A Method to Investigate Potential Time Variation in the Cosmic-Ray Anisotropy

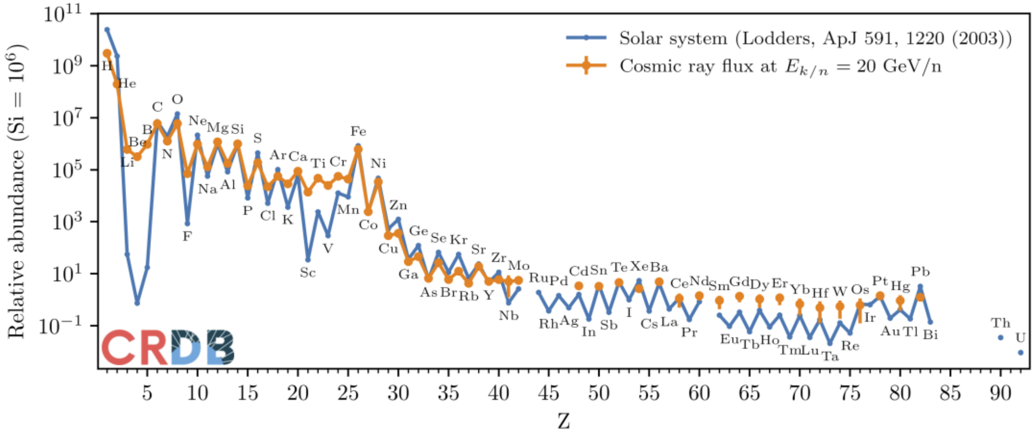
Perri Zilberman for the IceCube Collaboration
University of Wisconsin - Madison
pzilberman@wisc.edu

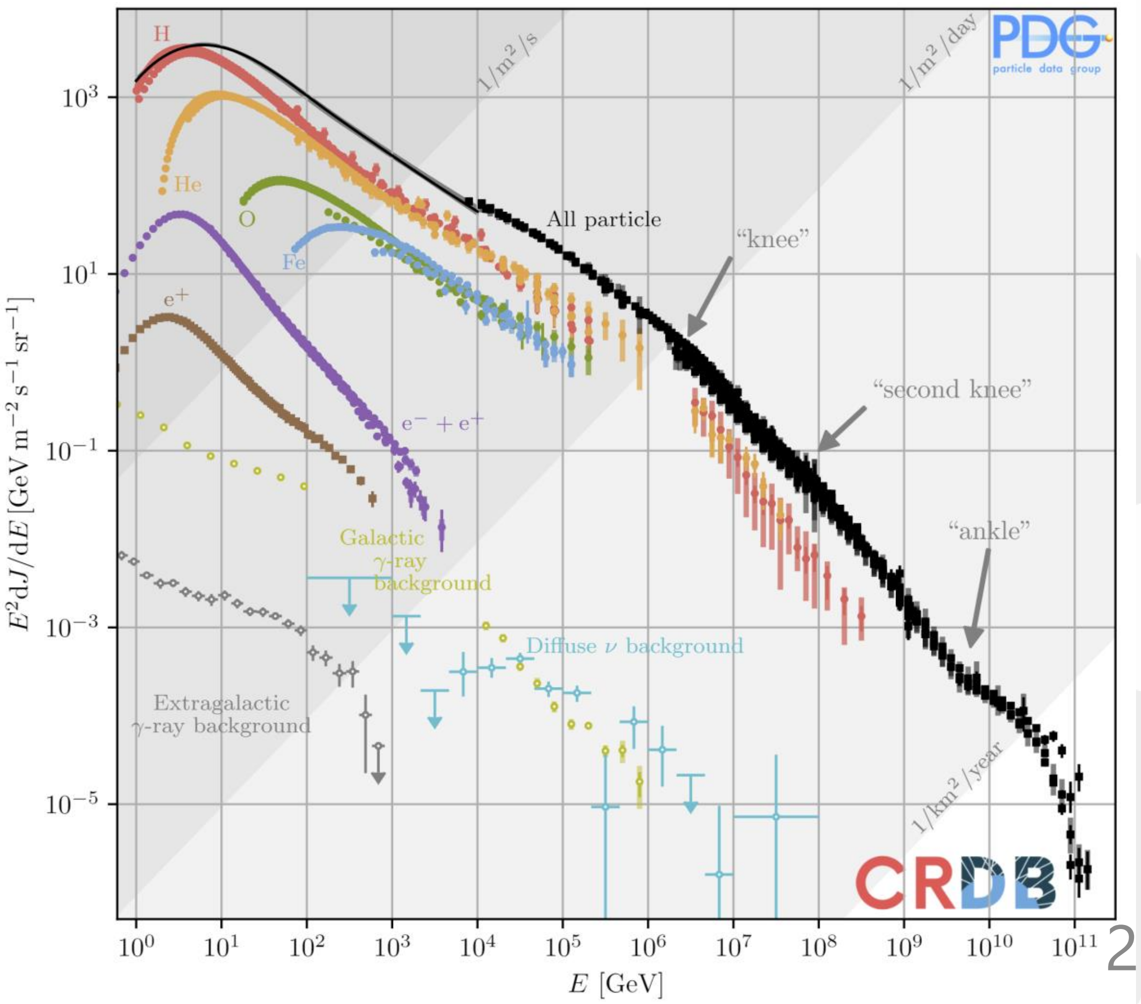
Cosmic Rays

Background

Left: Figure 30.1 in [1]
Right: Figure 30.2 in [1]

- The Earth is constantly bombarded by energetic nuclei
  - Mostly protons and helium, trace amounts of heavier elements
- Follows a power-law like spectrum with a few notable features
  - The knee
  - The second knee
  - The Ankle
- Diffusion in interstellar magnetic fields causes TeV cosmic rays to lose directional information





The Cosmic Ray Anisotropy
Background

- There is a well-known anisotropy in the arrival direction of TeV cosmic rays
- It has been studied by a number of experiments*
  - Milagro
  - GRAPES-3
  - ARGO-YBJ
  - Tibet ASγ
  - LHAASO
  - HAWC
  - IceCube
- Quite small – maximum anisotropy of order 10^{-3}
- Has both large-scale and small-scale features
- Energy dependent (dipole flips at larger energies)
- Source of small-scale anisotropy remains active research topic

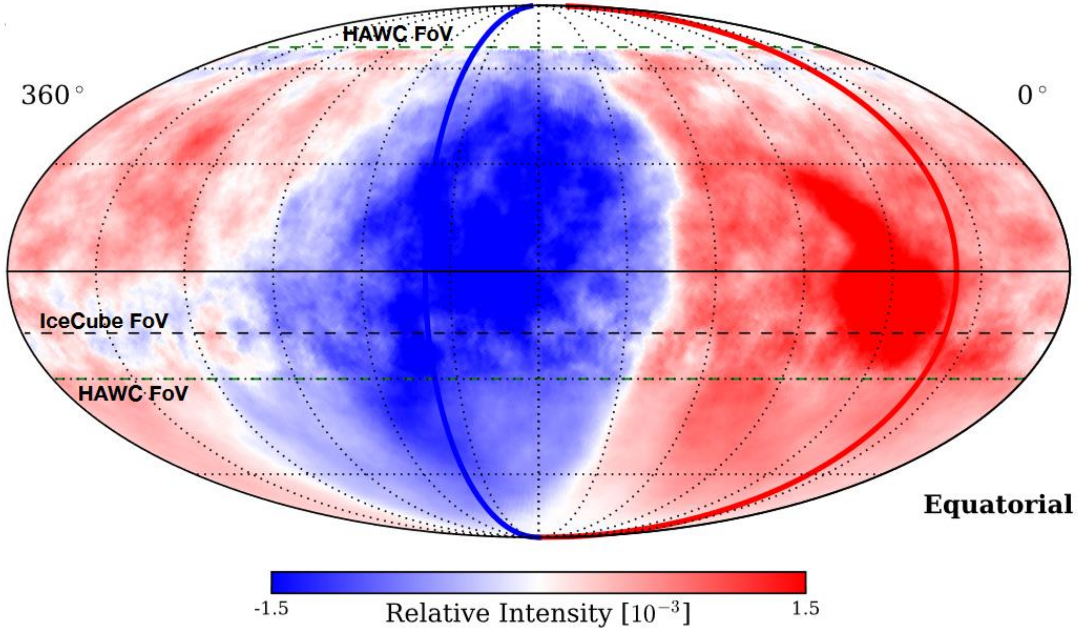


Figure 4a. in [2]

Quantified by a "Relative Intensity"

Data (Counts) Background

$$R = \frac{N - \langle N \rangle}{\langle N \rangle}$$

*This is not an exhaustive list

Cosmic Ray Anisotropy Reconstruction

Background

Many methods to reconstruct the cosmic ray anisotropy, but all have similar limitation:

- Measuring the anisotropy requires knowing your detector's response to an isotropic cosmic ray flux
- Uncertainty in simulations tend to be larger than anisotropy
- Requires determining your detector's response via the data itself

<u>This results in being unable to reconstruct the anisotropy along Earth's rotation axis</u>

- In other words, decomposing the anisotropy into spherical harmonics will artificially have the power in all m=0 terms be zero

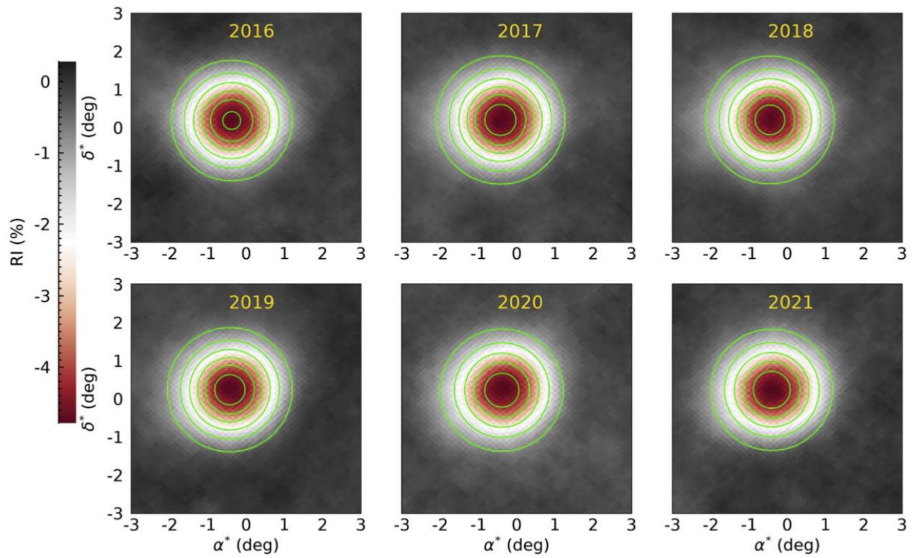
Time Dependence?

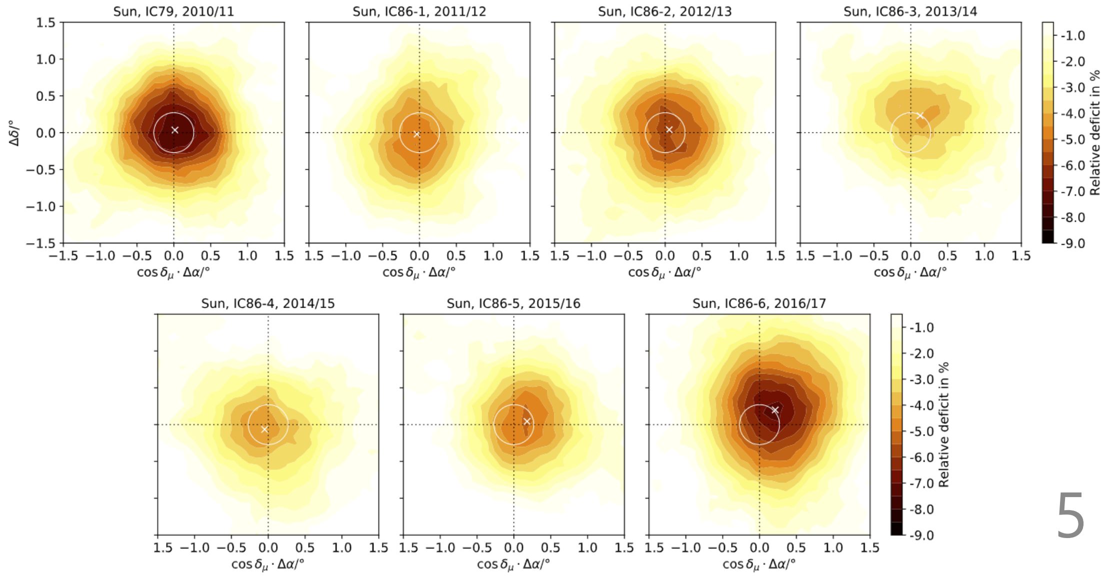
Background

- Is there time dependence in the cosmic ray anisotropy (CRA)?

There's good reasons to think so:

- The Heliosphere changes over time due to the 11-year solar cycle
- This effect has been seen in its effect on TeV cosmic rays via analyses of the time-dependent cosmic ray sun shadow
- Interactions with the heliosphere is a likely cause of some features in the cosmic ray anisotropy
- If the heliosphere changes over time, cosmic ray interactions with the time-dependent heliosphere may cause the cosmic ray anisotropy to have a time-dependence as well





Top: Figure 1. in [3]
Bottom: Figure 7. in [4]

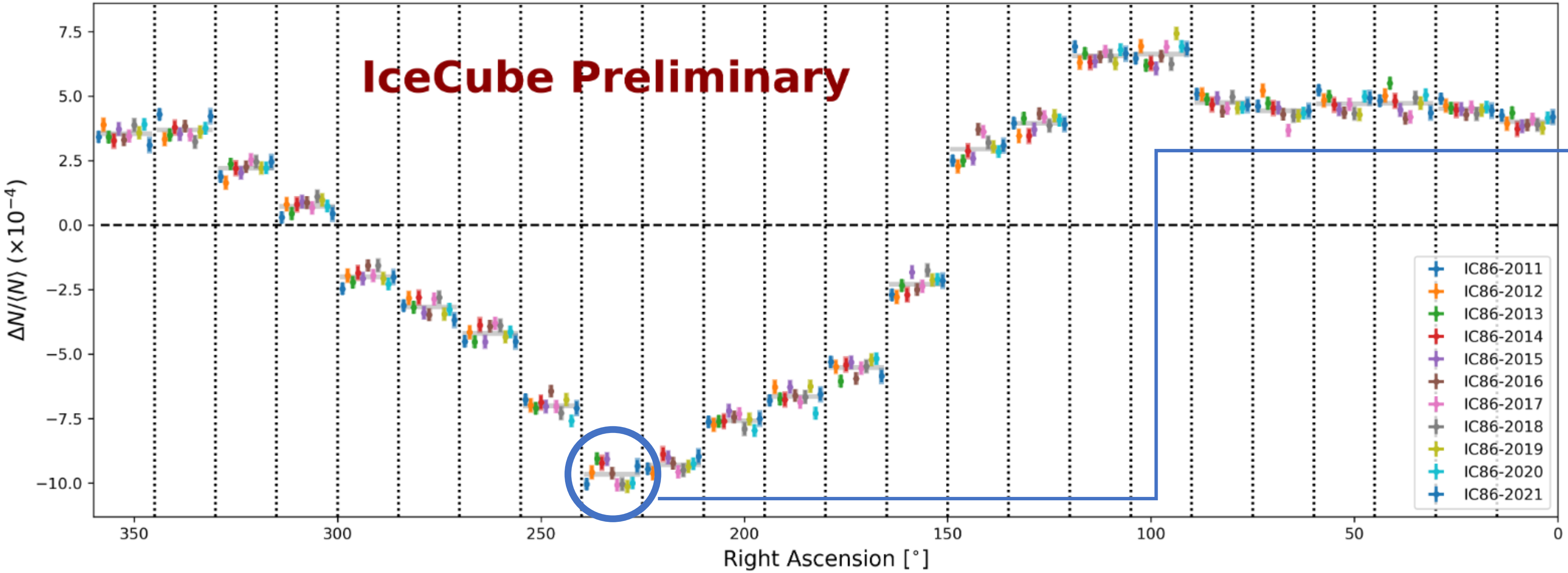
Prior Work on Time Variation

Background

- Prior work has been done looking at time dependence in the cosmic ray anisotropy

But generally, only focusing on the large-scale* anisotropy

- Find no time variation in the large-scale structure – but potential hints of time variation



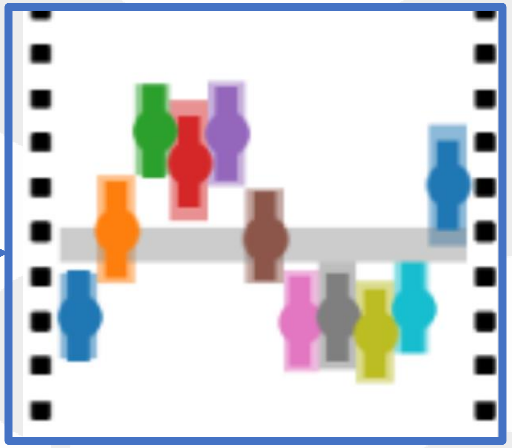


Figure 6. in [5]

*First few multipoles

This Work

We Present a General Method to Study Time Variation in the Cosmic Ray Anisotropy at All Scales

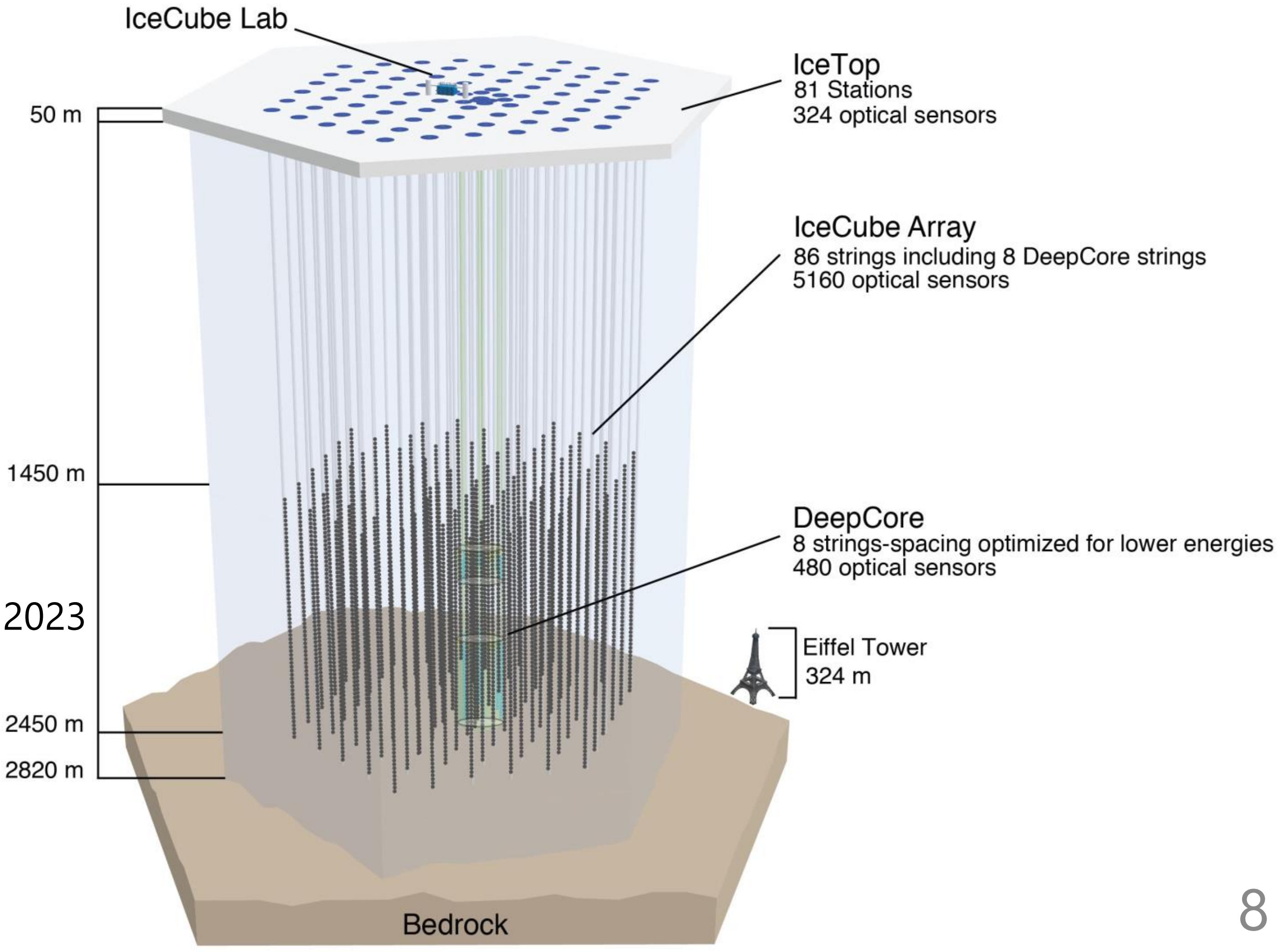
IceCube Neutrino Observatory

Data

- Operating in full 86-string layout since 2011
- Duty cycle of ~98%
- Median cosmic ray energy of 20 TeV
- Cosmic ray FoV constrained to <-25° Declination
- Has recorded ~800 billion cosmic ray muons

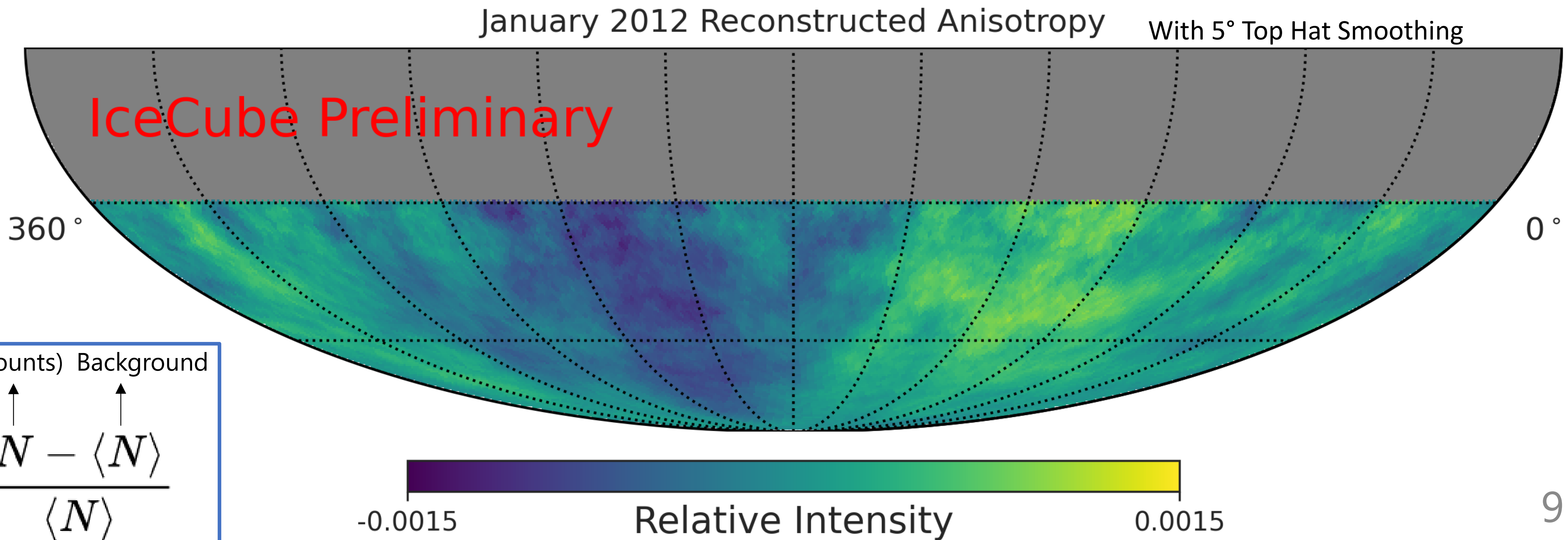
Our Sample:

- Use a burn sample of every January from 2012 – 2023
- Use in-ice muons
- Minimizes effect of seasonal variation
- Binned using HEALPix sky pixelization
    - Pixels ~0.9° across



Example Relative Intensity Map January 2012

Data



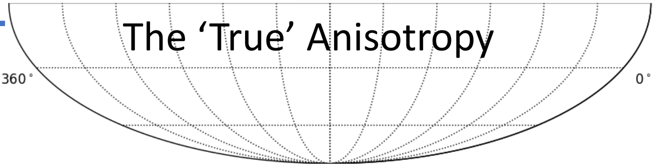
Data (Counts) Background

$$R = \frac{N - \langle N \rangle}{\langle N \rangle}$$

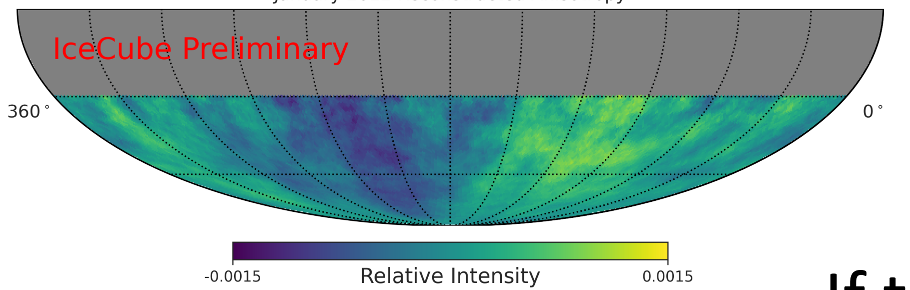
What Could Time Variation Look Like?

Methodology

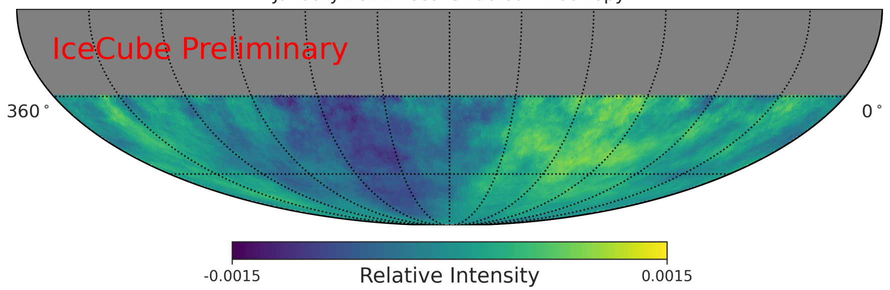
If there is **no** time variation:



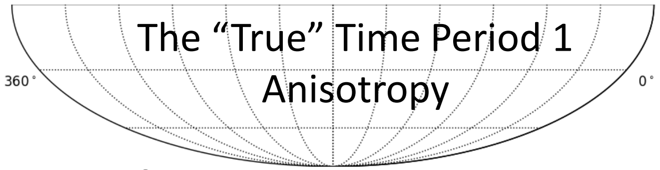
Measurement During Time Period 1



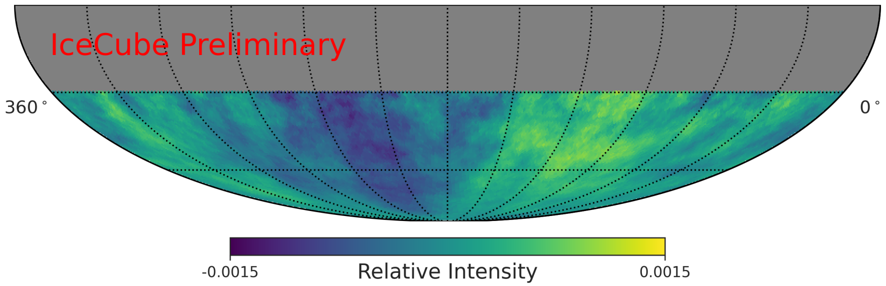
Measurement During Time Period 2



If there **is** time variation:



Measurement During Time Period 1



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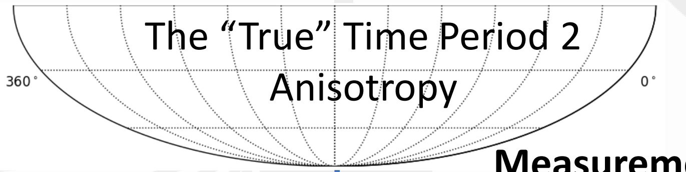
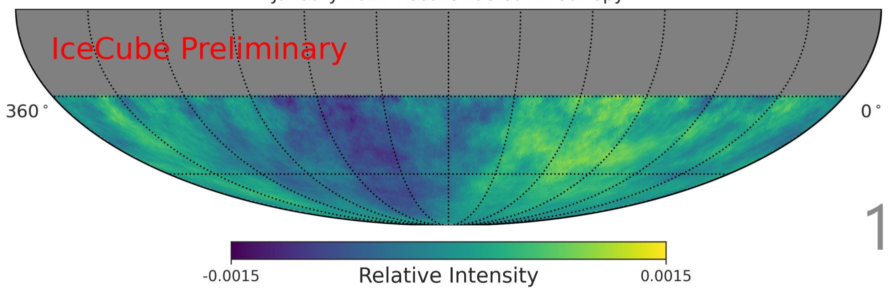


Measurement During Time Period 2



<u>The Goal:</u>

Distinguish between these two cases

A Quantitative Time Variation Test

Methodology

To quantify, can use a two-sample χ^2 test

Relative intensity during time period 1,2 in pixel i

$$\chi_i^2 = \frac{(R_{1i} - R_{2i})^2}{\sigma_{R_{1i}}^2 + \sigma_{R_{2i}}^2}$$

χ^2 of pixel i

Uncertainty in relative intensity during time period 1,2 in pixel i

Number of Pixels to Sum Over

$$\chi^2 = \sum_{i=0}^{n} \chi_i^2$$

Total χ^2

If pixels i through n are statistically compatible, total χ^2 will be sampled from a χ^2 distribution with degrees of freedom n - i

p-value

$$S = \sqrt{2}\,\mathrm{erf}^{-1}(1 - 2p)$$

Relative Intensity in pixels i through n measured during time period 1 and 2 are statistically incompatible at [x]σ level

Some Potential Applications

Methodology

- This is a very flexible methodology – potential studies include
  - Global changes in anisotropy sky-maps
  - Appearance/disappearance of excess/deficit regions
  - Evolution of excess/deficit regions over time
  - Stability of spherical harmonics
  - etc.

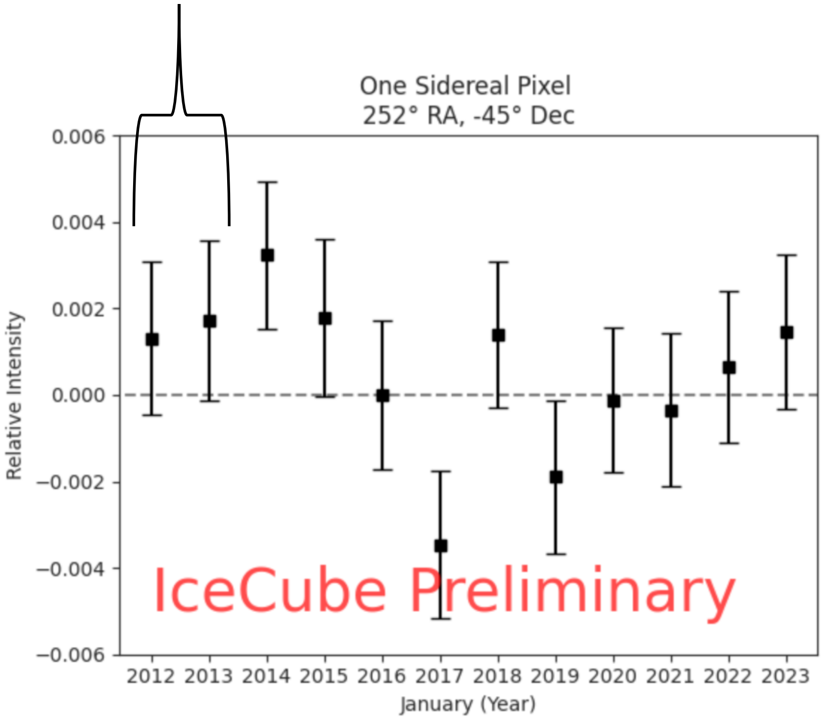
Month-wise Anisotropy Comparison

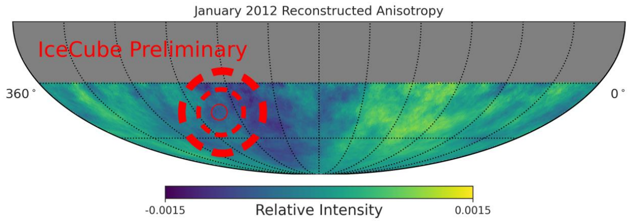
Methodology

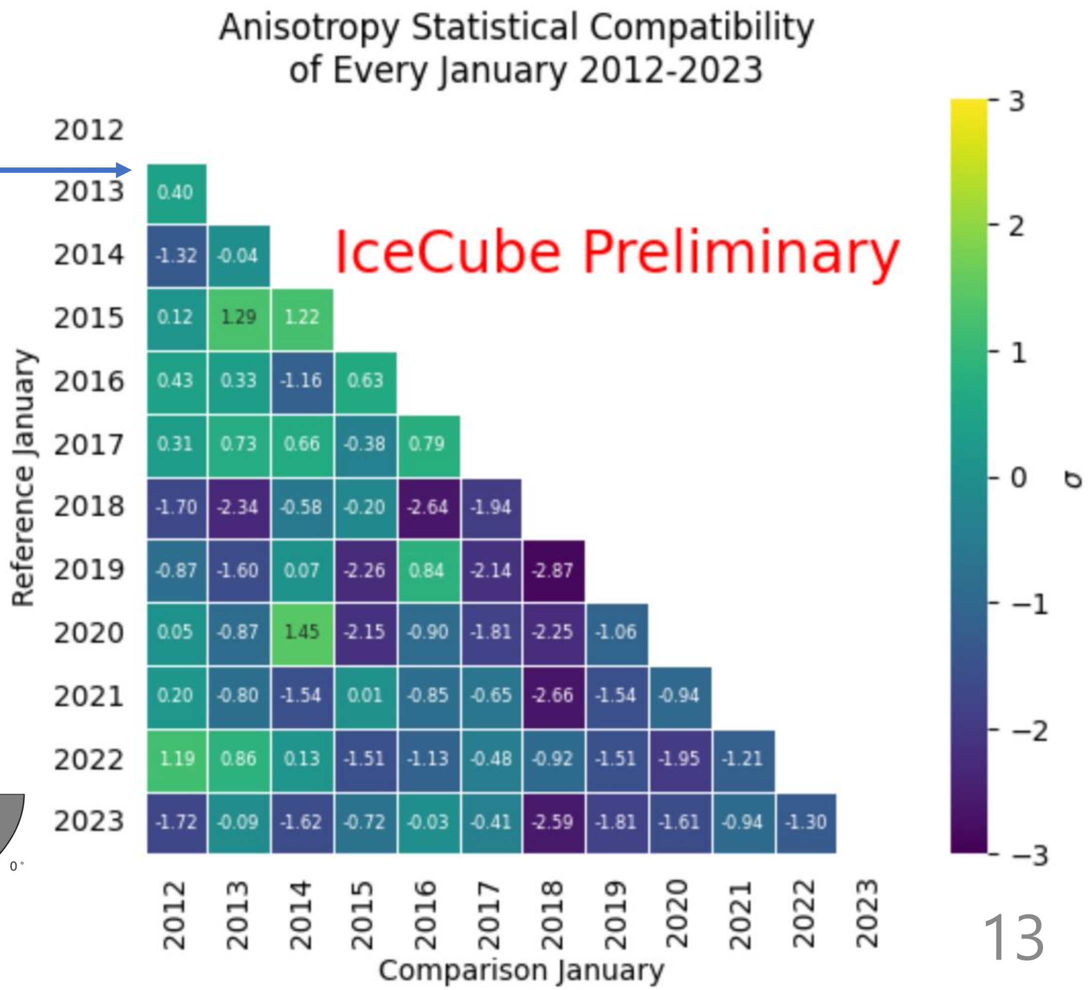
A Simple test – compare every month in our sample

$$\chi_i^2 = \frac{(R_{1i} - R_{2i})^2}{\sigma_{R_{1i}}^2 + \sigma_{R_{2i}}^2} \rightarrow \chi^2 = \sum_{i=0}^{n} \chi_i^2 \rightarrow \text{p-value}$$

$$S = \sqrt{2}\,\mathrm{erf}^{-1}(1 - 2p)$$





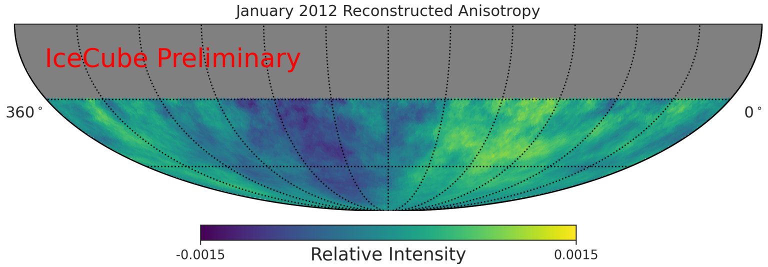


Reference \ Comparison	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
2012												
2013	0.40											
2014	-1.32	-0.04										
2015	0.12	1.29	1.22									
2016	0.43	0.33	-1.16	0.63								
2017	0.31	0.73	0.66	-0.38	0.79							
2018	-1.70	-2.34	-0.58	-0.20	-2.64	-1.94						
2019	-0.87	-1.60	0.07	-2.26	0.84	-2.14	-2.87					
2020	0.05	-0.87	1.45	-2.15	-0.90	-1.81	-2.25	-1.06				
2021	0.20	-0.80	-1.54	0.01	-0.85	-0.65	-2.66	-1.54	-0.94			
2022	1.19	0.86	0.13	-1.51	-1.13	-0.48	-0.92	-1.51	-1.95	-1.21		
2023	-1.72	-0.09	-1.62	-0.72	-0.03	-0.41	-2.59	-1.81	-1.61	-0.94	-1.30	

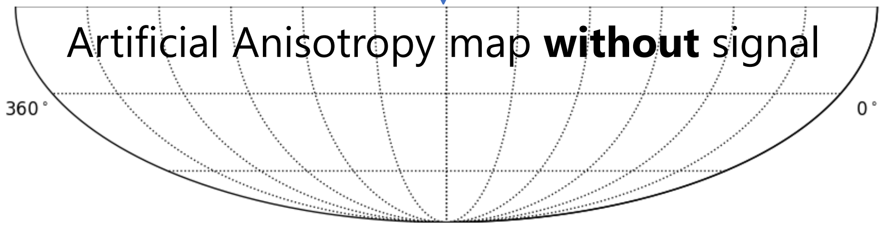
Sensitivity to Sudden Appearance of an Excess Region

Methodology

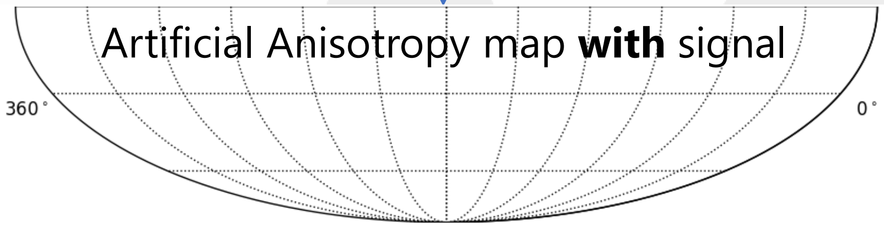
Reconstruct One Month of Data



Artificial Anisotropy map **without** signal



Artificial Anisotropy map **with** signal



Two-Sample χ^2 test

Repeat and take median to get median χ^2

Calculate probability of finding that median χ^2

Sensitivity to Sudden Appearance of an Excess Region

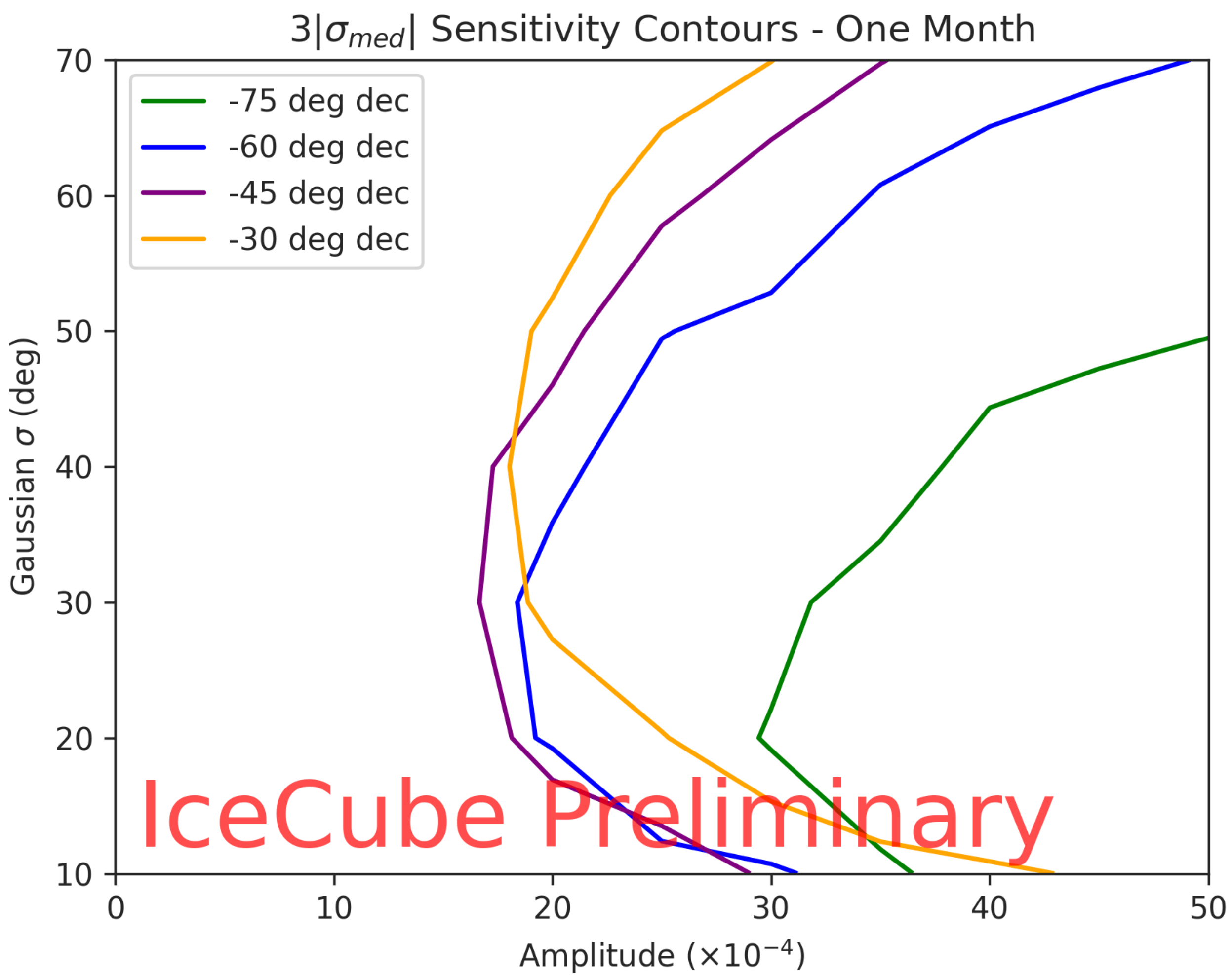
Methodology

- We do **not** have a theoretical model for what a signal could be – but can use a simple phenomenological model
- We would like to know IceCube's response to a signal based on
  - The signal's spatial extent
  - The signal's strength
  - The signal's location on the sky
- A Simple phenomenological model that satisfies this is a *Gaussian signal*

Sudden Appearance of an Excess Region Sensitivity Contours

Results

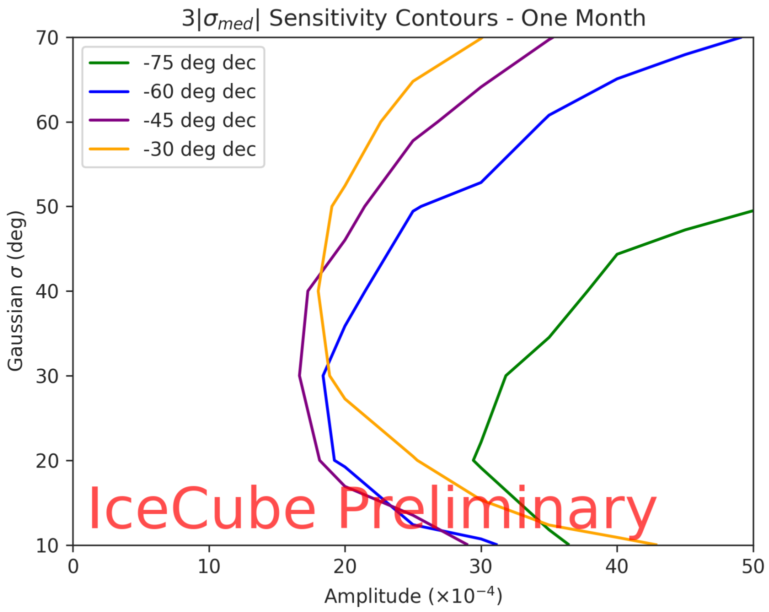
- Most sensitive* to signal ~30° across
- With one month of data, sensitive to signals of amplitude $> 2 \times 10^{-3}$*
  - Around maximum amplitude of anisotropy
- Low sensitivity for signals near zenith because m = 0 terms unable to be reconstructed

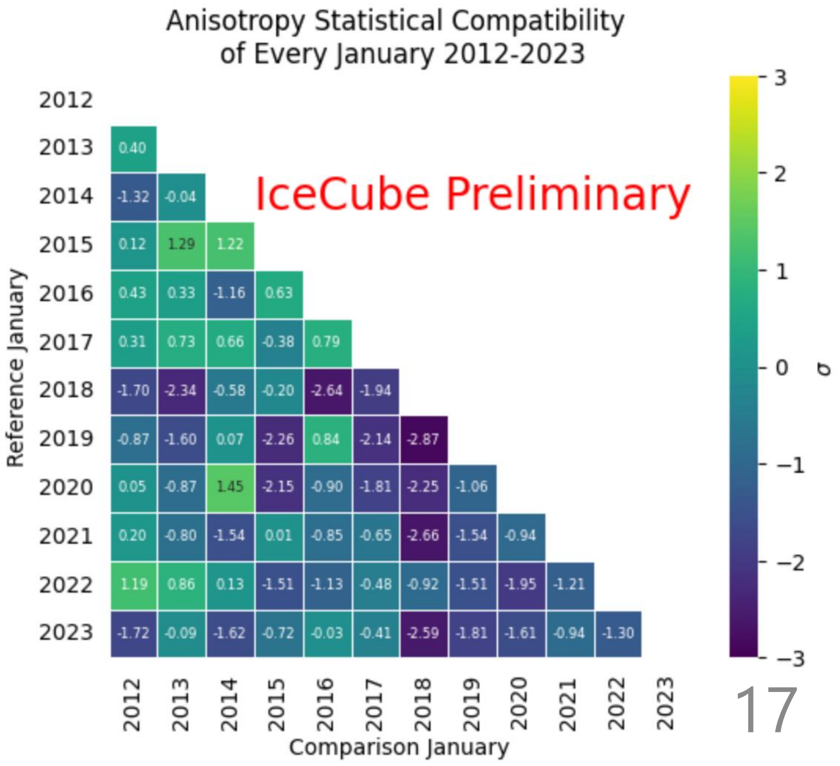


*For a full-sky analysis

Conclusions

- There is a well-known anisotropy in the arrival direction of TeV cosmic rays across a wide variety of angular scales
- Previous studies have only studied the time variation of the large-scale features of this anisotropy
- We developed a flexible, model-independent method to study time variation in the cosmic ray anisotropy across a variety of angular scales
- We validated this methodology by:
  1. Testing to see if there were global changes in anisotropy sky-maps for every January from 2012 – 2023
  2. Determined IceCube's sensitivity to the sudden appearance of a gaussian signal





References

[1] Navas, S., Amsler, C., Gutsche, T., et al. 2024, Phys Rev D, 110, 030001

[2] Abeysekara, A. U., Alfaro, R., Alvarez, C., et al. 2019, Astrophys J, 871, 96

[3] Alfaro, R., Alvarez, C., Arteaga-Velázquez, J. C., et al. 2024, Astrophys J, 966, 67

[4] Aartsen, M. G., Abbasi, R., Ackermann, M., et al. 2020, Phys Rev D, 103, 042005

[5] McNally, F., Abbasi, R., Desiati, P., et al. 2023, arXiv

[6] Ahlers, M., BenZvi, S. Y., Desiati, P., et al. 2016, ApJ, 823, 10, https://dx.doi.org/10.3847/0004-637X/823/1/10

Thank You!

Backup

Cosmic Ray Anisotropy Reconstruction

Methodology

- We use a maximum likelihood estimation method
  - Described in Ahlers et al. 2016 [6]

- If we bin cosmic ray counts (in local coordinates) into sky pixels (i) and sidereal time bins (τ), each measurement $n_{\tau i}$ is sampled from a Poisson distribution with mean $\mu_{\tau i}$

$$\mathcal{L}(n|I,\mathcal{N},\mathcal{A}) = \prod_{\tau i} \frac{(\mu_{\tau i})^{n_{\tau i}} e^{-\mu_{\tau i}}}{n_{\tau i}!}$$

Detector Response to Isotropic Flux

$$\mu_{\tau i} \simeq I_{\tau i}\mathcal{N}_\tau\mathcal{A}_i$$

- $\mathcal{A}_i$ → Acceptance at local pixel i
- $\mathcal{N}_\tau$ → Norm - Total counts in sidereal time bin τ assuming no anisotropy
- $I_{\tau i}$ → Anisotropy in local pixel i and sidereal time bin τ

We maximize the likelihood ratio:

$$\lambda = \frac{\mathcal{L}(n|I,\mathcal{N},\mathcal{A})}{\mathcal{L}(n|I^{(0)},\mathcal{N}^{(0)},\mathcal{A}^{(0)})}$$

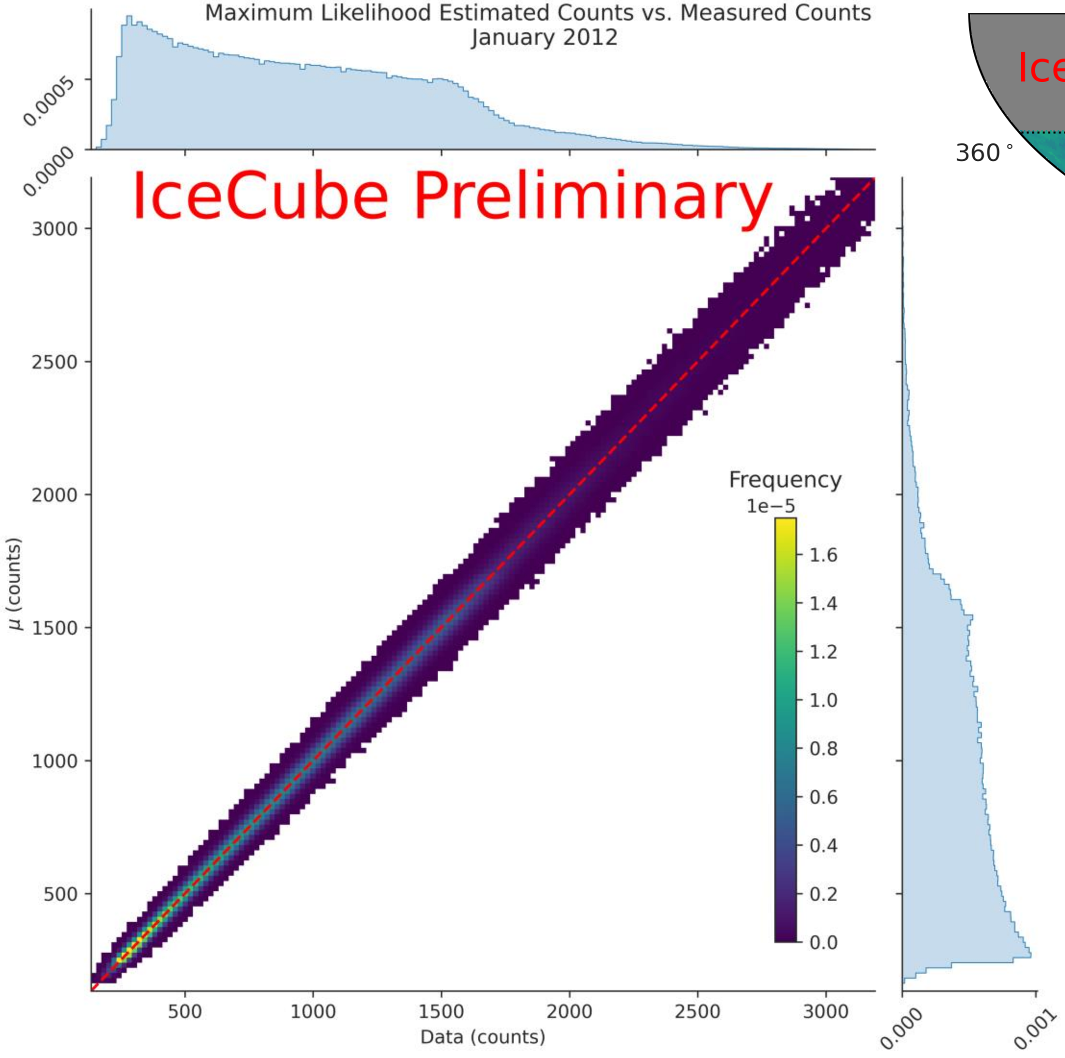
$I^{(0)},\mathcal{N}^{(0)},\mathcal{A}^{(0)}$ → MLE of $I,\mathcal{N},\mathcal{A}$ assuming no anisotropy (i.e. $I = 1$)

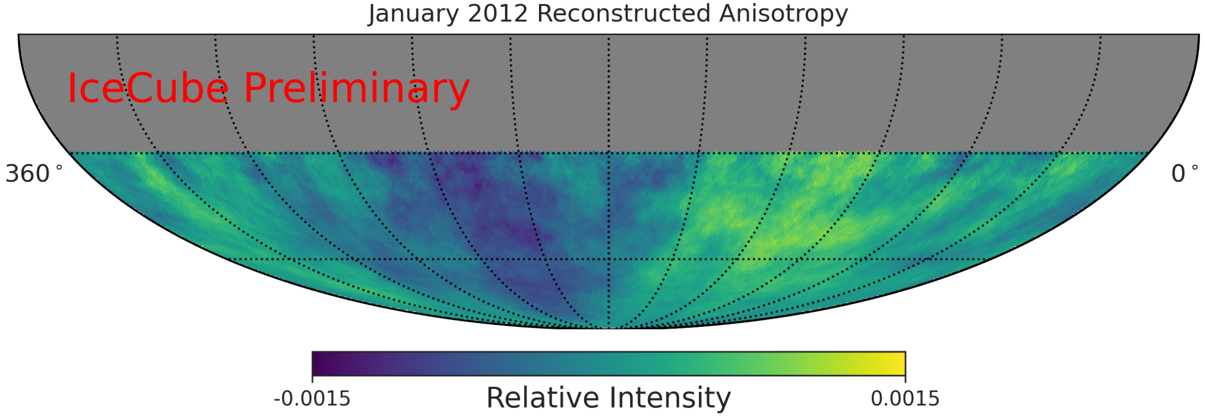
Has several benefits compared to other methods:

- Fast computation time
- Simple to incorporate multiple detectors

Cosmic Ray Anisotropy Reconstruction

Methodology



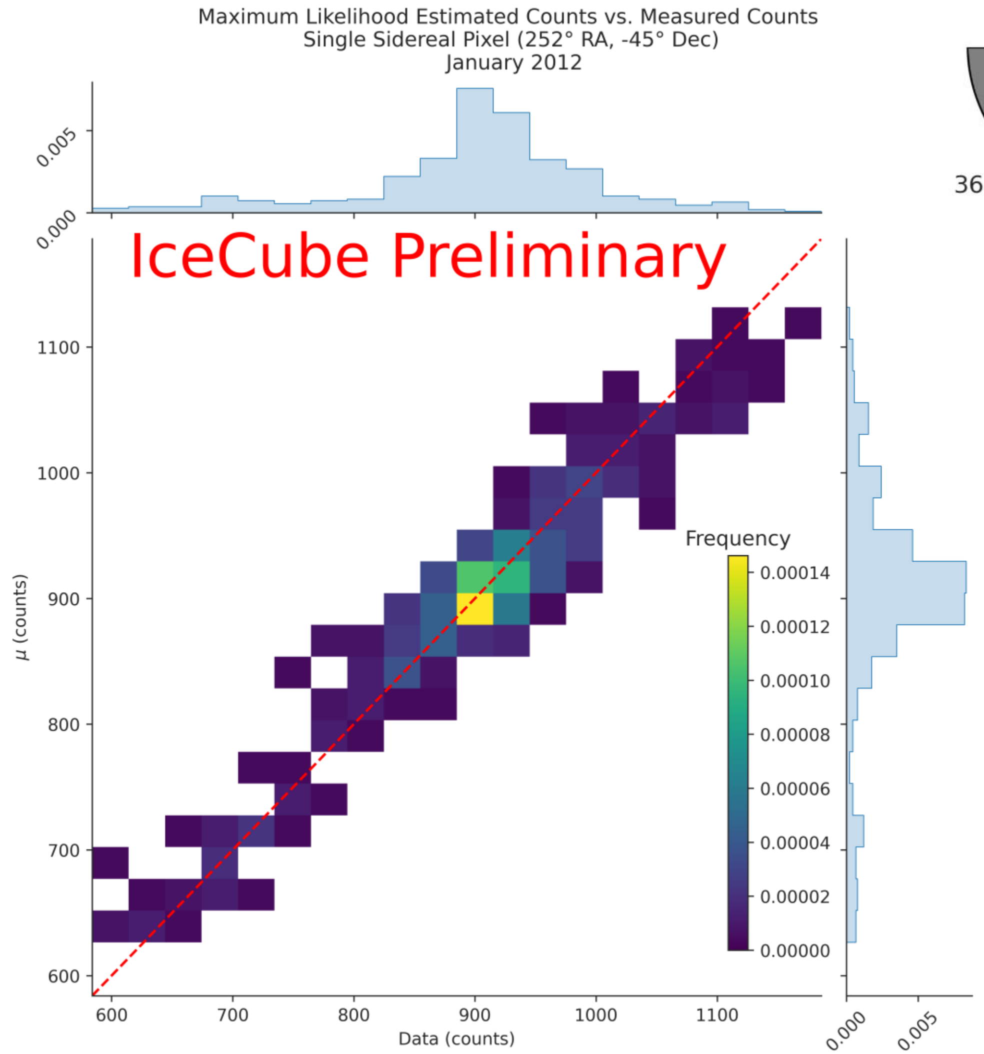


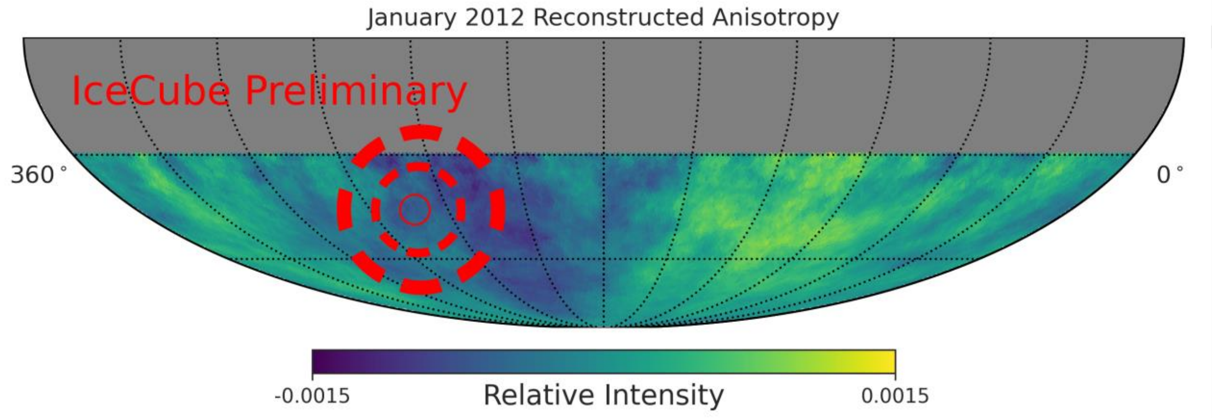
$$\lambda = \frac{\mathcal{L}(n|I,\mathcal{N},\mathcal{A})}{\mathcal{L}(n|I^{(0)},\mathcal{N}^{(0)},\mathcal{A}^{(0)})}$$

$$\mathcal{L}(n|I,\mathcal{N},\mathcal{A}) = \prod_{\tau i} \frac{(\mu_{\tau i})^{n_{\tau i}} e^{-\mu_{\tau i}}}{n_{\tau i}!}$$

Cosmic Ray Anisotropy Reconstruction

Methodology





$$\lambda = \frac{\mathcal{L}(n|I,\mathcal{N},\mathcal{A})}{\mathcal{L}(n|I^{(0)},\mathcal{N}^{(0)},\mathcal{A}^{(0)})}$$

$$\mathcal{L}(n|I,\mathcal{N},\mathcal{A}) = \prod_{\tau i} \frac{(\mu_{\tau i})^{n_{\tau i}} e^{-\mu_{\tau i}}}{n_{\tau i}!}$$

Sensitivity to Sudden Appearance of an Excess Region

Methodology

<u>General Question:</u>

- If we measure a relative intensity of R one month and $R + s$ the next month, at what point can we claim a detection of signal s?
- In other words, what signals s are we sensitive to?

<u>To obtain this sensitivity:</u>

1. Define a known signal s
2. Inject it into artificial *local* sky-map
3. Run anisotropy reconstruction
4. Do a Two-Sample χ^2 test against a “reference” map reconstructed without signal
5. Repeat many time for many different signals s to get median significance of signal

Sudden Appearance of an Excess Region

- If we inject a signal $R \rightarrow R + s$ how does this manifest in terms of counts?
  - Recall we want to inject the signal into a local sky-map

$$\mu \rightarrow (I + s)\mathcal{N}\mathcal{A} \qquad \mathcal{N}\mathcal{A} = B \qquad \mu \rightarrow \mu + sB$$

$$\mathcal{L}(n|I,\mathcal{N},\mathcal{A}) = \prod_{\tau i} \frac{(\mu_{\tau i})^{n_{\tau i}} e^{-\mu_{\tau i}}}{n_{\tau i}!} \longrightarrow$$

We maximize the likelihood ratio:

$$\lambda = \frac{\mathcal{L}(n|I,\mathcal{N},\mathcal{A})}{\mathcal{L}(n|I^{(0)},\mathcal{N}^{(0)},\mathcal{A}^{(0)})}$$

Steps to make artificial local sky-maps:

1. Reconstruct one month of data from burn sample (arbitrarily January 2012)
2. Determine MLE μ and MLE background B
3. $\mu \rightarrow \mu + sB$
4. Poisson fluctuate to get artificial local-sky maps

Sudden Appearance of an Excess Region