Beyond the Standard Model with leptogenesis and neutrino data

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Abstract. I review [1] how high energy (type I) seesaw models can be nicely embedded within grand-unified models and reproduce the observed matter-antimatter asymmetry with leptogenesis. In particular, after discussing general features and results in leptogenesis, I focus on $SO(10)$-inspired leptogenesis and on a particular solution, the strong thermal $SO(10)$-inspired solution, that provides an interesting way to understand neutrino mixing parameters: the non-vanishing reactor mixing angle, the emerging negative sign of $\sin\delta$ and the slight hints favouring normally ordered neutrino masses and an atmospheric mixing angle in the first octant. I also briefly discuss leptogenesis within two right-handed seesaw neutrino models. In this case a a third decoupled right-handed neutrino can provide a candidate for very heavy cold decaying dark matter produced from right-handed neutrino mixing with a mass in the TeV-EeV range and its decays would give a contribution to the IceCube high energy neutrino events in addition to an astrophysical component.

1. Introduction

The ΛCDM cosmological model has so far resisted all experimental efforts to unearth sound evidences motivating a modification or an extension. Therefore, it nowadays provides a minimal model able to describe all cosmological observations [1, 2]. However, within the Standard Model of particle physics and fundamental interactions (SM), we cannot explain the nature and origin of some of the features of the ΛCDM, in particular the observed matter-antimatter asymmetry of the Universe and the necessity of a non-baryonic dark matter component. For this reason these *cosmological puzzles* have to be regarded as strong motivations for new physics beyond the SM. Neutrino masses and mixing also call for an extension of the SM and it is then reasonable that the same new physics should also address the cosmological puzzles.

Here I focus on a simple extension based on the introduction of right-handed (RH) neutrinos with Yukawa couplings, generating a Dirac mass term for neutrinos as for the other massive fermions, and an additional Majorana mass term. This simple extension leads to the seesaw formula for the light neutrino masses and mixing and opens the opportunity to solve some of the cosmological puzzles in quite a minimal way that moreover can be easily embedded within well motivated realistic models beyond the SM such as grand-unified models.

[1] Compendium of talks given at Neutrino 2016 and NuFact 2016.

1.1. Baryon asymmetry of the Universe

The small CMB deviations from a thermal equilibrium distribution combined with stringent constraints from cosmic rays place a tight upper bound on the abundance of primordial ordinary anti-matter in our observable Universe [3]. The energy density of ordinary matter is today dominated by baryons (in the form of nucleons) and, therefore, the baryon contribution to the energy density of the Universe can be regarded as a measure of the matter-antimatter asymmetry of the Universe.

This is one of the cosmological parameters that is more precisely and accurately measured by CMB temperature anisotropies, since it directly enters an expression of the sound velocity in the primordial plasma at recombination, affecting quite remarkably the height of the CMB acoustic peaks [4]. The *Planck* satellite collaboration finds for the baryon abundance [2]

$$\Omega_{B0}^{(CMB)} h^2 = 0.02222 \pm 0.00023 \,. \tag{1}$$

This can be translated into a measurement of the *baryon-to-photon number ratio*

$$\eta_{B0} \equiv \frac{n_{B0}}{n_{\gamma 0}} \simeq \frac{\Omega_{B0}\, \varepsilon_{c0}}{m_N\, n_{\gamma 0}} \simeq 273.5 \times 10^{-10}\, \Omega_{B0}\, h^2 \Rightarrow \eta_{B0}^{(CMB)} = (6.05 \pm 0.06) \times 10^{-10} \,, \tag{2}$$

where m_N is the (properly averaged) mass of nucleons, $\varepsilon_{\rm c}$ is the critical energy density of the Universe and, as usual, the subscript "0" indicates quantities at present.

1.2. Neutrino masses and mixing

Neutrino mixing experiments are well explained, barring anomalies hinting at possible light sterile neutrino states, by neutrino mixing among three active neutrino mass eigenstates with masses $m_1 < m_2 < m_3$ and with mass squared differences given in the case of normal (inverted) ordering by $m_3^2 - m_1^2 \equiv m^2_{\rm atm} \simeq (0.05\,{\rm eV})^2$ and $m_2^2 - m_1^2\,(m_3^2 - m_2^2) \equiv m^2_{\rm sol} \simeq (0.009\,{\rm eV})^2$ [5]. Neutrino flavour eigenstates can be in general expressed as an admixture of neutrino mass eigenstates described by a leptonic mixing matrix U such that $\nu_\alpha = \sum_i U_{\alpha i}\, \nu_i$ [6].

Latest neutrino oscillation experiments global analyses find for the mixing angles and the Dirac phase δ, in the case of NO, the following best fit values and 1σ errors (3σ ranges) [5]:

$$\begin{aligned} \theta_{13} &= 8.4^\circ \pm 0.2^\circ \quad (7.8^\circ\text{—}9.0^\circ)\,, \\ \theta_{12} &= 33^\circ \pm 1^\circ \quad (30^\circ\text{—}36^\circ)\,, \\ \theta_{23} &= 41^\circ \pm 1^\circ \quad (38^\circ\text{—}51^\circ)\,, \\ \delta &= -108^\circ \pm 36^\circ \quad (-207^\circ\text{—}27^\circ)\,. \end{aligned} \tag{3}$$

It is interesting that there is already a 3σ exclusion interval $\delta \ni [27^\circ, 153^\circ]$ and that $\sin\delta > 0$ is excluded at more than 2σ clearly favouring $\sin\delta < 0$ (a lower statistical significance is found in [7]). There are no experimental constraints on the Majorana phases and there is no signal from $00\nu\beta$ experiments that, therefore, place an upper bound on the $00\nu\beta$ effective neutrino mass m_{ee}. Currently, the most stringent reported upper bound comes from the KamLAND-Zen collaboration finding, at 90% C.L., $m_{ee} \leq (61\text{–}165)\,{\rm meV}$ [8], where the range accounts for nuclear matrix element uncertainties.

Cosmological observations place an upper bound on the sum of the neutrino masses, in particular the *Planck* satellite collaboration finds $\sum_i m_i \lesssim 230\,{\rm meV}$ at 95%C.L. [2] that, taking into account the measured values of the solar and atmospheric neutrino mass scales, translates into an upper bound on the lightest neutrino mass $m_1 \lesssim 70\,{\rm meV}$.

1.3. Minimally extended SM

In order to account for neutrino masses and mixing, one could extend the SM minimally, just adding RH neutrinos with Yukawa couplings h giving an additional term $-\mathcal{L}_Y^{\nu} = \bar{\nu}_L\, h\, \nu_R$, as for the other fermions. After spontaneous symmetry breaking this generates a neutrino Dirac mass term $-\mathcal{L}^{\nu}_{\rm mass} = v\, \bar{\nu}_L\, m_D\, \nu_R$, where m_D is the neutrino Dirac mass matrix. It is always possible to find two unitary transformations V_L and U_R that, acting respectively on LH and RH neutrino fields, bring to the Yukawa basis, where the neutrino Dirac mass matrix is diagonal and given by $D_{m_D} \equiv {\rm diag}(m_{D1}, m_{D2}, m_{D3})$, with $m_{D1} \leq m_{D2} \leq m_{D3}$, in a way that one can write (singular value decomposition)

$$m_D = V_L^{\dagger}\, D_{m_D}\, U_R\,. \tag{4}$$

Within this picture, the neutrino masses would be simply given by the eigenvalues of the neutrino Dirac mass matrix, $m_{\nu i} = m_{Di}$ and the leptonic mixing matrix by $U = V_L^{\dagger}$. However, this minimal extension does not address different issues [2]:

- why neutrino masses are much lighter than all other massive fermions;
- why we observe much large mixing angles in U compared to the quark sector;
- the cosmological puzzles;
- why there is not a Majorana mass term in addition to the Dirac mass term.

1.4. Seesaw mechanism

Neutrinos only carry lepton number as a global charge and, therefore, having introduced RH neutrinos and without modifying the SM Higgs sector, one can also have, in addition to the Dirac mass term, a right-right Majorana mass term without conflicting with any experimental bound. This term would violate lepton number at tree level and can have interesting phenomenological consequences potentially testable. In this way after spontaneous symmetry breaking the total neutrino mass term now would read

$$-\mathcal{L}^{\nu}_{\rm mass} = (\bar{\nu}_L^c, \bar{\nu}_R) \left(\begin{array}{cc} 0 & m_D \\ m_D^T & M \end{array}\right) \left(\begin{array}{c} \nu_L \\ \nu_R^c \end{array}\right) + {\rm h.c.} \quad . \tag{5}$$

In the *seesaw limit*, $M \gg m_D$, the mass spectrum splits into 2 sets: a set of three light neutrinos (dominantly LH) with masses given by the seesaw formula

$${\rm diag}(m_1, m_2, m_3) = -U^{\dagger}\, m_D\, M^{-1}\, m_D^T\, U^{\star}\,, \tag{6}$$

and a set of N very heavy (dominantly RH) neutrinos with masses $M_1 \leq M_2 \leq M_3$ (almost) coinciding with the eigenvalues of the Majorana mass matrix M. The number of RH neutrinos N cannot be lower than two in order to reproduce the solar and the atmospheric neutrino mass scale but, model independently, there is no upper bound. However, for definiteness and since we will be interested in $SO(10)$-inspired models, we will refer to the case $N = 3$.

These new very heavy RH neutrinos can now play a cosmological role, as we will see, being either responsible for the matter-antimatter asymmetry or providing a candidate for cold dark matter or both.

[2] This of course does not exclude the possibility that neutrino are of Dirac nature, but this minimal picture has to be supplemented by further ingredients such as extra-dimensions within a Randall-Sundrum setup [9].

2. Minimal scenario of leptogenesis

The minimal scenario of leptogenesis [10] relies on two main assumptions.

i) The first one is the (type I) seesaw extension of the SM discussed above. In the flavour basis, where both charged lepton and Majorana mass matrices are diagonal, h, that is in general complex, encodes all source of *CP* violation that can translate into a macroscopic $B-L$ asymmetry, injected in the form of a lepton asymmetry, thanks to the out-of-equilibrium decays of the very heavy RH neutrinos. A RH neutrino can decay either into lepton and higgs doublets with rate Γ_i or into anti-leptons and (h.c.) higgs doublets with rate $\bar{\Gamma}_i$. The two rates are in general because of *CP* violation and one can define the total *CP* asymmetries

$$\varepsilon_i \equiv -\frac{\Gamma_i - \bar{\Gamma}_i}{\bar{\Gamma}_i + \bar{\Gamma}_i}\,. \tag{7}$$

Each decay of a RH neutrino N_i will then generate on average a $B-L$ asymmetry, in the form of lepton asymmetry, given by ε_i. However, the final $B-L$ asymmetry has to take into account also the inverse processes that wash-out the asymmetry produced from decays and moreover this wash-out can also be flavour dependent. In general we can anyway write that the final $B-L$ asymmetry will be the sum of the contributions from each RH neutrino species, so that $N_{B-L}^{\rm f} = \sum_i N_{B-L}^{(i){\rm f}}$.

ii) *Thermal production* of the RH neutrinos in the early Universe. This implies a reheat temperature at the end of inflation $T_{RH} \gtrsim T_{\rm lep} = M_i/z_B$, where M_i is the mass of the RH neutrino whose decays dominantly produce the asymmetry and $z_B = 2$—10 is a factor taking into account that the surviving asymmetry is generated in a relatively sharp range of temperatures below M_i, about the value corresponding to a departure of equilibrium, while at higher temperature all asymmetry is quite efficiently washed-out. This is true for the a production in a (mildly) strong wash-out regime that however is strongly favoured (and desirable) by the measured values of the solar and atmospheric neutrino mass scales.

A necessary condition for successful leptogenesis is $T_{\rm lep} \gtrsim T_{\rm sph}^{\rm off}$, where $T_{\rm sph}^{\rm off} \simeq 140\,{\rm GeV}$ is the temperature below which sphaleron processes switch off and go out-of-equilibrium (i.e. when $\Gamma_{\rm sph} \lesssim H$ where H is the expansion rate) [11]. In this way sphalerons can convert part of the lepton asymmetry into a baryon asymmetry conserving the $B-L$ asymmetry and one obtains for the baryon-to-photon number ratio predicted by leptogenesis

$$\eta_{B,0}^{\rm lep} = a_{\rm sph}\,\frac{N_{B-L}^{\rm f}}{N_{\gamma,0}}\,, \tag{8}$$

where $a_{\rm sph} \simeq 1/3$ is the fraction of $B-L$ asymmetry that ends up into a baryon asymmetry. Successful leptogenesis of course requires $\eta_{B,0}^{\rm lep} = \eta_{B,0}^{(CMB)}$.

2.1. A problem with too many parameters

The seesaw parameter space contains 18 additional parameters: 3 RH neutrino masses and 15 additional parameters in the Dirac mass matrix. Thanks to the seesaw formula, the 15 parameters in the Dirac mass matrix can be re-expressed through the 9 low energy neutrino parameters, 3 light neutrino masses and 6 parameters in U, the 3 M_i and 6 parameters in a orthogonal matrix Ω, explicitly

$$m_D = U\,D_m^{1/2}\,\Omega\,D_M^{1/2}\,. \tag{9}$$

The orthogonal matrix Ω [12] encodes information on the 3 lifetimes and the 3 total *CP* asymmetries of the RH neutrinos. Therefore, low energy neutrino experiments by themselves cannot test the seesaw mechanism. The baryon-to-photon number ratio calculated from leptogenesis, $\eta_B^{\rm lep}$, depends on all 18 seesaw parameters in general. The successful leptogenesis condition is conceptually very important since introduces a constraint on the RH neutrino parameters: with leptogenesis we are able to read the result of a very special experiment occurred in the early Universe, the origin of matter, getting information on the physics at those very high energies. However, by itself in general, it is clearly insufficient to over-constraint the seesaw parameter space providing a conclusive phenomenological test. On the other hand a few things might help in this direction:

- Successful leptogenesis might be satisfied only about *peaks*, i.e. only for very special regions in parameter space that can correspond to testable constraints on some low energy neutrino parameter;
- Some of the parameters might cancel out in the calculation of $\eta_B^{\rm lep}$;
- Imposing some cosmologically motivated condition to be respected such as the *strong thermal leptogenesis* (independence of the initial conditions) or, even stronger, that one of the heavy RH neutrino species is the dark matter candidate;
- Adding particle physics phenomenological constraints, such as collider signatures, charged LFV, EDM's, . . . ;
- Embedding the seesaw within a model leading to conditions on m_D and M_i.

2.2. Vanilla leptogenesis

A particular successful scenario that well illustrates the possible above mentioned strategies to reduce the number of parameters in order to obtain testable constraints or predictions on observables, is represented by so called *vanilla leptogenesis*. It relies on the following set of assumptions:

i) the flavour composition of the final leptons does not influence the calculation of the final asymmetry;

ii) a hierarchical RH neutrino spectrum ($M_2 \gtrsim M_1$);

iii) the asymmetry produced by the heavier RH neutrino is negligible.

iv) (momentum integrated) Boltzmann equations fairly describes the kinetic evolution.

Under these four assumptions the predicted baryon-to-photon number ratio gets a contribution only by the lightest RH neutrino decays and one obtains a very simple expression [13],

$$\eta_B^{\rm lep} \simeq 0.01\, \varepsilon_1\, \kappa^{\rm f}(K_1)\, \exp\left[-\frac{\omega}{z_B}\,\frac{M_1}{10^{10}\,{\rm GeV}}\,\frac{\sum_i m_i^2}{{\rm eV}^2}\right]\,, \tag{10}$$

where the final *efficiency factor* $\kappa^{\rm f}(K_1)$ depends only on the lightest RH neutrino decay parameter $K_1 \equiv \widetilde{\Gamma}_1/H(T = M_1)$, with $\widetilde{\Gamma}_1$ indicating the lightest RH neutrino decay width, and is basically corresponding to the number of RH neutrinos decaying out-of-equilibrium. The exponential factor is an effect of $\Delta L = 2$ wash-out processes and $\omega \simeq 0.186$ while $z_B \simeq 2$ —10 has a logarithmic dependence on K_1. If in addition to the four above mentioned assumptions one also v) bars fine-tuned cancellations in the see-saw formula, one obtains the upper bound [14]

$$\varepsilon_1 \lesssim 10^{-6}\,\frac{M_1}{10^{10}\,{\rm GeV}}\,\frac{m_{\rm atm}}{m_1+m_3}\,. \tag{11}$$

When these results are combined, from the successful leptogenesis condition one finds a lower bound $M_1 \gtrsim 10^9\,{\rm GeV}$ [14, 15] and an upper bound $m_1 \lesssim 0.1\,{\rm eV}$ [16, 13] that is mainly the consequence of the $\Delta L = 2$ wash-out exponential suppression in Eq. (10) and is now interestingly confirmed by the cosmological upper bound $m_1 \lesssim 0.07\,{\rm eV}$ placed by the *Planck* collaboration. This upper bound is also very interesting, since it provides an example of how, despite one starts from 18 parameters, the successful leptogenesis condition can indeed produce testable constraints. The reason is that the final asymmetry in vanilla leptogenesis does not depend on the 6 parameters in U, since this cancels out in ε_1, and on the 6 parameters associated to the two heavier RH neutrinos. There are only 6 parameters left $(m_1, m_{\rm atm}, m_{\rm sol}, M_1, \Omega^2_{11})$ of which two are measured leaving only 4 free parameters. The asymmetry however has a peak strongly suppressed by the value of m_1, due mainly to the exponential suppression from $\Delta L = 2$ wash-out processes in Eq. (10), that is where the upper bound on m_1 comes from.

Another interesting feature of *vanilla leptogenesis* is that the value of the decay parameter K_1 varies typically within an interval $K_1 \in [10, 50]$, where the wash-out is moderately strong: not too strong to prevent successful leptogenesis but strong enough to wash-out a large pre-existing asymmetry (including an asymmetry generated by the heavier RH neutrinos) since its relic value is given by

$$N_{B-L}^{\rm pre-ex,f} = N_{B-L}^{\rm pre-ex,i} \exp\left[-\frac{3\pi}{8}\,K_1\right] \,. \tag{12}$$

There is, however, a corner in the parameter space where $K_1 \lesssim 1$ and in this case the asymmetry can be generated by the N_2's: this is the N_2-dominated scenario of leptogenesis [17] that, within an unflavoured description, has to be regarded as an exception to vanilla leptogenesis, that is strictly N_1-dominated. We will see, however, how accounting for flavour effects this scenario becomes much more important and easy to realise.

An unpleasant feature of vanilla leptogenesis is that, imposing so called $SO(10)$-inspired conditions with $V_L \simeq V_{CKM}$, and $(m_{D1}, m_{D2}, m_{D3}) \sim (m_{\rm up}, m_{\rm charm}, m_{\rm top})$, and barring very fine-tuned crossing level solutions, one has $M_1 \sim 10^5\,{\rm GeV}$, well below the lower bound on M_1 for successful N_1-dominated leptogenesis. N_2-dominated leptogenesis also cannot be realised since in $SO(10)$-inspired leptogenesis one has strictly $K_1 \gg 1$. We will be back on $SO(10)$-inspired leptogenesis and see how this problem can be circumvented.

3. Flavour effects

The stringent lower bound on M_1 has been one of the main motivations to investigate scenarios of leptogenesis beyond vanilla leptogenesis. There have been 4 main directions of investigation:

- Leptogenesis with quasi-degenerate RH neutrino spectrum leading to a resonant enhancement of the CP asymmetry (resonant leptogenesis) [18].
- Beyond the minimal scenario of leptogenesis, either considering non-minimal versions of the seesaw mechanism (such as type II see-saw, inverse see-saw, double seesaw) [19] or relaxing the thermal RH neutrino production assumption considering non-thermal leptogenesis scenarios [20].
- Improved kinetic description beyond simple rate Boltzmann equation: momentum dependence [21], density matrix equations [22, 23], Kadanoff-Baym and closely related closed-time path formalism [24].
- Charged lepton and heavy neutrino flavour effects and their interplay.

All these four directions have stimulated intense investigations with a much deeper insight into the calculation of the asymmetry in leptogenesis and the possibility to evade the bounds from the vanilla leptogenesis scenario. However, the most far-reaching implications, certainly in connection with models and low energy neutrino experiments, are those from flavour effects and for this reason here we focus on this particularly important development.

3.1. Charged lepton flavour effects

Let us first consider the N_1-dominated scenario. If $5\times 10^8\,{\rm GeV} \lesssim M_1 \lesssim 5\times 10^{11}\,{\rm GeV}$ then the flavour composition of the leptons (and anti-leptons) produced in the N_1-decays influence the value of the final asymmetry since leptons have to be described as an incoherent mixture of a tauon component and, of a coherent superposition of the electron and muon components due to the fast τ-interactions [22, 25]. In this situation a *two-flavoured regime* is realised and the final asymmetry has to be calculated as the sum of a tauon component and of a electron+muon component, since the two in general experience a difference wash-out, i.e. a different kinetic evolution. An approximated expression valid for $K_1 \gg 1$ in this case is given by [26]

$$N_{B-L}^{\rm f} \simeq 2\,\varepsilon_1\,\kappa(K_1) + \frac{\Delta p_{1\tau}}{2}\,\left[\kappa(K_{1e+\mu}) - \kappa(K_{1\tau})\right]\,, \tag{13}$$

where $K_{1\alpha}$ ($\alpha = e, \mu, \tau$) are the decay flavoured parameters ($K_{1e+\mu} \equiv K_{1e} + K_{1\mu}$) and $\Delta p_{1\tau}$ is the difference between the probability that a lepton produced by N_1 decays is in a tauon flavour and the probability that the anti-lepton produced by N_1-decays is in a anti-tauon flavour: it is a measurement of *CP* flavour violation. If the second term vanishes, then the inclusion of flavour effects simply double the asymmetry but if the second term is non-vanishing then there are much more important implications, in particular now even though $\varepsilon_1 = 0$ one can still produce the correct asymmetry and in this the second term is strongly depending by the low energy neutrino parameters, in particular the Majorana phases play quite an important role in establishing whether in the difference the two terms cancel out so that the second term is suppressed or one dominates over the other and there is no suppression. Basically the term $\Delta p_{1\tau}$ introduces an additional source of *CP* violation (a flavoured one) that in some cases can be dominant.

If $M_1 \lesssim 5 \times 10^8\,{\rm GeV}$ then also muon interactions are fast enough to break the coherence of the electron-muon component and one has to consider a three flavoured regime where the final asymmetry has to be calculated as the sum of three different contributions from each charged lepton flavour.

3.2. Heavy neutrino flavour effects

In general one should also consider the asymmetry produced by the out-of-equilibrium decays of the heavier RH neutrinos. In an unflavoured approximation, one would obtain that this is efficiently washed-out and can be neglected except for a special region in parameter space [17]. However, when charged lepton flavour effects are considered, the wash-out has to be considered along different flavour directions and is in general reduced [27]. Even when all three masses are above $10^{12}\,{\rm GeV}$ and charged lepton effects are absent, one still has to consider that a lighter RH neutrino N_i can only wash-out the asymmetry along the ℓ_i flavour direction but not along the orthogonal direction in flavour space [22, 28].

When both charged lepton and heavy neutrino flavour effects are considered, one has to consider 10 different RH neutrino hierarchical mass spectra, shown in Fig. 1, giving rise to different expressions for the calculation of the final asymmetry with Boltzmann equations [29]. The dashed intervals indicate RH neutrino mass ranges corresponding to transition regimes between two different fully flavoured regimes. In these transition regimes density matrix equations should be used instead of Boltzmann equations applyiable in fully flavoured regimes. The top-left panel corresponds to the heavy neutrino flavoured scenario with all three $M_i \gg 10^{12}\,{\rm GeV}$. This scenario of leptogenesis typically emerges within models with discrete flavour symmetries [30].

3.3. N_2-dominated scenario

An important case is obtained for $M_1 \ll 10^9\,{\rm GeV}$ since in this case necessarily the asymmetry has to be generated by the two heavier RH neutrinos and typically the one generated by the heaviest is negligible so that one obtains a N_2-dominated scenario (corresponding to the three panels in the third row of Fig. 1). While in the unflavoured approximation it is realised only for

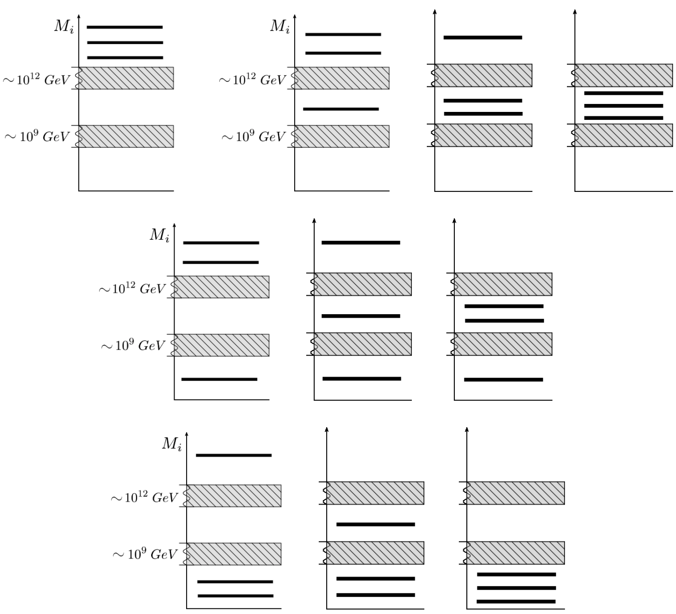

Figure 1. The 10 RH neutrino mass patterns corresponding to leptogenesis scenarios with different sets of classical Boltzmann equations for the calculation of the final asymmetry.

quite a special choice of parameters [17], when flavour effects are taken into account the region of applicability greatly enlarges [27, 31]. This scenario (specifically the central panel in the third row) has two interesting features: it emerges naturally when $SO(10)$-inspired conditions are imposed [32] and it is the only one that can realise independence of the initial conditions, quite an interesting combination of completely independent features [33].

4. $SO(10)$-inspired leptogenesis

In the unflavoured case we have seen that imposing $SO(10)$-inspired conditions and barring fine-tuned crossing level solutions, successful leptogenesis cannot be attained since $M_1 \ll 10^9\,\mathrm{GeV}$ and the N_2 contribution to the final asymmetry is efficiently washed-out. However, when flavour effects are considered, then the N_2 asymmetry can escape the N_1-washout for a set solutions satisfying successful leptogenesis. Typically the final asymmetry is in the tauon flavour [34]. Interestingly this set of solutions requires certain constraints on the low energy neutrino parameters. For example the lightest neutrino mass cannot be below $\simeq 1\,\mathrm{meV}$, i.e. one expects some deviation form the hierarchical limit though right now we do not know any experimental way to fully test this lower bound. It should be added that $SO(10)$-inspired leptogenesis also strongly favours normally ordered neutrino masses and that for $m_1 \simeq m_{\rm sol} \simeq 10\,\mathrm{meV}$ it is allowed only for θ_{23} in the first octant.

4.1. Decrypting $SO(10)$-inspired leptogenesis

Imposing $SO(10)$-inspired conditions and barring crossing level solutions, it is possible to find quite accurate expressions for all important quantities necessary to calculate the asymmetry. We refer the reader to [36] for a detailed discussion, here we just give the results for the RH neutrino masses, given by

$$M_1 \simeq \alpha_1^2\,\frac{m_{\rm up}^2}{|(\widetilde{m}_\nu)_{11}|}\,, \quad M_2 \simeq \alpha_2^2\,\frac{m_{\rm charm}^2}{m_1\,m_2\,m_3}\,\frac{|(\widetilde{m}_\nu)_{11}|}{|(\widetilde{m}_\nu^{-1})_{33}|}\,, \quad M_3 \simeq \alpha_3^2\,m_{\rm top}^2\,|(\widetilde{m}_\nu^{-1})_{33}|, \tag{14}$$

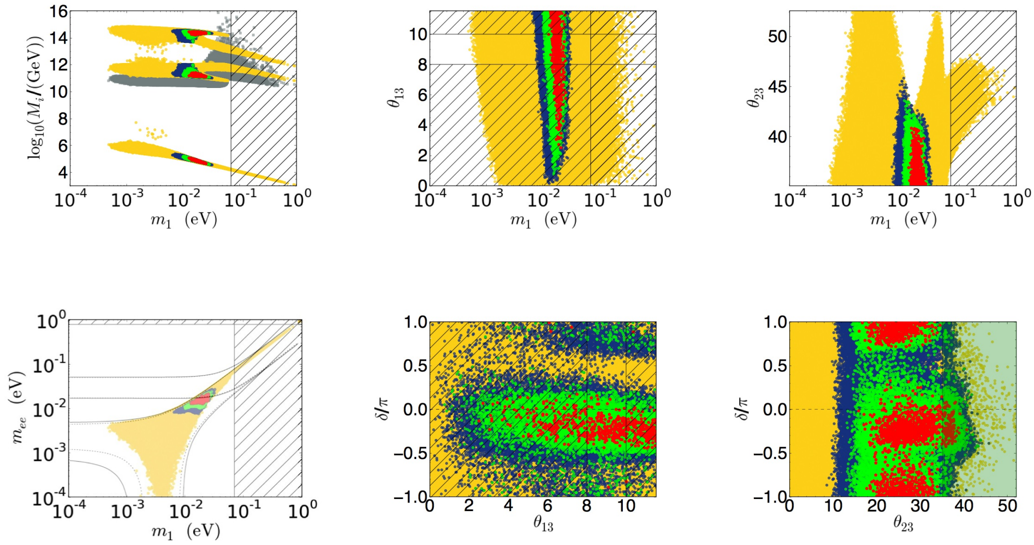

Figure 2. Some of the constraints on low energy neutrino parameters deriving from $SO(10)$-inspired leptogenesis (from [35]). The yellow points are obtained imposing successful $SO(10)$-inspired leptogenesis but without imposing strong thermal condition (wash-out of a large pre-existing asymmetry). The blue, green and red points correspond respectively to the subset of solutions also respecting the strong thermal leptogenesis (the strong $SO(10)$-inspired leptogenesis solution) respectively for an initial value of the pre-existing asymmetry $N_{B-L}^{\rm pre-ex,i} = 10^{-3}, 10^{-2}, 10^{-1}$.

where we defined $(\alpha_1, \alpha_2, \alpha_3) \equiv (m_{D1}/m_{\rm up}, m_{D2}/m_{\rm charm}, m_{D3}/m_{\rm top})$ and $\widetilde{m}_\nu \equiv V_L\, m_\nu\, V_L^T$. In this way one arrives to a fully analytical expression for $\eta_B^{\rm lep}(m_\nu; \alpha_i, V_L)$.

4.2. Strong thermal $SO(10)$-inspired leptogenesis

When flavour effects are taken into account there is only one scenario of (successful) leptogenesis allowing for independence of the initial conditions: the tauon N_2-dominated scenario, where the asymmetry is produced by the N_2 decays in the tauon flavour [33]. The conditions are quite special since it is required that a large pre-existing asymmetry is washed-out by the lightest RH neutrino in the electron and muon flavours. The next-to-lightest RH neutrinos both wash-out a large pre-existing tauon asymmetry and also produce the observed asymmetry in the same tauon flavour escaping the lightest RH neutrino wash-out.

It is then highly non trivial that this quite special set of conditions can be realised by a subset of the $SO(10)$-inspired solutions satisfying successful leptogenesis [35]. For this subset the constraints are quite stringent and they pin down a quite well defined solution: the strong $SO(10)$-inspired solution. This is characterised by non-vanishing reactor mixing angle, normally ordered neutrino masses, atmospheric mixing angle in the first octant and δ in the forth quadrant ($\sin\delta < 0$ and $\cos\delta > 0$). In addition the lightest neutrino mass has to be within quite a narrow range of values about $m_1 \simeq 20\,\mathrm{meV}$ corresponding to a sum of neutrino masses, the quantity tested by cosmological observations, $\sum_i m_i \simeq 95\,\mathrm{meV}$, implying a deviation from the normal hierarchical limit predicting $\sum_i m_i \simeq 60\,\mathrm{meV}$ detectable during next years. At the same time the solution also predicts a $00\beta\nu$ signal with $m_{ee} \simeq 0.8\, m_1 \simeq 16\,\mathrm{meV}$. Some of these constraints are shown in Fig. 2. In light of the latest experimental results discussed in the introduction, this solution is quite intriguing since, in addition to rely on the same moderately strong wash-out as in vanilla leptogenesis and due to the fact that both the solar and the atmospheric scale are $\sim 10\,\mathrm{meV}$, the leptogenesis conspiracy [31], it has also correctly predicted a non-vanishing reactor mixing angle and it is currently in very good agreement with the best fit parameters from neutrino mixing experiments (to our knowledge is the only model that has truly predicted $\sin\delta < 0$). Notice that the possibility to have a large pre-existing asymmetry prior to the onset of leptogenesis at the large reheat temperatures required, is quite a plausible possibility (in particular one could have a traditional GUT baryogenesis followed by leptogenesis), so that the assumption of strong thermal leptogenesis should be regarded as a reasonable setup.

It is also possible to consider a supersymmetric framework for $SO(10)$-inspired leptogenesis [37]. In this case the most important modification to be taken into account is that the critical values for M_1 setting the transition from one flavour regime to another are enhanced by a factor $1 + \tan^2\beta$ [25] and for sufficiently large values of $\tan\beta$ the production might occur in a three flavoured regime rather than in a two-flavour regime. This typically goes in the direction of enhancing the final asymmetry since the wash-out at the production is reduced.

4.3. Realistic models

A first example of realistic models satisfying $SO(10)$-inspired conditions and able to fit all lepton and quark mass and mixing parameters are of course $SO(10)$ models. A specific example is given by renormalizable $SO(10)$-models for which the Higgs fields belong to 10-, 120-, 126-dim representations yielding specific mass relations among the various fermion mass matrices [38]. Recently reasonable fits have been obtained typically pointed to compact RH neutrino spectrum with all RH neutrino masses falling in the two-flavour regime. However, also fits realising the N_2-dominated scenario have been obtained [39, 40]. Note however that $SO(10)$-inspired conditions can be also realised ebyond $SO(10)$-models. For example recently a Pati-Salam model combined with A_4 and Z_5 discrete symmetries has been proposed satisfying $SO(10)$-inspired conditions [41] and also successful $SO(10)$-inspired leptogenesis [42]. On the other hand a realistic model realising strong thermal $SO(10)$-inspired leptogenesis has not yet been found.

5. Two RH neutrino models and dark matter

Another popular scenario of leptogenesis is realised within a 2 RH neutrino model [43] (corresponding to the third panel in Fig. 1). In this case the heaviest RH neutrino has a mass $M_3 \gg 10^{15}\,\mathrm{GeV}$ and it effectively decouples from the seesaw formula. In this case there is a lower bound $M_1 \gtrsim 2\times 10^{10}\,\mathrm{GeV}$ from leptogenesis [44]. Also in this case there are regions in the parameters space, though more special, where the N_2-production is essential to get successful leptogenesis.

Recently a realistic 2 RH neutrino scenario of leptogenesis has been shown to emerge within a $A4 \times SU(5)$ SUSY GUT model [45] and also within a $\Delta(27) \times SO(10)$ model [46], showing that a a $SO(10)$ model combined with a discrete symmetry does not necessarily give rise to a very hierarchical spectrum of RH neutrino masses with $M_1 \ll 10^9\,\mathrm{GeV}$.

Intriguingly, within a 2 RH neutrino seesaw scenario, one can also consider the case when the third RH neutrino decouples from the seesaw formula not because it is very heavy but because its Yukawa coupling is very small. In the limit when it basically vanishes, the RH neutrino becomes stable and can play the role of dark matter [47]. The difficulty is to find a plausible production mechanism. A minimal way the does not require to lower all neutrino Yukawa couplings in order to enhance the LH-RH neutrino mixing as in the νMSM model, is to introduce a non-renormalizable Higgs portal-like operator $(\lambda_{ij}/\Lambda)\,\phi\,\phi^\dagger\,N_i\,\bar{N}_j^c$, where Λ is the scale of new physics (or a combination of more scales). The very interesting feature of this operator is that it can at the same time be responsible for the RH neutrino production through Landau-Zener non adiabatic resonant conversion, enhancing medium effects, and at the same time make the RH neutrino unstable. Interestingly an allowed region exists such that both requirements of production and stability on cosmological scales can be satisfied and this region is for a mass of the DM RH neutrino in the range EeV $\gtrsim M_{DM} \gtrsim$ TeV. However at the same time one can have some very high energy neutrino flux that might give a detectable contribution at IceCube [48]. [3] The scenario is also compatible with resonant leptogenesis in a two RH neutrino model, realising in this way a unified picture of leptogenesis and dark matter that will be tested in next years at IceCube.

6. Conclusions

Despite the absence of new physics at colliders so far, with neutrino physics and cosmology (and hopefully with high energy neutrinos at Neutrino Telescopes) there are well motivated ways in the next years to disclose the nature of the SM extension that is necessary in order to explain neutrino masses and the cosmological puzzles. High energy seesaw models embedded within GUT theories provide a very simple and attractive way in this respect to address the matter-antimatter asymmetry and dark matter of the Universe with testable predictions.

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