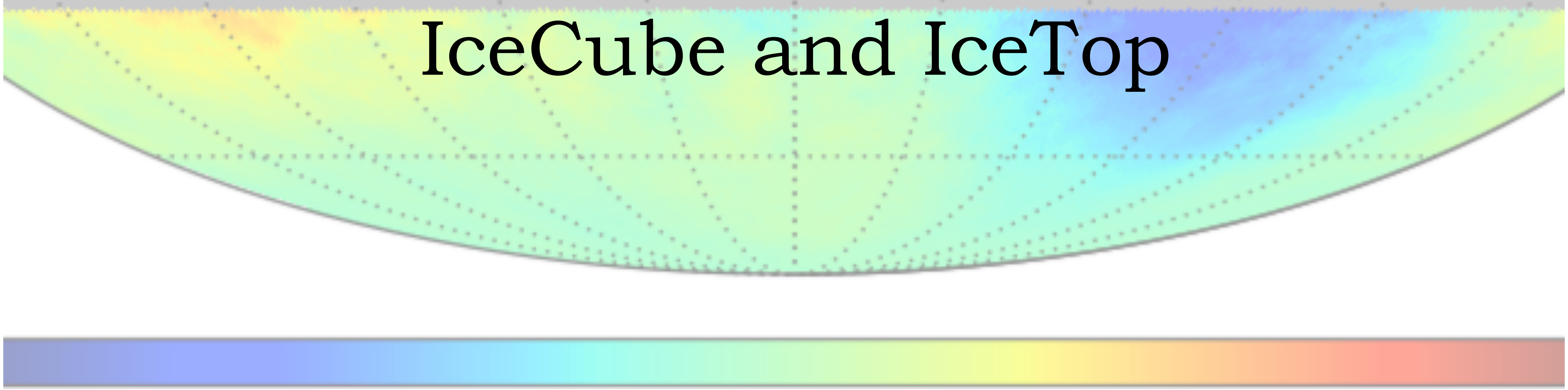
Anisotropy in Cosmic Ray Arrival Directions Using IceCube and IceTop



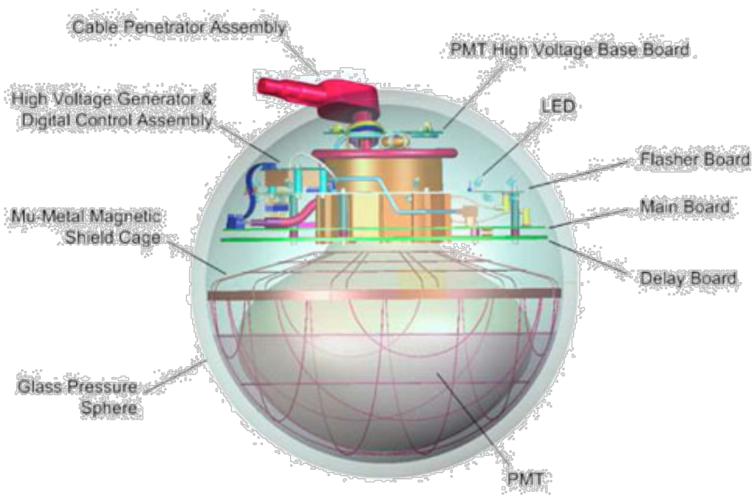
Frank McNally
IPA 2015

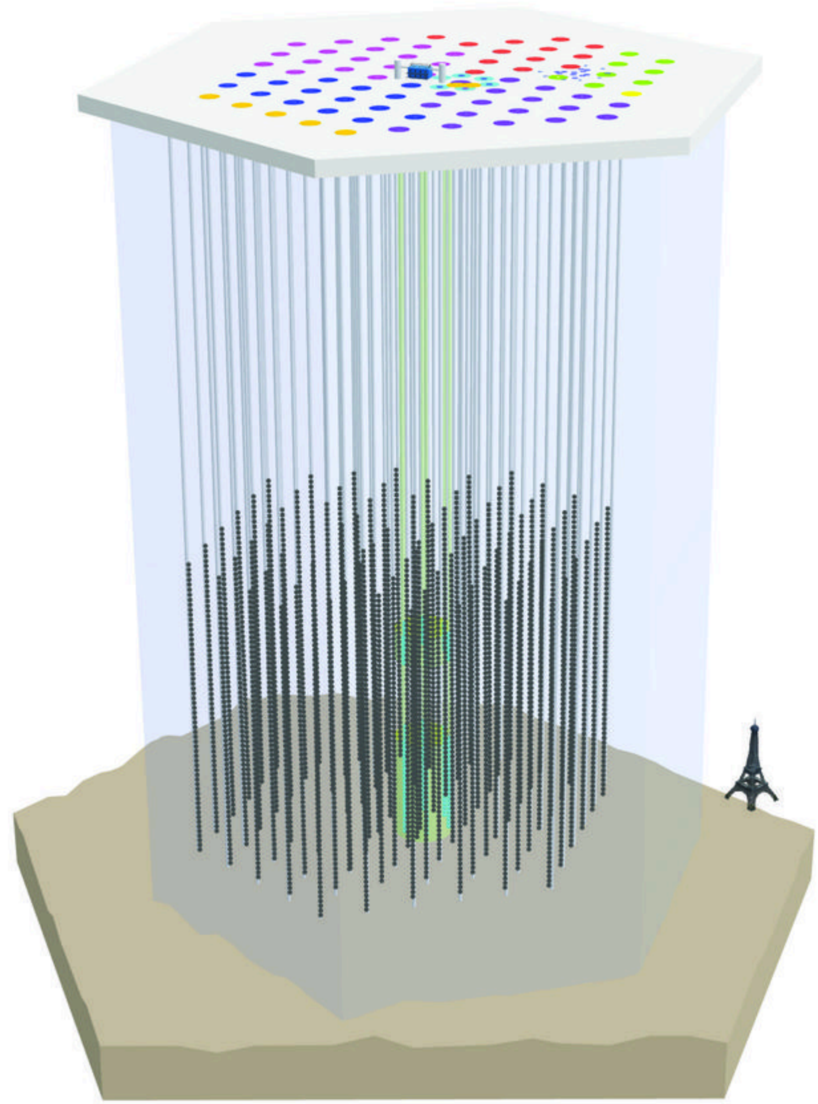
Outline

- Detector Overview
- Large and Small-Scale Structure
- Energy Transition
  - Energy transition in IceCube
  - IceCube / IceTop overlap
- Other Studies
  - Solar dipole
  - Time-dependence
- Theory
- Summary

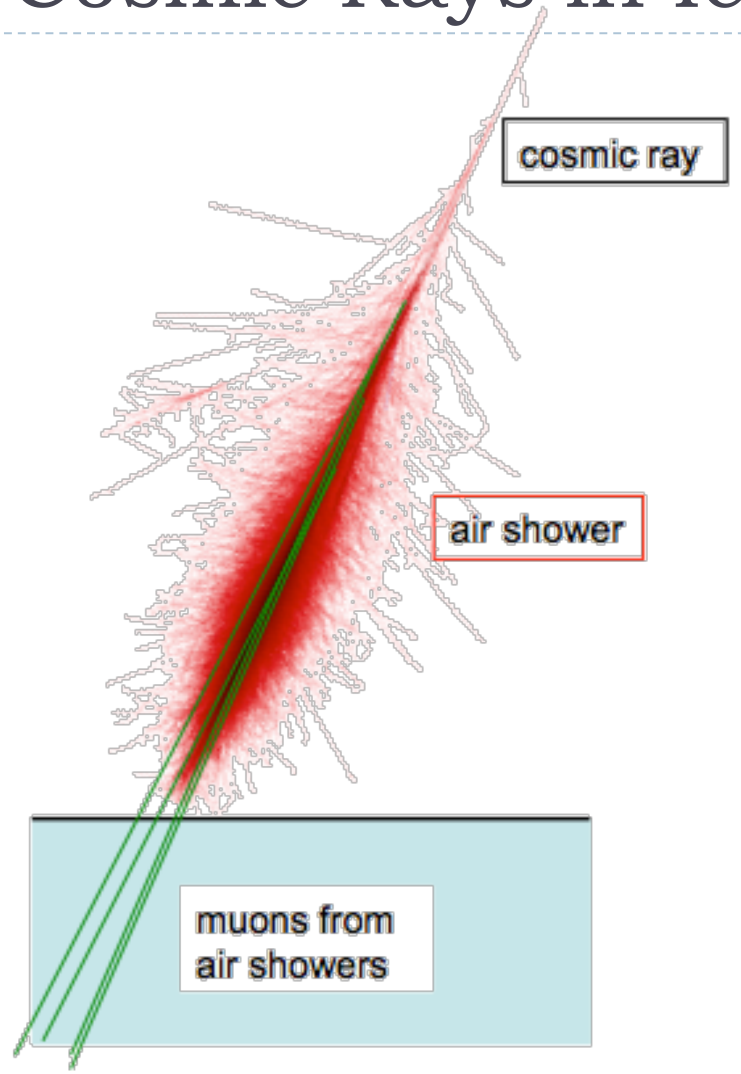
IceCube

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





Cosmic Rays in IceCube



- Designed to detect up-going neutrinos
- Sensitive to down-going muons produced by cosmic ray showers
- Cosmic-ray primaries up to knee
- Rate: ~ 2 kHz (172 million events/day!)
- 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
- 81 stations
  - Two tanks per station
  - Two DOMs per tank
- Close to shower maximum

Cosmic Rays in IceTop

- Sensitive to electromagnetic component of down-going showers
- Cosmic ray primary energies knee to ankle
- Rate: ~20 Hz
- Retains more information per event
  - potentially better energy and angular resolution

Outline

- Detector Overview
- Large and Small-Scale Structure
- Energy Transition
  - Energy transition in IceCube
  - IceCube / IceTop overlap
- Other Studies
  - Solar dipole
  - Time-dependence
- Theory
- Summary

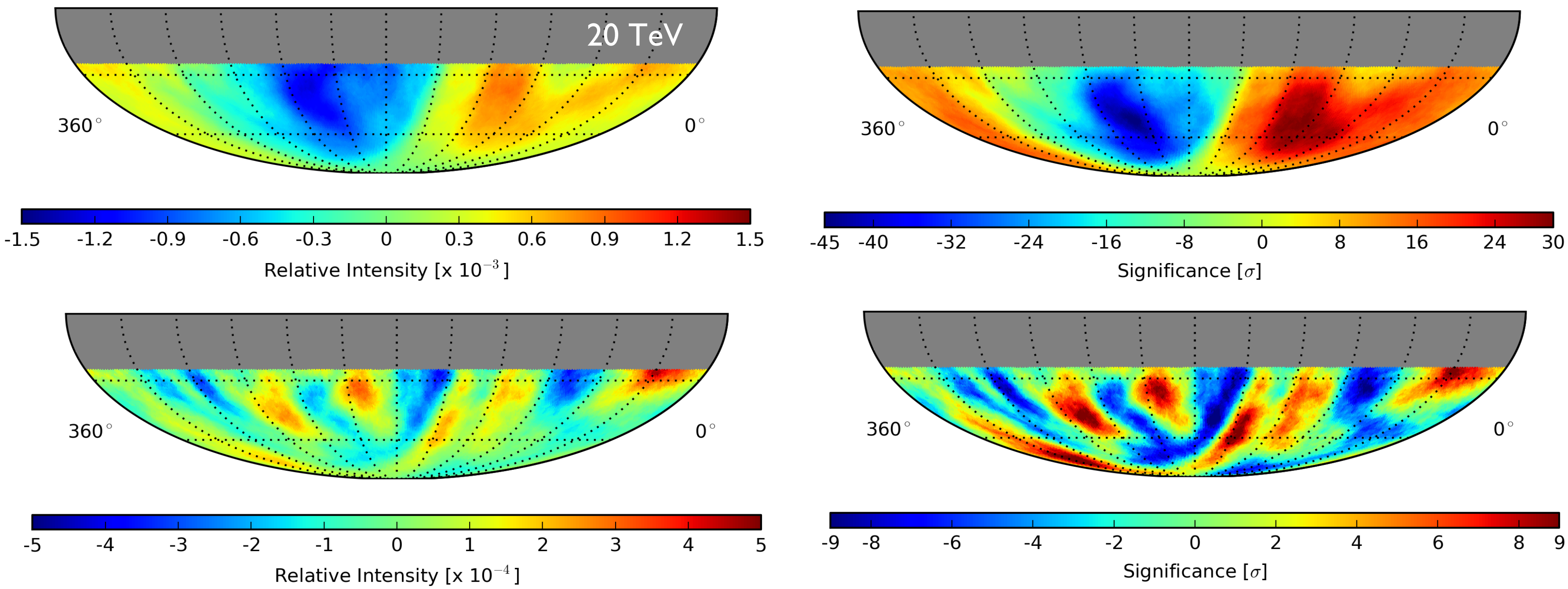
Dataset Size

Configuration	Number of Events
IC59	3.579×10^{10}
IC79	4.131×10^{10}
IC86	5.906×10^{10}
IC86-II	5.630×10^{10}
IC86-III	6.166×10^{10}
Total	2.541×10^{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}
IT81-III	3.096×10^{7}
Total	1.718×10^{8}

Anisotropy in IceCube

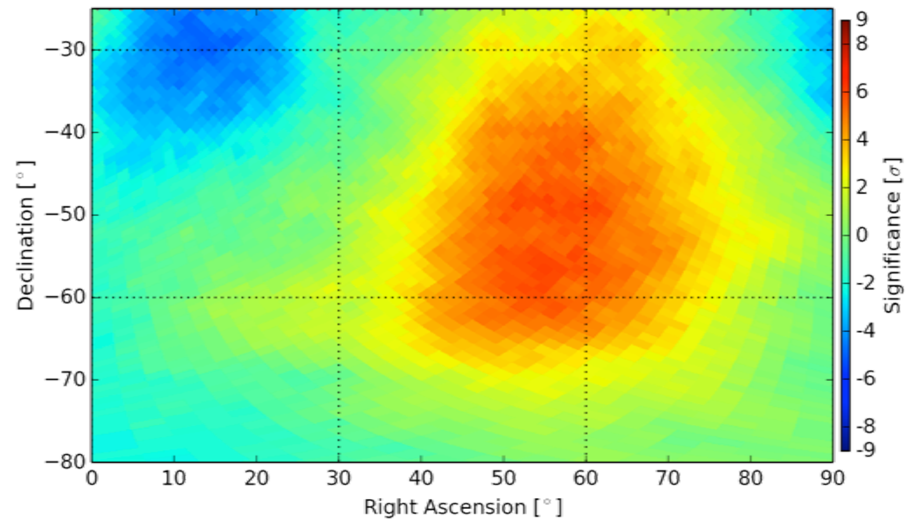
5 years of data (IC59 – IC86-III) 2.5×10^{11} events

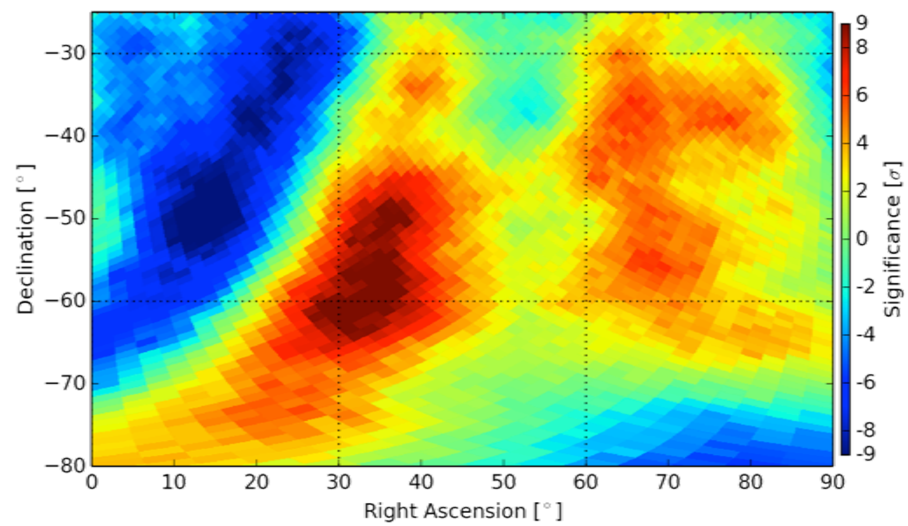


- Relative intensity (*left*) and pre-trial statistical significance (*right*)
- Before (*top*) and after (*bottom*) dipole- and quadrupole-subtraction
- Angular smoothing radius of 5°

Advantage of New Dataset

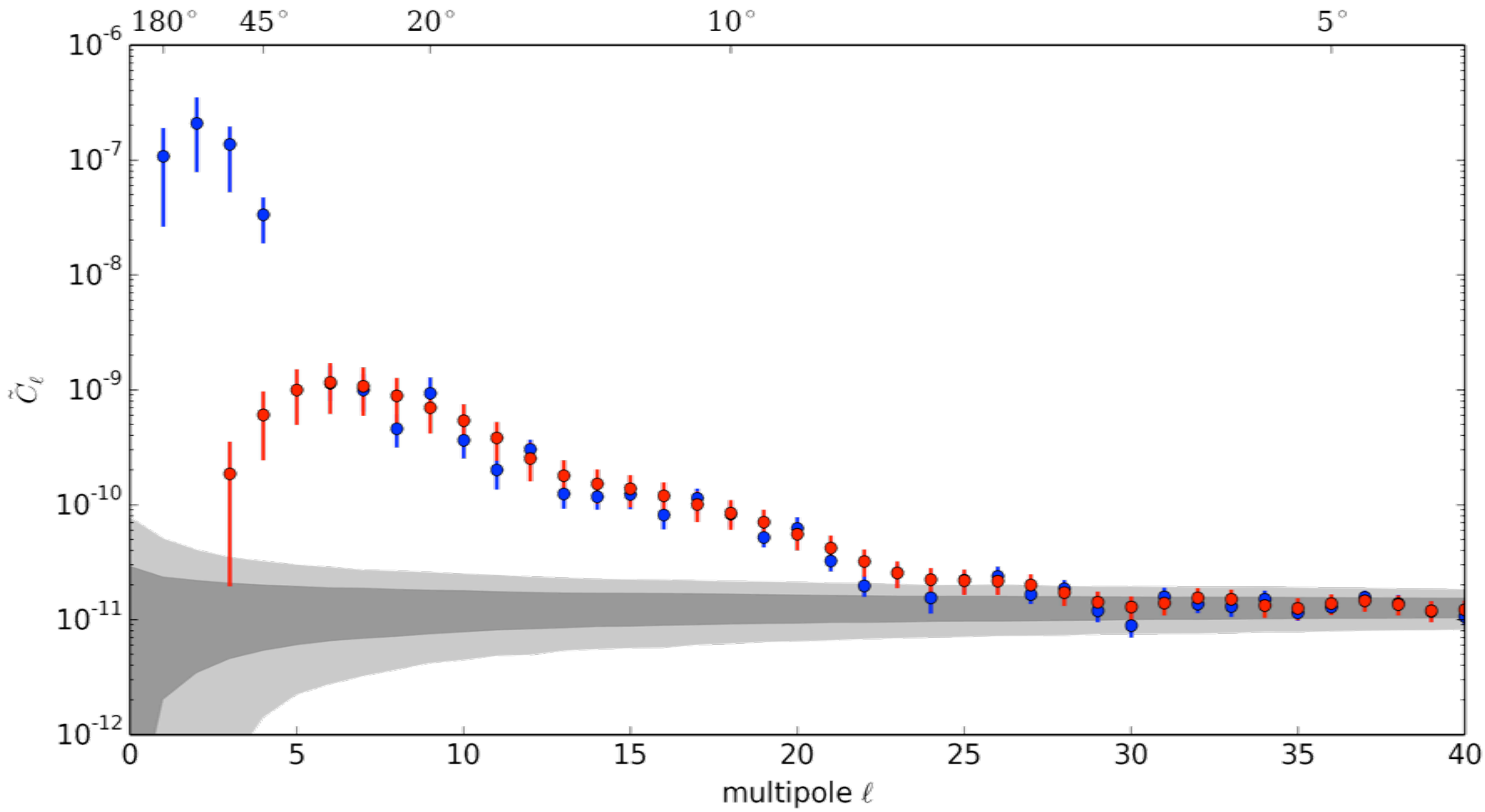
- Finer structure visible at higher significance
- Example:
  - IC59 (top) with 20° smoothing radius vs.
  - IC59—IC86-III (bottom) with 5° smoothing radius
- Note: structure in new map visible in IC59 map at lower significance





IceCube Preliminary

Power Spectrum

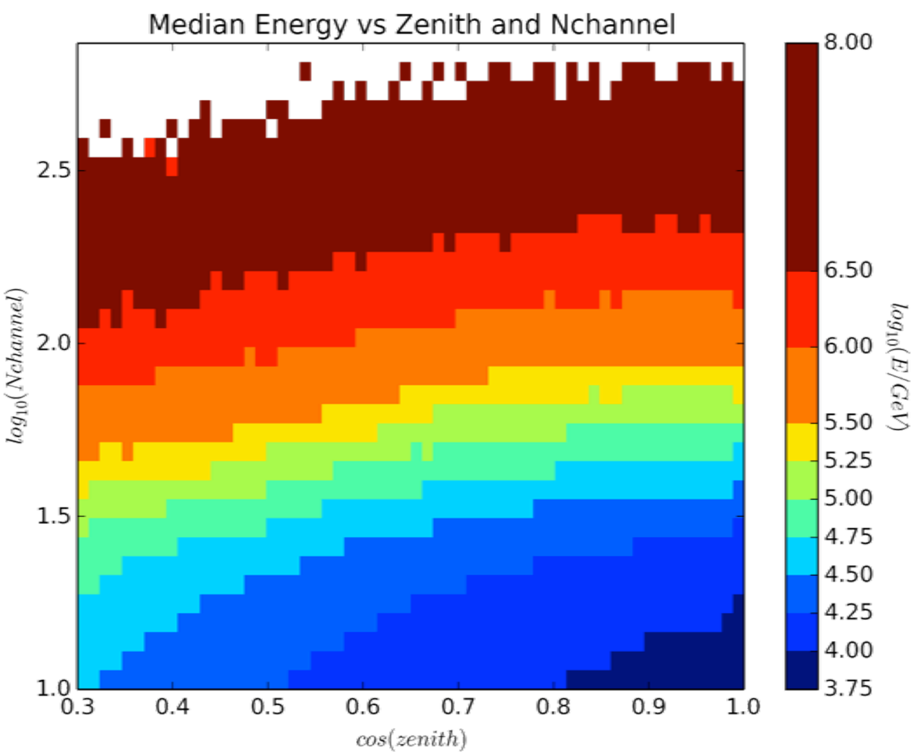


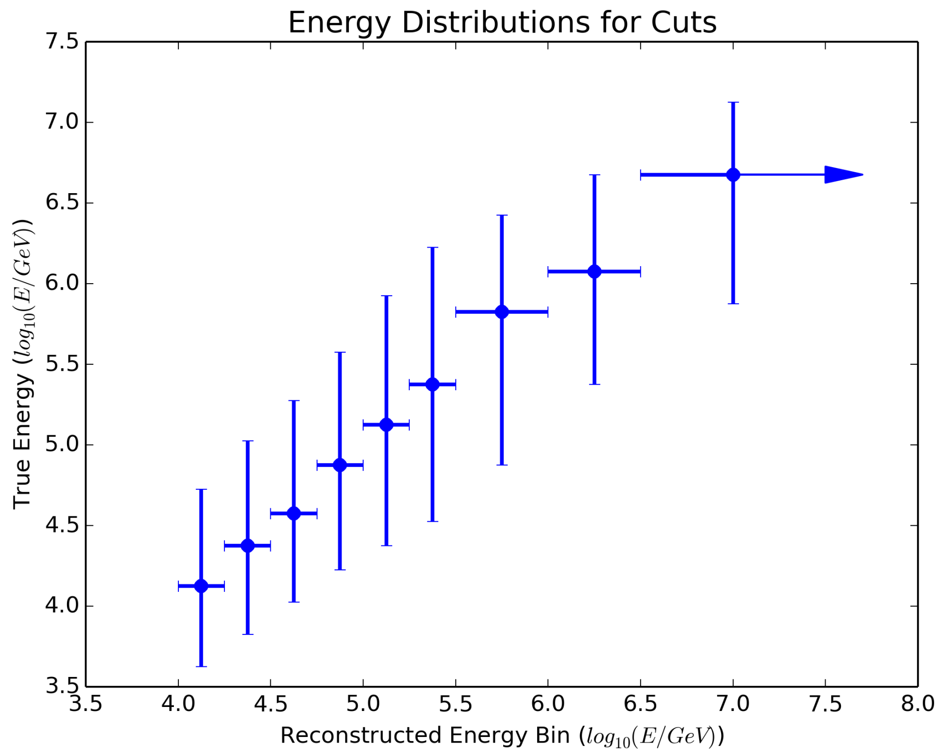
- Power spectrum for 5 years of IceCube data (*blue*)
- With best-fit dipole and quadrupole moments subtracted (*red*).
- Dark/light-gray bands represent isotropic flux at the 68% and 90% C.Ls.

Outline

- Detector Overview
- Large and Small-Scale Structure
- Energy Transition
  - Energy transition in IceCube
  - IceCube / IceTop overlap
- Other Studies
  - Solar dipole
  - Time-dependence
- Theory
- Summary

Energy Separation

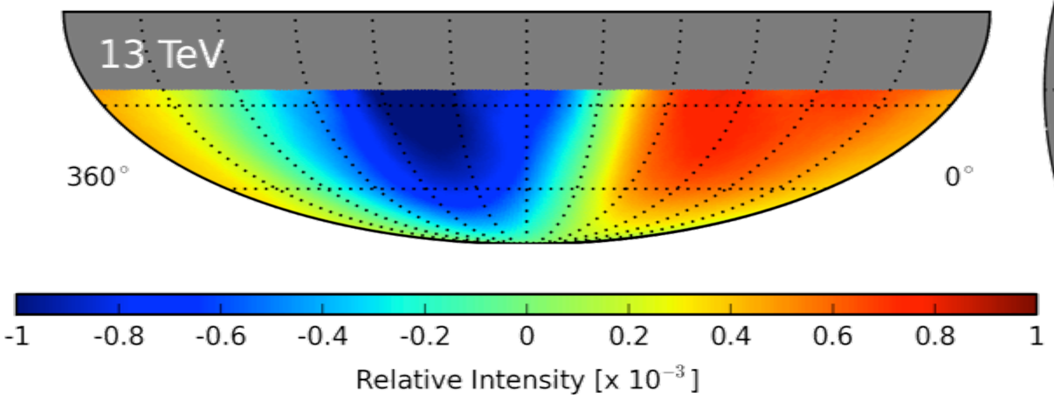


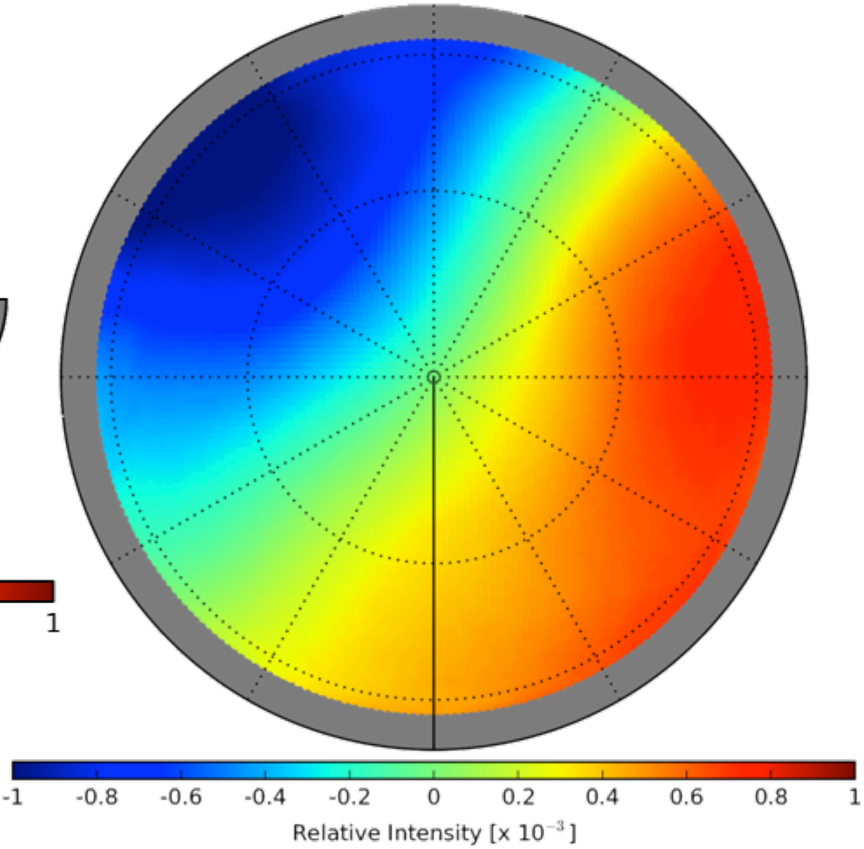


- Bin simulation in $N_{channel}$ and reconstructed zenith
- Split into energy bands based on median true energy of cosmic-ray primaries
- Result: bins that overlap but rise in median energy

IceCube Preliminary

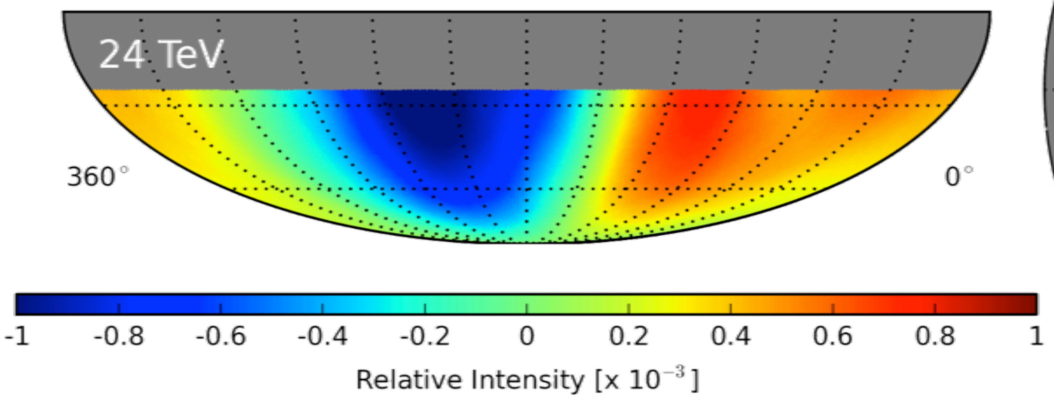
Energy Dependence

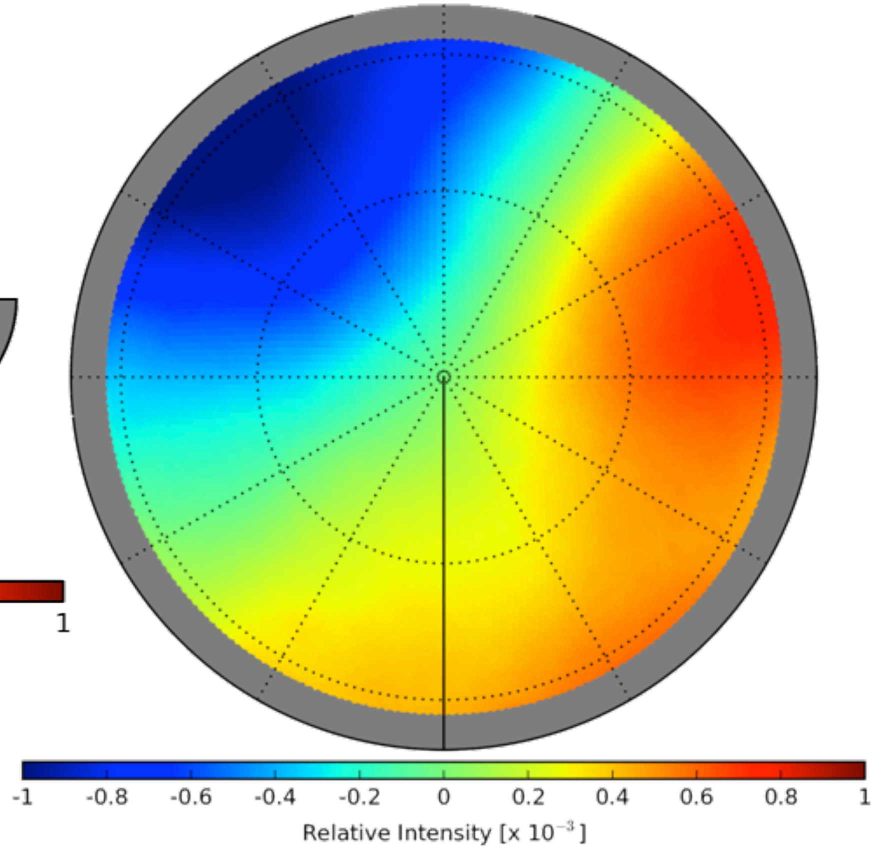




IceCube Preliminary

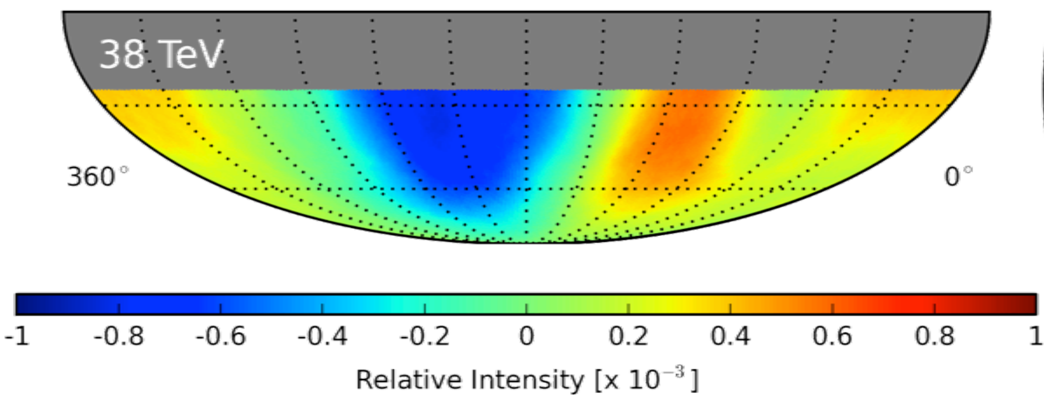
Energy Dependence

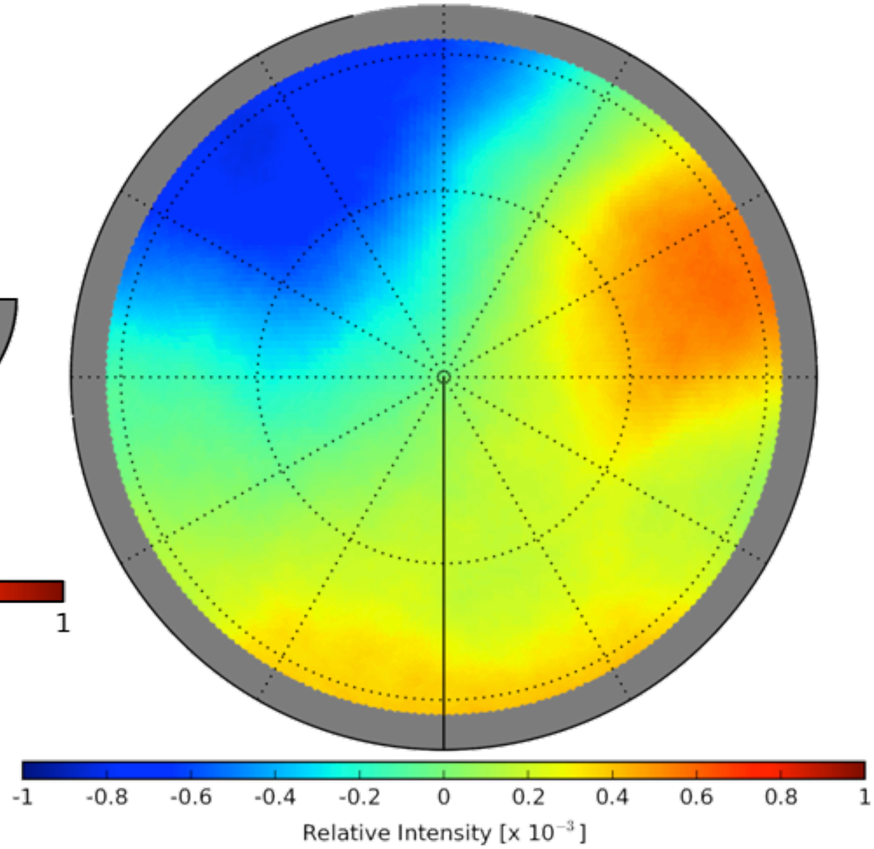




IceCube Preliminary

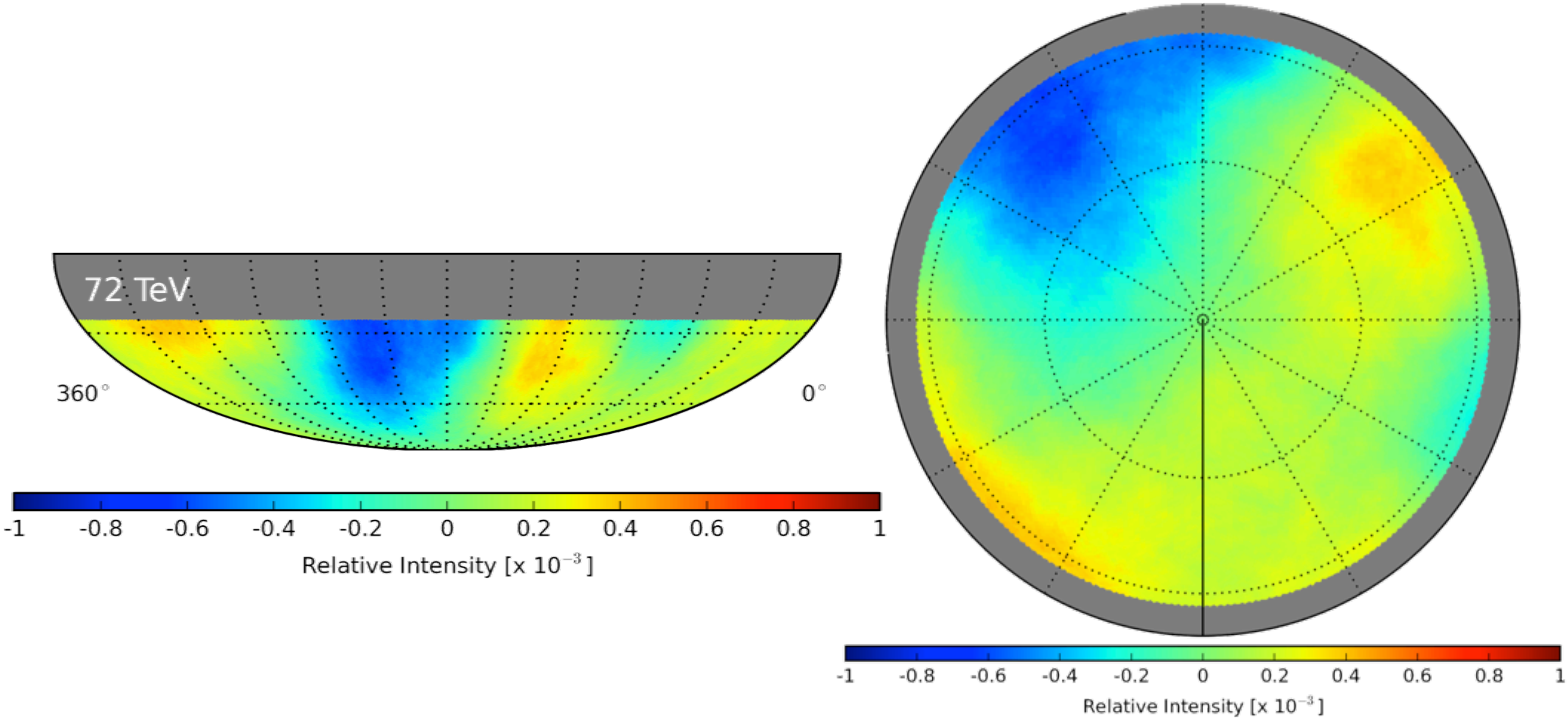
Energy Dependence





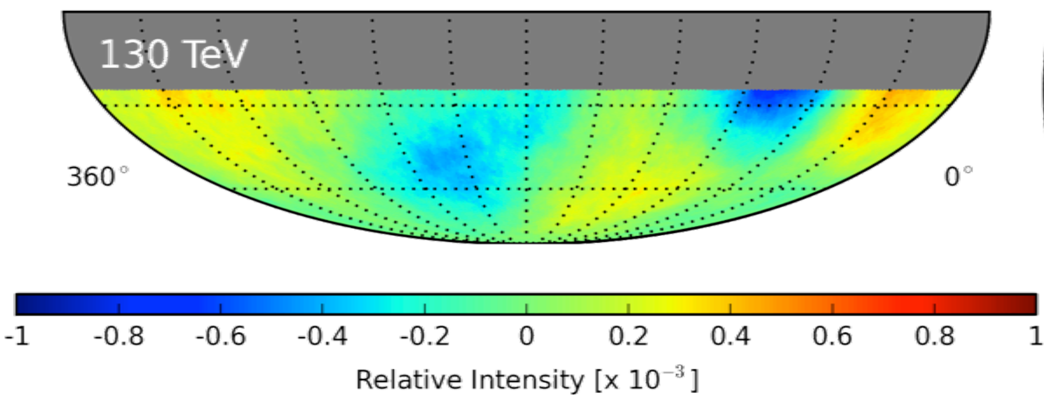
IceCube Preliminary

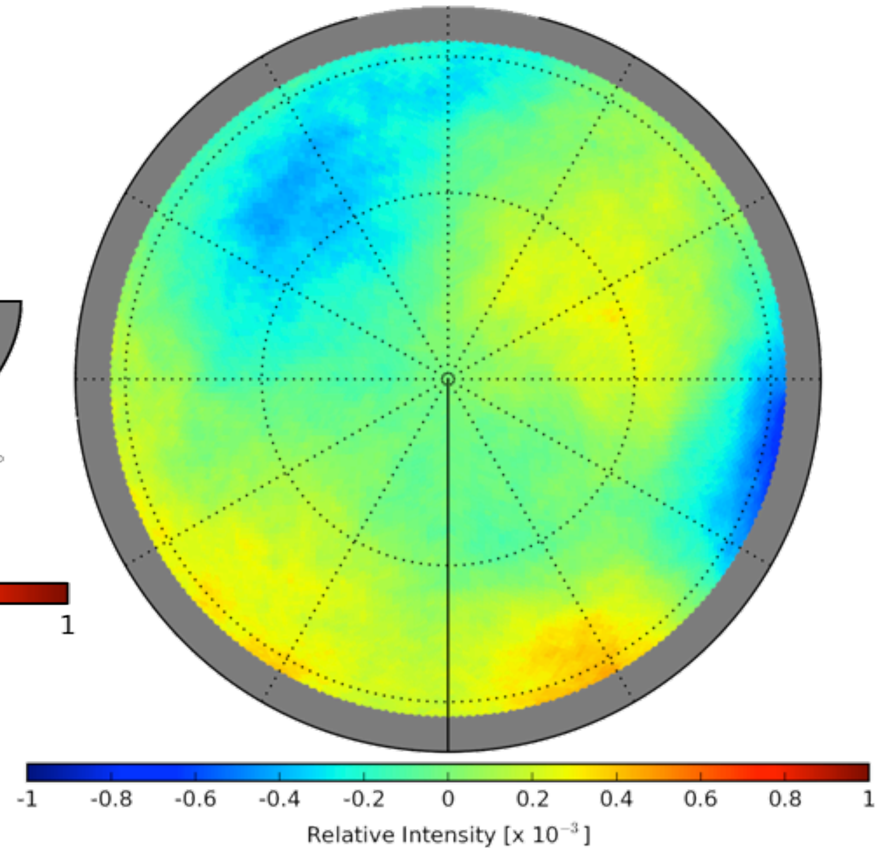
Energy Dependence



IceCube Preliminary

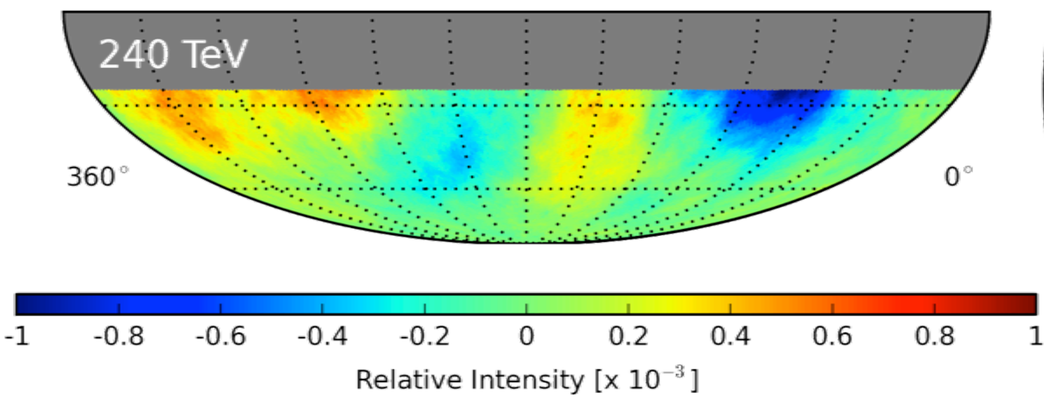
Energy Dependence

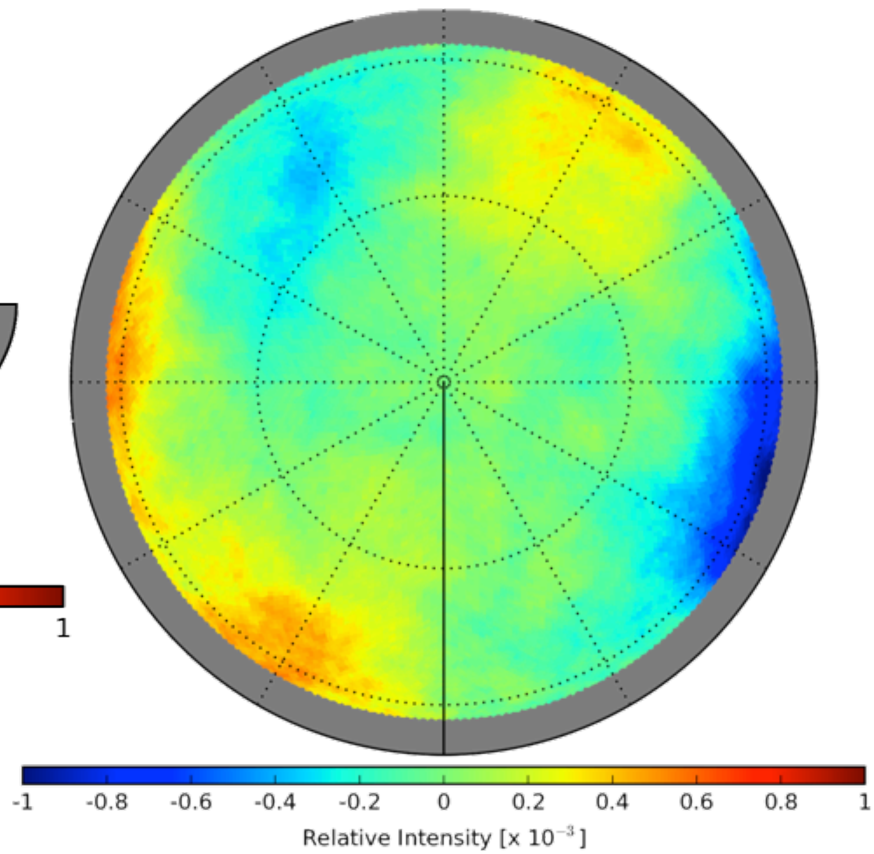




IceCube Preliminary

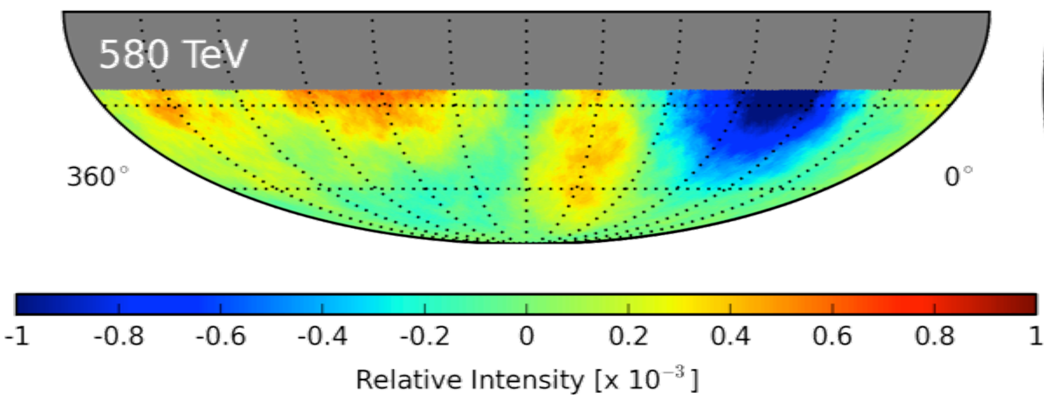
Energy Dependence

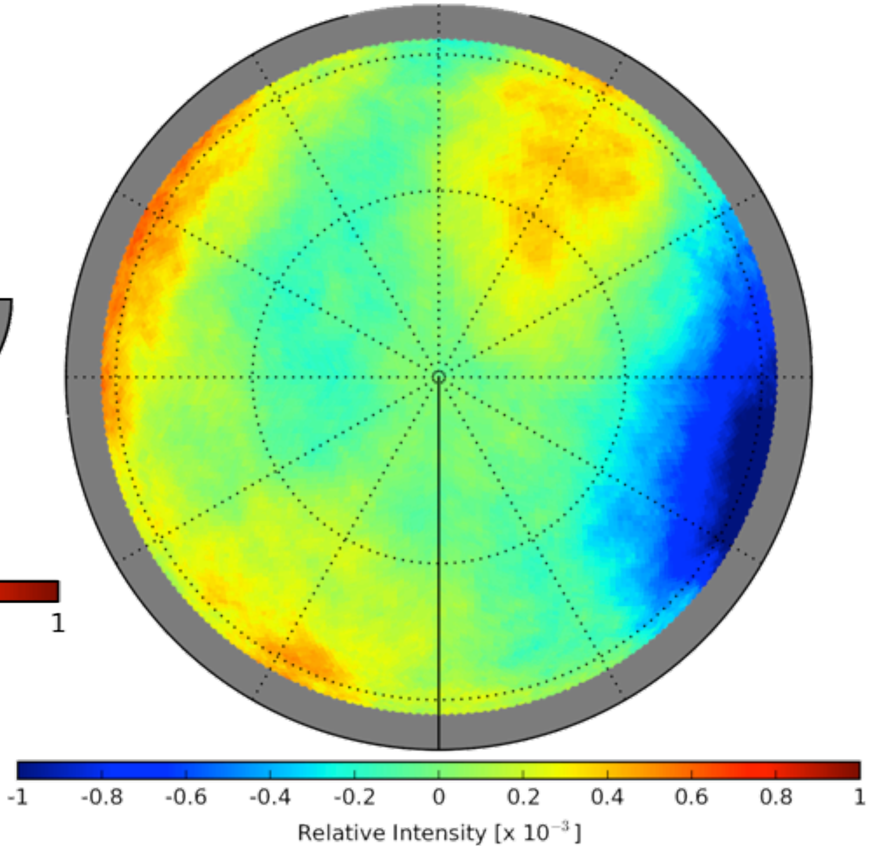




IceCube Preliminary

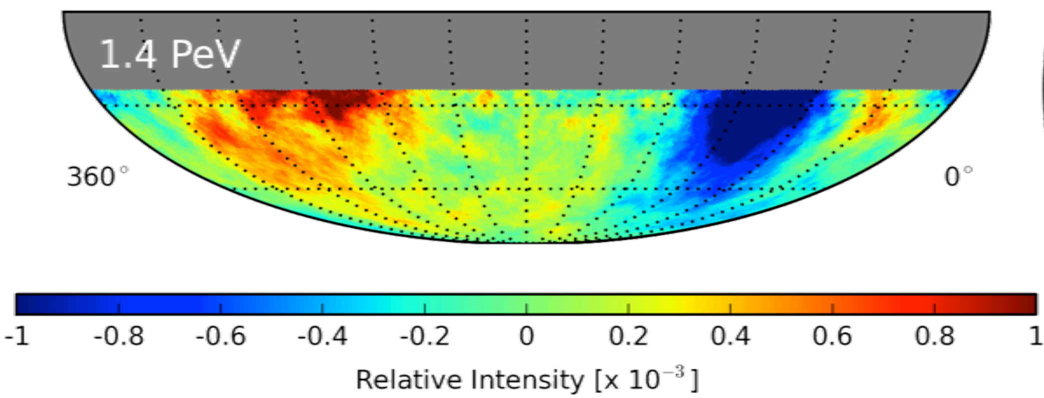
Energy Dependence

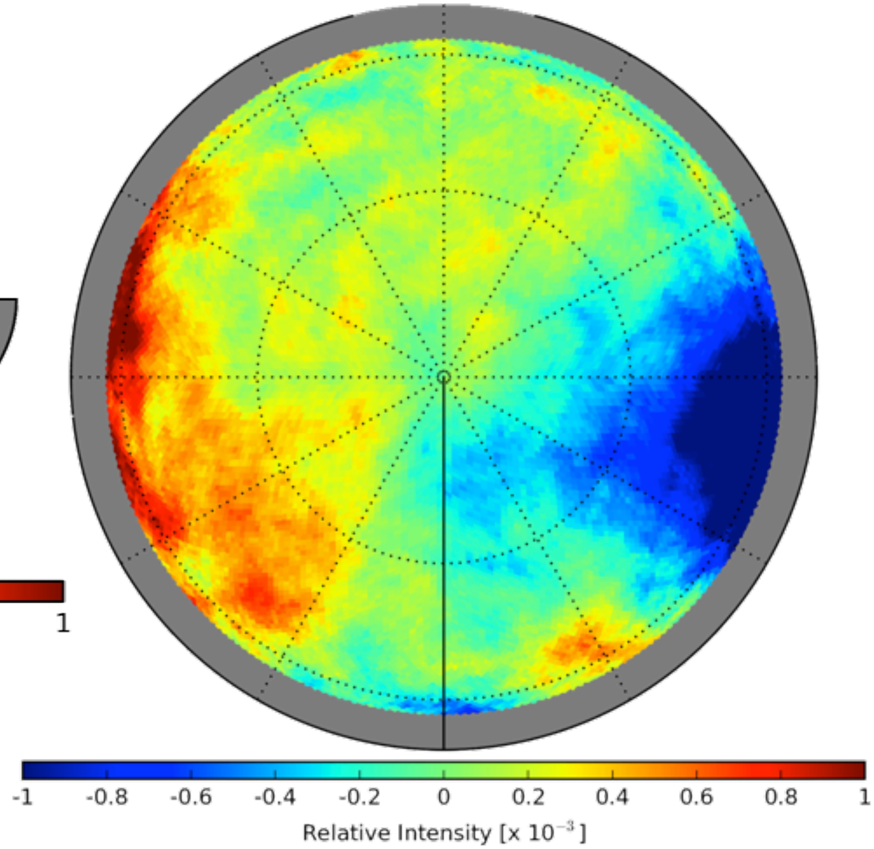




IceCube Preliminary

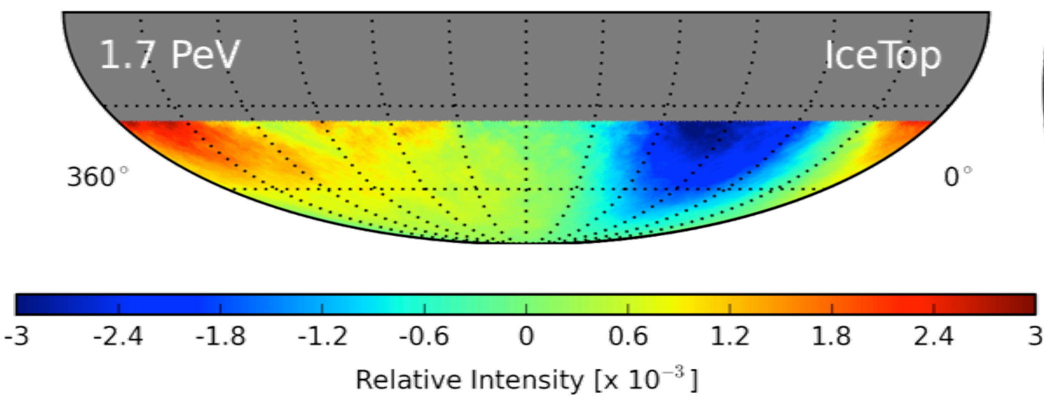
Energy Dependence

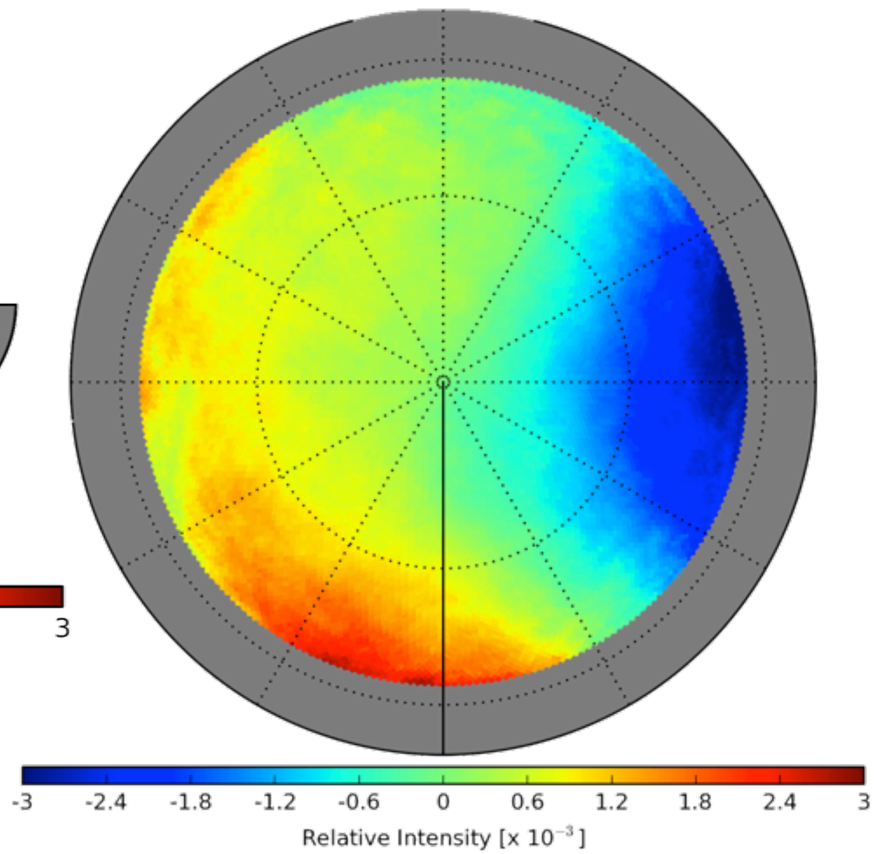




IceCube Preliminary

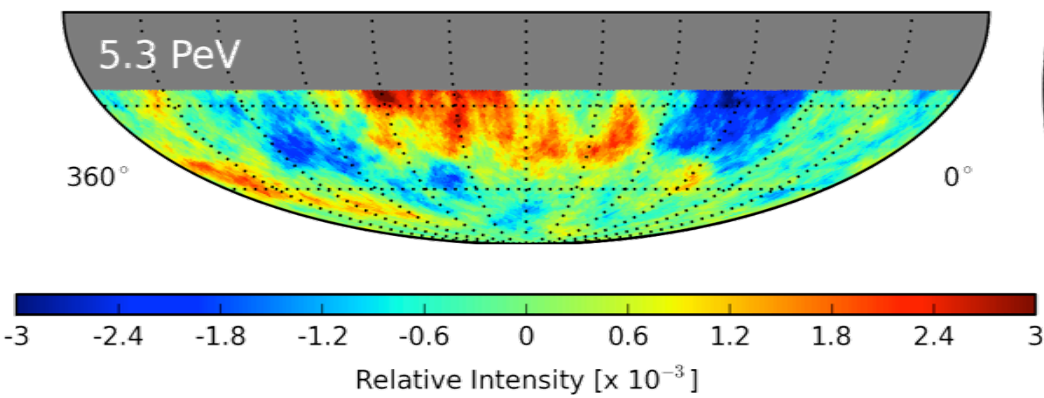
Energy Dependence

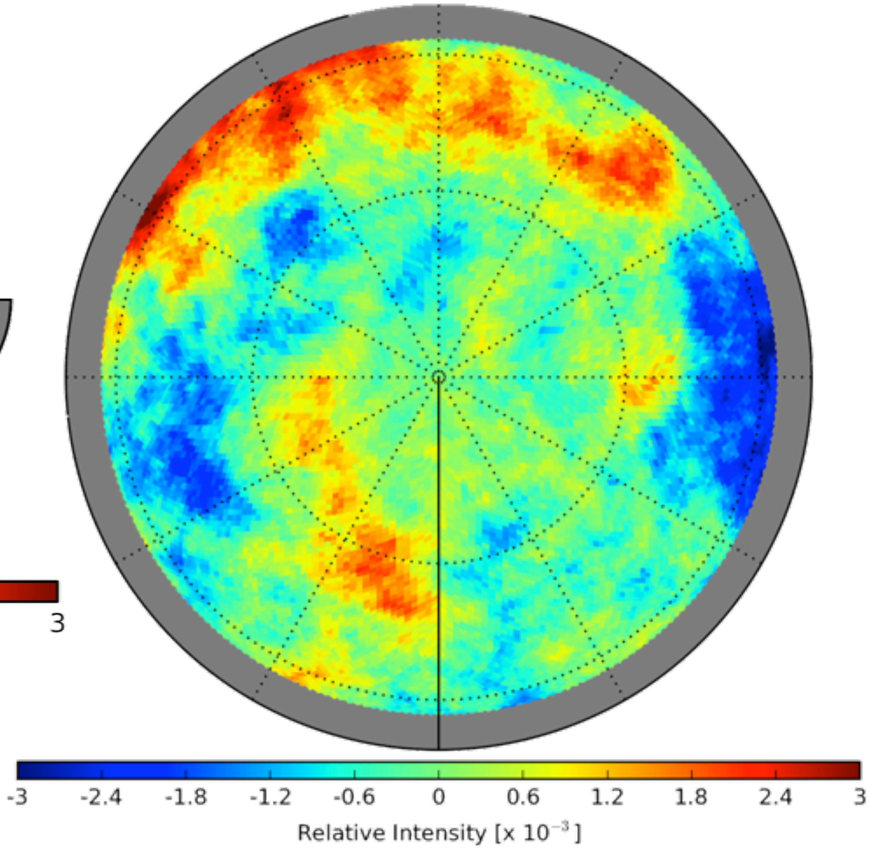




IceCube Preliminary

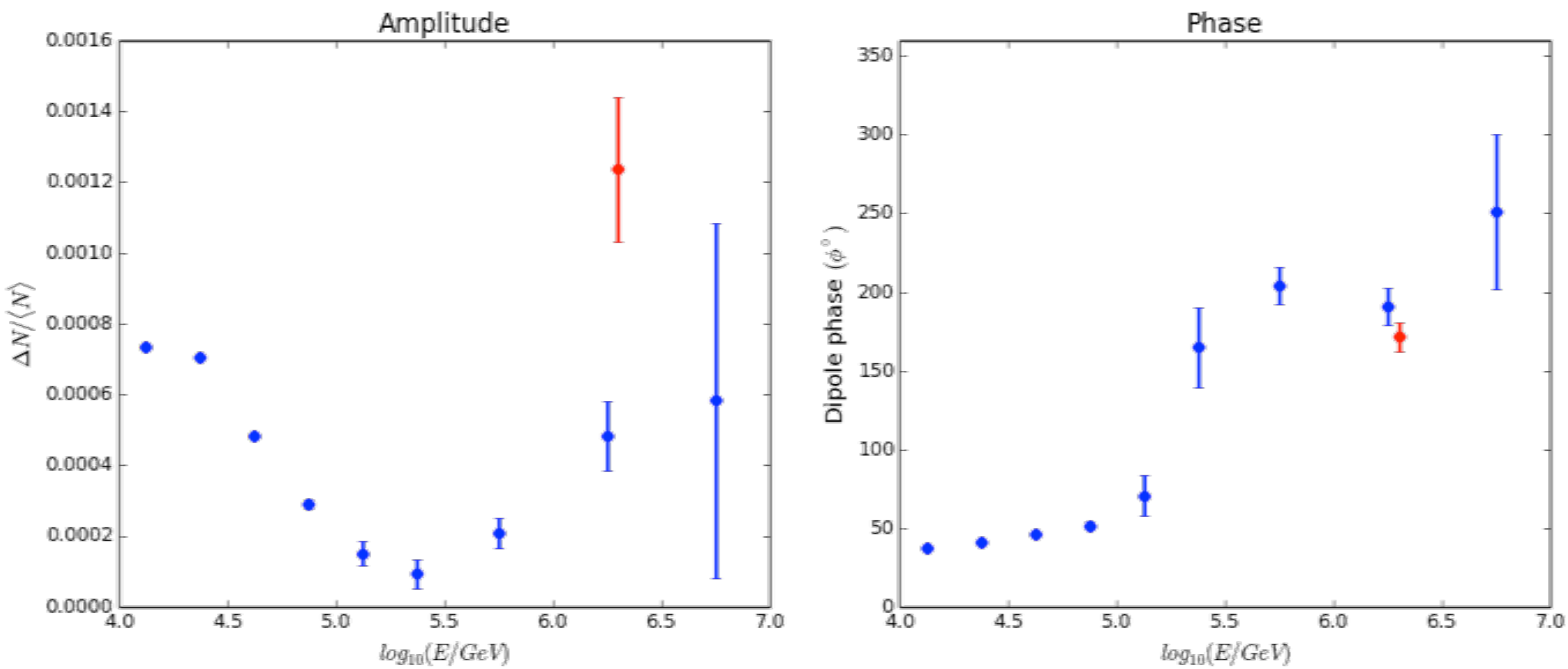
Energy Dependence





IceCube Preliminary

Dipole Amplitude and Phase



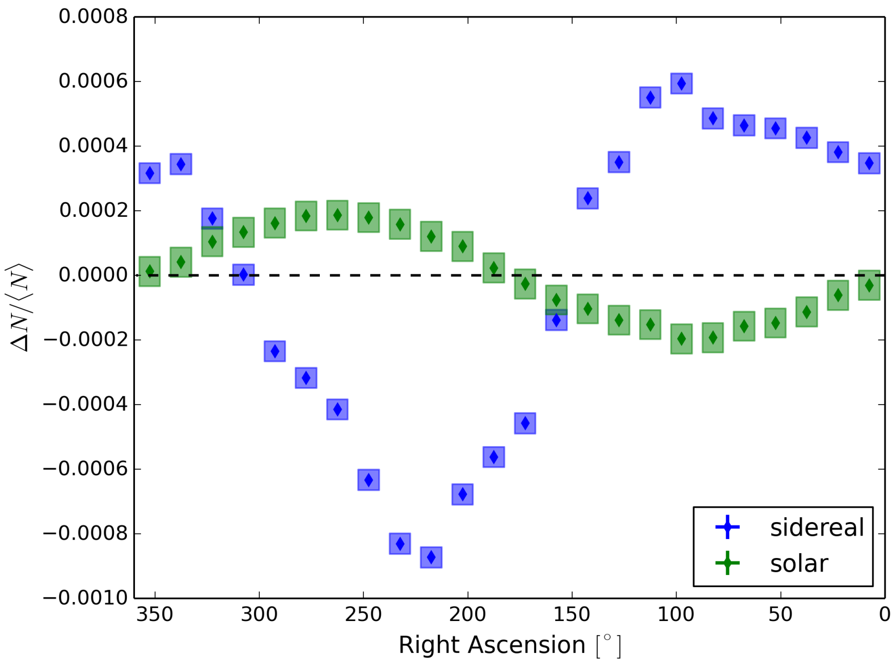
- Harmonic analysis of 1-D projection in right ascension
- Amplitude and phase for dipole component shown
- IceCube (*blue*) and IceTop (*red*) data

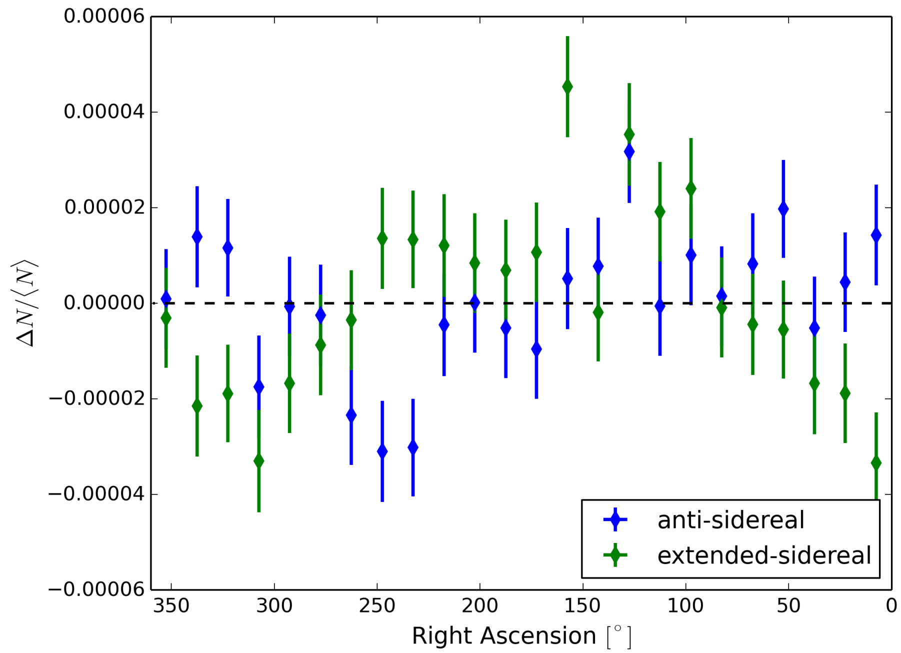
IceCube Preliminary

Outline

- Detector Overview
- Large and Small-Scale Structure
- Energy Transition
  - Energy transition in IceCube
  - IceCube / IceTop overlap
- Other Studies
  - Solar dipole
  - Time-dependence
- Theory
- Summary

Solar Dipole



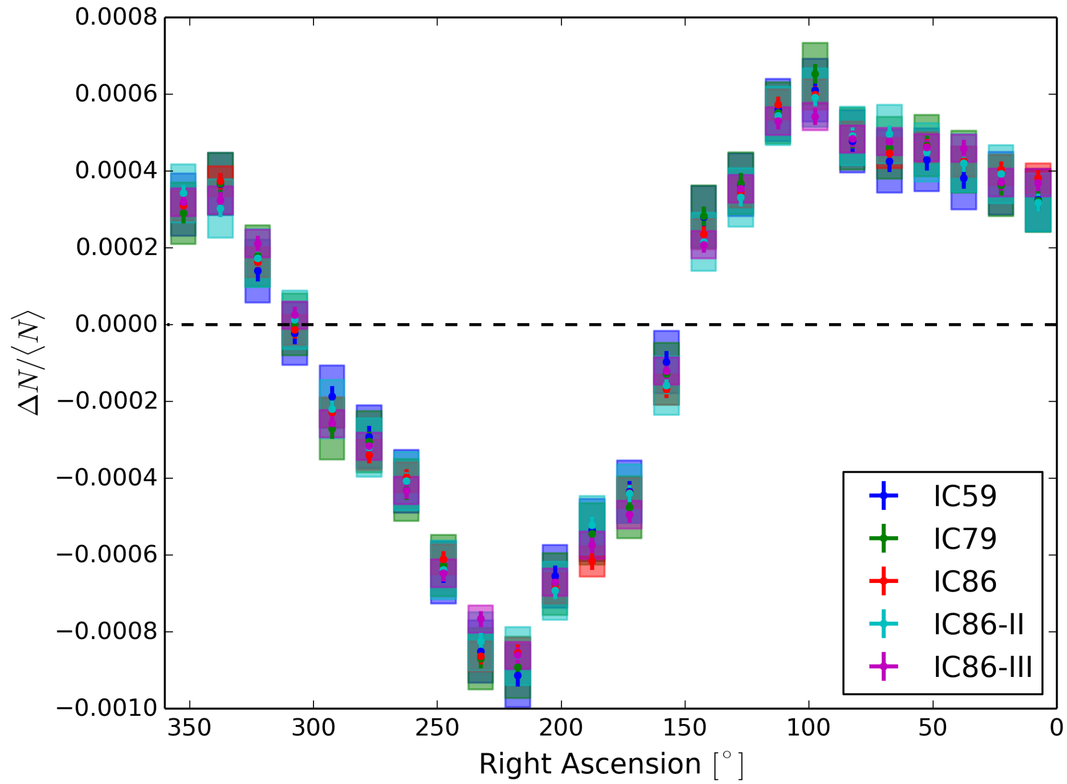


- One-dimensional projection of relative intensity in right ascension
- Sidereal projection not well fit by dipole (or any low-multipole fit)
- Predicted dipole visible in solar time (*left*)
- Systematic errors estimated from the anti- and extended-sidereal frames (*right*)

 IceCube Preliminary

Time Stability

- Qualitative:
  - 1D right ascension for each year of data
  - Systematic error bars calculated from anti-sidereal frame



- Quantitative:
  - Calculate chi-squared by comparing each year to the collected sample

Config	Counts	χ^2	Ndof	p-value
IC59	3.58×10^{10}	20.52	23	0.61
IC79	4.13×10^{10}	16.07	23	0.85
IC86	5.91×10^{10}	19.11	23	0.69
IC86-II	5.63×10^{10}	13.88	23	0.93
IC86-III	6.21×10^{10}	27.59	23	0.23

IceCube Preliminary

Outline

- Detector Overview
- Large and Small-Scale Structure
- Energy Transition
  - Energy transition in IceCube
  - IceCube / IceTop overlap
- Other Studies
  - Solar dipole
  - Time-dependence
- Theory
- Summary

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(s).

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

  - But – the dipole direction does not coincide with direction of sources

    Mertsch & Funk, Phys. Rev. Lett. 114 (2015) 021101

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

  Giacinti & Sigl, PhysRevLett. 109, 071101 (2012)
  Ahlers, PhysRevLett. 112, 021101 (2014)

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

Summary

- With over 250 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 100 TeV.
- 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.

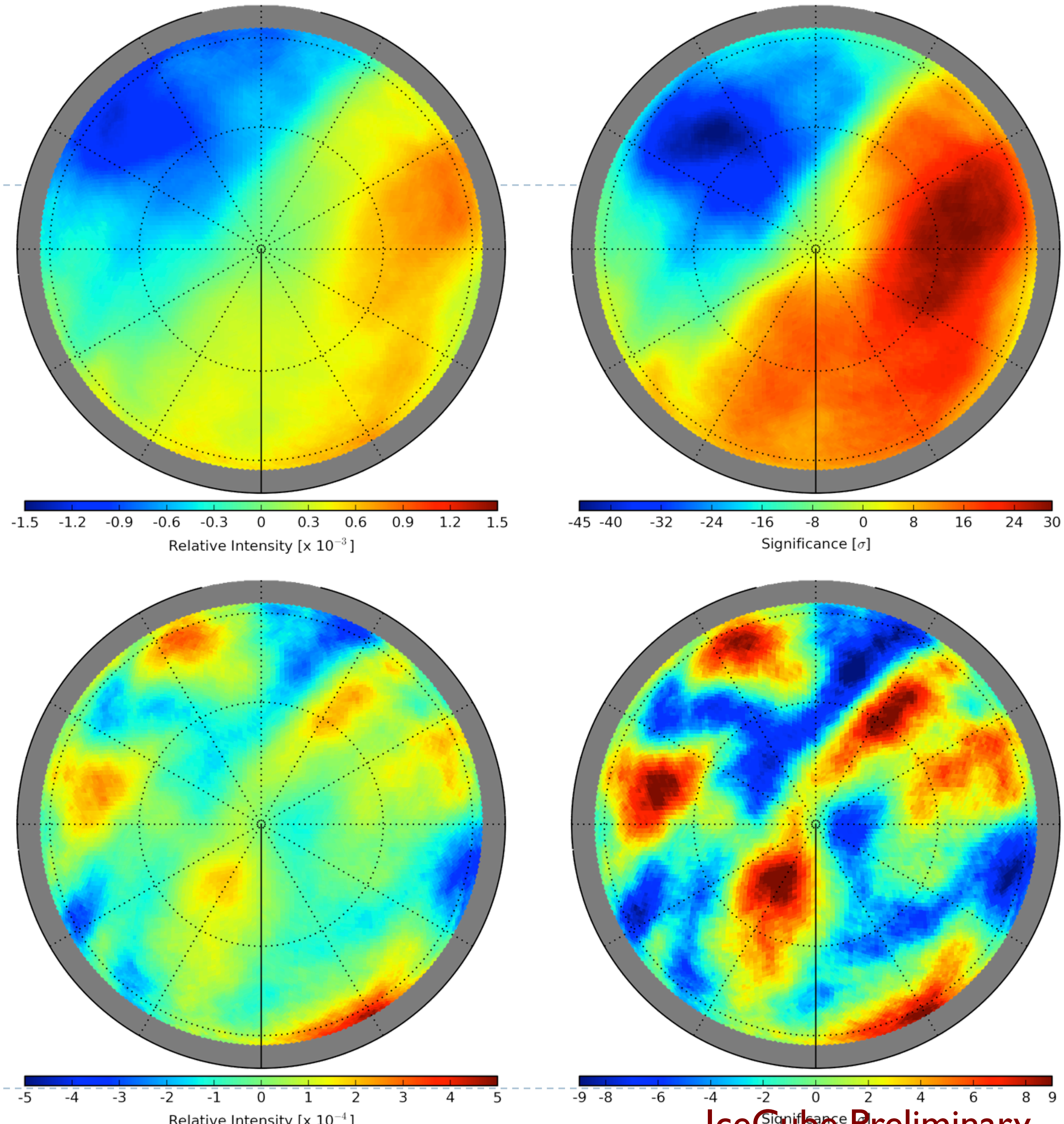
Table of Contents

- Detector Overview
- Large and Small-Scale Structure
- Energy Transition
  - Energy transition in IceCube
  - IceCube / IceTop overlap
- Other Studies
  - Solar dipole
  - Time-dependence
- Theory
- Summary

Backup Slides

Polar Maps

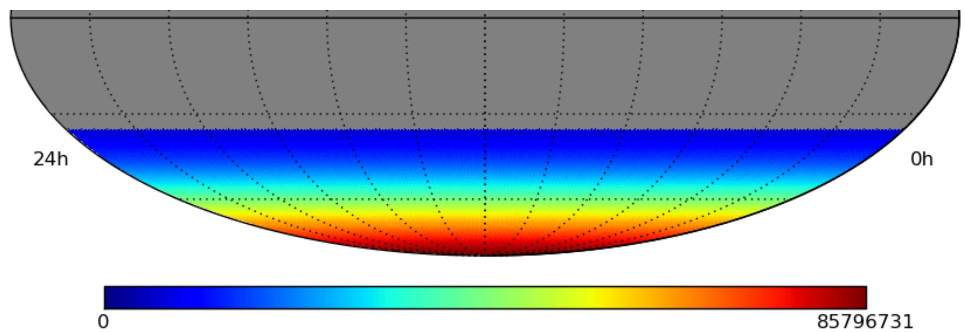
- Relative intensity (*left*) and significance (*right*) for large (*top*) and small-scale (*bottom*) structure



Looking at Anisotropy – Producing Maps

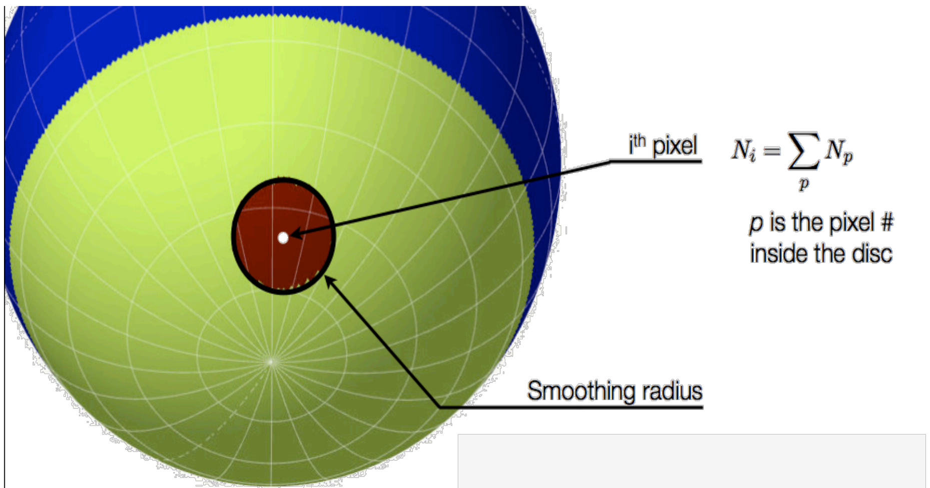
- Store local arrival coordinates: θ ,ϕ, t
- Create 20 fake events by choosing random times within a given time window: Δ t
- Convert to equatorial coordinates: α,
- Store in background map with $^{1}/_{20}$ weight
- Δ t determines size of visible structures
  - Δ t = 4h → 15° x 4 → structures larger than 60° cannot be seen
  - IceTop capable of 24h time scrambling

IT73 Data



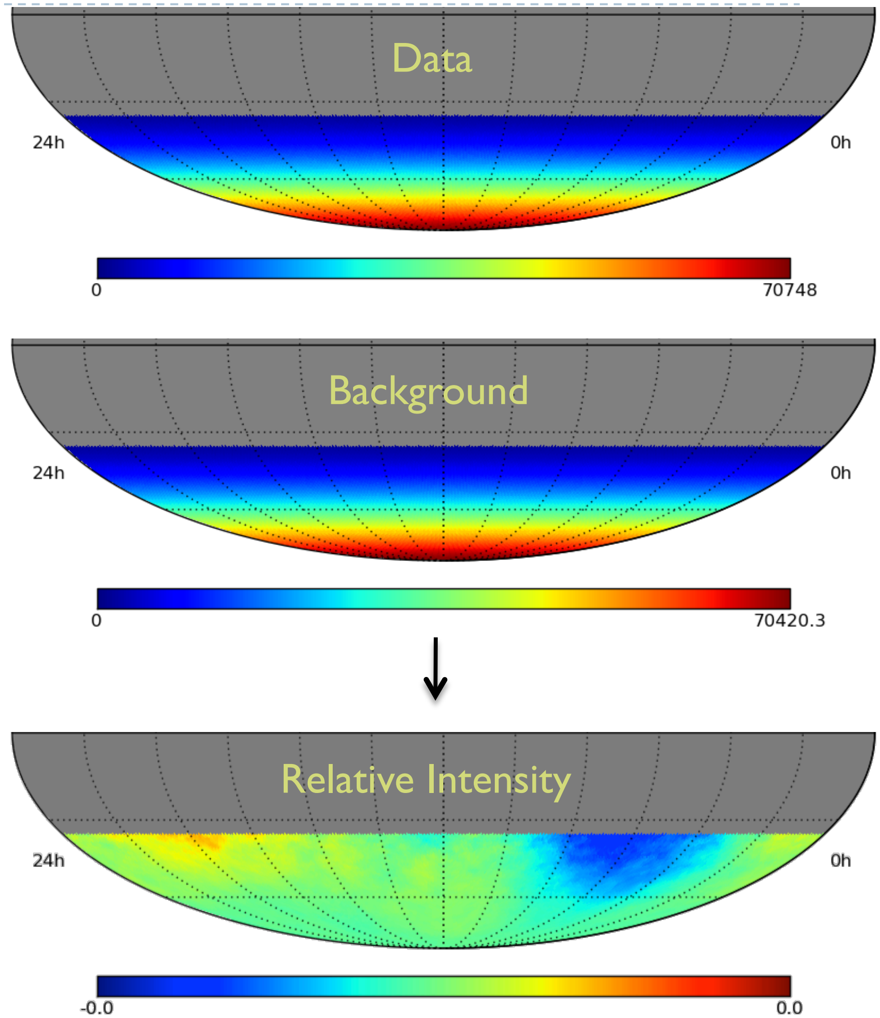
Looking for Signal

- Build background map out of data
- Apply smoothing



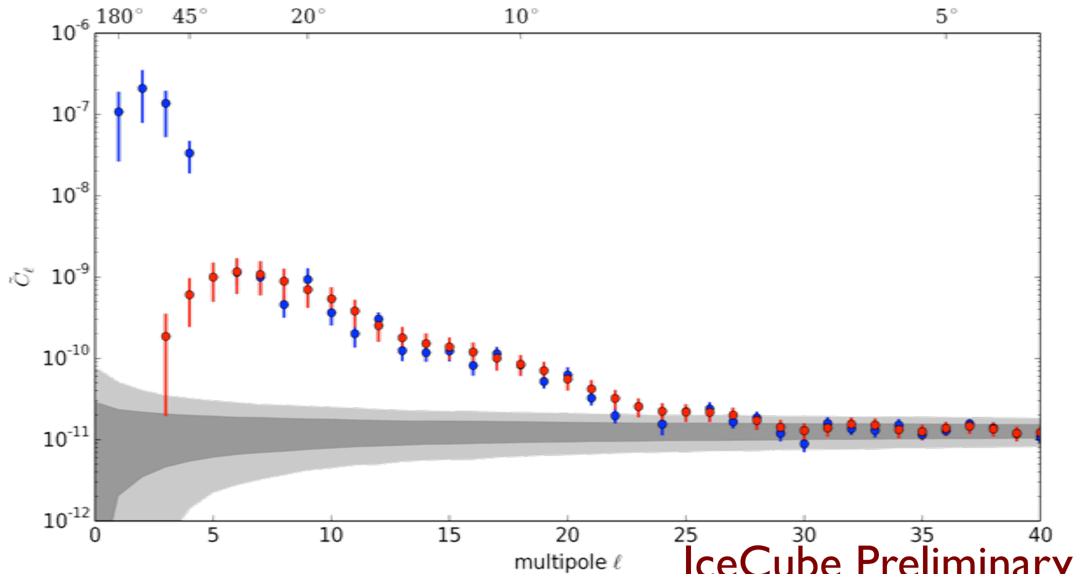
- Relative Intensity:

$$\delta I_i = \frac{\Delta N_i}{\langle N \rangle_i} = \frac{N_i - \langle N \rangle_i}{\langle N \rangle_i}$$

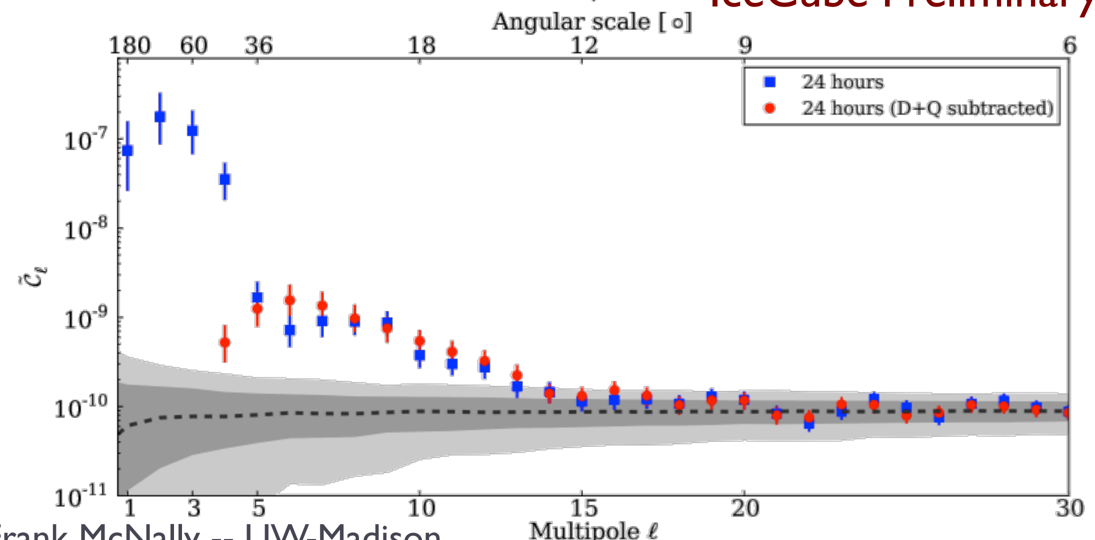


Power Spectrum

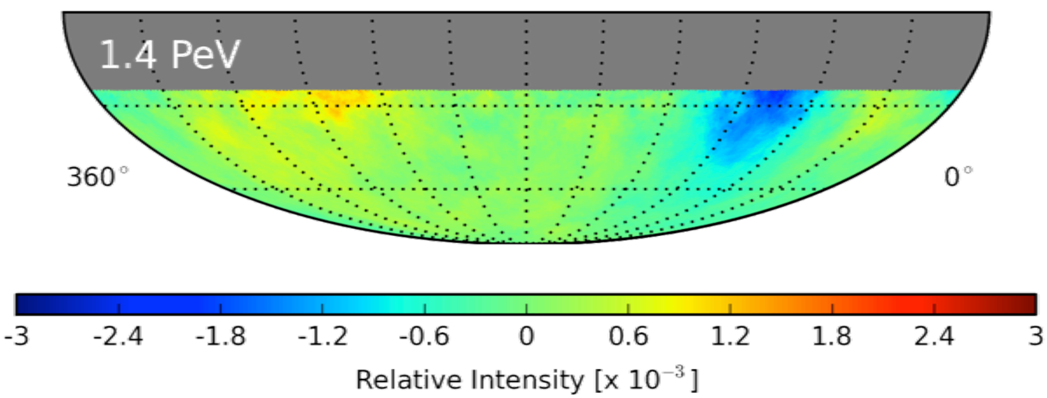
- 5-year combined dataset

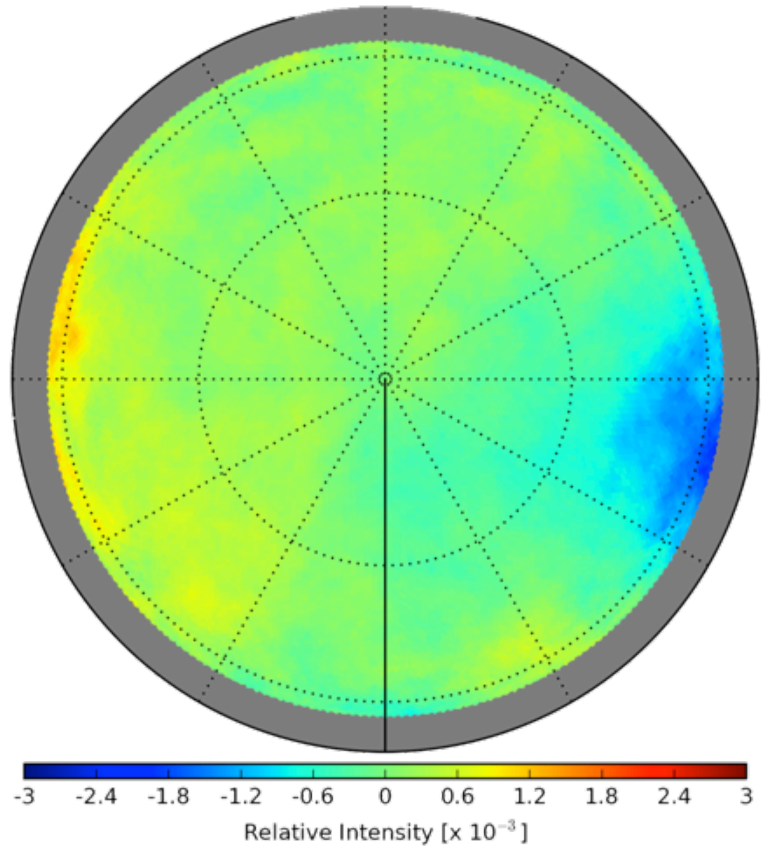


- Previously published (IC59)



Energy Dependence



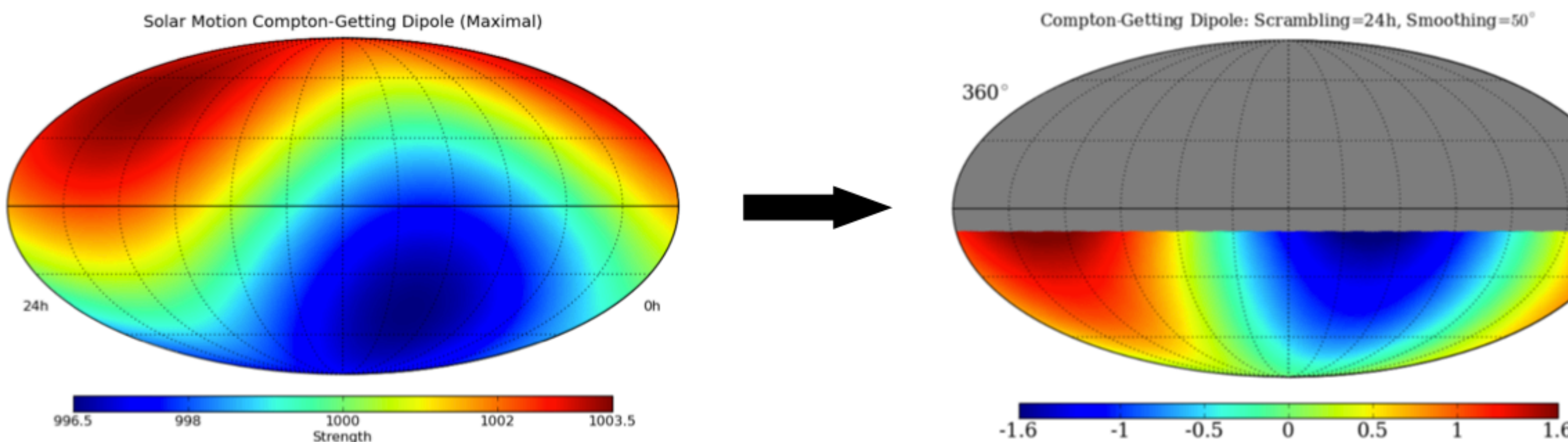


IceCube Preliminary

measuring cosmic ray anisotropy

relative intensity

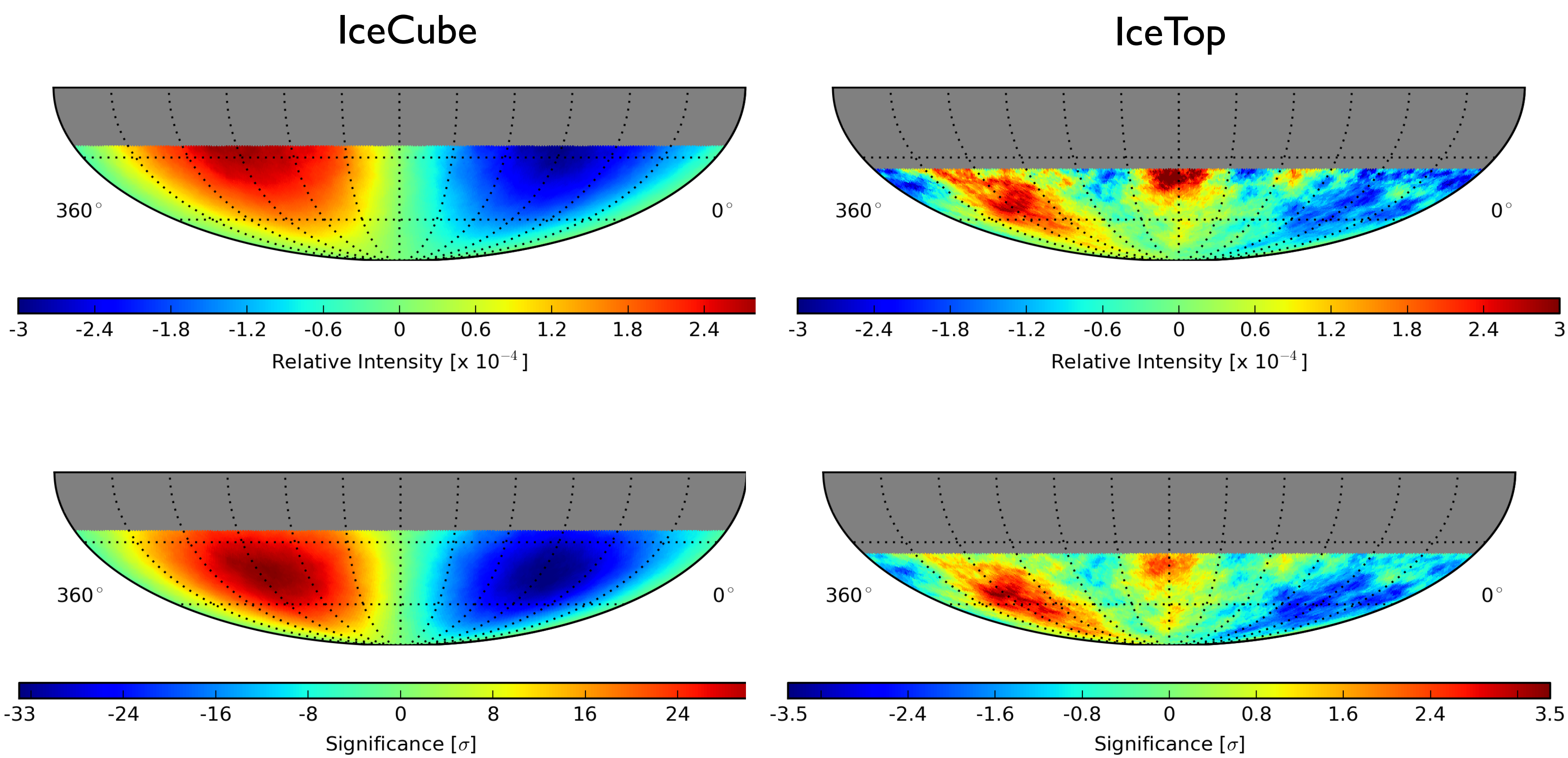
DISCLAIMER



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

- dipole anisotropy (Compton-Getting Effect) is distorted by observation: **cannot point**
- ***recover*** the ***horizontal*** component of the dipole (and multipole components)

Solar Dipole



IceCube Preliminary