A unified model of

neutrino masses  dark matter  

leptogenesis

(testable at neutrino telescopes)

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Why going beyond the SM?

Even ignoring:
- (more or less) compelling theoretical motivations (quantum gravity theory, flavour problem, hierarchy and naturalness problems,...) and
- Experimental anomalies (e.g., (g-2)$_\mu$, $R_K$, $R_{K^*}$,...)

The SM cannot explain:

- **Cosmological Puzzles**:
  1. Dark matter
  2. Matter - antimatter asymmetry
  3. Inflation
  4. Accelerating Universe

- **Neutrino masses and mixing**
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\[ \implies \text{It is reasonable to look for extensions of the SM providing a unified picture of neutrino masses and mixing and cosmological puzzles} \]
Neutrino masses \((m_1' < m_2' < m_3')\)

\[
\begin{align*}
NO: m_2 &= \sqrt{m_1^2 + m_{\text{sol}}^2}, & m_3 &= \sqrt{m_1^2 + m_{\text{atm}}^2} \\
IO: m_2' &= \sqrt{m_1'^2 + m_{\text{atm}}^2 - m_{\text{sol}}^2}, & m_3' &= \sqrt{m_1'^2 + m_{\text{atm}}^2}
\end{align*}
\]

\[
\begin{align*}
m_{\text{sol}} &= (8.6 \pm 0.1) \text{ meV} \\
m_{\text{atm}} &= (50.3 \pm 0.3) \text{ meV}
\end{align*}
\]

\(\text{(νfit 2019)}\)

\[
\sum_i m_i < 0.23 \text{ eV (95\% C.L.)}
\]

\[
\Rightarrow m_{1'} \leq 0.07 \text{ eV (Planck 2015)}
\]

\[
\sum_i m_i < 0.146 \text{ eV} \Rightarrow m_{1'} \leq 0.041 \text{ eV (NO, 95\% C.L.)}
\]

\[
\sum_i m_i < 0.172 \text{ eV} \Rightarrow m_{1'} \leq 0.042 \text{ eV (IO, 95\% C.L.)}
\]

\(\text{(Choudury, Hannestad 1907.12598)}\)
Neutrino mixing: \( \nu_\alpha = \sum_i U_{\alpha i} \nu_i \)

\[
U_{\alpha i} = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix} = \begin{pmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{13}e^{i\delta} \\
s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}e_{13}
\end{pmatrix} \begin{pmatrix}
e^{i\rho} & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & e^{i\sigma}
\end{pmatrix}
\]

\( \alpha_{31} = 2(\sigma - \rho) \)
\( \alpha_{21} = -2\rho \)

**CP violating phase**

\( c_{ij} \equiv \cos\theta_{ij}, \ s_{ij} \equiv \sin\theta_{ij} \)

**3\sigma ranges (NO)**

\( \theta_{12} = [31.6^\circ, 36.3^\circ] \)
\( \theta_{13} = [8.2^\circ, 9.0^\circ] \)
\( \theta_{23} = [41.1^\circ, 51.3^\circ] \)
\( \delta = [144^\circ, 357^\circ] \)
\( \rho, \sigma = [0, 360^\circ] \)

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**(vfit July 2019)**

**NO favoured over IO:**

\( \Delta\chi^2 \text{ (IO-NO)} = 10.4 \)
Minimally extended SM

\[ \mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}^\nu \]
\[-\mathcal{L}^\nu = \bar{\nu}_L h^\nu \nu_R \phi \Rightarrow -\mathcal{L}^\nu = \bar{\nu}_L m_D^\nu \nu_R \]

(in a basis where charged lepton mass matrix is diagonal)

\[ m_D = V_L^\dagger D m_D U_R \]
\[ D_{m_D} = \begin{pmatrix}
  m_{D1} & 0 & 0 \\
  0 & m_{D2} & 0 \\
  0 & 0 & m_{D3}
\end{pmatrix} \]

neutrino masses: \[ m_i = m_{D_i} \]

leptonic mixing matrix: \[ U = V_L^\dagger \]

But many unanswered questions:

- Why neutrinos are much lighter than all other fermions?
- Why large mixing angles (differently from CKM angles)?
- Cosmological puzzles?
- Why not a Majorana mass term as well?
In the see-saw limit \( (M \gg m_D) \) the mass spectrum splits into 2 sets:

- 3 light Majorana neutrinos with masses (seesaw formula):
- 3(?) very heavy Majorana neutrinos \( N_1, N_2, N_3 \) with \( M_3 > M_2 > M_1 \gg m_D \)

1 generation toy model:

\[
m_D \sim m_{\text{top}}, \quad m \sim m_{\text{atm}} \sim 50 \text{ meV} \\
\Rightarrow M \sim M_{\text{GUT}} \sim 10^{16} \text{GeV}
\]
3 generation seesaw models: two extreme limits

In the flavour basis (both charged lepton mass and Majorana mass matrices are diagonal):

\[
-\mathcal{L}_{\text{mass}}^{\nu+\ell} = \overline{\nu_L} m_\alpha \alpha_R + \overline{\nu_L} m_{D\alpha I} \nu_{RI} + \frac{1}{2} \overline{\nu_{RI}} M_I \nu_{RI} + \text{h.c.}
\]

\[
\alpha = e, \mu, \tau
\]

\[
I = 1, 2, 3
\]

bi-unitary parameterisation:

\[
m_D = V_L^\dagger D m_D U_R \quad D_{m_D} = \text{diag}(m_{D1}, m_{D2}, m_{D3})
\]

**FIRST (EASY) LIMIT: ALL MIXING FROM THE LEFT-HANDED SECTOR**

- \( U_R = I \) \( \Rightarrow \) again \( U = V_L^\dagger \) and neutrino masses:
  \[
  m_i = \frac{m_{D_i}^2}{M_I}
  \]

If also \( m_{D1} = m_{D2} = m_{D3} = \lambda \) then simply:

\[
M_I = \frac{\lambda^2}{m_i}
\]

**Exercise:** \( \lambda \sim 100 \text{ GeV} \)

\[
m_1 \sim 10^{-4} \text{ eV} \quad \Rightarrow \quad M_3 \sim 10^{17} \text{ GeV}
\]

\[
m_2 = m_{\text{sol}} \sim 10 \text{ meV} \quad \Rightarrow \quad M_2 \sim 10^{15} \text{ GeV}
\]

\[
m_3 = m_{\text{atm}} \sim 50 \text{ meV} \quad \Rightarrow \quad M_1 \sim 10^{14} \text{ GeV}
\]

Typically RH neutrino mass spectrum emerging in simple discrete flavour symmetry models
A SECOND (LESS EASY) LIMIT:  ALL MIXING FROM THE RH SECTOR
(Branco et al. '02; Nezri, Orloff '02; Akhmedov, Frigerio, Smirnov '03; PDB, Riotto '08; PDB, Re Fiorentin '12)

\[
V_L = I \Rightarrow M_1 = \frac{m_{D1}^2}{m_{\beta\beta}}; \quad M_2 = \frac{m_{D2}^2 m_{\beta\beta}}{m_1 m_2 m_3 \left| (m_V^{-1})_{\tau\tau} \right|}; \quad M_3 = m_{D3}^2 \left| (m_V^{-1})_{\tau\tau} \right|
\]

If one also imposes (SO(10)-inspired models)

\[
m_{D1} = \alpha_1 m_{up}; \quad m_{D2} = \alpha_2 m_{charm}; \quad m_{D3} = \alpha_3 m_{top}; \quad \alpha_i = O(1)
\]

very hierarchical
RH neutrino
mass spectrum

WHAT CAN HELP UNDERSTANDING WHICH IS THE RIGHT MODEL OR CLASS OF MODELS?
Baryon asymmetry of the universe

(Hu, Dodelson, astro-ph/0110414)

Consistent with (older) BBN determination but more precise and accurate

Asymmetry coincides with matter abundance since there is no evidence of primordial antimatter

Though all 3 Sakharov conditions are satisfied in the SM, any attempt to reproduce the observed value fails by many orders of magnitude \(\Rightarrow\) it requires NEW PHYSICS!

\[
\Omega_{B0} h^2 = 0.02242 \pm 0.00014
\]

\[
\eta_{B0} = \frac{n_{B0} - \bar{n}_{B0}}{n_{\gamma 0}} \approx \frac{n_{B0}}{n_{\gamma 0}} \approx 273.5 \Omega_{B0} h^2 \times 10^{-10} = (6.12 \pm 0.04) \times 10^{-10} = \eta_{B0}^{CMB}
\]
Minimal scenario of leptogenesis
(Fukugita, Yanagida '86)

- **Type I seesaw mechanism**
- **Thermal production of RH neutrinos:** $T_{RH} \approx T_{lep} \approx M_i / (2 \div 10)$

Heavy neutrinos decay

\[ N_I \xrightarrow{\Gamma_I} L_I + \phi^\dagger \quad N_I \xrightarrow{\bar{\Gamma}} \bar{L}_I + \phi \]

**Total CP asymmetries**

\[ \varepsilon_I \equiv -\frac{\Gamma - \bar{\Gamma}}{\bar{\Gamma} + \Gamma} \]

\[ \Rightarrow N_{B-L} \text{ production} \]

- **Sphaleron processes in equilibrium**

\[ \Rightarrow T_{lep} \geq T_{off}^{sphalerons} \sim 140 \text{ GeV} \]

(Kuzmin, Rubakov, Shaposhnikov '85)

**$\Delta B = \Delta L = 3$**

\[ \eta_{lep}^{B0} = a_{sph} \frac{N_{fin}^{B-L}}{N_{rec}^\gamma} \]
Vanilla leptogenesis $\Rightarrow$ upper bound on $\nu$ masses

(Buchmüller, PDB, Plümacher ’04; Blanchet, PDB ’07)

1) Lepton flavor composition is neglected

2) Hierarchical spectrum ($M_2 \gtrsim 2M_1$)

3) Strong lightest RH neutrino wash-out

\[ \eta_{B_0} \approx 0.01N_{B-L}^{\text{final}} \approx 0.01\epsilon_1\kappa_1^{\text{fin}}(K_1,m_1) \]

decay parameter: \( K_1 \equiv \frac{\Gamma_{N_1(T=0)}}{H(T=M_1)} \)

All the asymmetry is generated by the lightest RH neutrino decays!

4) Barring fine-tuned cancellations

(Davidson, Ibarra ’02)

\[ \epsilon_1 \leq \epsilon_1^{\text{max}} \approx 10^{-6} \left( \frac{M_1}{10^{10} \text{ GeV}} \right) \frac{m_{\text{atm}}}{m_1 + m_3} \]

IS SO(10)-INSPIRED LEPTOGENESIS RULED OUT?

\[ m_1 < 0.12 \text{eV} \]

No dependence on the leptonic mixing matrix \( U \): it cancels out!
Flavor composition of lepton quantum states matters!

\[ |l_1\rangle = \sum_\alpha \langle l_\alpha | l_1 \rangle |l_\alpha\rangle \quad (\alpha = e, \mu, \tau) \]

\[ |\bar{l}_1\rangle = \sum_\alpha \langle l_\alpha | \bar{l}_1 \rangle |\bar{l}_\alpha\rangle \]

- \( T << 10^{12} \text{ GeV} \) \( \Rightarrow \) \( \tau \)-Yukawa interactions are fast enough to break the coherent evolution of \( |l_1\rangle \) and \( |\bar{l}_1\rangle \)

\( \Rightarrow \) incoherent mixture of a \( \tau \) and of an \( \mu + e \) components \( \Rightarrow \) 2-flavour regime

- \( T << 10^9 \text{ GeV} \) then also \( \mu \)-Yukawas in equilibrium \( \Rightarrow \) 3-flavour regime

\( N_{B-L}^{\text{final}} = \varepsilon_1 \kappa_1^{\text{fin}} \)

\[ \varepsilon_{1\tau} \kappa_1^{\text{fin}} (K_{1\tau}) + \varepsilon_{1e+\mu} \kappa_1^{\text{fin}} (K_{1e+\mu}) \]

\[ \varepsilon_{1\mu} \kappa_1^{\text{fin}} (K_{1\mu}) + \varepsilon_{1e} \kappa_1^{\text{fin}} (K_{1e}) \]
N\textsubscript{2} leptogenesis

Unflavoured case: asymmetry produced from N\textsubscript{2} - RH neutrinos is typically washed-out

\[ \eta_{B0}^{lep(N_2)} \simeq 0.01 \cdot \varepsilon_2 \cdot \kappa^{fin}(K_2) \cdot e \frac{-3\pi K_1}{8} \ll \eta_{B0}^{CMB} \]

Adding flavour effects: lighest RH neutrino wash-out acts on individual flavour ⇒ much weaker

\[
N_{B-L}^{(N_2)} = \varepsilon_2 e \kappa(K_2) e^{\frac{-3\pi K_1}{8}} + \varepsilon_2 \mu \kappa(K_2) e^{\frac{-3\pi K_1}{8}} + \varepsilon_2 \tau \kappa(K_2) e^{\frac{-3\pi K_1}{8}}
\]

- With flavor effects the domain of successful N\textsubscript{2} dominated leptogenesis greatly enlarges: the probability that K_1 < 1 is less than 0.1% but the probability that either K_{1e} or K_{1\mu} or K_{1\tau} is less than 1 is ~23%

- Existence of the heaviest RH neutrino N\textsubscript{3} is necessary for the \varepsilon_2a's not to be negligible

- It is the only hierarchical scenario that can realise strong thermal leptogenesis (independence of the initial conditions) if the asymmetry is tauon-dominated and if m_1 \geq 10 \text{ meV} (corresponding to \Sigma_i m_i \geq 80\text{meV})

N\textsubscript{2}-leptogenesis rescues SO(10)-inspired models!

\[ V_L \sim V_{CKM}; m_{D1}=a_1 m_{up}; m_{D2}=a_2 m_{charm}; m_{D3}=a_3 m_{top} \]
N$_2$ leptogenesis rescues SO(10)-inspired leptogenesis

(PDB, Riotto 0809.2285;1012.2343;He, Lew, Volkas 0810.1104)

• dependence on $\alpha_1$ and $\alpha_3$ cancels out $\Rightarrow$

the asymmetry depends only on $\alpha_2 \equiv m_{D2}/m_{charm}$: $\eta_B \alpha \alpha_2^2$

$\alpha_2=5$  NORMAL ORDERING  $I \leq V_L \leq V_{CKM}$  $V_L = I$

- Lower bound $m_1 \geq 10^{-3}$ eV
- $\theta_{23}$ upper bound

- Majorana phases constrained about specific regions

- Effective $0\nu\beta\beta$ mass can still vanish but bulk of points above meV

- INVERTED ORDERING IS EXCLUDED
- What are the blue regions? It is a subset of solutions allowing `strong' thermal leptogenesis
SO(10)-inspired leptogenesis confronting long baseline and absolute neutrino mass experiments

If the current tendency of data to favour second octant for $\theta_{23}$ is confirmed, then SO(10)-inspired leptogenesis predicts a deviation from the hierarchical limit that can be tested by absolute neutrino mass scale experiments (PDB, Samanta in preparation)

In particular current best fit values of $\delta$ and $\theta_{23}$ would imply $m_{ee} \gtrsim 10$ meV $\Rightarrow$ testable signal at $00\beta\nu$ experiments

NOTICE THAT SO(10)-inspired leptogenesis clearly disproves the statement that high scale leptogenesis is “untestable”
Which heavy neutrino spectrum?

Heavy neutrino flavored scenario

Typically rising in discrete flavour symmetry models

It emerges in SO(10)-inspired models

2 RH neutrino scenario

Low scale see-saw models
The degenerate limit

(Covi, Roulet, Vissani '96; Pilaftsis '97; Blanchet, PDB '06)

Different possibilities, for example:

• partial hierarchy: $M_3 \gg M_2, M_1$

$\Rightarrow |\varepsilon_3| \ll |\varepsilon_2|, |\varepsilon_1|$ and $\kappa_3^{\text{fin}} \ll \kappa_2^{\text{fin}}, \kappa_1^{\text{fin}}$

CP asymmetries get enhanced $\propto 1/\delta_2$

$\Rightarrow N_{B-L}^{\text{fin}} \uparrow$

For $\delta_2 \lesssim 0.01$ (degenerate limit):

$$(M_1^{\text{min}})^\text{DL} \simeq 4 \times 10^9 \text{ GeV} \left( \frac{\delta_2}{0.01} \right) \quad \text{and} \quad (T_{\text{reh}}^{\text{min}})^\text{DL} \simeq 5 \times 10^8 \text{ GeV} \left( \frac{\delta_2}{0.01} \right)$$

The reheating temperature lower bound is relaxed

The required tiny value of $\delta_2$ can be obtained e.g. in radiative leptogenesis (Branco, Gonzalez, Joaquim, Nobre'04, '05)
Dark Matter

At the present time DM acts as a cosmic glue keeping together Stars in galaxies.... ... and galaxies in clusters of galaxies (such as in Coma cluster).

\[ \Omega_{CDM,0} h^2 = 0.11933 \pm 0.0009 \sim 5 \Omega_{B,0} h^2 \]

But it has to be primordial to understand structure formation and CMB anisotropies (Hu, Dodelson, astro-ph/0110414 ) (Planck 2018, 1807.06209 )
Dark matter from LH-RH neutrino mixing

(Asaka, Blanchet, Shaposhnikov '05)

- **LH-RH neutrino mixing**

\[
\nu = (\nu_L + \nu_L^c) + \frac{m_D}{M} (\nu_R + \nu_R^c)
\]

\[
N = (\nu_R + \nu_R^c) - \frac{m_D}{M} (\nu_L + \nu_L^c)
\]

- For \( M_1 \ll m_e \) \( \Rightarrow \) \( \tau_1 = 5 \times 10^{28} \, s \left( \frac{M_1}{\text{keV}} \right)^{-5} \left( \frac{10^{-8}}{\theta^2} \right) \gg t_0 \left( |\theta|^2 \equiv \sum_{\alpha} |m_{D\alpha1} / M_1|^2 \right) \)

- **Solving Boltzmann equations abundance is produced at **\( T \sim 100 \, \text{MeV} \)**:

(Dodelson Widrow '94)

\[
\Omega_{N_1} h^2 \sim 0.1 \left( \frac{\bar{\theta}}{10^{-4}} \right)^2 \left( \frac{M_1}{\text{keV}} \right)^2 \sim \Omega_{DM,0} h^2
\]

- The lightest neutrino mass is \( \lesssim 10^{-5} \, \text{eV} \) \( \Rightarrow \) hierarchical limit

- The \( N_1 \)'s also radiatively decay and this produces constraints from X-rays (or opportunities to observe it).

- Considering also structure formation constraints, one is forced to consider a resonant production induced by a large lepton asymmetry (Shi, Fuller '99, Dolgov and Hansen '00)

- **L \sim 10^{-4} \ (3.5 \, \text{keV line?})**. (Horiuchi et al. '14; Bulbul at al. '14; Abazajian '14)
vMSM model

(Asaka, Blanchet, Shaposhnikov '05; Asaka, Shaposhnikov '06; Canetti, Drewes, Shaposhnikov 1208.4607)

- In addition to DM from resonant production in the presence of large asymmetry also the observed BAU is explained by leptogenesis from oscillations (Akhmedov, Rubakov, Smirnov '99)

- The mixing of the two heavier RH neutrinos with quasi-degenerate masses $M_{2,3} \sim 1\text{GeV}$ and $\Delta M \sim 1\text{eV}$ can reproduce BAU and produce the large asymmetry after sphaleron freeze-out necessary for DM resonant production. Moreover if $M_{2,3} \lesssim 5\text{ GeV}$ direct tests from meson decays are possible at SHiP.

\begin{align*}
M_{2,3} & \sim 5\text{ GeV} \\
M_1 & \sim \text{keV}
\end{align*}

- However, recent analyses fails to reproduce both asymmetry and DM for such low $M_{2,3}$ masses and $M_1 = 7\text{ keV}$ (M.Laine 1905.08814)
An alternative solution

(Anisimov, PDB '08)

1 RH neutrino has vanishing Yukawa couplings (enforced by some symmetry such as $Z_2$):

\[
m_D \simeq \begin{pmatrix}
0 & m_{De2} & m_{De3} \\
0 & m_{D\mu2} & m_{D\mu3} \\
0 & m_{Dt2} & m_{Dt3}
\end{pmatrix}, \text{ or } \begin{pmatrix}
m_{De1} & 0 & m_{De3} \\
m_{D\mu1} & 0 & m_{D\mu3} \\
m_{Dt1} & 0 & m_{Dt3}
\end{pmatrix}, \text{ or } \begin{pmatrix}
m_{De1} & m_{De2} & 0 \\
m_{D\mu1} & m_{D\mu2} & 0 \\
m_{Dt1} & m_{Dt2} & 0
\end{pmatrix},
\]

What production mechanism? For high masses just a tiny abundance is needed:

\[
N_{DM} \simeq 10^{-9} (\Omega_{DM,0} h^2) N_{\gamma}^{\text{prod}} \frac{TeV}{M_{DM}}
\]

Turning on tiny Yukawa couplings?

Yukawa basis:

\[
m_D = V_L^\dagger D_{m_D} U_R
\]

\[
D_{m_D} \equiv \nu \text{ diag}(h_A, h_B, h_C) \quad \text{with } h_A \leq h_B \leq h_C
\]

\[
\tau_{DM} = \frac{4\pi}{h_A^2 M_{DM}} = 0.87 h_A^2 10^{-23} \text{ GeV} \times \tau_{DM} \Rightarrow \tau_{DM} > \tau_{\text{min}} \simeq 10^{28} \text{ s} \Rightarrow h_A < 3 \times 10^{-26} \sqrt{\frac{\text{GeV}}{M_{DM}} \times \frac{10^{28} \text{ s}}{\tau_{\text{min}}}}
\]

Too small to reproduce the correct abundance with any production mechanism
Higgs portal RH neutrino mixing DM
(Anisimov ’06, Anisimov, PDB ’08)

Assume new interactions with the *standard* Higgs:

\[
L_{5\text{dim}} = \frac{\lambda_{IJ}}{\Lambda} \phi^\dagger \phi \mathcal{N}_J^c \mathcal{N}_I
\]

(In, J = A, B, C)

In general they are non-diagonal in the Yukawa basis: this generates a RH neutrino mixing. Consider a 2 RH neutrino mixing for simplicity and consider medium effects:

**From the Yukawa interactions:**

\[
V^Y_J = \frac{T^2}{8E_J} h^2_J
\]

**From the new interactions:**

\[
V^\Lambda_{JK} \approx \frac{T^2}{12\Lambda} \lambda_{JK}
\]

**Mixing from misalignment:**

\[
sin 2\theta_\Lambda(T) \equiv T^3/(\tilde{\Lambda} \Delta M^2)
\]

\[
\tilde{\Lambda} = \Lambda / \lambda_{DM-S}
\]

**Effective mixing Hamiltonian (in monocromatic approximation):**

\[
\Delta H \simeq \left( \begin{array}{cc}
-\frac{\Delta M^2}{4p} & \frac{T^2}{12\Lambda} - \frac{\Delta M^2}{16p} h_S^2 \\
\frac{T^2}{12\Lambda} & \frac{T^2}{16p} + \frac{\Delta M^2}{4p} h_S^2
\end{array} \right) \Rightarrow
\]

\[
sin 2\theta^m_\Lambda = \frac{sin 2\theta_\Lambda}{\sqrt{(1 + v^Y_S)^2 + sin^2 2\theta_\Lambda}}
\]

**If** \(\Delta m^2 < 0 (M_{DM} > M_S)\) **there is a resonance for** \(v^Y_S = -1\) **at:**

\[
z_{\text{res}} = \frac{M_{DM}}{T_{\text{res}}} = \frac{h_S M_{DM}}{2 \sqrt{M_{DM}^2 - M_S^2}}
\]
Non-adiabatic conversion

(Anisimov,PDB '08; P.Ludl.PDB,S.Palomarez-Ruiz '16)

Adiabaticity parameter at the resonance

\[ \gamma_{\text{res}} \equiv \frac{|E_{\text{DM}} - E_{\text{S}}|}{2|\theta_m|} = \sin^2 2\theta_A \left( \frac{T_{\text{res}}}{12T_{\text{res}}H_{\text{res}}} \right) |\Delta M^2|, \]

Landau-Zener formula (more accurate calculation employing density matrix solution is needed)

\[ \frac{N_{\text{DM}}}{N_{\text{S}}} \bigg|_{\text{res}} \simeq \frac{\pi}{2} \gamma_{\text{res}} \]

(remember that we need only a small fraction to be converted so necessarily \( \gamma_{\text{res}} \ll 1 \))

\[ \Omega_{\text{DM}} h^2 \simeq \frac{0.15}{\alpha_S z_{\text{res}}} \left( \frac{M_{\text{DM}}}{M_{\text{S}}} \right) \left( \frac{10^{20} \text{ GeV}}{\tilde{\Lambda}} \right)^2 \left( \frac{M_{\text{DM}}}{\text{GeV}} \right) \]

For successful dark-matter genesis

\[ \tilde{\Lambda}_{\text{DM}} \simeq 10^{20} \sqrt{\frac{1.5}{\alpha_S z_{\text{res}}} \frac{M_{\text{DM}}}{M_{\text{S}}} \frac{M_{\text{DM}}}{\text{GeV}}} \text{ GeV} \]

2 options: either \( \Lambda \ll M_{\text{Pl}} \) and \( \lambda_{\text{AS}} \ll 1 \) or \( \lambda_{\text{AS}} \sim 1 \) and \( \Lambda \gg M_{\text{Pl}} \):

it is possible to think of models in both cases.
A possible GUT origin

\[ \Lambda_{\text{eff}} \gg M_{\text{GUT}} \]

\[ \frac{1}{\Lambda_{\text{eff}}} = \frac{h\mu}{M_{\text{GUT}}^2} \]

(Anisimov, PDB, 2010, unpublished)
Constraints from decays
(Anisimov,PDB '08; Anisimov,PDB'10; P.Ludl.PDB,S.Palomarez-Ruiz'16)

2 body decays
DM neutrinos unavoidably decay today into $A+\text{leptons (A=H,Z,W)}$ through the same mixing that produced them in the very early Universe

$$\theta_{\Lambda 0} = \frac{2 v^2/\Lambda}{M_{\text{DM}} (1 - M_S/M_{\text{DM}})}.$$ 

Lower bound on $M_{\text{DM}} (\tau_{28} \equiv \tau_{\text{DM}}/10^{28} \text{s})$

$$M_{\text{DM}} \geq M_{\text{DM}}^{\text{min}} \approx 54 \text{ TeV} \alpha_s \tau_{28} \left( \frac{M_S}{M_{\text{DM}}} \right)$$

4 body decays

Upper bound on $M_{\text{DM}} (\tau_{28} \equiv \tau_{\text{DM}}/10^{28} \text{s})$

$$M_{\text{DM}} \lesssim 5.3 \text{ TeV} \alpha_s^{-\frac{2}{3}} z_{\text{res}}^{-\frac{1}{3}} \tau_{28}^{-\frac{1}{3}} \left( \frac{N_{NS}}{N_\gamma} \right)_{\text{res}}^{\frac{1}{3}} \left( \frac{M_{\text{DM}}}{M_S} \right)^{\frac{2}{3}}$$

3 body decays and annihilations also can occur but yield weaker constraints
Decays: a natural allowed window on $M_{DM}$

Increasing $M_{DM}/M_S$ relaxes the constraints since it allows higher $T_{res}$ ($\Rightarrow$ more efficient production) keeping small $N_S$ Yukawa coupling (helping stability)! But there is an upper limit to $T_{res}$ from usual upper limit on reheat temperature.
Unifying Leptogenesis and Dark Matter

(PDB, NOW 2006; Anisimov, PDB, 0812.5085; PDB, P. Ludl, S. Palomarez-Ruiz 1606.06238+see recent v3)

- Interference between $N_A$ and $N_B$ can give sizeable CP decaying asymmetries able to produce a matter-antimatter asymmetry but since $M_{DM}>M_S$ necessarily $N_{DM}=N_3$ and $M_1 \approx M_2 \Rightarrow$ leptogenesis with quasi-degenerate neutrino masses

$$\delta_{DM} \equiv (M_3 - M_S)/M_S$$

$$\delta_{lep} \equiv (M_2 - M_1)/M_1$$

Efficiency factor

Analytical expression for the asymmetry:

$$\eta_B \simeq 0.01 \frac{\bar{\varepsilon}(M_1)}{\delta_{lep}} f(m_\nu, \Omega),$$

$$f(m_\nu, \Omega) \equiv \frac{1}{3} \left( \frac{1}{K_1} + \frac{1}{K_2} \right) \sum_\alpha \kappa(K_1 \alpha + K_2 \alpha) \left[ T_{12}^\alpha + J_{12}^\alpha \right],$$

- $M_S \gtrsim 2 \ T_{sph} \approx 300 \ GeV \Rightarrow \ 10 \ TeV \lesssim M_{DM} \lesssim 1 \ PeV$
- $M_S \lesssim 10 \ TeV$
- $\delta_{lep} \sim 10^{-5} \Rightarrow$ leptogenesis is not fully resonant
Nicely predicted a signal at IceCube

(Anisimov, PDB.0812.5085; PDB, P. Ludl, S. Palomarez-Ruiz 1606.06238)

- DM neutrinos unavoidably decay today into $A$+leptons ($A=H,Z,W$) through the same mixing that produced them in the very early Universe
- Potentially testable high energy neutrino contribution

Energy neutrino flux

Potential high energy testable component

Flavour composition at the detector

**Neutrino events at IceCube:** 2 examples

$M_{DM} = 300$ TeV

$M_{DM} = 8$ PeV
Density matrix calculation of the relic abundance

(P. Di Bari, K. Farrag, R. Samanta, Y. Zhou, 1908.00521)

Density matrix equation for the DM-source RH neutrino system

$$\frac{dN_{IJ}}{dt} = -i [H, N]_{IJ} - \left( \begin{array}{cc} 0 & \frac{1}{2}(\Gamma_D + \Gamma_S) N_{DM-S} \\ \frac{1}{2}(\Gamma_D + \Gamma_S) N_{S-DM} & (\Gamma_D + \Gamma_S)(N_{NS} - N_{NS}^{eq}) \end{array} \right)$$

A numerical solution shows that a Landau-Zener overestimated the relic abundance by a few orders of magnitude (especially in the hierarchical case)
Density matrix calculation of the relic abundance

(P.Di Bari, K. Farrag, R. Samanta, Y. Zhou, 1908.00521)

Solutions only for initial thermal $N_S$ abundance, unless $M_S \sim 1 \, \text{GeV}$
Unifying Leptogenesis and Dark Matter

(PDB, K. Farrag, R. Samanta, Y. Zhou, 1908.00521)

A solution for initial thermal $N_S$ abundance:

$M_{DM} = 220 \text{ TeV}, \quad \tau_{DM} = 1.07 \times 10^{28} \text{ s}, \quad M_S = 1 \text{ TeV}, \quad T_{RH} = 10^{15} \text{ GeV}$
SUMMARY

• Seesaw neutrino mass models can not only reproduce neutrino masses and mixing but also address cosmological origin of matter.

• Moreover Cosmology helps to constraint neutrino models: reproducing matter-antimatter asymmetry and dark matter of the universe imposes important constraints and within specific classes of models can lead to predictions on low energy neutrino parameters and new signals (e.g., at neutrino telescopes).

• Absolute neutrino mass scale experiments combined with neutrino mixing will in the next year test SO(10)-inspired leptogenesis predicting some deviation from the hierarchical limit. If $0\nu\beta+\text{CP}$ violation is discovered, it would be a very strong case (discovery?) in favour of leptogenesis and would particularly favour SO(10)-inspired leptogenesis.

• If no deviation from the hierarchical limit is observed then two RH neutrino models will be favoured, in this case an intriguing unified picture of neutrino masses + leptogenesis + dark matter is possible with the help of Higgs induced RH neutrino mixing (Anisimov operator).

• Density matrix calculations are crucial and seem to suggest new possibilities that are currently explored.
**ΛCDM model**

It is a minimal flat cosmological model with only 6 parameters: baryon and cold dark matter abundances, angular size of sound horizon at recombination, reionization optical depth, amplitude and spectral index of primordial perturbations.

**ΛCDM best fit to the Planck 2018 data (TT+TE+EE+low E+lensing)**

(Planck Collaboration, *arXiv* 1807.06209)

**Planck results are in good agreement with BAO, SNe and galaxy lensing observations.** The only significant (~4σ) tension is with local measurement of the Hubble constant.

*In the ΛCDM model, expansion is described by a flat Friedmann-Lemaître cosmological model.*