> 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

the astrophysics of cosmic ray anisotropy

a short review

Paolo Desiati

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University of Wisconsin - Madison

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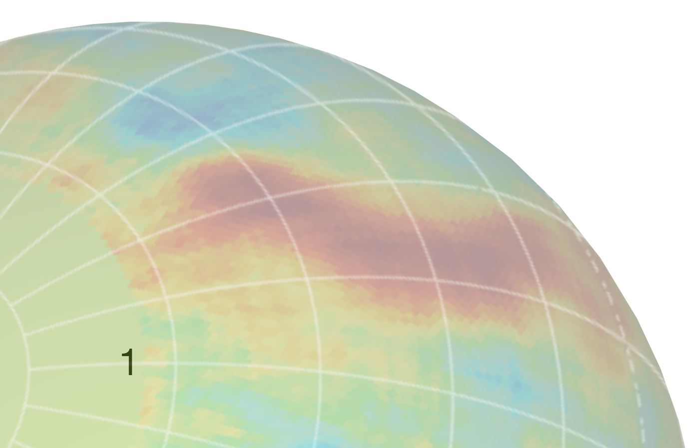
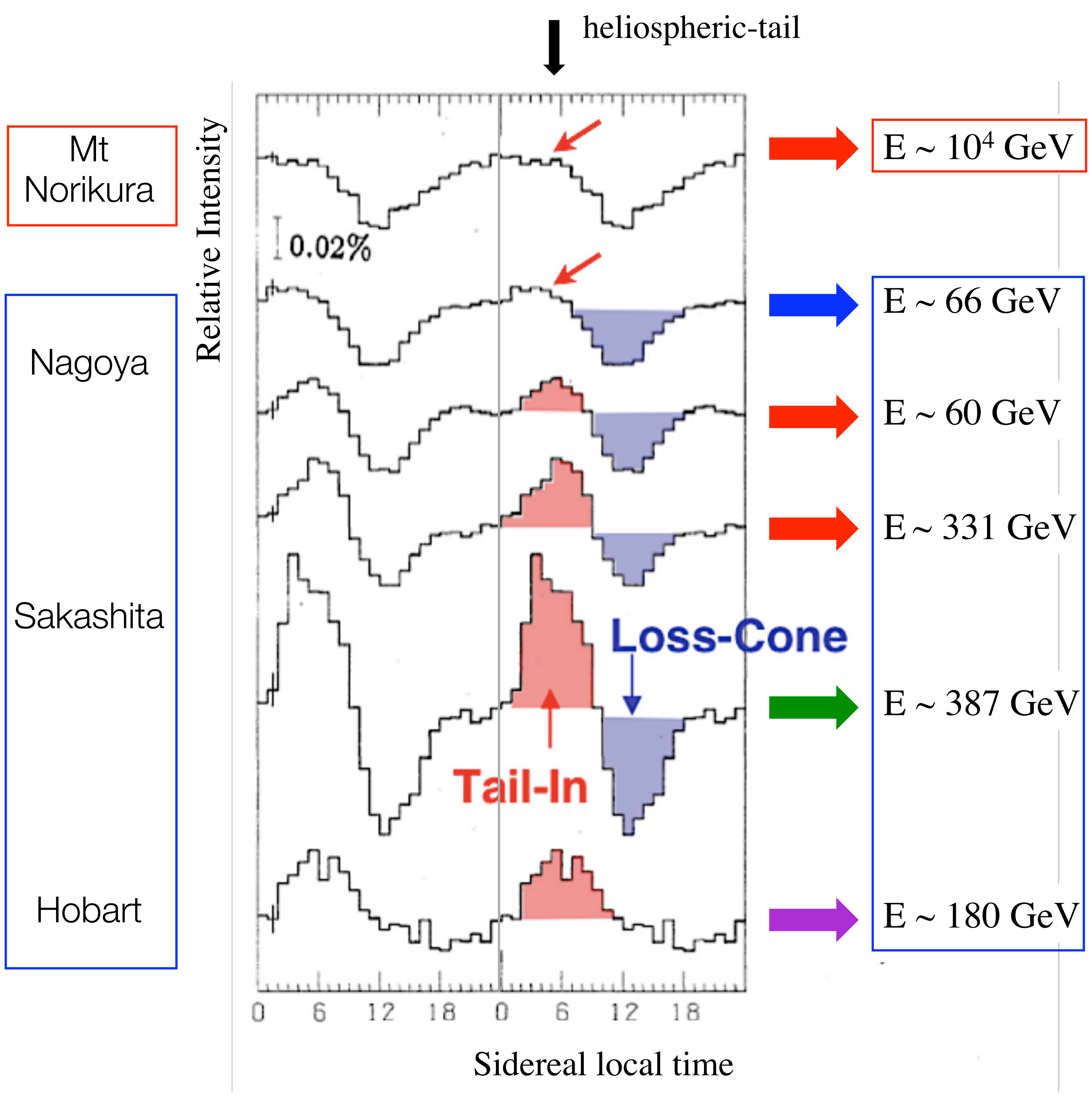


Cosmic Ray Anisotropies 2015
Bad Honnef, Germany **- January 26, 2015**

low energy cosmic rays

Nagashima et al., J. Geophys. Res., Vol 103, No. A8, Pag. 17,429 (1998)



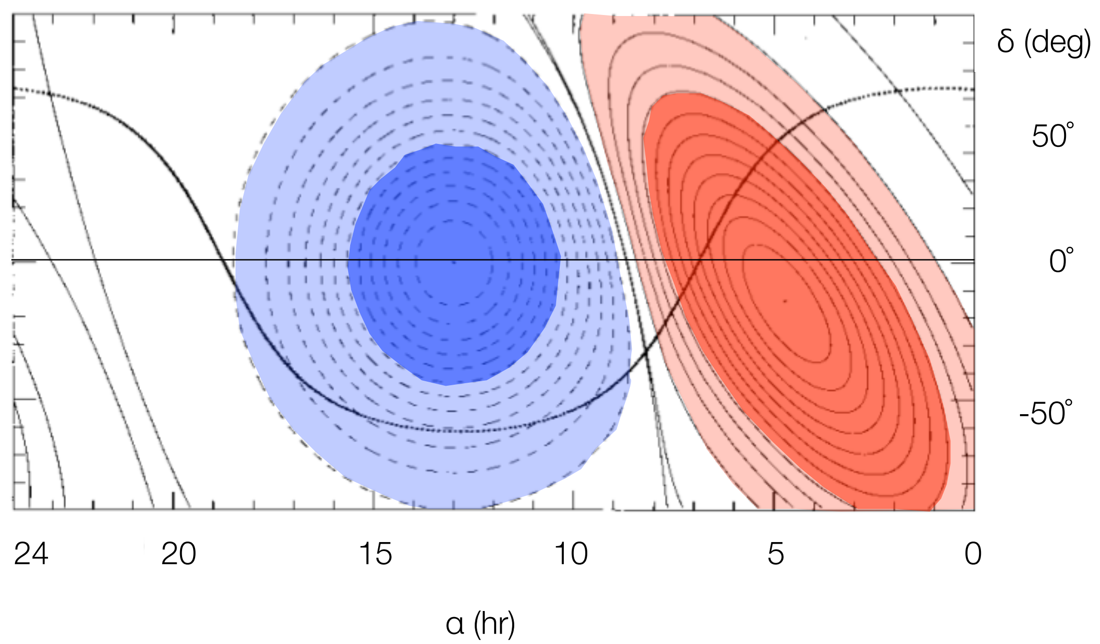
- anisotropy in **celestial coordinates**
- visible as sidereal diurnal modulation
  - galactic anisotropy
  - heliotail-in anisotropy
- north-south asymmetry

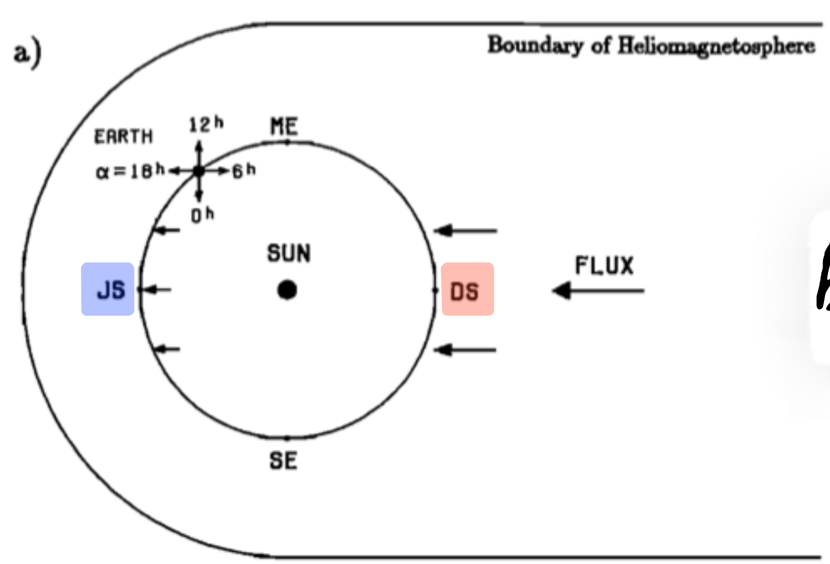
  Jacklyn, Nature 211, 690 (1966)

  - 1^{st} & 2^{nd} harmonic terms

low energy cosmic rays

Nagashima et al., J. Geophys. Res., Vol 103, No. A8, Pag. 17,429 (1998)
Hall et al., J. Geophys. Res., Vol 104, No. A4, Pag. 6737 (1999)





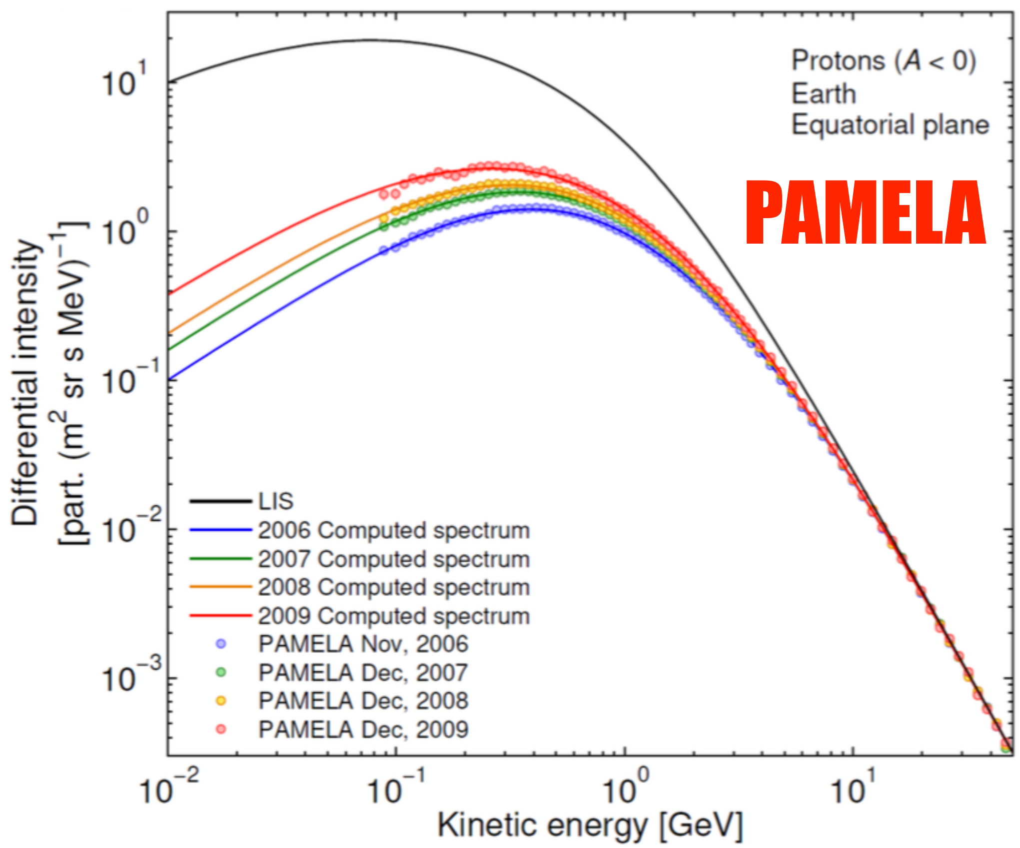
conjectural sketch showing a plausible annual variation of the excess flux (i.e., the anisotropy) from the heliomagnetotail.

- **global anisotropy** with complex structure: **first** and **second** harmonic contributions
- galactic and tail-in contributions with different **energy dependences**
- **annual variation** of tail-in (sidereal) anisotropy associated to heliospheric influence
  - higher flux in December & lower flux in June

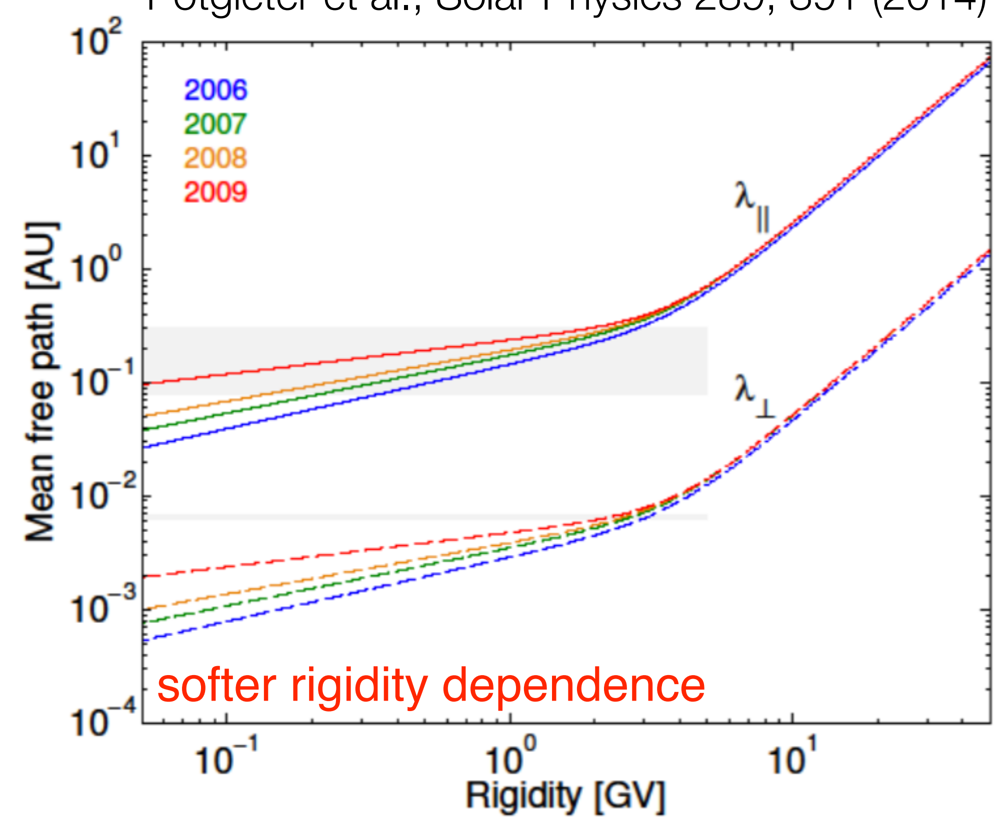
sub-TeV cosmic rays
and heliospheric physics

Panico & Karelin talk

< 10 GV



Potgieter et al., Solar Physics 289, 391 (2014)



modulation of galactic protons during **unusual** solar minimum 2006-2009

highest proton flux observed in December 2009 (since beginning of space age)

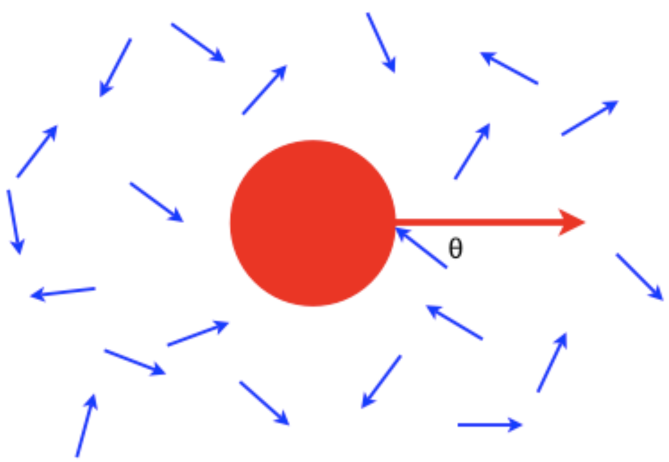
more diffusion in 2009 than previous solar minima, drifts still important (50%-50%)

inner heliosphere is an ideal laboratory to study CR propagation

a known anisotropy

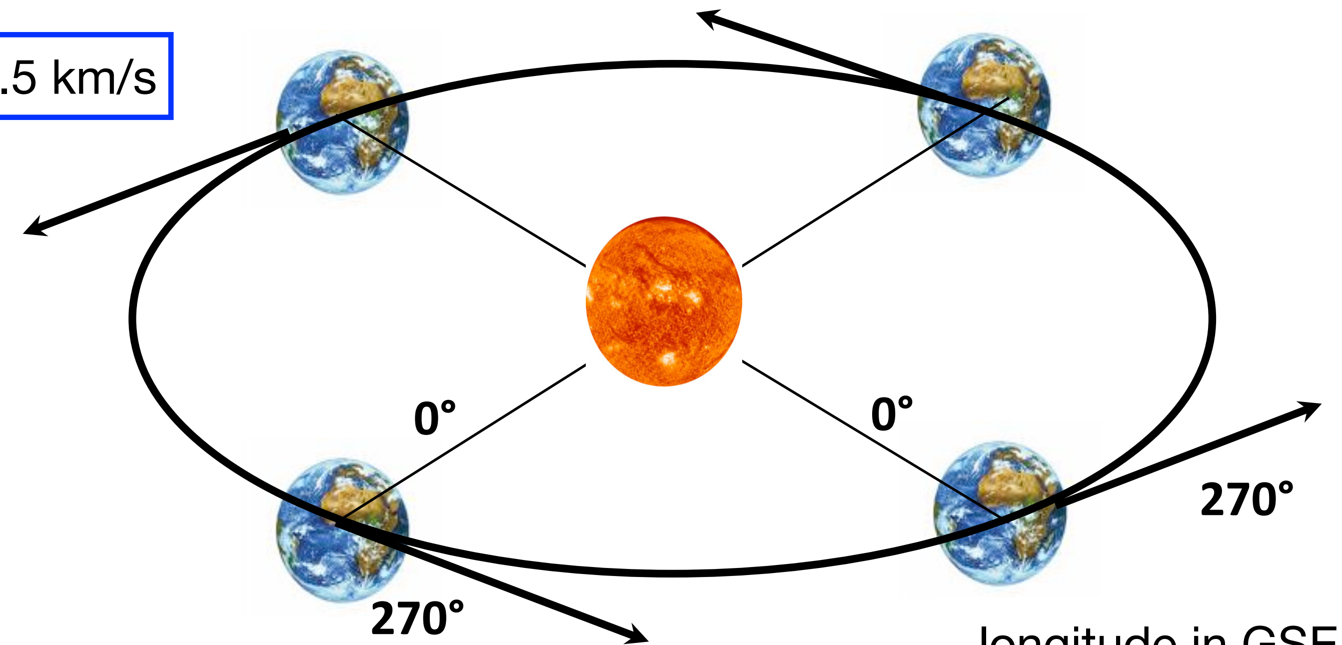
Earth's motion around the Sun

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

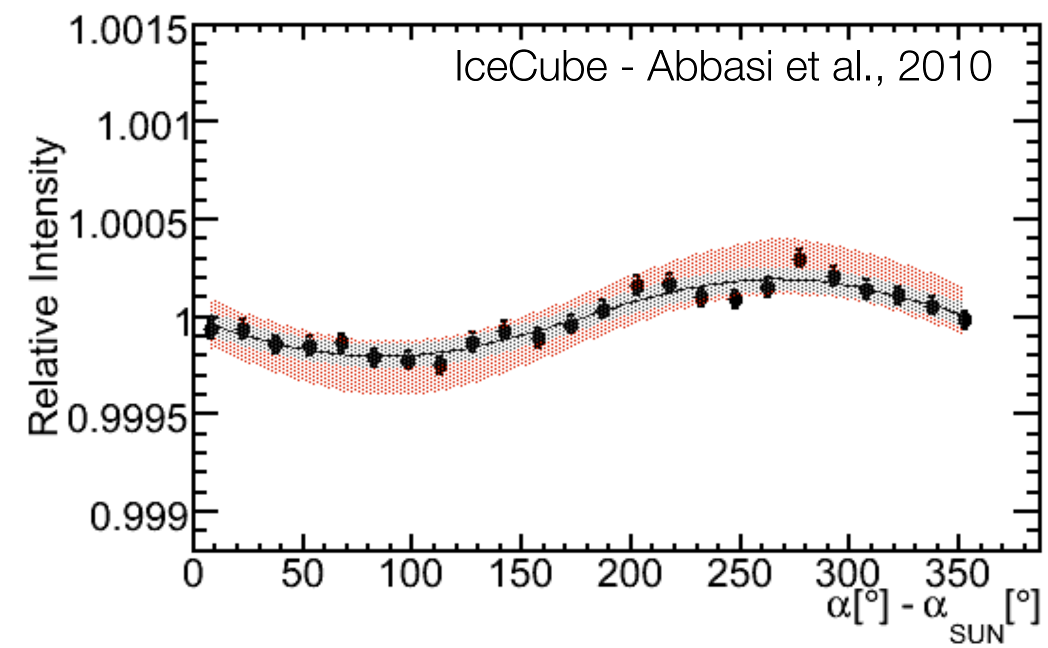


v = 29.8 ± 0.5 km/s

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

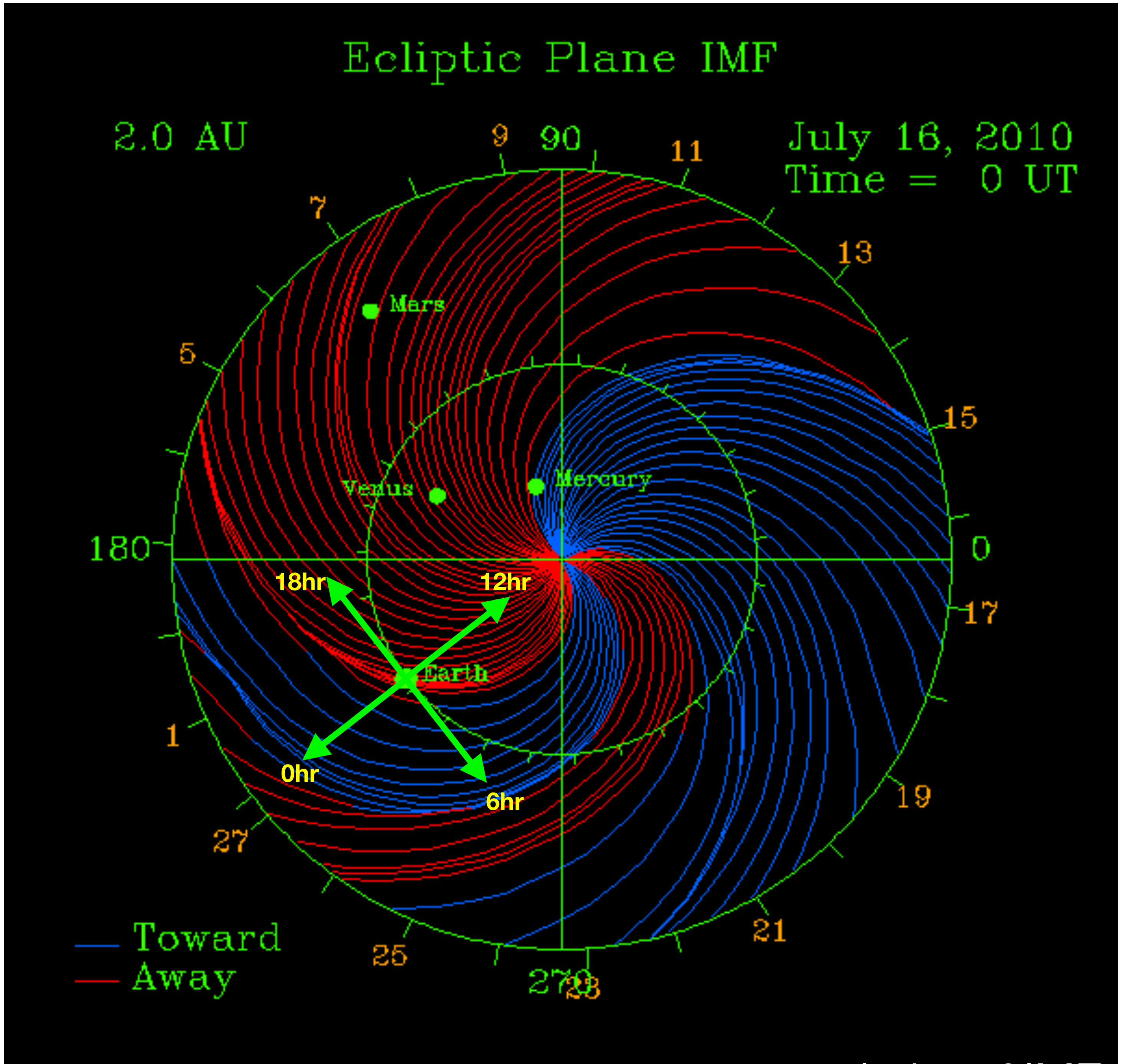


- produced by Earth's revolution around the Sun
- visible as **solar diurnal modulation**
- **predictable** and used as **benchmark**
- **heliospheric physics** effects below O(100) GeV



low energy cosmic rays
and heliospheric physics

< 100 GV



sector polarity of IMF

after CG & geomagnetic corrections

cosmic ray anisotropy =

2 components on ecliptic plane +

1 component ⊥ ecliptic plane =

solar diurnal anisotropy +

North-South asymmetry

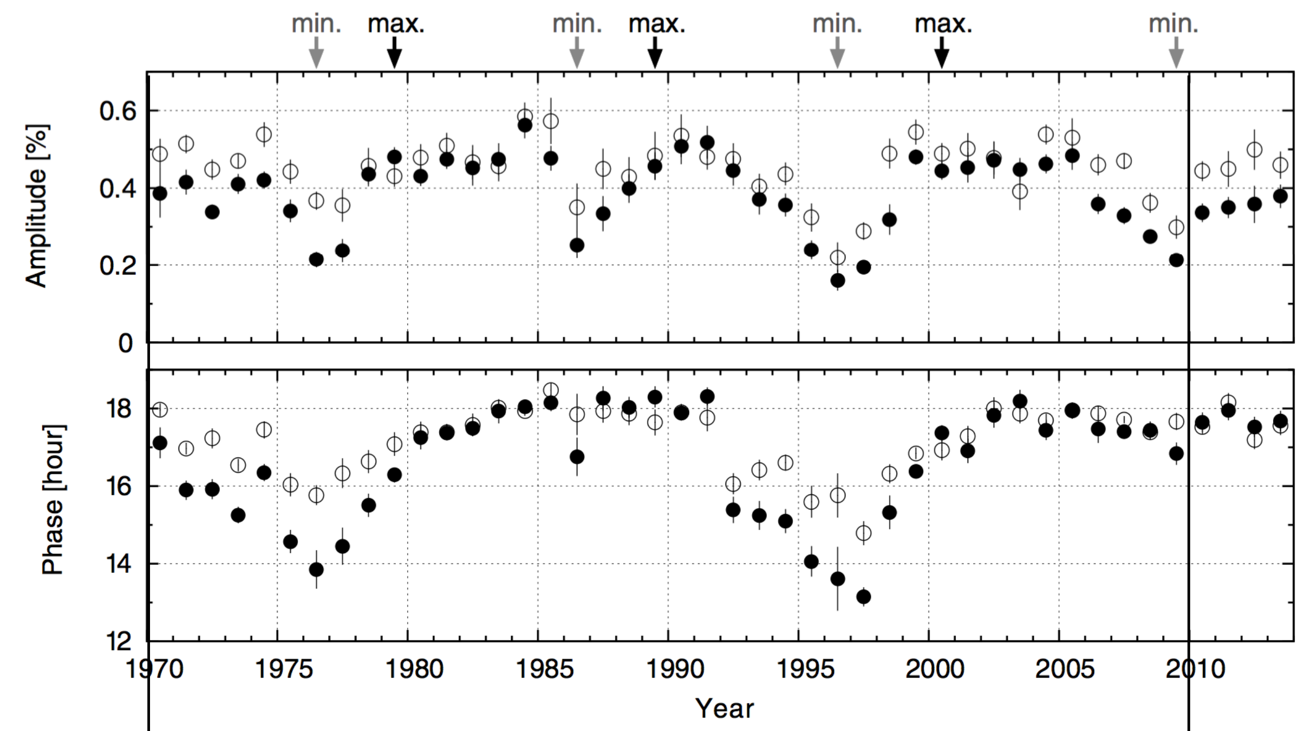
solar cycles influence on cosmic ray **arrival distribution**

Munakata et al., ApJ 791, 22 (2014)

solar diurnal anisotropy

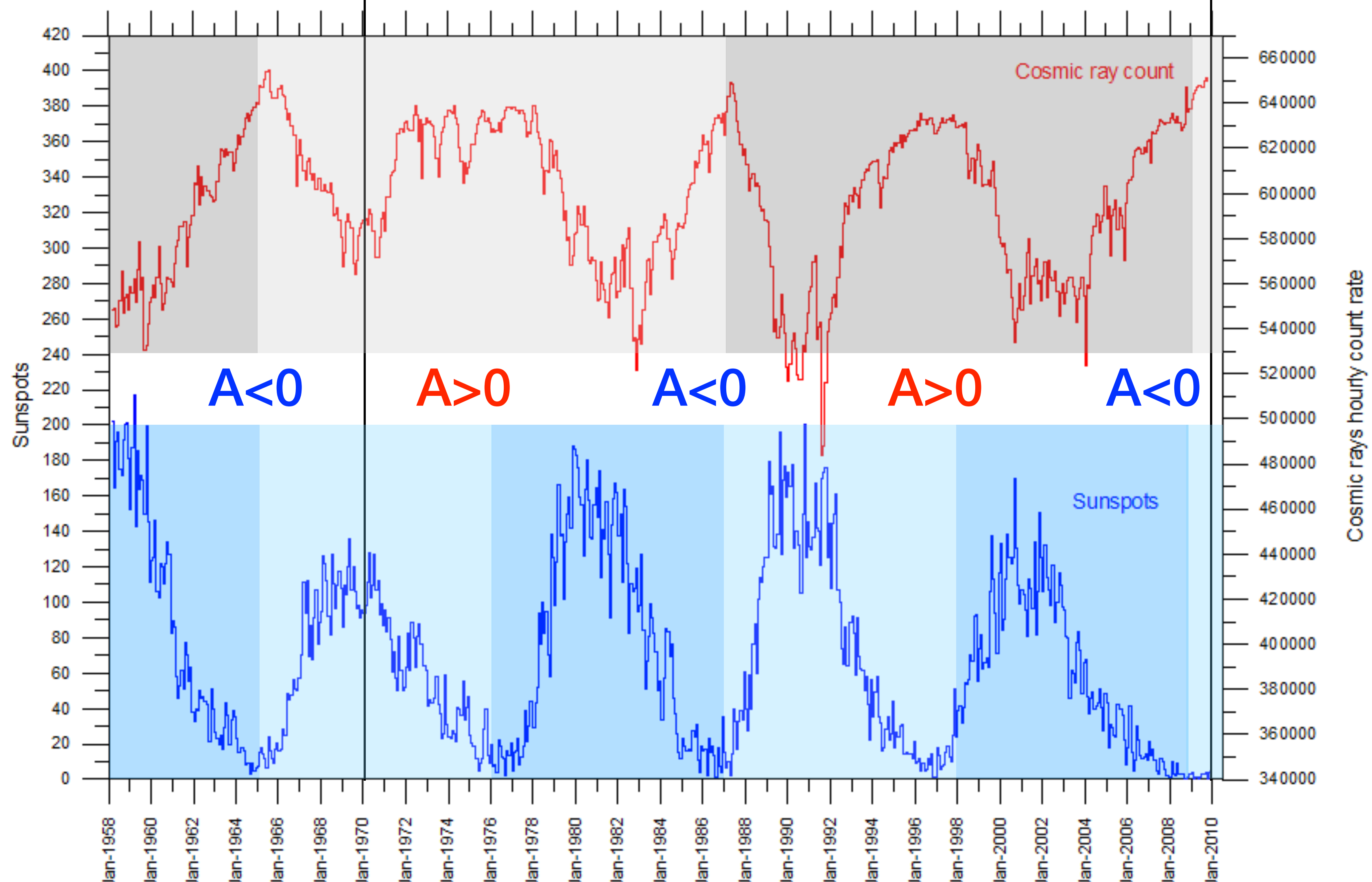
- ● μ (Nagoya) @ 60 GV
- ○ neutron monitors @ 17 GV

Munakata et al., ApJ 791, 22 (2014)



phase (∥ anisotropy, *z* density gradient) @ 22 yr modulation (**drift model**)

radial density gradient @ 11 yr modulation



several talks

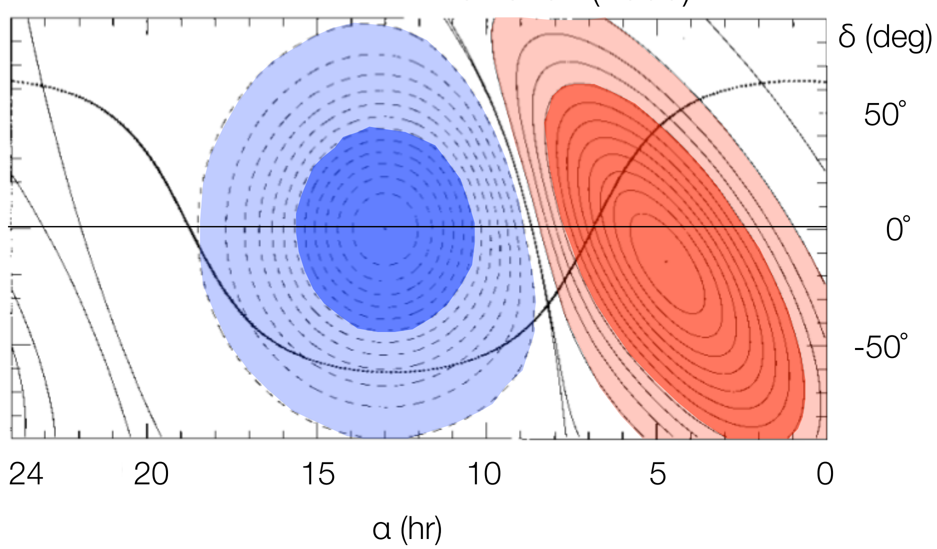
high energy cosmic rays

sidereal anisotropy

$\sim 10^{-3}$

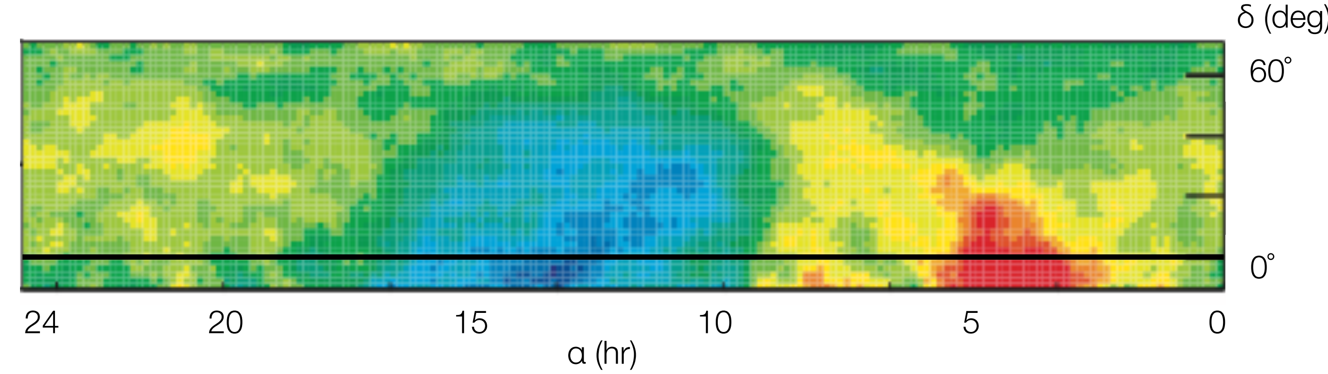
< 1 TeV

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

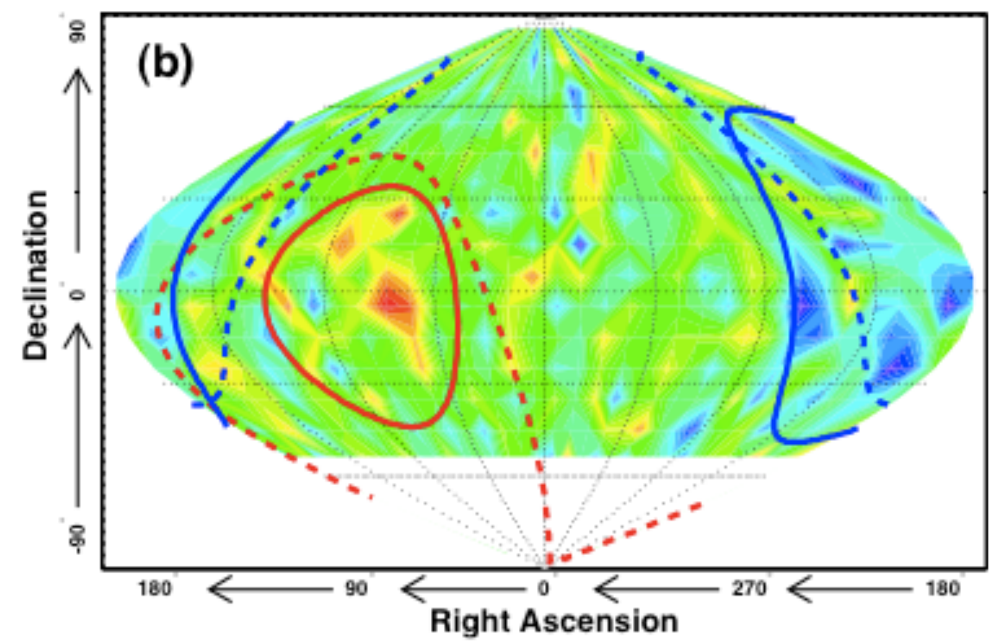


4 TeV

Tibet ASγ
Amenomori et al. (2006)



10 TeV

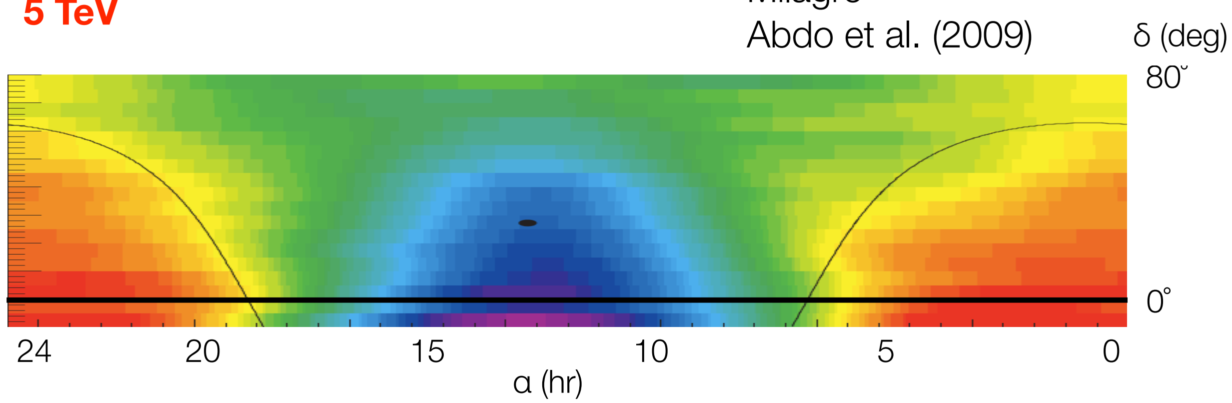


Super Kamiokande
Guillian et al. (2007)

equatorial coordinates

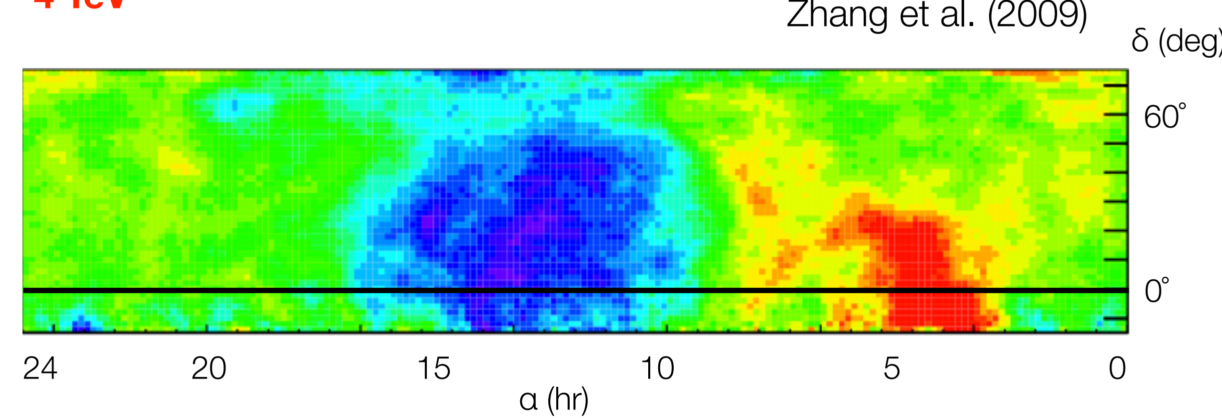
5 TeV

Milagro
Abdo et al. (2009)



4 TeV

ARGO-YBJ
Zhang et al. (2009)

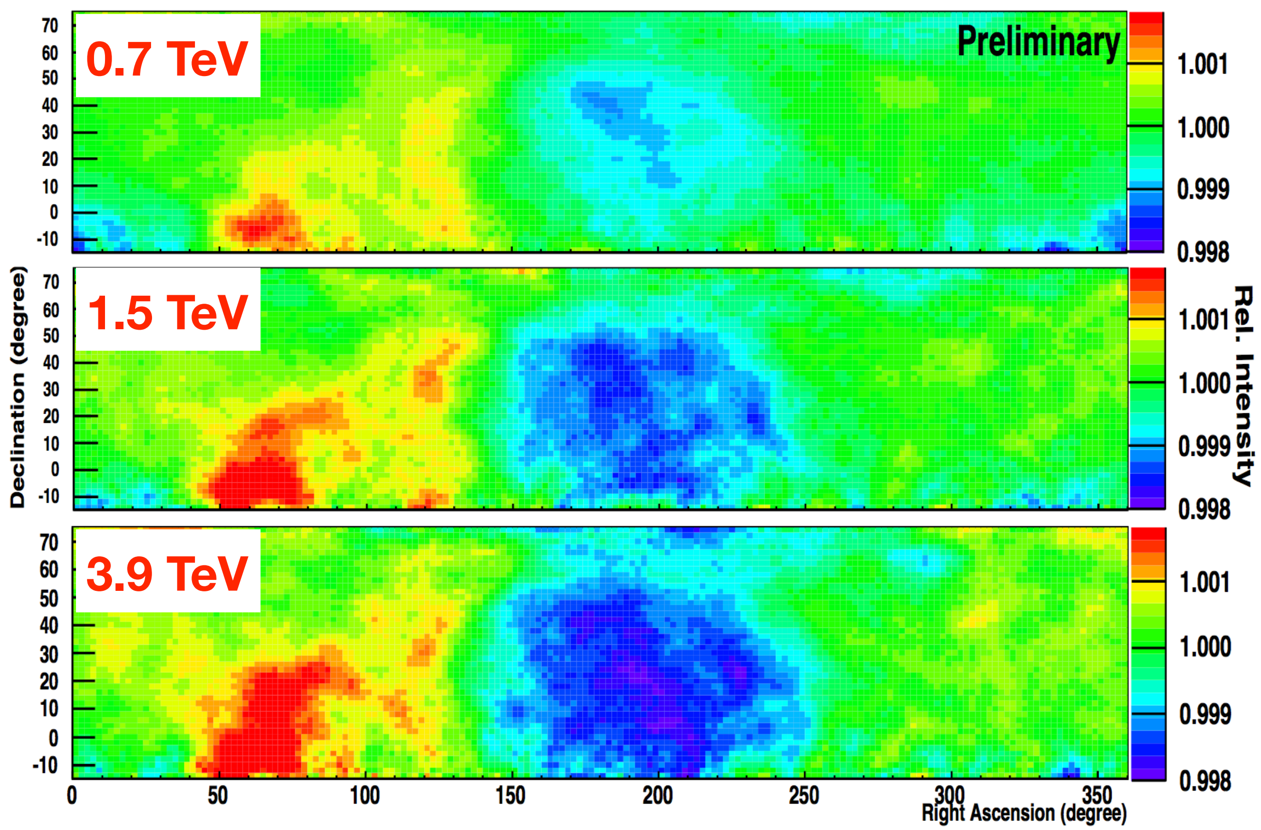


large scale anisotropy
energy dependence

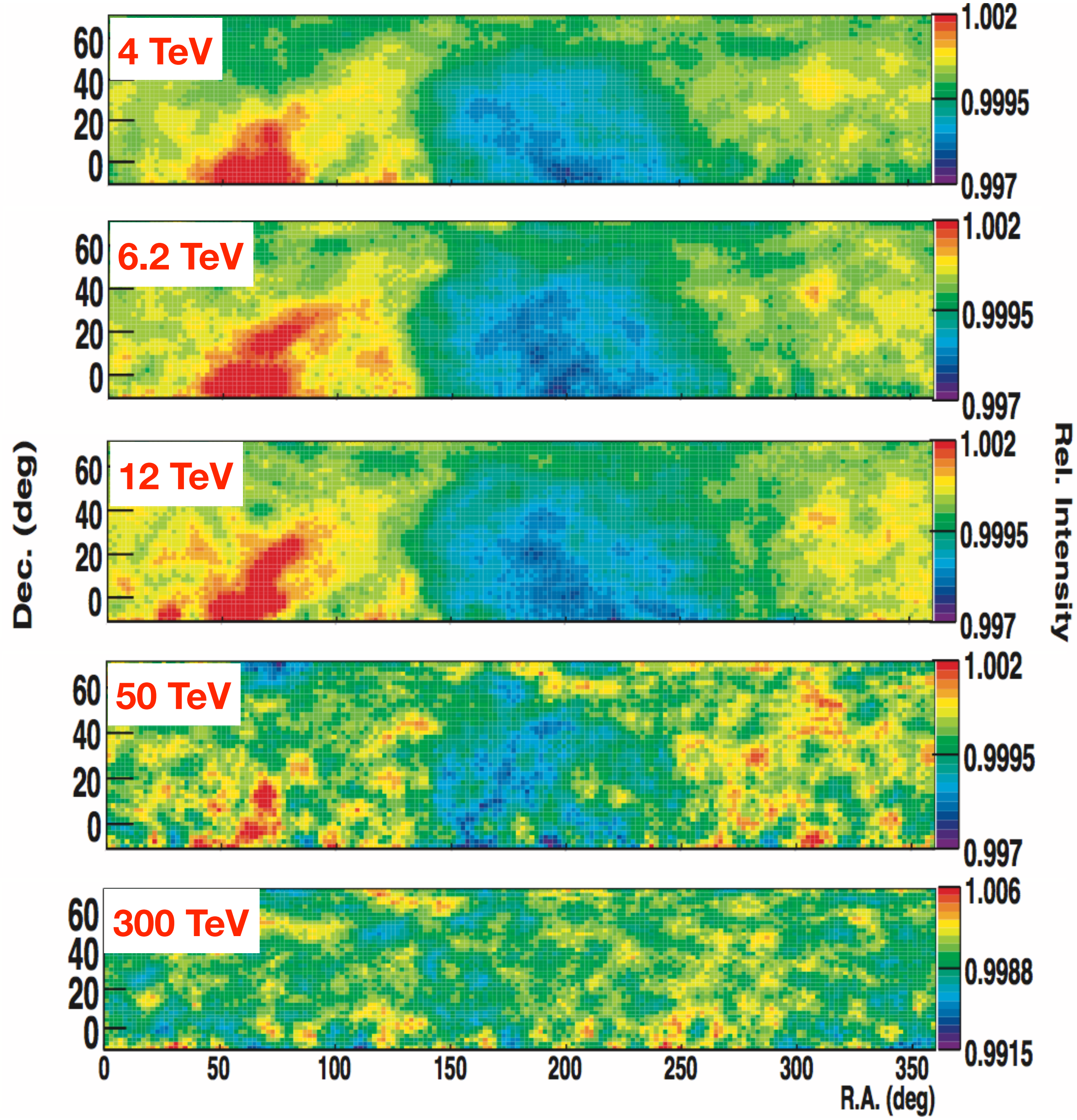
ANISOTROPY IS NOT A DIPOLE

Di Sciascio & Takita talks

ARGO-YBJ Zhang et al., ICRC 2009



Tibet ASγ Amenomori et al., 2006

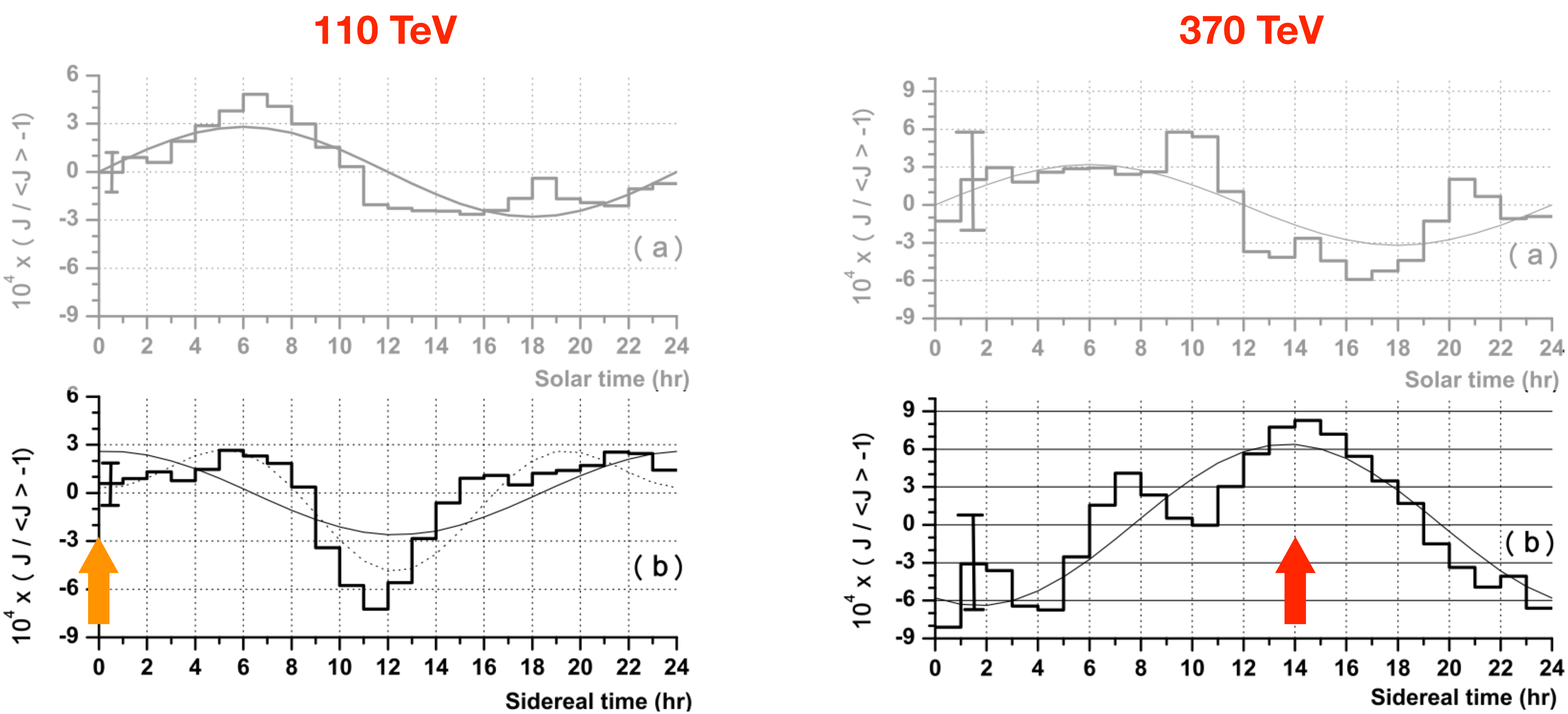


anisotropy amplitude increases with energy up to **10 TeV** scale

large scale anisotropy
energy dependence

ANISOTROPY CHANGES WITH ENERGY

EAS TOP Aglietta et al., 2009

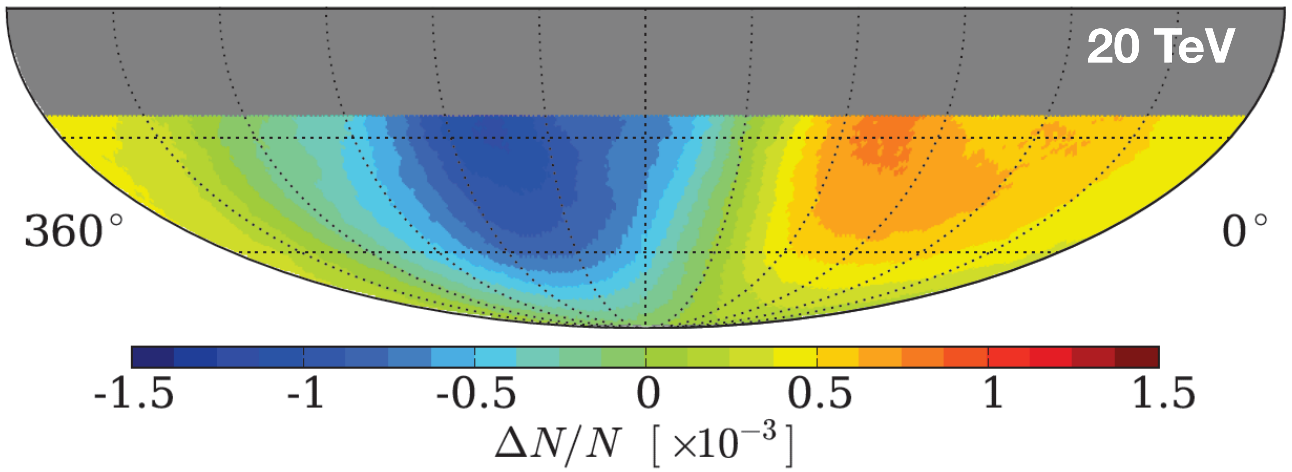


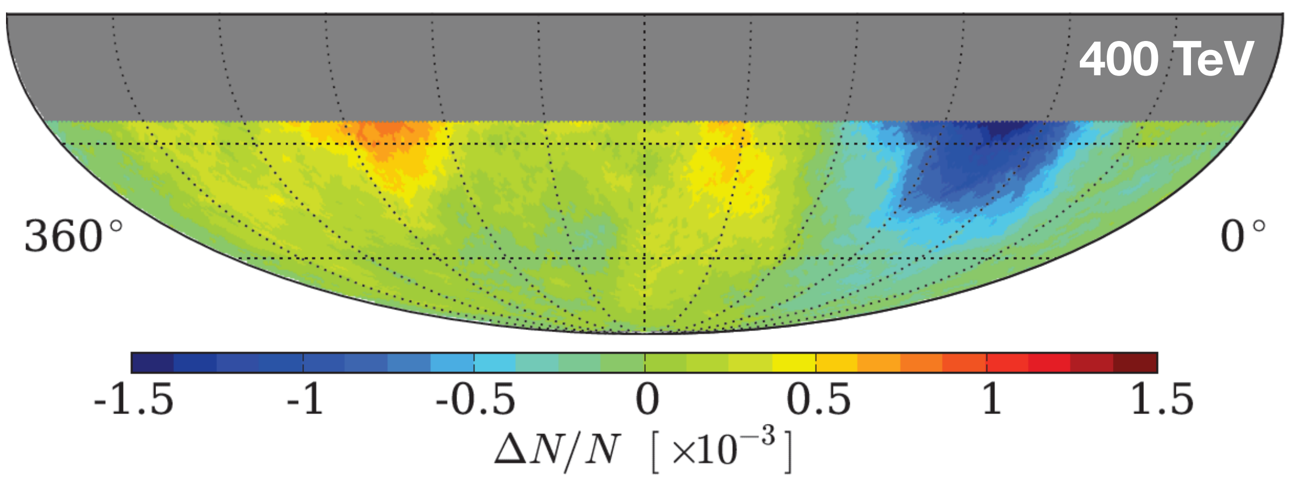
anisotropy ***flips direction*** between 100 TeV and 400 TeV

large scale anisotropy
energy dependence

McNally talk Thursday

IceCube

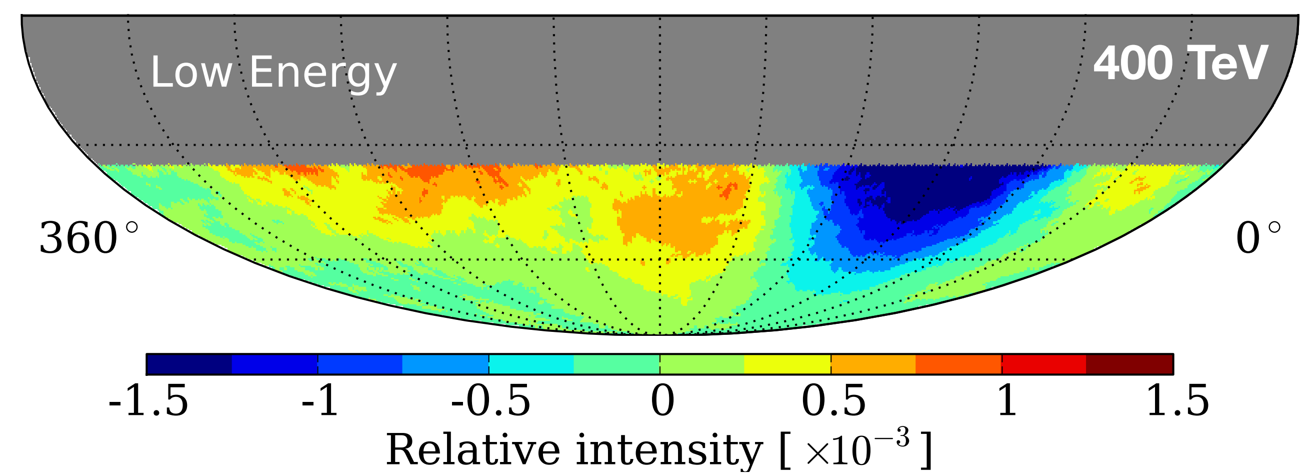


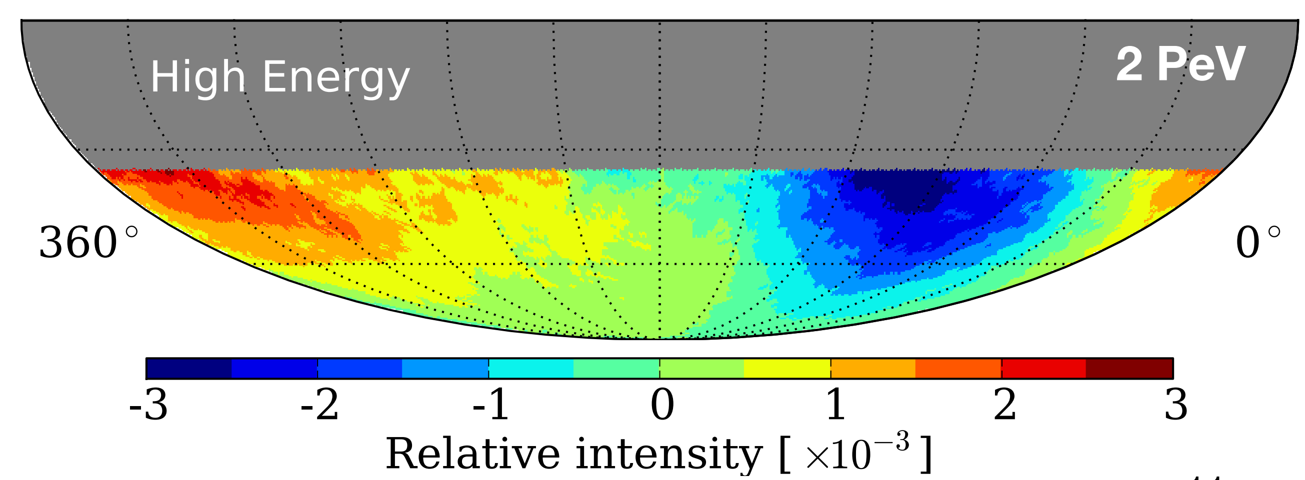


Abbasi et al., 2010, 2012

IceTop

Aartsen et al., 2013

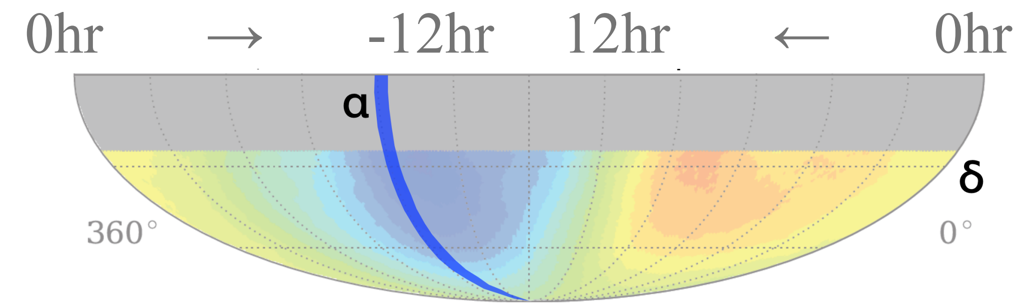




anisotropy **changes topology** between 20 TeV and 400 TeV

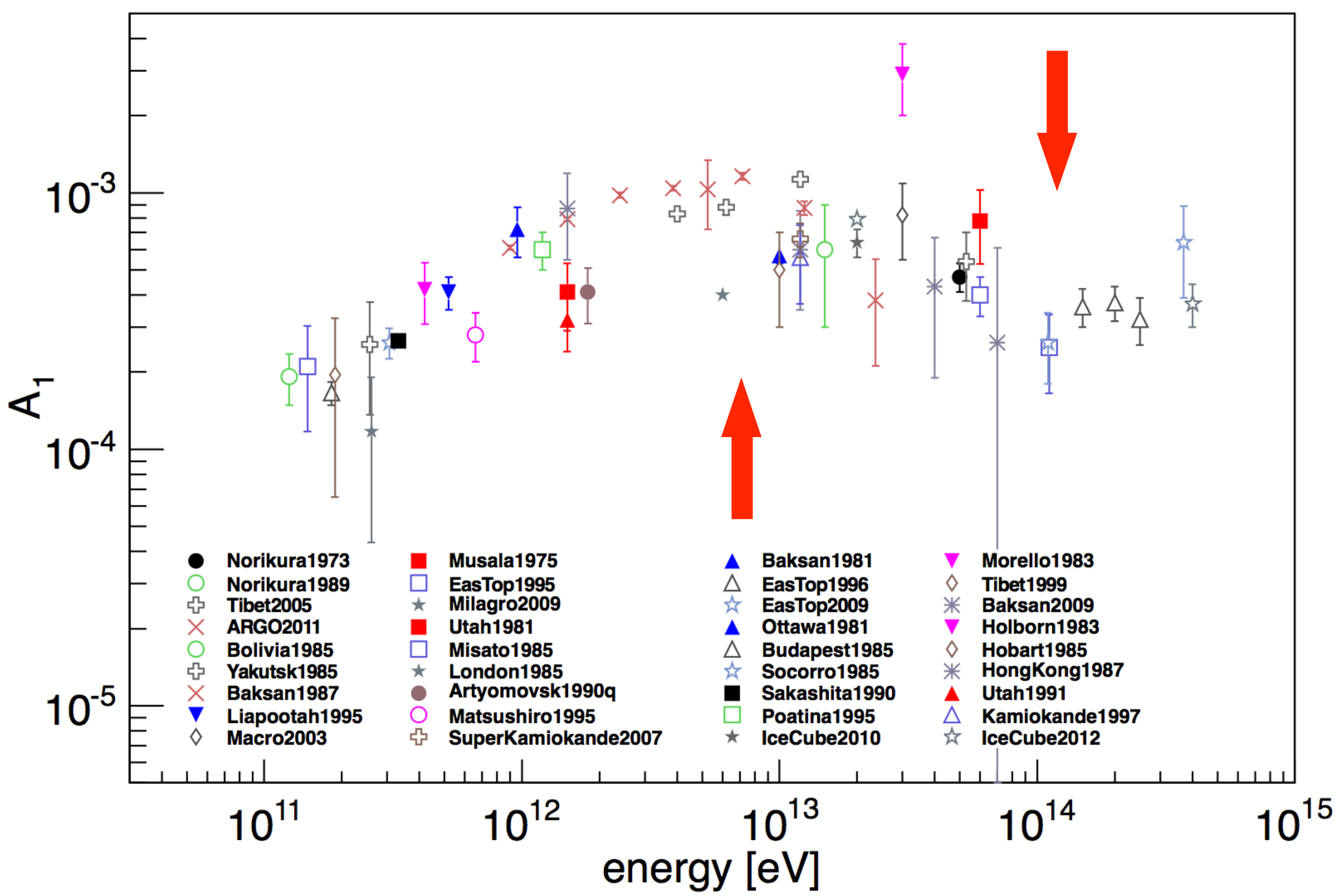
large scale anisotropy

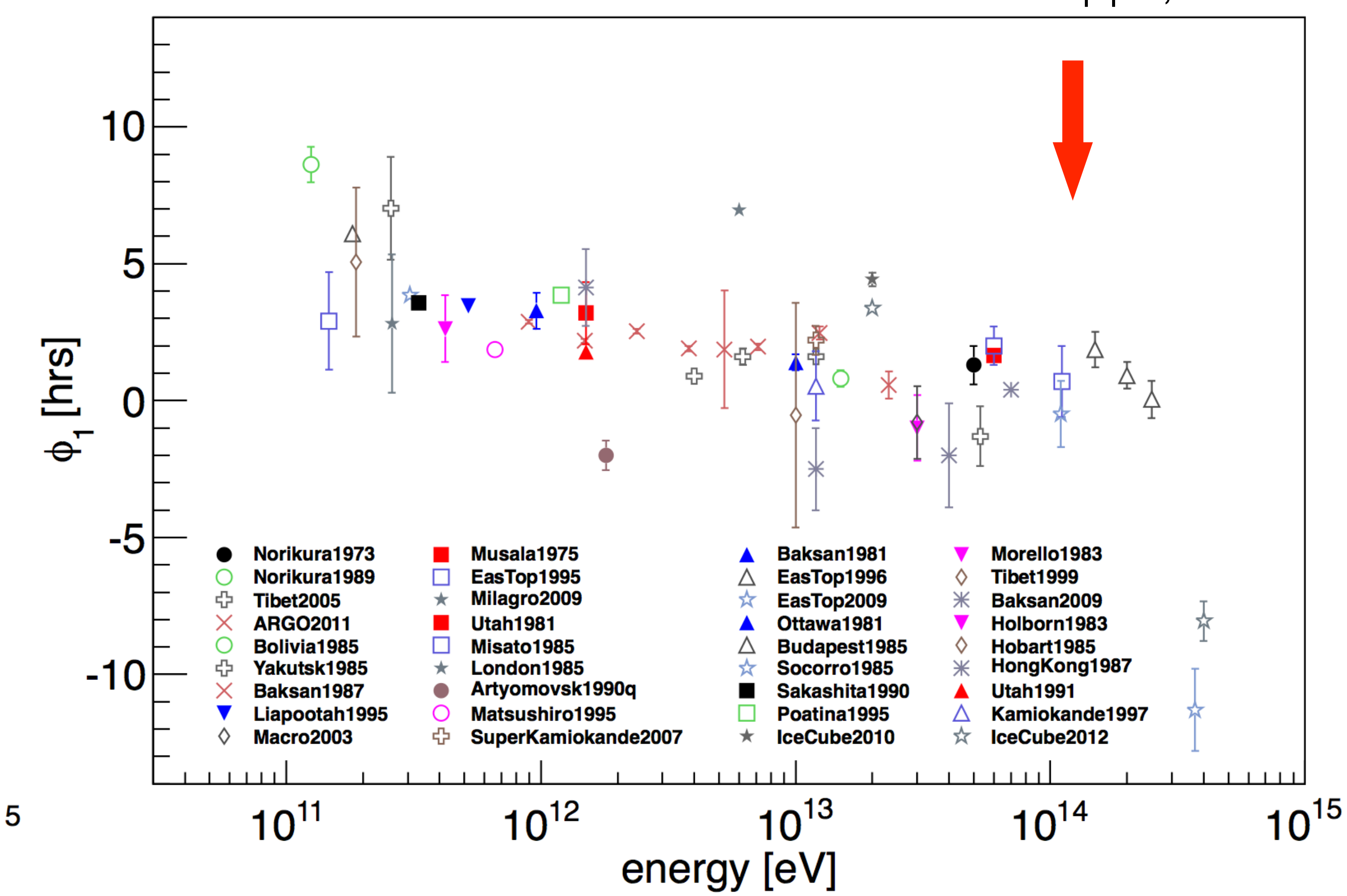
energy dependence



amplitude & phase of first harmonic component (dipole)

Di Sciascio & Iuppa, 2014

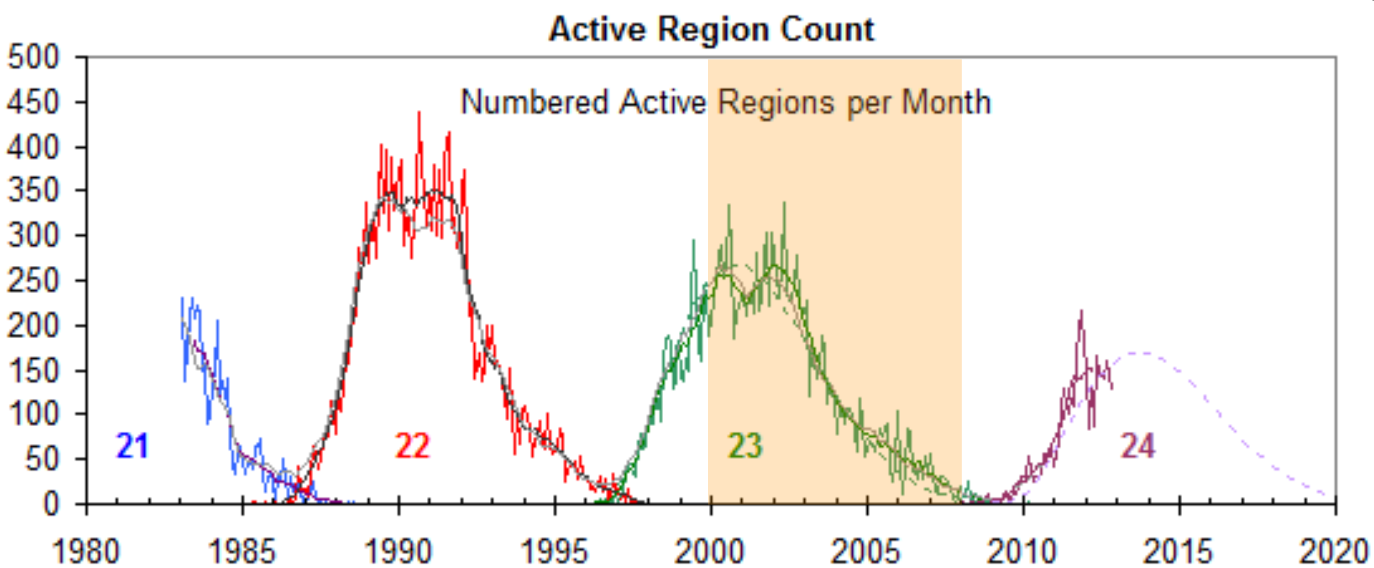




dipole amplitude increases up to order **10 TeV** and then it **decreases**

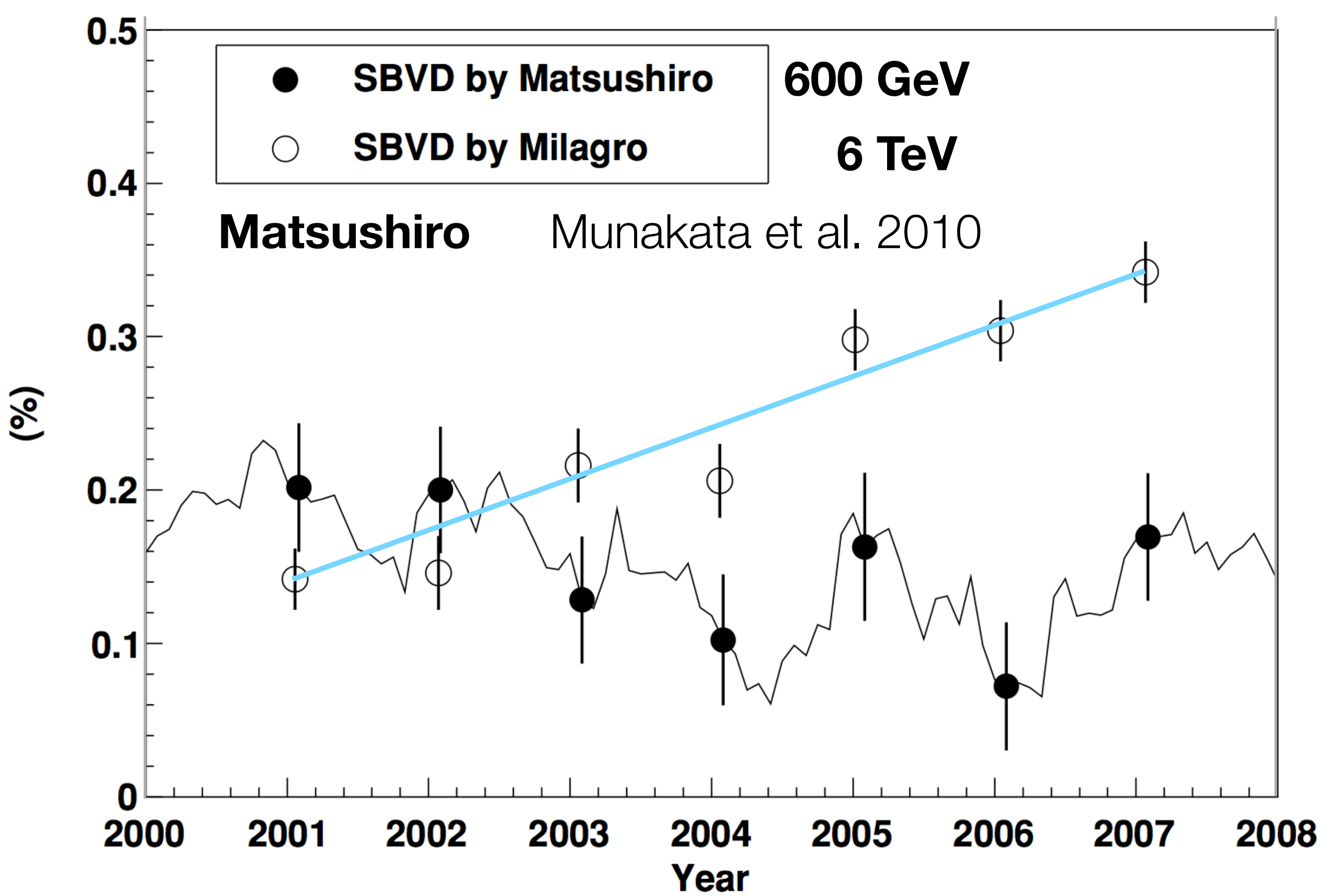
phase of **dipole** steadily migrates & suddenly **changes** or **flips**

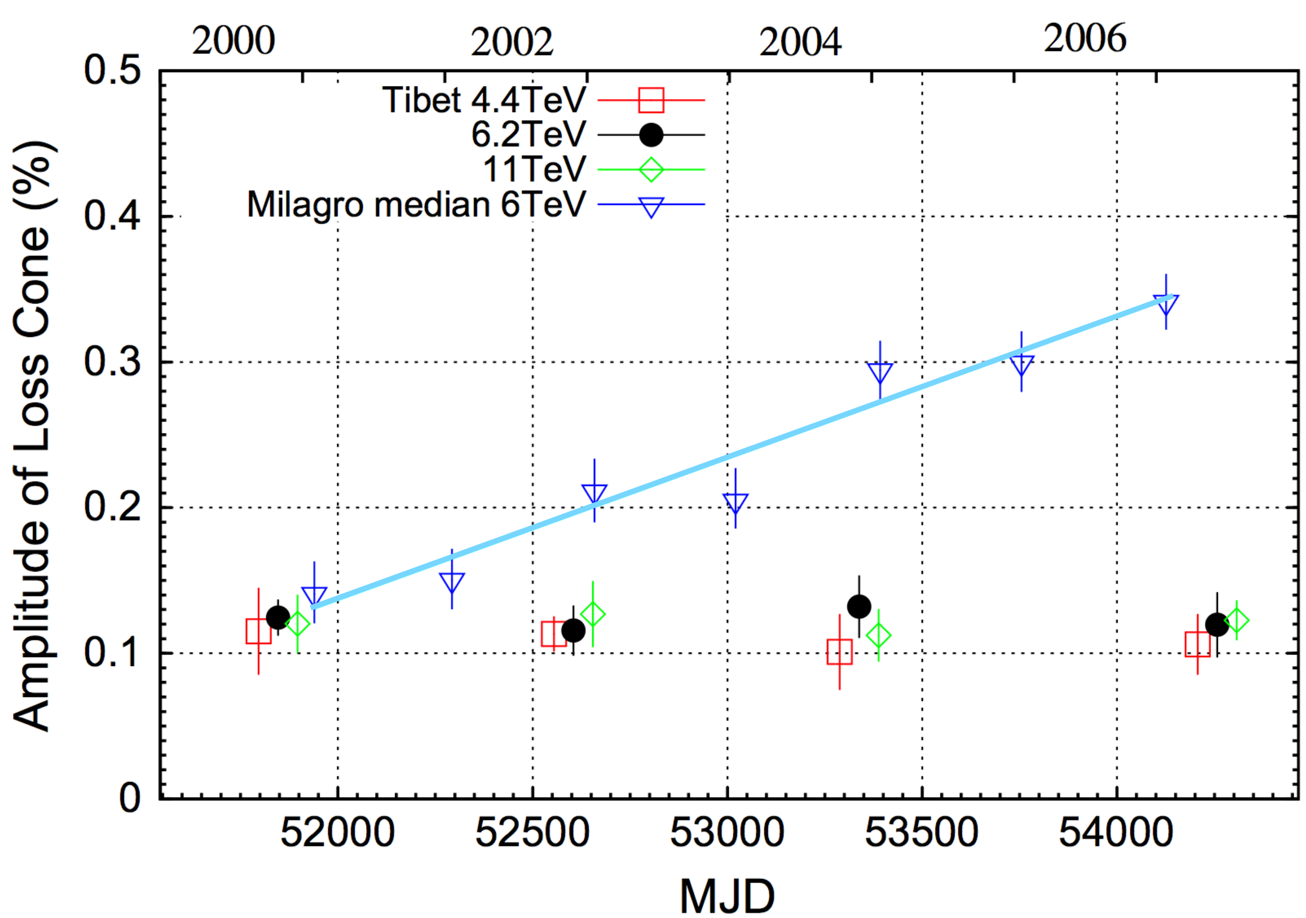
large scale anisotropy
time dependence



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

no correlation with solar cycles





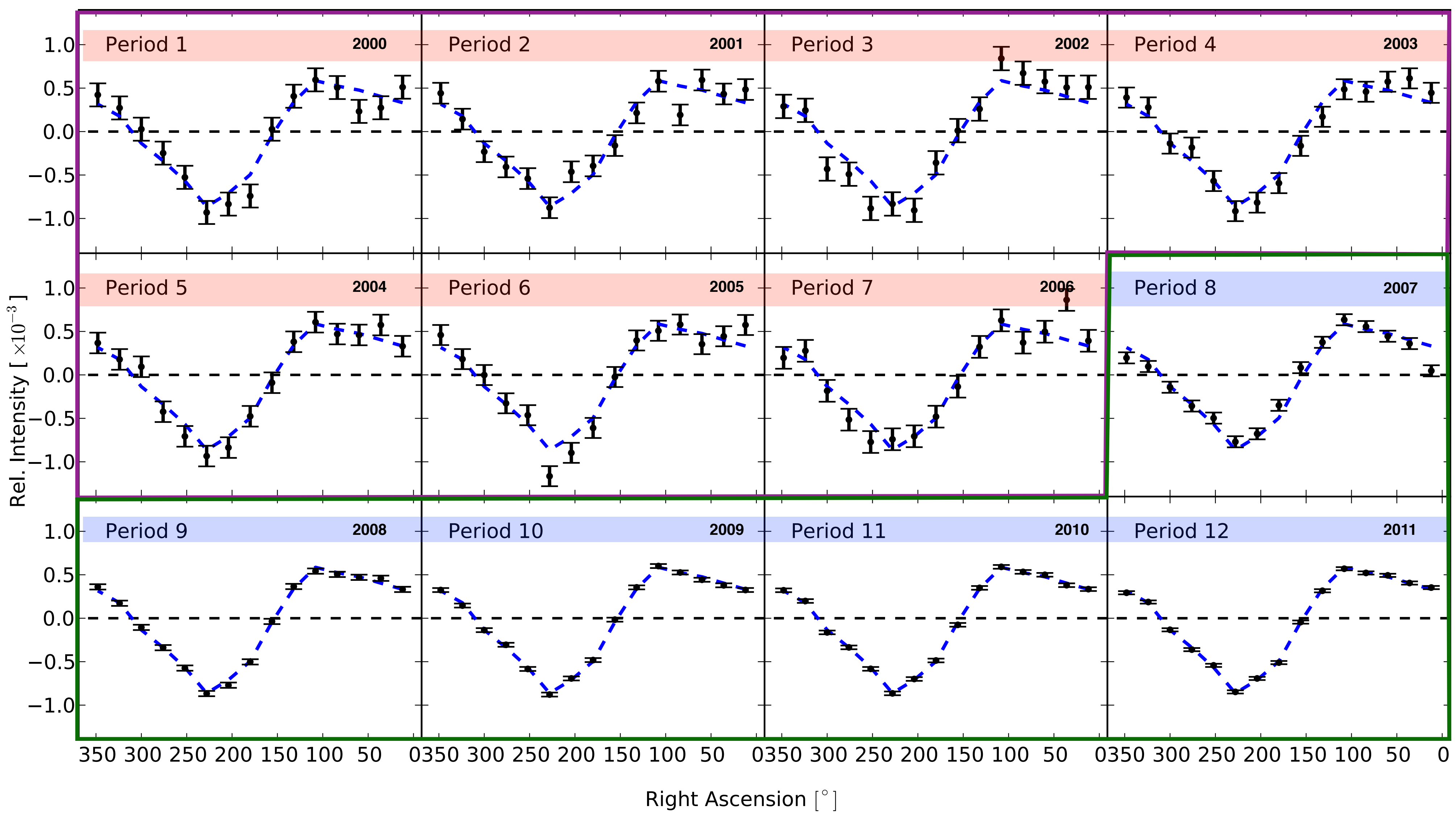
cosmic ray anisotropy
AMANDA-IceCube 2000-2011

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

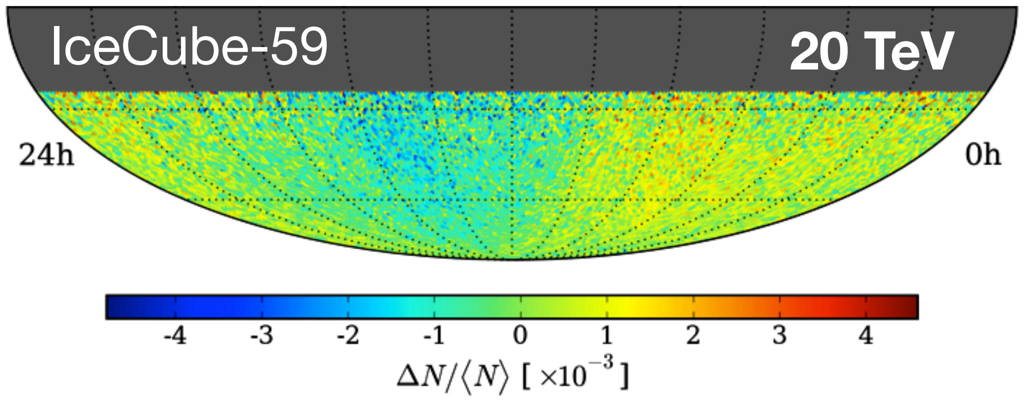


TeV sidereal anisotropy
angular power spectrum

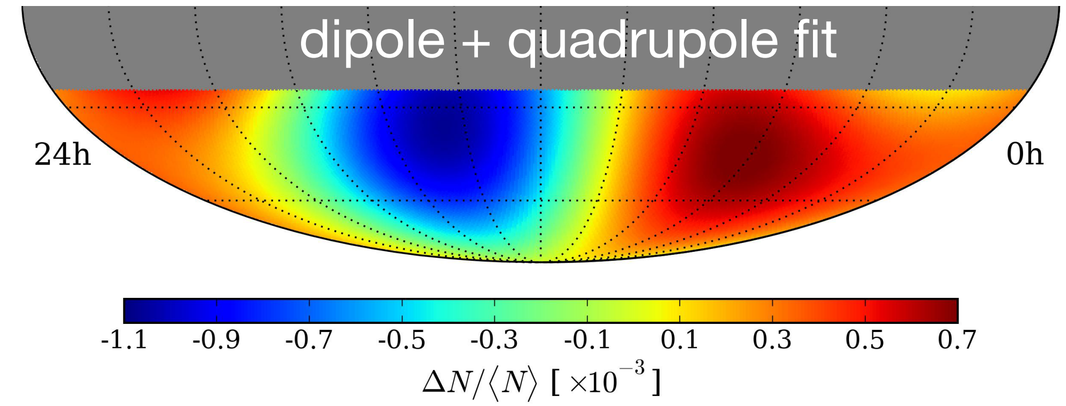
IceCube

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

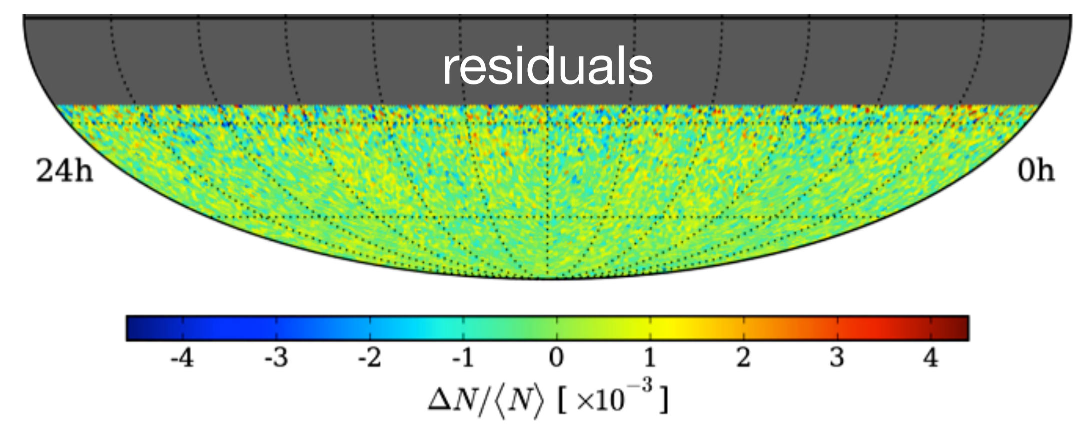
relative intensity raw map

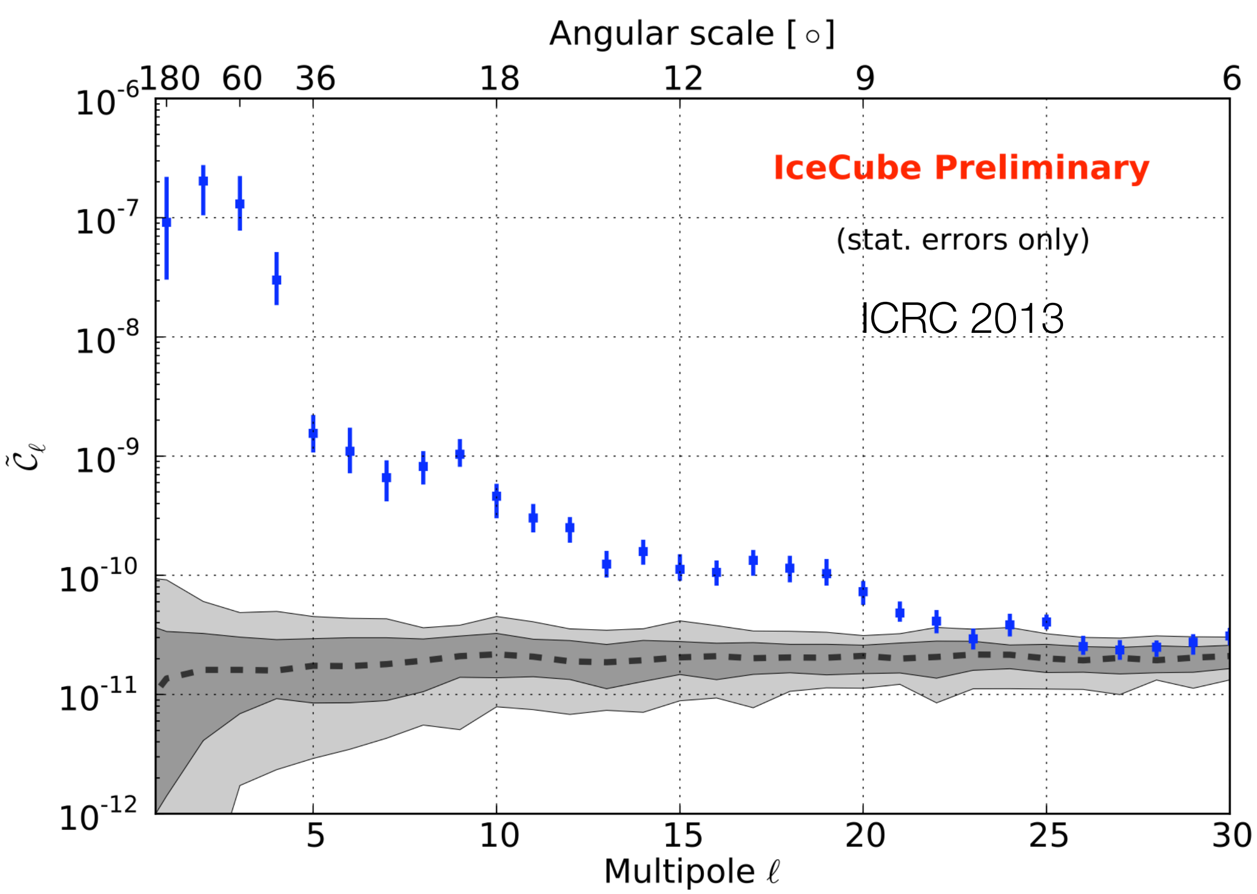


χ^2/ndf = 14743.4 / 14187 (prob = 0.05%)



filter high CR density gradient structures





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

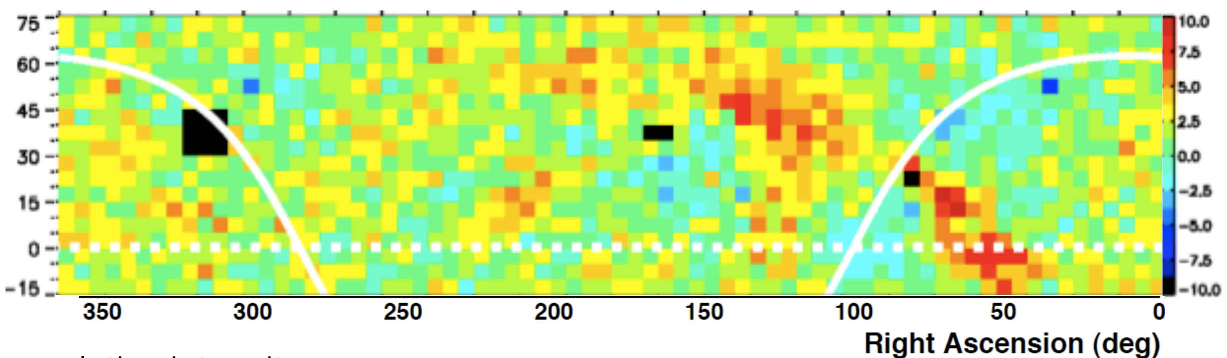
high energy cosmic rays

small scale anisotropy

1-5 TeV $\sim 10^{-4}$

Tibet-III

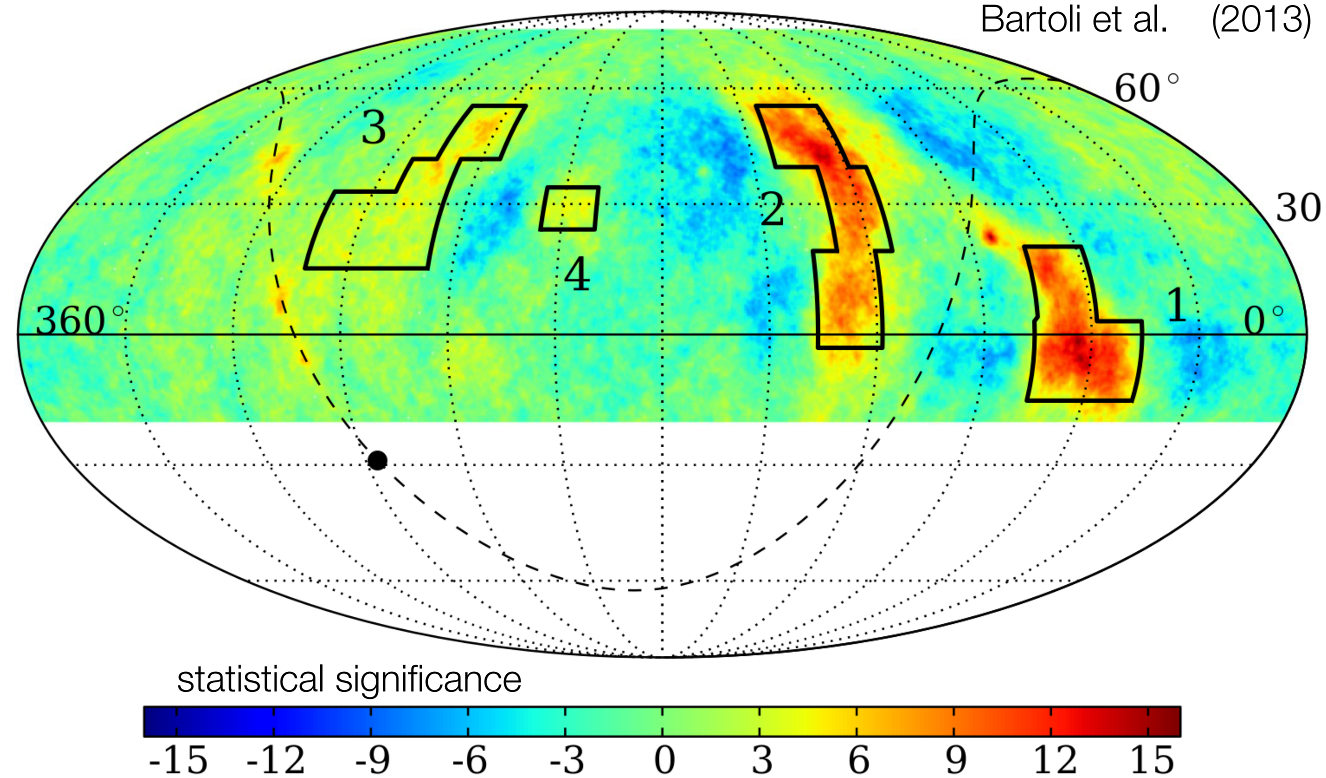
Amenomori et al. ICRC (2007)



relative intensity

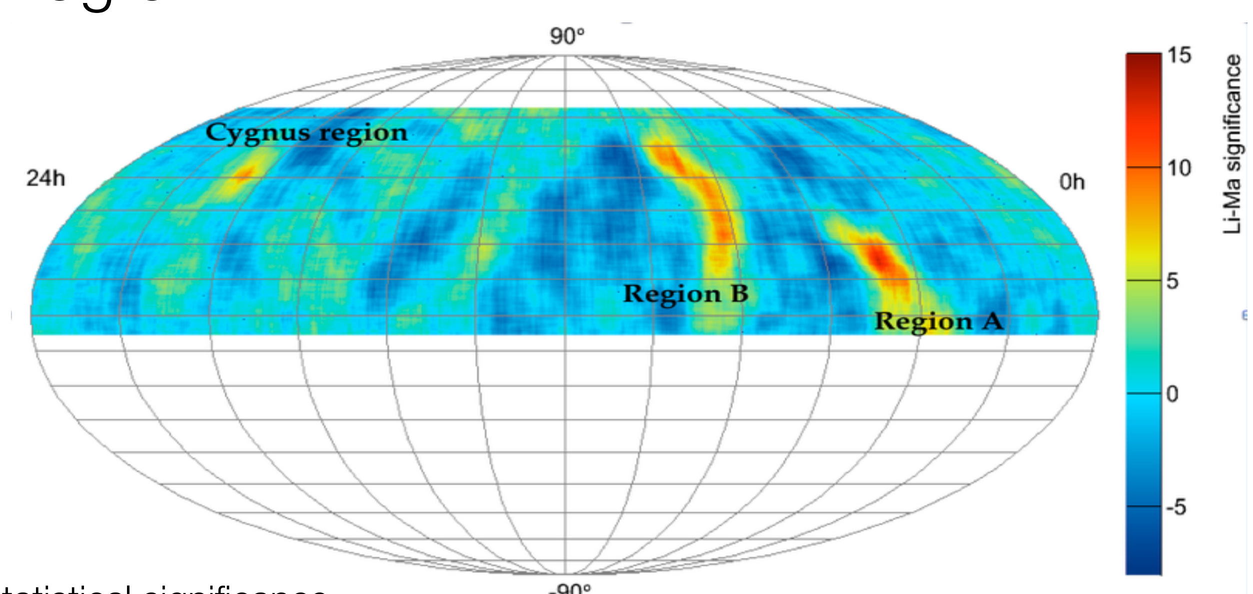
ARGO-YBJ

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



Milagro

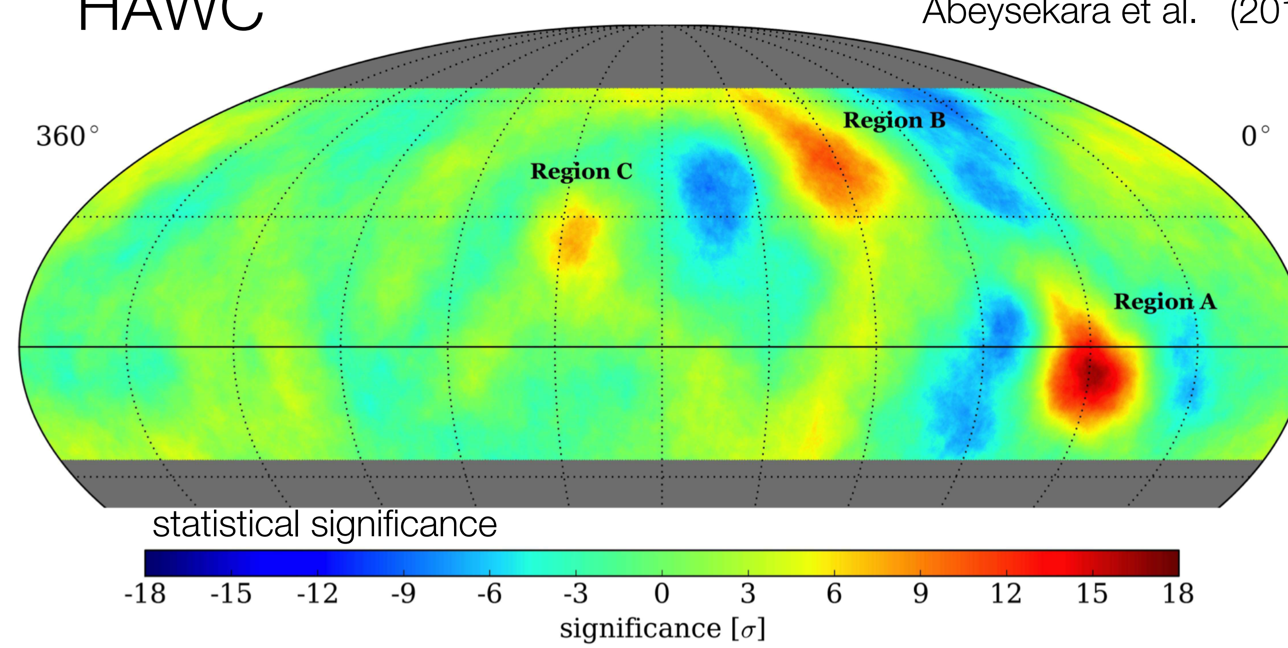
Abdo et al. (2008)



statistical significance

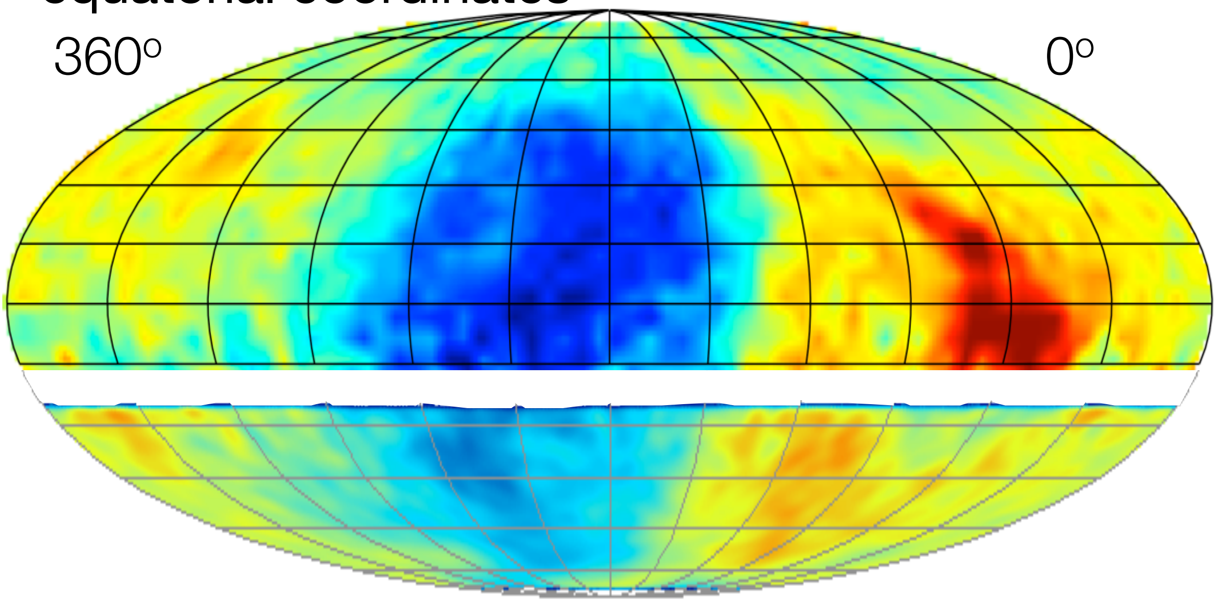
HAWC

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

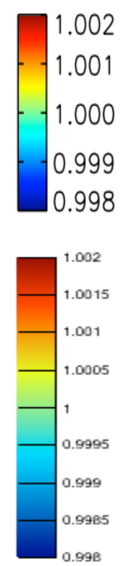


cosmic ray anisotropy large scale → small scale

equatorial coordinates



relative intensity

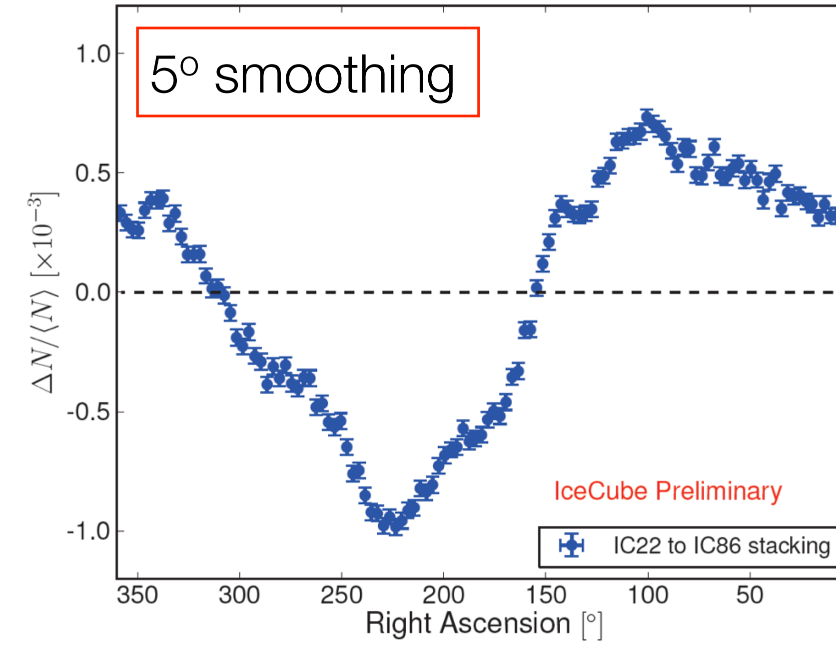


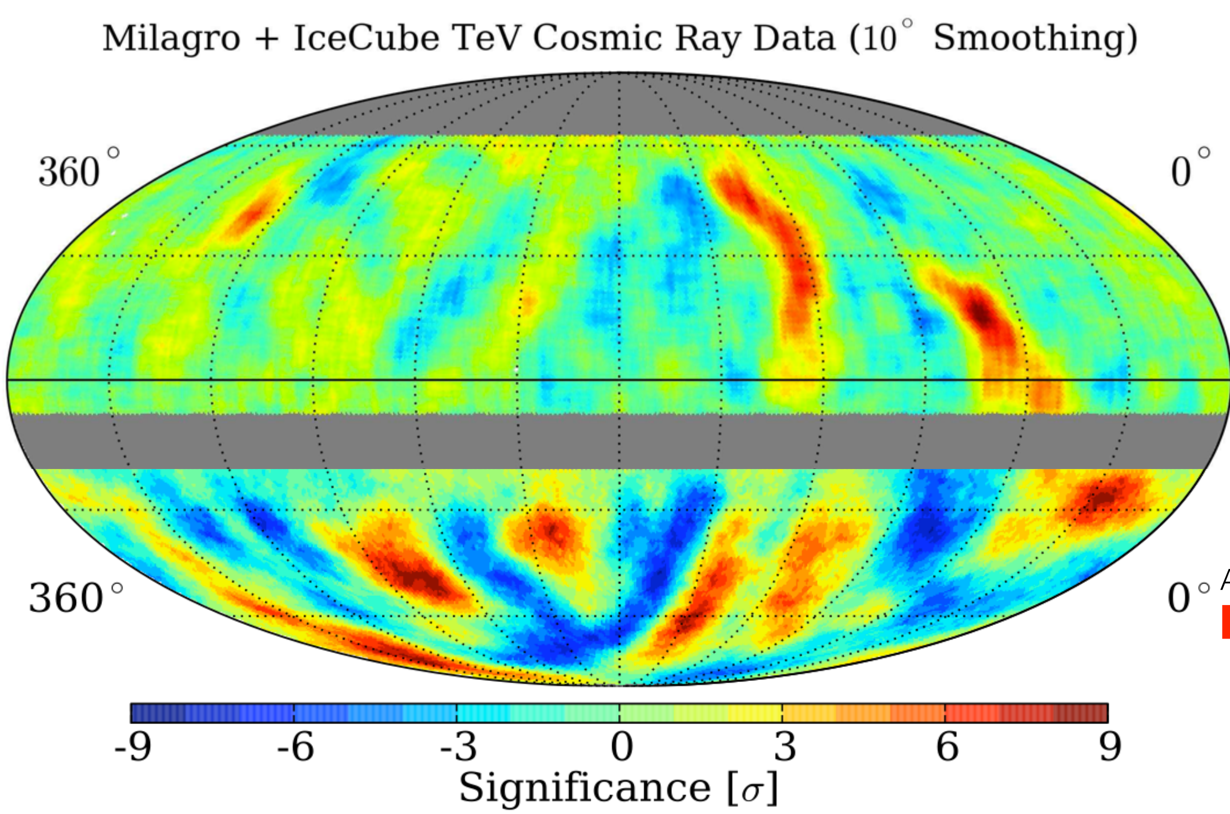
Tibet-III 5 TeV

Amenomori et al., ICRC 2011

IceCube-59 20 TeV

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





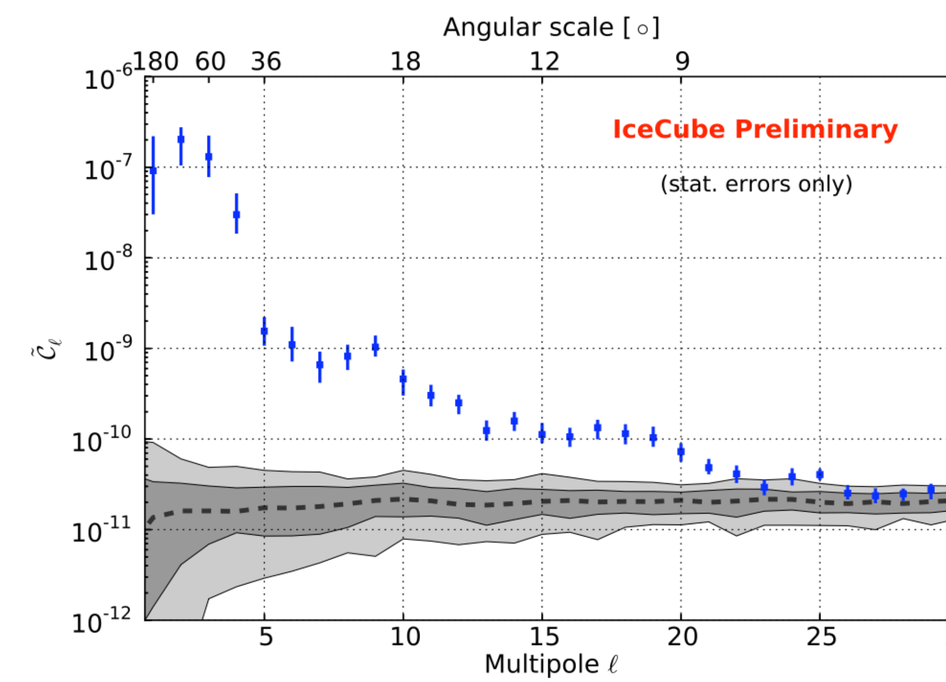
Milagro 1 TeV

Abdo et al., PRL, **101**, 221101, 2008

IceCube 20 TeV

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

PRELIMINARY - ICRC 2013

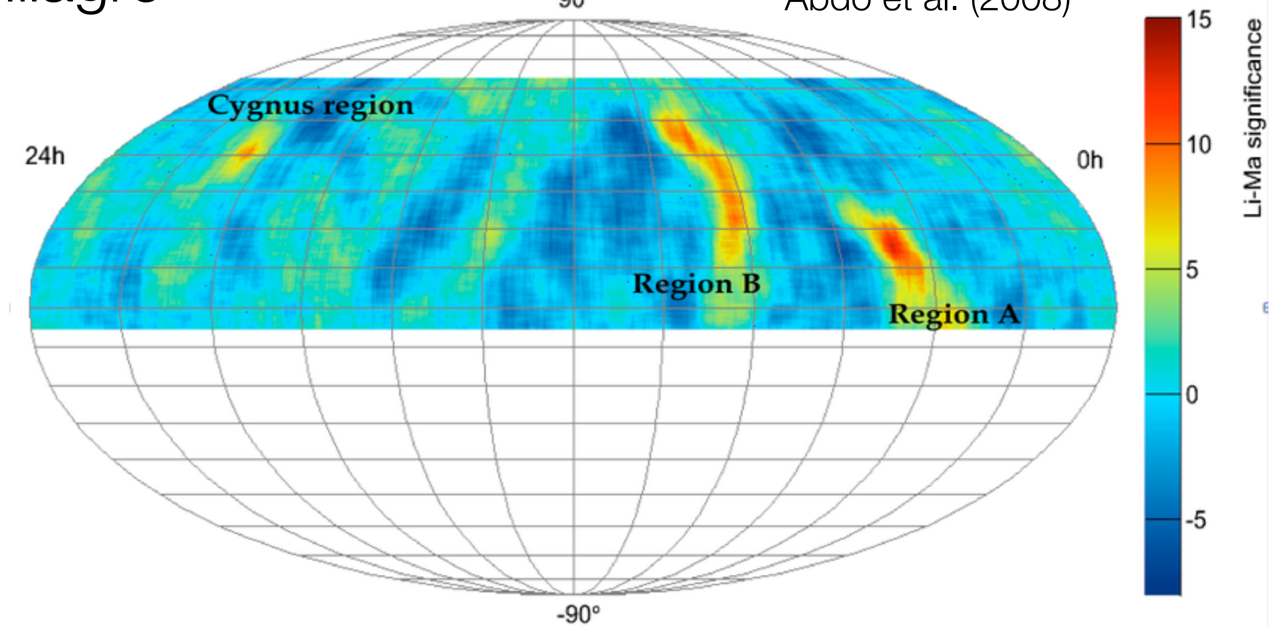


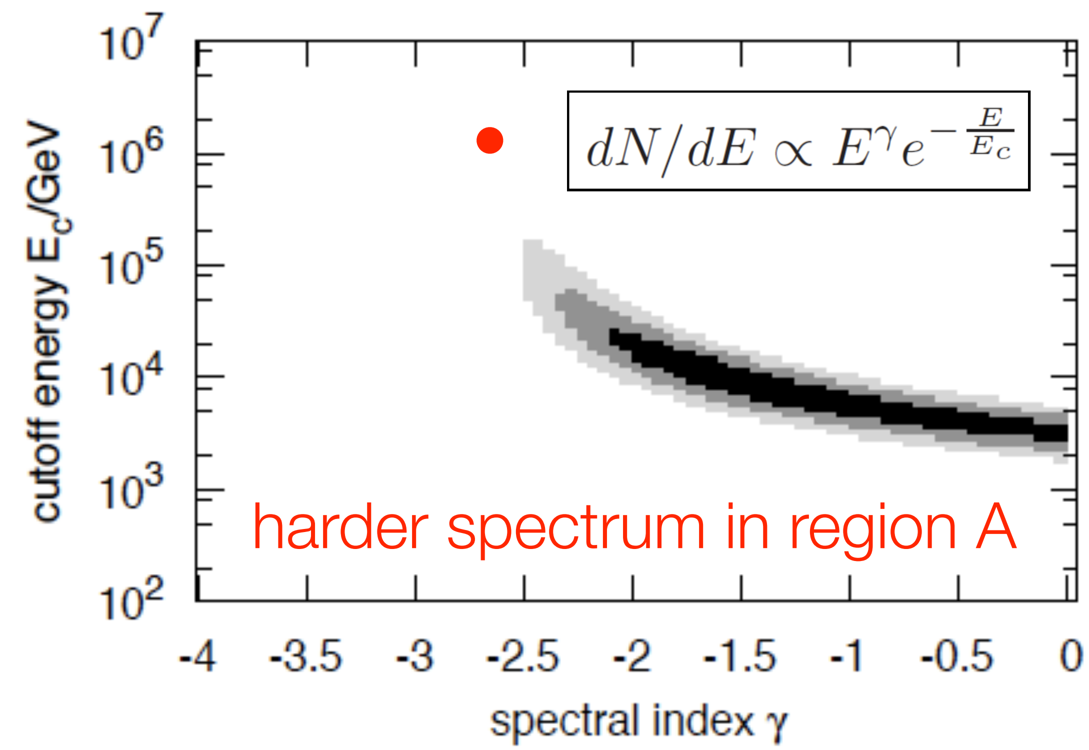
high energy cosmic rays
anisotropy & energy spectrum

Díaz Vélez talk on HAWC today

Milagro

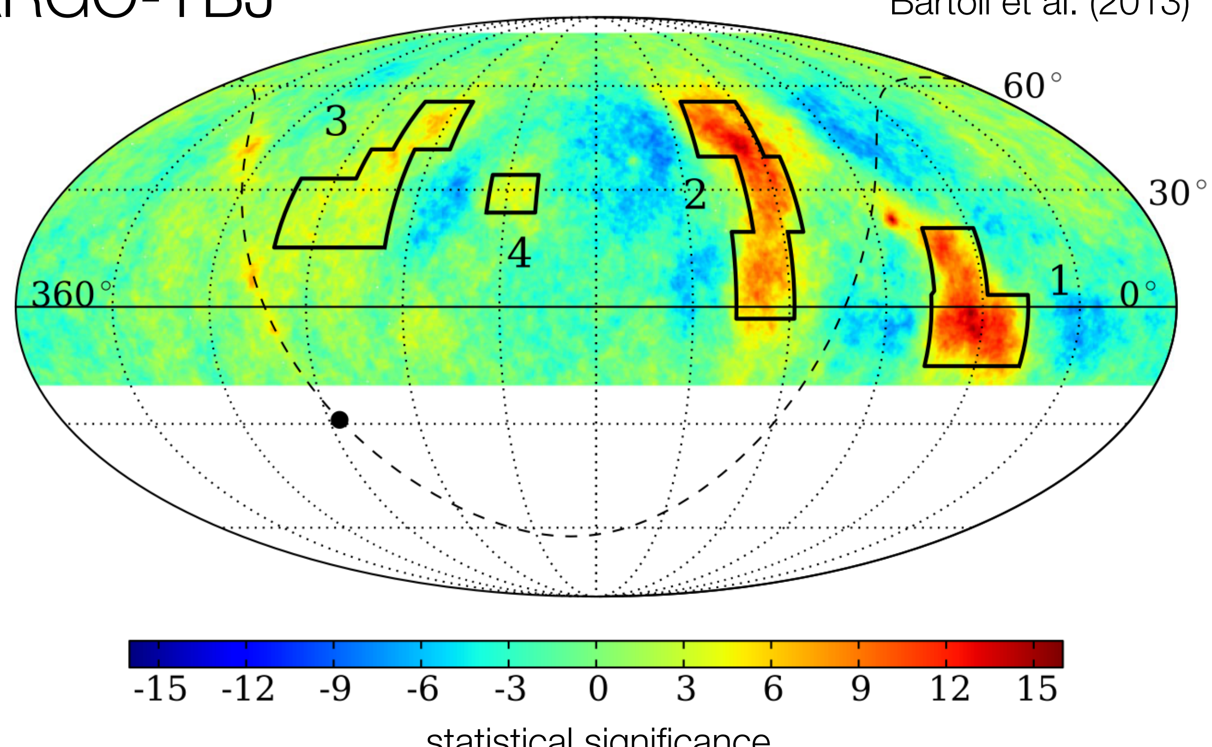
Abdo et al. (2008)

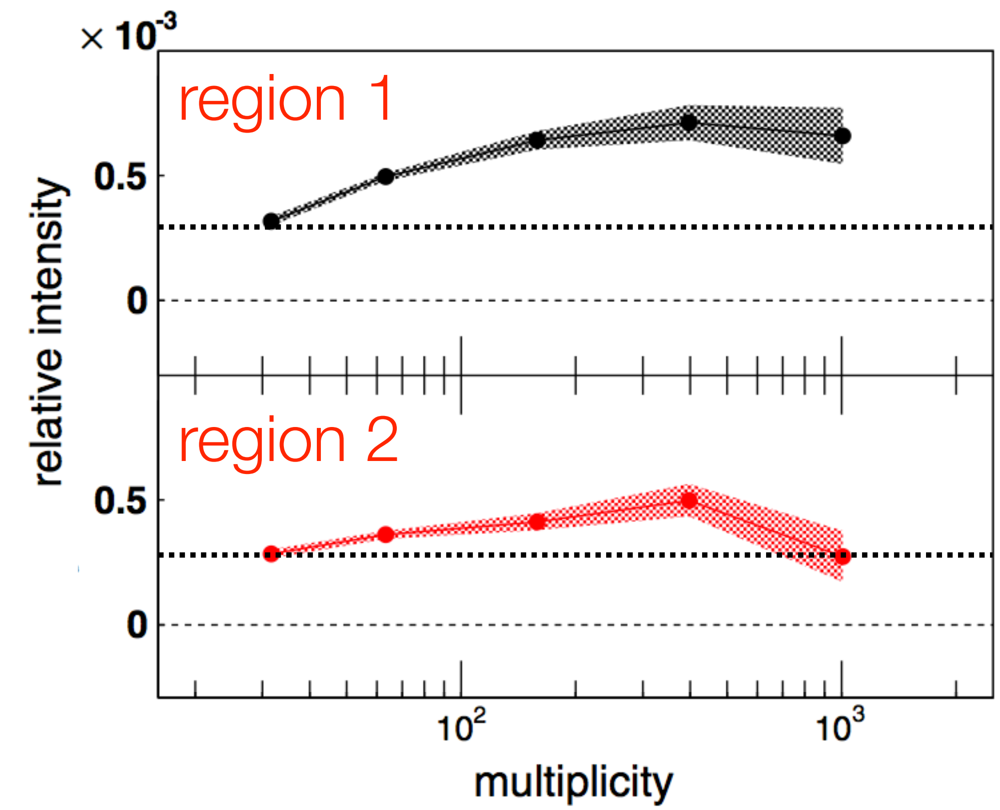




ARGO-YBJ

Bartoli et al. (2013)



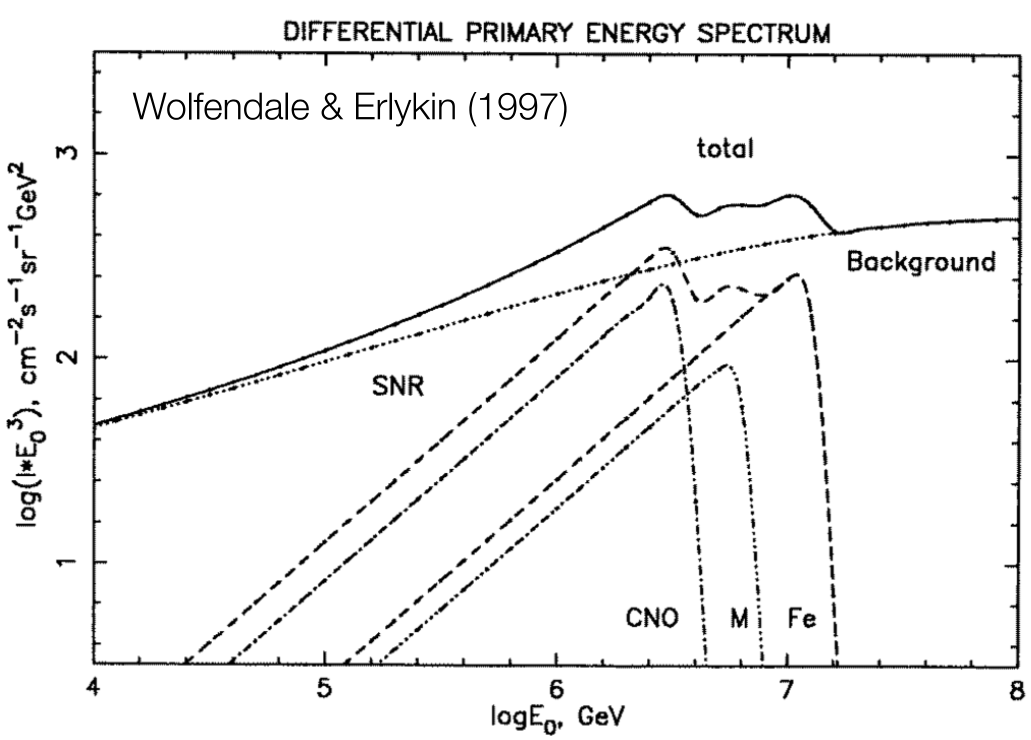


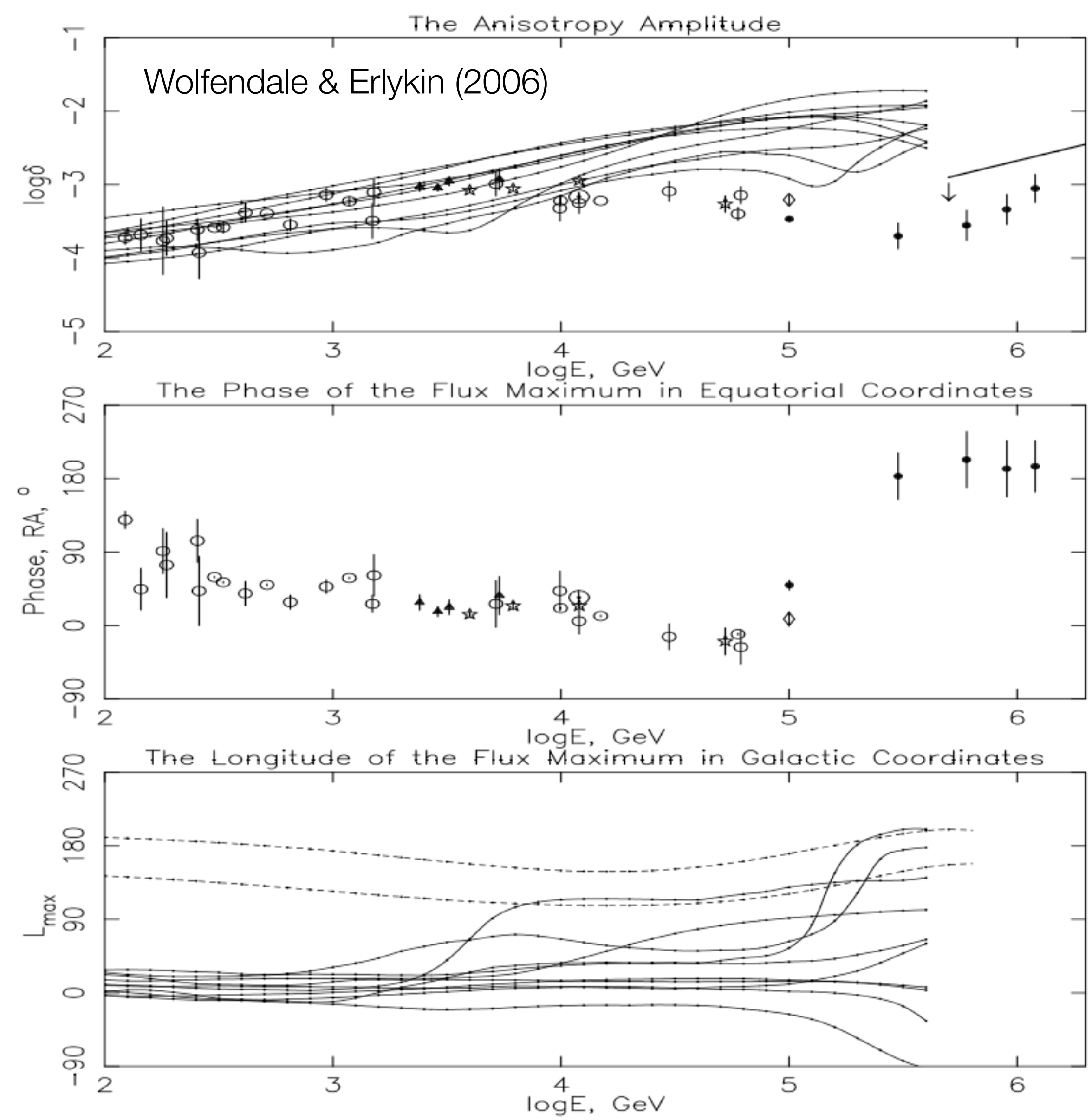
astrophysics of cosmic ray anisotropy

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 ?**

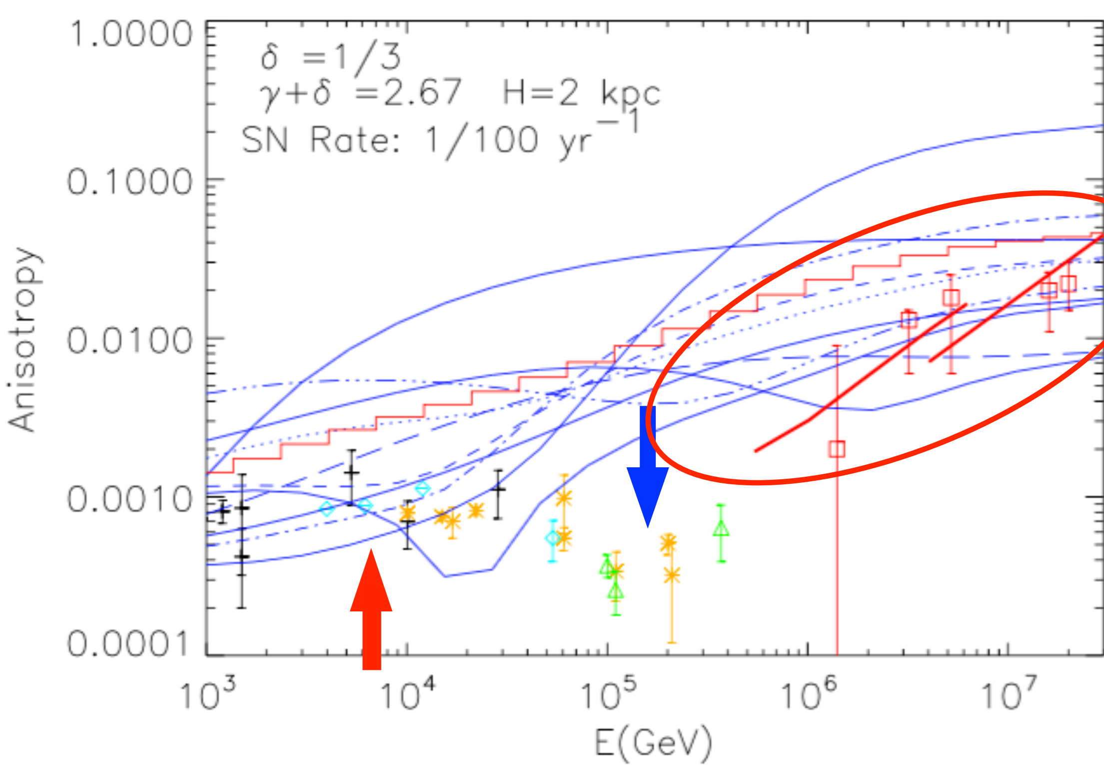
astrophysics of cosmic ray anisotropy

probing sources & propagation of cosmic rays ?

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

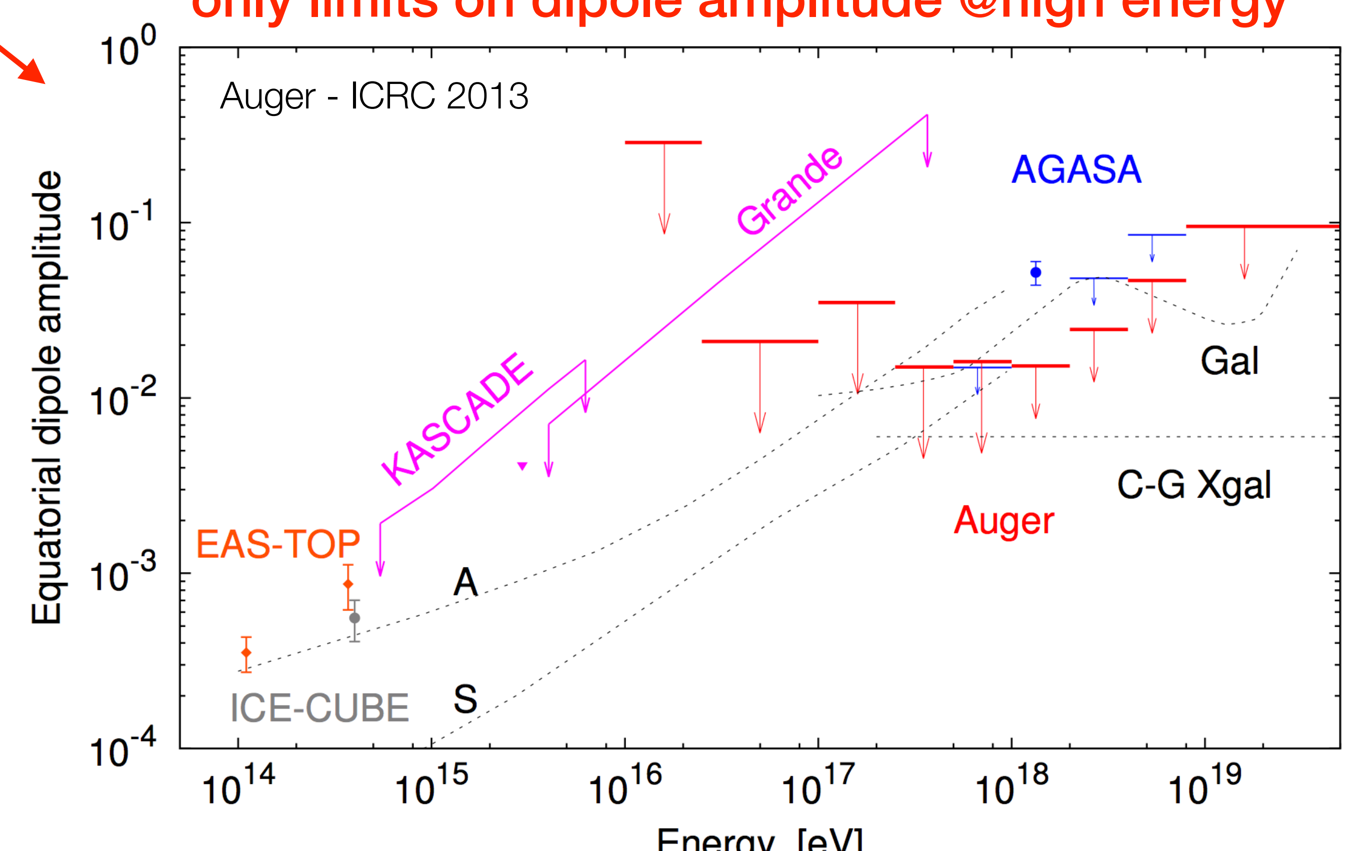
Erlykin & Wolfendale, Astropart. 2006
Blasi & Amato, 2011
Ptuskin+, 2012
Pohl & Eichler, 2012
Sveshnikova+, 2013
Kumar & Eichler, 2014
Mertsch & Funk, 2014

dipole amplitude **Blasi & Amato, 2011**



not dipole observations

only limits on dipole amplitude @high energy



dipole components of the anisotropy typically overestimates by models

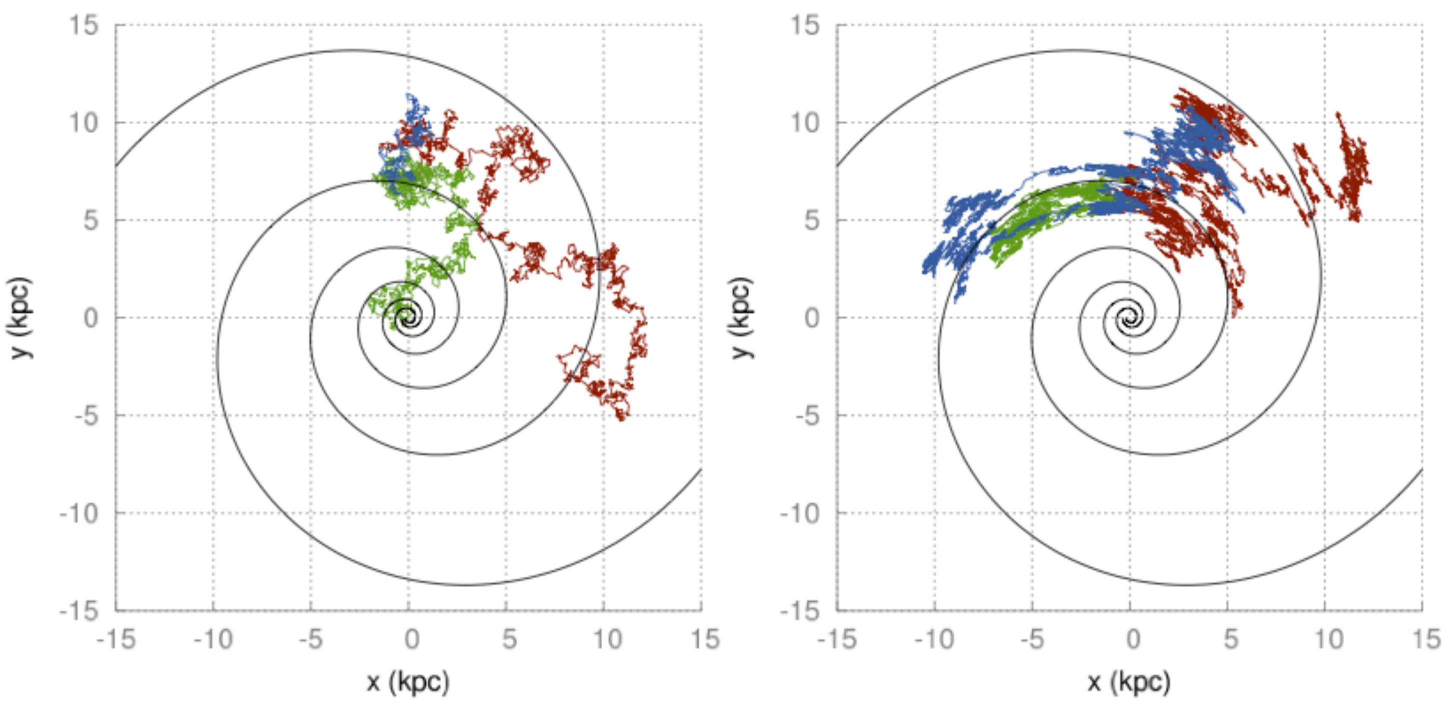
large fluctuations from stochastic nature of individual sources in space & time

cosmic ray anisotropy

probing diffusion properties

anisotropic diffusion

Effenberger+, 2012

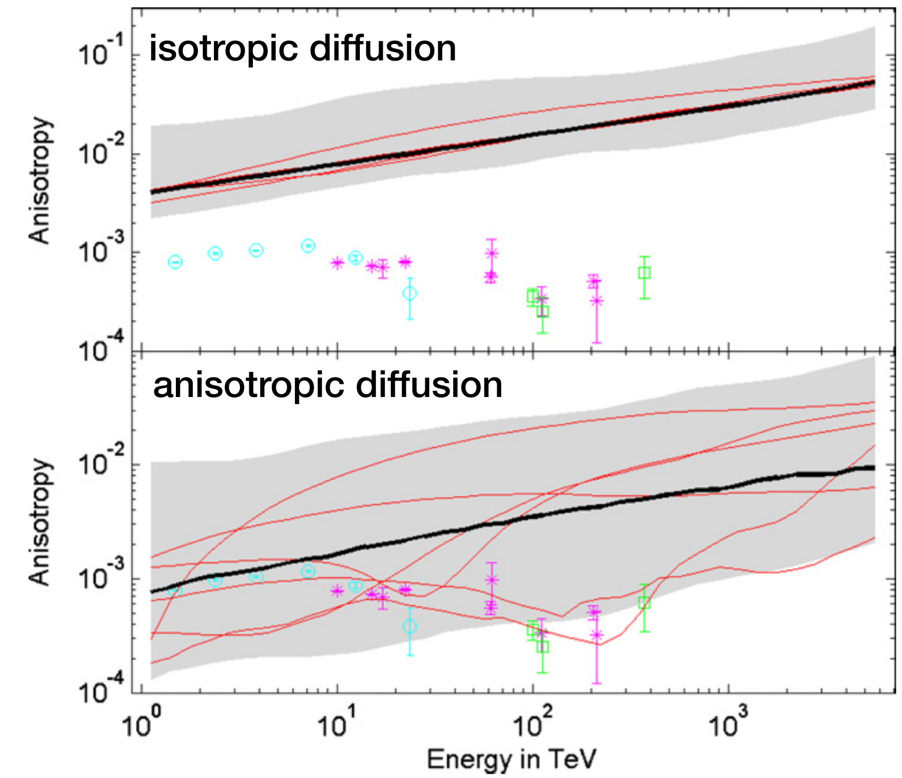


- **D⊥/D∥ << 1** - parallel projection of anisotropy
- cosmic ray **sources concealed** by propagation effects

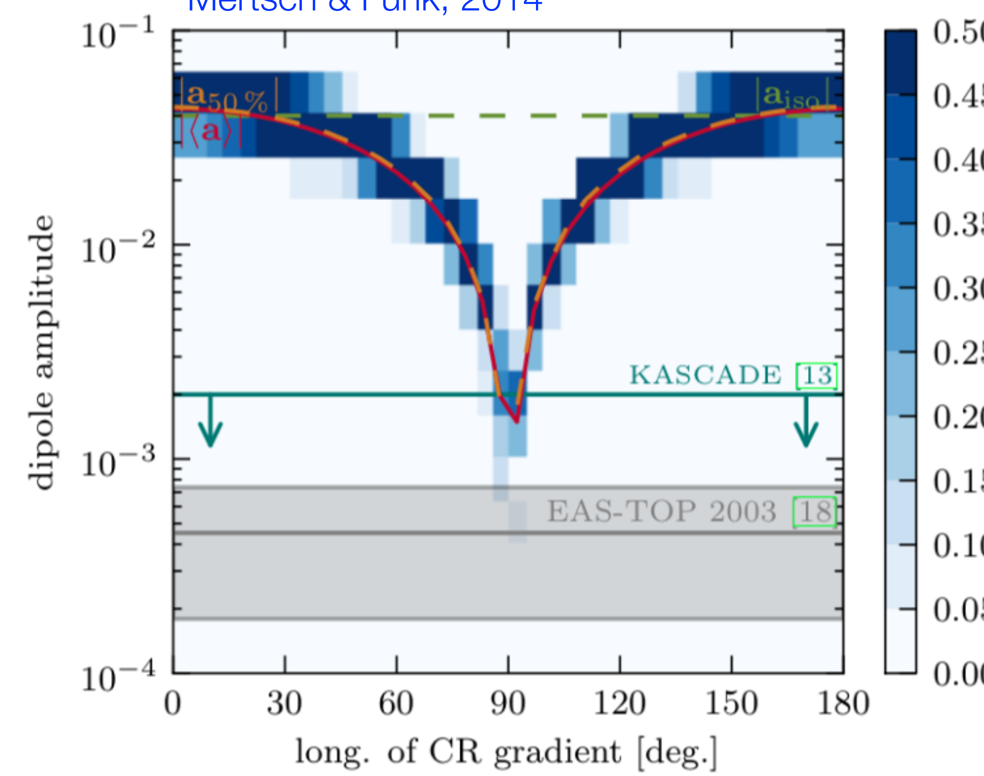
several talks

diffusion coefficient hardly a single power law, homogeneous and isotropic

Kumar & Eichler, 2014



Mertsch & Funk, 2014



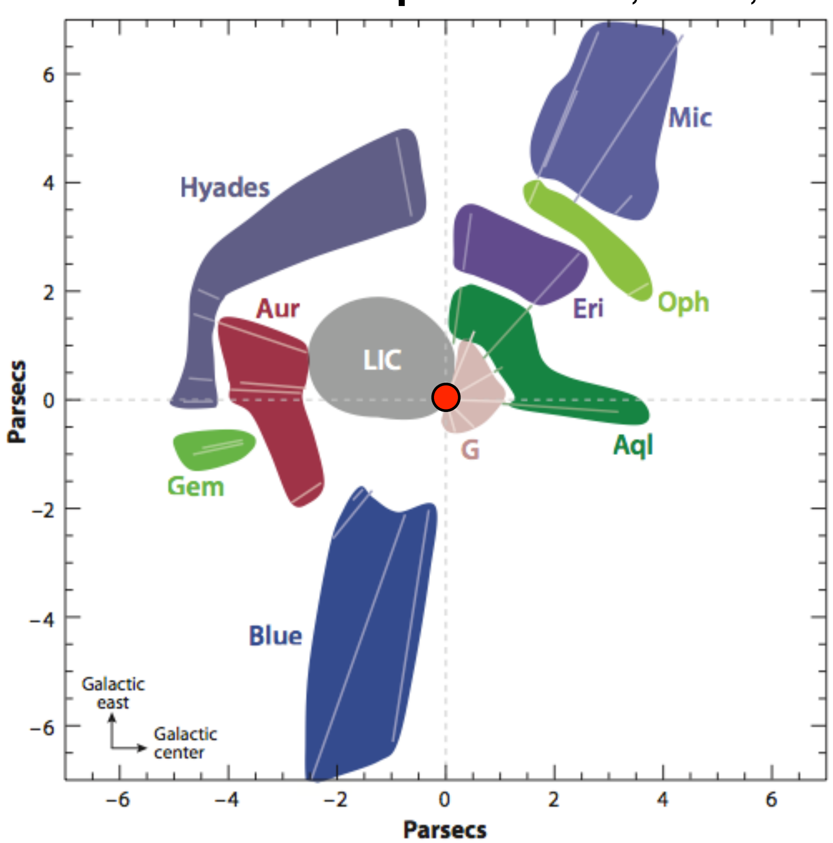
cosmic ray anisotropy

local interstellar medium

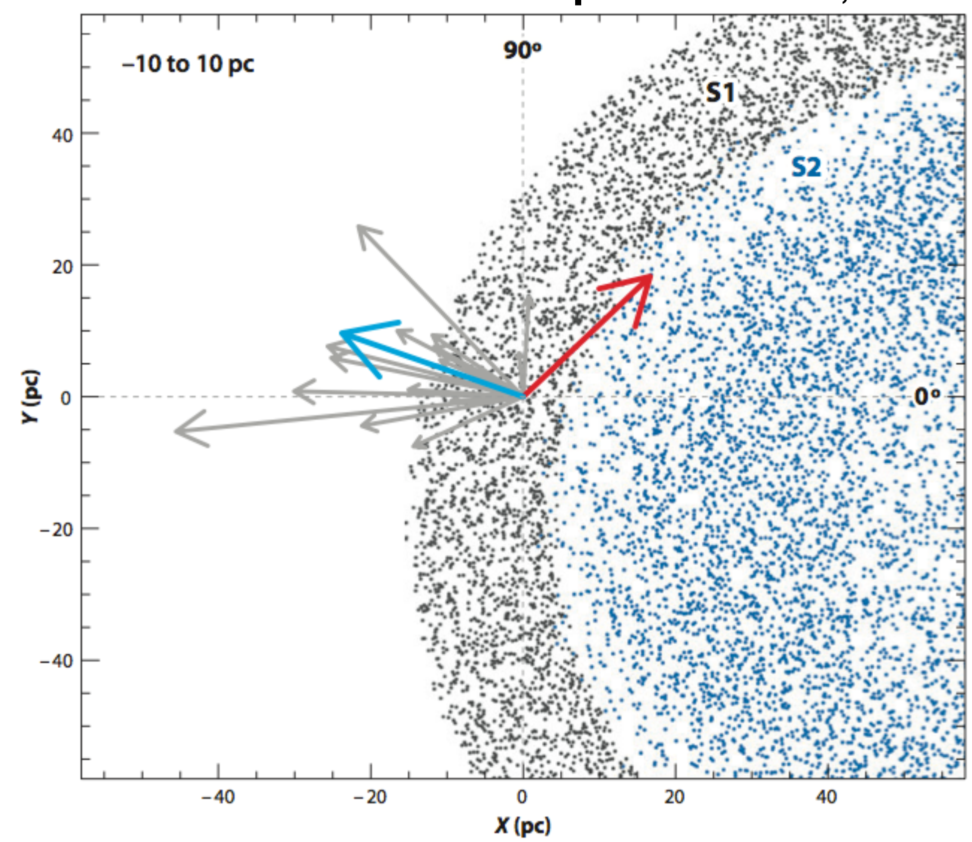
local ISMF shaped by LOOP I expansion sub-shell (with center ~60 pc away in Scorpius-Centaurus OB Association)

local cloudlets fragments of the shell moving at similar velocities

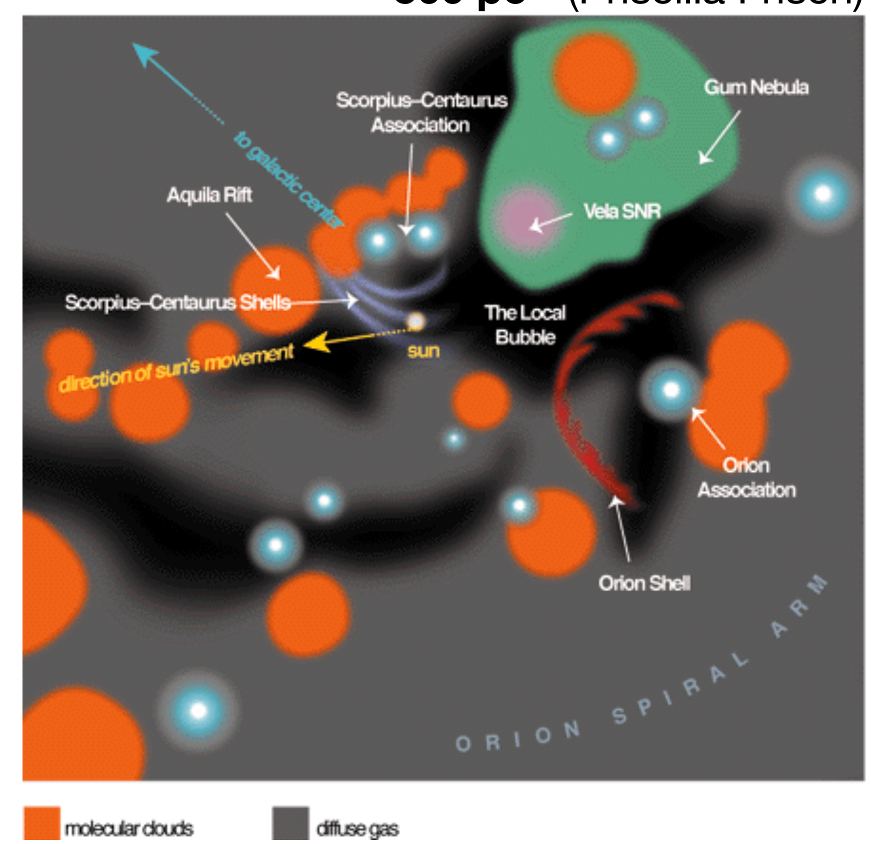
14 pc - Frisch+, 2011, 14



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 order 60-100 pc (**inter-arm**)

Frisch+, 2012,14

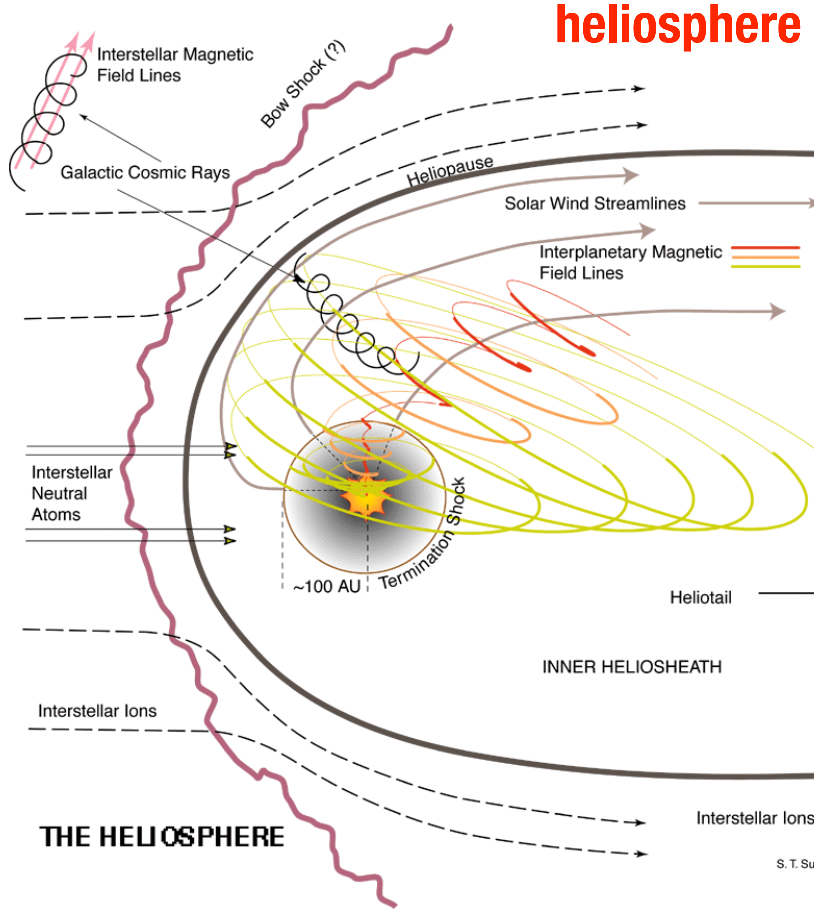
- magnetic turbulence affects propagation and diffusion properties

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

cosmic ray anisotropy
heliosphere

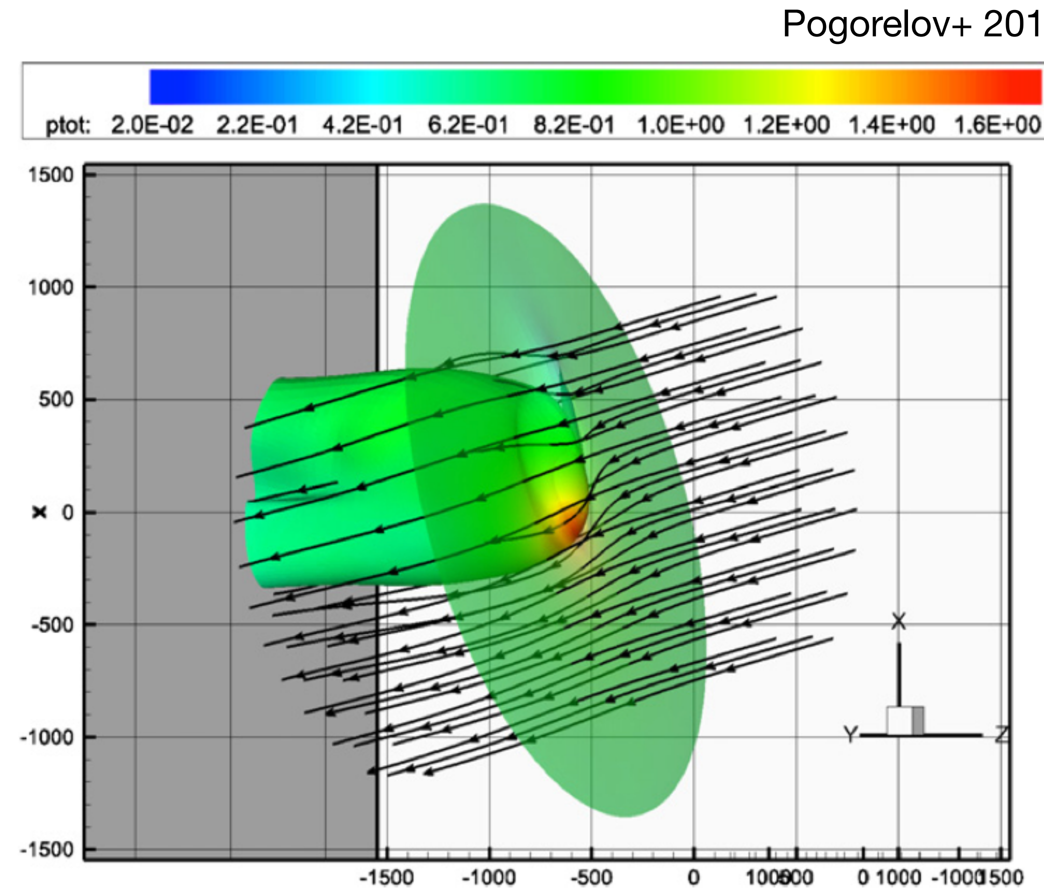
several talks

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



heliotail

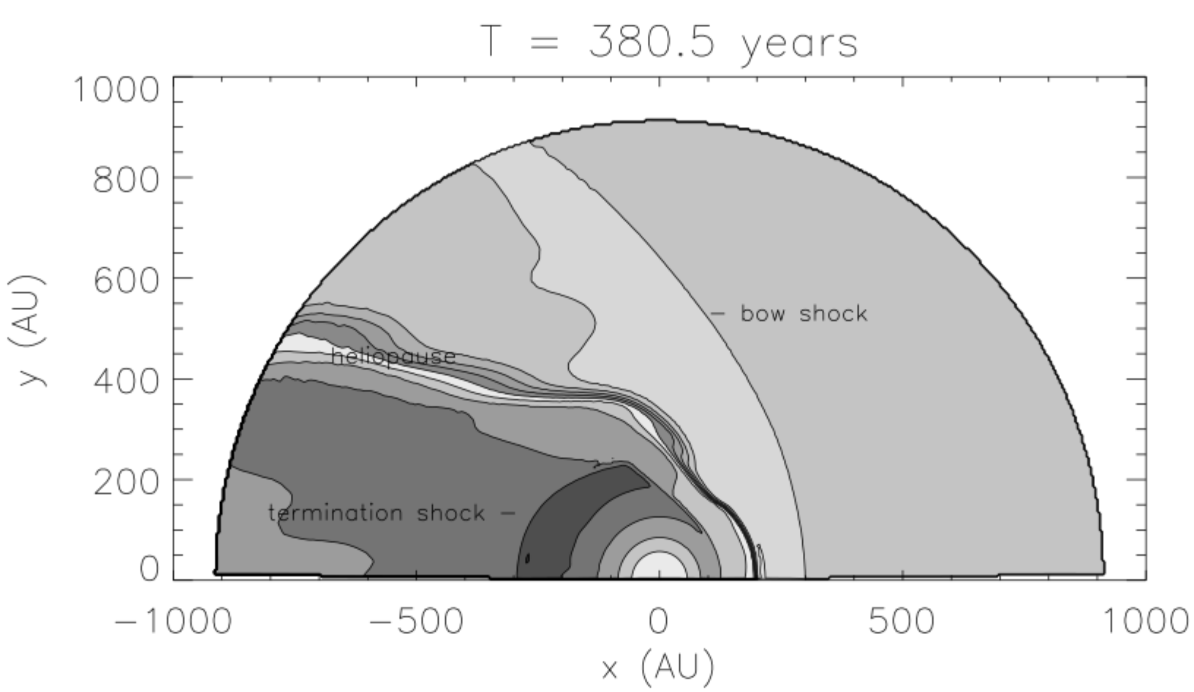
local ISMF draping around heliosphere



- 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**)

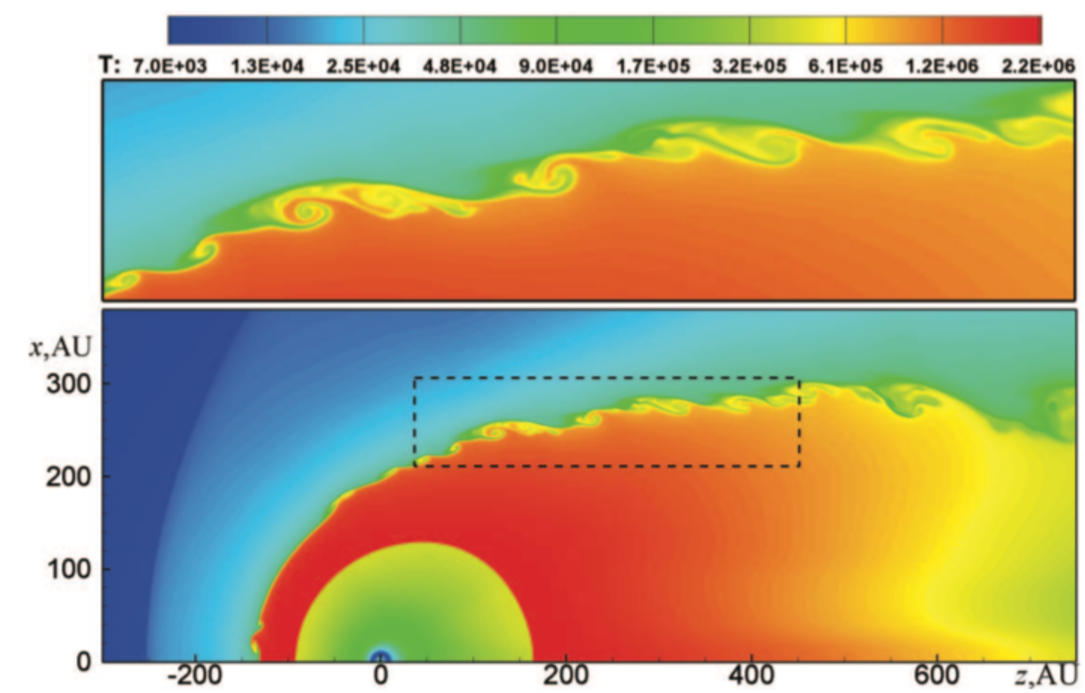
heliospheric perturbations
heliopause instabilities

- 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

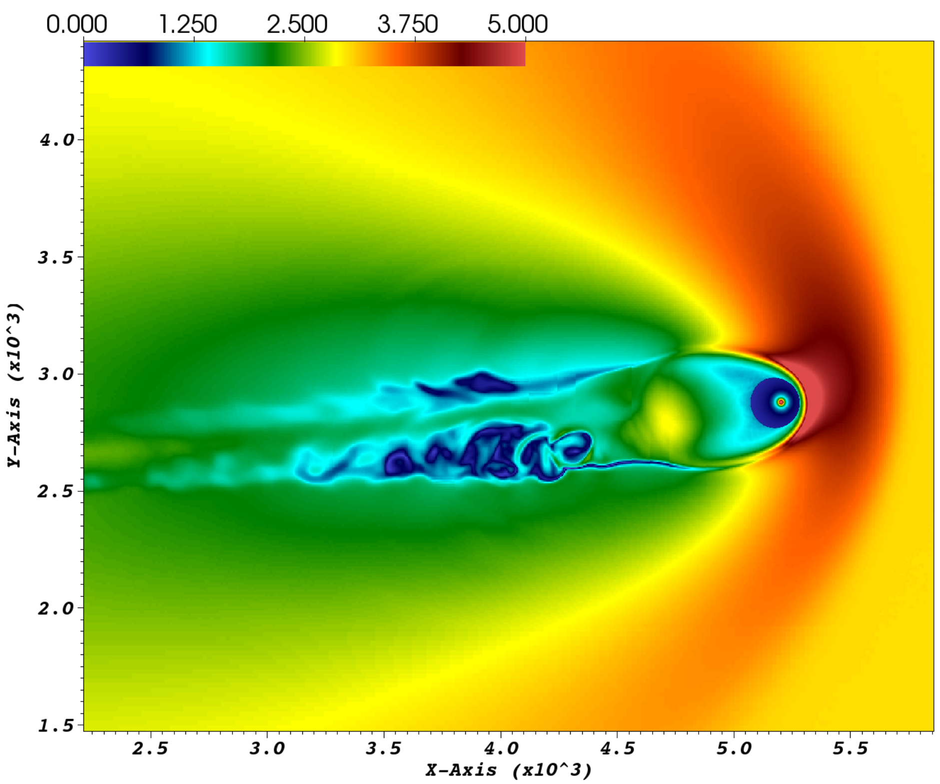


Zank 1999
Florinski++ 2005
Borovikov+ 2008
Zank 2009
Shaikh & Zank 2010

Pogorelov talks Tuesday

cosmic ray anisotropy

probing heliospheric magnetic structure



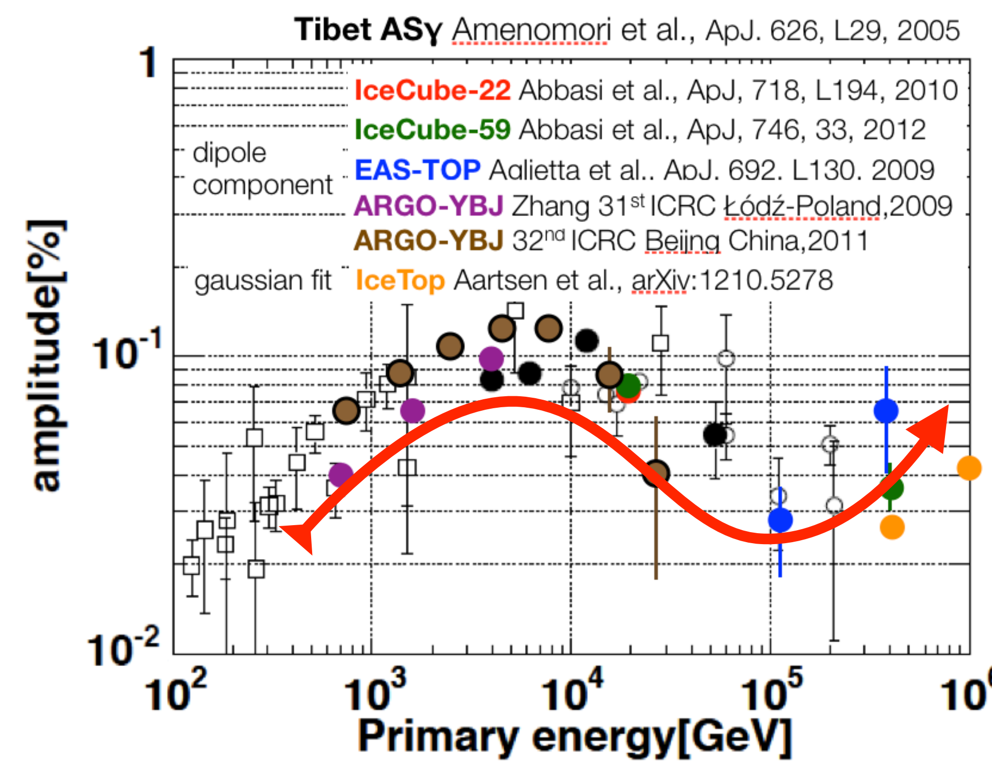
Borovikov, Heerikhuisen, Pogorelov

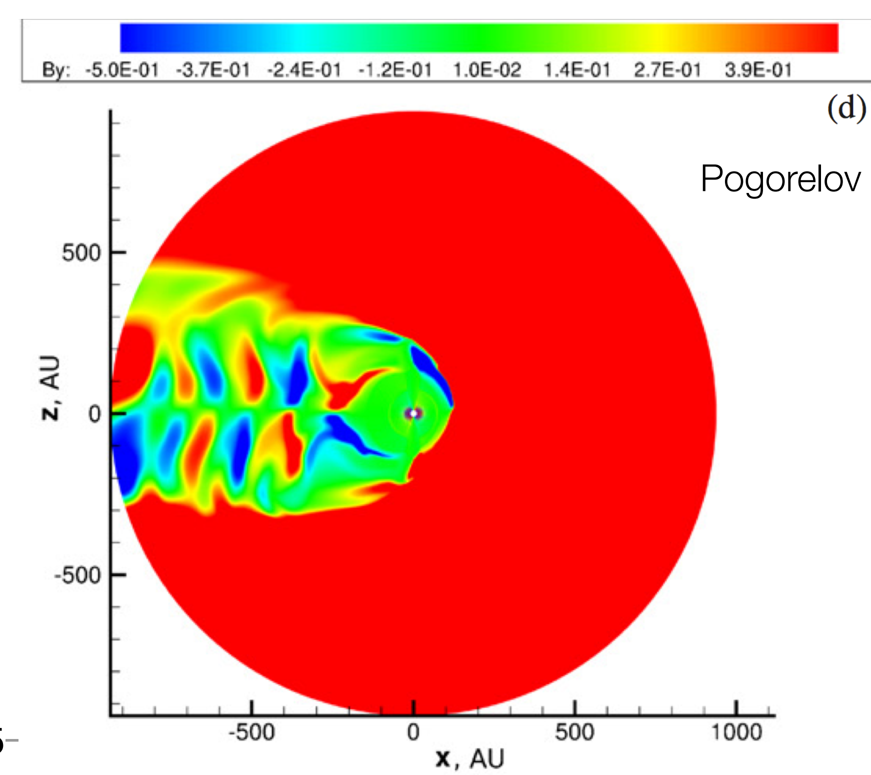
downstream instabilities on the flanks of heliotail

resonant scattering

PD & Lazarian 2013

López-Barquero, Xu, PD, Lazarian **IN PROGRESS**





Pogorelov et al., 2009

effects of magnetic polarity reversals from solar cycles

explain spectral anomaly @heliotail ?

magnetic reconnection

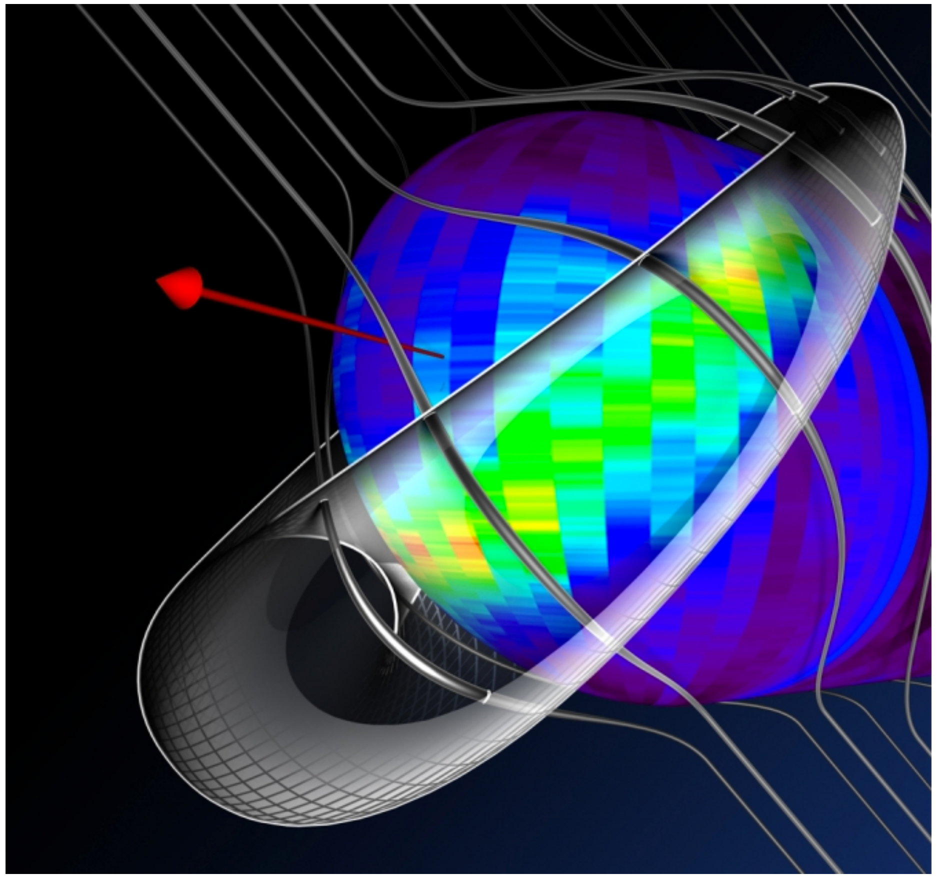
Lazarian & PD 2010
PD & Lazarian 2012

anisotropy and local galactic environment

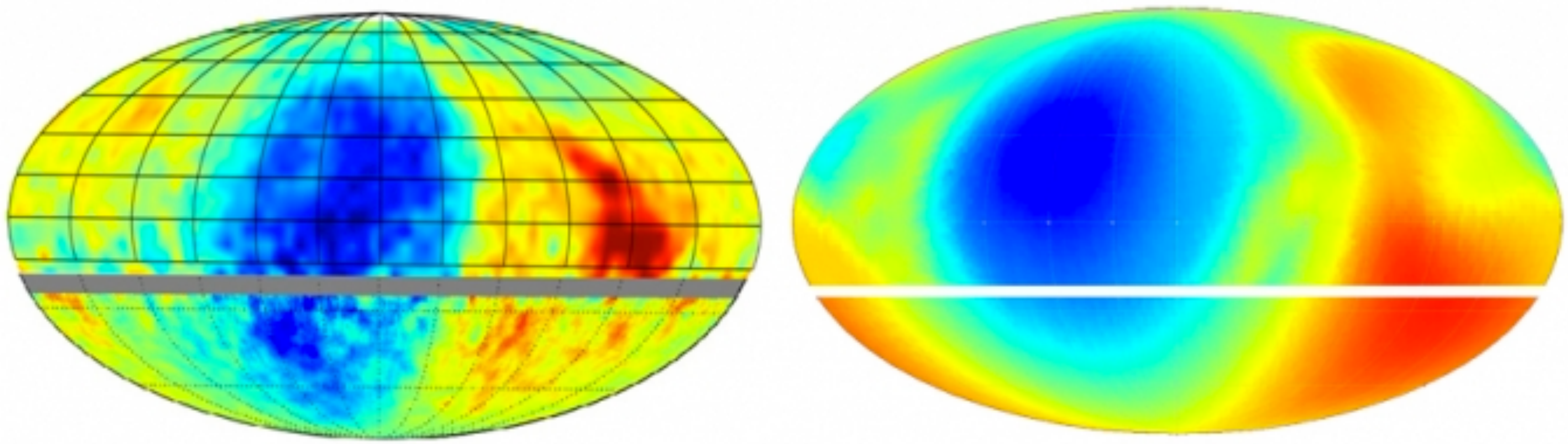
low to high energy connection

- 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)



Schwadron and Pogorelov talks Tuesday

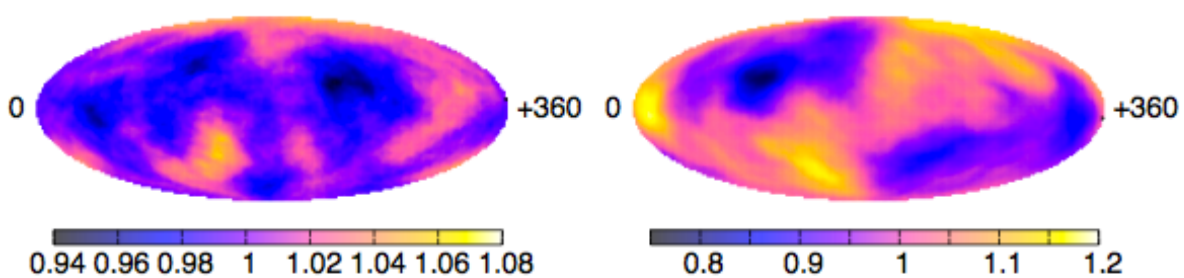
Zhang, Zuo & Pogorelov ApJ 790, 5 (2014)

cosmic ray anisotropy
probing magnetic field turbulence ?

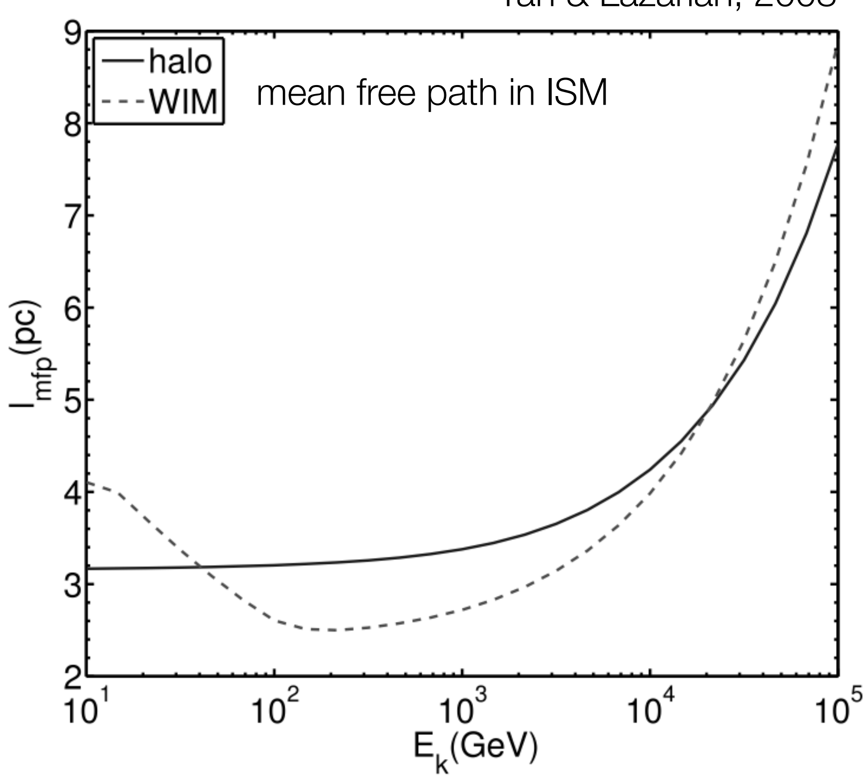
Ahlers and Giacinti talks this week

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

Giacinti & Sigl, 2012
Biermann+, 2012

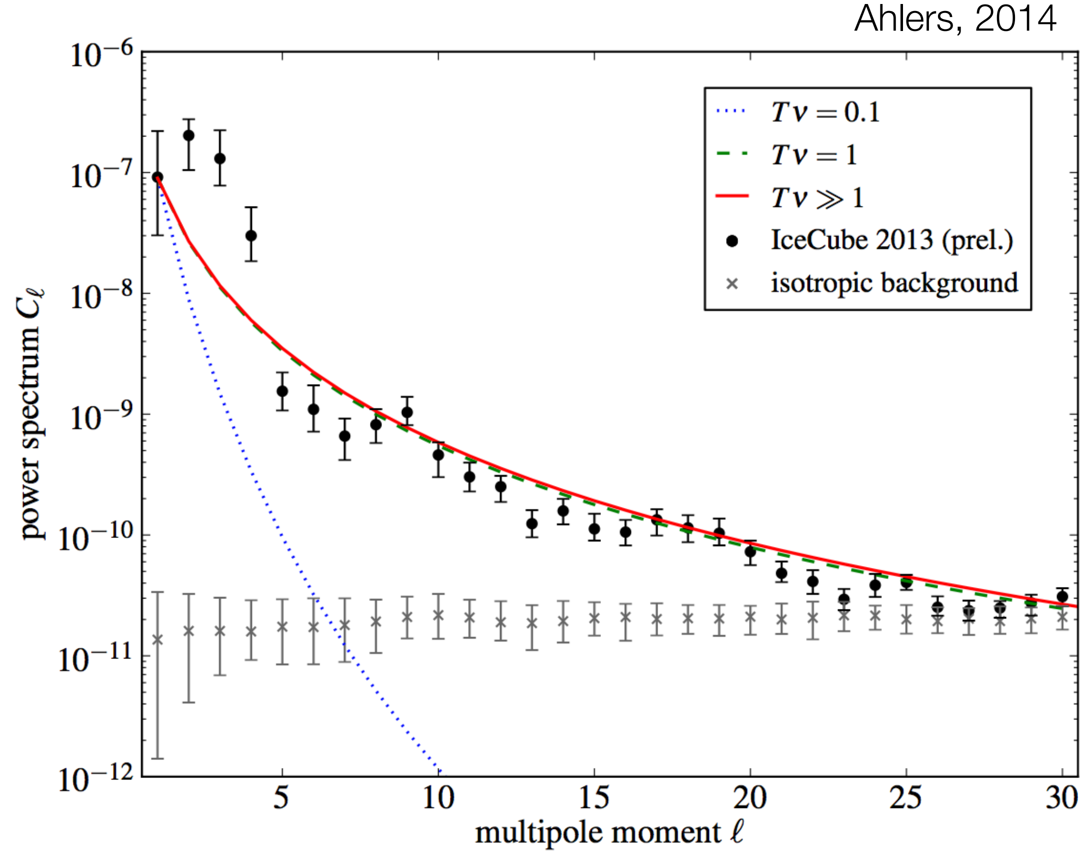


Yan & Lazarian, 2008



- 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)

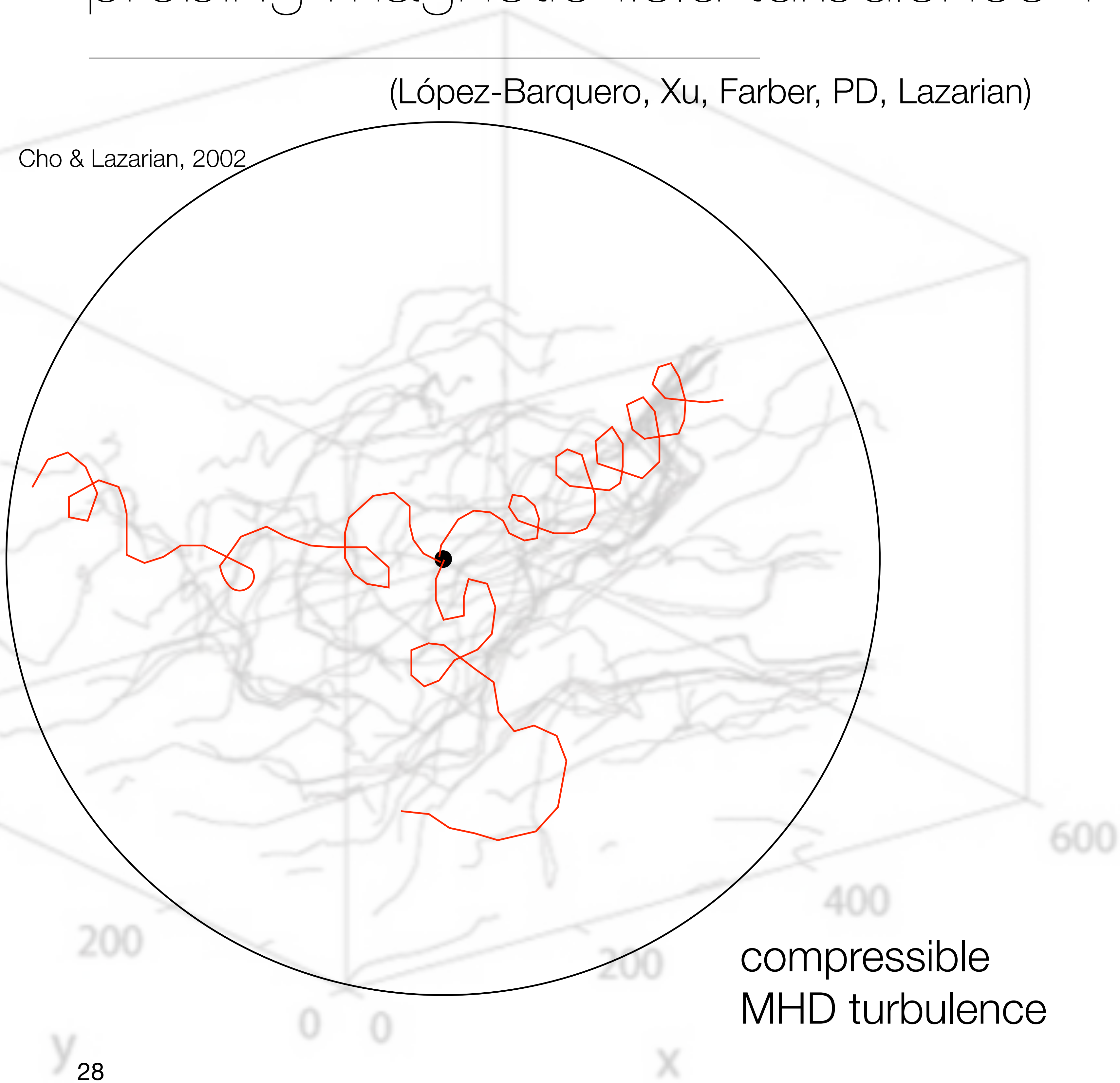
Ahlers, 2014



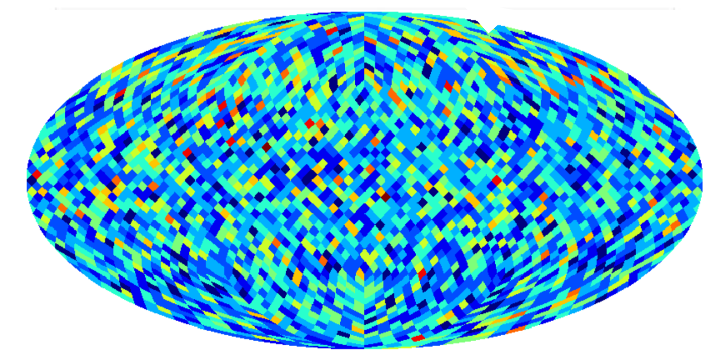
cosmic ray anisotropy
probing magnetic field turbulence ?

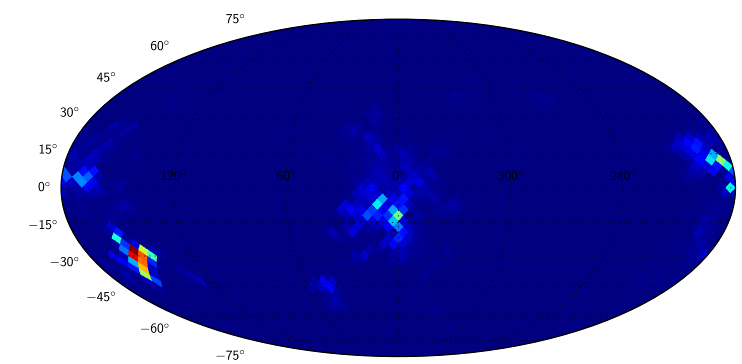
(López-Barquero, Xu, Farber, PD, Lazarian)

Cho & Lazarian, 2002



compressible
MHD turbulence



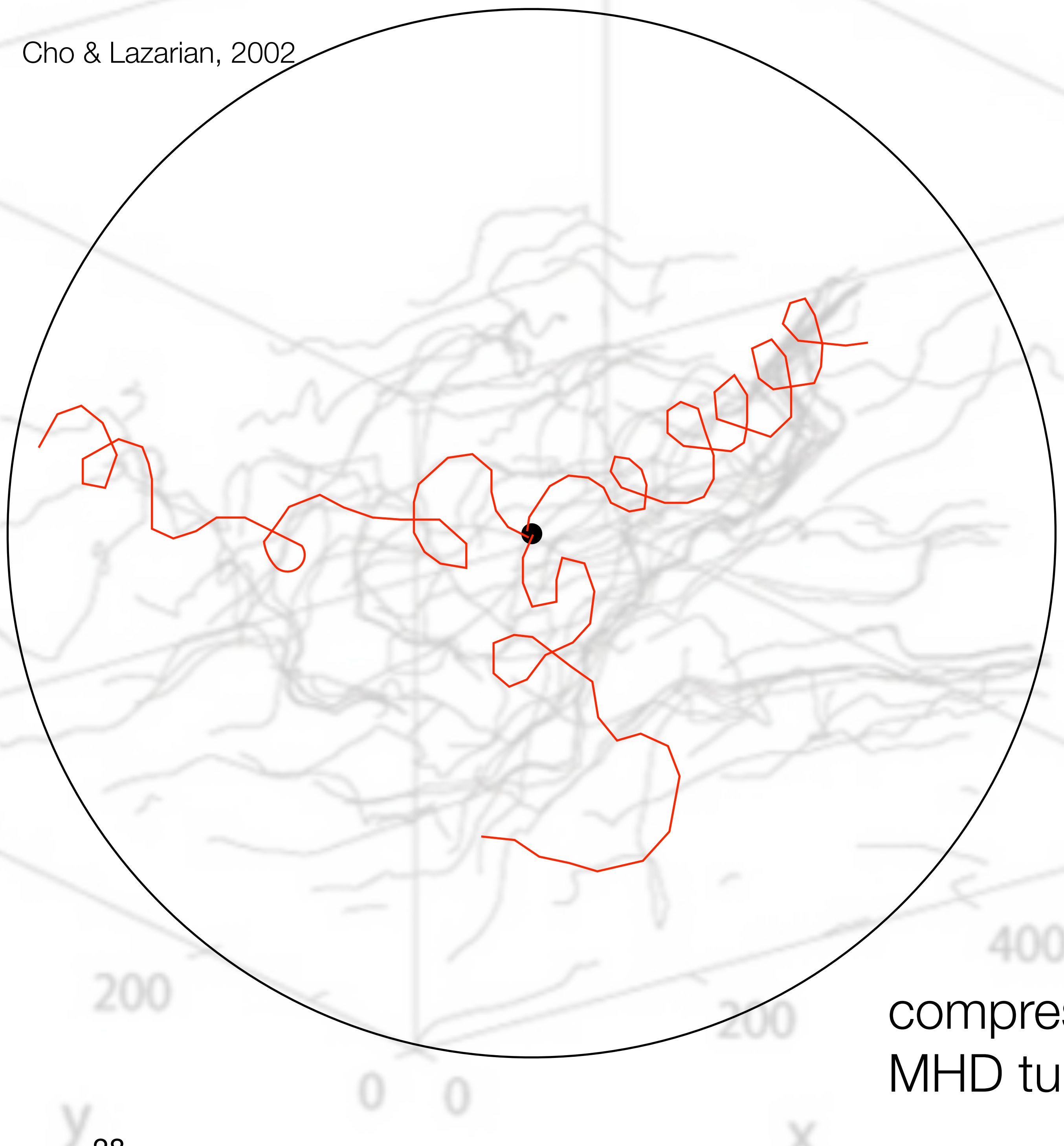


cosmic ray anisotropy
probing magnetic field turbulence ?

López-Barquero talks Wednesday

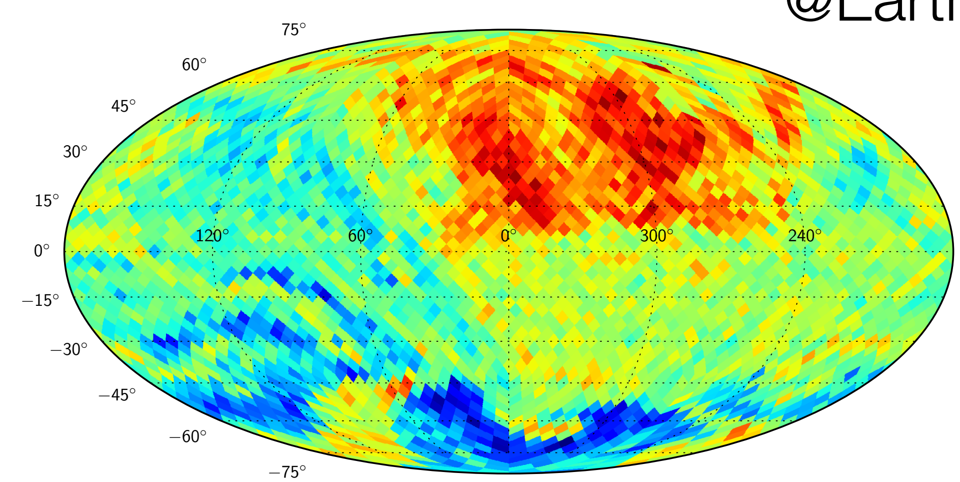
(López-Barquero, Xu, Farber, PD, Lazarian)

Cho & Lazarian, 2002



compressible
MHD turbulence

@Earth

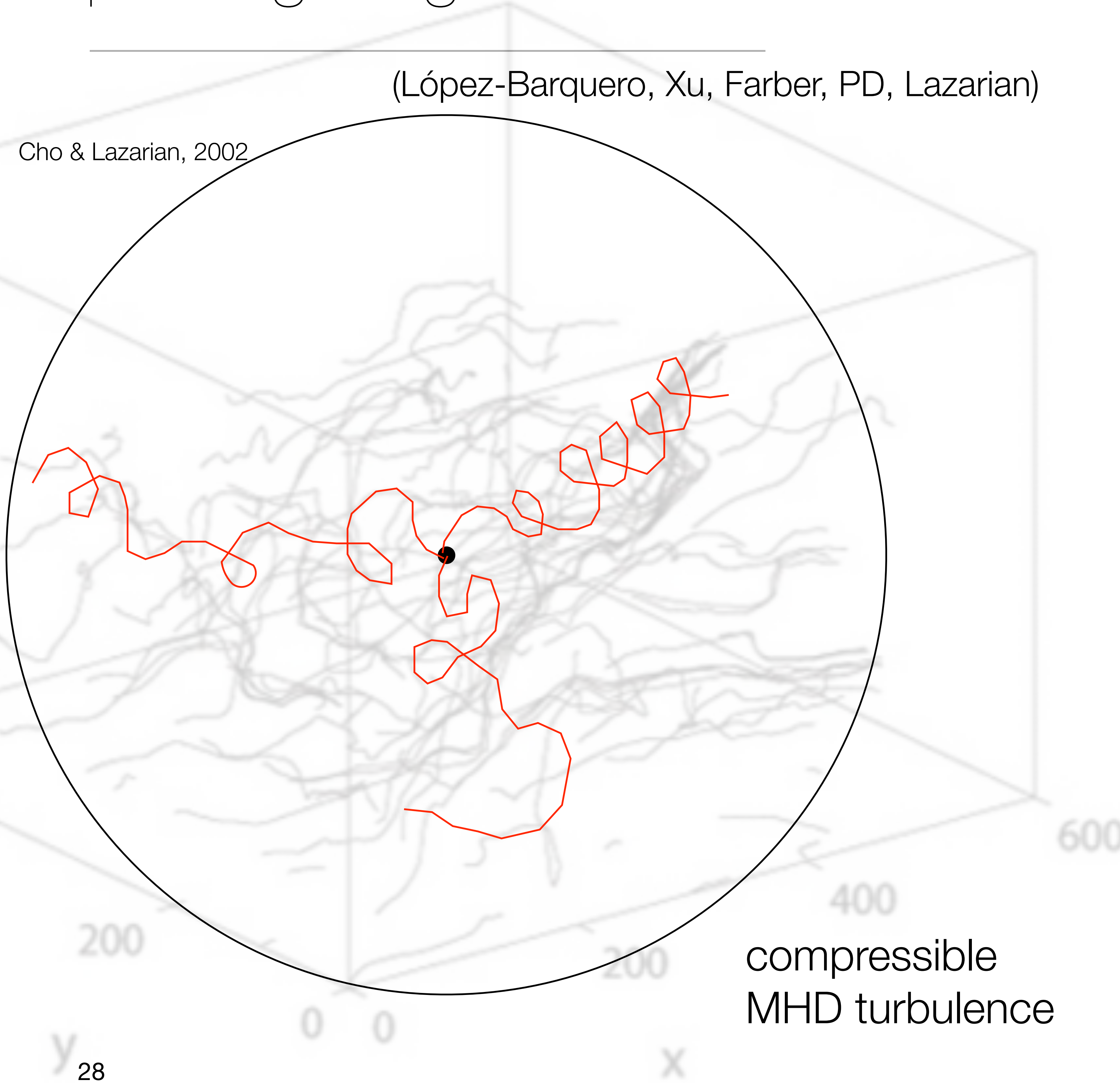


cosmic ray anisotropy
probing magnetic field turbulence ?

López-Barquero talks Wednesday

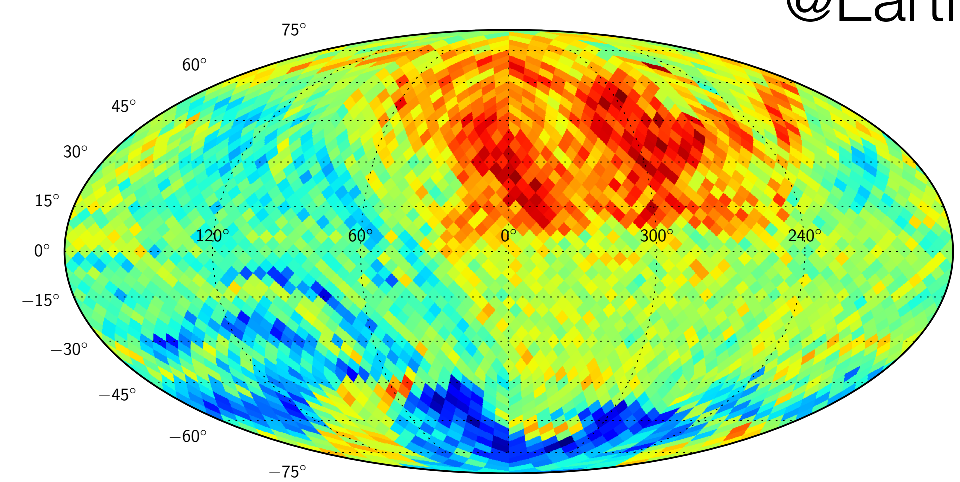
(López-Barquero, Xu, Farber, PD, Lazarian)

Cho & Lazarian, 2002

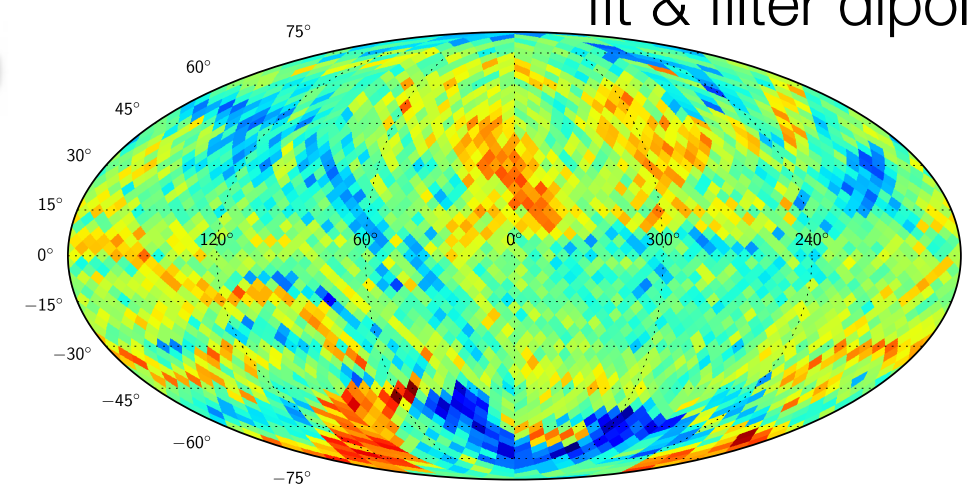


compressible MHD turbulence

@Earth



fit & filter dipole



summary

experimental

- full sky anisotropy: satellite @low energy & combine hemispheres data
- wider energy range dependence: probe solar, heliospheric, ISM, galactic field
- anisotropy at different angular scales: turbulence, scattering, large gradients
- anisotropy for individual primary masses vs energy: rigidity effects, propagation

termination shock
inner heliosheath
heliopause, heliotail
local interstellar medium
Loop I superbubble
thickness of Galaxy
confinement
extragalactic protons

heliospheric influence **interstellar medium** **extra-galactic**

summary
general

- disentangle effects of **propagation** and **source distribution** of CRs
- understand **propagation** effects in different magnetic environments
- role of **perpendicular** transport, drifts, magnetic turbulence, scattering
- understand correlation between **spectral** and **directional** anomalies
- cosmic ray anisotropy as a **probe** into global properties of magnetic fields

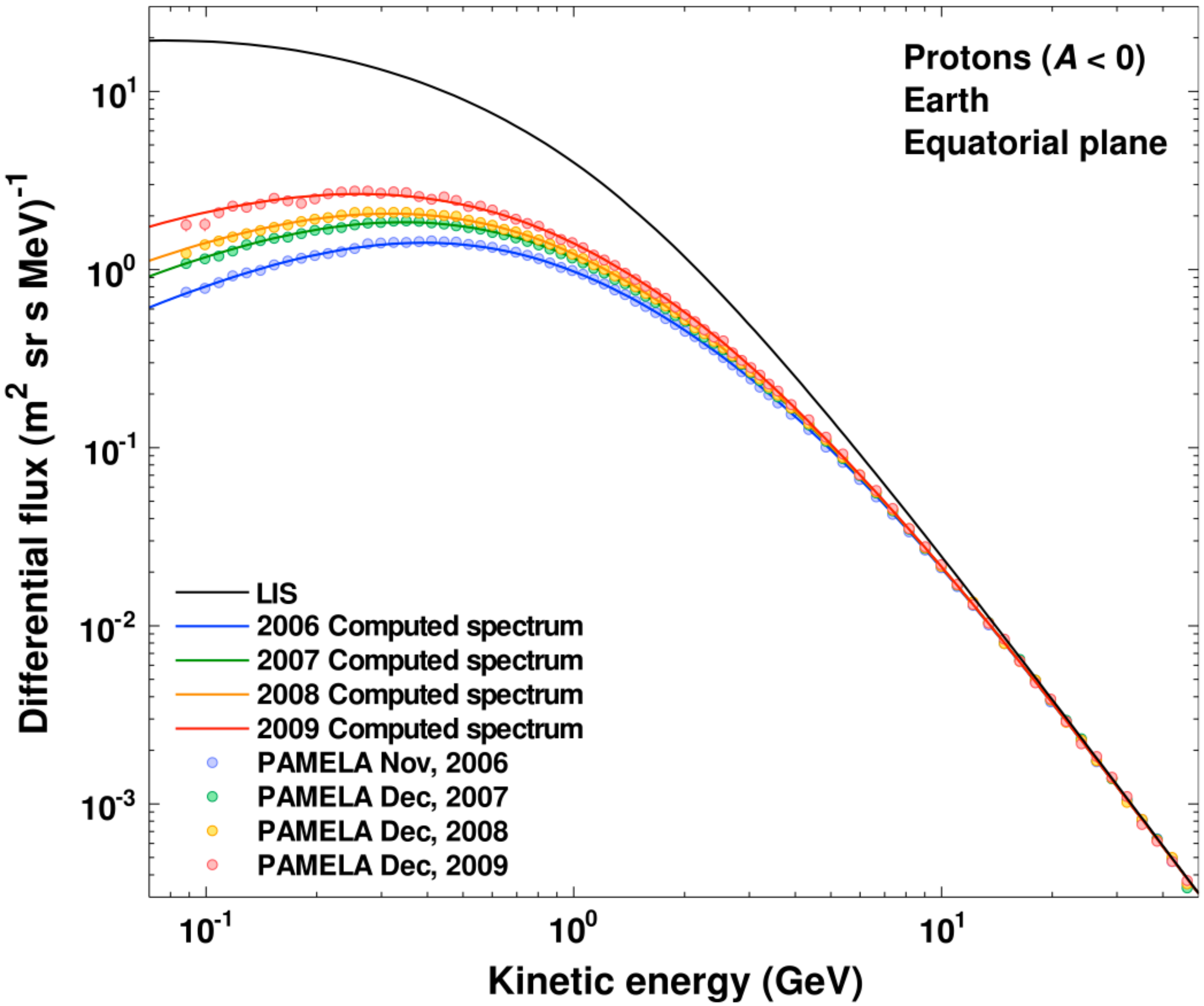
backup slides

low energy cosmic rays
and heliospheric physics

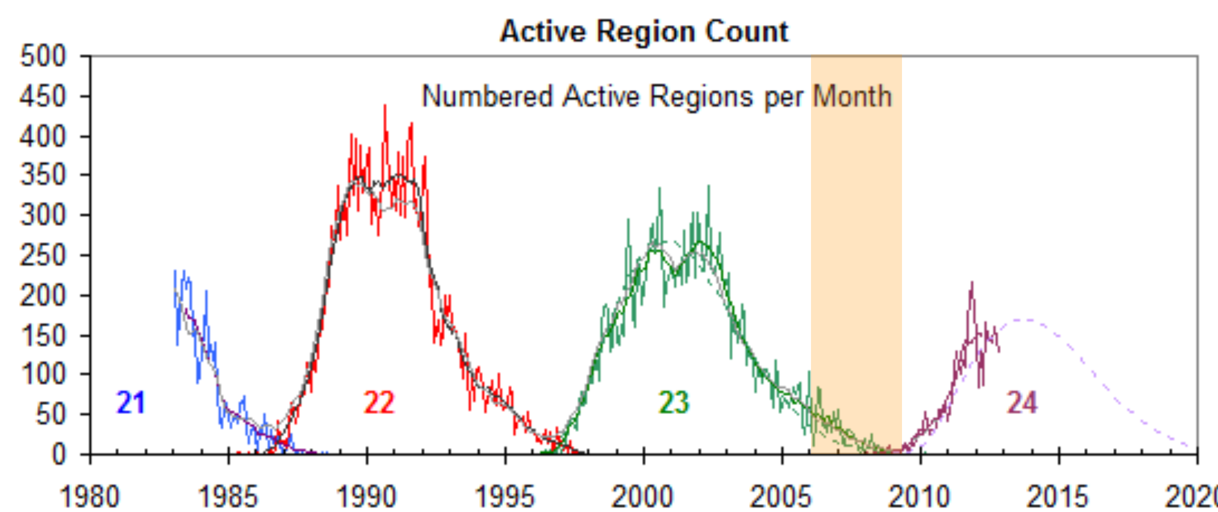
< 20-30 GV

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

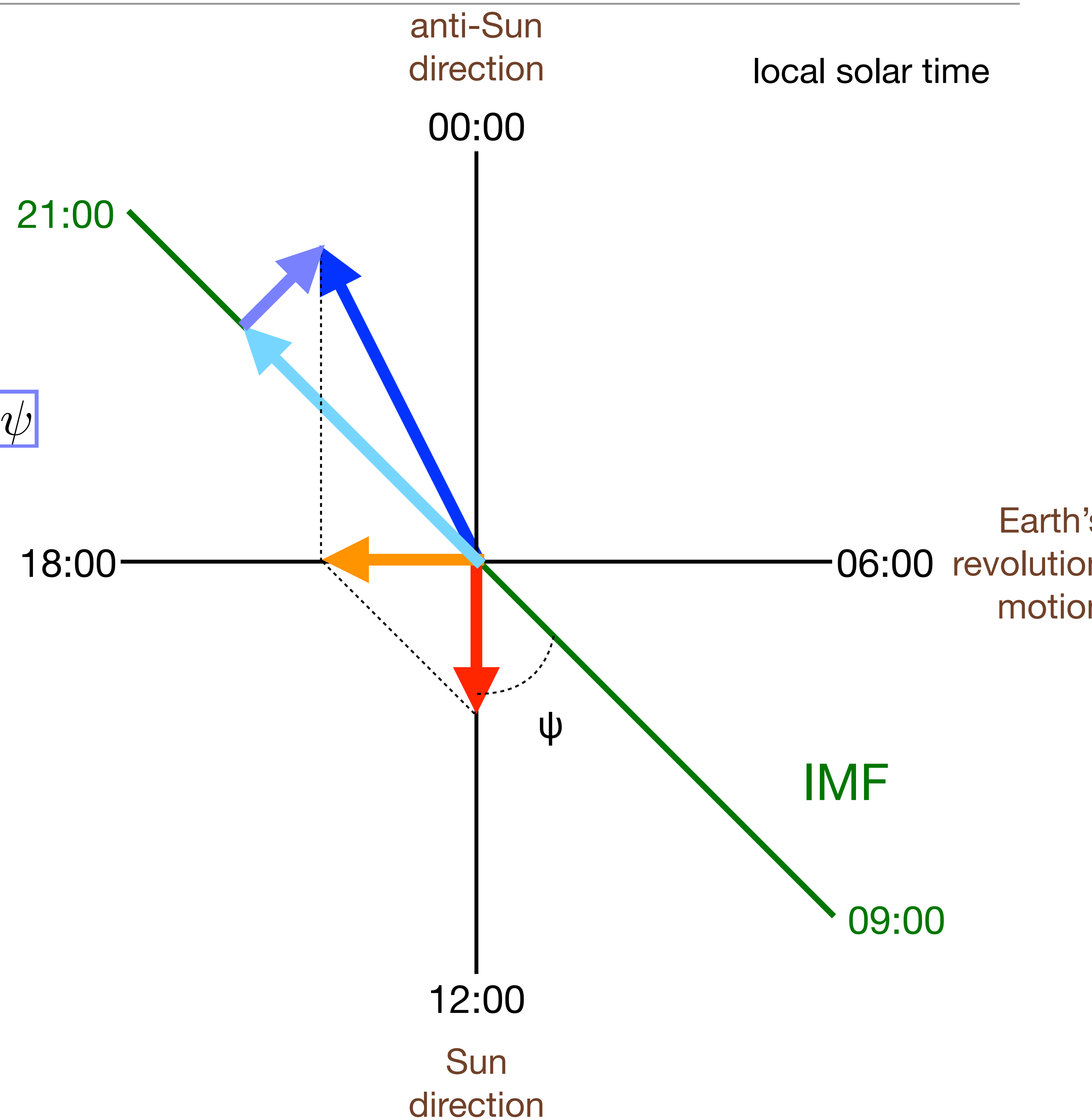
total diffusion

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

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

co-rotation

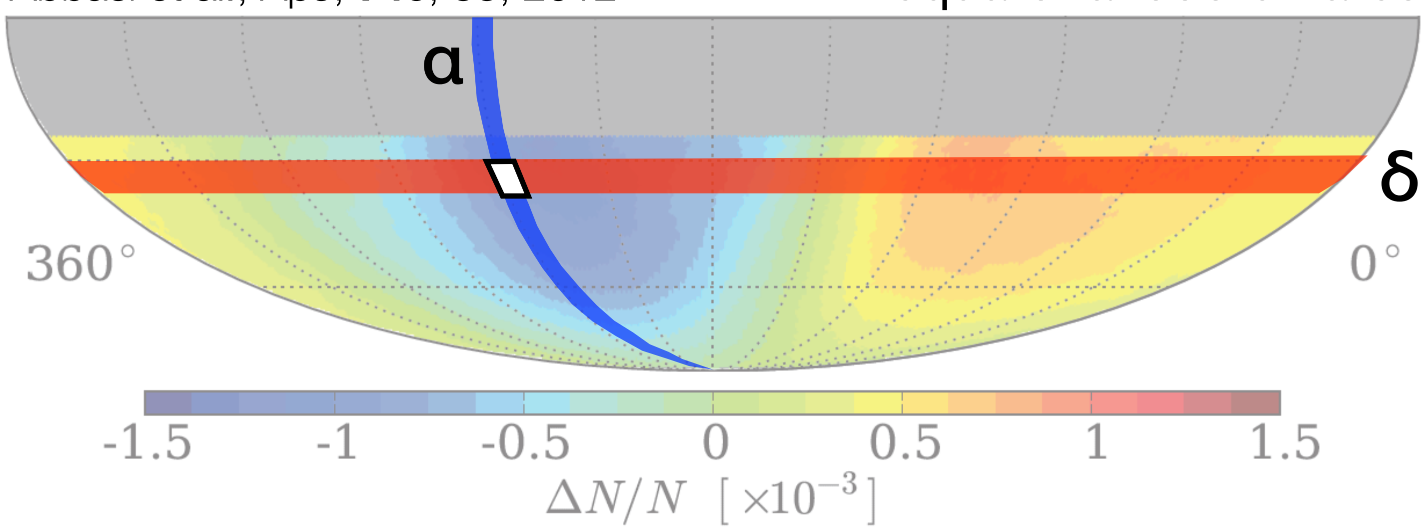
convection (solar wind)



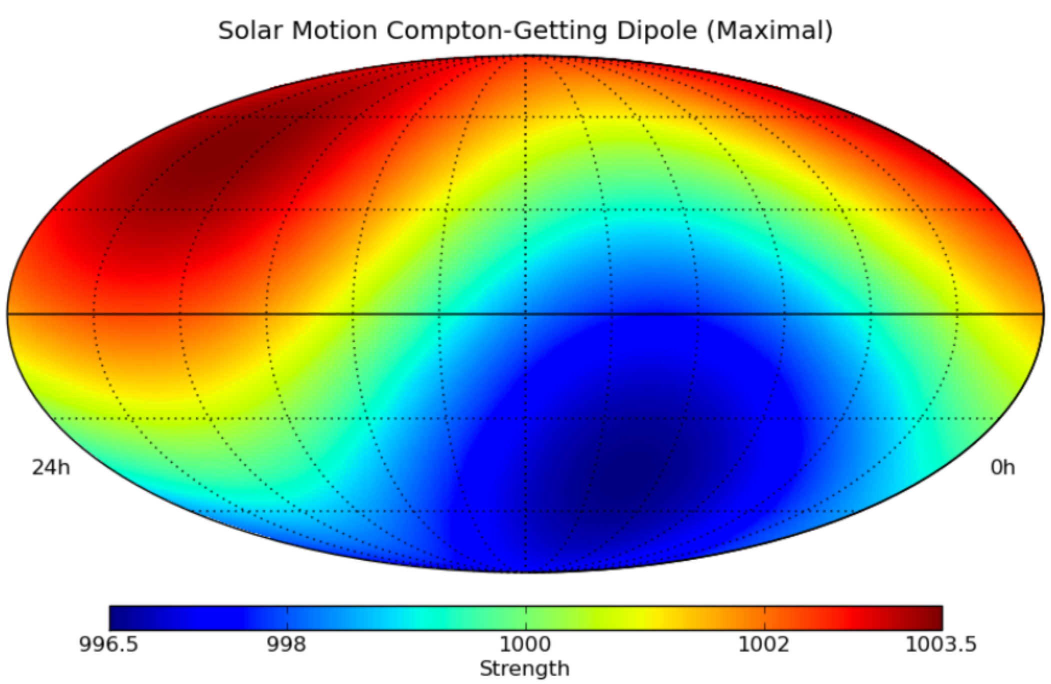
From K. Munakata

measuring cosmic ray anisotropy
relative intensity

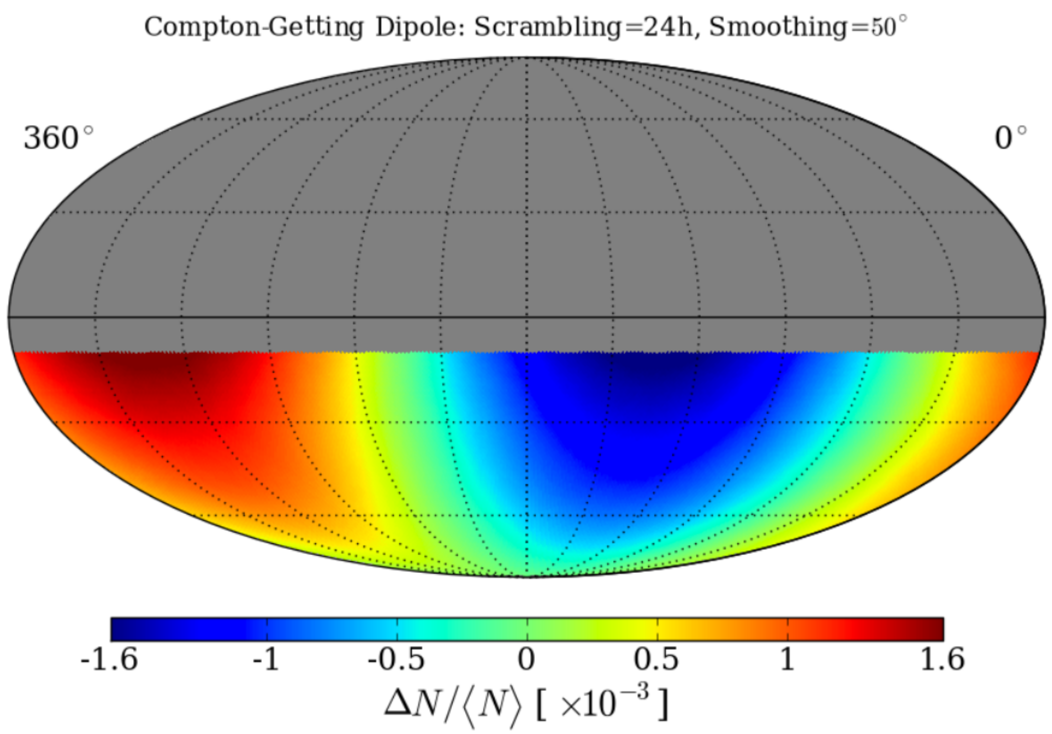
DISCLAIMER



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



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



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

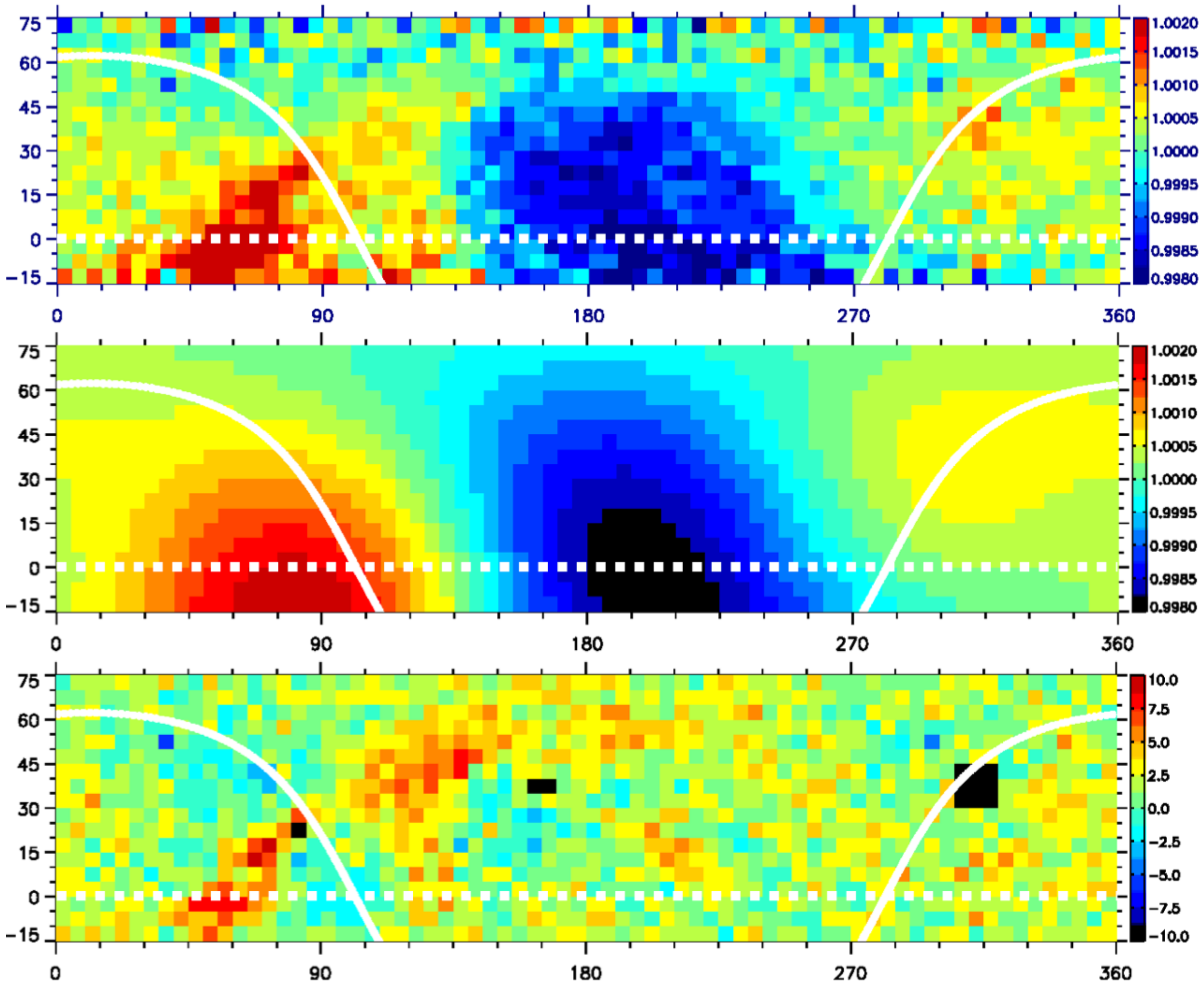
large scale anisotropy

topology

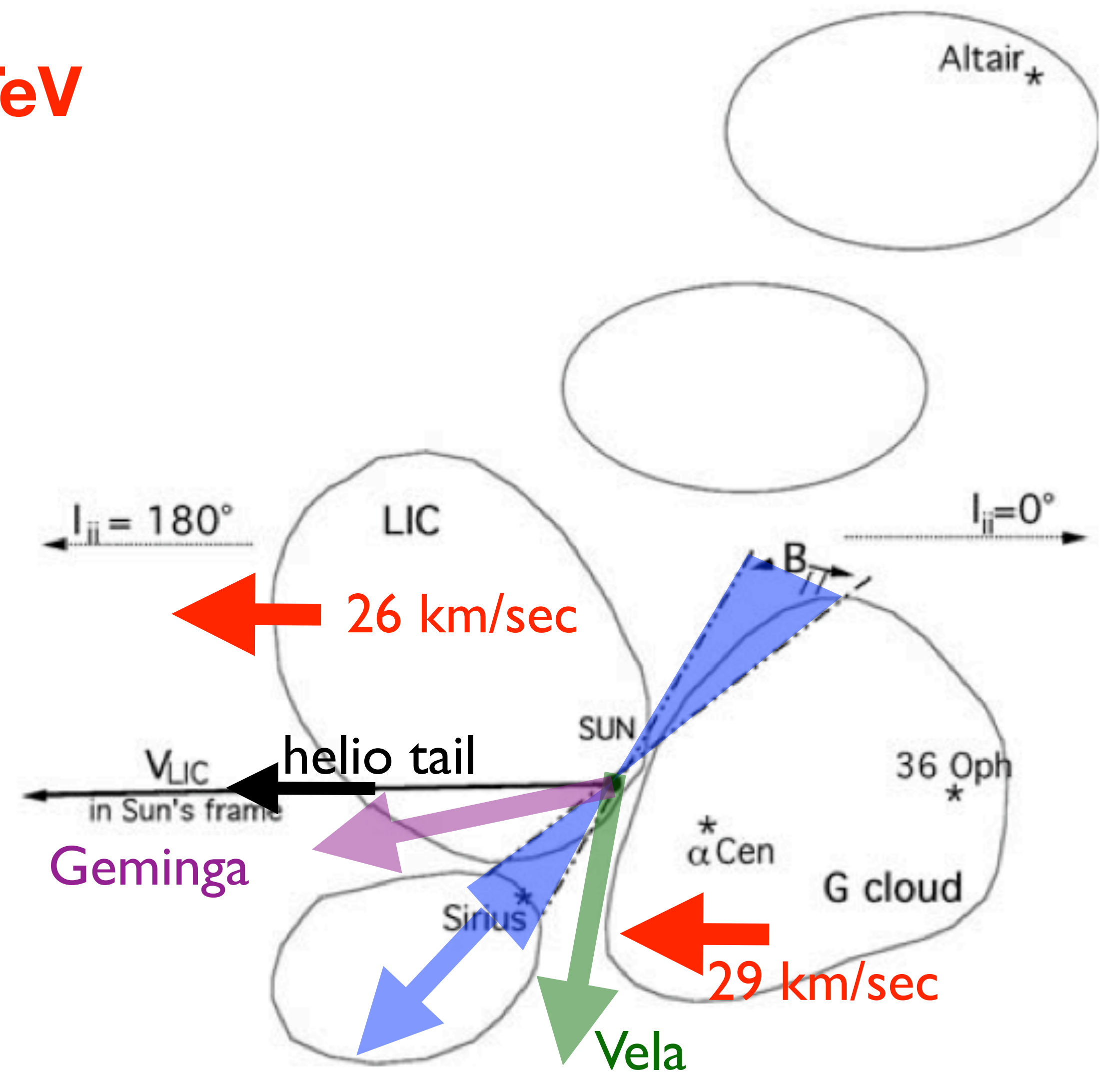
ANISOTROPY IS NOT A DIPOLE

Local Interstellar Medium

Tibet ASγ Amenomori et al., ICRC 2007



4 TeV



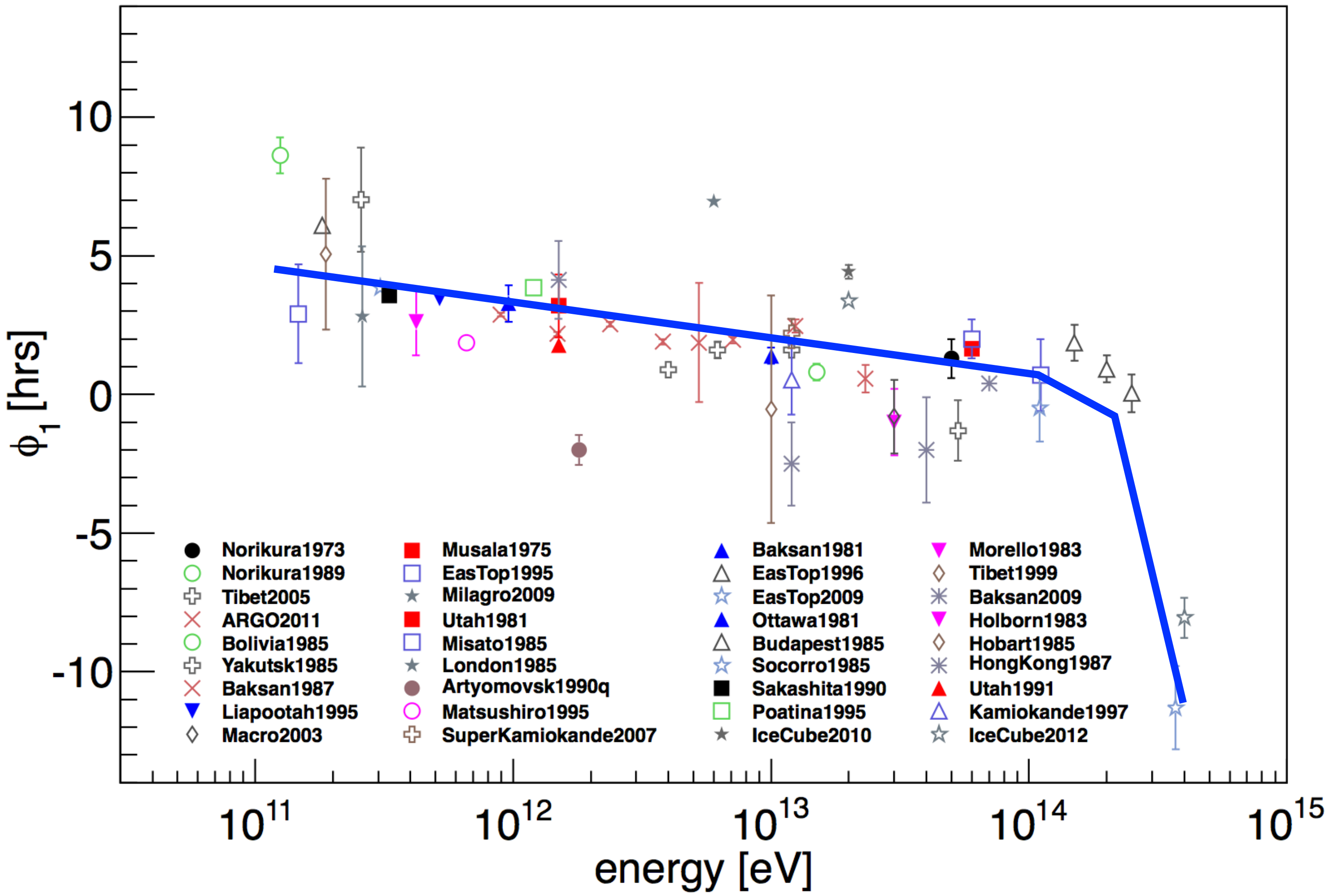
uni-directional (**dipole**) & bi-directional (**quadrupole**) anisotropy from CR density and Local Magnetic Field **gradients**

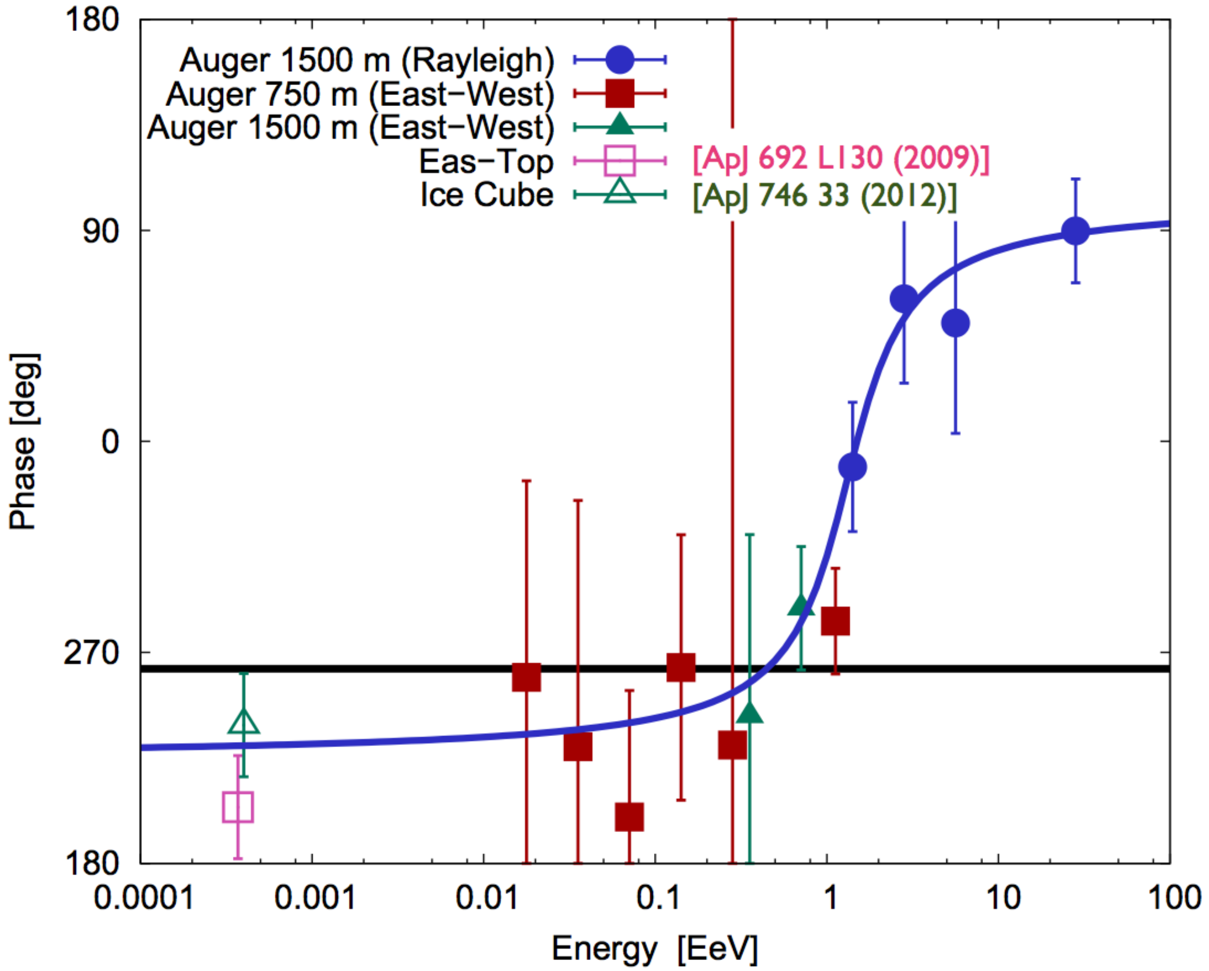
sidereal anisotropy

energy dependency of *dipole* phase

termination shock
inner heliosheath
heliopause, heliotail
local interstellar medium
Loop I superbubble
thickness of Galaxy
extragalactic protons

heliospheric influence **interstellar medium** **extra-galactic**

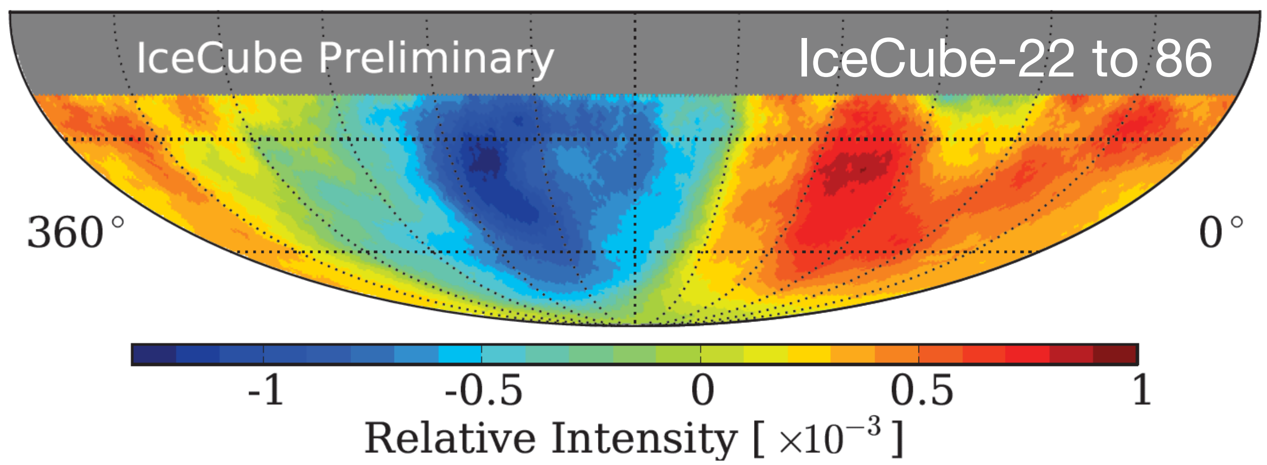




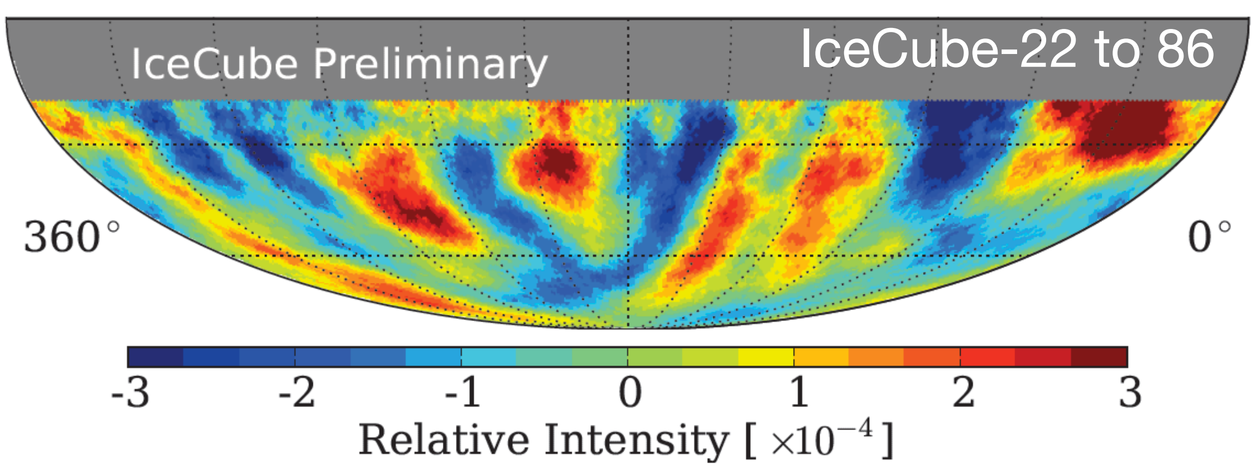
cosmic ray anisotropy
IceCube 2007-2012

PRELIMINARY

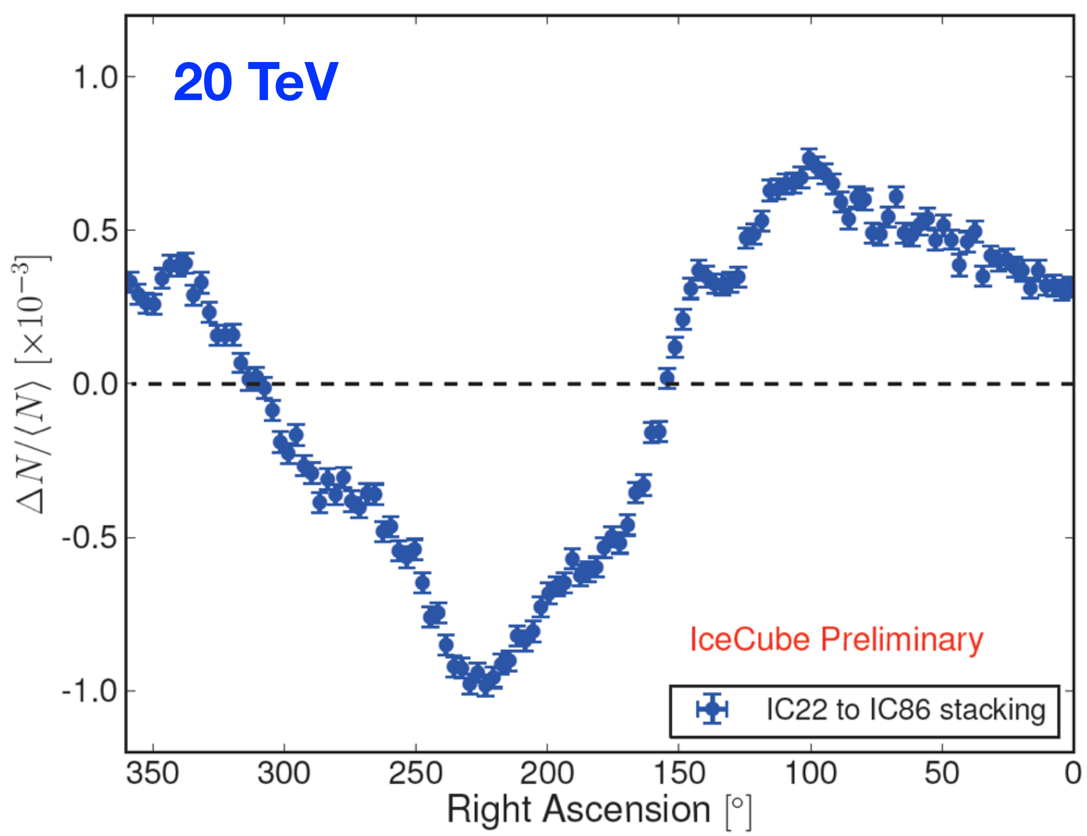
relative intensity — equatorial coordinates



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

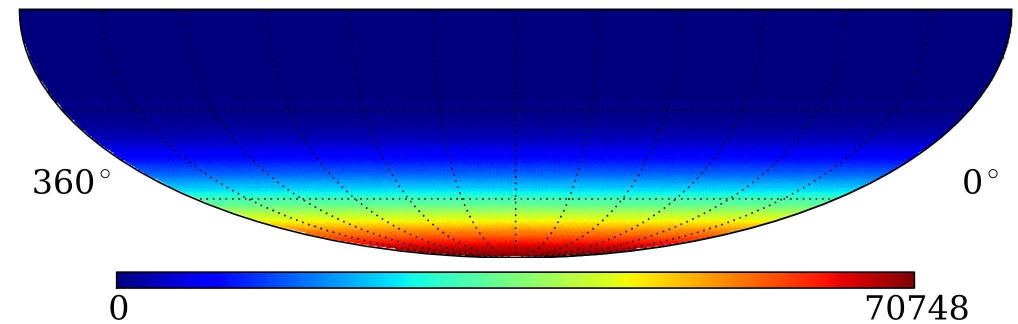


5° smoothing

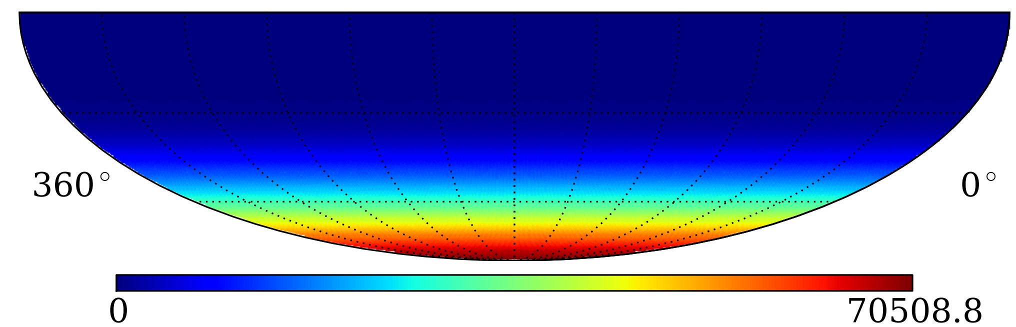


cosmic ray anisotropy *analysis technique*

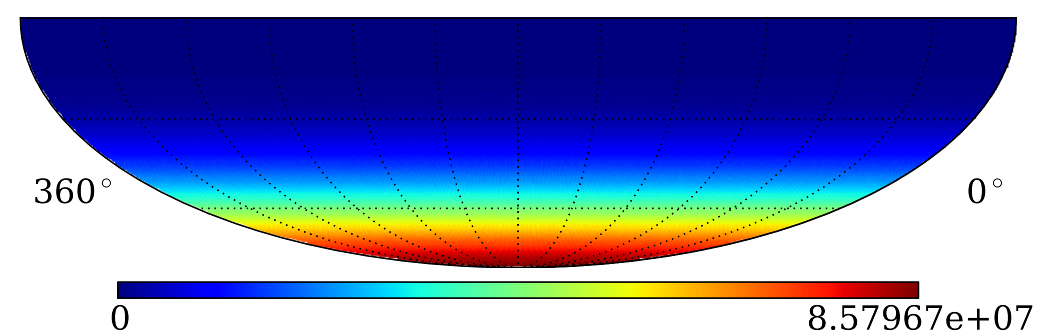
raw map of events in equatorial coordinates $(\alpha,\delta)_i$



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

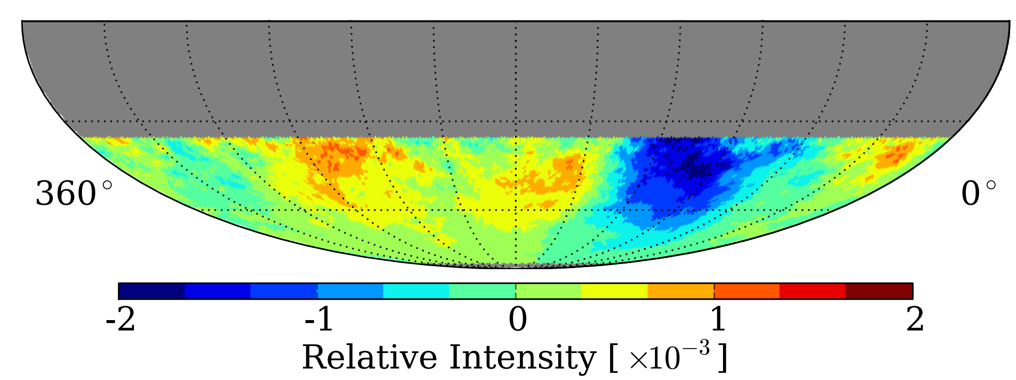


rebin raw and reference maps to enhance inter-bin correlations



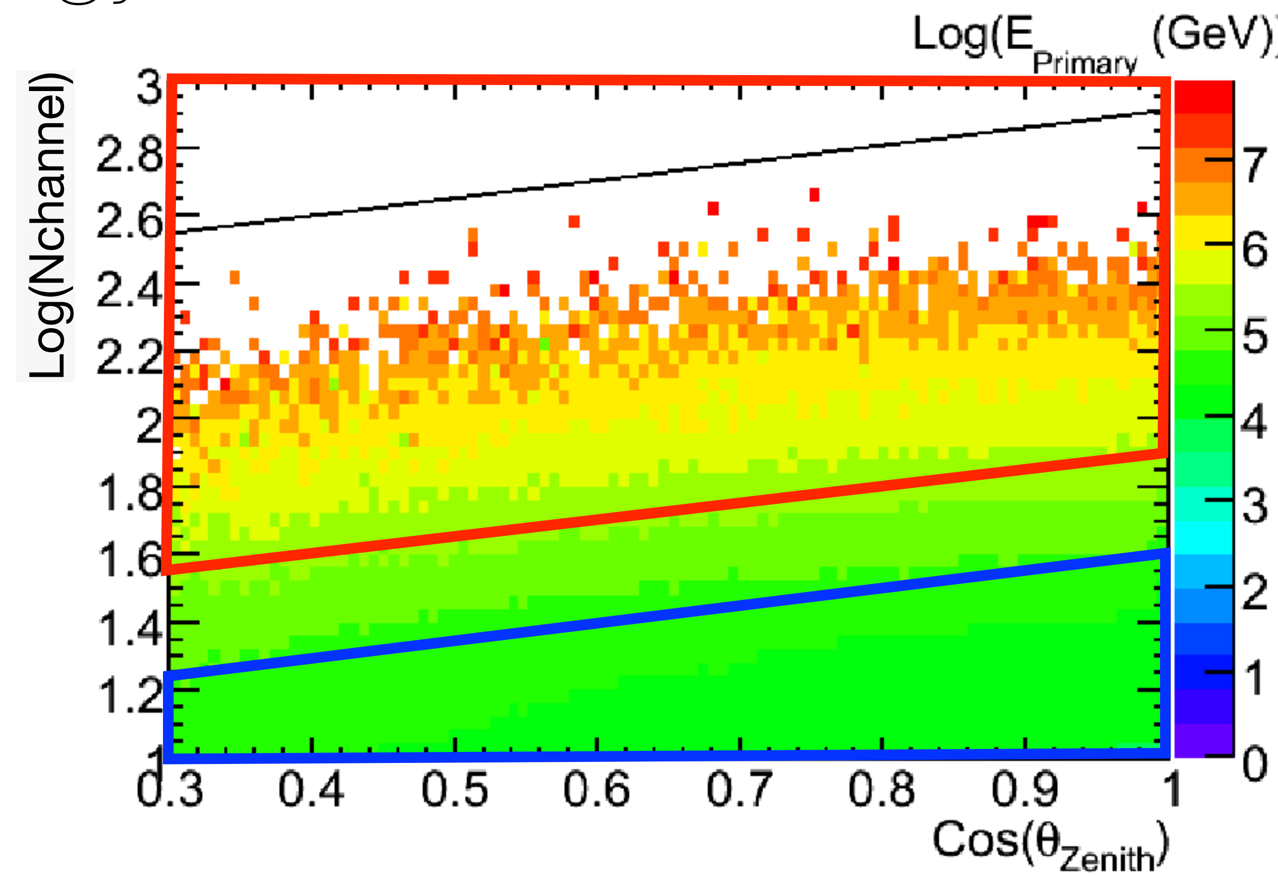
subtract reference map from raw map to determine the residual *relative intensity* map

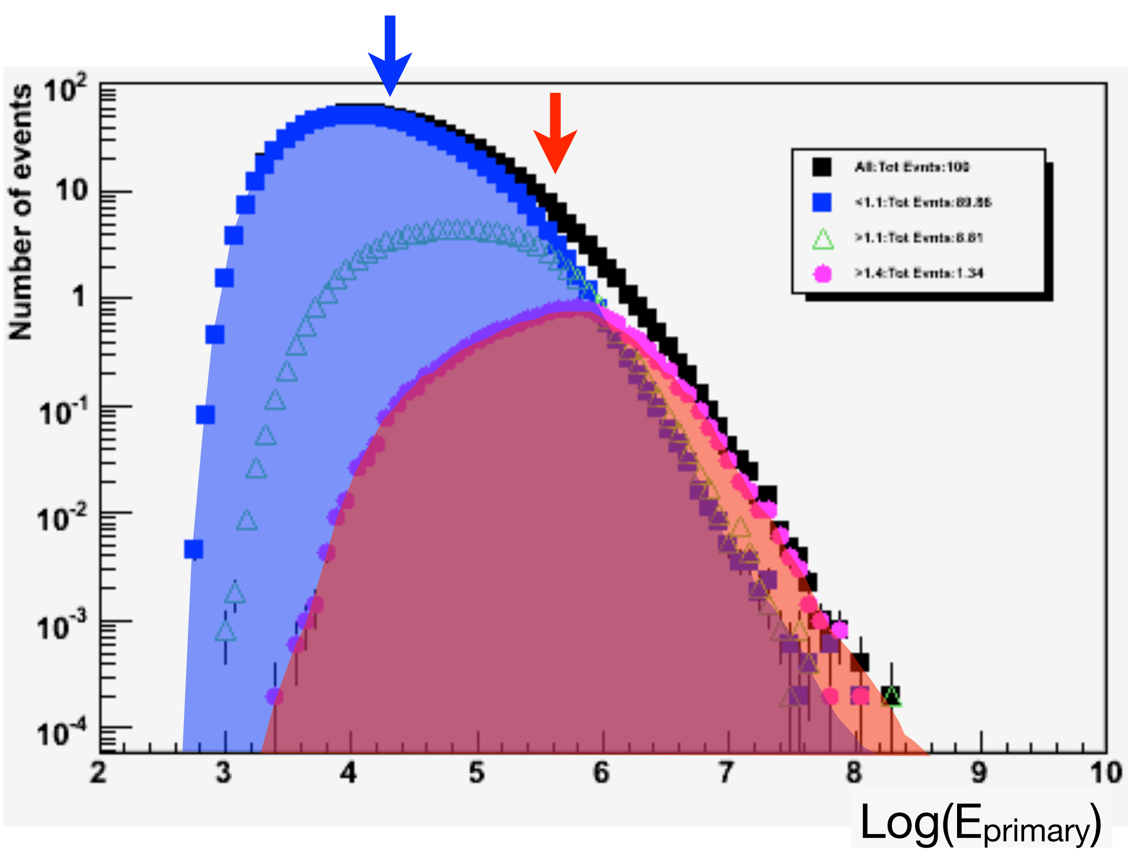
$$\frac{\Delta I}{\langle I \rangle} = \frac{N_i - \langle N \rangle}{\langle N \rangle}$$

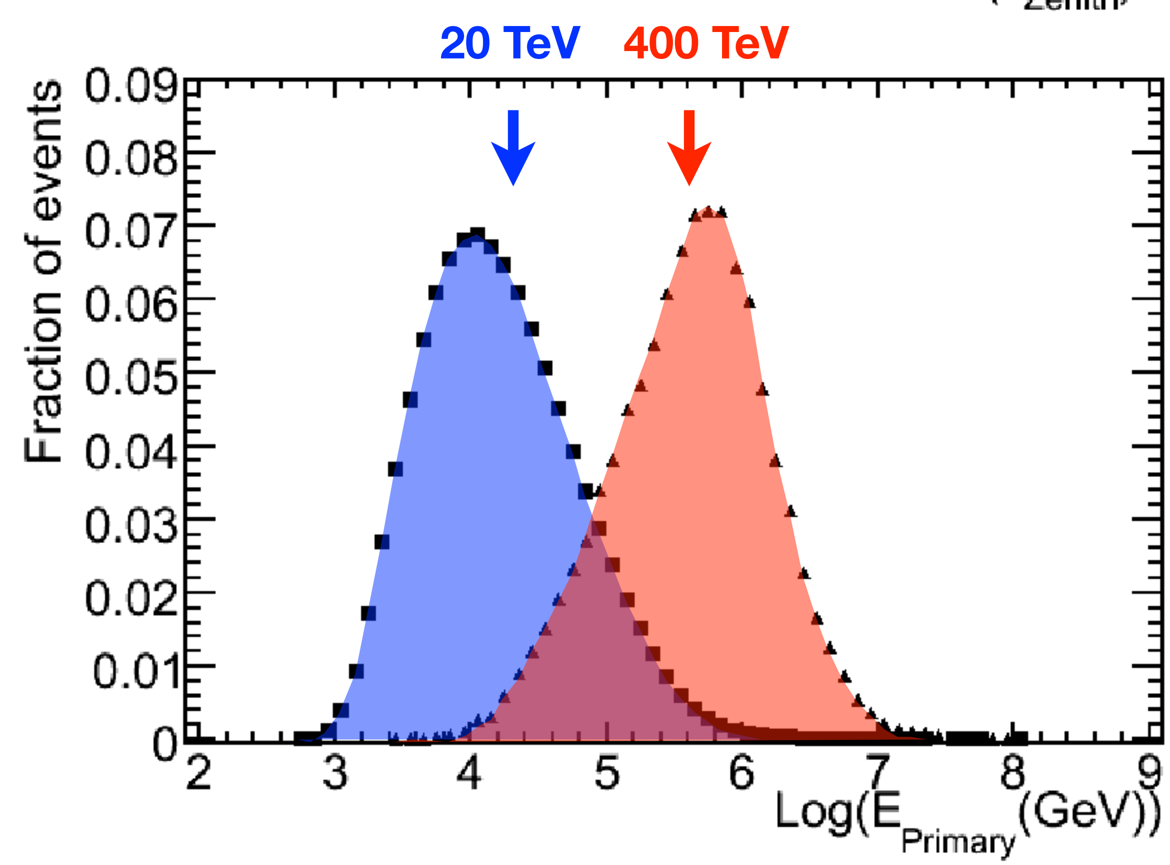


cosmic ray anisotropy *energy selection*

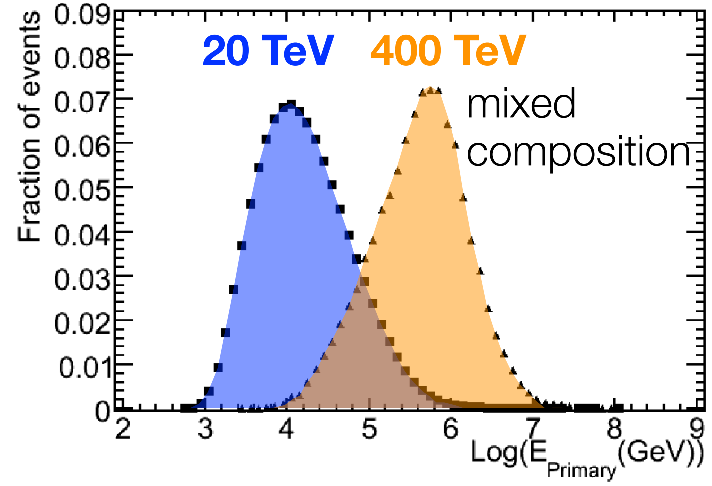
IceCube



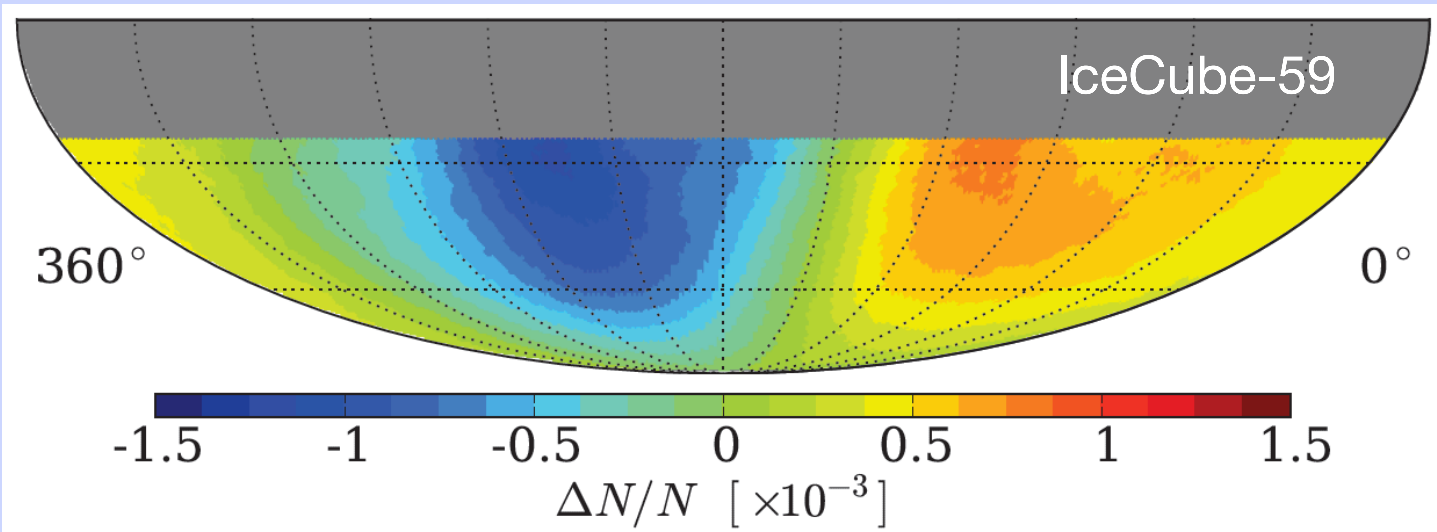




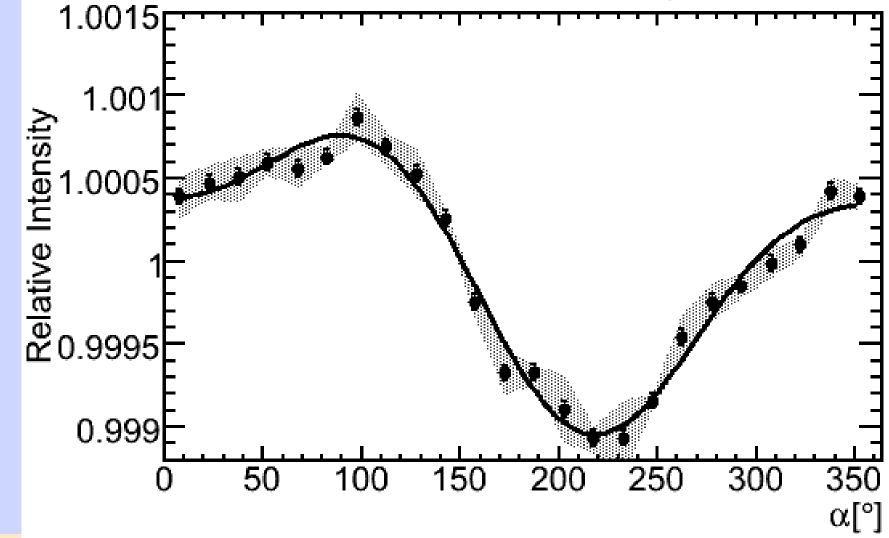
cosmic ray anisotropy large scale IceCube

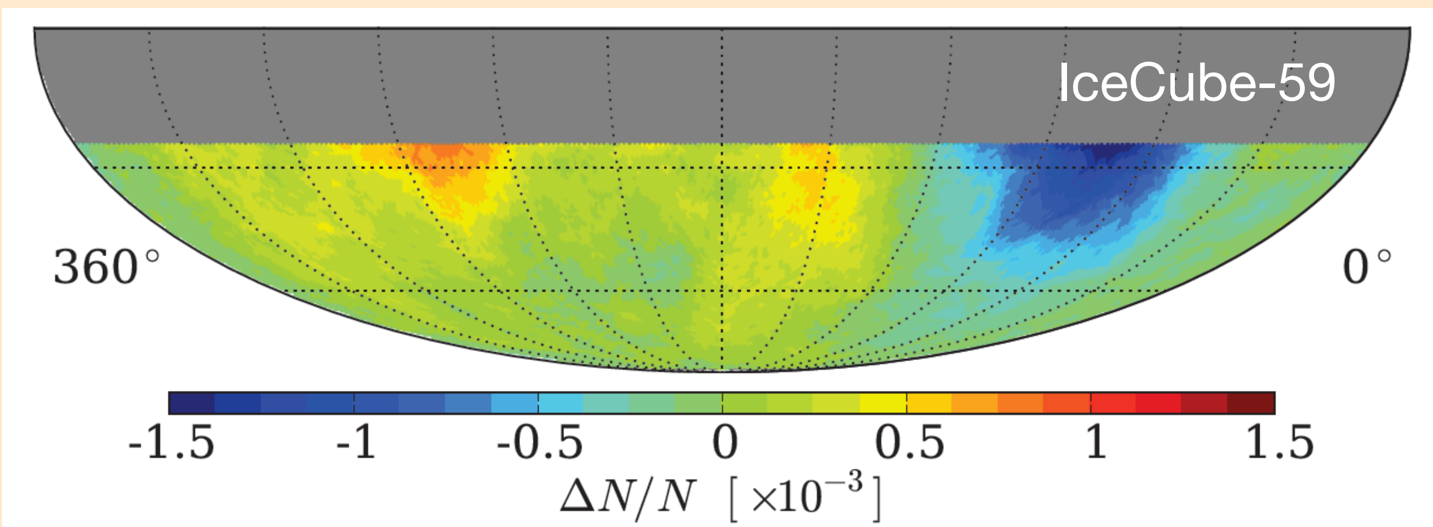


relative intensity equatorial coordinates



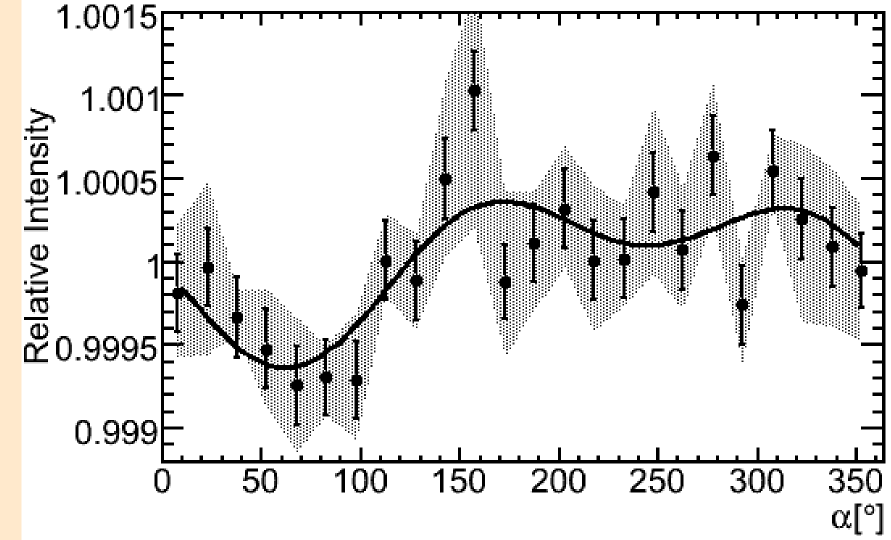
20 TeV





400 TeV

deficit
6.3 σ_{post}

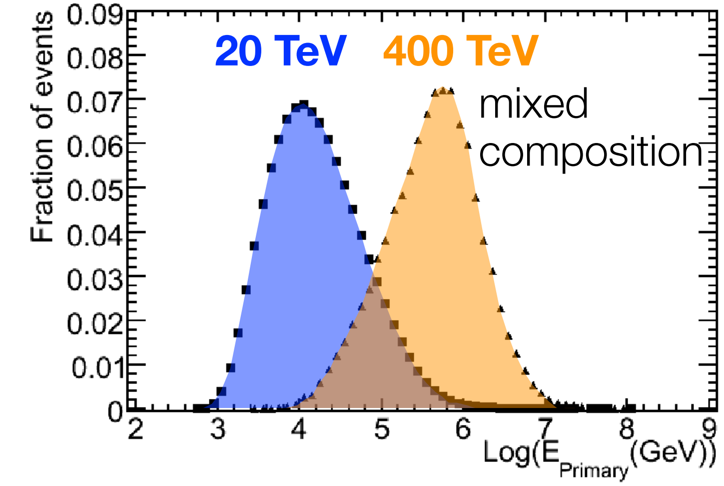


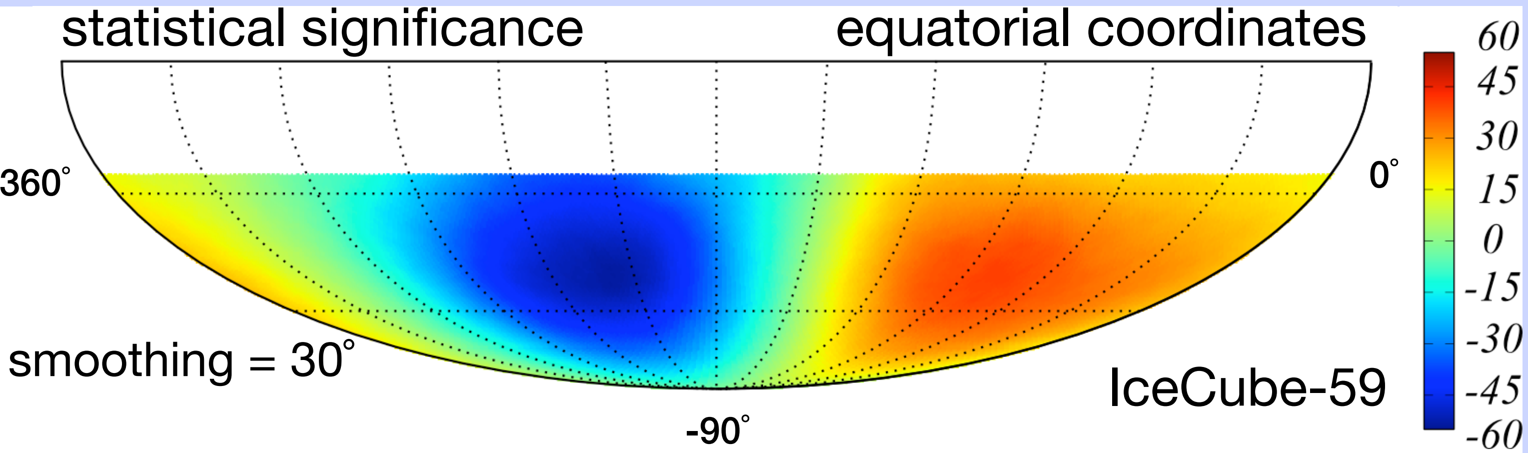
NOTE: anisotropy is not a dipole
topology changes at high energy

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

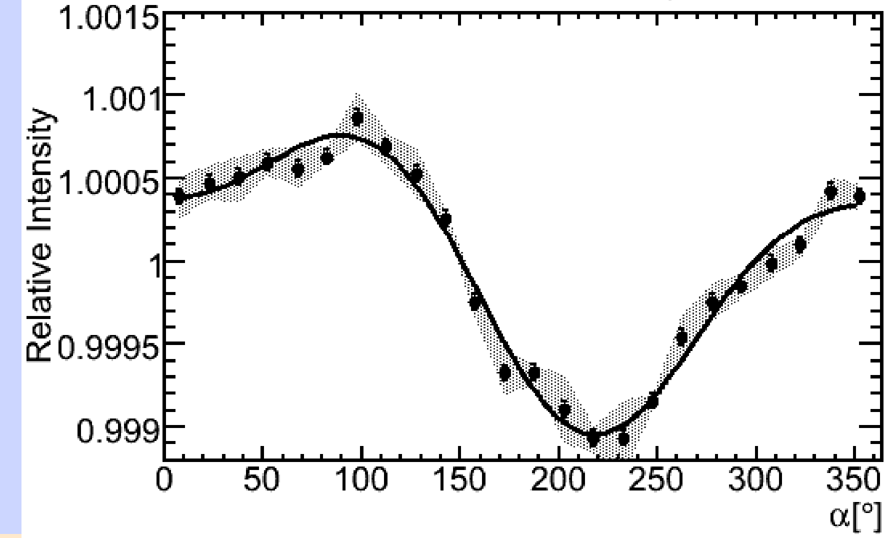
IC22 Abbasi et al., ApJ, **718**, L194, 2010

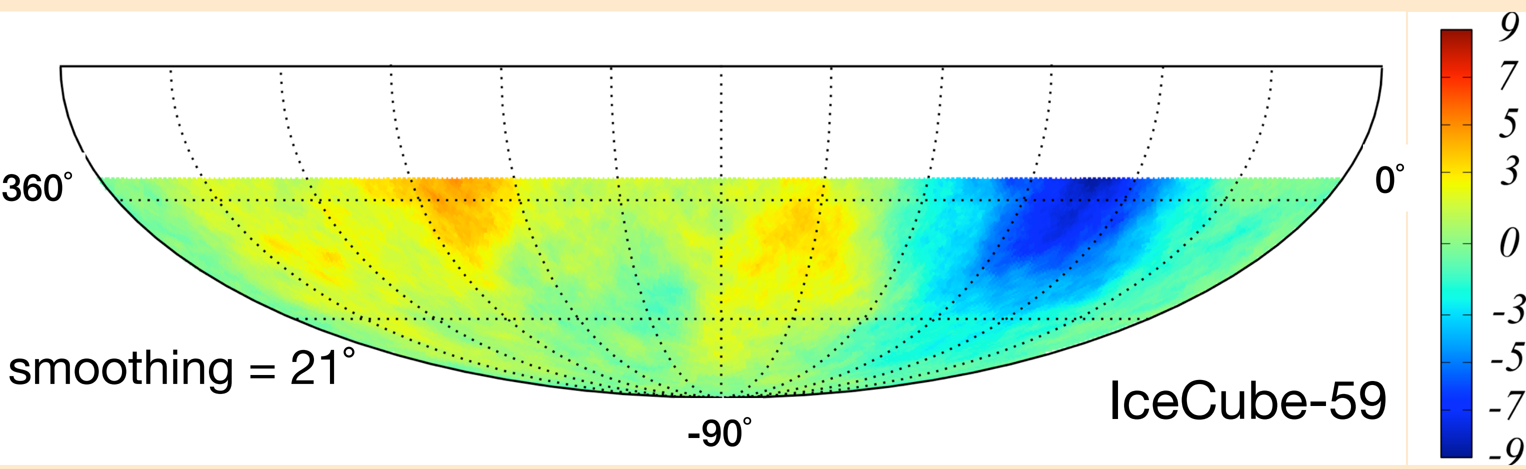
cosmic ray anisotropy large scale IceCube





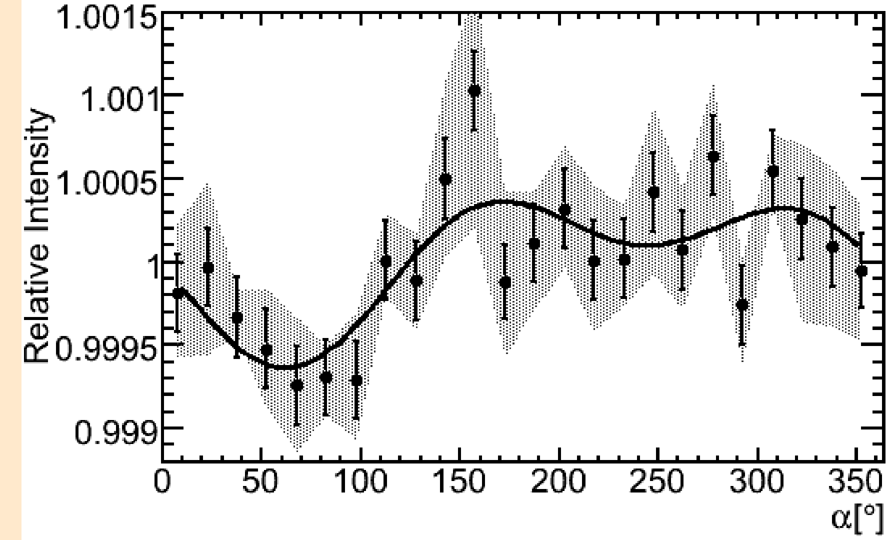
20 TeV





400 TeV

deficit $6.3\ \sigma_{post}$



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

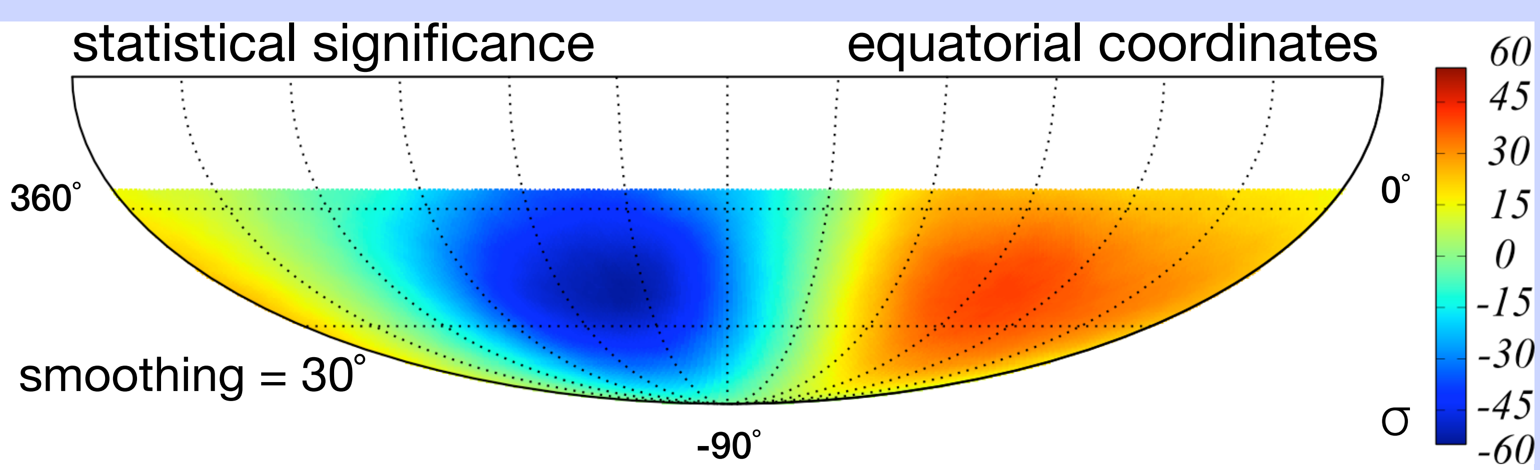
X

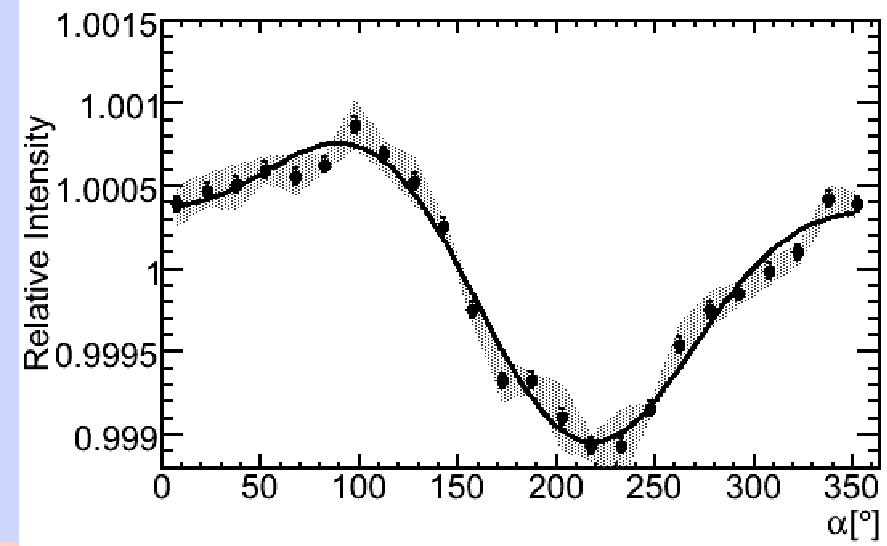
cosmic ray anisotropy vs energy in IceCube-59

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

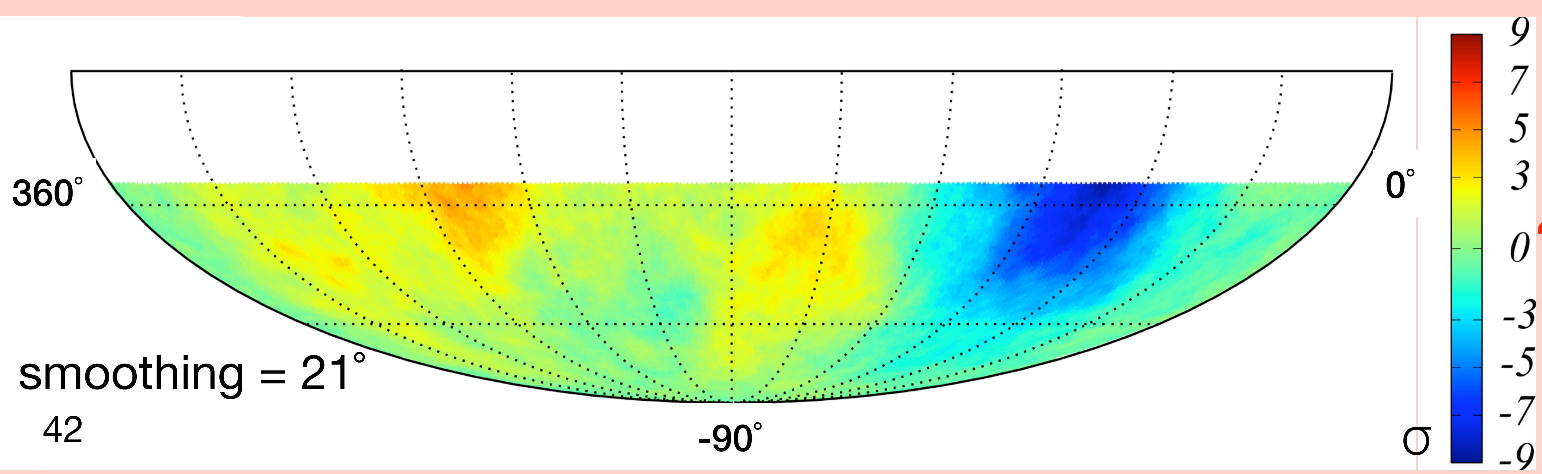
$$s = \sqrt{2}\left\{N_{\rm on}\ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\rm on}}{N_{\rm on}+N_{\rm off}}\right)\right] + N_{\rm off}\ln\left[(1+\alpha)\left(\frac{N_{\rm off}}{N_{\rm on}+N_{\rm off}}\right)\right]\right\}^{1/2} \quad \alpha = 1/20$$

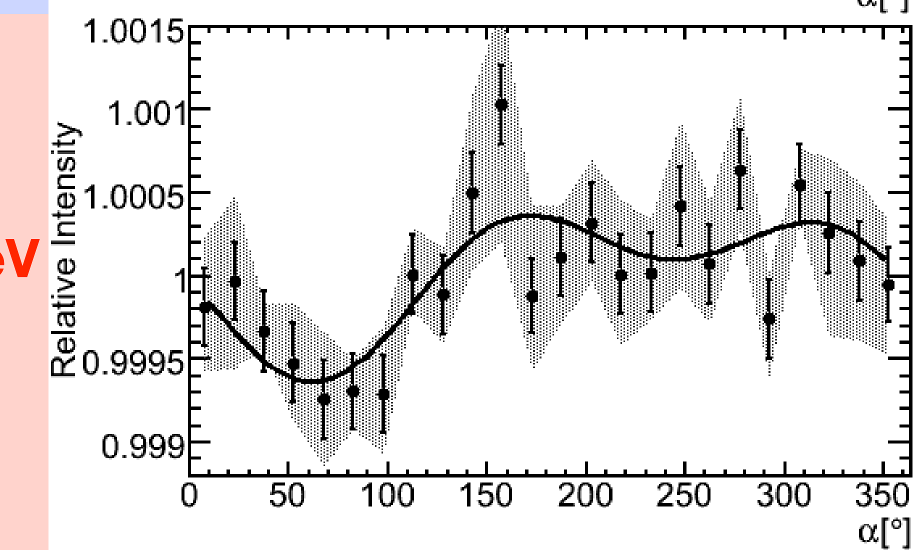
Li, T., & Ma, Y. 1983, ApJ, 272, 317

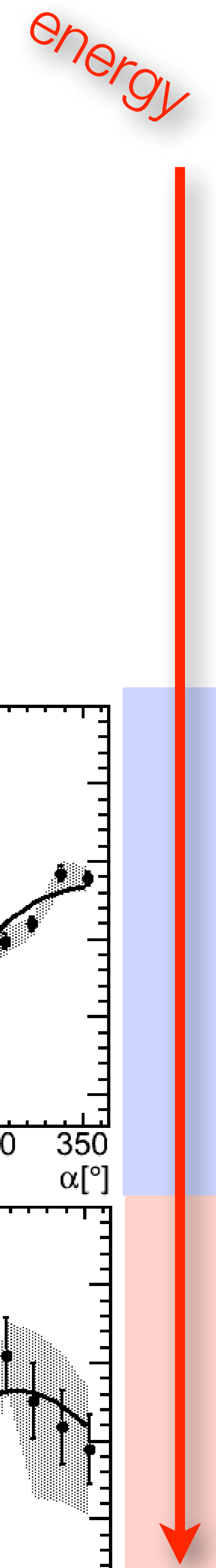




Abbasi et al., ApJ, **746**, 33, 2012

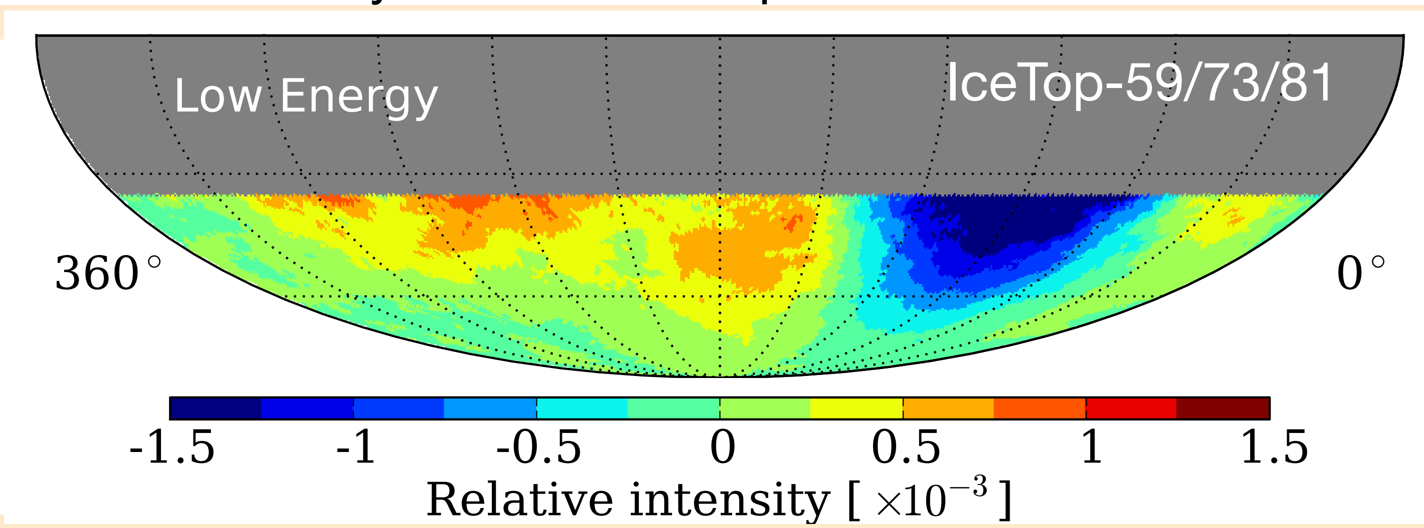






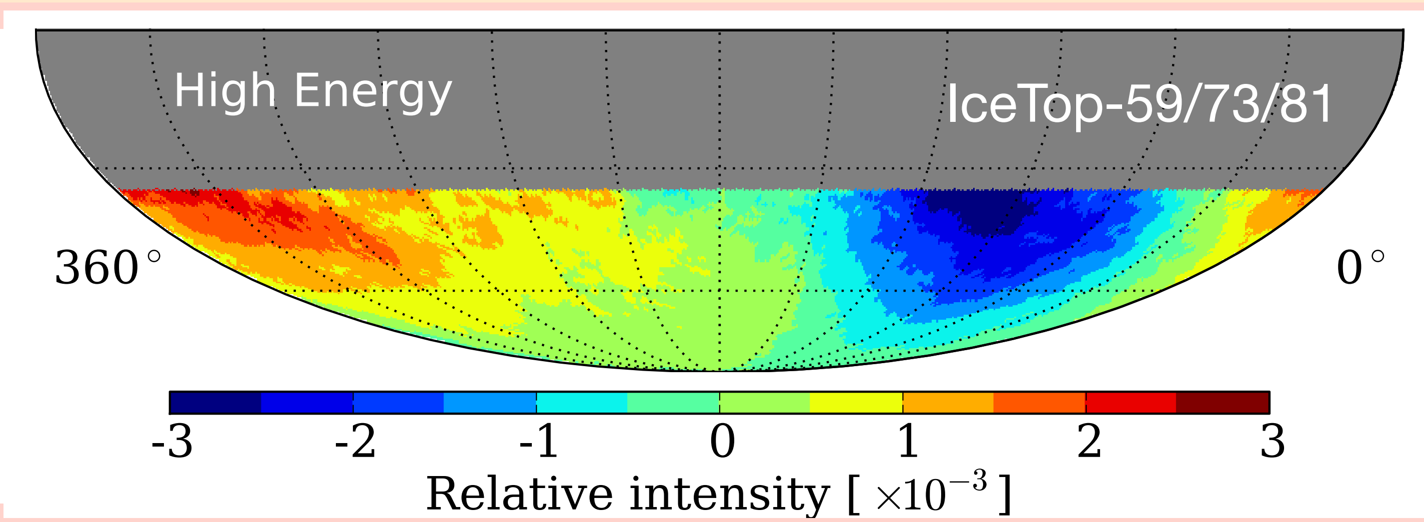
cosmic ray anisotropy large scale
IceTop

relative intensity   equatorial coordinates



deficit
7 σ_{post}

400 TeV



2 PeV

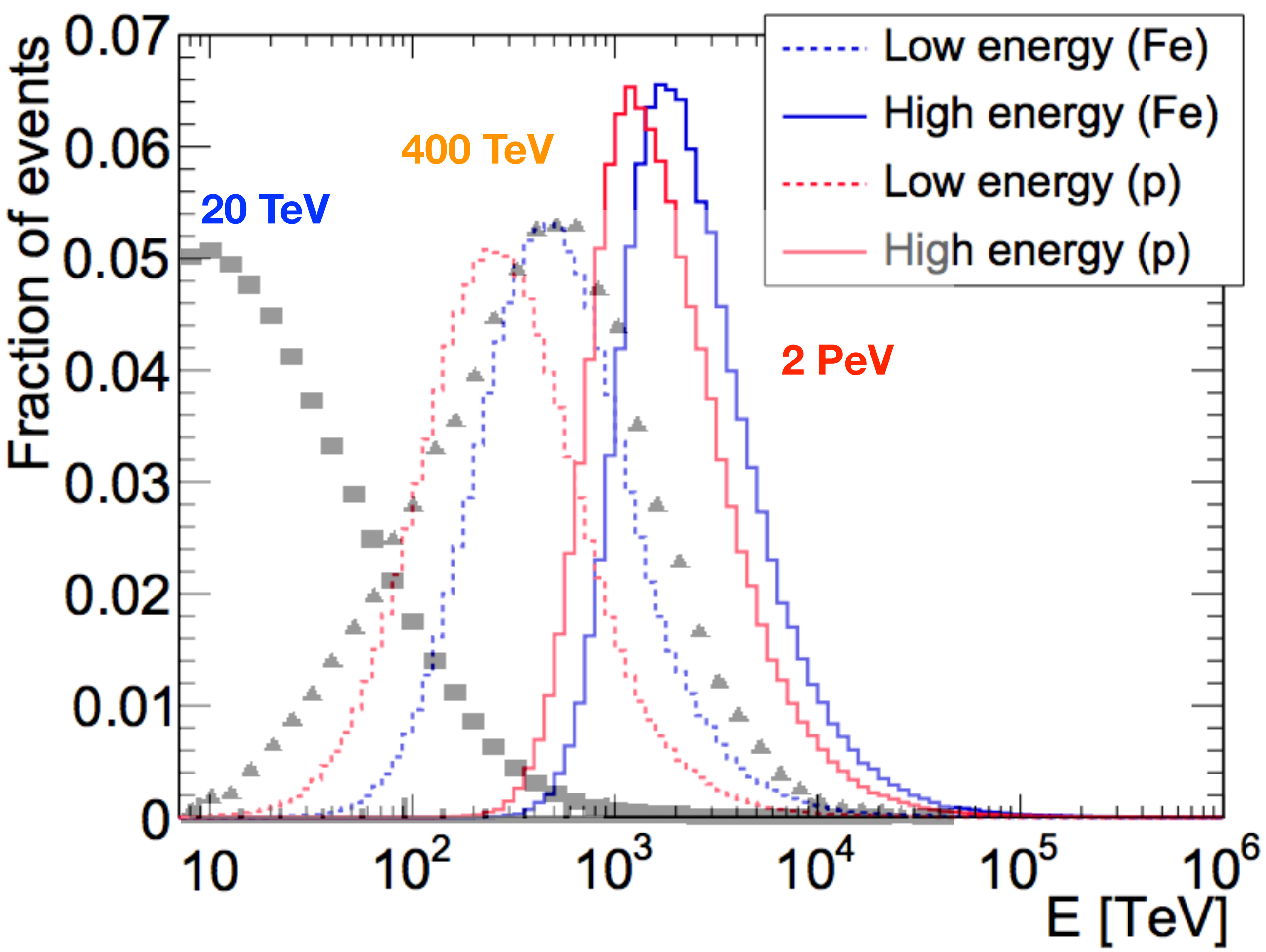
Aartsen et al., ApJ, **765**, 55, 2013

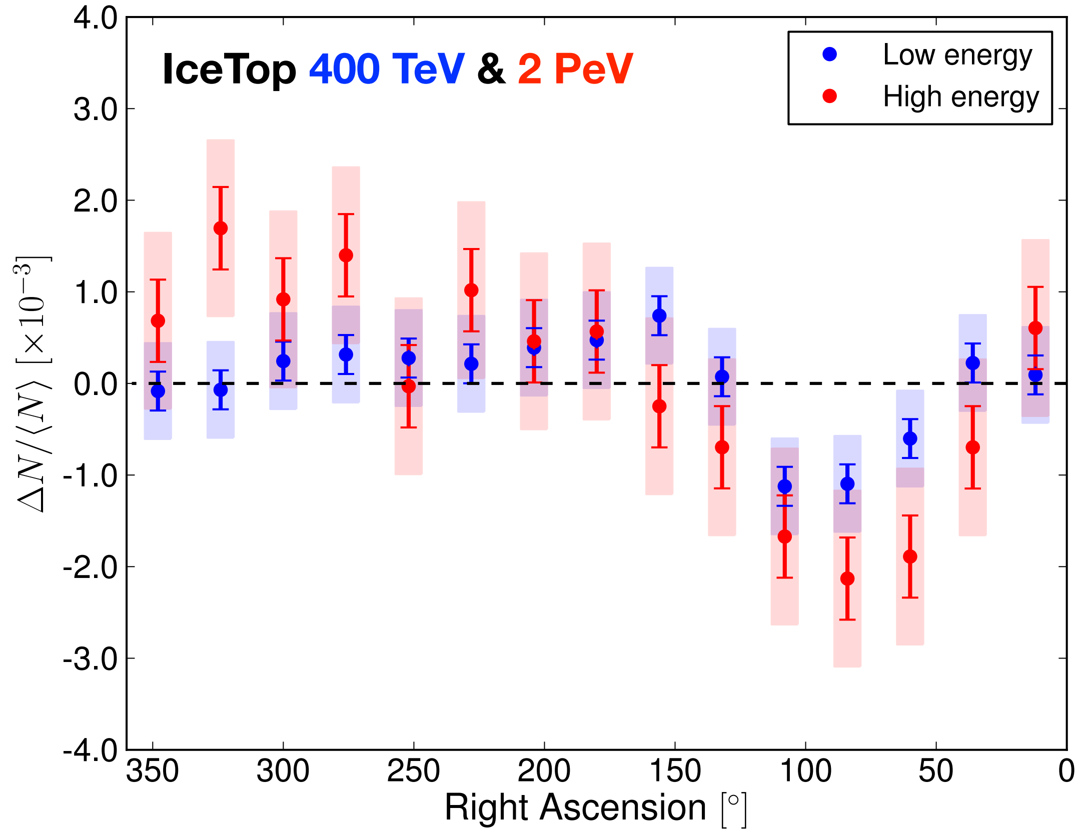
NOTE: global topology does not change

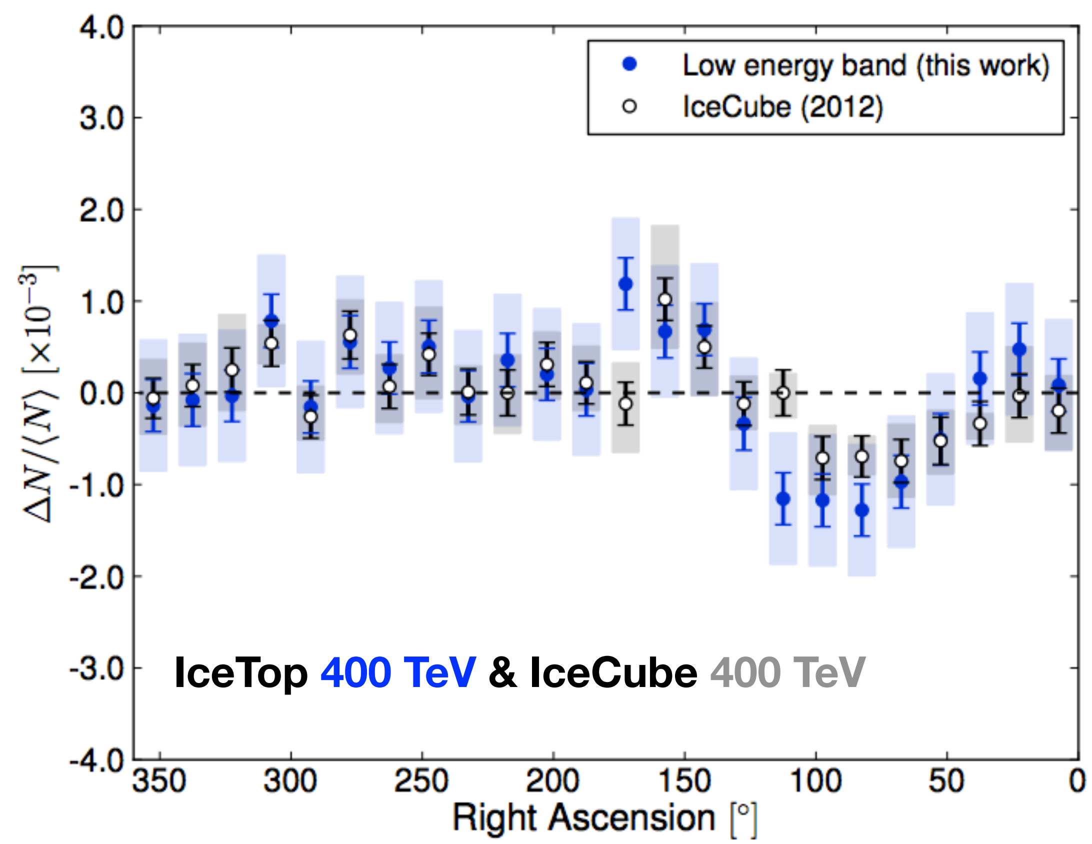
deficit amplitude increases with energy

cosmic ray anisotropy large scale
IceCube & IceTop

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





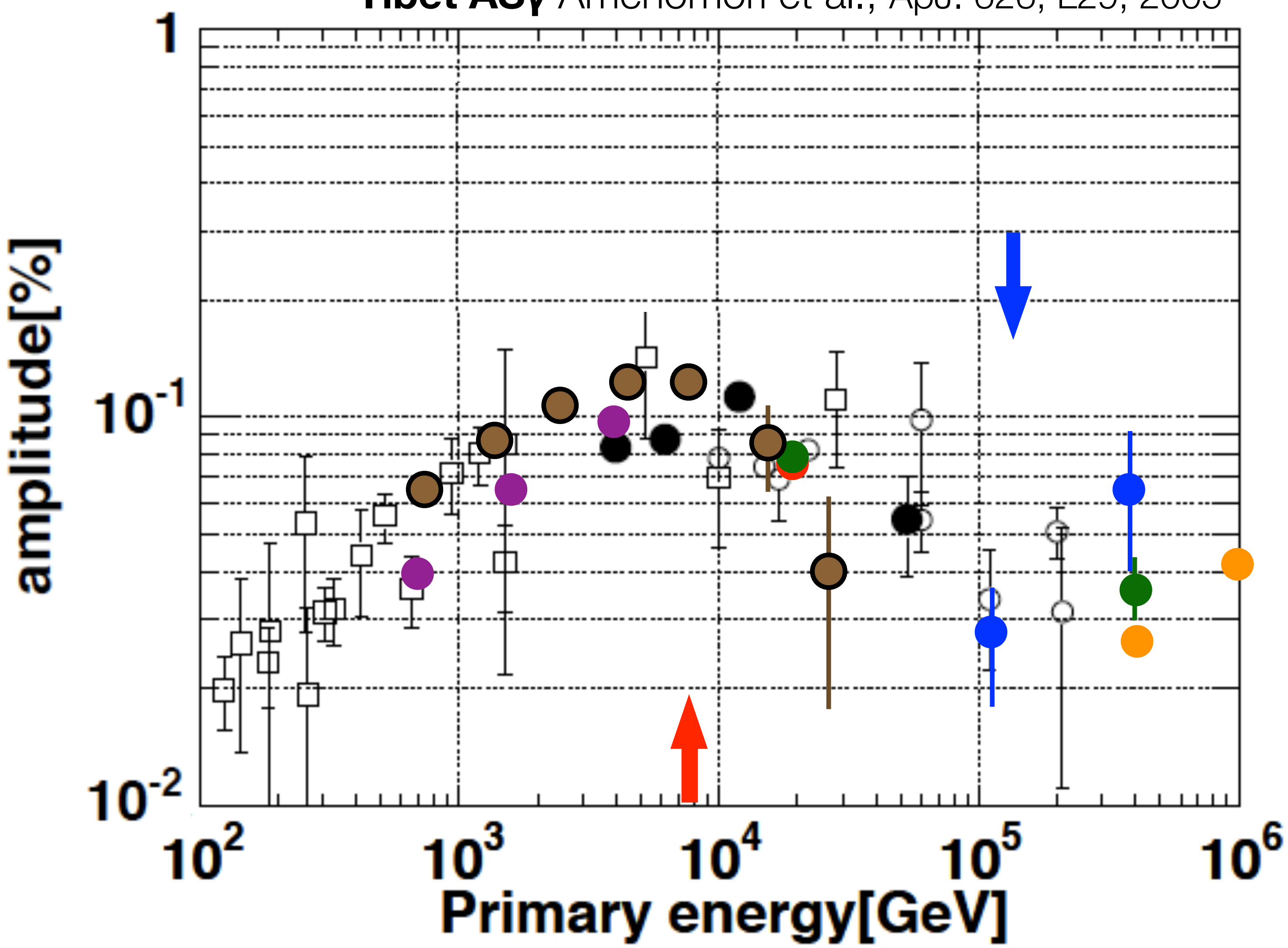


NOTE: different energy response distribution

IceTop with *sharper* low energy threshold

might explain IC/IT amplitude differences

cosmic ray anisotropy large scale
energy dependency



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

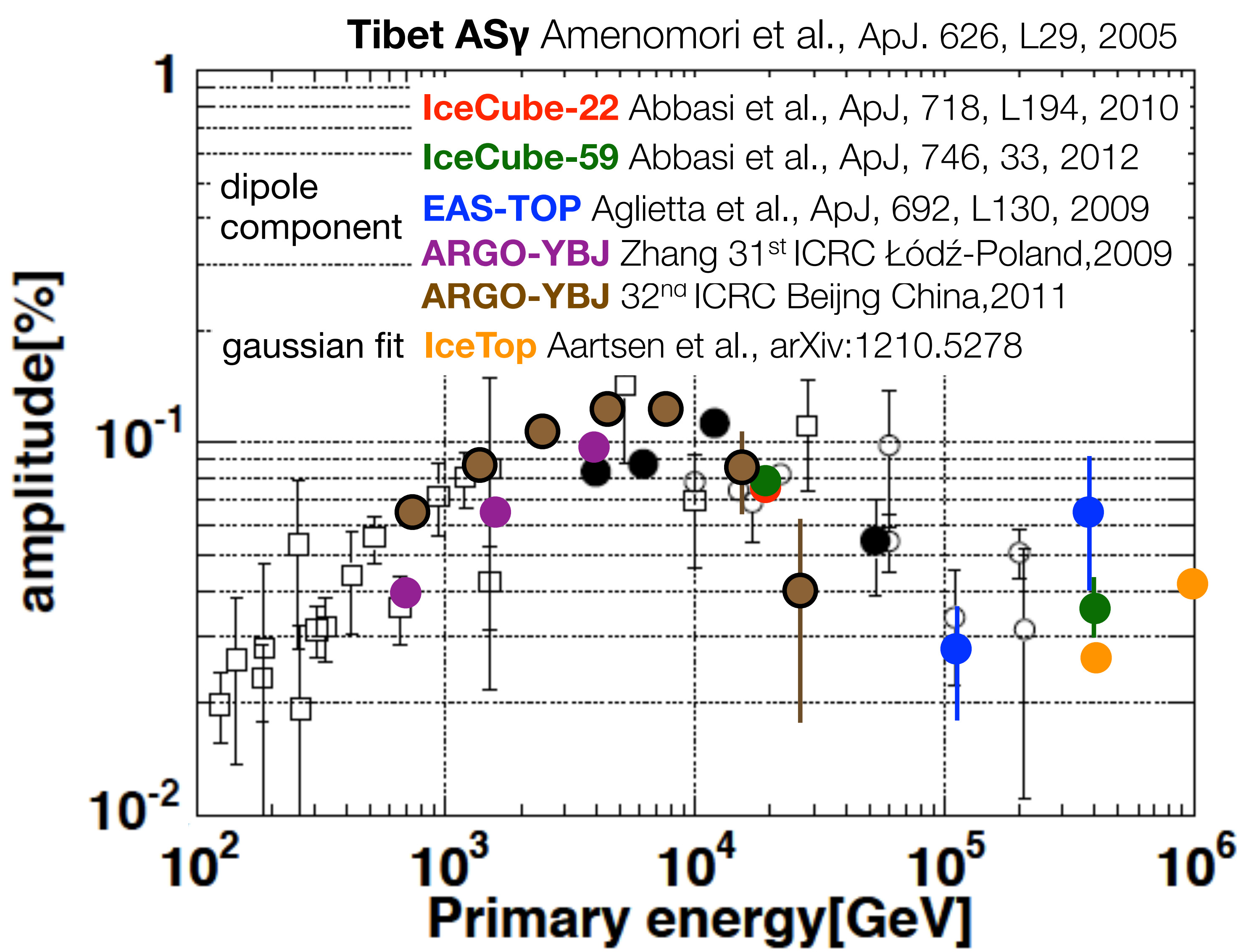
ARGO-YBJ Zhang 31st ICRC Łódź-Poland,2009

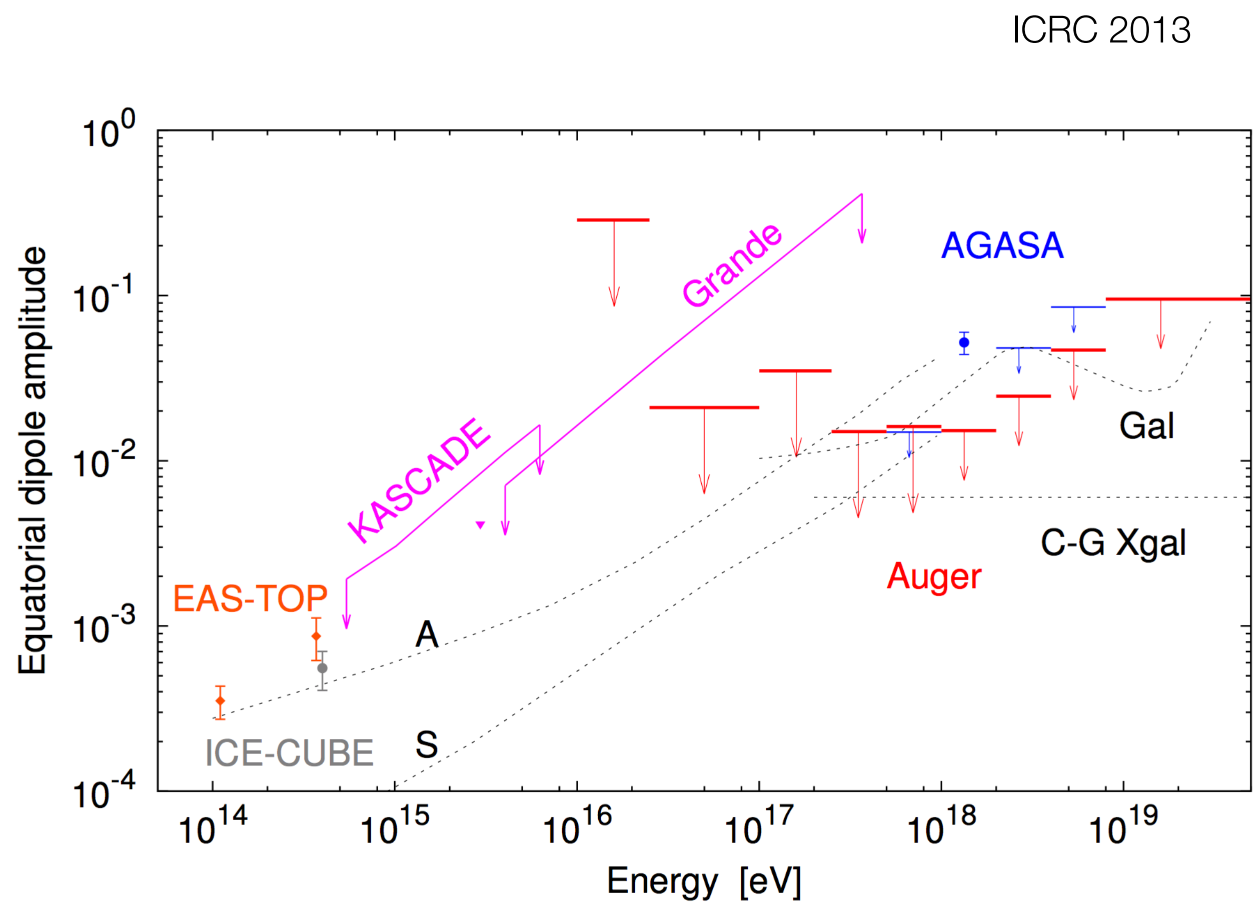
ARGO-YBJ 32nd ICRC Beijng China,2011

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

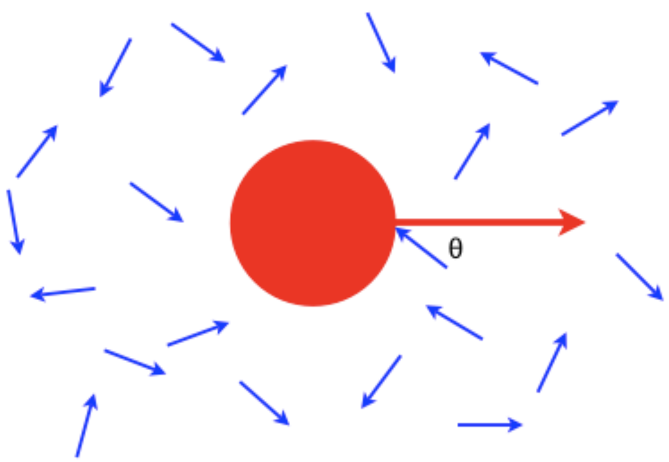




a known anisotropy

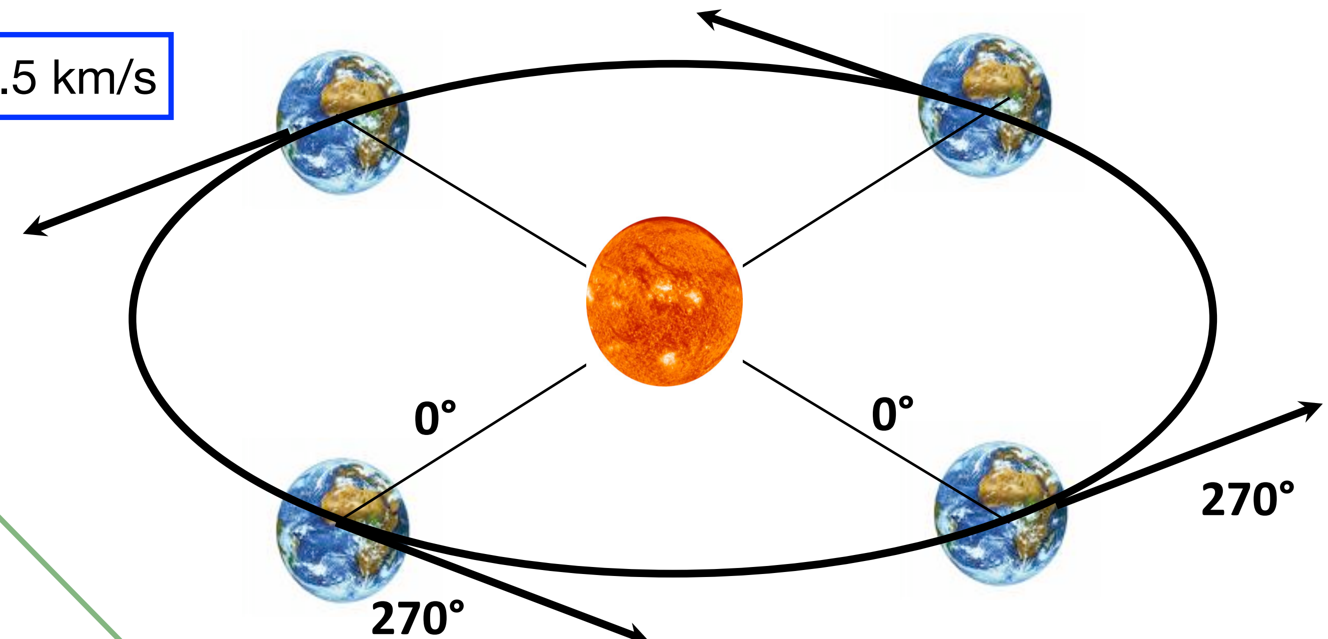
Earth's motion around the Sun

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

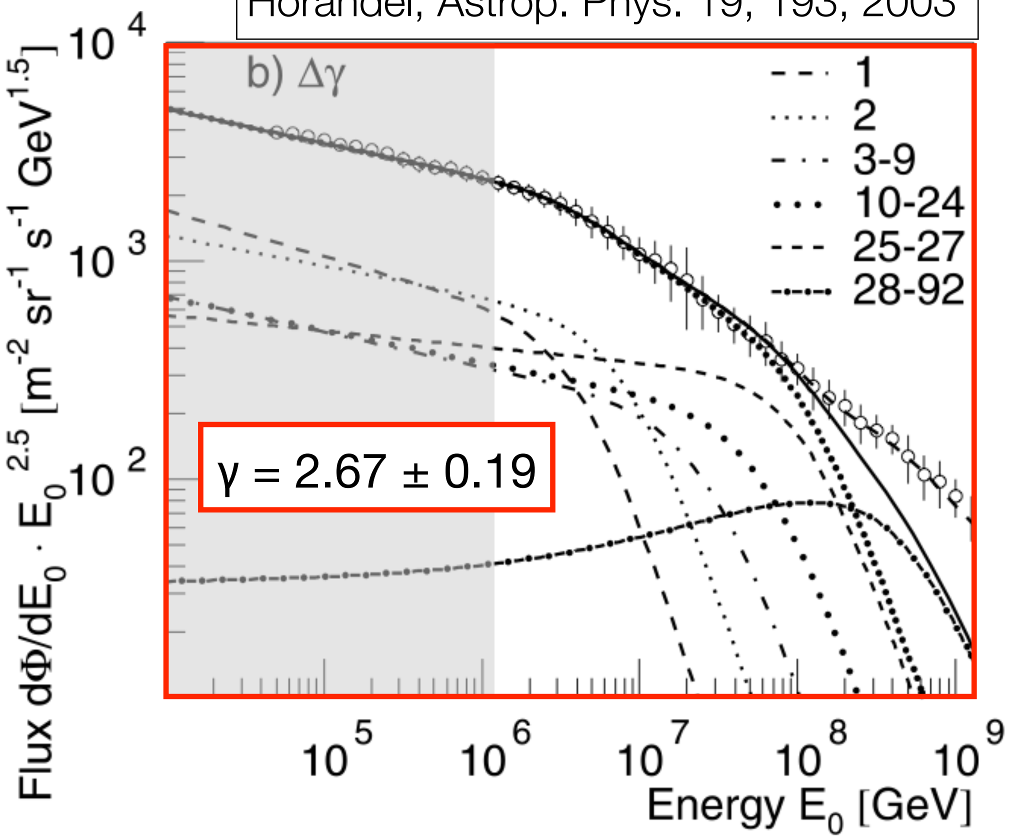


v = 29.8 ± 0.5 km/s

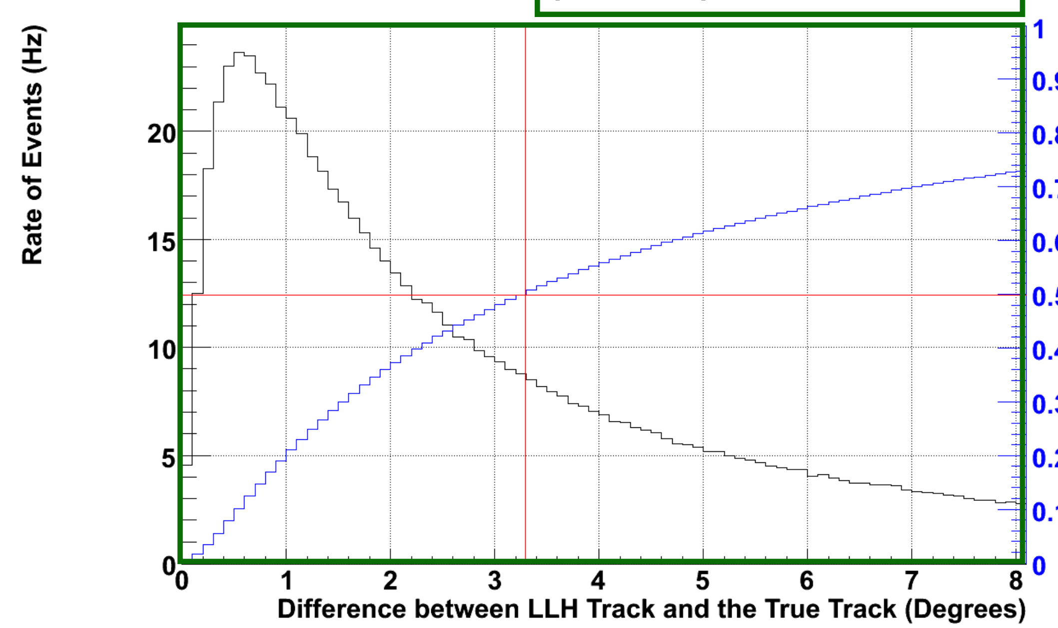
$$\frac{\Delta I}{I} = (\gamma + 2)\frac{v}{c}\cos\theta$$



Hörandel, Astrop. Phys. 19, 193, 2003



point spread function



a known anisotropy
Earth's motion around the Sun

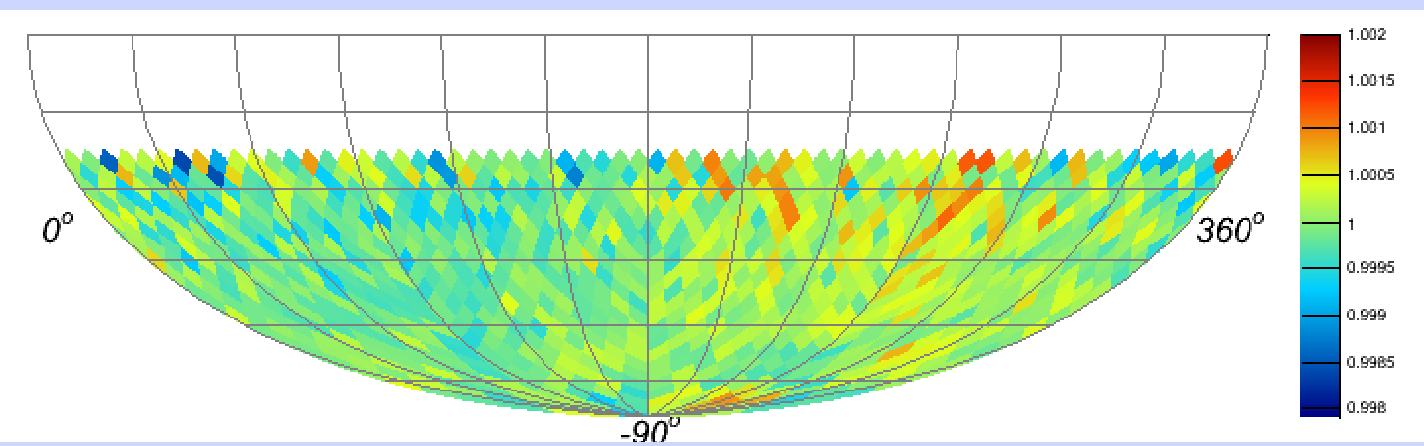
- the observation of the **solar dipole** supports the observation of the sidereal anisotropy in cosmic ray arrival direction

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

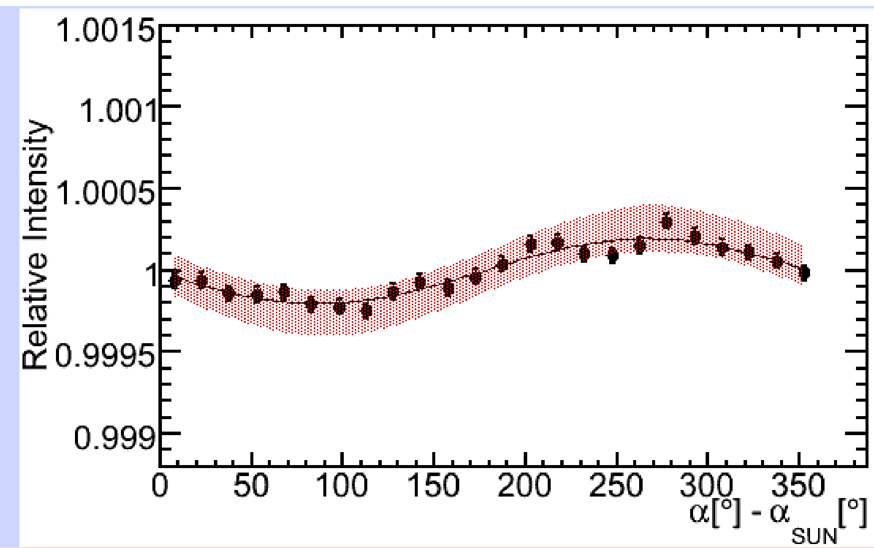
relative intensity

α [°] - α_{SUN} [°]

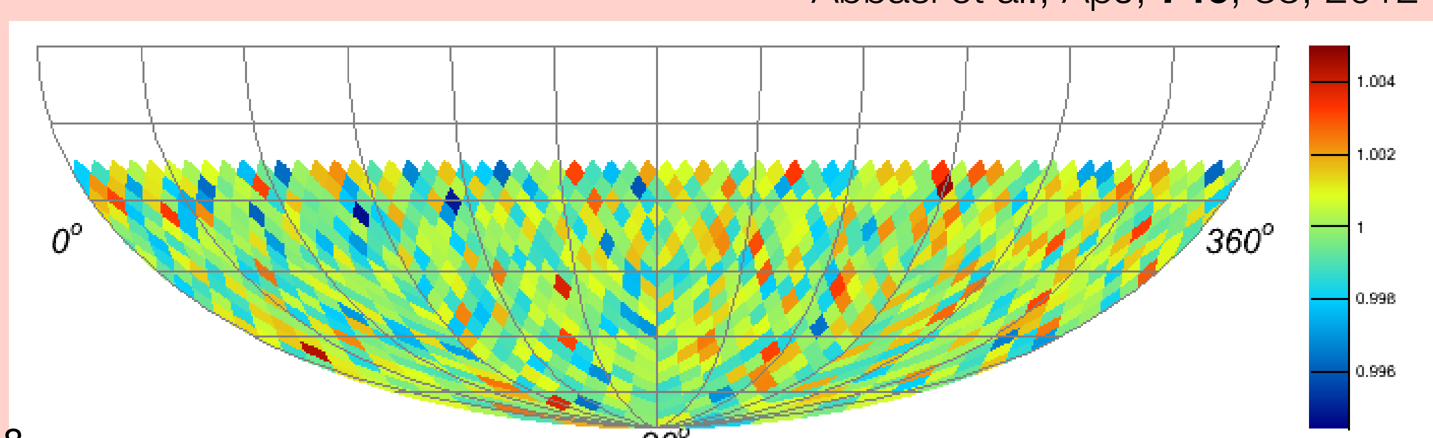
IC59 Abbasi et al., ApJ, **746**, 33, 2012



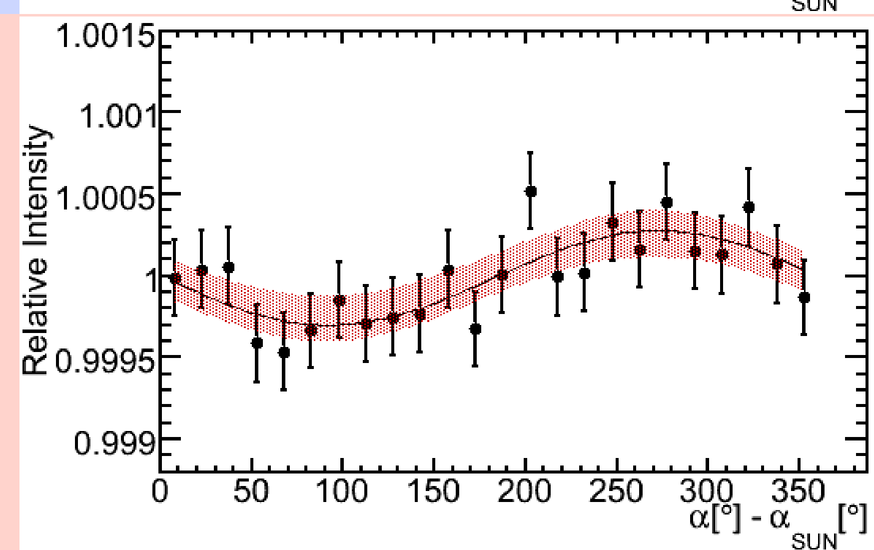
20 TeV



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

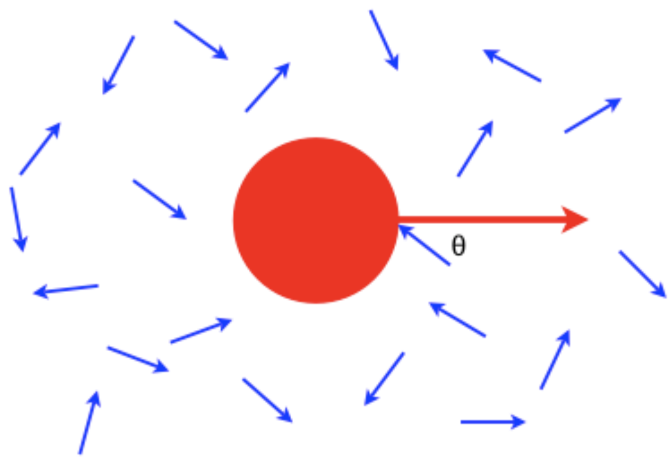


400 TeV



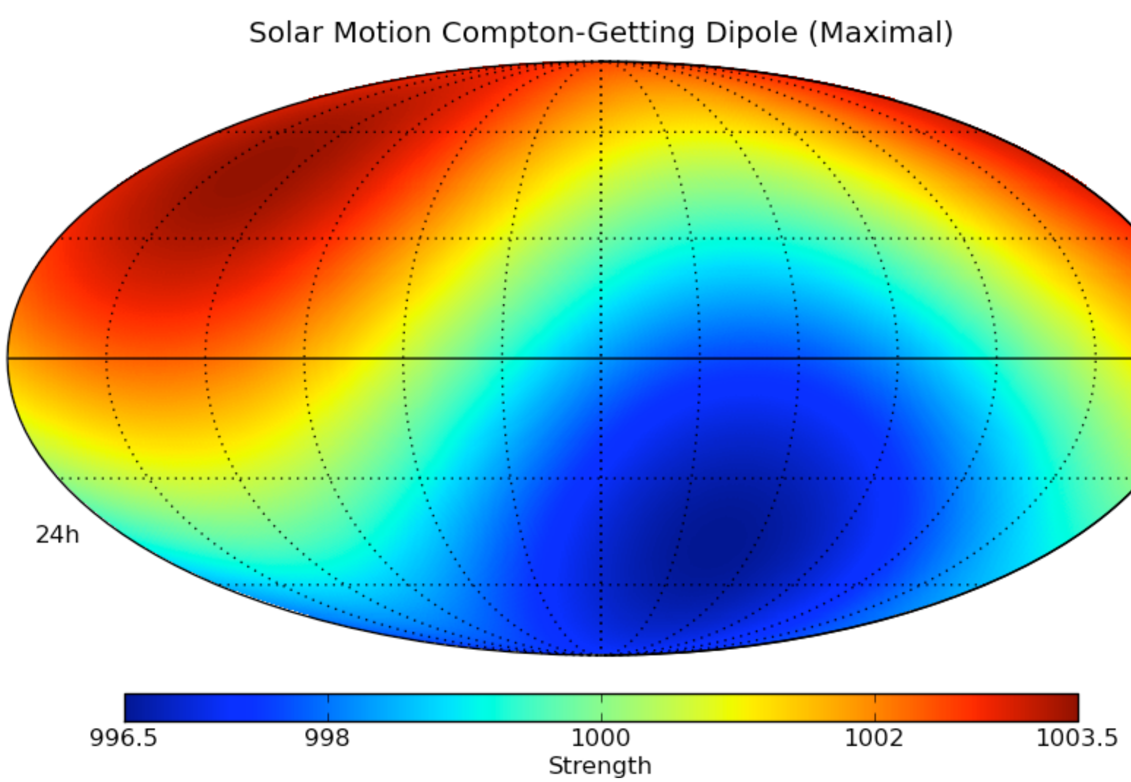
origin of large scale anisotropy : Compton-Getting Effect ?

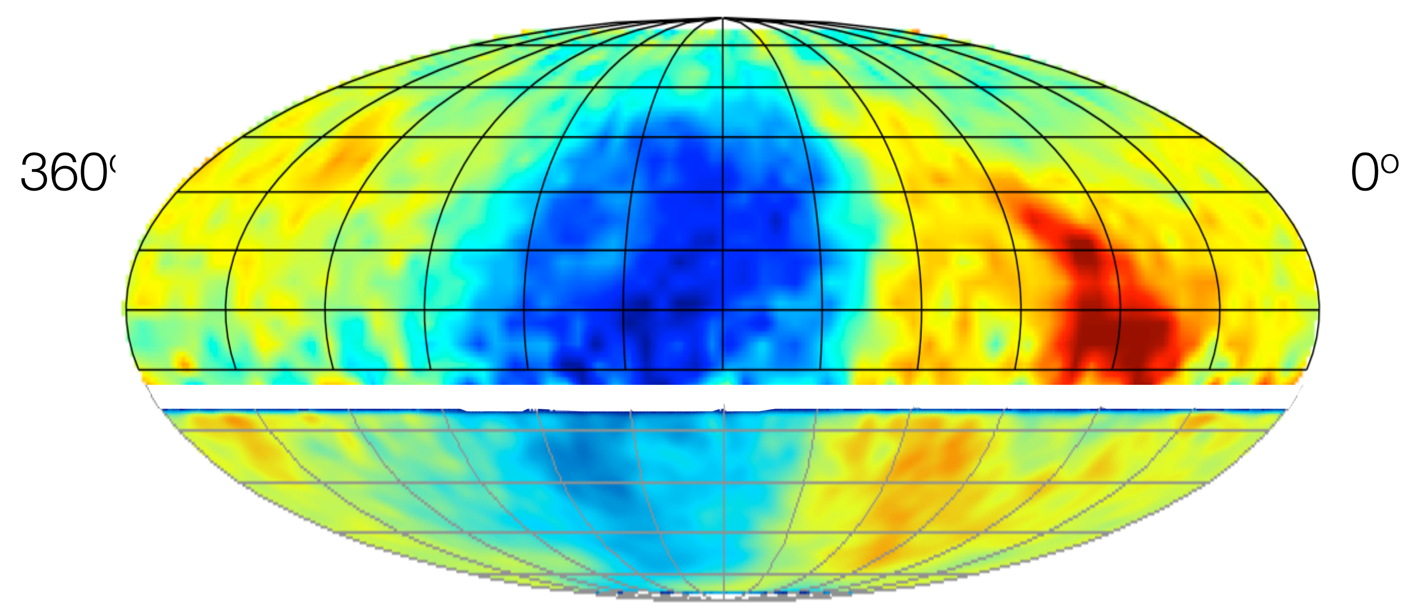
Compton & Getting, Phys. Rev. 47, 817 (1935)
Gleeson, & Axford, Ap&SS, 2, 43 (1968)



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

- 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

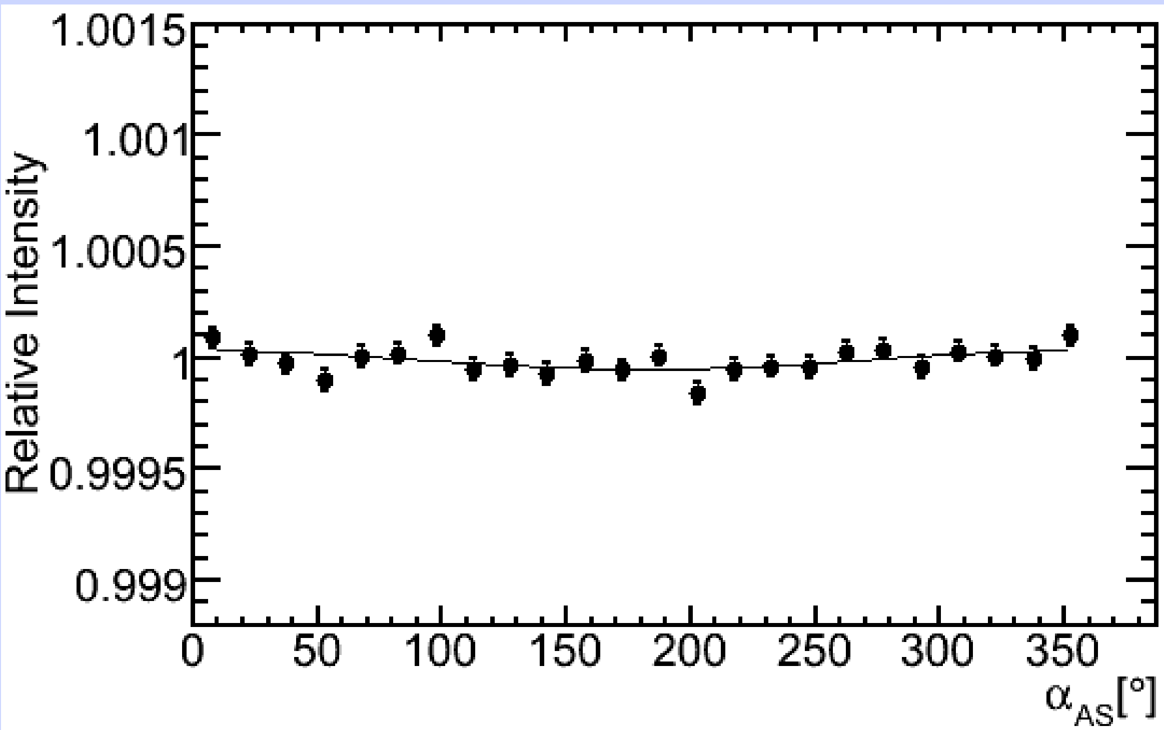




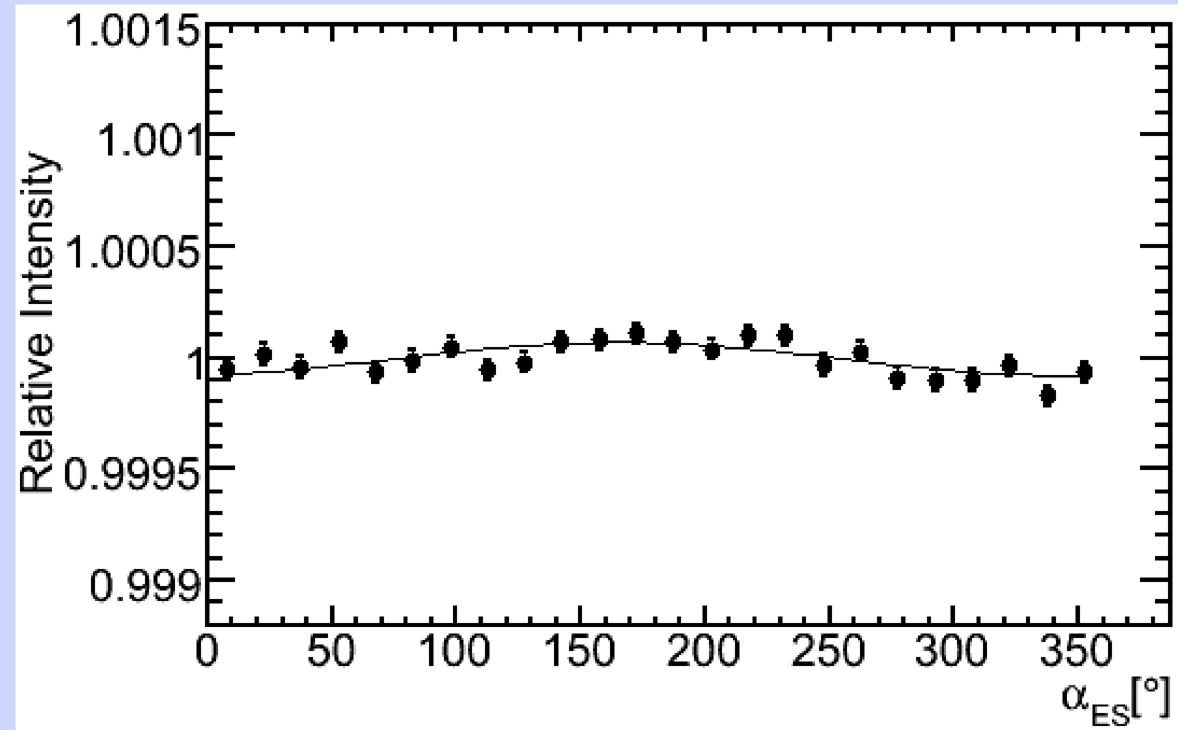
anti-/extended-sidereal distributions vs energy in IceCube-59

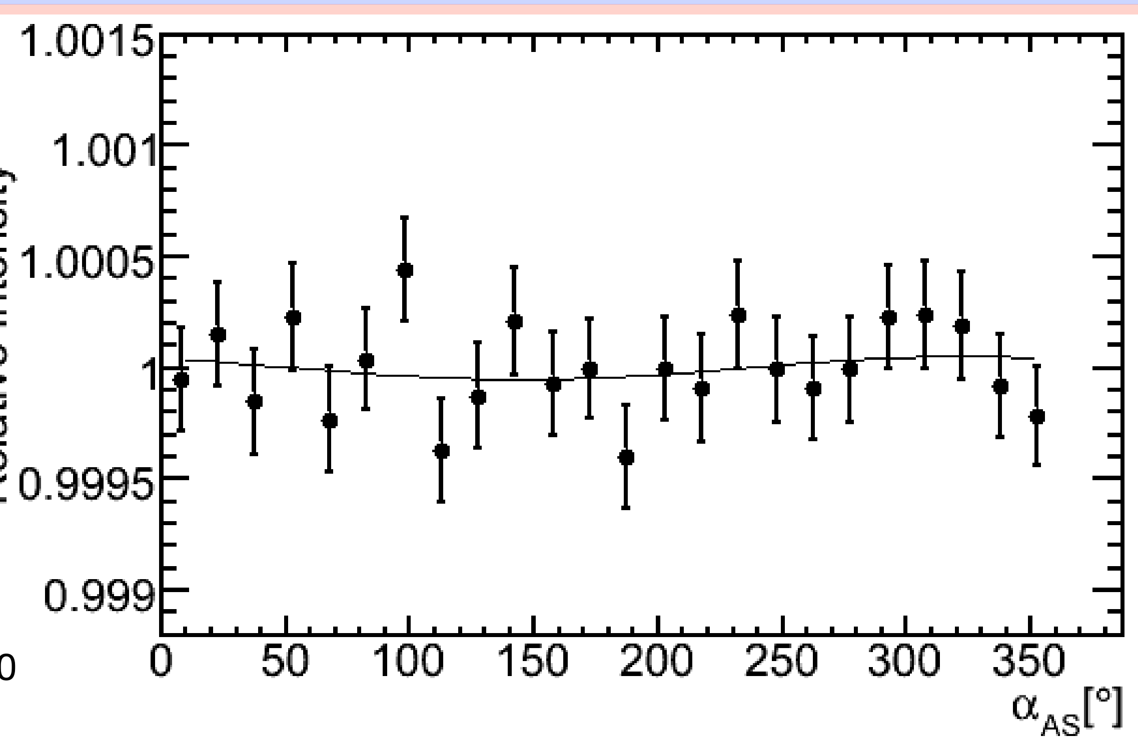
anti-sidereal distribution ~ solar dipole variability

extended-sidereal distribution ~ sid. anis. variability

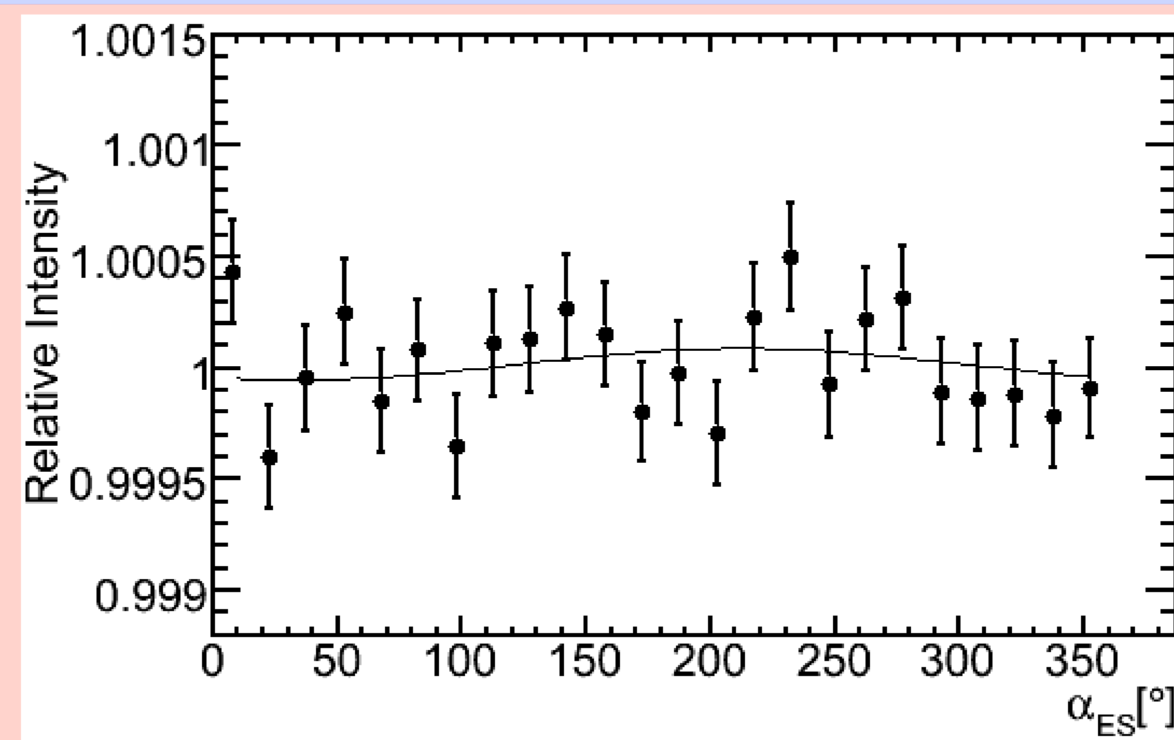


20 TeV





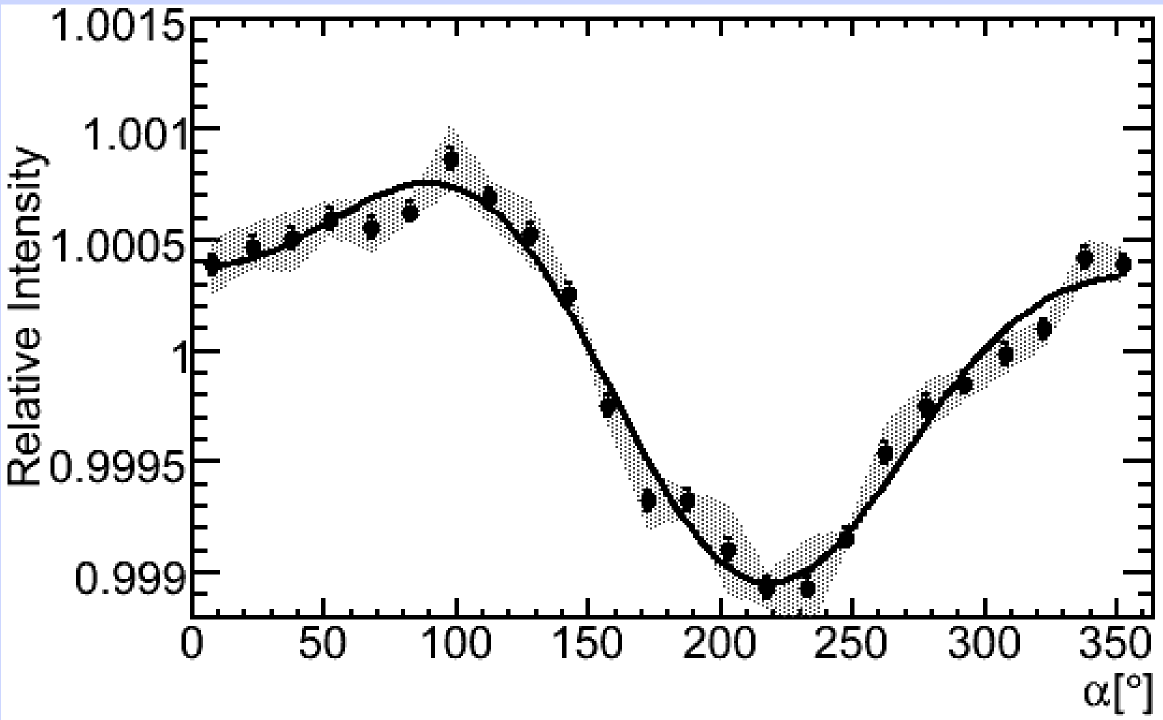
400 TeV

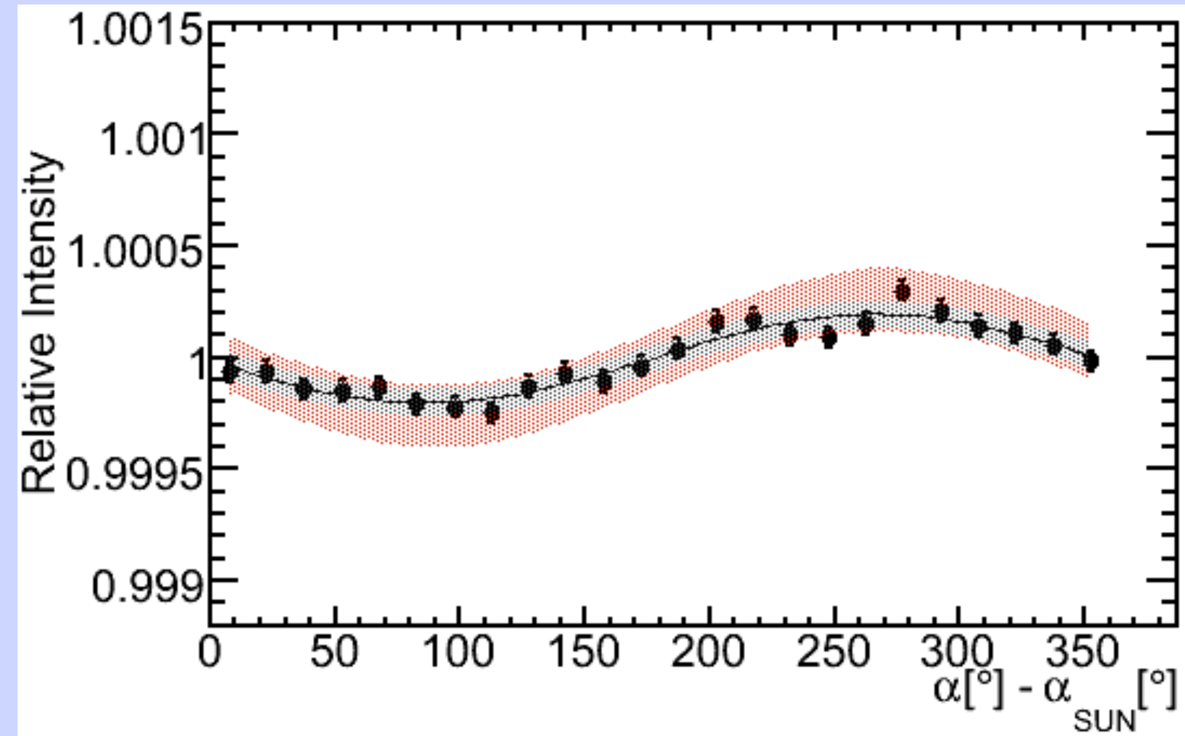


systematic uncertainties IceCube-59

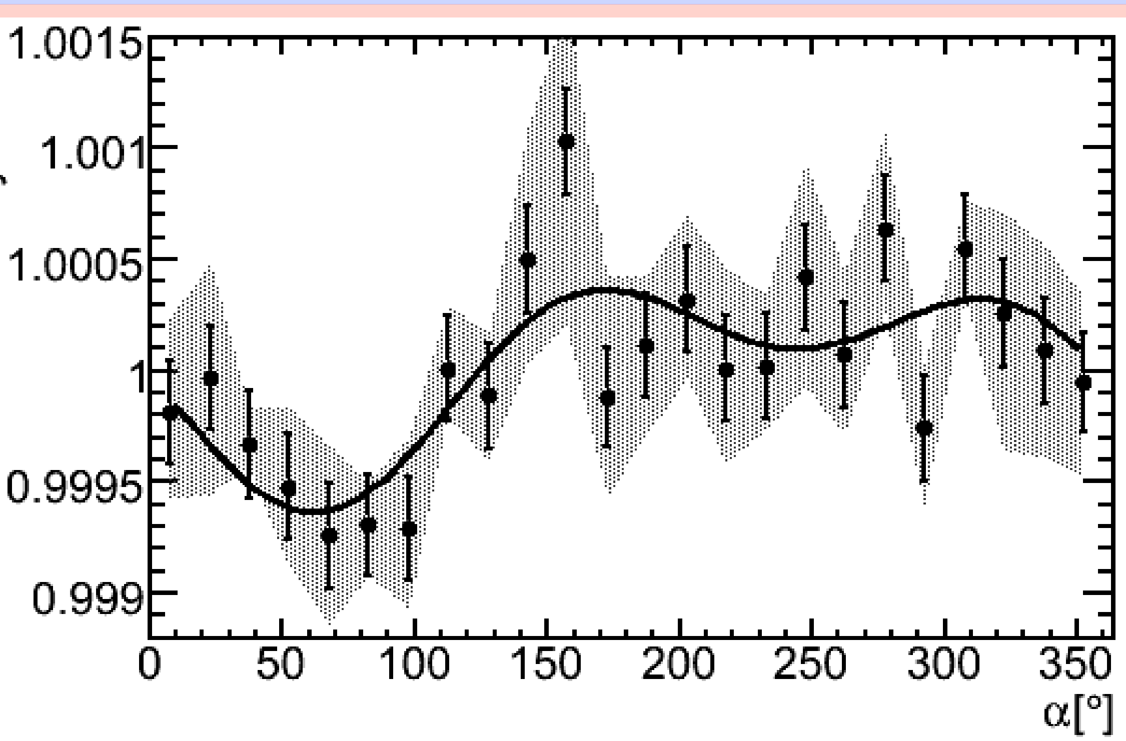
statistical stability tests + anti-sidereal effect

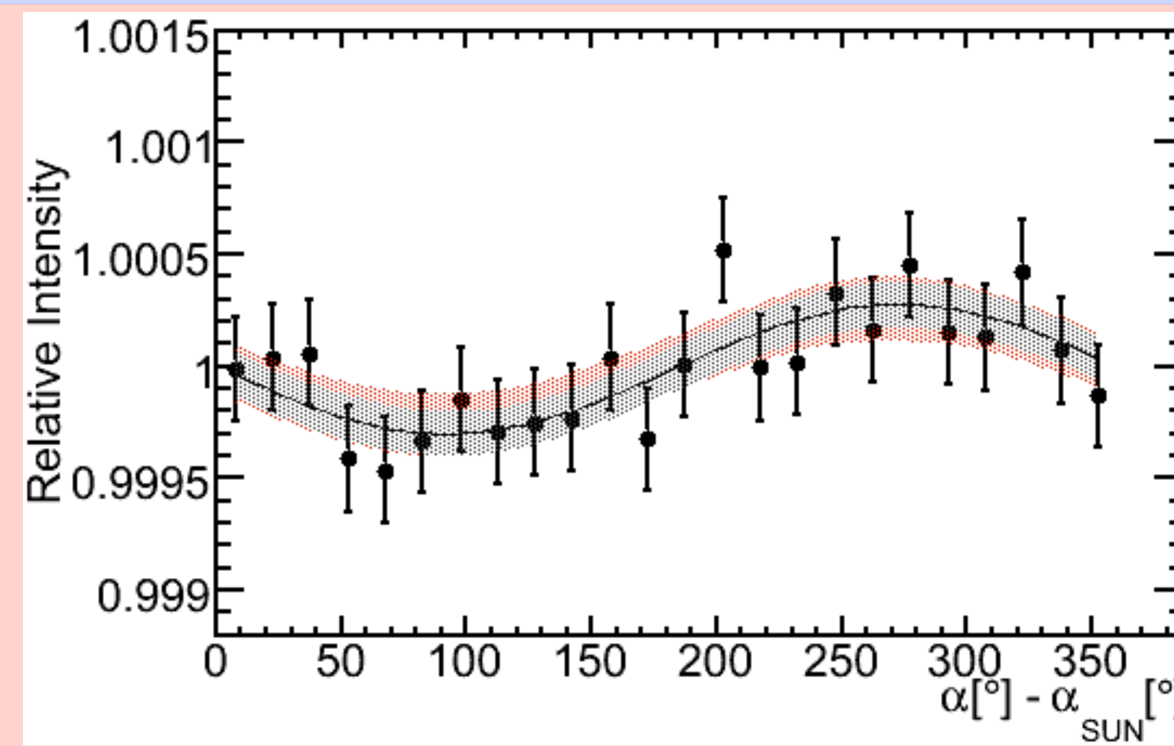
extended-sidereal effect





20 TeV

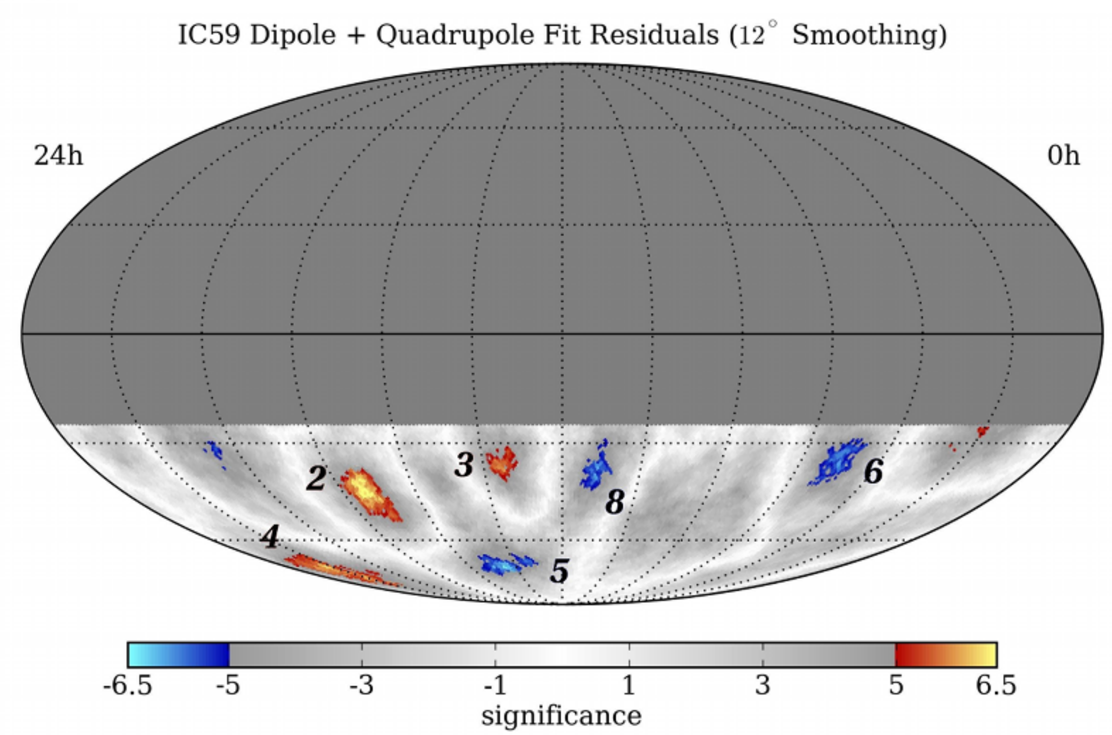


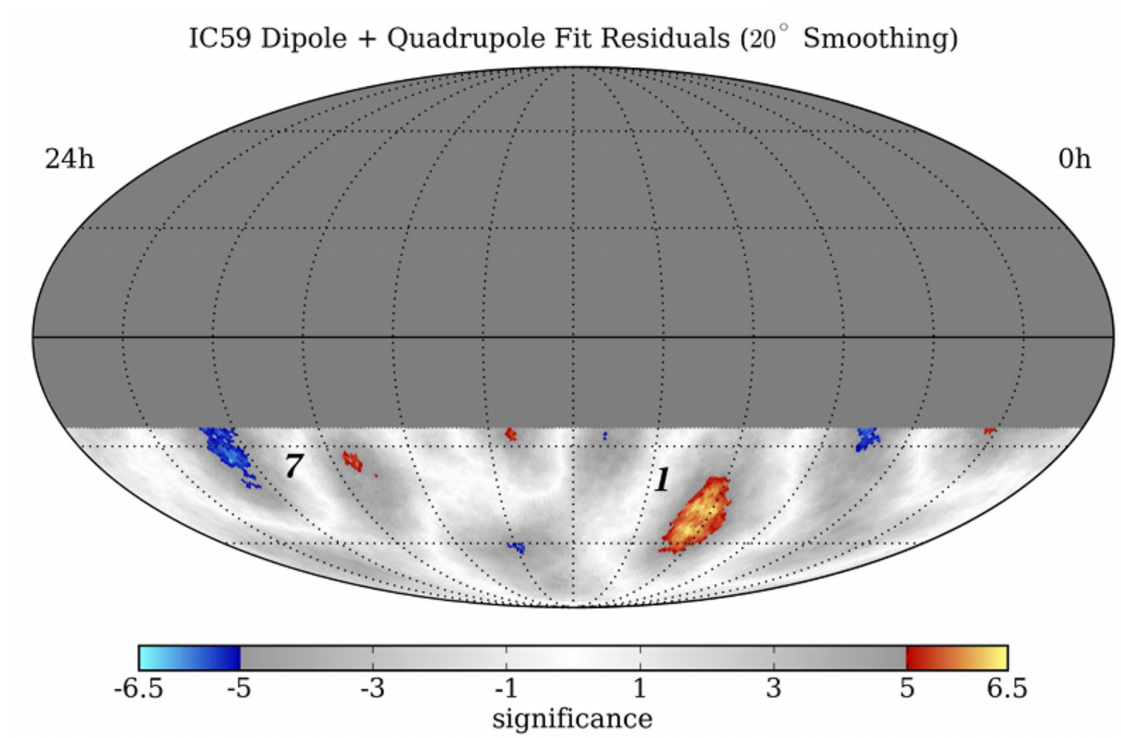


400 TeV

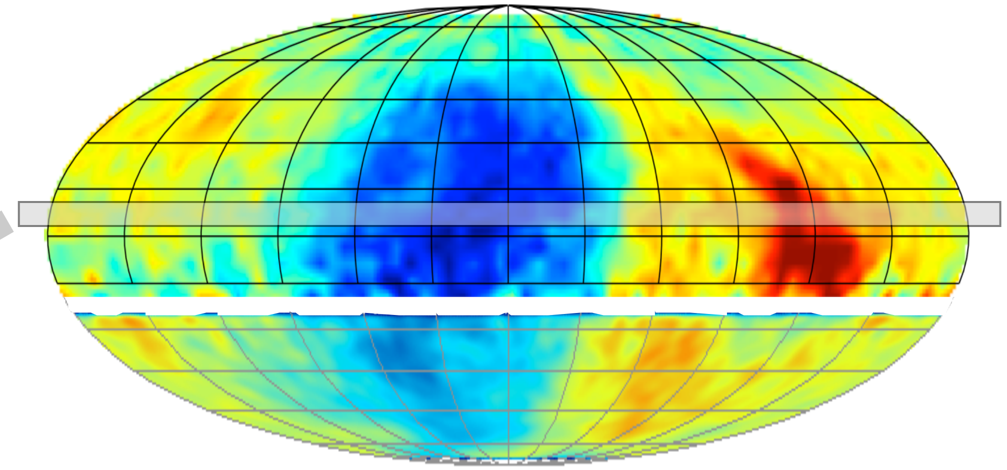
cosmic ray anisotropy small scale
IceCube

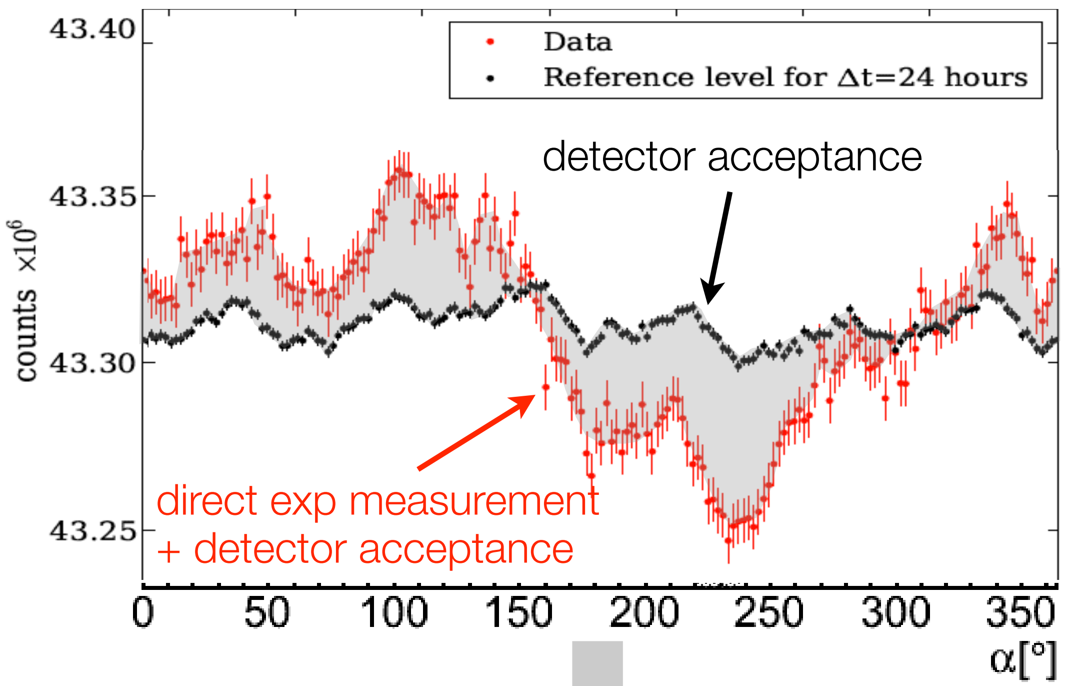
region	right ascension	declination	optimal scale	peak significance	post-trials	IC79 (post-trials)
1	$(122.4^{+4.1}_{-4.7})^\circ$	$(-47.4^{+7.5}_{-3.2})^\circ$	22°	7.0σ	5.3σ	6.8σ
2	$(263.0^{+3.7}_{-3.8})^\circ$	$(-44.1^{+5.3}_{-5.1})^\circ$	13°	6.7σ	4.9σ	5.4σ
3	$(201.6^{+6.0}_{-1.1})^\circ$	$(-37.0^{+2.2}_{-1.9})^\circ$	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

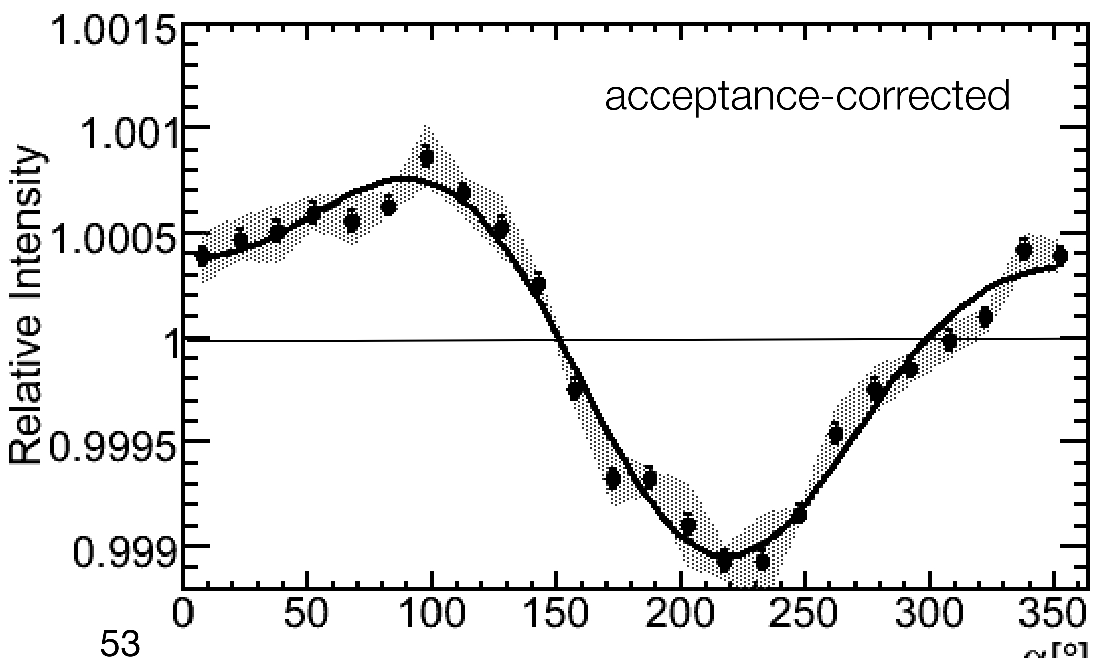


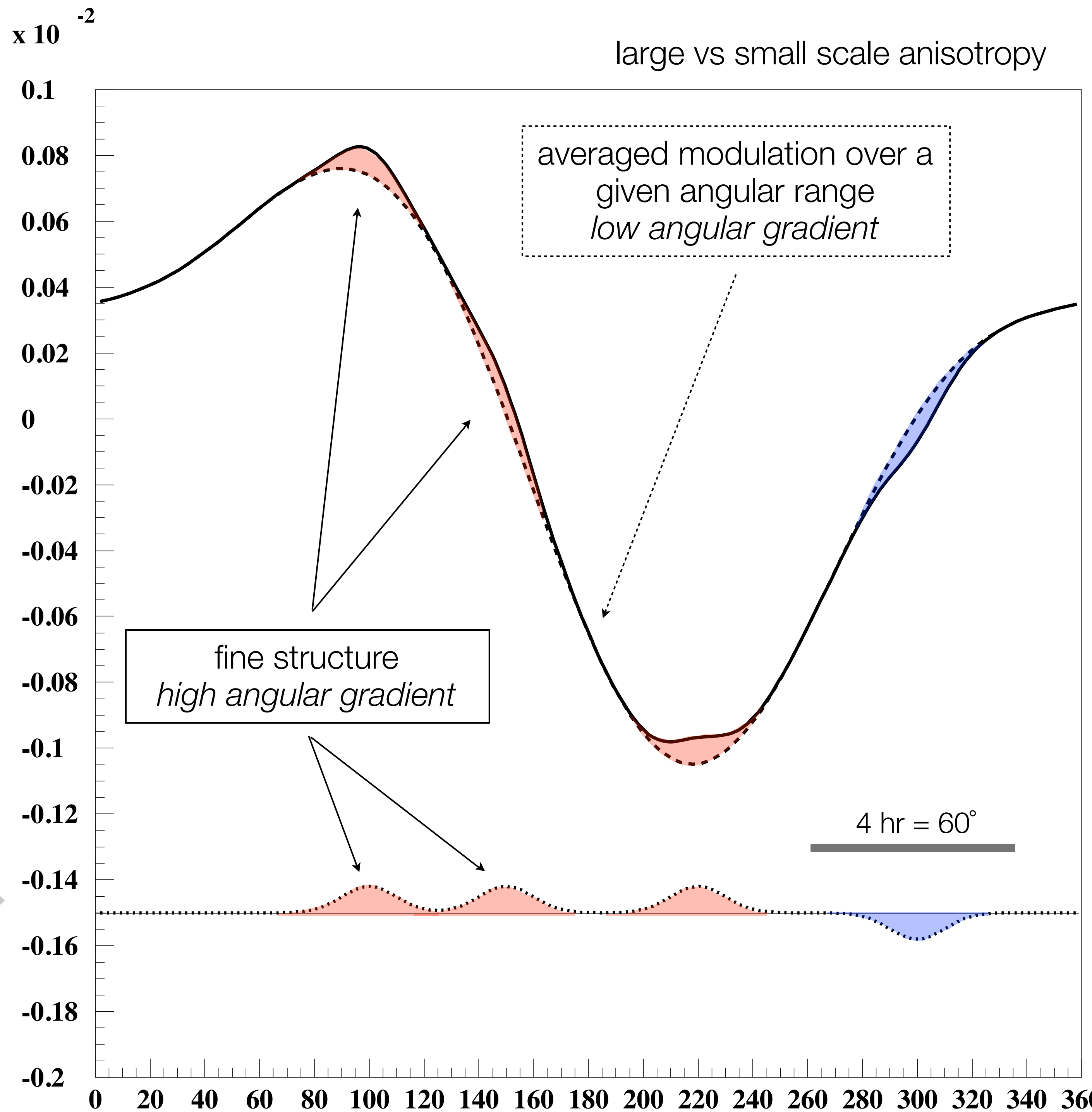


anisotropy vs. angular scale







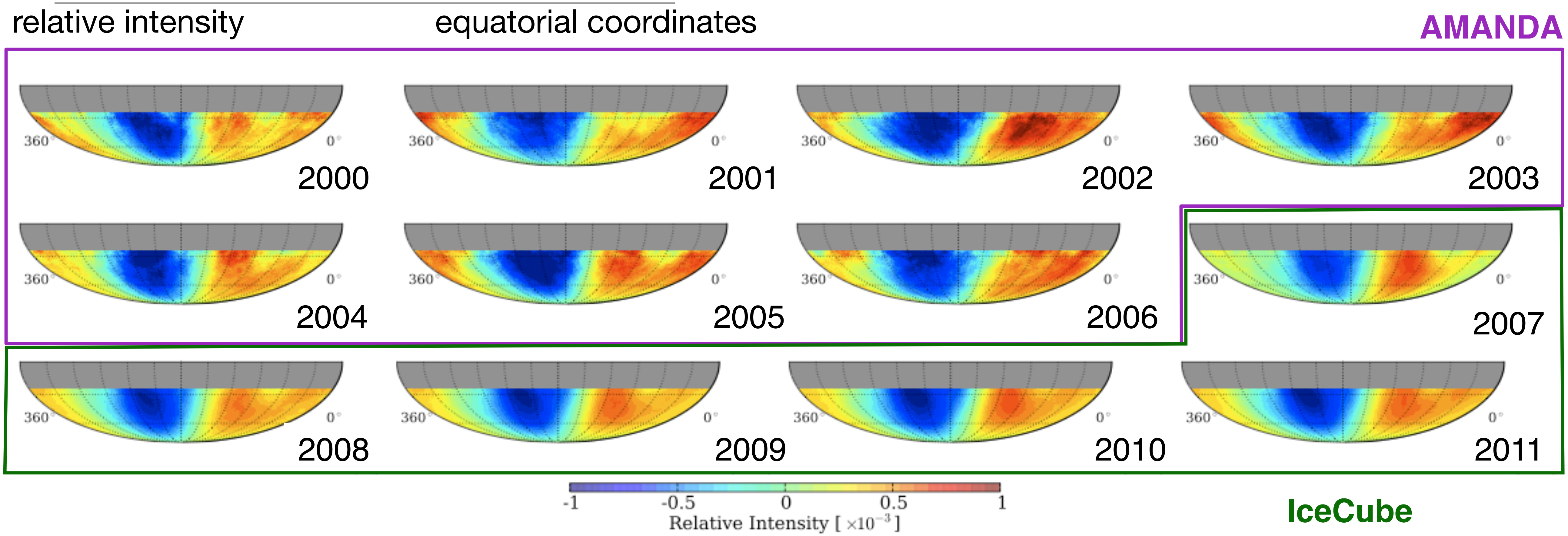


cosmic ray anisotropy
AMANDA-IceCube 2000-2011

PRELIMINARY

20 TeV

relative intensity equatorial coordinates



- AMANDA and IceCube yearly data show long **time-scale stability** of global anisotropy within statistical uncertainties

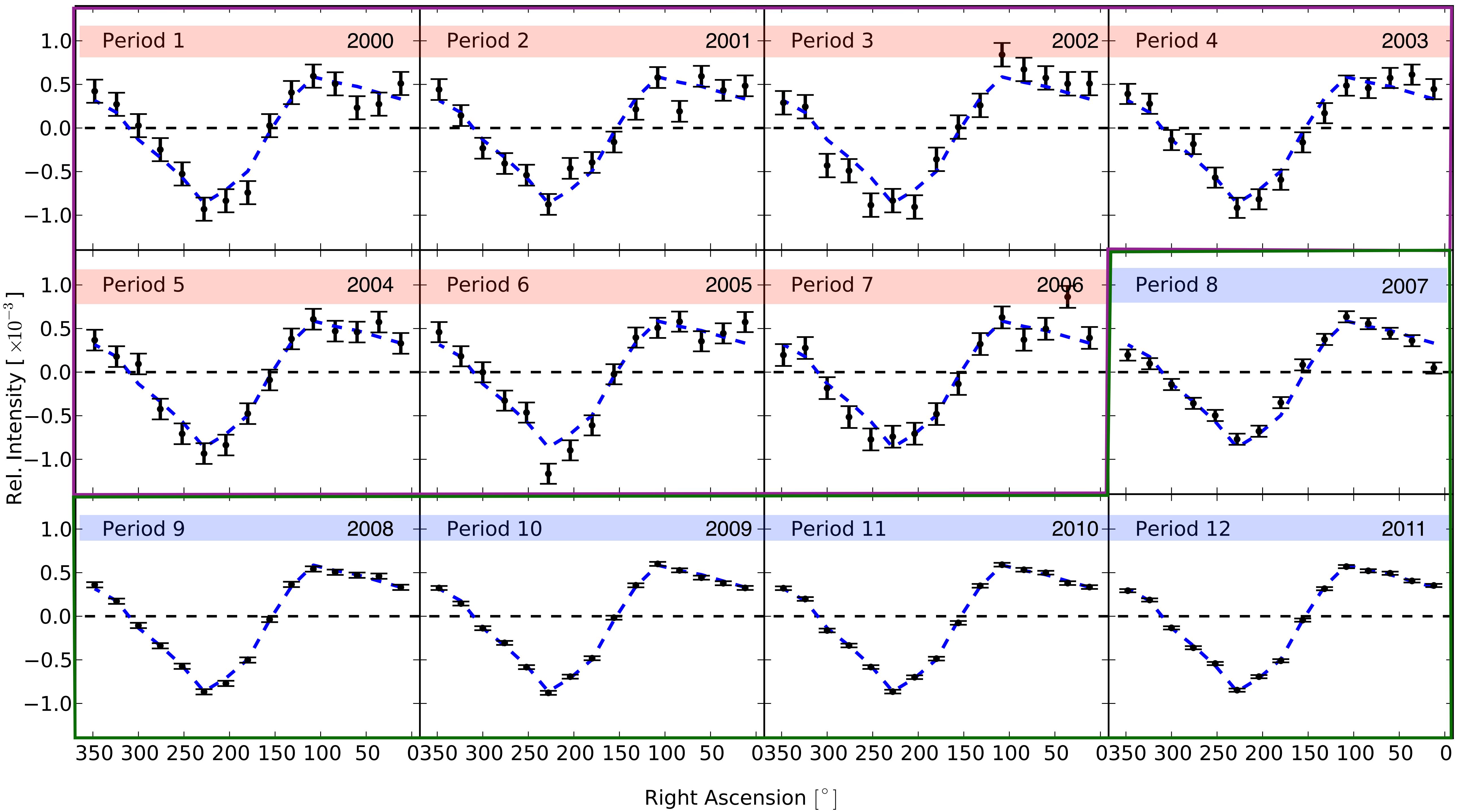
  - no apparent effect correlated to solar cycles

cosmic ray anisotropy

AMANDA-IceCube 2000-2011

PRELIMINARY

20 TeV



Paolo Desiati

cosmic ray anisotropy

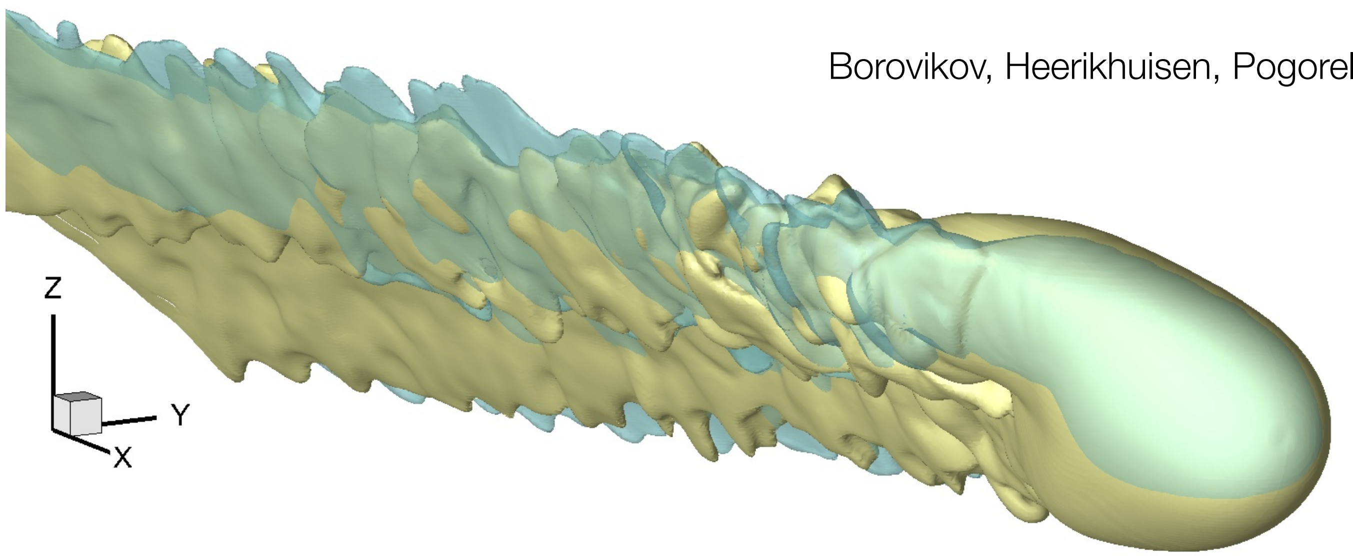
AMANDA-IceCube 2000-2011

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

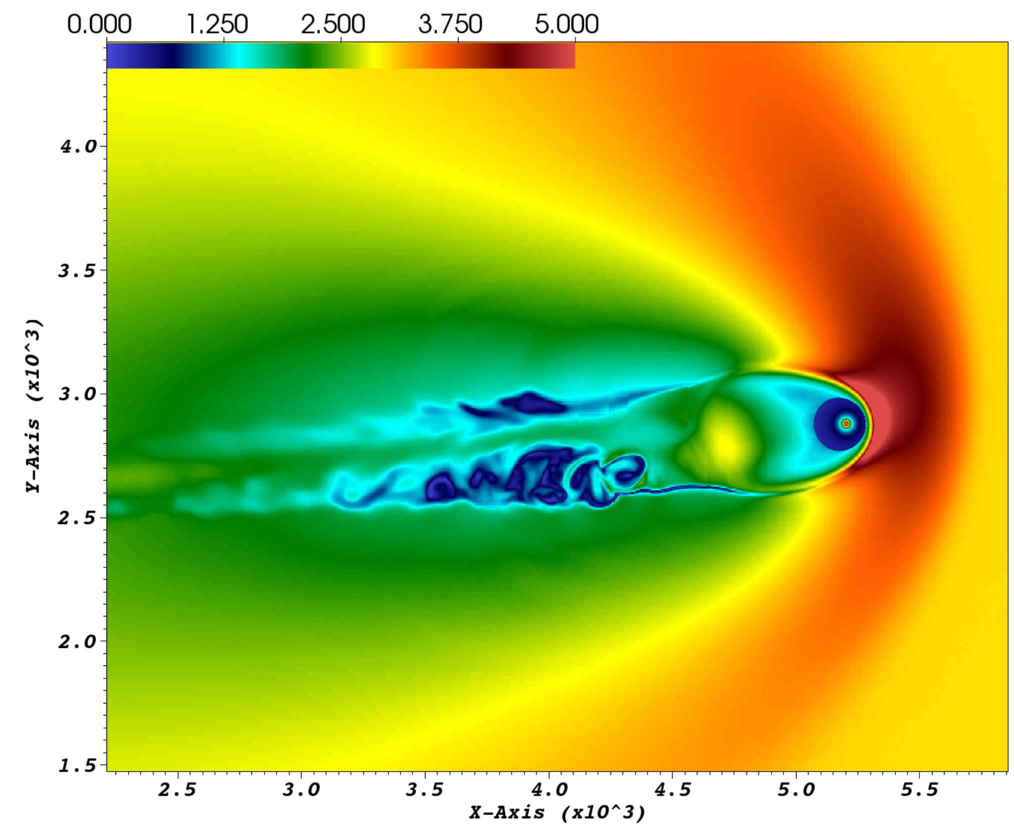
statistical uncertainties only

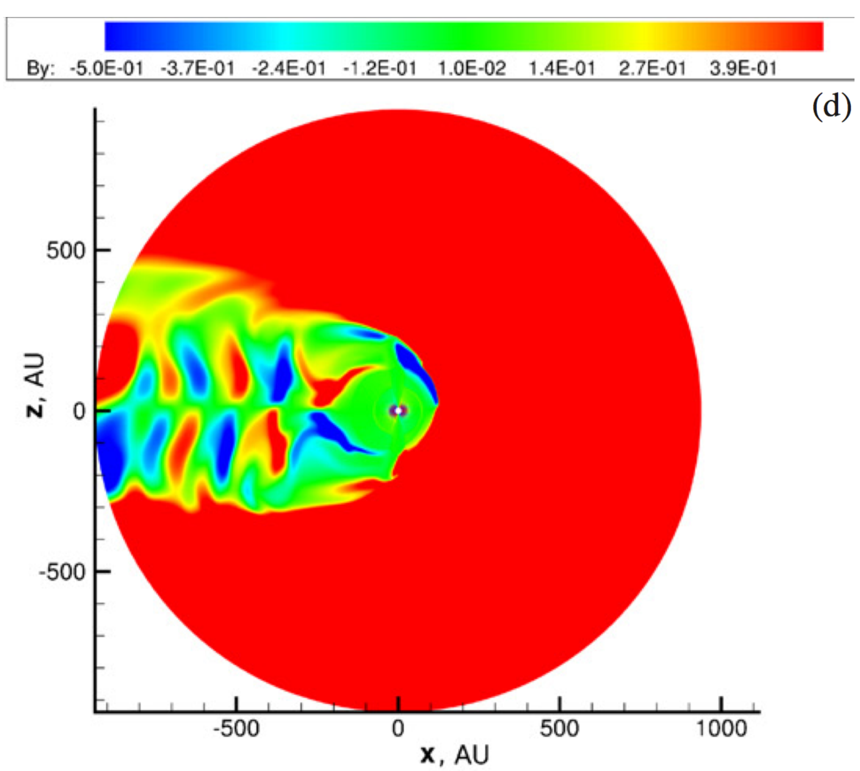
cosmic ray anisotropy
probing heliospheric magnetic structure



Borovikov, Heerikhuisen, Pogorelov

downstream instabilities on the flanks of heliotail





Pogorelov et al., 2009

effects of magnetic polarity reversals from solar cycles