NEUTRINO MASSES AND LEPTOGENESIS FROM SMALL LEPTON NUMBER VIOLATION

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Low-scale leptogenesis combined with symmetry protected neutrino mass generation leads to a testable explanation of the matter antimatter asymmetry of our Universe. We review some recent achievements, methods and limitations of this scenario.

1 Introduction

Explaining the asymmetry between matter and anti-matter in our Universe, $Y_B = (n_B - n_{\bar{B}})/s = 8.6 \times 10^{-11}$ is one of the key challenges of particle cosmology. With n_B ($n_{\bar{B}}$) denoting the number density of (anti-) baryons and s denoting the entropy of the thermal bath, this small number reflects a tiny asymmetry in the properties of particles and anti-particles. In 1967, Sakharov [1] identified three conditions to dynamically create this imbalance between matter and anti-matter from symmetric initial conditions: (i) violation of $B-L$, the difference between baryon and lepton number, (ii) violation of C and CP and (iii) departure from thermal equilibrium.

A beautiful implementation of these conditions goes under the name of thermal leptogenesis. In the generic type-I seesaw mechanism, the observed light neutrino masses m_ν can be explained by introducing heavy neutral leptons N_I of mass M and with a Yukawa-coupling Y to the Standard Model (SM) lepton and Higgs doublets,

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{N}_I \not{\partial} N_I - \left(Y_{\alpha I} \bar{l}_\alpha \phi N_I + \frac{1}{2} M_{IJ} \bar{N}_I^c N_J + h.c. \right) \qquad \to m_\nu \simeq Y^* \frac{v^2}{M} Y^\dagger \,, \tag{1}$$

where $v = 174$ GeV denotes the vacuum expectation value of the Higgs. For thermal initial conditions, right-handed neutrinos in the mass range of about $10^{12} - 10^{15}$ GeV with 'natural' Yukawa couplings (from $\mathcal{O}(1)$ down to the electron Yukawa coupling) can not only explain the light neutrino masses but the CP-violating decays of these heavy right-handed neutrinos can also generate the observed baryon asymmetry of the Universe [2]. We emphasize that this mechanism is well rooted in particle physics and yields the correct baryon asymmetry for very well motivated parameters, without the need to choose any special initial conditions. On the downside, it is essentially impossible to verify experimentally, due to the high mass scale involved.

With testability in mind, we focus hence here on a different variant of leptogenesis, proposed by Akhmedov, Rubakov and Smirnov in 1998 [3], referred to ARS leptogenesis hereafter. In particular, we will consider a minimal implementation of this model, based on only two right-handed neutrinos participating in leptogenesis. Equipped with smaller Yukawa couplings, $Y \sim 10^{-7\pm 2}$ and masses in the MeV-GeV range, the right-handed neutrinos in this model reach thermal equilibrium only around the electroweak (EW) phase transition. The baryon asymmetry is generated during this departure from thermal equilibrium from the CP-violating oscillations and wash-out processes involving the right-handed and active neutrinos.[a] In the limit of vanishing generalized lepton number violating processes (which are suppressed in the non-relativistic limit), an asymmetry of equal magnitude but opposite sign is generated in the active and sterile sector.[b] When the SM sphalerons freeze out around the EW phase transition, they transform the lepton asymmetry of the active sector (and only of the active sector) into a baryon asymmetry. This leads to the net baryon asymmetry observed today. A key ingredient of this mechanism is a very small splitting between the two right-handed neutrinos ($\Delta m/M \sim 10^{-3}$), ensuring strong oscillations and hence efficient leptogenesis just before the electroweak phase transition. This has often been criticized as a strong and 'unnatural' fine-tuning in this model.

Here we argue that this 'tuning' may indeed instead be an indication of an underlying symmetry, linking the smallness of neutrino masses as well as the smallness of lepton-number-violating processes to a small symmetry breaking parameter. We demonstrate the power of this hypothesis by illustrating a model building limitation: contrary to naive expectations, the model parameters are so constrained that our attempt to explain dark matter using a keV-scale sterile neutrino fails. Along the way, we stress the importance of the two different regimes of ARS leptogenesis, dubbed the weak- and strong-washout regime. This proceeding is mainly based on two publications by the same authors [4,5].

2 Symmetry versus fine-tuning

In analogy to thermal leptogenesis, we start our quest for a well motivated implementation of ARS leptogenesis with the question of neutrino mass generation. Two particularly instructive effective neutrino mass models are the Inverse Seesaw [6] (ISS) and the Linear Seesaw [7] (LSS) mechanism. In both cases, the neutrino mass matrix in the flavour basis is split into a lepton number conserving part and a small lepton number violating part. The latter is parametrized by the parameter ξ (for the ISS) and ϵ (for the LSS), respectively:

$$M_\nu = \underbrace{\begin{pmatrix} 0 & \frac{1}{\sqrt{2}}h_\nu v & 0 \\ \frac{1}{\sqrt{2}}h_\nu v & 0 & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix}}_{\text{L conserving}} + \xi \underbrace{\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \Lambda \end{pmatrix}}_{\Delta L^{ISS}=2} + \epsilon \underbrace{\begin{pmatrix} 0 & 0 & \frac{1}{\sqrt{2}}h'_\nu v \\ 0 & 0 & 0 \\ \frac{1}{\sqrt{2}}h'_\nu v & 0 & \frac{\xi}{\epsilon}\Lambda \end{pmatrix}}_{\Delta L^{LSS}=2} . \quad (2)$$

In this schematic representation, to first row/column is understood to stand for the active flavours, the second for truly sterile neutrinos (no coupling to the SM degrees of freedom) and the third for mostly sterile neutrinos. As we will see in a moment, the neutrinos of these last two columns will pair up to form pseudo-Dirac fermions. In the limit of $\xi, \epsilon \to 0$, lepton number is conserved and the smallness of these parameters may hence be seen as 'technically natural'. A more fundamental motivation and UV-completion of this ansatz is an important question, for now, we will contain ourselves with this effective parametrization of this approximate symmetry.

Diagonalizing this mass matrix in the limit of small ξ and ϵ yields

$$\Rightarrow \quad m_\nu \simeq \frac{\xi (Y v)^2}{2\Lambda} + \frac{\epsilon (Y v)^2}{\Lambda} , \qquad \Delta m^2 = M_2^2 - M_1^2 \simeq 2\xi\Lambda^2 + 2\epsilon (Y v)^2 . \quad (3)$$

Note that the contributions from the LSS are only relevant below the EW phase transition (when $v \neq 0$), in particular the corresponding mass splitting between the heavy neutrinos

[a] We will use the terminology 'active' for the SM-like neutrinos, and the terms 'right-handed', 'heavy', 'neutral' or 'sterile' for the new particles. Since the mixing between these two sectors is experimentally constrained to be very small, we will apply this terminology loosely to both the flavour and mass eigenbasis.

[b] Generalized lepton number refers to an extension of the SM lepton number to the helicity states of the heavy neutral leptons. For the remainder of this paper we assume generalized lepton number to be conserved.

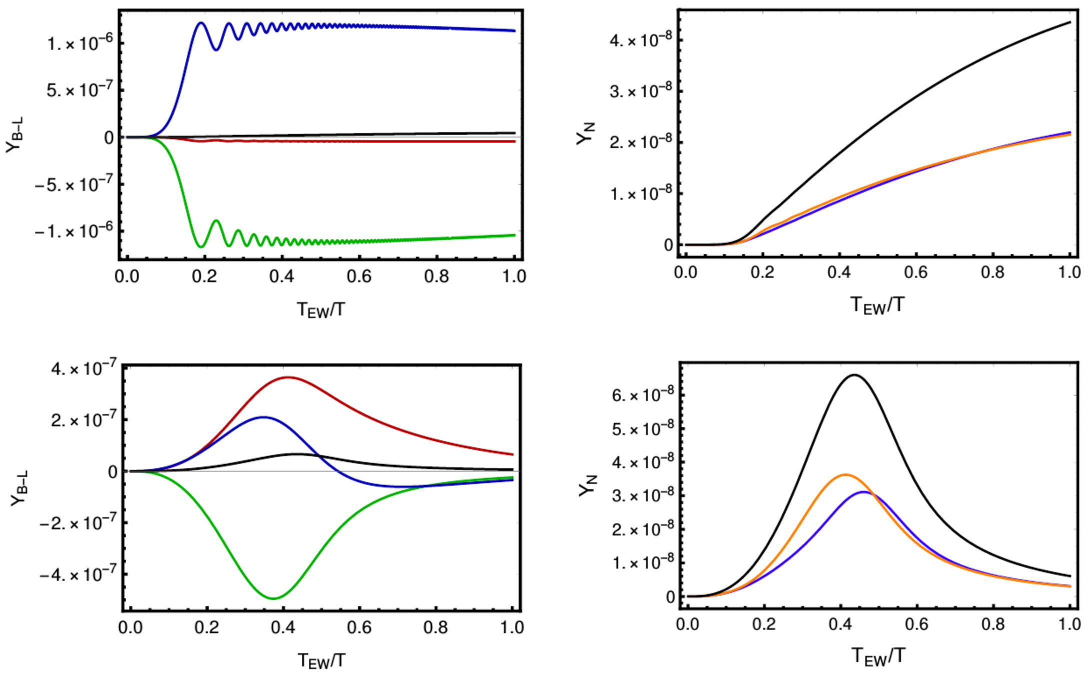

Figure 1 – Typical evolution of the asymmetries in the individual flavours in the weak washout regime (upper row) and in the strong washout regime (lower row). The left (right) column shows the asymmetries in the active (sterile) flavours. In all plots, the black curve refers to the total asymmetry of the corresponding sector.

vanishes in the regime relevant for ARS leptogenesis. For this reason, we will consider the following two scenarios in this report: Pure ISS ($\xi \neq 0, \epsilon = 0$) and a mixed scenario, dubbed 'linear plus inverse seesaw' (LISS), with $\xi \neq 0, \epsilon \neq 0$. Moreover, we will focus on the minimal particle content which can reproduce the observed neutrino oscillation data[8], which leads us to the LISS(1,1), the ISS(2,2) and the ISS(2,3). Here the first number in paranthesis denotes the number of weakly coupled right-handed neutrinos whereas the second number refers to the number of truly sterile right-handed neutrinos(in the flavour basis).

3 Two regimes of ARS leptogenesis

The Boltzmann equations encoding ARS leptogenesis are conveniently described by means of kinetic equations for the neutrino density matrix ρ [9],

$$i\frac{d\rho}{dt} = [H, \rho] - \frac{i}{2}\left\{\Gamma^d, \rho\right\} + \frac{i}{2}\left\{\Gamma^p, I - \rho\right\} , \tag{4}$$

where H denotes the Hamiltonian (containing a vacuum contribution and an effective potential), whereas Γ^d and Γ^p encode the decay and production processes, respectively. Observing that due to the large mass difference the active-sterile oscillations are suppressed, assuming kinetic equilibrium for the right-handed neutrinos ($\rho_{NN}(T,k) = R_N(T)\rho^{eq}_{NN}(T,k)$) and thermal equilibrium for the active neutrinos ($\rho_{\nu\nu} \sim \rho^{eq}(T,k)\exp(\pm\mu)$), the Boltzmann equations for the right-handed neutrinos (described by R_N) and the active neutrinos (described by the diagonal matrix of chemical potentials μ) read [10]

$$\begin{aligned} \frac{dR_N}{dt} &= -i\left[\langle H\rangle, R_N\right] - \frac{1}{2}\langle\gamma^{(0)}\rangle\left\{F^\dagger F, R_N - I\right\} - \frac{1}{2}\langle\gamma^{(1b)}\rangle\left\{F^\dagger \mu_L F, R_N\right\} \\ &\quad +\langle\gamma^{(1a)}\rangle F^\dagger \mu_L F\,, \\ \frac{d\mu_{\Delta\alpha}}{dt} &= -\frac{9\,\zeta(3)}{2N_D\,\pi^2}\left\{\langle\gamma^{(0)}\rangle\left(FR_NF^\dagger - F^* R_{\bar{N}} F^T\right) - 2\langle\gamma^{(1a)}\rangle\mu_L FF^\dagger + \right. \end{aligned} \tag{5}$$

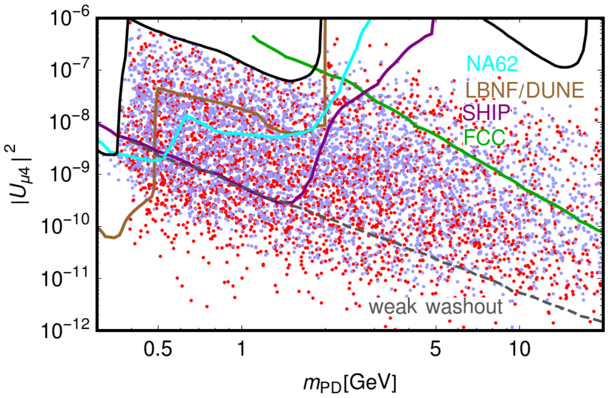

Figure 2 – Example of large mixing angles in the strong washout regime of the LISS model from inverted (red) and normal (blue) ordering of the active neutrino mass hierarchy. The maximal values reached in the weak washout regime of this model are indicated by the dashed gray line.

$$+ \langle\gamma^{(1b)}\rangle\mu_L \left(FR_NF^\dagger + F^*R_{\bar{N}}F^T\right)\Big\}_{\alpha\alpha} . \tag{6}$$

Here $\langle\gamma^{(x)}\rangle$ refers to thermally averaged rates, F denotes the Yukawa coupling in the mass eigenbasis and the corresponding equation for the right-handed antineutrinos is obtained by replacing $F \mapsto F^*$ and $\mu \mapsto -\mu$ in Eq. (5). More details on the notation and derivation can be found in the existing literature [4,5]. Instead, here we provide some intuition for the system by showing the evolution of the asymmetries for two representative parameter points in Fig. 1. The upper panel shows an example from the weak washout regime ($|F| < 10^{-7}$). The coloured curves indicate the asymmetry in the individual flavours. At about $T_L = (\Delta m^2 M_0/12)^{1/3}$, with $M_0 = 7 \times 10^{17}$ GeV, the asymmetries in the active sector grow and then remain approximately constant until the EW phase transition. The total lepton asymmetry in this sector is much smaller, as shown as the black line, indicating a high degree of cancellation between the different active flavours. In fact, the black line in the left and right panel is identical, reflecting the same absolute value of the asymmetry obtained in both sectors. The lower panel shows an example from the intermediate or strong washout regime, characterized by $|F| \sim 10^{-6}$. After an initial increase the asymmetry strongly decreases due to the washout effects. As long as all relevant processes occur close enough to the EW phase transition, enough asymmetry survives to explain the observed matter antimatter asymmetry.

Numerical methods for the efficient computation of the final baryon asymmetry were developed in Refs. [4,5]. In the weak washout regime, the baryon asymmetry can estimated analyically [3,10], in excellent agreement with the full numerical result. In the strong washout regime, a systematic perturbative expansion in terms of the chemical potentials leads to a system of differential equations which is well suited for numerical investigations of the parameter space [5]. The results obtained in this way are in good agreement with other methods [11,12]. In particular, in the strong washout regime (and only in the strong washout regime) large mixings between the SM-like and right-handed neutrinos are obtained, which may be in reach for upcoming experiments such as NA62, SHIP, DUNE and the FCC [13], see Fig. 2.

4 The question of dark matter

To illustrate the constraining power of our symmetry inspired ansatz (2), let us consider the idea of keV sterile neutrino dark matter (DM) in the ISS(2,3). With an unequal number of weakly coupled and fully sterile fermions, one neutrino is 'left over' after two pseudo-Dirac pairs are formed. The mass scale of this neutrino is predicted to be of a similar size as the mass splitting within the pseudo-Dirac pairs. The two heavy pseudo-Dirac pairs are necessary to accommodate neutrino oscillation data [8]. Let us consider the simplest possible scenario: The heaviest

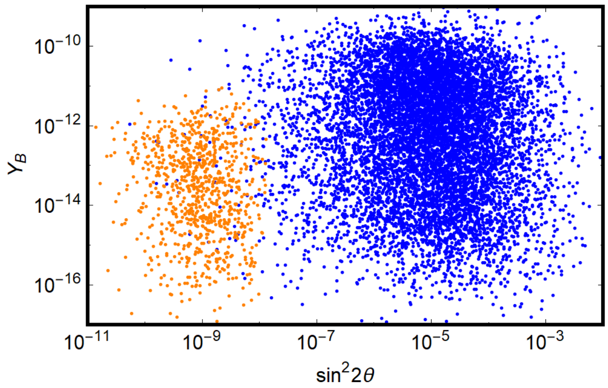

Figure 3 – Leptogenesis and dark matter in the ISS(2,3). While both dark matter (orange points) and leptogensis ($Y_B > 8.6 \times 10^{-11}$) can be implemented successfully independently, the simultaneous realization is at best possible at the cost of strong tuning.

pseudo-Dirac pair decouples early and does not influence leptogenesis. The lighter pseudo-Dirac pair (with an average mass M and a mass splitting Δm) is responsible for ARS leptogenesis. The lightest right-handed neutrino with a mass scale of $m_{DM} \sim$ keV contributes to dark matter. An irreducible production channel of the latter is the Dodelson-Widrow mechanism [14], i.e. oscillations between the active neutrinos and the DM candidate. A rough estimate leads to

$$\frac{m_{DM}}{M} \simeq \frac{\Delta m}{M} \simeq 10^{-3} \left(\frac{10^{-5}}{|F|}\right) \left(\frac{M}{\text{GeV}}\right)^{1/2} \left(\frac{m_\nu}{0.05\,\text{eV}}\right)^{1/2}, \tag{7}$$

indicating that a keV DM-candidate as studied in previous works [15] implies a mass splitting in the correct ballpark to yield successful leptogenesis in the strong washout regime. A full analysis along the lines described above however yields a different result, see Fig. 3. The parameter space which yields successful leptogenesis comes with a too large active-DM mixing and hence overproduces dark matter in this model. On the other hand, the parameter space which yields a sizable contribution to dark matter (without over-producing it) does not generate a sufficiently large baryon asymmetry. This illustrates the constraining power of our symmetry-inspired ansatz, despite the fairly large number of degrees of freedom and parameters involved.

5 Conclusion

Neutrino mass models with an approximate lepton number symmetry provide a natural implementation for ARS leptogenesis. This proves to be an efficient parametrization both in the weak and strong washout regime. This symmetry inspired ansatz minimizes the number of parameters (as opposed to the orthogonal ansatz which minimizes the degrees of freedom). The simplifications performed on the set of differential equations describing ARS leptogenesis are however independent of this ansatz, and may be applied for efficient numerical studies in a broader class of models.

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