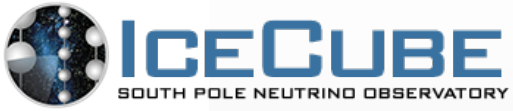


Anisotropy in Cosmic-Ray Arrival Directions Using IceCube and IceTop

Stefan Westerhoff[1] for the IceCube Collaboration

[1]*University of Wisconsin-Madison*

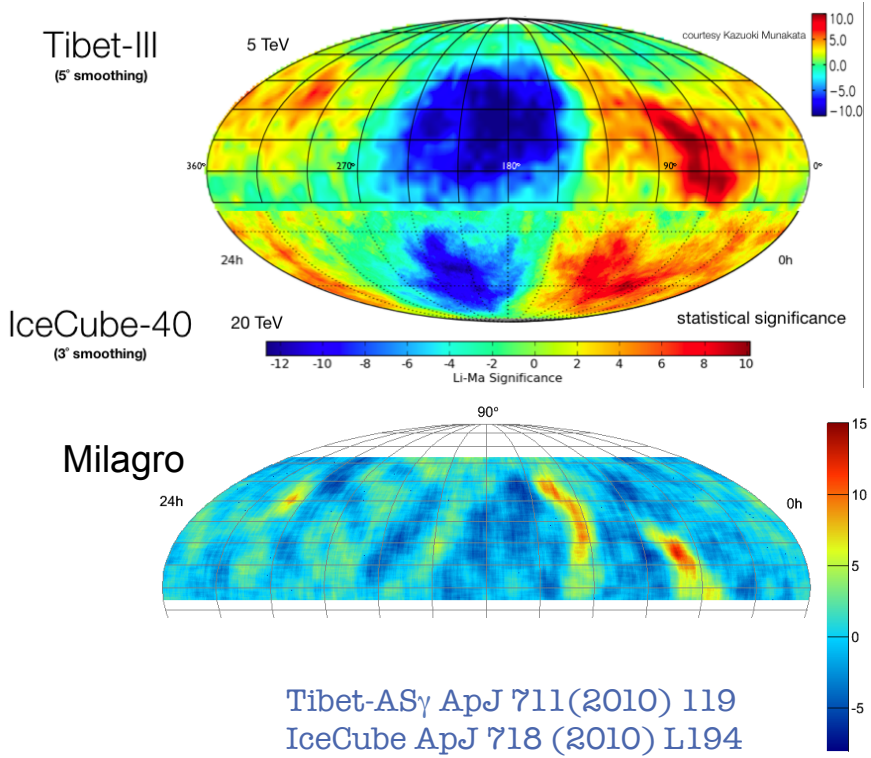
34th International Cosmic-Ray Conference
The Hague, 30 July – 6 August, 2015

Cosmic-Ray Anisotropy

- Several experiments observe significant anisotropy in the arrival direction distribution of cosmic rays from tens of GeV to tens of PeV.

- Large-scale structure (>60°) with relative intensity 10^{-3} .
  - Result of diffusive propagation?
- Small-scale structure also present, relative intensity 10^{-4} to 10^{-5} .

- Topology and strength of anisotropy changes with energy.

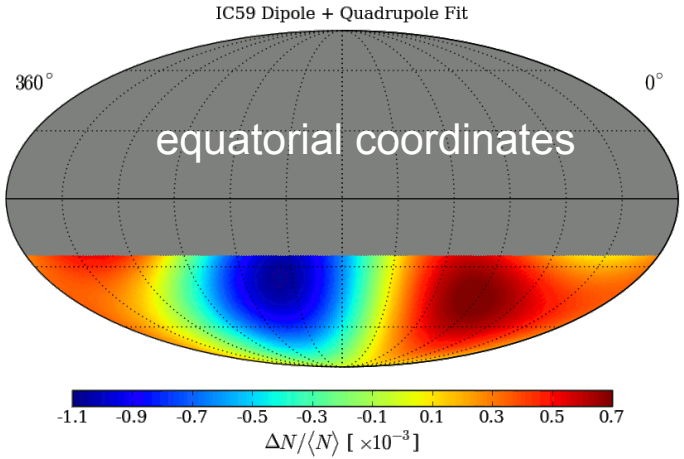


Tibet-ASγ ApJ 711(2010) 119
IceCube ApJ 718 (2010) L194
Milagro PRL 101 (2008) 221101

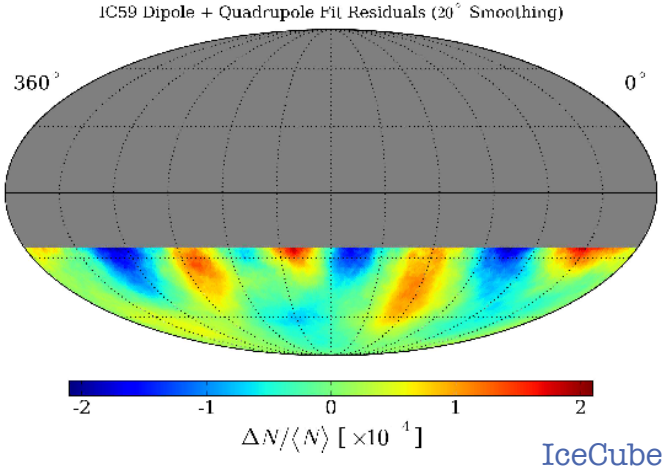
Tibet ASγ, SuperKamiokande, Milagro, EAS-TOP, MINOS, ARGO-YBJ, HAWC, IceCube

IceCube Cosmic-Ray Skymap

- IceCube and IceTop are currently the only instruments covering the Southern Hemisphere.
- Anisotropy in the southern sky also shows the large- and small-scale features.



large-scale
relative intensity ~10^{-3}



small-scale
relative intensity ~10^{-4}

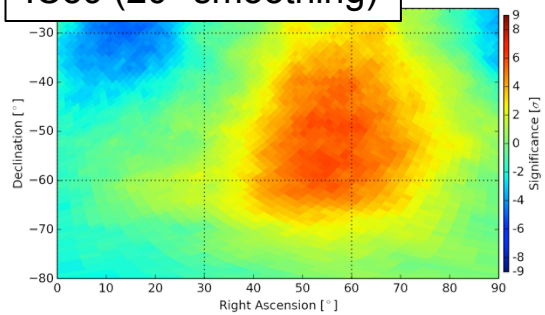
IceCube ApJ 740 (2011) 16

Data Set

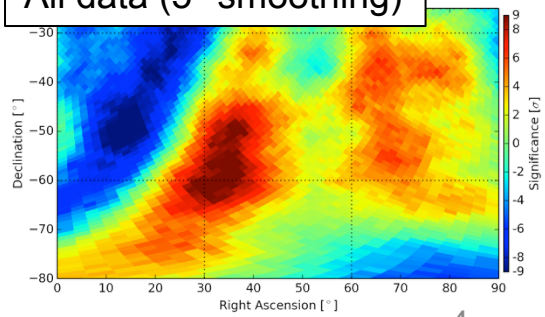
- IceCube data set has increased to 250 billion events, recorded over a period of 5 years (2009 – 2014).
- Studies with this data set:
  - Energy dependence in the range ~10 TeV to ~5 PeV.
  - Time dependence of the small- and large-scale structure.
- Increased resolution (smoothing can be reduced to angular resolution).

	Period	Events
IC59	2009 – 2010	3.579×10^{10}
IC79	2010 – 2011	4.131×10^{10}
IC86	2011 – 2012	5.906×10^{10}
IC86-II	2012 – 2013	5.630×10^{10}
IC-86-III	2013 – 2014	6.214×10^{10}
Total	**2009 – 2014**	**2.546×10^{11}**

IC59 (20° smoothing)



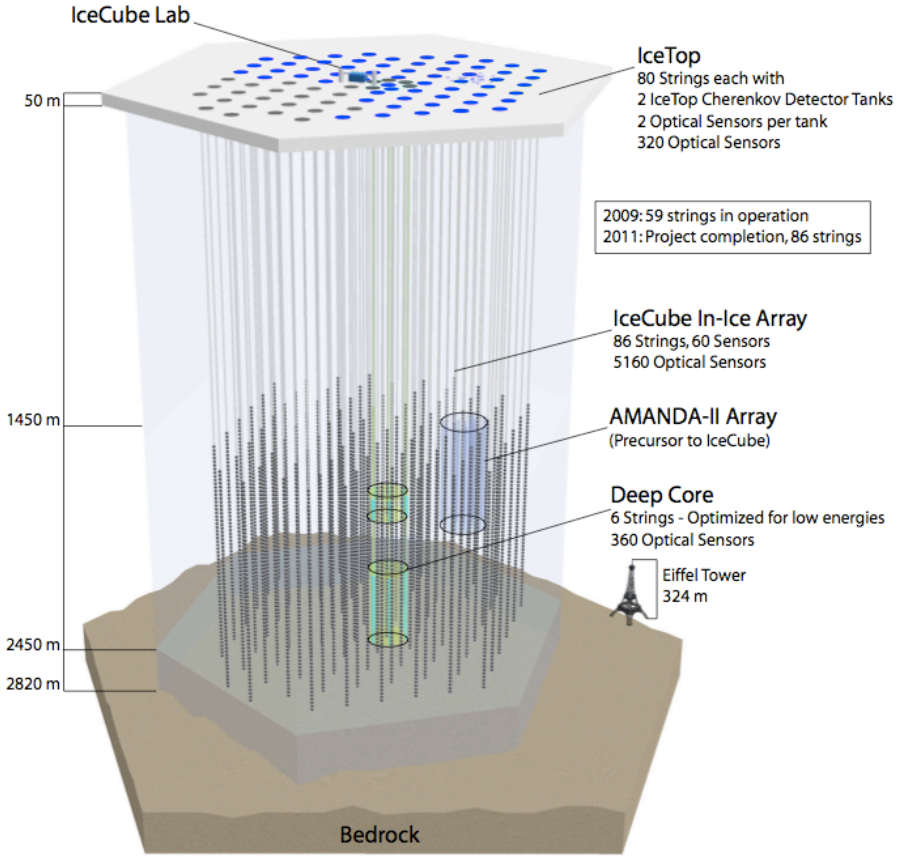
All data (5° smoothing)



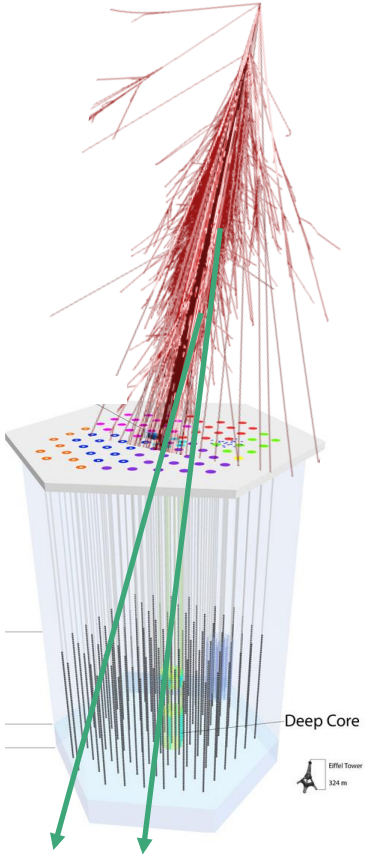
IceCube Neutrino Observatory

- 86 strings at a depth of 1.4 km – 2.4 km.
- 5160 DOMs (Digital Optical Modules).
- 17 m vertical spacing.
- 125 m between strings.

- *IceTop* air-shower array measures cosmic-ray air showers.



Cosmic Rays in IceCube/IceTop



IceCube

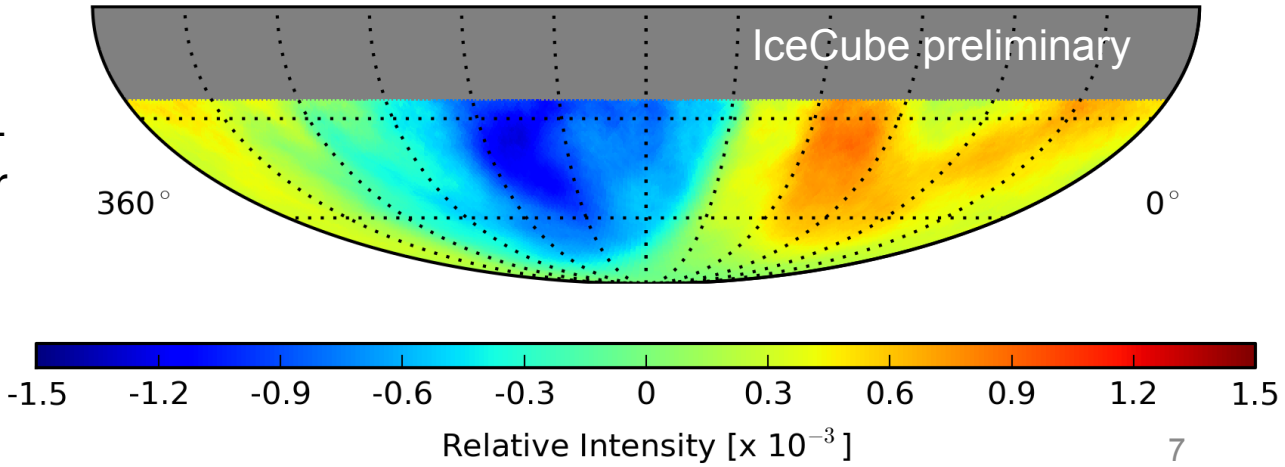
- Sensitive to down-going muons produced by cosmic-ray showers
- Rate: ~ 2 kHz
- Median angular resolution 3°
- Median energy 20 TeV
- Limited event information stored in data storage & transfer (DST) format
  - Basic directional fit
  - Number of DOMs hit

IceTop

- Air-shower array
- Rate: ~ 30 Hz
- Threshold ~400 TeV, median energy in this analysis 1.6 PeV (more than 8 stations).

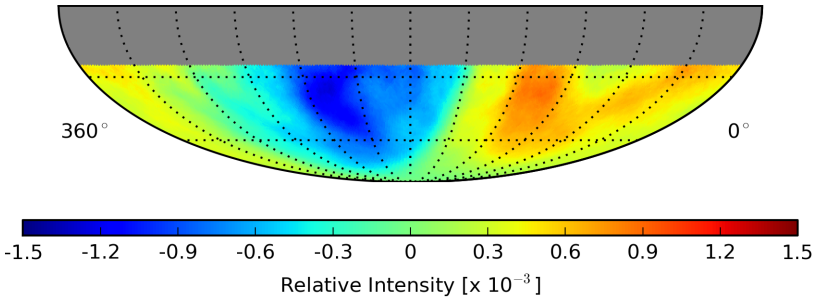
Analysis Strategy

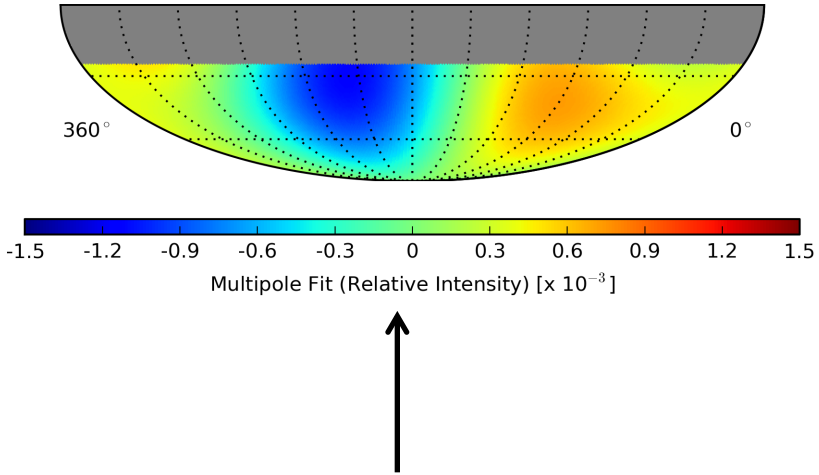
- Create a sky map of relative cosmic-ray intensity by comparing the data map to a reference map which represents the detector response to an isotropic cosmic-ray flux. Due to detector effects and diurnal and seasonable variations, the reference map is not in itself isotropic.
- We estimate the reference level from the data by generating “fake” events from the same local arrival direction distribution and the same event time distribution as the data.
- Sky map in equatorial coordinates of cosmic-ray relative intensity for 5 years of IceCube data:



Large- and Small-Scale Anisotropy

IceCube preliminary

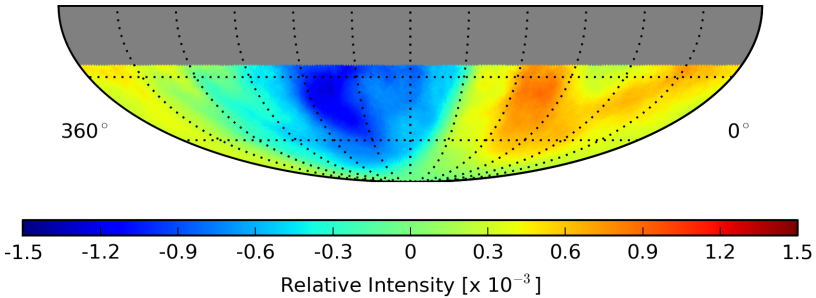


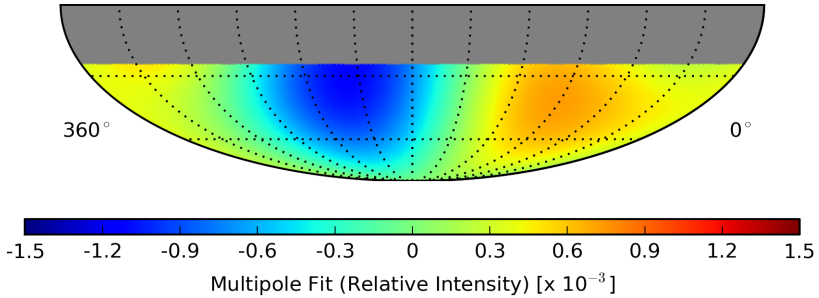


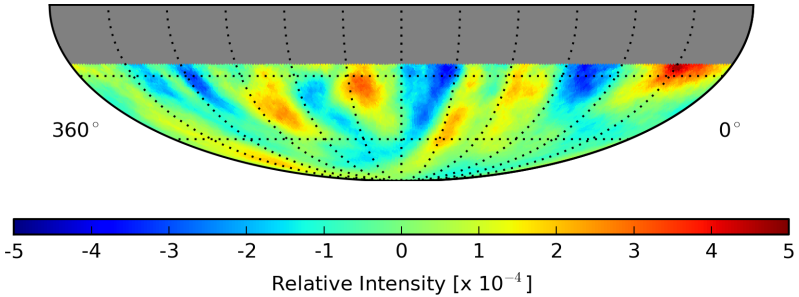
Dipole and quadrupole fit to the relative intensity map

Large- and Small-Scale Anisotropy

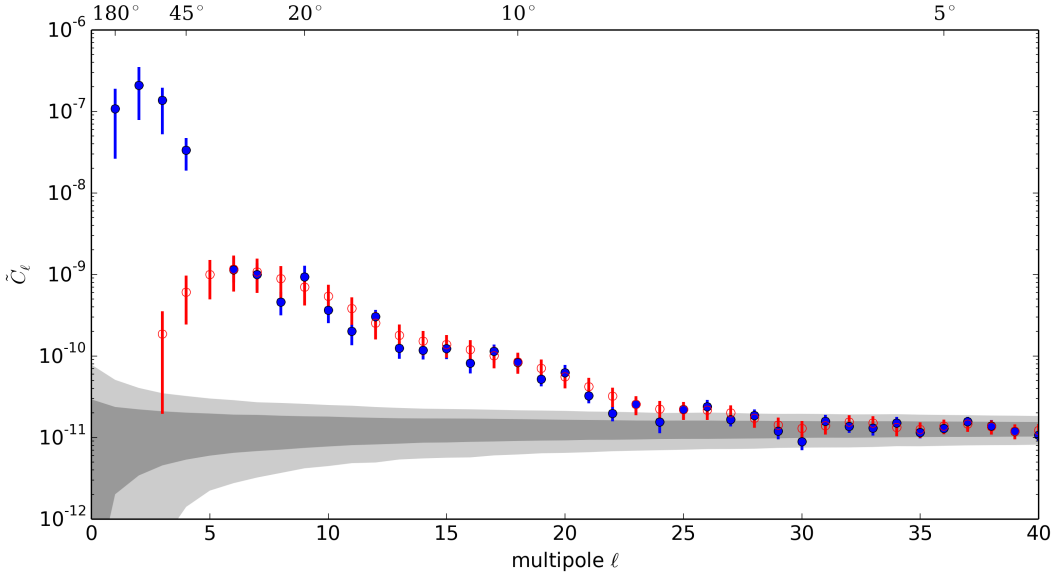
IceCube preliminary



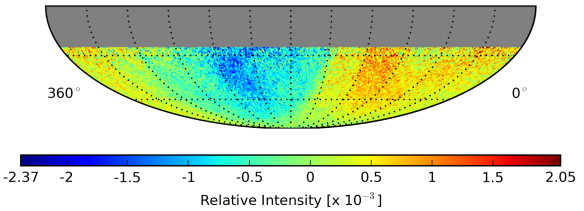




Angular Power Spectrum



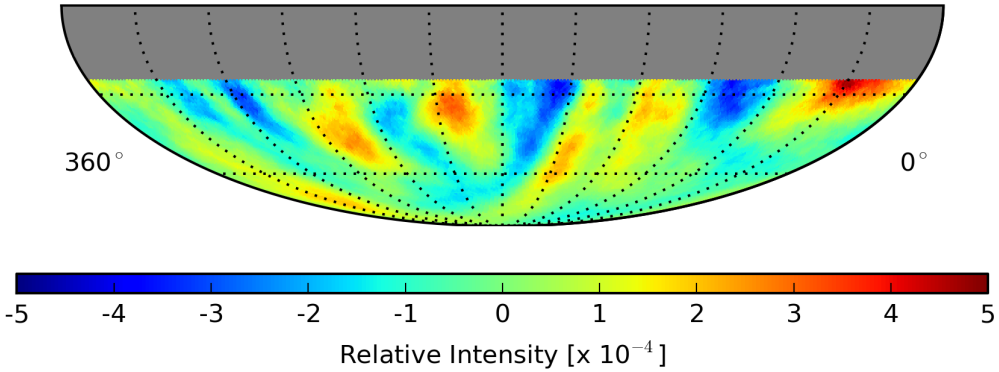
IceCube preliminary

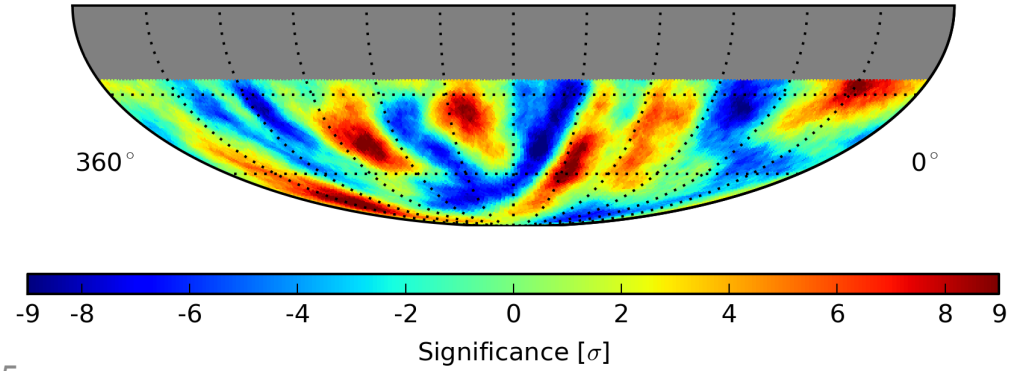


raw (unsmoothed) sky map

- Power spectrum for 5 years of IceCube data (*blue*).
- With best-fit dipole and quadrupole moments subtracted (*red*).
- Dark/light-gray bands represent isotropic flux at the 68% and 95% confidence levels.

Small-Scale Anisotropy



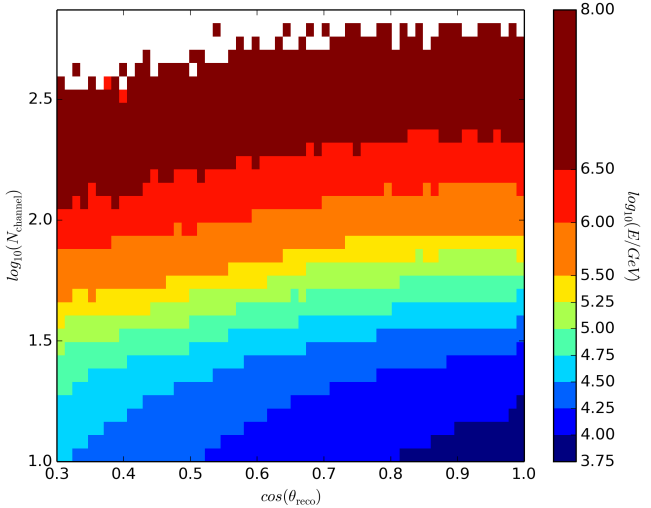


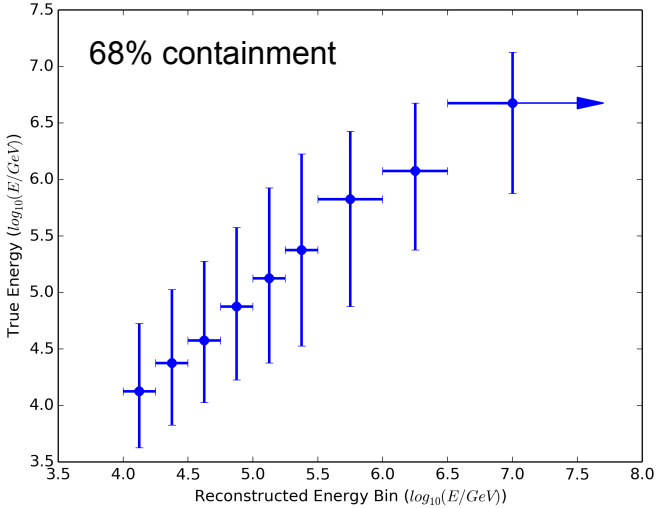
Residual map after best-fit dipole and quadrupole subtraction:

relative intensity
$\Delta N/N$

significance

Energy Dependence

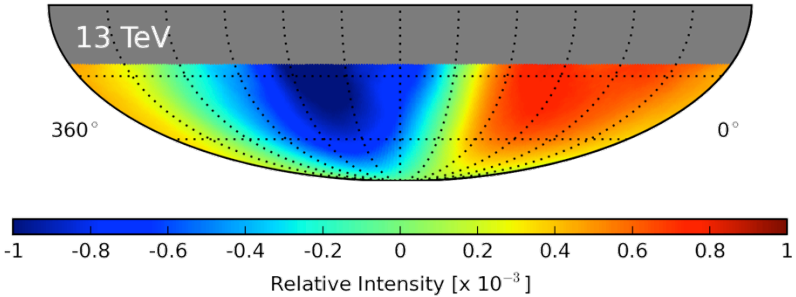


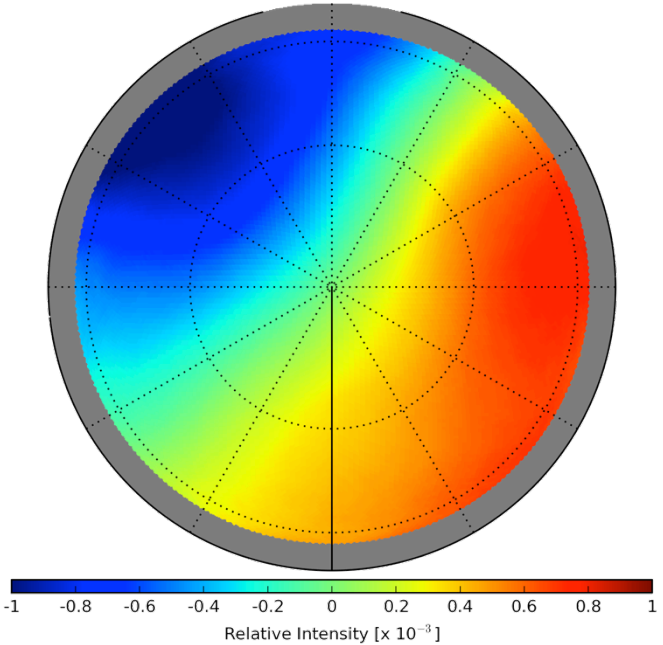


- Data is split into 9 energy bands with median energy from 13 TeV to 5.3 PeV based on the number of PMTs with signal and zenith angle.
- Energy distributions of the bins have considerable overlap due to the limited energy resolution of IceCube for cosmic rays.

Energy Dependence

IceCube preliminary

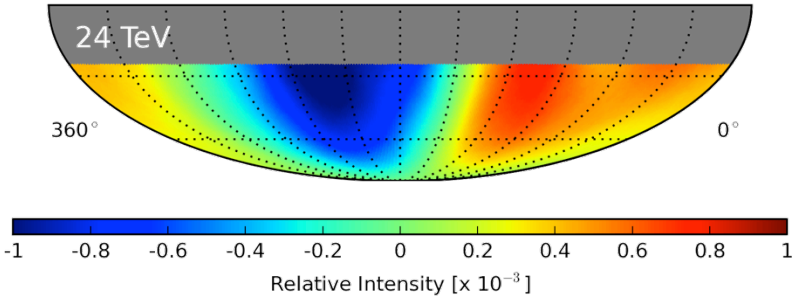


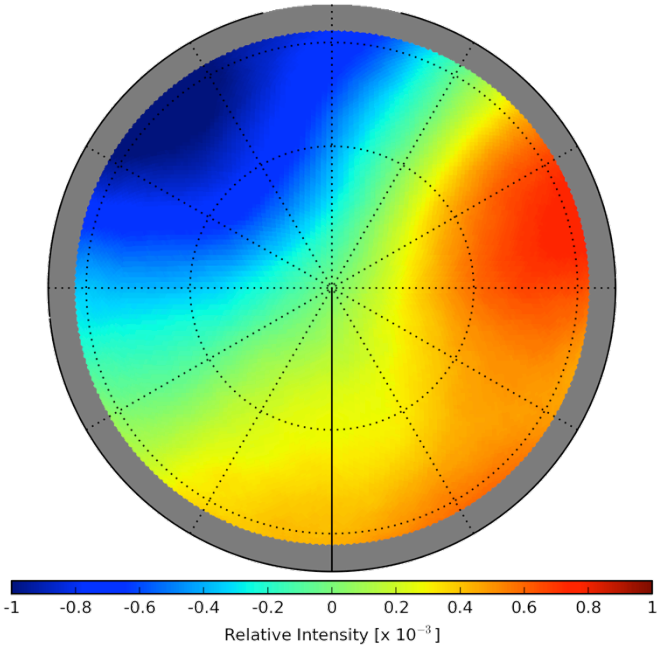


13 TeV

Energy Dependence

IceCube preliminary

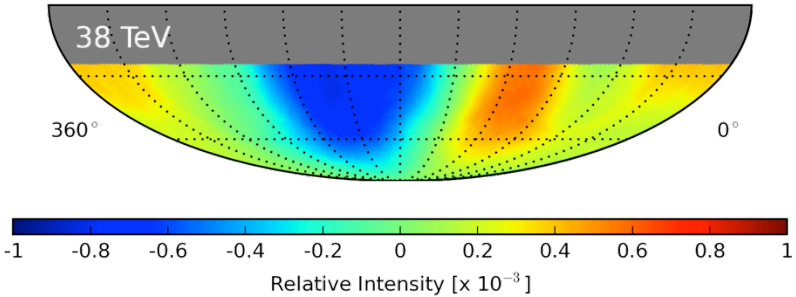


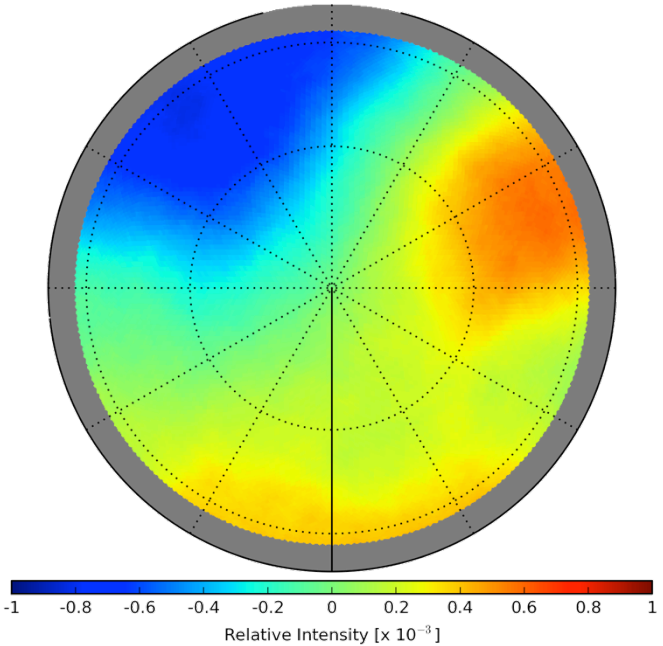


24 TeV

Energy Dependence

IceCube preliminary

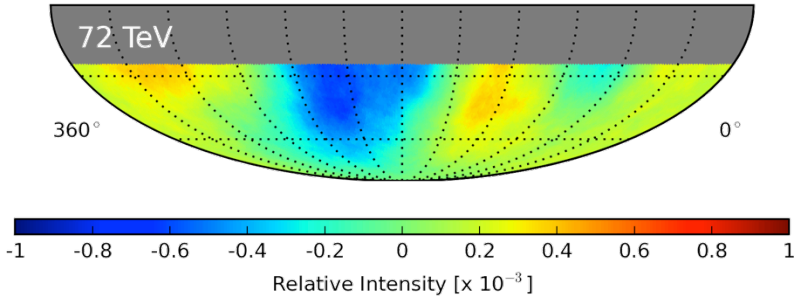


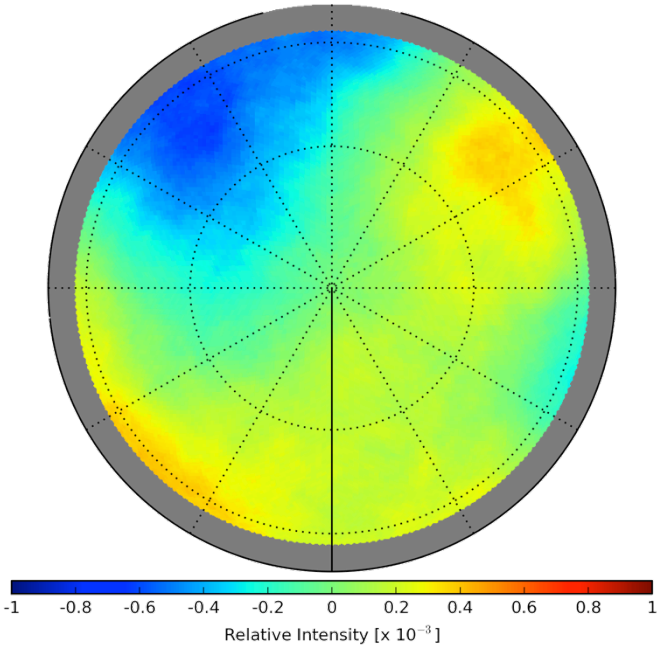


38 TeV

Energy Dependence

IceCube preliminary

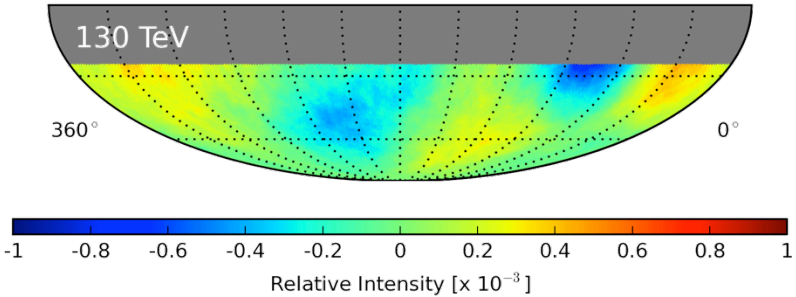


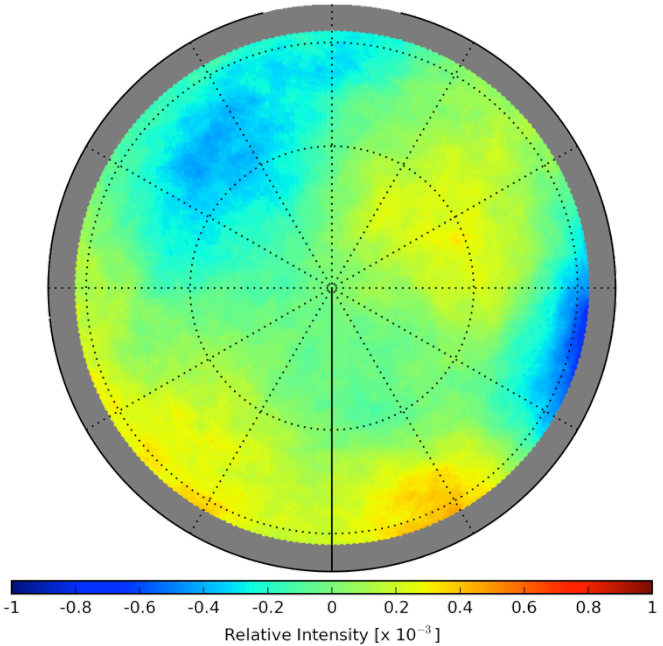


72 TeV

Energy Dependence

IceCube preliminary

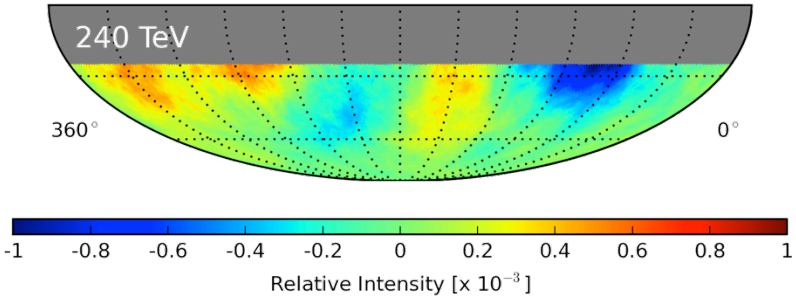


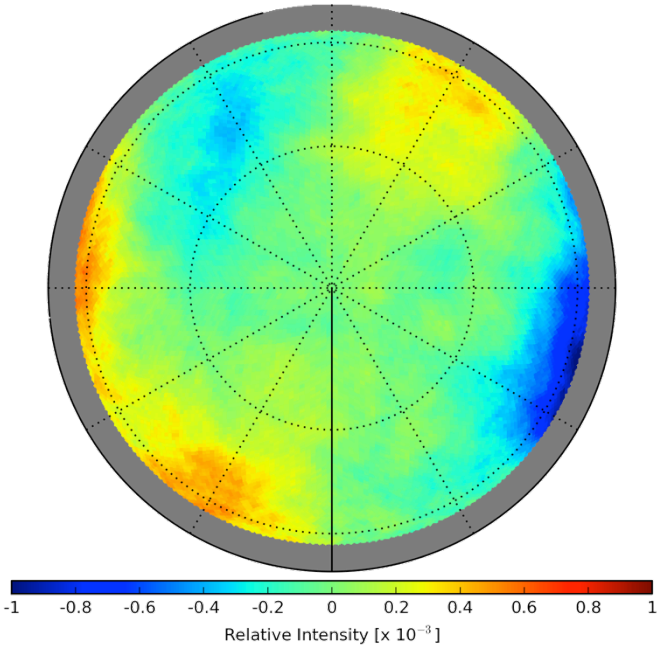


130 TeV

Energy Dependence

IceCube preliminary

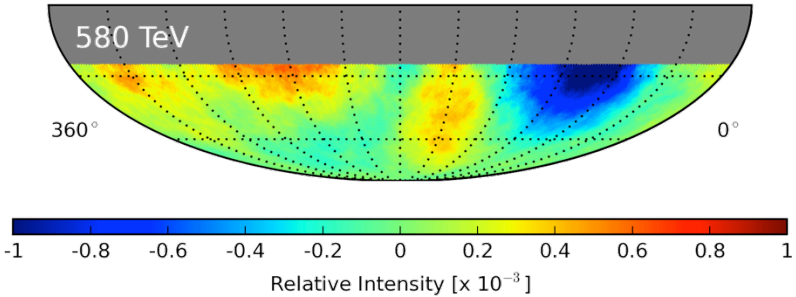


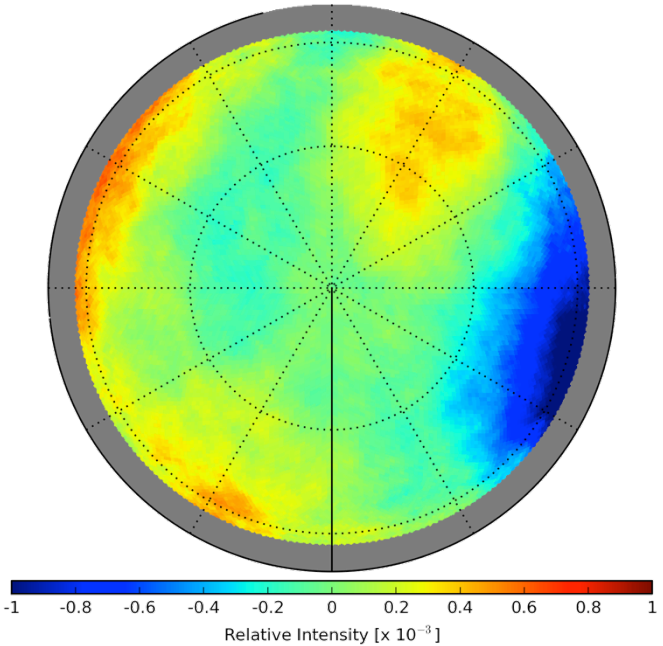


240 TeV

Energy Dependence

IceCube preliminary

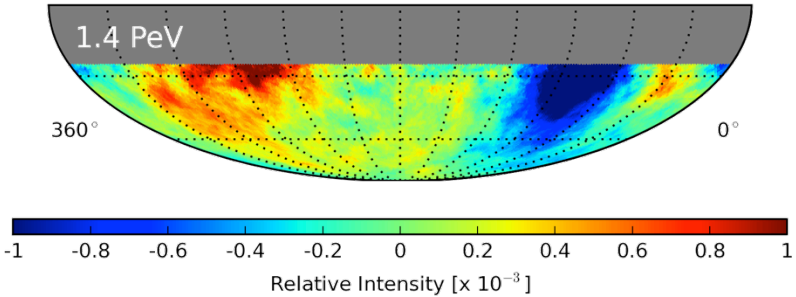


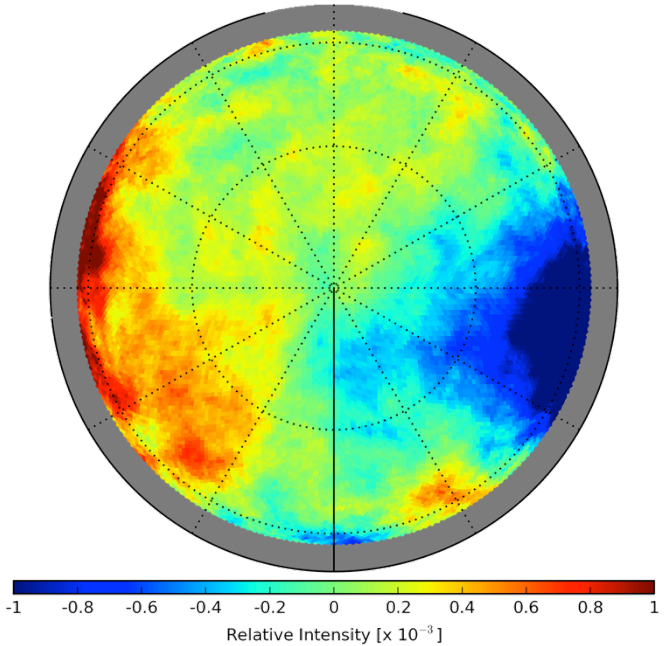


580 TeV

Energy Dependence

IceCube preliminary

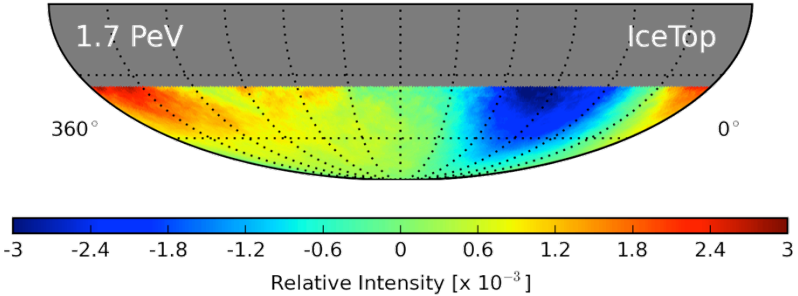


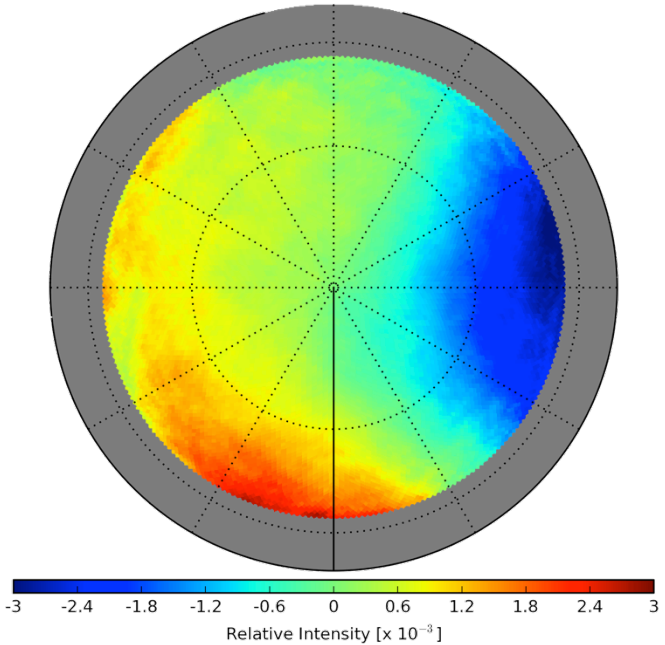


1.4 PeV

Energy Dependence

IceCube preliminary

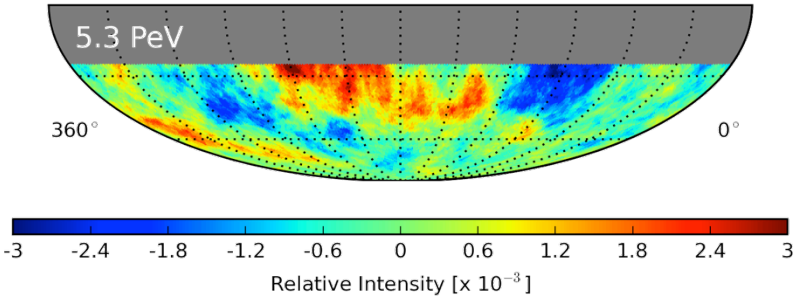


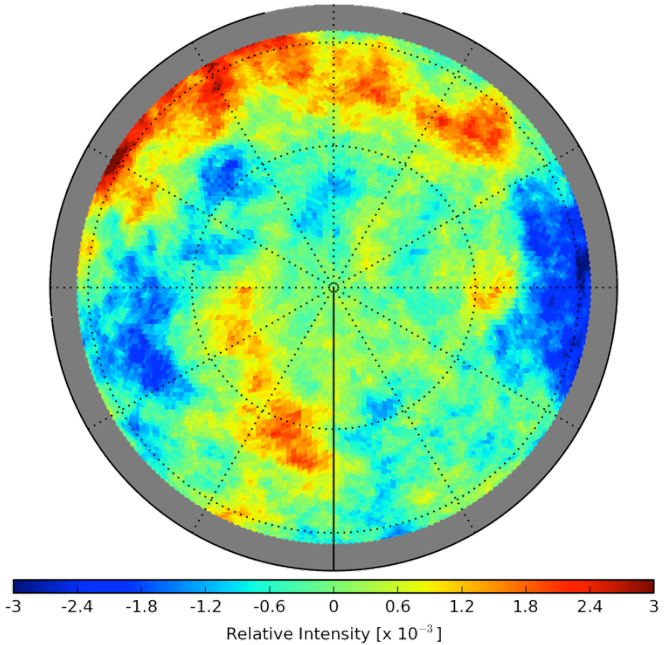


1.7 PeV

Energy Dependence

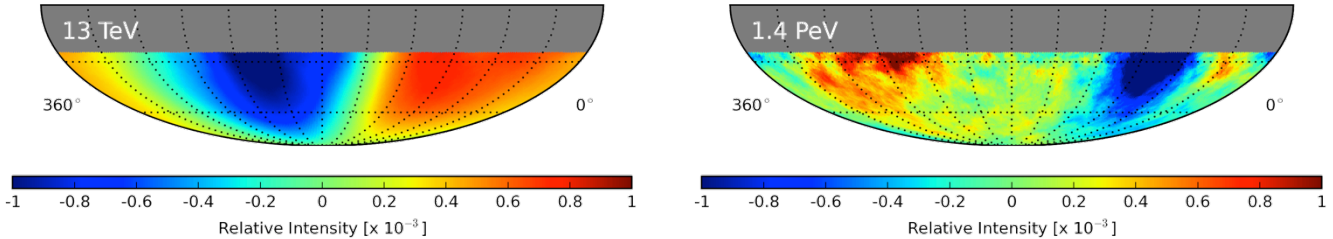
IceCube preliminary



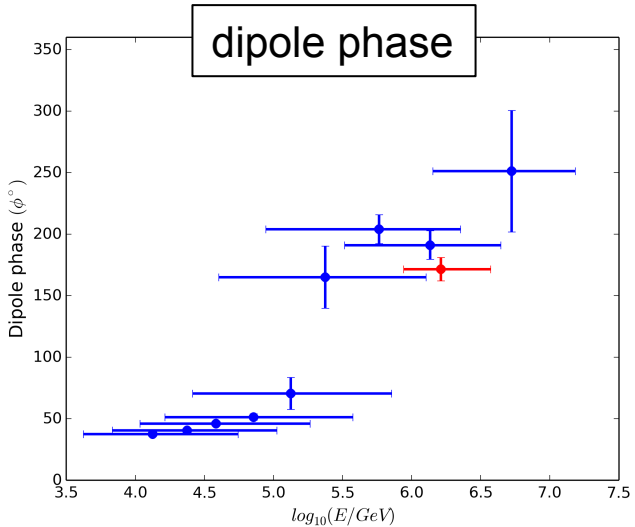


5.3 PeV

Energy Dependence: Phase Shift



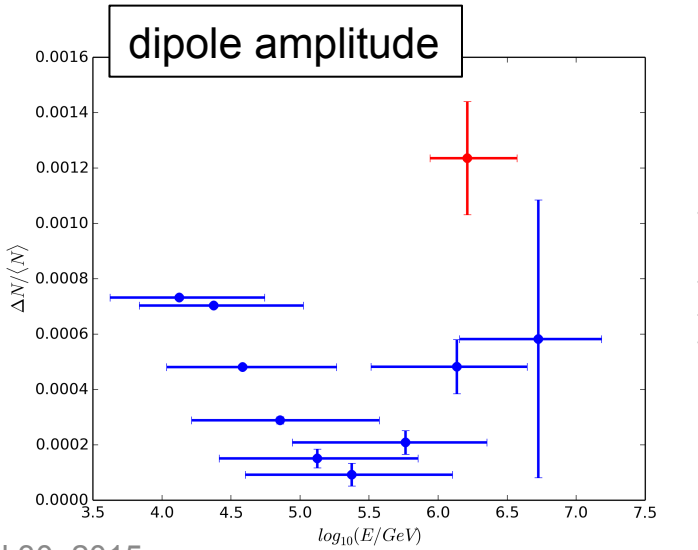
IceCube preliminary



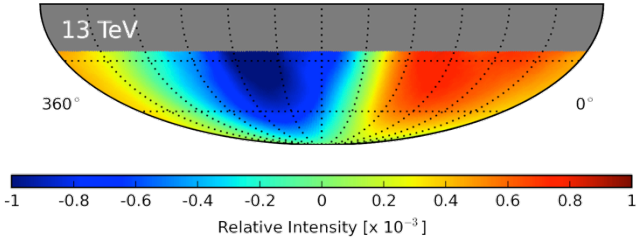
- Harmonic analysis of one-dimensional projection of relative intensity in right ascension, for IceCube (*blue*) and IceTop (*red*) data.
- Above 100 TeV, the dipole phase shifts rather abruptly from a large-scale maximum around 50° to 200° in right ascension.

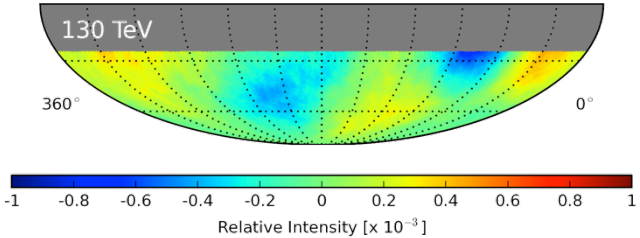
Energy Dependence: Amplitude

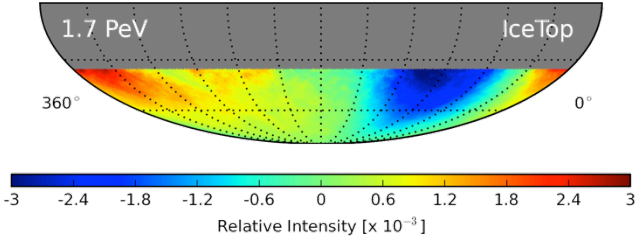
- The amplitude of the large-scale structure strongly depends on energy, decreasing steadily up to ~200 TeV, then increasing up to 5 PeV, the highest energy currently accessible to IceCube.



IceCube preliminary



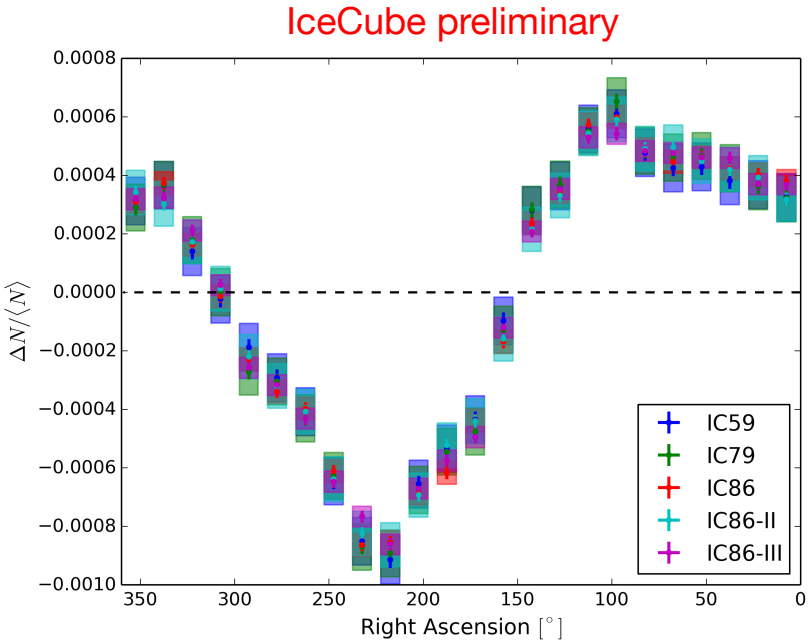




Time Dependence

- Qualitative:
  - One-dimensional projection of relative intensity in right ascension for each year of data.
  - Systematic error bars calculated from anti-sidereal frame.

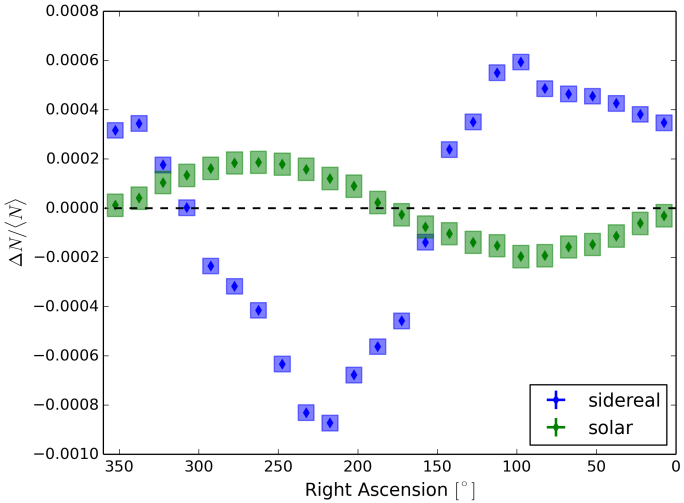
- Quantitative:
  - Calculate χ^2 by comparing each year to the collective ensemble.

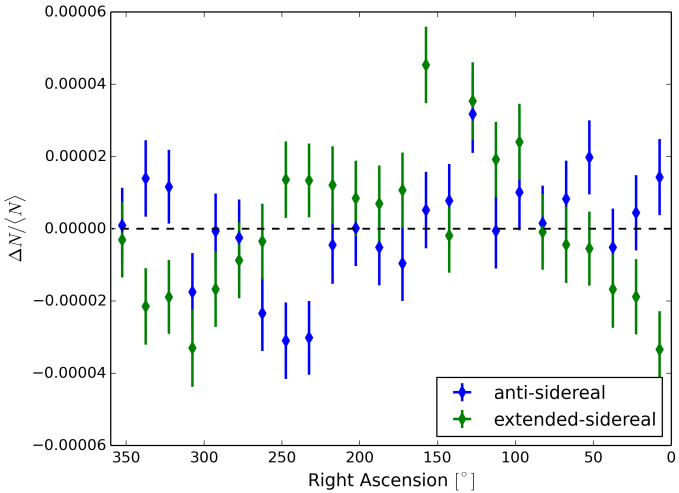


Config	Counts	χ^2	*p*-value
IC59	3.58 x 10^{10}	20.52	0.61
IC79	4.13 x 10^{10}	16.07	0.85
IC86	5.91 x 10^{10}	19.11	0.69
IC86-II	5.63 x 10^{10}	13.88	0.93
IC86-III	6.21 x 10^{10}	27.59	0.23

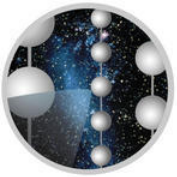
Systematics

IceCube preliminary





- One-dimensional projection of relative intensity in right ascension.
- Sidereal projection not well fit by dipole (or any low-multipole fit).
- Predicted dipole visible in solar time (*left*).
- Systematic errors estimated from the anti- and extended-sidereal frames (*right*).



Summary

- With over 250 billion cosmic-ray events, IceCube can study anisotropy in the cosmic-ray arrival direction distribution in the Southern Hemisphere at less than the part-per-mille level.
- IceCube observes both large- and small-scale anisotropy in cosmic-ray arrival directions at a median energy of 20 TeV.
- At higher energies, IceCube and IceTop data show significant anisotropy that is substantially different from the anisotropy at 20 TeV, with IceCube data indicating the transition occurs around 100 TeV.
- There is no evidence for a time dependence in the large- or small-scale anisotropy over the five-year period covered by this analysis (2009-2014).
- In the near future, we hope to use the superior energy resolution of IceTop to learn more about the location of Galactic cosmic-ray sources, diffusion, Galactic magnetic fields, and other related topics.