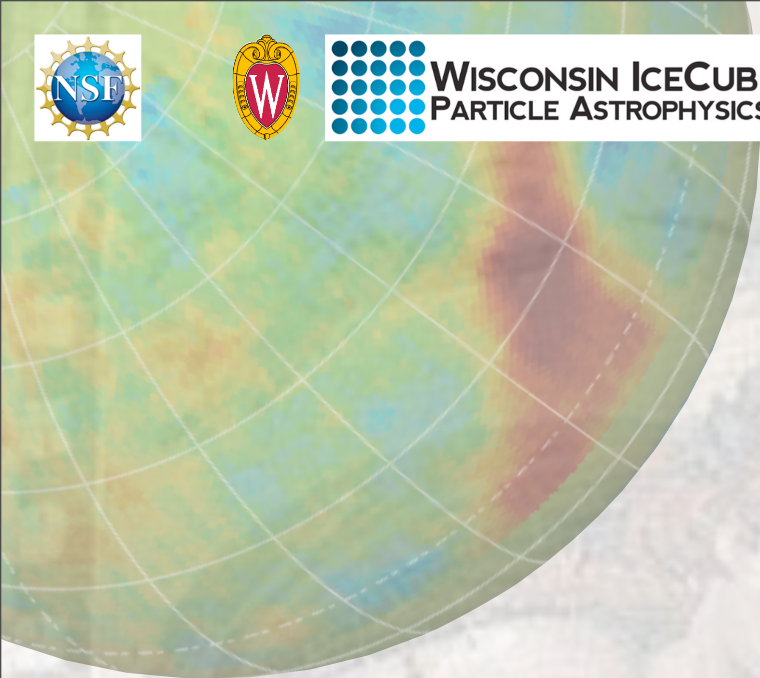

Study of TeV-PeV cosmic-ray anisotropy with the IceCube, IceTop and AMANDA detectors

Paolo Desiati, for the IceCube Collaboration

WIPAC & Department of Astronomy
University of Wisconsin - Madison

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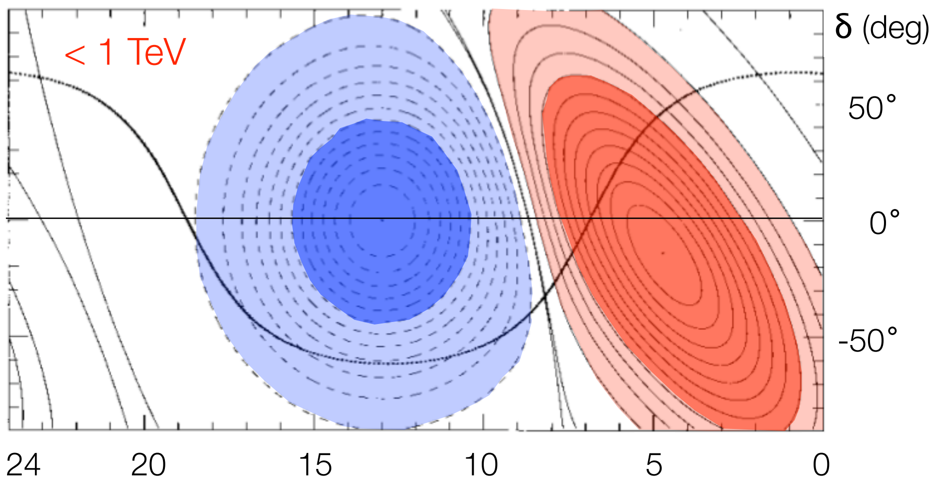
Roma International Conference on Astroparticle Physics - RICAP 2013
La Sapienza Università di Roma - May 22-24, 2013

Outline

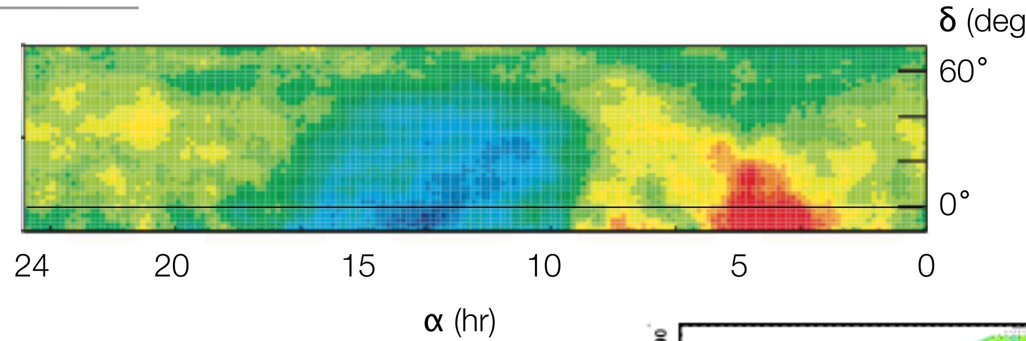
- cosmic ray spectrum and anisotropy - the legacy
- anisotropy with IceCube & IceTop
  - *energy dependency*
  - *angular structure*
- anisotropy with AMANDA & IceCube
  - *long time-scale stability*

cosmic ray anisotropy observations

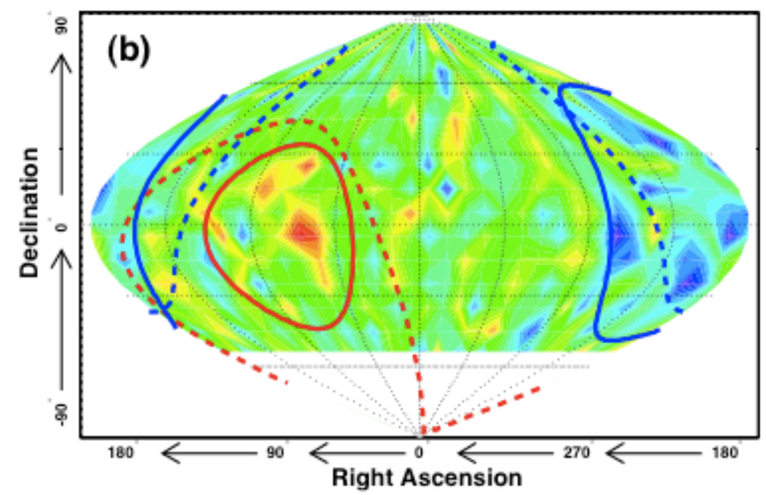
the legacy



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

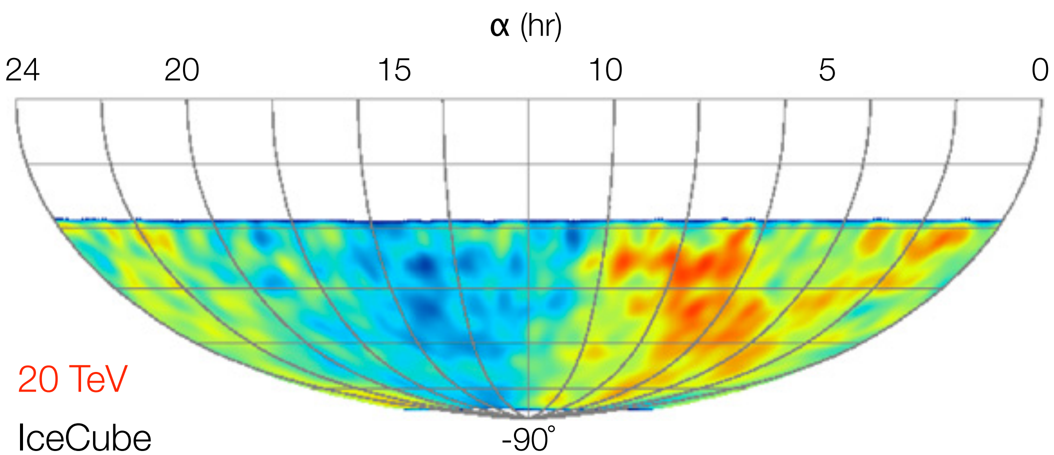


4 TeV
Tibet ASγ
Amenomori et al. (2006)

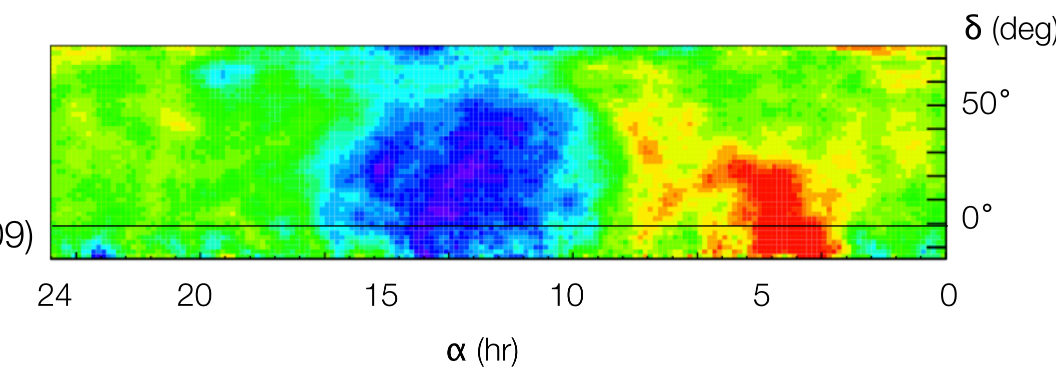


10 TeV
Super Kamiokande
Guillian et al. (2007)

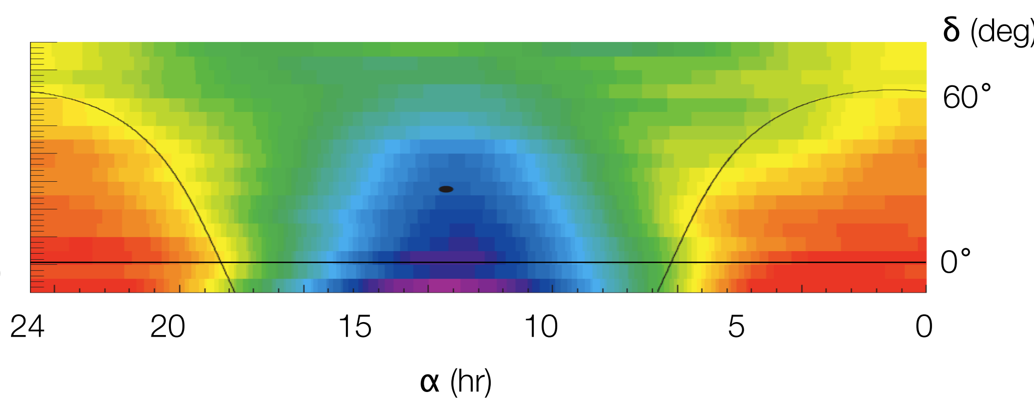
equatorial coordinates



20 TeV
IceCube
Abbasi et al. (2010)

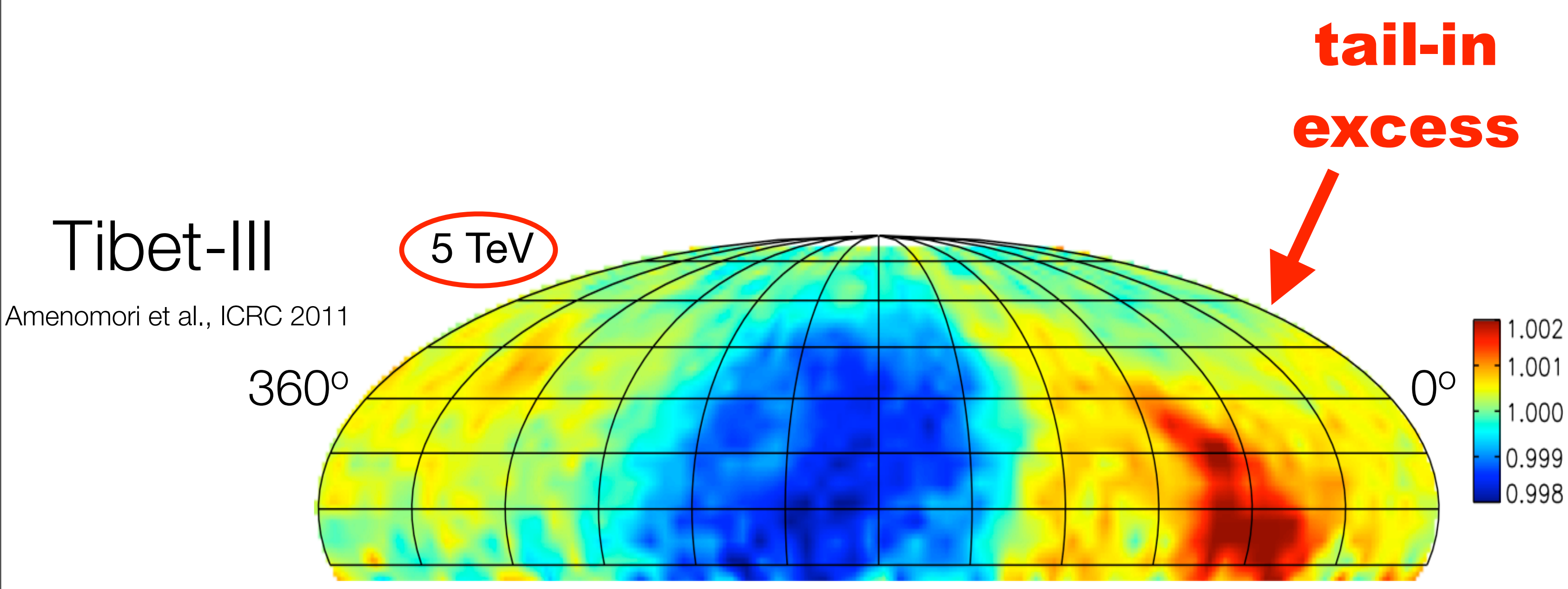


4 TeV
ARGO-YBJ
Zhang et al. (2009)



5 TeV
Milagro
Abdo et al. (2009)

cosmic ray anisotropy observations
the legacy



- cosmic rays possess anisotropy of order

$$10^{-4} - 10^{-3}$$

- **from 10's GeV to 10's TeV** with consistent topology

- anisotropy *amplitude* increases with energy (up to ~10 TeV)

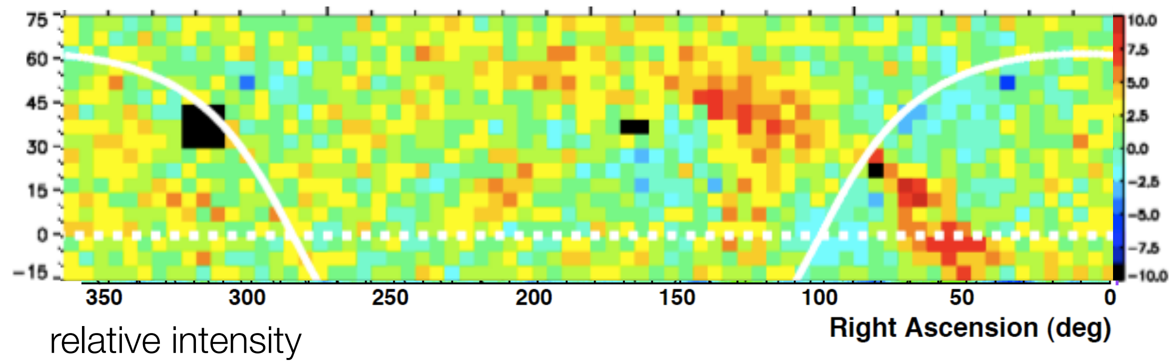
- anisotropy has strong **dipole & quadrupole** components

Paolo Desiati

cosmic ray anisotropy observations
the legacy

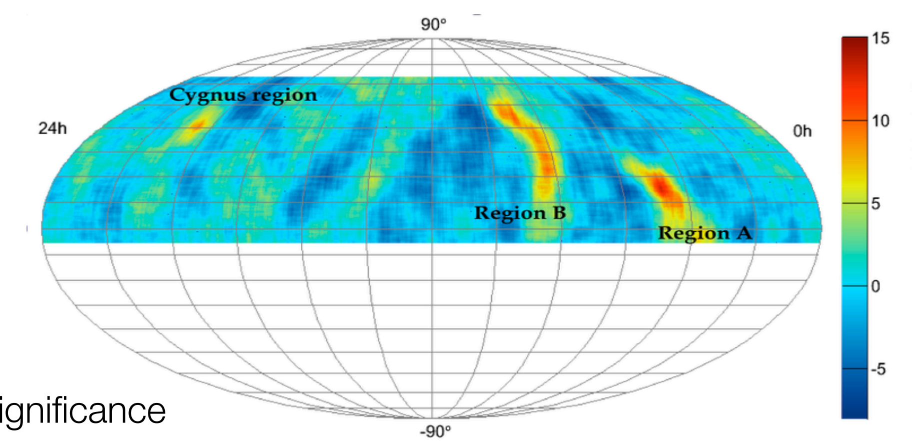
- significant **small angular scale** features ~10x smaller amplitude over global anisotropy
- the **tail-in excess region** composed of smaller structures above TeV energy
- observation of **spectral anomalies** associated to localized excess regions (Milagro, ARGO-YBJ)

Tibet-III (global fit) Amenomori et al. (2006)



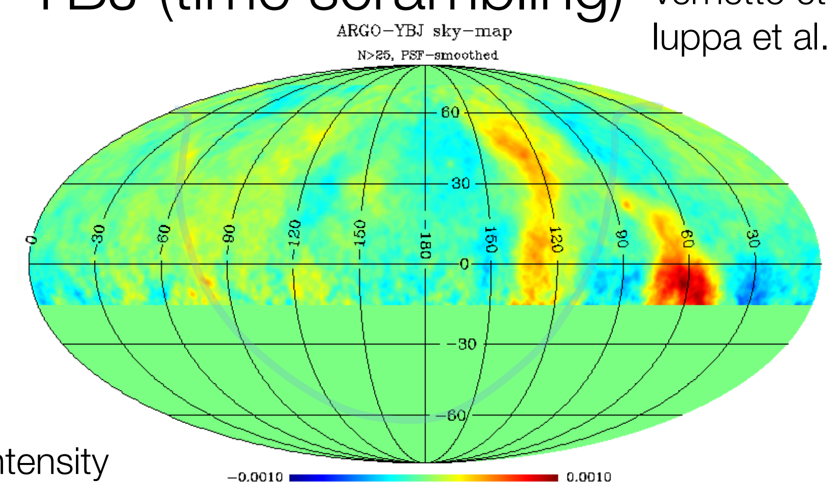
relative intensity

Milagro (direct integration) Abdo et al. (2008)



statistical significance

ARGO-YBJ (time scrambling) Vernetto et al. (2009) Iuppa et al. (2011)



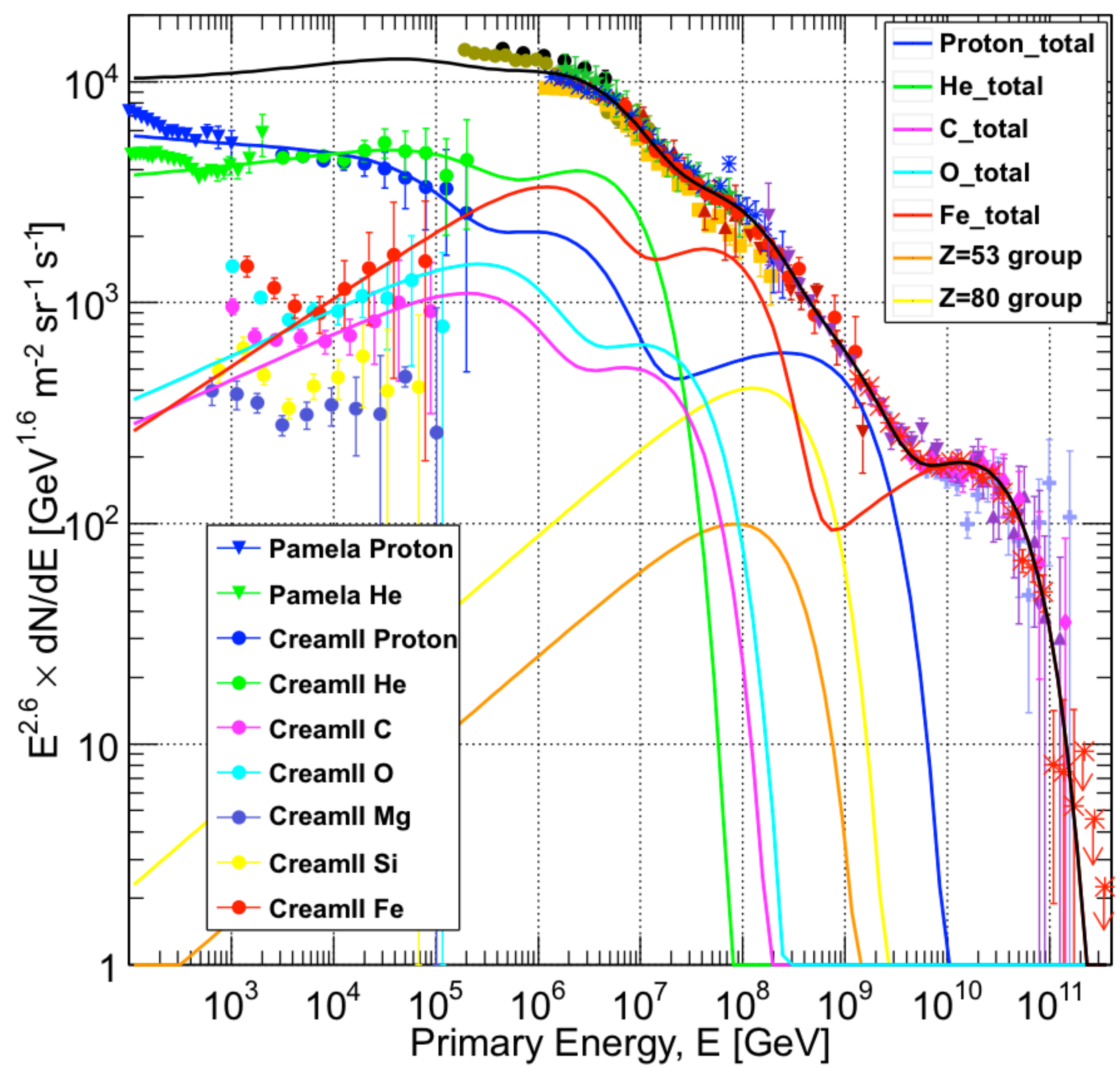
relative intensity

cosmic ray anisotropy observations

the legacy

- cosmic rays < 10's GeV affected by solar activity (short time-scale variability)
    - **heliospheric physics** as laboratory to study particle **diffusion properties** in interplanetary magnetic field
- cosmic rays > 100 GeV influenced by magnetic perturbations > O(10) AU
- snapshot of magnetic field influence at **larger distance** with **higher energy**

Gaisser, Stanev, Tilav, 2013 - arXiv:1303.3565




The IceCube Collaboration
University of Alberta
Clark Atlanta University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Ohio State University
Pennsylvania State University
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California-Berkeley
University of California-Irvine
University of Delaware
University of Kansas
University of Maryland
University of Wisconsin-Madison
University of Wisconsin-River Falls
Chiba University
University of Oxford
Université Libre de Bruxelles
Université de Mons
University of Gent
Vrije Universiteit Brussel
University of Adelaide
University of Canterbury
Stockholm University
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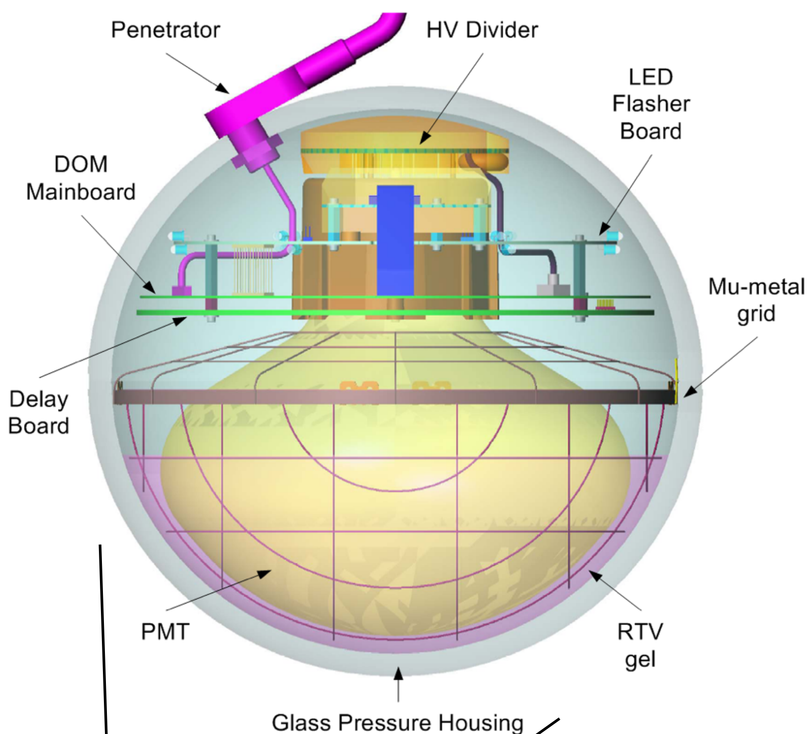
Universität Bonn
Universität Dortmund
Universität Mainz
Universität Wuppertal
Ecole Polytechnique
Fédérale de Lausanne
University of Geneva
International Funding Agencies
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

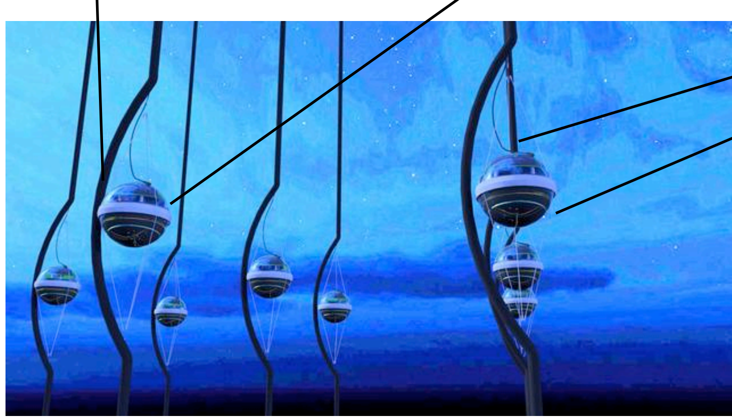
IceCube Observatory

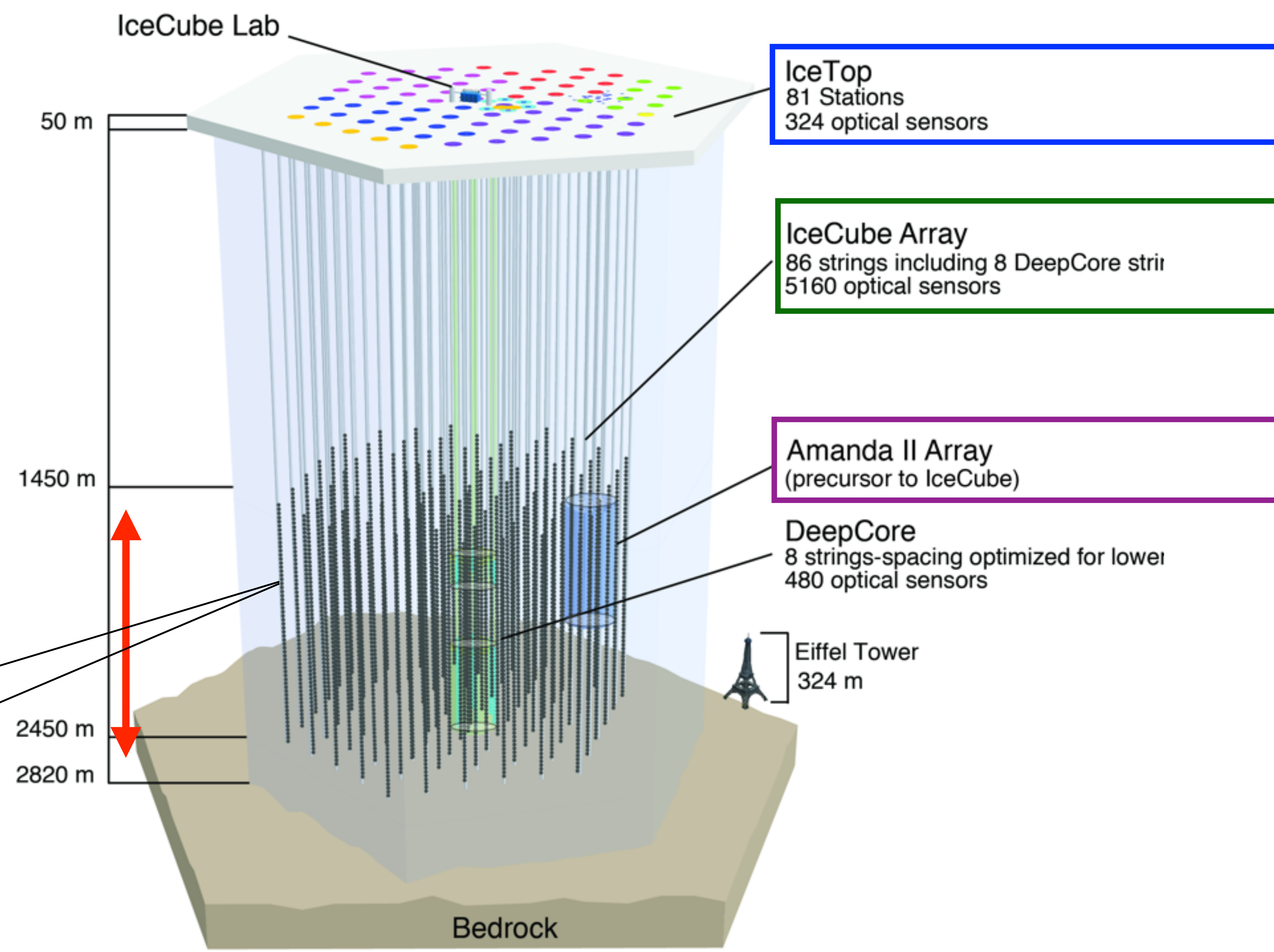
air shower detection @ 2835 m altitude (680 g/cm^2)

muon detection @ 1450-2450 m depth

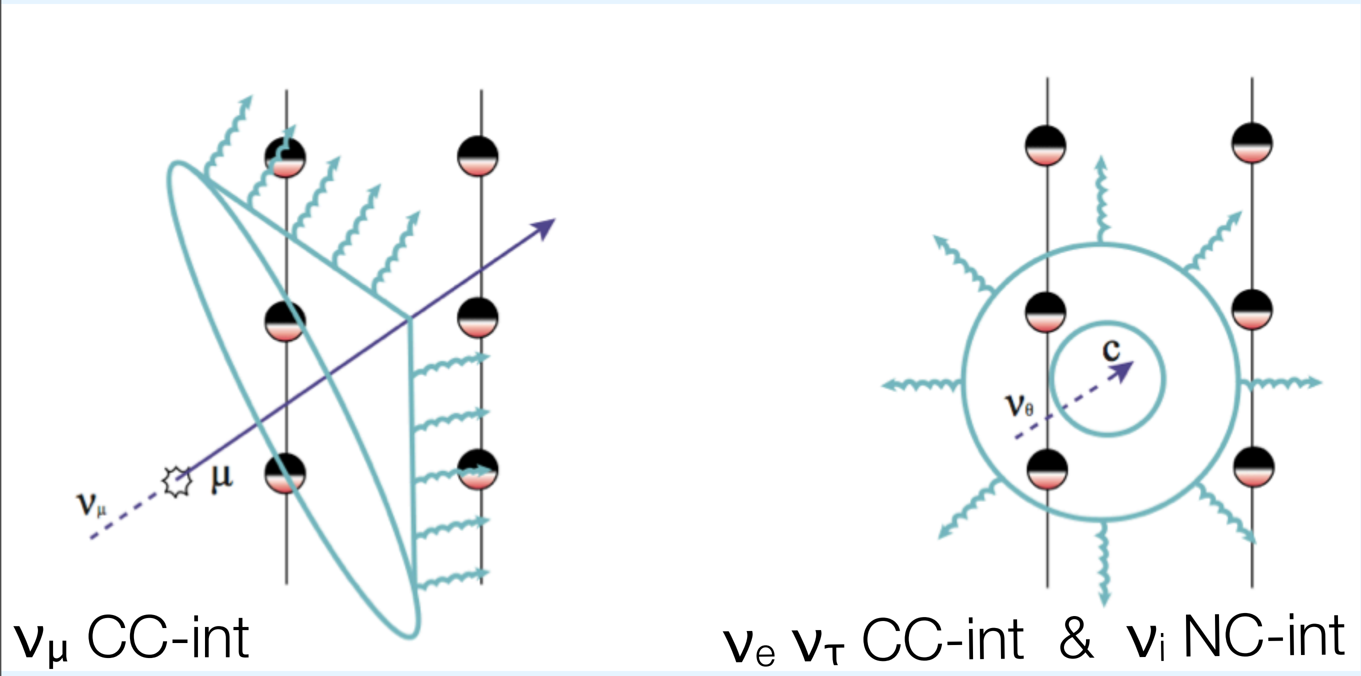
Digital Optical Module - DOM
with 10” PMT &
local DAQ electronics

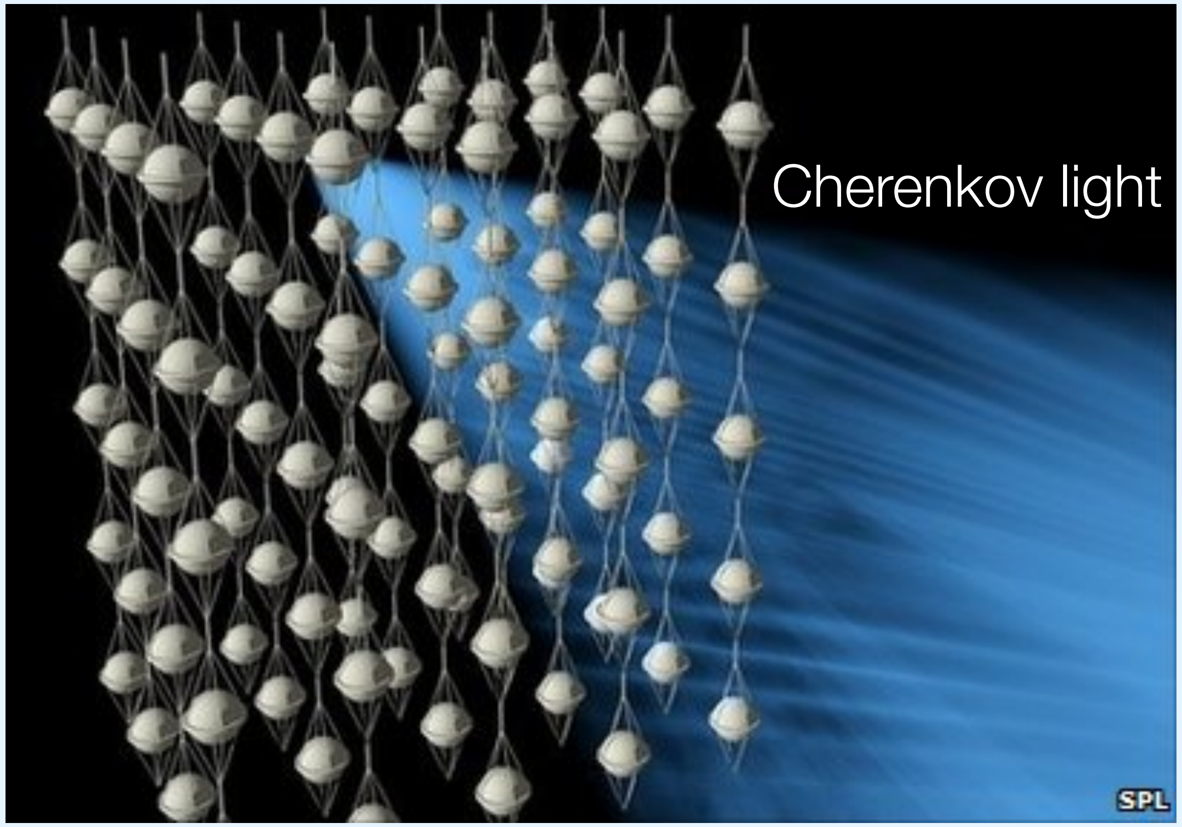


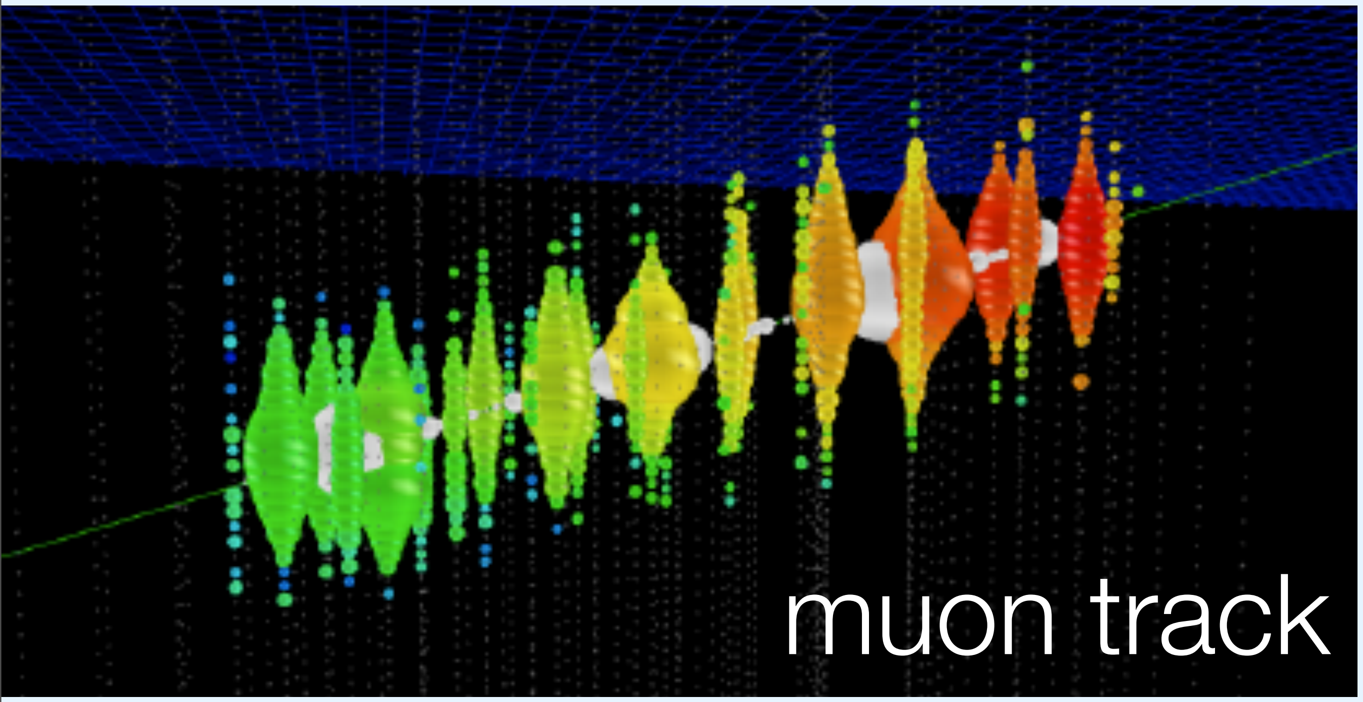


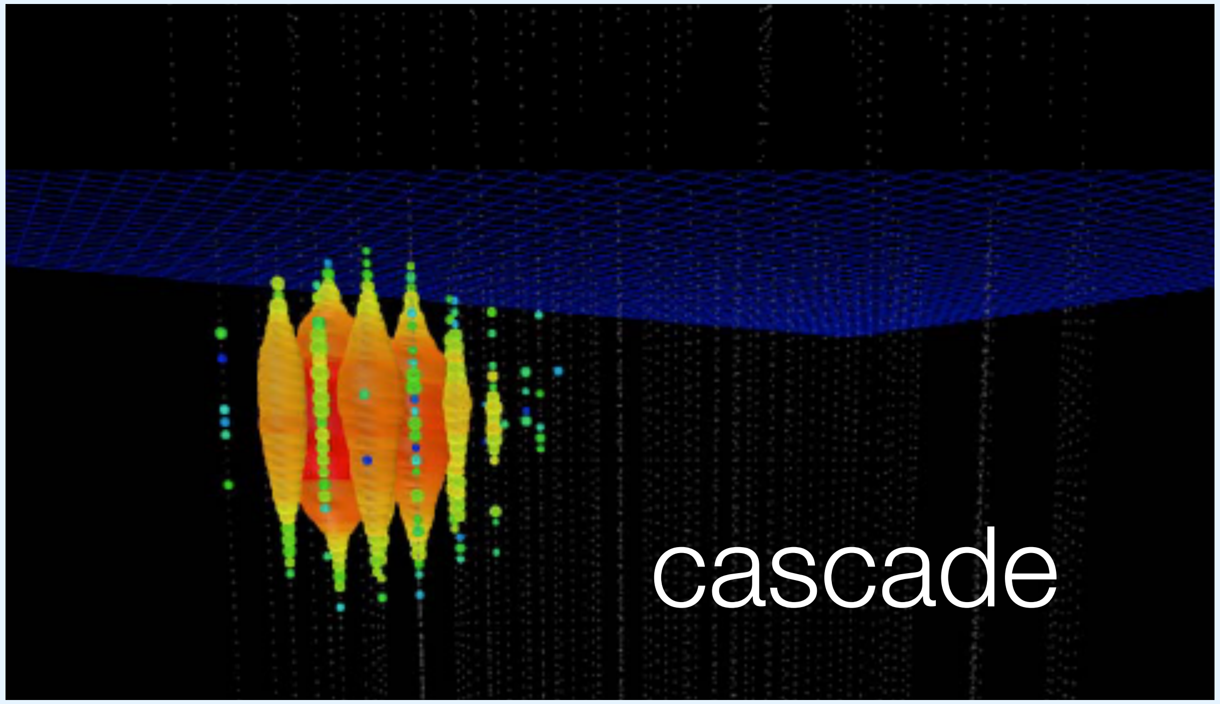


detection principle

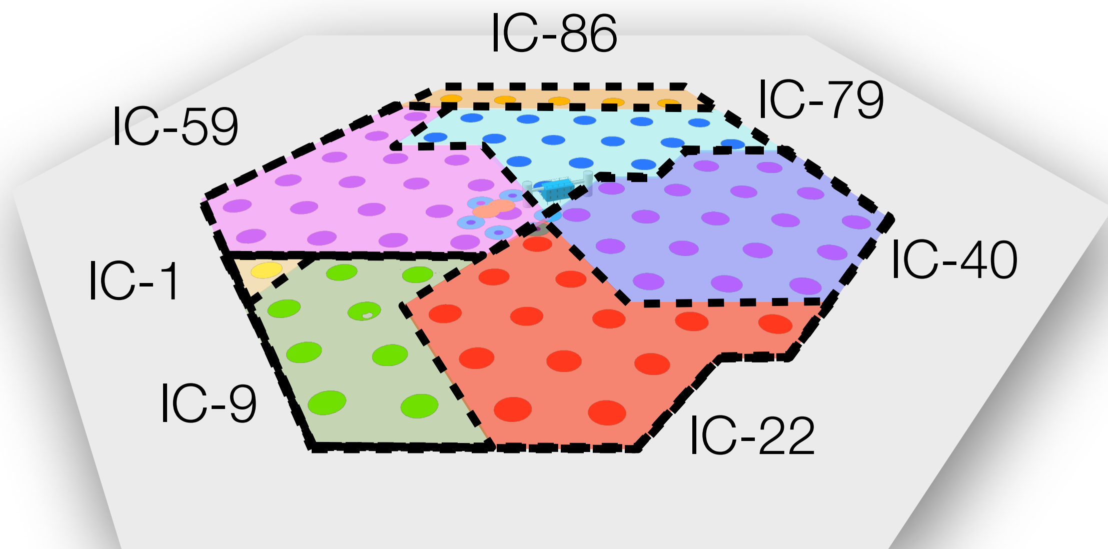




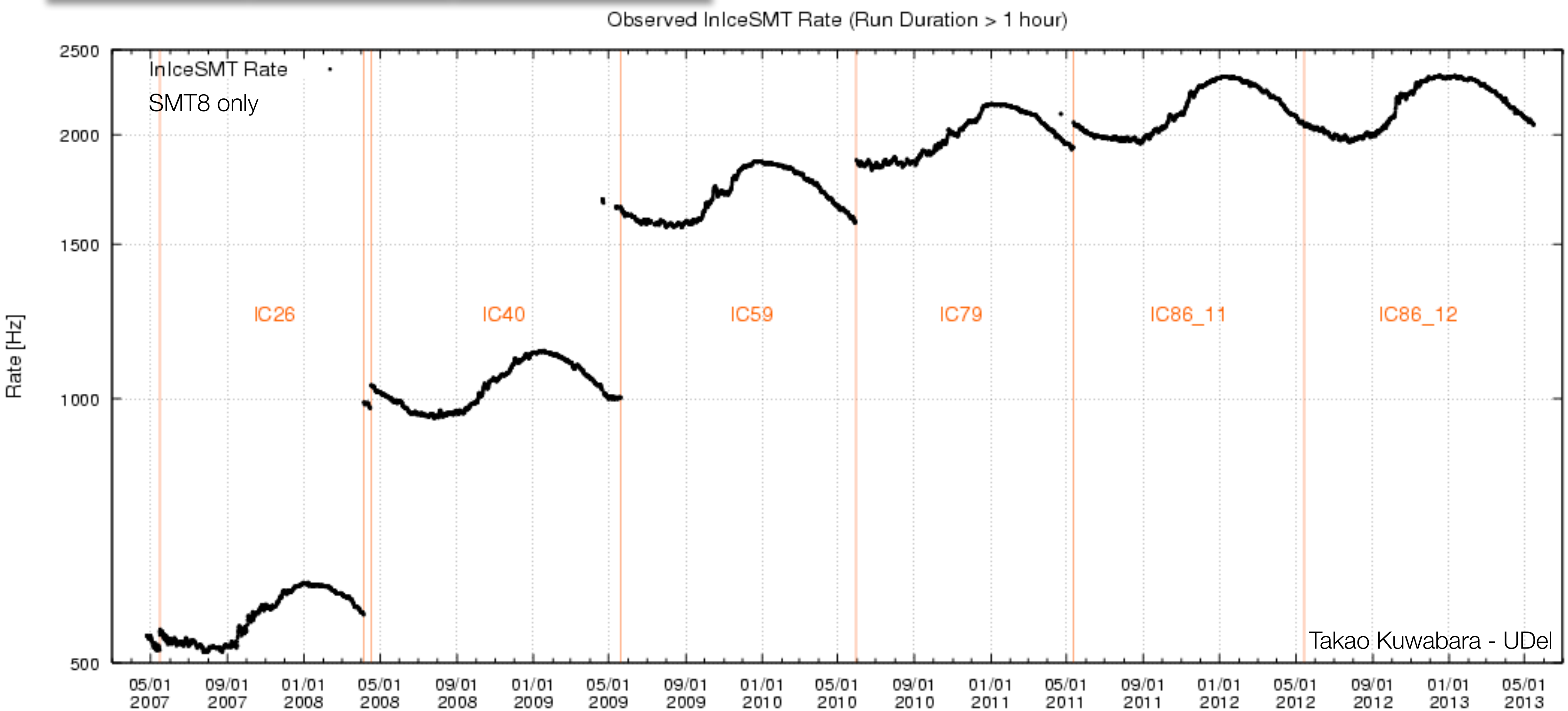




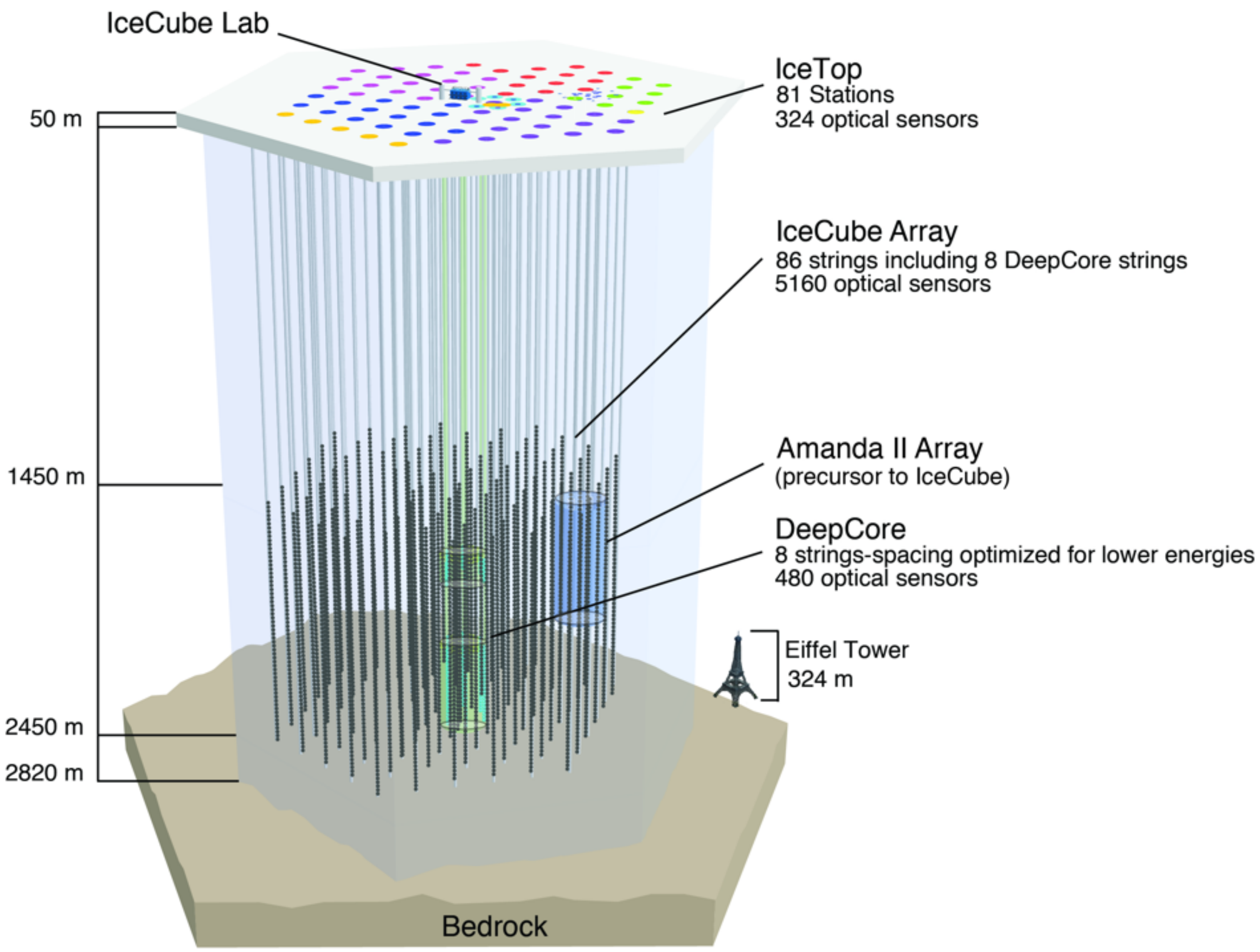
growing IceCube
& event collection



Year	µ rate (SMT8)	CR shower rate (STA3)
2007	500 Hz	13 Hz
2008	1100 Hz	15 Hz
2009	1700 Hz	25 Hz
2010	2000 Hz	30 Hz
2011+	2200 Hz	35 Hz



growing IceCube
& historical data



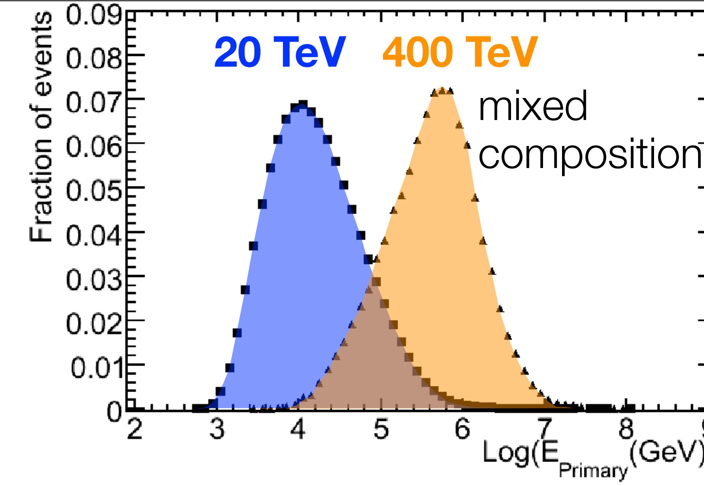
AMANDA - μ bundle rate (>1 TeV) ~ **0.1 kHz**
2×10^{9} events/yr
data from 2000-2006
decommissioned in 2009

+

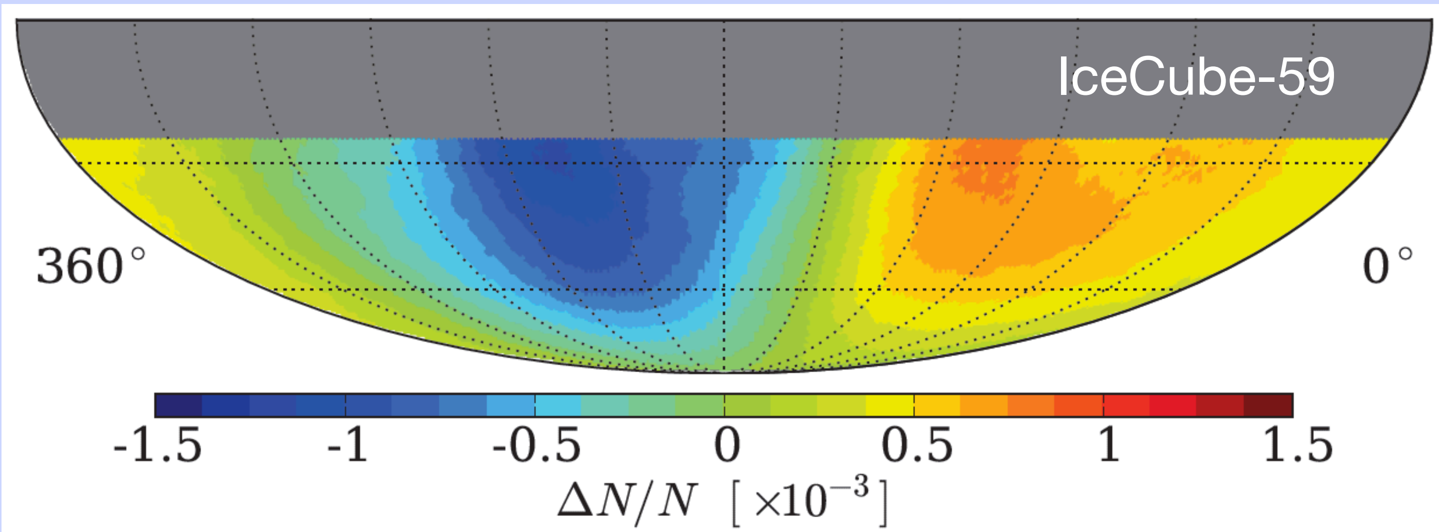
IceCube - μ bundle rate (>1 TeV) ~ **2.5 kHz**
8×10^{10} events/yr
sensitive to asymmetries $O(10^{-5})$

IceTop - CR shower rate (>100 TeV) ~ **10 Hz**
3×10^{8} events/yr
sensitive to asymmetries $O(10^{-4})$

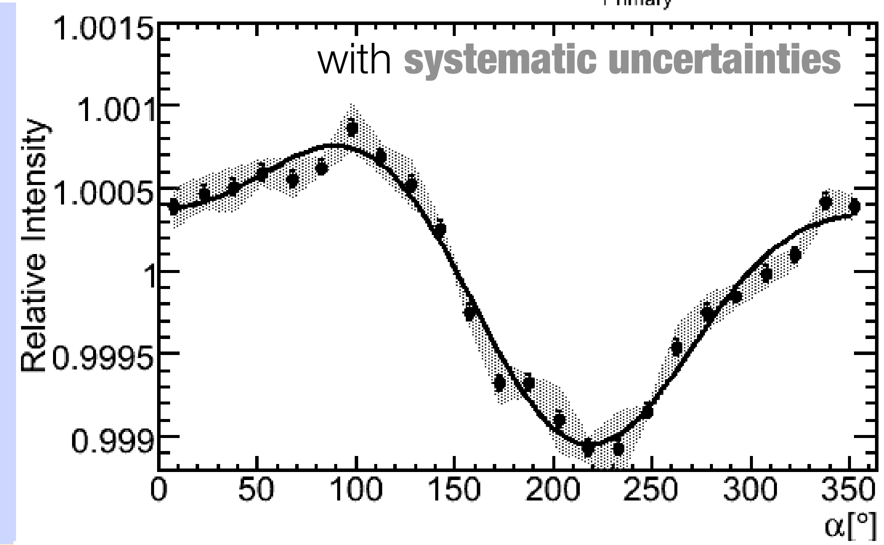
cosmic ray anisotropy large scale
IceCube

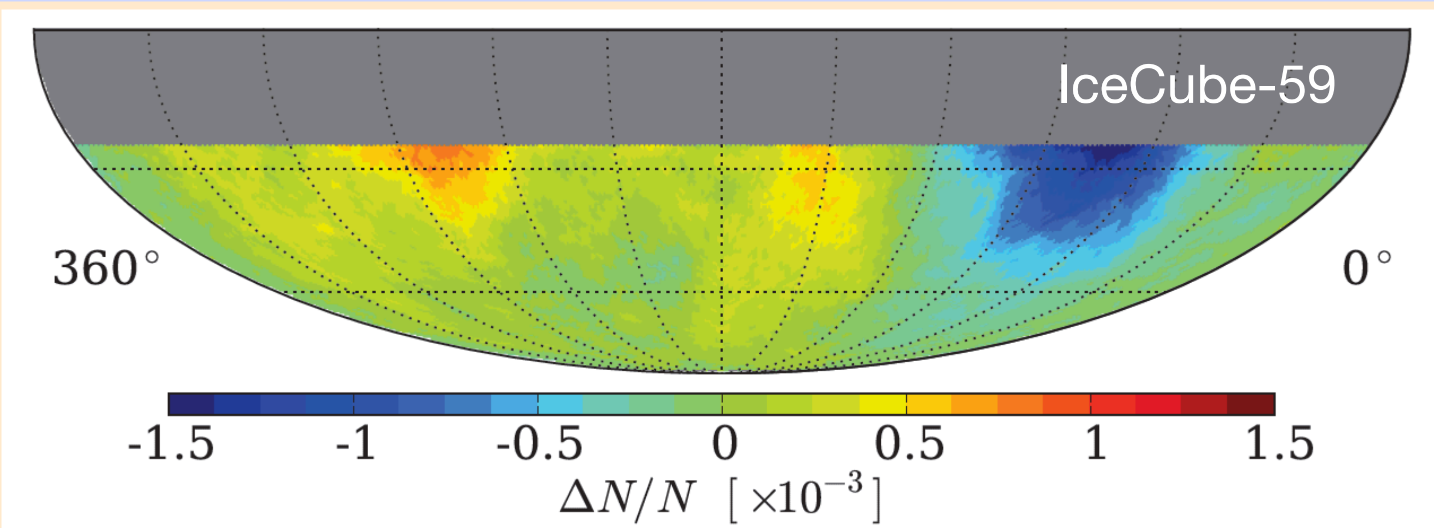


relative intensity equatorial coordinates



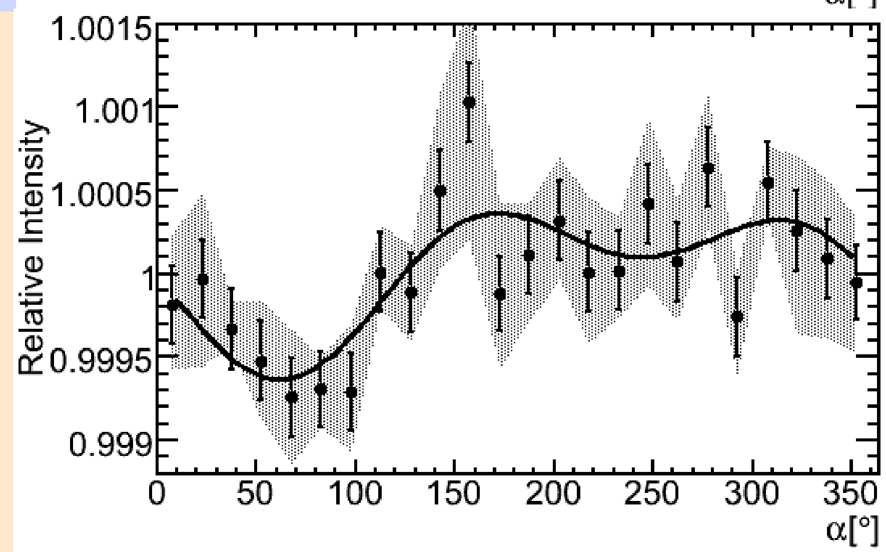
20 TeV





400 TeV

deficit
6.3 σ_{post}



NOTE: anisotropy is **not a dipole**
topology changes above ~ 100 TeV

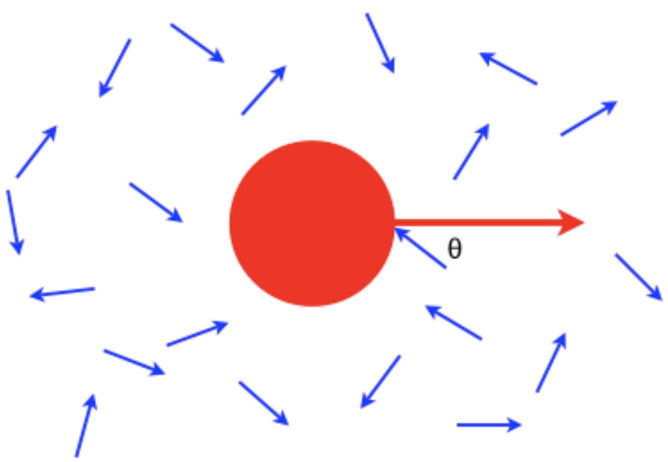
IC59 Abbasi et al., ApJ, **746**, 33, 2012

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

a known anisotropy

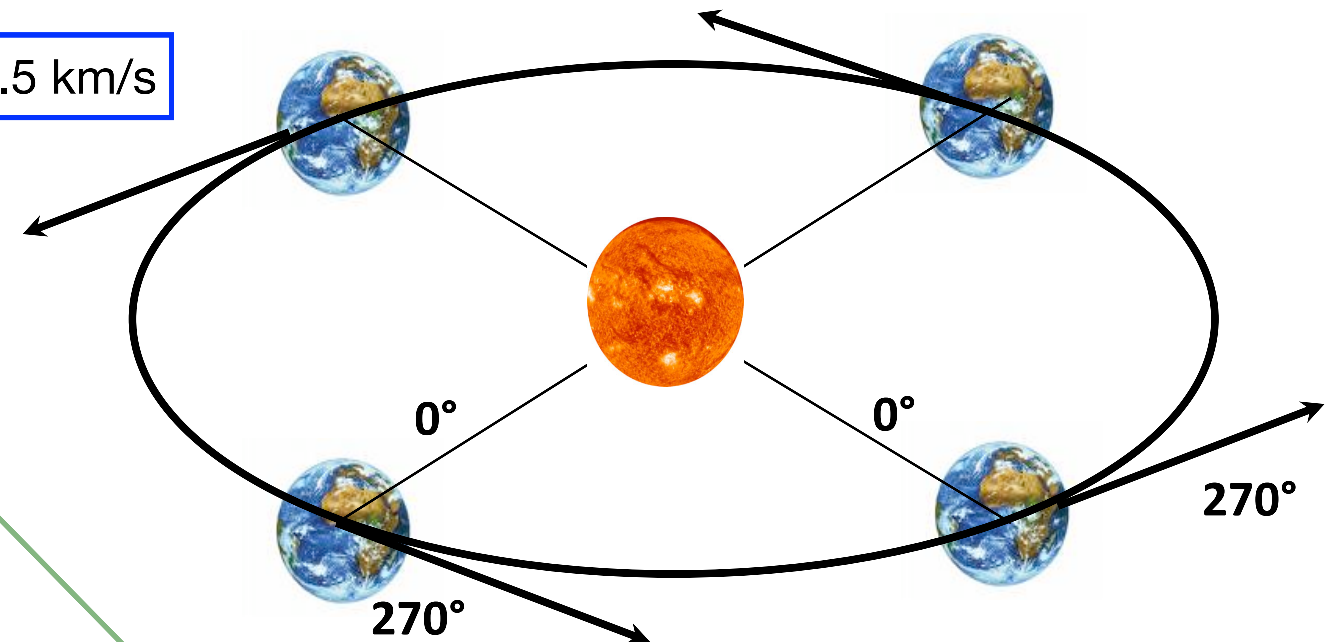
Earth's motion around the Sun

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

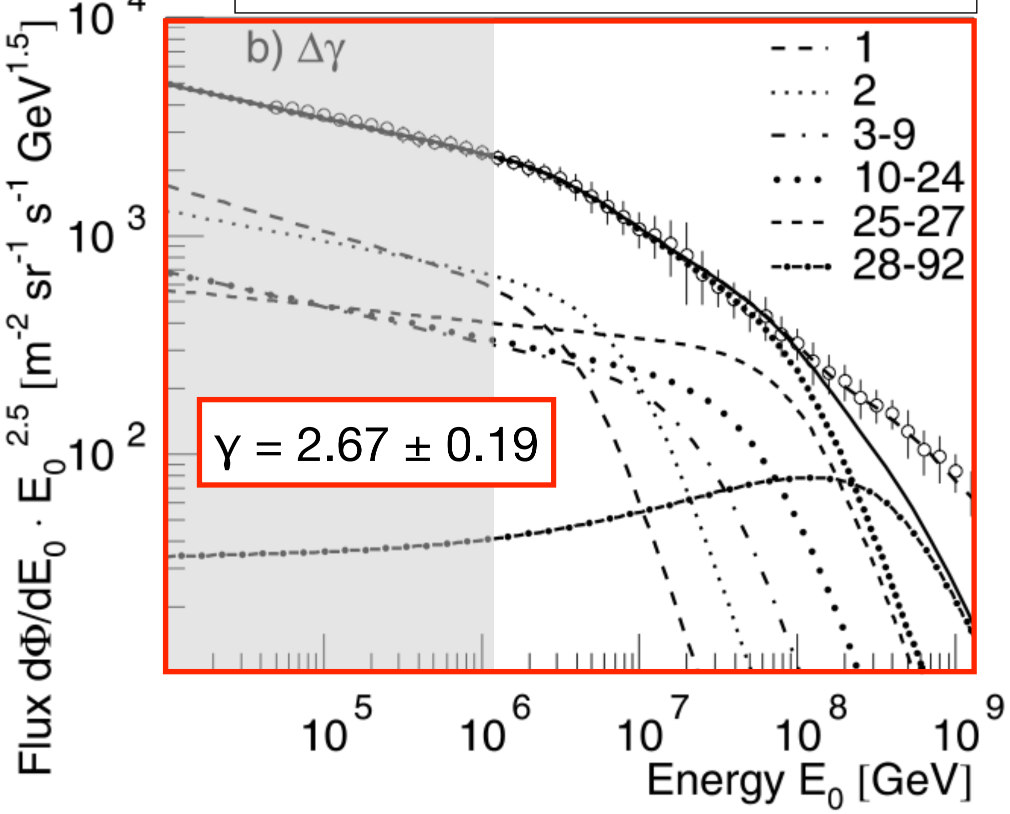


v = 29.8 ± 0.5 km/s

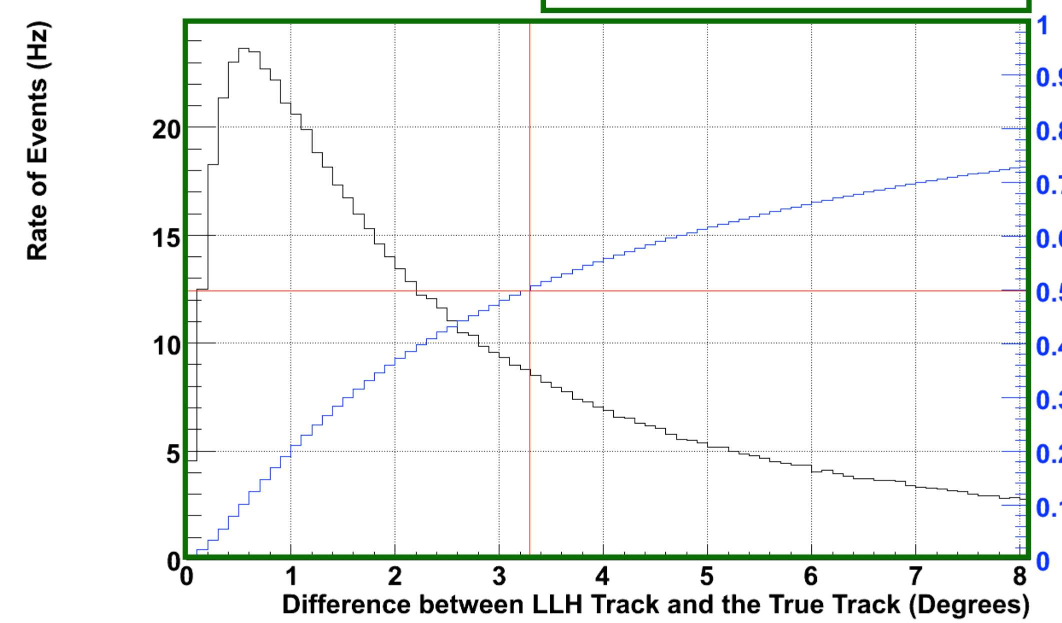
$$\frac{\Delta I}{I} = (\gamma + 2)\frac{v}{c}\cos\theta$$



Hörandel, Astrop. Phys. 19, 193, 2003



point spread function



a known anisotropy

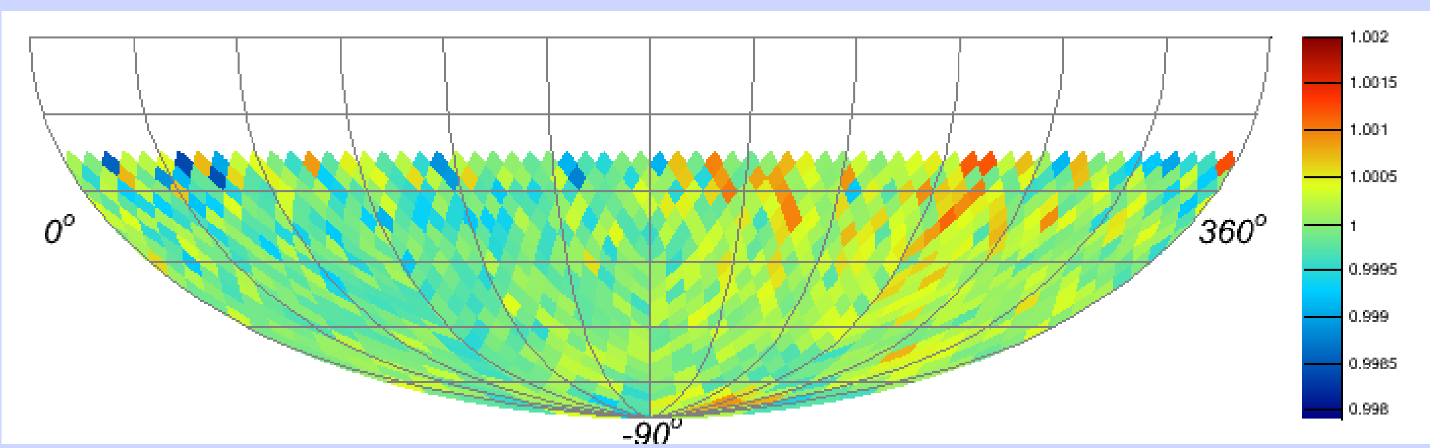
Earth's motion around the Sun

- 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

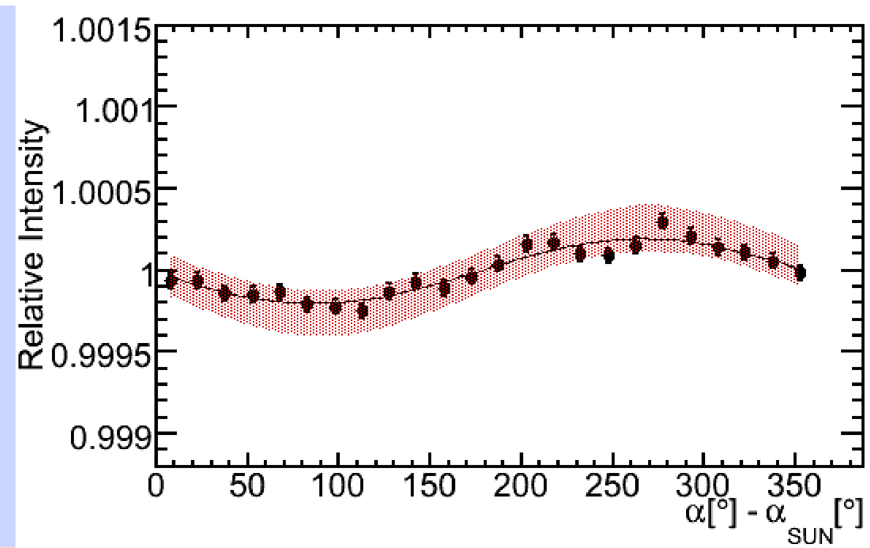
relative intensity

α [˚] - α_{SUN} [˚]

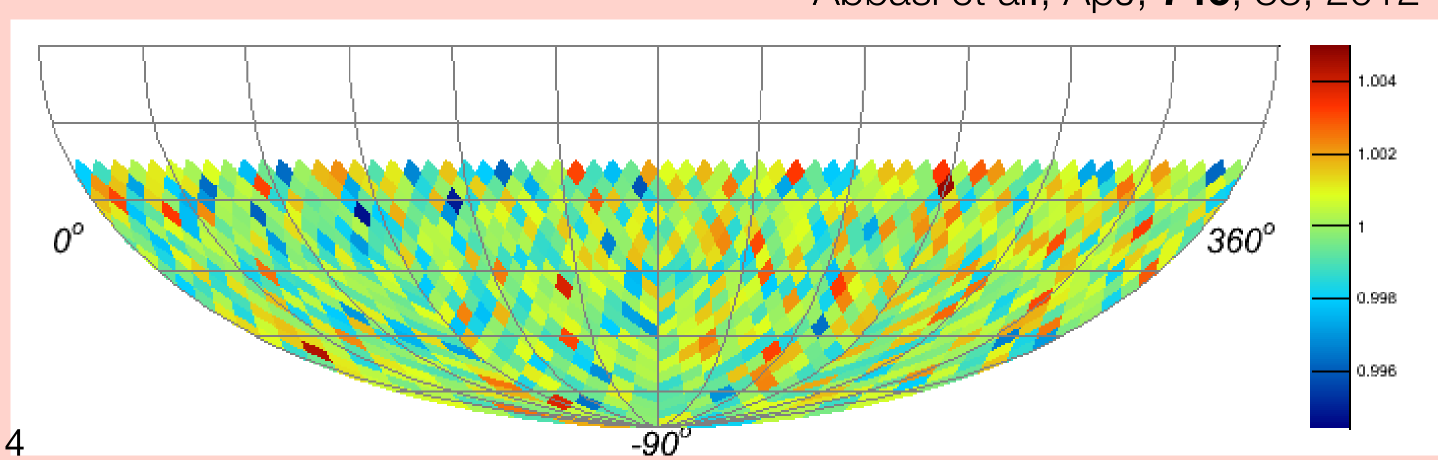
IC59 Abbasi et al., ApJ, **746**, 33, 2012



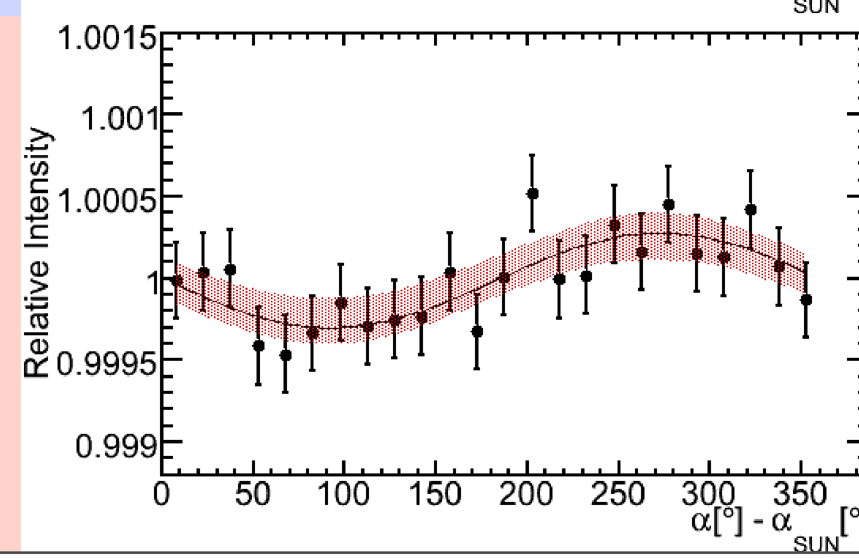
20 TeV



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

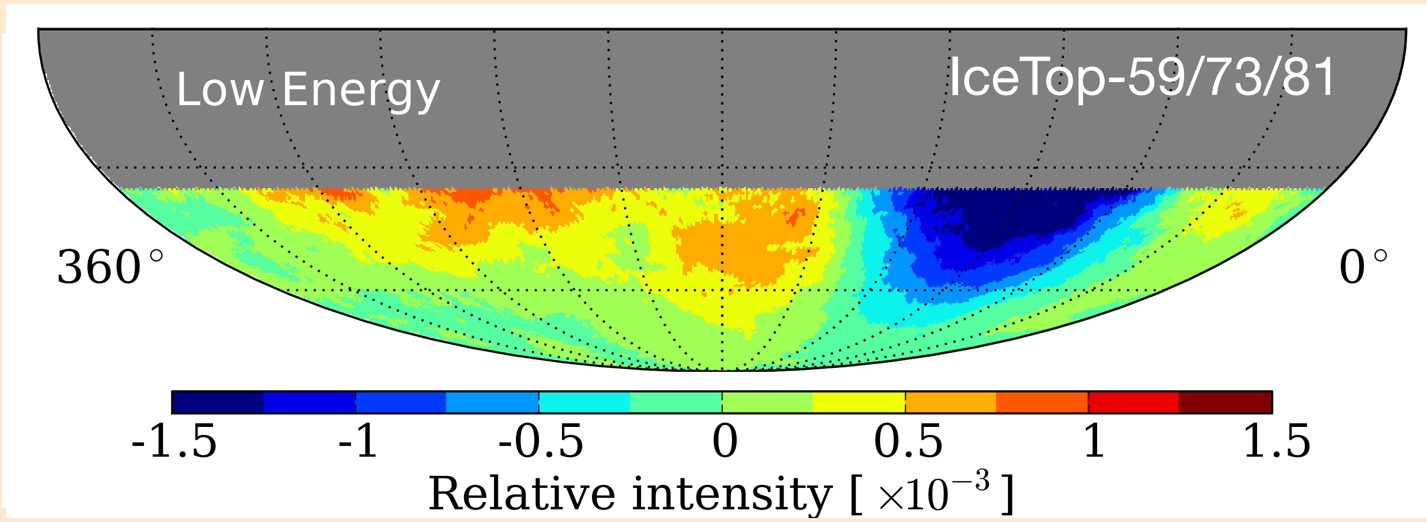


400 TeV

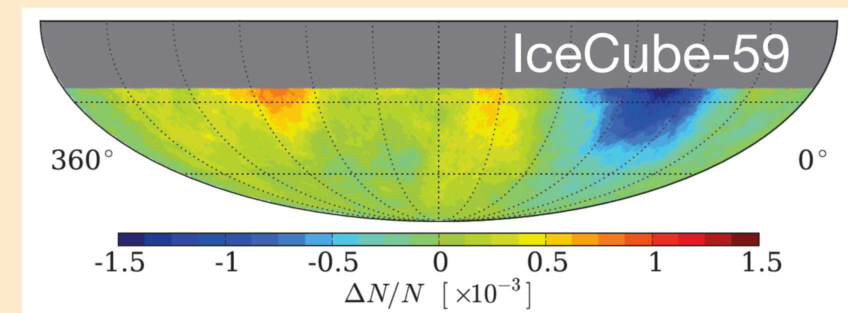


cosmic ray anisotropy large scale
IceTop

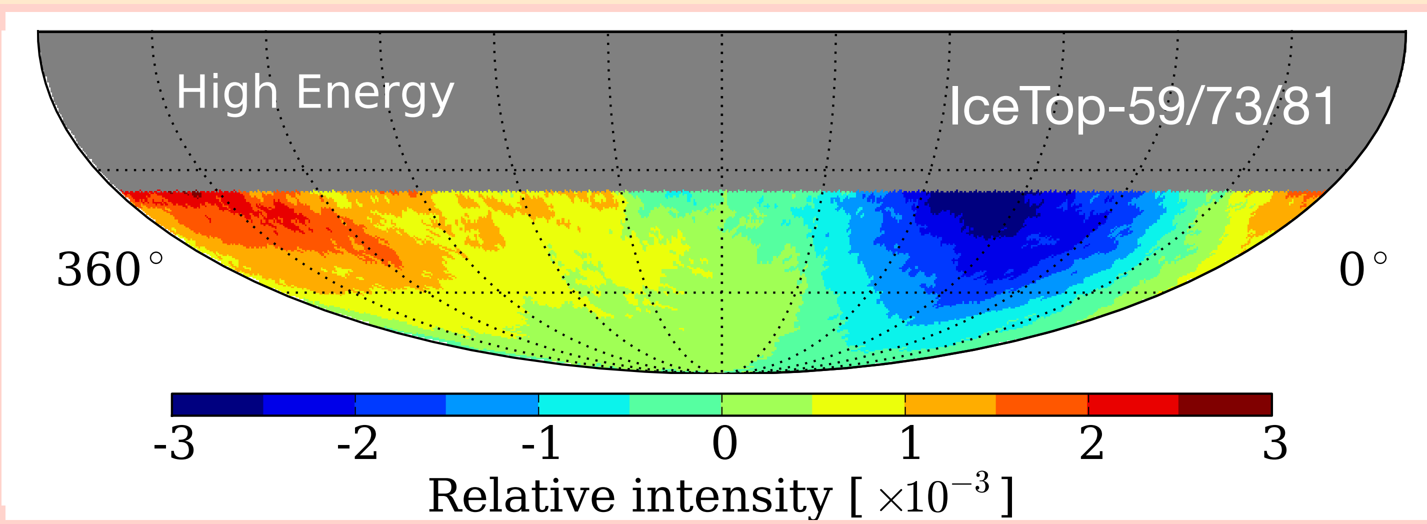
relative intensity equatorial coordinates



deficit
7 σ_{post}



400 TeV



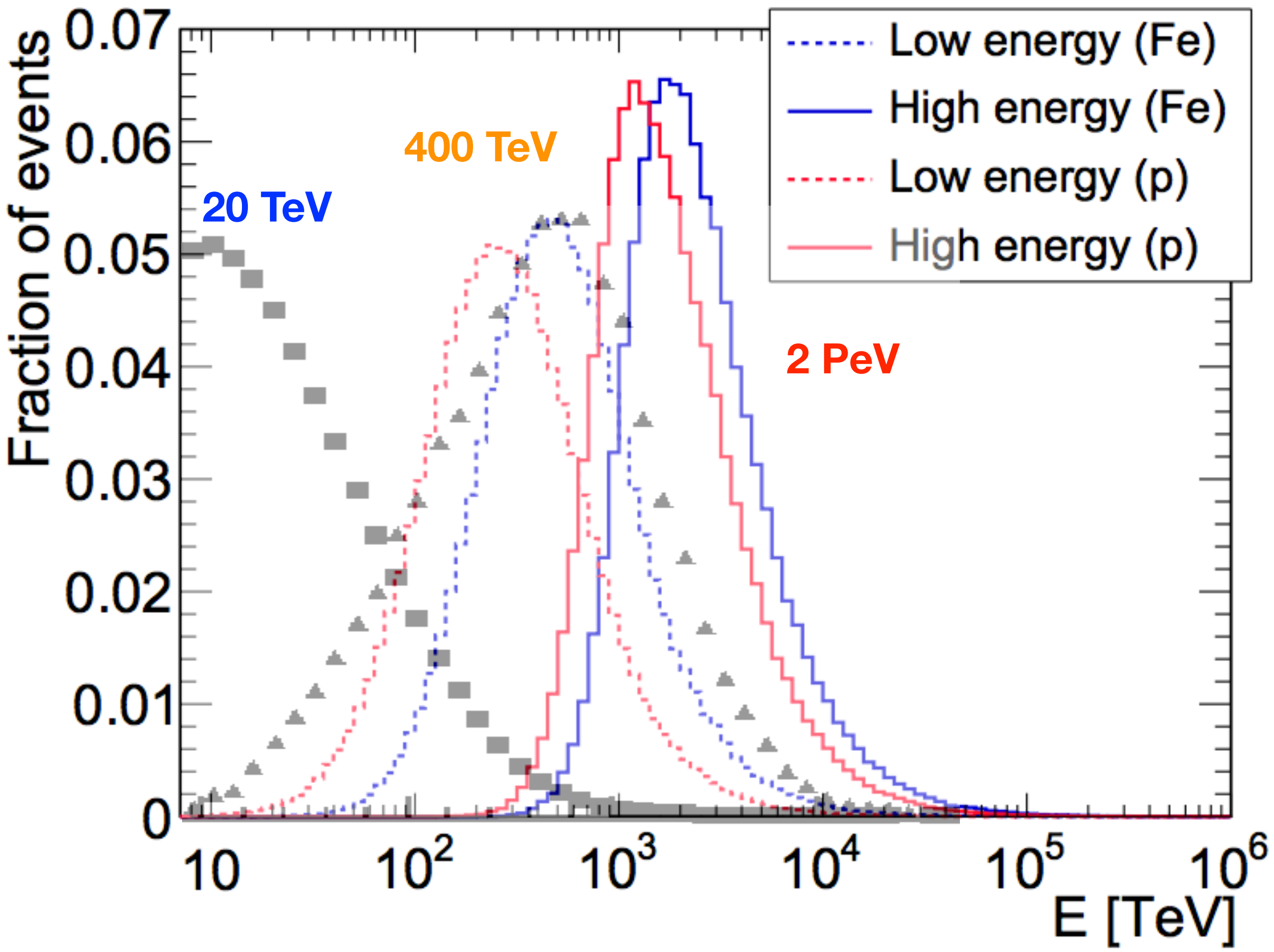
2 PeV

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

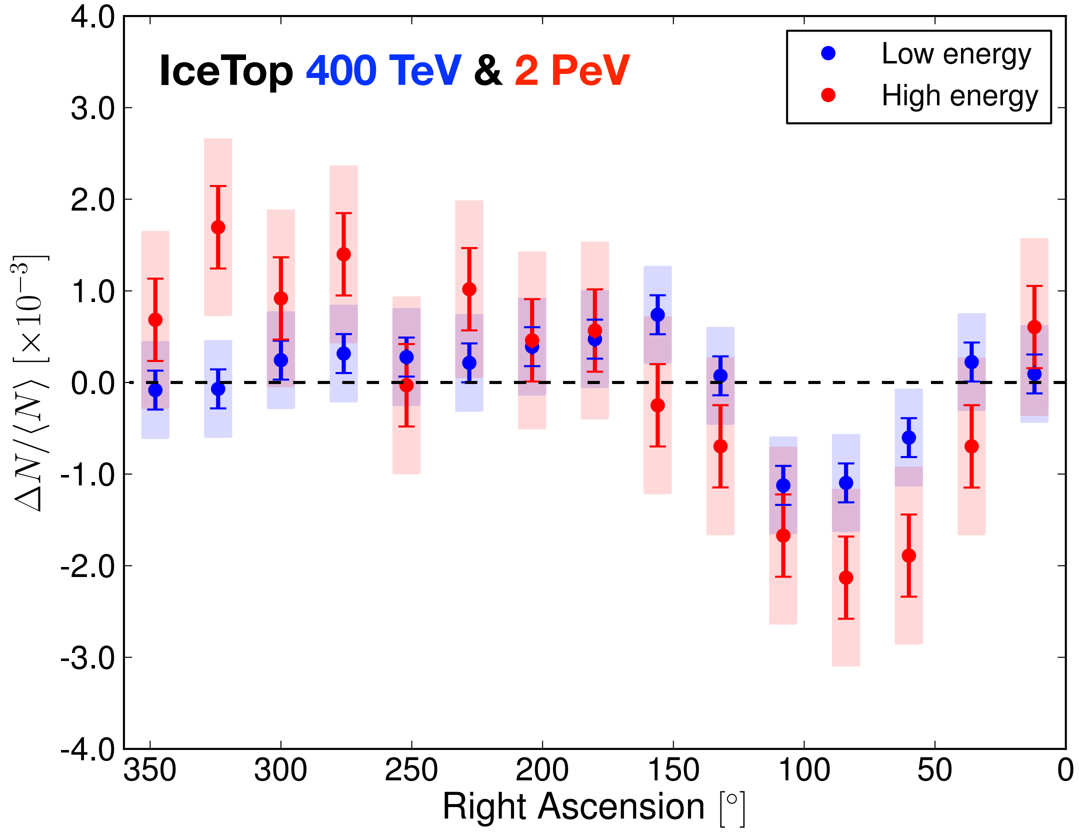
NOTE: global topology does not change above ~100 TeV

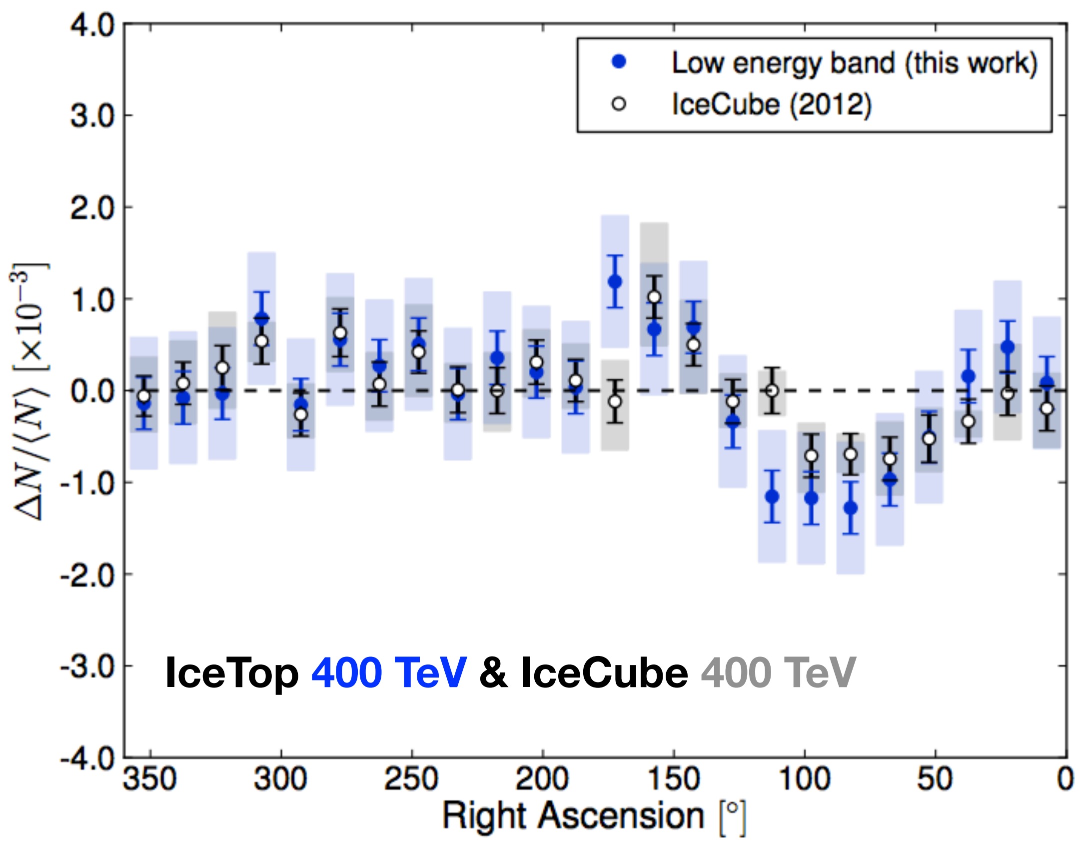
deficit amplitude increases with energy

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

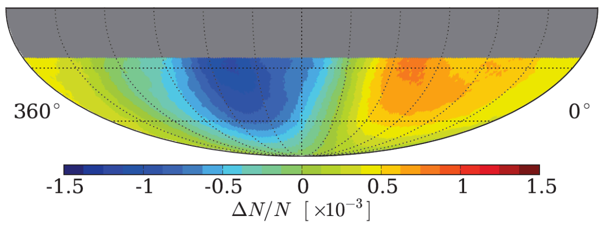
might explain IC/IT amplitude differences

Gaisser, Stanev, Tilav, 2013 - arXiv:1303.3565

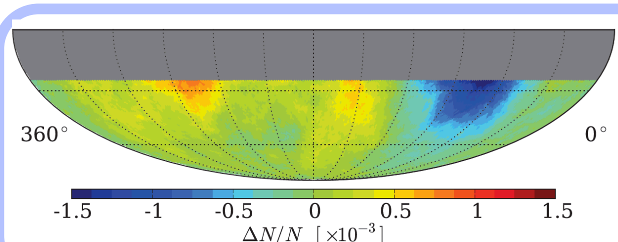
cosmic ray anisotropy
large scale

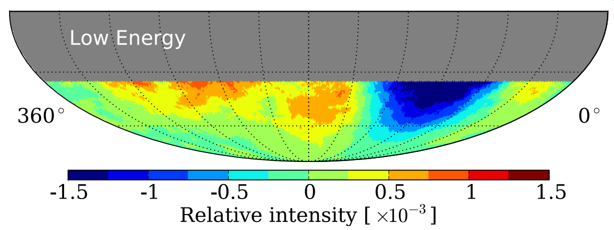
IceCube IceTop

20 TeV

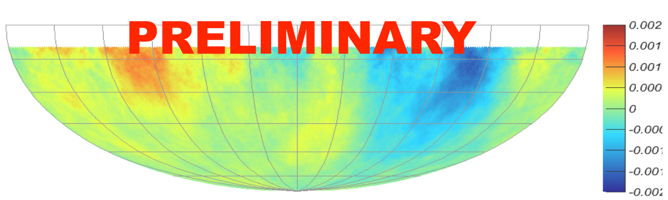


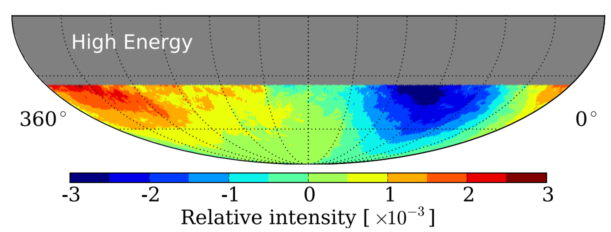
400 TeV



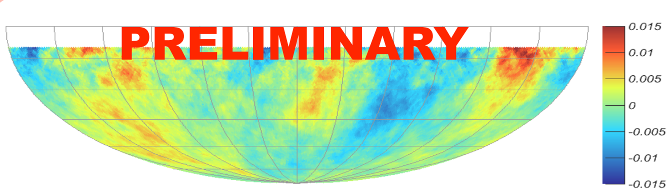


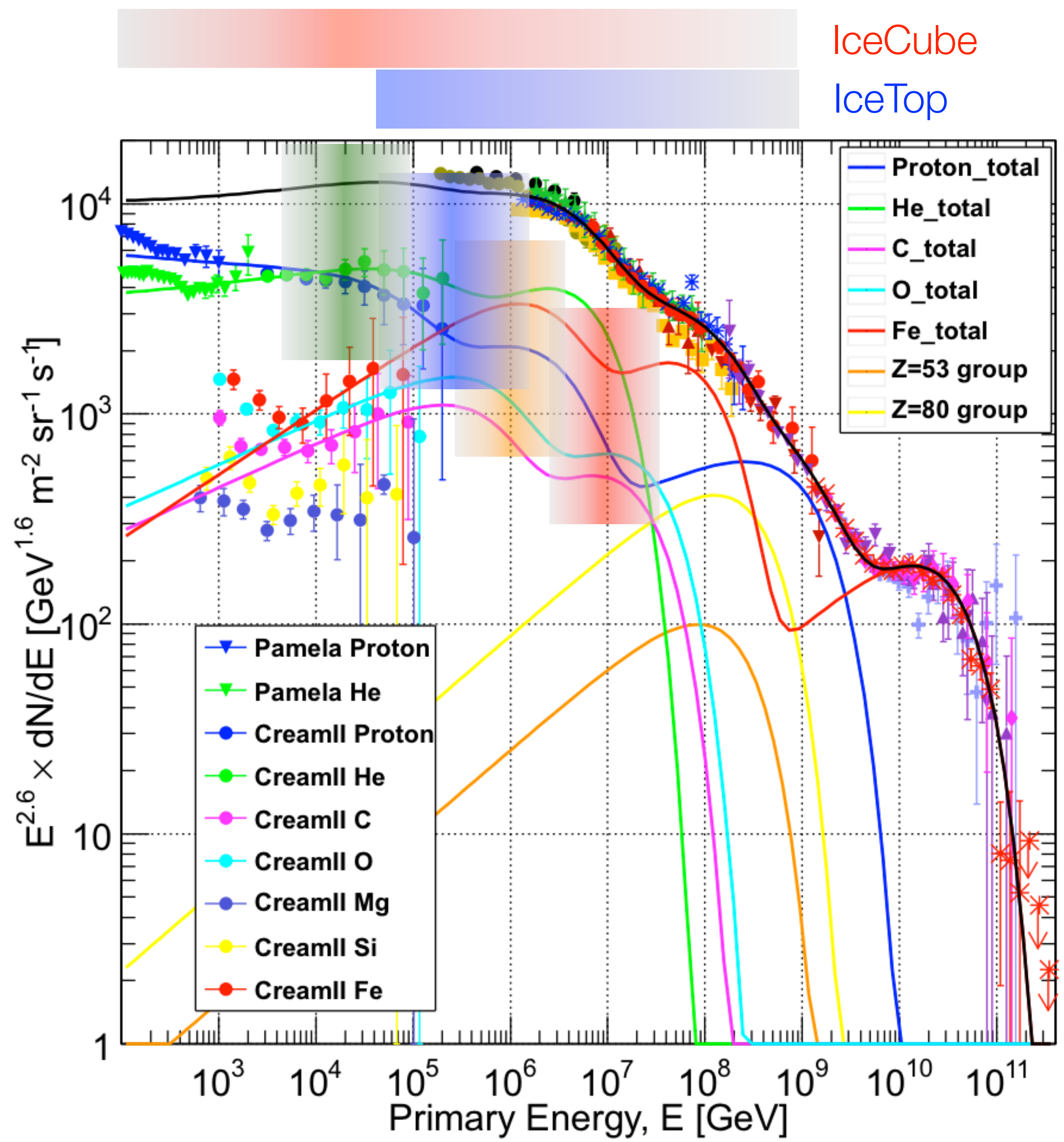
2 PeV





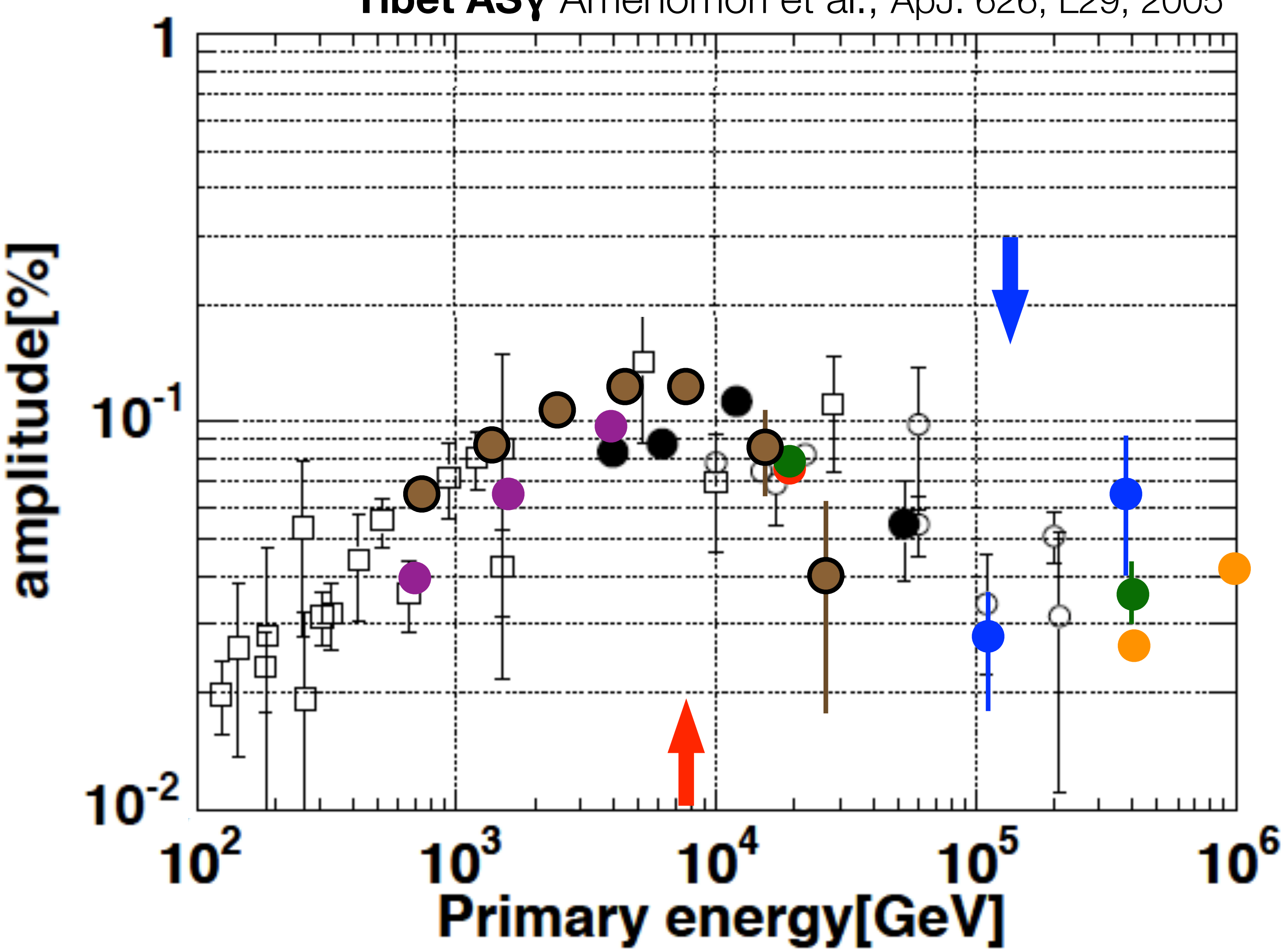
10 PeV





- extend observation above PeV range
- primary mass dependency
- primary spectrum at excess/deficit

cosmic ray anisotropy large scale energy dependency



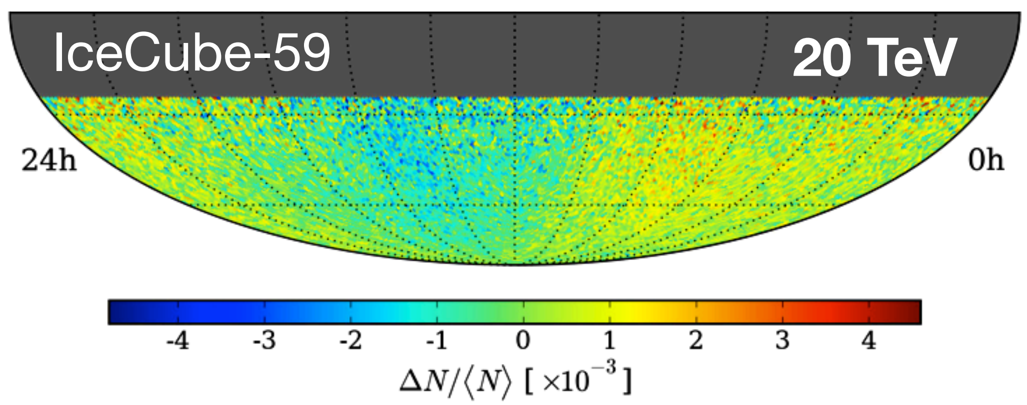
dipole component
- **IceCube-22** Abbasi et al., ApJ, 718, L194, 2010
- **IceCube-59** Abbasi et al., ApJ, 746, 33, 2012
- **EAS-TOP** Aglietta et al., ApJ, 692, L130, 2009
- **ARGO-YBJ** Zhang 31st ICRC Łódź-Poland,2009
- **ARGO-YBJ** 32nd ICRC Beijng China,2011

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

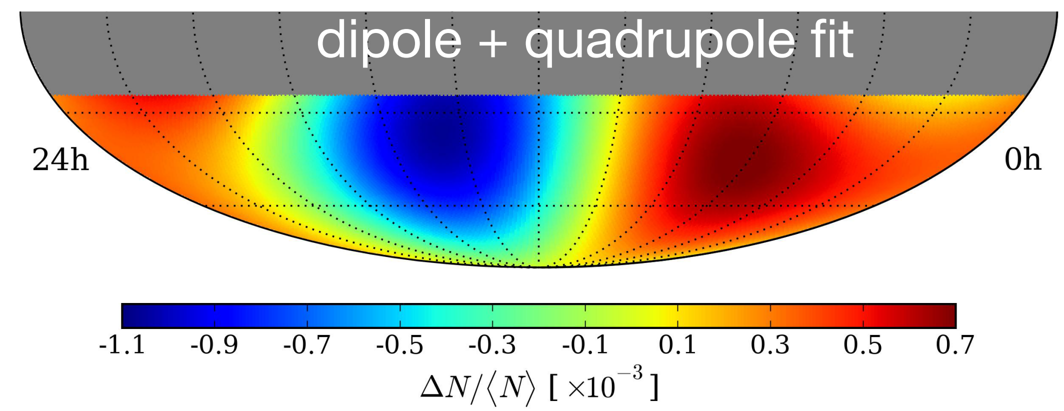
- modulation in amplitude of **dipole** component
- corresponds to **transition** in anisotropy topology

cosmic ray anisotropy small scale
IceCube

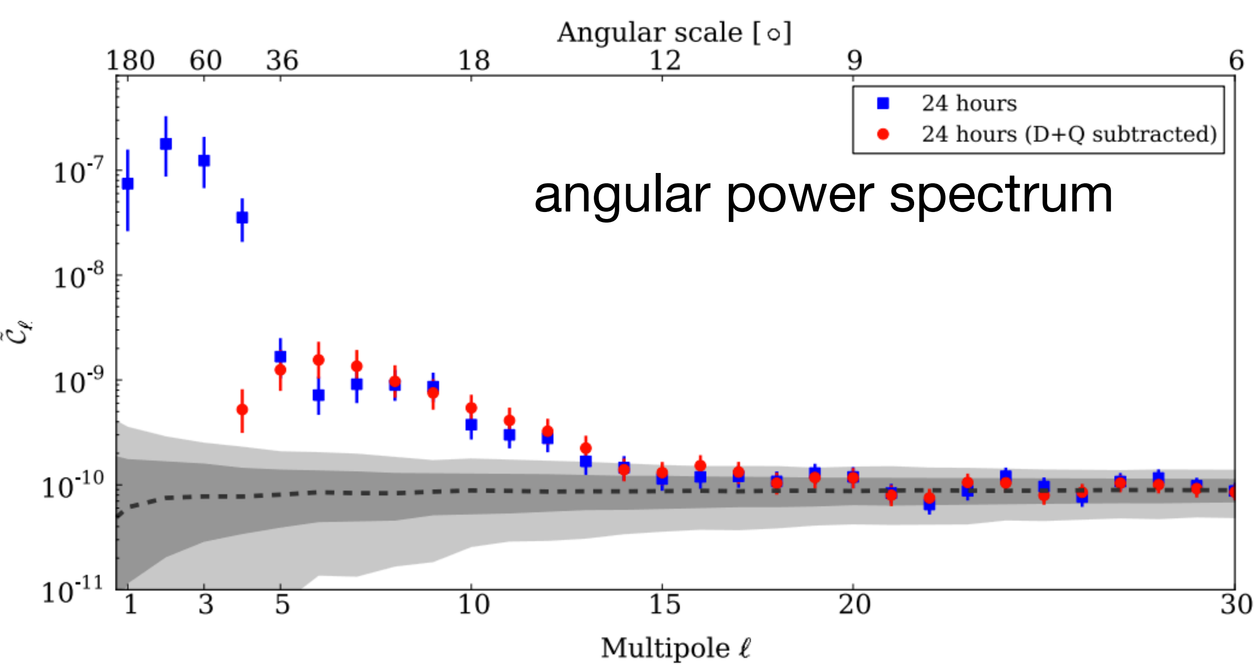
relative intensity raw map

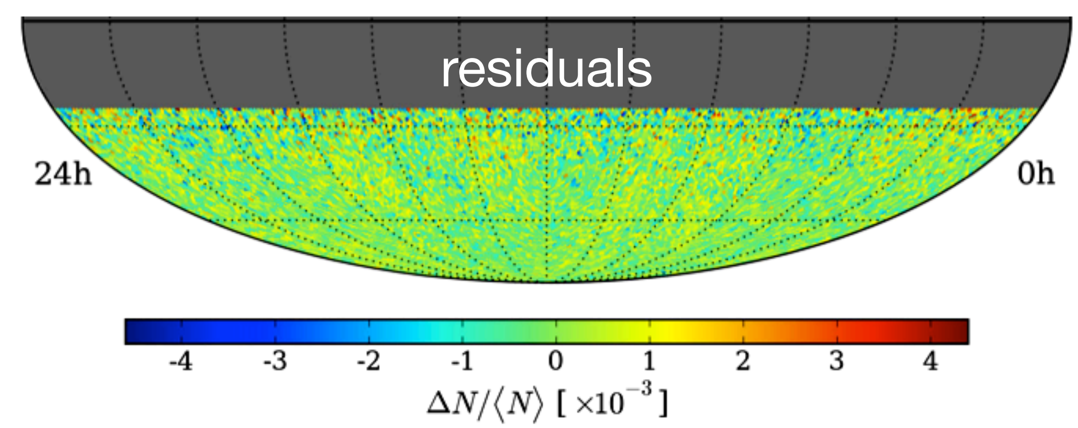


χ^2/ndf = 14743.4 / 14187 (prob = 0.05%)



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



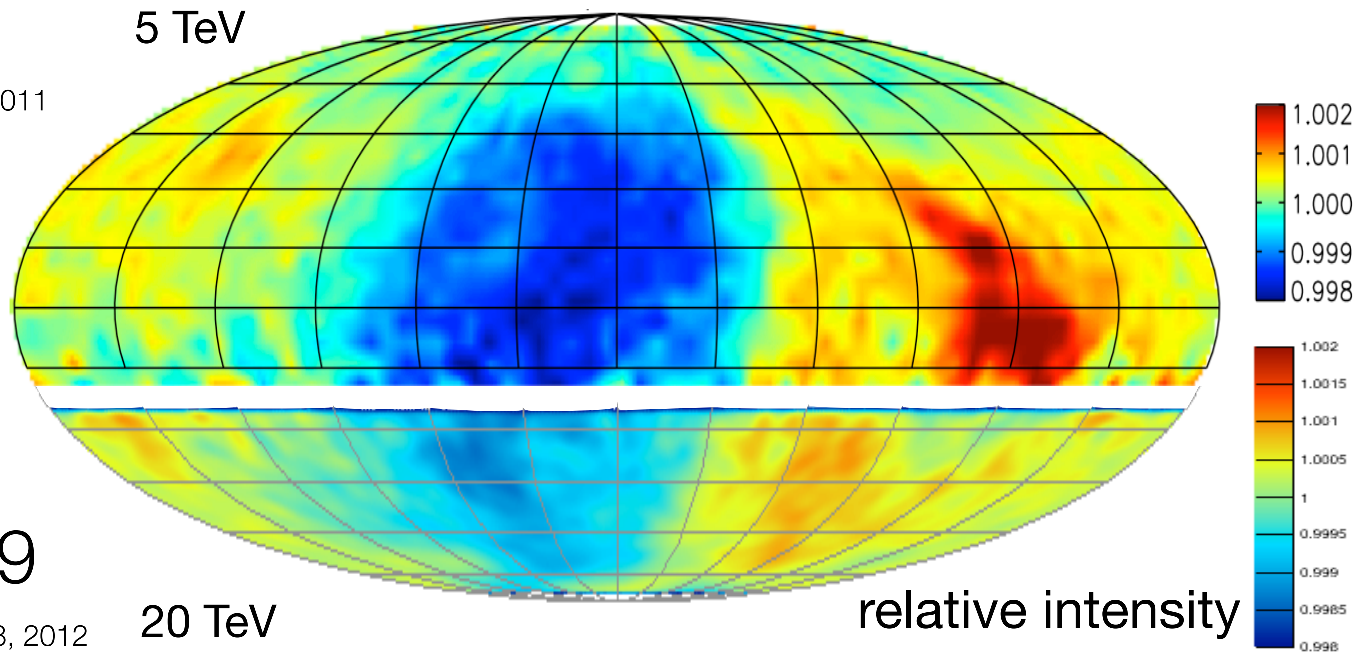


cosmic ray anisotropy

- full sky map at **comparable energy**
  - to better determine low ℓ spherical harmonic components
  - to analyze fine angular structures across the sky

Tibet-III 5 TeV

Amenomori et al., ICRC 2011



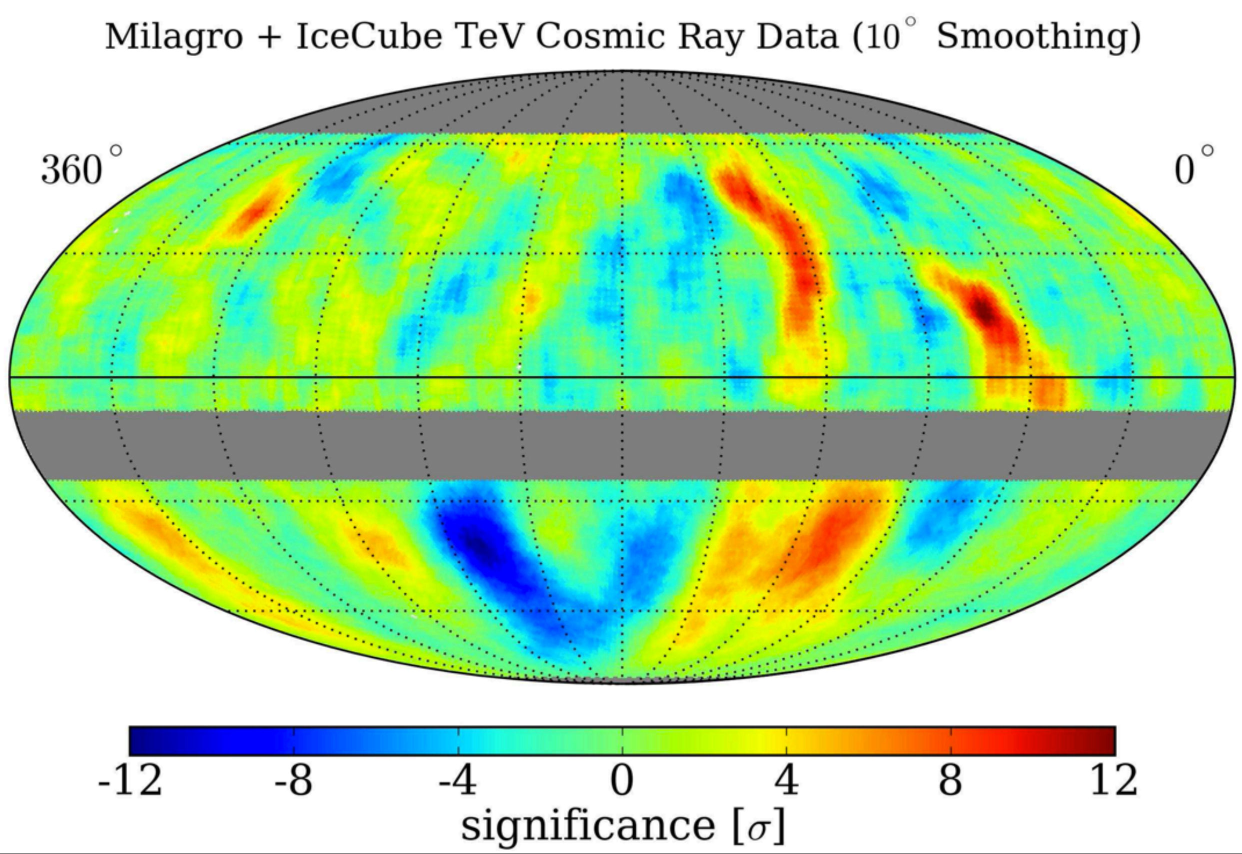
IceCube-59 20 TeV

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

relative intensity

2 hr = 30°

4 hr = 60°



Milagro 1 TeV

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

IceCube-59 20 TeV

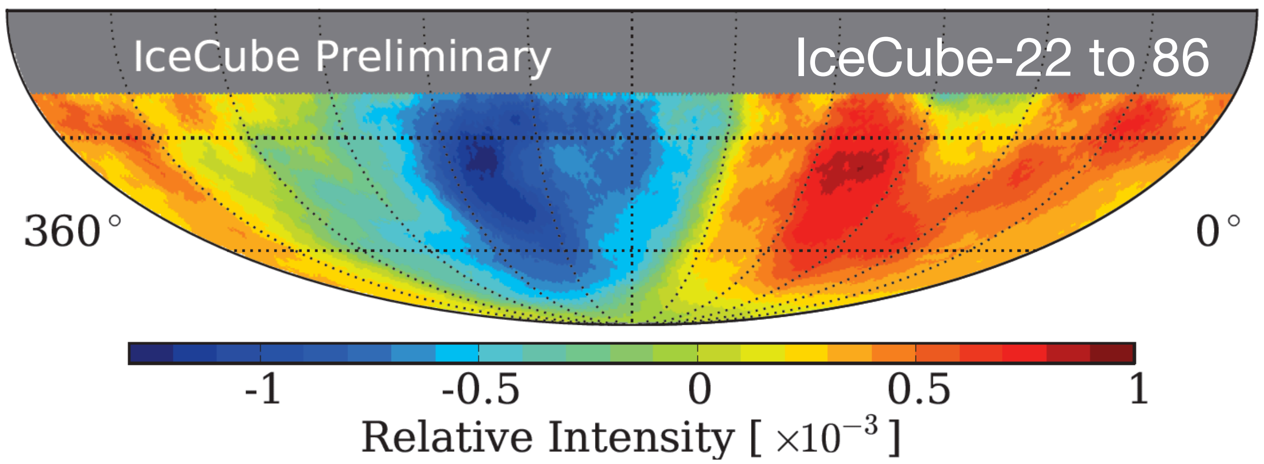
Abbasi et al., ApJ, **740**, 16, 2011

equatorial coordinates

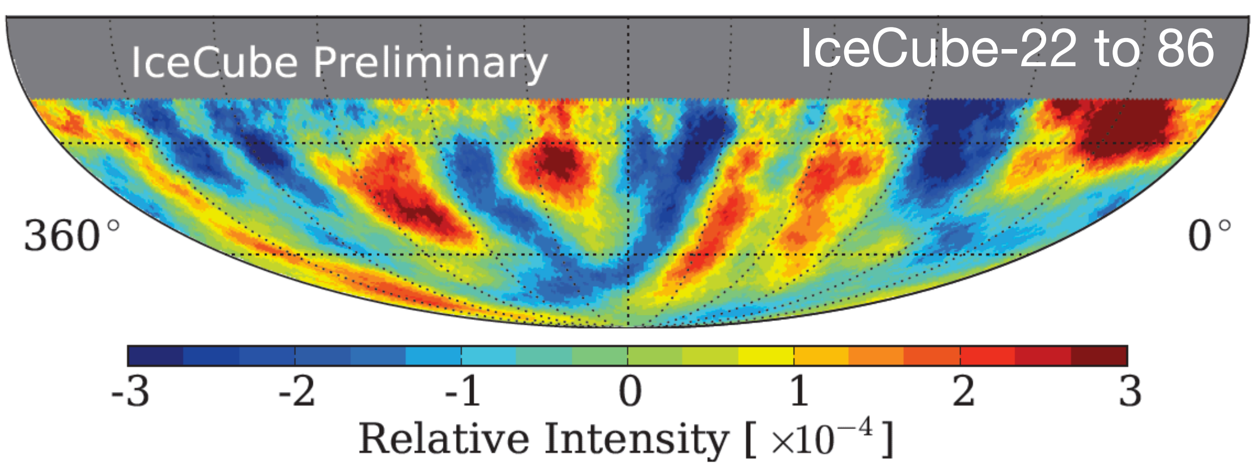
cosmic ray anisotropy
IceCube 2007-2012

PRELIMINARY

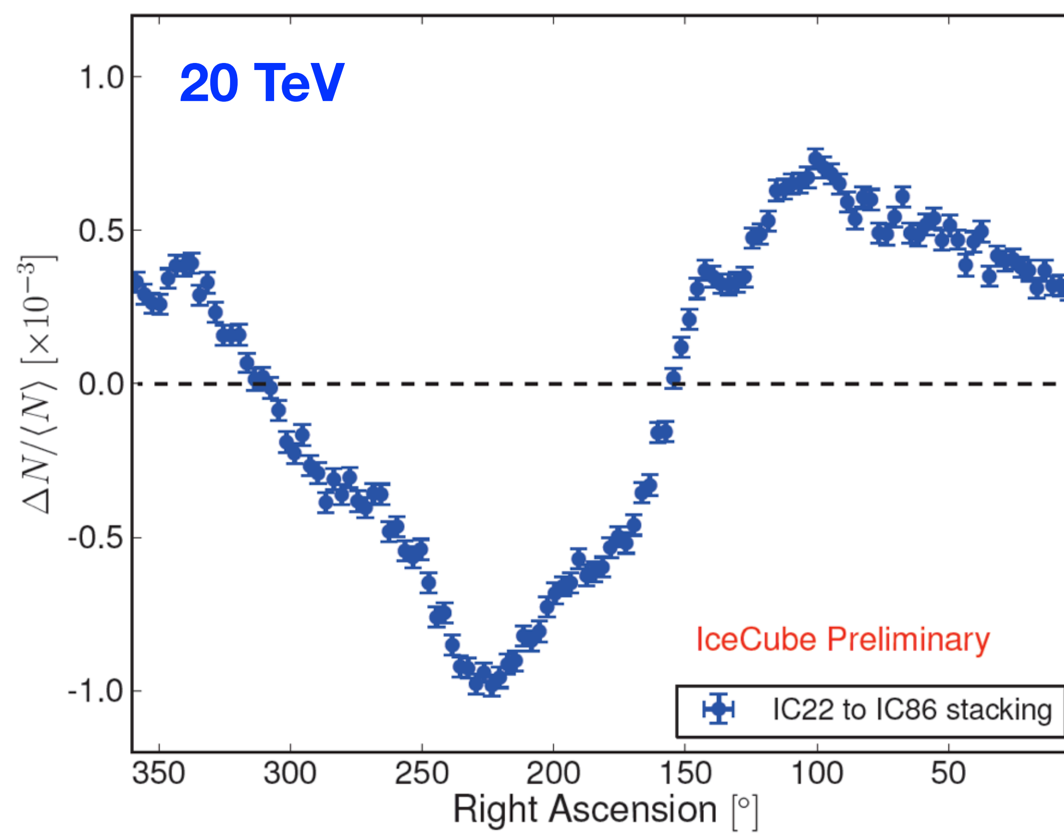
relative intensity | equatorial coordinates



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

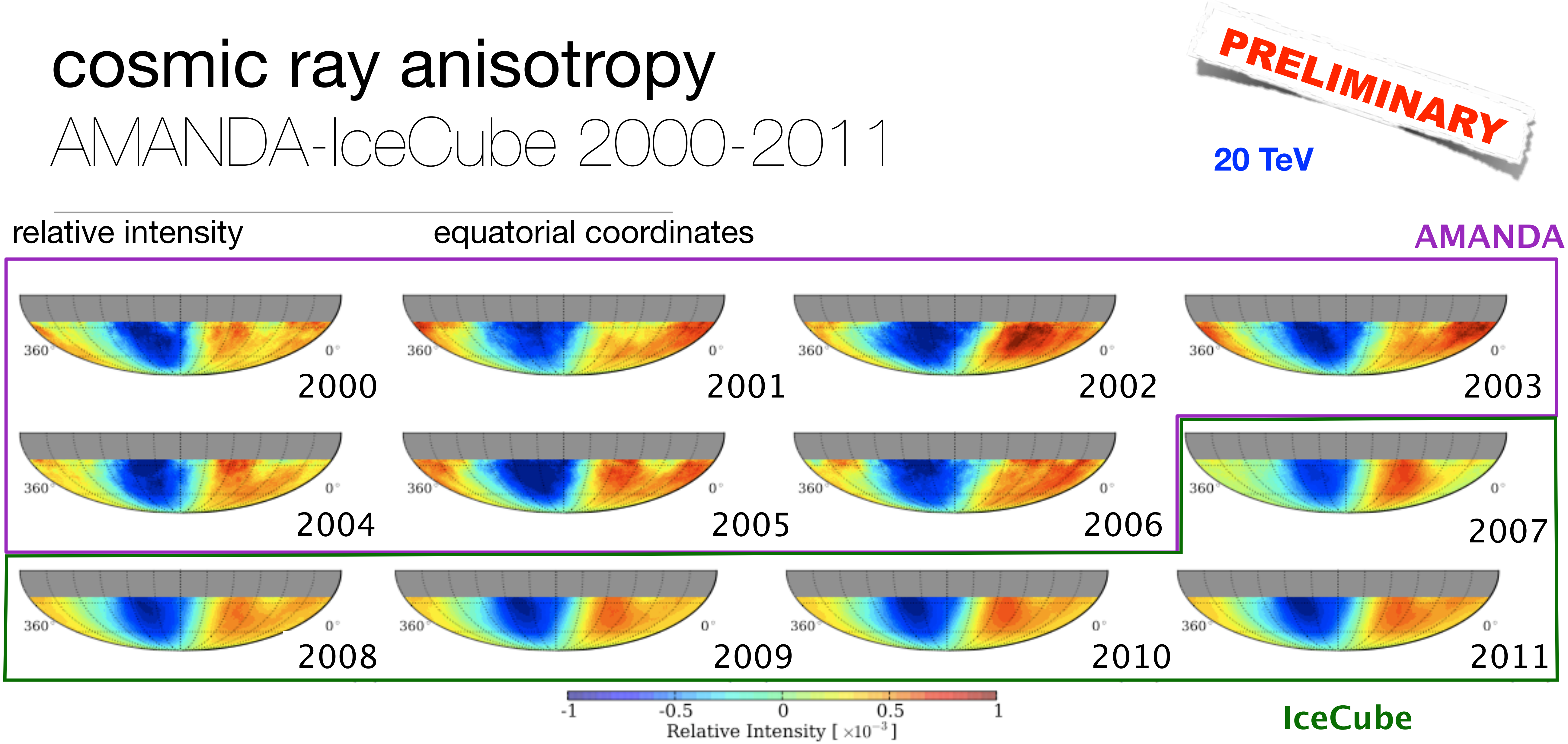


5° smoothing



cosmic ray anisotropy

AMANDA-IceCube 2000-2011



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

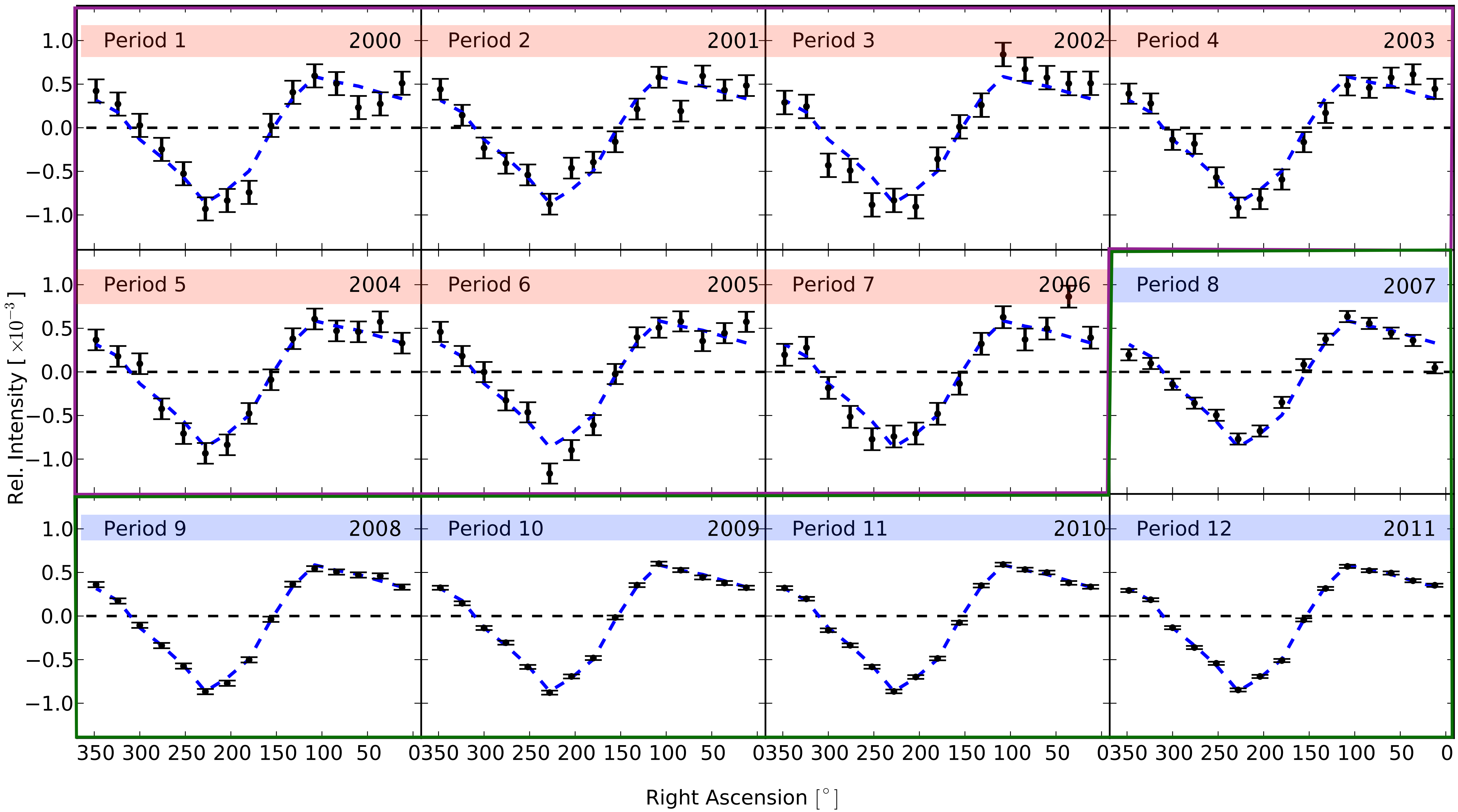
- no apparent effect correlated to solar cycles

cosmic ray anisotropy

AMANDA-IceCube 2000-2011

PRELIMINARY

20 TeV



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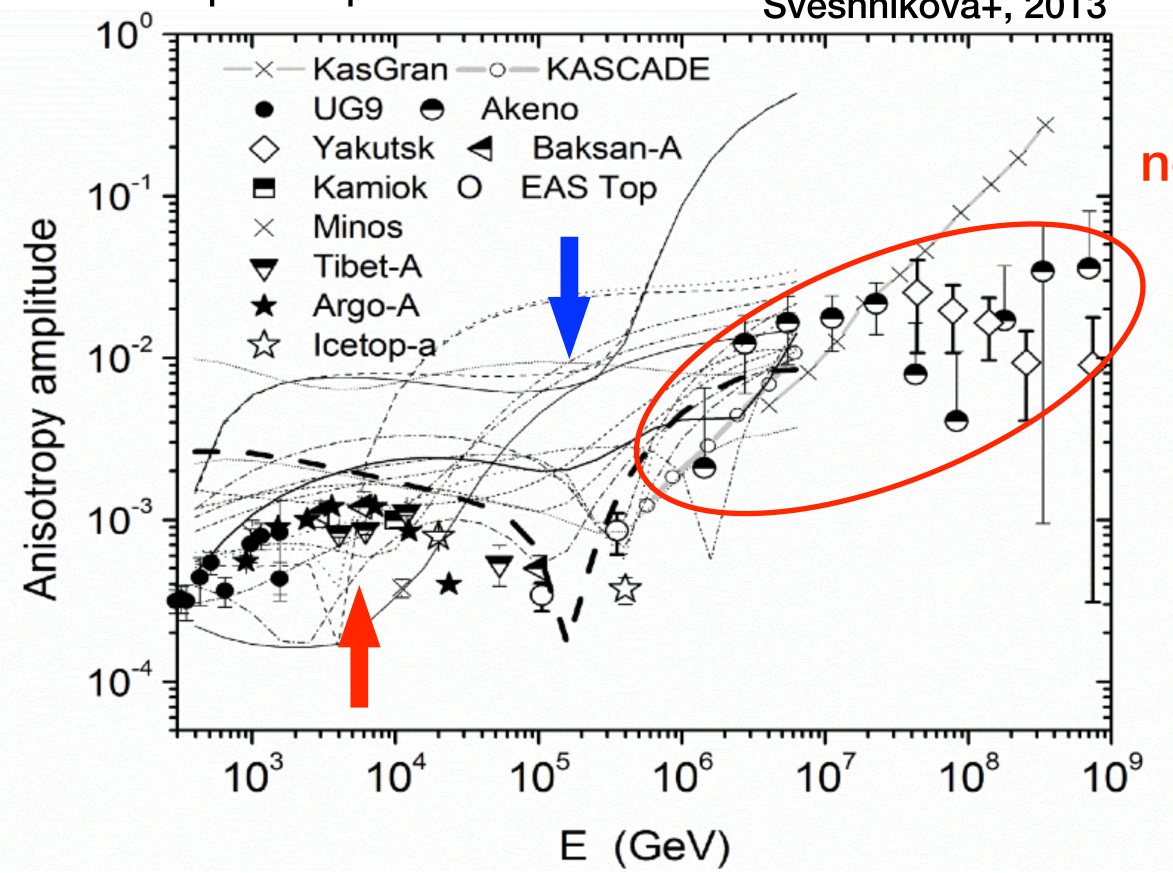
cosmic ray anisotropy

probing sources & propagation of cosmic rays ?

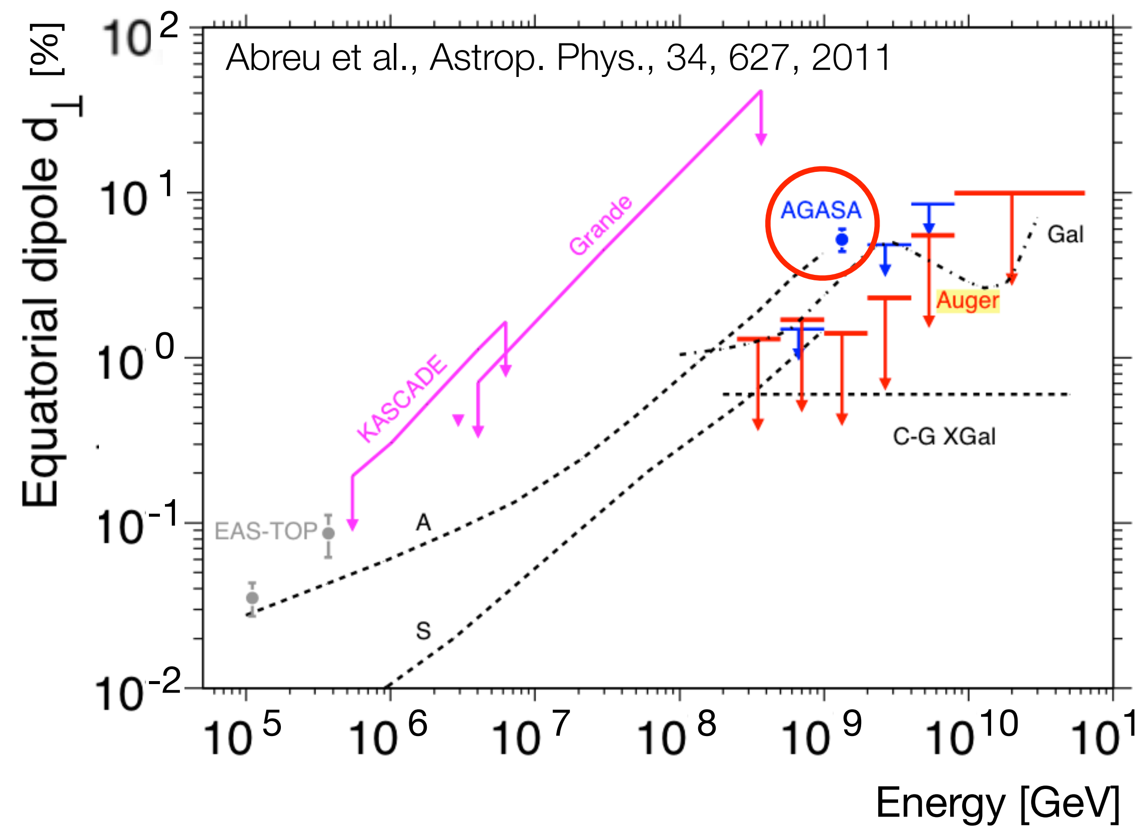
- stochastic effect of **nearby & recent sources** & temporal correlations

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



not dipole observations

dipole components of the anisotropy



cosmic ray anisotropy
probing sources & propagation of cosmic rays ?

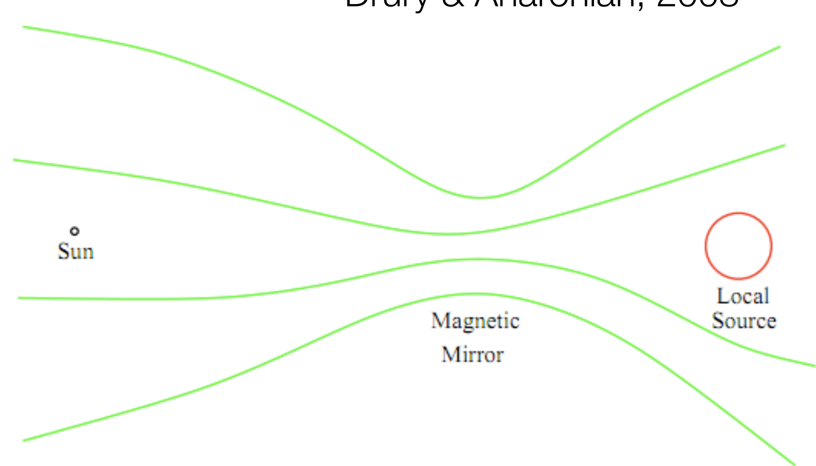
- stochastic effect of **nearby & recent sources** & temporal correlations

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

- propagation effect from a near by source to produce localized excess

Salvati & Sacco, 2008
Drury & Aharonian, 2008
Salvati, 2010
Malkov+, 2010

Drury & Aharonian, 2008



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cosmic ray anisotropy
probing sources & propagation of cosmic rays ?

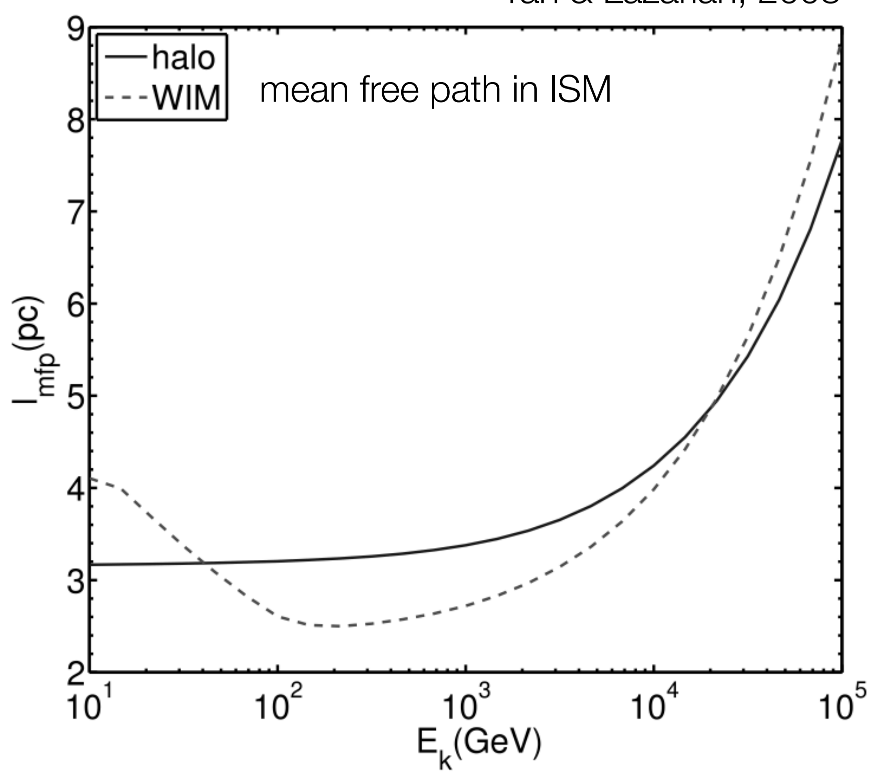
- stochastic effect of **nearby & recent sources** & temporal correlations

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

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

Giacinti & Sigl, 2012
Biermann+, 2012

Yan & Lazarian, 2008



Giacinti & Sigl, 2012

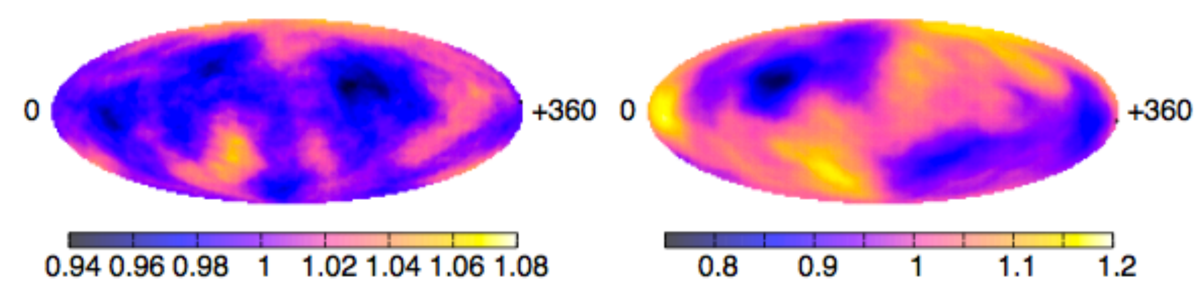
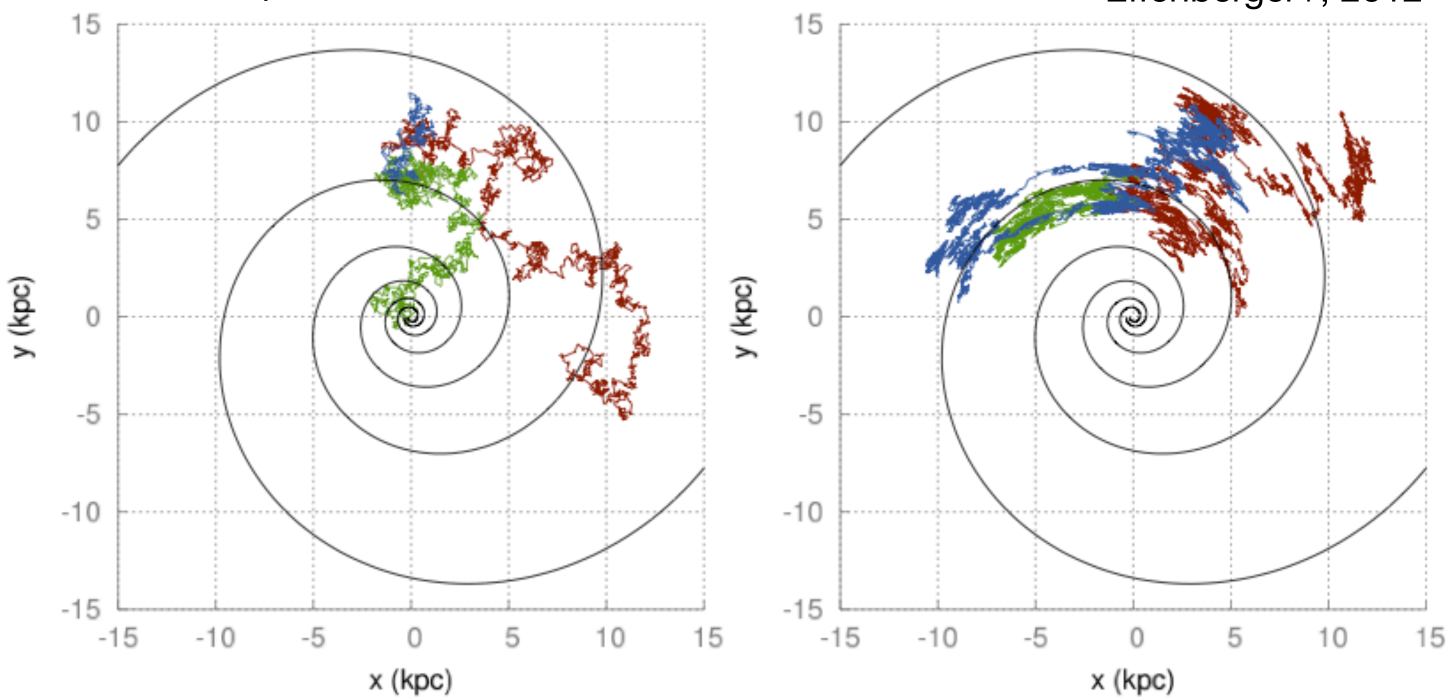


FIG. 1. Renormalized CR flux predicted at Earth for a concrete realization of the turbulent magnetic field, *after subtracting the dipole* and smoothing on 20° radius circles. Primaries with rigidities $p/Z = 10^{16}$ eV (*left panel*) and 5×10^{16} eV (*right panel*). See text for the field parameters and boundary conditions on the sphere of radius $R = 250$ pc.

cosmic ray anisotropy

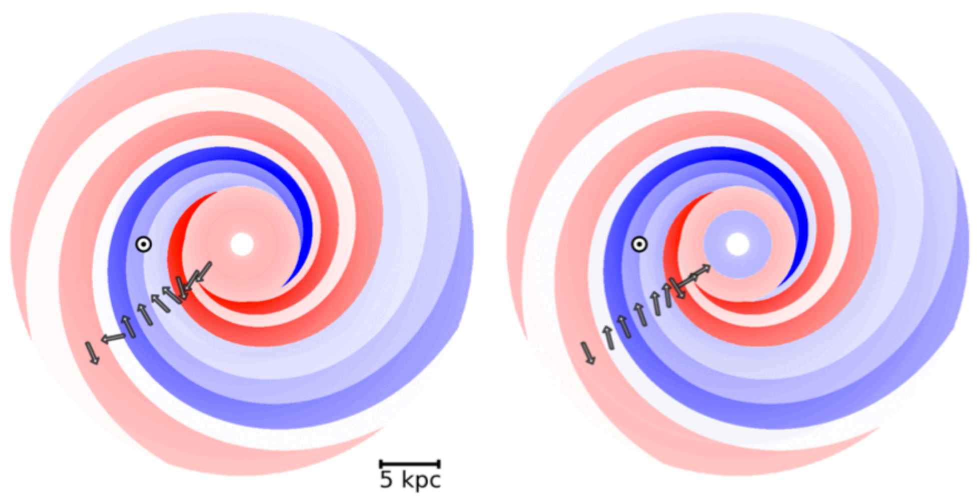
probing sources & propagation of cosmic rays ?

anisotropic diffusion



Effenberger+, 2012

Jansson & Farrar, 2012

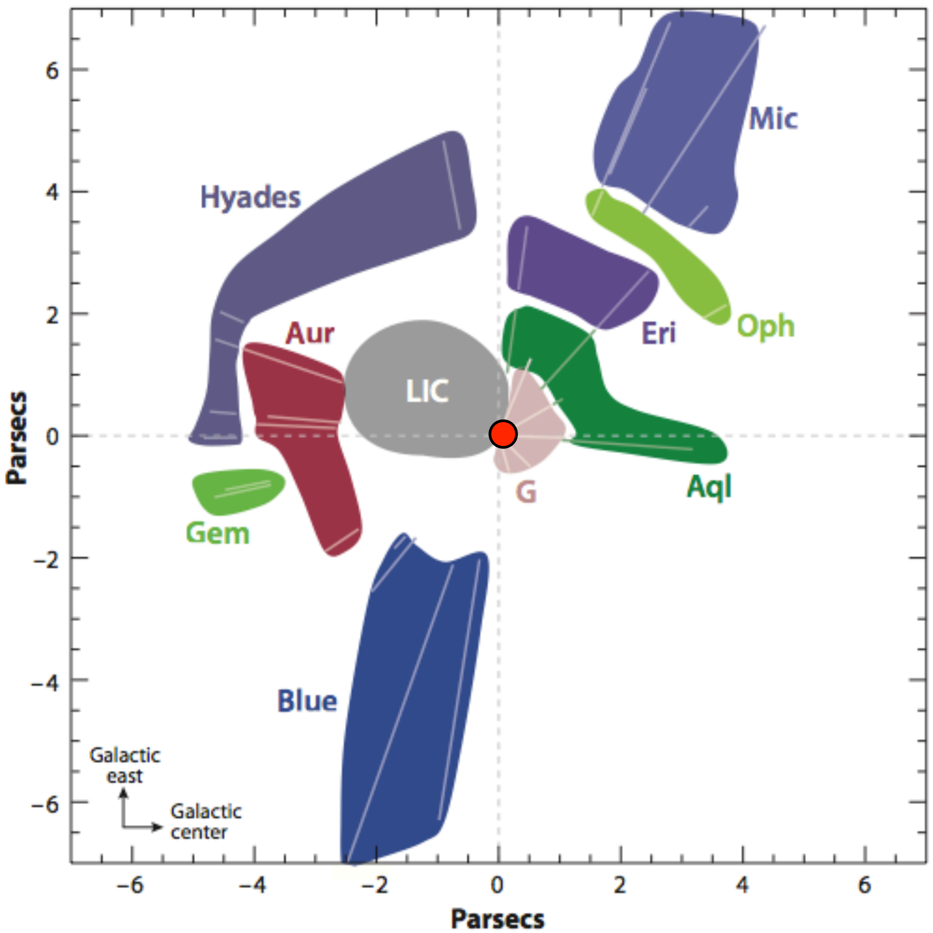


- diffusion coefficient hardly a single power law, homogeneous and isotropic

Effenberger+, 2012

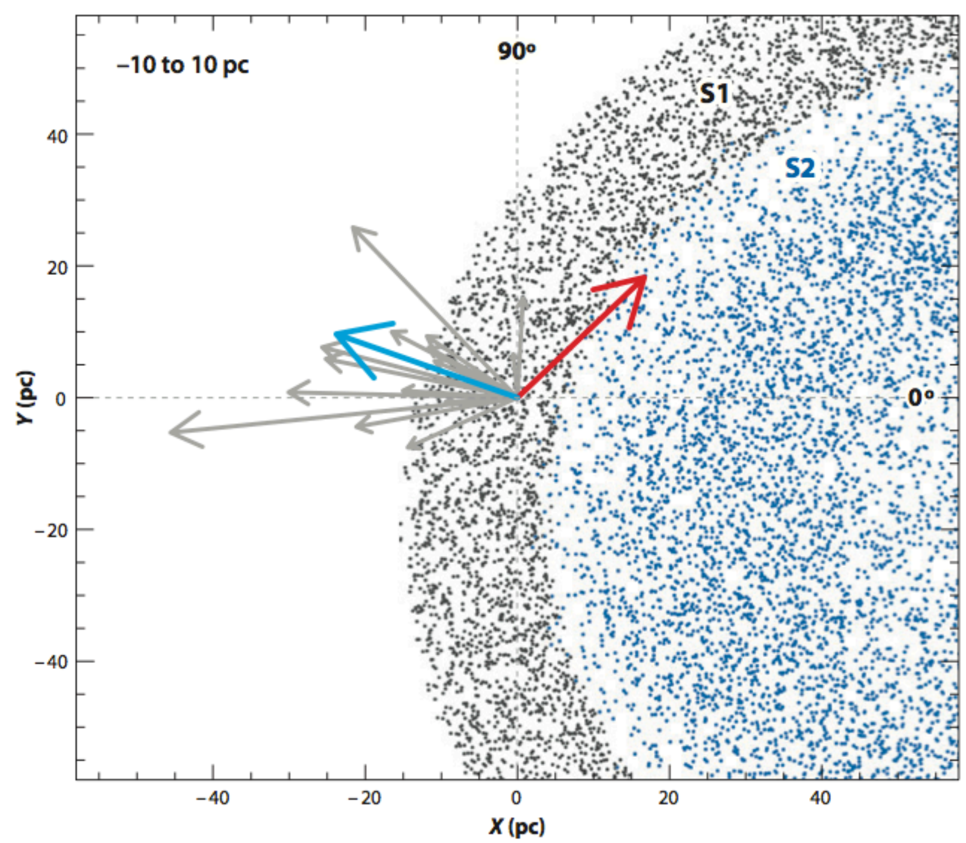
cosmic ray anisotropy

probing sources & propagation of cosmic rays ?



Frisch+, 2011

(Wolleben, 2007)



local ISMF shaped by LOOP I expansion sub-shell (with center ~90 pc away in Scorpius-Centaurus OB Association)

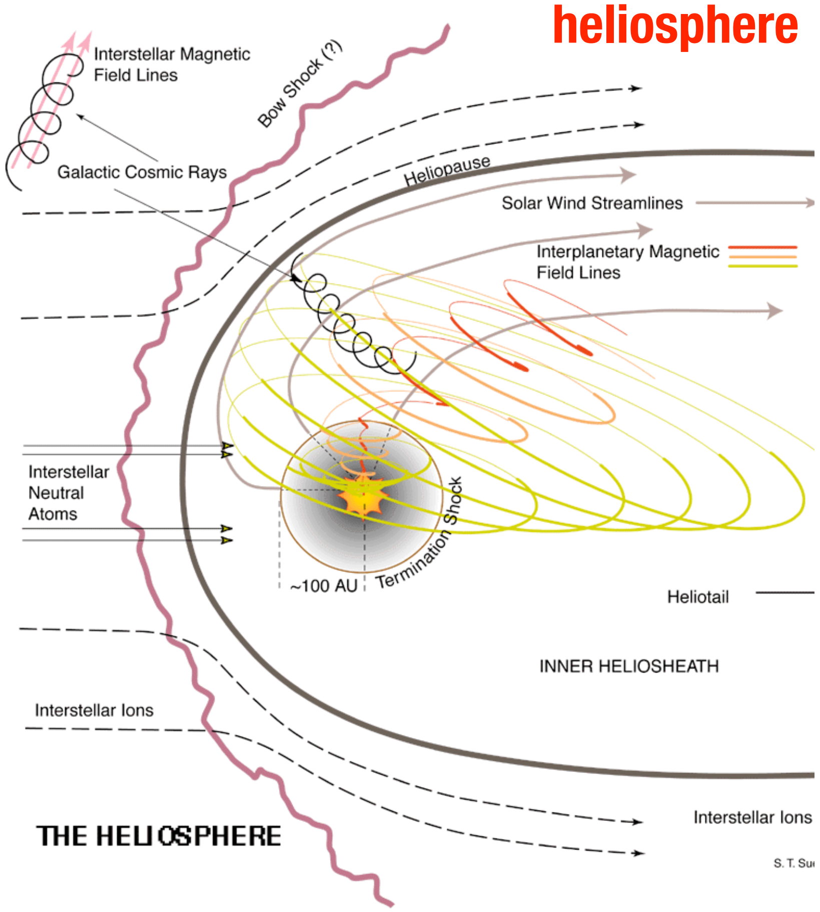
local cloudlets fragments of the shell moving at similar velocities

- interstellar magnetic field affected by inhomogeneities — Redfield & Linsky, 2008; Frisch+, 2011
- local ISMF relatively uniform over spacial scales of order 100-200 pc (**inter-arm**) — Frisch+, 2012

cosmic ray anisotropy

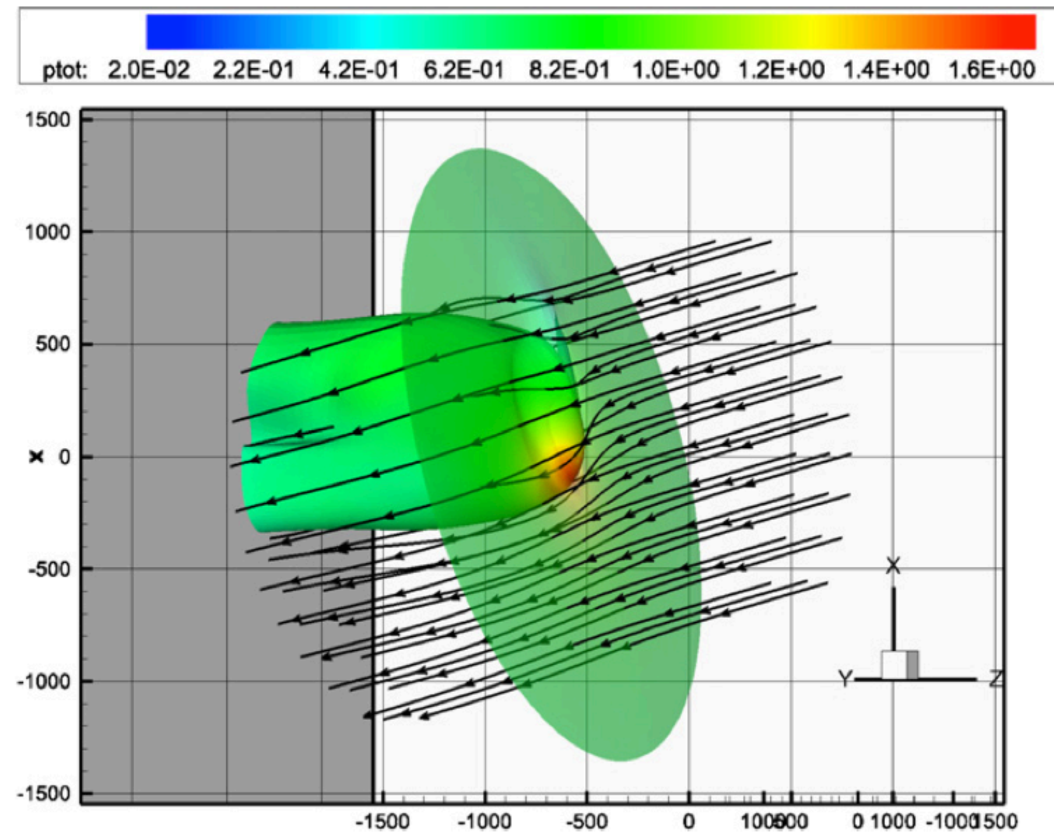
probing sources & propagation of cosmic rays ?

heliosphere



heliotail

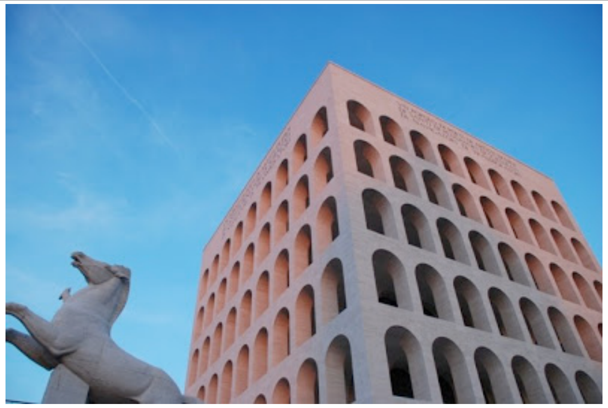
Pogorelov+ 2011



local ISMF draping around heliosphere

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

conclusions



- cosmic ray anisotropy observed **up to PeV scale** & **down to 5º** with IceCube & IceTop
- anisotropy **not a dipole**, **changes topology** with energy and has **complex structure**
- AMANDA & IceCube **global anisotropy stable over one solar cycle**

➡ study **correlation** between anisotropy & spectral anomalies vs **primary mass**

- high energy cosmic ray anisotropy to probe into their **origin and propagation**
- understanding of **interstellar medium** towards astrophysical scenarios for the observations
- better understand particle **diffusion in magnetic fields**

thanks for your attention

SEPTEMBER 26-28, 2013

UNION SOUTH — 1308 W DAYTON ST — MADISON, WI

Scientific Program

The goal of the workshop is to bring together different scientific communities to discuss the origin of the anisotropy of cosmic rays and their spectral anomalies in a variety of energy ranges. We invite experts in the detection of cosmic rays on the ground, with balloons, or in space and from a variety of fields — cosmic ray physics, astrophysics, plasma physics, heliospheric physics, interstellar medium, and particle interactions in magnetic fields. Participants will explore scenarios on the origin of cosmic rays and their acceleration and transport in the interstellar medium and in the heliosphere.

Topics

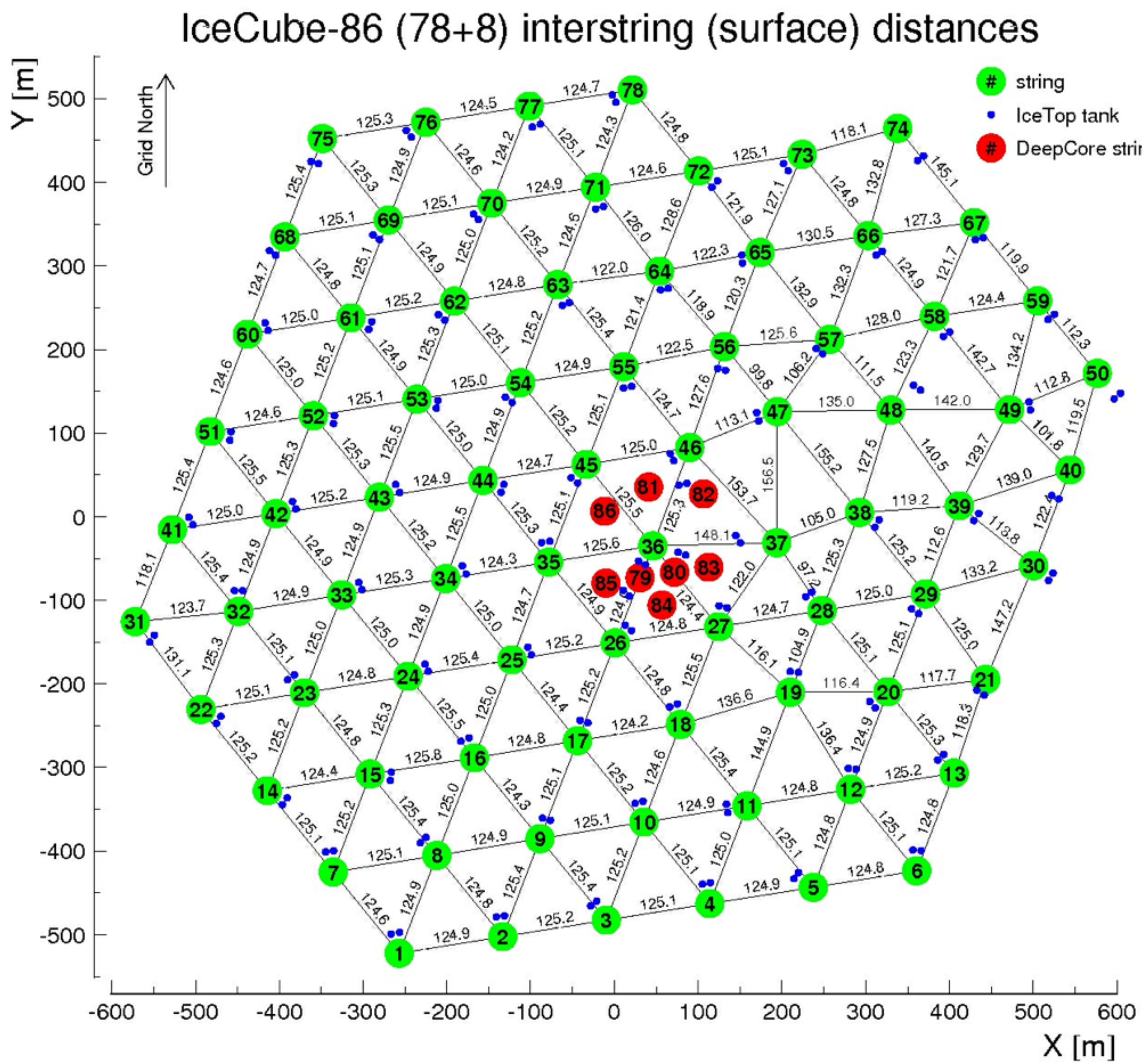
- Cosmic ray anisotropy
- Cosmic ray spectrum and composition
- Cosmic ray origin, acceleration and propagation
- Interstellar medium and interstellar magnetic field
- Isotopic composition of cosmic rays
- Heliosphere and its boundary region with the interstellar medium

Organizing Commitees

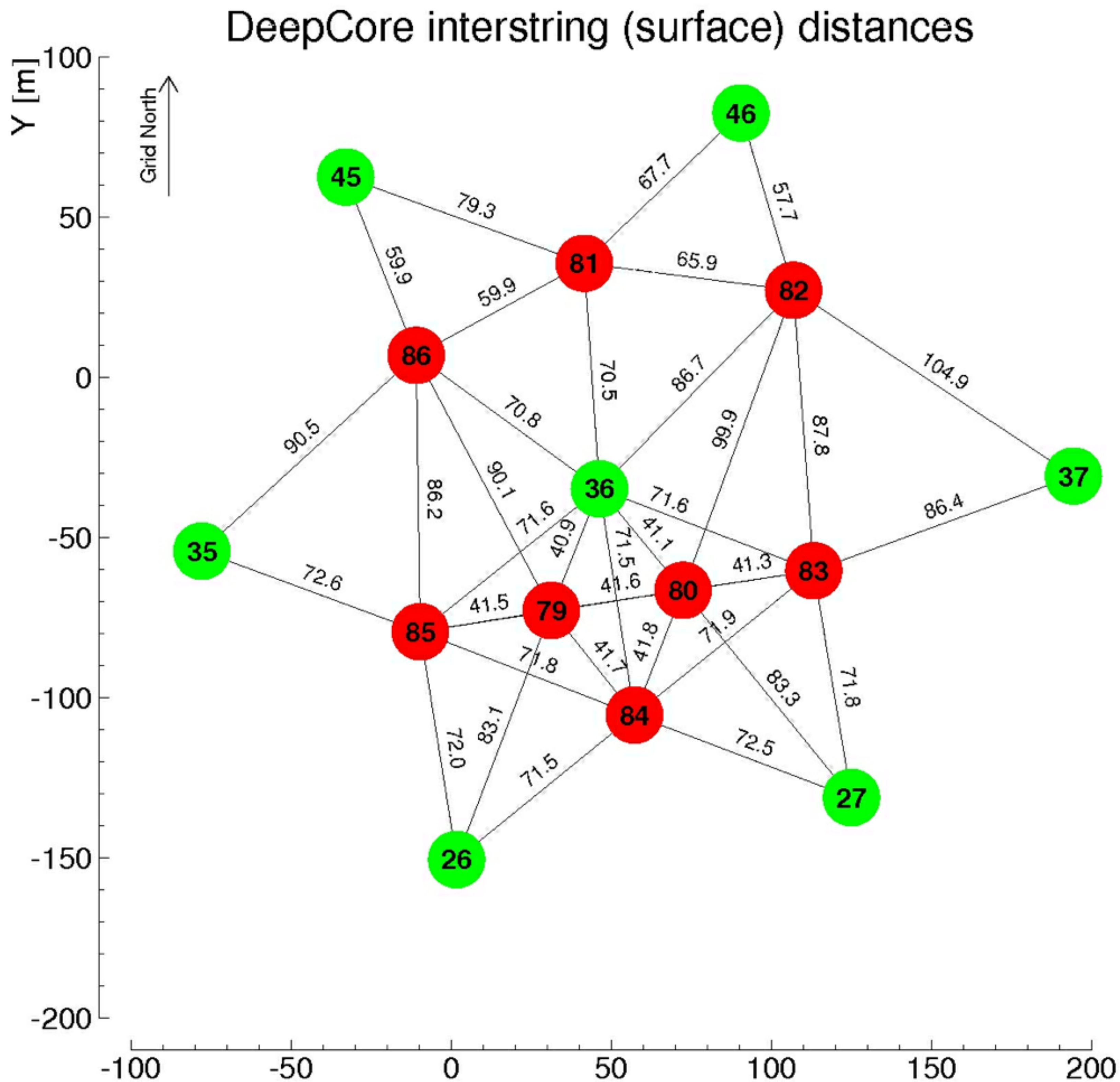
Scientific Committee:		**Local Committee:**	
Pasquale Blasi	Eun-Suk Seo	Markus Ahlers	Albrecht Karle
Priscilla Frisch	Gus Sinnis	Segev BenZvi	Kim Kreiger
Nikolai Pogorelov		Paolo Desiati	Marcos Santander
		Francis Halzen	Stefan Westerhoff

http://wipac.wisc.edu/CRA2013

backup slides

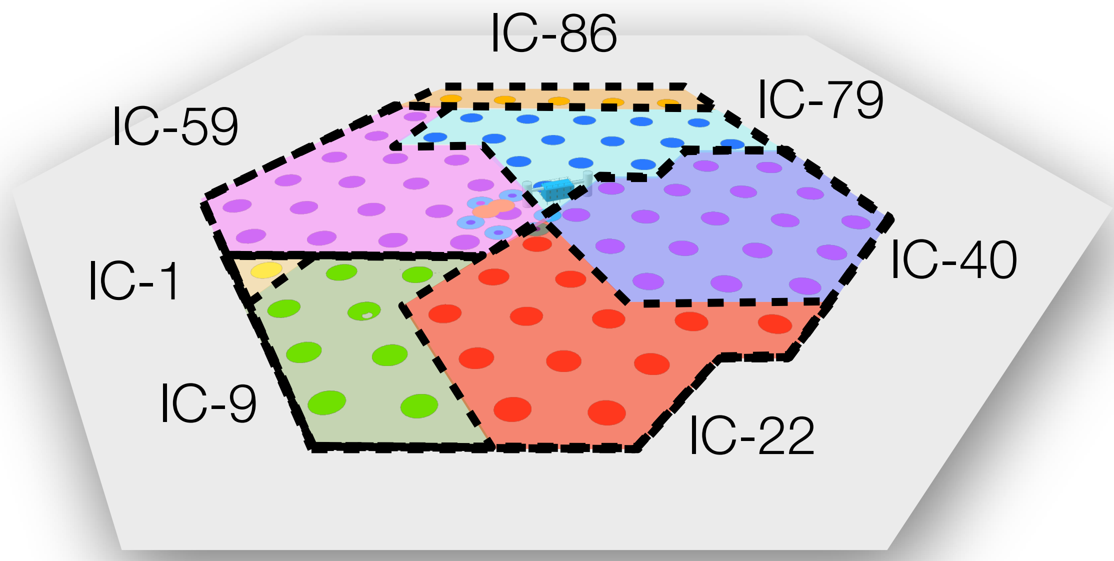


IceCube geometry

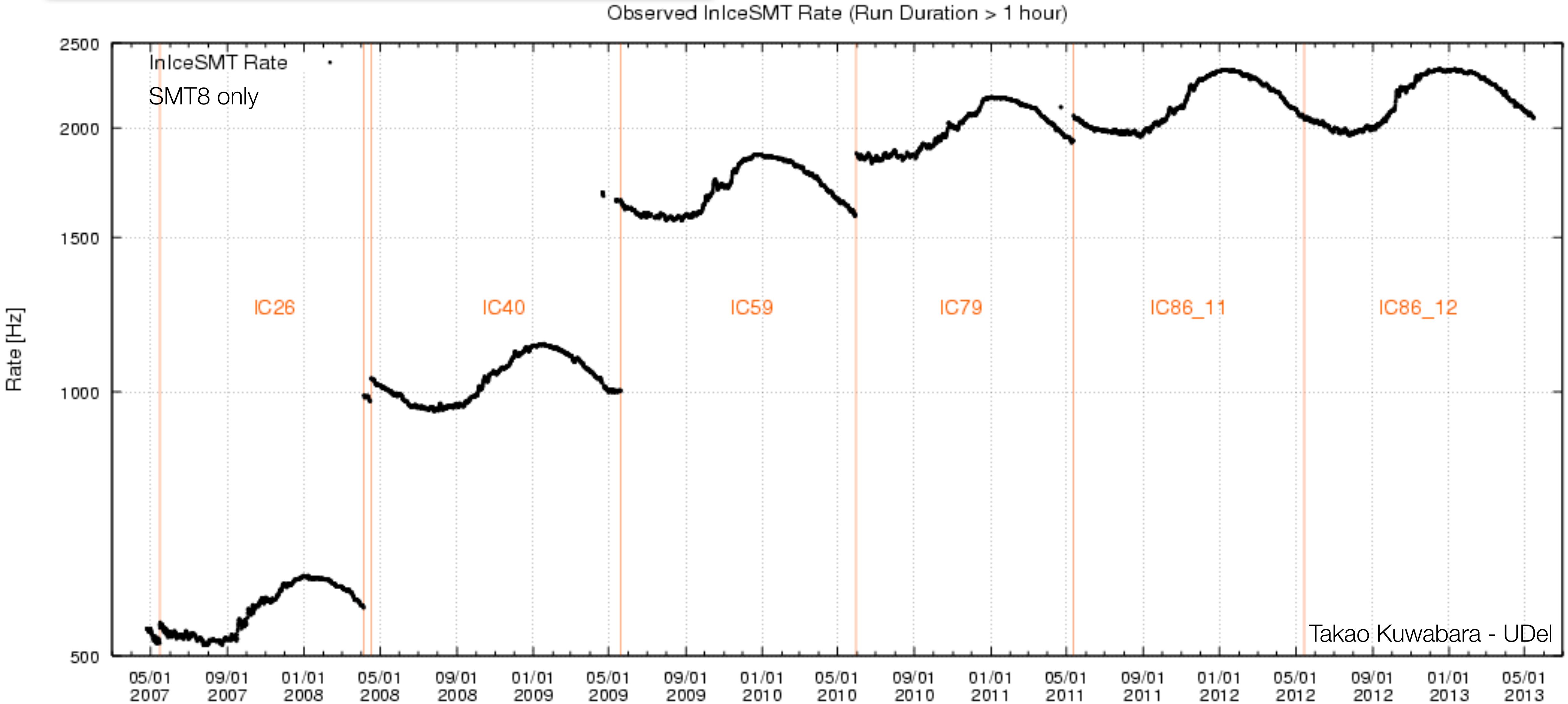


DeepCore geometry

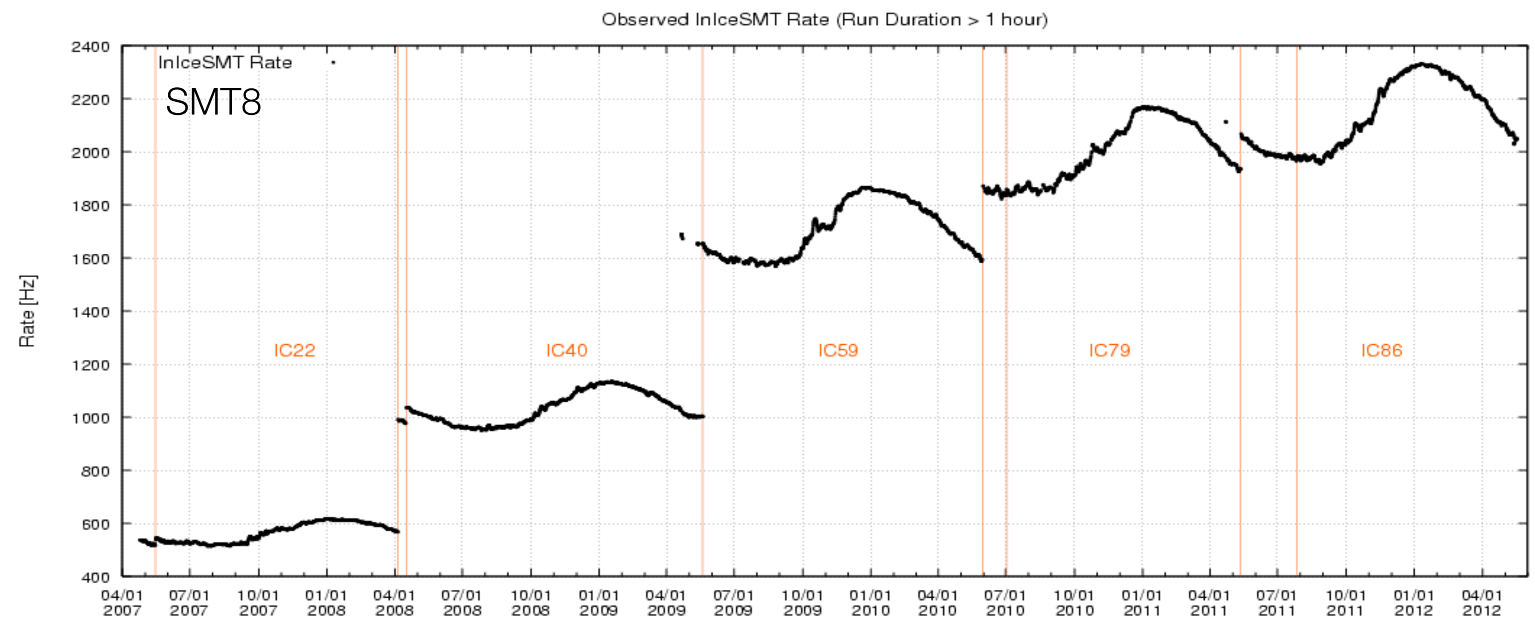
growing IceCube
& event collection

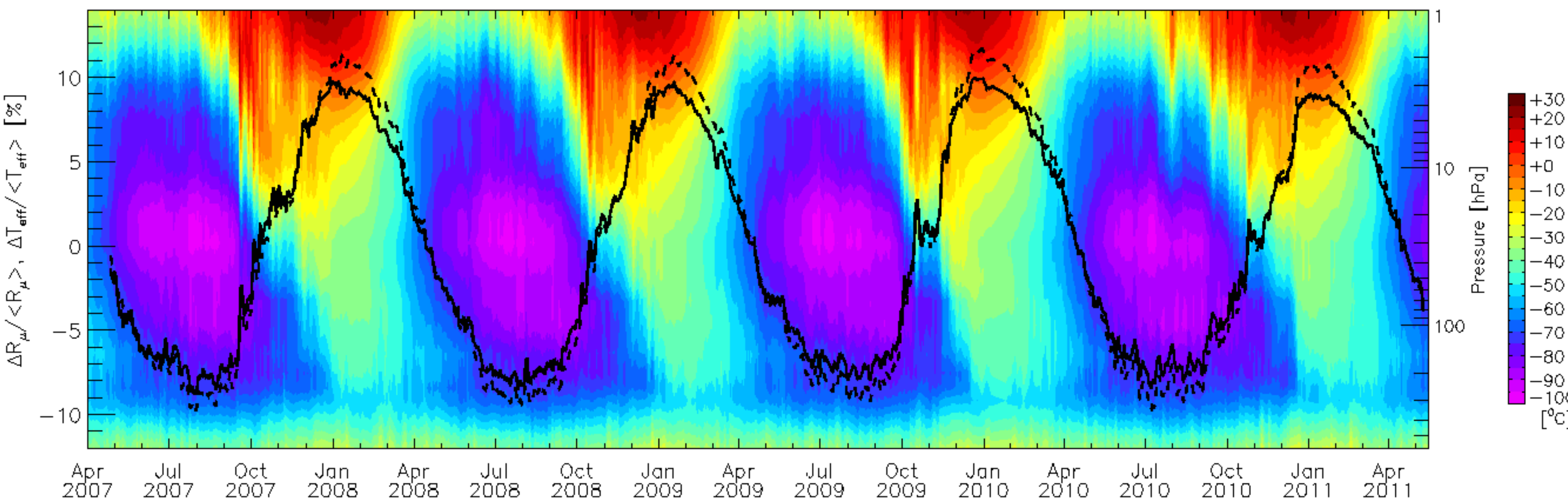


Year	µ rate (SMT8)	CR shower rate (STA3)
2007	500 Hz	13 Hz
2008	1100 Hz	15 Hz
2009	1700 Hz	25 Hz
2010	2000 Hz	30 Hz
2011+	2200 Hz	35 Hz



growing IceCube
& event collection





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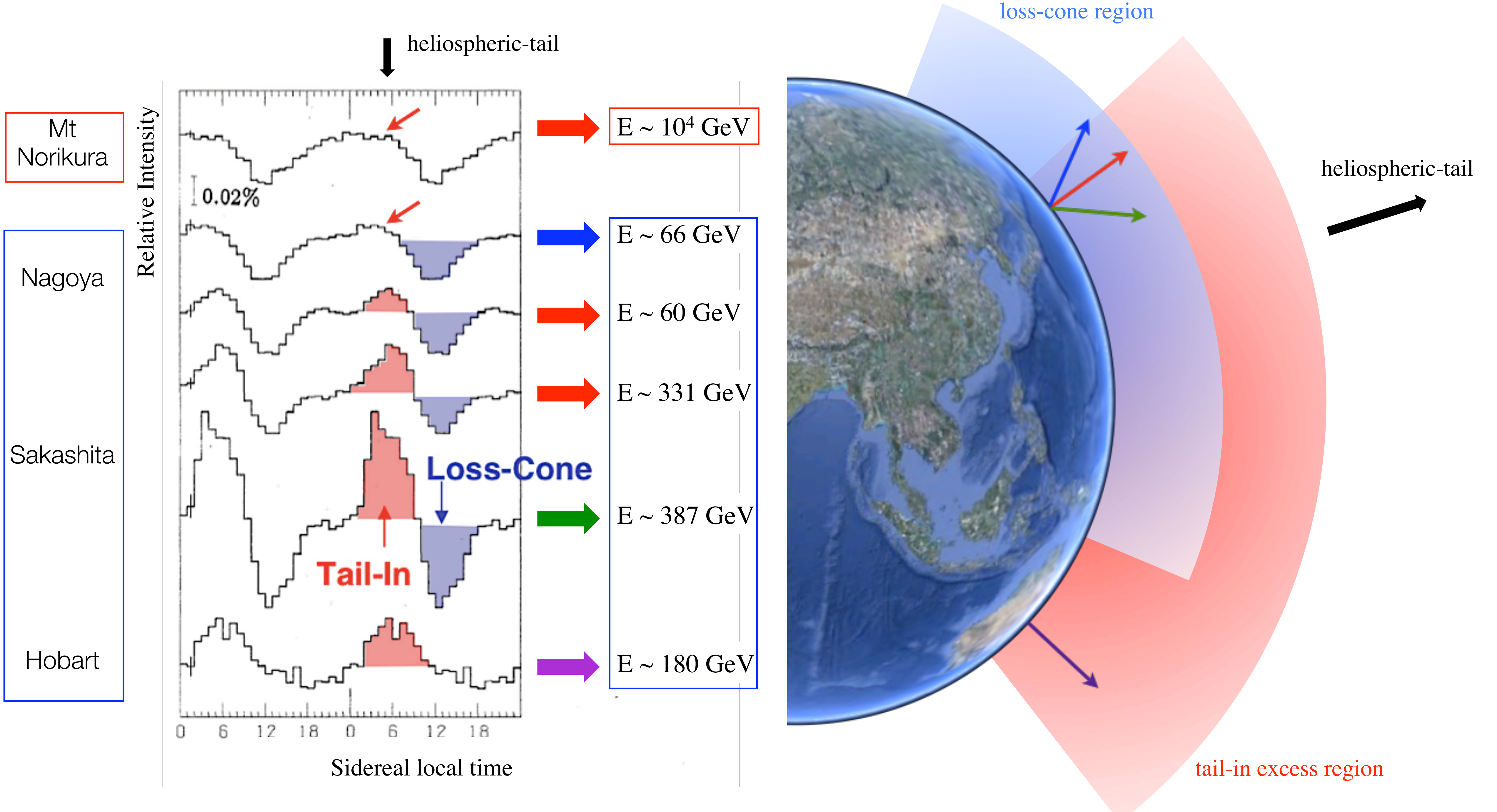
low energy cosmic ray anisotropy in arrival direction

Nagashima+,1998



cosmic ray anisotropy vs energy

J.L. Zhang et al., 31st ICRC Łódź - Poland, 2009

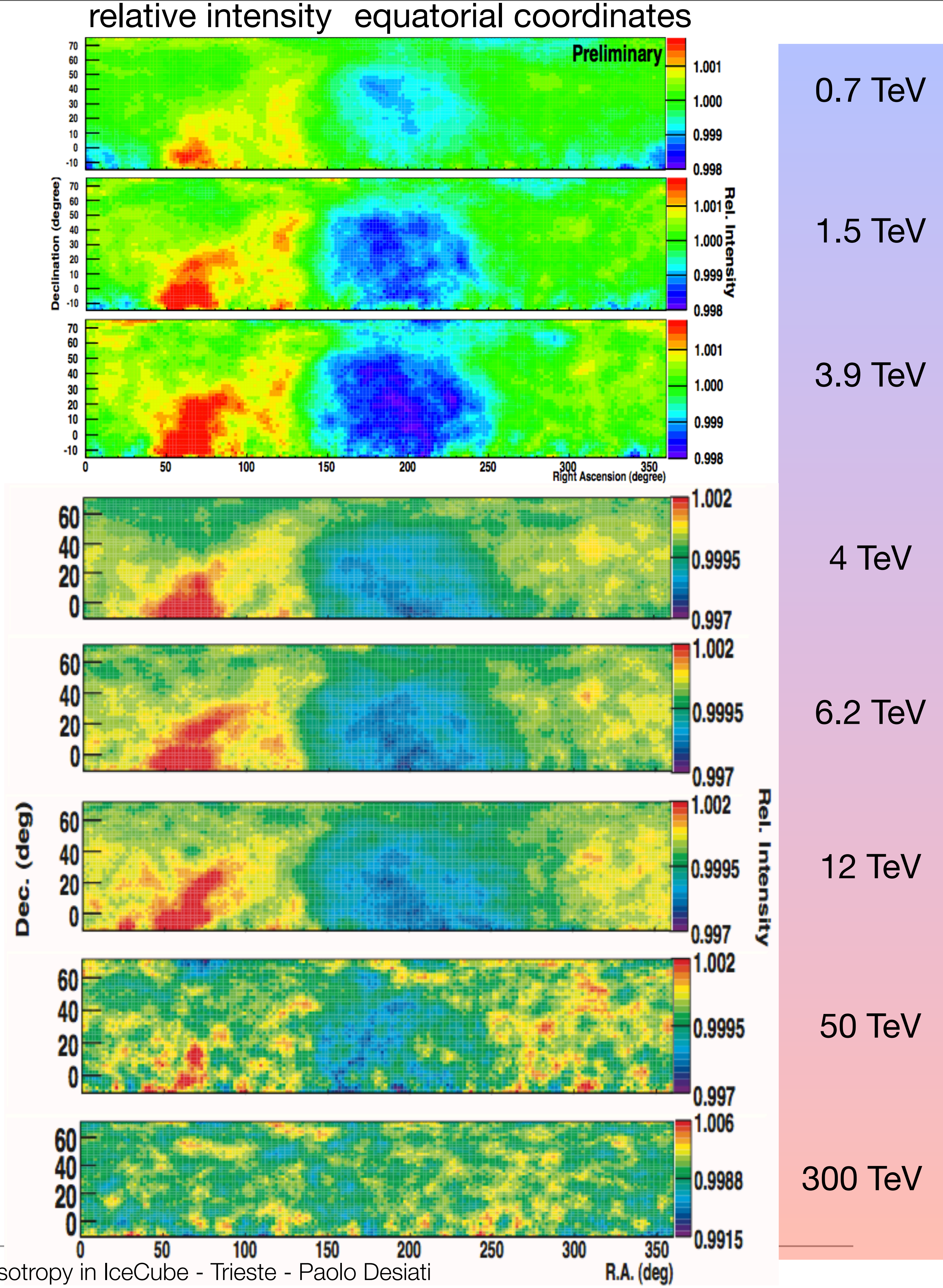
ARGO-YBJ

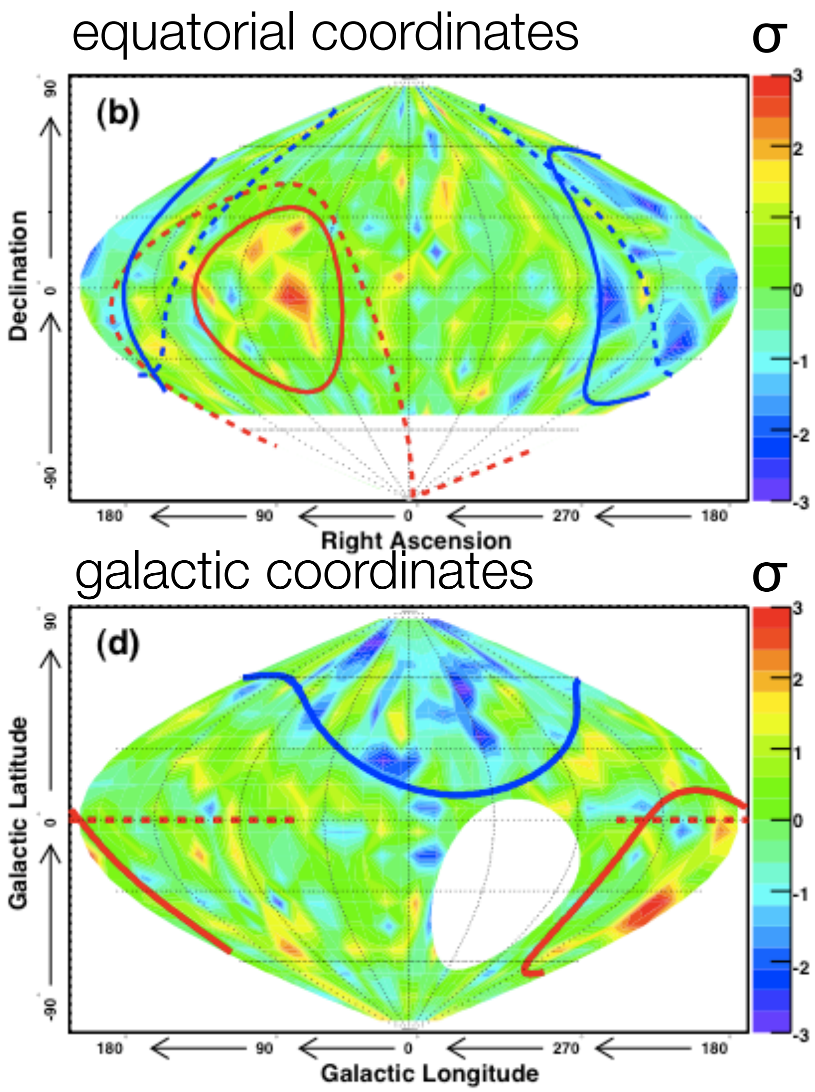
- data from 2008
- 365 days livetime
- $6.5 \cdot 10^{10}$ events
- median CR energy ~ 1.1 TeV

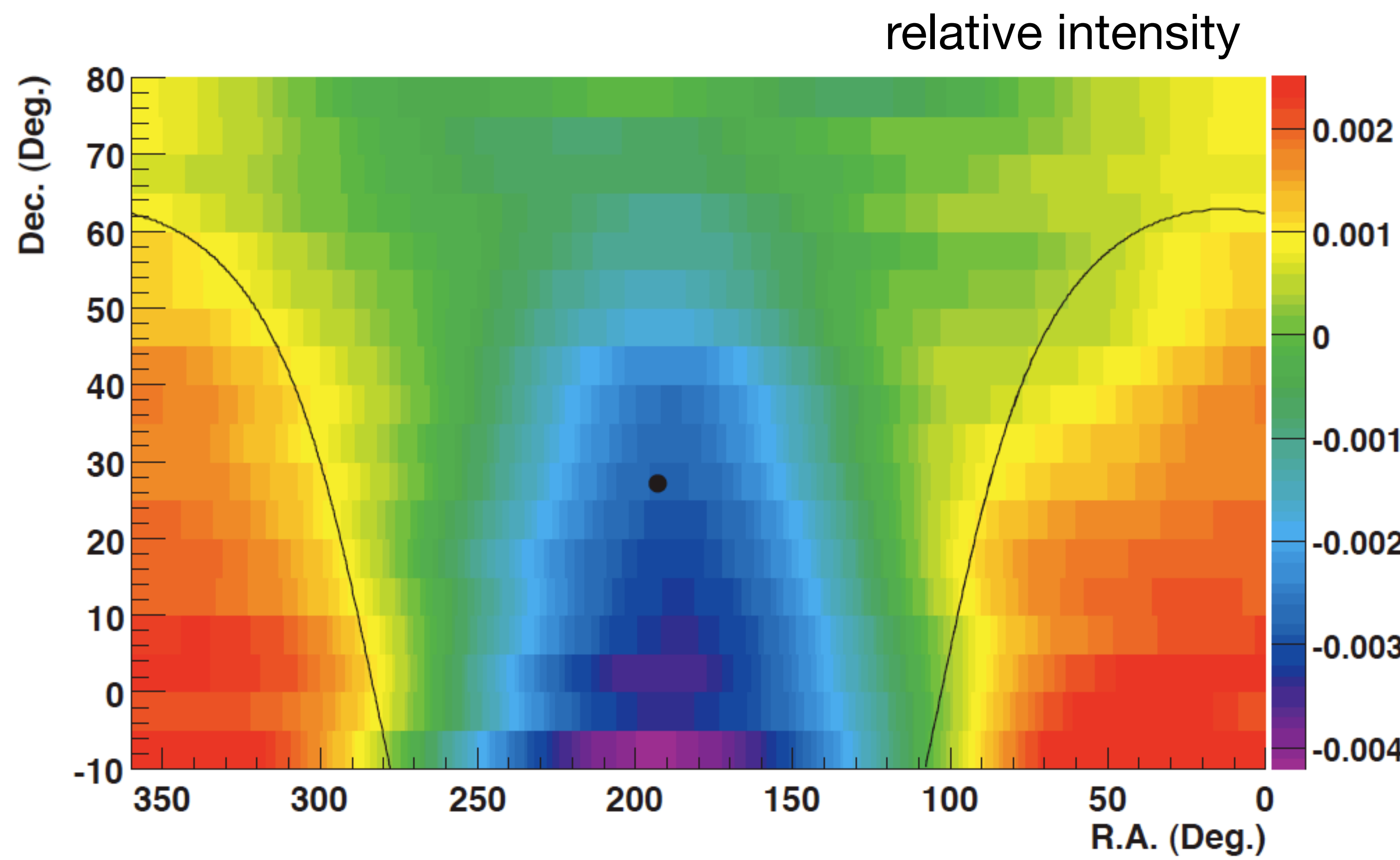
Amenomori et al., Science Vol. 314, pp. 439, 2006

Tibet-III

- data from 1997 to 2005
- 1874 days livetime
- $3.7 \cdot 10^{10}$ events
- angular resolution ~ 0.9°
- modal CR energy ~ 3 TeV







Super-Kamiokande

Guillian et al., Phys Rev D, Vol 75, 063002 (2007)

- data from 1996 to 2001
- 1662 days livetime
- $2.1 \cdot 10^{8}$ events
- angular resolution < 2°
- median CR energy ~ 10 TeV

Milagro

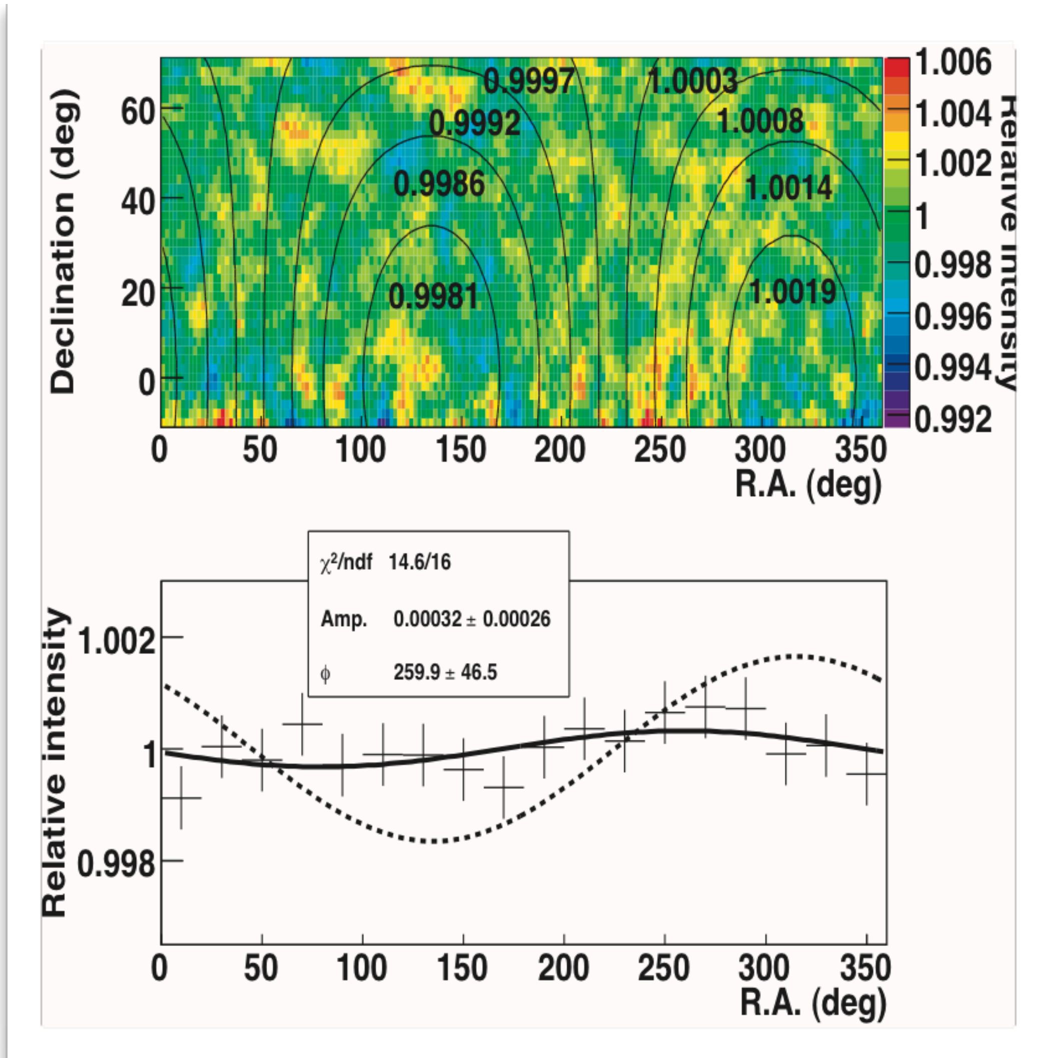
Abdo et al., ApJ, Vol 698-2, pag 2121 (2009)

- data from 2000 to 2007
- $9.5 \cdot 10^{10}$ events
- angular resolution < 1°
- median CR energy ~ 6 TeV

cosmic ray anisotropy vs energy

relative intensity

equatorial coordinates

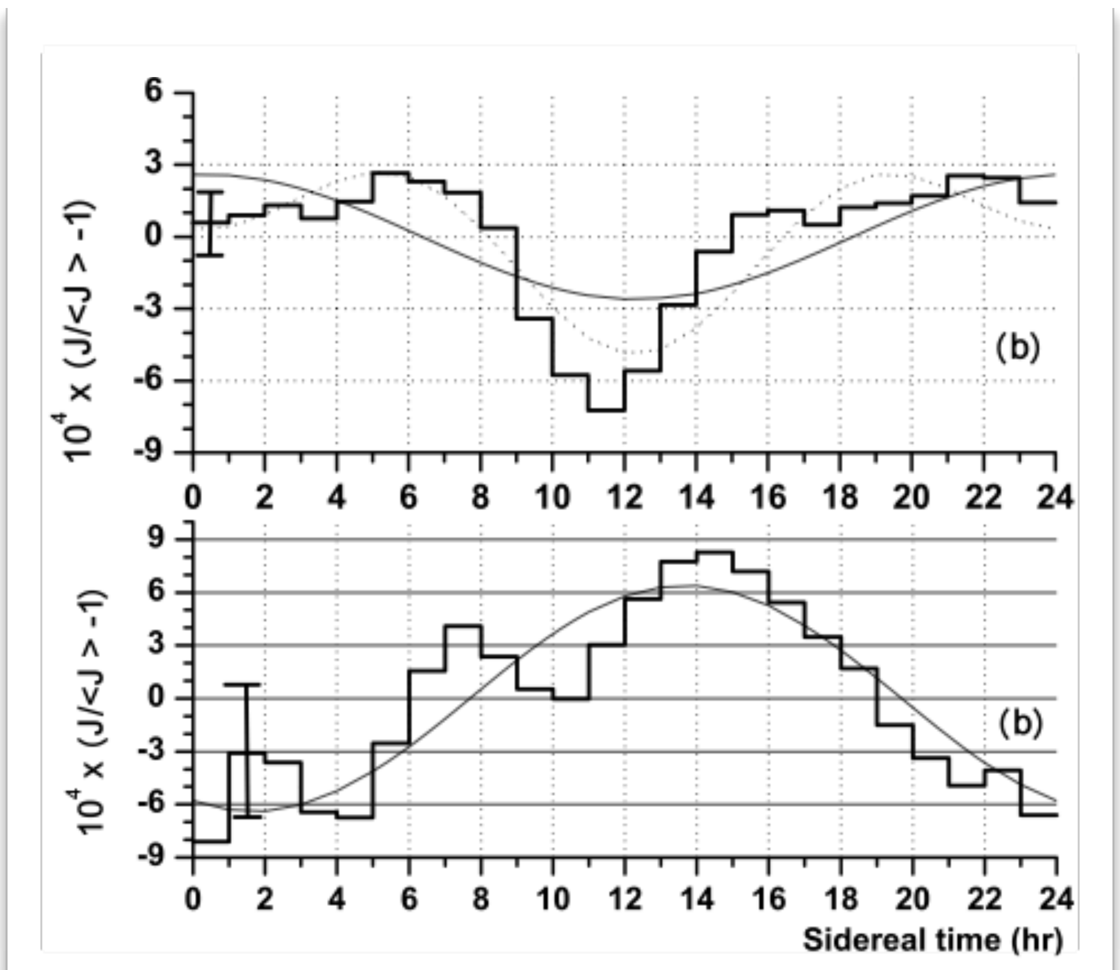


300 TeV

Tibet-III

Amenomori et al., Science Vol. 314, pp. 439, 2006

relative intensity



110 TeV

370 TeV

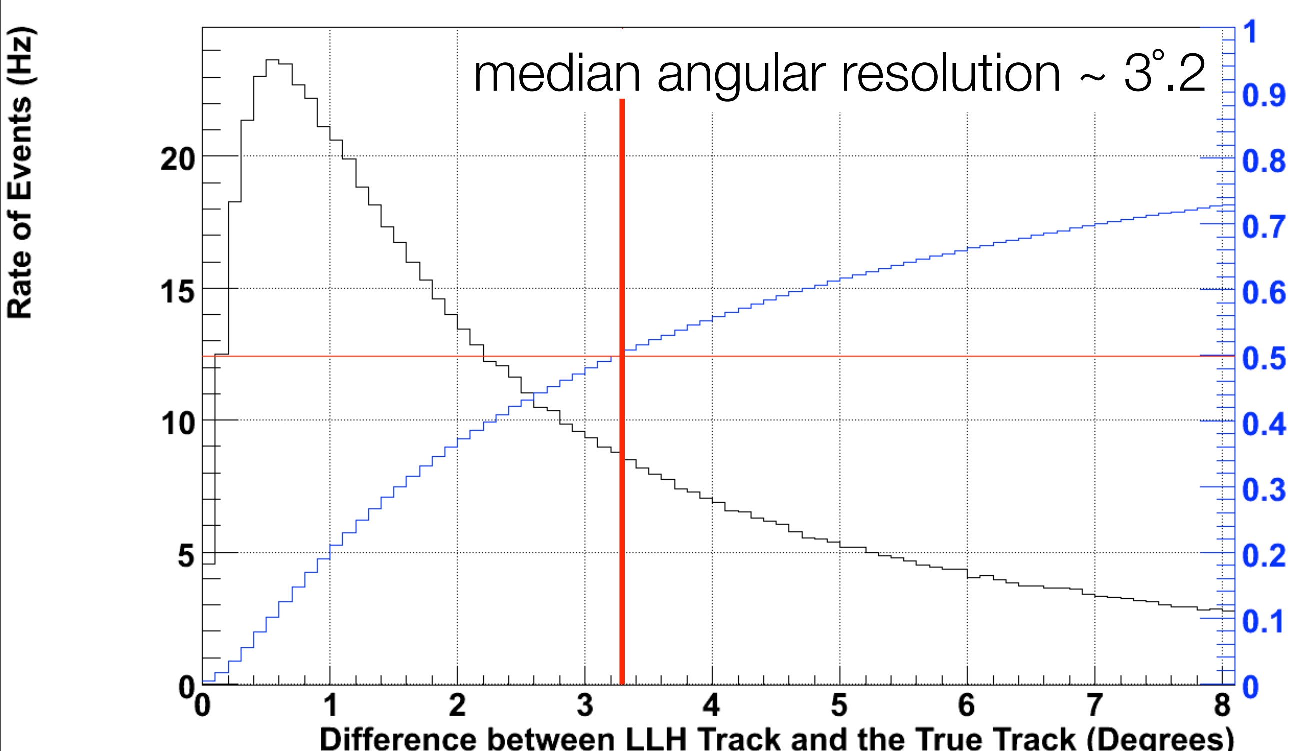
EAS-TOP

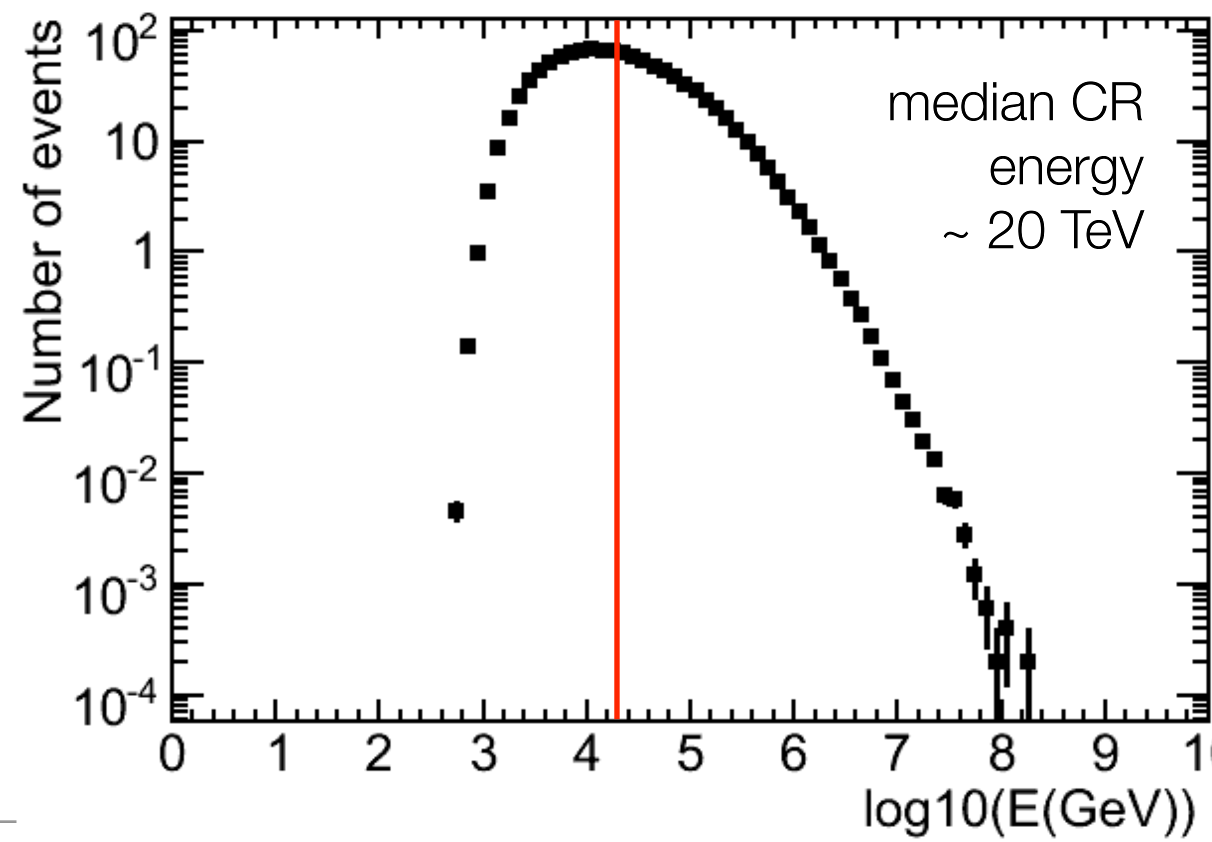
Aglietta et al., ApJ 692, L130, 2009

IceCube muon bundle trigger statistics

detector	trigger rate (Hz)	actual time (d)	livetime (d)	number of events (*)
IceCube-22	500	300	226	5.4×10^9
IceCube-40	1,100	358	324	19×10^9
IceCube-59	1,700	367	334.5	34×10^9
IceCube-79	2,000	365	337	40×10^9
IceCube-86	2,500	365 × 2	365 × 2	$50\times10^9 \times 2$

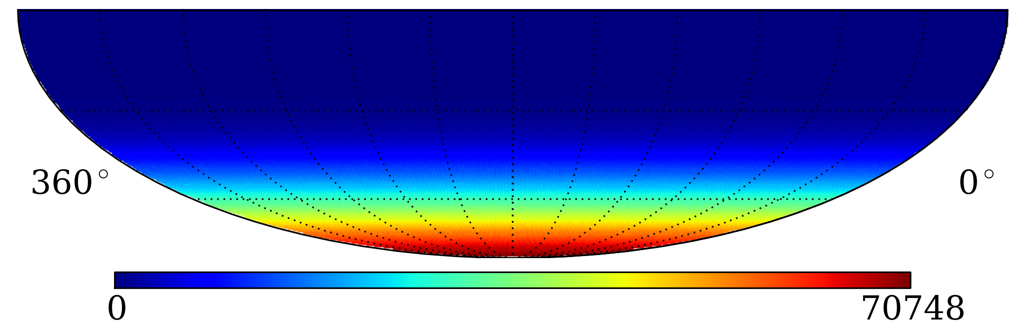
(*) number of events with LLH reconstruction from online-filter collected by DST



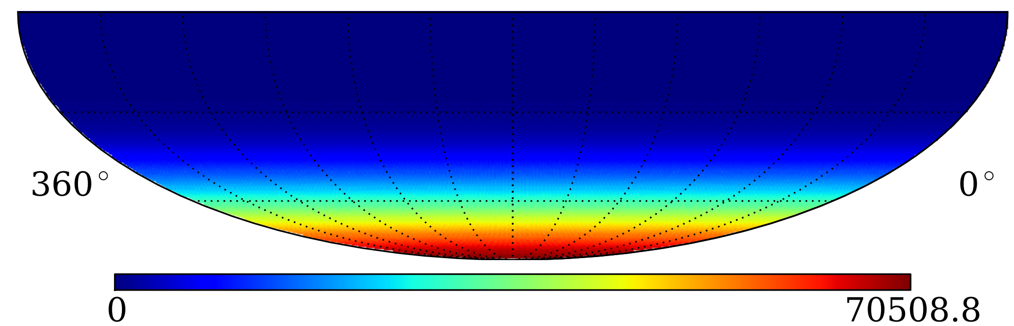


cosmic ray anisotropy *analysis technique*

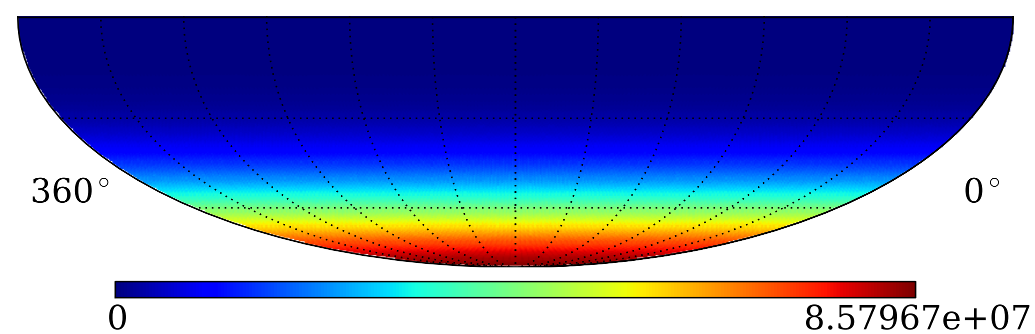
raw map of events in equatorial coordinates $(\alpha,\delta)_i$



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

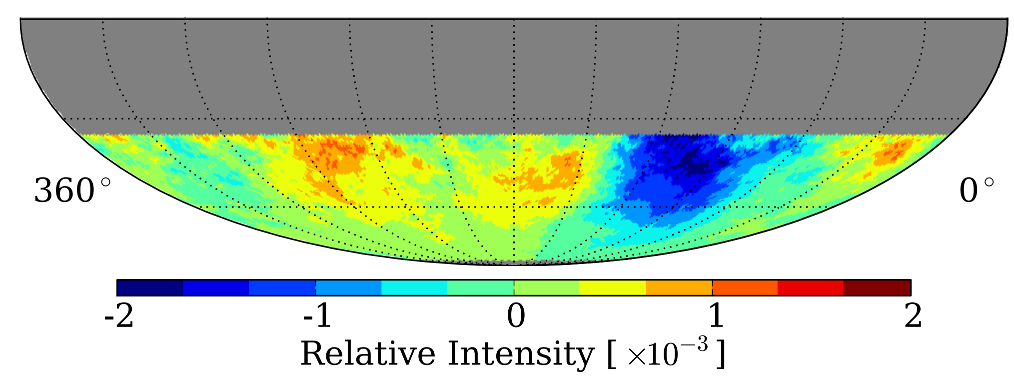


rebin raw and reference maps to enhance inter-bin correlations

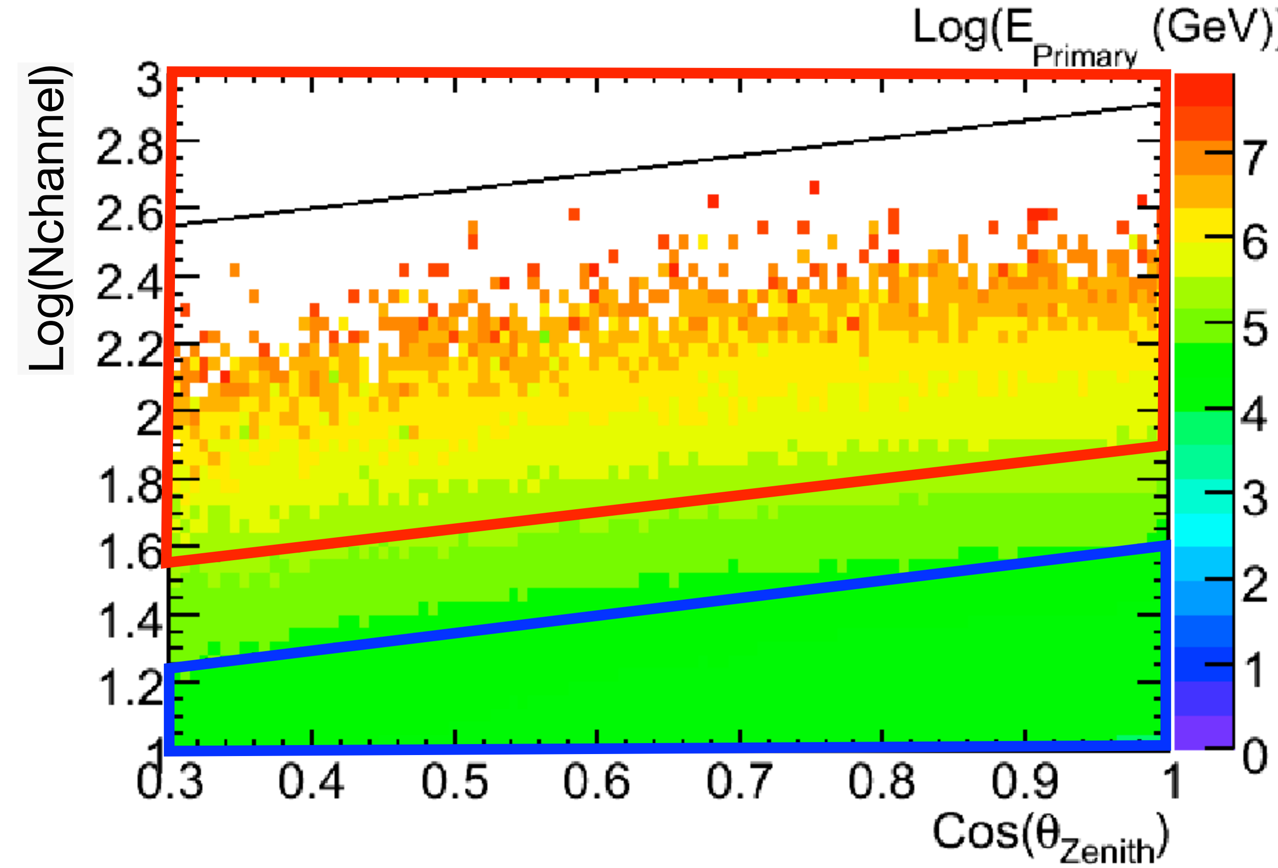


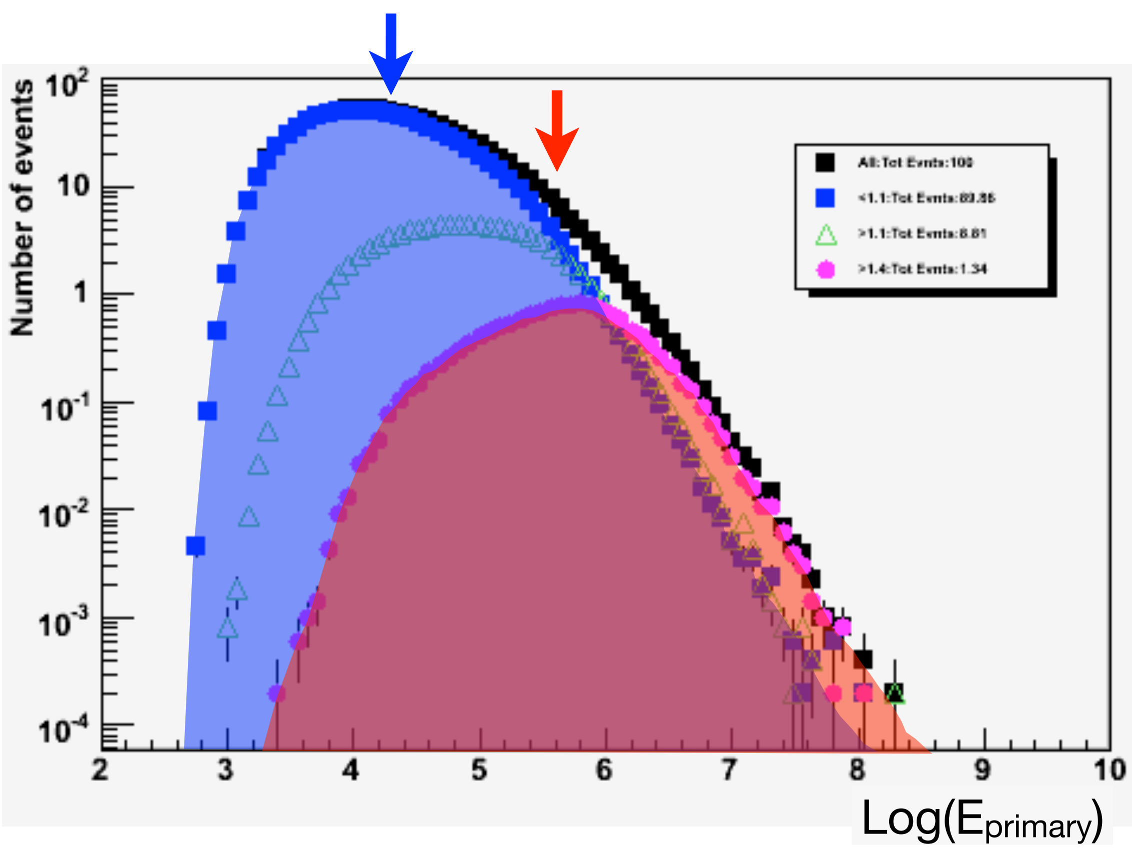
subtract reference map from raw map to determine the residual *relative intensity* map

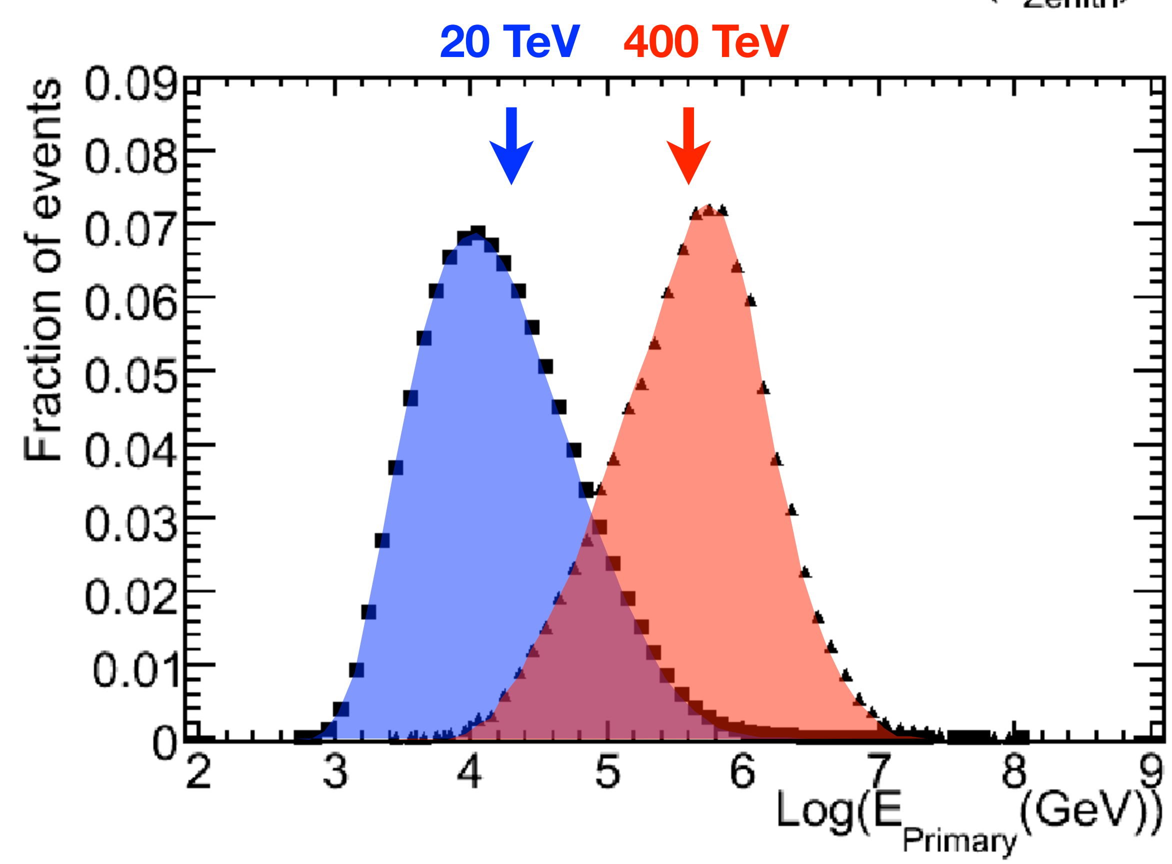
$$\boxed{\frac{\Delta I}{\langle I\rangle} \equiv \frac{N_i - \langle N\rangle}{\langle N\rangle}}$$



cosmic ray anisotropy energy selection
IceCube



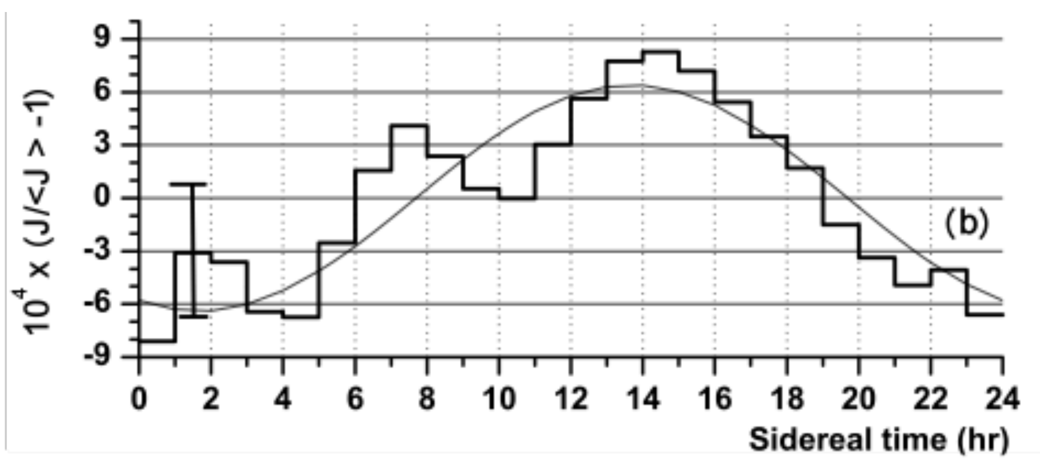




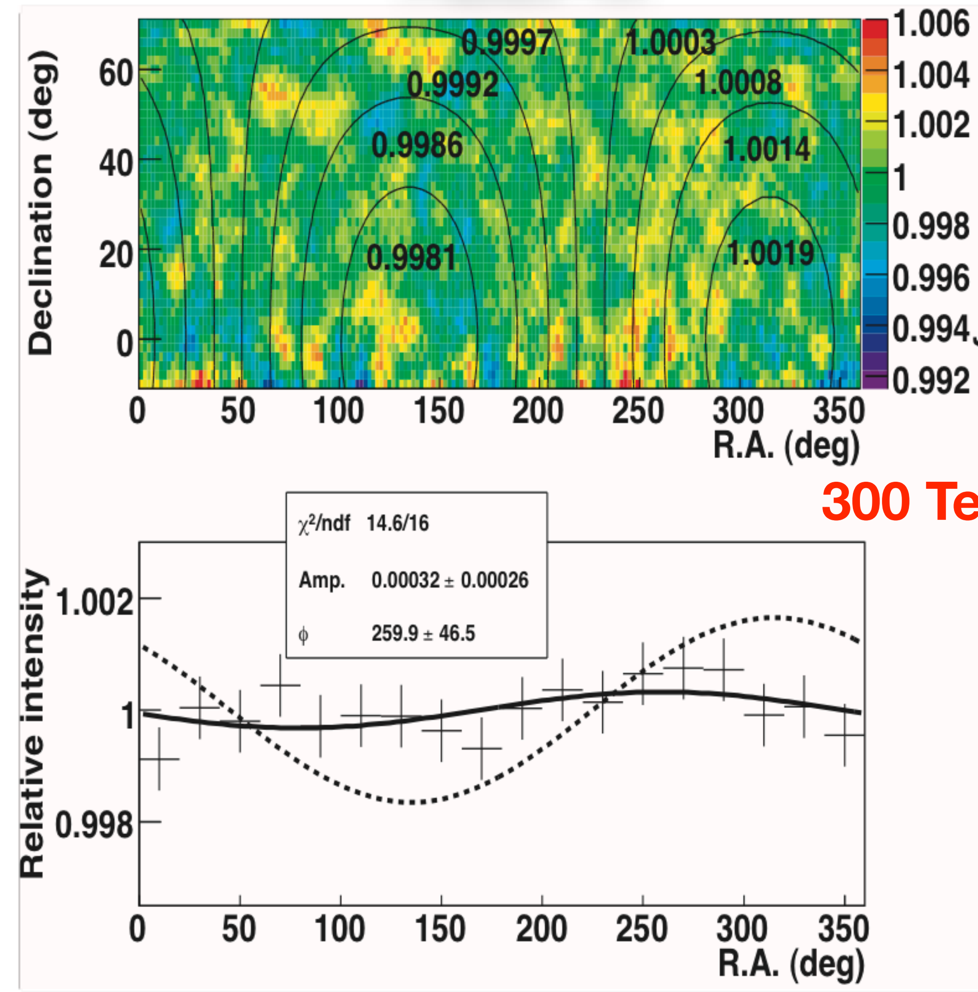
cosmic ray anisotropy vs energy in IceCube-59

EAS-TOP

370 TeV

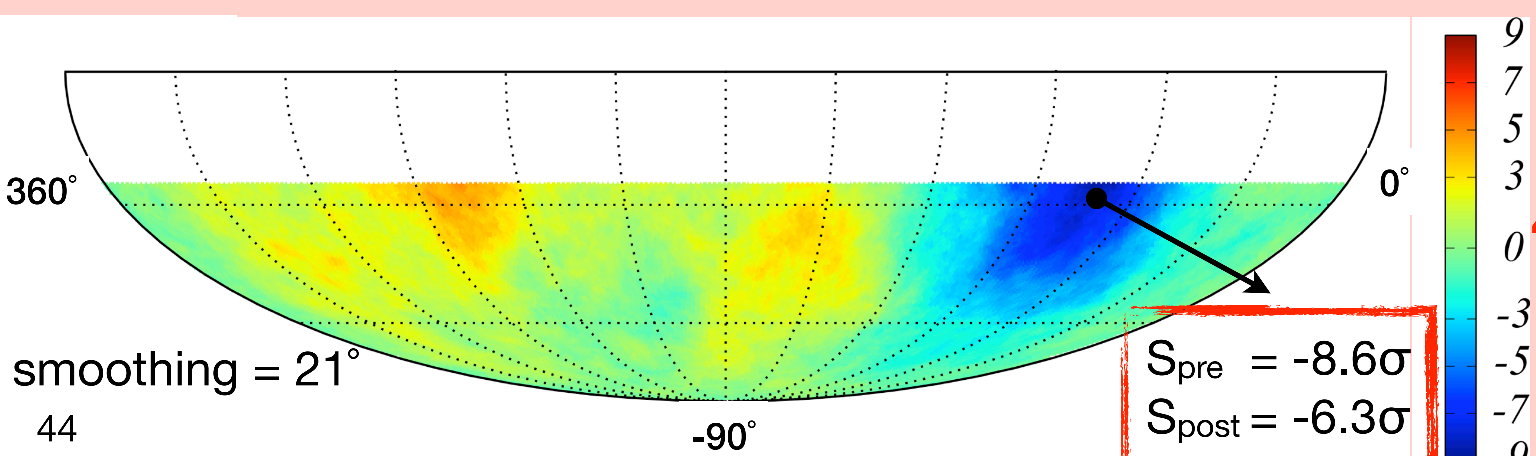


Tibet-III

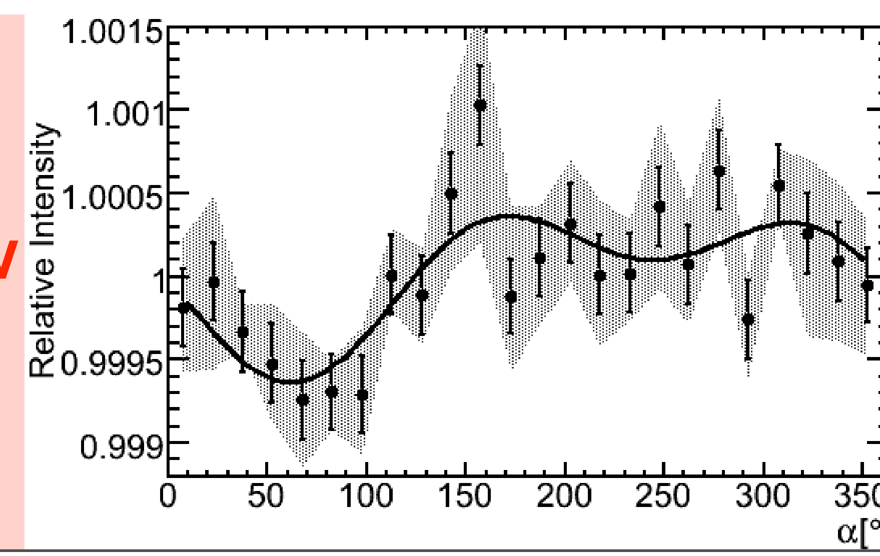


300 TeV

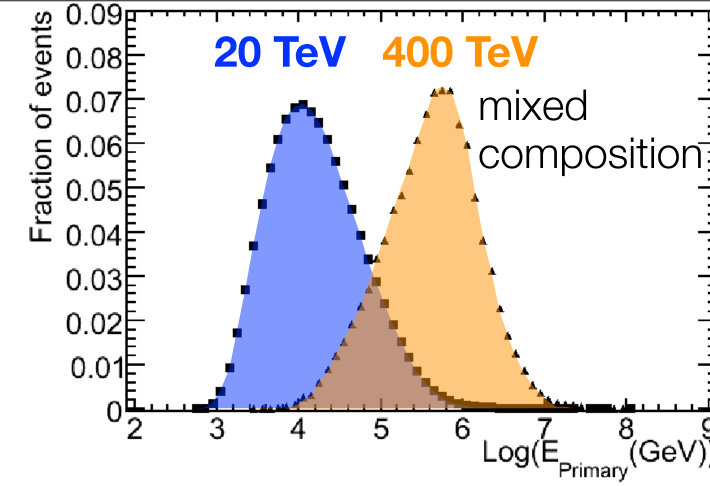
Abbasi et al., ApJ, **746**, 33, 2012



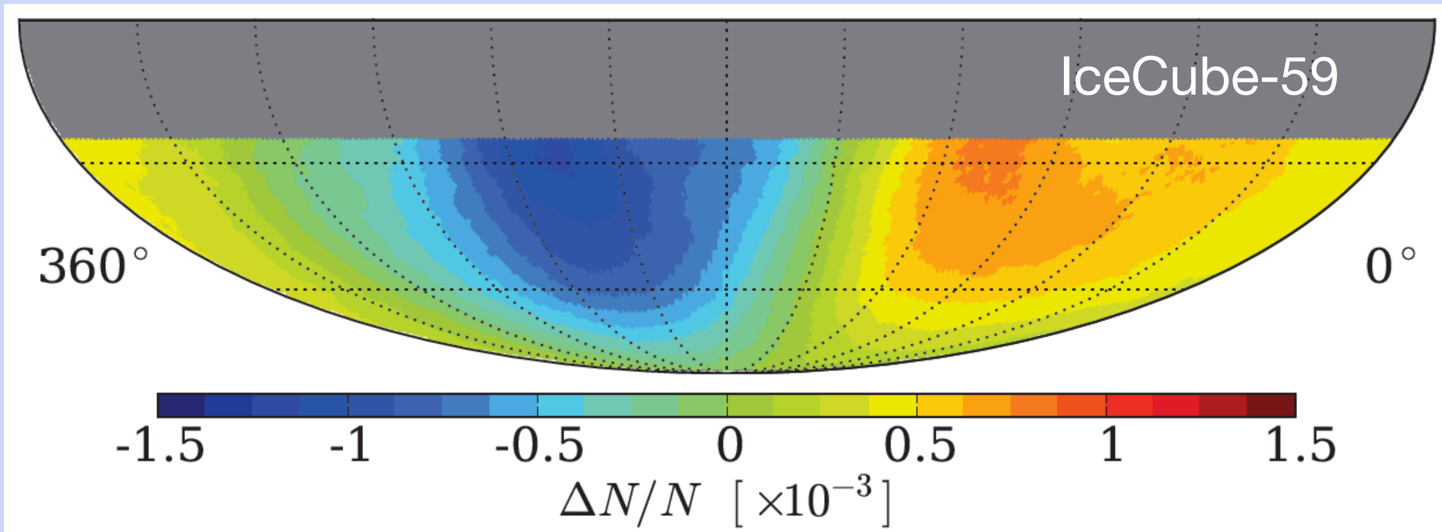
400 TeV



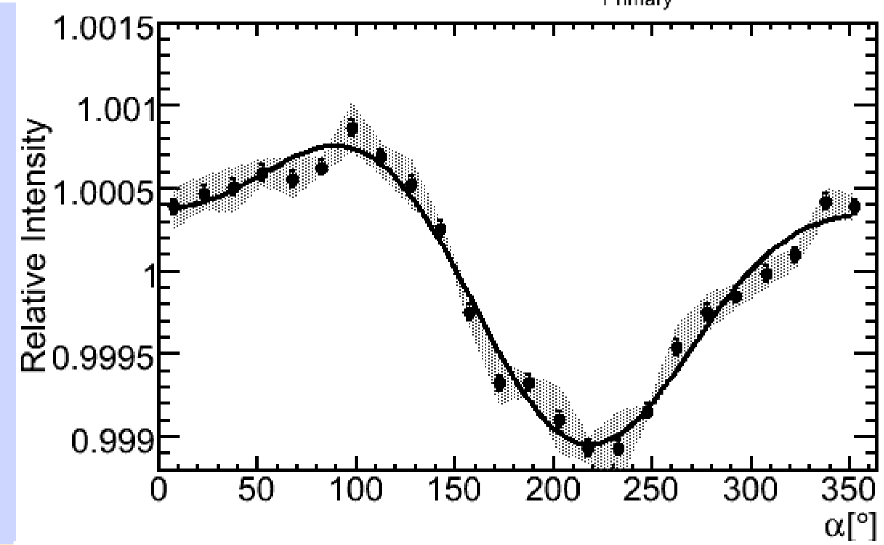
cosmic ray anisotropy large scale
IceCube

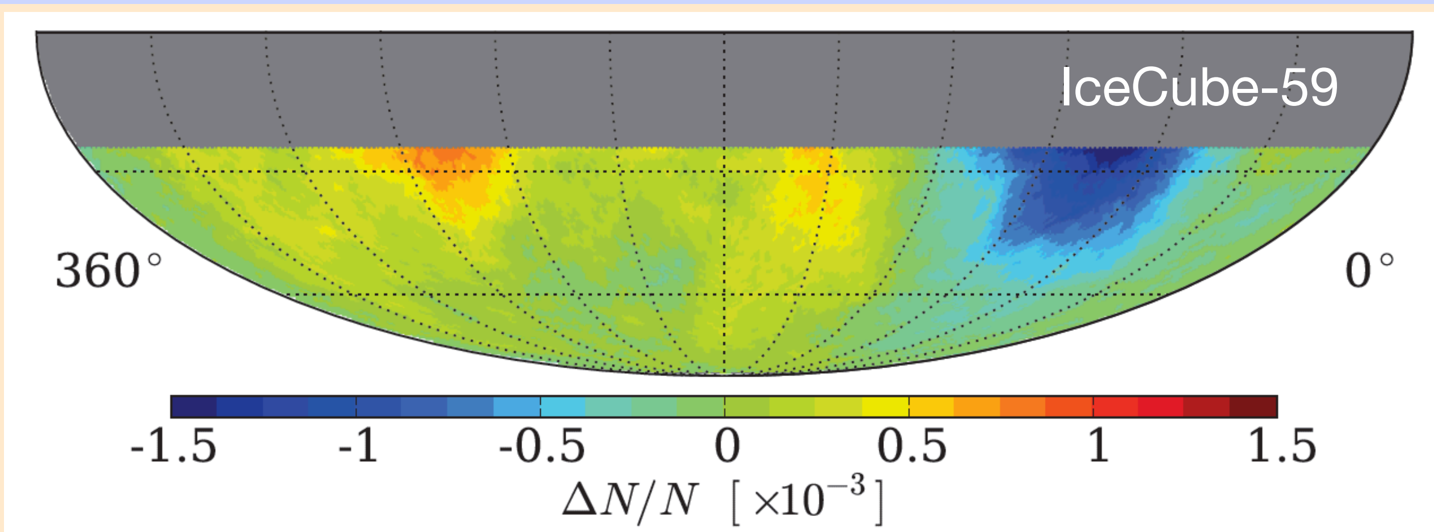


relative intensity equatorial coordinates



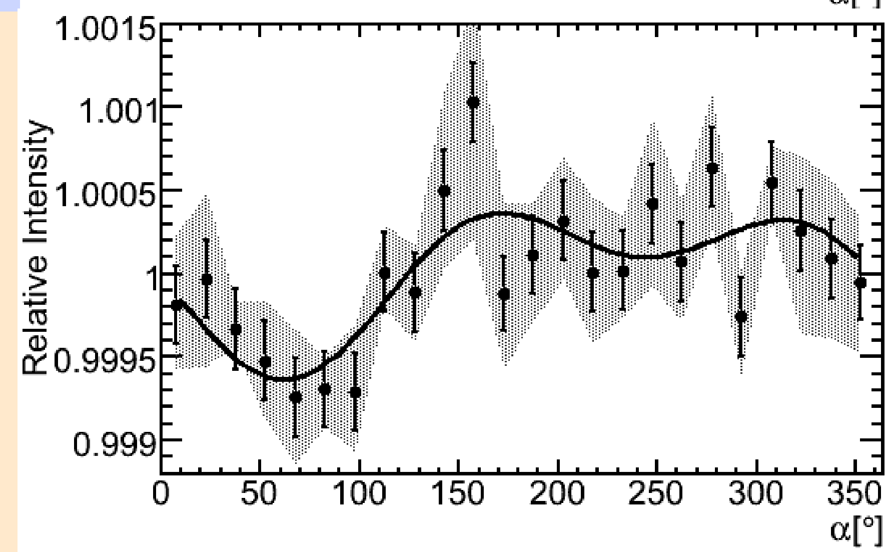
20 TeV





400 TeV

deficit
6.3 σ_{post}

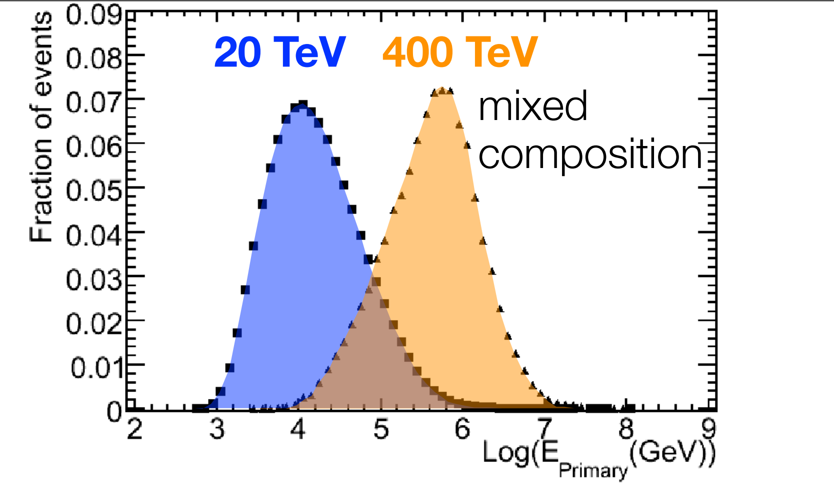


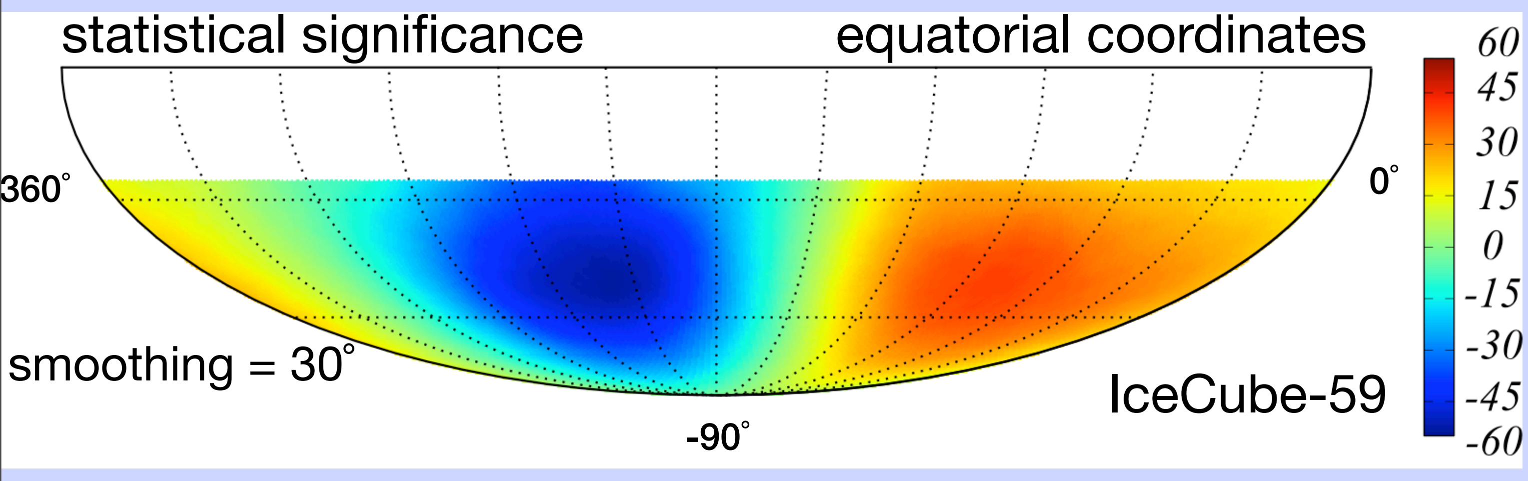
NOTE: anisotropy is not a dipole
topology changes at high energy

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

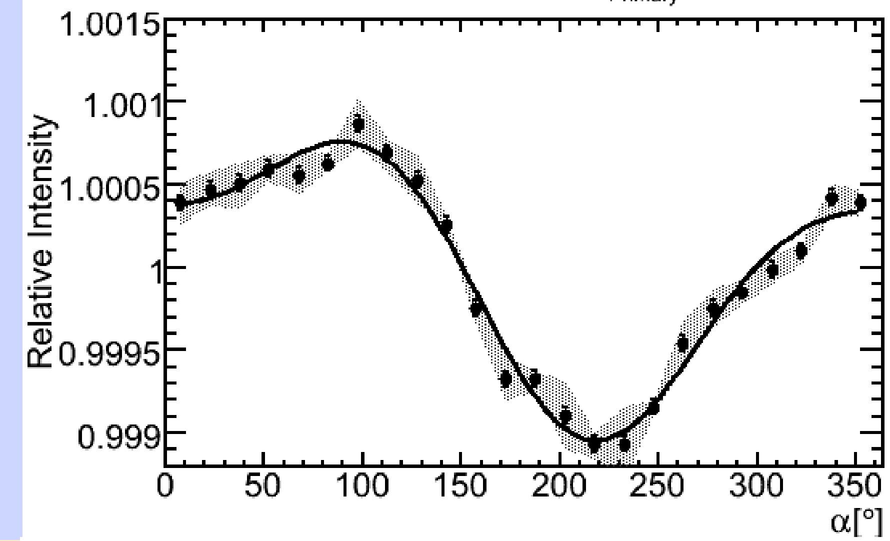
IC22 Abbasi et al., ApJ, **718**, L194, 2010

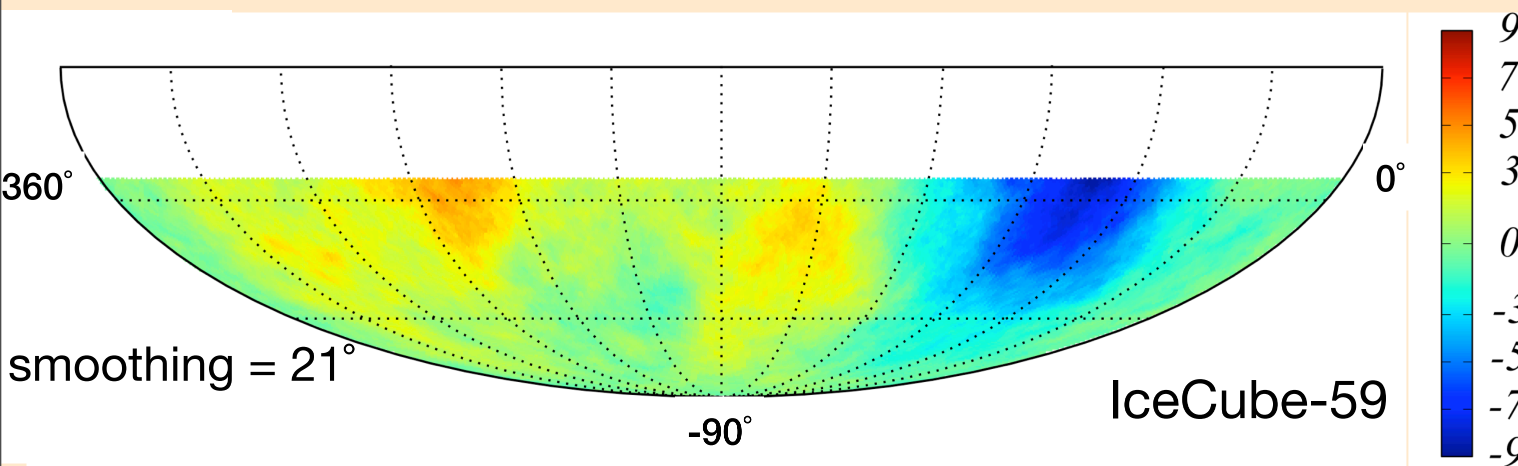
cosmic ray anisotropy large scale
IceCube





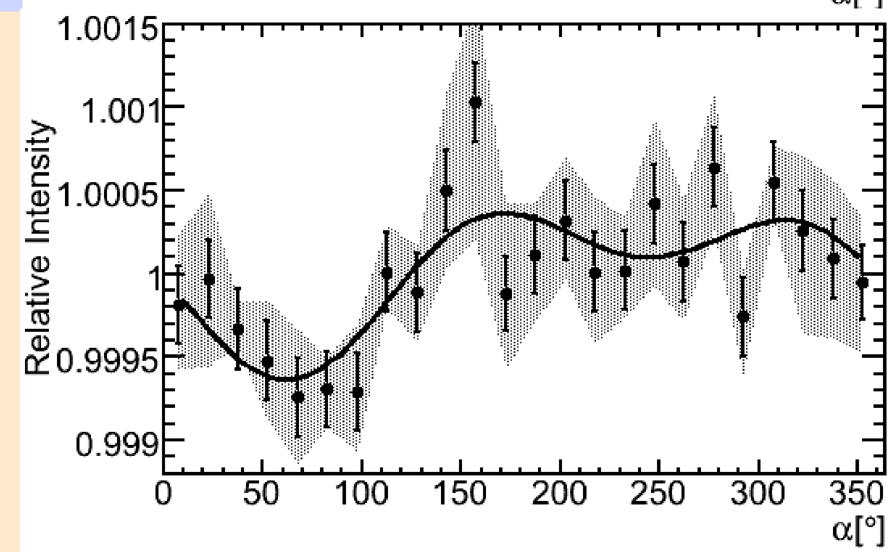
20 TeV





400 TeV

deficit
6.3 σ_{post}



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

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

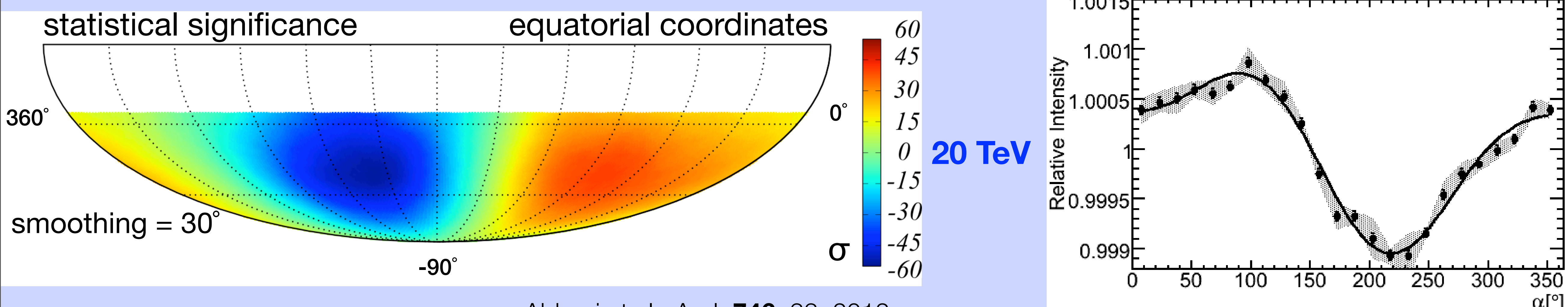
NOTE: anisotropy is not a dipole
topology changes at high energy

cosmic ray anisotropy vs energy in IceCube-59

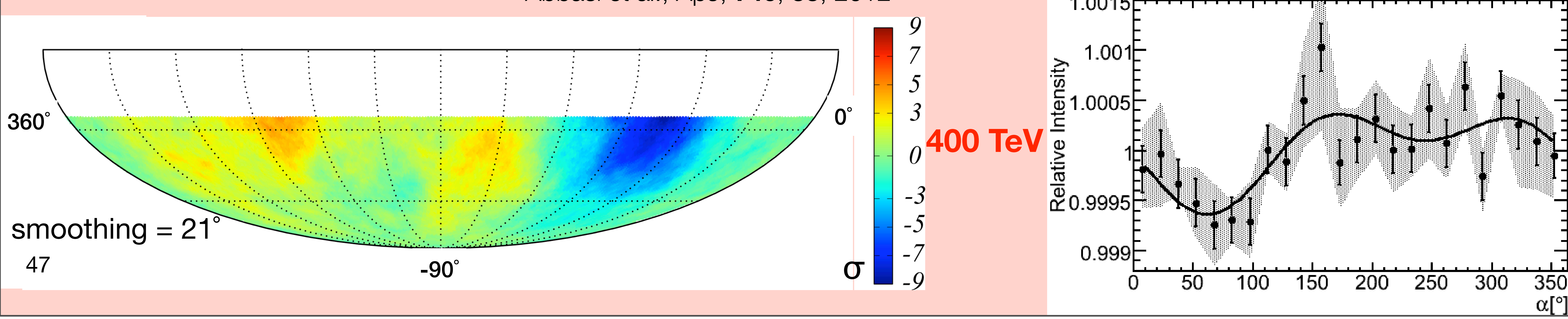
- reference map derived from data with time scrambling
- smoothing radius optimized on highest significance in excess/deficit region

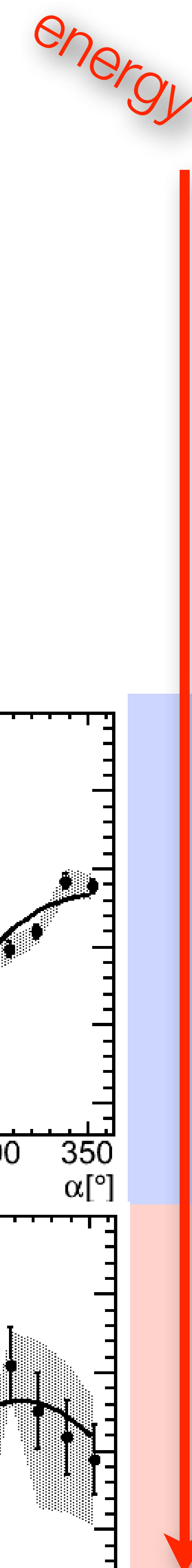
$$s = \sqrt{2}\left\{ N_{\rm on} \ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\rm on}}{N_{\rm on}+N_{\rm off}}\right)\right] + N_{\rm off}\ln\left[(1+\alpha)\left(\frac{N_{\rm off}}{N_{\rm on}+N_{\rm off}}\right)\right]\right\}^{1/2} \qquad \alpha = 1/20$$

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



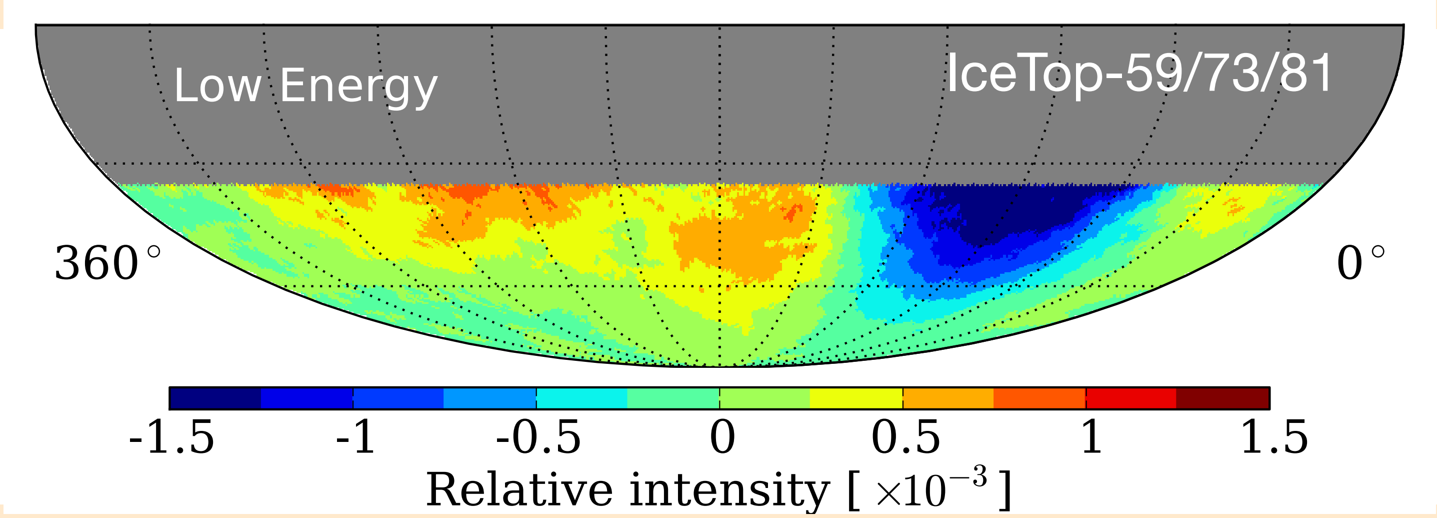
Abbasi et al., ApJ, **746**, 33, 2012





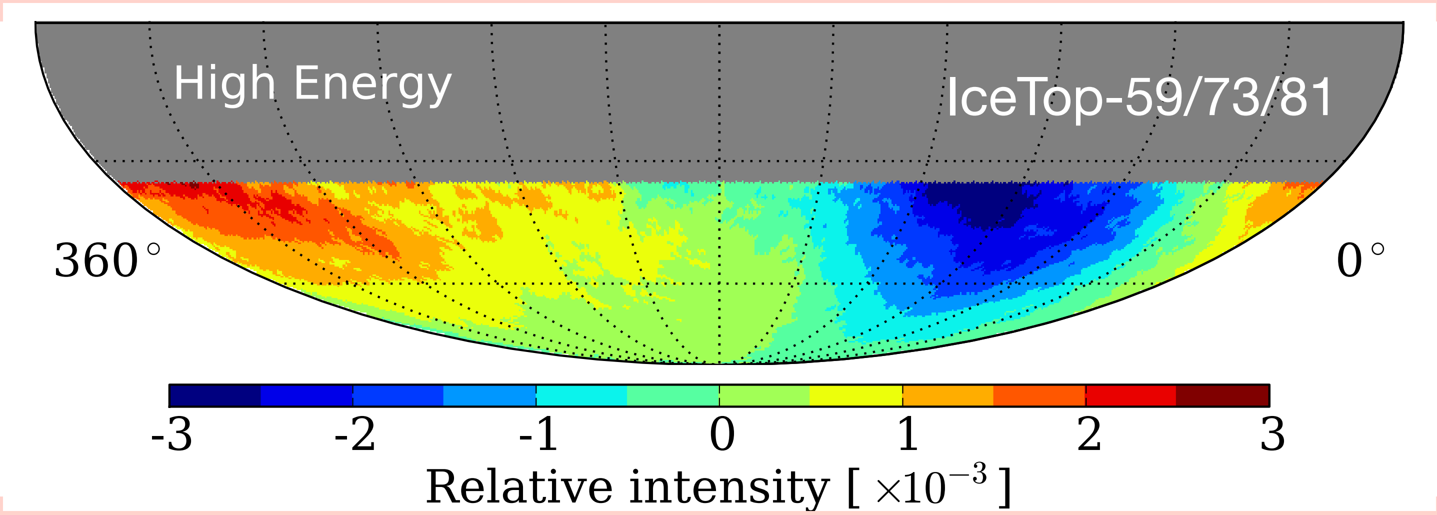
cosmic ray anisotropy large scale
IceTop

relative intensity equatorial coordinates



deficit
7 σ_{post}

400 TeV



2 PeV

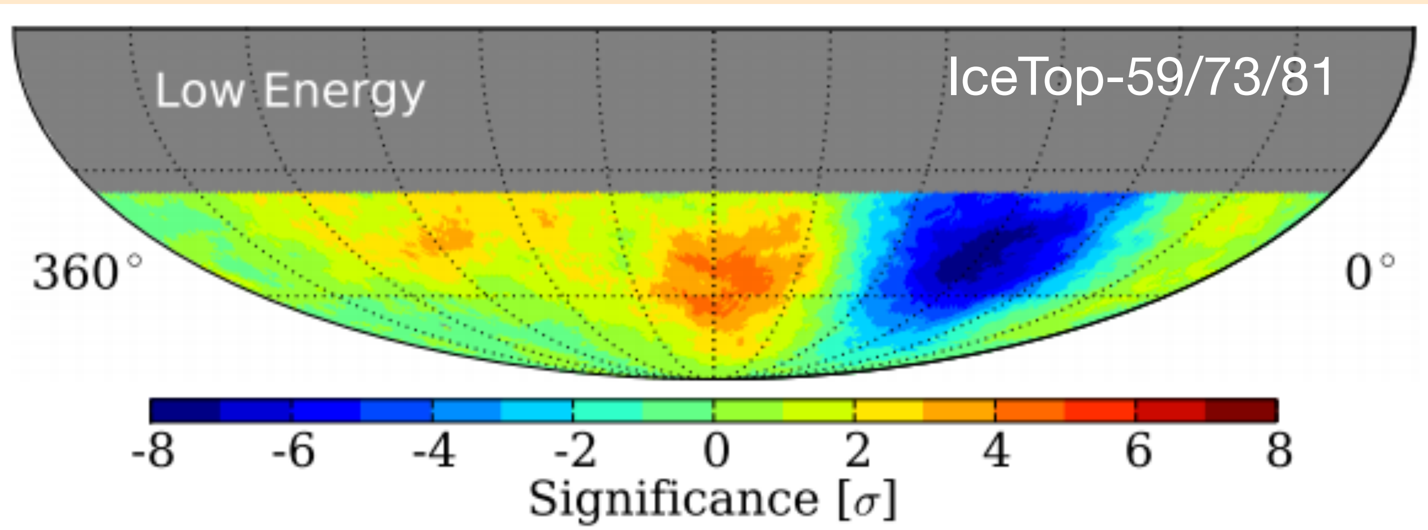
Aartsen et al., ApJ, **765**, 55, 2013

NOTE: global topology does not change

deficit amplitude increases with energy

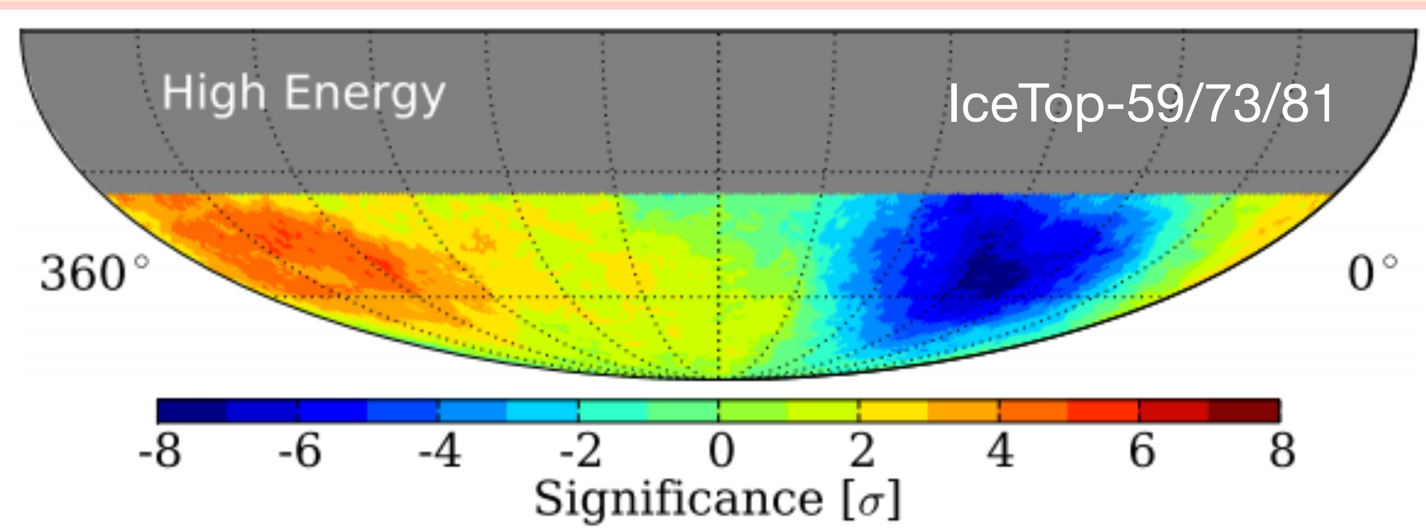
cosmic ray anisotropy large scale
IceTop

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

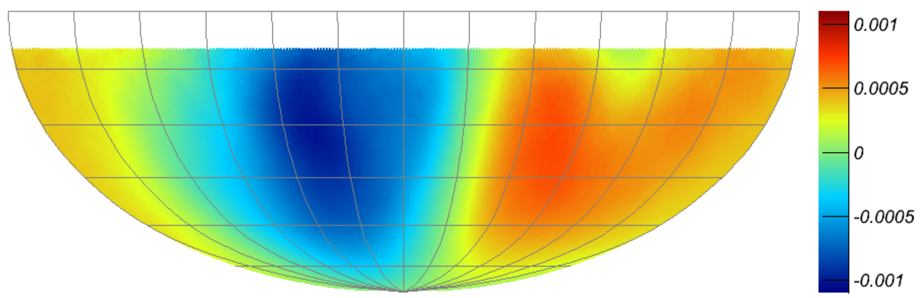
deficit amplitude increases with energy

cosmic ray anisotropy

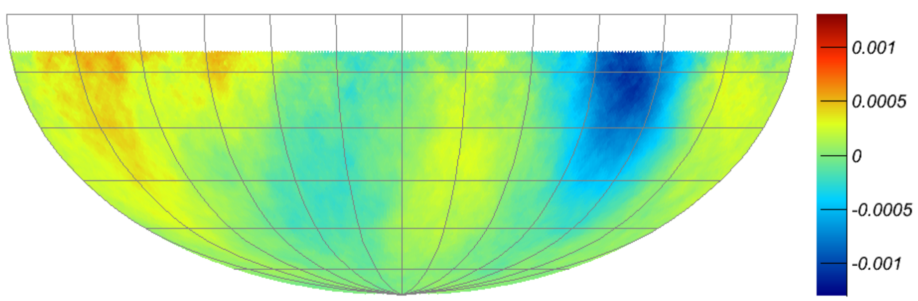
large scale

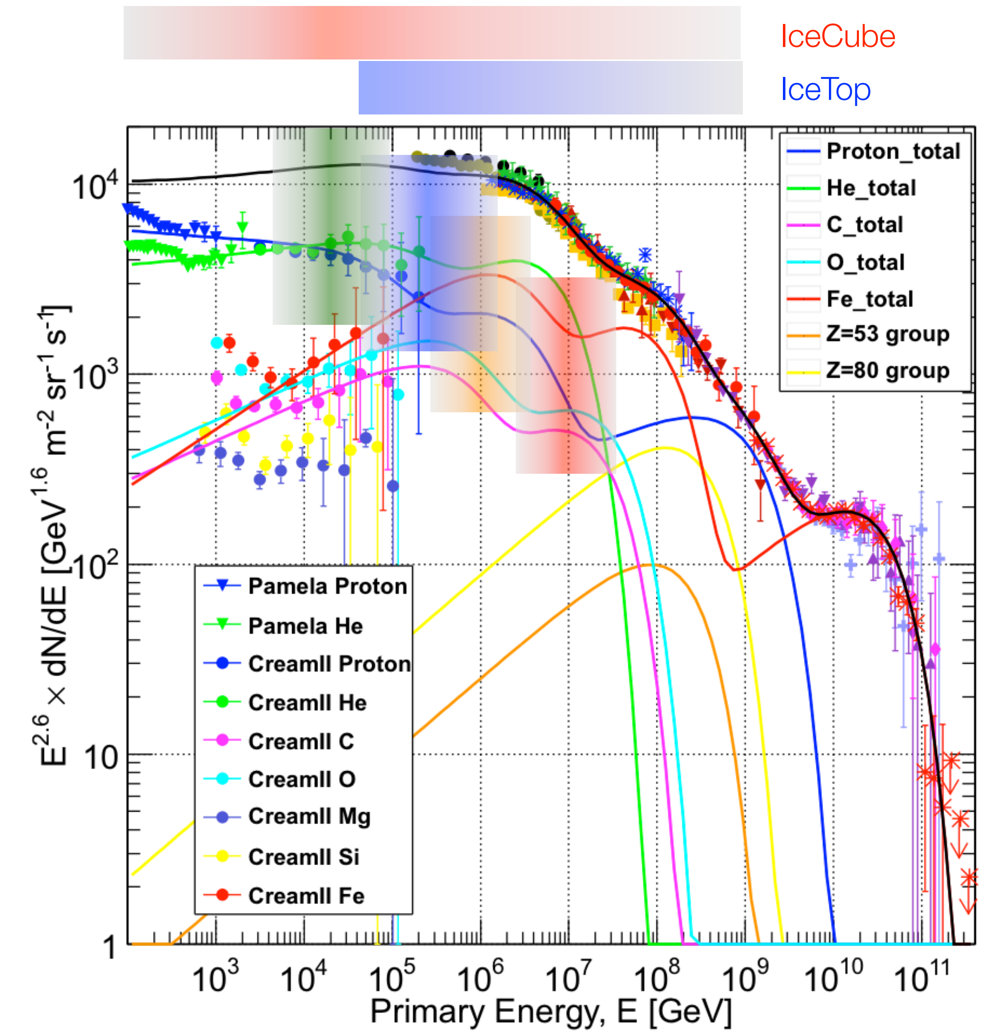
IceCube

20 TeV

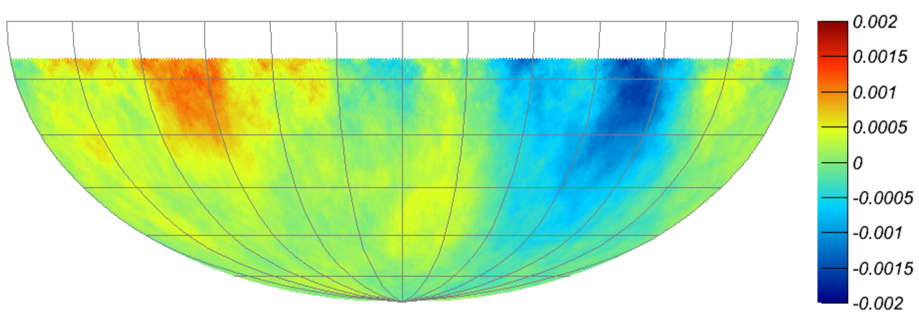


400 TeV



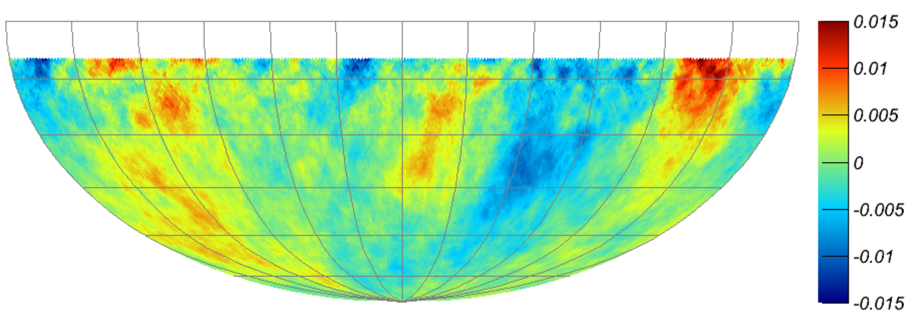


1 PeV



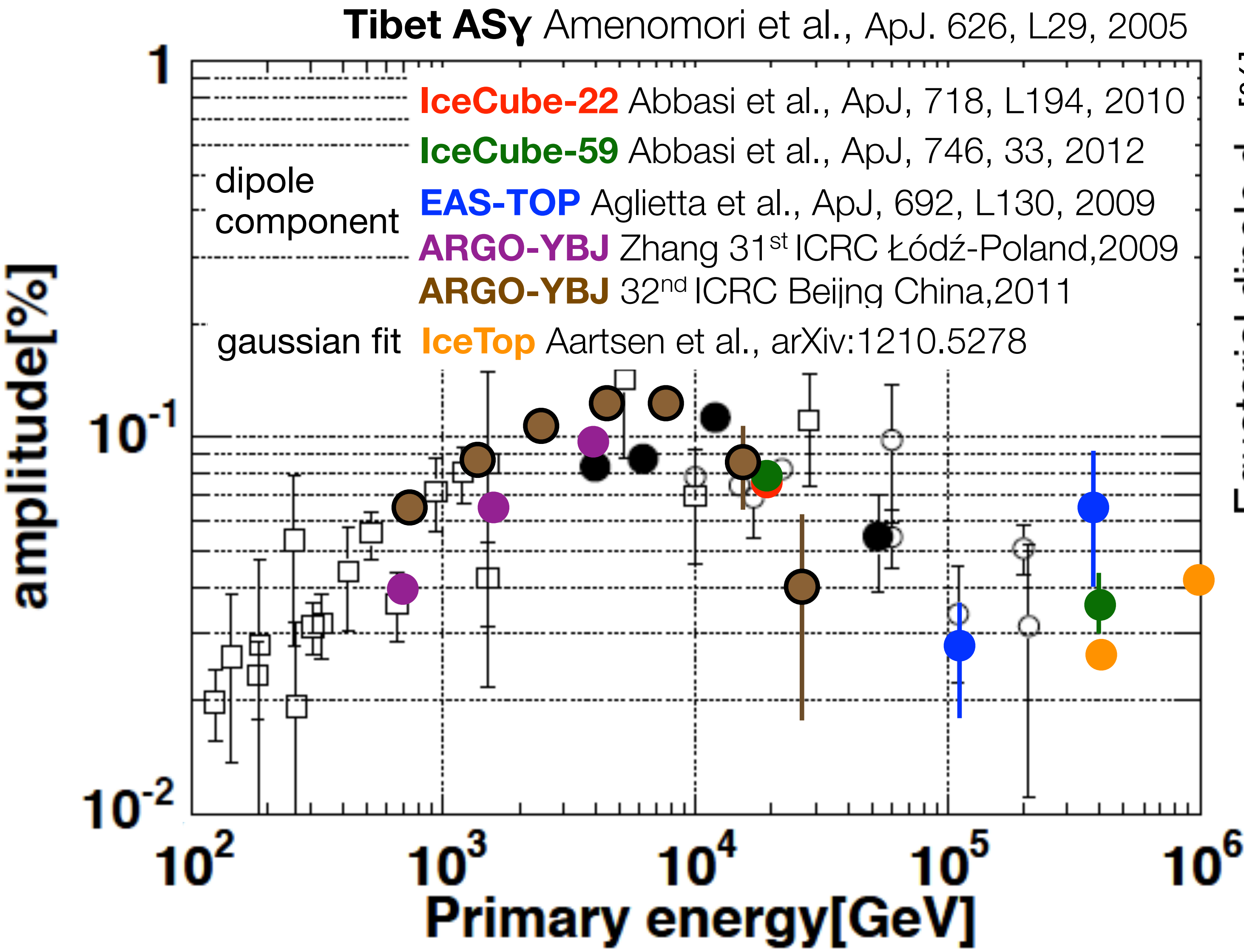
PRELIMINARY

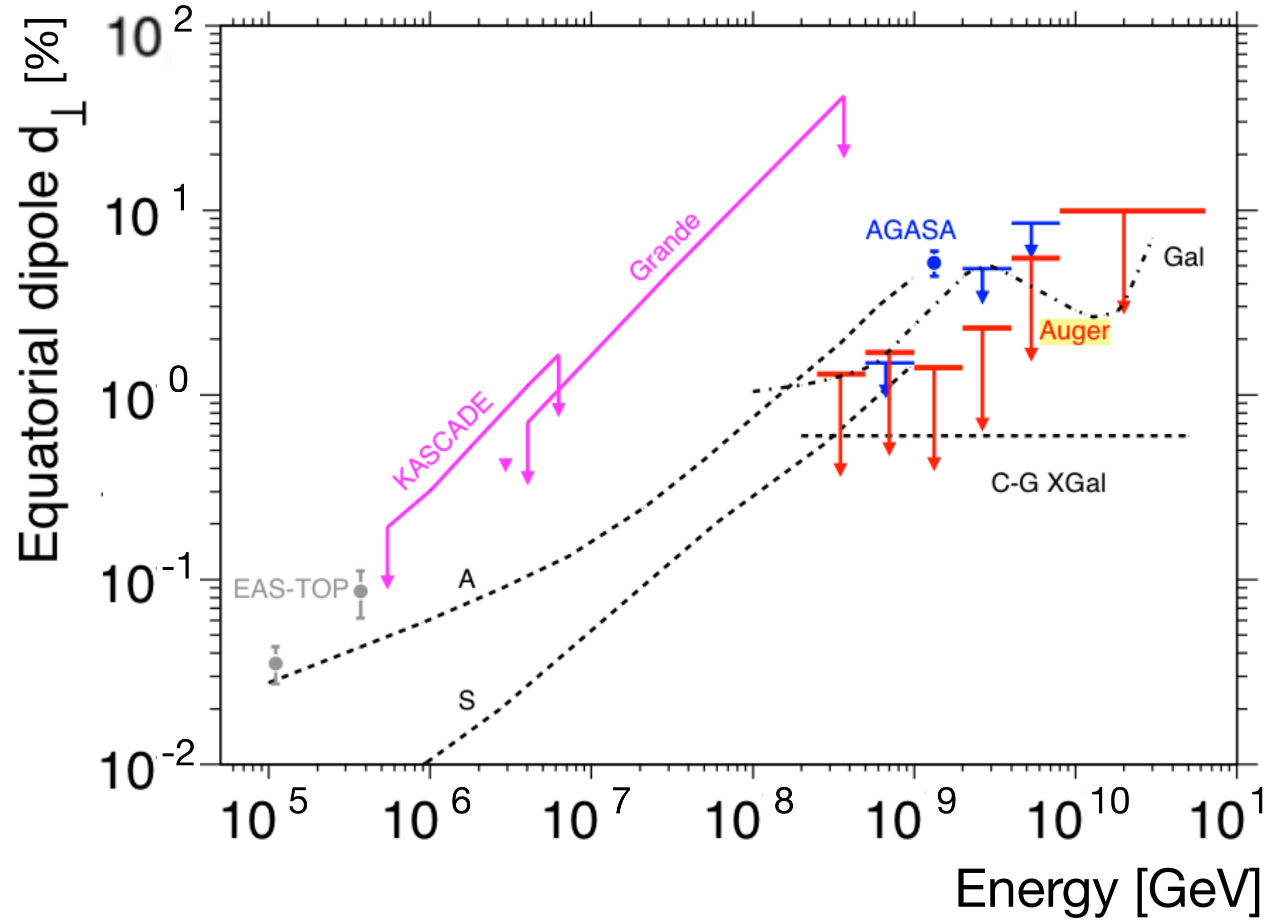
10 PeV



PRELIMINARY

cosmic ray anisotropy large scale energy dependency



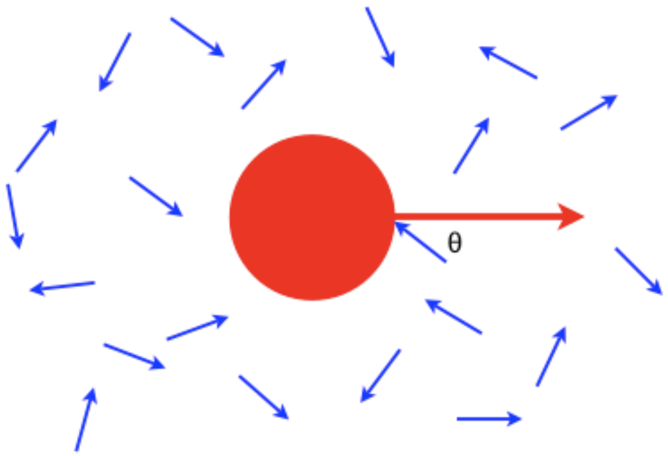


Abreu et al., Astrop. Phys., 34, 627, 2011

a known anisotropy

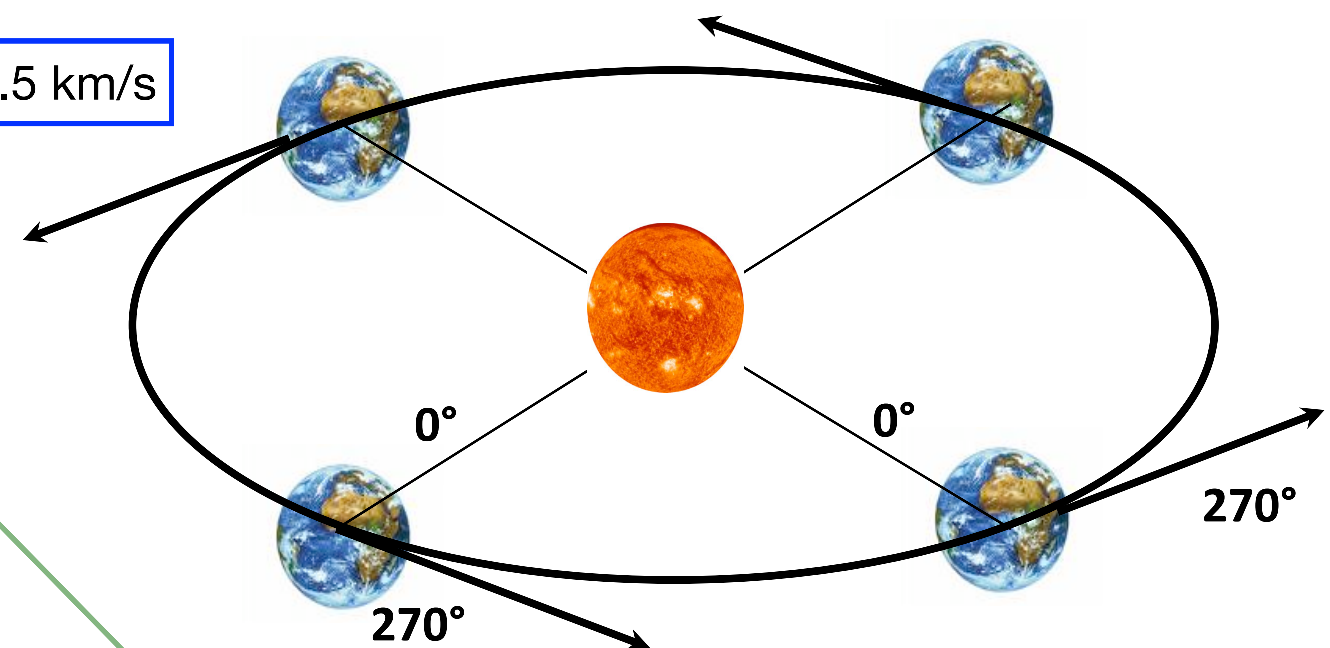
Earth's motion around the Sun

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

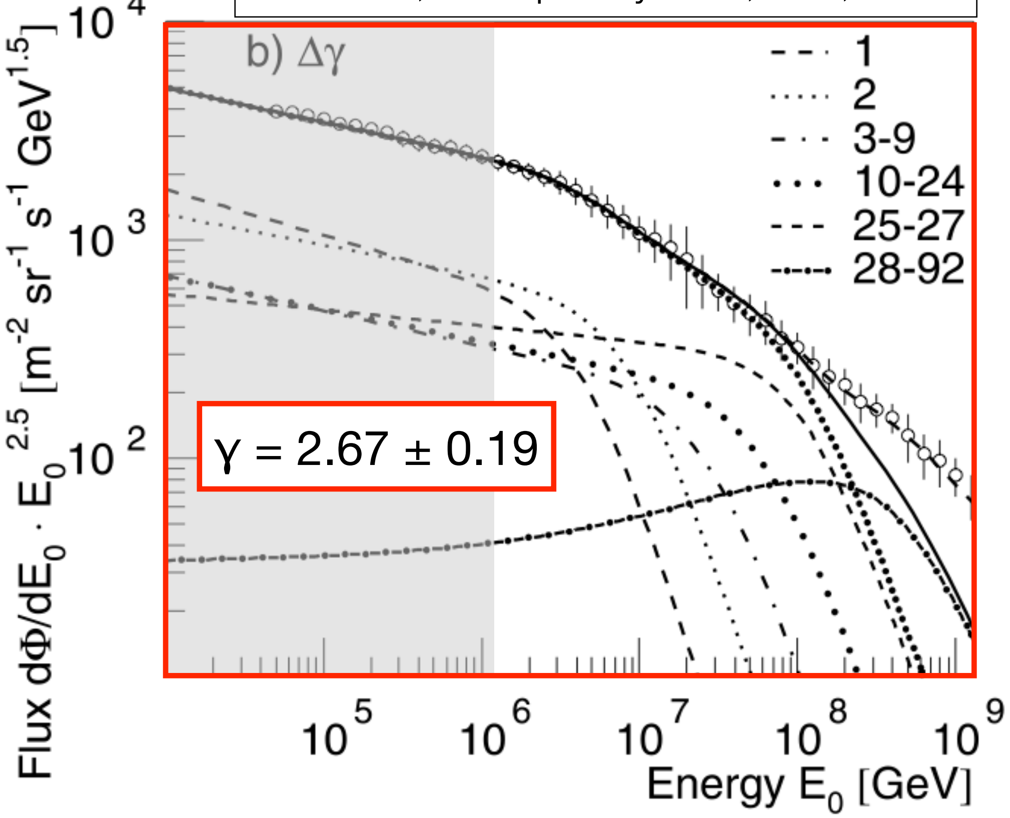


v = 29.8 ± 0.5 km/s

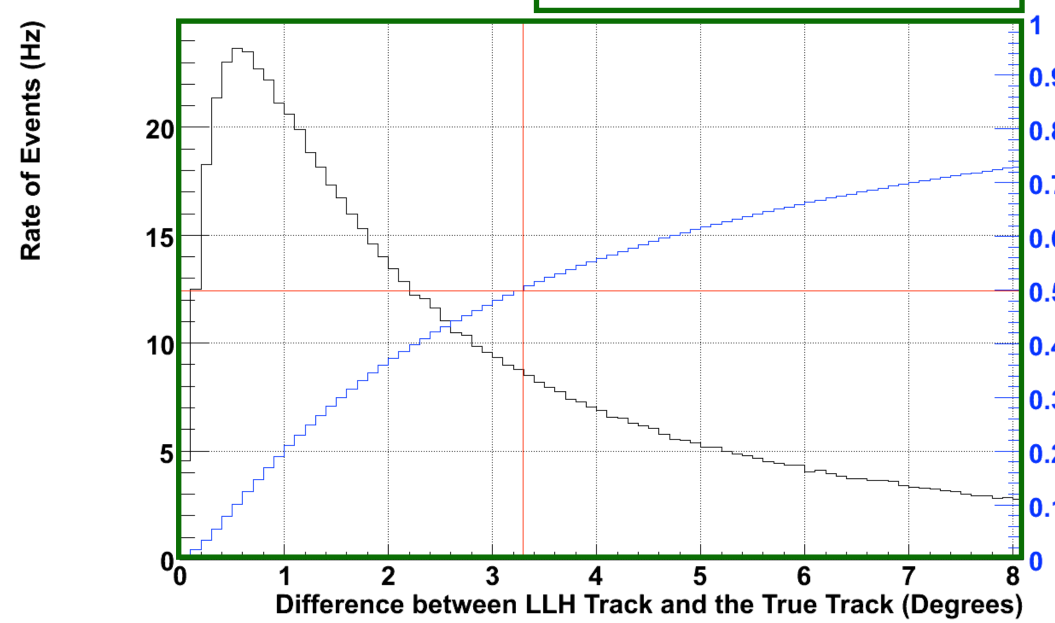
$$\frac{\Delta I}{I} = (\gamma + 2)\frac{v}{c}\cos\theta$$



Hörandel, Astrop. Phys. 19, 193, 2003



point spread function

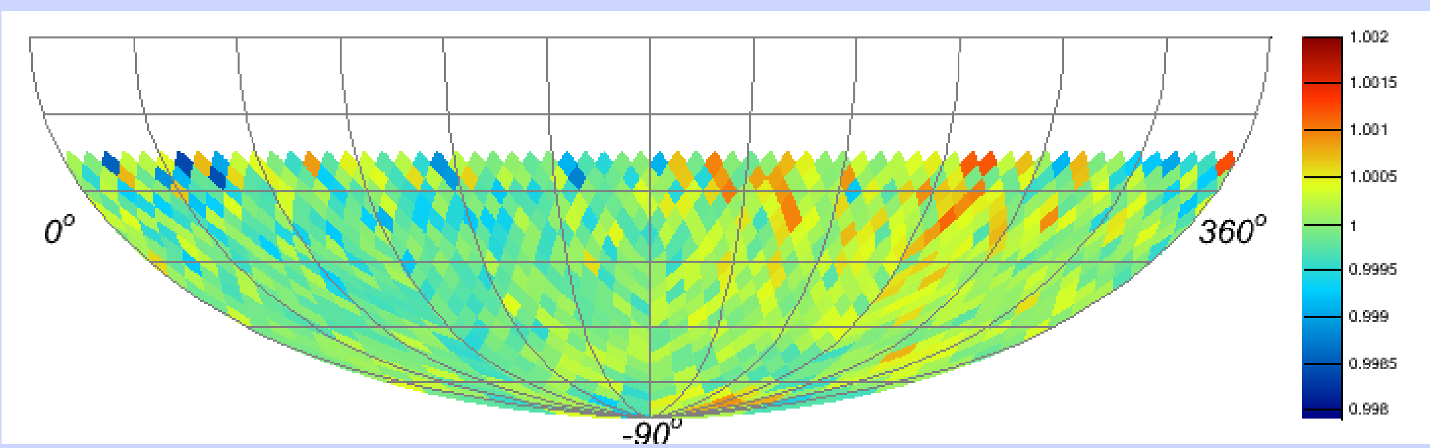


a known anisotropy
Earth's motion around the Sun

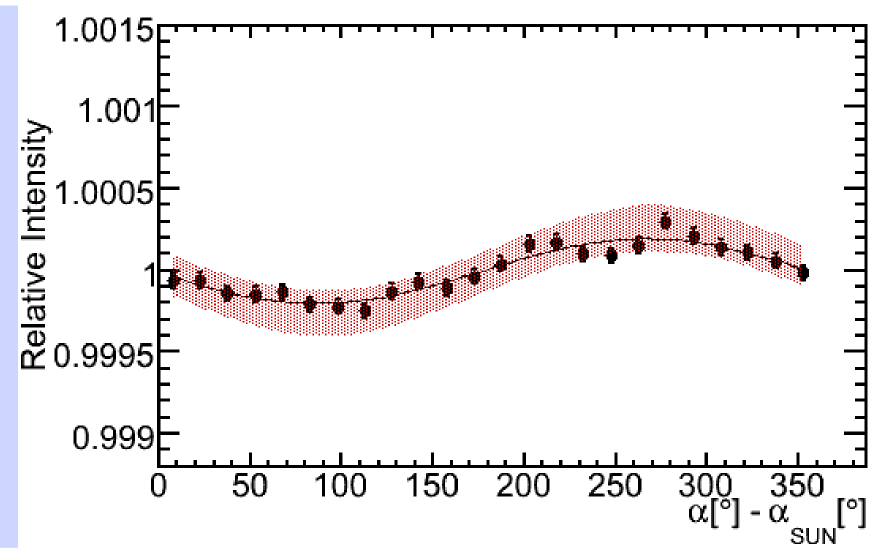
- the observation of the **solar dipole** supports the observation of the sidereal anisotropy in cosmic ray arrival direction

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

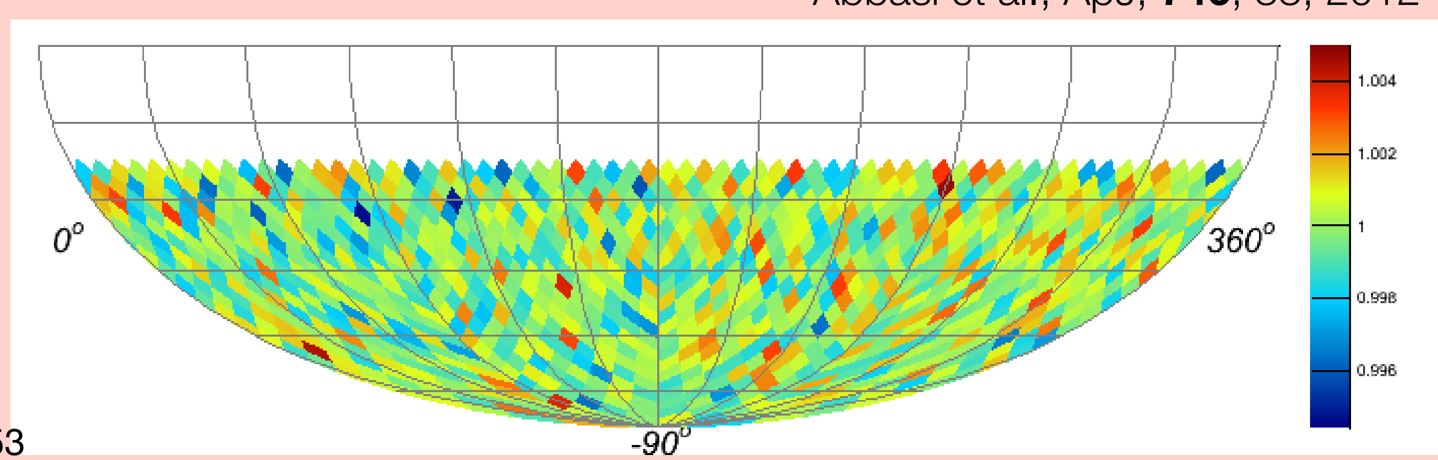
relative intensity $\quad$ $\alpha\,[^\circ] - \alpha_{SUN}\,[^\circ]$ $\quad$ IC59 Abbasi et al., ApJ, **746**, 33, 2012



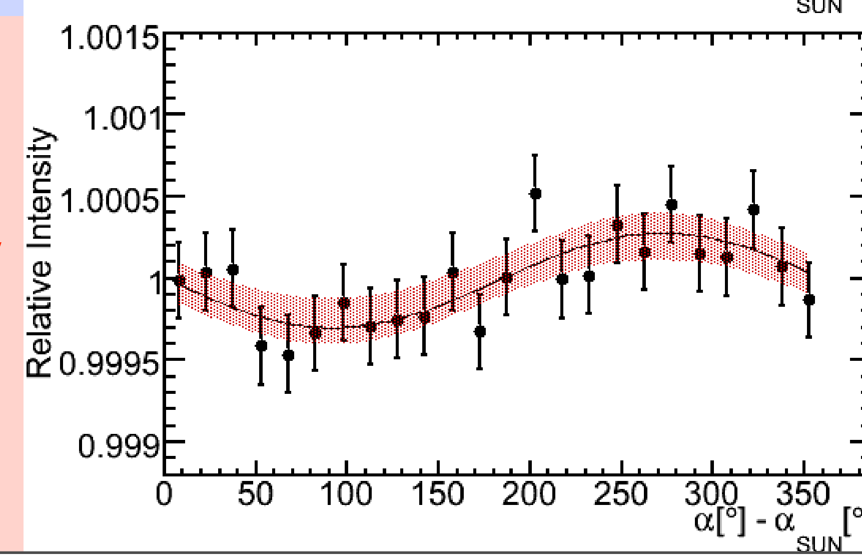
20 TeV



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

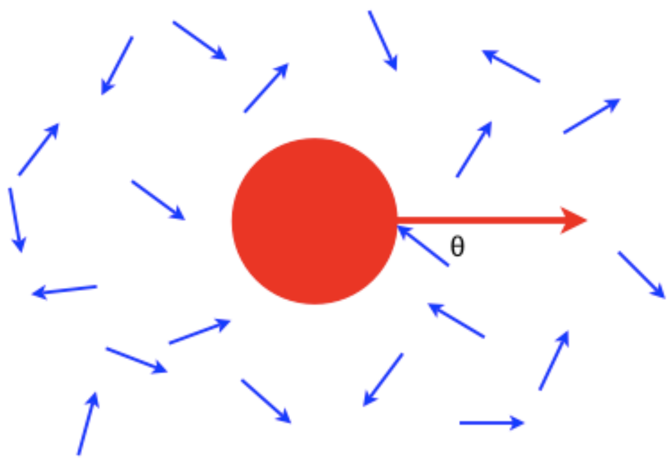


400 TeV



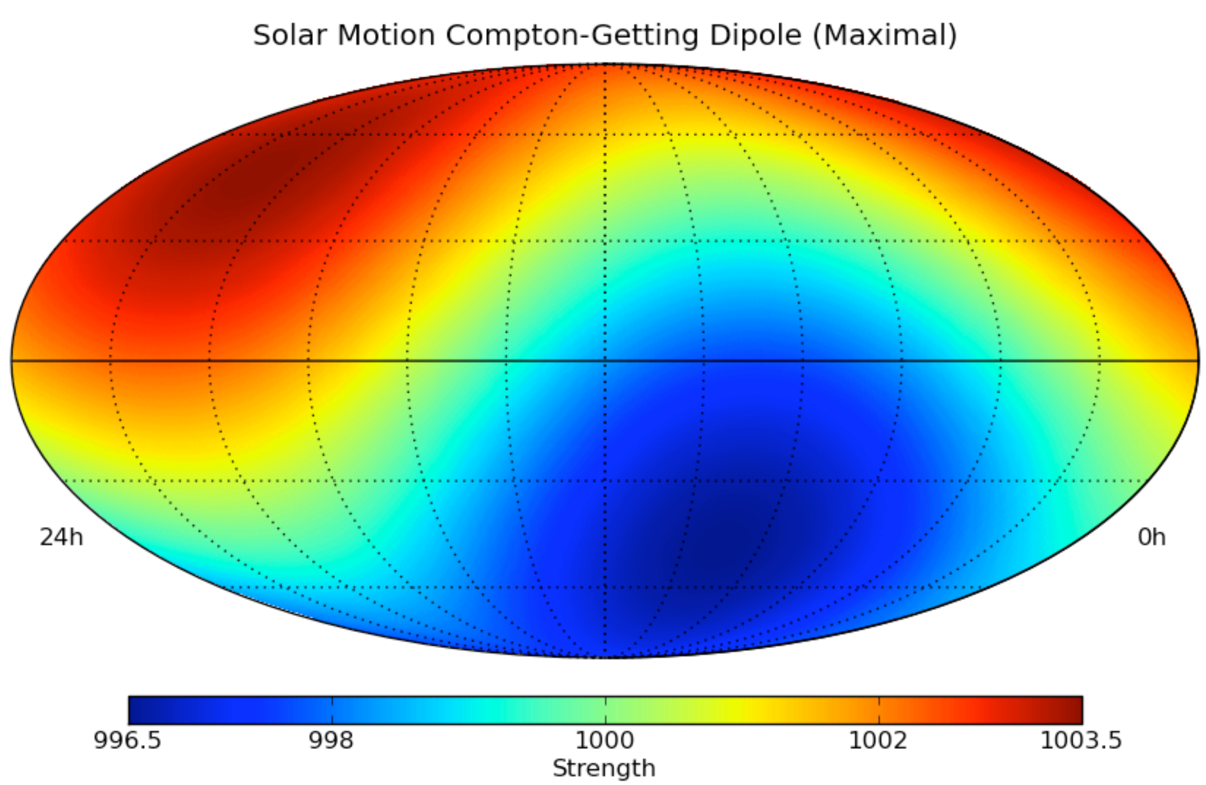
origin of large scale anisotropy : Compton-Getting Effect ?

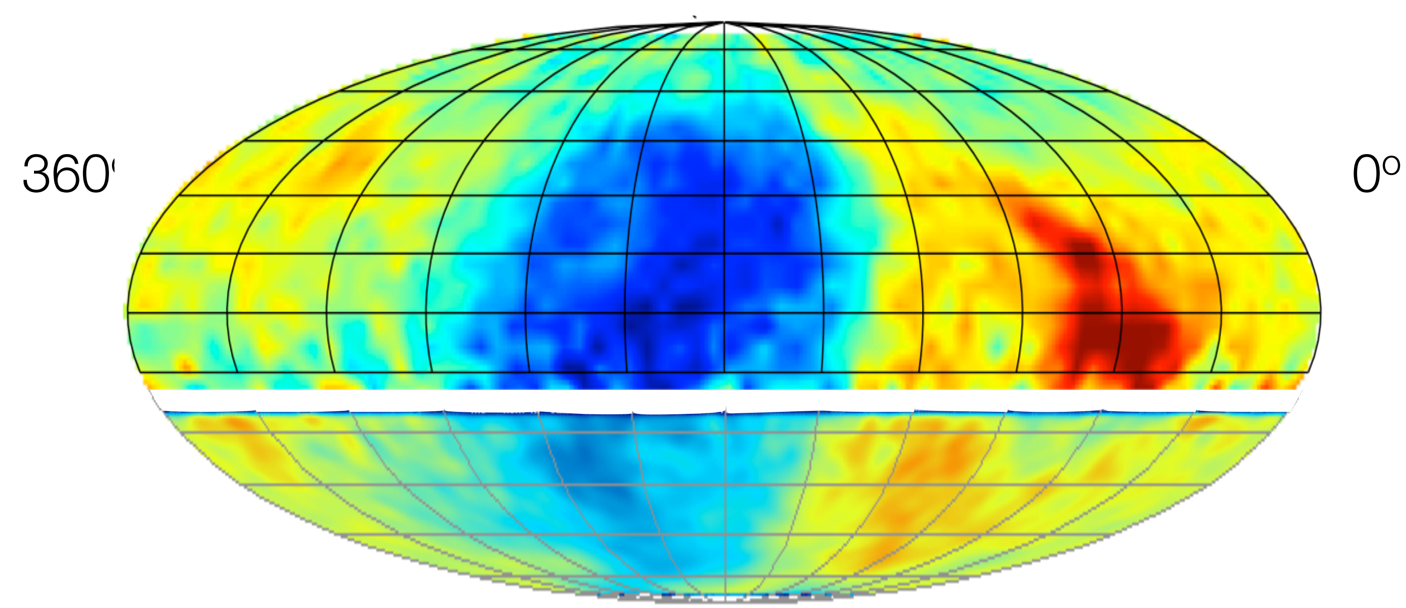
Compton & Getting, Phys. Rev. 47, 817 (1935)
Gleeson, & Axford, Ap&SS, 2, 43 (1968)



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

- 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

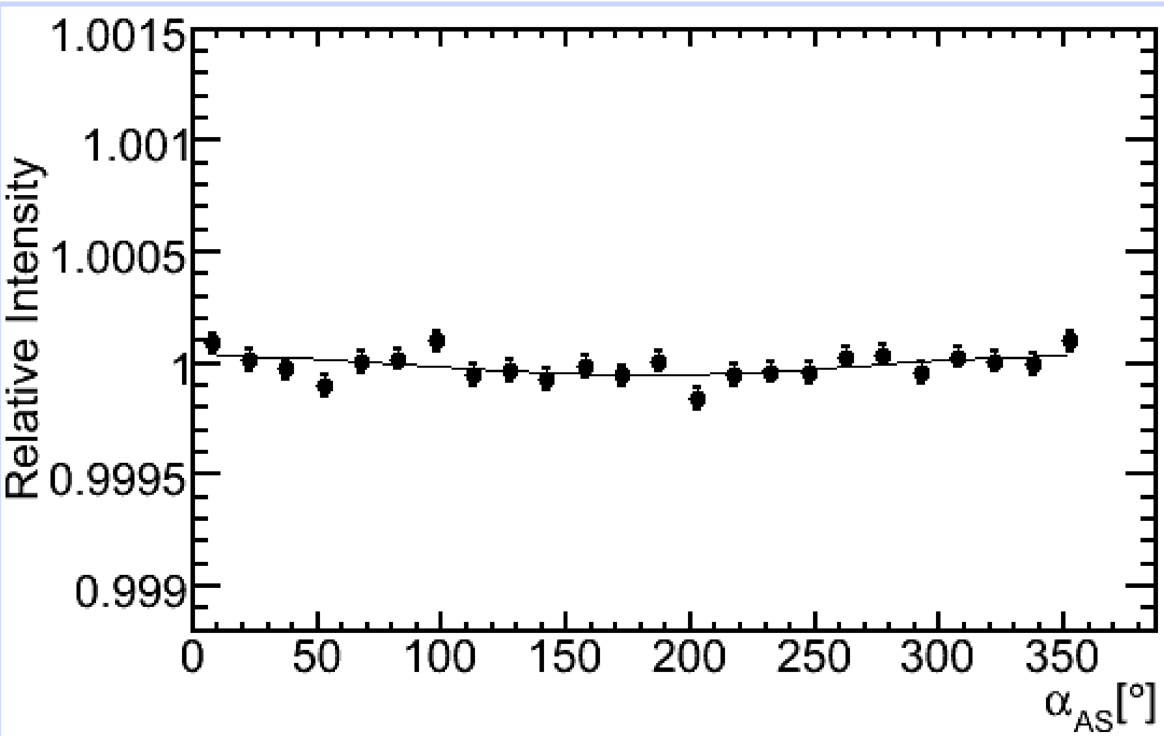




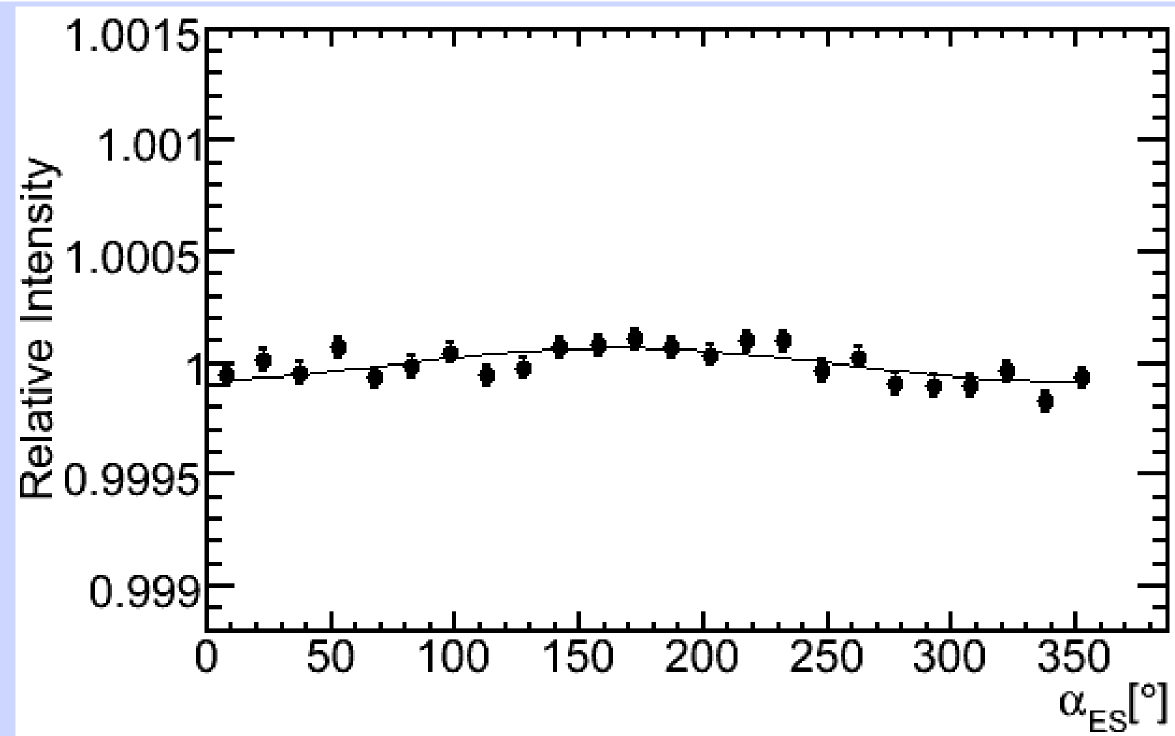
anti-/extended-sidereal distributions vs energy in IceCube-59

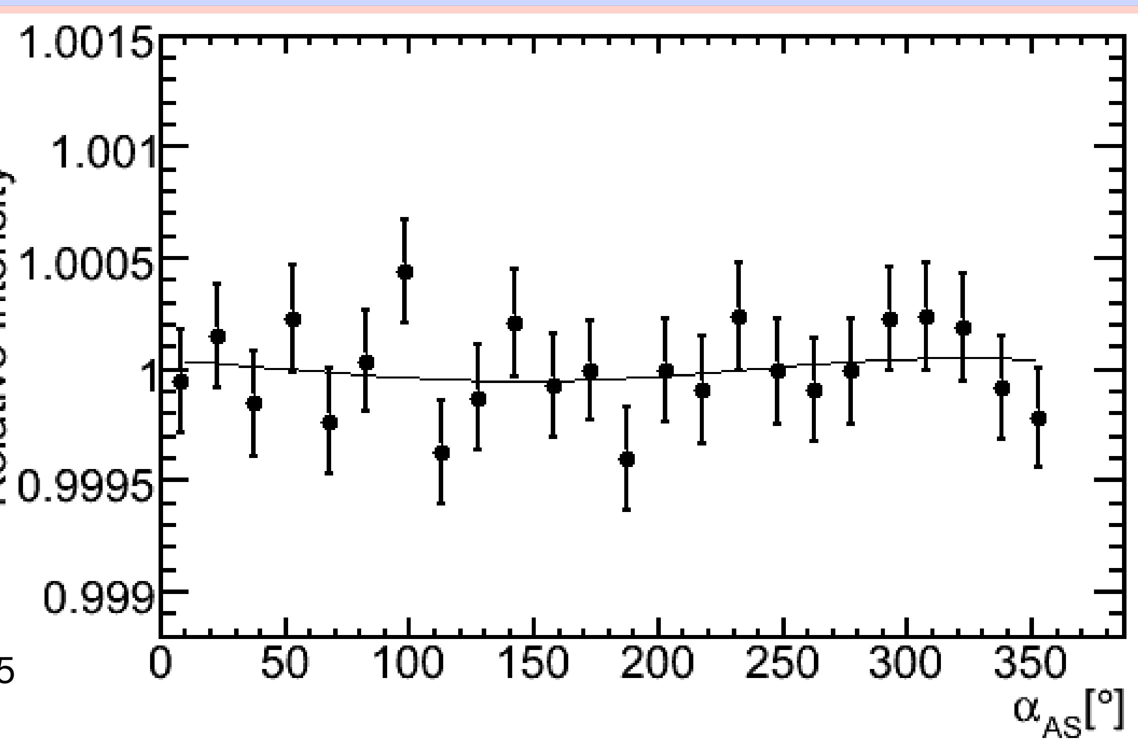
anti-sidereal distribution ~ solar dipole variability

extended-sidereal distribution ~ sid. anis. variability

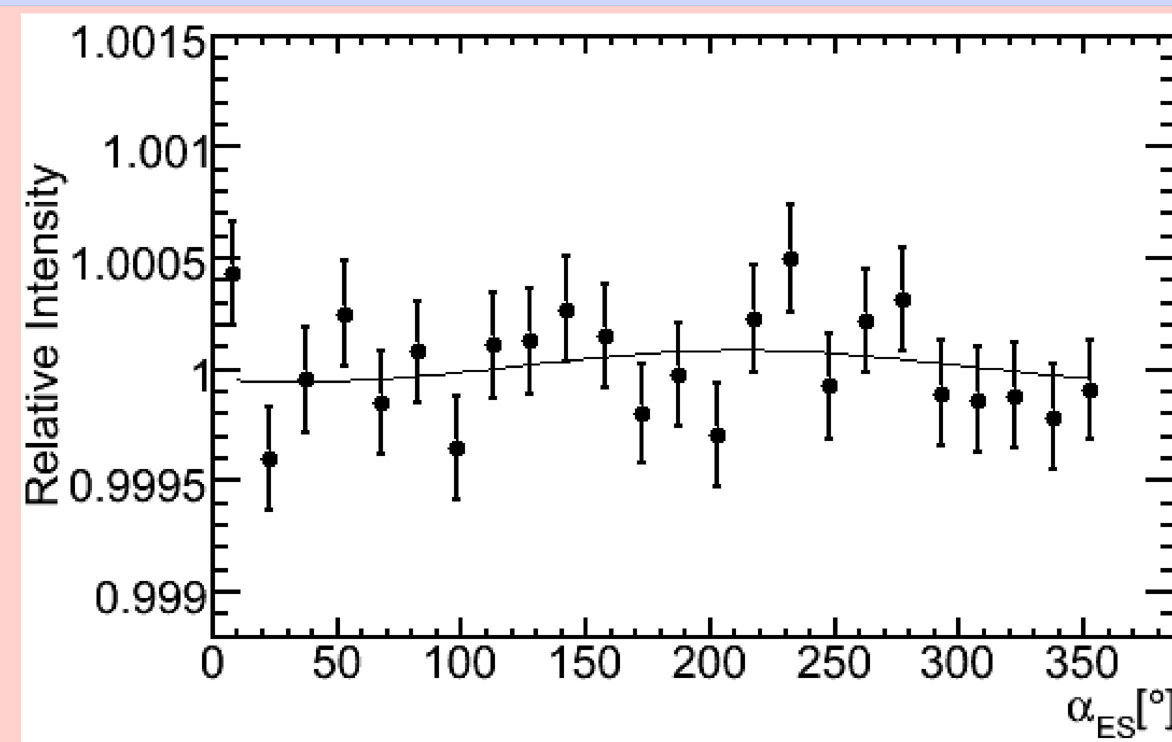


20 TeV





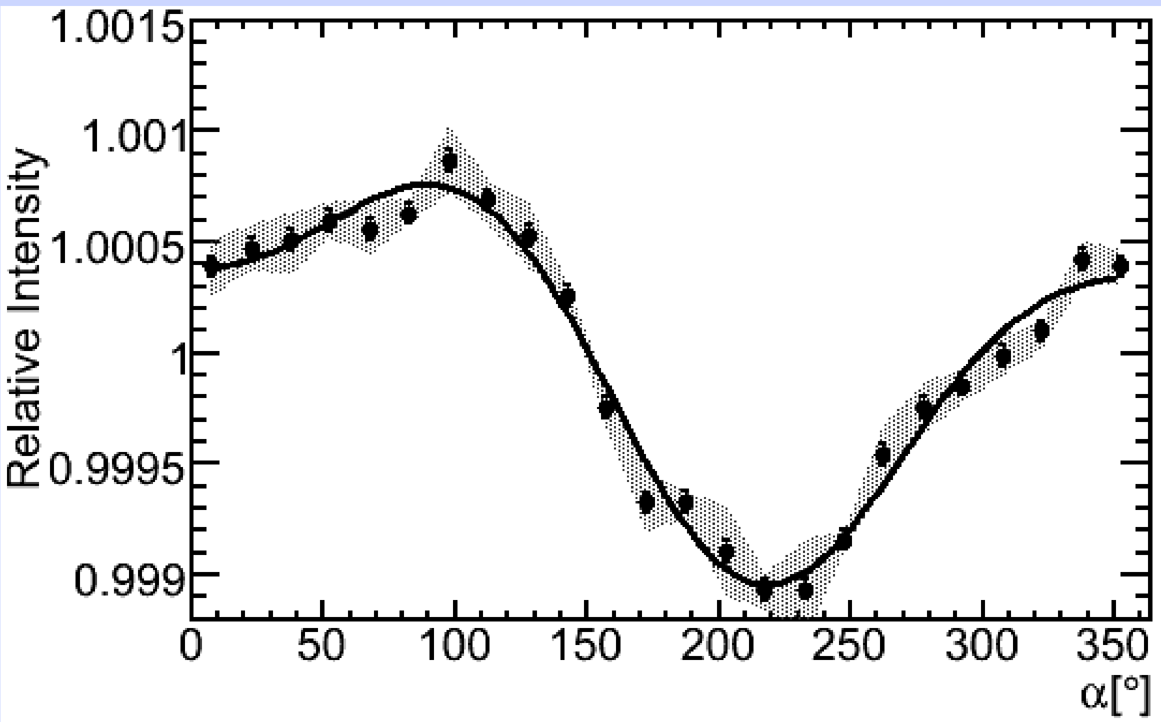
400 TeV



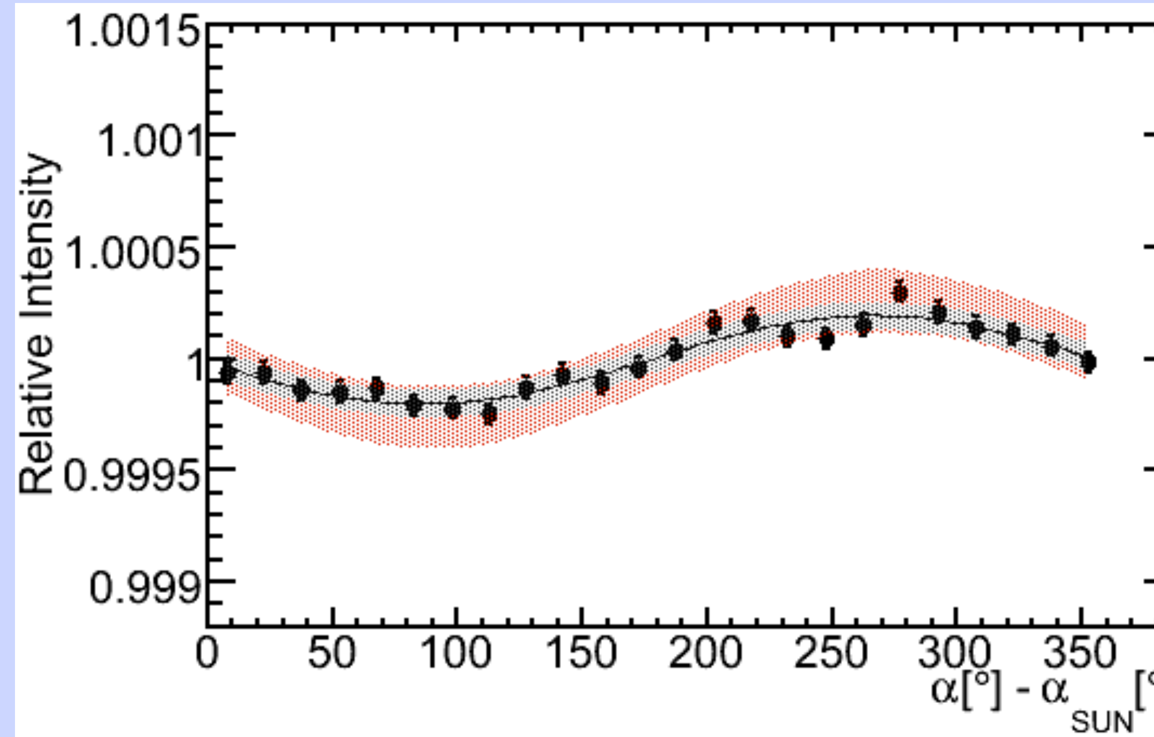
systematic uncertainties IceCube-59

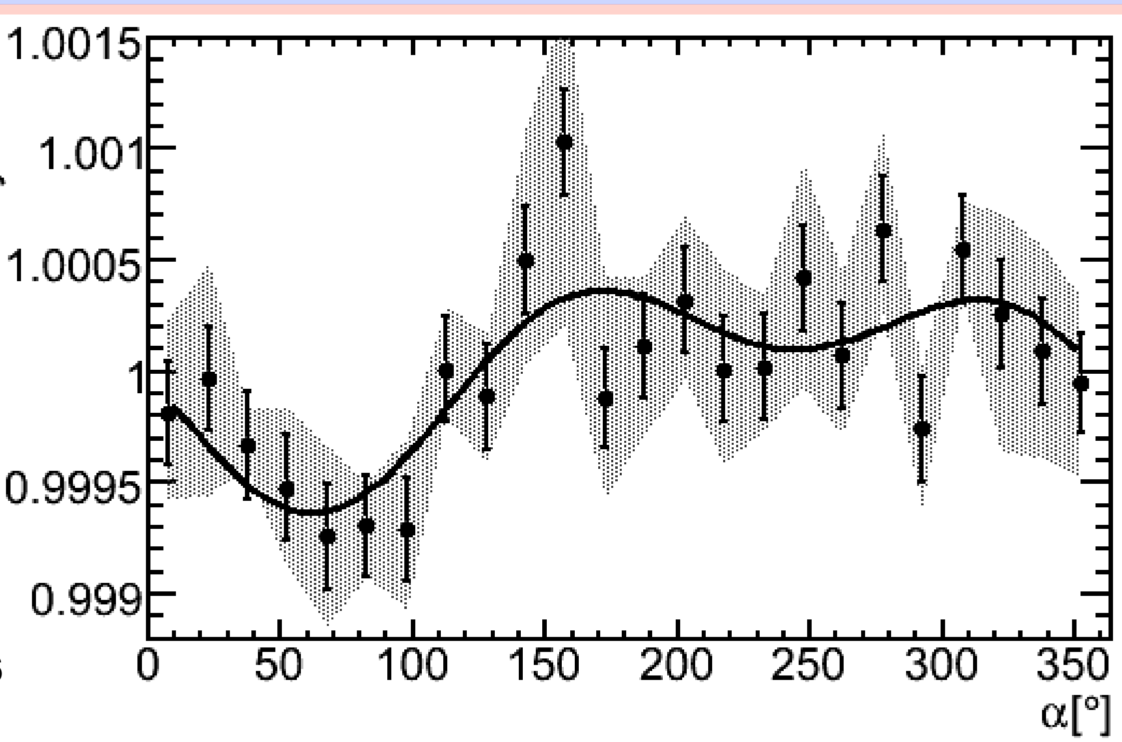
statistical stability tests + anti-sidereal effect

extended-sidereal effect

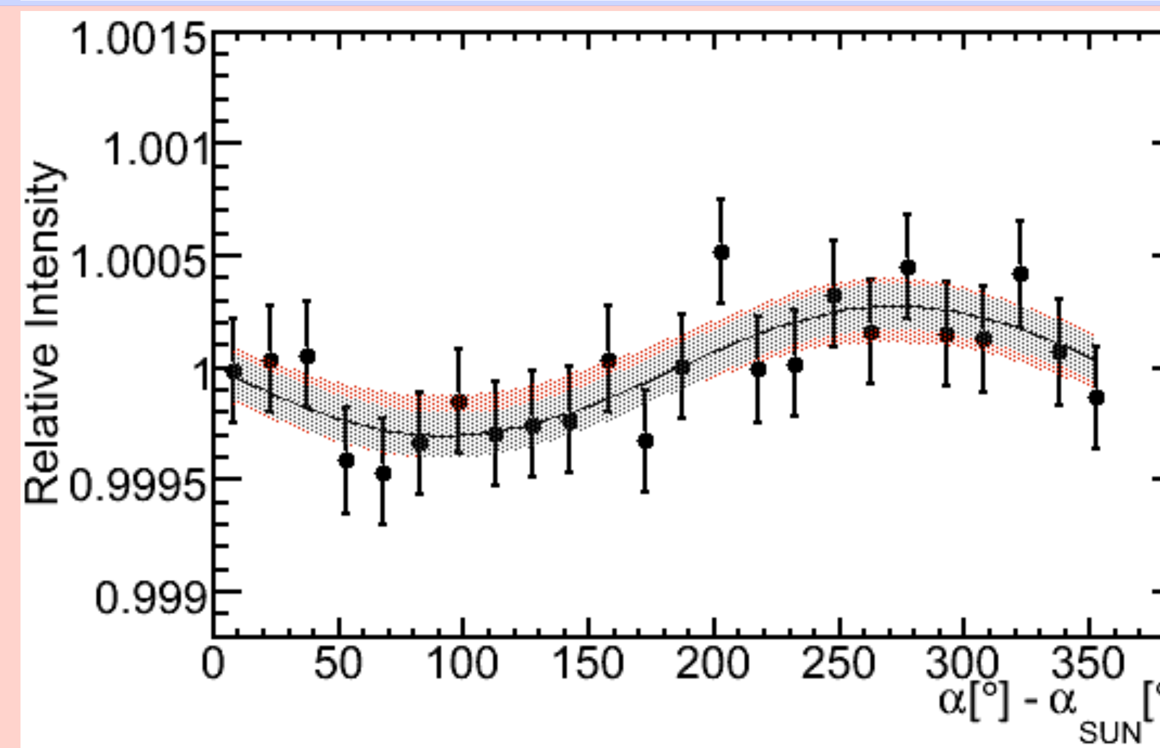


20 TeV



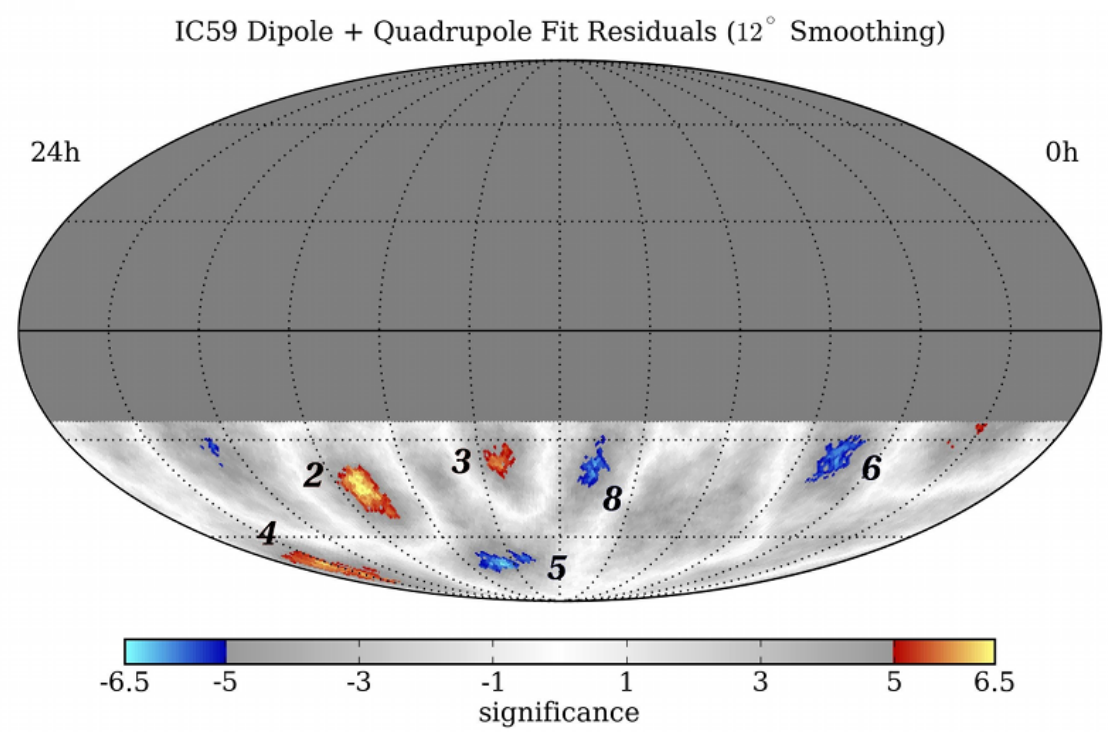


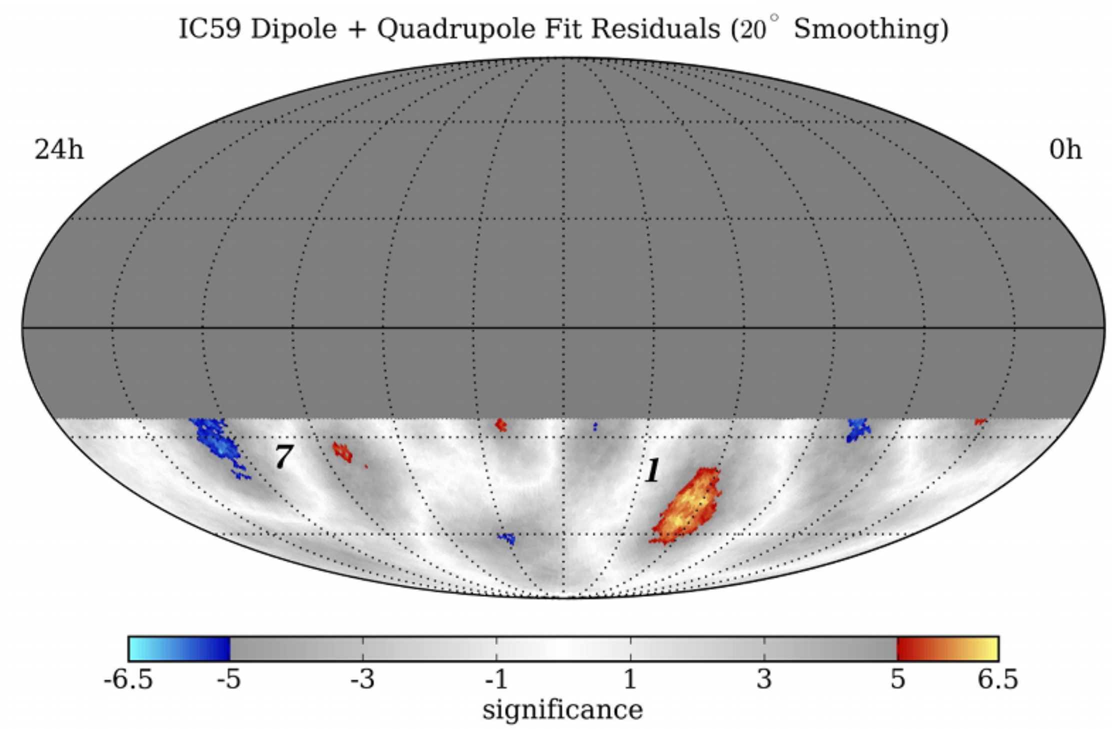
400 TeV



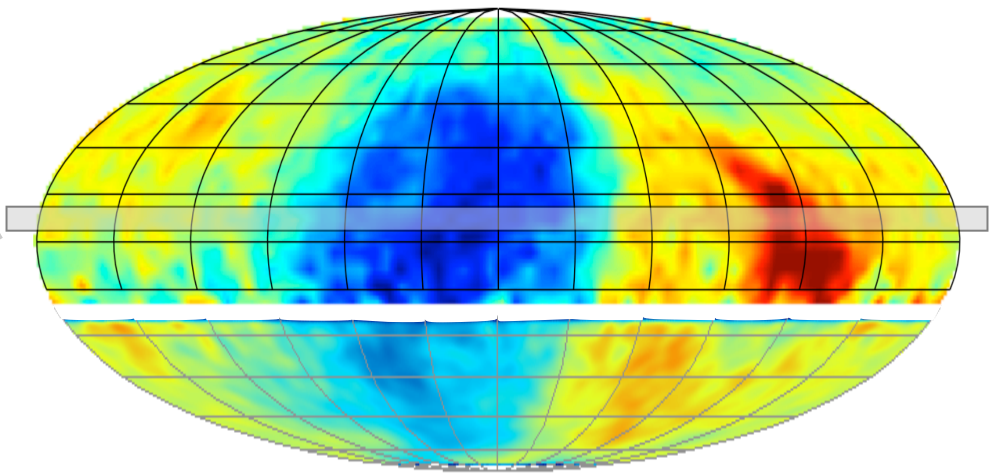
cosmic ray anisotropy small scale
IceCube

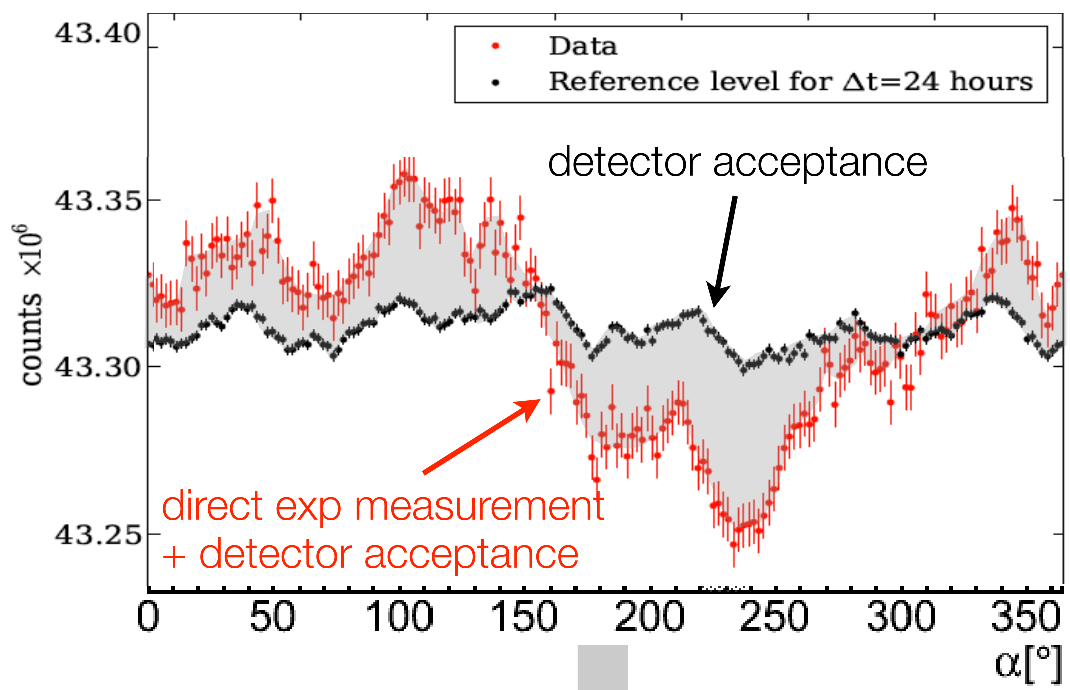
region	right ascension	declination	optimal scale	peak significance	post-trials	IC79 (post-trials)
1	$(122.4^{+4.1}_{-4.7})^\circ$	$(-47.4^{+7.5}_{-3.2})^\circ$	22°	7.0σ	5.3σ	6.8σ
2	$(263.0^{+3.7}_{-3.8})^\circ$	$(-44.1^{+5.3}_{-5.1})^\circ$	13°	6.7σ	4.9σ	5.4σ
3	$(201.6^{+6.0}_{-1.1})^\circ$	$(-37.0^{+2.2}_{-1.9})^\circ$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

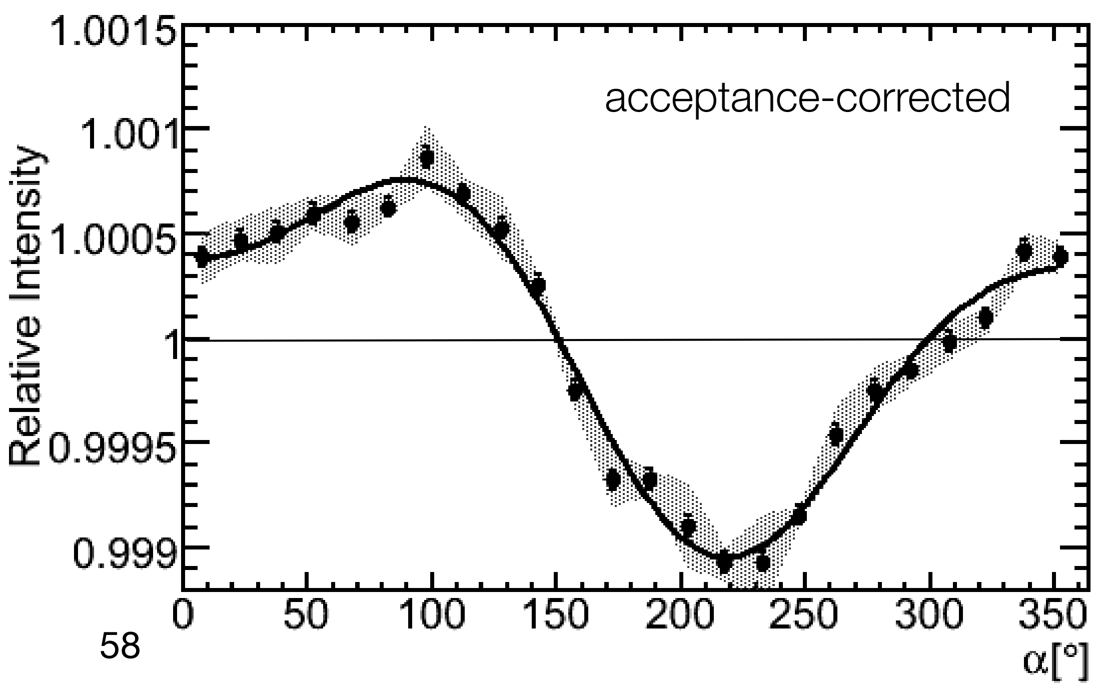


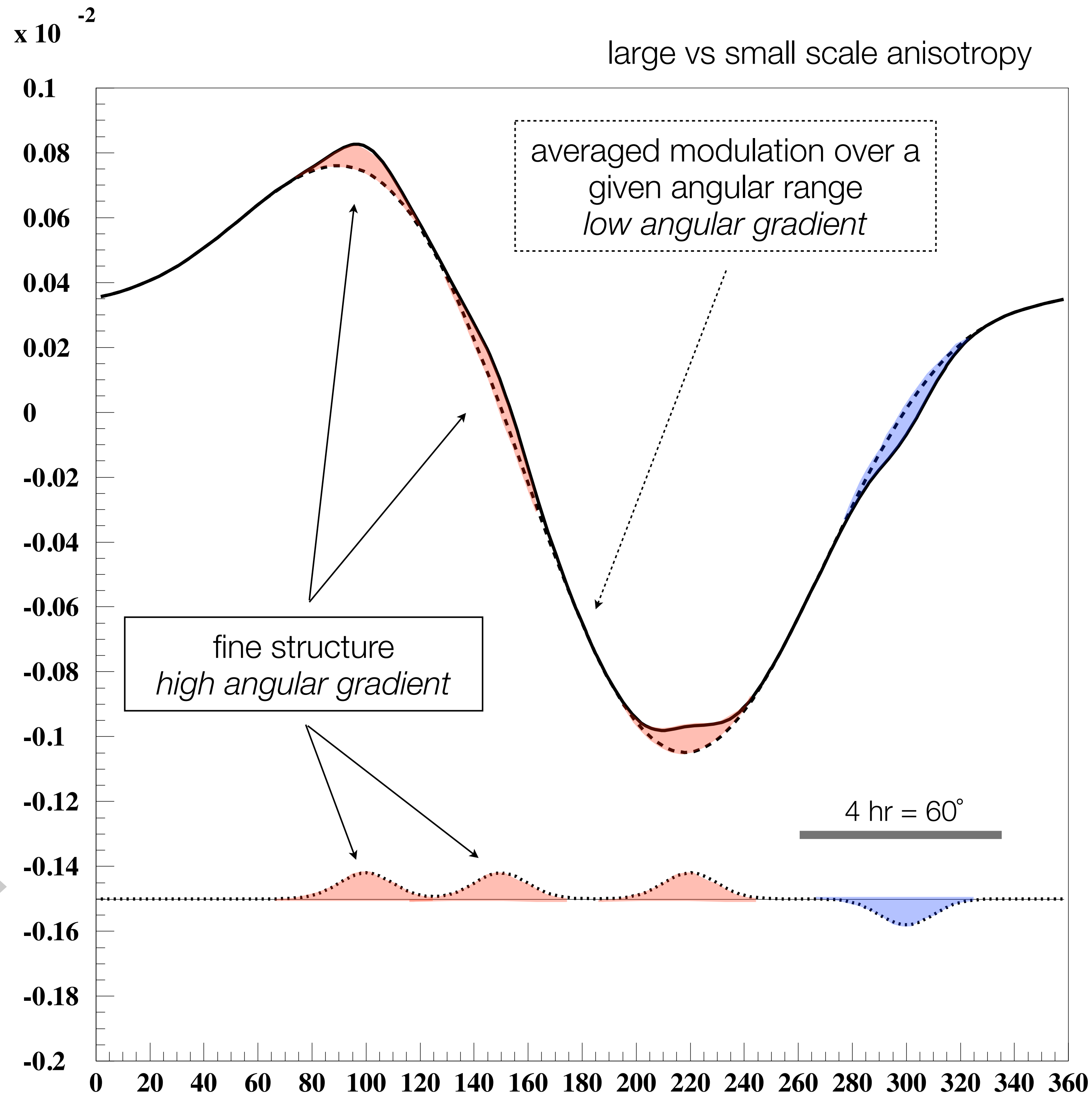


anisotropy vs. angular scale









Paolo Desiati

cosmic ray anisotropy
AMANDA-IceCube 2000-2011

Preliminary

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