Neutrino masses
leptogenesis
and dark matter

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Why going beyond the SM?

Even ignoring:

- (more or less) compelling theoretical motivations (quantum gravity theory, flavour problem, hierarchy problem, naturalness(?),...) 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**
Neutrino masses ($m_1' < m_2' < m_3'$)

\[ NO: m_2 = \sqrt{m_1^2 + m_{\text{sol}}^2}, \quad m_3 = \sqrt{m_1^2 + m_{\text{atm}}^2} \]

\[ IO: m_2' = \sqrt{m_1'^2 + m_{\text{atm}}^2 - m_{\text{sol}}^2}, \quad m_3' = \sqrt{m_1'^2 + m_{\text{atm}}^2} \]

$\text{sol} = (8.6 \pm 0.1) \text{ meV}$
$\text{atm} = (50.3 \pm 0.3) \text{ meV}$

($\nu$fit 2019)

\[ \sum_i m_i < 0.23 \text{ eV} \ (95\% CL) \]
\[ \Rightarrow m_1' \leq 0.07 \text{ eV} \quad \text{(Planck 2015)} \]

\[ \sum_i m_i < 0.12 \text{ eV} \ (95\% CL) \]
\[ \Rightarrow m_1' \leq 0.03 \text{ eV} \quad \text{(NO)} \]
\[ m_1' \leq 0.016 \text{ eV} \quad \text{(IO)} \quad \text{(Planck 2018)} \]
Neutrino mixing: \( \nu_\alpha = \sum_i U_{\alpha i} \nu_i \)

\[
U_{\alpha i} = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix} = \begin{pmatrix}
c_{12}c_{13} & -s_{12}c_{23} & s_{12}s_{23}s_{13}e^i\delta \\
c_{12}s_{13} & c_{12}c_{23} & c_{12}s_{23}s_{13}e^i\delta \\
s_{12}s_{23} & c_{12}s_{23} & c_{23}s_{13}e^i\delta
\end{pmatrix} \begin{pmatrix}
e^{i\rho} & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & e^{i\sigma}
\end{pmatrix}
\]

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

**CP violating phase**

**Atmospheric, LB**
**Reactors, Accel., LB**
**Solar, Reactors**
**\( \beta\beta 0\nu \) decay**

### 3σ ranges (NO)

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

**NO favoured over IO:**

\( \Delta \chi^2 (IO-NO) = 10.6 \)

(vfit July 2019)
Minimally extended SM

\[ \mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{\nu} \]

\[-\mathcal{L}_{Y}^{\nu} = \bar{\nu}_L h^\nu \nu_R \phi \Rightarrow -\mathcal{L}_{\text{mass}}^{\nu} = \bar{\nu}_L m_D \nu_R \]

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

diagonalising \( m_D \) :

\[ m_D = V_L^\dagger D m_D U_R \]

\[ D_{m_D} \equiv \begin{pmatrix} m_{D_1} & 0 & 0 \\ 0 & m_{D_2} & 0 \\ 0 & 0 & m_{D_3} \end{pmatrix} \]

\[ m_i = m_{Di} \]

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):

  \[
  \mathcal{L}_{\text{mass}}^\nu = \bar{\nu}_L m_D \nu_R + \frac{1}{2} \bar{\nu}_R^c M \nu_R + \text{h.c.}
  \]

- 3(?) very heavy Majorana neutrinos \(N_I, N_{II}, N_{III}\) with \(M_{III} > M_{II} > M_I \gg m_D\)

**1 generation toy model:**

\[
\begin{align*}
m_D & \sim m_{\text{top}} , \\
m & \sim m_{\text{atm}} \sim 50 \text{ meV} \\
M & \sim M_{\text{GUT}} \sim 10^{16} \text{GeV}
\end{align*}
\]

\[\text{diag}(m_1, m_2, m_3) = -U^T m_D \frac{1}{M} m_D^T U^*\]
Theory prediction:

$M \sim 10^{16} \text{ GeV}$

Experimentalist reaction
3 generation seesaw models: two extreme limits

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

\[-L^\nu+\ell_{\text{mass}} = \overline{\alpha_L} m_\alpha \alpha_R + \overline{\nu_L} m_D \alpha I \nu_R + \frac{1}{2} \overline{\nu_R} M_I \nu_R + h.c.\]

\[\alpha = e, \mu, \tau\]
\[I = 1, 2, 3\]

bi-unitary parameterisation: \[m_D = V_L^\dagger D_m U_R\]
\[D_m = \text{diag}(m_{D1}, m_{D2}, m_{D3})\]

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

- \[U_R = I \Rightarrow \text{again } U = V_L^\dagger\] and neutrino masses:

If also \[m_{D1} = m_{D2} = m_{D3} = \lambda\] then simply:

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

Exercise: \[\lambda \sim 100 \text{ GeV}\]

\[m_1 \sim 10^{-4} \text{ eV} \Rightarrow M_3 \sim 10^{17} \text{ GeV}\]
\[m_2 = m_{\text{sol}} \sim 10 \text{ meV} \Rightarrow M_2 \sim 10^{15} \text{ GeV}\]
\[m_3 = m_{\text{atm}} \sim 50 \text{ meV} \Rightarrow M_1 \sim 10^{14} \text{ GeV}\]

Typically RH neutrino mass spectrum emerging in simple discrete flavour symmetry models
If one also imposes (SO(10)-inspired models)

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

Barring very fine-tuned solutions, one obtains a very hierarchical RH neutrino mass spectrum.

Combining discrete flavour + grand unified symmetries one can obtain basically all mass spectra between these two limits (we will be back on this)

A SECOND (NOT SO 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)

\[
\begin{align*}
V_L = I & \implies M_1 = \frac{m_{D1}^2}{m_{\beta\beta}}; \quad M_2 = \frac{m_{D2}^2}{m_1 m_2 m_3 (m_{\nu}^{-1})_{\tau\tau}}; \quad M_3 = m_{D3}^2 |(m_{\nu}^{-1})_{\tau\tau}| \\
\end{align*}
\]

WHAT CAN HELP UNDERSTANDING WHICH IS THE RIGHT MODEL OR CLASS OF MODELS??
Minimal scenario of leptogenesis

(Fukugita, Yanagida '86)

• Type I seesaw mechanism

• Thermal production of RH neutrinos: \( T_{RH} \gtrsim T_{lep} \approx M_i / (2 \div 10) \)

heavy neutrinos decay

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

total CP asymmetries

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

\[\Rightarrow N_{B-L}^{\text{fin}} = \sum_{I=1,2,3} \varepsilon_I \times K_I^{\text{fin}}\]

efficiency factors

• Sphaleron processes in equilibrium

\[\Rightarrow T_{lep} \gtrsim T_{\text{sphalerons}} \sim 100 \text{ GeV}\]

(Kuzmin, Rubakov, Shaposhnikov '85)

\[
\eta_{B0}^{lep} = \frac{\alpha_{sph}}{} \frac{N_{B-L}^{\text{fin}}}{N_{\gamma}^{\text{rec}}} \approx 0.01 N_{B-L}^{\text{fin}}
\]

\[\Delta B = \Delta L = 3\]
Seesaw parameter space

Combining $\eta_{B0}^{lep} \approx \eta_{B0}^{CMB} \approx 6 \times 10^{-10}$ with low energy neutrino data can we test seesaw and leptogenesis? **Problem: too many parameters**

(Casas, Ibarra'01) $m_\nu = -m_D \frac{1}{M} m^T_D \Leftrightarrow \Omega^T \Omega = I$

Orthogonal parameterisation

(in a basis where charged lepton and Majorana mass matrices are diagonal)

- Popular solution: “low-scale” leptogenesis, though no signs so far of new physics at the TeV scale or below supporting this picture (talk by Juric Klaric)

- High scale leptogenesis is challenging to test but there are a few strategies able to reduce the number of parameters in order to obtain testable predictions on low energy neutrino parameters
Vanilla leptogenesis $\Rightarrow$ upper bound on $\nu$ masses

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

1) Lepton flavor composition is neglected

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

3) Strong lightest RH neutrino wash-out

$$\eta_{B0} \approx 0.01N_{B-L}^{final} \approx 0.01\varepsilon_1\kappa_1^{fin}(K_1, m_1)$$

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)

$$\varepsilon_1 \leq \varepsilon_1^{max} \approx 10^{-6} \left( \frac{M_1}{10^{10} \text{ GeV}} \right) \frac{m_{\text{atm}}}{m_1 + m_3}$$

No dependence on the leptonic mixing matrix $U$: it cancels out!

IS SO(10)-INSPIRED LEPTOGENESIS RULED OUT?
Independence of the initial conditions (strong thermal leptogenesis)

(Buchmüller, PDB, Plümacher '04)

wash-out of a pre-existing asymmetry $N_{B-L}^{P,\text{initial}}$

$N_{B-L}^{P,\text{final}} = N_{B-L}^{P,\text{initial}} e^{-\frac{3\pi}{8} K_1} \ll N_{B-L}^{f,N_1}$

decay parameter:

$K_1 \equiv \frac{\Gamma_{N_1}}{H(T = M_1)} \sim \frac{m_{\text{sol,atm}}}{m_*} \sim 10^{-3} \text{eV} \sim 10 \div 50$

equilibrium neutrino mass:

$m_* = \frac{16\pi^{5/2}}{3\sqrt{3}} \frac{v^2}{M_{Pl}} \sim 1.08 \times 10^{-3} \text{eV}$.

independence of the initial $N_1$-abundance as well

$K_1^{\text{fin}}$

Just a coincidence?
**Charged lepton flavour effects**

(Abada et al. '06; Nardi et al. '06; Blanchet, PDB, Raffelt '06; Riotto, De Simone '06)

**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\text{-Yukawa interactions are fast enough break the coherent evolution of } |l_1\rangle \text{ and } |\bar{l}_1\rangle**

  \Rightarrow \text{incoherent mixture of a } \tau \text{ and of a } \mu+e \text{ components} \Rightarrow \text{2-flavour regime}

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

\[ N_{B-L}^{\text{final}} = \varepsilon_1 \kappa_1^{\text{fin}} \]

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

\[ \varepsilon_{1\tau} \kappa_1^{\text{fin}} (K_{1\tau}) + \varepsilon_{1\mu} \kappa_1^{\text{fin}} (K_{1\mu}) + \varepsilon_{1e} \kappa_1^{\text{fin}} (K_{1e}) \]
Heavy neutrino lepton flavour effects: 10 scenarios

**Heavy neutrino flavored scenario**

Typically rising in discrete flavour symmetry models

- $M_i \sim 10^{12} \text{ GeV}$
- $M_i \sim 10^9 \text{ GeV}$

**2 RH neutrino scenario**

- $M_i \sim 10^{12} \text{ GeV}$
- $M_i \sim 10^9 \text{ GeV}$

**N}_2 \text{-dominated scenario:**

- $N_1$ produces negligible asymmetry;

Example: ARS leptog, (talk by Juraj Klaric)
Unflavoured case: asymmetry produced from $N_2$ - RH neutrinos is typically washed-out

$$\eta_{B0}^{lep(N_2)} \approx 0.01 \cdot \varepsilon_2 \cdot \kappa^{fin} (K_2) \cdot e^{-\frac{3\pi}{8} K_1} << \eta_{B0}^{CMB}$$

Adding flavour effects: lightest RH neutrino wash-out acts on individual flavour $\Rightarrow$ much weaker

$$N^f_{B-L} (N_2) = P^0_{2e} \varepsilon_2 \kappa(K_2) e^{-\frac{3\pi}{8} K_{1e}} + P^0_{2\mu} \varepsilon_2 \kappa(K_2) e^{-\frac{3\pi}{8} K_{1\mu}} + P^0_{2\tau} \varepsilon_2 \kappa(K_2) e^{-\frac{3\pi}{8} K_{1\tau}}$$

- With flavor effects the domain of successful $N_2$ 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 $\sim 23%$

- Existence of the heaviest RH neutrino $N_3$ 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 $m_1 \gtrsim 10$ meV (corresponding to $\sum_i m_i \gtrsim 80$ meV)

- $N_2$-leptogenesis rescues SO(10)-inspired models!

$$V_L \sim V_{CKM} ; \ m_{D1}\alpha_1 \ m_{up} ; \ m_{D2}\alpha_2 \ m_{charm} ; \ m_{D3}\alpha_3 \ m_{top}$$
SO(10)-inspired leptogenesis is predictive

(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 $\alpha_2 \equiv \frac{m_{D2}}{m_{\text{charm}}} : \eta_B \propto \alpha_2^2$

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

Lower bound $\quad m_1 \gtrsim 10^{-3}$ 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?
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).
Strong thermal SO(10)-inspired (STSO10) solution

(PDB, Marzola 09/2011, DESY workshop:1308.1107; PDB, Re Fiorentin, Marzola 1411.5478)

- **Strong thermal leptonesis** condition can be satisfied for a subset of the solutions only for **NORMAL ORDERING**

- \( \alpha_2 = 5 \)  
- Blue regions: \( N_{B-L}^{pre-ex} = 10^{-3} \) (\( I \leq V_L \leq V_{CKM} \); \( V_L = I \))

- Absolute neutrino mass scale: \( 8 \lesssim m_1/\text{meV} \lesssim 30 \leftrightarrow 70 \lesssim \sum_i m_i/\text{meV} \lesssim 120 \)

- Non-vanishing \( \Theta_{13} \);

- \( \Theta_{23} \) strictly in the first octant;
Strong SO(10)-inspired leptogenesis confronting long baseline experiments (PDB, Marco Chianese 1802.07690)

Pre-existing initial asymmetry: $N_{B-L}^{p,i} = 10^{-3}$

$$\alpha_2 = \frac{m_{D2}}{m_{charm}} = 5$$
Pre-existing initial asymmetry: $N_{B-L}^{p,i} = 10^{-3}$

$$\alpha_2 = \frac{m_{D2}}{m_{\text{charm}}} = 6$$

Second octant is compatible with strong thermal condition only if $\alpha_2 \gtrsim 6$: are there realistic models?
Heavy neutrino lepton flavour effects: 10 scenarios

**Heavy neutrino flavored scenario**

Typically rising in discrete flavour symmetry models

**2 RH neutrino scenario**

- $N_2$-dominated scenario:
  - $N_1$ produces negligible asymmetry;

Example: ARS leptog, (talk by Juraj Klaric)
They can be obtained from 3 RH neutrino models in the limit $M_3 \to \infty$;
- Number of parameters gets reduced to 11;
- Still further conditions needed to get predictions!
- Contribution to asymmetry from both 2 RH neutrinos: the contribution from the lightest ($N_1$) typically dominates but the contribution from next-to-lightest ($N_2$) opens new regions that correspond to light sequential dominated neutrino mass models realised in some GUT models. In any case there is still a lower bound

$$M_1 \gtrsim 2 \times 10^{10} \text{ GeV} \implies T_{RH} \gtrsim 6 \times 10^9 \text{ GeV}$$

- 2 RH neutrino model realised for example in $A4 \times SU(5)$ SUSY GUT model with interesting link between “leptogenesis phase” and Dirac phase
  (F. Bjorkeroth, S.F. King 1505.05504)
- 2 RH neutrino model can be also obtained from 3 RH neutrino models with 1 vanishing Yukawa eigenvalue ⇒ potential DM candidate
  (A. Anisimov, PDB hep-ph/0812.5085)
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)

But it has to be primordial to understand structure formation and CMB anisotropies

(Planck 2018, 1807.06209)

\[ \Omega_{CDM,0} h^2 = 0.11933 \pm 0.0009 \sim 5 \Omega_{B,0} h^2 \]
A first solution: lowering the scale of the 3 RH neutrinos masses (νMSM)

(Asaka, Blanchet, Shaposhnikov '05)

For $M_1 \ll m_e \Rightarrow \tau_{N_1} = 5 \times 10^{26} \text{ sec} \left( \frac{M_1}{1 \text{ keV}} \right)^{-5} \left( \frac{\bar{\theta}^2}{10^{-8}} \right)^{-1} \gg t_0 \left( |\bar{\theta}|^2 = \sum_a |m_{Da1}/M_1|^2 \right)$

The production is induced by (non-resonant) RH-LH mixing at $T\sim 100 \text{ MeV}$ (Dodelson-Widrow mechanism hep-ph/9303287):

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

- The $N_1$'s decay also radiatively 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 $L \sim 10^{-4}$ (Shi and Fuller astro-ph/9810076)
- $3.5 \text{ keV}$ line? (Horiuchi et al. '14; Bulbul at al. '14; Abazajian '14)
- Not clear whether such a large lepton asymmetry can be produced by the same (heavier) RH neutrino decays (next talk!!!)
An alternative solution: decoupling 1 RH neutrino \( \Rightarrow \) 2 RH neutrino seesaw

(Babu, Eichler, Mohapatra '89; Anisimov, PDB '08)

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

\[
\begin{pmatrix}
0 & m_{D e 2} & m_{D e 3} \\
0 & m_{D \mu 2} & m_{D \mu 3} \\
0 & m_{D \tau 2} & m_{D \tau 3}
\end{pmatrix}
\text{, or }
\begin{pmatrix}
m_{D e 1} & 0 & m_{D e 3} \\
m_{D \mu 1} & 0 & m_{D \mu 3} \\
m_{D \tau 1} & 0 & m_{D \tau 3}
\end{pmatrix}
\text{, or }
\begin{pmatrix}
m_{D e 1} & m_{D e 2} & 0 \\
m_{D \mu 1} & m_{D \mu 2} & 0 \\
m_{D \tau 1} & m_{D \tau 2} & 0
\end{pmatrix}
\]

What production mechanism? Turning on tiny Yukawa couplings?

Yukawa basis:

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

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

One could think of an abundance induced by RH neutrino mixing, considering that:

\[
\left( \frac{N_{DM}}{N_{\gamma}} \right)_{\text{prod}} \approx 10^{-6} \left( \Omega_{DM,0}^2 h^2 \right) \frac{GeV}{M_{DM}} \approx 10^{-7} \frac{GeV}{M_{DM}} \Rightarrow n_{DM,0} \sim 1 \frac{GeV}{M_{DM}}
\]

It would be enough to convert just a tiny fraction of ("source") thermalised RH neutrinos but it does not work with standard Yukawa couplings.
Proposed production mechanisms

Starting from a 2 RH neutrino seesaw model

\[
\begin{pmatrix}
0 & m_{D\nu_2} & m_{D\nu_3} \\
0 & m_{D\mu_2} & m_{D\mu_3} \\
0 & m_{D\tau_2} & m_{D\tau_3}
\end{pmatrix}, \text{ or } \begin{pmatrix}
m_{D\nu_1} & 0 & m_{D\nu_3} \\
m_{D\mu_1} & 0 & m_{D\mu_3} \\
m_{D\tau_1} & 0 & m_{D\tau_3}
\end{pmatrix}, \text{ or } \begin{pmatrix}
m_{D\nu_1} & m_{D\nu_2} & 0 \\
m_{D\mu_1} & m_{D\mu_2} & 0 \\
m_{D\tau_1} & m_{D\tau_2} & 0
\end{pmatrix},
\]

many production mechanisms have been proposed:

- from SU(2)$_R$ extra-gauge interactions (LRSM);
- from inflaton decays (Anisimov, PDB'08; Higaki, Kitano, Sato '14);
- from resonant annihilations through SU(2)' extra-gauge interactions (Dev, Kazanas, Mohapatra, Teplitz, Zhang '16);
- From new U(1)$_Y$ interactions connecting DM to SM (Dev, Mohapatra, Zhang '16);
- From U(1)$_{B-L}$ interactions (Okada, Orikasa '12);
- ..................

In all these models IceCube data are fitted through fine tuning of parameters responsible for decays (they are post-dictive)
**Higgs induced RH neutrino mixing DM (RH\text{HiNo} DM)**

(Anisimov, PDB ‘08; PDB, Ludl, Palomarez-Ruiz 2016; PDB, Farrag, Samanta, Zhou 2019)

Assume new interactions with the standard Higgs:

\[ \mathcal{L} = \frac{\lambda_{iJ}}{\Lambda} \phi_i^\dagger \phi N_i^c N_J \]  

\( (I,J=A,B,C) \)

Anisimov operator

(hep-ph 0612024)

In general they are non-diagonal in the Yukawa basis: this generates a RH neutrino mixing. Consider a 2 RH neutrino mixing for simplicity \((I,J=DM,S)\) and consider medium effects:

**From the Yukawa interactions:**

\[ V_s^Y \equiv \frac{T^2}{8E_s} h_S^2 \]

**From the new interactions:**

\[ V_{ij}^\Lambda \equiv \frac{T^2}{12 \Lambda} \lambda_{ij} \]  

\( (I,J=DM,S) \)

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

\[ \sin 2\theta^\Lambda = \frac{T^3}{\tilde{\Lambda} \Delta M^2} \]

**Define:**

\[ \Delta M^2 \equiv M_S^2 - M_{DM}^2 \]

\[ \Delta H \approx \begin{pmatrix} \frac{-\Delta M^2}{4p} - \frac{T^2}{16p} h_S^2 & \frac{T^2}{12\tilde{\Lambda}} \frac{\Delta M^2}{4p} + \frac{T^2}{16p} h_S^2 \\ \frac{T^2}{12\tilde{\Lambda}} \frac{\Delta M^2}{4p} - \frac{T^2}{16p} h_S^2 & \frac{T^2}{16p} h_S^2 \end{pmatrix} \]

\[ \sin 2\theta_{\Delta}^m = \frac{\sin 2\theta^\Lambda}{\sqrt{(1 + v_s^Y)^2 + \sin^2 2\theta^\Lambda}} \]

\[ v_s^Y \equiv \frac{T^2 h_S^2}{(4 \Delta M^2)} \]

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

If \( \Delta m^2 < 0 \) \((M_{DM} > M_S)\) there is a resonance for \( v_s^Y = -1 \) at:
Non-adiabatic conversion

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

Adiabaticity parameter at the resonance

\[
\gamma_{\text{res}} = \left| \frac{E_{\text{DM}}^m - E_{\text{S}}^m}{2 |\dot{\theta}_m|} \right|_{\text{res}} = \sin^2 2\theta_{\Lambda} \left( T_{\text{res}} \right) \frac{\Delta M^2}{12 T_{\text{res}} H_{\text{res}}},
\]

Landau-Zener formula

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

(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 \(\Lambda < M_{\text{Pl}}\) and \(\lambda_{AS} \ll 1\) or \(\lambda_{AS} \sim 1\) and \(\Lambda >> M_{\text{Pl}}\):

it is possible to think of models in both cases.
Decays: a natural allowed window on $M_{DM}$

The same Higgs induced interaction are also responsible for decays!

2 body decays

\[ \Gamma_{DM \rightarrow A + \ell_S}^{-1} = \frac{\pi}{h_S^2} \left( \frac{\Lambda}{v^2} \right)^2 M_{DM} \]

2 body decays lead to a lower bound on $M_{DM}$

IceCube data require

\[ \tau \simeq (\Gamma_{DM \rightarrow A + \ell_S} + \Gamma_{DM \rightarrow 3A + \ell_S})^{-1} > \tau_{DM}^{\text{min}} \simeq 10^{28} \text{ s} \]

4 body decays lead to an upper bound on $M_{DM}$

\[ \Gamma_{DM \rightarrow 3A + \nu}^{-1} \propto M_{DM}^{-3} \]
DM decays might help fitting IceCube data
(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

Flavour composition at the detector

Neutrino events at IceCube: 2 examples

- $M_{DM} = 300$ TeV
- $M_{DM} = 8$ PeV
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 $M_1 = M_2 \Rightarrow$ 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:

\[
\eta_B \approx 0.01 \frac{\overline{\varepsilon}(M_i)}{\delta_{lep}} f(m_\nu, \Omega),
\]

\[
f(m_\nu, \Omega) \equiv \frac{1}{3} \left( \frac{1}{K_1} + \frac{1}{K_2} \right) \sum_{\alpha} \kappa(K_{1\alpha} + K_{2\alpha}) [T_{12}^\alpha + J_{12}^\alpha],
\]

- $M_S \geq 2 T_{sph} \approx 300$ GeV $\Rightarrow$ 10 TeV $\leq M_{DM} \leq$ 1 PeV
- $M_S \leq 10$ TeV
- $\delta_{lep} \sim 10^{-5} \Rightarrow$ leptogenesis is not fully resonant
Allowed regions (from Landau-Zener)
Necessity of solving density matrix equation

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

\[N_{in}^{in} = 1\]

\[N_{in}^{in} = 0\]

Density matrix solutions show that LZ approximation does not work: the production is not resonant and much less efficient at least in the hierarchical case. However, production occurs at lower temperatures and this opens a new solution.
If one wants to combine DM with leptogenesis from deygcas then a thermalisation of the source rH neutrinos has to be assumed.....otherwise one might think of combining DM production with ARS leptogenesis (talk by Juric)
Seesaw neutrino mass models are an attractive explanation of neutrino masses and mixing easily embeddable in realistic grandunified models (with or without flavour symmetries).

However, they contain a great number of parameters and typically high scale. Cosmology helps in this respect: reproducing BAO with leptogenesis imposes important constraints and within specific classes of models can lead to predictions on low energy neutrino parameters (alternatively, one can go to low scale leptogenesis, next talk).

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 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. Soon, new results!