The Effects of Energy Densities on the CMB Power Spectrum

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Overview of CMB

The Cosmic Microwave Background radiation (CMB) is electromagnetic (EM) radiation from the time of the Big Bang. It was once incredibly hot but has over time has been red-shifted, and cooled significantly, and is now only ~2.7K.

At “cosmological scales” (~100Gpc), it may be considered to be homogeneous and isotropic, that is to say, the same in all locations and in all directions. However, we know this not to be the case.

Although it appears to be very uniform initially, there are temperature fluctuations of the order of μK. This is what we call the anisotropy.

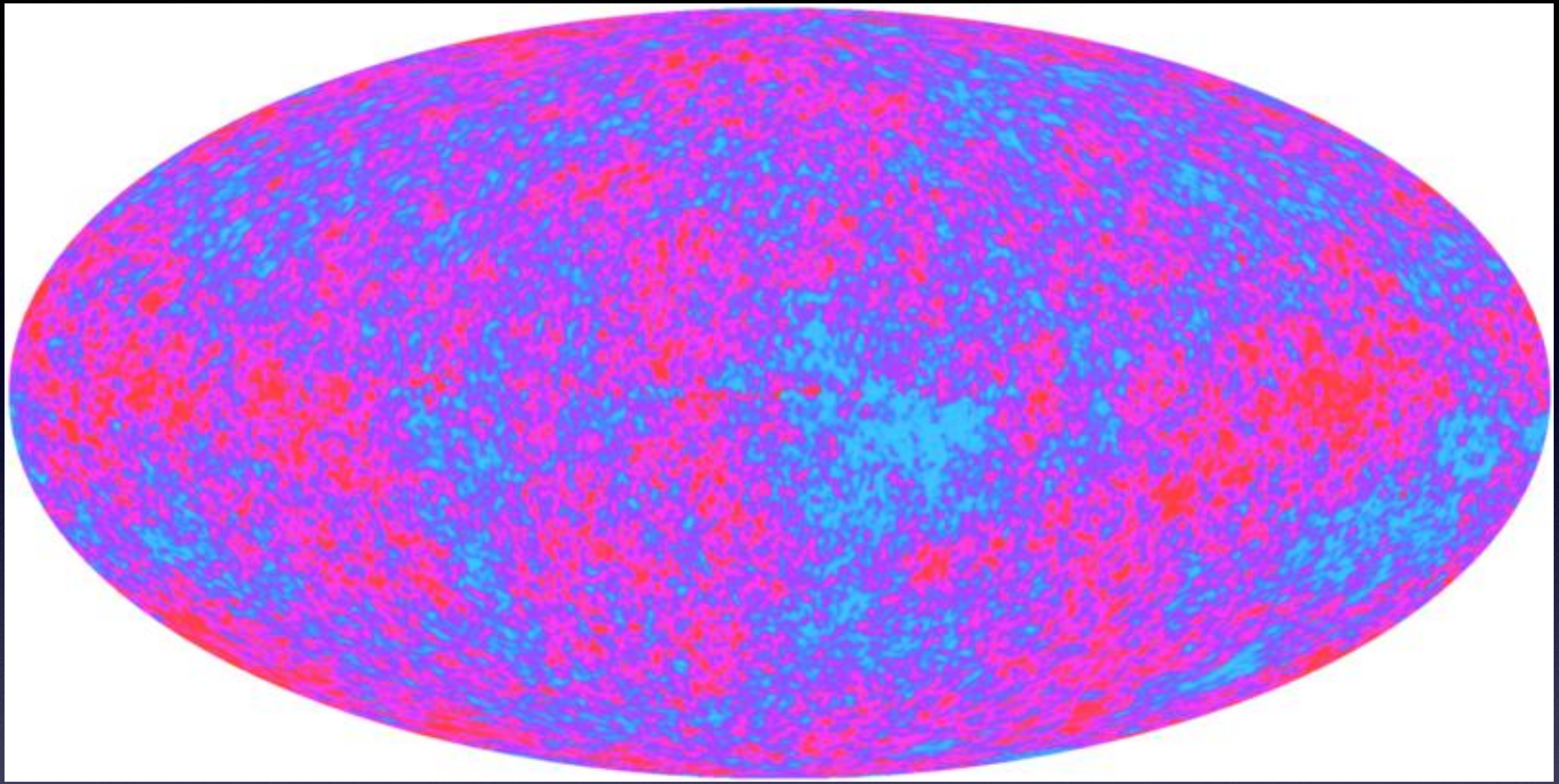

Figure 1: WMAP CMB Anisotropy Photo.

WMAP CMB Anisotropy

If the CMB were truly isotropic, this wouldn't have such a characteristic speckled appearance.

Overview of CMB

Because of the nature of the projection of the temperature fluctuations (specifically as that of a 2D sphere), we use spherical harmonics to describe the anisotropy. Having said that, the precise equations were not within the scope of this research.

Instead, the focus is on a particular expression, l. This is known as the multipole moment. As it turns out, the CMB spectrum is actually an angular power spectrum; each value of l corresponds to an angle in degrees, with higher values relating to smaller and smaller angles.

The smallest of these multipoles is a dipole; just two opposite poles, like a bar magnet. The more poles there are, the more opposite zones there will be.

CMB Power Spectrum

Plotting the multipole moment ℓ against the temperature fluctuations in μK^2 is what gives us the familiar CMB power spectrum. Note the correspondence between ℓ and the angle in degrees, specifically where ℓ~200 corresponds to a 1° shift between differing zones. This also happens to be where the highest temperature fluctuation occurs.

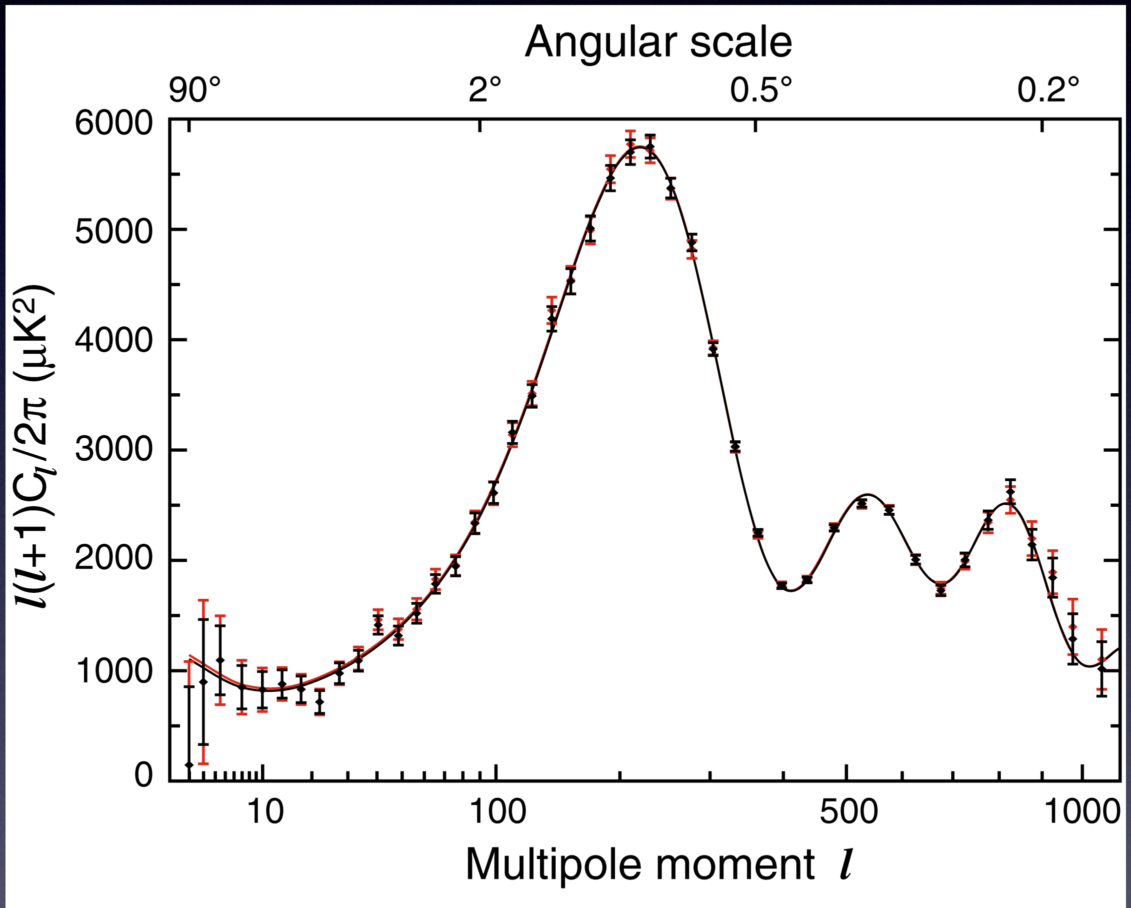

Figure 2: The WMAP din year power spectrum

CMB Power Spectrum

Here you can see exactly where ℓ=260 lands on the angular spectrum plot in the top left of fig. 3.

It is a cumulative image of the sky, and closely resembles the pattern observed in fig. 1.

So not only is there anisotropy in the CMB, but it's also unevenly dispersed.

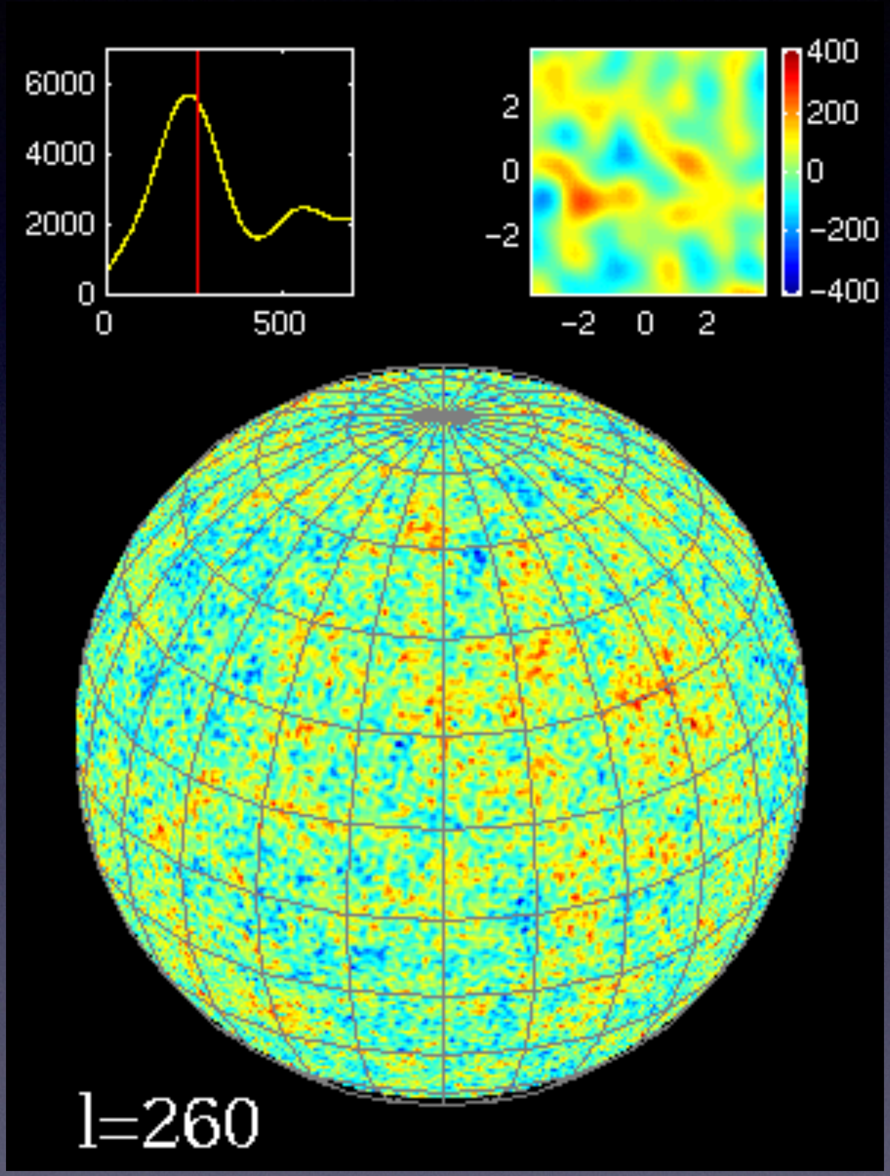

Figure 3: Image comprised of stacked multipoles

CMB Power Spectrum

The CMB spectrum also contains three well-known energy densities, denoted by Ω. These densities are ratios, such that $\Omega_{total}=1$.

These are Ω_b for baryonic matter, Ω_c for cold dark matter, and Ω_Λ for dark energy. They are largely considered to be the most important values as they can tell us a lot about our universe, specifically with how close they are to their critical density values.

However, they are not the only energy densities present in the CMB power spectrum. There is also Ω_ν which is the energy density of neutrinos, and it is a significantly smaller observed value than the aforementioned energy densities above. As such it is not included in many simulators for the CMB.

Creating a CMB Simulator

Having tried two simulators, I discovered that I wanted to try a mixture of the two; creating a simple plot of the data array values and introducing the option to vary them through a variable slider interface.

NASA's Lambda Tools had a static simulation in which you can input values for many more things than just the energy densities. However, it supplied me with the data array that I could get my program to read default values from.

This array also contained values for different kinds of CMB spectrum plots, however, the temperature-polarisation cross-power spectrum (TE) and the polarised spectrum (EE) were beyond the scope of this research, and so was the lensing effect; my goal was to recreate the temperature angular power spectrum (TT).

Creating a CMB Simulator

To facilitate the creation of my version of a simulator, I used Python 2.7 and wrote the code in Jupyter Notebook. GitHub was used to store all of my files.

```python
import camb
import matplotlib
import matplotlib.pyplot as plt
import numpy as np
from ipywidgets import interact
import ipywidgets as widgets

params = camb.read_ini('camb_interface/camb_params.ini')
```

This was the beginning stage, where I imported all of the necessary packages and initialised the base parameters using CAMB.

Creating a CMB Simulator

```
%matplotlib inline
def camb_plot_tt(ombh2, omch2, omnuh2):
    params.ombh2 = ombh2
    params.omch2 = omch2
    params.omnuh2 = omnuh2
    results = camb.get_results(params)

    unlensed = results.get_cmb_unlensed_scalar_array_dict(lmax=2200,
        CMB_unit='muK')

    tt = unlensed['TxT']

    fig, ax = plt.subplots()
    tt = np.delete(tt, [0, 1])
    ax.plot(tt, linewidth=1)
    ax.set_xlim([None, 2500])
    ax.set_ylim([None, 7000])
    ax.set(xlabel='Multipole Moment (l)', ylabel='CMB_Unit (uK^2)',
        title='Cl TT CMB Power Spectrum')
    fig.savefig("Cl-TT-vs-l.pdf")
    plt.show()
```

Creating a CMB Simulator

After creating the function, I could then use interact to add variable sliders to my plot.

```
params = camb.read_ini('camb_interface/camb_params.ini')
interact(camb_plot_tt,
         ombh2=widgets.FloatSlider(value=params.ombh2, min=0, max=1,
            step=0.001, readout_format='.5f'),
         omch2=widgets.FloatSlider(value=params.omch2, min=0, max=1,
            step=0.001, readout_format='.5f'),
         omnuh2=widgets.FloatSlider(value=params.omnuh2, min=0, max=1,
             step=0.001, readout_format='.5f'));
```

Creating a CMB Simulator

The end result was me creating a graph that was near identical to the one in figure 2.

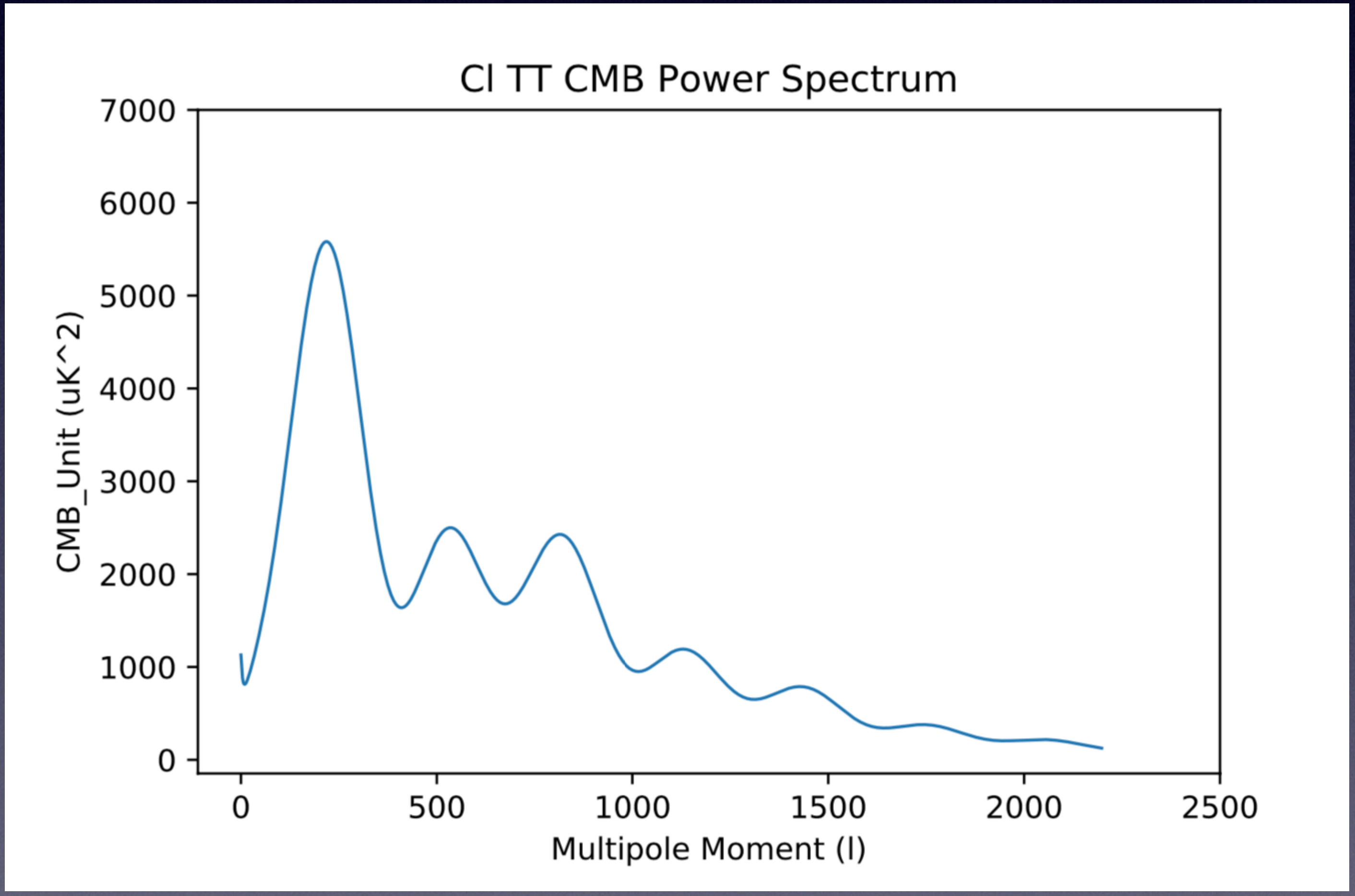

Figure 4: My simulated TT CMB Spectrum

Interpreting Results

My initial predictions for what would happen didn't end up quite lining up with the results of my experiment.

I expected the plot to become "smeared" and smoothed out by an excess of baryon energy density; expected the plot to have an increase in amplitude if there was more dark matter energy density; expected the graph to become very muddy from a large value of neutrino energy density.

I was partially correct for Ω_b and wholly correct for Ω_ν, but I was very wrong about Ω_c.

Interpreting Results

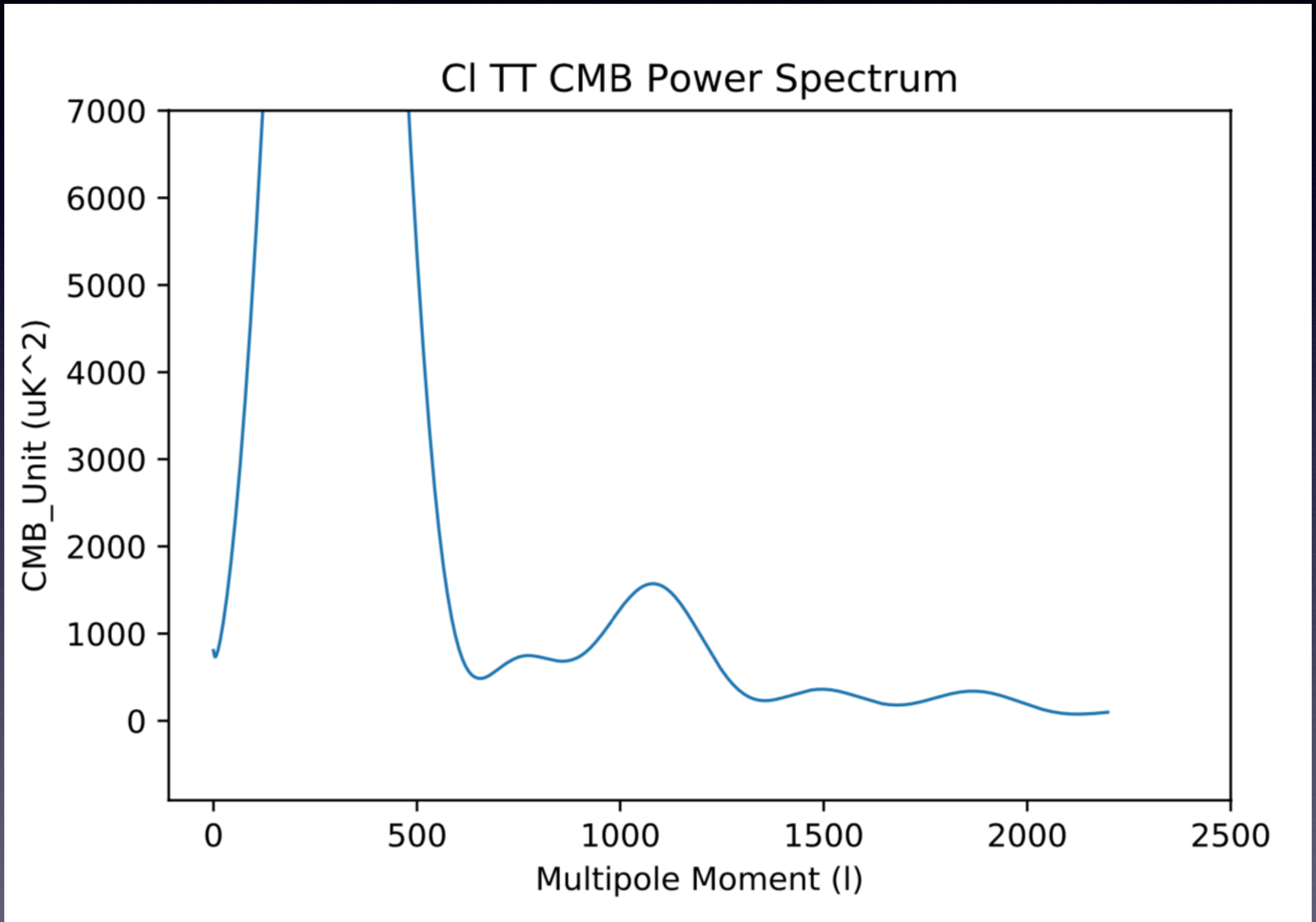

Figure 5: TT graph biased with high Ω_b

Interpreting Results

This was very interesting to see; the first peak maximum had shot up well past the maximum y-axis limit I had assigned in the code. This means that if this situation were true, there would be immense temperature fluctuations at the first peak maximum—almost 0.1µK, significantly larger than anything we've observed in our real universe.

But upon further inspection it was more than just that. The entire first peak had expanded, both upwards and outwards, thereby shifting the second and third peaks to the right. Additionally, I can infer that from the shape of the first peak, the maximum has also been shifted further to the right, and now is likely closer to ℓ=300 instead of 200, suggesting that the corresponding angle has also gone below 1°.

This is where I was half correct about my initial prediction. Apart from the first peak, the rest of the graph had in fact gotten very smeared. This shows that the anisotropy after the first peak becomes more uniform, but that its average value for the temperature fluctuations has also drastically risen.

Interpreting Results

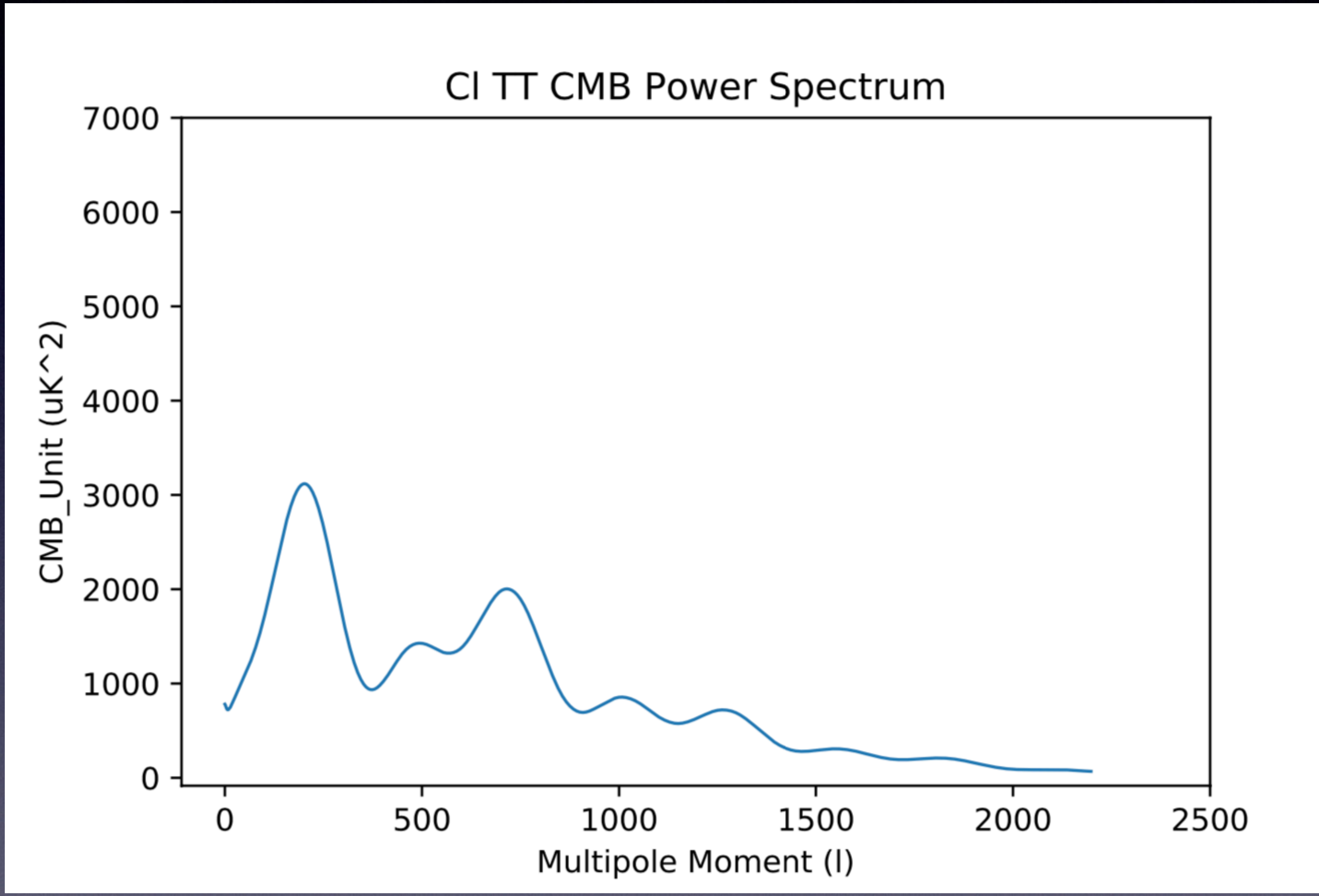

Figure 6: TT graph biased with high Ω_c

Interpreting Results

Increasing the value of the energy density of dark matter completely went against my initial prediction, but that did confirm something I wasn't entirely aware of.

The overall amplitude went down quite a bit, resulting in a much lower maximum temperature fluctuation, but unlike in fig. 5 past the first peak, fig. 6 shows us that the maximum value for the fluctuation is the only thing that has changed.

No values were shifted to either side, and each peak is still very well defined; there is no smearing that I am able to notice. This means that the maximum stays at $\ell=200$.

We know from the preliminary research that the third peak of the CMB spectrum relates to the amount of dark matter in the universe, and this third peak is now roughly half the size of the first peak, where in fig. 4, it's perhaps not even a quarter. This shows that the variable I'm choosing to affect really is the energy density of dark matter.

Interpreting Results

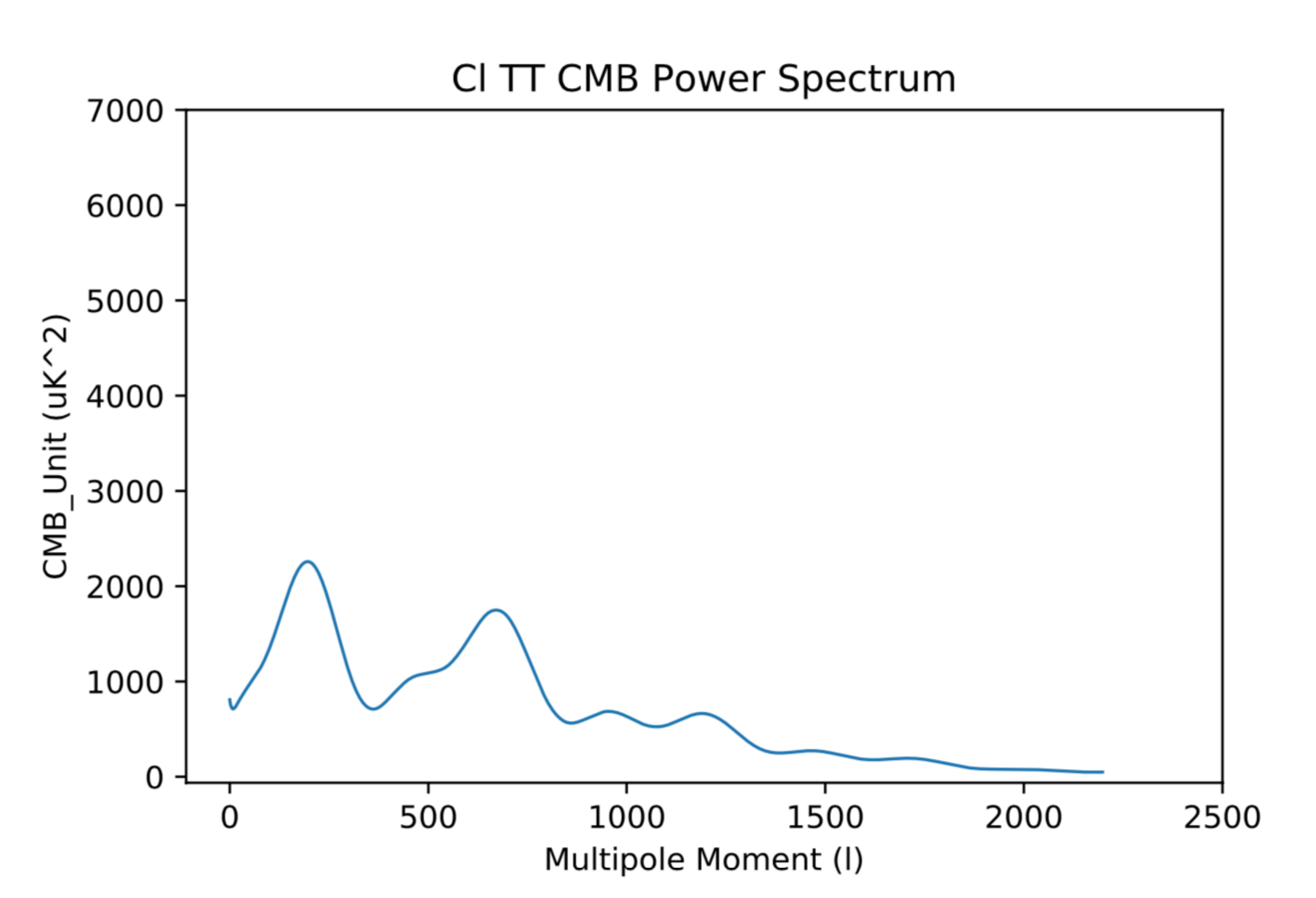

Figure 7: TT graph biased with Ω_ν

Interpreting Results

This was completely expected, and thankfully proved to be true. If there's a larger portion of neutrinos occupying the space in each multipole, that means there's less space for baryonic matter and dark matter, meaning it will have a somewhat similar effect to what we observed the dark matter spectrum doing.

But the neutrinos are achieving this a different way; neutrinos are very nearly massless, have zero charge, interact only via weak interaction and are extremely tiny. They react very rarely. Having an excess of neutrinos would cause there to be more "empty space" between interacting particles; what is essentially the equivalent of having that space be empty due to their extreme unwillingness to react at all.

This is what results in the graph appearing smeared and having its amplitude reduced, essentially increasing homogeneity between the multipole moments.

Conclusions

The positions of each of the three peaks in our real universe are very precise, and each one tells us something about the universe. If there was an imbalance in the energy densities, it could have severe consequences for various phenomena; differing values for dark matter would impact such things as galaxy clusters, their lensing effects, and possibly black holes, whereas higher amounts of baryonic matter could alter the curvature of the universe, turning it from the very nearly flat amount it is now to a closed spherical curvature instead.

Most interestingly, personally, is how similar of an effect neutrinos had on the CMB spectrum compared to dark matter, especially considering that Ω_ν only needed to be increased by a fraction of the amount of Ω_c to achieve a similar transformation.

I predict there must be a maximum mass for neutrinos, otherwise they would too heavily affect the CMB spectrum and likely the rate of expansion. This research topic could definitely be expanded upon in future, and will likely yield some very interesting results concerning relations between dark matter and neutrinos.