Anna Gosling

20 April 2018

Summary for Diverse Audiences

Presenting modern physics topics to a young audience is a significant challenge in the field. This project uses narrative to explain major theories about dark matter and explore research occurring in this field to students in grades 4–6. This research also goes more in depth into the work being done at Jefferson Lab (JLab) on dark matter. The JLab researchers uses a technique called the “bump hunt” to search for instances of the heavy photon, one of the most popular candidates for dark matter, in the mass spectrum of electron-positron pair generated by shooting an electron beam at a heavy metal target. This project used bump hunt techniques with data produced by a simulation developed by the Heavy Photon Search experiment (HPS) team. This project combines hands-on research at JLab with a review of recent research in the field of dark matter to create a book that makes learning about dark matter accessible for young readers.

The Heavy Photon Search for a Wider Audience

A thesis submitted in partial fulfillment of the requirement
for the degree of Bachelor of Science in
Physics from the College of William and Mary in Virginia,

by

Anna K. Gosling

Accepted

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Advisor: Prof. Keith Griffioen

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Williamsburg, Virginia
May 2018

Contents

Acknowledgments

I would like to thank Dr. Keith Griffioen for his advice and moral support throughout the research process. I would also like to thank graduate students Sebouh Paul and Bradley Yale for their immense help in teaching me the modeling programs. Finally, I would like to thank Lena Menton for using her incredible artistic skills to make my story come alive.

List of Figures

Abstract

The Heavy Photon Search Experiment (HPS) at the Thomas Jefferson National Accelerator Facility (JLab) is part of the world-wide search for the heavy photon. Successful analysis of this experiment's results requires accurate modeling. This project examines some of the modeling used by HPS. It also explores the search techniques used for finding the mass of the heavy photon, specifically the "bump hunt" technique.

On a larger level, the research at JLab, and physics research as a whole, is dependent on funding from sources outside the physics community and is a collaboration between many physicists over long periods of time. As a result, being able to explain the research to a wider audience is key to ensuring its continued existence. To ensure that this research continues in the future, explaining its purpose to a young audience is necessary. To achieve this goal, a book was written that uses stories, images, and metaphors to explain the search for dark matter as well as important principles of scientific research as a whole. This book will be aimed at students in the concrete operational stage of development, specifically students ages 9-11.

Chapter 1

Introduction

1.1 The Goal of the Experiment

The goal of the experiment at Jefferson Lab in general is to search for a heavy photon with mass in the range of 20 $\frac{MeV}{c^2}$ to 1 $\frac{GeV}{c^2}$. One goal of this research project in particular is to use the models created to predict the results of the experiment and to explore the implementation of the "bump hunt" technique. The other purpose of this project is to explore the ways in which complex concepts in modern physics can be explained to the wider world, specifically focusing on methods of conveying these ideas to children in the concrete-operational stage of cognitive development.

Chapter 2

Theory

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2.1 The Heavy Photon Search Experiment at Jefferson Lab

If the universe consists only of the things that interact with electromagnetic forces then some aspects of its compositionthe rotation of spiral galaxies and gravitational lensingdo not fit with the standard model of physics. As a result, physicists have proposed the existence of a new kind of matter, called dark matter, which interacts gravitationally, but not electromagnetically (hence, "dark" matter). This hypothesis has spurred a range of different experiments, particularly in the fields of astrophysics and particle physics, in an effort to find the force carrier for dark matter.

Multiple beyond-standard model theories predict the existence of an additional gauge symmetry, associated with the boson A', known colloquially as the dark photon or heavy photon [1] [2]. This particle interacts with standard-model matter through extremely weak quantum mechanical kinematic mixing of wave functions [1]. If this symmetry exists, then normal and heavy photons have similar mathematical structure [3]. As a result, heavy photons can theoretically be radiated by electrons colliding with a heavy metal target, and will also be able to decay into e^+e^- pairs [2]. By determining the four-momentum of these pairs the mass of the heavy photon can be reconstructed using the relativistic equation in energy units ($c^2 = 1$),

$$m^2 = E^2 - |\vec{p}|^2 \tag{2.1}$$

With detectors that can measure the energy and momentum of the e^+e^- pair, the pair's proper mass can be calculated.

Although this coupling can occur, it is much weaker than the background electromagnetic coupling. When the electron beam hits the heavy metal target, the electromagnetic interaction between the beam and the target also generates unstable "virtual" photons that decay into e^+e^- pairs. [2]. However, the virtual photons generated through this electromagnetic interaction, have a continuous mass spectrum, whereas the heavy photon would have a specific mass.

The "bump hunt" method involves plotting a histogram of this e^+e^- mass spectrum. After generating a curve of best fit for the histogram, this curve can be subtracted from the measured data. If the heavy photon has not been detected, the fit subtracted from the data should be a straight line at zero, assuming the fit model is a good one. If the heavy photon has been detected, there will be a peak in the fitted data that rises above the background. For a peak to be considered significant, it must have a statistical significance 5σ above the background events.

2.2 Educational Theories

Because the primary goal of this project is to make dark matter accessible to middle-grade readers, it is important to integrate research on both cognitive development and pedagogical methods.

Cognitive Development

Piaget's theory of cognitive development is one of the most widely-accepted developmental models. Piaget splits development into four different stages: sensorimotor, pre-operational, concrete operational, and formal operational [4]. Different cognitive abilities are associated with each stage. Because the audience for this book is in the concrete operational stage of development, it is important to keep in mind the cognitive abilities and limitations of children in this developmental stage.

Children in the concrete operational stage, ages 7-12 are capable of understanding reversible operations and finding relationships between different things. However, they have not yet developed the ability to understand abstractions and ideas [4]. For example, a student in this stage of development might have trouble understanding the kind of symbolic thought central to mathematics [4]. As a result, teaching children at this stage requires making abstract ideas concrete using real-world examples.

Pedagogical Methods

This project hinges on two key pedagogical theories: William James' writings on the power of cognitive connections and Robert Sternberg, Elena Grigorenko, and Li-fang Zhang's theory of successful intelligence. James' theory is centered on the importance of making connections for effective learning. According to James, the mind can be taught to link different ideas together, helping the student better understand the linked ideas [5].

Sternberg et *al* divide both learning and teaching into three distinct methods: analytic, creative, and practical. They suggest that the strongest students are able to use all three methods, encouraging teachers to use all three approaches when introducing material [6]. Although the analytic method is commonly used in education, it is important to look for ways to incorporate creative and practical styles of learning and teaching [6]. Using these three different approaches to education will help students better understand and be able to interact with the material being taught.

Chapter 3

Experimental Technique

3.1 Modeling

The first part of this research requires generating events using the MadGraph simulation [7]. The event generators used were developed by the heavy photon search team at Jefferson Lab to generate both a model of the background trident events and the peak indicative of the heavy photon. Fig. 1 shows what one generated event looks like.

```
<event>
 6   1  0.4437111E+06  0.1712432E+03  0.7297358E-02  0.1081109E+00
      11    -1     0     0     0     0  0.00000000000E+00  0.00000000000E+00  0.10559998764E+01  0.10560000000E+01  0.51100000000E-03 0.  -1.
 9000002    -1     0     0     0     0  0.00000000000E+00  0.00000000000E+00 -0.67124084069E-12  0.17124000000E+03  0.17124000000E+03 0.  -1.
      11     1     1     2     0     0  0.24903682383E-02 -0.11939600383E-02  0.39494253159E+00  0.39495251847E+00  0.51100000000E-03 0.  -1.
 9000002     1     1     2     0     0  0.93822352335E-03  0.22176104807E-02  0.18618840491E-03  0.17124000002E+03  0.17124000000E+03 0.  -1.
     -11     1     1     2     0     0  0.64506017786E-03  0.61031168725E-02  0.17851603085E+00  0.17862222294E+00  0.51100000000E-03 0.  -1.
      11     1     1     2     0     0 -0.40736519395E-02 -0.71267673148E-02  0.48235512552E+00  0.48242524156E+00  0.51100000000E-03 0.   1.
```

Figure 3.1: Generated event. The first and last columns identify the particle. For this research, only the last two rows are relevant because they represent the generated e^-e^+ pair. Columns 7-11 contain the data needed for calculating the mass of the electron.

This simulation generated 1000 background events.

After generating a simulation of the background radiation, 40 events with a mass of 0.1 GeV were added to the simulated background radiation to simulate the peaking behavior of the heavy photon. The background was analyzed both with and without the added peak.

3.2 Writing

The writing side of this experiment began with a survey of scientific writing, in which a variety of popular science articles, written for both adults and children, were read and analyzed for writing techniques. The goal of this portion of the experiment was to develop an understanding of rhetorical devices used when explaining science to a wider audience.

The next portion of the writing section of the experiment involved exploring educational psychology. The goal of this stage of the research was to better understand the approaches educators can take in explaining complex scientific ideas to a young audience by learning both cognitive development theory and pedagogical methods.

The third part of this section was writing a book for children about the search for dark matter. This book uses narrative to explore different experiments in the search for dark matter, introducing young readers to both dark matter theory and the process by which scientific discovery is accomplished.

Chapter 4

Results and Conclusions

4.1 Modeling the Heavy Photon Search

When using the ”bump-hunt” technique, data is analyzed by plotting the mass of each virtual photon in a histogram. By doing local fits on the histogram data and subtracting these fits from the data set itself, the residuals can be plotted. Ideally, these residuals will be zero, though in reality there will be some fluctuations. If the heavy photon is present, there will be a peak in the plot of the residuals.

For the background radiation, the equation

$$m^2 = E^2 - |\vec{p}|^2 \tag{4.1}$$

was used to calculate the proper mass of each e^-e^+ pair, and therefore the mass of the virtual photon that produced the pair. The masses found were plotted in a histogram using a Python script, included in Appendix A.

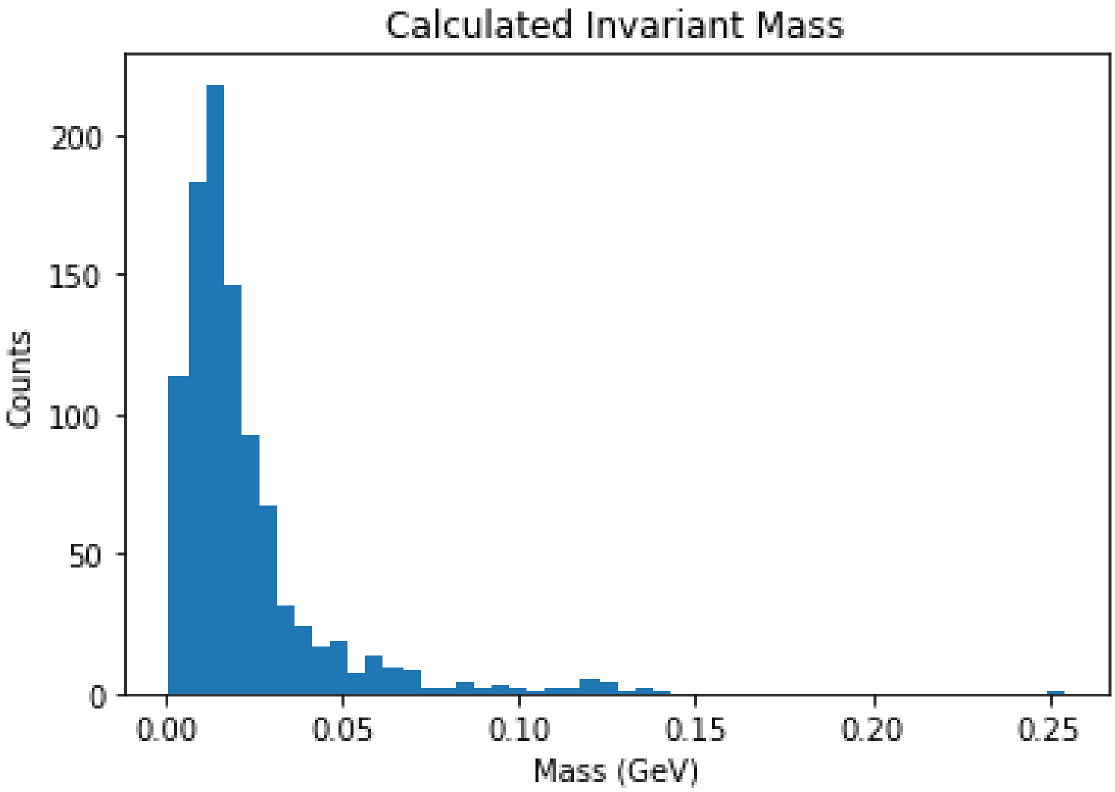

Figure 4.1: Histogram of Background Radiation. This is a histogram of the background radiation. This model separates the data into 50 bins.

To find peaks, a series of fit models were tested to determine which one was the most accurate. For this project, the most useful fit model is the one that results in zero, with fluctuations, when subtracted from the initial histogram. After testing a series of models, the skewed Gaussian distribution function was found to yield the best fit, as can be seen below.

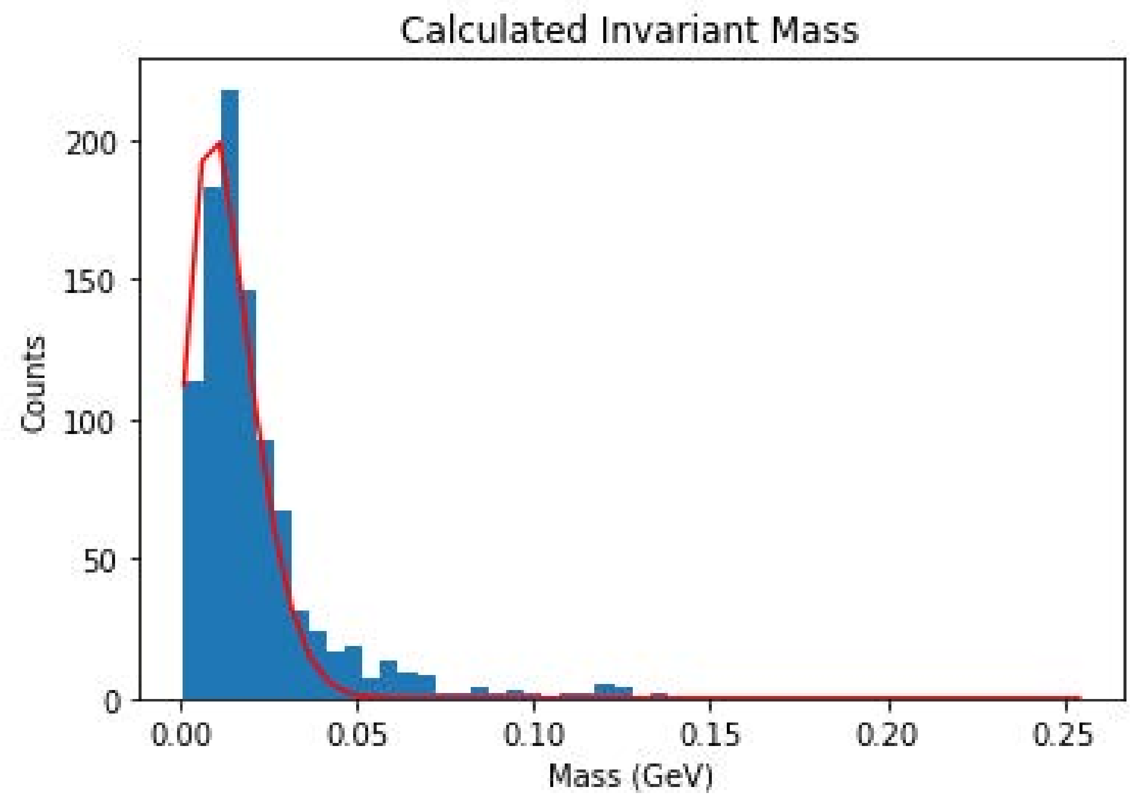

Figure 4.2: Histogram of Background Radiation with Fit. This is a histogram of the background radiation with a global skewed Gaussian fit.

With this global fit, however, the background residuals are significant, as the plot below shows.

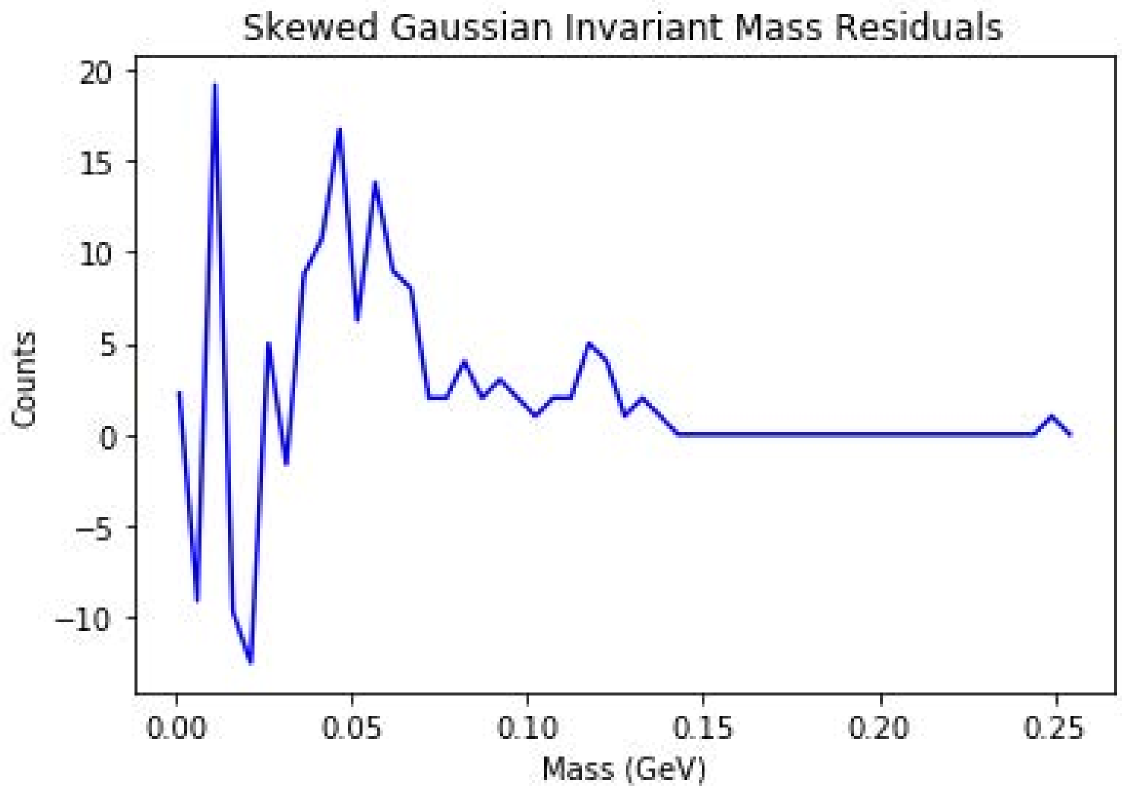

Figure 4.3: Global Skewed Gaussian Invariant Mass Residuals. This plot demonstrates the problem with doing a global fit, since the background residuals remain significant.

As can be seen above, it is not particularly useful to do a global fit because finding a fit that works for the full data set is difficult and unnecessary. Instead, the data close to possible peaks is what must be fitted. In this case, a 20-event peak was added at 0.102 GeV.

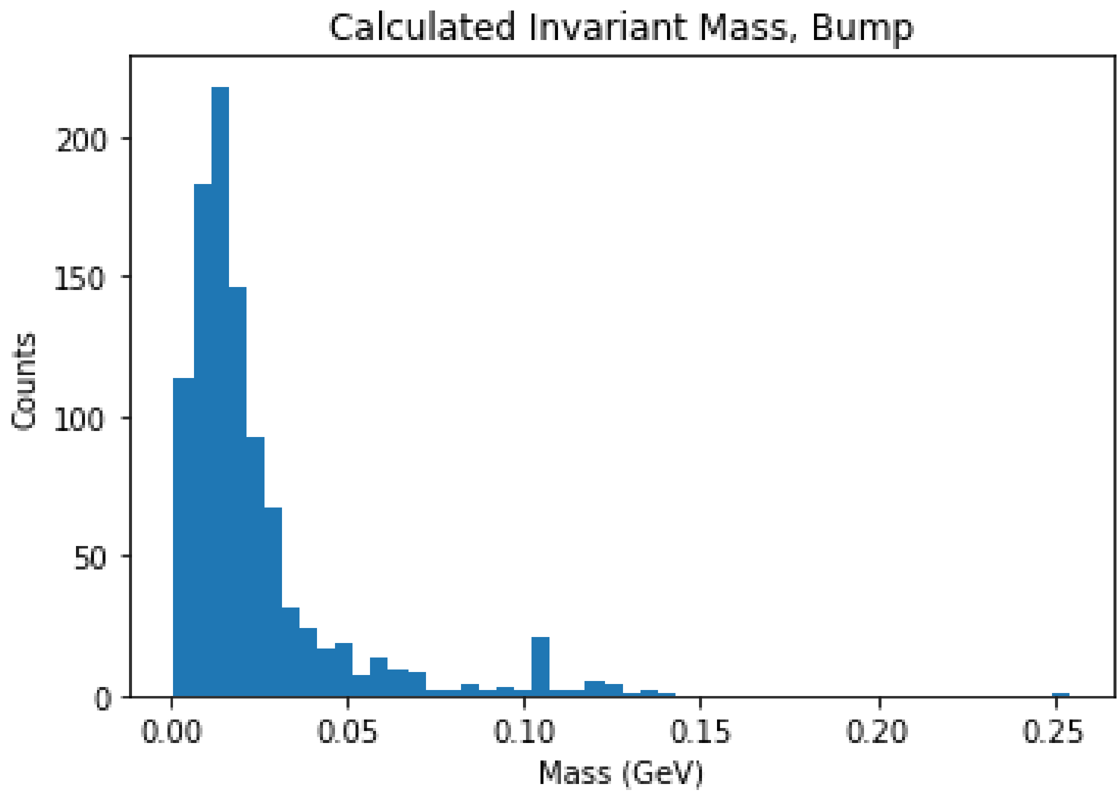

Figure 4.4: Histogram with Peak. This image shows the histogram of the data with an added peak of 20 events at 0.102 GeV.

A skewed Gaussian fit was done on each side of the peak, looking specifically at the data points near the peak. The plot below demonstrates the appropriateness of a skewed Gaussian fit.

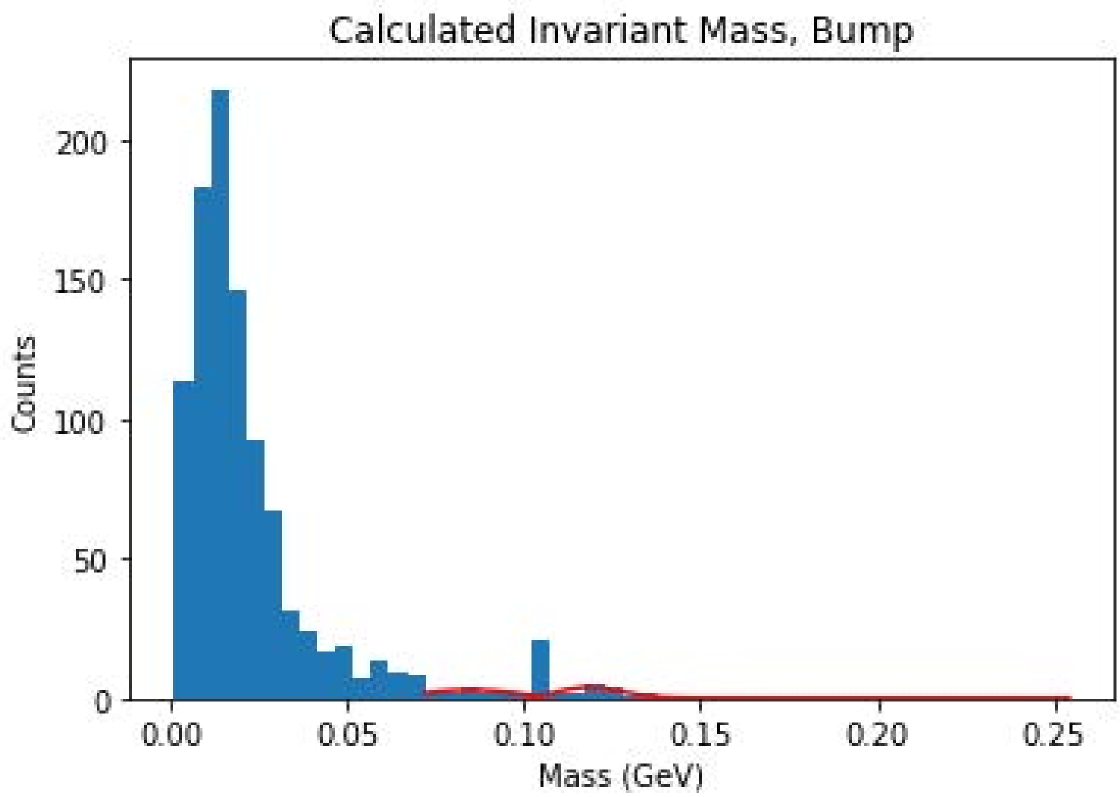

Figure 4.5: Local Fit. This image shows the histogram with an added peak at 0.102 GeV and a local skewed Gaussian fit on both sides of the peak.

When the local skewed Gaussian fit is subtracted from the background radiation, the resulting plot is has residuals of approximately zero, with fluctuations.

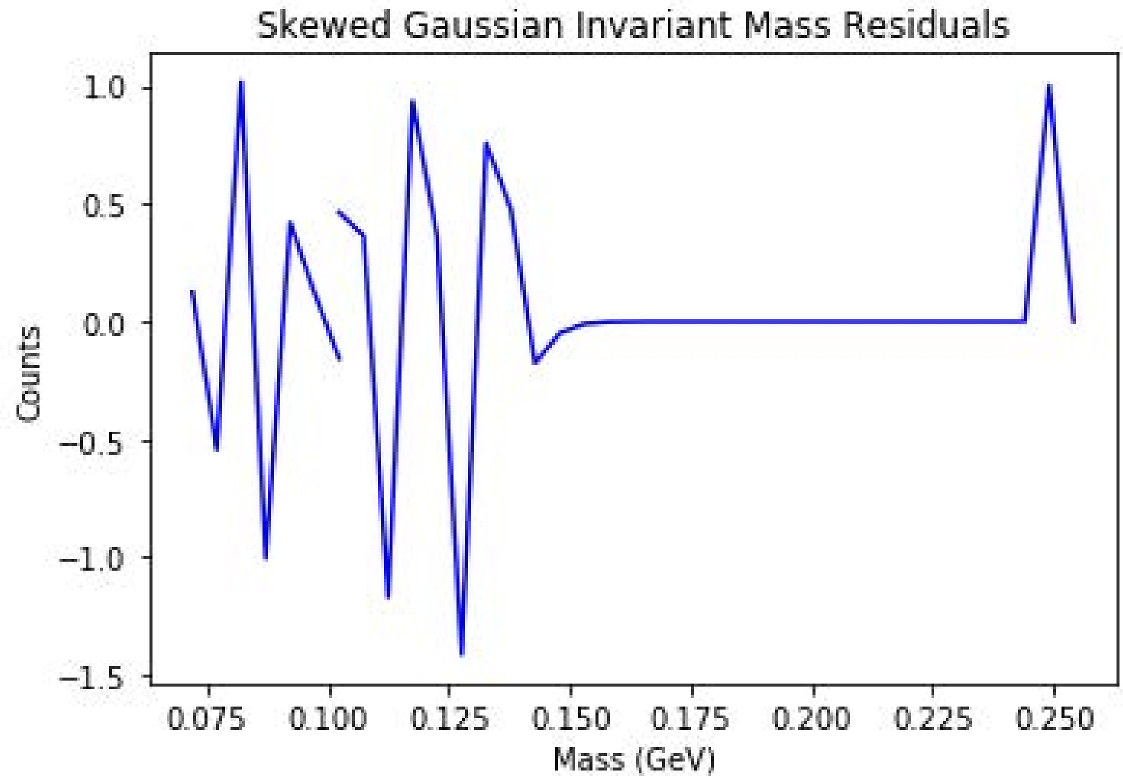

Figure 4.6: Background Residuals. This image shows the residuals when the local skewed Gaussian fit is subtracted from the background radiation.

When this fit is performed on the data with the added peak, the fluctuations from the background residuals become inconsequential when compared to the magnitude of the residuals for the added peak, as shown in the plot below.

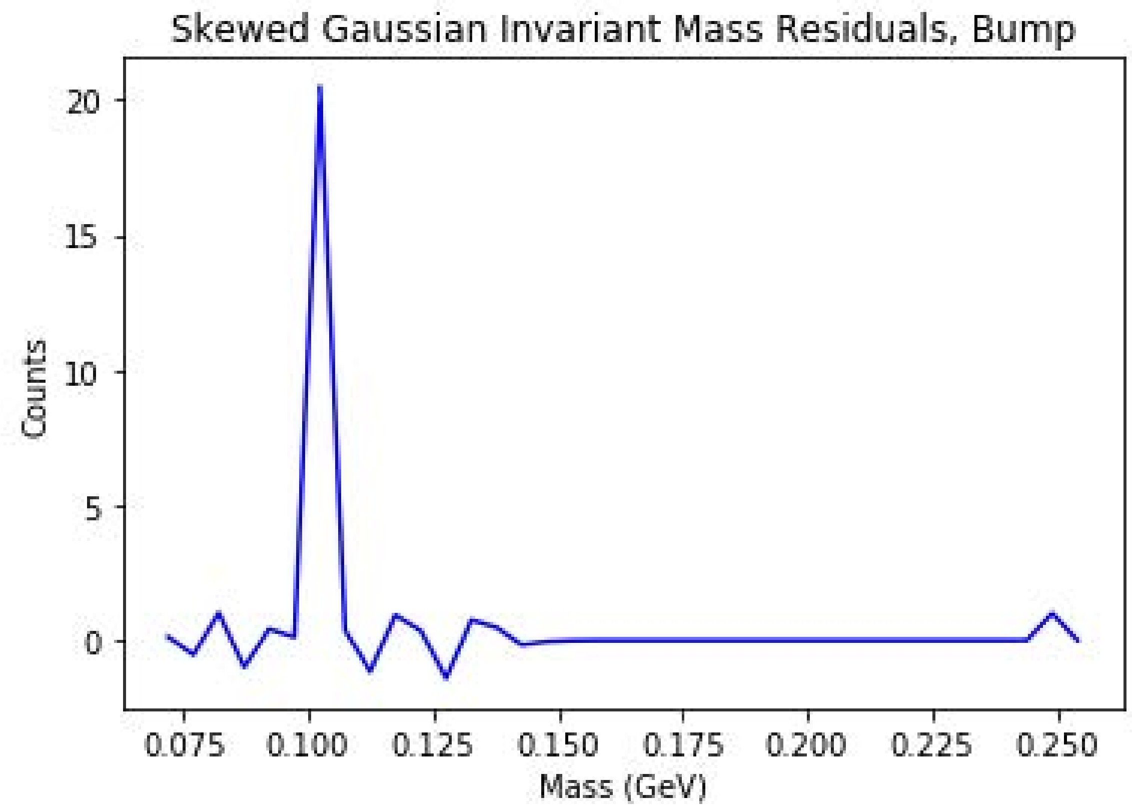

Figure 4.7: Peak Residuals. This image shows the residuals when the local skewed Gaussian is subtracted from the background with the added peak.

To determine the significance of the peak, its area must be compared to the width of the Gaussian being used to search for peaks. If its area is greater than five times the width of the Gaussian being used, then we have a significant result. If we assume a width the size of five bins, or 0.0498 GeV, the area under the curve for the five bins surrounding the peak must be greater than 0.249. In the plot above, the area under the curve is 30.44, which is greater than the barrier for significance. In the above example, then, the peak would be considered a significant one.

4.2 Writing

The book takes the reader through the tale of the main character's arrest for breaking the law of gravity. The main character subsequently has to prove her innocence by showing a jury that dark matter exists. Throughout the book, different detectives working to find dark matter are introduced, each of whom different experiment or theory about dark matter.

Over the course of the story, the reader learns first and foremost about what dark matter is and how physicists are searching for it. The reader also learns about different theories about the nature of dark matter. The reader also learns about some important principles of science, such as the importance of researching a range of different theories, and the necessity of taking all evidence into account. The full text of the book is attached to the end of this research paper.

4.3 Conclusions and Future Plans

The program used to model the background radiation demonstrated the expected shape of the background radiation. Furthermore, the analysis methods used to identify possible heavy photon events demonstrated the utility of using curves of best fit to identify peaks. Finally, a simple integration tool was used to demonstrate the relative ease with which the significance of peaks can be identified.

The most significant next step for this project is to use this fitting technique for real data, which is far less likely to have a visible peak. As a result, fitting real data is more difficult. Furthermore, in a real data set the resolution is determined by the resolution of the experimental setup, which would greatly affect the process of searching for peaks.

The book has been successfully written. It uses narrative to explain dark matter to children in the concrete operational stage of development. One possible next step is using a similar narrative model to explain other modern scientific topics, perhaps even creating a series of books combining story and STEM. Another useful area of research is finding ways to encourage students to think creatively and practically in STEM classes by developing lesson plans that approach STEM education through an interdisciplinary lens.

Appendix A

Plotting Program

A.1 Code sample

The following is the Python code which creates the background radiation histogram, fits it, and determines the integral of the peak.

```
/********************************************************/

#!/usr/bin/env python2
# -*- coding: utf-8 -*-
"""
Created on Mon Apr 16 19:19:30 2018

@author: agosling20
"""

import xlrd
import numpy as np
import matplotlib.pyplot as plt
from lmfit.models import SkewedGaussianModel, GaussianModel
import scipy.integrate as integrate

data = xlrd.open_workbook('data_final.xlsx')

sheet = data.sheet_by_name('Sheet2') #upload data from Excel doc

x = []
y = []


for rownum in range(1,984):
    x.append(sheet.cell(rownum, 11).value) #create array of masses

mu = sheet.cell(1,13).value
sigma = sheet.cell(2,13).value #upload mean and standard deviation from Excel sheet

fig, ax = plt.subplots()
```

```
num_bins = 50

n, bins, patches = ax.hist(x, num_bins) #generates histogram

print bins

l = np.append(n,0) #used to maintain array size
p = l[14:21]
bens = bins[14:21]
o = l[20:]
buns = bins[20:]



model1 = GaussianModel() #model used to fit
params1 = model1.make_params(amplitude=10, center=mu, sigma=sigma, gamma=0) #initial guess
result1 = model1.fit(l, prefix=params1, x=bins)
z1 = l - result1.best_fit

model2 = SkewedGaussianModel() #model used to fit
params2 = model2.make_params(amplitude=10, center=mu, sigma=sigma, gamma=0) #initial guess
result2 = model2.fit(o, prefix=params2, x=buns)
z2 = o - result2.best_fit

model3 = SkewedGaussianModel() #model used to fit
params3 = model3.make_params(amplitude=10, center=mu, sigma=sigma, gamma=0) #initial guess
result3 = model3.fit(p, prefix=params3, x=bens)
z3 = p - result3.best_fit


print (result1.fit_report())
print (result2.fit_report())
print (result3.fit_report())

 #subtract fit from histogram data, shift plot up

a = []
b = []

for rownum in range(1,1004):
    a.append(sheet.cell(rownum, 11).value) #create array of masses

fig1, ax1 = plt.subplots()

num_byns = 50

m, byns, patches = ax1.hist(a, num_byns)

r = np.append(m,0)
s = r[14:21]
```

```
baens = byns[14:21]
t = r[20:]
bions = byns[20:]

z4 = t - result2.best_fit
z5 = s - result3.best_fit


plt.figure(1)
ax.plot(bens,result3.best_fit, 'r-')
ax.plot(buns,result2.best_fit, 'r-')
ax.plot(bins, result1.best_fit, 'r-')
plt.title('Calculated Invariant Mass')
plt.xlabel('Mass (GeV)')
plt.ylabel('Counts')

plt.figure(2)
ax1.plot(bens,result3.best_fit, 'r-')
ax1.plot(buns,result2.best_fit, 'r-')
plt.title('Calculated Invariant Mass, Bump')
plt.xlabel('Mass (GeV)')
plt.ylabel('Counts')

plt.figure(3)
plt.plot(buns,z2, 'b-', bens, z3, 'b-')
plt.title('Skewed Gaussian Invariant Mass Residuals')
plt.xlabel('Mass (GeV)')
plt.ylabel('Counts')

plt.figure(4)
plt.plot(baens,z5, 'b-', bions, z4, 'b-')
plt.title('Skewed Gaussian Invariant Mass Residuals, Bump')
plt.xlabel('Mass (GeV)')
plt.ylabel('Counts')

plt.figure(5)
plt.plot(bins,z1, 'b-')
plt.title('Skewed Gaussian Invariant Mass Residuals')
plt.xlabel('Mass (GeV)')
plt.ylabel('Counts')

z6 = np.append([z5],[z4])
print z6

I = integrate.simps(z6[6:10])#area under whole flat part of curve
Q = I #area at bump point

plt.show()

print Q
```

Appendix B

References

This page contains references used for the book, but that are not cited in the text, while the formal bibliography contains the sources used in this paper. Although these references could be cited in the text of the book itself, acknowledging the authors of these references is necessary, as this project could not have been completed without their work.

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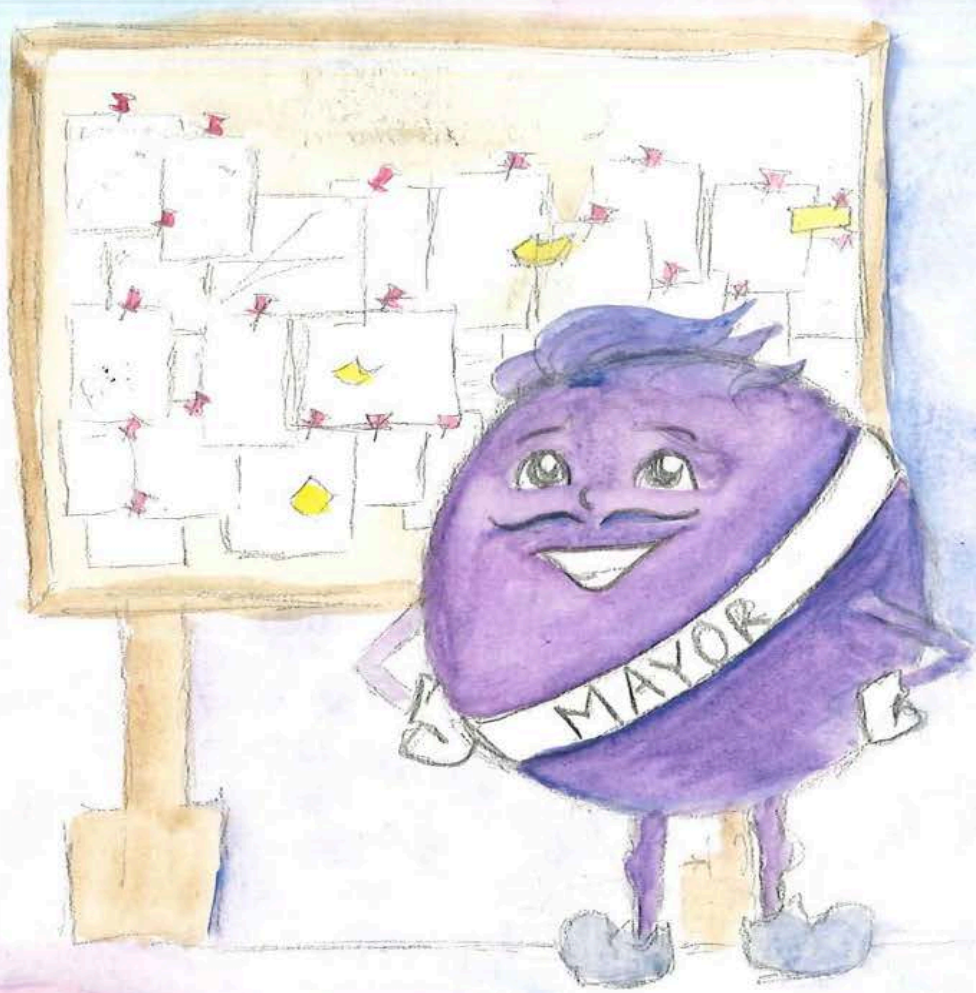
Dark Matter: the Completely True Story of My Run-in with the Law

By A.K. Gosling
Illustrated by Lena Menton

Chapter 1: In the Beginning

This is me

Here's my neighborhood:



Like any neighborhood, my neighborhood in the Milky Way has rules, and they're very strict. As a citizen of the Milky Way, I am required to follow all of its laws. Most of them are easy to follow, but a few are important to know.

Law of Gravity

All objects that have mass must be attracted to one another. The attraction will be greater if masses are closer to one another. Large masses will create stronger gravity fields than small masses.

Law of Electricity

Some objects may have positive or negative charges. Objects with a negative charge must be attracted to objects with a positive charge. Objects with a positive charge must be attracted to objects with a negative charge. Objects with the same charge must be repelled from one another.

Law of Magnetism

When charges move, they must create magnetic fields. If charges move, it must be called a current. All currents must interact with perpendicular currents, but may not interact with parallel currents. Magnetic fields must wrap around the currents generating them.

Requirements for Electromagnetic Waves

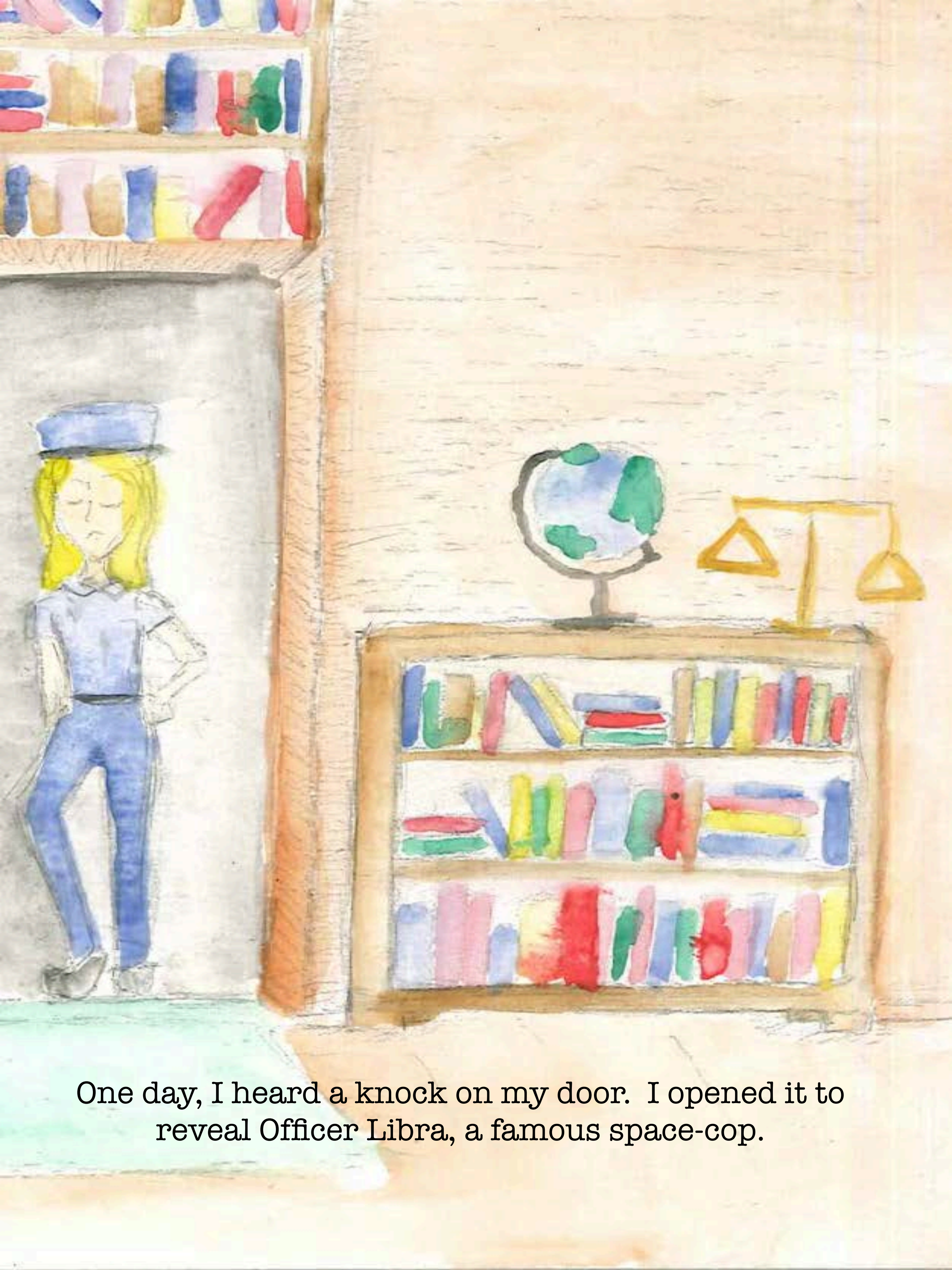
Electromagnetic waves are required to be made of electric and magnetic fields. Electric and magnetic fields must be perpendicular to one another. Electromagnetic waves must be able to move in any situation, even if no matter is present.

Law of Force

Forces must cause masses to accelerate. For this law, acceleration is defined as any change in the speed or direction of an object's movement. Only forces are allowed to cause masses to accelerate.

I had always been a law-abiding citizen. After all, the Laws of the Universe are easy to follow.

Or so I thought...



One day, I heard a knock on my door. I opened it to reveal Officer Libra, a famous space-cop.

“Officer Libra! I’m so excited to meet you! Do you need my help with a case? Can I help you find the Rogue Comet? I lo---,” suddenly, before I could finish proclaiming my love for her work, she cut me off.

“Enough! You have been charged with breaking the Laws of the Universe. Anything you say can and will be used against you in a court of law. Will you come quietly?” she spat.

“But...but....I haven’t done anything wrong!” I protested.

“Enough with the act. The officers at the Universal Investigation Bureau have been watching you for quite a while. We know what you’re up to. You’ve been flouting the Law of Gravity for long enough. Officers, take her away”


Pulice

Chapter 2: Legal Advice

When I entered the police station, I looked around wildly, searching for friendly faces. But there were none. Everyone looked at me with disapproval. I remember hearing someone murmur under his breath about “kids these days,” while his friend looked on in disdain.

I was taken to a room and quickly photographed by one police officer. Another took my fingerprints. Neither one looked particularly sympathetic, and I was too scared to make eye contact.

Luckily, I travelled quickly through the station and was able to avoid having to talk to anyone. Unluckily, the room I ended up in was even less appealing than talking to the other people in the station. Even now, I remember it like it was yesterday.

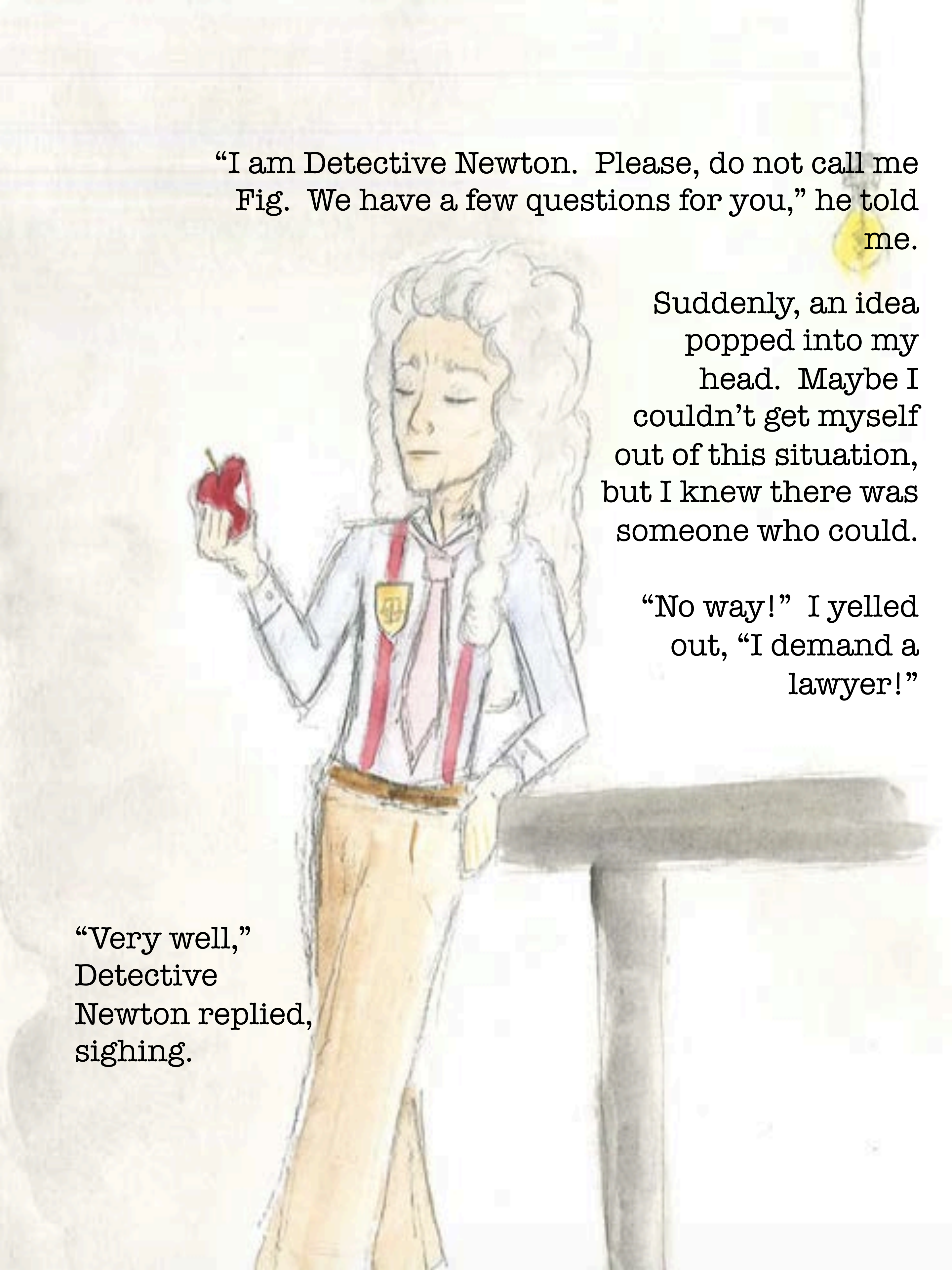

MILKY WAY
6.67×10^{-11}
DOB:3.14.159
MILKY W
6.67×10^{-11}
DOB 3.14.
L
R

Officer Libra marched me to the cold, metal chair and handcuffed me to the cold, metal table. Above me, a single, bare light bulb flickered slightly. On one wall of the room was a mirror. When I looked at it, my frightened eyes stare back.

Just imagine. Here I was, sitting in a cold, dark room in handcuffs. My favorite policewoman had arrested me for breaking one of the most important laws of the universe. And I had no idea why. Naturally, all sorts of horrible thoughts began running through my mind.

"How did I get into this situation? And how can I get out?" I asked myself. "What if I end up in prison? I could be there forever." I was terrified. The longer I sat there, the more worried I got.

After what felt like an eternity, a man came into the room.



"I am Detective Newton. Please, do not call me Fig. We have a few questions for you," he told me.

Suddenly, an idea popped into my head. Maybe I couldn't get myself out of this situation, but I knew there was someone who could.

"No way!" I yelled out, "I demand a lawyer!"

"Very well," Detective Newton replied, sighing.

I let go of a breath that I hadn't realized I was holding. Detective Newton turned around and gestured at the mirror, which I suddenly realized was actually one-way glass. Officer Libra came back into the room, unlocked my handcuffs, and escorted me to a much more appealing room. For the moment, I was out of the woods.

Although a guard remained outside the door to the room, I was happy to be free of my handcuffs and out of the interrogation room. However, I was still worried. I wasn't even sure what law I supposedly broke, let alone how to prove my innocence. Lost in thought, I don't notice the woman enter the room until she started talking.

She cleared her throat to get my attention before introducing herself. “Hello. I am Aletha. I’m here to help. What’s your situation?”

“I’ve been arrested for...well, I’m not sure exactly,” I stuttered out. “Officer Libra said something about the Law of Gravity? But I don’t really know much about it.”

“Ah, the Law of Gravity,” she replied, “that’s a tricky one. I’ve actually had a surprisingly large number of cases for people accused of breaking the Law of Gravity.”

“Did you...could you...were they acquited?” I asked.

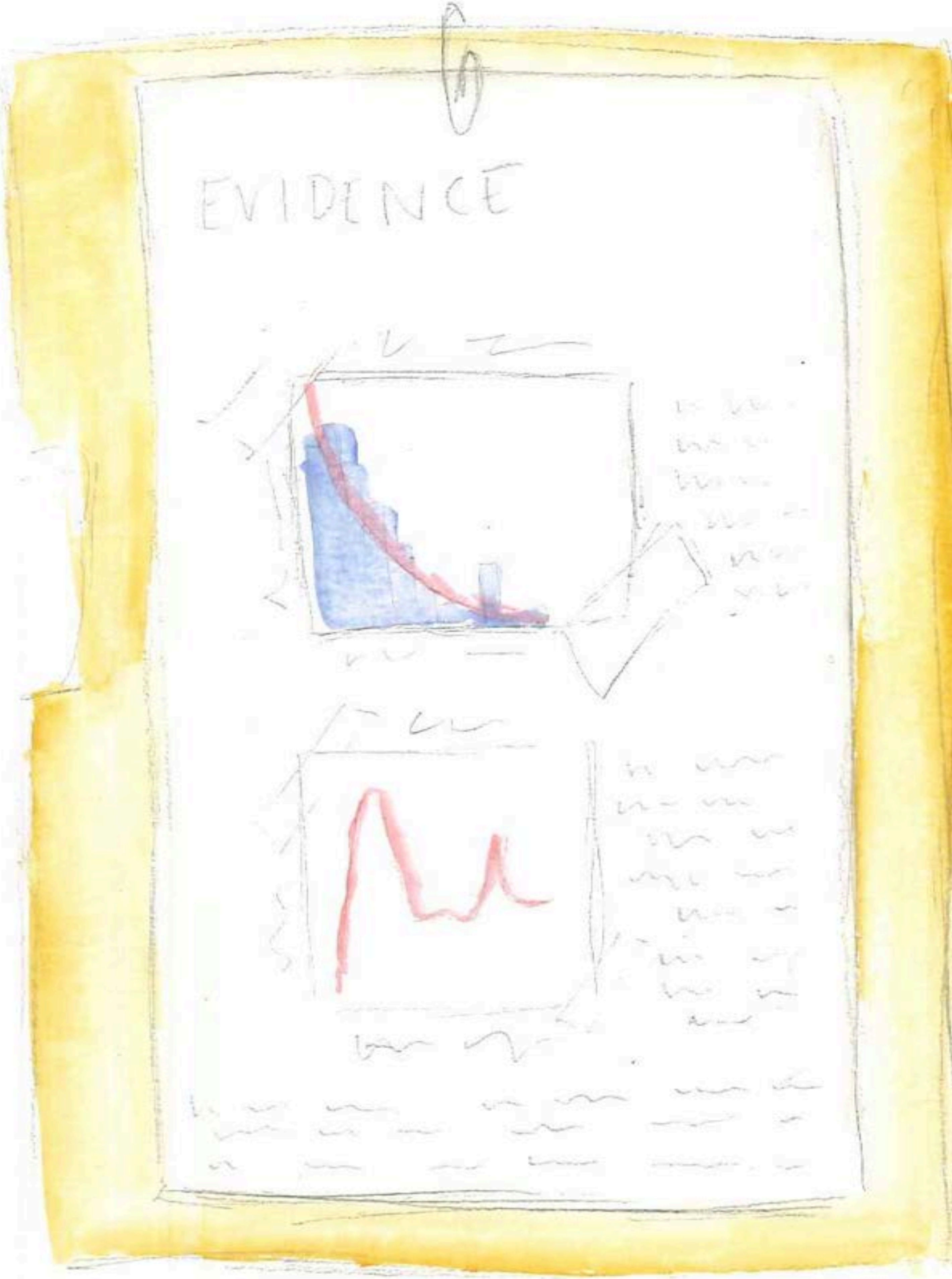
“They’re all serving long jail terms,” she replied. “The law is strict, and the evidence was air tight.”

When she said that, all the blood drained from my face. “But...but I didn’t do anything wrong!” I said. “Please, I need your help.”

"That's what my other clients all said. It didn't help them in court, but," she lowered her voice, "I think something is wrong. All of these people, sent to prison for breaking the Law of Gravity, and all of them claiming their innocence still. None of them even seemed to expect the police to come. Something is up."

"What do you mean?" I asked, whispering.

"Something is affecting the Law of Gravity," she says, her voice so quiet I could barely hear it, "something we can't see. Something we can't touch. I have my best detectives on the case." She pulled out a thin file and handed it to me.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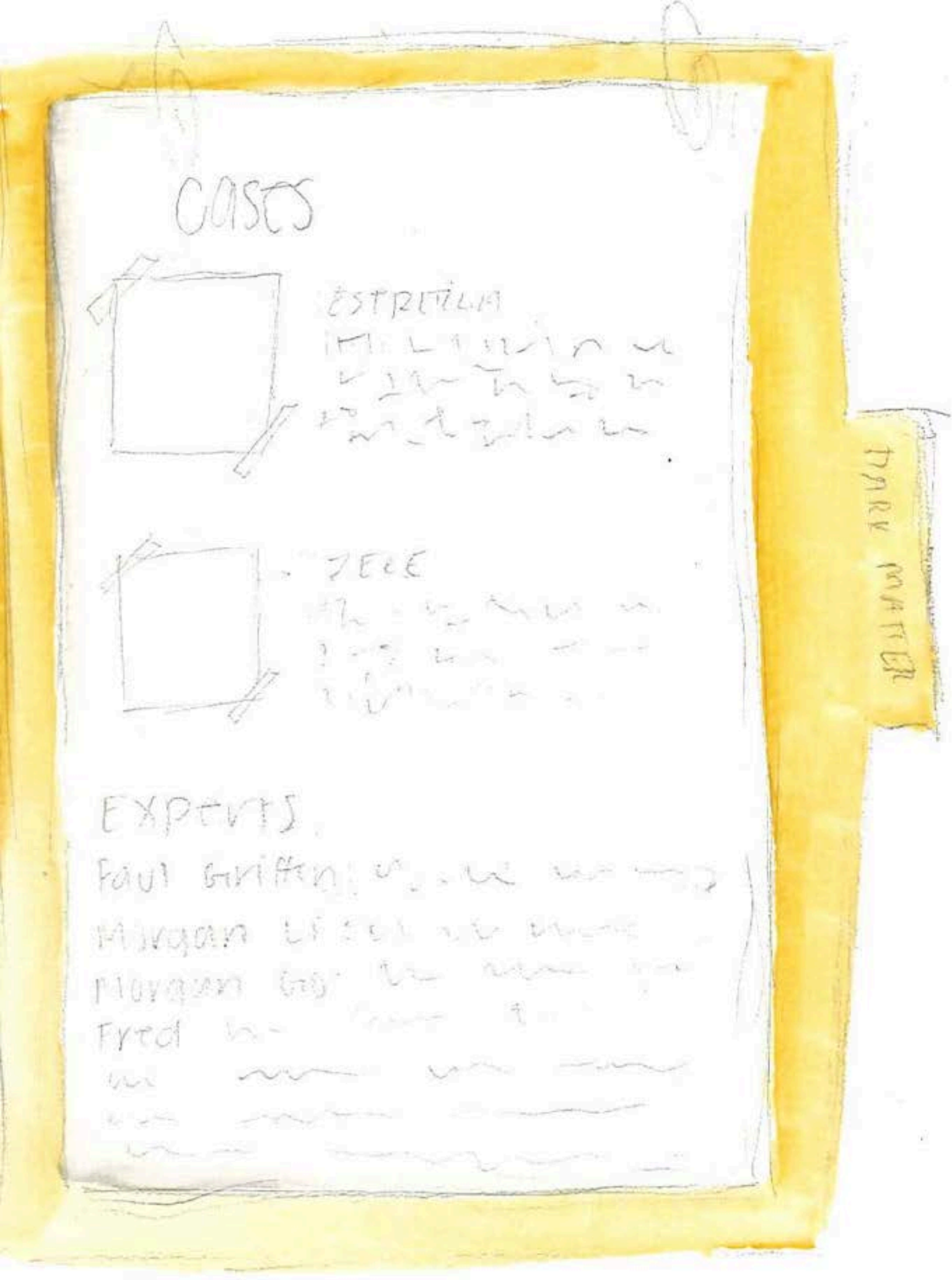


CASES
ESTRELLA
ZEKE
Experts
Paul Griffin
Morgan
Morgan
Fred
DARK MATTER

I looked up from the page. “What are you suggesting?” I asked Aletha.

“It’s all part of a massive conspiracy,” Aletha replies. “A criminal organization is affecting the Law of Gravity and making innocent people like you move too quickly. These criminals are why you’ve been arrested. You’ve been set-up!”

“It doesn’t really seem like you have any information on them,” I replied, unconvinced, “how do you even know they’re real? What kind of a name is ‘Dark Matter’ anyway? Did you just make it up?” It was a shame that the only person who believed me was a nutcase like Aletha who believed in some made-up criminal organization.

“What makes you think my arrest isn’t just a fluke?” I challenged. “What if I’m a hardened criminal?” I folded my arms and glared at her, trying to look tough.

“You?! A hardened criminal? You look like you’ve never even looked at a picture of a non-Newtonian fluid, let alone broken the Law of Gravity.” Aletha chuckled. I was a bit hurt. After all, I’m a pretty tough person. But before I could think too much about it, she continued talking.

“For your information, we call this criminal organization Dark Matter because it doesn’t interact with light but it does interact with gravity. And finding Dark Matter is your best hope for acquittal, so you'd better hope I can do it!"

"And how do you plan on doing that? You don't know what Dark Matter looks like, its name is made up…you don't even know how big it is!" Who was she to tell me what my situation was? She wasn't the one who might go to prison.

"I have a plan." Aletha handed me the next page in the file.

"You have leads?" I asked. For the first time, it seemed like I might have a hope of winning my trial. From that moment on, I knew I had to trust Aletha. She was my only hope.

"Not just leads," she replied, "experts. Brilliant in their field, and all trying to find this sneaky group."

"I want to meet them," I announced, "I need to see what they've found. I need to find this 'Dark Matter.'"

"Very well," she replied. "I will bring the first detective in to talk to you tomorrow."

With a bright smile, I hugged her. "Sounds like a plan!" I said. I was so excited. I knew that going free was a long shot, but her ideas gave me hope for the future.

Chapter 3: The First Detective

The next day, I woke up completely confused. "Where am I?" I wondered, my eyes darting around the room. As I took in my surroundings, I remembered everything that happened yesterday. Officer Libra arresting me for breaking the Law of Gravity, Detective Newton and his strange jokes, Aletha and her kind words, and, most importantly, the mysterious Dark Matter.

"What am I going to do? How can I get myself out of this mess?" Thankfully, I had a chance to talk to one of Aletha's experts that day. Just as I was about to get lost in thought again, one of the prison guards opened the door.

"You have a visitor," he said. "Follow me."

I was escorted out of my cell and into the conference room from the day before. Waiting for me were Aletha and a tall man with dark hair and glasses. The guard left, locking the door behind him.

"Good morning," Aletha said. "I'd like to introduce you to Paul Griffin, the first of our experts."

"It's very nice to meet you, Paul. Aletha tells me you are searching for this Dark Matter," I said with a nervous smile.

"That I am," he responded. "She tells me that you are Dark Matter's newest victim."

"What?" I asked. I was completely confused. How was I a victim? Dark Matter hadn't attacked me, as far as I could tell.

"Well, yes. Isn't Dark Matter framing you for breaking the Law of Gravity?"

I was shocked. I hadn't thought about my situation that way. "I…I guess you're right," I told him.

"People like you are why I and my team are so intent on finding this crook," he told me with a kind smile. "It's not right for so many innocent people to be locked up for a crime they didn't commit."

With a small smile, I looked up at him. For the first time, it felt like I might have a chance of being freed. And to have someone so firmly believe in my innocence! After only one day in prison I had already begun to believe that no one cared that I was innocent. It seemed like everyone thought I was guilty. But Paul's kind words were a reminder--people did love me, care about me, and believe in me.

"How are you finding Dark Matter?" I asked him, hope rising in my chest.

"I'm glad you asked!" he said. His eyes lit up, a giant smile broke out across his face, and he began his explanation.

"Dark Matter is a tricky beast to find. As Aletha told you yesterday, the reason we call it DARK Matter is because it doesn't interact with electromagnetic forces, including light. This means that we can't see it with our eyes, even with the help of a telescope or microscope.

However, because it is Dark **MATTER** it does interact with gravity. Detectives looking for Dark Matter say that something has matter if it has both mass and volume, which means that it has to weigh something and take up space.

Aletha told me she showed you the file on Dark Matter. Now, many experts in my field think that Dark Matter is a large organization. It's a big group of tricky little beasts. Each one has very little mass and volume on its own, but as a group they weigh a lot and take up a lot of space."

"Wait, what?" I exclaimed. "How many people are in this crime ring, exactly? I thought it was just a few, but it sounds like you think Dark Matter is huge."

"It's complicated," Paul Griffin responded. "We think that Dark Matter is a bunch of copies of one person. It's as though one evil mastermind cloned himself in order to wreak havoc on the Law of Gravity and send innocent people like you to jail. But please, let me continue."

Although I was still confused, I let him finish talking. Maybe it would all make more sense after he finished. He began explaining once more.

"What you must know is that anything with mass affects the Law of Gravity. What you may not know is that Detective Newton was the man who wrote the Law of Gravity. There are two important parts to the Law of Gravity. First, if you weigh the same as two books, your gravity field will be twice as strong as the field of one book. Second, if you are one foot away from a baseball your gravity field will be four times stronger than if you are two feet away from a baseball.

Detective Newton's Law of Gravity determines where everything in the galaxy is and how quickly it is moving. But the Law of Gravity only takes regular matter, things we can see like you or me, into account. Since we can't see Dark Matter, people like you sometimes seem like they're moving too quickly and they get thrown in jail."

“I know that! Can you please tell me something new?” I asked. I had been thrown in jail for breaking the Law of Gravity, and now all Paul was doing was telling me exactly what I did wrong. As far as I could tell, that was about as helpful as telling a person in a sinking ship that ships should try to avoid running into rocks.

“Calm down,” Aletha scolded me. “Paul is just trying to help.” She turned to Paul, “I know you like explaining your work from the beginning, but I think my client is more concerned with how you’ll help us win the court case. After all, her future is on the line.”

“Are you sure?” Paul Griffin responded. “The whole situation is just so interesting! Don’t you want to know all the details?”

“I’m sure it is,” I said, “but I just want to get out of here. I miss my family, and I’m scared I’ll never be able to go back to them.” I teared up a bit thinking about it.

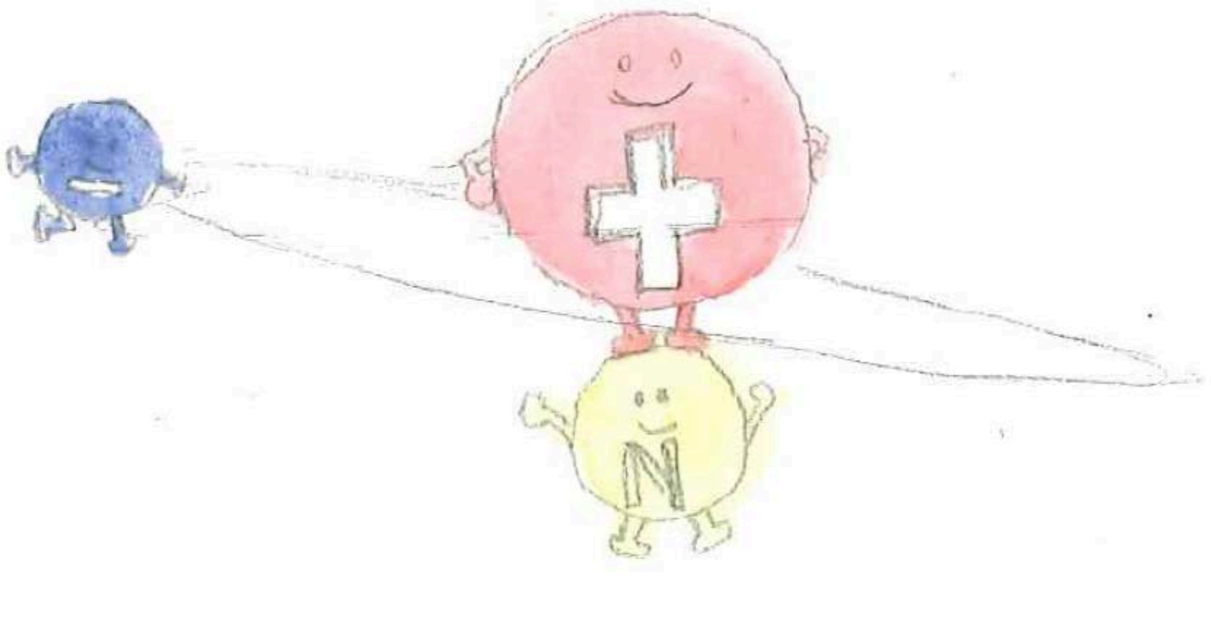
Paul’s eyes softened, and he gave a kind smile. “I understand,” he said. “I have a bit of a tendency to get caught up in the search and forget how much you have at stake. Let’s get down to business.”

He continued his explanation. I just hoped he’d get to the point soon.

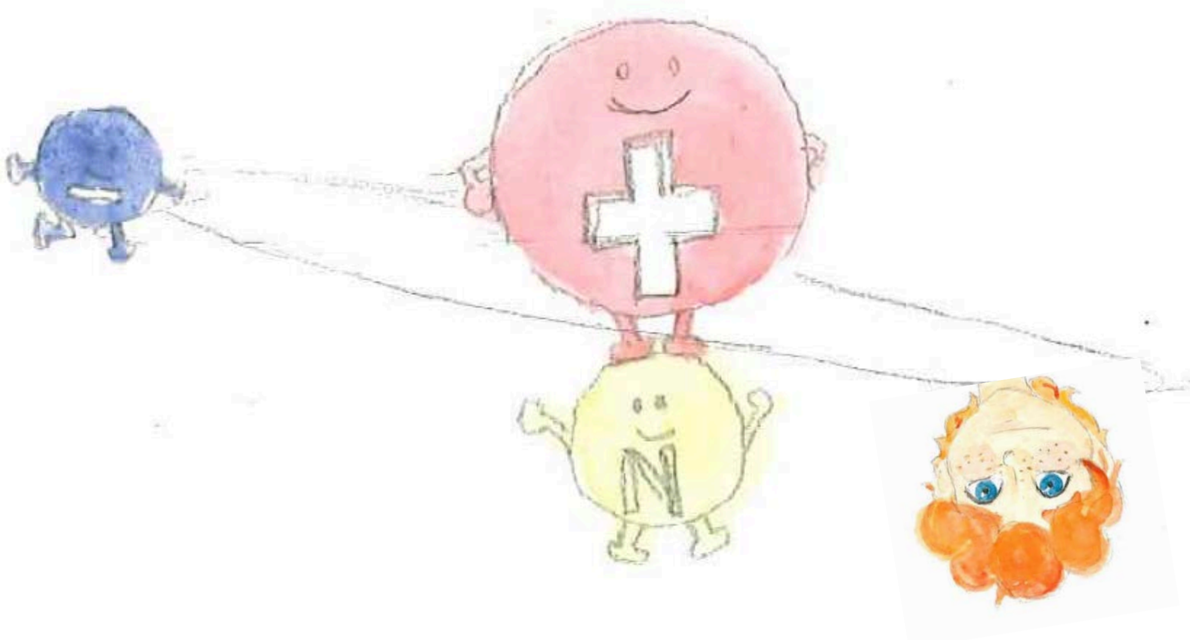
"My detective agency bases our work off of a very strange principle. You see, very small things tend to move in waves, like an ocean. For example, electromagnetic waves like light are made up of very small particles called photons. Photons are very small and they don't have any mass!

One important small particle is the electron. One of the things that makes electrons special is their charge. Electrons have a negative charge.

When you combine electrons with two other particles, positively charged protons and neutral neutrons, you can make different kinds of atoms. Atoms have protons and neutrons in their centers and electrons spinning around them."



"Atoms are the building blocks of everything. For example, water is made up of hydrogen and oxygen atoms.



Electrons spin around the center of an atom. They can only spin at certain distances from the center of the atom. These distances each have a different energy. The positively charged protons in the middle of the atom pull more strongly on the electrons close to the middle of the atom than the ones far away from the middle of the atom.

"Paul, I thought you said you were getting to the point!" you interrupt, "it seems to me as though you're farther away from Dark Matter than you were before."

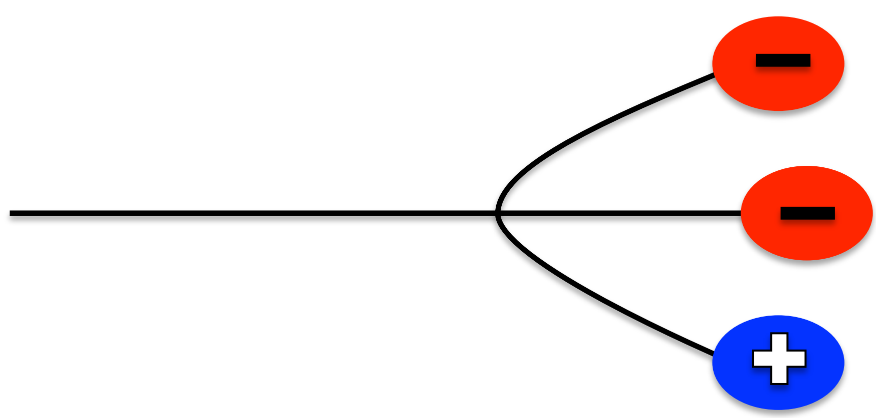
"I'm getting there," Paul responds, "but I really can't explain my search if I don't explain this."

When an electron is hit by something with higher energy, it moves to a higher energy level. But eventually, it falls down to a lower energy level, just like how someone can get a sugar high ...

...but then a little bit later will crash

When it falls down, it releases a photon. Now, we believe that Dark Matter might also be small enough to move in waves. We also think that Dark Matter could be released when an electron changes energy levels.

In our search for Dark Matter, we are trying to find out if Dark Matter could be released when an electron hits a heavy metal target. When the electron hits the target, Dark Matter might be produced. However, the Dark Matter will decay into an electron and a positron. A positron is exactly the same as an electron but with a positive charge.



We can find Dark Matter by reconstructing what it looks like. Now, another detective showed that mass can turn into energy. Dark Matter creates an electron and a positron that are both moving very quickly. If we add together the mass and energy of the electron and the positron, we can figure out the mass of the Dark Matter that created the electron and the positron.

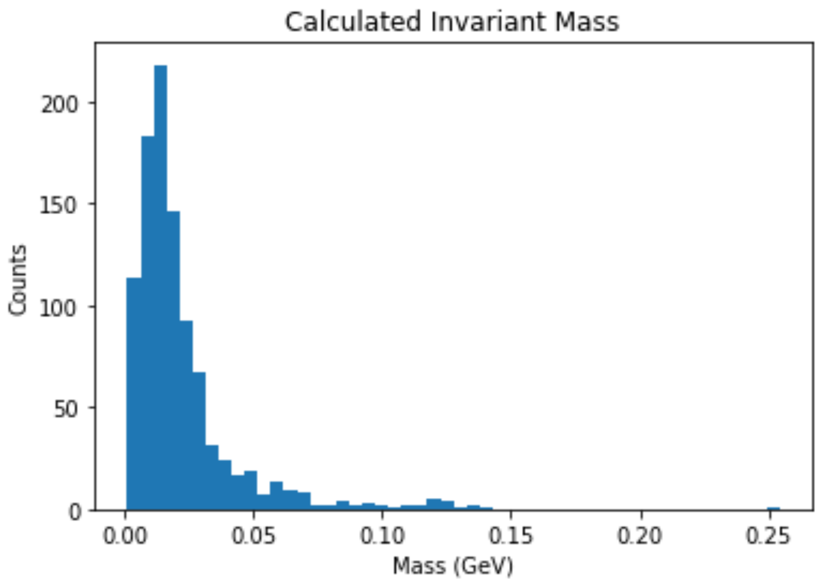
Your explanation sounds pretty straightforward," you interrupt, "why haven't you found it yet?"

"Ahh," sighs Paul, "I haven't explained our problem yet. You see, the amount of electron-positron pairs produced by the Dark Matter is a lot smaller than the number of pairs produced by the regular photons that we know are produced in this interaction. We also can't determine if a photon or Dark Matter made each electron-positron pair."

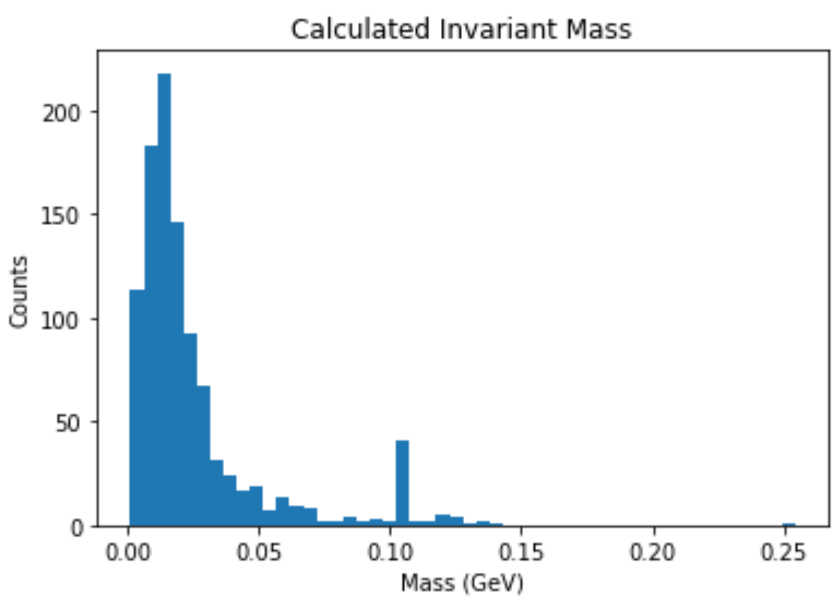
Well, that made the whole thing more complicated. I decided it was time for me to ask another question, just to make sure he could actually find Dark Matter. "So how do you figure out if Dark Matter is hiding among the photons?"

"What a good question!" Paul Griffin's voice rose in excitement, "I'm so glad you asked. Finding Dark Matter is our current task."

You see, we can use math and the laws of our universe to predict what the range of energy produced by just photons radiating looks like.



But if Dark Matter is hiding, then there will be a bump in the graph right at the mass of Dark Matter.



If we can find a bump in the graph, then we'll have caught Dark Matter red-handed!

“Did you find a bump?!” I asked, jumping out of my seat in excitement. “Show me your graphs! Maybe I can find one!”

“Woah there, bud! Slow down a bit!” Paul said as he backed away from me. “You need to have a certain amount of experience to help me, because there are some bumps in the graph that happened because of random chance instead of Dark Matter. You need some training to figure out which bumps are real, and I don’t think you have enough time before your trial for that.”

Calming down, I sat back in my chair.

“Sorry, I was just excited,” I said, blood rushing to my cheeks. In a more normal voice I asked, “can I help with the hunt? I would love to get out of here as soon as possible.”

“I appreciate your offer, but there’s not much for you to do,” said Paul. “I have a team of experts working on it. They’ll come up with the results in a few months. If we get even a hint that Dark Matter is hiding out in electron beams, we’ll let you know!”

“But…but…but I thought you were here to help with my court case!” I stuttered, “Aletha said you were an expert! She said you would get me out of here! I can’t wait a few years!”

“I said he was on the case,” Aletha reminded me. “It’s hard to find someone as elusive as Dark Matter. You need to give Paul Griffin and his team time so they can get definitive proof."

"I don't have time to wait for them to get proof! My court date is in two months! Please tell me you have a better expert than this guy. I need evidence." I was terrified. If Aletha's experts couldn't find Dark Matter then I would get thrown in prison.

"I'm working as quickly as I can," Paul said, trying to soothe me.

"But not quickly enough to help me," I retorted.

"Paul, do you have any early results I could use?" Aletha asked. "All I need is a reasonable suspicion that Dark Matter is framing her for this crime. I don't need perfect proof."

"Not yet, Aletha, but I'll get them to you as soon as I do. If we don't wait for perfect proof, maybe I'll have them ready in time for your trial."

"Thank you so much, Paul!" I exclaimed. I was so excited that I wrapped him in a bear hug.

He seemed surprised. He starts a bit before returning my hug. He whispered in my ear, "it's all going to be okay. You can get through this."

“I’ll bring in new experts, Morgan & Morgan, Private Eyes, for you to talk to tomorrow,” Aletha told me. “Paul is only one of the people searching for Dark Matter. I have a few other detectives on the case.”

With a smile, I called for the guard and was escorted back to my cell. This morning it had been scary, cold, and dark. When I got back it was still cold and dark, but it felt more welcoming because I had hope for the future.