Muon Observing.

Royston Morgan PhD

Astronomy Activities

- Deep Sky Astrophotography
- Photometry (BAA, AAVSO, Exoplanet (Exoclock))
- Radio Astronomy (Muons, Hydrogen Line, Meteors)
- Member of: Fairlight Astronomers, ESAS and HERC (Ham Radio)

Chasing Muons

Exploring the arrival of cosmic rays

Royston Morgan PhD

What is a Muon?

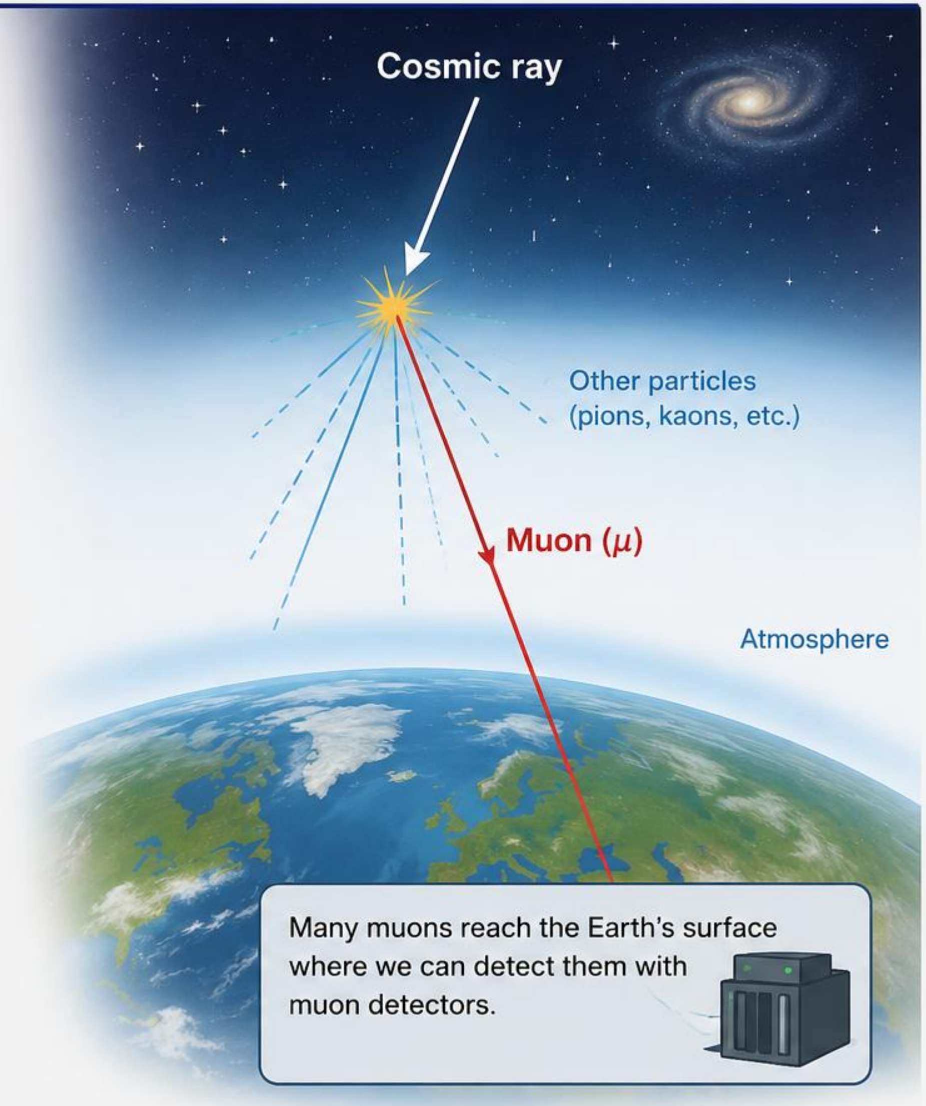
A muon (μ) is a fundamental particle created by cosmic rays high in the Earth's atmosphere.

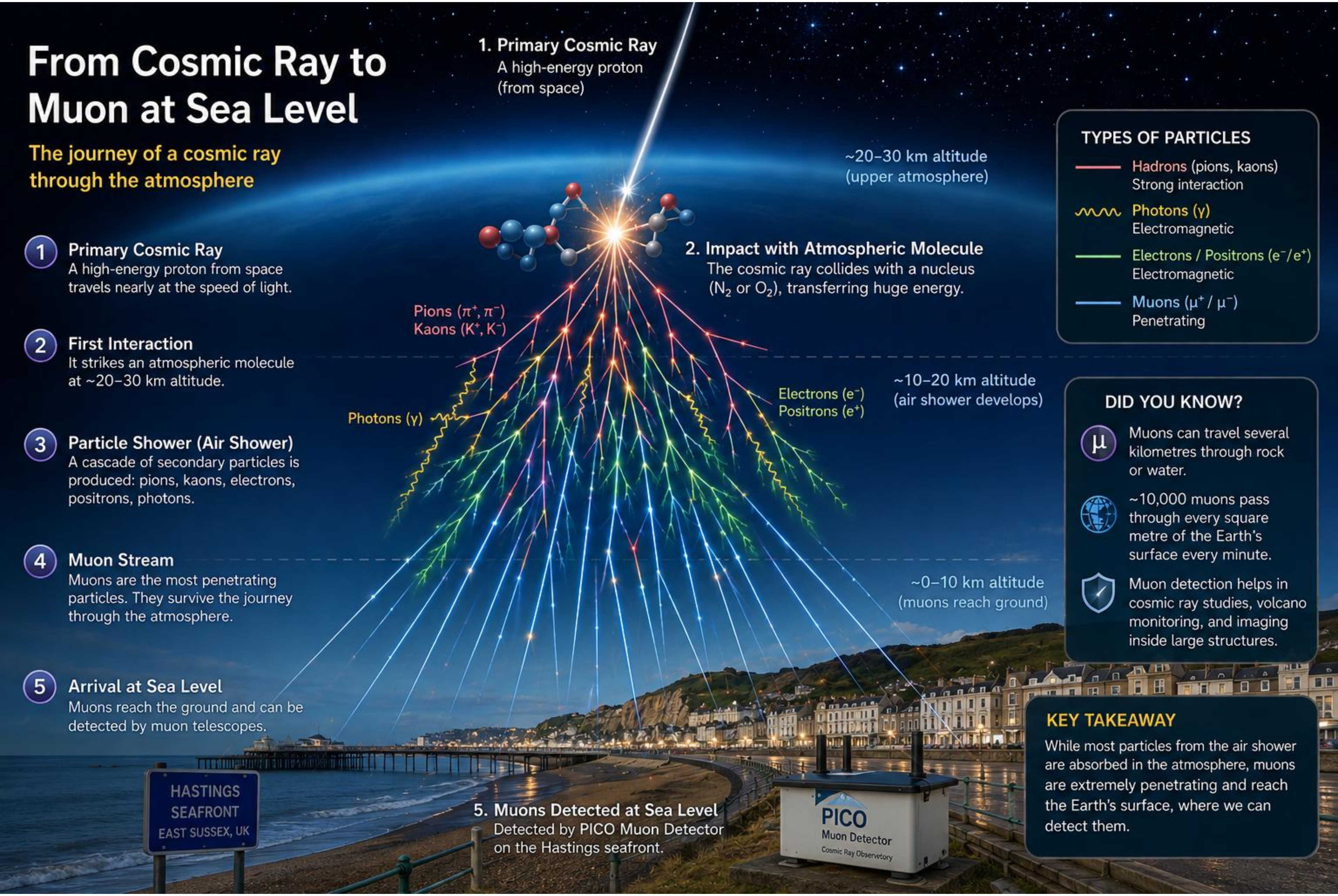
What is it?
A muon is a lepton, similar to an electron but about 200 times more massive.

Charge
Muons have a negative charge (μ^-) or a positive charge (μ^+).

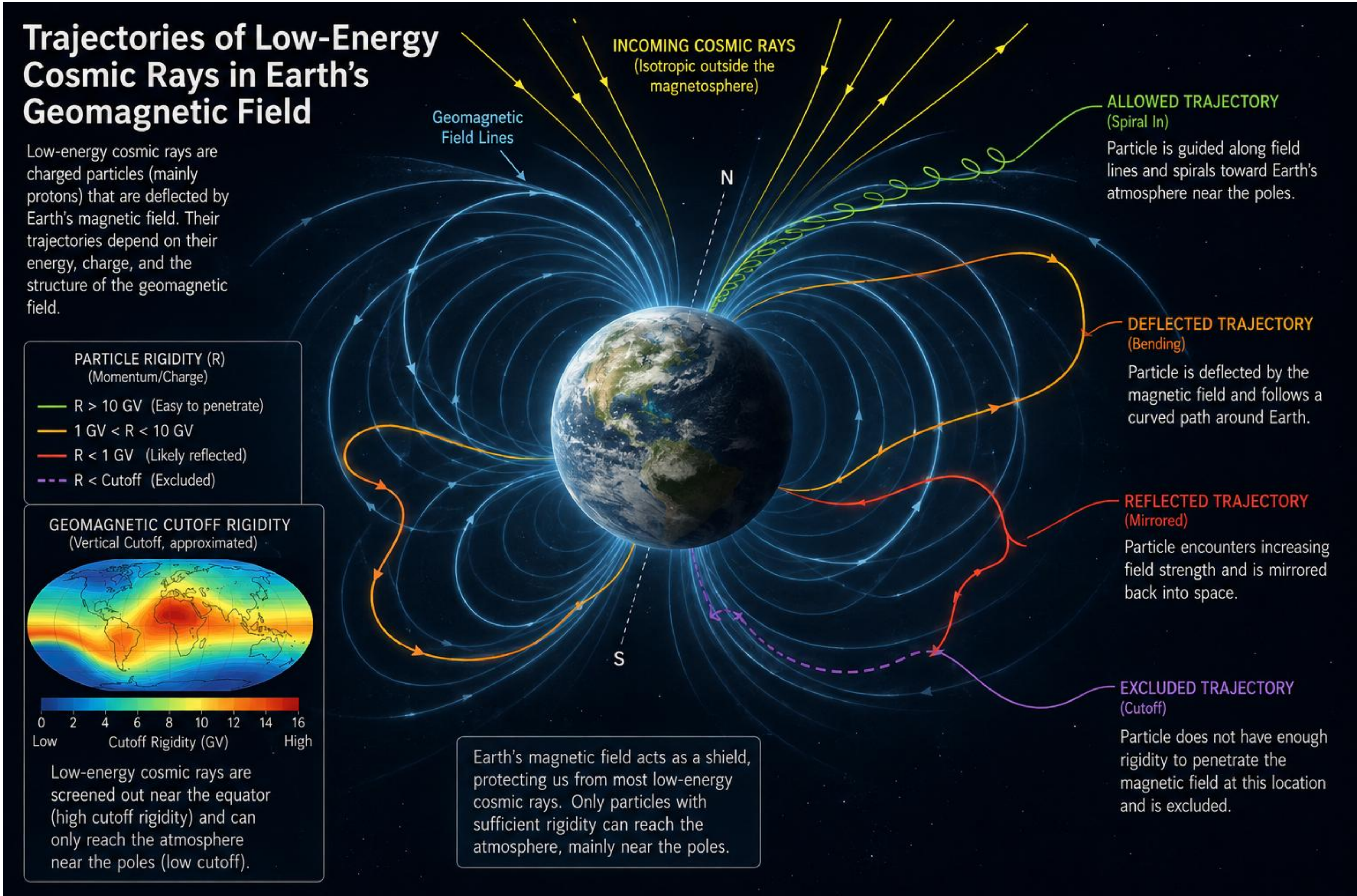
Lifetime
Muons are unstable and short-lived, with a lifetime of about 2.2 microseconds.

Penetrating Power
Muons can travel through the atmosphere and even through hundreds of metres of rock or concrete before decaying.





From Cosmic Ray to Muon at Sea Level
The journey of a cosmic ray through the atmosphere
1 Primary Cosmic Ray
A high-energy proton from space travels nearly at the speed of light.
2 First Interaction
It strikes an atmospheric molecule at ~20–30 km altitude.
3 Particle Shower (Air Shower)
A cascade of secondary particles is produced: pions, kaons, electrons, positrons, photons.
4 Muon Stream
Muons are the most penetrating particles. They survive the journey through the atmosphere.
5 Arrival at Sea Level
Muons reach the ground and can be detected by muon telescopes.
1. Primary Cosmic Ray
A high-energy proton (from space)
~20–30 km altitude (upper atmosphere)
2. Impact with Atmospheric Molecule
The cosmic ray collides with a nucleus (N_2 or O_2), transferring huge energy.
Pions (π^+, π^-)
Kaons (K^+, K^-)
Photons (γ)
Electrons (e^-)
Positrons (e^+)
~10–20 km altitude (air shower develops)
~0–10 km altitude (muons reach ground)
5. Muons Detected at Sea Level
Detected by PICO Muon Detector on the Hastings seafront.
HASTINGS SEAFRONT
EAST SUSSEX, UK
PICO
Muon Detector
Cosmic Ray Observatory
TYPES OF PARTICLES
Hadrons (pions, kaons)
Strong interaction
Photons (γ)
Electromagnetic
Electrons / Positrons (e^-/e^+)
Electromagnetic
Muons (μ^+ / μ^-)
Penetrating
DID YOU KNOW?
μ
Muons can travel several kilometres through rock or water.
~10,000 muons pass through every square metre of the Earth's surface every minute.
Muon detection helps in cosmic ray studies, volcano monitoring, and imaging inside large structures.
KEY TAKEAWAY
While most particles from the air shower are absorbed in the atmosphere, muons are extremely penetrating and reach the Earth's surface, where we can detect them.



Trajectories of Low-Energy Cosmic Rays in Earth's Geomagnetic Field
Low-energy cosmic rays are charged particles (mainly protons) that are deflected by Earth's magnetic field. Their trajectories depend on their energy, charge, and the structure of the geomagnetic field.
PARTICLE RIGIDITY (R) (Momentum/Charge)
R > 10 GV (Easy to penetrate)
1 GV < R < 10 GV
R < 1 GV (Likely reflected)
R < Cutoff (Excluded)
GEOMAGNETIC CUTOFF RIGIDITY (Vertical Cutoff, approximated)
0 2 4 6 8 10 12 14 16
Low Cutoff Rigidity (GV) High
Low-energy cosmic rays are screened out near the equator (high cutoff rigidity) and can only reach the atmosphere near the poles (low cutoff).
Geomagnetic Field Lines
INCOMING COSMIC RAYS (Isotropic outside the magnetosphere)
N
S
ALLOWED TRAJECTORY (Spiral In)
Particle is guided along field lines and spirals toward Earth's atmosphere near the poles.
DEFLECTED TRAJECTORY (Bending)
Particle is deflected by the magnetic field and follows a curved path around Earth.
REFLECTED TRAJECTORY (Mirrored)
Particle encounters increasing field strength and is mirrored back into space.
EXCLUDED TRAJECTORY (Cutoff)
Particle does not have enough rigidity to penetrate the magnetic field at this location and is excluded.
Earth's magnetic field acts as a shield, protecting us from most low-energy cosmic rays. Only particles with sufficient rigidity can reach the atmosphere, mainly near the poles.

Primary cosmic rays need an energy of around 1 to 6 Gev to start atmospheric particle showers

By Type

Protons ≈ 90%

Alpha Particles ≈ 9%

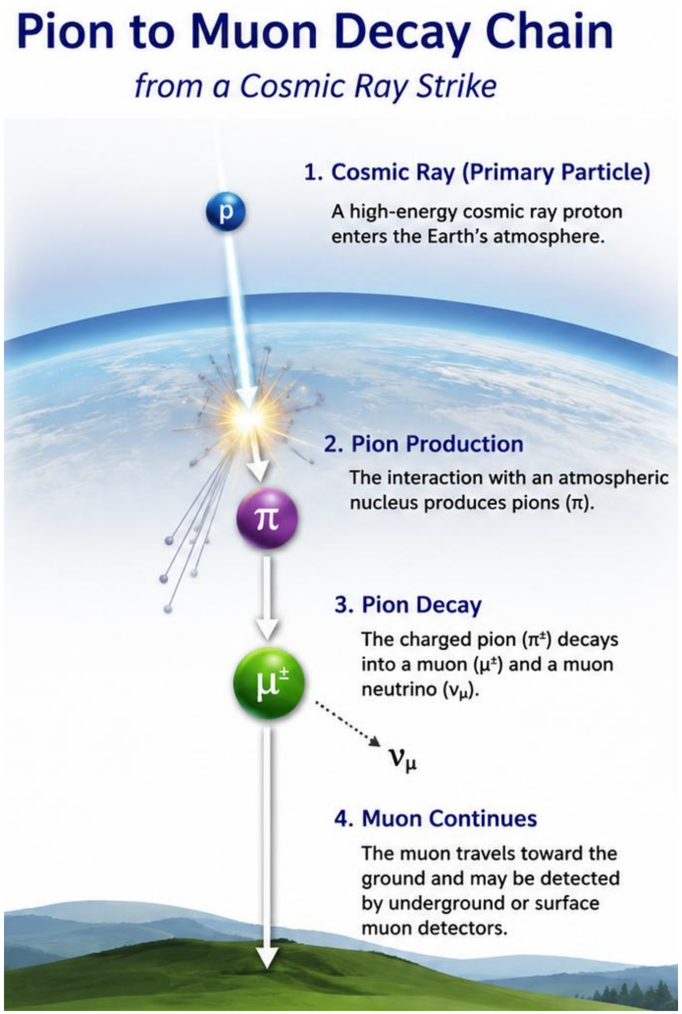
Heavy Nuclei ≈ 1%
e.g. C, O, Fe

Cosmic Origin

Galactic Cosmic Rays are the primary source

Solar particle events, flares CME can have energies > 1Gev

Extra Galactic Cosmic Rays



The calculation of the Barometric Pressure Attenuation constant is what this project is about

Muon intensity decreases with atmospheric depth because muons are ***lost*** on the way down by:

1. Decay: muons are unstable and can decay into electrons (or positrons) and neutrinos.
2. **Interactions:** muons can interact with atoms in the air, losing energy or producing secondaries.

1. Decay Loss

Muons have a mean lifetime $\tau_0 = 2.2\ \mu s$ (at rest).

As they travel, the probability of decay increases.

The higher the atmospheric depth X, the more muons decay before reaching the ground.

$$P_{\text{survive}} = e^{-X/\Lambda_{\text{decay}}}$$

where Λ_{decay} is the decay attenuation length (depends on muon energy).

2. Interaction Loss

Muons can interact with nuclei in the air via ionization, bremsstrahlung, pair production, or hadronic interactions.

These processes remove muons from the primary beam (by absorption or large energy loss).

$$P_{\text{survive}} = e^{-X/\Lambda_{\text{int}}}$$

where Λ_{int} is the interaction attenuation length.

Combined Effect

The total muon intensity decreases approximately exponentially with atmospheric depth X (in g cm^{-2}):

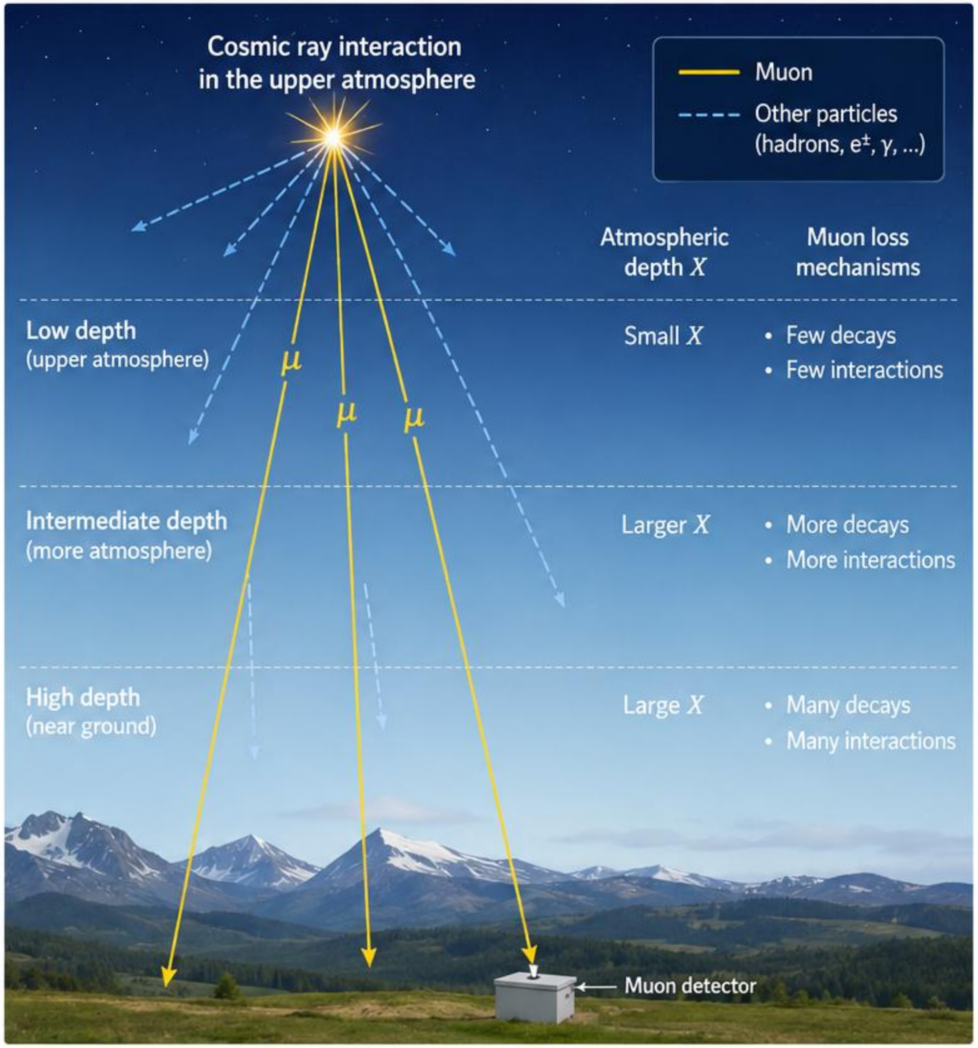
$$I(X) = I_0 e^{-X/\Lambda_\mu}$$

$I(X)$ = muon intensity at depth X

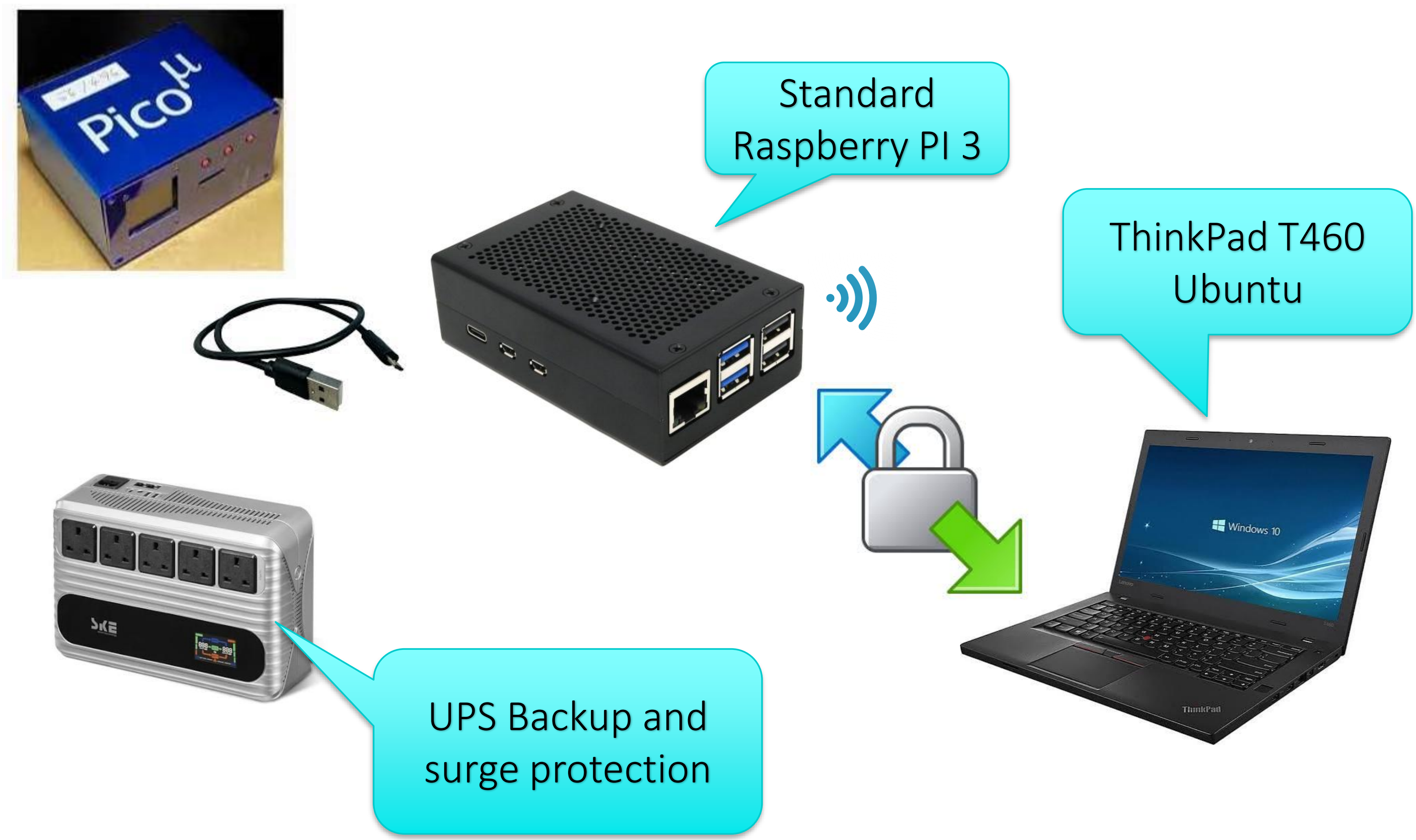
I_0 = intensity at top of atmosphere

Λ_μ = effective attenuation length

where Λ_μ is the effective attenuation length that includes both decay and interaction losses.



Standard single detector layout pre-processed data only extracted (monthly series) – all analysis in Python3



Some issues arose quite early on and still bug me…

Raspberry PI operating system on the micro-SD card can be subject to corruption of the file system during a power loss.

- Power-cuts plus overzealous night shut down of equipment
- Can load the built-in overlay file system via 'sudo raspi-config' and change card as read only
- Boot from USB SSD Drive (handle outages better than flash memory apparently) Pi4 or Pi5 as they will natively boot from USB
- Install a UPS Battery Backup either a small one to allow controlled shut down or an over the top one that I use.

Occasional loss of WIFI connection

- Not serious as I can use a small HDMI monitor and wireless keyboard to reset Wi-Fi

Occasional corruption of processed files

- More serious as can lead to many days lost data with NaN replacing the data
- Moving processing steps to accessing PI remotely from Linux machine then the raw files to move to Thinkpad to do the preprocessing/processing.
- If I continue with Pico Muon will need to upgrade current Raspberry with a mini-Linux pc or version 5 Raspberry Pi

Overall workflow of first part of the analysis

- Import muon detector and sunspot data.
- Cleanup and preprocess measurements.
- Compute the moving averages (flux, muons, neutrons).
- Calculate some basic statistical properties.
- Graph pressure effects on muon rates (simple regression).
- Estimate the solar radio flux from sunspot numbers.
- Download and import sunspot data series
- Produce several diagnostic plots.
- Start main analysis: Calculation barometric coefficient (β).
- Set down next steps and corrections from initial analysis
- Possible future projects

A pandas DataFrame is a two-dimensional, table data structure in Python that organizes data into labeled rows and columns for easier manipulation and analysis

Import Libraries

```
import pandas as pd
import numpy as np
import seaborn as sns
import matplotlib.dates as mdates
import matplotlib.pyplot as plt
import scipy.stats as stats
from scipy.stats import linregress
```

Data Frame: index definition

```
cols = [ "time", "det1", "det2", "coincidence", "temp", "pressure", "neutrons"]

spots = [ "year", "month", "day", "decdate", "estspots", "STD", "stat1", "stat2"]
```

Defining the Data Frame

```
df_muons = pd.read_csv( "/home/roymogg/Muons/MuonData/pico_data_may.txt", names=cols, parse_dates=["time"])

df_spots = pd.read_csv( "/home/roymogg/Muons/MuonData/Sunspot_estimate_2026.txt",    sep=r'\s+', names=spots)
```

The approach is to use the same structure and order of play across projects so some aspects can be reused.

Some clean up was needed to remove NaN and impossible temperatures

```
df_spots['Date'] = pd.to_datetime(df_spots[['year', 'month', 'day']])
```

Spots date data reformatted to standard python

```
df_spots["solarflux"] = (df_spots["estspots"] + 73.21) / 1.14
```

Regression formula Dr Kenneth Tapping 1999 originally to convert 10.7cm radio flux to an estimated sunspot number.

```
#Replace impossible temperatures

df_muons.loc[df_muons["temp"] > 60, "temp"] = np.nan
```

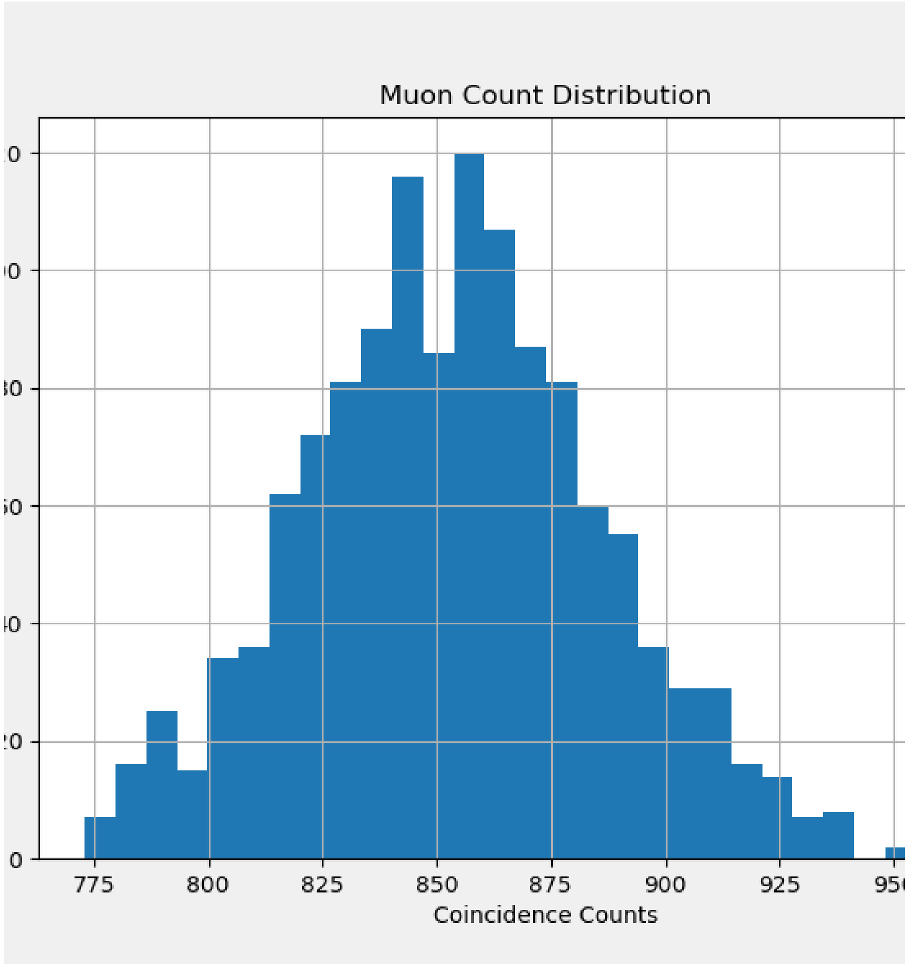
Missing, undefined or invalid numerical format

```
# Remove missing rows

df_muons = df_muons.dropna()

# A few simple calculations such as moving averages

df_muons["rate_ma_24h"] =df_muons["coincidence"].rolling(24).mean()
df_muons["pressure_ma_24h"] = df_muons["pressure"].rolling(24).mean()
df_muons["neutrons_ma_24h"] = df_muons["neutrons"].rolling(24).mean()
```

Simple statistics performed first to check consistency in data stream

Simple Histogram Plot

```
plt.figure(figsize=(8,6))
plt.hist(df_muons["coincidence"], bins=30)
plt.xlabel("Coincidence Counts")
plt.ylabel("Frequency")
plt.title("Muon Count Distribution")
plt.grid(True)
```



Initial Analyses included:

That Muon counting followed approximate Poisson statistics: sigma = sqrt(N) where N is the count total and sigma is the statistical uncertainty.

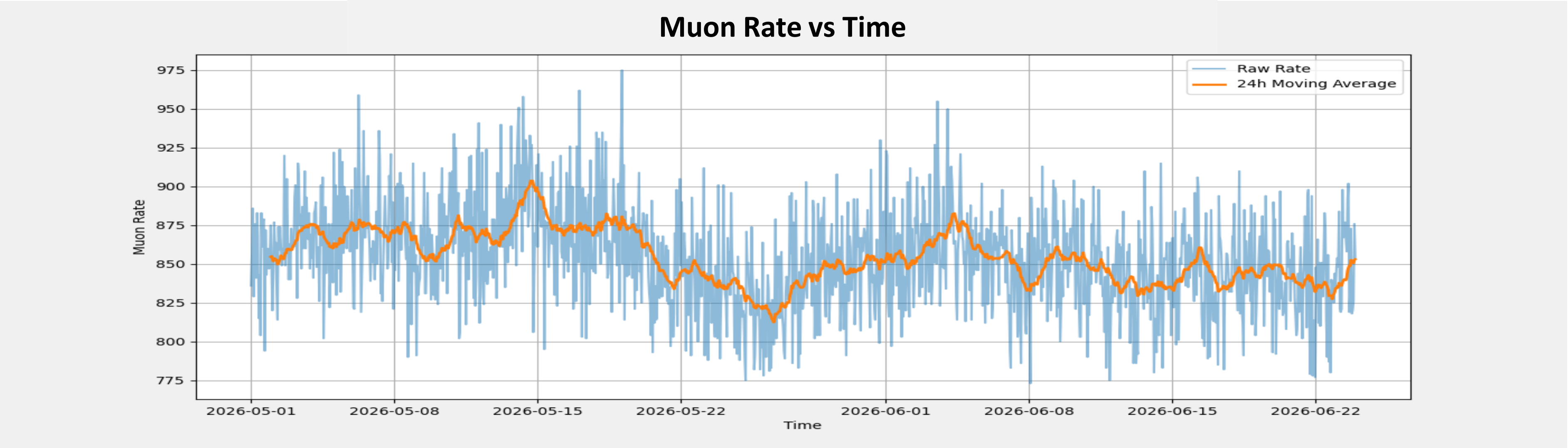
Histograms of count distributions

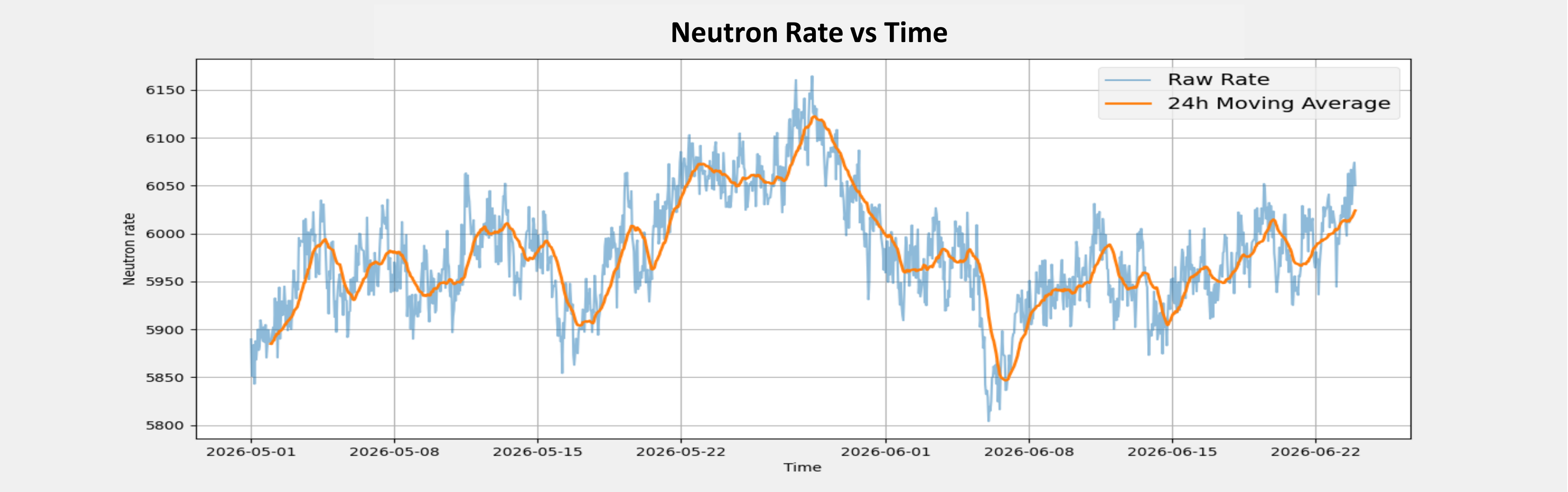
Standard deviation and variance analysis

Useful to check things are working

```
print(df_muons.describe())
```

Simple consistent figure creation



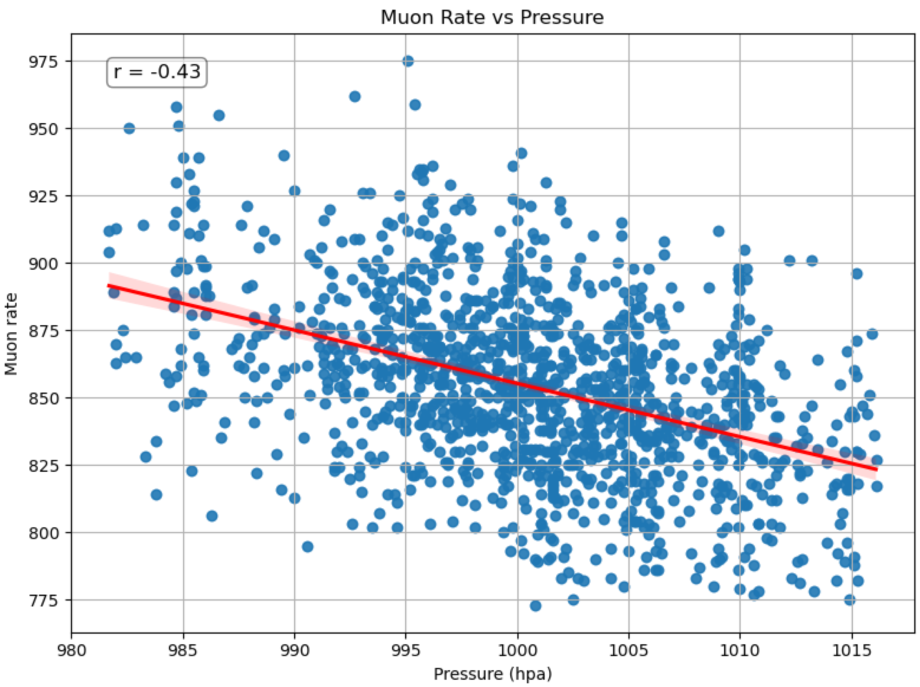


Next Step was to carry out a elementary regression plot

```
plt.figure(figsize=(8,6))
plt.scatter(df_muons["pressure"], df_muons["coincidence"], alpha=0.5)

x = "pressure“
y = "coincidence“
slope, intercept, r_value, p_value, std_err =
stats.linregress(df_muons[x], df_muons[y])
sns.regplot( data=df_muons, x=x, y=y, ci=95, line_kws={"color": "red"},
label= f"Regression Line (r = {r_value:.2f})")

#plt.style.use('fivethirtyeight’)
plt.grid(True)
plt.title("Muon Rate vs Pressure")
plt.xlabel('Pressure (hPa)'.capitalize())
plt.ylabel('Muon Rate'.capitalize())
plt.grid(True)
plt.gca().text(0.05, 0.95, f'r = {r_value:.2f}’,
transform=plt.gca().transAxes,
fontsize=12,
verticalalignment='top’,
bbox=dict(boxstyle='round,pad=0.3', facecolor='white', alpha=0.5))
```

Atmospheric Pressure Effect from initial simple regression

- A clear negative-correlation exists between atmospheric pressure and measured muon rate.
  - Higher pressure means more atmosphere above the detector, causing increased absorption and decay of secondary muons before they reach ground level.
- This produces the classic barometric effect:
- Pressure increases -> muon rate decreases.



For comparison of data side by side create a grid then target subplots to a grid slot (example regression plot)

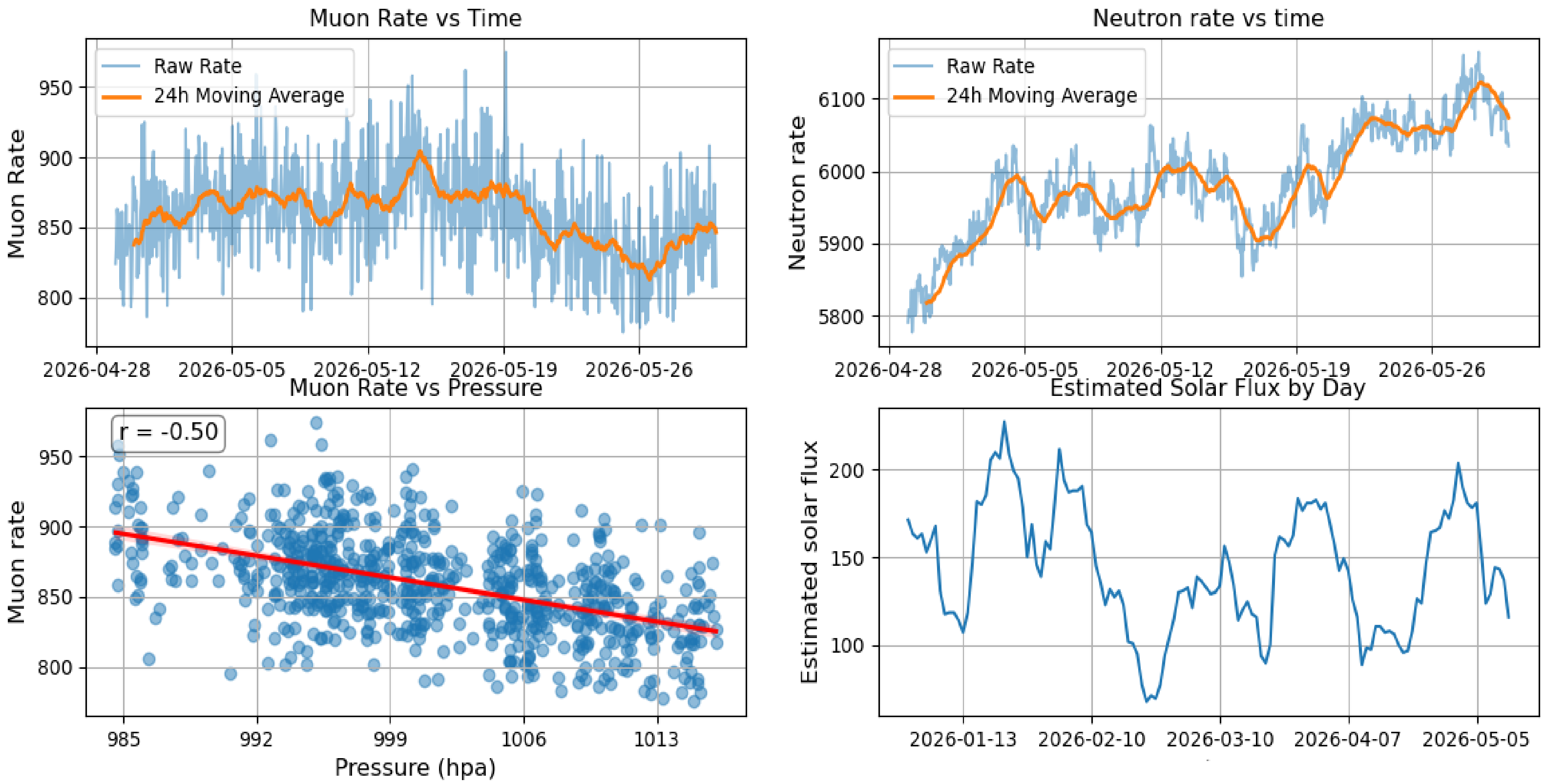
First define the grid using the subplot method (e.g., 2 rows, 2 columns)

```
fig, axs = plt.subplots(2, 2, figsize=(14, 6))
```

Then target our plots to the grid : plot 1(0,0), plot2(0,1), plot3(0,1), plot4(1,1)

```
slope, intercept, r_value, p_value, std_err = linregress(    df_muons["pressure"],
df_muons["coincidence"])

axs[1,0].scatter(df_muons["pressure"], df_muons["coincidence"], alpha=0.5)
x = "pressure“
y = "coincidence“
sns.regplot(data=df_muons, x=x, y=y, ci=95, scatter=False, line_kws={"color": "red"},
ax=axs[1,0])
axs[1,0].set_title("Muon Rate vs Pressure")
axs[1,0].xaxis.set_major_locator(mdates.WeekdayLocator(interval=1))
axs[1,0].set_xlabel('Pressure (hPa)'.capitalize(), fontsize=12)
axs[1,0].set_ylabel('Muon Rate'.capitalize(), fontsize=12)
axs[1,0].grid(True)
axs[1,0].text(0.05, 0.95, f"r = {r_value:.2f}", transform=axs[1, 0].transAxes,
fontsize=12, verticalalignment="top", bbox=dict(boxstyle="round,pad=0.3",
facecolor="white", alpha=0.5),)
```

Adapting the earlier plots and mapping them to the grid created the following figure



Classic cosmic ray experiment measuring the barometric coefficient

- As ground-level atmospheric pressure increases, the measured muon count rate decreases.
- This inverse correlation happens because a higher barometric pressure means there is physically more air mass above the detector.
- This extra mass forces the muons to travel through a thicker, denser atmosphere, causing them to lose more energy via ionization and allowing more of them to decay before hitting the Pico sensor.
- This experiment replicates:

Stevanato, L. et al, (2022) An Alternative Incoming Correction for Cosmic-Ray Neutron Sensing Observations Using Local Muon Measurement, Geophysical Research Letters

Atmospheric density drops exponentially with altitude; pressure is directly proportional to the total overhead airmass

The exponential model:

M is the measured muon count rate at pressure P.

M_0 is the baseline muon count rate at standard reference pressure – I used the average over the measurement period.

β is the barometric attenuation coefficient

$$f_p = e^{-\beta_\mu (P - P_{ref})} = e^{-\beta_\mu (\Delta P)}$$

$$M = M_0 * e^{-\beta_\mu (\Delta p)}$$

$$\boldsymbol{ln\left(\frac{M}{M_0}\right) = -\beta_\mu * \Delta P}$$

Dorman, L. I. (2004). *Cosmic rays in the Earth's atmosphere and under-ground*. Kluwer.

This relationship is modelled in Python with a simple change to the regression model

- Establish reference values (means over the entire period)

```
M2 = df["coincidence"].mean()    P_ref = df["pressure"].mean()
```

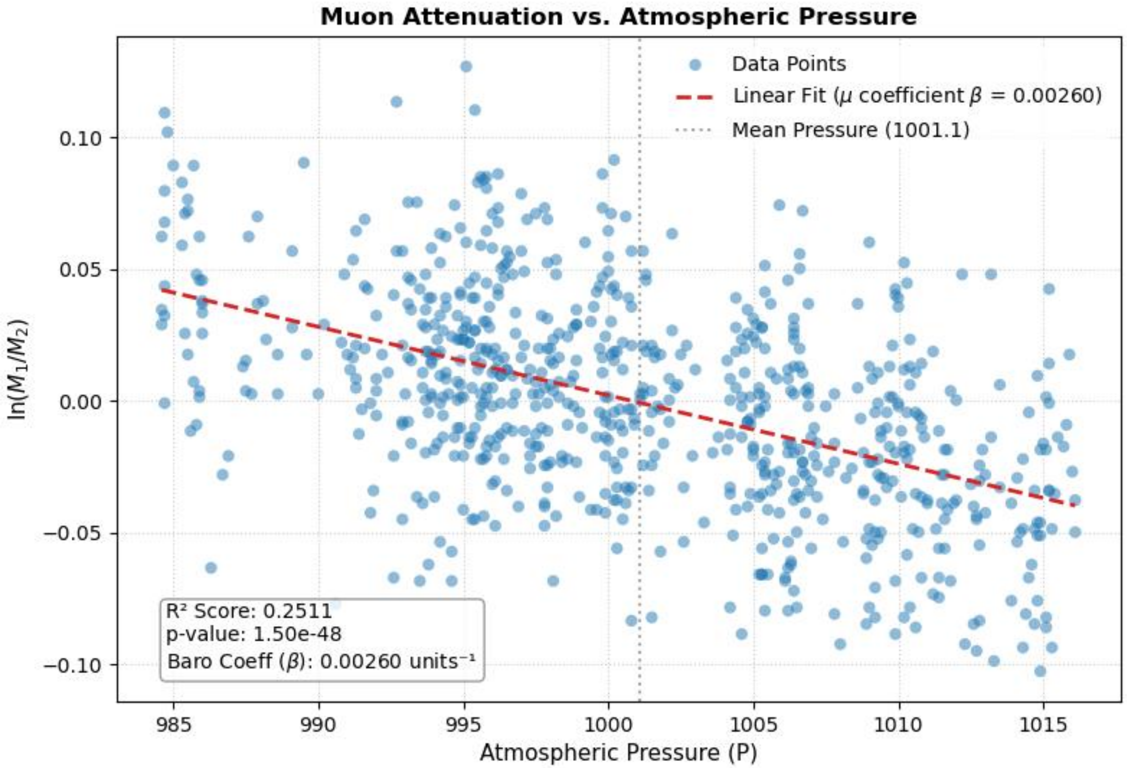
- Calculate the Y-axis variable: ln(M1 / M2)

```
df_filtered["ln_M1_M2"] = np.log(df_filtered["coincidence"] / M2)
x_pressure = df_filtered["pressure"].values
y_ln_ratio = df_filtered["ln_M1_M2"].values
```

- Linear regression to find the attenuation slope (-beta)

```
slope, intercept, r_value, p_value, std_err = linregress(x_pressure, y_ln_ratio )
beta = -slope  #  This is the Barometric coefficient
```

Plot shows a regression curve and enables an estimate of the Barometric constant to be made



Typical Beta values from the literature -0.1% to 0.2%/mbar so we were high on this run.

From the paper used in this replication quoted **β** 0.21%/mbar we are in the ballpark but a way to go.

The barometric constant can be used to predict muon intensity by altitude

The barometric constant **β** describes how the muon intensity I decreases with atmospheric depth X (in g cm^{-2}):

$$I(X) = I_0 e^{-X/\beta}$$

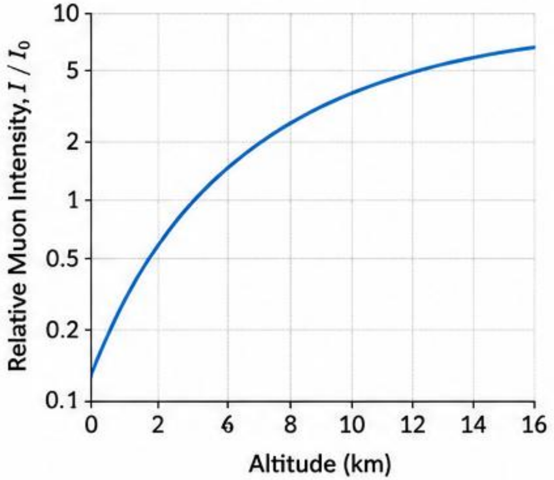
If **β** for muons is known (from measurement or literature), you can:

- **Estimate muon abundance at different altitudes**
  Atmospheric depth X decreases with altitude, so muon intensity increases.
- **Convert between measured intensities and atmospheric depth**
  Useful for comparing data from different locations or times.

Muon Intensity vs Altitude (Example)

Using $I(X) = I_0 e^{-X/\beta}$ and the standard atmosphere to relate altitude to depth.

Example for β = 120 g cm^{-2} (illustrative only)



Typical Values

- Sea level (0 km): $I \sim 0.1\ I_0$
- 5 km altitude: $I \sim 1.5\ I_0$
- 10 km altitude: $I \sim 3\text{–}4\ I_0$
- 15 km altitude: $I \sim 6\text{–}7\ I_0$

Missing analysis in this first pass

The script plots solar flux but does not quantitatively compare it with:

- muon rate as observed at the detector
- neutron rate (local pressure data at the detector site needed) - Attempting to download relevant data from Oulu Neutron Monitor

Next steps

- Daily Muon Rate versus the Daily Solar Flux I will replace sunspot surrogate with actual observed solar flux data

Useful comparison datasets:

- - NOAA F10.7 solar radio flux
- - SILSO sunspot number database
- - NOAA space weather indices

The pressure correction has not been applied

- β coefficient but a calculated a pressure-corrected muon rate not done
- Muon falloff also correlated to atmospheric temperature due to path effect but what temperature to use?

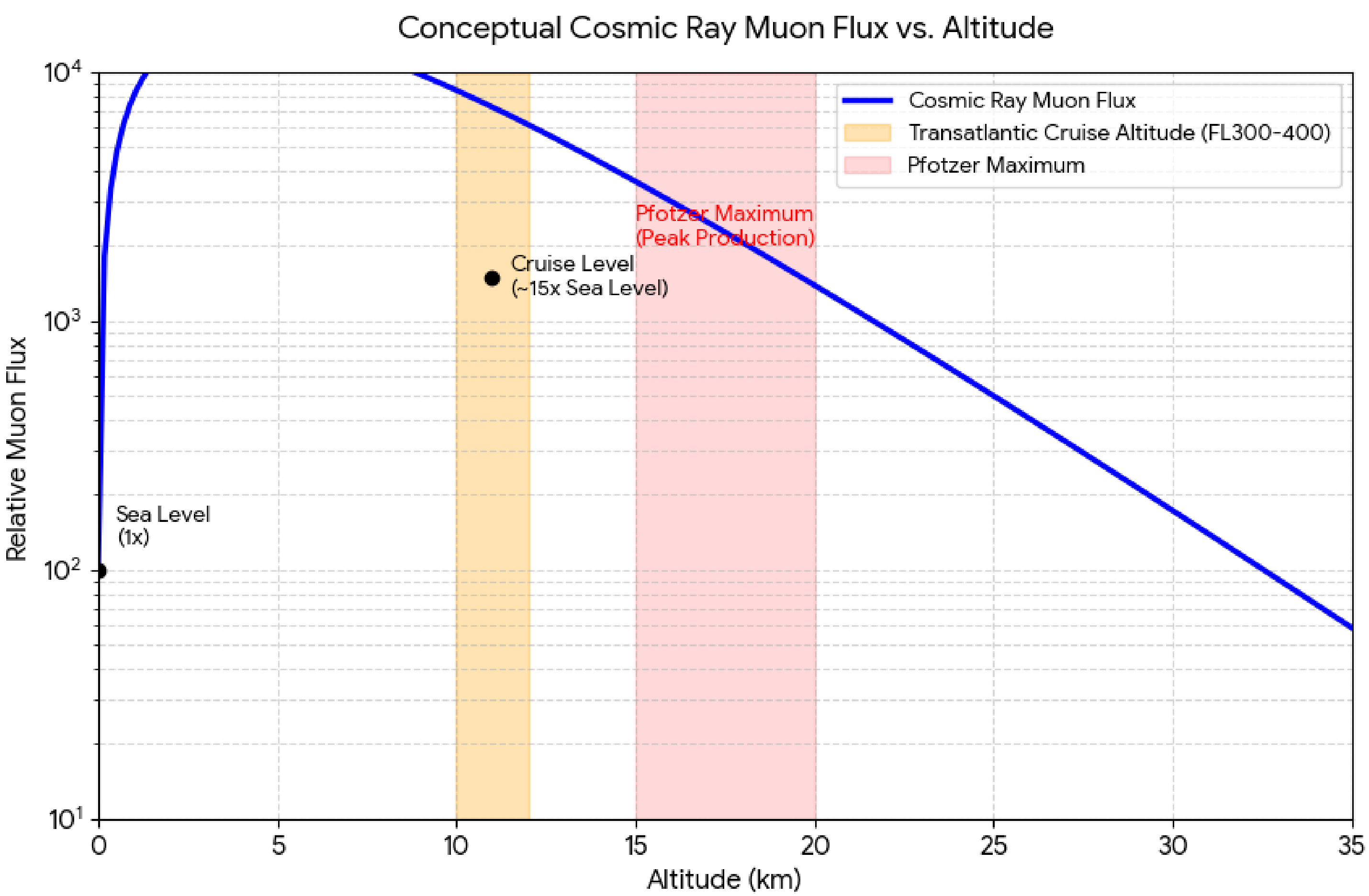
Competing Physics changes by season – but will need much longer consistent data sets

Season	Atmospheric State	Primary effect on Muons
Hot Summer	Expanded, stable, and less dense.	**Positive Effect Dominates:** Parent pions have a longer mean free path in the thin air, allowing them to decay into muons rather than colliding with air atoms. This elevates the baseline count.
Cold Winter	Highly contracted, dense, and turbulent. (sudden stratospheric warming)	**Negative Effect Dominates:** Pions are forced into premature atomic collisions in the dense air, choking off the muon production chain. Combined with polar vortex disruptions, the winter temperature correction factors change wildly day by day.

S. Abubakar (2026) Explanation of the seasonal variation of cosmic multiple muon events observed with the NOvA Near Detector, Physical Review

To Summarise: Possible next step studies

- Pressure-corrected flux measurements with error bars
- Diurnal variation analysis
- Fourier transform periodicity studies
- Forbush decrease detection (CME, Helio-spheric disturbances causing sudden drop in galactic cosmic rays)
- Cross-correlation with neutron monitor networks
- Seasonal effects : decreased count rate in summer due to decay path effect.
- East-West asymmetry: higher rates looking West than looking East



Conceptual Cosmic Ray Muon Flux vs. Altitude
Cosmic Ray Muon Flux
Transatlantic Cruise Altitude (FL300-400)
Pfotzer Maximum
Pfotzer Maximum
(Peak Production)
Cruise Level
(~15x Sea Level)
Sea Level
(1x)
Relative Muon Flux
Altitude (km)
10^4
10^3
10^2
10^1
0
5
10
15
20
25
30
35