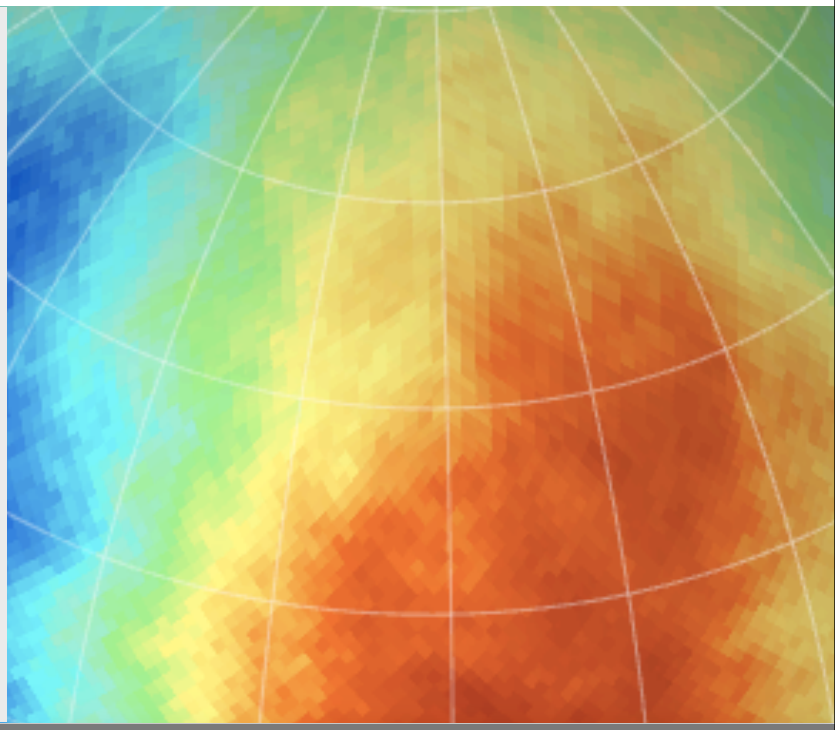
Study of cosmic-ray anisotropy with IceCube, IceTop, and AMANDA



Marcos Santander

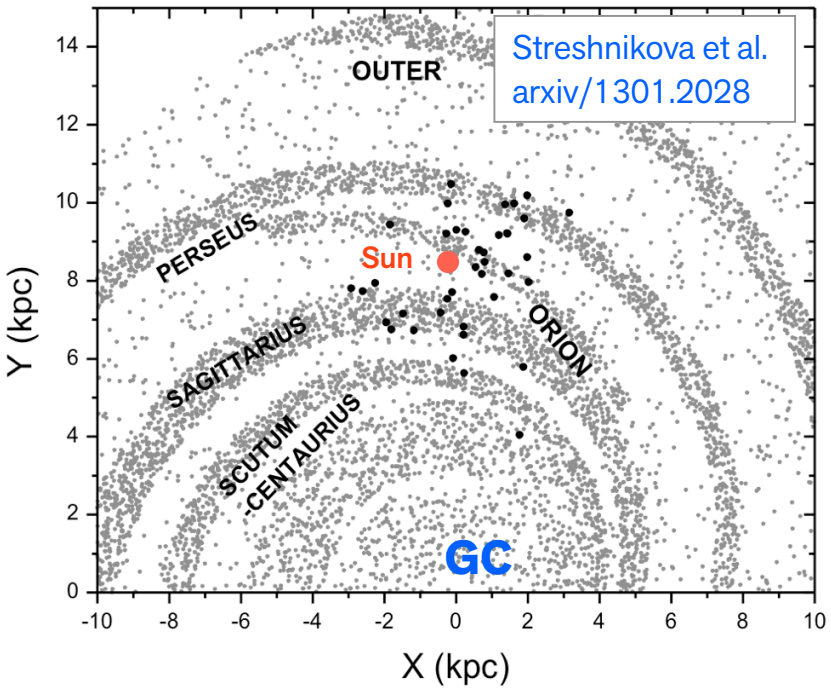
WIPAC, University of Wisconsin-Madison

WIPAC
Wisconsin IceCube Particle Astrophysics Center

WISCONSIN
University of Wisconsin–Madison

Cosmic ray propagation and anisotropy

Distribution of nearby SNRs in the galaxy



"Standard model" of galactic cosmic rays:

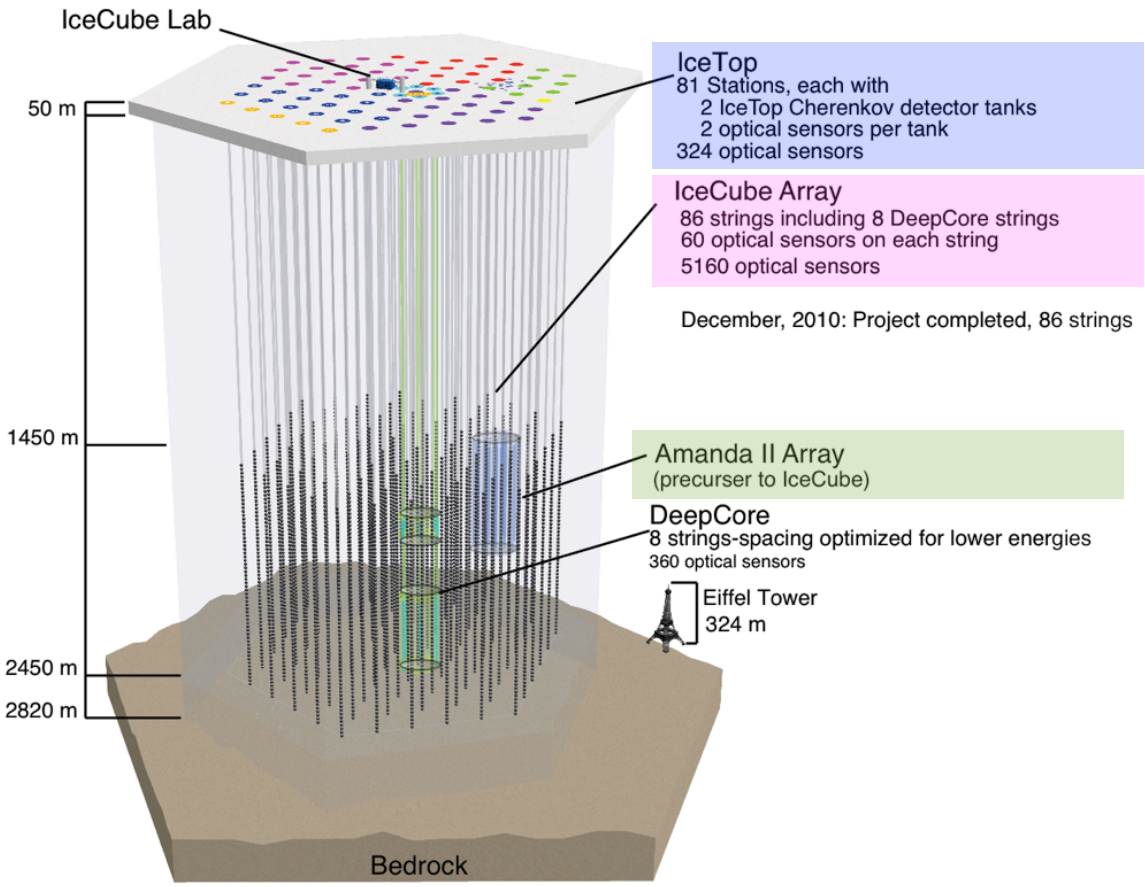
- Discrete sources (SNRs?) inject CRs with a power-law spectra.
- CRs propagate **diffusively** from their sources in the galactic magnetic field (2-6 μG) which isotropizes the trajectories.

Consequences for anisotropy:

- CR density gradients are visible as anisotropy.
- Anisotropy **amplitude ≤ 10^{-2}**.
- Amplitude **increases with energy**.
- **Dipole** shape.
- **Phase** should point towards the most significant source.

Small-amplitude anisotropy studies require large data sets ($> 10^8$ events)

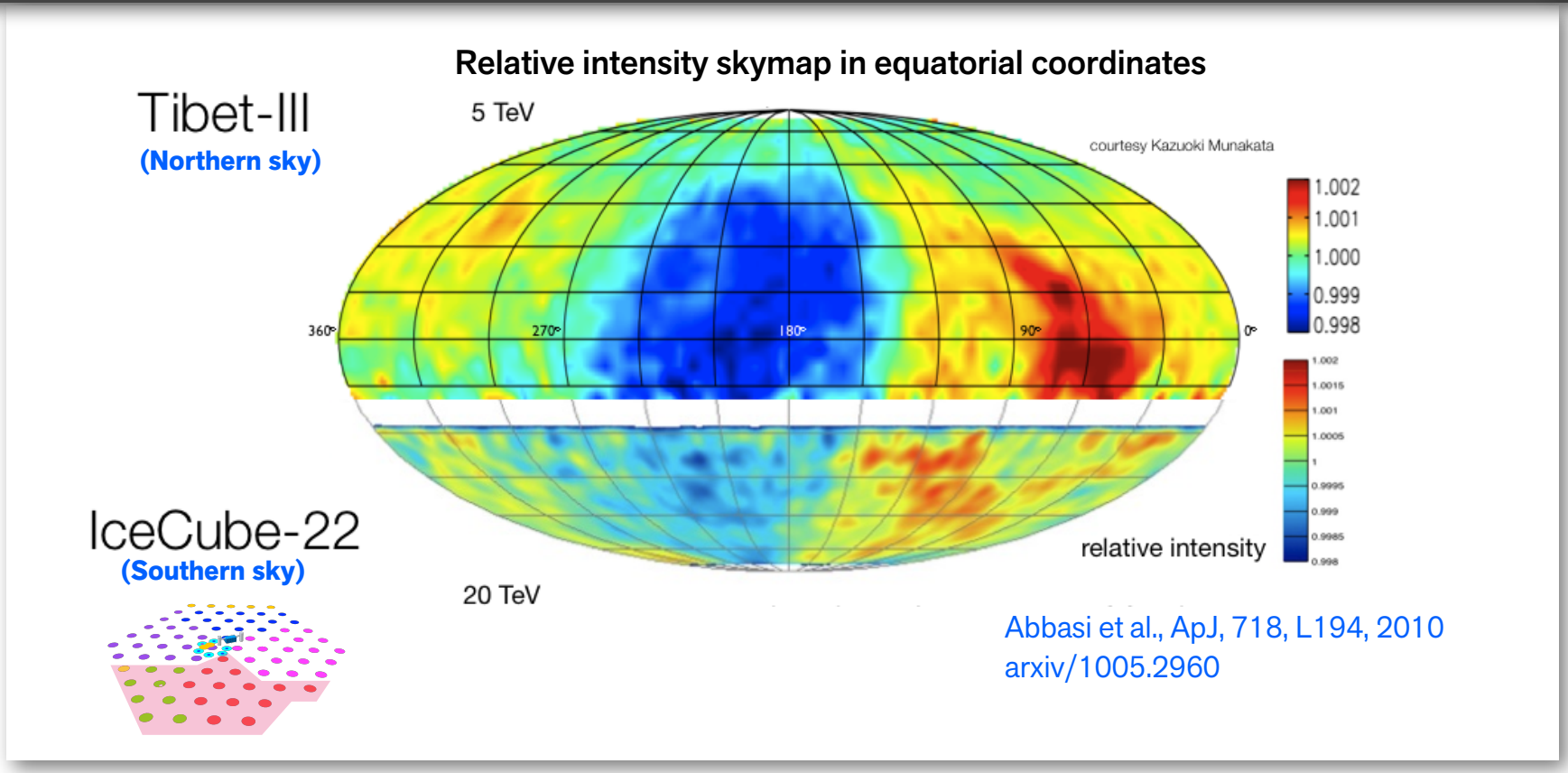
IceCube, IceTop, and AMANDA



- **IceTop**
  - CR rate ~ 10 Hz in IT81
  - ~ 3 x 10^8 CR events/year
  - sensitive to $\delta > 10^{-4}$ anisotropy
- **IceCube**
  - CR muon rate ~ 2 kHz in IC86
  - ~ 6 x 10^{10} CR events/year
  - sensitive $\delta > 10^{-5}$ anisotropy
- **AMANDA**
  - ~ 2 x 10^9 CR events/year
  - Data from 2000-2006

All three detectors have collected samples large enough to be sensitive to anisotropy at and below the per-mille level.

IceCube - Large scale anisotropy

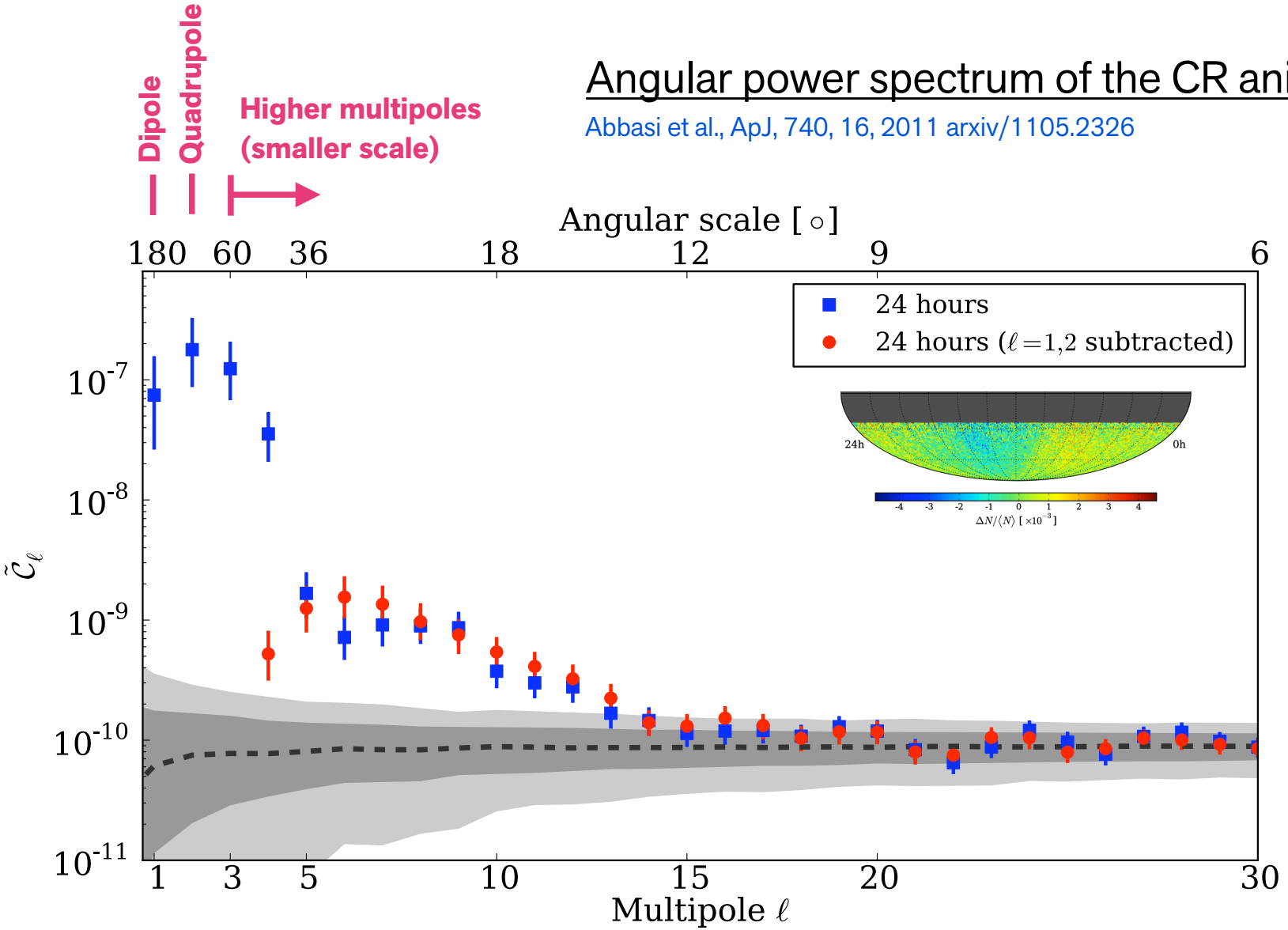


- IC22 detector, 4 x 10^9 events, Median energy ~ 20 TeV
- First indication of large scale ~10^{-3} anisotropy observed in the South.
- Good match to observations in the North.

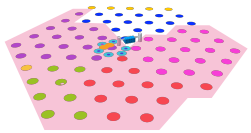
IceCube - Looking for smaller structure

Angular power spectrum of the CR anisotropy

Abbasi et al., ApJ, 740, 16, 2011 arxiv/1105.2326



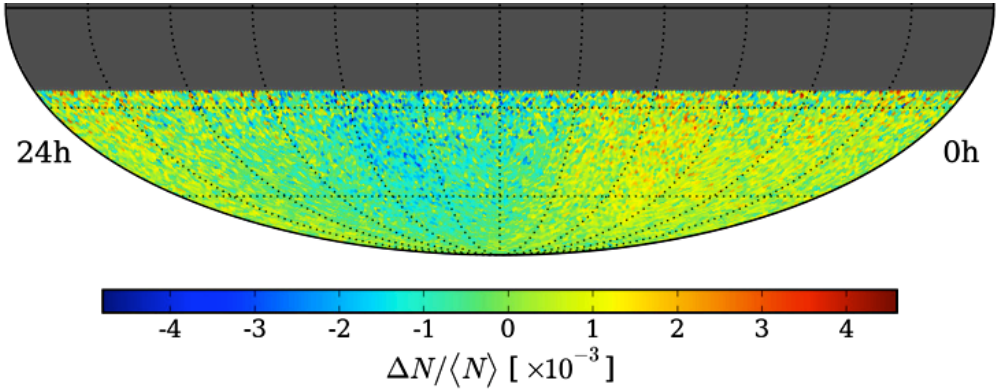
IceCube - Small scale anisotropy



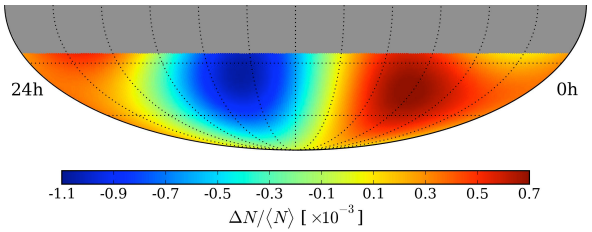
59-string detector

Abbasi et al., ApJ, 740, 16, 2011 arxiv/1105.2326

Input relative intensity map

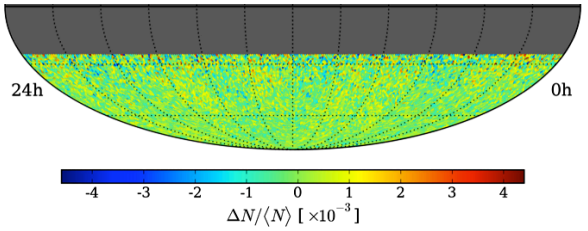


Dipole and quadrupole fit (Large scale)



+

Fit residuals (Small scale)

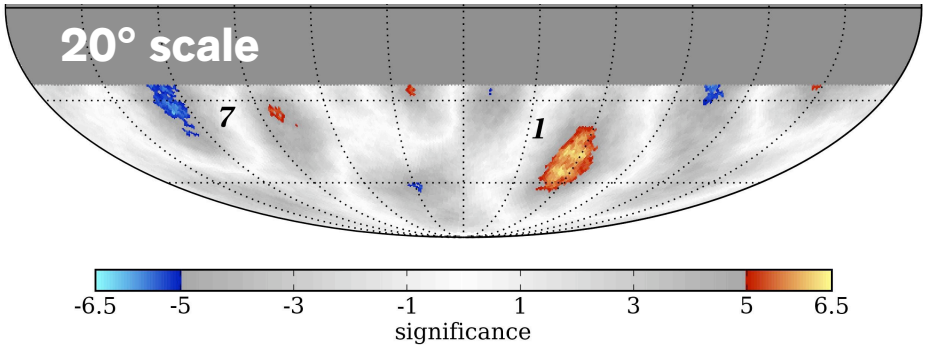


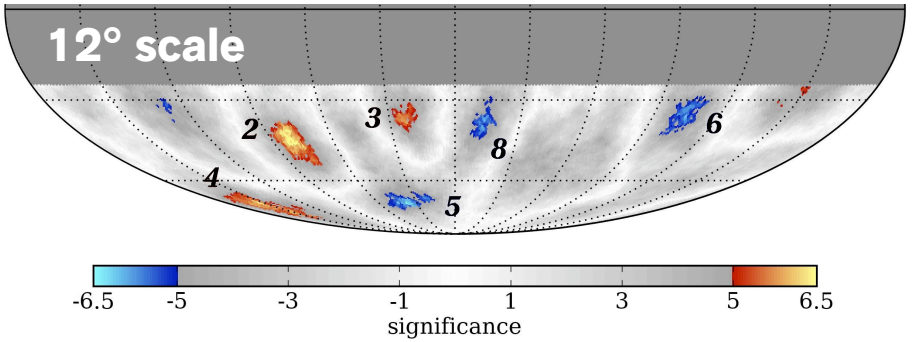
- Correlate pixels to increase sensitivity to different angular scales.

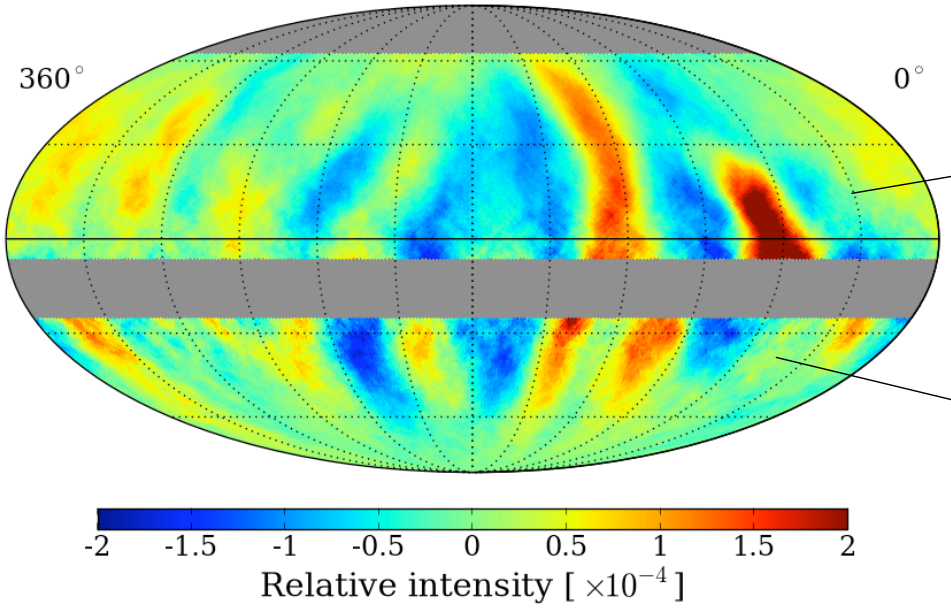
IceCube - Small scale anisotropy

- Statistically significant structure with typical sizes of 10°-20°

  Abbasi et al., ApJ, 740, 16, 2011 arxiv/1105.2326







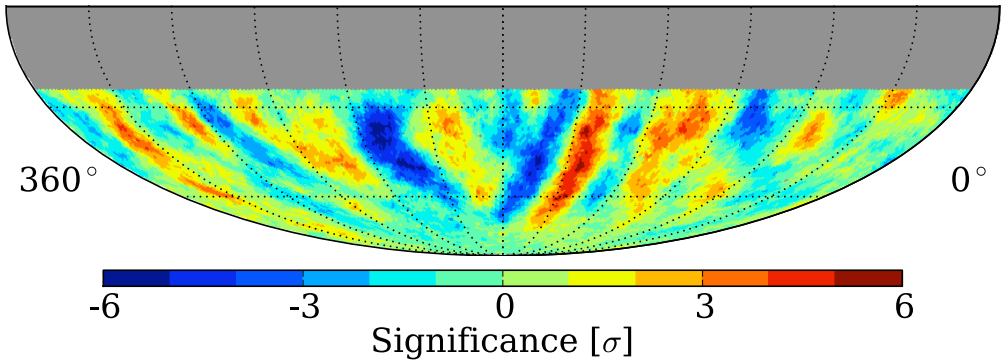
Milagro small-scale anisotropy (~ 1TeV)
Abdo, A. A., et al. 2008, Phys. Rev. Lett., 101, 221101

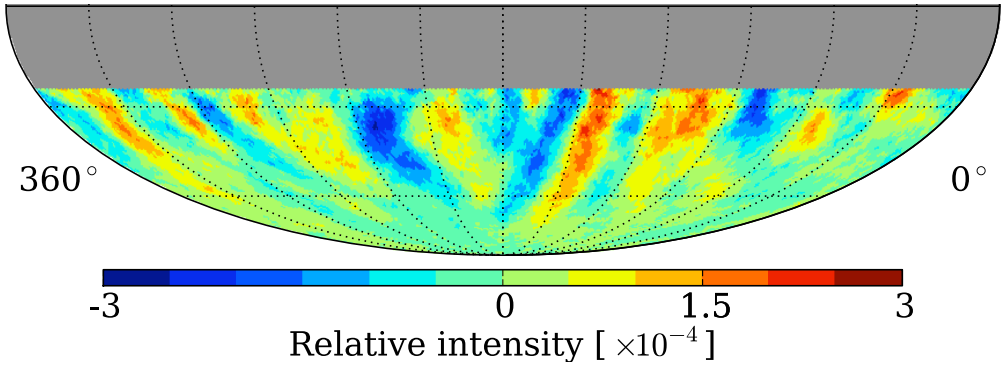
IceCube IC79 small-scale anisotropy (~ 20 TeV)

IceCube - Small scale anisotropy

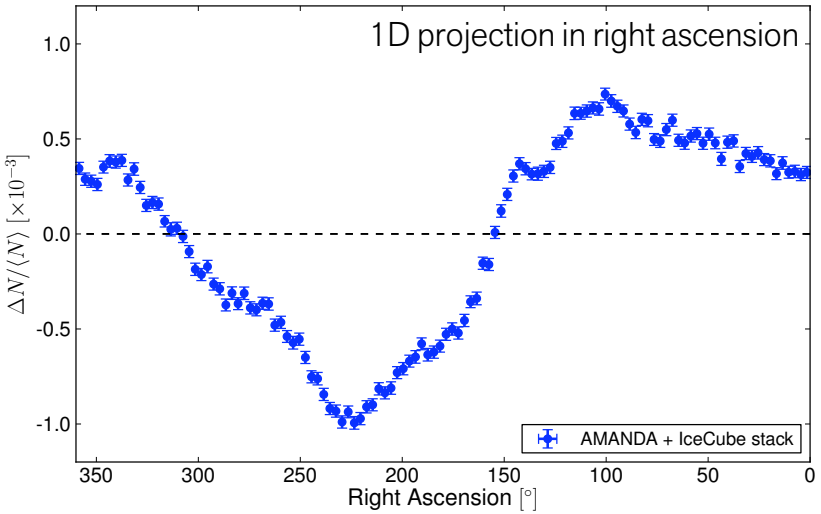
Preliminary

IC40-IC86 detector, **5° scale**



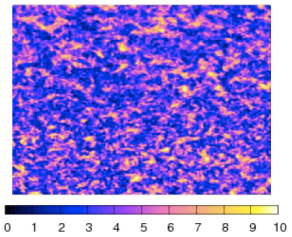


- IC40-IC86: 1.4 x 10^{11} events.
- Significant 10^{-4} structure at very small scales (~ limit of our angular resolution of 3°).

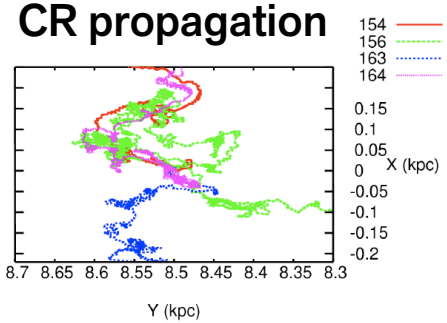


Origin of small-scale anisotropy

Turbulent B-field



CR propagation



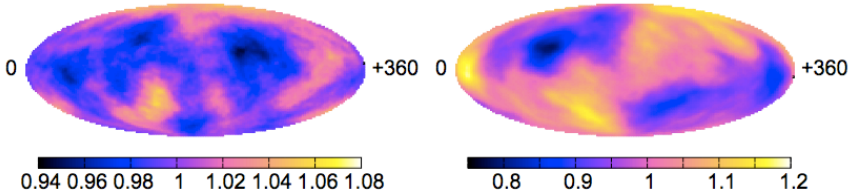
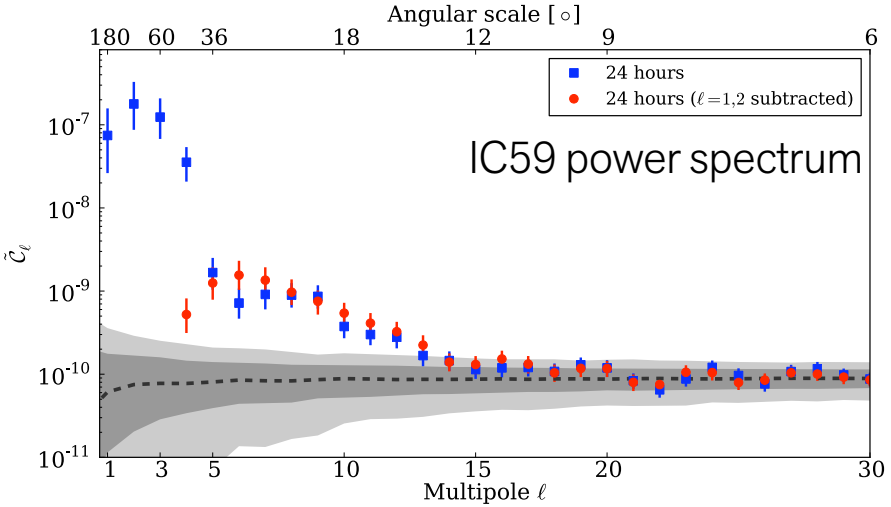


FIG. 1. Renormalized CR flux predicted at Earth for a concrete realization of the turbulent magnetic field, *after subtracting the dipole* and smoothing on 20° radius circles. Primaries with rigidities $p/Z = 10^{16}$ eV (*left panel*) and 5×10^{16} eV (*right panel*). See text for the field parameters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

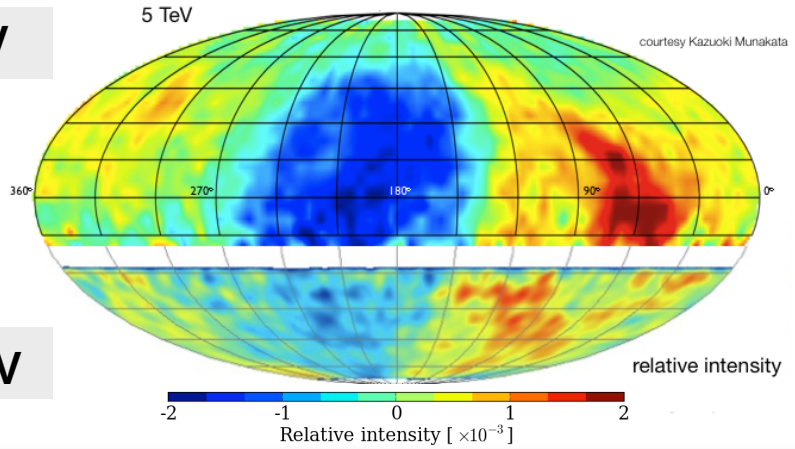
Giacinti & Sigl
arxiv/1111.2536

- Anisotropy at multiple scales arises from turbulent propagation in the GMF
- Different energies probe different distances
- Possible signature in the CR angular power spectrum



Comparison between different energies

5 TeV

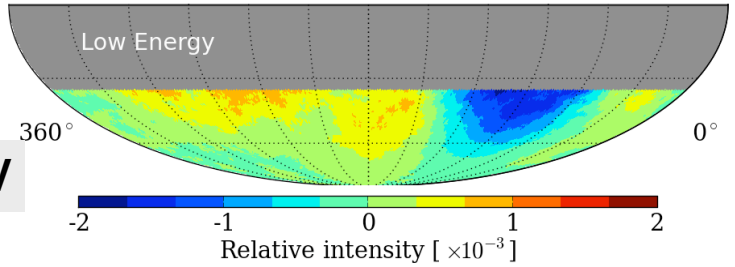


20 TeV

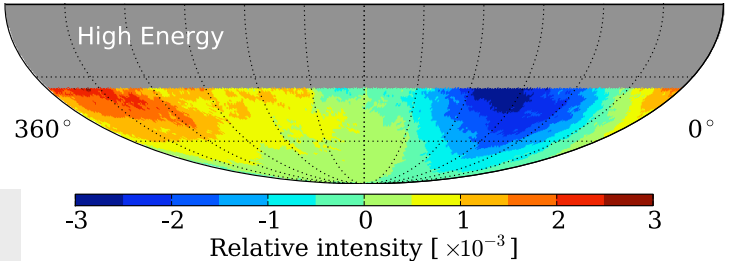
IceTop

Aarsten et al., 2013 ApJ 765 55
arxiv/1210.5278

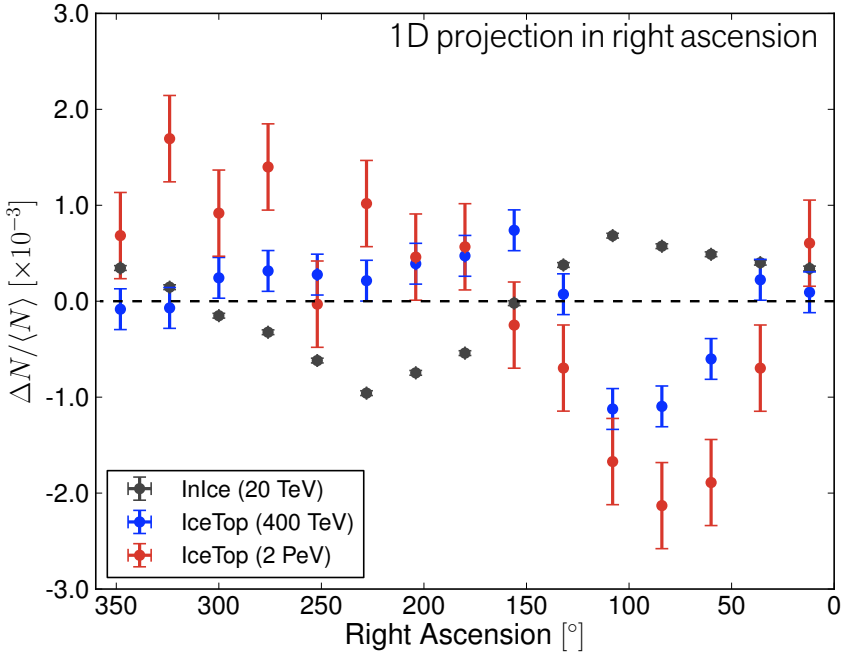
400 TeV



2 PeV



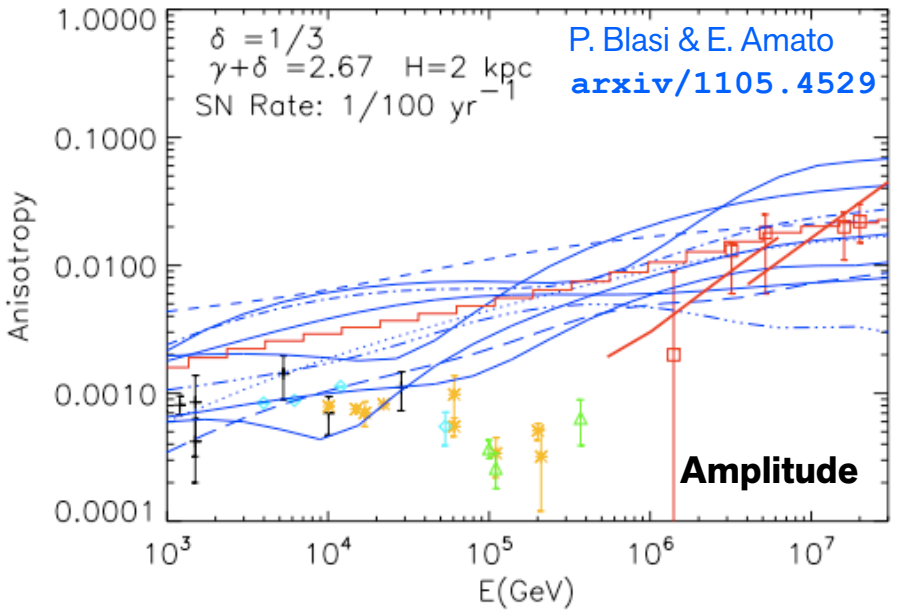
- The anisotropy changes position
- Similar peak-to-peak strength
- Smaller characteristic size at high energies

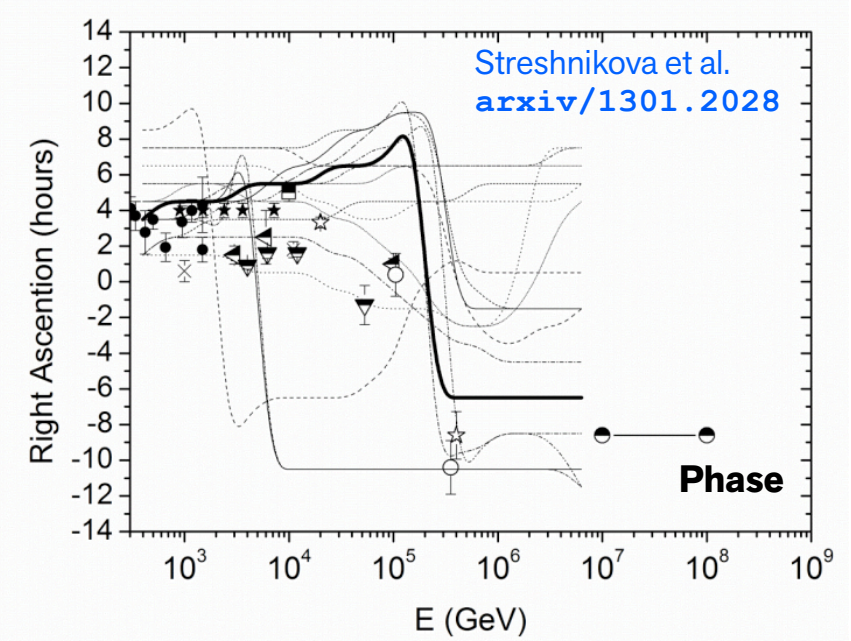


IceTop @ 400 TeV agrees with IceCube @ 400 TeV
Abbasi et al., 2012 ApJ 746 33 arxiv/1109.1017

Interpretation of energy dependence

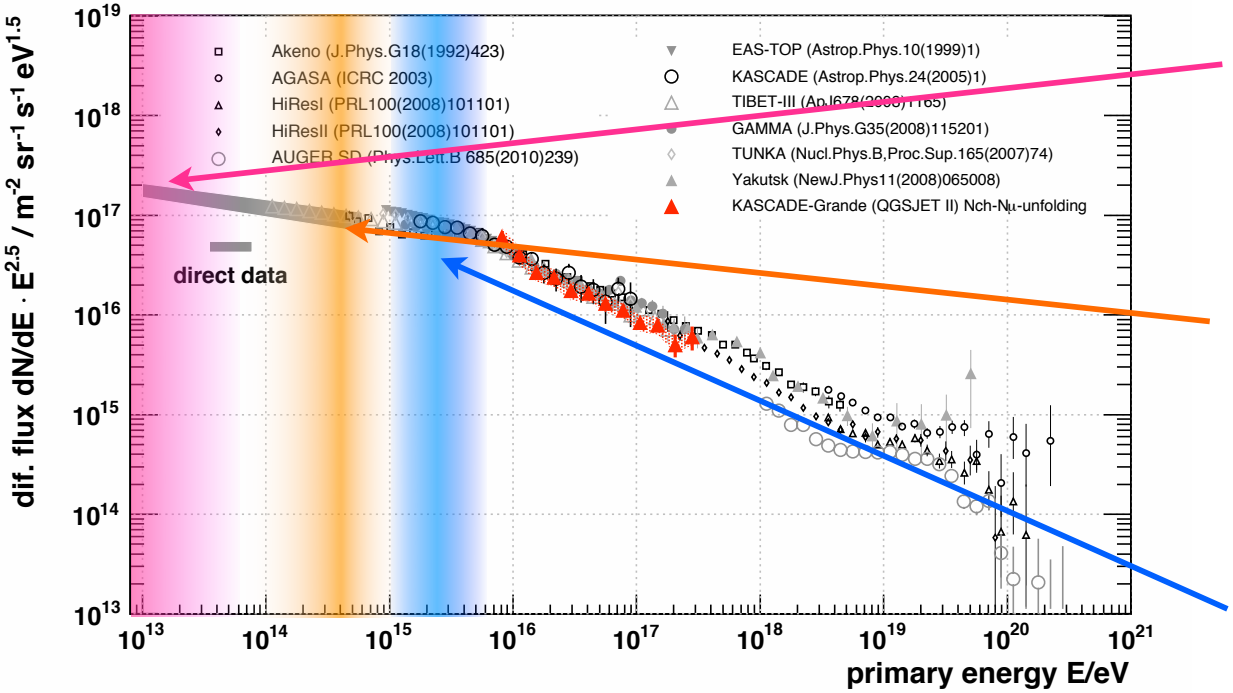
Similar to Erlykin & Wolfendale (2006)

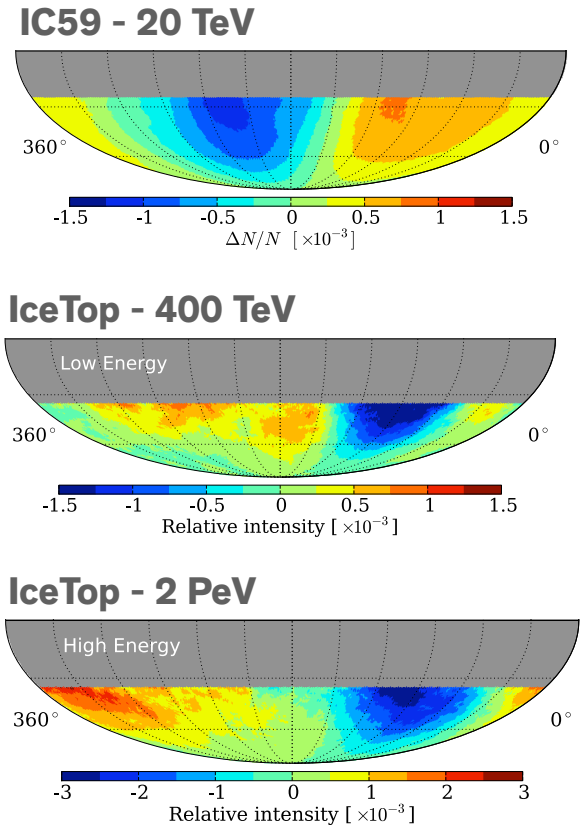




- Anisotropy arises from discrete distribution of sources
- Phase changes according to galaxy parameters and location of nearby sources
- Strength increases with energy (diffusion coefficient)
- *Problem*: anisotropy not dipolar, not strong enough.

Anisotropy vs. energy





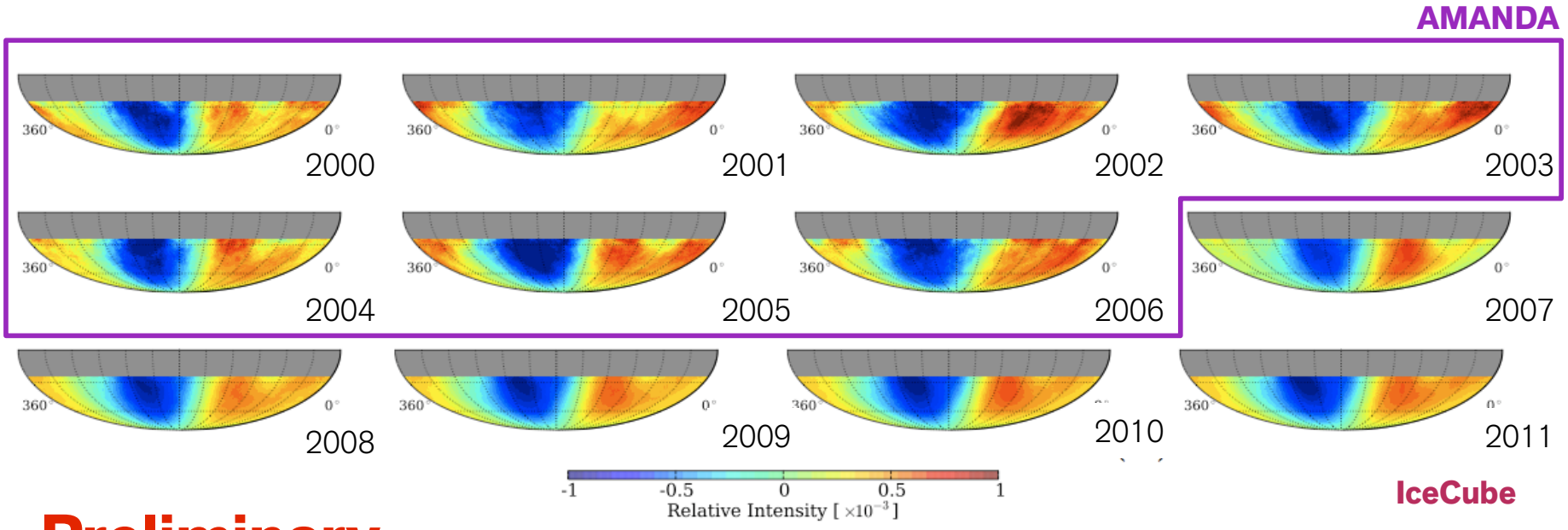
- Anisotropy changes in position, size
- Above 400 TeV there's indication of an increase in strength approaching the CR knee.

Time-dependence studies

- Possible heliospheric effects on the 20 TeV anisotropy
- Solar cycle (11 year) dependence?

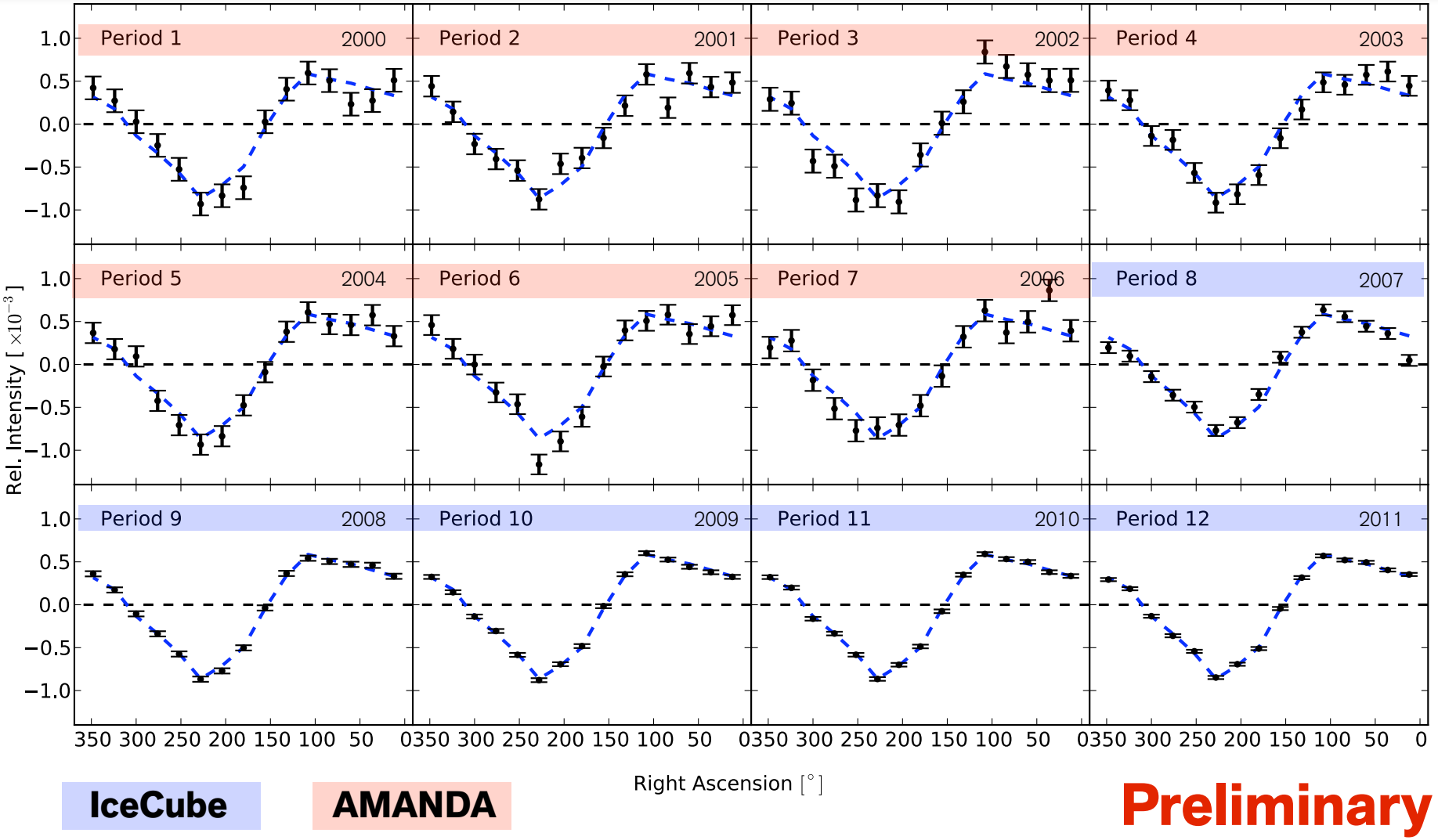
Desiati & Lazarian, ApJ, 762, 44, 2013
arxiv/1111.3075

IceCube + AMANDA data: 1.6 x 10^{11} events (dominated by IceCube) over the last **12 years (2000 - 2011)**



Preliminary

Time-dependence studies



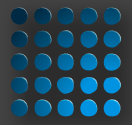
IceCube **AMANDA**

Preliminary

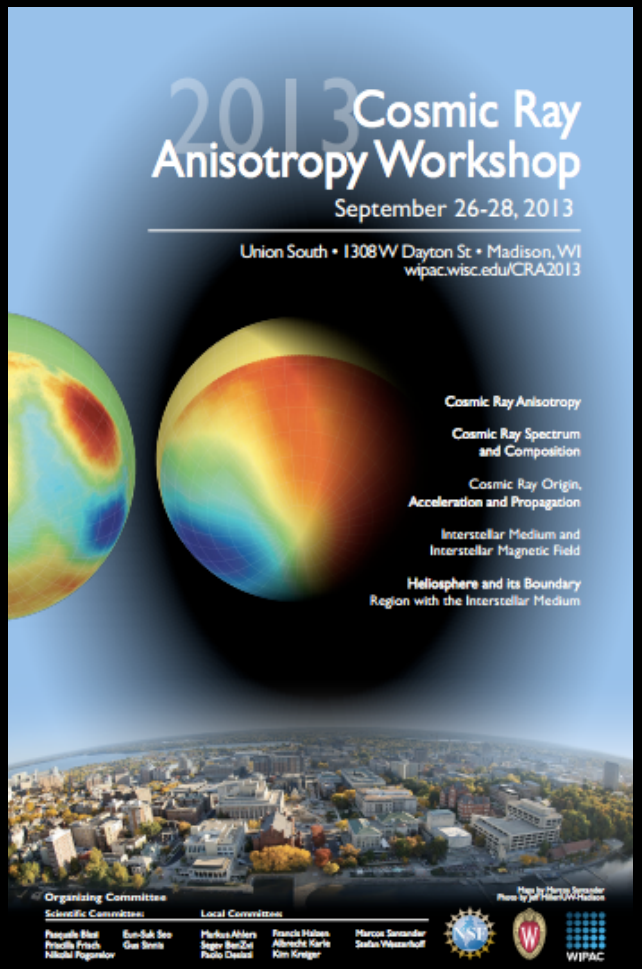
Preliminary studies show a deviation for Period 8.

Statistical uncertainties considered, systematic uncertainties will follow soon.

Conclusions



- Anisotropy observed with *IceCube*, *IceTop*, and *AMANDA*
- Anisotropy studied as a function of **angular scale**, **energy**, and **time**. Composition studies starting.
- Wide angular scale range (**10°-180°**)
- Strength in the **10^{-4}-10^{-3}** range
- Different energies: **20 TeV to 2 PeV**
- 20 TeV anisotropy matches that observed in the North
- Change in shape, orientation from 20 to 400 TeV, larger amplitude at 2 PeV
- No significant time variability over 12 years.



Advertisement

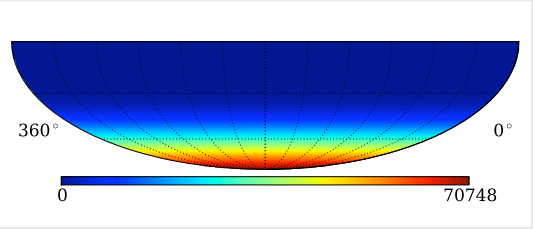
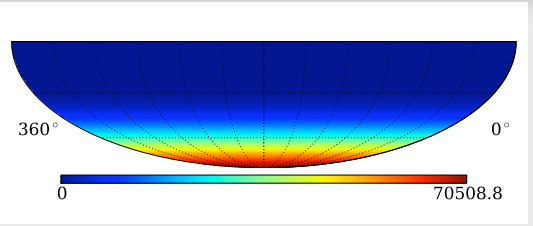
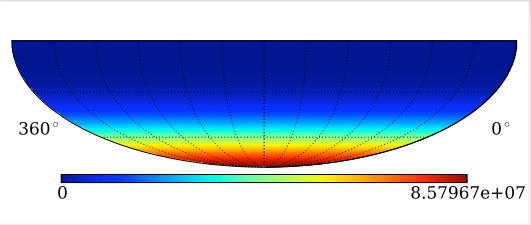
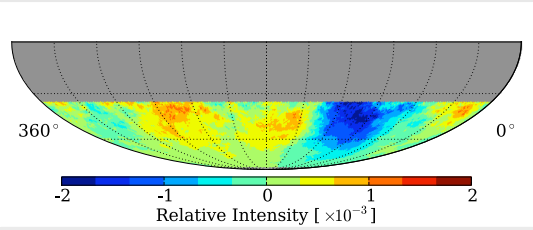
2nd Cosmic Ray Anisotropy Workshop
Sept 26th-28th - Madison, WI

- CR anisotropy, spectrum, and composition measurements (from GeV to EeV)
- Heliospheric physics
- Interstellar Medium
- Cosmic ray origin and propagation
- Galactic magnetic fields

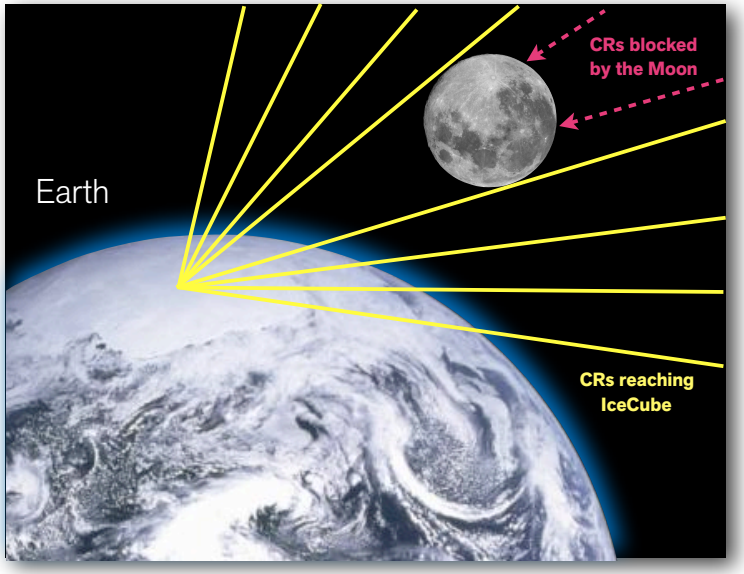
http://wipac.wisc.edu/cra2013

Backup slides

Method to search for CR anisotropy

1	Build a binned data map using the equatorial coordinates of the events	
2	Construct a “reference” map by time scrambling over 24 hours.	
3	Correlate pixels to increase sensitivity to different angular scales	
4	Calculate relative differences between data and reference with significance.	

Moon shadow

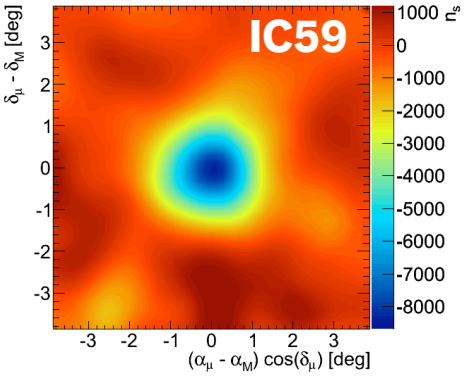


- Moon blocks cosmic rays coming from its direction.
- Shadow observed in IC40 and IC59.
- Used to verify pointing, resolution.

Deficit: ~ 8700 events

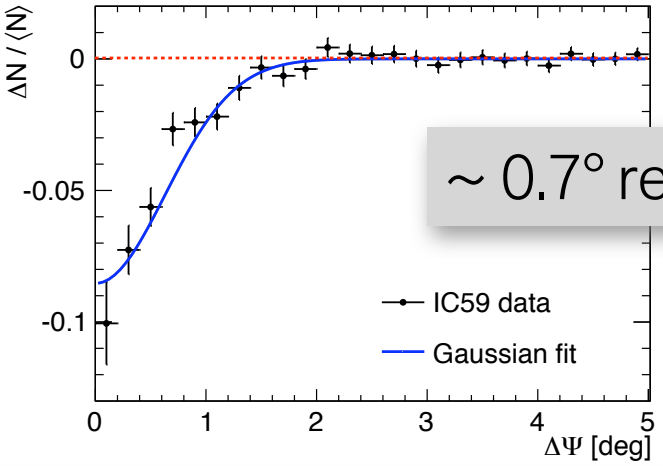
Significance: **13.9σ**

2D Likelihood fit for total number of missing events



Resolution

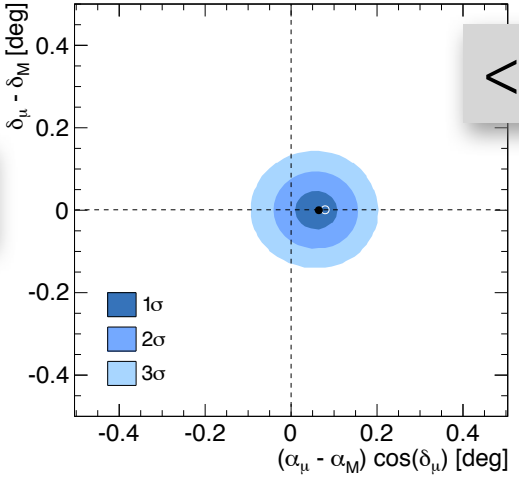
Shadow profile vs. angular distance from the Moon



~ 0.7° resolution

Absolute pointing

Most likely location of shadow center



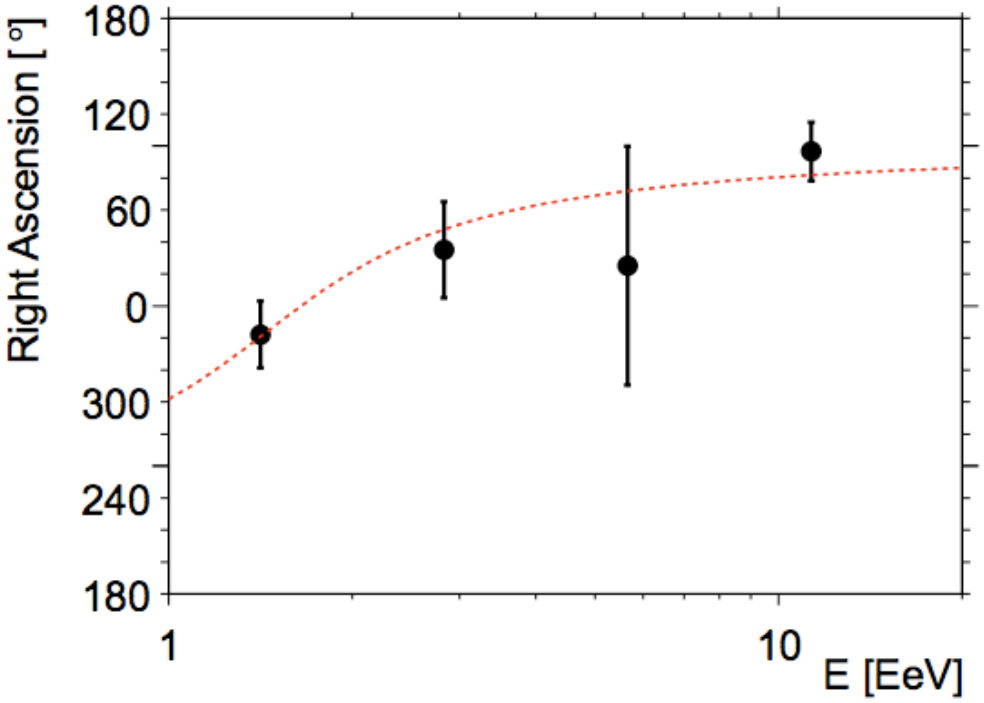
< 0.1° pointing res.

- Accounts for magnetic deflection effects

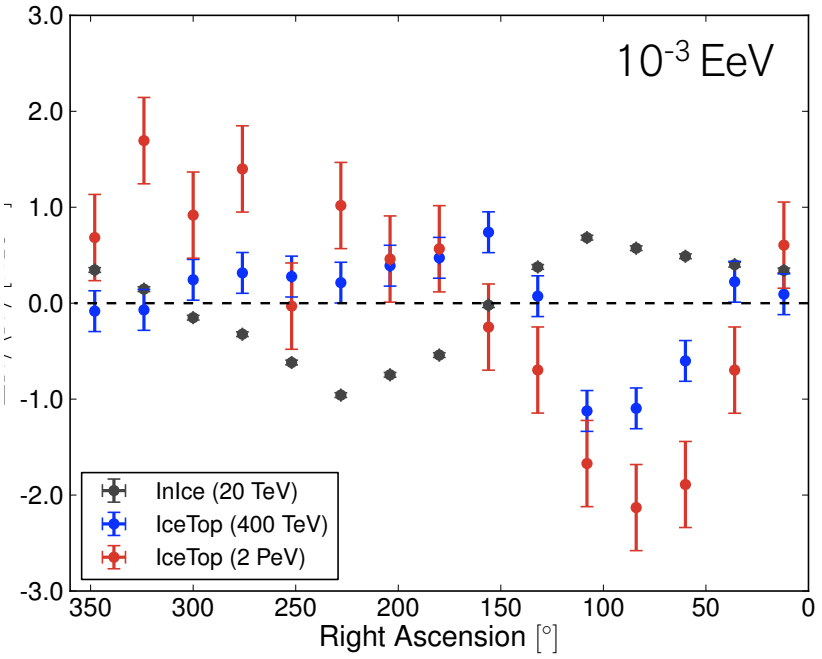
UHE anisotropy

P. Abreu et al. (Auger Collaboration)
arxiv/1212.3083

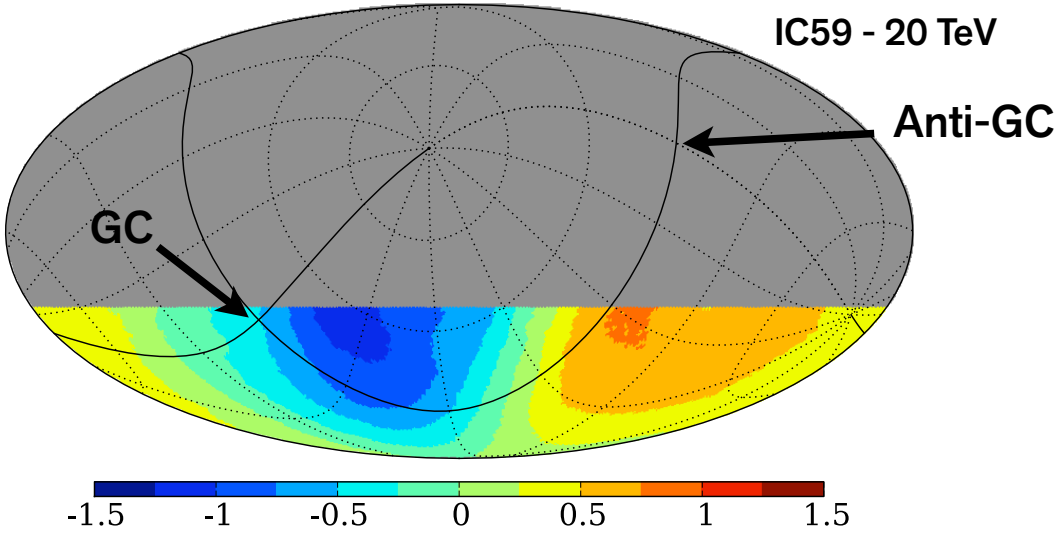
Dipole phase



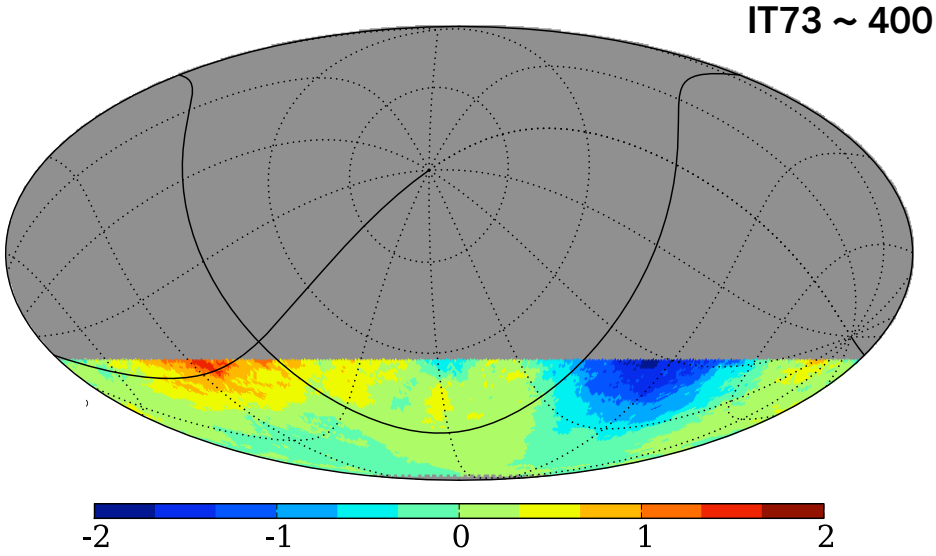
1D projection in right ascension (IceTop)

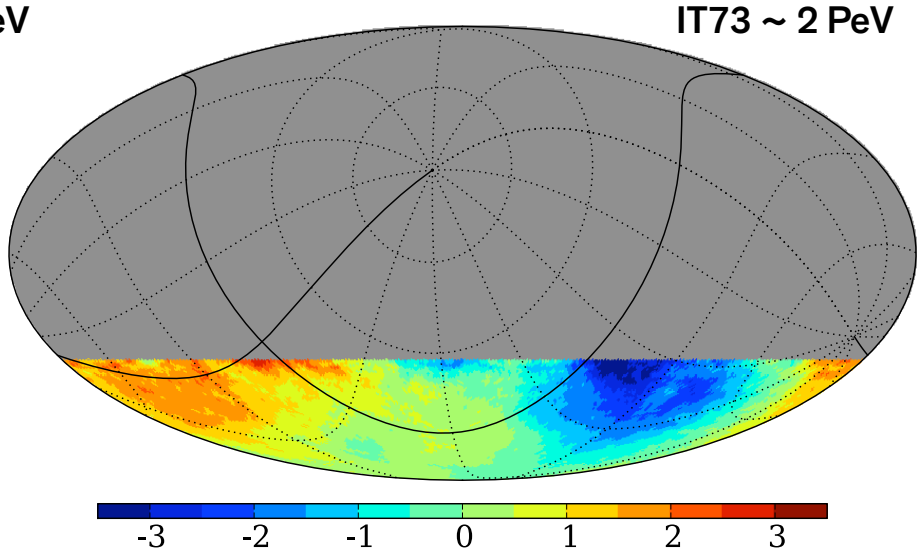


Anisotropy in galactic grid



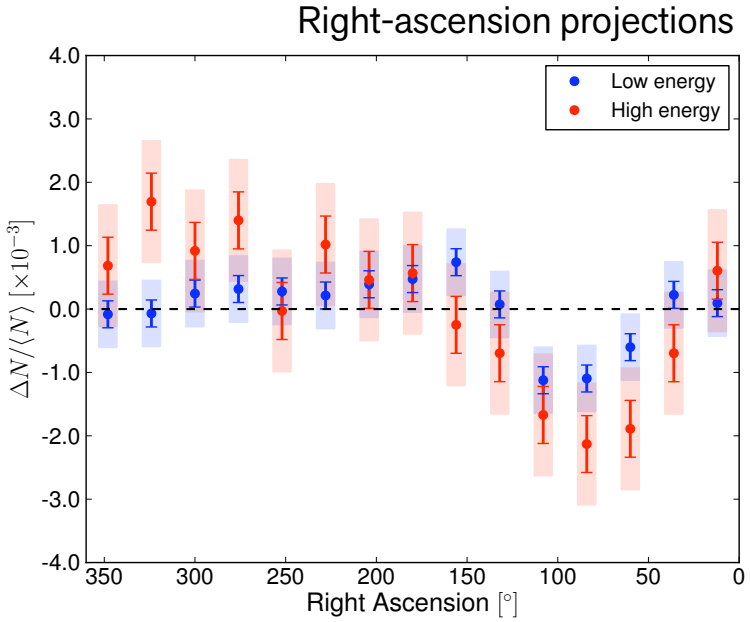
- All amplitudes x 10^{-3}
- Caveat: The background estimation technique could introduce features in the equatorial frame that do not translate to the galactic frame.





Observation of anisotropy by IceTop

- IceTop data, 2009-2011: 3.5 x 10^8 events
  - Low-energy band (400 TeV): 0.65 x 10^8 events
  - High-energy band (2 PeV): 2.85 x 10^8 events
- Deficit region similar to that observed by IceCube @ 400 TeV (significance ~ 8σ)
- Anisotropy increases with energy
- Not a dipole



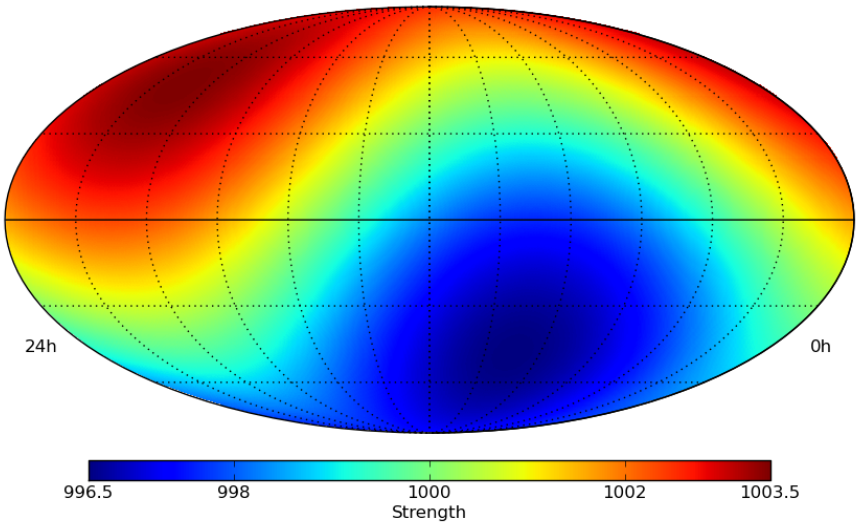
Time dependence studies

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

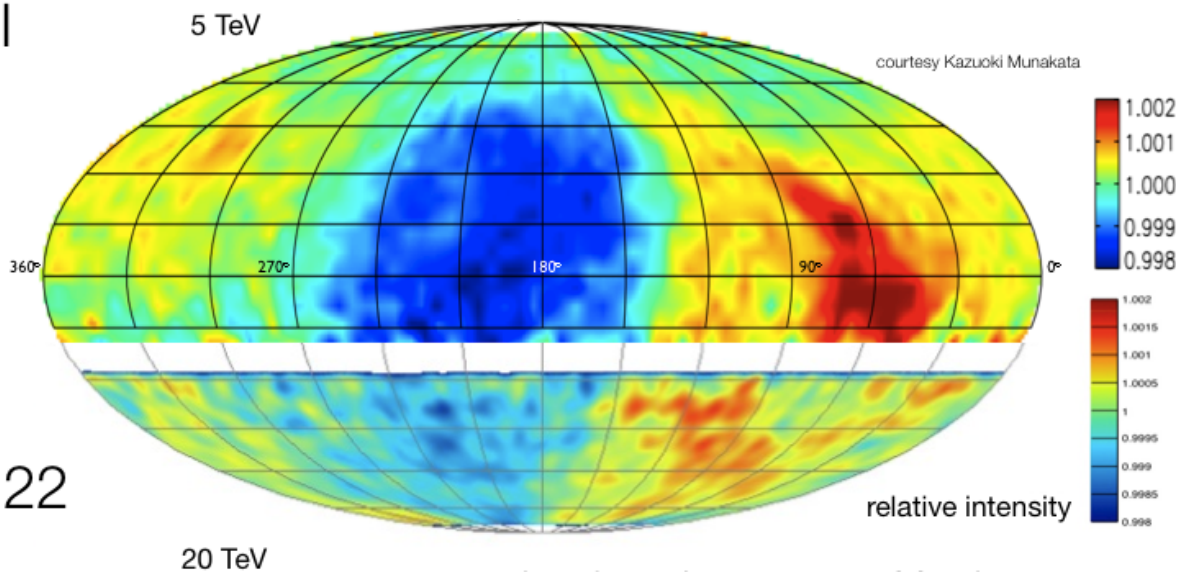
* Statistical uncertainties only

Compton-Getting effect



Expected C-G dipole

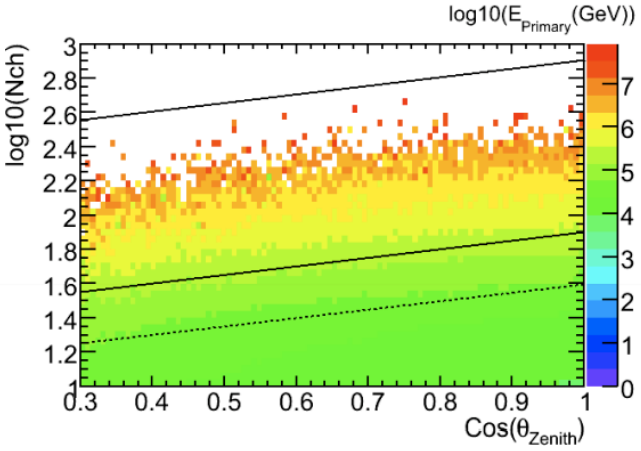
Tibet-III

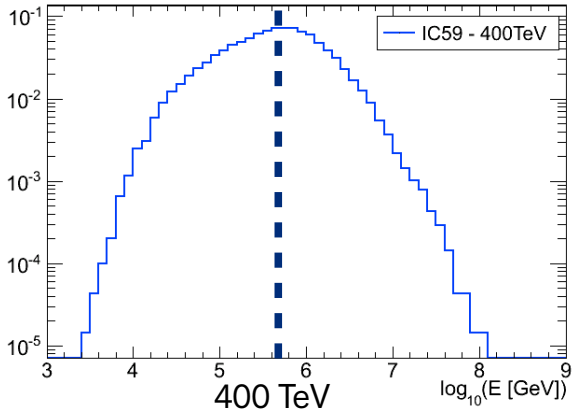


IceCube-22

IceCube - Anisotropy at 400 TeV

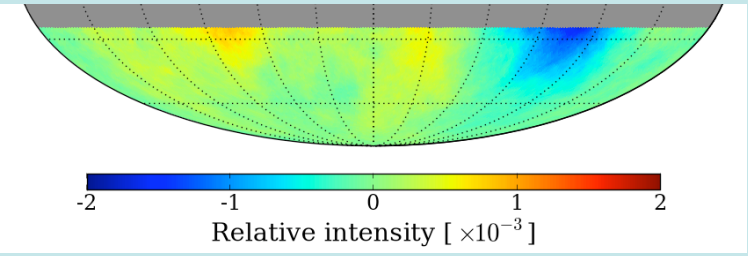
Abbasi et al., 2012 ApJ 746 33
arxiv/1109.1017



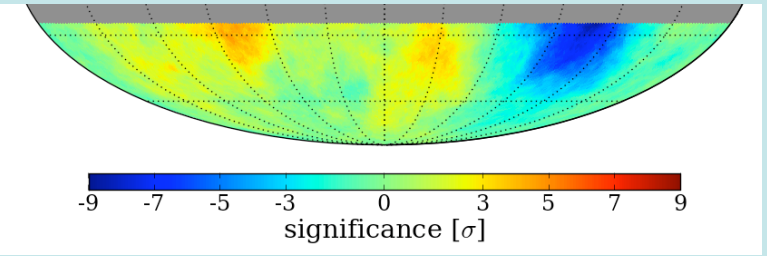


- Cut on zenith angle and number of triggered DOMs in IceCube to get a higher energy data sample. Final sample: **6.1 x 10^8 events**

Relative intensity map



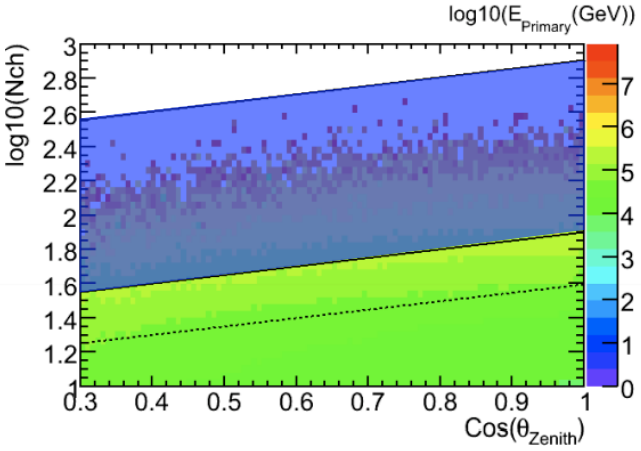
Statistical significance map

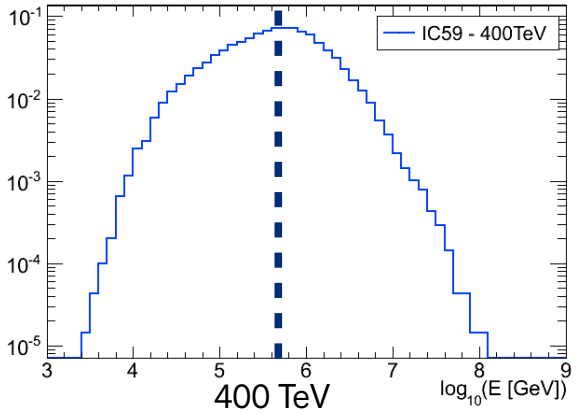


- **400 TeV** median energy, anisotropy at **10^{-3}** level, size ~ **20°**, significance **6.3σ**

IceCube - Anisotropy at 400 TeV

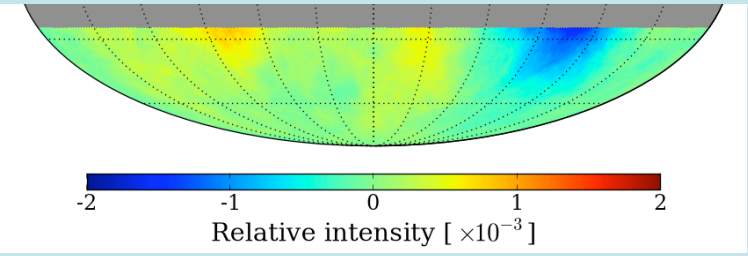
Abbasi et al., 2012 ApJ 746 33
arxiv/1109.1017



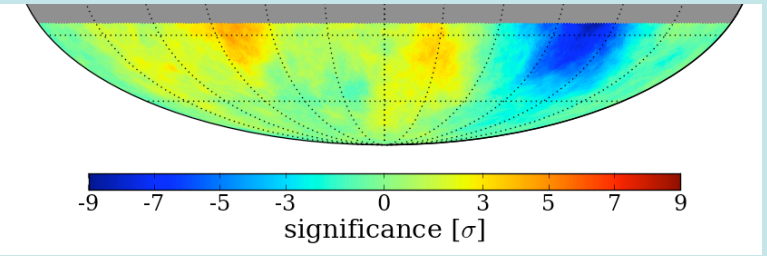


- Cut on zenith angle and number of triggered DOMs in IceCube to get a higher energy data sample. Final sample: **6.1 x 10^8 events**

Relative intensity map

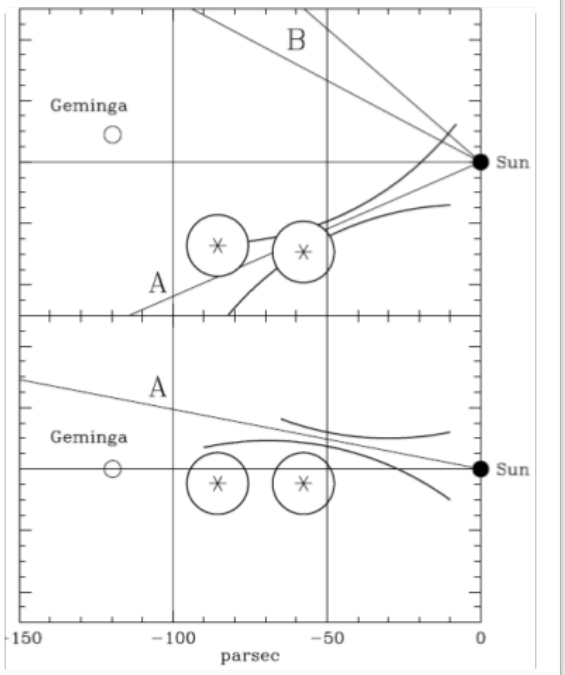


Statistical significance map



- **400 TeV** median energy, anisotropy at **10^{-3}** level, size ~ **20°**, significance **6.3σ**

Possible sources for Milagro hotspots

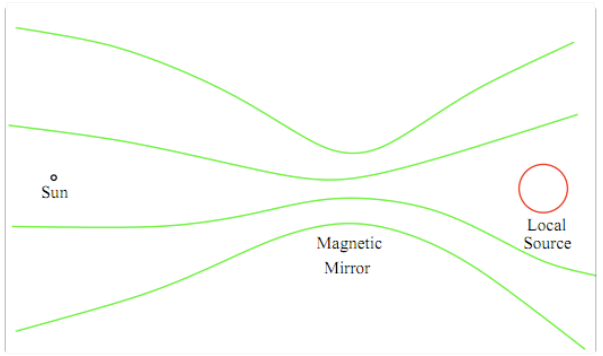


- Non-standard magnetic fields and diffusion mechanisms
- Geminga? (155 pc)

Salvati and Sacco. A&A 485, 527-529 (2008)

- CR beams

Malkov, M. A., Diamond, P. H., Drury, L. O. C., & Sagdeev, R. Z. 2010, Astrophys. J., 721, 750

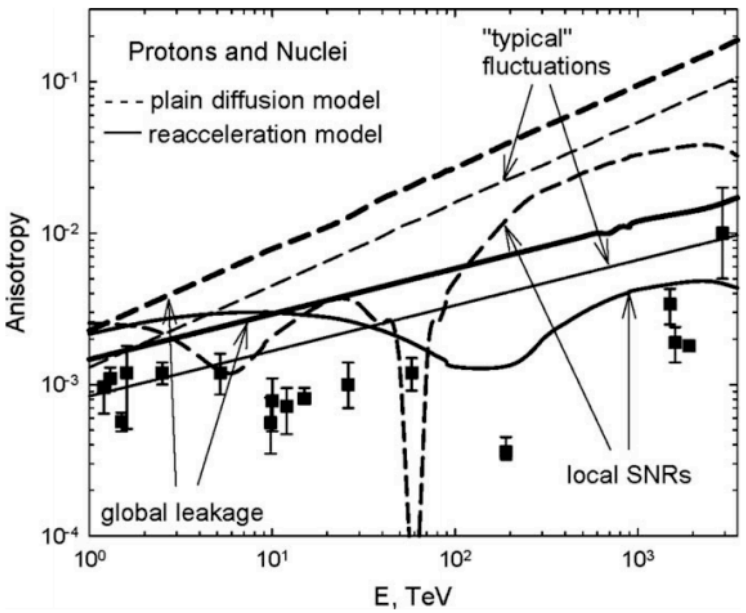


- Magnetic mirroring and funneling from nearby source

Drury and Aharonian. Astropart. Phys. 29 420-423 (2008)

Possible implications of anisotropy (large scale)

From Ptuskin, Jones, Seo, Sina (2006)



Name	Distance	Age
SN 185	0.95 kpc	1800 yrs
RX J1713.7-3946	1 kpc	2000 yrs
S 147	0.8 kpc	4600 yrs
G114.3 + 0.3	0.7 kpc	7700 yrs
Cygnus Loop	0.77 kpc	20000 yrs
G65.3+5.7	0.8 kpc	20000 yrs
Vela	300 kpc	11000 yrs
HB21	800 kpc	23000 yrs

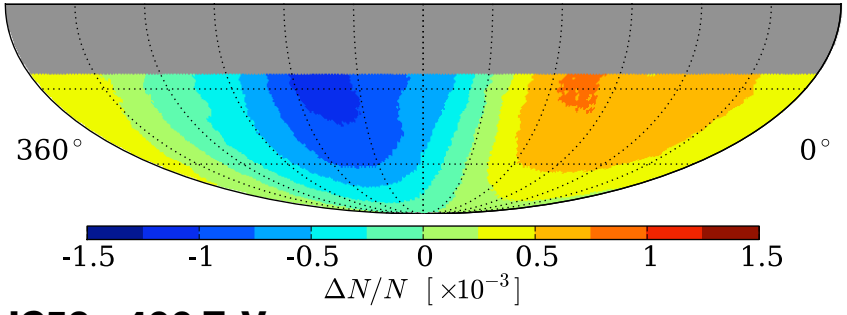
- Effect of real local sources
- No Vela Junior (anisotropy too large)
- Are the propagation assumptions too "local"?

  Isotropic diffusion, connection to other observables.

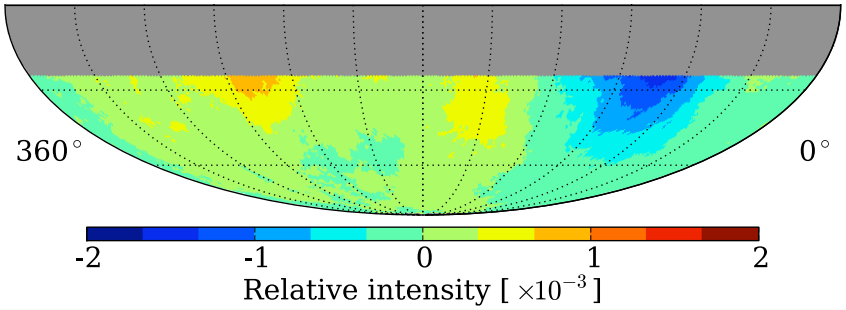
Problem:
Anisotropy not dipolar

Comparison to IC59 400 TeV

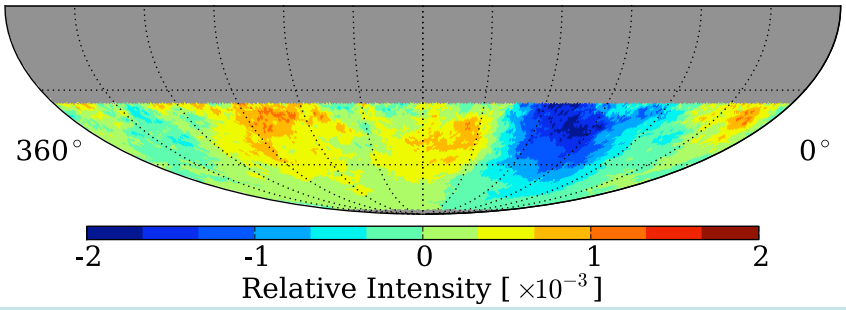
IC59 - 20 TeV

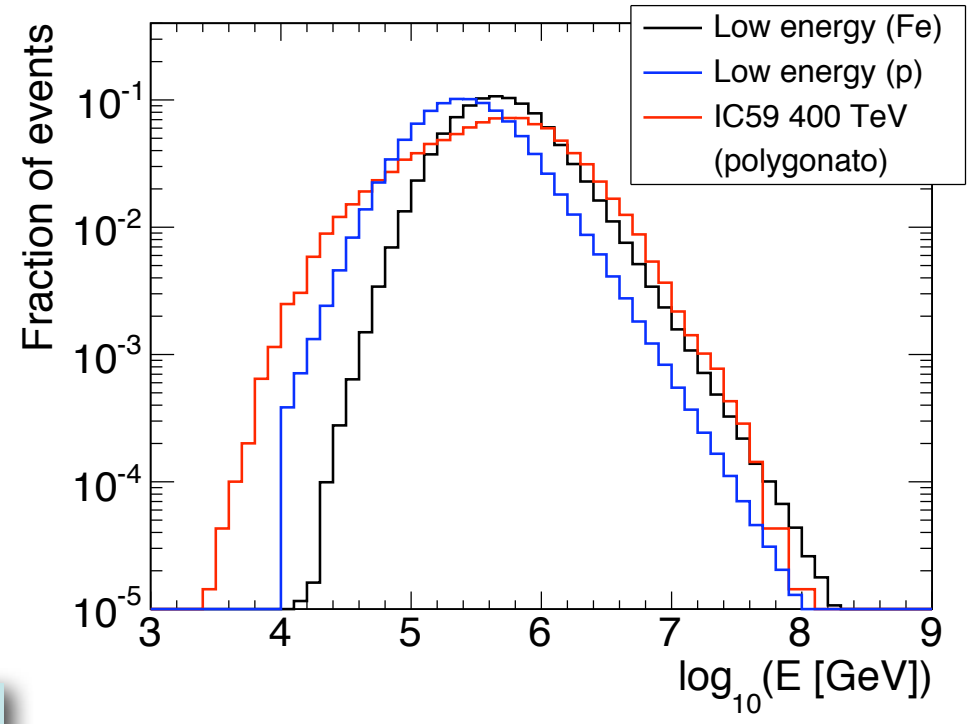


IC59 - 400 TeV



IT73 - Low energy (300-500 TeV)

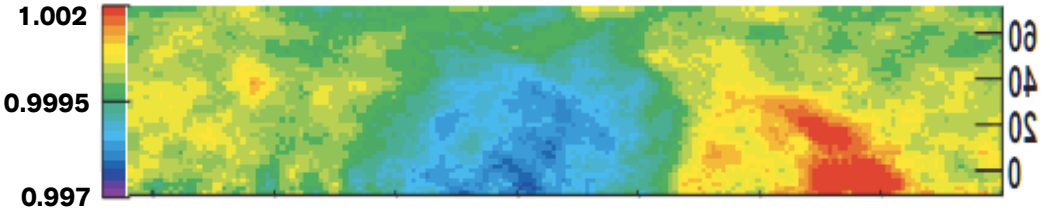




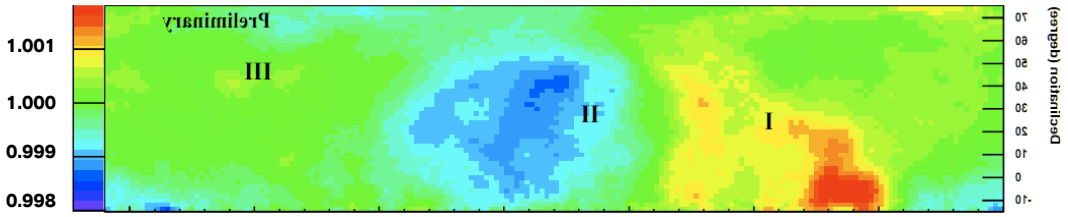
- Anisotropy stronger than IC59 400 TeV
- Low-E tail in IceCube

Large scale anisotropy observations

Tibet-III Amenomori et al, astro-ph/0610671

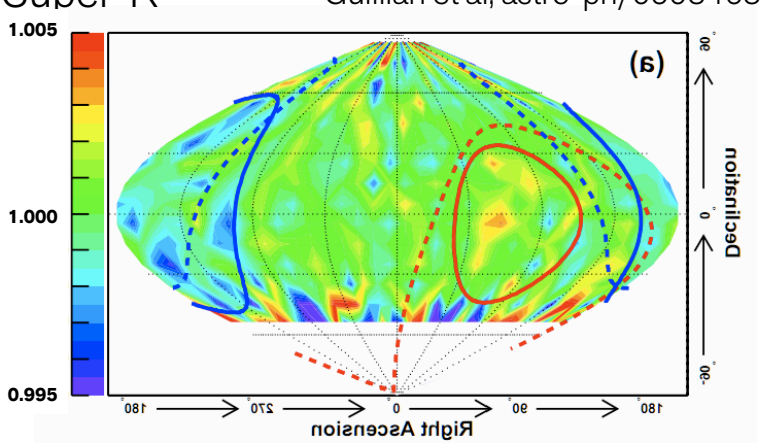


Argo-YBJ Zhang et al, Proc. of the ICRC 2009

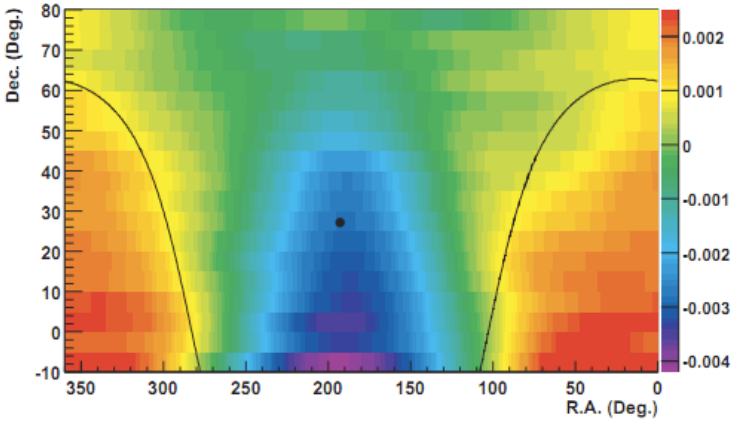


- Several observations of large scale anisotropy in the north
- **~10^{-3}** strength
- **1-100 TeV** energy range

Super-K Guillian et al, astro-ph/0508468



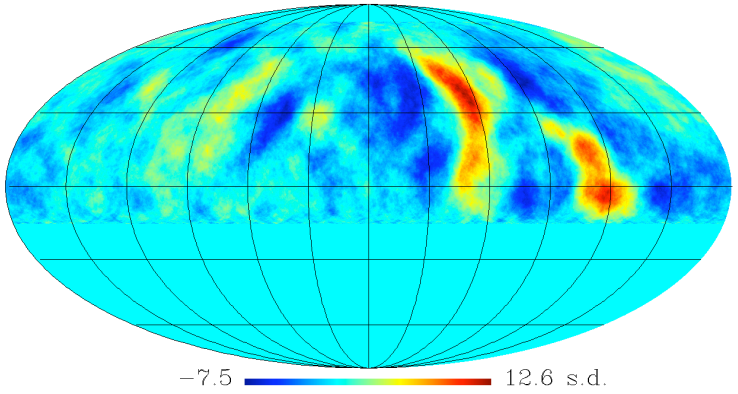
Milagro Abdo et al, arxiv/0806.2293



Small scale anisotropy observations

Argo-YBJ

Vernetto et al, Proc. of the ICRC 2009



- Milagro, Tibet and ARGO report small scale structures with **significance > 10σ**
- **~10^{-4}** strength

Milagro

Abdo et al. arxiv/0801.3827