Atmospheric Pressure Corrections In Cosmic Ray Anisotropy Measurement With HAWC

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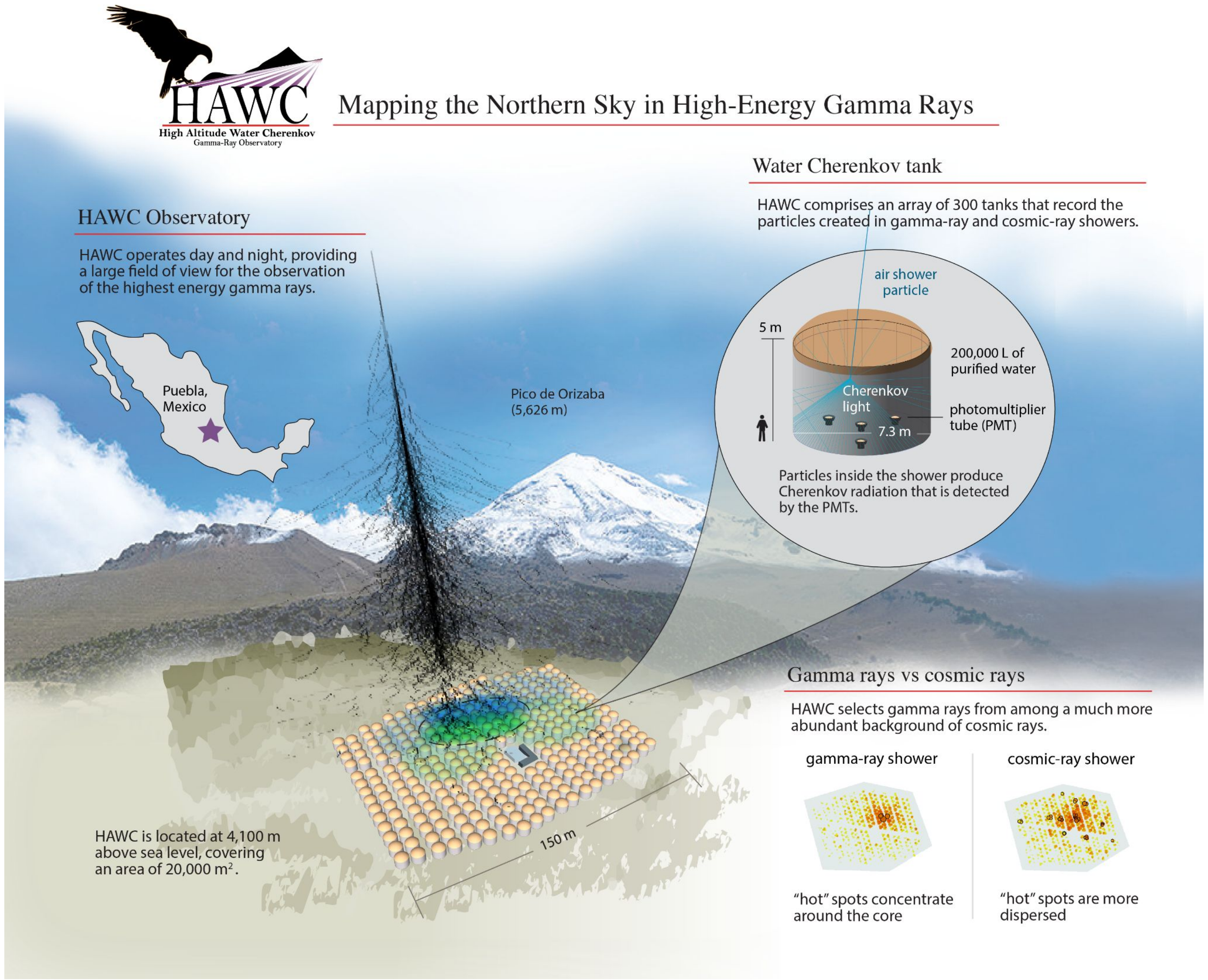
Overview

- **Background:** HAWC Observatory, Cosmic Ray Anisotropy, Pressure Dependent Factors.
- **Research Methods:** Correlation Coefficients, Weight Factor, Correcting Rates
- **Results and Conclusion**
- **Current work in progress**

Background

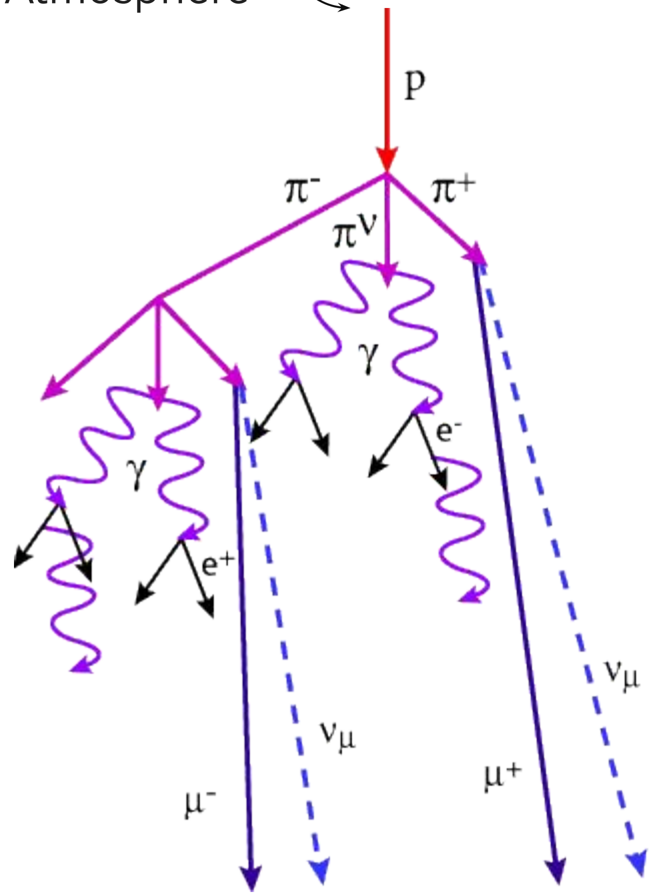
High Altitude Water Cherenkov Observatory (HAWC)



Credit: HAWC/WIPAC

WIPAC Wisconsin IceCube Particle Astrophysics Center
The University of Wisconsin Madison

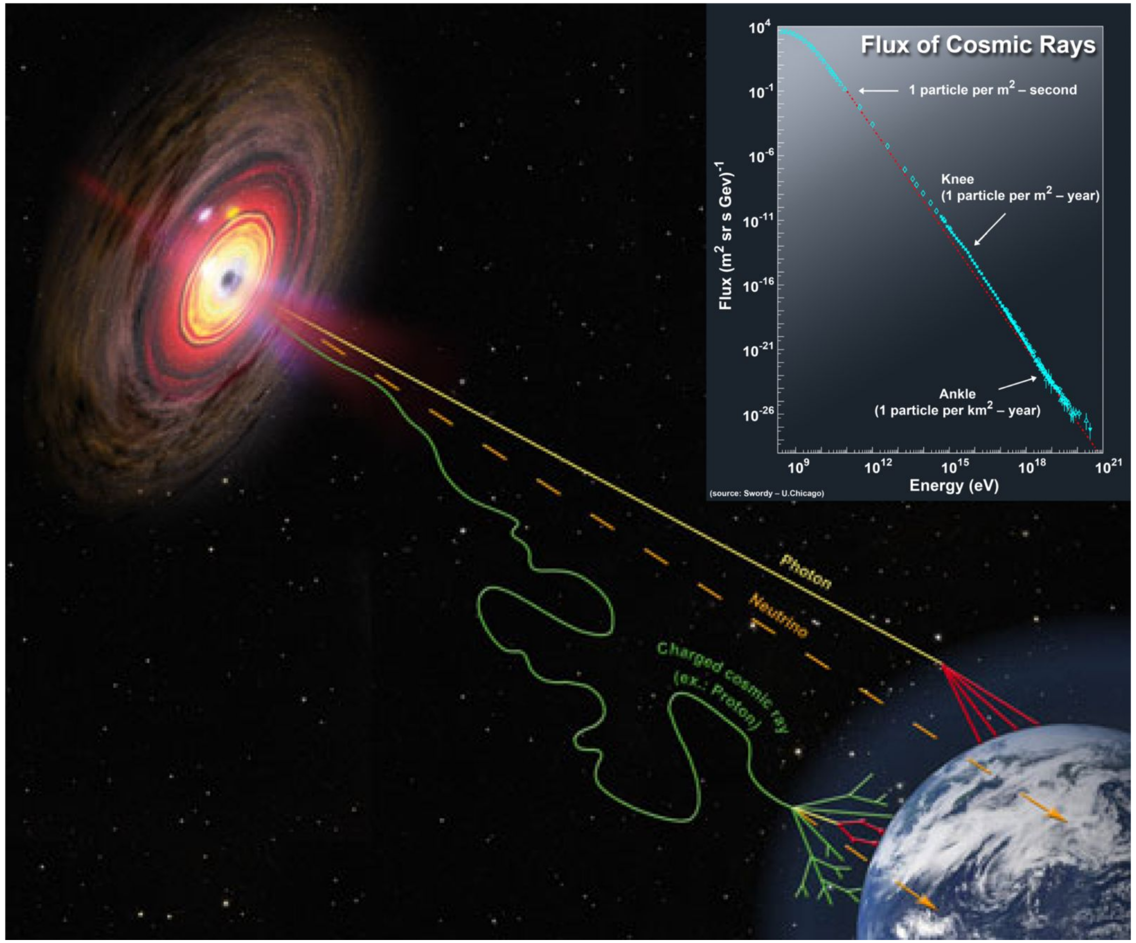
Proton entering the Earth's Atmosphere



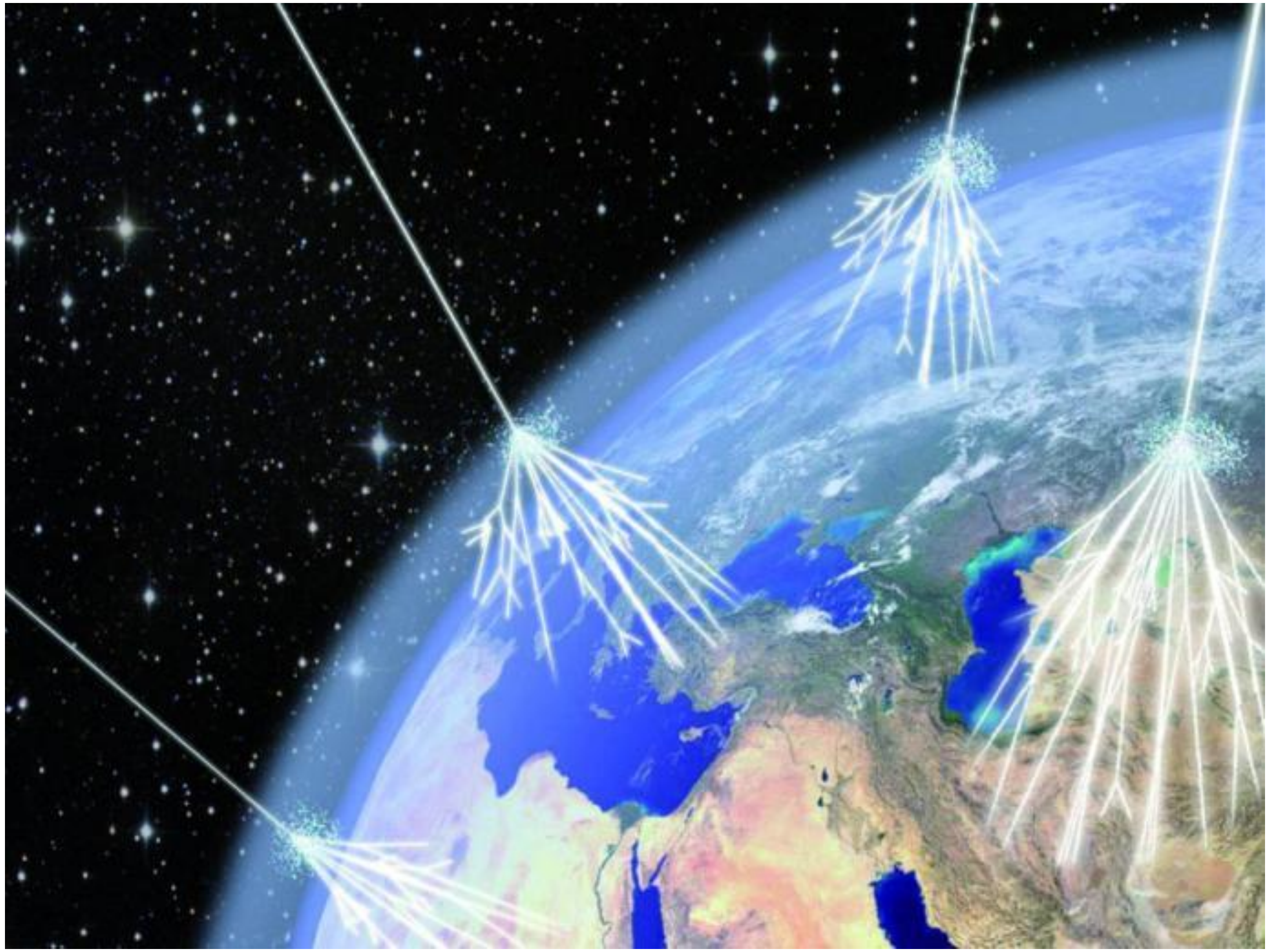
Cosmic ray air shower

Credit: HAWC

Path of cosmic rays compared to neutrinos and photons



Credit: HAP/A. Chantelauze



Credit: UChicago

Theoretical models predict an anisotropy in the cosmic ray arrival direction which is time-independent

"raw anisotropy"

Factors adding to the raw anisotropy

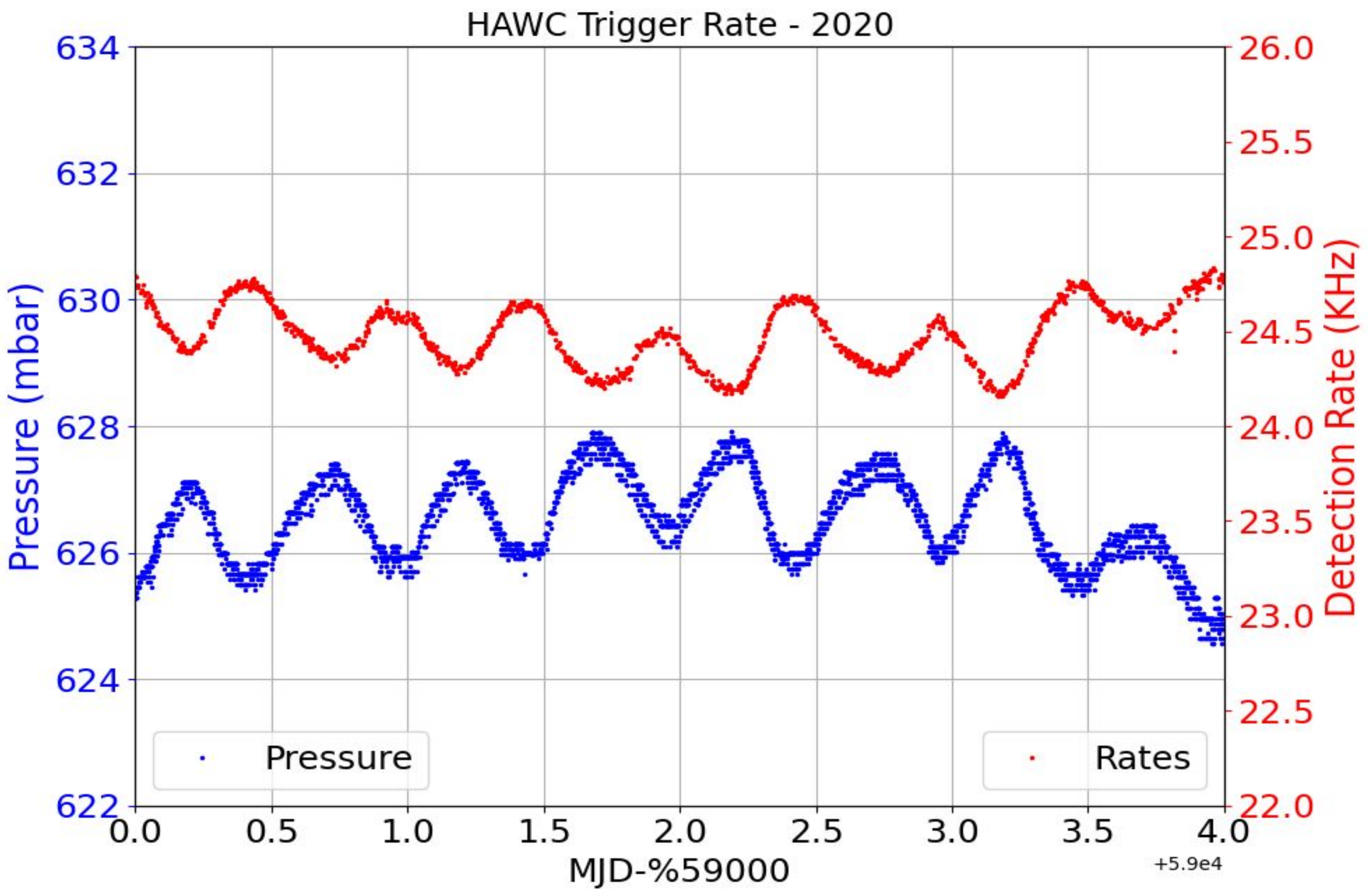
1. **Compton Getting Effect:** Difference between the solar and sidereal dipoles caused by the Earth's motion through space

2. **Daily Pressure Variations:** Temperature and pressure dependence
   - Increase in pressure reduces detection rates (atmospheric shielding)
   - Decrease in surface pressure enhances detection rates
     - Lunar Gravitational Tides
     - Thermally driven tides
     - Weather (Seasonal Variations)

3. **Possible Unknown Factors**

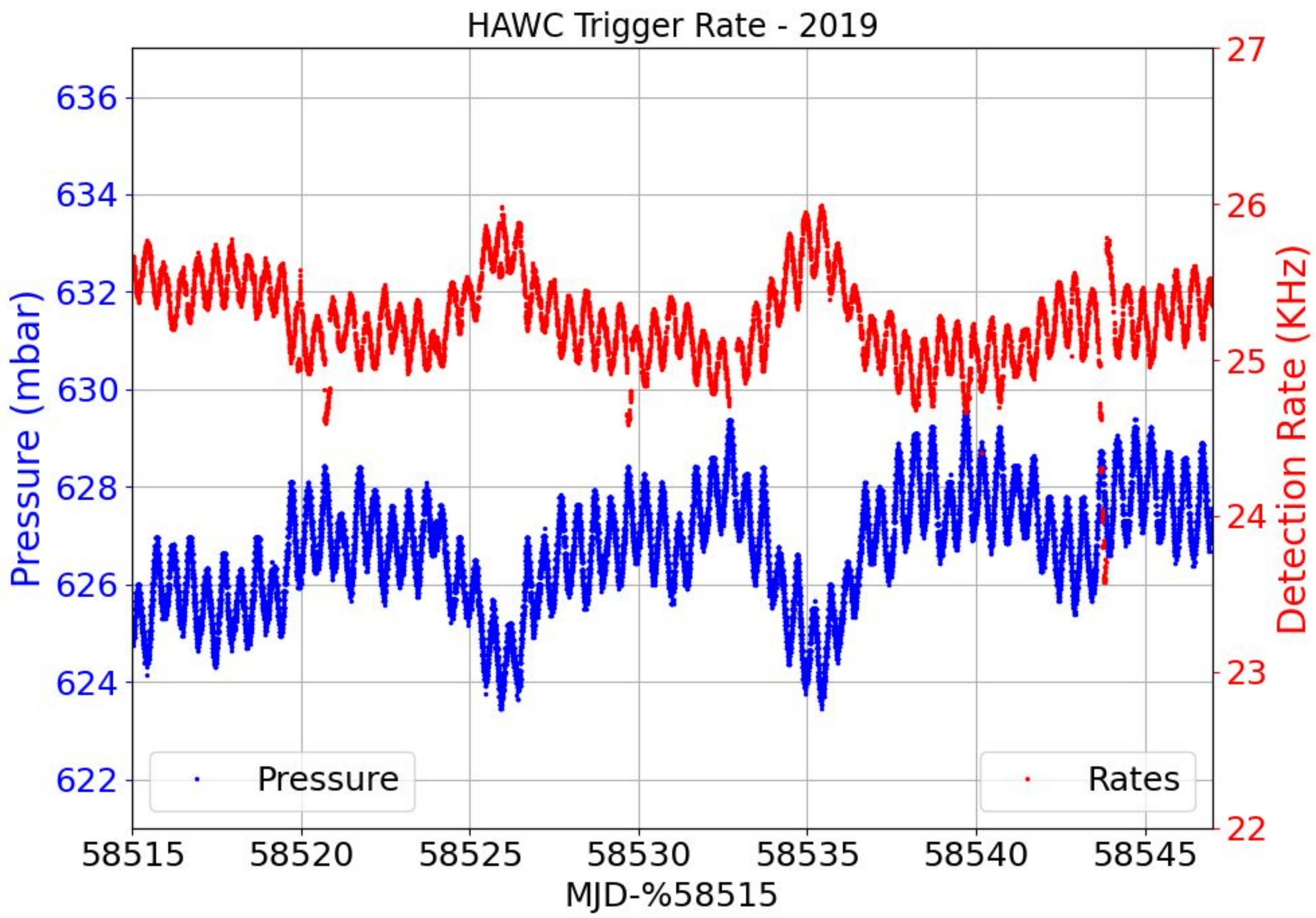
raw anisotropy + time dependent factors = "overall anisotropy" detected by HAWC

Daily Pressure Variations



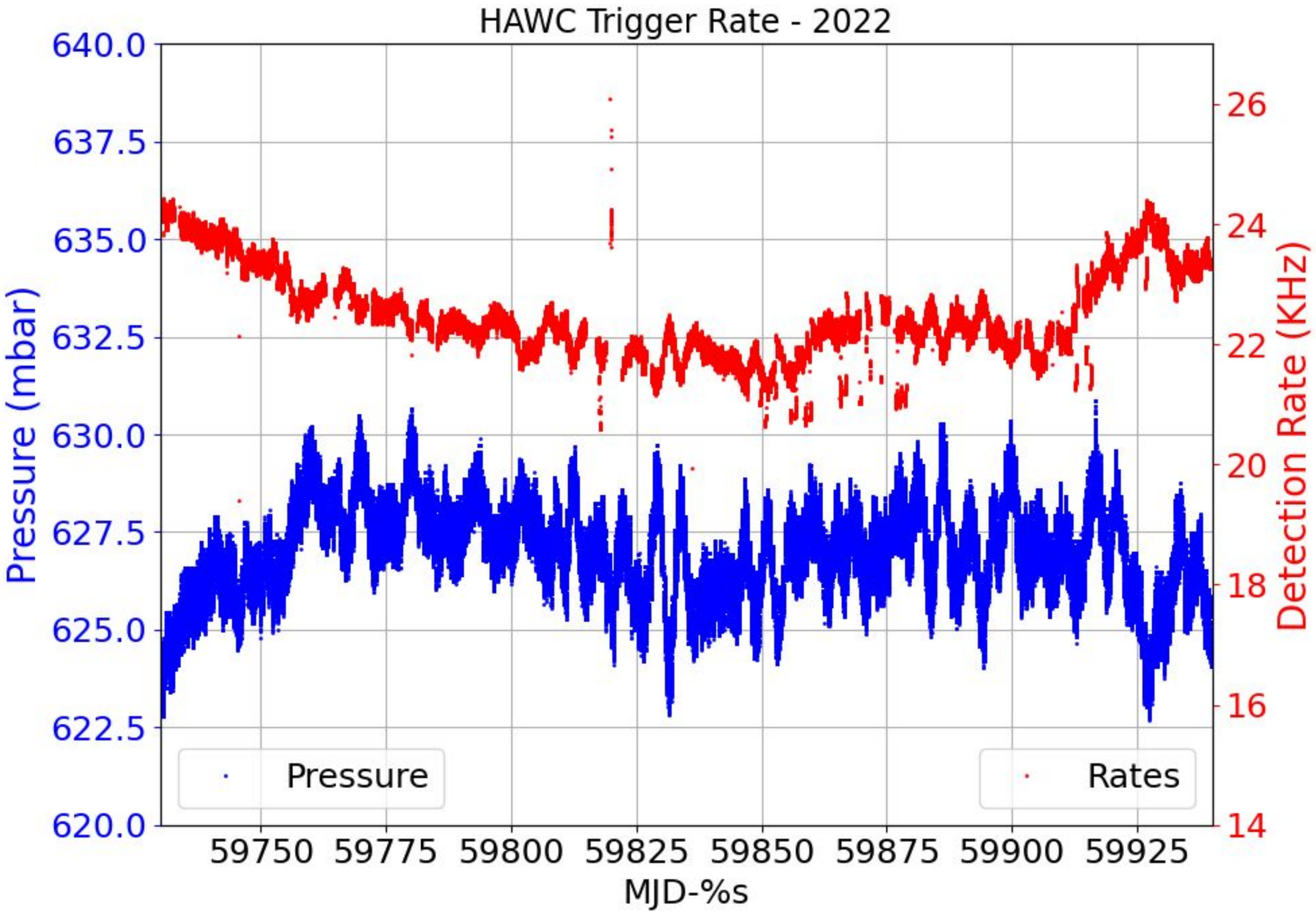
Pressure and Rates for 4 days in the year 2020

Monthly Pressure Variations



Pressure and Rates for 32 days (about a month) in the year 2019

Seasonal Variations



Pressure and Rates for a 6 months in the year 2022

The goal of my research

- Analyze how the Pressure Variations contribute to the overall anisotropy
- Find the correlation coefficient
- Minimize the pressure dependence from rates

Overall Goal: Identify the sources of cosmic rays and the mechanism by which they are accelerated and injected into the ISM.

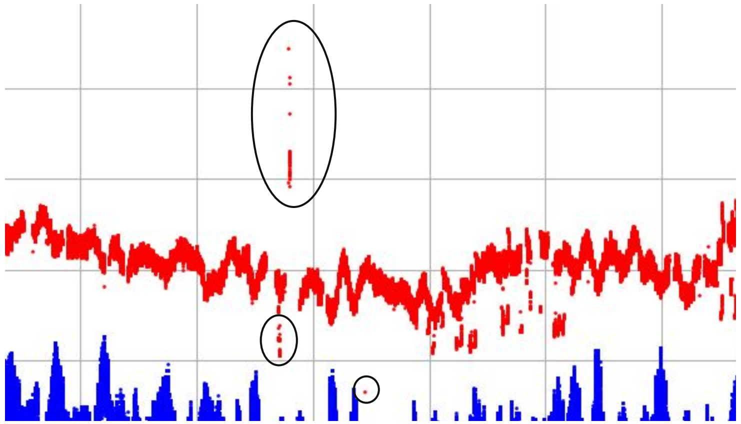
Research Methods

- Detection rates and pressure data from the years 2015 - 2023
- Rates data is collected every 4 minutes
- Pressure data is collected every minute

Calculate the correlation coefficient. Let's call this β → Calculate the weight factor. Let's call this ω → Apply this weight factor to the rates data to minimize the pressure dependent factors.

Step 1: Cleaning and Binning the data

Problem: How to get rid of some values from the rates data that go haywire because of instrumental errors?



Solution: Exclude the rates data that is 5σ away from the mean for each year.

Problem: How to get the same timestamp for rates and pressure data so as to properly match and work with them?

Solution:

1. Bin the pressure and rate timestamps in 8 minute increments.
2. Apply this binning to the rates and pressure data simultaneously to get the same timestamp for each bin.

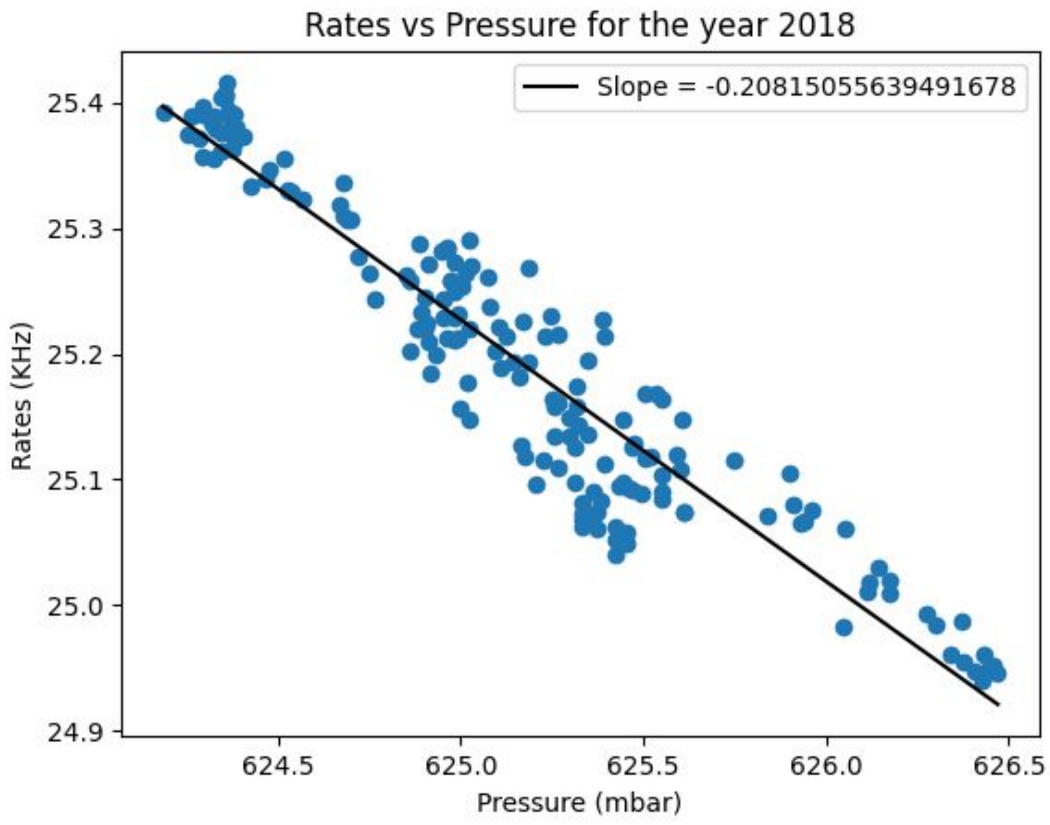
Step 2: Calculating the correlation coefficient

β = slope of the line of best fit when rates are plotted as a function of pressure

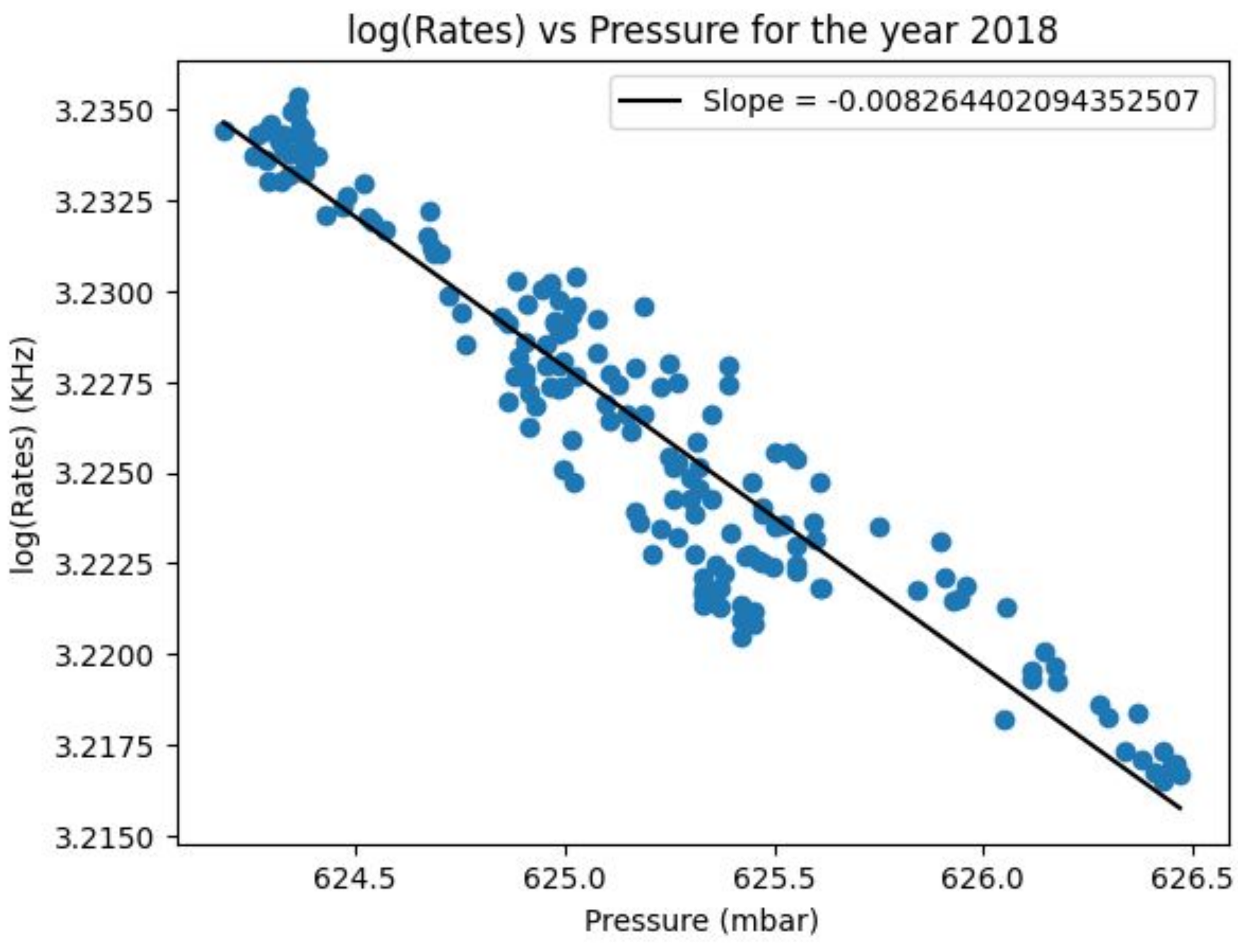
Two methods to get β:

1. Linear correlation
2. Exponential correlation

Linear: $\Delta R = \beta_{lin} \Delta P$



Rates as a function of pressure for a random day in the year 2018

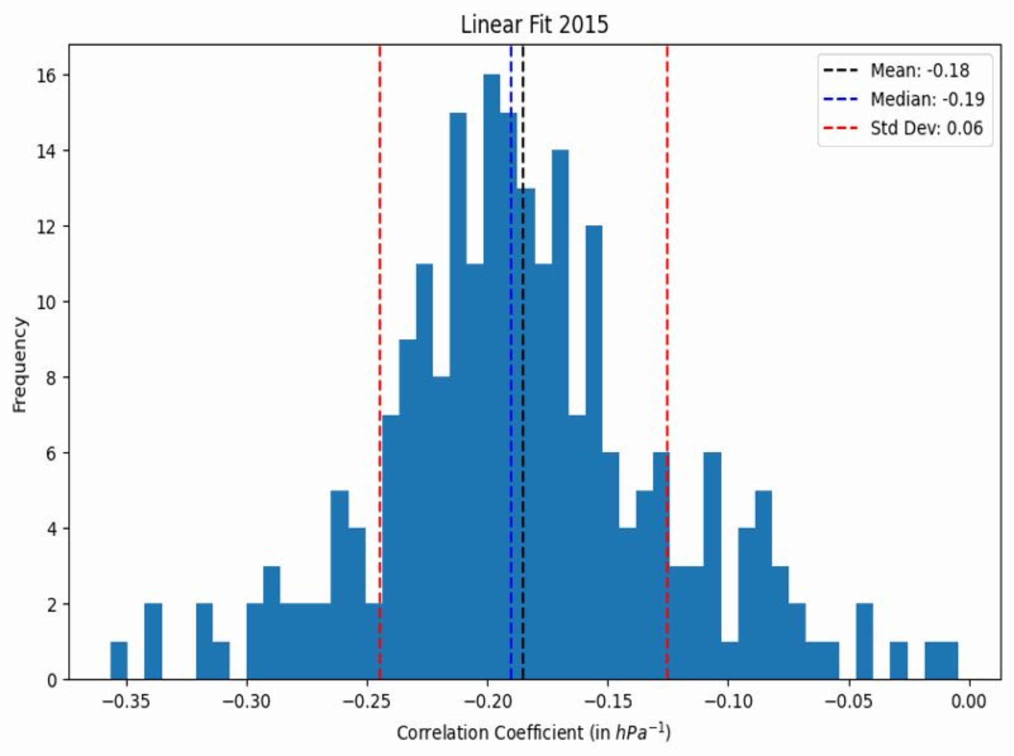


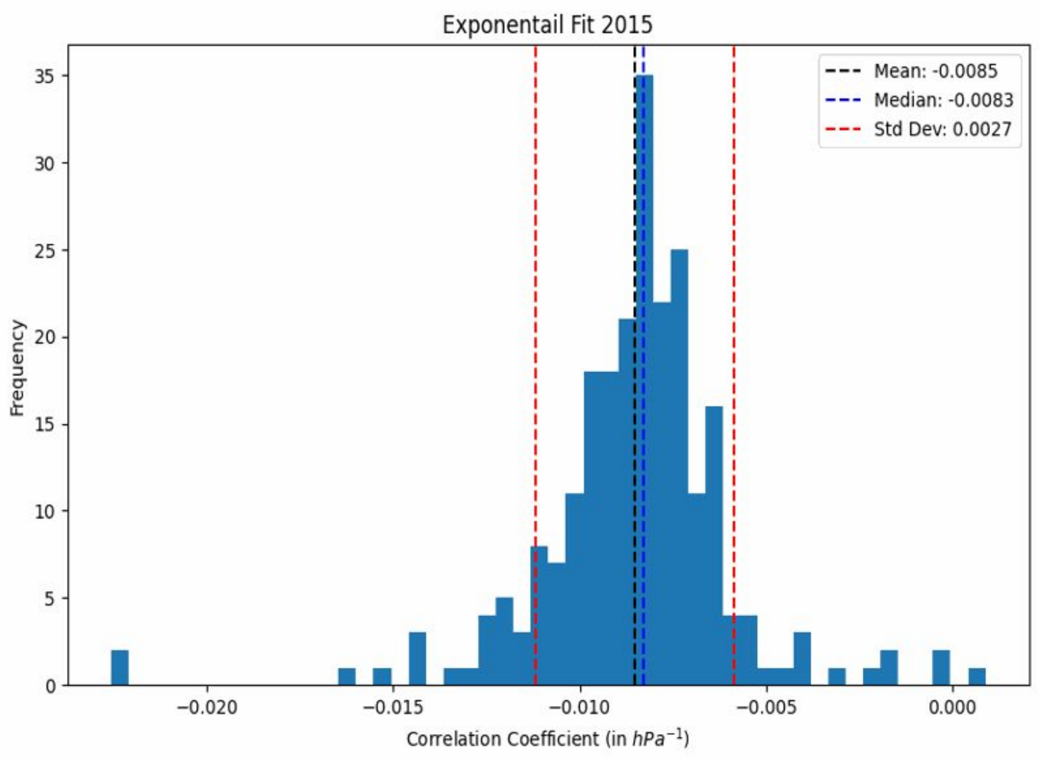
Log(Rates) as a function of pressure for a random day in the year 2018

Exponential: $\Delta\{\ln R\} = \beta_{exp}\Delta P$

- calculated this for each day of each year.

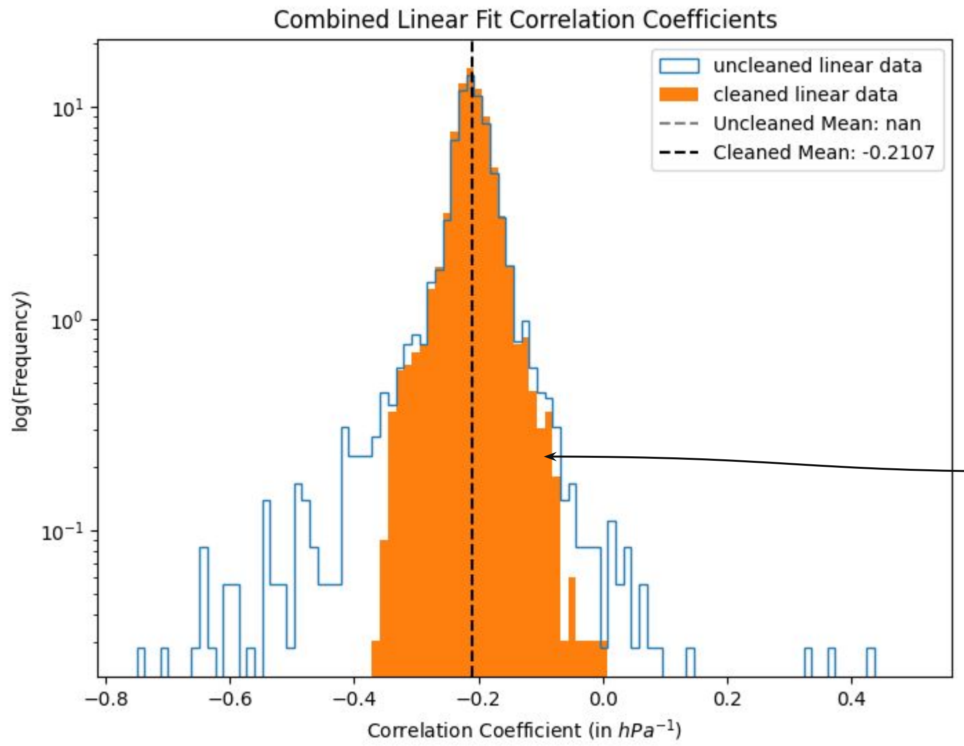
Step 3: Making β "time-independent"



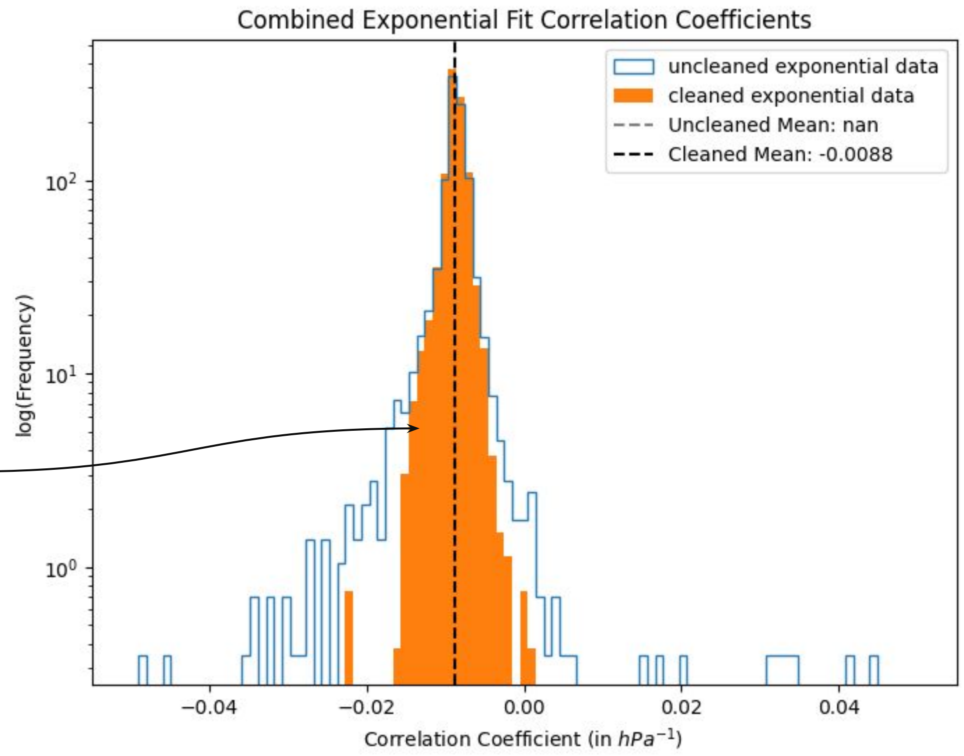


Gaussian Distribution of the linear and exponential correlation coefficients for each year

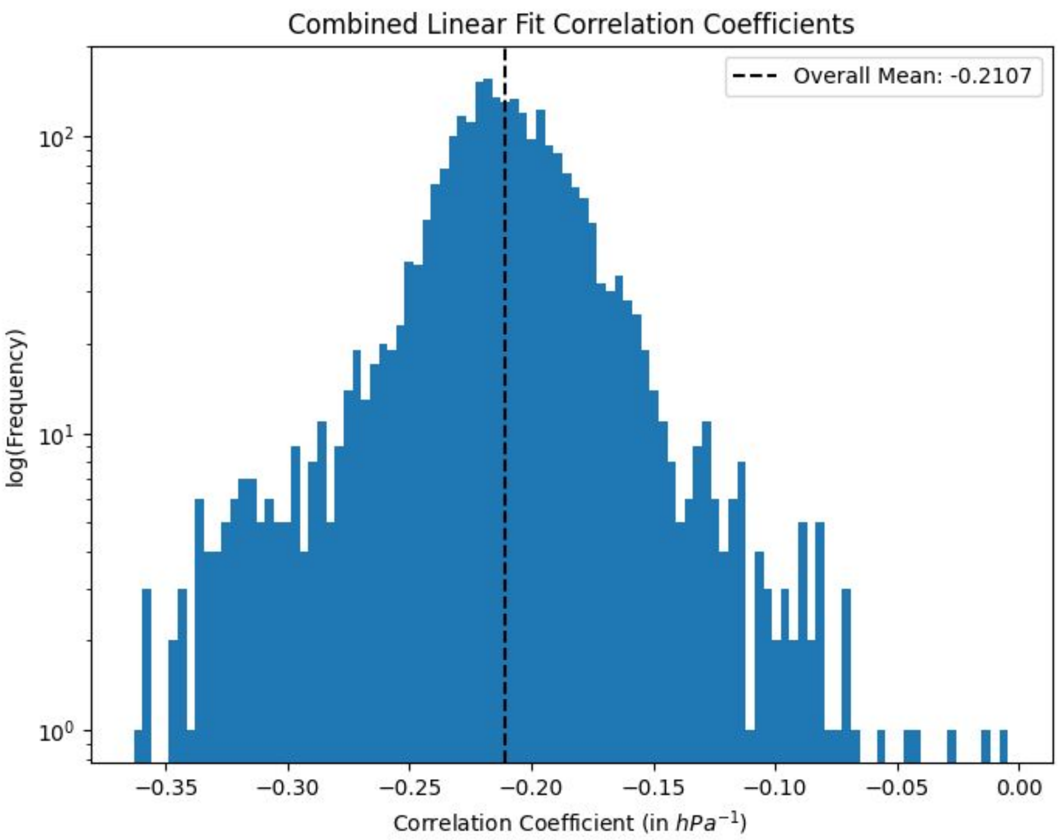
- Only considered the **β values 1σ away from the mean** for each year
- **Combined the cleaned data** from all the years into one **single histogram** (for linear and exponential, respectively)

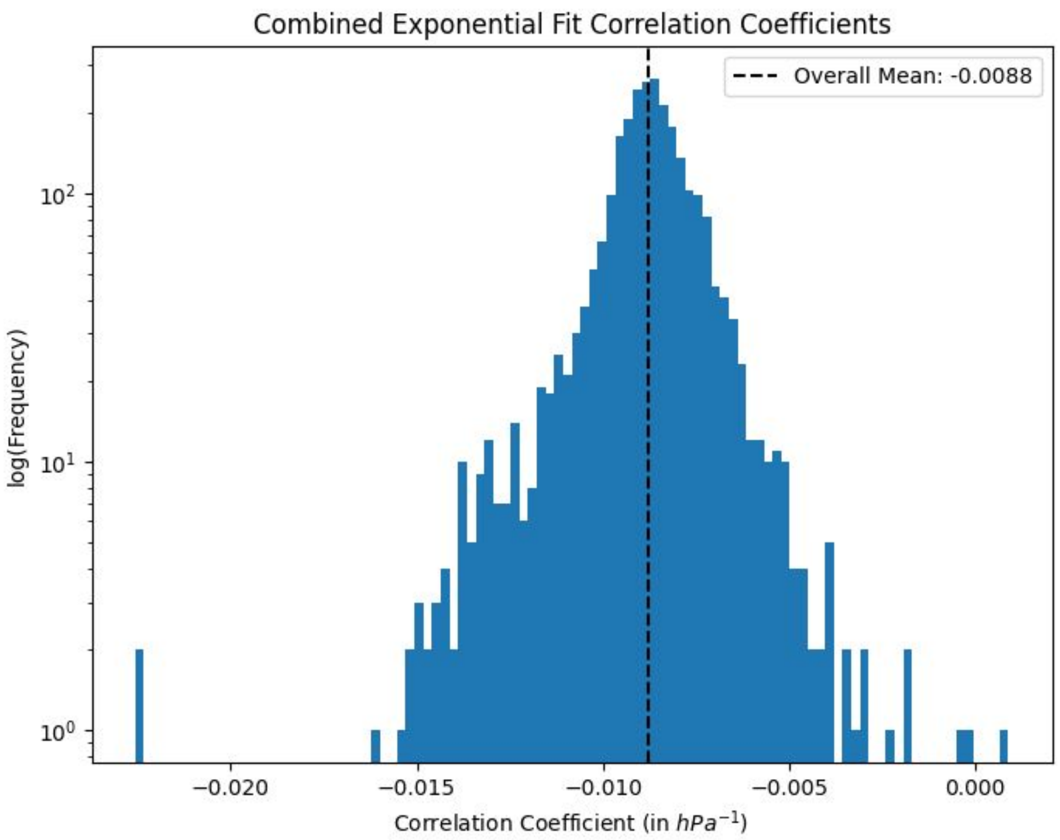


Cut gives us a more accurate value of the final β



Cut **eliminated** the detector anomalies.





The mean of these histograms give us the “time-independent” linear and exponential correlation coefficients.

Final β_{lin} = -0.2107 s hPa^{-1}
Final β_{exp} = -0.0088 hPa^{-1}

Step 4: Calculating the weight factor

Linear weight factor

$$\omega_{lin} = 1 + \frac{\beta_{lin}}{r_o}(p(t) - p_o)$$

Mean rate
for each
year in Hz

Mean Pressure
for each year
hPa

Exponential weight factor

$$\omega_{exp} = e^{\beta_{exp}(p(t) - p_o)}$$

Binned pressure
data for that
timestamp for
each year

Step 5: Correcting rates

Multiplying the weight factor with the binned rates data to get the corrected rates

Linear "corrected rates"

$$rcorr_{lin}(t) = r(t) \times \omega_{lin}$$

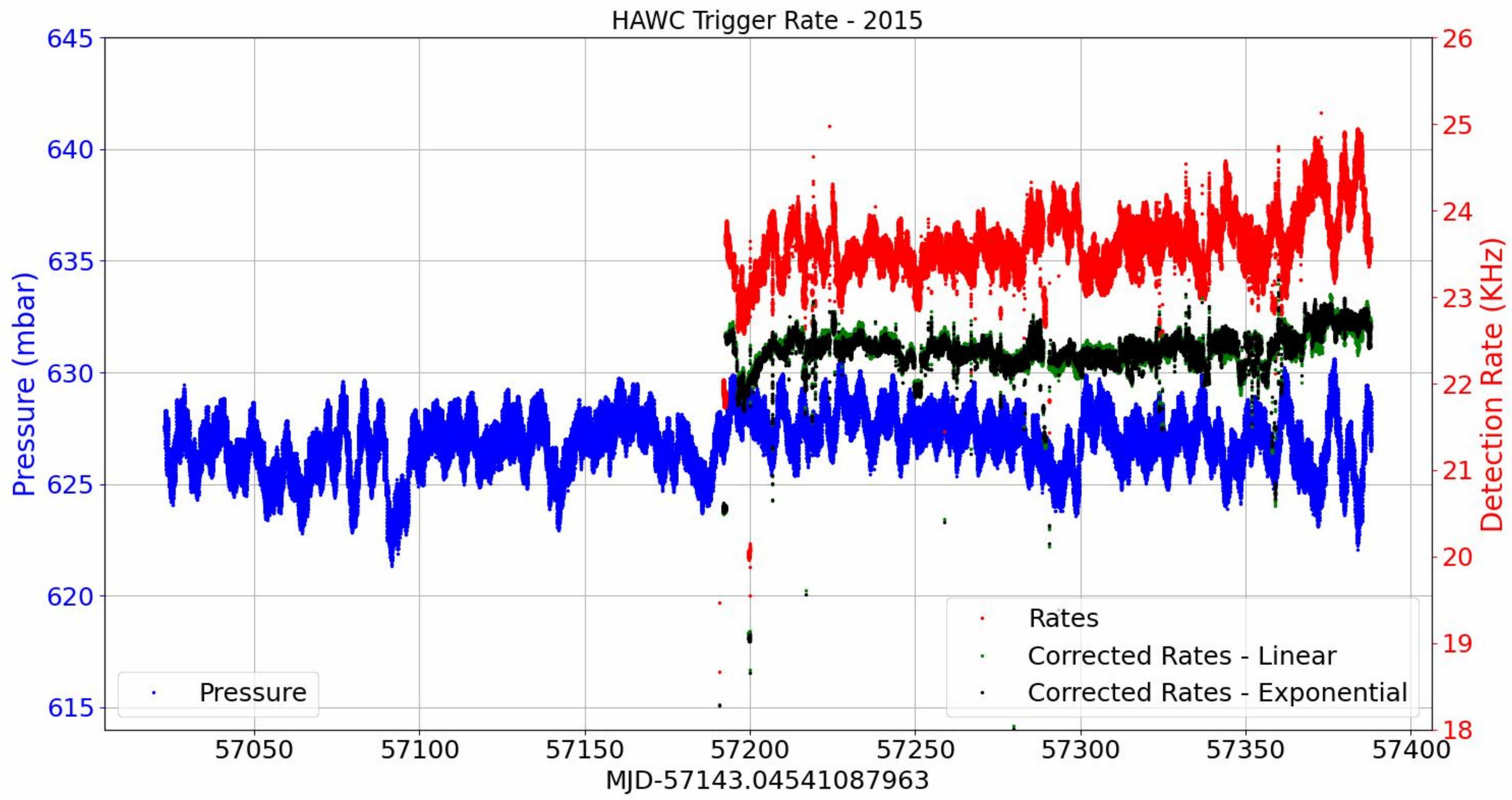
Exponential "corrected rates"

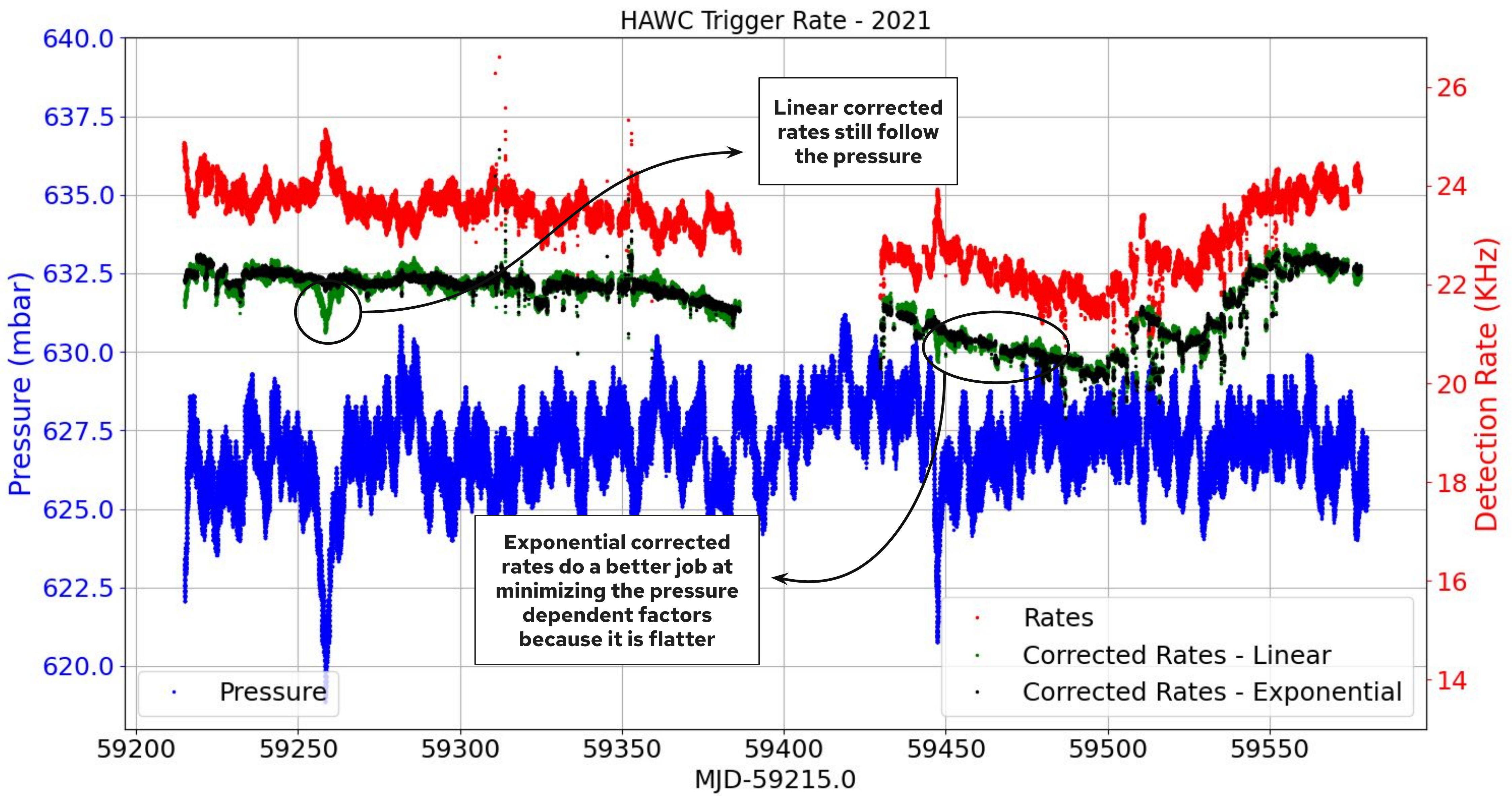
$$rcorr_{exp}(t) = r(t) \times \omega_{exp}$$

The aim was to minimize the pressure dependent factors affecting the rates data

Results!

Plotted the pressure, rates, linear and exponential corrected rates for each year





Conclusion: This is why we went forward with the exponential fit to extract the raw anisotropy.

Future Directions

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

Pressure correction

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

Compton Getting Effect correction

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

Combined weight factor with both the corrections

Current work in progress

- Work on minimizing the contribution of the Compton Getting effect.
- Look at how cosmic ray particles at different energy levels and different arrival directions are detected by HAWC so as to see the Zenith angle and energy dependence of the rates data.

Main Goal: Identify the sources of cosmic rays and their mechanism of acceleration into the interstellar medium.

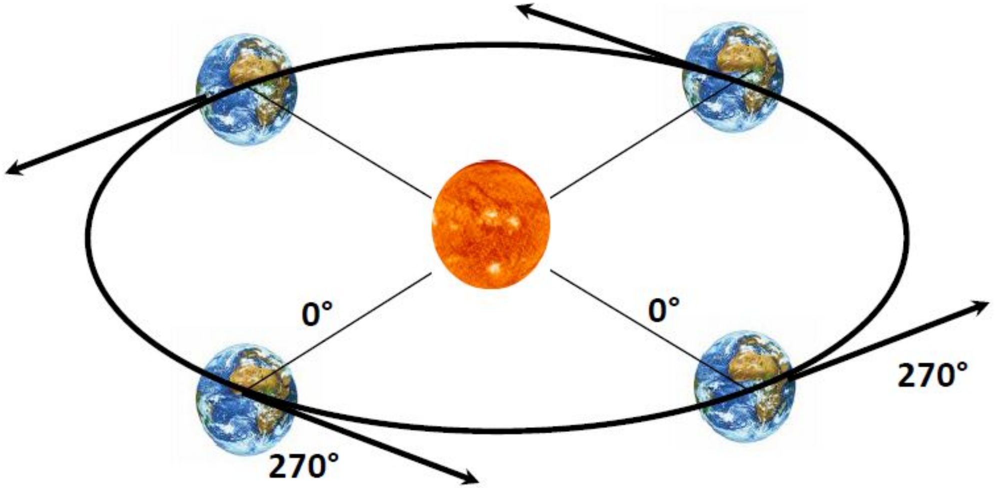
References

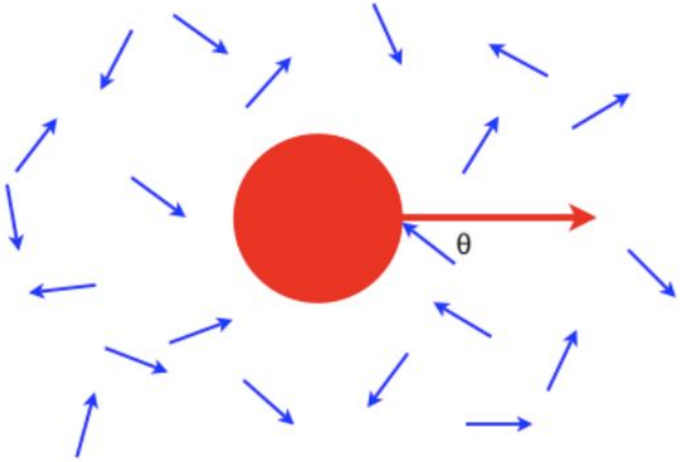
- Cosmic Ray Anisotropy with 11 years of IceCube Data https://arxiv.org/abs/2308.02331
- "HAWC Detector" HAWC group at UW-Madison https://hawc.wipac.wisc.edu/gallery/view/1695
- "Cosmic Rays" HAWC: High-Altitude Water Cherenkov Observatory https://www.hawc-observatory.org/
- Juan Carlos Diaz Velez, Riya Kore, Ferris Wolf, Paolo Desiati. Presentation for HAWC Collaboration Meeting. "Analysis of Cosmic-Ray Anisotropy with 8 years of HAWC data."

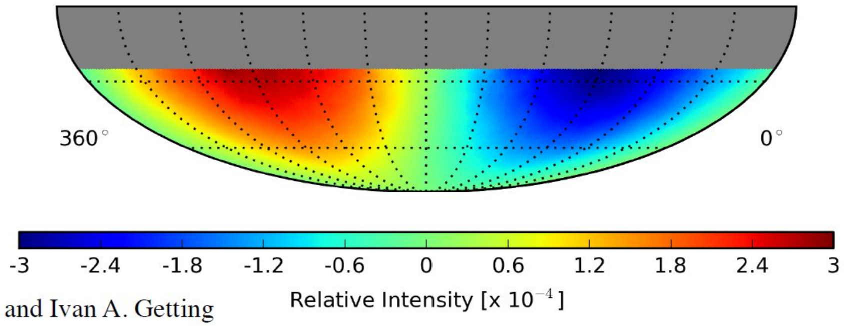
Thank You!

Backup Slides

The Compton Getting effect







$$\frac{\Delta I}{I} = (\gamma + 2)\frac{v}{c}\cos\theta$$

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