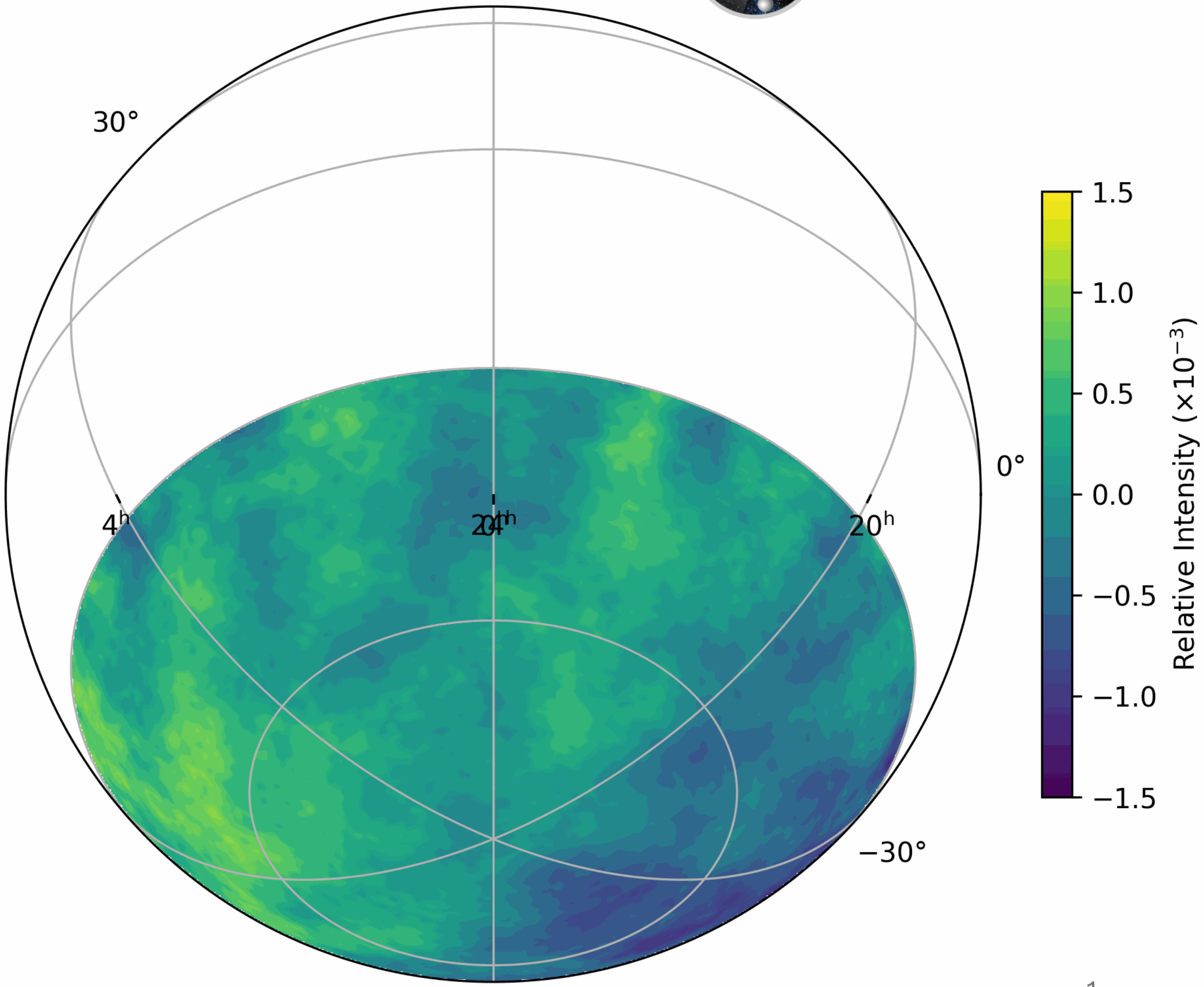
Department of Physics
UNIVERSITY OF WISCONSIN–MADISON

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

The TeV Cosmic Ray Anisotropy

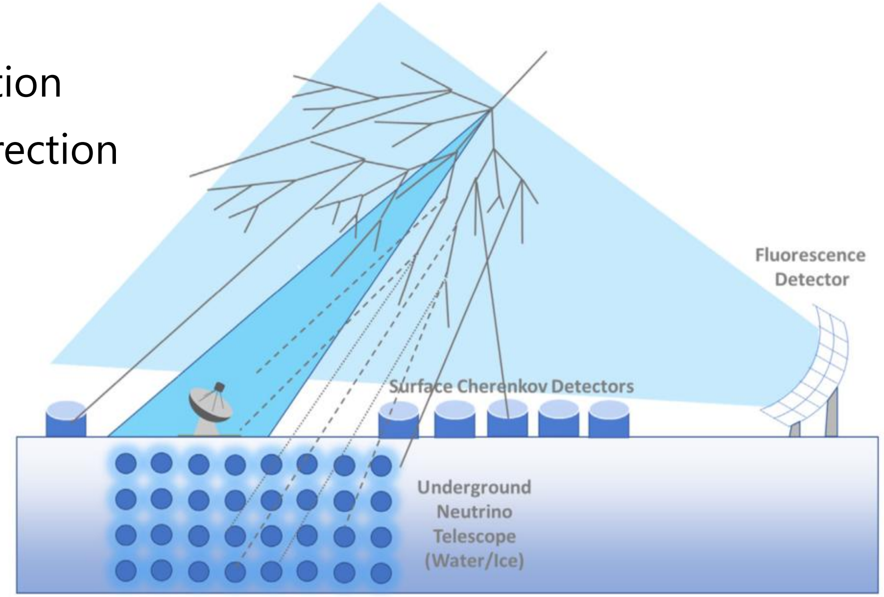
IceCube Summer School 2025

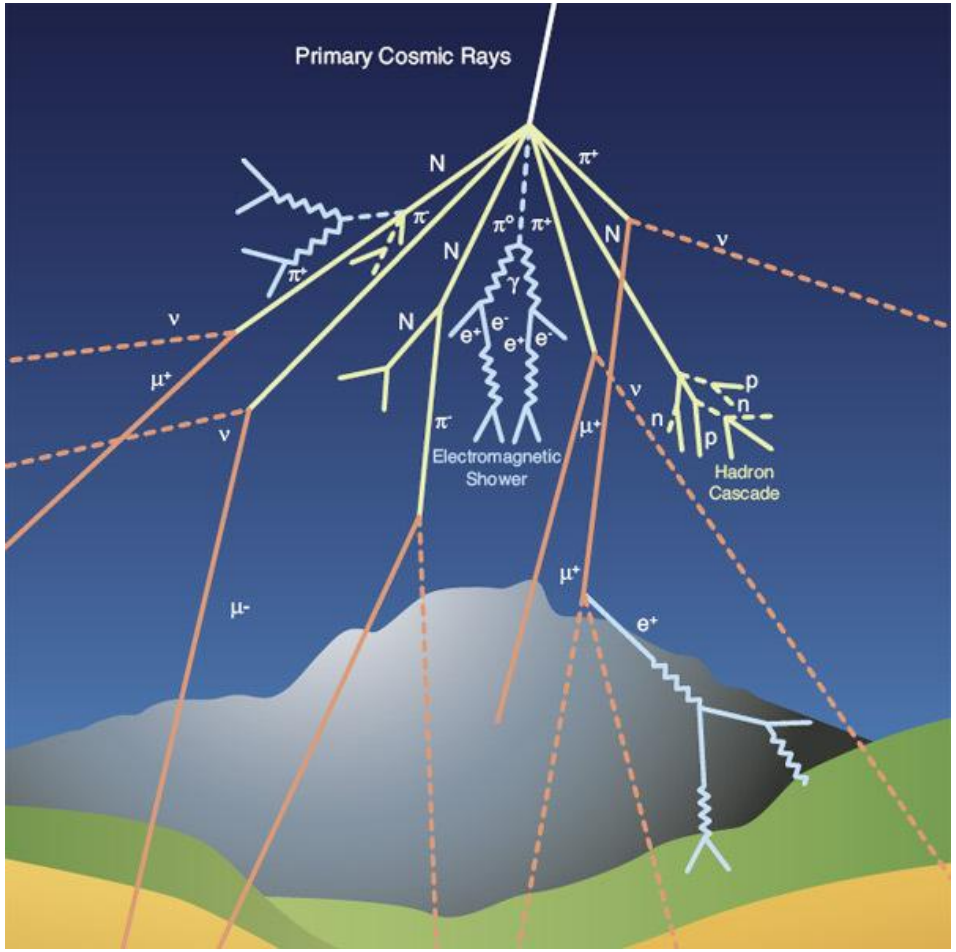


Perri Zilberman
University of Wisconsin - Madison
pzilberman@wisc.edu

A Review

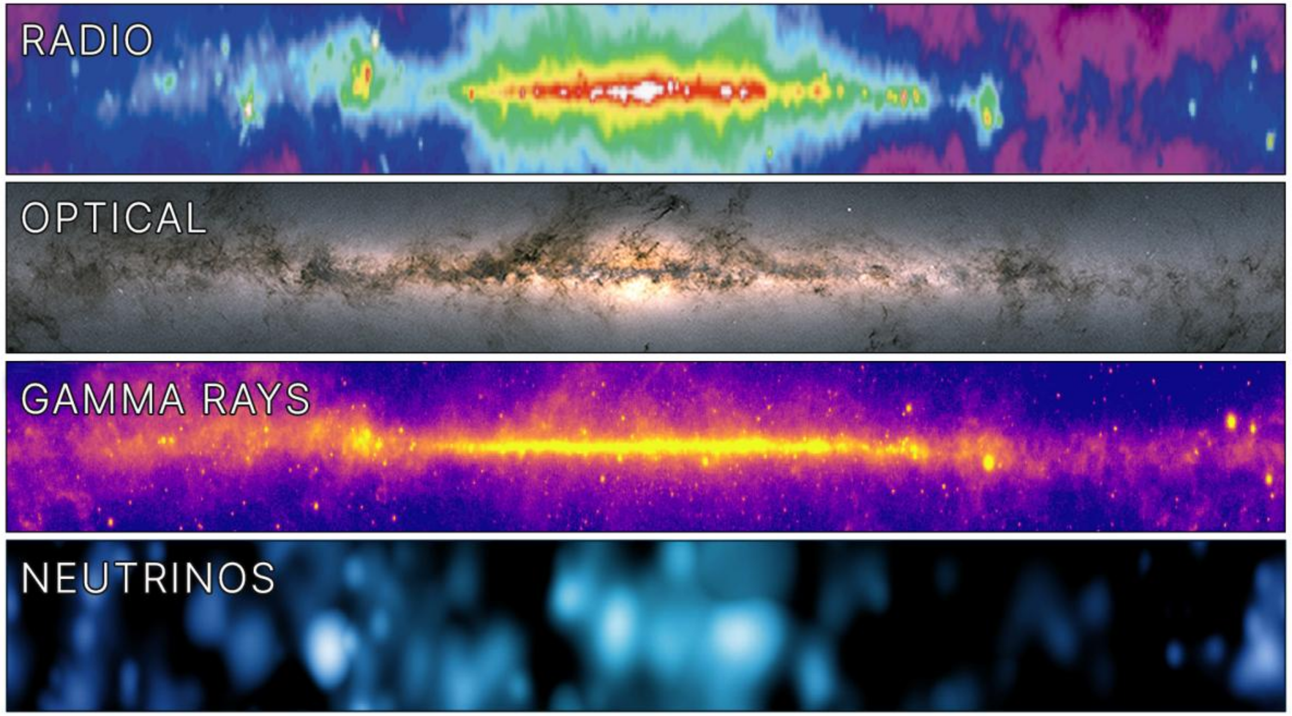
- Charged particles constantly bombarding the Earth
- Mostly protons and helium, trace amounts of other particles
- Create extensive air showers when they interact with a particle in the atmosphere
  - These are what we measure
- Key properties:
  - Energy
  - Composition
  - Arrival direction

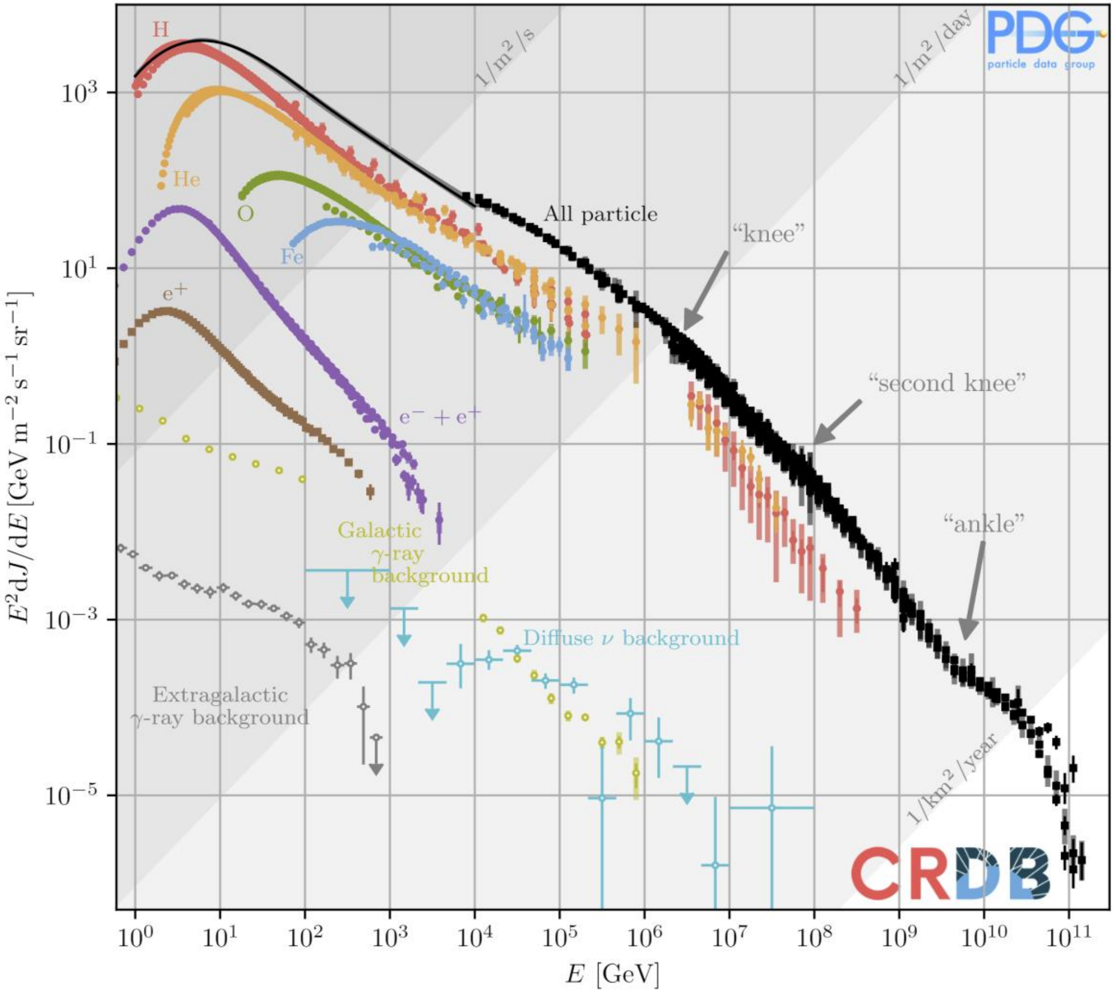




Cosmic Ray Measurements

- Usually care about all three observables for neutrinos and photons, including arrival direction
- For Cosmic Rays, arrival direction is often of less interest – this is a mistake!
- Why?



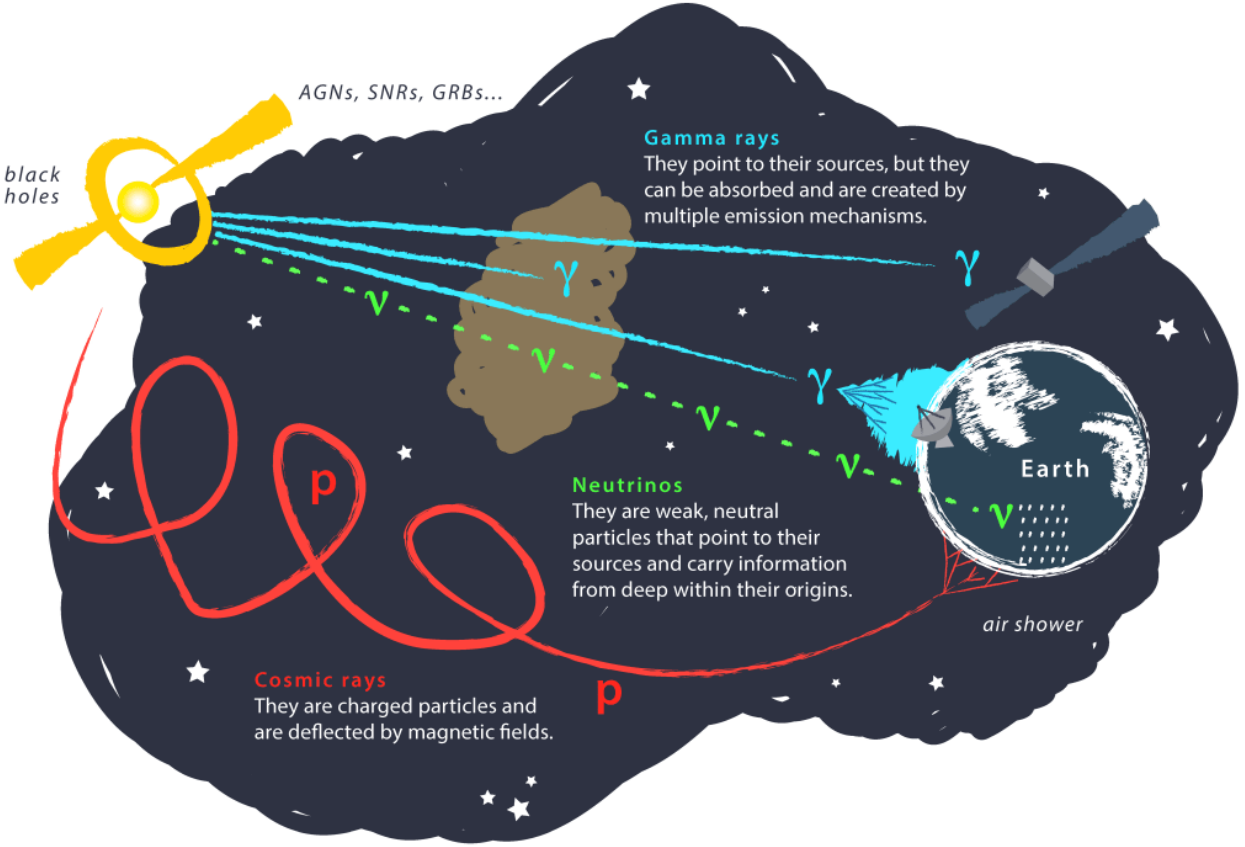


Magnetic Fields

- The Universe is permeated by magnetic fields, which alter the paths of charged particles

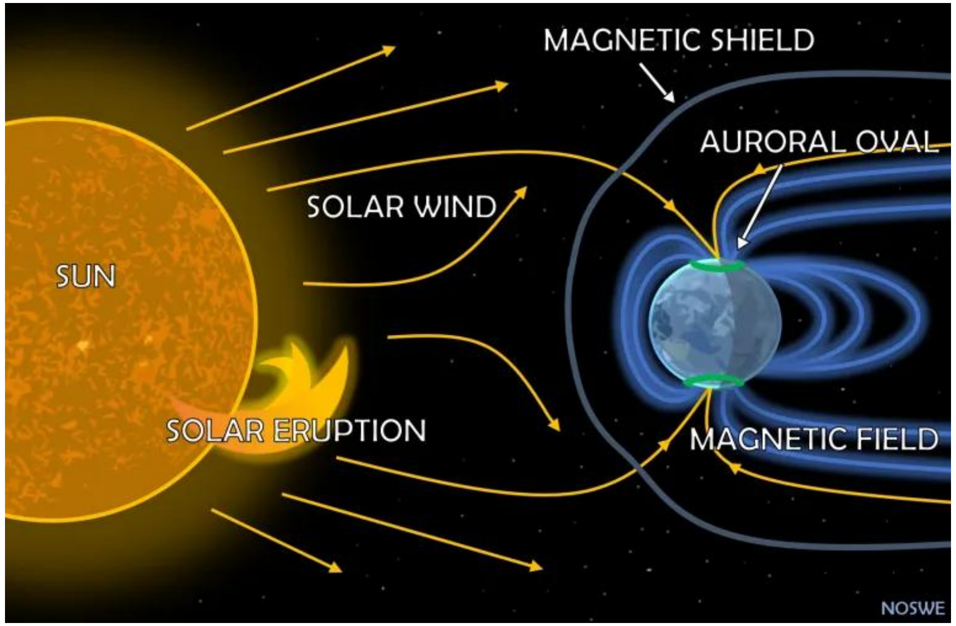
Lorentz Force Law: $\mathbf{F} = \mathrm{q}(\mathbf{E} + \mathbf{v} \times \boldsymbol{B})$

- Photons and neutrinos are neutral – they travel directly(ish) from the source to us!
- Cosmic rays, meanwhile, get bounced around by magnetic fields, losing directional information
- In principle, could backtrack cosmic rays to their sources if we knew exact configuration of magnetic fields everywhere – but that's not feasible



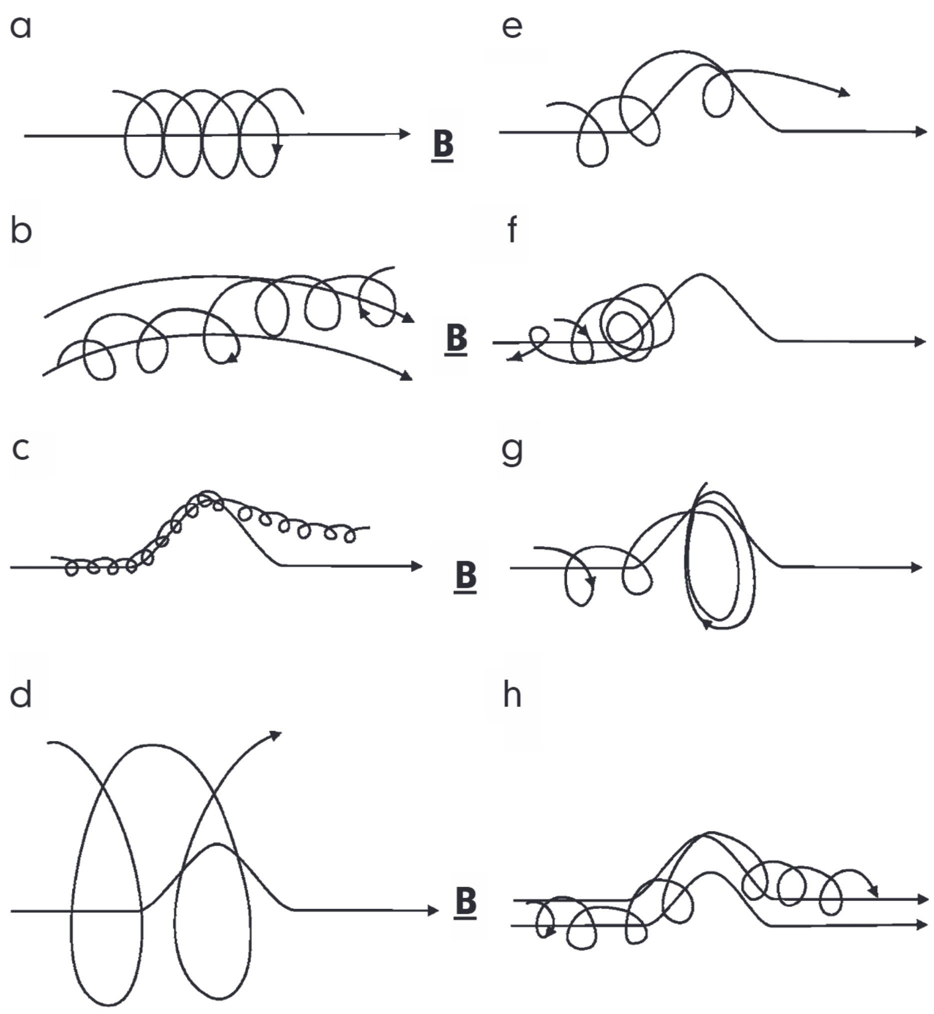
A Non Cosmic Ray Example – The Solar Wind

- The Sun constantly emits charged particles – the Solar Wind
- The Earth is surrounded by a self-produced magnetic field – the magnetosphere
- The magnetosphere redirects the solar wind around the Earth, shielding us
- On occasion, redirected solar wind particles can be seen as aurorae



The Result

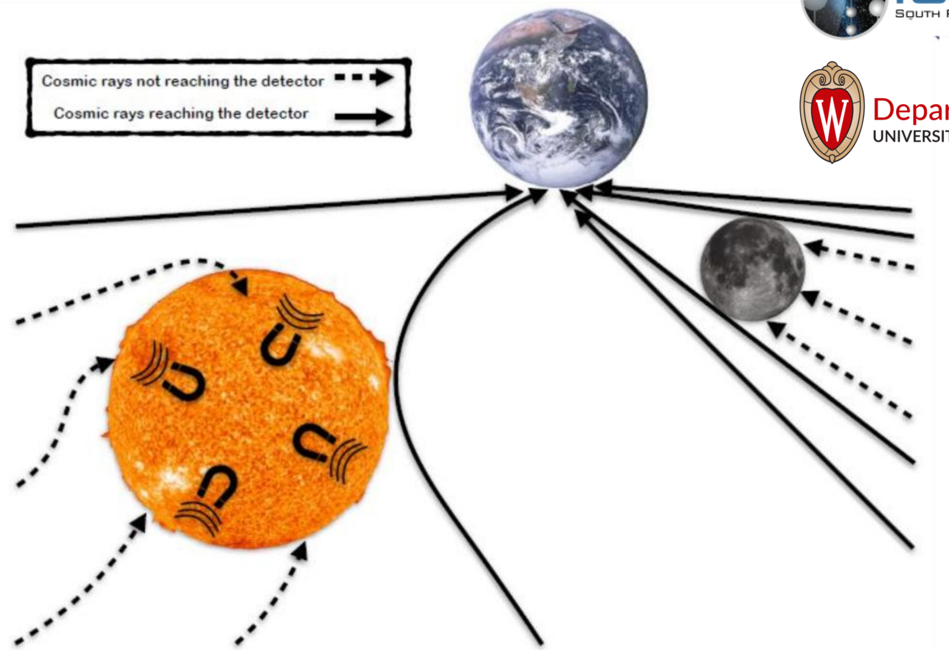
- Turbulent magnetic fields permeate the galaxy, scattering cosmic rays until they arrive *almost* isotopically at the Earth
- **But**, not *completely* isotropically – small differences from one part of the sky to the other
- Any *anisotropies* encode interesting physics
- Some things which can cause anisotropies:
    - Something blocks the cosmic rays
    - We move relative to the Cosmic Rays
    - Cosmic Rays move preferentially in some direction
- Lots of room for interesting physics!

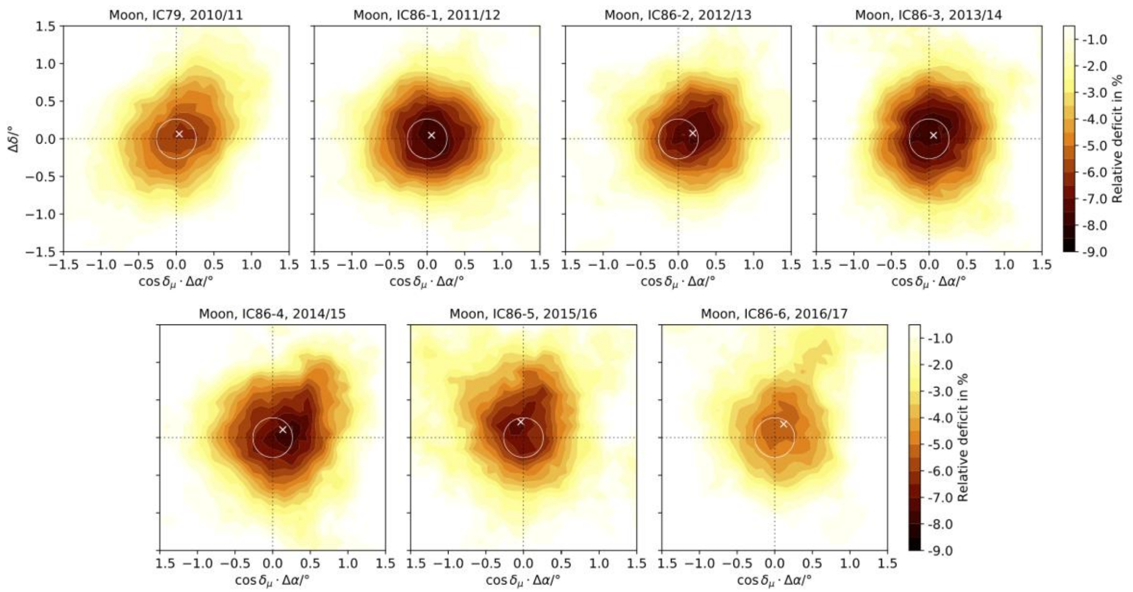


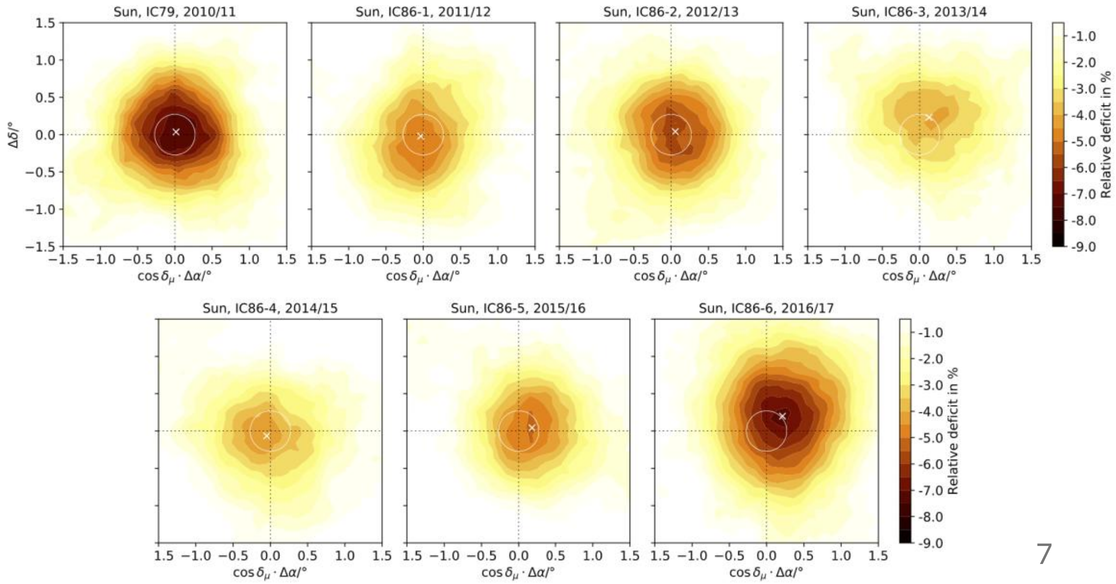
Gaisser, T. K., Engel, R., & Resconi, E. 2016, Cosmic Rays and Particle Physics (Second edition; Cambridge: Cambridge University Press)

The Sun and Moon Shadow

- The Sun and the Moon block Cosmic Rays, creating a Cosmic Ray Shadow
- Has been measured by IceCube (as well as a number of other observatories)
- Typically about a couple percent
- Some interesting features…







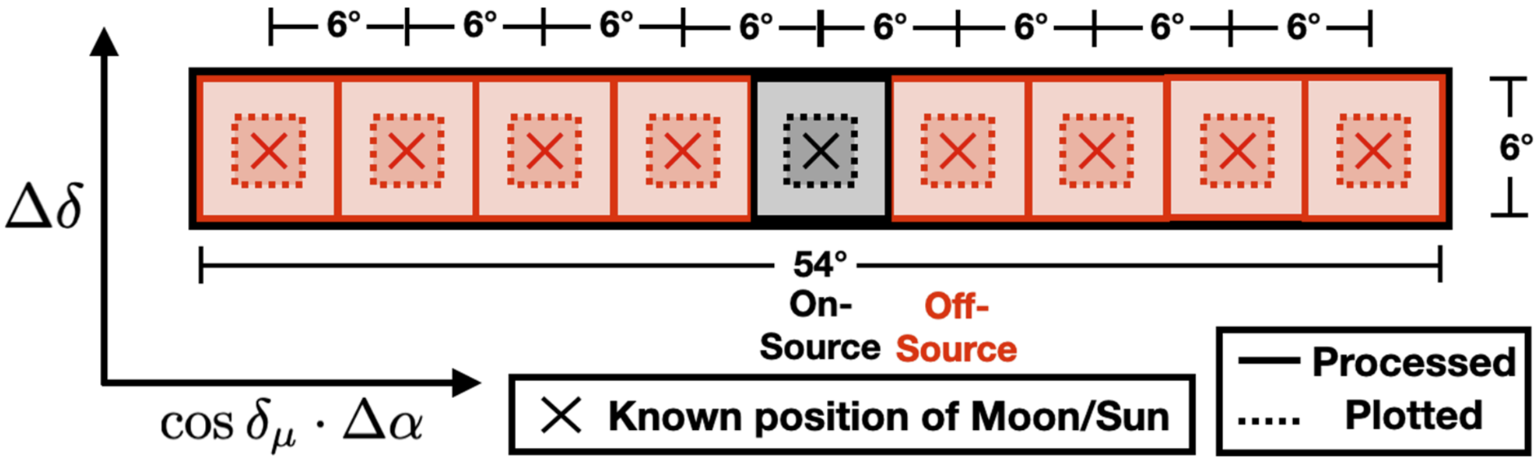
Aartsen, M. G., Abbasi, R., Ackermann, M., et al. 2020, Phys Rev D, 103, 042005

But First, What Are We *Specifically* Looking At?

- The Cosmic Ray Anisotropy is typically given as a *Relative Intensity*

Data (Counts) **Background**

$$R = \frac{\overset{\text{Data (Counts)}}{N} - \overset{\text{Background}}{\langle N \rangle}}{\langle N \rangle}$$

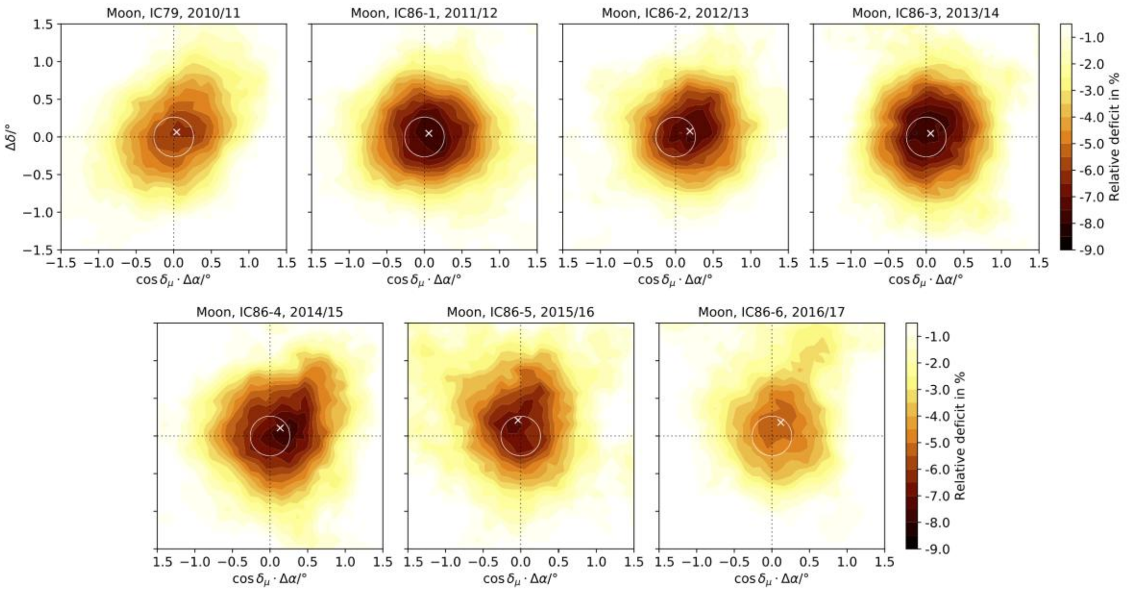


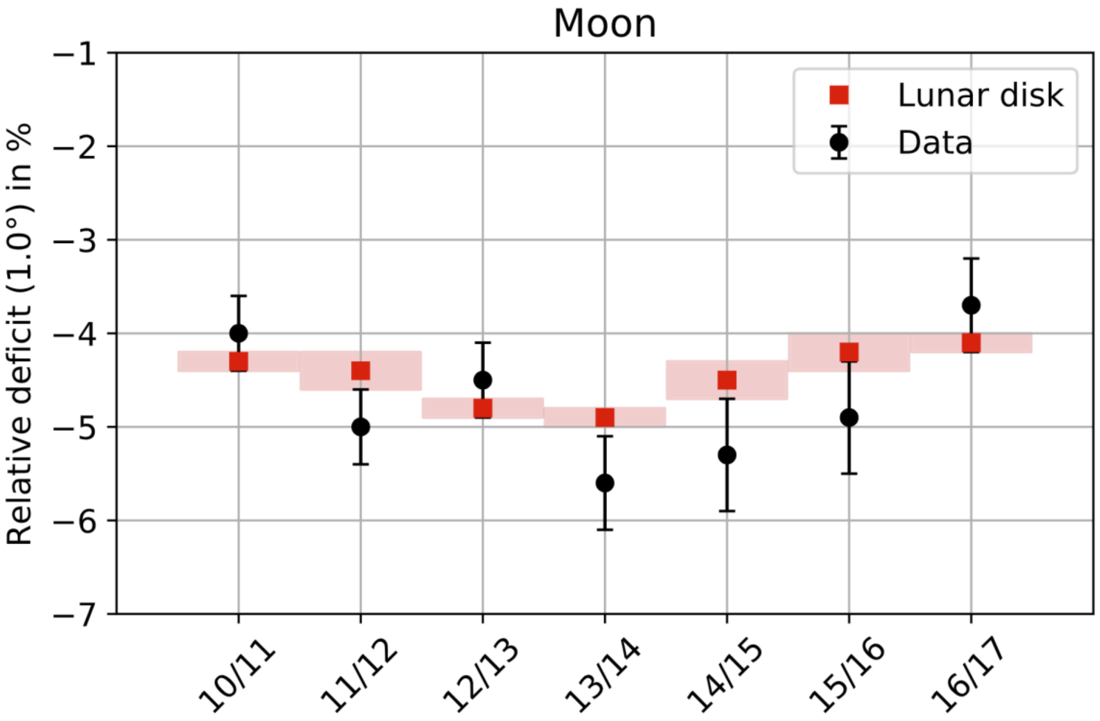
- For the Sun and Moon shadow: how many cosmic rays do you actually see ("on" counts) vs. how many do you expect to see if there was nothing there ("off" counts or background)

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

The Moon Shadow

- Essentially just a solid circle on the sky
- Can predict, with good accuracy, the amount of cosmic rays blocked based purely on how much of the sky the moon covers
- This makes it a good angular resolution test

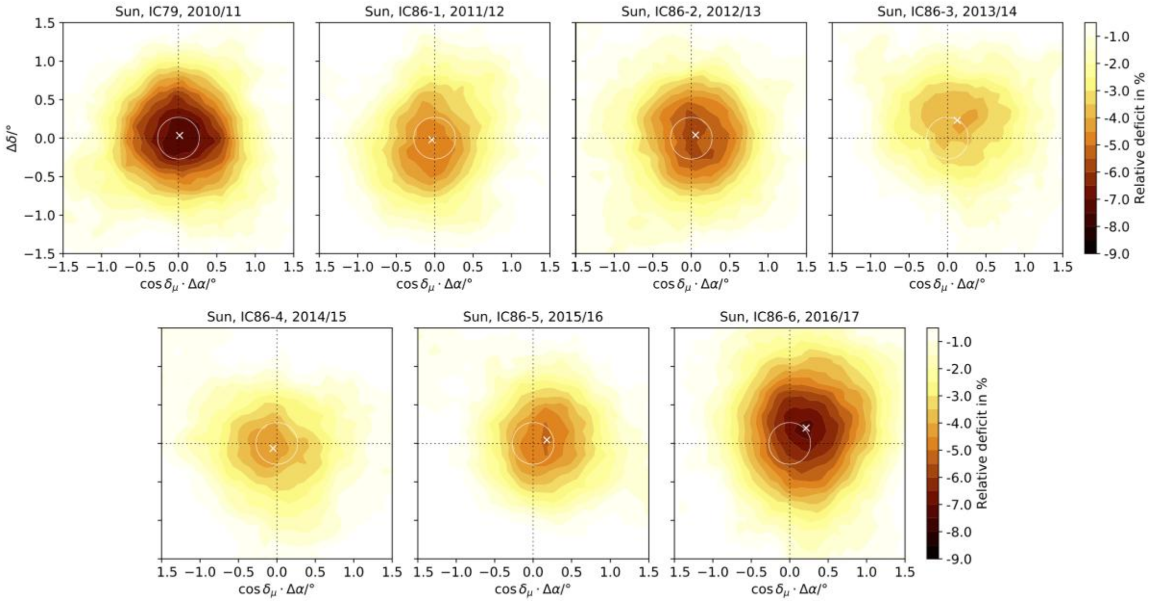


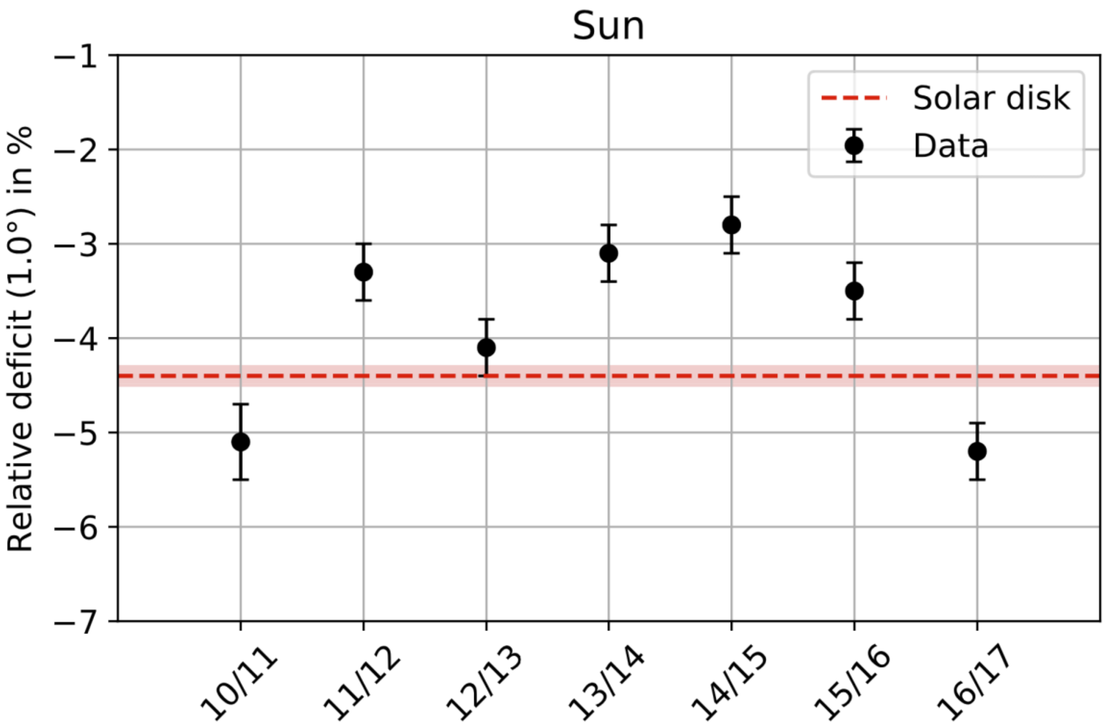


Aartsen, M. G., Abbasi, R., Ackermann, M., et al. 2020, Phys Rev D, 103, 042005

The Sun Shadow

- Unlike the Moon, has a *magnetic field* – one which changes in time due to the 11 year solar cycle!
- The shadow appears to change in time with the solar cycle – provides a way to study the magnetic field near the Sun

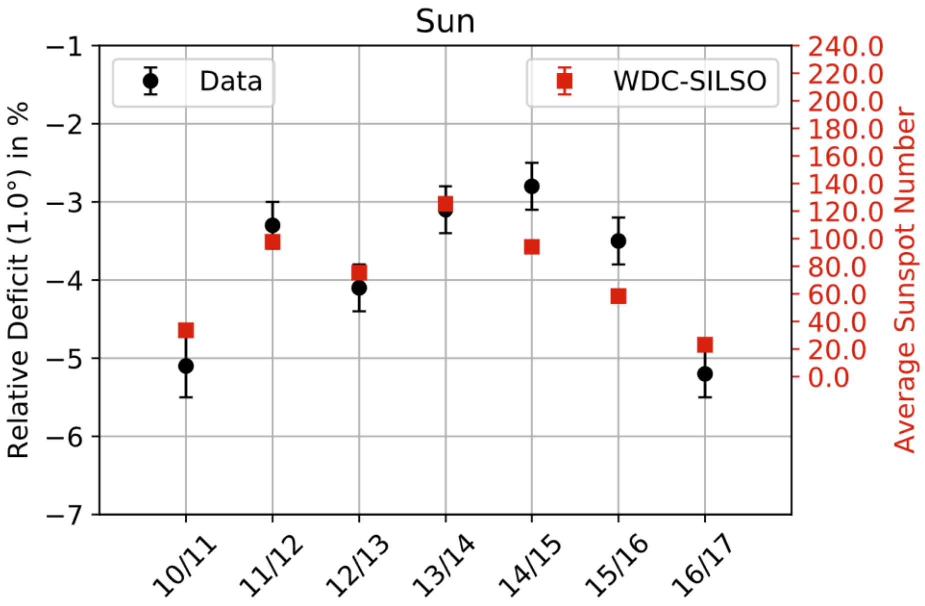


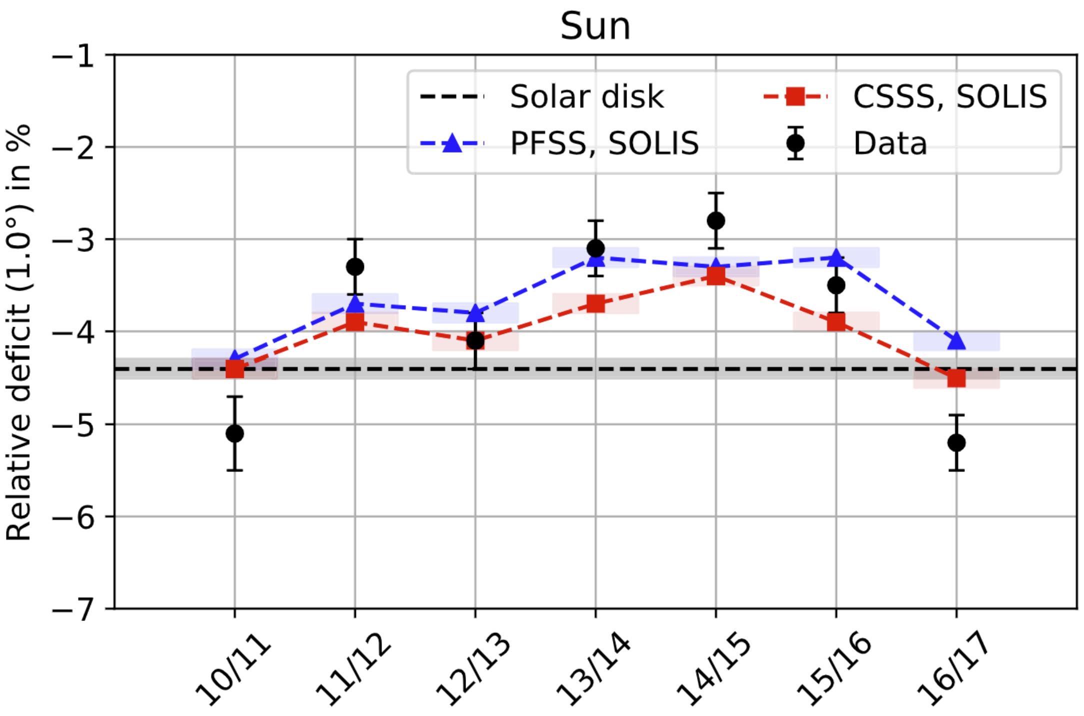


Aartsen, M. G., Abbasi, R., Ackermann, M., et al. 2020, Phys Rev D, 103, 042005

The Sun Shadow

- Unlike the Moon, has a *magnetic field* – one which changes in time due to the 11 year solar cycle!
- The shadow appears to change in time with the solar cycle – provides a way to study the magnetic field near the Sun



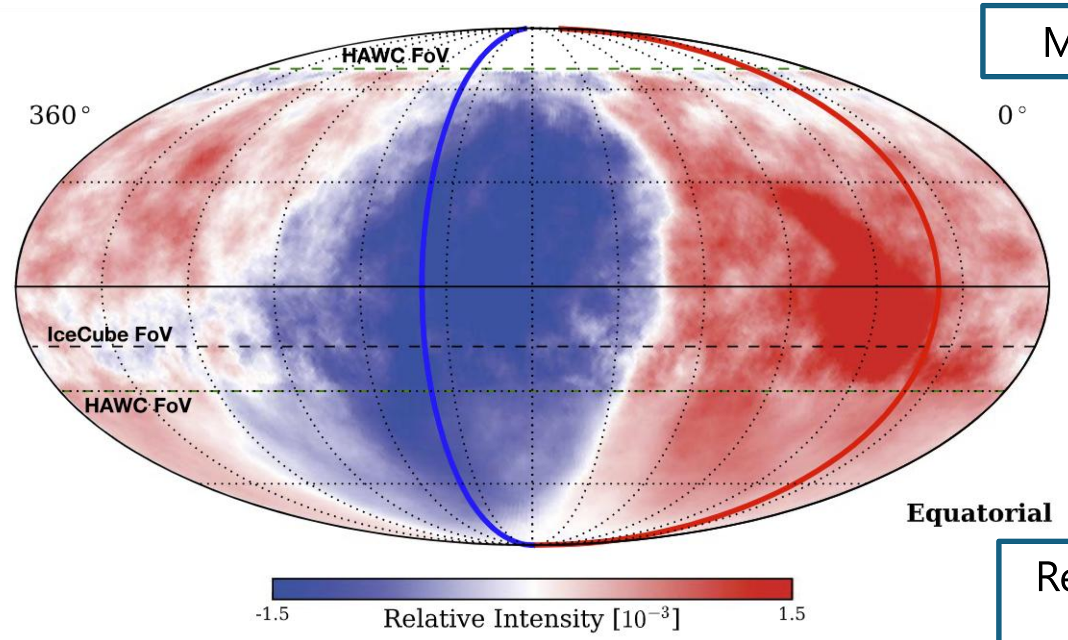


Aartsen, M. G., Abbasi, R., Ackermann, M., et al. 2020, Phys Rev D, 103, 042005

Let's Look at the Whole Sky Now

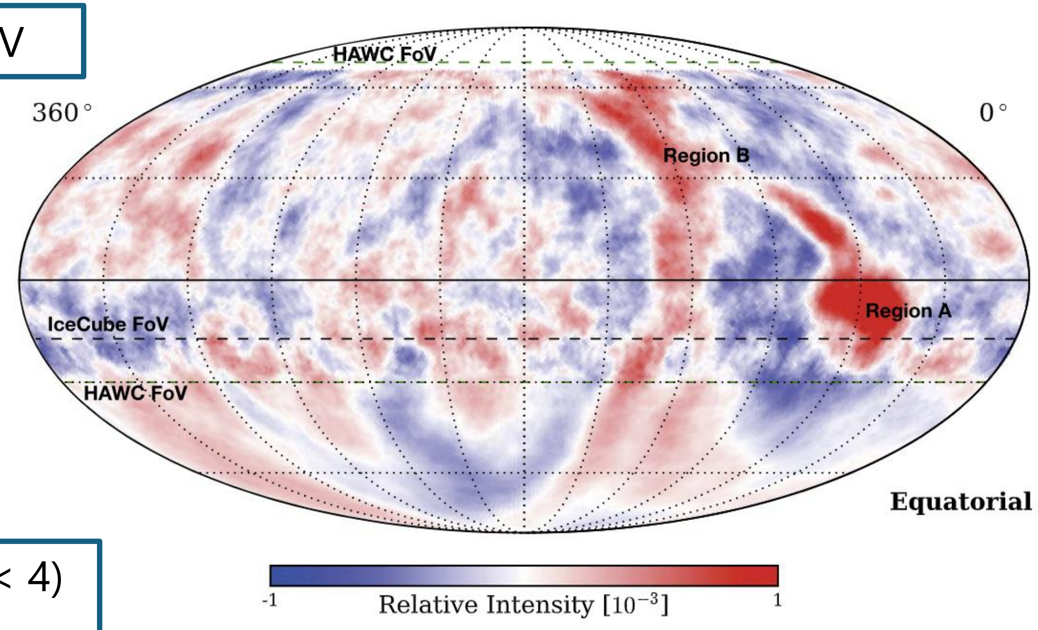
- Anisotropy of order 0.1% across entire sky
- Most prominent feature is dipole-like feature
- Many prominent smaller features as well though
- <u>Note:</u> Due to reconstruction method, every declination essentially reconstructed independently

As a result, unable to measure anisotropy across different right ascensions



Median Energy = 10 TeV

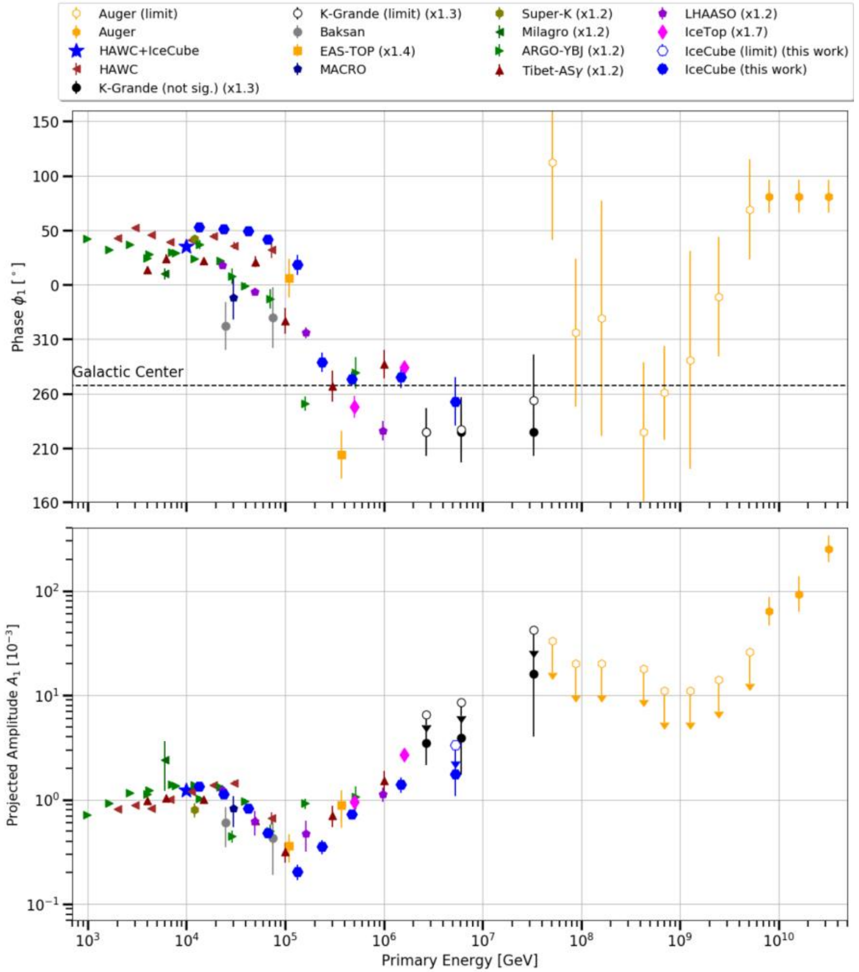
Remove large-scale (ℓ < 4) Components

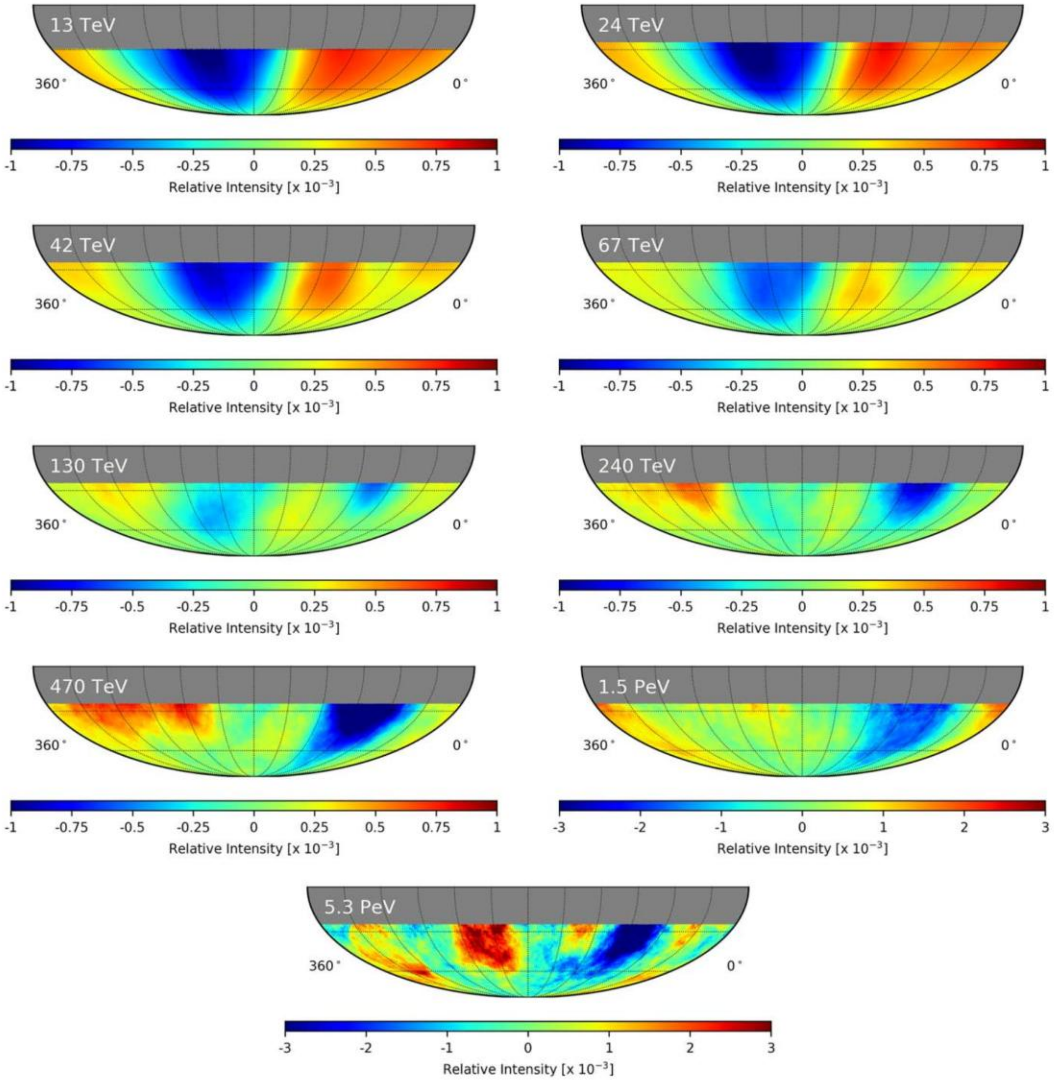


Abeysekara, A. U., Alfaro, R., Alvarez, C., et al. 2019, Astrophys J, 871, 96

The Large-Scale Dipole

- Not only is it the most prominent feature – it's energy dependent!



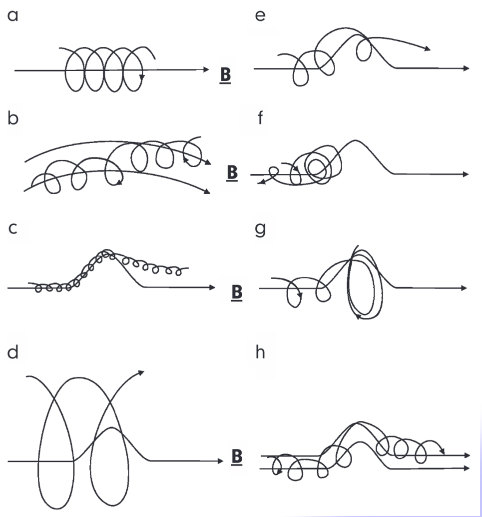


Abbasi, R., Ackermann, M., Adams, J., et al. 2025, Astrophys J, 981, 182

Potential Dipole Causes

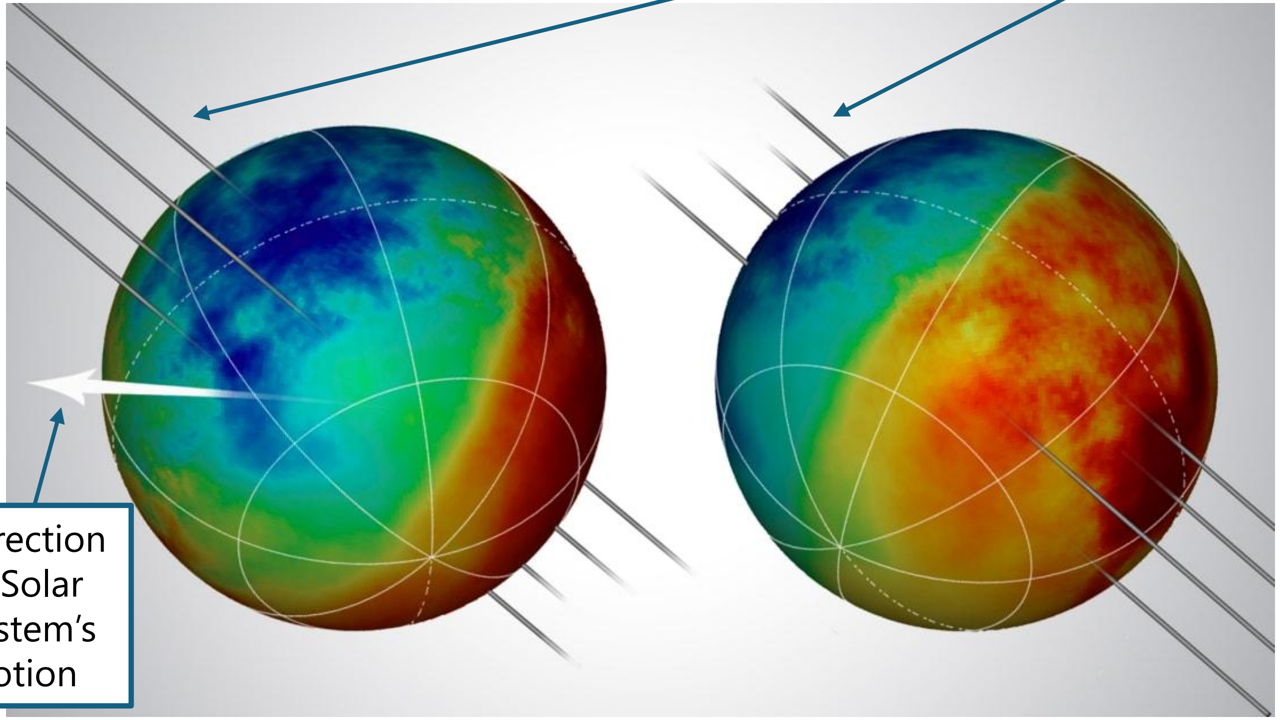
- Likely due to two potential causes:
  - Cosmic rays streaming along local magnetic field lines
  - The Compton-Getting Effect
- For streaming, can expect particles to spiral around

Local Interstellar Magnetic Field lines (LIMF)



Gaisser, T. K., Engel, R., & Resconi, E. 2016, Cosmic Rays and Particle Physics (Second edition; Cambridge: Cambridge University Press)

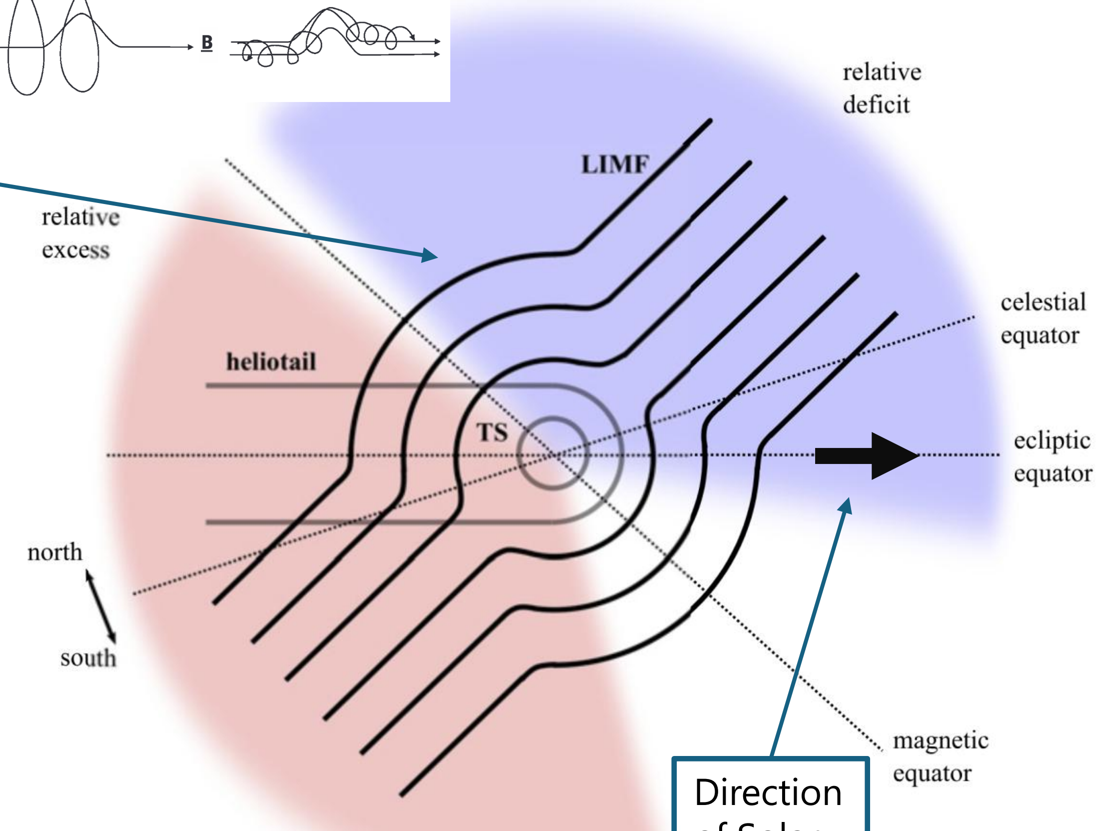
LIMF Lines



Direction of Solar System's Motion

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

*Same Anisotropy as from slide 12

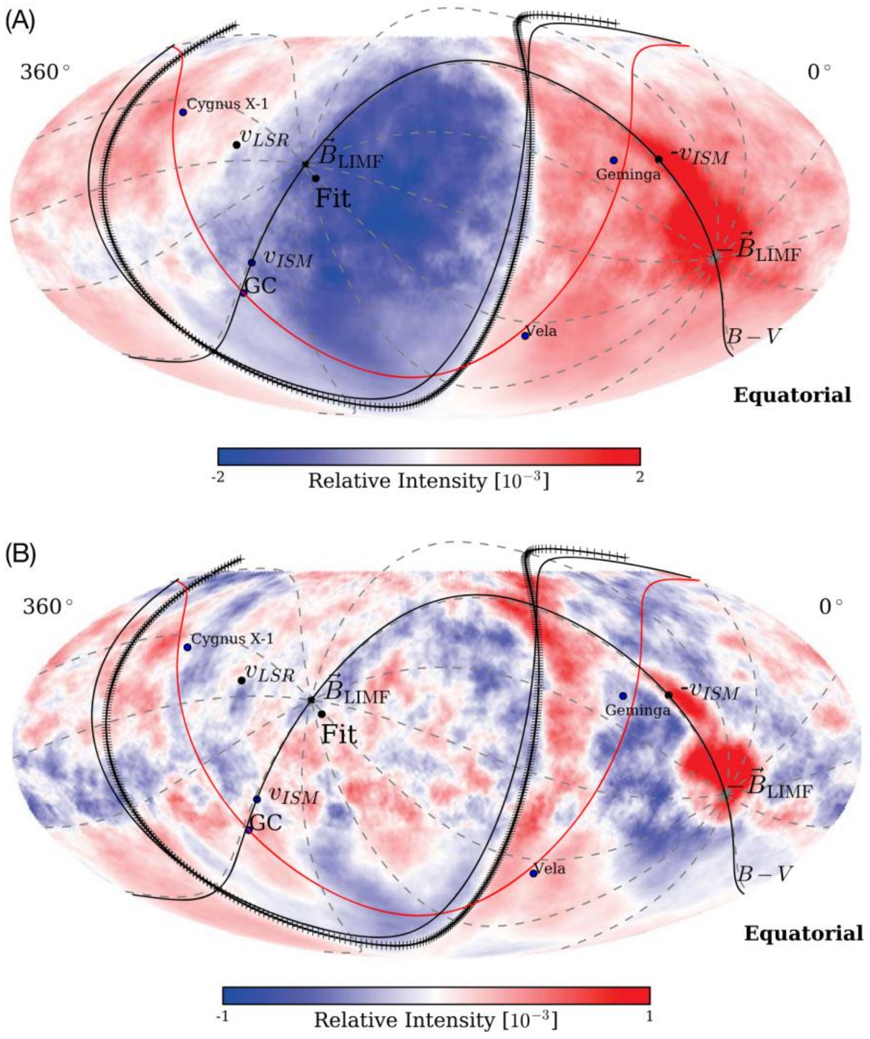


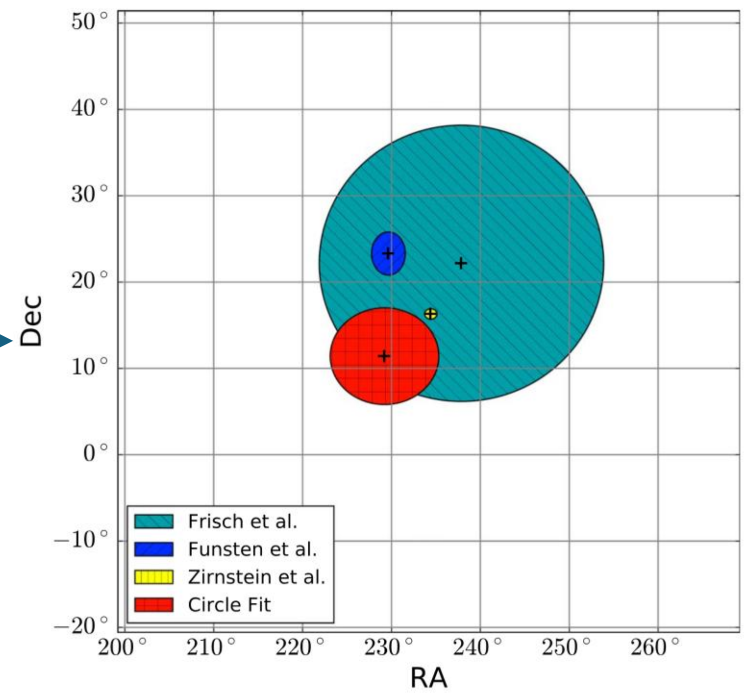
Direction of Solar System's Motion

Desiati, P., & Lazarian, A. 2011, arXiv, 762, 44

Local Interstellar Magnetic Field

- Under hypothesis, allows measurement of LIMF
- Amplitude of dipole depends on diffusion tensor – allows measurement of how particles diffuse in the Interstellar Medium

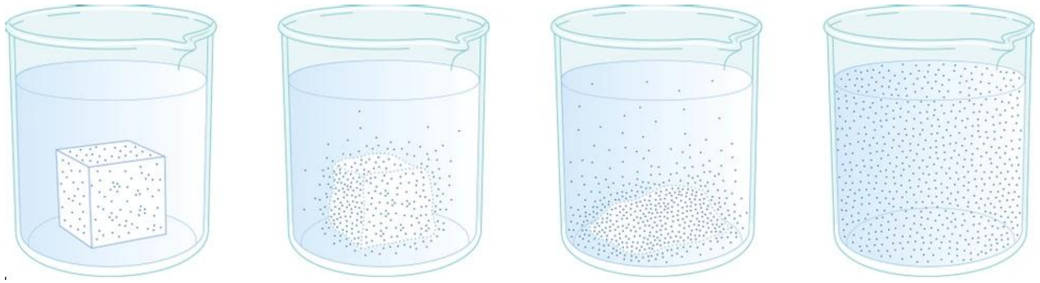




Measurement of LIMF direction by fitting boundary of large-scale excess and deficit region (in red)

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

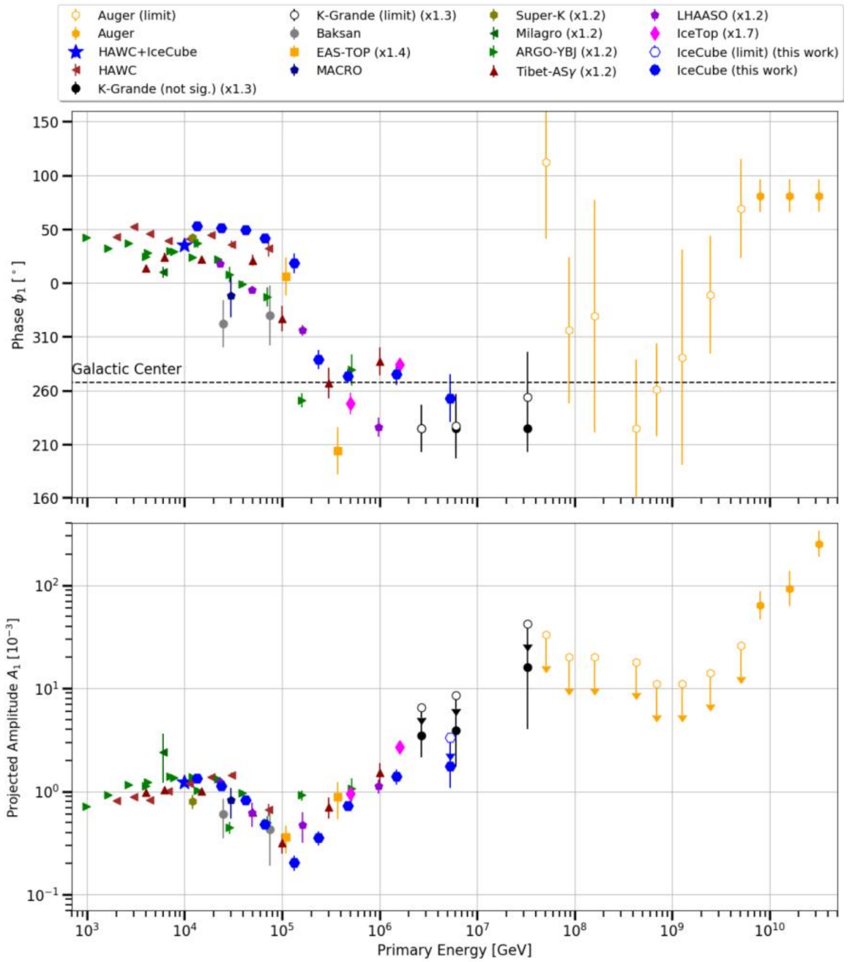
Dipole Energy Shift



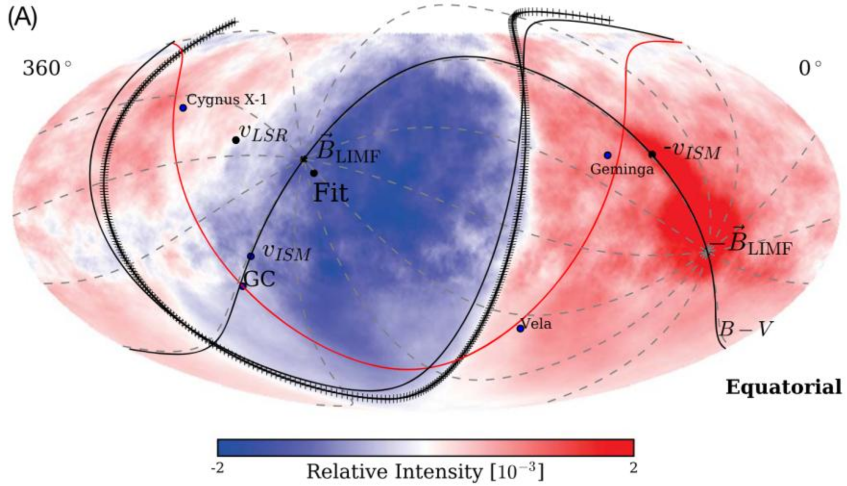
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Department of Physics
UNIVERSITY OF WISCONSIN–MADISON

- Cosmic Rays will move preferentially in one direction if there is a cosmic ray *density gradient* due to diffusion
- Expect higher cosmic ray density towards galactic center
    - might expect them to stream from that direction
- They generally do for higher energies, but at lower energies stream from opposite direction
- Potential cause: local sources contribute at lower energy
- Plausible sources:
    - Vela
    - Geminga



Median Energy = 10 TeV

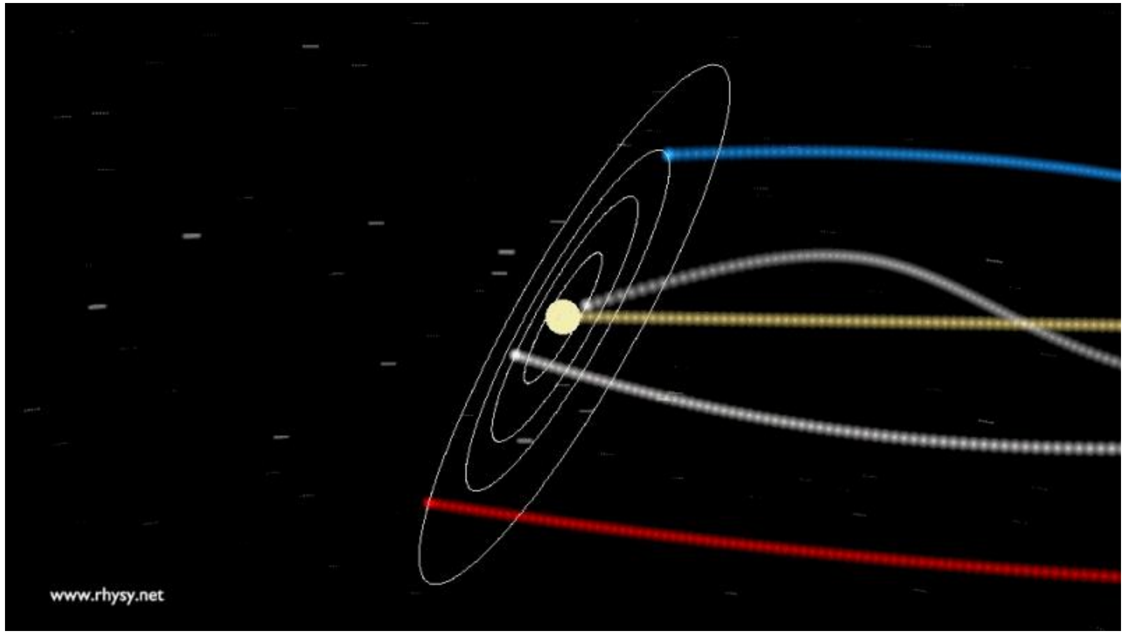


Another Dipole-Causing Phenomenon: The Compton-Getting Effect

- Expect to see excess in Cosmic Rays in direction of motion with respect to rest frame of cosmic rays with amplitude

$$A = \frac{v}{c}(\gamma + 2)$$

- Might consider two frames where the CG is important:
  - The frame moving with the solar system
  - The frame moving with the Earth
- If we assume cosmic rays move with the ISM, our speed relative to cosmic ray plasma rest frame is about 23 km/s
  - A = 3.6 x 10^{-4} (taking spectral index γ = 2.7)
  - Smaller than measured dipole with different expected direction – see last slide – so can't explain dipole measurement on its own

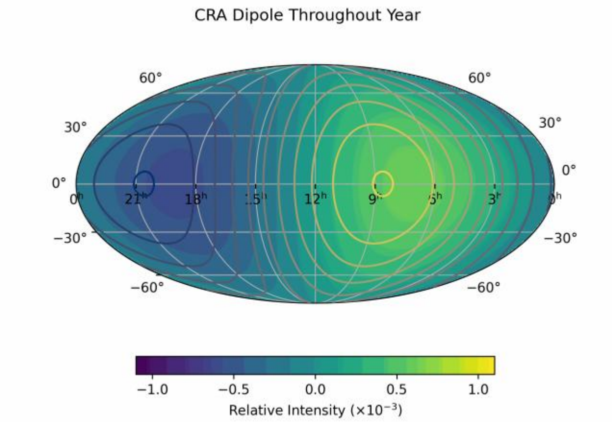


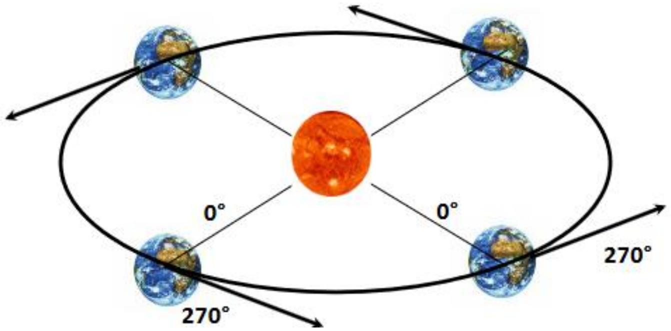
Another Dipole-Causing Phenomenon: The Compton-Getting Effect

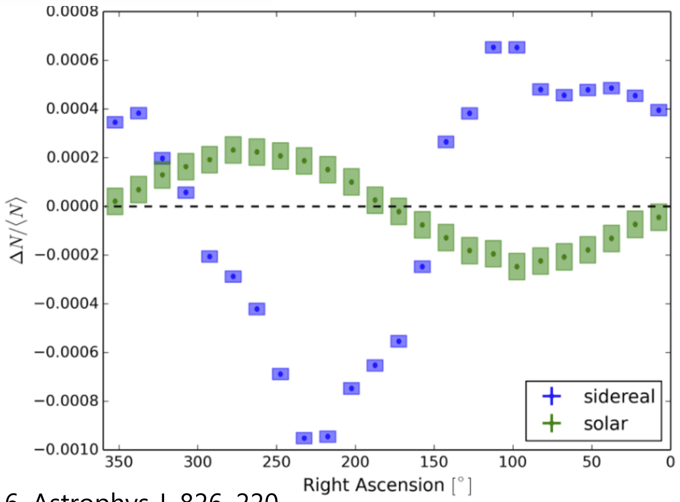
IceCube South Pole Neutrino Observatory
Department of Physics
University of Wisconsin–Madison

- The Earth moves around the Sun at ~30 km/s
- expect to see excess in direction of Earth's velocity with A = 4.7 x 10^{-4}
- This is the so-called "solar dipole"
- Interferes with the sidereal dipole
- In sidereal frame the solar dipole cancels out if integrating over one year
- In solar frame – where the Sun is stationary on the sky – the sidereal dipole cancels out if integrating over one year
- Provides an excellent calibration for a cosmic ray detector!

- Because the amplitude of the solar dipole depends on the CR spectral index, can use this is a way to measure γ!



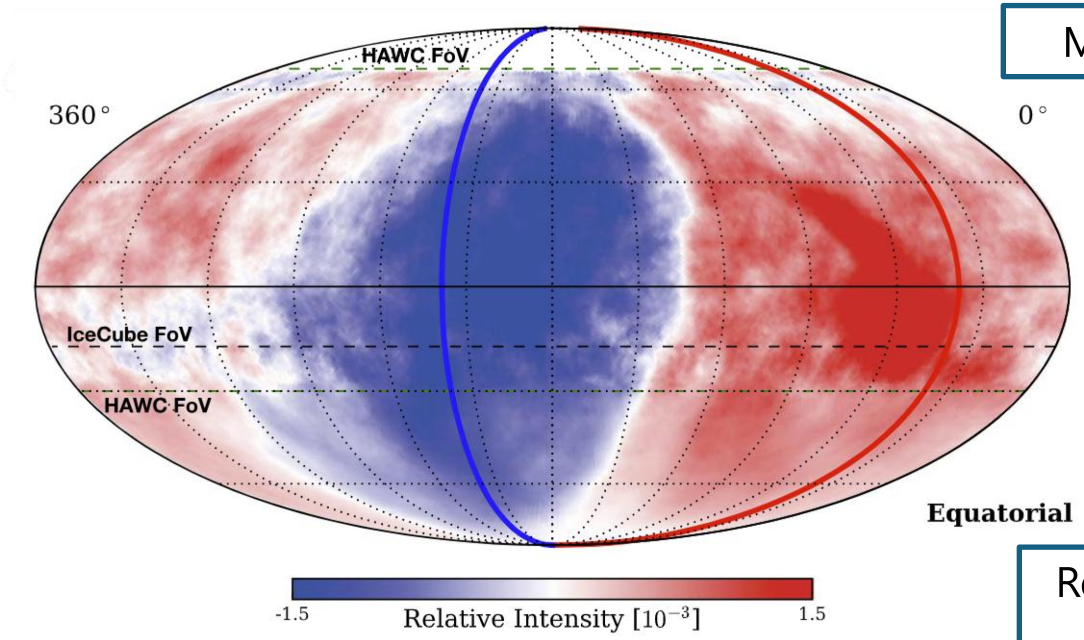




Aartsen, M. G., Abraham, K., Ackermann, M., et al. 2016, Astrophys J, 826, 220

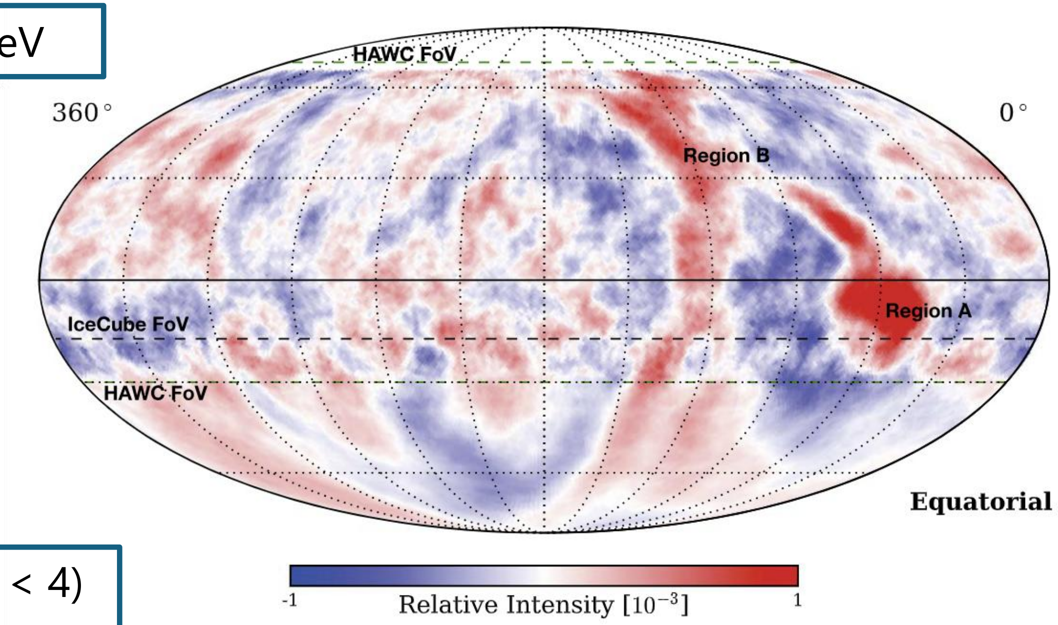
What About the Smaller Scale Anisotropy?

- Smaller scale features much less understood, but lots of discussion in the literature
- To better quantify them, typically take power spectrum of the CRA sky-map



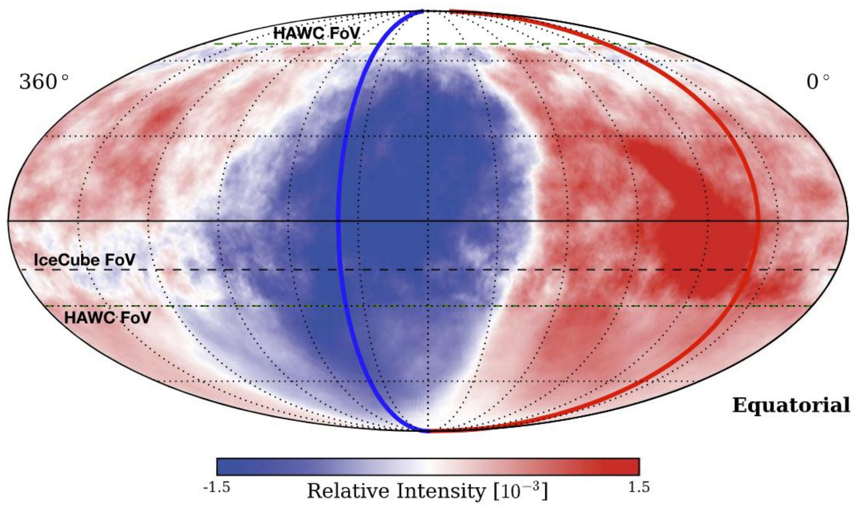
Median Energy = 10 TeV

Remove large-scale (ℓ < 4) Components

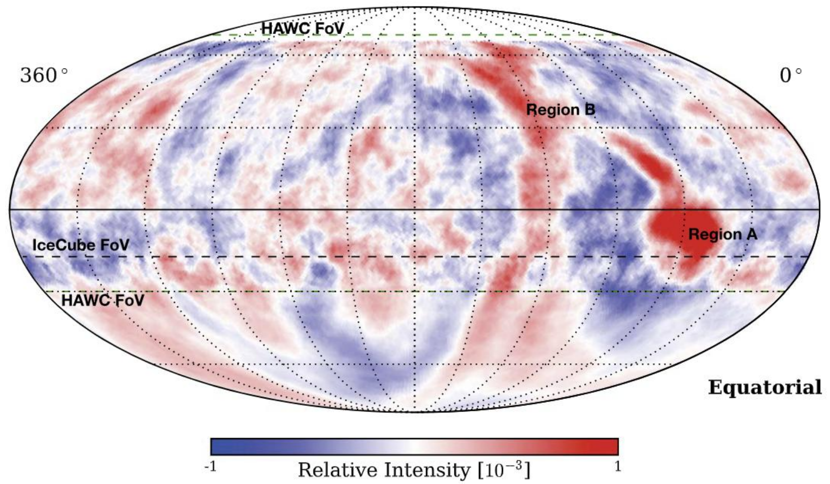


Abeysekara, A. U., Alfaro, R., Alvarez, C., et al. 2019, Astrophys J, 871, 96

TeV Cosmic Ray Power Spectrum

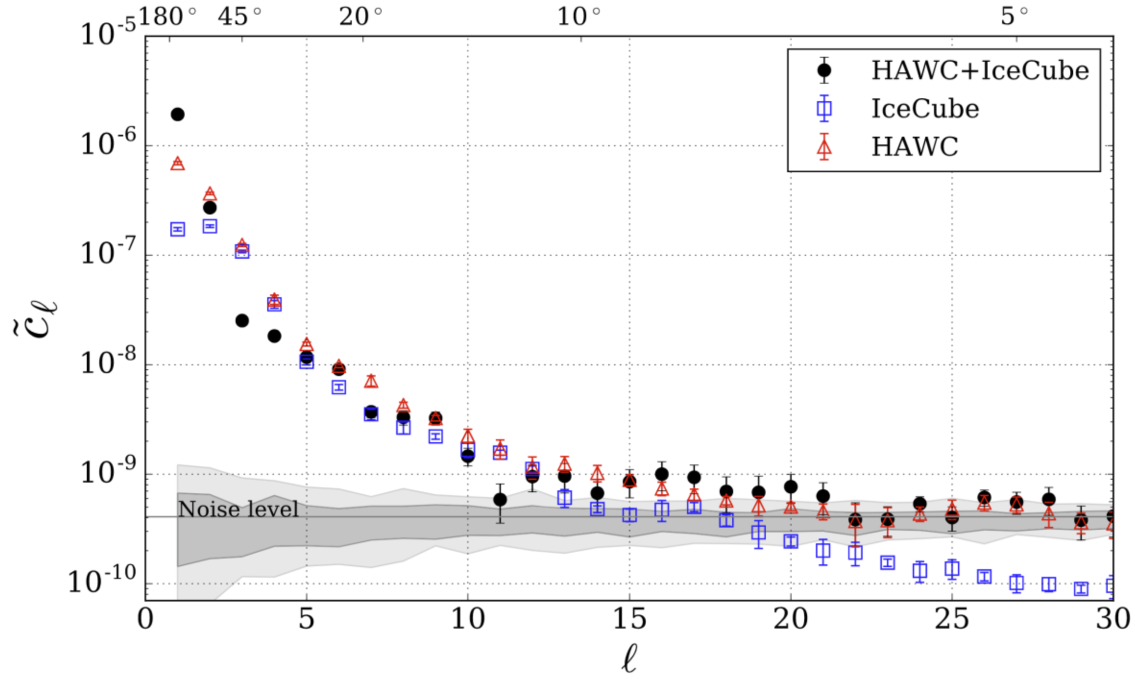


Remove large-scale (ℓ < 4) Components



- Measures power in a given angular scale
- Essentially Fourier transform on a sphere
- m = 0 term unable to be reconstructed

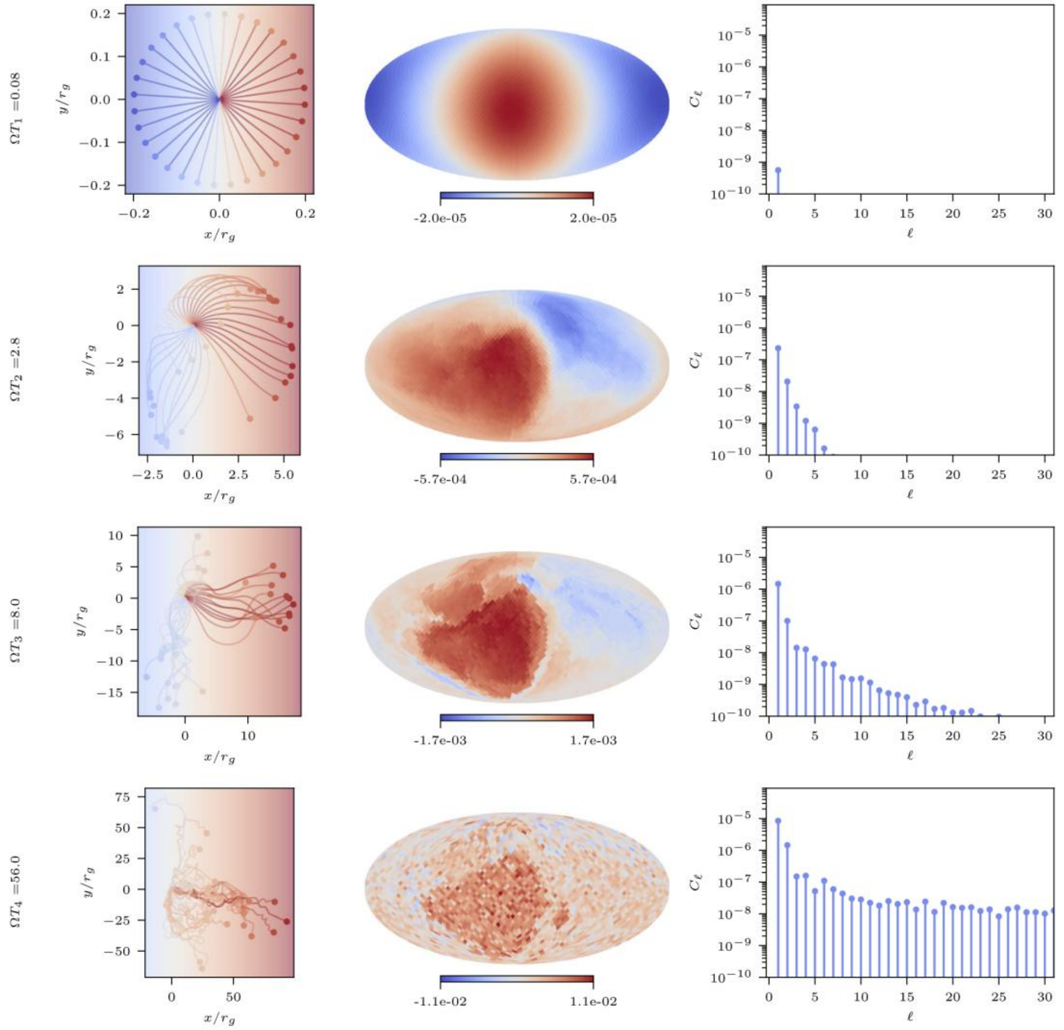
(if this means anything to you)



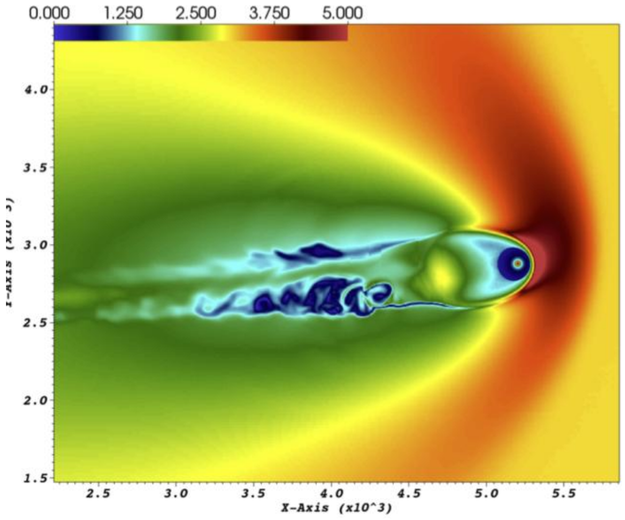
Abeysekara, A. U., Alfaro, R., Alvarez, C., et al. 2019, Astrophys J, 871, 96

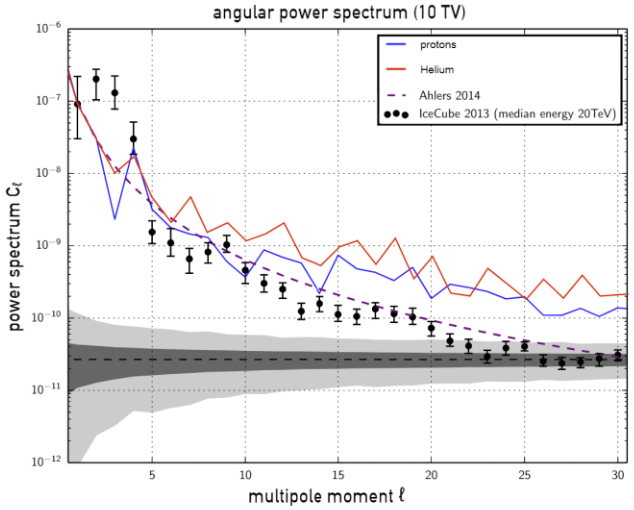
Some Potential Causes

More complex diffusion processes



Interactions with the Heliosphere



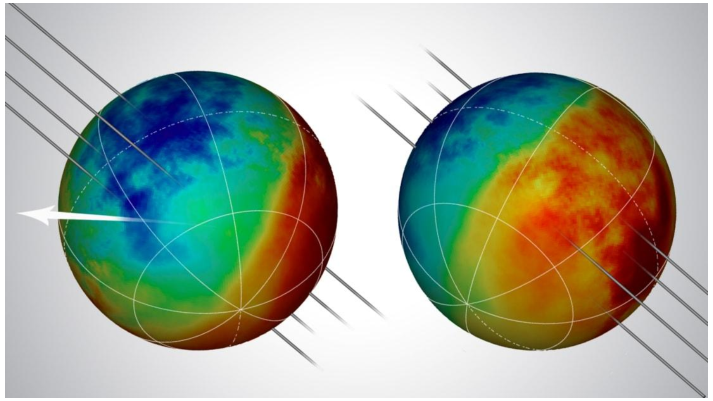


López-Barquero, V., Xu, S., Desiati, P., et al. 2016, arXiv

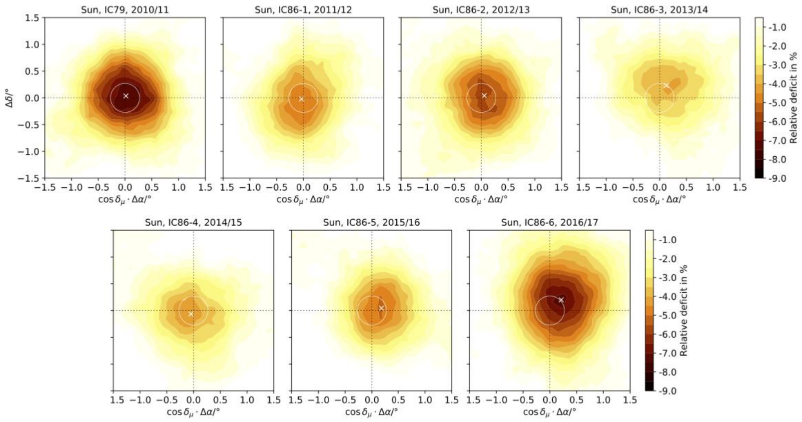
Kuhlen, M., Phan, V. H. M., & Mertsch, P. 2022, Astrophys J, 927, 110

Conclusion: Lots of Interesting Physics in the Arrival Directions of Cosmic Rays!

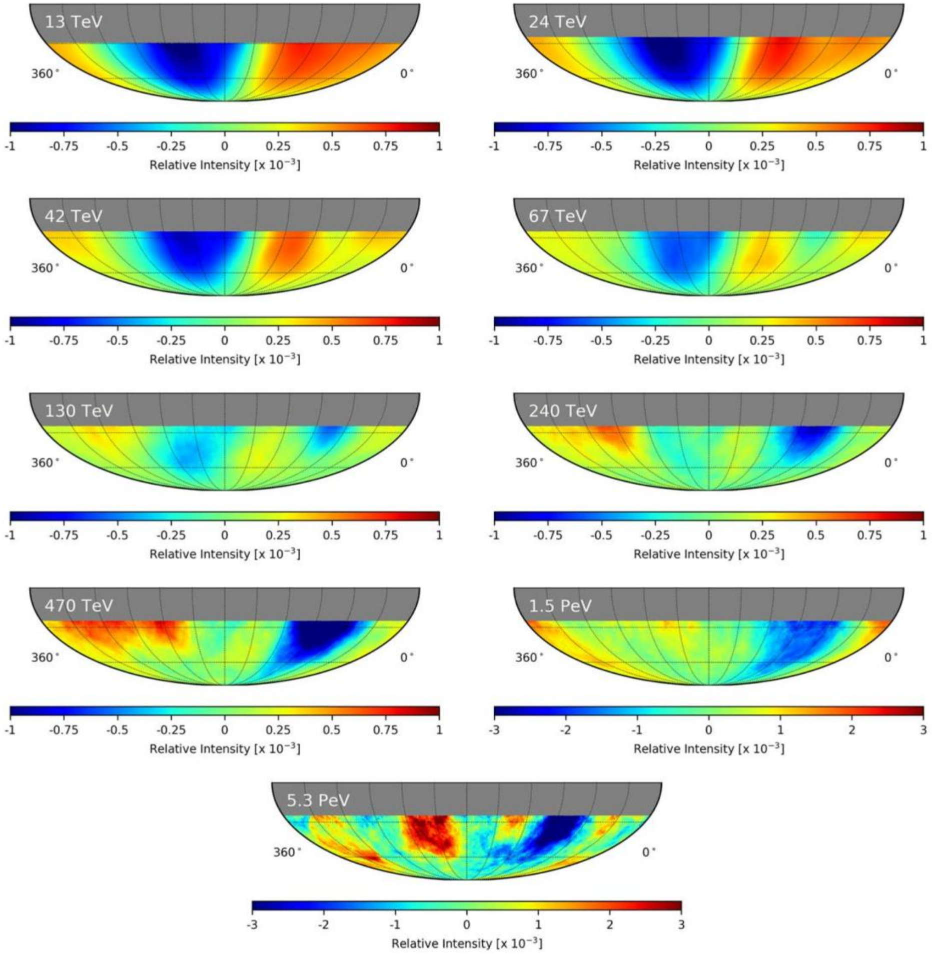
- Study the magnetic field extremely close to the Sun
- Study the Interstellar Magnetic field
- Measure the cosmic ray spectral index
- Study the edges of the Heliosphere
  - where there are very few measurements!
- Study cosmic ray diffusion in the ISM
- Get us closer to finding the sources of cosmic rays
- Gives amazing detector calibration tools



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



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



Abbasi, R., Ackermann, M., Adams, J., et al. 2025, Astrophys J, 981, 182

Thank You!

Backup

Sun Shadow Simulation

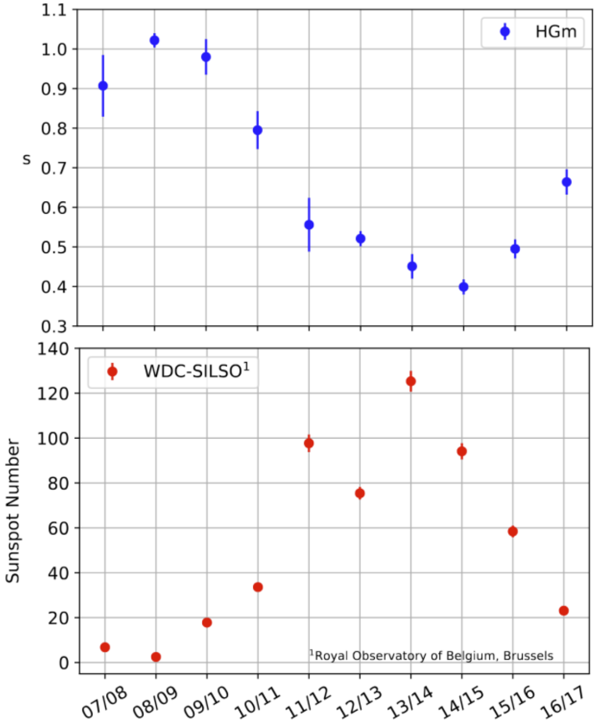


Fig. 15. Temporal behavior of shadow ratio s (assuming the HGm model) and the sunspot number in the years from 2007 through 2017. Sunspot numbers are taken from SILSO World Data Center (2007-2017).

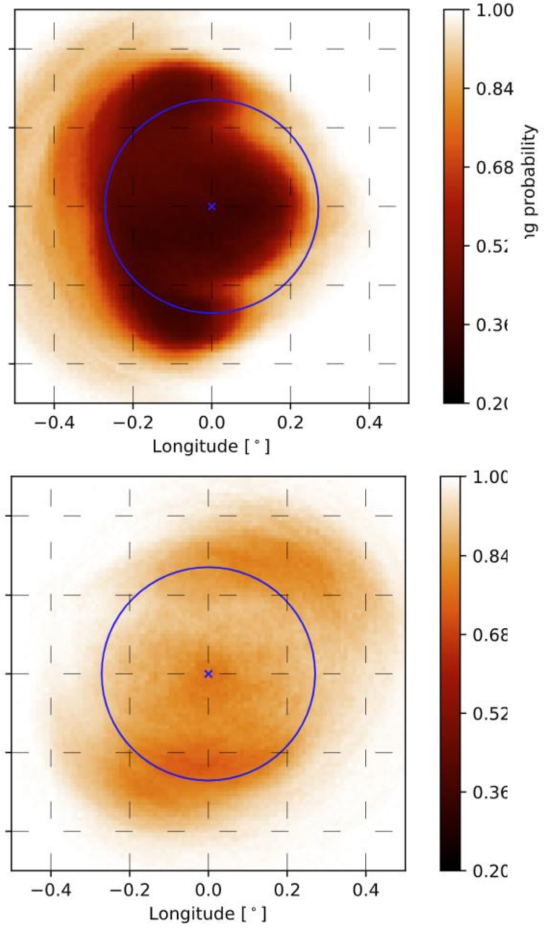
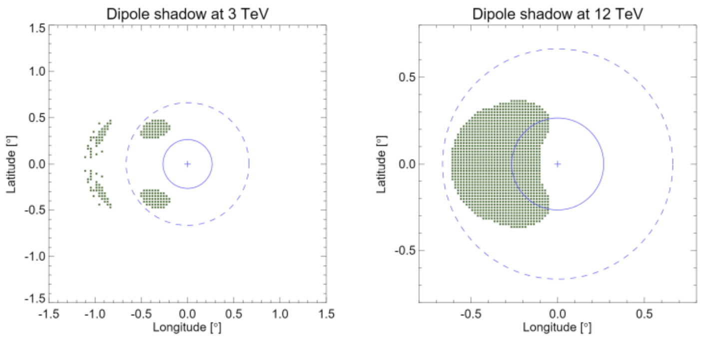
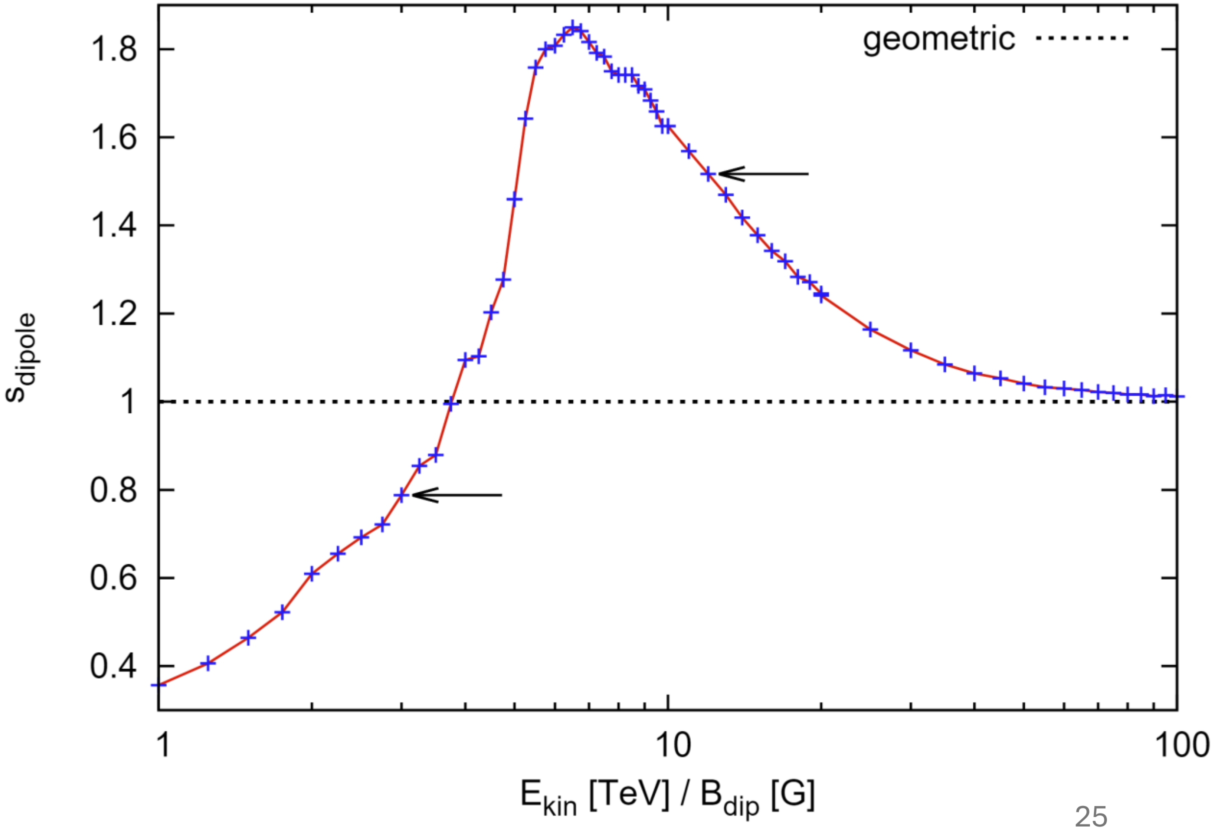


Fig. 6. Examples of visualizing the calculated Sun shadow, 09 (*top*; year of least solar activity) and 2014-15 (*bottom*; solar activity) seasons are shown, using the energy spectru position according to the GH model.





Tjus, J. B., Desiati, P.,
Döpper, N., et al. 2020,
Astron Astrophys, 633, A83

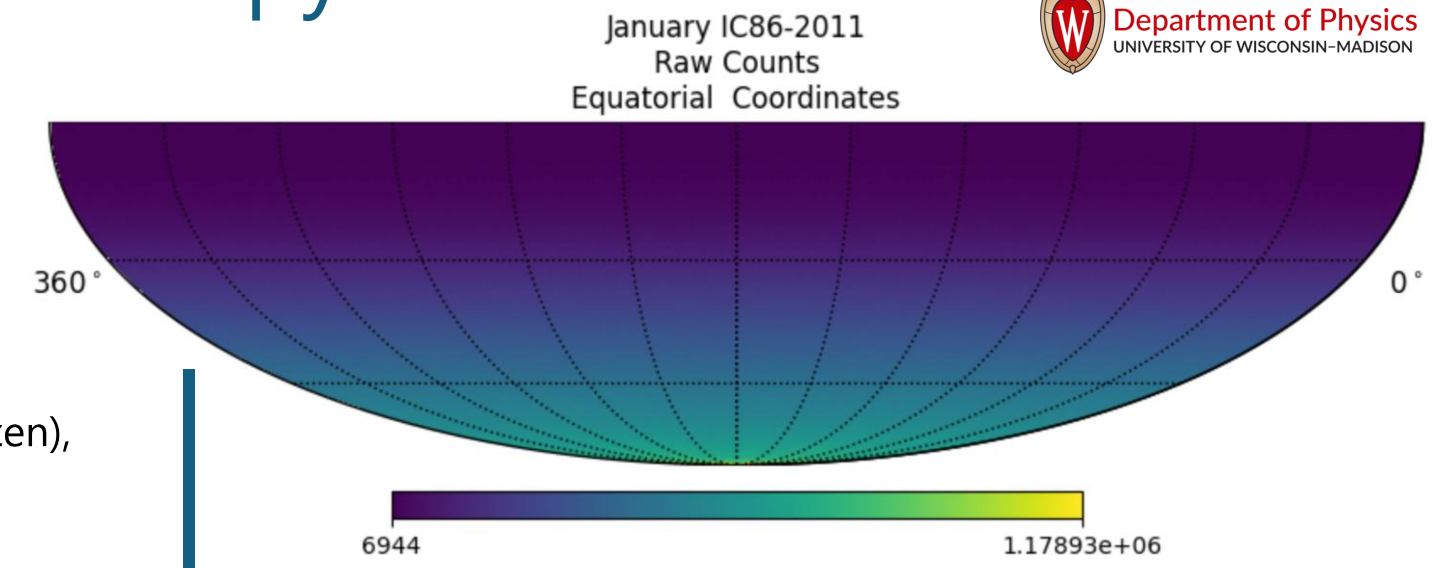
Reconstructing the Anisotropy

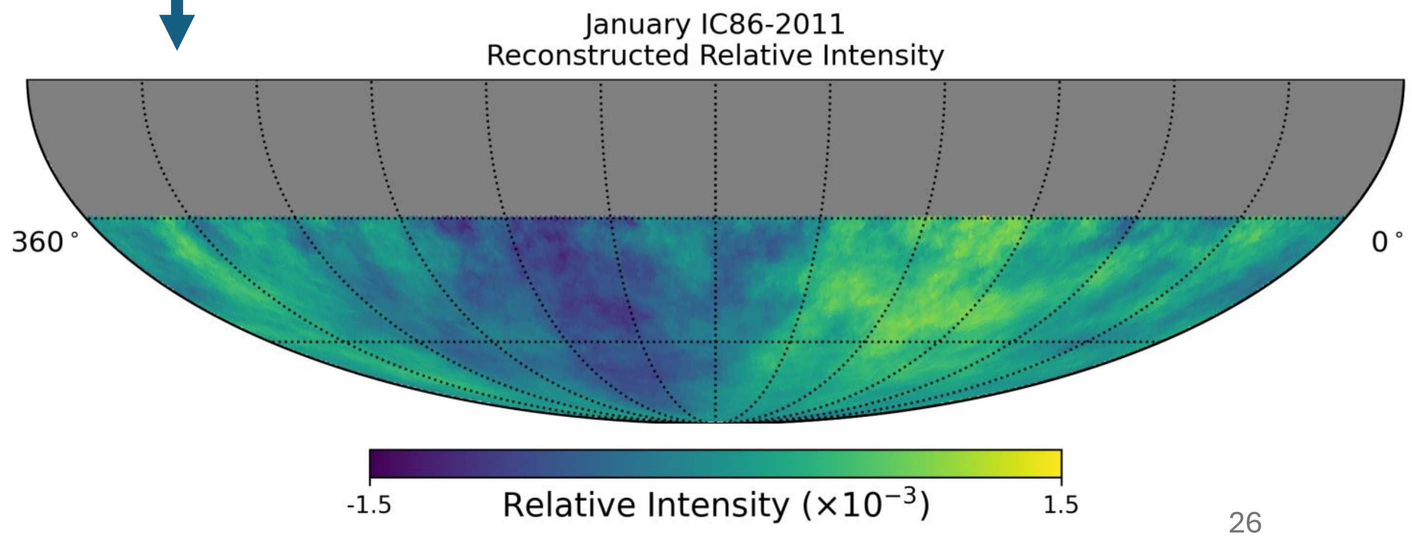
- Variation in counts over sky much larger than Anisotropy
- This is because of detector acceptance and atmospheric effects
  - Flux of cosmic rays typically falls as $\cos^n$ (zen), with n~2 for lower energy rays
  - I'll refer to both as acceptance
- We need to know the detector's response to an isotropic cosmic ray flux!

Quantified by a "Relative Intensity"

Data (Counts) **Background**

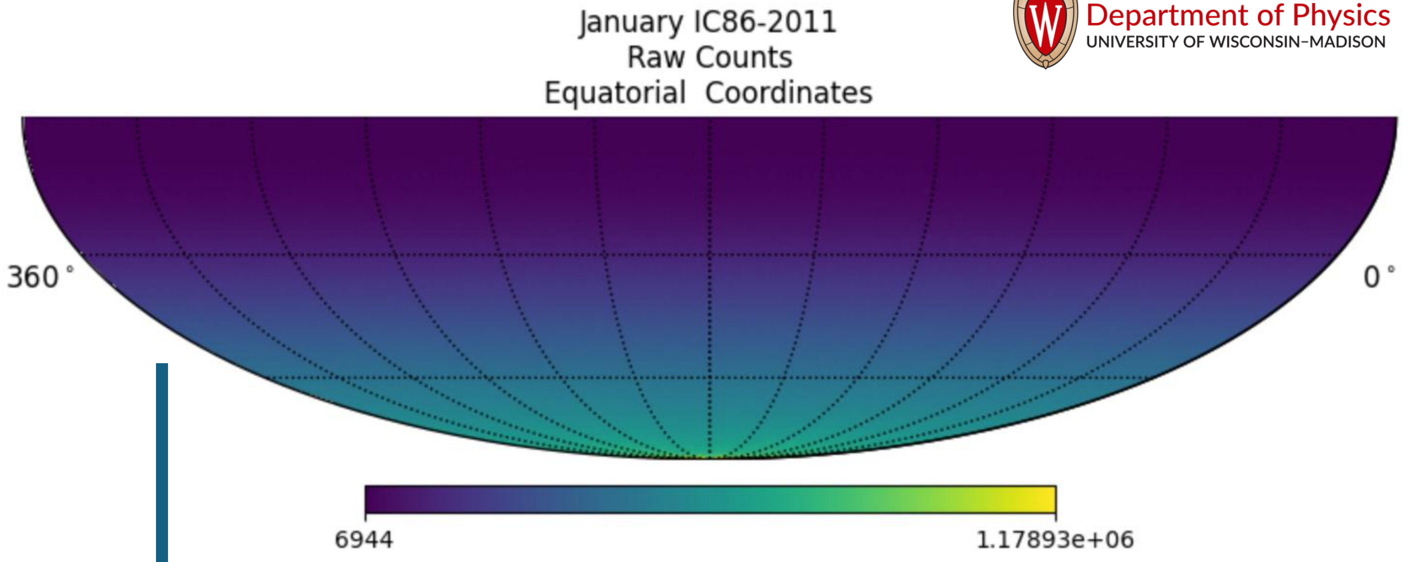
$$R = \frac{N - \langle N \rangle}{\langle N \rangle}$$

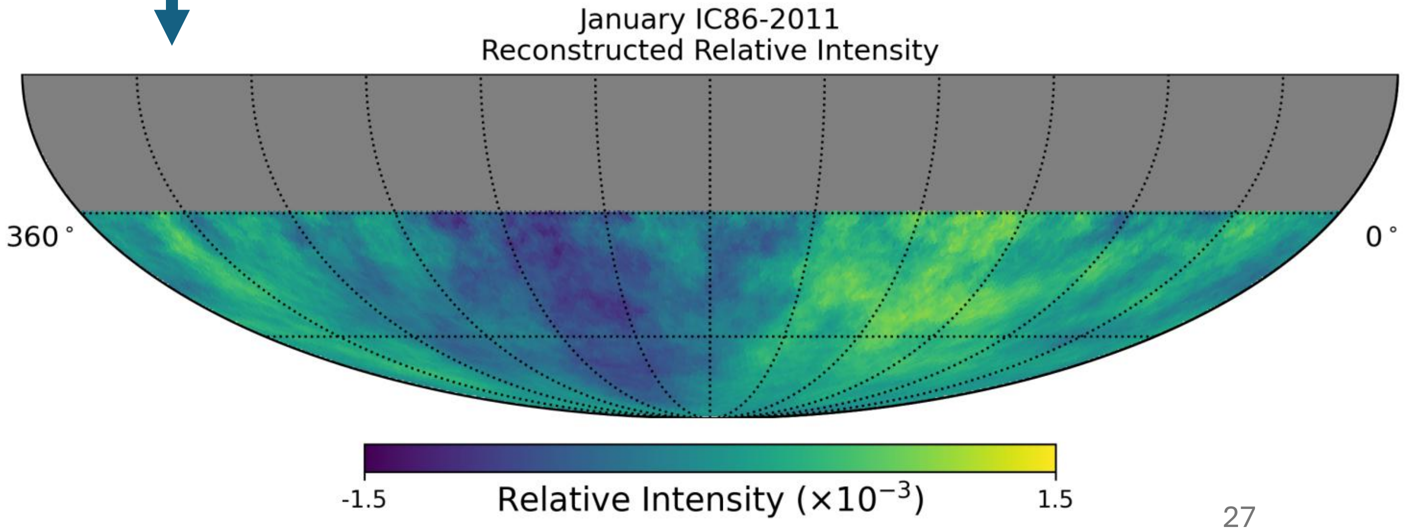




Getting Expected Counts

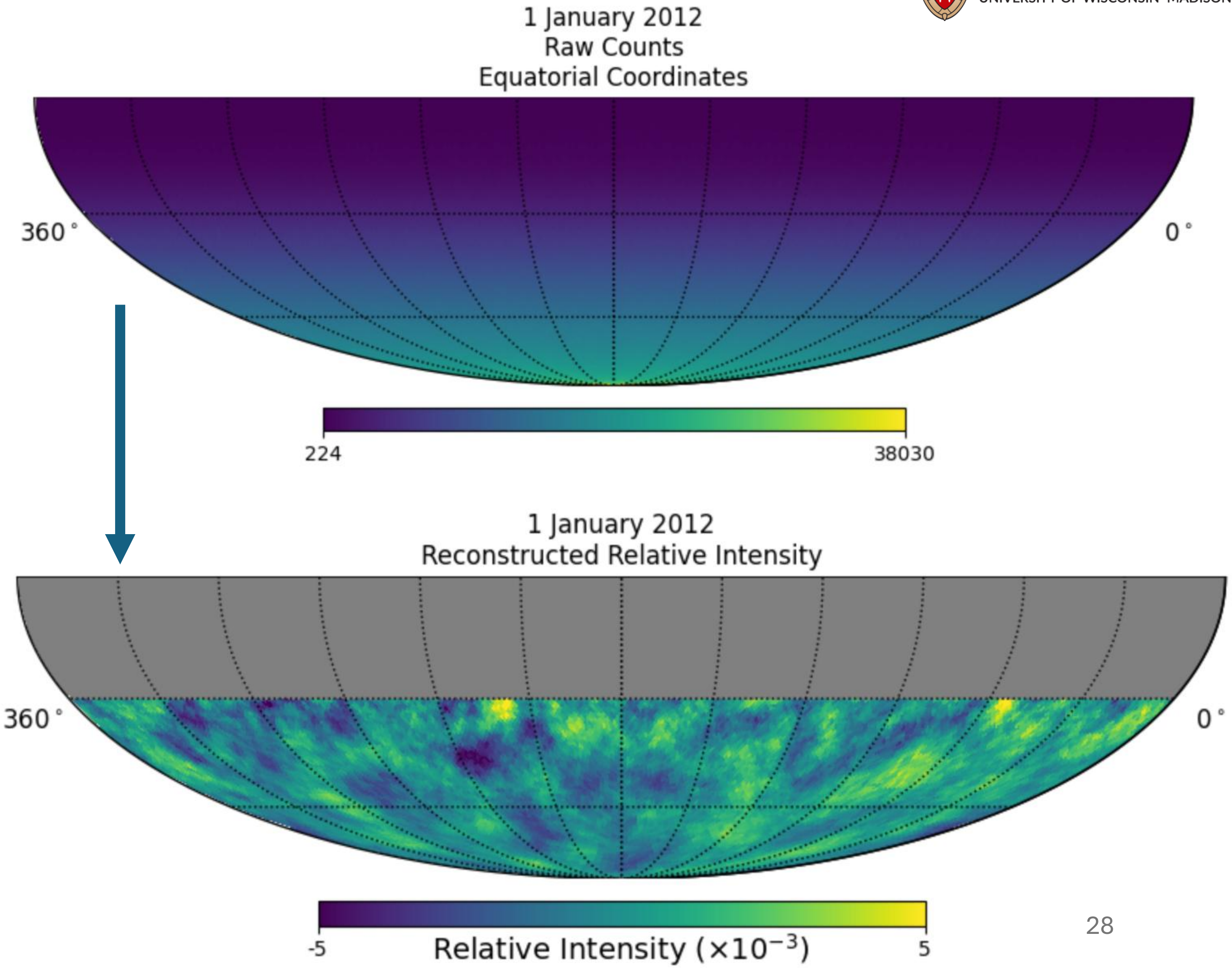
- Need to know detector's response to an isotropic cosmic ray flux…maybe use Monte-Carlo?
- Relative intensity of order 0.1%
- Need to know detector's response to an isotropic cosmic ray flux to with relative error less than this
- Models of Cosmic Ray showers have uncertainty of order 10%
    - Far too high!
- Need another way to separate anisotropy from acceptance…





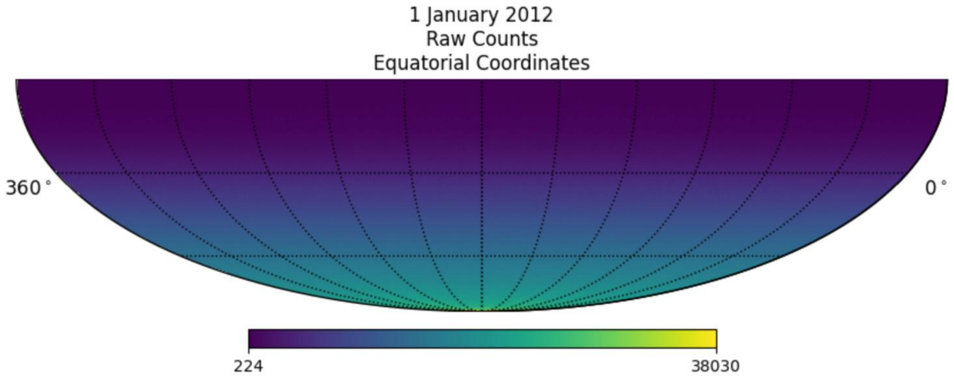
One Day of Data

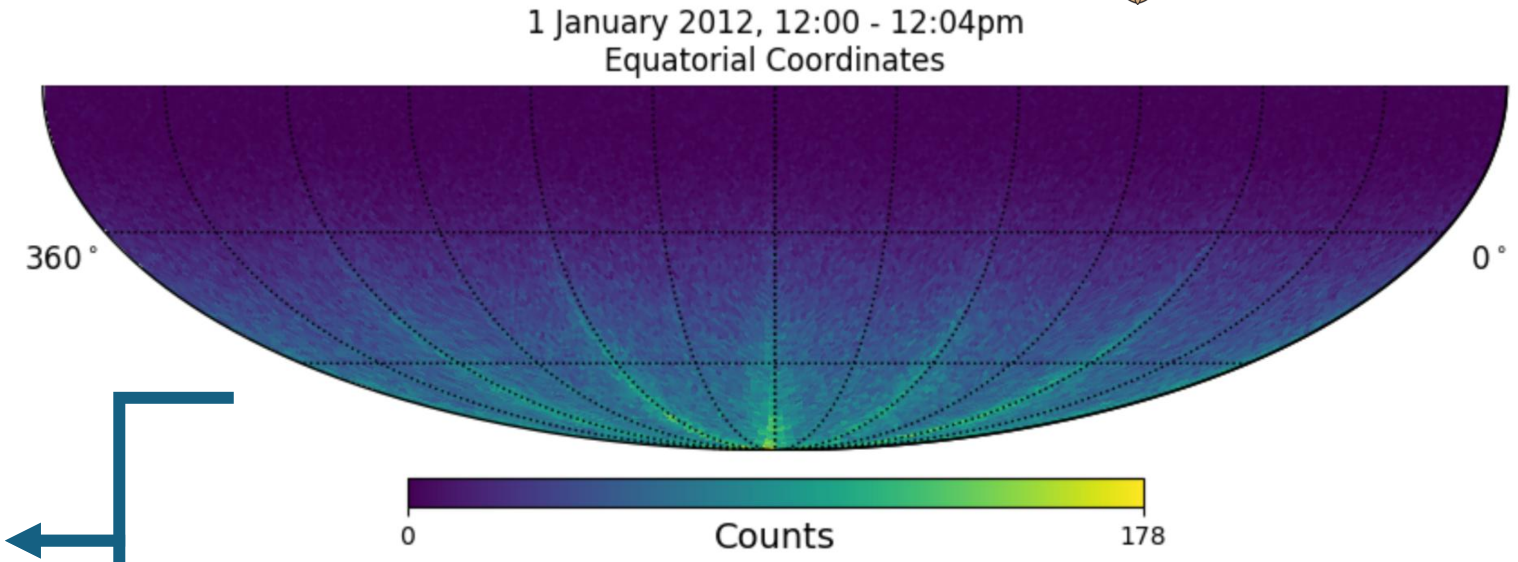
For convenience, let's look at just <u>one day</u> of data: 1 January 2012

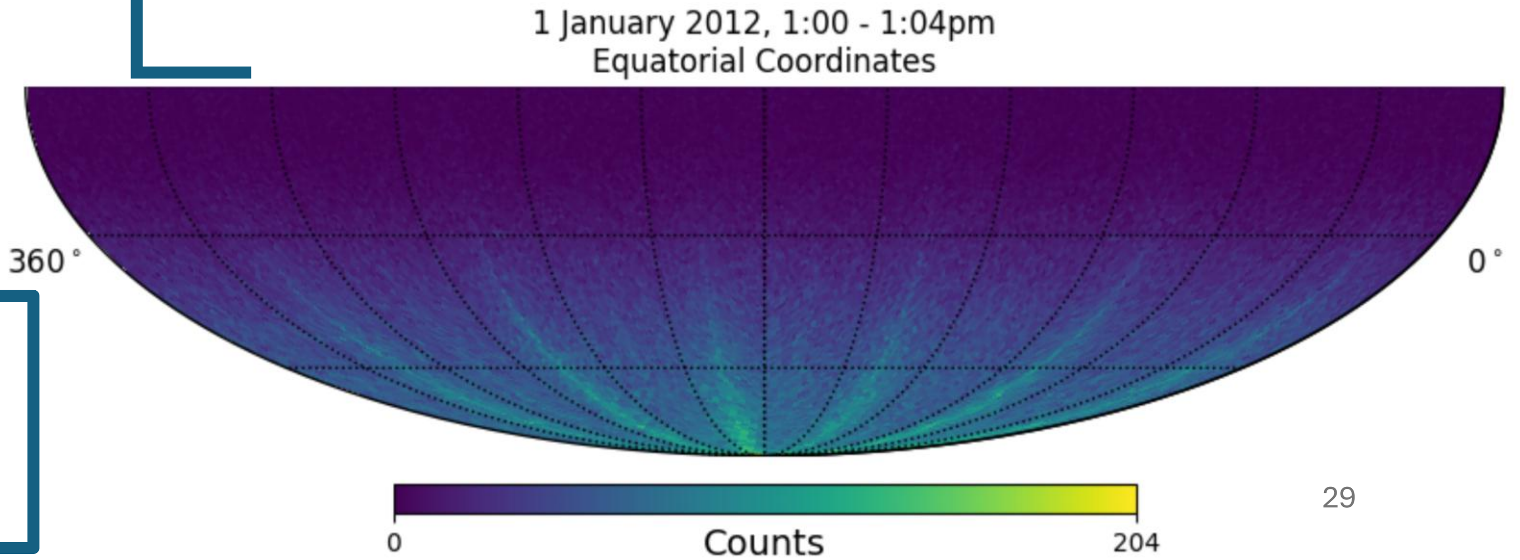


A Difference Between Acceptance and Anisotropy

<u>An idea:</u> Let's look at the <u>raw counts</u> for <u>small time bins</u>..



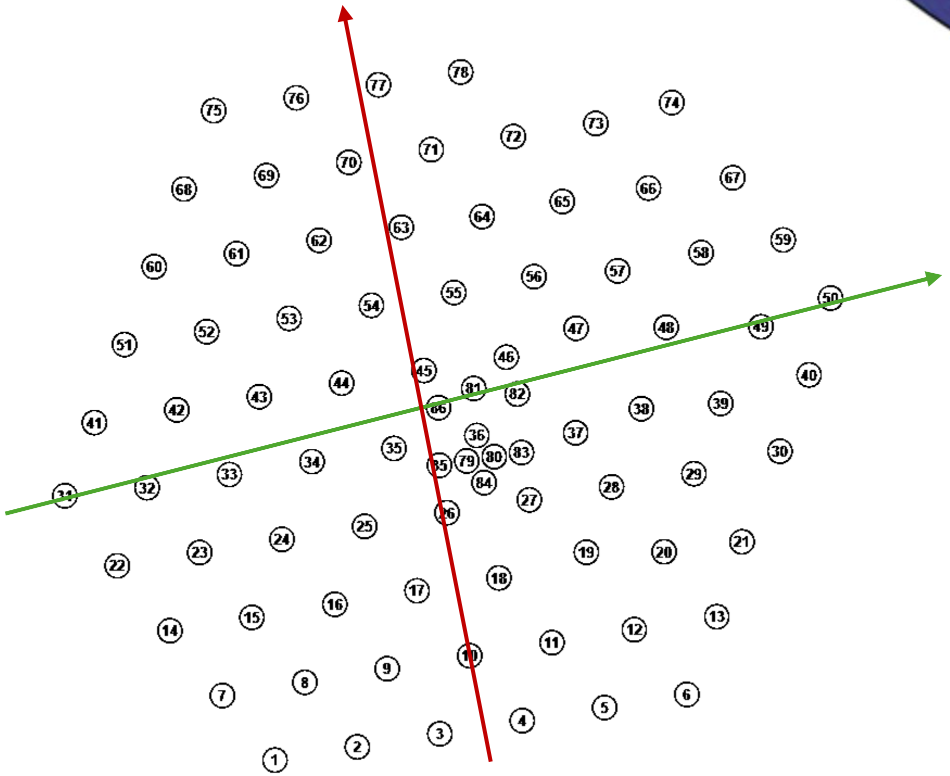


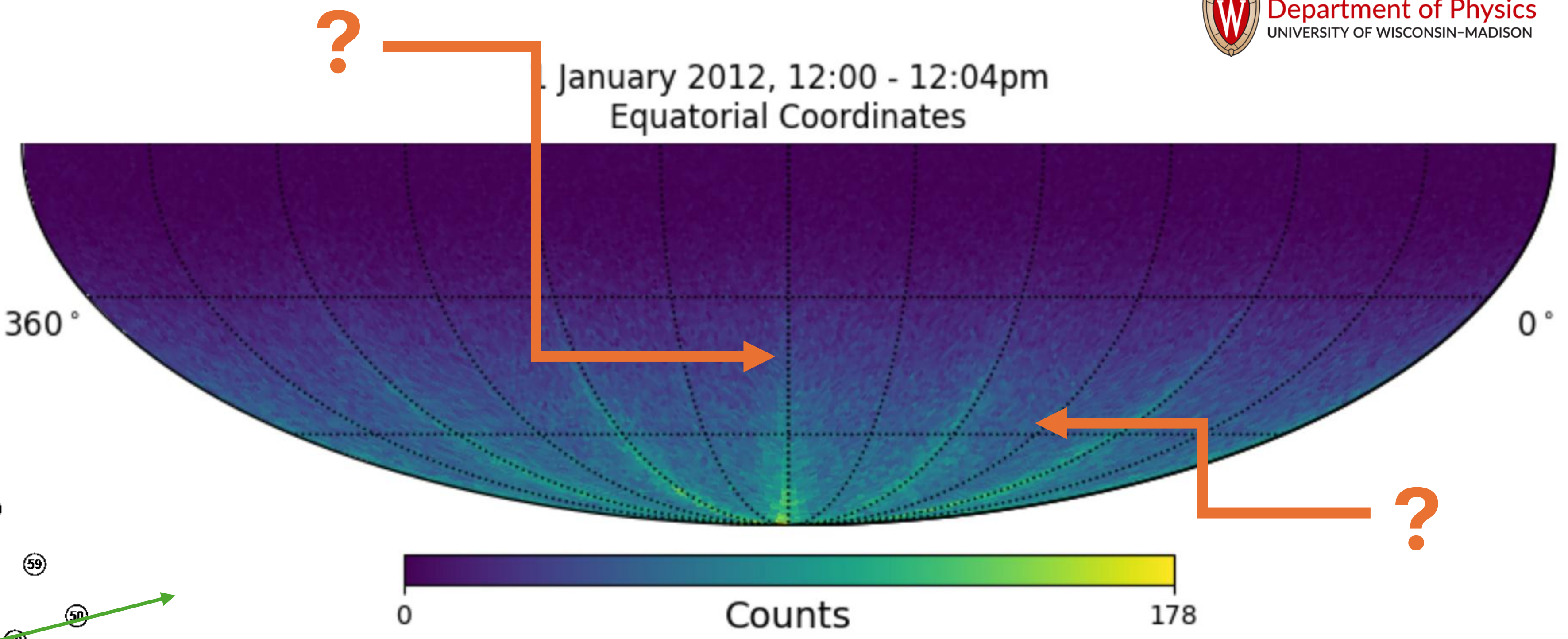


The counts per pixel <u>change over time</u> because of IceCube rotating! The Anisotropy doesn't

A Brief Aside...

Why the vertical lines?





IceCube is a hexagon(ish)

More DOMs along diagonals, so higher sensitivity along diagonals

Leveraging Acceptance vs. Anisotropy

- Acceptance per bin changes over time, anisotropy doesn't – how can we quantify this?
- Assuming no anisotropy, for time bin *t* and pixel *i*

$$\mu_{ti} = \mathcal{N}_t \mathcal{A}_{ti}$$

Acceptance in time bin *t* and pixel *i*

Total counts integrated across entire sky during time bin *t*

Expected counts in time bin *t* and pixel *i*

Note: original paper* uses *i* to refer to pixels in local/detector coordinates

Measured counts in time bin *t* in pixel *i* – n_{ti} - sampled from a Poisson distribution with mean μ_{ti}

$$\mathrm{PDF} = \frac{(\mu_{ti})^{n_{ti}} e^{-\mu_{ti}}}{n_{ti}!}$$

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

Leveraging Acceptance vs. Anisotropy

IceCube South Pole Neutrino Observatory

Department of Physics
University of Wisconsin–Madison

If we allow there to be anisotropy

$$\mu_{ti} = \mathcal{N}_t \mathcal{A}_{ti} \rightarrow \mu_{ti} = I_i \mathcal{N}_t \mathcal{A}_{ti}$$

Expected counts in time bin *t* and pixel *i*

Anisotropy in pixel *i*, equal to $R_i + 1$

Quantified by a "Relative Intensity"

Data (Counts) **Background**

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

Measured counts in time bin *t* in pixel *i* – n_{ti} - sampled from a Poisson distribution with mean μ_{ti}

$$\mathrm{PDF} = \frac{(\mu_{ti})^{n_{ti}} e^{-\mu_{ti}}}{n_{ti}!}$$

A Likelihood

We have

$$\mu_{ti} = I_i \mathcal{N}_t \mathcal{A}_{ti}$$

With measured counts in time bin t in pixel i – n_{ti} - sampled from a Poisson distribution with mean μ_{ti}

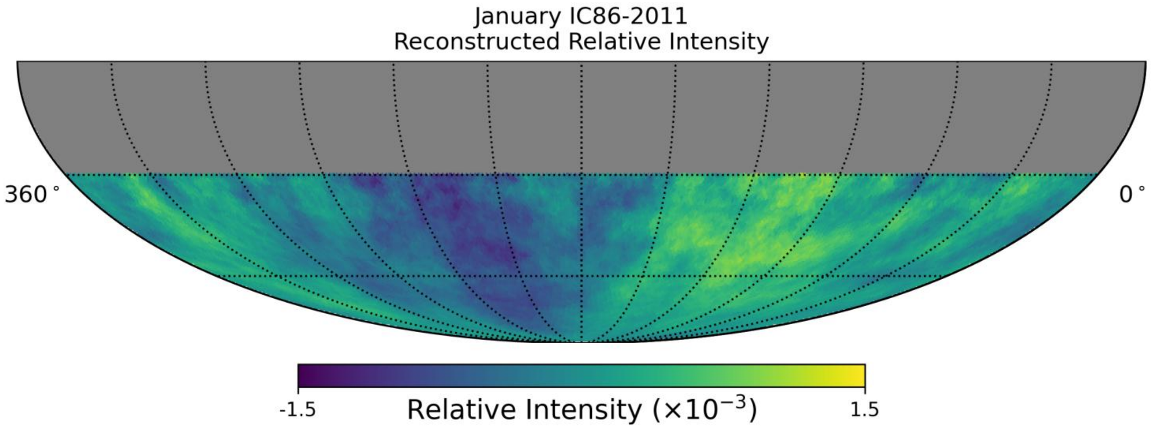
$$\mathrm{PDF} = \frac{(\mu_{ti})^{n_{ti}} e^{-\mu_{ti}}}{n_{ti}!}$$

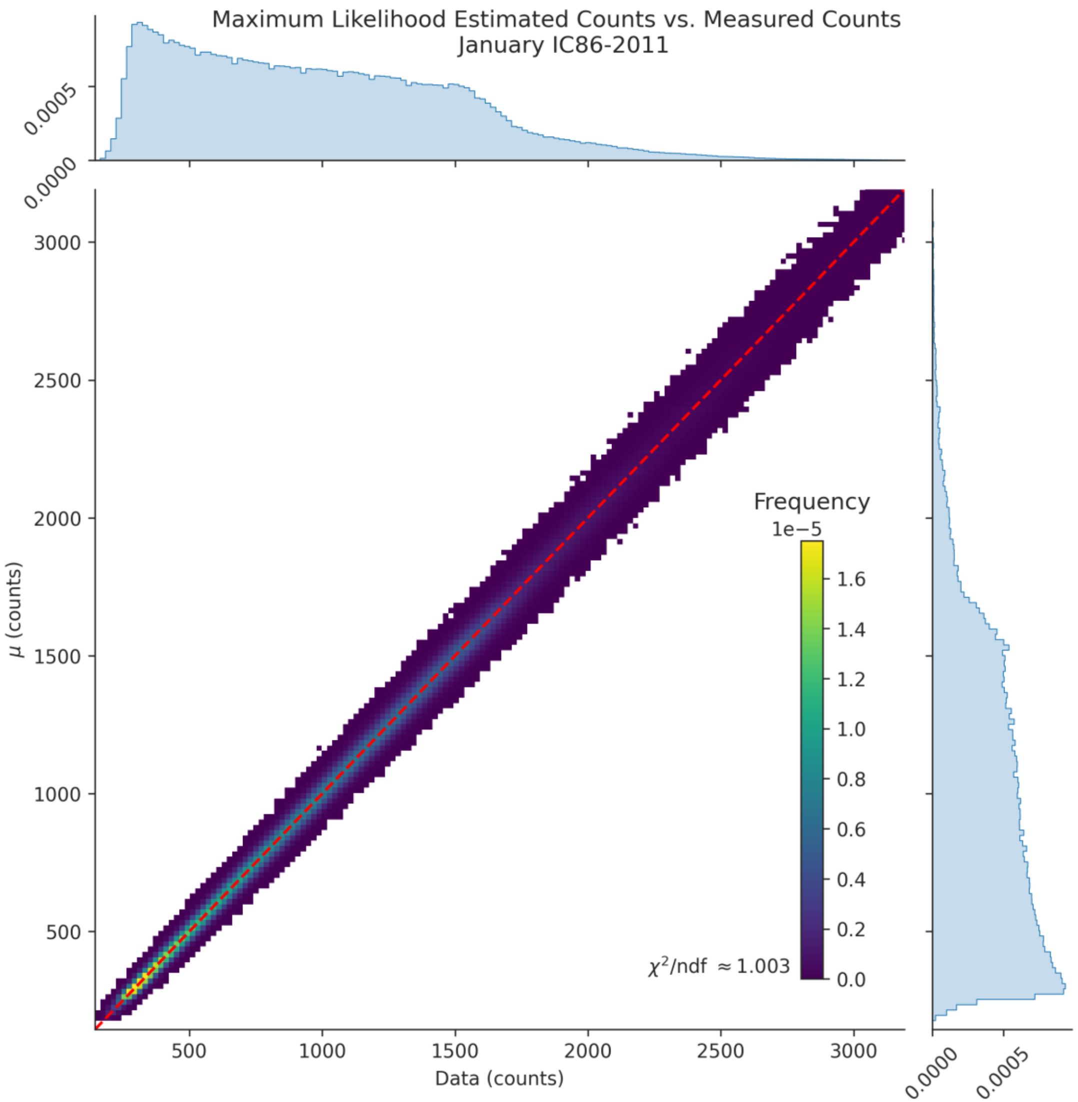
This let's us define a likelihood

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

And if we have a likelihood, we can maximize it!

January 2012





$$\mu_{ti} = I_i \mathcal{N}_t \mathcal{A}_{ti}$$

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

Local Coordinates – Another Point of View

Let's recalculate the anisotropy in local coordinates, with local coordinate pixels *a*

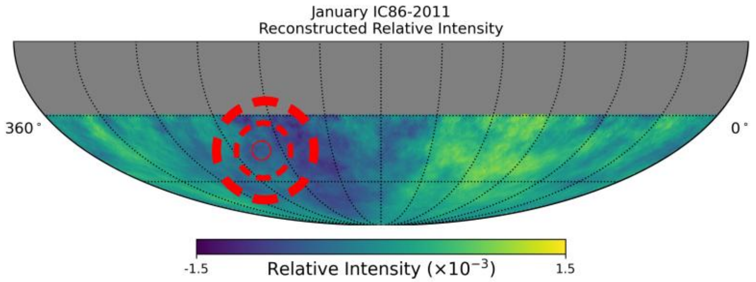
$$\mu_{ti} = I_i \mathcal{N}_t \mathcal{A}_{ti} \longrightarrow \mu_{ta} = I_{ta} \mathcal{N}_t \mathcal{A}_a$$

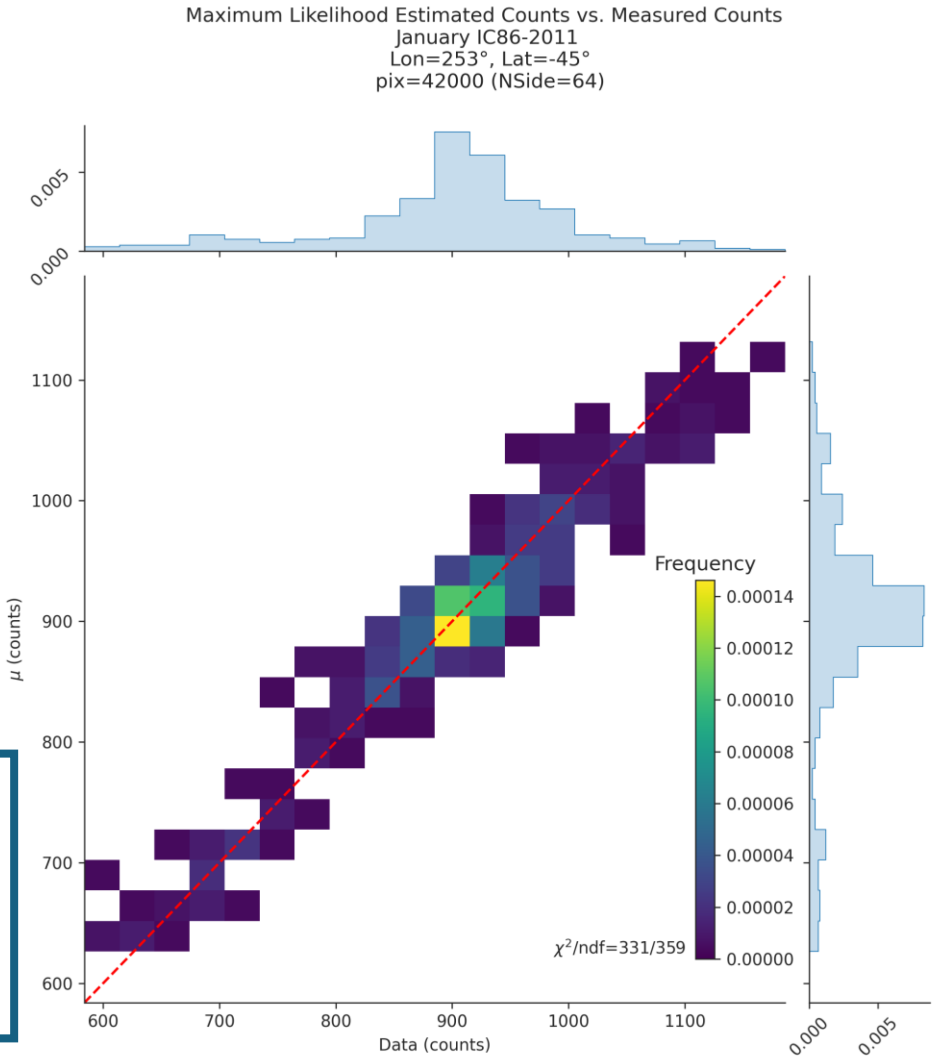
Essentially going from stationary celestial sphere and rotating detector **to** rotating celestial sphere and stationary detector

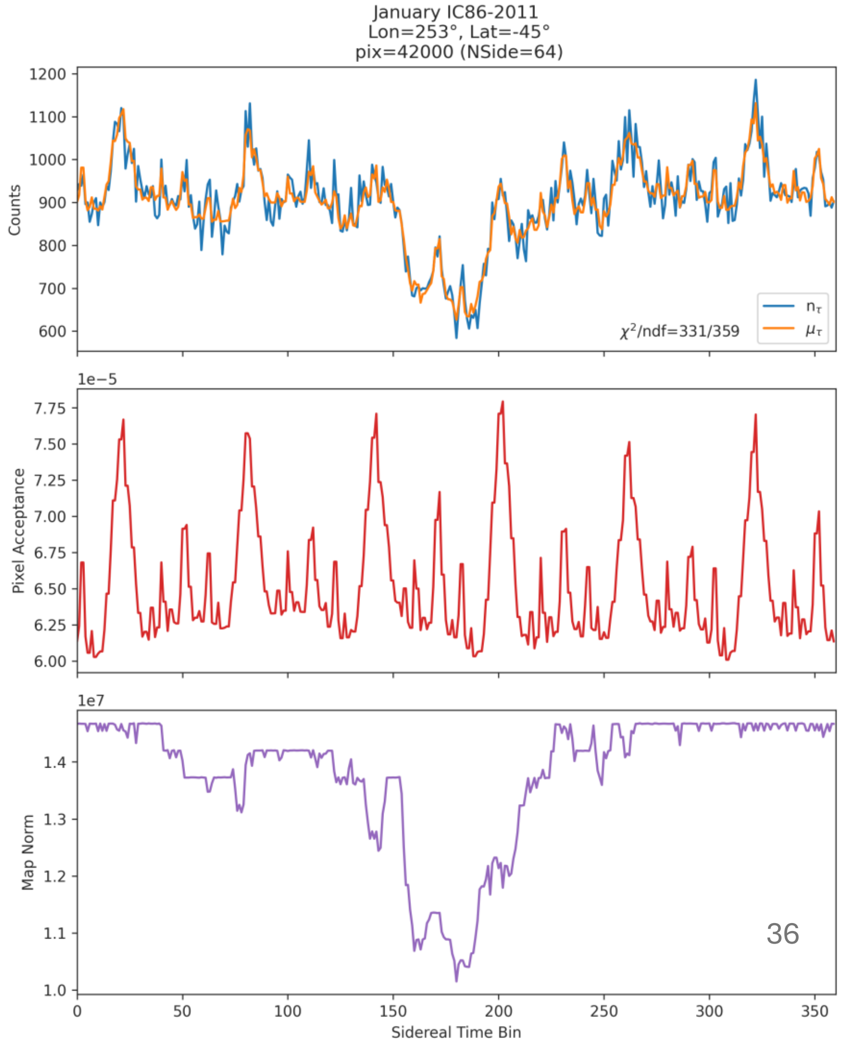
$$\mathcal{L}(n|I,\mathcal{N},\mathcal{A}) = \prod_{\tau i} \frac{(\mu_{\tau i})^{n_{\tau i}} e^{-\mu_{\tau i}}}{n_{\tau i}!}$$

Both formulations give equivalent values

Another View – January 2012
A Pixel



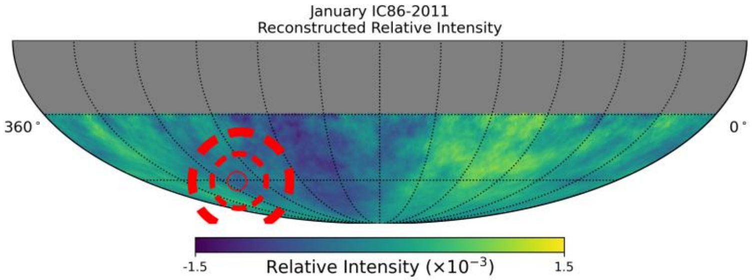


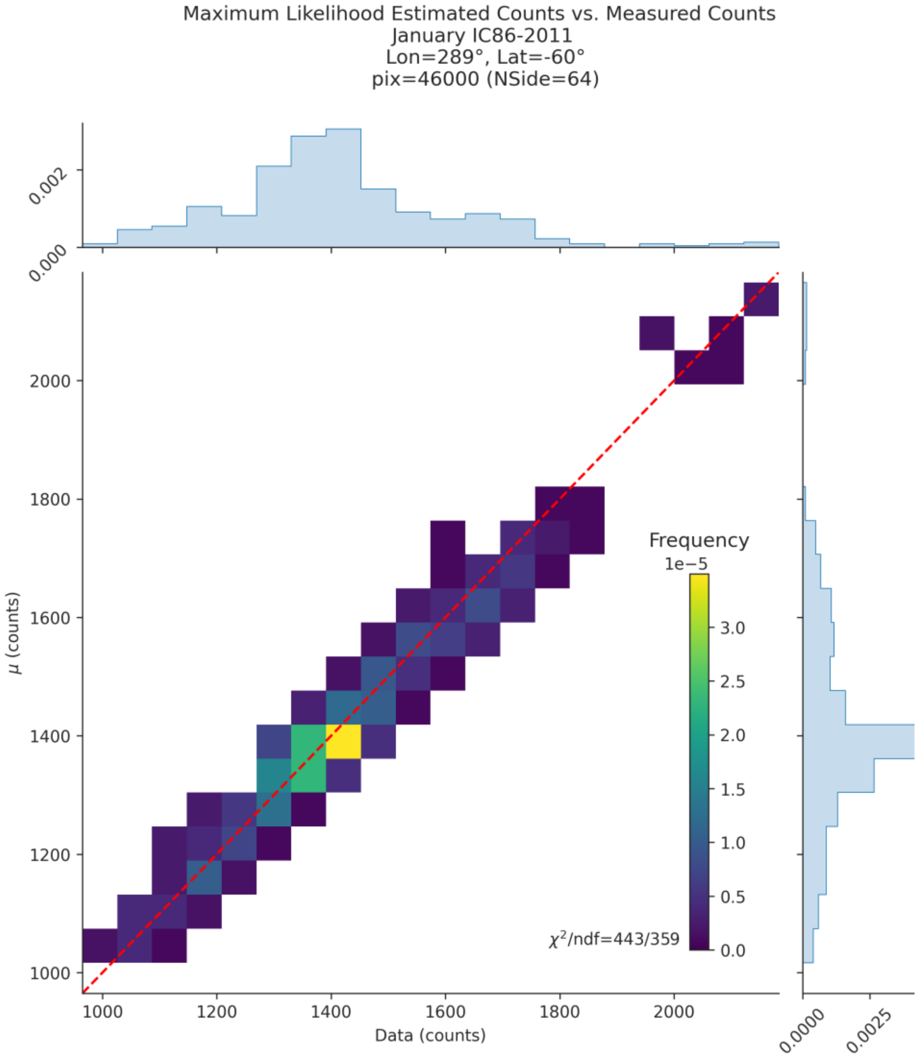


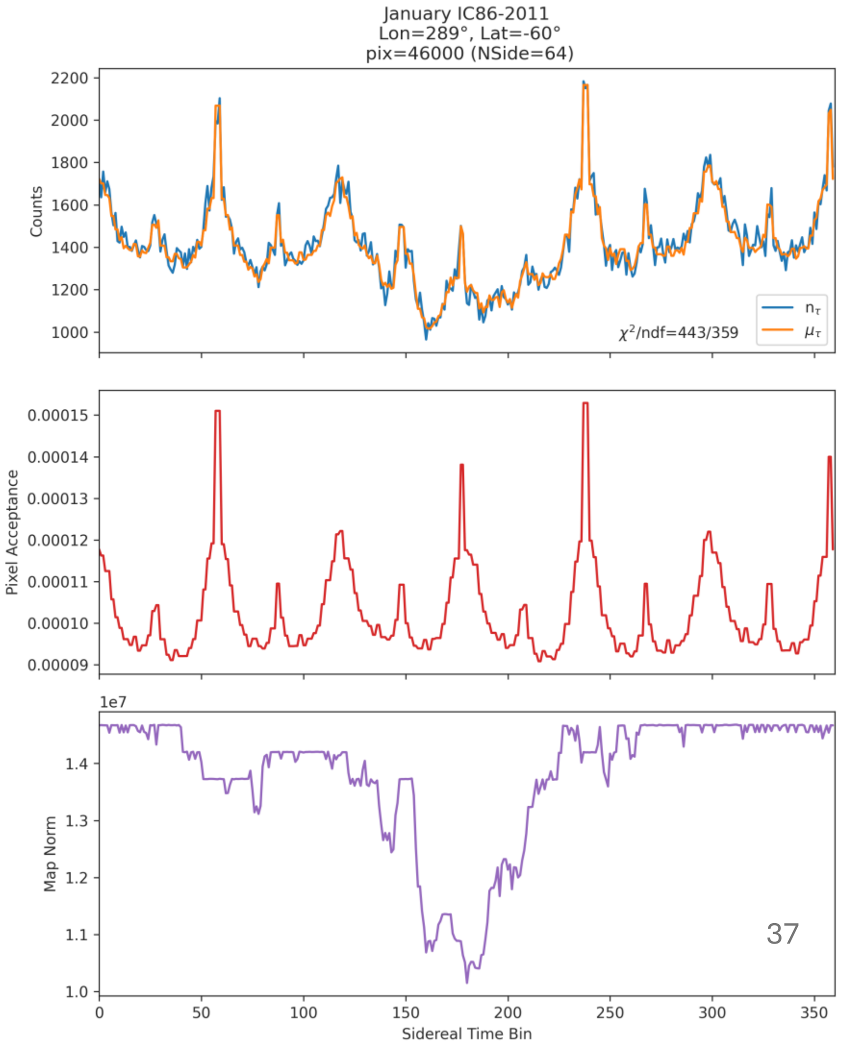
$$\mu_{ta} = I_{ta}\mathcal{N}_t\mathcal{A}_a$$

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

Another View – January 2012
A Pixel



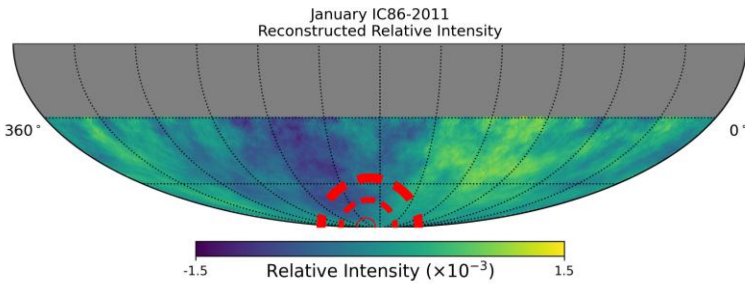


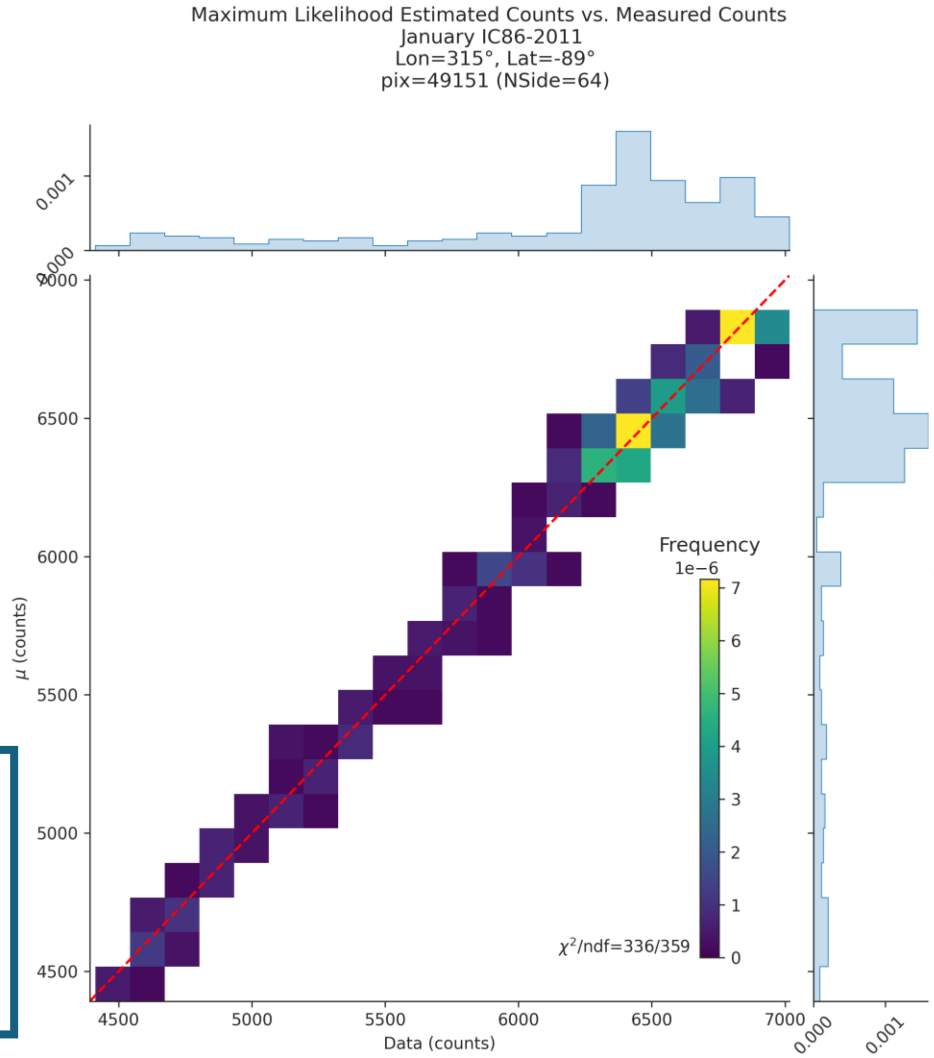


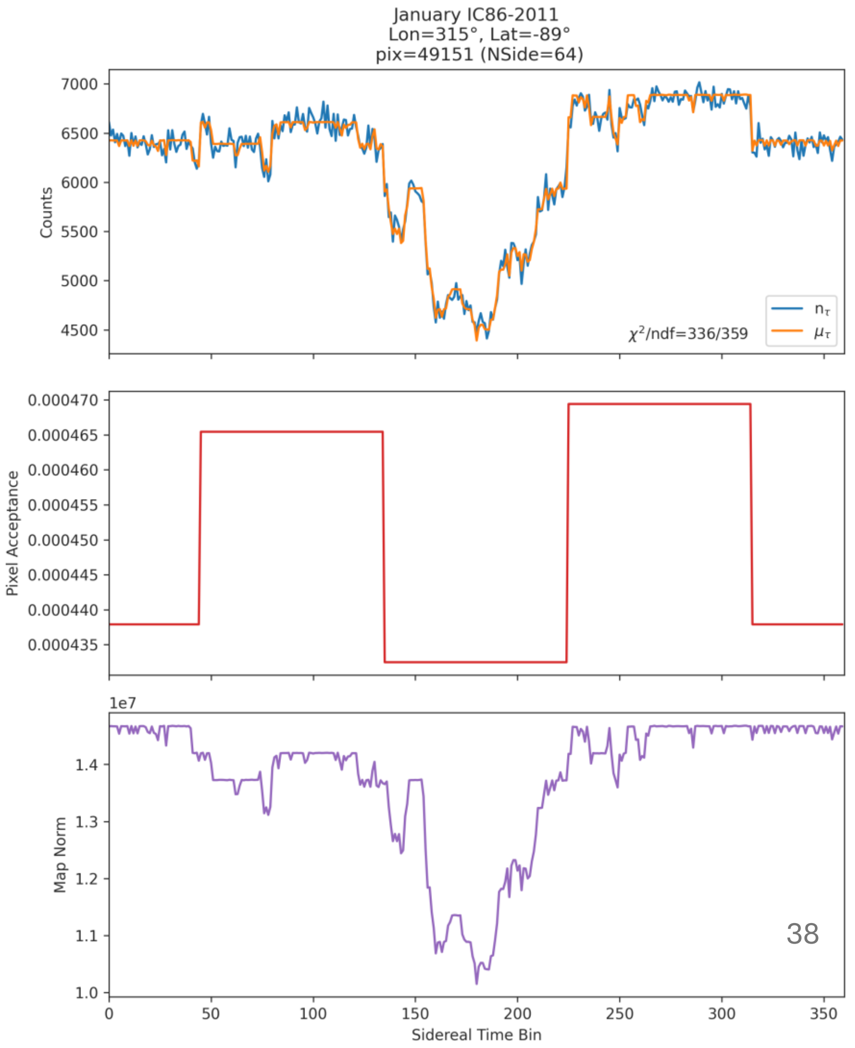
$$\mu_{ta} = I_{ta}\mathcal{N}_t\mathcal{A}_a$$

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

Another View – January 2012
A Pixel







$$\mu_{ta} = I_{ta} \mathcal{N}_t \mathcal{A}_a$$

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

A Declination Deficiency

- Reconstructing the anisotropy is essentially <u>splitting local acceptance</u> and <u>equatorial anisotropy</u>
  - Anisotropy is <u>constant in equatorial coordinates</u>
  - Acceptance is <u>constant in local coordinates</u>

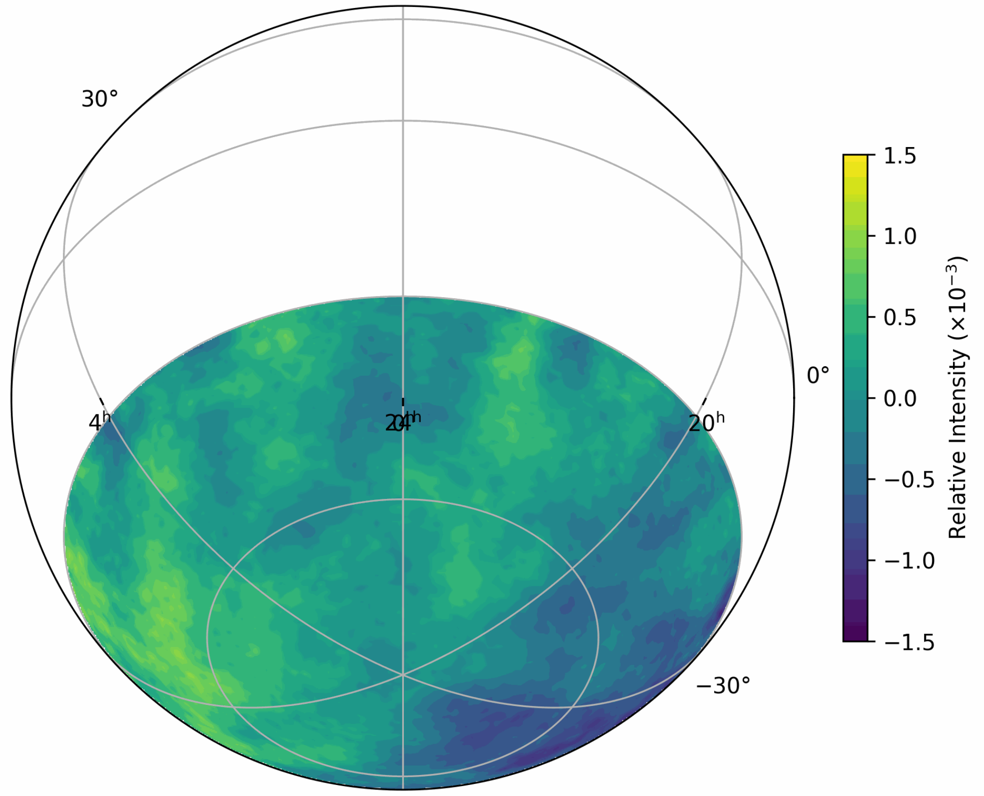
- We can split them because the Earth rotates around its axis
  - Creates a coupling between local acceptance and equatorial anisotropy

$$\mu_{ti} = I_i \mathcal{N}_t \mathcal{A}_{ti}$$

- **But** not every equatorial pixel is coupled with every local acceptance pixel

- <u>Local acceptance and equatorial anisotropy only coupled within a single declination band</u>

- What does this mean?



Cosmic Ray Anisotropy Reconstruction

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Department of Physics
UNIVERSITY OF WISCONSIN–MADISON

- We use a maximum likelihood estimation 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

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

$\mathcal{A}_i$ → 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>

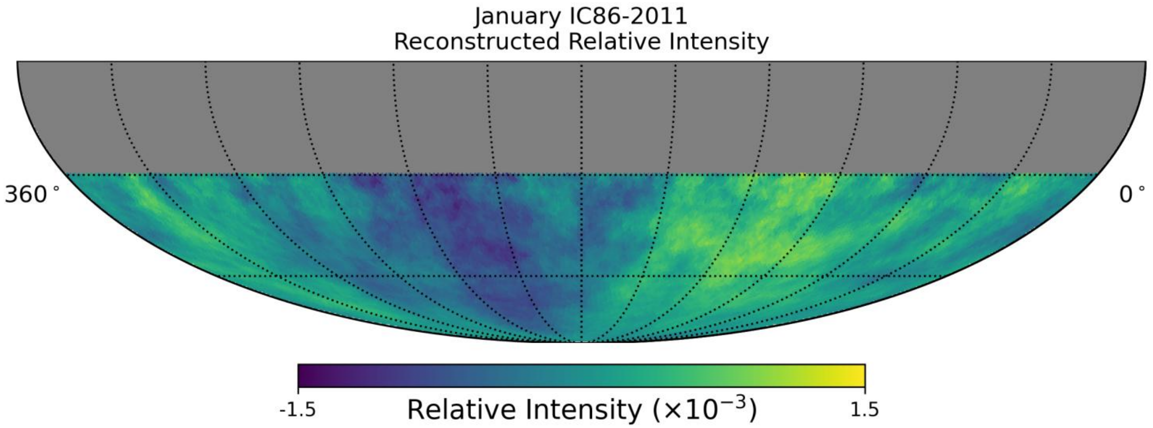
$$\lambda = \frac{\mathcal{L}(n|I,\mathcal{N},\mathcal{A})}{\mathcal{L}(n|I^{(0)},\mathcal{N}^{(0)},\mathcal{A}^{(0)})}$$

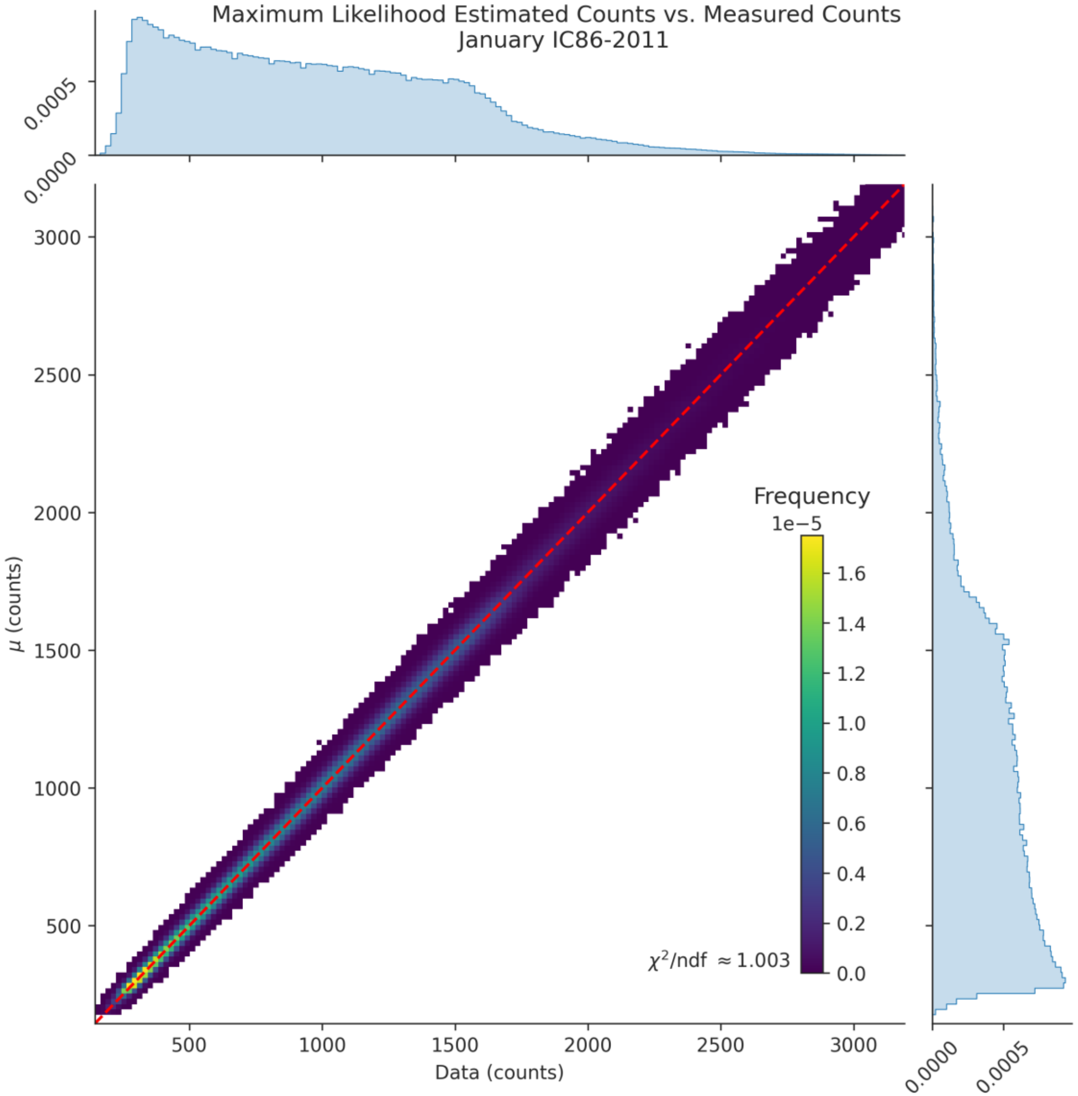
$I^{(0)}, \mathcal{N}^{(0)}, \mathcal{A}^{(0)}$ → MLE of $I, \mathcal{N}, \mathcal{A}$ assuming no anisotropy (i.e. $I = 1$)

Has several benefits compared to other methods:
- Fast computation time
- Simple to incorporate multiple detectors

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

Cosmic Ray Anisotropy Reconstruction

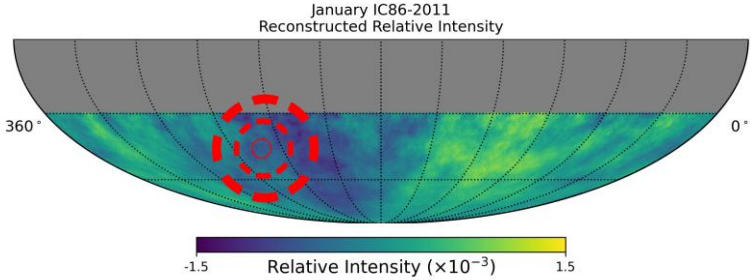


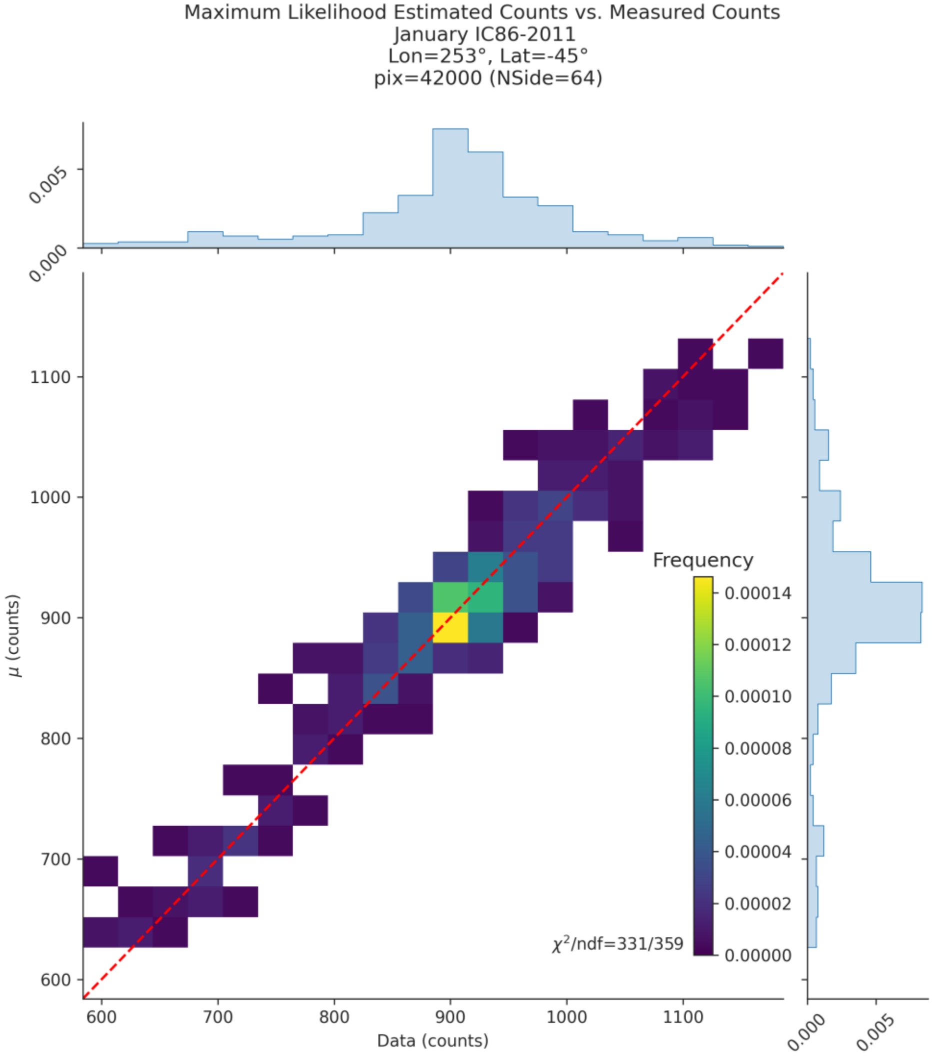


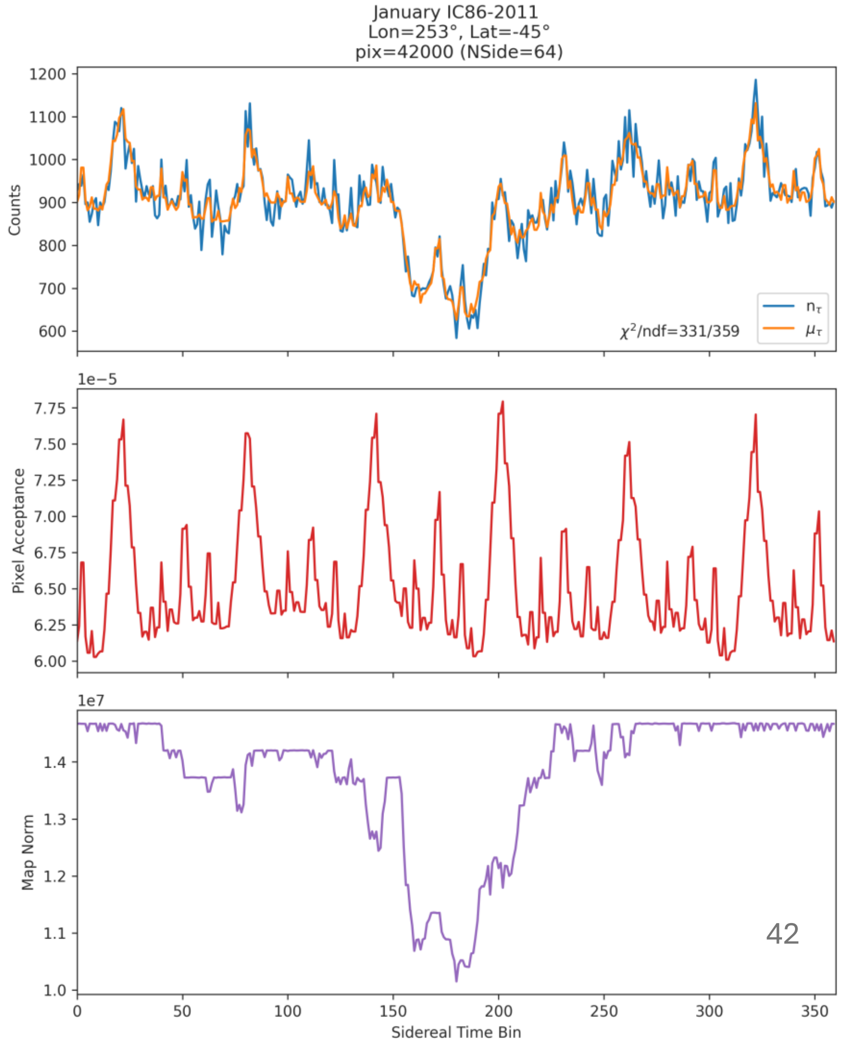
$$\lambda = \frac{\mathcal{L}(n|I,\mathcal{N},\mathcal{A})}{\mathcal{L}(n|I^{(0)},\mathcal{N}^{(0)},\mathcal{A}^{(0)})}$$

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

Cosmic Ray Anisotropy Reconstruction Example Sidereal Pixel







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

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

Jan. IC86-2011 Reconstructed Acceptance