Cosmic ray sidereal time variation of galactic origin provides valuable information concerning the origin of cosmic rays and their propagation and modulation in space.

K. NAGASHIMA

WISCONSIN ICECUBE PARTICLE ASTROPHYSICS CENTER

SuGAR

Searching for the sources of galactic cosmic rays

the astrophysics of cosmic ray anisotropy

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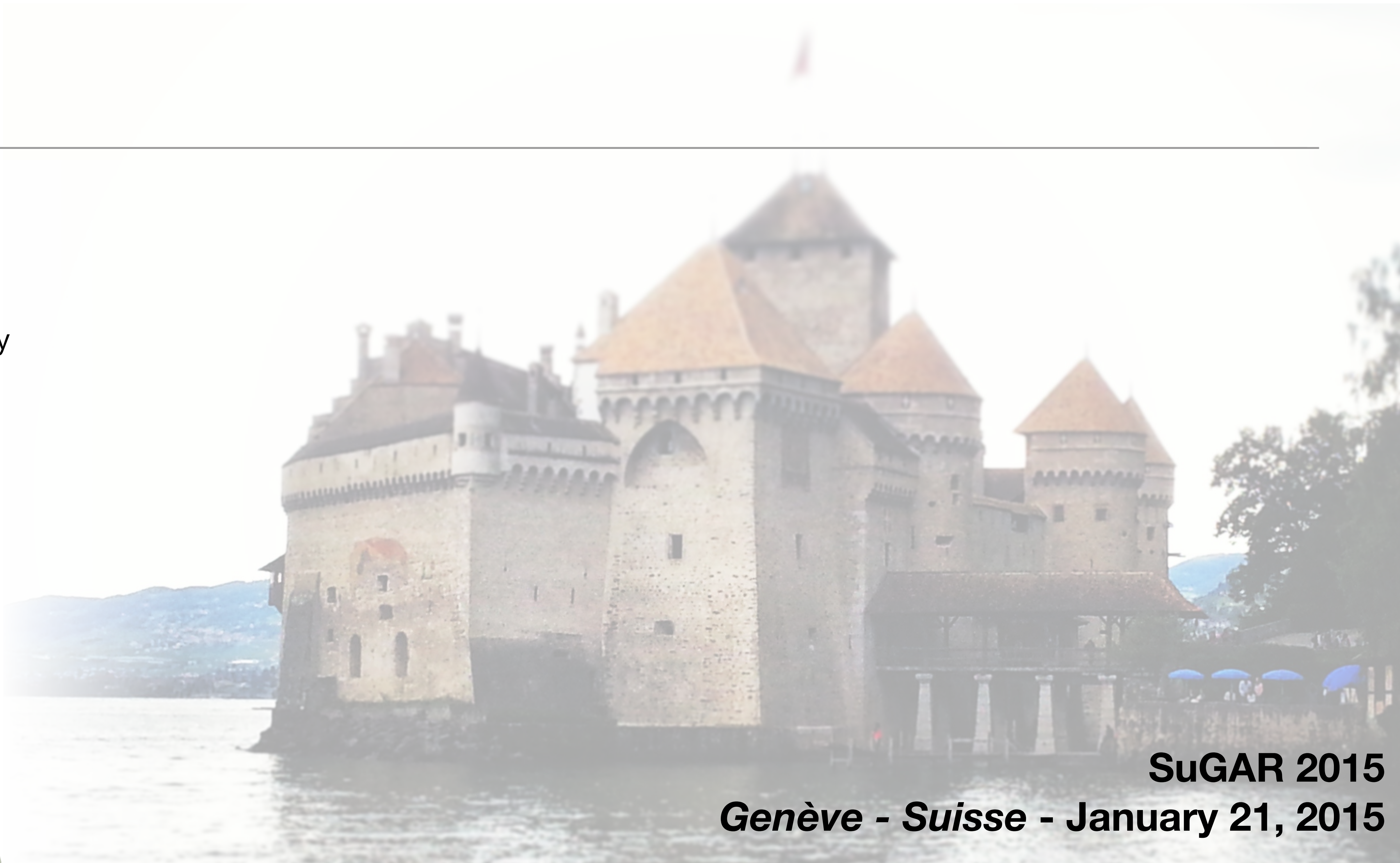
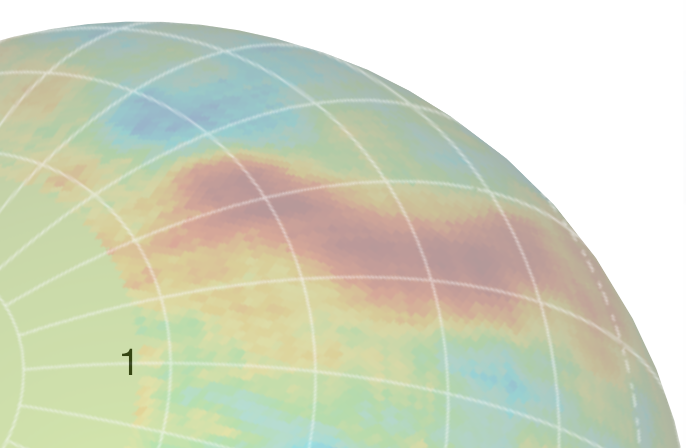




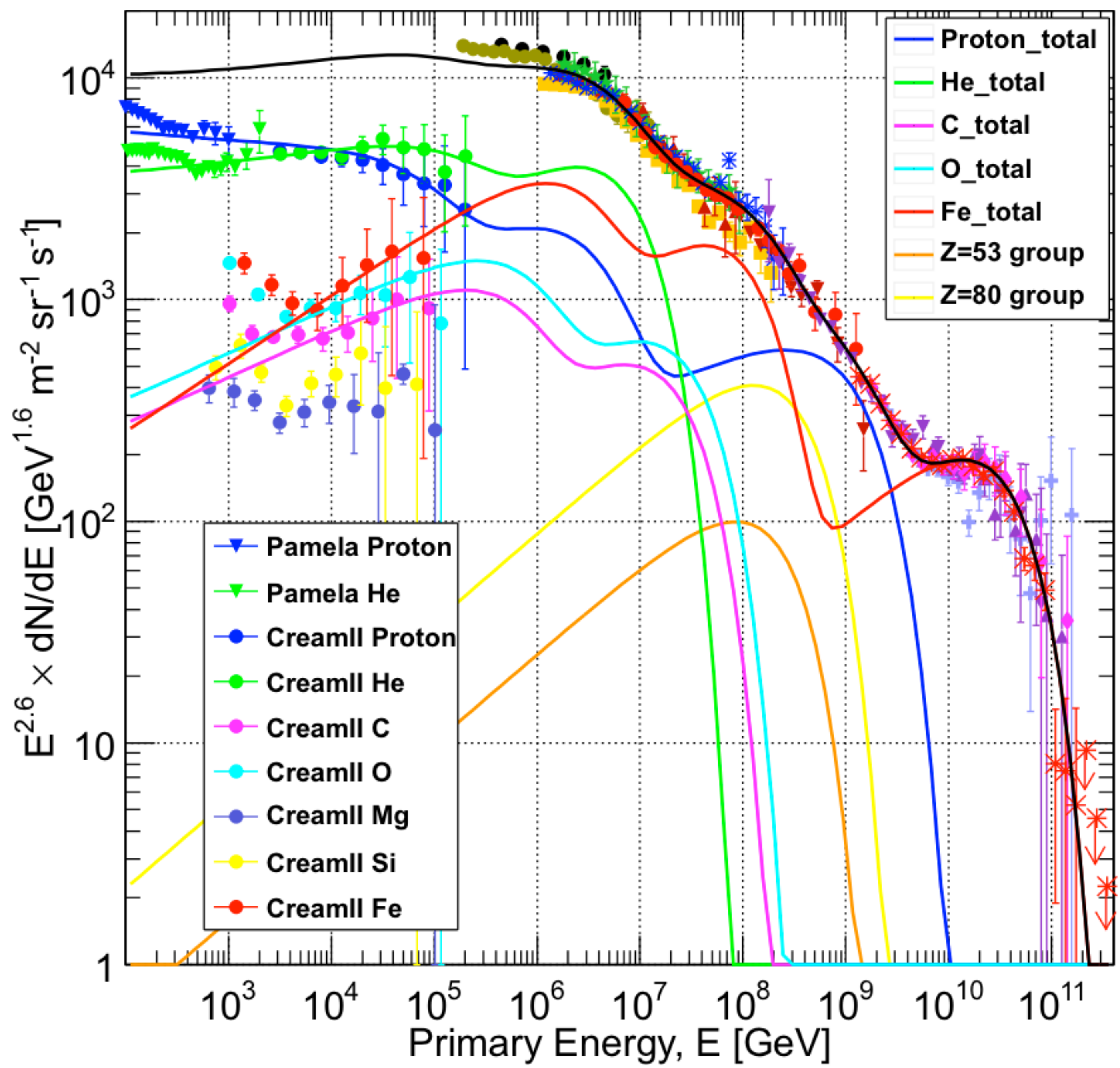
SuGAR 2015

Genève - Suisse - January 21, 2015

cosmic ray observations

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

Gaisser, Stanev, Tilav, 2013 - arXiv:1303.3565



THE
PHYSICAL REVIEW
A Journal of Experimental and Theoretical Physics
VOL. 47, No. 11 JUNE 1, 1935 SECOND SERIES

An Apparent Effect of Galactic Rotation on the Intensity of Cosmic Rays

ARTHUR H. COMPTON, *University of Chicago and Oxford University* AND IVAN A. GETTING, *Oxford University*
(Received April 12, 1935)

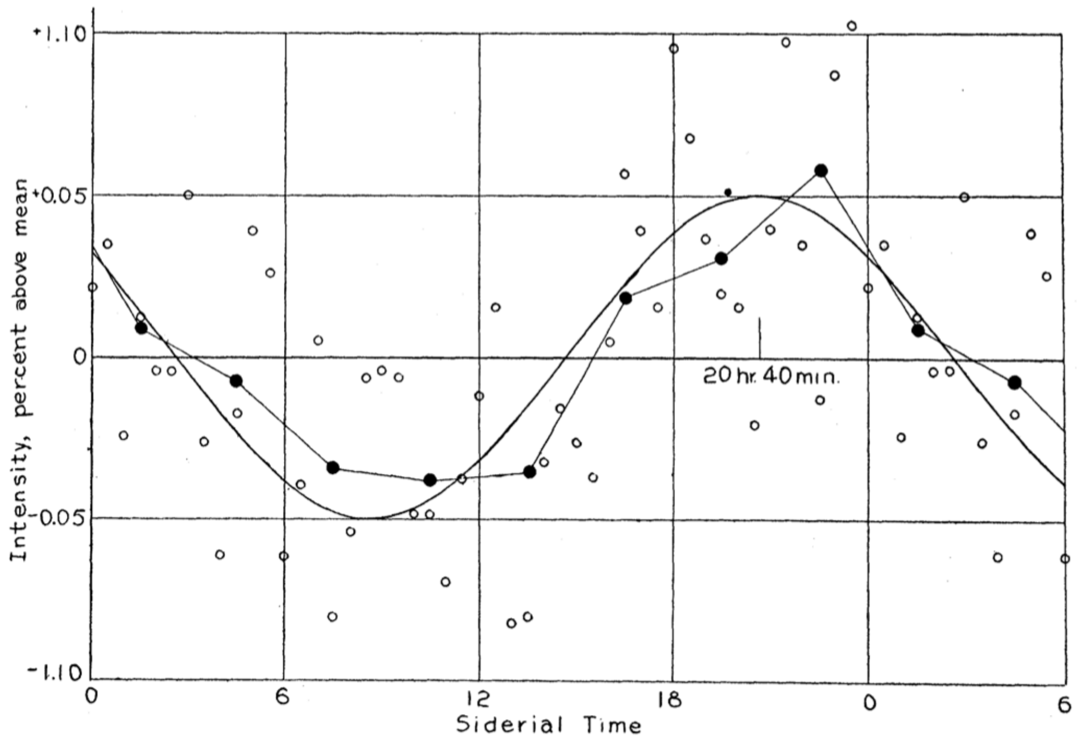
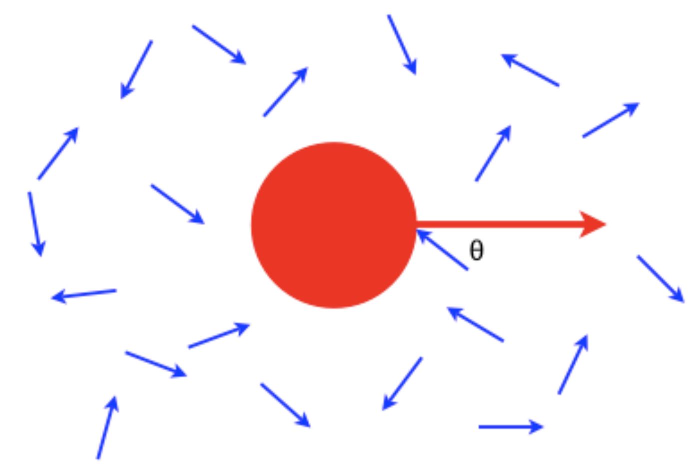


FIG. 2. Percentage variation in intensity of the cosmic rays with sidereal time. Curve, predicted effect due to galactic rotation. Data, Hess and Steinmaurer; open circles, half-hour means; solid circle, 3-hour means.

Its existence would imply that an important part of the cosmic rays originates outside of our galaxy. If its magnitude is found to be as great as we have predicted, it will imply that practically all the cosmic radiation has an extragalactic origin.

Compton-Getting Effect



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

convective effect to produce a **dipole** anisotropy (**sidereal diurnal** anisotropy)

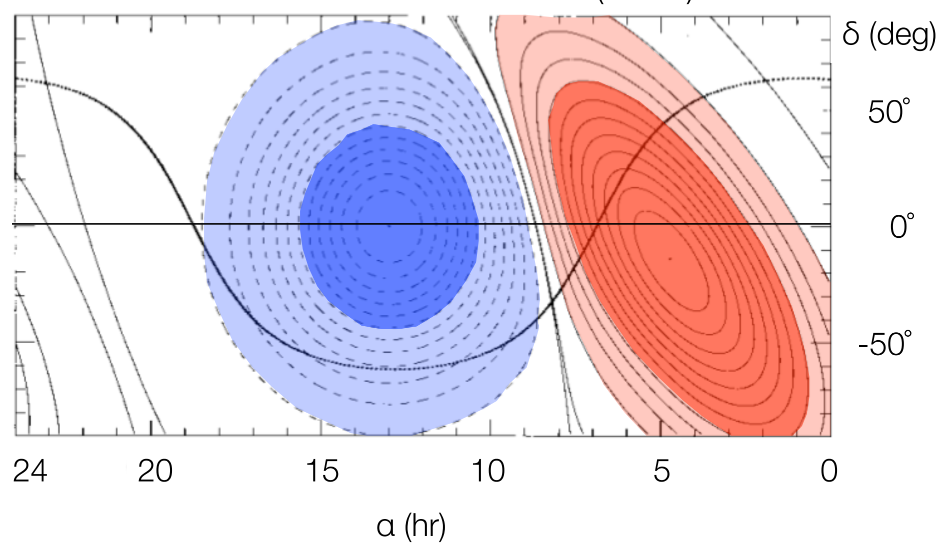
Compton & Getting, Phys. Rev. 47, 817 (1935)
Gleeson, & Axford, Ap&SS, 2, 43 (1968)

high energy cosmic rays
sidereal anisotropy

$\sim 10^{-3}$

< 1 TeV

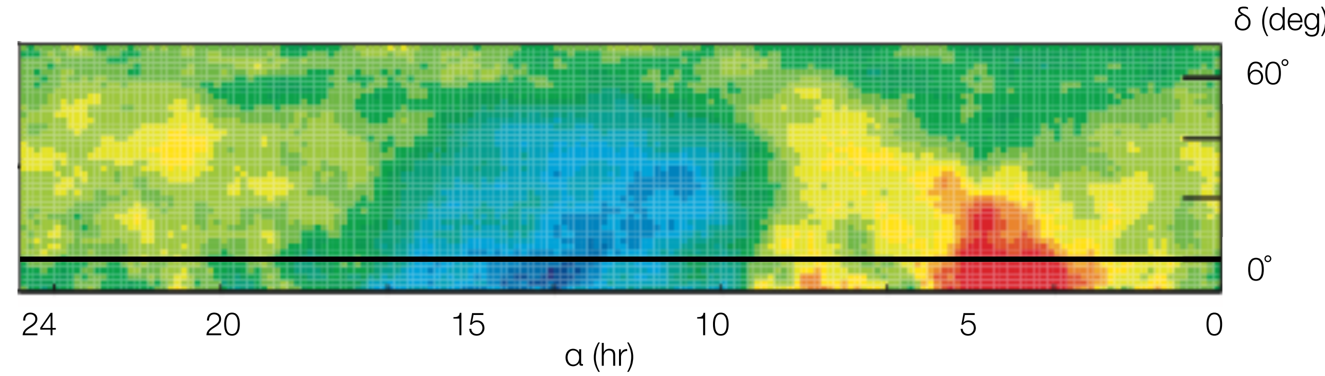
Nagashima et al. (1998)
Hall et al. (1999)



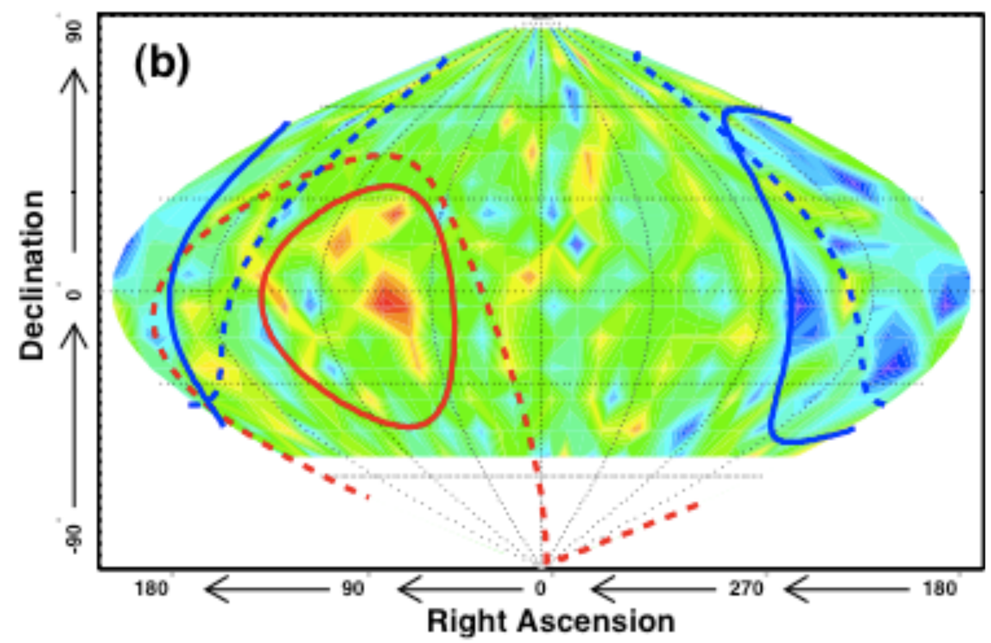
equatorial coordinates

4 TeV

Tibet ASγ
Amenomori et al. (2006)



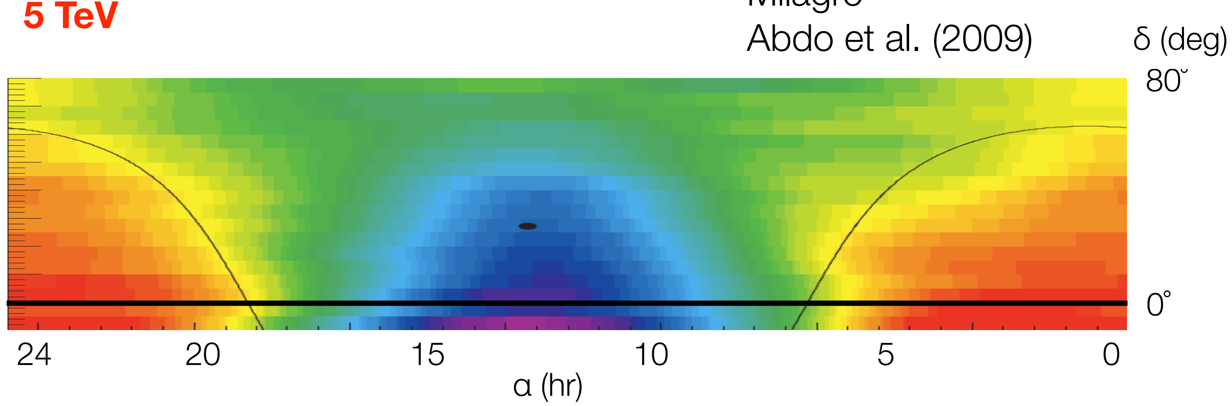
10 TeV



Super Kamiokande
Guillian et al. (2007)

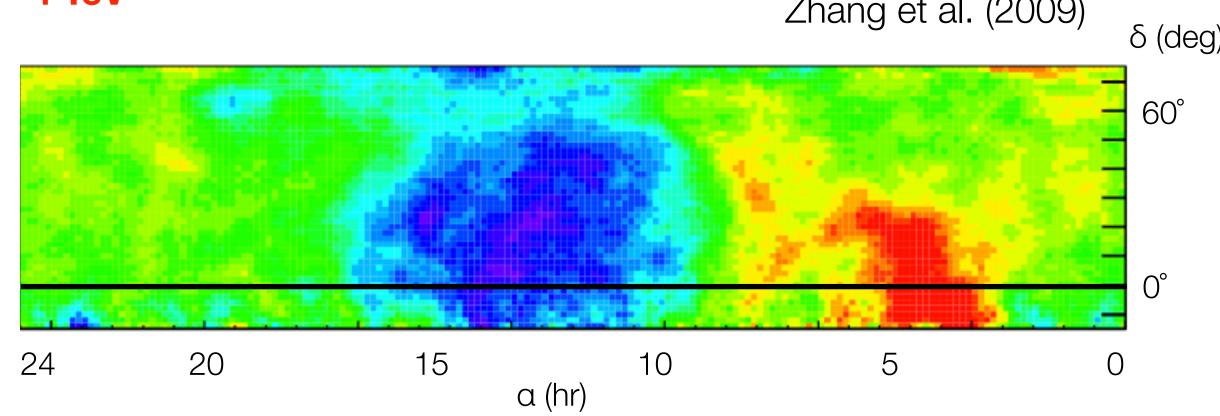
5 TeV

Milagro
Abdo et al. (2009)



4 TeV

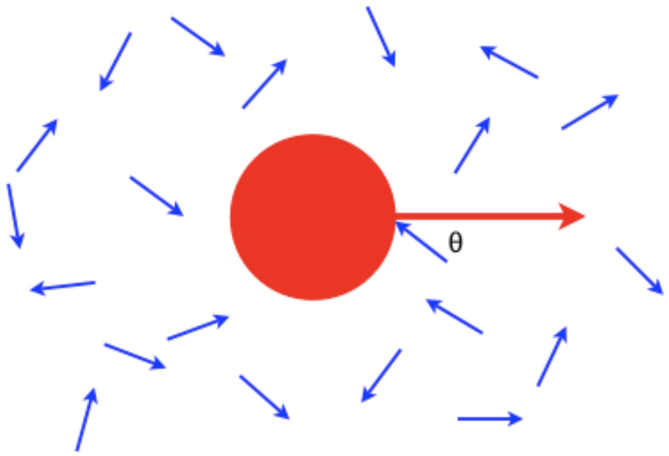
ARGO-YBJ
Zhang et al. (2009)



a known anisotropy

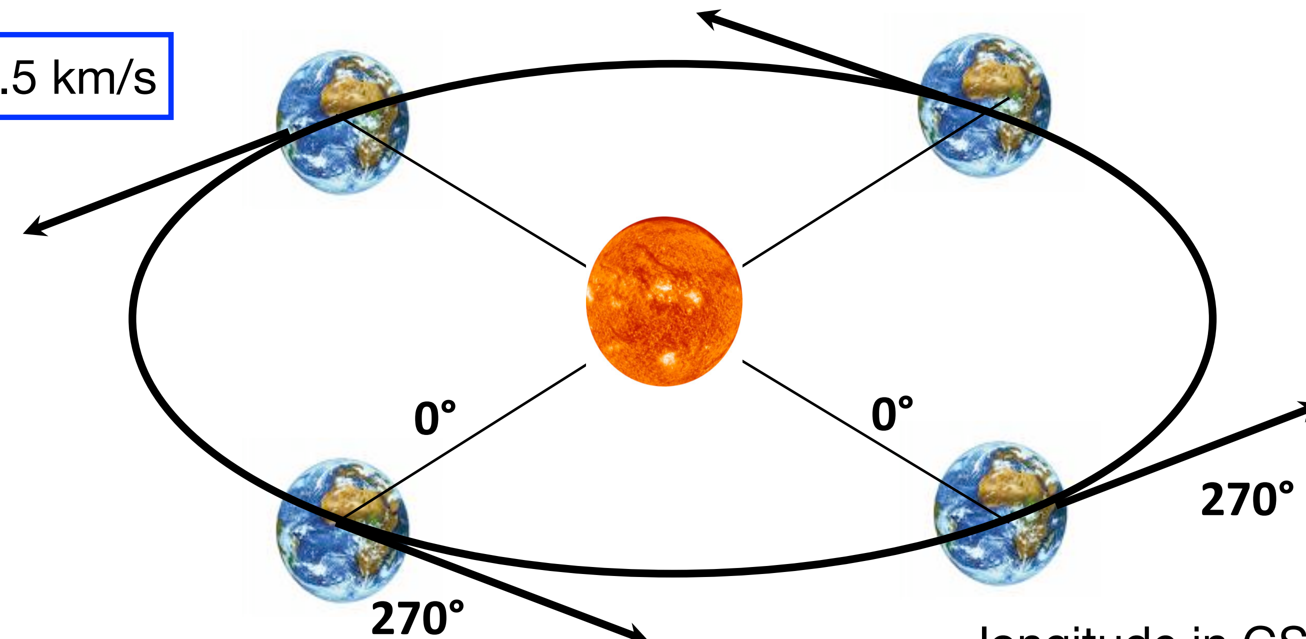
Earth's motion around the Sun

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

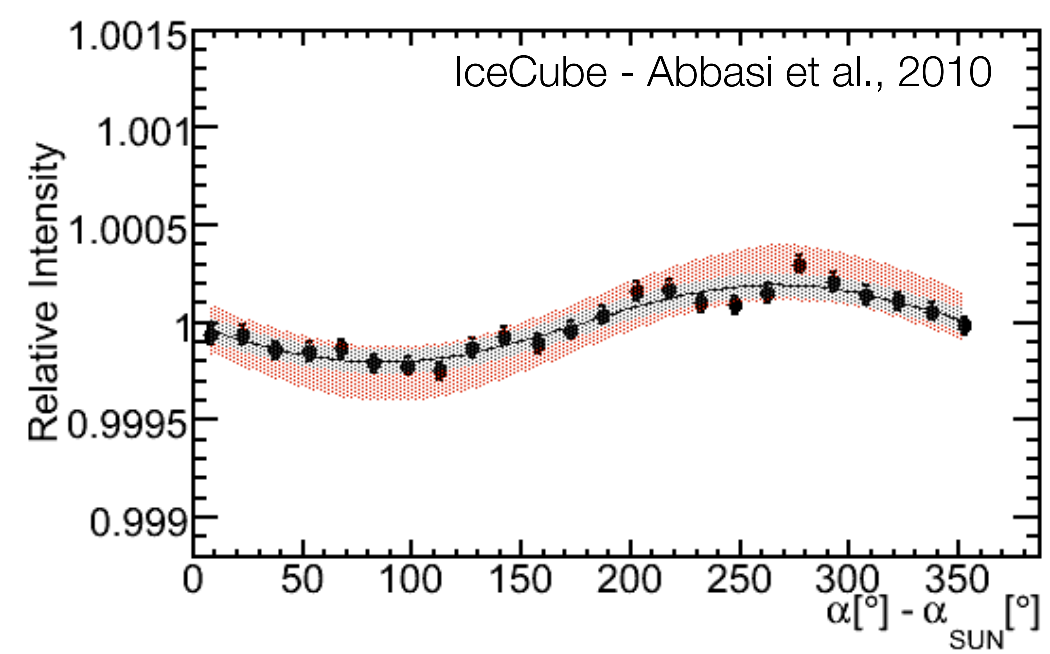


v = 29.8 ± 0.5 km/s

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



- produced by Earth's revolution around the Sun
- visible as **solar diurnal modulation**
- **predictable** and used as **benchmark**
- **heliospheric physics** effects below O(100) GeV

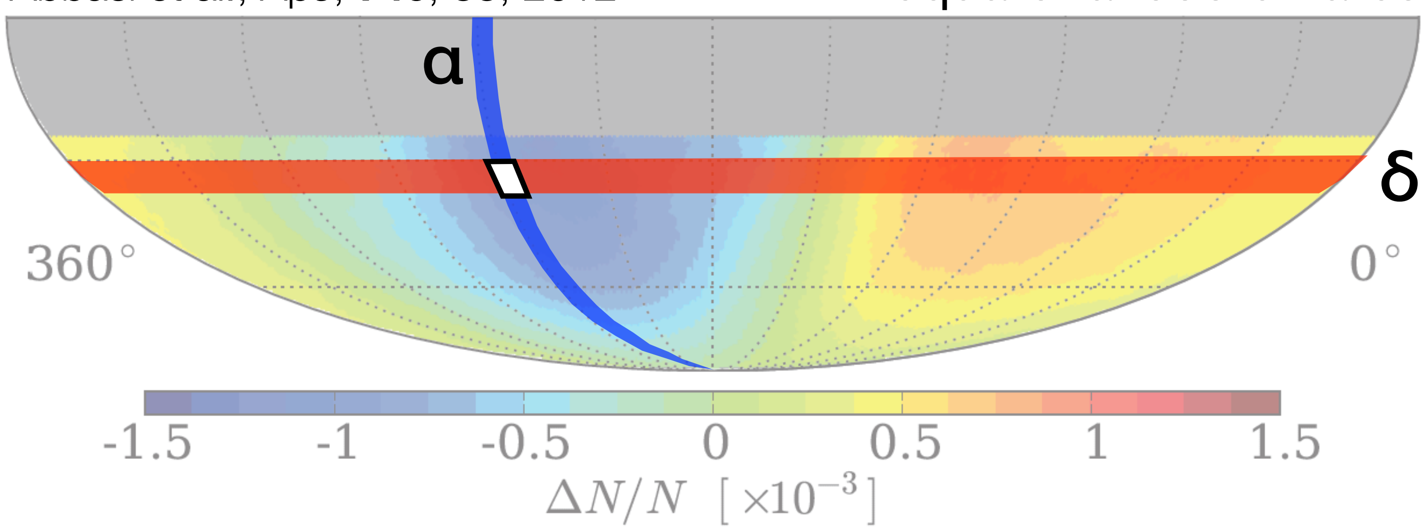


measuring cosmic ray anisotropy

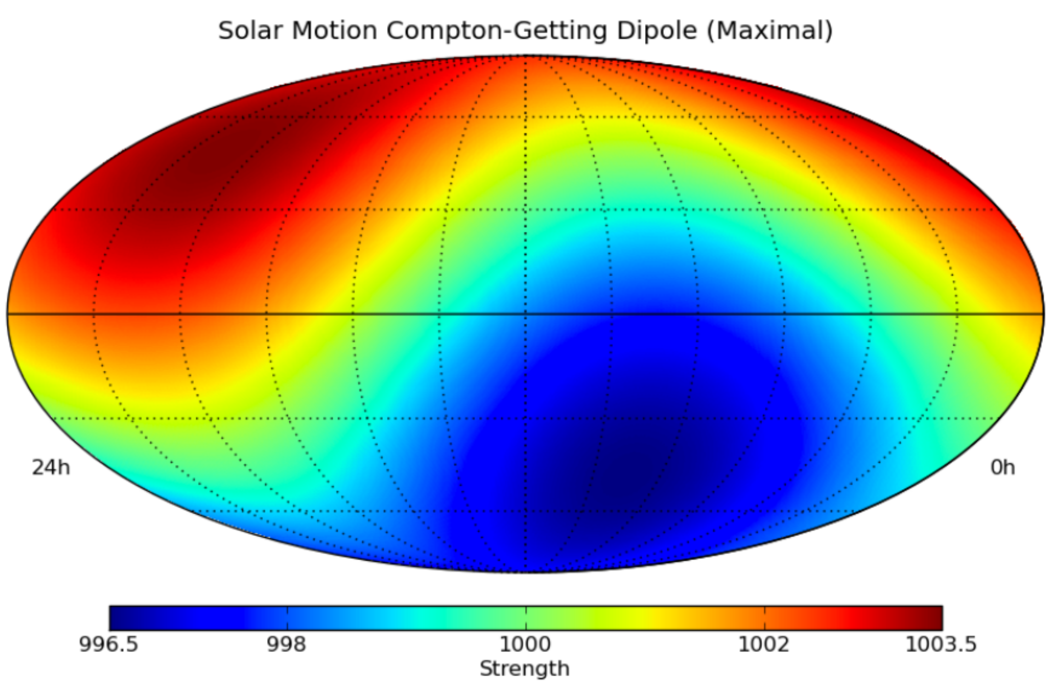
relative intensity

DISCLAIMER

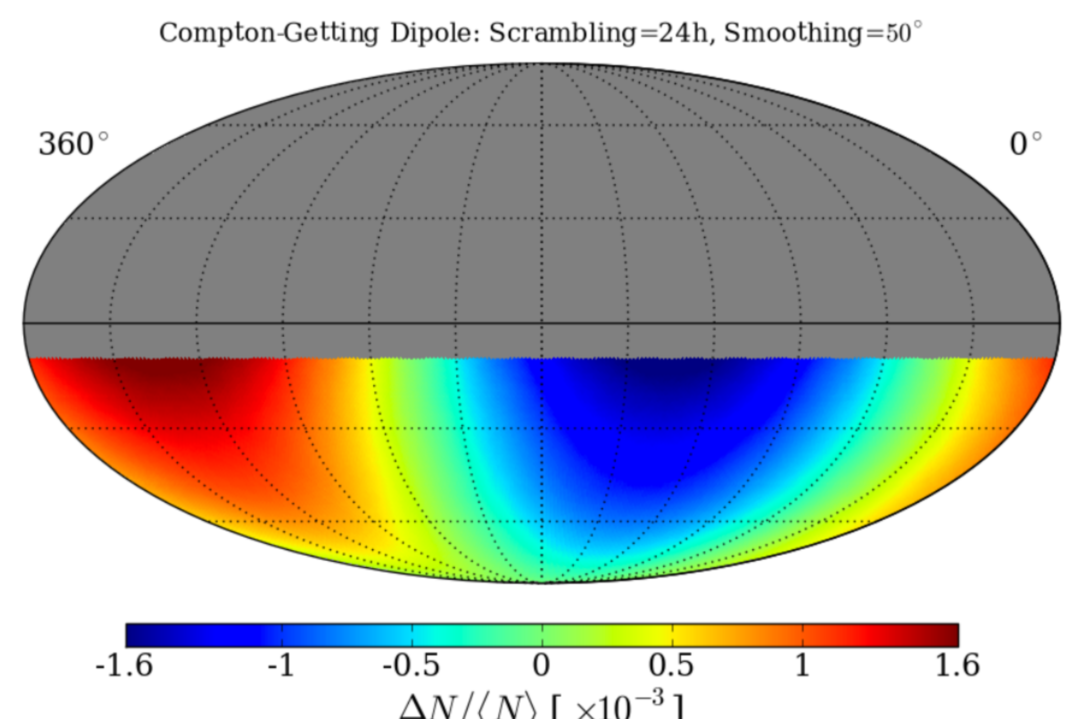
Abbasi et al., ApJ, **746**, 33, 2012



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



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



- sky maps show **ONLY** modulations across right ascension and **NOT** declination

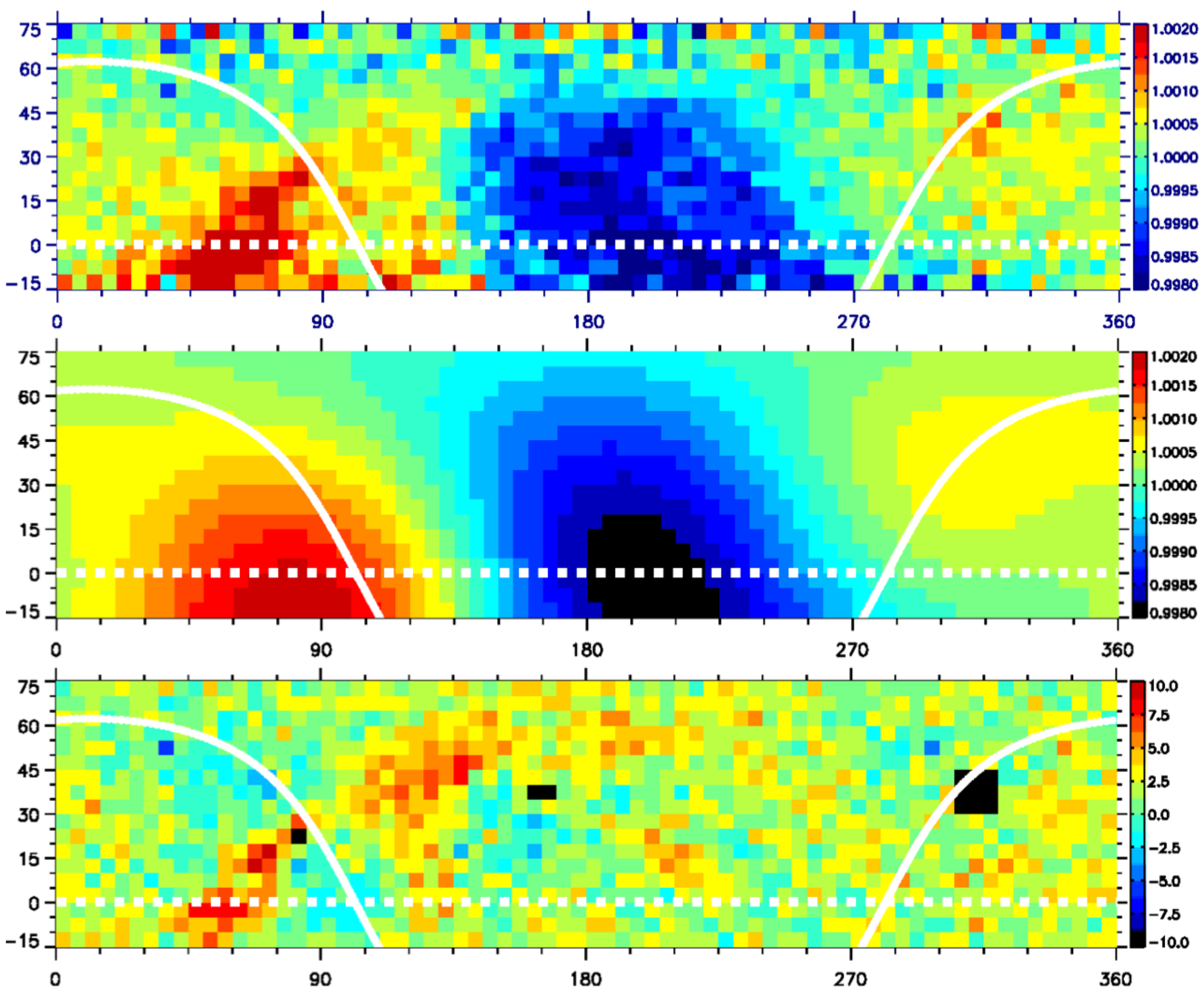
large scale anisotropy

topology

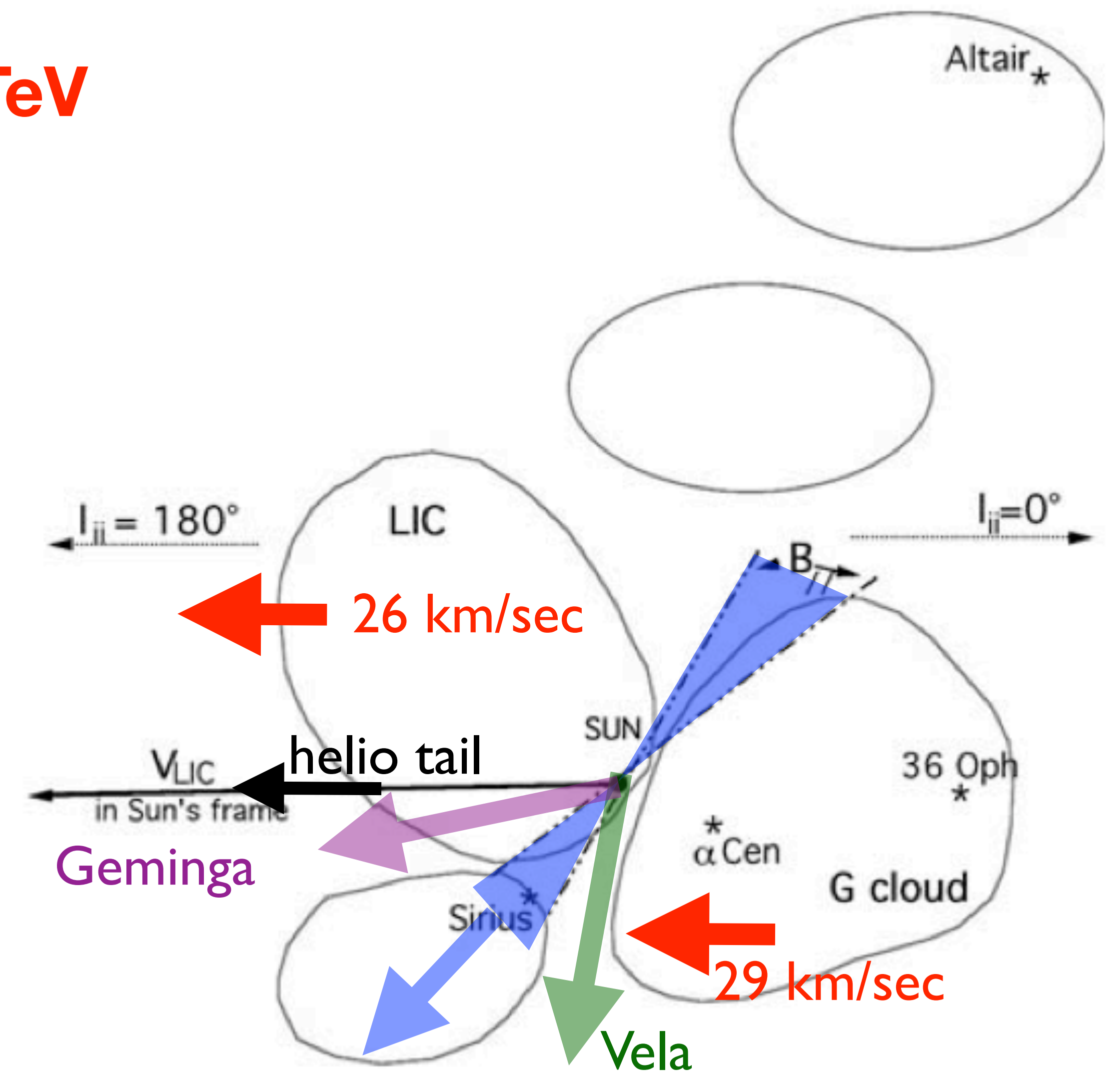
ANISOTROPY IS COMPLEX

Local Interstellar Medium

Tibet ASγ Amenomori et al., ICRC 2007



4 TeV

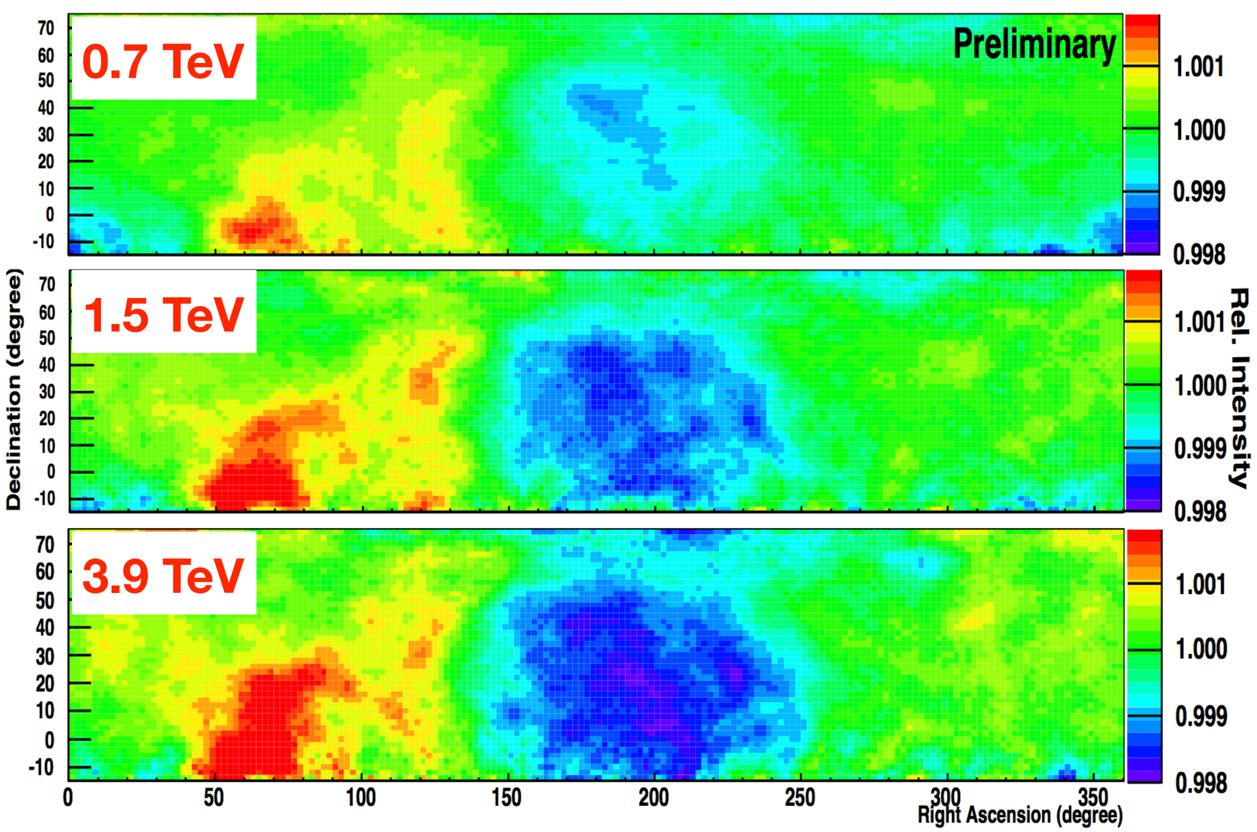


uni-directional (**dipole**) & bi-directional (**quadrupole**) anisotropy from CR density and Local Magnetic Field **gradients**

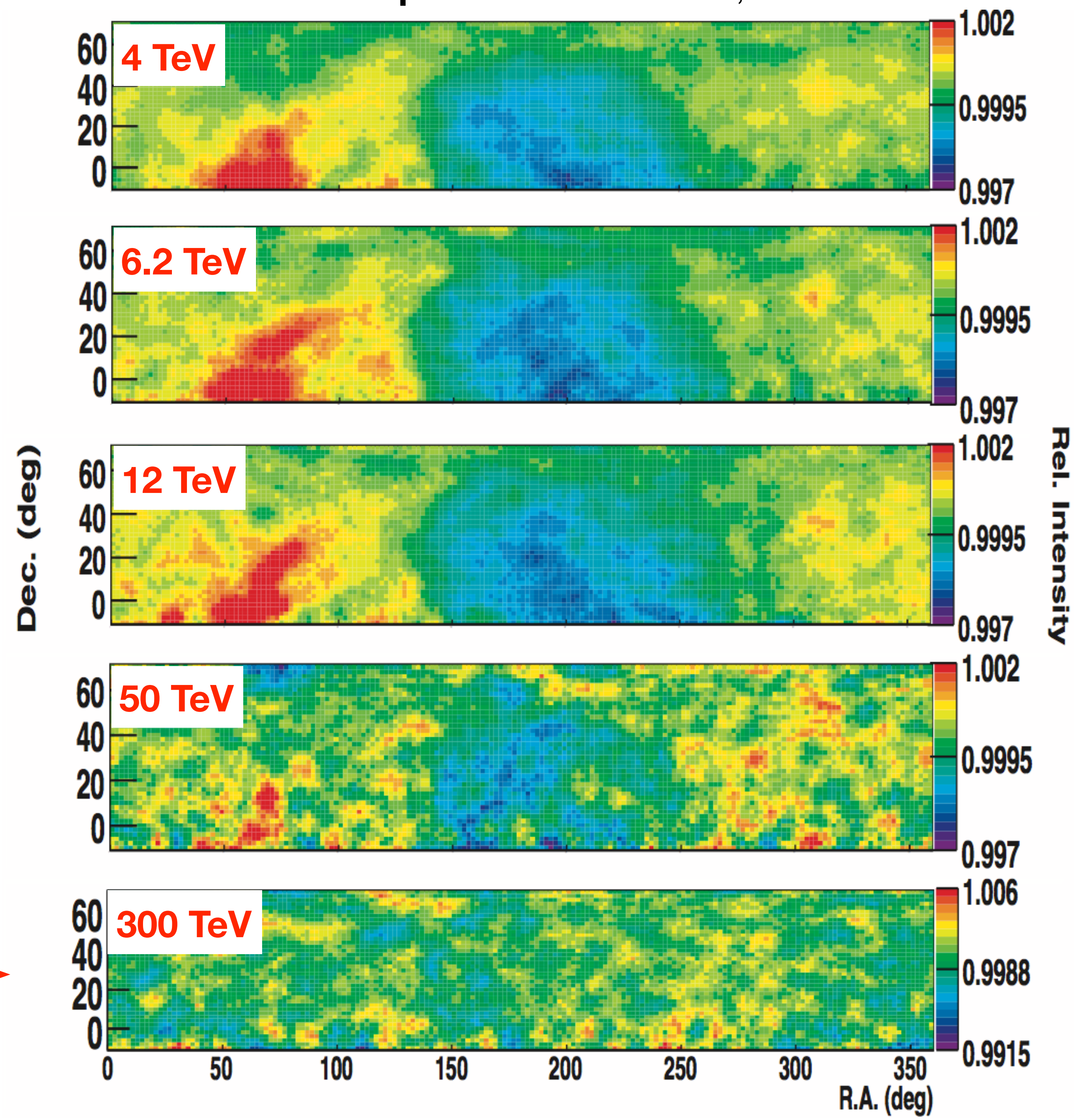
large scale anisotropy
energy dependence

anisotropy amplitude increases with energy up to **10 TeV** scale

ARGO-YBJ Zhang et al., ICRC 2009



Tibet ASγ Amenomori et al., 2006

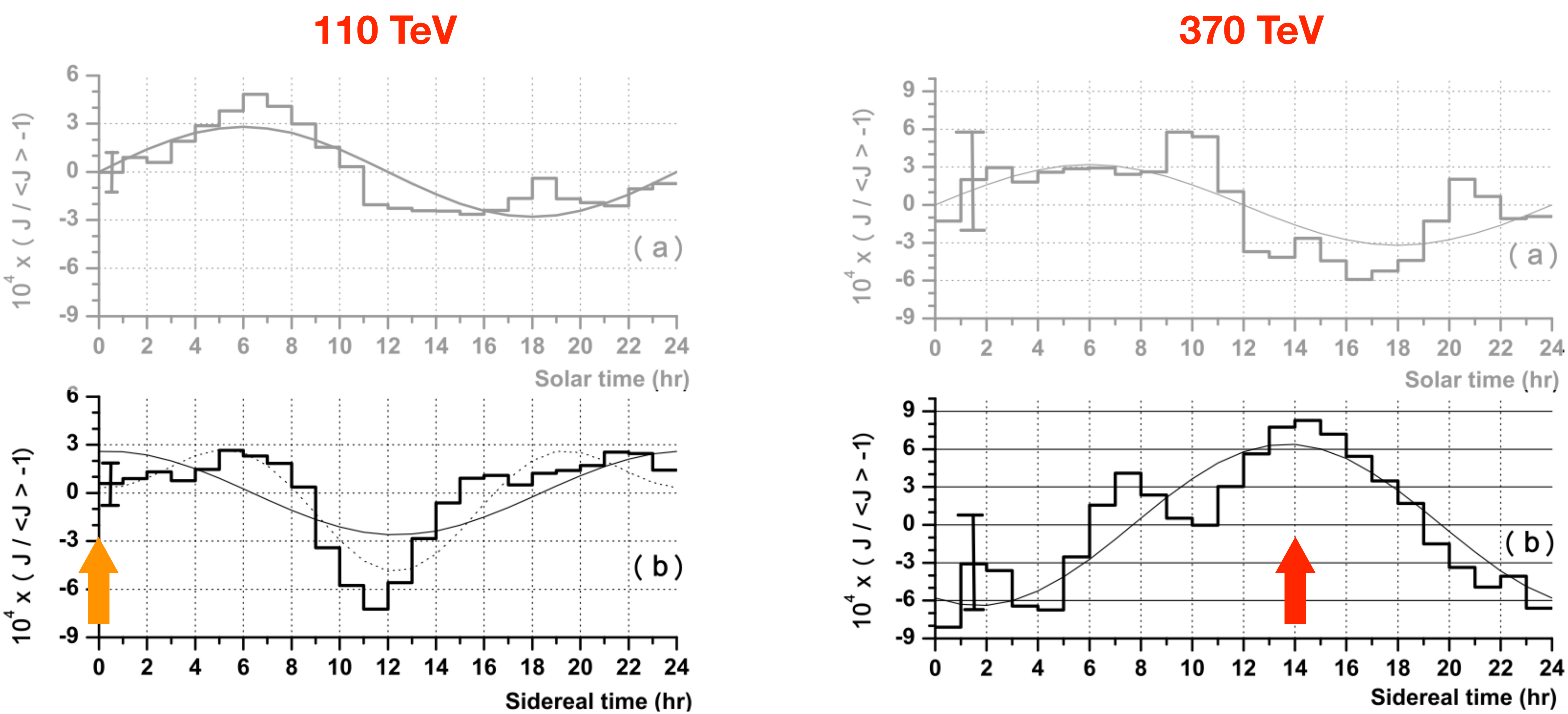


galactic co-rotation?

large scale anisotropy
energy dependence

ANISOTROPY CHANGES WITH ENERGY

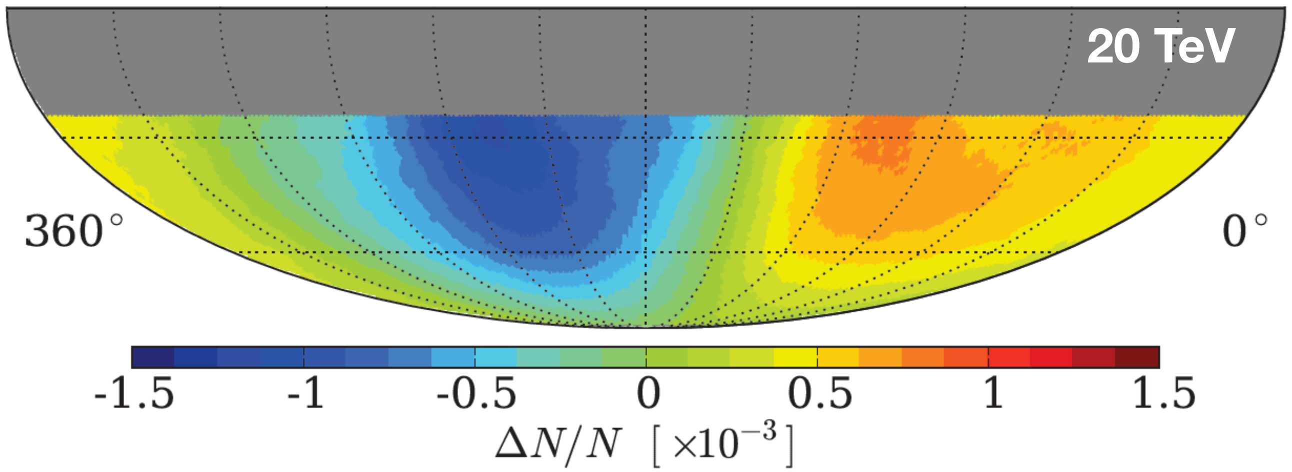
EAS TOP Aglietta et al., 2009

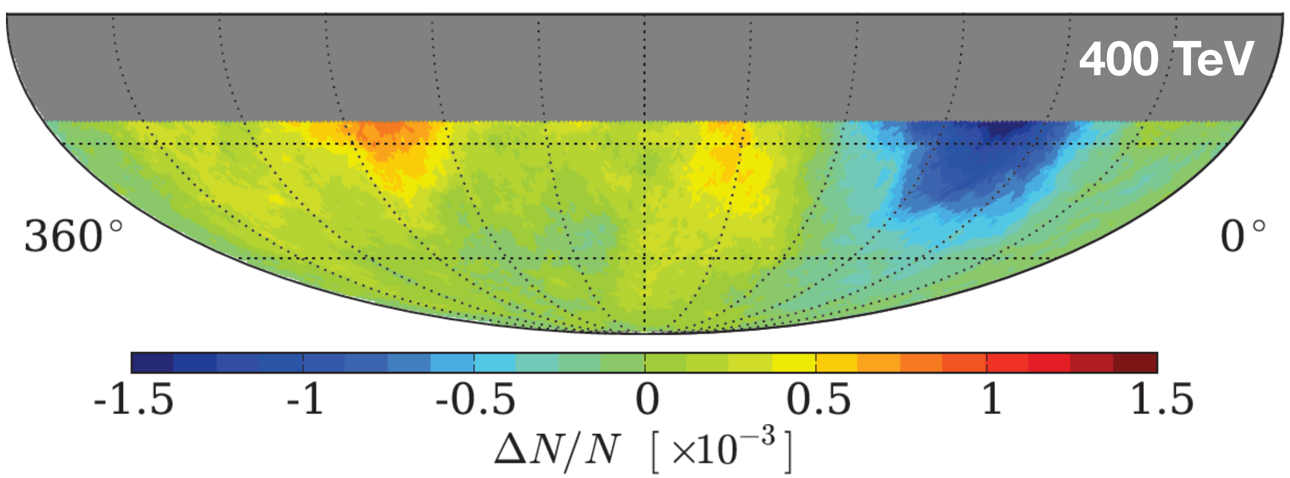


anisotropy ***flips direction*** between 100 TeV and 400 TeV

large scale anisotropy
energy dependence

IceCube



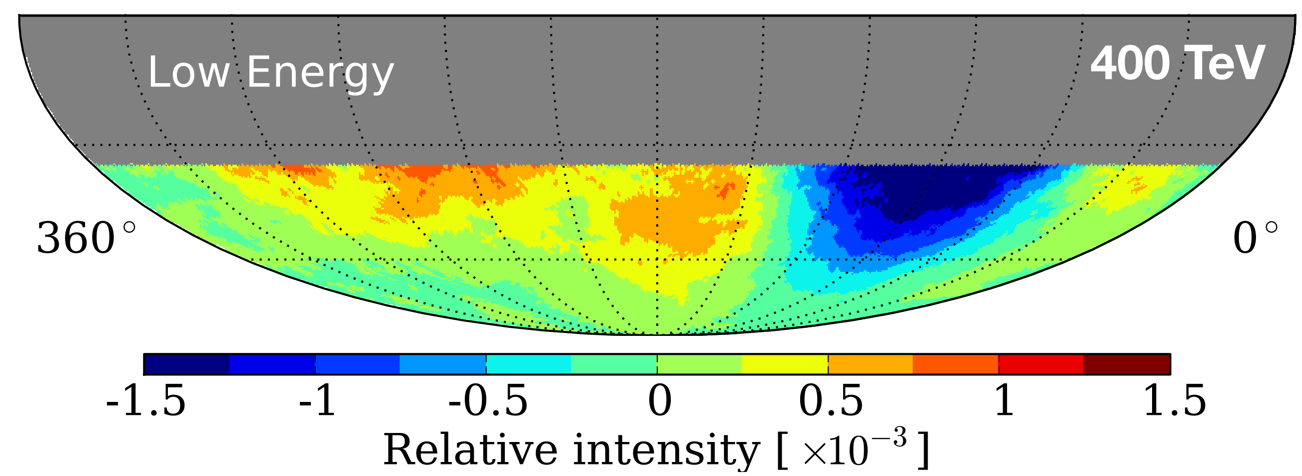


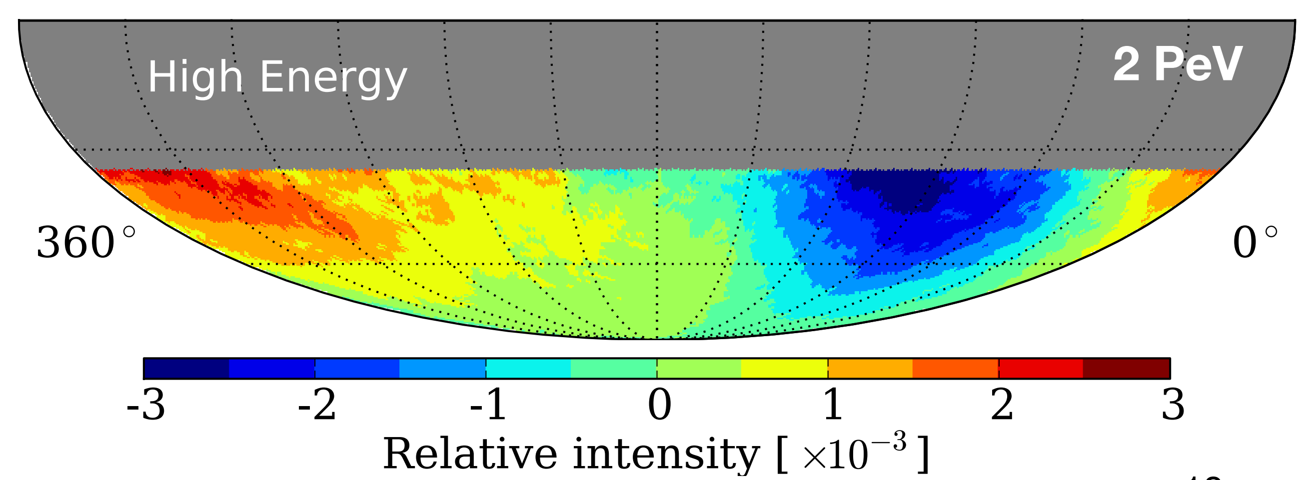
Abbasi et al., 2010, 2012

anisotropy **changes topology**
between 20 TeV and 400 TeV

IceTop

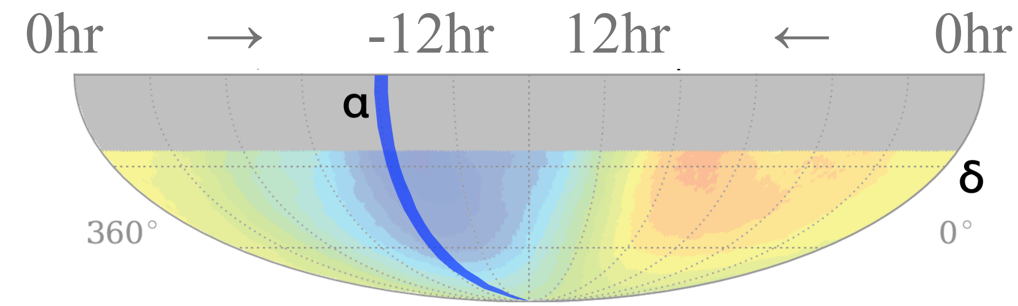
Aartsen et al., 2013





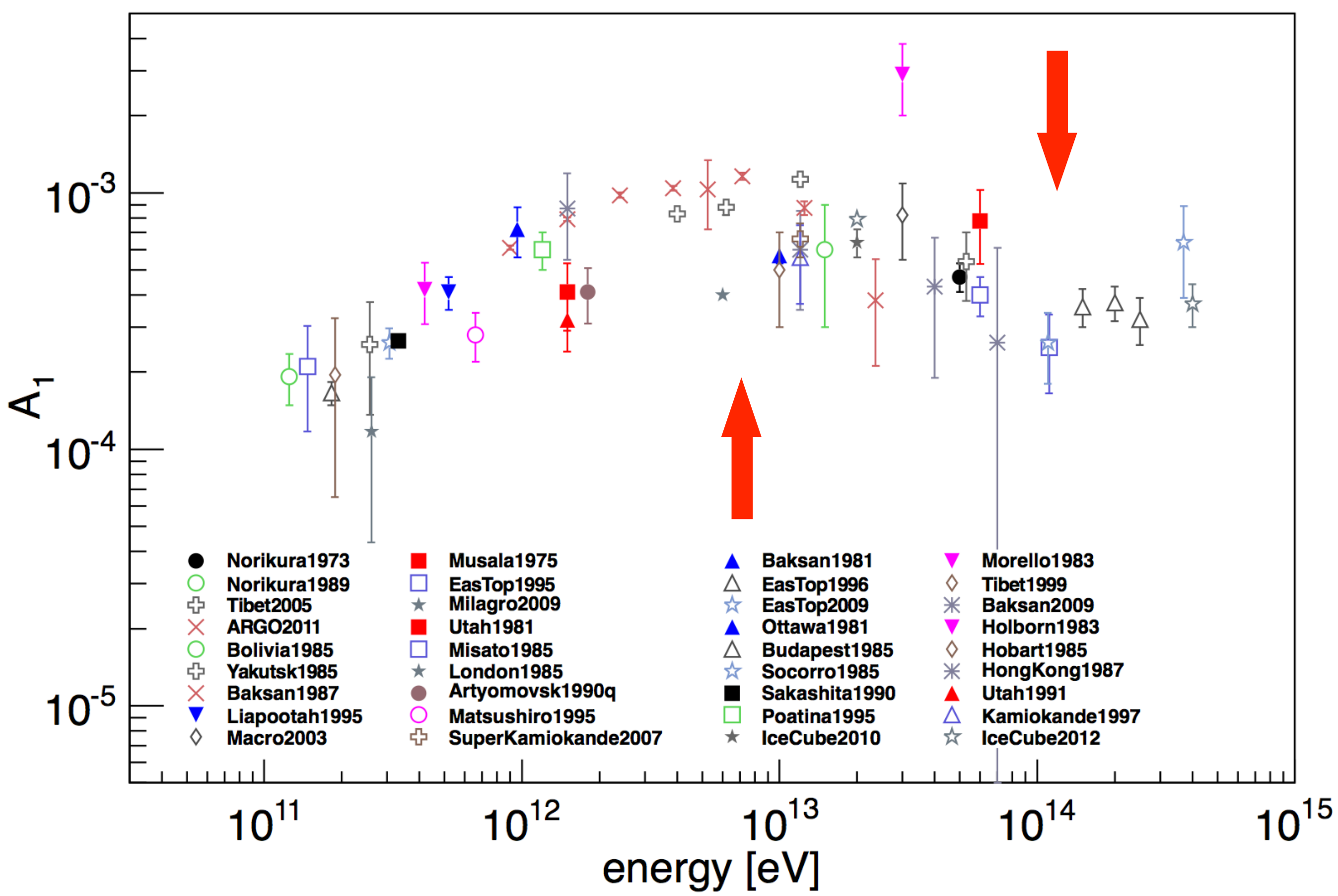
large scale anisotropy

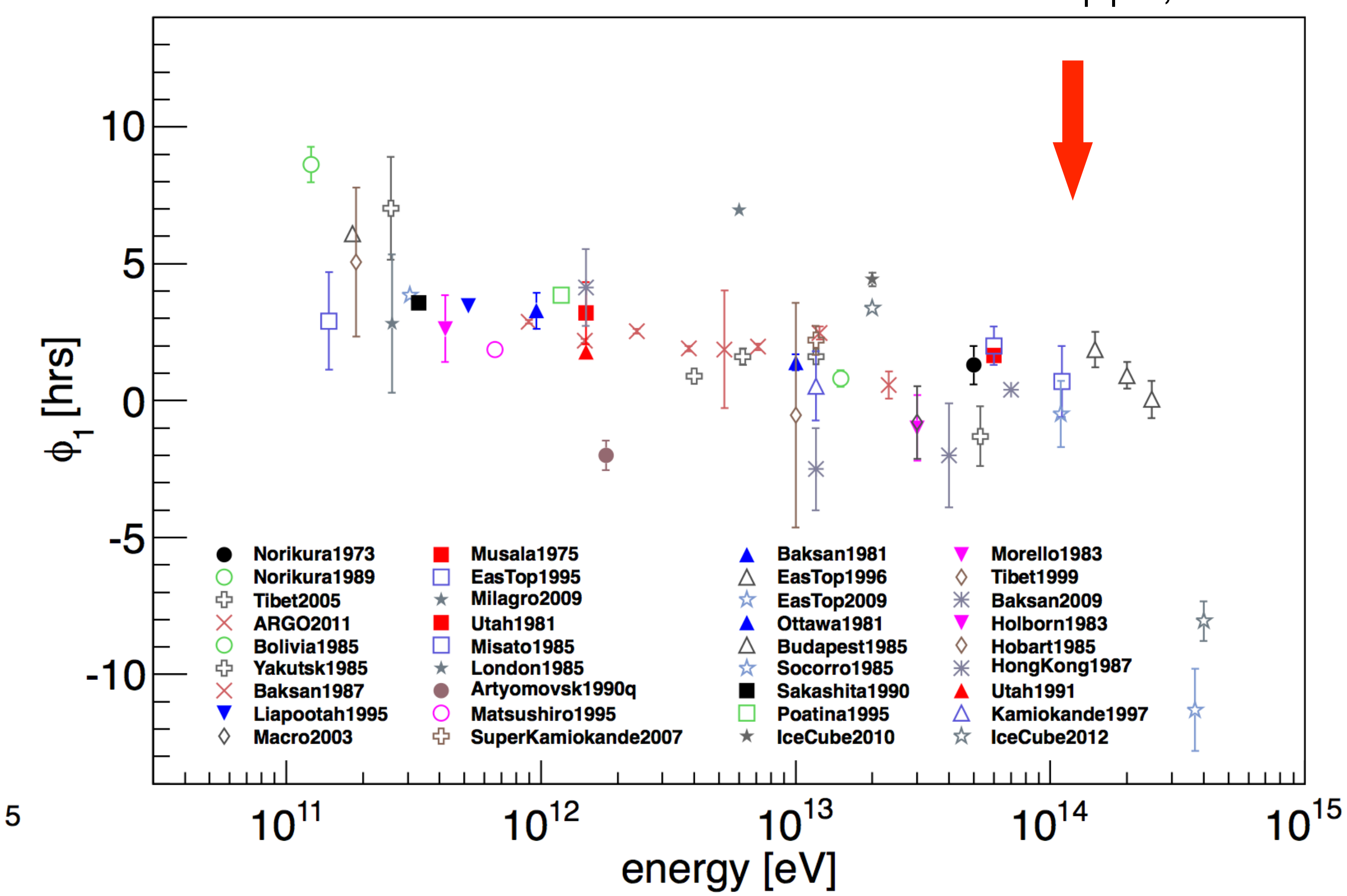
energy dependence



amplitude & phase of first harmonic component (dipole)

Di Sciascio & Iuppa, 2014

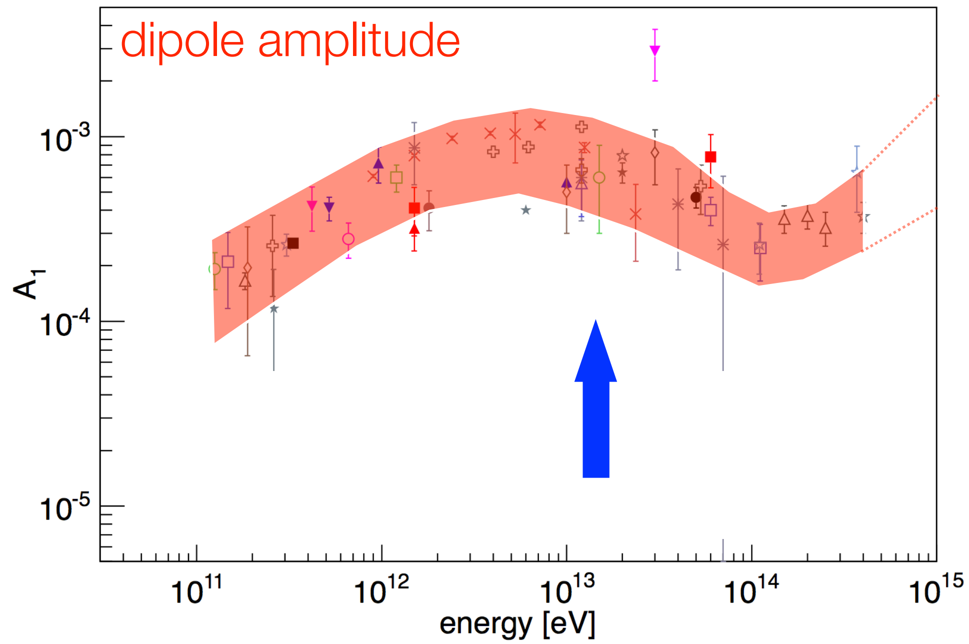


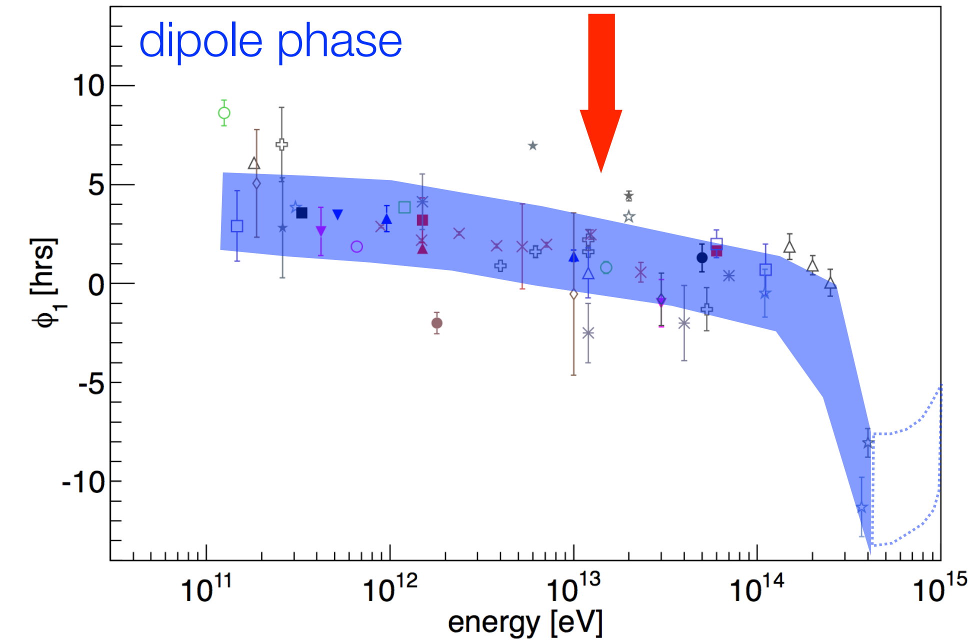


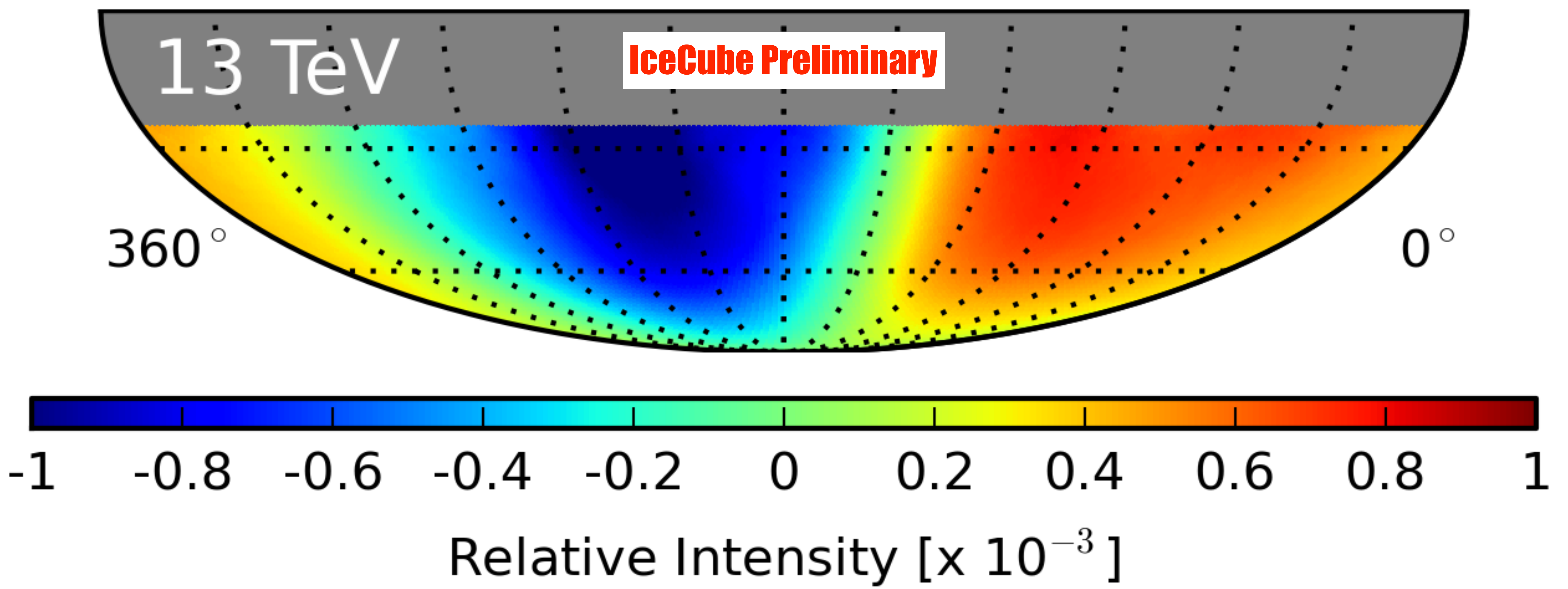
dipole amplitude increases up to order **10 TeV** and then it **decreases**

phase of **dipole** steadily migrates & suddenly **changes** or **flips**

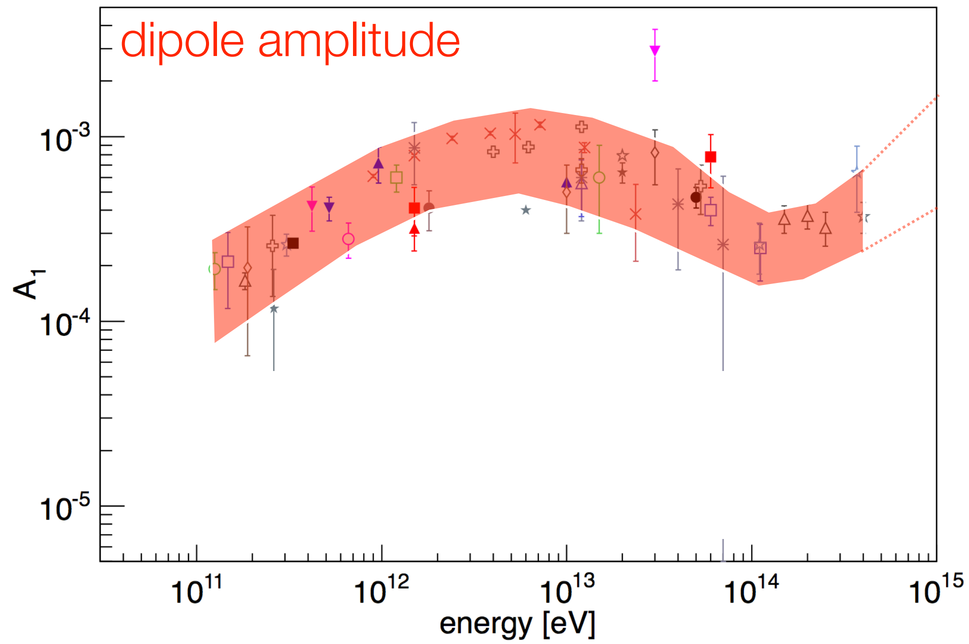
Di Sciascio & Iuppa, 2014

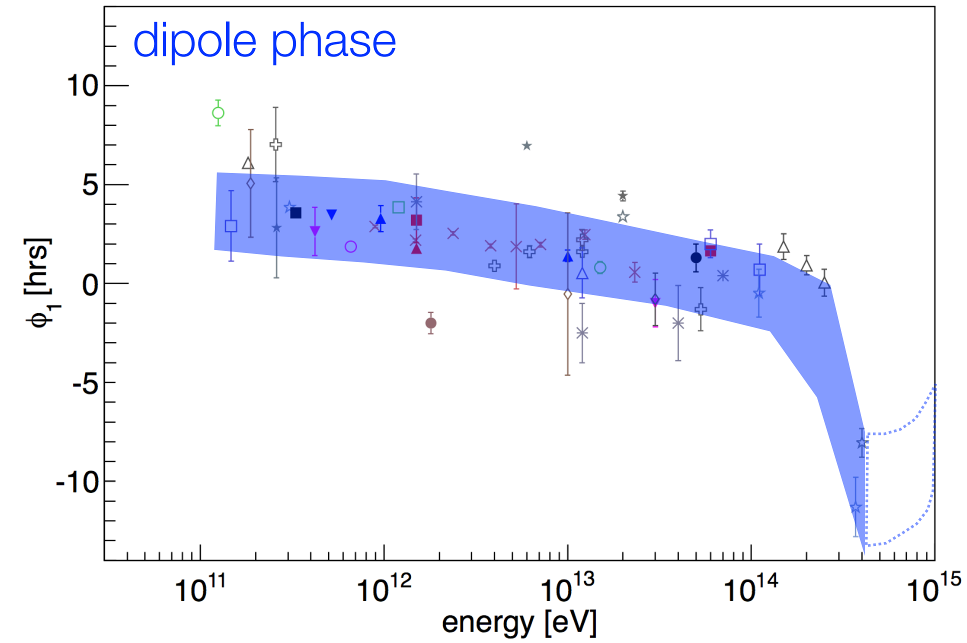


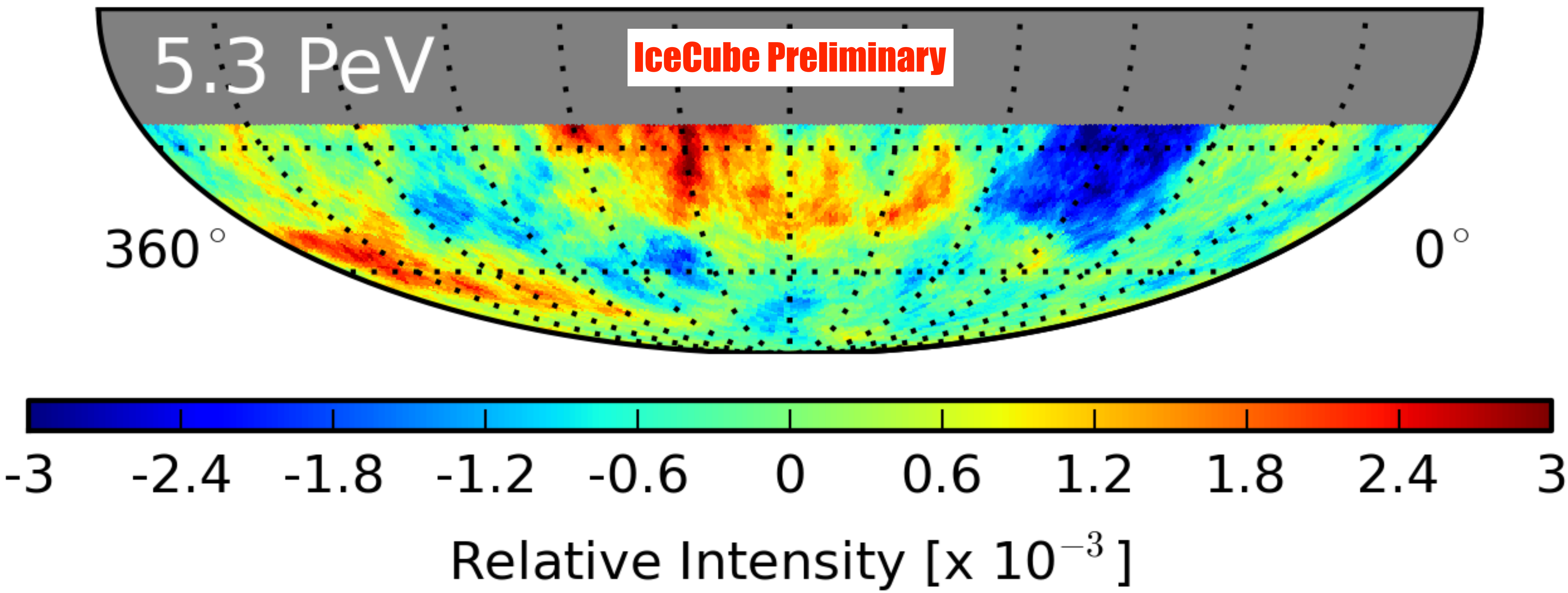




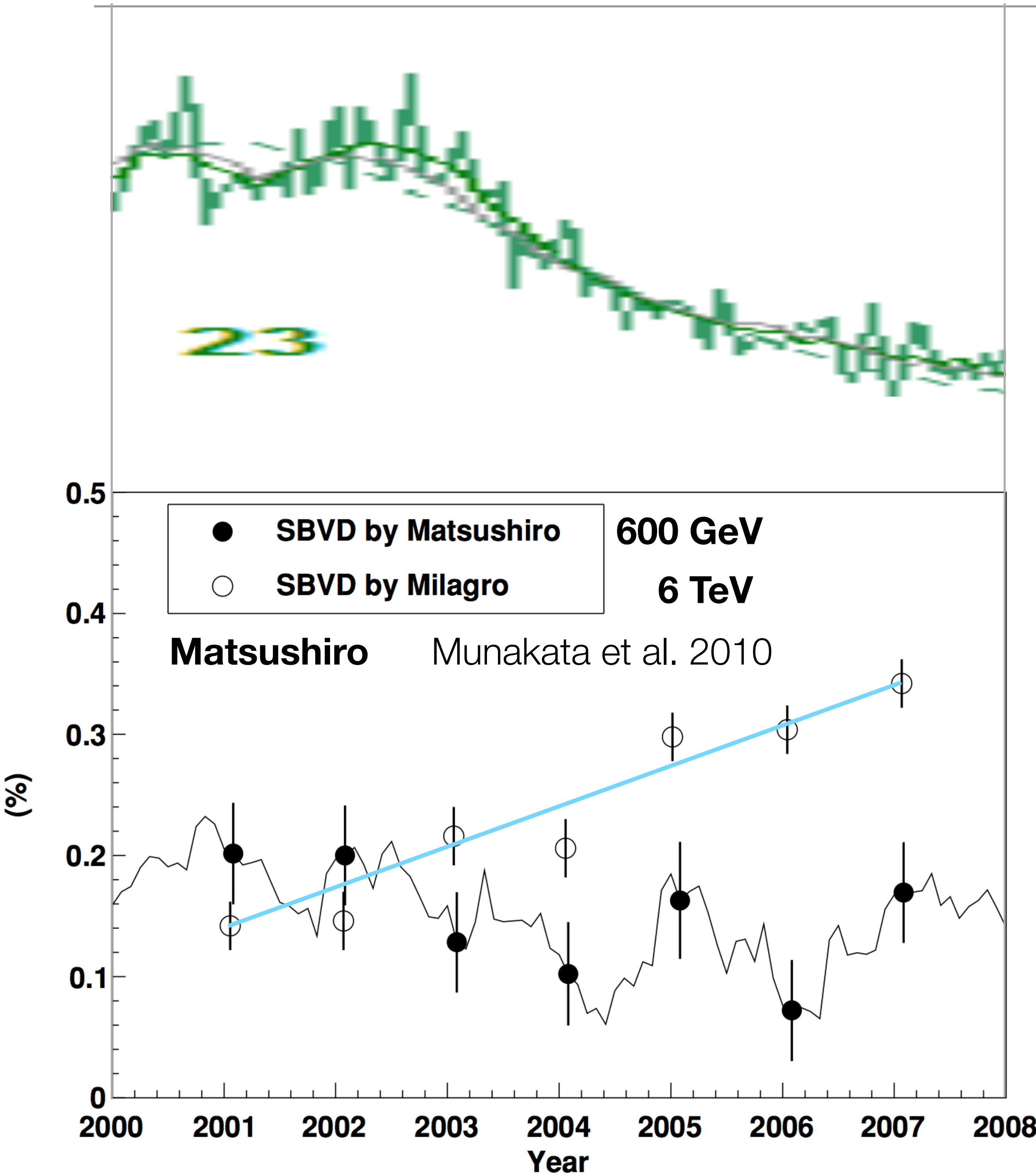
Di Sciascio & Iuppa, 2014





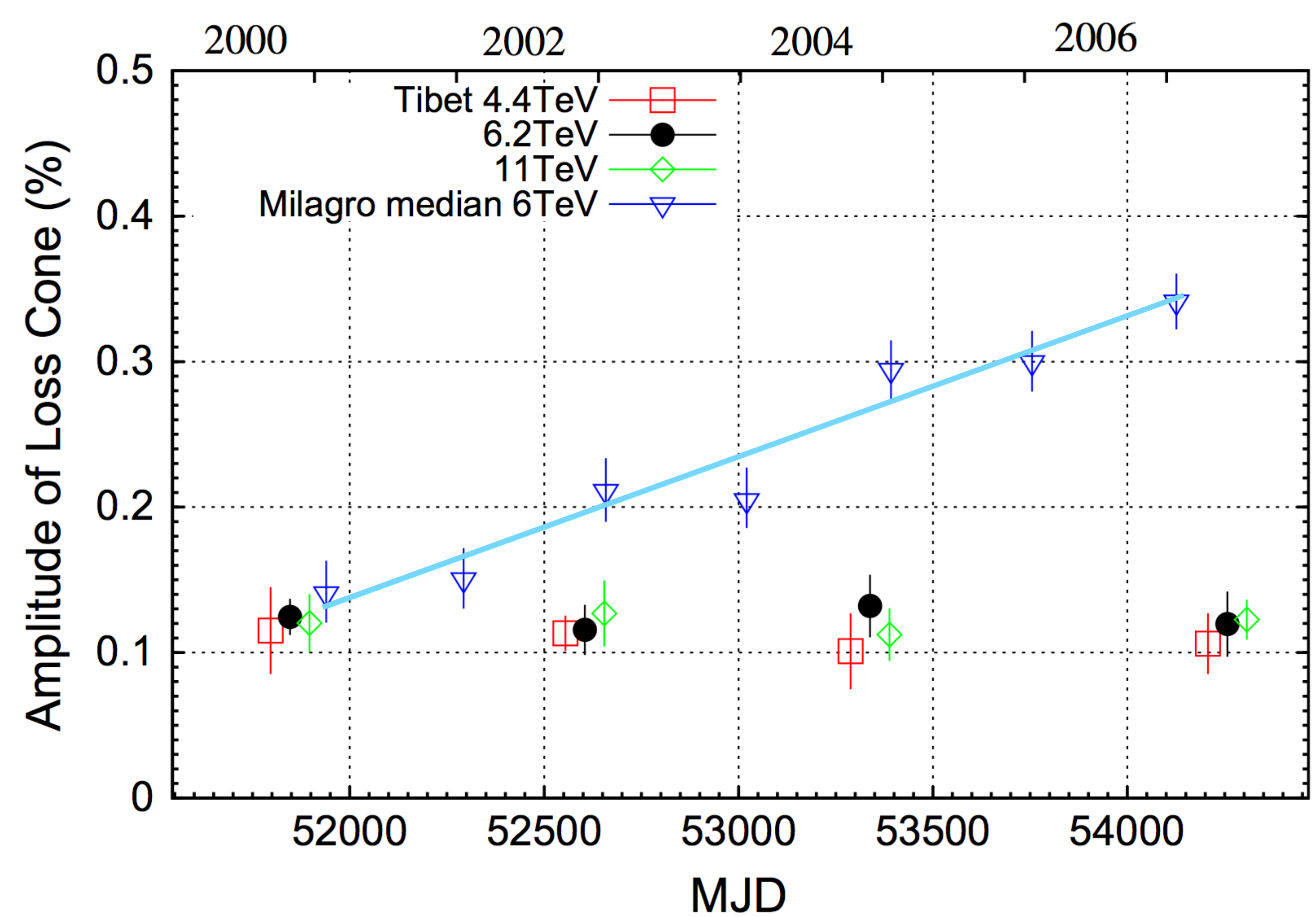


large scale anisotropy
time dependence



time stability of Single-Band Valley Depth (depth of *Loss Cone*)

no correlation with solar cycles

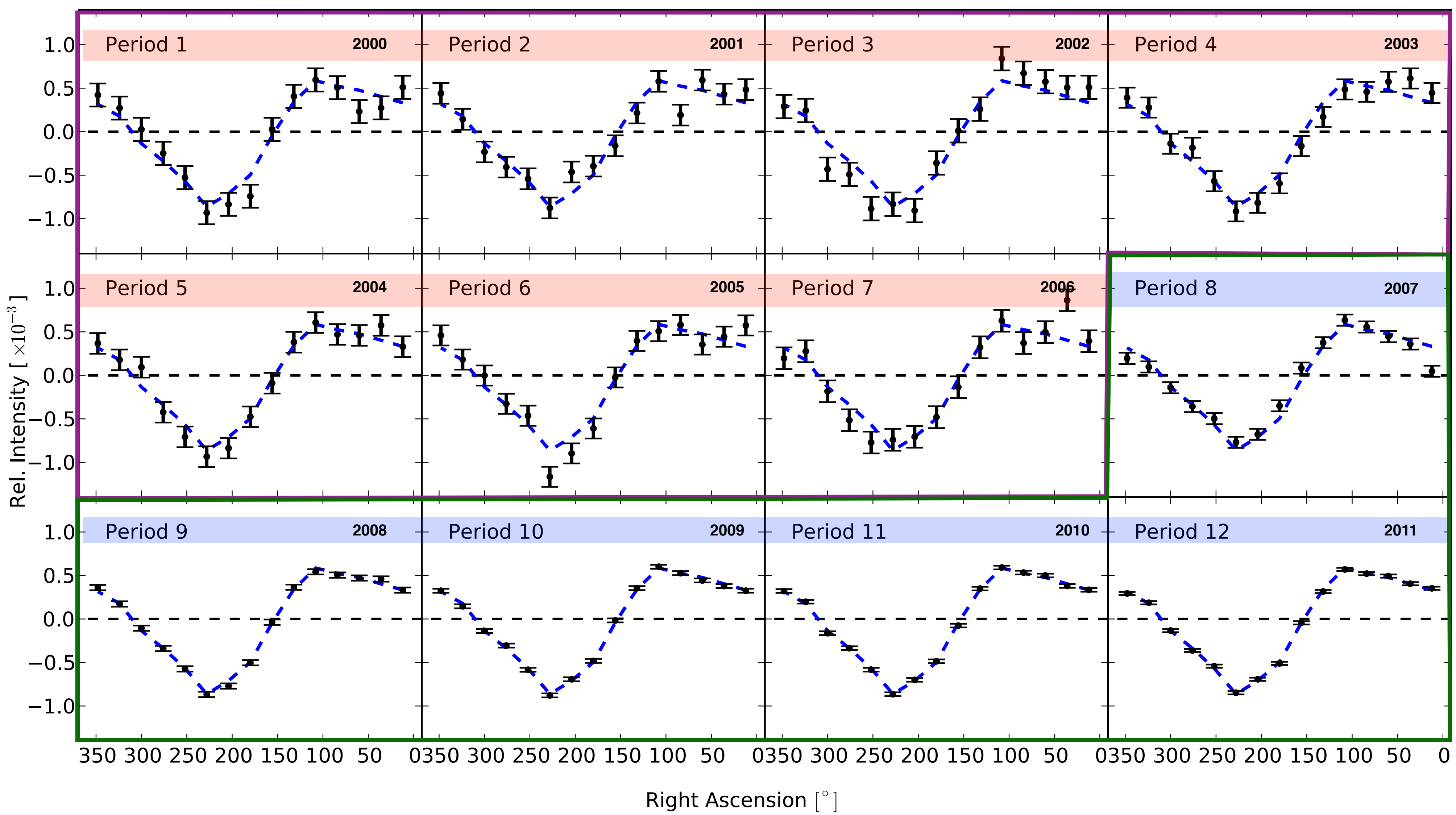


cosmic ray anisotropy
AMANDA-IceCube 2000-2011

PRELIMINARY

20 TeV

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

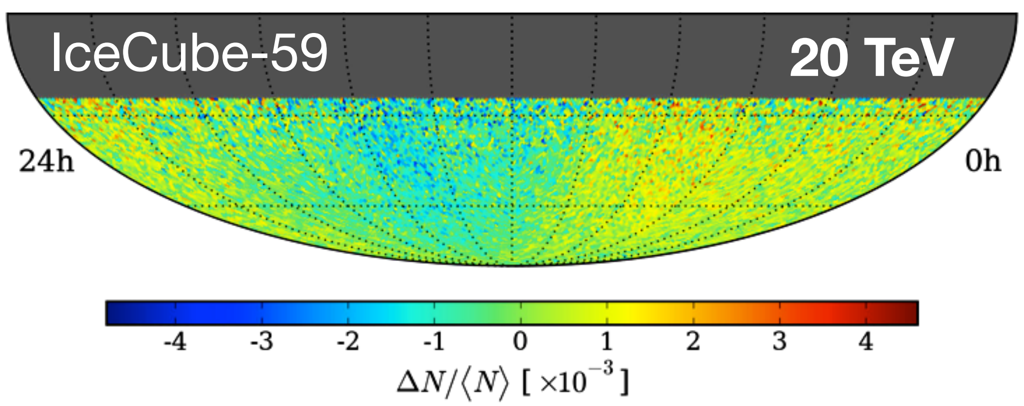


IceCube

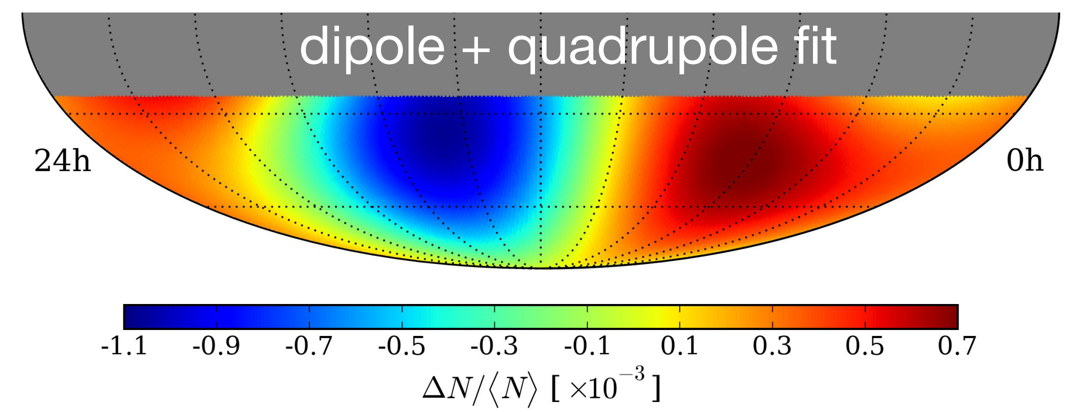
TeV sidereal anisotropy
angular power spectrum

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

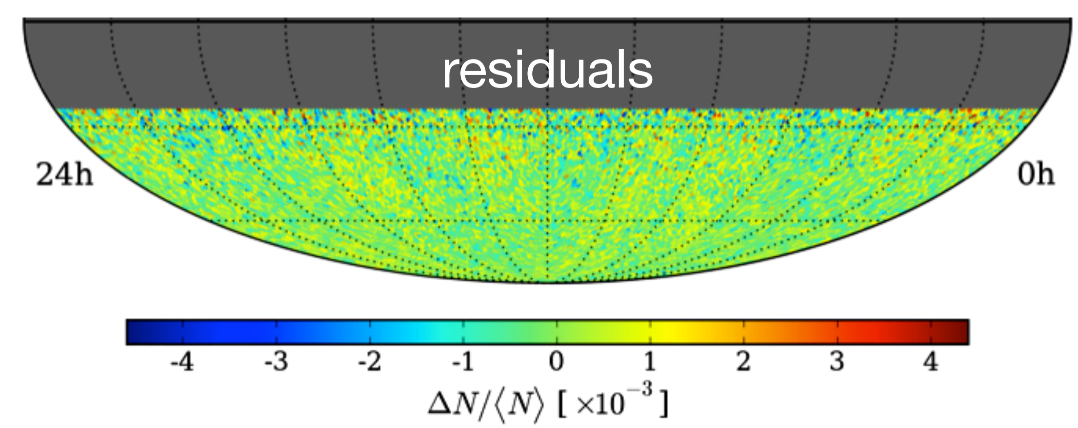
relative intensity raw map

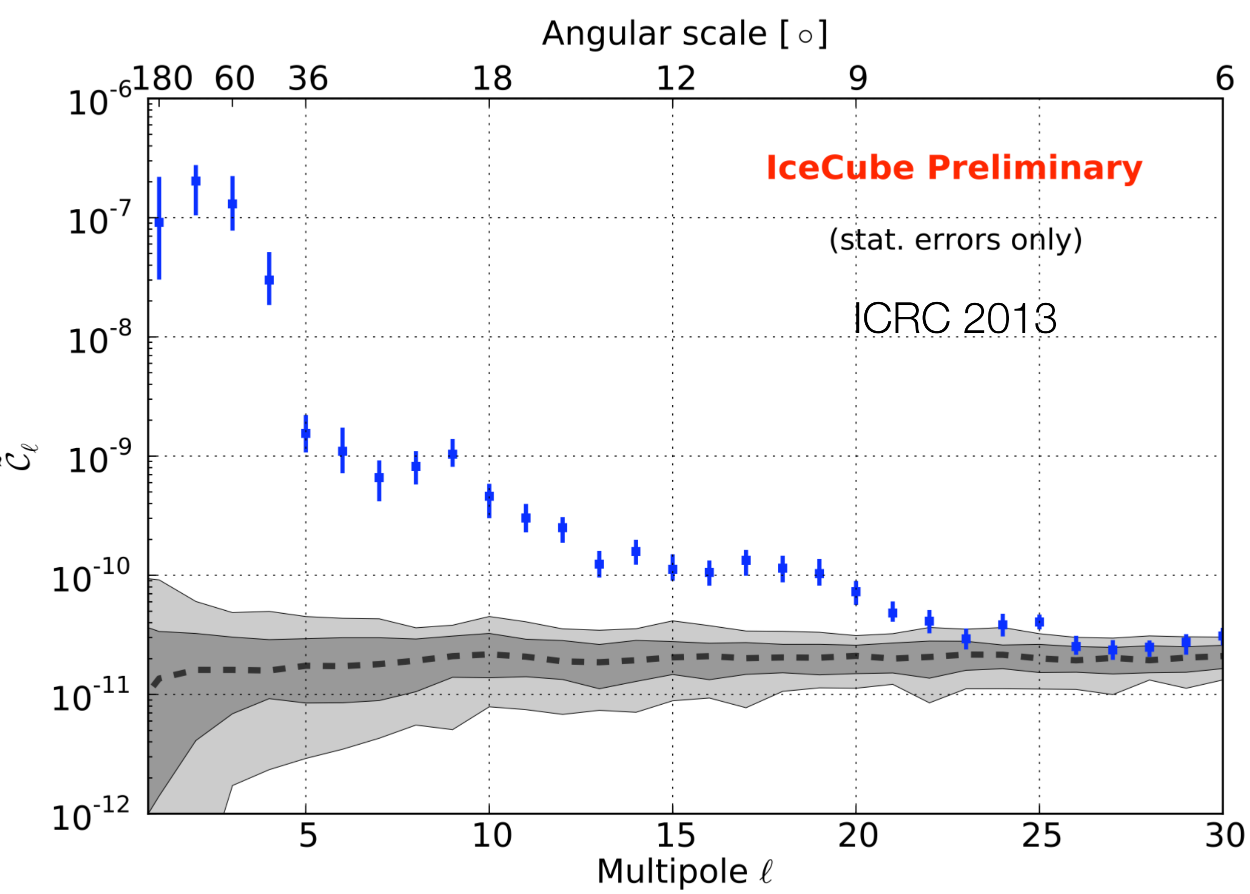


χ^2/ndf = 14743.4 / 14187 (prob = 0.05%)



filter high CR density gradient structures





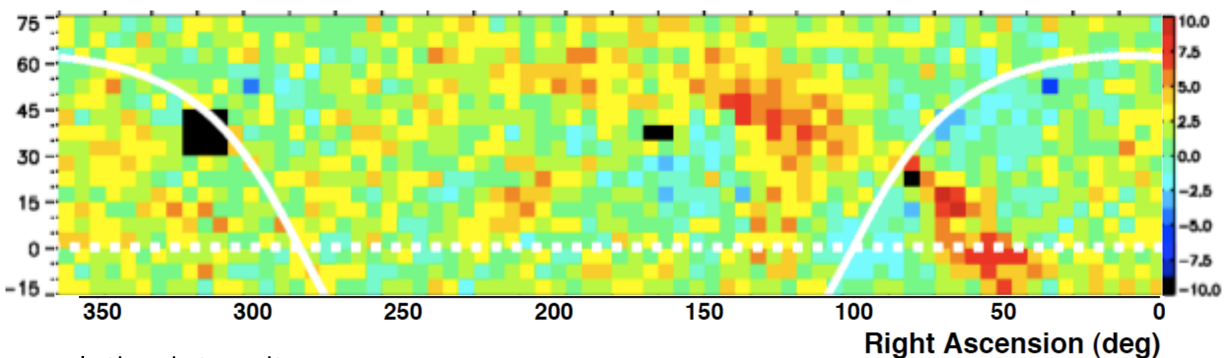
contributions from several angular scales (**multipoles**)

high energy cosmic rays
small scale anisotropy

1-5 TeV

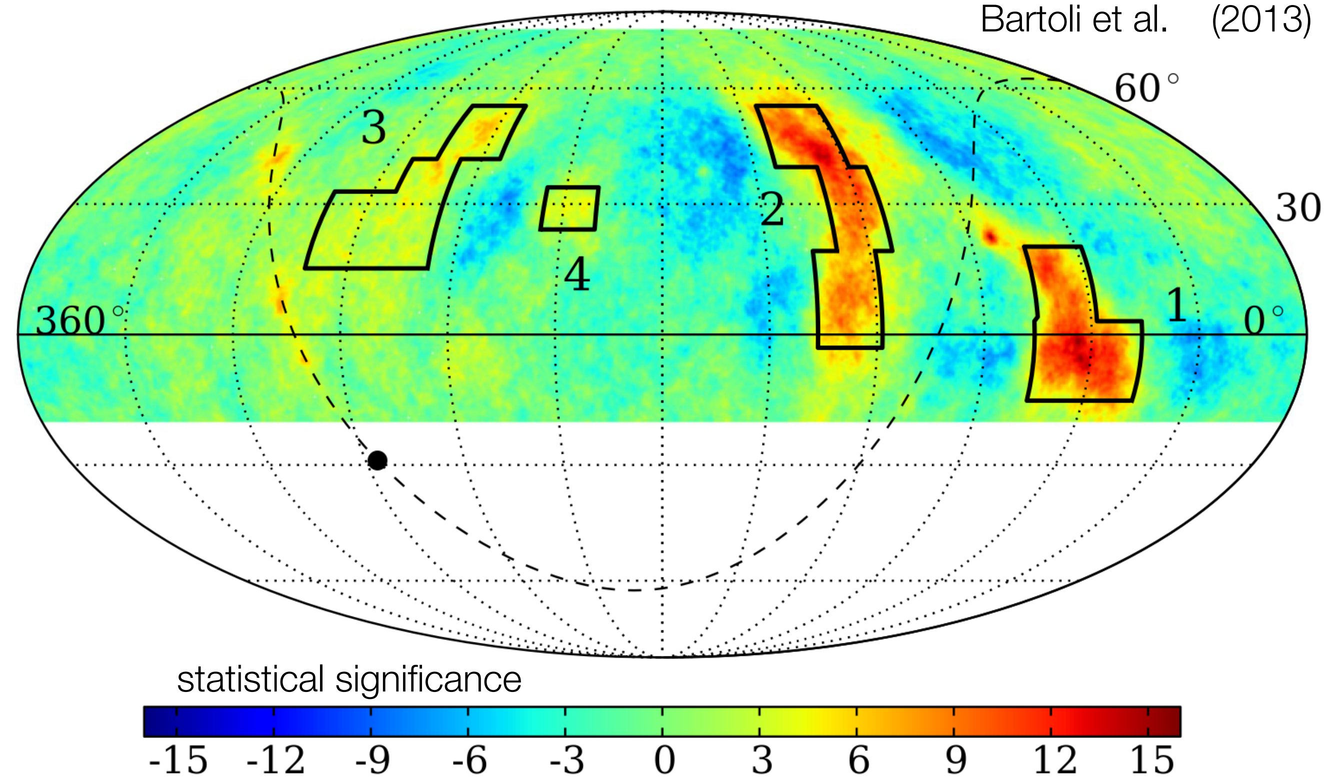
$\sim 10^{-4}$

Tibet-III
Amenomori et al. ICRC (2007)

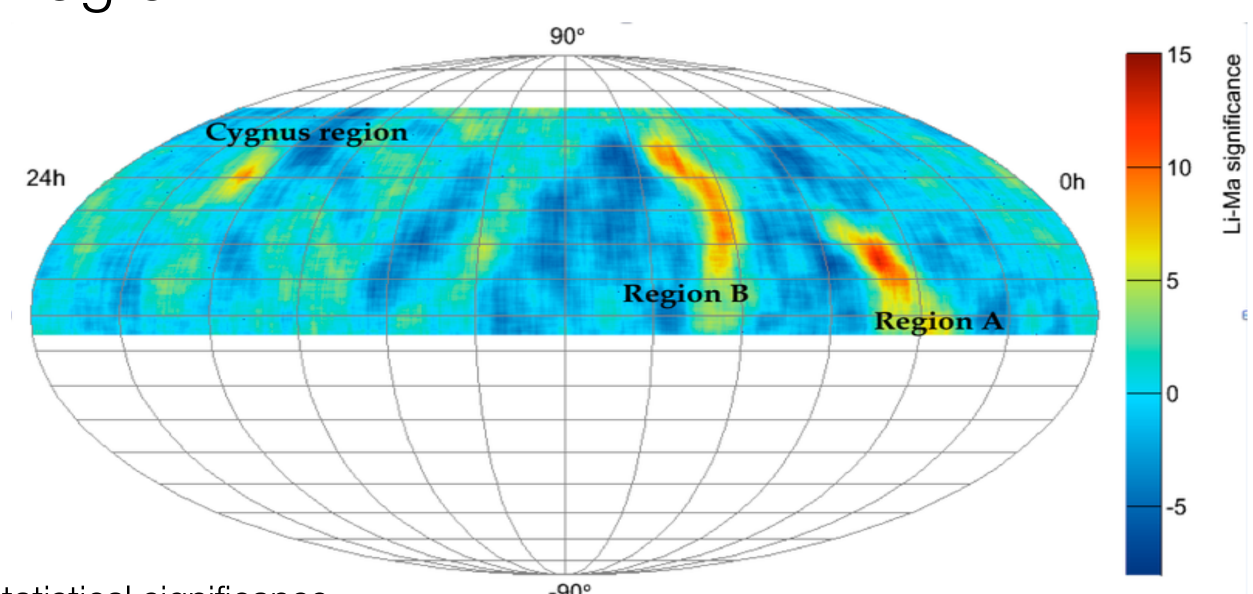


relative intensity

ARGO-YBJ
Vernetto et al. (2009)
Iuppa et al. (2011)
Bartoli et al. (2013)

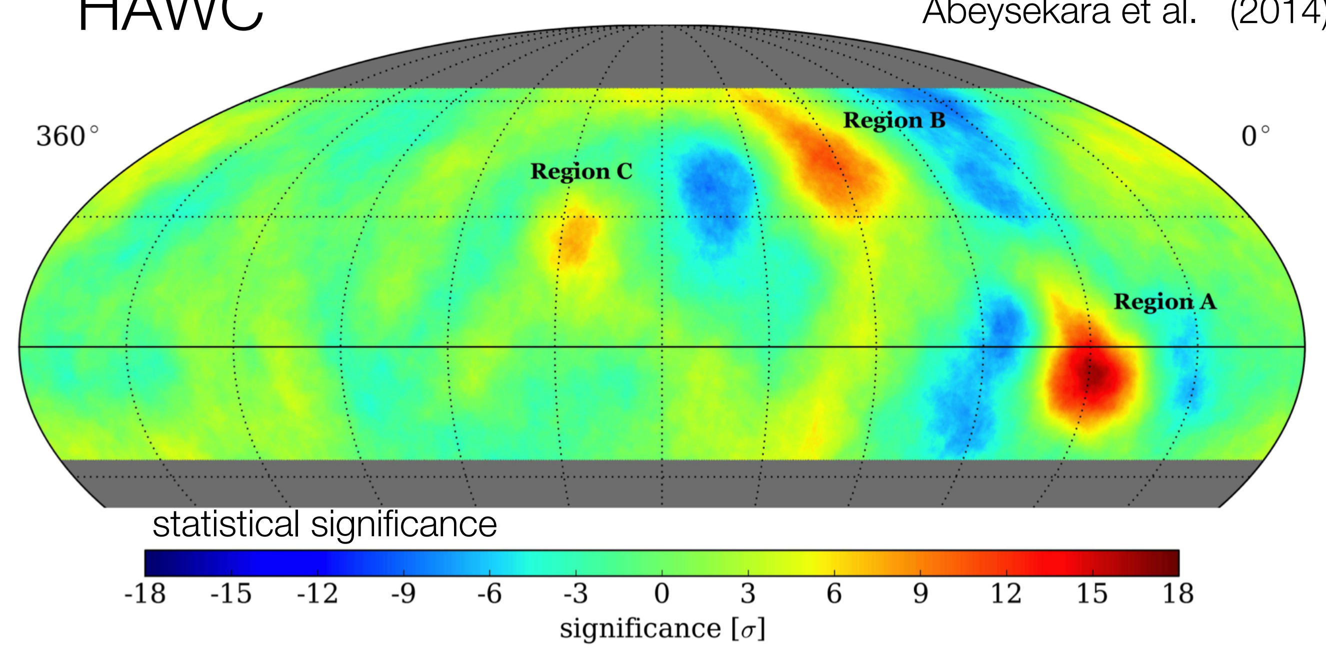


Milagro
Abdo et al. (2008)

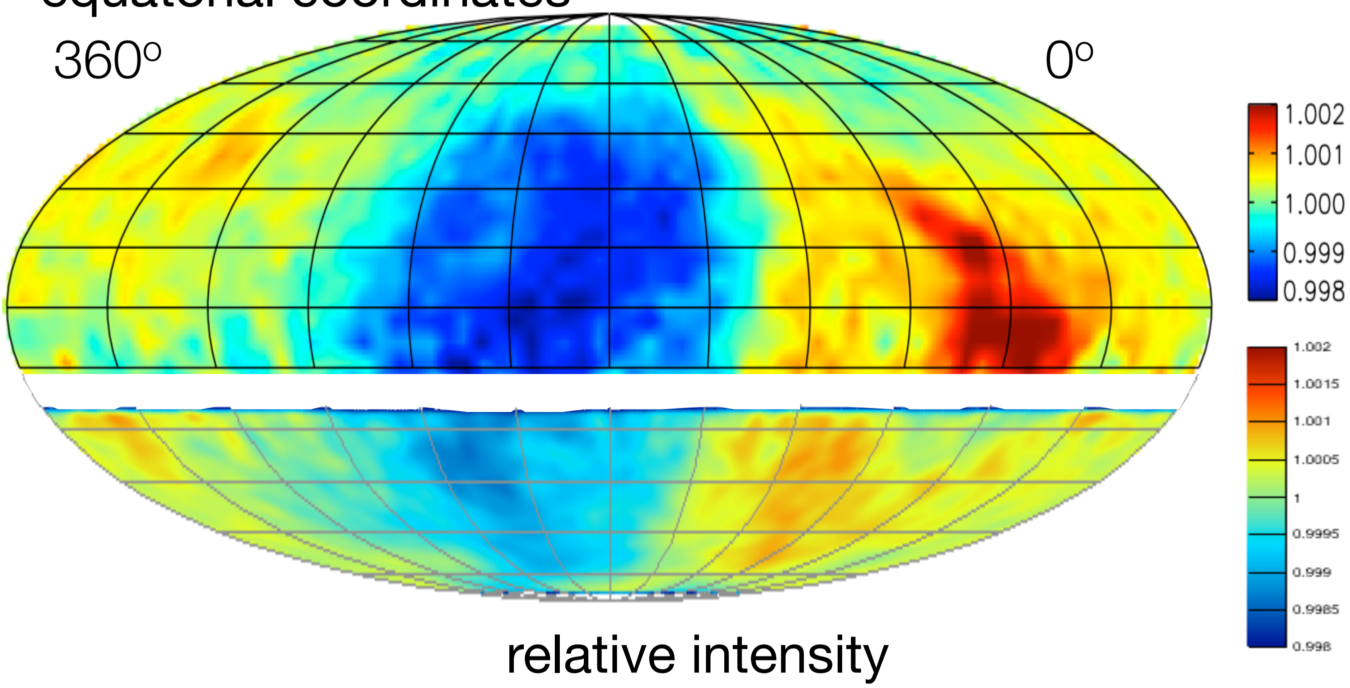


statistical significance

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

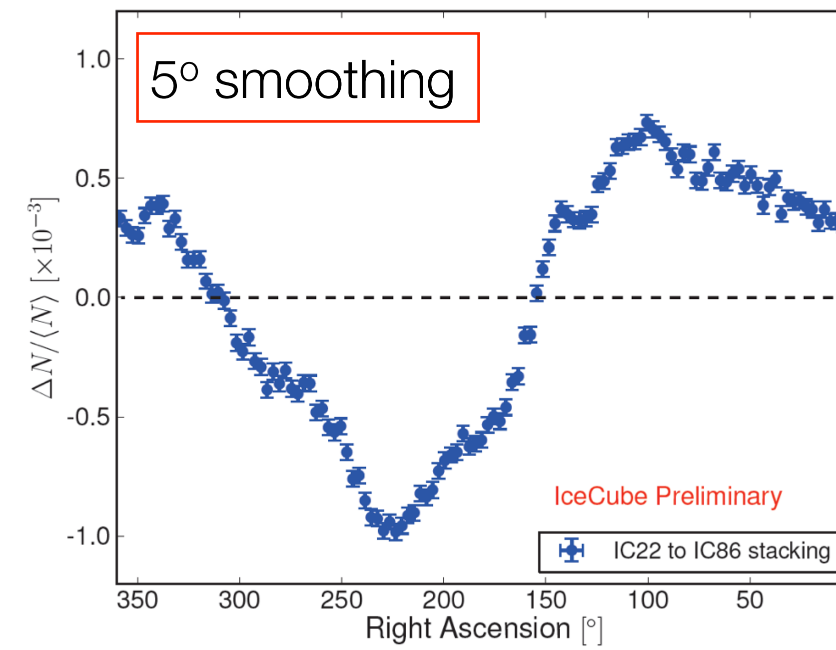


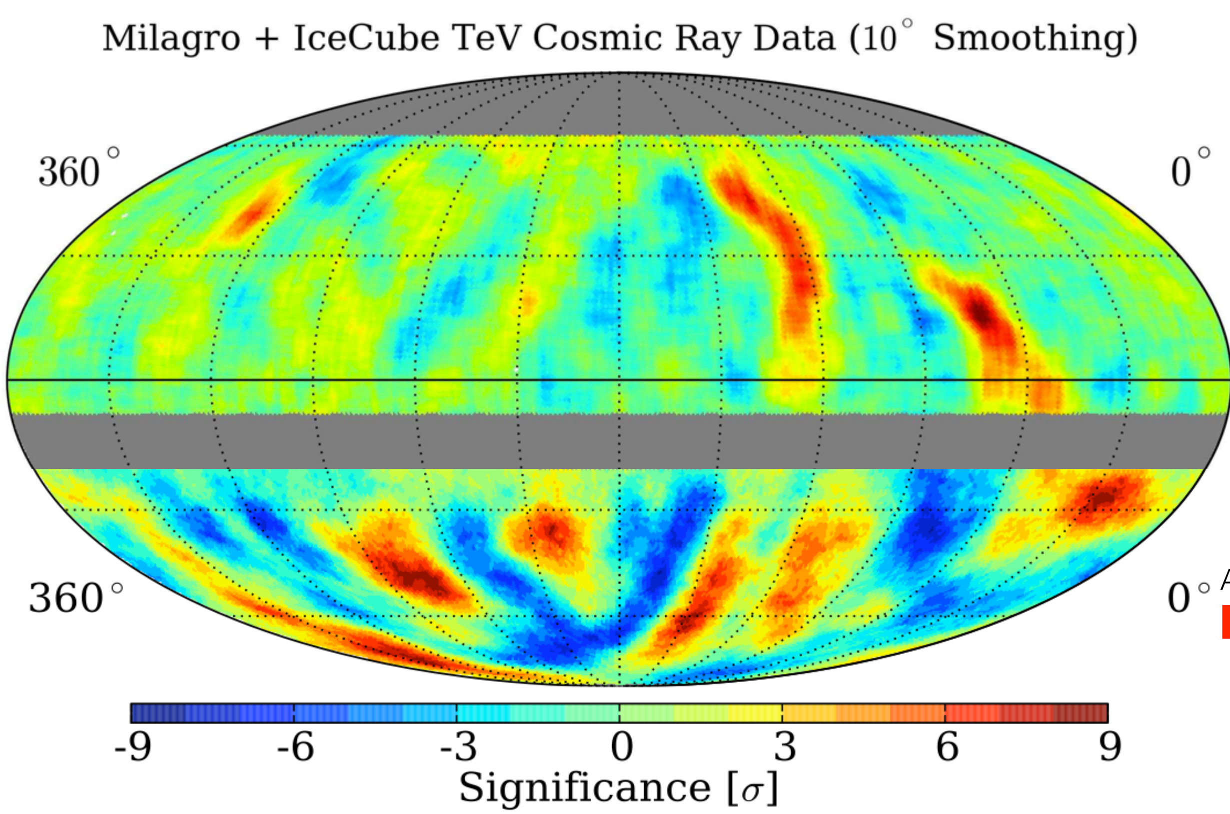
cosmic ray anisotropy large scale → small scale



Tibet-III 5 TeV
Amenomori et al., ICRC 2011

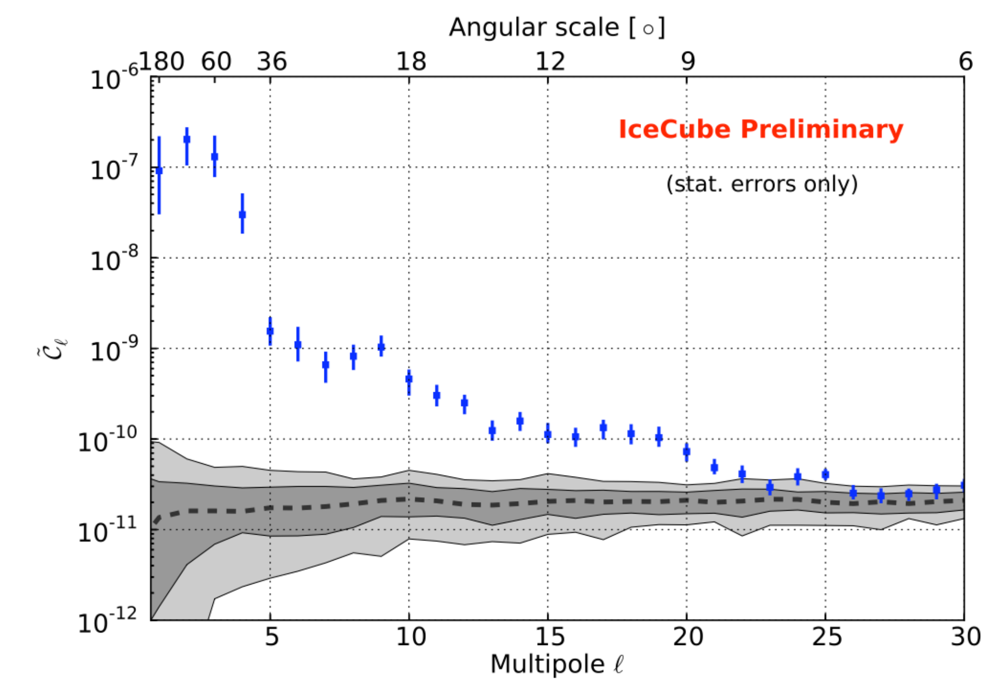
IceCube-59 20 TeV
Abbasi et al., ApJ, **746**, 33, 2012





Milagro 1 TeV
Abdo et al., PRL, **101**, 221101, 2008

IceCube 20 TeV
Abbasi et al., ApJ, **740**, 16, 2011
PRELIMINARY - ICRC 2013

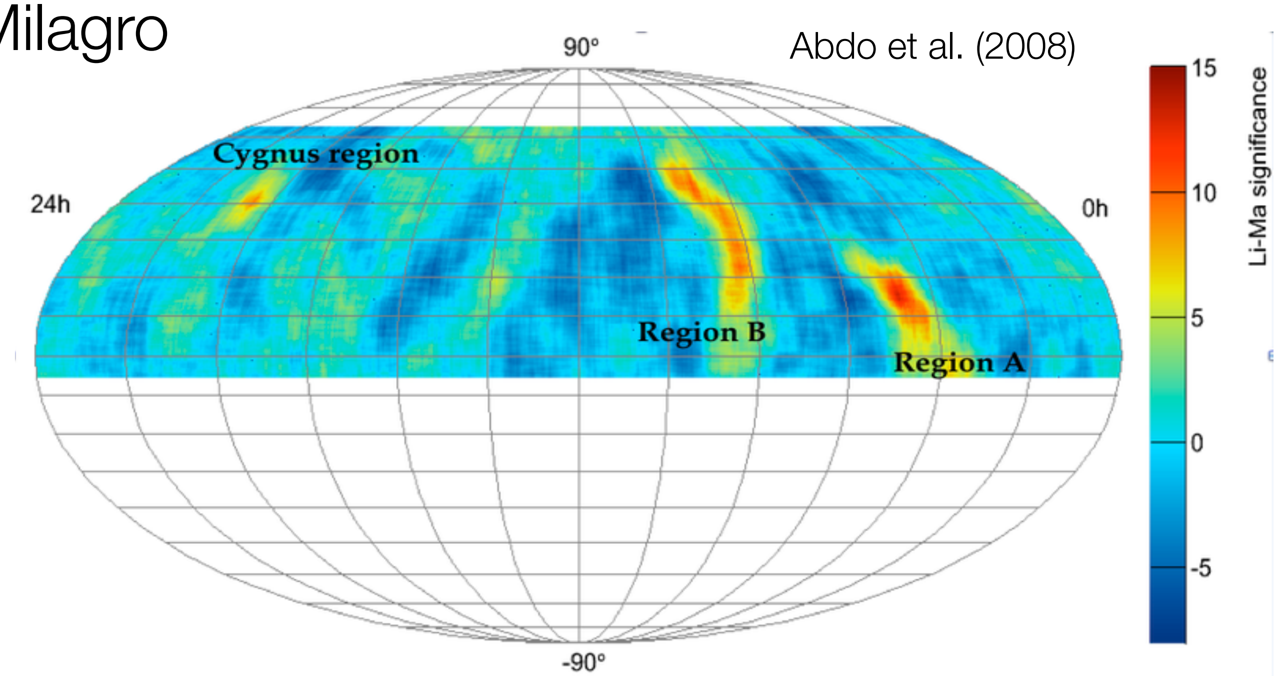


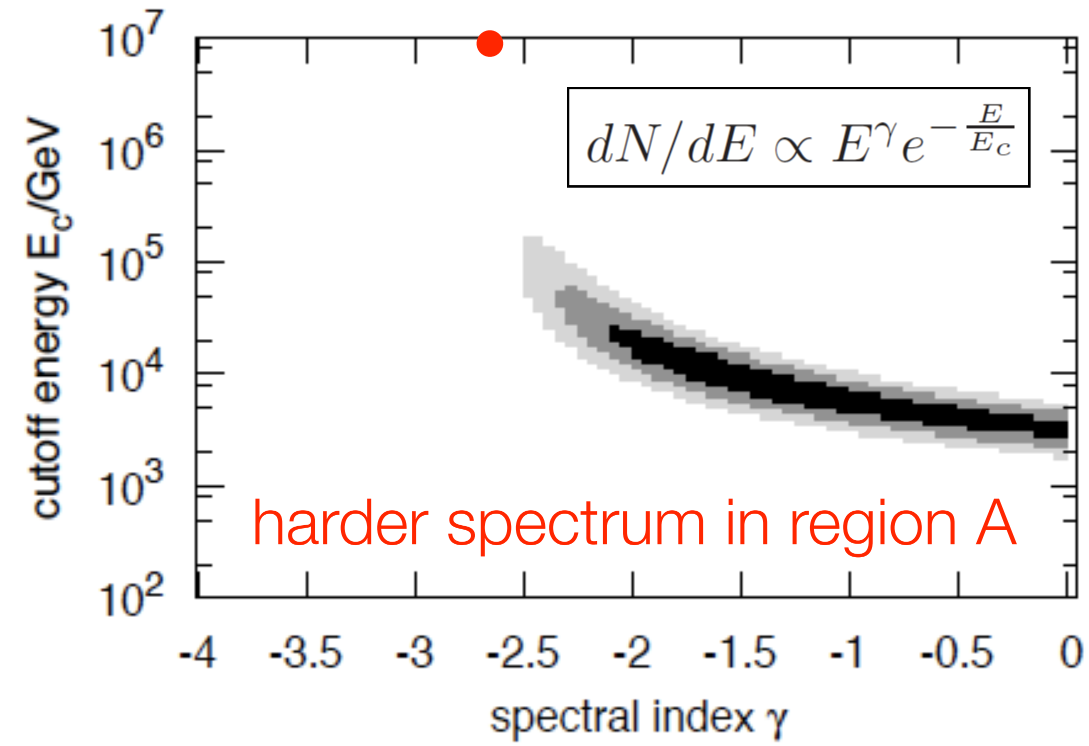
high energy cosmic rays
anisotropy & energy spectrum

HAWC results by S. BenZvi

Milagro

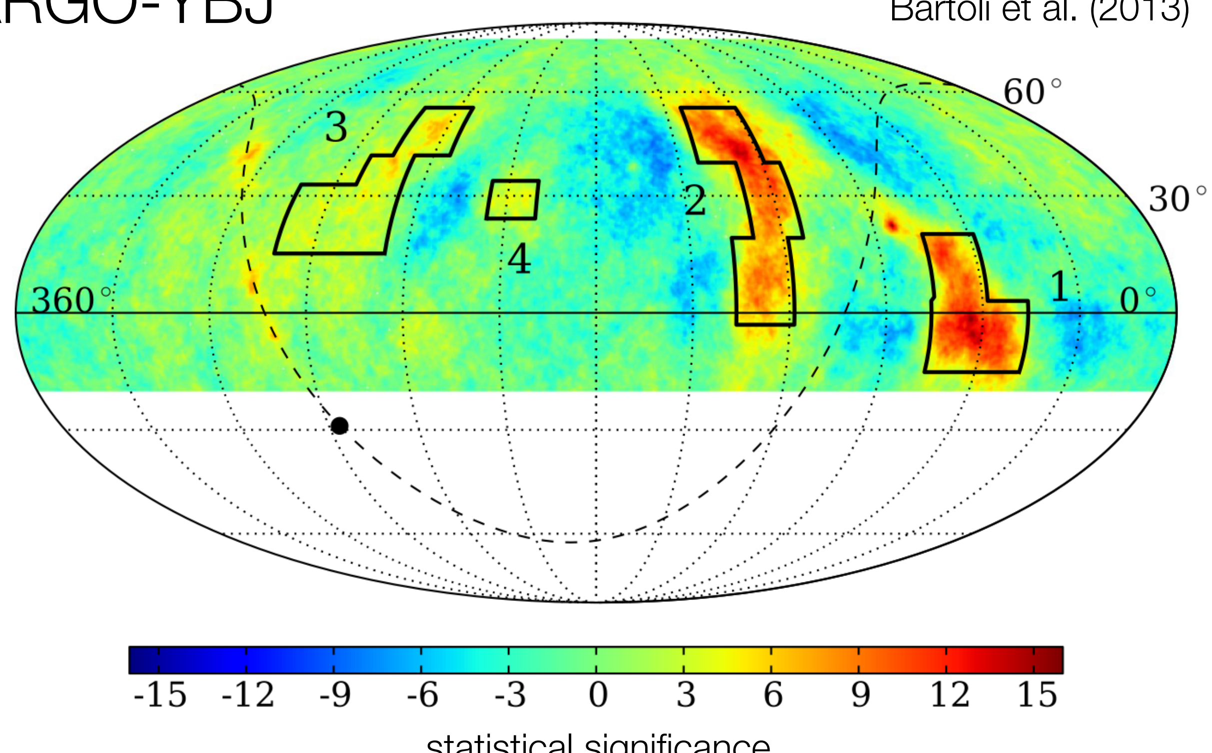
Abdo et al. (2008)

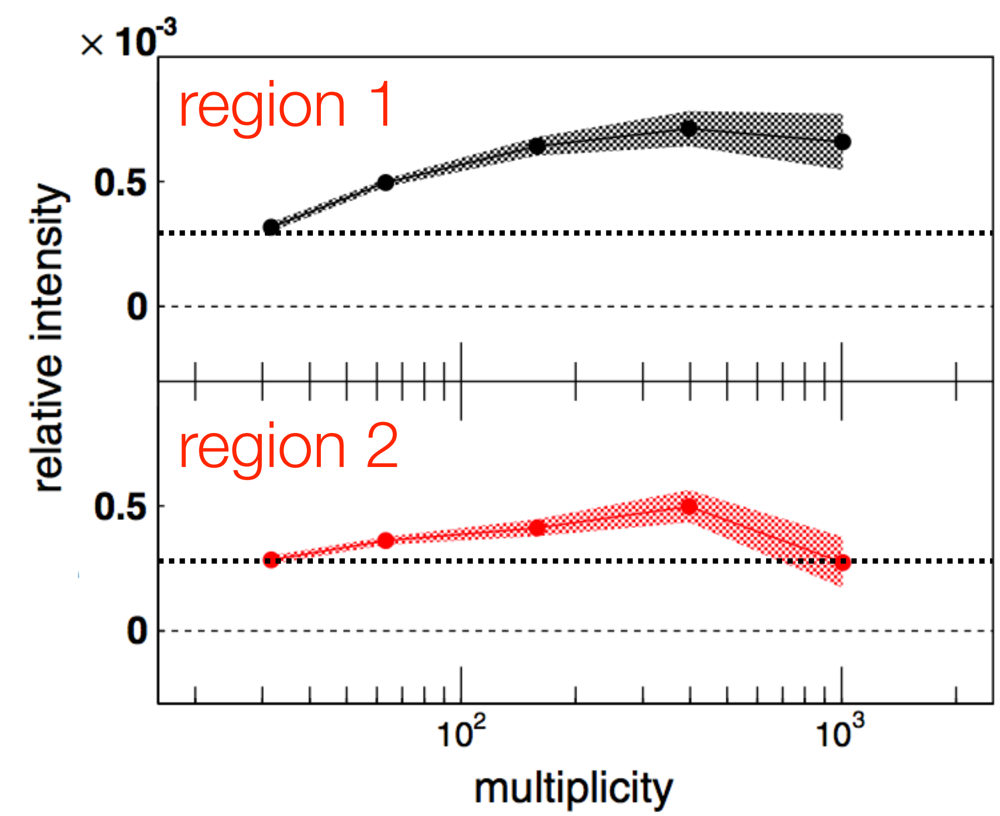




ARGO-YBJ

Bartoli et al. (2013)



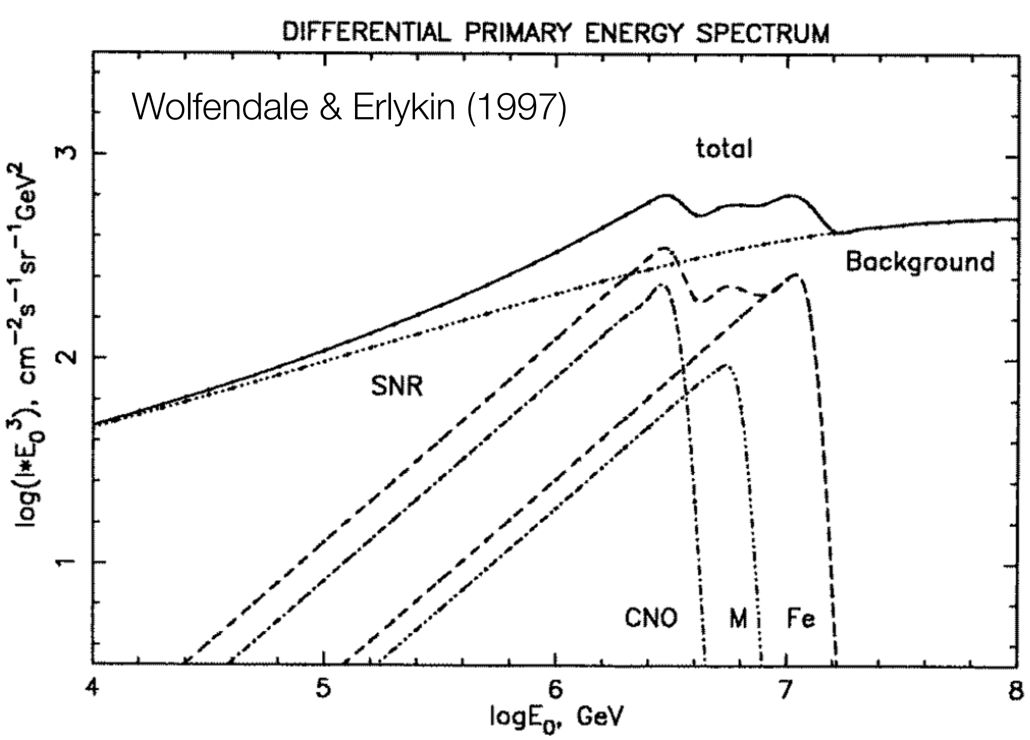


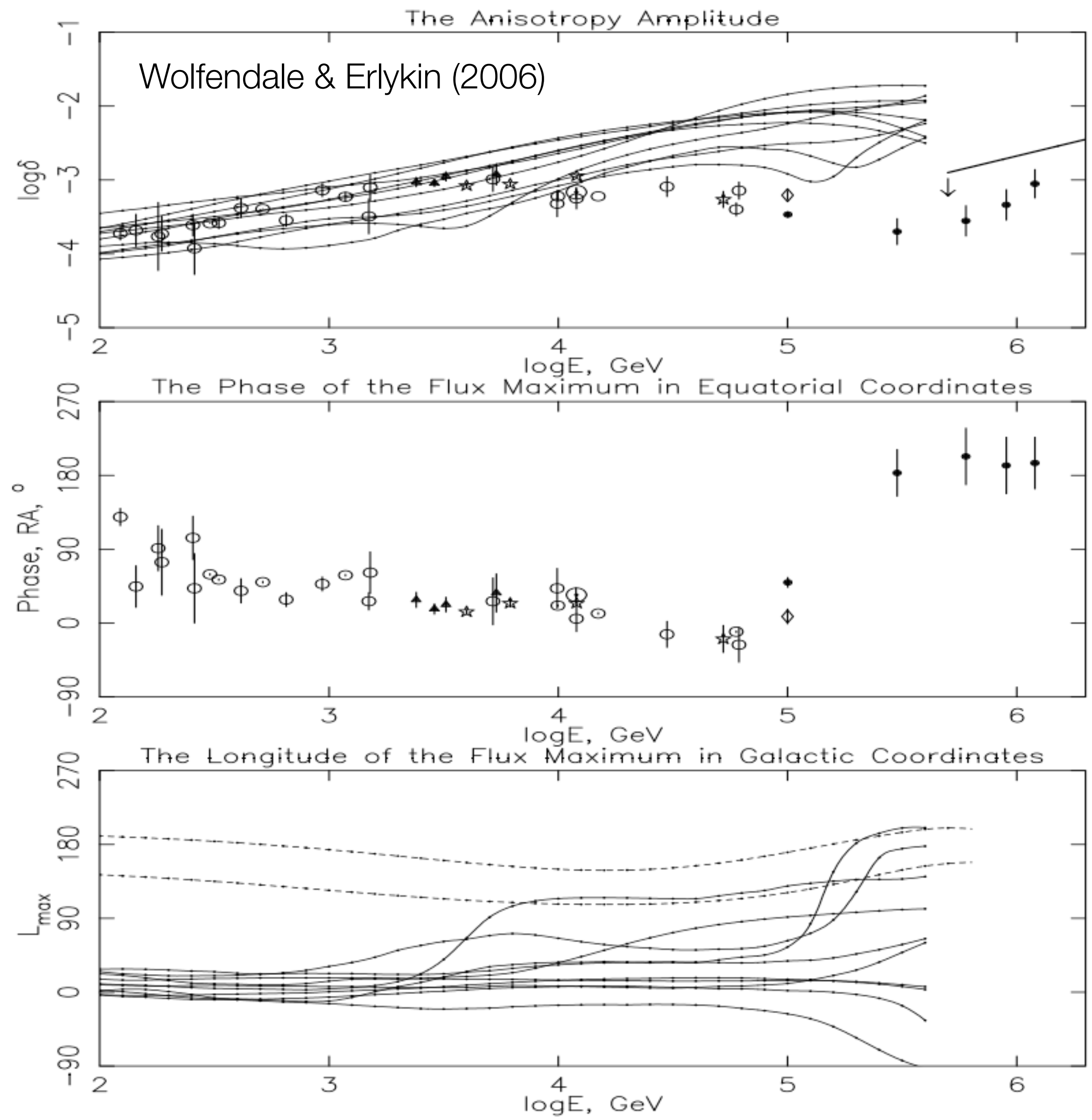
astrophysics of cosmic ray anisotropy

probing sources & propagation of cosmic rays ?

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

Erlykin & Wolfendale, Astropart. 2006
Blasi & Amato, 2011
Ptuskin+, 2012
Pohl & Eichler, 2012
Sveshnikova+, 2013
Kumar & Eichler, 2014
Mertsch & Funk, 2014





single source hypothesis ***explaining*** **spectral structure & anisotropy connections ?**

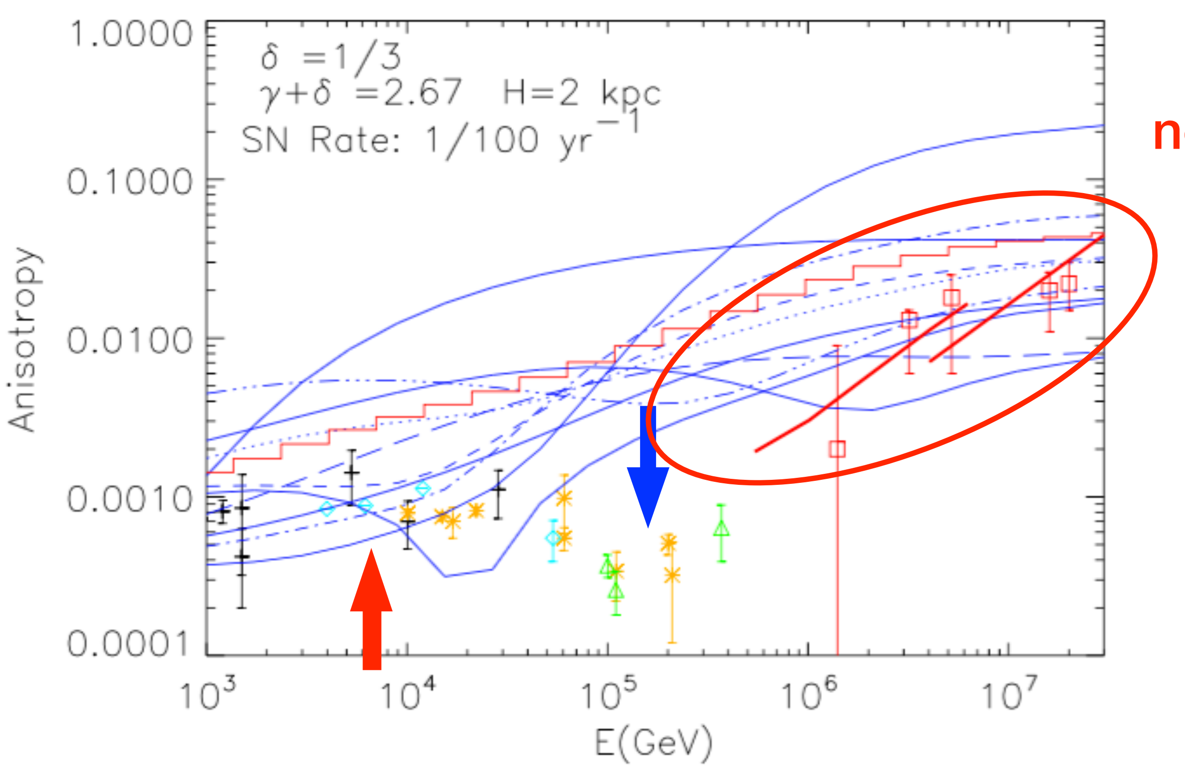
astrophysics of cosmic ray anisotropy

probing sources & propagation of cosmic rays ?

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

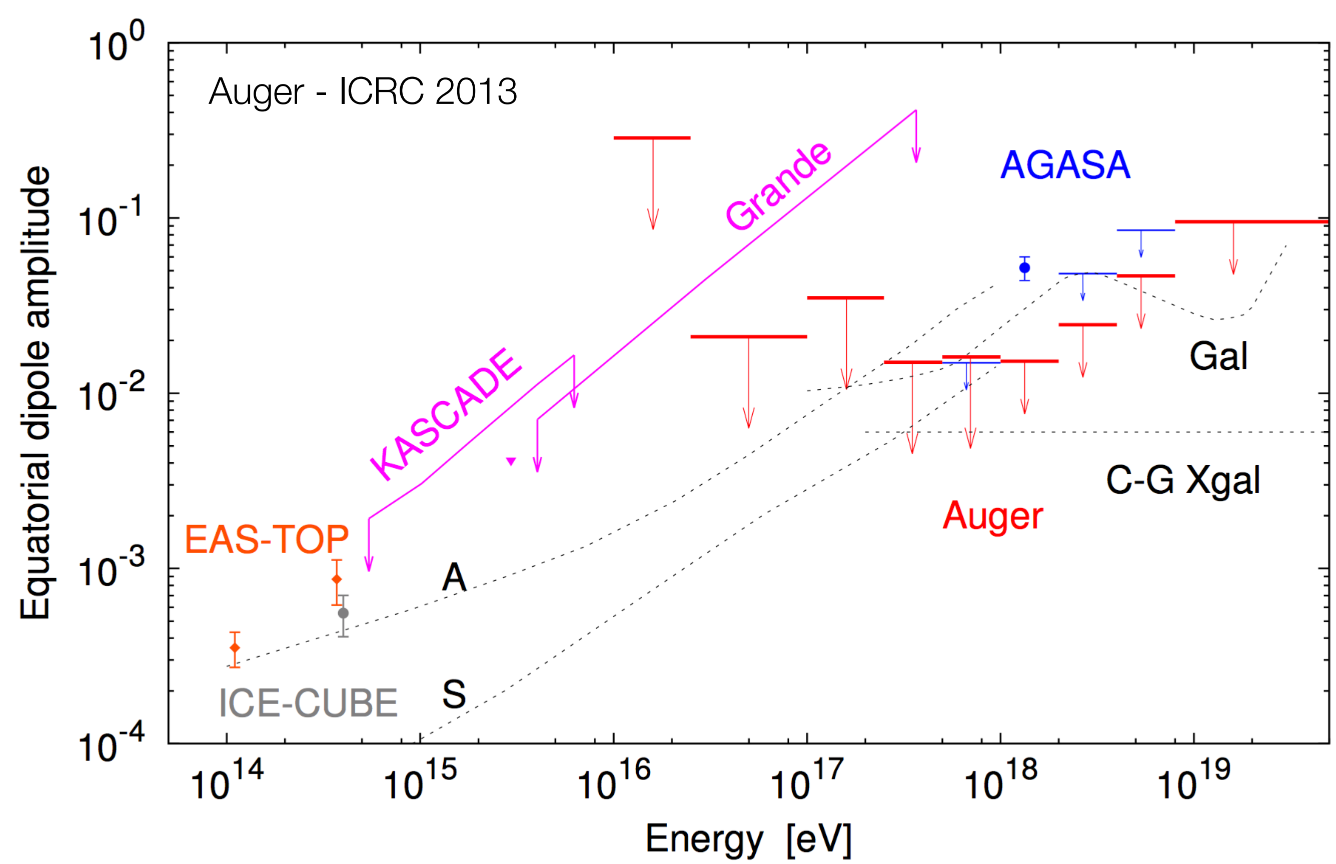
Erlykin & Wolfendale, Astropart. 2006
Blasi & Amato, 2011
Ptuskin+, 2012
Pohl & Eichler, 2012
Sveshnikova+, 2013
Kumar & Eichler, 2014
Mertsch & Funk, 2014

dipole amplitude **Blasi & Amato, 2011**



not dipole observations

dipole components of the anisotropy typically overestimated by models

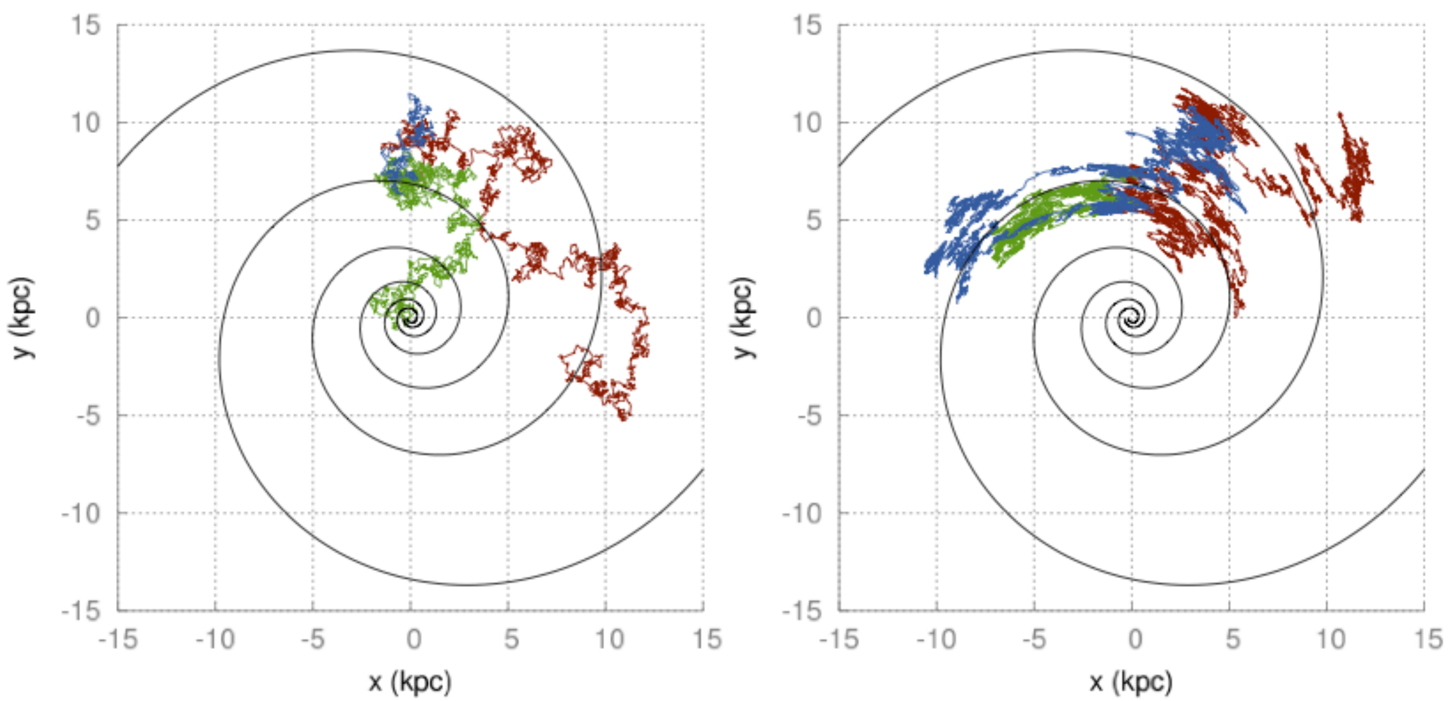


Paolo Desiati

cosmic ray anisotropy
probing diffusion properties

anisotropic diffusion

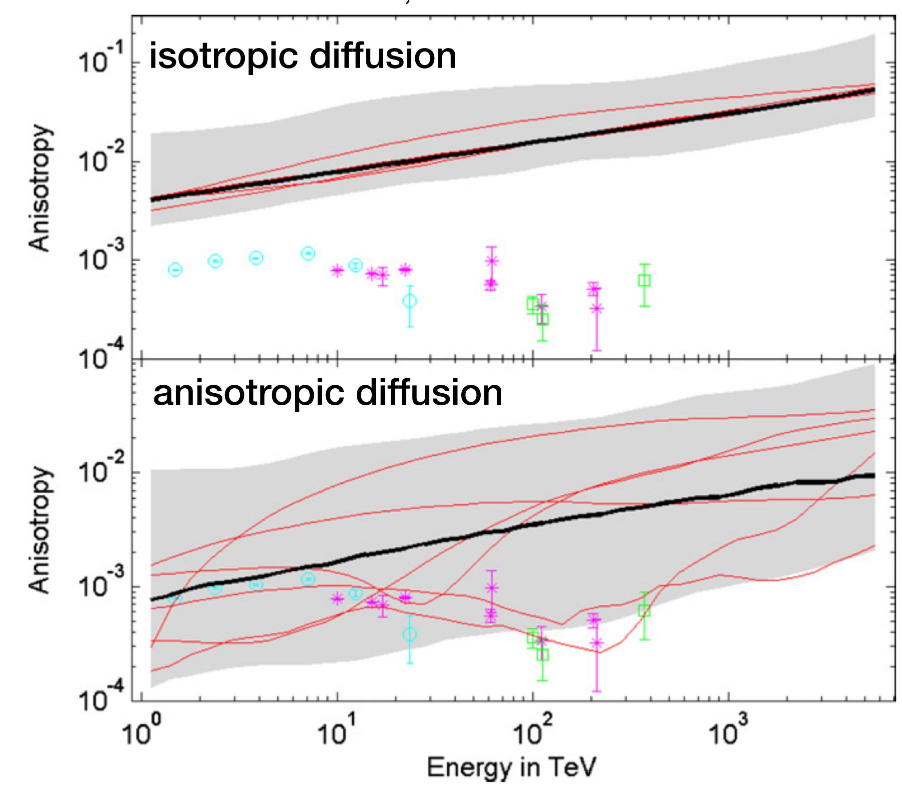
Effenberger+, 2012



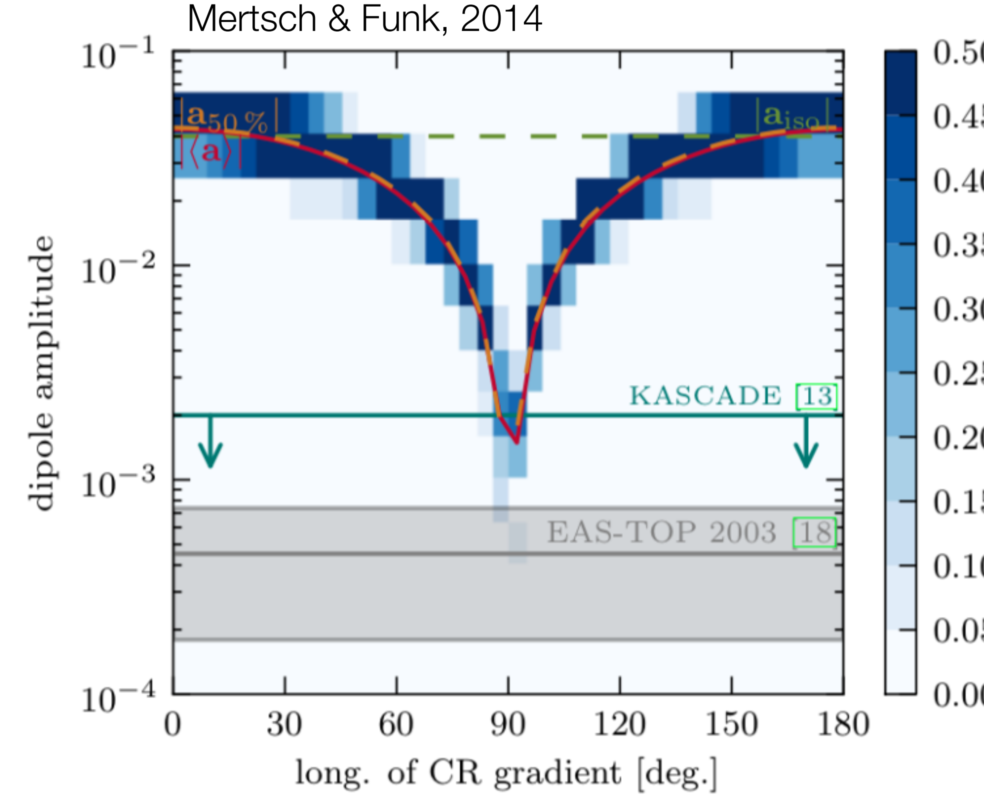
- **D⊥/D∥ << 1** - parallel projection of anisotropy
- cosmic ray **sources concealed** by propagation effects

diffusion coefficient hardly a single power law, homogeneous and isotropic

Kumar & Eichler, 2014



Mertsch & Funk, 2014

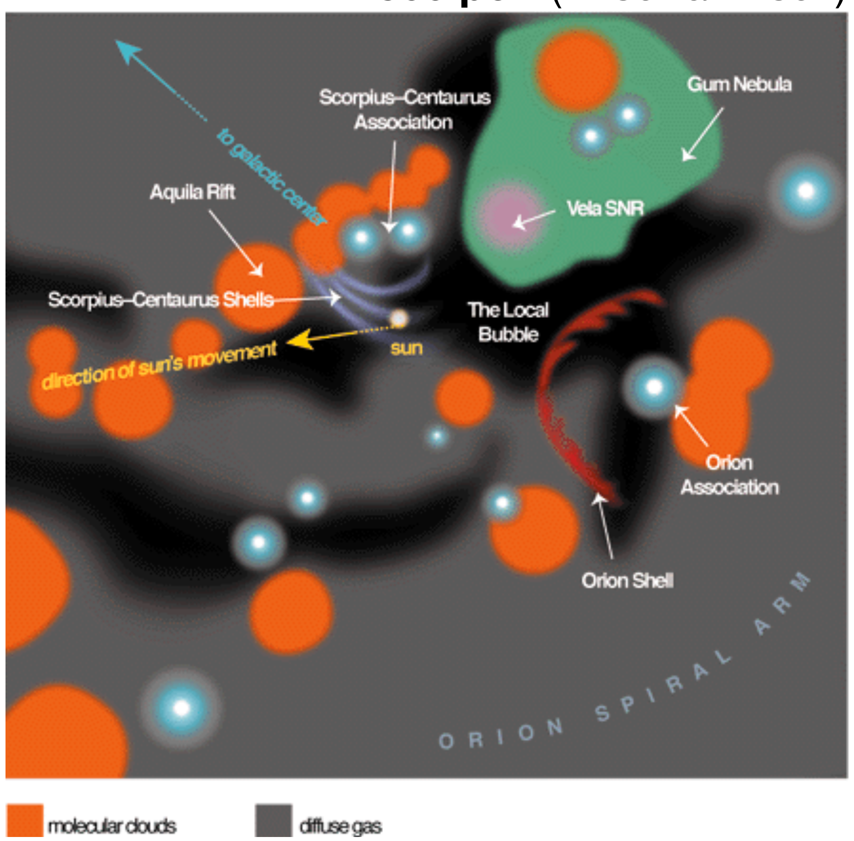


cosmic ray anisotropy
local interstellar medium

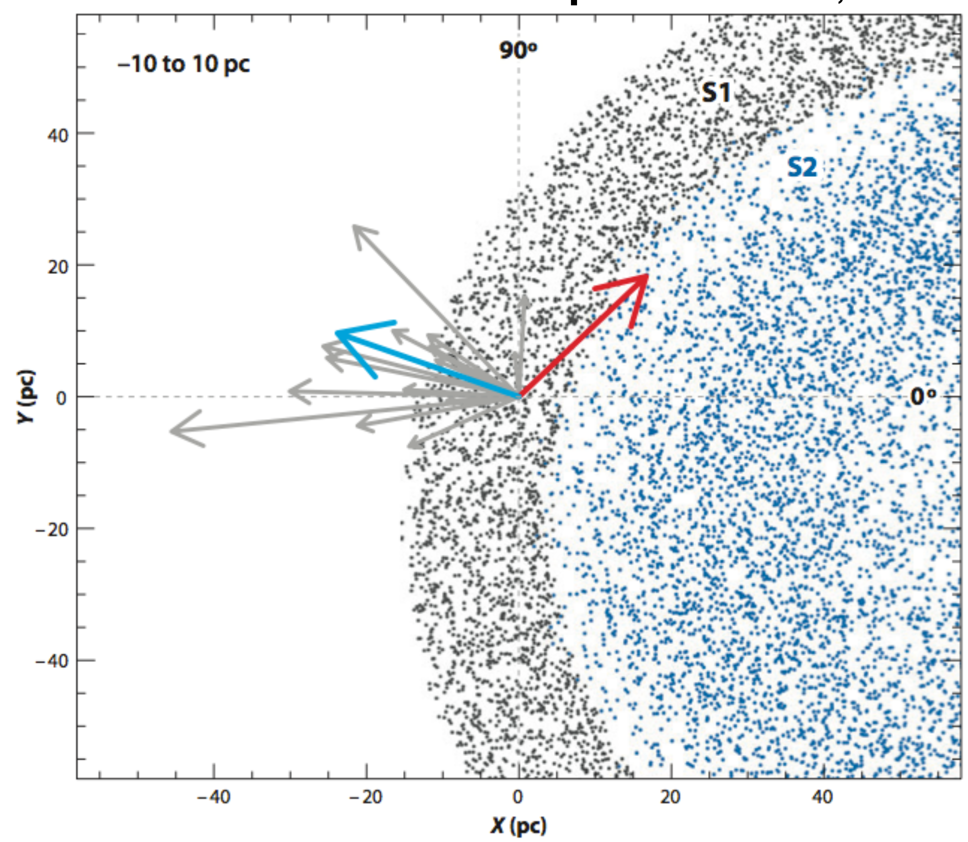
local ISMF shaped by LOOP I expansion sub-shell (with center ~60 pc away in Scorpius-Centaurus OB Association)

local cloudlets fragments of the shell moving at similar velocities

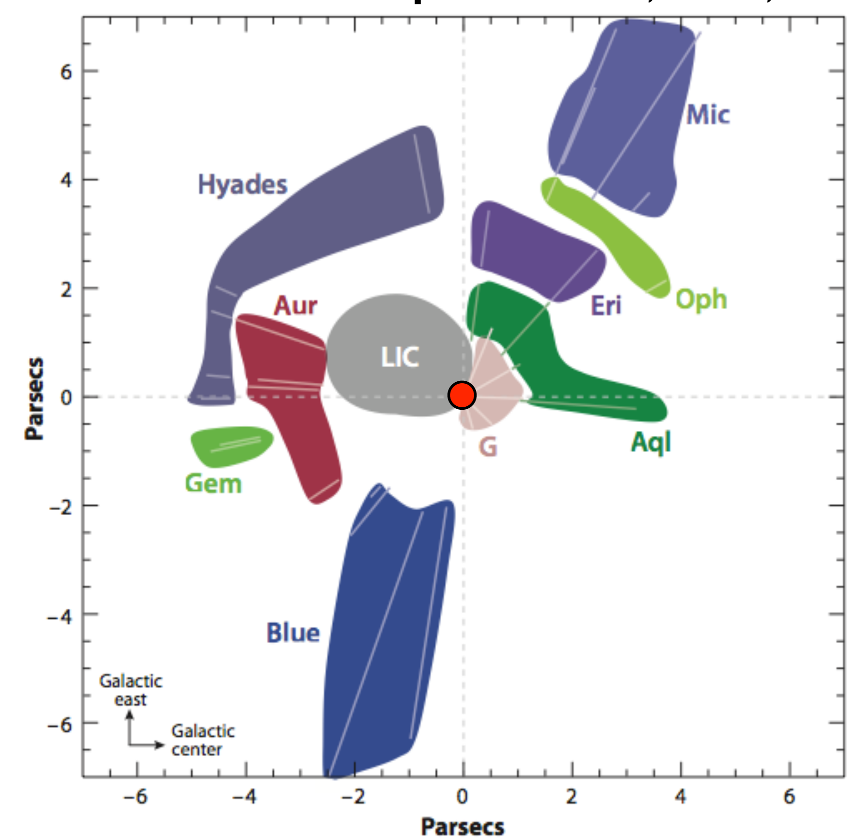
500 pc - (Priscilla Frisch)



100 pc - Wolleben, 2007



14 pc - Frisch+, 2011, 14



- interstellar magnetic field affected by inhomogeneities

Redfield & Linsky, 2008

Frisch+, 2011

- local ISMF relatively uniform over spacial scales of order 60-100 pc (**inter-arm**)

Frisch+, 2012

- magnetic turbulence affects propagation and diffusion properties

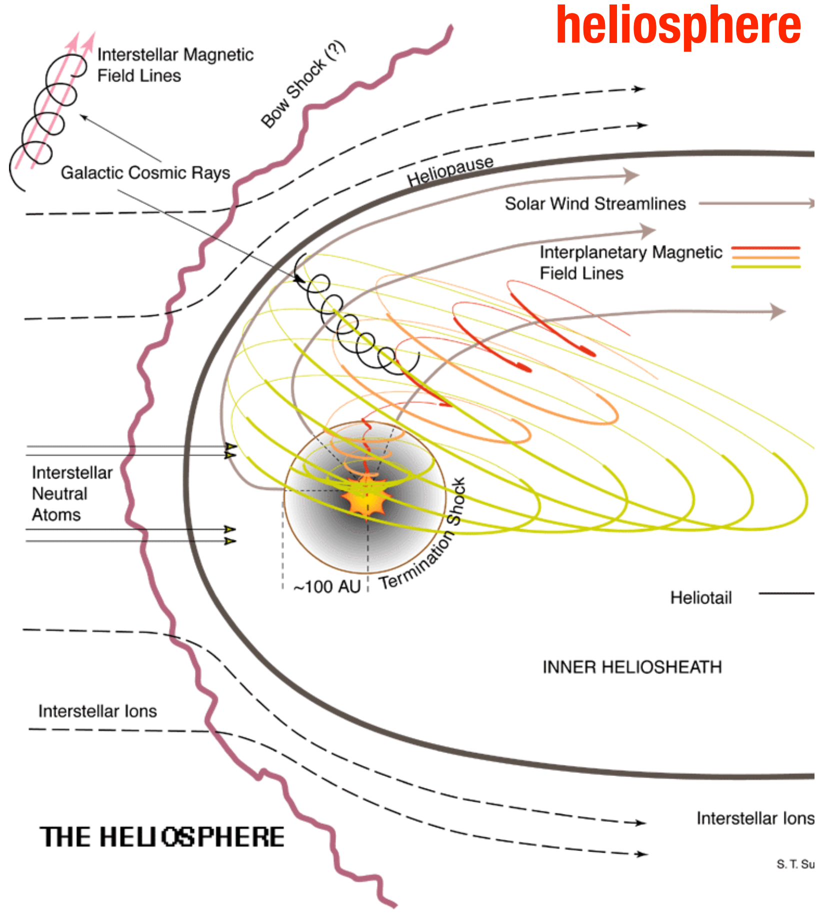
Giacalone & Jokipii, 1994, 99
Yan, Lazarian, 2002,04,08

cosmic ray anisotropy

heliosphere

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

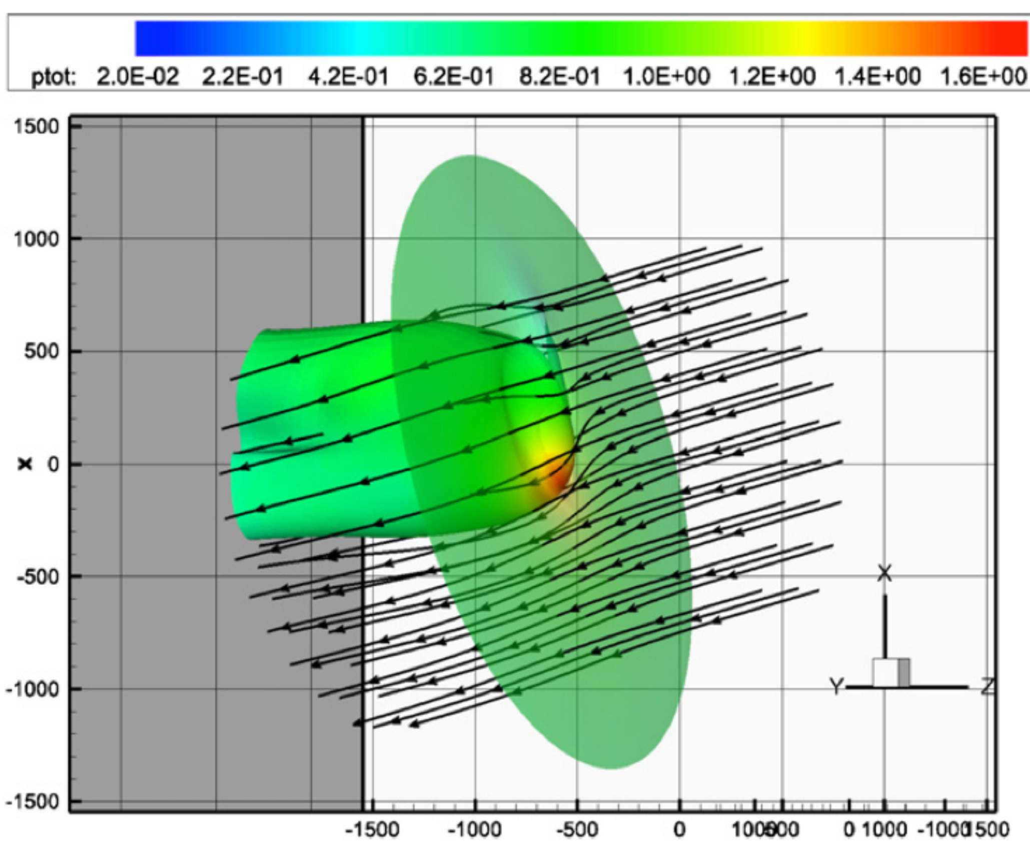
heliosphere



heliotail

local ISMF draping around heliosphere

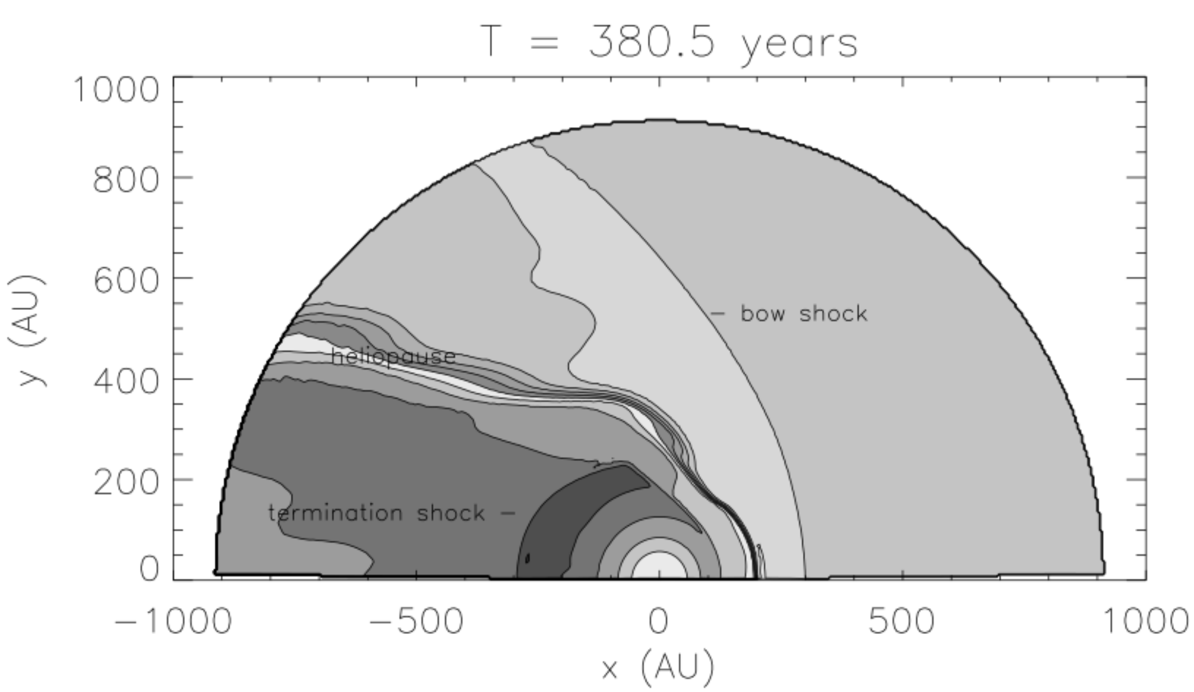
Pogorelov+ 2011



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

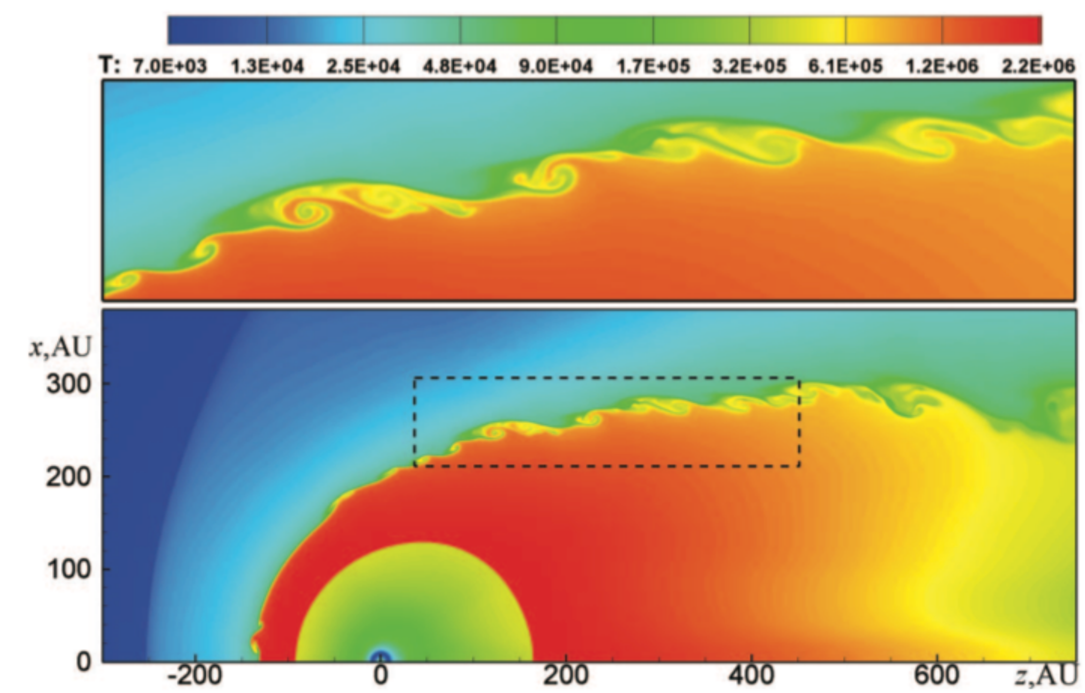
heliospheric perturbations
heliopause instabilities

- Rayleigh-Taylor instabilities driven and mediated by interstellar neutral atoms



Liewer+ 1996
Zank+ 1996

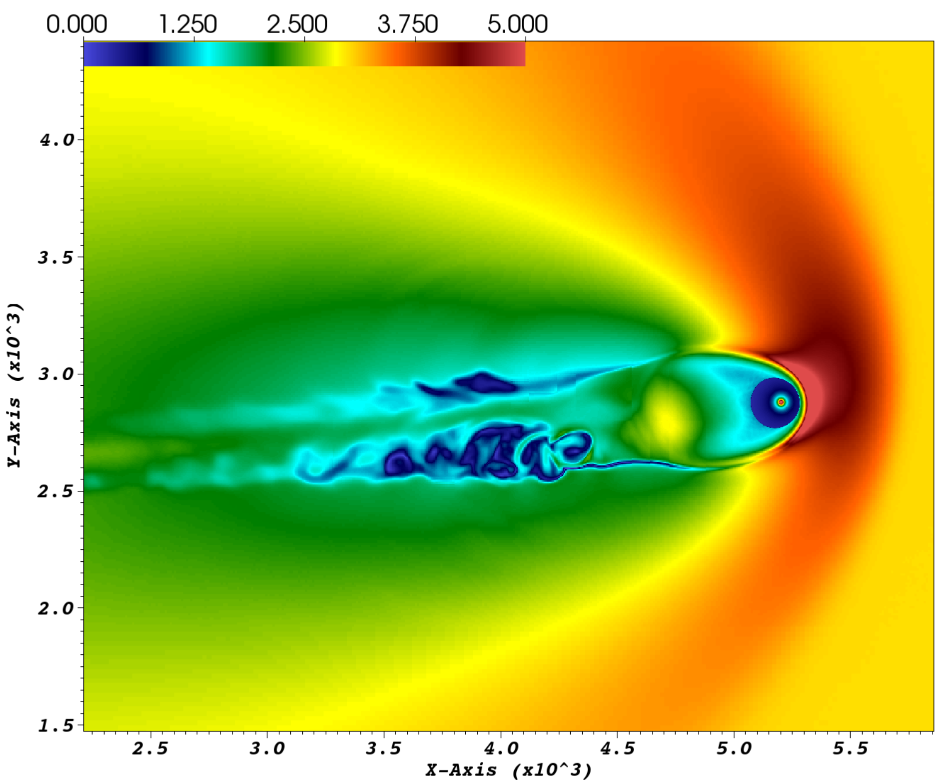
- plasma-fluid instabilities at the flank of HP by charge exchange processes



Zank 1999
Florinski++ 2005
Borovikov+ 2008
Zank 2009
Shaikh & Zank 2010

cosmic ray anisotropy

probing heliospheric magnetic structure

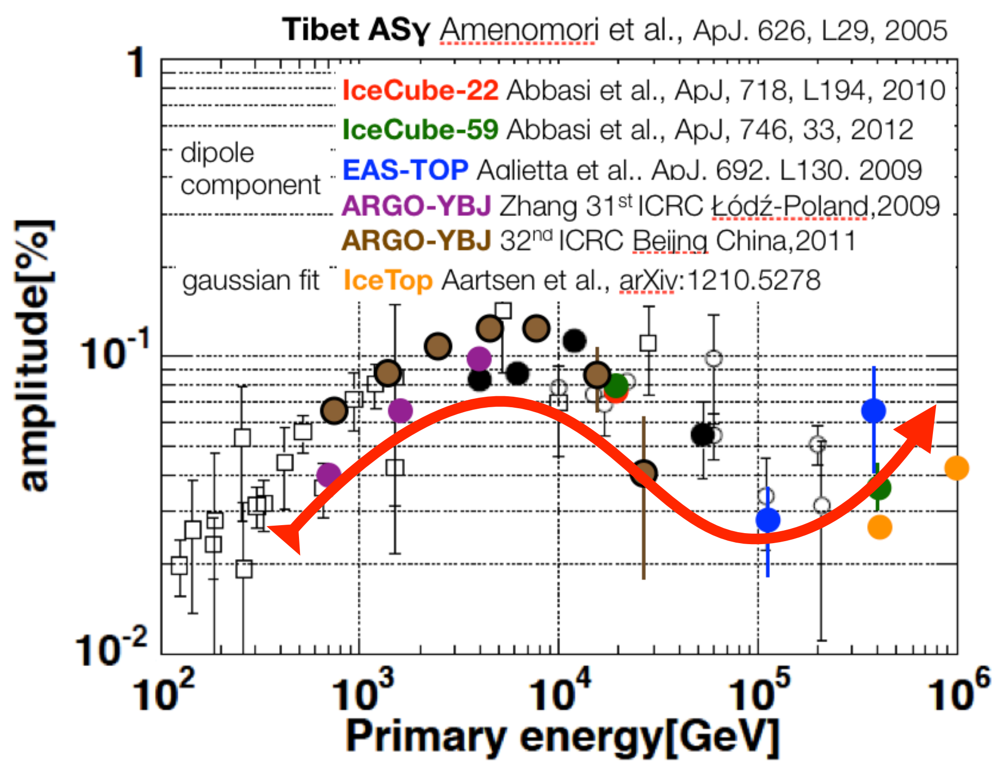


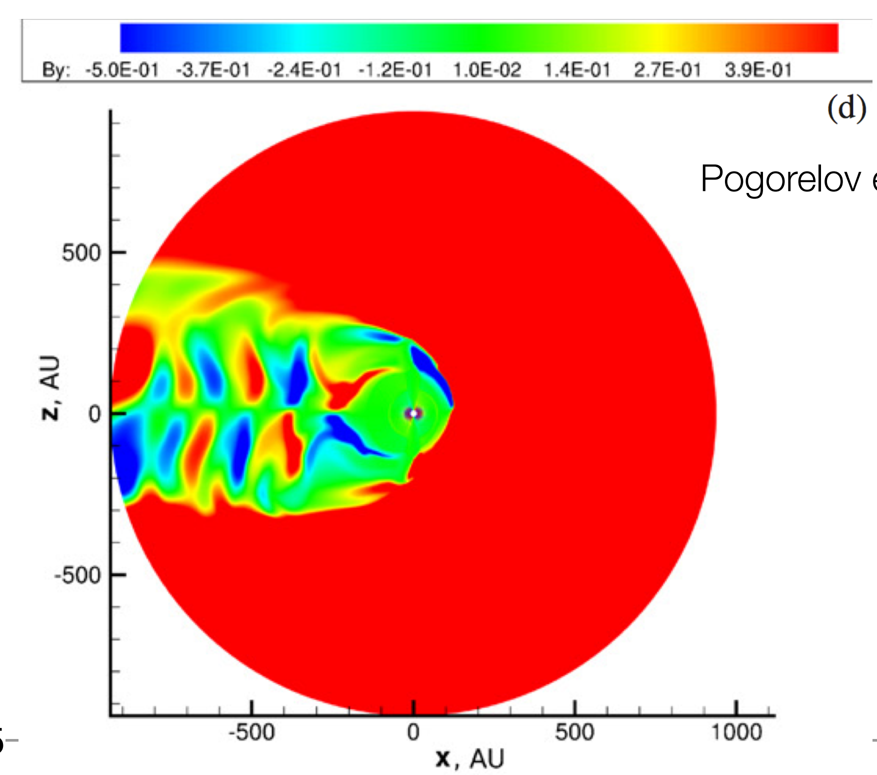
Borovikov, Heerikhuisen, Pogorelov

downstream instabilities on the flanks of heliotail

PD & Lazarian 2013

López-Barquero, Xu, PD, Lazarian





Pogorelov et al., 2009

effects of magnetic polarity reversals from solar cycles

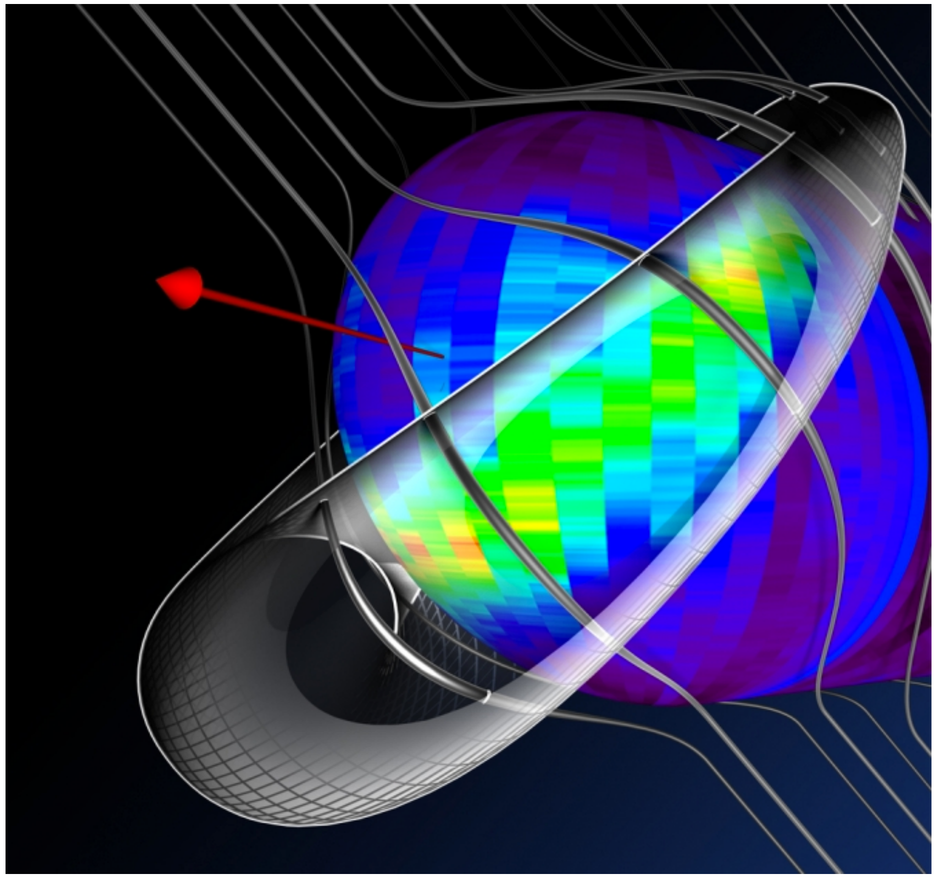
magnetic reconnection

Lazarian & PD 2010
PD & Lazarian 2012

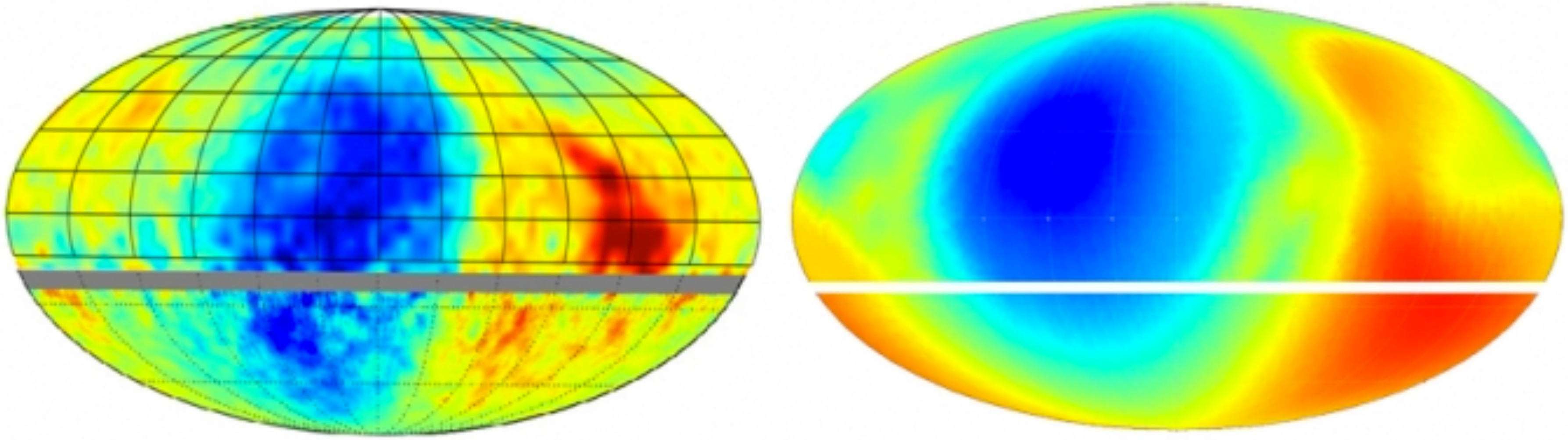
anisotropy and local galactic environment
low to high energy connection

- IBEX observations of keV Energetic Neutral Atoms
- determination of interstellar flow direction
- determination of interstellar magnetic field direction

- large scale heliosphere to induce **perturbations** in arrival direction of TeV cosmic rays



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

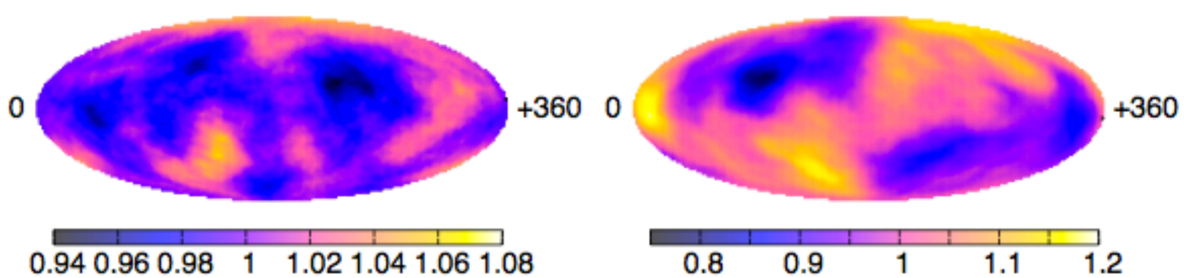


Zhang, Zuo & Pogorelov ApJ 790, 5 (2014)

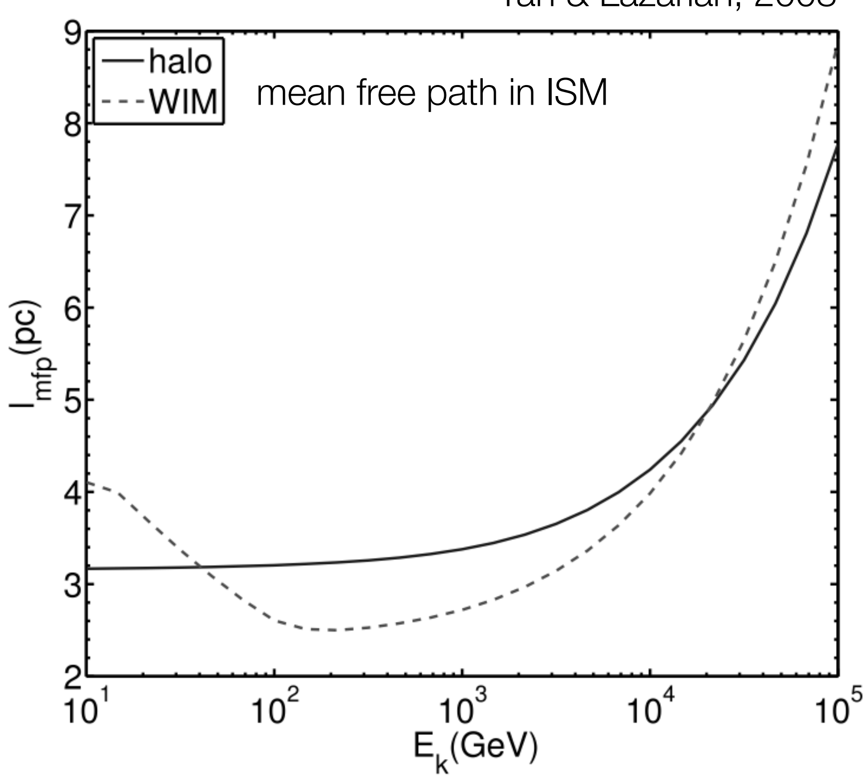
cosmic ray anisotropy
probing magnetic field turbulence ?

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

Giacinti & Sigl, 2012
Biermann+, 2012

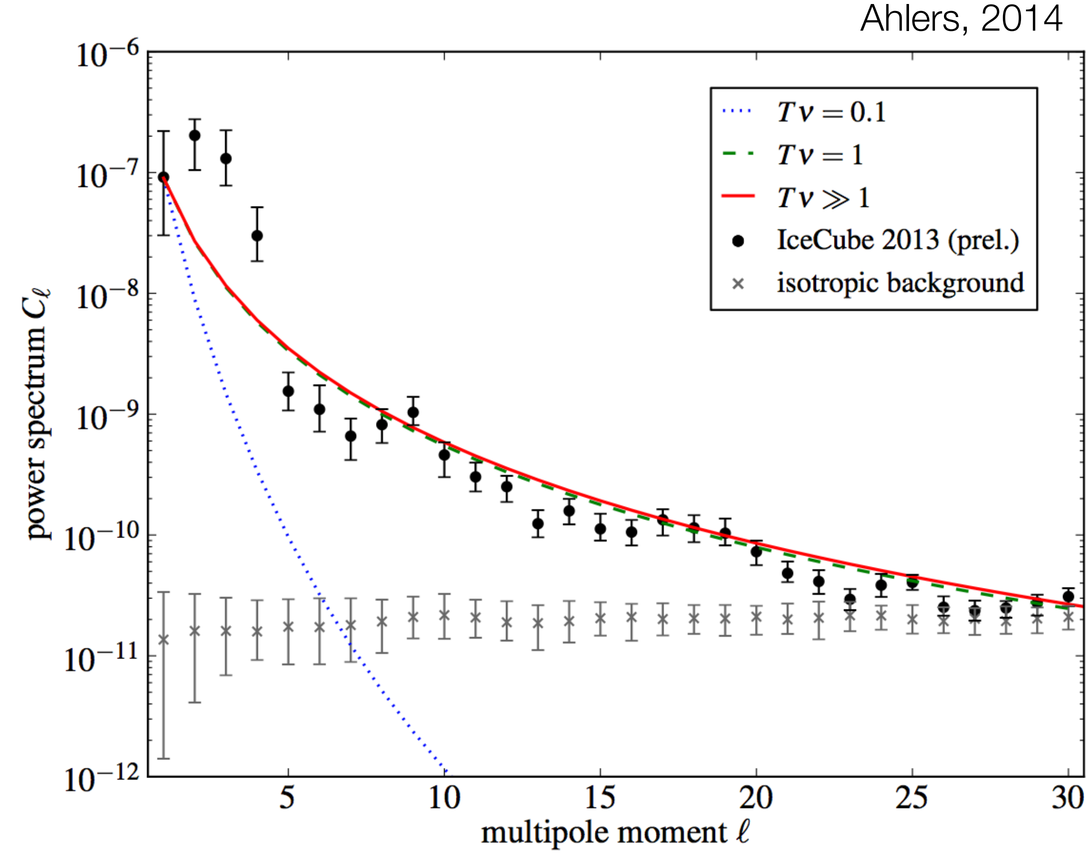


Yan & Lazarian, 2008

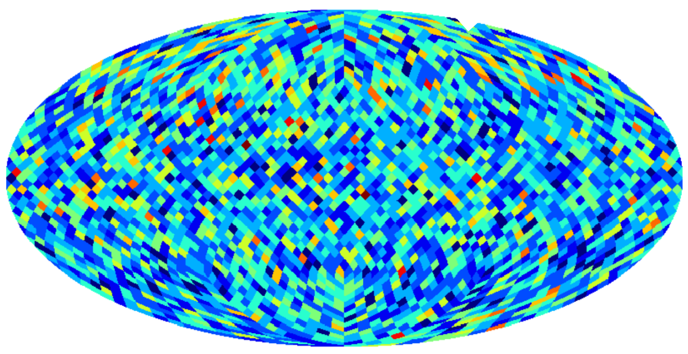


- angular structure of anisotropy spontaneously generated from a global dipole anisotropy as a consequence of Liouville Theorem in the presence of a local turbulent magnetic field (sum of multipoles is conserved)

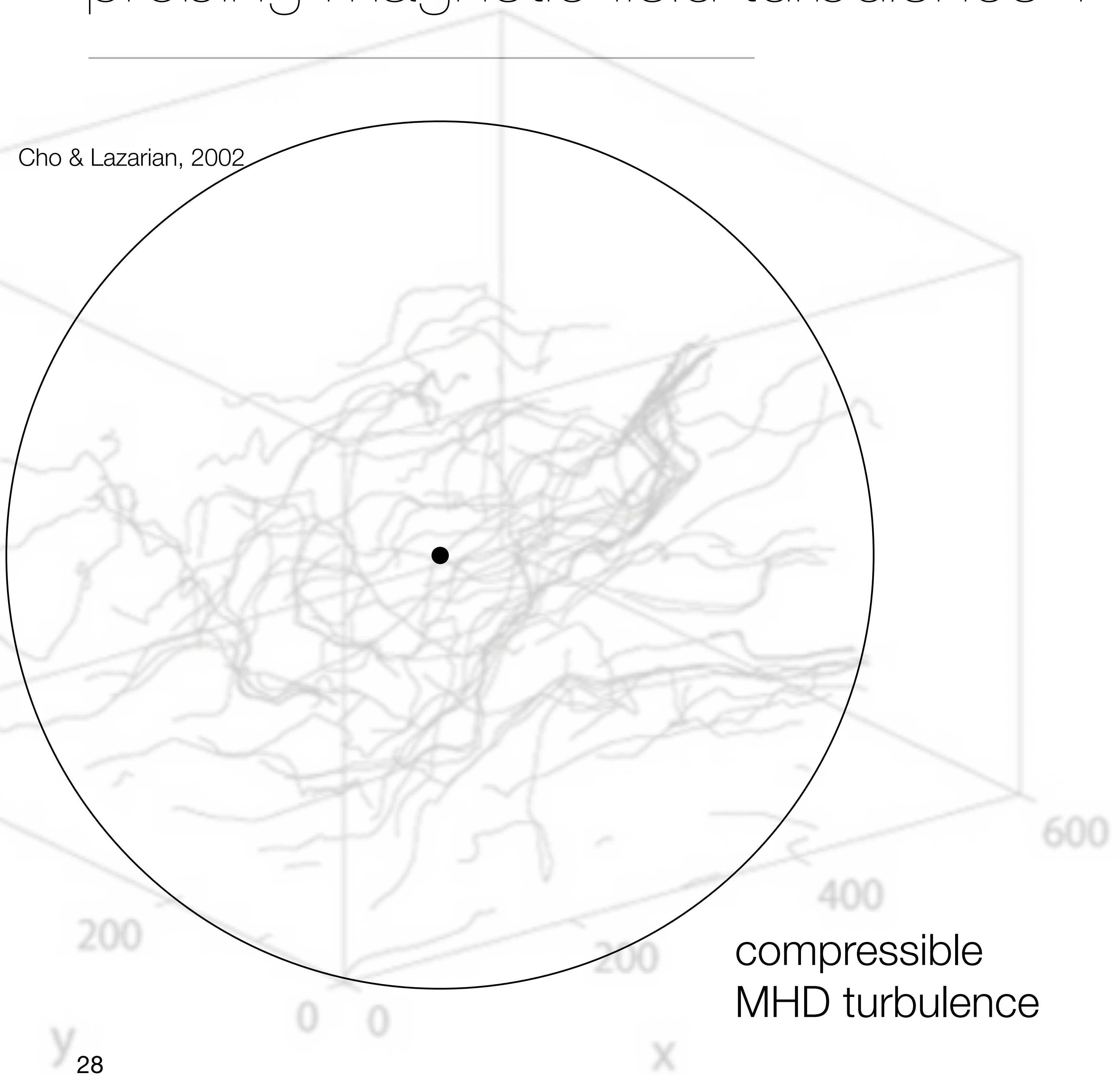
Ahlers, 2014



cosmic ray anisotropy
probing magnetic field turbulence ?

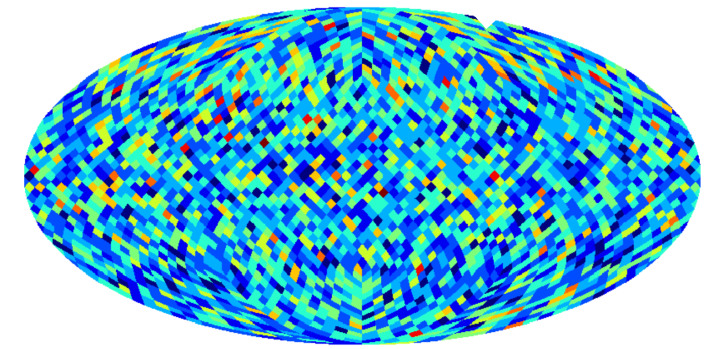


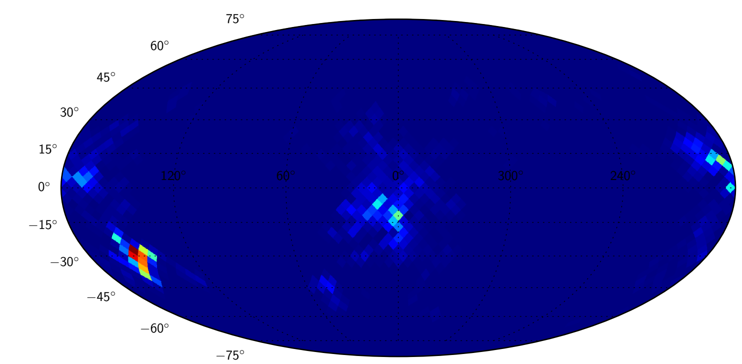
Cho & Lazarian, 2002



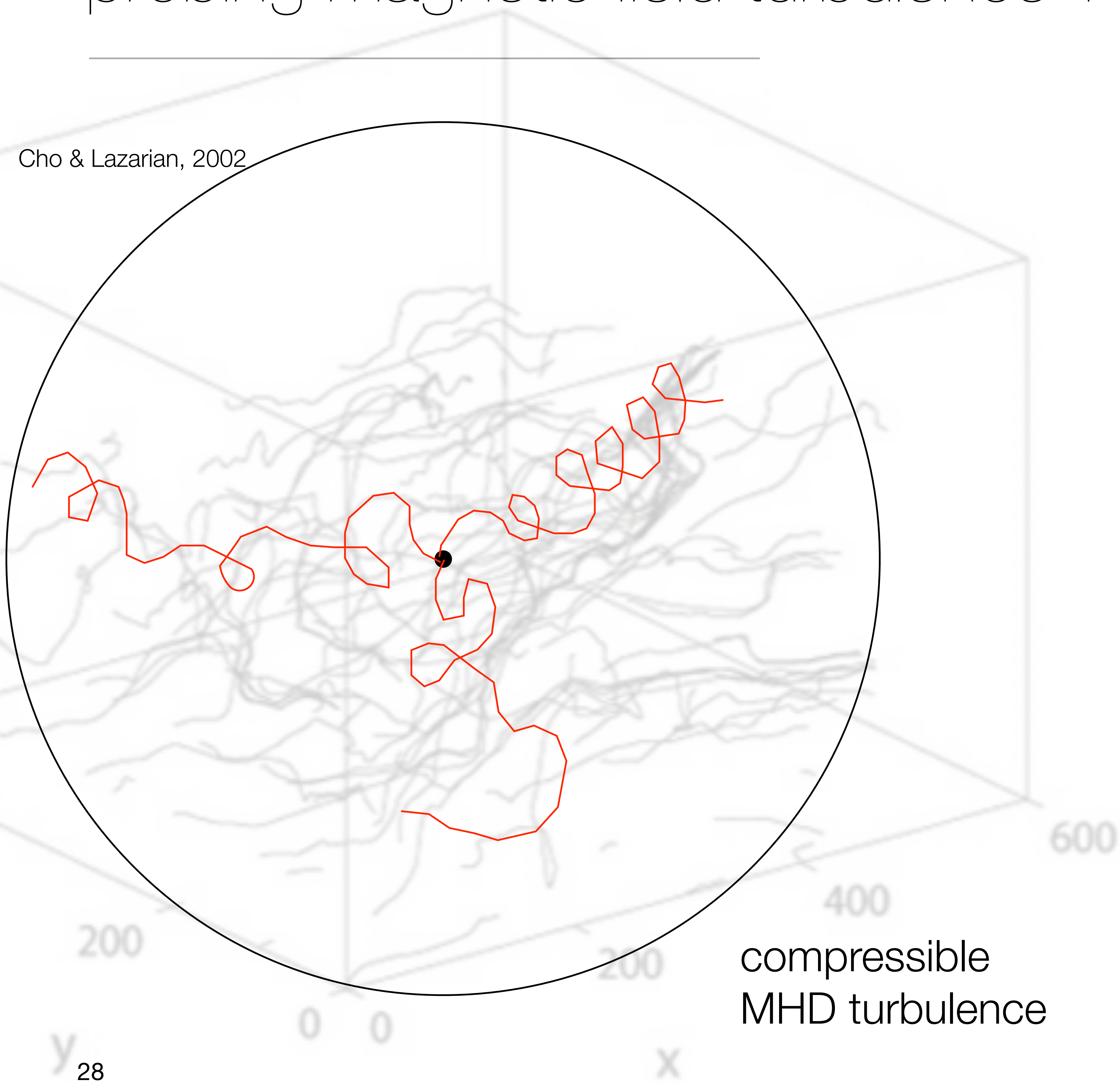
compressible
MHD turbulence

cosmic ray anisotropy
probing magnetic field turbulence ?



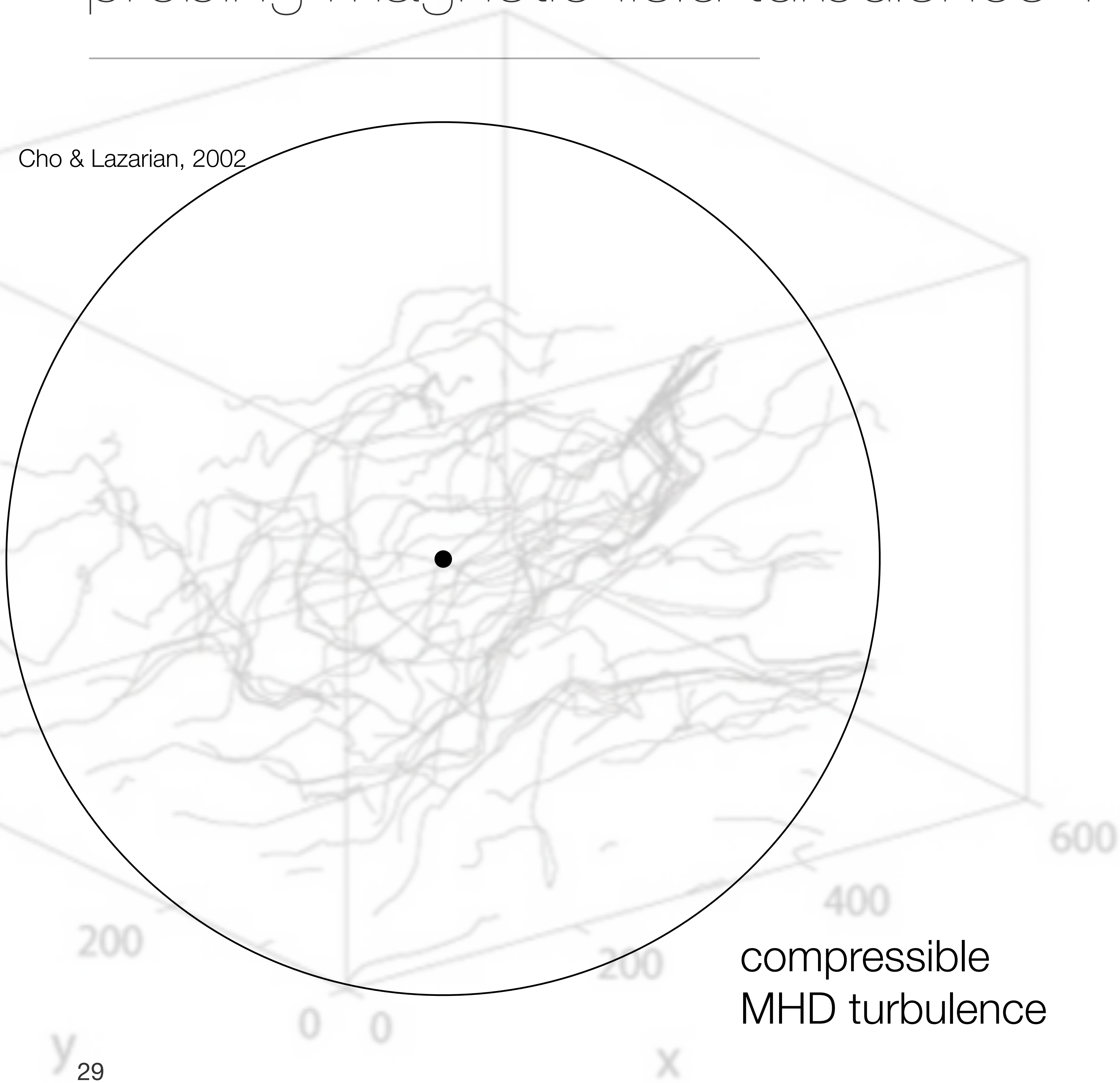


Cho & Lazarian, 2002



compressible
MHD turbulence

cosmic ray anisotropy
probing magnetic field turbulence ?



Cho & Lazarian, 2002

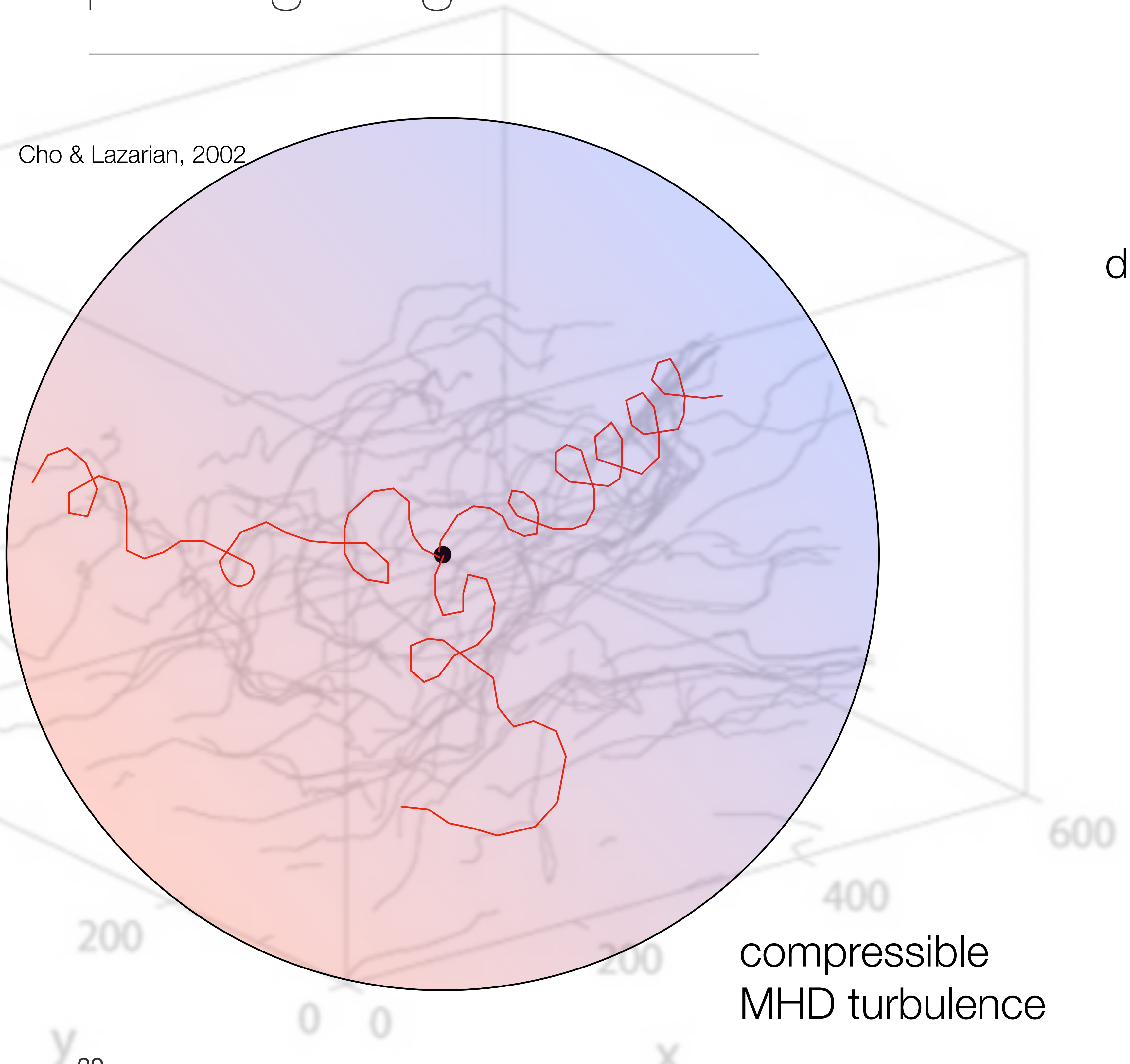
compressible
MHD turbulence

cosmic ray anisotropy
probing magnetic field turbulence ?

Liouville Theorem - time inversion

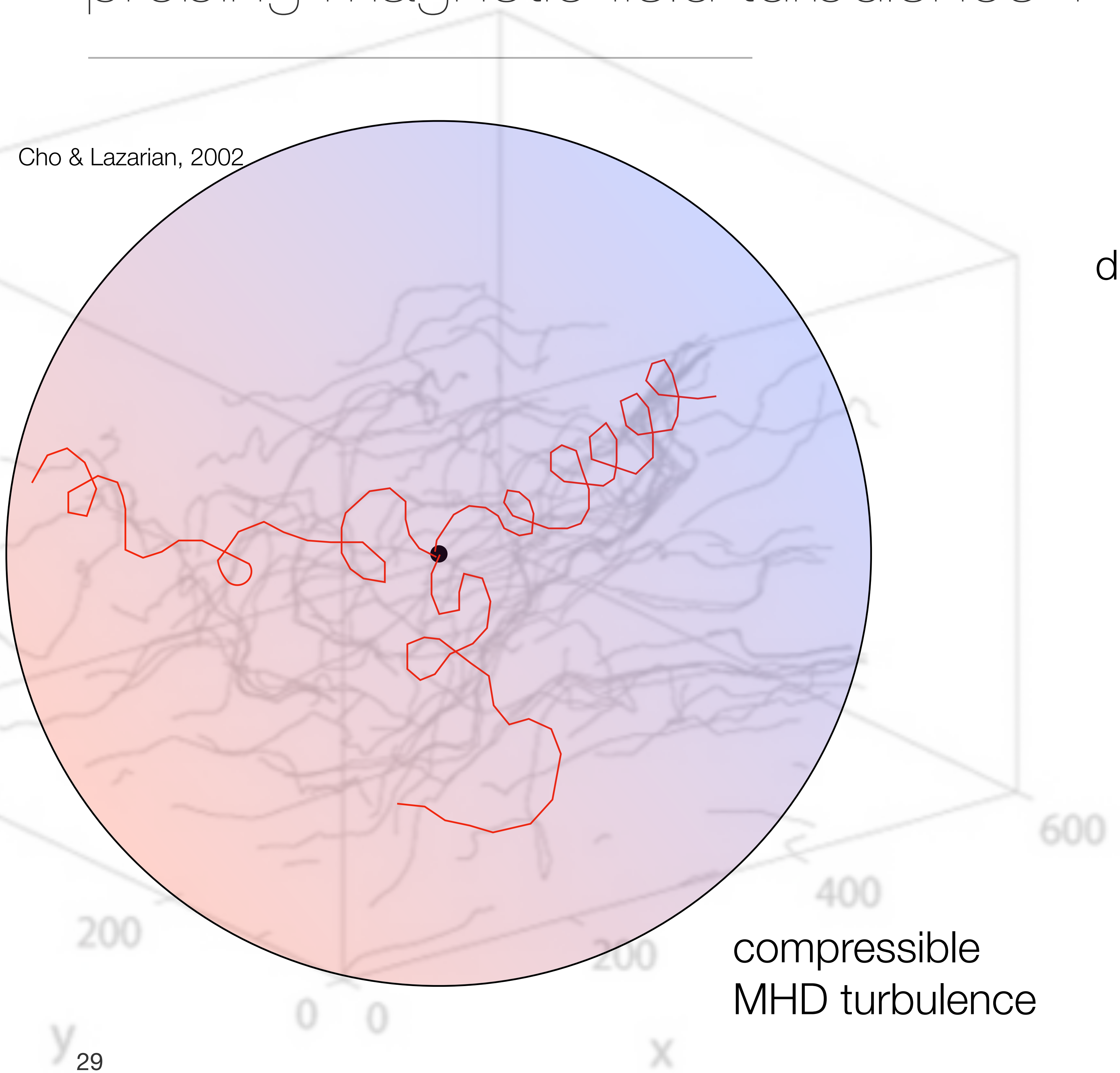
dipole distribution >> mean free path

Cho & Lazarian, 2002



compressible
MHD turbulence

cosmic ray anisotropy
probing magnetic field turbulence ?

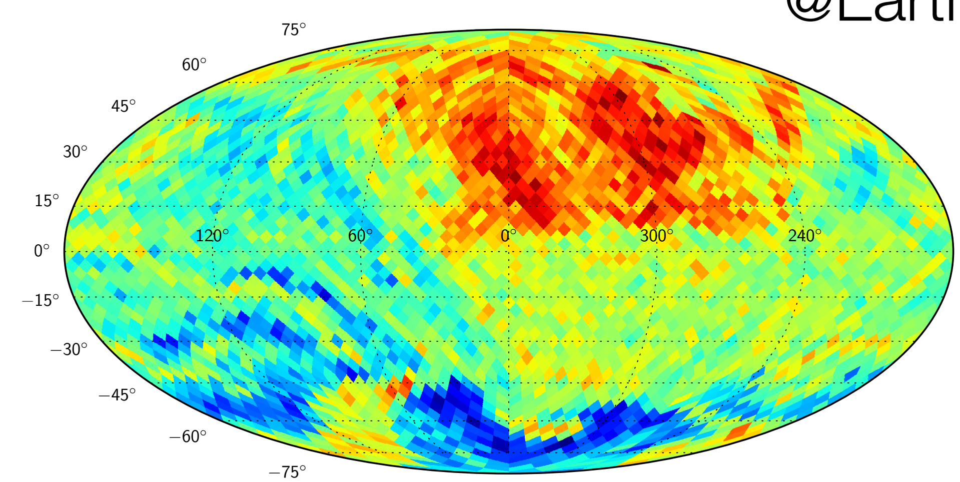


compressible
MHD turbulence

Liouville Theorem - time inversion

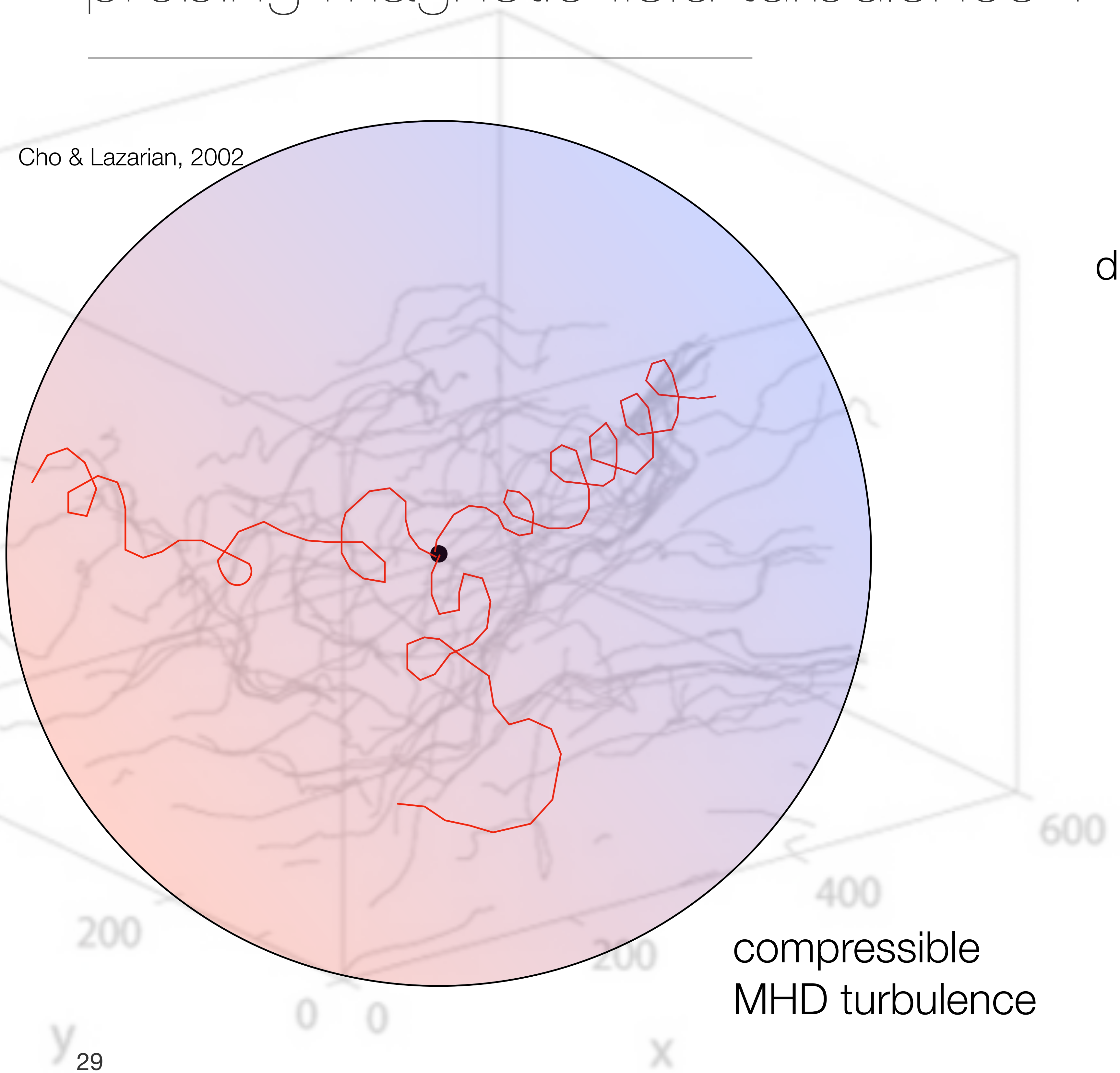
dipole distribution >> mean free path

@Earth



cosmic ray anisotropy
probing magnetic field turbulence ?

Cho & Lazarian, 2002

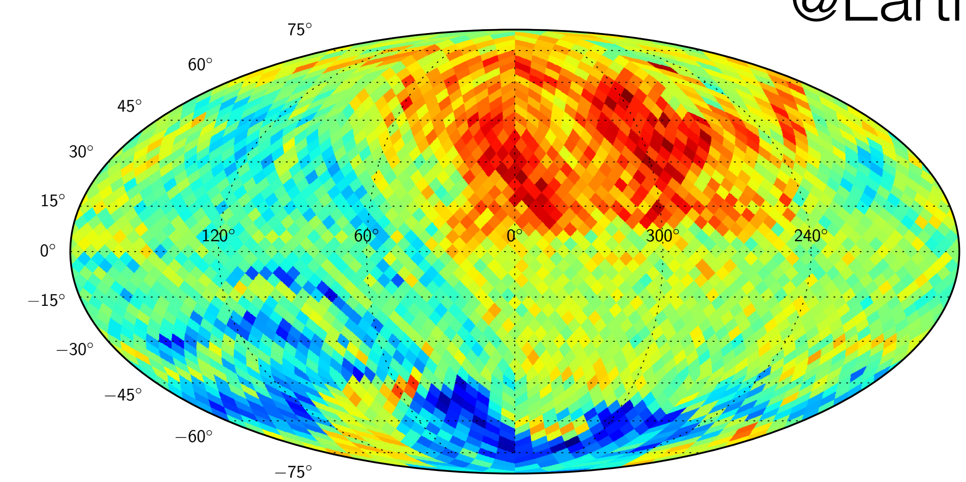


compressible
MHD turbulence

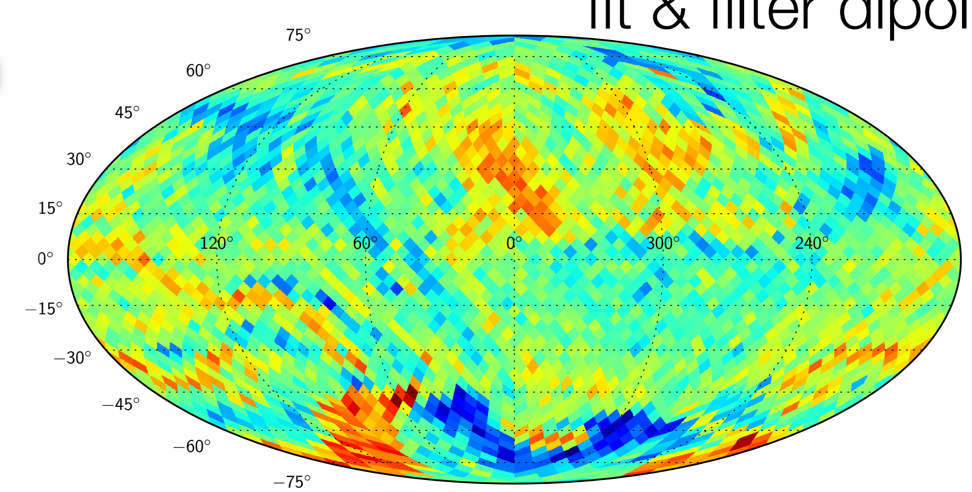
Liouville Theorem - time inversion

dipole distribution >> mean free path

@Earth



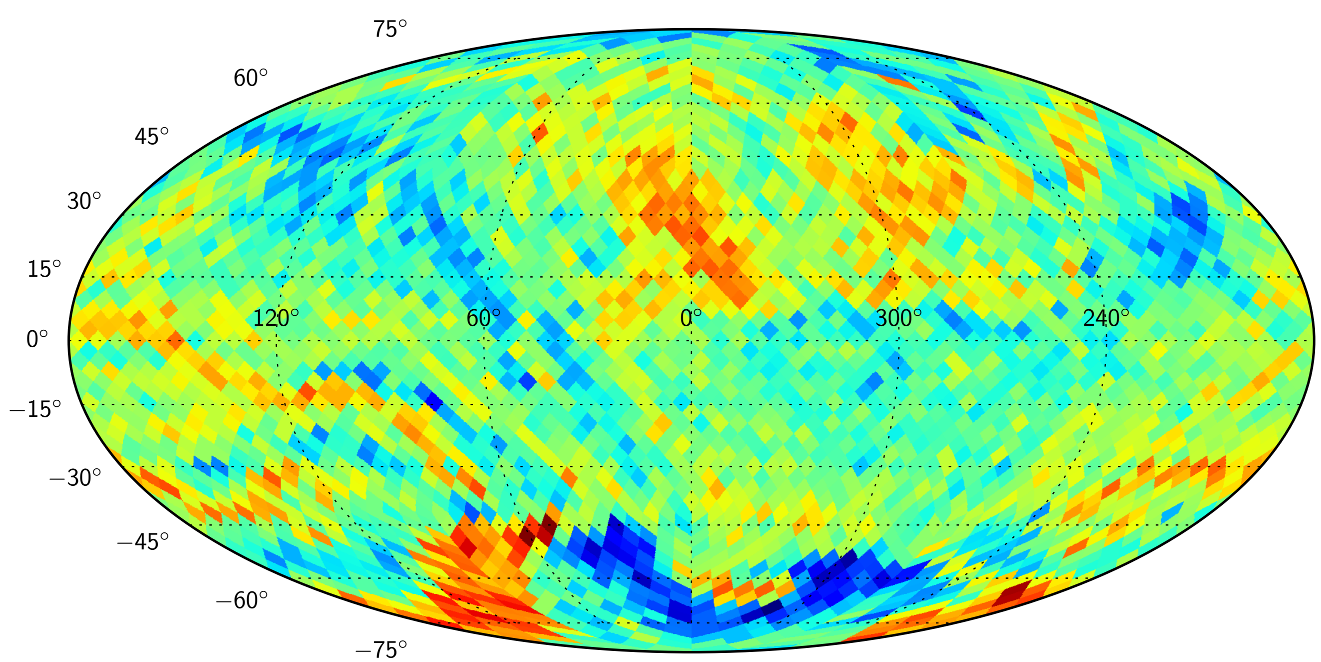
fit & filter dipole

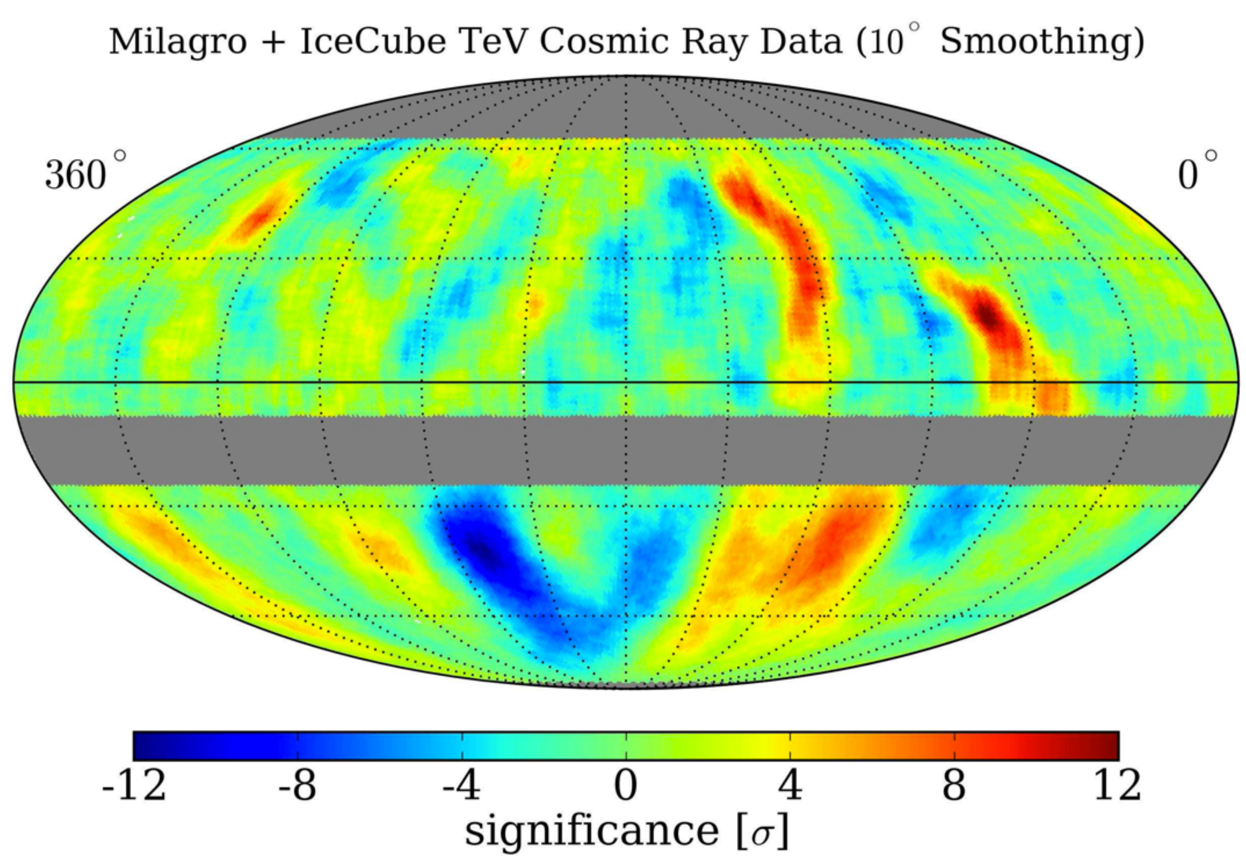


cosmic ray anisotropy
probing magnetic field turbulence ?

- effect of MHD turbulence with ⟨B⟩ = 3 μG and M_A ~ 0.7

(López-Barquero, Xu, Farber, PD, Lazarian)





750 TeV proton - λ_{mfp} ~ 5 pc (L_{inj} ~ 10 pc)

cosmic ray anisotropy
probing magnetic field turbulence ?

- effect of MHD turbulence with ⟨B⟩ = 3 μG and M_A ~ 0.7

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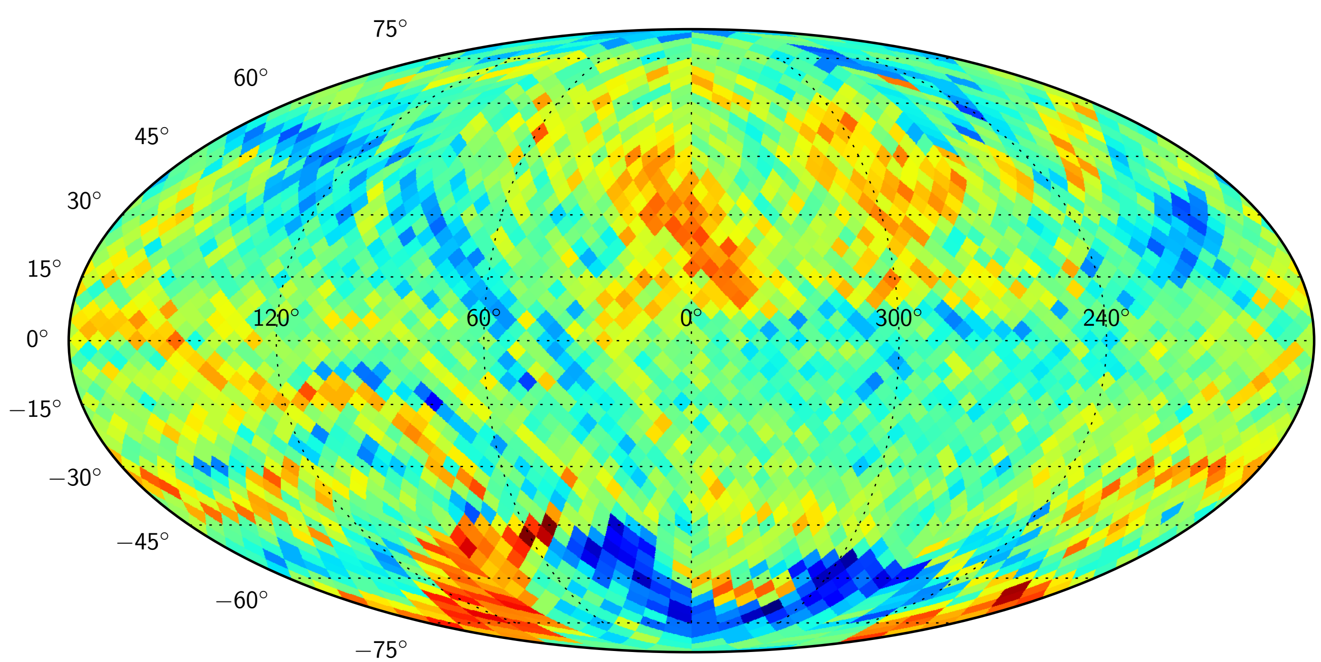
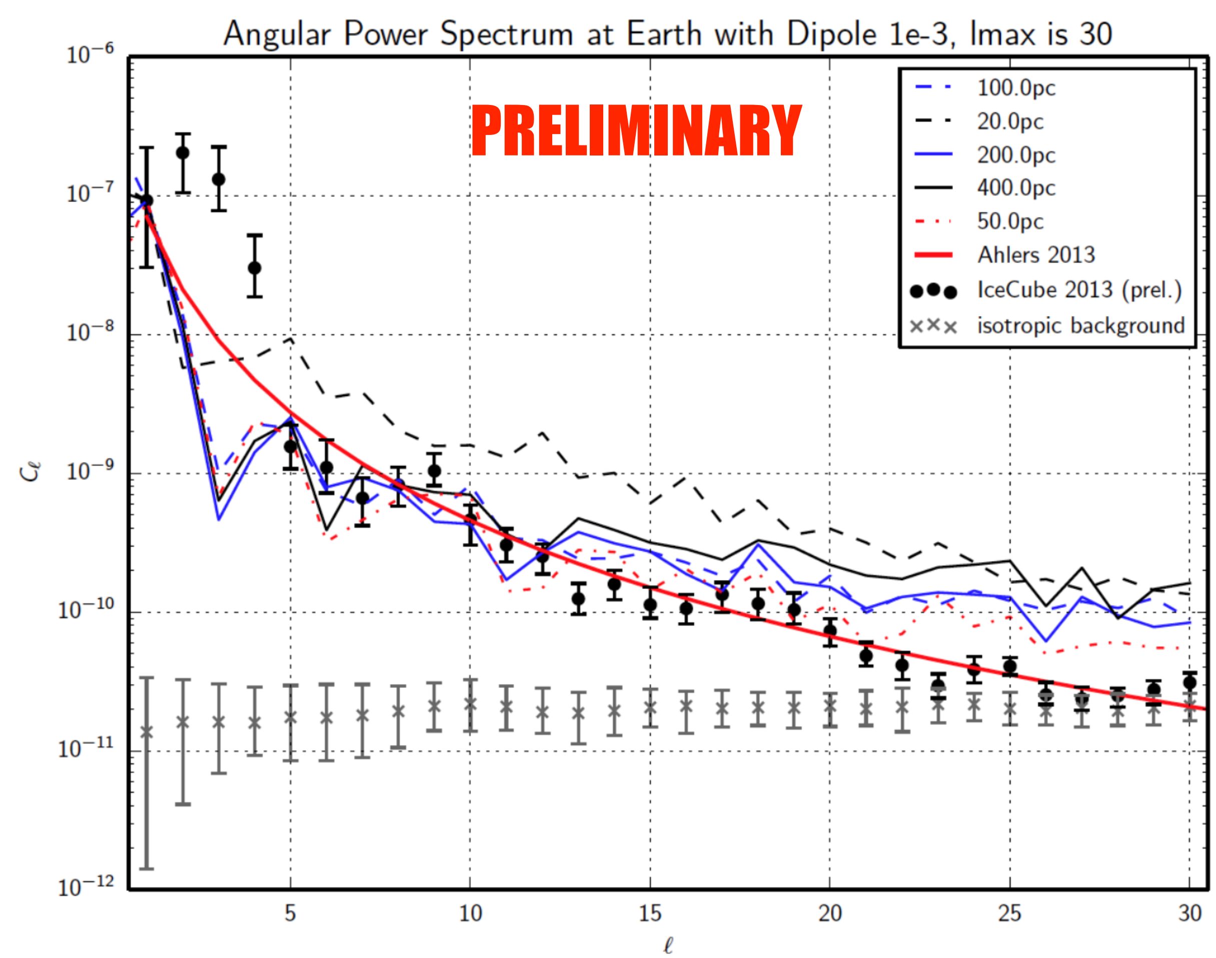




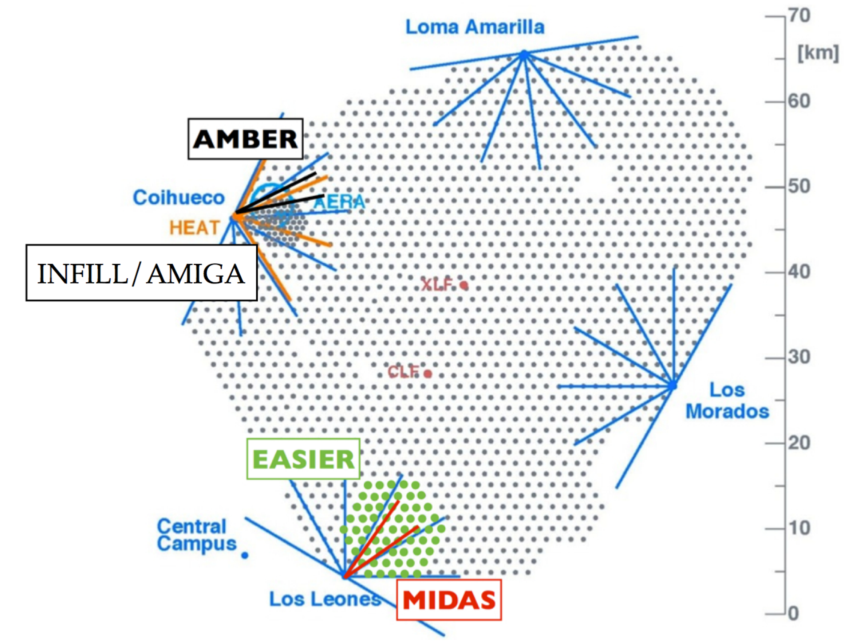
750 TeV proton - λ_{mfp} ~ 5 pc (L_{inj} ~ 10 pc)

ultra-high energy cosmic rays

sidereal anisotropy

Mollerach & Roulet, JCAP 0508 (2005) 004

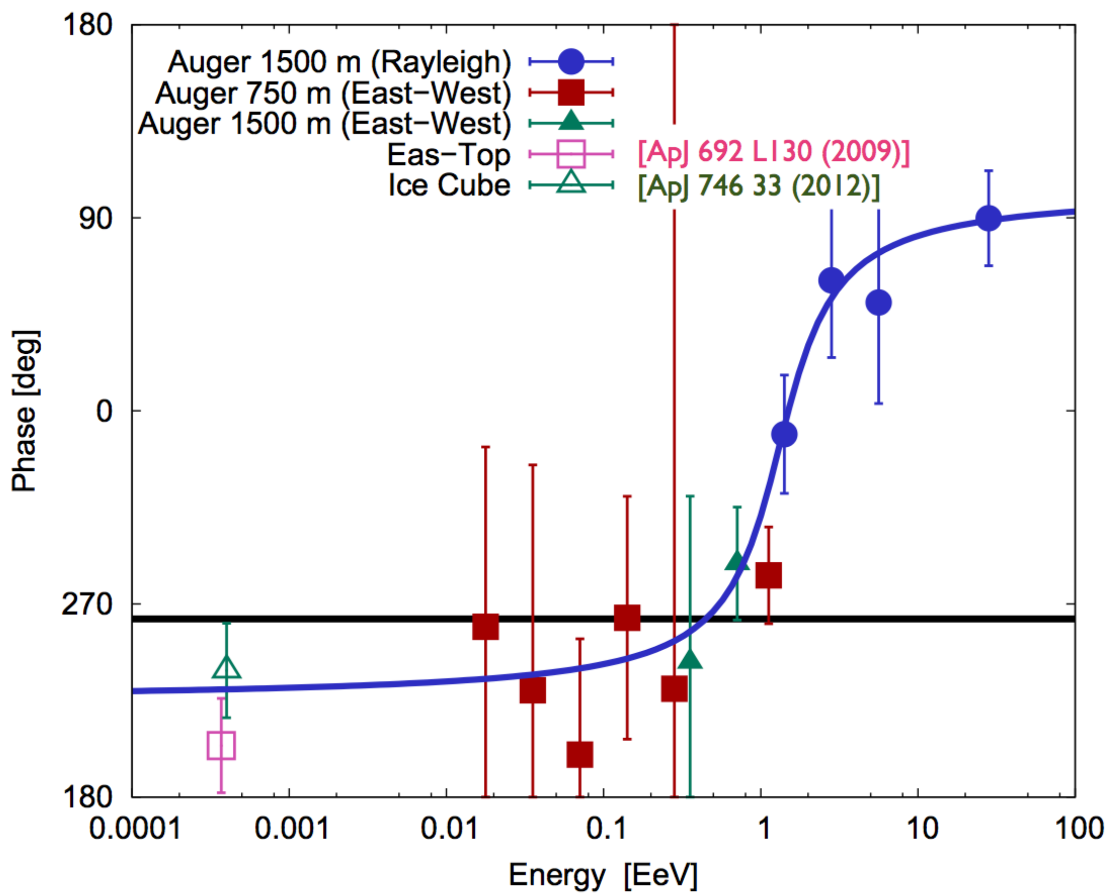
R. Bonino et al., ApJ 738 (2011) 67



Pierre Auger Observatory Abreu et al. (2011)

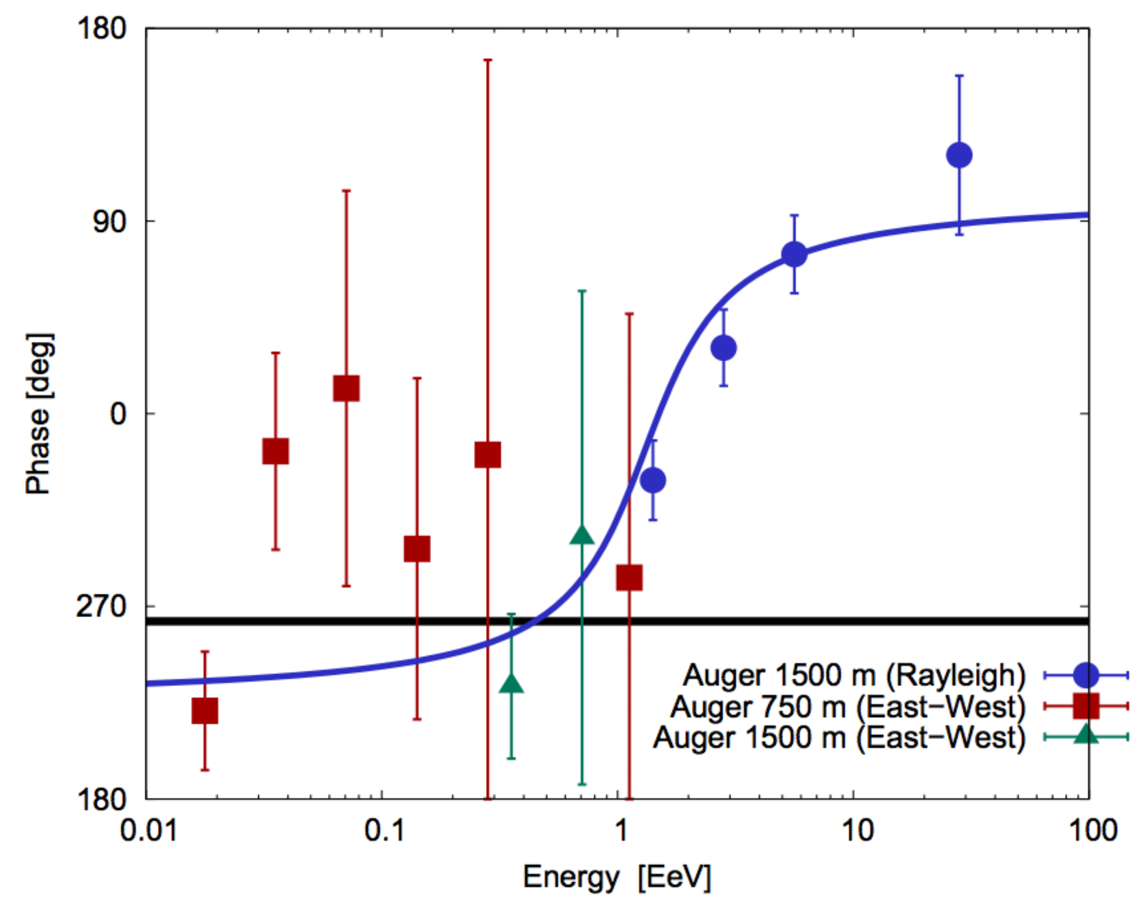
Prescription set:

data set from 1/1/2004 to 31/12/2010



Prescription status:

data set from 25/6/2011 to 31/12/2012



sidereal anisotropy

energy dependency of *dipole* phase

termination shock

inner heliosheath

heliopause, heliotail

local interstellar medium

Loop I superbubble

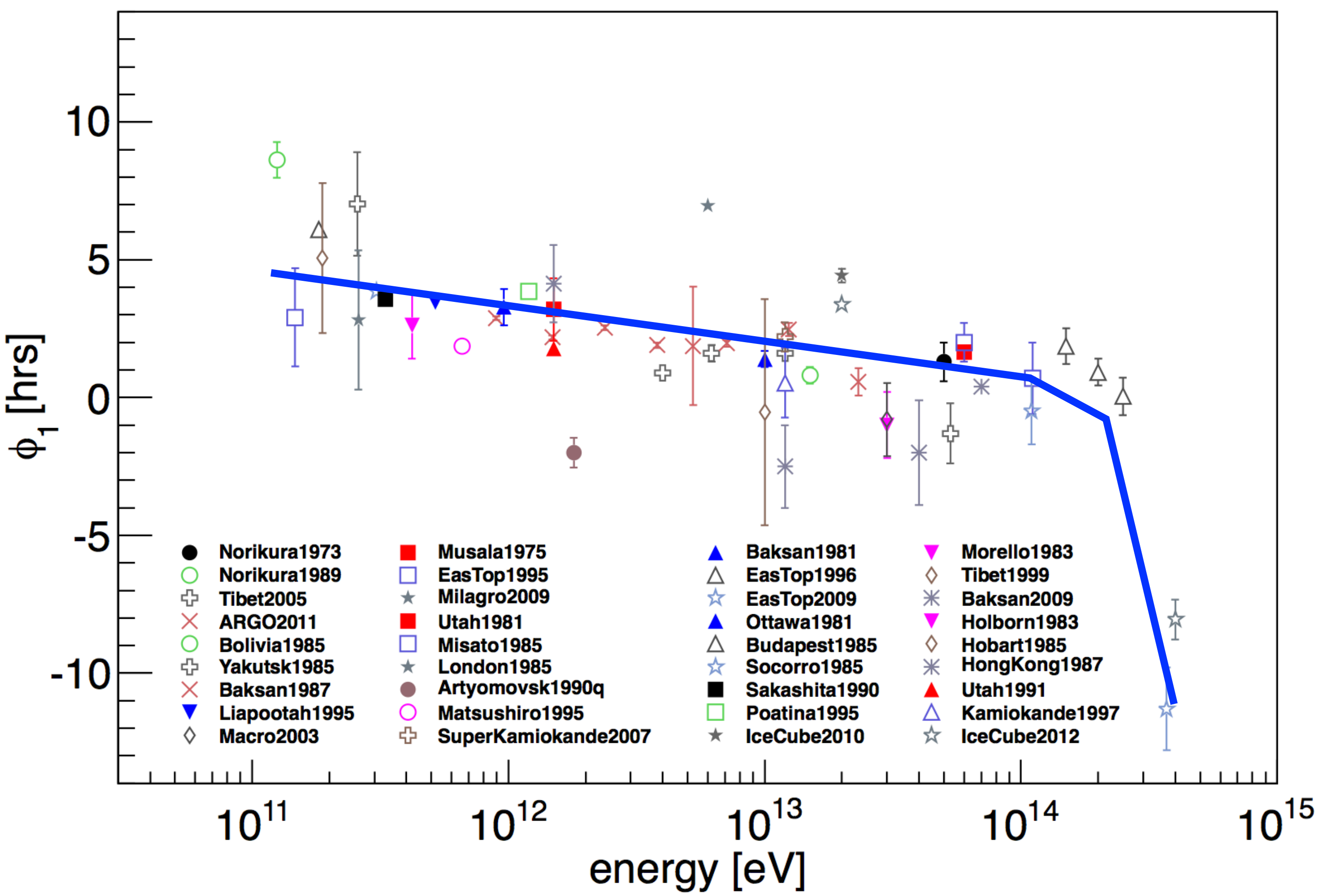
thickness of Galaxy

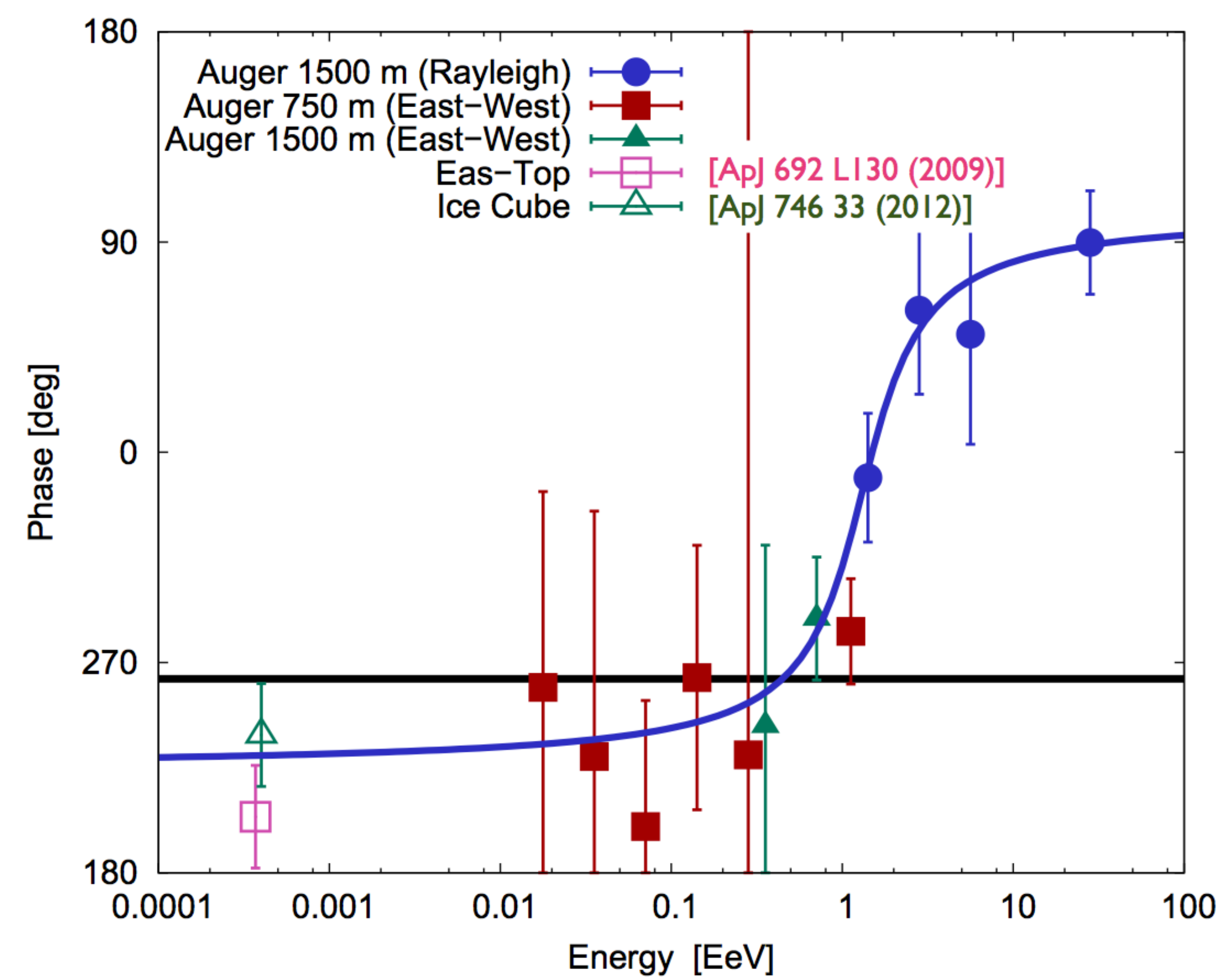
uncontained protons

heliospheric influence

interstellar medium

extra-galactic





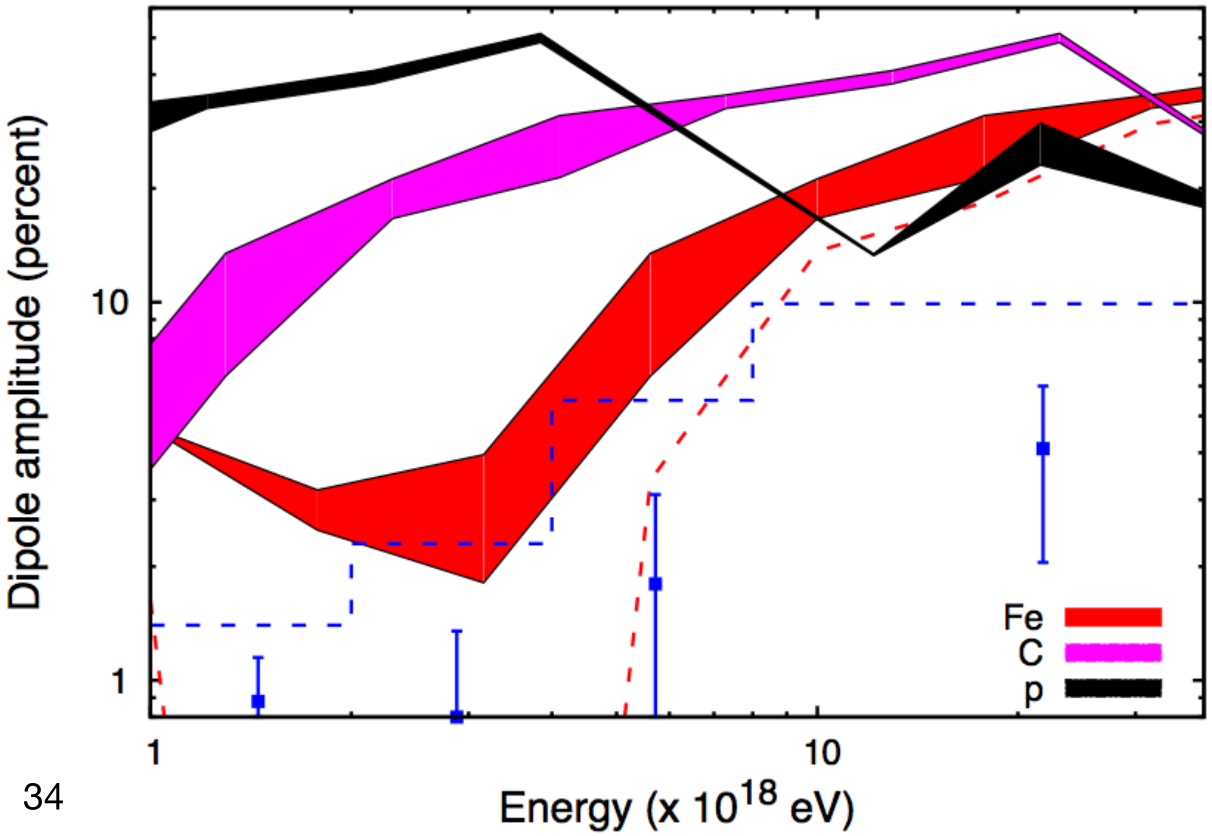
Paolo Desiati

ultra-high energy cosmic rays
transition to extra-galactic

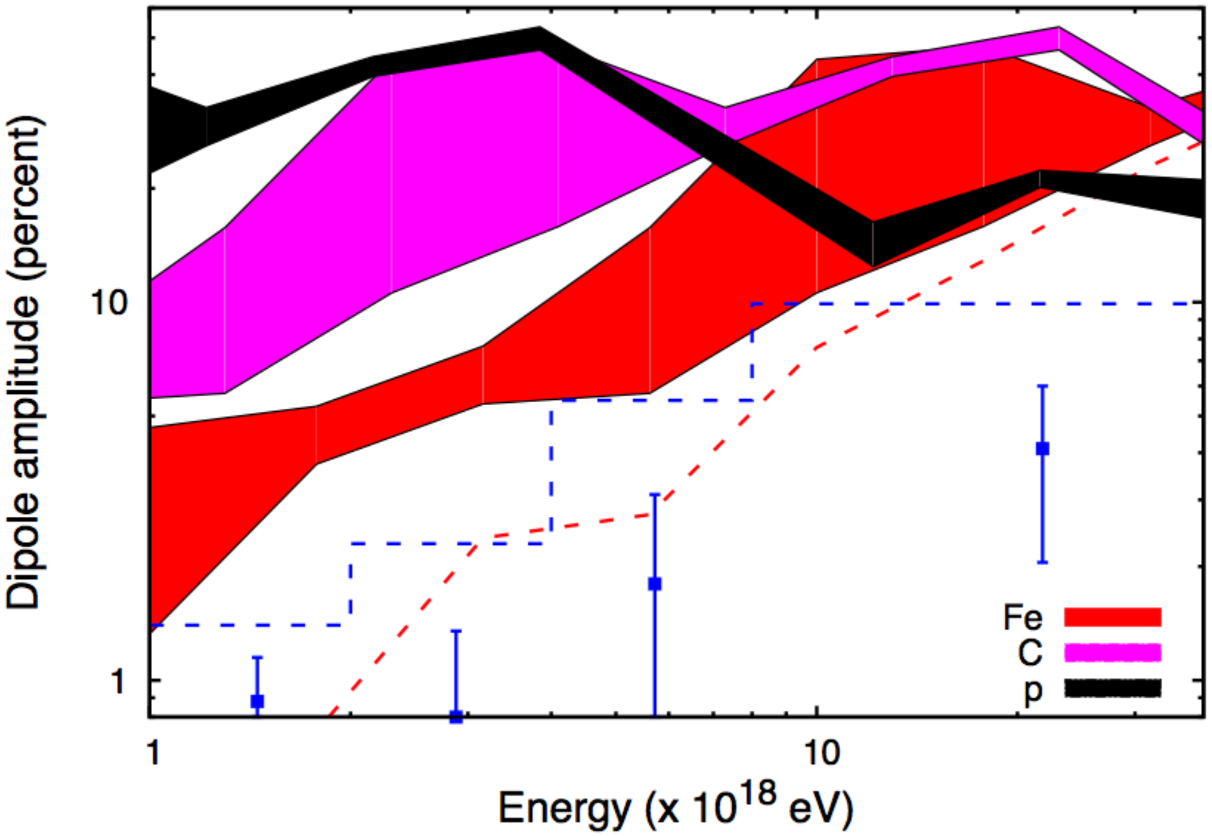
Giacinti, Kachelrieß & Semikoz (2014)
Abreu et al. (2011,2012, 2013)

- assuming **frequent** galactic sources, the **dipole** amplitude for light CR exceeds Auger limit @ EeV
- anisotropy transition requires heavy galactic or light extra-galactic composition

turbulent spectrum
δ=3/2 (Kraichnan), 5/3 (Kolmogorov)



turbulence injection scale
L = 100 pc, 300 pc



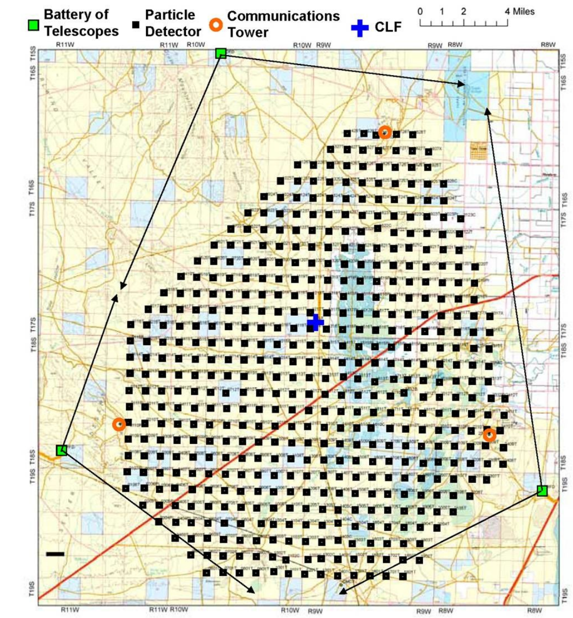
ultra-high energy cosmic rays

sidereal anisotropy

Abbasi, ApJL, 79, 21 (2014)

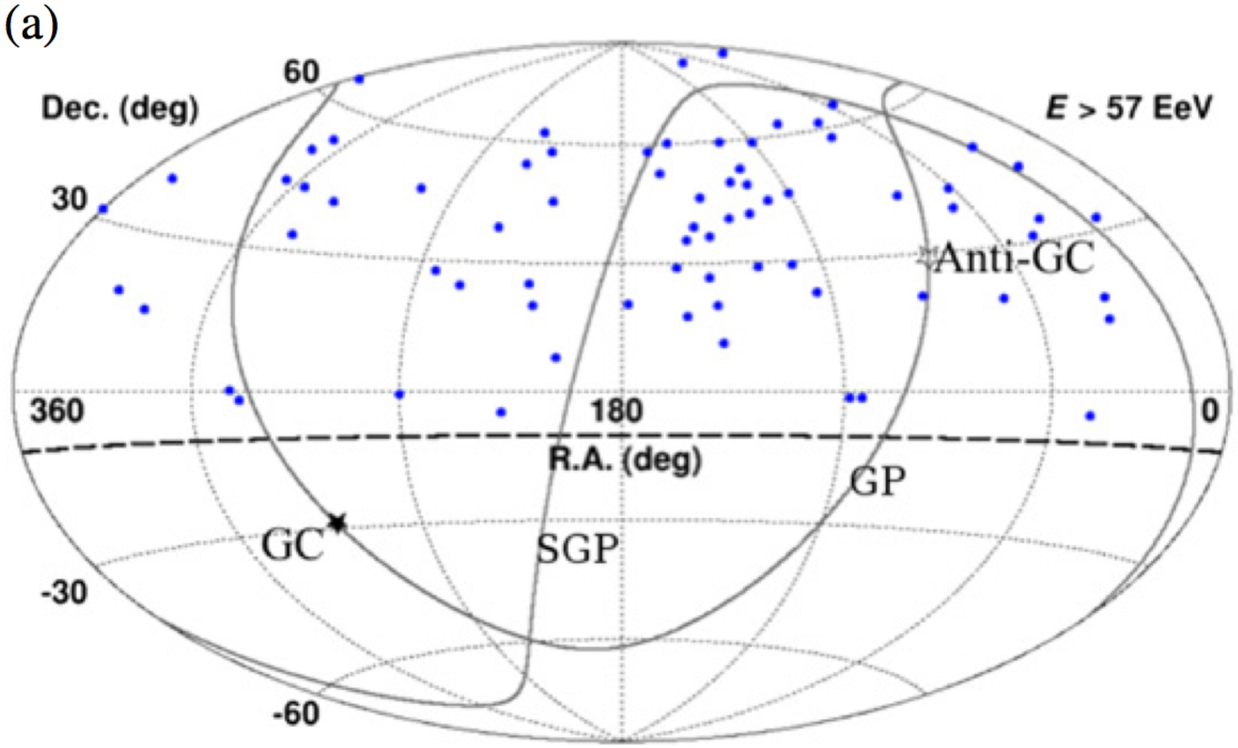
events with E > 57 EeV (small galactic influence)

10° wide clustering in northern hemisphere (5.1 σ)

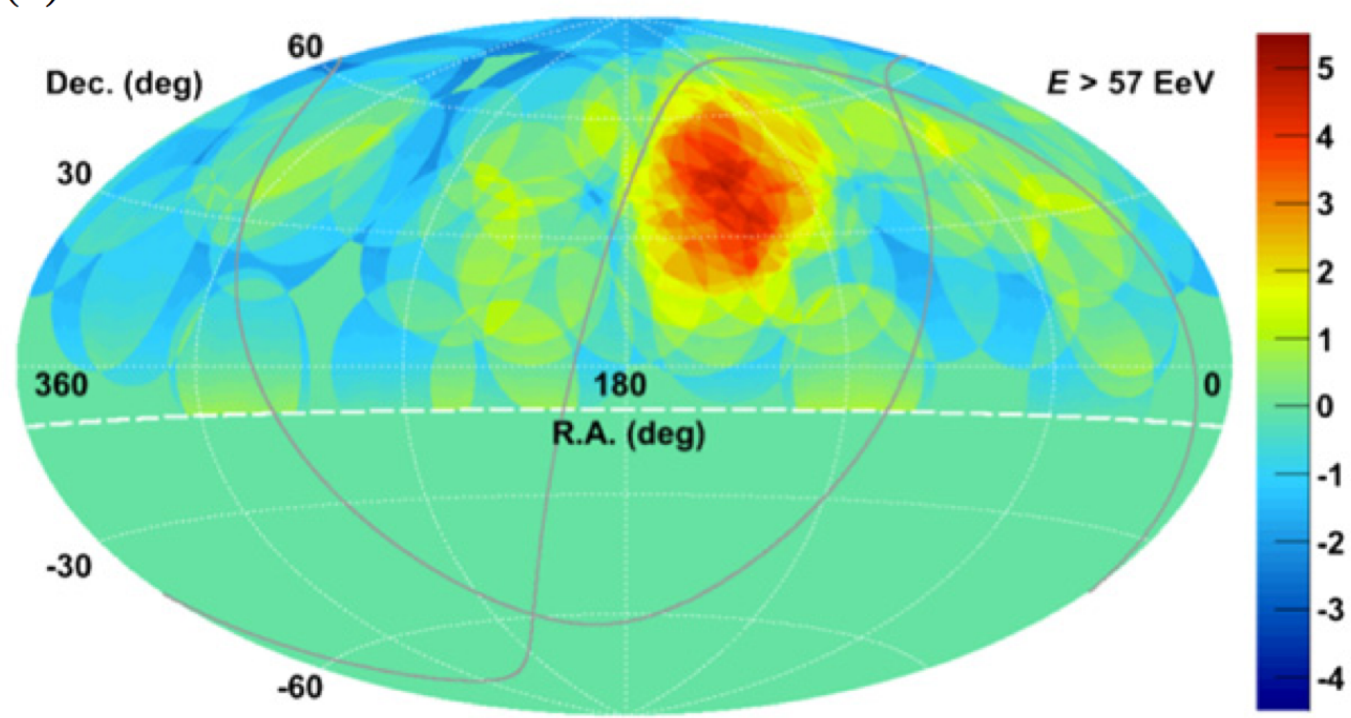


Telescope Array

(a)



(d)



summary

- **propagation** effects are relevant to describe **spectrum** and **anisotropy** of CR
- anisotropy resulting from **different origins** (drift, diffusion, turbulence)
- each mechanism has its own **temporal** & **rigidity** dependence
- **complexity** in topology and **consistency** with propagation effects on CR spectrum
- **spectral structures** in correlation with anisotropy
- cosmic ray anisotropy as a **probe** into global properties of magnetic fields

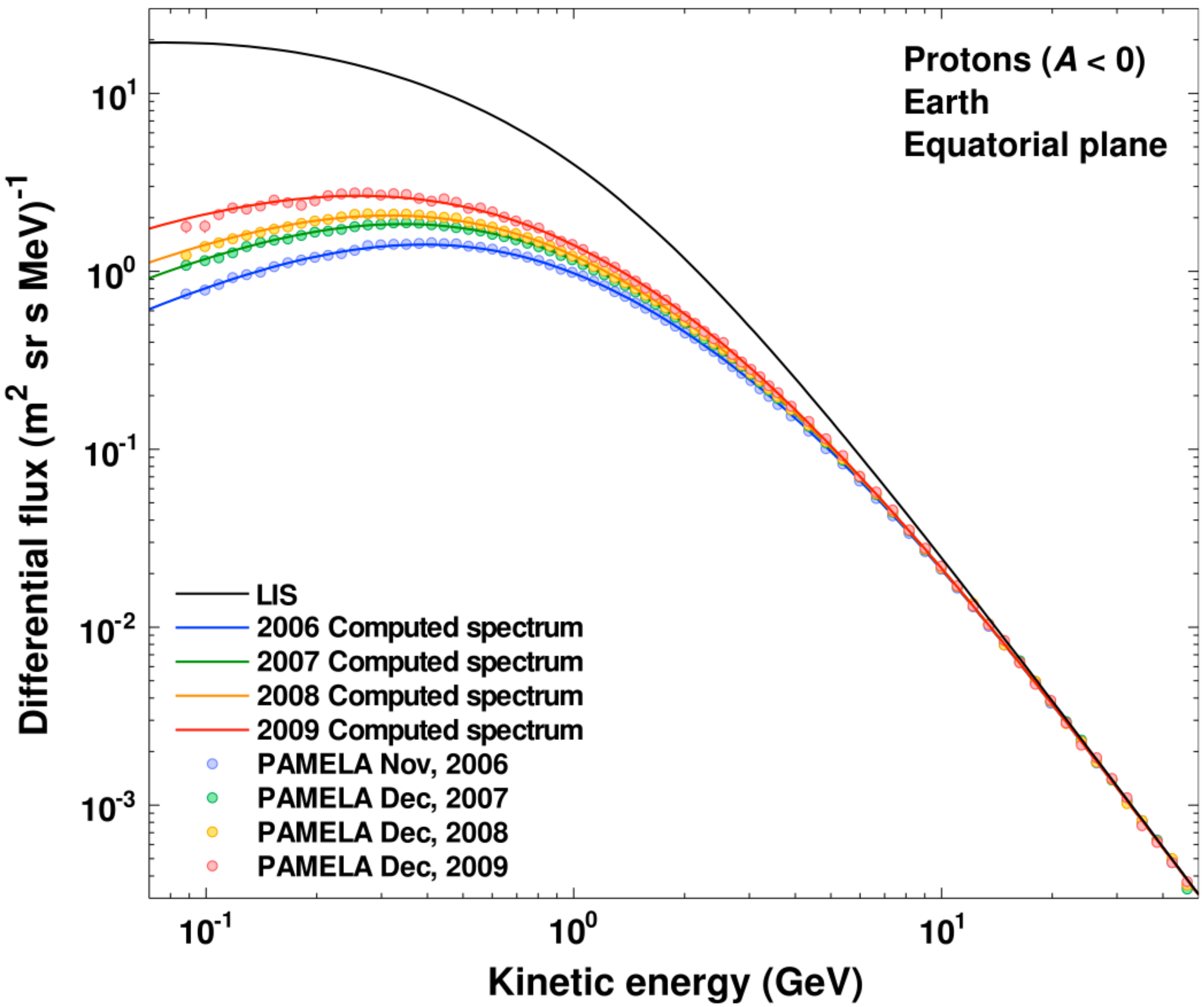
backup slides

low energy cosmic rays
and heliospheric physics

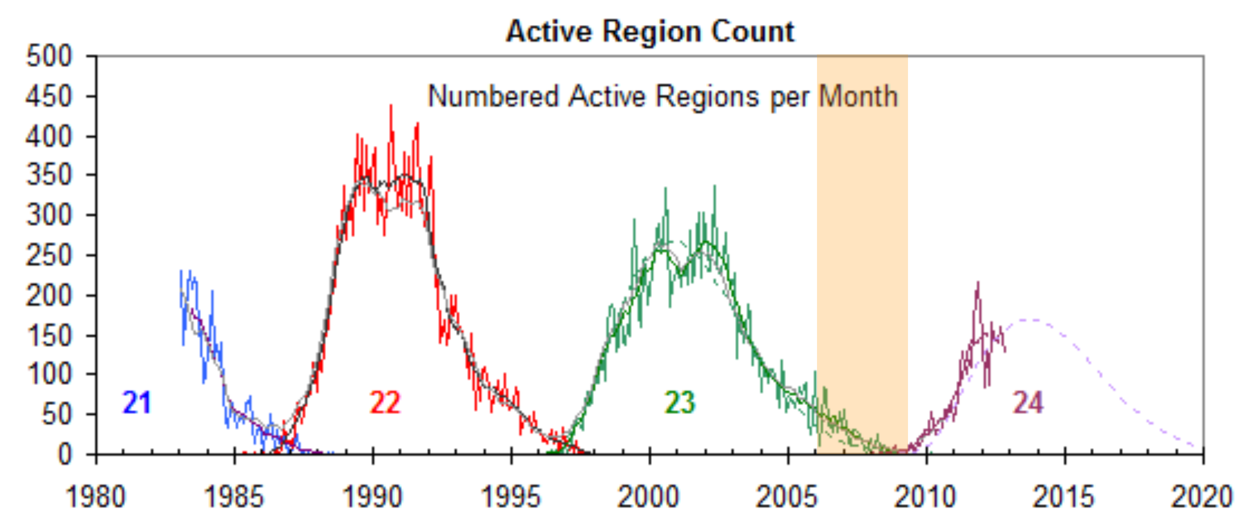
< 20-30 GV

PAMELA

Adriani et al., Physics Reports (2014)
Vos & Potgieter (2012)



solar cycles influence on cosmic ray **spectrum**



low energy cosmic rays
and heliospheric physics

GCR: 1-100 GeV

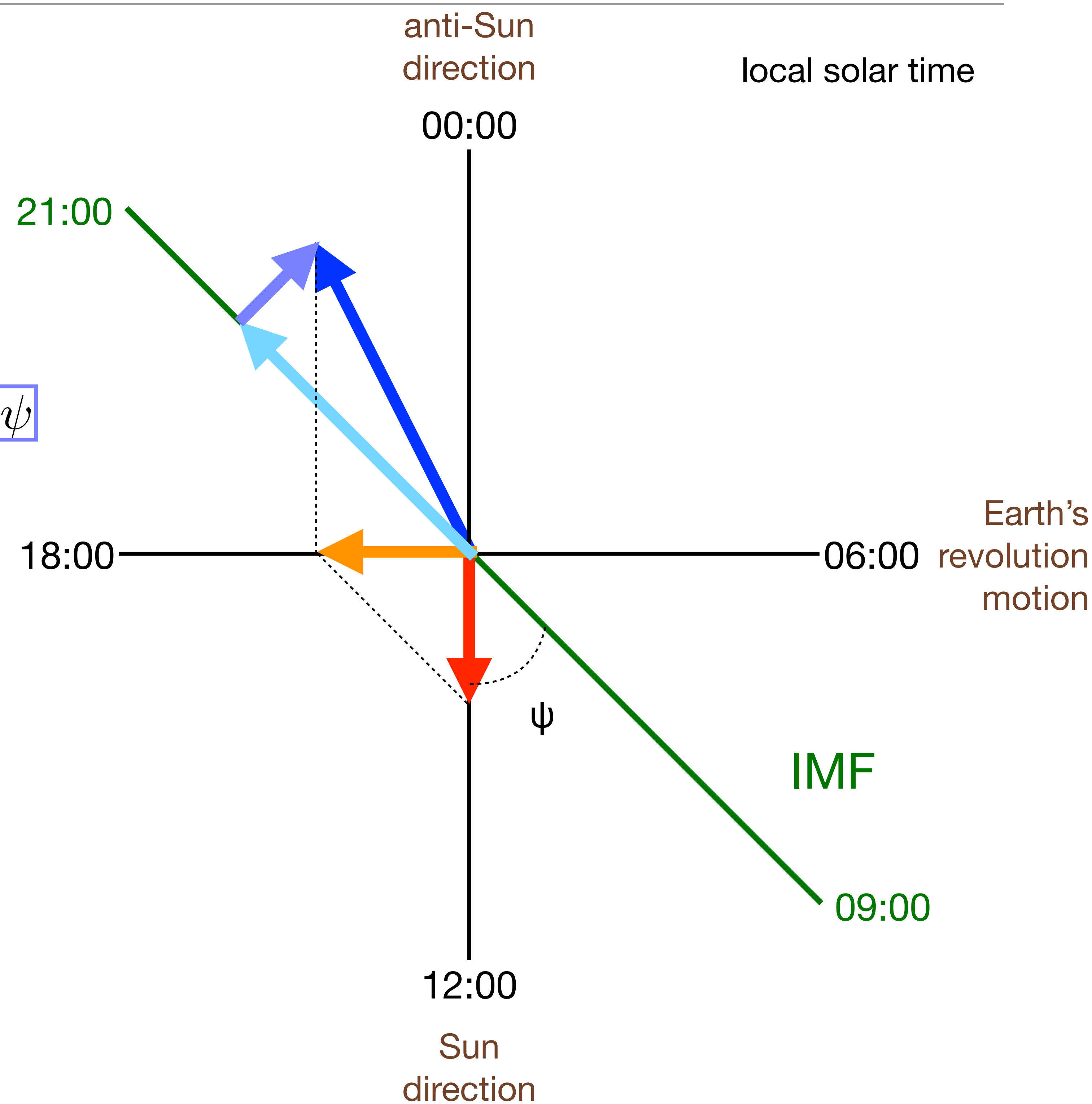
total diffusion

perpendicular diffusion $\boxed{R_L\, G_z + \lambda_\perp\, G_r\, \sin\psi}$

parallel diffusion $\boxed{\lambda_{||}\, G_r\, \cos\psi}$

co-rotation

convection (solar wind)

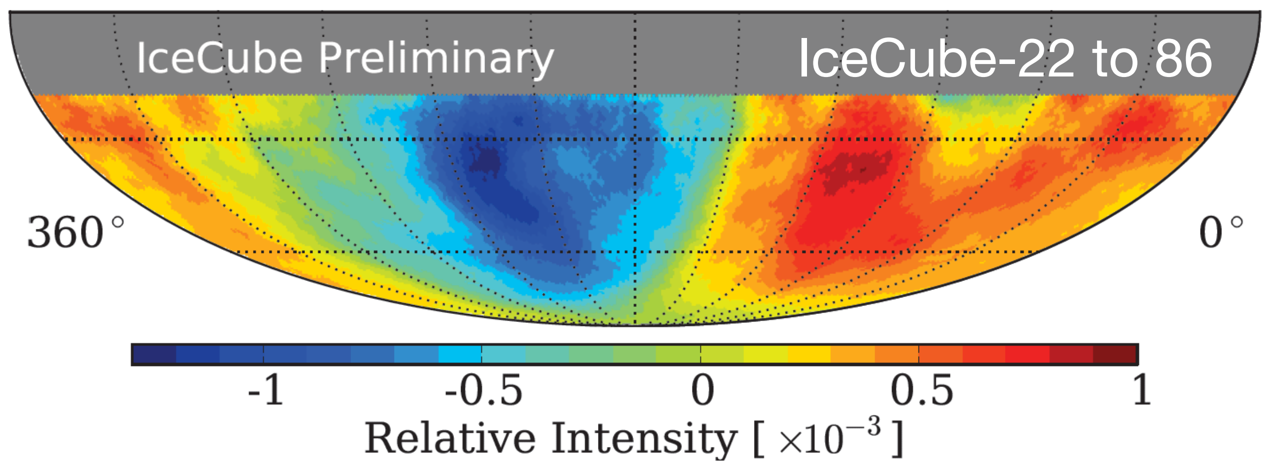


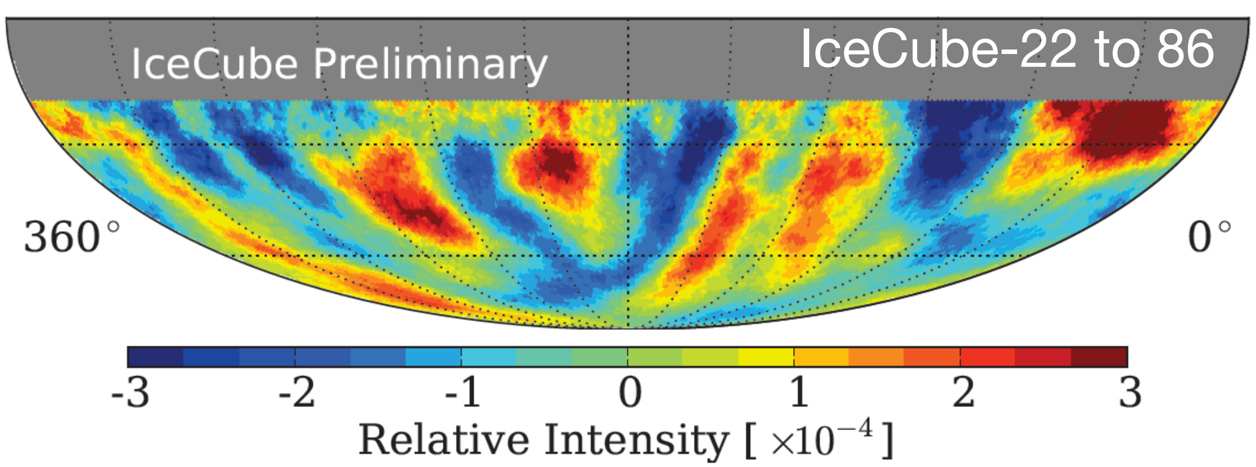
From K. Munakata

cosmic ray anisotropy
IceCube 2007-2012

PRELIMINARY

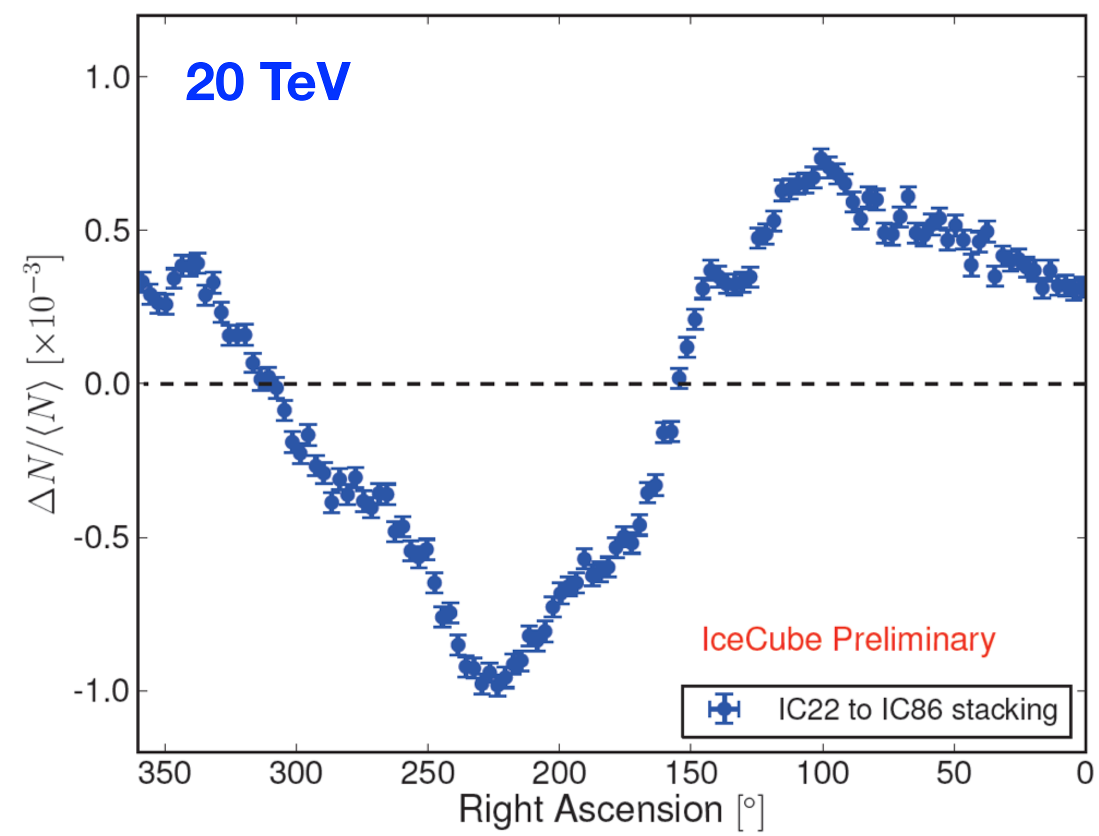
relative intensity equatorial coordinates





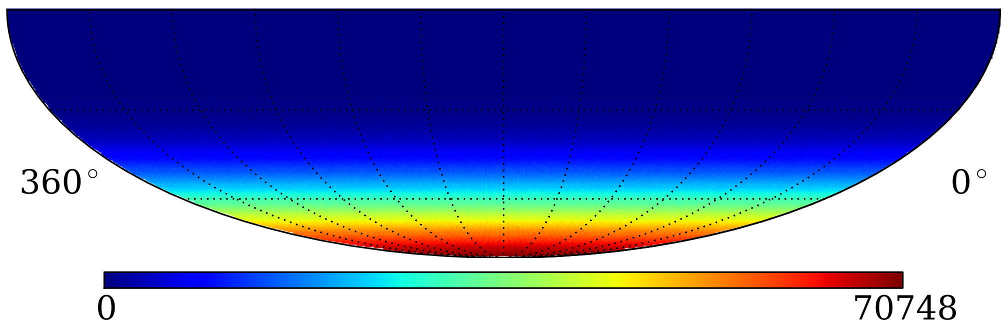
5° smoothing

- 1.4×10^{11} events from 2007 to 2012
    - sensitivity to 5° structures with relative intensity of $O(10^{-4})$

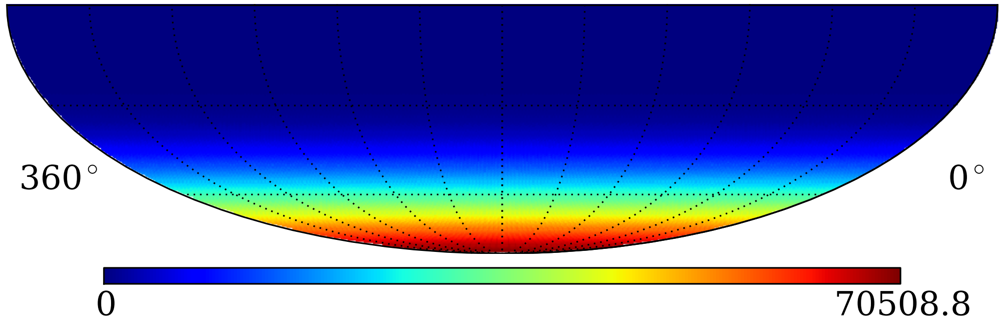


cosmic ray anisotropy analysis technique

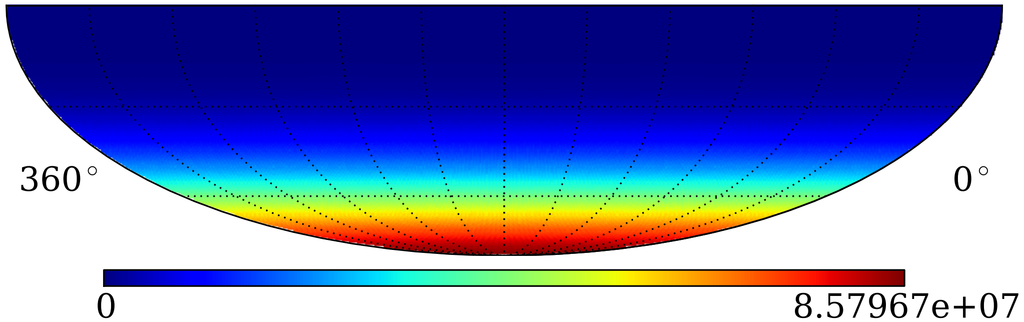
raw map of events in equatorial coordinates $(\alpha,\delta)_i$



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

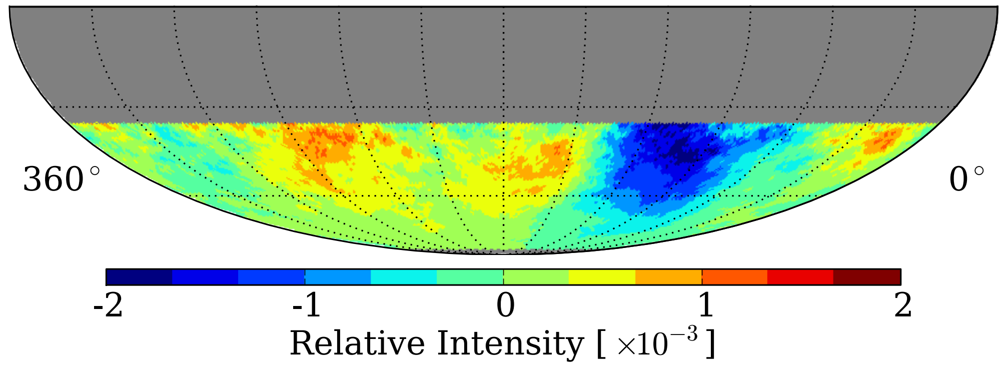


rebin raw and reference maps to enhance inter-bin correlations

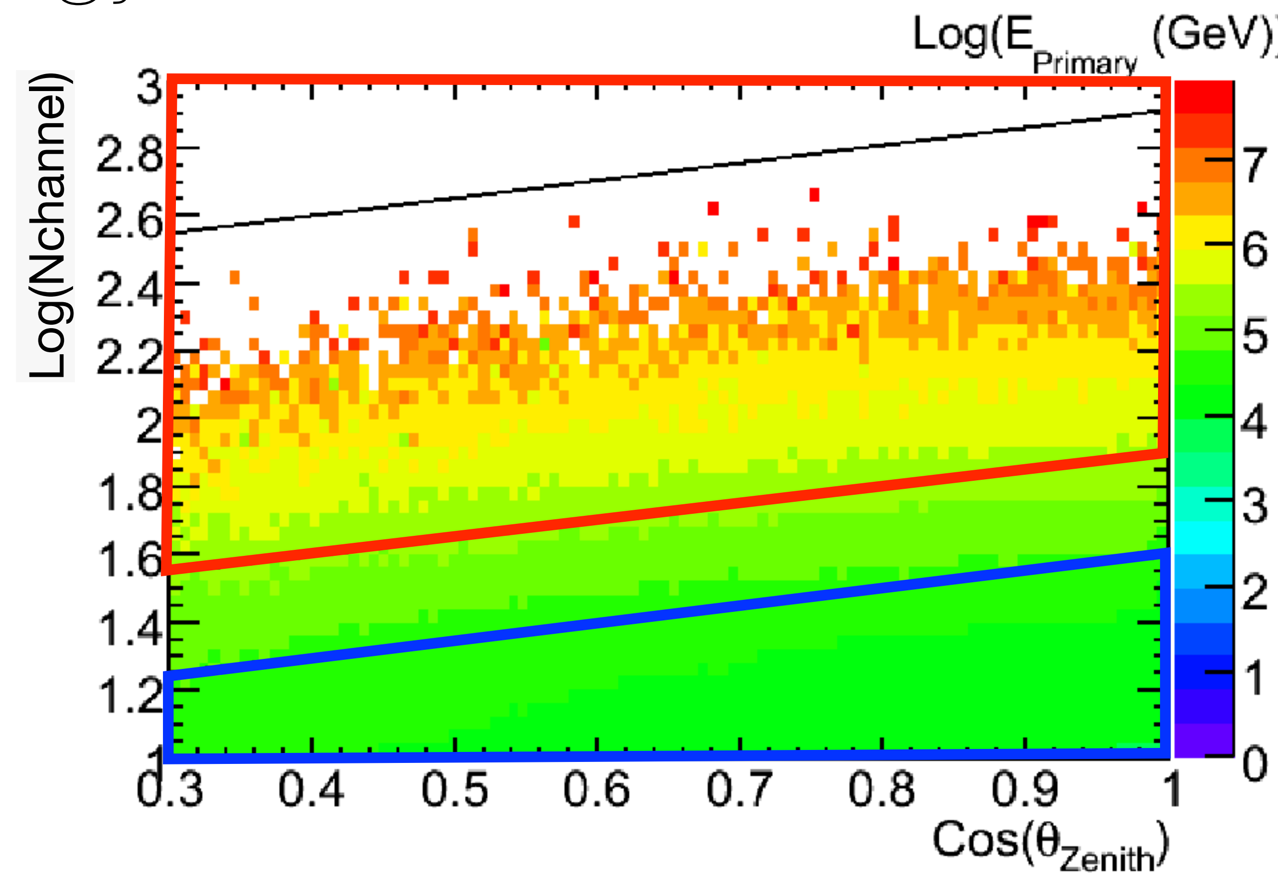


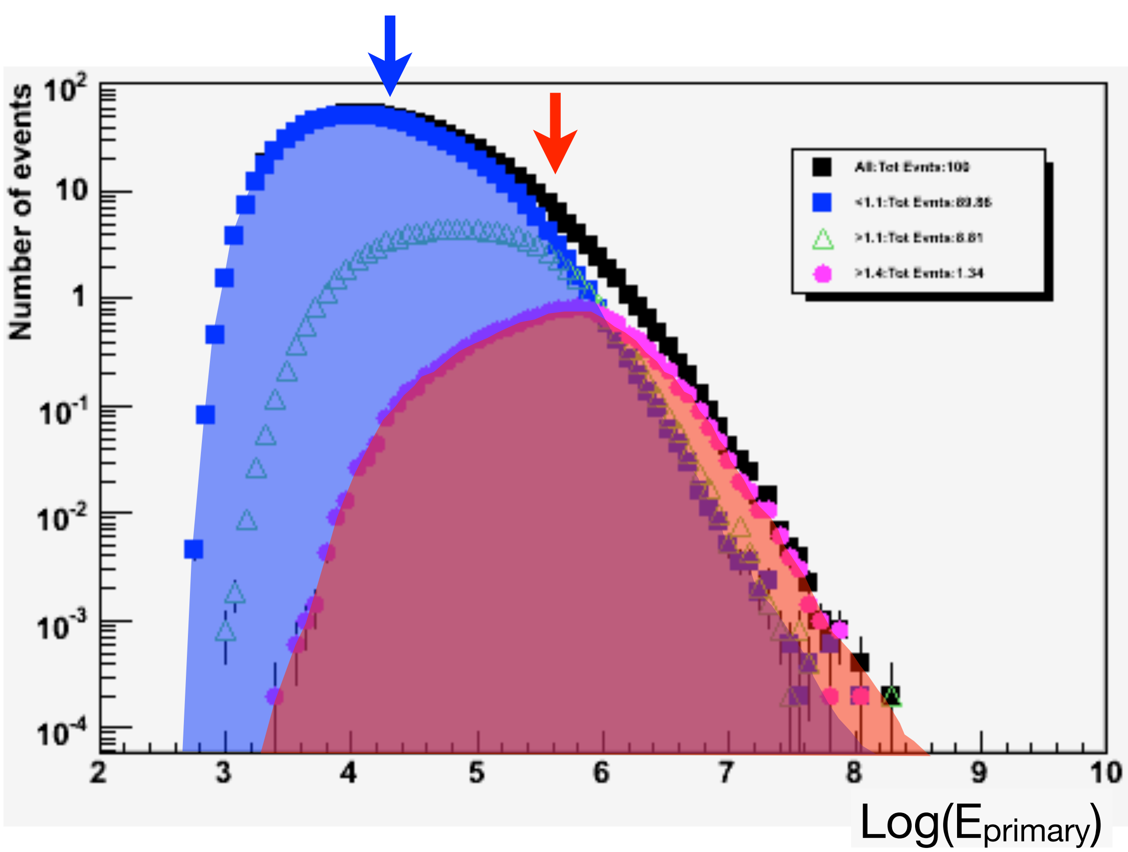
subtract reference map from raw map to determine the residual *relative intensity* map

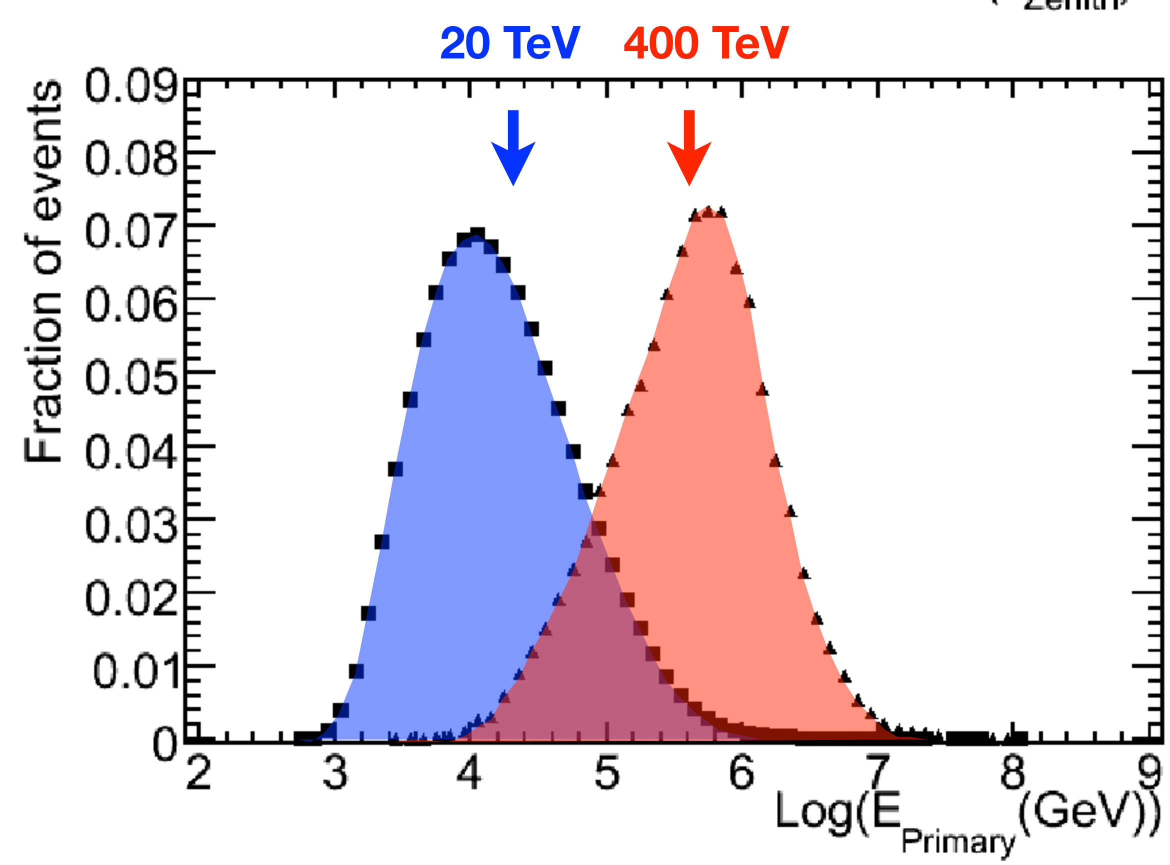
$$\boxed{\frac{\Delta I}{\langle I \rangle} = \frac{N_i - \langle N \rangle}{\langle N \rangle}}$$



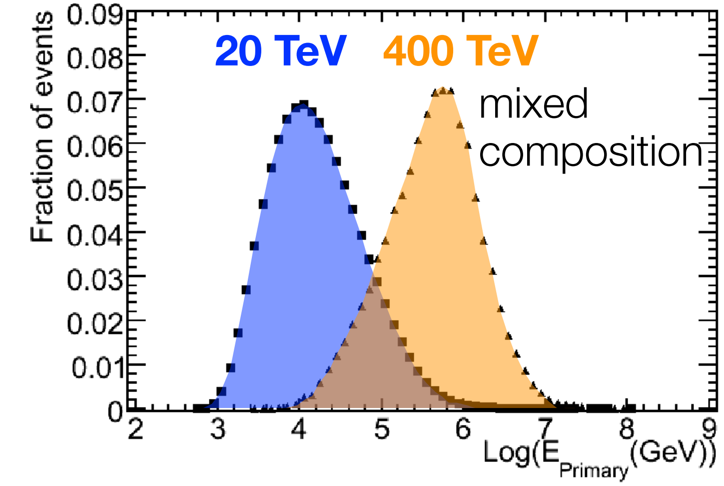
cosmic ray anisotropy energy selection
IceCube



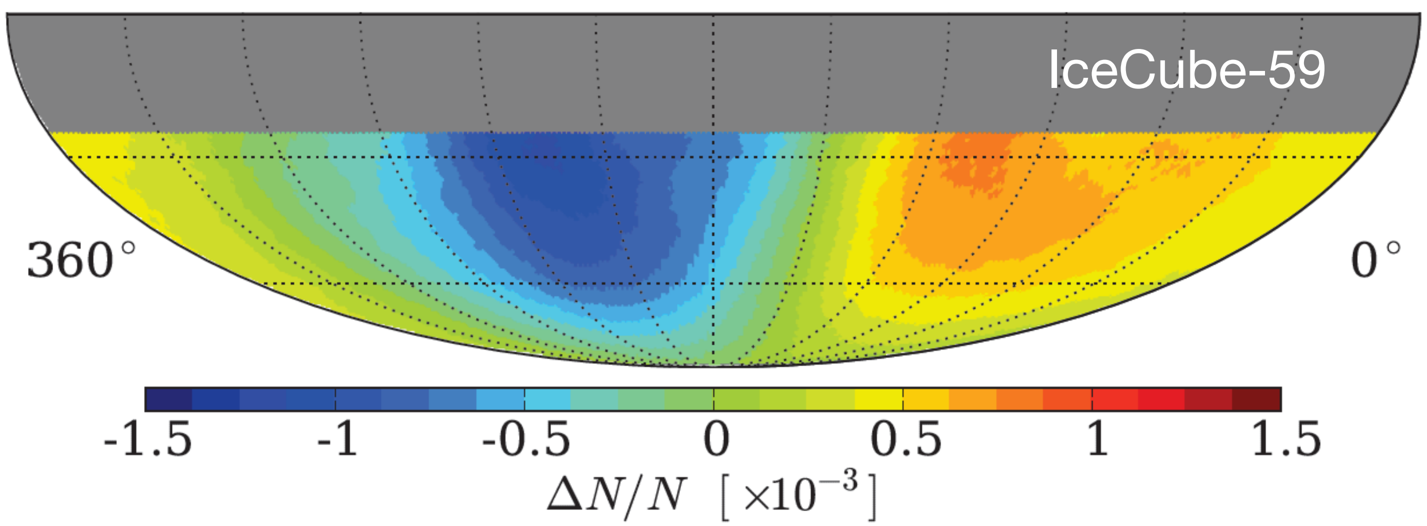




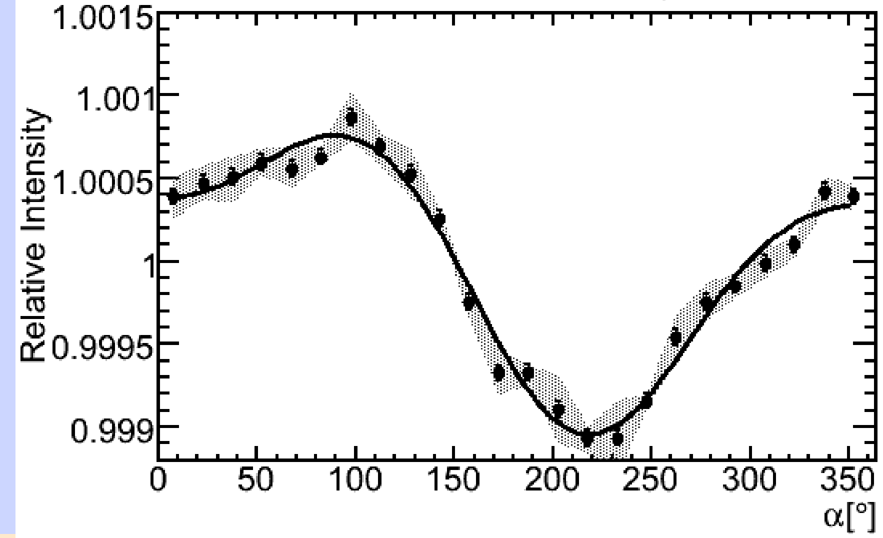
cosmic ray anisotropy large scale
IceCube

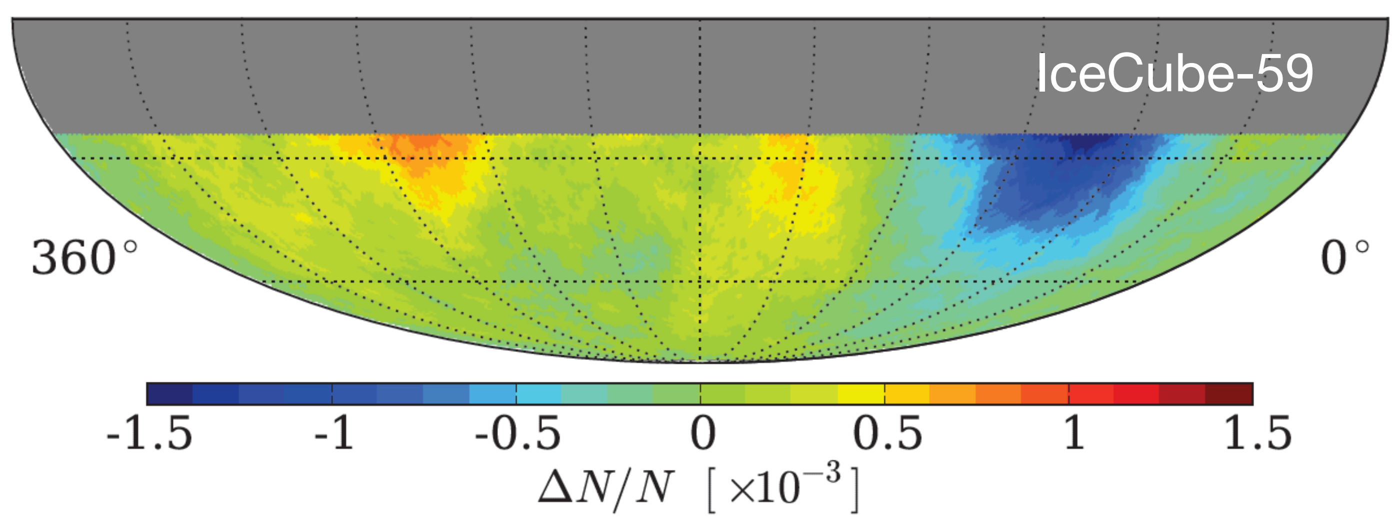


relative intensity equatorial coordinates



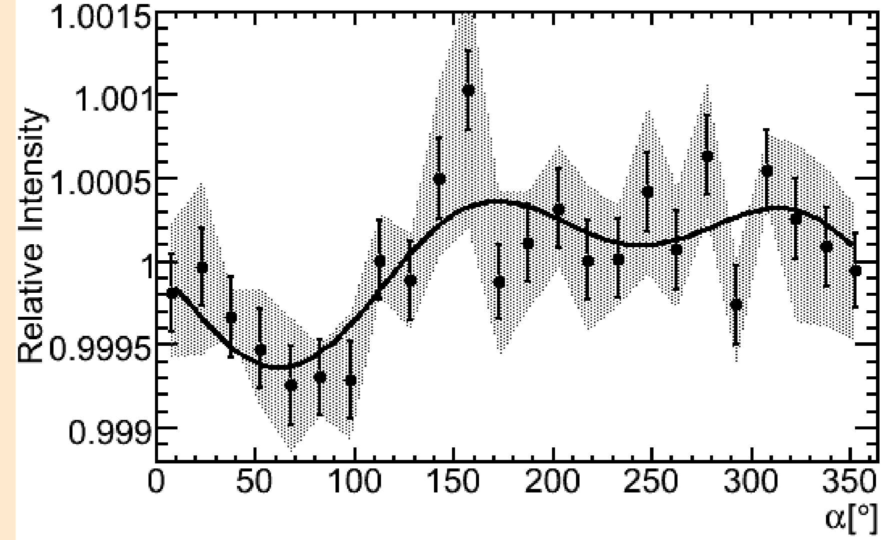
20 TeV





400 TeV

deficit
6.3 σ_{post}

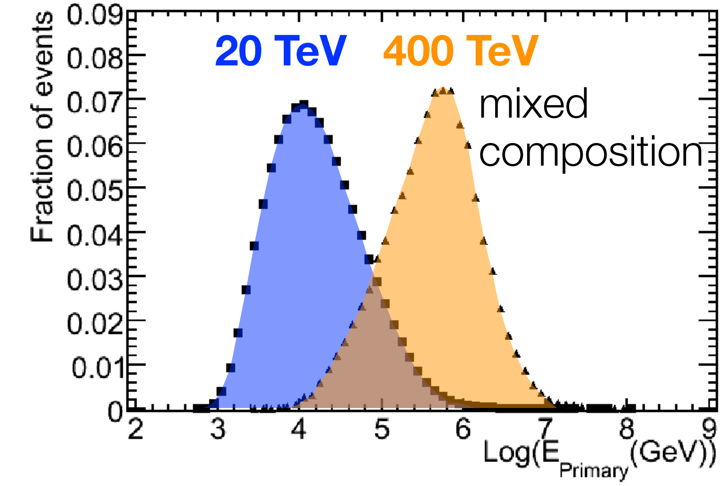


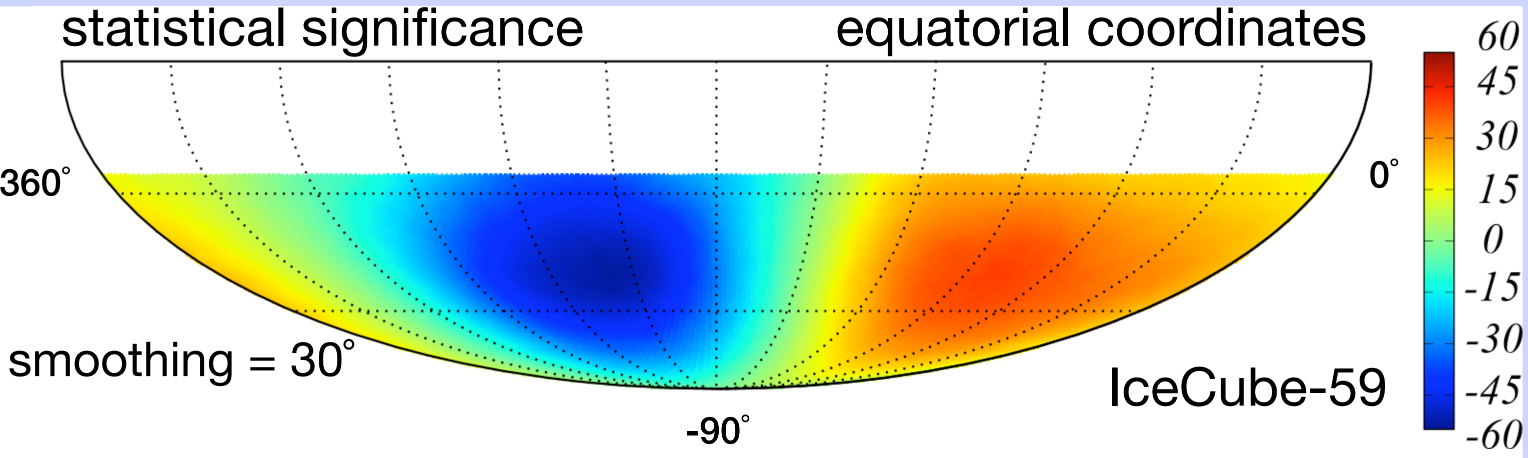
IC59 Abbasi et al., ApJ, **746**, 33, 2012

IC22 Abbasi et al., ApJ, **718**, L194, 2010

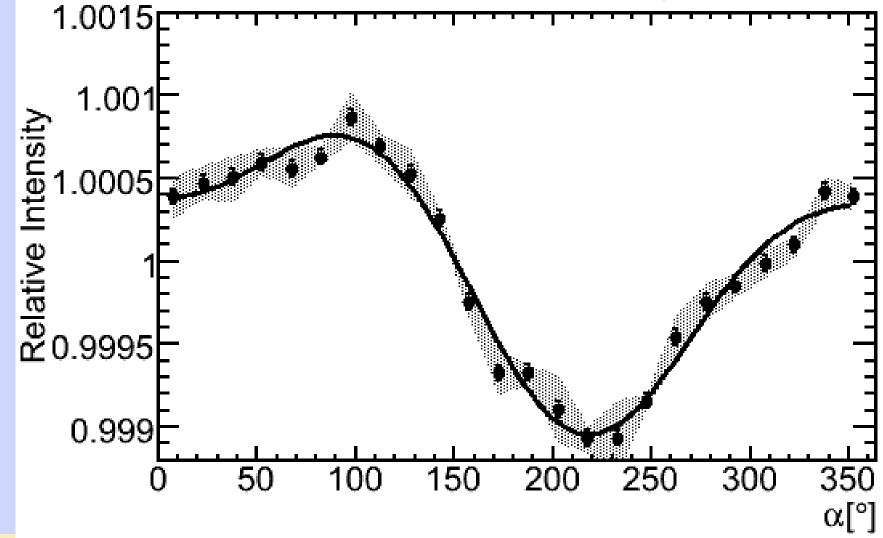
NOTE: anisotropy is not a dipole
topology changes at high energy

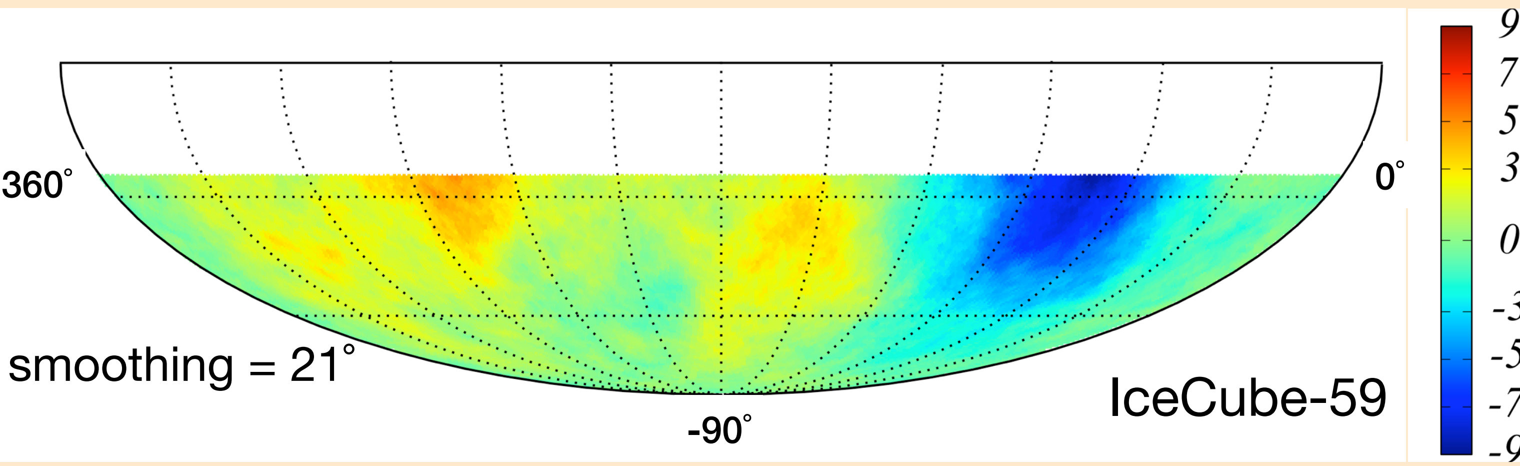
cosmic ray anisotropy large scale
IceCube





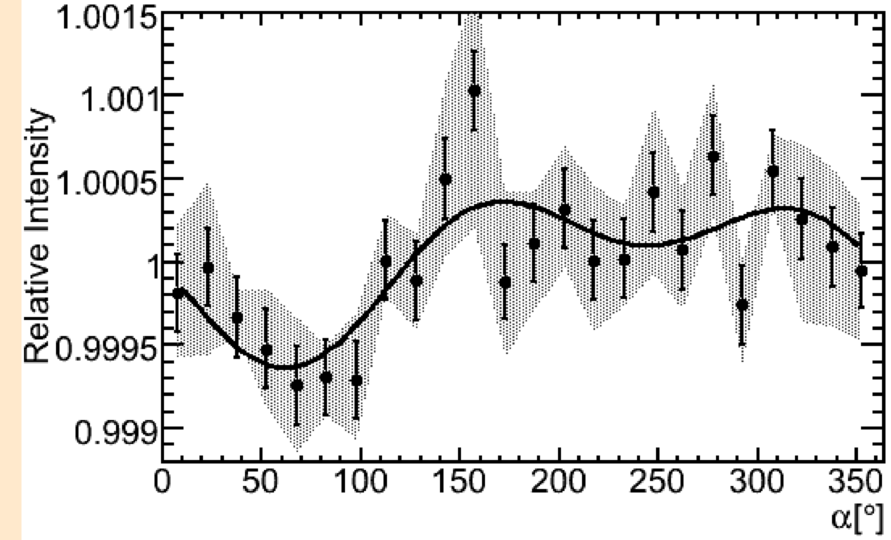
20 TeV





400 TeV

deficit
6.3 σ_{post}



IC59 Abbasi et al., ApJ, **746**, 33, 2012

IC22 Abbasi et al., ApJ, **718**, L194, 2010

NOTE: anisotropy is not a dipole
topology changes at high energy

x

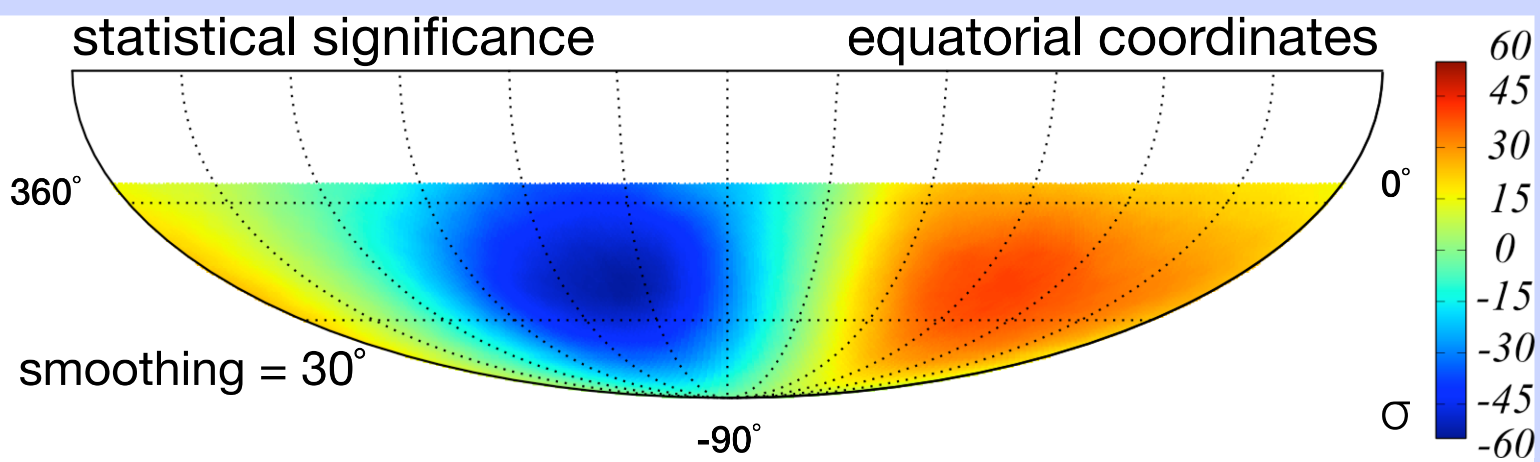
cosmic ray anisotropy vs energy in IceCube-59

energy

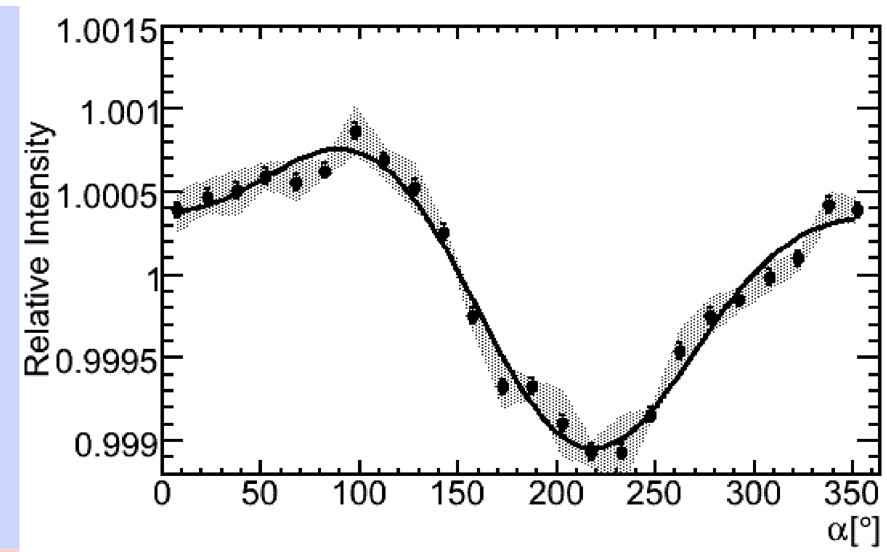
- reference map derived from data with time scrambling
- smoothing radius optimized on highest significance in excess/deficit region

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

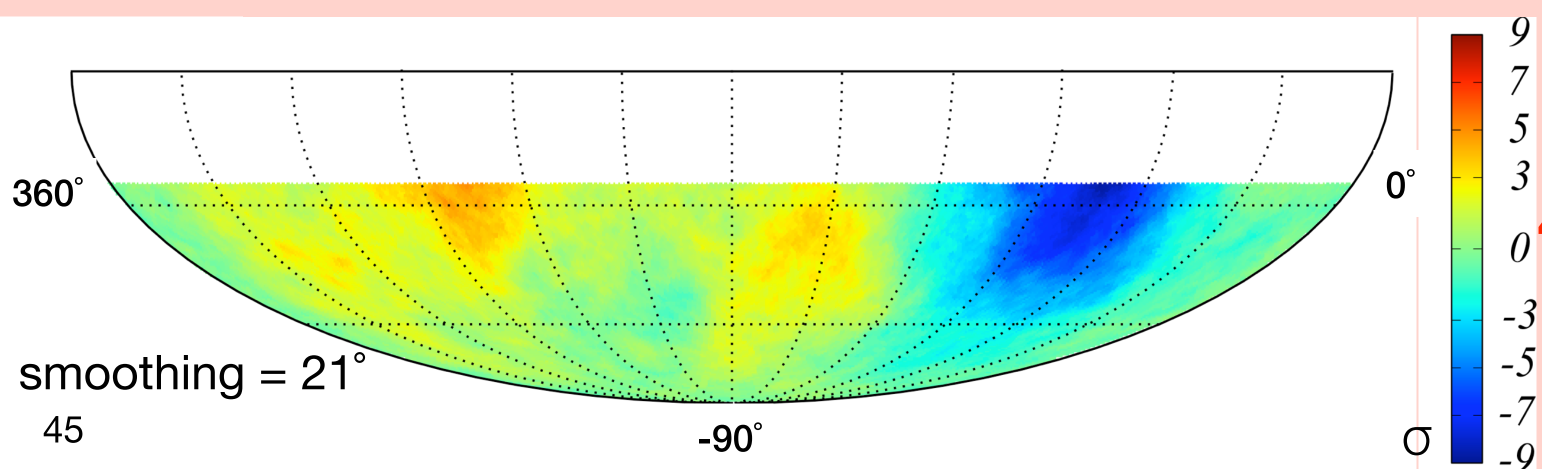
Li, T., & Ma, Y. 1983, ApJ, 272, 317



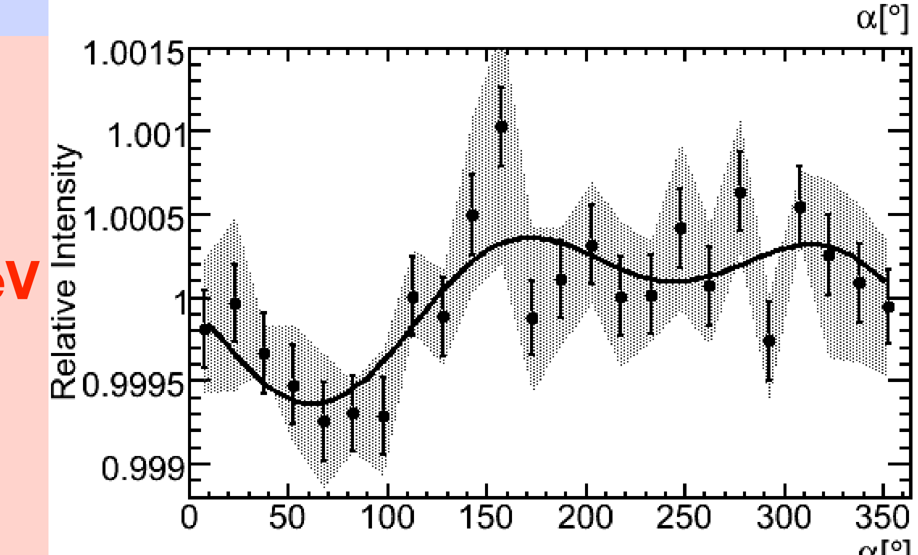
20 TeV



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

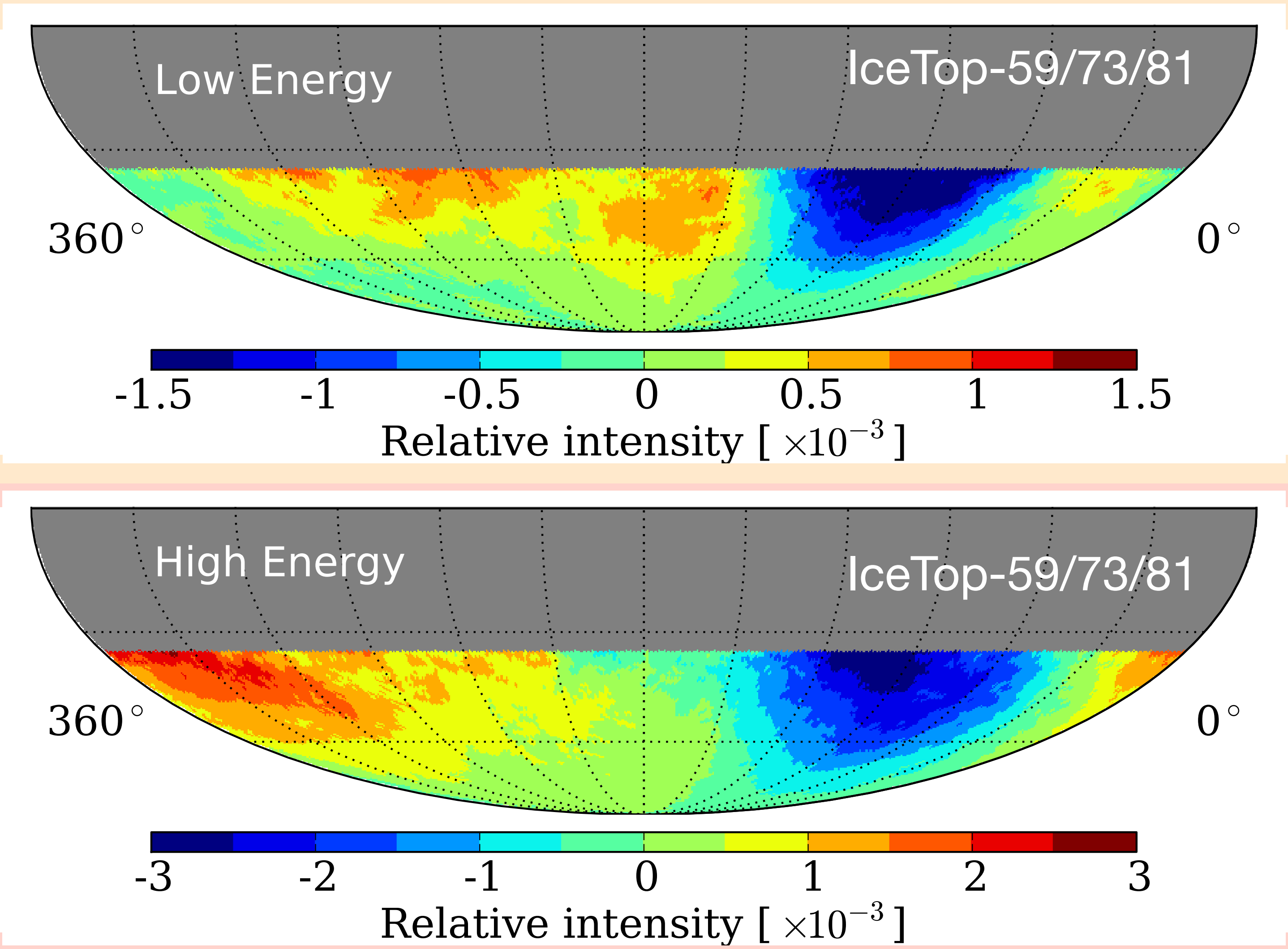


400 TeV



cosmic ray anisotropy large scale
IceTop

relative intensity equatorial coordinates



deficit
7 σ_{post}

400 TeV

2 PeV

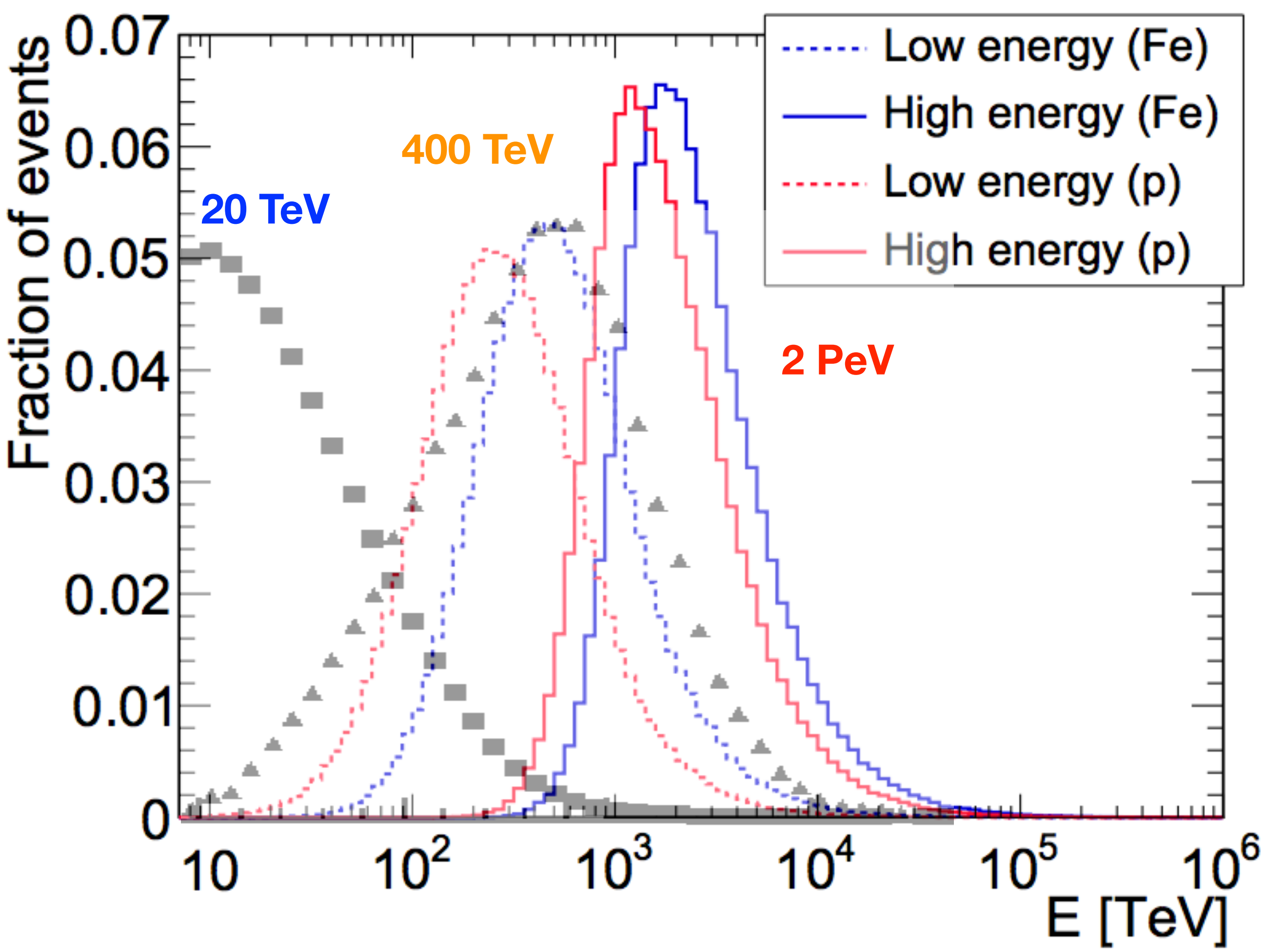
Aartsen et al., ApJ, **765**, 55, 2013

NOTE: global topology does not change

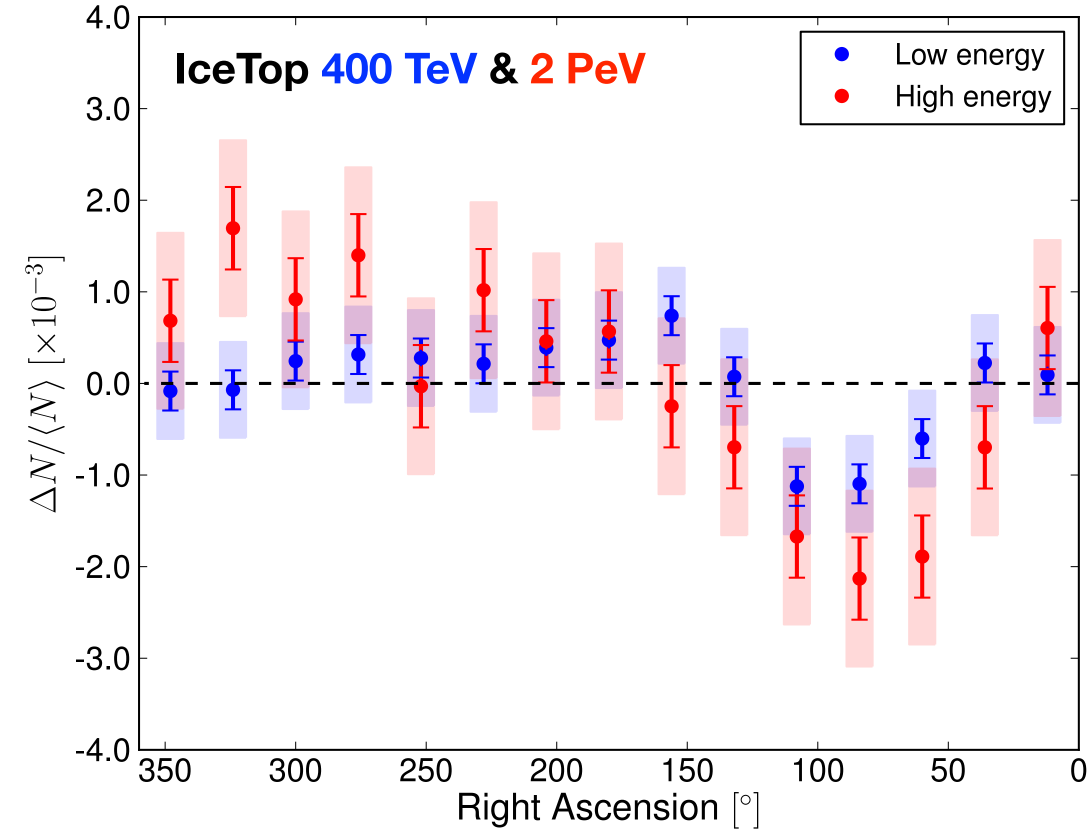
deficit amplitude increases with energy

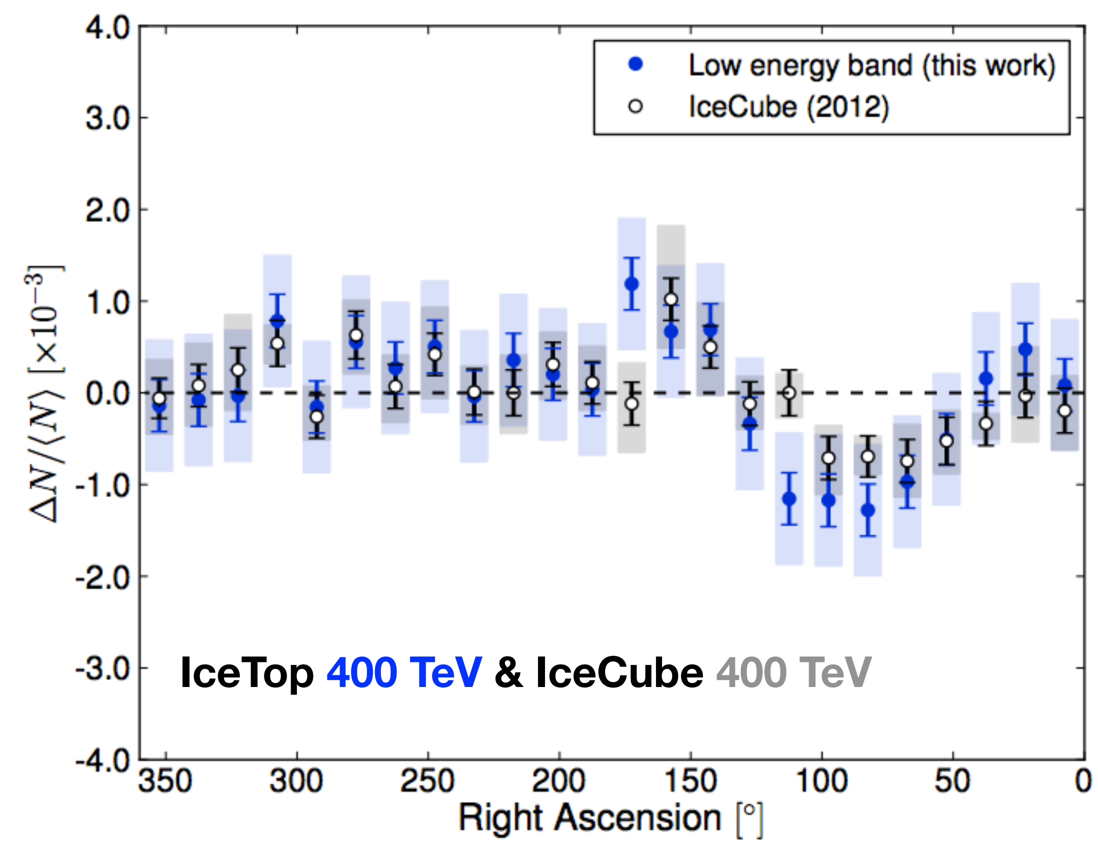
Paolo Desiati

cosmic ray anisotropy large scale
IceCube & IceTop



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





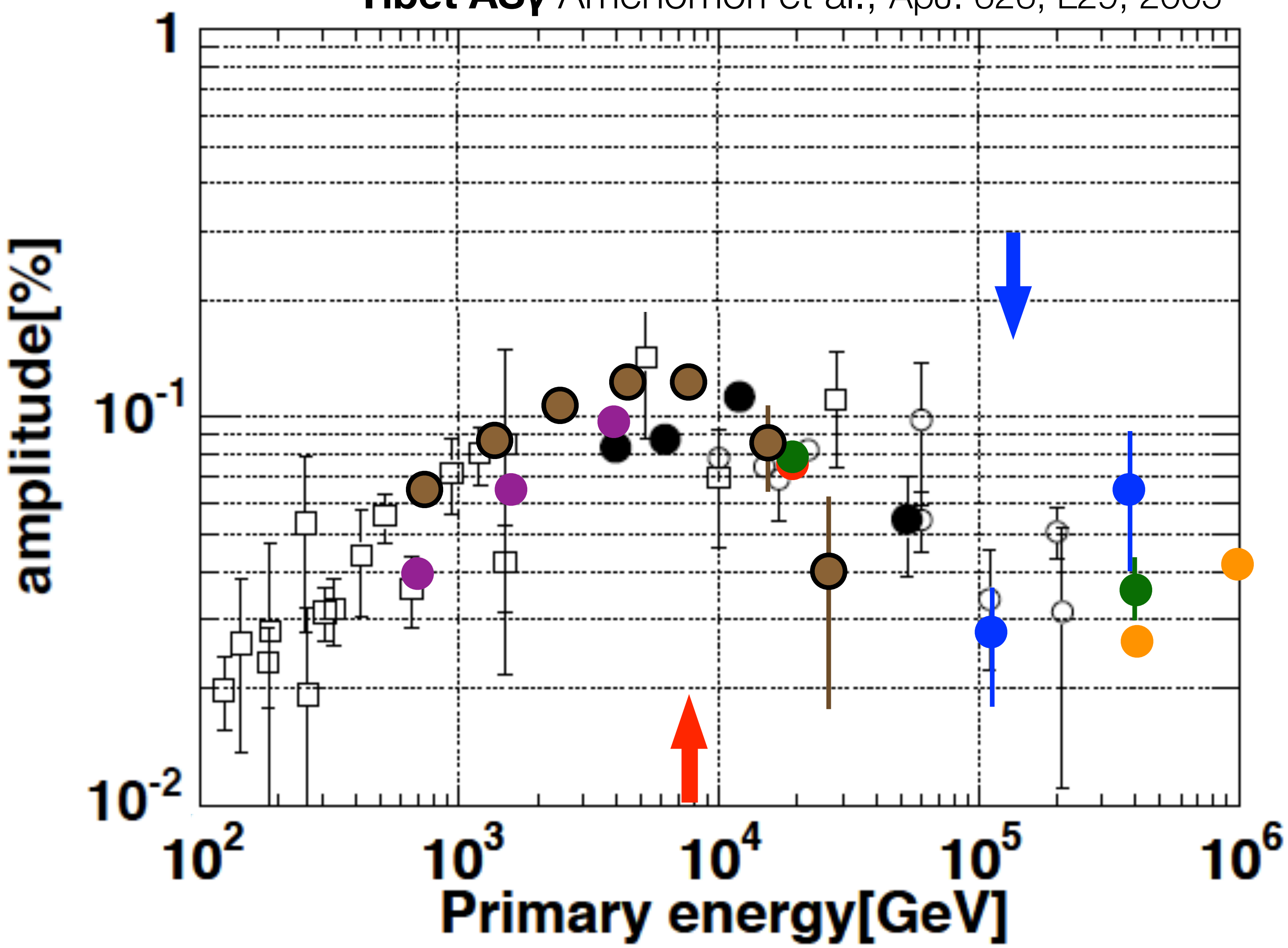
NOTE: different energy response distribution

IceTop with *sharper* low energy threshold

might explain IC/IT amplitude differences

cosmic ray anisotropy large scale energy dependency

Tibet ASγ Amenomori et al., ApJ. 626, L29, 2005



dipole component

IceCube-22 Abbasi et al., ApJ, 718, L194, 2010

IceCube-59 Abbasi et al., ApJ, 746, 33, 2012

EAS-TOP Aglietta et al., ApJ, 692, L130, 2009

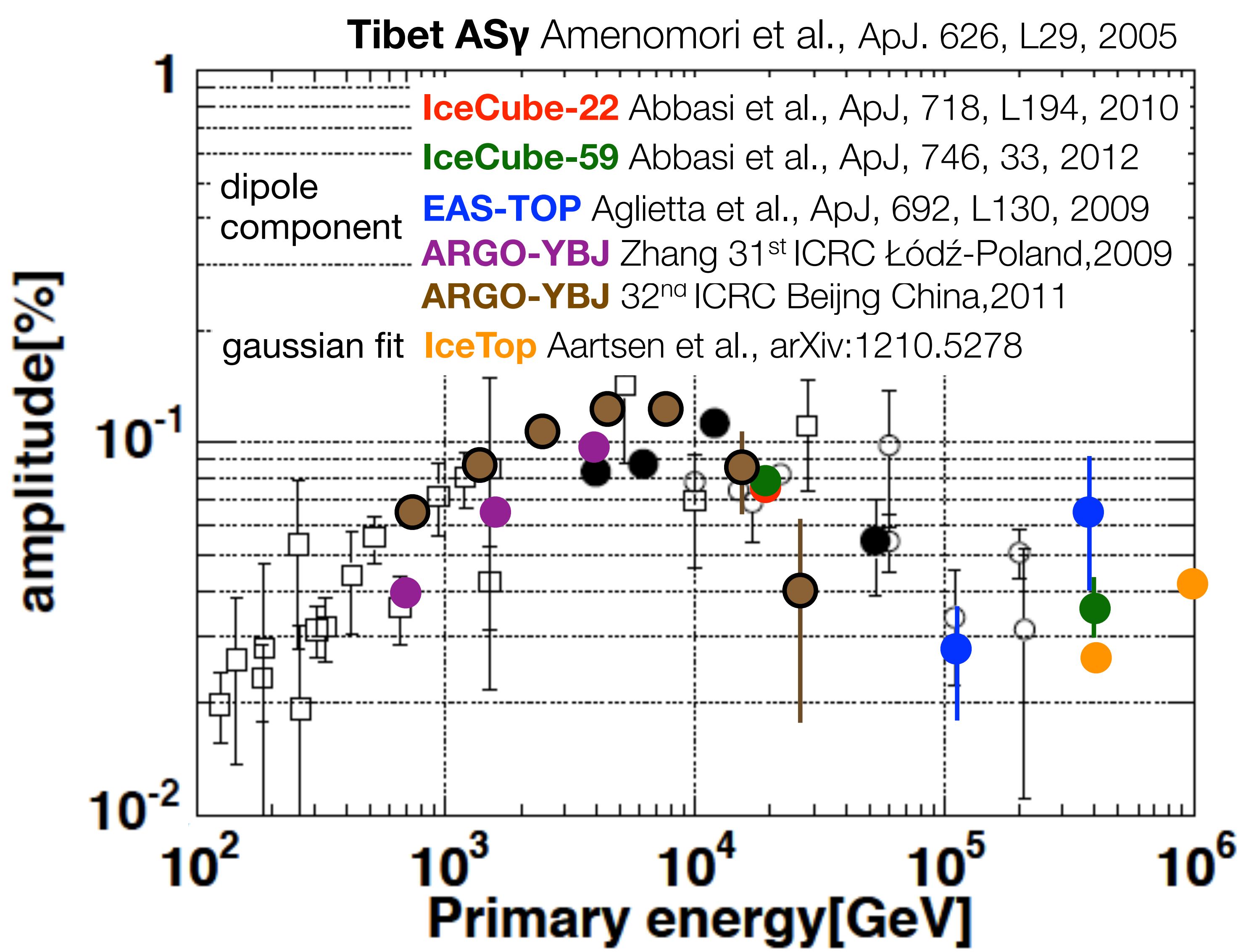
ARGO-YBJ Zhang 31st ICRC Łódź-Poland,2009

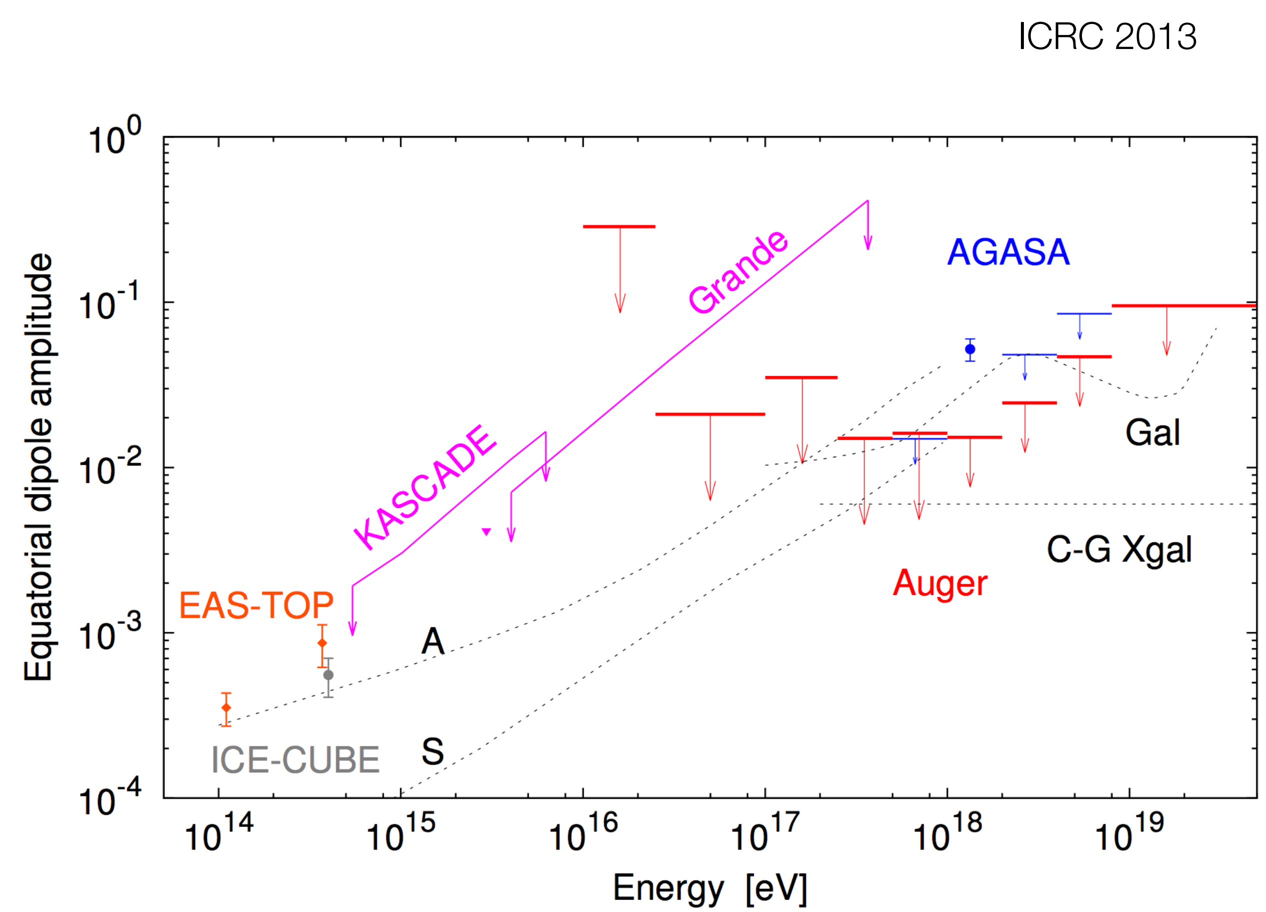
ARGO-YBJ 32nd ICRC Beijng China,2011

gaussian fit **IceTop** Aartsen et al., ApJ, 765, 55, 2013

- modulation in amplitude of **dipole component**
- corresponds to **transition in** anisotropy topology

cosmic ray anisotropy large scale energy dependency

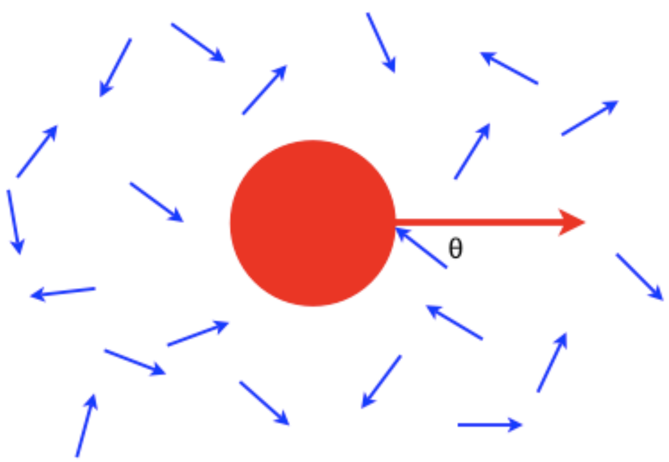




a known anisotropy

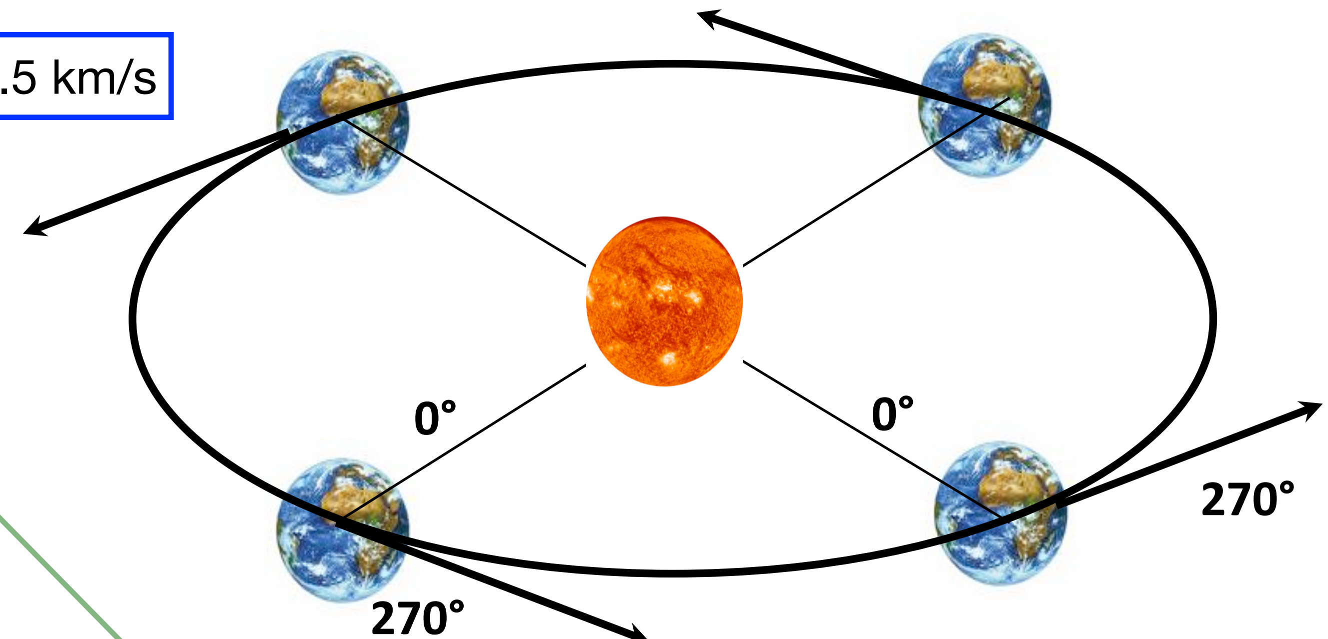
Earth's motion around the Sun

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

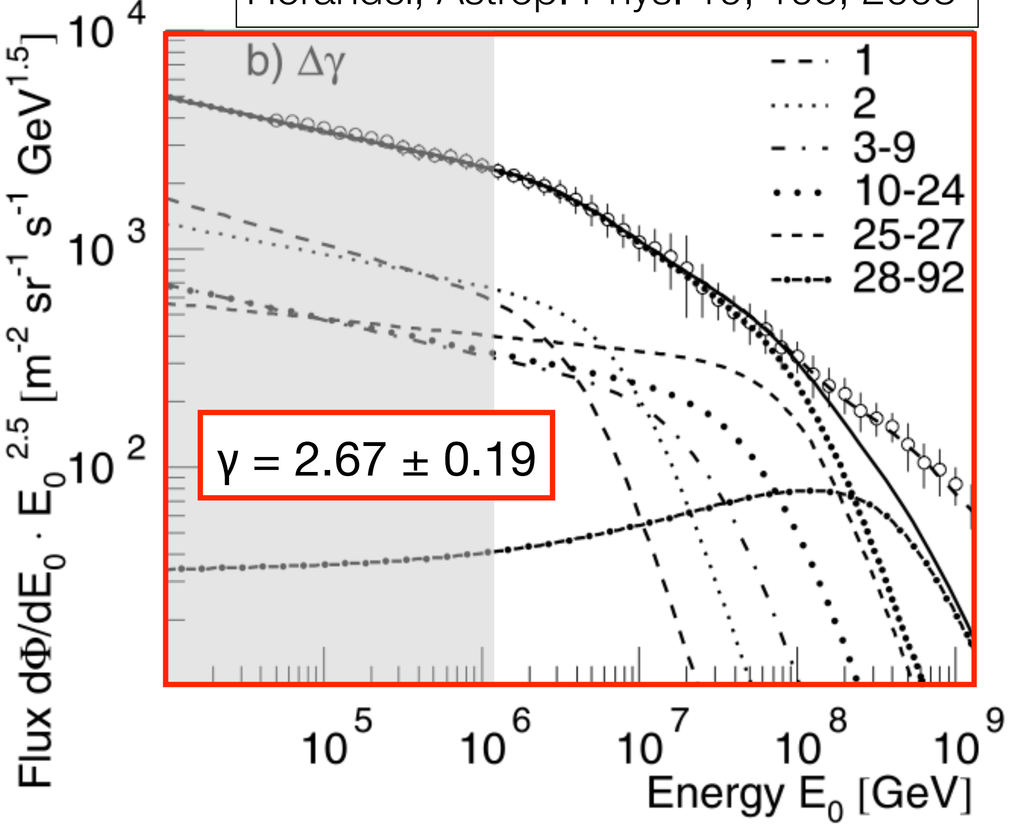


v = 29.8 ± 0.5 km/s

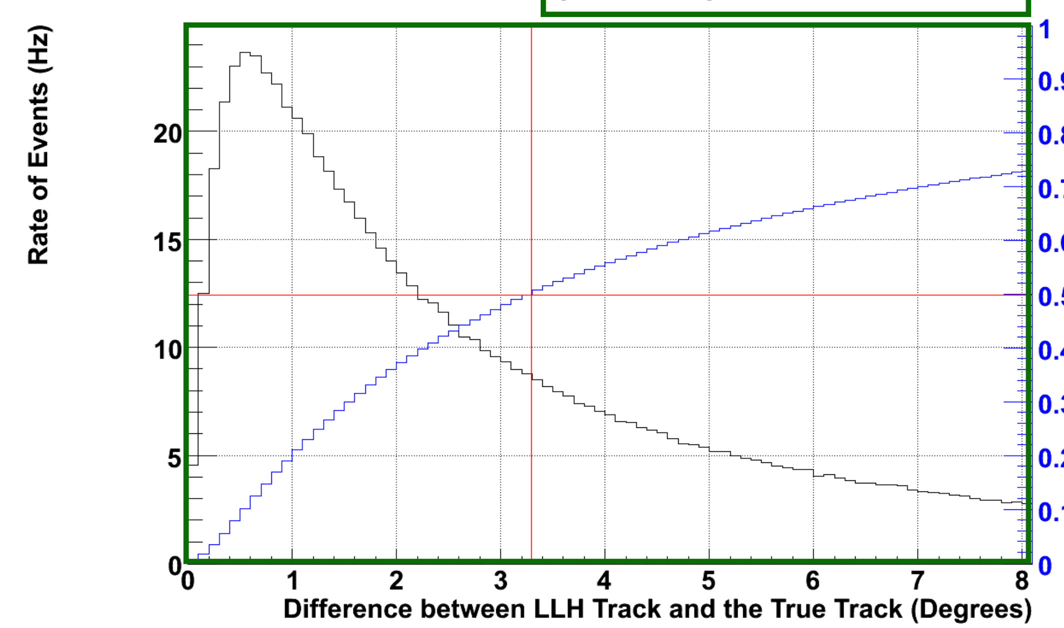
$$\frac{\Delta I}{I} = (\gamma + 2)\frac{v}{c}\cos\theta$$



Hörandel, Astrop. Phys. 19, 193, 2003



point spread function

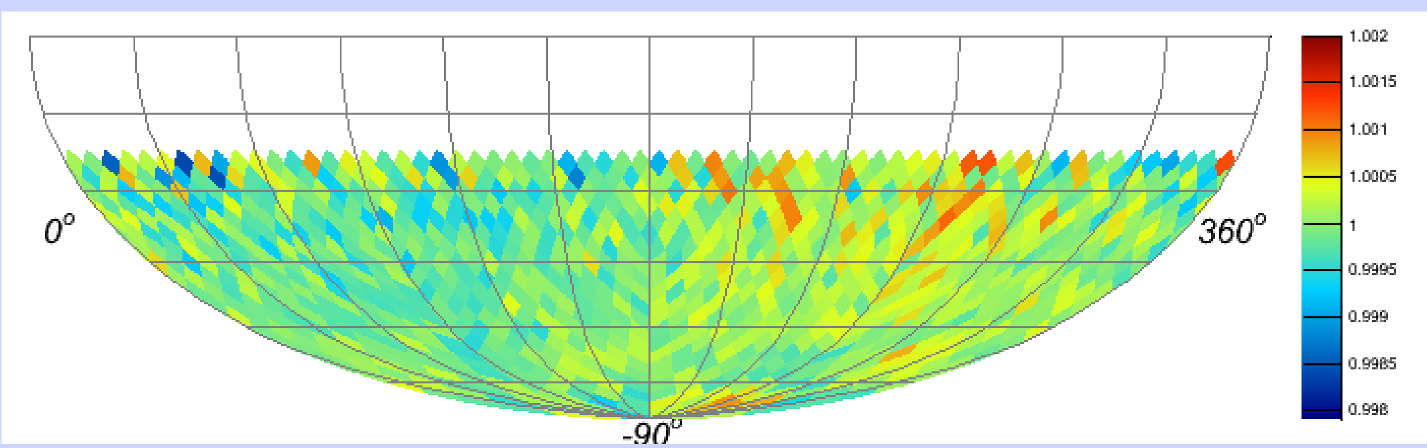


a known anisotropy
Earth's motion around the Sun

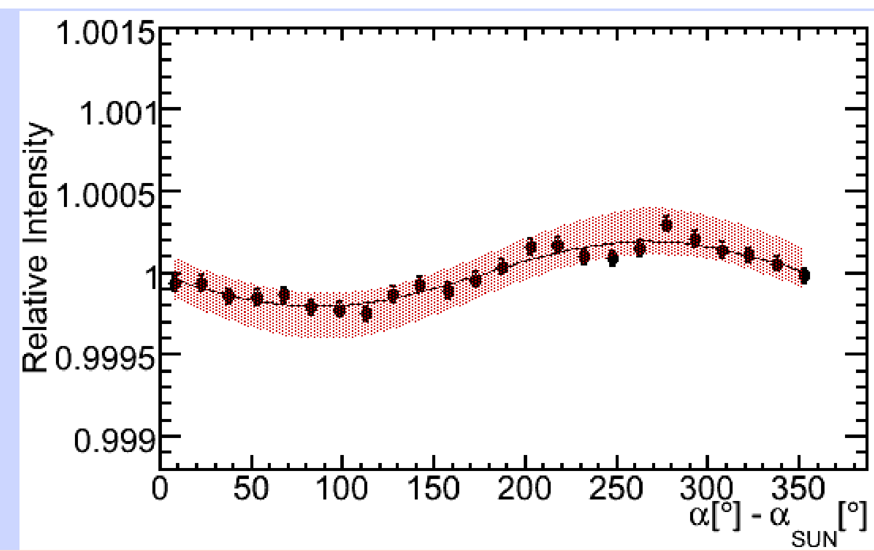
- the observation of the **solar dipole** supports the observation of the sidereal anisotropy in cosmic ray arrival direction

- **NO Compton-Getting Effect** signature from galactic rotation observed

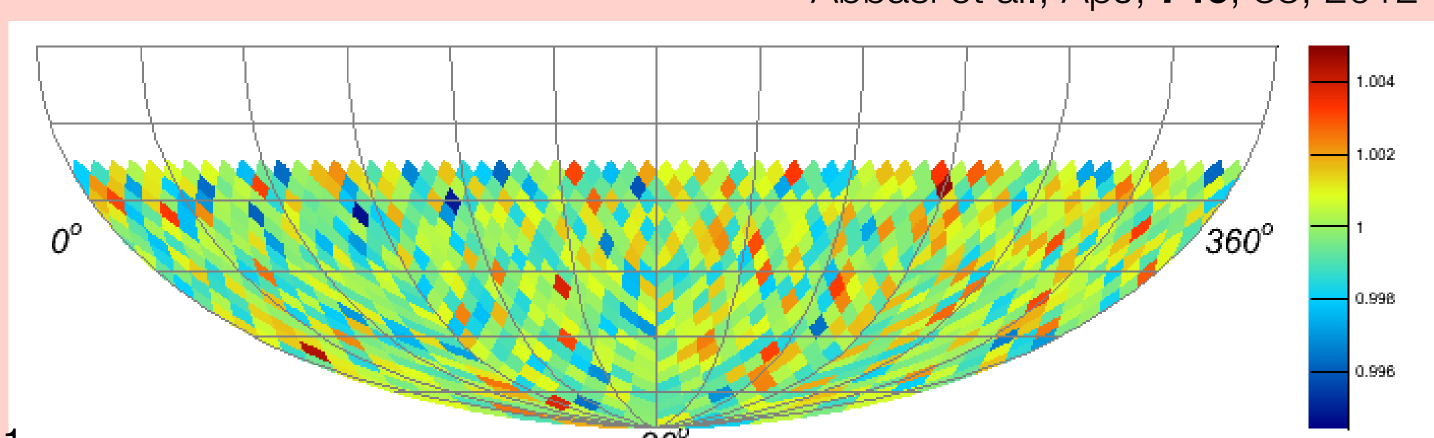
relative intensity $\alpha\,[^\circ] - \alpha_{SUN}\,[^\circ]$ IC59 Abbasi et al., ApJ, **746**, 33, 2012



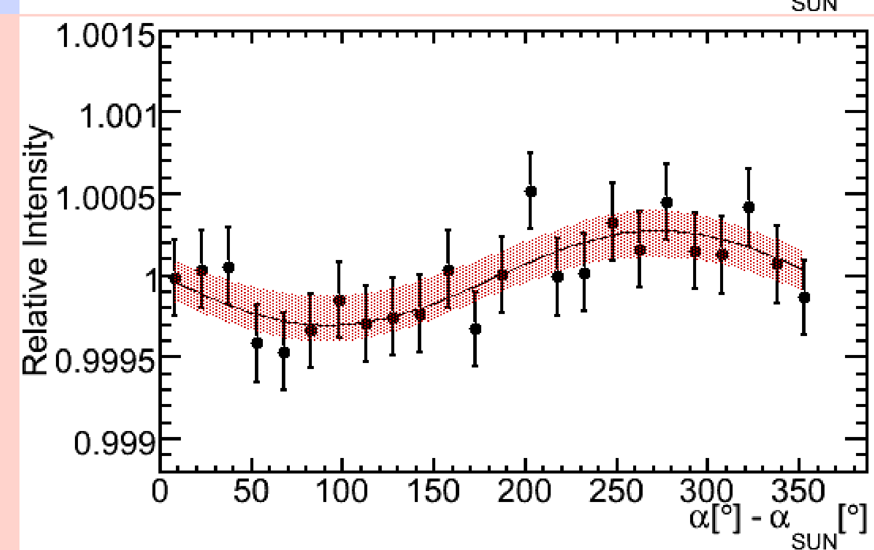
20 TeV



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

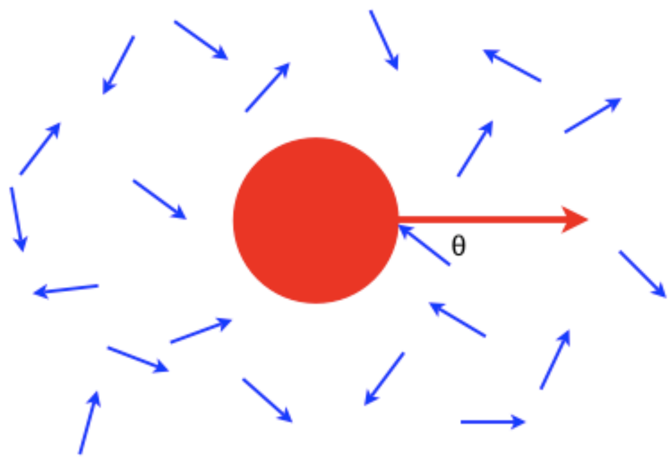


400 TeV



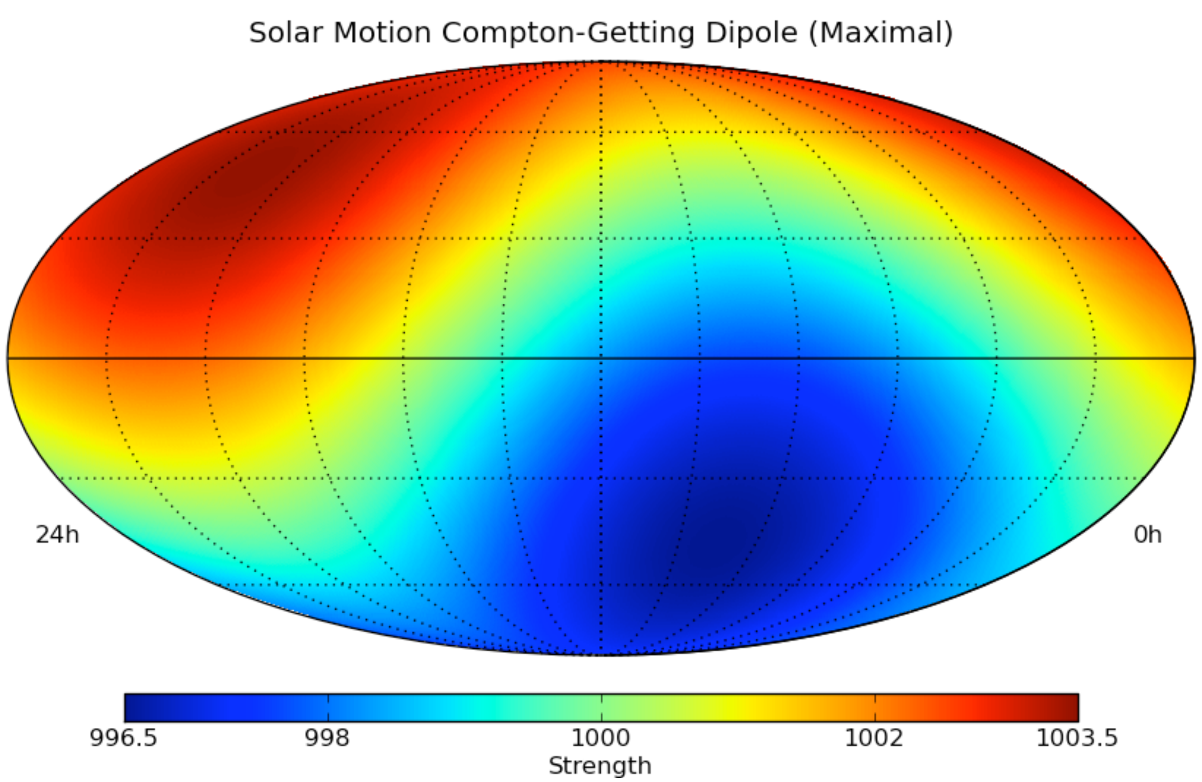
origin of large scale anisotropy : Compton-Getting Effect ?

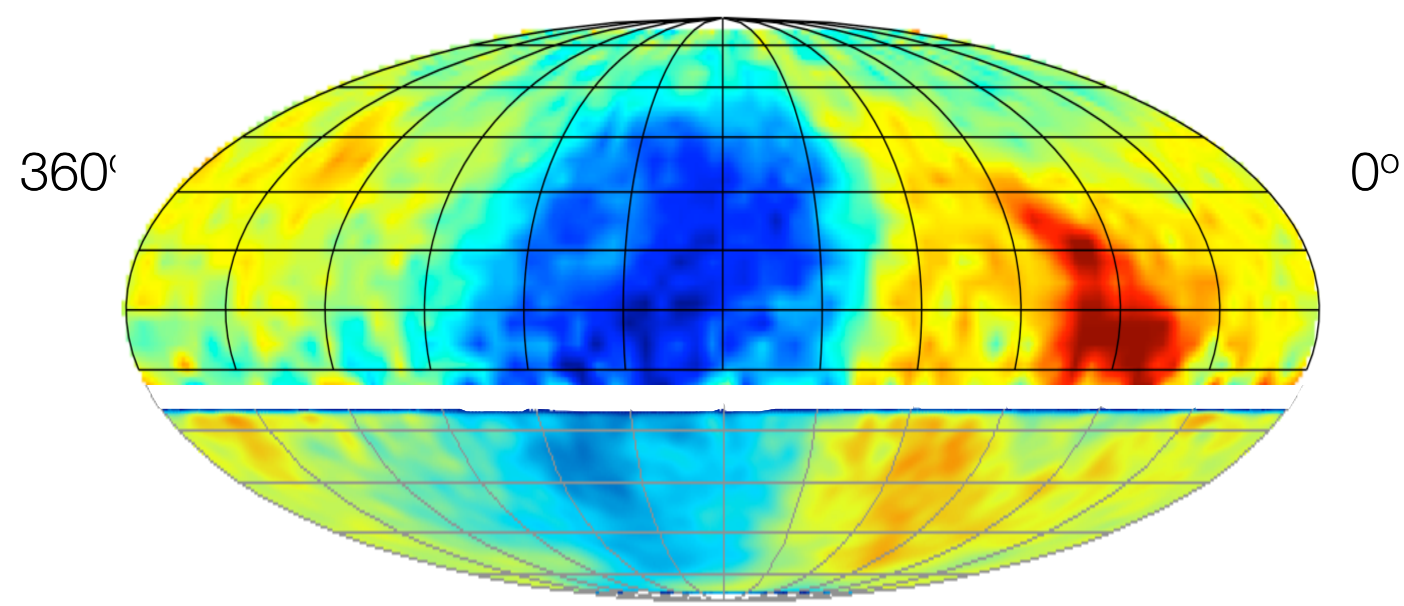
Compton & Getting, Phys. Rev. 47, 817 (1935)
Gleeson, & Axford, Ap&SS, 2, 43 (1968)



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

- motion of solar system around galactic center ~ 220 km/s
- reference system of cosmic rays is **unknown**
  - at most one dipole component of the observation

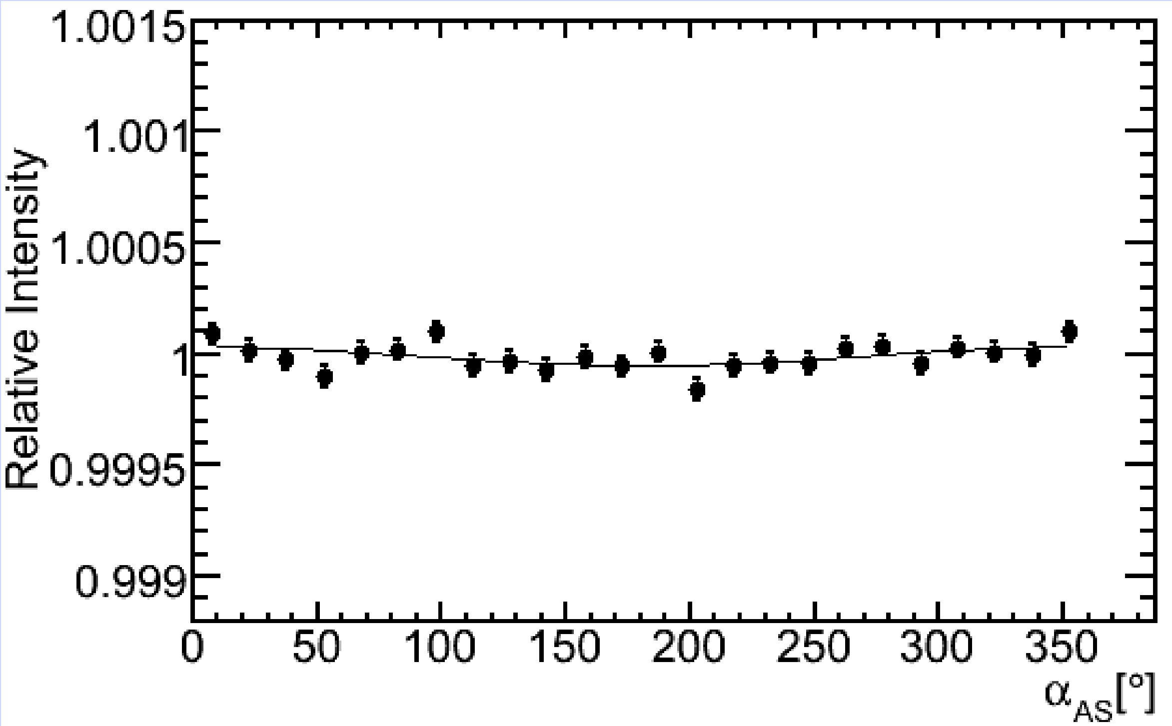




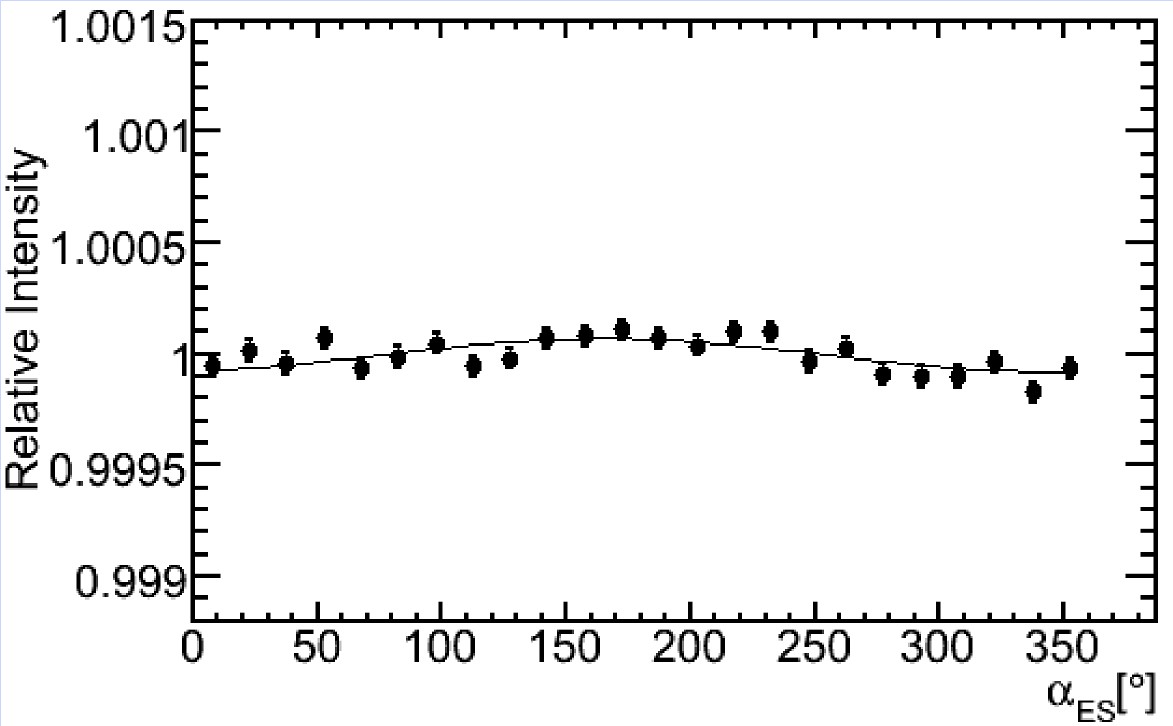
anti-/extended-sidereal distributions vs energy in IceCube-59

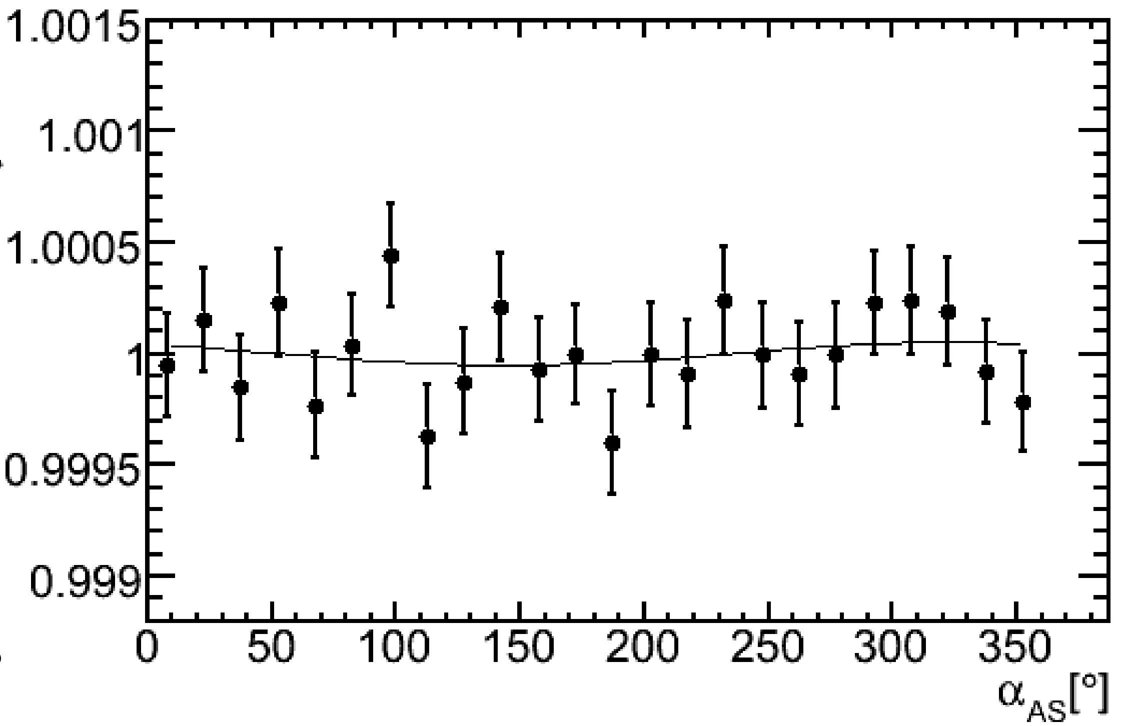
anti-sidereal distribution ~ solar dipole variability

extended-sidereal distribution ~ sid. anis. variability

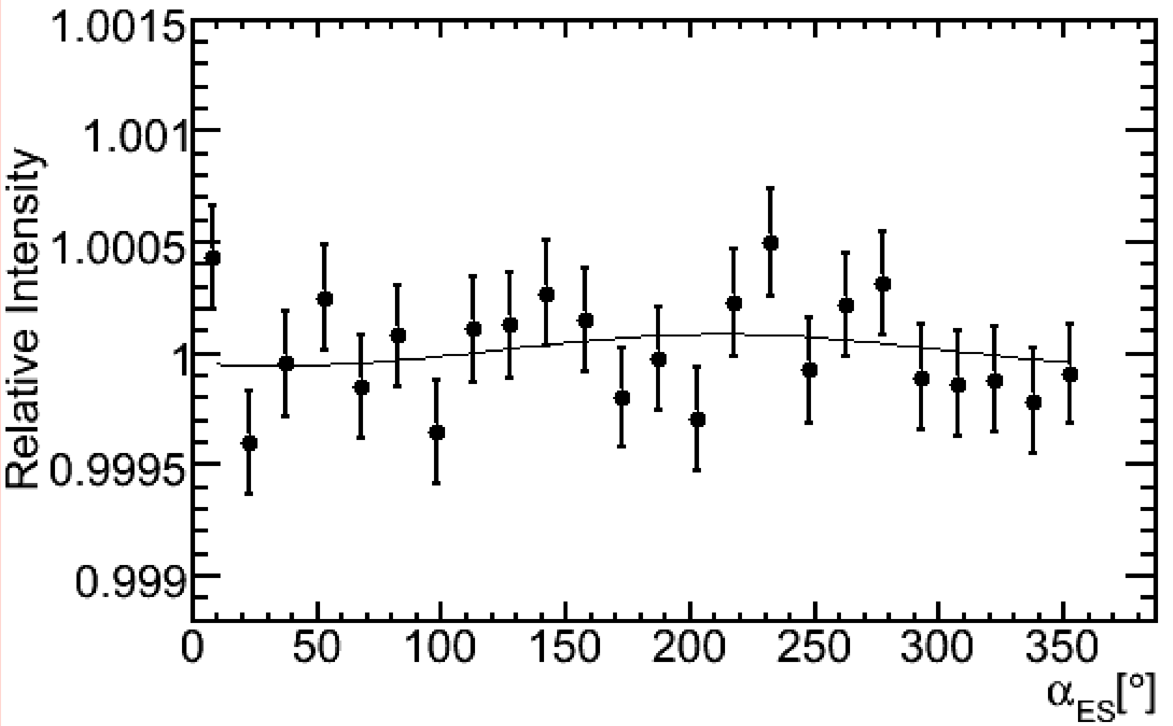


20 TeV





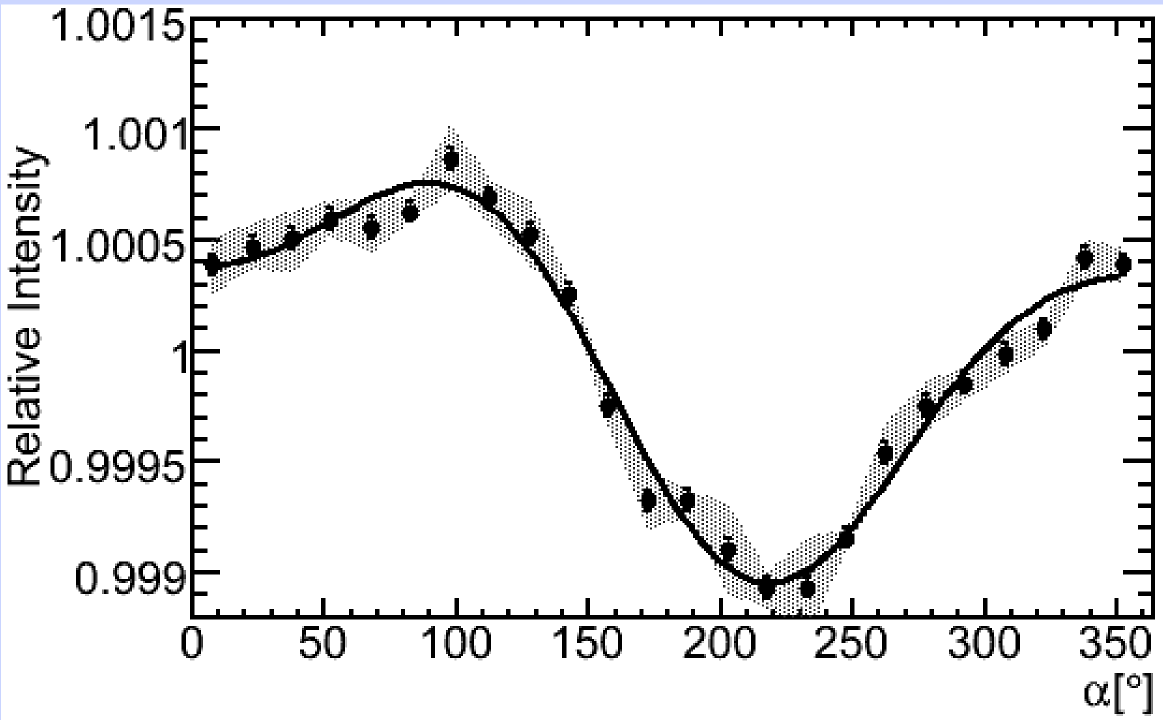
400 TeV



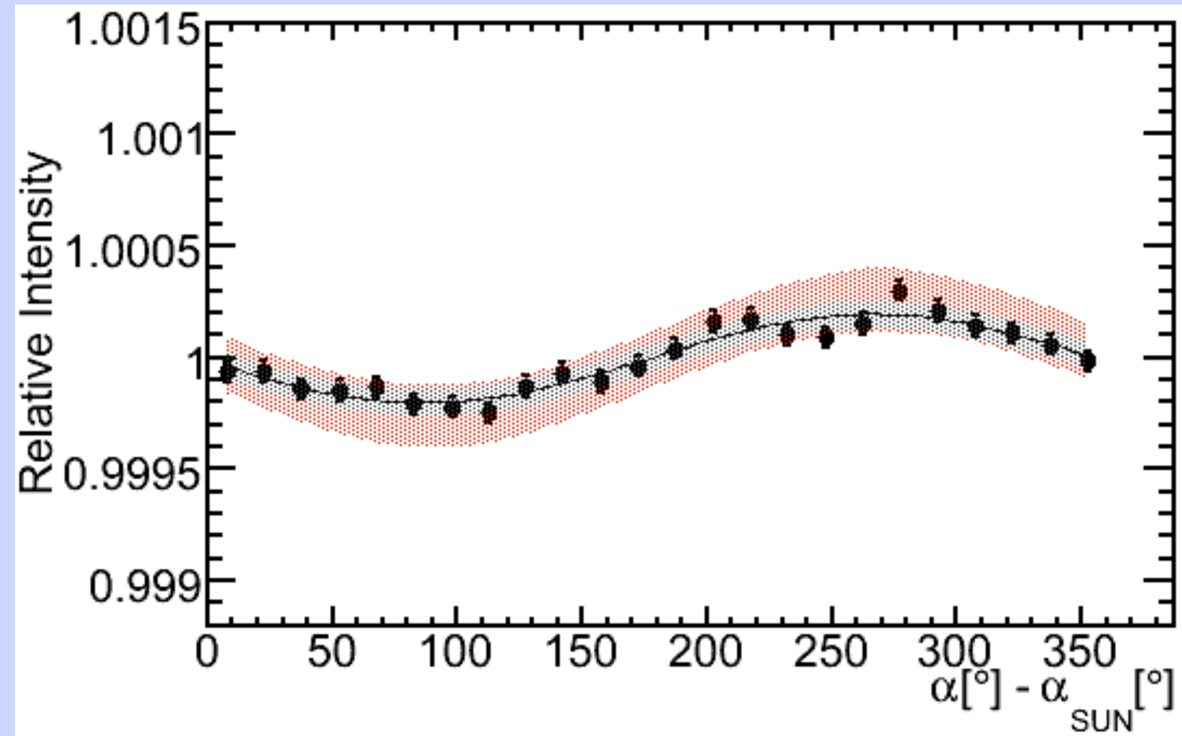
systematic uncertainties IceCube-59

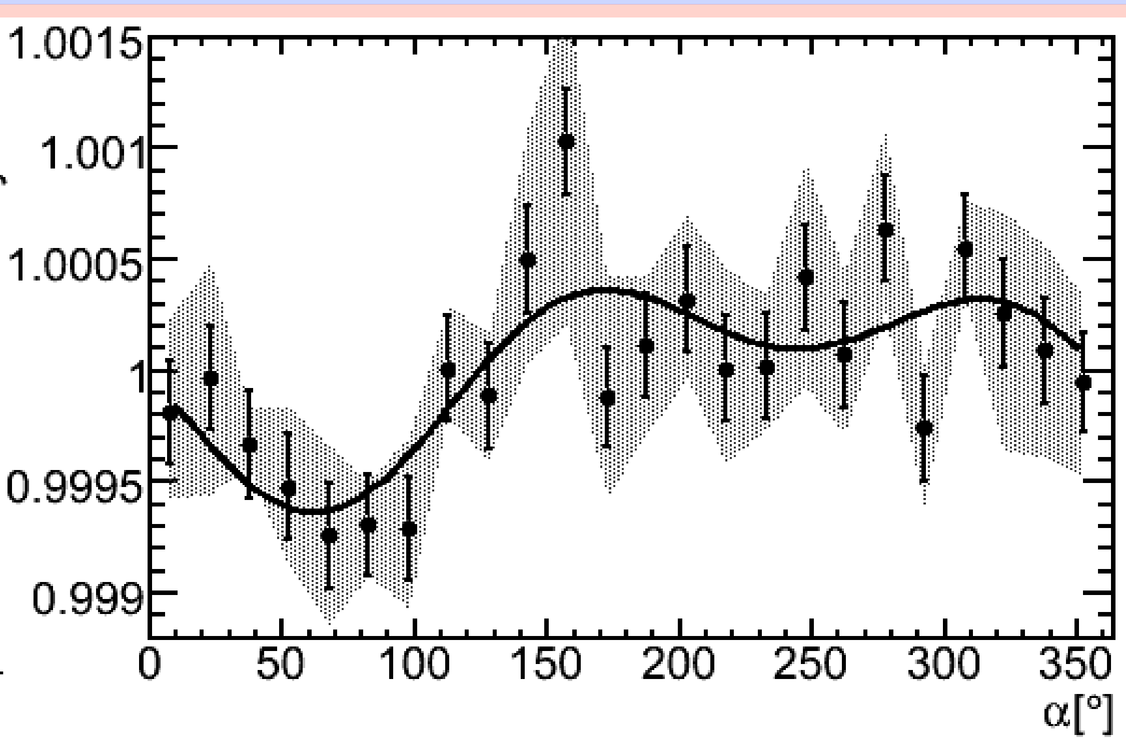
statistical stability tests + anti-sidereal effect

extended-sidereal effect

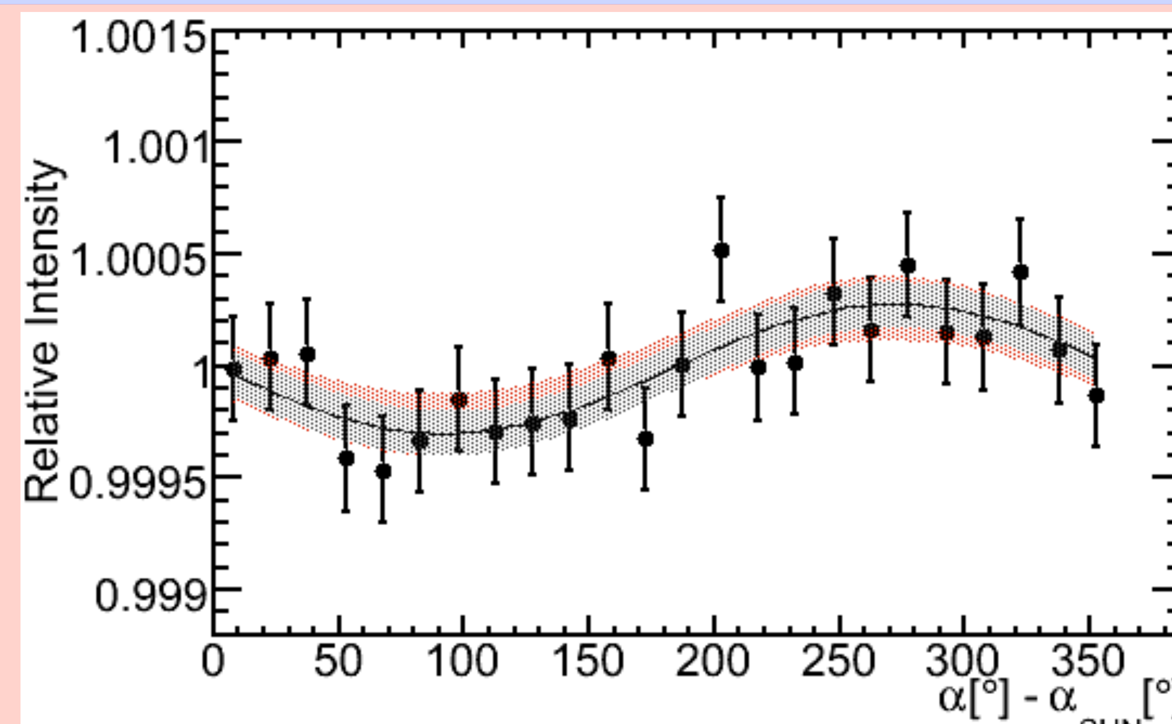


20 TeV



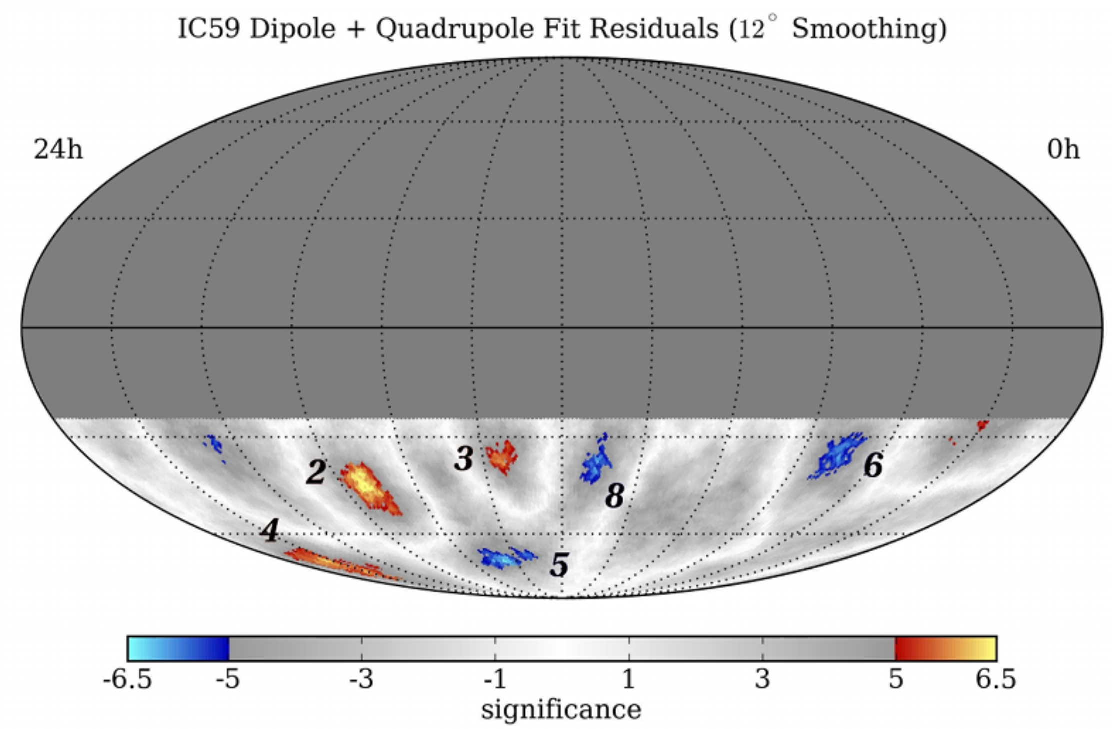


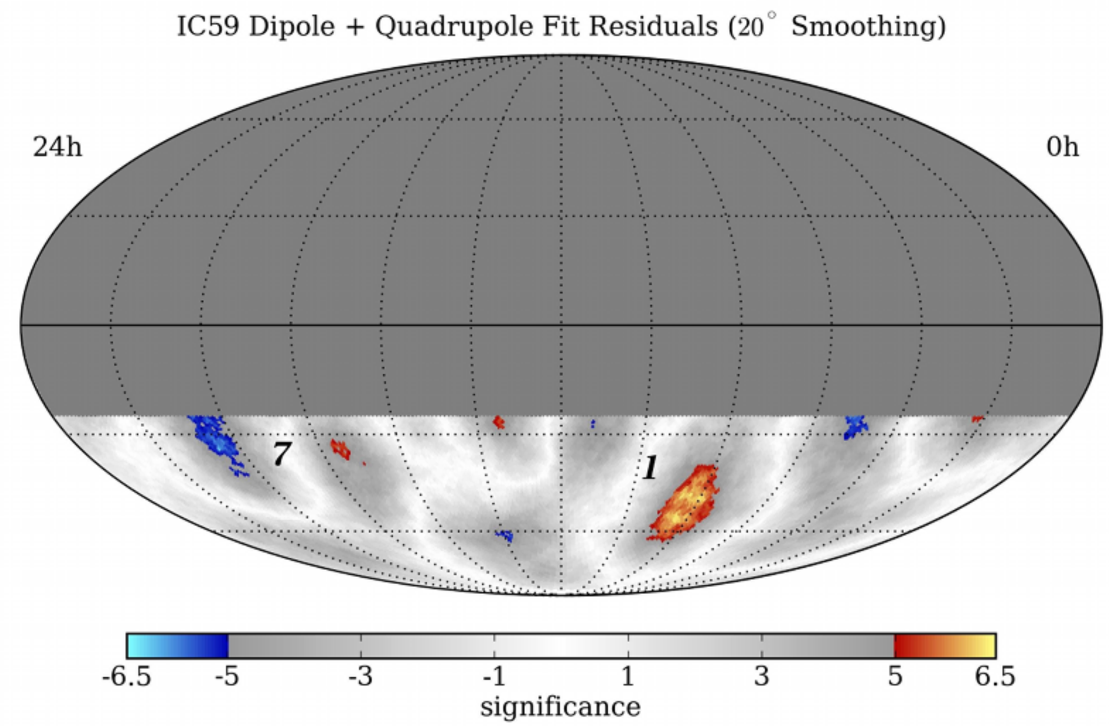
400 TeV



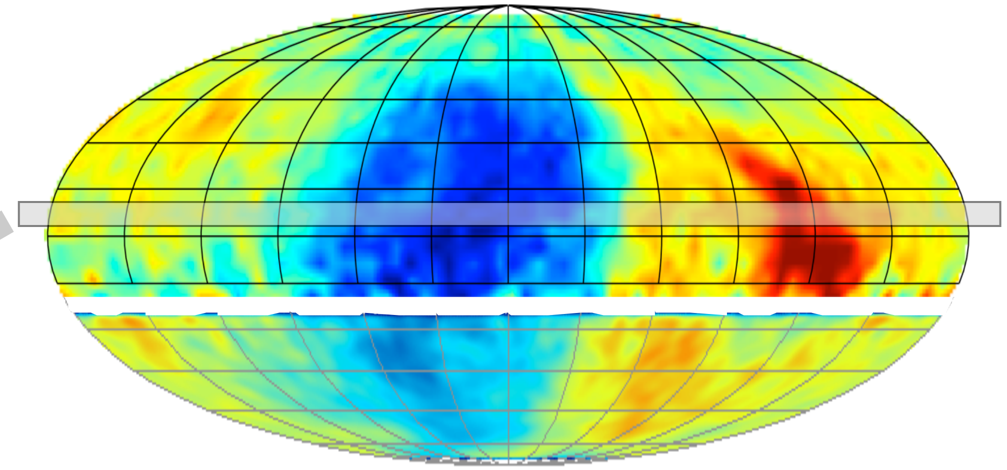
cosmic ray anisotropy small scale
IceCube

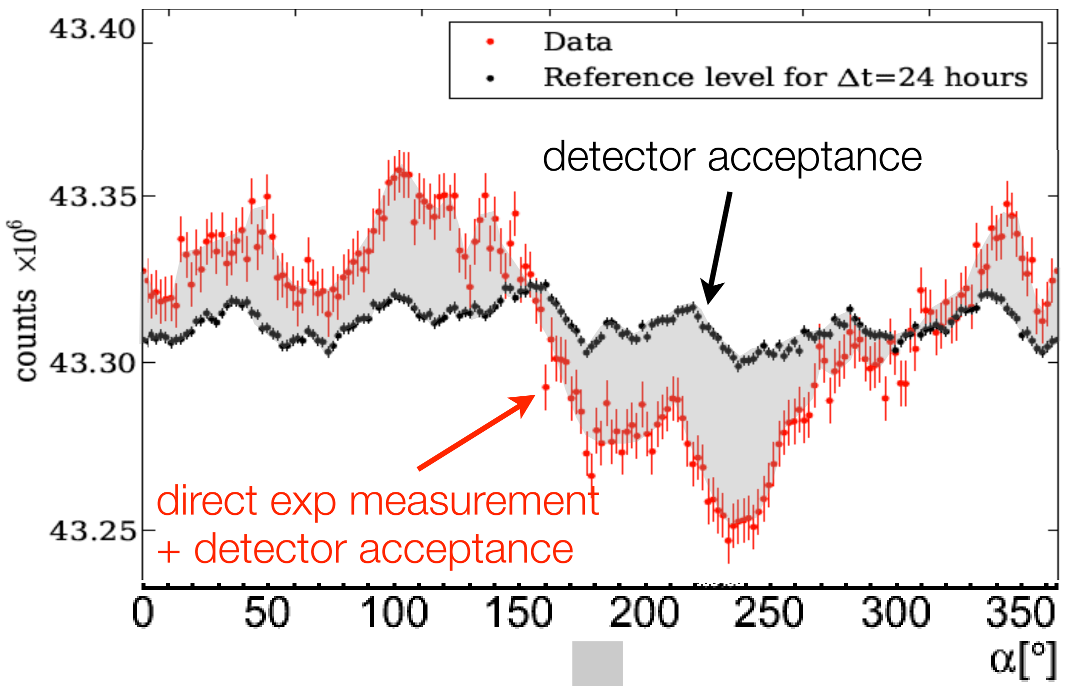
region	right ascension	declination	optimal scale	peak significance	post-trials	IC79 (post-trials)
1	$(122.4^{+4.1}_{-4.7})^{\circ}$	$(-47.4^{+7.5}_{-3.2})^{\circ}$	22°	7.0σ	5.3σ	6.8σ
2	$(263.0^{+3.7}_{-3.8})^{\circ}$	$(-44.1^{+5.3}_{-5.1})^{\circ}$	13°	6.7σ	4.9σ	5.4σ
3	$(201.6^{+6.0}_{-1.1})^{\circ}$	$(-37.0^{+2.2}_{-1.9})^{\circ}$	11°	6.3σ	4.4σ	6.4σ
4	$(332.4^{+9.5}_{-7.1})^{\circ}$	$(-70.0^{+4.2}_{-7.6})^{\circ}$	12°	6.2σ	4.2σ	6.1σ
5	$(217.7^{+10.2}_{-7.8})^{\circ}$	$(-70.0^{+3.6}_{-2.3})^{\circ}$	12°	-6.4σ	-4.5σ	-6.1σ
6	$(77.6^{+3.9}_{-8.4})^{\circ}$	$(-31.9^{+3.2}_{-8.6})^{\circ}$	13°	-6.1σ	-4.1σ	-4.3σ
7	$(308.2^{+4.8}_{-7.7})^{\circ}$	$(-34.5^{+9.6}_{-6.9})^{\circ}$	20°	-6.1σ	-4.1σ	-4.4σ
8	$(166.5^{+4.5}_{-5.7})^{\circ}$	$(-37.2^{+5.0}_{-5.7})^{\circ}$	12°	-6.0σ	-4.0σ	-6.4σ

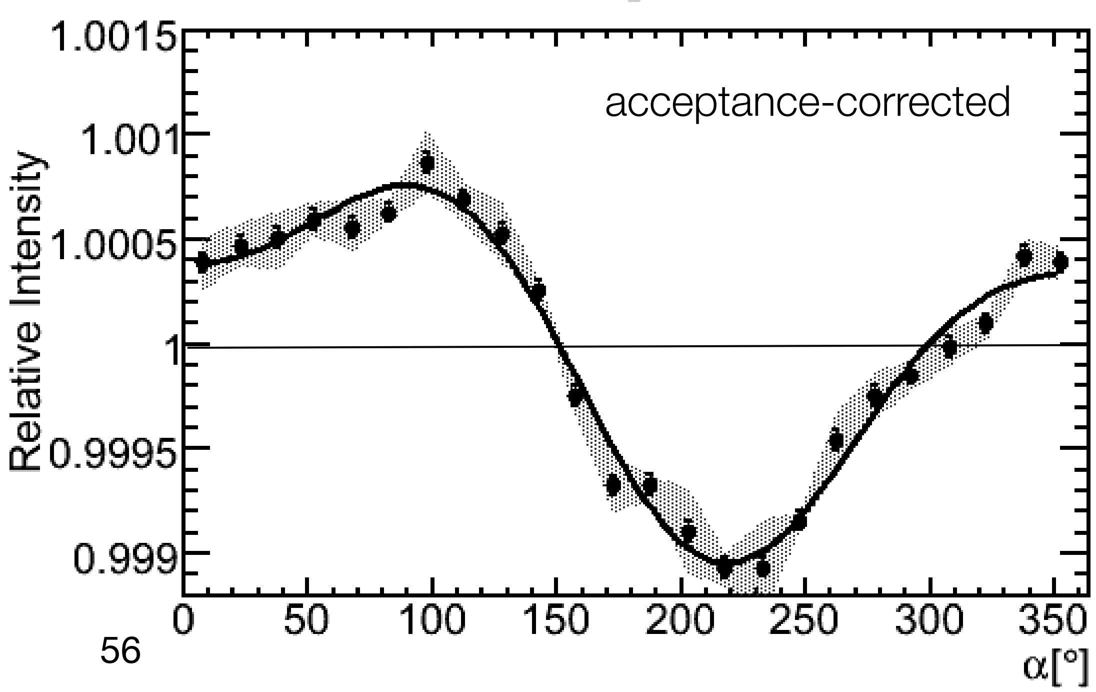


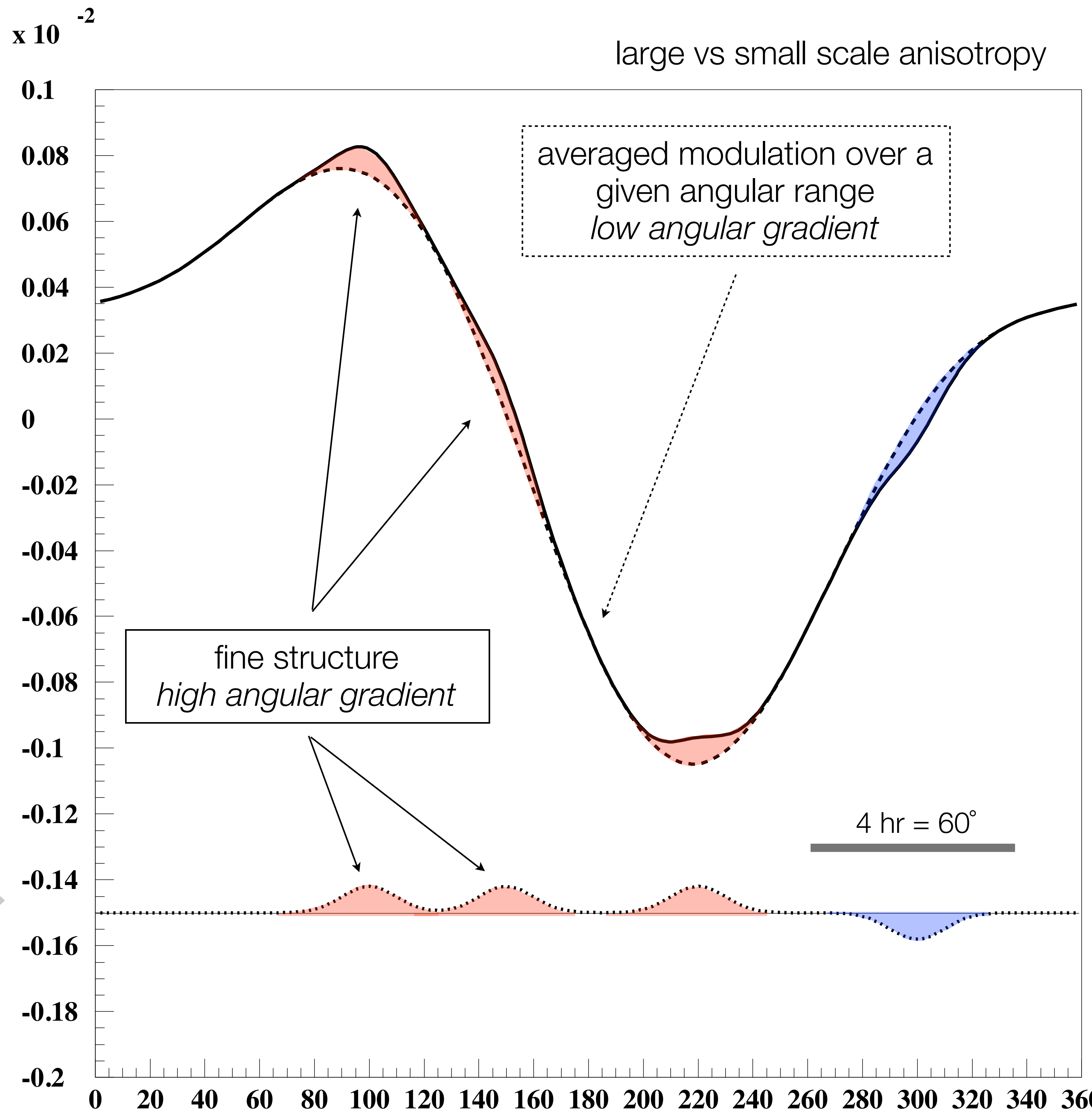


anisotropy vs. angular scale









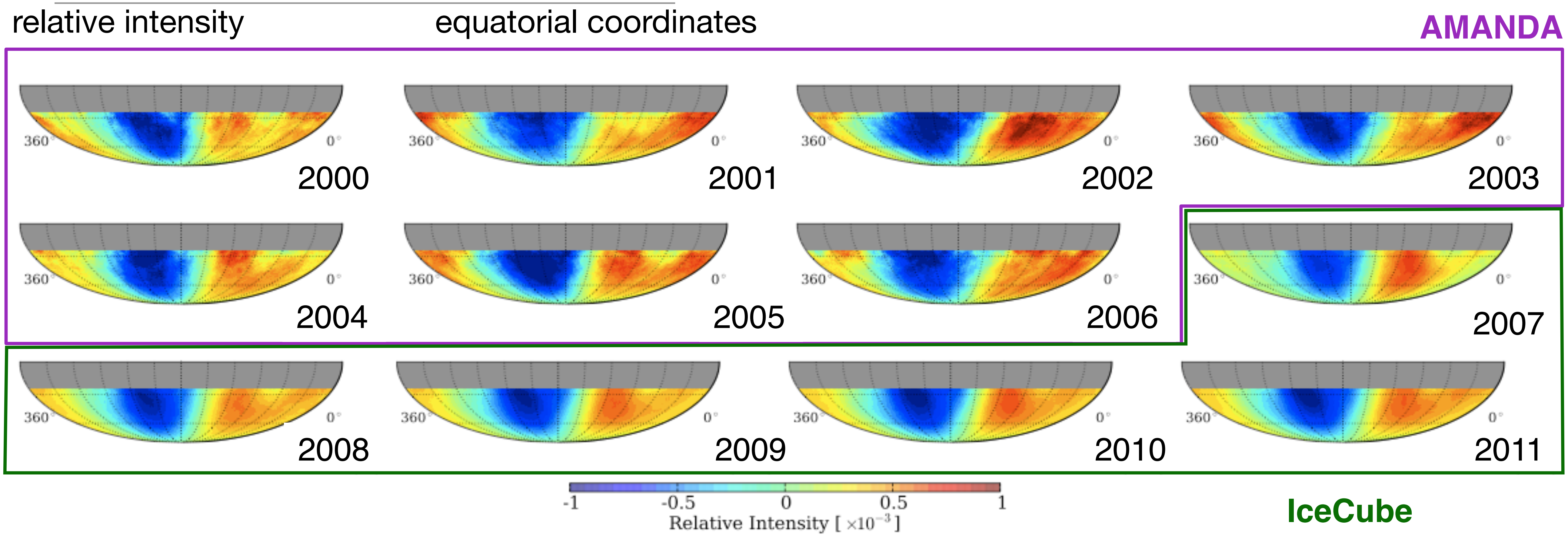
Paolo Desiati

cosmic ray anisotropy
AMANDA-IceCube 2000-2011

PRELIMINARY

20 TeV

relative intensity equatorial coordinates



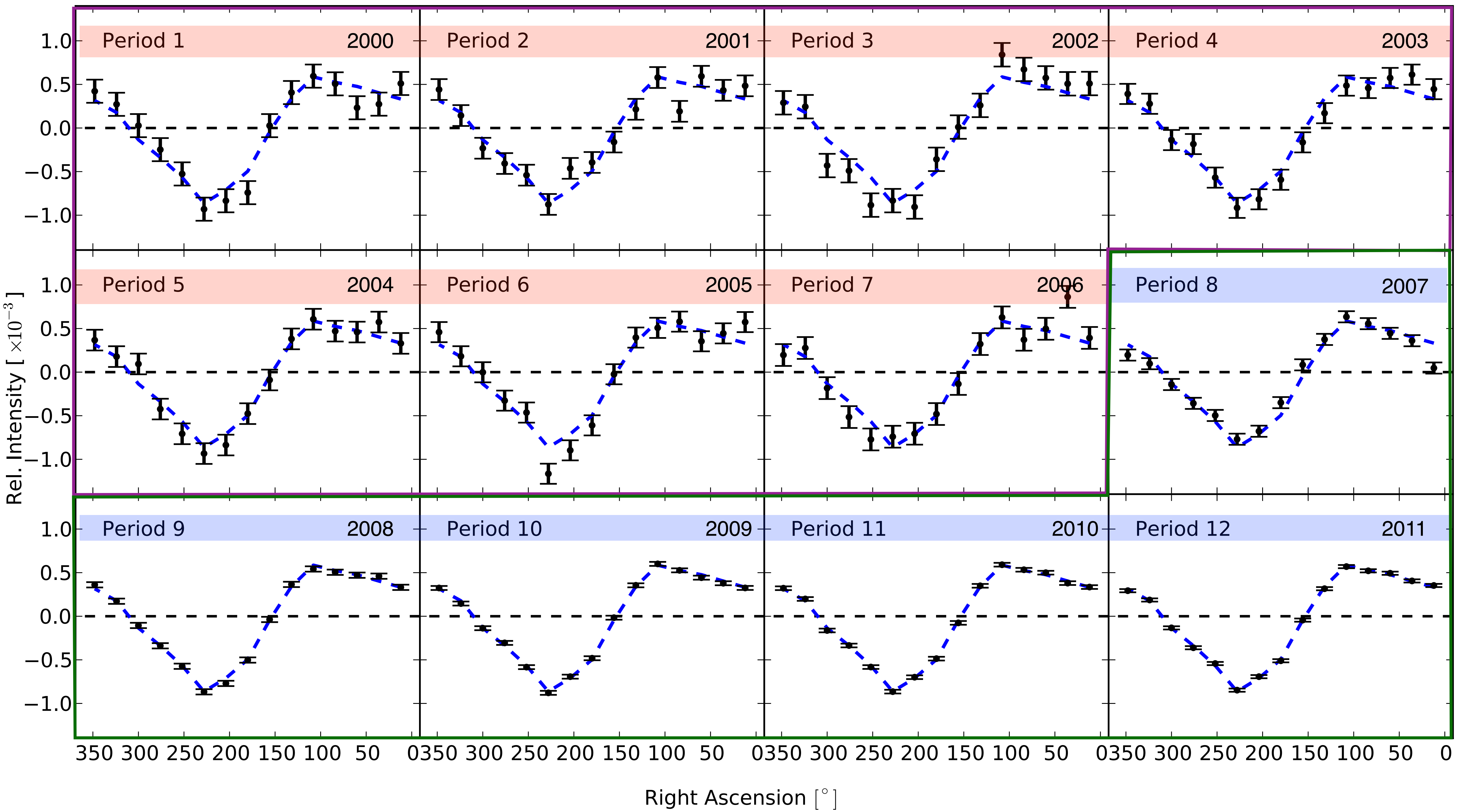
- AMANDA and IceCube yearly data show long **time-scale stability** of global anisotropy within statistical uncertainties
  - no apparent effect correlated to solar cycles

cosmic ray anisotropy

AMANDA-IceCube 2000-2011

PRELIMINARY

20 TeV



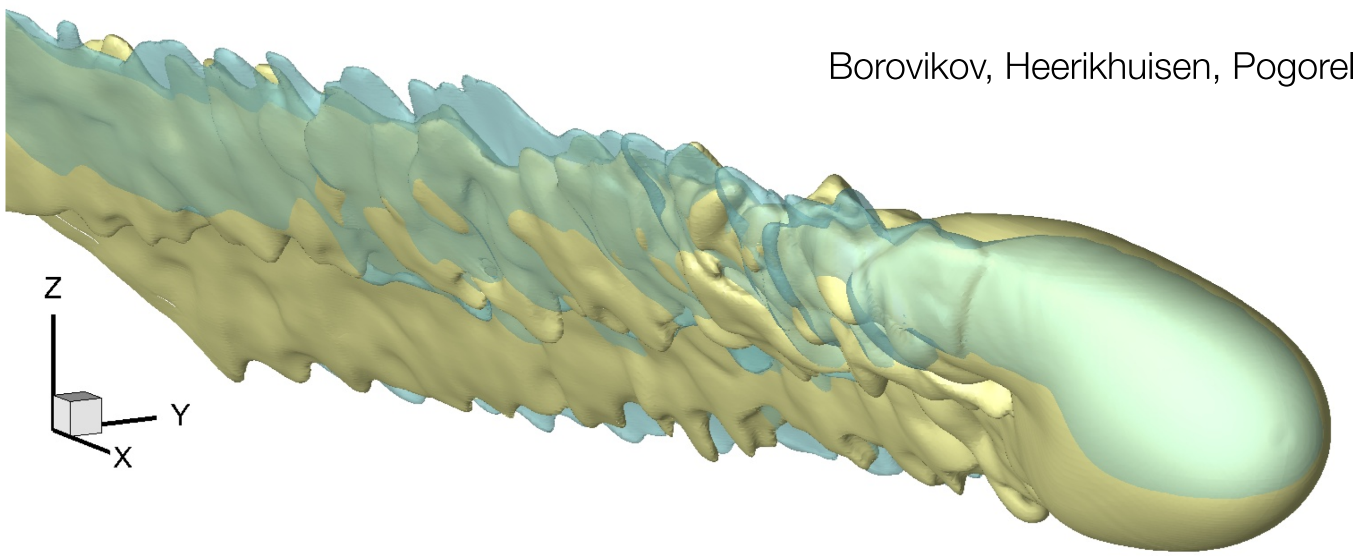
cosmic ray anisotropy
AMANDA-IceCube 2000-2011

Preliminary

Period	Detector	Start	End	Live-time (days)	No. of events ($\times 10^9$)	χ^2/dof	p-value
1	AM-II	02/13/2000	11/02/2000	213.4	1.4	11.3/15	0.73
2	AM-II	02/11/2001	10/19/2001	235.3	2.3	16.6/15	0.34
3	AM-II	01/01/2002	08/02/2002	169.2	2.4	26.0/15	0.04
4	AM-II	02/09/2003	12/17/2003	236.0	2.2	19.3/15	0.20
5	AM-II	01/05/2004	11/02/2004	225.8	2.5	14.3/15	0.50
6	AM-II	12/30/2004	12/23/2005	242.9	2.6	21.0/15	0.14
7	AM-II	01/01/2006	09/13/2006	213.1	2.4	24.4/15	0.06
8	IC22	06/01/2007	03/30/2008	269.4	5.3	45.2/15	7×10^{-5}
9	IC40	04/18/2008	04/30/2009	335.6	18.9	12.8/15	0.62
10	IC59	05/20/2009	05/30/2010	335.0	33.8	11.1/15	0.75
11	IC79	05/31/2010	05/12/2011	299.7	39.1	6.5/15	0.97
12	IC86	05/13/2011	05/14/2012	332.9	52.9	8.9/15	0.88

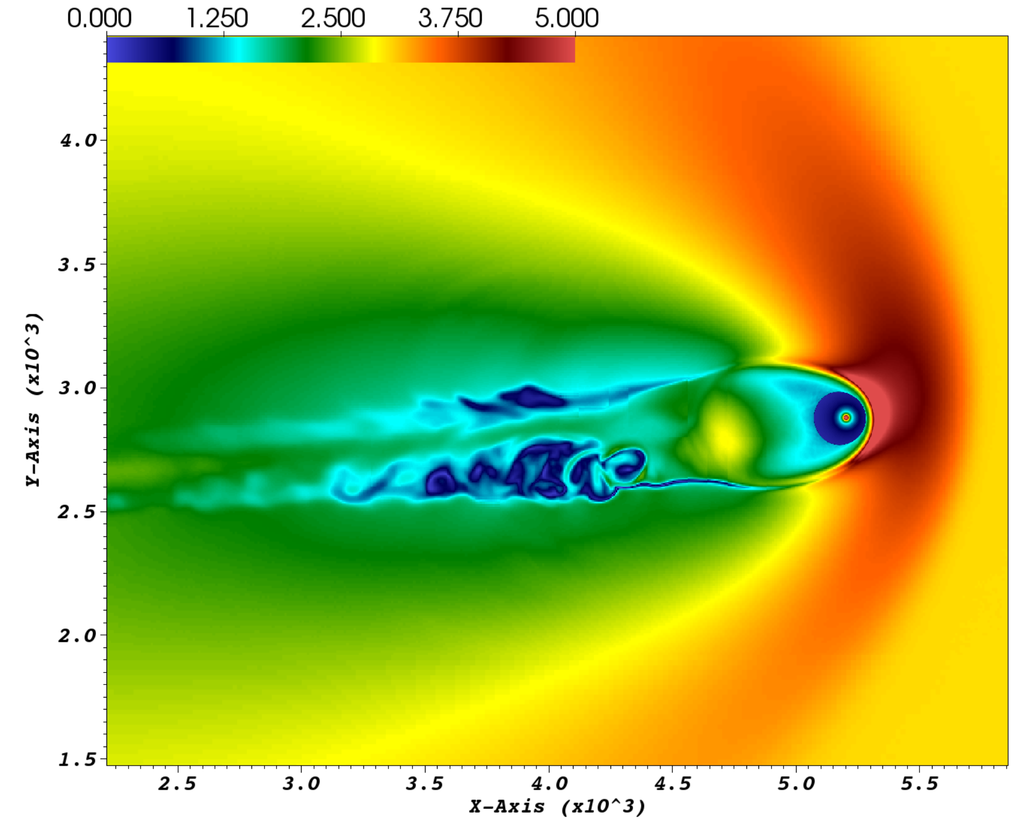
statistical uncertainties only

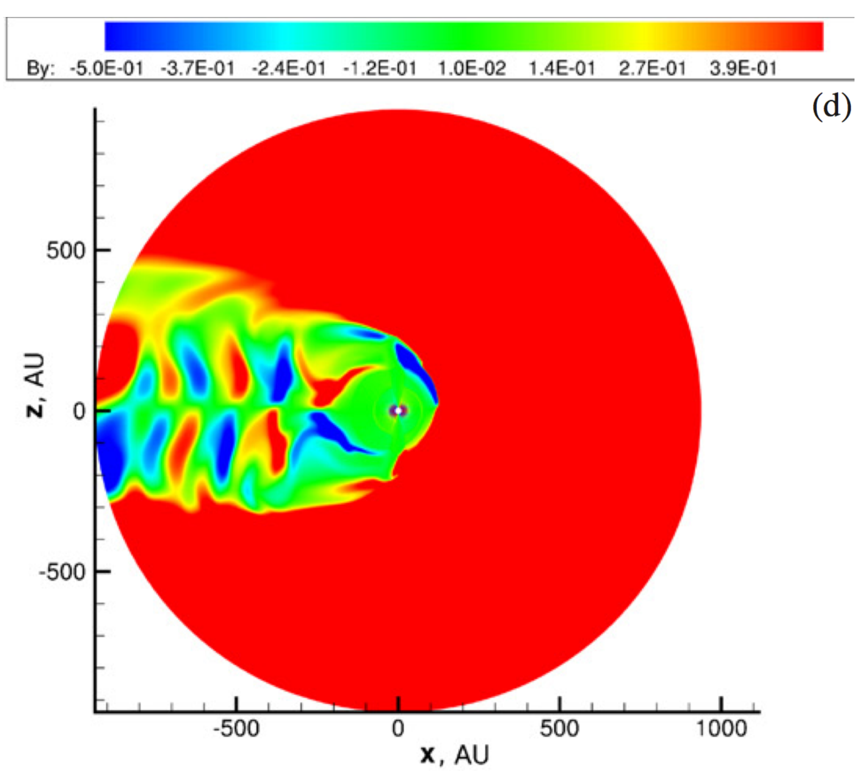
cosmic ray anisotropy
probing heliospheric magnetic structure



Borovikov, Heerikhuisen, Pogorelov

downstream instabilities on the flanks of heliotail





Pogorelov et al., 2009

effects of magnetic polarity reversals from solar cycles