Orbital Compton-Getting Dipole with IceCube Cosmic-Ray Muons

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for the IceCube Collaboration

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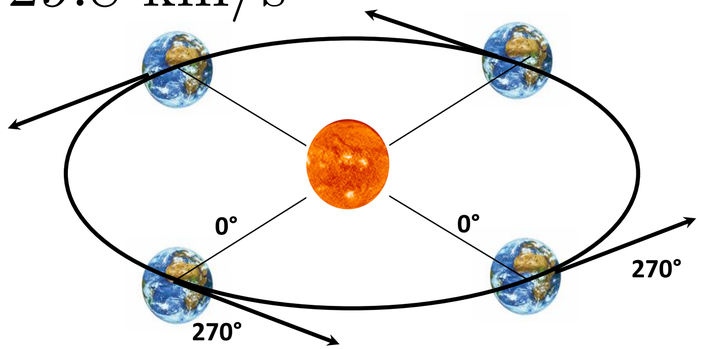
Solar Dipole: a known anisotropy
due to Earth's revolution around the Sun

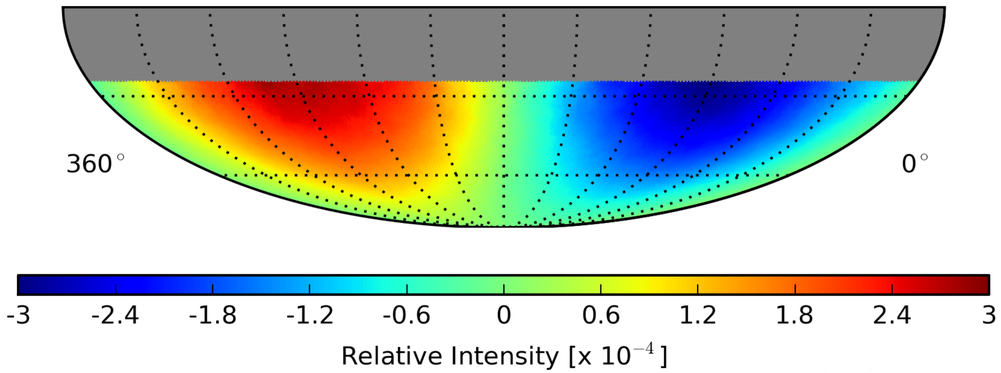
Arthur H. Compton and Ivan A. Getting
Phys. Rev. 47, 817 – Published 1 June 1935
doi:10.1103/PhysRev.47.817.

Apparent energy-independent ~10^{-4} dipole anisotropy due to relative motion of Earth around the Sun ~ 29 km/s

$$\frac{\delta I}{I} = \frac{v}{c}(\gamma + 2)\cos(\xi)$$

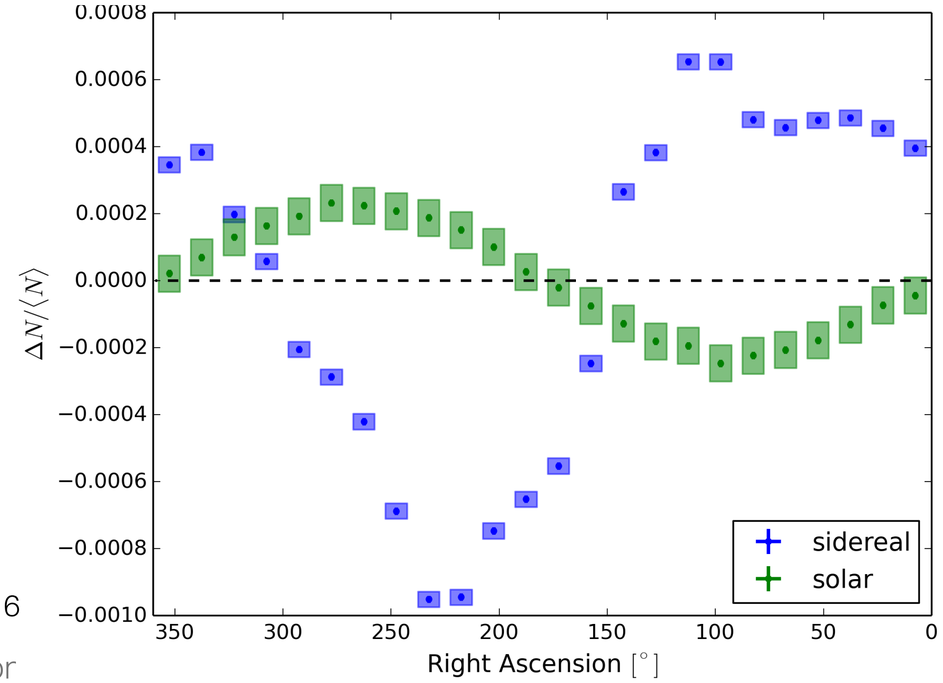
$$\langle v \rangle = 29.8 \text{ km/s}$$





IceCube - Aartsen et al., ApJ 826, 220, 2016

longitude in GSE



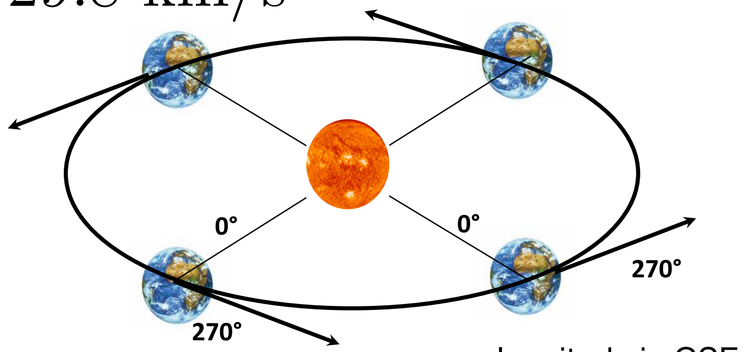
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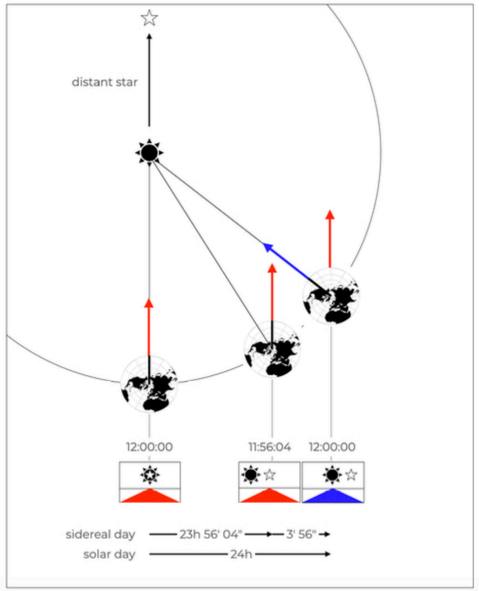
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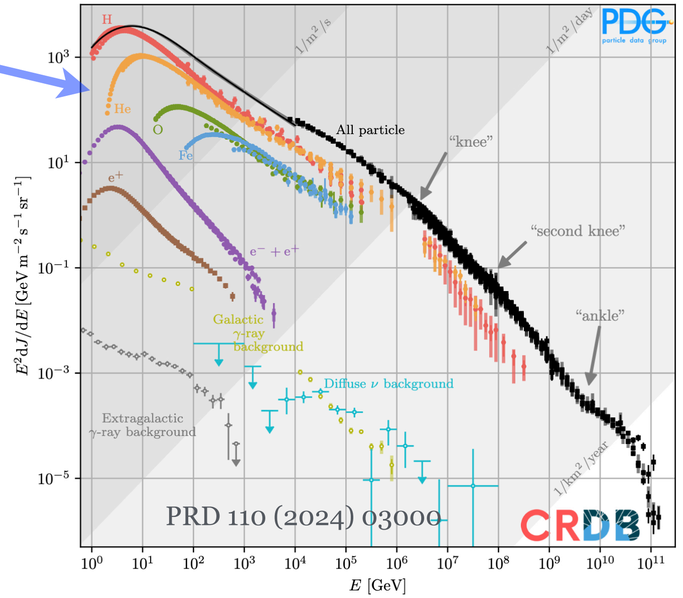
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longitude in GSE

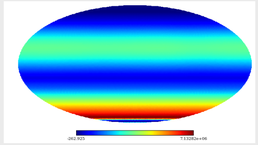


Left: the sidereal time with respect to solar time. As the Earth revolves around the Sun, the sidereal time zero stays fixed in the celestial sky while solar time's reference point moves away.

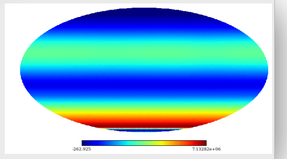


Method for measuring CR anisotropy

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



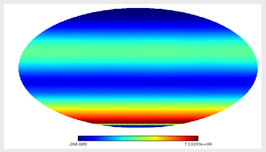
2 Construct a “reference” map by integrating acceptance over 24 hours.



Maximum LLH method (M. Ahlers, et al. 2016):

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

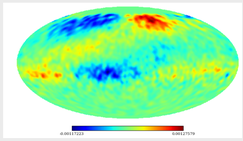
3 Correlate pixels to increase sensitivity to different angular scales



Relative Intensity

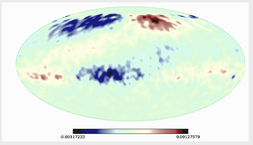
$$\delta I(\alpha,\delta)_i = \frac{N(\alpha,\delta)_i - \langle N\rangle(\alpha,\delta)_i}{\langle N\rangle(\alpha,\delta)_i}$$

4 Calculate relative differences between data and reference with significance.

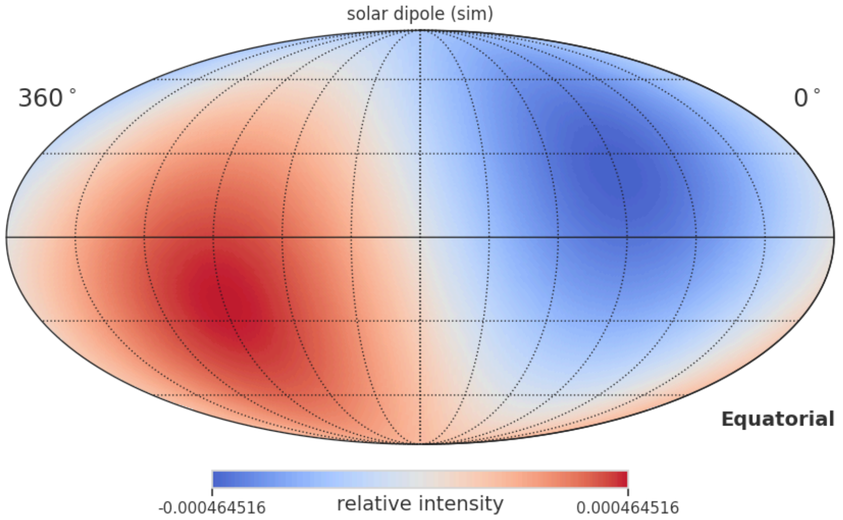


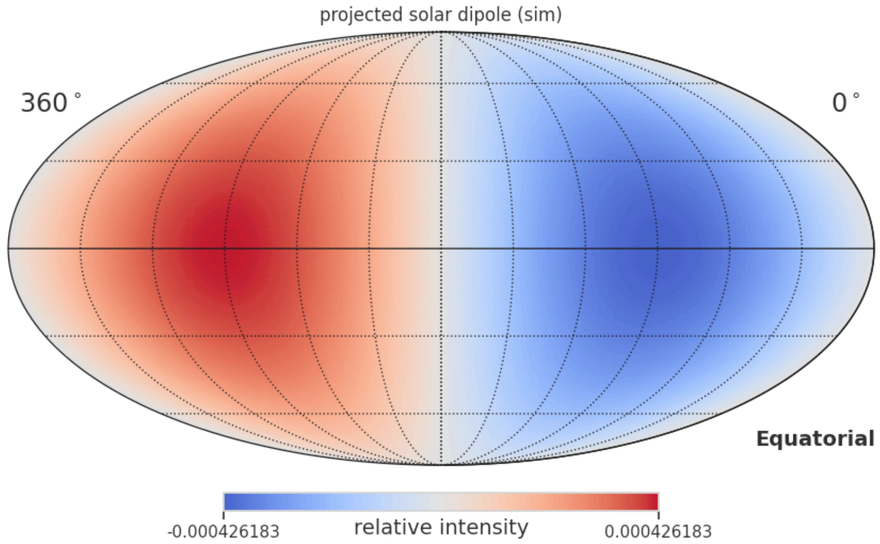
$$s_i = \sqrt{2}\left\{N_i \log\left[\frac{1+\alpha}{\alpha}\left(\frac{N_i}{N_i+N_o}\right)\right] + N_o \log\left[(1+\alpha)\left(\frac{N_o}{N_i+N_o}\right)\right]\right\}^{1/2}$$

5 Calculate statistical significance for each pixel

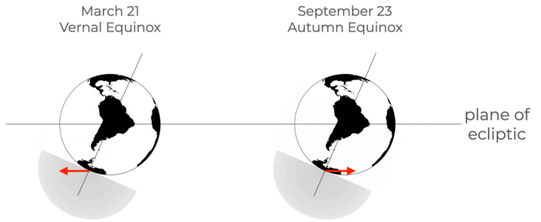


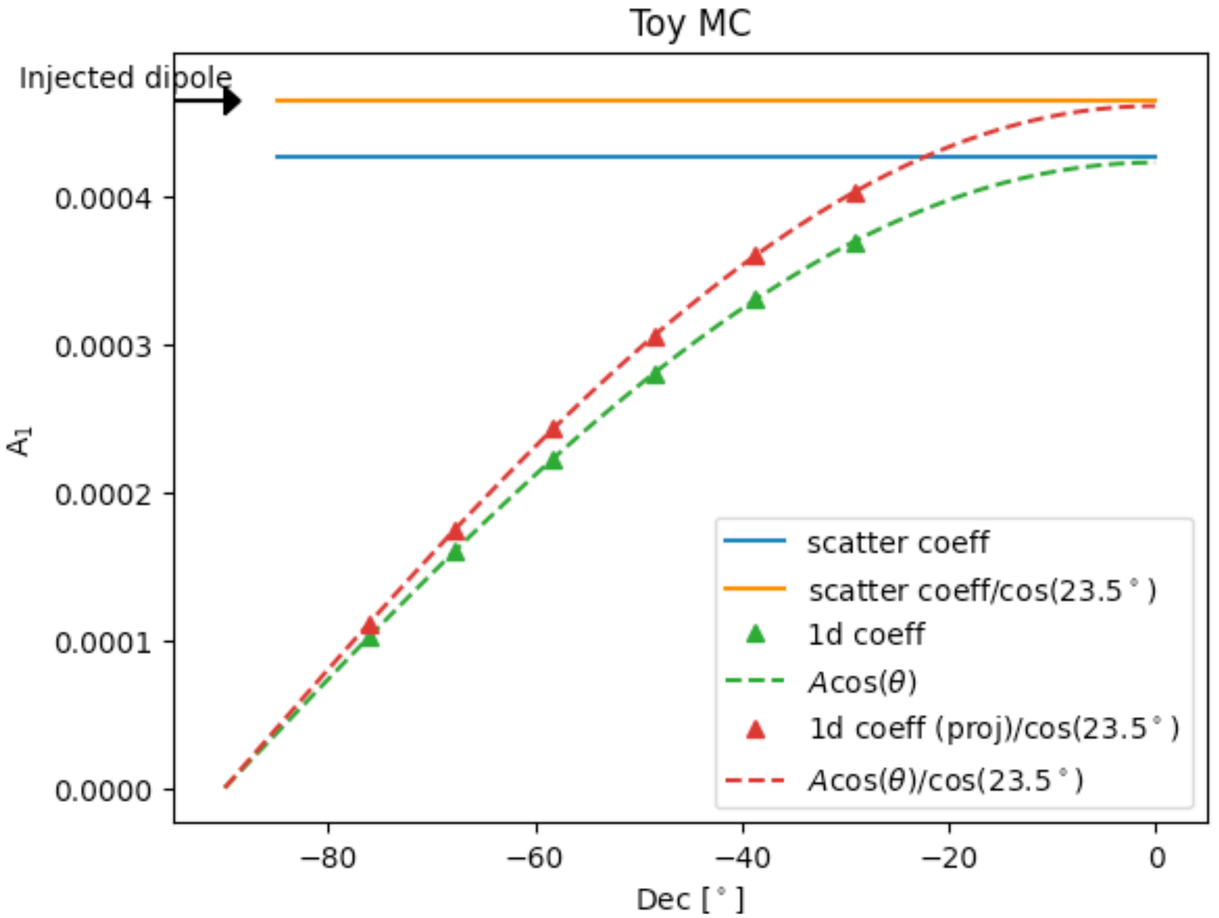
Equatorial Projection Bias





Correct for projection bias (dipole tilt is known) 23.5047°





Dipole Fit

Solar Dipole relative intensity is given by

$$\frac{\delta I_i}{I} = \frac{v}{c}(\gamma + 2)\cos(\xi_i)$$

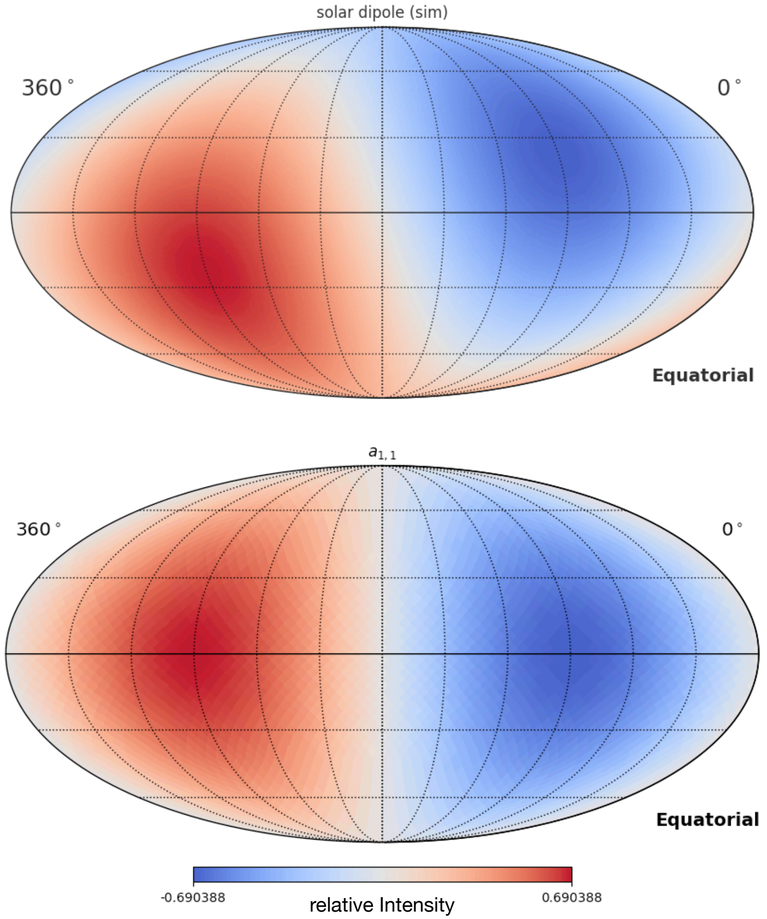
Where ξ_i is the opening angle between velocity direction and CR arrival direction (for pixel i).

Since the *m*=0 component is missing, this reduces to

$$\frac{\delta I_i}{I} = \frac{v}{c}(\gamma + 2)\sin\theta_i \cos(\phi_0 - \phi_i)$$

or, in equatorial coordinates (α,δ) coordinates

$$\frac{\delta I_i}{I} = \frac{v}{c}(\gamma + 2)\cos\delta_i \cos(\alpha_0 - \alpha_i)$$



Time series fit

Instead of producing maps in the Solar reference system, we fit daily sidereal maps by pixel as a function of (time, Ra, Dec) and subtract the mean distribution.

Advantage: daily maps insensitive to gaps in data taking.

The reference map still sensitive to gaps but bias due to leakage is smaller.

Given the data in the form

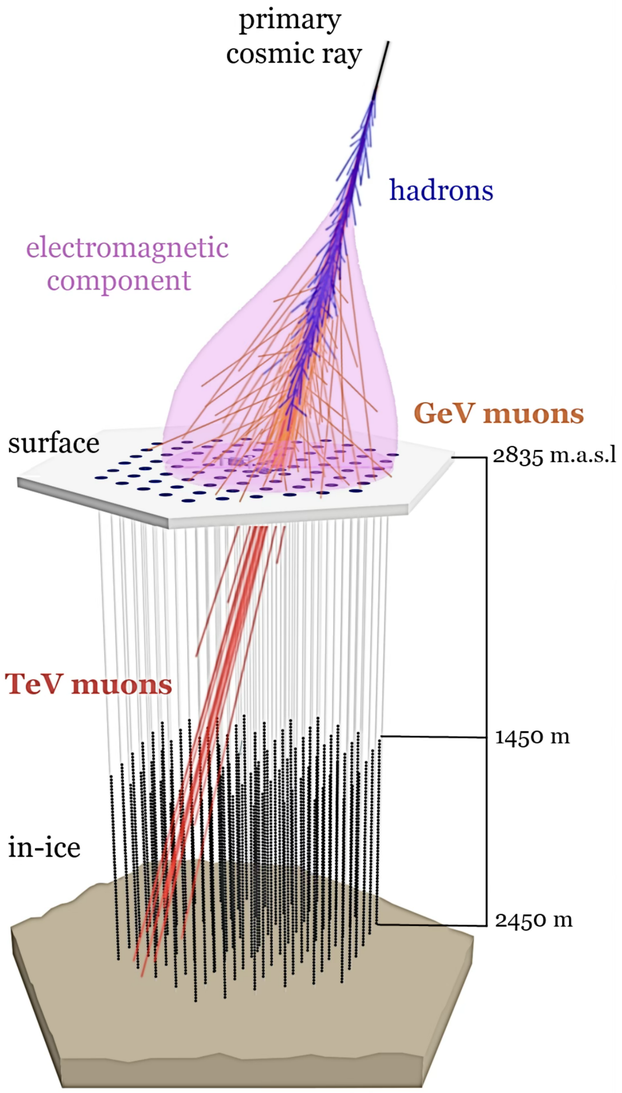
$$\delta I_{i,\tau} = \frac{N_{i,\tau}}{\langle N \rangle_{i,\tau}} - \frac{\sum_t N_{i,t}}{\sum_t \langle N \rangle_{i,t}}$$

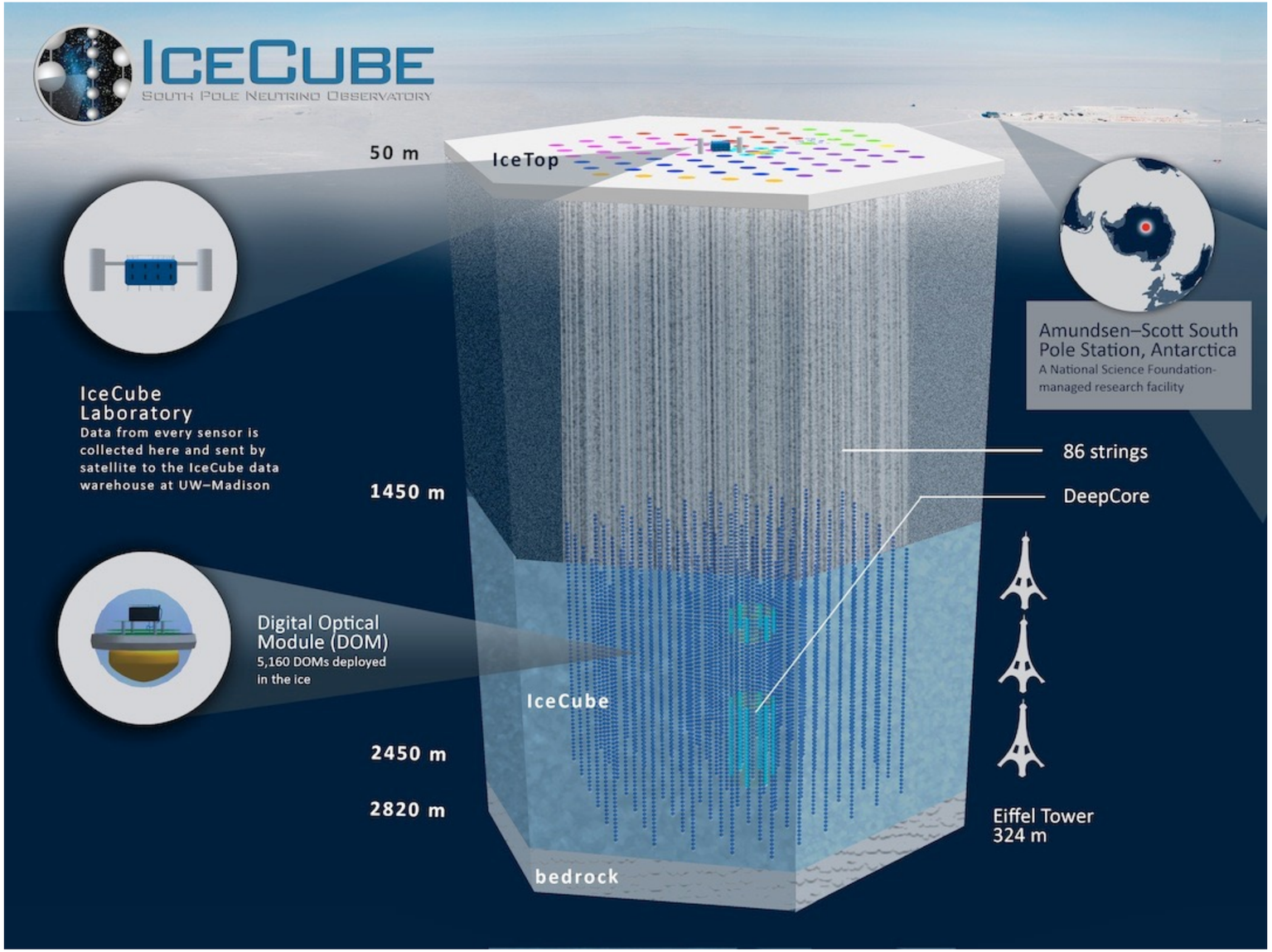
we fit

$$f(A, \delta, \alpha, t, \phi) = A \cos(\delta) \cos(\alpha - 2\pi t/365 + \phi)$$

over the time series of pixels for all daily maps with A and ϕ as free parameters.

The IceCube Observatory

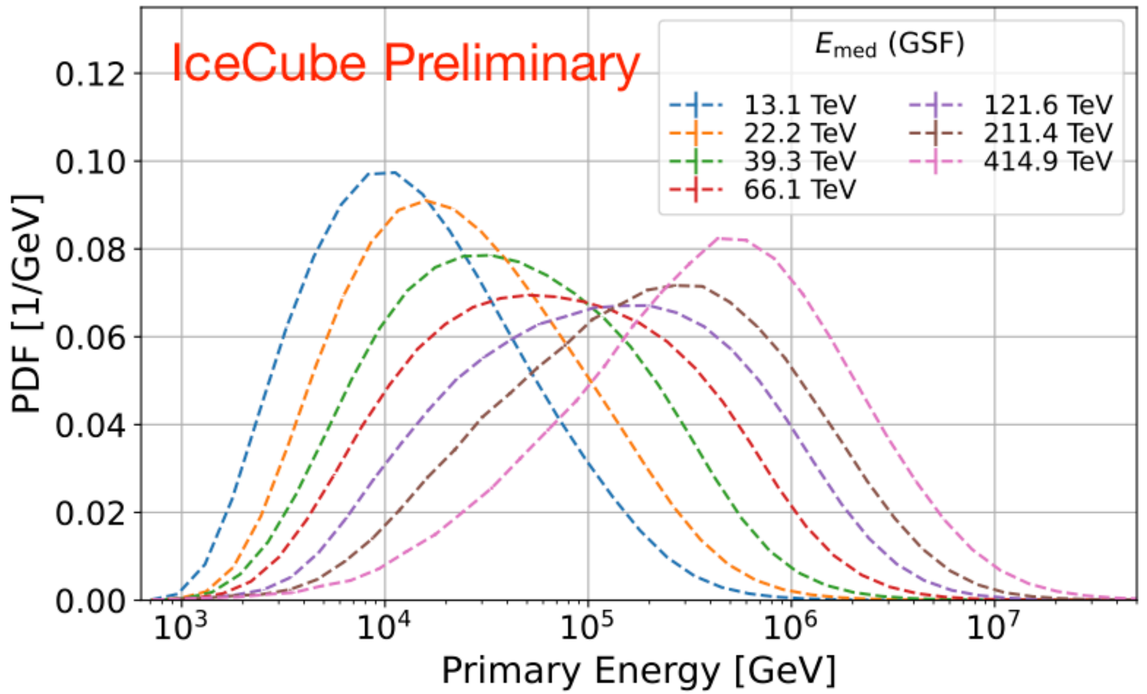




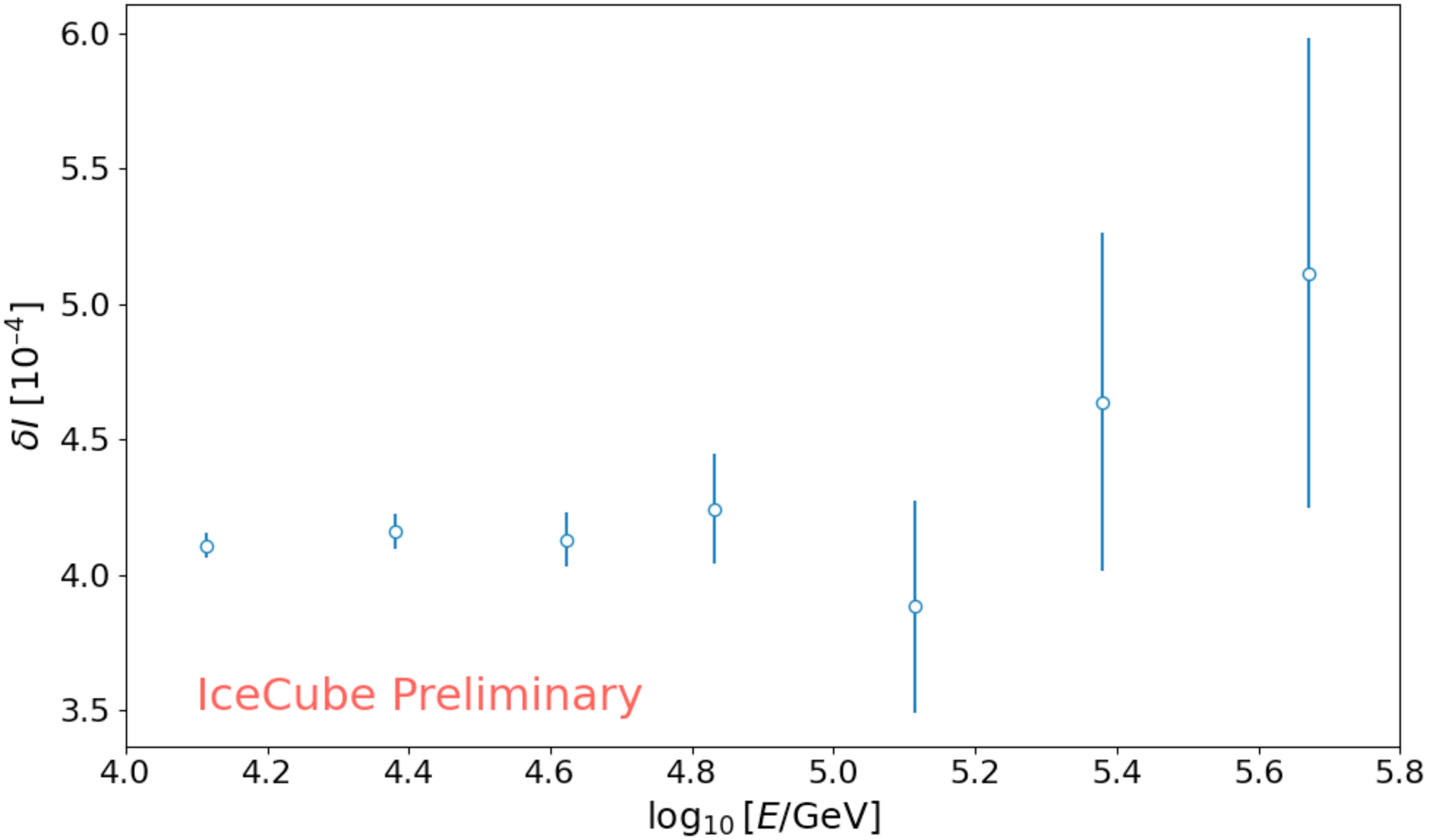
IceCube cosmic-ray muon data

Year	2011	2012	2013	2014	2015	2016	
Livetime [days]	341.33	343.88	357.91	357.68	361.47	359.89	
Duty Cycle	93.26%	94.21%	98.06%	97.99%	98.76%	98.60%	
Events ($\times 10^{10}$)	4.94	5.21	5.42	5.43	5.44	5.45	
Year	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**Total**
Livetime [days]	359.31	361.84	361.62	363.28	364.25	362.85	**4295.29**
Duty Cycle	98.44%	99.13%	98.80%	99.53%	99.80%	99.41%	**98.00%**
Events ($\times 10^{10}$)	5.44	5.45	5.50	5.46	5.46	5.46	**64.7**

- True energy distribution of cosmic-ray primaries from 7 energy bins.
- Cuts correspond to the ones in 12-year analy. (2025)
- $\log_{10}$(NChannel) vs cos(θ)
- re-weighted according to the GSF model (Dembinski et al. 2017).
- The median value for each distribution is indicated in the legend.



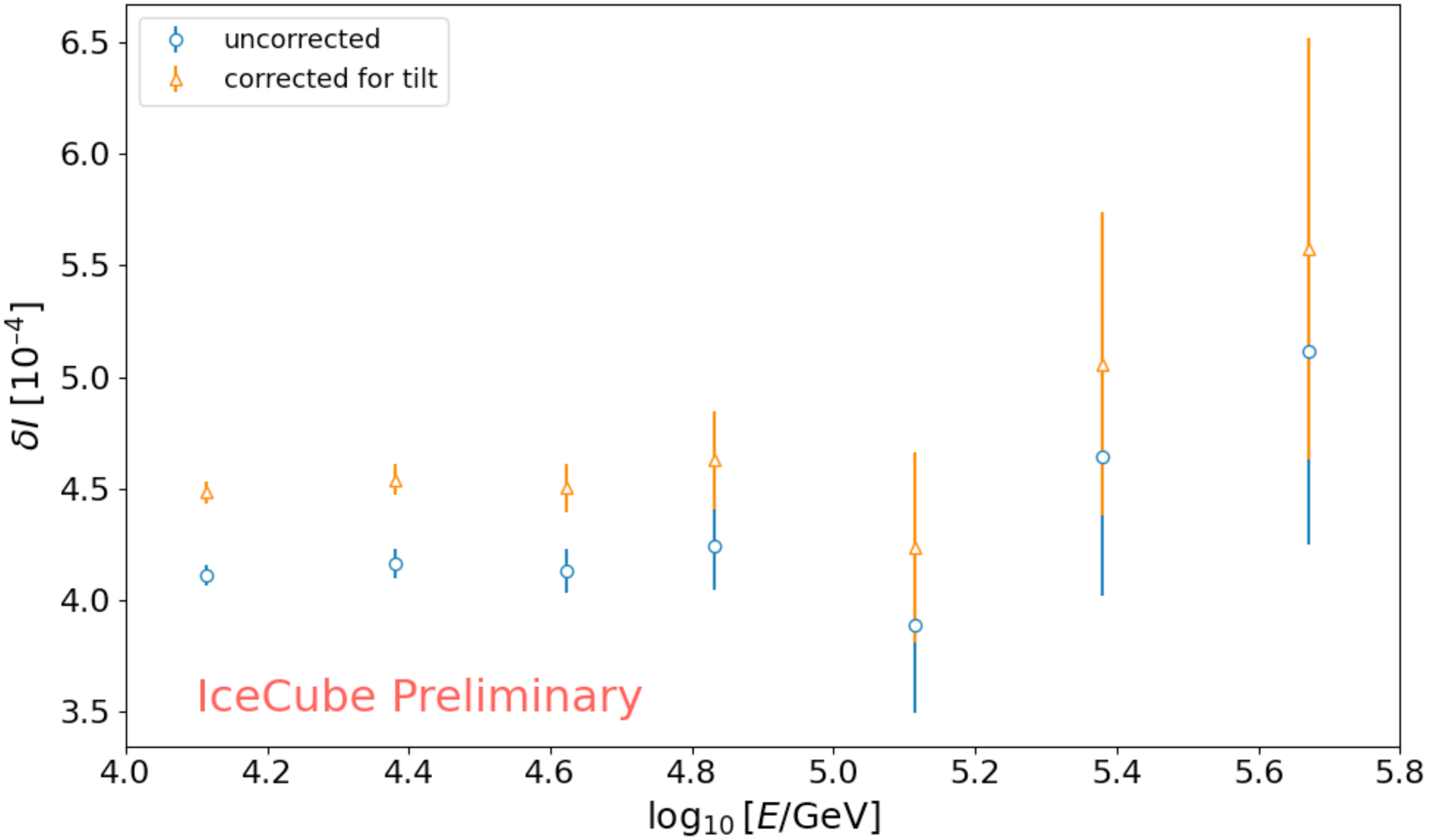
Time series fit

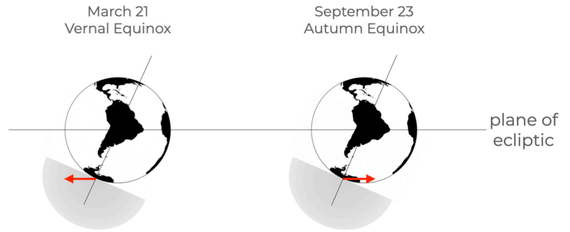


Projection of Compton-Getting amplitudes vs Energy onto the equatorial plane.

Missing North-South dipole component corresponding to ℓ=1, m=0 term in spherical harmonics.

Time series fit

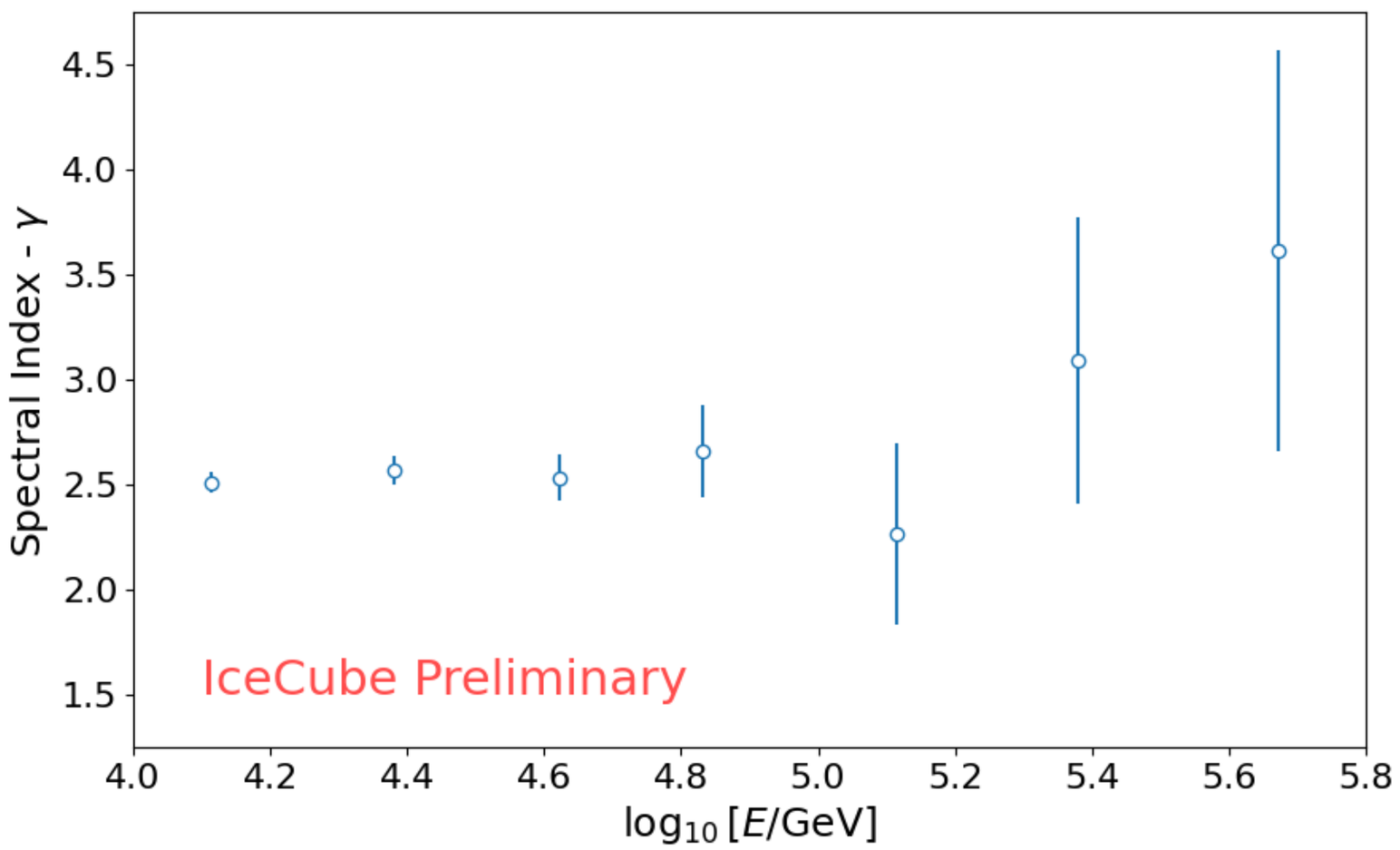




Correct for projection bias (dipole tilt is known) 23.5047°

Figure: Compton-Getting amplitudes vs Energy Corrected for the tilt of Earth axis with respect to the ecliptic 1/cos(23.5°).

Time series fit



Left: Spectral index γ vs Energy for 7 anisotropy bins, calculated from the dipole amplitude according to

$$\gamma = \delta I \frac{c}{v} - 2$$

Errors are statistical corresponding the fit error scaled by the ratio c/v.

Bias from Yearly modulation of solar anisotropy

Because the C-G dipole amplitude is ~3x smaller than the sidereal dipole, the anti-sidereal and spurious sidereal sidebands are comparably smaller.

PoS(ICRC2021)085

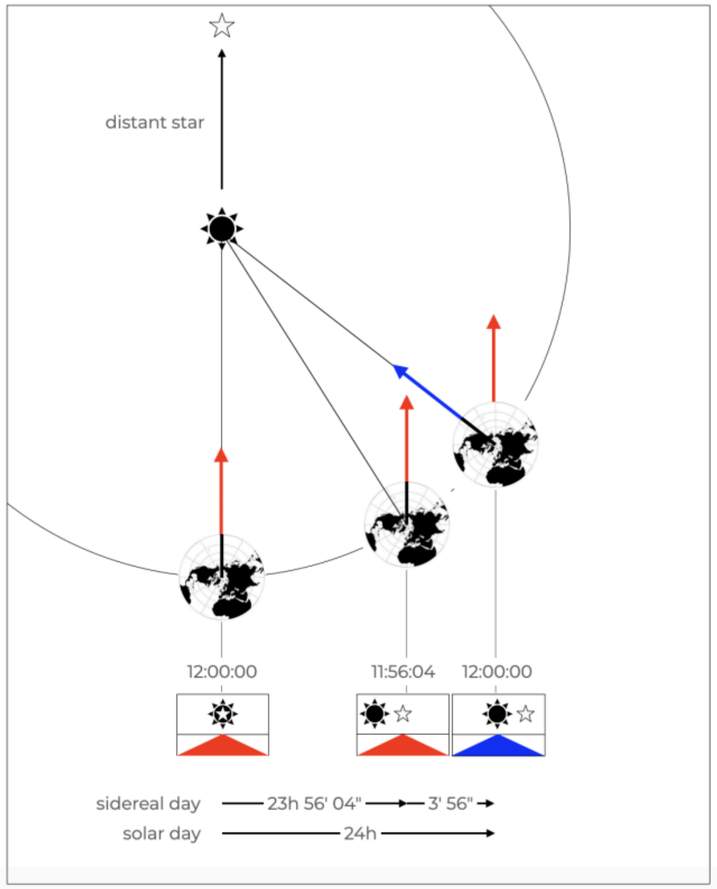


Figure 2: *Left:* the sidereal time with respect to solar time. Time starts at 12:00:00 on the local meridian with the Sun at the same location as a distant star. Then, as the Earth revolves around the Sun, the sidereal time zero point stays fixed in the celestial sky while the solar time's reference point moves away. They

anti-sidereal distribution is produced by a **yearly modulation** of the solar-dipole amplitude and it **deforms** the sidereal distribution

Anti-sidereal Correction Phase

Farley & Storey, Proc. Phys. Soc., 67, 996 1954
Nagashima, et al., Nuovo 907 Cimento C, 6, 550, 1983

$$R(t) = 1 + \underbrace{[A_{\rm sol} + 2B_{\rm sb}\cos(2\pi\delta f t - \phi_2)]}_{\text{seasonal modulation}}\underbrace{\cos(2\pi f t - \phi_1)}_{\text{solar variation}} + \underbrace{C_{\rm sid}\ \cos\{2\pi(f+\delta f)t - \phi_3\}}_{\text{true sidereal variation}}\ .$$

$$R(t) = 1 + \underbrace{A_{\rm sol}\ \cos(2\pi f t - \phi_1)}_{\text{solar}} + \underbrace{B_{\rm sb}\ \cos\{2\pi(f+\delta f)t - (\phi_1+\phi_2)\}}_{\text{spurious sidereal}} + \underbrace{C_{\rm sid}\ \cos\{2\pi(f+\delta f)t - \phi_3\}}_{\text{true sidereal}} + \underbrace{B_{\rm sb}\ \cos\{2\pi(f-\delta f)t - (\phi_1-\phi_2)\}}_{\text{anti-sidereal}}$$

ϕ_1 phase of solar dipole

$\phi_1 + \phi_2$ phase of anti-sidereal dipole

$\alpha = \phi_1 - \phi_2$ phase of sidereal correction term

Systematic uncertainty (time series): $\delta I_{\rm as} \to \delta I_{\rm as}\cos\alpha$

Super-Kamiokande CR Anisotropy Paper arxiv:0508468

Bias from Yearly modulation of solar anisotropy

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anti-sidereal distribution is produced by a **yearly modulation** of the solar-dipole amplitude and it **deforms** the sidereal distribution

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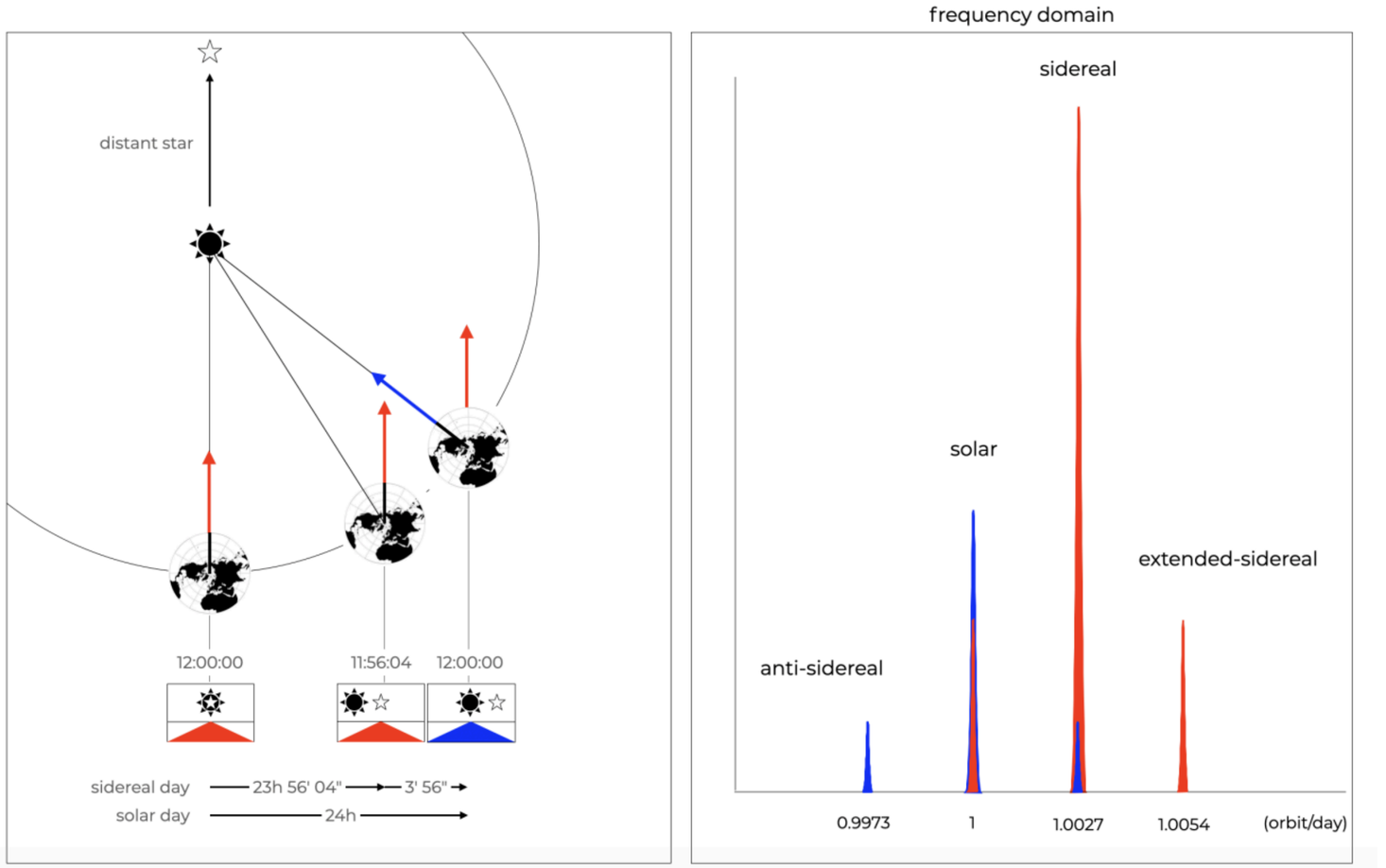
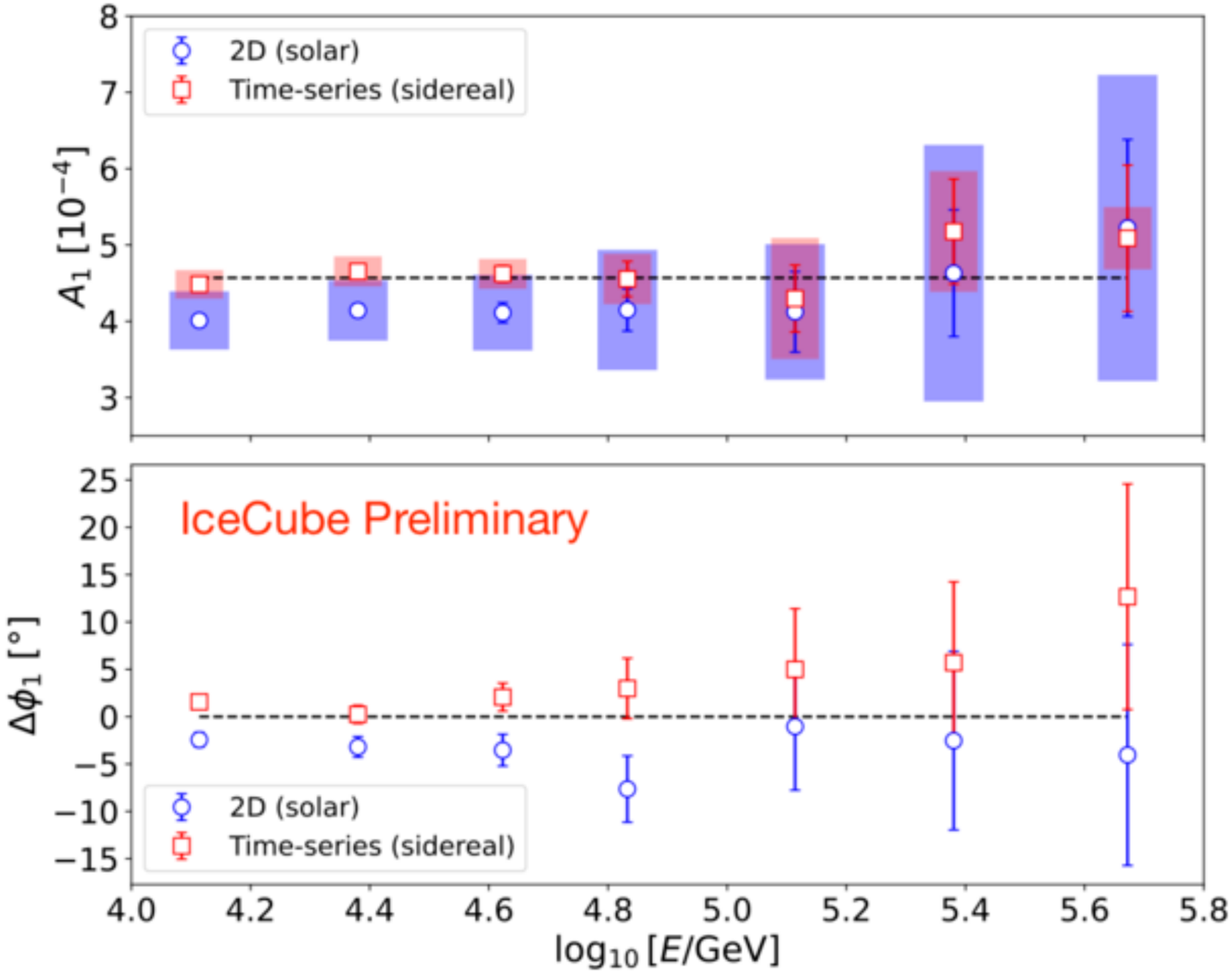


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Time series fit

Top: solar dipole amplitudes calculated from 2D fit in the solar reference frame (blue) and using a time series in the sidereal frame (red) compared to a single power-law hypothesis of $\gamma = -2.6$ including systematic uncertainties.

Bottom: phase offset from the direction of the velocity vector. Leakage from the sidereal reference can produce a dipole that interferes constructively or destructively with the solar dipole, changing both the amplitude and direction. Systematic uncertainty from signal leakage is larger in the solar frame



Systematic check:

1st six years compared to 2nd six years.

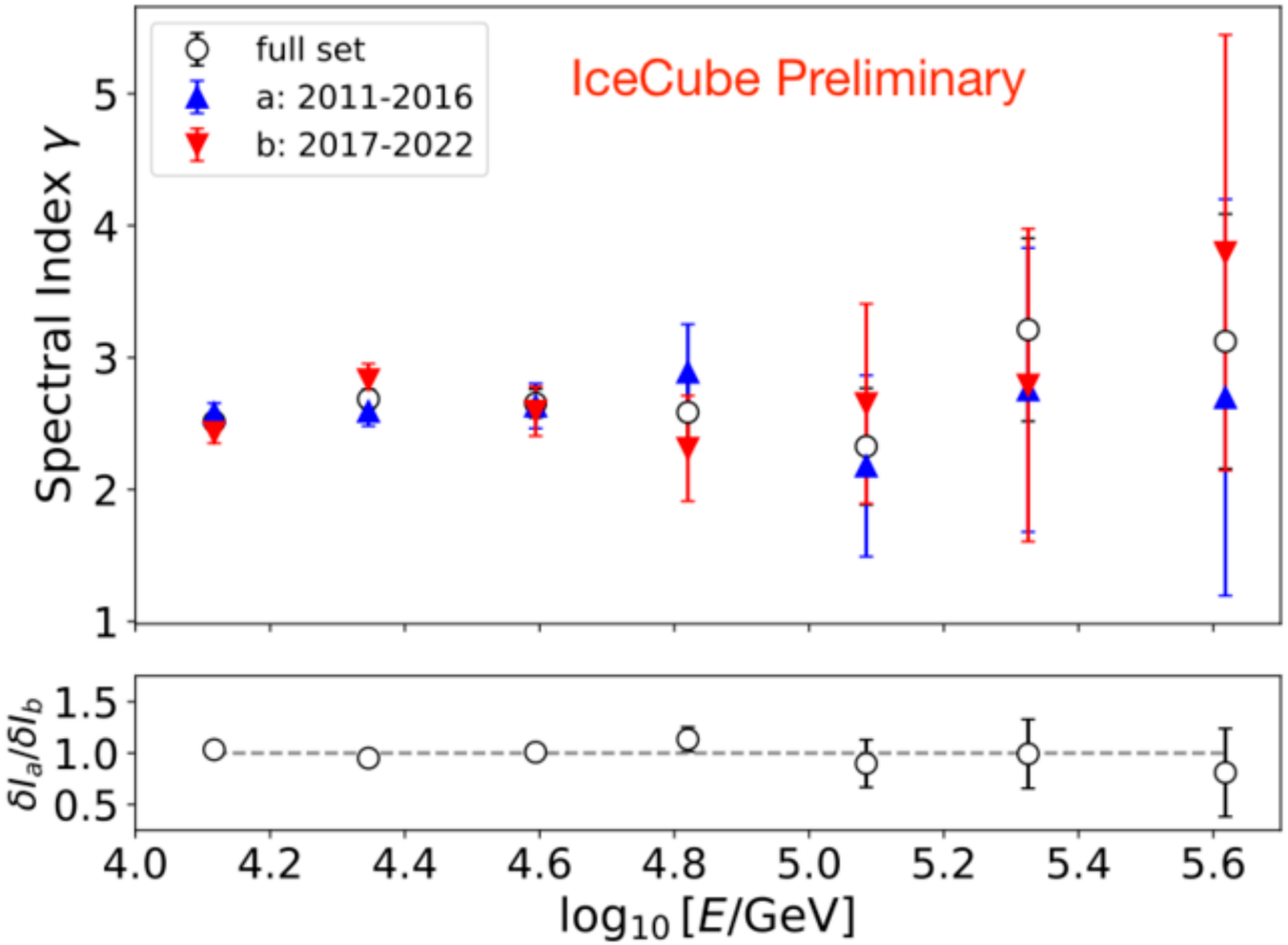
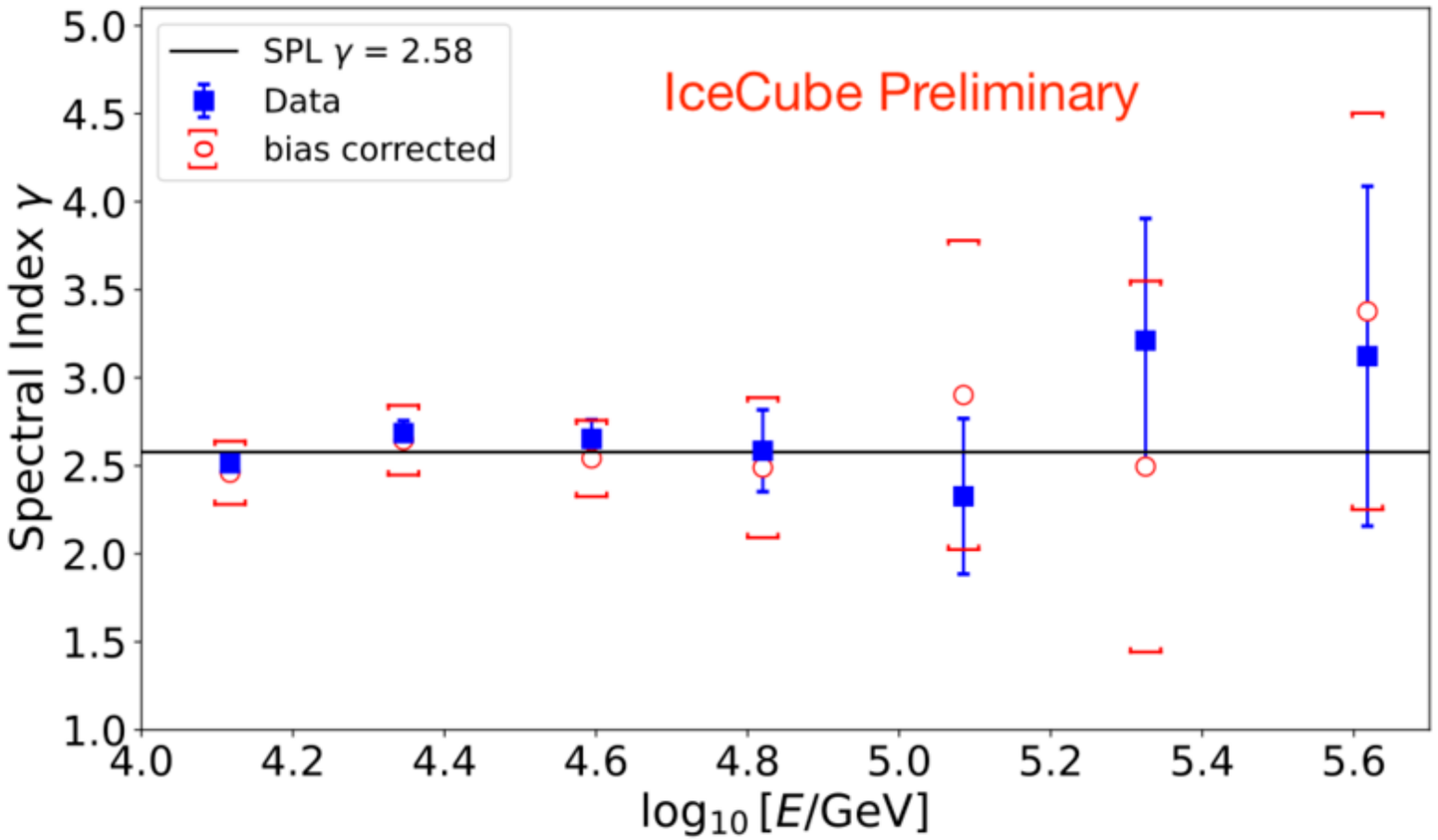


Figure: Dipole measurements differ between first 6 years (2011-2016) vs. second 6 years (2017-2022).

Measurements are consistent within statistical uncertainties.

Time series fit

(Systematic Uncertainties)



Systematic uncertainties:

Amplitude is reduced by factor cos(α).

Direction of bias is determined from angle

$$\alpha = \phi_1 - \phi_2$$

where

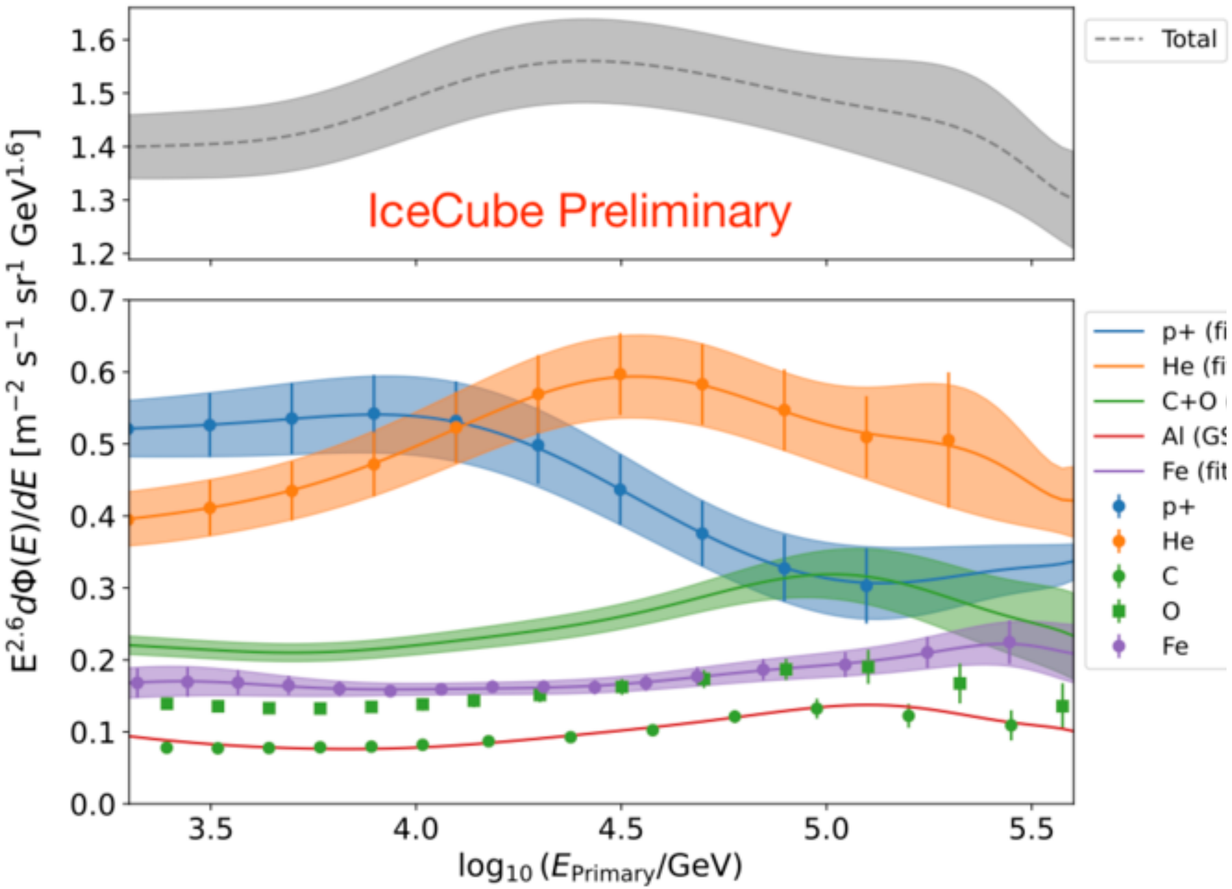
$$\phi_1$$

is the phase of solar dipole, and

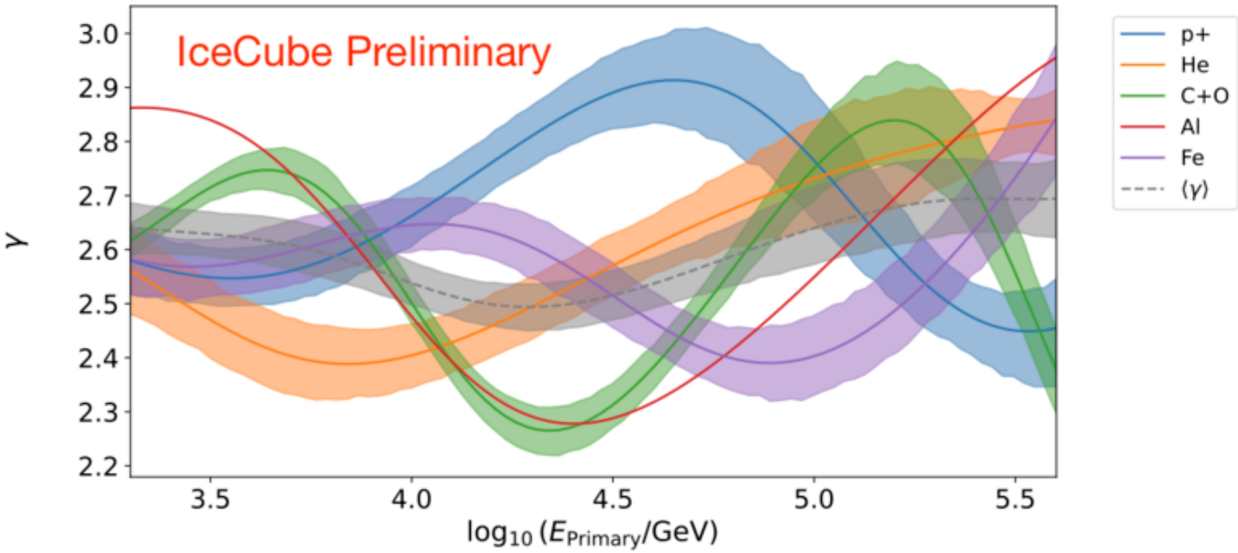
$$\phi_1 + \phi_2$$

is the phase of anti-sidereal dipole.

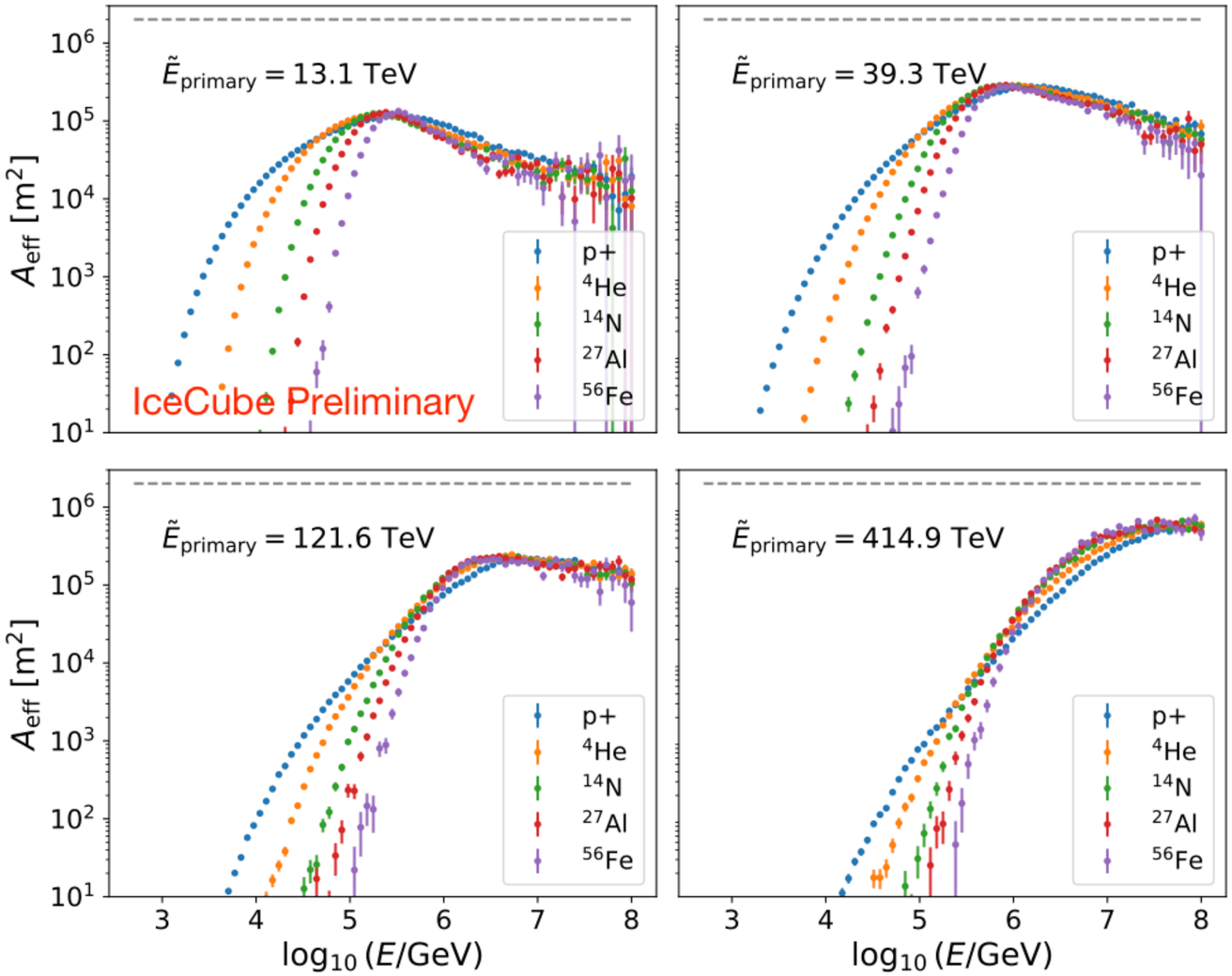
Hypotheses



$$\Phi_z \equiv \frac{d\phi_z(E)}{dE} \approx E^{-2.6} \sum_{n=0}^{11} a_{z,n} \left[\log_{10}(E/\mathrm{GeV})\right]^n ,$$



Effective areas (with bin cuts)



Once we have the value of gamma for each mass group z, we can convolve it the the effective area and calculate the expected mean value of gamma for each bin.

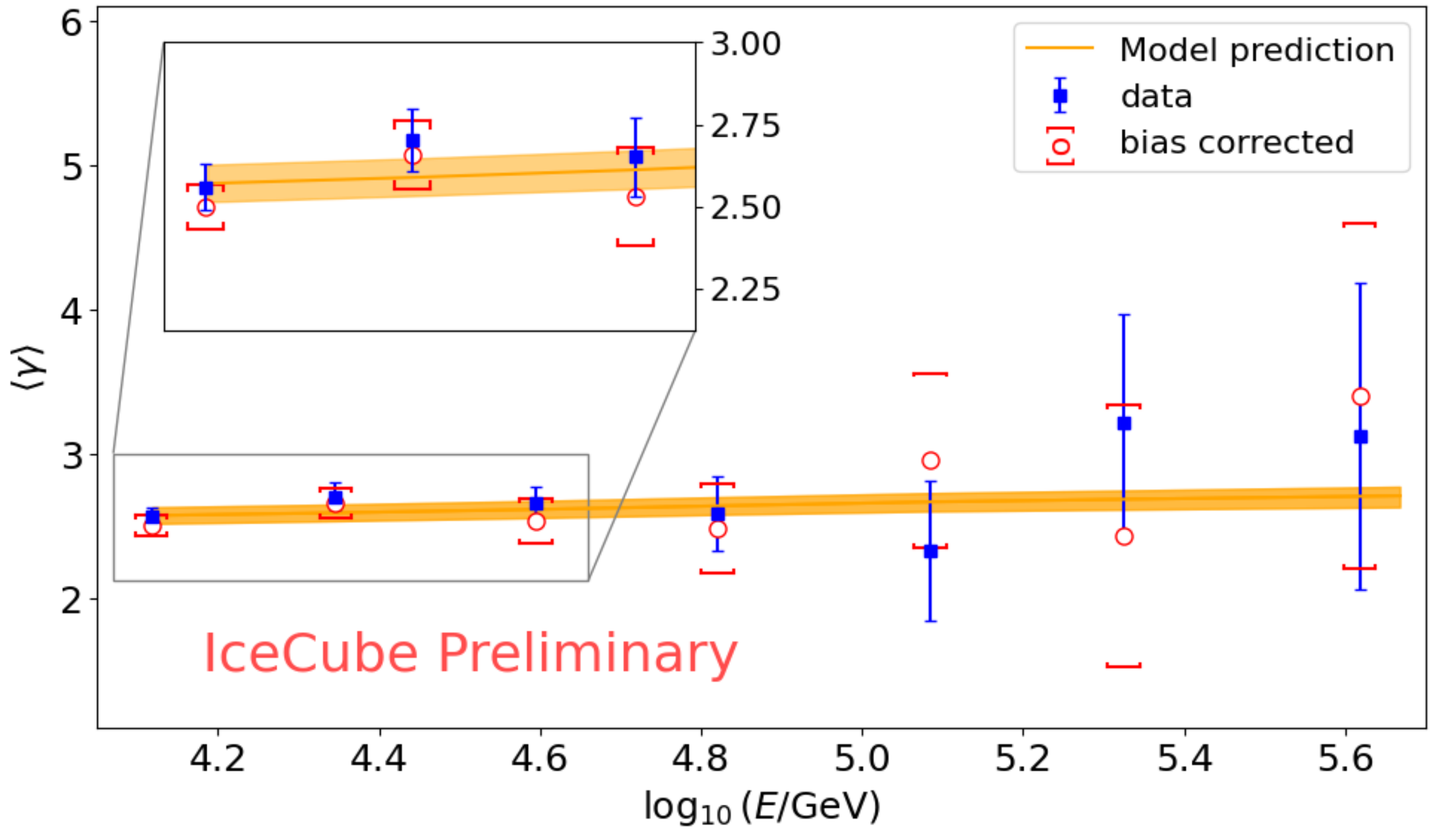
$$\langle\gamma\rangle_i = \frac{\sum_z \gamma_z \Phi_z * A_{\text{eff}_{z,i}}}{\sum_z \Phi_z * A_{\text{eff}_{z,i}}}$$

where

$$(\Phi_z * A_{\text{eff}_{z,i}})(E) = \int \Phi_z(E-e) A_{\text{eff}_{z,i}}(e) de$$

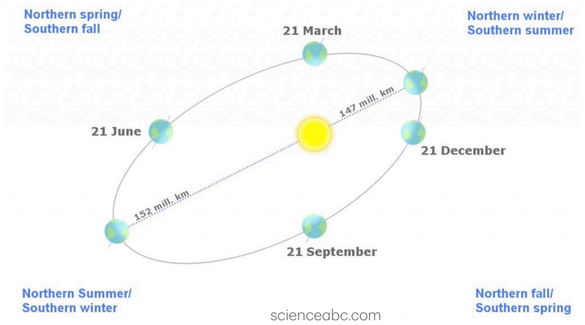
Time series fit

(Hypothesis Test)



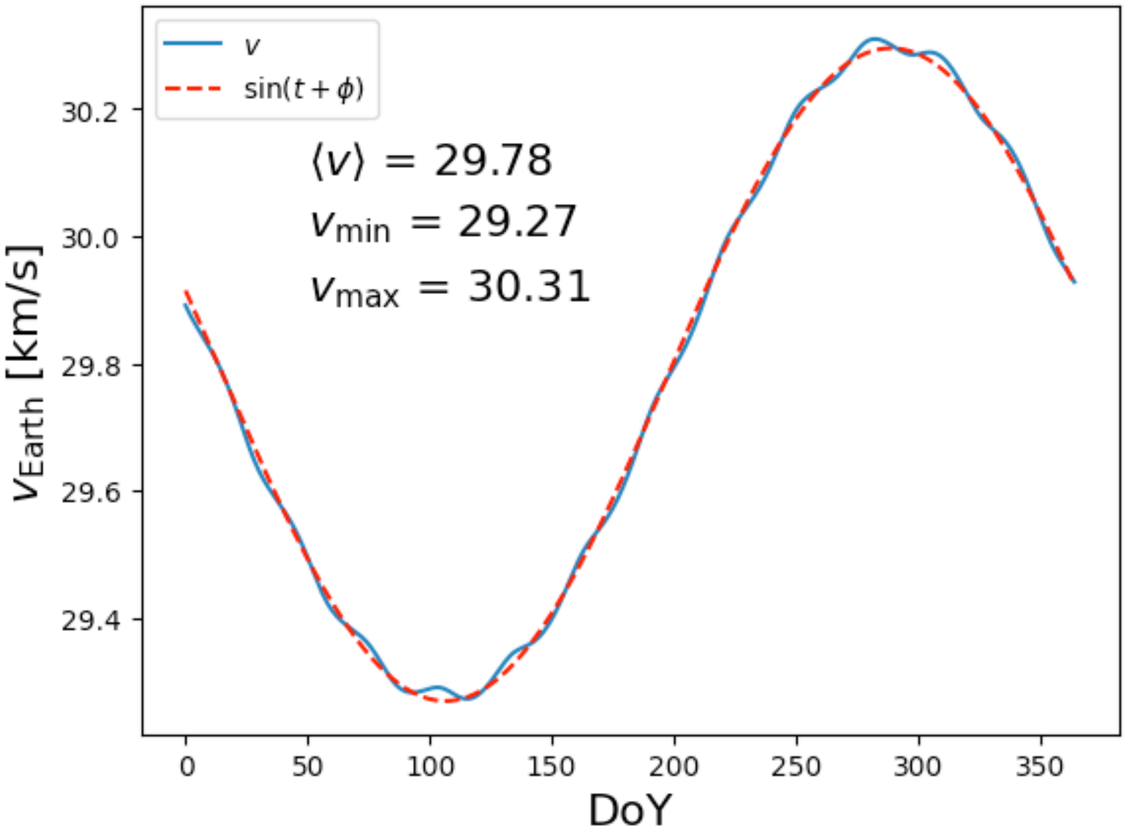
Measurement of spectral index γ as a function of energy obtained from measurements of the Compton-Getting effect compared to model prediction based on IceCube effective areas and direct measurements from DAMPE. The inset is a zoom in of the first three energy bins where the errors are relatively small.

Solar Dipole Modulation (Time Dependence)

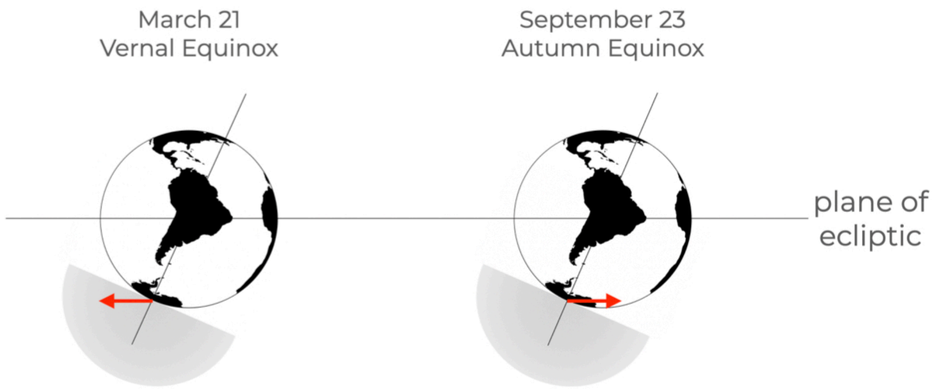


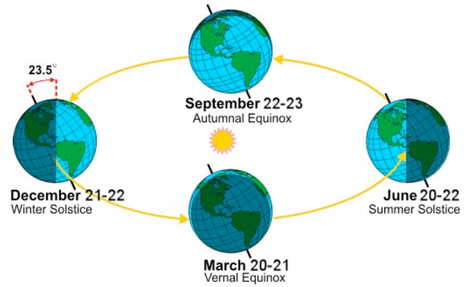
Orbital speed of Earth vs Time is nearly sinusoidal but there is an asymmetry due to the eccentricity of the orbit. The 28-day frequencies observed are caused by variations from the Earth-Moon system.

$$\delta I \approx (\gamma+2)\frac{\langle v \rangle}{c} + (\gamma+2)\frac{(v_{\max}-v_{\min})}{c}\cos(\omega t - \phi)$$



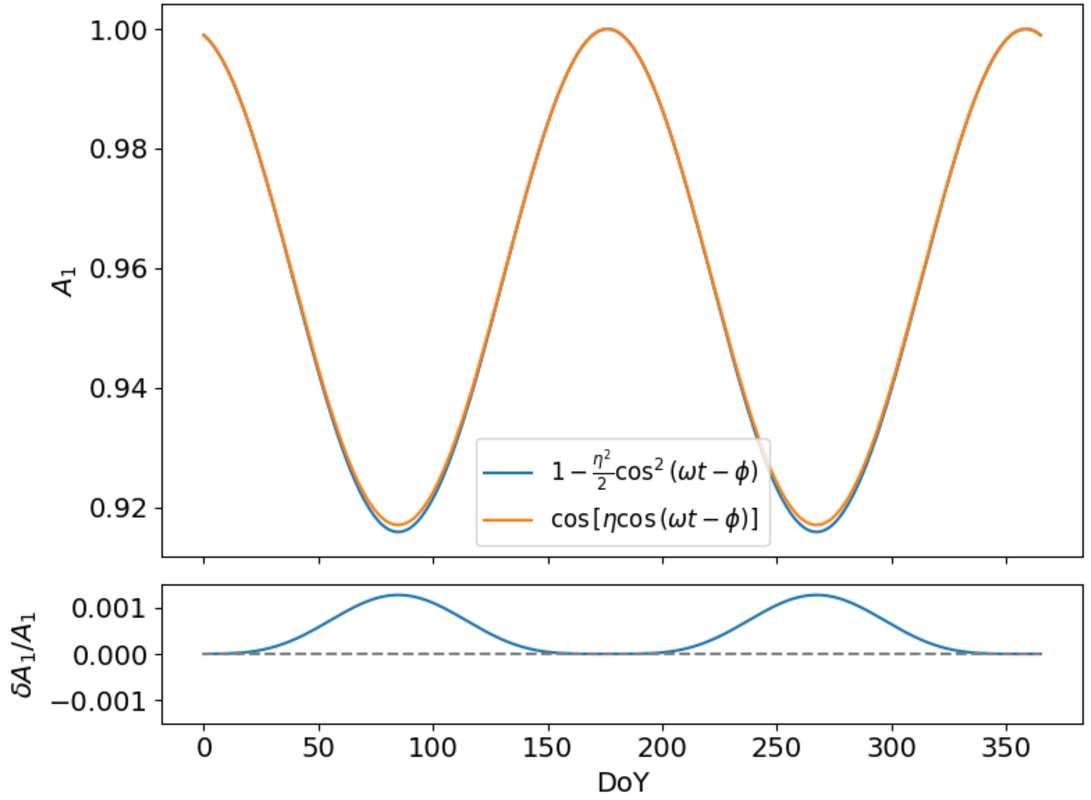
Solar Dipole Modulation (Time Dependence)





In addition to the yearly modulation due to the orbital s
the Earth tilt relative to the velocity vector peaks during
equinoxes and oscillates between $\eta = \pm 23.5°$ by

$$\cos\left[\eta\cos\left(\omega t-\phi\right)\right] \approx 1-\frac{\eta^2}{2}\cos^2\left(\omega t-\phi\right)$$



Solar Dipole Modulation (Time Dependence)

So the total expected yearly variation is

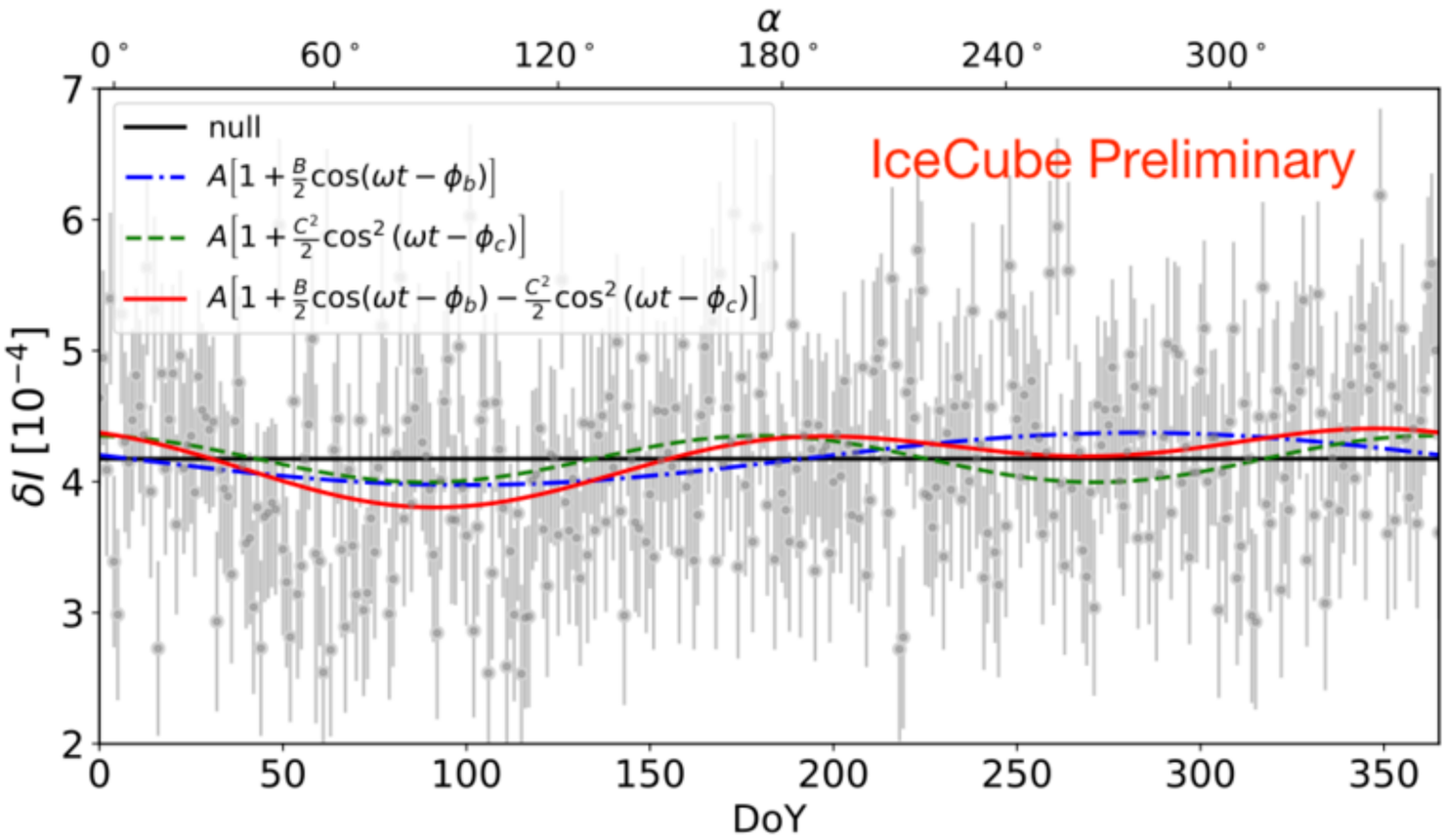
$$A_{\odot+\oslash}(t) \approx A_1 \left[1 + \frac{\epsilon_v}{2}\cos\left(\omega t - \phi_b\right) - \frac{\eta^2}{2}\cos^2\left(\omega t - \phi_c\right)\right]$$

Where A_1 is the mean amplitude and

$$\epsilon_v = \Delta v / \langle v \rangle \sim 3.4\%$$

is the variation due to the orbital speed (~10%)

Solar Dipole Modulation (Time Dependence)



Daily solar amplitude vs. time: We get the best fit for the first and second harmonic representing the variation in orbital speed and tilt shadow, respectively.

Solar Dipole Modulation (Time Dependence)

Fit results

Daily solar amplitude vs. time. We get the best fit for the first and second harmonic representing the variation in orbital speed and tilt shadow, respectively.

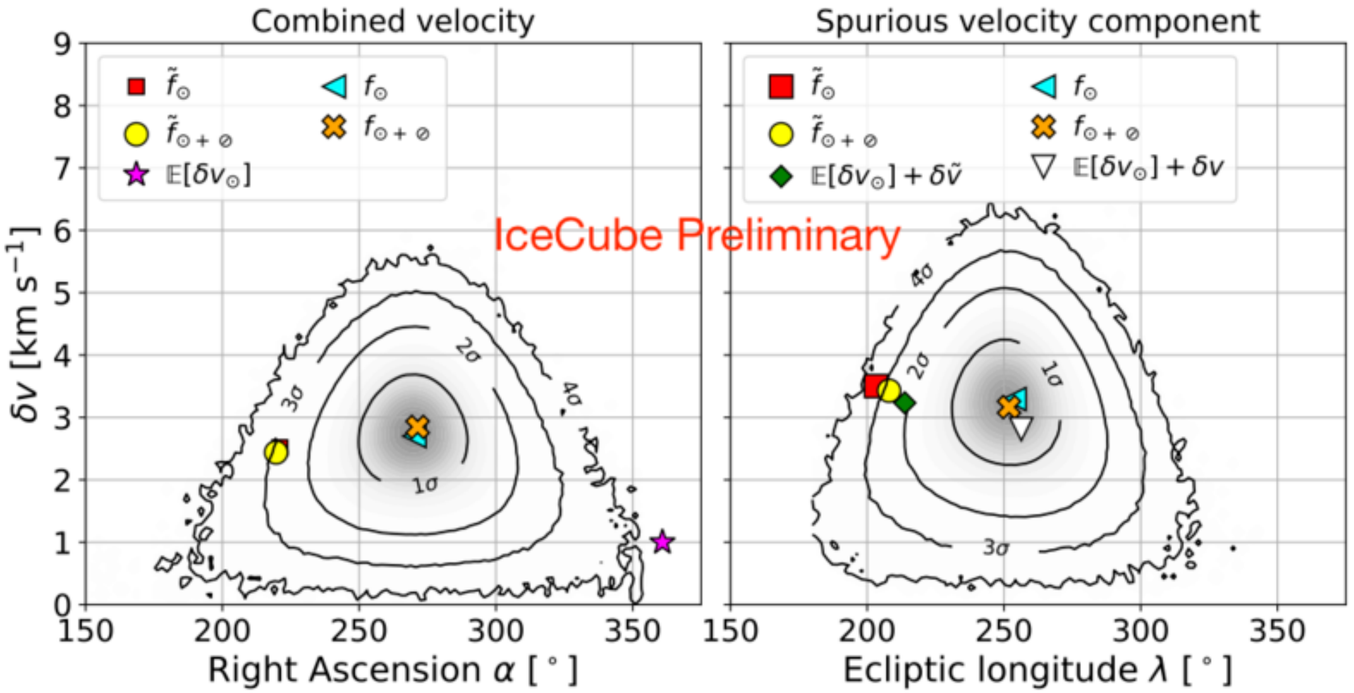
	$\delta v_\odot$ [km/s]	η [°]	A_1 [$\times 10^{-4}$]	ϕ_b [°]	ϕ_c [°]
f_0	–	–	4.175±0.032	–	–
$f_\odot$	2.8±0.6	–	4.174±0.032	278±13	–
$f_\oslash$	–	23.2±2.8	4.35±0.06	–	267±8
$f_{\odot+\oslash}$	2.7±0.6	23.0±2.8	4.35±0.06	277±14	268±8
$\mathbb{E}[f_{\odot+\oslash}]$	1.000±0.016	23.45	~4.58†	4±8	260±5

	f_0	$f_\odot$	$f_\oslash$
f_0	–	–	–
$f_\odot$	3.57σ	–	–
$f_\oslash$	2.81σ	–	–
$f_{\odot+\oslash}$	4.40σ	3.07σ	3.92σ

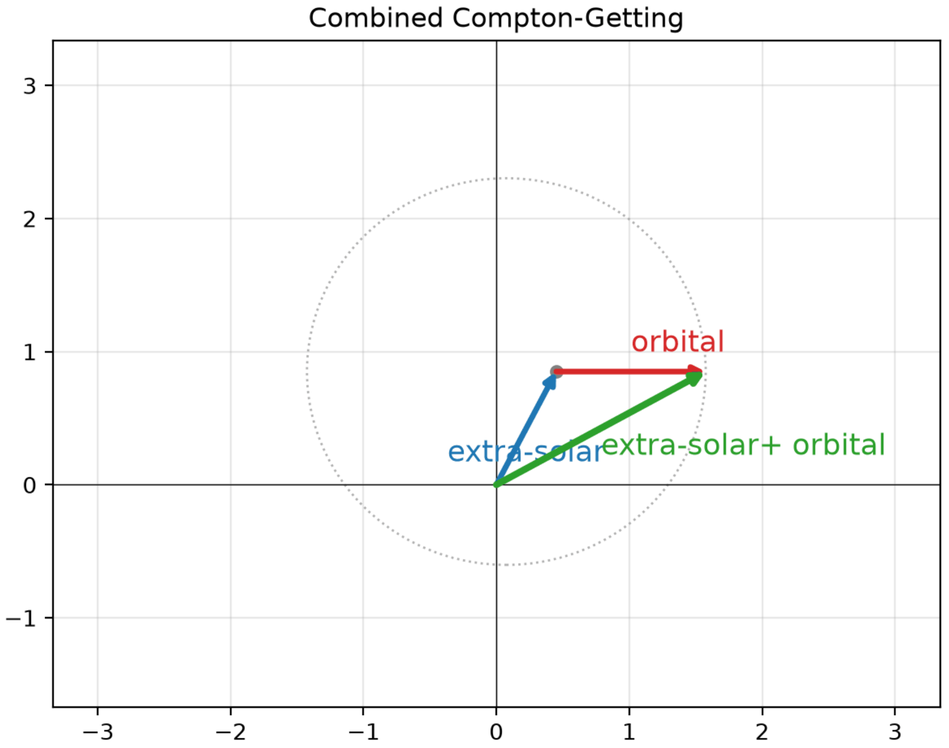
The the yearly variation in amplitude due to the eccentricity of the orbit is a better fit than the null hypothesis but has a larger amplitude and different phase than the prediction.

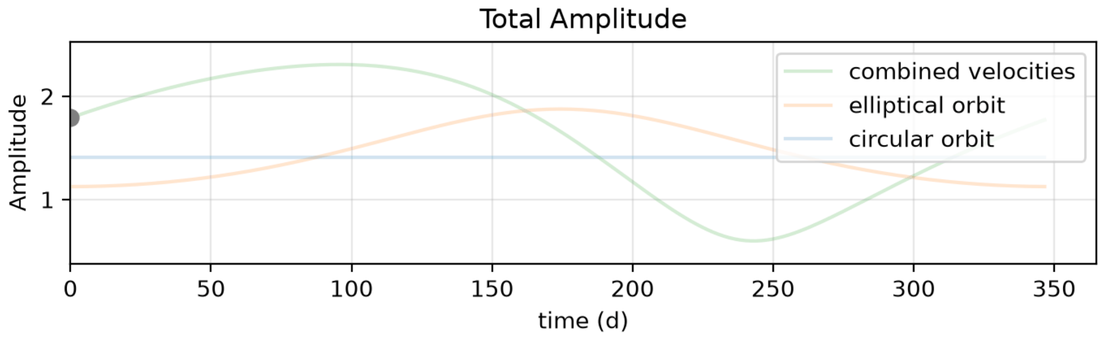
Residual velocity

$$\delta\vec{v}_{\mathrm{res}} = \delta\vec{v}_{\odot} - \mathbb{E}[\delta\vec{v}_{\odot}]$$

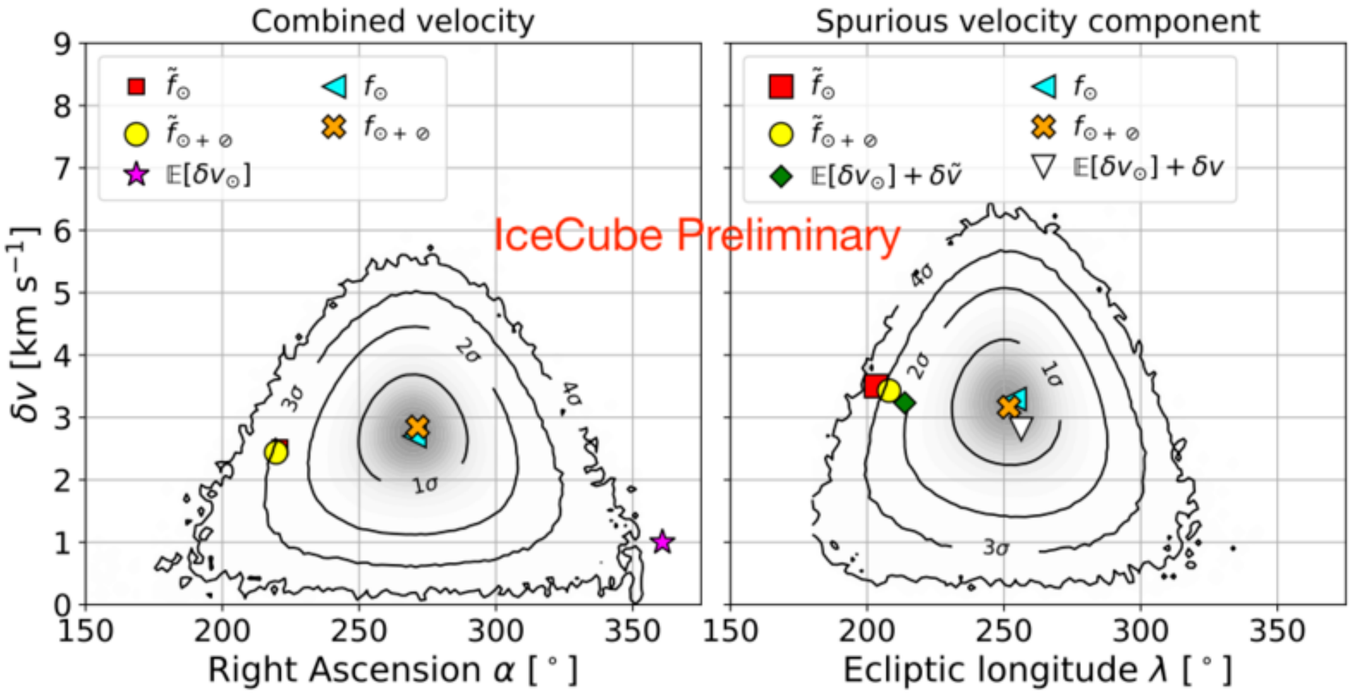


Fit	$\delta v_{\odot}$ [km s^{-1}]	ϕ_b [°]	δv_{res} [km s^{-1}]	ϕ_{res} [°]	$\delta v^{\parallel}_{\mathrm{ecl}}$ [km s^{-1}]	λ_{ecl}	marg. pre-trial	joint pre-trial
$f_{\odot}$	2.8±0.6	278±13	2.9±0.6	258±13	3.2±0.6	258±13	3.00σ	6.38σ
$f_{\odot+\oslash}$	2.7±0.6	277±14	2.8±0.6	256±14	3.1±0.6	256±14	2.83σ	6.09σ
f_{res}	2.7±0.6	277±14	2.8±0.6	256±14	3.0±0.6	256±14	2.78σ	6.07σ





$$\delta\vec{v}_{\mathrm{res}} = \delta\vec{v}_{\odot} - \mathbb{E}[\delta\vec{v}_{\odot}]$$



Fit	$\delta v_{\odot}$ [km s^{-1}]	ϕ_b [°]	δv_{res} [km s^{-1}]	ϕ_{res} [°]	$\delta v_{\mathrm{ecl}}^{\parallel}$ [km s^{-1}]	λ_{ecl}	marg. pre-trial	joint pre-trial
$f_{\odot}$	2.8±0.6	278±13	2.9±0.6	258±13	3.2±0.6	258±13	3.00σ	6.38σ
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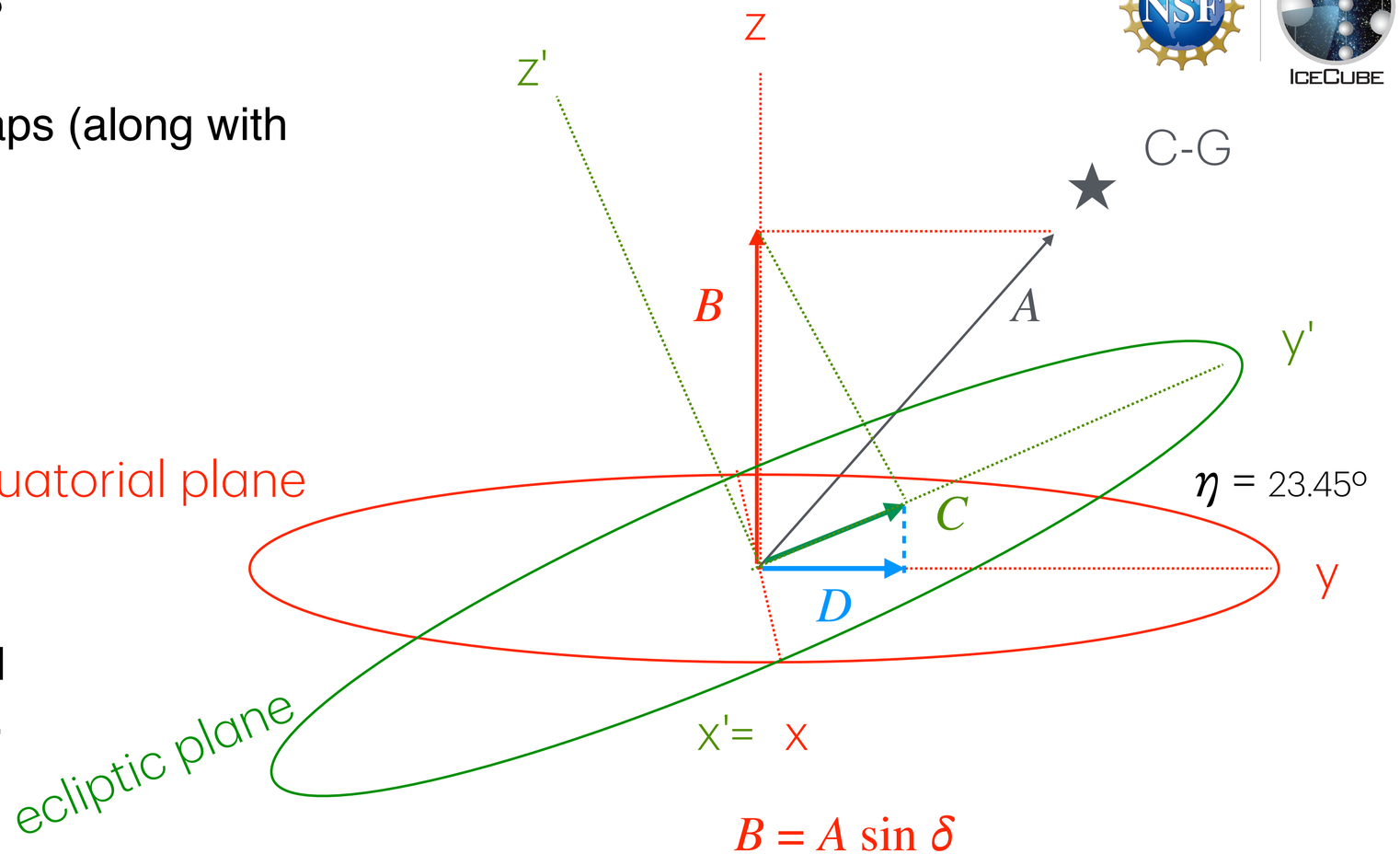
But what exactly is this 'extra-solar' dipole?

extra-solar C-G is subtracted from daily maps (along with sidereal anisotropy)

$$\delta I_{i,\tau} = \frac{N_{i,\tau}}{\langle N \rangle_{i,\tau}} - \frac{\sum_t N_{i,t}}{\sum_t \langle N \rangle_{i,t}}$$

...but not the z-component.

We can observe the z-component projected onto the ecliptic (but only in the y-direction).



$B = A \sin\delta$

$C = B \sin\eta$

$D = C \cos\eta$

$$\delta v = A \sin\delta \sin\eta \cos\eta = \frac{A}{2} \sin\delta \sin 2\eta$$

Conclusions

- **Main measurement:** Using 12 years of IceCube muon data (10–400 TeV, seven energy bins), the authors measured the solar Compton-Getting dipole caused by Earth's orbital motion. The resulting spectral index is consistent with a single power law, $\gamma = 2.58 \pm 0.04$, or $\gamma = 2.52 \pm 0.04$ after correcting for spurious dipoles using anti-sidereal data.
- **Improved statistics:** The study improves on earlier results from Tibet-III (10 TeV) and the Mexico City Neutron Monitor (1.5 TeV), with the highest statistics yet at around 20 TeV.
- **Model comparison:** A model built from direct measurements of several nuclei plus the Global Spline Fit, folded with IceCube's effective area, predicts a nearly constant spectral index across the range. It can't be distinguished from a single power law given the uncertainties.
- **Second-order effects:** At 18.7 TeV median energy, variations in Earth's orbital speed (from eccentricity and axial obliquity) appear at 4.4σ pre-trial significance. The fit gives an obliquity of $23.0° \pm 2.7°$ and a speed variation of 2.7 ± 0.6 km/s.
- **Possible extra-solar effect:** A small residual Compton-Getting amplitude of $4.4 \pm 0.9 \times 10^{-5}$ shows up in the annual speed variation (2.8σ in amplitude alone, over 4σ when phase is included). Its phase differs from the seasonal atmospheric muon variation (peak around January 1 vs. early September), so seasonal effects are an unlikely explanation. Independent confirmation is still needed.
- **Residual velocity:** only sensitive to z-component of extra-solar Compton-Getting dipole.

The presenter acknowledges support from NSF Grant #2209483

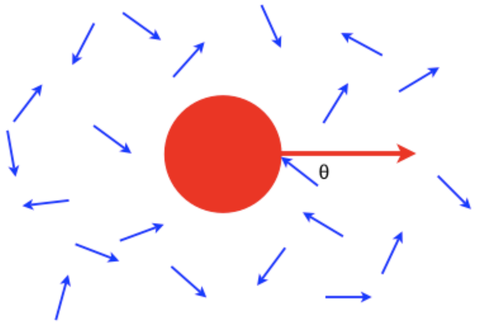
Backup

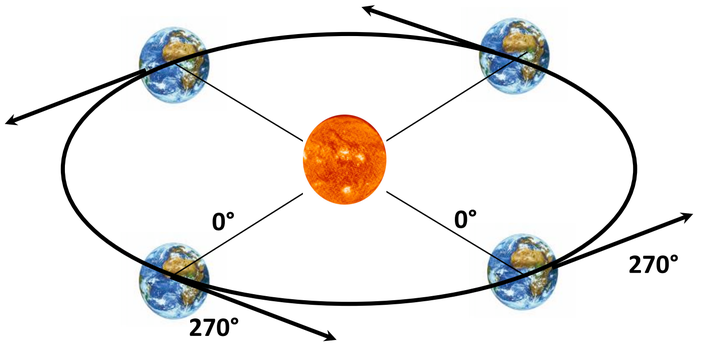
Compton-Getting Effect

Arthur H. Compton and Ivan A. Getting
Phys. Rev. 47, 817 – June 1935 doi:10.1103/PhysRev.47.817.

MIRIAM A. FORMAN, Planet. Space Sci. 1970, Vol. 18, pp. 25 to 31.

Any particle distribution function in phase space is invariant under Lorentz transformation.





$$f'(\mathbf{p}') = f(\mathbf{p})$$

The observer's motion speed is v ≪ c (e.g., Earth's orbital speed is about 30 km/sec, much smaller than the speed of light) so

$$\mathbf{p}' = \mathbf{p} + \frac{\gamma - 1}{v}(\mathbf{v}\cdot\mathbf{p})\mathbf{v} - \gamma\frac{E}{c^2}\mathbf{v} \longrightarrow \mathbf{p}' \approx \mathbf{p} - \frac{E}{c^2}\mathbf{v}$$

And since cosmic-ray particles are ultra-relativistic, E ≈ pc

$$\mathbf{p}' \approx \mathbf{p} - \frac{p}{c}\mathbf{v}$$

Compton-Getting Effect

MIRIAM A. FORMAN, Planet. Space Sci. 1970, Vol. 18, pp. 25 to 31.

By Taylor expansion the Lorentz invariance $f'(\mathbf{p}') = f(\mathbf{p})$ becomes

$$f'(\mathbf{p}') \simeq f_0(\mathbf{p}) - \underbrace{\frac{v}{c}(\mathbf{p}\cdot\mathbf{v})p\frac{\partial f_0}{\partial p}}_{\text{first order term}} + \underbrace{\frac{1}{2}\left(\frac{v}{c}\right)^2\left[(\mathbf{p}\cdot\mathbf{v})^2p^2\frac{\partial^2 f_0}{\partial p^2} + (1-(\mathbf{p}\cdot\mathbf{v})^2)\,p\frac{\partial f_0}{\partial p}\right]}_{\text{second order term}}$$

where $f'(\mathbf{p}) \equiv f_0(\mathbf{p})$ is the isotropic cosmic-ray particle distribution function in the *un-primed* reference system.

First Order C-G

MIRIAM A. FORMAN, Planet. Space Sci. 1970, Vol. 18, pp. 25 to 31.

The first-order term

$$f'(\mathbf{p}') \simeq f_0(\mathbf{p}) - \frac{v}{c}(\mathbf{p}\cdot\mathbf{v})p\frac{\partial f_0}{\partial p}$$

can be rewritten as

$$f'(\mathbf{p}') \simeq f_0(\mathbf{p})\left[1 - \frac{v}{c}\cos\theta\frac{p}{f_0}\frac{\partial f_0}{\partial p}\right] = f_0(\mathbf{p})\left[1 - \frac{v}{c}\cos\theta\,\frac{\partial \ln f_0}{\partial \ln p}\right]$$

First Order C-G

MIRIAM A. FORMAN, Planet. Space Sci. 1970, Vol. 18, pp. 25 to 31.

..or in terms of particle intensity

$$I' \simeq I_0 \left[1 - \frac{v}{c}\cos\theta \, \frac{\partial \ln I_0}{\partial \ln p}\right]$$

typically expressed as

$$I(E) \equiv \frac{dN}{dE} \propto E^{-\gamma}$$

or in momentum

$$I(p) \equiv \frac{dN}{p^2 dp} \propto p^{-(2+\gamma)}$$

Relative intensity:

$$\boxed{\frac{dI}{I} \simeq \frac{v}{c}(2+\gamma)\cos(\theta)}$$

Horizontal Multi-pole Fit

The dipole component is given by the $Y_{\ell m}$, terms

$$Y_1^{-1}(\alpha,\delta) = \frac{1}{2}\sqrt{\frac{3}{2\pi}}\cos\delta e^{-i\alpha}\,,$$

$$Y_1^{0}(\alpha,\delta) = \frac{1}{2}\sqrt{\frac{3}{\pi}}\sin\delta\,,$$

$$Y_1^{1}(\alpha,\delta) = -\frac{1}{2}\sqrt{\frac{3}{2\pi}}\cos\delta e^{i\alpha}$$

So, for a dipole oriented along the x-y plane,

$$F(\alpha_i,\delta_i) = a_{1,-1}Y_1^{-1} + a_{1,1}Y_1^{1} = A_1\cos(\delta_i)\cos(\alpha_i-\phi_1)$$

We fit parameters: A_1, ϕ_1 over the pixels in the FoV

