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Probing Sterile Neutrino Decays in the Adolescent Universe with Big Bang Nucleosynthesis and Large Scale Structure

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FACULTY APPROVAL

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Abstract

The early universe provides a unique opportunity for researching neutrinos because in these dense and hot places, neutrinos have significant interactions with each other and everything else in the plasma of the early universe. One issue in the current cosmological paradigm is the lithium problem, where there is a discrepancy between predicted versus observed abundances of lithium produced during Big Bang Nucleosynthesis. In this paper, we look beyond the Standard Model to try and address this discrepancy by using the early universe as a laboratory to study the decay of sterile neutrinos into Standard model particles and its effect on cosmological observables. These decays create nonthermal neutrino spectra as opposed to nearly thermal spectra predicted by standard cosmology. These altered spectra affect the production of primordial elements during BBN and the formation of large scale structure.

I. INTRODUCTION

Neutrinos are tiny electrically neutral particles that rarely interact with anything. Of the four fundamental forces (gravity, strong nuclear, weak nuclear, and electromagnetism) neutrinos only interact with other particles via the weak nuclear force and with gravity. Simply put, the weak nuclear force is responsible for interactions on the subatomic scale, and it is precisely the force that is responsible for beta decay. Gravity is the force of attraction between all things. Neutrinos are so small in fact and so unlikely to interact due to the weak nuclear force, that there are trillions that are created in the sun that are passing through you at this very moment.

Quantum mechanics tells us that we must think of neutrinos differently when they are traveling versus when they are interacting with other particles. When neutrinos interact, we describe them either as an electron, muon, or tau neutrino. These are known as the three flavors of neutrinos. These flavors are what interacts with all the matter in our universe, and each flavor interacts differently. When neutrinos are traveling, we think of them in terms of three different mass states. It is important to mention that these flavors and mass states do not coincide with one another. In quantum mechanics we might say mass states are superpositions of the three flavors of neutrinos, and the three flavors of neutrinos are superpositions of the three mass states. Essentially, when neutrinos are traveling, there is a nonzero probability that it can interact like each of the three flavors of neutrinos. This leads to a phenomenon known as neutrino flavor changing. A neutrino can start its journey to the Earth at the Sun interacting as an electron neutrino, but it can arrive at Earth at a detector interacting as a muon or tau neutrino. How long a neutrino travels dictates its flavor interaction.

One may ask the question: what are the masses of these different mass states? We haven't yet measured the masses of these mass states but do know they are at least one million times smaller than an electron. There is also a proposed fourth type of neutrino called a sterile neutrino which interacts only with gravity. This sterile neutrino does not interact with particles via the weak nuclear force like the other flavors mentioned. The Standard Model predicts the existence of sterile neutrinos, but we do not know anything about their properties. Neutrino experiments are extremely difficult to conduct on Earth for a multitude of different reasons. We can't simply "catch" a neutrino and take measurements and experiment with it as one may do with other physical phenomena in a laboratory. Furthermore, neutrinos are very difficult to detect. We would need to build huge detectors and even then they would only detect a small number of neutrinos.

Neutrinos play an important role in the evolution of the beginnings of our universe and because of this, neutrinos are very interesting particles to study in this environment. The early universe is a very dense and hot place with lots of neutrinos created at the Big Bang. The early universe provides the conditions necessary for researching and understanding neutrinos because in these dense and hot places, neutrinos are able to interact plenty with everything else in the universe. Laboratories on Earth cannot provide the hot and dense environment present at the beginnings of our universe, and thus we can use the universe as our laboratory to study neutrinos. Cosmologists measure the Cosmic Microwave Background (CMB) which in simple terms is leftover radiation from the Big Bang, study Big Bang Nucleosynthesis (BBN) which encompasses the creation of atomic nuclei a few minutes after the Big Bang, and study the early formation of galaxies in our universe. The early universe's neutrinos play an important role in each of these three things. Specifically, neutrinos play an important role in the conversion between neutrons to protons and protons to neutrons. This means that neutrinos play an important role in the creation of hydrogen, lithium and helium during BBN. Moreover, the energy density of neutrinos also influences the expansion rate of the universe which affects the formation of the CMB and BBN.

Within the next 10 years astrophysical observations will drastically improve. Current measurements from the CMB will get more precise with next generation experiments like the CMB-S4 experiment. JWST along with 30 meter telescopes will provide better precision on BBN abundances and provide better observations on the formations of galaxies. The largest current telescopes are only 10 meters in diameter, so this 30 meter telescope will contain nine times the light collecting ability. As these measurements improve there may be further tension between the observed values and those predicted based on the Standard Model. Within the current cosmological paradigm, there exists the lithium problem which is a discrepancy between the predicted versus measured amount of primordial lithium. In this thesis, we look beyond the Standard Model to study the decay of sterile neutrinos in the early universe into Standard model particles and examine its effect on the cosmological observables mentioned. We are interested to see if the lithium problem is a signal for beyond Standard model physics.

II. METHODS

A. Active Neutrino Spectra

We consider a thermal population of sterile neutrinos of mass 300 MeV with decay lifetimes between 0.01 and 1 second. These sterile neutrinos will decay into the three active flavors of neutrinos as well as other standard model particles. The electromagnetic decay products nearly immediately thermalize with the hot and dense plasma of the early universe. The high energy neutrinos and anti-neutrinos that are created in the decay subsequently collide and scatter with the plasma of the early universe. We expect the decay of the sterile neutrino and subsequent scattering of the high energy neutrinos and anti-neutrinos to severely distort the neutrino spectra. Our work builds upon the work of Hannah Rasmussen and other students in our group, that calculated the evolution of the neutrino spectra [1].

Shown in Figure 1 is the results of the decay of a sterile neutrino population with mass 300 MeV and a mean lifetime of 0.91 seconds. Each panel plots the active neutrino number density spectrum is plotted against scaled energy $\varepsilon = E/T_{\mathrm{cm}}$. T_{cm} is the co-moving temperature of the universe which decreases as the universe expands and is inversely proportional to the scale factor of the universe, a. We utilize the scaled energy to account for the expansion of the universe and ensure our spectra is only altered by the decay of sterile neutrinos into active neutrinos and subsequent scattering. When the temperature of universe is still very hot and little time has elapsed, we can see that the active neutrinos are in thermodynamic equilibrium as they rapidly scatter with the hot and dense plasma of the early universe. As time further elapses, the universe expands, the temperature of the plasma decreases, and we can start to see the distinctive decay spectrum created by the decay of the steriles. Once all steriles have decayed, we can see the the scattering of the high energy neutrinos and anti-neutrinos with the plasma have smoothed out the spectrum into an out of equilibrium distribution. The final result is a severely distorted neutrino spectra with a high energy tail.

B. Matter Power Spectrum

The altered neutrino spectra displayed in the final panel of Figure 1 will affect the formation of large scale structure. Assuming a standard model where the neutrinos can be described by a thermal distribution, measurements of the CMB and of large scale structure are sensitive to the

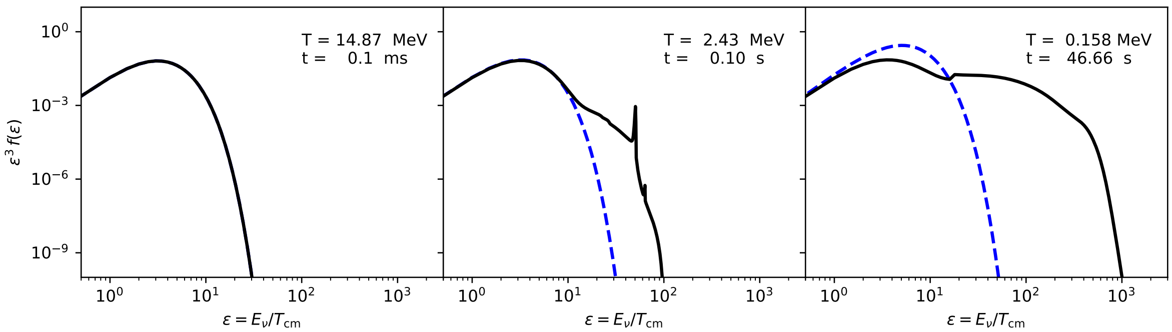


FIG. 1: Using a 300 MeV sterile neutrino with a mean lifetime of 0.91 seconds, we plot the active neutrino spectra at three snapshots in time as a function of scaled energy ε. The dashed curve represents the evolution of the neutrino spectra in a standard model, whereas the solid black curve shows the evolution of the active neutrino spectra in our sterile decay model.

neutrino masses. Such a spectra will modify the matter power spectrum, $P(k)$, which in simple terms calculates the amount of mass clustering together we see in the early universe on various length scales. By mass clustering on various length scales, we mean the formation of super-clusters of galaxies to the formation of a single galaxy. To calculate the effect on the matter power spectra from our neutrino spectra, we utilize CLASS code which works best with an analytical estimate of that neutrino spectra [2].

Our analytical estimate, $f_{\text{est}}(\varepsilon)$, is our best estimate for the neutrino spectra,

$$\varepsilon^2 f_{\text{est}}(\varepsilon) = \frac{N\varepsilon^2}{e^{\varepsilon/T}+1} + \varepsilon^2 e^q. \tag{1}$$

T is an effective neutrino temperature, N is an effective thermal neutrino number, q is a polynomial of maximum order 3. This equation looks similar to a thermal distribution plus an extra term to account for the high energy tail as shown in the final phase of Figure 1. We first look at the thermal distribution which fits the bump in the spectra at $\varepsilon \sim 3$ to find ε_{max}, the ε value of the peak of our spectra. Once we have this value, ε_{max}, we can ask what value of the dimensionless quantity x maximizes $Nx^2T^2/(e^x+1)$ where $x = \varepsilon_{\text{max}}/T$. Maximizing this value of x allows us to create an estimate of T. Once we have this estimate for T, we can find an estimate of N through the following relationship

$$\varepsilon_{\text{max}}^2 f(\varepsilon_{\text{max}}) = \frac{N\varepsilon_{\text{max}}^2}{e^{\varepsilon_{\text{max}}/T}+1}, \tag{2}$$

where T is now the estimate value we have just solved for. Once we have our estimates for T and N, we utilize a least squares fit by testing a grid of T and N values around our estimates. Specifically, we introduce the function

$$\Delta(T,N) = \sum_i \left[\varepsilon_i^2 f(\varepsilon_i) - \frac{N\varepsilon_i^2}{e^{\varepsilon_i/T}+1} \right]^2, \tag{3}$$

where we sum over all data points $(\varepsilon_i, f(\varepsilon_i))$ in the thermal bump. $\Delta(T,N)=0$ would indicate a perfect fit, so we choose values of T and N that minimizes $\Delta(T,N)$. Once we have these best values of T, N, we can find a best fit for the polynomial q. This requires a calculation of the cumulative distribution function (CDF),

$$CDF(\varepsilon) = \frac{\int_0^{\varepsilon} \varepsilon'^2 f(\varepsilon')\, d\varepsilon'}{\int_0^{\infty} \varepsilon'^2 f(\varepsilon')\, d\varepsilon'}, \tag{4}$$

which we calculate using the results of our sterile model, $f(\varepsilon)$, as well as the analytical estimate, $f_{\rm est}(\varepsilon)$. We make sure to choose the coefficients of the polynomial that minimize the difference between the CDF for our sterile neutrino model and our analytical estimate. Finally, we made sure that $\int_0^\infty \varepsilon'^3 f(\varepsilon')\, d\varepsilon'$ is the same for our sterile neutrino model and our analytical estimate because this is proportional to the neutrino energy density. We can normalize the entire estimate by multiplying by a constant so that the integral is the same for both. This has an affect of multiplying by N and adding to the constant term in the polynomial.

This analytic work allows us to take an analytical estimate of our neutrino spectra and insert it into CLASS code and retrieve the corresponding matter power spectrum.

C. BBN

The altered neutrino spectra also affects the creation of the light elements during BBN in 3 different ways. First, the energy density of neutrinos affects the expansion rate of the universe, which will impact BBN yields. Additionally, the decay of these sterile neutrinos generates a lot of entropy, which heats the early universe and alters the time-temperature relationship. Lastly, the high energy neutrinos and anti-neutrinos will alter the neutron to proton inter conversion rates. We must add to the standard BBN paradigm the evolution of these quantities.

To start, I calculated the energy density of neutrinos in the early universe, ρ_ν given by

$$\rho_\nu = \frac{T_{\rm cm}^4}{2\pi^2}\int_0^\infty \varepsilon^3 f(\varepsilon)\, d\varepsilon. \tag{5}$$

We also needed to calculate the rate at which thermal energy was transferred into the plasma due to sterile decays, dQ/dt. This includes the near immediate thermalization of the electromagnetic products, and the subsequent scattering of the neutrinos. Equation 12 in Ref. [1] is the rate at which thermal energy is deposited into a co-moving volume of the plasma by out-of-equilibrium sterile neutrino decays and scattering, dQ/da, and is given by

$$\frac{dQ}{da} = \frac{m_s n_s a^3}{\tau_s}\frac{dt}{da} - \frac{T_{\rm cm}^4 a^3}{2\pi^2}\int \frac{df}{da}\varepsilon^3\, d\varepsilon, \tag{6}$$

where m_s is the mass of the sterile neutrino, n_s is the number density of sterile neutrinos, τ_s is the lifetime of the sterile neutrino, a is the scale factor of the universe, and df/da is the derivative of the occupation fraction of neutrinos. The number density of sterile neutrinos is given by

$$n_s = \frac{D3\zeta(3)}{2\pi^2} T_{cm}^3 e^{-t/\tau_s}, \tag{7}$$

where D describes the dilution of sterile neutrinos from the time of their decoupling, prior to the QCD transition, to the time of weak decoupling described by our model, and $\zeta(3)$ is the Riemann Zeta function evaluated at 3. The quantity df/da describes the changes to the distribution function and has two independent effects, the decay of sterile neutrinos and the scattering of neutrinos with the plasma. It is given by

$$\frac{df}{da} = \left(\frac{df}{da}\bigg|_{\nu_s \text{decay}} + \left(\frac{df}{da}\bigg|_{\text{scattering}}\right.\right. . \tag{8}$$

An expression for dQ/da allows us to obtain an expression for dQ/dt given by

$$\frac{dQ}{dt} = \frac{m_s n_s a^3}{\tau_s} - \frac{T_{cm}^4 a^3}{2\pi^2}\frac{da}{dt}\int \frac{df}{da}\varepsilon^3\, d\varepsilon, \tag{9}$$

where da/dt is the universal expansion rate given by the Friedmann equation, and it can be shown that

$$\frac{da}{dt} = \sqrt{\frac{8\pi}{3m_{\rm pl}^2}}\cdot a\rho^{1/2}. \tag{10}$$

In Equation 10, $m_{\rm pl}$ is the Planck mass, and ρ is the energy density of all particles in the early universe. In our model, this includes the contributions of photons, electrons and positrons, and neutrinos and sterile neutrinos. Thus, ρ is given by

$$\rho = \rho_\gamma + \rho_{e\pm} + \rho_\nu + \rho_{\nu_s}, \tag{11}$$

where it is important to mention that contributions from baryons and dark matter are insignificant in this radiation dominated era. An expression for ρ_ν is given by Equation 5, and the energy density of photons, electrons and positrons, and sterile neutrinos are given by

$$\rho_\gamma = \frac{\pi^2}{15} T^4 \tag{12}$$

$$\rho_{\nu_s} = m_s n_s \tag{13}$$

$$\rho_{e\pm} = \frac{2T^4}{\pi^2} \int_0^\infty \frac{\zeta^3 \sqrt{\zeta^2 + x^2}}{e^{\sqrt{\zeta^2+x^2}} + 1} d\zeta, \tag{14}$$

where ζ and x are both dimensionless quantities with values $\zeta = p/T$ and $x = m_e/T$.

As I mentioned earlier, neutrinos and anti-neutrinos play a role in the neutron to proton interconversion rates. Specifically, they are affected by electron neutrinos and electron anti-neutrinos because their decays are given by

$$n + \nu_e \rightleftharpoons p + e^- \tag{15}$$

$$p + \overline{\nu}_e \rightleftharpoons n + e^+ \tag{16}$$

$$n \rightleftharpoons p + e^- + \overline{\nu}_e. \tag{17}$$

The neutron to proton rates as a result of our sterile neutrino decay are calculated in Ref. [1] using expressions from Ref. [3].

D. N_{eff}

This altered neutrino spectra will also affect the value of N_{eff}. N_{eff} is a parameter inferred from CMB observations that is proportional to the energy density of neutrinos. In our model, we can calculate the value of N_{eff} by first calculating the value of ρ_ν as given in Equation 5 and then get a value of N_{eff} via the following relationship

$$N_{\text{eff}} = \frac{120\rho_\nu}{7\pi^2 T^4}\left(\frac{4}{11}\right)^{-4/3}. \tag{18}$$

III. RESULTS

A. N_{eff}

Using a 300 MeV sterile neutrino, we simulate their decay for various lifetimes, and Figure 2 below shows the various value of N_{eff} for each model.

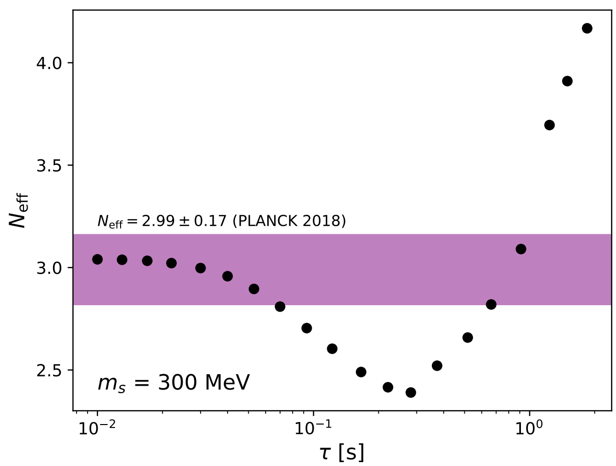
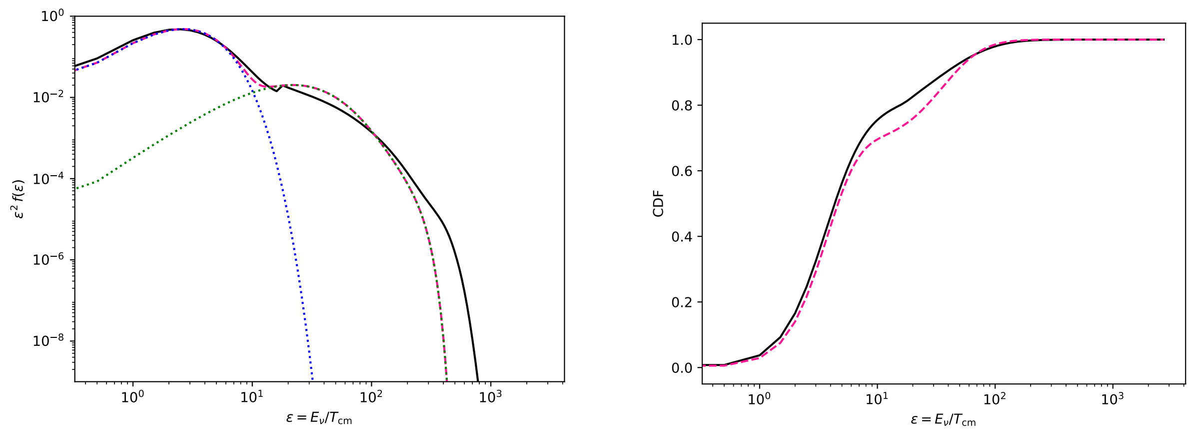


FIG. 2: Various values of N_{eff} plotted as a function of sterile neutrino lifetime. The purple band displays observational constraints from PLANCK.

The horizontal band shown in Figure 2 displays observational constraints from PLANCK [4], which provide a first check on these models. Either very short-lived models (lifetime less than around 0.06 s) or lifetimes around 0.9 s fall within these constraints. The neutrino spectra in Figure 1 corresponds to a lifetime of 0.91 sec, and yields an N_{eff} value of 3.09

B. Matter Power Spectrum

Before looking at the matter power spectrum plots I first show the results of our analytic work in estimating our neutrino spectra shown in Figure 3.



(a) Analytic fit of the neutrino spectra (black) from the final phase of Figure 1. The sum of the thermal (blue dotted) and exponential (green dotted) terms act as our estimate (red dashed).

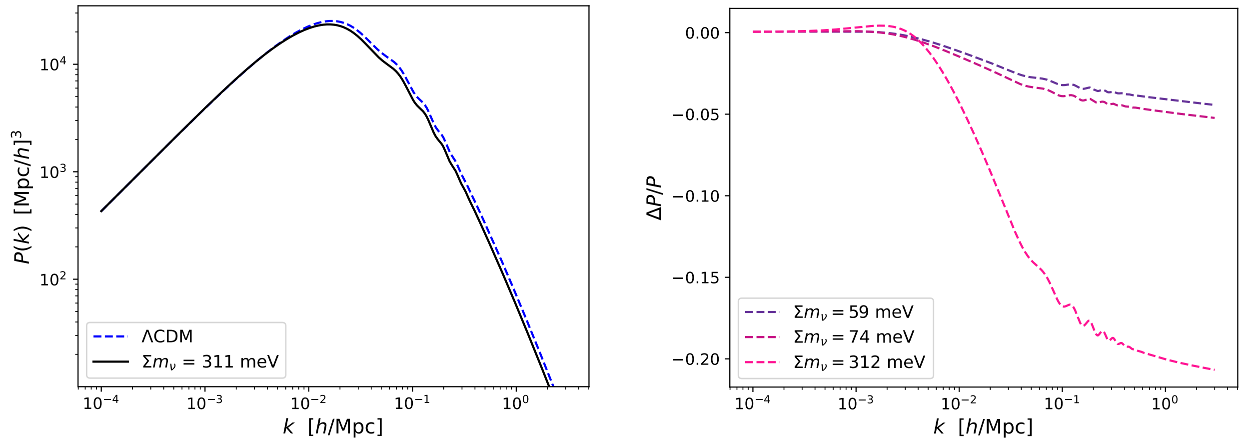
(b) The CDF of our neutrino distribution is shown in the solid black line. The CDF of our analytical best estimate of the neutrino spectra is shown in the red dashed line.

FIG. 3: The results in our analytic work in estimating the neutrino spectra with sterile neutrino decay.

The solid black curve in Figure 3a is the active neutrino distribution at the end of the simulation (300 MeV, 0.91 s lifetime). We look to fit the distribution according to the model presented in Equation 1. The two dotted components on the graph are the thermal (blue dotted) and the exponential (green dotted) terms, with the red-dashed line representing the sum of the two which approximates the active neutrino distribution. The fit is $N = 0.72$, $T = 1.18$; and the polynomial is $q = ae^3 + be^2 + ce + d$ with $a = -4.84 \times 10^{-7}$, $b = 3.16 \times 10^{-4}$, $c = -0.10$, and $d = -7.93$. Our metric for success in our analytic work is the cumulative distribution function plotted in Figure 3b. The CDF of our neutrino distribution is giving us probabilities that our neutrinos have certain energies. Looking at Figure 3b, the solid black curve is the CDF for the neutrino distribution and the dashed curve is the CDF for the best fit.

Before looking at how a nonthermal active neutrino spectra affects the matter power spectrum, we first looked at how nonzero neutrino mass affects the matter power in a standard (thermal) model. As stated prior, in the standard model, the neutrinos are described by a thermal spectrum with $T_\nu = (4/11)^{1/3} T$.

Figure 4 shows the effects of a thermal model on the matter power spectrum. Specifically, Figure 4a displays the matter power spectrum in two standard models as a function of wavenumber k. The dashed curve represents a ΛCDM model where neutrinos are modeled as massless. The



(a) Matter power spectrum for two standard models as a function of wavenumber with zero and nonzero neutrino mass

(b) Fractional difference of the matter power spectrum as a function of wavenumber for various neutrino masses

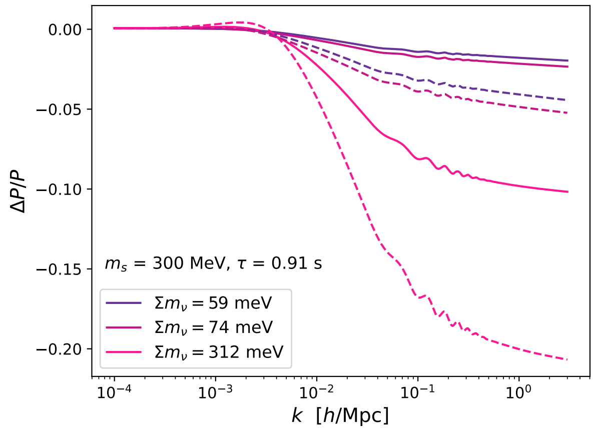
FIG. 4: The effects of standard models on the matter power spectrum

solid black curve displays the same ΛCDM model but with large neutrino masses. In our plots, we look at $\sum m_\nu$ which is the sum of all neutrino mass states. We can tell from looking at this plot that nonzero neutrino mass exhibits as a suppression of power on small scales which corresponds to large wavenumbers k. This means that that we would essentially see less mass clustering together on these smaller length scales.

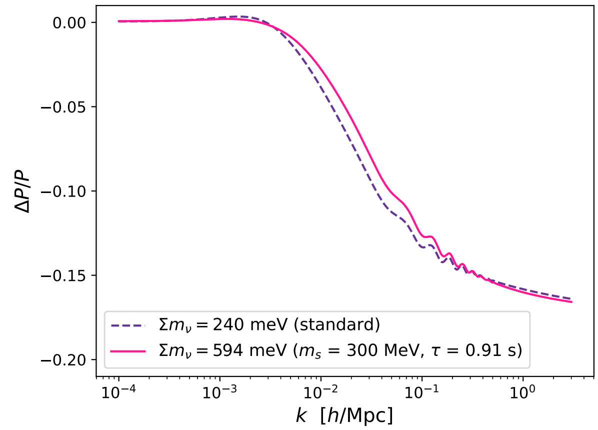
Figure 4b displays the fractional difference of the matter power spectrum as a function of wave number. It compares two models: a ΛCDM model with non-zero neutrino mass to the same ΛCDM model, except with zero neutrino mass. Just like Figure 4a, this graph also shows a suppression of power on small scales, or large wave numbers. We can also tell that the larger the neutrino mass, the more reduction in clustering on these small scales.

Observations of the CMB and of structure formation to probe the neutrino masses assume that the neutrinos have a thermal spectrum. However, in our model, they do not, and so we can look at how this might affect things like structure formation.

Figure 5a shows the same three plots from Figure 4b accompanied with the results from sterile neutrino decays. The standard, thermal case are the dashed curves, whereas the non-thermal spectra are the solid curves. We can see with this nonthermal model there is less suppression of power on smaller scales. For example, if we look at a sum of neutrino masses of 312 meV with thermal spectra there's a relative suppression of about 21% at small scales, while the nonthermal



(a) Fractional difference of the matter power spectrum as a function of wavenumber for various neutrino masses accompanied with results from sterile decays



(b) Fractional difference of the matter power spectrum as a function of wavenumber for specific neutrino masses in both a thermal and nonthermal regime

FIG. 5: The affect of sterile neutrino decays on the matter power spectrum. The dashed curves are plotted with a thermal active neutrino spectra whereas the solid curves are plotted with our sterile neutrino model.

model has a 10% suppression of power. The non-thermal spectra with a high energy tail causes the massive neutrinos to act "more relativistic" which would be similar to less massive neutrinos with a thermal spectrum.

Figure 5b shows a model with a thermal spectrum and sum of neutrino masses 240 meV, shown with the dashed line. This is currently the upper limit of sensitivity from CMB observations alone [4]. Also shown is results from the same sterile neutrino decay model with sum of neutrino mass of nearly 600 meV. In a way, if we could somehow know that the 300 MeV sterile neutrino decaying with a lifetime of 0.91 s model was accurate, then instead of saying that the CMB data constrain the sum of the neutrino masses to less than 240 meV, we'd say the constraint is less than 600 meV. Coincidentally, this limit complements current terrestrial experiments to measure neutrino mass, whose ultimate sensitivity hopes to constrain the sum of the neutrino masses to be *greater than* 600 meV [5].

C. BBN

Using a decaying 300 MeV sterile neutrino, for different sterile lifetimes, we looked at BBN yields of helium, deuterium, and lithium-7.

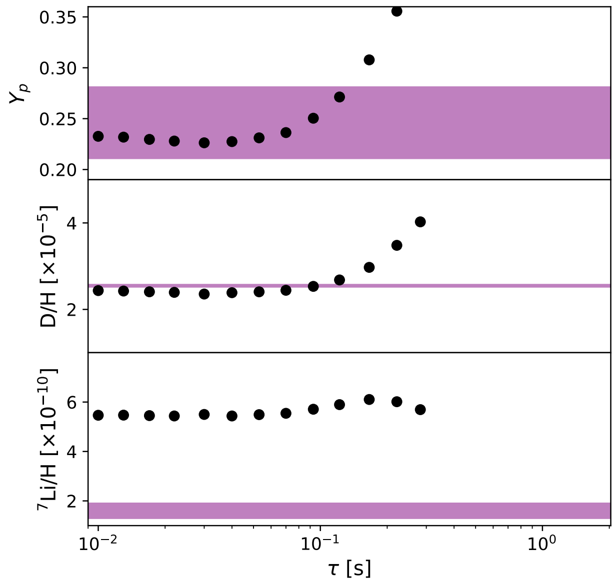


FIG. 6: Using our sterile neutrino model, for different sterile lifetimes, we looked at BBN yields of helium, deuterium, and lithium-7. The horizontal bands represent observational constraints.

The top plot above in Figure 6 is the mass fraction of helium, and deuterium and lithium are also plotted as a ratio with hydrogen. In these graphs, the horizontal bands show observational measurements of the primordial element abundances: helium from the CMB alone [4], deuterium from quasar lines of sight [6], and lithium from the atmospheres of old halo stars [7]. We see that while relatively short lived 300 MeV sterile neutrinos way be consistent with helium and deuterium measurements, they cannot rectify the lithium problem, where expected lithium abundances are roughly three times larger than measured [7].

IV. DISCUSSION

In this thesis, we have introduced a model of sterile neutrino decay, and how this sterile neutrino decay alters the active neutrino spectra. Our sterile neutrino model significantly alters the thermal distribution of the active neutrinos as predicted by standard cosmology and creates a non-thermal spectra with a distinct high energy tail. This altered spectra affects cosmological observables, and we examine its affects on the formation of large scale structure, the formation of the light elements during BBN, and N_{eff}.

We see via Figure 2 that varying sterile neutrino lifetimes affects the inferred value of N_{eff}. In our model with $m_s = 300$ MeV only those steriles with relatively short lifetimes or that just under

1 second fall within observational constraints. If we look at our matter power spectrum plots in Figure 5, we can notice two key takeaways. First, in our nonthermal model, we see relatively less suppression of power at smaller length scales for the same neutrino masses. Secondly, heavier neutrinos in the non-thermal model seem to masquerade (act more relativistic) as lighter neutrinos in a thermal spectra. Lastly, Figure 6 tells us that relatively short sterile lifetimes seem to agree with observational constraints of deuterium and helium abundances, but we are unable to address the lithium problem.

Within the next decade, next generation experiments like CMB-S4 looks to have increased precision that will shrink error bars on $N_{\rm eff}$ [8]. A clear sign of non-thermal neutrino spectra would be $N_{\rm eff}$ that does not agree with the expected value of 3.04 [9]. Moreover, this increased precision could result in a structure formation-inferred value for the sum of the neutrino masses. In a complementary search, terrestrial experiments may also detect neutrino masses. If both approaches produce a measurement, it's possible that they'll be inconsistent with each other. This would be a tell-tale signal of the types of non-thermal neutrino spectra with a high-energy tail if neutrino masses inferred from the CMB are less then those inferred from terrestrial experiments. Further, BBN yields will highly constrain the types of models discussed here. Our future work looks to understand the sensitivity of all the observables, including BBN yields, on the model. Specifically, we look to explore different sterile masses, but we can also look into the initial abundance of the steriles, as well as the relative abundance of steriles and anti-steriles.

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