Neutrino masses, leptogenesis and dark matter

Pasquale Di Bari

School of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, UK

Despite the lack of evidence of new physics at colliders, neutrino masses, dark matter and matter-antimatter asymmetry of the universe require an extension of the Standard Model. After discussing some new concepts and tools in the description of seesaw neutrino models, such as motion in flavour lepton space and the introduction of the bridging matrix that nicely complements the orthogonal matrix, I discuss recent developments in the connections between neutrino data and scenarios of leptogenesis within some well motivated extensions of the Standard Model. Finally, I briefly review a simple unified picture of neutrino masses, leptogenesis and dark matter based on an extension of the seesaw Lagrangian where a non-renormalizable effective operator coupling right-handed neutrinos to the Higgs is introduced. This operator enhances the right-handed neutrino mixing between a coupled heavy right-handed neutrino and a decoupled one playing the role of dark matter. Interference between the two coupled RH neutrinos generate usual $CP$ violation so that one can also achieve successful leptogenesis. Although the dark matter right-handed neutrino escapes direct and collider searches, its decays produce a detectable contribution to the very high energy neutrino flux now discovered by IceCube, so that the model is predictive and can be tested at neutrino telescopes.

PRESENTED AT

NuPhys 2018: Prospects in Neutrino Physics
Cavendish Centre, London, 19-21 December, 2018

$^{1}$PDB acknowledges financial support from the STFC Consolidated Grant L000296/1. This project has received funding/support from the European Union Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreements number 690575 and 674896.
1 Introduction

Despite the lack of evidence of new physics at colliders, there are clear phenomenological reasons to extend the Standard Model (SM): the explanation of neutrino masses and mixing, understanding the nature of dark matter (DM) and the origin of the matter-antimatter asymmetry of the universe. It is reasonable that these three compelling evidences of new physics should be described within a unified picture. We discuss how a simple extension of the SM based on the introduction of right-handed neutrinos with Yukawa couplings and a Majorana mass term and a non-renormalisable effective operator, allows to address all three of them. Neutrino masses and mixing are explained by a simple type-I seesaw mechanism, matter anti-matter asymmetry of the universe by leptogenesis, while a decoupled right-handed neutrino can play the role of DM. The picture also predicts a contribution to the very high energy neutrino flux that makes it testable at neutrino telescopes. The recent discovery by the IceCube detector is then extremely interesting and provides a way to test this unified model.

Seesaw neutrino models and scenarios of leptogenesis are nicely embeddable within models of new physics, in particular grand-unified models, models of flavour and combinations of both. I will discuss in general how these models can point to different regions in the seesaw parameter space that, especially thanks to leptogenesis, can imply different predictions on low energy neutrino parameters. From this point of view, I will mainly emphasise the importance of absolute neutrino mass scale experiments. I will also discuss some recent developments in representing neutrino models in lepton flavour space and how the introduction of a new matrix, the bridging matrix, nicely complements the orthogonal matrix in describing and understanding seesaw neutrino models.

2 Neutrino masses and mixing

Neutrino mixing experiments measure two neutrino mass squared differences that can be expressed in terms of the atmospheric neutrino mass scale, \( m_{\text{atm}} \equiv \sqrt{|m_3^2 - m_1^2|} = (49.9 \pm 0.3) \text{ meV} \), and the solar neutrino mass scale, \( m_{\text{sol}} \equiv \sqrt{m_2^2 - m_1^2} = (8.6 \pm 0.1) \text{ meV} \), where the numerical values are those found by a recent global analysis [1]. This necessarily implies that for \( m_1 \gg m_{\text{atm}} \) all three neutrino masses are quasi-degenerate, while for \( m_1 \ll m_{\text{sol}} \) one obtains either the normal or the inverse hierarchical limit, depending on the sign of \( m_3^2 - m_1^2 \) that is still unknown. If we indicate with \( m_{1'} \) the lightest neutrino mass, coinciding with \( m_1 \) in the case of normal ordering for positive \( m_3^2 - m_1^2 \) and with \( m_3 \) in the case of inverted ordering for negative \( m_3^2 - m_1^2 \), cosmological observations combined with neutrino mixing results, place the most stringent upper bound on \( m_{1'} \lesssim 0.07 \text{ eV} \) (95% CL) excluding quasi-degenerate
neutrinos

In the case of normal ordering, favoured over inverted ordering at \( \sim 3\sigma \), latest global analyses find the following 3\( \sigma \) ranges for the mixing angles and Dirac phase in the leptonic mixing matrix \( U \) (switching from mass to weak eigenstates such that \( \nu_\alpha = U_{\alpha i} \nu_i \))

\[
\begin{align*}
\theta_{12} &= 32^\circ - 36^\circ, \\
\theta_{13} &= 8.2^\circ - 9.0^\circ, \\
\theta_{23} &= 41^\circ - 52^\circ,
\delta &= 135^\circ - 366^\circ.
\end{align*}
\]

An easy (and economical) way to extend the SM to account for neutrino masses and mixing is just to introduce right-handed (RH) neutrinos with Yukawa couplings \( h^\nu \) to left-handed (LH) neutrinos and Higgs so that, in the flavour basis where the Yukawa charged lepton matrix is diagonal, the charged lepton and neutrino Yukawa interactions can be written as

\[
-L^{\nu+\ell}_Y = \overline{L}_{\alpha} h^\ell_{\alpha \alpha} \ell_R \Phi + \overline{L}_{\alpha} h^\nu_{\alpha J} N_{RJ} \tilde{\Phi},
\]

where \( L^T \equiv (\nu_L, \alpha_L) \) are the leptonic doublets, \( M_I \leq \ldots \leq M_N \) are the heavy neutrino masses and we indicate with Greek indexes, \( \alpha = e, \mu, \tau \), the charged lepton flavour, and with Roman indexes, \( J = I, II \ldots, N \), the heavy neutrino flavour. For definiteness we can consider the simple and well motivated case \( N = 3 \). After spontaneous symmetry breaking the Higgs vev generates a neutrino Dirac mass matrix \( m_D = v h^\nu \) and charged lepton masses \( m_\alpha = v h^\ell_{\alpha \alpha} \). In this way the leptonic mass term in the Lagrangian for neutrinos and charged leptons reads

\[
-L^\nu m = \overline{\nu}_L m_\alpha \alpha_R + \overline{\nu}_L m_{D\alpha J} N_{RJ}.
\]

If we now operate a bi-unitary transformation of the LH and RH neutrino fields, \( N_{Ri} = U_{RiJ} N_{RJ} \) and \( \nu_{Li} = V_{L\alpha} \nu_L \) \( (i = 1, 2, 3) \), that switches to the Yukawa basis where the neutrino Dirac mass matrix is diagonal, one obtains a bi-unitary parameterisation of the neutrino Dirac mass matrix (mathematically, its singular value decomposition)

\[
m_D = V_L^T D_{m_D} U_R,
\]

where \( D_{m_D} \equiv \text{diag}(m_{D1}, m_{D2}, m_{D3}) \) and \( m_{D1} < m_{D2} < m_{D3} \) are the Dirac neutrino masses. In this case one has that the Yukawa basis coincides with the neutrino mass

*The latest results from the Planck collaboration \[3\], place an upper bound on the sum of neutrino masses \( \sum_i m_i \lesssim 0.12 \text{eV} \) (95\%CL). Combining this upper bound with the neutrino mixing results, this implies \( m_Y \lesssim 0.03 \text{(0.017)eV} \) for normal (inverted) ordering. It should also be noticed that inverted ordering is disfavoured at \( \sim 1.6\sigma \). This goes in the same direction of latest results from neutrino mixing experiments also disfavouring normal ordering as mentioned in the text.
eigenstate basis. The neutrino masses simply coincide with the neutrino Dirac masses, 
\( m_i = m_{Di} \) and the leptonic mixing matrix is given by \( U = V_L^\dagger \).

However, this simple option, by itself, does not address the cosmological puzzles and also implies that neutrino Yukawa couplings are much smaller than those of the other massive fermions, especially when the comparison is made within the same family, so that, for example, \( m_3/m_{\text{top}} \sim 10^{-12} \).†

However, if in addition to RH neutrinos and a Yukawa coupling term one also allows for lepton number violation and considering that neutrinos are neutral, then in general one also has a right-right Majorana mass term in the Lagrangian, so that after spontaneous symmetry breaking for the lepton mass term (3) one now has

\[
-L_{m}^{\ell+\nu} = \bar{\alpha}_L m_\alpha \alpha_R + \bar{\nu}_{L\alpha} m_D \alpha J N_{RJ} + \frac{1}{2} \bar{N}_{RJ}^c M_J N_{RJ} + \text{h.c.},
\]

in a basis where both charged lepton Dirac mass matrix and Majorana mass matrix are diagonal (we will refer to it as the \textit{flavour} basis) and where \( M_I \leq M_{II} \leq M_{III} \). In the seesaw limit, for \( M_I \gg m_{D3} \), the spectrum of mass eigenstates splits into a heavy set, with masses basically coinciding with the three \( M_J 's \) and the eigenstates with the RH neutrinos, and into a light set with the mass weigenstates almost coinciding with the LH neutrinos and with masses given by the seesaw formula (3) one now has

\[
m_i = U^\dagger_{i\alpha} m_{D\alpha J} M_J^{-1} (m_D^T)_{J\beta} U^*_{\beta i}.
\]

†Neutrinos are predicted to be Majorana neutrinos and, therefore, in the parameterisation of the leptonic mixing matrix, one has also to include two Majorana phases that cannot be reabsorbed in the fields and can in principle be measured in new physical processes involving lepton number violation. In practice, currently we can just hope to observe neutrinoless double beta decay that would correspond to measure just one Majorana phase.

The seesaw formula is equivalent to the orthogonality of the matrix (8)

\[
\Omega_{iJ} = \frac{(U^\dagger m_D)_{iJ}}{\sqrt{m_i M_J}},
\]

providing a useful (orthogonal) parameterisation of the neutrino Dirac mass matrix

\[
m_{D\alpha J} = U_{\alpha i} \sqrt{m_i} \Omega_{iJ} \sqrt{M_J}.
\]

†This does not mean that Dirac neutrinos cannot emerge within well motivated models, but these involve additional ingredients compared to the minimal extension we are considering so that the picture is actually less minimal that one can think. For example, ways to justify the lightness of Dirac neutrinos are found within frameworks with large \( \text{4} \) or warped \( \text{5} \) extra-dimensions. Also a mechanism of leptogenesis with Dirac neutrinos has been proposed \( \text{6} \) but it still requires some external source, such as GUT baryogenesis, of an initial \( B + L \) asymmetry.
The orthogonal matrix elements provide the fractional contribution to the light neutrino mass \( m_i \) from the term proportional to the inverse heavy neutrino mass \( M^{-1}_J \) and, very importantly, they tell how fine-tuned are phase cancellations in the seesaw formula to get each \( m_i \) as a sum of terms \( \propto M^{-1}_J \).

Another interesting matrix, useful in the study of the seesaw neutrino mass models and recently introduced in [9], is the bridging matrix, defined as

\[
B_{iJ} \equiv \frac{(U^\dagger m_D)_{iJ}}{\sqrt{(m_D^T m_D)_{JJ}}}.
\] (9)

This operates the transformation between the lepton flavour basis determined by the neutrino mass eigenstates to that one determined by heavy neutrino lepton flavour states (and vice-versa). If one considers lepton doublet states, one has indeed \( |L_J\rangle = B_{iJ}|L_i\rangle \) (or considering lepton doublet fields one has \( L_J = (B^\dagger)_{ji} L_i \)).

The orthogonal parameterisation (8) clearly shows that within a standard seesaw extension of the SM with three RH neutrinos, eighteen new parameters are introduced: nine low energy neutrino parameters and nine high energy neutrino parameters that escape completely the information from laboratory experiments. In particular the mass spectrum of the three heavy (mostly RH) neutrinos is one of the main unknowns. From this point of view, as we will discuss in the next section, leptogenesis plays an important role in connecting the heavy neutrino mass spectrum to the matter-antimatter asymmetry of the universe.

However, from the bi-unitary parameterisation of the neutrino Dirac mass matrix Eq. (4), one can get important insight in the the different classes of seesaw neutrino models that can be built. If we plug the bi-unitary parameterisation into the seesaw formula (6), this can be written as

\[
m_\nu \equiv U_D m_U^T = V_L^\dagger D_m U_R D_M^{-1} U_R^T D_m V_L^*,
\] (10)

where \( m_\nu \) is the light neutrino mass matrix (in the weak basis), \( D_m \equiv \text{diag}(m_1, m_2, m_3) \) and \( D_M \equiv \text{diag}(M_I, M_{II}, M_{III}) \).

**All mixing from LH sector: form-dominance models**

We have seen that in the absence of a Majorana mass term, all the mixing is described by the mismatch in the LH sector between the Yukawa basis and the charged lepton flavour basis so that \( U = V_L^\dagger \). In the presence of a Majorana mass term this is still a perfectly viable possibility. This means that in this case Majorana mass and neutrino Dirac mass matrices are diagonal in the same basis and \( U_R = I \). From Eq. (10) then it immediately follows that indeed again \( U = V_L^\dagger \), as in the case of Dirac neutrinos, but this time with seesawed neutrino masses, since one has \( m_i = m_D^2_{Dj}/M_j \).
In these models the orthogonal matrix $\Omega$ is simply given by the permutation matrix and the fine-tuning is minimal \cite{10} and they are usually referred to as form-dominance models \cite{11}. The three flavour bases of light neutrino mass eigenstates, Yukawa basis and heavy neutrino flavour basis coincide. In the figure we show in lepton flavour space, using the light neutrino mass eigenstate as reference basis, the weak basis (left panel) and the heavy neutrino flavour basis (right panel) in the case that this coincides with light neutrino basis. If, as mentioned, one parameterises

$$
\begin{align*}
\theta_{12} &= 1 \\
\theta_{13} &= 0 \\
\theta_{23} &= 0 \\
\theta_{13} &= 0 \\
\sin^2 \theta_{12} &= 1 \\
\sin^2 \theta_{13} &= 2 \\
\sin^2 \theta_{23} &= 3 \\
\end{align*}
$$

the orthogonal matrix as the product of a rotation times a Lorentz boost in flavour space, this class of models corresponds just to the simple trivial identity case (or a trivial permutation of light and heavy flavour states). Interestingly, these models typically arise imposing a discrete flavour symmetry. The bridging matrix $B$ of course also coincides with the identity. As we will see leptogenesis necessarily implies that some deviation from form-dominance is necessary to reproduce the observed baryon asymmetry of the universe.

**All mixing from the RH sector and $SO(10)$-inspired models**

The extreme opposite case is when all leptonic mixing is generated by the RH sector, meaning that $V_L = I$. In this case one still obtains analytical expressions for the RH neutrino masses, though not so simple as before, explicitly \cite{12}

$$
M_1 = \frac{m_{\nu ee}^2}{|m_{\nu ee}|}, \quad M_2 = \frac{m_{\nu ee}^2}{m_1 m_2 m_3} \left| m_{\nu ee} \right|, \quad M_3 = m_{D3}^2 \left| (m_\nu^{-1})_{\tau\tau} \right|. \quad (11)
$$

In the case of $SO(10)$-inspired models \cite{13} one has $V_L \simeq V_{CKM} \simeq I$ and in addition the Dirac neutrino masses are not too different from the up quark masses. In this case the

![Figure 1: Representation of different lepton bases in lepton flavour space. The light neutrino mass eigenstates is used as reference basis. In the left panel the weak basis is shown with an indication of the three lepton mixing angles and in the right panel the heavy neutrino flavour basis is shown in the simple case of form-dominance models, when it coincides with the light neutrino basis (from \cite{9}).](image-url)
RH neutrino mass spectrum is highly hierarchical and when current neutrino mixing data are plugged into the expressions, barring strongly fine tuned case of compact spectrum when both $|m_{\nu e}|$ and $|(m_{\nu}^{-1})_{\tau\tau}|$ are very small, one has $M_1 \ll 10^9 \text{GeV}$, with important consequences for leptogenesis.

We do not give here an expression for $U_R$ (see [12]) but it is interesting that in the hierarchical case, for $m_1 \to 0$, one has $U_R \to I$ and the expressions for the heavy neutrino masses correctly tend to the form-dominance case. This might sound like a paradox since we are assuming $V_L = I$ but the point is that in this case the mixing is the result of a balance between numerator and denominator in the seesaw formula and this is a perfectly viable case considering that this balance can well explain the observed large mixing angles. Of course one can wonder whether this corresponds to a too special (though not fined-tuned) choice of parameters to be true but it is still interesting that it naturally emerges as a perfectly viable solution within $SO(10)$-inspired models barring fine-tuning in the seesaw formula and taking into account the experimental data. Since in the exact limit all $CP$ asymmetries vanish, this might be seen as a reason why one could expect a deviation from the hierarchical limit within these models. We will see that indeed leptogenesis sets a strict lower bound on $m_1$ within $SO(10)$-inspired models.

### Two right-handed neutrino models

In the limit $M_3 \gg 10^{15} \text{GeV}$, one necessarily has $m_1 \ll 10^{-5} \text{eV}$ and in the seesaw formula the heaviest RH neutrino decouples and one obtains an effective two RH neutrino formula with a great parameter reduction (from eighteen to only eleven) [14]. These models are interesting because they are realised in different grand-unified models combined with a discrete flavour symmetry (see for example [15]).

However, these models can be also realised in the limit when one Yukawa coupling, or equivalently one neutrino Dirac mass $m_{DI}$, vanishes. This is quite interesting since in this case the decoupled heavy neutrino can have any mass and can be a candidate of dark matter [16], as we discuss in Section 4.

### 3 Leptogenesis

We do not observe primordial antimatter in the universe. The baryon-to-photon number ration measured very precisely by cosmological observations [3],

$$\eta_{B0} = (6.12 \pm 0.04) \times 10^{-10},$$

(12)

can then be considered as a measurement of the baryon asymmetry of the universe that survived the sequence of different particle species annihilations occurred in the early universe. A model of baryogenesis, where the asymmetry is generated dynamically after the inflationary stage, is considered as the most attractive explanation. A
successful model of baryogenesis cannot be found within the SM and, therefore, the baryon asymmetry of the universe is regarded as a strong evidence of new physics. Leptogenesis is a scenario of baryogenesis relying on neutrino properties and the discovery of neutrino masses and mixing have made it greatly attractive. Currently many versions exist but the minimal original one \[17\] still remains not only viable but also the appealing since it is the most natural one to be embedded within models of new physics such as grand-unified models and/or models of flavour or combinations.

The minimal scenario of leptogenesis (for a review see \[18\]) relies on the type-I seesaw extension of the SM we discussed in the previous section and on the assumption of thermal production of the heavy neutrinos, implying that the reheat temperature has to be sufficiently high compared to the mass of the RH neutrinos whose decay produce the contribution to the final asymmetry reproducing the measured one. Heavy RH neutrino decays produce a $B - L$ asymmetry that is injected in the form of lepton number that is rapidly partly reprocessed by sphaleron non-perturbative processes into a baryon asymmetry if the temperature of production is higher than the sphaleron freeze-out temperature ($T_{\text{sph}}^{\text{off}} \simeq 132 \text{ GeV}$ \[19\]). The baryon-to-photon number ratio predicted by leptogenesis can then be expressed in terms of the final $B - L$ asymmetry $N_{B-L}^{\text{fin}}$ as $\frac{\eta_{B0} = a_{\text{sph}} N_{B-L}^{\text{fin}}}{N_{\gamma}}$, where $a_{\text{sph}} \simeq 1/3$ is the fraction of $B - L$ asymmetry in the form of a baryon asymmetry.

When flavour effects are taken into account the final asymmetry is given, in general, by a sum of contributions both on heavy neutrino flavours and on charged lepton flavours. This crucially depends on the RH neutrino mass spectrum and here is why imposing successful leptogenesis somehow imposes constraints on the RH neutrino mass spectrum. The most important one is that the mass of RH neutrinos that dominantly produces the asymmetry, not necessarily the lightest ones, has to be higher than $\sim 10^9 \text{ GeV}$ if one considers a hierarchical RH neutrino spectrum and barring fine-tuning in the seesaw formula. This lower bound also translates into a similar lower bound on $T_{RH}$ \[20, 10\].

If we go back to the case of models where all mixing stems from the LH sector, with $U = V_L^\dagger$ and if one imposes a discrete flavour symmetry, then this requires $m_{D1} = m_{D2} = m_{D3}$ and one obtains a very simple RH neutrino mass spectrum. If in addition one also imposes $m_1 \ll 10^{-5} \text{ eV}$, effectively the heaviest RH neutrino decouples and one can consider an effective two RH neutrino model. In this case the lower bound on the lightest RH neutrino is $\sim 10^9 \text{ GeV}$ \[21\]. The flavour symmetry needs to be broken to have non-vanishing $CP$ asymmetries \[22, 23\]. In these models one does not get, in general, definite predictions on the mixing parameters. These can be obtained within a specific model typically combining a discrete flavour symmetry with grand-unification \[24\].

If we combine $SO(10)$-inspired models with leptogenesis ($SO(10)$-inspired leptogenesis), then the predictive power greatly increases and one gets predictions also on the mixing parameters. The reason is that in that case, as anticipated, since the
asymmetry produced by the lightest RH neutrinos is negligible, this has necessarily to be produced from next-to-lightest RH neutrinos, realising a so-called $N_2$-leptogenesis scenario [10, 25]. In this case one has also to worry that the wash-out from lightest RH neutrinos is weak enough that an asymmetry in some flavour can survive prior to the freeze-out of sphalerons. This condition, combined of course with the successful leptogenesis condition, produces constraints on all low energy neutrino parameters [26, 27]. In particular a very robust constraint is given by a lower bound on the lightest neutrino mass $m_1 \gtrsim 1$ meV and also it should be said that $SO(10)$-inspired leptogenesis works only for normal ordering, as now favoured by the latest data.

An interesting feature is that $SO(10)$-inspired leptogenesis, for a much more restricted region of parameters, can be also strong, meaning that the final asymmetry can be independent of the initial conditions, and in particular large pre-existing asymmetries, in all three charged lepton flavours, can be efficiently washed-out. This requires quite a specific set of constraints on low energy neutrino parameters whose full realisation could be basically interpreted as a signature. For example, the lightest neutrino mass has to be comprised within quite a narrow range of values, $m_1 \simeq (10–30$) meV (the exact range depends on how large is the pre-existing asymmetry to be washed-out, see [28] for details) that starts to be right now to be tested by cosmological observations (see footnote at page 2). Also, quite interestingly, the solution successfully predicted a non-vanishing value of $\theta_{13}$. Another important feature of strong thermal $SO(10)$-inspired leptogenesis is that it can be hardly compatible with the atmospheric neutrino mixing angle in the second octant, as currently slightly favoured by global analyses. In the next years it will certainly very interesting whether new experimental results will further support this solution or rule it out.

It should be noticed that $SO(10)$-inspired conditions are not necessarily realised within $SO(10)$ models. For example in [29] it has been shown that a model based on a combination of a $A_4$ discrete flavour symmetry with Pati-Salam grand-unified group, leads to $SO(10)$-inspired conditions and one can reproduce lepton parameters and also obtain successful $N_2$ leptogenesis. Interestingly, in this case the atmospheric neutrino mixing angle needs to be in the second octant as favoured by latest global analyses. If one wants also to get in addition a realistic fit of quark parameters, this has been found within a $SO(10) \times S_4 \times Z_4^R \times Z_4^3$ model, where $Z_4^R$ is an R symmetry while the other three $Z_4$’s symmetries are shaping symmetries [30].

4 Dark matter

Cosmological observations measure with great precision the abundance of cold dark matter in the universe. The latest results from the Planck collaboration find [3] $\Omega_{CDM} h^2 = 0.11933 \pm 0.00091$. Can the simple type-I seesaw Lagrangian [5] also address the dark matter puzzle? In this case one of the three heavy RH neutrinos
should play the role of dark matter particle. A solution is obtained, the so-called \( \nu \)MSM model [31], if the lightest RH neutrino mass is much smaller than the electron mass in a way that the dominant decay channel is into three neutrinos and the rate can be so strongly suppressed to have a life-time much longer with the age of the universe. This points to a mass of order of keV that is interesting since the dark matter RH neutrino would behave as warm dark matter, potentially able to solve some claimed problems in the large scale structure at scales of the galactic sub-halos. The dark matter RH neutrino would be produced by the mixing with the LH neutrinos and interestingly the correct abundance can be produced while at the same time the seesaw formula can satisfy the experimental results from neutrino mixing experiments. However dark matter RH neutrinos would also sub-dominantly decay radiatively and X-ray constraints right now exclude a non-resonance production from the mixing. One has then to introduce further ingredients in the picture that becomes much more contrived. Also in the \( \nu \)MSM neutrino Yukawa coupling need sill to be much smaller than those of other massive fermions so that one of the original motivations of the seesaw mechanisms is actually not satisfied.

An alternative solution, with more usual values of the RH neutrino masses above the TeV scale, is to consider one of the three RH neutrinos decoupled and stable. This implies that its Yukawa couplings have basically to vanish and this can be justified imposing some symmetry. In order to produce the dark matter RH neutrino however it is necessary to introduce some new interaction. An attractive option is to consider the existence of new interactions described by the the 5-dim non renormalizable operator [16]

\[
\mathcal{O}_A = \frac{\lambda_{IJ}}{\Lambda} \Phi^\dagger \Phi N^c_i N_J, \tag{13}
\]

inducing a RH-RH neutrino mixing able to produce via non-adiabatic resonant conversions a RH neutrino DM abundance. The same operator is however ultimately responsible also for the decays of the dark matter RH neutrinos and this implies both a lower bound and an upper bound on the mass singling out a window within 100 TeV–10 PeV that is quite interesting since it implies some contribution to the high energy neutrino flux that is now detected by the IceCube neutrino telescope, this providing a way to test the mechanism. Interestingly, the other two coupled RH neutrino decays can also reproduce the observed baryon asymmetry via leptogenesis [32]. In this way one realises a unified picture of neutrino masses, leptogenesis and dark matter testable at neutrino telescopes.

In conclusion a solution to the cosmological puzzles of matter-antimatter asymmetry and dark matter of the universe related to neutrino properties is not only possible but also an attractive possibility that will be tested during next years with neutrino telescopes.
ACKNOWLEDGEMENTS

It is a great pleasure to thank the organisers for such an interesting conference. I also wish to thank Marco Chianese, Kareem Farrag, Michele Re Fiorentin, Teppei Katori, Roma Samanta, Ye-Ling Zhou for a fruitful collaboration on the topics discussed.

References

[1] I. Esteban, M. C. Gonzalez-Garcia, A. Hernandez-Cabezudo, M. Maltoni and T. Schwetz, Global analysis of three-flavour neutrino oscillations: synergies and tensions in the determination of $\theta_{23}, \delta_{CP}$, and the mass ordering, JHEP 1901 (2019) 106 [arXiv:1811.05487 [hep-ph]].

[2] P. A. R. Ade et al. [Planck Collaboration], Planck 2015 results. XIII. Cosmological parameters, Astron. Astrophys. 594 (2016) A13 [arXiv:1502.01589].

[3] Y. Akrami et al. [Planck Collaboration], Planck 2018 results. I. Overview and the cosmological legacy of Planck, arXiv:1807.06205 [astro-ph.CO]; See also talk by M. Lattanzi at this conference.

[4] N. Arkani-Hamed, S. Dimopoulos, G. R. Dvali and J. March-Russell, Neutrino masses from large extra dimensions, Phys. Rev. D 65 (2001) 024032 [hep-ph/9811448].

[5] Y. Grossman and M. Neubert, Neutrino masses and mixings in nonfactorizable geometry, Phys. Lett. B 474 (2000) 361 [hep-ph/9912408].

[6] K. Dick, M. Lindner, M. Ratz and D. Wright, Leptogenesis with Dirac neutrinos, Phys. Rev. Lett. 84 (2000) 4039 [hep-ph/9907562].

[7] P. Minkowski, Phys. Lett. B 67 (1977) 421; T. Yanagida, in Proceedings of the Workshop on Unified Theory and Baryon Number of the Universe, eds. O. Sawada and A. Sugamoto (KEK, 1979) p.95; P. Ramond, Invited talk given at Conference: C79-02-25 (Feb 1979) p.265-280, CALT-68-709, [hep-ph/9809459] M. Gell-Mann, P. Ramond and R. Slansky, in Supergravity, eds. P. van Nieuwenhuizen and D. Freedman (North Holland, Amsterdam, 1979) Conf.Proc. C790927 p.315, PRINT-80-0576; R. Barbieri, D. V. Nanopoulos, G. Morchio and F. Strocchi, Phys. Lett. B 90 (1980) 91; R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44 (1980) 912.

[8] J. A. Casas and A. Ibarra, Oscillating neutrinos and $\mu \to e + \gamma$, Nucl. Phys. B 618 (2001) 171 [hep-ph/0103065].
[9] P. Di Bari, M. Re Fiorentin and R. Samanta, *Representing seesaw neutrino models and their motion in lepton flavour space*, arXiv:1812.07720 [hep-ph].

[10] P. Di Bari, *Seesaw geometry and leptogenesis*, Nucl. Phys. B **727** (2005) 318 [hep-ph/0502082].

[11] M. C. Chen and S. F. King, JHEP **0906** (2009) 072 doi:10.1088/1126-6708/2009/06/072 [arXiv:0903.0125 [hep-ph]].

[12] P. Di Bari, L. Marzola and M. Re Fiorentin, *Decrypting SO(10)-inspired leptogenesis*, Nucl. Phys. B **893** (2015) 122 [arXiv:1411.5478 [hep-ph]].

[13] A. Y. Smirnov, Phys. Rev. D **48** (1993) 3264 [hep-ph/9304205]; W. Buchmuller and M. Plumacher, Phys. Lett. B **389** (1996) 73 [hep-ph/9608308]; E. Nezri and J. Orloff, JHEP **0304** (2003) 020 [hep-ph/0004227]; F. Buccella, D. Falcone and F. Tramontano, Phys. Lett. B **524** (2002) 241 [hep-ph/0108172]; G. C. Branco, R. Gonzalez Felipe, F. R. Joaquim and M. N. Rebelo, Nucl. Phys. B **640** (2002) 202 [hep-ph/0202030].

[14] S. F. King, Nucl. Phys. B **576** (2000) 85 [arXiv:hep-ph/9912492]; P. H. Frampston, S. L. Glashow and T. Yanagida, Phys. Lett. B **548** (2002) 119 [arXiv:hep-ph/0208157]. P. H. Chankowski and K. Turzynski, Phys. Lett. B **570** (2003) 198 [arXiv:hep-ph/0306059]; A. Ibarra and G. G. Ross, Phys. Lett. B **591** (2004) 285.

[15] F. Björkeroth, F. J. de Anda, I. de Medeiros Varzielas and S. F. King, *Leptogenesis in minimal predictive seesaw models*, JHEP **1510** (2015) 104 [arXiv:1505.05504 [hep-ph]].

[16] A. Anisimov and P. Di Bari, *Cold Dark Matter from heavy Right-Handed neutrino mixing*, Phys. Rev. D **80** (2009) 073017 [arXiv:0812.5085 [hep-ph]].

[17] M. Fukugita and T. Yanagida, *Baryogenesis Without Grand Unification*, Phys. Lett. B **174** (1986) 45.

[18] S. Blanchet and P. Di Bari, *The minimal scenario of leptogenesis*, New J. Phys. **14** (2012) 125012 [arXiv:1211.0512 [hep-ph]].

[19] M. D’Onofrio, K. Rummukainen and A. Tranberg, *Sphaleron Rate in the Minimal Standard Model*, Phys. Rev. Lett. **113** (2014) no.14, 141602 [arXiv:1404.3565].

[20] S. Davidson and A. Ibarra, Phys. Lett. B **535** (2002) 25 [hep-ph/0202239]; W. Buchmuller, P. Di Bari and M. Plumacher, Nucl. Phys. B **643** (2002) 367 Erratum: [Nucl. Phys. B **793** (2008) 362] [hep-ph/0205349]; S. Blanchet and
P. Di Bari, JCAP 0703 (2007) 018 [hep-ph/0607330]; S. Blanchet and P. Di Bari, Nucl. Phys. B 807 (2009) 155 [arXiv:0807.0743 [hep-ph]].

[21] S. Antusch, P. Di Bari, D. A. Jones and S. F. King, Leptogenesis in the Two Right-Handed Neutrino Model Revisited, Phys. Rev. D 86 (2012) 023516 [arXiv:1107.6002 [hep-ph]].

[22] E. E. Jenkins and A. V. Manohar, Tribimaximal Mixing, Leptogenesis, and theta(13), Phys. Lett. B 668 (2008) 210 [arXiv:0807.4176 [hep-ph]].

[23] E. Bertuzzo, P. Di Bari, F. Feruglio and E. Nardi, Flavor symmetries, leptogenesis and the absolute neutrino mass scale, JHEP 0911 (2009) 036 [arXiv:0908.0161].

[24] See for example F. Björkeroth, F. J. de Anda, I. de Medeiros Varzielas and S. F. King, Leptogenesis in a $\Delta(27) \times SO(10)$ SUSY GUT, JHEP 1701 (2017) 077 [arXiv:1609.05837 [hep-ph]].

[25] O. Vives, Flavor dependence of CP asymmetries and thermal leptogenesis with strong right-handed neutrino mass hierarchy, Phys. Rev. D 73 (2006) 073006 [hep-ph/0512160].

[26] P. Di Bari and A. Riotto, Successful type I Leptogenesis with SO(10)-inspired mass relations, Phys. Lett. B 671 (2009) 462 [arXiv:0809.2285 [hep-ph]].

[27] P. Di Bari and A. Riotto, Testing SO(10)-inspired leptogenesis with low energy neutrino experiments, JCAP 1104 (2011) 037 [arXiv:1012.2343 [hep-ph]].

[28] P. Di Bari and L. Marzola, SO(10)-inspired solution to the problem of the initial conditions in leptogenesis, Nucl. Phys. B 877 (2013) 719 [arXiv:1308.1107].

[29] P. Di Bari and S. F. King, Successful $N_2$ leptogenesis with flavour coupling effects in realistic unified models, JCAP 1510 (2015) no.10, 008 [arXiv:1507.06431].

[30] F. J. de Anda, S. F. King and E. Perdomo, SO(10) $\times S_4$ grand unified theory of flavour and leptogenesis, JHEP 1712 (2017) 075 Erratum: [JHEP 1904 (2019) 069] [arXiv:1710.03229 [hep-ph]].

[31] T. Asaka, S. Blanchet and M. Shaposhnikov, The $\nu$ MSM, dark matter and neutrino masses, Phys. Lett. B 631 (2005) 151 [hep-ph/0503065].

[32] P. Di Bari, P. O. Ludl and S. Palomares-Ruiz, Unifying leptogenesis, dark matter and high-energy neutrinos with right-handed neutrino mixing via Higgs portal, JCAP 1611 (2016) no.11, 044 [arXiv:1606.06238 [hep-ph]].