Observation of Cosmic Ray Anisotropy with Eleven Years of Data

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On behalf of the IceCube Collaboration

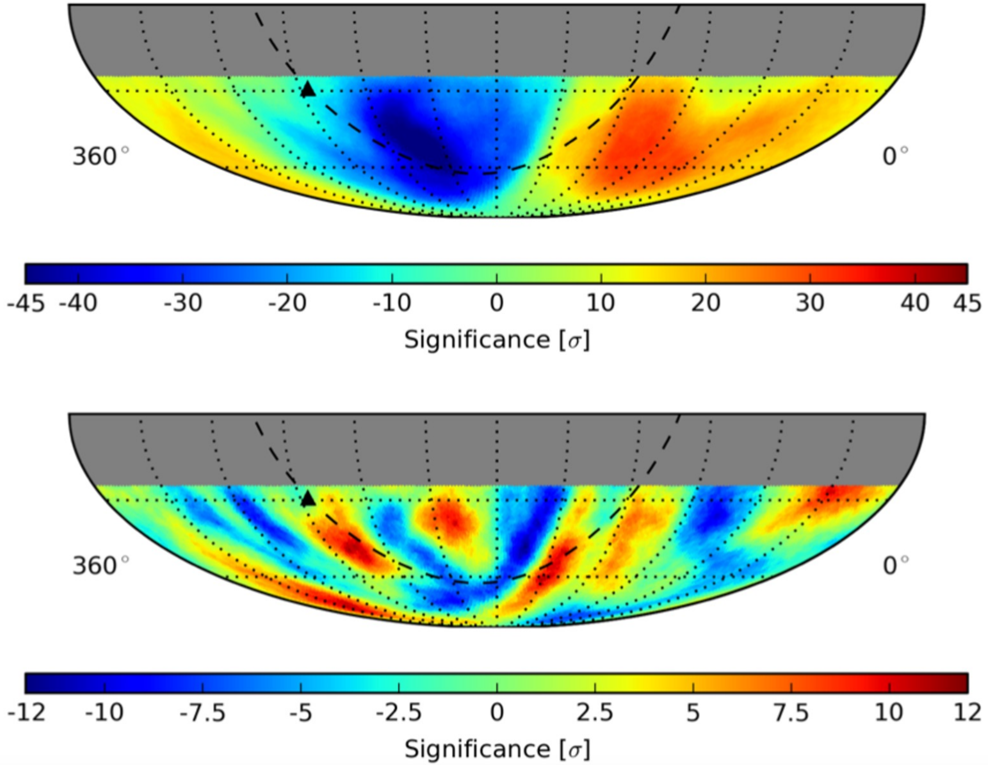
6 Dec. 2022

Cosmic Rays in the Multi-Messenger Era

APC Laboratory (Paris)

History

- Six years of data (~3.2 x 10^{11} events) ApJ 2016
  - 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 (~5.4 x 10^{11} events) ICRC 2021



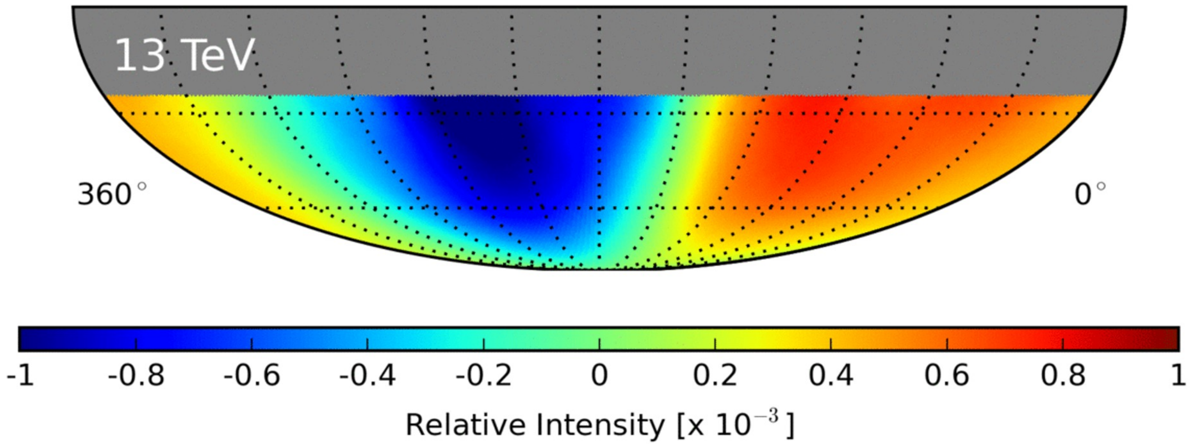
Aartsen et al., "Anisotropy in Cosmic-Ray Arrival Directions in the Southern Hemisphere based on Six Years of Data from the IceCube Detector", Astrophys.J. **826** (2016) no.2, 220

Objective: Update Paper

1. Improved statistics: Eleven years of data in a consistent detector configuration (IC86) (~6.9 x 10^{11} events)

2. Improved simulation: Newer, dataset-specific, increased statistics

3. Improved systematics: Shift from detector to calendar years

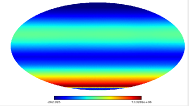


Energy dependence of large-scale anisotropy

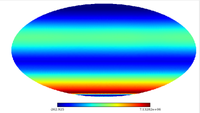
(Created from Astrophys.J. **826** (2016) no.2, 220 (arXiv:1603.01227))

Method for measuring CR anisotropy

1 Build a binned data map using the equatorial coordinates of the events



2 Construct a “reference” map by integrating acceptance over 24 hours.



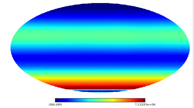
Time-scrambling:

$$(\theta, \phi, t) \rightarrow (\alpha, \delta)$$
$$(\theta, \phi, t') \rightarrow (\alpha', \delta')$$

Direct integration:

$$\langle N(\alpha, \delta)\rangle = \int dt \int d\Omega A(ha, \delta) \cdot R(t) \cdot \epsilon(ha, \alpha, t)$$

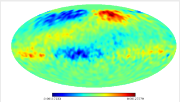
3 Correlate pixels to increase sensitivity to different angular scales



Relative Intensity

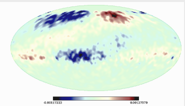
$$\delta I(\alpha, \delta)_i = \frac{N(\alpha, \delta)_i - \langle N\rangle(\alpha, \delta)_i}{\langle N\rangle(\alpha, \delta)_i}$$

4 Calculate relative differences between data and reference with significance.



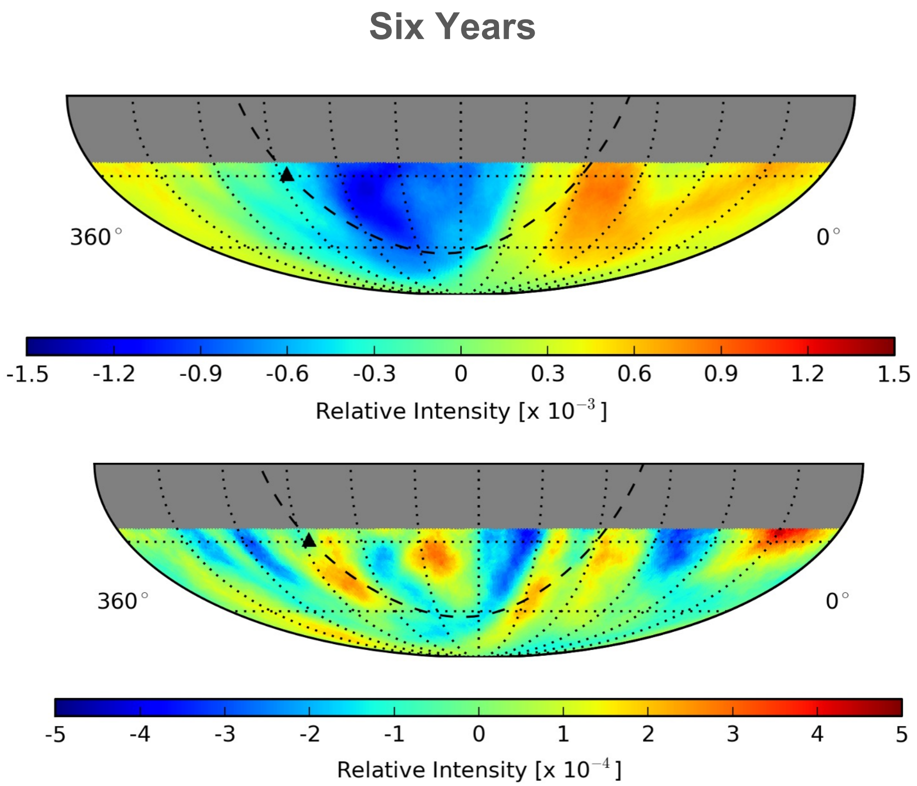
$$s_i = \sqrt{2}\left\{N_i \log\left[\frac{1+\alpha}{\alpha}\left(\frac{N_i}{N_i+N_o}\right)\right] + N_o \log\left[(1+\alpha)\left(\frac{N_o}{N_i+N_o}\right)\right]\right\}^{1/2}$$

5 Calculate statistical significance for each pixel

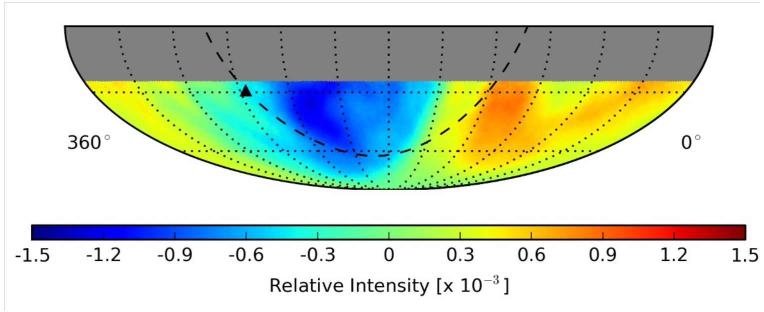
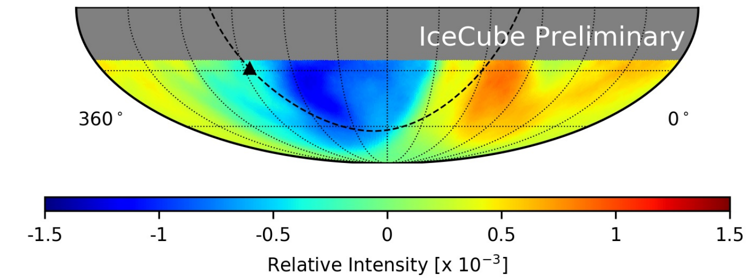
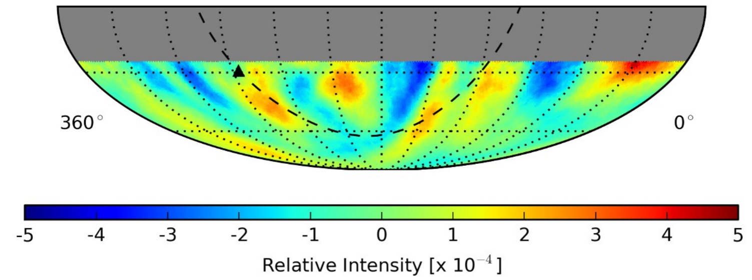
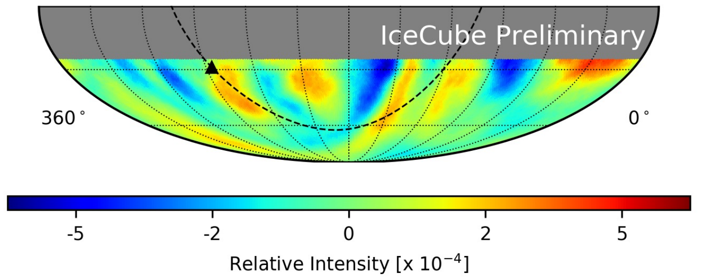


How to Read a Map

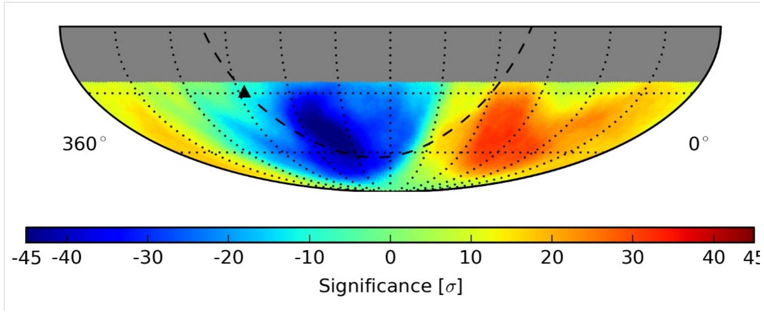
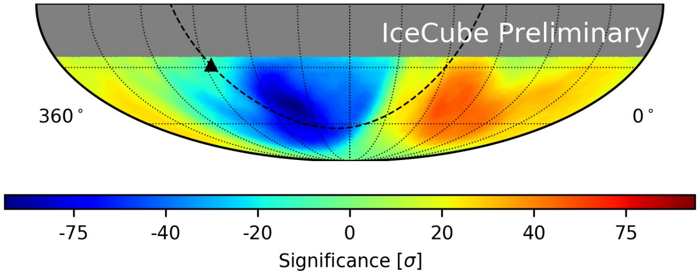
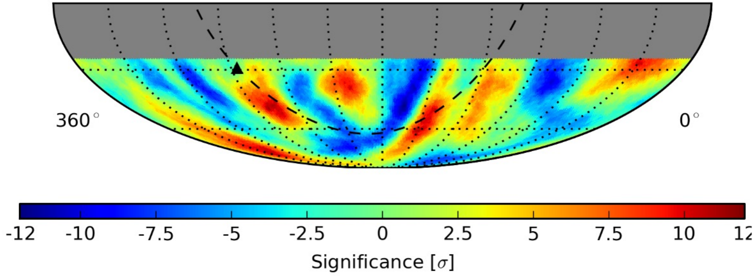
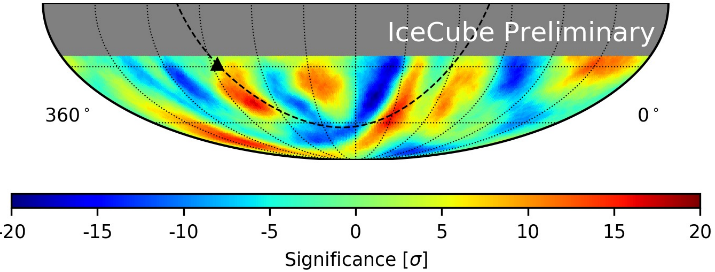
- Mollweide projections in equatorial coordinates
    - Background (reference) map produced using time-scrambling
    - 5º radius top-hat smoothing
    - Small-scale map created by subtracting dipole and quadrupole terms from a fit using spherical harmonics
    - Galactic plane and center indicated by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



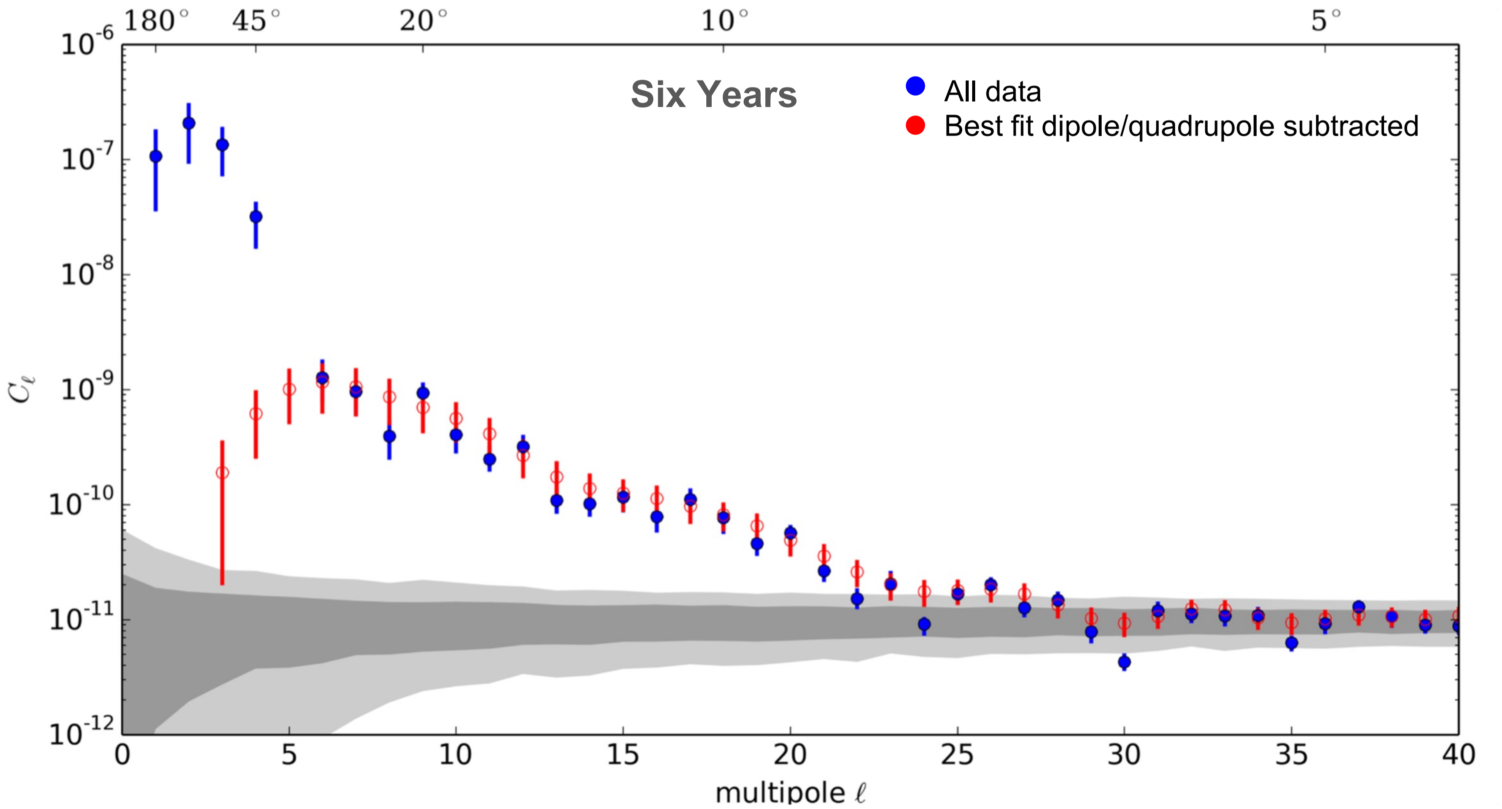
Increased Statistics: Large- and Small-Scale Structure

Relative Intensity	Six Years	Eleven Years
Large-Scale Structure		
Small-Scale Structure		

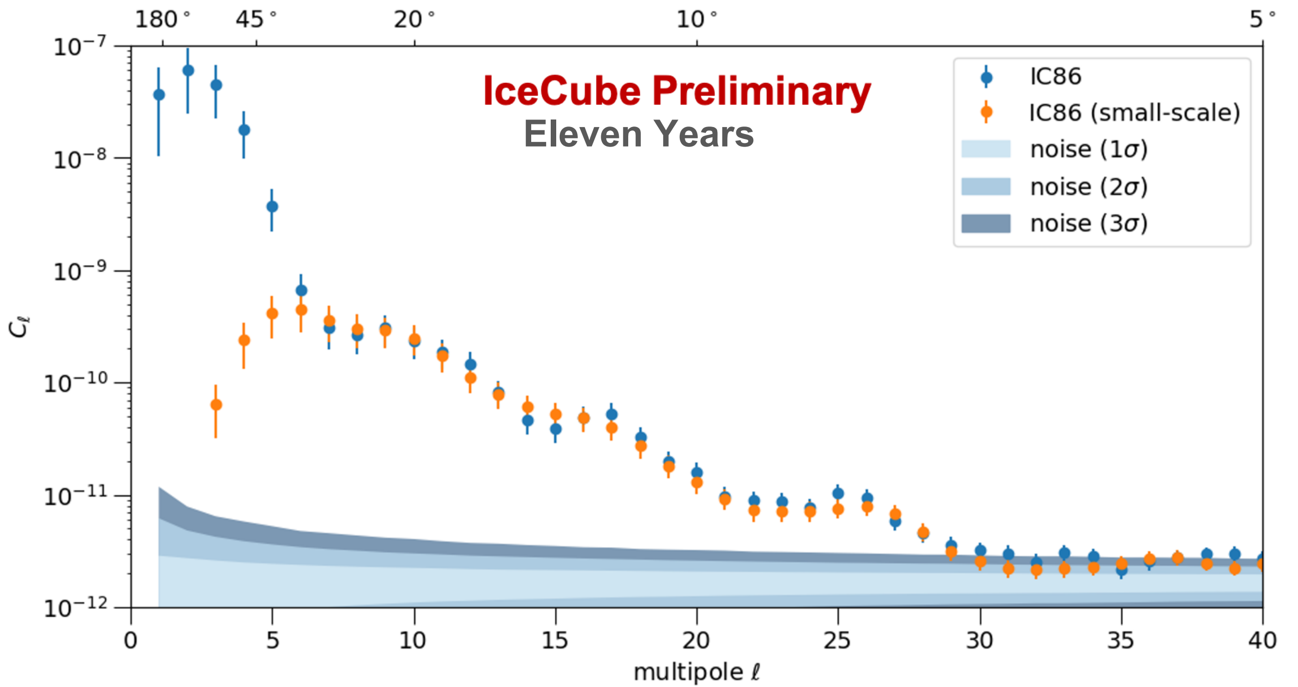
Increased Statistics: Large- and Small-Scale Structure

Significance	Six Years	Eleven Years
Large-Scale Structure		
Small-Scale Structure		

Increased Statistics: Angular Power Spectrum



Increased Statistics: Angular Power Spectrum

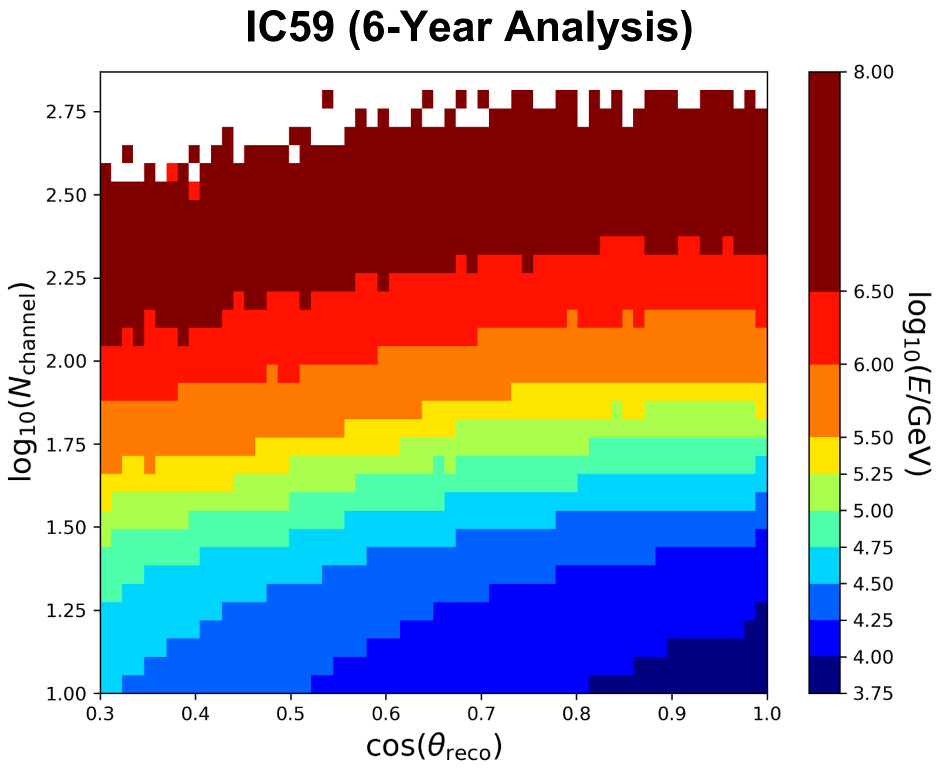


Angular power spectrum for large- and small-scale structure maps. Error bars represent the spread of calculated C_l values for maps randomly generated from the observed C_l values. The bands at the bottom represent 68%, 95%, and 99.7% containment of power spectra produced from an isotropic signal.
Shown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



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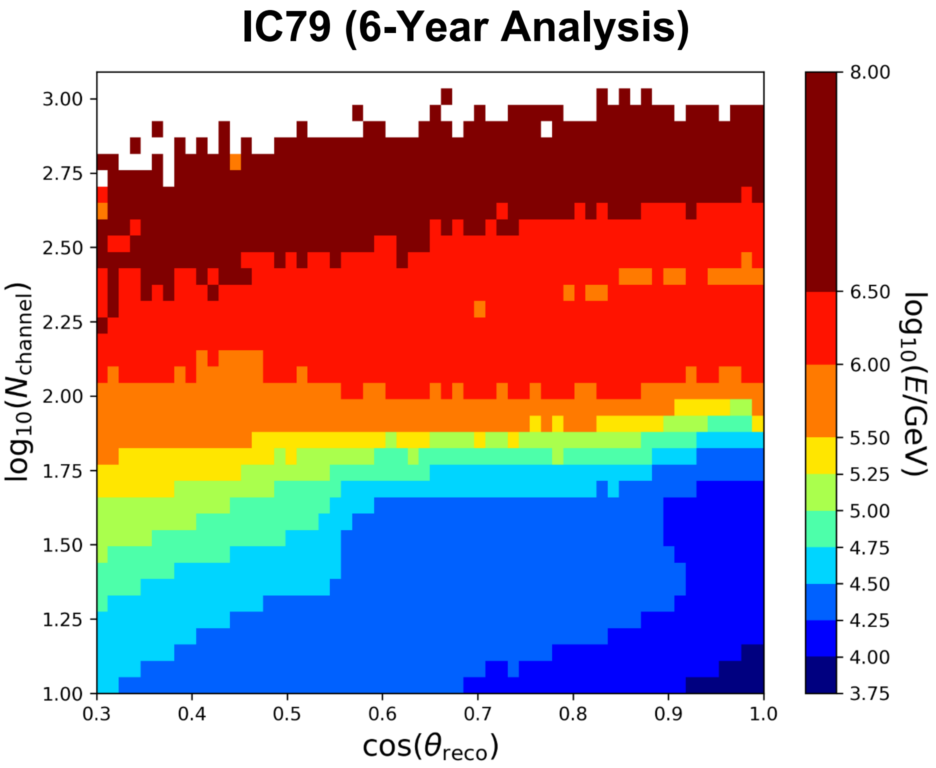

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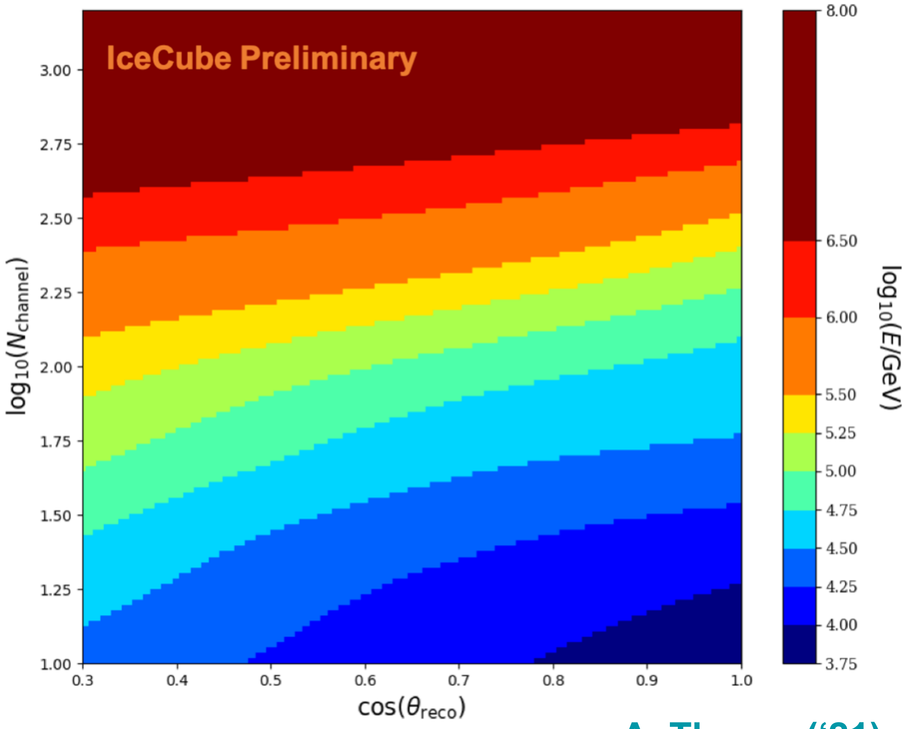
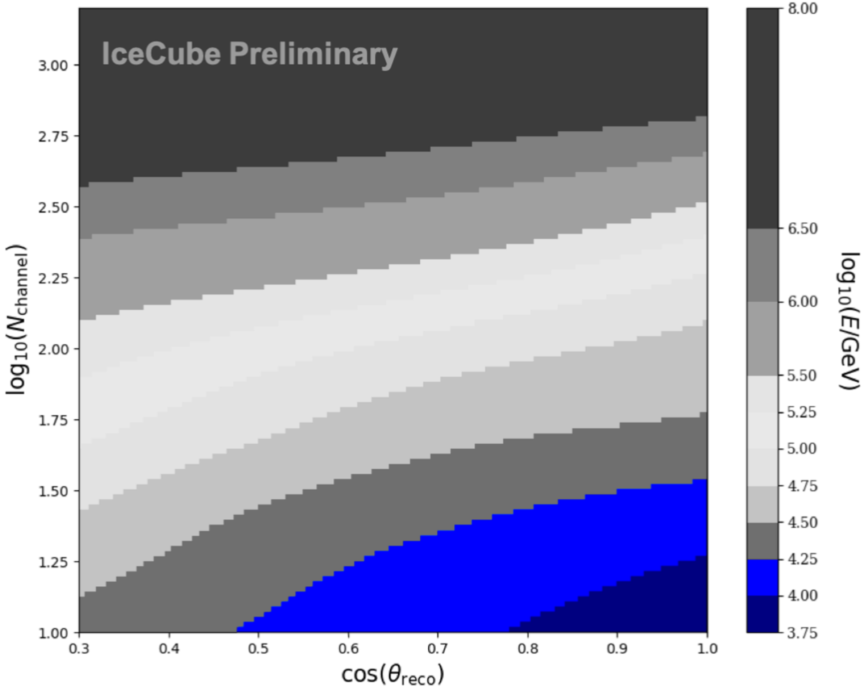
- Median value for each bin shown in plot
- Given hits and reconstructed zenith of event, use splined version to determine median energy value
- Previous concern: limited detector-specific simulation
- New simulation: events that pass SMT08 trigger, IC86 only (splined version shown)

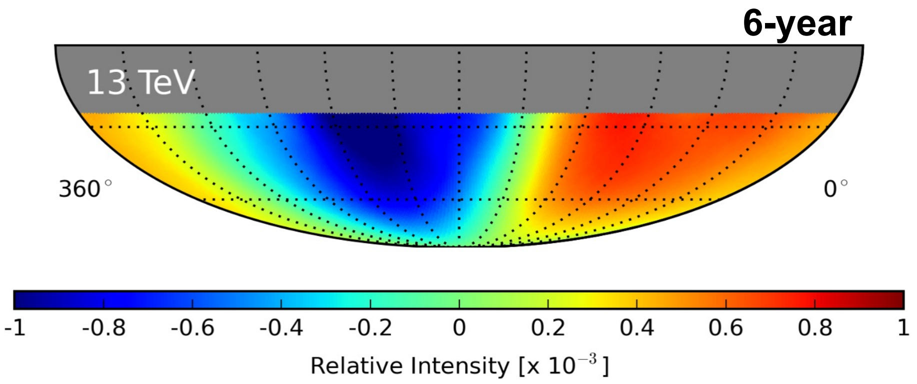
IC86 (11-Year Analysis)

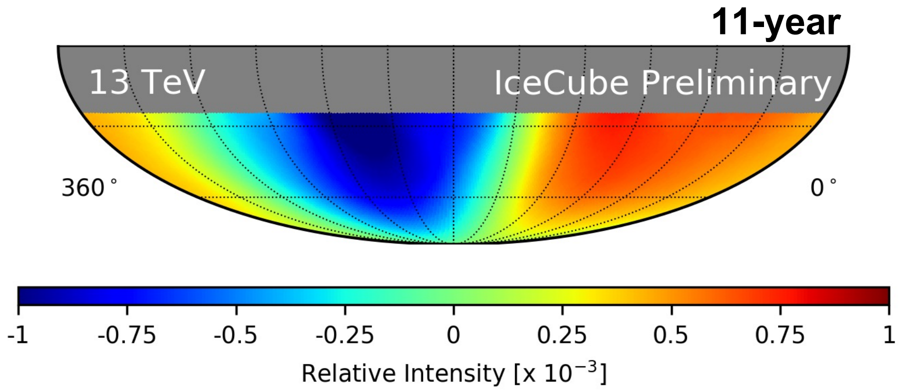


A. Thorpe ('21)

Improved Statistics/Simulation: Energy Maps







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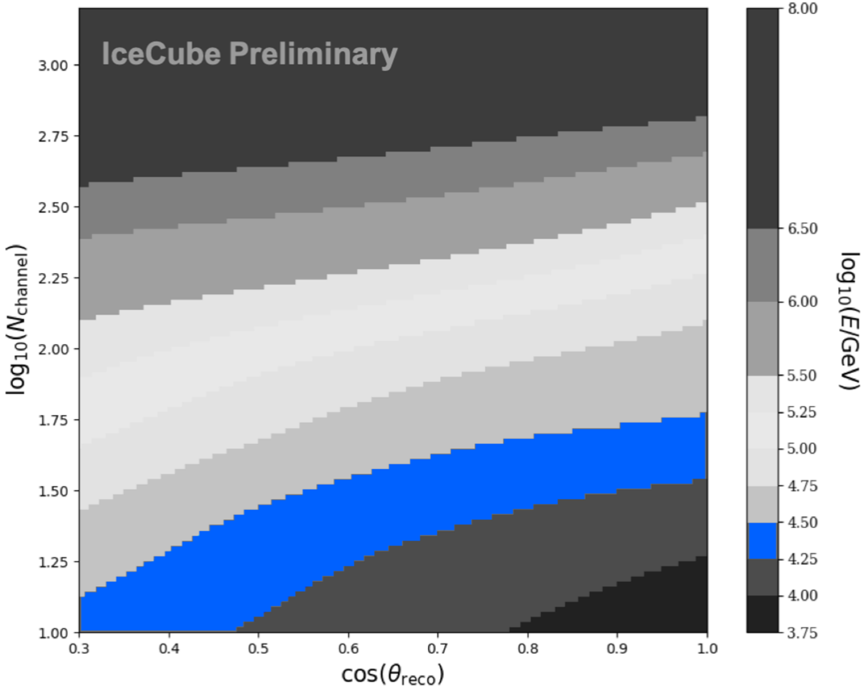

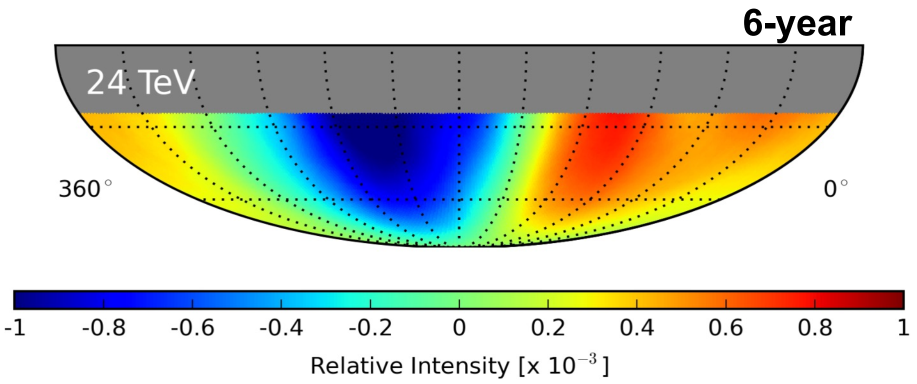

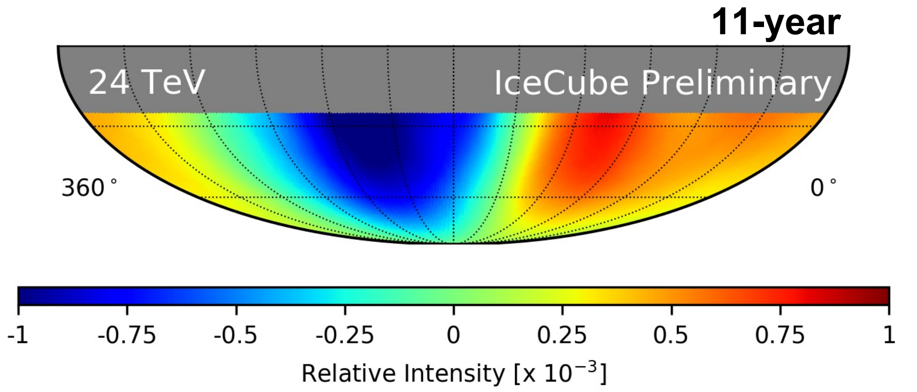

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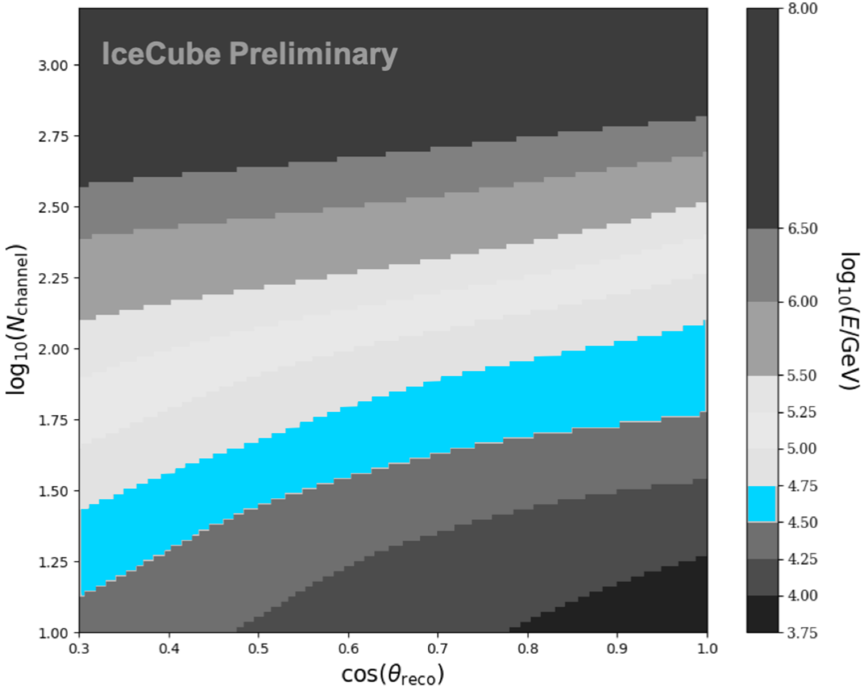

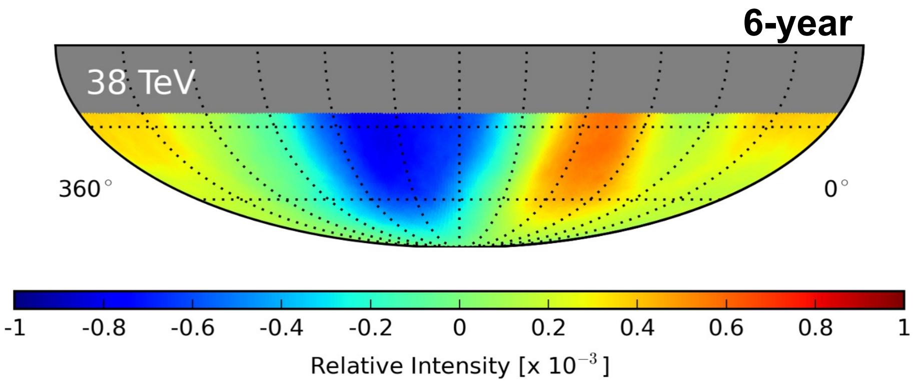

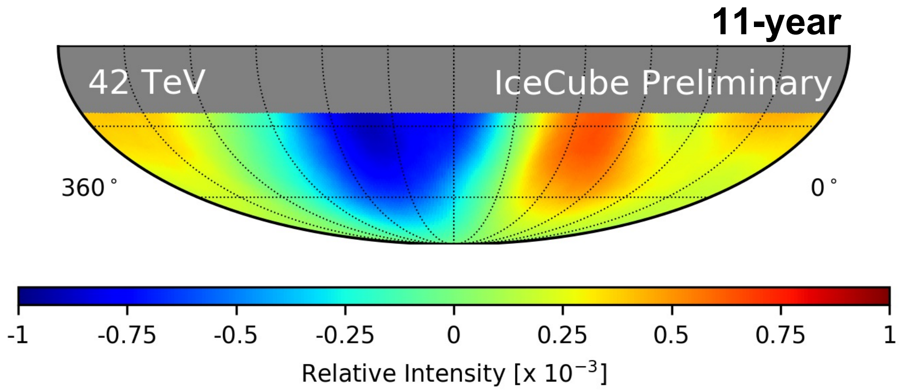

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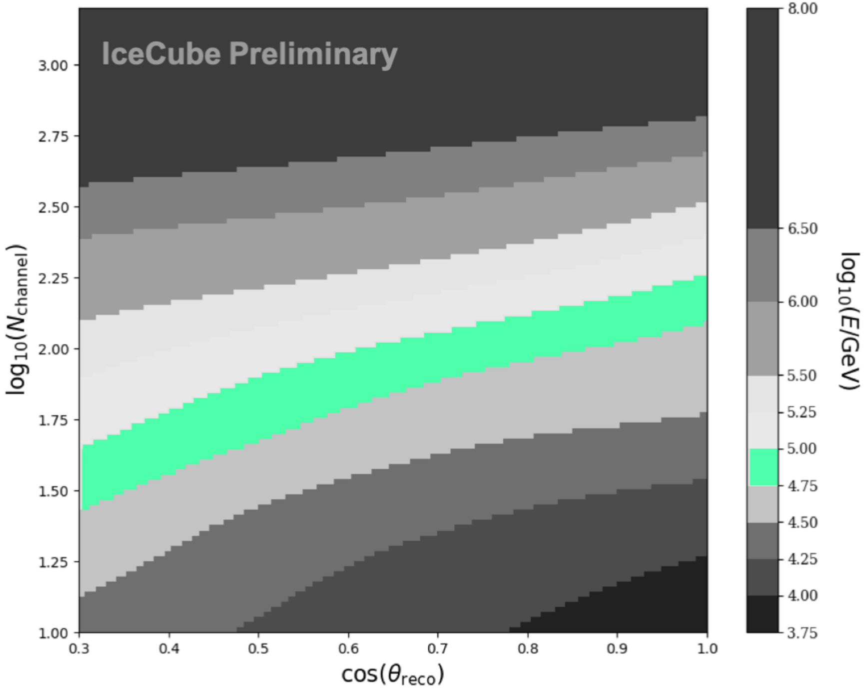

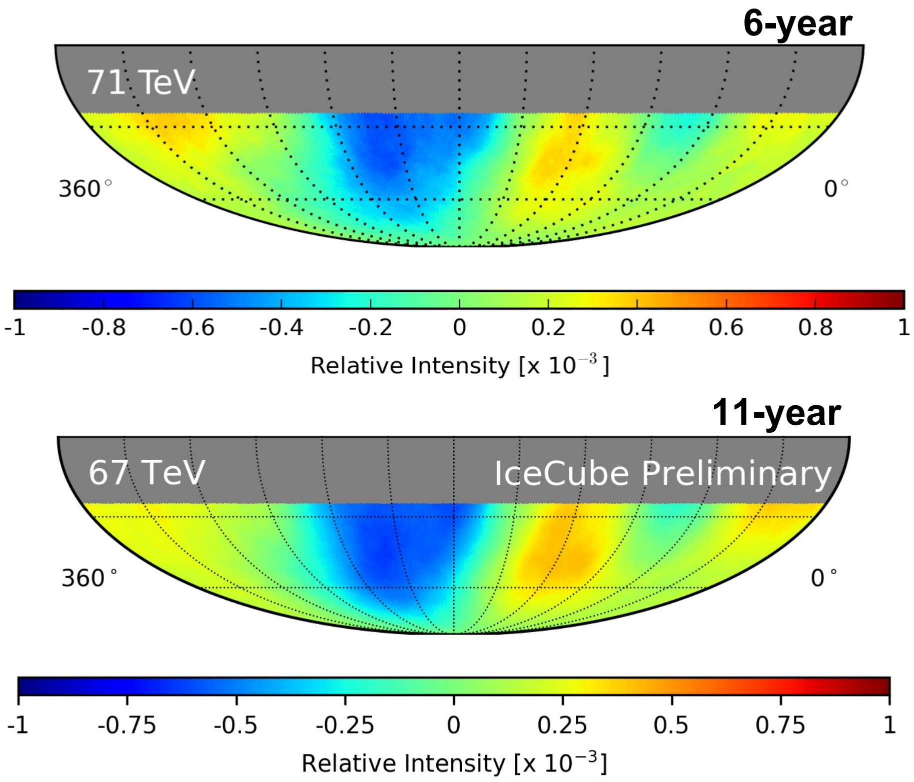

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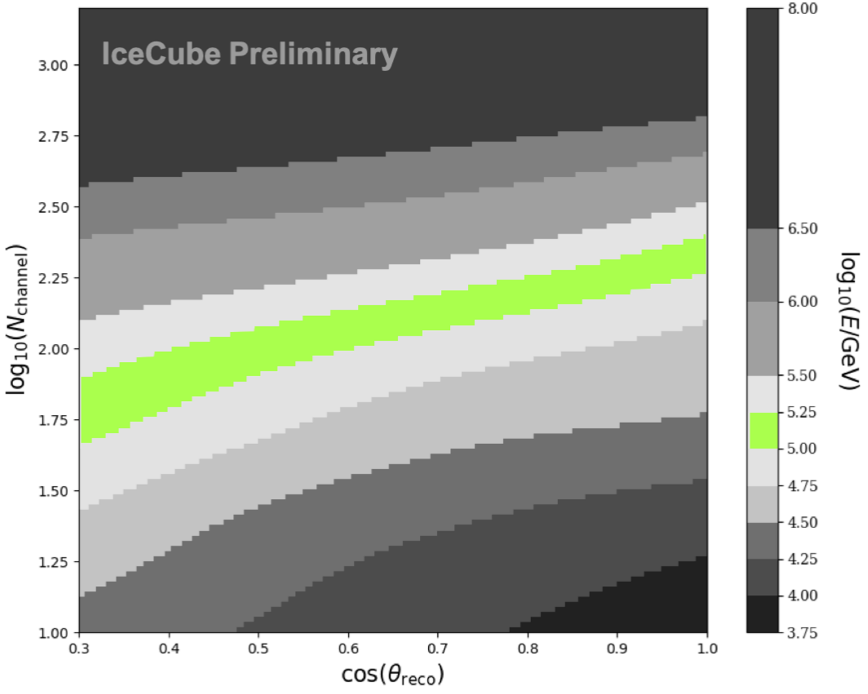

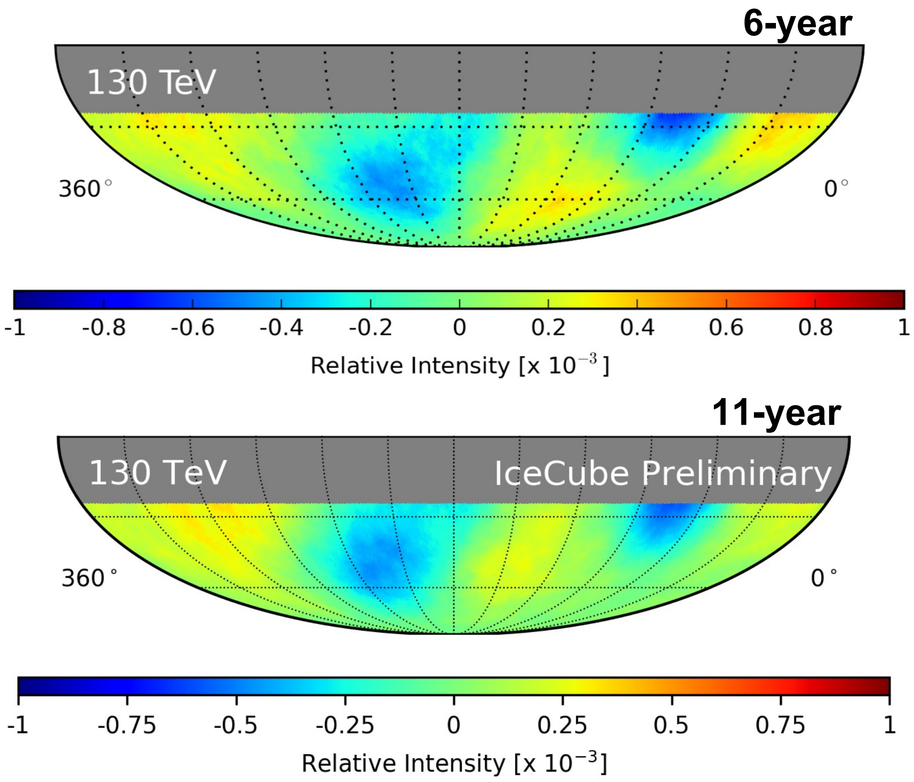

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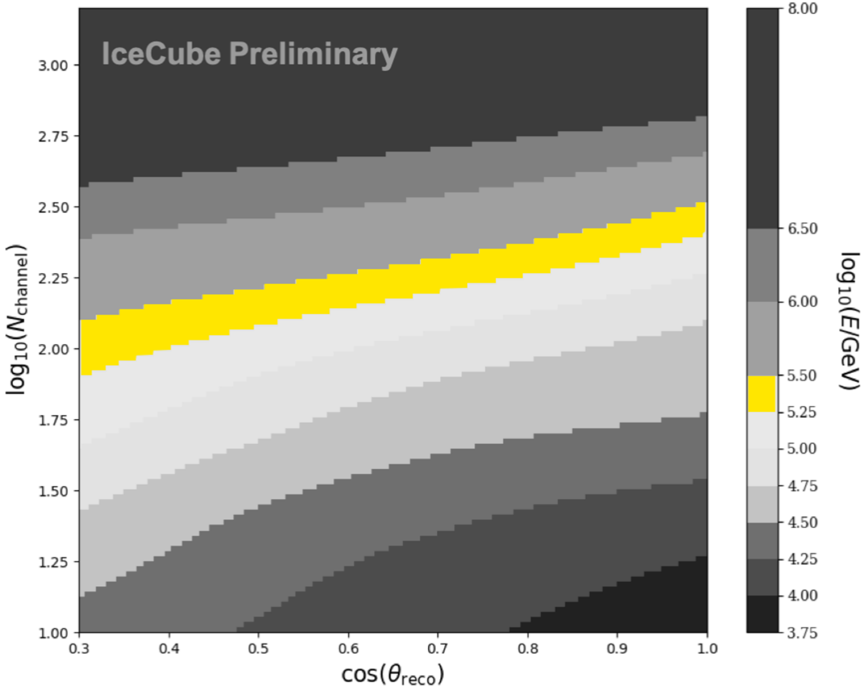

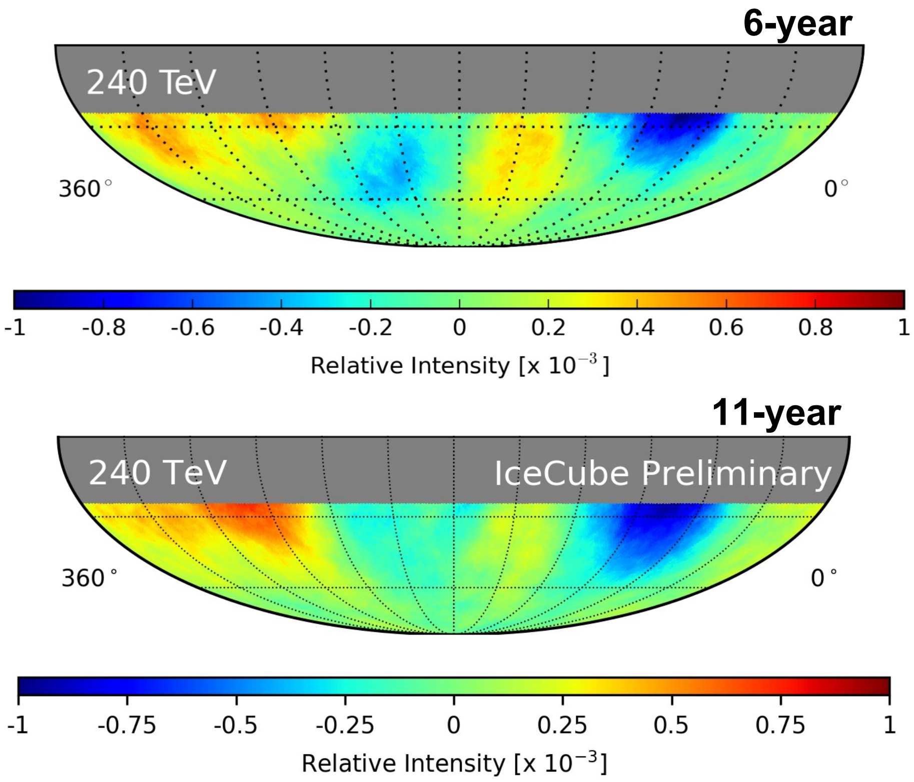

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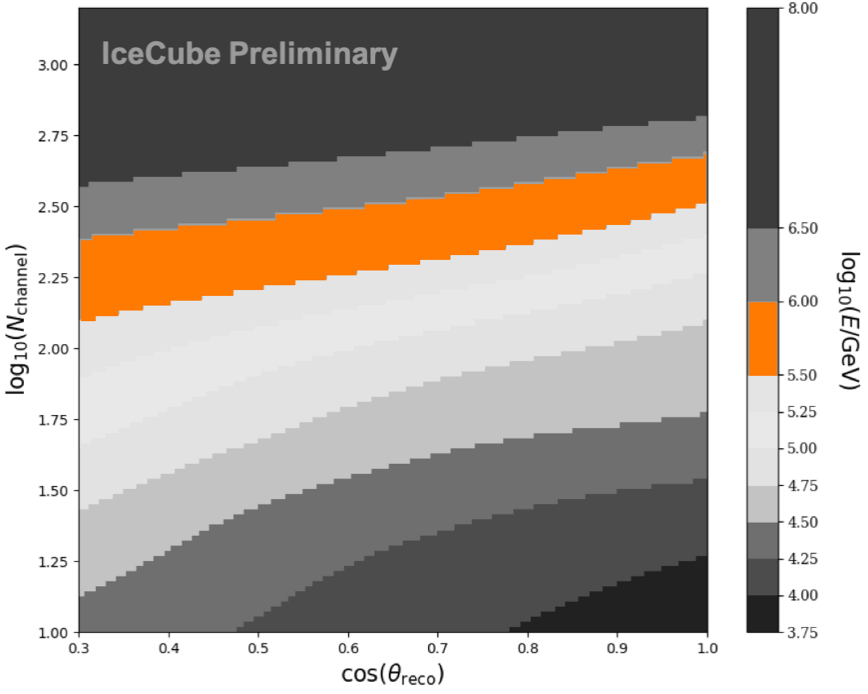

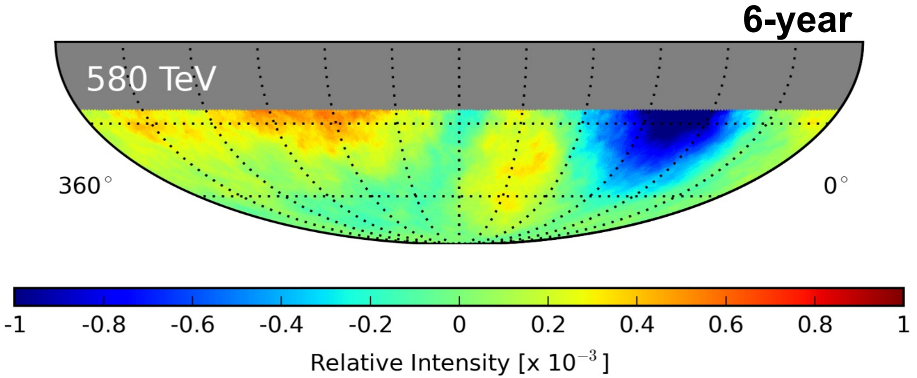

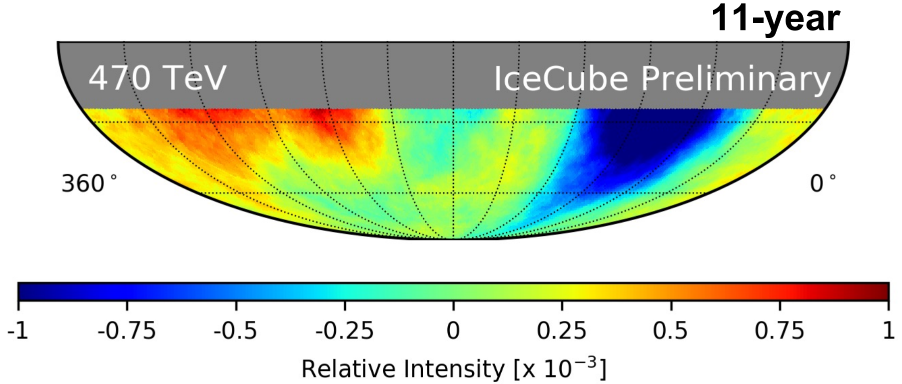

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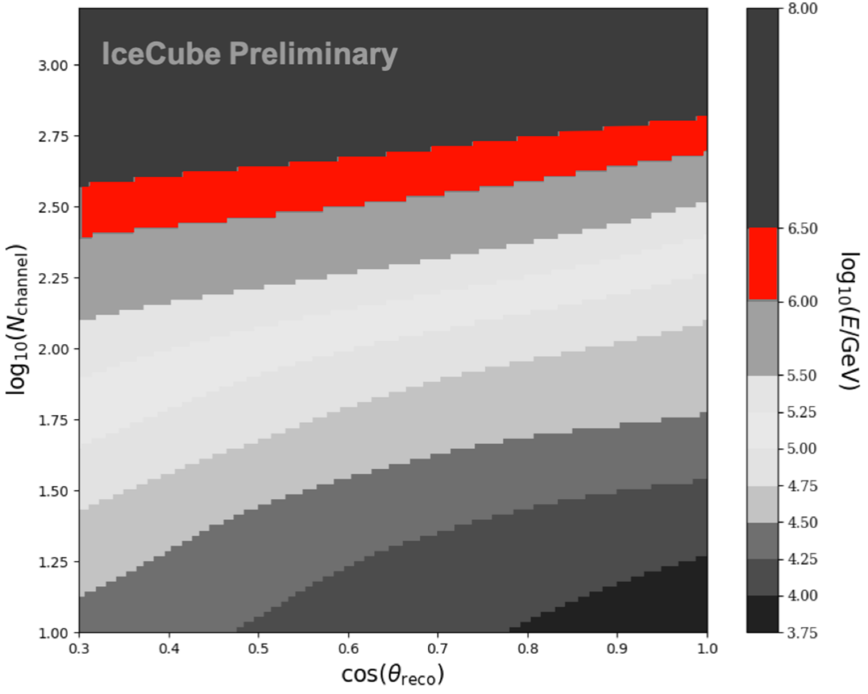

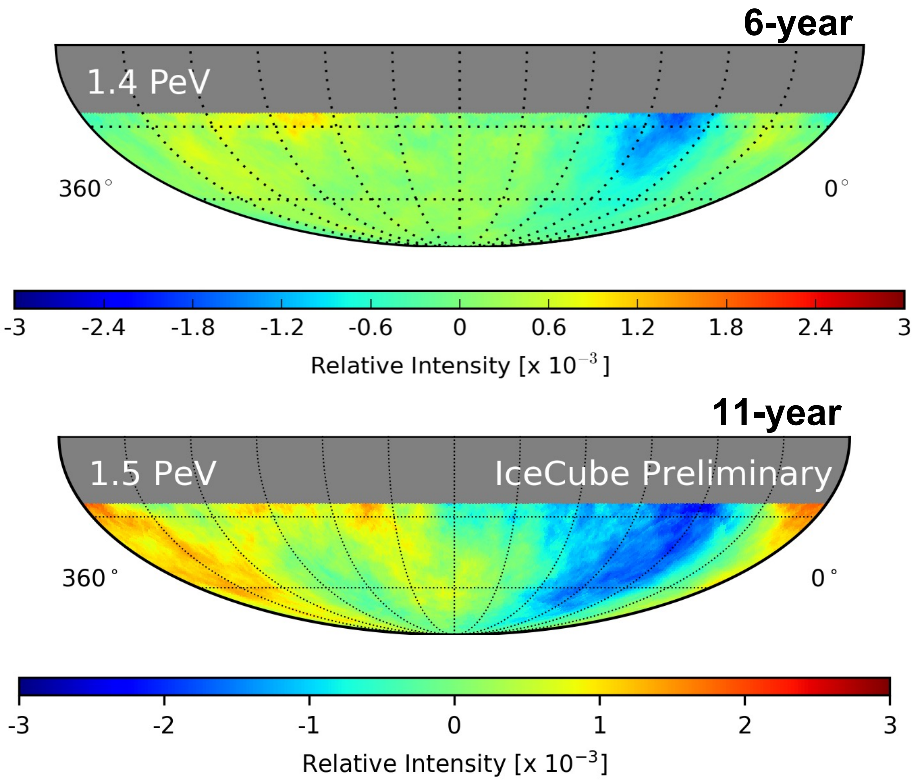

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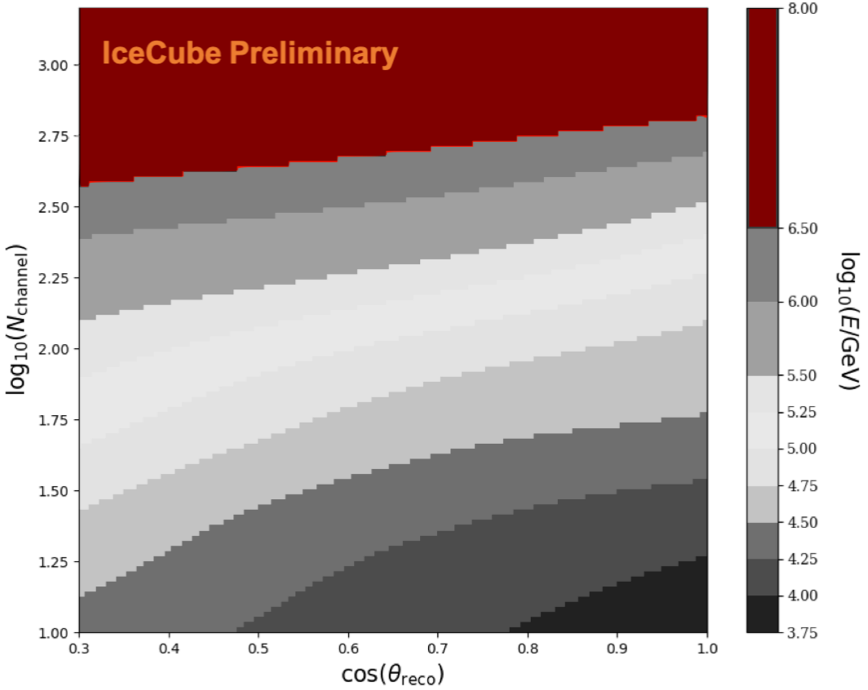
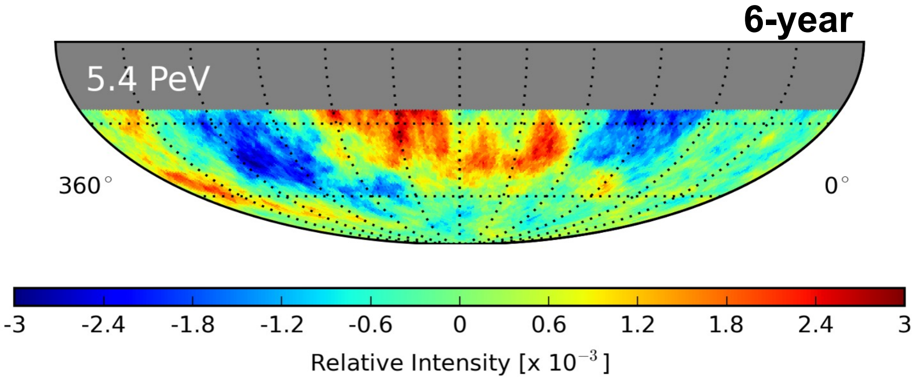
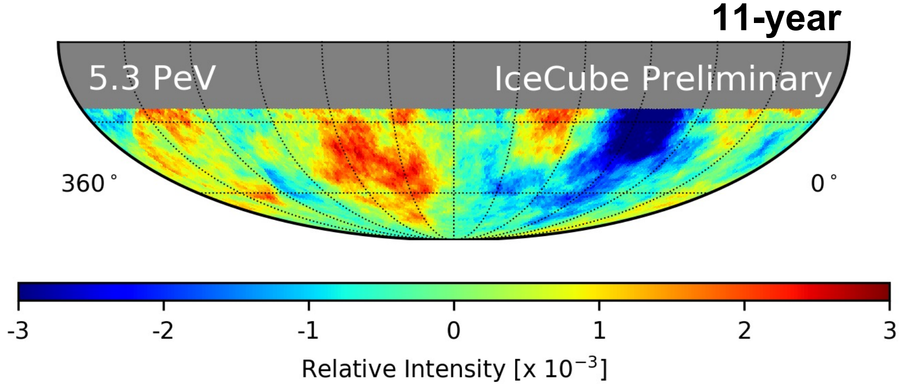
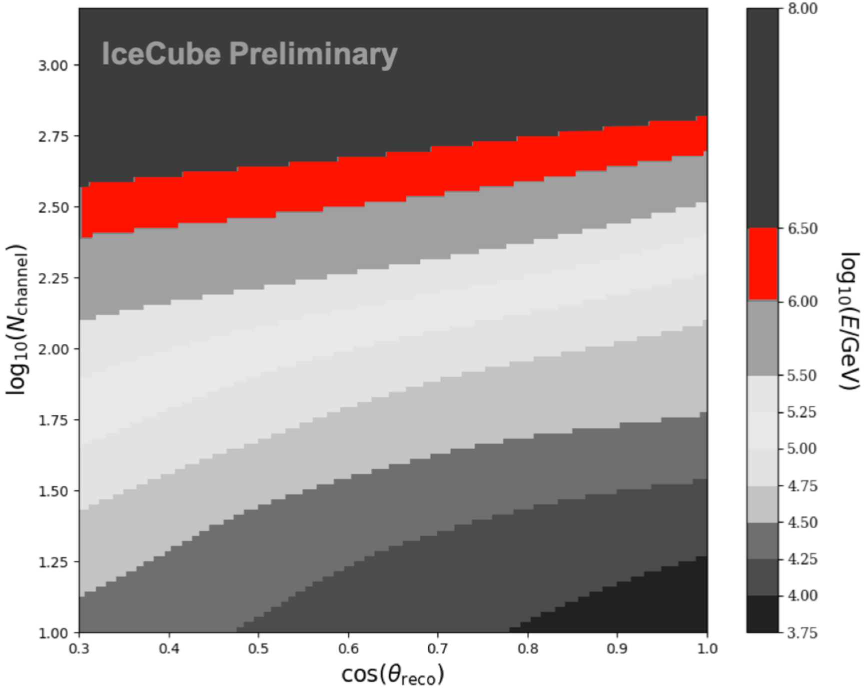
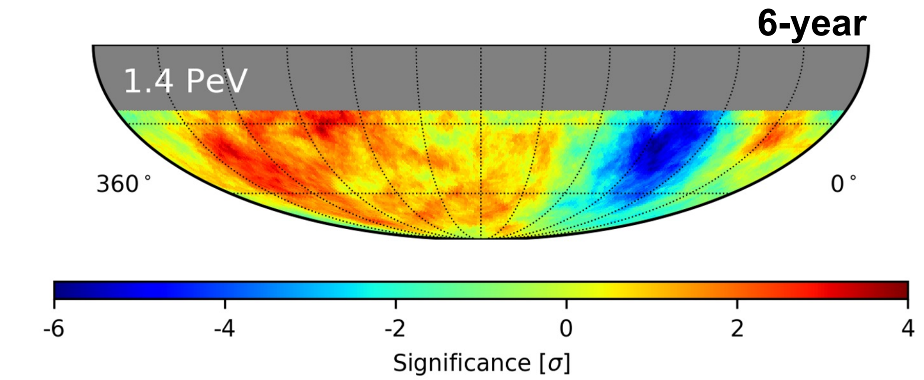


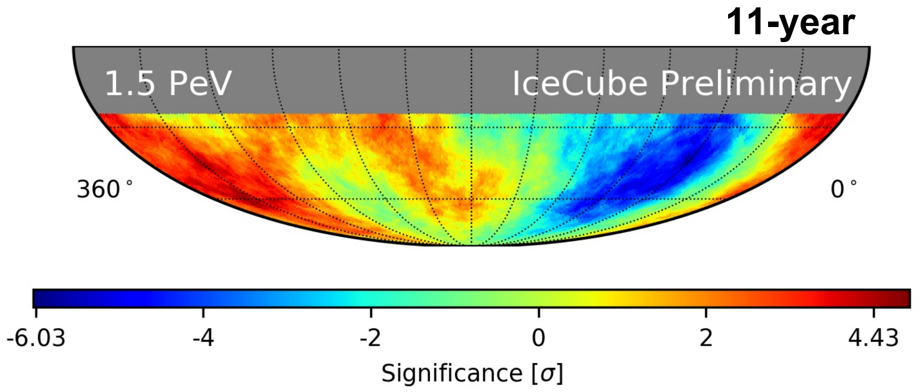




Improved Statistics/Simulation: High-Energy Significance







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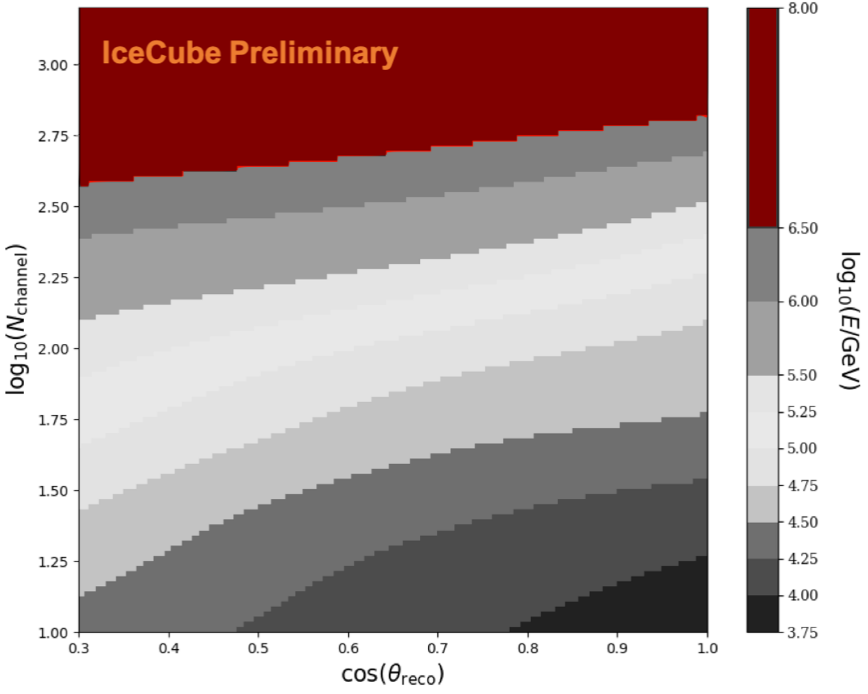
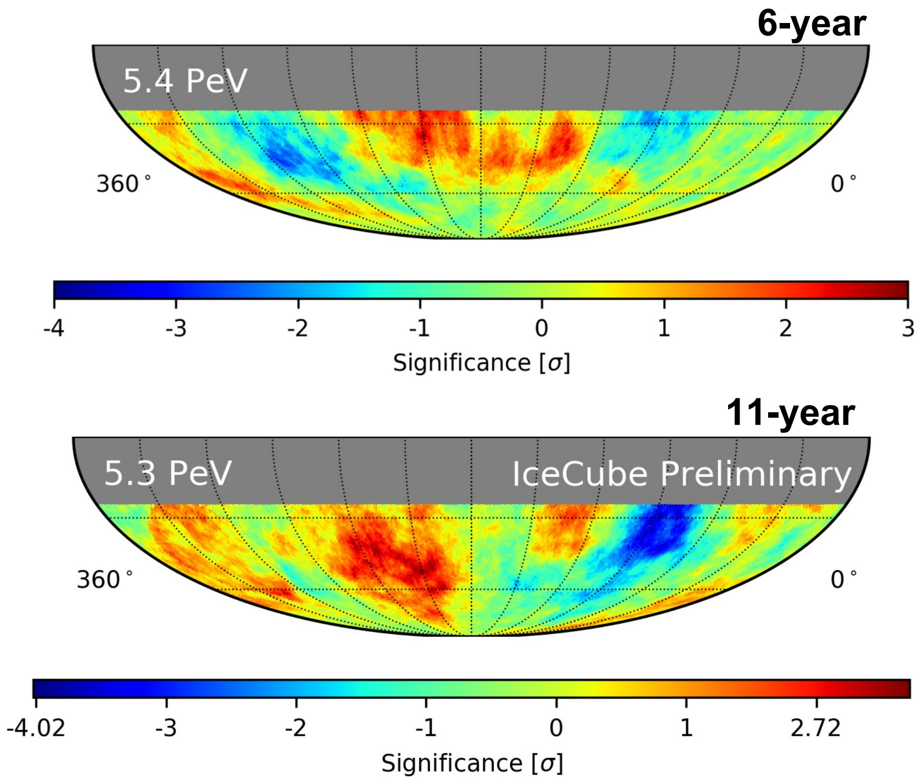
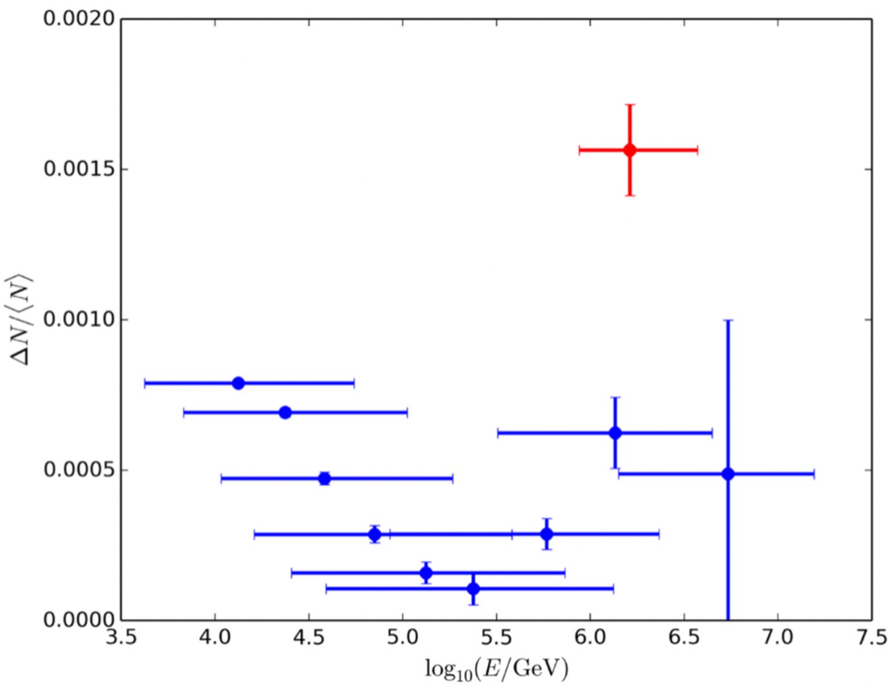
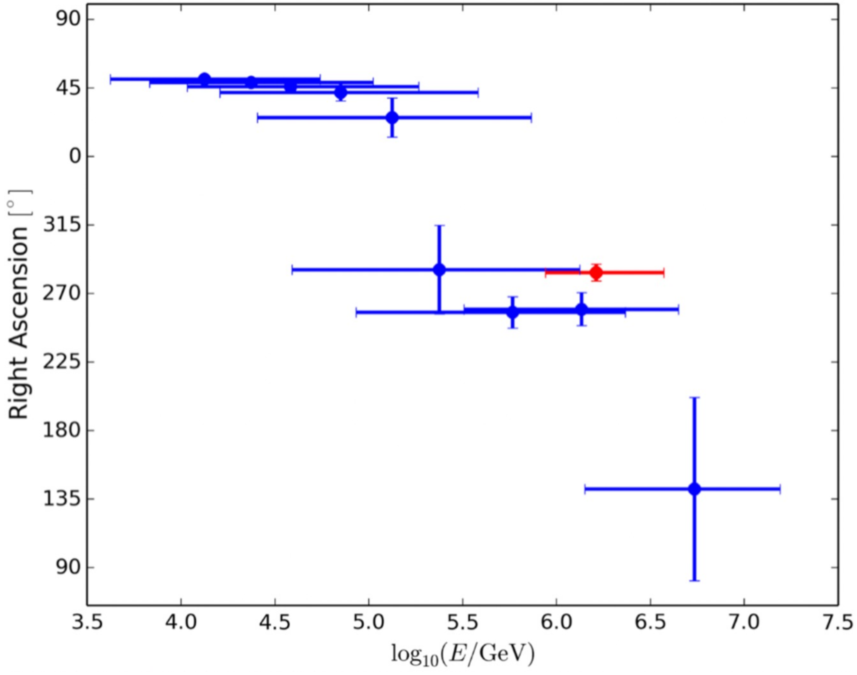




Improved Statistics/Simulation: Dipole Phase & Amplitude

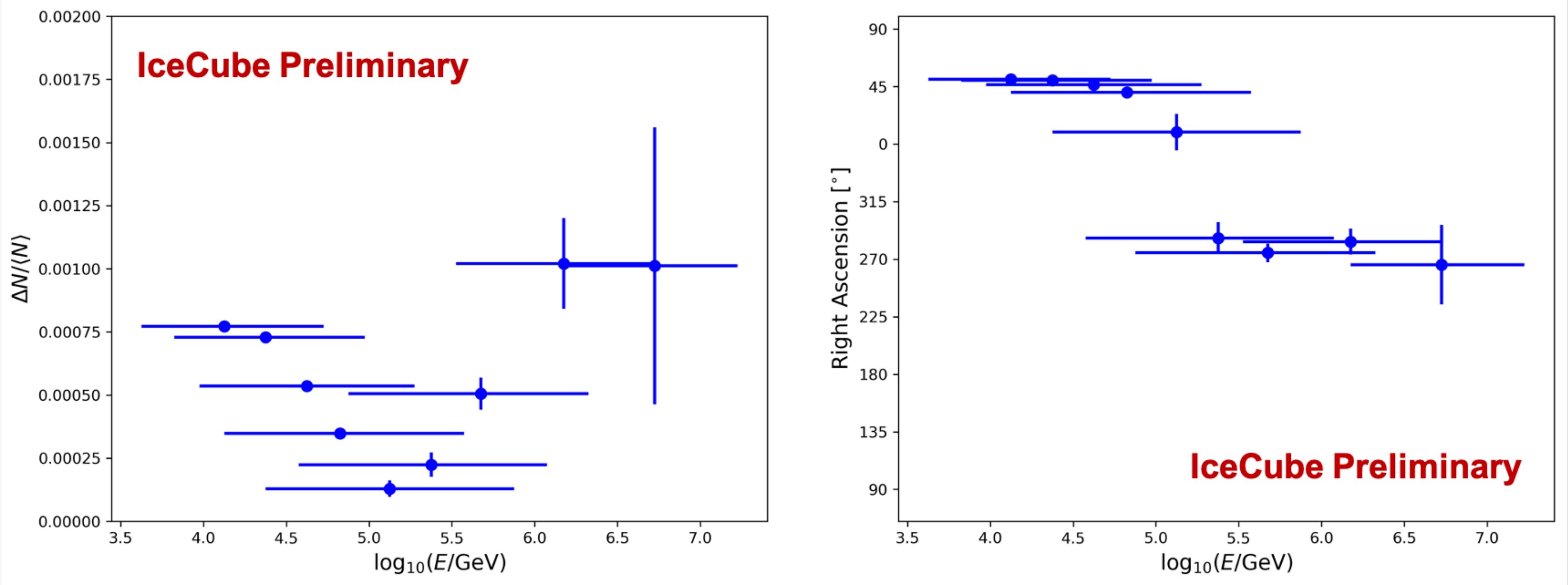
Six Years





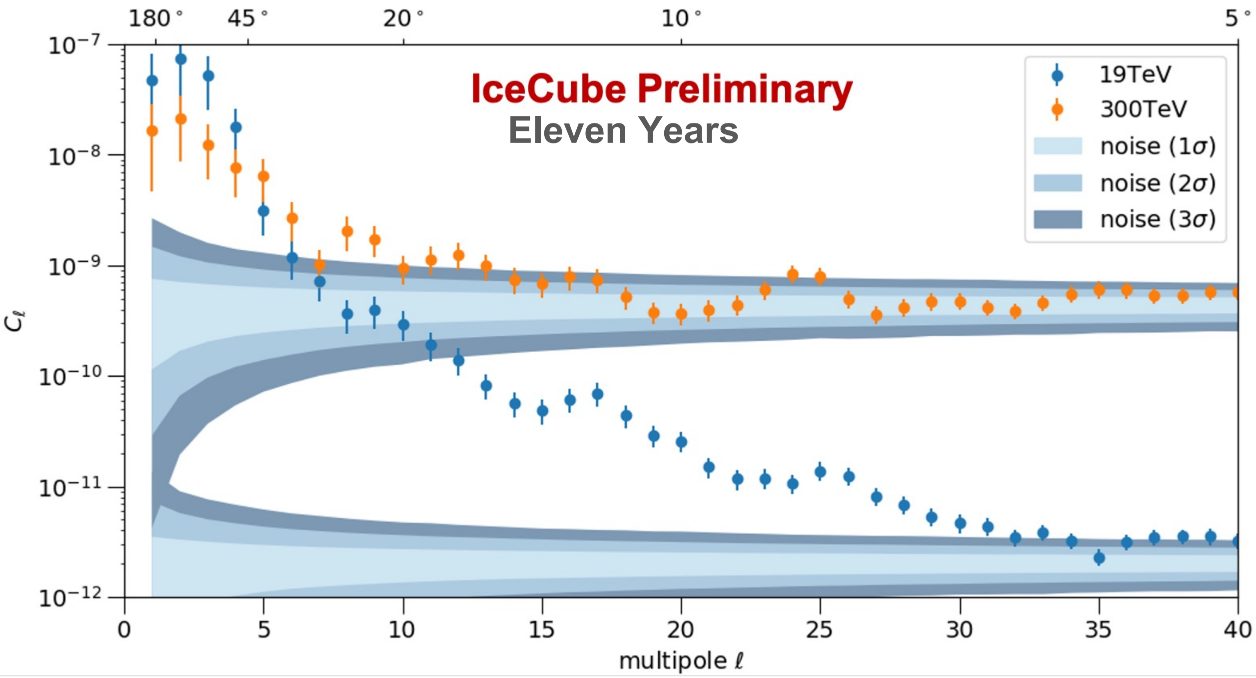
Improved Statistics/Simulation: Dipole Phase & Amplitude

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



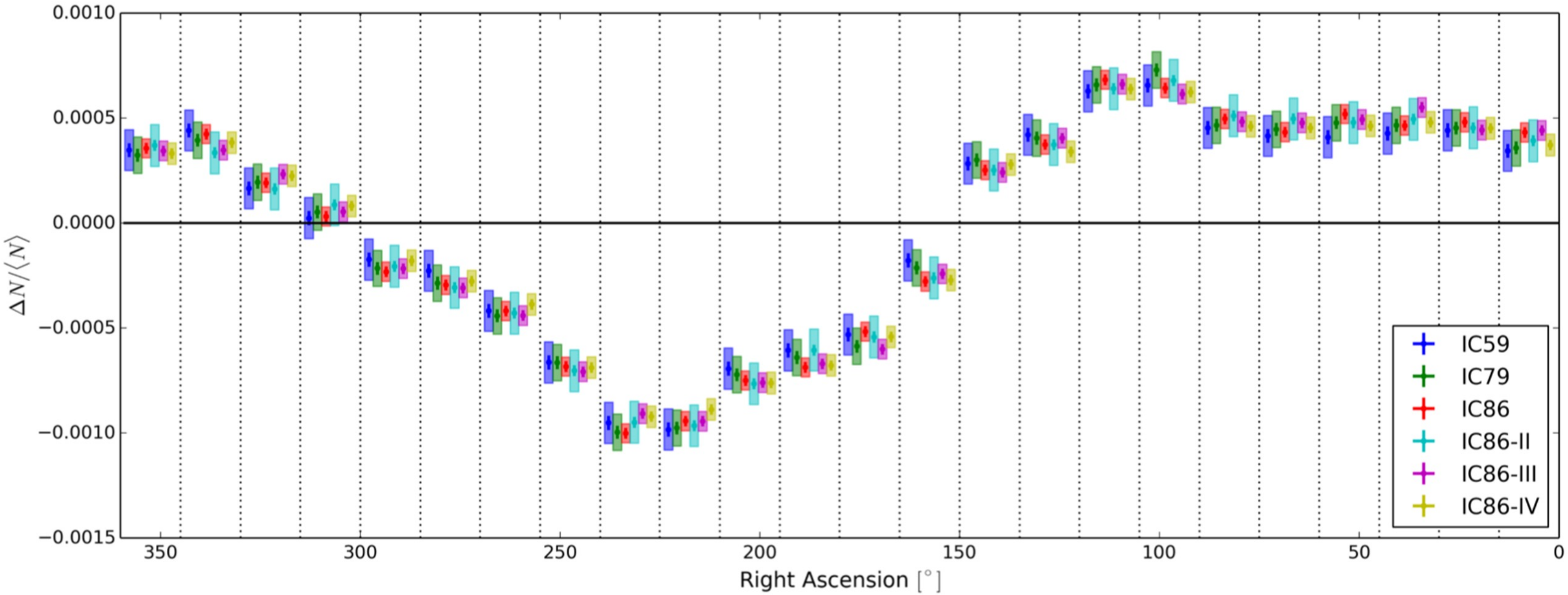
Angular power spectra for low (19 TeV) and high (300 TeV) energy bins. Error bars represent the spread of calculated C_l values for maps randomly generated from the observed C_l values. The noise bands represent 68%, 95%, and 99.7% containment of power spectra produced from an isotropic signal, and differ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

C. Cochling ('23)

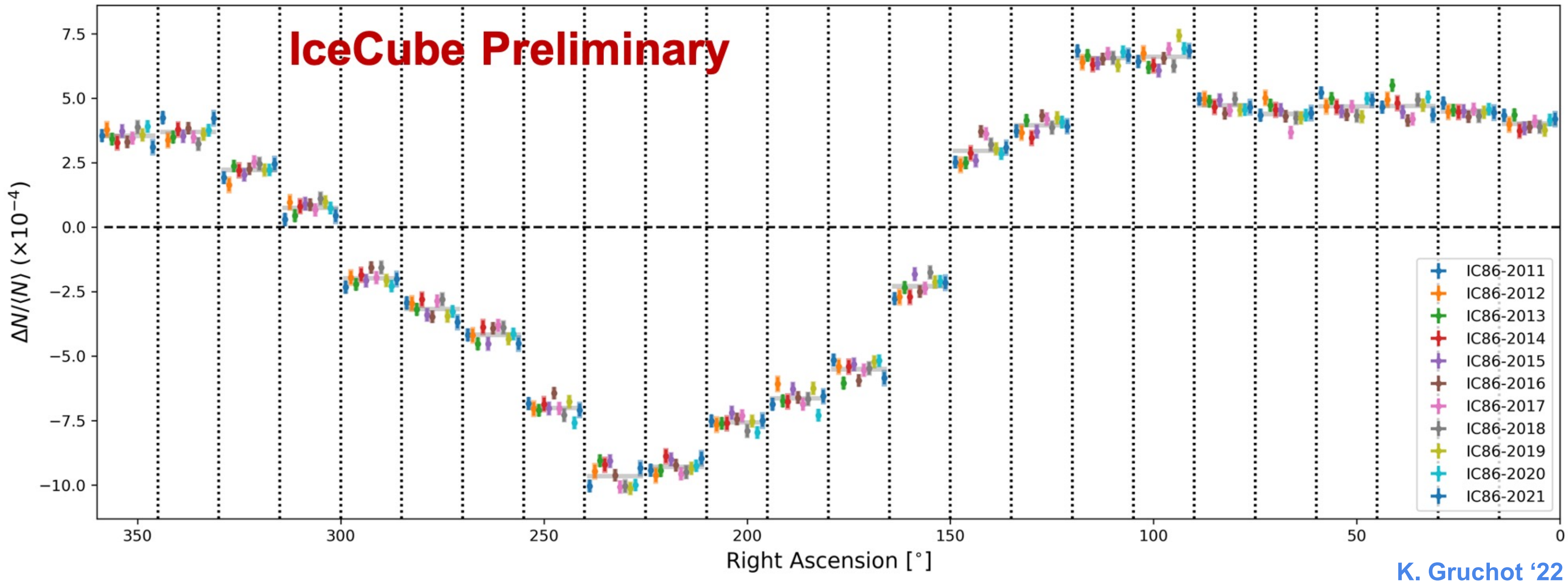
Improved Systematics

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



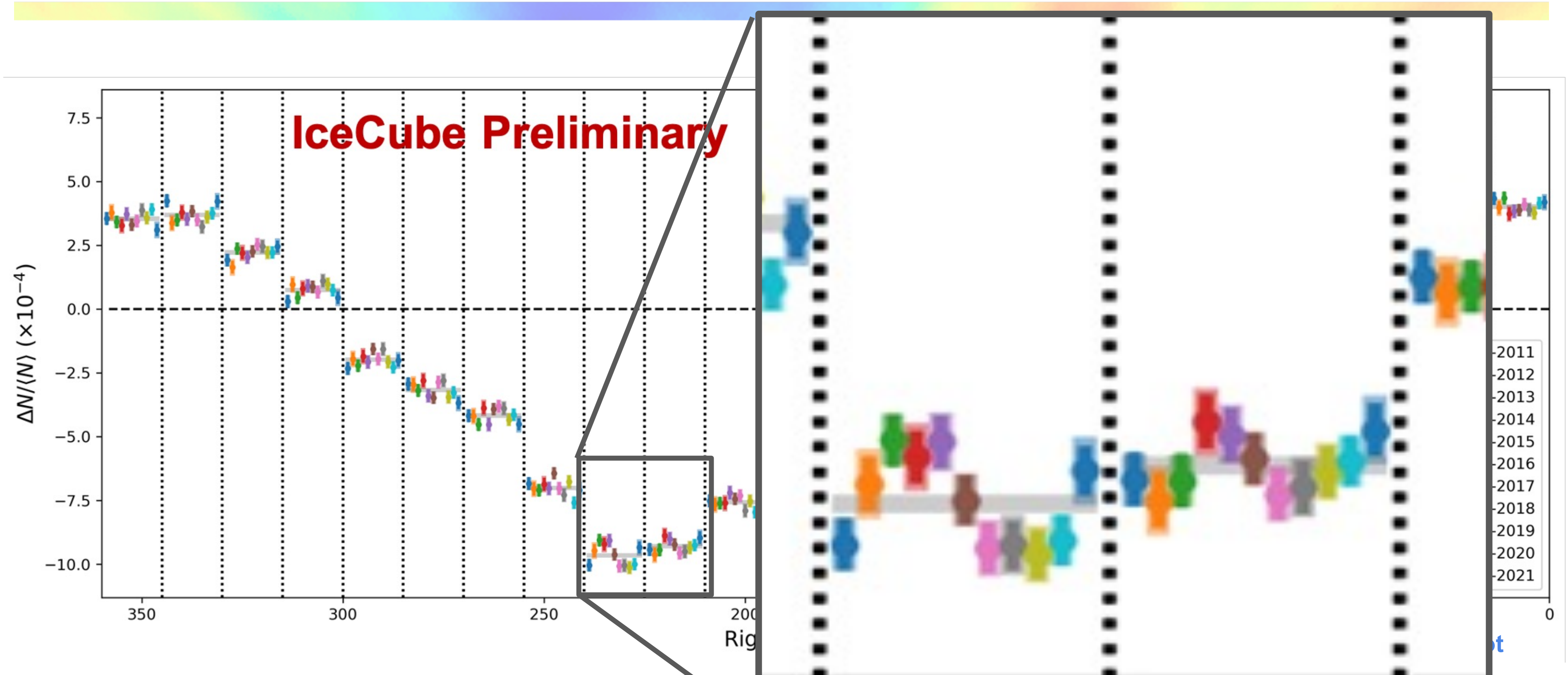
Improved Systematics: Sidereal 1D Projection



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
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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	Angular power spectrum
Alexis Hardy	Event rate analysis
Emily Schmidt	Time gap analysis
Alex Simmons	Systematic checks across detector seasons
Andrew Thorpe	Energy estimation and true energy distributions

- **Loyola**

Katherine “Jo” Gruchot	Anisotropy time dependence
Andrew Moy	Anisotropy time/energy dependence
Will Hays	Events livetime/rates
Joe Summers	IceTop simulation/Data comparison
Grace Bratude	IceTop Data processing/analysis

- **UW-Madison**

Hannah Woodward	Extended- and anti-sidereal distributions
(Summer 2020 REU)	Comparing detector and calendar years
(University of Virginia)	

Backup Slides

Improved Systematics

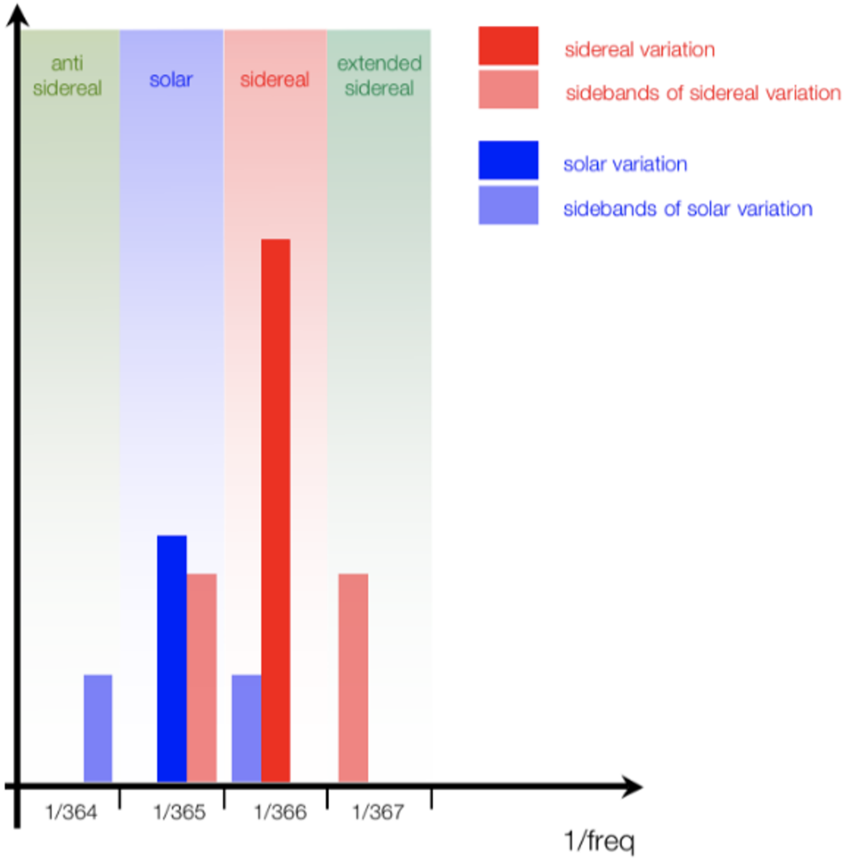
Review: Yearly Variation

- Consider four time frames:

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

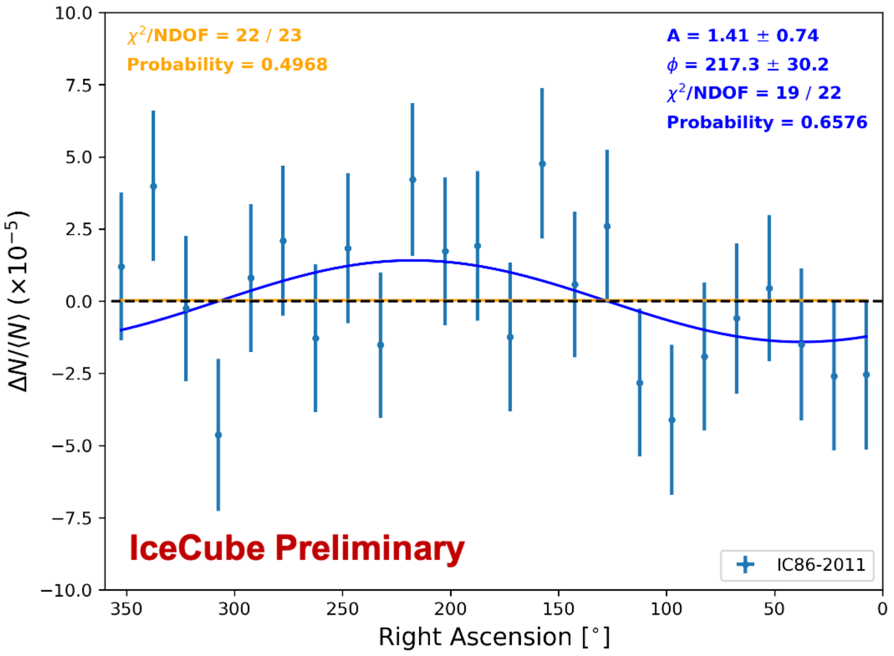
- What is the mutual influence of the signals in the solar and sidereal frames?

- 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 ~100x 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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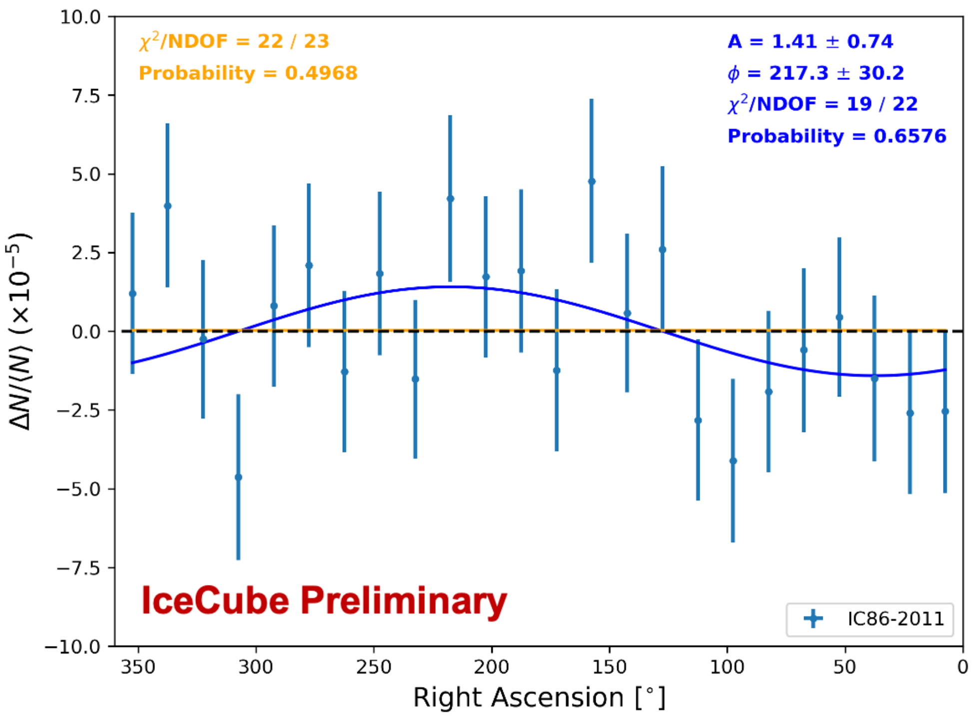

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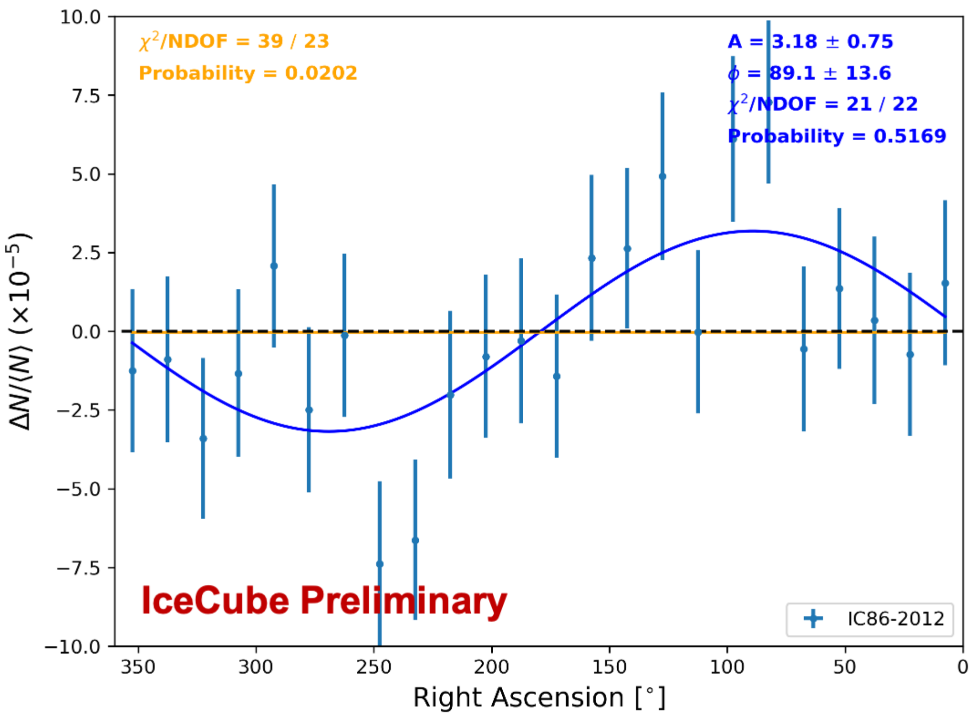

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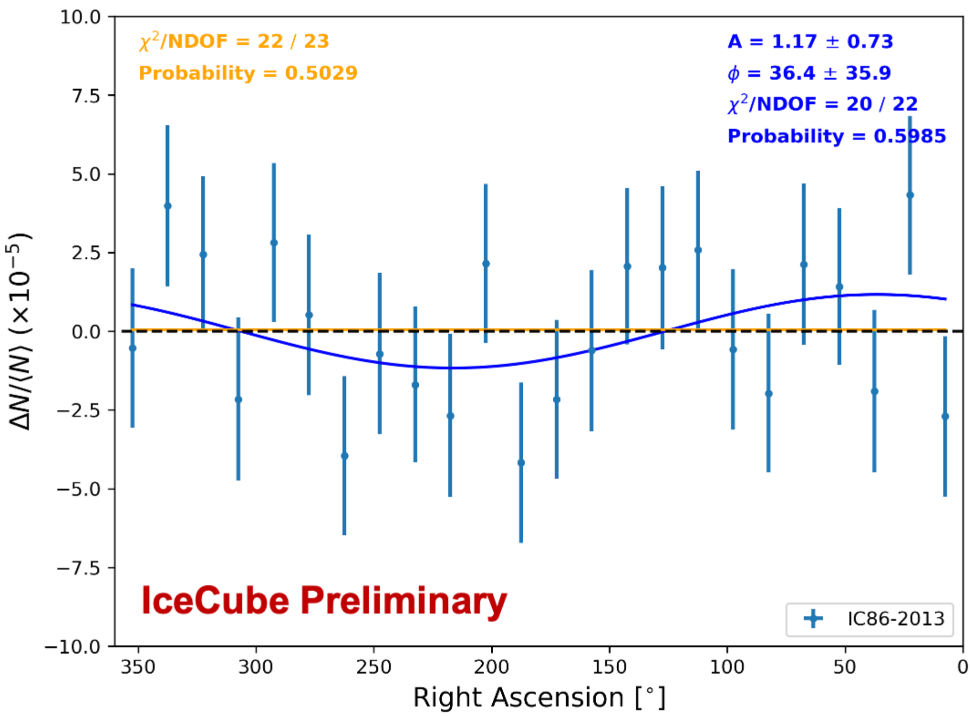

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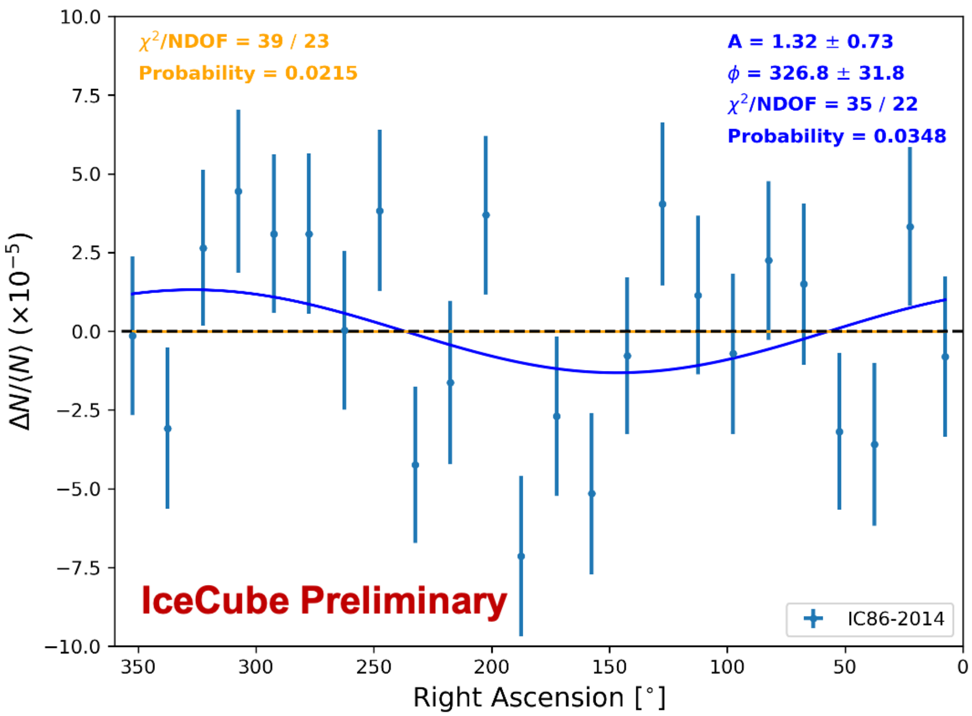

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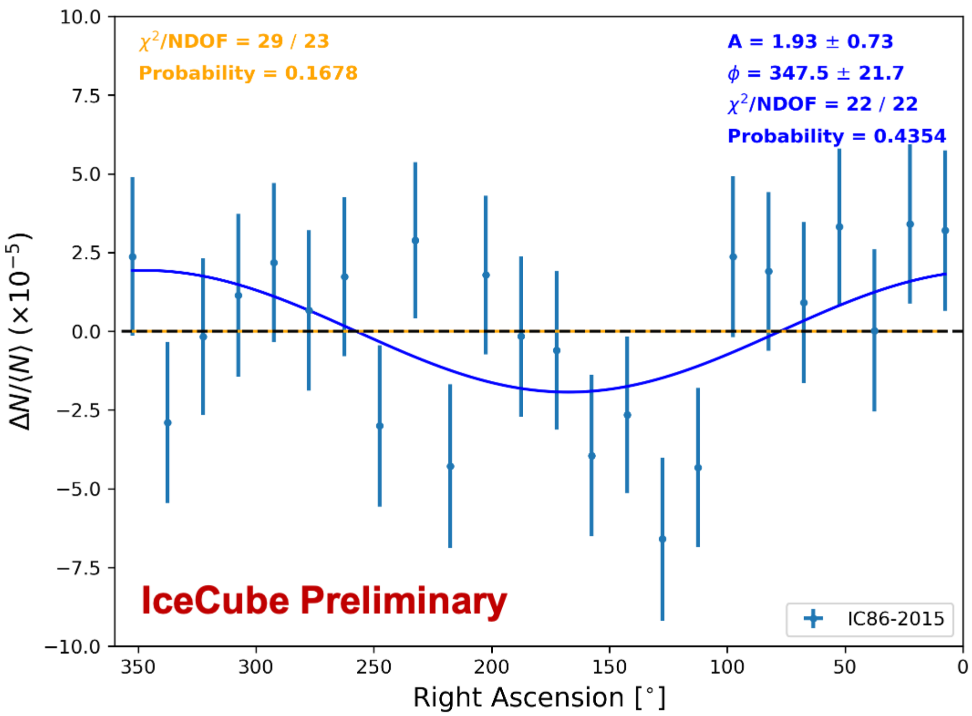

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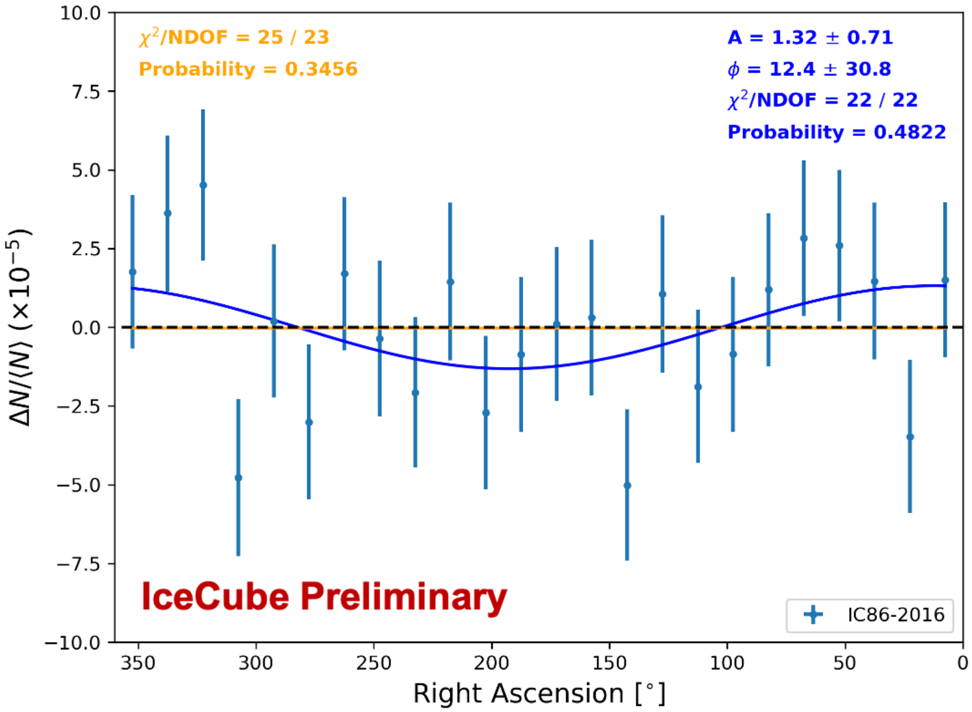

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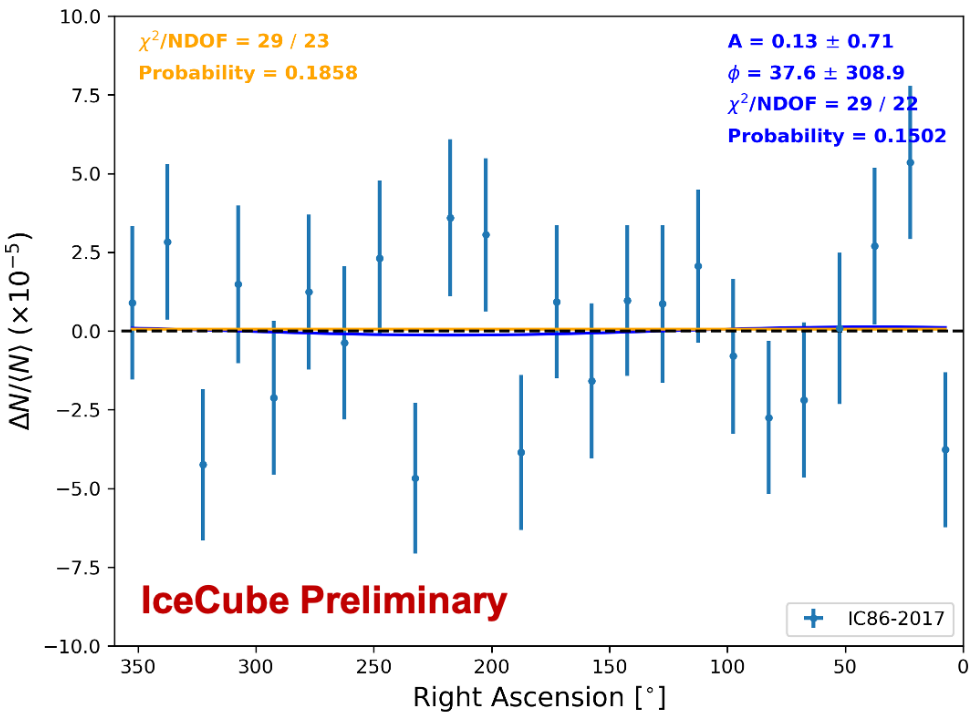

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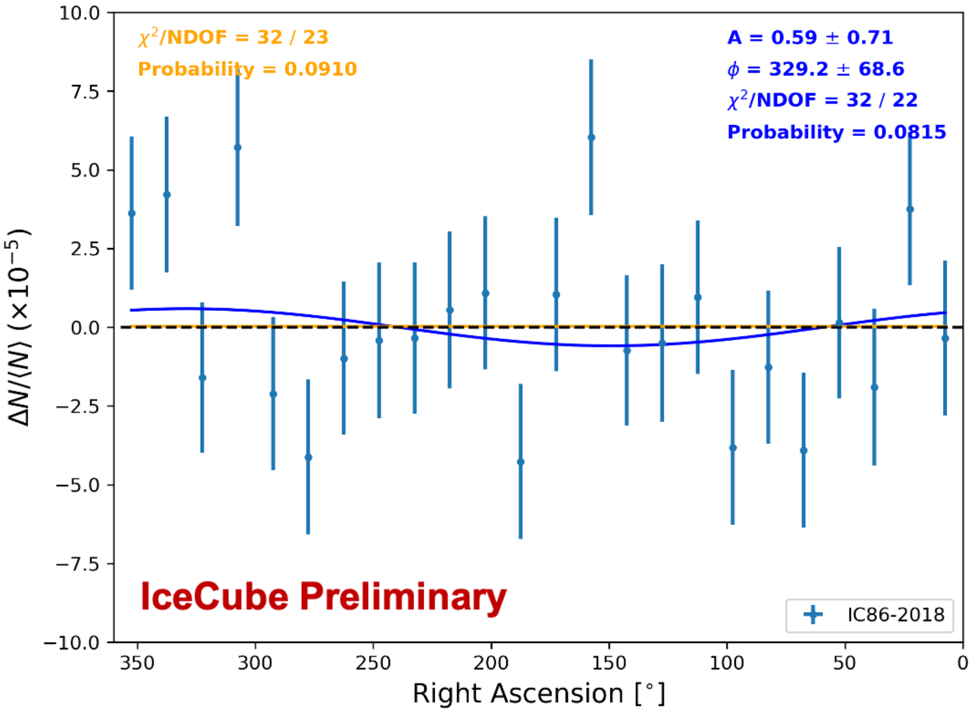

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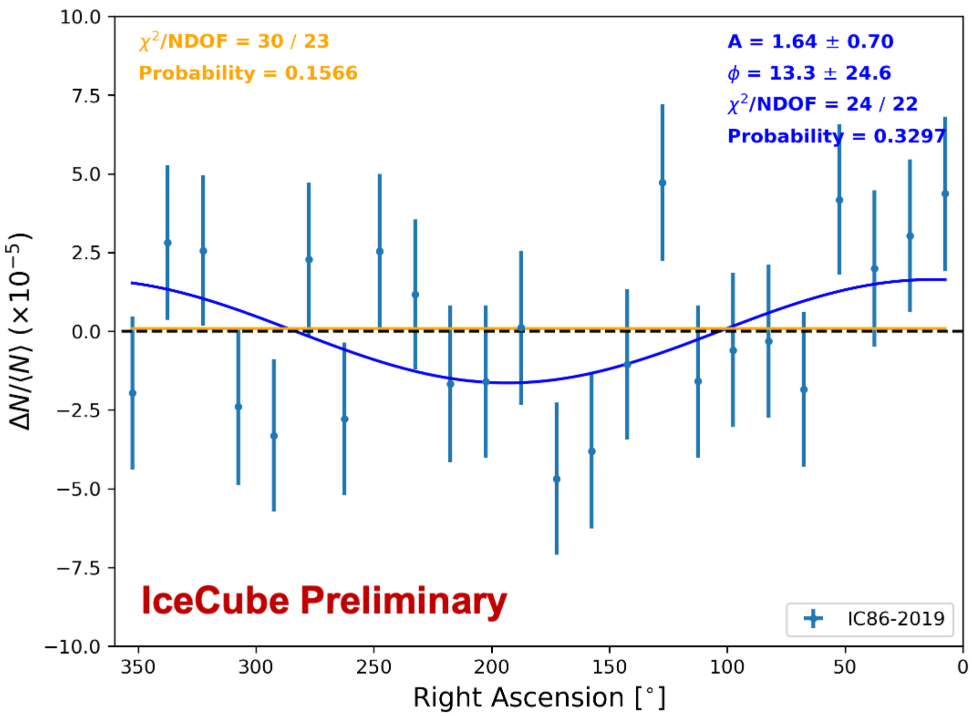

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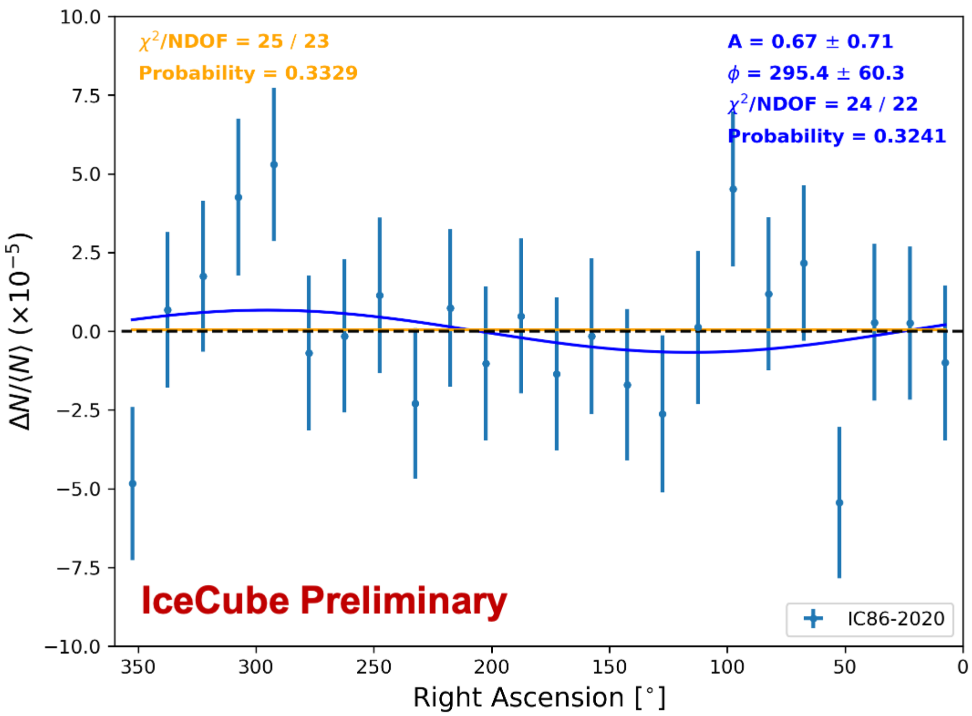

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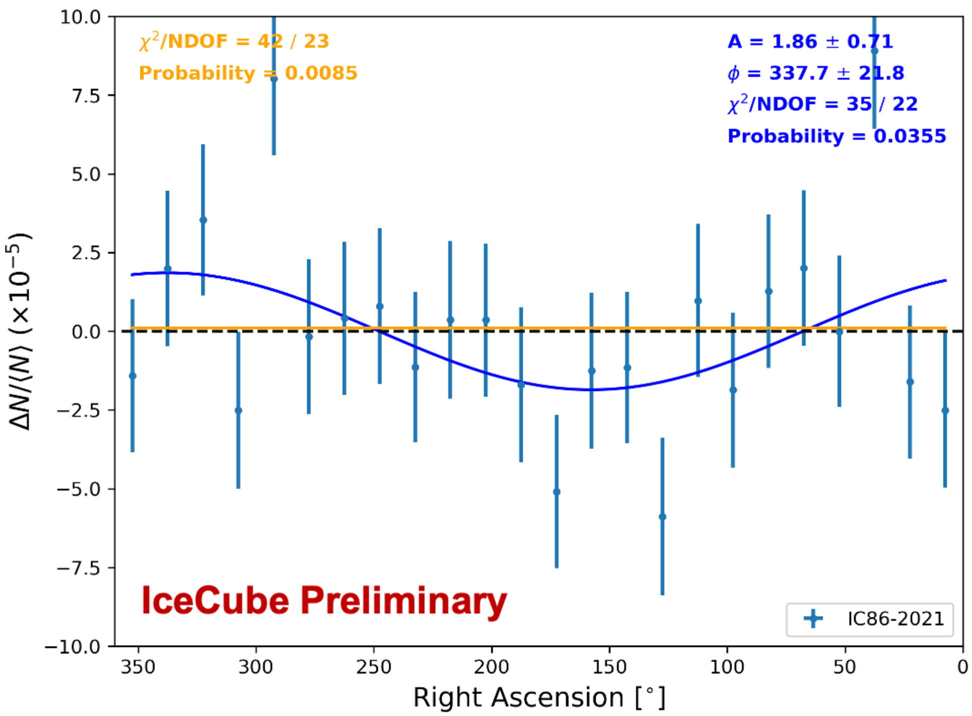

Improved Systematics: Calendar Years

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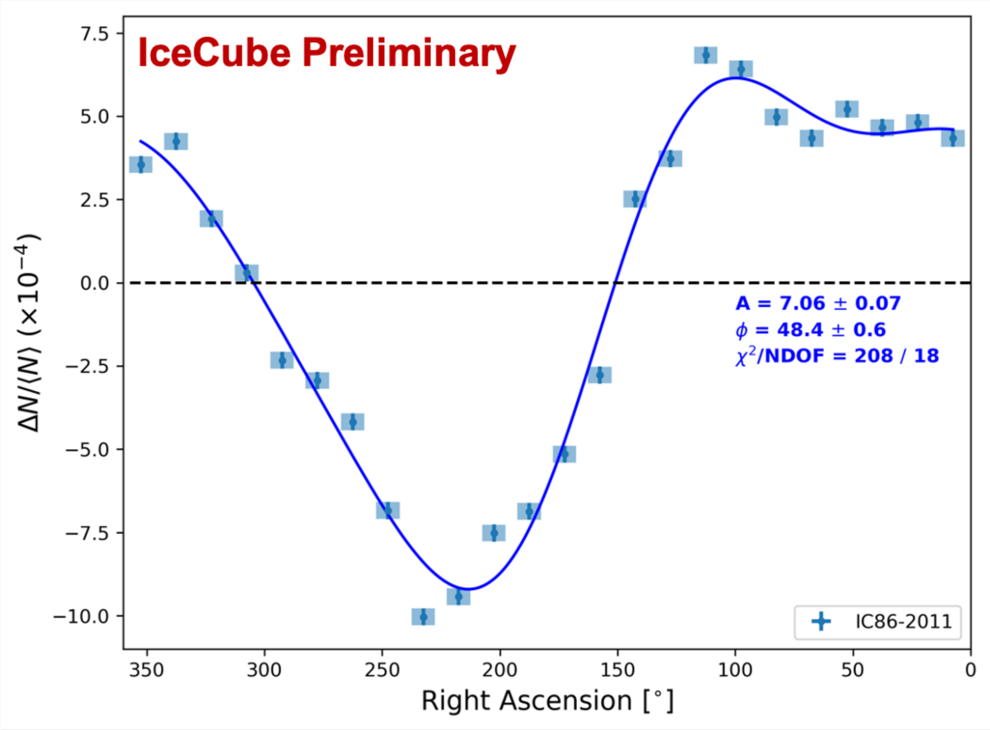
  - Best-fit phase and amplitude for dipole component



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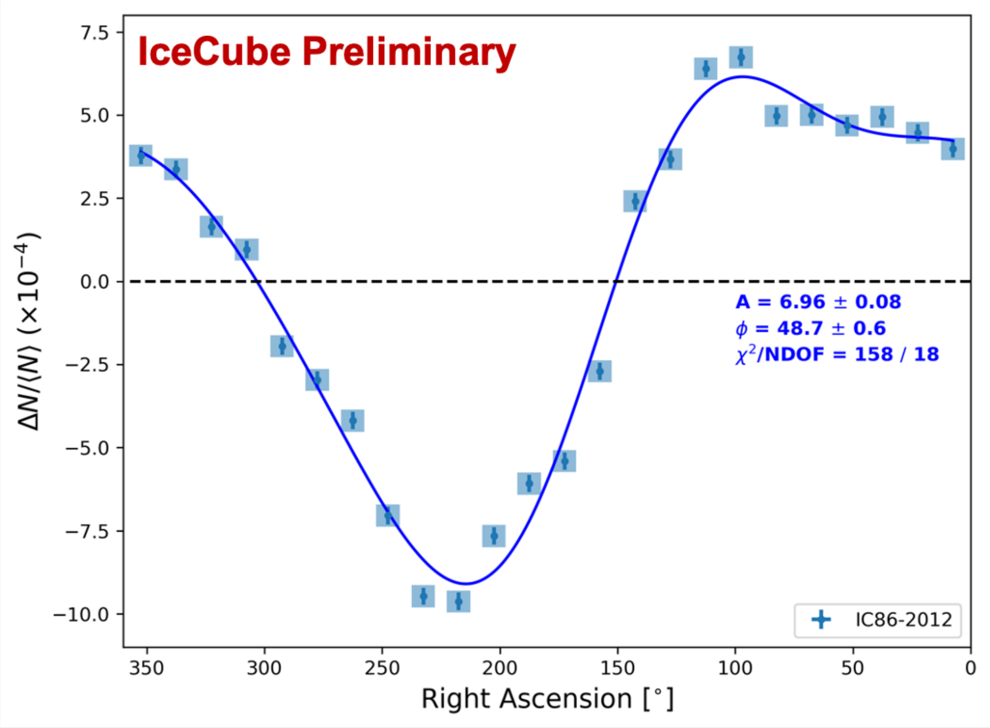

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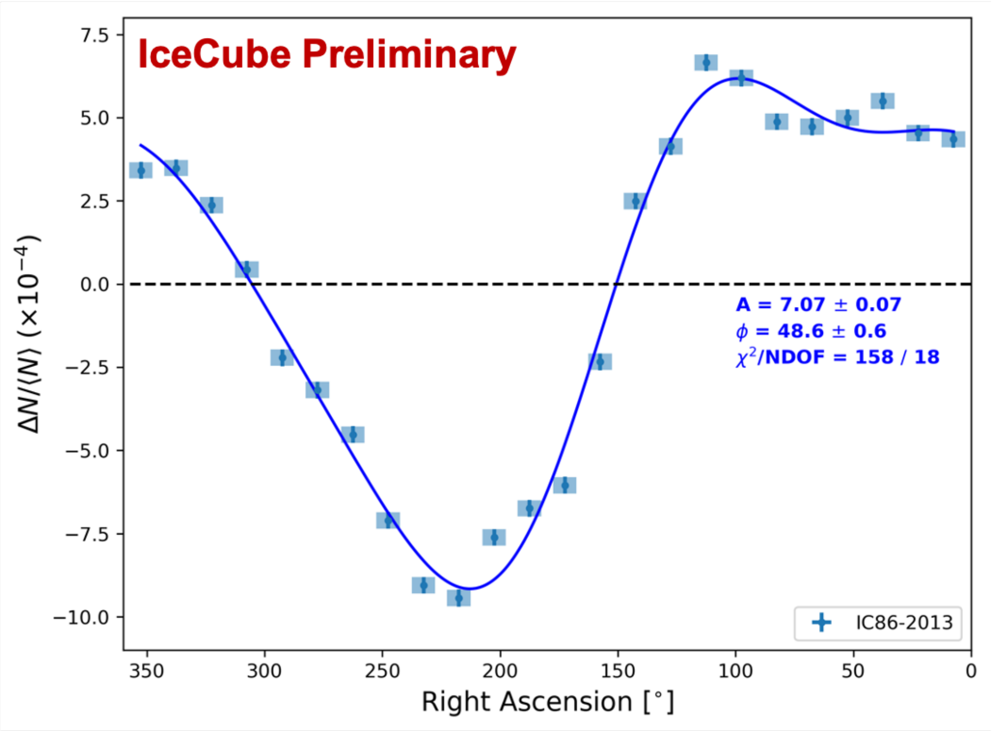

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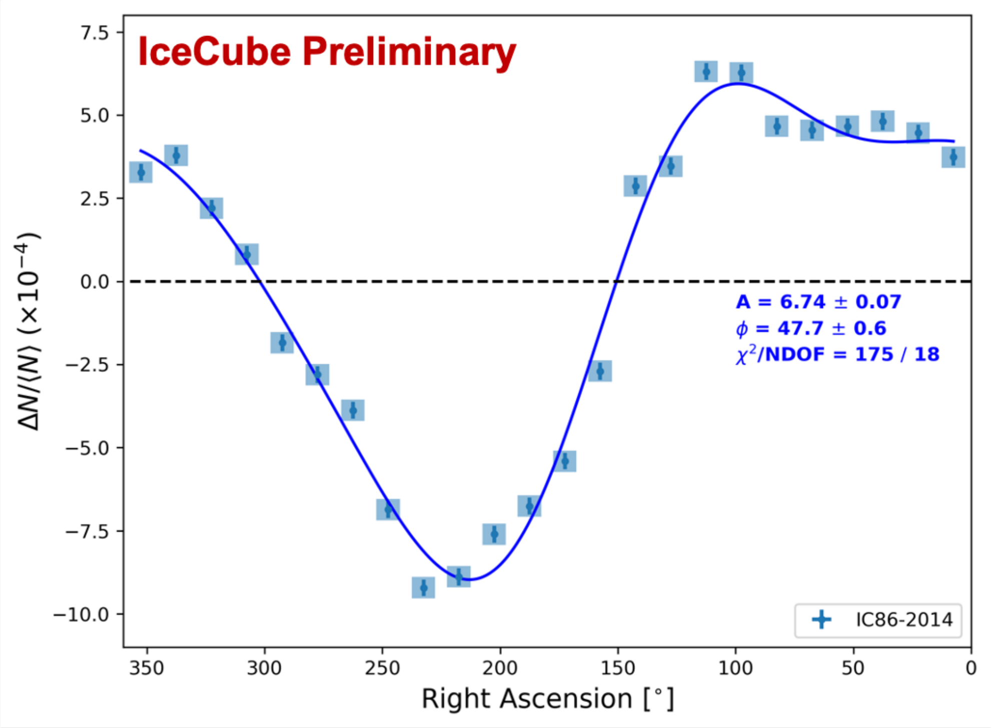

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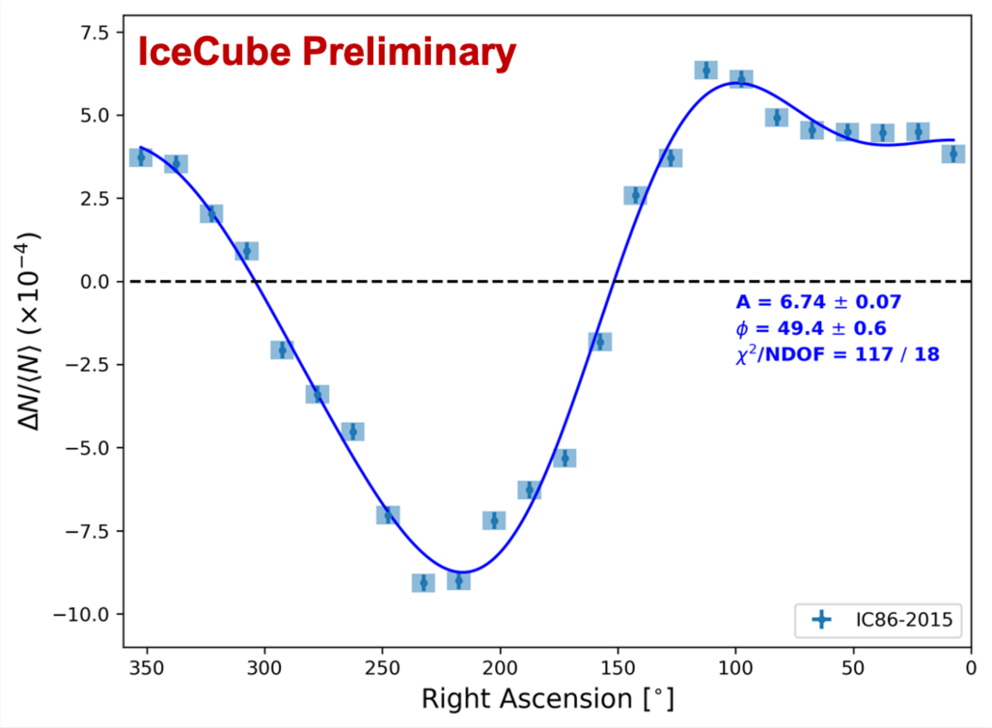

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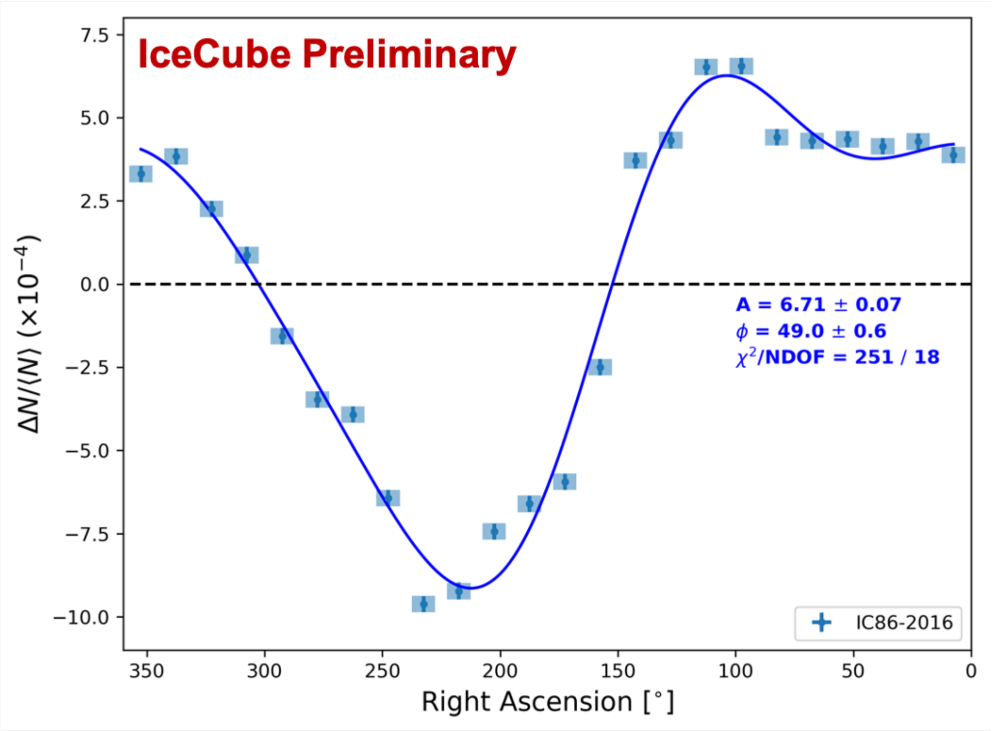

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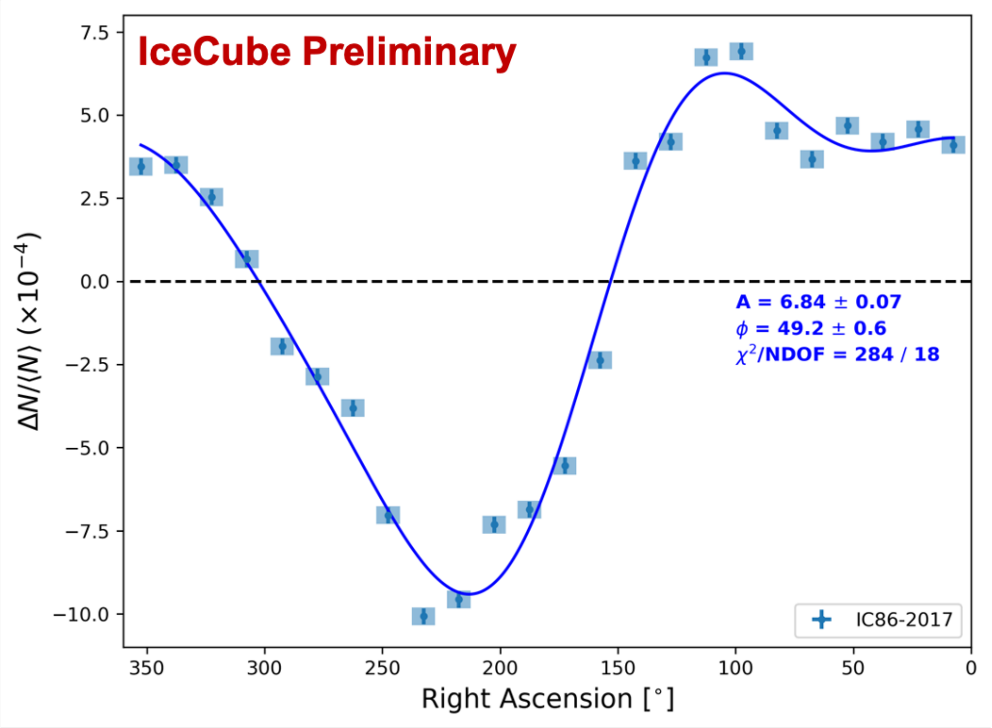

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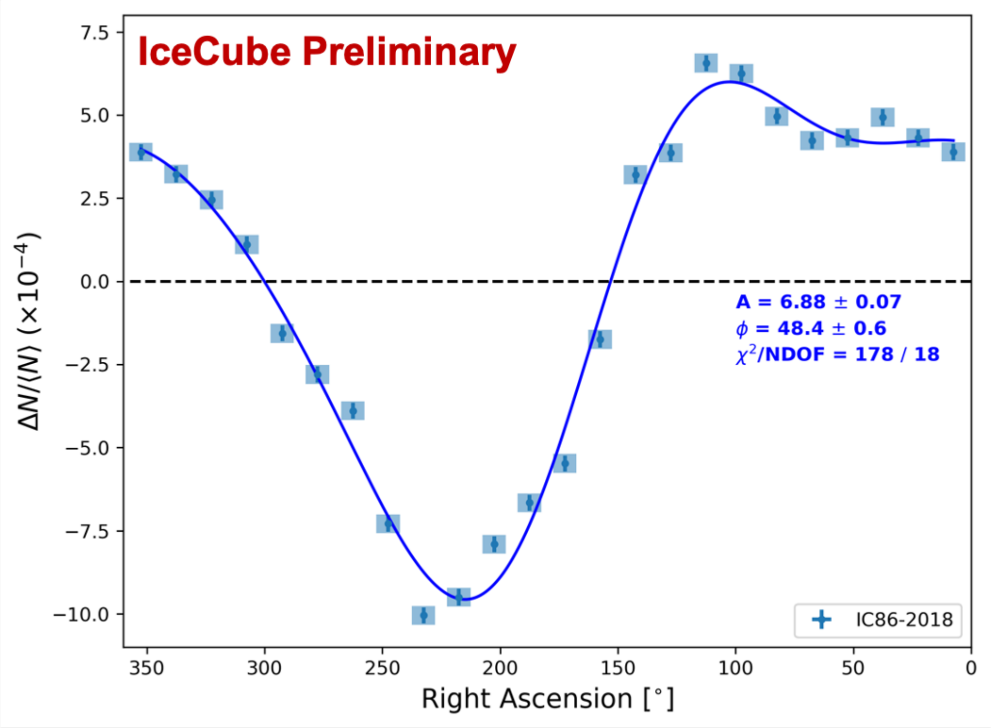

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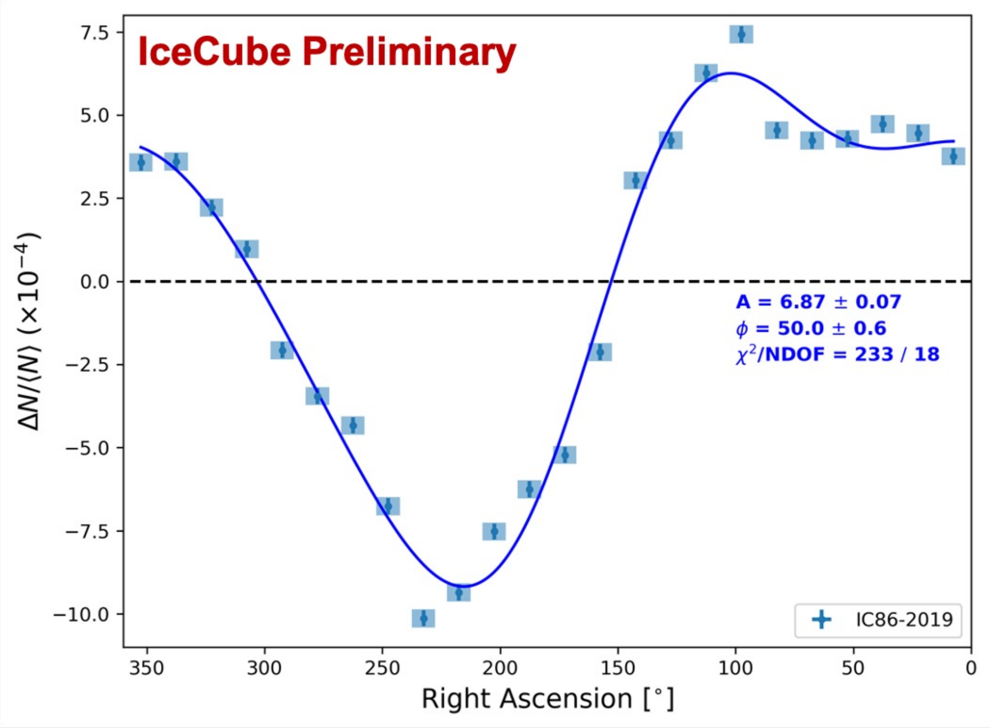

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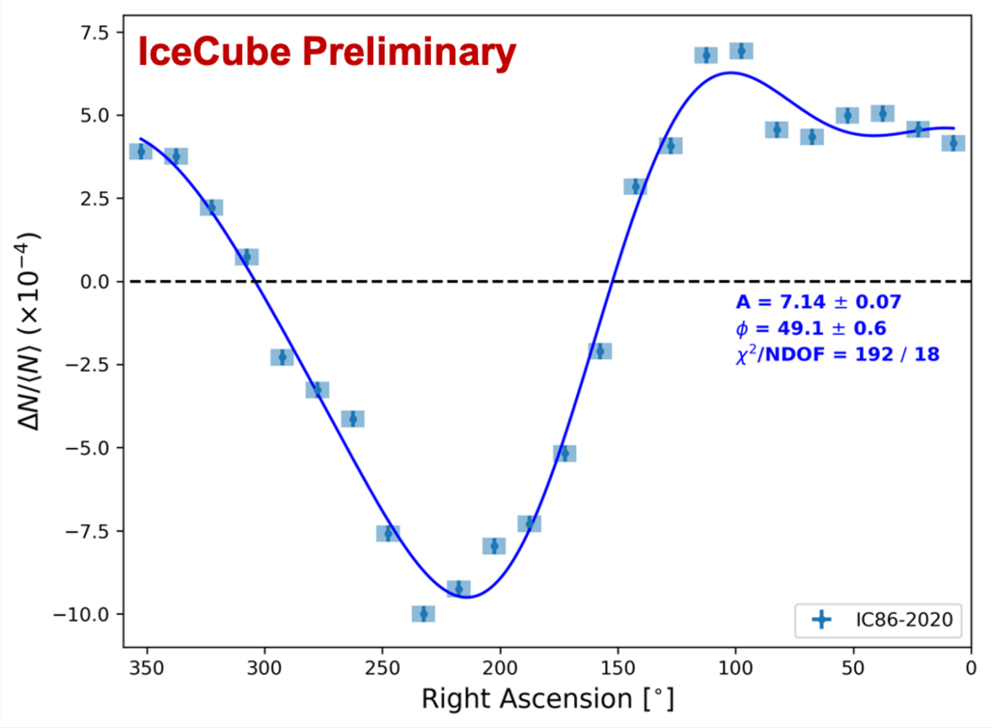

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