Low-scale seesaw from neutrino condensation

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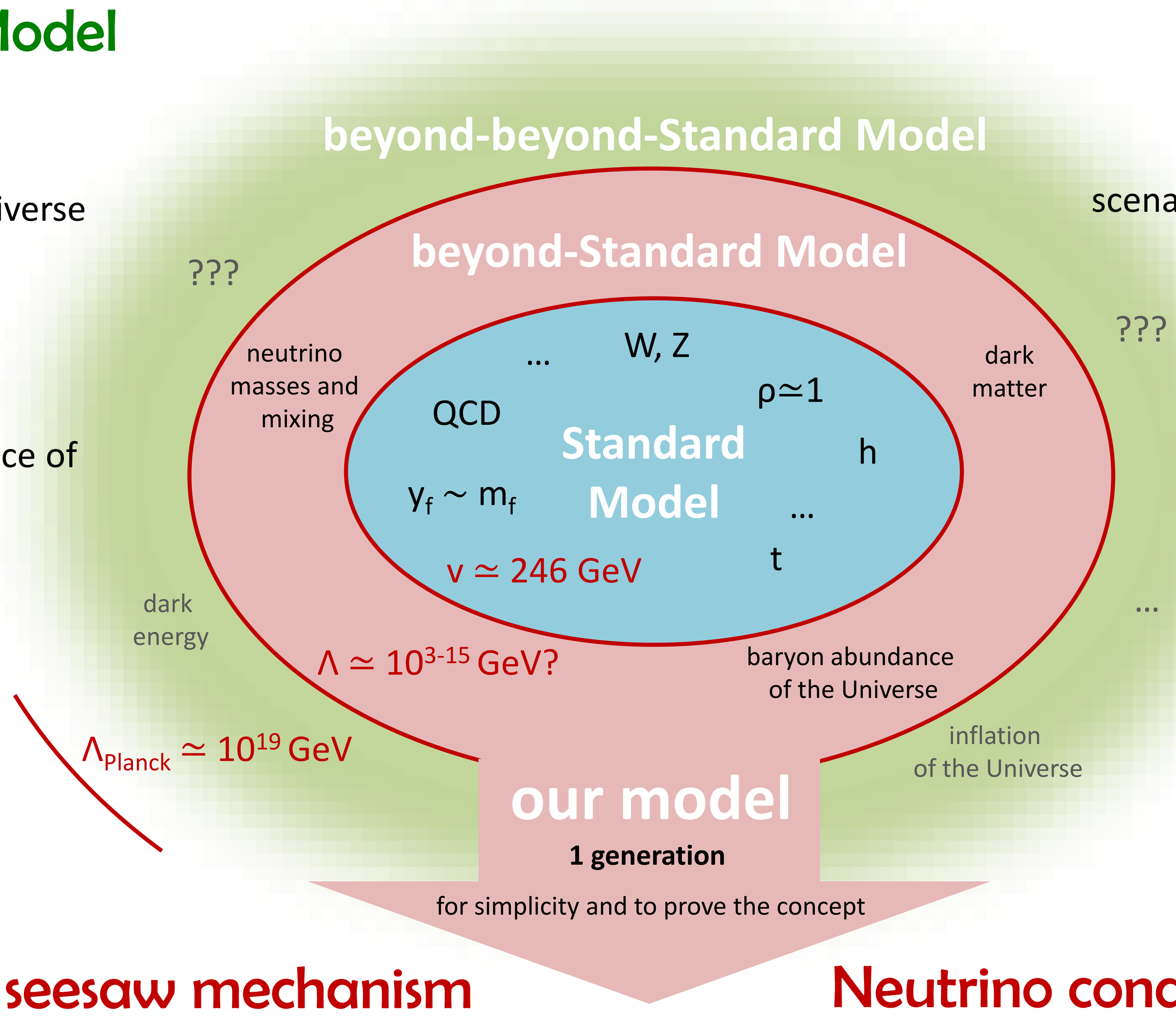
Why going beyond the Standard Model

The Standard Model (SM) of elementary particles is an extremely successful description of what we observe at colliders. Neutrino oscillations and properties of the Universe show that SM is not the ultimate theory.

The SM does not contain the masses of neutrinos and their mixing. The SM does not explain almost 5/6 of matter in the Universe. The SM does not provide sufficiently strong origin of the baryon abundance of the Universe.

Therefore the new physics characterized by some scale Λ is expected.

The Lepton Number Violation (LNV) realized via the seesaw mechanism for neutrino masses appears as the guiding principle interconnecting the missing pieces of the particle physics puzzle.



ABSTRACT

We propose an **extension** of the Standard Model (SM) where neutrino mass is generated within the **low-scale seesaw** scenario via the lepton number violating **condensation of neutrinos**. To prove the concept we elaborate a model of just **single neutrino generation** and provide an **order-of magnitude test** of its phenomenology.

Leptogenesis completes fixing of the model parameters. Properties of a **dark matter** (DM) candidate and **light neutrino mass** are then completely determined.

Despite a small room for parameter tuning and without ordering it, surprisingly, we get the decay rate of our DM close to what is needed.

Neutrino mass turns out to be extremely small. That should not be seen as a problem if it will be the case solely of the lightest neutrino within the future realistic three-generational model.

Low-scale seesaw mechanism

a combination of inverse and linear seesaw

Two types of right-handed neutrinos (electroweak singlets) are introduced in a way that the **lepton number** is

- respected by M_R, m_D
- violated by $\mu_{\rm inv}$, $\mu_{\rm lin}$

Among the mass eigenstates there are

- one light Majorana active neutrino
- two heavy quasi-degenerate Majorana neutrinos.

$$M = \begin{pmatrix} 0 & m_D & \mu_{\rm lin} \\ m_D & \mu'_{\rm inv}=0 & M_R \\ \mu_{\rm lin} & M_R & \mu_{\rm inv} \end{pmatrix} \longleftarrow \begin{pmatrix} \nu_L \\ \nu_R^c \\ S_R^c \end{pmatrix} \qquad L = \begin{bmatrix} +1 \\ -1 \\ +1 \end{bmatrix}$$

$$\text{If} \quad M_R \gg m_D \gg \mu_{\rm inv}, \mu_{\rm lin}$$

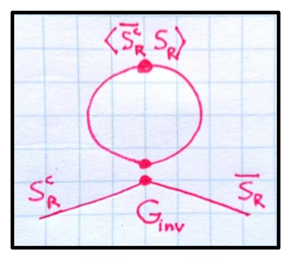
$$m_\nu \simeq \mu_{\rm inv}\frac{m_D^2}{M_R^2} - 2\mu_{\rm lin}\frac{m_D}{M_R}\,, \quad m_{N_\pm} \simeq \pm M_R + \frac{1}{2}\mu_{\rm inv}$$

Neutrino condensation

triggered by a new attractive force effectively described as four-fermion interaction

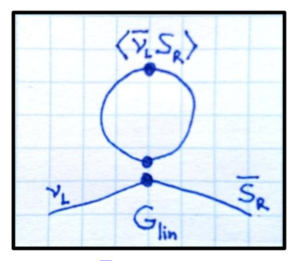
$$\mathcal{L} \;=\; \mathcal{L}'_{SM} - (y_H \bar{\ell}_L \tilde{H}\nu_R + \overline{S_R^c} M_R \nu_R + h.c.) - G_{\rm inv}(\overline{S_R^c}S_R)(\overline{S_R}S_R^c) - G_{\rm lin}(\bar{\ell}_L S_R)(\overline{S_R}\ell_L)$$

The fermion condensation from four-fermion interaction may be treated according to Nambu—Jona-Lasinio by solving gap equations



$G_{\rm inv}\langle\overline{S_R^c}S_R\rangle(\overline{S_R}S_R^c)$

$\mu_{\rm inv} = G_{\rm inv}\langle\overline{S_R^c}S_R\rangle$



$G_{\rm lin}\langle\bar{\ell}_L S_R\rangle(\overline{S_R}\ell_L)$

$\mu_{\rm lin} = G_{\rm lin}\langle\bar{\ell}_L S_R\rangle$

Effective lagrangian description - 2 Higgs doublet + 1 Higgs singlet model

to derive the low-energy phenomenology of the model

RGE threshold | effective lagrangian and its RGE running

size of lepton number violating vevs | Standard Model | bound state formation; neutrino condensates form as vevs of bound states; spontaneous lepton number violation | UV complete dynamics of neutrino attraction near Λ effectively described by 4-fermion interaction

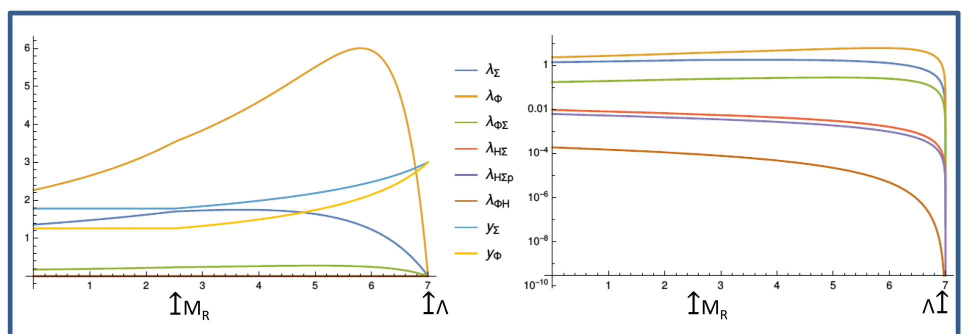
energy/mass scale: v_Σ, v_Φ, v≐246 GeV, M_R~10 TeV < Λ in order to avoid decoupling of right-handed neutrinos before they have chance to condense, Λ~100 TeV condensation scale

$$H \longrightarrow v_H \longrightarrow m_D = \frac{v_H}{\sqrt{2}}y_H$$
$$\Sigma \sim (\overline{S_R}\ell_L) \longrightarrow v_\Sigma \longrightarrow \mu_{\rm lin} = \frac{v_\Sigma}{\sqrt{2}}y_\Sigma$$
$$\Phi \sim (\overline{S_R^c}S_R) \longrightarrow v_\Phi \longrightarrow \mu_{\rm inv} = \frac{v_\Phi}{\sqrt{2}}y_\Phi$$

The elementary Higgs doublet field H is the same as in the SM. Lepton scalar composite Higgs fields (doublet Σ and singlet Φ) are formed below the condensation scale Λ. All three Higgs fields They acquire vevs which generate the neutrino mass matrix entries.

$$\begin{aligned}\mathcal{L}_{\rm eff} \;=\; & \mathcal{L}'_{\rm SM} + D^\mu H^\dagger D_\mu H + \mu_H^2 H^\dagger H - \frac{\lambda_H}{2}(H^\dagger H)^2 \\ & + i\bar{\nu}_R\partial\!\!\!/\nu_R + i\bar{S}_R\partial\!\!\!/S_R - (\overline{S_R^c}M_R\nu_R + y_H\overline{\ell_L}\tilde{H}\nu_R + y_\Sigma\bar{\ell}_L\Sigma S_R + y_\Phi\overline{S_R}\Phi S_R^c + \text{h.c.}) \\ & + D^\mu\Sigma^\dagger D_\mu\Sigma + \partial^\mu\Phi^\dagger\partial_\mu\Phi + \mu_\Sigma^2\Sigma^\dagger\Sigma + \mu_\Phi^2\Phi^\dagger\Phi - (\kappa\,\Phi^\dagger(H^\dagger\tilde{\Sigma}) + \text{h.c.}) \\ & - \frac{\lambda_\Sigma}{2}(\Sigma^\dagger\Sigma)^2 - \frac{\lambda_\Phi}{2}(\Phi^\dagger\Phi)^2 - \lambda_{\Phi H}(\Phi^\dagger\Phi)(H^\dagger H) - \lambda_{\Phi\Sigma}(\Phi^\dagger\Phi)(\Sigma^\dagger\Sigma) - \lambda_{H\Sigma}(H^\dagger H)(\Sigma^\dagger\Sigma) - \lambda'_{H\Sigma}(\Sigma^\dagger\tilde{H})(\tilde{H}^\dagger\Sigma)\end{aligned}$$

At the condensation scale Λ, the four fermion interactions can be equivalently substituted for the blue and red terms by the Hubbard-Stratonovich identity by means of non-dynamical auxiliary fields Σ and singlet Φ. They become dynamical fields below Λ, as their kinetic terms are radiatively generated together with all other relevant operators allowed by symmetry – the purple terms.



The parameters of the effective lagrangian are subject of the RGE running. The dynamical origin of the parameters is translated into boundary conditions at the condensation scale Λ. Here we show a typical solution.

Higgs boson particle spectrum

10 degrees of freedom

- $\pi^\pm$, π^0 electroweak would-be Nambu–Goldstone bosons
- η^0 Nambu–Goldstone boson of LNV
- $h^\pm$, a^0 charged and pseudo-scalar Higgs bosons
- h, H, s scalar Higgs bosons

Hierarchy of scales

$$\Lambda > M_R \gg v_H \gg v_\Phi \gg v_\Sigma$$

A key result dictated by phenomenology, as it is shown in the following.

Higgs boson particle spectrum

- heavy bosons

$$m_{h^\pm,a,H} \approx \sqrt{\frac{v_\Phi}{v_\Sigma}m_D M_R}$$

$\frac{v_\Phi}{v_\Sigma} \gg 1$ in order to make

$$m_{h^\pm,a,H} > 500\,\text{GeV}$$

- light bosons

$$m_h \approx \sqrt{\lambda_H}v_H \qquad m_s \approx \sqrt{\lambda_\Phi}v_\Phi \qquad m_\eta = 0$$

The additional bosons should be either heavy or sterile enough in order not to be observed yet at colliders.

Parameters of the model

Λ, M_R, v_H, v_Σ, v_Φ, y_H, y_Σ, y_Φ, λ_H, λ_Σ, λ_Φ, $\lambda_{H\Sigma}$, $\lambda'_{H\Sigma}$, $\lambda_{H\Phi}$, $\lambda_{\Phi\Sigma}$, κ

The purple parameters are fixed by the RGE running and by the boundary condition at Λ, where the original lagrangian with the four-fermion interactions must be reproduced.

We fix:

$\Lambda = 100\,\text{TeV}$ 1-loop vacuum stability

$v_H \doteq 246\,\text{GeV}$ W, Z masses

$\lambda_H = 0.258$ Higgs boson mass

Free parameters

$$M_R,\ v_\Phi,\ v_\Sigma,\ y_H$$

Leptogenesis

the baryon abundance from sphaleron conversion of the lepton abundance.

Three Sacharov conditions:

1. B-violation from L-violation ← LNV neutrino masses
   $\Gamma(N \to \ell + h) \neq \Gamma(\bar{N} \to \ell + h)$
2. CP violation ← resonant enhancement due to the small mass splitting of heavy neutrinos
   $\Gamma(N \to \ell + h) \neq \Gamma(N \to \bar{\ell} + h)$
   $|m_{N_+} - m_{N_-}| = \mu_{\rm inv} = 10^{-8}M_R$
3. Out-of-equilibrium ← decay rate should be neither too big nor too small compared to the Hubble rate
   $\Gamma(N \to \ell + h) \neq \Gamma(\ell + h \to N)$
   $y_N \lesssim 10^{-7} - 10^{-6}$

Parameter fixing

from leptogenesis

To be specific we choose $M_R = 10\,\text{TeV}$

The heavy neutrino mass splitting is given by the inverse seesaw mass parameter which is given by the Φ vev: $v_\Phi = 100\,\text{keV}$

The Yukawa coupling constants corresponding to two strongest decays are the following:

1. The SM-like Higgs boson channel fixes y_H and thus m_D.
   $$y_{N\nu h} \approx -\frac{y_H}{2} \Rightarrow y_H = 10^{-7} \Rightarrow \frac{m_D}{M_R} \approx 10^{-9}$$
2. The heavy Higgs boson ($X = a, H$) channel has to be forbidden kinematically ($m_X > M_R$), because the dynamically generated is unavoidably large ~$O(1)$ from RGE.
   $$y_{N\nu X} \approx -\frac{y_\Sigma}{2} \Rightarrow \frac{M_R}{m_D} \leq \frac{v_\Phi}{v_\Sigma} = 10^9 \Rightarrow v_\Sigma = 0.1\,\text{meV}$$

Model predictions

candidate for dark matter candidate

Dark matter candidate should be a particle which is massive, stable and sterile enough. Stability = lifetime longer than the age of the Universe:

$$\Gamma_{DM} = \frac{y_{DM}^2}{8\pi}m_{DM} \;<\; 10^{-33}\,\text{eV}$$

In our model the candidate is the s Higgs boson.

Its mass is $m_s = \sqrt{\lambda_\Phi v_\Phi} \approx 100\,\text{keV}$ and it is a warm dark matter candidate.

It can decay as $s \to \nu + \nu$ with the decay rate

$$\Gamma_s = \frac{y_{s\nu\nu}^2}{8\pi}m_s \approx 10^{-32}\,\text{eV}$$

light neutrino mass

$$m_\nu \simeq \frac{v_\Phi}{\sqrt{2}}\frac{m_D}{M_R}\left(\frac{m_D}{M_R}y_\Phi - \frac{2}{r_{\Phi\Sigma}}y_\Sigma\right) \approx 10^{-13}\,\text{eV}$$