Anisotropy in Cosmic Ray Arrival Directions Using IceCube and IceTop

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UHECR 2014

Outline

- Detector Overview
- Large and Small-Scale Structure
  - Updated skymaps for IceTop and IceCube
- Energy Transition
  - Energy transition in IceCube
  - IceCube / IceTop overlap
- Theory
- Summary


The IceCube Collaboration
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Georgia Institute of Technology (USA)
Lawrence Berkeley National Laboratory (USA)
Ohio State University (USA)
Pennsylvania State University (USA)
Southern University and A&M College (USA)
Stony Brook University (USA)
University of Alabama (USA)
University of Alaska Anchorage (USA)
University of California, Berkeley (USA)
University of California, Irvine (USA)
University of Delaware (USA)
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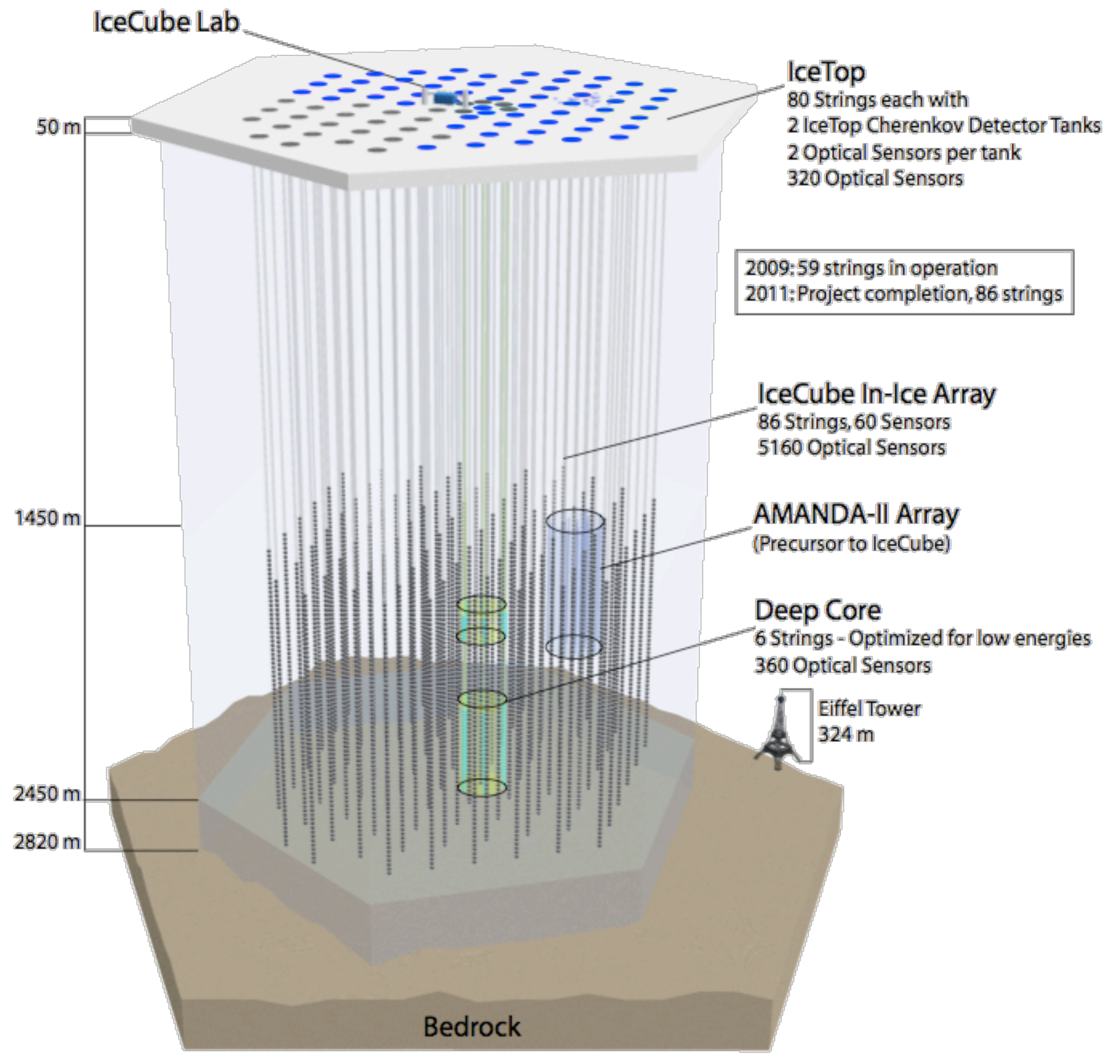
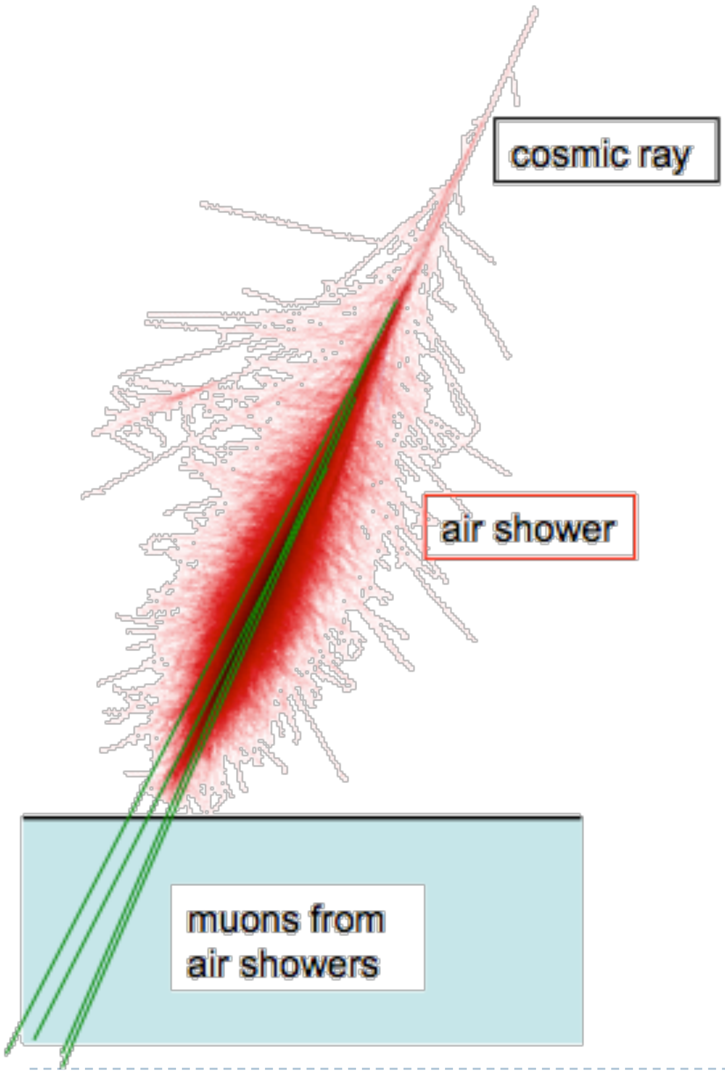
IceCube

- Neutrino detector deep in the Antarctic ice
- 1 km^3 of instrumented volume
- 1.5 – 2.5 km under the surface
- Completed in 2011
  - Took data in partial detctor configurations
- 86 strings
- 60 Digital Optical Modules (DOMs) per string
- ~125 m spacing



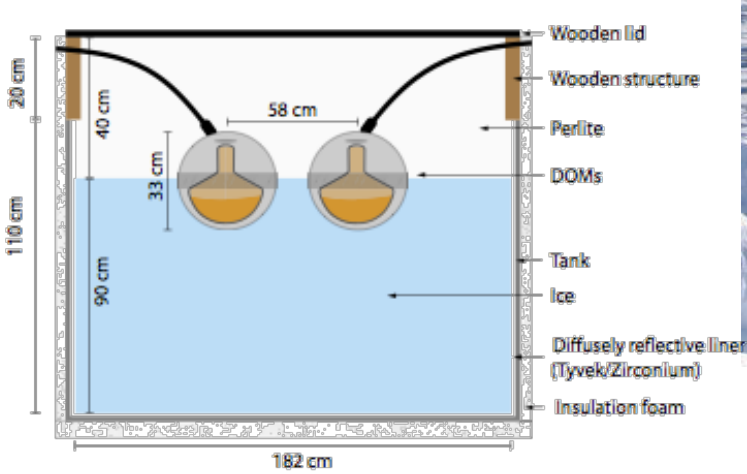
Cosmic Rays in IceCube



- Designed to detect upgoing neutrinos produced by cosmic ray sources in the northern hemisphere
- Sensitive to downward going muons produced by cosmic ray showers in the southern hemisphere
- Cosmic-ray primary energies of order ~ 100 GeV – 1 PeV
- Rate: ~ 2 kHz
- Limited event information stored in data storage & transfer (DST) format
  - Basic directional fit
  - Number of DOMs hit

IceTop

- Air shower array on top of IceCube
- 80 stations
  - Two tanks per station
  - Two DOMs per tank
- Close to shower maximum



Cosmic Rays in IceTop

- Sensitive to electromagnetic component of downgoing showers
- Cosmic ray primary energies ~100 TeV – 1 EeV
- Rate: ~20 Hz
- Retains more information per event, allowing for more detailed energy and angular resolution

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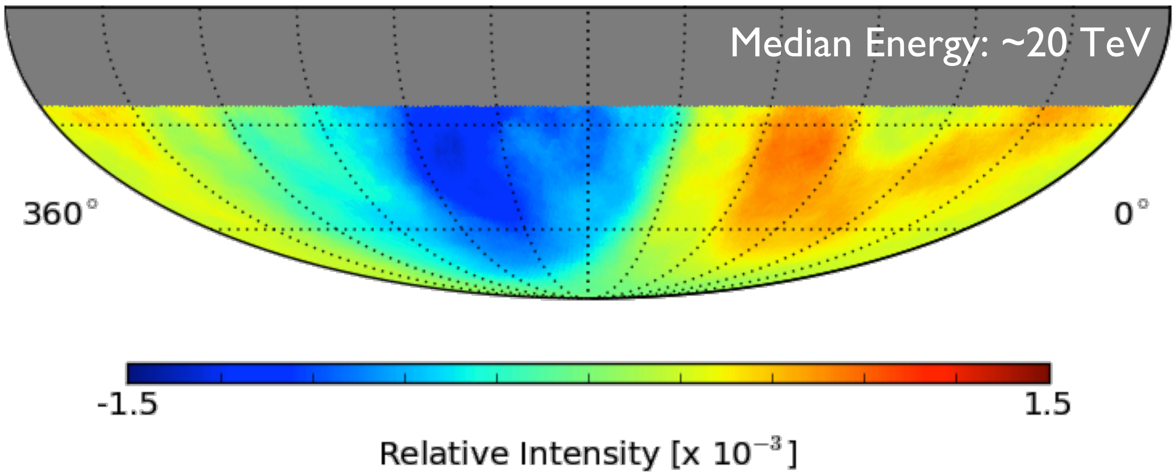
Dataset Size

Configuration	Number of Events
IC59	3.403×10^{10}
IC79	3.914×10^{10}
IC86	5.702×10^{10}
IC86-II	5.338×10^{10}
Total	1.836×10^{11}

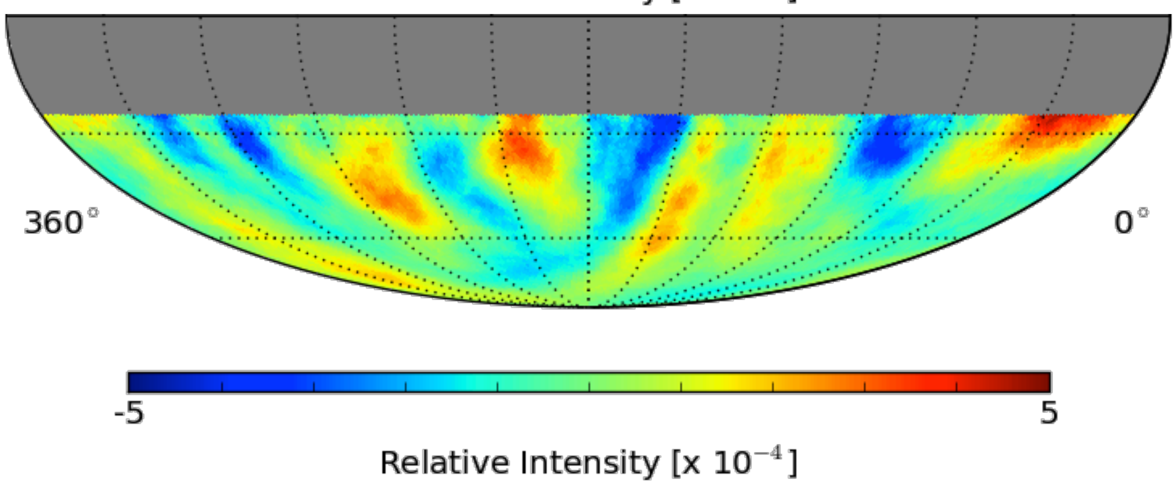
Configuration	Number of Events (STA8)
IT59	2.887×10^{7}
IT73	3.690×10^{7}
IT81	3.796×10^{7}
IT81-II	3.713×10^{7}
Total	1.409×10^{8}

Anisotropy in IceCube

4 years of data (IC59 – IC86-II) 1.84 x 10^{11} events



- Relative Intensity
- 5° smoothing



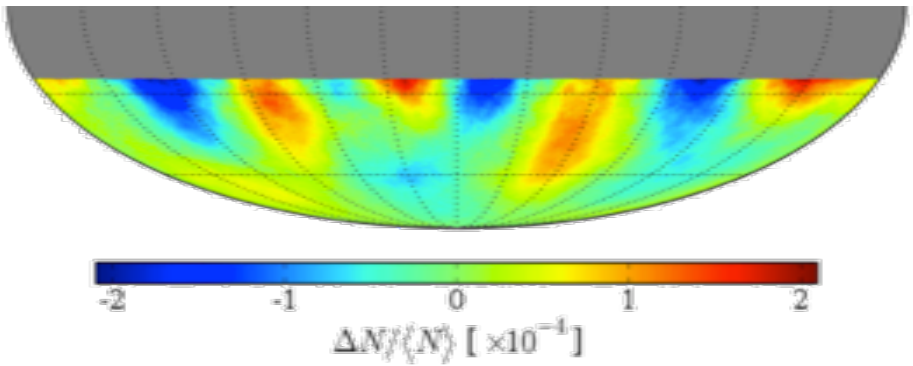
- Dipole/quadrupole fit residual map
- Relative Intensity
- 5° smoothing

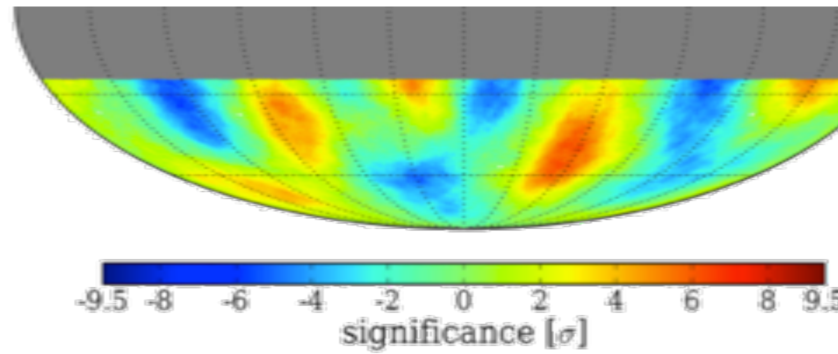
IceCube Preliminary

Anisotropy in IceCube

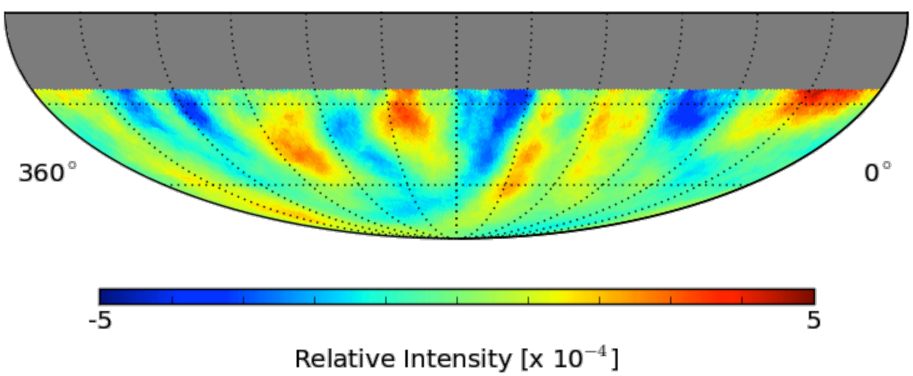
IC59 Dipole & Quadropole Fit Residuals (20° smoothing)

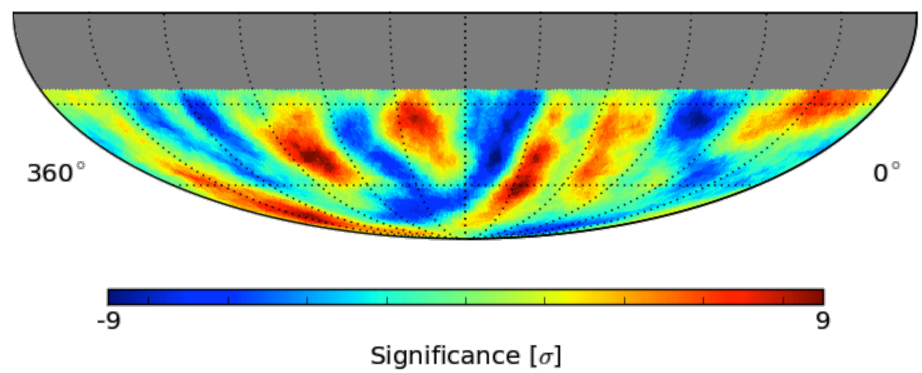
Abbasi et al., ApJ, 740, 16, 2011 arxiv/1105.2326





IC59+IC79+IC86+IC86-II Dipole & Quadropole Fit Residuals (5° smoothing)





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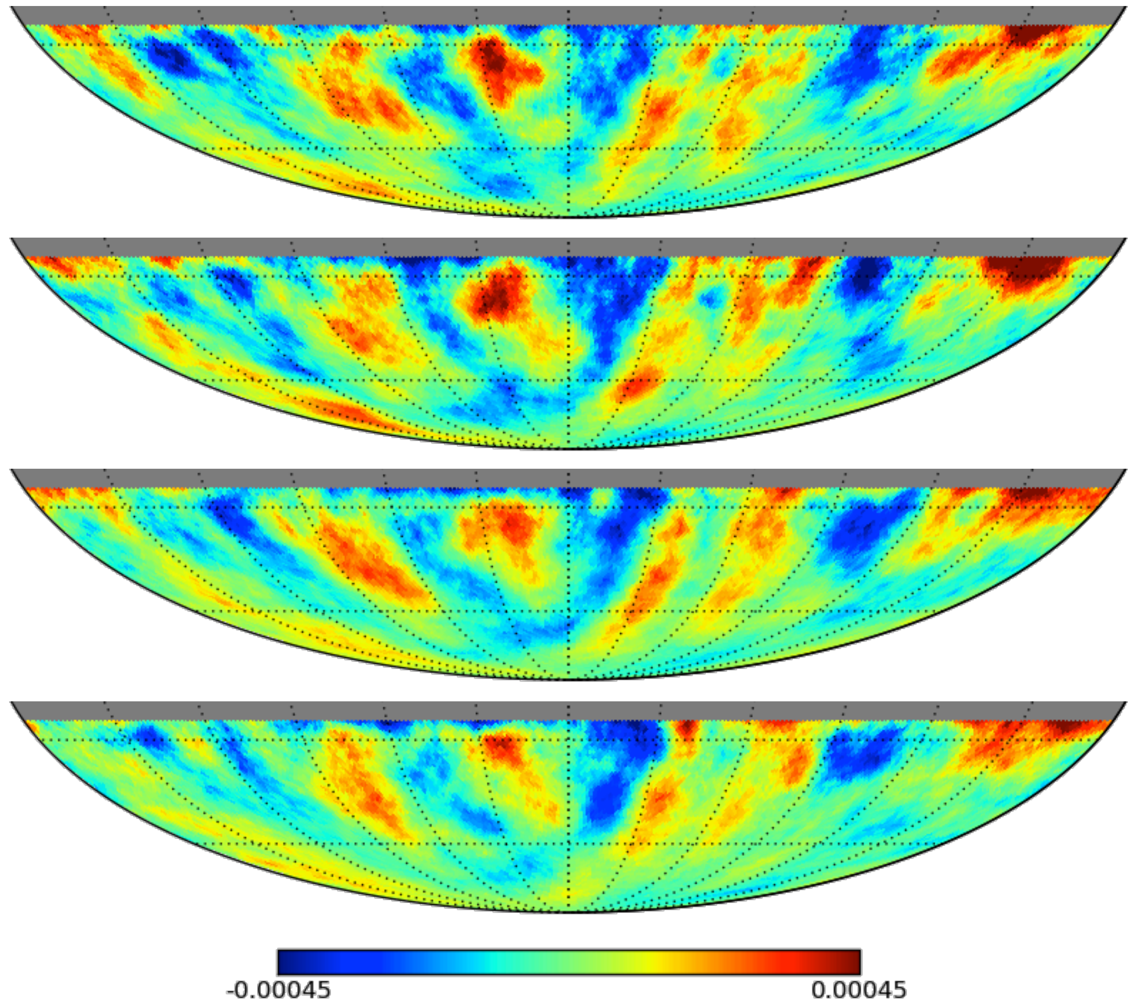
Fit Residuals Over Time

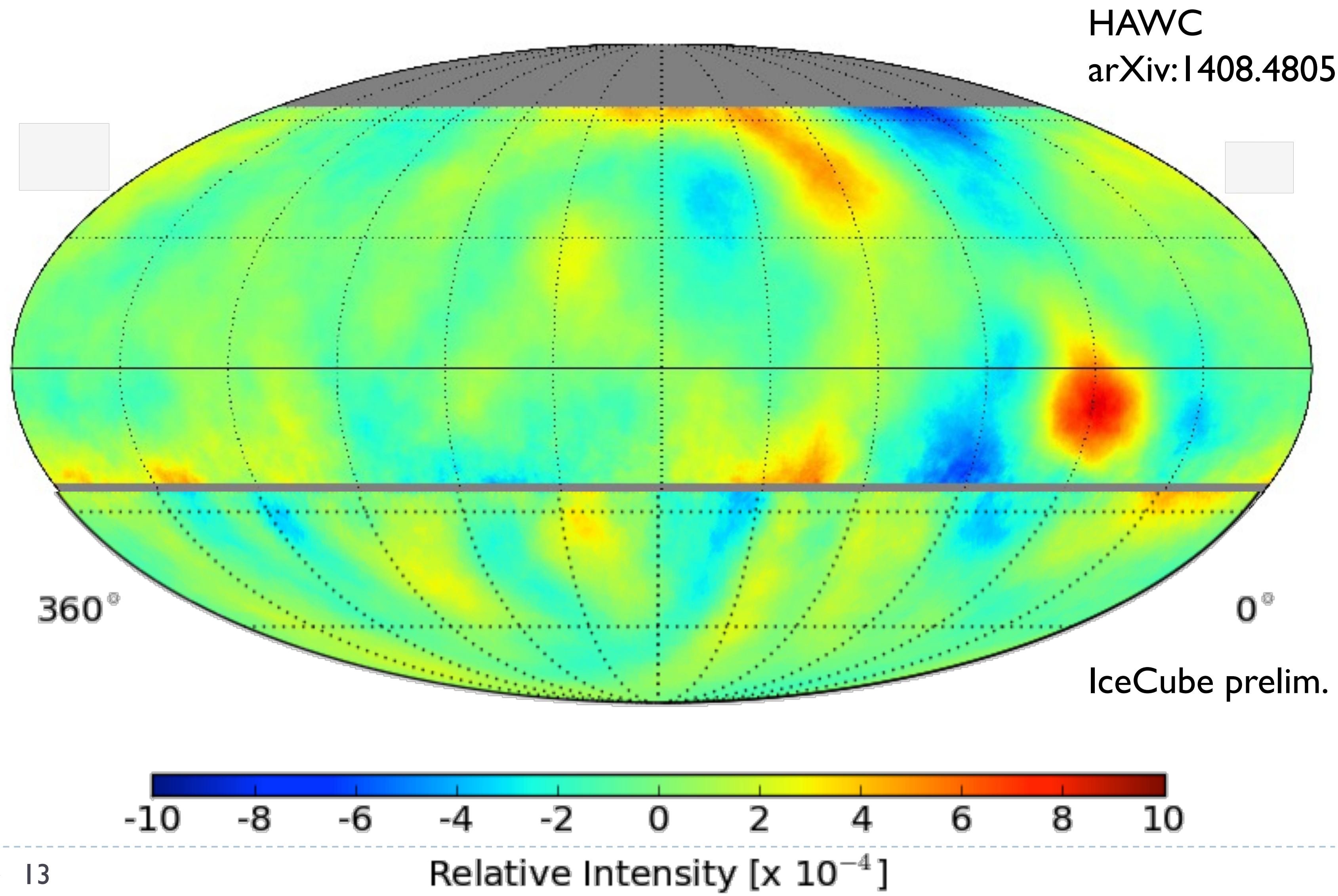
Relative Intensity
-4.5 – 4.5 x 10^{-3}
5° smoothing

- IC59
- IC79
- IC86
- IC86-II



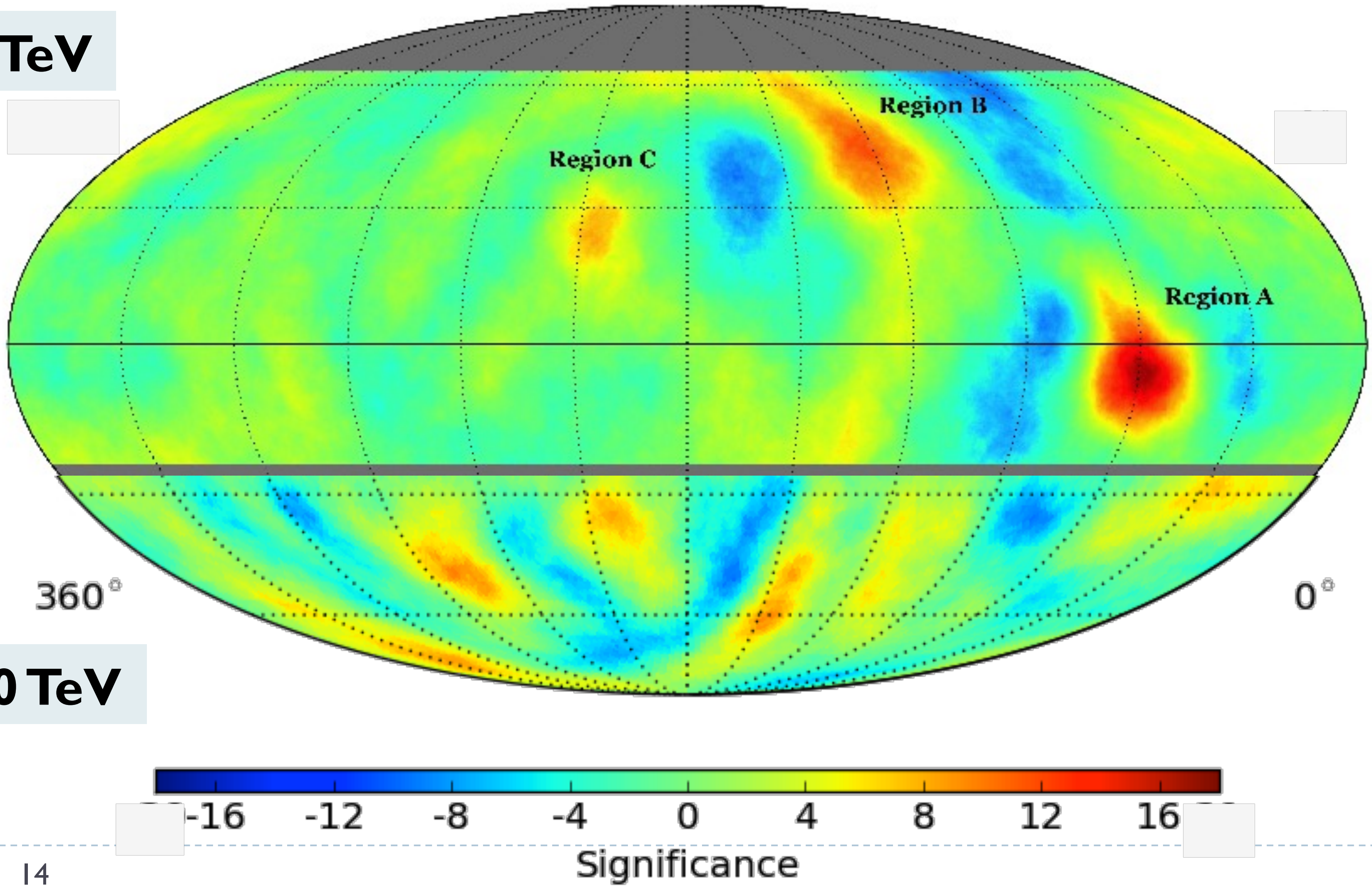
IceCube Preliminary

Comparison with HAWC – Relative Intensity



Comparison with HAWC – Significance

2 TeV



20 TeV

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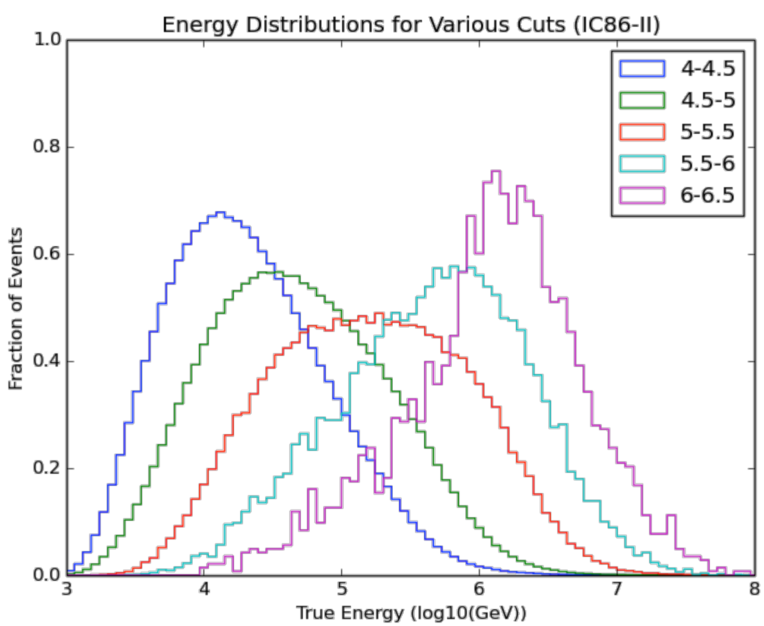
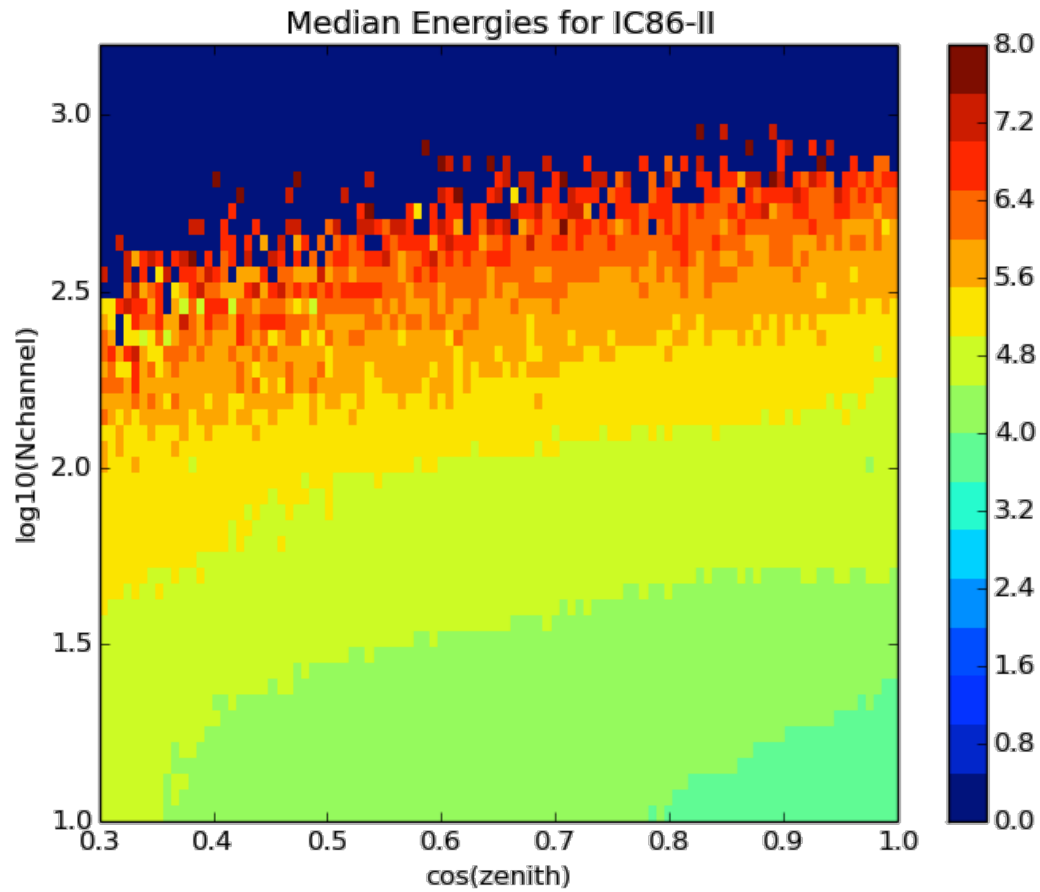
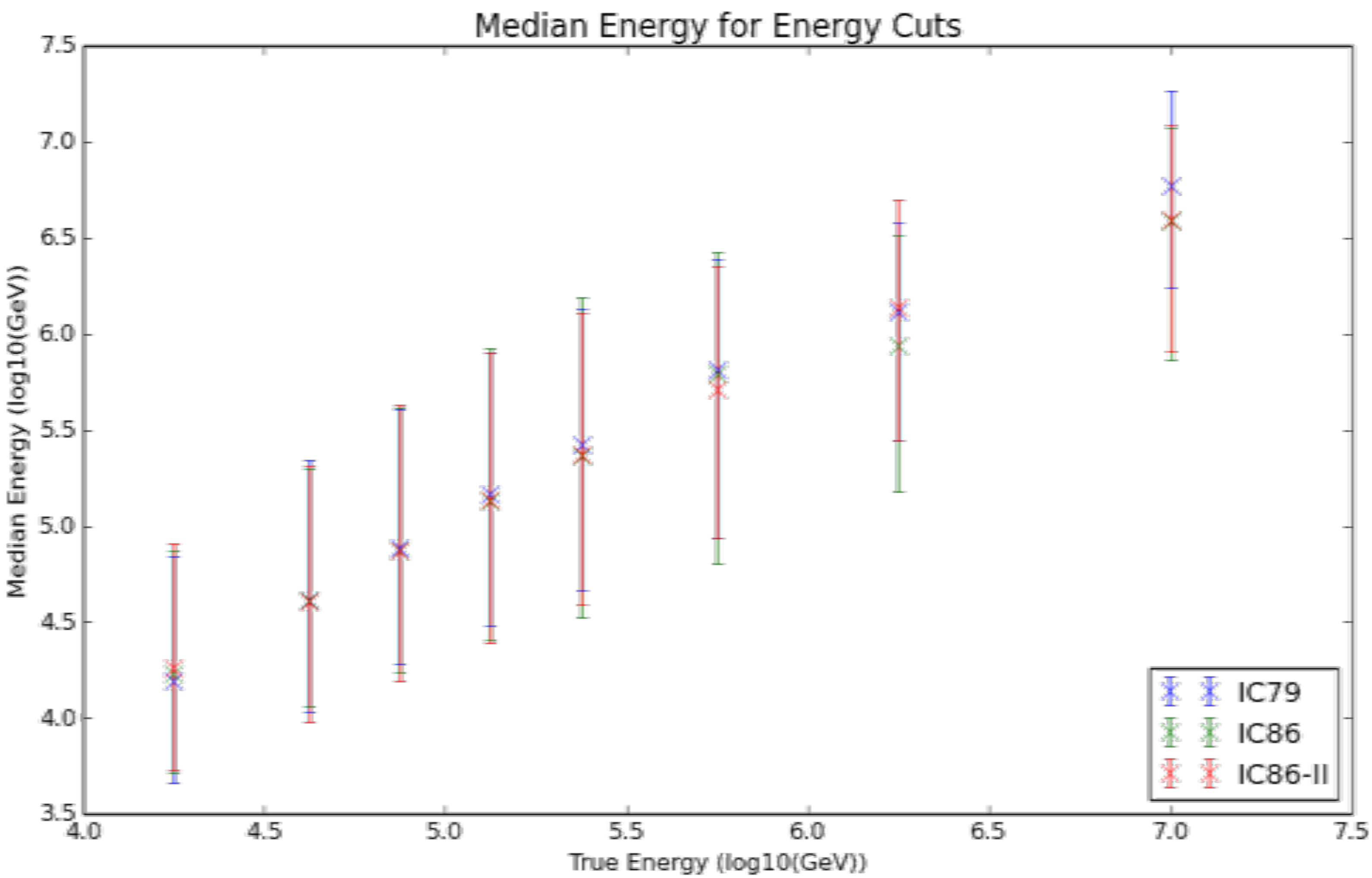
Energy Separation in IceCube

- Cut into energy bands based on Nchannel / cos(zenith) plot (right)
- Repeat procedure for each detector configuration





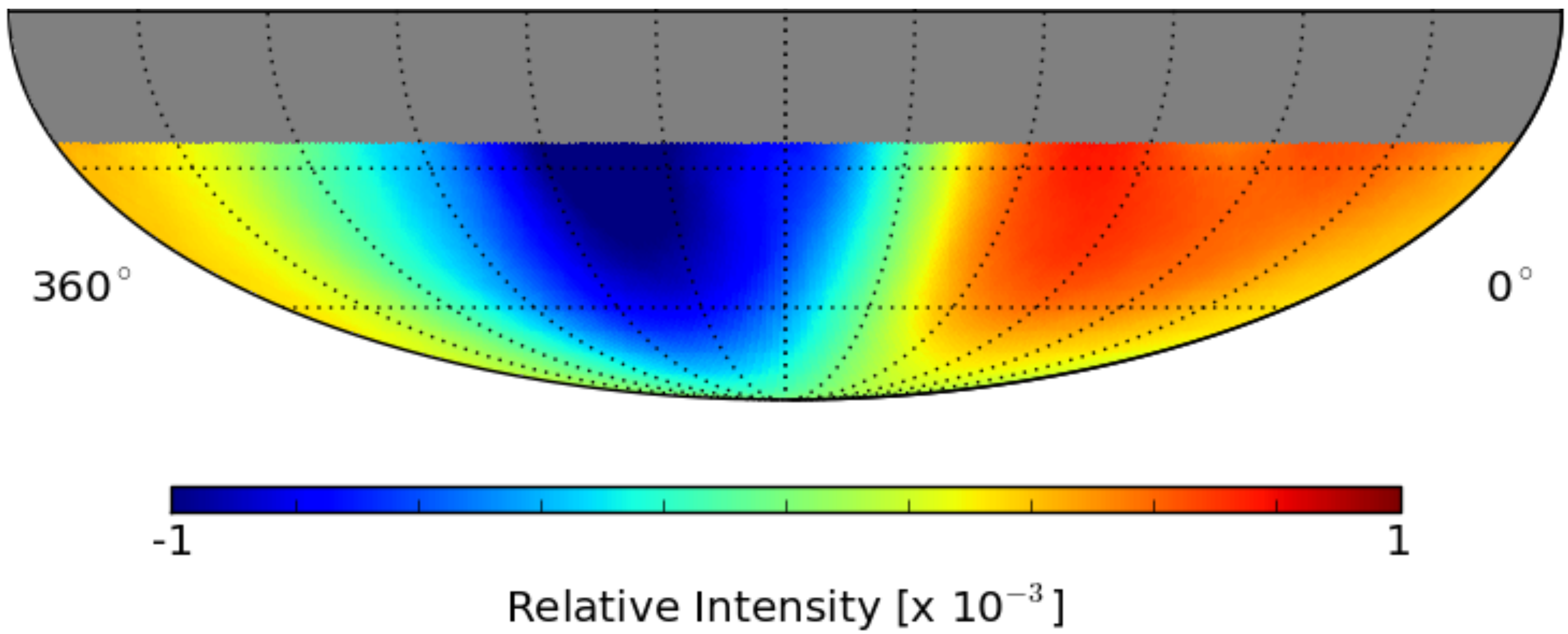
Energy Distributions



IceCube Preliminary

Energy Transition in IceCube

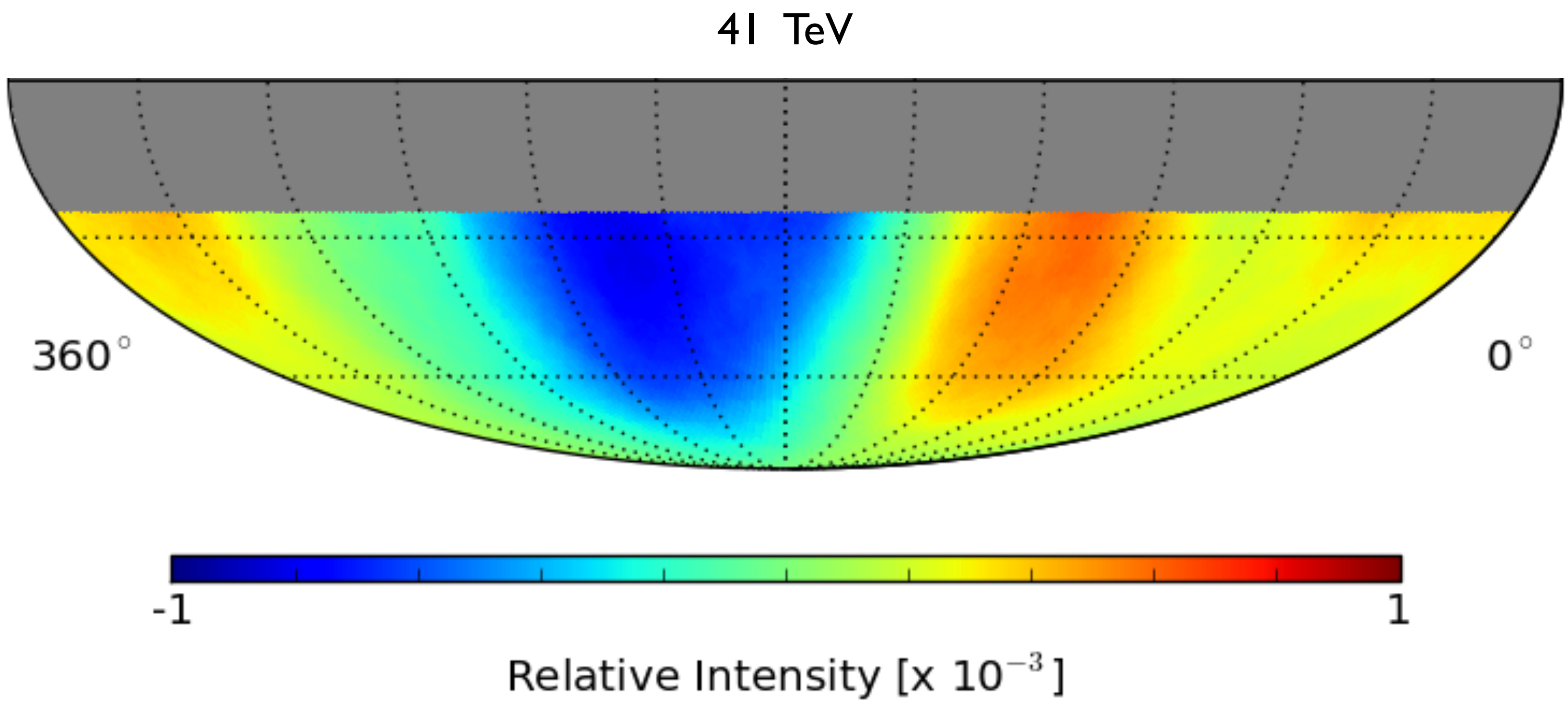
17 TeV



Note: Wide energy distributions – maps are statistically correlated

IceCube Preliminary

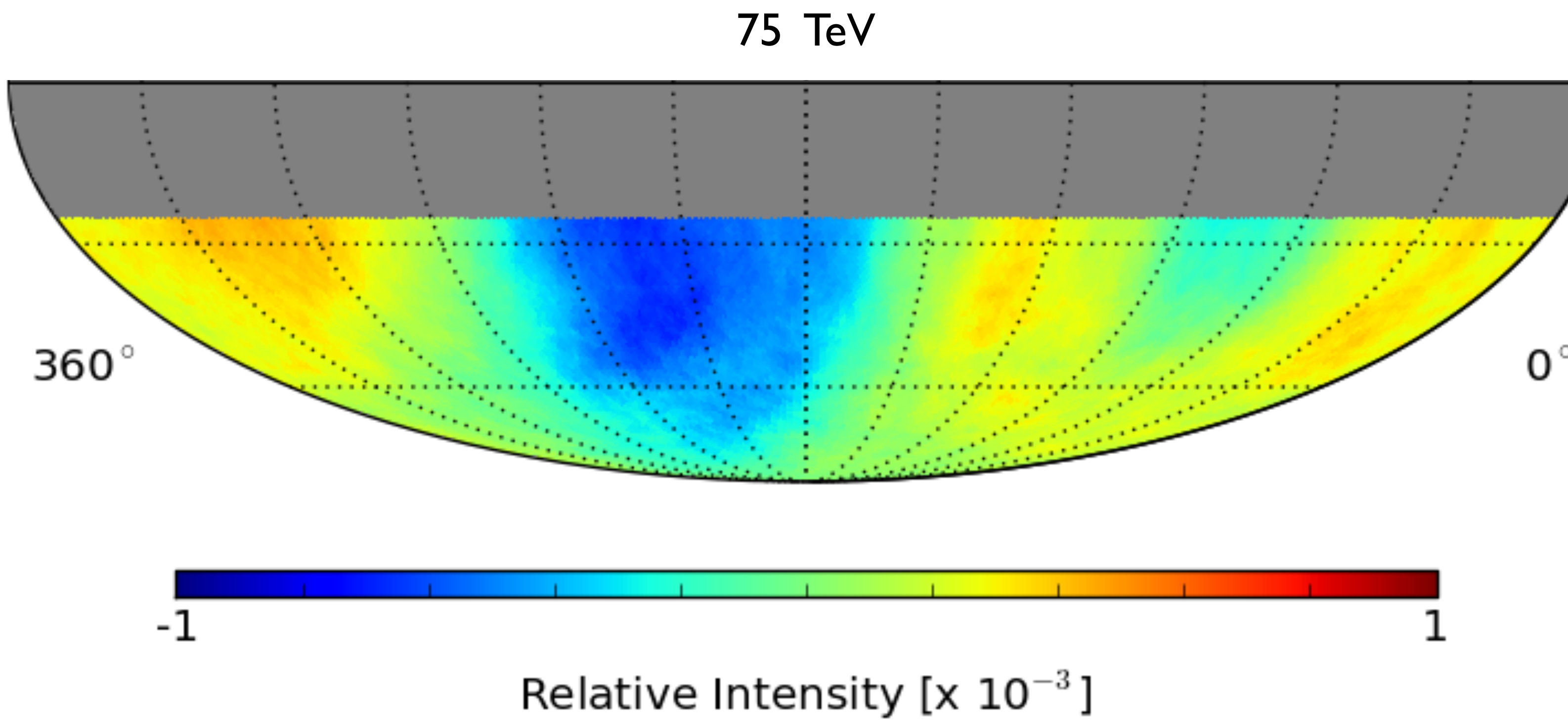
Energy Transition in IceCube



Note: Wide energy distributions – maps are statistically correlated

IceCube Preliminary

Energy Transition in IceCube

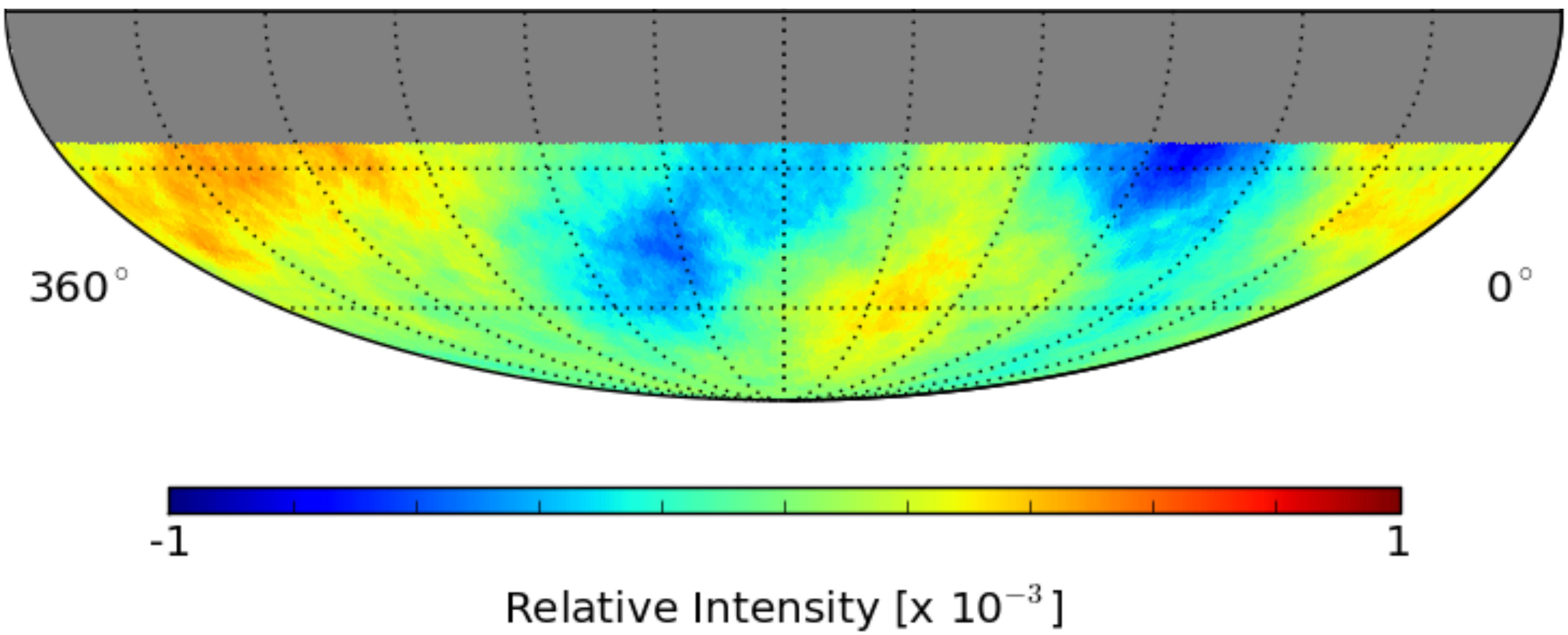


Note: Wide energy distributions – maps are statistically correlated

IceCube Preliminary

Energy Transition in IceCube

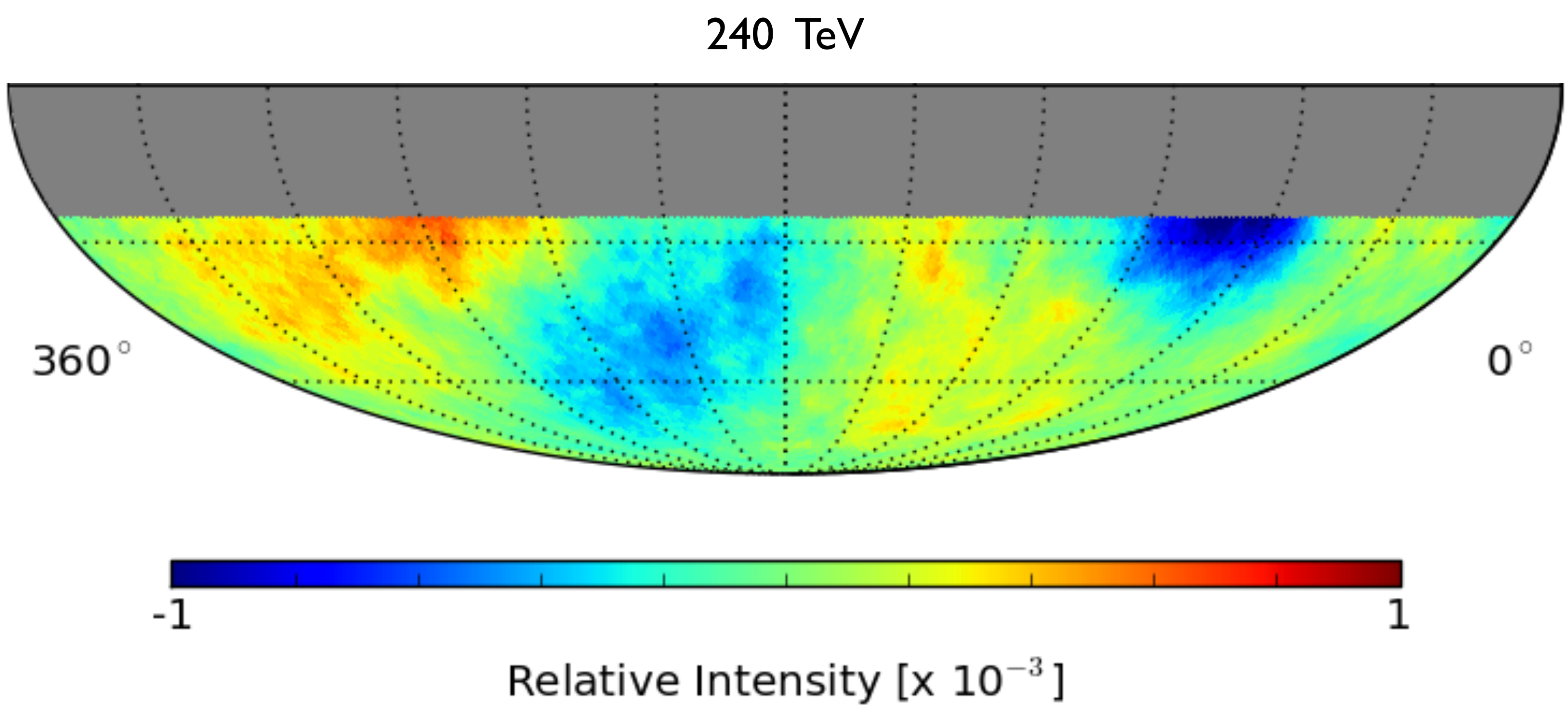
140 TeV



Note: Wide energy distributions – maps are statistically correlated

IceCube Preliminary

Energy Transition in IceCube



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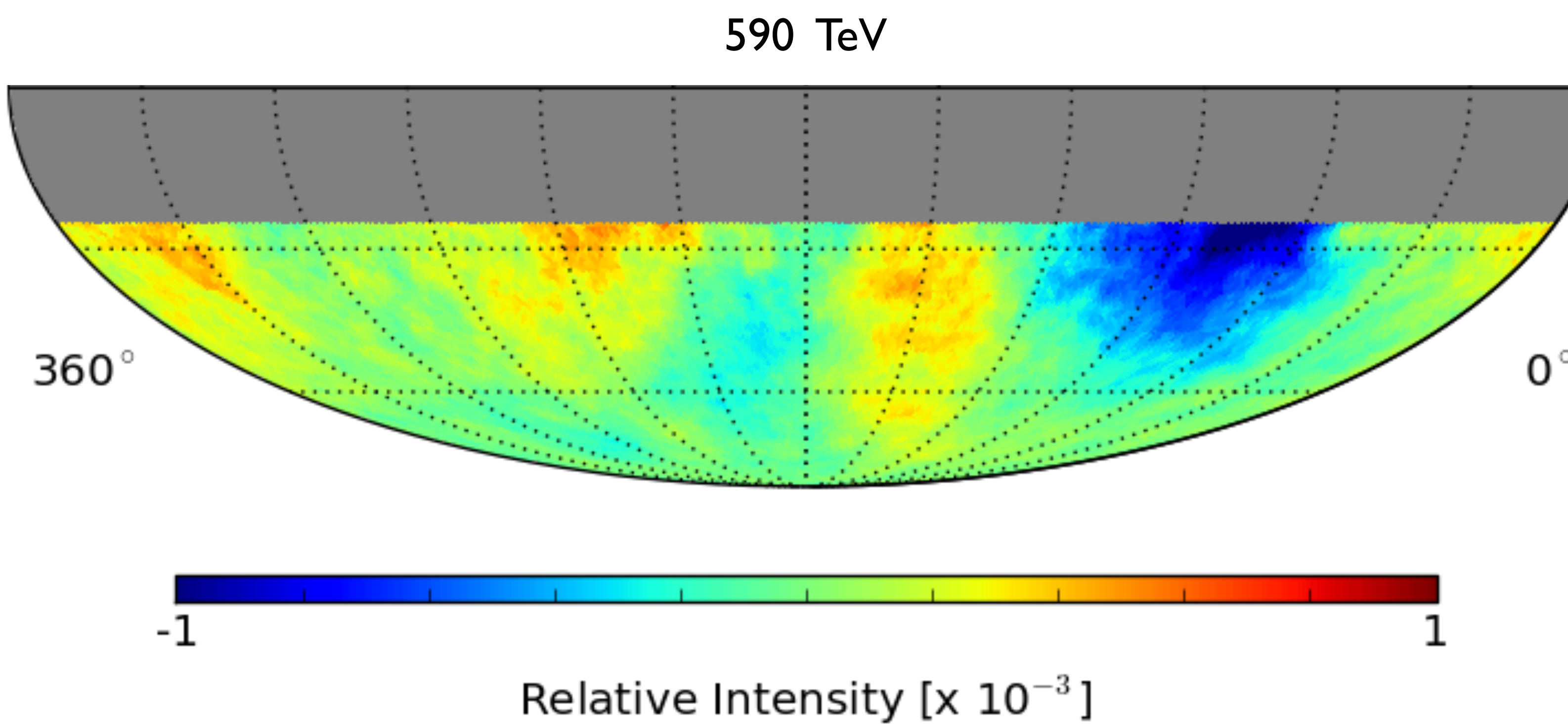
IceCube Preliminary

Energy Transition in IceCube

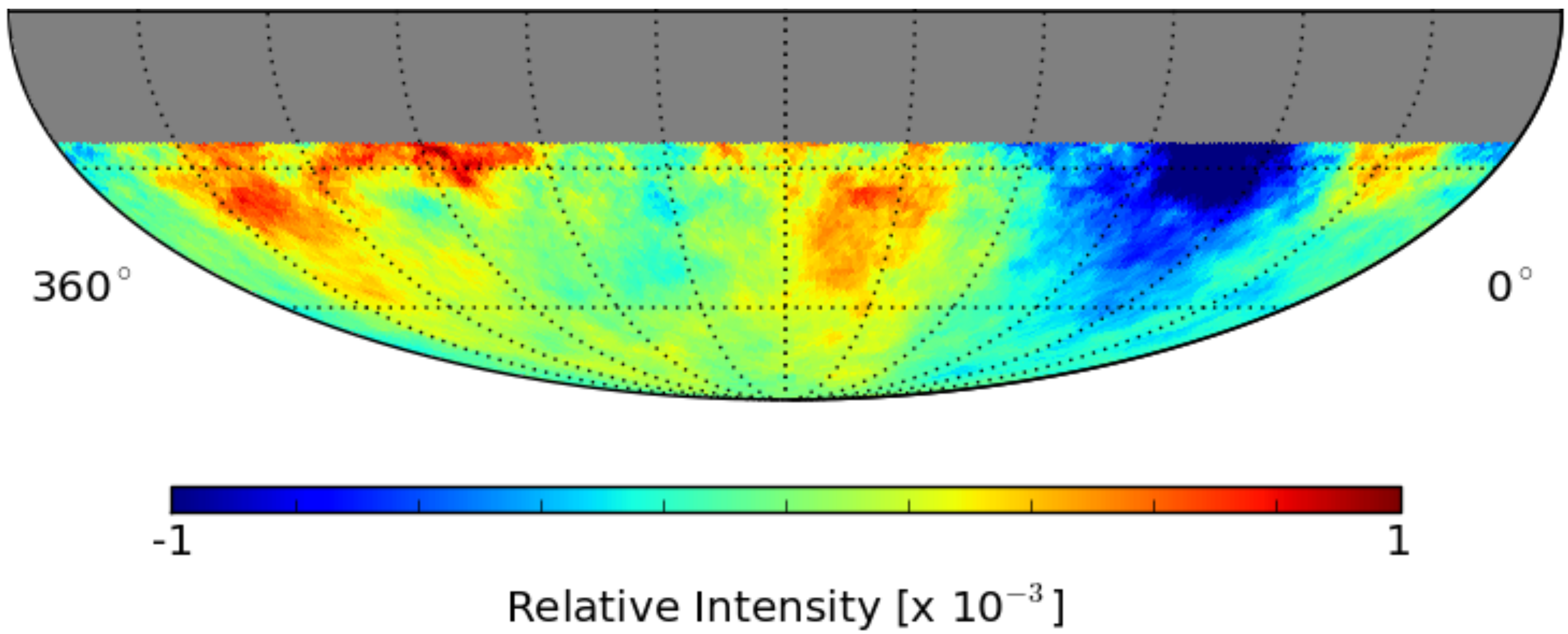


Note: Wide energy distributions – maps are statistically correlated

IceCube Preliminary

Energy Transition in IceCube

1.2 PeV

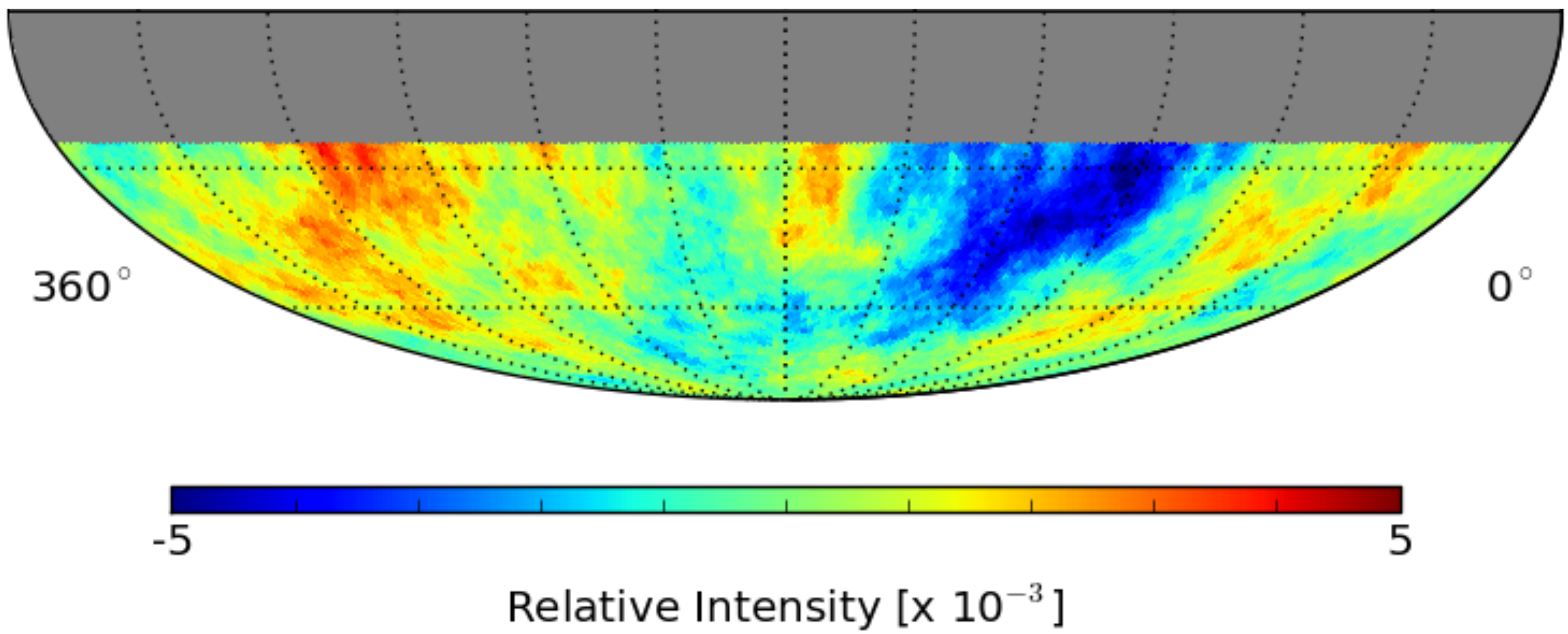


Note: Wide energy distributions – maps are statistically correlated

IceCube Preliminary

Energy Transition in IceCube

4.5 PeV



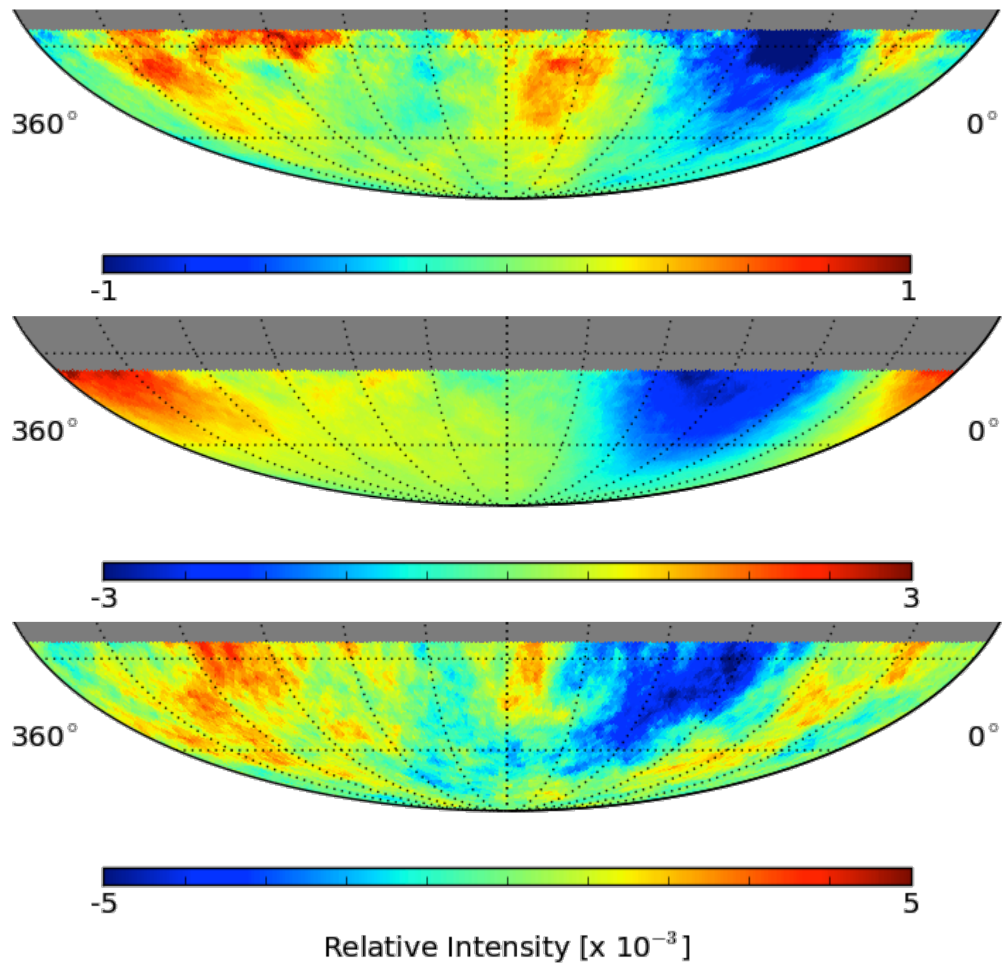
Note: Wide energy distributions – maps are statistically correlated

-- Scale has changed

IceCube Preliminary

Comparing IceCube and IceTop

- IceCube 1.2 PeV
  - -1×10^{-3} to 1×10^{-3}
- IceTop 2 PeV
  - -3×10^{-3} to 3×10^{-3}
- IceCube 4.5 PeV
  - -5×10^{-3} to 5×10^{-3}



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Anisotropy in Theory

- Large-scale anisotropy could be indicative of nearby cosmic ray sources
  - Cosmic rays accelerated at source – e.g. shock of a supernova remnant (SNR)
  - Transport of TeV – PeV cosmic rays in the Galactic magnetic field is diffusive.
  - Flux observed on Earth as a dipole with its maximum towards the source.
  - Observed (large-scale) structure would be the sum of the contributions from a few nearby recent SNRs and the large scale distribution of SNRs in our Galaxy.

Erlykin & Wolfendale, Astropart. Phys. 25 (2006) 183
Blasi & Amato, JCAP 1201 (2012) 11

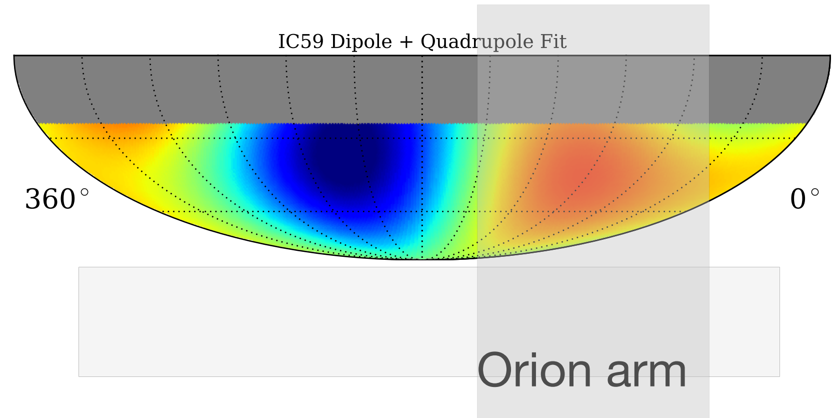
- Small-scale anisotropy could be caused by cosmic ray propagation in turbulent magnetic fields within a few tens of parsecs from Earth.

Giacinti & Sigl, arXiv:1111.2536

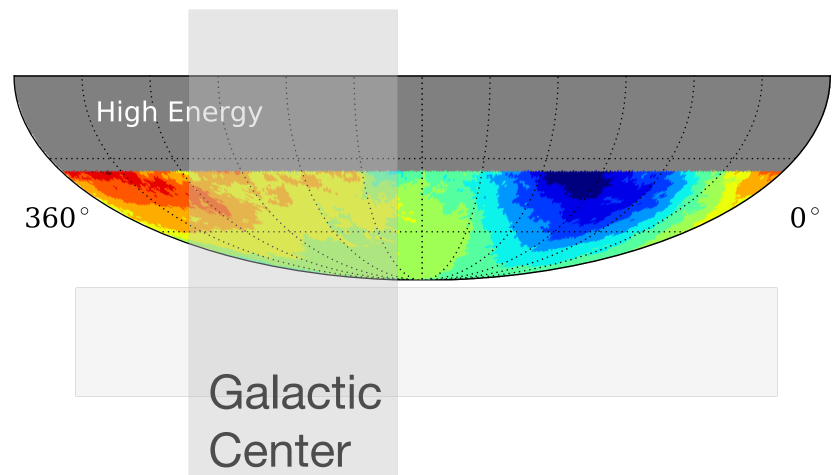
- Both models predict a dependence of the anisotropy on energy…

Nearby Supernova Remnants?

- Simulation of anisotropy amplitude and phase done by Sveshnikova, Strelnikova & Putskin (arXiv:1301.2028), using actual source distributions from radio-, X-ray, and gamma-ray catalogs.



- Models show that the fluctuations in the large-scale cosmic-ray anisotropy are mainly caused by the contributions of the nearest and youngest sources.
  - SNRs with $T < 10^5$ years and distance < 3 kpc are concentrated in the spiral arms.



- At TeV energies, anisotropy dominated by contribution from nearest sources in the Orion arm

- At higher energies Galactic center dominates

Summary

- With over 180 billion cosmic ray events, IceCube can study anisotropies in the cosmic ray arrival direction distribution in the southern hemisphere at less than the part-per-mille level.

- IceCube has found both large and small-scale anisotropies 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 140 TeV.

- In the near future, we hope to use the superior energy and angular resolution of IceTop to learn more about the location of Galactic cosmic ray sources, diffusion, Galactic magnetic fields, and other related topics.