Anisotropy in Cosmic-Ray Arrival Directions with Six Years of Data from the IceCube Detector

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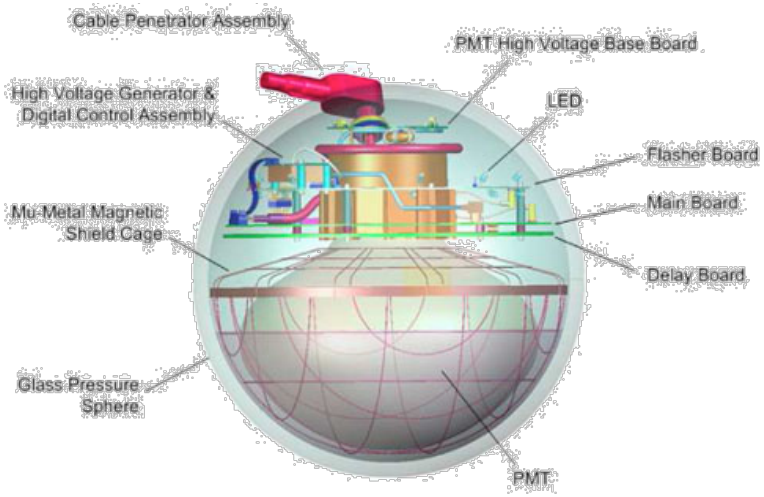
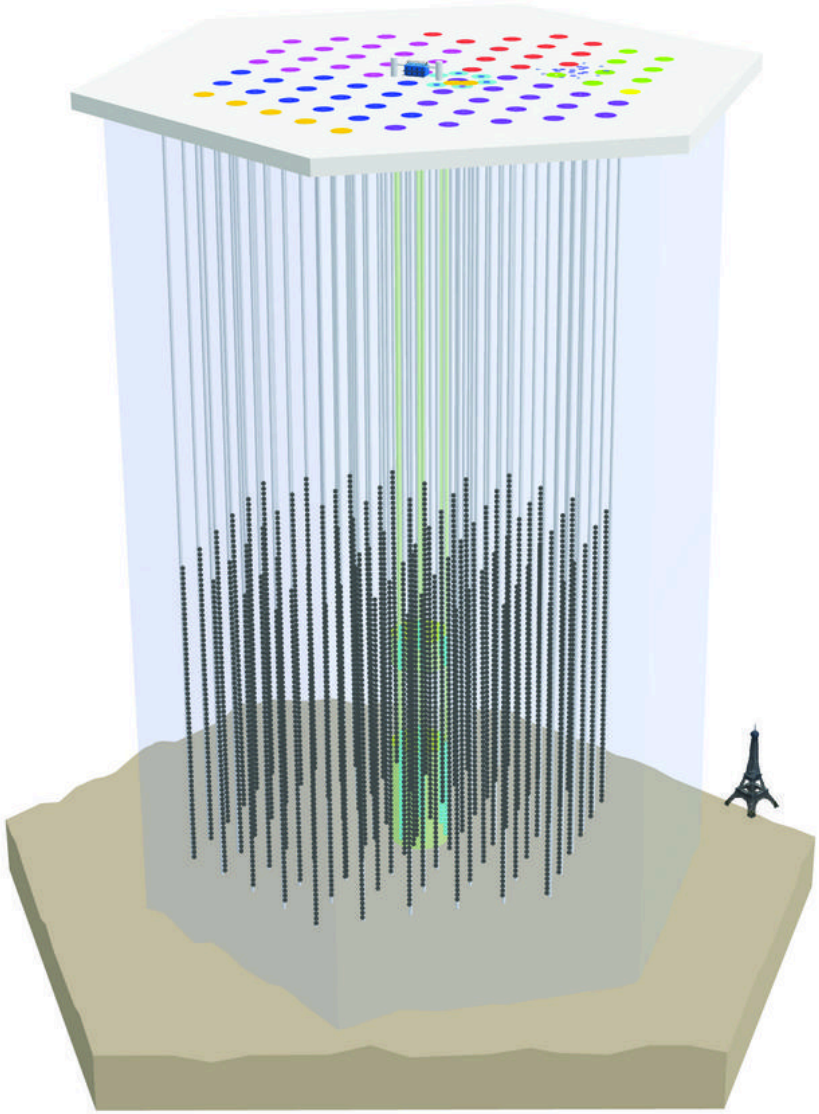
Outline

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

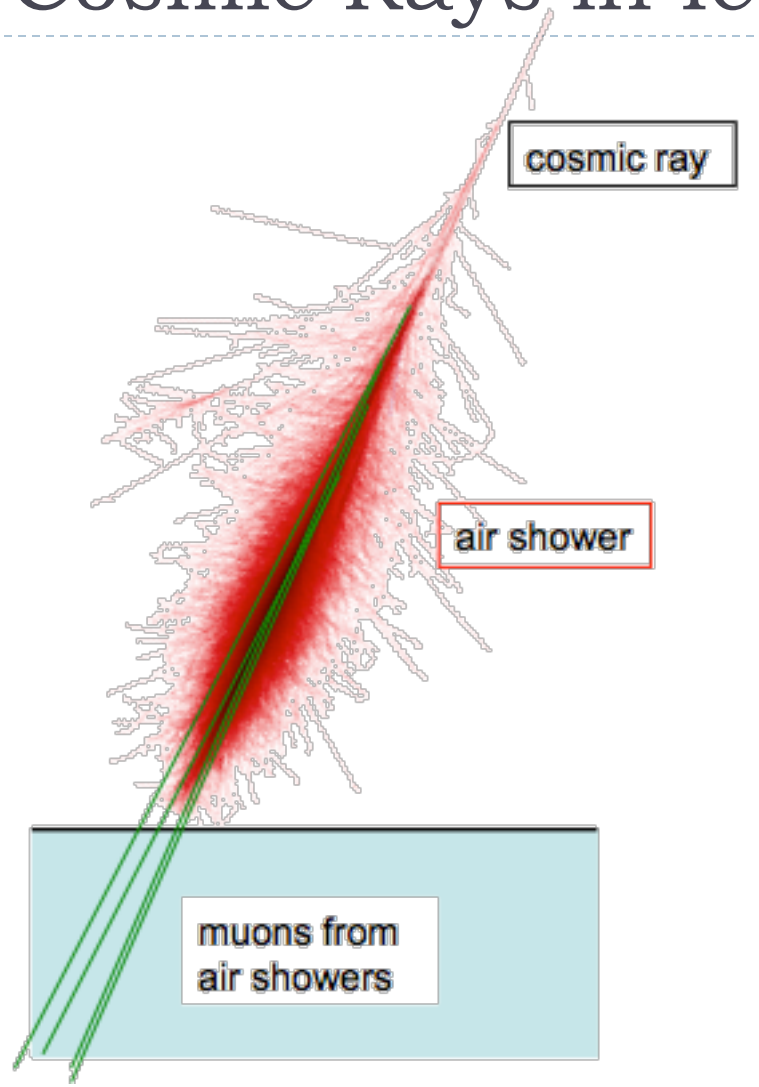
IceCube

- 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

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Dataset

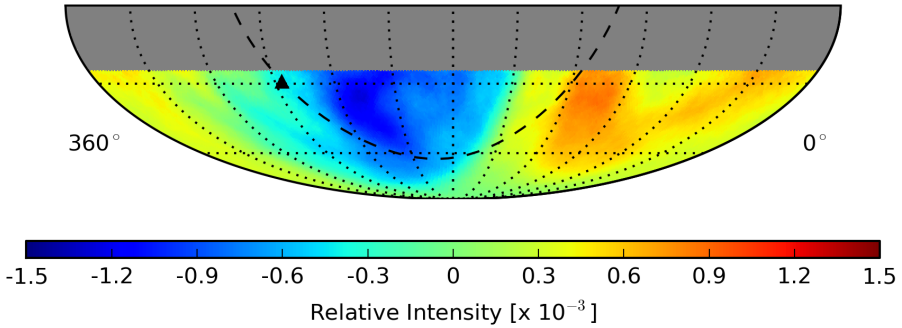
- Over 300 billion events in IceCube
- Over 170 million events in IceTop
- Excellent detector uptime!

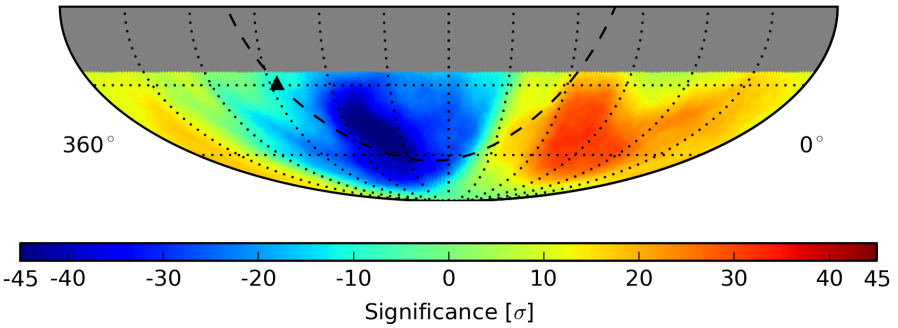
Configuration	Livetime (days)	Number of Events
IC59	339.38 (91.7%)	3.579×10^{10}
IC79	315.76 (92.6%)	4.131×10^{10}
IC86	343.04 (93.0%)	5.906×10^{10}
IC86-II	331.92 (94.0%)	5.630×10^{10}
IC86-III	362.20 (97.9%)	6.214×10^{10}
IC86-IV	369.76 (97.8%)	6.327×10^{10}
Total	2062.06 (94.5%)	3.179×10^{11}

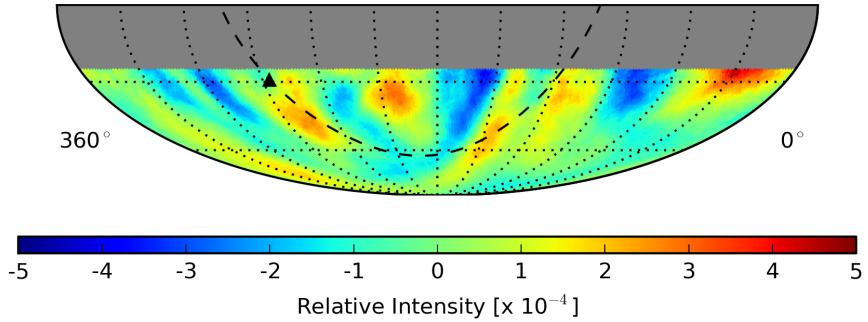
Configuration	Livetime (days)	Number of Events
IT59	338.25 (91.4%)	2.887×10^{7}
IT73	312.66 (91.7%)	3.690×10^{7}
IT81	343.04 (93.0%)	3.800×10^{7}
IT81-II	332.26 (94.1%)	3.713×10^{7}
IT81-III	361.20 (97.6%)	3.101×10^{7}
IT81-IV	362.61 (95.9%)	2.810×10^{7}
Total	2050.01 (94.0%)	1.719×10^{8}

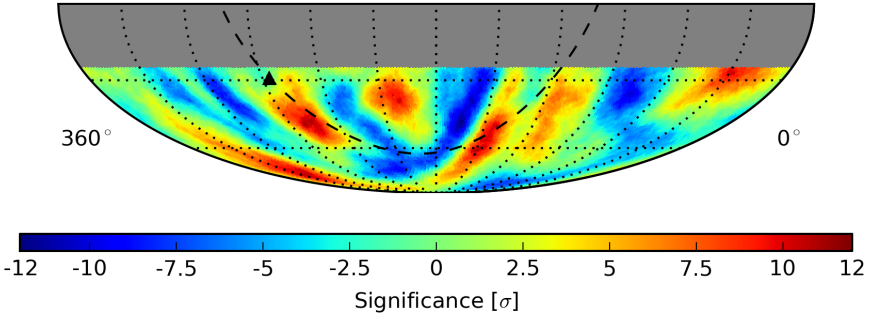
Anisotropy in IceCube

6 years of data (IC59 – IC86-IV) 3.18 x 10^{11} events





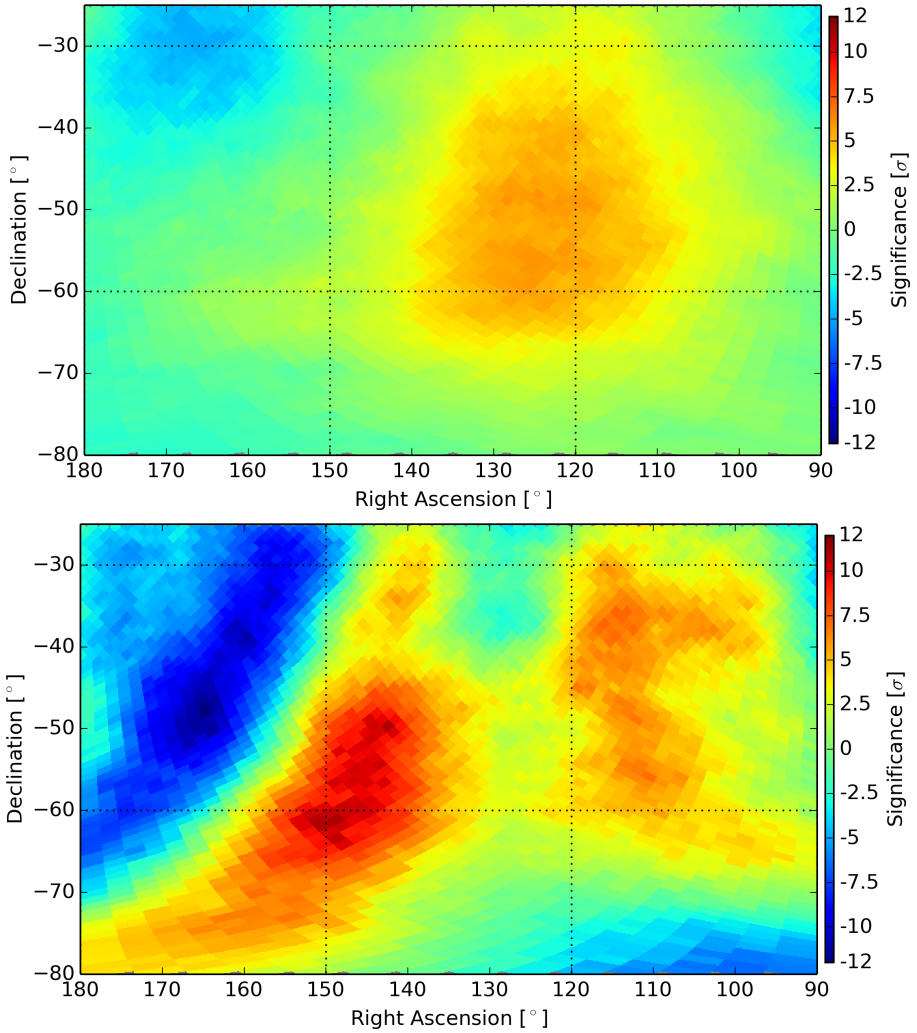




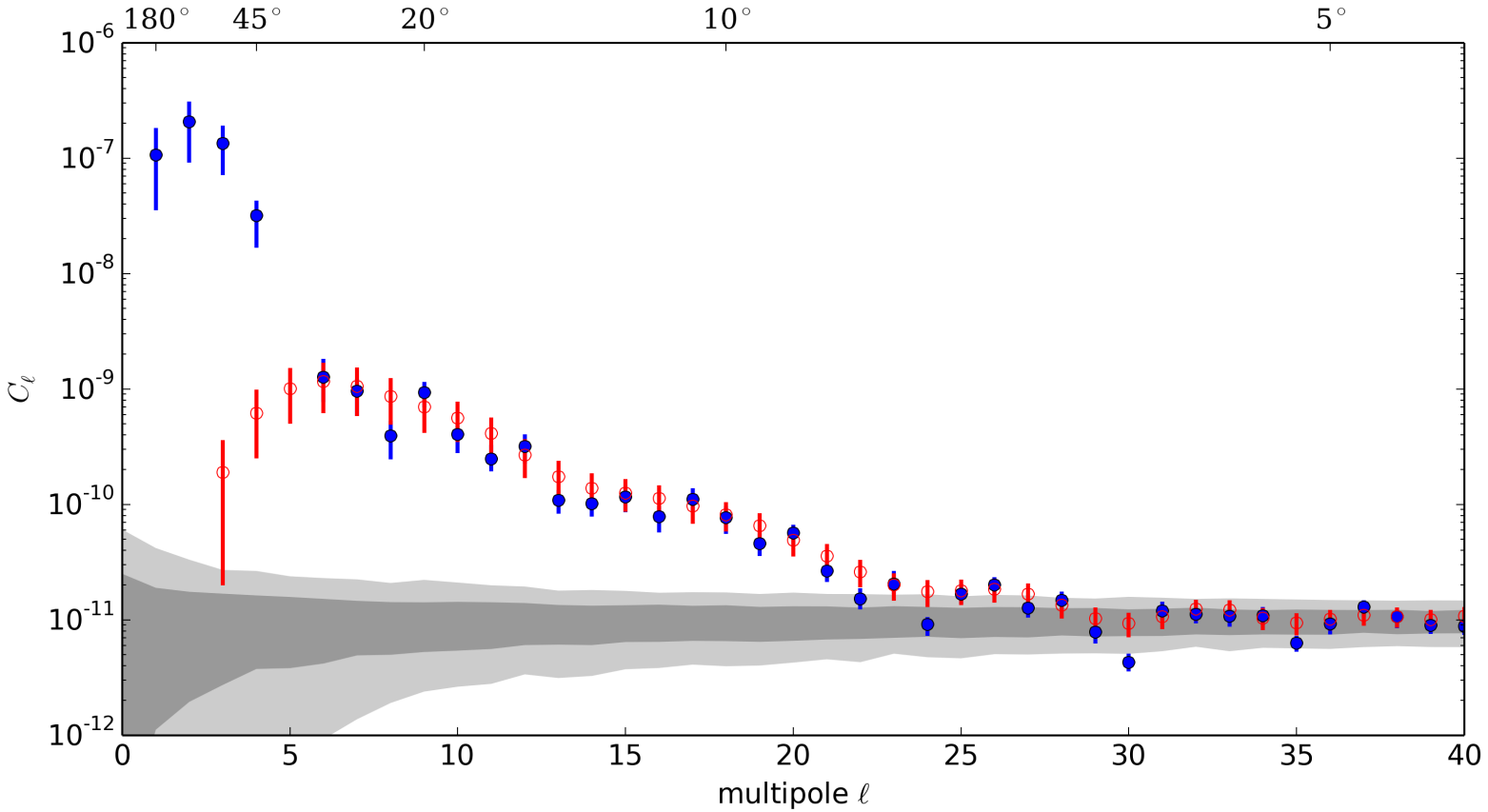
- Relative intensity (*left*) and pre-trial statistical significance (*right*)
- Before (*top*) and after (*bottom*) dipole- and quadrupole-subtraction
- Angular smoothing radius of 5°

Advantage of New Dataset

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



Power Spectrum



- Power spectrum for 6 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.

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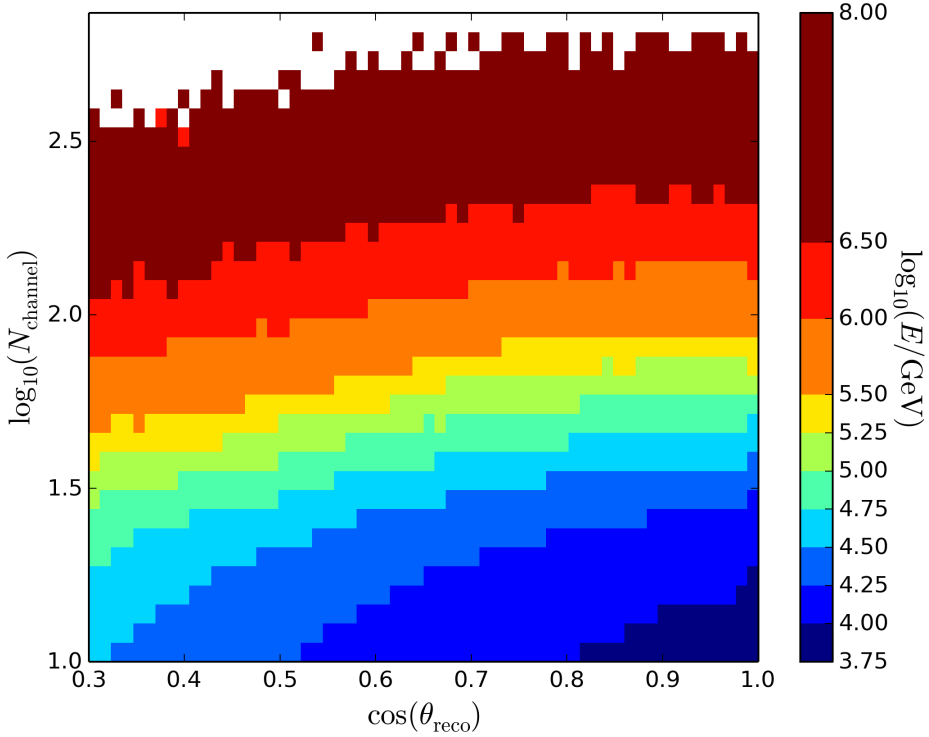
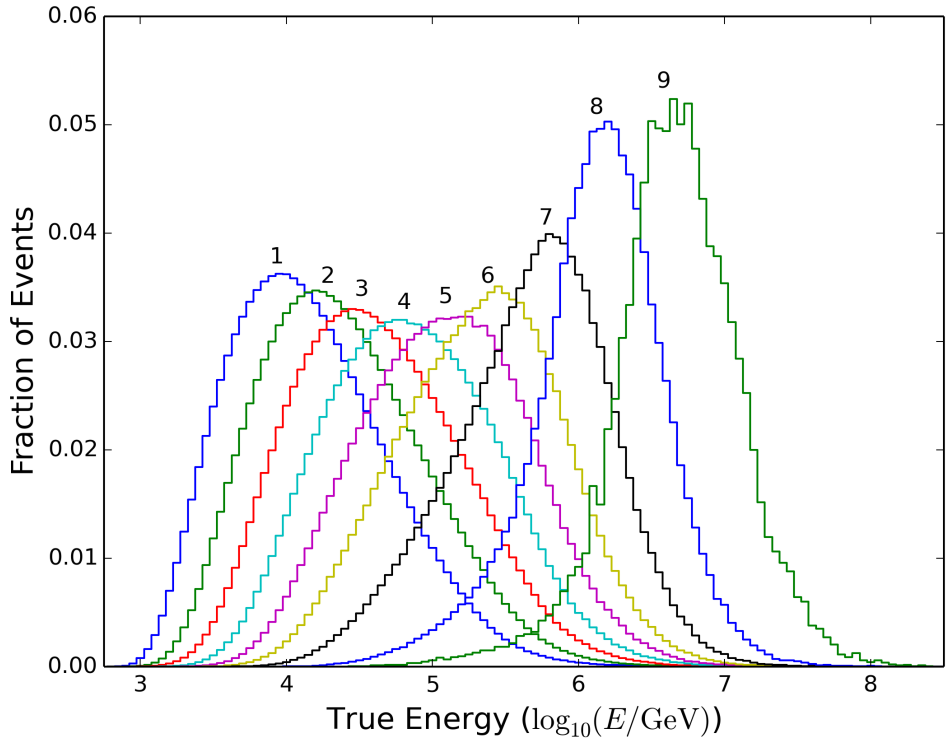
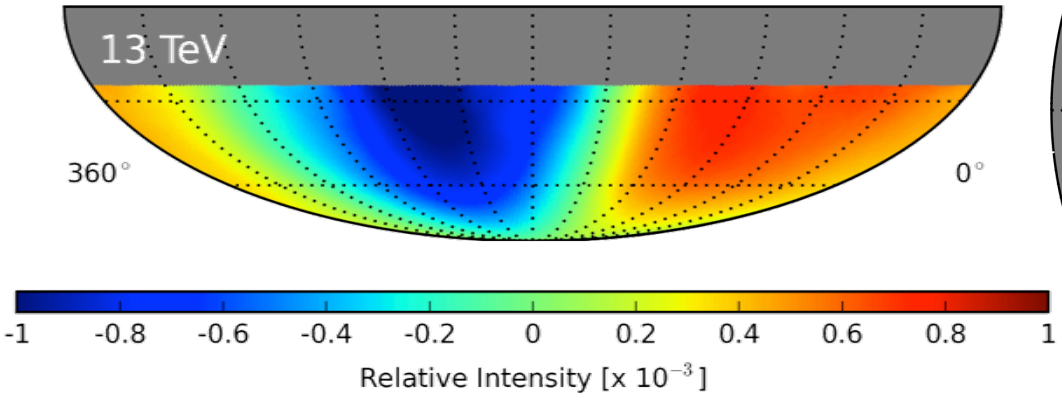
Energy Separation

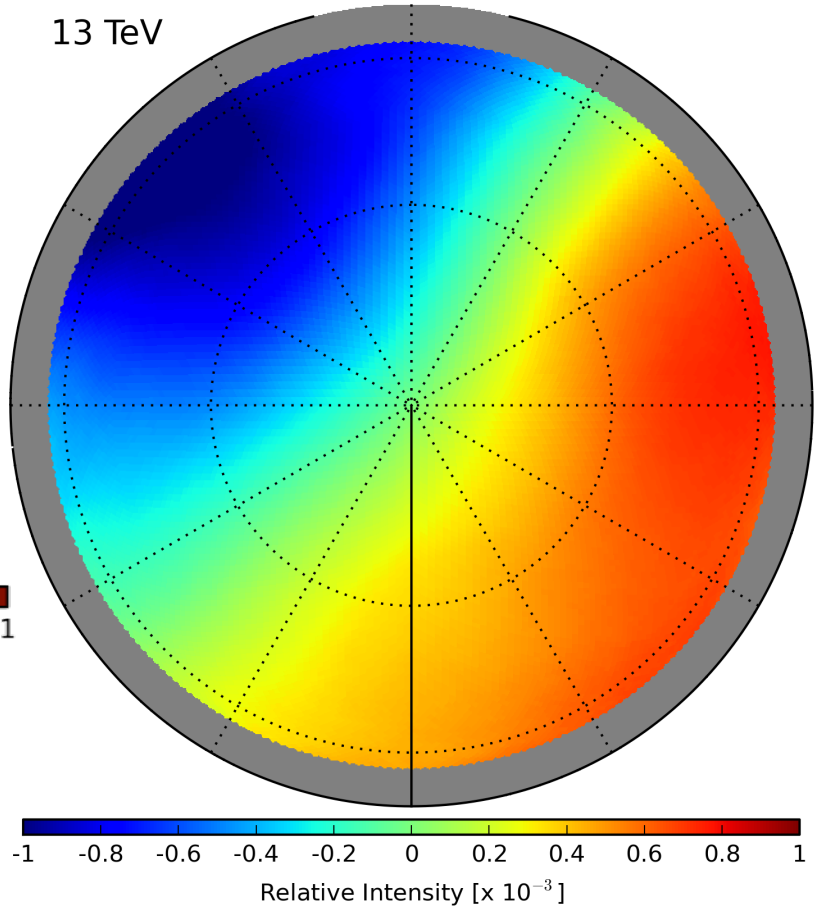




- Bin simulation based on hits and reconstructed zenith
- Split into energy bands based on median true energy of cosmic-ray primaries
- Result: bins that overlap but rise in median energy

Energy Dependence





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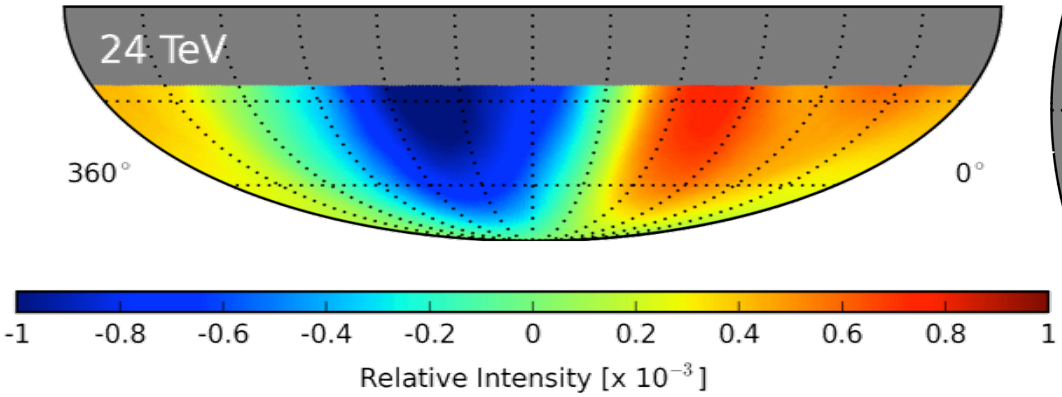

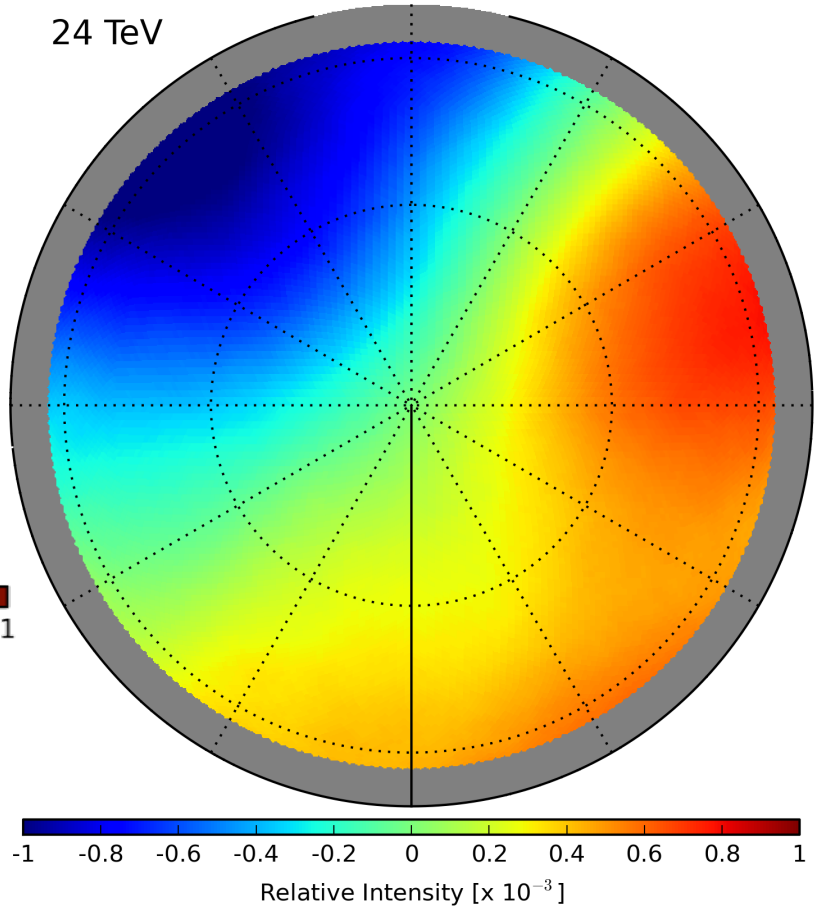

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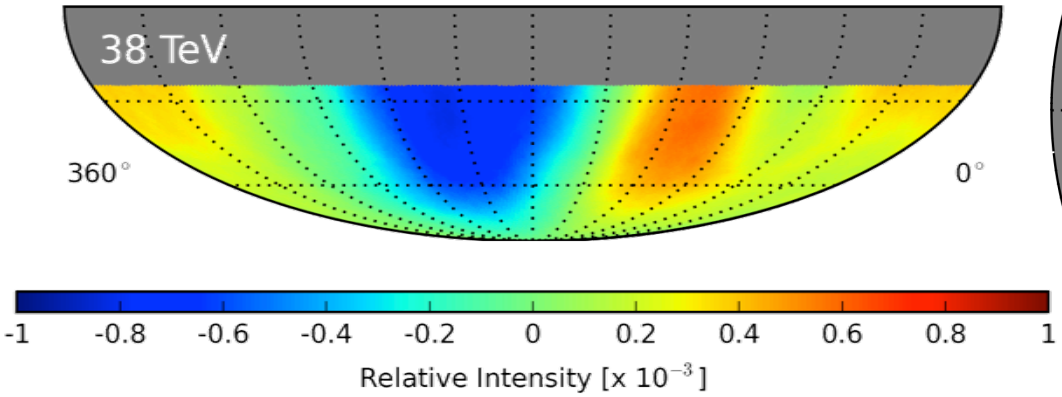

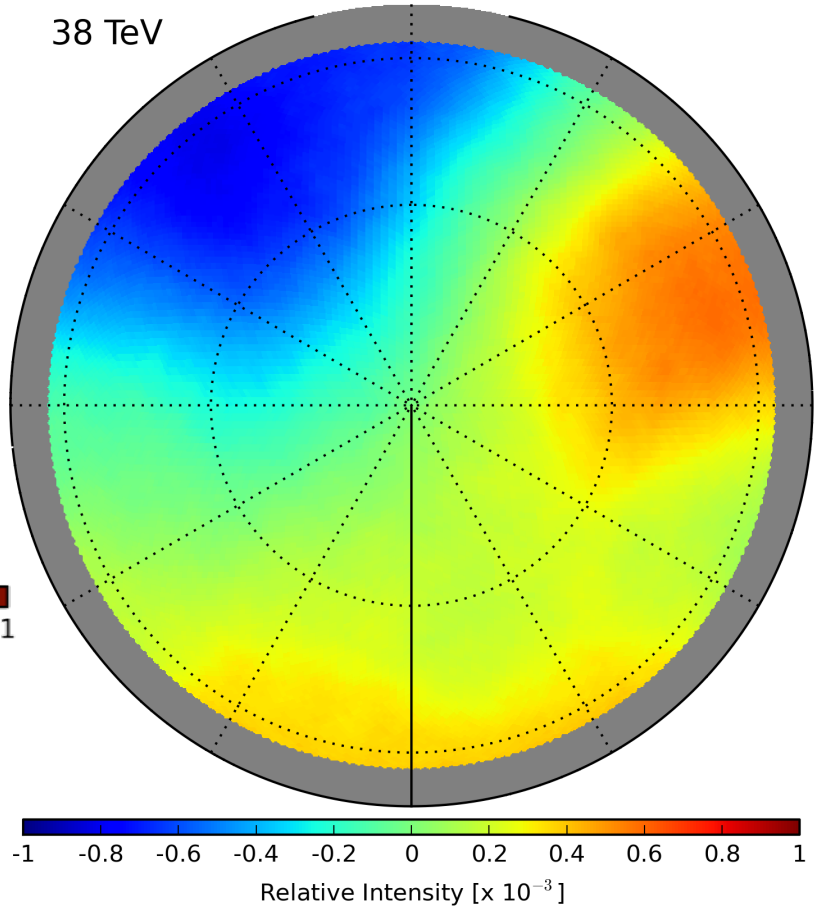

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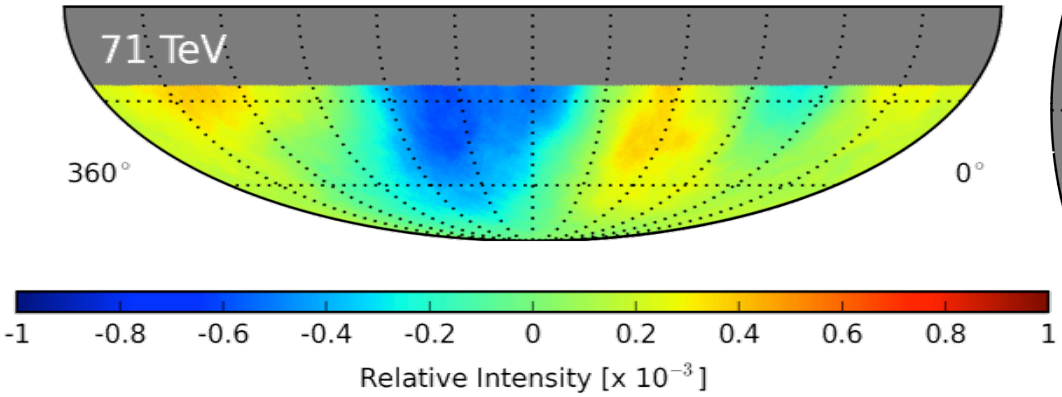

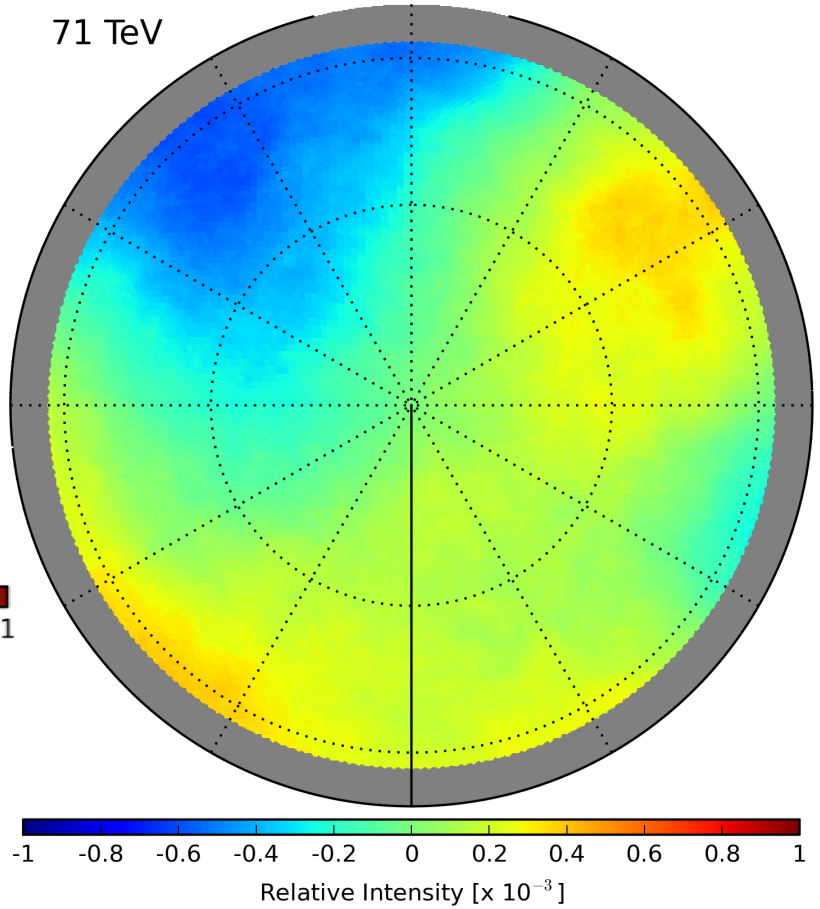

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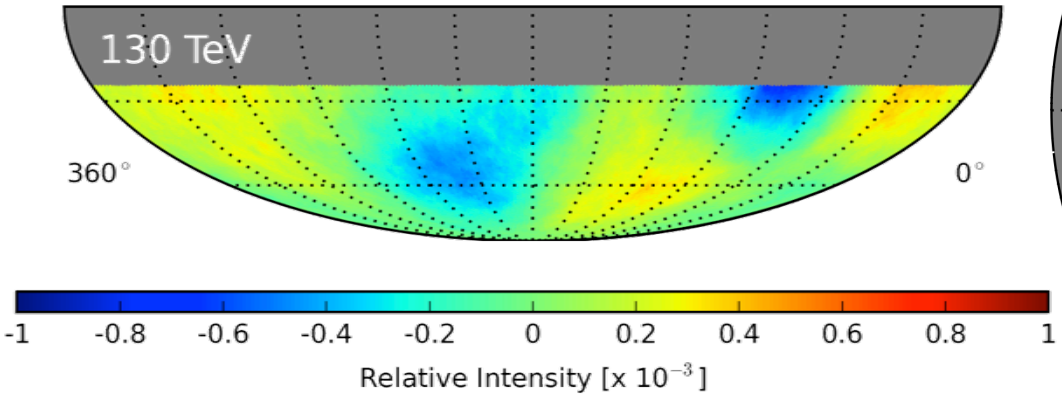

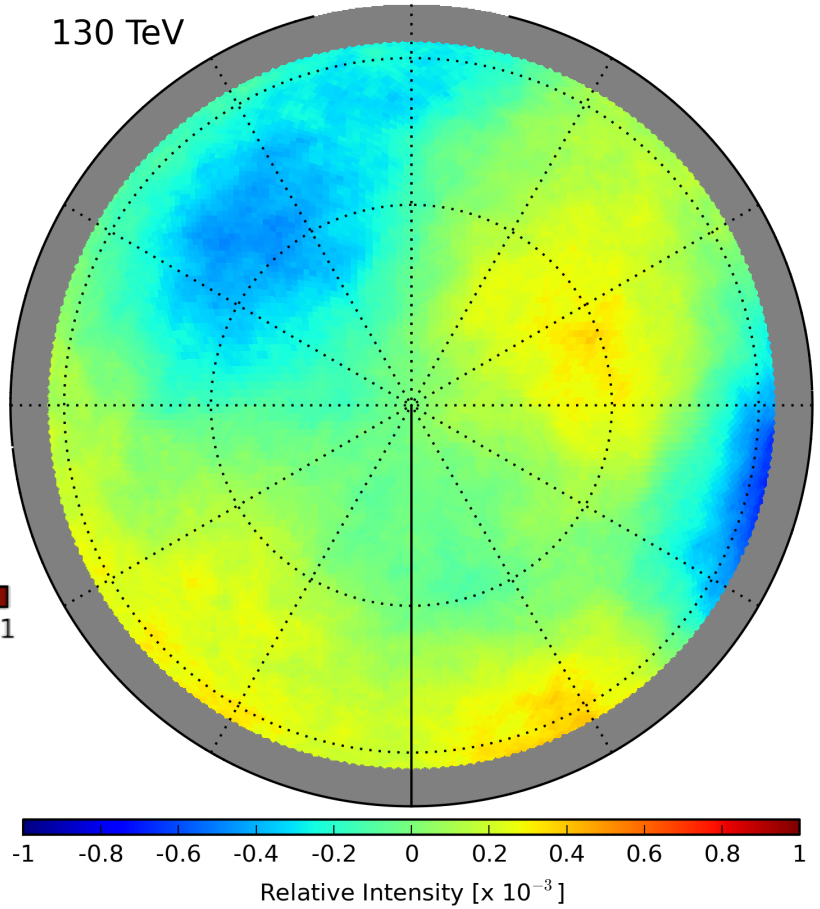

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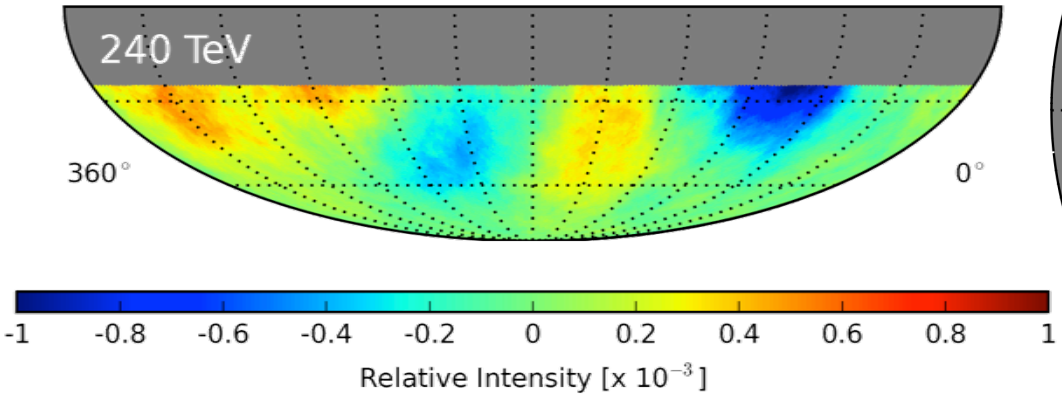

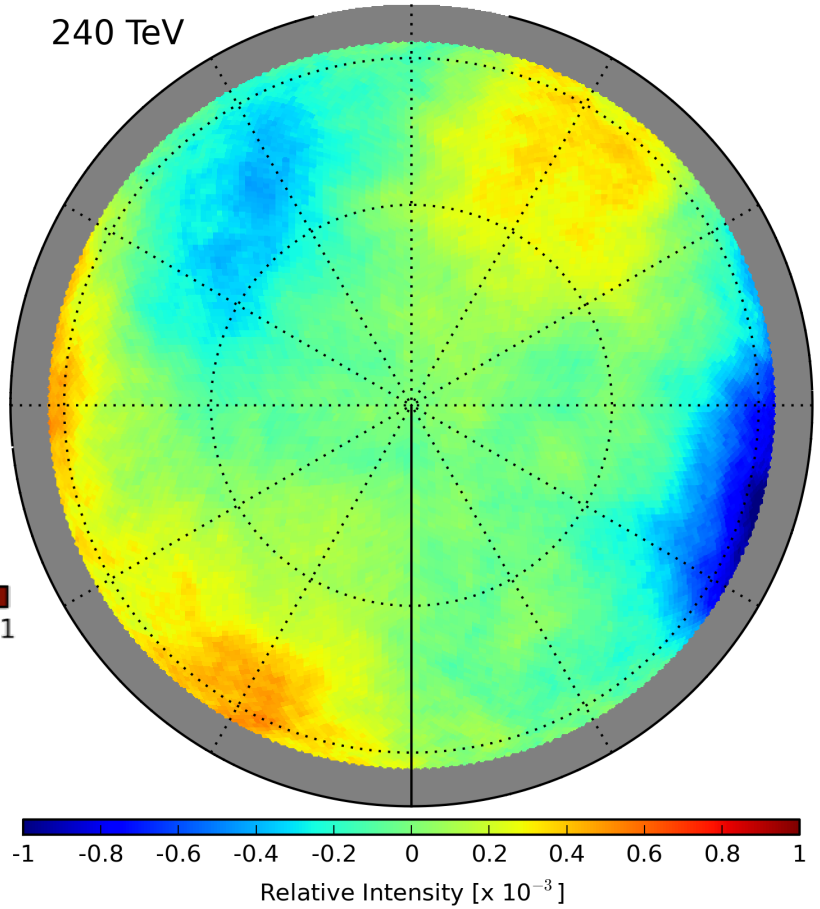

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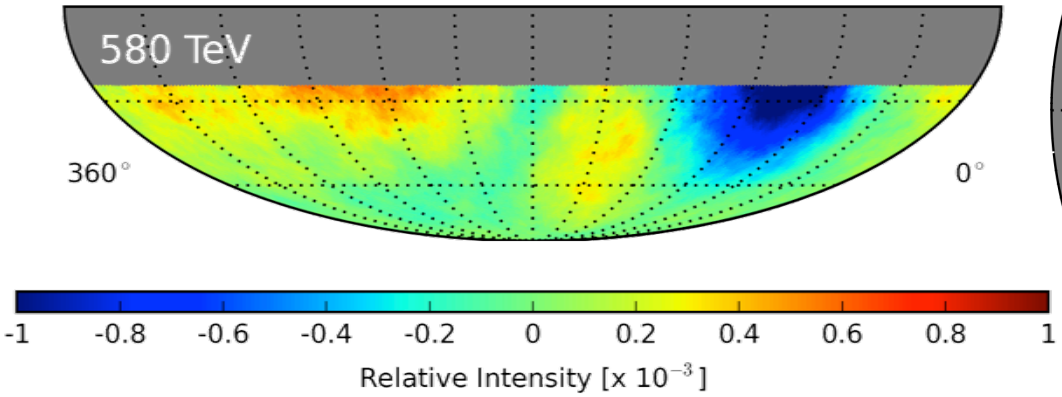

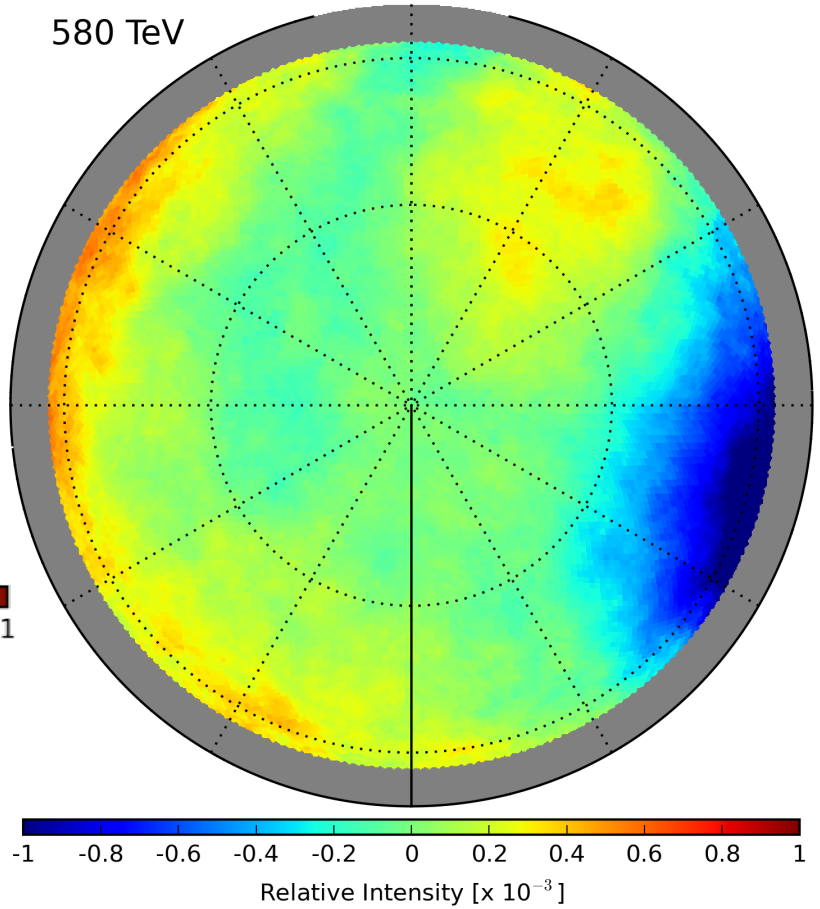

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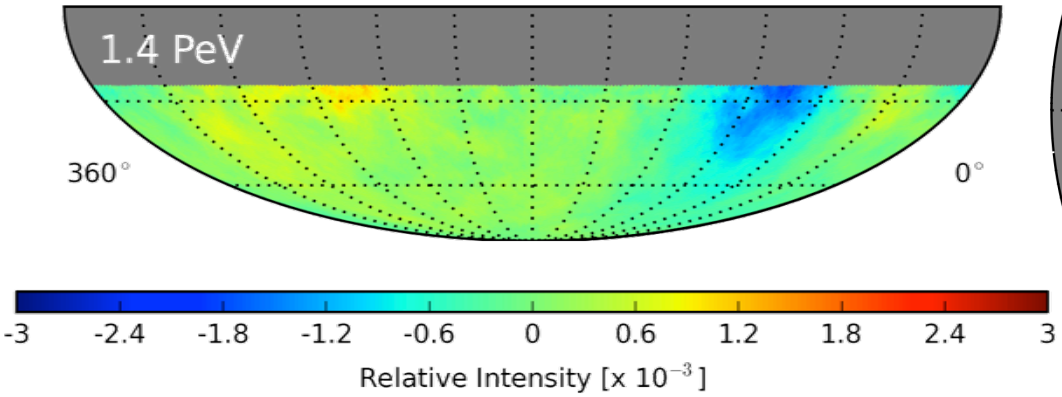

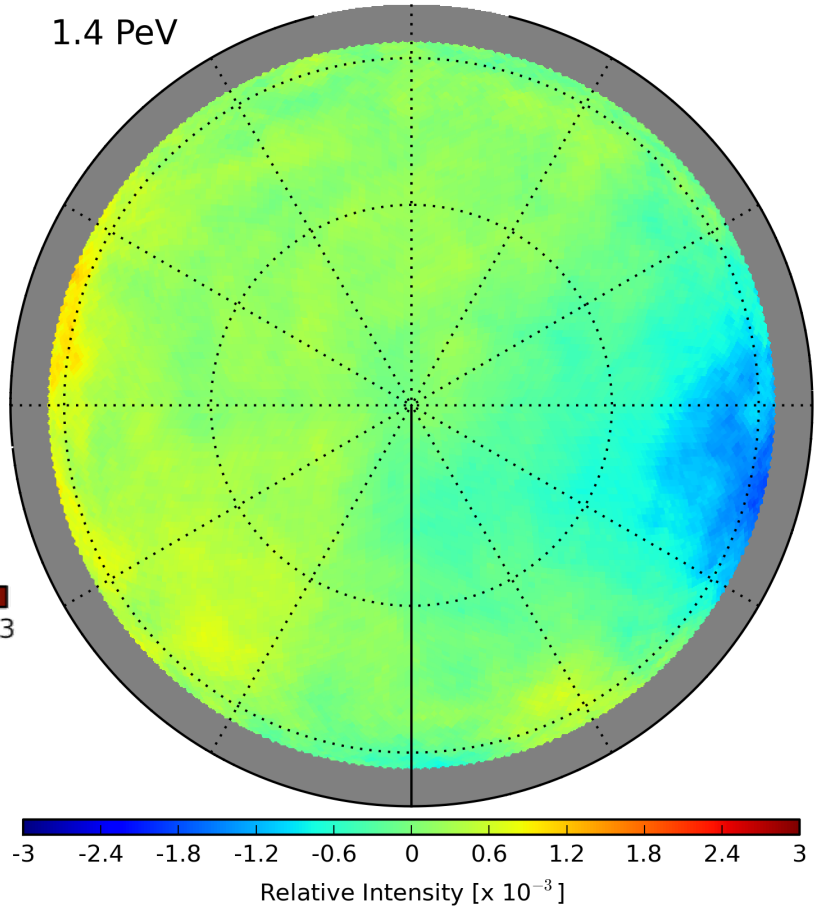

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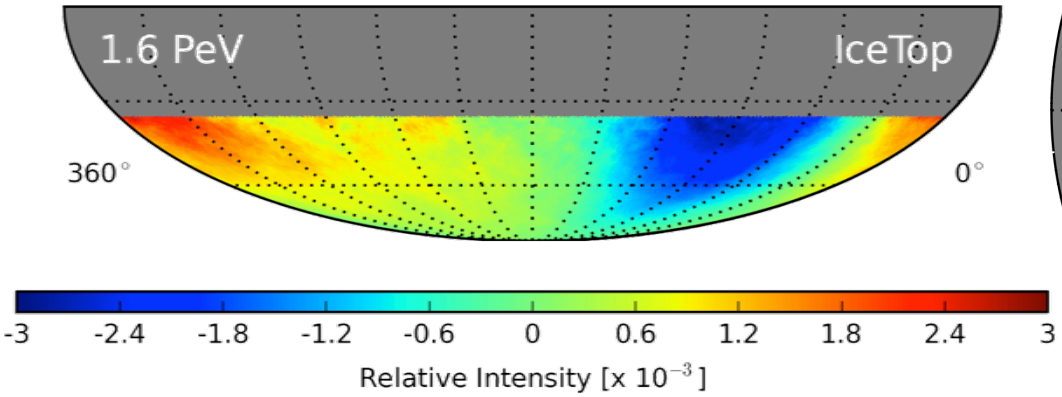

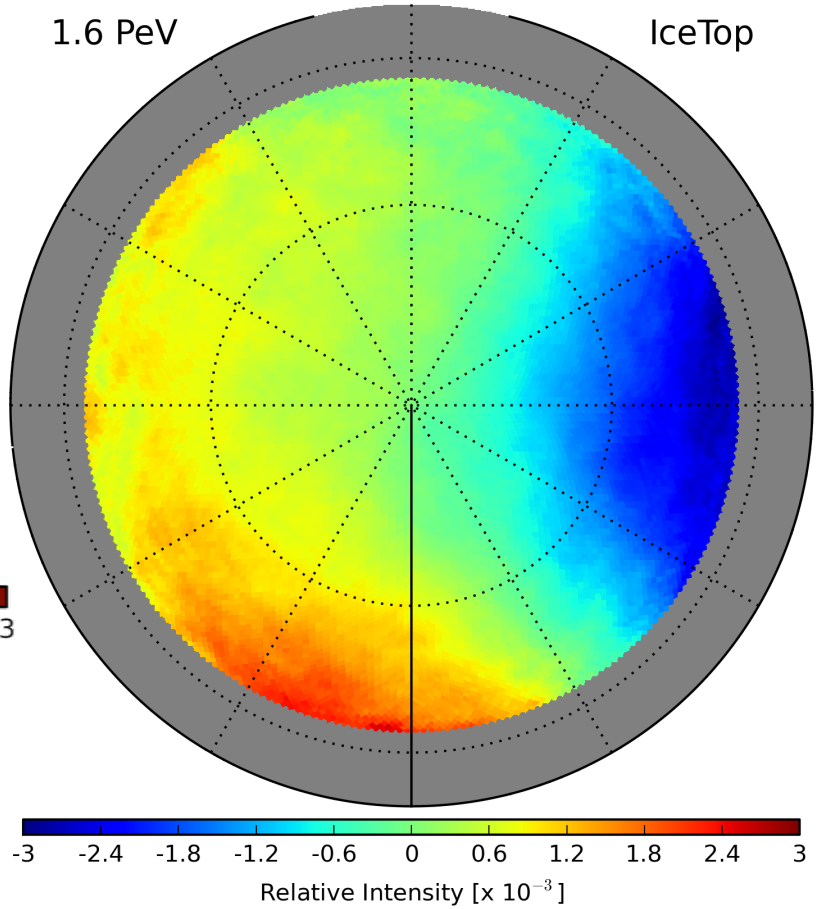

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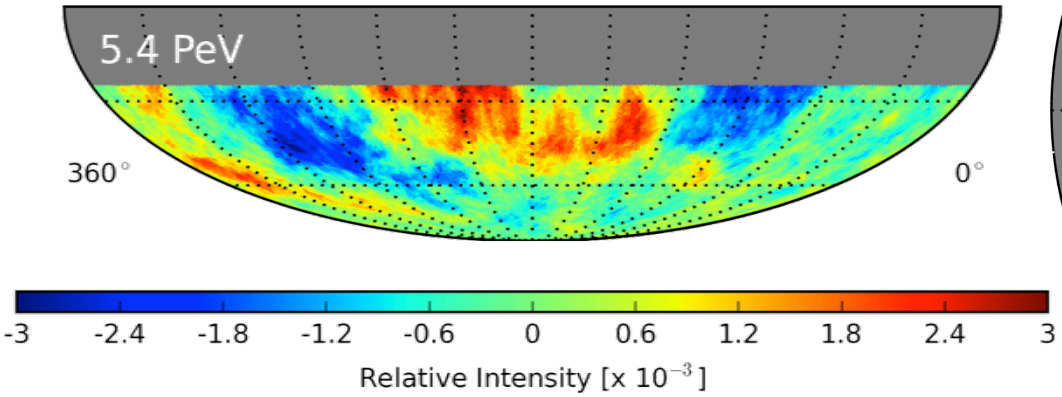

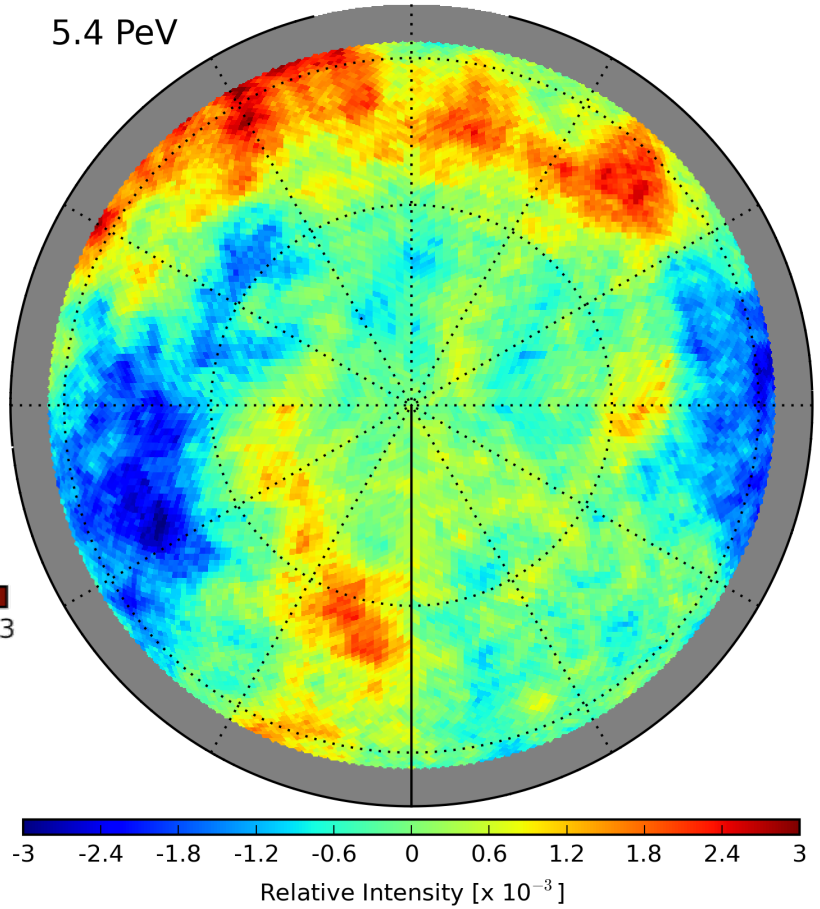

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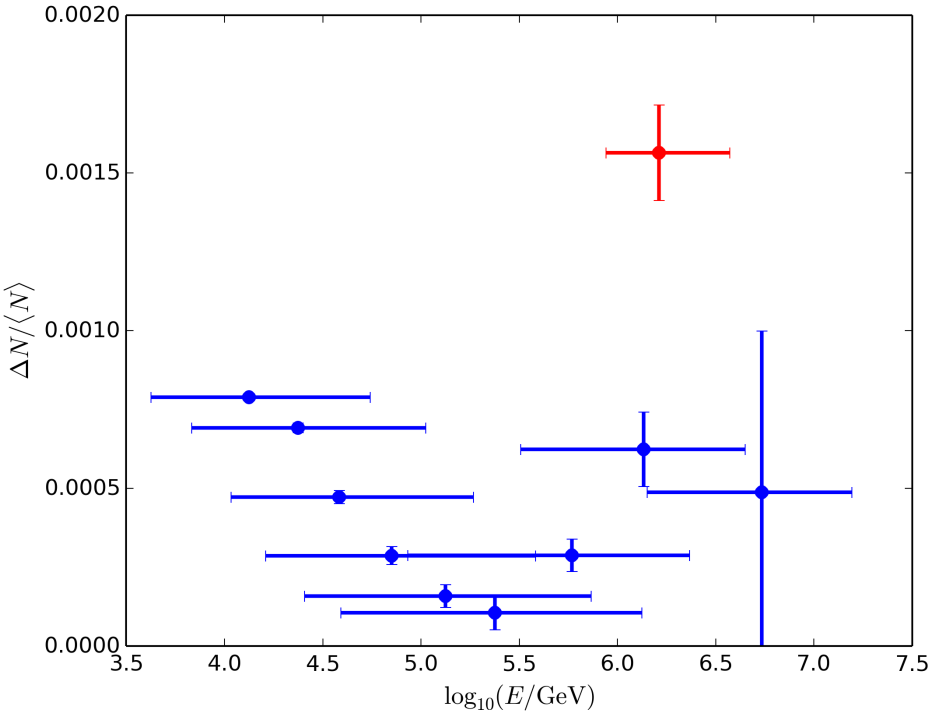

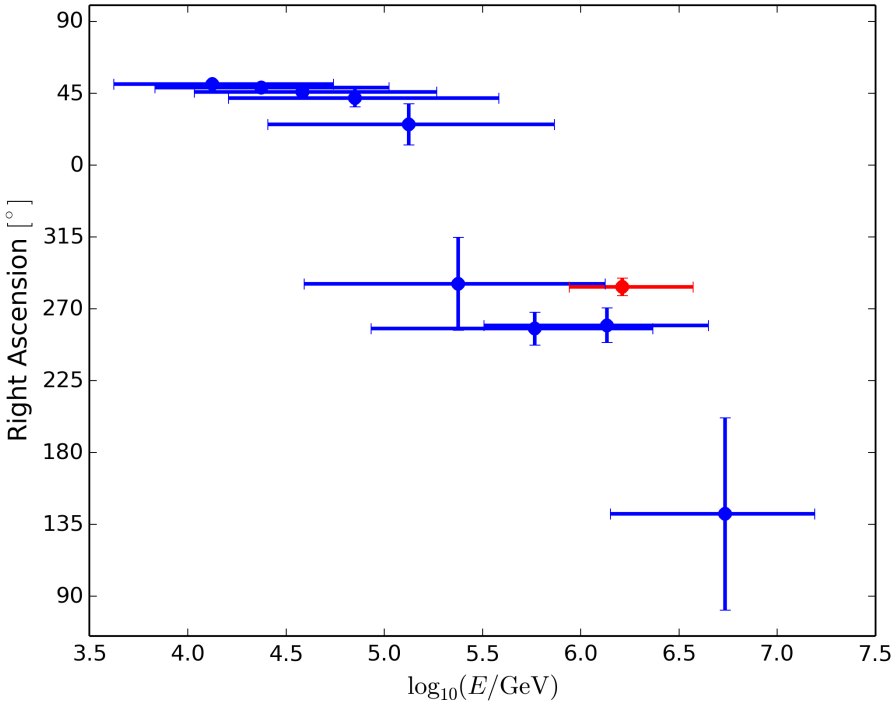

- Strength of dipole decreases up to transition, increases afterward
- Phase transition occurs above 100 TeV
- IceCube (*blue*) and IceTop (*red*) data

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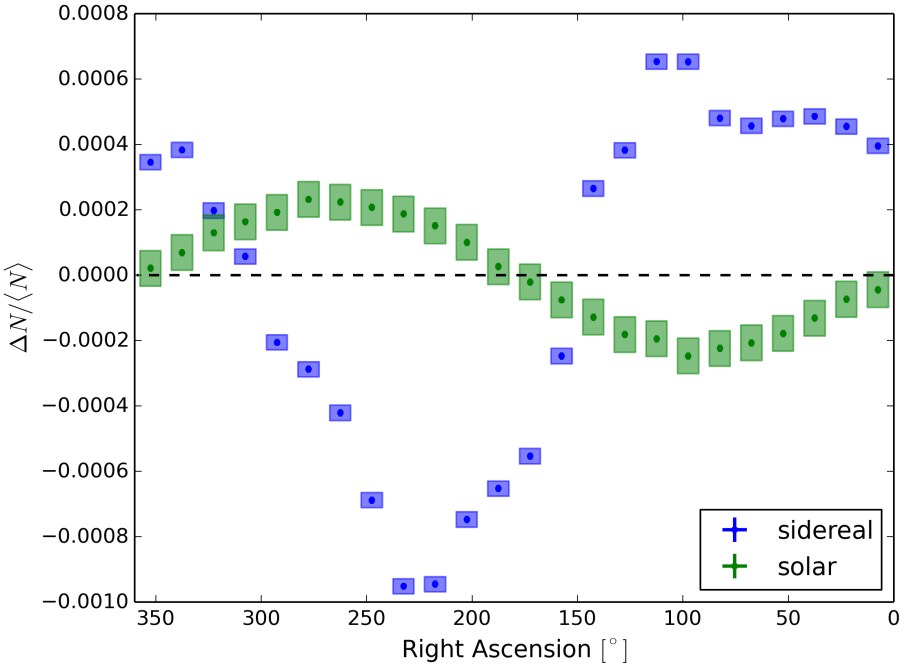
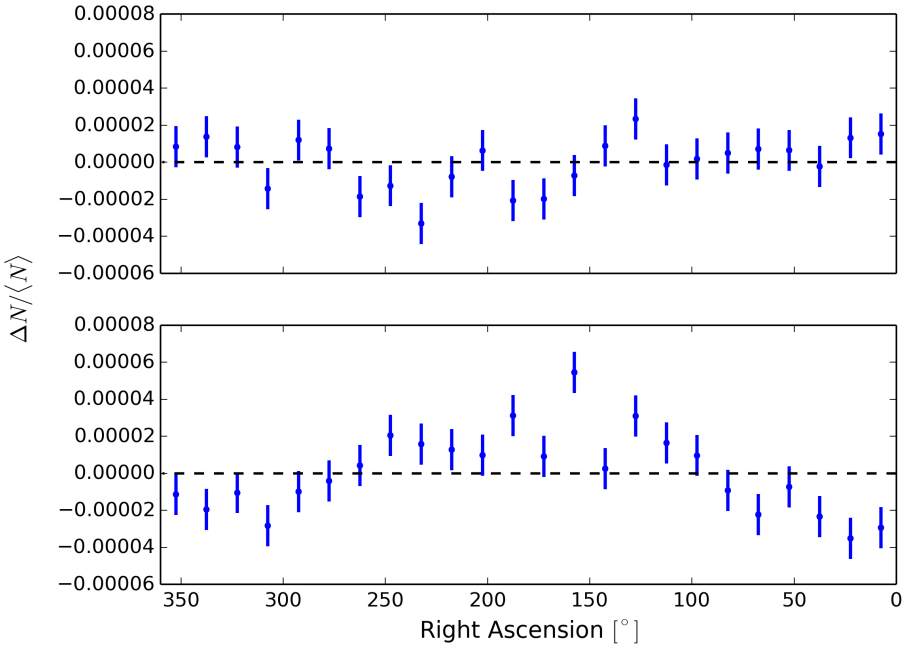
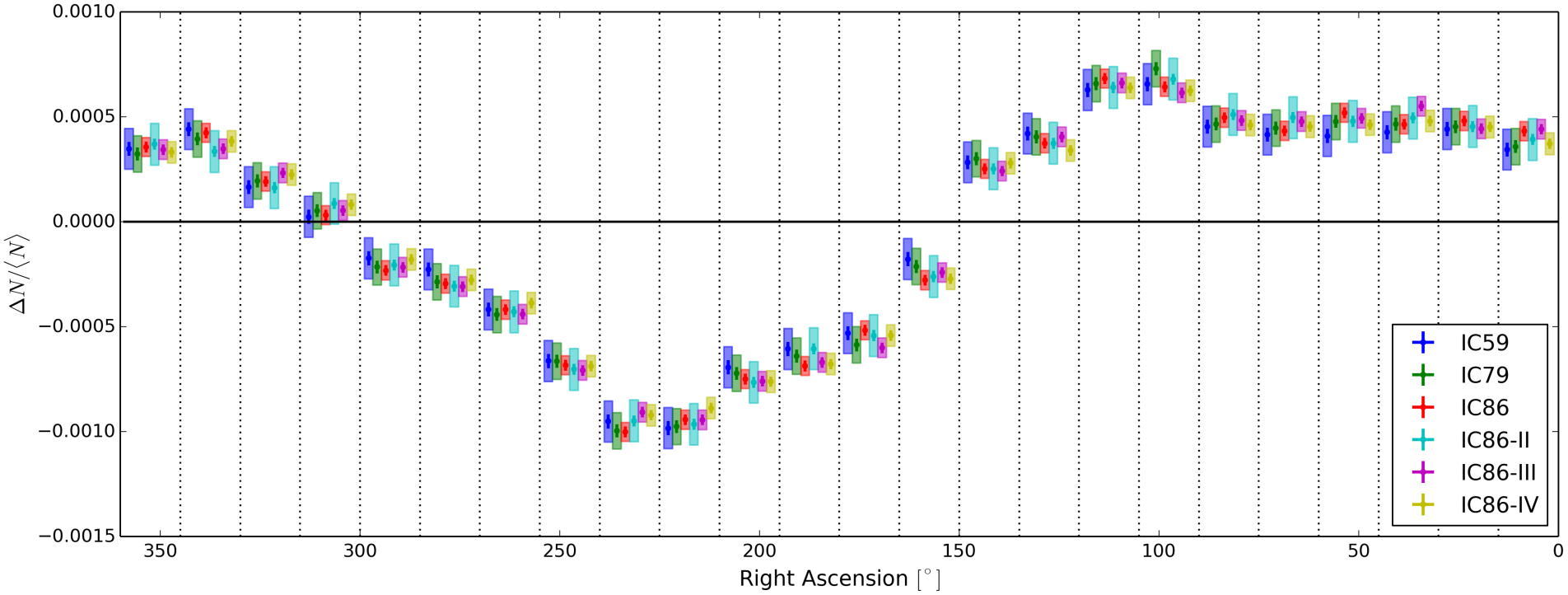
Solar Dipole





- 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- (*top-right*) and extended-sidereal (*bottom-right*) frames

Time Dependence – Large Scale



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

Time Dependence – Large Scale

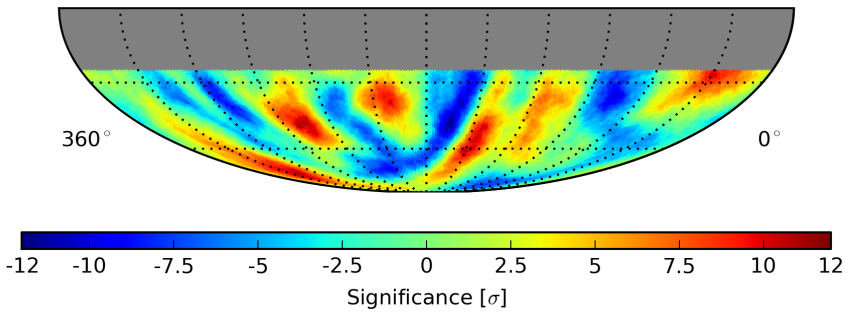
- Quantitative:
  - Calculate chi-squared by comparing each year to the collected sample

Configuration	χ^2	N	p-value
IC59	31.42	23	0.11
IC79	16.12	23	0.85
IC86	19.66	23	0.66
IC86-II	15.44	23	0.88
IC86-III	24.27	23	0.39
IC86-IV	18.16	23	0.75

Notes. The table provides χ^2 values, number of degrees of freedom, N, and corresponding p-values.

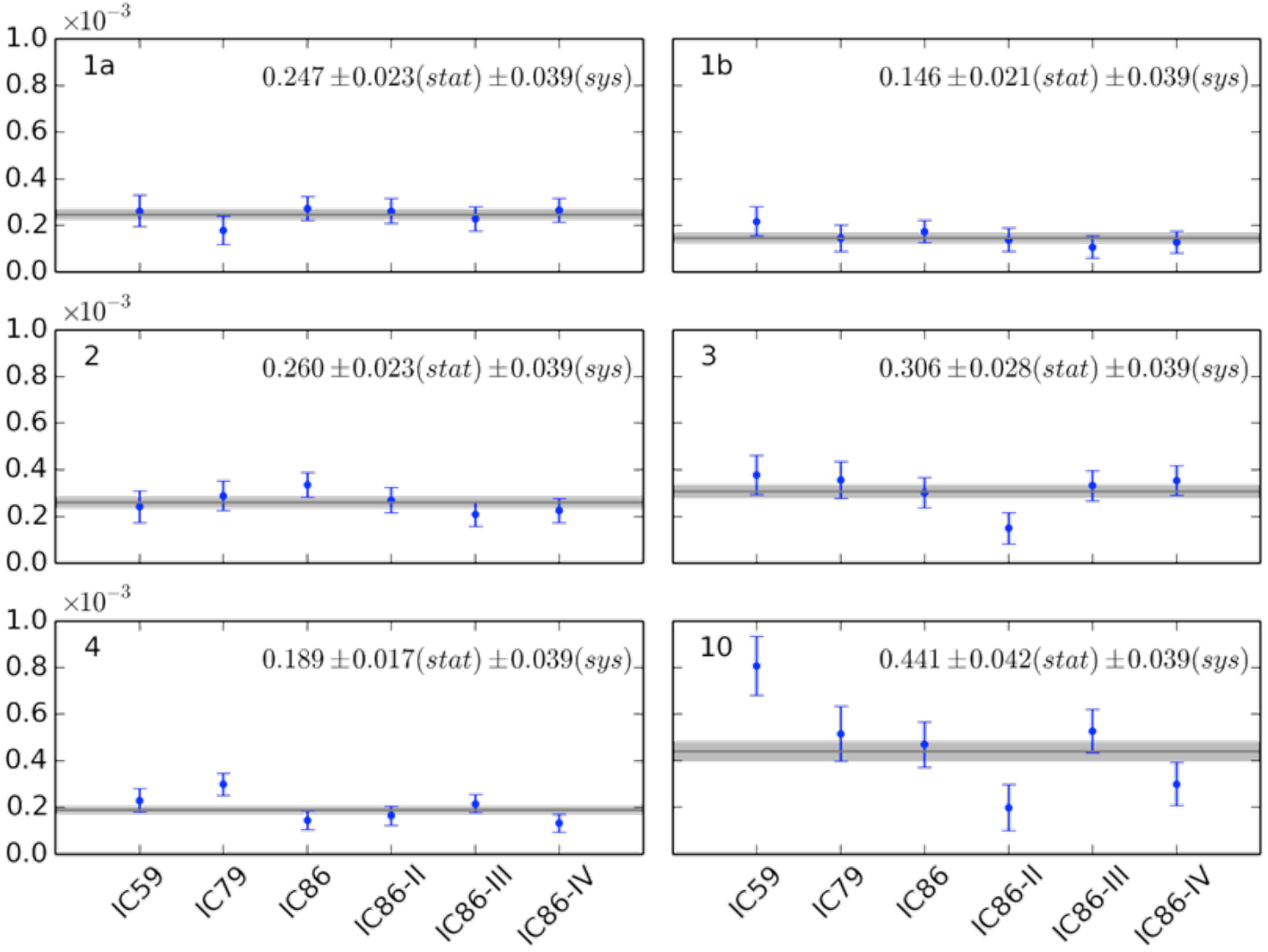
Time Dependence – Small Scale

- Label regions with pre-trial significance > 5 σ
- Look at evolution over time

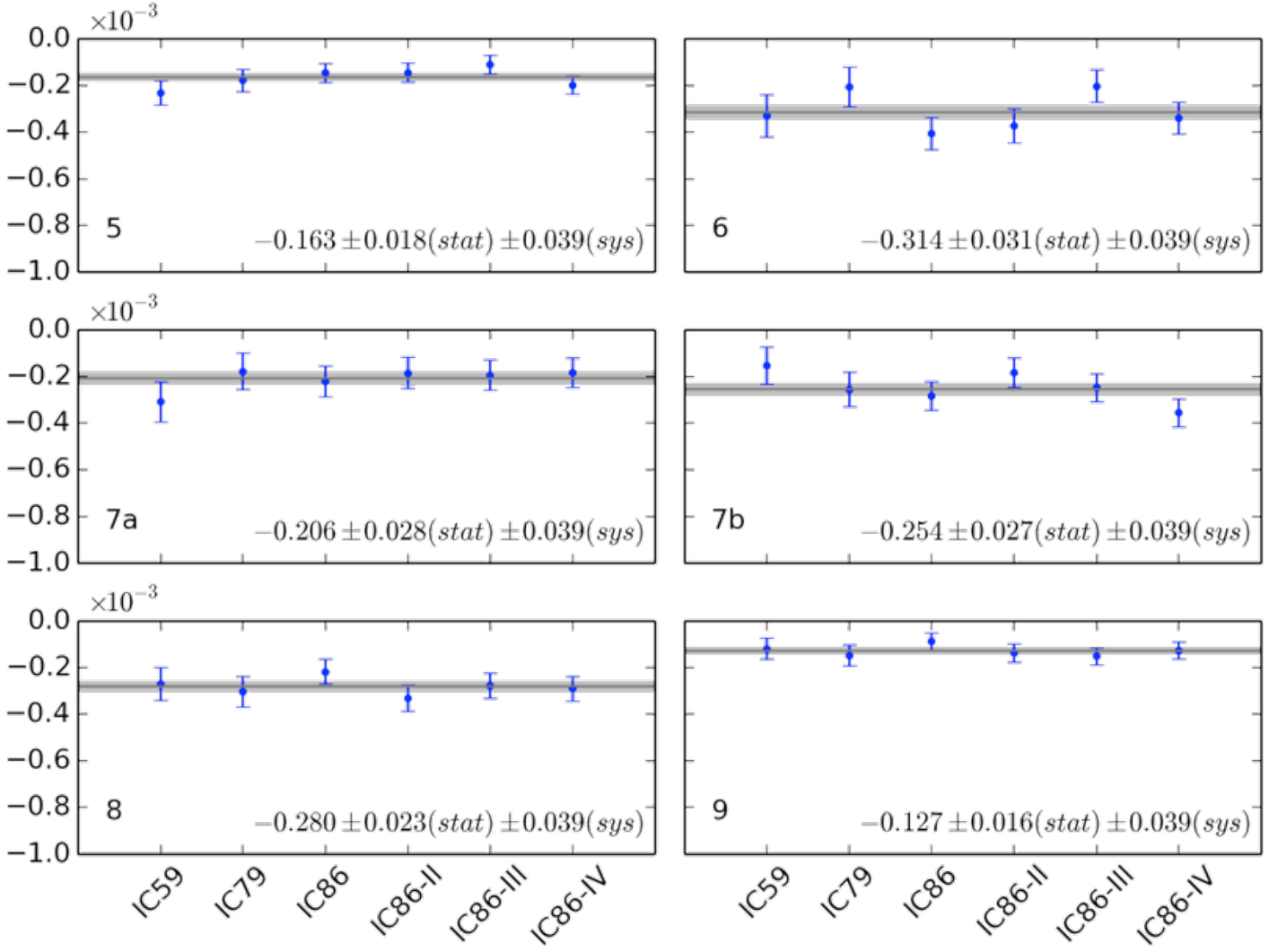


Region	Right Ascension (deg)	Declination (deg)	Peak Significance
1a	$142.5^{+4.9}_{-2.4}$	$-49.7^{+2.3}_{-3.9}$	11.0σ
1b	$110.5^{+5.3}_{-3.5}$	$-55.9^{+5.4}_{-2.3}$	6.9σ
2	$261.0^{+3.4}_{-8.5}$	$-48.9^{+4.7}_{-2.3}$	11.4σ
3	$200.4^{+2.8}_{-1.4}$	$-38.7^{+2.3}_{-2.3}$	10.8σ
4	$327.9^{+11.9}_{-16.8}$	$-74.6^{+4.4}_{-4.4}$	11.0σ
5	$215.6^{+18.7}_{-8.6}$	$-72.4^{+5.2}_{-2.2}$	-9.3σ
6	$74.5^{+4.2}_{-4.2}$	$-36.4^{+5.0}_{-3.8}$	-10.3σ
7a	$317.1^{+4.2}_{-2.1}$	$-38.7^{+5.2}_{-1.5}$	-7.2σ
7b	$292.5^{+1.4}_{-1.4}$	$-41.0^{+1.6}_{-1.6}$	-9.6σ
8	$164.7^{+3.2}_{-2.9}$	$-48.1^{+4.7}_{-3.9}$	-11.9σ
9*	$94.1^{+9.4}_{-40.9}$	$-82.0^{+5.1}_{-2.2}$	-7.9σ
10*	$27.4^{+4.9}_{-1.4}$	$-27.3^{+3.3}_{-2.0}$	10.6σ

Time Dependence – Small Scale



Time Dependence – Small Scale



Summary

- With over 300 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.
- No time dependence observed over the six year period in large- or small-scale structures.
- 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.

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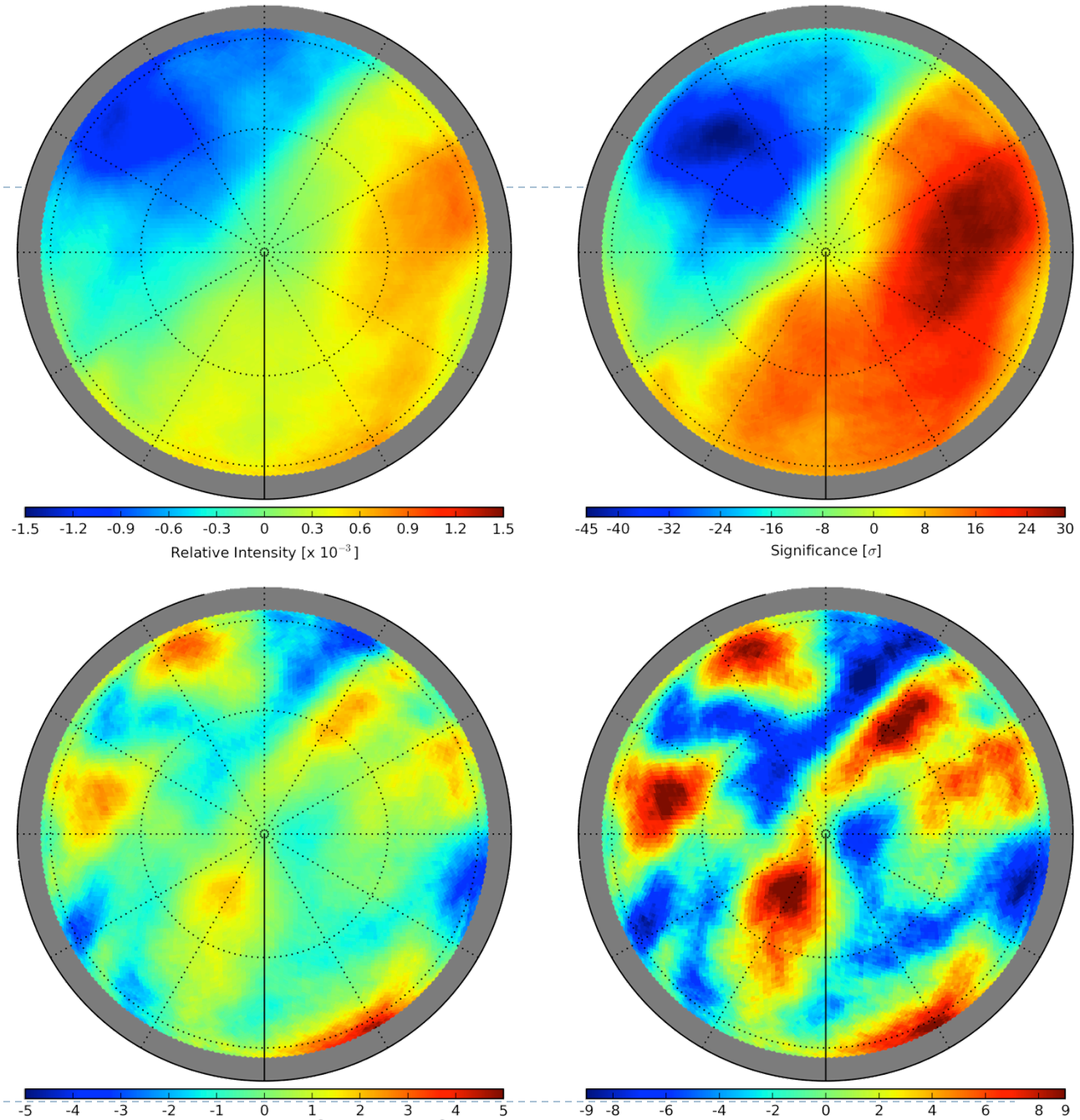
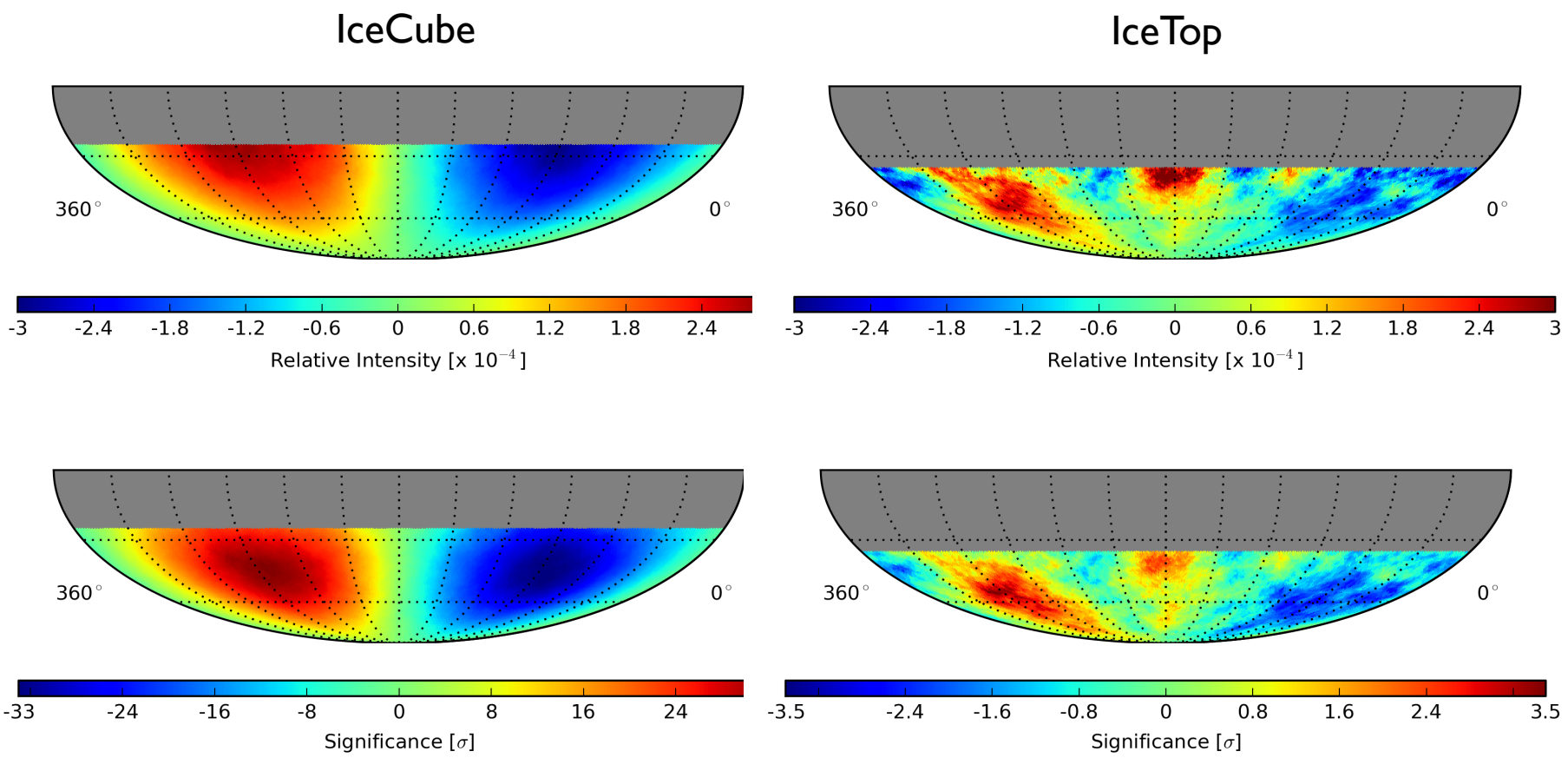
Polar Maps

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



IceCube Preliminary

Solar Dipole



IceCube Preliminary