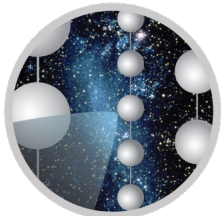


Observation of Cosmic Ray Anisotropy with Ten (Eleven) Years of Data

Rasha Abbasi
Paolo Desiati
Juan Carlos Díaz-Vélez
Frank McNally



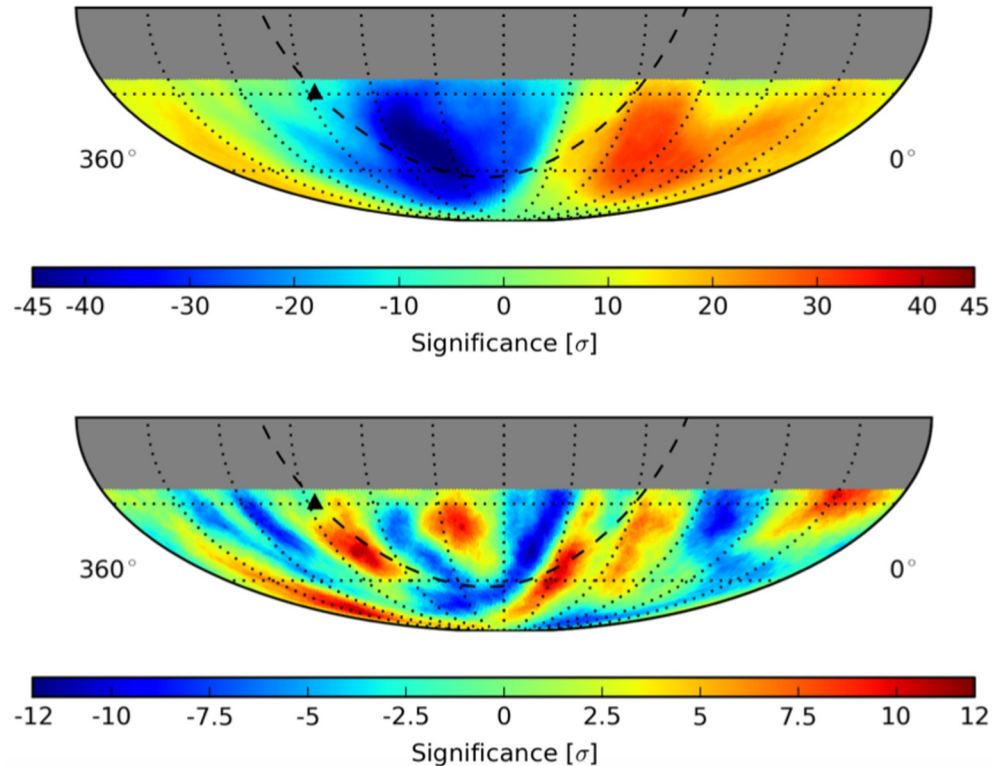
ICECUBE

TeVPA 2022



History

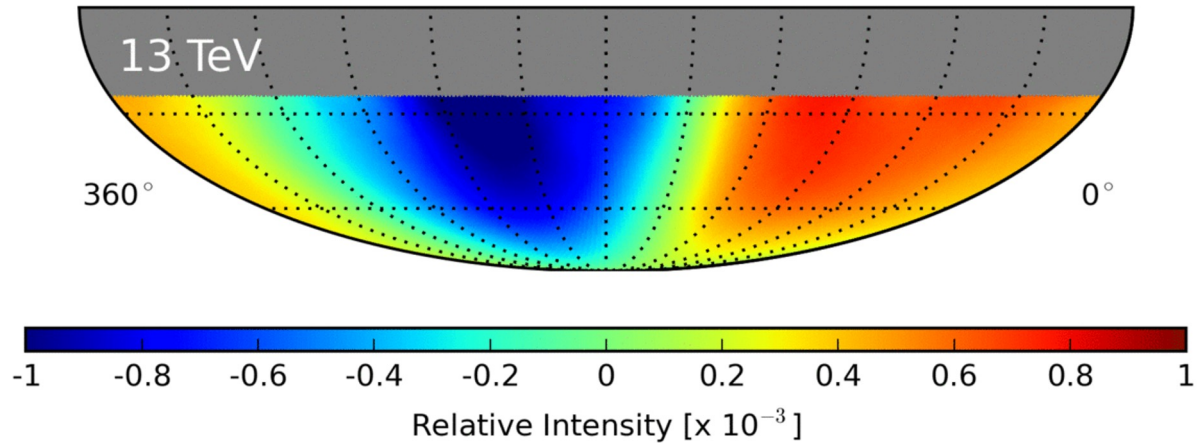
- Six years of data [ApJ 2016](#)
($\sim 3.2 \times 10^{11}$ events)
 - In-ice and surface (IceTop) events
 - Includes two years of partial detector configurations (IC59, IC79)
- Topics considered:
 - Large- and small-scale structure
 - Energy dependence
 - Angular power spectrum
 - Time dependence
- Nine year update [ICRC 2021](#)
($\sim 5.4 \times 10^{11}$ events)



Aartsen et al., "Anisotropy in Cosmic-Ray Arrival Directions in the Southern Hemisphere based on Six Years of Data from the IceCube Detector", *Astrophys.J.* **826** (2016) no.2, 220

Objective: Update Paper

1. **Improved statistics:** Eleven years of data in a consistent detector configuration (IC86)
($\sim 6.9 \times 10^{11}$ events)
2. **Improved simulation:**
Newer, dataset-specific,
increased statistics
3. **Improved systematics:**
Shift from detector to
calendar years

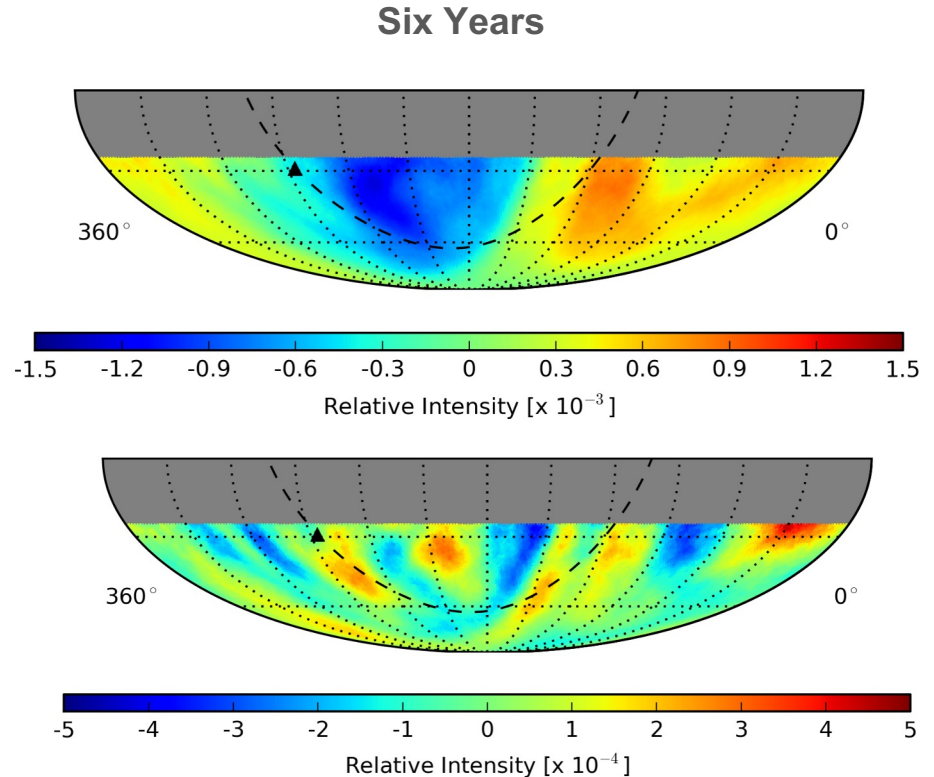


Energy dependence of large-scale anisotropy

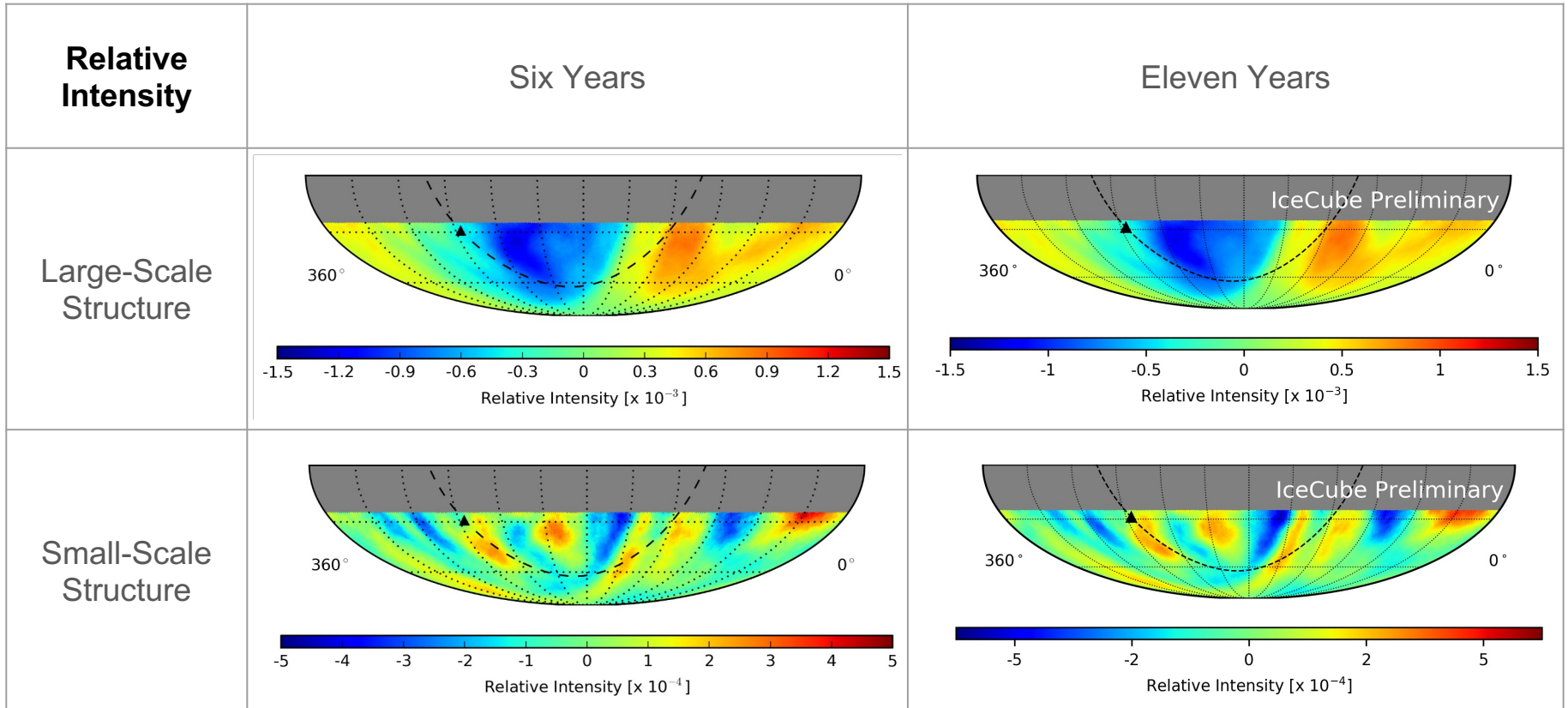
(Created from *Astrophys.J.* **826** (2016) no.2, 220 ([arXiv:1603.01227](https://arxiv.org/abs/1603.01227)))

How to Read a Map

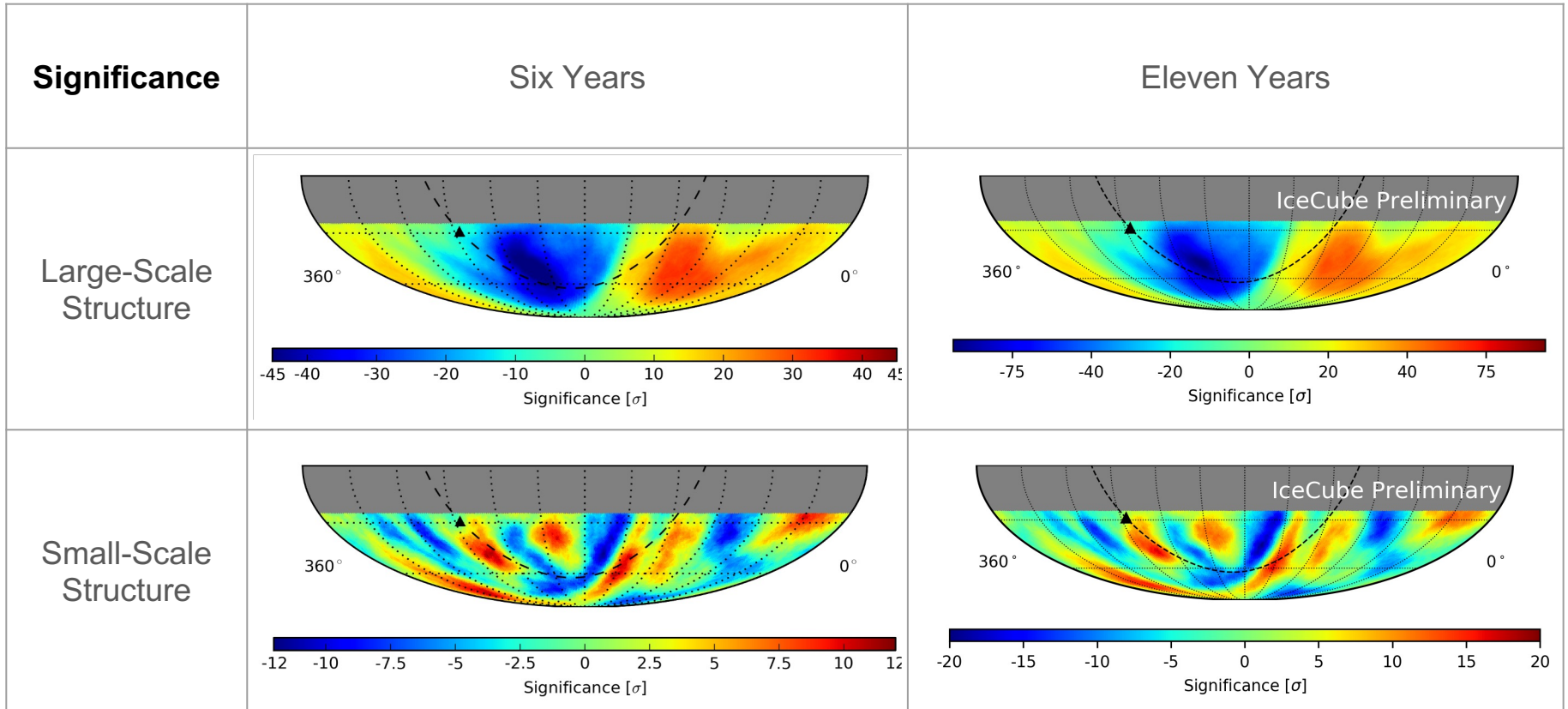
- Mollweide projections in equatorial coordinates
 - Background (reference) map produced using time-scrambling
 - 5° radius top-hat smoothing
 - **Small-scale map** created by subtracting dipole and quadrupole terms from a fit using spherical harmonics
 - Galactic plane and center indicated by dashed line and triangle, respectively



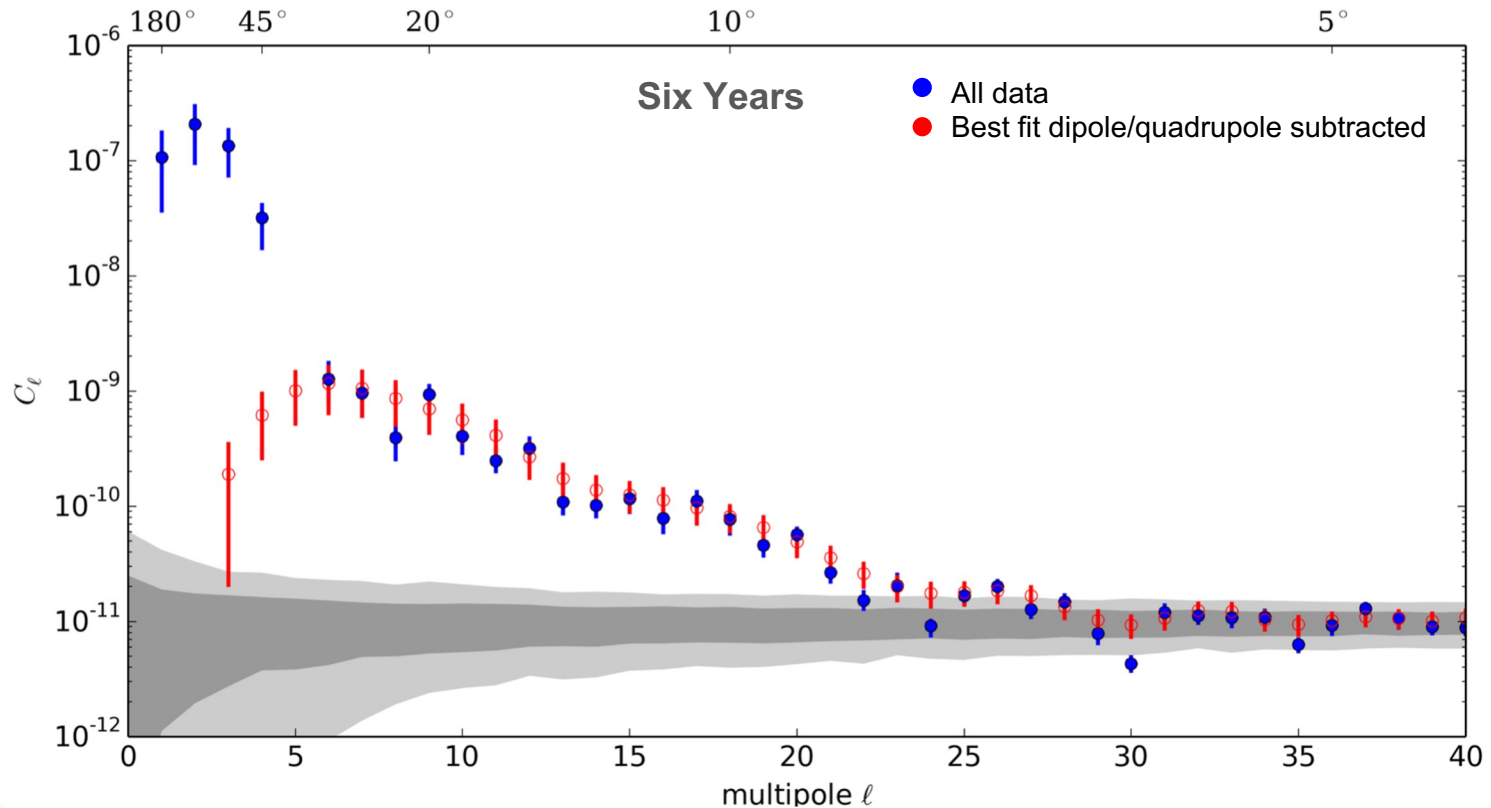
Increased Statistics: Large- and Small-Scale Structure



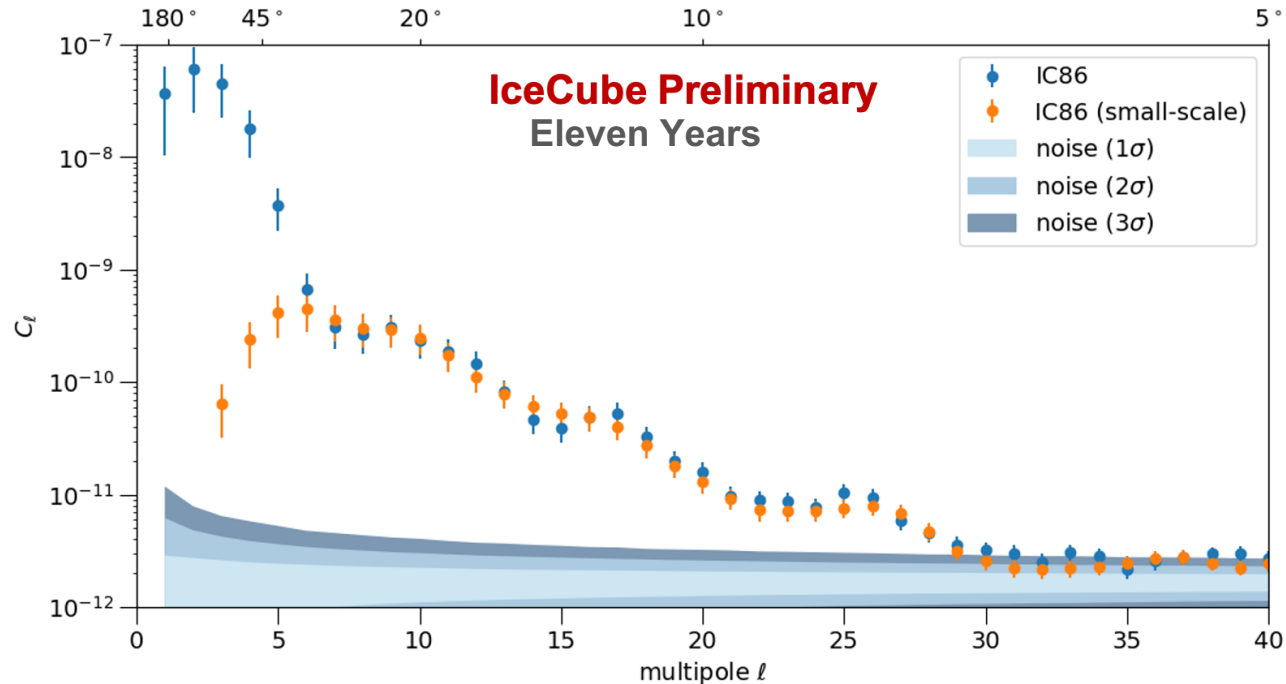
Increased Statistics: Large- and Small-Scale Structure



Increased Statistics: Angular Power Spectrum



Increased Statistics: Angular Power Spectrum



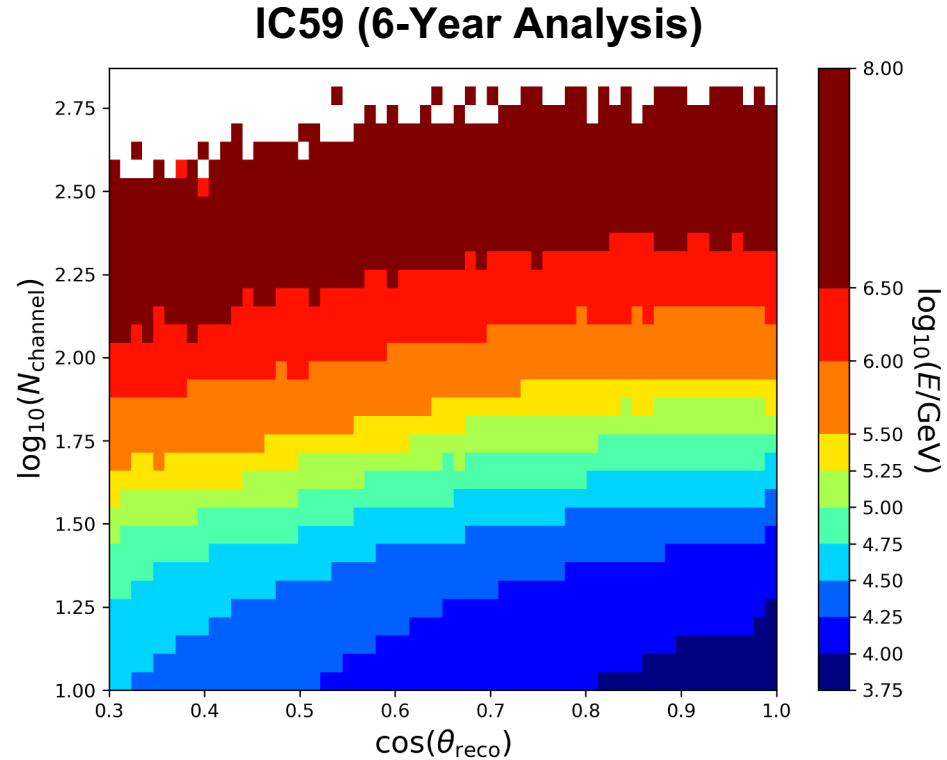
Angular power spectrum for large- and small-scale structure maps. Error bars represent the spread of calculated C_ℓ values for maps randomly generated from the observed C_ℓ values. The bands at the bottom represent 68%, 95%, and 99.7% containment of power spectra produced from an isotropic signal.

Shown for 11 years of in-ice data: 2011-05-13 – 2022-05-13

C. Cochling ('23)

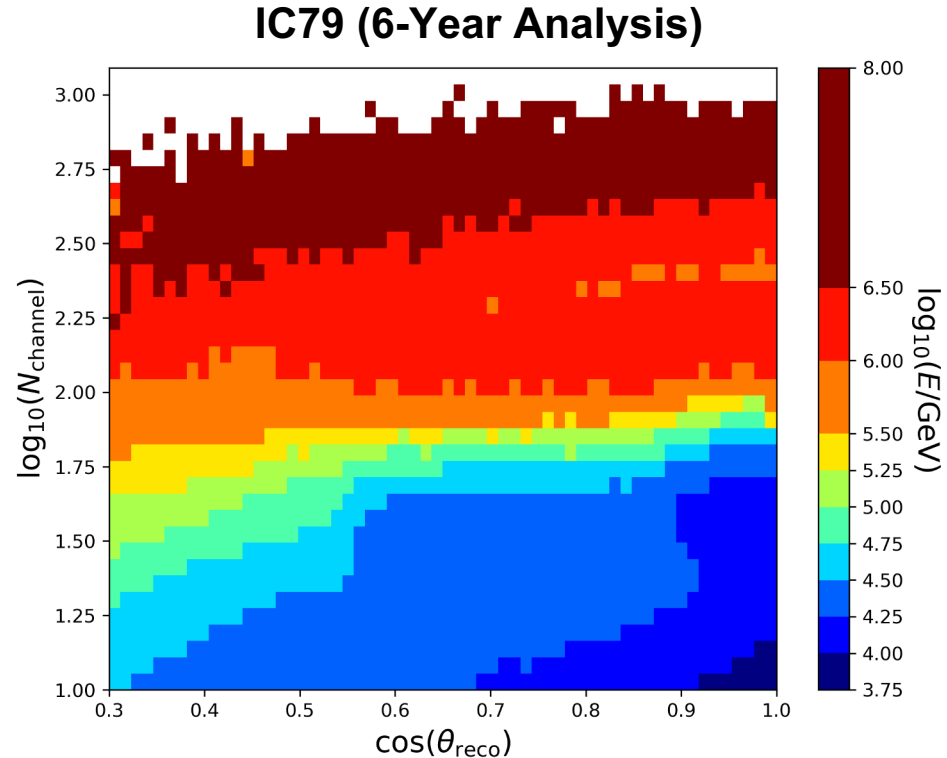
Improved Simulation: Energy Estimation

- Simulation binned based on number of digital optical modules hit and cosine of reconstructed zenith angle
- Median value for each bin shown in plot
- Given hits and reconstructed zenith of event, use splined version to determine median energy value
- **Previous concern:** limited detector-specific simulation



Improved Simulation: Energy Estimation

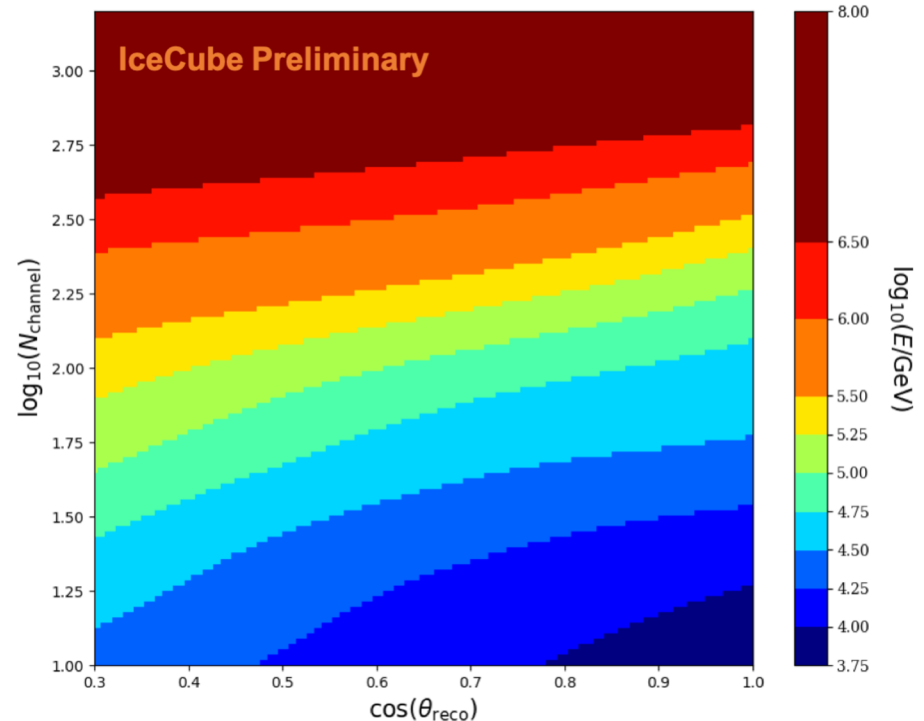
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Improved Simulation: Energy Estimation

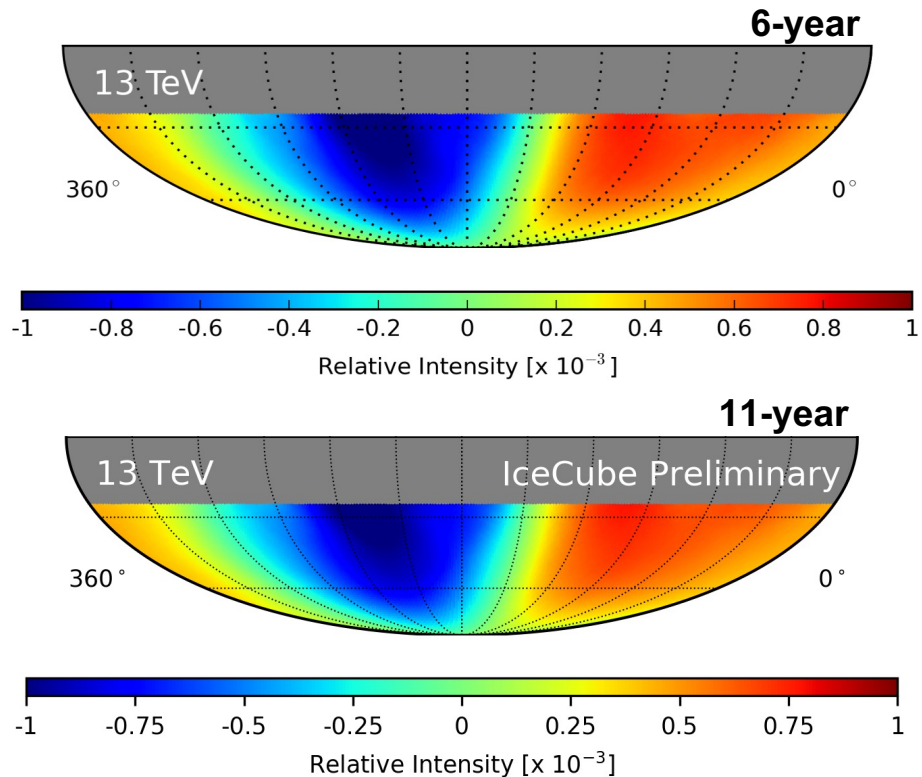
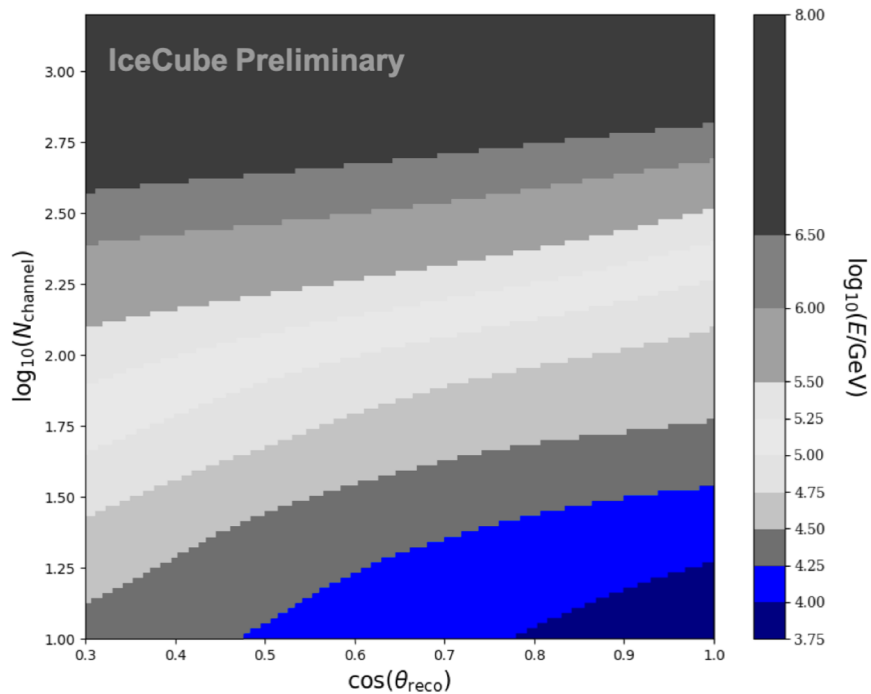
- Simulation binned based on number of digital optical modules hit and cosine of reconstructed zenith angle
- Median value for each bin shown in plot
- Given hits and reconstructed zenith of event, use splined version to determine median energy value
- Previous concern: limited detector-specific simulation
- **New simulation:** events that pass SMT08 trigger, IC86 only (splined version shown)

IC86 (11-Year Analysis)

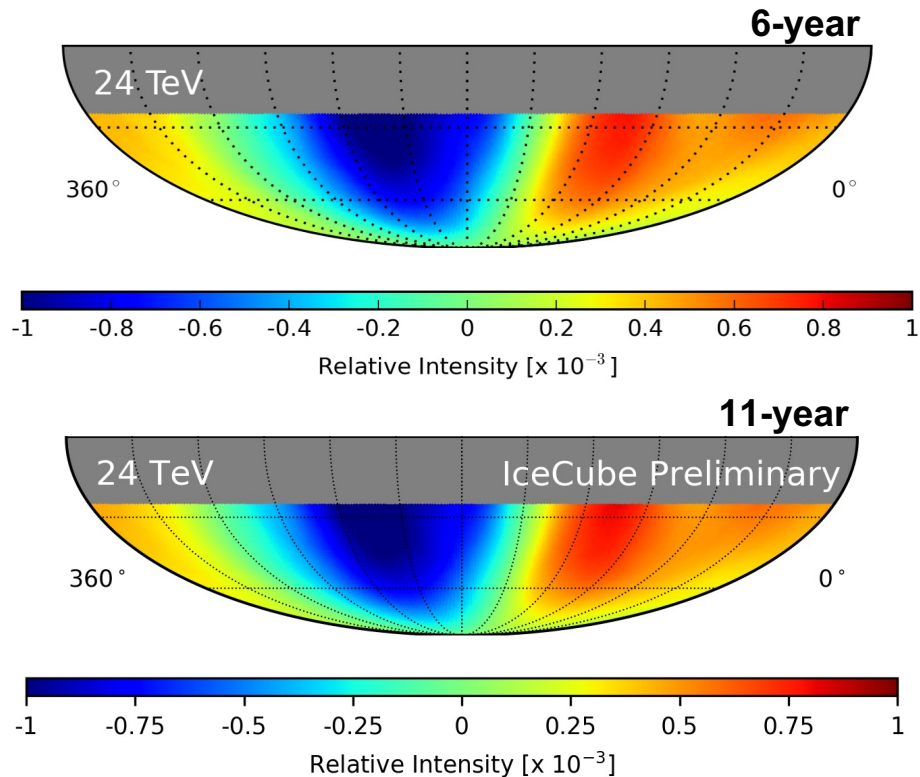
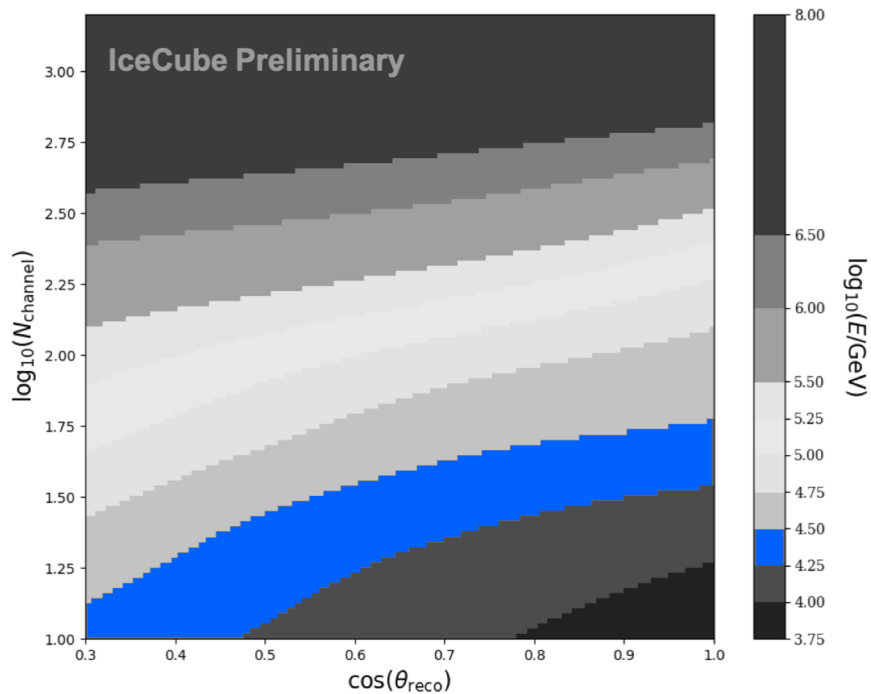


A. Thorpe ('21)

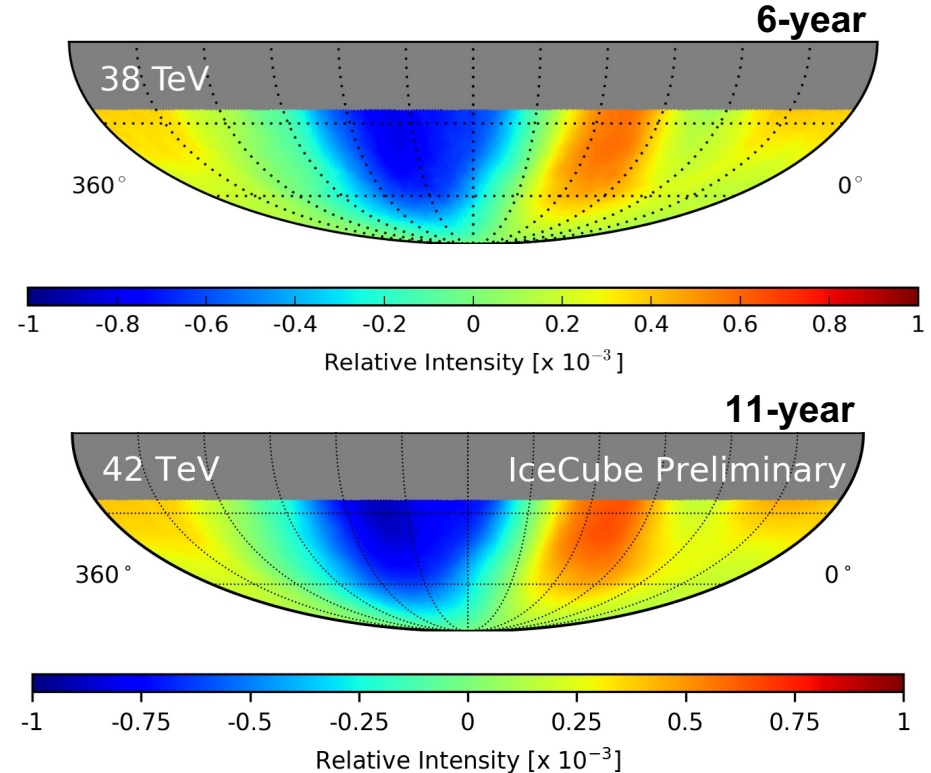
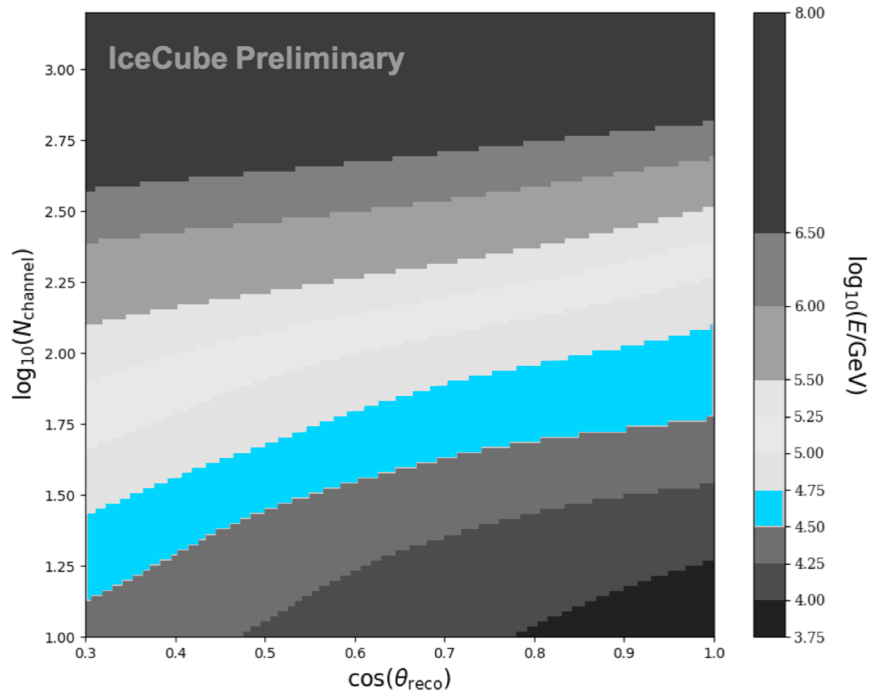
Improved Statistics/**Simulation**: Energy Maps



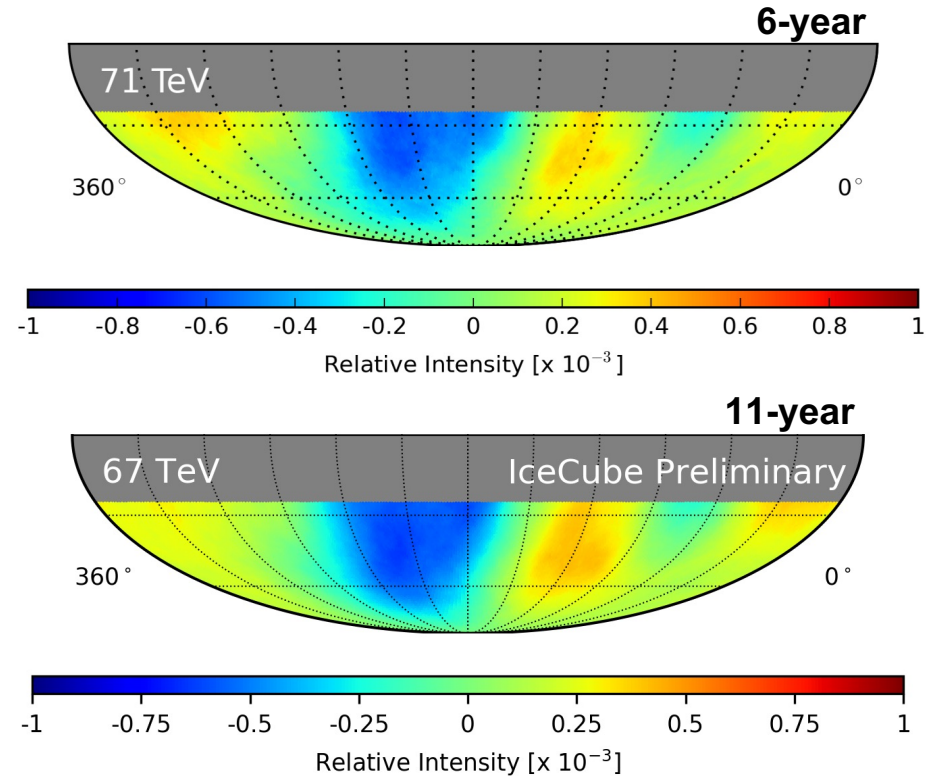
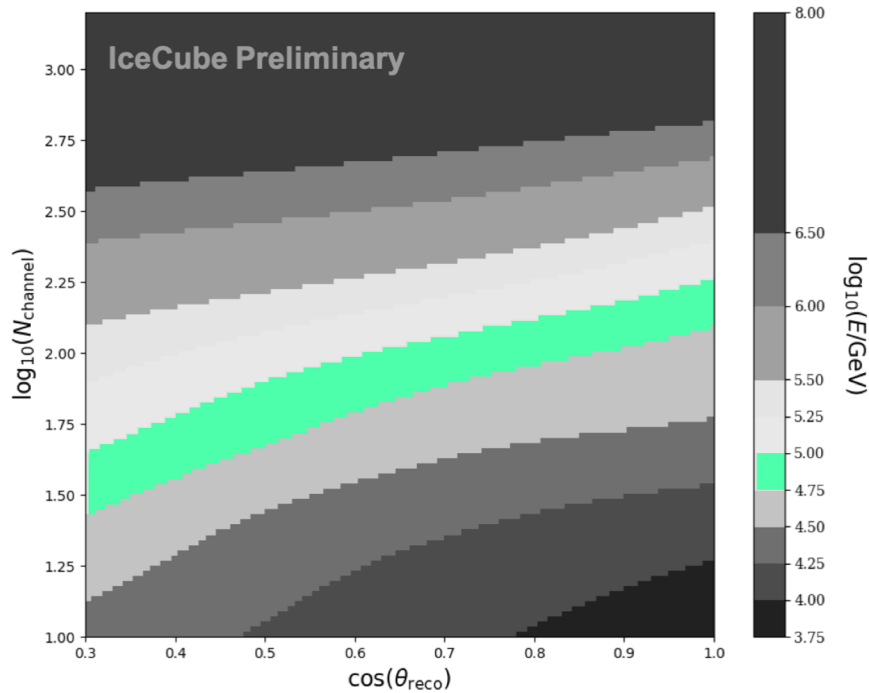
Improved Statistics/Simulation: Energy Maps



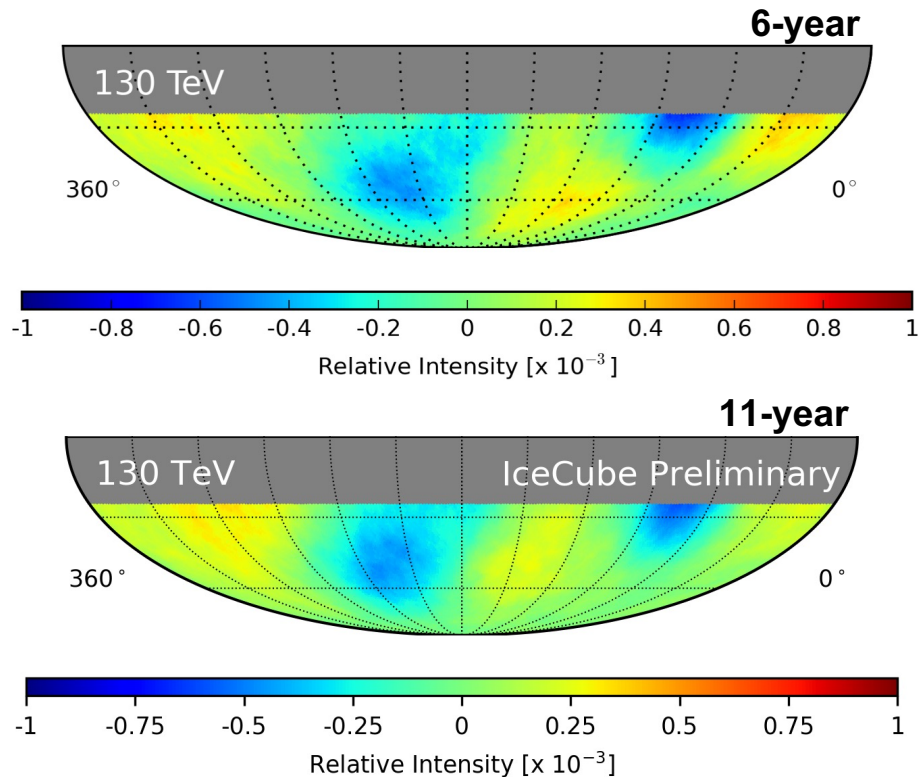
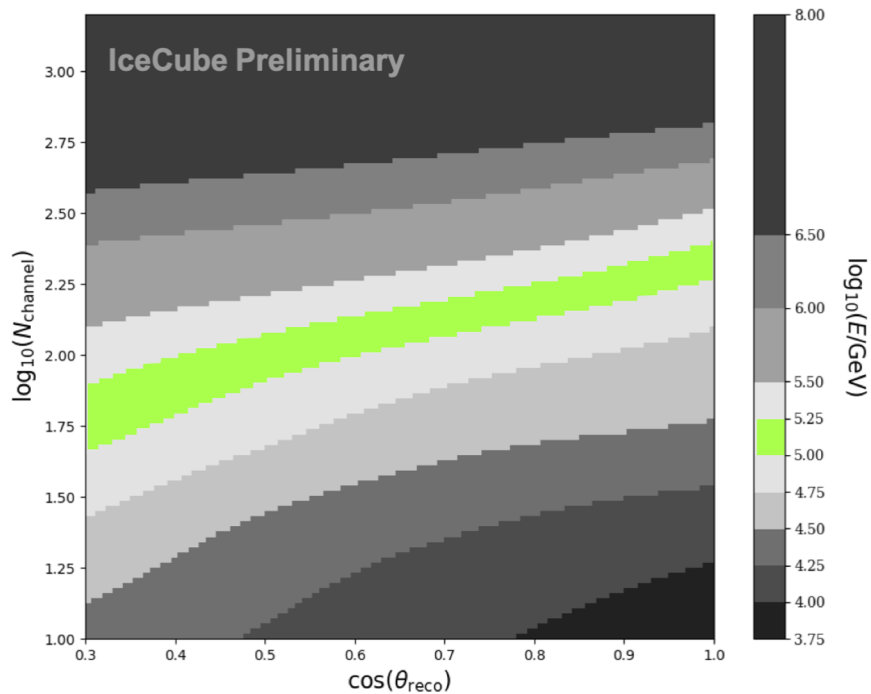
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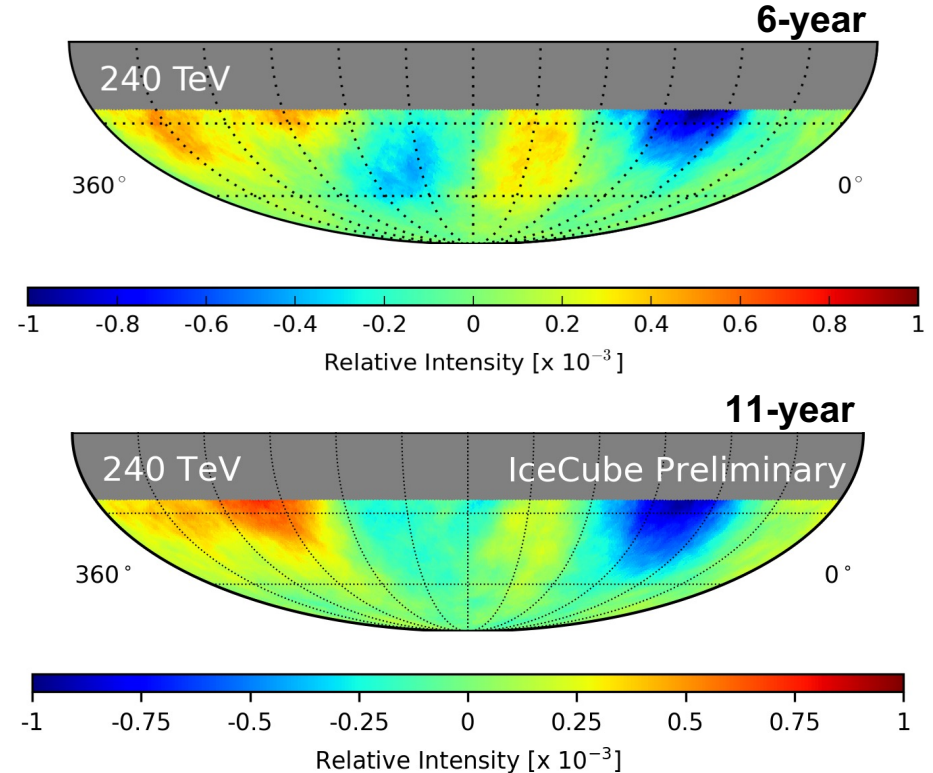
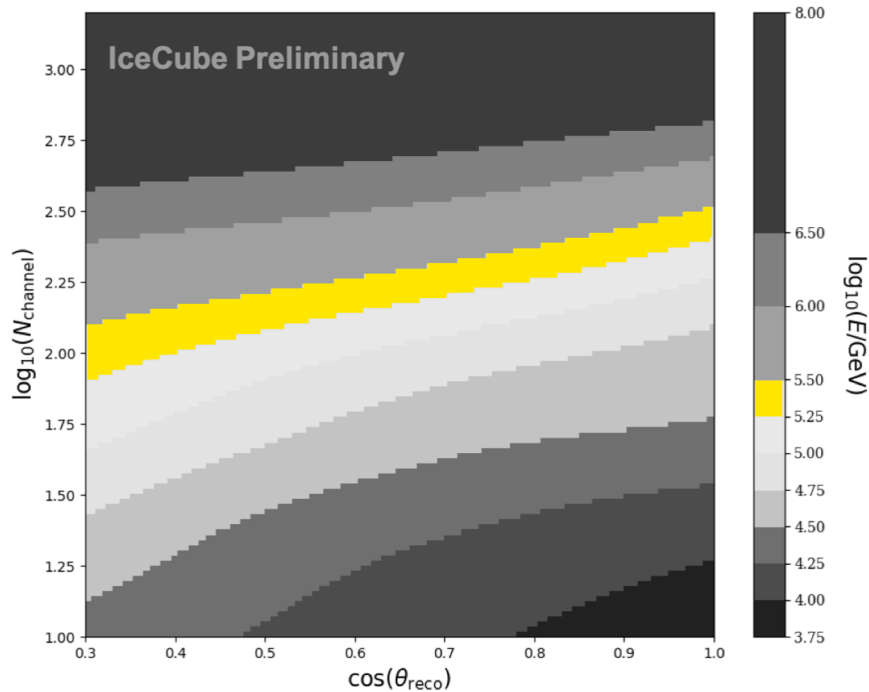
Improved Statistics/Simulation: Energy Maps



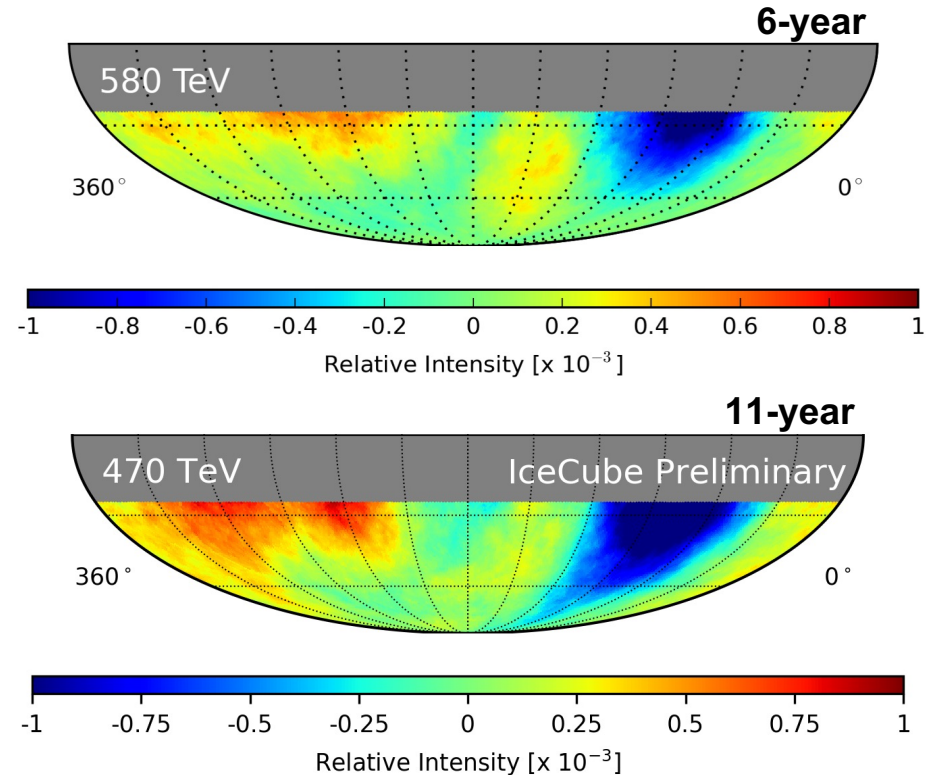
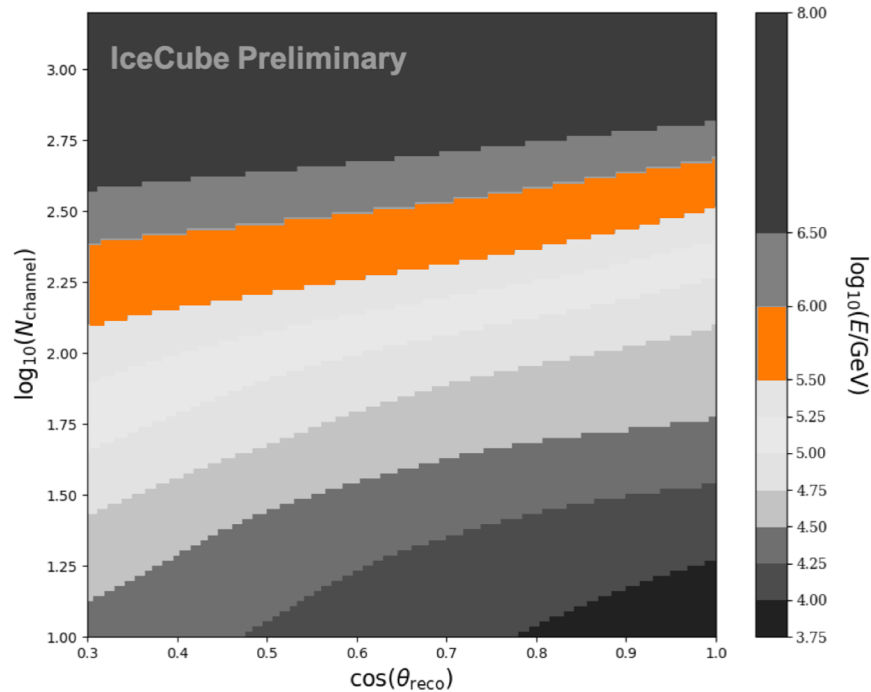
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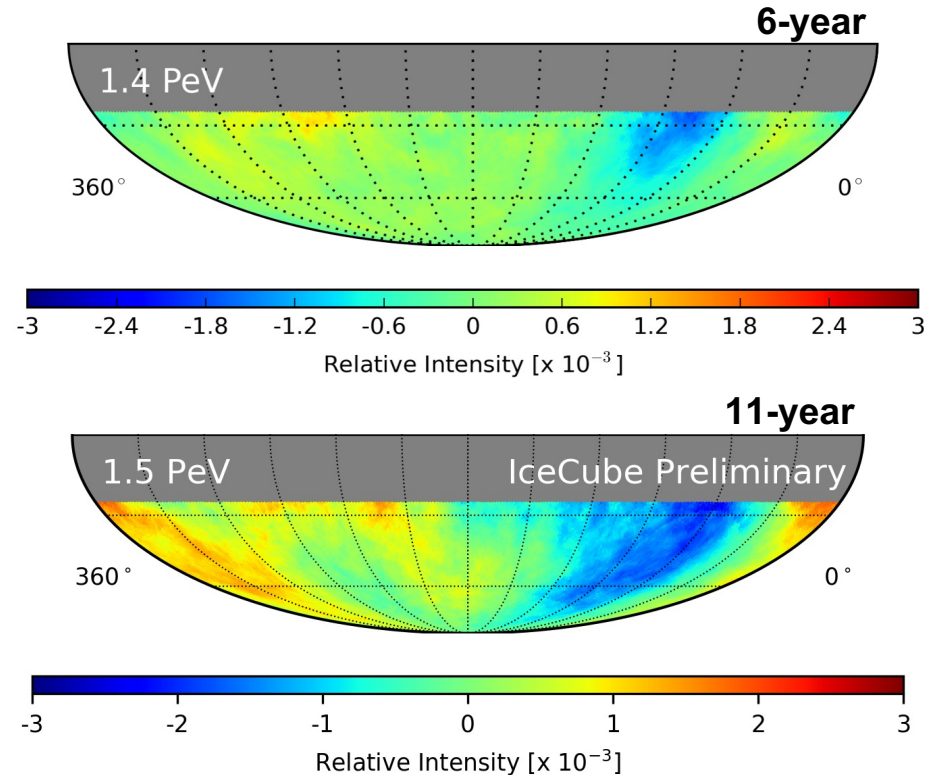
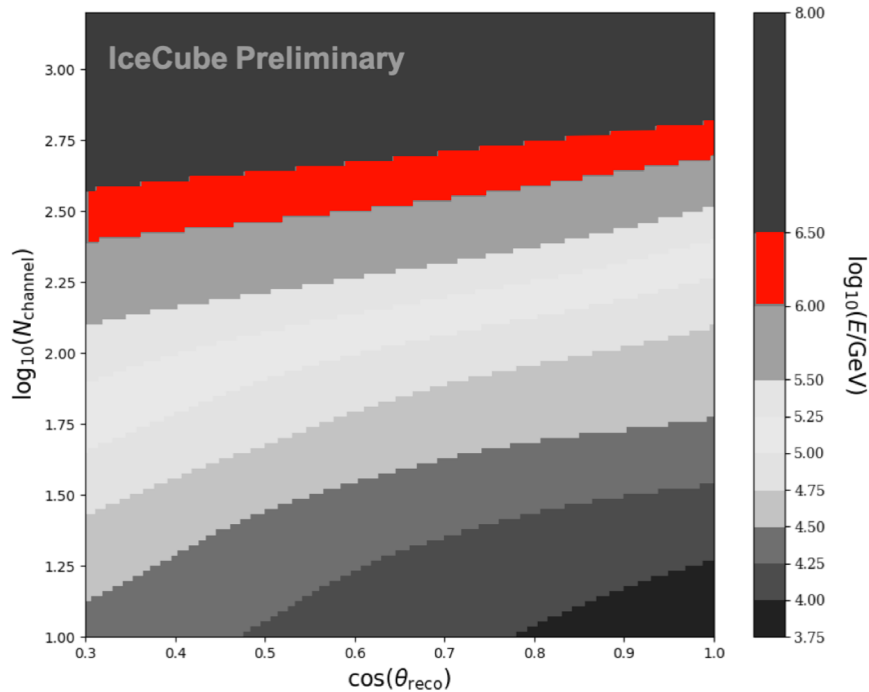
Improved Statistics/Simulation: Energy Maps



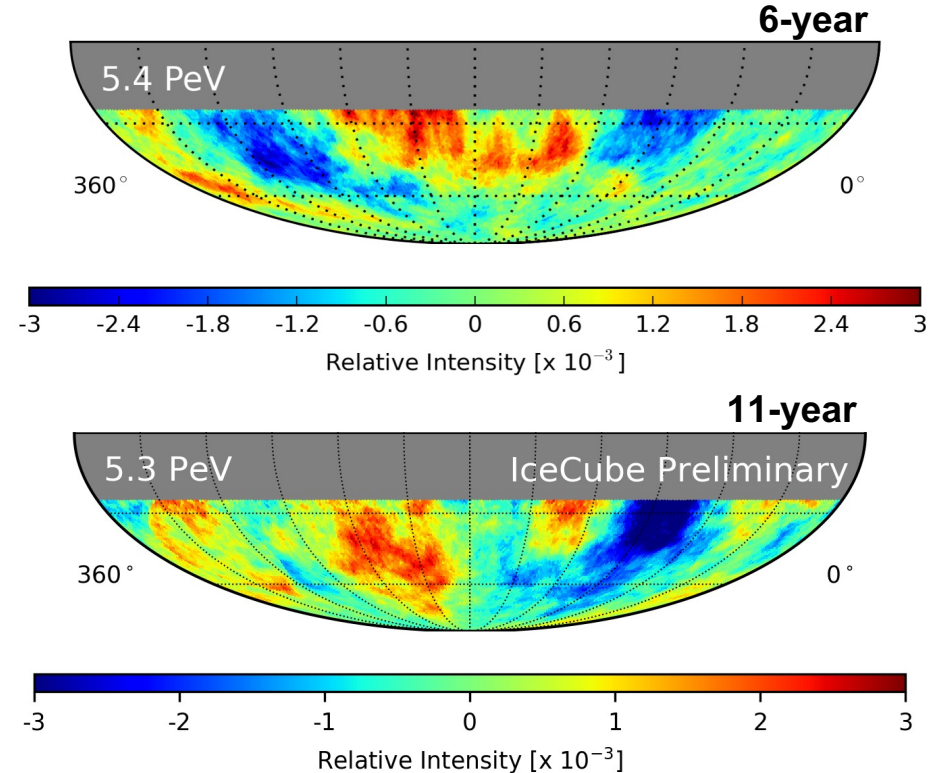
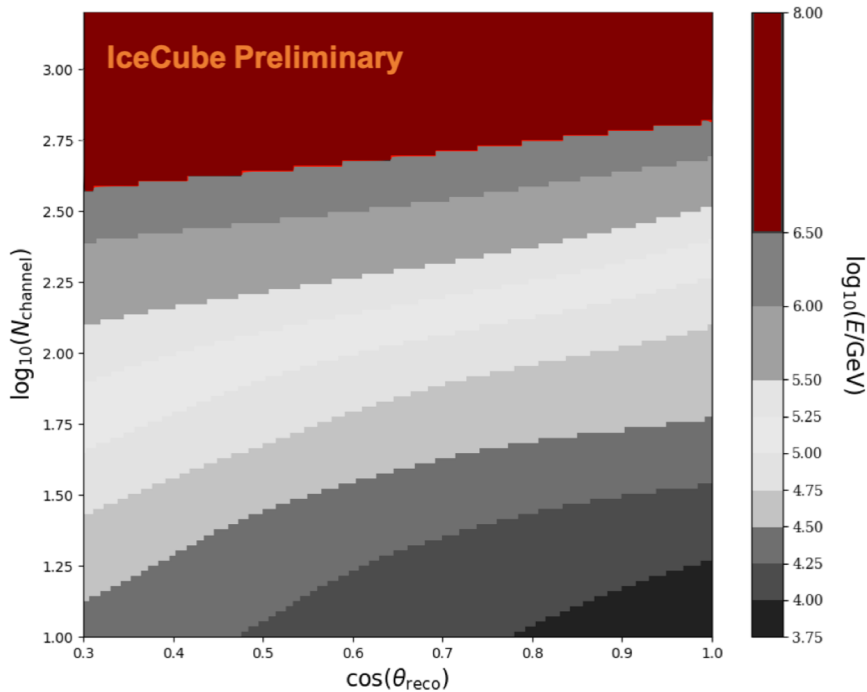
Improved Statistics/Simulation: Energy Maps



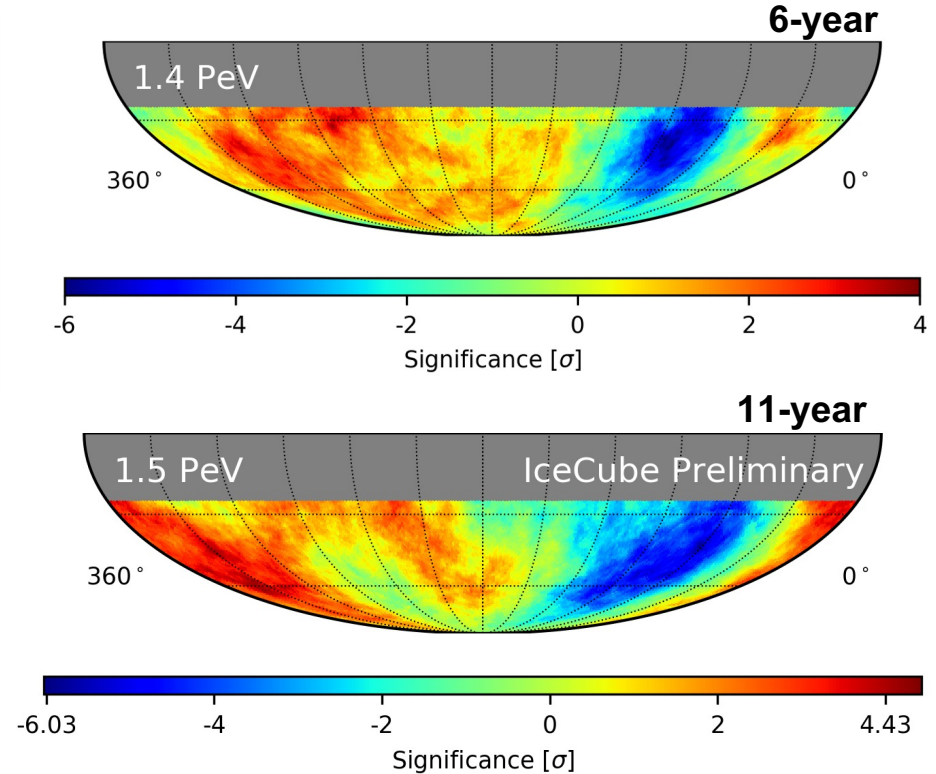
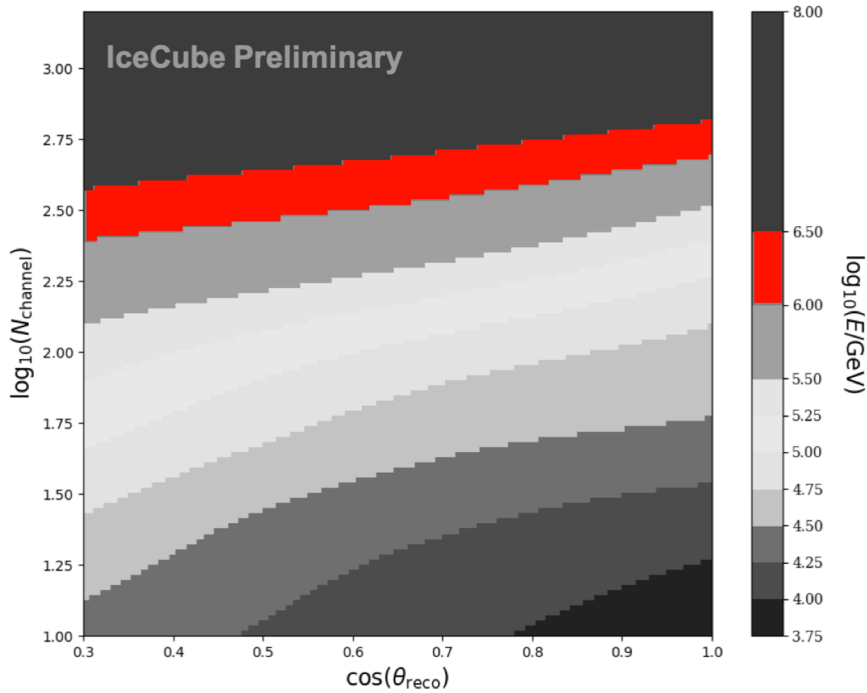
Improved Statistics/Simulation: Energy Maps



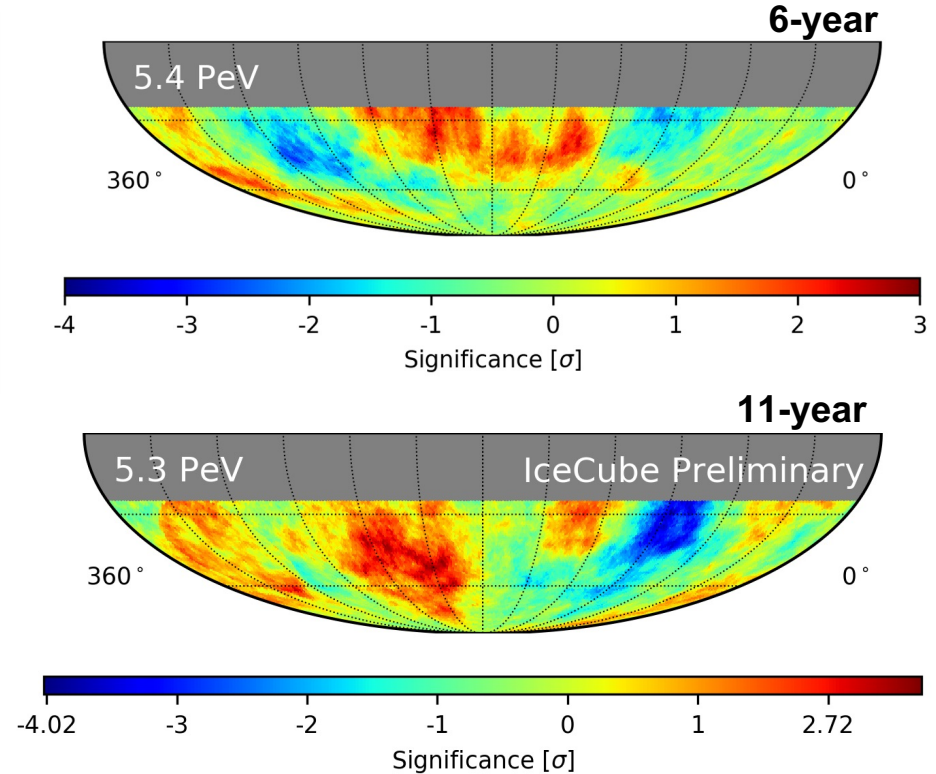
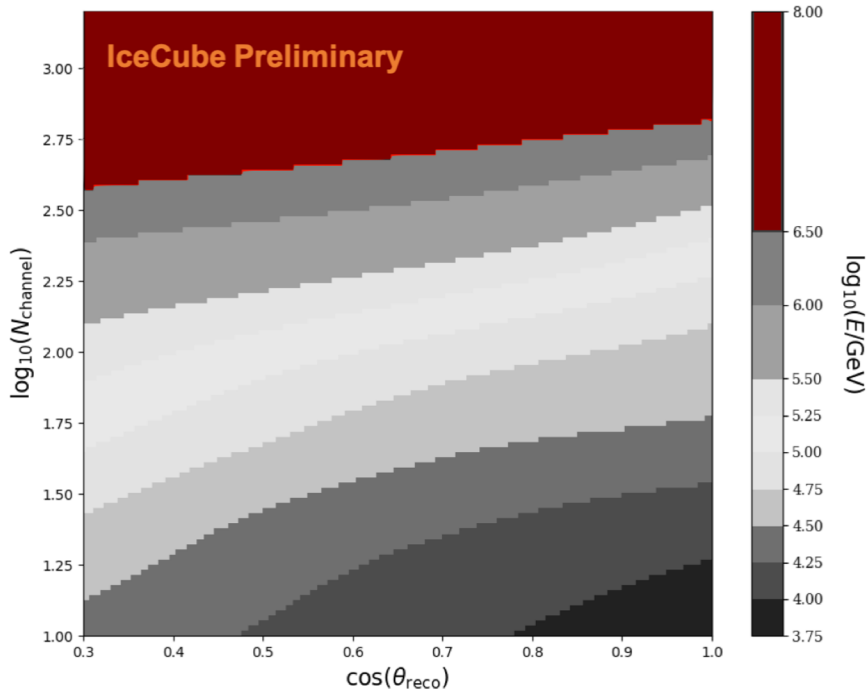
Improved Statistics/Simulation: Energy Maps



Improved Statistics/Simulation: High-Energy Significance

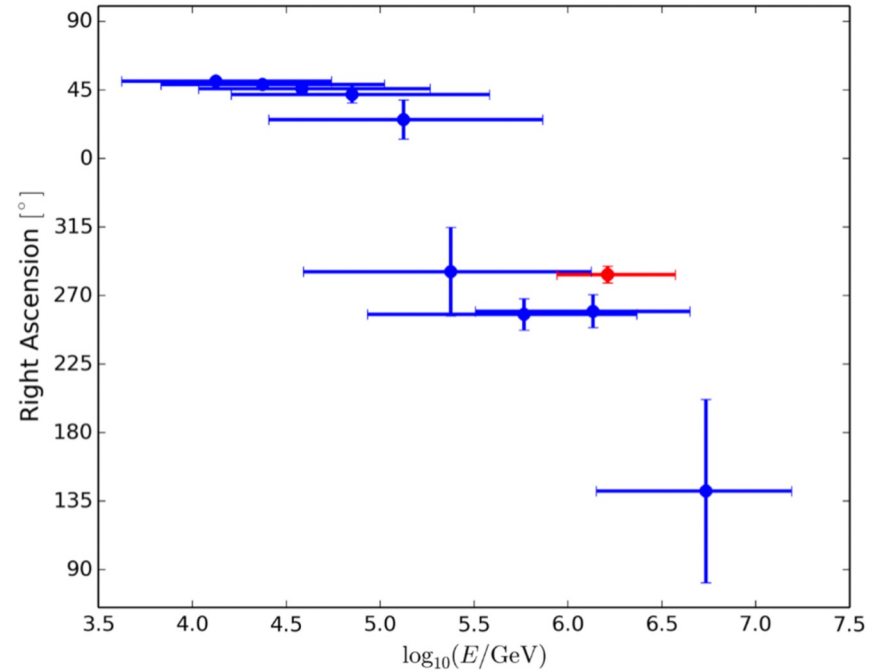
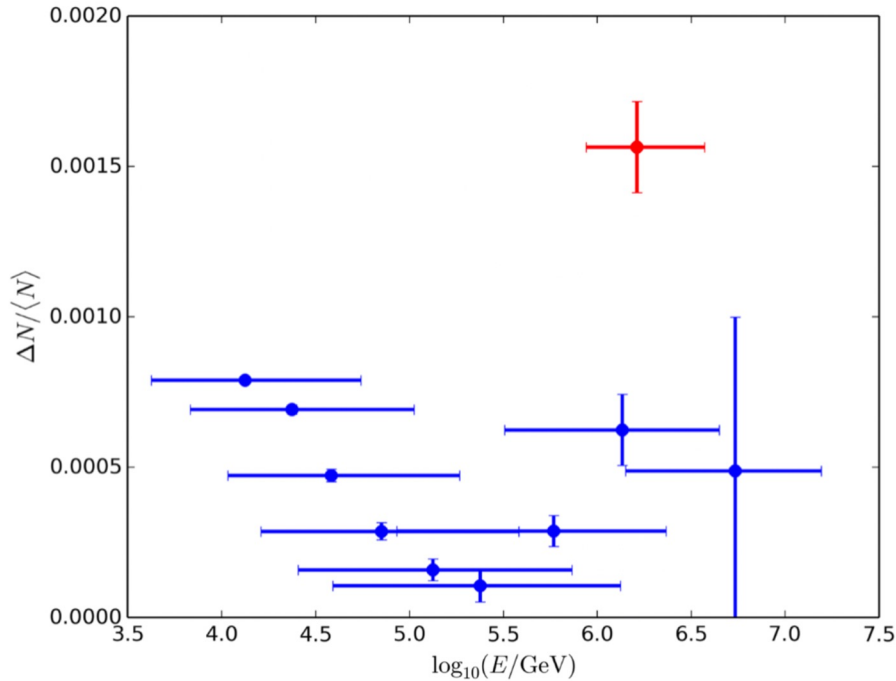


Improved Statistics/Simulation: High-Energy Significance



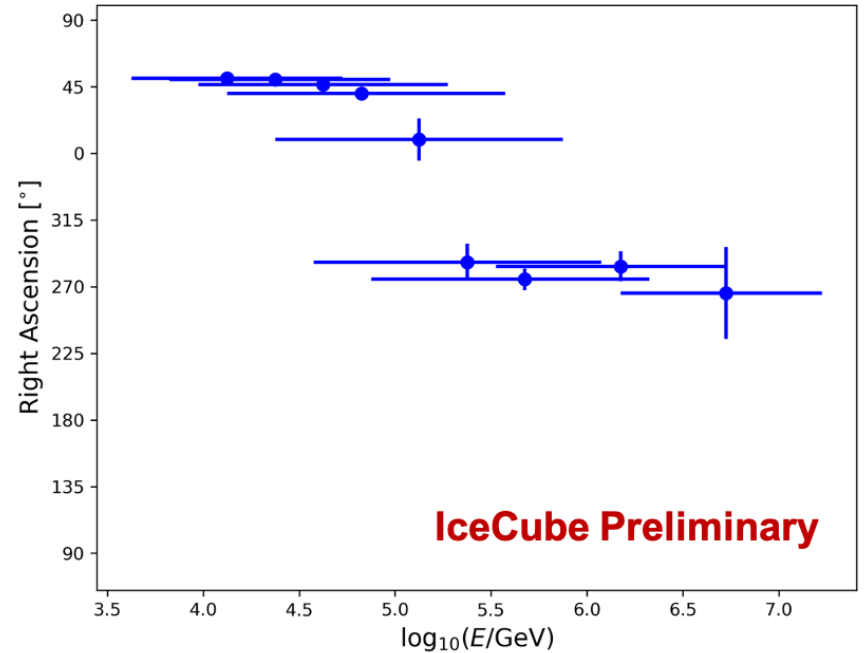
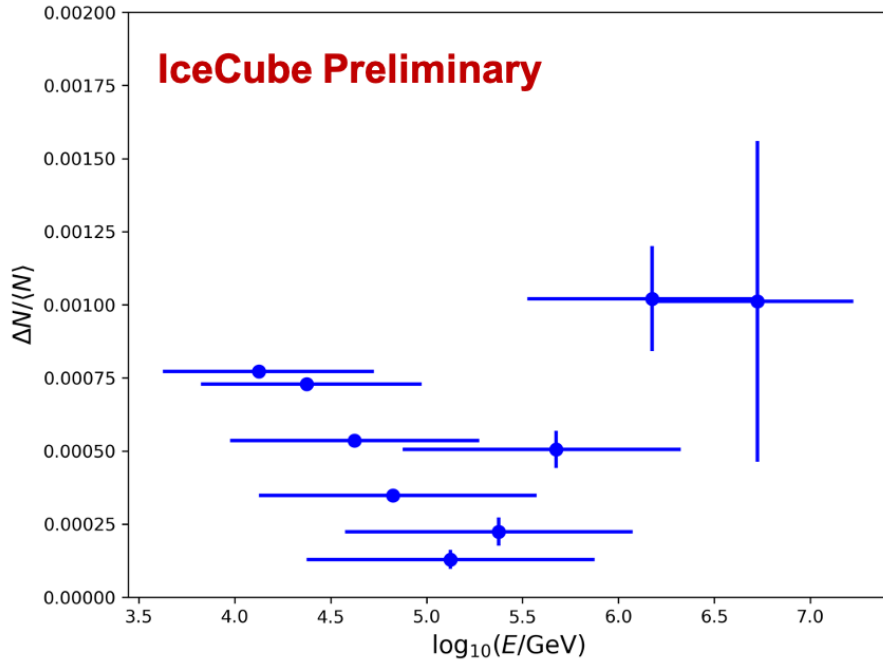
Improved Statistics/Simulation: Dipole Phase & Amplitude

Six Years



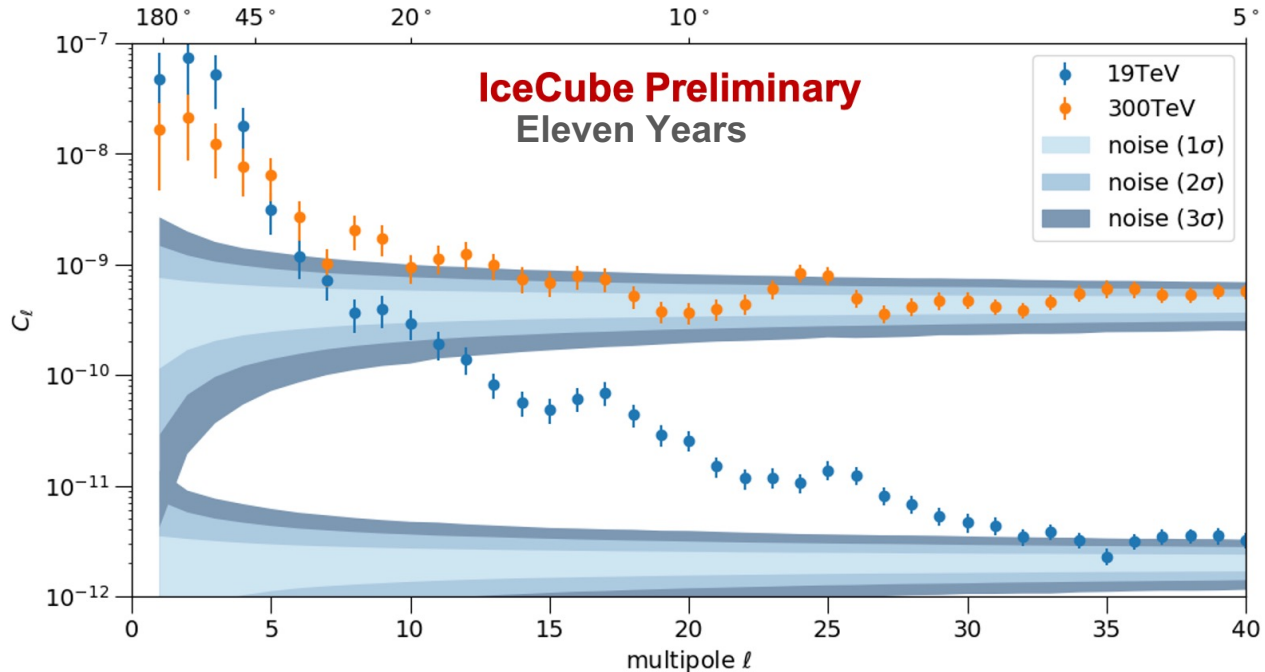
Improved Statistics/**Simulation**: Dipole Phase & Amplitude

Eleven Years



Best-fit dipole phase and amplitude as a function of energy. Relative intensity maps were projected along right ascension, then fit with a sinusoidal series up to octupole terms. Horizontal error bars represent 68% containment of each reconstructed energy bin (from simulation). Vertical error bars are statistical. Shown for 11 years of in-ice data: 2011-05-13 – 2022-05-13

Improved Statistics/**Simulation**: Angular Power Spectrum

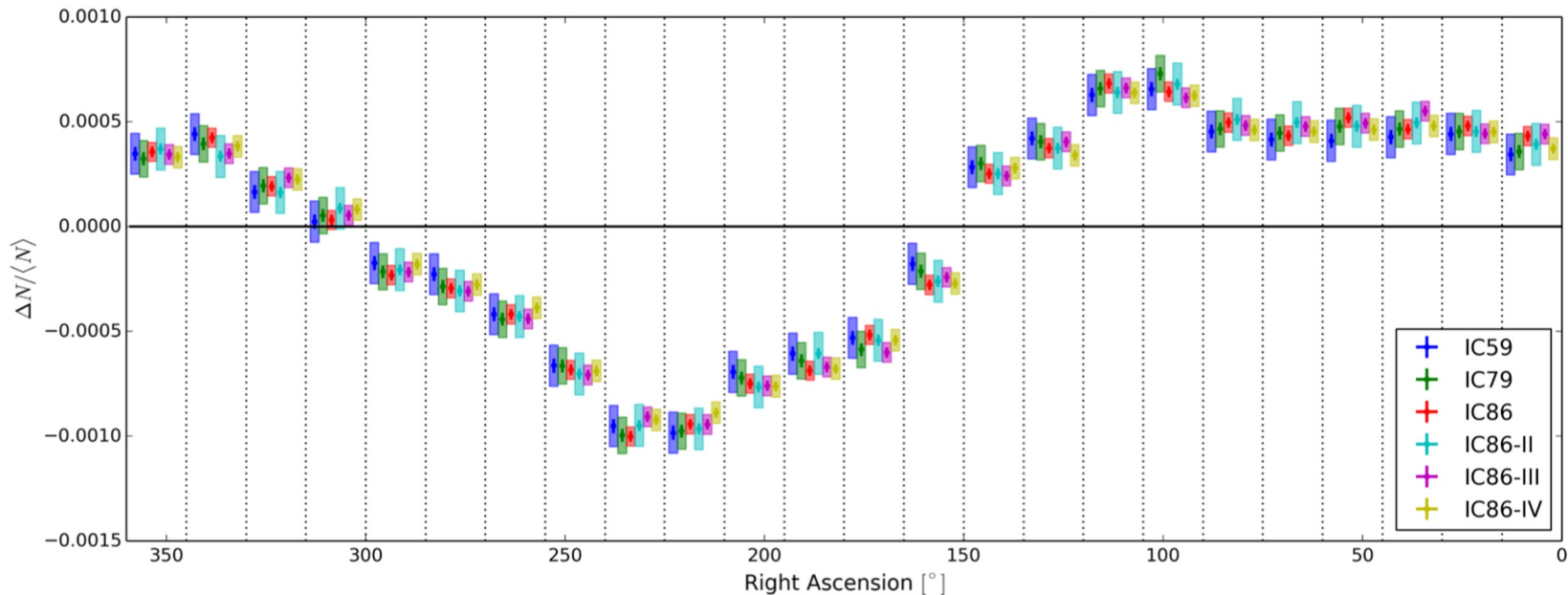


Angular power spectra for low (19 TeV) and high (300 TeV) energy bins. Error bars represent the spread of calculated C_l values for maps randomly generated from the observed C_l values. The noise bands represent 68%, 95%, and 99.7% containment of power spectra produced from an isotropic signal, and differ due to the differences in event statistics. Shown for 11 years of in-ice data: 2011-05-13 – 2022-05-13

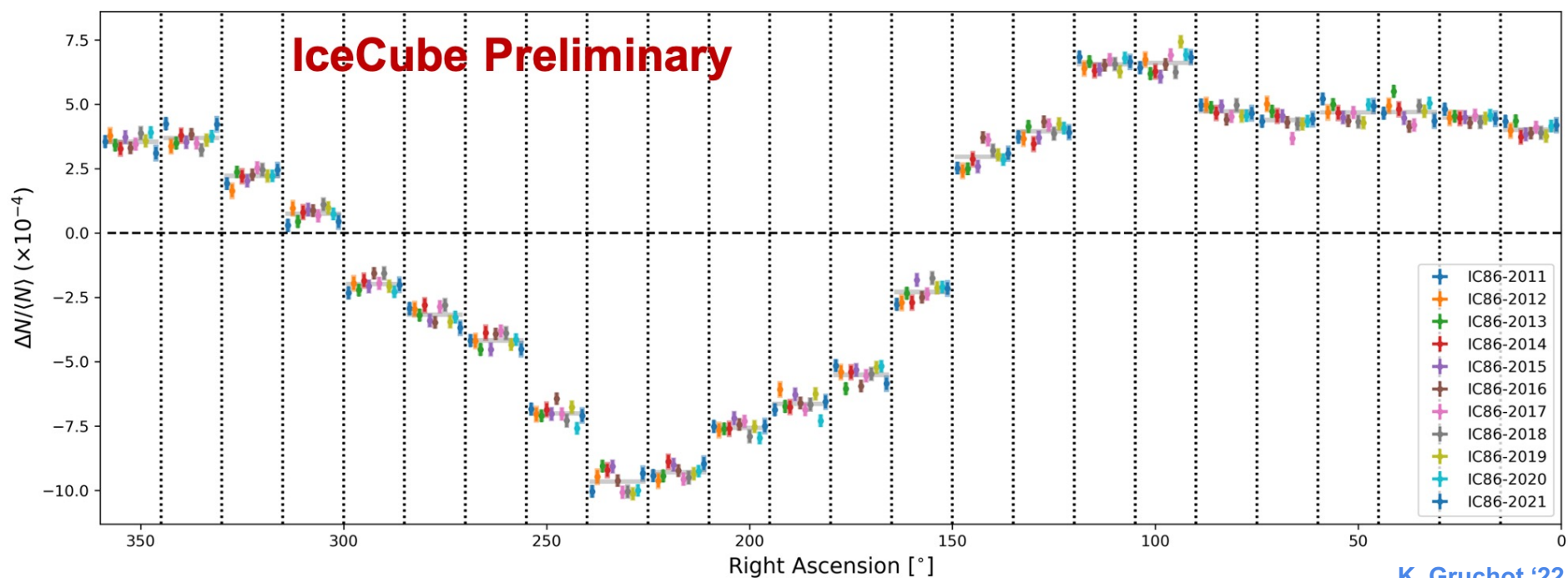
Improved Systematics

Goal: look for **time-dependence** of sidereal signal

- One-dimensional projection of relative intensity along right ascension, by detector year
- **Six-year sample**, all events included



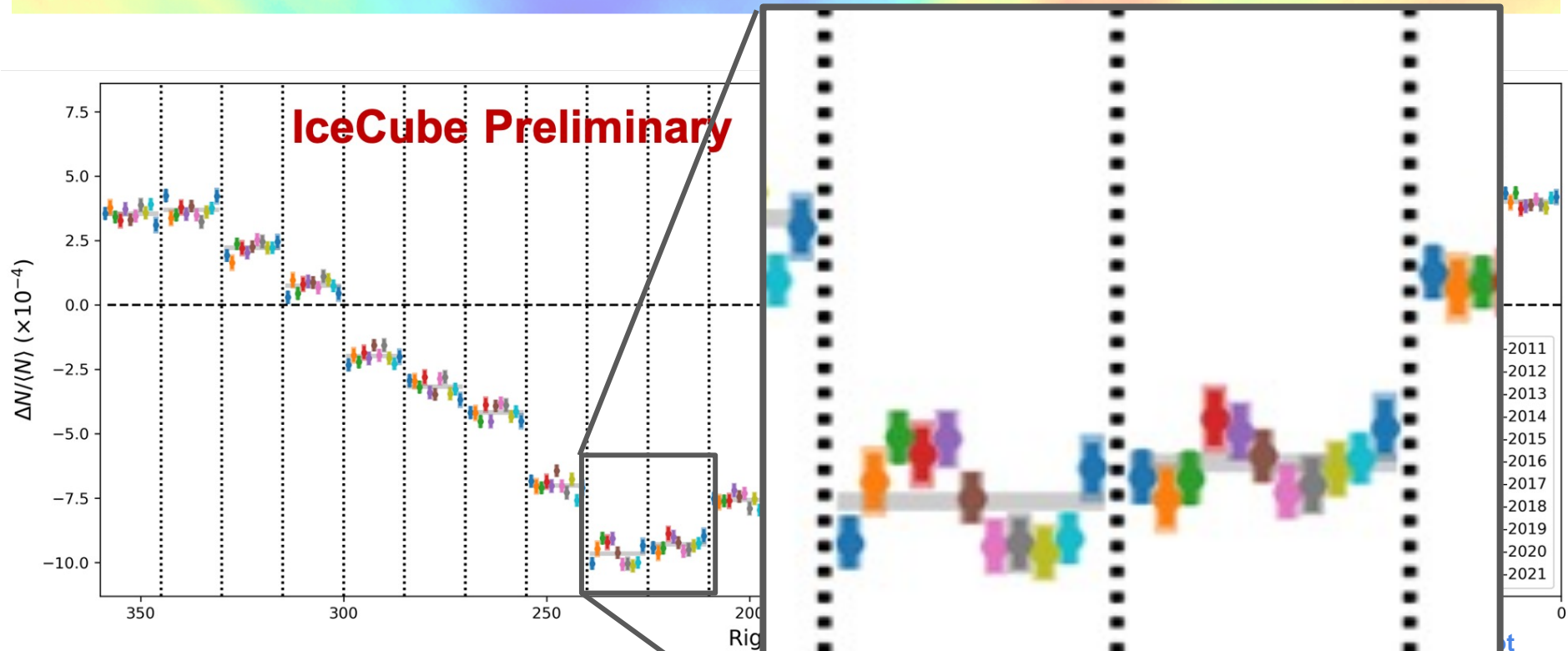
Improved Systematics: Sidereal 1D Projection



K. Gruchot '22

One-dimensional projection of relative intensity as a function of right ascension, split by calendar year. Solid error bars are statistical. Shaded error bars are systematic and calculated from the anti-sidereal anisotropy for each year. Because the annual anti-sidereal distributions appear random, the rms value is used.

Improved Systematics: Sidereal 1D Projection



One-dimensional projection of relative intensity as a function of
Shaded error bars are systematic and calculated from the anti

distributions appear random, the rms value is used.

Summary



Results

- Analysis has improved **statistics**, **simulation**, and **systematics**
- Structures in large-scale, small-scale, and energy-split maps appear consistent, with higher significance
- Better agreement between dipole phase and amplitude at highest energies
- Time-dependent trend possible in some right ascension bins

Upcoming Work

- Time modulation, anti- and extended-sidereal frames
- Anisotropy in IceTop
- Joint IceTop / TALE analysis
- Joint in-ice / HAWC analysis
- Spectral anisotropy

Coauthors: Undergraduate Personnel

- **Mercer**

Christina Cochling

Alexis Hardy

Emily Schmidt

Alex Simmons

Andrew Thorpe

Angular power spectrum

Event rate analysis

Time gap analysis

Systematic checks across detector seasons

Energy estimation and true energy distributions

- **Loyola**

Katherine “Jo” Gruchot

Andrew Moy

Will Hays

Joe Summers

Grace Bratude

Anisotropy time dependence

Anisotropy time/energy dependence

Events livetime/rates

IceTop simulation/Data comparison

IceTop Data processing/analysis

- **UW-Madison**

Hannah Woodward

(Summer 2020 REU)

(University of Virginia)

Extended- and anti-sidereal distributions

Comparing detector and calendar years

Backup Slides

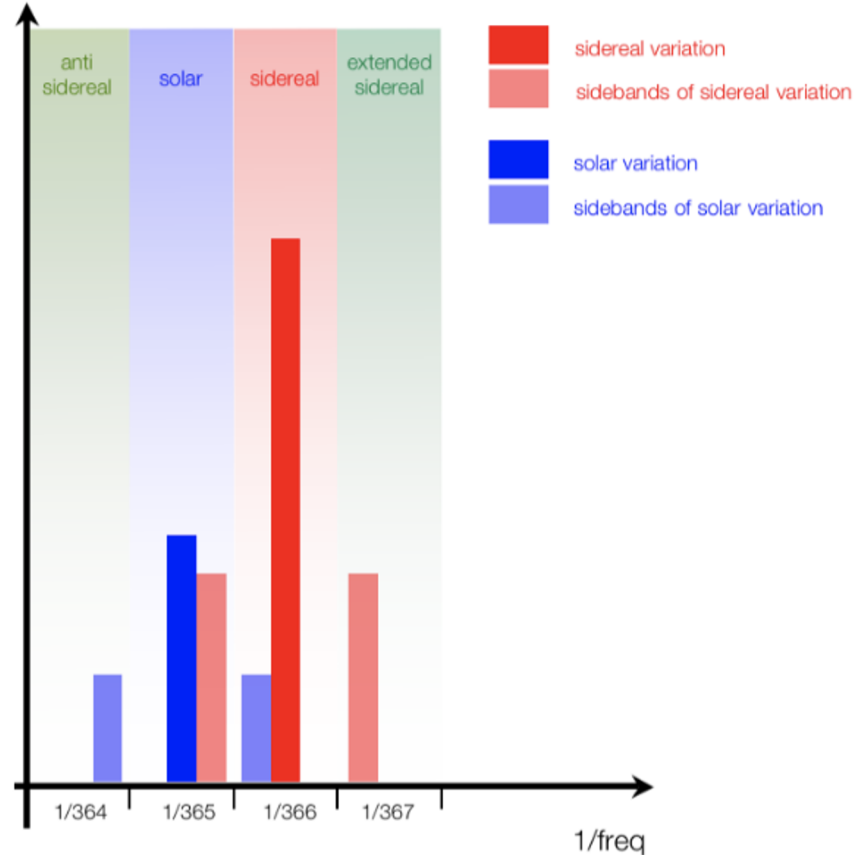
Improved Systematics

Review: Yearly Variation

- Consider four time frames:

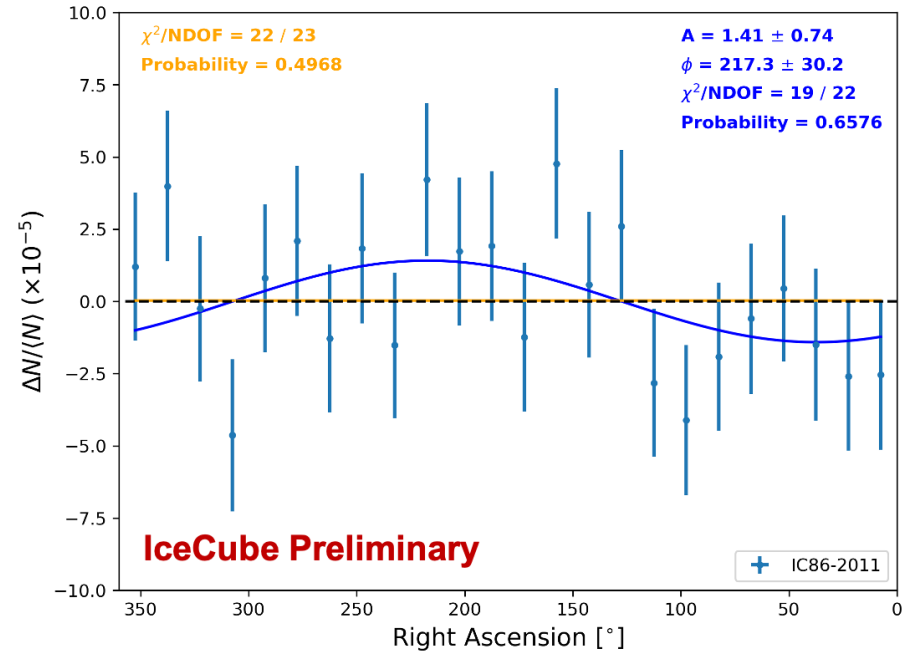
	(hrs/day)	(days/year)	
○ Anti-sidereal		364	24:04
○ Solar		365	24:00
○ Sidereal		366	23:56
○ Extended-sidereal		366	23:52
		377	

- What is the mutual influence of the signals in the solar and sidereal frames?
- **Anti-sidereal**: effect of solar on sidereal
- **Extended-sidereal**: effect of sidereal on solar



Improved Systematics: Calendar Years

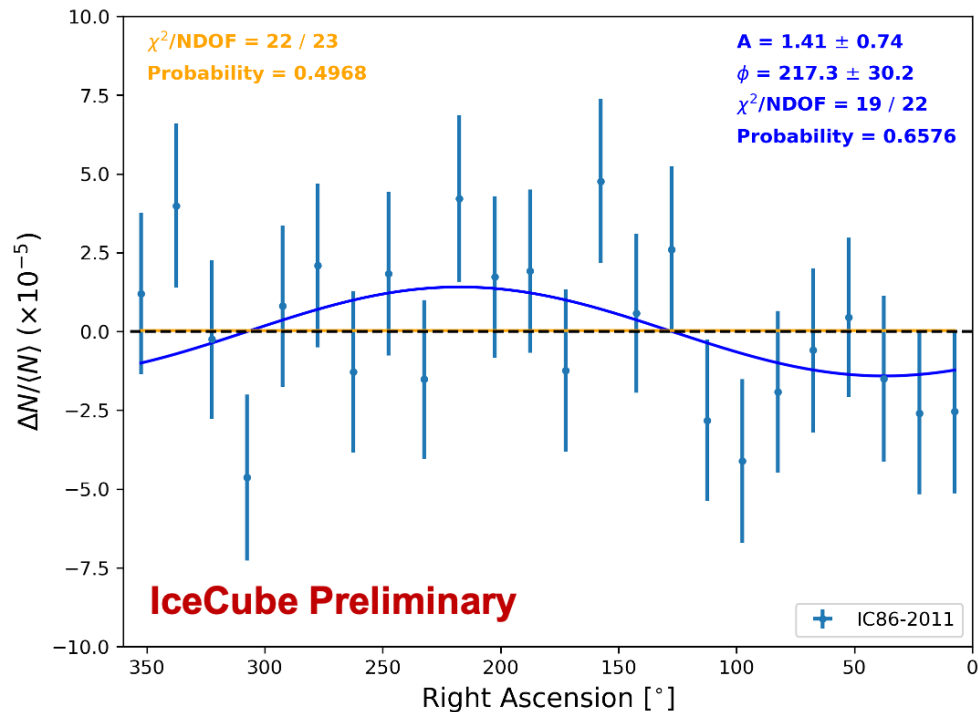
- **Signal due to annual orbit should cancel out over a solar year**
 - Systematic uncertainty in sidereal signal derived from anti-sidereal frame
- “Detector years” inconsistent in size
- **Consistent detector configuration:** systematic uncertainty calculated using calendar years
 - Shown: IC86-2011
 - Amplitude $\sim 100\times$ smaller than sidereal



One-dimensional projection of anti-sidereal relative intensity as a function of right ascension. Parameters for the best-fit dipole (blue) and flat line (orange) are shown. Shown for 2011-05-13 – 2012-05-13

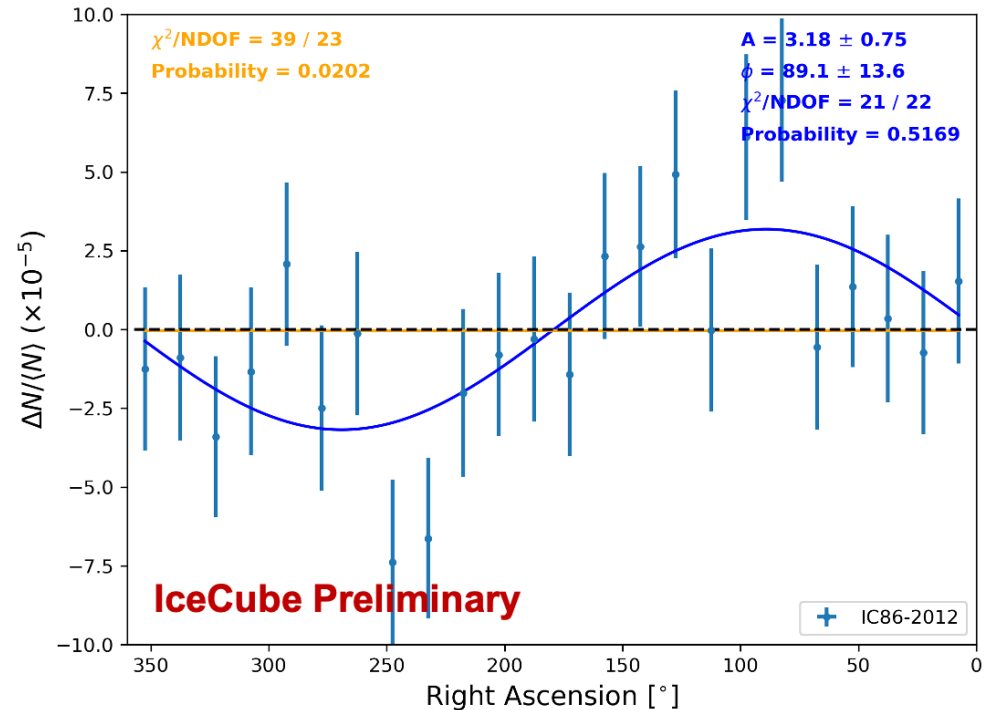
Improved Systematics: Calendar Years

- **Anti-sidereal:** measures influence of solar signal on sidereal anisotropy
 - Systematic uncertainty in sidereal signal derived from anti-sidereal frame
- **Shown:**
 - Best-fit to a flat line at 0 (orange)
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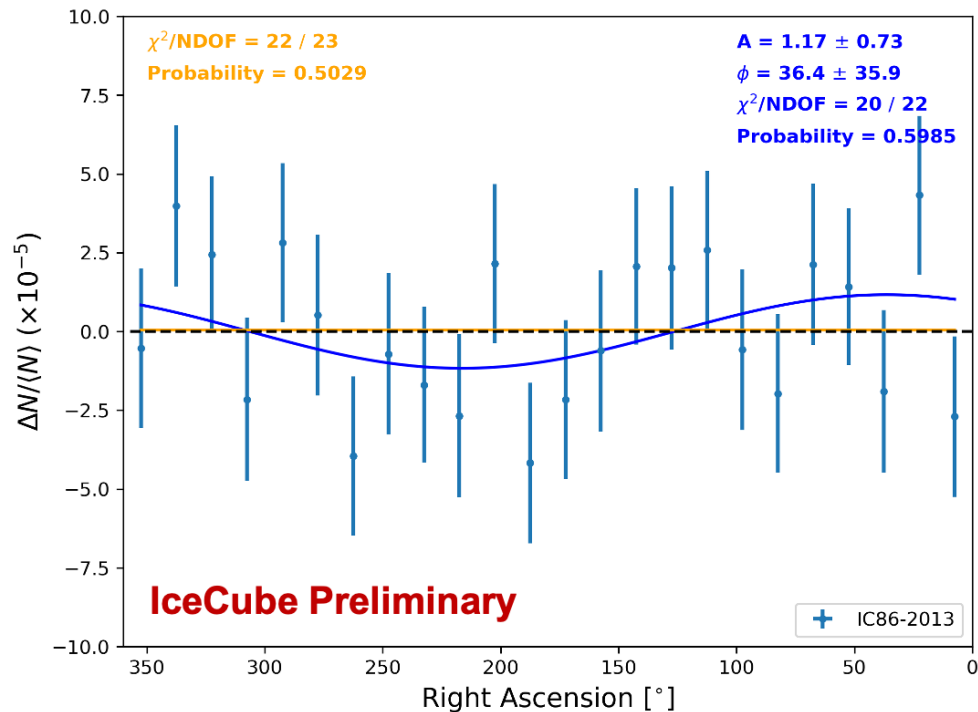
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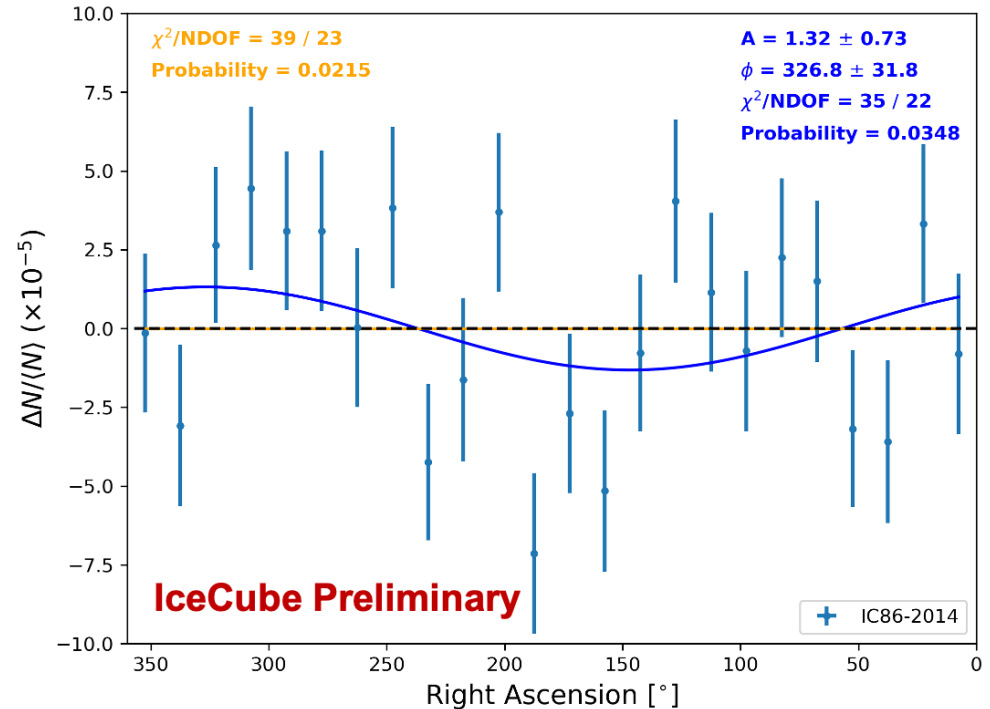
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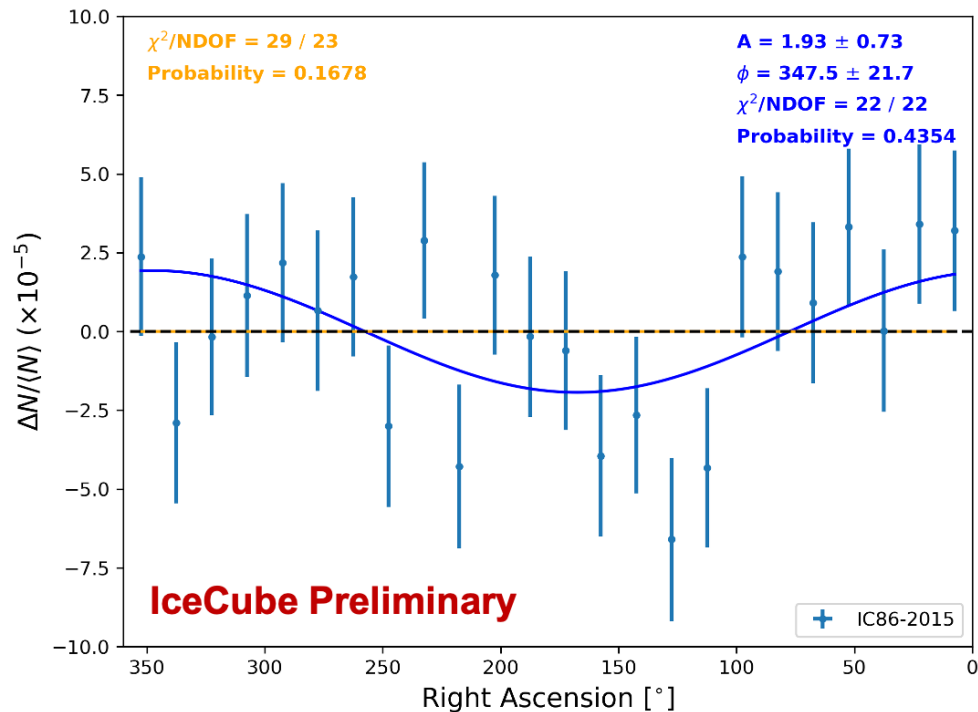
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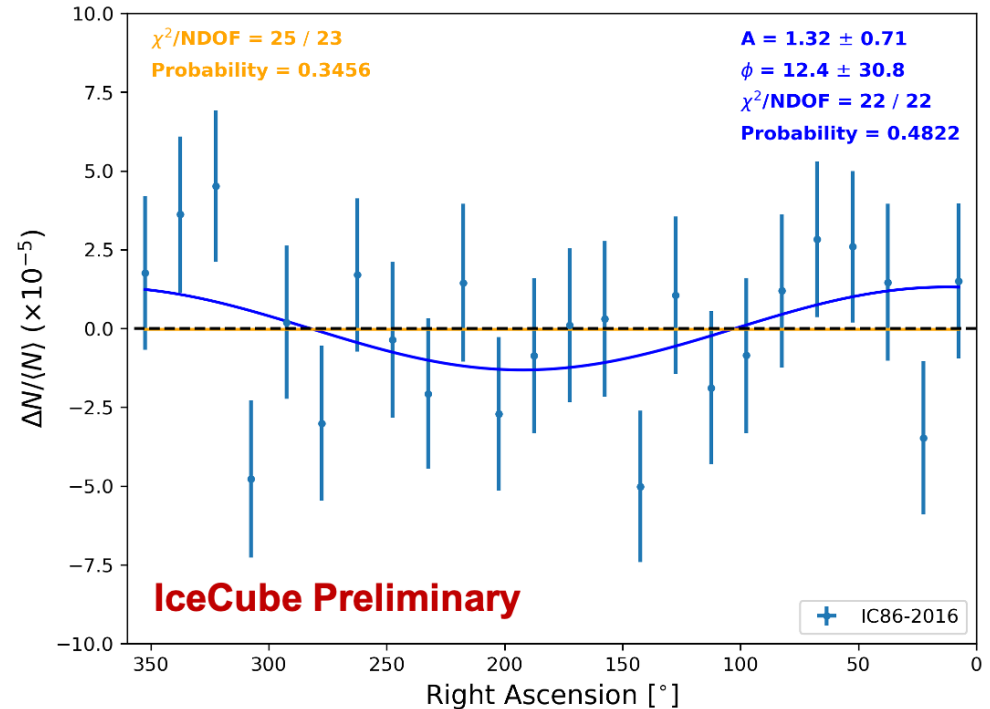
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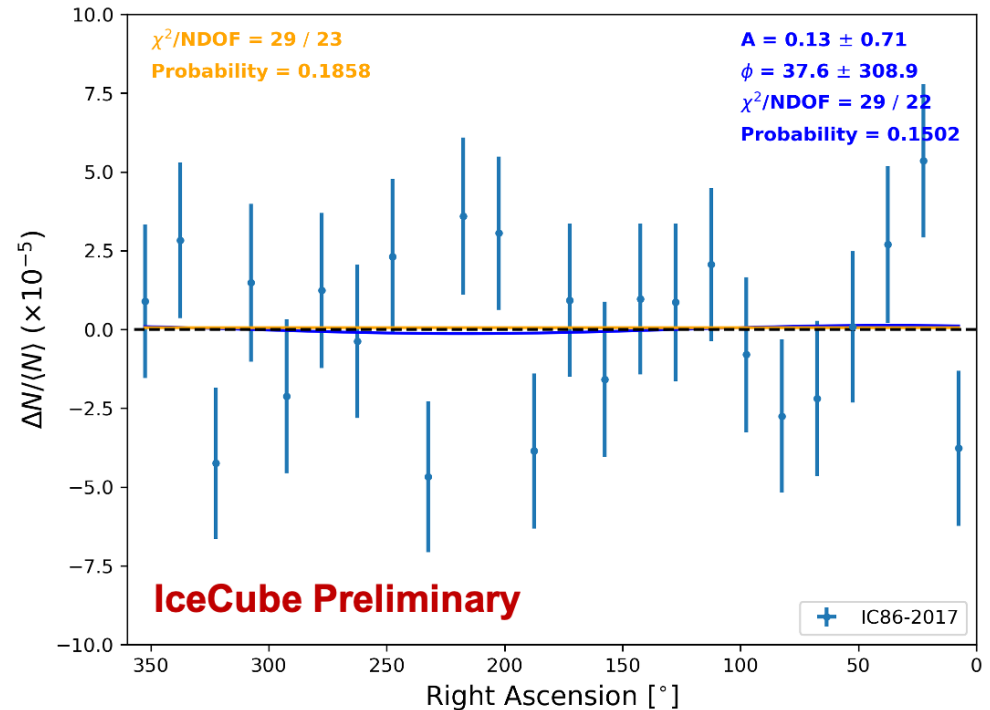
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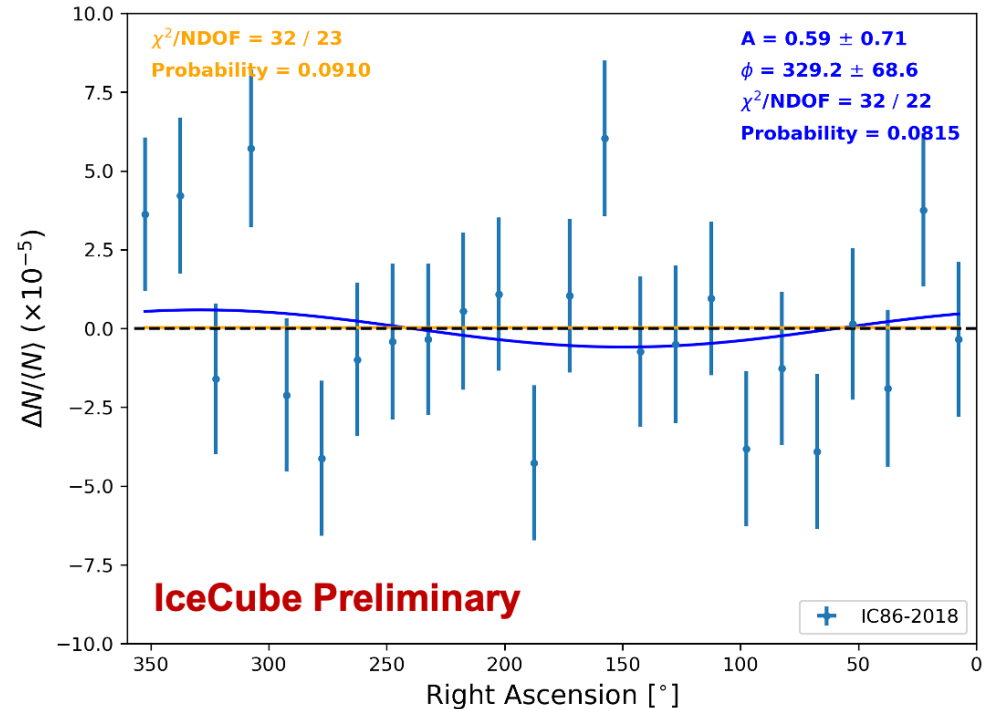
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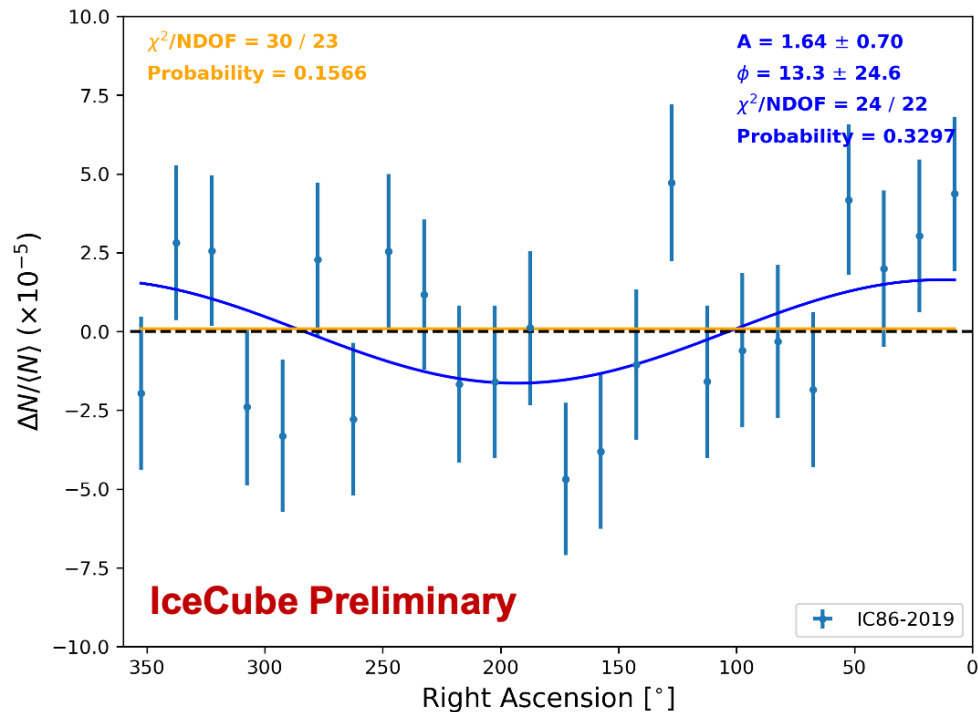
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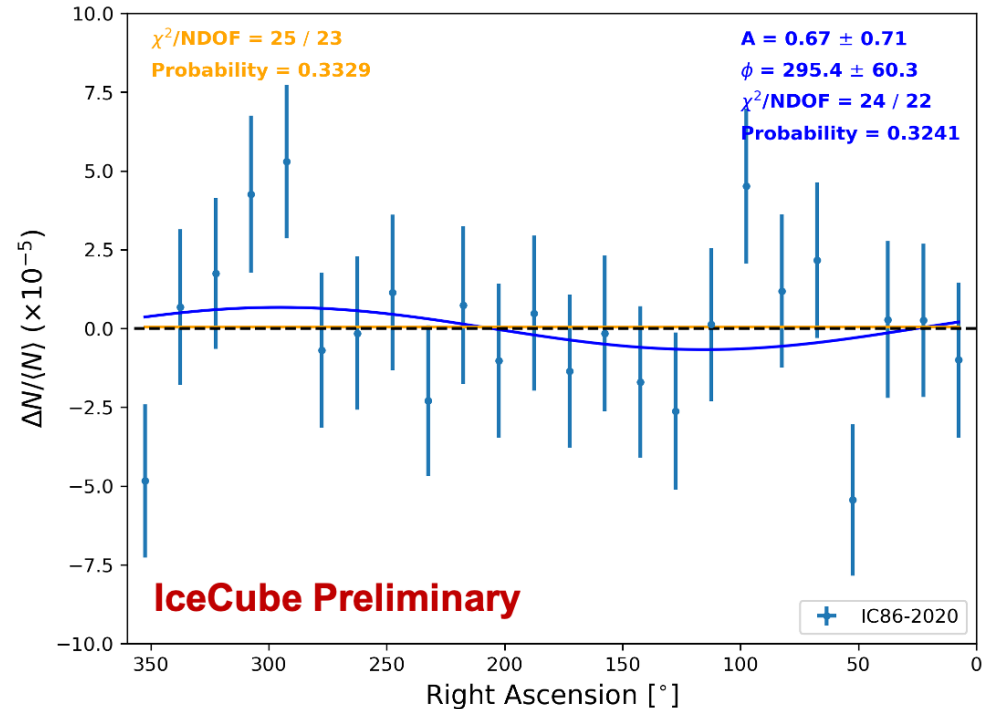
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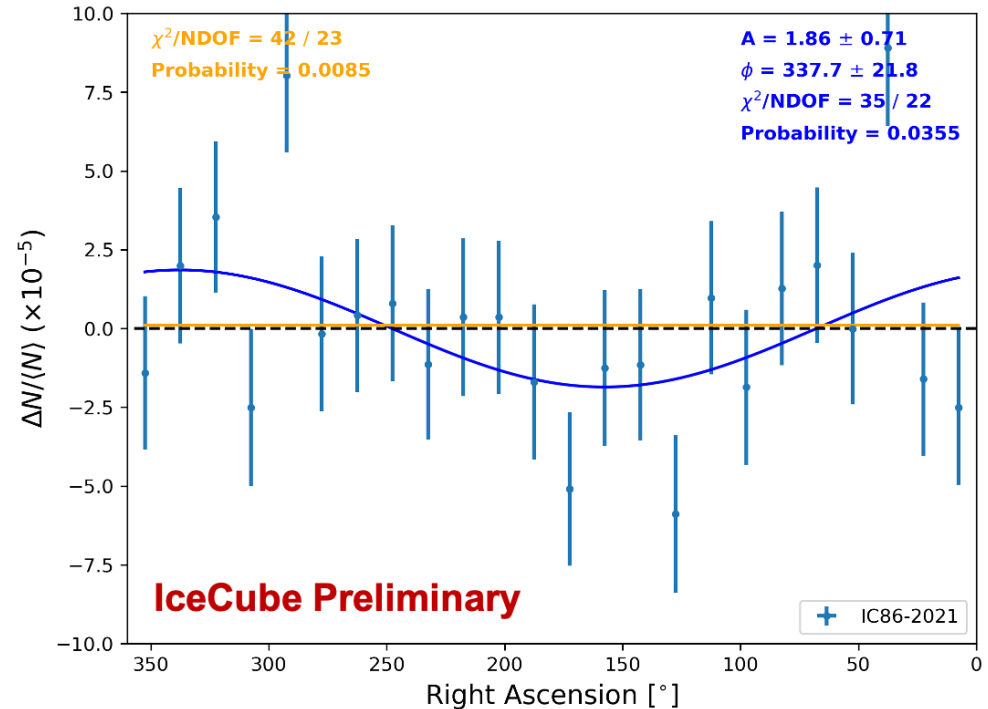
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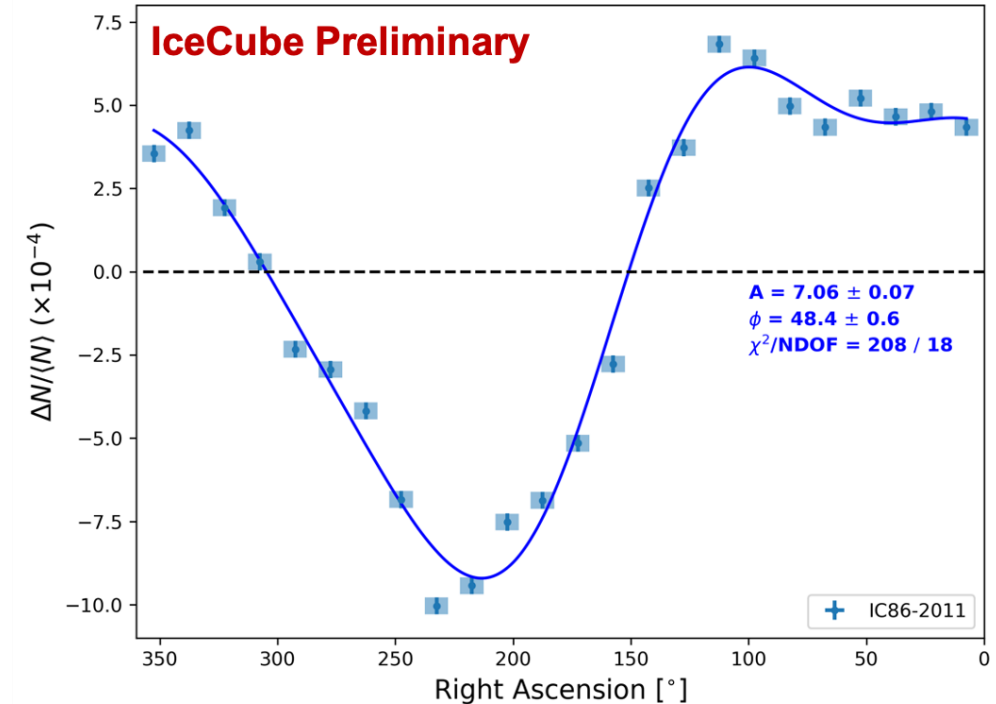
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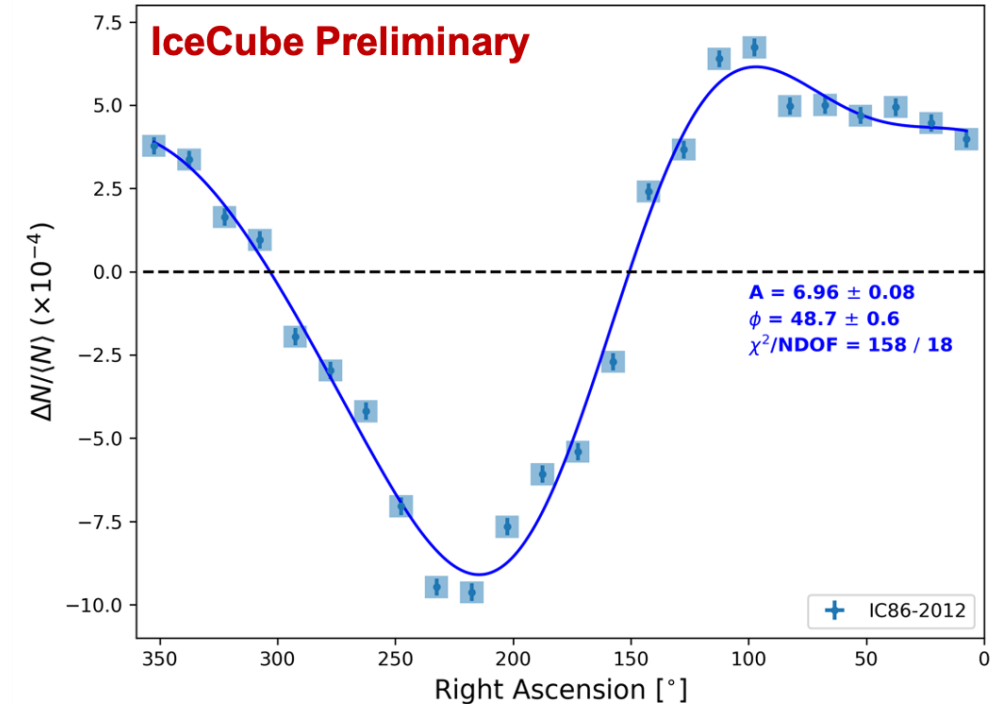
Improved Systematics: Calendar Years

- **Sidereal:** one-dimensional projection along right ascension
 - Systematic uncertainty in sidereal signal derived from rms value of corresponding anti-sidereal frame
- **Shown:**
 - Best-fit line with $\ell = 3$
 - Best-fit phase and amplitude for dipole component



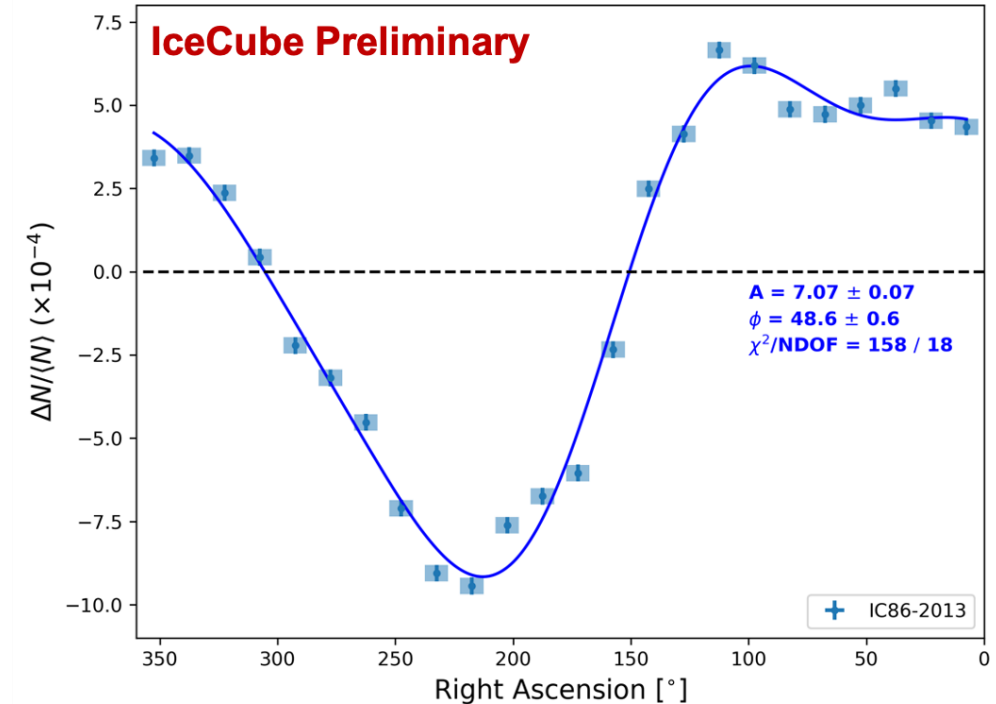
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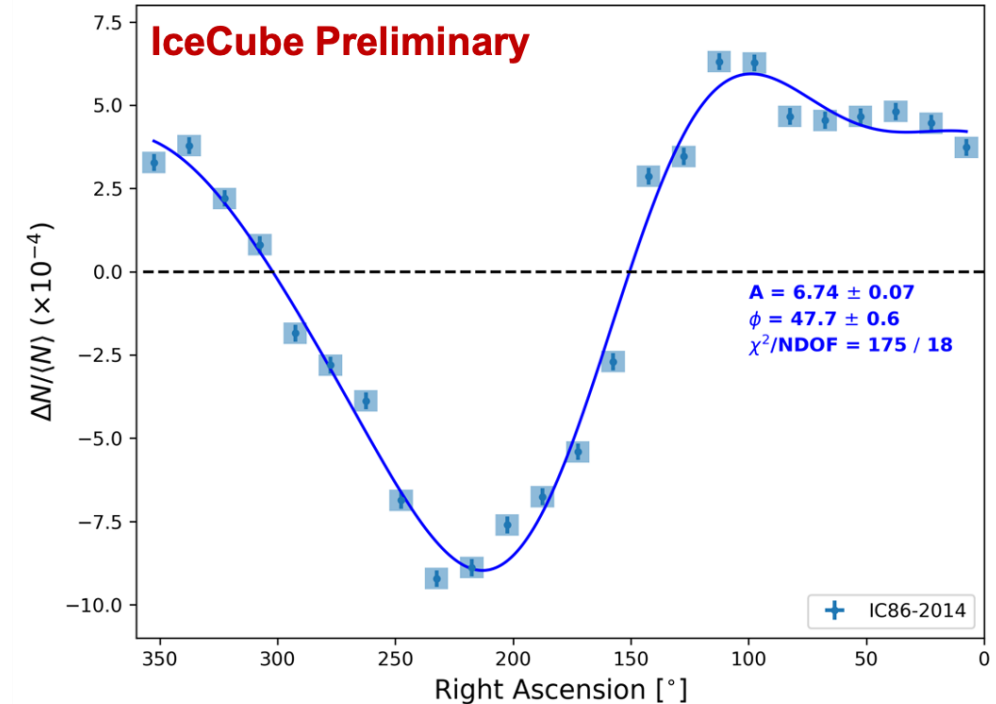
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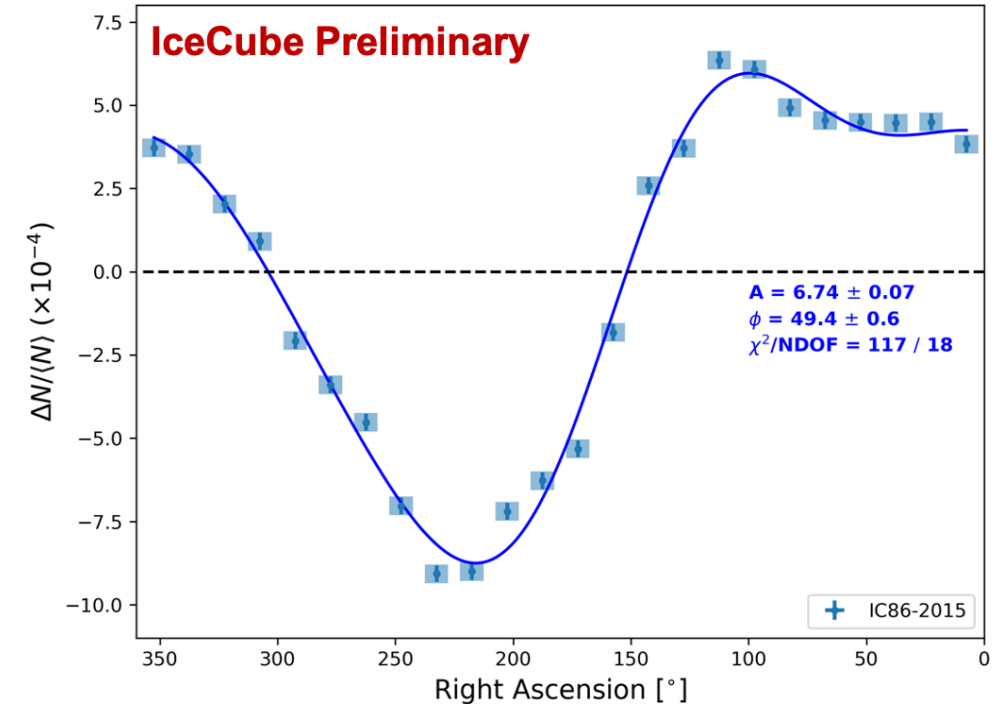
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 - Best-fit phase and amplitude for dipole component



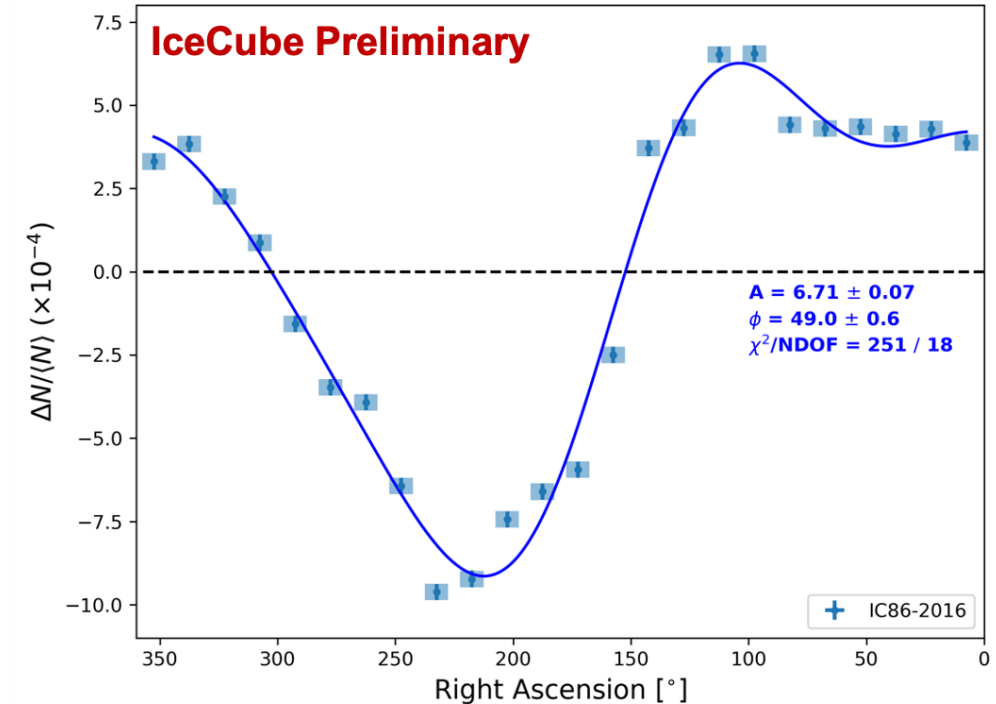
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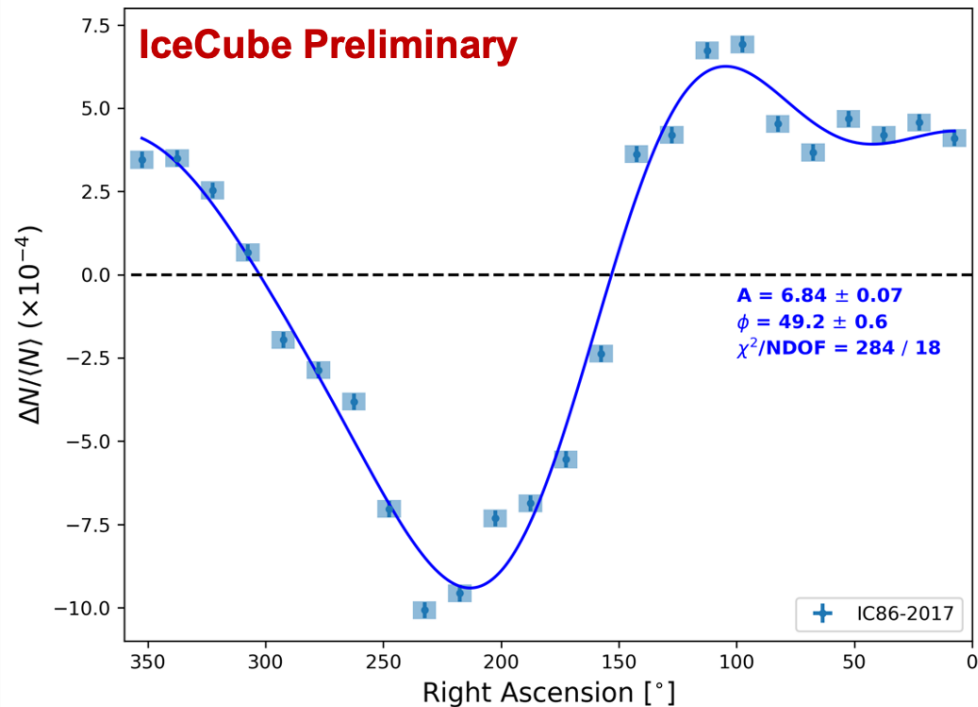
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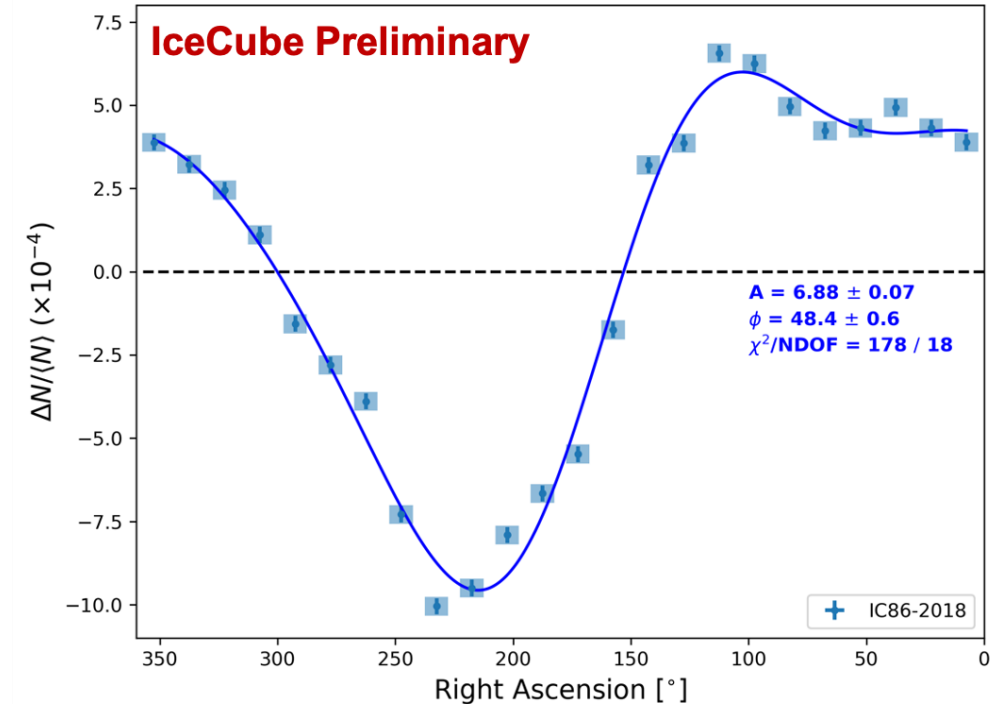
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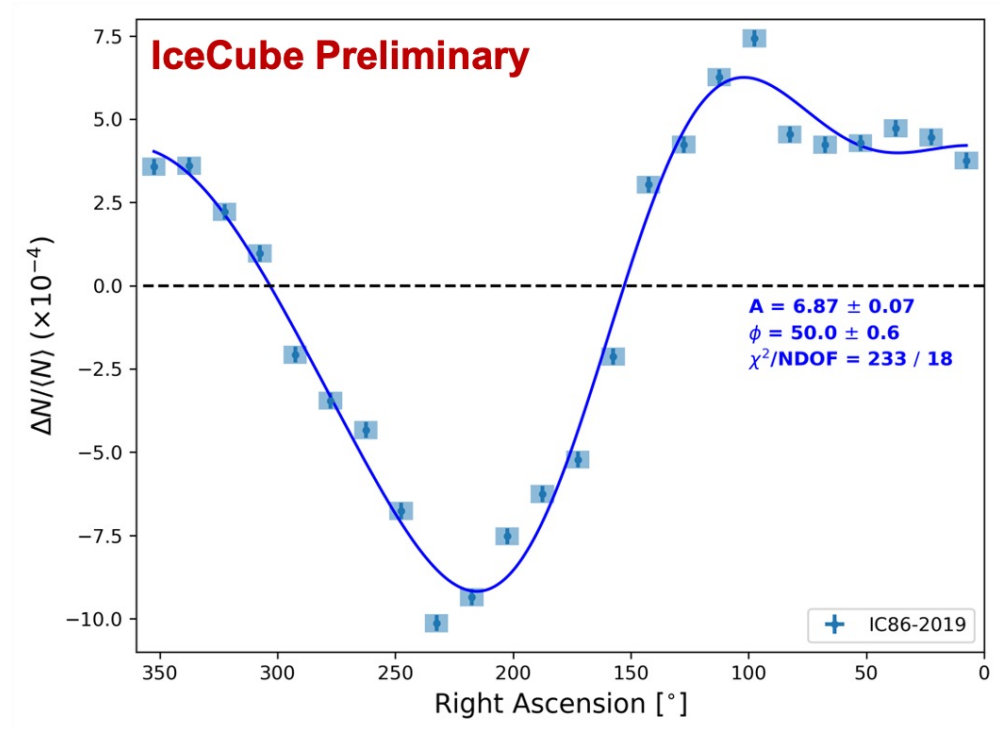
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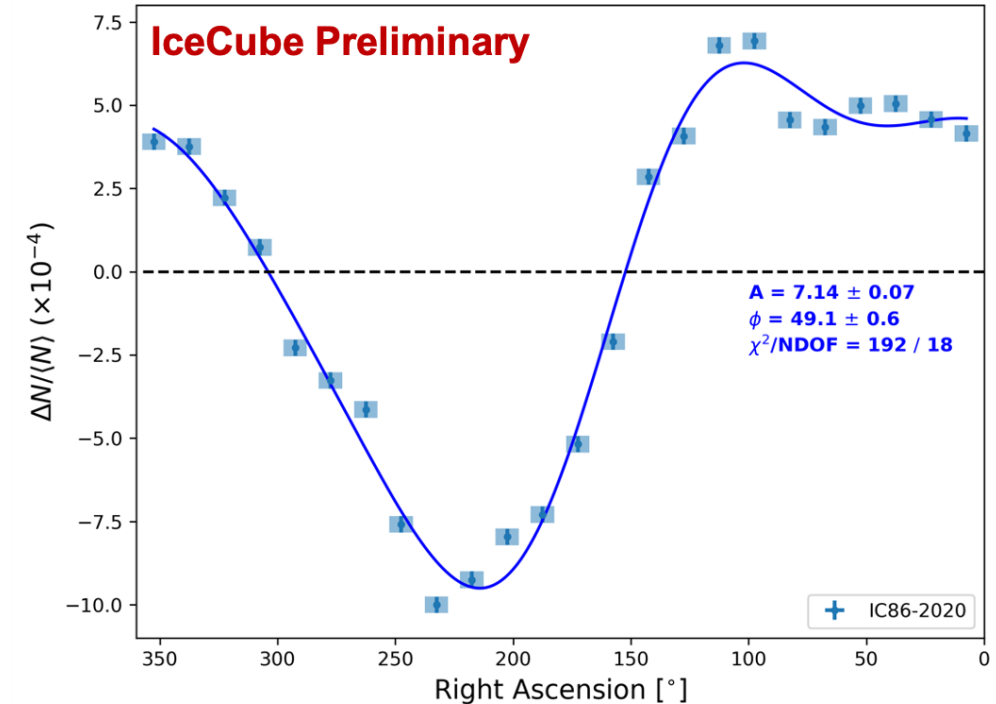
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