Orbital Compton-Getting Dipole Measurement with Eleven Years of IceCube Cosmic-Ray Muon Data

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TeVPA Chicago 2024

August 29, 2024

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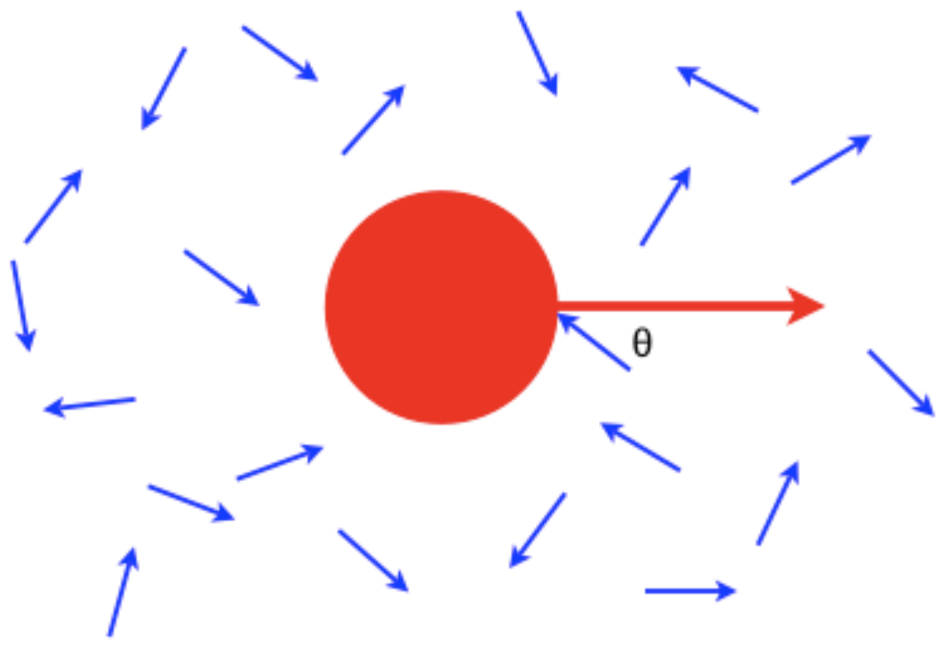
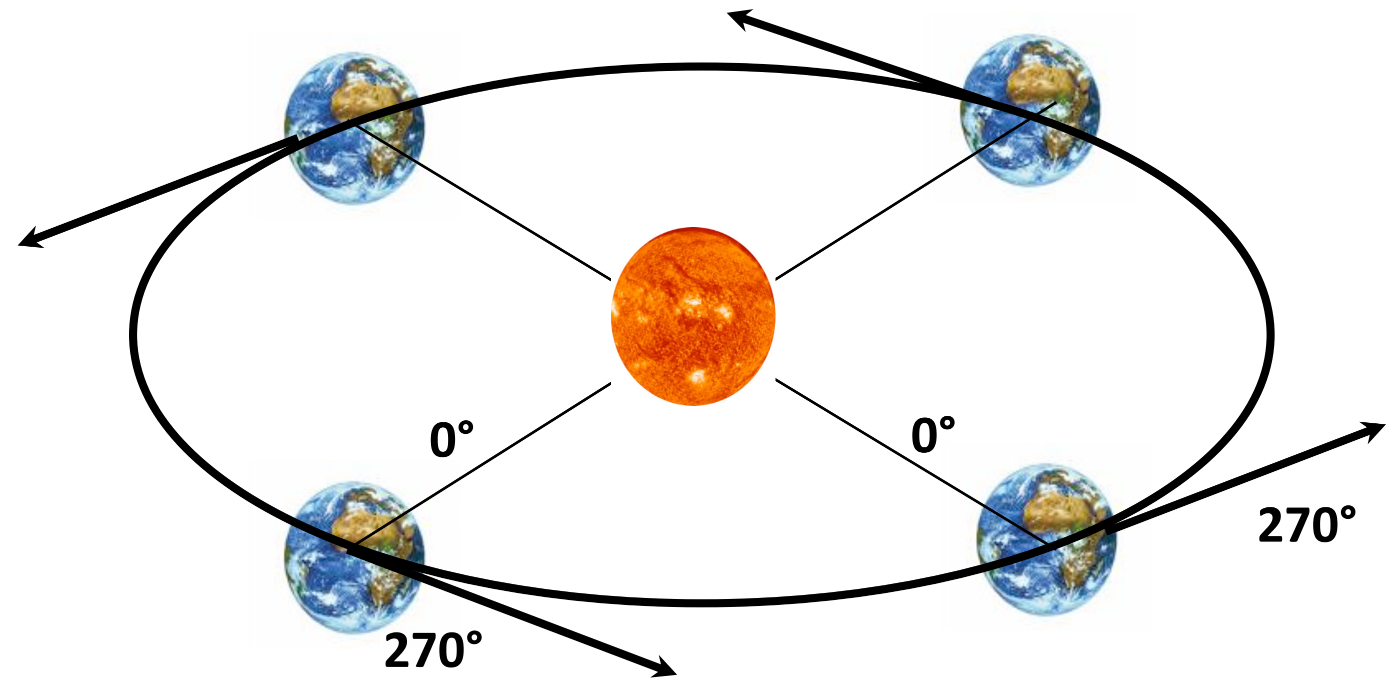
Solar Dipole: a known anisotropy

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.

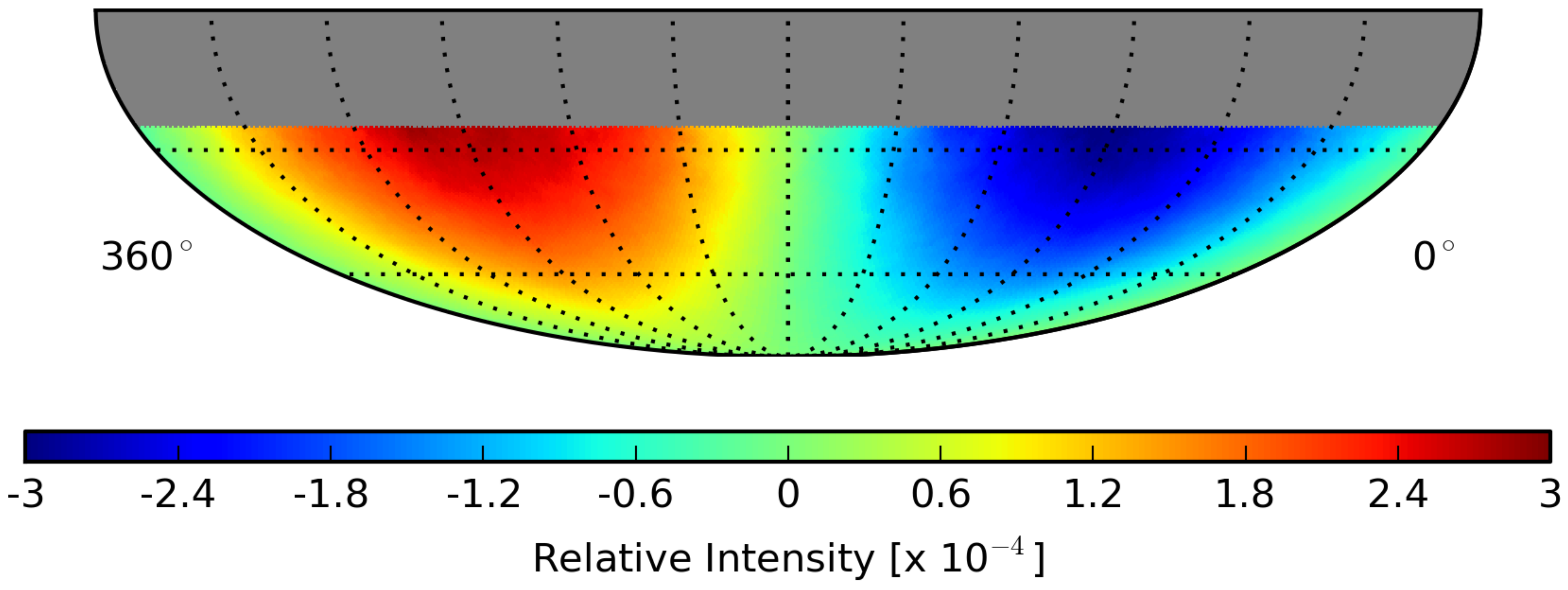


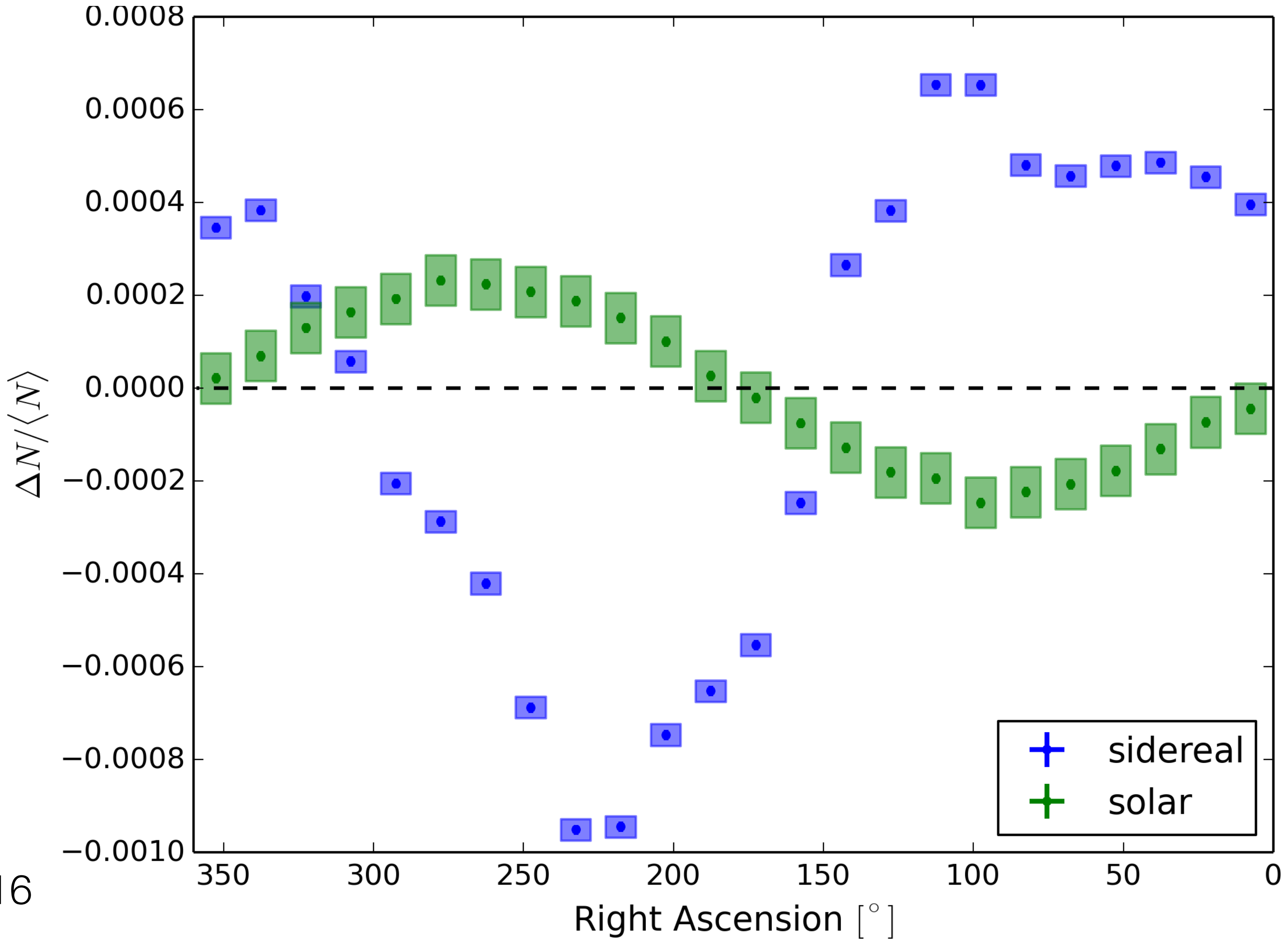
<v> = 29.8 ± 0.5 km/s



longitude in GSE

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





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

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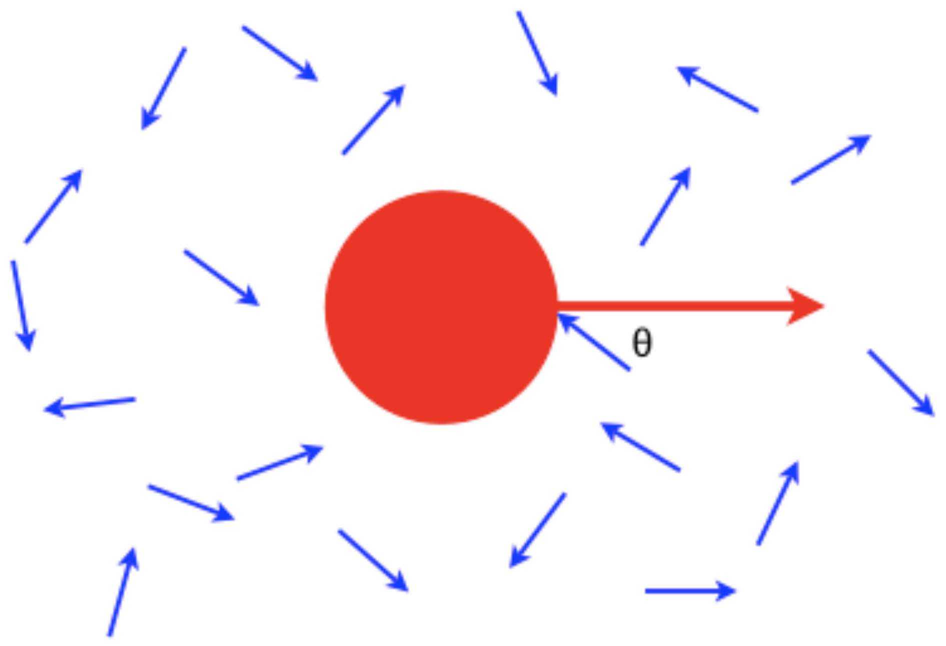

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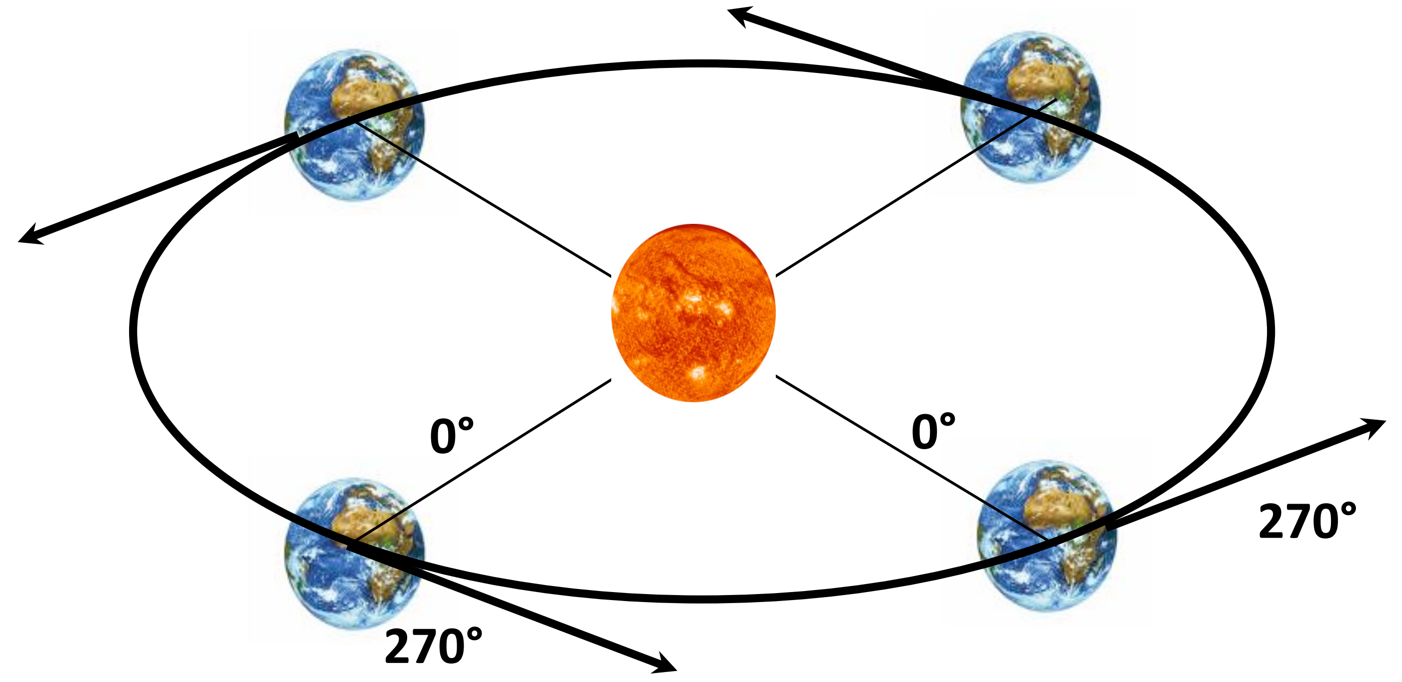

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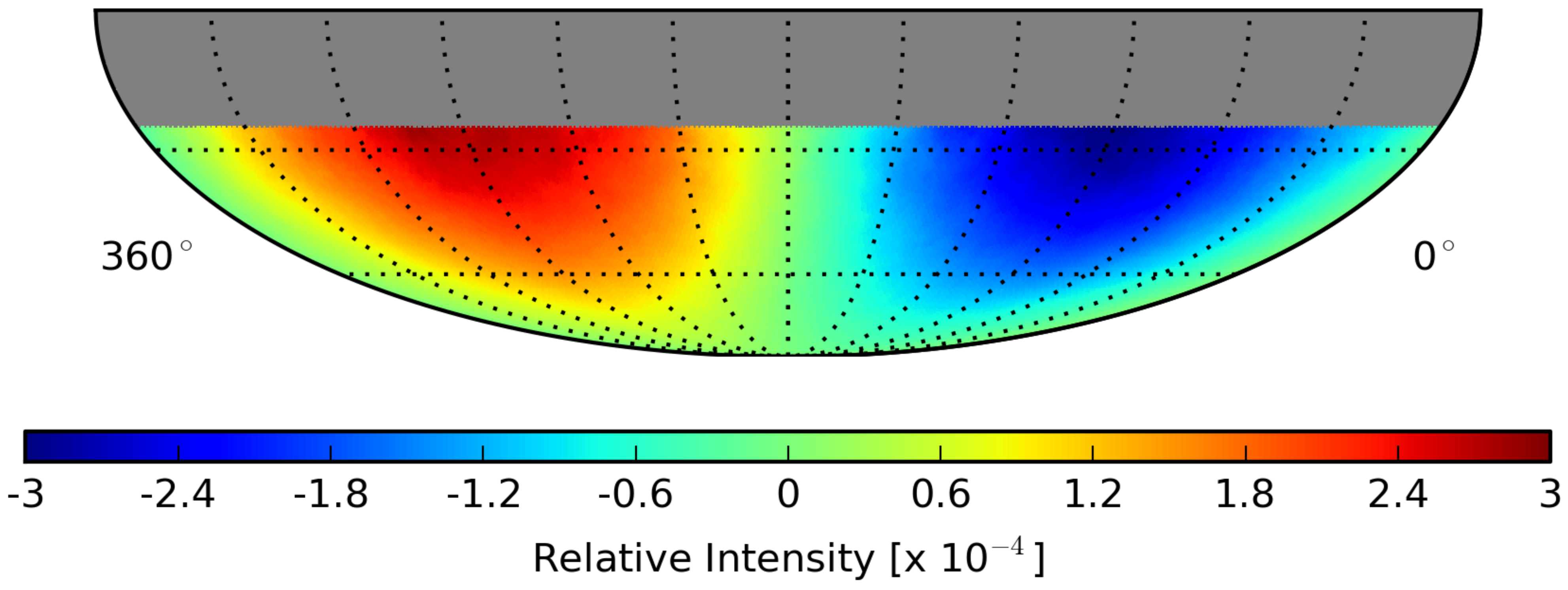
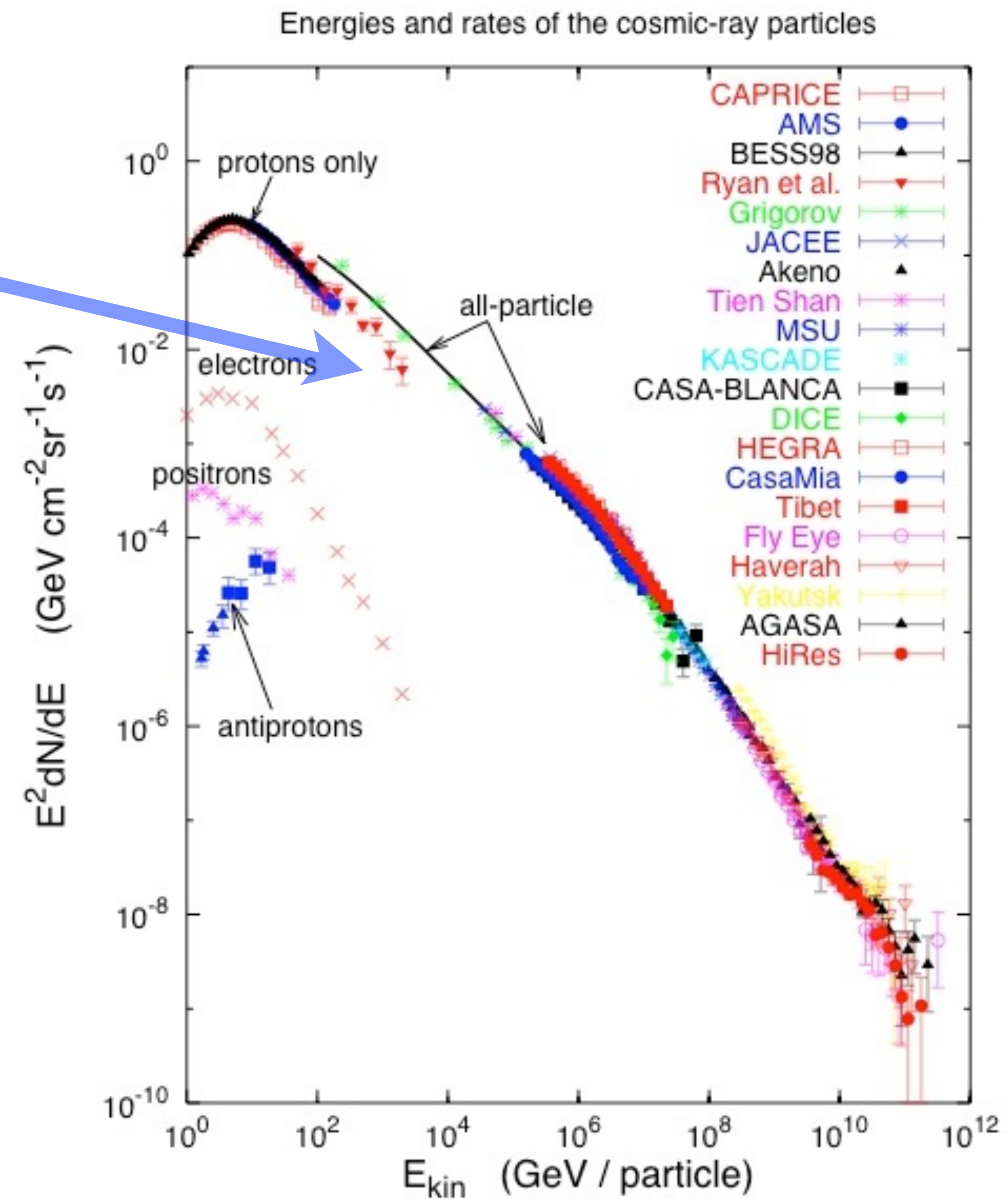




Method 1: Dipole Fit

Solar Dipole is given by
$$\frac{\delta I_i}{I} = \frac{v}{c}(\gamma + 2)\cos(\xi_i)$$

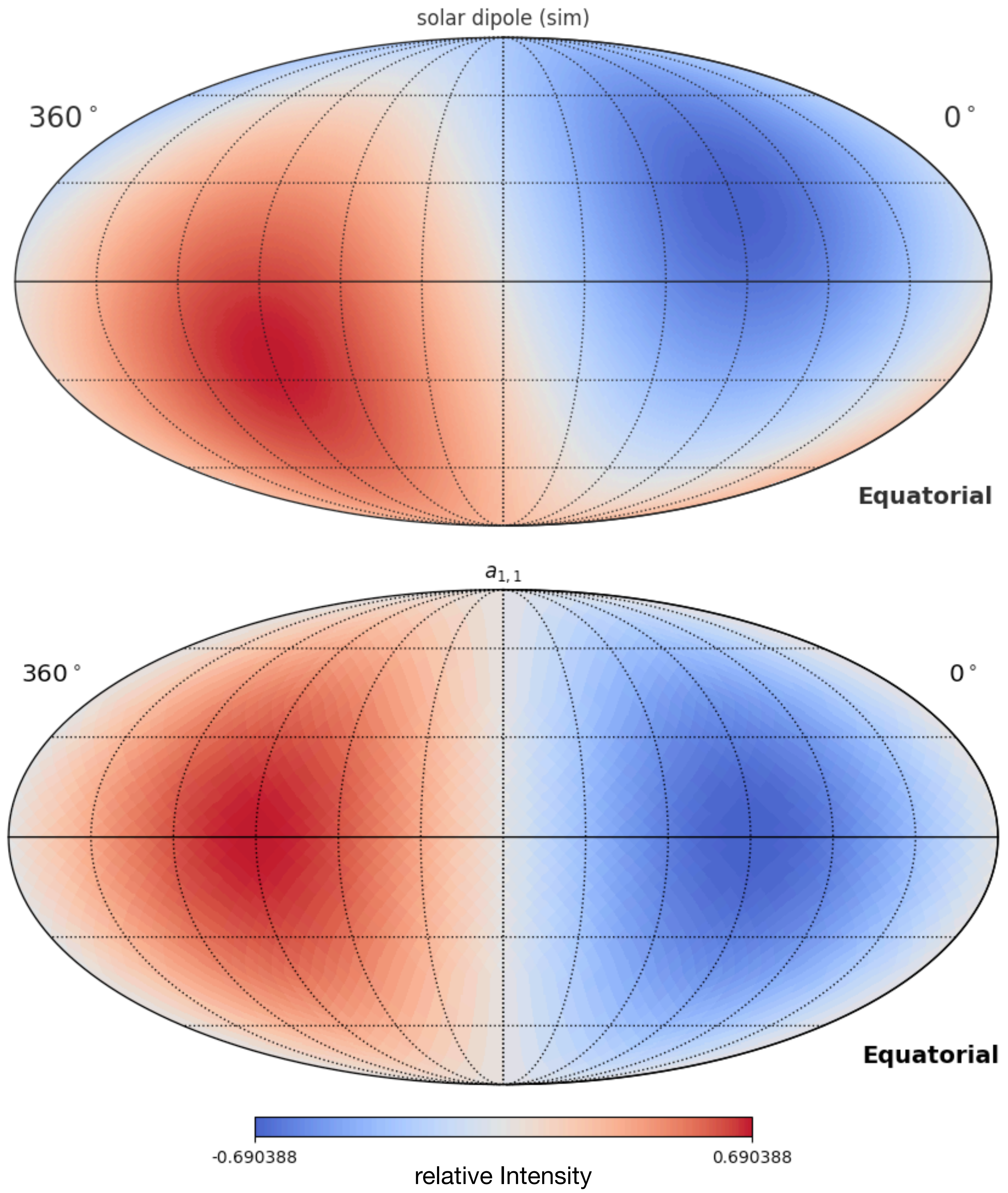
Where ξ_i is the opening angle between velocity direction and CR arrival direction (for pixel i).

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

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



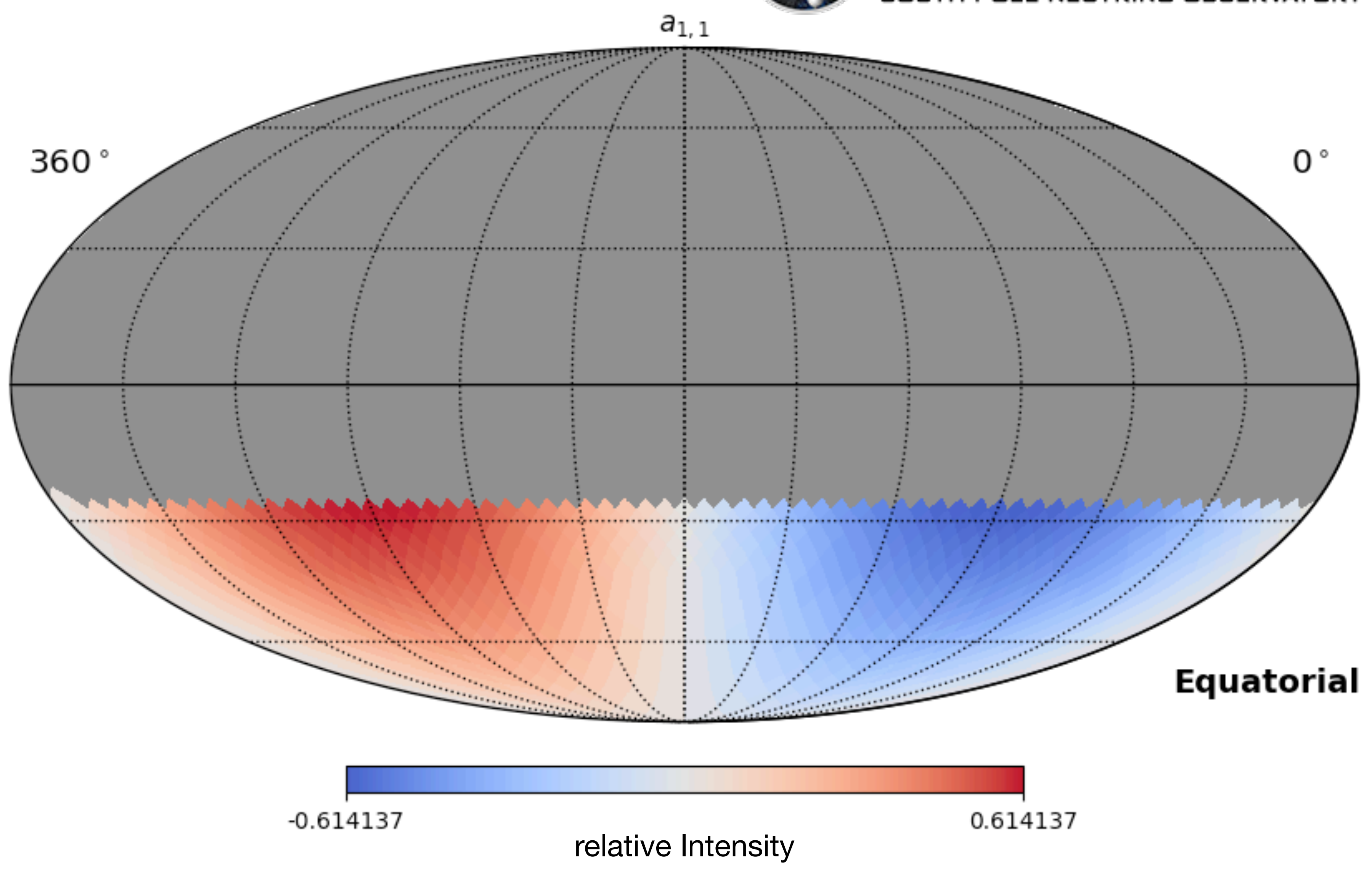
Horizontal Multi-pole Fit

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

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

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

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



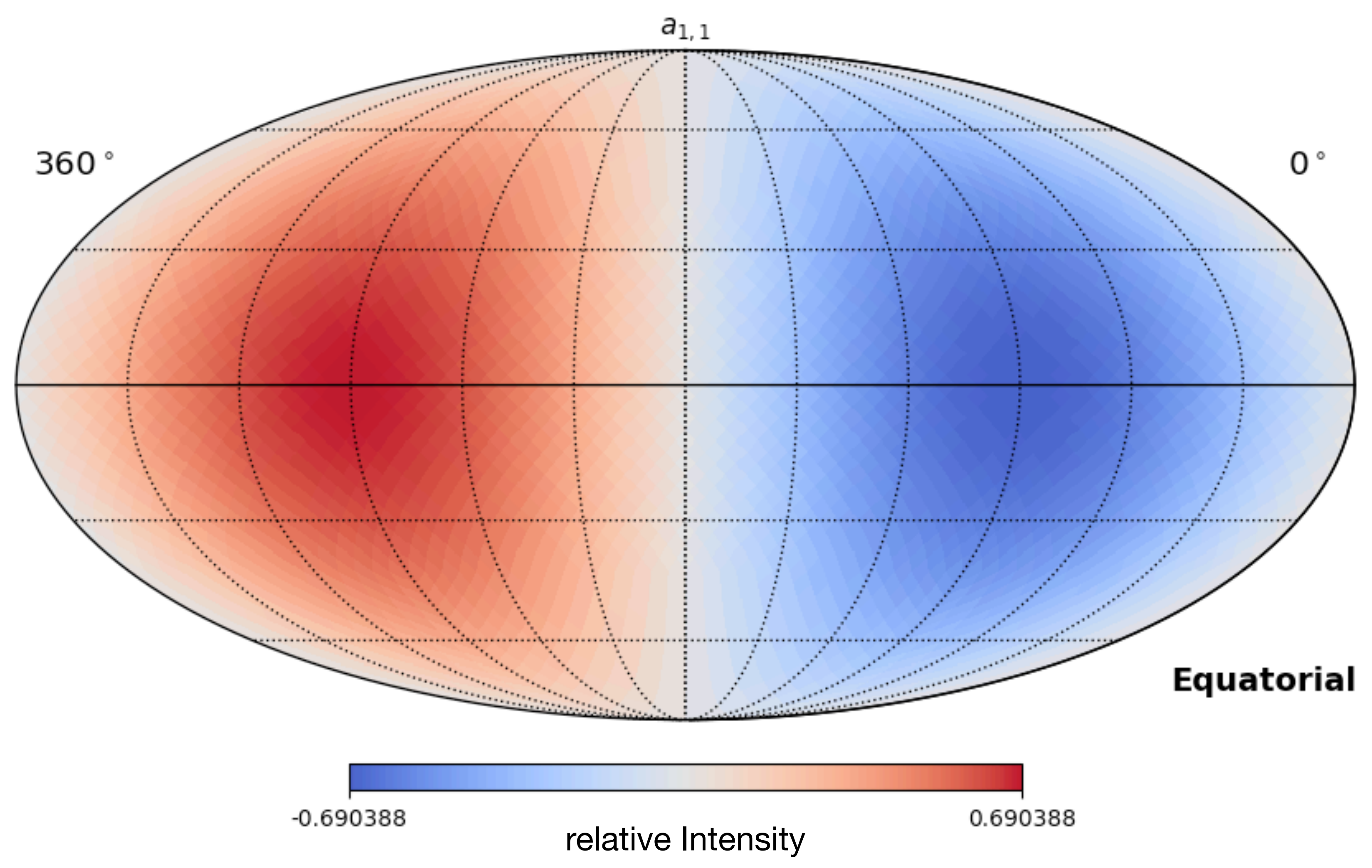
So, for a dipole oriented along the x-y plane,

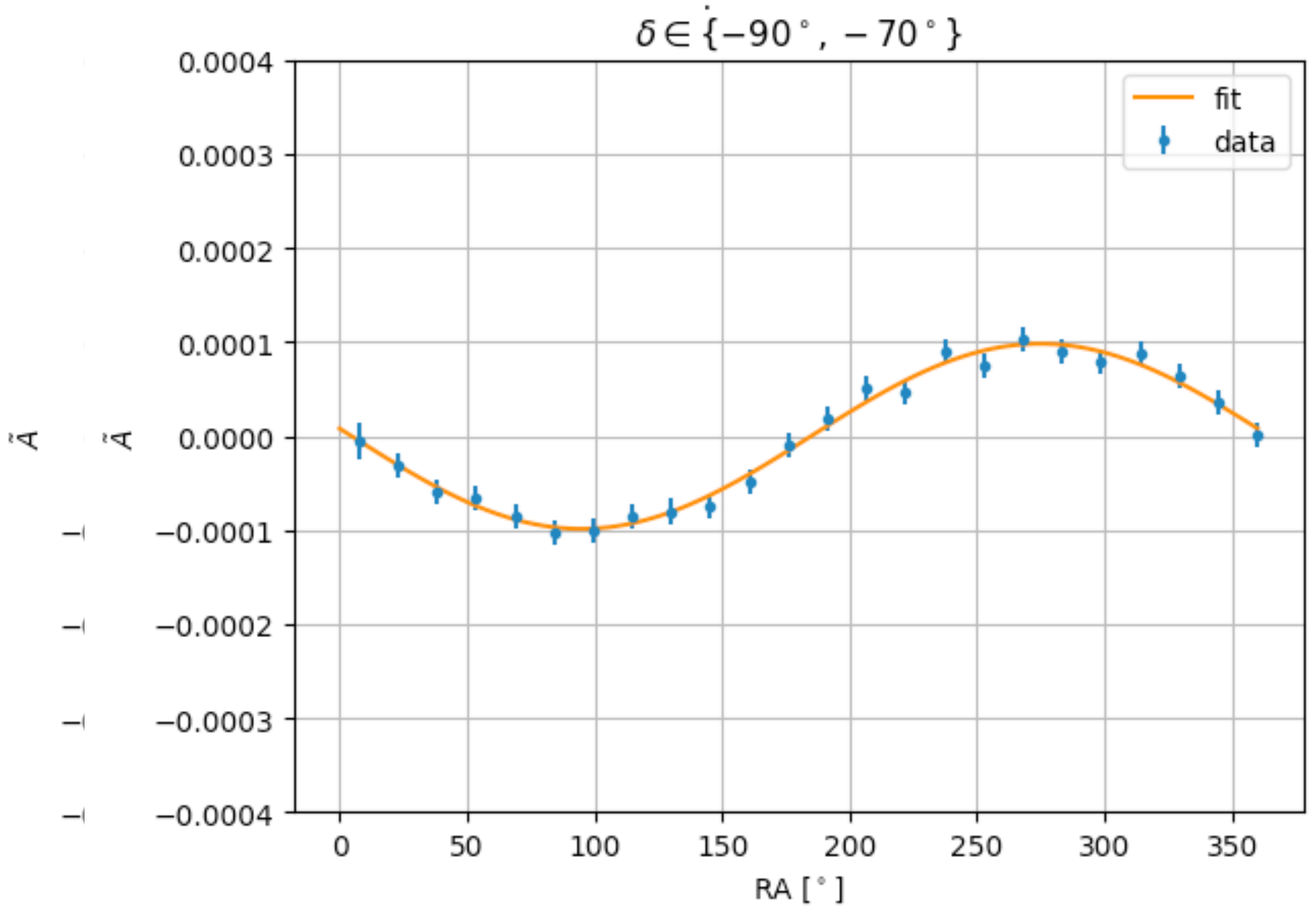
$$F(\alpha_i,\delta_i) = a_{1,-1}Y_1^{-1} + a_{1,1}Y_1^{1} = A_1\cos(\delta_i)\cos(\alpha_i - \phi_1)$$

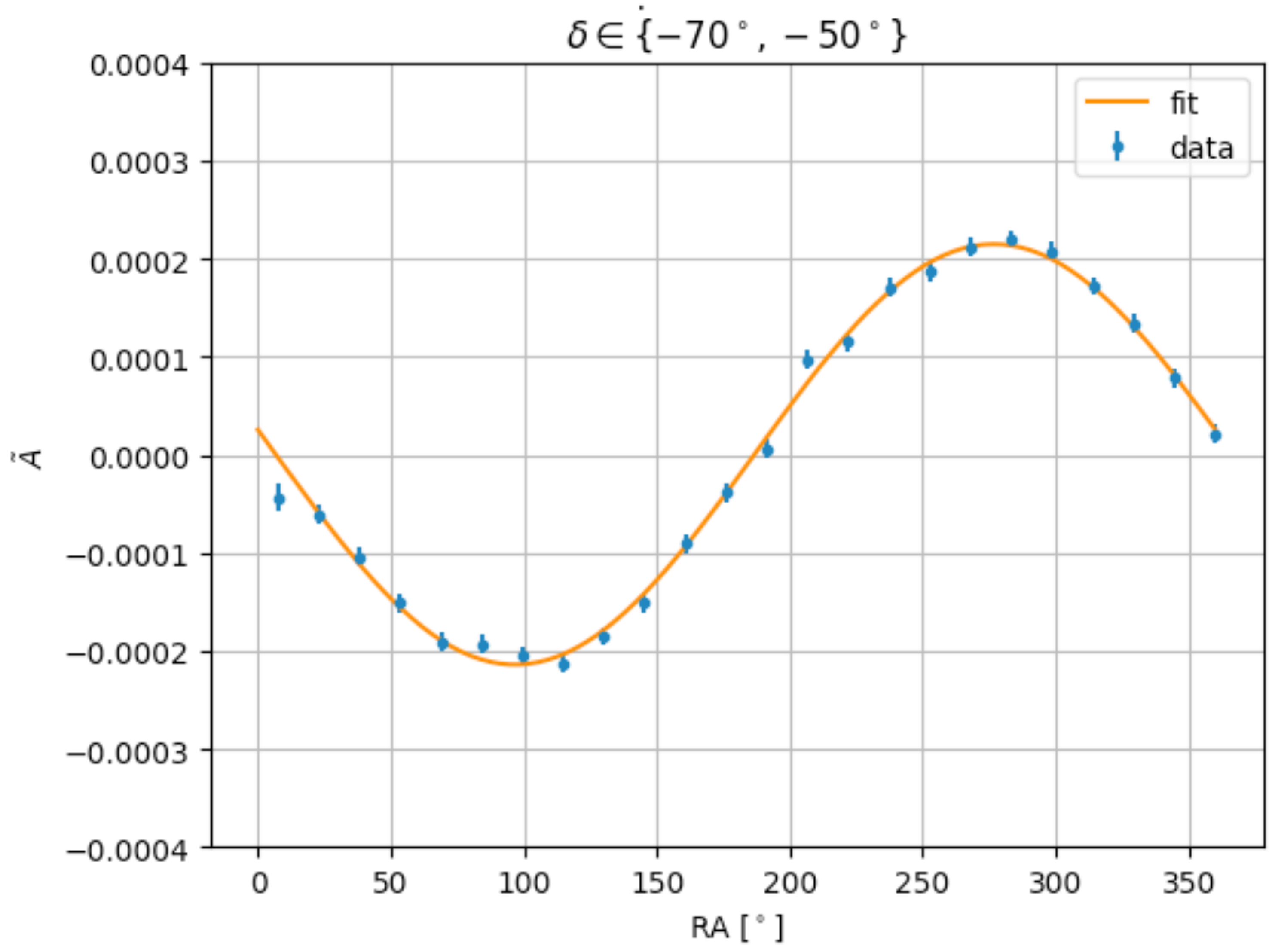
We fit parameters: A_1, ϕ_1 over the pixels in the FoV

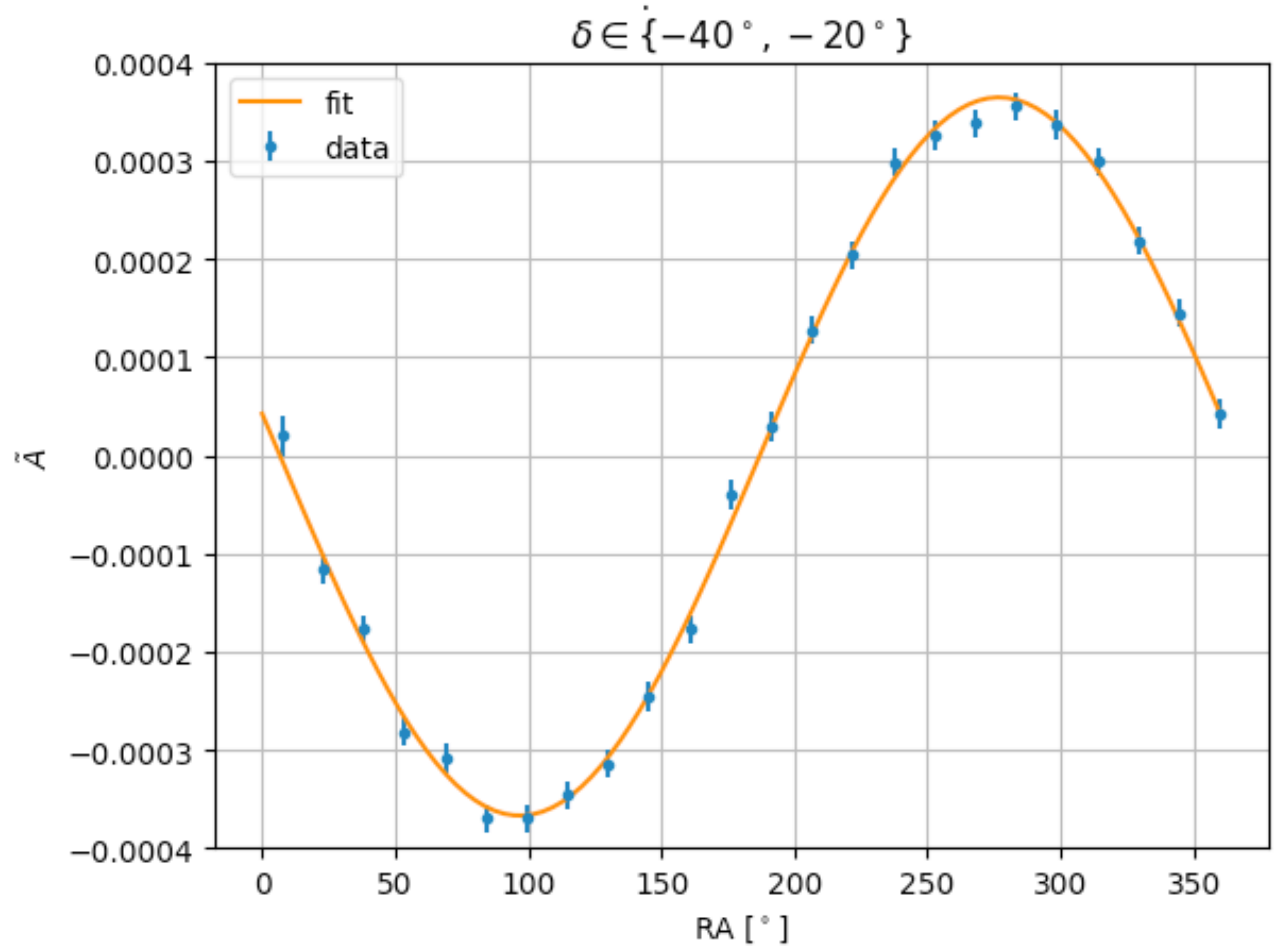
Method 2: 1D Projection (Toy MC)

- Amplitude is maximum towards equator and zero at poles
- 1d measurement corresponds to the average amplitude over declination bands



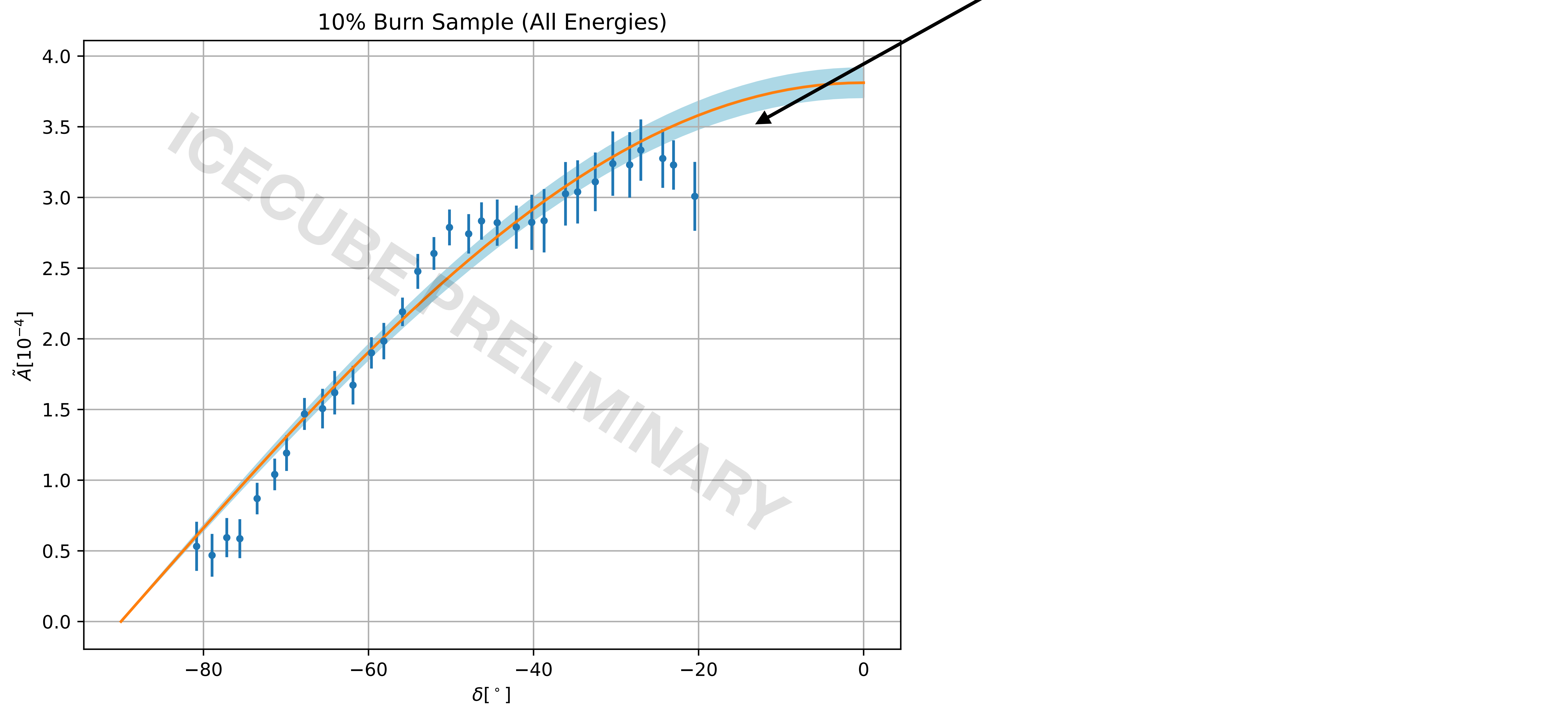






Extrapolation of 1D Amplitude

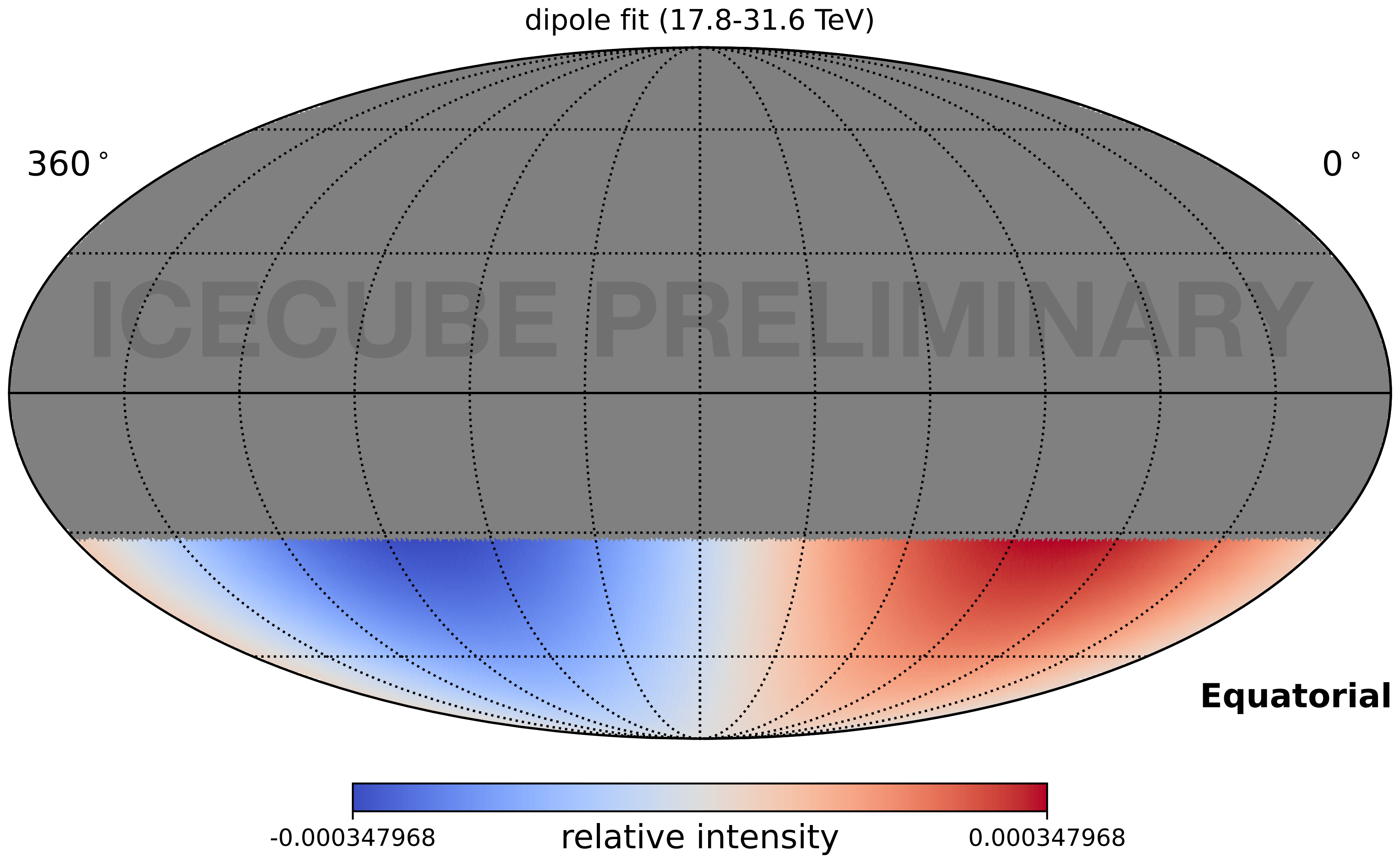
1. Plot amplitude of 1d fit in RA. as a function of declination
2. Fit cosine of declination and extrapolate to horizon

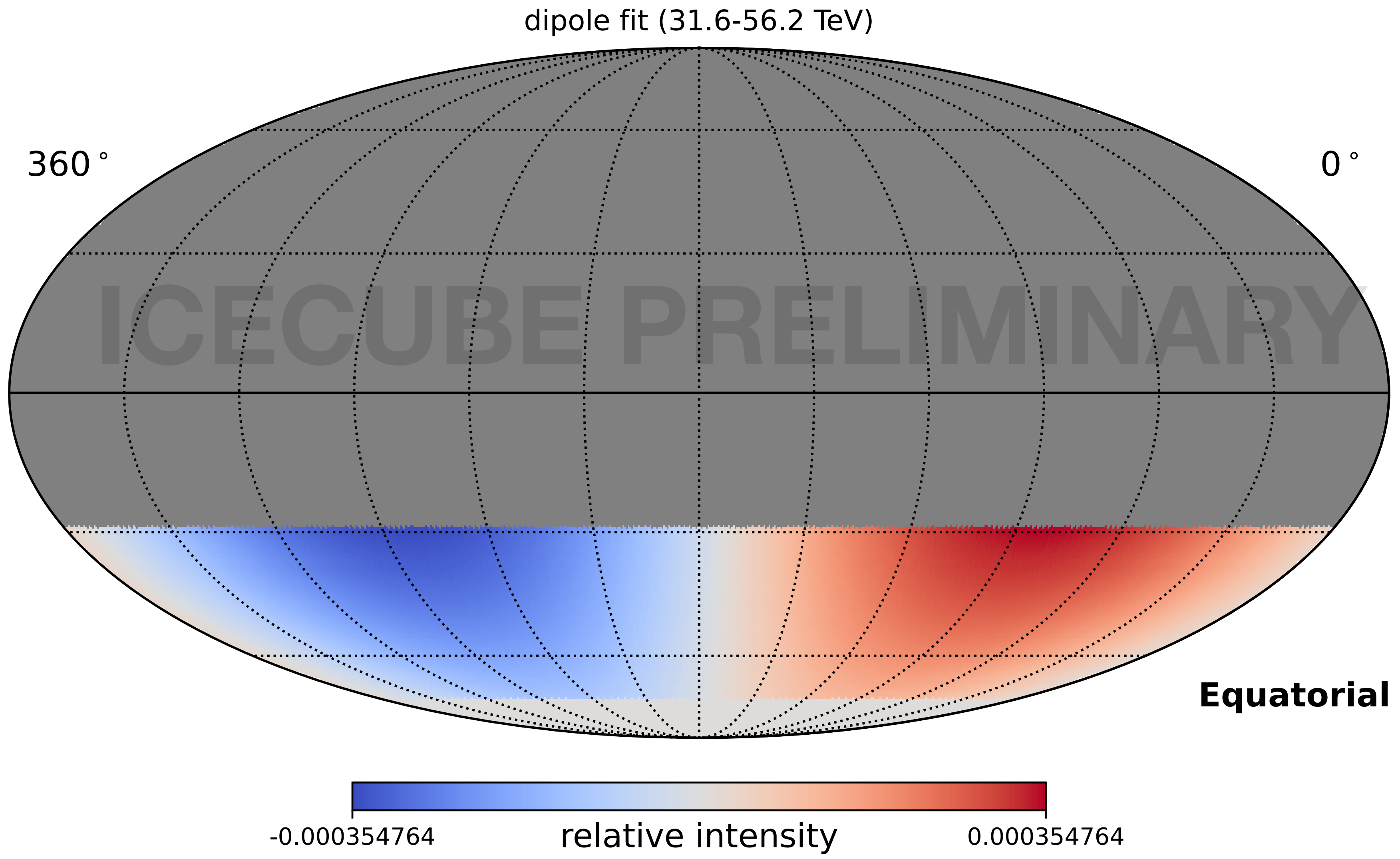


Horizontal dipole Fit

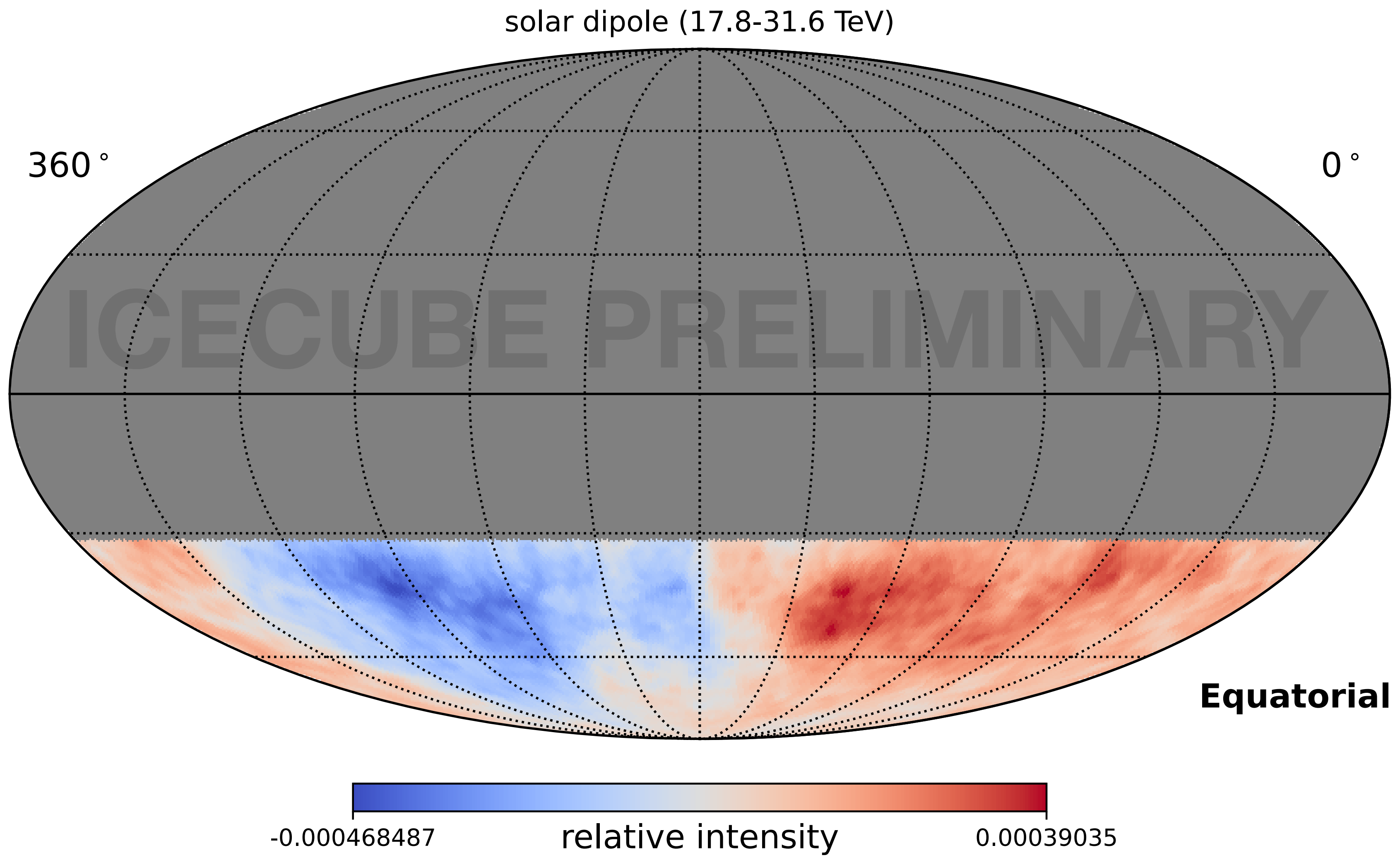
Fit comparisons to data

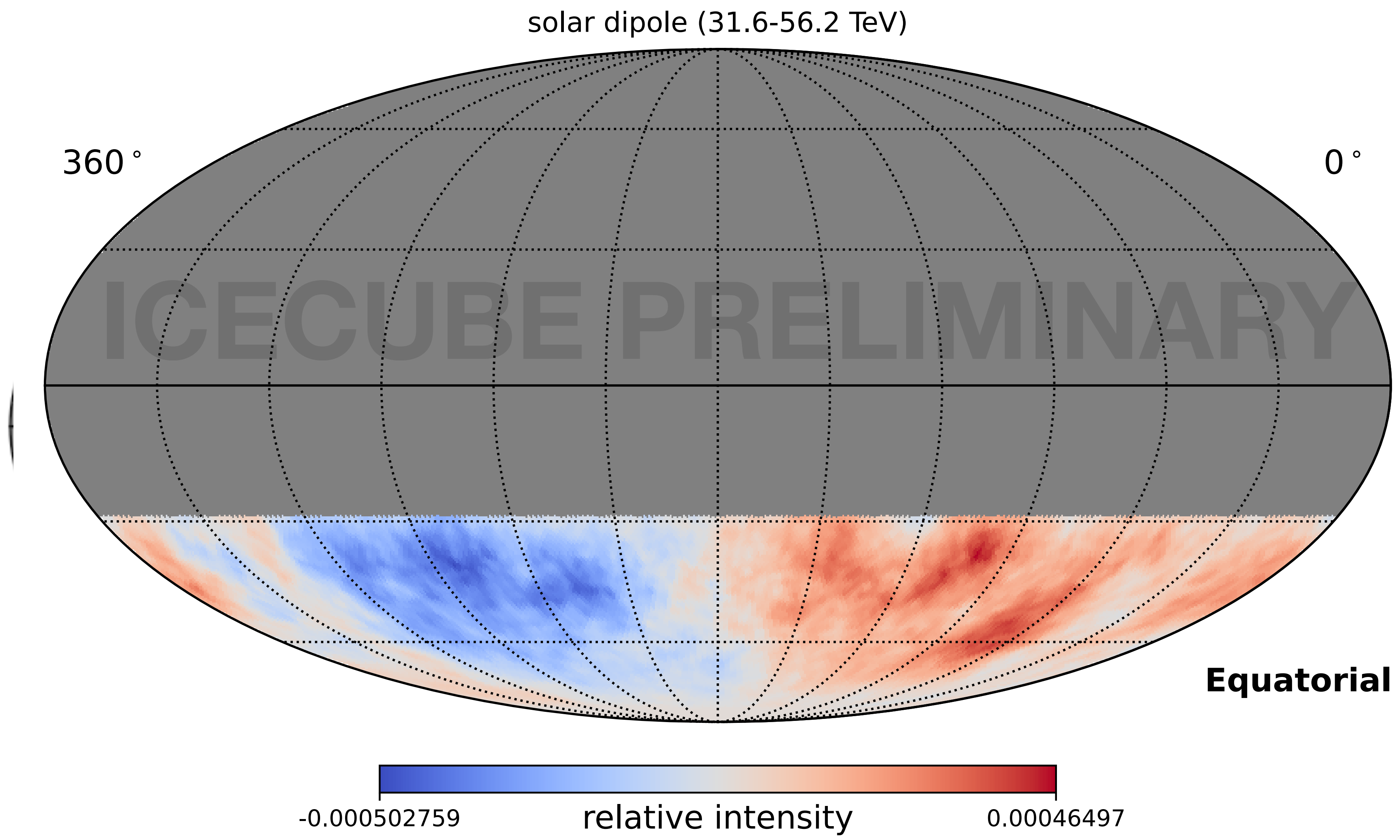
2D Fit (horizontal)





Data

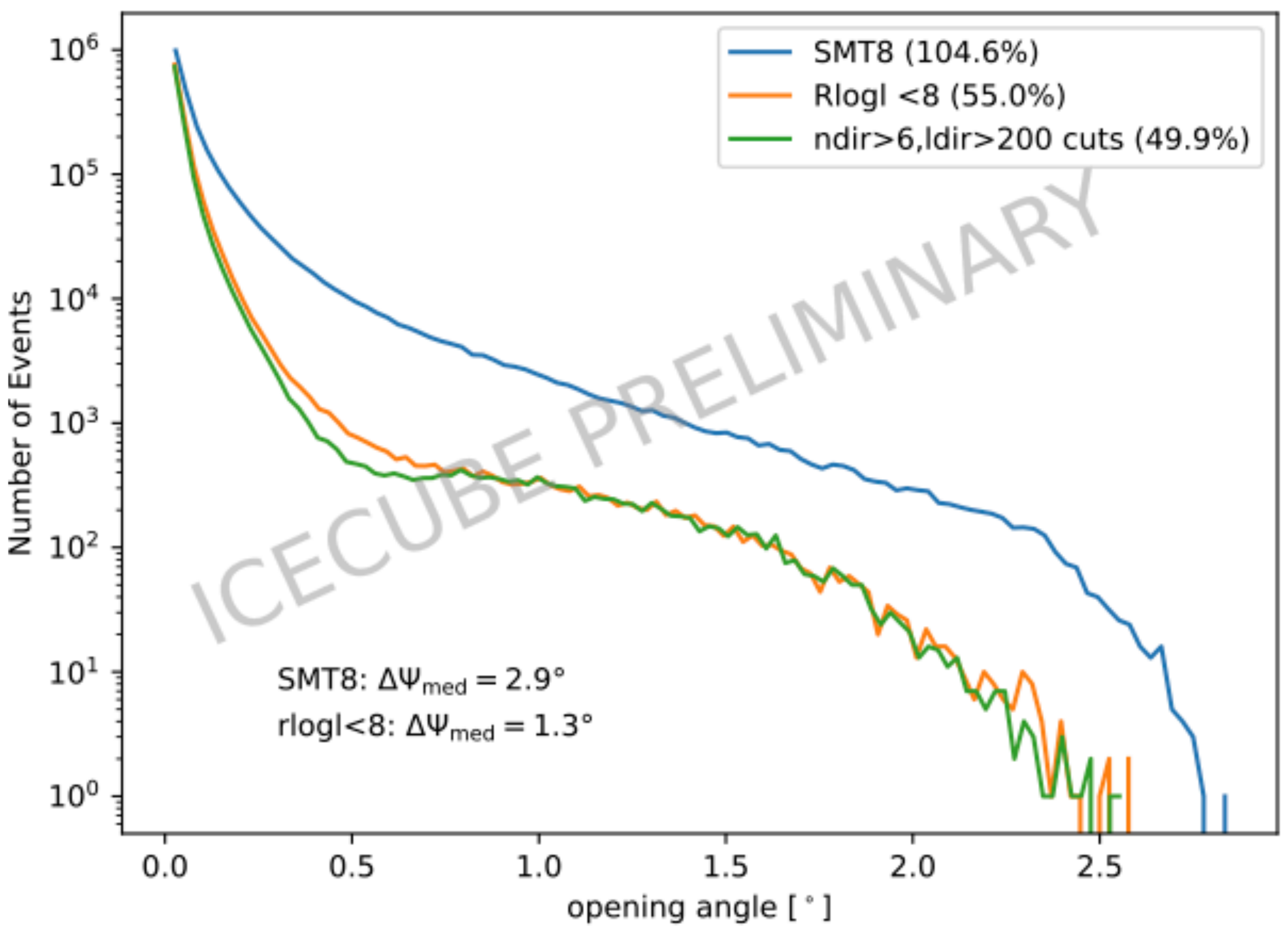


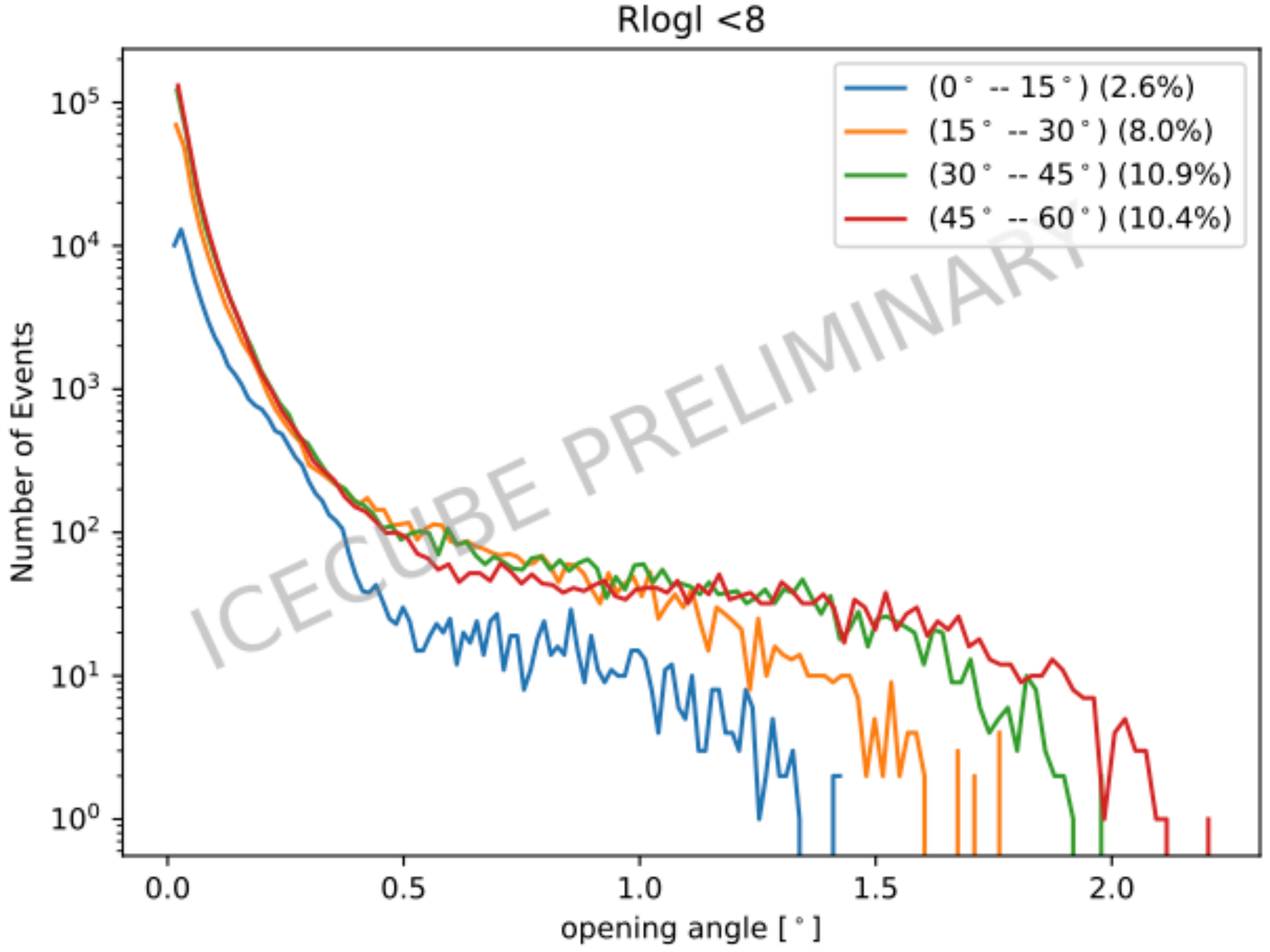


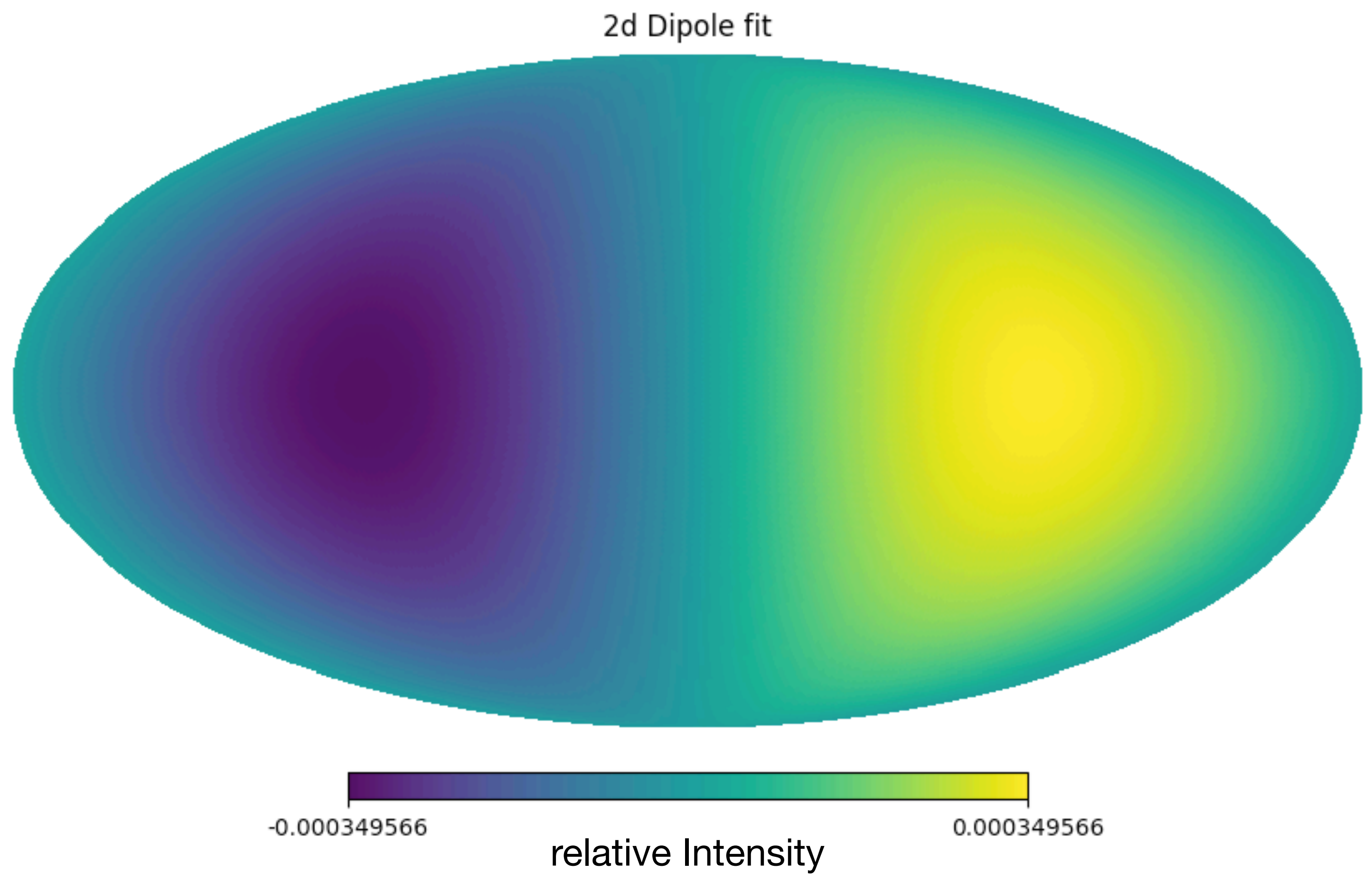
24 TeV **42 TeV**

Solar Dipole:
A Calibration Source

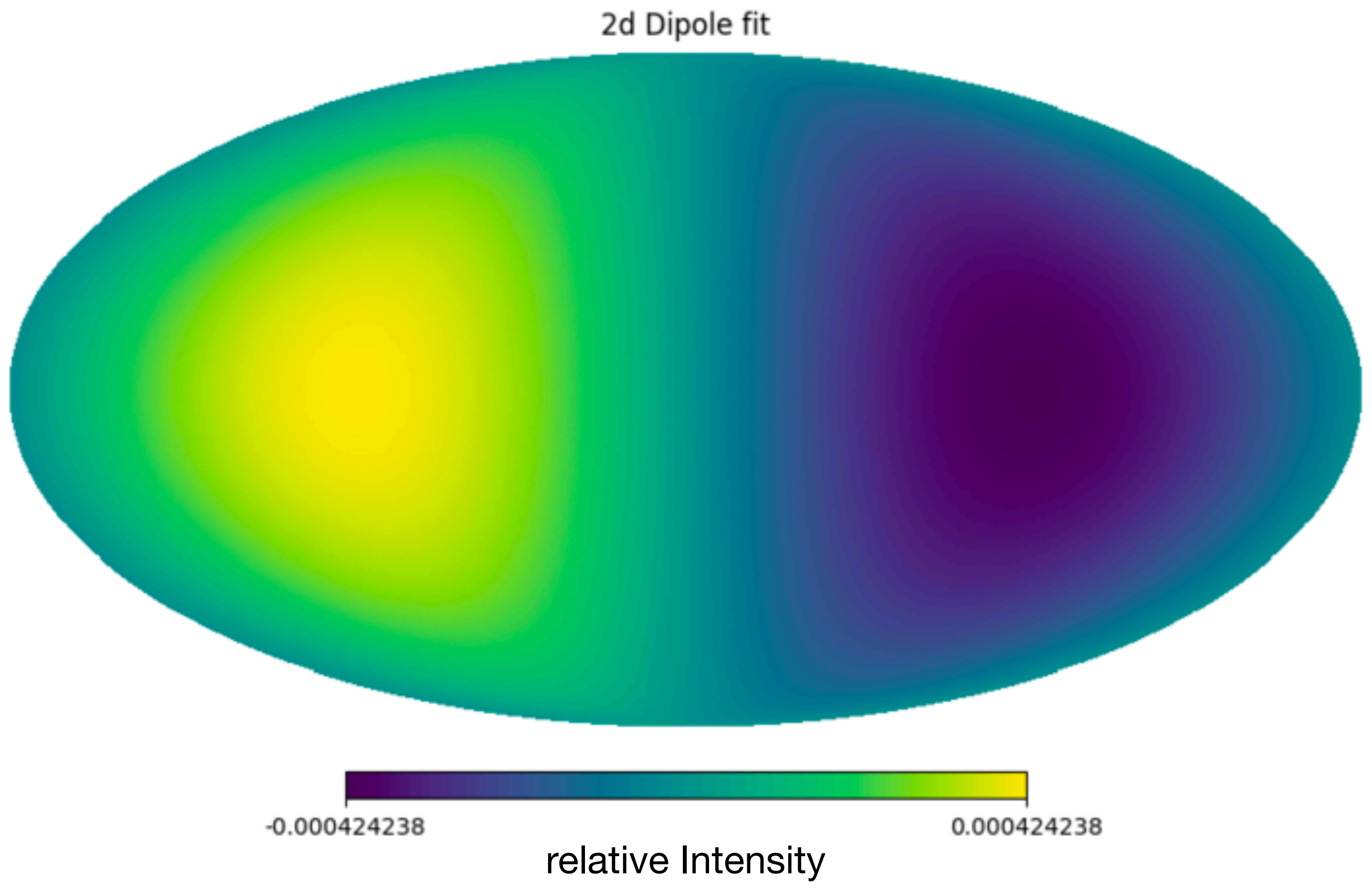
If no quality cuts are applied on the track reconstruction, the level of mis-reconstructed events increases the isotropic background (and decreases signal), thus reducing the amplitude of the anisotropy.





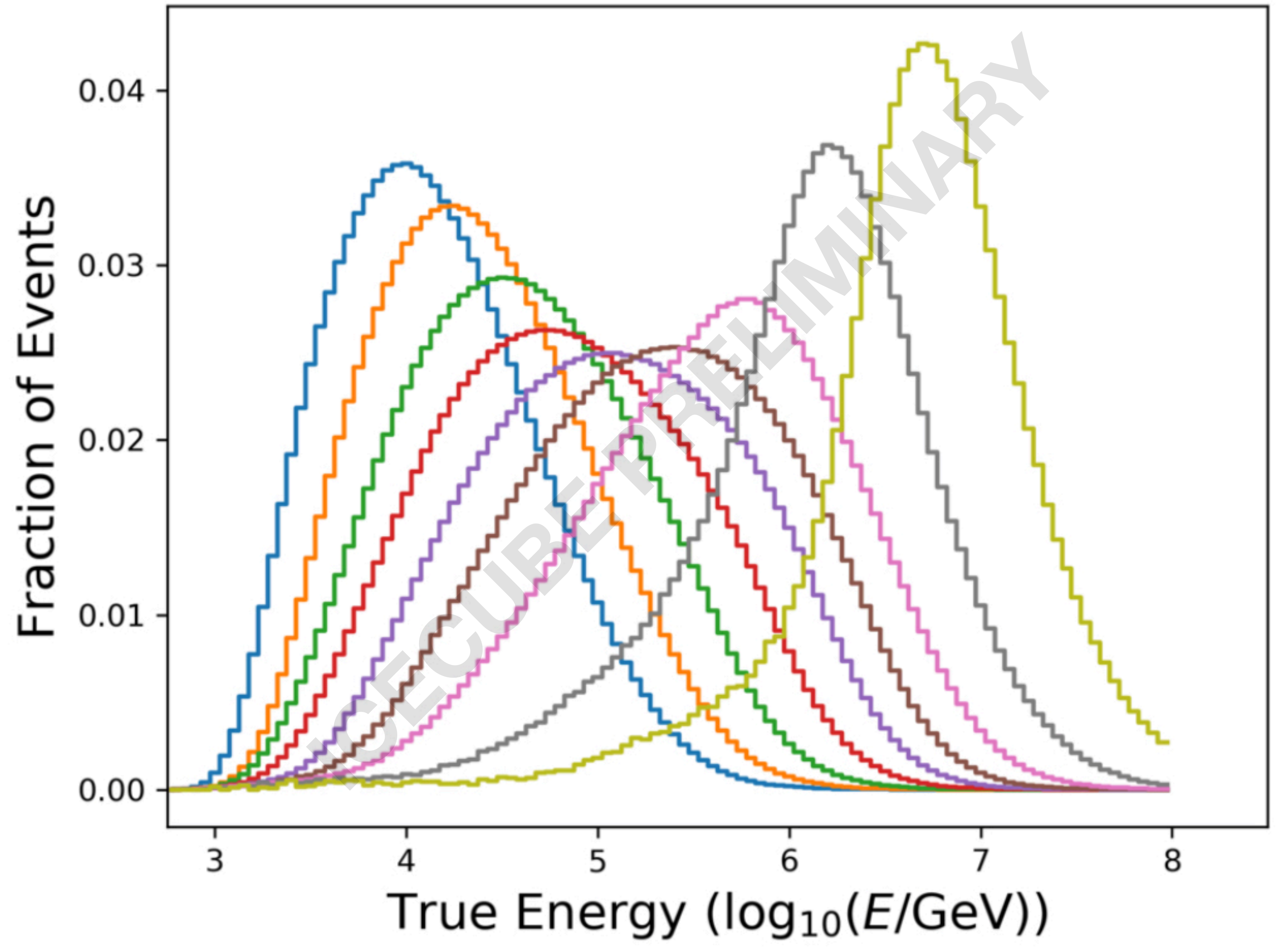


$\gamma = 1.5167$
correcting projection 23.5°:
$\gamma = 1.8347$

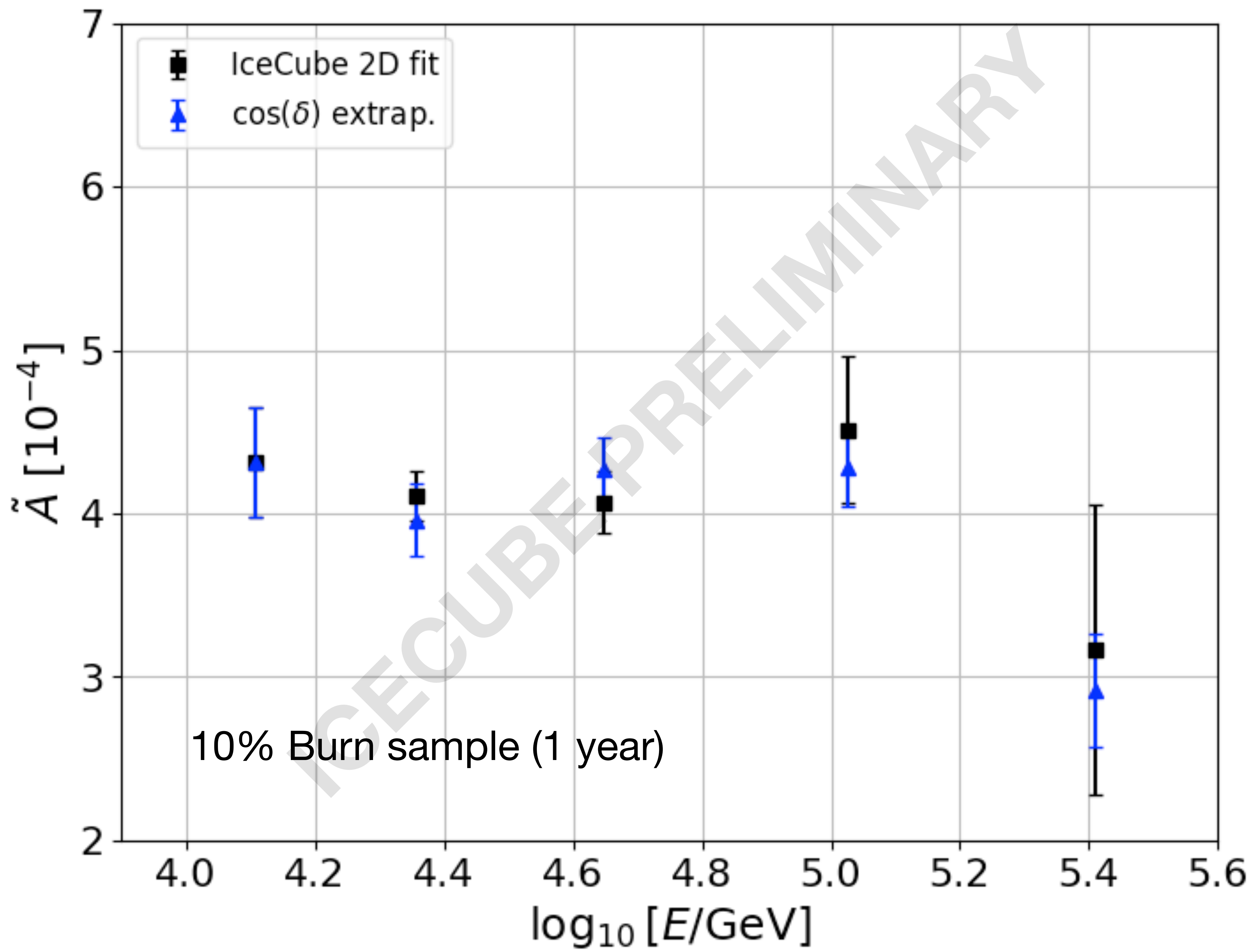


$\gamma = 2.2679$
correcting projection 23.5°:
$\gamma = 2.6539$

Amplitude vs. Energy

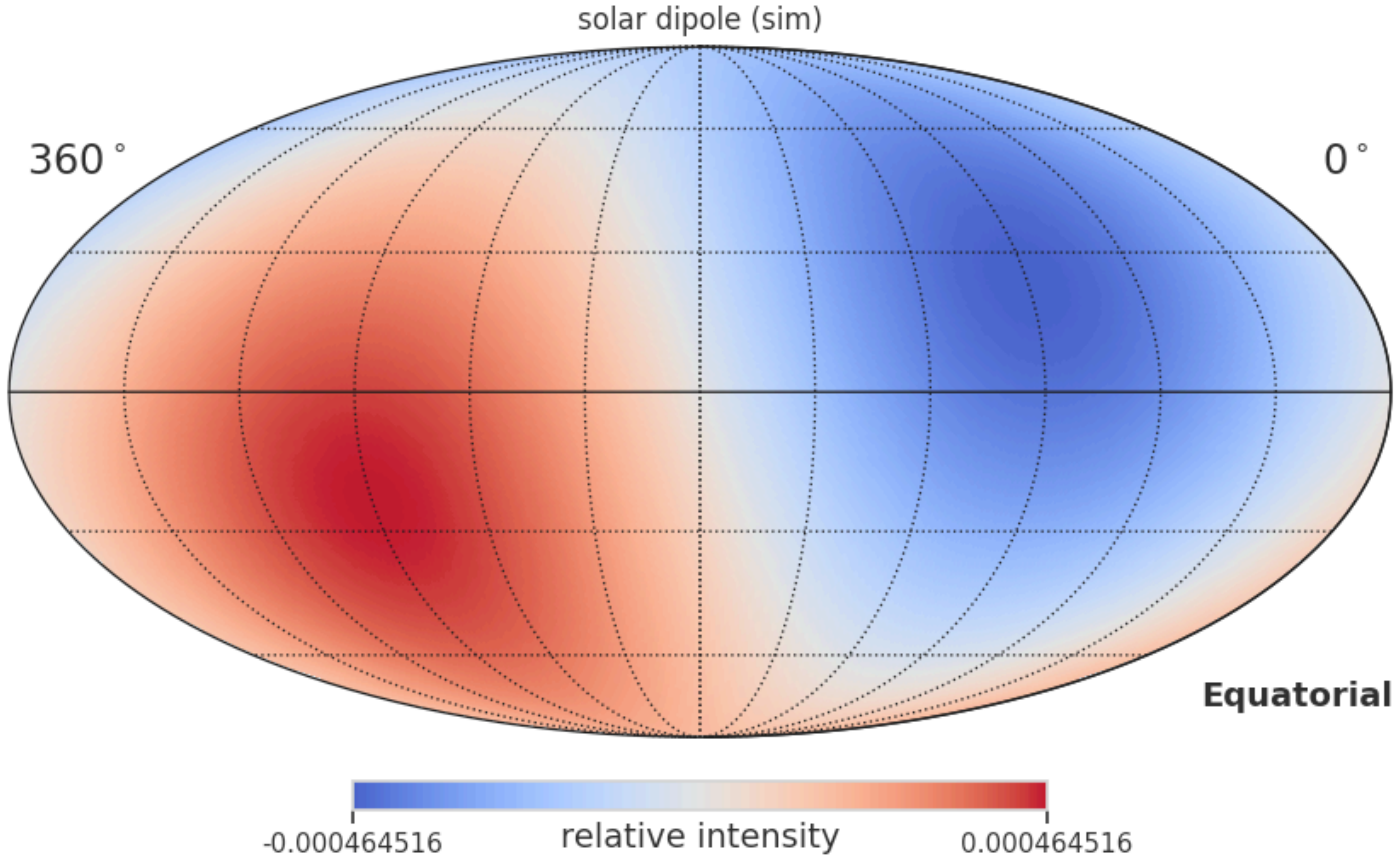


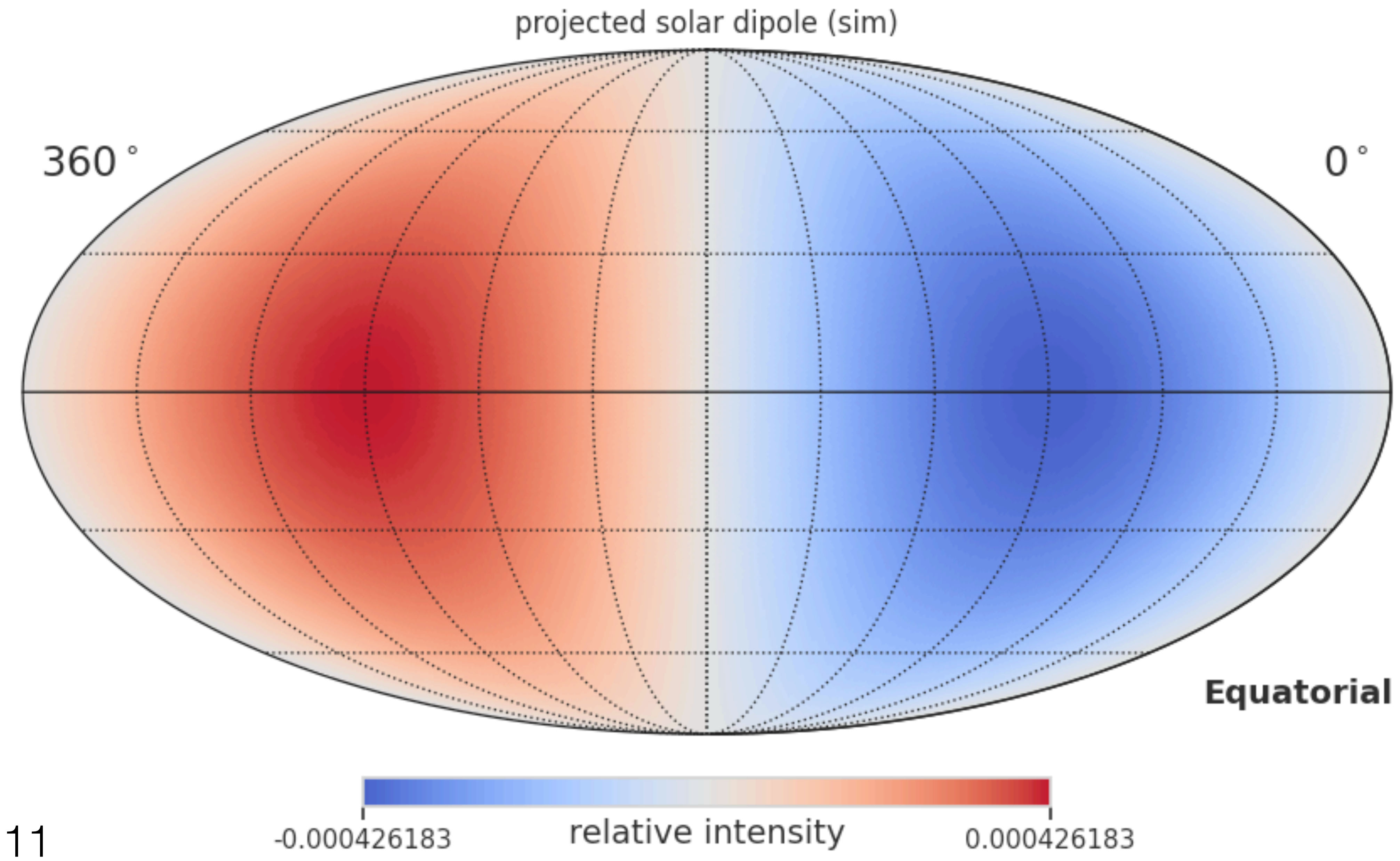
Energy bins from 12-year Anisotropy Study



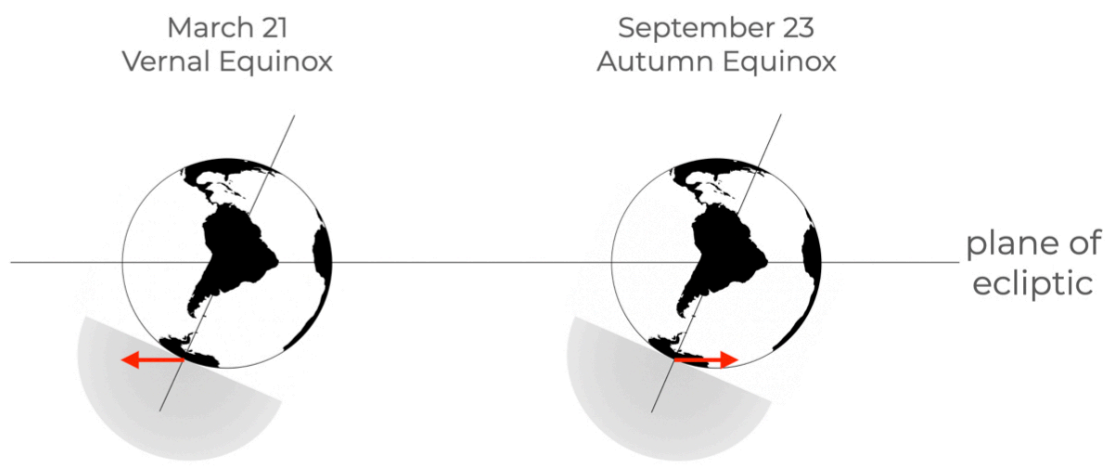
10% Burn sample (1 year)

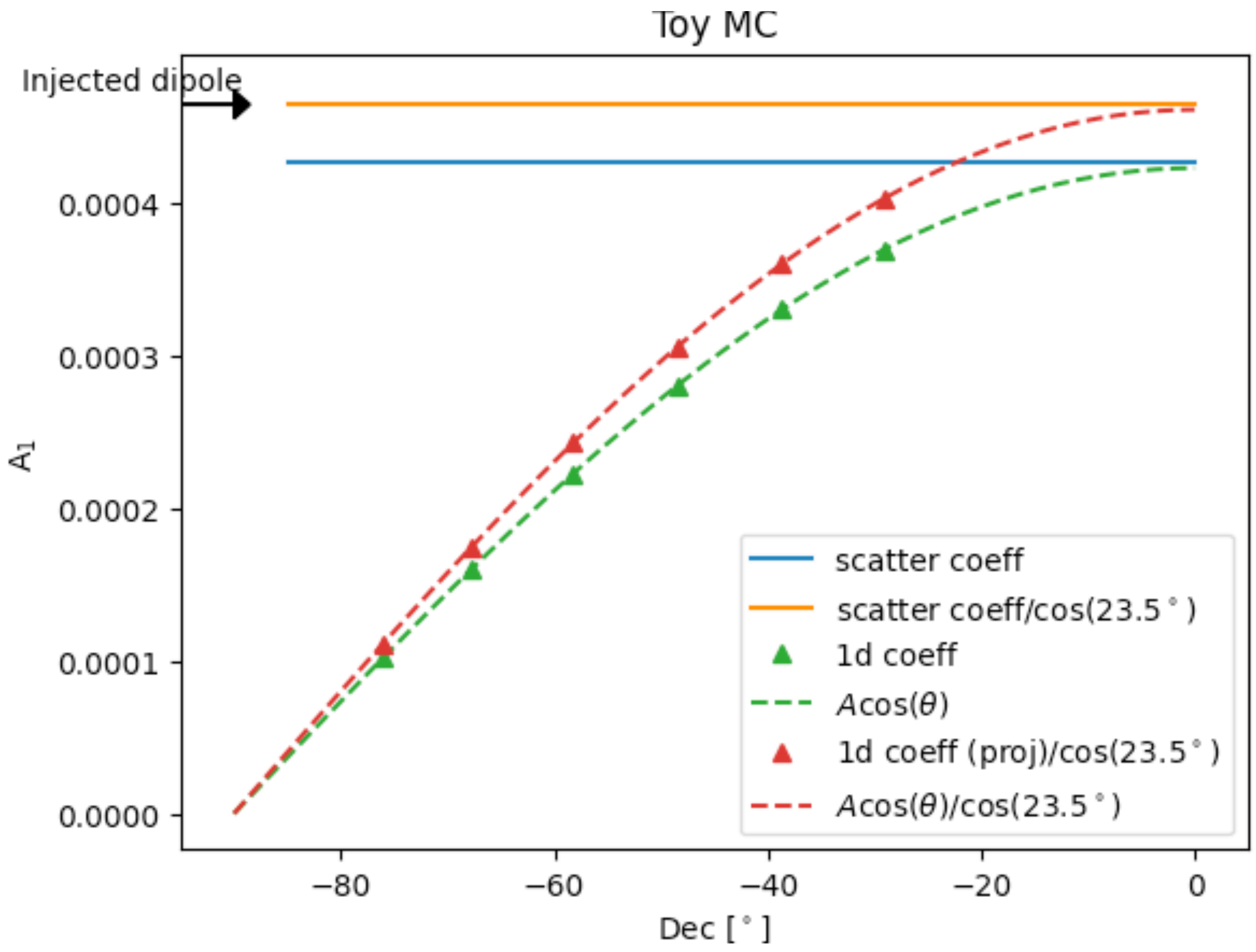
Equatorial Projection Bias





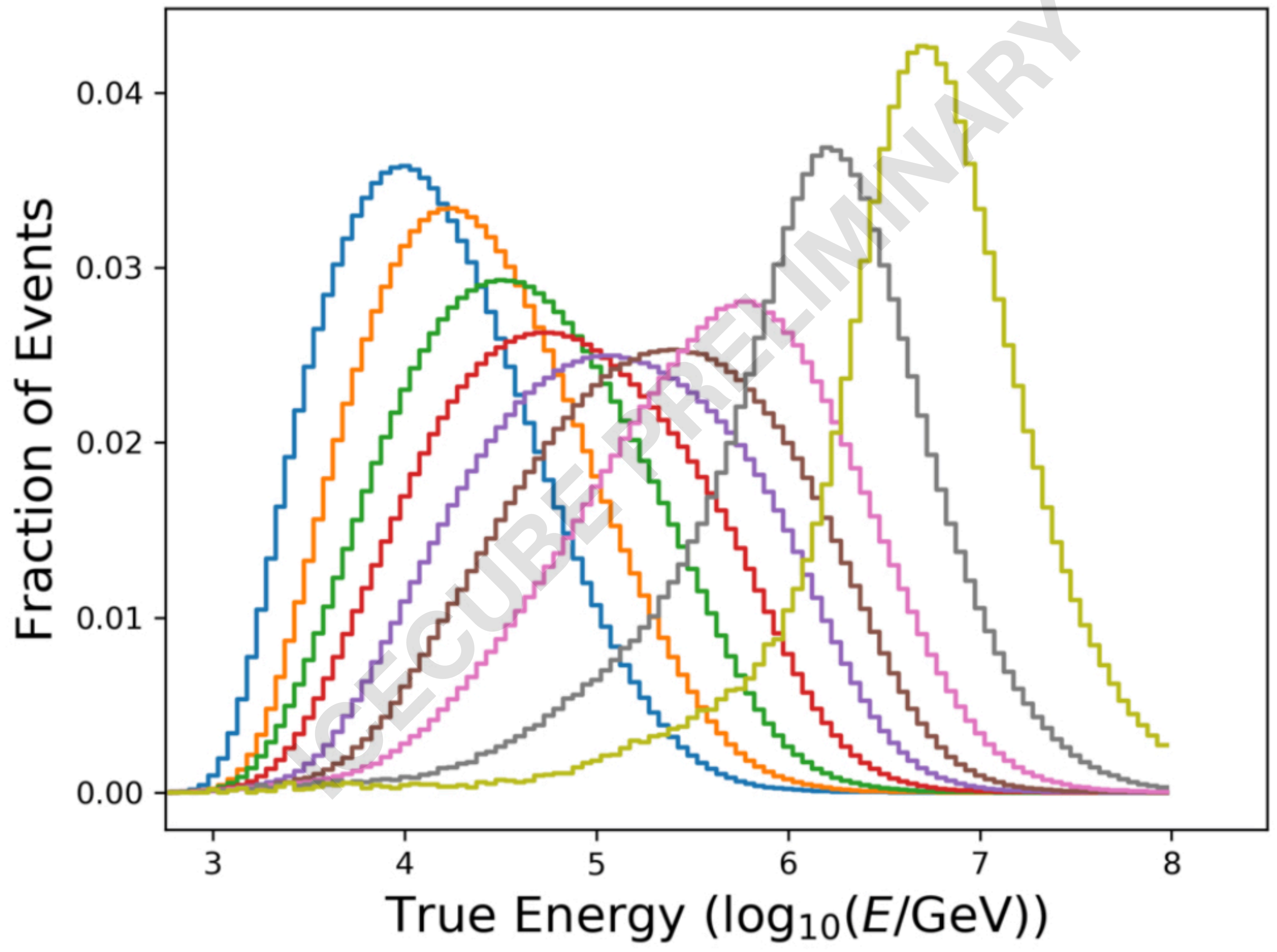
Correct for projection bias (dipole tilt is known) 23.5047°





Amplitude vs. Energy

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



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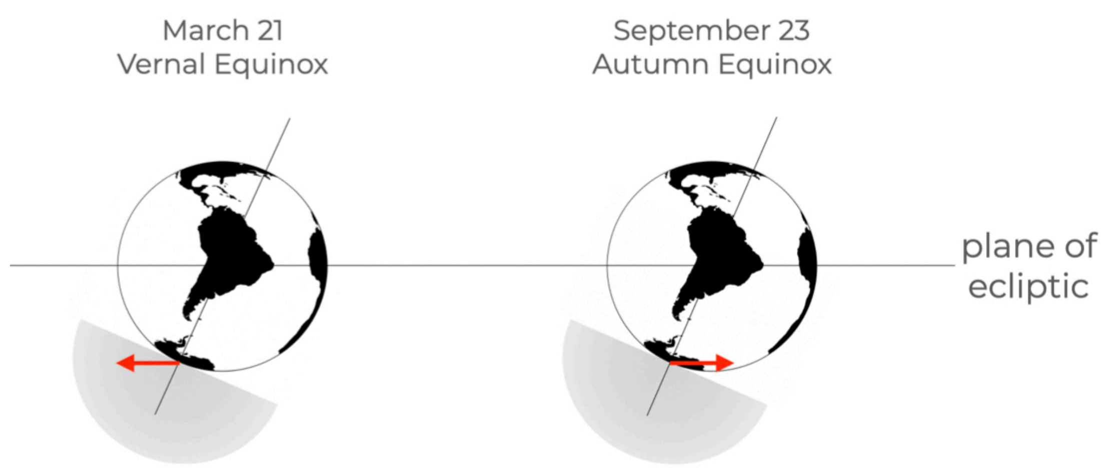

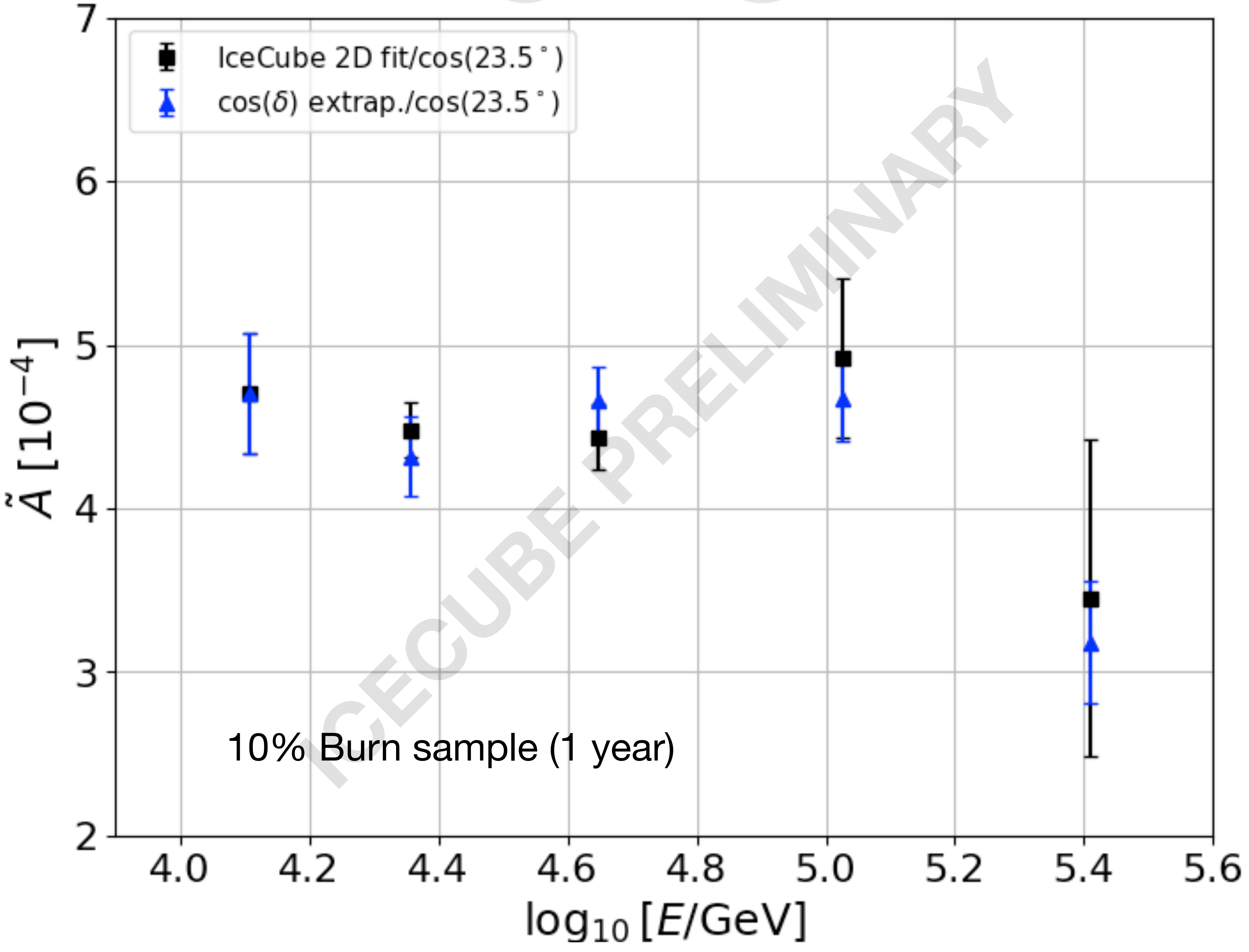

Bias from Yearly modulation of sidereal anisotropy

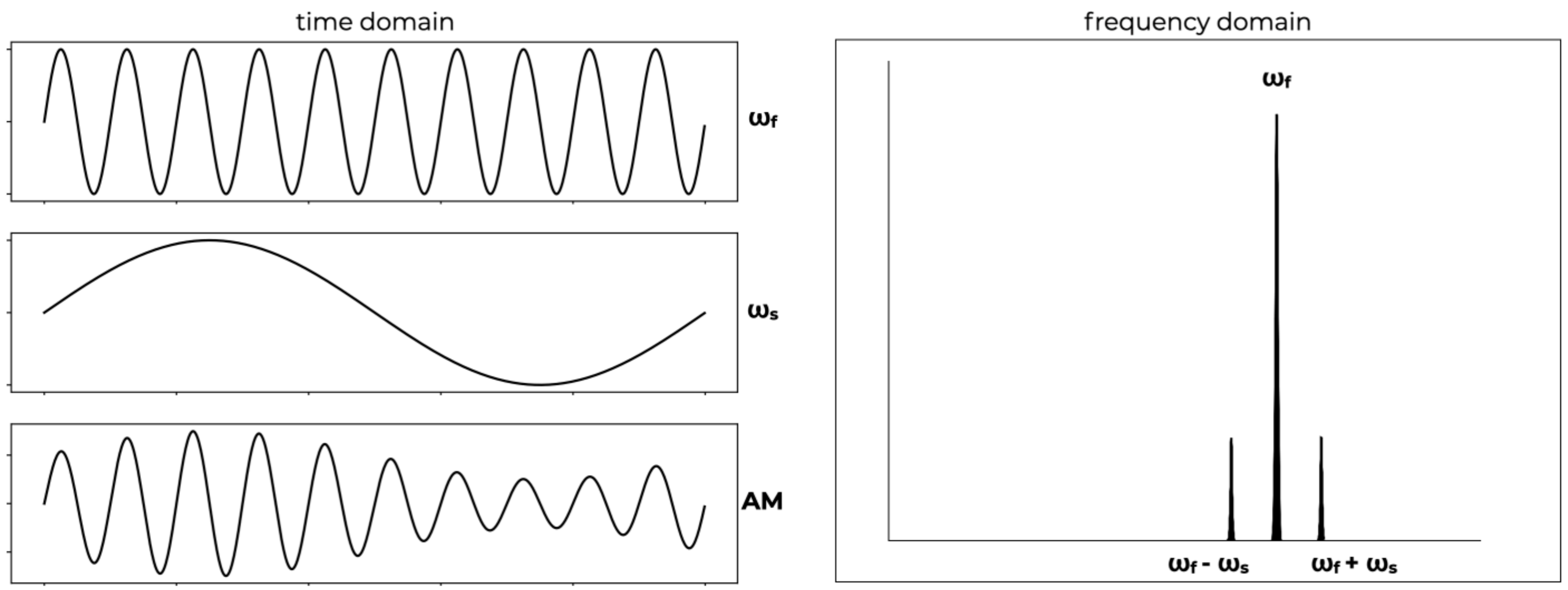

Figure 1: *Left:* a carrier wave with frequency ω_f modulated by a wave with frequency $\omega_s < \omega_f$ produces an amplitude modulated (AM) wave in time domain. *Right:* the AM wave decomposition in frequency domain, with the carrier frequency surrounded by side-bands with frequencies $\omega_f \pm \omega_s$.

PoS(ICRC2021)085

extended-sidereal distribution is produced by a **yearly modulation** of the sidereal-dipole amplitude

and it **deforms** the solar distribution

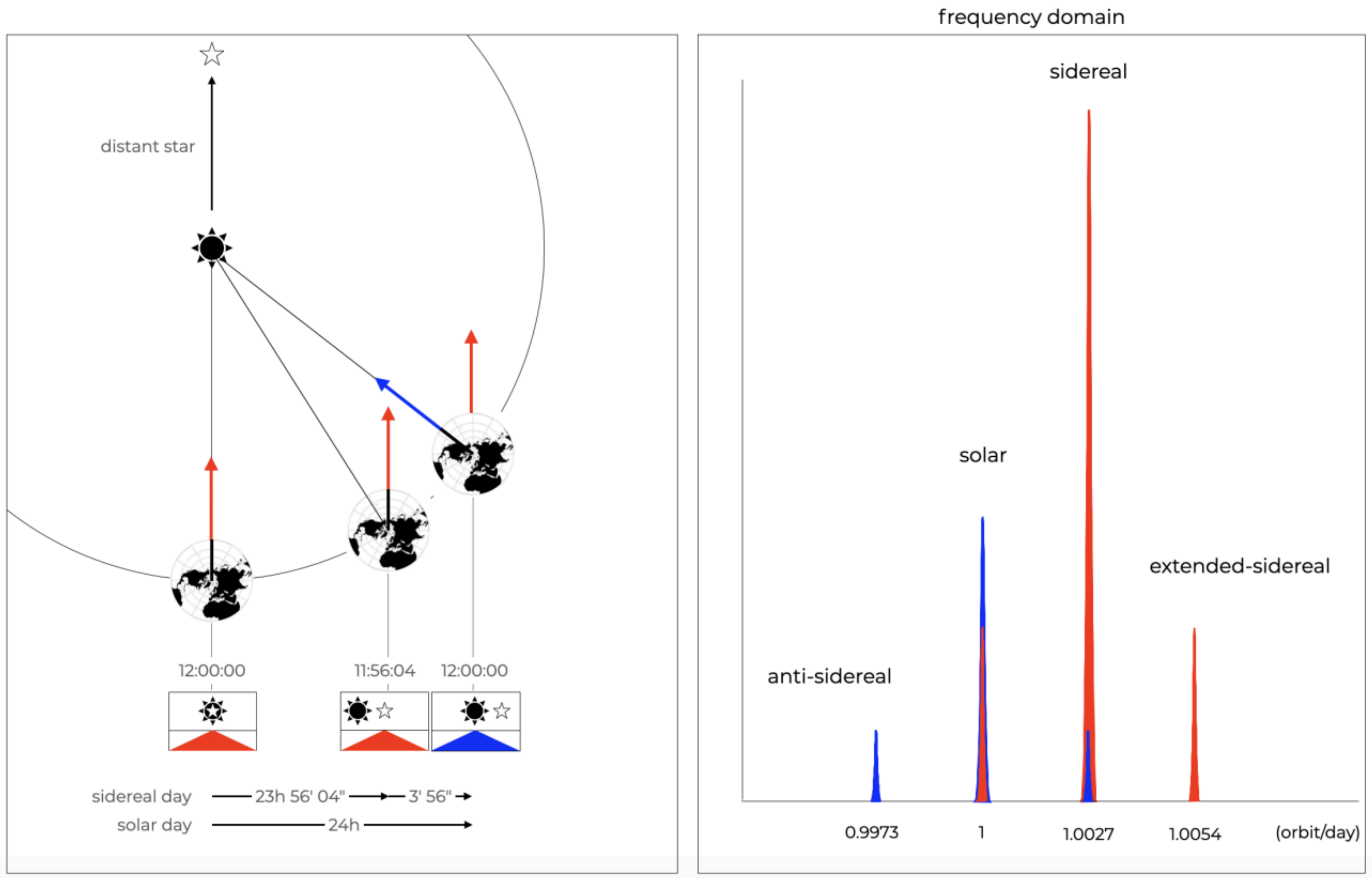

Figure 2: *Left:* the sidereal time with respect to solar time. Time starts at 12:00:00 on the local meridian with the Sun at the same location as a distant star. Then, as the Earth revolves around the Sun, the sidereal time zero point stays fixed in the celestial sky while the solar time's reference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

HAWC PoS(ICRC2023)364

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

HAWC measurements on the total energy spectrum of cosmic rays

J. A. Morales-Soto[a,*] **and J. C. Arteaga-Velázquez**[a] **for the HAWC collaboration**
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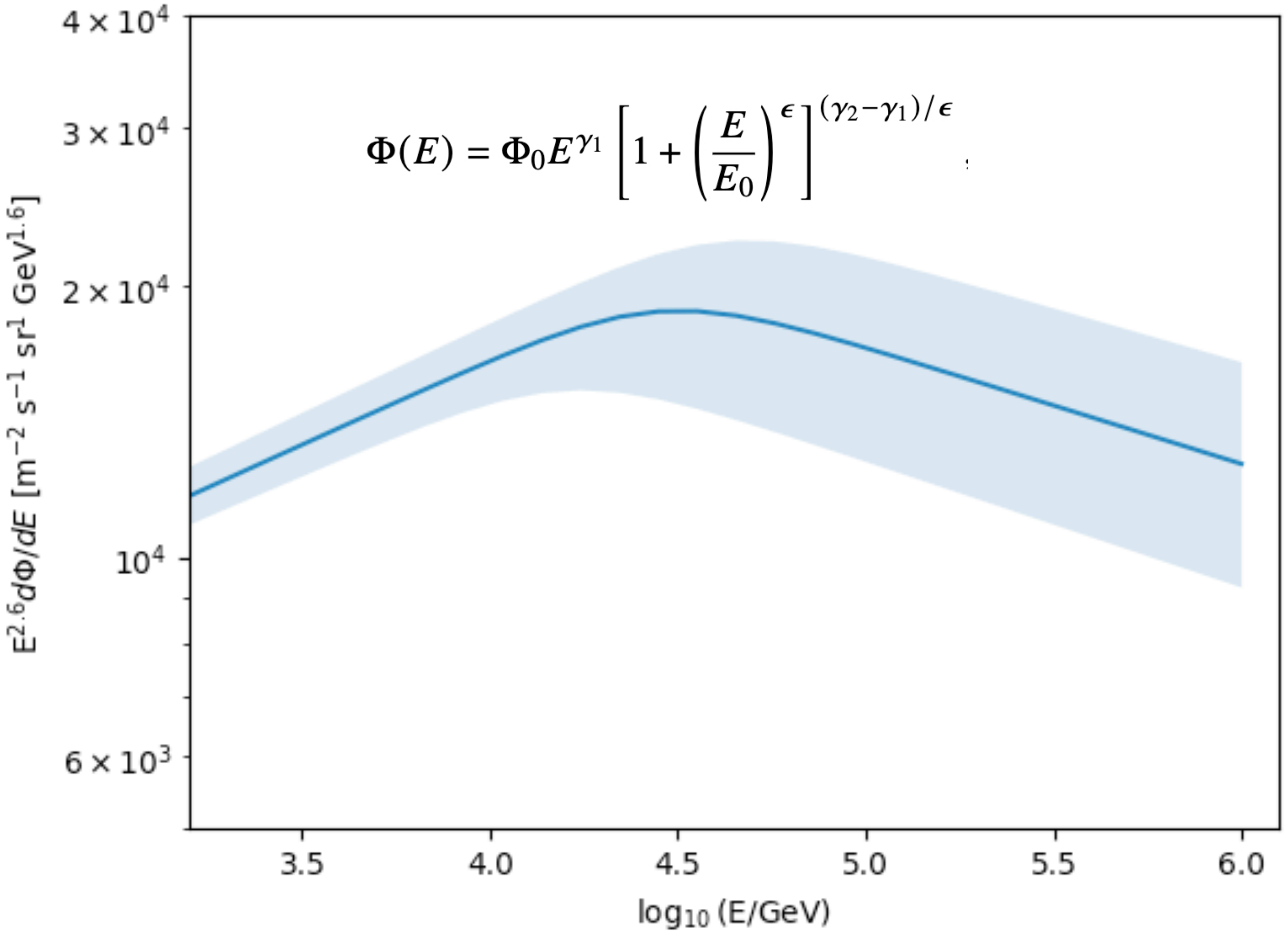
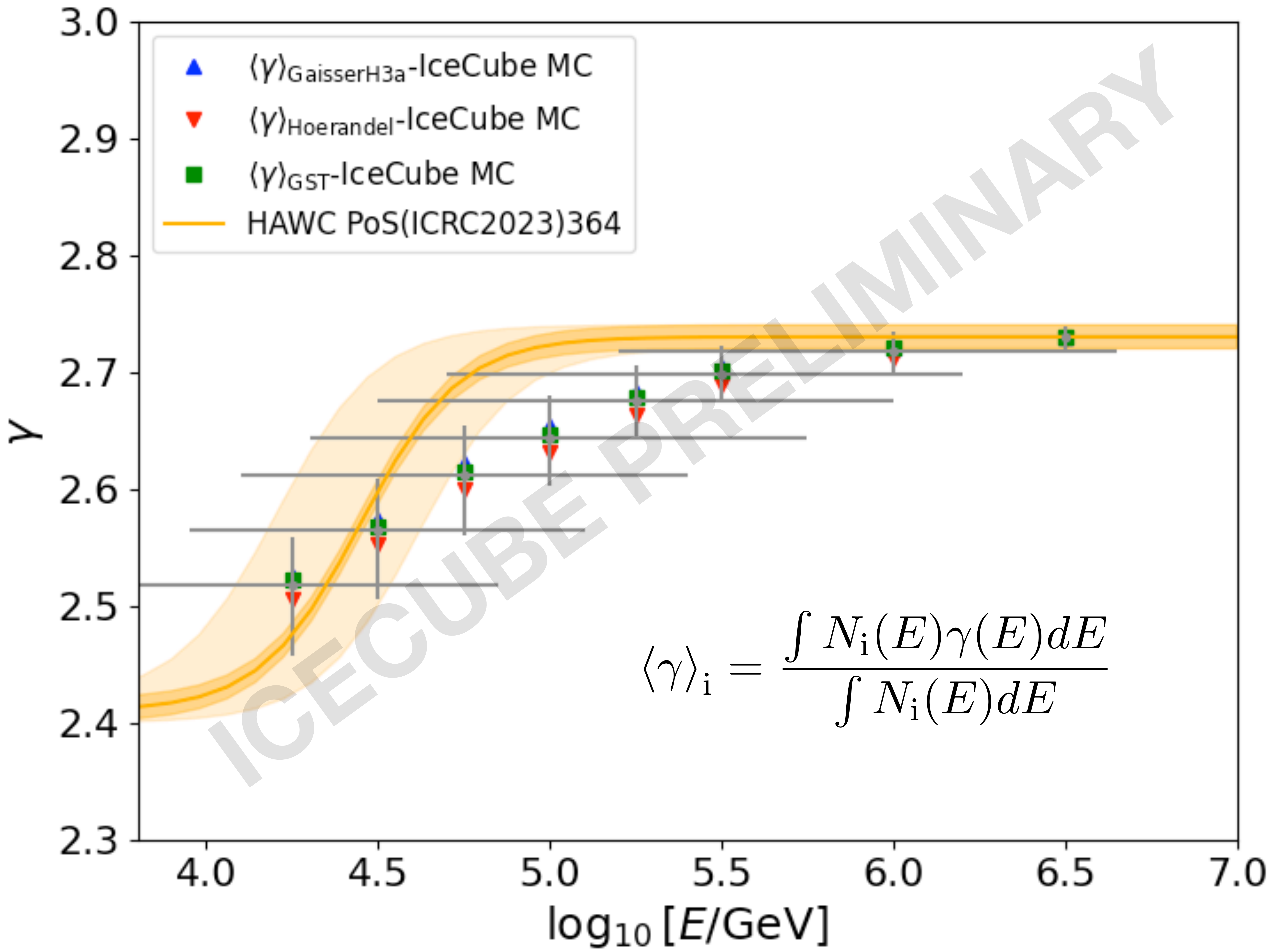




Systematic Uncertainties

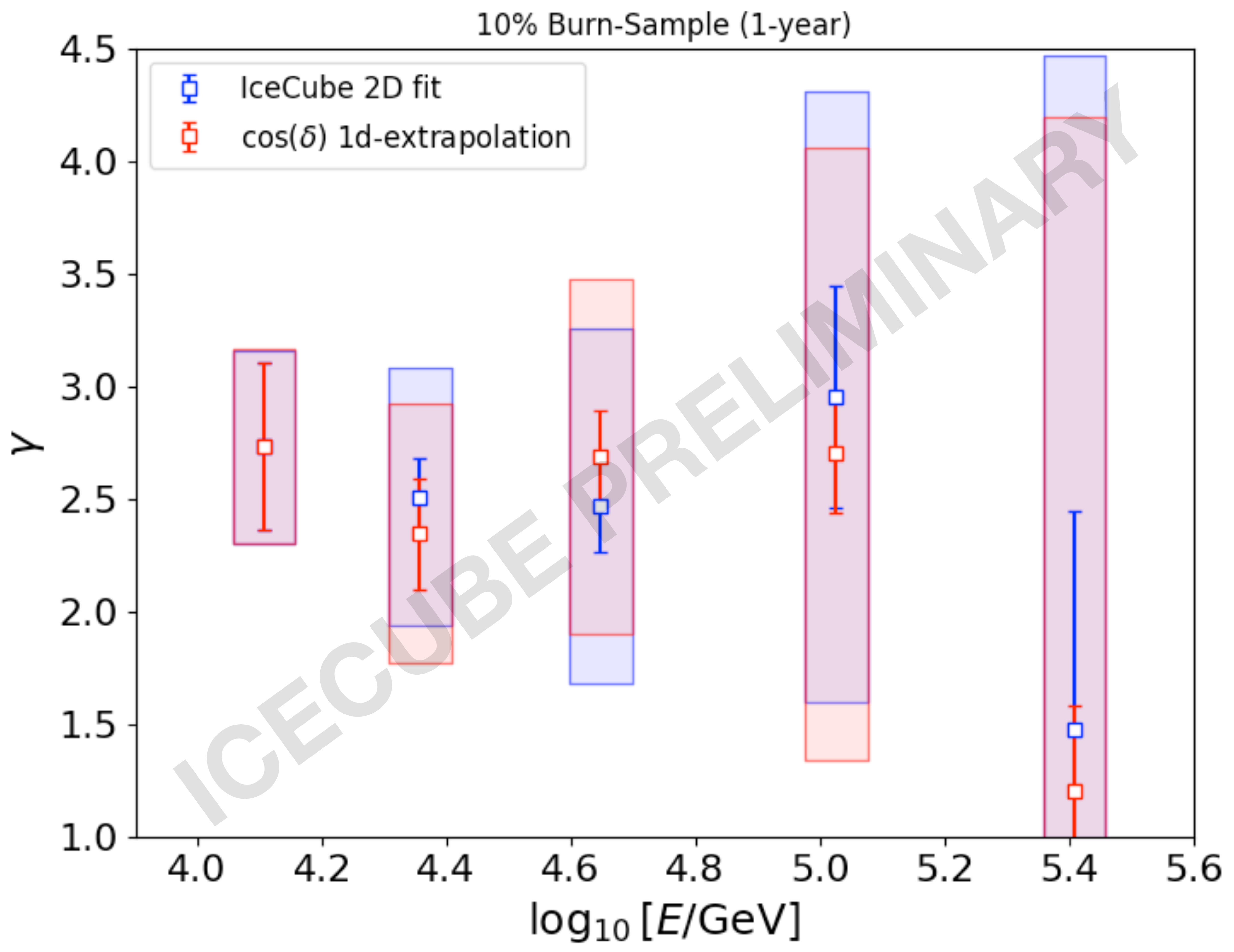
10% Burn sample (1 year)

- Derived spectral index vs energy (after correction for projection bias).
- Boxes correspond to systematic uncertainties

 1. Variation in Earth's orbital speed,

 2. Interference from Extended-Sidereal distribution.

- Low statistics at high energies produce large uncertainties in the extended sidereal amplitude



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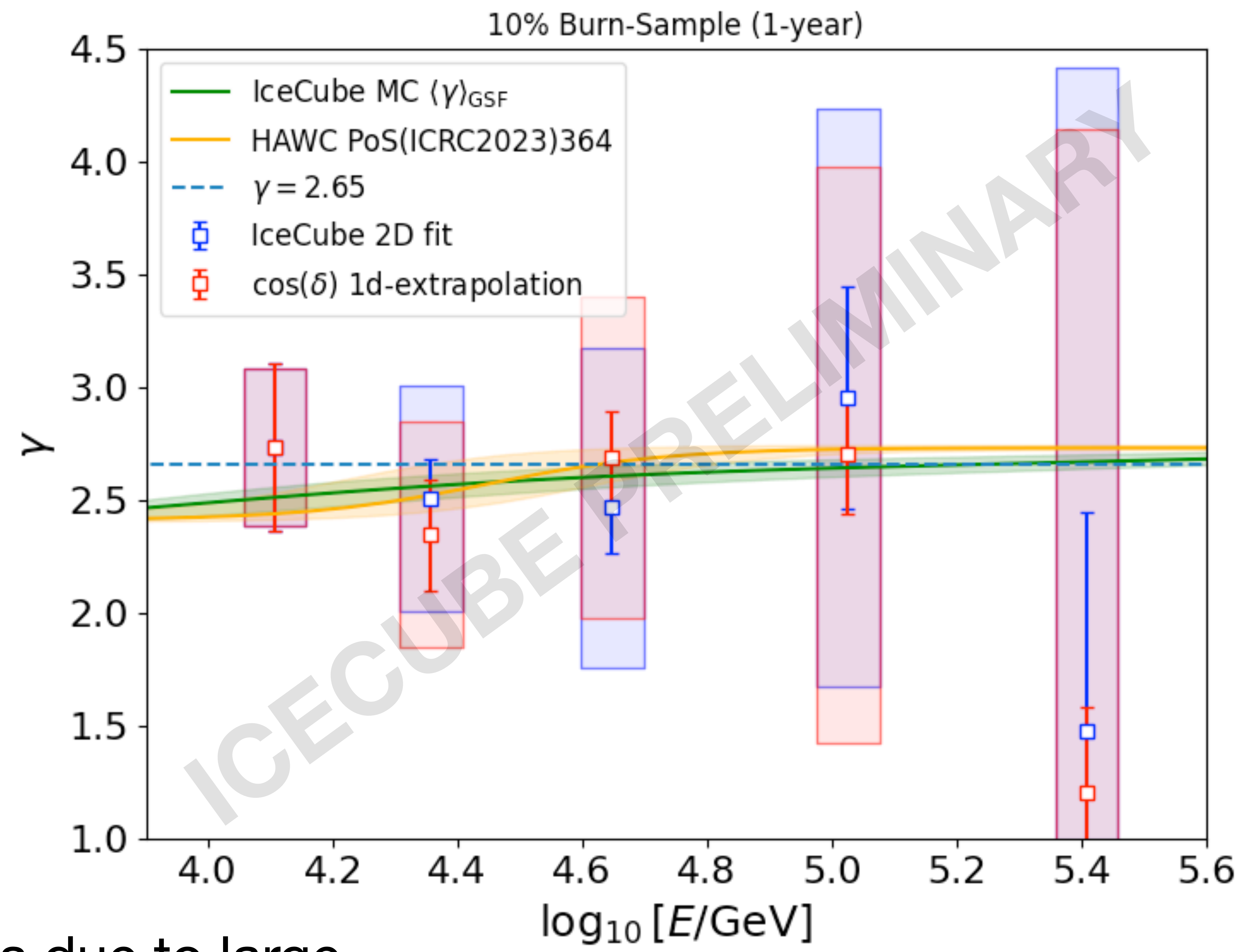

Data are consistent with all three hypotheses due to large uncertainties.

Conclusions

- Applied quality cuts to improve angular reconstruction
- Measured the solar dipole amplitude for different energy bins using a 10% burn sample
- Derived the corresponding spectral index from Compton-Getting formula.
- Data are consistent with both, single and broken power law scenarios due to large uncertainties
- Statistical uncertainties will decrease with 10x data with full 12-year sample
- Systematic uncertainties:
  - Uncertainties on amplitude and phase of extended-sidereal distribution (should also decrease with more statistics).
  - Variation of Earth's orbital speed due to eccentricity.

https://events.icecube.wisc.edu/event/183/overview

SuGAR MADISON 2024

SEARCHING FOR THE SOURCES OF GALACTIC COSMIC RAYS

OCTOBER 14-17

NSF ICECUBE WIPAC W WARF Wisconsin Alumni Research Foundation

Science Goals

The symposium aims to investigate the long-standing mystery surrounding the origin of cosmic rays within our galaxy. This event will bring together renowned experts to discuss both experimental and theoretical aspects of cosmic ray physics, with a particular emphasis on galactic sources.

Despite ongoing research, the question of where cosmic rays originate within the Milky Way remains unanswered. The symposium will host a number of invited speakers who are experts in various aspects of galactic multi-messenger astrophysics.

Furthermore, two dedicated discussion panels will provide opportunities for open discussion. One panel will delve into the current status and challenges of multi-messenger observations and theoretical modeling. The other will address the future of observations and instrumentation required to make a breakthrough in our understanding of the galactic origin of cosmic rays.

Scientific Organizing Committee

- Pasquale Blasi (GSSI, L'Aquila, Italy)
- Damiano Caprioli (University of Chicago, U.S.A.)
- Ke Fang (University of Wisconsin–Madison, U.S.A.)
- Francis Halzen (University of Wisconsin–Madison, U.S.A.)
- Szabolcs Marka (Columbia University, U.S.A.)
- Simona Toscano (Université Libre de Bruxelles, Belgium)

OCTOBER 14-17

List of Confirmed Speakers

- Markus Ahlers (Niels Bohr Institute, Denmark)
- Pasquale Blasi (GSSI, Italy)
- Zhen Cao (IHEP, China)
- Damiano Caprioli (University of Chicago, U.S.A.)
- Ivan De Mitri (GSSI, Italy)
- Juan Carlos Díaz Vélez (University of Wisconsin - Madison, U.S.A.)
- Ke Fang (University of Wisconsin - Madison, U.S.A.)
- Gwenael Giacinti (Tsung-Dao Lee Institute, China)
- Jordan Goodman (University of Maryland, U.S.A.)
- Sarah Gossan (Hofstra University, U.S.A.)
- Francis Halzen (University of Wisconsin - Madison, U.S.A.)
- Dan Hooper (University of Wisconsin - Madison, University of Chicago, U.S.A.)
- Kazumasa Kawata (University of Tokyo, Japan)
- John F. Krizmanic (NASA, U.S.A.)
- Tim Linden (Stockholm University, Sweden)
- Rubén López-Coto (Instituto del Astrofísica de Andalucía, Spain)
- Lukas Merten (Ruhr University Bochum, Germany)
- Philipp Mertsch (RWTH Aachen University, Germany)
- Pravata Mohanty (Tata Institute of Fundamental Research, India)
- Giovanni Morlino (INAF - Firenze, Osservatorio di Arcetri, Italy)
- Igor Moskalenko (Stanford University, U.S.A.)
- Michela Negro (Louisiana State University, U.S.A.)
- Nahee Park (Queen's University, Canada)
- Simona Toscano (Université Libre de Bruxelles, Belgium)
- Paolo Zuccon (University of Trento, Italy)
- Ellen Zweibel (University of Wisconsin - Madison, U.S.A.)

List of Confirmed Panelists

- Panel on the Current Status of Multimessenger Astrophysics
  - Petra Huentermeyer (Michigan Technological University, U.S.A.)
  - Andrii Neronov (Ecole Polytechnique Federale de Lausanne, Switzerland)
  - Justin Vandenbroucke (University of Wisconsin - Madison, U.S.A.)
- Panel on the Future of Multimessenger Astrophysics
  - Szabolcs Marka (Columbia University, U.S.A.)
  - Kotha Murase (Penn State University, U.S.A.)
  - Eli Waxman (Weizmann Institute of Science, Israel)

Thank you