Chapter 2

Baryon Asymmetry of the Universe and Dark Matter

2.1 What is a Baryon

A baryon is a type of subatomic particle that is made up of three quarks bound together by the strong force, one of the four fundamental forces in nature. Baryons are a subset of a larger family of particles known as hadrons, which are particles that experience the strong nuclear force. They are composed of three quarks. Quarks come in six flavors, up(u), down(d), strange(s), charm(c), top(t) and bottom(b). The combination of these quarks determines the type of baryon. The most common baryons are the proton (two up quarks, one down quark) and the neutron (two down quarks, one up quark). Together, protons and neutrons form the nuclei of atoms, which make up all the ordinary matter in the universe. Baryons carry a quantum number called the baryon number, which is +1 for baryons, -1 for antibaryons and 0 for non-baryonic particles like leptons. This number is generally conserved in most physical processes. Each baryon has a corresponding antibaryon, which is made up of three antiquarks. For example, the antiproton consists of two anti-up quarks and one anti-down quark. Baryons are crucial for the structure of matter in the universe. Protons, for instance, are positively charged and play a critical role in the structure of atoms, while neutrons help stabilize atomic nuclei. In cosmology, baryons are important in understanding phenomena like the baryon asymmetry (why there is more matter than antimatter in the universe).

2.2 Baryon Asymmetry Observations

The matter-antimatter asymmetry, or baryon asymmetry, refers to the observation that the universe contains vastly more matter than antimatter, despite theories predicting their equal production in the early universe.

2.2.1 Evidence of BAU

Here are some evidence that supports Baryon asymmetry of the universe.

1. CP Violation in Particle Physics: Experiments in particle physics have demonstrated CP violation, which refers to processes where the laws of physics differentiate between matter and antimatter. This was first observed in neutral kaon decays in the 1960s and later in B mesons. While the amount of CP violation observed in the Standard Model is too small to fully explain the matter-antimatter asymmetry, it is a crucial piece of the puzzle, as CP violation is a necessary condition for generating the observed imbalance, as per the Sakharov conditions.

2. Cosmic Microwave Background (CMB): The CMB, the afterglow of the Big Bang, offers clues about the early universe. If matter and antimatter existed in comparable amounts, the recombination period (when electrons and protons combined to form neutral atoms) would have been significantly different, leaving distinct signatures in the CMB. However, CMB observations by the WMAP and Planck satellites show no such indications of equal amounts of matter and antimatter. Instead, the data support a universe overwhelmingly dominated by matter.

3. Big Bang Nucleosynthesis (BBN): The observed abundances of light elements like hydrogen, helium, and lithium provide crucial evidence of the baryon asymmetry. Theoretical predictions from Big Bang nucleosynthesis (BBN) match the observed abundances only if there was an excess of baryons (matter) over antibaryons (antimatter) in the early universe. If antimatter had been equally abundant, the nuclear processes during BBN would have resulted in a different distribution of these elements.

2.2.2 Sakharov's Condition

Sakharov's Conditions are three necessary criteria proposed by Russian physicist Andrei Sakharov in 1967 to explain how the universe could have evolved from an initial state with equal amounts of matter and antimatter to its current state, where there is a clear dominance of matter. These conditions are fundamental to understanding the observed BAU. Below are the requirements set by Sakharov [1]:

1. Baryon Number Violation: For a universe to develop a matter-antimatter asymmetry, there must be processes that violate baryon number conservation. Baryon number is a quantum number representing the number of baryons (protons, neutrons, etc.) minus the number of antibaryons. In most particle interactions today, baryon number is conserved, meaning baryons and antibaryons are created or destroyed in equal amounts. However, if there were processes in the early universe that allowed for the creation of more baryons than antibaryons (or vice versa), this would create the imbalance we observe[2].

2. C and CP violation: Charge (C) symmetry means that the laws of physics are the same for particles and their antiparticles if you swap their charges. CP symmetry is the combination of C symmetry and parity (P) symmetry, where the laws of physics should remain the same if spatial coordinates are inverted (mirror symmetry). For a matter-antimatter asymmetry to develop, both C and CP symmetries must be violated, meaning the behavior of par-

ticles and antiparticles is not perfectly symmetric. This has been observed experimentally in certain processes, such as in the decay of K mesons and B mesons, but the observed CP violation in the Standard Model of particle physics is too small to fully account for the observed asymmetry, indicating the need for new physics beyond the Standard Model.

3. Interaction out of Thermal Equilibrium: Sakharov's third condition is that the universe must have been out of thermal equilibrium at some point during its early evolution. In a state of thermal equilibrium, particles and their antiparticles are created and annihilated at the same rates, preventing any lasting imbalance. However, if the universe went through periods where equilibrium was disrupted, such as during phase transitions in the early universe then processes could have occurred that favored the production of more matter than antimatter. One example of such a period is the rapid expansion during cosmic inflation.

2.2.3 Leptogenesis

Leptogenesis is a theory that attempts to explain the observed asymmetry between matter and antimatter in the universe. According to the theory, the universe started out with equal amounts of matter and antimatter, but over time, the amount of matter increased while the amount of antimatter decreased. This asymmetry is known as baryogenesis[3]. Leptogenesis proposes that this asymmetry was caused by the decay of heavy, hypothetical particles known as neutrinos. According to the theory, in the early universe, these particles were produced in large numbers and decayed in a way that favored the production of more matter than antimatter. The excess matter then went on to form the structures we see in the universe today. Leptogenesis is an active area of research in both particle physics and cosmology, and scientists are working to develop and test models that can explain the observed asymmetry between matter and antimatter.

In the standard leptogenesis scenario, heavy Right-handed (RH) neutrinos (N_i)

decay into standard model particles, typically producing a lepton (L) and a Higgs boson (H):

$$N_i \to l_\alpha + H; \quad N_i \to \bar{l_\alpha} + \bar{H} \tag{2.1}$$

These decays can violate lepton number and, through CP-violating phases in the neutrino sector, generate a net lepton asymmetry. The total lepton asymmetry ϵ_i produced by the decay of N_i can be decomposed into flavor-dependent asymmetries $\epsilon_{i\alpha}$. The flavor-dependent CP asymmetry $\epsilon_{i\alpha}$ for the decay of the RH neutrino N_i into a specific lepton flavor α is defined as:

$$\varepsilon_{i\alpha} = \frac{\Gamma\left(N_i \to l_\alpha + H\right) \; - \; \Gamma\left(N_i \to \bar{l}_\alpha + \bar{H}\right)}{\sum_\alpha \Gamma\left(N_i \to l_\alpha + H\right) \; + \; \Gamma\left(N_i \to \bar{l}_\alpha + \bar{H}\right)} \tag{2.2}$$

The mass scales of RH neutrinos are dependent on the specific model being considered, resulting in varying mass ranges across different frameworks. In this thesis, we explore low-scale leptogenesis, targeting RH neutrino masses around the order of 1 TeV. In the framework of thermal leptogenesis, assuming a hierarchical right-handed neutrino mass spectrum, a lower limit on the mass of the lightest right-handed neutrino, $M_1 \simeq 10^9$ GeV, has been established [4]. However, this bound can be relaxed in scenarios featuring nearly degenerate neutrino masses, commonly referred to as resonant leptogenesis [5, 6]. In such a situation, one-loop self-energy contribution is enhanced resonantly and the flavour-dependent asymmetry produced from the decay of right-handed neutrino into lepton and Higgs is given by [7–11],

$$\varepsilon_{i\alpha} = \sum_{i \neq j} \frac{\mathrm{Im}\left[\left(Y_\nu^*\right)_{\alpha i}\left(Y_\nu^*\right)_{\alpha j}\left(Y_\nu^\dagger Y_\nu\right)_{ij} + \xi_{ij}\left(Y_\nu^*\right)_{\alpha i}\left(Y_\nu^*\right)_{\alpha j}\left(Y_\nu^\dagger Y_\nu\right)_{ji}\right]}{\left(Y_\nu^\dagger Y_\nu\right)_{ii}\left(Y_\nu^\dagger Y_\nu\right)_{jj}} \cdot \frac{\xi_{ij}\zeta_j\left(\xi_{ij}^2 - 1\right)}{\left(\xi_{ij}\zeta_j\right)^2 + \left(\xi_{ij}^2 - 1\right)^2}. \tag{2.3}$$

where $\xi_{ij} = M_i/M_j$ and $\zeta_j = \left(Y_\nu^\dagger Y_\nu\right)_{jj}/(8\pi)$ with $Y_\nu = m_D/v$.

2.3 Dark Matter

Dark matter is a mysterious form of matter that does not emit, absorb, or reflect light, making it invisible, but its gravitational effects on galaxies and the large-scale structure of the universe are well-documented. While the standard neutrinos (ν_e, ν_μ, ν_τ) have very small masses, they are classified as hot dark matter candidates due to their high velocities. However, simulations show that hot dark matter cannot account for the formation of galaxies and cosmic structures as we observe them.

Attention has turned to sterile neutrinos, a hypothetical type of neutrino that interacts only via gravity, making them good candidates for warm dark matter. Warm dark matter is a form of dark matter that moves slower than hot dark matter but is not as cold as traditional cold dark matter. Sterile neutrinos could provide an explanation for dark matter in a way that is consistent with both the cosmic microwave background and large-scale structure of the universe. There are other important lines of evidence for dark matter (DM), such as Fritz Zwicky's 1933 observations of galaxy clusters, gravitational lensing (which Zwicky 1937 proposed could allow galaxy clusters to act as gravitational lenses), galaxy rotation curves in 1970, cosmic microwave background, and the most recent cosmology data provided by the Planck satellite [12]. It is known that dark matter (DM) makes up around 27% of the universe, which is almost five times more than baryonic matter, based on the most current data from the Planck spacecraft. According to reports, the current dark matter abundance is given as[13],

$$\Omega_{DM} h^2 = 0.1187 \pm 0.0017$$

The physics community has faced enormous challenges in its search for potential dark matter candidates with new mechanisms beyond the standard model. The important criteria that a particle must have in order to be taken into consideration as a viable DM candidate. All of the SM particles are not eligible to be DM candidates due to these restrictions. The particle physics community became motivated to investigate several BSM frameworks that may provide accurate DM phenomenology and can be evaluated in many experiments.

2.3.1 Evidence of Dark Matter

Multiple astrophysical and cosmological observations provide compelling evidence for the existence of dark matter:

1. Galaxy Rotation Curves: The rotational velocities of stars in galaxies remain constant or even increase at large radii, contrary to the expectations from visible mass distributions. This discrepancy implies the presence of an extended dark matter halo surrounding galaxies.

$$v_{rot}^2(r) = \frac{GM(r)}{r} \tag{2.4}$$

   where, v_{rot} is the rotational velocity, G is the gravitational constant, and $M(r)$ is the mass enclosed within radius r. Observations show that $M(r)$ continues to grow linearly with r, indicating dark matter dominance.

2. Gravitational Lensing: The bending of light from distant objects by massive foreground structures (gravitational lensing) reveals mass distributions that exceed those inferred from visible matter alone.

3. Cosmic Microwave Background (CMB): Precision measurements of the CMB anisotropies, particularly from missions like Planck, constrain the total matter density and indicate that a significant portion is non-baryonic dark matter.

2.3.2 Sterile Dark matter

Sterile dark matter refers to hypothetical particles that do not interact via the Standard Model (SM) forces except gravity. Unlike active neutrinos, which interact through the weak nuclear force, sterile particles lack these additional interactions. This makes them difficult to detect directly as they would not emit, absorb, or scatter light or other electromagnetic radiation, aligning with the elusive nature of dark matter. The most discussed candidate within sterile dark matter models is the sterile neutrino which is a right-handed neutrino that does not participate in the weak interaction. If such particles exist with appropriate mass and mixing parameters, they could account for the dark matter in the universe.

The Standard Model of particle physics can accommodate sterile dark matter without requiring resonant production. Sterile neutrinos with masses around a few keV are ideal warm DM candidates. They interact with Standard Model particles only through mixing with active neutrinos. This mixing enables DM abundance buildup from primordial plasma, known as the Dodelson-Widrow (DW) mechanism [14, 15]. In the absence of lepton asymmetry, sterile neutrinos are produced non-resonantly. However, significant lepton asymmetry leads to resonant production, resulting in colder momenta. This Shi-Fuller (SF) mechanism produces sterile neutrinos with smaller mixing angles [16]. Non-resonant production sets a minimum contribution to dark matter, determined by DM mass and mixing angle.

For any species, the relic abundance may be expressed as [17],

$$\Omega h^2 = \frac{\rho_{x_o}}{\rho_{crit}} = \frac{s_o Y_\infty m}{\rho_{crit}} \tag{2.5}$$

where, ρ_{crit} is the critical energy density of the universe, ρ_{x_o} is present energy density of x, Y_∞ is the present abundance of the particle x and s_o is the present day entropy. Also we can get the values of $\rho_{crit} \approx 1.054 \times 10^{-5}$ h^2 GeV cm^{-3} and $s_o \approx 2886$ cm^{-3} from Particle Data Group (PDG). For sterile neutrinos, it can be expressed as[18]:

$$\Omega_{\alpha x} = \frac{m_x Y_{\alpha x}}{3.65 \times 10^{-9}\mathrm{h}^2\mathrm{GeV}} \tag{2.6}$$

where $\alpha = e, \mu, \tau$. According to the active-sterile mixing and the sterile mass, which is proportional to the resultant relic abundance of a sterile neutrino state with a non-vanishing mixing to the active neutrinos is expressed as [19, 20],

$$\Omega_{\alpha S} h^2 = 1.1 \times 10^7 \sum C_\alpha(m_s)|V_{\alpha s}|^2 (\frac{m_s}{\mathrm{keV}})^2 \tag{2.7}$$

where,

$$C_\alpha = 2.49 \times 10^{-5} \frac{Y_{\alpha s}\text{keV}}{sin^2(\theta_{\alpha s})m_s} \tag{2.8}$$

Using the solution of the Boltzmann equation [21], C_α, the active flavor-dependent coefficients, may be determined numerically. We replace s with DM in the following formula for relic abundance, taking into account the sterile neutrino as a potential dark matter candidate and using the parametrization $|V_{\alpha s}| \simeq sin(\theta_{\alpha s})$. Consequently, the relic abundance simplified equation for non-resonantly generated dark matter takes the form [18, 22]:

$$\Omega_{DM} h^2 \simeq 0.3 \times 10^{10} Sin^2(2\theta_{DM})(\frac{M_{DM} \times 10^{-2}}{\text{keV}})^2 \tag{2.9}$$

where, Ω_{DM} is directly proportional to m_{DM} which is the DM mass as mentioned earlier and $sin^2(2\theta_{DM})$ is the active-DM mixing angle.

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