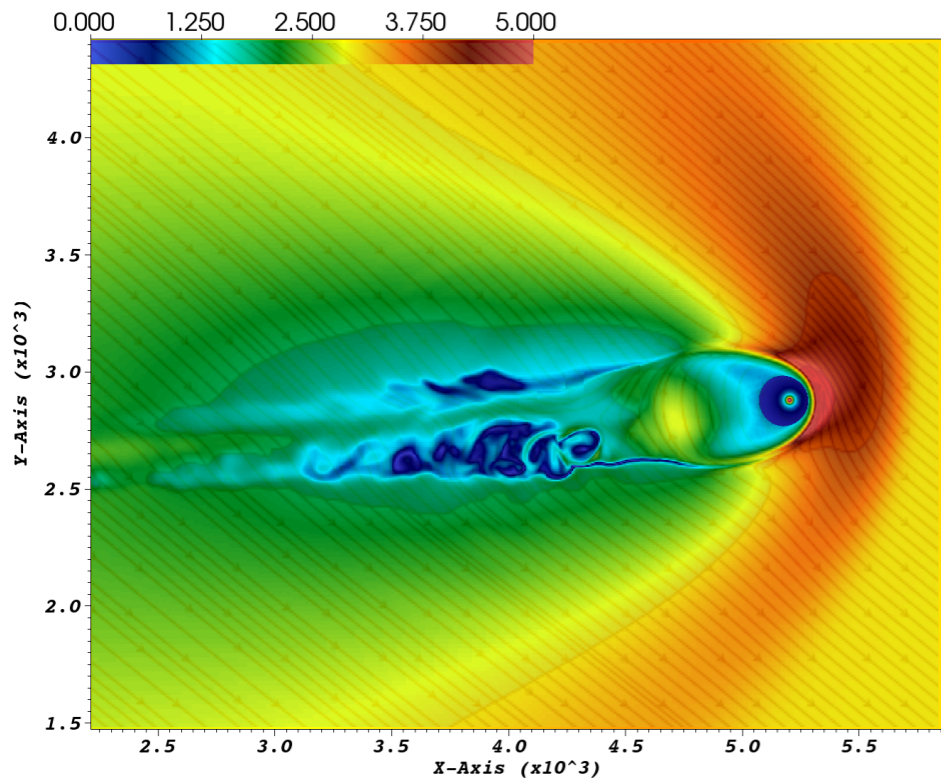
López-Barquero, Xu, PD, Lazarian, Pogorelov, Yan  
ApJ in print - arXiv:1610.03097

trajectories of  
1 TeV protons



# anisotropy and local magnetic environment

## probing heliospheric magnetic structure



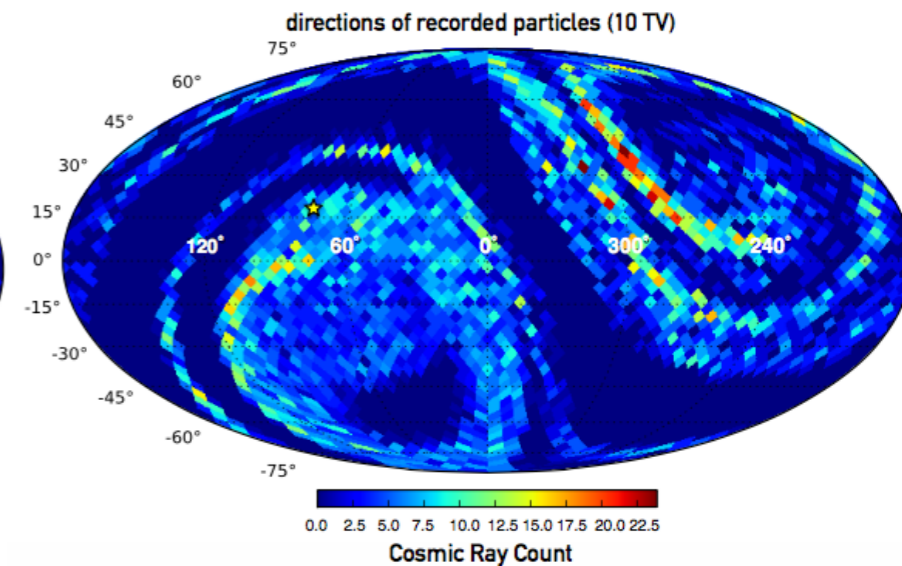
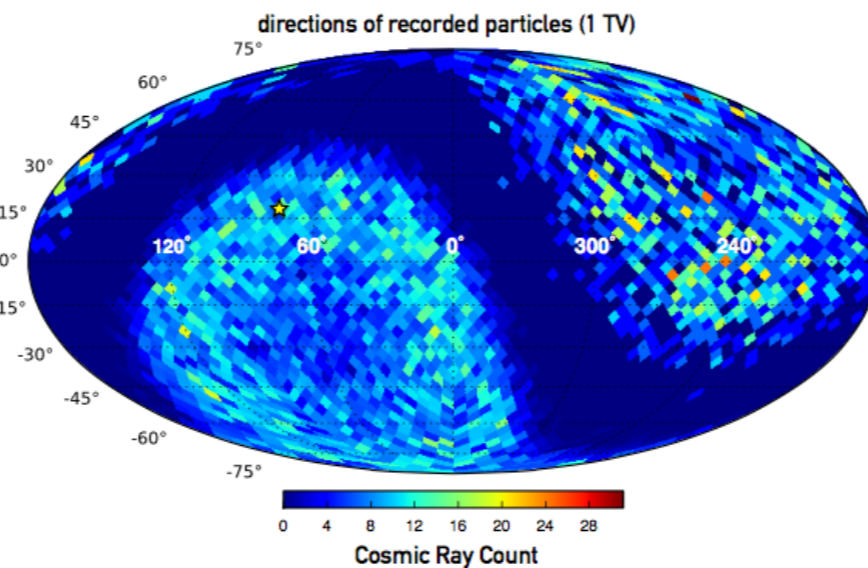
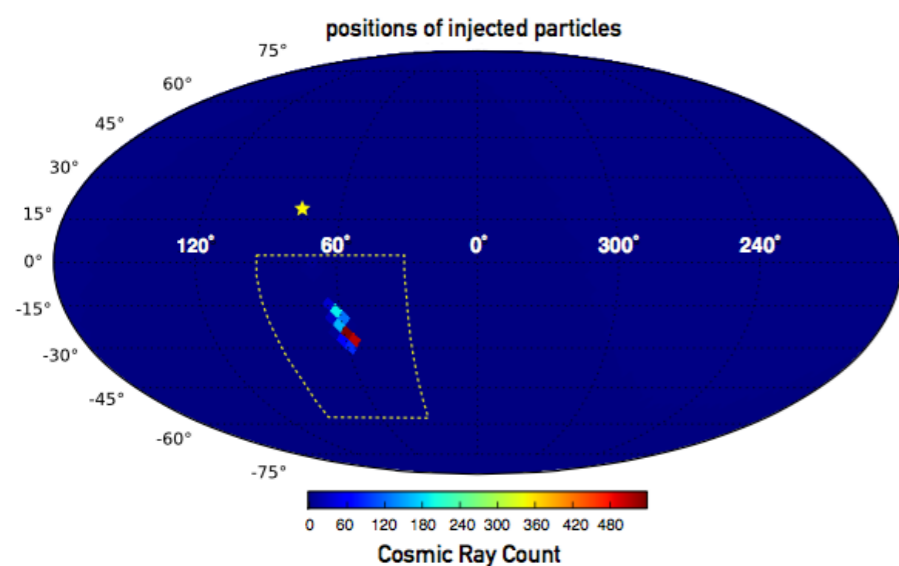
Borovikov, Heerikhuisen, Pogorelov

downstream  
instabilities on the  
flanks of heliotail

**strong scattering**

PD & Lazarian 2013

López-Barquero, Xu, PD, Lazarian, Pogorelov, Yan  
ApJ in print - arXiv:1610.03097



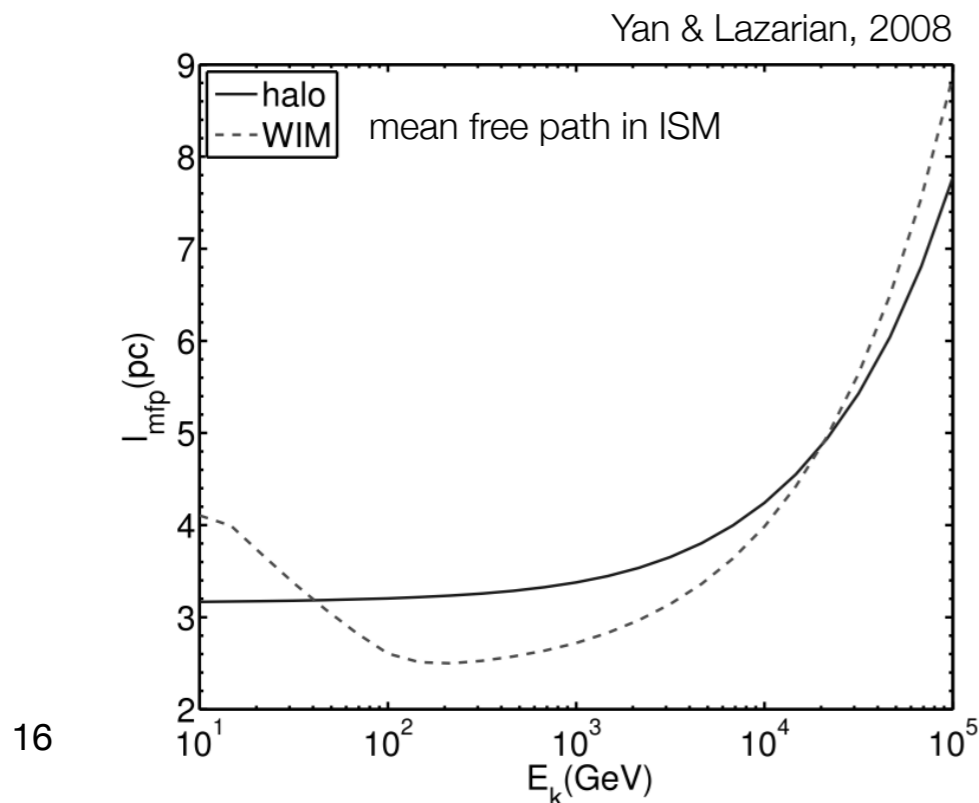
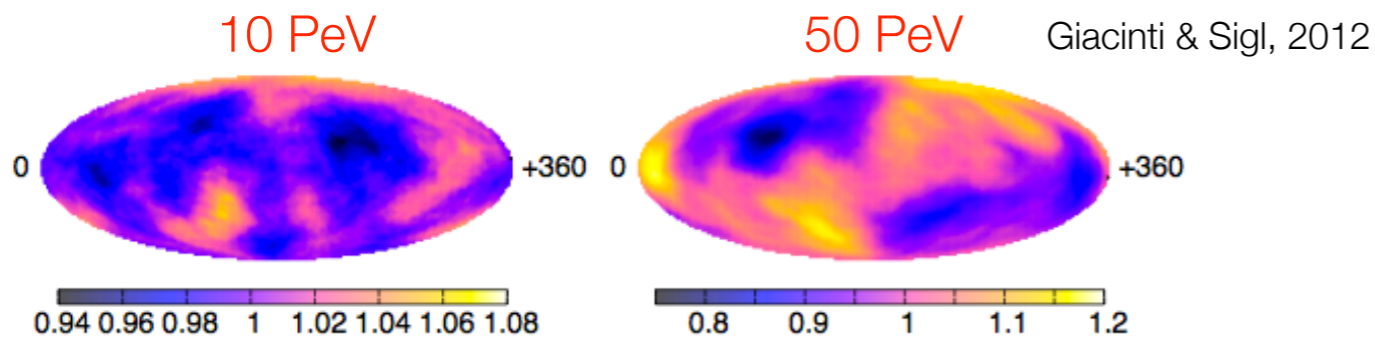
**forward propagation**

injection sphere 6000 AU - target sphere 200 AU

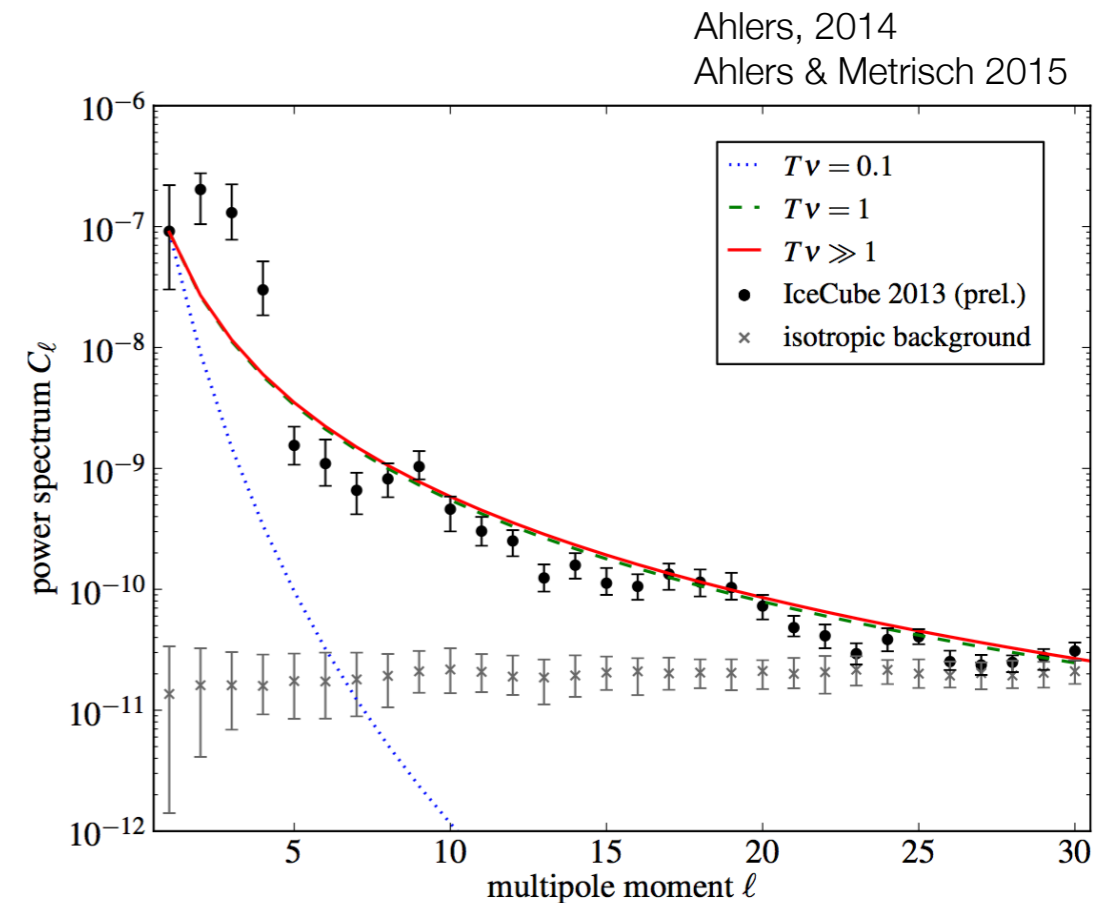
# cosmic ray anisotropy

## non-diffusive phenomena

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



- 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)





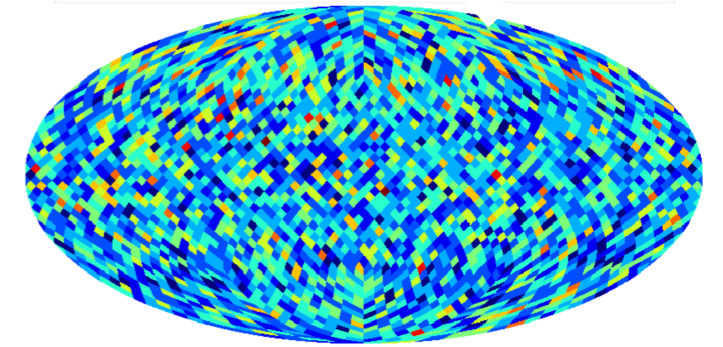
# cosmic rays anisotropy

probing magnetic field turbulence ?

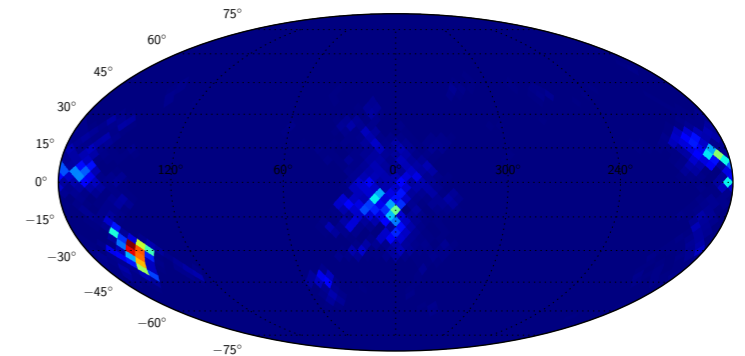
- compressible MHD turbulence (Cho & Lazarian, 2002)
- angular structures by scattering on turbulence within mean free path
- dipole oriented along average fields within mean free path (different from *regular field*)
- small angular structure depends on actual realization. But its fingerprint is power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

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

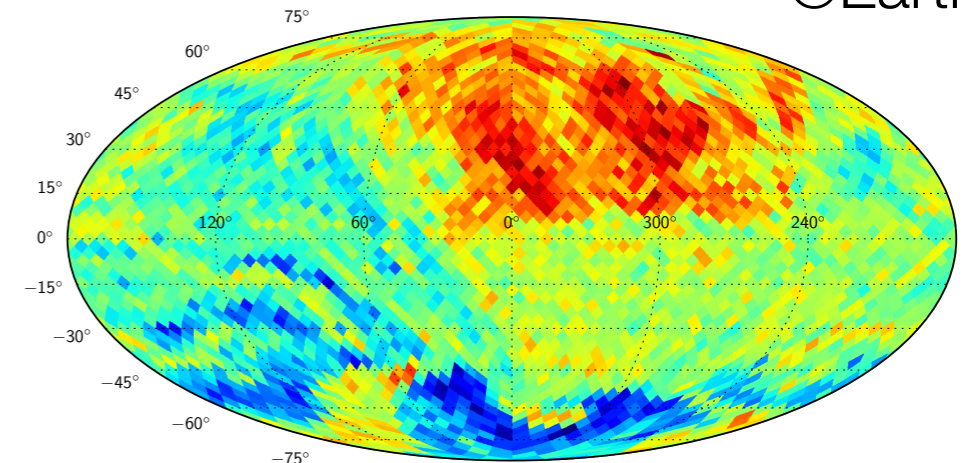
backward propagation



positions

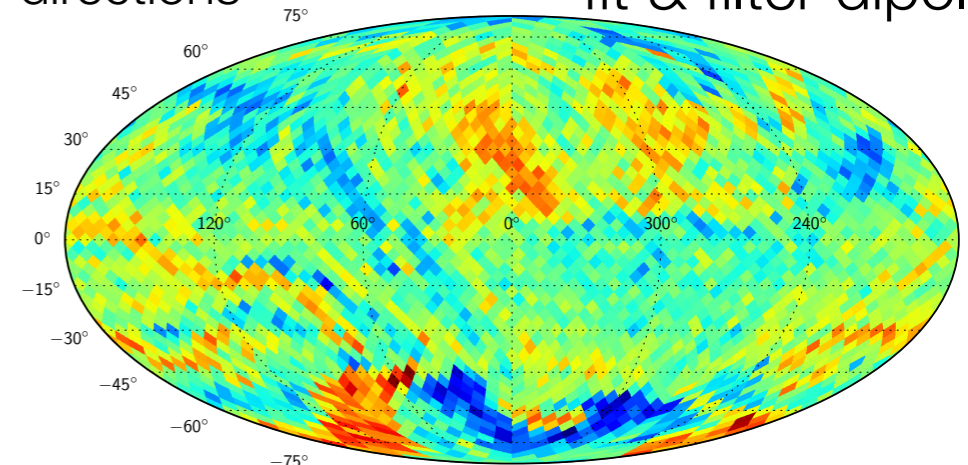


@Earth



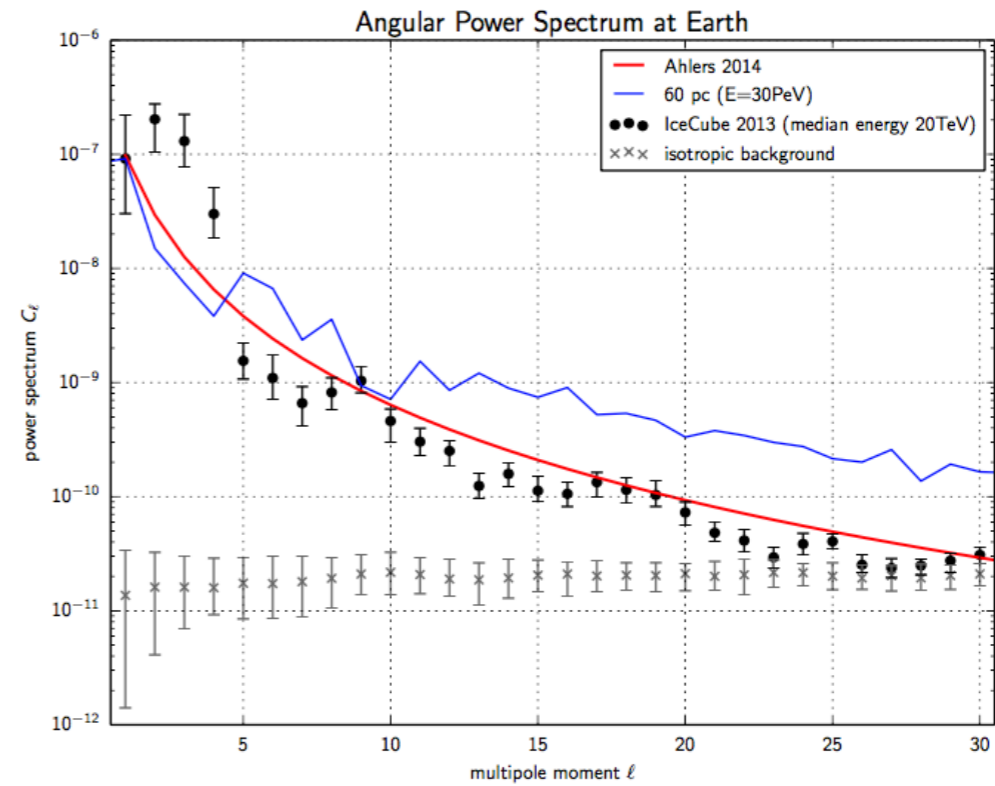
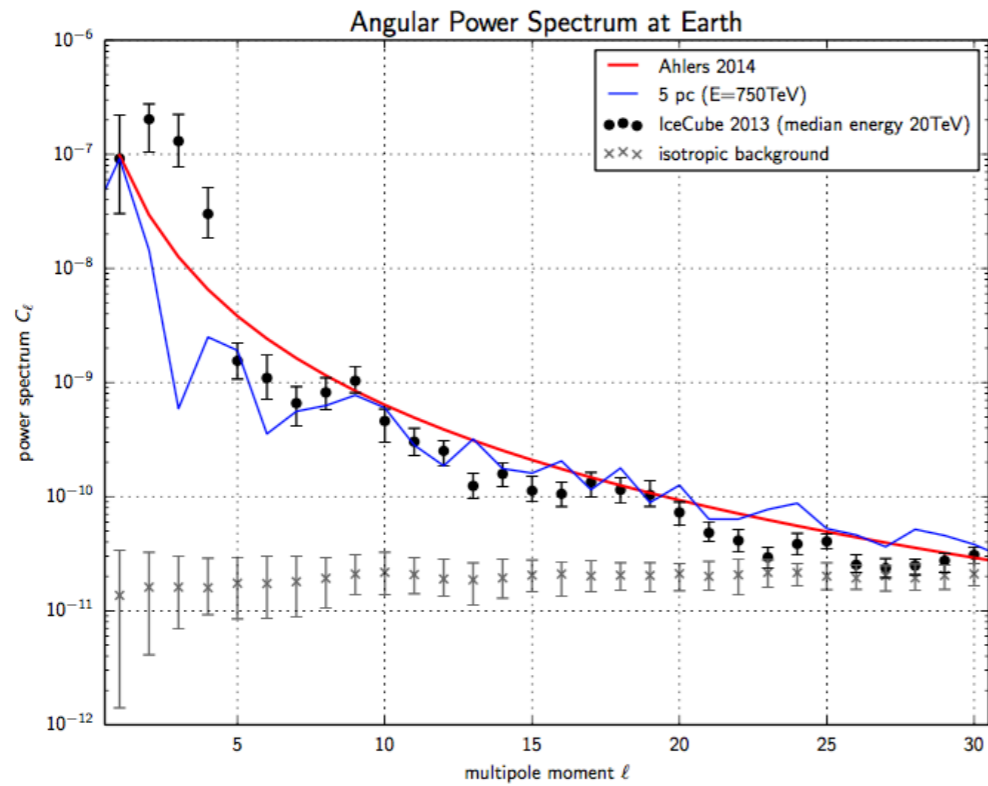
directions

fit & filter dipole

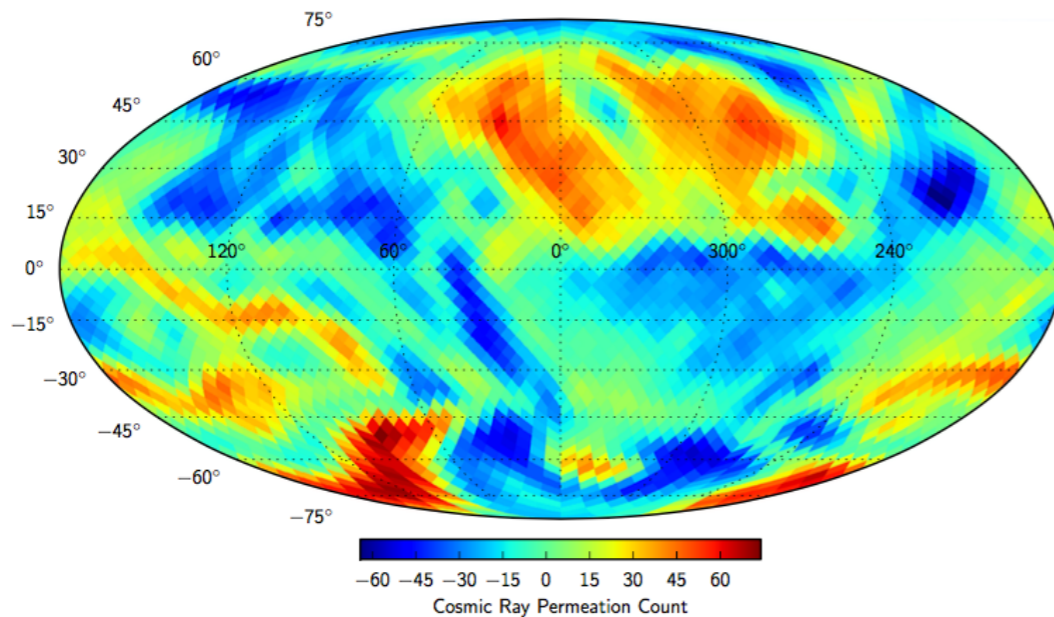


# cosmic rays anisotropy

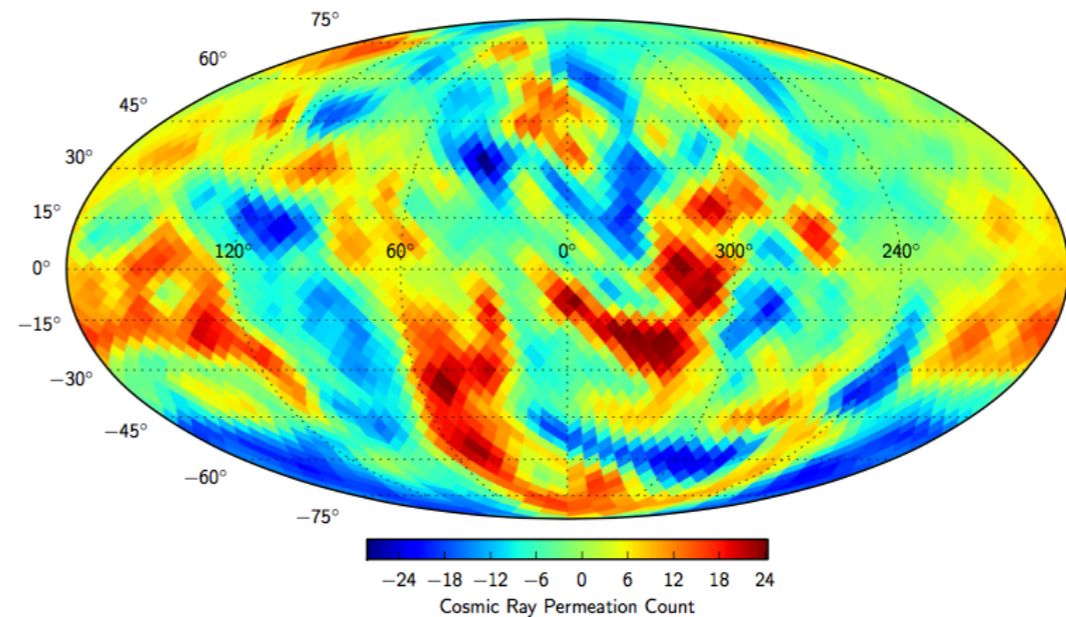
probing magnetic field turbulence ?



## 750 TeV protons



## 30 PeV protons

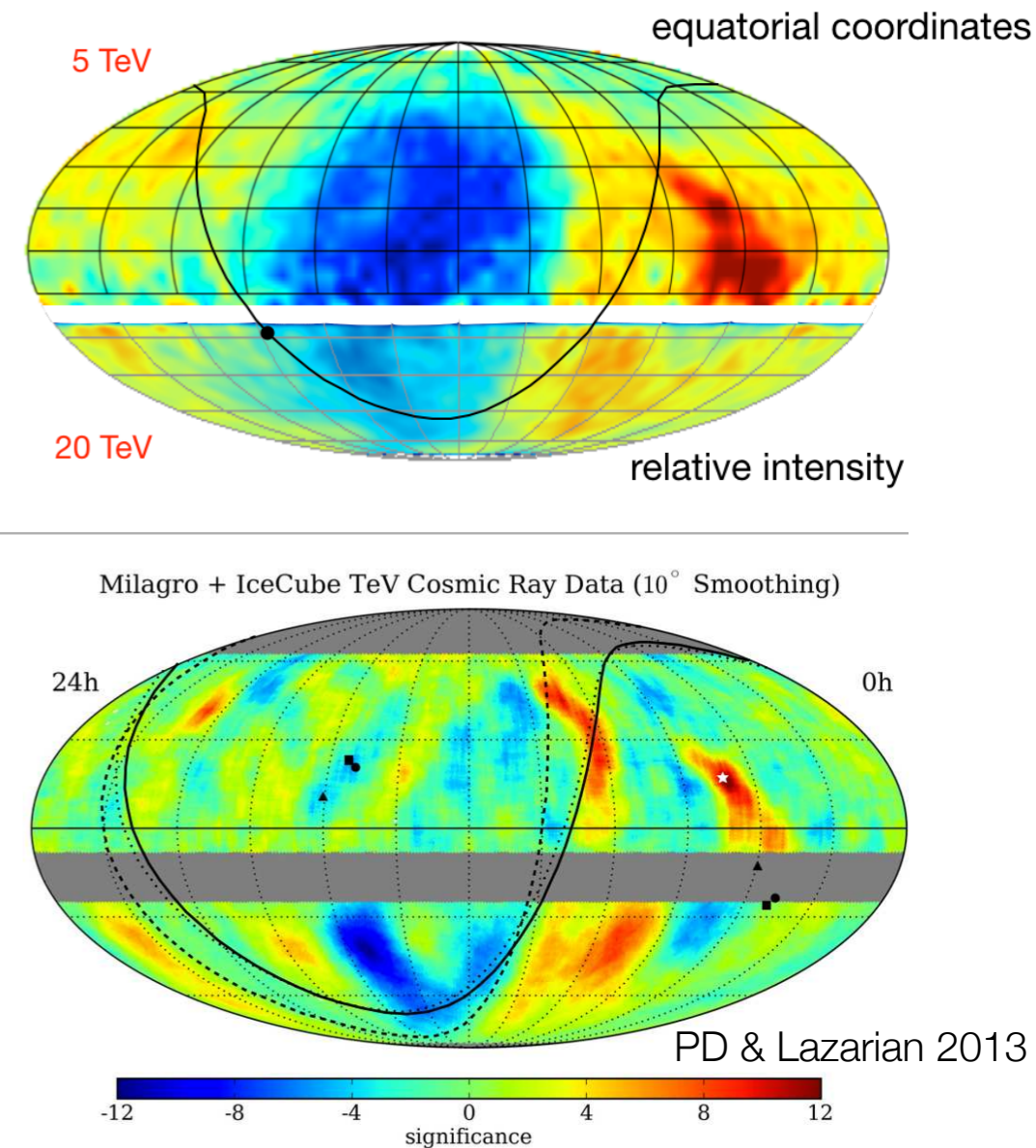




# conclusions

- cosmic ray anisotropy as fingerprint for their **origin** and **propagation**
  - large-scale **standard diffusion** (dipole, sources) & **non-diffusive processes** (angular structure)
  - **probe** into propagation properties, Local Bubble, LIMF, heliosphere, ...
- ➔ full-sky observation of cosmic ray anisotropy (**IceCube-HAWC**)
- ➔ anisotropy vs. rigidity (cosmic ray particle mass)
- ➔ energy spectra features

Lazarian & PD 2010  
PD & Lazarian 2012





# thank you



Hotel Krystal Urban Guadalajara

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Col. Arcos Vallarta

Guadalajara, Jalisco, 44130

### Local organizing committee:

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Cosmic Ray Anisotropy  
Cosmic Ray Spectrum  
and Composition  
Cosmic Ray Origin,  
Acceleration and Propagation  
Interstellar Medium and  
Interstellar Magnetic Field  
Heliosphere and its Boundary  
Region with the Interstellar Medium

