Analysis of Cosmic-Ray Anisotropy with 8 years of HAWC data

Juan Carlos Díaz Vélez,
Riya Yogesh Kore, Ferris Wolf, Paolo Desiati
UW-Madison

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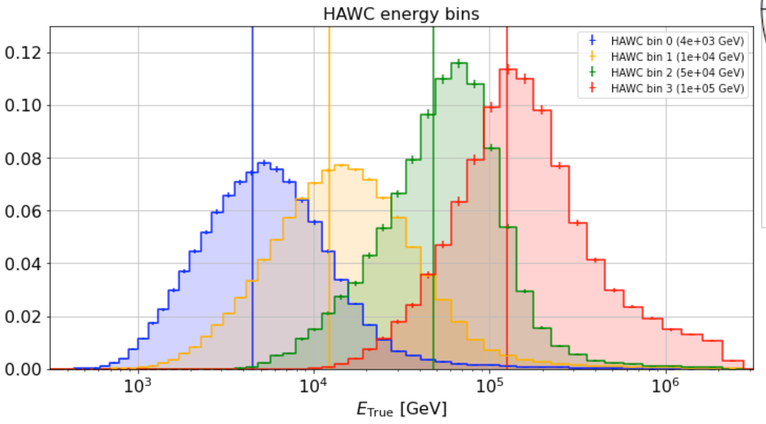
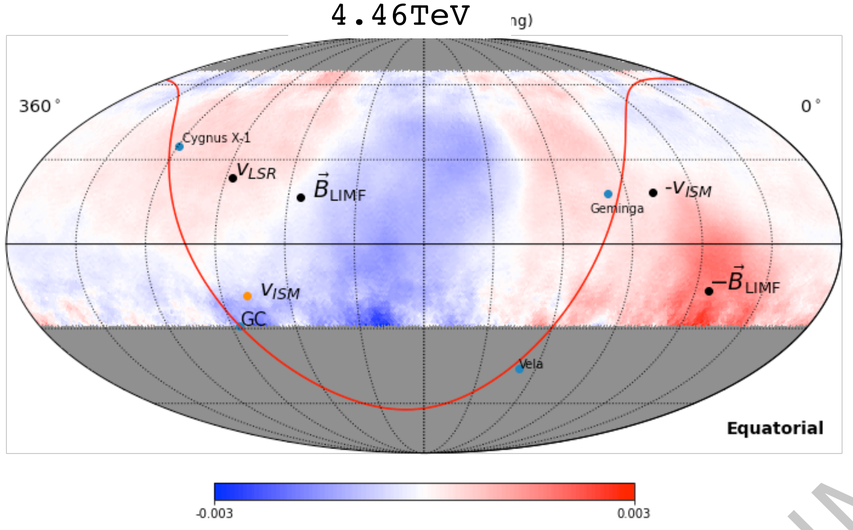
HAWC Collaboration Meeting
CdMX, México

HAWC Relative Intensity (7-years)

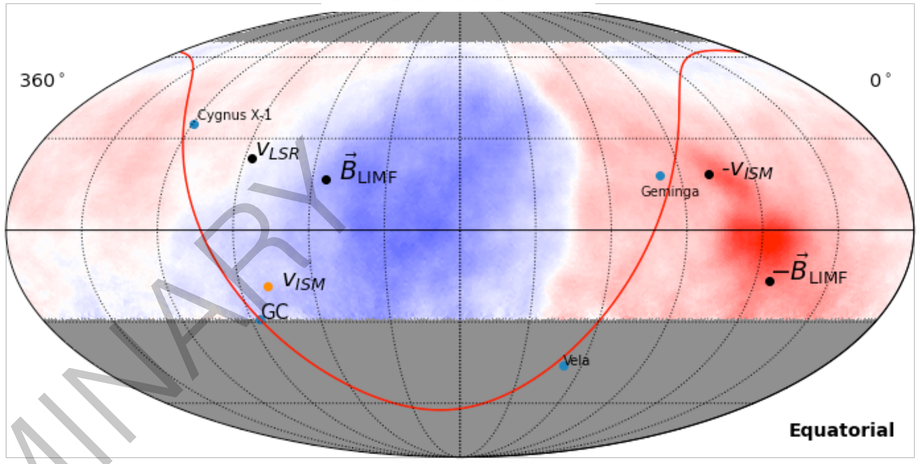
bin0: E_med=4.46 (-2.01, +9.95)
bin1: E_med=10.5 (-4.15, +27.1)
bin2: E_med=47.6 (-20.2, +91.8)
bin3: E_med=126 (-56.8, +307)



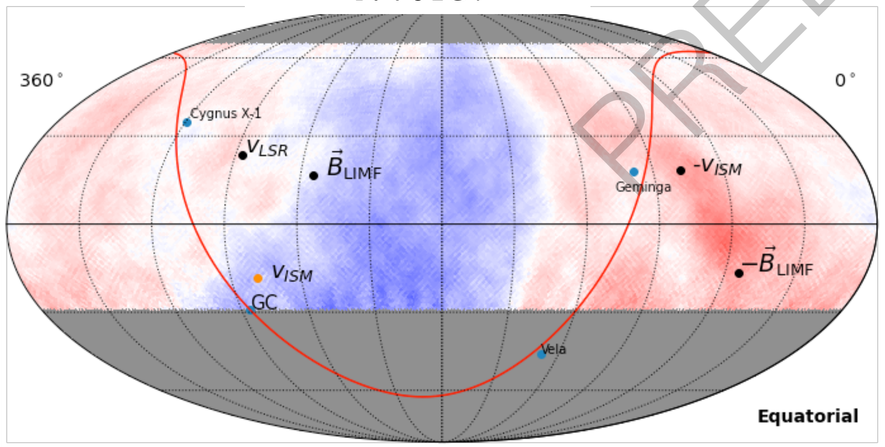
4.46TeV

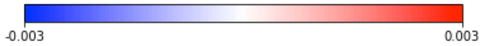


10.5TeV

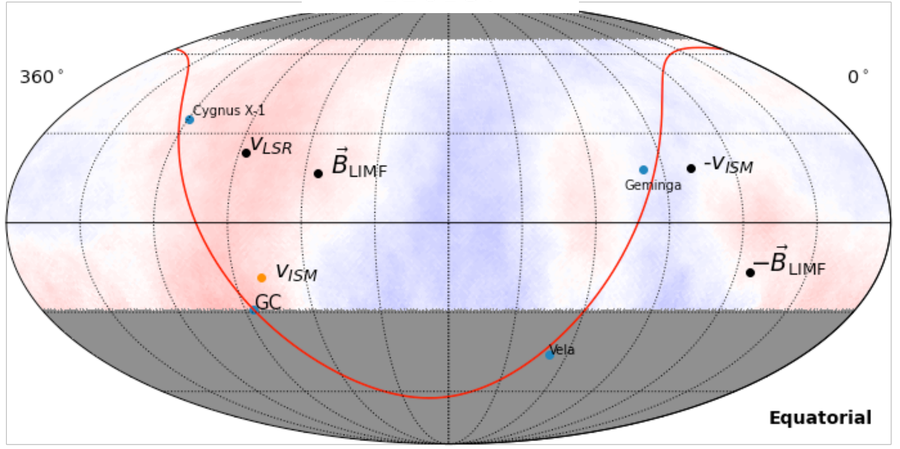


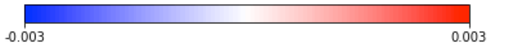
47.6TeV





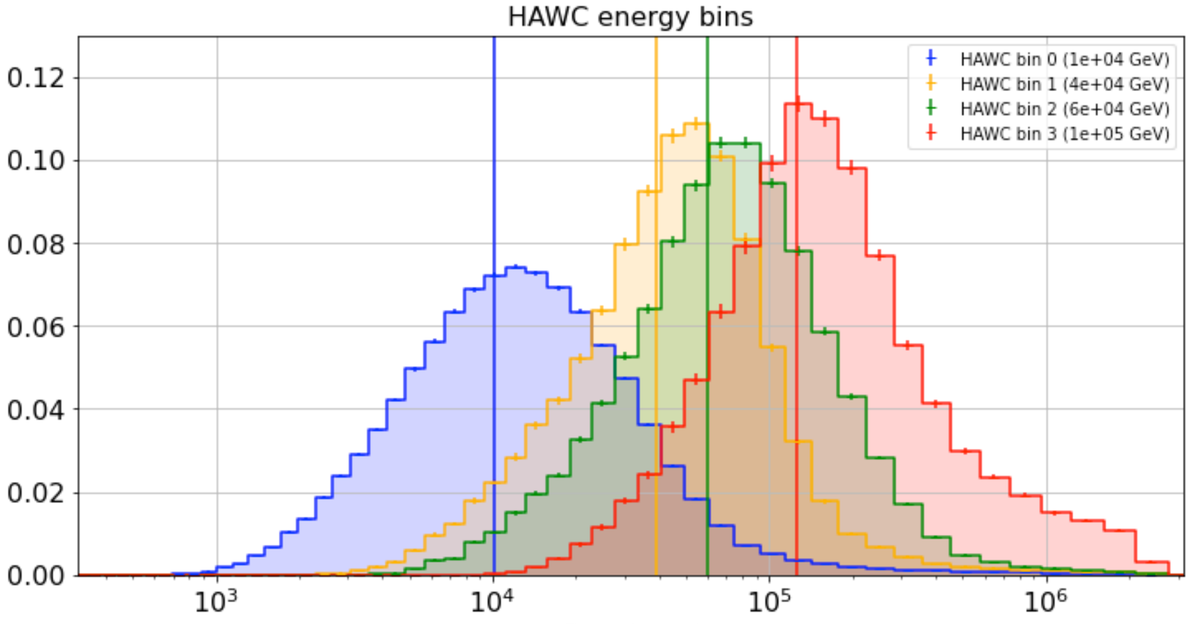
126TeV



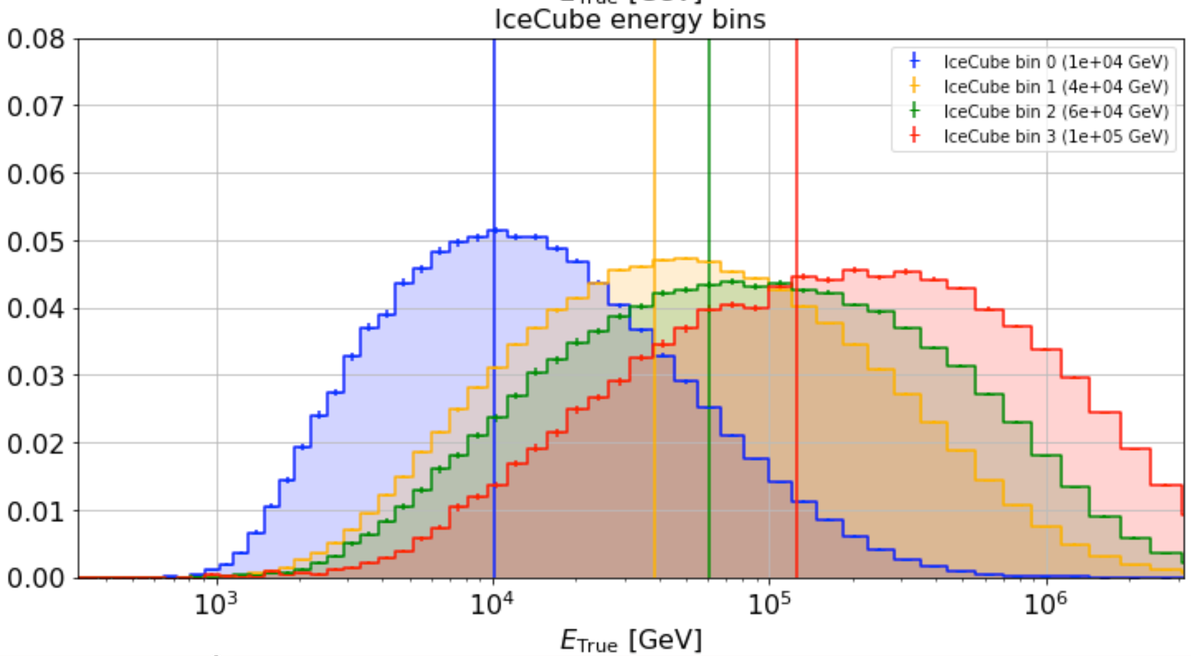


New IceCube/HAWC Energy Bins

E_med=10.2 (-4.04, +25.6)
E_med=39 (-15.8, +76.7)
E_med=60.3 (-24.9, +131)
E_med=126 (-56.9, +307)

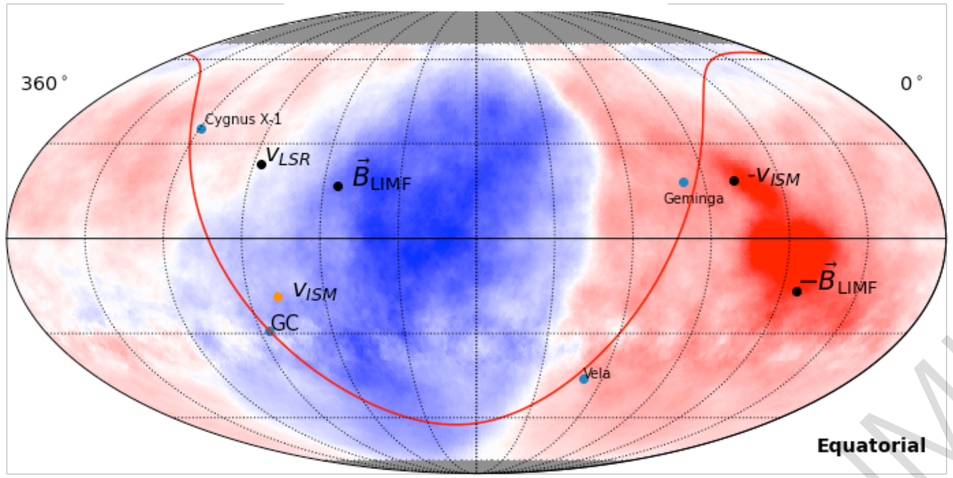


E_med=10.1 (-3.32, +37.5)
E_med=38.7 (-9.26, +184)
E_med=60.8 (-12.4, +333)
E_med=126 (-22.2, +701)

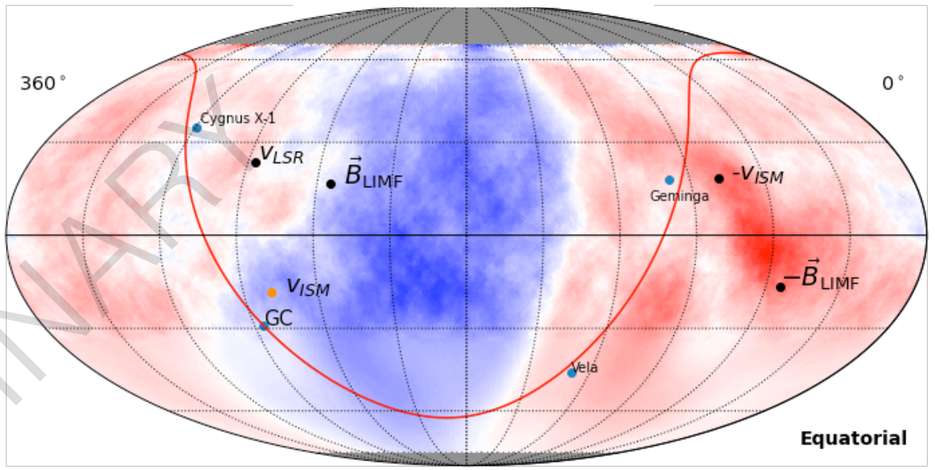


Combined IceCube-HAWC

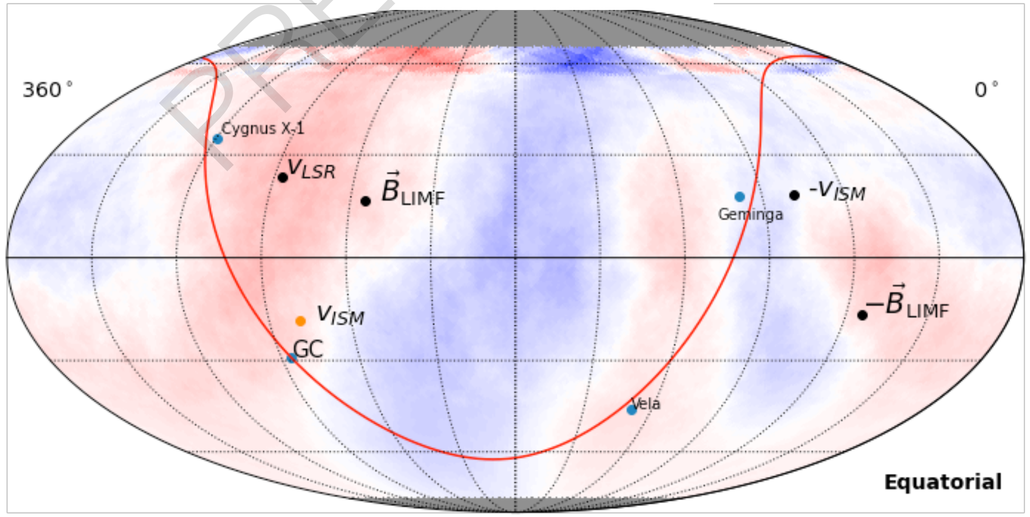
10.5TeV

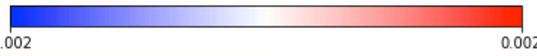


47.6TeV

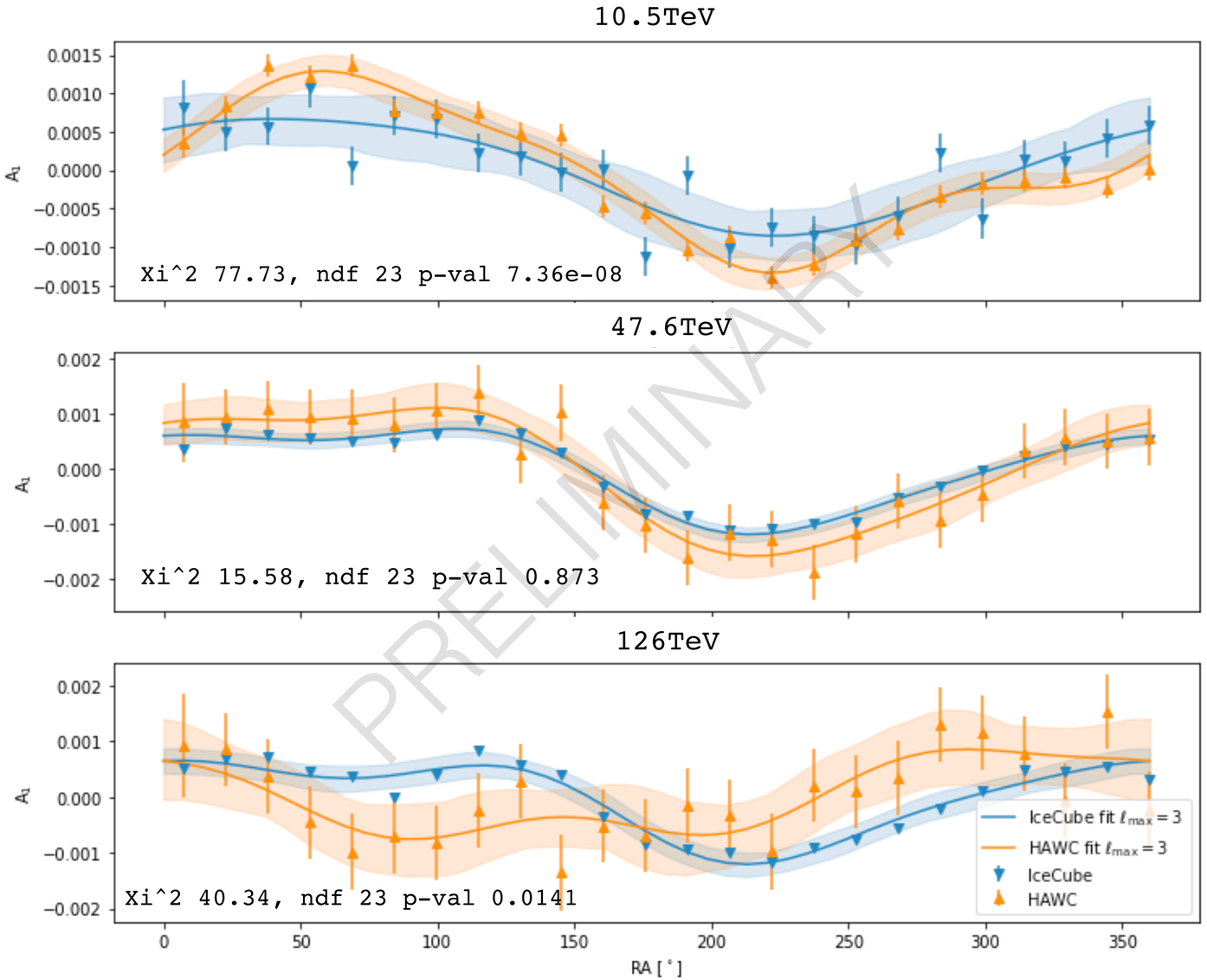


126TeV

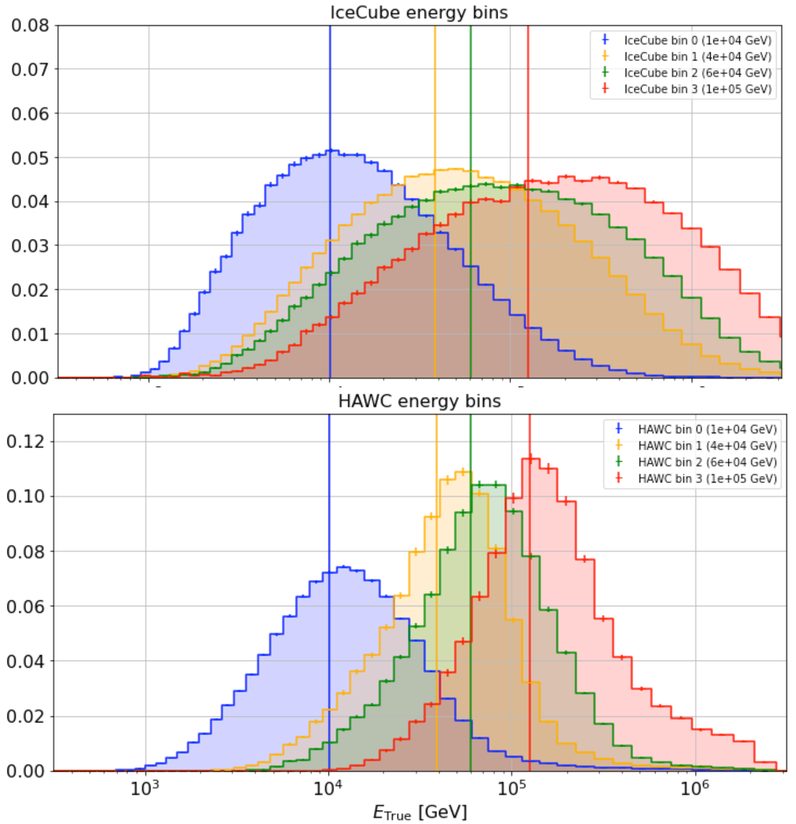




Overlapping Region

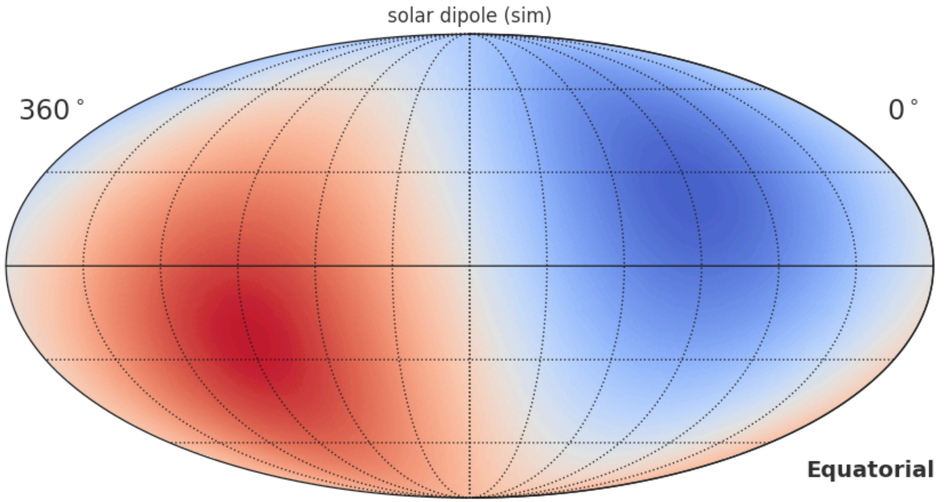


- Bins 2 & 3 are (statistically compatible) in the overlapping region
- Poor statistics and systematic in reconstructions near the horizon make the comparison difficult



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

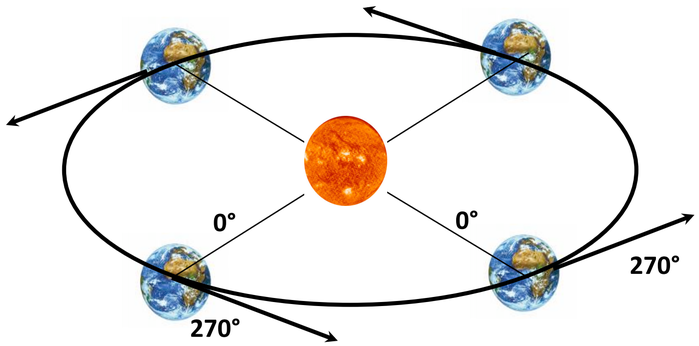
Arthur H. Compton and Ivan A. Getting
Phys. Rev. 47, 817 – Published 1 June 1935
doi:10.1103/PhysRev.47.817.



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).



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

Bias from Yearly modulation of sidereal anisotropy

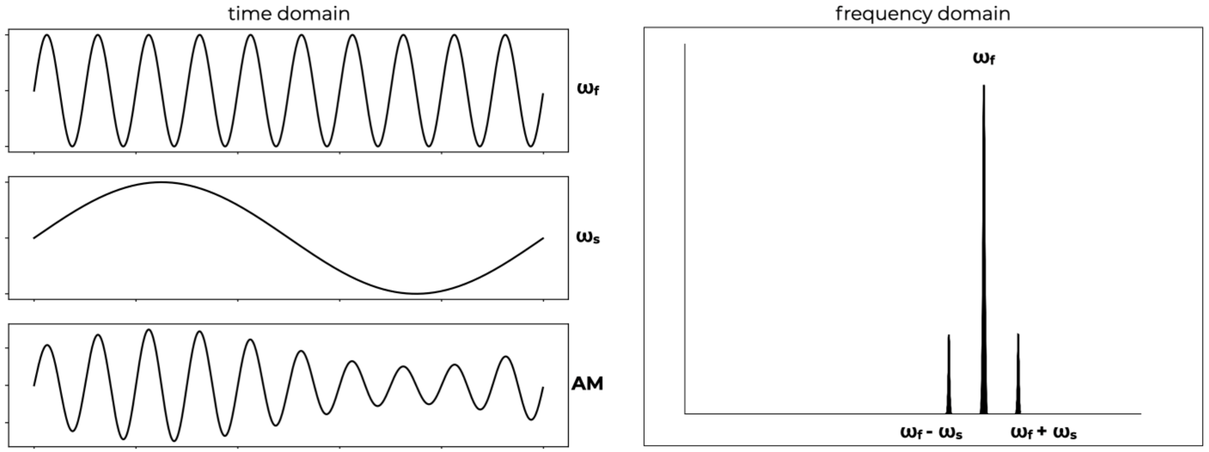


Figure 1: *Left:* a carrier wave with frequency ω_f modulated by a wave with frequency $\omega_s < \omega_f$ produces an amplitude modulated (AM) wave in time domain. *Right:* the AM wave decomposition in frequency domain, with the carrier frequency surrounded by side-bands with frequencies $\omega_f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

PoS(ICRC2021)085

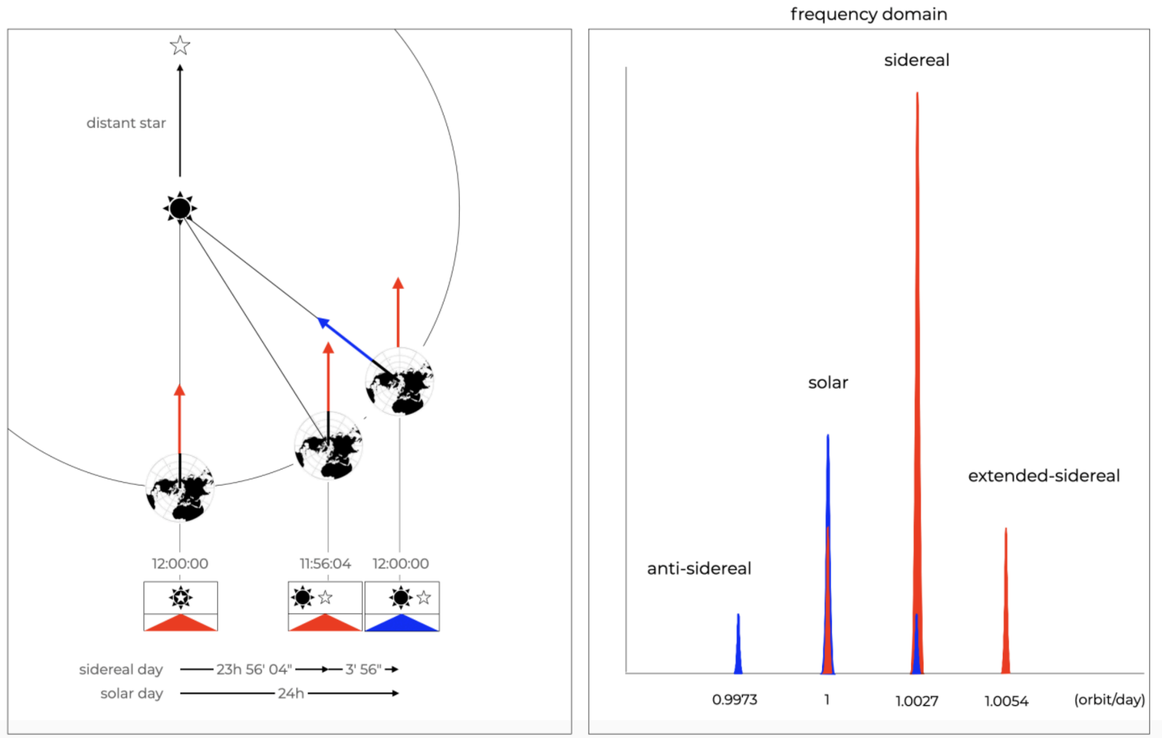


Figure 2: *Left:* the sidereal time with respect to solar time. Time starts at 12:00:00 on the local meridian with the Sun at the same location as a distant star. Then, as the Earth revolves around the Sun, the sidereal time zero point stays fixed in the celestial sky while the solar time's reference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

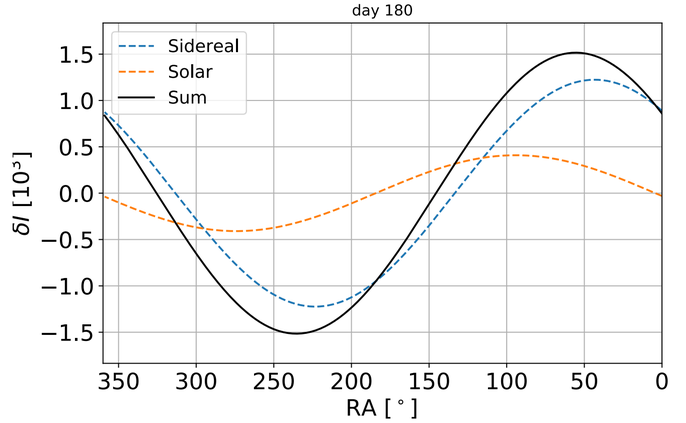
extended-sidereal distribution is produced by a **yearly modulation** of the sidereal-dipole amplitude

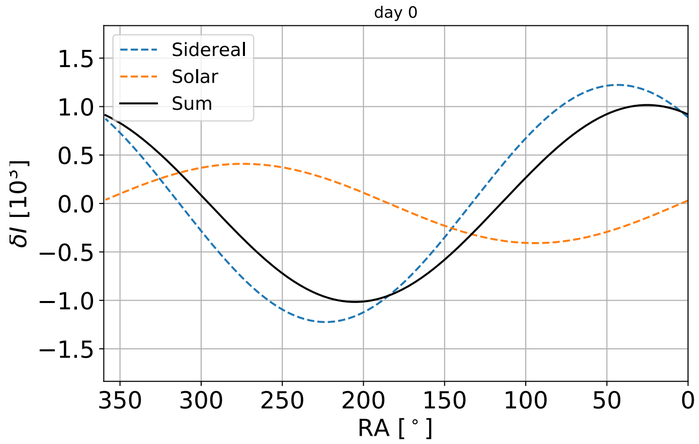
and it **deforms** the solar distribution

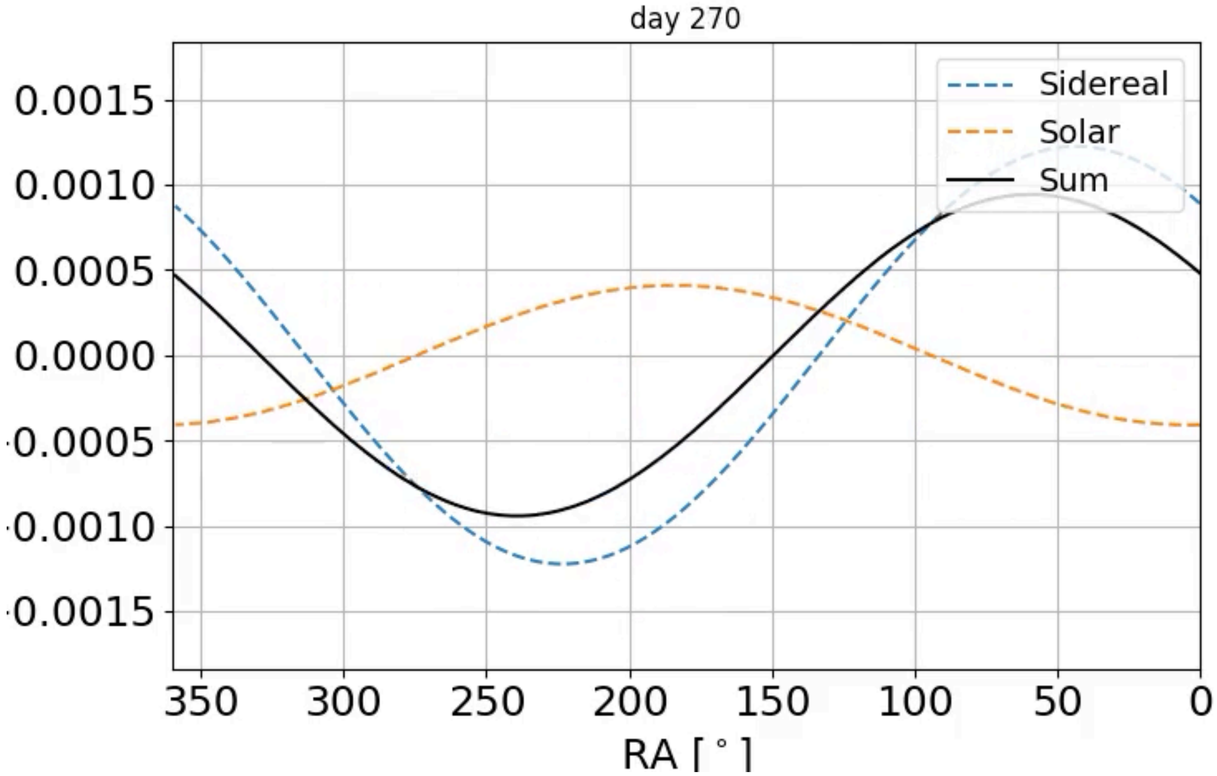
Interaction of the Solar and Sidereal frames

Interference between solar and sidereal dipole anisotropies as observed in the sidereal reference frame at two different times during the year. The solar dipole introduces a bias in both amplitude and phase of the sidereal dipole

Díaz-Vélez, *et al* 2021 PoS(ICRC2021)085



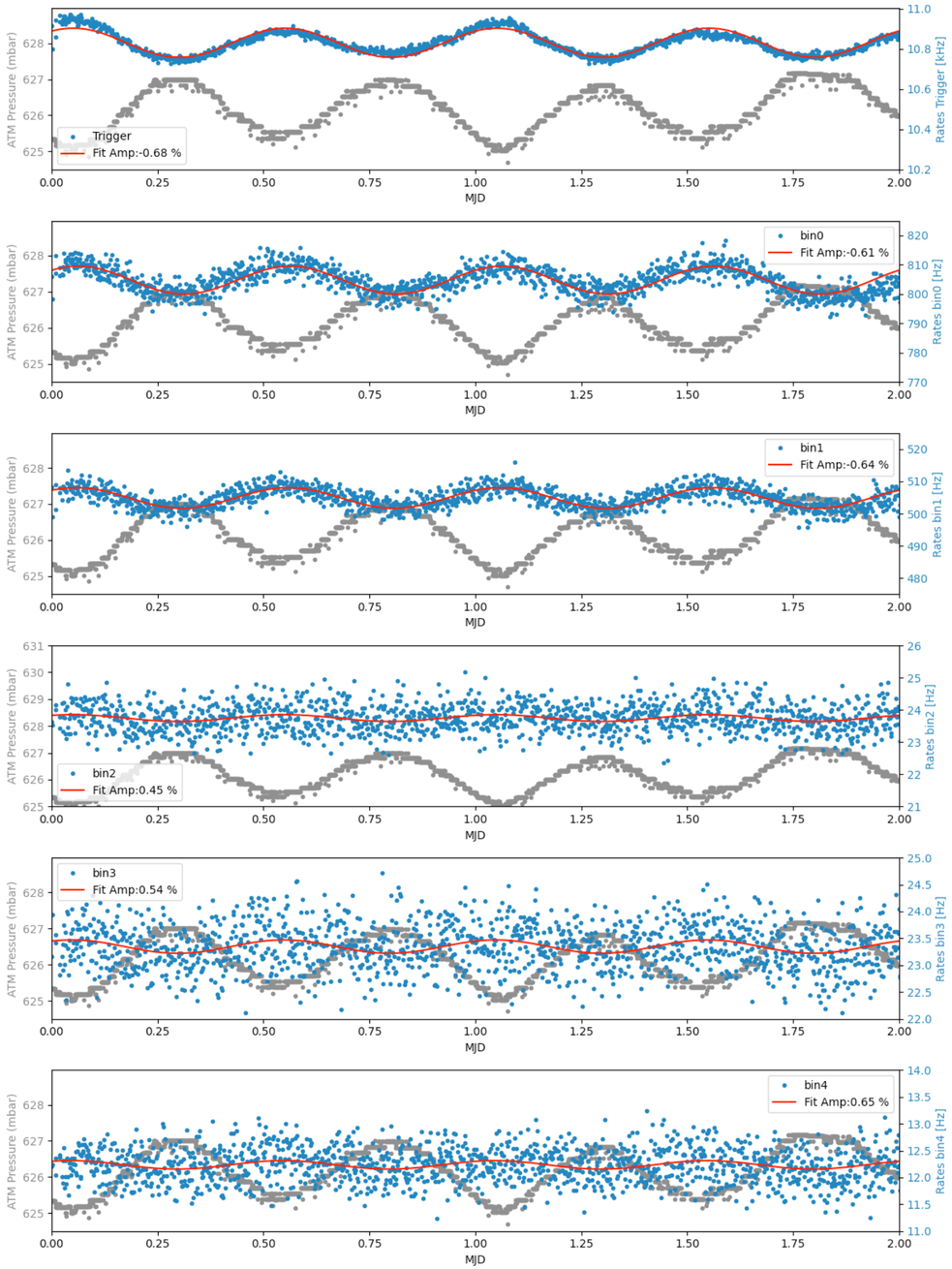




Pressure correction

- Atmospheric tides:
  - Lunar gravitational tides.
  - Thermally driven tides: heating associated with solar radiation. Dynamics determined by both the Coriolis force and gravity. (X. Zhang, et a. J. Geoph. Res.: Space Physics (2010))

- Weather data released through 2022 (Thank you Alberto Carramiñana, Esperanza Carrasco, Jorge Reyes & Xavier Alcántara
- To do: calculate data rates for each cut
- Determine correlation coefficients
- Remake maps with pressure correction



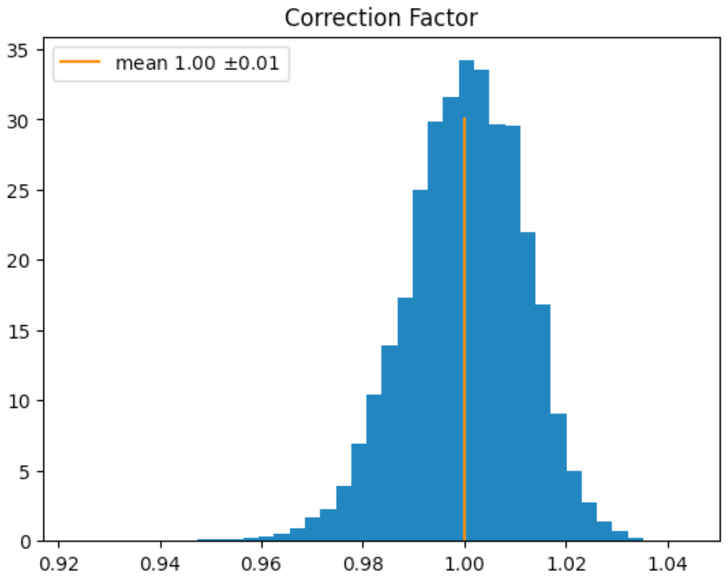
Pressure correction

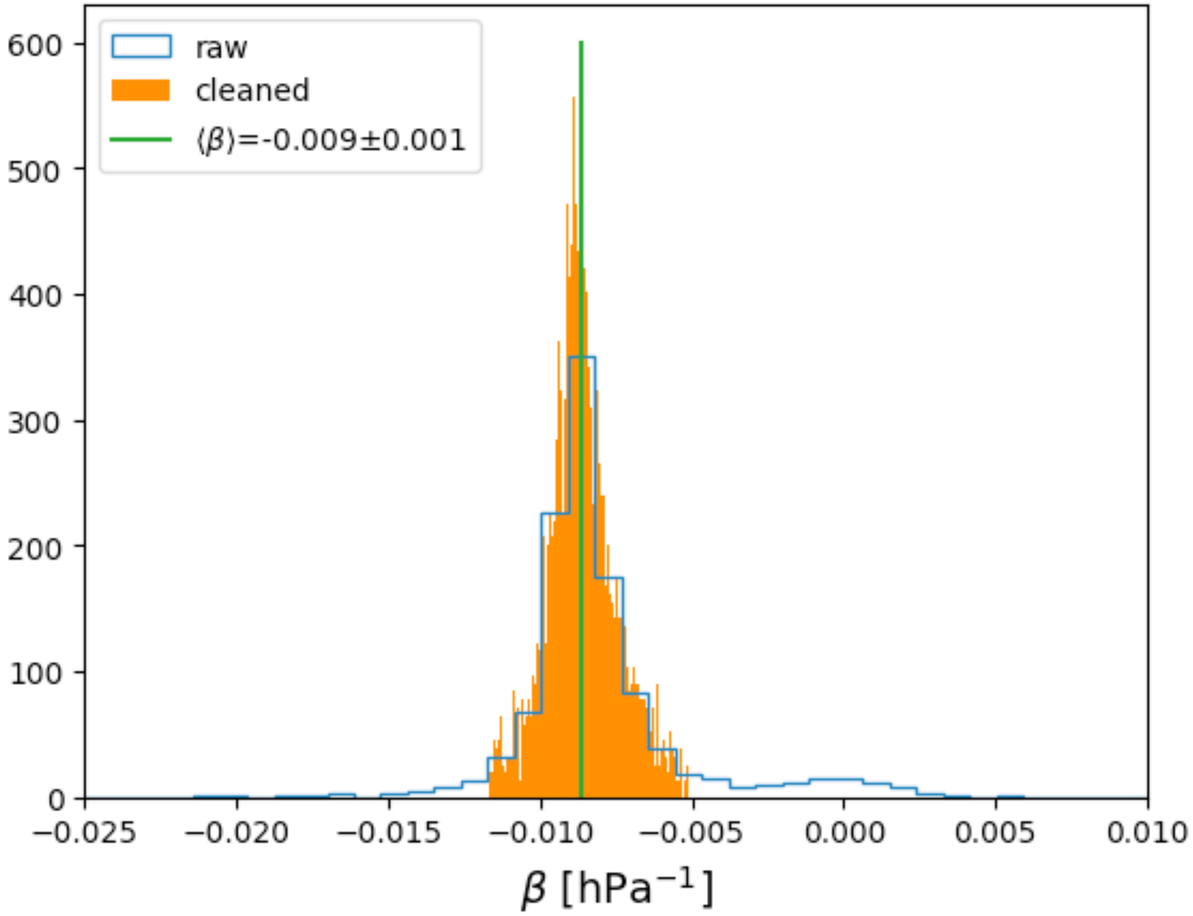
- Calculate data rates for each run between 2015 - 2023
- Determine correlation coefficients for each run
- Calculate mean/std
- Cut tails of distribution (1σ)
- Re-calculate mean/std
- weigh events by correction factor

$$\Delta\{\ln R\} = \beta \Delta P$$

$$\beta = -0.009 \pm 0.001\,\mathrm{hPa}^{-1}$$

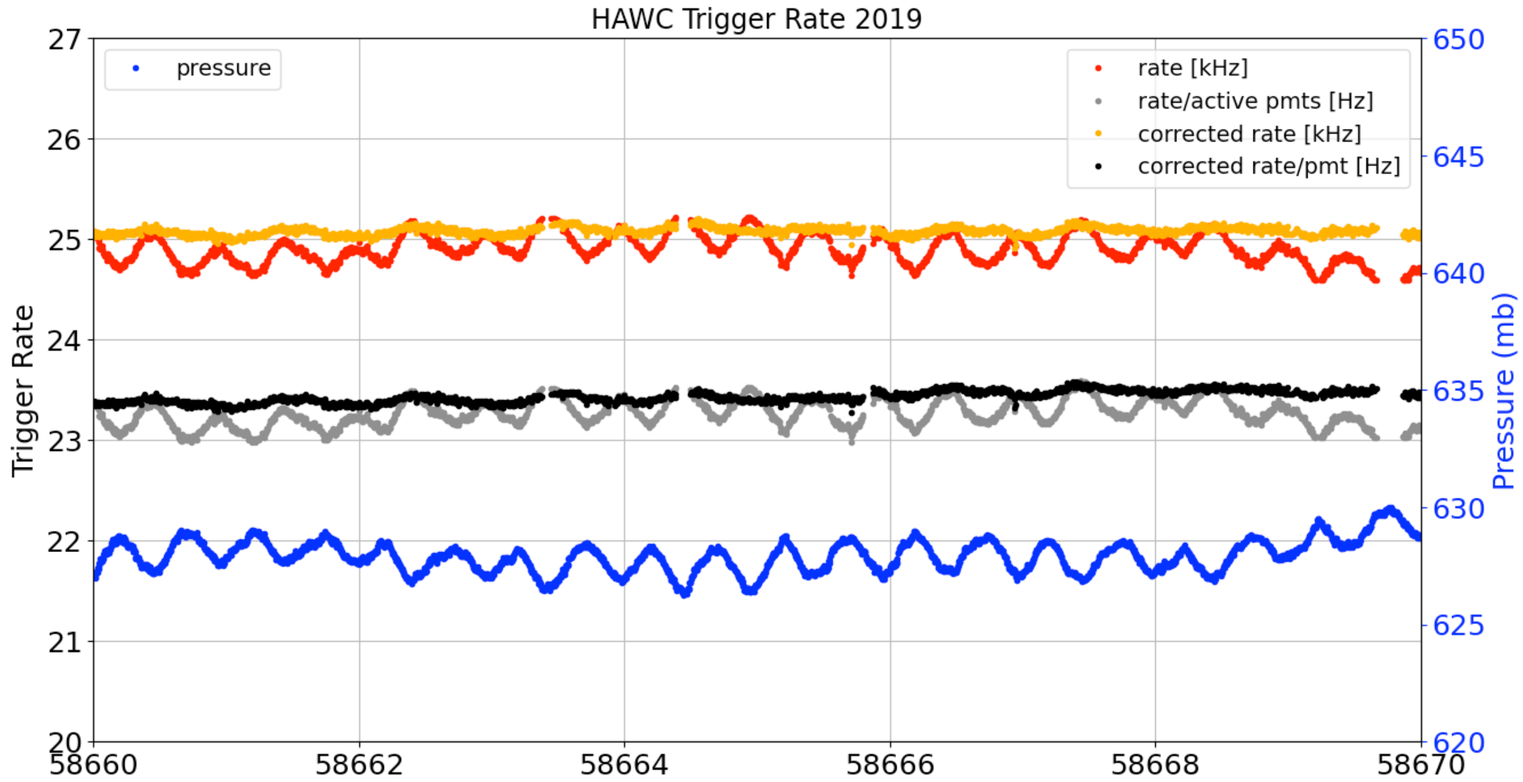
$$w_i = e^{-\beta(p(t_i)-p_0)}$$

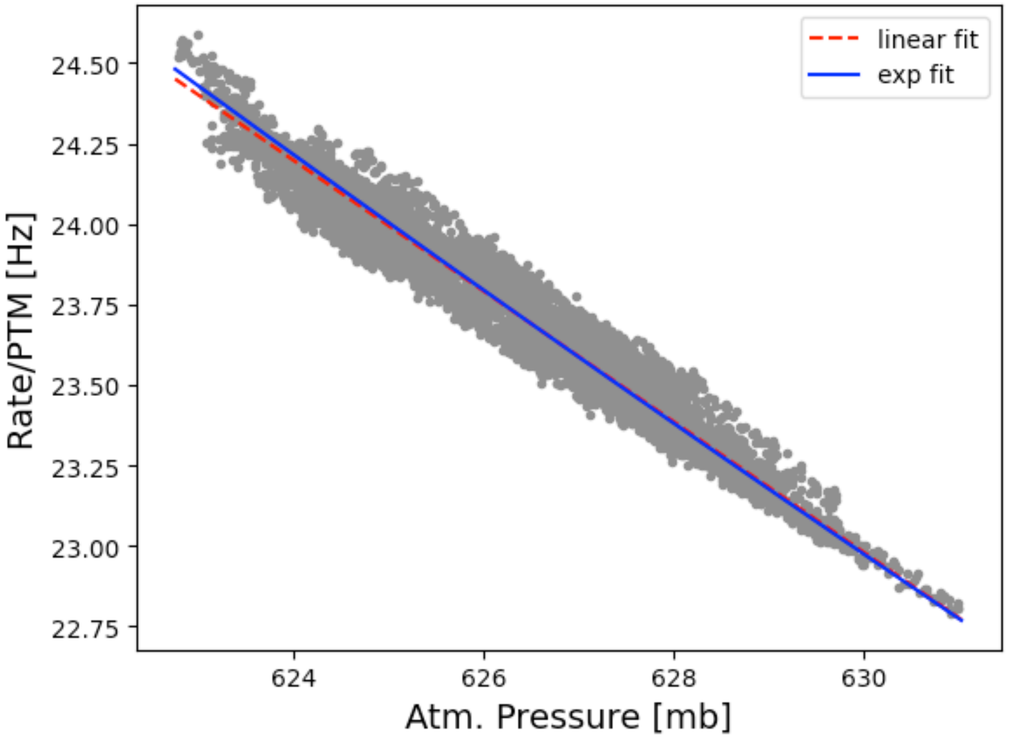




Pressure correction

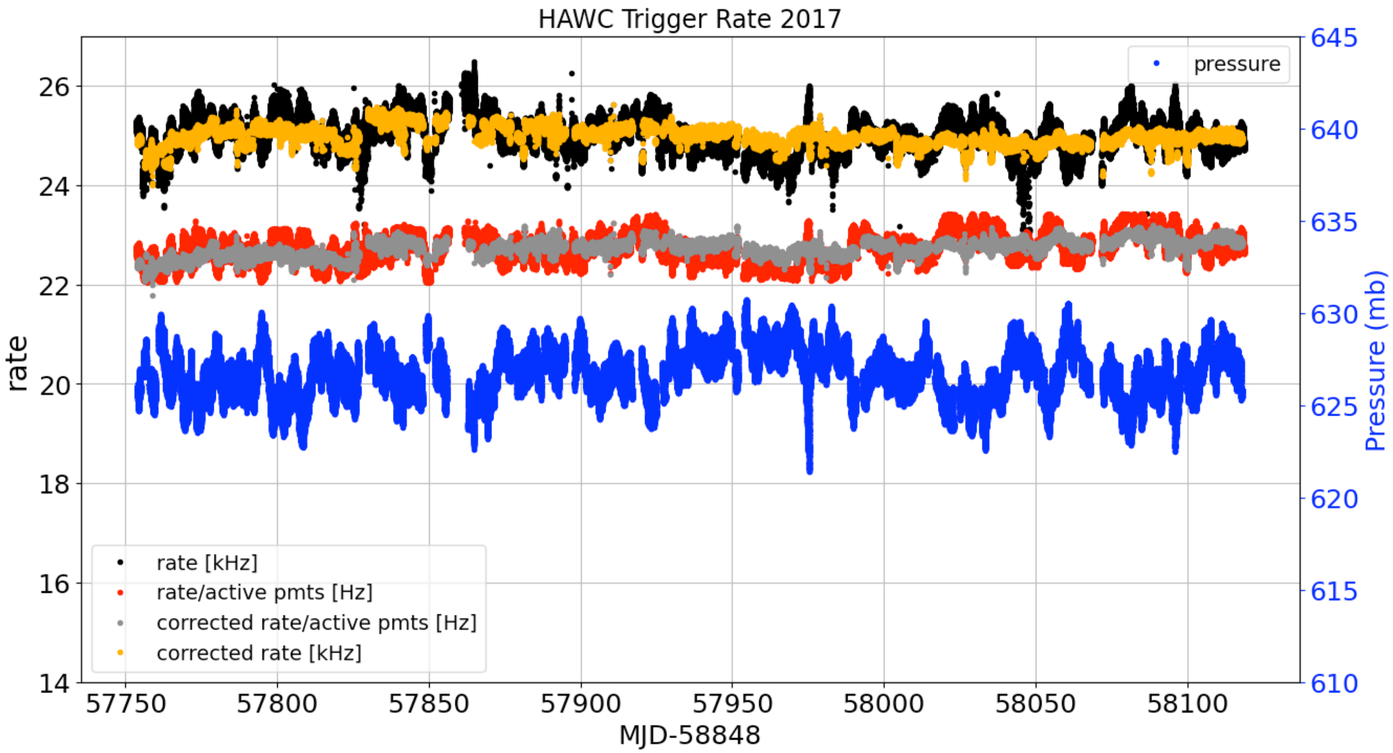
- Pressure corrected rates
- Residual **daily** variations
  - Solar Dipole
  - Solar heating of stratosphere (first interaction)

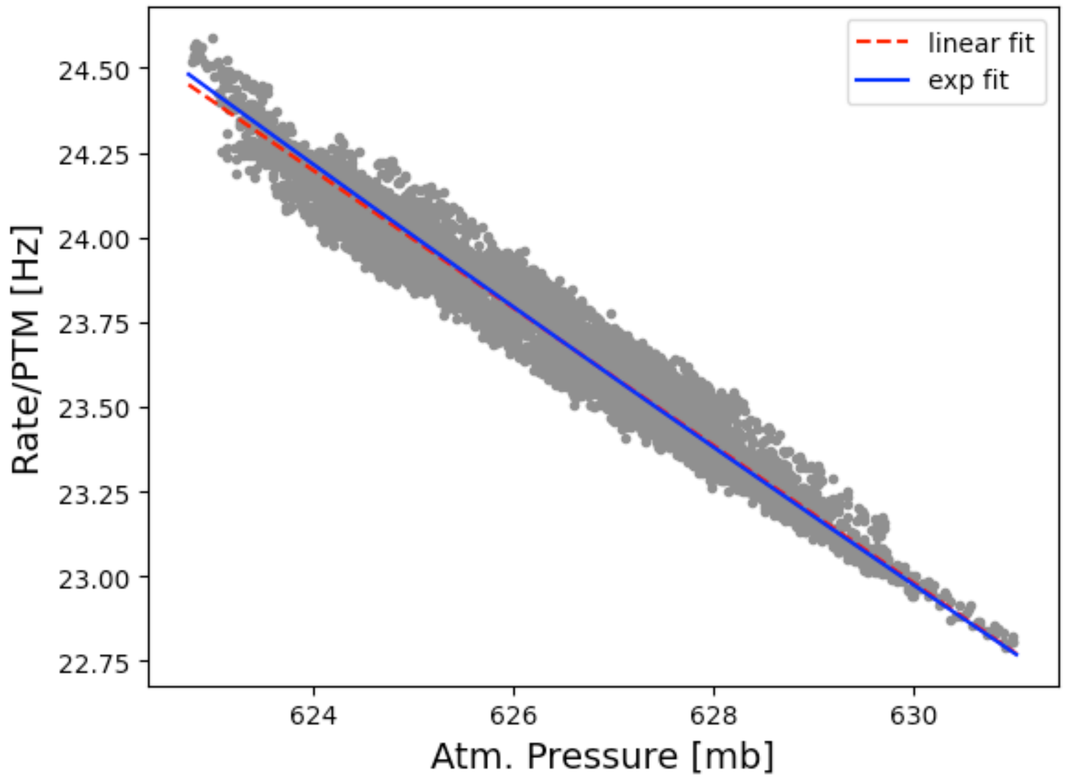




Pressure correction

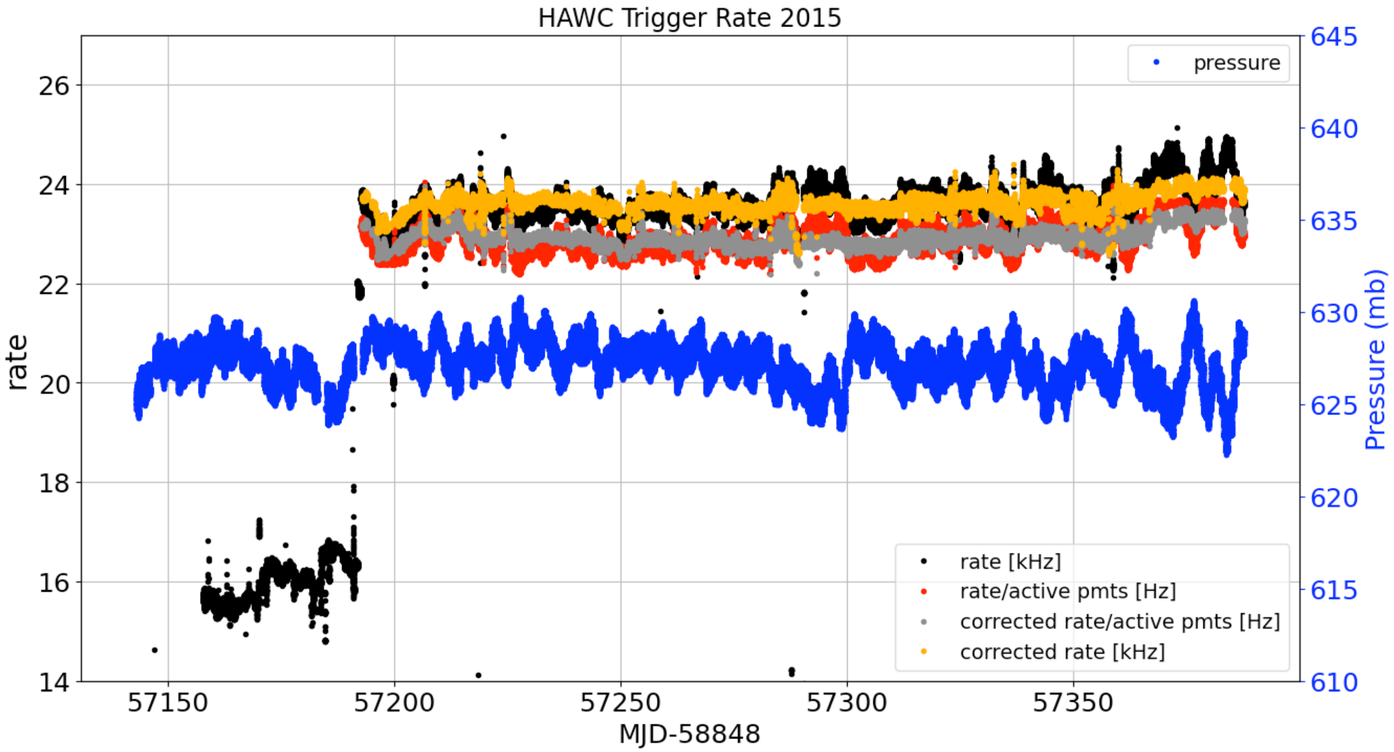
- Test correction factor
- Residual daily variations
  - Atmospheric tides:
    - Lunar gravitational tides.
    - Thermally driven tides: heating associated with solar radiation. Dynamics determined by both the Coriolis force and gravity. (X. Zhang, et a. J. Geoph. Res.: Space Physics (2010))

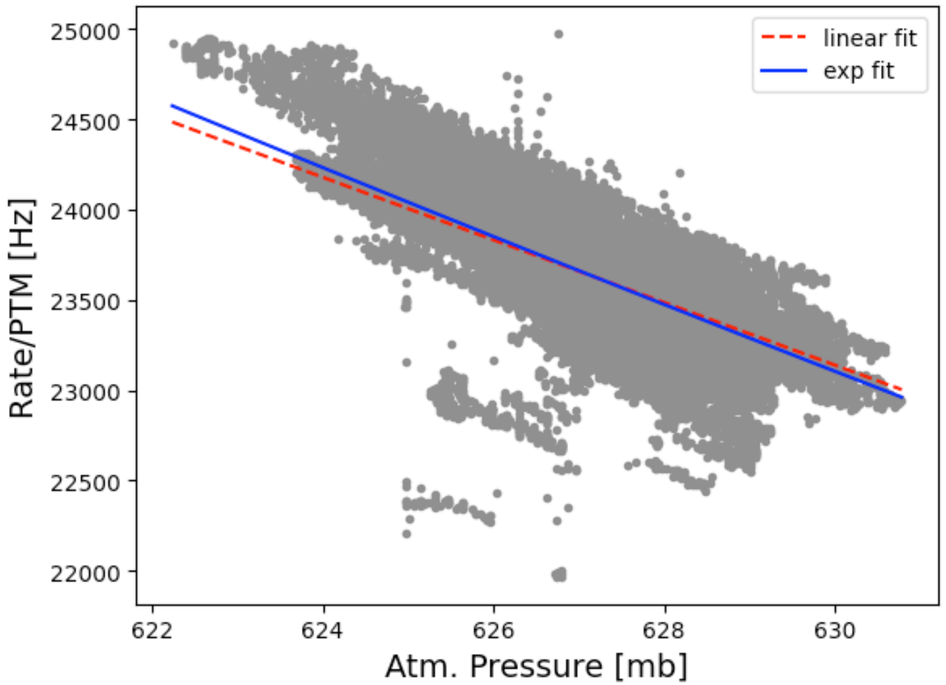




Pressure correction

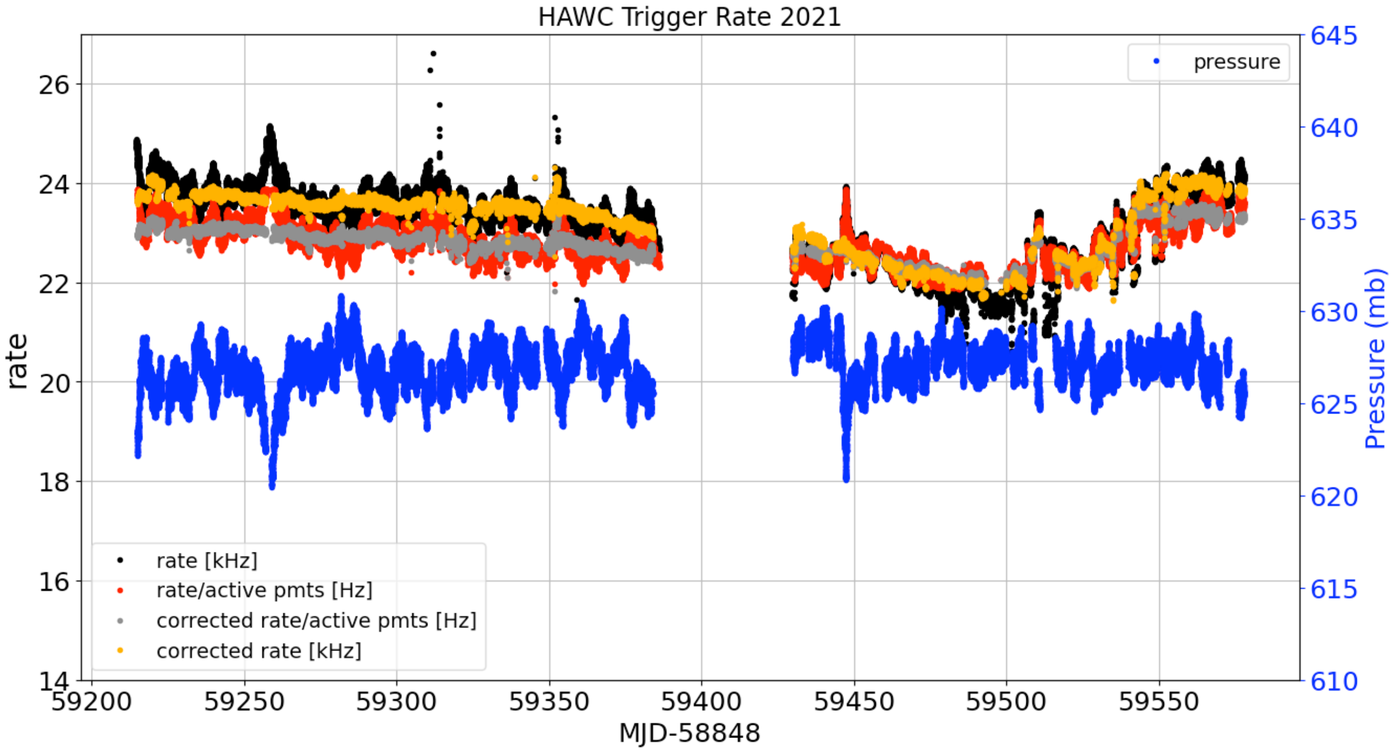
Some years are more stable than others

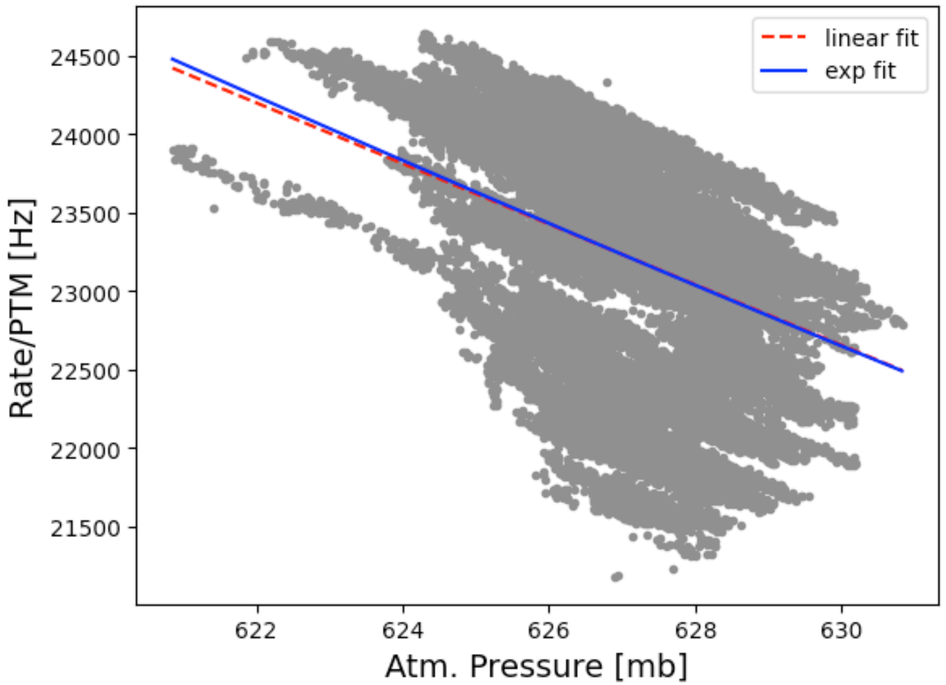




Pressure correction

Some years are more stable than others



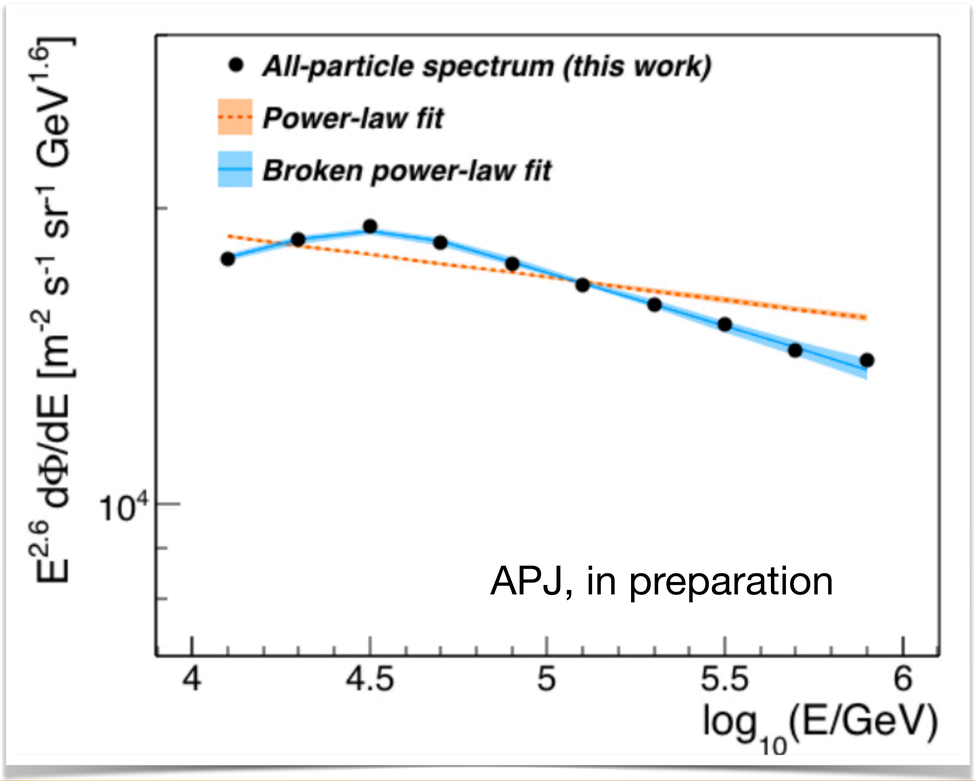


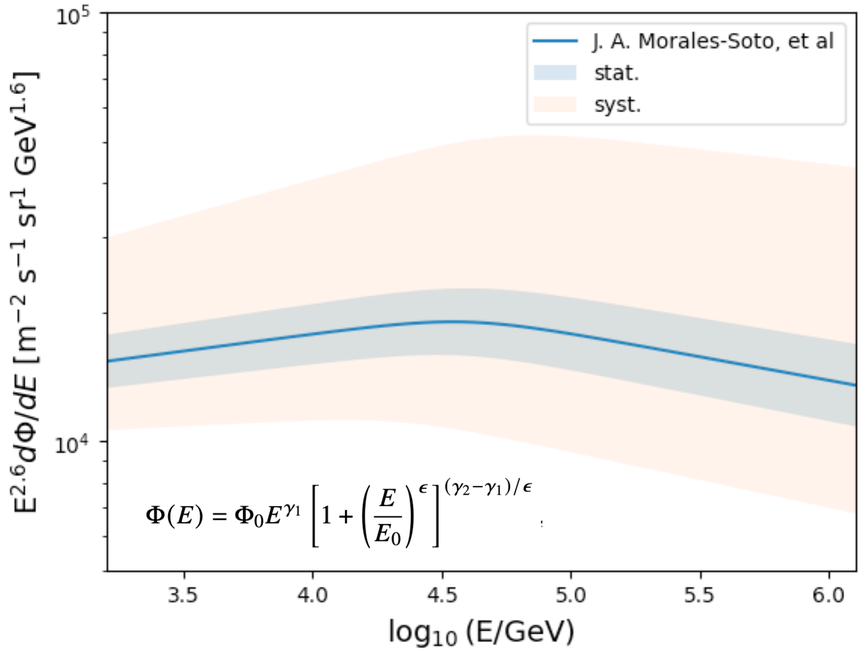
Solar Dipole Modulation (Energy Dependence)

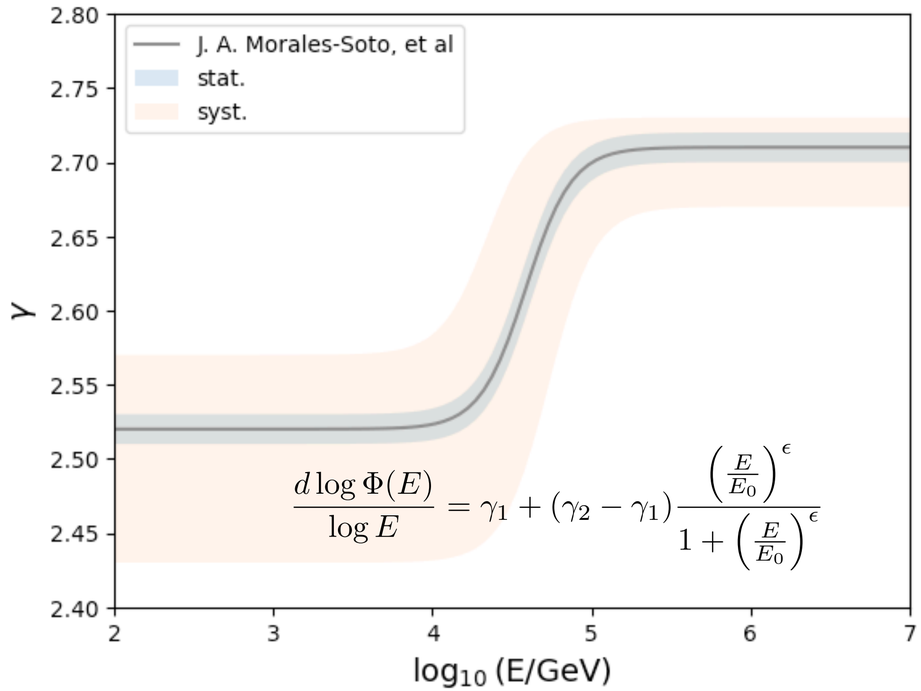
A measurement of the intensity spectrum of cosmic rays from 10^{13} to 10^{15} eV using HAWC

J. A. Morales Soto*[1] and J. C. Arteaga-Velázquez*[1]

[1]Instituto de Física y Matemáticas, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Mexico

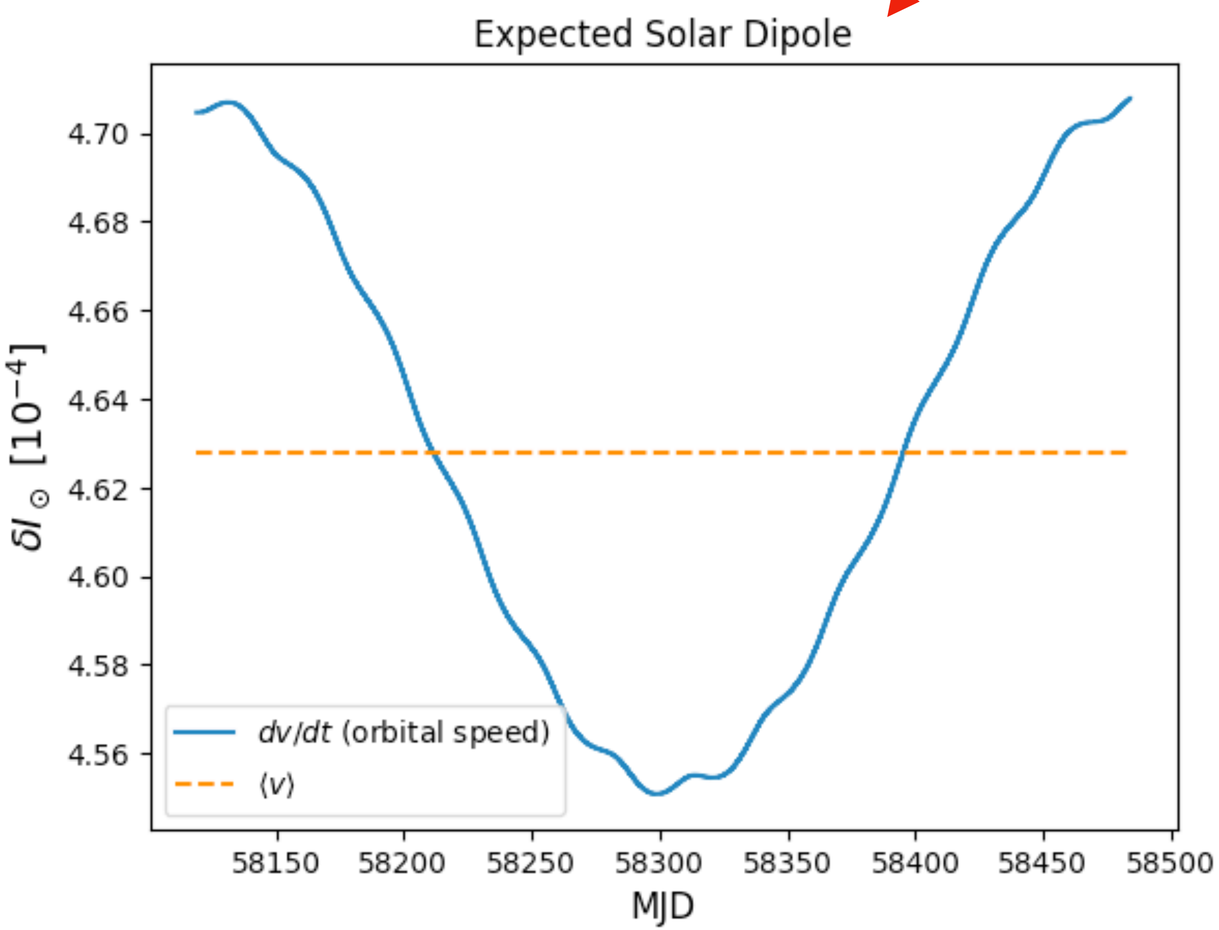


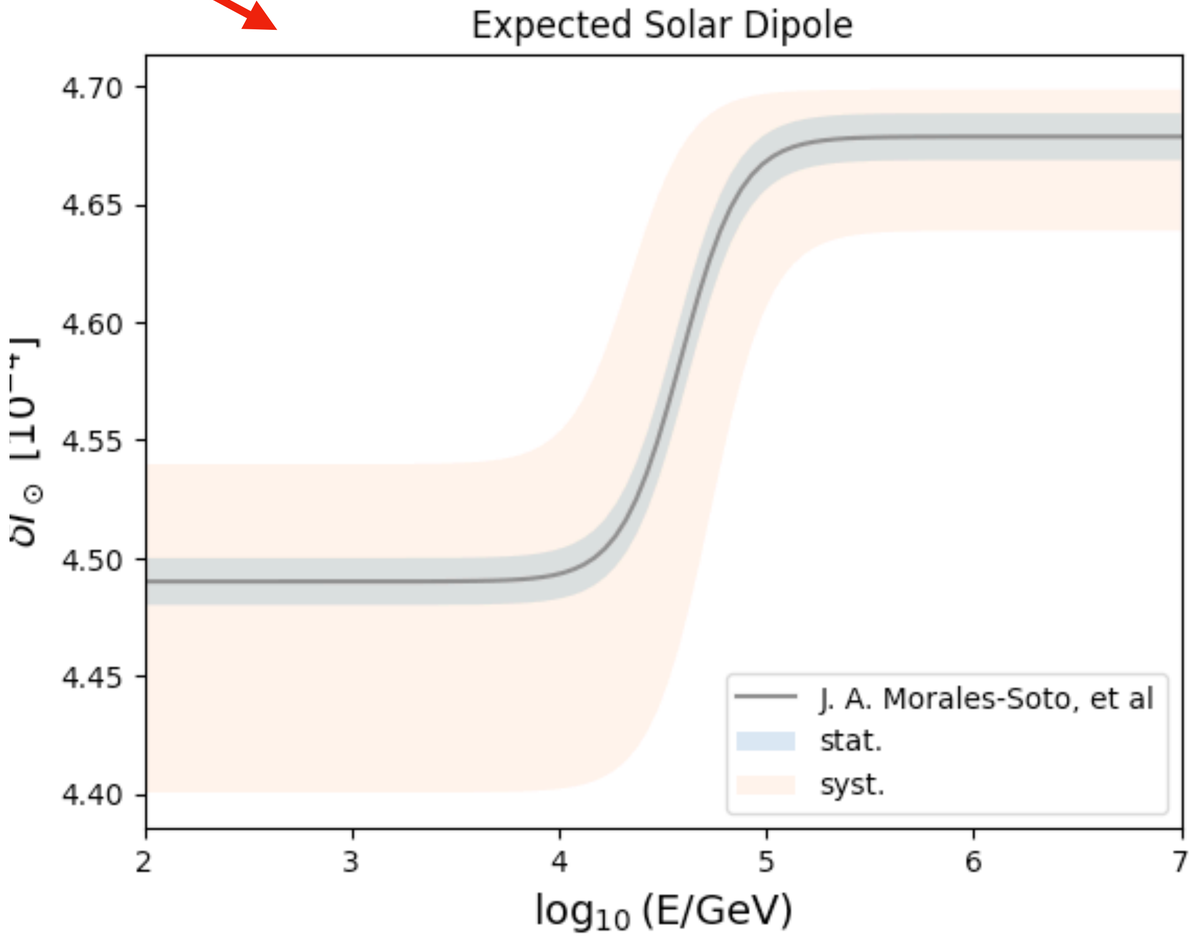




Solar Dipole Modulation

$$\delta_\odot = \frac{v(t)}{c}\left[\gamma(E) + 2\right]\cos\xi$$





Software updates

aerie-apps-make-local-hawc-maps

```
Configuration:
  --input arg                           HAWC rec XCDF file(s). Events NEED to be time ordered
                                                      ....
  --cutFile arg                         Cut file of boolean expressions
  --cutString arg                       boolean expression for event cuts (use
                                         Reconstructed XCDF field names)
  --evtFlagCut                          Apply eventFlags data quality cut.
  --preCutString arg                    Same as cutString but for use as a preliminary cut with cutFile option
  --pressurefile arg                    ATM pressure file
  --mean-pressure arg                   mean ATM pressure
  --pressure-coefficient arg            ATM pressure corretion coeff
```

col0: counts n_i

col1: weights $\sum_j^n w_{ji}$

col2: weights^2 $\sum_j^n w_{ji}^2$

$$w_{ij} = e^{-\beta(p(t_j)-p_0)}\left(1 - \frac{v(t_j)}{c}\left[\gamma(E_j)+2\right]\cos\xi_j\right)$$

Current Anisotropy Work in Progress

- Update on HAWC CR-Anisotropy
  - ✓ Determine pressure correlation
  - ✓ Implement software changes for instantaneous $v_{\oplus}$
  - ✓ Weather data for 2023 ready
  - ✓ Determine energy bins
    - Zenith angle dependence not understood
    - differential maps?

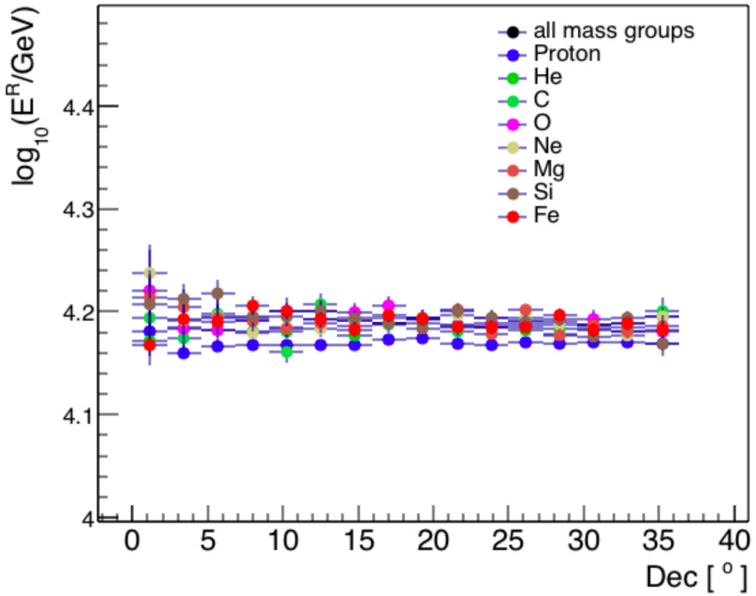
- Update on IceCube / HAWC analysis (shortly after HAWC paper)
- Composition/Rigidity-dependence of anisotropy *(with U. Michoacán)*
  - Same-energy/different-mass
  - Same-rigidity/different-energy

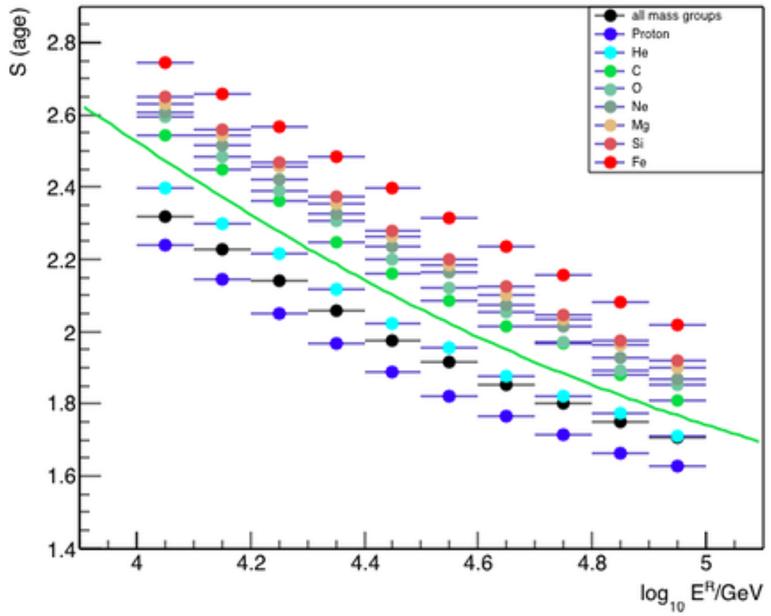
- Spectral anisotropy (energy spectrum) *(Jorge Antonio Morales)*

- Time modulation of sidereal anisotropy

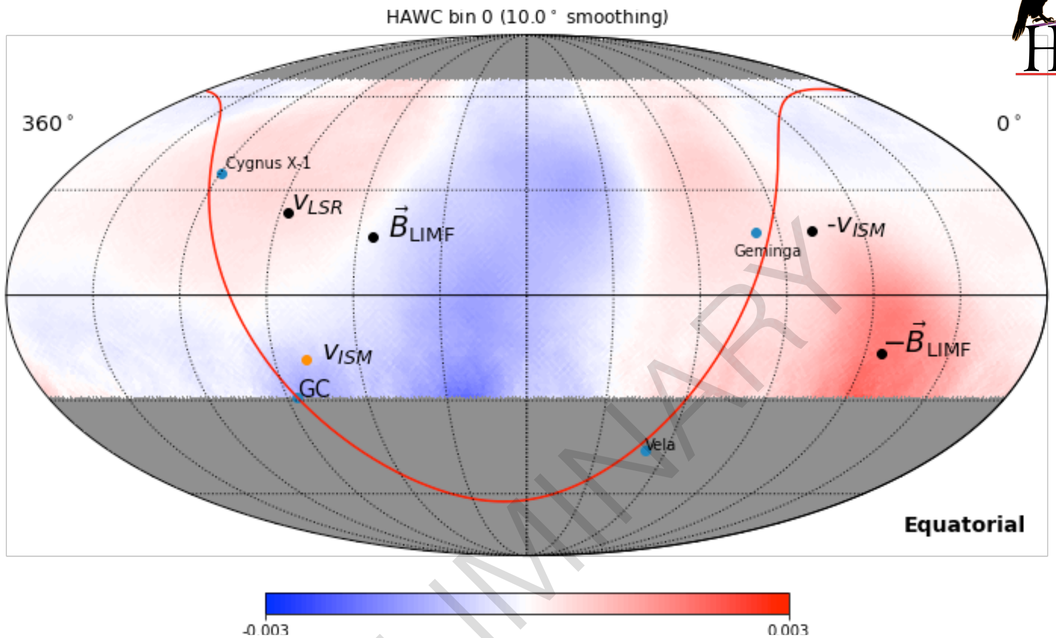
Composition

PASS5 simulations

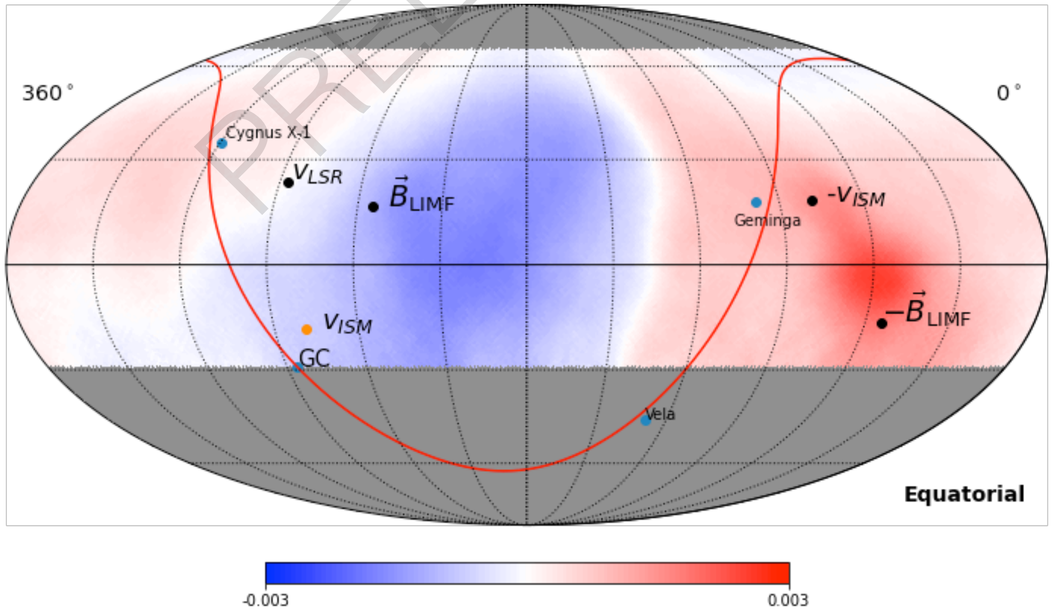




Light

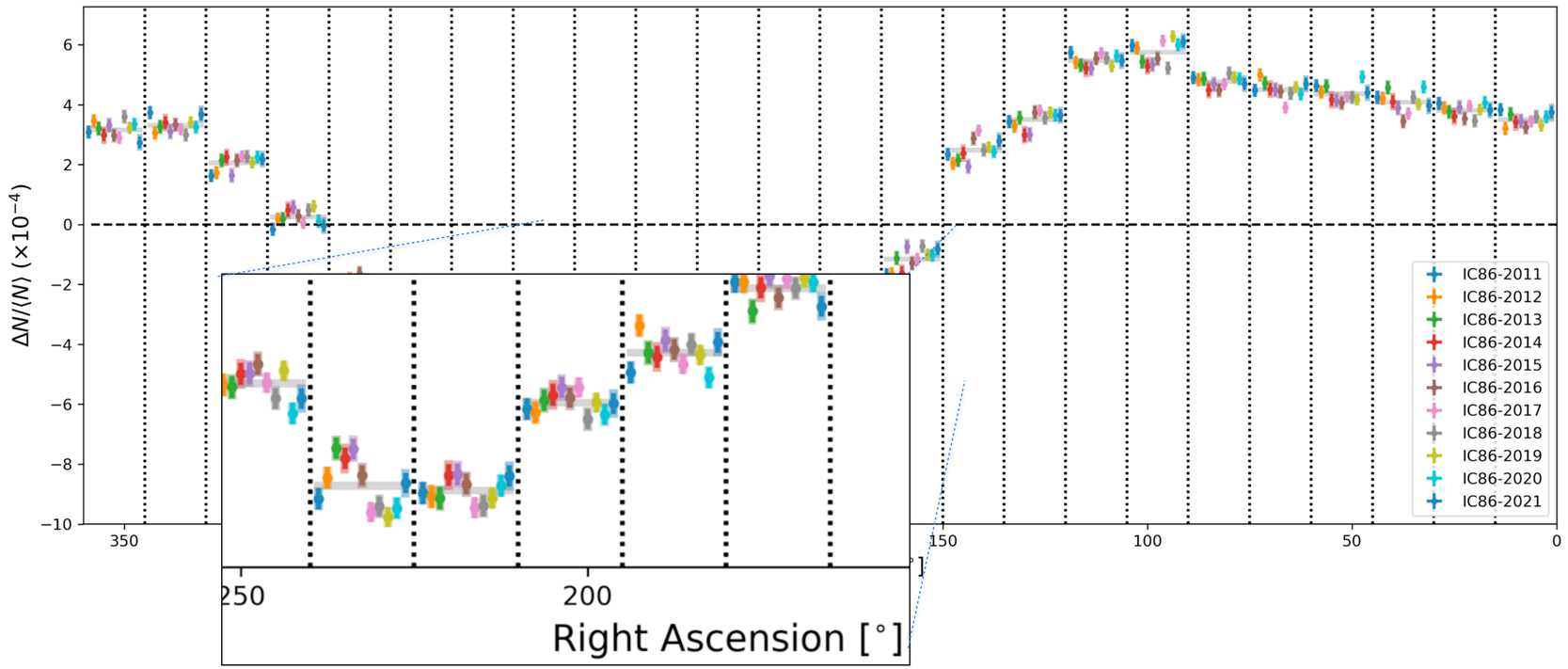


Heavy



https://indico.cern.ch/event/1082486/contributions/4878736/

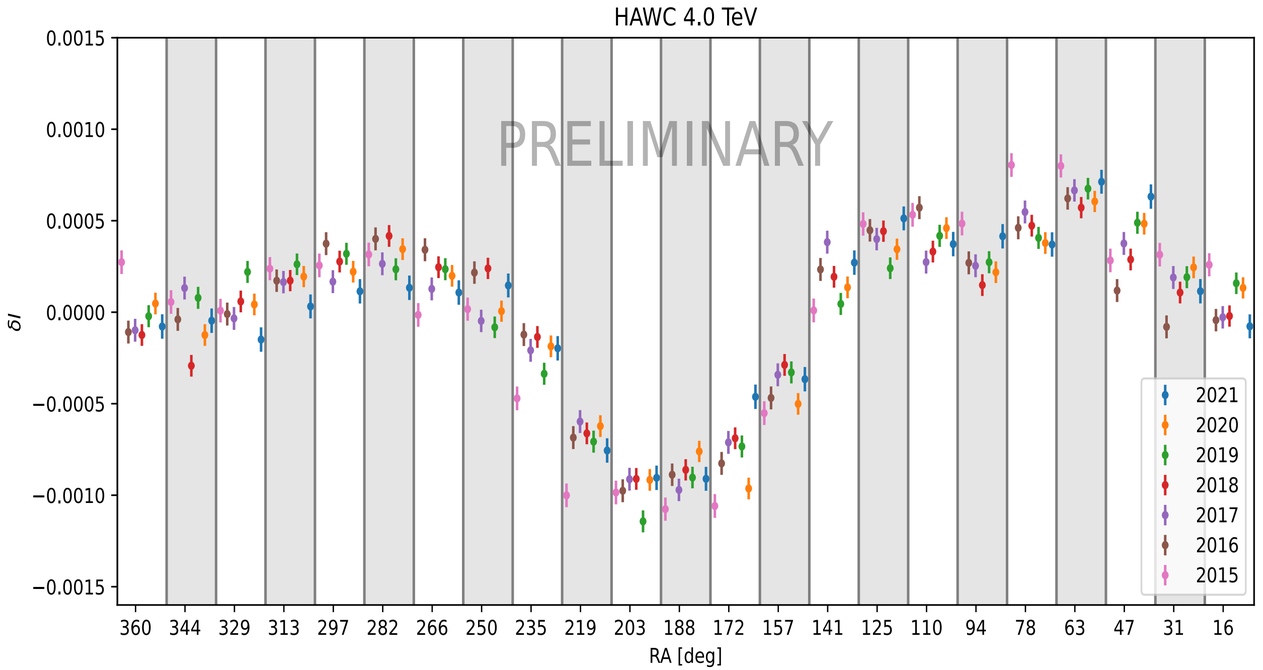
Possible time-variability in 11-year cycle

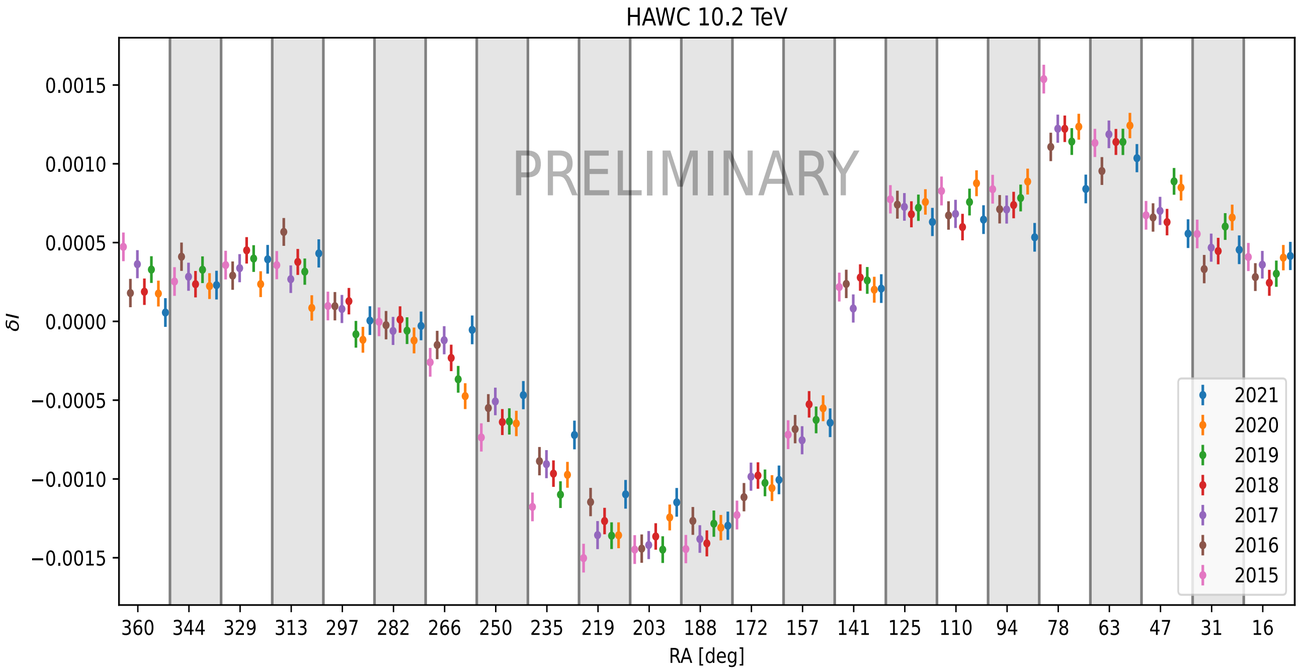


IceCube: Year to year variations in small angular-scale features appear to be larger than statistical+systematic uncertainty

Possible time-variability in 11-year cycle

Similar patterns observed by HAWC*





Determine the significance per pixel in 2D:

$$\chi_i^2 = \frac{\left(\delta_{i,y_0} - \delta_{i,y_j}\right)^2}{\sigma_{i,y_0}^2 + \sigma_{i,y_j}^2} \qquad \sigma_i = \left(\frac{D}{B}\right)^2 \frac{1}{D}$$

*many systematics to address

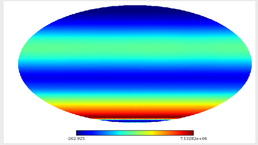
Thank you

HAWC

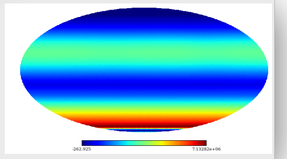
Backup

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.

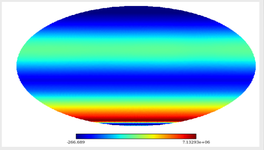


Time-scrambling: $(\theta, \phi, t) \rightarrow (\alpha, \delta)$

$(\theta, \phi, t') \rightarrow (\alpha', \delta')$

Direct integration: $\langle N(\alpha, \delta) \rangle = \int dt \int d\Omega A(ha, \delta) \cdot R(t) \cdot \epsilon(ha, \alpha, t)$

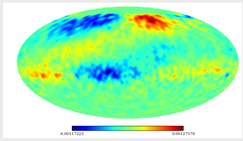
3 Correlate pixels to increase sensitivity to different angular scales



Relative Intensity

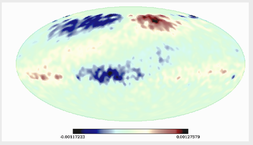
$$\delta I(\alpha, \delta)_i = \frac{N(\alpha, \delta)_i - \langle N \rangle(\alpha, \delta)_i}{\langle N \rangle(\alpha, \delta)_i}$$

4 Calculate relative differences between data and reference with significance.



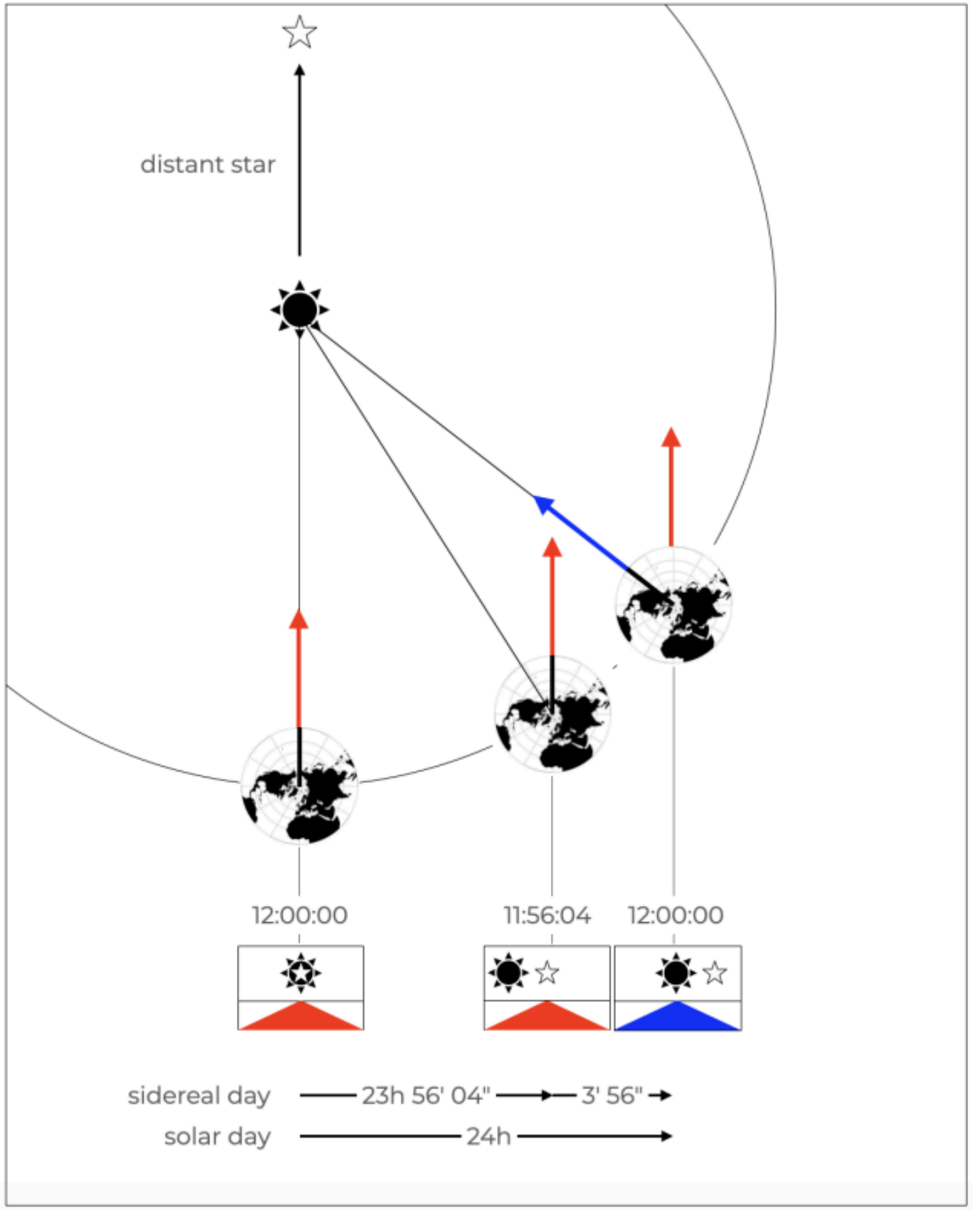
$$s_i = \sqrt{2}\left\{ N_i \log\left[\frac{1+\alpha}{\alpha}\left(\frac{N_i}{N_i + N_o}\right)\right] + N_o \log\left[(1+\alpha)\left(\frac{N_o}{N_i + N_o}\right)\right]\right\}^{1/2}$$

5 Calculate statistical significance for each pixel



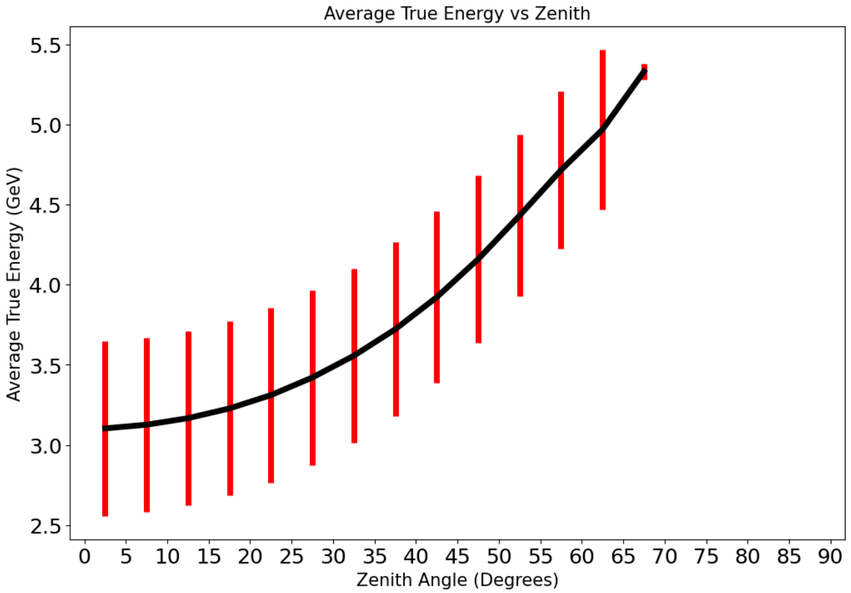
Solar and Sidereal Frames

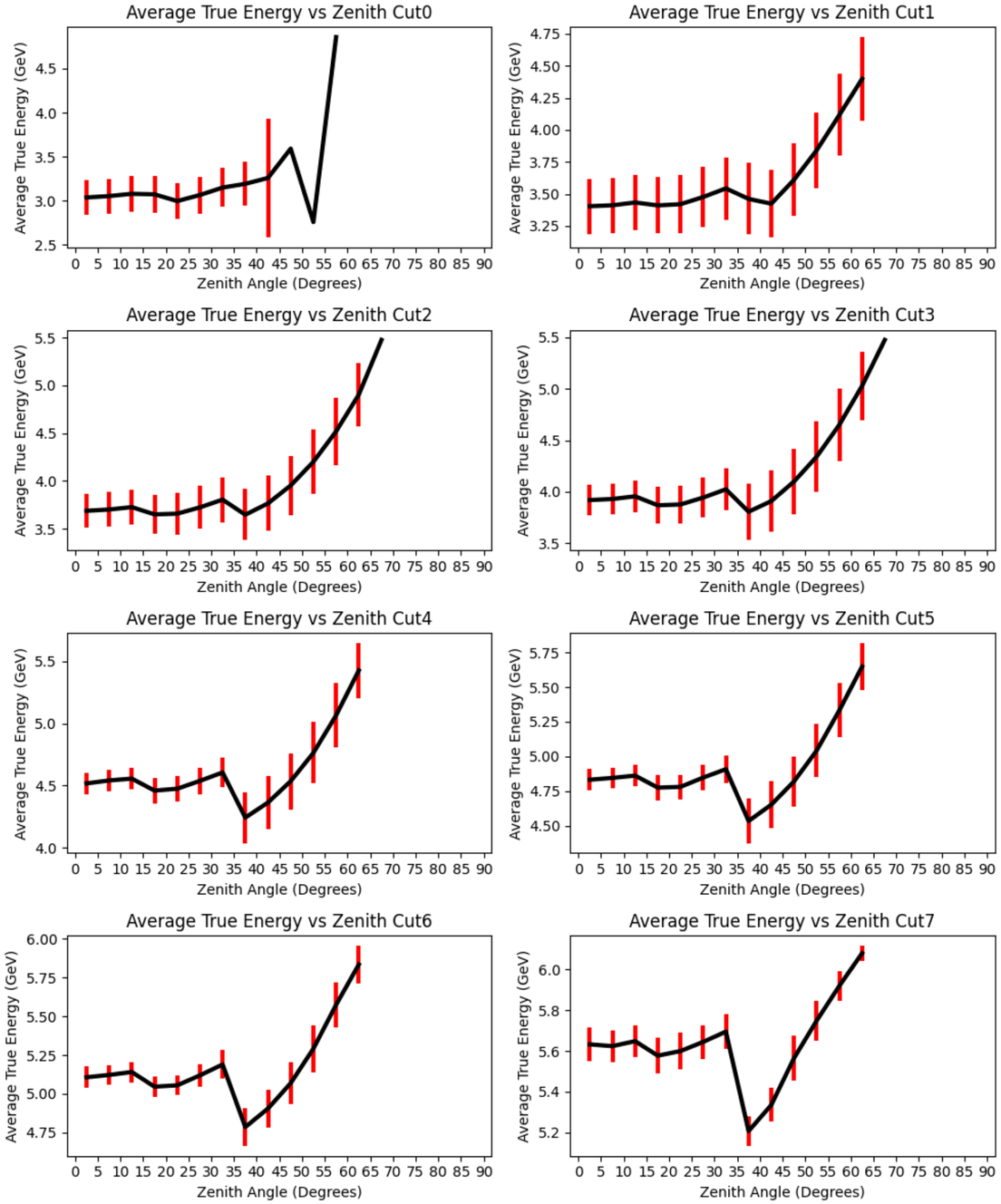
- Sidereal time with respect to solar time.
- Time starts at 12:00:00 on the local meridian with the Sun at the same location as a distant star.
- As the Earth revolves around the Sun, the sidereal time zero point stays fixed in the celestial sky while the solar time's reference point moves away.
- They will not coincide at 12:00 again for one solar year.



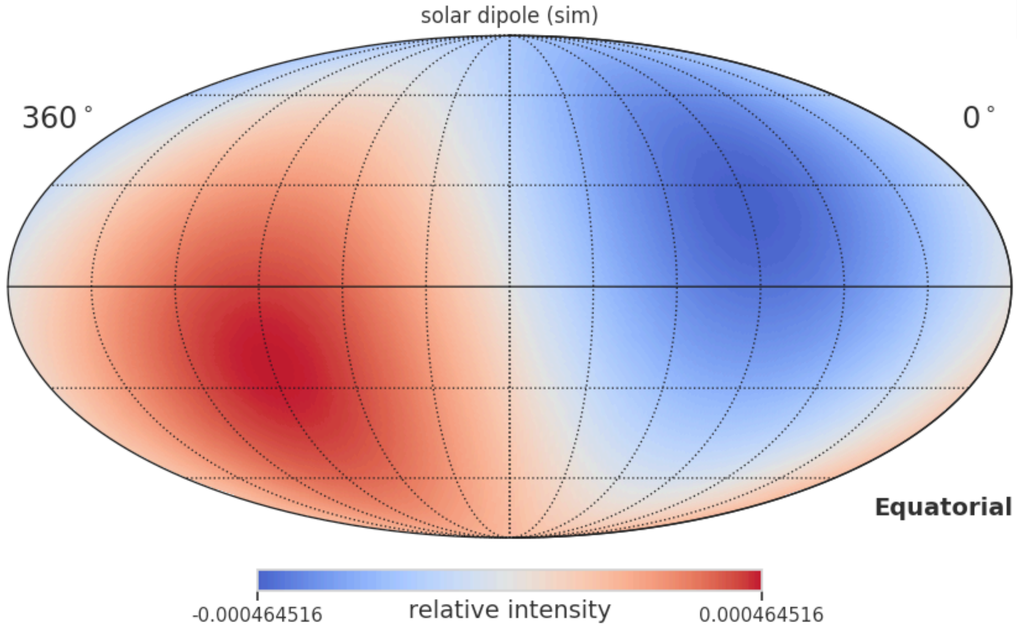
Energy Bins

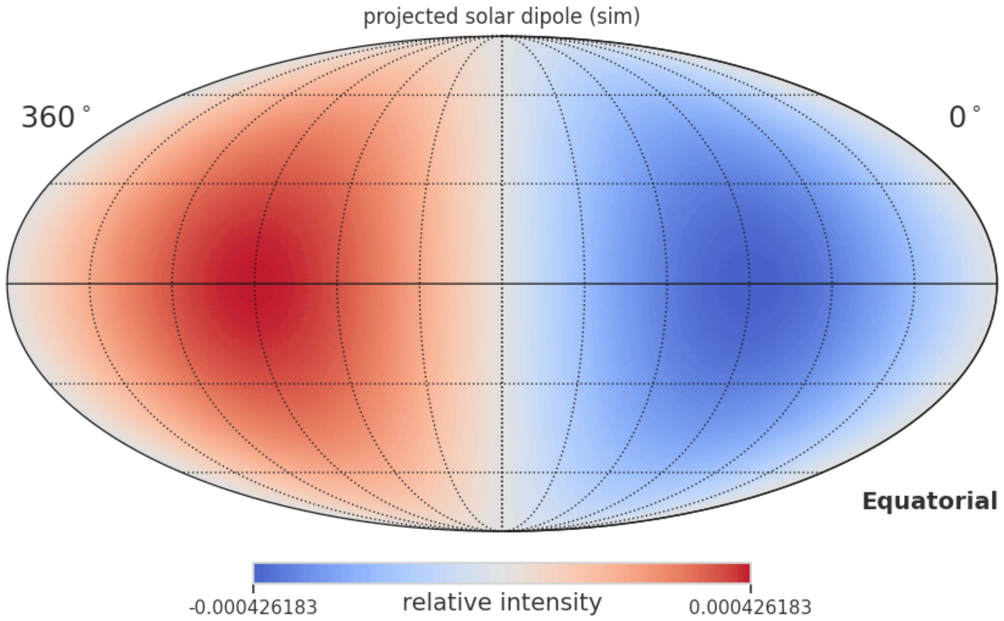
Odd behavior beyond 30º?



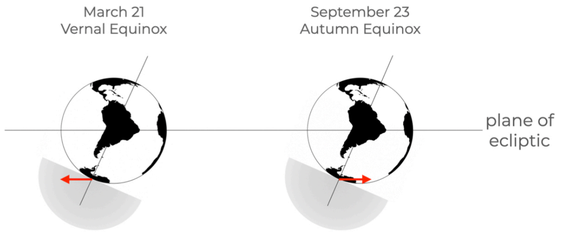


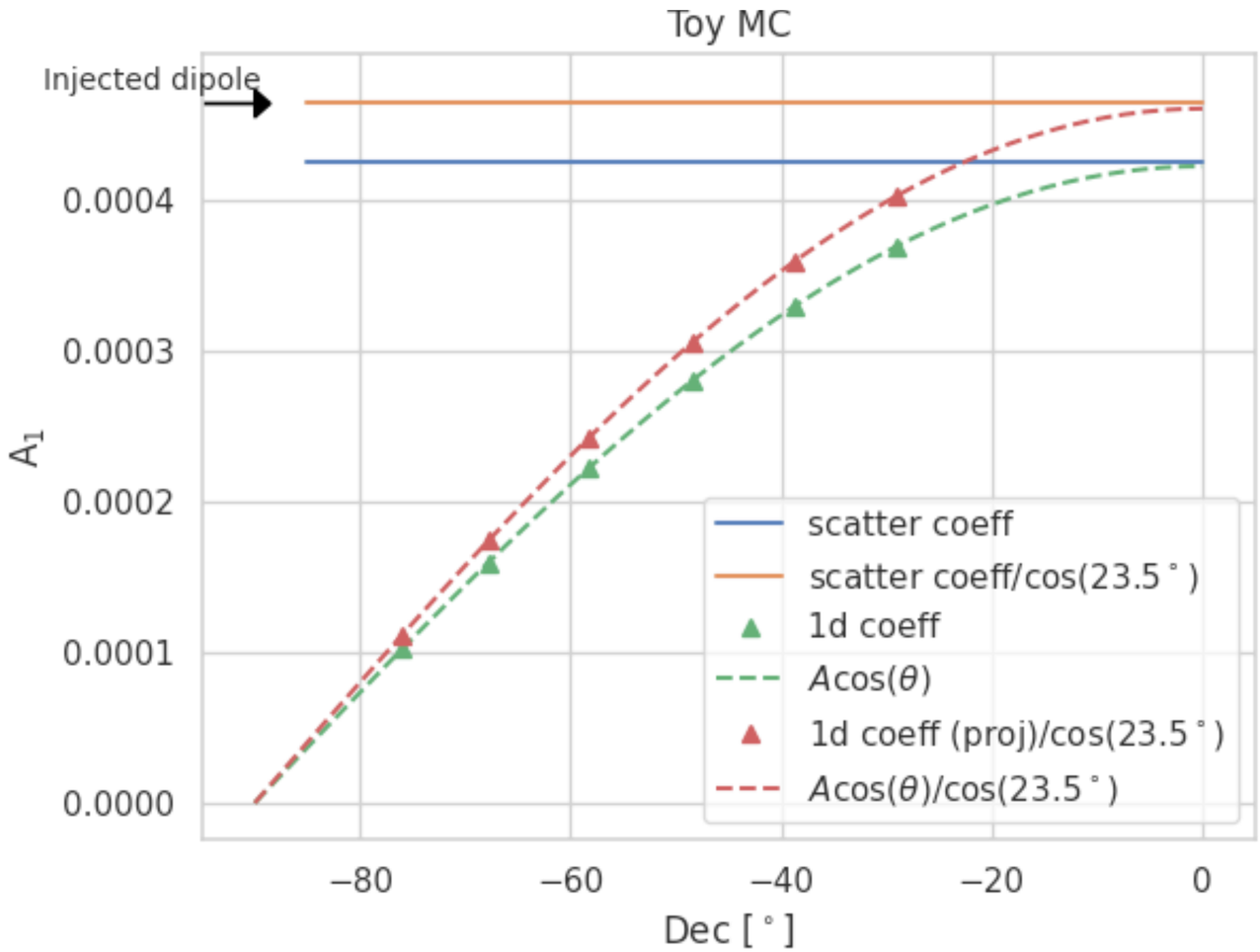
Equatorial Projection Bias





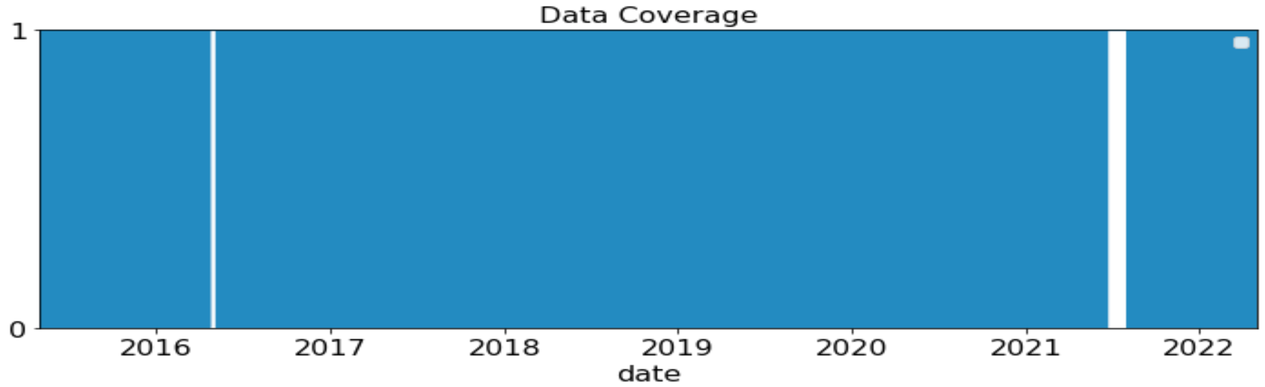
Correct for projection bias (dipole tilt is known) 23.5047°

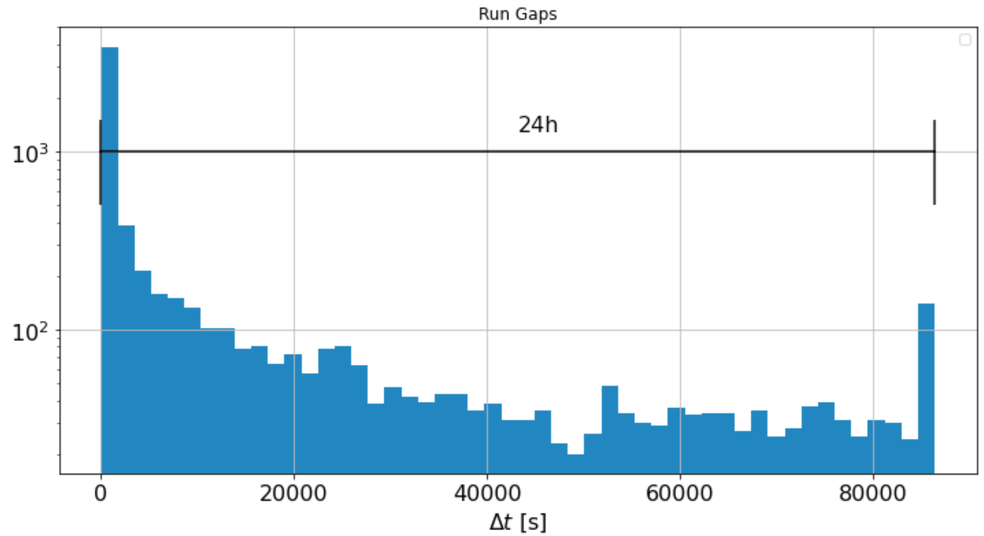


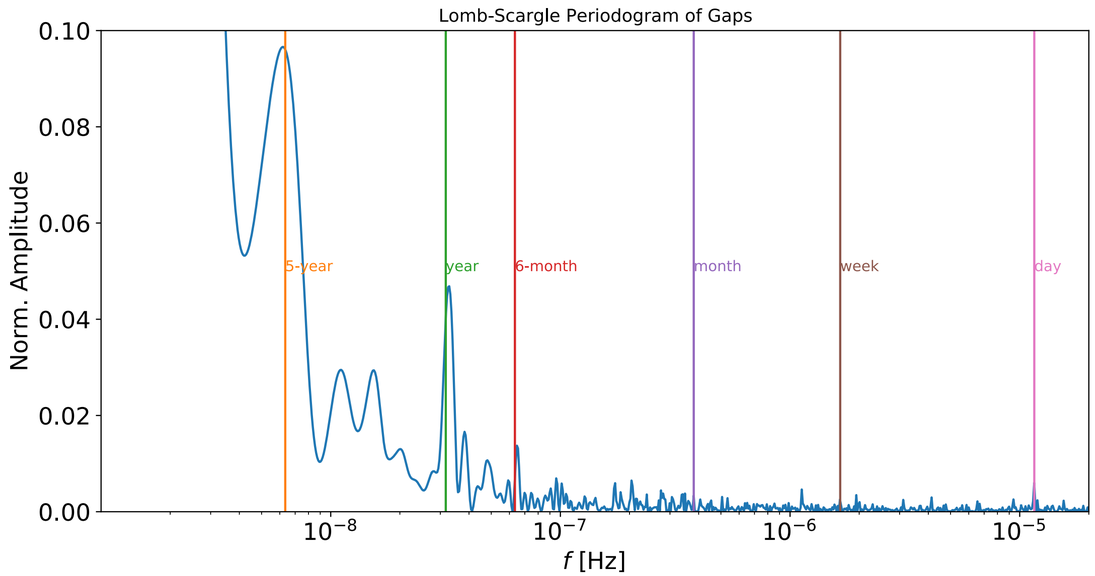


Data Coverage

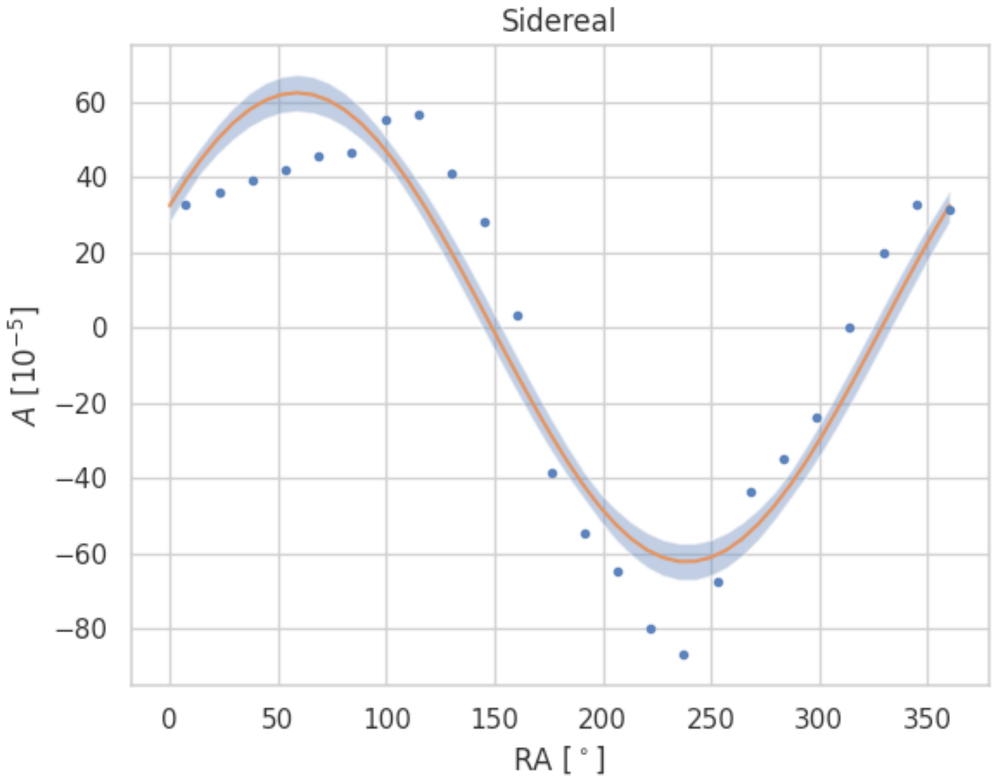
- 90% of gaps are under 15h
- Median gap size is 866s
- Large systematic gaps can produce biases from solar Compton-Getting dipole interference

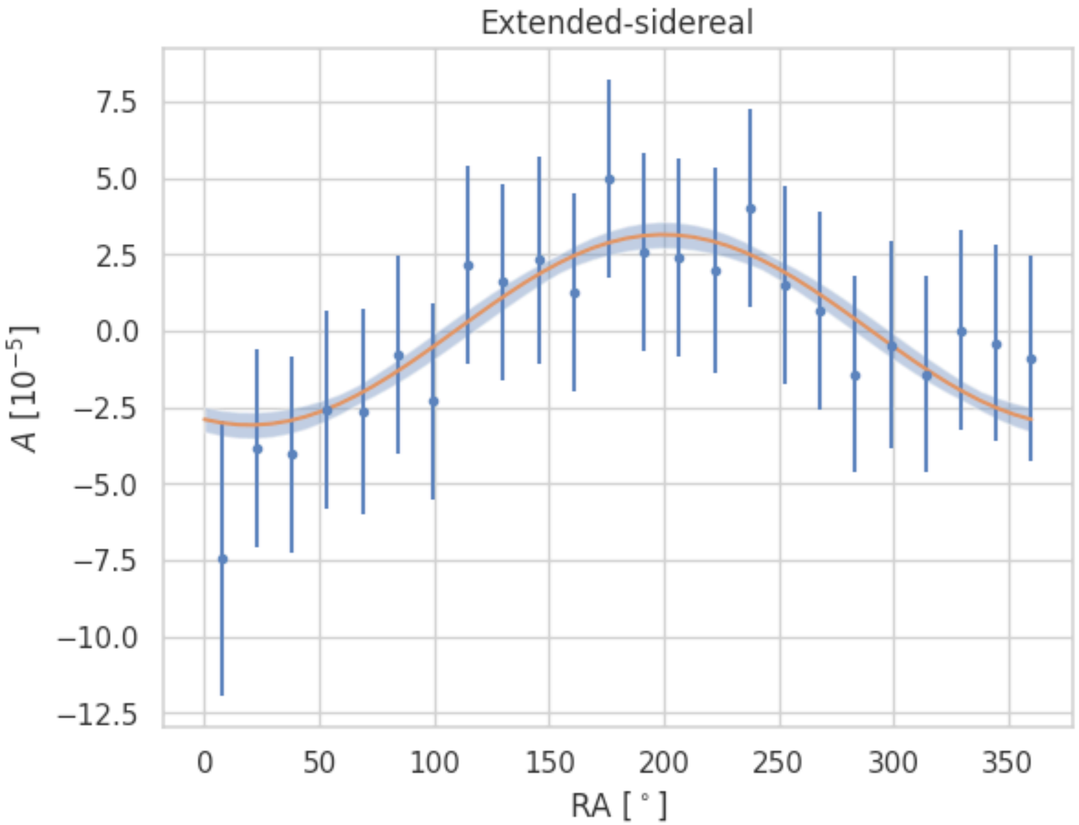






The 1-year and 6-moth periodicity likely corresponds to the storm season which appears to peak in early Spring and early Fall





A = 1.21e-05
phi = 15.89

A = 3.47e-05
phi = 192.34 deg

Non-physical reference frames

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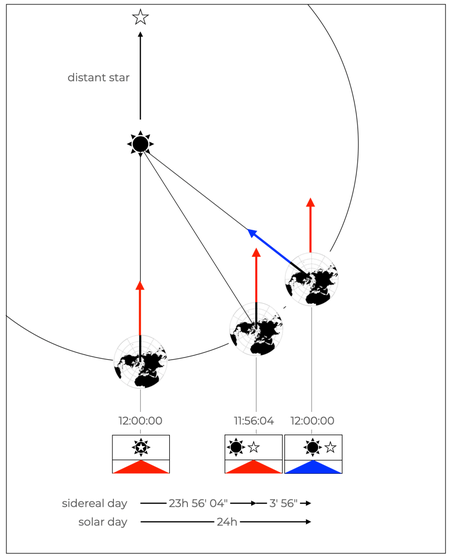
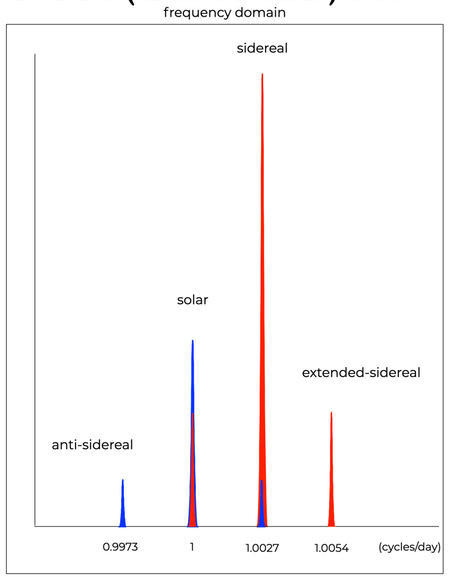
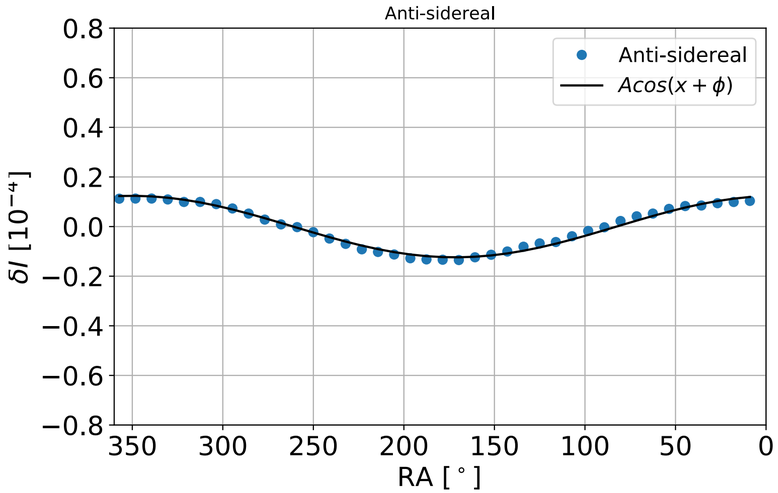
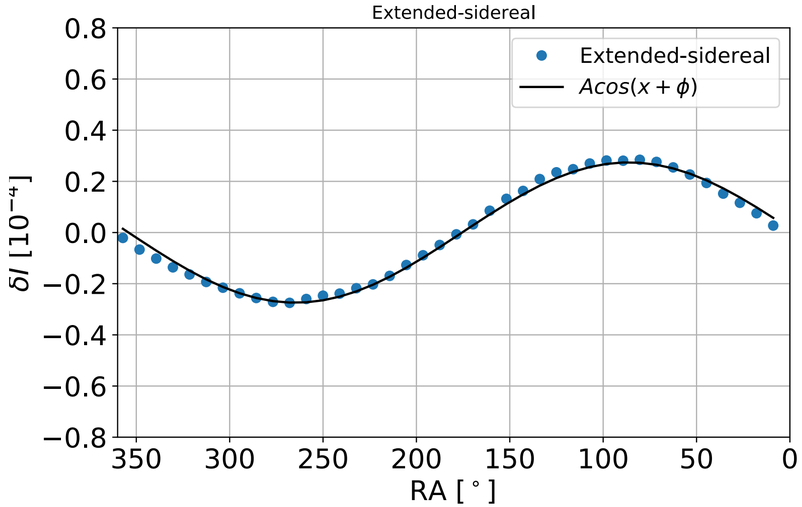
The mutual interference between modulations in the solar and sidereal frames produces frequency side-bands around the respective peaks in the frequency domain.

The side-bands overlap with the sidereal and solar frequencies, respectively, producing a deformation of the CRA.







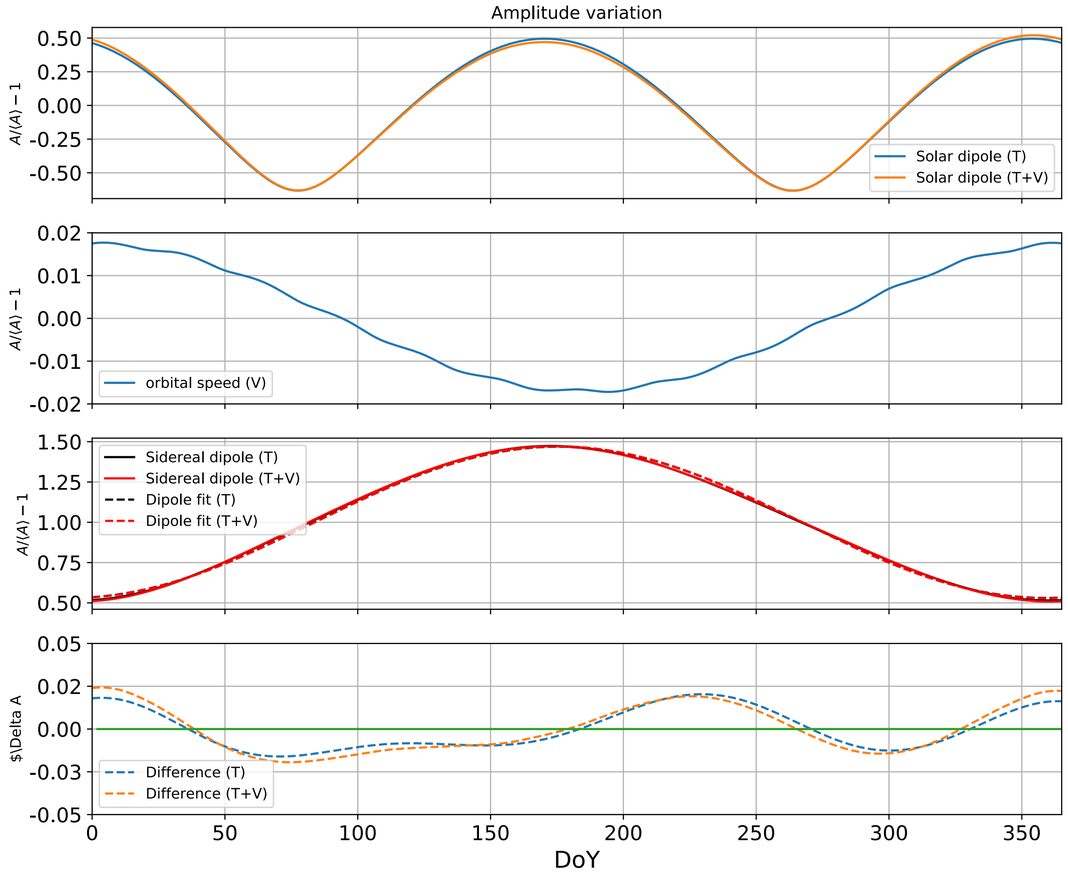


A toy simulation shows that, even with full coverage over 365 days, the solar and sidereal dipoles don't cancel out in their respective frames, resulting in a residual anti-sidereal (left), and extended-sidereal (right) distributions

An additional asymmetry in the amplitude of the solar dipole results the time dependence of the orbital velocity, primarily due to the eccentricity of Earth's orbit and to a lesser extent, from the orbit around the Earth-Moon center of mass.

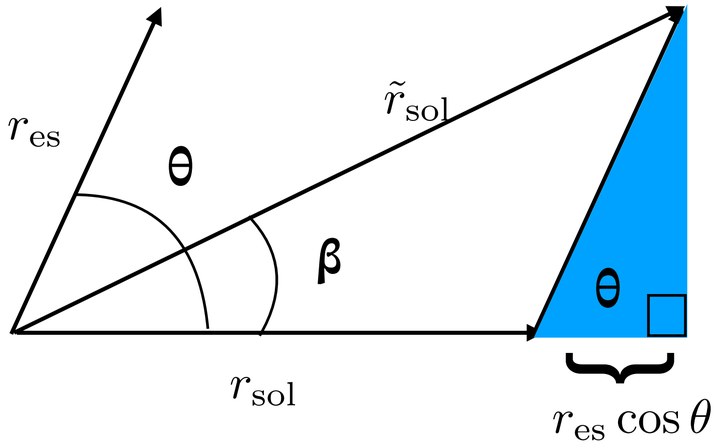
The rate of this change in amplitude is also not symmetric because of the eccentricity of Earth's orbit.

Díaz-Vélez, *et al* 2021 PoS(ICRC2021)085



A dipole fit to the amplitude modulation over one year results in a residual signal due to the asymmetric nature of Earth's orbit.

Using the phase offset of the solar dipole fit



As a result of the eccentricity of Earth's orbit, even with a completely stable detector with no dead time or variability in acceptance, we can expect a dipole with amplitude of order 10^{-5} in the extended-sidereal frame and a slightly smaller one in the anti-sidereal frame.

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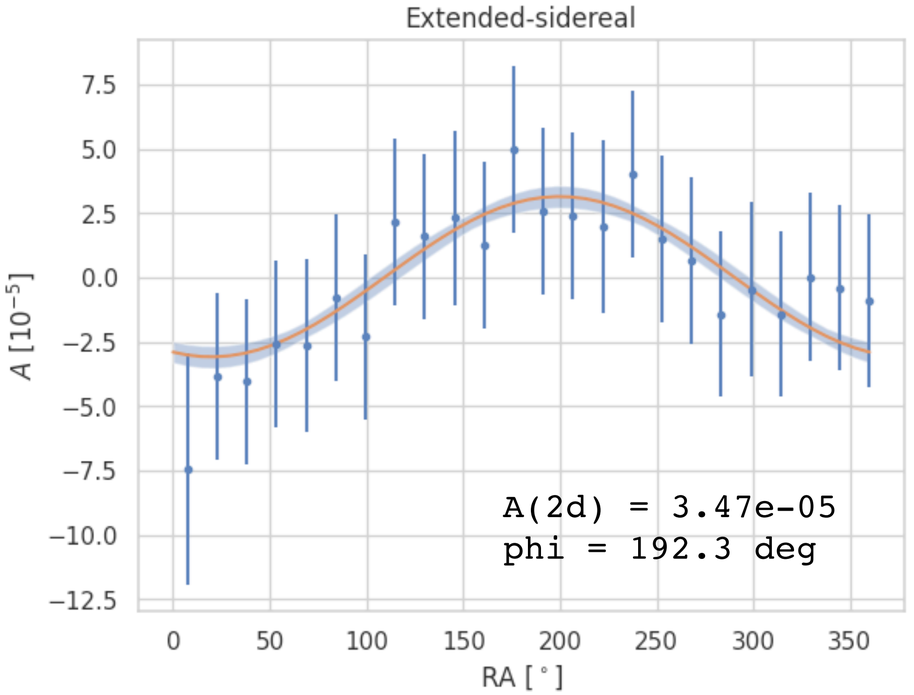
$$\beta = \phi - 270^{\circ}$$

$$\theta = sin^{-1}\left(\frac{\tilde{r}_{sol}}{r_{es}} \sin\beta\right)$$

$$r_{sol} = \tilde{r}_{sol} \cos\beta \pm r_{es} \cos\theta$$



The direction of the dipole should be at 270°. The measured offset indicates the presence of a perpendicular component from the spurious solar dipole.