PREDICTING THE BARYON ASYMMETRY

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SM+3 massive neutrinos

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[\theta_{12} \sim 34^\circ\]
\[\theta_{23} \sim 42^\circ \text{ o } 48^\circ\]
\[\theta_{13} \sim 8.5^\circ\]
\[\delta \sim ?\]

normal hierarchy

\[\text{inverted hierarchy}\]

\[7.5 \cdot 10^{-5}\text{eV}^2\]

\[2.5 \cdot 10^{-3}\text{eV}^2\]
Why are neutrinos so much lighter?
Neutral vs charged hierarchy?
Why so different mixing?

\[ V_{CKM} \approx \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

\[ |V_{PMNS}| \approx \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix} \]

Harrison, Perkings, Scott
A new physics scale?

Neutrinos are different...they can have majorana masses:

\[ -\mathcal{L}_{\text{Majorana}} = \bar{\nu}_L m_\nu \nu^c_L + h.c. \leftrightarrow \bar{L} \tilde{\Phi} \alpha \tilde{\Phi} L^c + h.c. \]

\[
[\alpha] = -1
\]

\[
\alpha = \frac{\lambda}{\Lambda}
\]

Scale at which new particles will show up (mass of the neutrino mass mediators)

\[
m_\nu = \lambda \frac{v^2}{\Lambda}
\]
Seesaw mechanism:

Minkowski
Gell-Mann, Ramond Slansky
Yanagida, Glashow
Mohapatra, Senjanovic
What originates the neutrino mass?

Could be $\Lambda \gg \nu \ldots$ the standard lore (theoretical prejudice?)

$$\Lambda = M_{\text{GUT}}$$
$$\lambda \sim O(1) \quad \left\{ \begin{array}{c} m_{\nu} \checkmark \end{array} \right.$$
What originates the neutrino mass?

Could be $\Lambda \gg v$... the standard lore (theoretical prejudice?)

$$\begin{align*}
\Lambda &= M_{\text{GUT}} \\
\lambda &\sim \mathcal{O}(1)
\end{align*}$$

Hierarchy problem

$$m_\nu \quad \checkmark$$

$$m_H^2 \propto \Lambda^2$$

not natural in the absence of SUSY/other solution to the hierarchy problem
The Standard Model is healthy as far as we can see...

Could be naturally $\Lambda \sim v$ ?

Yes! $\lambda$ in front of neutrino mass operator must be small...
Resolving the neutrino mass operator at tree level

**Type I see-saw:**
a heavy singlet scalar

\[
m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N
\]

Minkowski; Yanagida; Glashow; Gell-Mann, Ramond Slansky; Mohapatra, Senjanovic...

\[\lambda \sim O(Y^2)\]

**Type II see-saw:**
a heavy triplet scalar

\[
m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Delta \frac{\mu_\Delta}{M_\Delta} v^2
\]

Konetschny, Kummer; Cheng, Li; Lazarides, Shafi, Wetterich ...

\[\lambda \sim O(Y \mu / M_\Delta)\]

**Type III see-saw:**
a heavy triplet fermion

\[
m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma
\]

Foot et al; Ma; Bajc, Senjanovic...

\[\lambda \sim O(Y^2)\]
$M_N \sim \text{GUT}$

$M_N \sim \nu$
Where is the new scale?

“Once you eliminate the impossible, whatever remains, no matter how improbable/unnatural, must be the truth.”
Where is the new scale?

Generic predictions

- there is **neutrinoless double beta** decay at some level ($\Lambda > 100\text{MeV}$)

  model independent contribution from the neutrino mass
Where is the new scale?

Generic predictions:

- a matter-antimatter asymmetry if there is CP violation in the lepton sector via leptogenesis

model dependent...
Generic predictions:

- there are other states out there at scale $\Lambda$: new physics beyond neutrino masses

potential impact in cosmology, EW precision tests, LHC, rare searches, $\beta\beta 0\nu$, ...

model dependent...
Where is the new scale?

The EW scale is an interesting region: new physics underlying the matter-antimatter asymmetry could be tested!
Minimal model of neutrino masses:

Type I seesaw: SM+right-handed neutrinos

\[ \mathcal{L}_\nu = -\bar{l}Y\tilde{\Phi}N_R - \frac{1}{2}\bar{N}_R M N_R + h.c. \]

\[ m_\nu = \lambda \frac{\nu^2}{\Lambda} \equiv Y^T \frac{\nu^2}{M} Y \]

Minkowski; Yanagida; Glashow; Gell-Mann, Ramond Slansky; Mohapatra, Senjanovic...
Type I seesaw models

\( n_R = 3 \): 18 free parameters (6 masses + 6 angles + 6 phases)
out of which we have measured 2 masses and 3 angles...

\[ m_1 \quad m_2 \quad m_3 \quad M_1 \quad M_2 \quad M_3 \]

Light neutrinos

\( M_N \)

Dirac

Seesaw
Type I seesaw models

Phenomenology (beyond neutrino masses) of these models depends on the heavy spectrum and the size of active-heavy mixing:

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = U_{ll}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix} + U_{lh}
\begin{pmatrix}
N_1 \\
N_2 \\
N_3
\end{pmatrix}
\]

Strong correlation between active-heavy mixing and neutrino masses
Baryon asymmetry

Sakharov’s necessary conditions for baryogenesis

- Baryon number violation
- C and CP violation
- Deviation from thermal equilibrium

It does not seem to work in the SM with massless neutrinos ...

- CP violation too small ✗
- EW phase transition too weak ✗

Massive neutrinos provide new sources of CP violation and non-equilibrium conditions
Models with massive neutrinos generically lead to generation of lepton and therefore baryon asymmetries.

Standard leptogenesis in out-of-equilibrium decay \( M_N > 10^7 \text{GeV} \)

Fukuyita, Yanagida...; Davidson, Nardi, Nir rev

Can be extended to lower scales at the expense of a extreme degeneracy of the heavy states: resonant leptogenesis

Pilaftsis,...
High-scale leptogenesis

New sources of CP violation and L violation in the neutrino sector can induce CP asymmetries in decays of heavy Majorana $\nu$

Fukuyita, Yanagida
High-scale leptogenesis

\[ \Gamma_N \leq H(M_N) \]

(decay rate < hubble expansion)
Leptogenesis

Leptogenesis from neutrino oscillations
$0.1\text{GeV} < M < 100\text{GeV}$

Akhmedov, Rubakov, Smirnov;
Asaka, Shaposhnikov,...
Low-scale Leptogenesis

CP asymmetries arise in production of sterile states oscillations

\[ L_\alpha \rightarrow L_\beta \neq \bar{L}_\alpha \rightarrow \bar{L}_\beta \]

\[ \sum \Delta_{CP}^\alpha = 0 \quad Y_B \propto \sum \Delta_{CP}^\alpha \eta_\alpha \]

Different flavours different efficiency in transferring it to the baryons
Low-scale leptogenesis

\[ \Gamma_s(T_{EW}) \leq H(T_{EW}) \]

(scattering rate < hubble expansion)
Testability/predictivity?

- $Y_B$ cannot be determined from neutrino masses and mixings only

- More information from the heavy sector is needed:
  
  High-scale scenarios: very difficult for $M_N > 10^7$ GeV
  
  Low-scale scenarios: N’s can be produced in the lab and could be in principle detectable!
Full exploration of the minimal model N=2

Bayesian posterior probabilities (using nested sampling Montecarlo Multinest)

\[ \mathcal{L} = - \left( \frac{Y_B(\text{param}) - Y_B^{\text{obs}}}{\sigma_{Y_B}} \right)^2 \]

Use Casas-Ibarra parametrization: fix light neutrino masses and mixings to the best fit oscillation points (IH/NH) and vary

\[ R(\theta + i\gamma); \ U_{PMNS}(\delta, \phi_1); M_1, M_2 \]

Flat priors in:

\[ \theta = [0, \pi]; \delta = [0, 2\pi]; \phi_1 = [0, 2\pi]; \gamma = [-9, 9]; \]
\[ \log_{10} M_1 \text{ and } \log_{10} M_2 / \log_{10}(M_2 - M_1) \]
Full exploration of the minimal model $N=2$

Inverted neutrino ordering (IH)

PH, Kekic, Lopez-Pavon, Racker, Salvado
arxiv:1606.06719
In the minimal model with just $n_R = 2$ neutrinos (IH)

Colored regions: posterior probabilities of successful $Y_B$

PH, Kekic, Lopez-Pavon, Racker, Salvador
arxiv:1606.06719
Predicting $Y_B$ in the minimal model $n_R=2$?

Assume a point within SHIP reach that gives the right baryon asymmetry

- SHIP measurement could provide (if states not too degenerate)
  \[ M_1, M_2, |U_{e1}|^2, |U_{\mu_1}|^2, |U_{e2}|^2, |U_{\mu_2}|^2 \]

- Future neutrino oscillations: $\delta$ phase in the $U_{\text{PMNS}}$
Predicting $Y_B$ in the minimal model $n_R=2$ (IH)

- Grey band: standard light neutrino contribution to $m_{\beta\beta}$ for IH
- Significant interference between light/heavy neutrino contributions to $m_{\beta\beta}$

Obs. $Y_B = 8.6 \times 10^{-11}$
Predicting $Y_B$ in the minimal model $n_R=2$

Heavy states also contribute to the $\beta\beta_{0v}$ amplitude...

$$m_{\beta\beta} = \sum_{i=1}^{3} [(U_{PMNS})_{ei}]^2 m_i + \sum_{i=1}^{3} U_{ej}^2 M_j \frac{M_{0\nu\beta\beta}(M_j)}{M_{0\nu\beta\beta}(0)}$$

Light states

Heavy states

$$M_j \rightarrow \infty \quad \frac{M_{0\nu\beta\beta}(M_j)}{M_{0\nu\beta\beta}(0)} \propto \left( \frac{100 \text{ MeV}}{M_j} \right)^2$$

the heavy contribution is sizeable for $M_i$ of $O(\text{GeV})$

Blennow, Fernandez-Martinez, Lopez-Pavon, Menendez; Lopez-Pavon, Pascoli, Wong; Lopez-Pavon, Molinaro, Petcov

The non standard contributions bring essential information of some CP phases and other unknown parameters
Predicting $Y_B$ in the minimal seesaw model $M \sim \text{GeV}$

![Graph showing predictions for $Y_B$ and $|m_{\beta\beta}|$ vs. $Y_B(10^{-11})$.](image)

**Obs. $Y_B = 8.6 \times 10^{-11}$**

IH active $\nu$’s

- $\Delta |U|^2 = 1\%$, $\Delta M = 0.1\%$
- $\Delta |U|^2 = 1\%$, $\Delta M = 0.1\%$, $\Delta \delta = 17\ rad$

**PH, Kekic, Lopez-Pavon, Racker, Salvado**

arxiv:1606.06719

**The GeV-miracle**: the measurement of the mixing to $e/\mu$ of the sterile states, neutrinoless double-beta decay and $\delta$ in neutrino oscillations have a chance to give a prediction for $Y_B$
What is this Sample point?

\[ d, s, b, u, c, t, e, \mu, \tau \]

Yukawa

\[ \delta = 234^\circ \quad \alpha = 254^\circ \]

\[ M_1 \sim M_2 \sim 0.77 \text{ GeV}, \; \Delta M/M \sim 10^{-2} \]
How fine-tuned is the range of parameters for successful leptogenesis?

The very degenerate regions could be understood in terms of an approximate global symmetry $U(1)_L$

Wyler, Wolfenstein; Mohapatra, Valle; Branco, Grimus, Lavoura, Malinsky, Romao; Kersten, Smirnov; Abada et al; Gavela et al....many others

$L(N_1) = +1, \ L(N_2) = -1$

$-\mathcal{L}_\nu \supset \bar{N}_1 M N_2^c + Y \bar{L} \tilde{\Phi} N_1 + h.c.$

\[
\begin{pmatrix}
0 & Y \nu & 0 \\
Y \nu & 0 & M_N \\
0 & M_N & 0
\end{pmatrix}
\]

Degenerate heavy neutrinos and massless light neutrinos...
How natural is the range of parameters for successful Leptogenesis?

The very degenerate regions could be understood in terms of an approximate global symmetry $U(1)_L$

Wyler, Wolfenstein; Mohapatra, Valle; Branco, Grimus, Lavoura, Malinsky, Romao; Kersten, Smirnov; Abada et al; Gavela et al....many others

How small must the small entries be?

$$
\begin{pmatrix}
0 & Y_1\nu & \epsilon Y_2\nu \\
Y_1\nu & \mu' & M_N \\
\epsilon Y_2\nu & M_N & \mu
\end{pmatrix}
$$

➢ How small must the small entries be?
How natural is the range of parameters for successful ARS leptogenesis?

- Blue region prefers a mild hierarchy in all $U(1)_L$ breaking terms.
- Red region points requires $\mu, \mu'$ entries significantly smaller than $\epsilon$. 

$Log_{10} \left[ \frac{\epsilon Y_2}{Y_1} \right]$  
$Log_{10} \left[ \frac{\mu + \mu'}{M} \right]$
How large can the mixing be (even if less probable) and still have successful baryogenesis?

Drewes, Garbrecht, Gueter, Klaric
arxiv: 1606.06690

Abada, Arcadi, Domcke, Lucente
arxiv: 1709.00415
The seesaw path to leptonic CP violation:
flavour ratios of heavy lepton mixings strongly correlated with ordering, $U_{\text{PMNS}}$ matrix: $\delta, \phi_1$

In minimal model ($N=2$):

Superb sensitivity to Majorana CP phases: complementary to oscillations

Caputo, PH, Lopez-Pavon, Salvado  arxiv:1611.05000
If SHIP/FCC-ee measures the heavy neutrinos and their mixings to e/\mu:

Can we exclude a real $U_{\text{PMNS}}$ matrix i.e. discover leptonic CP violation in mixing?

$$(\delta, \phi_1) \neq (0/\pi, 0/\pi)$$
Leptonic CP violation 5σ CL discovery regions (SHIP)

$R_{\text{CP}}=5\sigma$ CP-fraction =
fraction of the area of the CP rectangle which is colored

Caputo, PH, Lopez-Pavon, Salvado arxiv:1611.05000
Leptonic CP violation $5\sigma$ CL discovery regions (SHIP)

Normal Hierarchy

Inverted Hierarchy

(no systematic error included)

Caputo, PH, Lopez-Pavon, Salvado  arxiv:1611.05000

$R_{CP}=5\sigma$ CP-fraction =
fraction of the area of the CP rectangle which is colored
Conclusions

• Exploring the EW-> TeV region for NP related to neutrino masses is very well motivated

• A minimal model of neutrino masses with a new scale near GeV can explain the baryon asymmetry and might do so in a testable way (IH more promising)

• Testability in simplest model will require the contribution of very different type of experiments:

  SHIP/FCCee: masses and mixings of the heavy neutrino states

  DUNE/HyperK: CP violation \nu neutrino oscillations

  ββ0ν: non-standard contributions from heavy sector

• Flavour mixings of the heavy states high sensitivity to CP phases in \text{U}_{\text{PMNS}} (in particular Majorana phases!)

• Mediators of neutrino mass at the EW provide a new portal to BSM physics
Beyond the minimal model

Many possibilities:

Examples: type I +W', Z', left-right symmetric models GUTs, etc

Keung, Senjanovic; Pati, Salam, Mohapatra, Pati; Mohapatra, Senjanovic; Ferrari et al + many recent refs...

- Generically gauge interactions can enhanced the production in colliders
- But they make leptogenesis more challenging (out-of-equilibrium condition harder to meet)
Interesting possibility:

- Effective theory SM+N’s
- SM + neutrino mass mediator (N)
- Extra interactions (LR, etc)
- TeV
- EW
Model independent approach: EFT

\[ \mathcal{L}_{BSM} = \mathcal{L}_{mSS} + \sum_{d,i} \frac{1}{\Lambda^{d-4}} O_i^{(d)} \]

The seesaw portal to BSM:

\[
O_W = \sum_{\alpha,\beta} \frac{(\alpha_W)_{\alpha\beta}}{\Lambda} \overline{L_\alpha} \tilde{\Phi} \Phi^\dagger L_\beta + h.c.,
\]

\[
O_{N\Phi} = \sum_{i,j} \frac{(\alpha_{N\Phi})_{ij}}{\Lambda} \overline{N_i} N^c_j \Phi^\dagger \Phi + h.c.,
\]

\[
O_{NB} = \sum_{i \neq j} \frac{(\alpha_{NB})_{ij}}{\Lambda} \overline{N_i} \sigma_{\mu\nu} N^c_j B_{\mu\nu} + h.c.
\]

S. Weinberg ’79; M. Graesser ’07; F. Del Aguila et al ’09; Aparici et al, ’09; Caputo et al ’17
Corrections to $|U_{ei}|^2/|U_{\mu i}|^2$ the minimal model correlated to the lightest neutrino mass

$$m_{1(3)} \sim 0.1 \sqrt{\left|\Delta m_{\text{sol}}^2\right|}$$
could lead to spectacular signals at LHC/colliders of two displaced vertices from higgs decays (production independent of U)

\( \mathcal{O}_{N \Phi} \)

\[ \left| \frac{\alpha_{N \Phi} v}{\sqrt{2} \Lambda} \right| \leq 10^{-3} - 10^{-2} \rightarrow \frac{\alpha_{N \Phi}}{\Lambda} \leq 6 \times (10^{-3} - 10^{-2}) \text{TeV}^{-1}. \]

LHC: 300 fb\(^{-1}\), 13 TeV

Caputo, PH, LopezPavon, Salvado, arxiv:1704.08721
could lead to spectacular signals at LHC/colliders of two displaced vertices from higgs decays (production independent of U)

A large hierarchy between the coefficients would be needed since the Weinberg operator is much more strongly suppressed: technically natural with $U(1)_L$