CR Anisotropy with IceCube

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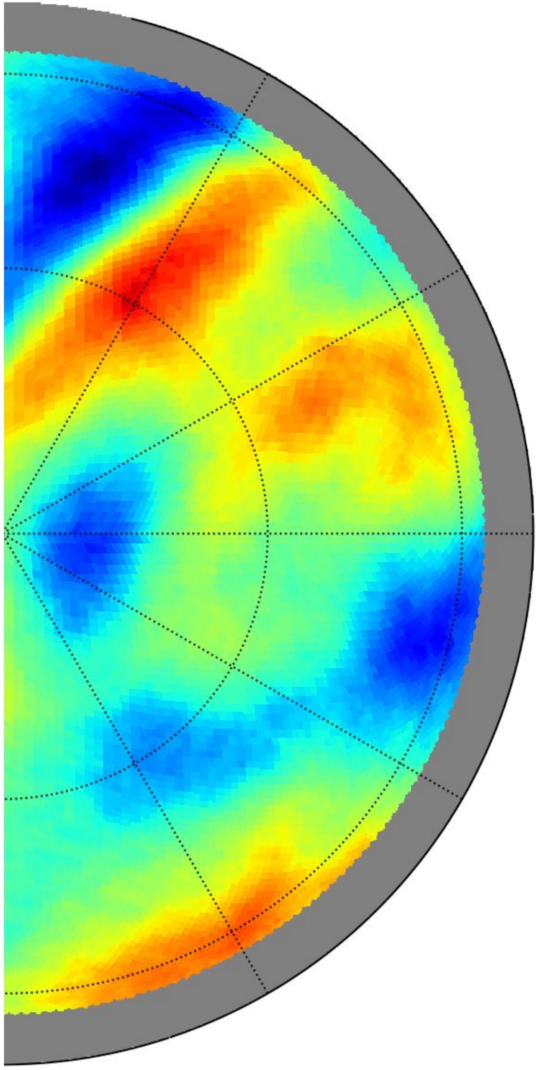
CRA 2023

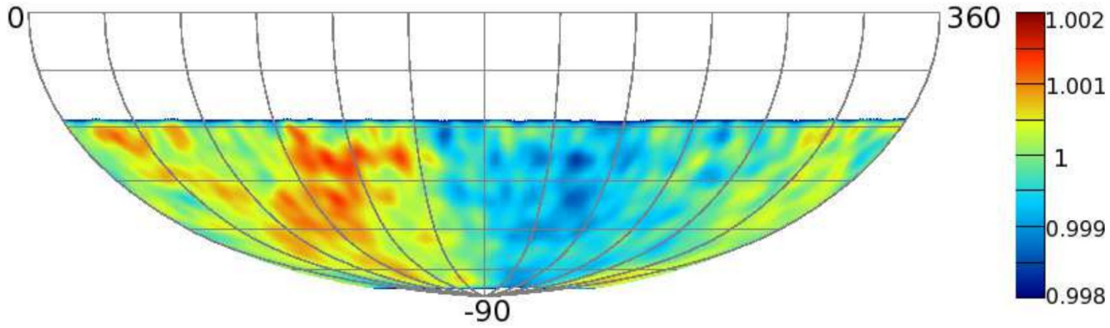


Anisotropy in IceCube

2010: First observation

1 year of data from 22-string configuration (IC22)

Shown: relative intensity



Abbasi et al., “Measurement of the Anisotropy of Cosmic Ray Arrival Directions with IceCube”, Astrophys.J. **718** (2010) L194 (arXiv:1005.2960)

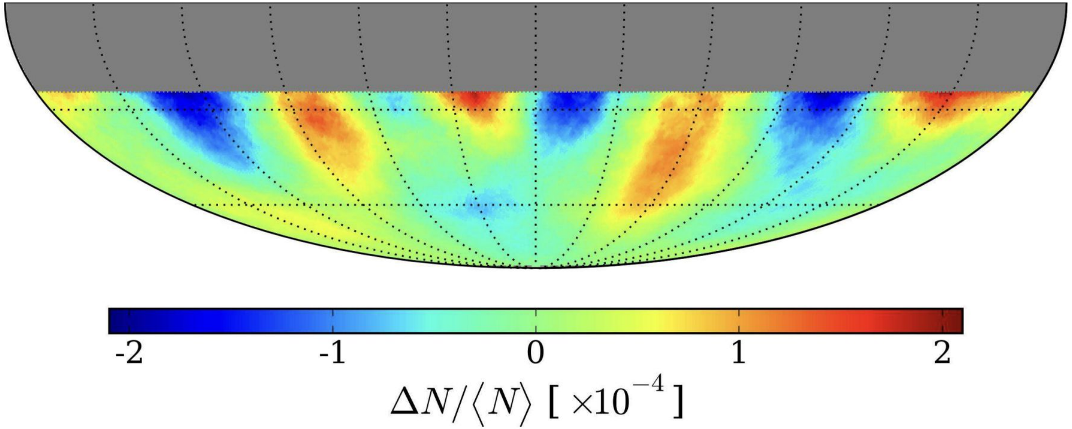
History

2010: First observation

2011: Observation at multiple angular scales

1 year of data from 59-string configuration (IC59)

Shown: relative intensity of small-scale structure



Abbasi et al., “Observation of Anisotropy in the Arrival Directions of Galactic Cosmic Rays at Multiple Angular Scales with IceCube”, Astrophys.J. **740** (2011) 16 (arXiv:1105.2326)

History

Anisotropy in IceCube

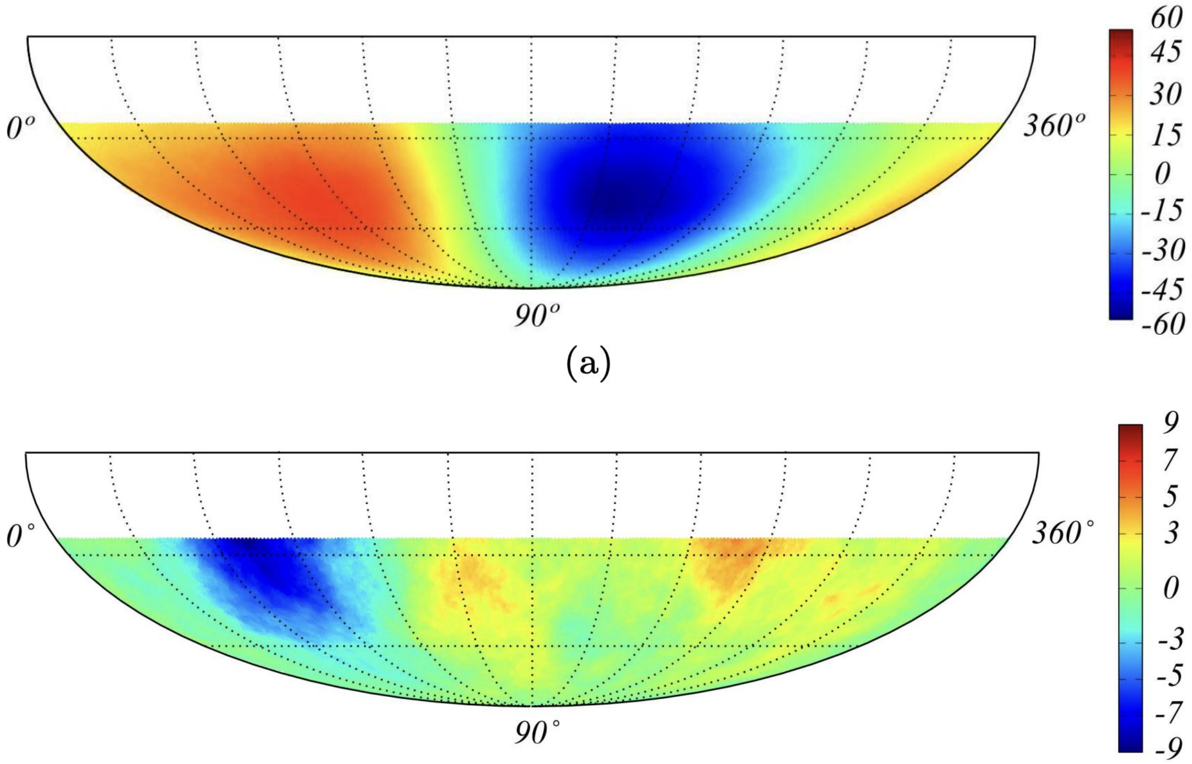
2010: First observation

2011: Observation at multiple angular scales

2012: Energy dependence

1 year of data from 59-string configuration (IC59)

Shown: significance at median energies of 20 TeV (*top*) and 400 TeV (*bottom*)



Abbasi et al., "Observation of Anisotropy in the Galactic Cosmic Ray Arrival Directions at 400 TeV with IceCube", Astrophys.J. **746** (2012) 33 (arXiv:1109.1017)

History

2010: First observation

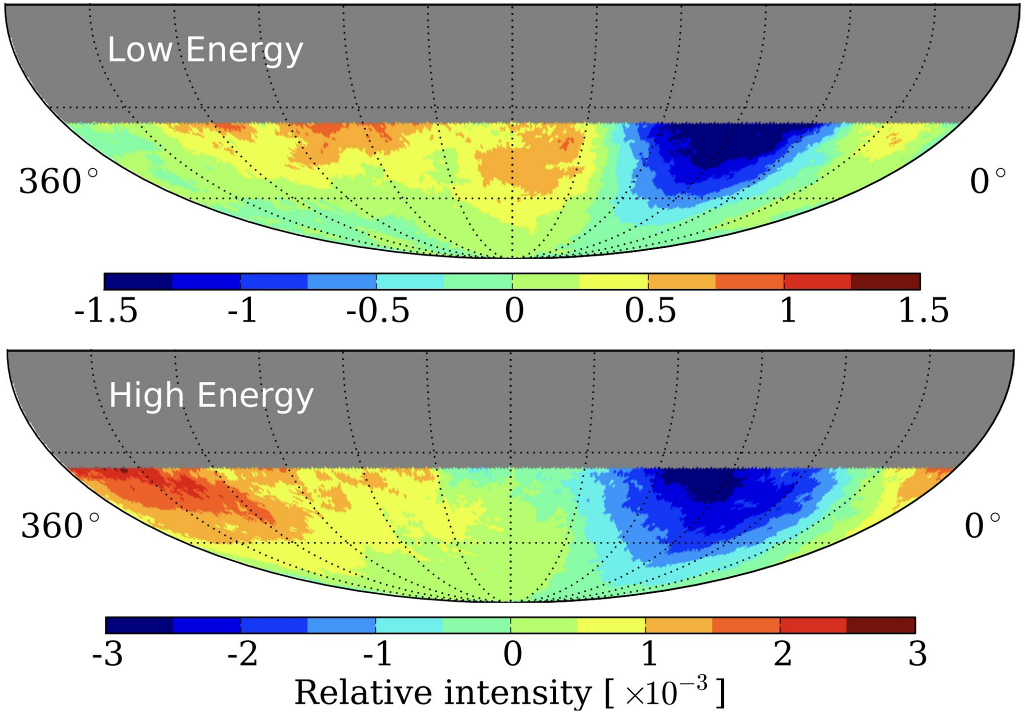
2011: Observation at multiple angular scales

2012: Energy dependence

2013: Observation with IceTop

3 years of data from 2009-2012 (IC59 - IC86-2011)

Shown: relative intensity at median energies of 400 TeV (*top*) and 2 PeV (*bottom*)



Aartsen et al., "Observation of Cosmic Ray Anisotropy with the IceTop Air Shower Array", Astrophys.J. **765** (2013) 55 (arXiv:1210.5278)

History

2010: First observation

2011: Observation at multiple angular scales

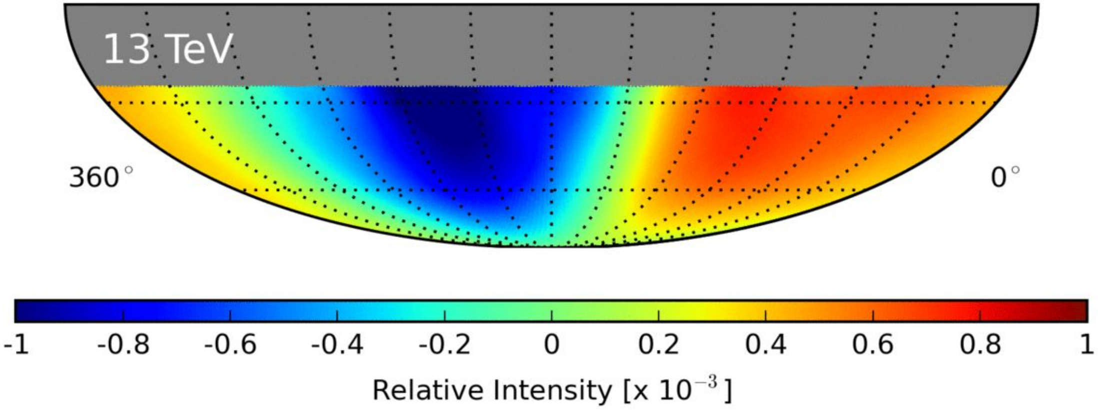
2012: Energy dependence

2013: Observation with IceTop

2015: Six-Year Update

6 years of data from 2009-2015 (IC59 - IC86-2014)

Shown: relative intensity as a function of energy



Aartsen et al., “Anisotropy in Cosmic-Ray Arrival Directions in the Southern Hemisphere with Six Years of Data from the IceCube Detector”, Astrophys.J. **826** (2016) no.2 220 (arXiv:1603.01227)

History

2010: First observation

2011: Observation at multiple angular scales

2012: Energy dependence

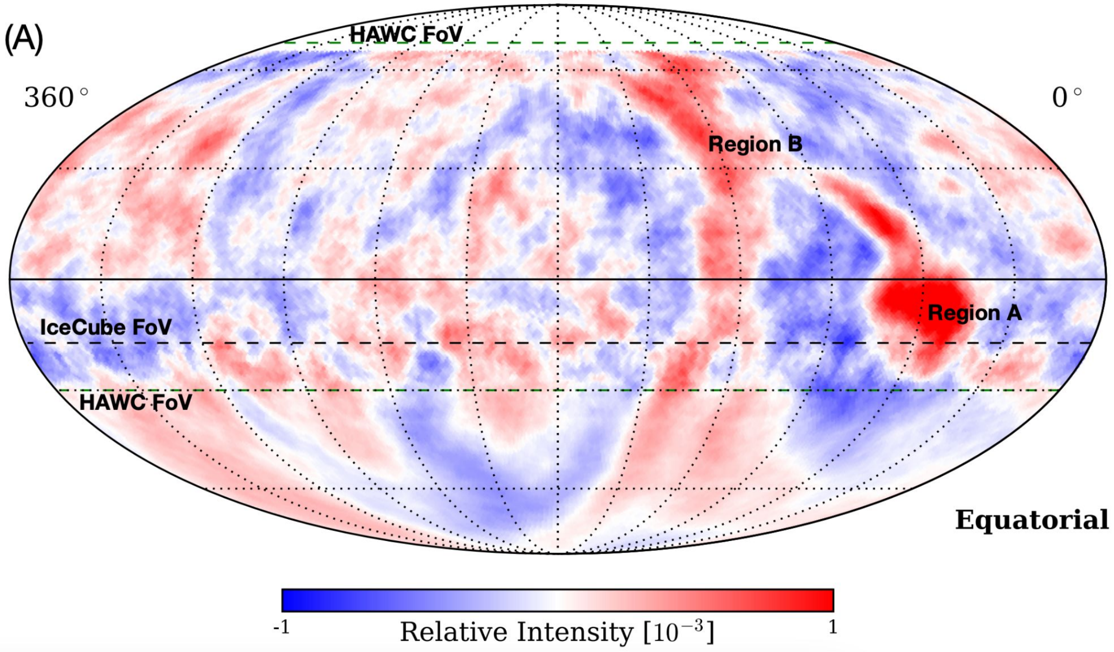
2013: Observation with IceTop

2015: Six-Year Update

2019: Full-Sky with HAWC

5 years of IceCube data,
2 years of HAWC

Shown: relative intensity of small-scale structures at 10 TeV



Abeysekara et al., “All-Sky Measurement of the Anisotropy of Cosmic Rays at 10 TeV and Mapping of the Local Interstellar Magnetic Field”, Astrophys.J. **871** (2019) 96 (arXiv:1812.05682)

Present Day

Objective: Revisit 6-year analysis with enhanced tools

Improved statistics:

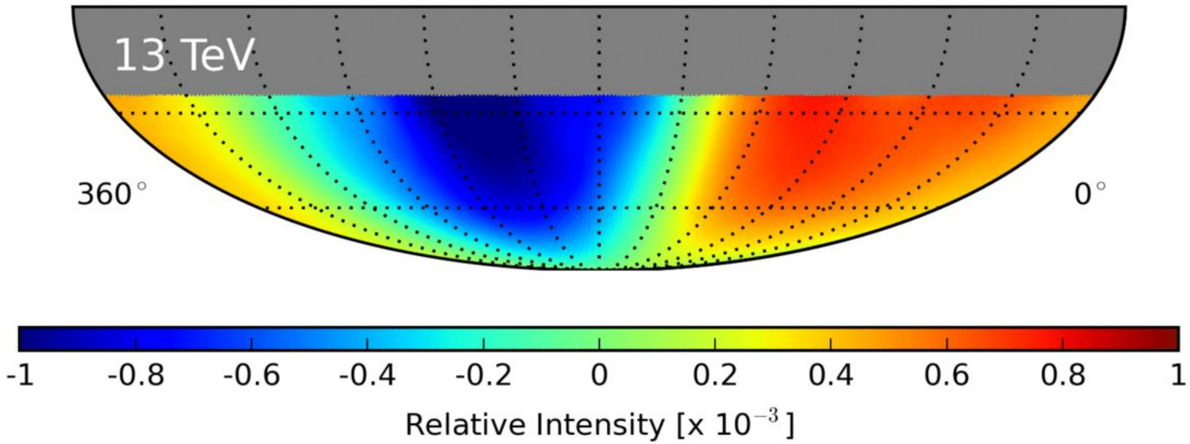
Eleven years of data
(~700 billion events)

Improved simulation:

Newer, dataset-specific,
increased statistics

Improved systematics:

Shift from detector to
calendar years, stable
detector configuration

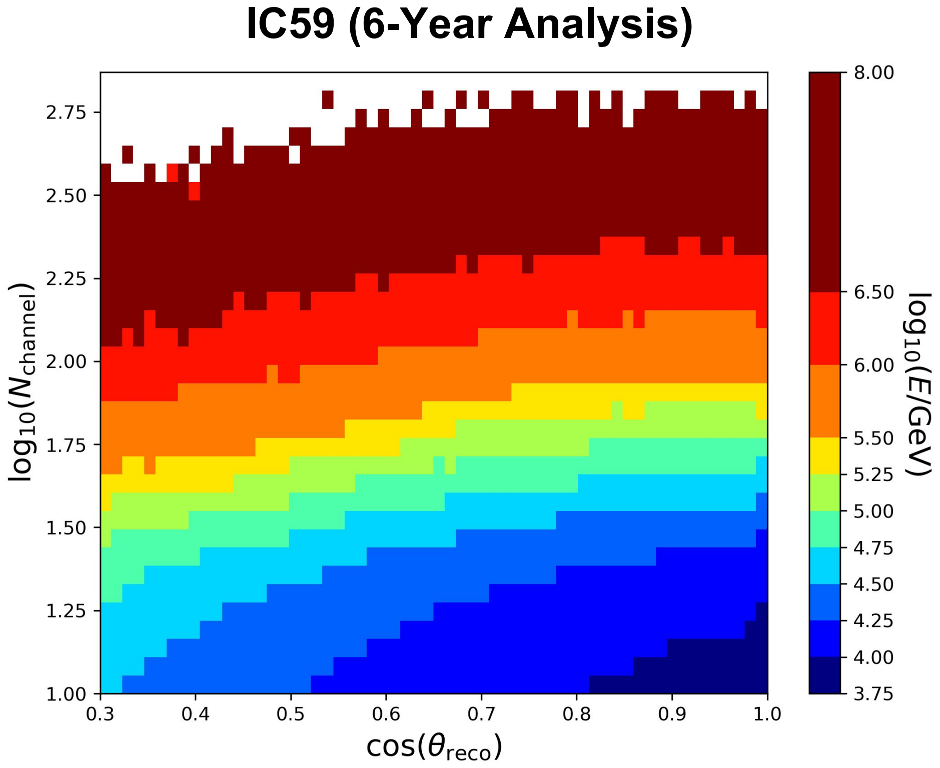


Energy dependence of large-scale anisotropy

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

Simulation

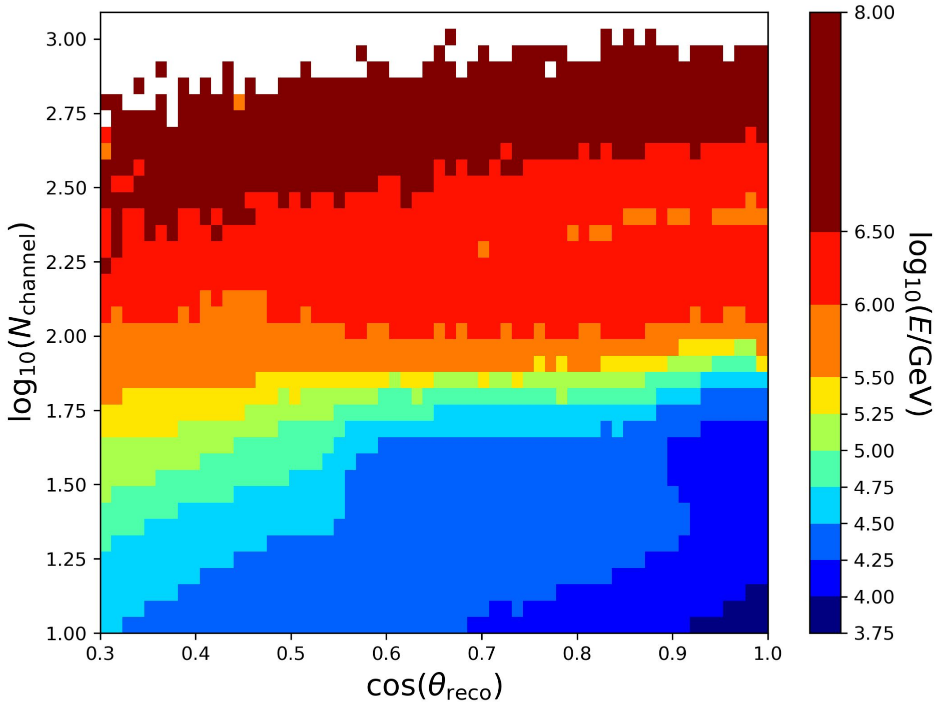
- Simulation binned based on number of digital optical modules hit and cosine of reconstructed zenith angle
- Median value for each bin shown in plot
- Given hits and reconstructed zenith of event, use splined version to determine median energy value
- Previous concern: artifacts caused by limited detector-specific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



Simulation

- 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: artifacts caused by limited detector-specific simulation

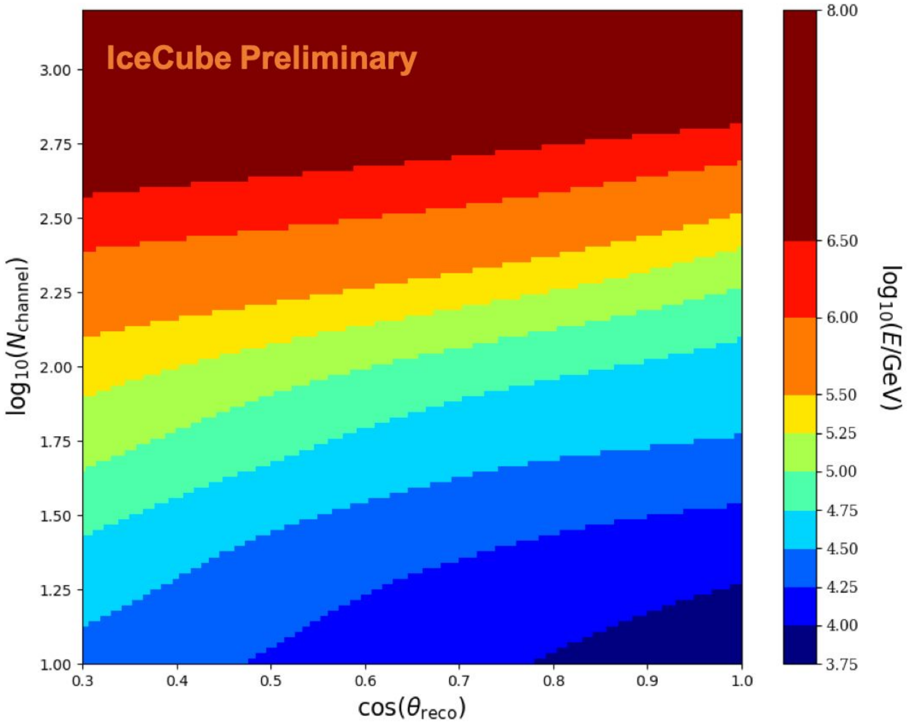
IC79 (6-Year Analysis)



Simulation

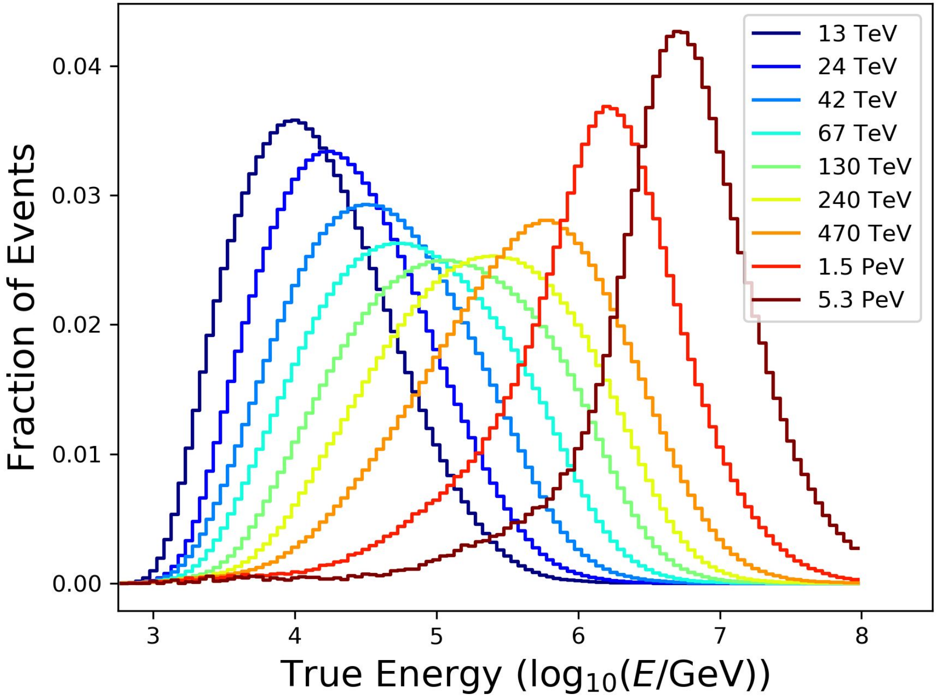
- Simulation binned based on number of digital optical modules hit and cosine of reconstructed zenith angle
- Median value for each bin shown in plot
- Given hits and reconstructed zenith of event, use splined version to determine median energy value
- Previous concern: limited detector-specific simulation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

IC86 (11-Year Analysis)



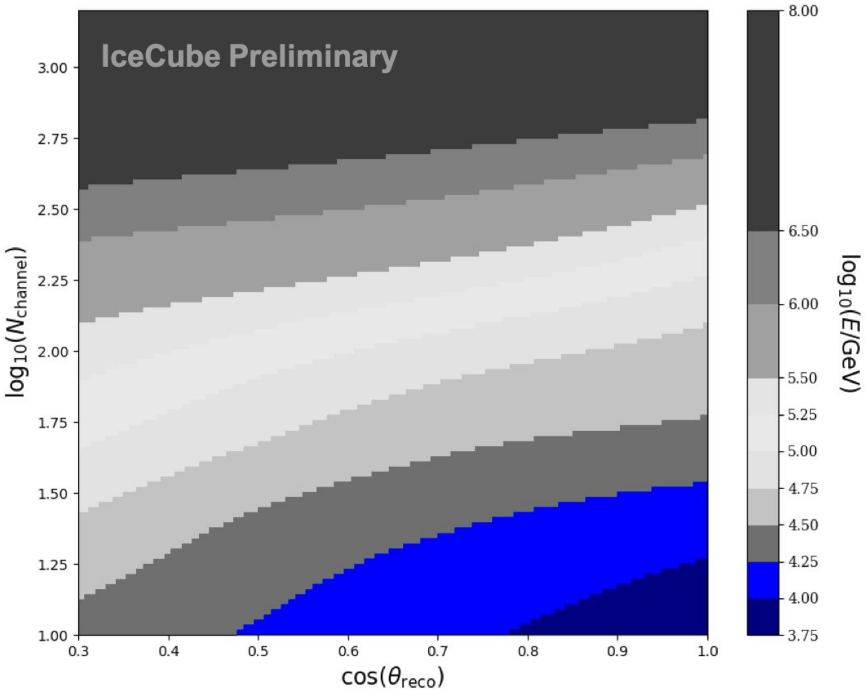
Simulation

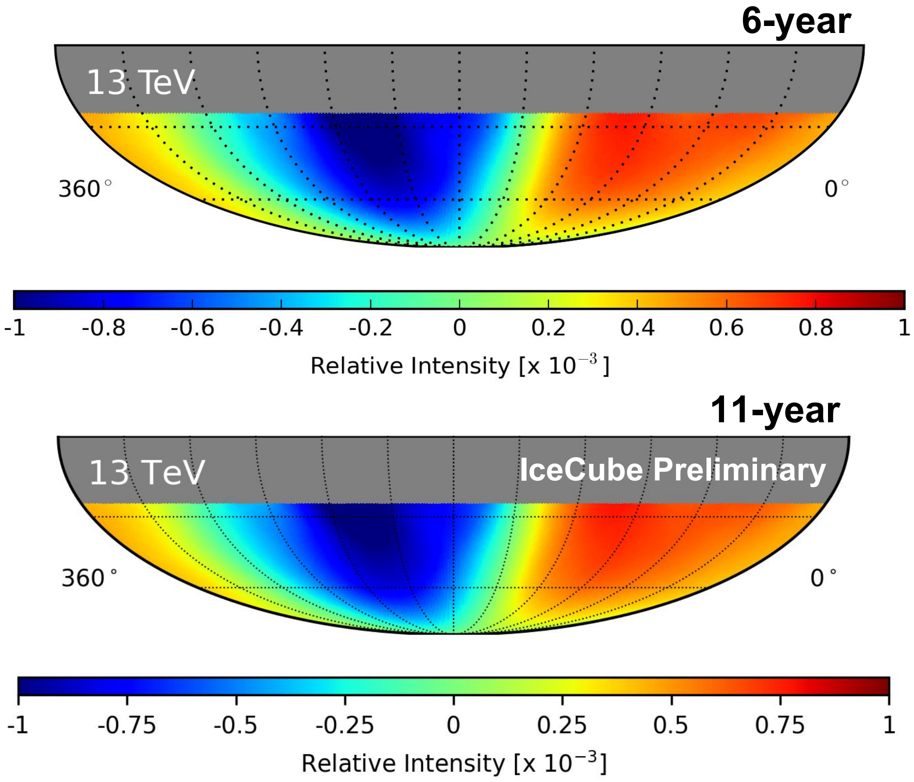
- Simulation binned based on number of digital optical modules hit and cosine of reconstructed zenith angle
- Median value for each bin shown in plot
- Given hits and reconstructed zenith of event, use splined version to determine median energy value
- Note: wide, correlated energy bins



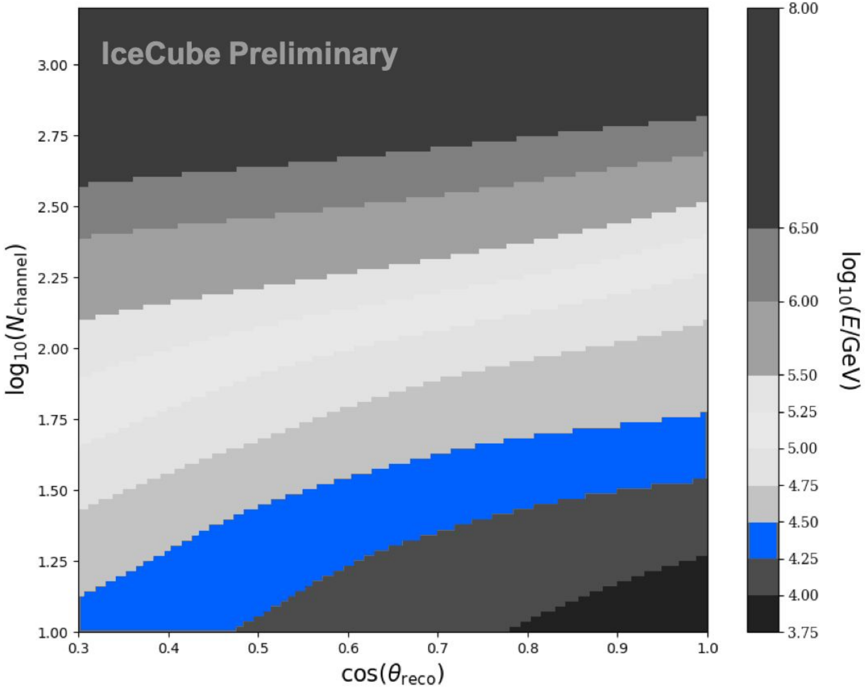
Statistics/Simulation

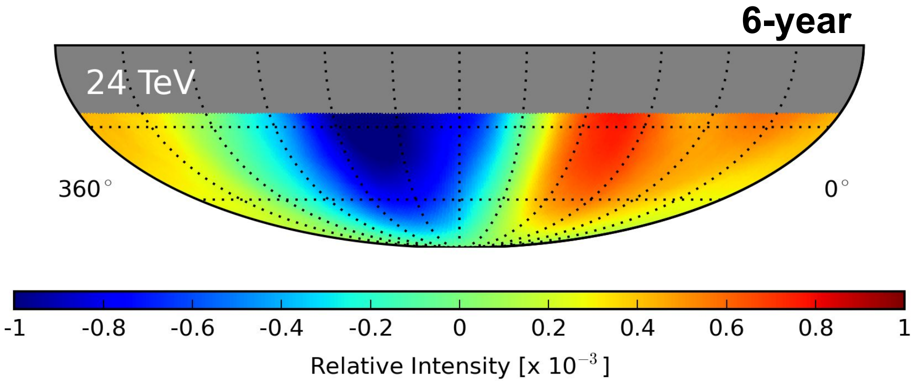
Energy Dependence

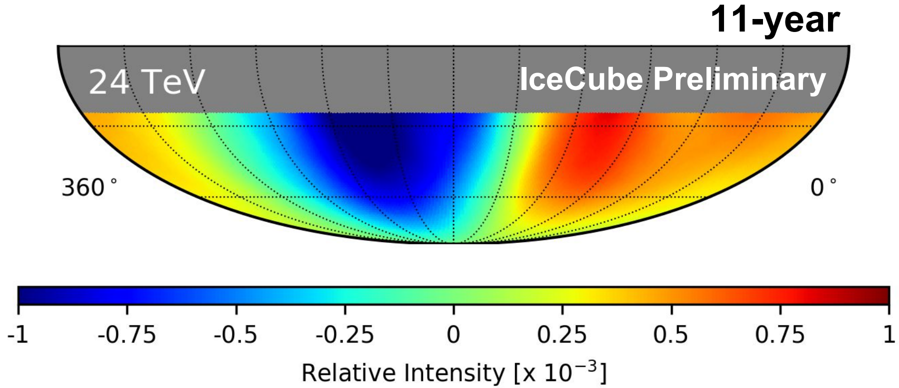




Energy Dependence

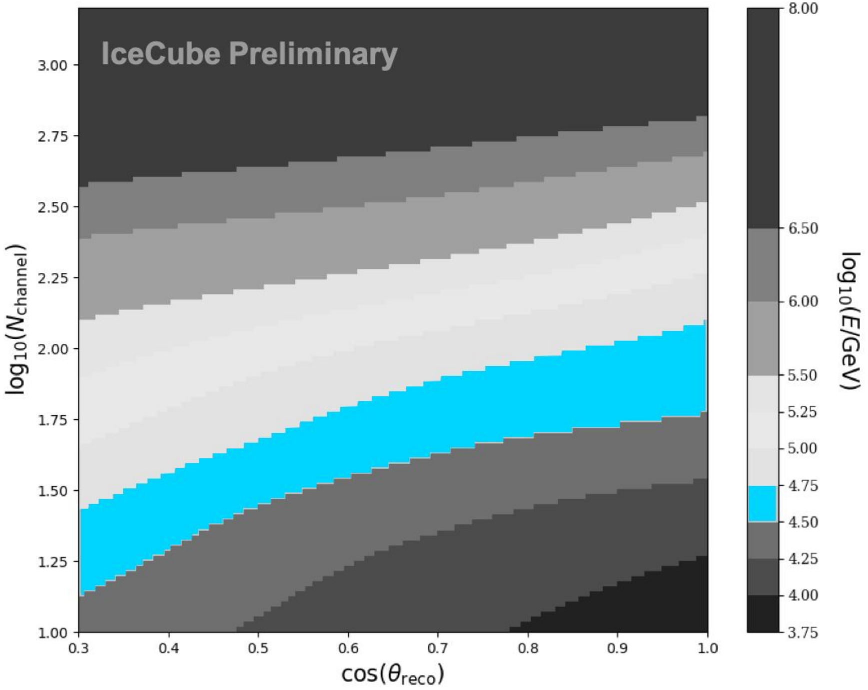


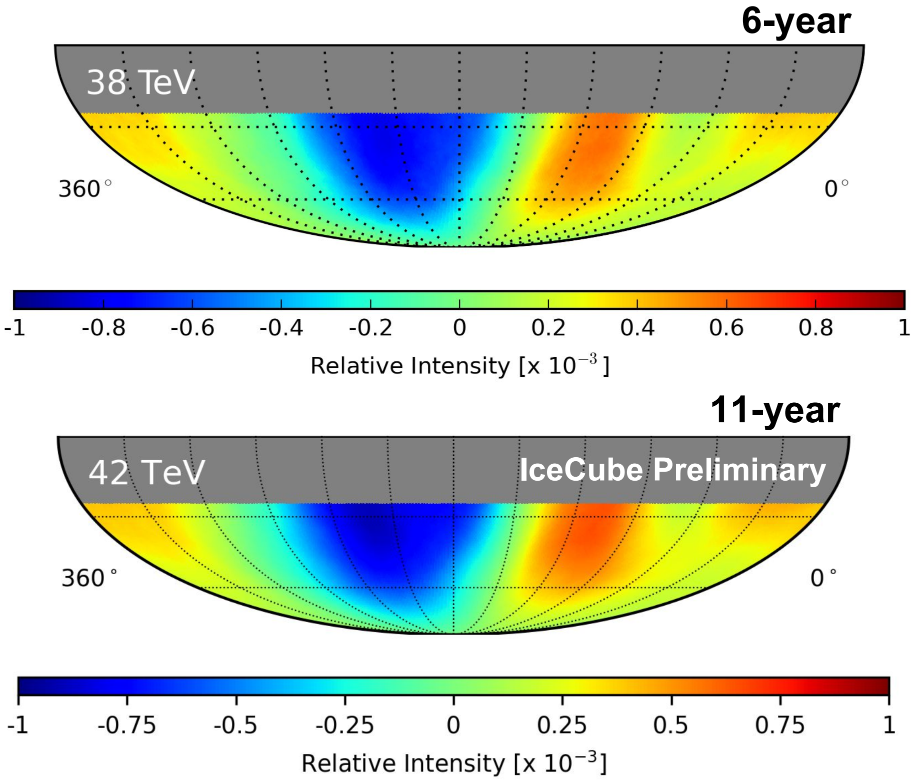




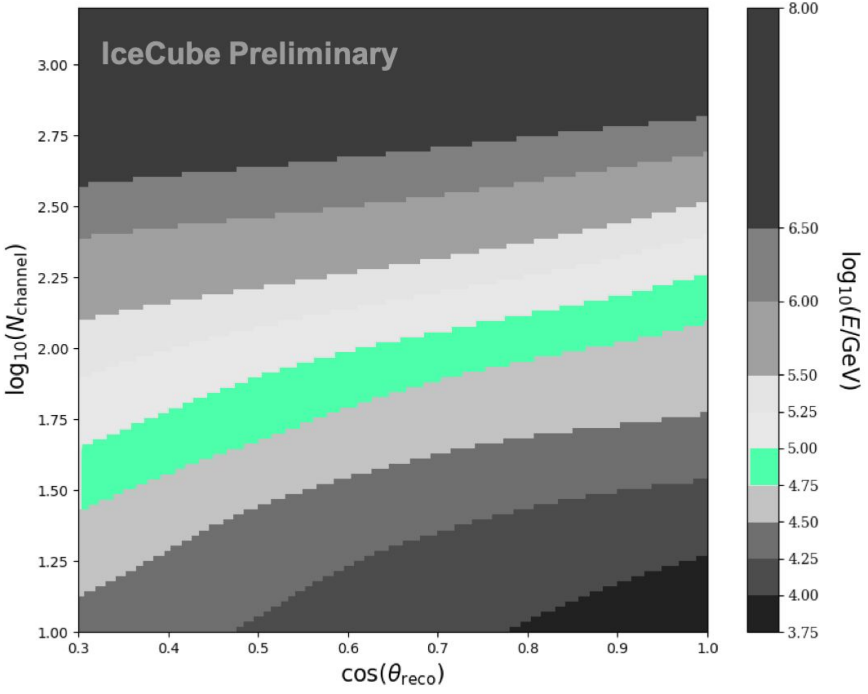
Statistics/Simulation

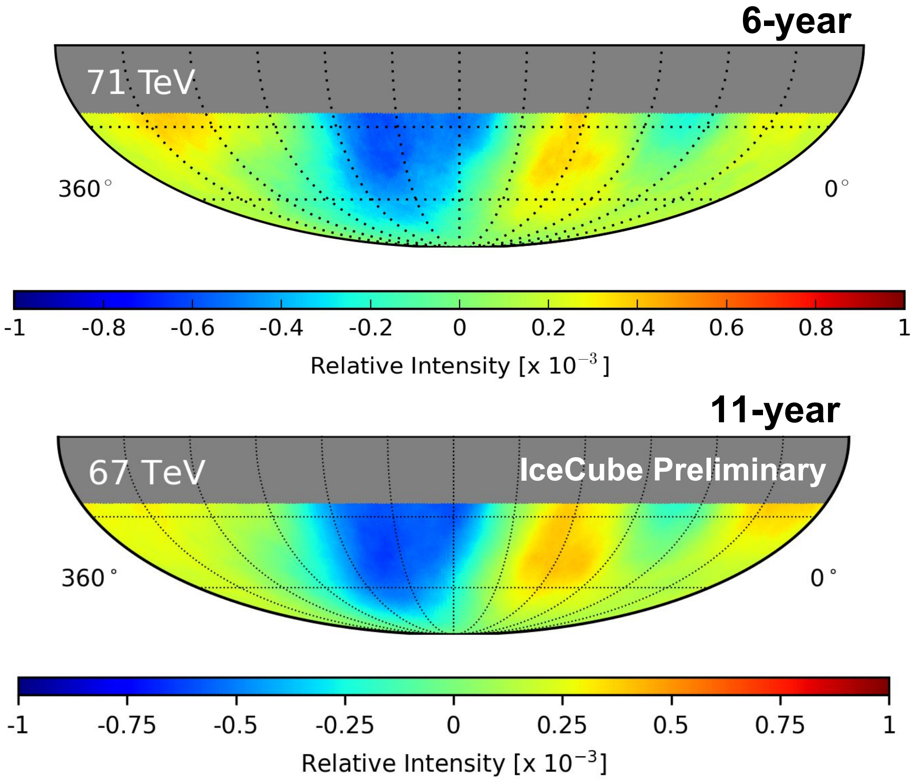
Energy Dependence





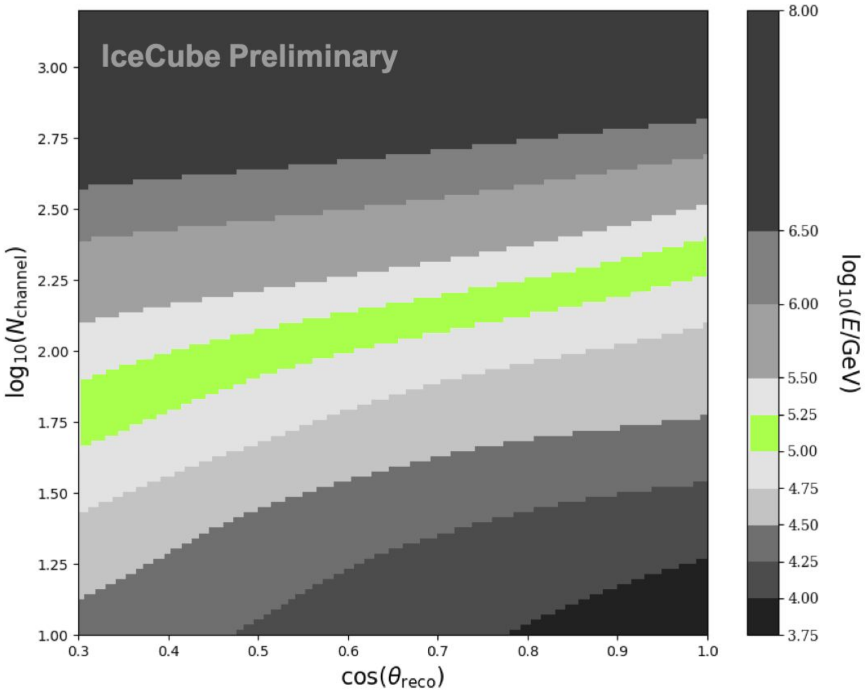
Statistics/Simulation



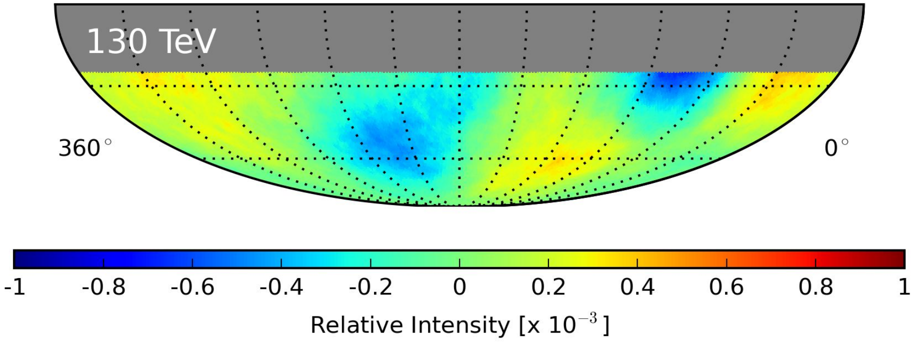


Statistics/Simulation

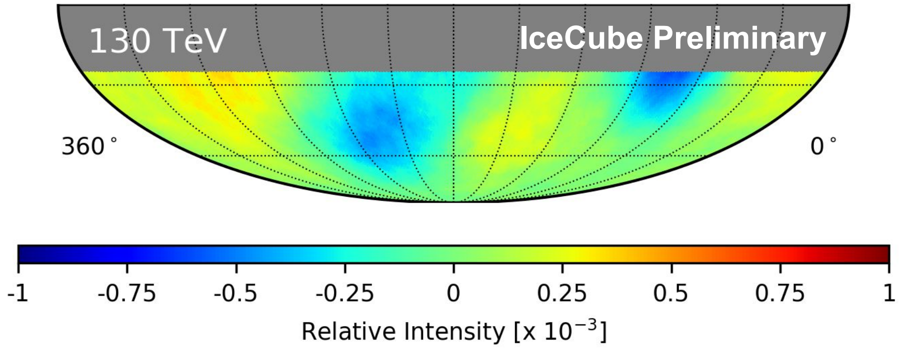
Energy Dependence



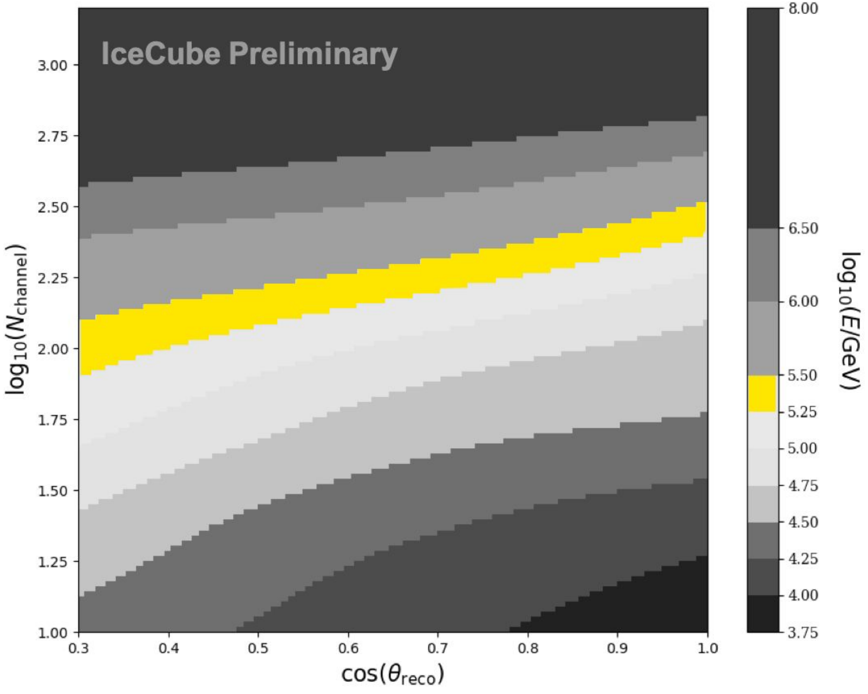
6-year

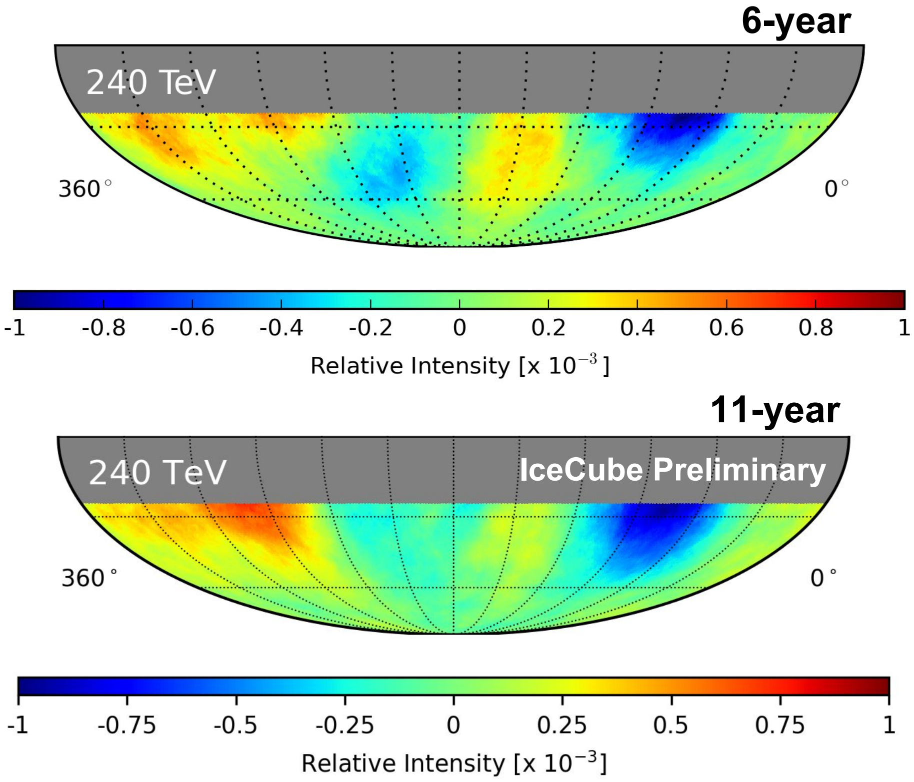


11-year

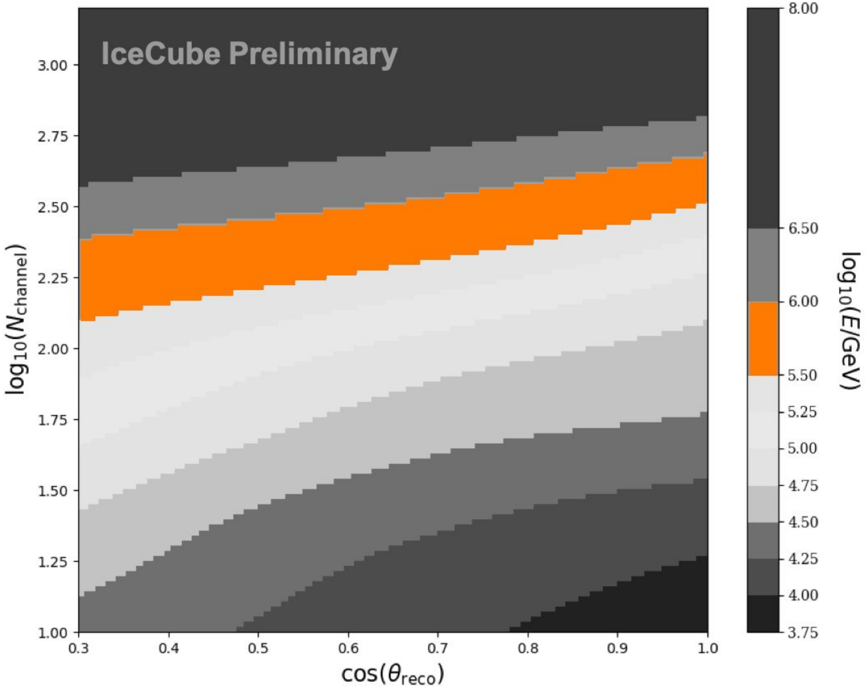


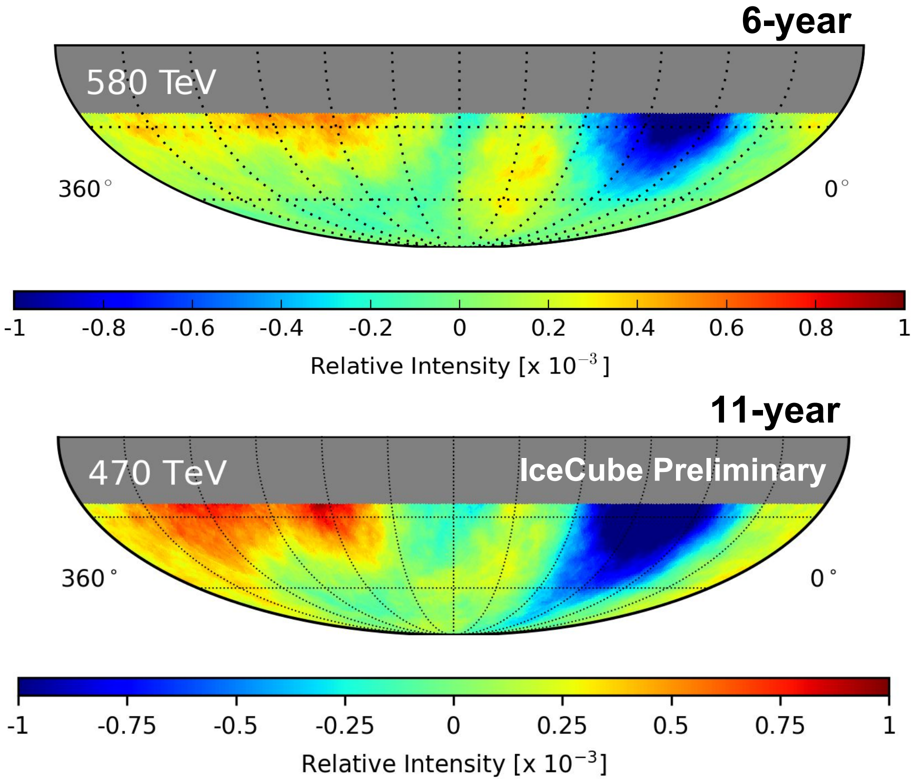
Statistics/Simulation





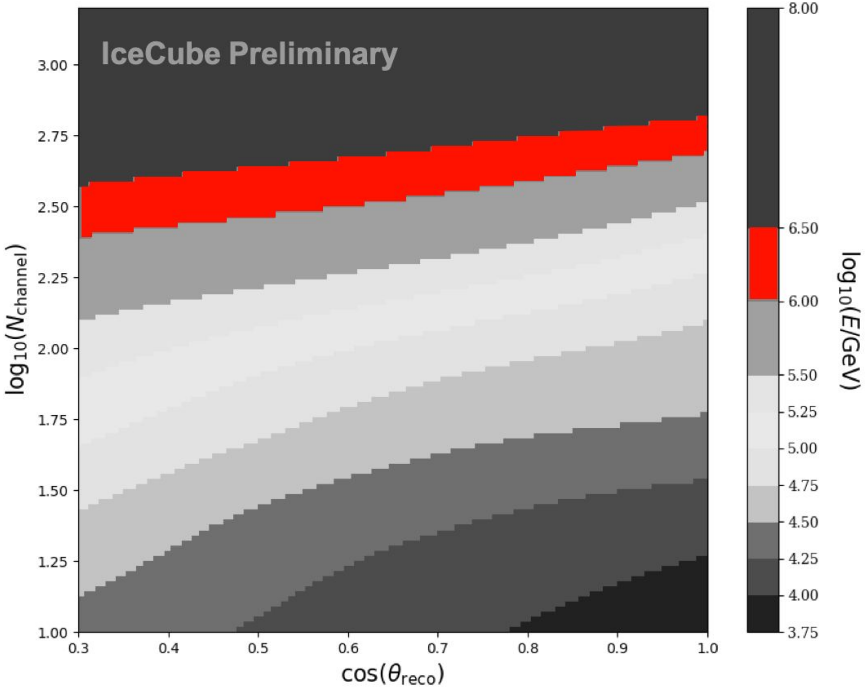
Statistics/Simulation

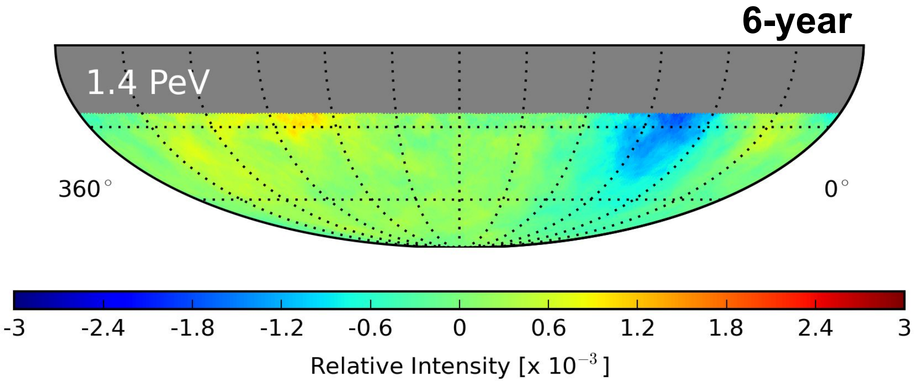


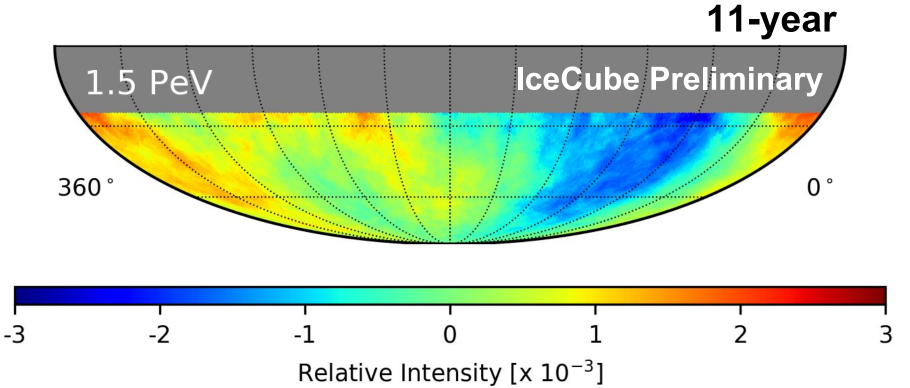


Statistics/Simulation

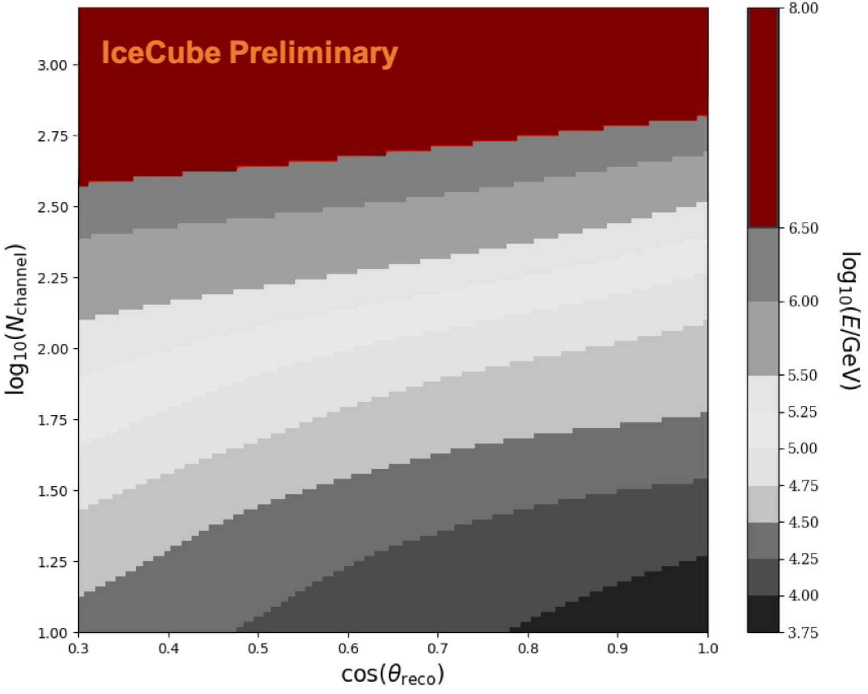
Energy Dependence

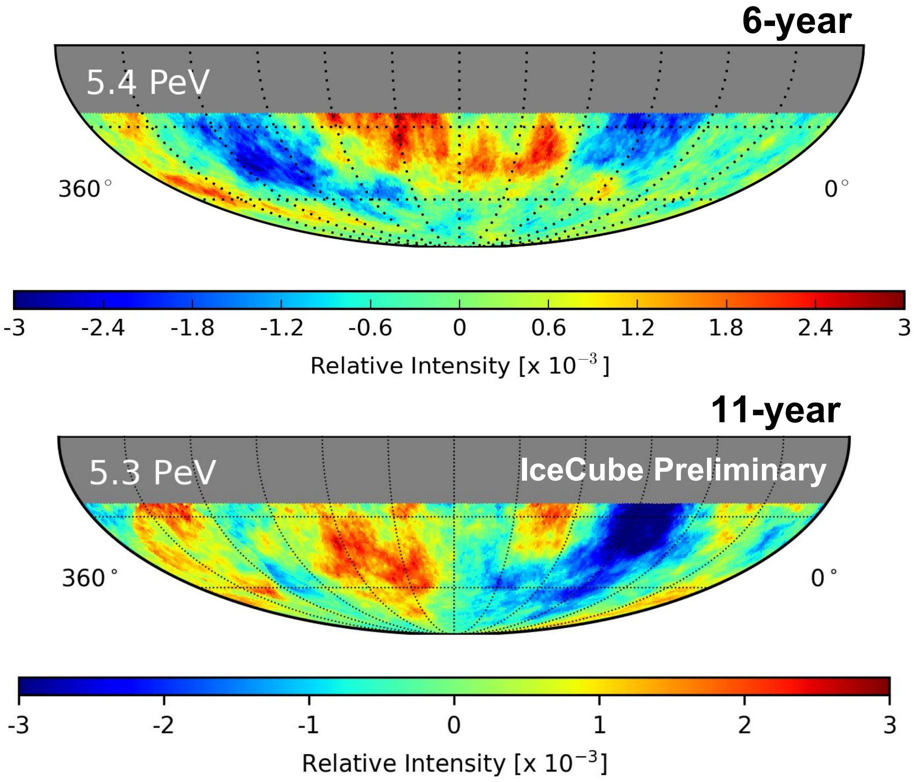




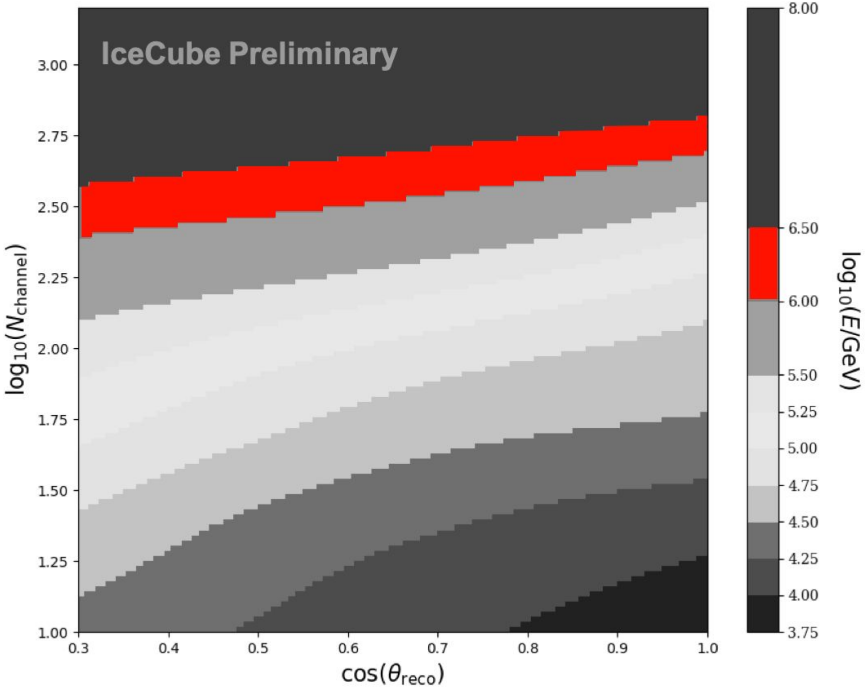


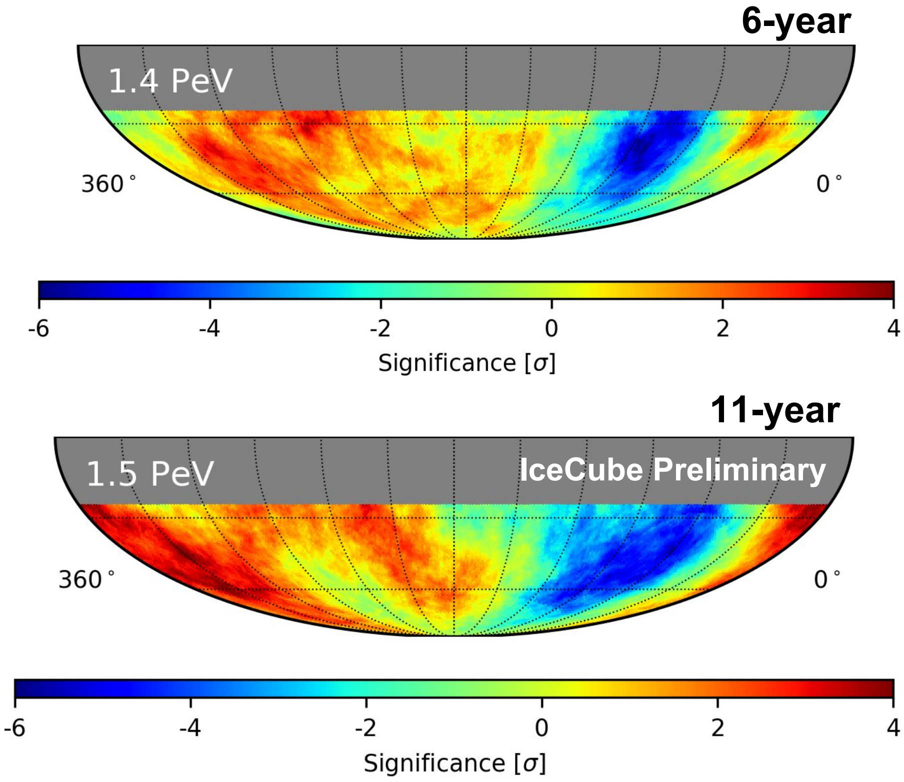
Statistics/Simulation — Energy Dependence



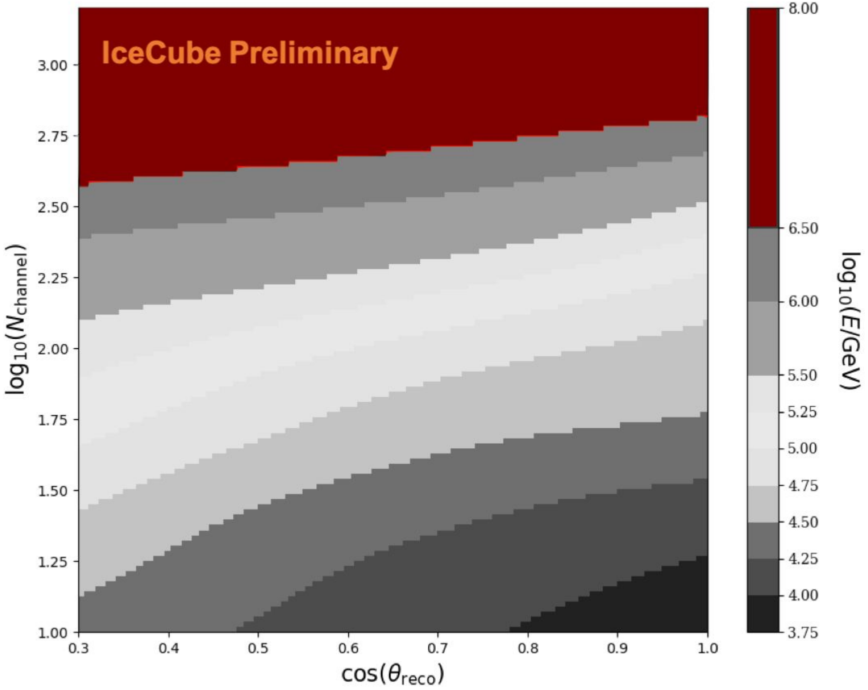


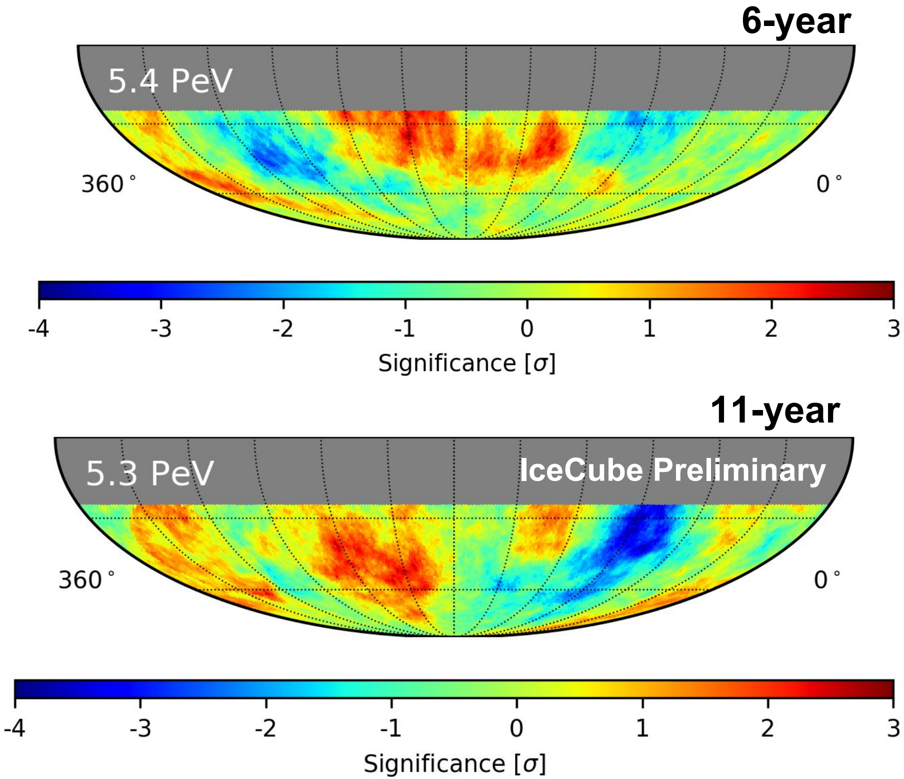
Statistics/Simulation High-Energy Significance



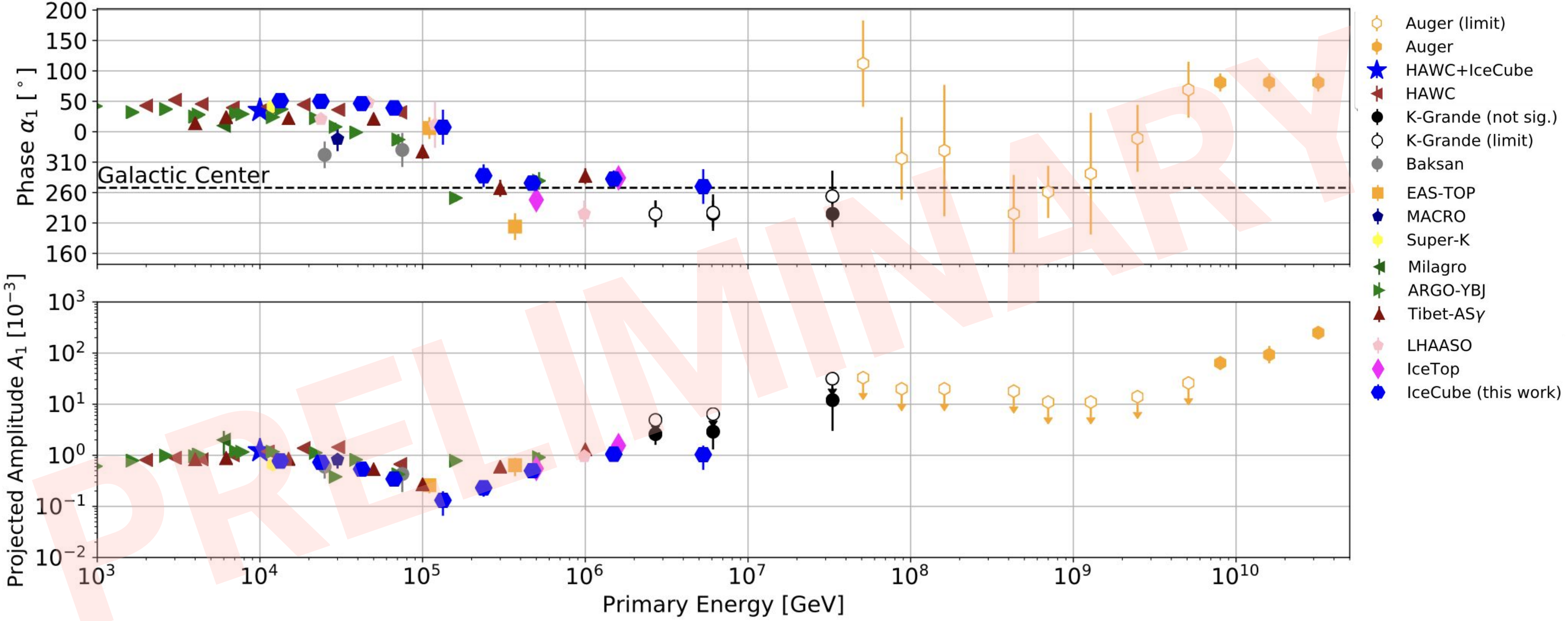


High-Energy Significance





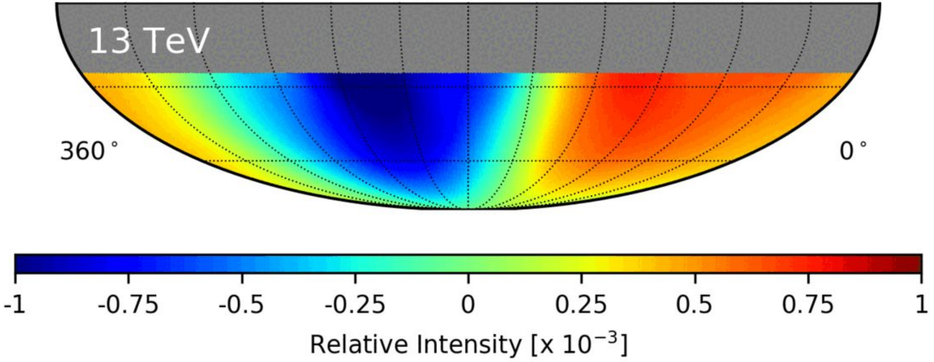
Statistics/Simulation Dipole Phase & Amplitude

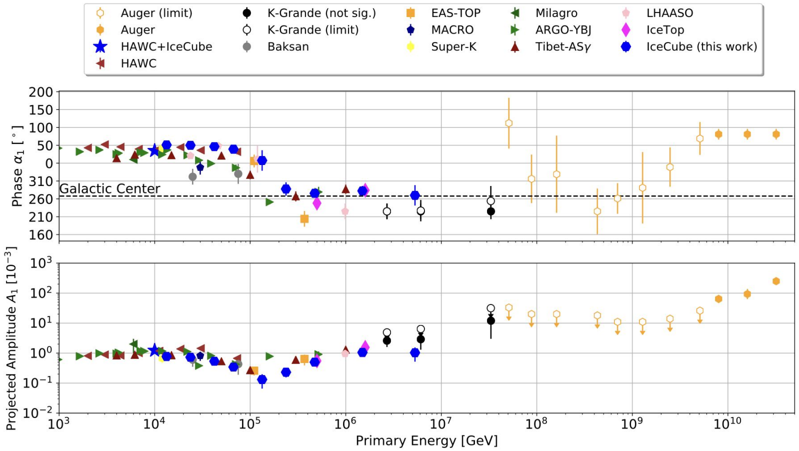


Reconstructed R.A. component of the dipole amplitude and phase including other experiments (adopted from Ahlers & Mertsch 2017). The results shown are from Abeysekara et al. (2018b), Chiavassa et al. (2015), Alekseenko et al. (2009), Aglietta et al. (2009), Ambrosio et al. (2003), Guillian et al. (2007), Abdo et al. (2009), Bartoli et al. (2015), Amenomori et al. (2005), and Aartsen et al. (2013, 2016), A. Aab *et al* (2020), W. Gao et al (2021).

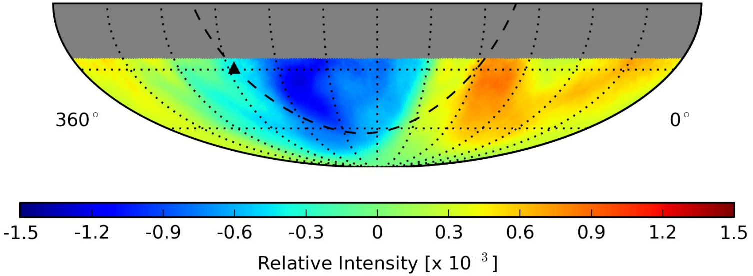
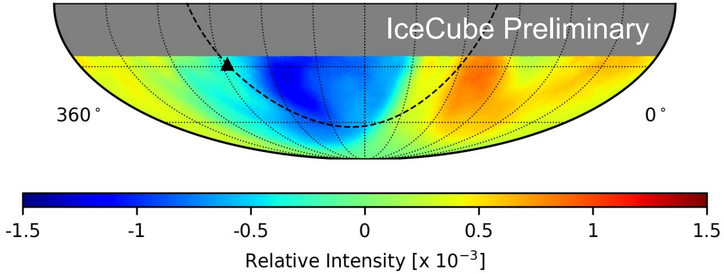
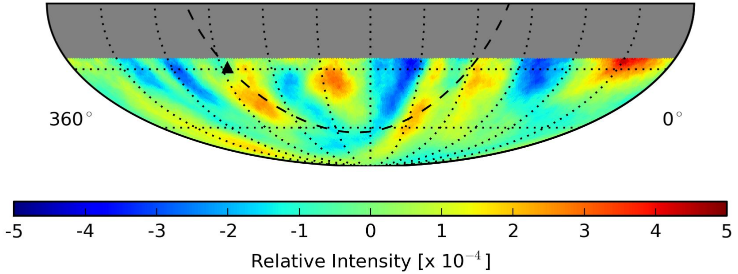
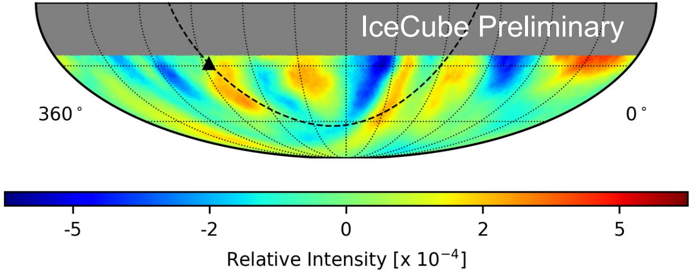
Statistics/Simulation

- New simulation and statistics only slightly change energy maps
- Transition still occurs around 100 TeV
- Structure at highest energy now consistent with other PeV measurements
- Phase and amplitude of best-fit dipole consistent with other experiments



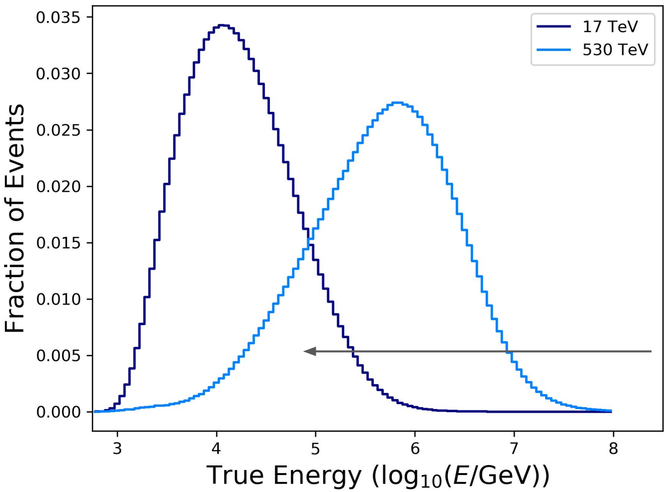


Large- and Small-Scale Structure

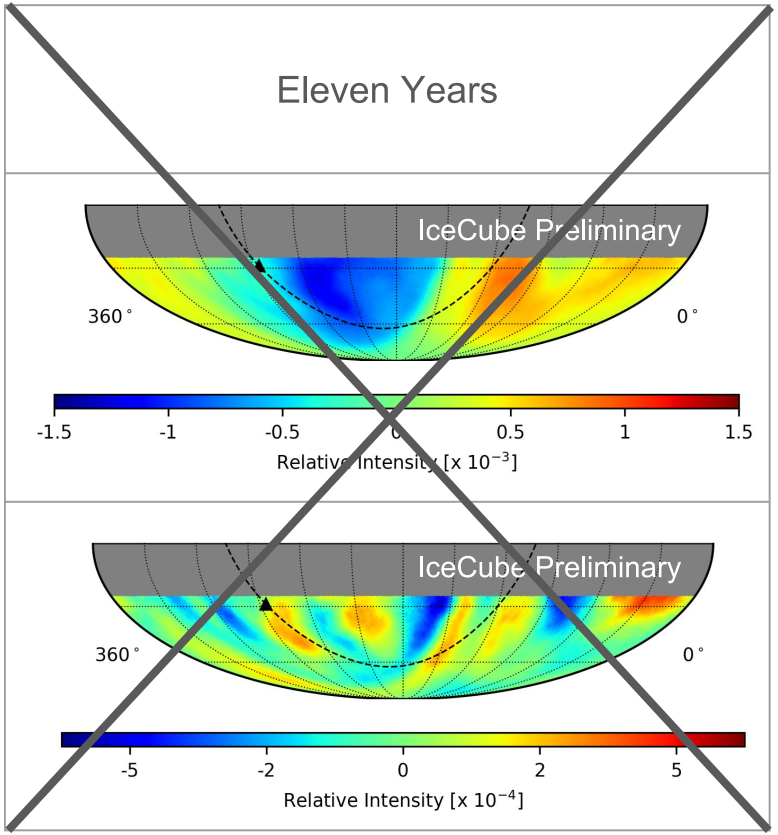
Relative Intensity	Six Years	Eleven Years
Large-Scale Structure		
Small-Scale Structure		

Large- and Small-Scale Structure

- **Concern:** traditional maps with all data show the conflicting overlay of two structures
- New approach: large- and small-scale structure maps for low- and high-energy collections

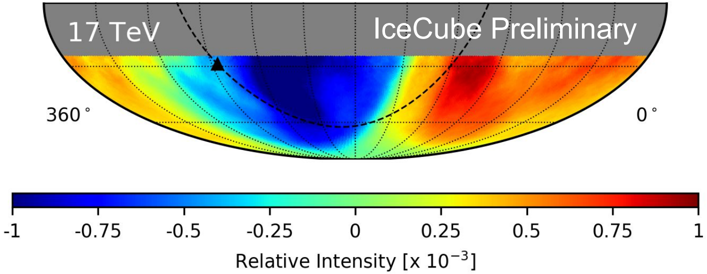
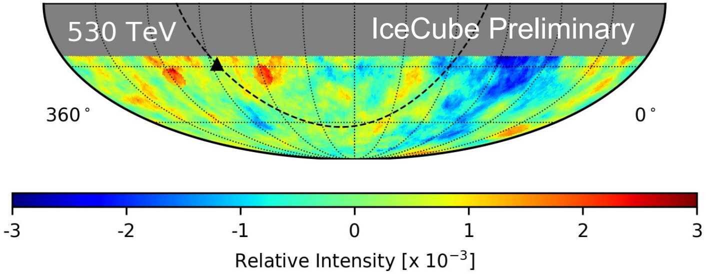


29% overlap



Statistics

Large- and Small-Scale Structure

<table>
<tr><td>Relative Intensity</td><td>Low Energy</td><td>High Energy</td></tr>
<tr><td>Large-Scale Structure</td><td>
</td><td>
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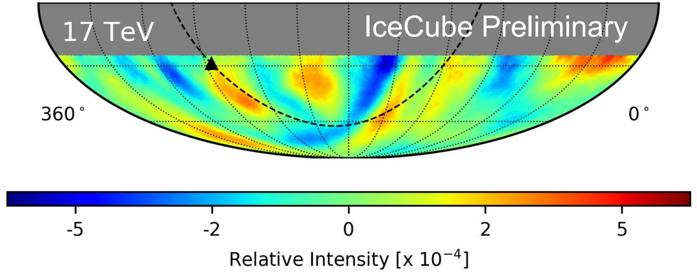
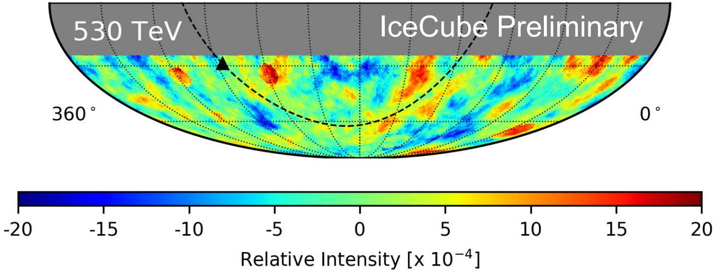
<tr><td>Small-Scale Structure</td><td>
</td><td>
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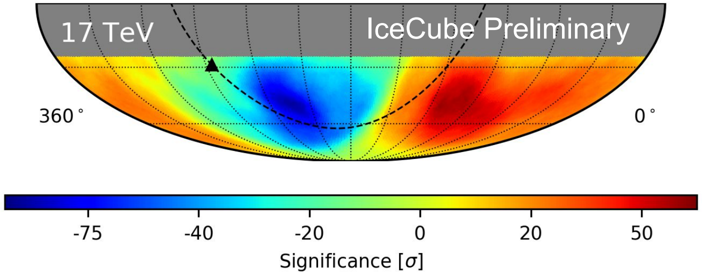
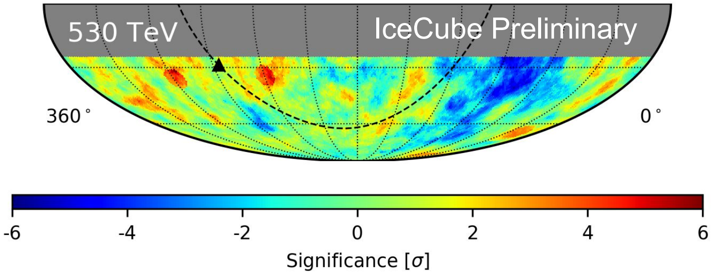
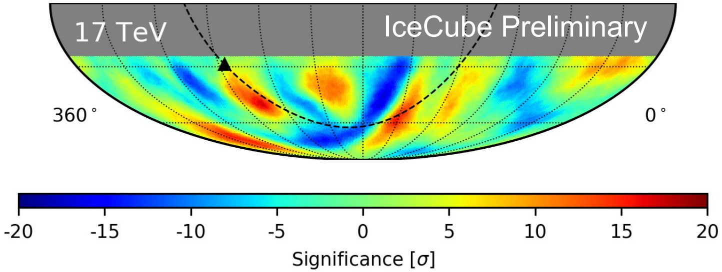
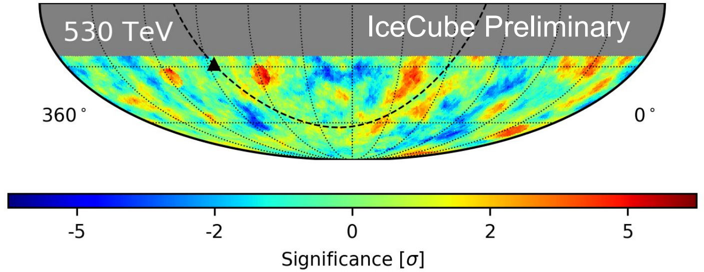
Statistics

Large- and Small-Scale Structure

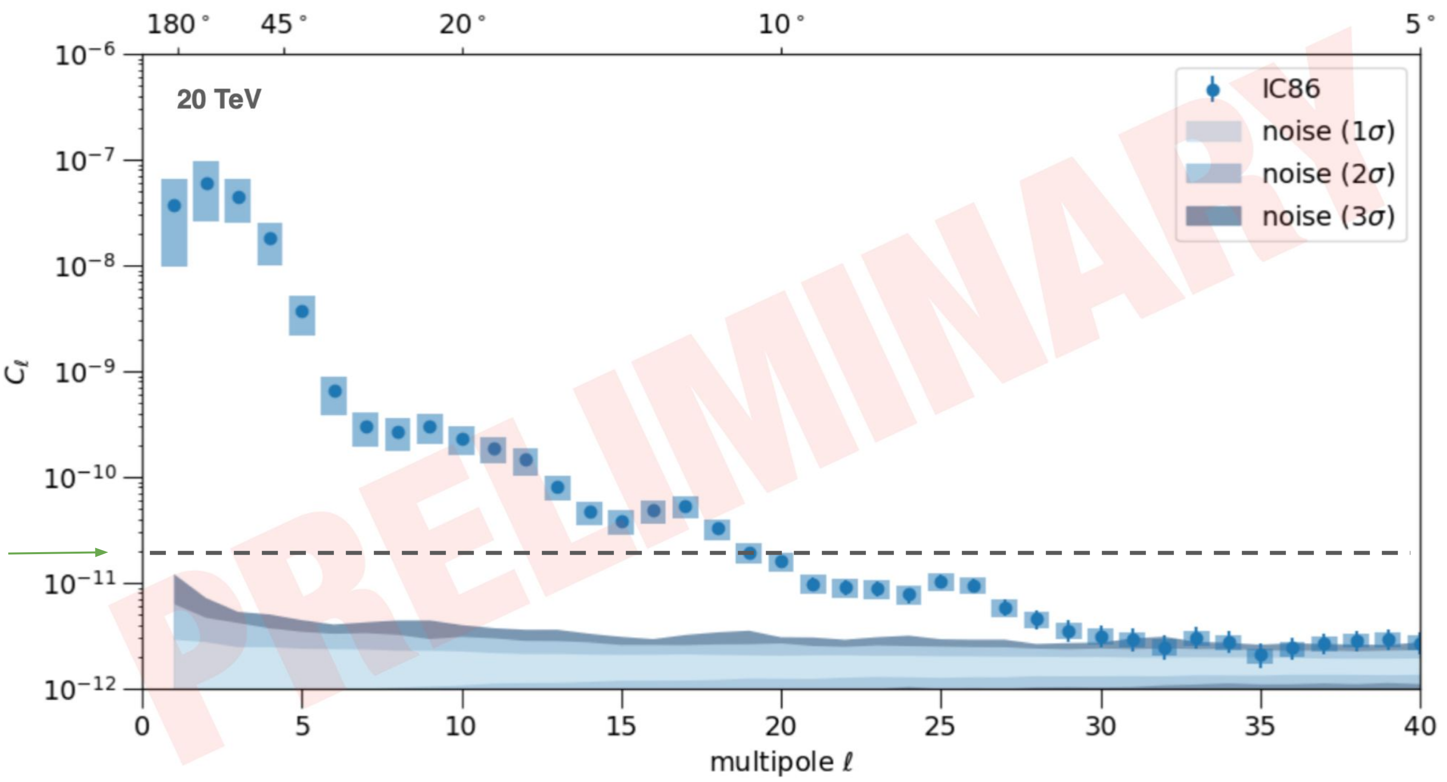
Significance	Low Energy	High Energy
Large-Scale Structure		
Small-Scale Structure		

Angular Power Spectrum

Uncertainties:

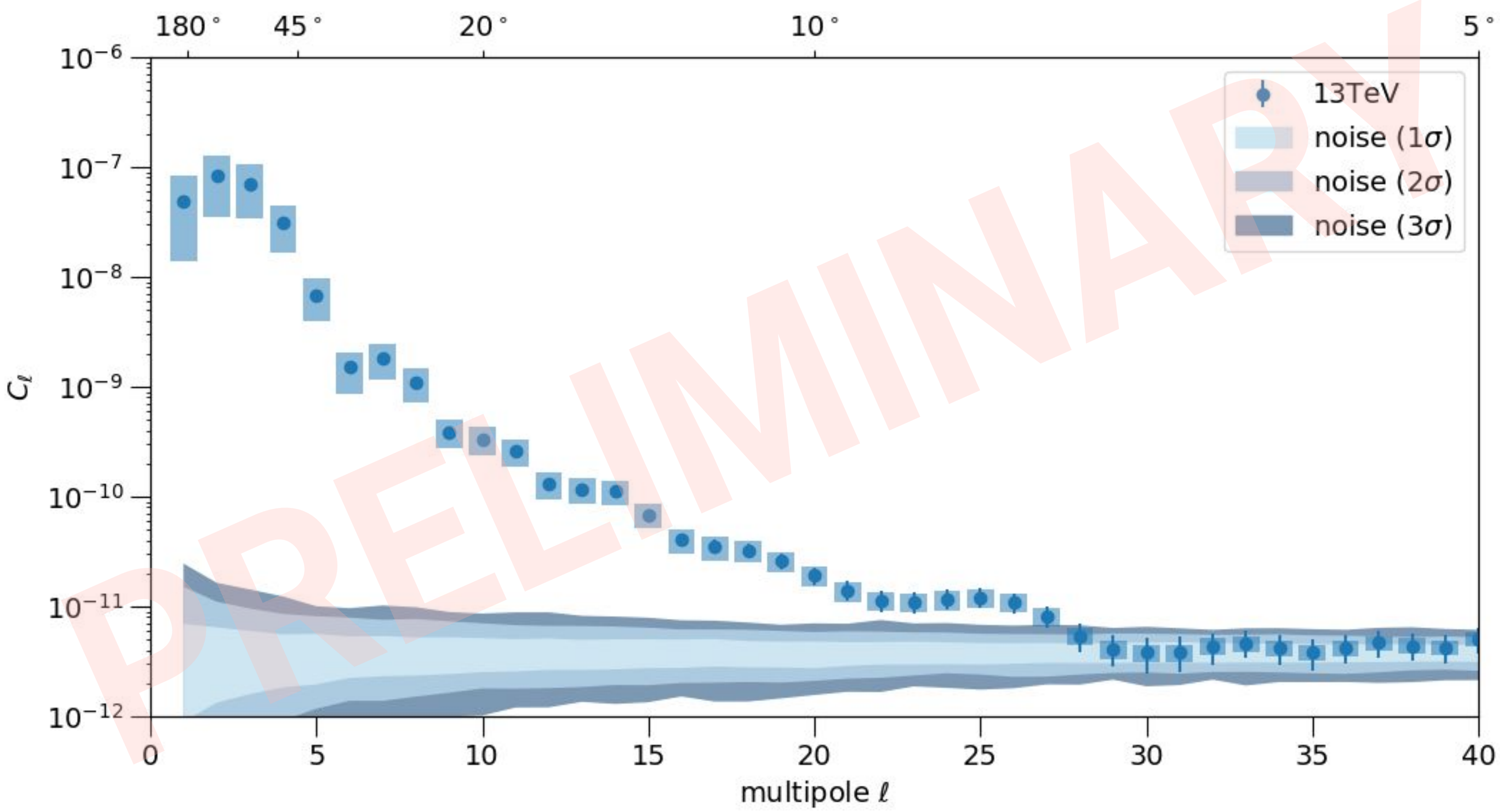
- statistical
- systematic

Previous 2σ noise limit



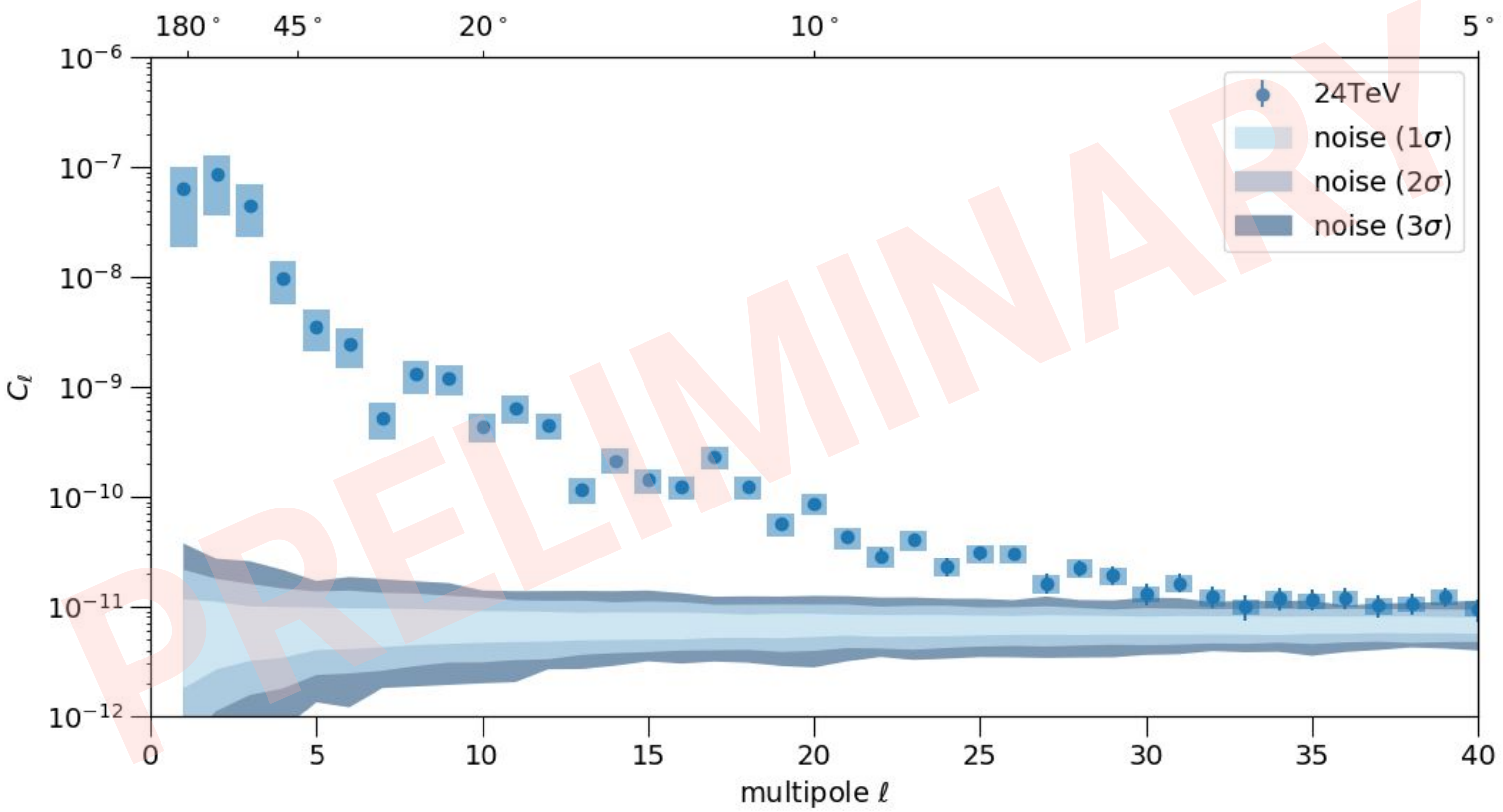
Statistics/Simulation

Angular Power Spectrum

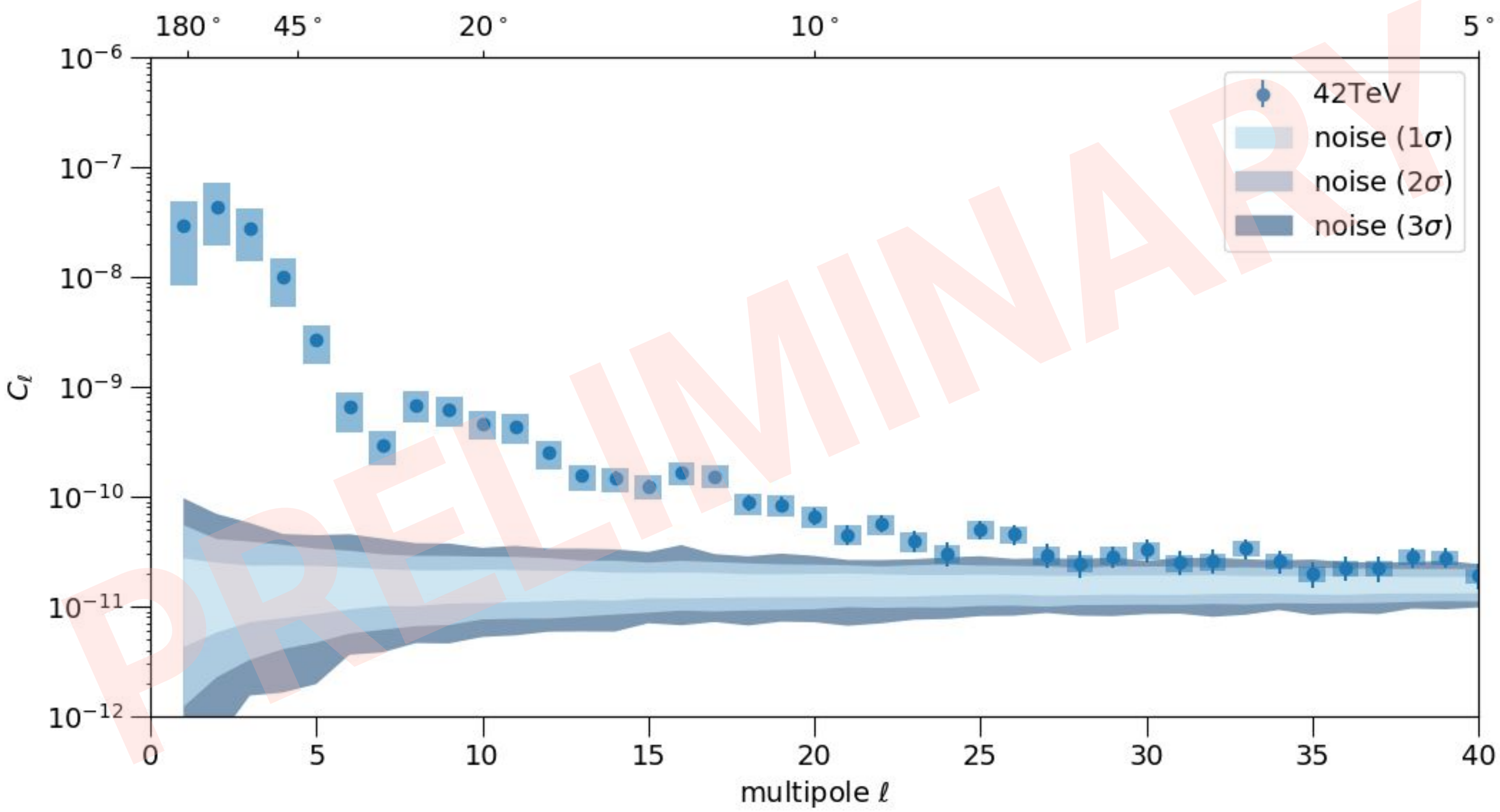


Statistics/Simulation

Angular Power Spectrum

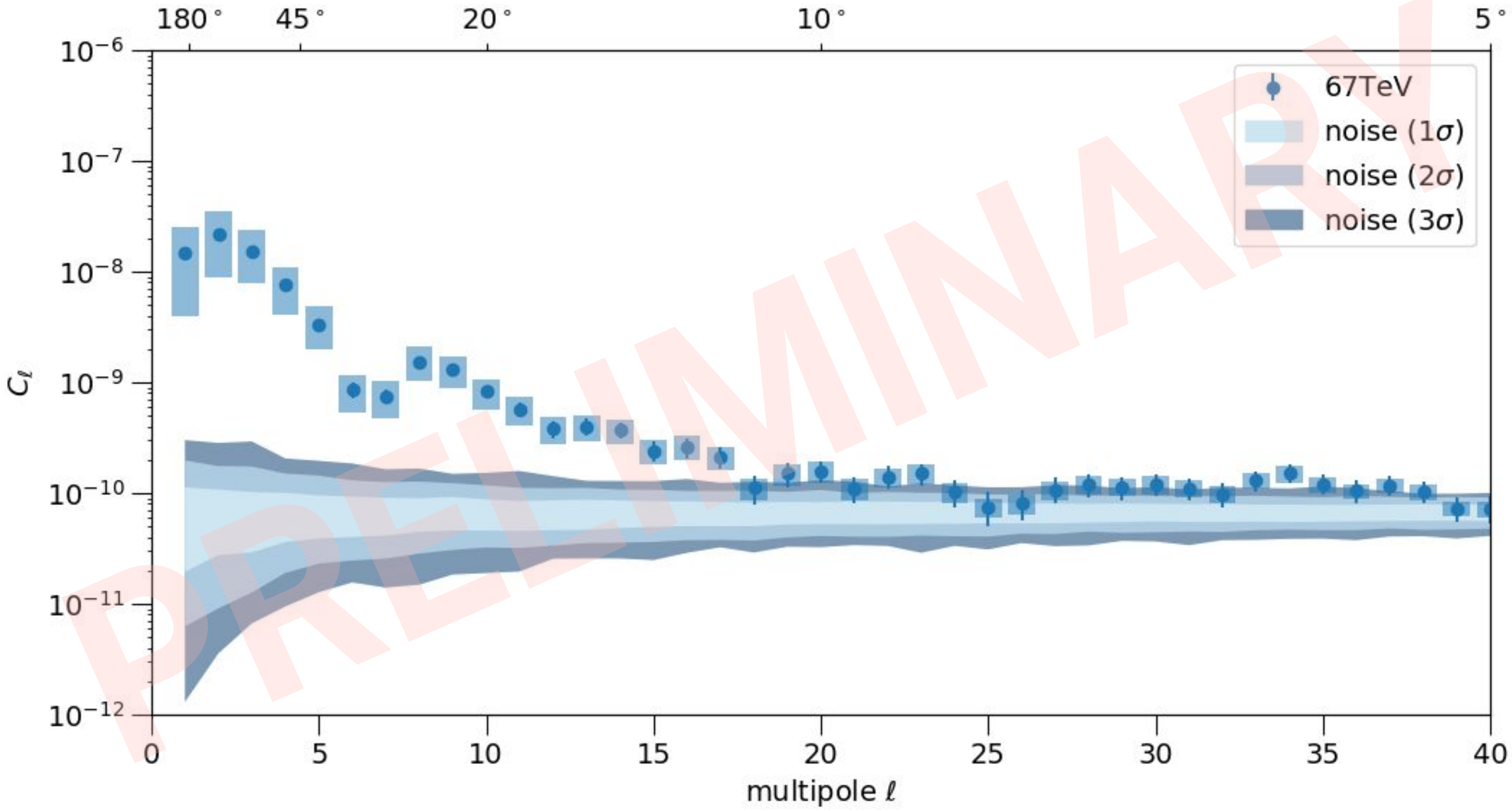


Angular Power Spectrum



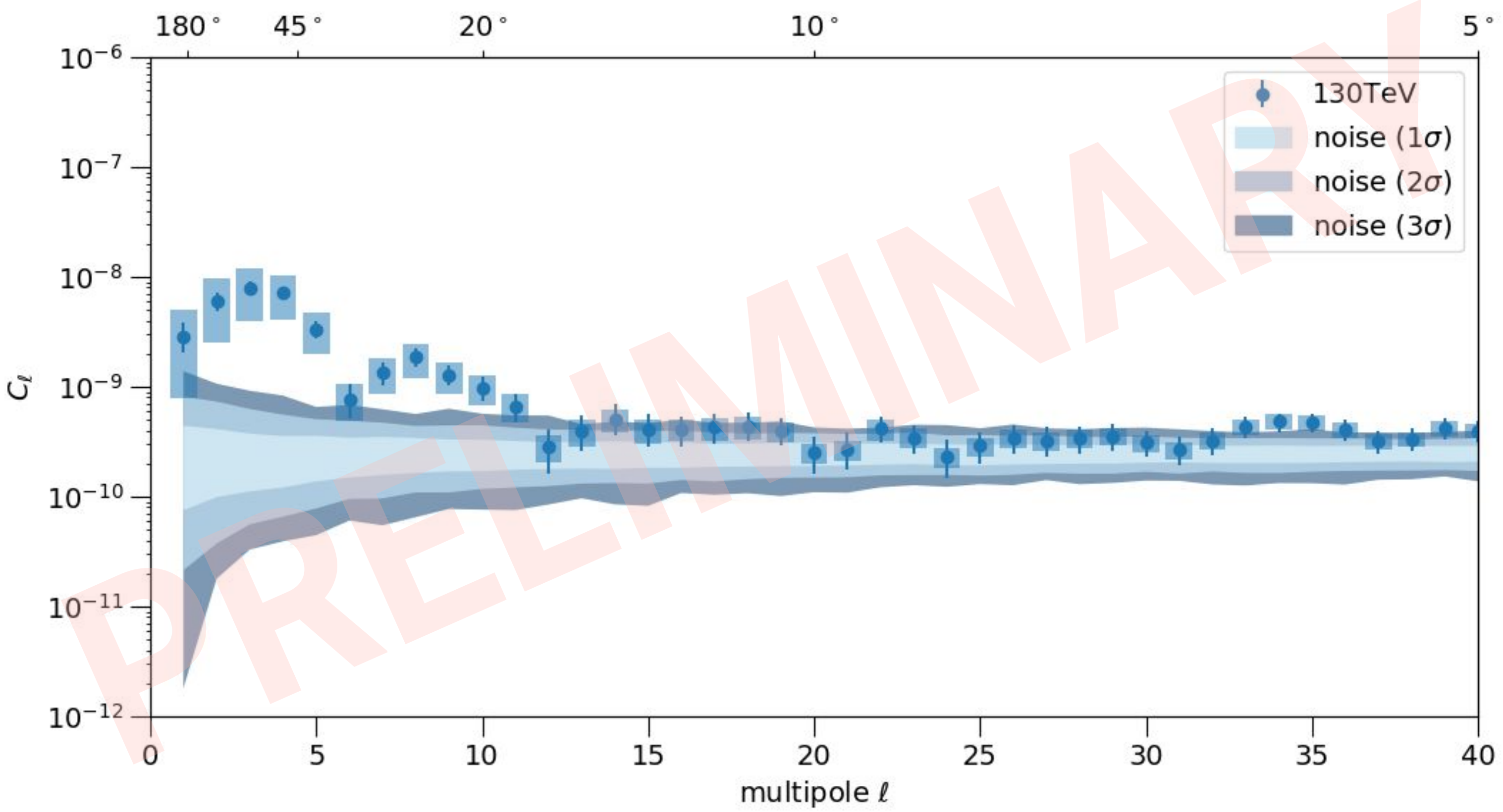
Statistics/Simulation

Angular Power Spectrum



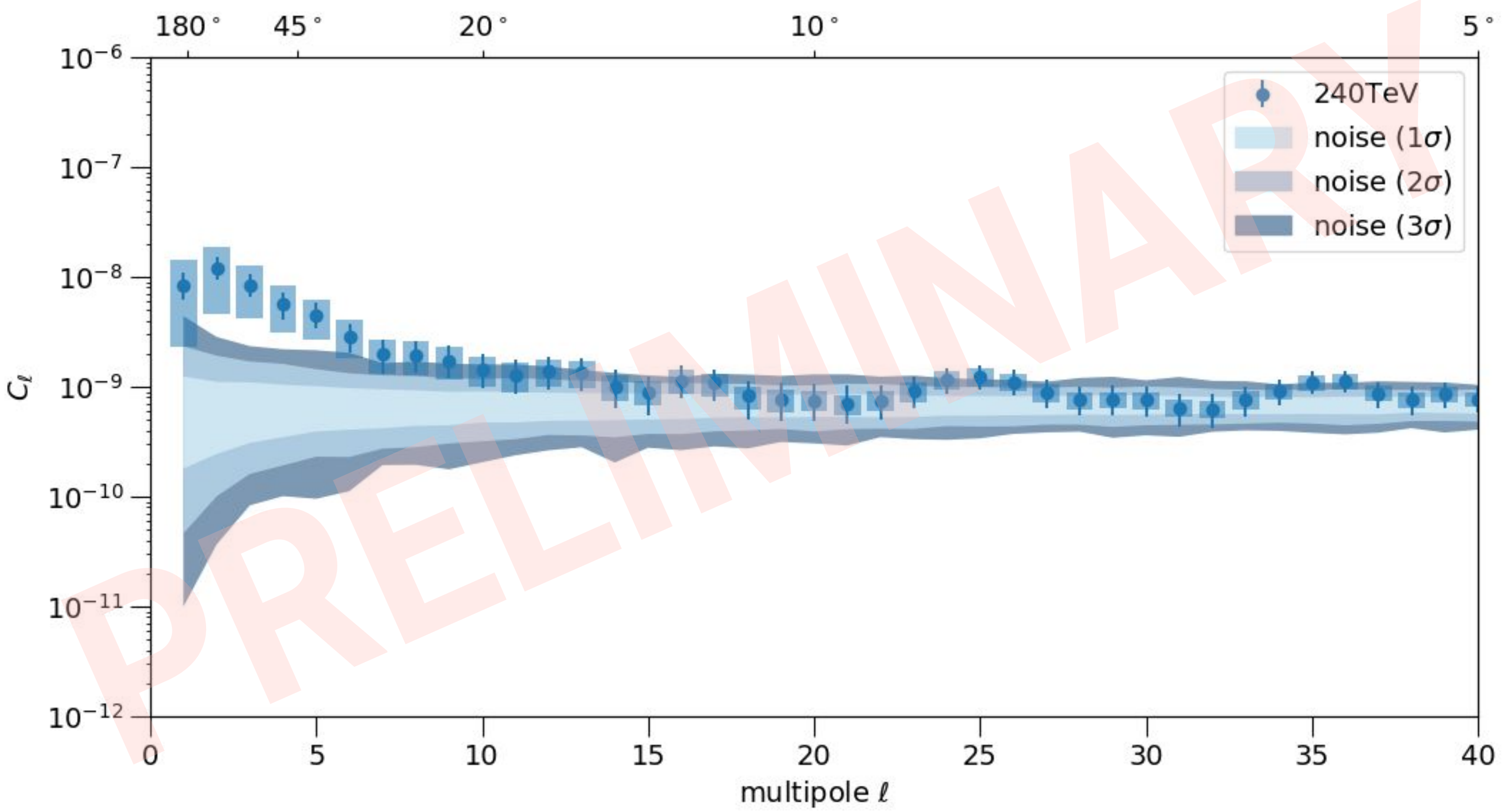
Statistics/Simulation

Angular Power Spectrum

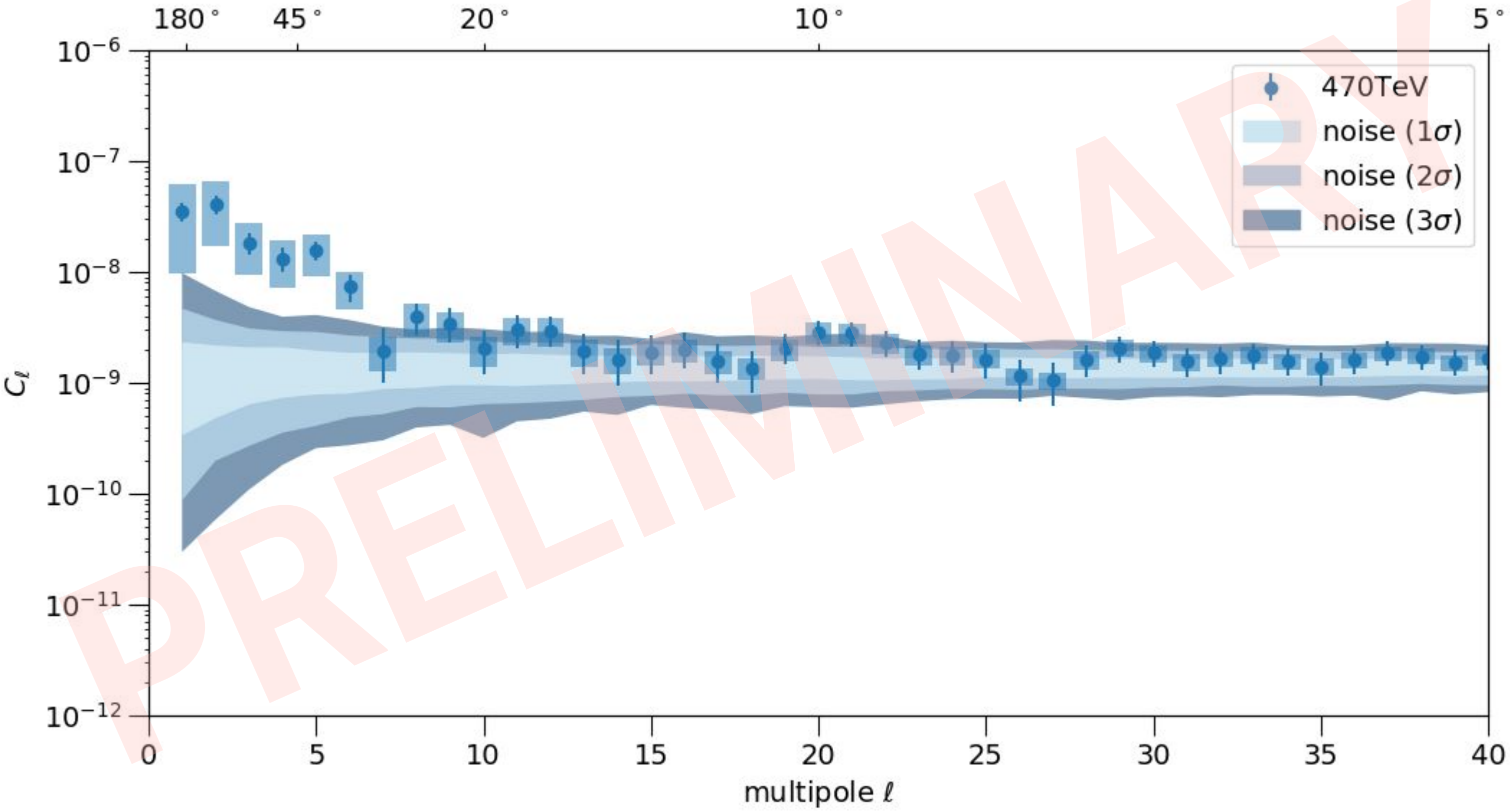


Statistics/**Simulation**

Angular Power Spectrum

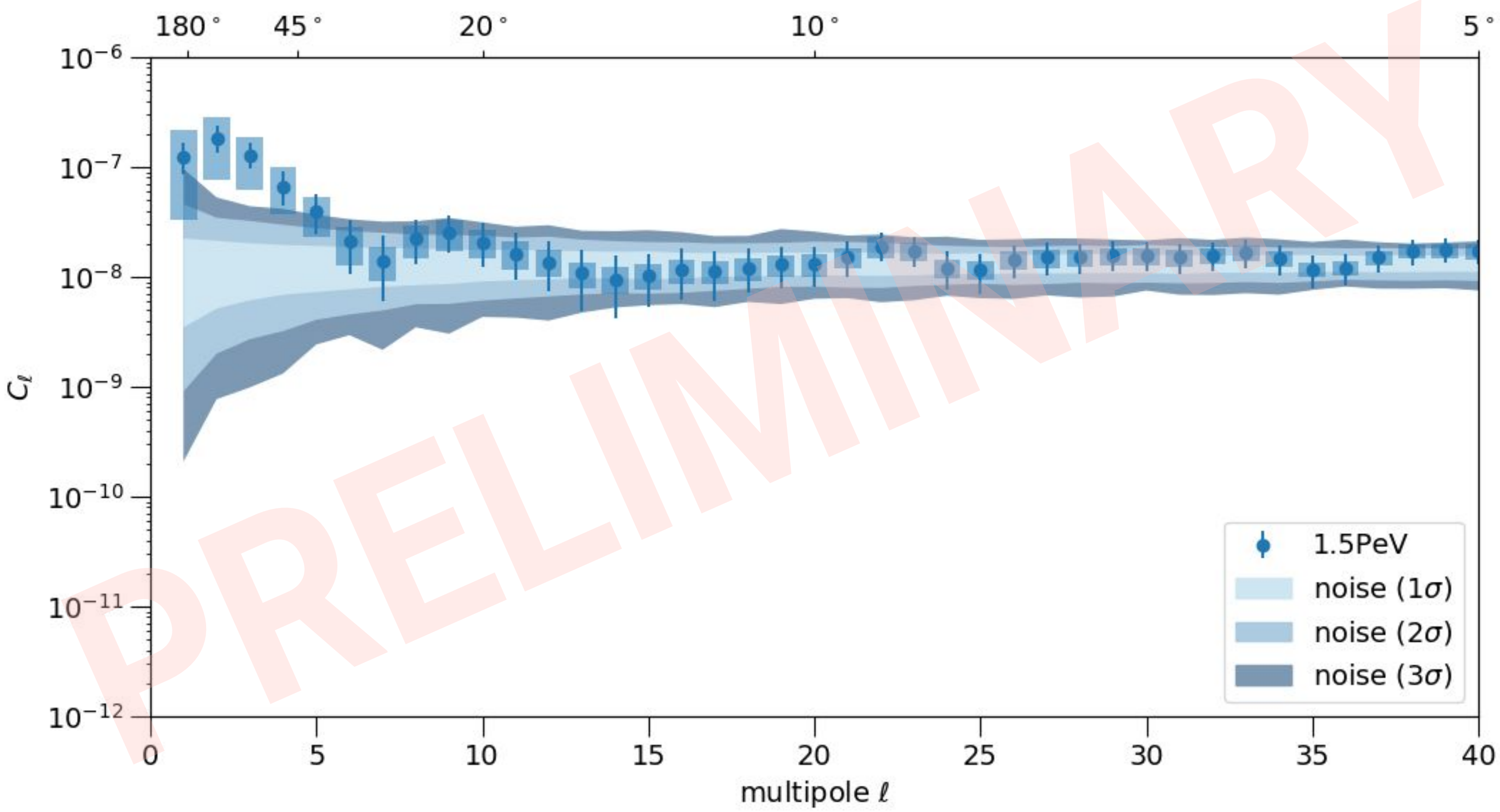


Statistics/Simulation

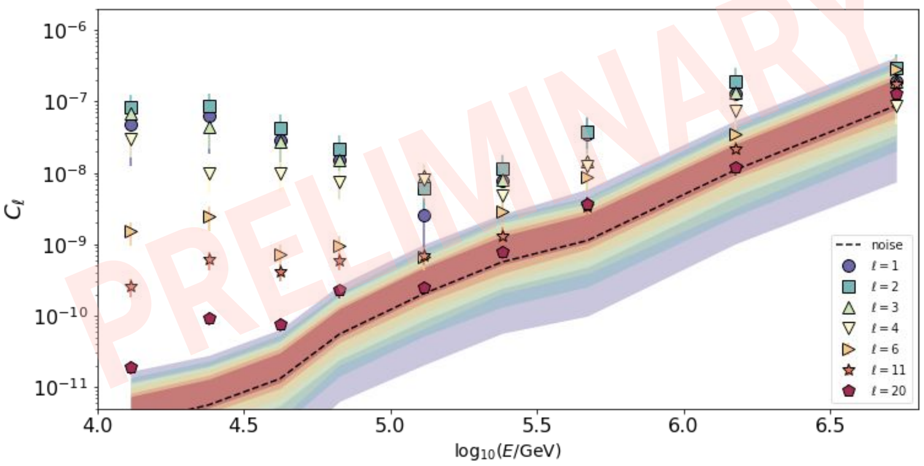


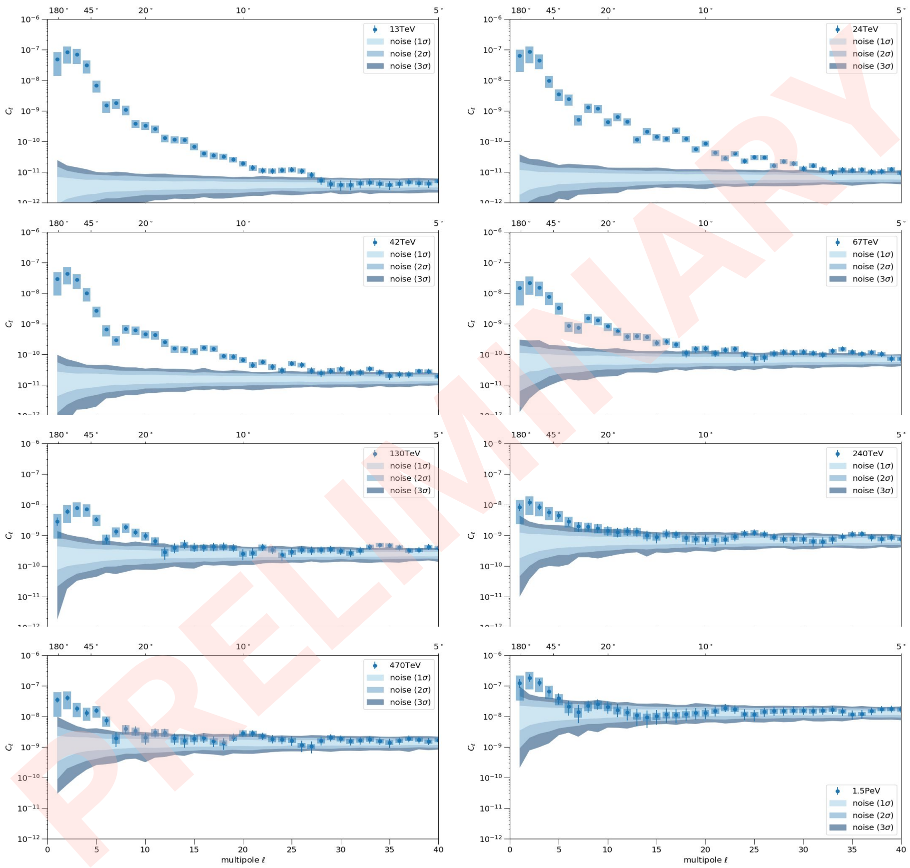
Statistics/Simulation

Angular Power Spectrum



Angular Power Spectrum





Alternative visualization

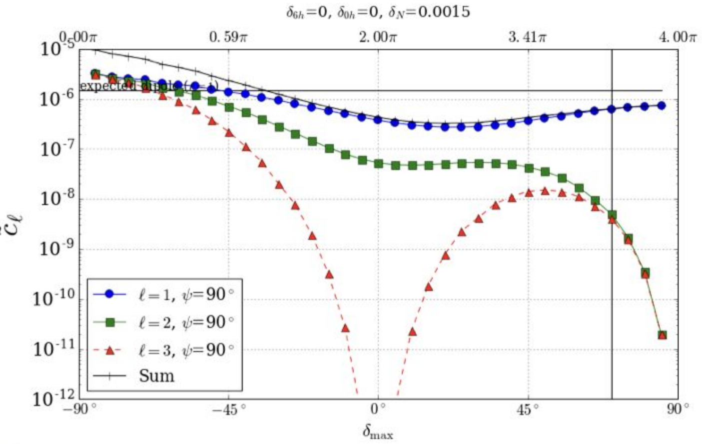
Display amplitude of select multipole moments as a function of energy

systematics studies

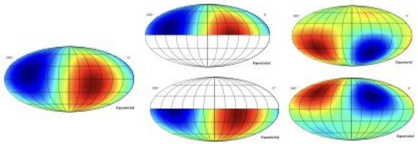
Effect of Partial sky-coverage on APS

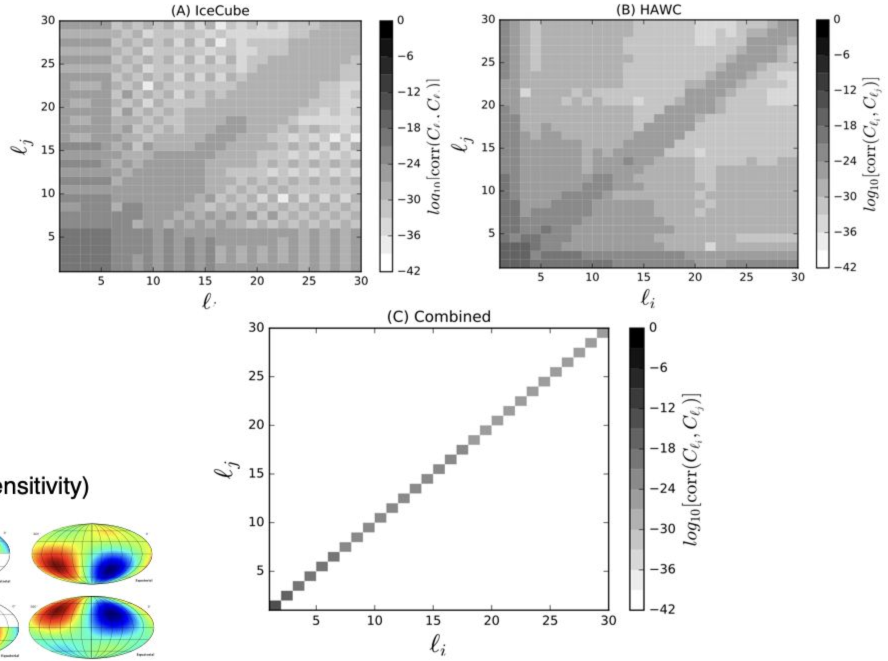
Multipole components are subject to correlations caused by partial sky coverage since there is a degeneracy between different ℓ-modes.

A pure dipole can result in an artificial quadrupole due to partial sky coverage.



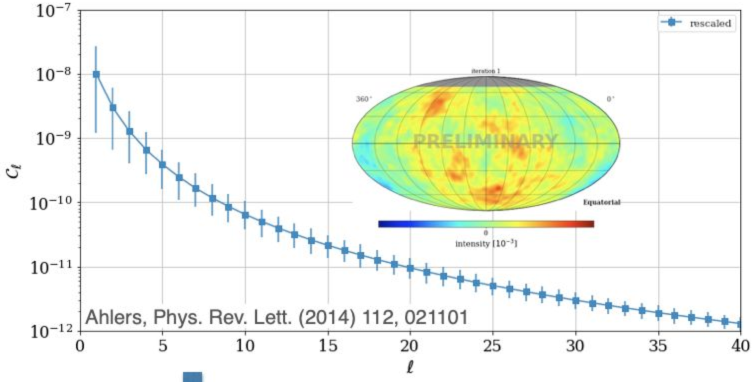
Pure dipole (3D sensitivity)

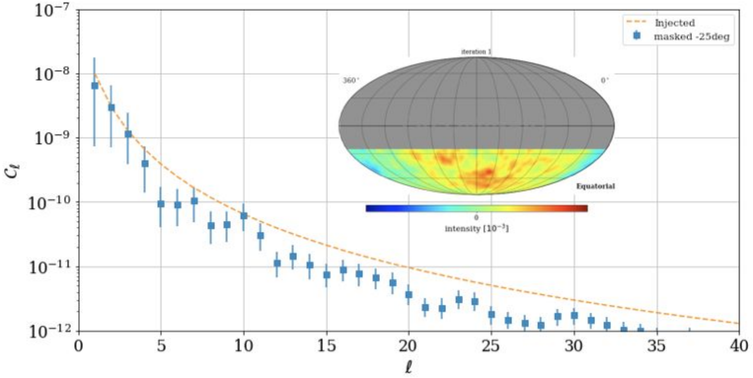




Abeysekara et al., ApJ (2019) 871 96

systematics studies

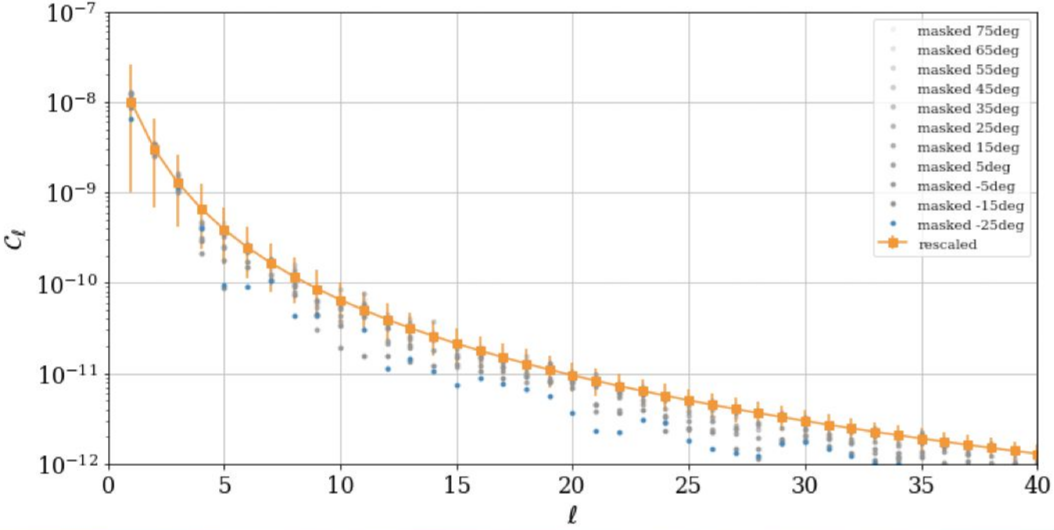




Effect of Partial sky-coverage on APS

Reconstructed APS with partial sky-map is biased:

- Structures at different angular scales are not uniformly spread between the two hemispheres
- Partial sky results in correlated ℓ-modes

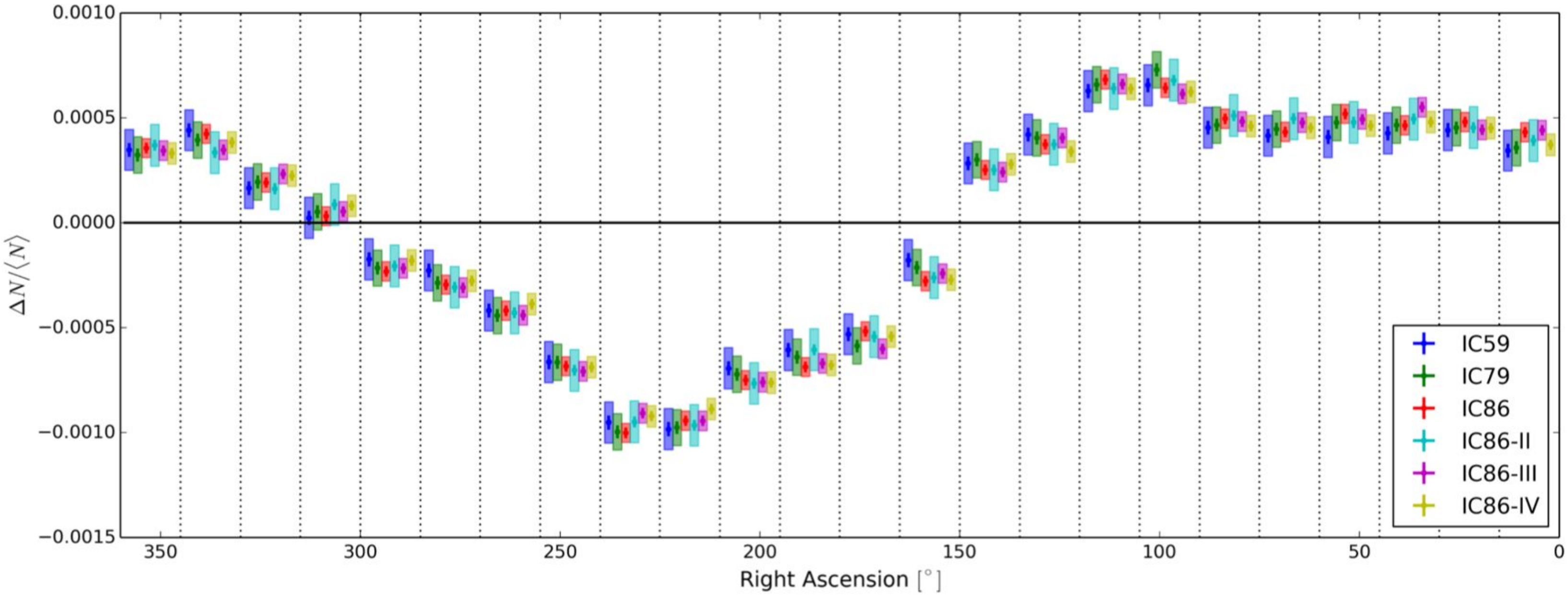


Systematics

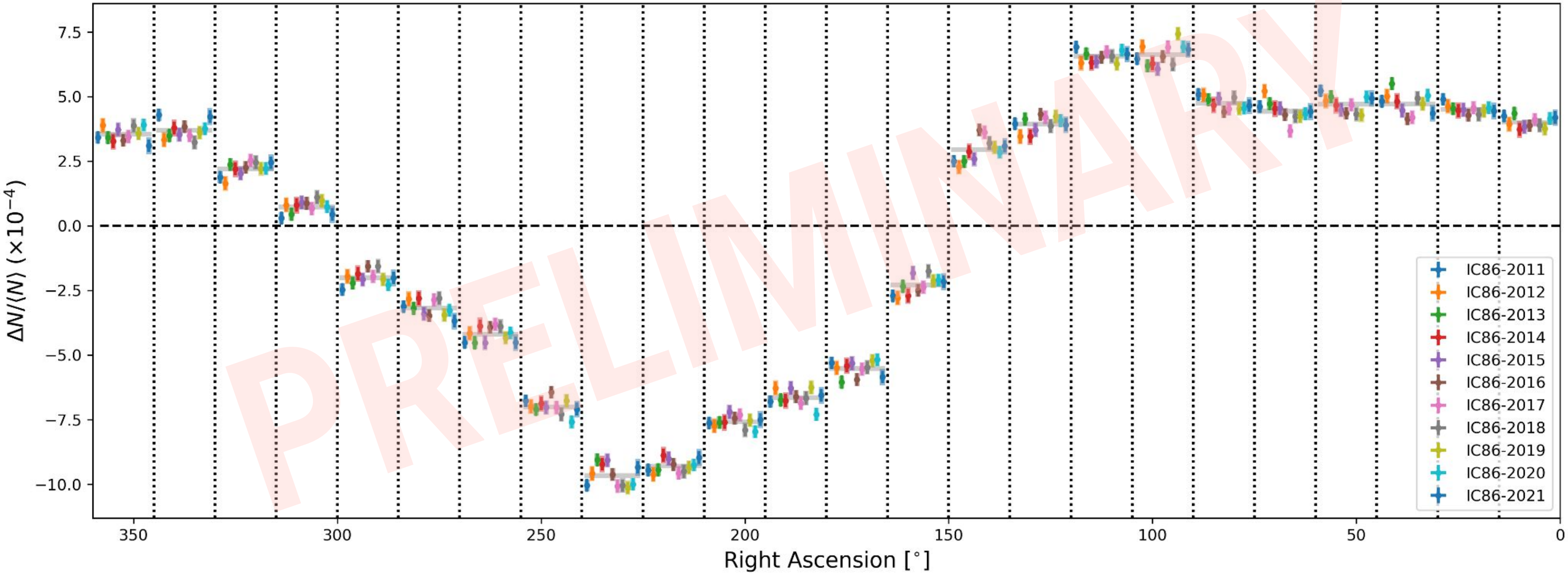
Time Dependence

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

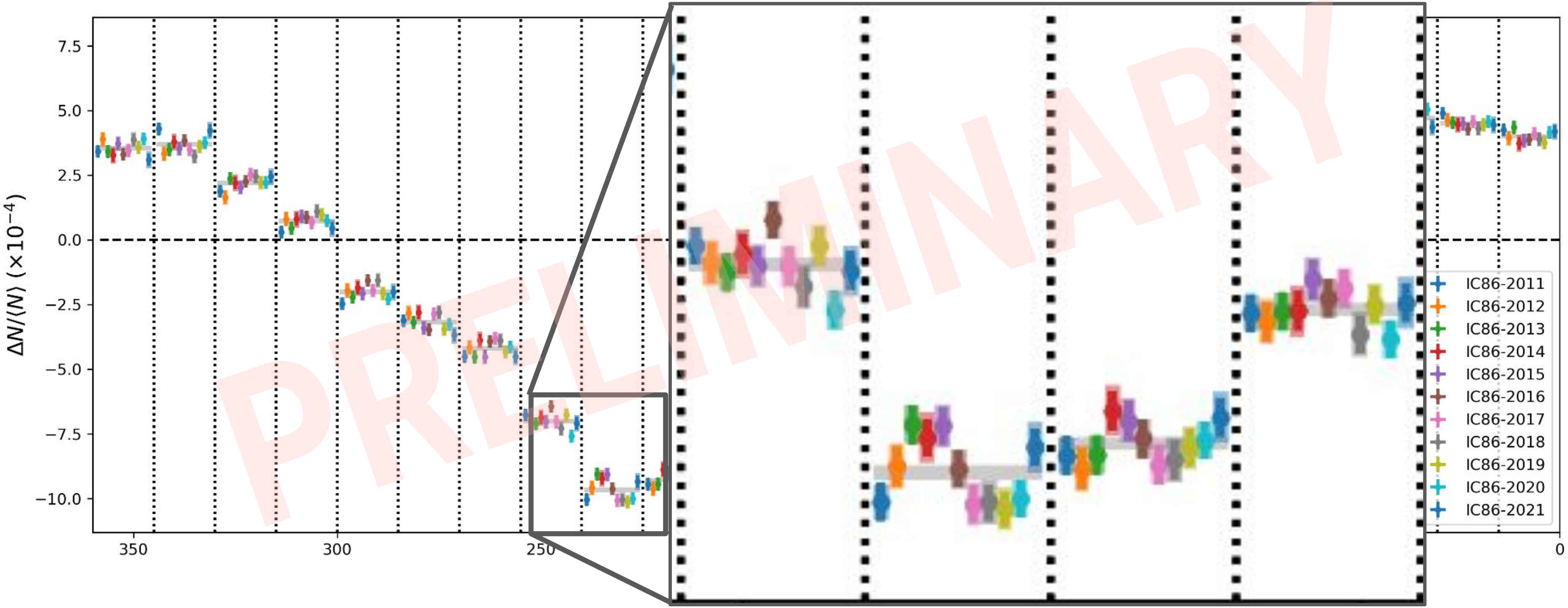


Systematics



Systematics

Time Dependence



Summary

Results

- Update analysis features improved statistics, simulation, and systematics
- Structures in large-scale, small-scale, and energy-split maps appear consistent, with higher significance
- Dipole phase and amplitude consistent with measurements from other experiments
- New energy-dependent views of the angular power spectrum
- 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
- Rigidity-dependence of 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
Gunwati Agrawal	IceTop Data processing/analysis
Savannah Lehrman	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

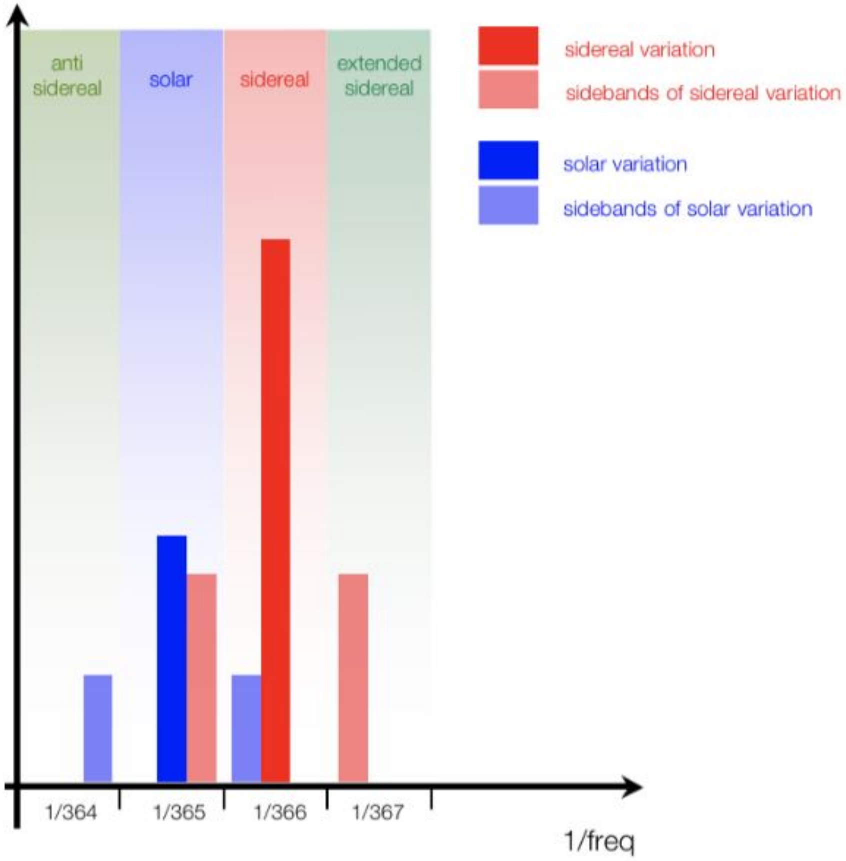
Review: Yearly Variation

- 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

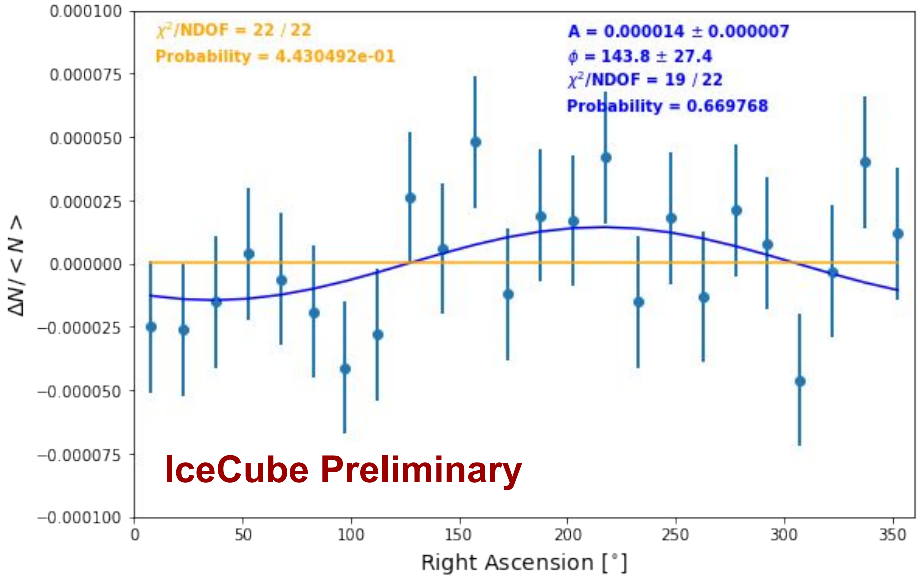
- What is the mutual influence of the signals in the solar and sidereal frames?

- Anti-sidereal: effect of solar on sidereal
- Extended-sidereal: effect of sidereal on solar



Improved Systematics: Calendar Years

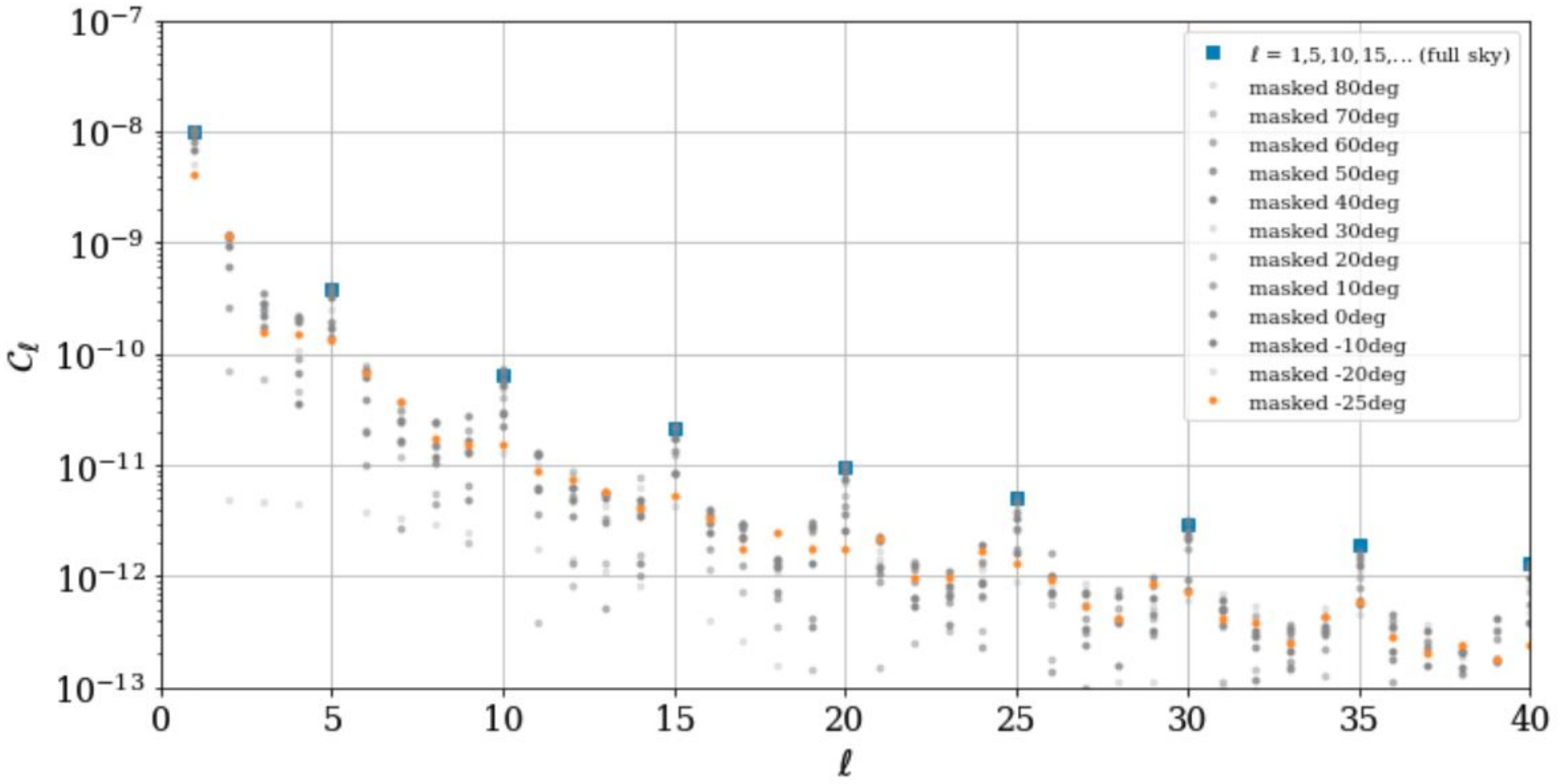
- **Signal due to annual orbit should cancel out over a solar year**
  - Systematic uncertainty in sidereal signal derived from anti-sidereal frame
- “Detector years” inconsistent in size
- Consistent detector configuration: systematic uncertainty calculated using calendar years
  - Shown: IC86-2011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



Andrew Moy

One-dimensional projection in RA of relative intensity in the anti-sidereal frame. The amplitude of a best-fit dipole (blue curve) is used as the systematic uncertainty for the sidereal signal in the corresponding year.

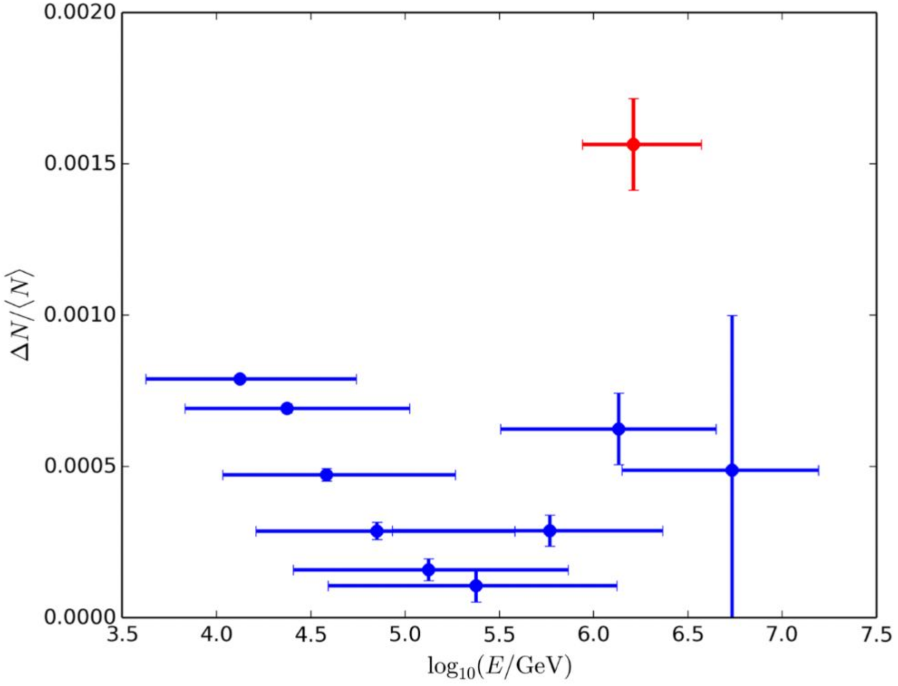
Systematics

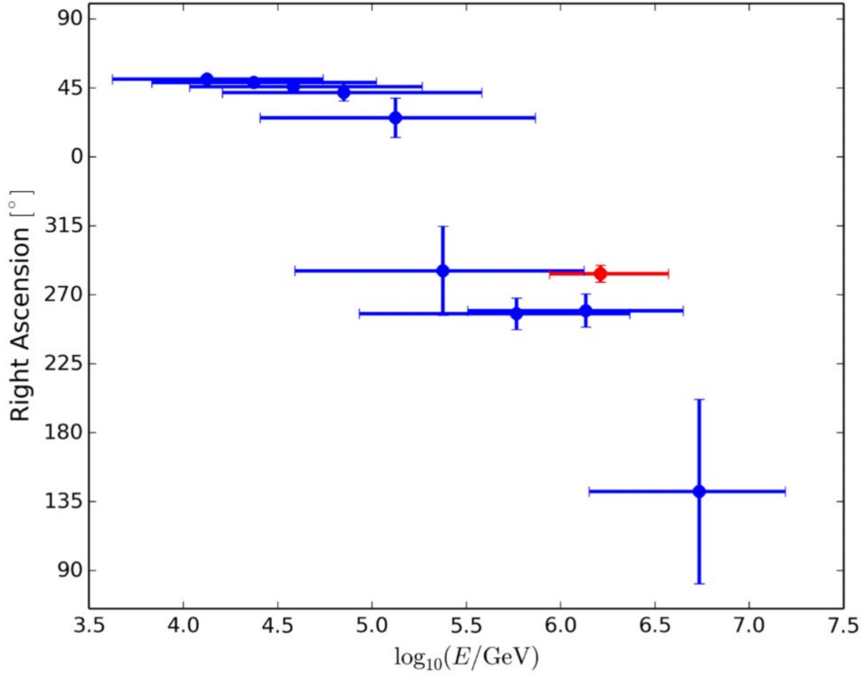


Statistics/Simulation

Dipole Phase & Amplitude

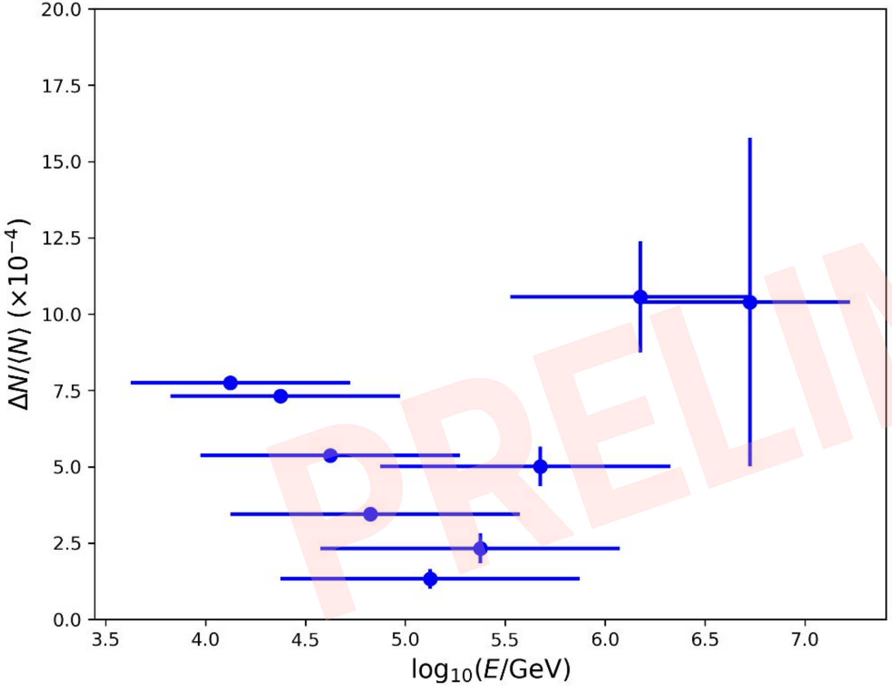
Six Years

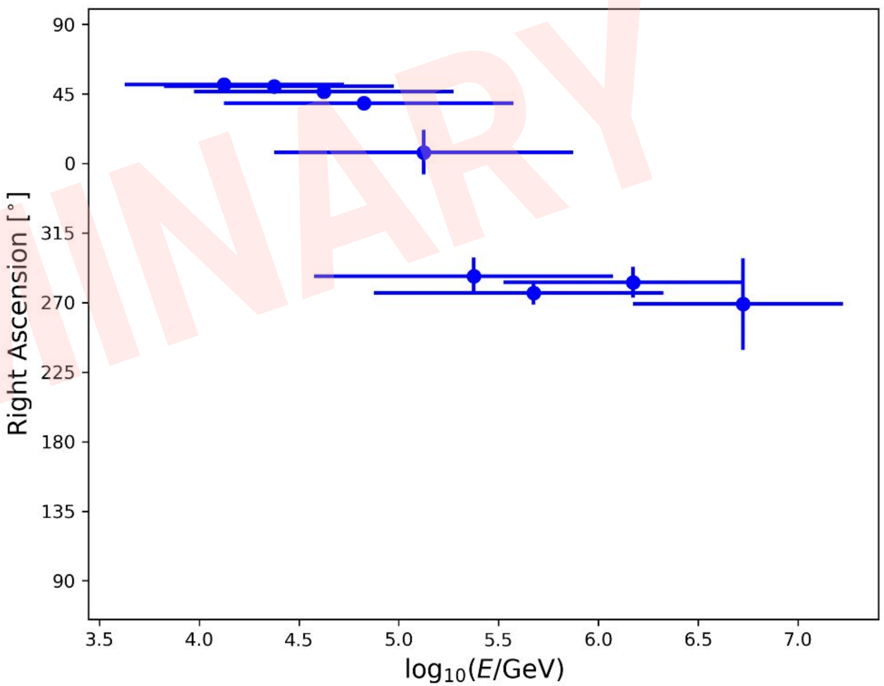




Dipole Phase & Amplitude

Eleven Years

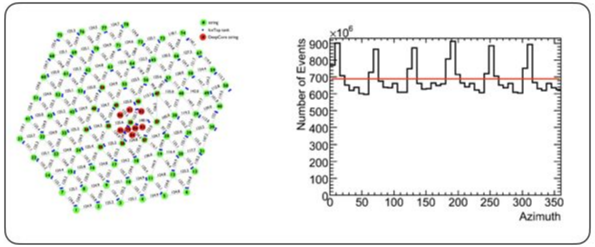




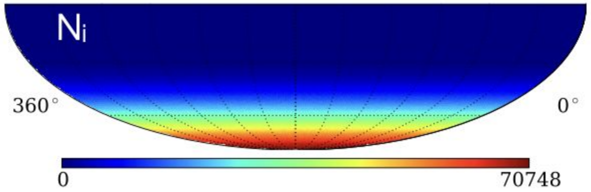
determination of anisotropy

arrival direction distribution

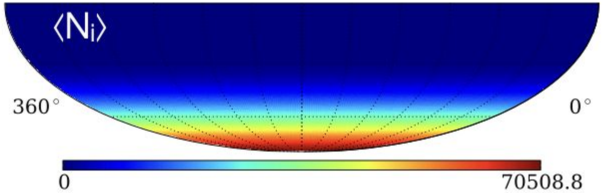
IceCube local coordinates



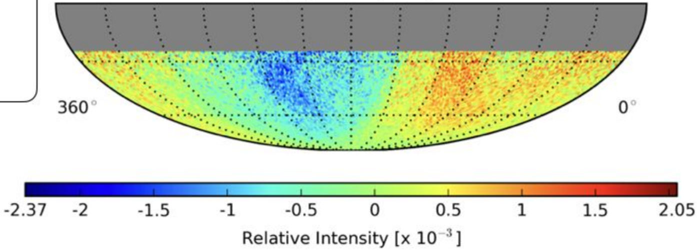
1 month of data



1 month of data



IceCube - Aartsen et al., ApJ 826, 220, 2016 6 years of data



raw map of events in equatorial coordinates $(\alpha,\delta)_i$

reference map of events *scrambled* over 24hr in α (or time) within same δ band

→ **response map to isotropic flux**

residual map as relative intensity normalized in each δ band: equal deficit/excess.

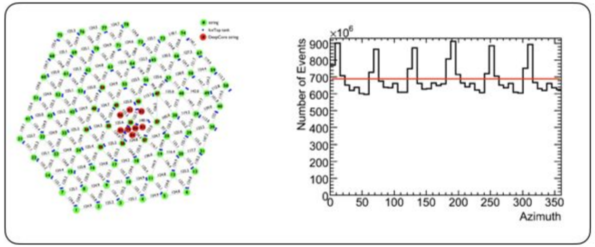
→ **equal deficit/excess contribution**

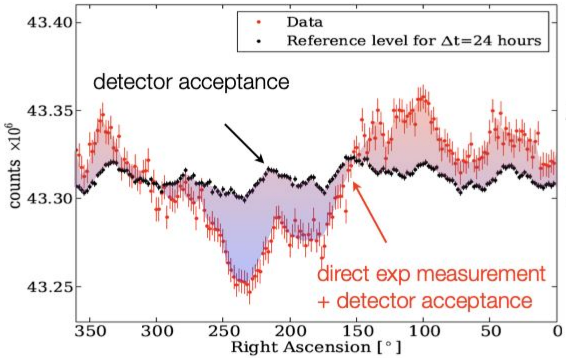
$$\frac{\Delta I}{\langle I \rangle} \equiv \frac{N_i - \langle N \rangle}{\langle N \rangle}$$

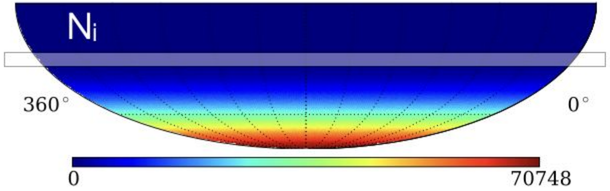
determination of anisotropy

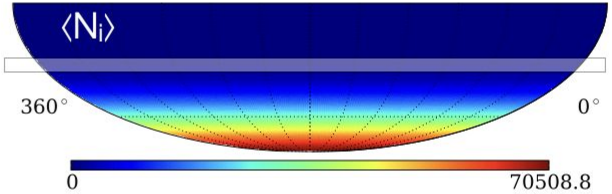
arrival direction distribution

IceCube local coordinates









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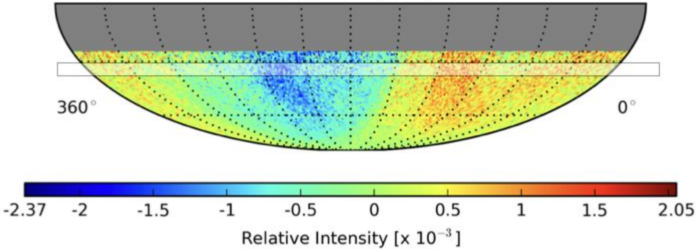
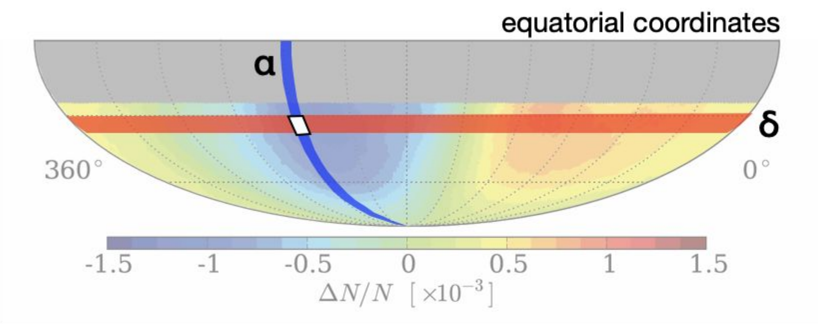


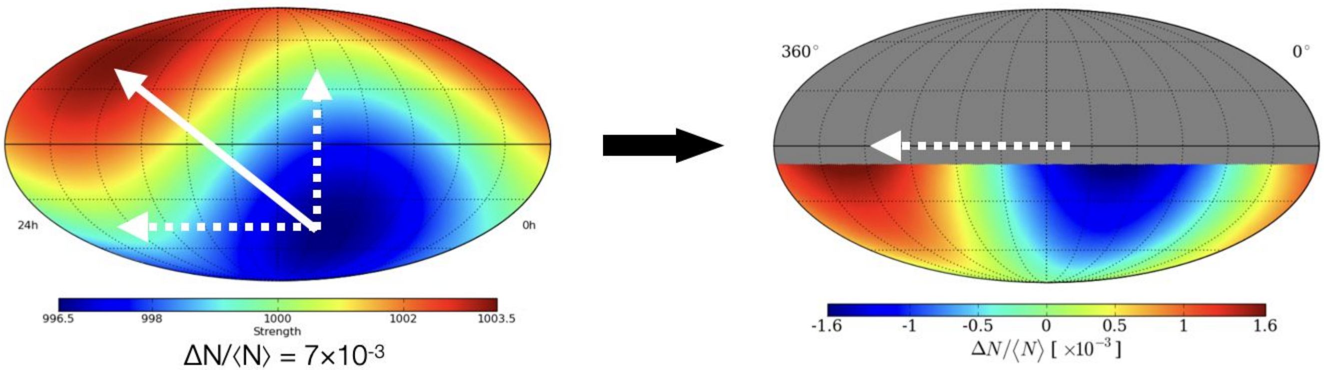
$$\boxed{\frac{\Delta I}{\langle I \rangle} \equiv \frac{N_i - \langle N \rangle}{\langle N \rangle}}$$

observing cosmic ray anisotropy
projection blindness



$$\frac{\Delta N_i}{\langle N\rangle_i} = \frac{N_i(\alpha,\delta) - \langle N_i(\alpha,\delta)\rangle}{\langle N_i(\alpha,\delta)\rangle}$$

declination bands
independently normalized



sky maps show **ONLY** modulations projected on **equatorial plane**