Low-scale seesaw from neutrino condensation

Adam Smetana

Institute of Experimental and Applied Physics
Czech Technical University in Prague

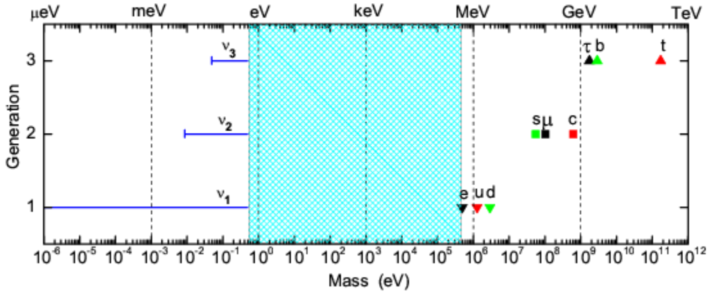
Claudio Dib, Sergey Kovalenko and Ivan Schmidt

UTFSM & CCT de Valparaíso

30/05/2019
MEDEX'19 in Prague

Motivation

dark matter | **neutrino masses** | **baryogenesis via leptogenesis**



$$\mathcal{L}_M = \begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D^{\mathrm{T}} \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} \implies \begin{array}{l} m_\nu \simeq \frac{m_D^2}{M_R} \\ m_N \simeq M_R \end{array}$$

νMSM – Shaposhnikov

Motivation for low-scale seesaw and for neutrino condensation

Low-scale seesaw

- new physics at scale accessible to colliders
- improvement of leptogenesis - enough CP asymmetry

Neutrino condensation

- economic solutions with not many parameters
- spontaneous lepton number violation (LNV)
- opens a gate towards new physics

Side remark:

1. "condensation" of virtual particles of vacuum fluctuations
   - Lorentz invariant
2. condensation of real particles in many-particle systems
   - Lorentz non-invariant

Low-scale seesaw mechanism for neutrino masses

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

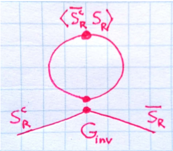
$$\text{If} \quad M_R \gg m_D \gg \mu_{\text{inv}}, \mu_{\text{lin}}$$

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

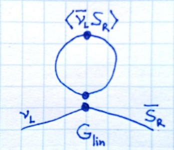
Lepton Number Violation (LNV) by neutrino condensation

we propose:

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



$$G_{\rm inv} \langle \overline{S^c_R} S_R \rangle (\overline{S_R} S^c_R) \longrightarrow \mu_{\rm inv} = G_{\rm inv} \langle \overline{S^c_R} S_R \rangle$$



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

for simplicity 1 generation
just to prove the concept

Effective model

2 Higgs doublet + 1 Higgs singlet model

$$H \longrightarrow v_H \longrightarrow m_D = \frac{v_H}{\sqrt{2}} y_H$$

$$\Sigma \sim (\overline{S_R} \ell_L) \longrightarrow v_\Sigma \longrightarrow \mu_{\mathrm{lin}} = \frac{v_\Sigma}{\sqrt{2}} y_\Sigma$$

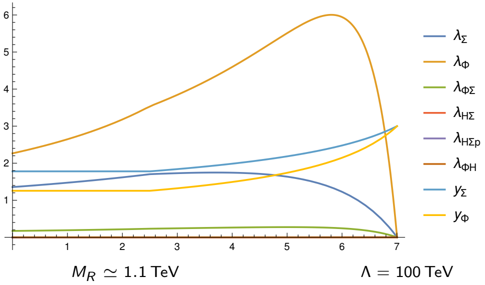
$$\Phi \sim (\overline{S_R^c} S_R) \longrightarrow v_\Phi \longrightarrow \mu_{\mathrm{inv}} = \frac{v_\Phi}{\sqrt{2}} y_\Phi$$

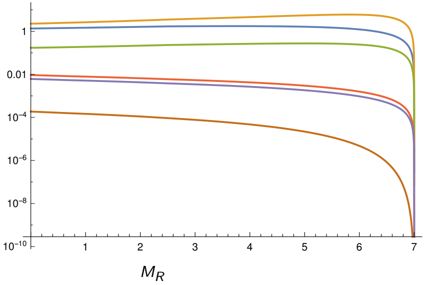
- $\pi^\pm$, π^0 electroweak would-be Nambu–Goldstone bosons
- η^0 Nambu–Goldstone boson of LNV
- $h^\pm$, a^0 charged and pseudo-scalar Higgs bosons
- h, H, s scalar Higgs bosons

parameters: 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.

Renormalization Group Equation (RGE)

credit to pyR@TE





- Yukawa $y_X(M_Z) \gtrsim 1$
- quartic $\lambda_X(M_Z) \gtrsim 1$
- quartic $\lambda_{XY}(M_Z) \ll 1$
- triple $\kappa \sim y_H M_R$

Hierarchy of scales

to satisfy 1-loop vacuum stability (not a serious criteria):

$$\Lambda = 100\,\mathrm{TeV}$$

non-decoupling and seesaw and leptogenesis:

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

SM parameter fixing:

$$v = \sqrt{v_H^2 + v_\Sigma^2} = 246\,\mathrm{GeV} \qquad \longrightarrow \qquad v_H \doteq 246\,\mathrm{GeV}$$

$$m_h \approx \sqrt{\lambda_H} v_H \doteq 125\,\mathrm{GeV} \qquad \longrightarrow \qquad \lambda_H = 0.258$$

Three groups of Higgs bosons: heavy, SM-like and sterile

- heavy bosons

$$m_{h^\pm,a,H} \approx \sqrt{r_{\Phi\Sigma} m_D M_R} \qquad \longrightarrow \qquad r_{\Phi\Sigma} \equiv \frac{v_\Phi}{v_\Sigma} \gg 1$$

- light bosons

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

Free parameters

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

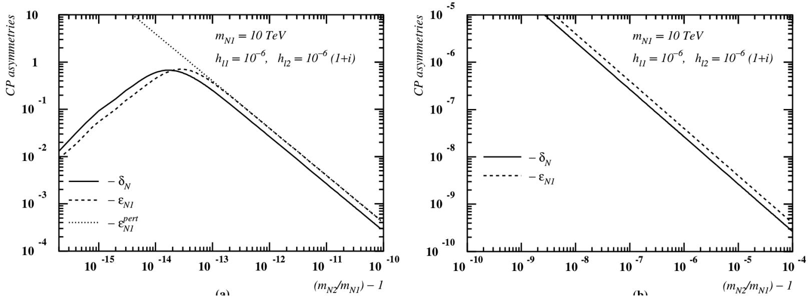
or

$$M_R,\ v_\Phi,\ r_{\Phi\Sigma},\ y_H$$

Leptogenesis

$$\text{LNV:} \quad N \to \ell + \phi^\dagger$$
$$CP \text{ viol.:} \quad N \to \ell + \phi^\dagger \neq \bar{N} \to \bar{\ell} + \phi$$
$$\text{out-of-eq.:} \quad N \to \ell + \phi^\dagger \neq \ell + \phi^\dagger \to N$$

[Pilaftsis1997]



out-of-equilibrium $\rightarrow$ $H(T = M_N) \gtrsim \frac{\Gamma_N}{2} \simeq |M_{N1} - M_{N2}|$ $\leftarrow$ $\not{CP}$ resonance

$$\Gamma_N = \frac{y_N^2}{8\pi} M_N \quad \Longrightarrow \quad \boxed{y_N \lesssim 10^{-7} - 10^{-6}}$$

$$\not{CP} > 10^{-7} \quad \Longrightarrow \quad \boxed{\frac{|M_{N1} - M_{N2}|}{M_N} < 10^{-7}}$$

Parameter fixing from leptogenesis

1. near $\not{CP}$ resonance:

$$|m_{N_+} - m_{N_-}| = \boxed{\mu_{\rm inv} = 10^{-8} M_R} \longrightarrow \boxed{M_R = 10\,{\rm TeV}} < \Lambda \rightarrow \boxed{v_\Phi = 100\,{\rm keV}}$$

2. out-of-equilibrium:

$$N \to \ell + X \qquad \boxed{y_N = 10^{-7}}$$

- heavy bosons $X = a, H$ or $h^\pm$ emitted:

$$y_{N\nu X} \approx -\frac{y_\Sigma}{2} \longrightarrow m_X > M_R \longrightarrow \frac{M_R}{m_D} \leq \boxed{r_{\Phi\Sigma} = 10^9}$$

$$y_{Neh} \approx y_H^2 \frac{v_\Sigma}{2M_R} \sim 10^{-31} \qquad \boxed{v_\Sigma = 0.1\,{\rm meV}}$$

- light bosons $X = h, s, \eta$ emitted:

$$y_{N\nu h} \approx -\frac{y_H}{2} \longrightarrow \boxed{y_H = 10^{-7}} \longrightarrow \frac{m_D}{M_R} \approx 10^{-9}$$

$$y_{N\nu s,\eta} \approx \frac{1}{2r_{\Phi\Sigma}} y_\Sigma - \frac{m_D}{M_R} y_\Phi \sim 10^{-9}$$

Dark matter

massive stable sterile particle

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

$$m_{DM} = 1\,\mathrm{MeV} \quad \Longrightarrow \quad \boxed{y_{DM} < 10^{-19}}$$

$$m_{DM} = 0.1\,\mathrm{keV} \quad \Longrightarrow \quad \boxed{y_{DM} < 10^{-17}}$$

Dark matter in our model

$$m_s = \sqrt{\lambda_\Phi} v_\Phi \approx 100\,\mathrm{keV}$$

$$s \to \nu + \nu$$

$$y_{s\nu\nu} = \sqrt{2} y_\Sigma \frac{m_D}{M_R} \left(\frac{1}{r_{\Phi\Sigma}} - \frac{m_D}{M_R} \right) \approx 10^{-18}$$

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

[Lattanzi et.al 2007]
Decaying Warm Dark matter $m_{DM} \sim \mathrm{keV}$ and $\Gamma_{DM} < 10^{-35}\,\mathrm{eV}$

Neutrino mass

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

Conclusions and outlook

We propose an extension of SM and analyse its simplified 1-flavor version which

- is defined by adding just few new fields (ν_R, S_R),
- addresses LNV, neutrino masses, leptogenesis and DM,
- is very correlated,
- has a viable particle spectrum.

The model predicts

- heavy additional Higgs bosons $m_X > M_R$,
- majoron particle η,
- light and very sterile scalar s, potential DM candidate,
- almost massless neutrino mass eigenstate

We will work on

- analysis of other observables,
- realistic version with three generations,
- UV completion.

Other observables

Invisible Z decays

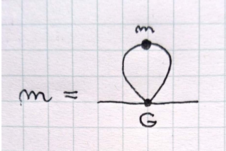
- $Z \longrightarrow s + \bar{f} + f$
- $Z \longrightarrow s + s + \bar{f} + f$

Astro and Cosmo

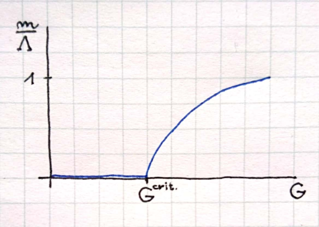
- $s \longrightarrow \gamma + \gamma$
- $s \longrightarrow \eta + \eta$
- $\nu_1 \longrightarrow \nu_2 + \eta$

Origin of the hierarchy

In order to explain the hierarchy of v_Σ and v_Φ we need to assume something about the underlying dynamics.



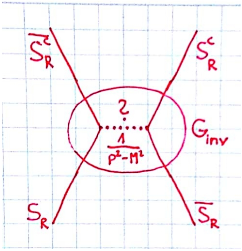
$\Longrightarrow$



$$\frac{m}{\Lambda} = \sqrt{1 - \frac{G^{\text{crit.}}}{G}}$$

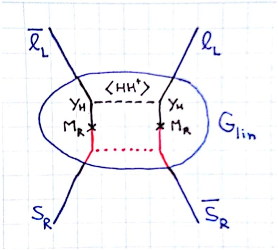
Origin of the hierarchy (1)

Maybe $G_{\rm inv}$ is the fundamental one, and $G_{\rm lin}$ is the induced one? (subject of future work)



$\Longrightarrow$

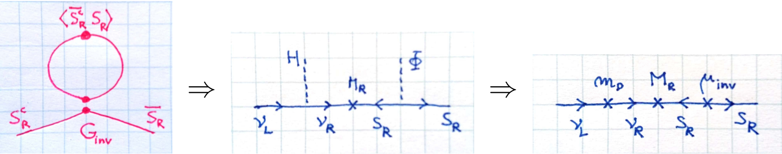
$G_{\rm inv} \gg G_{\rm lin}$



for $v_\Phi \ll \Lambda \sim M$
$G_{\rm inv} \to G_{\rm inv}^{\rm crit.}$ $\Longrightarrow$ $G_{\rm lin}$ subcritical

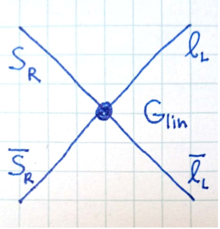
Maybe $v_\Sigma = 0$?

- The consistency of the "2+2+1" model with $\kappa \neq 0$ requires that $v_\Sigma \neq 0$.
- The "2+1" model without Σ being even formed can be formulated. (subject of future work)

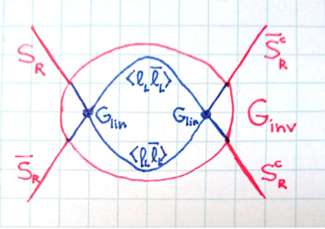


$$\mu_{\text{lin}} \sim \mu_{\text{inv}} \frac{m_D}{M_R}$$

Maybe $G_{\rm lin}$ is the fundamental one, and $G_{\rm inv}$ is the induced one? (subject of future work)



$\Longrightarrow$



Tuning the number of fermions $(\ell_L, \dots)$ coupled to S_R one can achieve that:

$$G_{\rm lin} \to G_{\rm lin}^{\rm crit.} \sim \Lambda^{-2} \quad \Longrightarrow \quad G_{\rm inv} \sim G_{\rm lin}^2 \Lambda^2 \sim G_{\rm inv}^{\rm crit.} + \mathcal{O}\left(\frac{M_R^2}{\Lambda^2}\right)$$

Equations

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

Fermion condensation

At the condensation scale Λ bound states are formed:

$$G(\bar{\psi}_L\psi_R)(\bar{\psi}_R\psi_L) \quad \longleftrightarrow \quad -(y\phi\bar{\psi}_L\psi_R + \mathrm{h.c.}) + \mu^2\phi^\dagger\phi$$

where ϕ is a composite boson:

$$\phi \sim (\bar{\psi}_R\psi_L)$$

below Λ the composite boson becomes dynamical:

$$\mathcal{L}_{\mathrm{eff}} = \partial\phi^\dagger \cdot \partial\phi + \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2 - (y\phi\bar{\psi}_L\psi_R + \mathrm{h.c.})$$

$\Longrightarrow$ boundary condition at Λ for dynamically generated running parameters

$$\begin{aligned} \mu^2(\Lambda) &= \frac{y^2(\Lambda)}{G} & \longrightarrow \quad & v_\phi = \frac{\mu}{\sqrt{\lambda}} \\ \lambda(\Lambda) &= 0 & & \\ y(\Lambda) &= \infty & \longrightarrow \quad & y(\Lambda) = 3 \end{aligned}$$

the composite boson develops its v.e.v. $\sim$ fermion condensate:

$$\phi = \frac{1}{\sqrt{2}}(h + v_\phi + \mathrm{i}a) \quad \longrightarrow \quad m_\psi = \frac{v_\phi}{\sqrt{2}}y(\mu = m_\psi)$$