Searches for Time Variation in the TeV Cosmic-Ray Anisotropy

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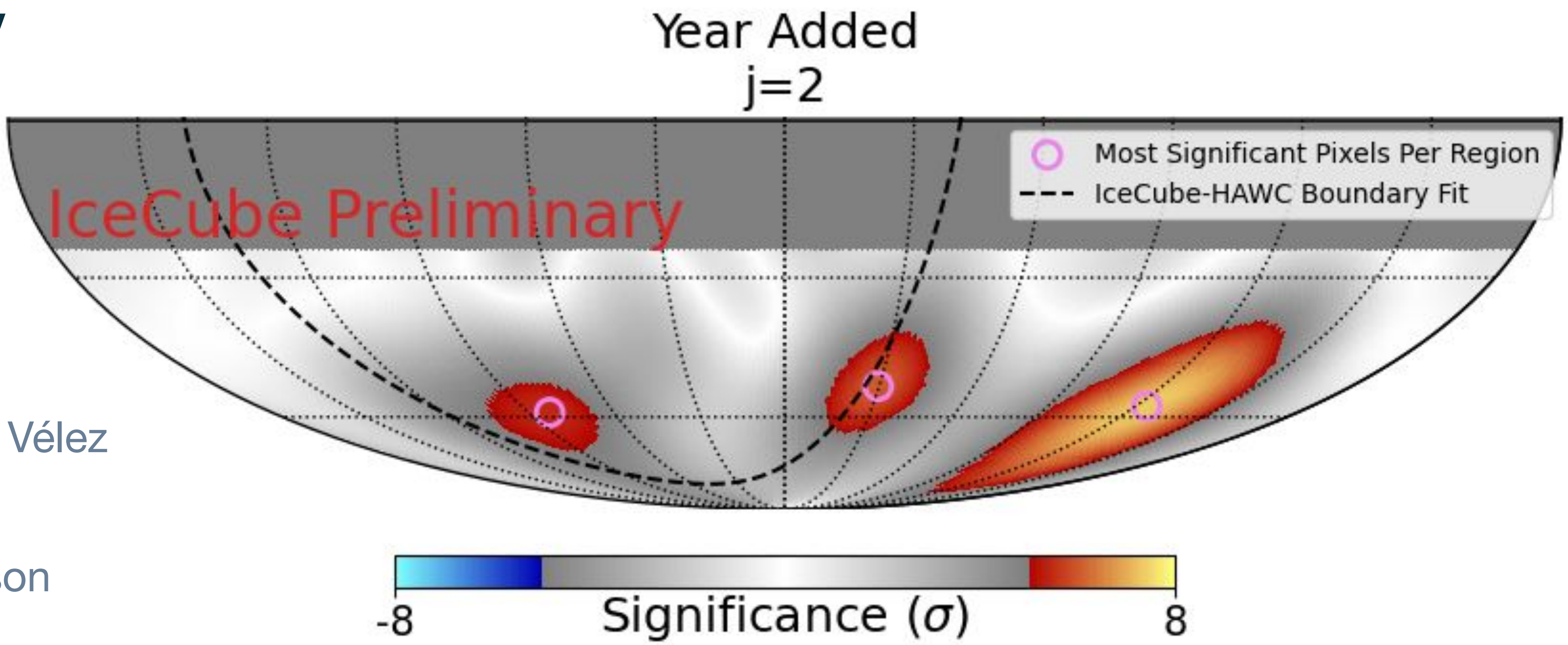
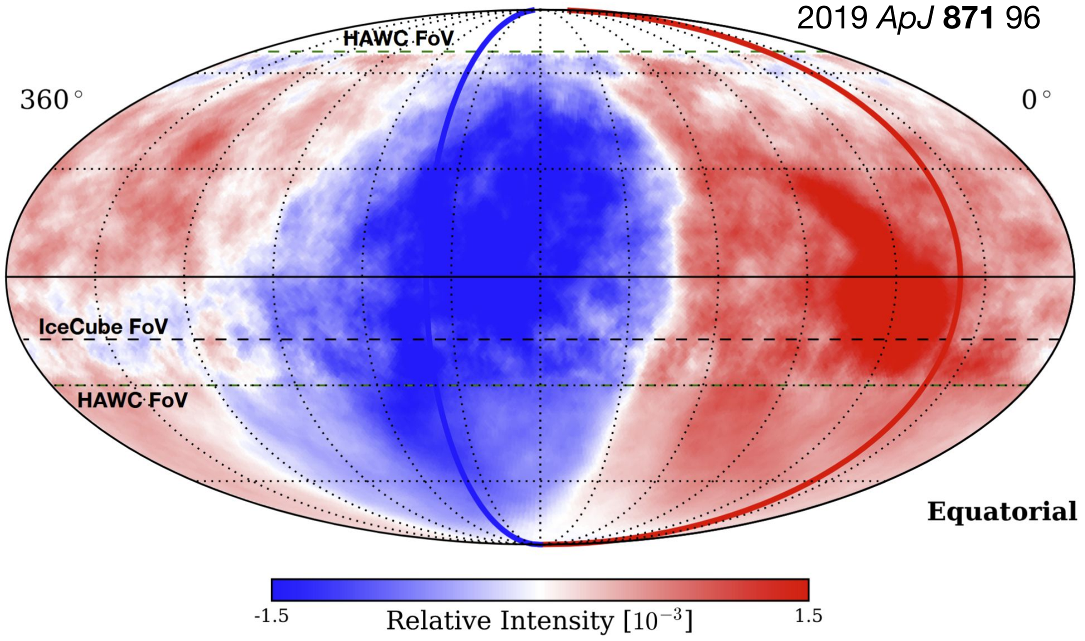


The Cosmic Ray Anisotropy (CRA)

- There is a well-known anisotropy in the arrival directions of TeV CRs
- Has been studied by a number of experiments*
    - Milagro
    - GRAPES-3
    - Tibet ASγ
    - LHAASO
    - HAWC
    - IceCube
- Small - maximum anisotropy of order 10^{-3}
- Has both large-scale and small-scale features
- Large-scale (dipole, quadrupole) features can be explained by diffusion in the Interstellar Medium (ISM)

**This is not an exhaustive list*

A. U. Abeysekara *et al* 2019 *ApJ* **871** 96



$$I = \frac{N}{\langle N \rangle}$$

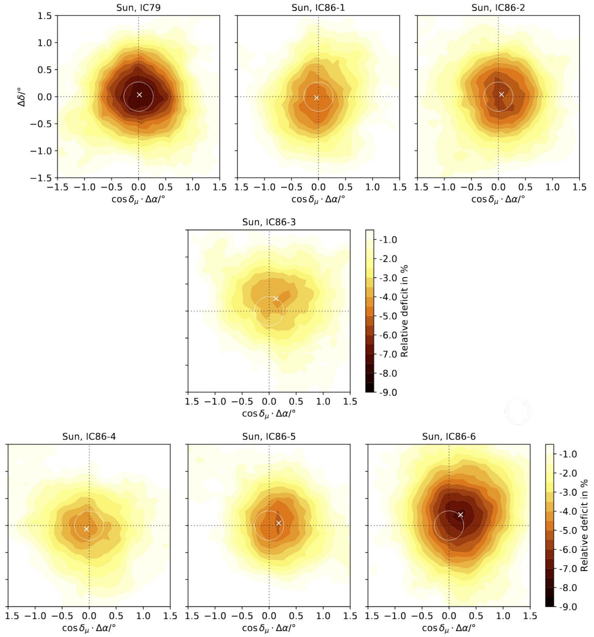
→ Measured Counts

→ Expected Counts Assuming Isotropic Flux

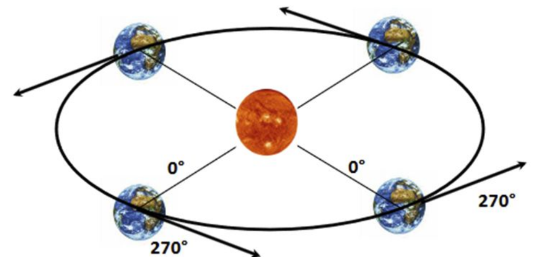
$$\delta I = I - 1$$

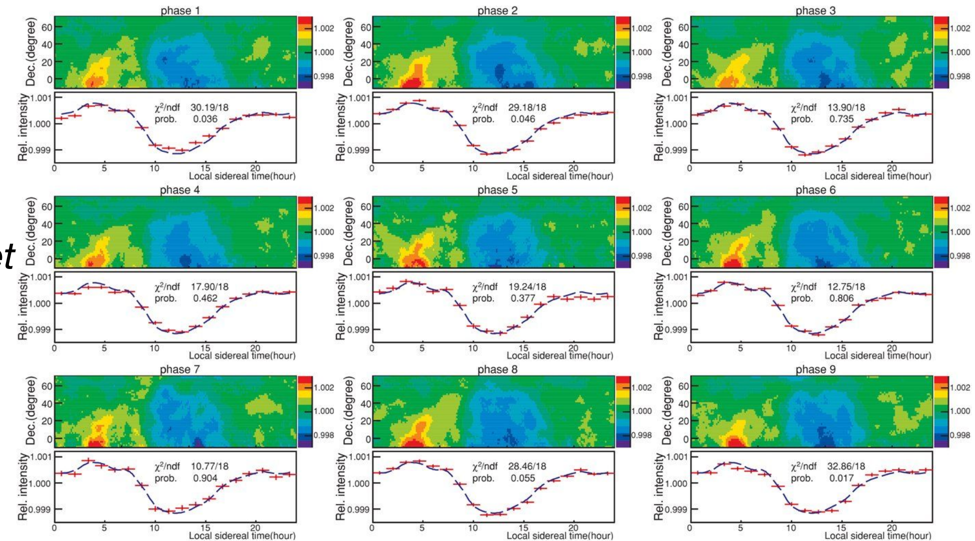
Cosmic Ray Anisotropy Time Dependence

- Does this map change in time?
- Several known time-variations:
  - Sun / Moon Shadow
    - Cosmic ray deficit in direction of Sun / Moon
  - Compton-Getting Effect / Solar Dipole
    - Dipole excess in direction of Earth's velocity around Sun
- Previous studies looked time-variations of the large-scale features (not due to the solar dipole), but found no evidence for it
- Time variations can take any form, across any angular or temporal scale
- Global modulation in the heliospheric magnetic field might lead to changes in cosmic ray arrival distribution



Abbasi *et al.* 2021 *Phys. Rev. D* **103** 042005





M. Amenomori *et al* 2010 *ApJ* **711** 119

The Goal

Search for time variation in the TeV cosmic ray anisotropy across all angular scales in a model-independent way

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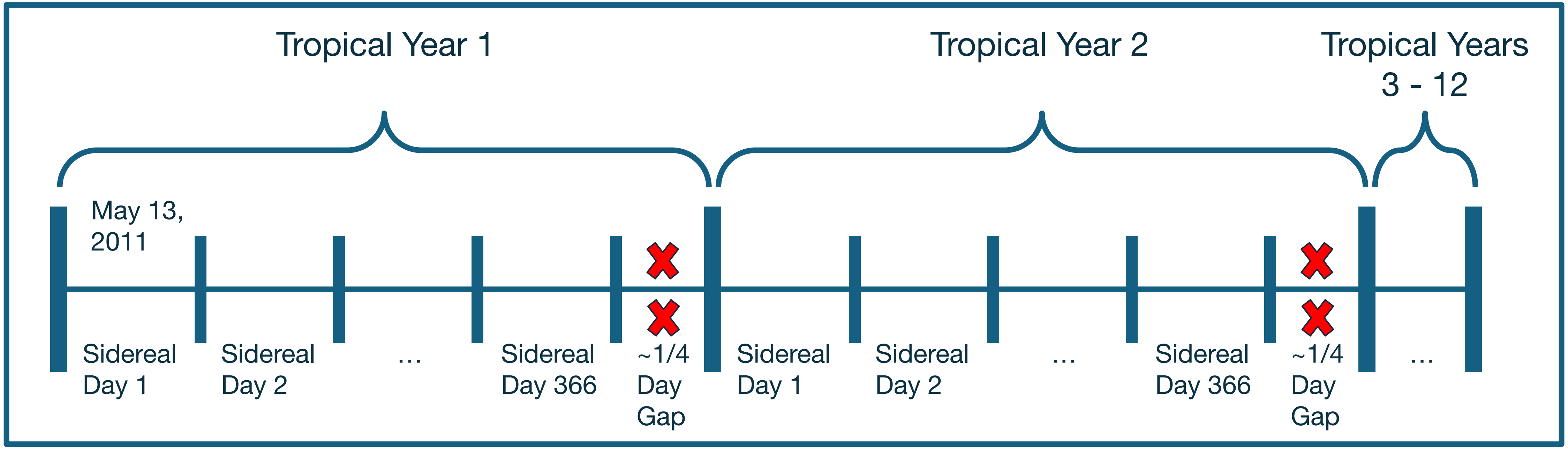
Search for time variation in the TeV cosmic ray anisotropy across all angular scales in a model-independent way

Do this by:

1. Creating a methodology which can detect known time variations without explicitly searching for them
2. Apply this to anisotropy sky-maps without known time variations

Time Binning



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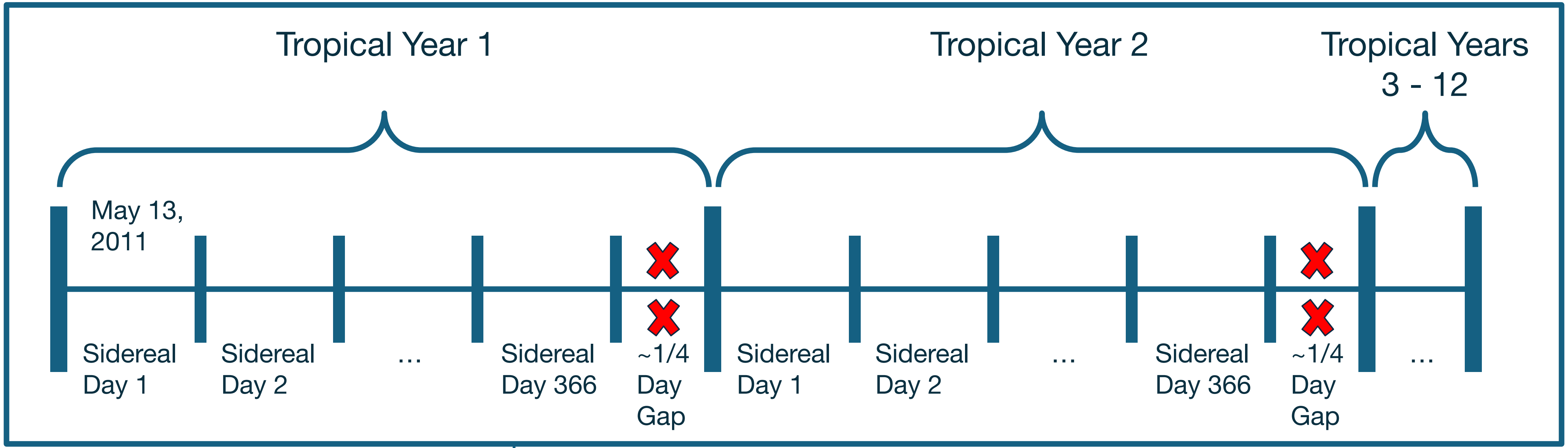
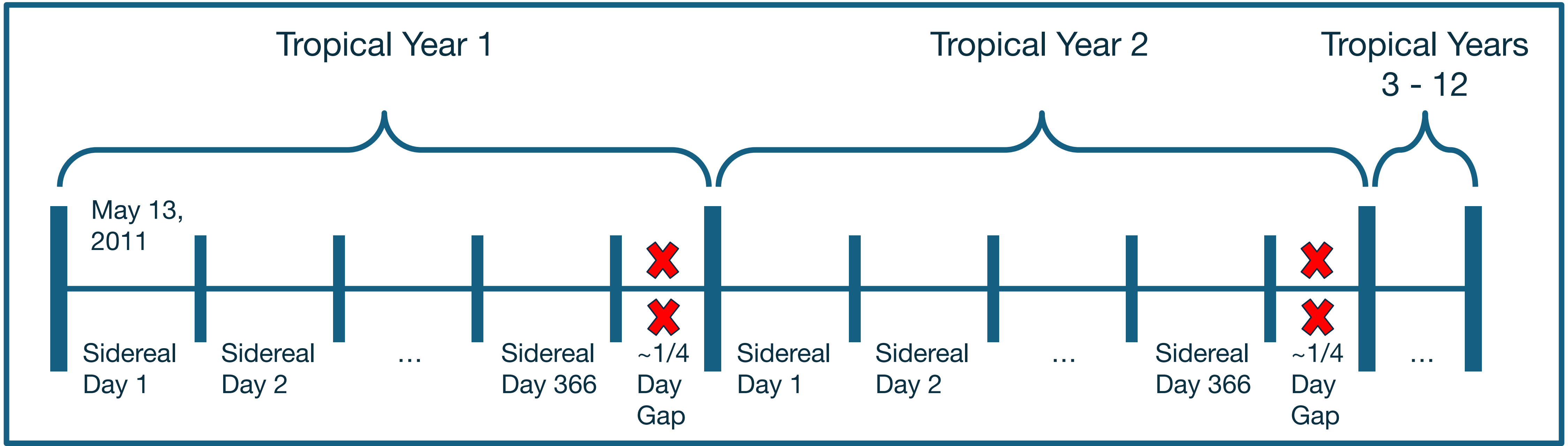


<u>Fold every tropical year onto each other:</u>

- Our "year folded" data set
- Cut at -10° dec
- Emphasizes signals with one year periodicity
  - Solar dipole and Sun Shadow
- **Used for calibration and verification**

Time Binning



<u>Fold every tropical year onto each other:</u>

- Our “year folded” data set
- Cut at -10° dec
- Emphasizes signals with one year periodicity
    - Solar dipole and Sun Shadow
- **Used for calibration and verification**

<u>Add every map within a given tropical year</u>

- Our “year added” data set
- Cut at -25° dec
- Solar dipole averaged out
- Sun shadow cut
- **Use to search for time variations of astrophysical origin**

A Representative Data Set

- For the purpose of **illustrating** our methodology, we will **first consider a burn sample** consisting of every January from 2012 - 2023
  - Sidereal days 234 - 264 in our time binning

- Easier to look at 30 days compared to 366
- Sun is in our field of view throughout these time periods
  - Increases Sun Shadow signal
- Solar Dipole is still visible

- Once the methodology is illustrated, we will **show results obtained using entire data set**

A Model Independent Test

- If there is no time variation in $\delta I(\theta, \phi, t)$ then

$$\delta I(\theta, \phi, t) = \delta I(\theta, \phi) \ \forall \theta, \phi, t$$

- For a pixelated sky (for equatorial pixels *i*)

$$\delta I_{it} = \delta I_i \ \forall i, t$$

- The simplest approach: just fit the above!
- Covariance between measurements
  - Use generalized least squares
- Essentially fit mean relative intensity per pixel on the sky:

$$\delta I_{it} = \hat{\delta I_i} = \langle \delta I_i \rangle$$

- Obtain residuals per pixel and time slice:

$$r_{it} = \delta I_{it} - \langle \delta I_i \rangle$$

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The Null Hypothesis:

$$H_0 : r_{it} = 0$$

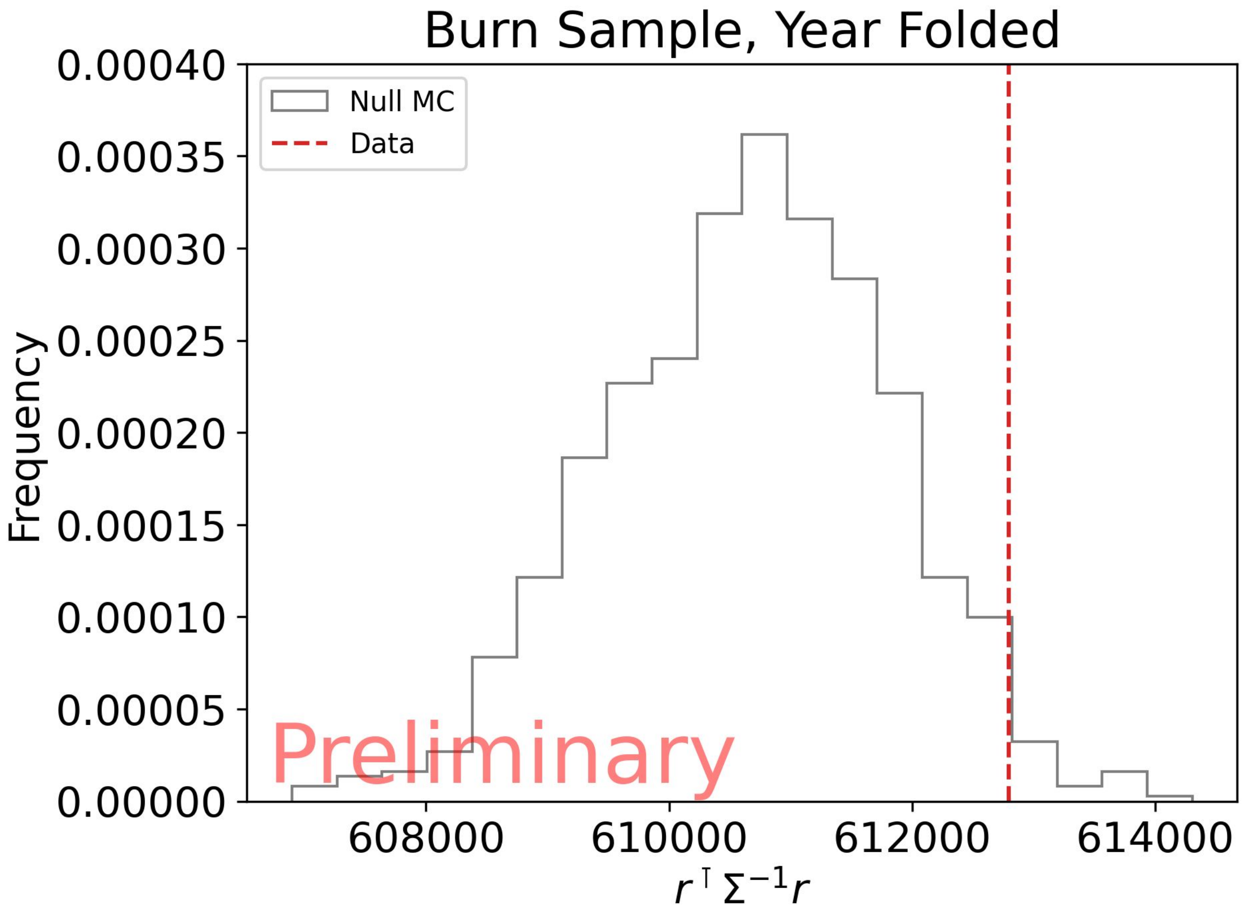
A General Goodness-of-Fit Test

- Let's look at the year folded set
- We know there are signals in this set
- As a general catch-all test, can look at the goodness of fit
- Generalized least square minimizes the generalized χ^2 statistic

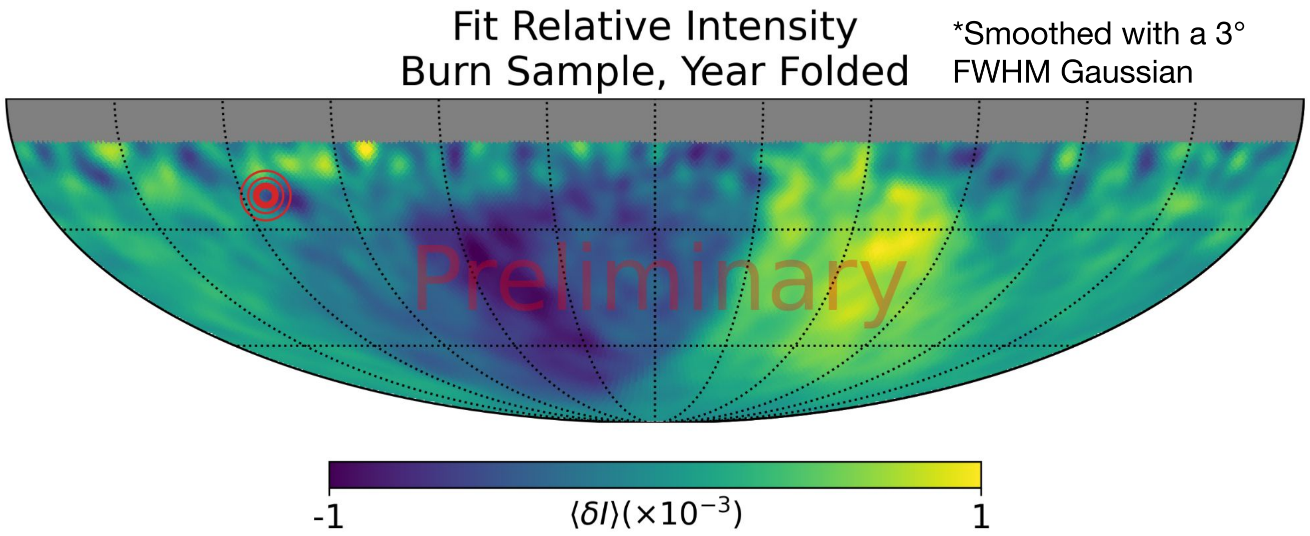
$$\chi^2_{\text{generalized}} = r^\intercal \Sigma^{-1} r$$

- Where Σ is the covariance matrix of δI_{it}

- p-value: 0.022



Looking at One Pixel



*Smoothed with a 3° FWHM Gaussian

Looking at One Pixel

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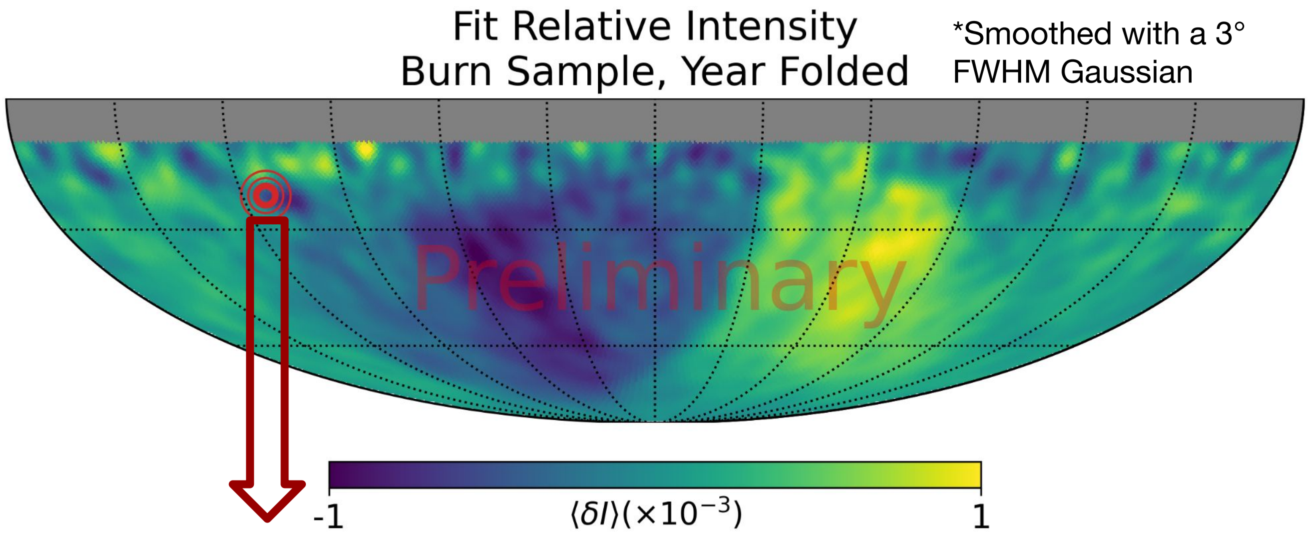

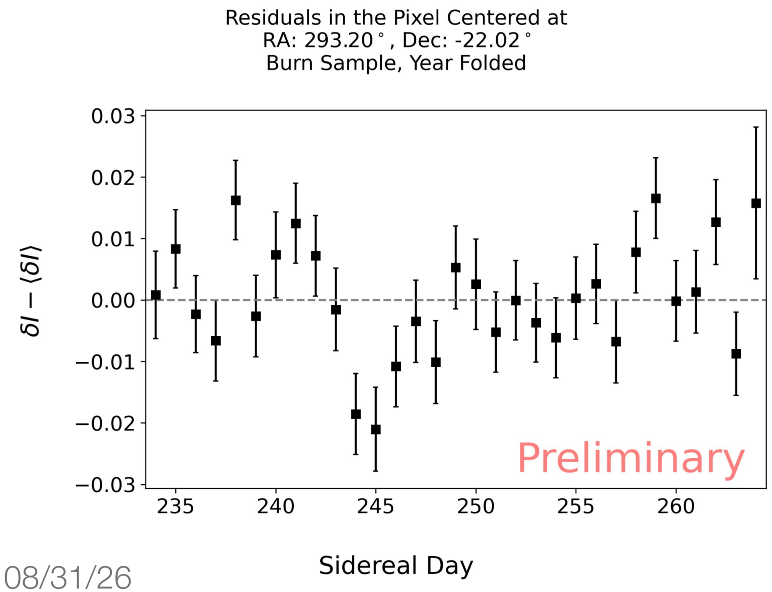

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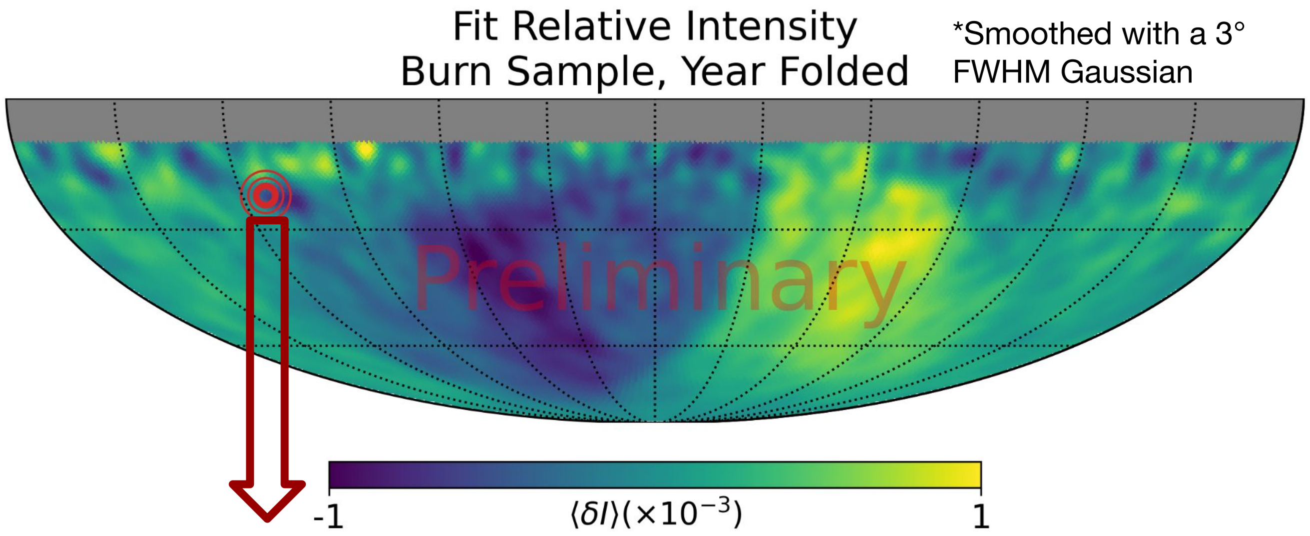

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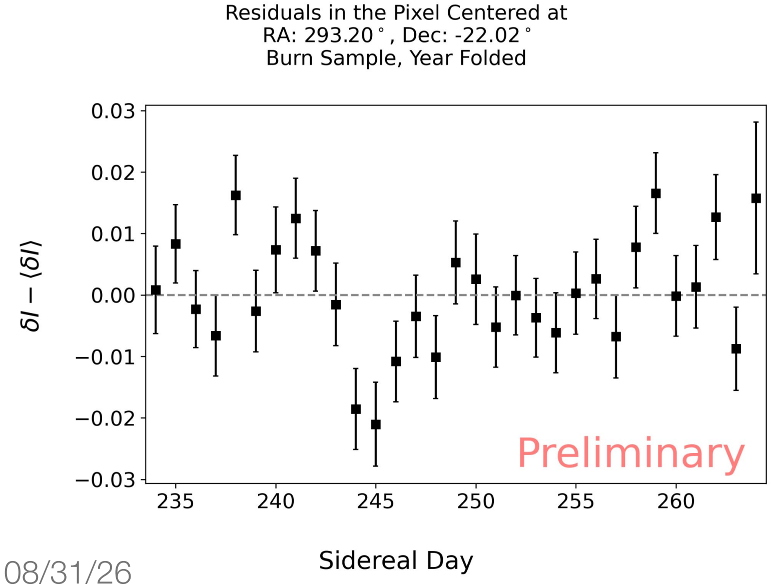

Get goodness of fit

$$\chi^2 = \sum \left(\frac{r}{\sigma_r} \right)^2$$

Looking at One Pixel

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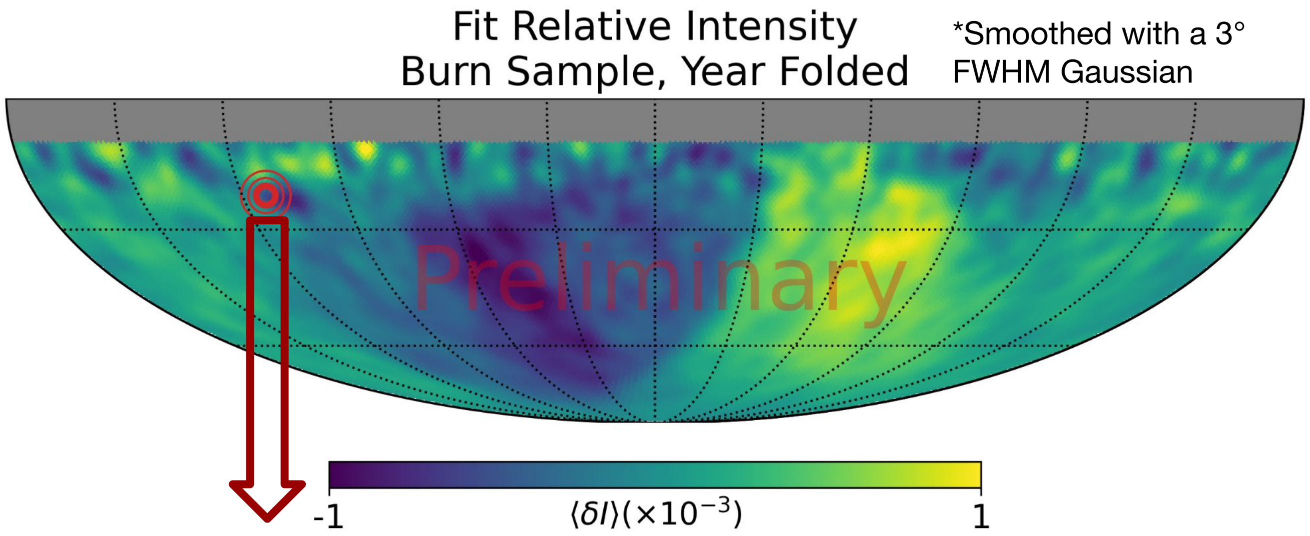
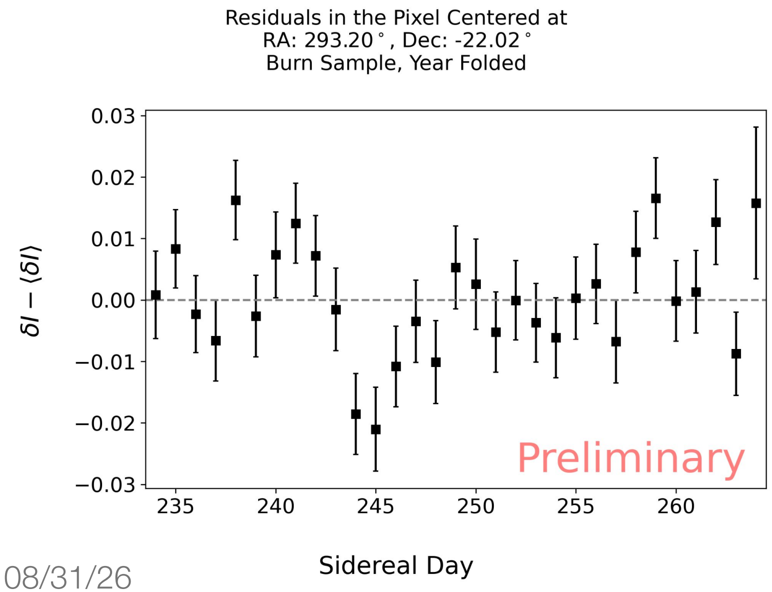




Get goodness of fit

$$\chi^2 = \sum \left(\frac{r}{\sigma_r}\right)^2$$

$$\chi^2 = 56.34$$

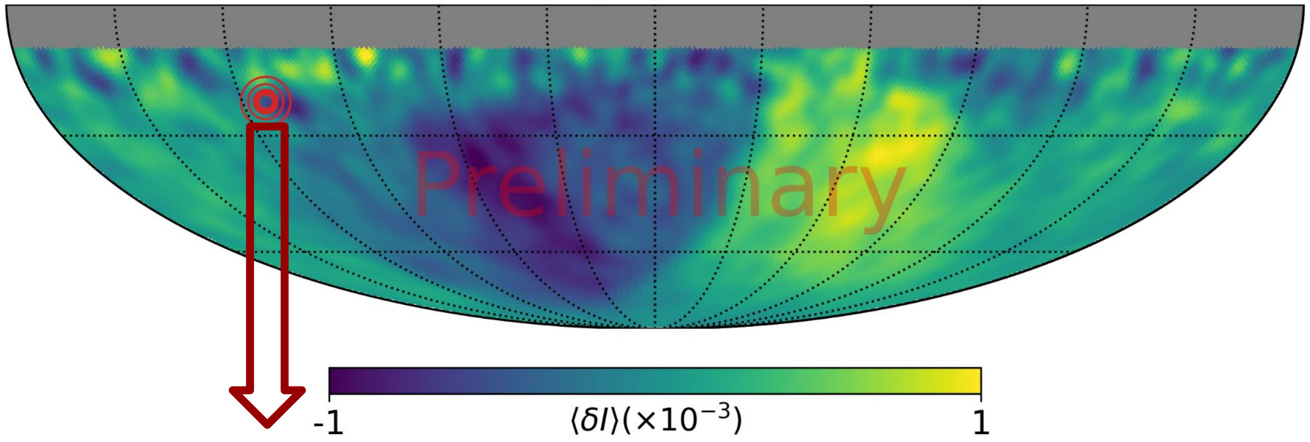
~30 dof

Local p-value: 0.002

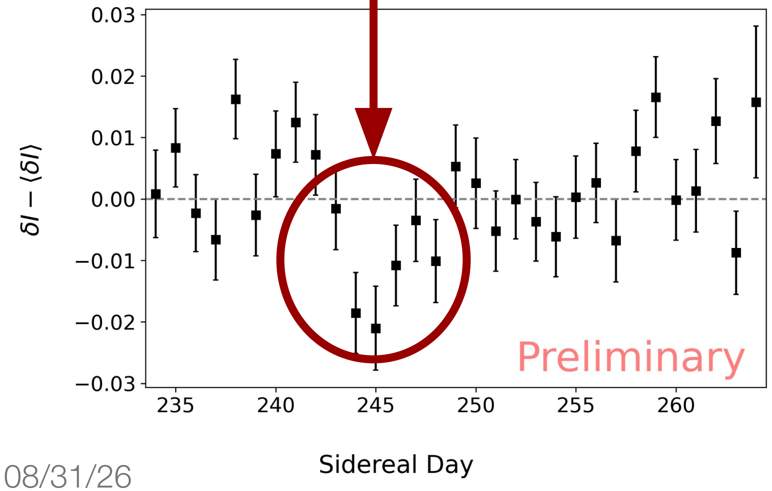
Looking at One Pixel

Fit Relative Intensity
Burn Sample, Year Folded

*Smoothed with a 3° FWHM Gaussian



Residuals in the Pixel Centered at
RA: 293.20°, Dec: -22.02°
Burn Sample, Year Folded



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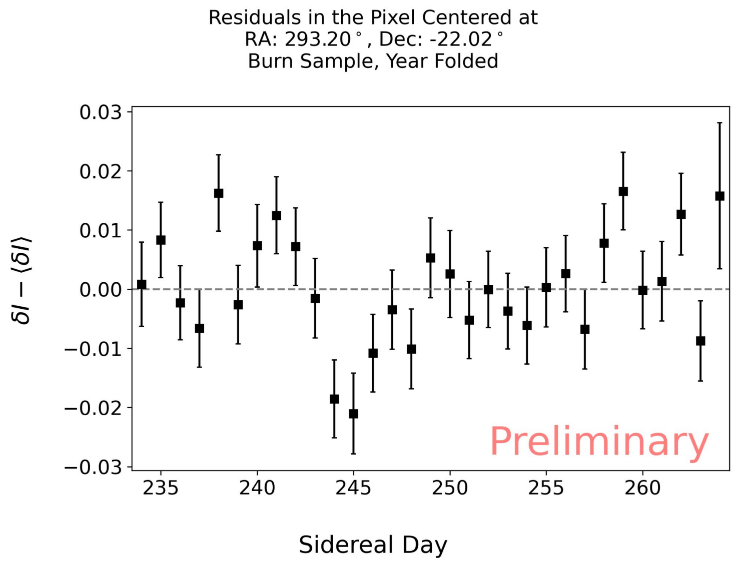
Largely driven by dip around sidereal day 245

Residuals Across the Sky



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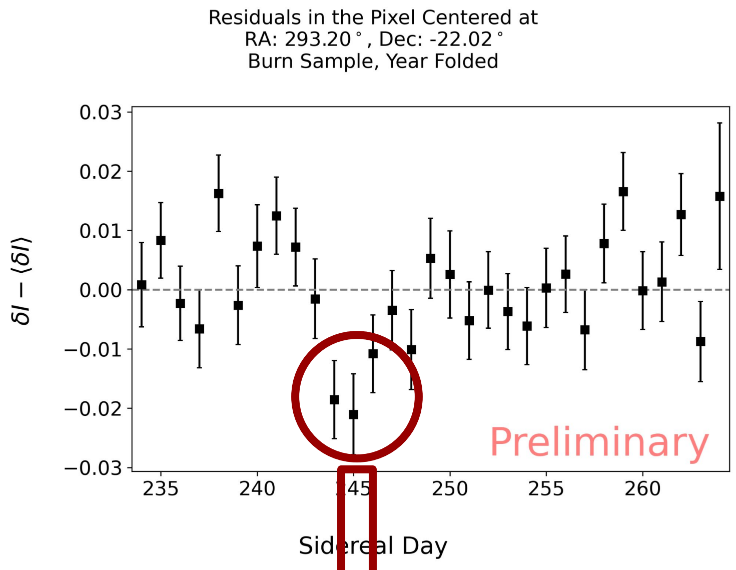
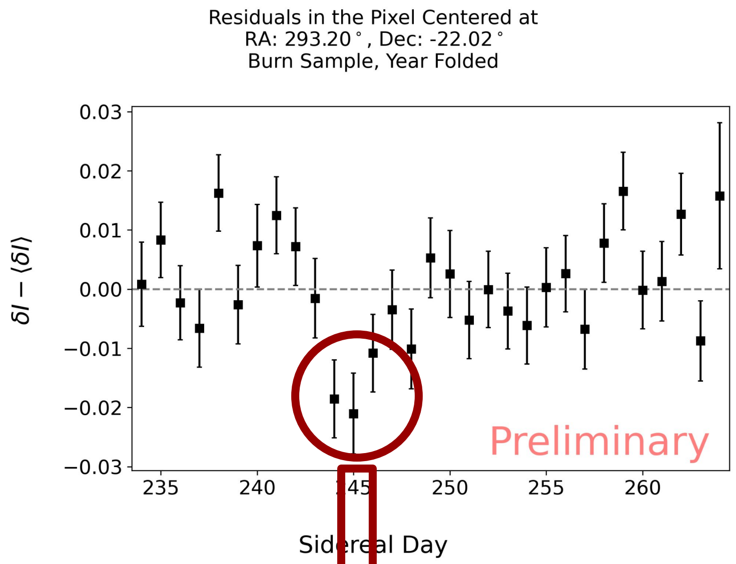


What do residuals across the rest of the sky look like at this point in time?

Residuals Across the Sky



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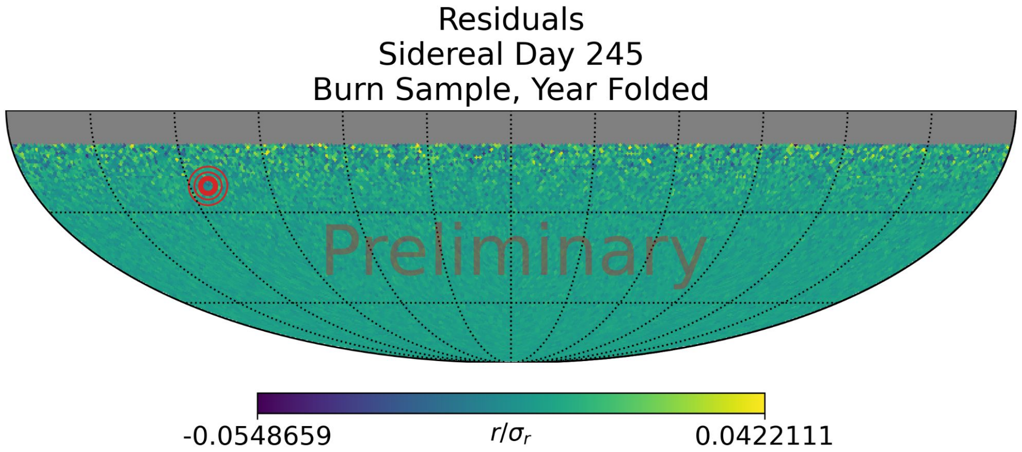

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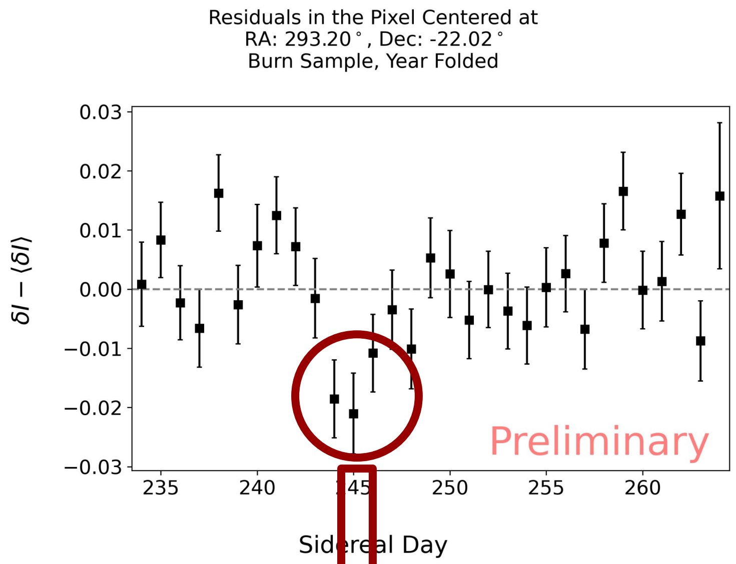

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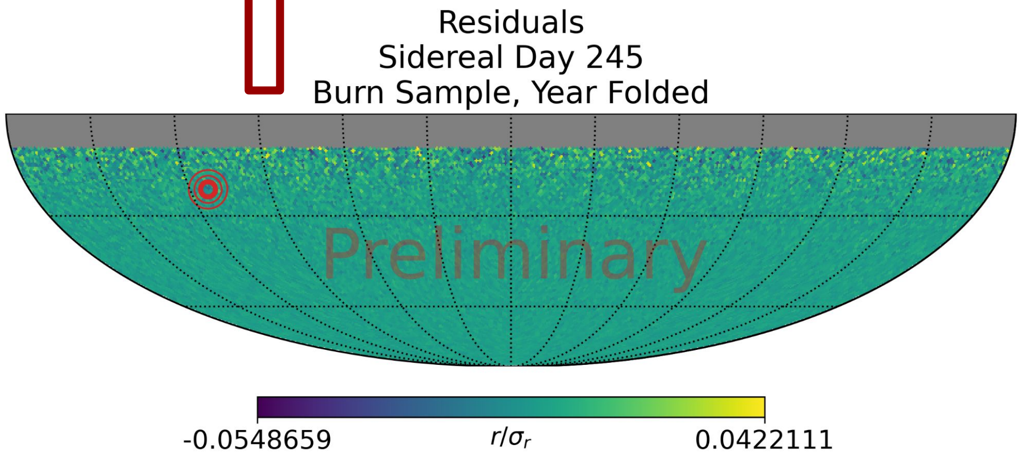
Large variation in residuals due to statistics - standardize the residuals



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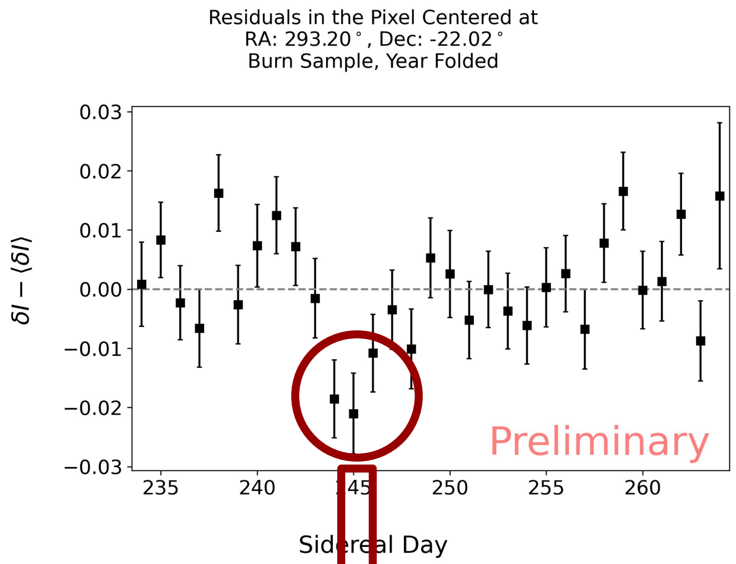

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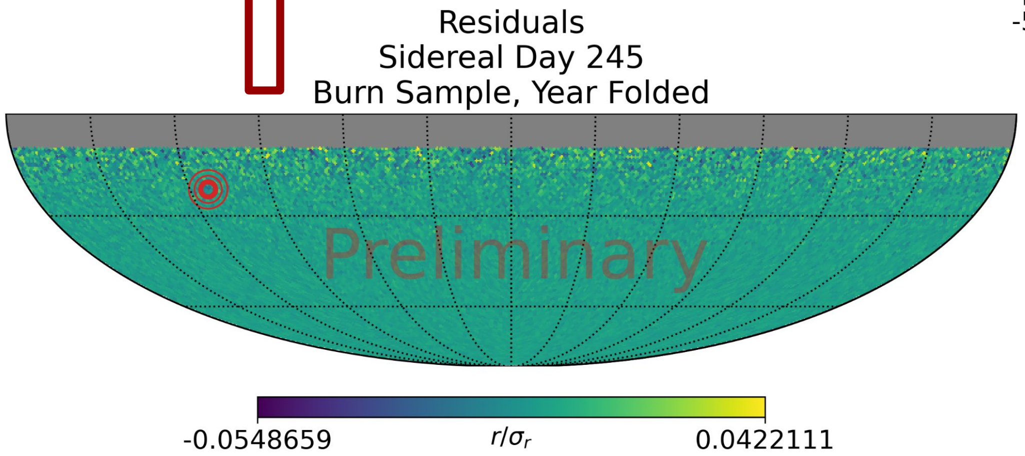

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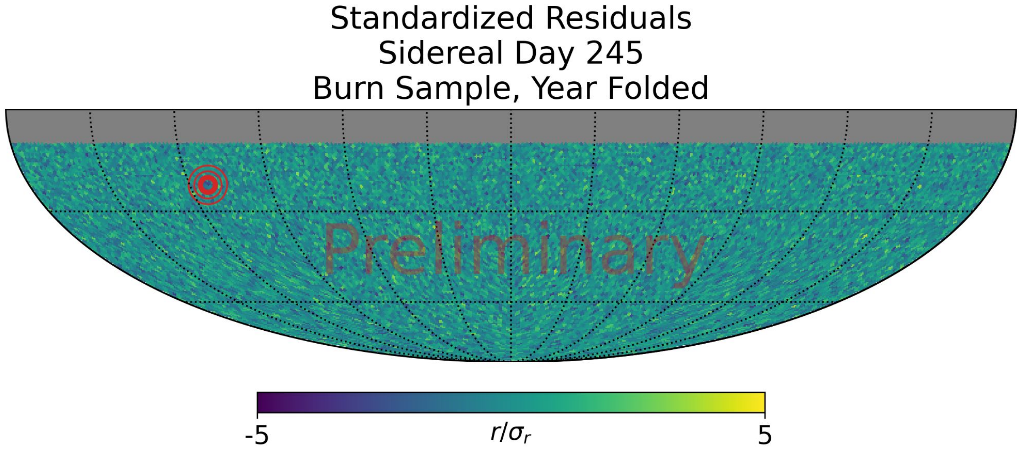

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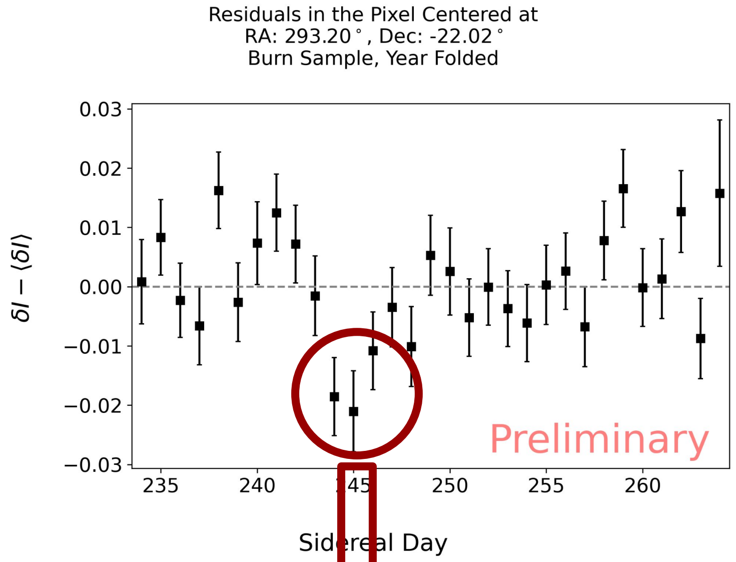

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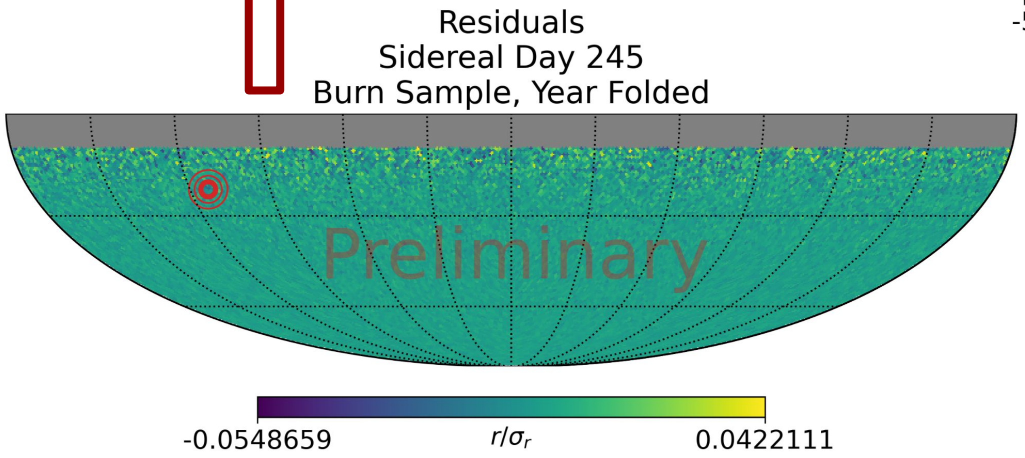

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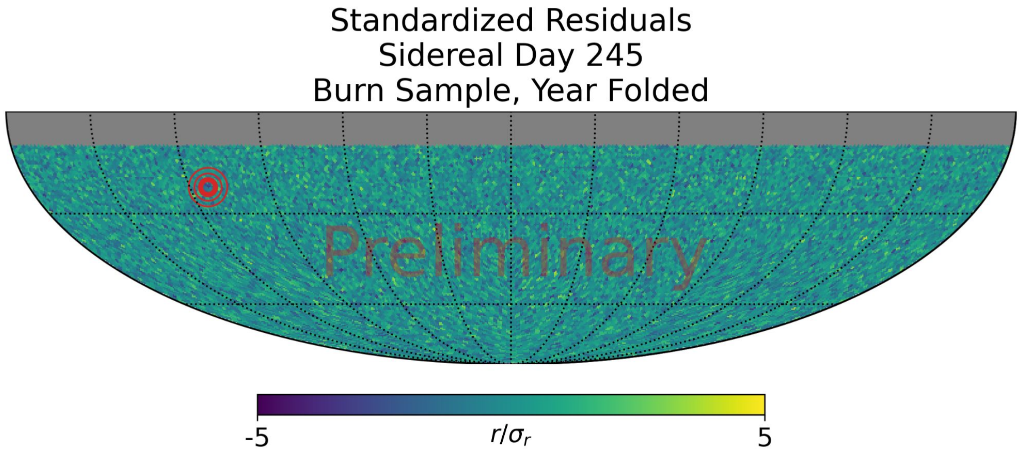
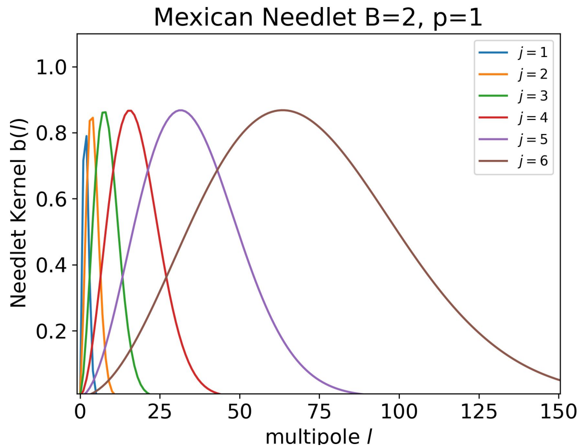
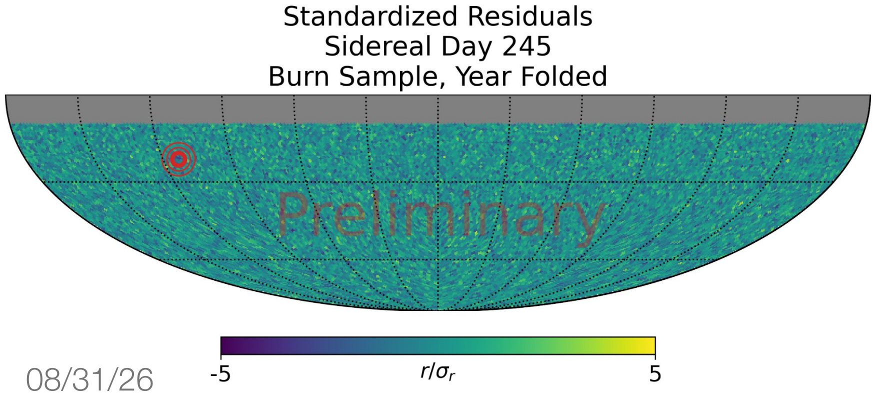


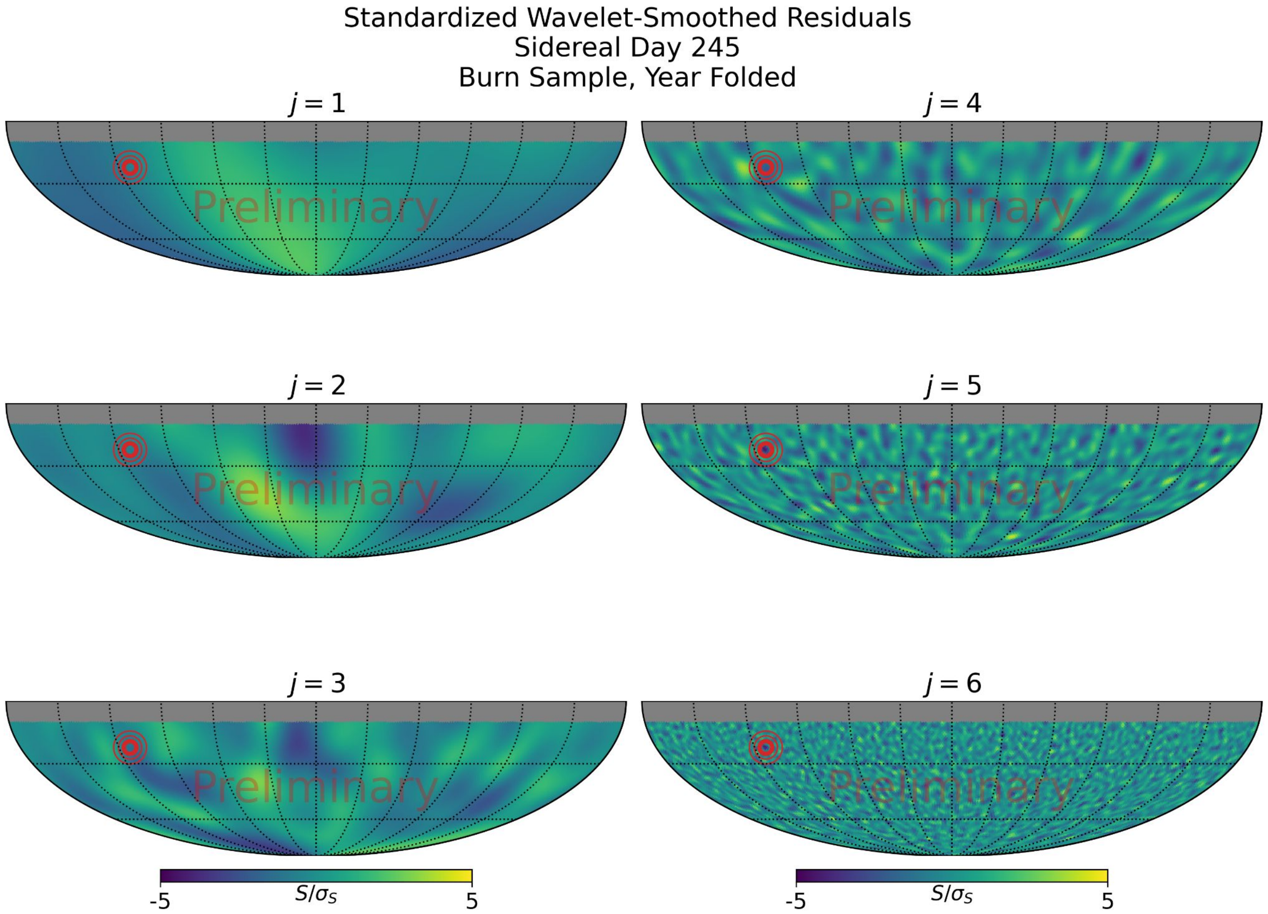
There is a local dip - to see if there is any angular structure smooth the standardized residual map

Smoothing the Residuals

- Smooth with Mexican needlets:
  - Probe 6 angular scales
  - Larger *j* probe smaller angular scales



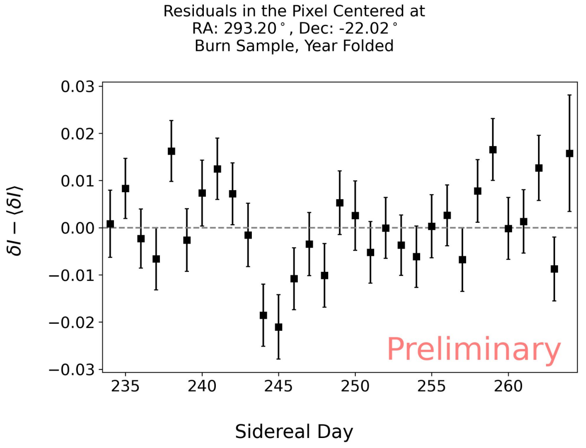


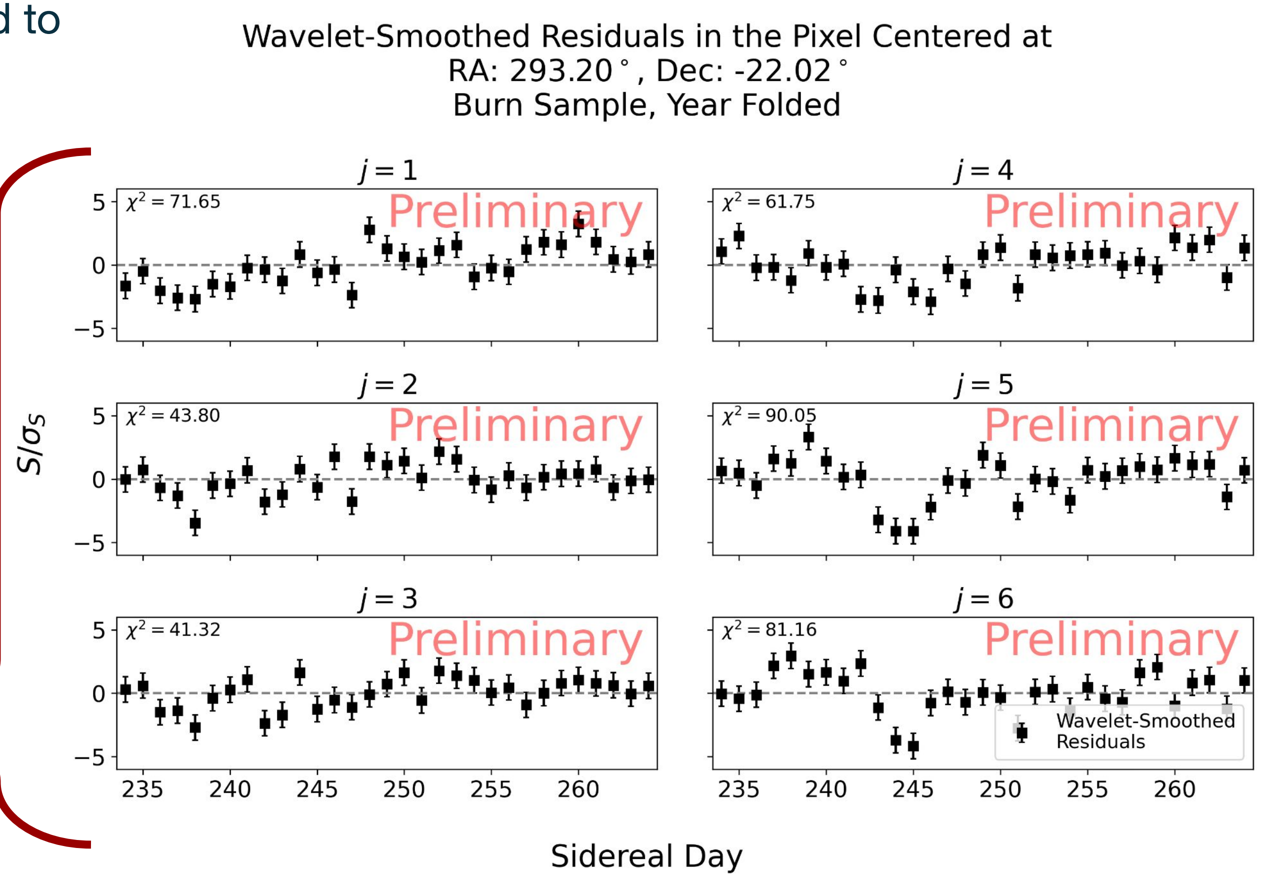


*Wavelet-smoothed residuals have been standardized to bring them to the same scale

Looking at One Pixel (Revisited)

- Do smoothing for all time bins and look at *scale-dependent* time series'
- See elevated signal at small-scale *j=4,5,6* compared to unsmoothed case ($\chi^2 = 56.34$)
- See elevated signal in large-scale *j=1*
- Small-scale and large-scale elevated signals qualitatively different
- small-scale:
  - Dip around sidereal day ~245
- large-scale:
  - Linearly increasing (linear fit preferred at 4σ)





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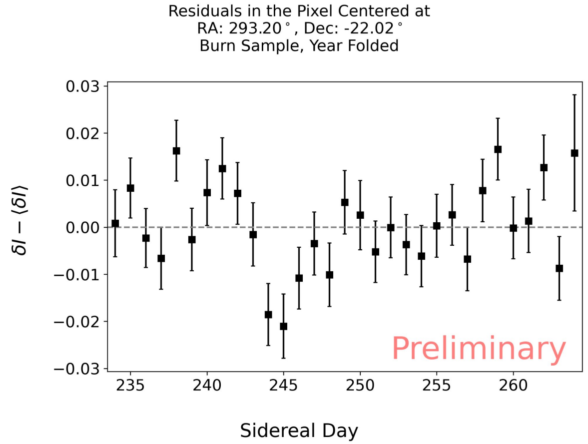

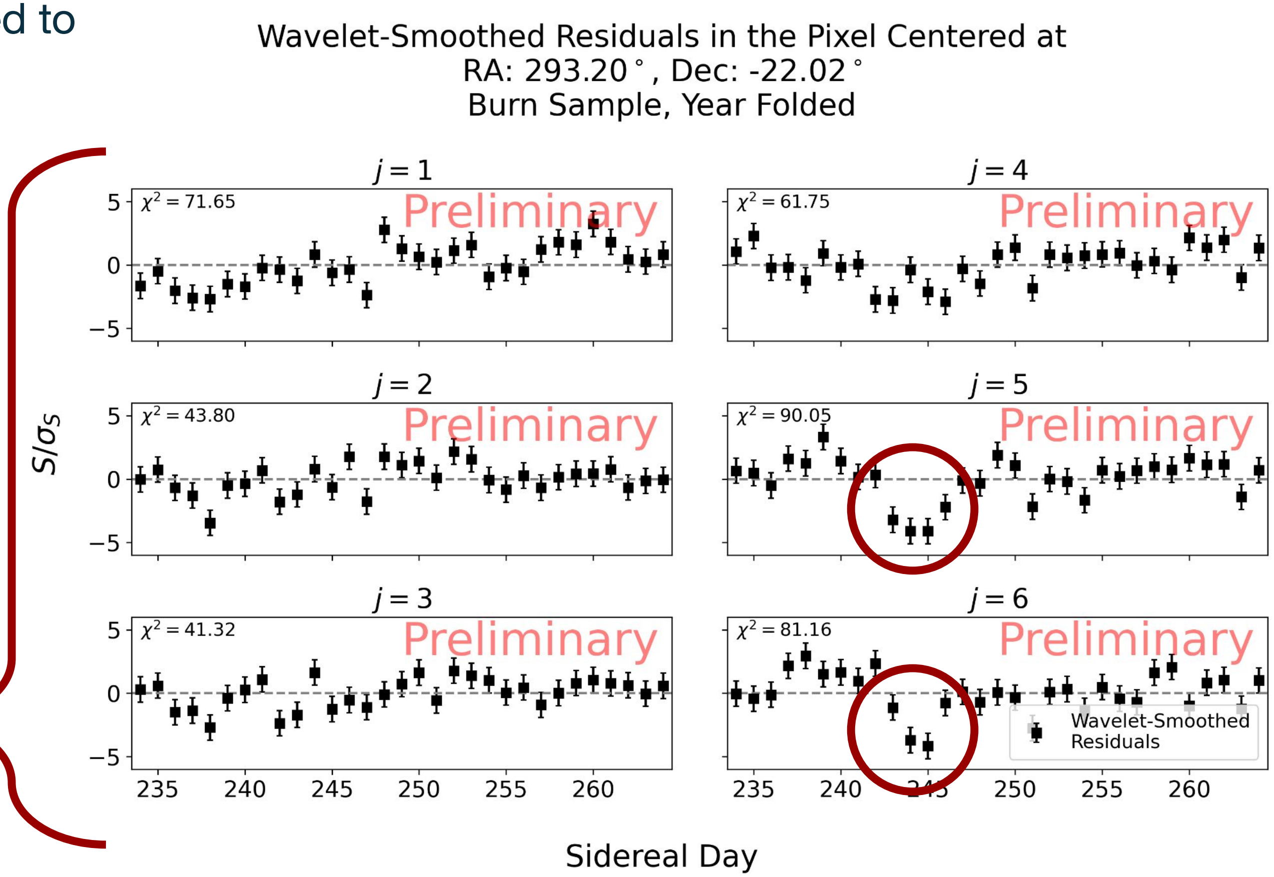

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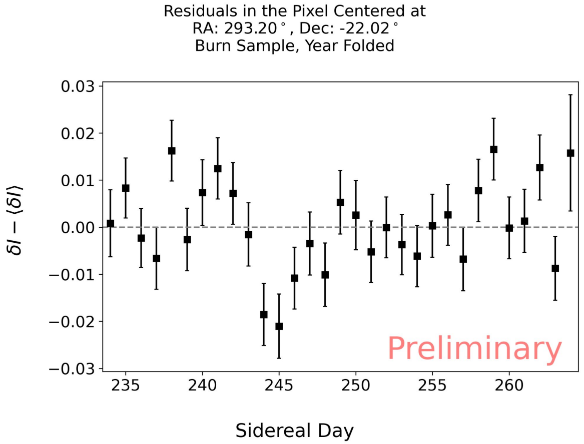

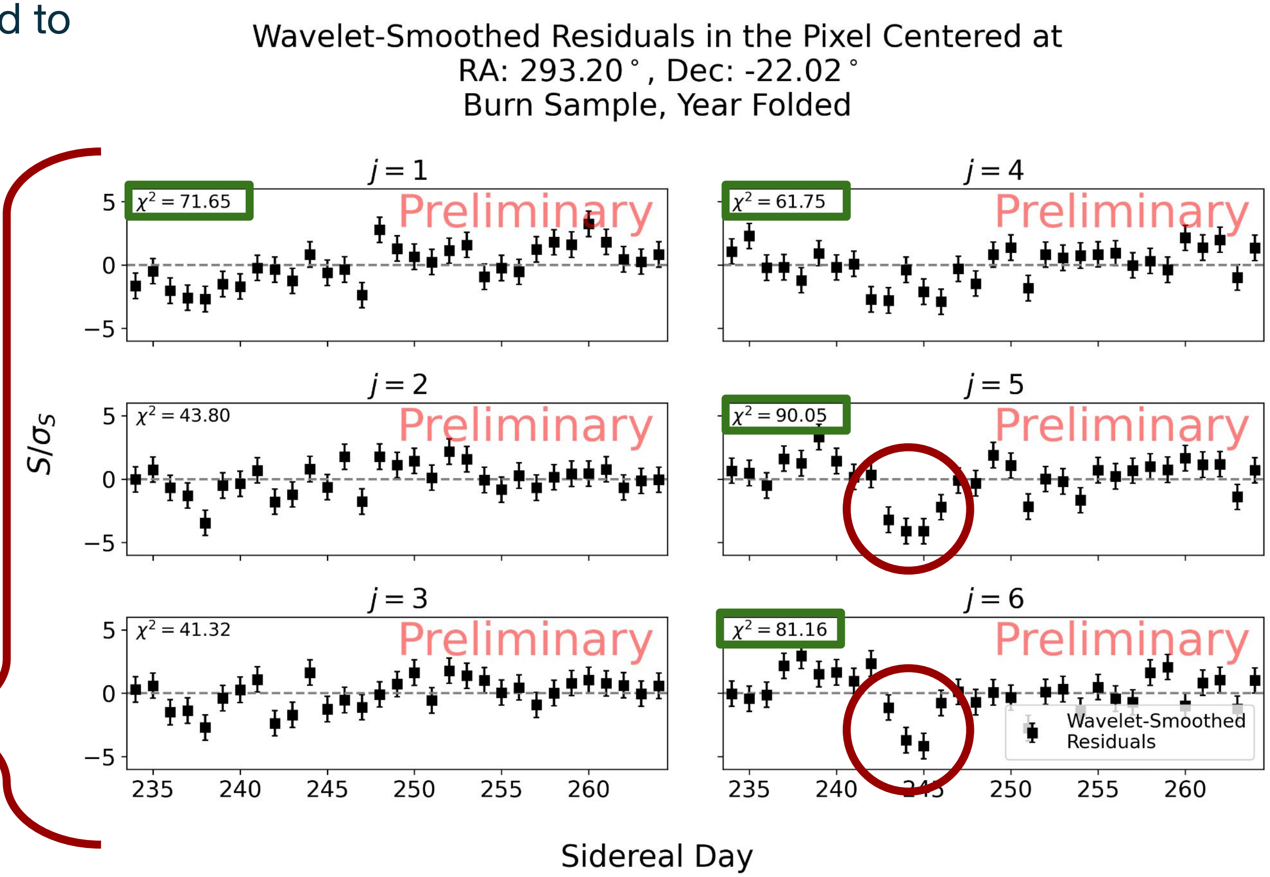

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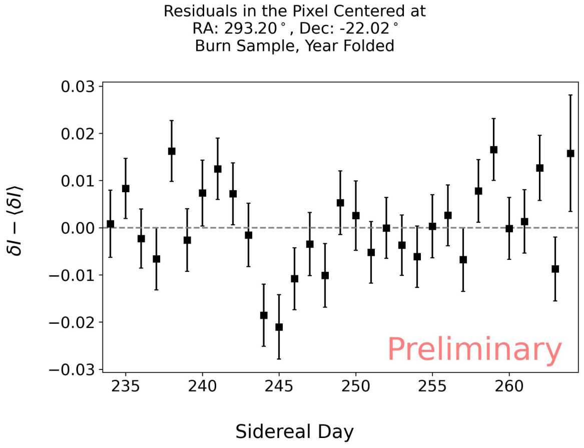
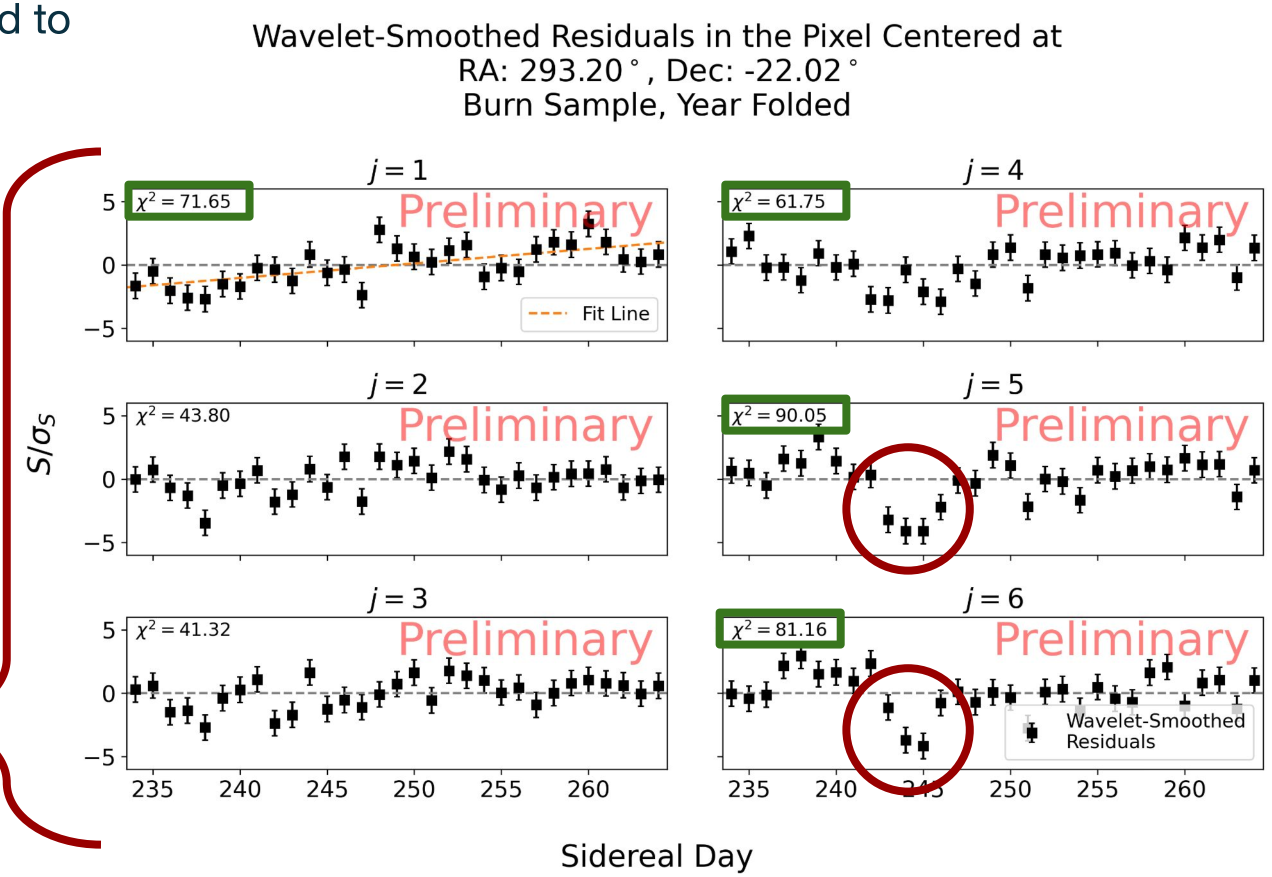
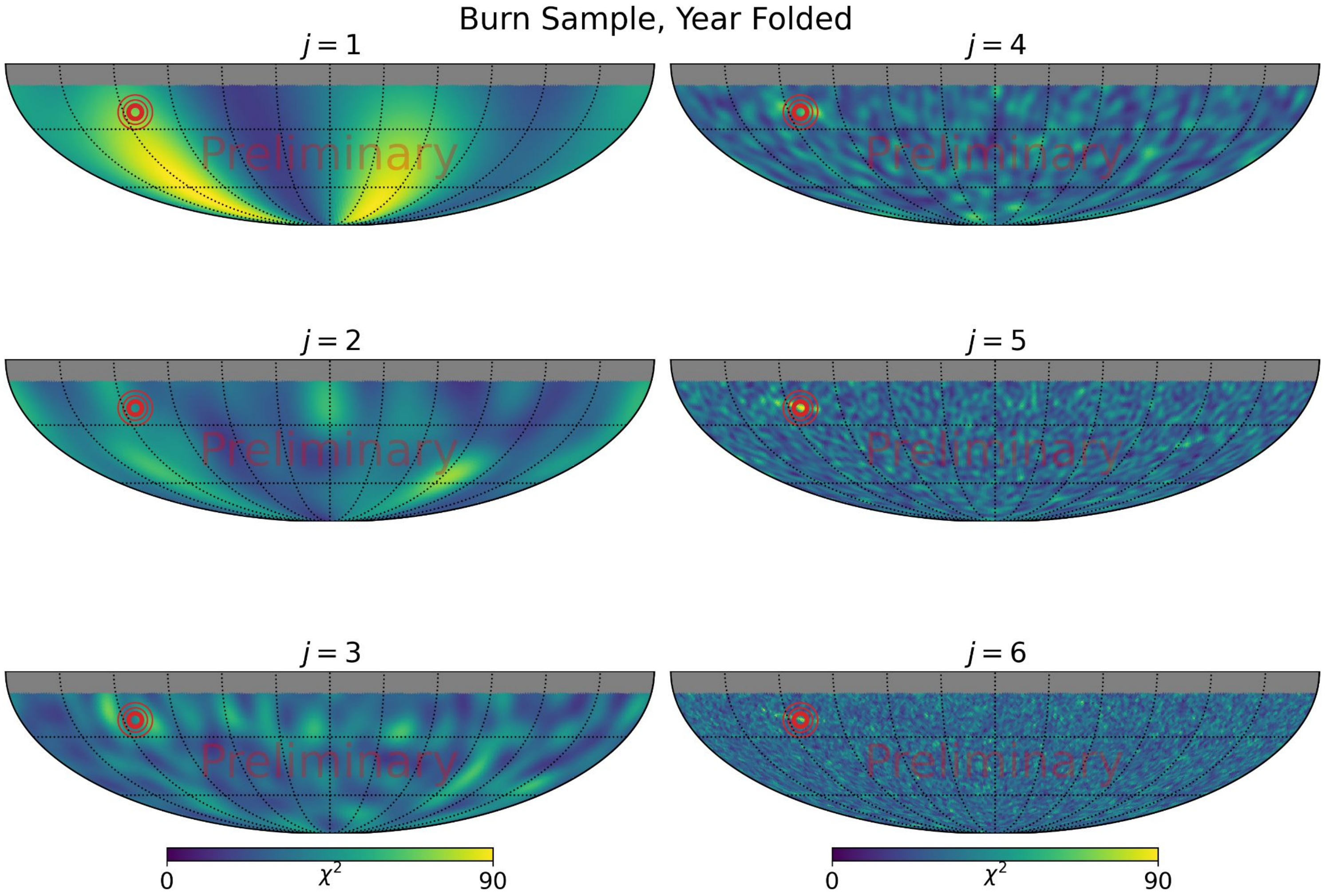




Full Sky Tests

- Performing equivalent procedure for all pixels shows exactly what we were seeing in the last slide:



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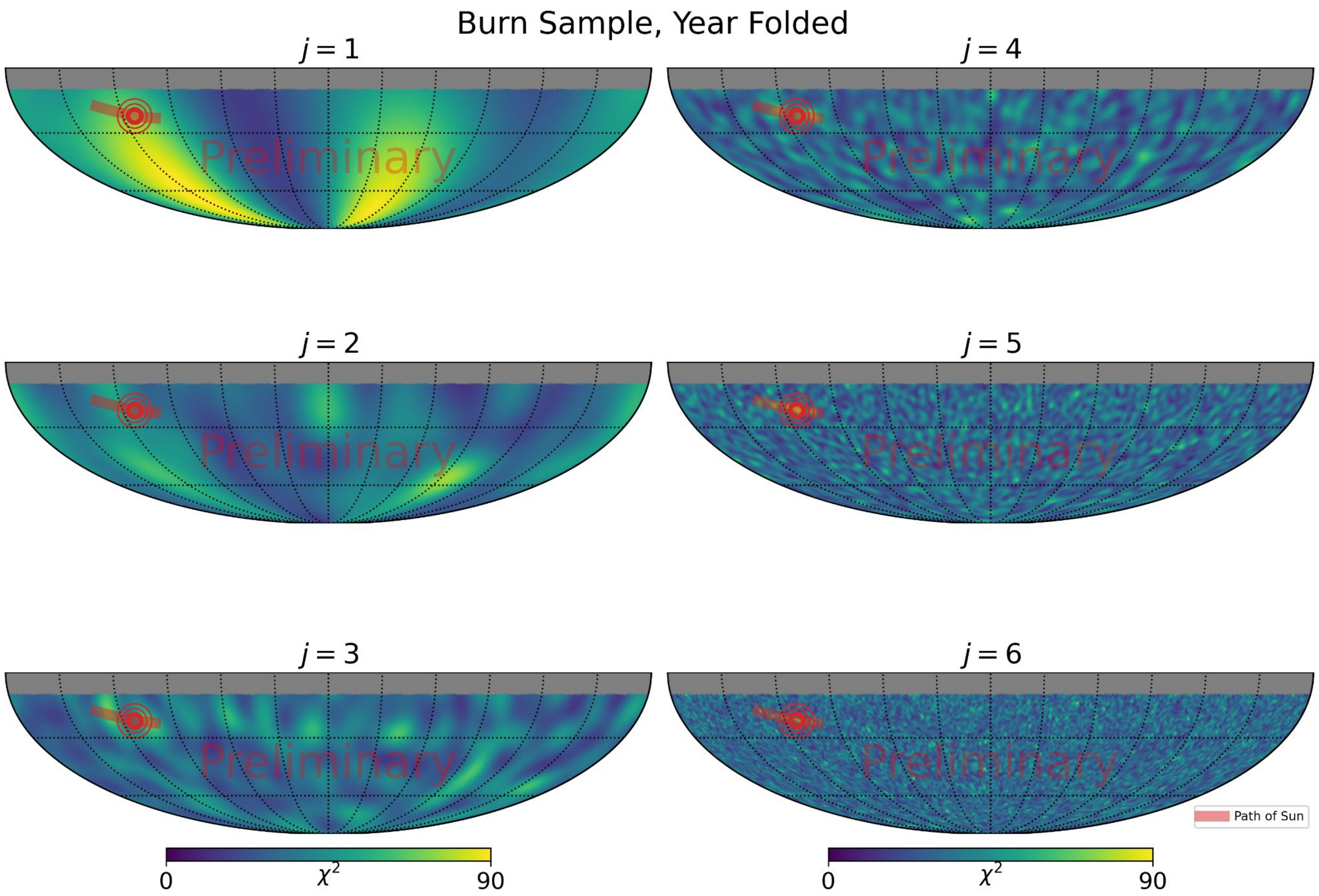

Full Sky Tests

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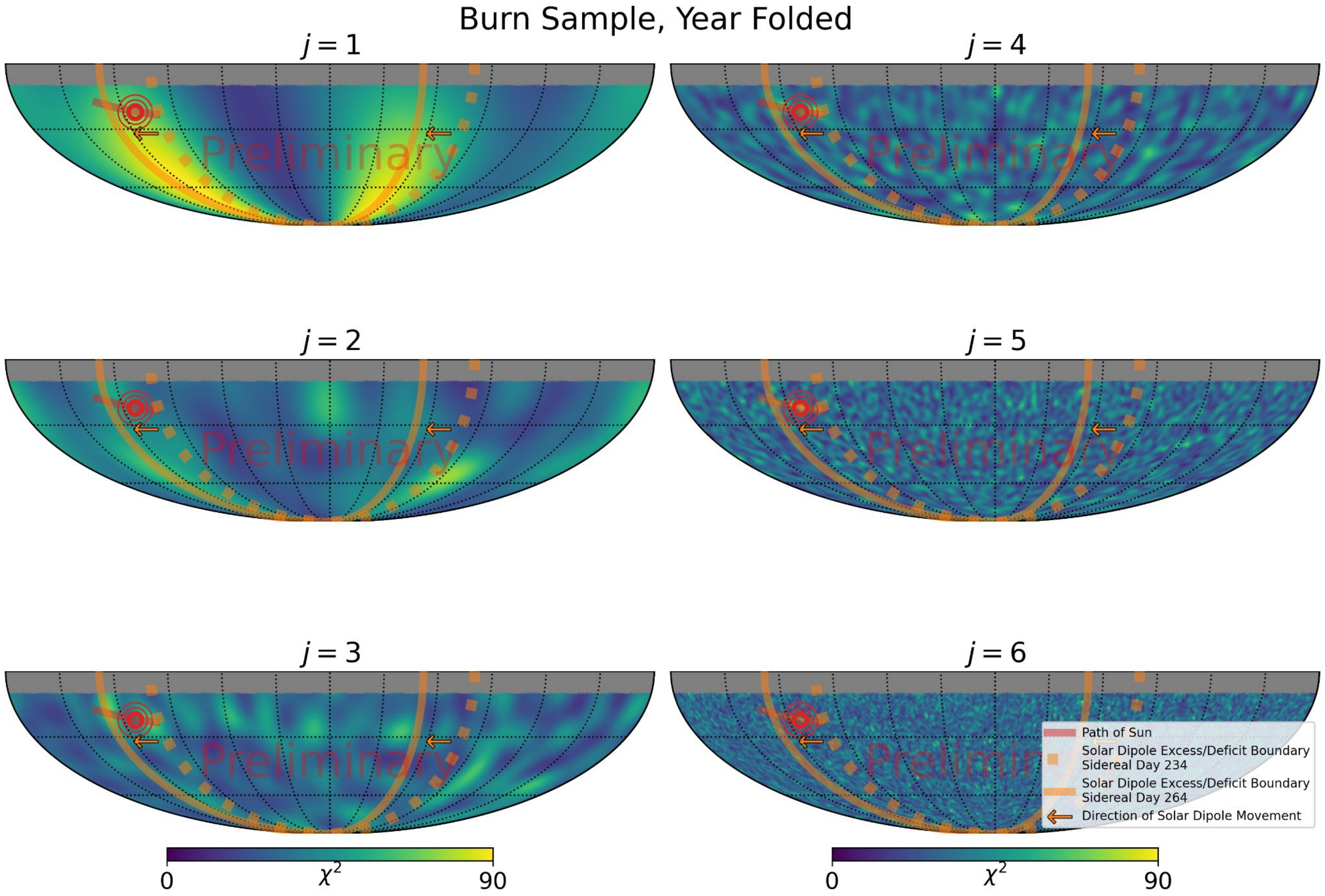
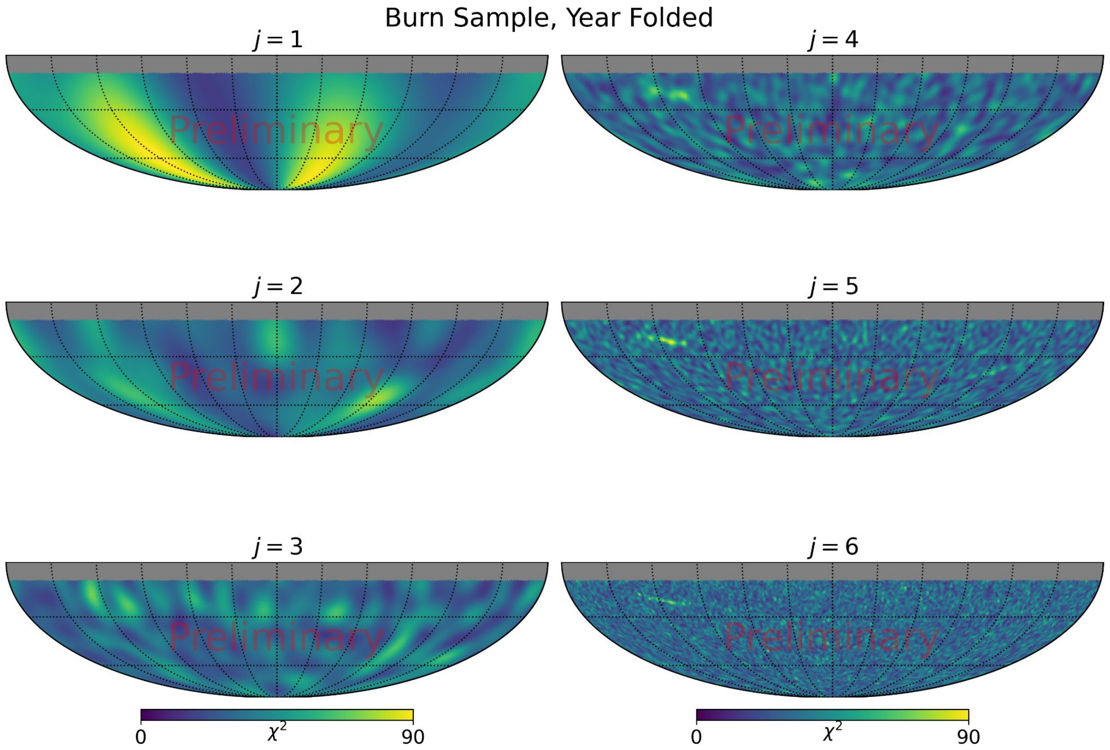
  - *j=4,5,6* scales show sun-shadow moving through our pixel, along the ecliptic
  - *j=1* scale shows solar dipole gradient moving across the pixel continuously

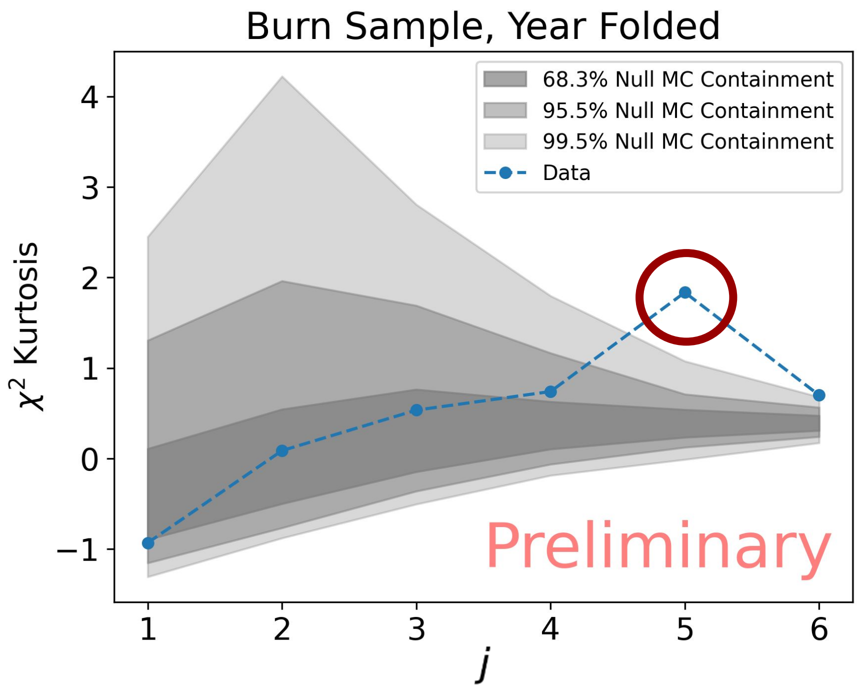


Perri Zilberman
CRA Time Variation

Full Sky Tests

- Create full-sky test statistics per map
- Find kurtosis of χ^2 distributions is a sensitive test statistic
- See strong signal at *j=5* - corresponding to the Sun shadow
    - p-value < 0.001

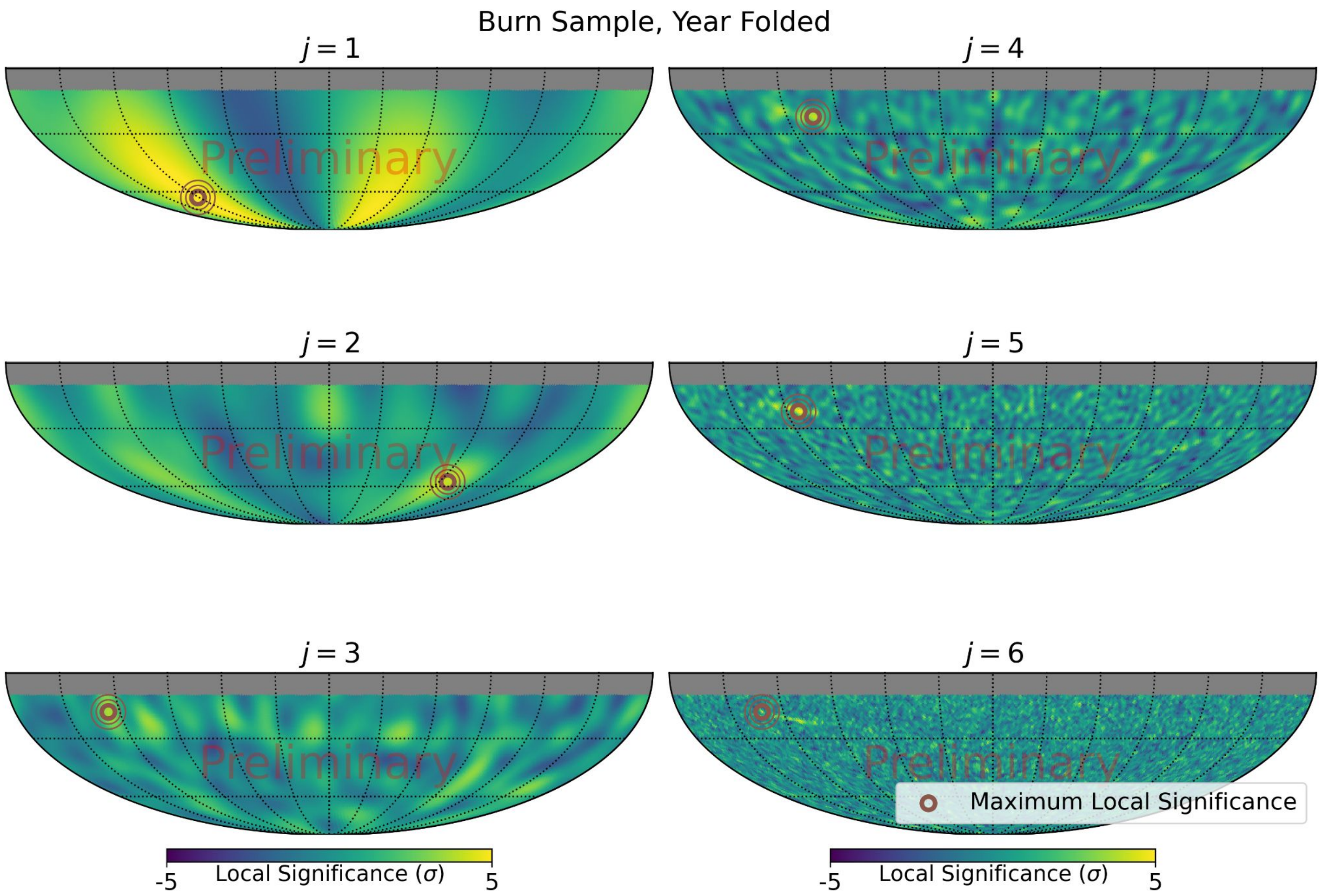




Local Significance Maps

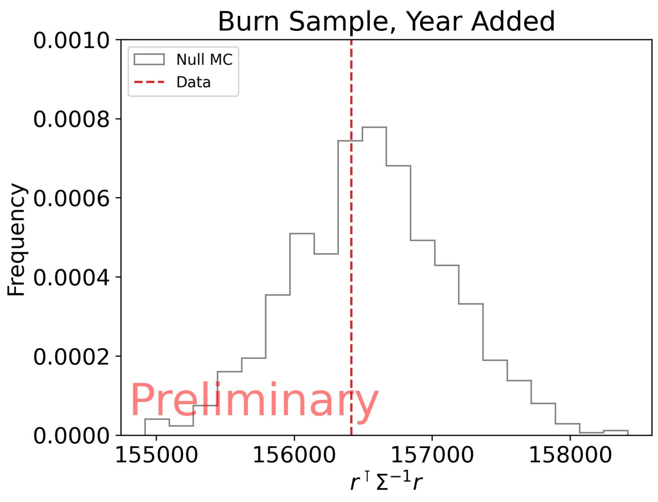
- Create local significance maps by fitting scaled χ^2 distributions to distribution expected from MC in null case

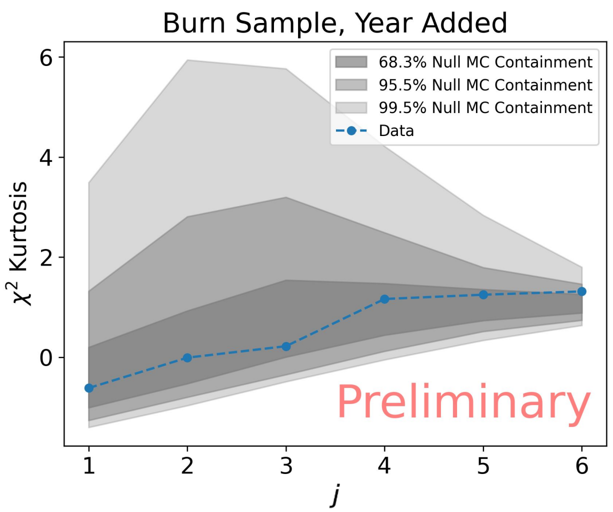
Angular Scale (*j*)	**Maximum Local Significance (σ)**
1	**5.1**
2	4.2
3	3.7
4	4.1
5	**5.1**
6	4.9

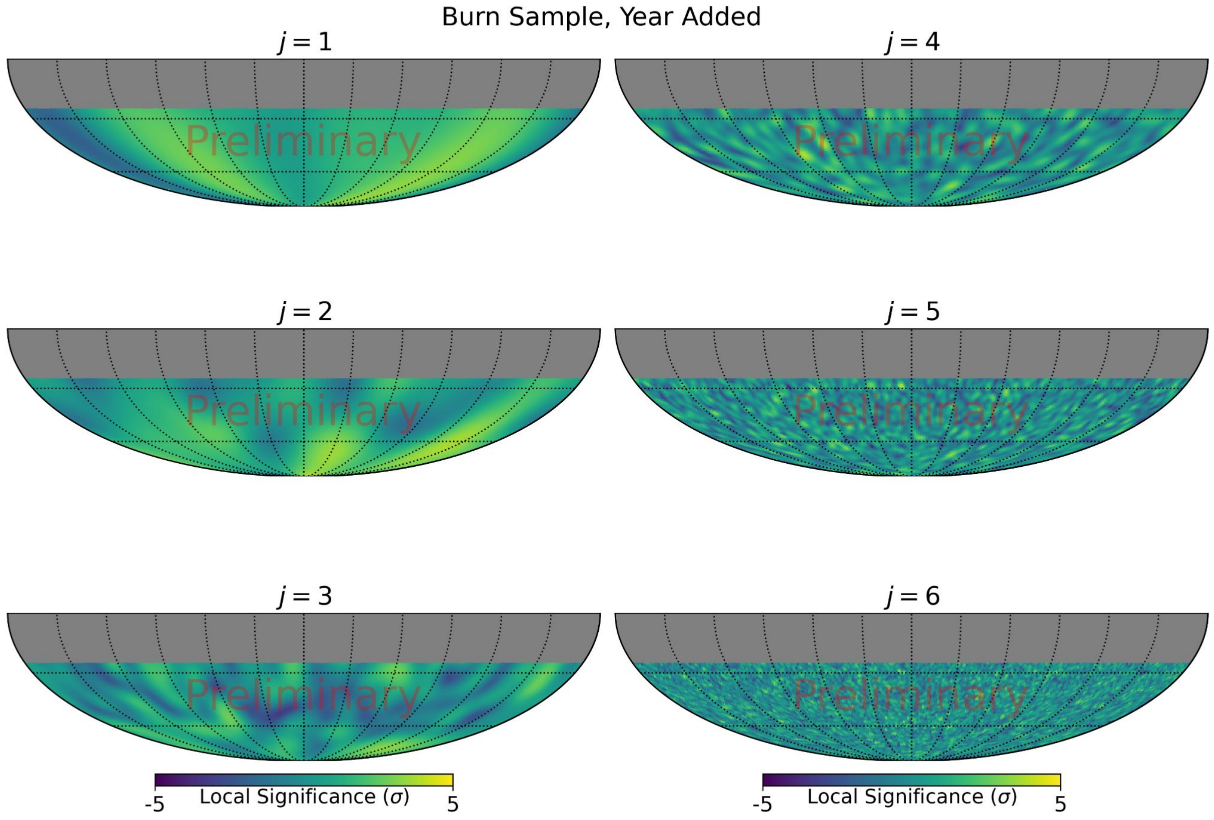


Searching for Astrophysical Time Variation with our **Burn Sample**

- We can detect the known solar dipole and Sun shadow signals in our validation data set!
- We apply the exact same methodology to the **burn sample** “year added” data set
- No astrophysical time variation seen in the burn sample







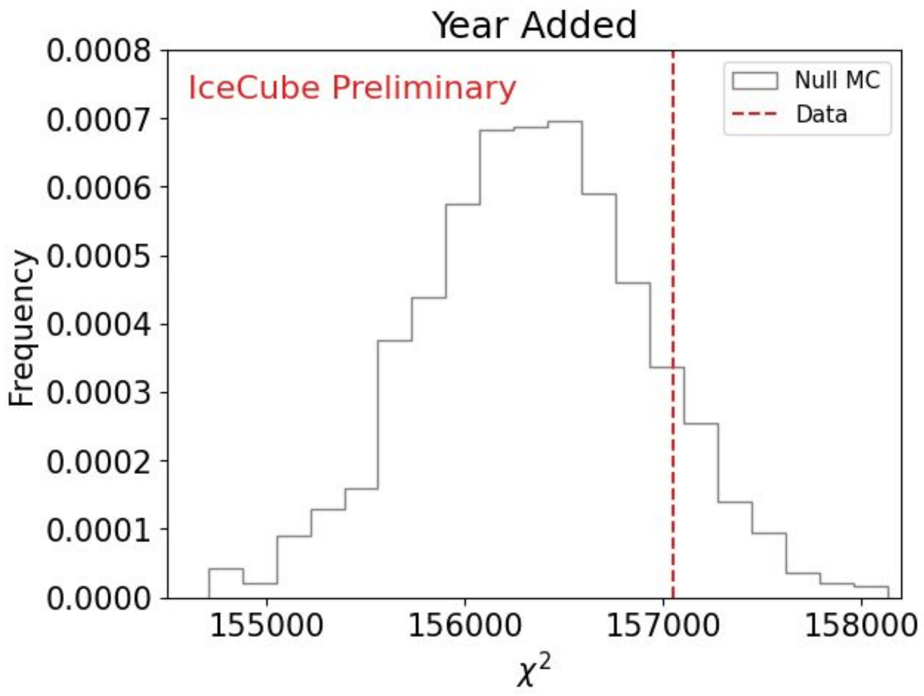
*No local significance >5σ

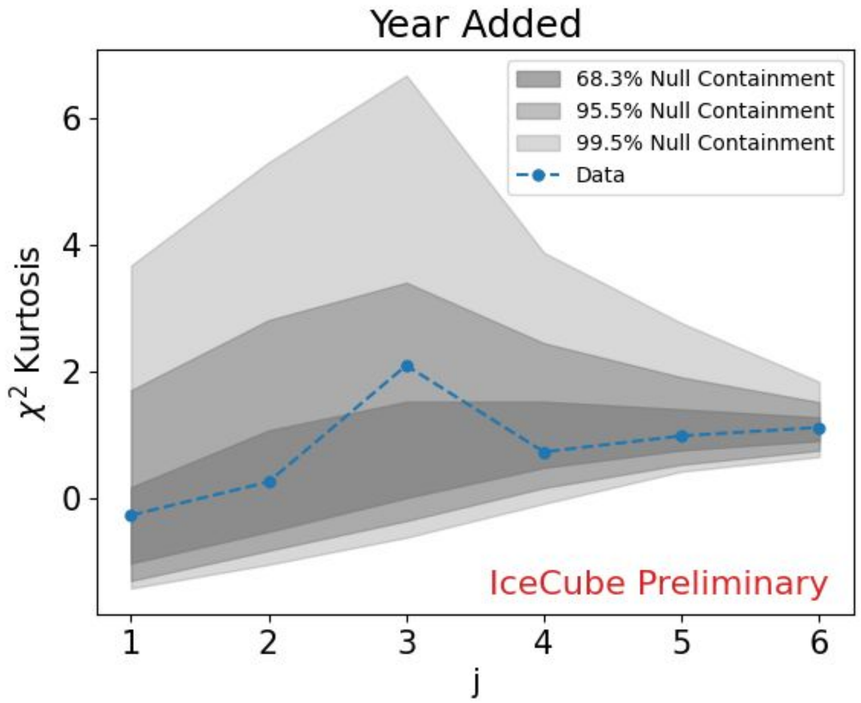
The Entire Data Set

With the Methodology Understood,
Let's Unblind!

Unblinded Year Added Full Sky Tests

- No significant signals seen



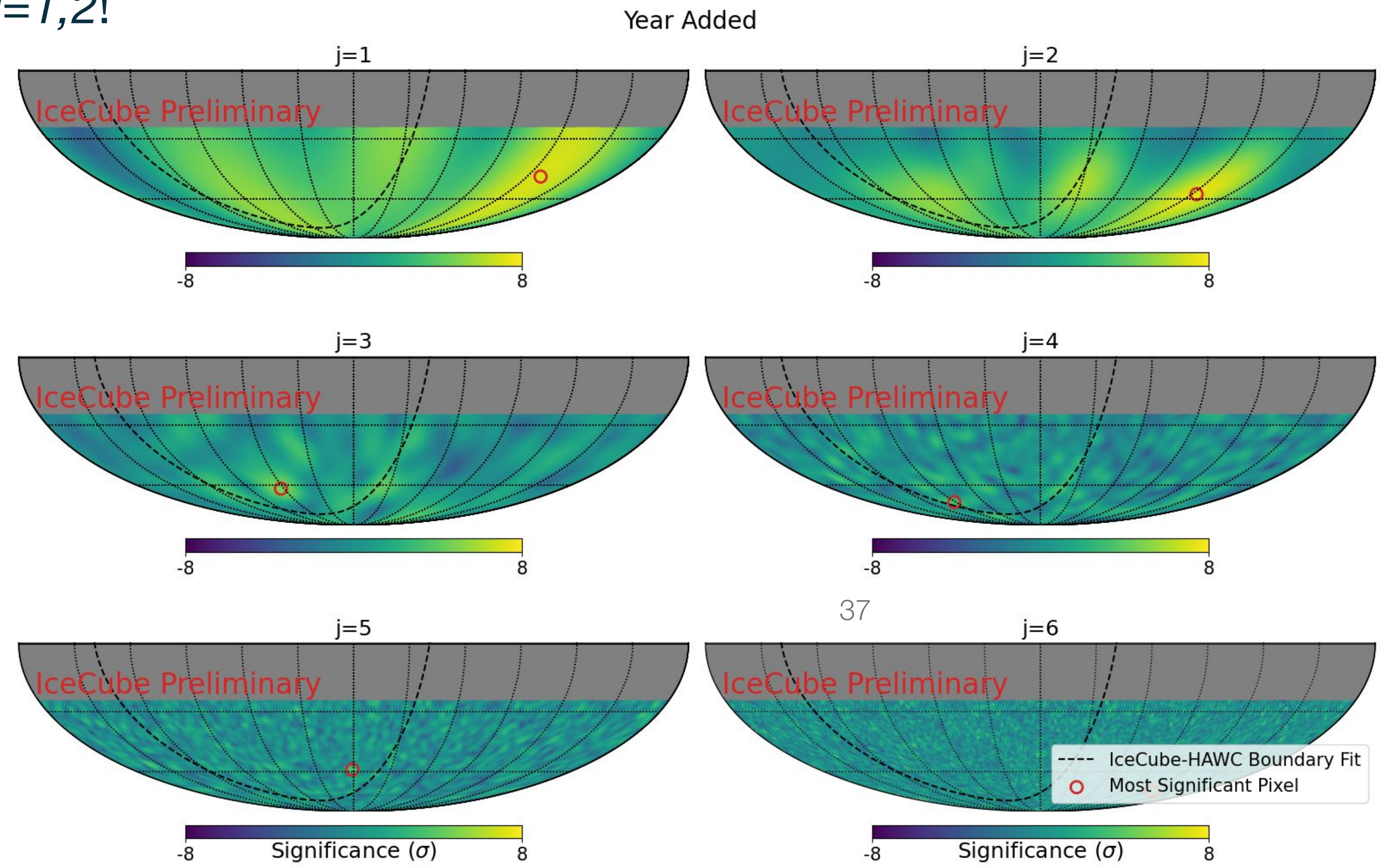


Test	**Significance (σ)**
Full sky χ^2	1.2
χ^2 Kurtosis, *j=1*	0.5
χ^2 Kurtosis, *j=2*	0.3
χ^2 Kurtosis, *j=3*	1.3
χ^2 Kurtosis, *j=4*	0.4
χ^2 Kurtosis, *j=5*	0.1
χ^2 Kurtosis, *j=6*	0.4

Unblinded Year Added Local Significance Maps

- See **>5σ** local significance at *j=1,2*!

Angular Scale (*j*)	**Maximum Local Significance (σ)**
1	**7.1**
2	**7.4**
3	4.9
4	3.6
5	3.9
6	3.9

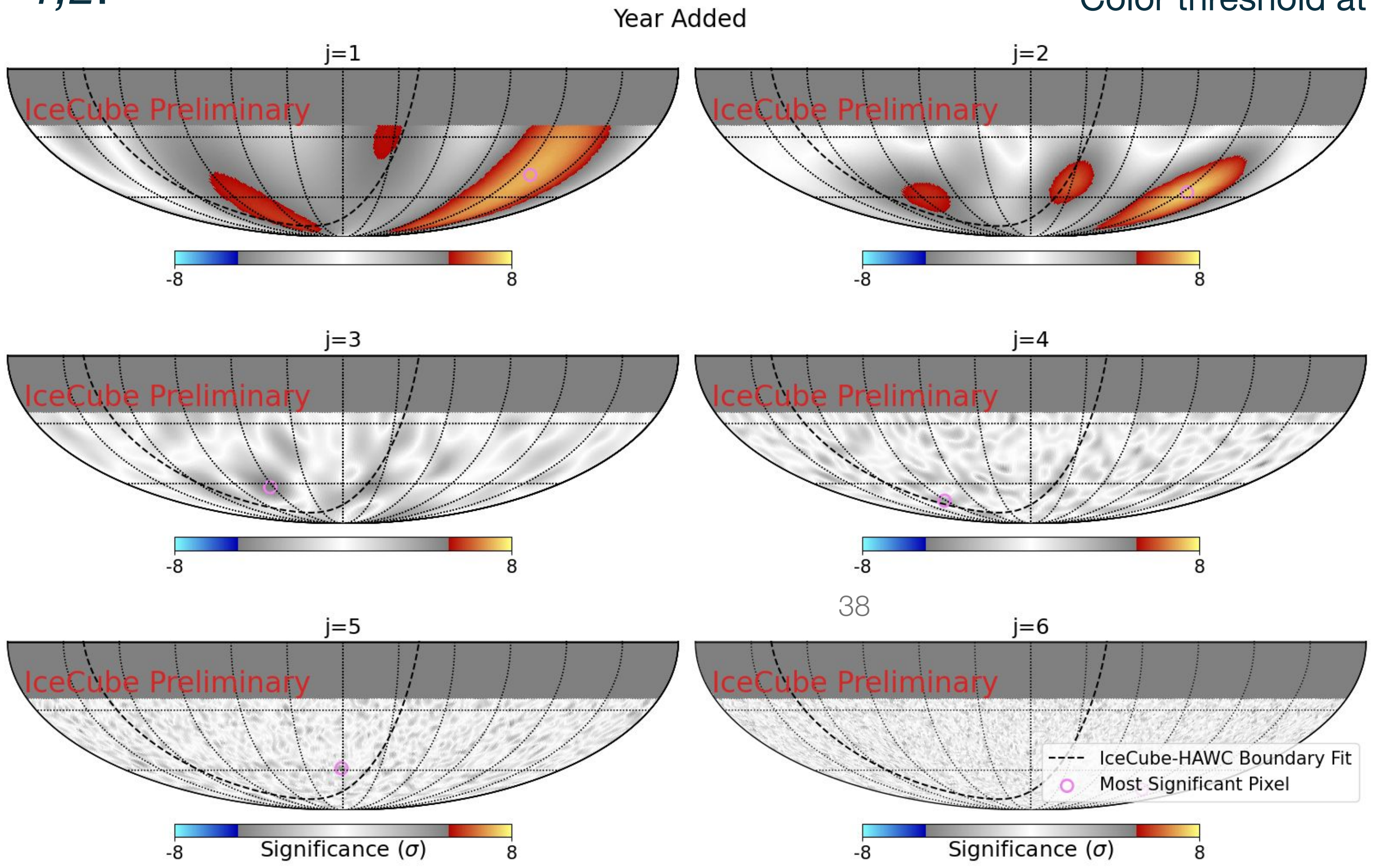


Unblinded Year Added Local Significance Maps

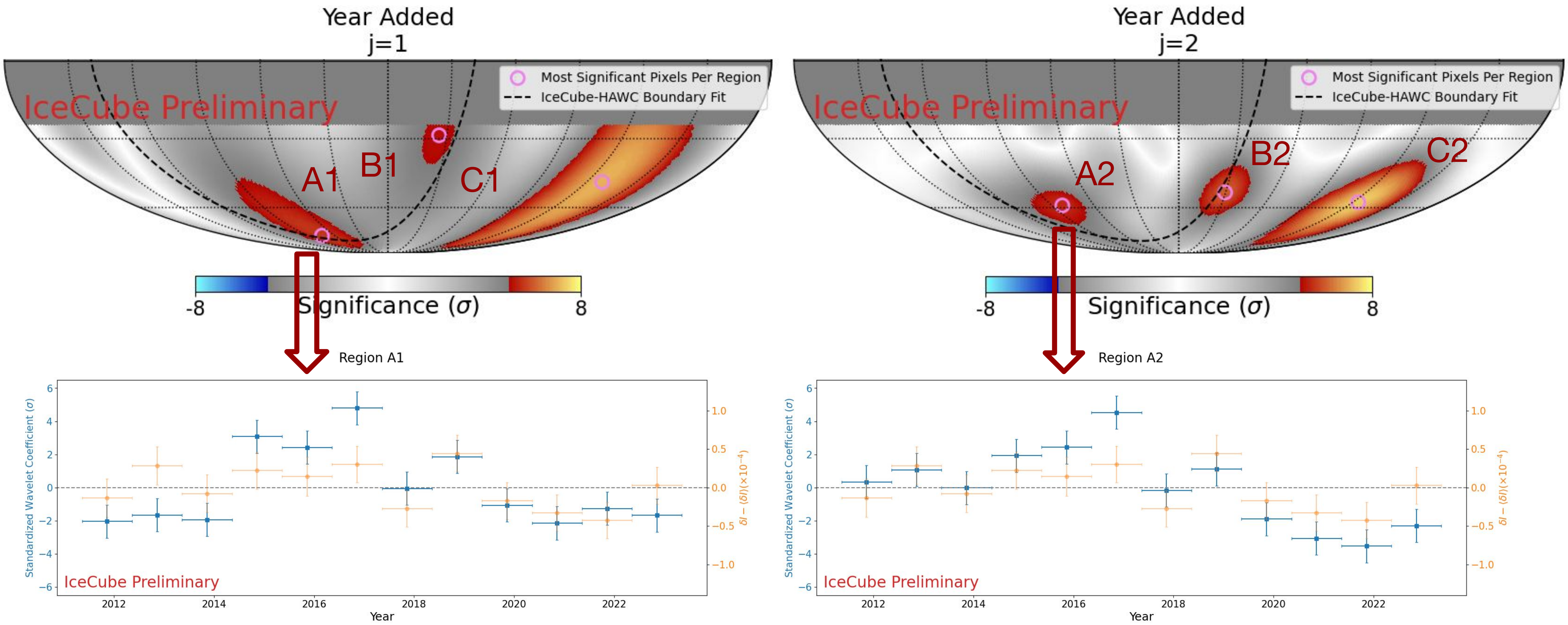
- See **>5σ** local significance at *j=1,2*!
- 3 distinct regions **>5σ**

Angular Scale (*j*)	**Maximum Local Significance (σ)**
1	**7.1**
2	**7.4**
3	4.9
4	3.6
5	3.9
6	3.9

*Color threshold at 5σ



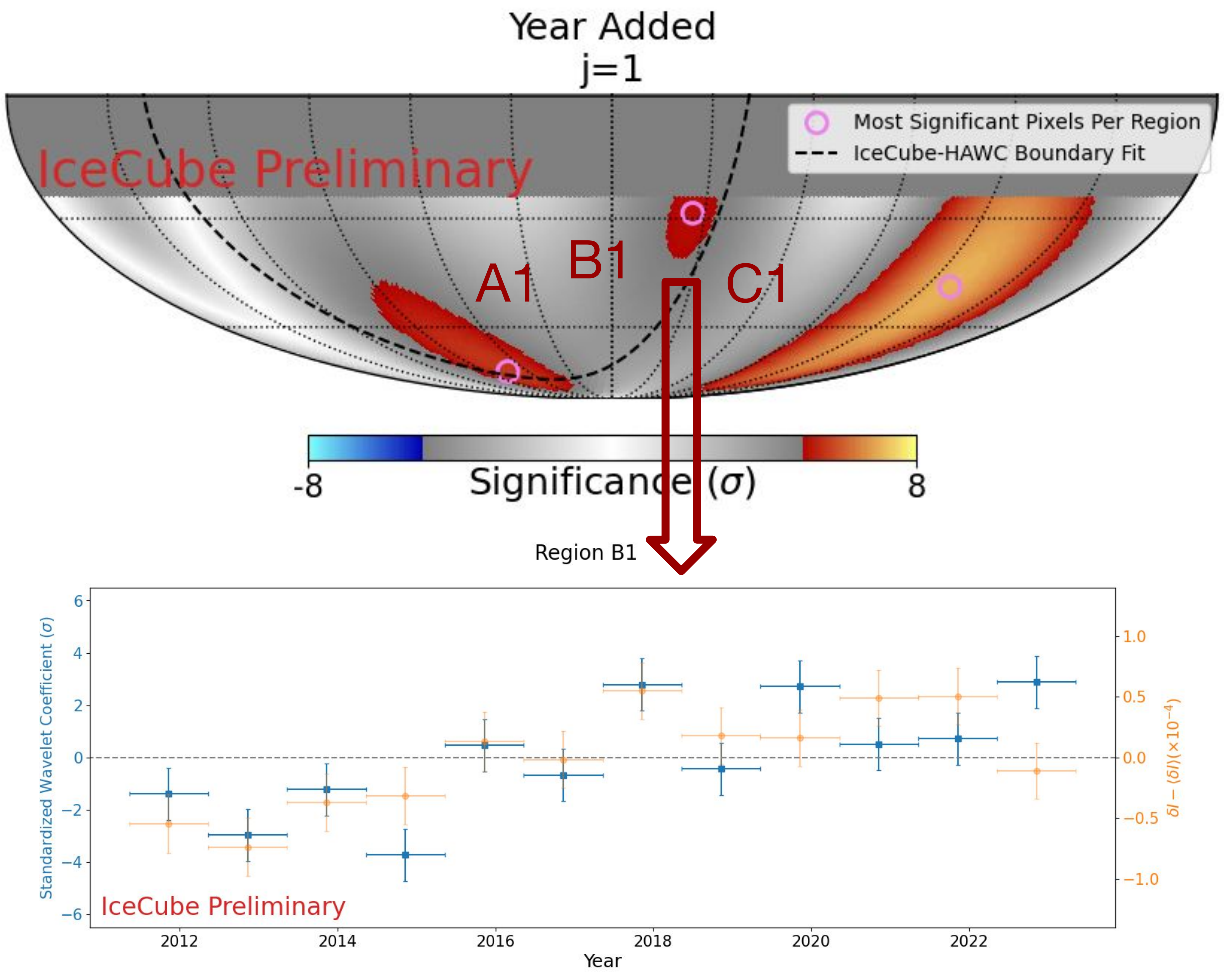
Region A Significance Time Series

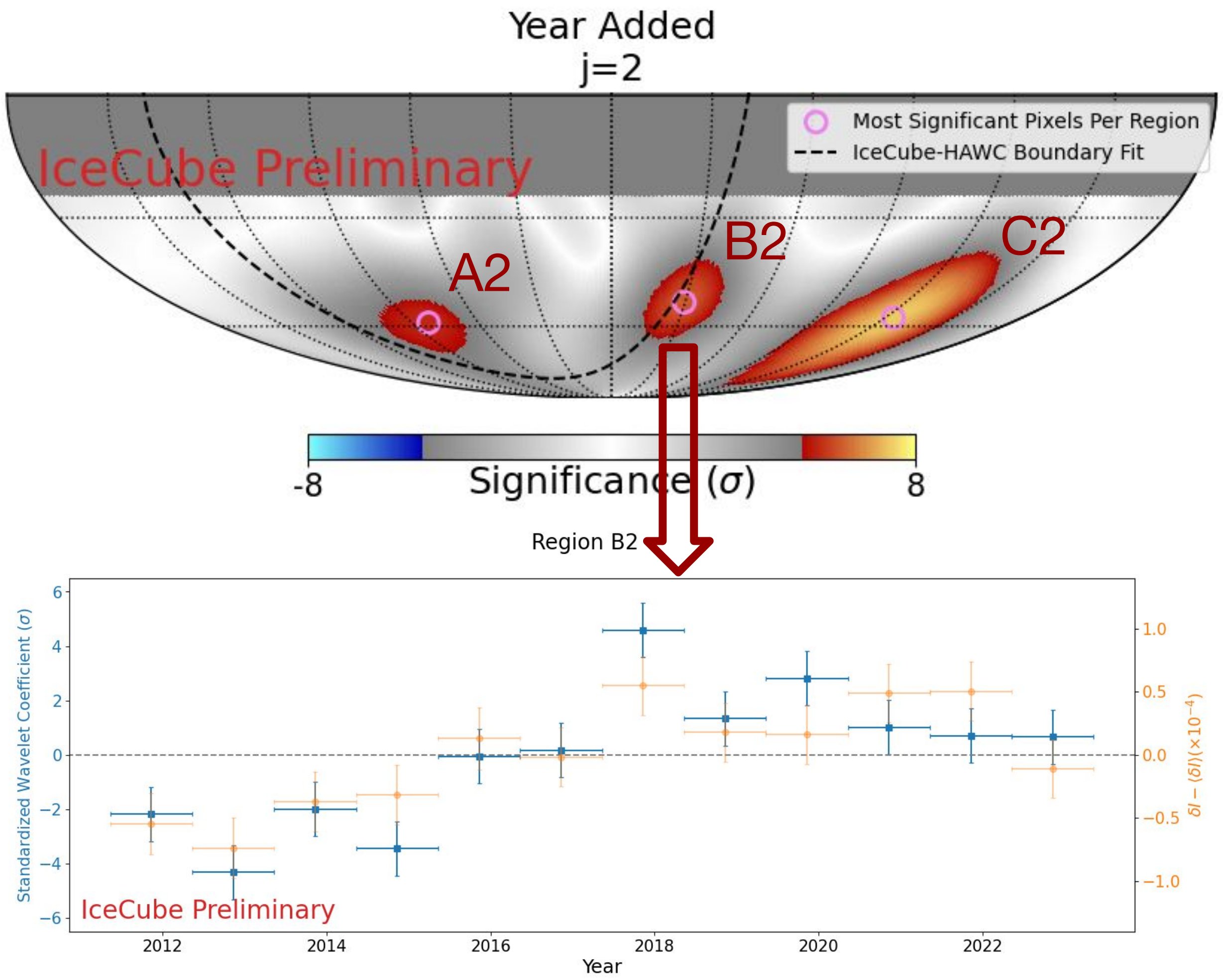


Local Significance: 5.63σ

Local Significance: 5.47σ

Region B Significance Time Series

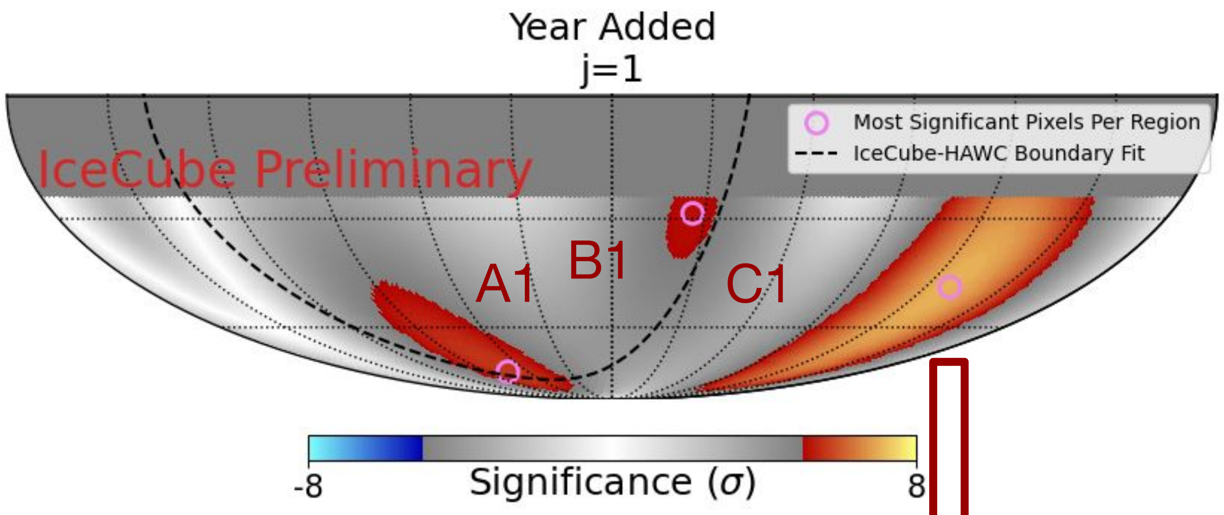


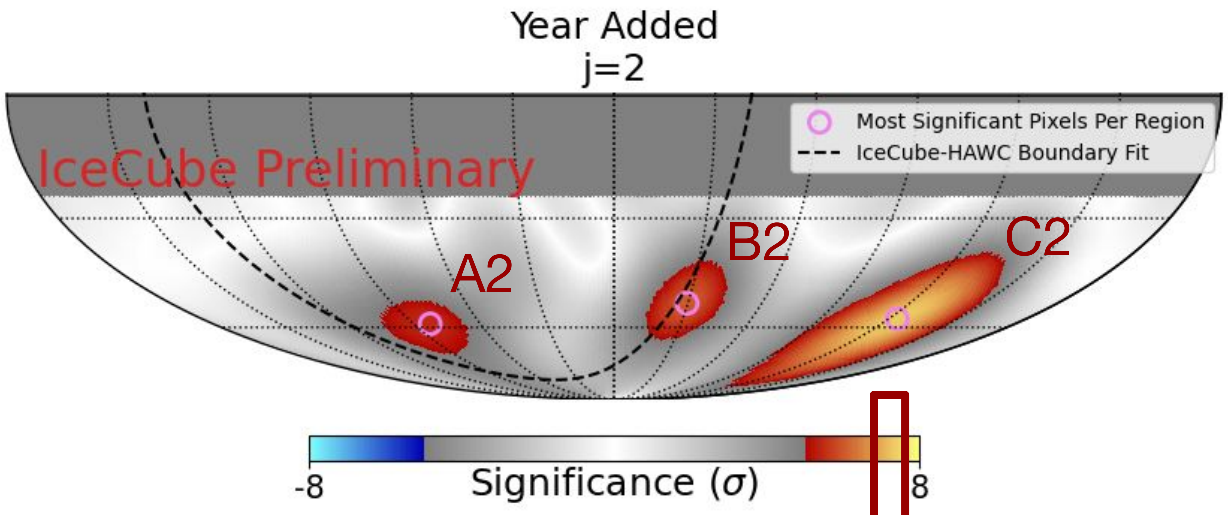


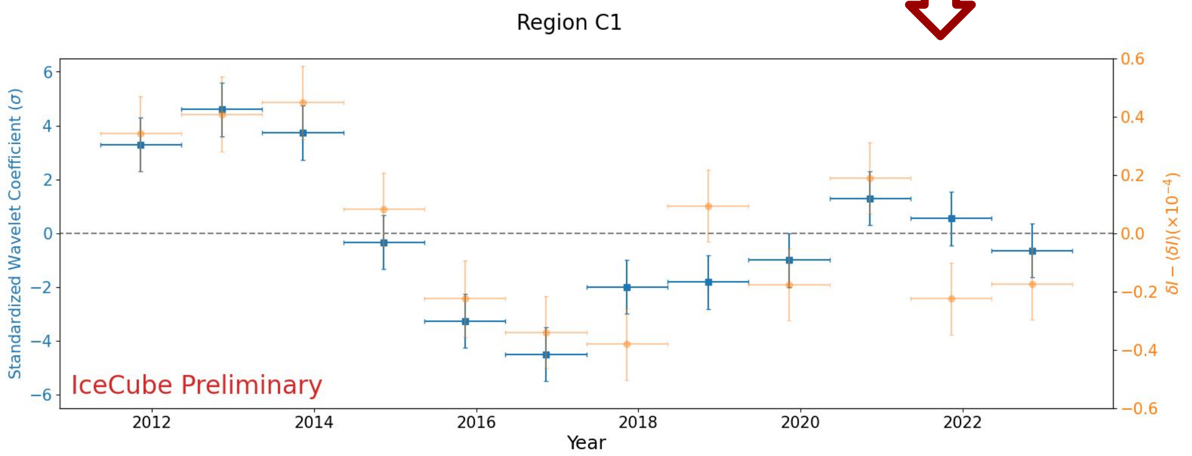
Local Significance: 5.14σ

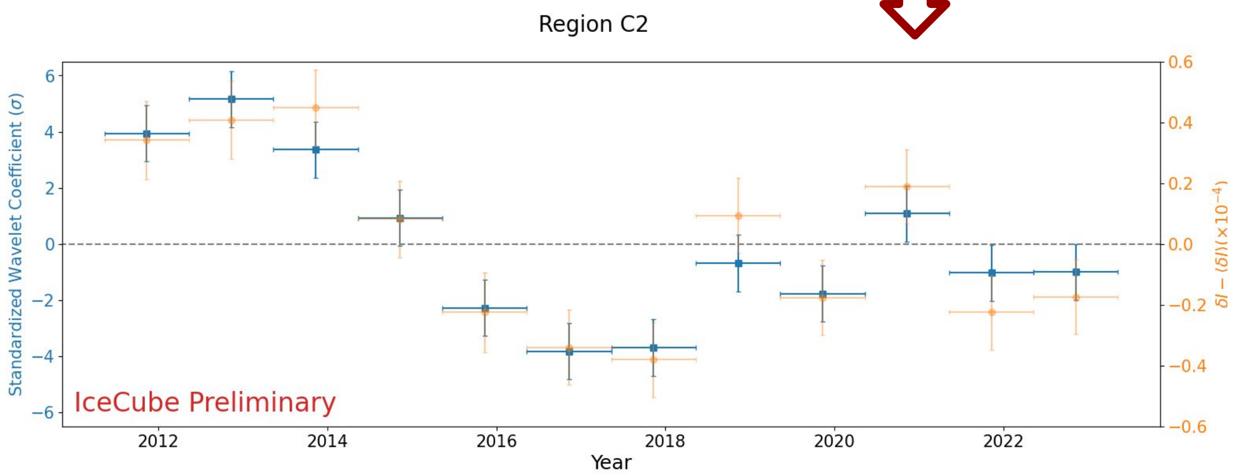
Local Significance: 6.04σ

Region C Significance Time Series





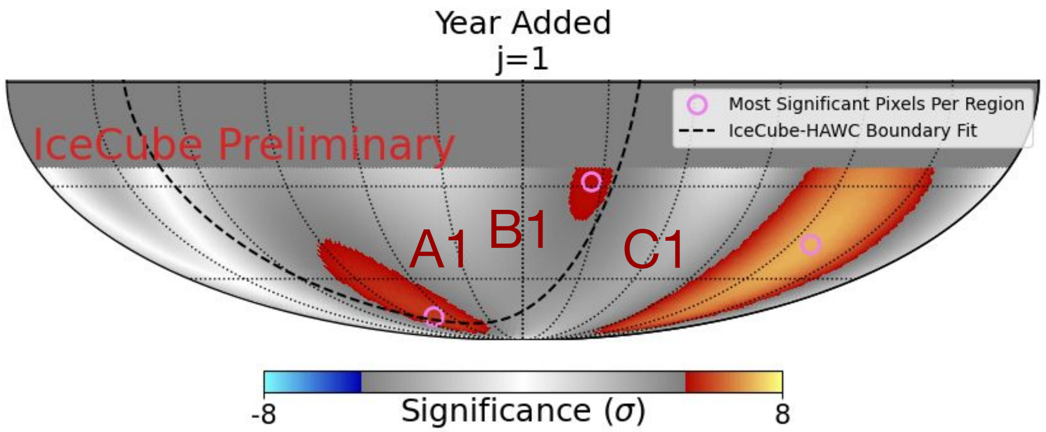


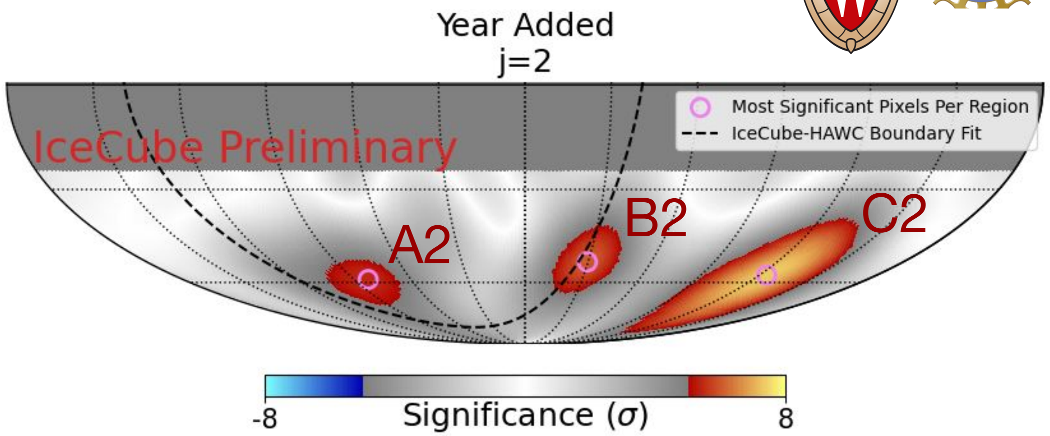


Local Significance: 7.07σ

Local Significance: 7.37σ

Trials Corrected Significances



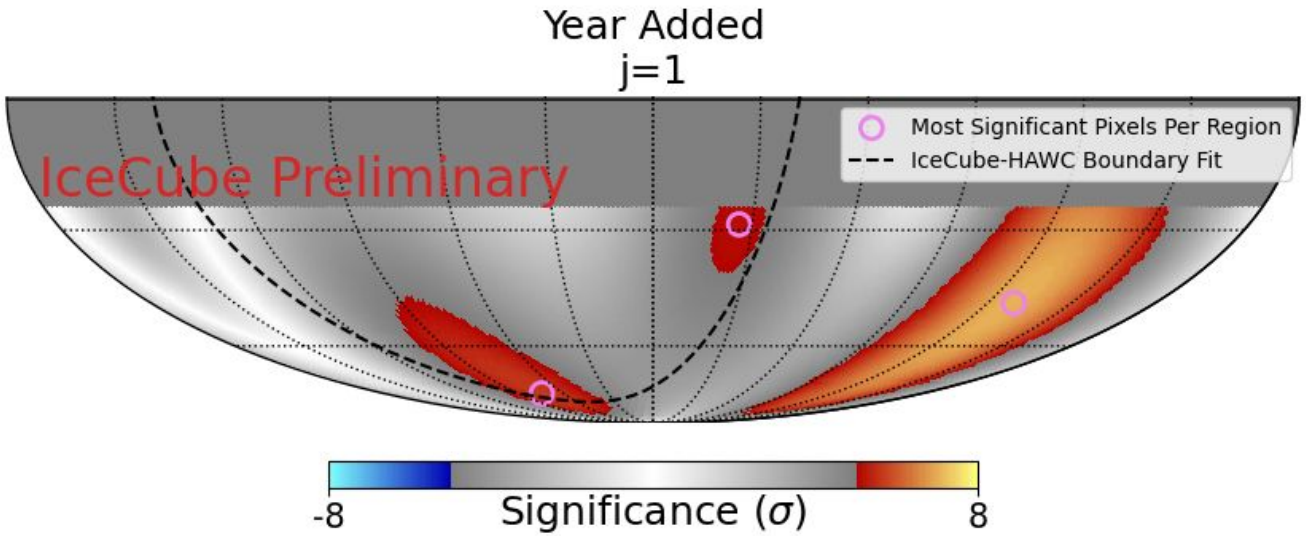


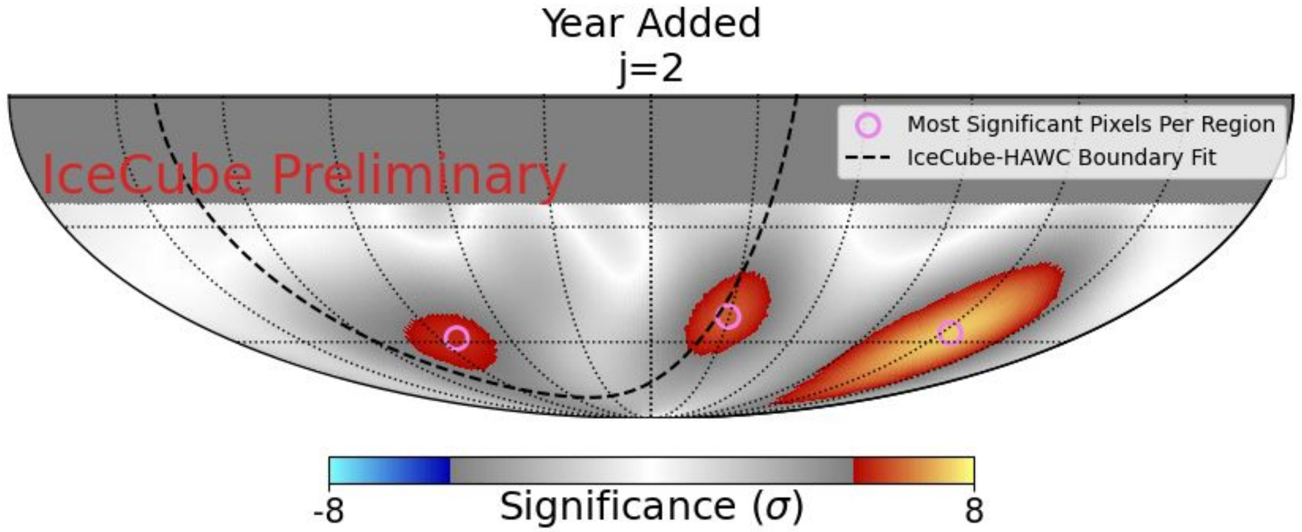
Region	Local Significance (σ)	Trials Corrected Significance (σ) Within angular Scale	Trials Corrected Significance (σ) Across angular Scales
A1	5.63	4.82	3.48
B1	5.14	4.26	2.66
C1	7.07	6.37	5.46
A2	5.47	4.34	3.21
B2	6.04	5.01	4.08
C2	7.37	6.49	5.83

*For trials corrections, use method described in: Vitells and Gross, 2011 *Astroparticle Physics*, **35** 230

Conclusions

- See time variation in the Cosmic Ray Anisotropy Sky at **>5σ** significance
- Take form of three distinct regions with **post-trials** significances of **5.83σ**, **4.08σ**, and **3.48σ**
- Currently searching for any unaccounted for systematics which could lead to this signal



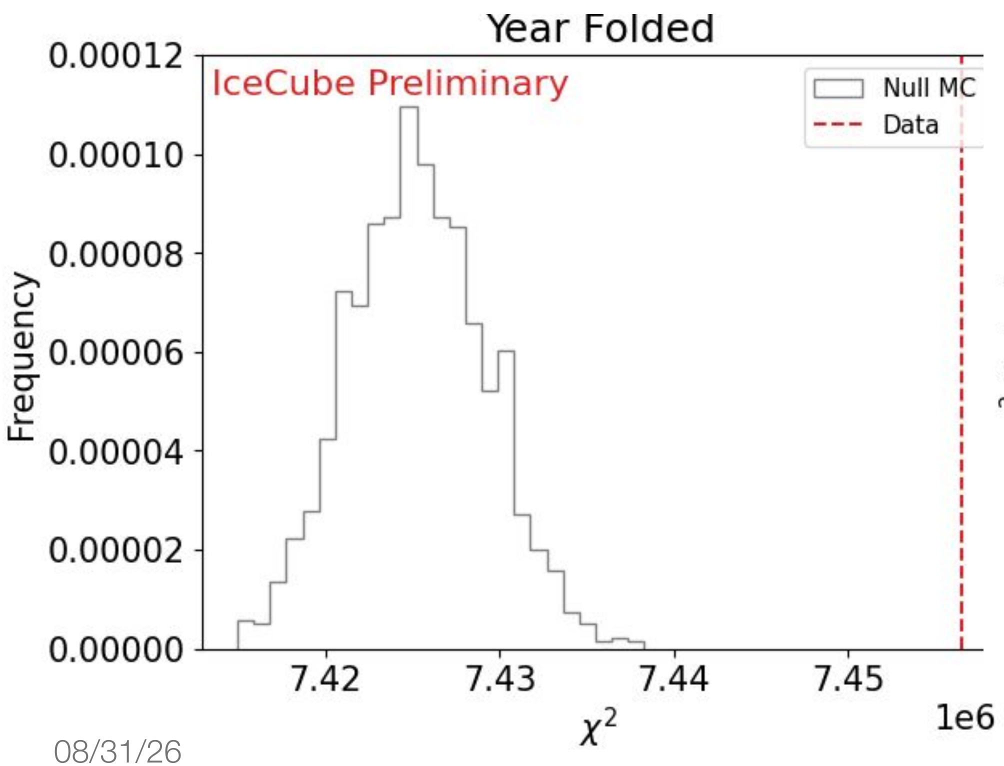


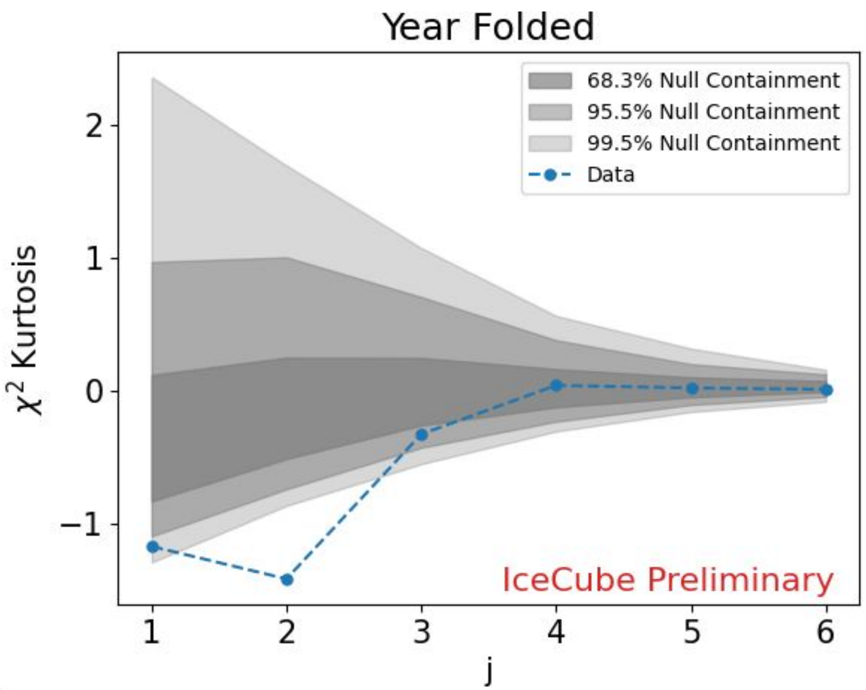
Thank you!

Backup

Unblinded Year Folded Full Sky Tests

- As expected, see significant signal!
- From χ^2 kurtosis test, signal has a large angular scale





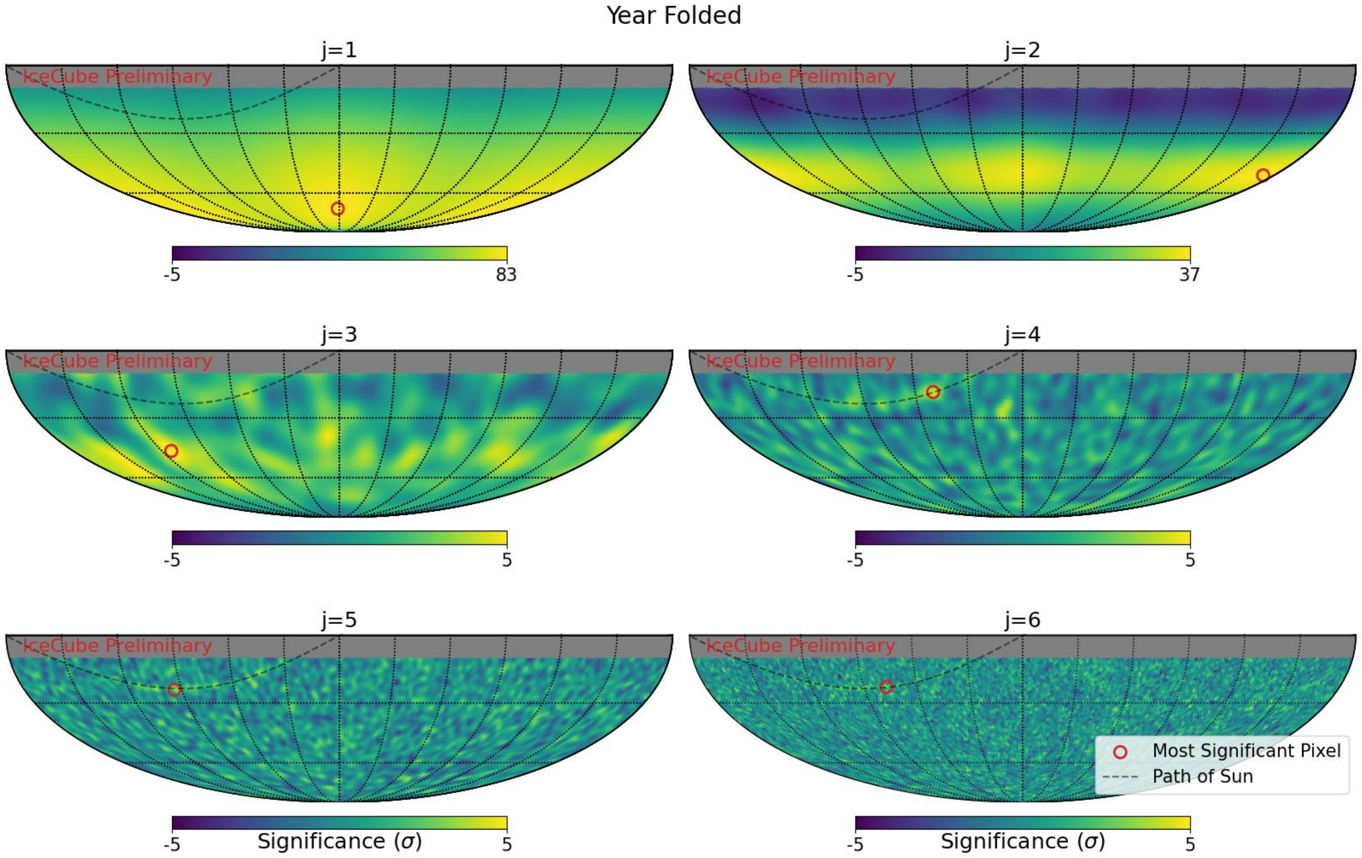
*pre-trials

Test	Significance (σ)
Full sky χ^2	**8.0**
χ^2 Kurtosis, *j=1*	2.3*
χ^2 Kurtosis, *j=2*	**>3***
χ^2 Kurtosis, *j=3*	1.4*
χ^2 Kurtosis, *j=4*	0.2*
χ^2 Kurtosis, *j=5*	0.0*
χ^2 Kurtosis, *j=6*	0.5*

Unblinded Year Folded Local Significance Maps

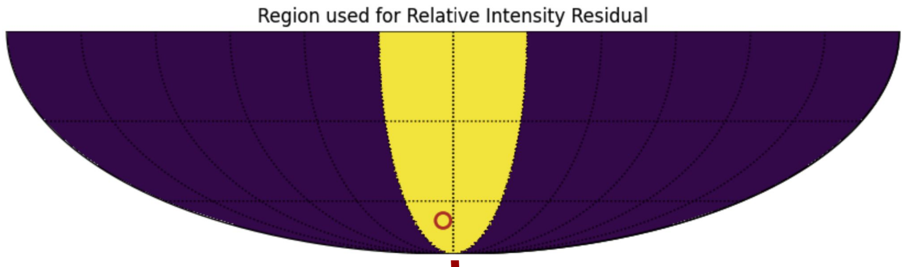
- Expect solar dipole to appear as a strip of strong significance in small *j* maps - we see this!
- Expect to see sun shadow, but at marginal significance - we see this!

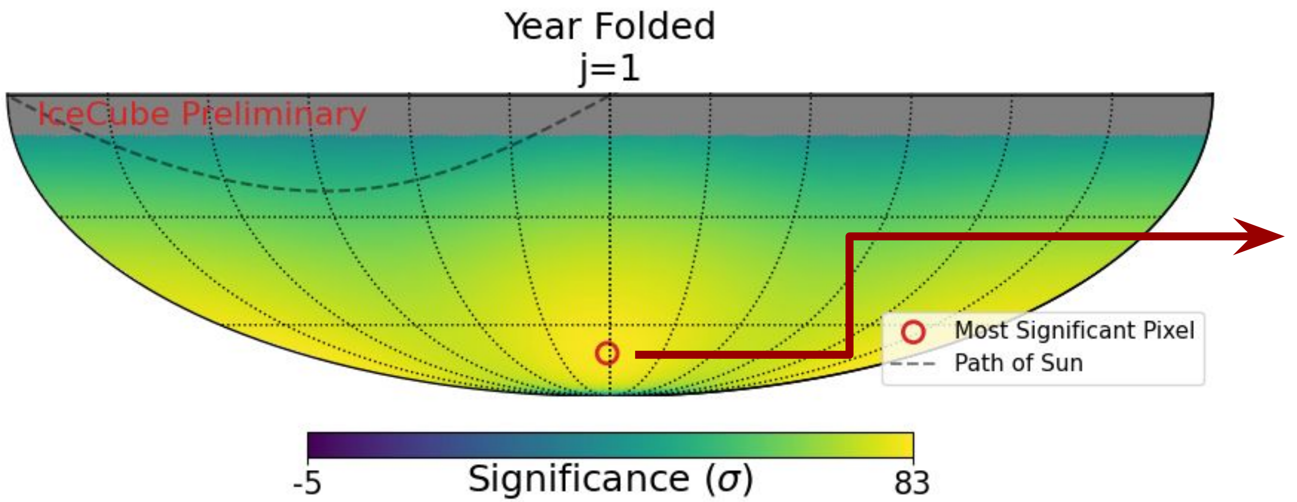
Angular Scale (*j*)	**Maximum Local Significance (σ)**
1	**82.5**
2	**37.0**
3	**5.3**
4	4.3
5	4.0
6	4.0

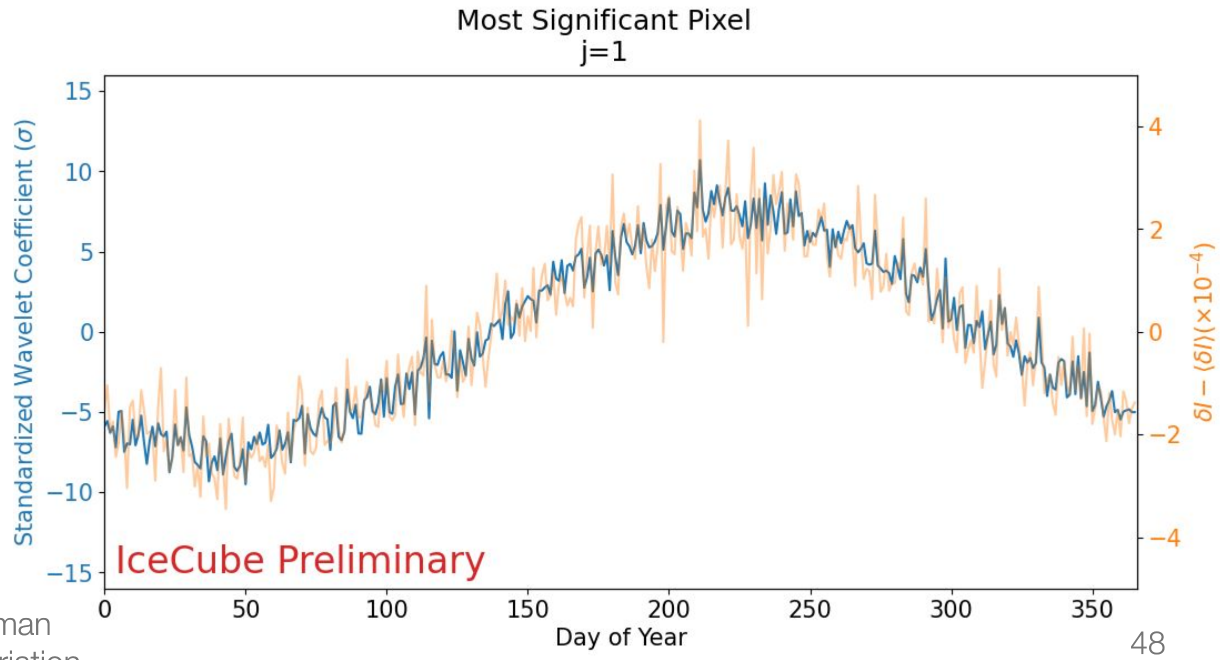


Inspecting Local Significance Maps

- For *j=1*, can see the the large local significance is due to a sinusoidal signal
- This is the Solar Dipole!

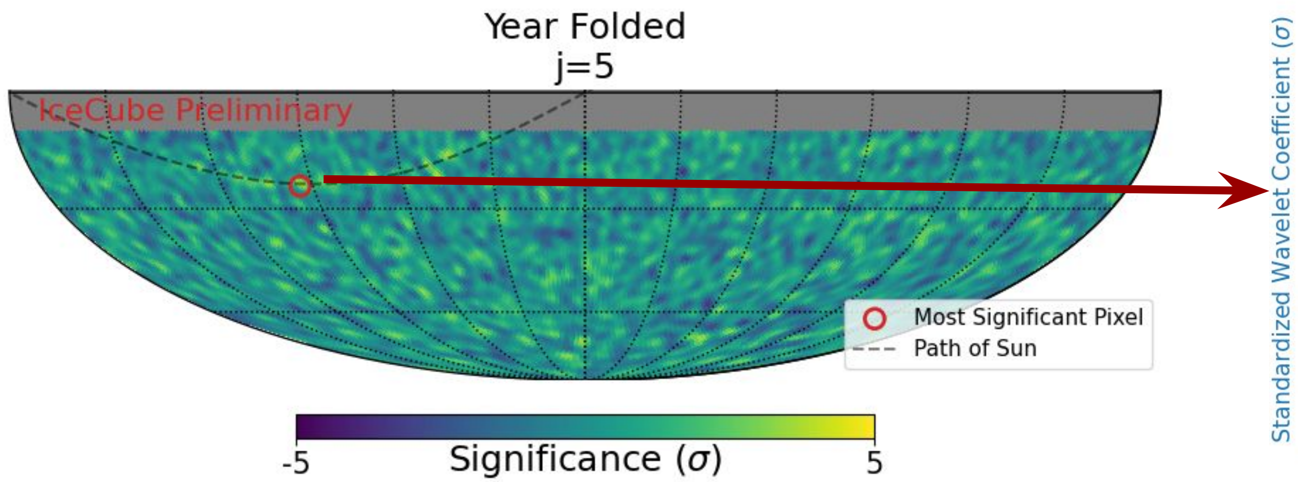


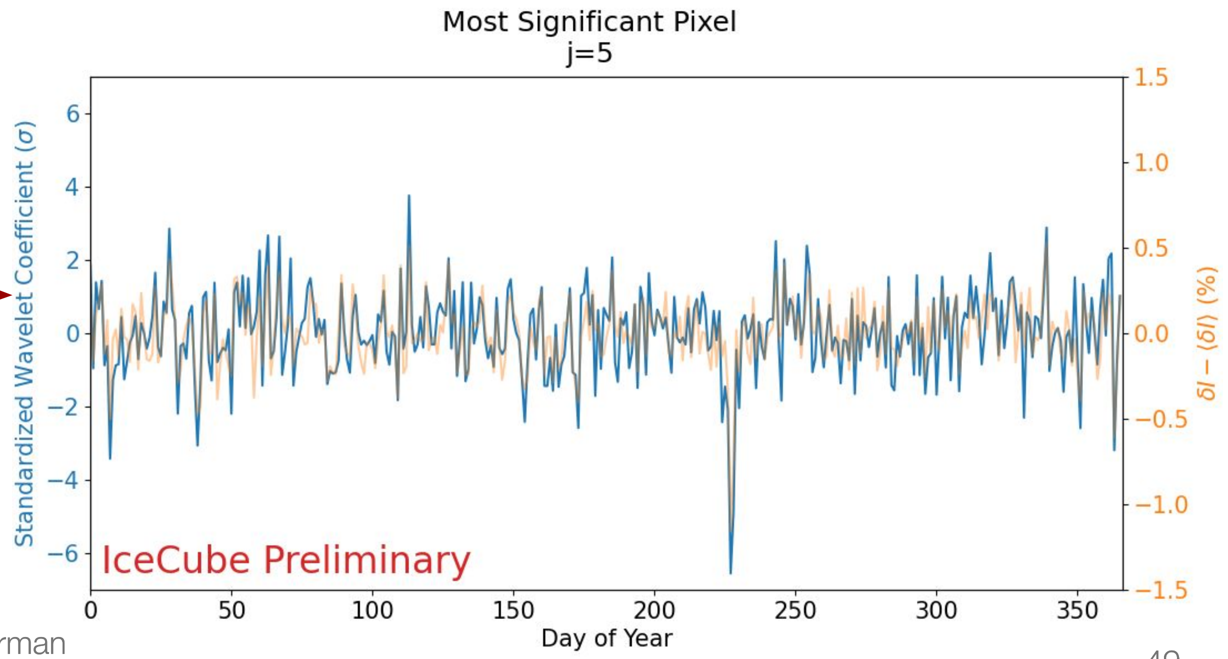




Inspecting Local Significance Maps

- At *j=5* can clearly see the sun shadow passing through the most significant pixel around day 227
- To obtain relative intensity residual, use a 2° top hat around the pixel

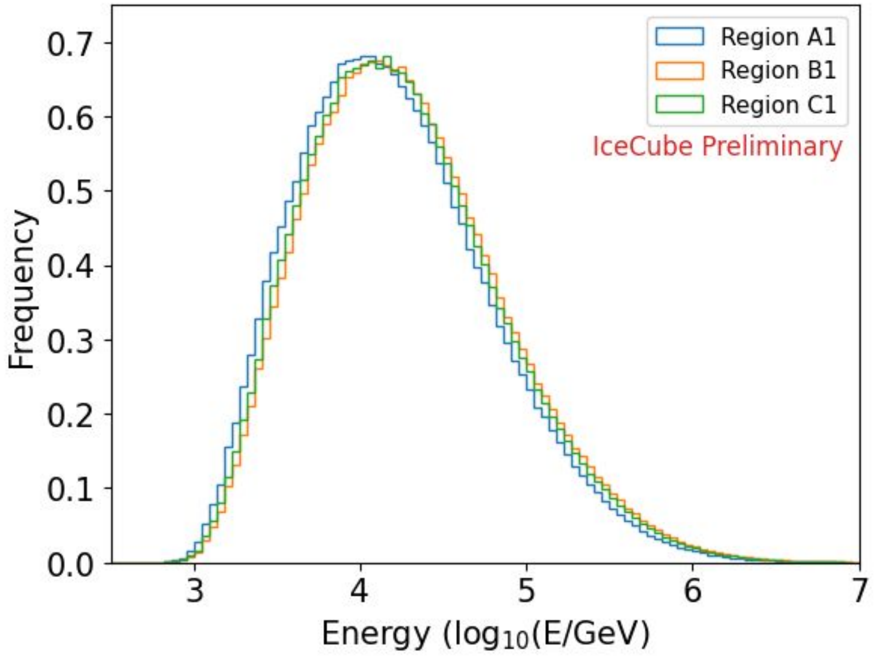


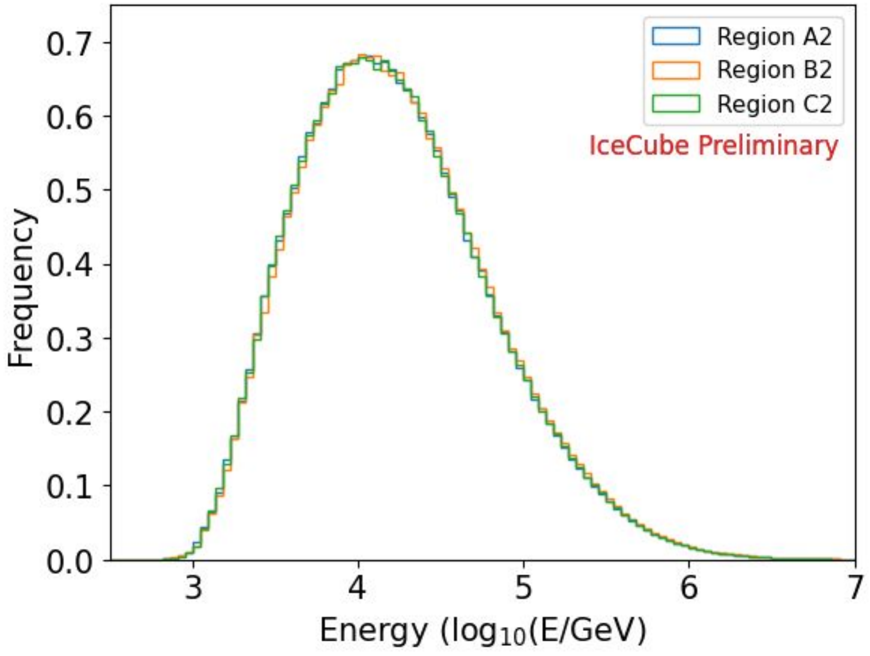


Local Significance Region Energy Distributions

- Because we do not make any cuts on energy, the median energy of our cosmic rays changes as a function of zenith
- As a result, the energy distributions for our significant regions are not the same

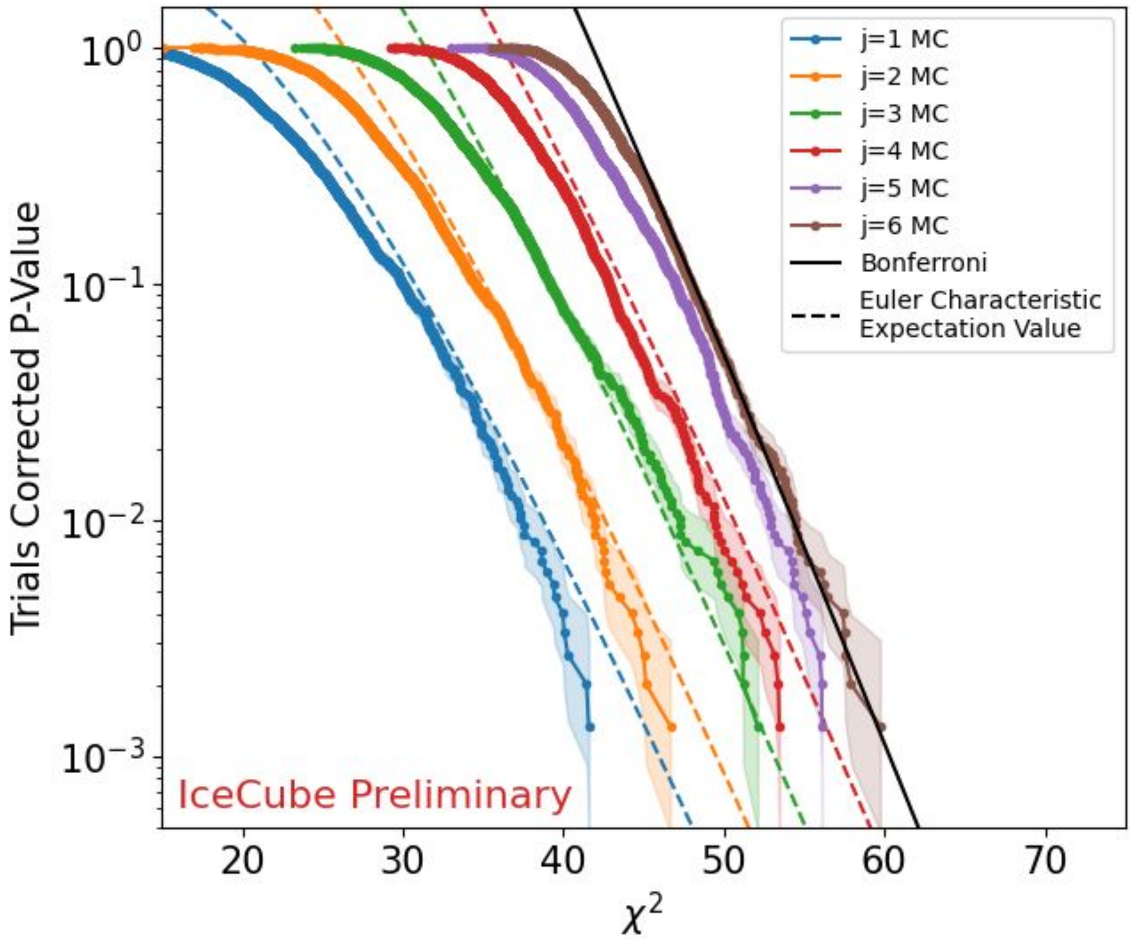
Region	Median Energy (TeV)
A1	14.1
B1	16.8
C1	15.9
A2	14.8
B2	15.2
C2	14.9





Trials Corrections

- Due to large significance of signals, can not do trials corrections entirely with MC
- Use method described in Vitells and Gross, 2011 *Astroparticle Physics*, **35** 230
- Fit Euler Characteristic of excursion region above a threshold for moderate threshold using small amount of MC
  - 1495 realizations used
- Extrapolate function to higher threshold, where it asymptotically approaches global p-value
- Used extensively in high energy physics



Cosmic Ray Anisotropy Reconstruction

- We use a Maximum Likelihood Estimation (MLE) method
- Described in Ahlers et al. 2016*
- 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*

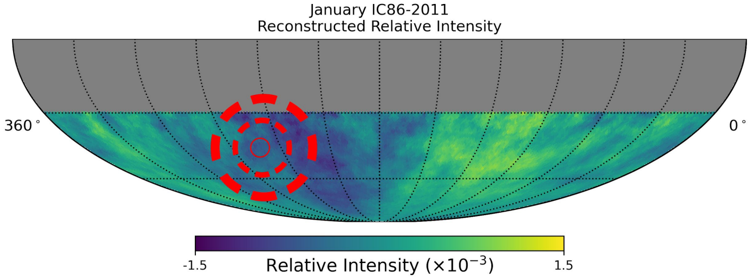
<u>We maximize the likelihood ratio</u>

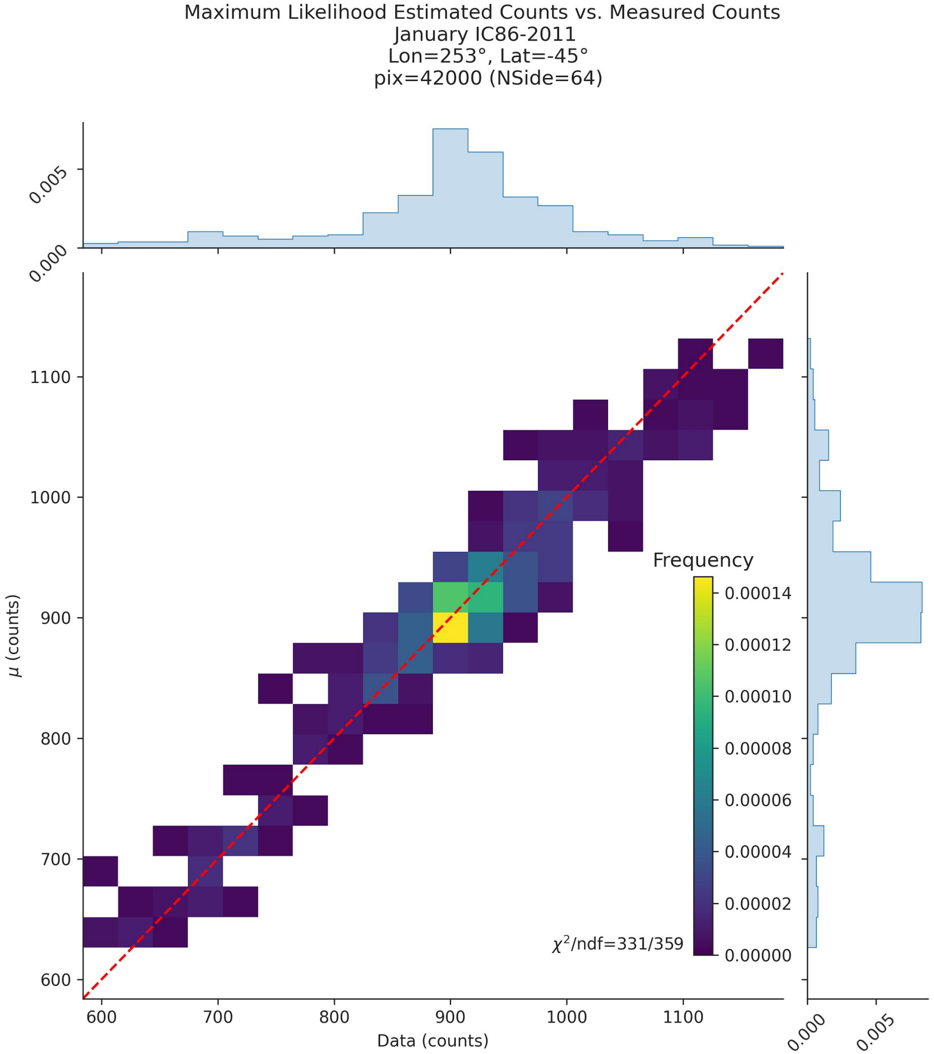
$$\lambda = \frac{\mathcal{L}(n|I,\mathcal{N},\mathcal{A})}{\mathcal{L}(n|I^{(0)},\mathcal{N}^{(0)},\mathcal{A}^{(0)})}$$

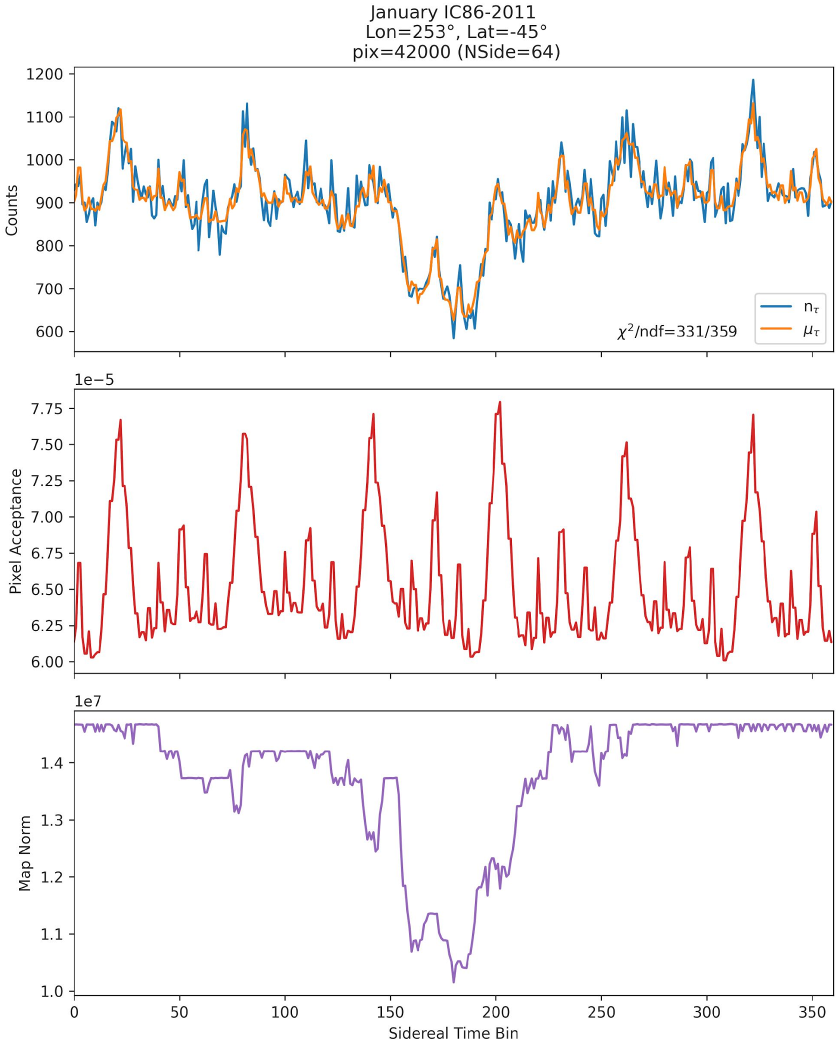
$I^{(0)},\mathcal{N}^{(0)},\mathcal{A}^{(0)}$ → MLE of $I,\mathcal{N},\mathcal{A}$ assuming no anisotropy (i.e. $I = 1$)

*Ahlers, M., BenZvi, S. Y., Desiati, P., *et al.* 2016, *ApJ*, **823**, 10

Cosmic Ray Anisotropy Reconstruction







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

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

Cosmic Ray Anisotropy Monte Carlo

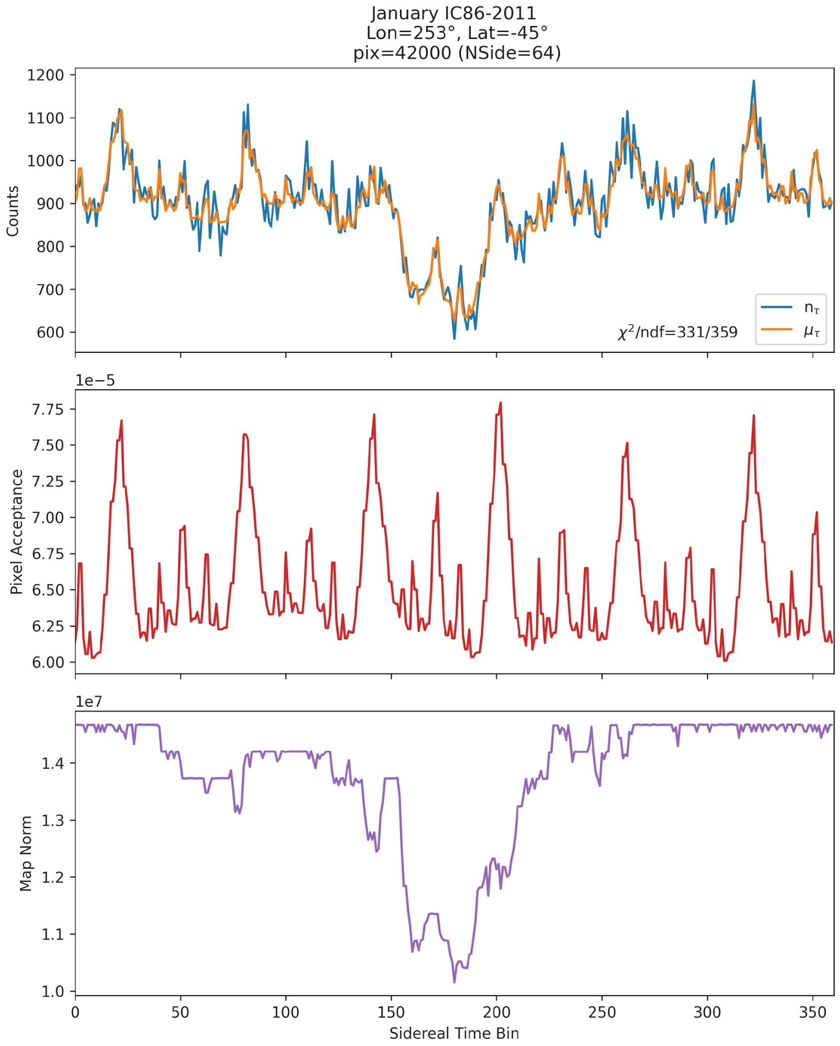
• We know each If we bin cosmic ray counts (in local coordinates) into sky bins (τ), each measurement $n_{\tau i}$ is sampled from a Poisson distribution with MLE mean $\mu_{\tau i}$

- Take $I_{\tau i} = 1$
- Creates sky-maps with *known* expectation value of $I_{\tau i}$ by construction
- Simplifies statistics

- To make MC anisotropy map:
  1. Calculate $\mu_{\tau i} = N_\tau A_i$
  2. Create MC local maps by taking $n_{\tau i} \sim \text{Poisson}(\mu_{\tau i})$
  3. Perform MLE reconstruction on MC local maps

Benefits:

- Takes into account detector dead time
- Takes into account biases from reconstruction (no m=0 terms)

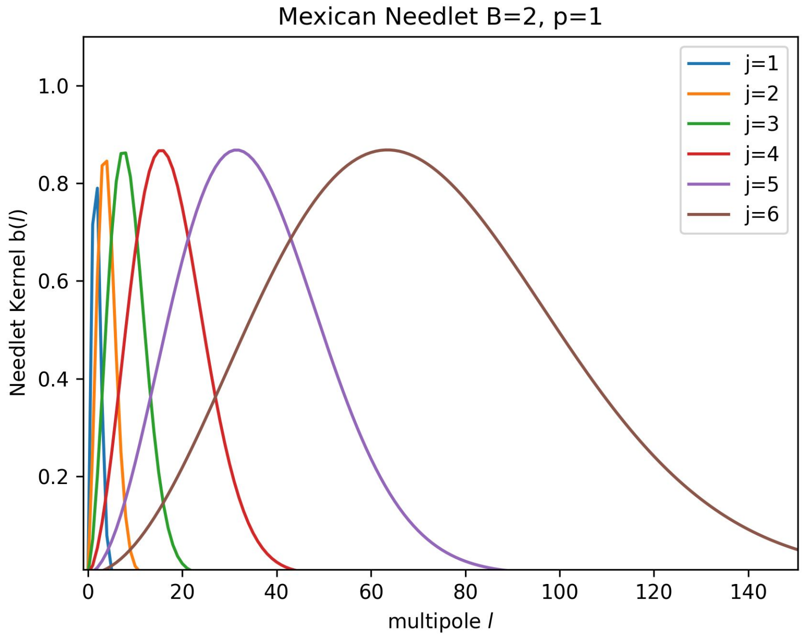


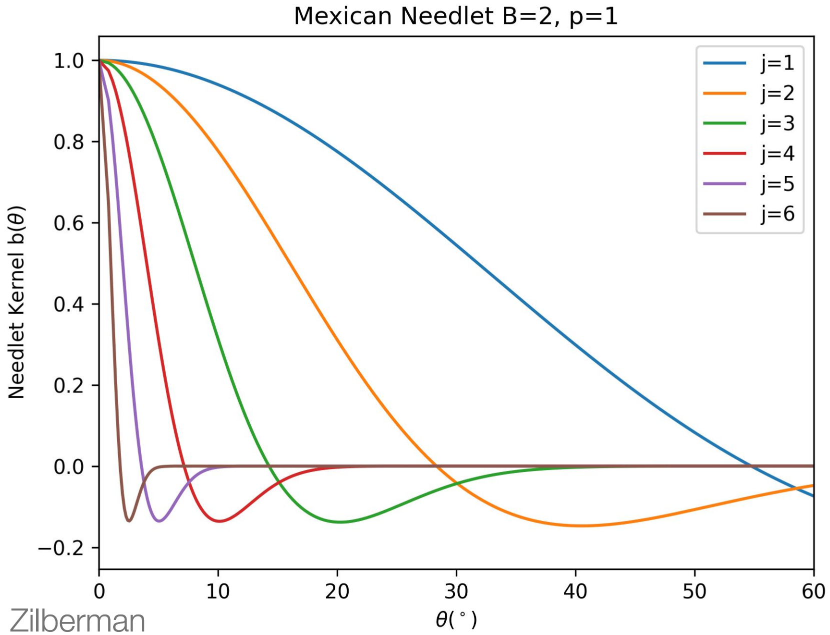
Wavelets

- Use Mexican needlets
- Similar to standard spherical needlets, but more powerful in pixel space at cost of power in harmonic space
- Defined in harmonic space as

$$b_l(B,p,j) = \left(\frac{l(l+1)}{B^{2j}}\right)^p e^{-\frac{l(l+1)}{B^{2j}}}$$

- 2 user-defined parameters: B and p
- B is a real number > 1
- p is integer ≥ 1
- Fixing both gives set of integer-valued angular scales we probe
- Maximum power in real-space at p=1
- B determines width of a given wavelet, so determines number of wavelets we test
- Probing 6 angular scales gives us B=2





Scodeller, S., Rudjord, Ø., Hansen, F. K., *et al.* 2011, *Astrophys J*, **733**, 121