Sterile Neutrino Dark Matter and Cold Electroweak Baryogenesis

Jan Smit
Institute for Theoretical Physics
University of Amsterdam & Utrecht University
Cosmo-04

with Laurens Keek

1. Introduction

2. Extended standard model (ESM) and the seesaw

3. Sterile-neutrino dark matter

4. Conclusion

Setting

The standard model (SM) of particle physics is a successful construction based on
i) experimental input
ii) renormalizability & gauge invariance

originally neutrinos taken to be massless
new *i*): neutrino oscillations
$\Rightarrow$ extend SM by adding terms that give mass to neutrinos à la *ii*): Extended SM (ESM)

How well does the ESM describe our universe?

- add inflaton
- cold electroweak baryogenesis:
after EW-scale inflation, tachyonic EW transition biased by CKM CP-violation
- dark energy: renormalized cosmological const.
- dark matter: sterile neutrinos?

ESM and Seesaw

Add ν_{R} and $\bar{\nu}_{\mathsf{R}}$ to the SM lagrangian

$$
\begin{aligned}
\mathcal{L}_{\mathsf{ESM}} &= \mathcal{L}_{\mathsf{SM}} + \Delta\mathcal{L} \\
\Delta\mathcal{L} &= -(\bar{e}\;\bar{\nu})\varphi\Lambda P_{\mathsf{R}}\nu - \bar{\nu}\Lambda^{\dagger}P_{\mathsf{L}}\varphi^{\dagger}\begin{pmatrix} e \\ \nu \end{pmatrix} \\
&\quad -\frac{1}{2}\bar{\nu}C^{\dagger}MP_{\mathsf{R}}\nu + \frac{1}{2}\bar{\nu}CM^{\dagger}P_{\mathsf{L}}\bar{\nu}^{T}
\end{aligned}
$$

three families

φ :	Higgs doublet
Λ :	Yukawa coupling matrix
M :	Majorana mass matrix

$$
P_{\mathsf{L}} = \frac{1-\gamma_5}{2}, \quad P_{\mathsf{R}} = \frac{1+\gamma_5}{2}
$$

C :	charge conjugation matrix

Higgs field v.e.v. $v = 246$ GeV

$$D = \Lambda v/\sqrt{2}: \quad \text{Dirac mass matrix}$$

$$\mathcal{L}_\nu^{\text{free}} = -\frac{1}{2} N^T C^\dagger (\gamma^\mu \partial_\mu \, \rho_1 + \mathcal{M}_\mathrm{R} P_\mathrm{R} + \mathcal{M}_\mathrm{L} P_\mathrm{L}) N$$

$$N = \begin{pmatrix} \nu \\ \nu^c \end{pmatrix}, \quad \nu^c = (\bar{\nu} C)^T, \quad \rho_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\mathcal{M}_\mathrm{R} = \begin{pmatrix} M & D^T \\ D & 0 \end{pmatrix}, \quad \mathcal{M}_\mathrm{L} = \begin{pmatrix} 0 & D^* \\ D^\dagger & M^\dagger \end{pmatrix}$$

diagonalize $\mathcal{M}$, unitary $\mathcal{V}_{\mathrm{R,L}}$, $\mathcal{V}_\mathrm{R}^T \rho_1 \mathcal{V}_\mathrm{L} = 1$

$$\mathcal{V}_\mathrm{R}^T \mathcal{M}_\mathrm{R} \mathcal{V}_\mathrm{R} = \mathcal{V}_\mathrm{L}^T \mathcal{M}_\mathrm{L} \mathcal{V}_\mathrm{L} = m$$

$$N = (\mathcal{V}_\mathrm{R} P_\mathrm{R} + \mathcal{V}_\mathrm{L} P_\mathrm{L})\, n, \quad n^c = n$$

$$\mathcal{L}_\nu^{\text{free}} = -\frac{1}{2} n^T C^\dagger (\gamma^\mu \partial_\mu + m) n$$

$$m = \begin{pmatrix} m_\mathrm{a} & 0 \\ 0 & m_\mathrm{s} \end{pmatrix} \quad \text{diagonal } 6 \times 6 \text{ matrix}$$

simplifying model

$$\mathcal{V}_\mathsf{L} = \begin{pmatrix} V & 0 \\ 0 & W \end{pmatrix} \begin{pmatrix} C & S \\ -S & C \end{pmatrix} \begin{pmatrix} i & 0 \\ 0 & 1 \end{pmatrix}$$

$$C = \begin{pmatrix} \cos\theta_1 & 0 & 0 \\ 0 & \cos\theta_2 & 0 \\ 0 & 0 & \cos\theta_3 \end{pmatrix}$$

$$S = \begin{pmatrix} \sin\theta_1 & 0 & 0 \\ 0 & \sin\theta_2 & 0 \\ 0 & 0 & \sin\theta_3 \end{pmatrix}$$

V, $W \Rightarrow$

$$\mathcal{M}_\mathsf{L} \to \begin{pmatrix} 0 & D_d \\ D_d & M_d \end{pmatrix} \quad \text{diagonal } D_d \text{ \& } M_d$$

$$\begin{pmatrix} C & -S \\ S & C \end{pmatrix} \begin{pmatrix} 0 & D_d \\ D_d & M_d \end{pmatrix} \begin{pmatrix} C & S \\ -S & C \end{pmatrix} = \begin{pmatrix} -m_\mathsf{a} & 0 \\ 0 & m_\mathsf{s} \end{pmatrix}$$

$$m_\mathsf{s} \simeq M_d, \quad m_\mathsf{a} \simeq \frac{D_d^2}{M_d} \quad \text{seesaw}$$

$$\theta \simeq \frac{D_d}{M_d}, \quad \theta^2 \simeq \frac{m_\mathsf{a}}{m_\mathsf{s}}$$

Sterile-Neutrino Dark-Matter

small mixing angles $\theta_k,\ k = 1, 2, 3$

m_{a} : active neutrino masses

m_{s} : sterile neutrino masses

incorporate neutrino-oscillation phenomenology

lightest sterile neutrino = dark matter?

assume

$1\,\text{keV} < m_{\mathsf{s}} < 1\,\text{MeV}$ little seesaw

Constraints:
seesaw, production, lifetime, diffuse extragalactic background radiation (DEBRA), supernova

□ seesaw

$$\theta_k^2 \;=\; \frac{m_{\mathsf{a}k}}{m_{\mathsf{s}k}}$$

WMAP, SDSS, Lyman-α

$$\sum_k m_{\mathsf{a}k} \;<\; 1\,\mathrm{eV}$$

$$\Rightarrow\;\; m_{\mathsf{s}k} < 1.0\,\theta_k^{-2}\,\mathrm{eV},\; k = 1,2,3$$

oscillations

$$\Delta m^2_{\mathsf{a}12} \approx 8\times 10^{-5}, \Delta m^2_{\mathsf{a}23} \approx 2.6\times 10^{-3}\ \mathrm{eV}$$

normal hierarchy

$$m_{\mathsf{a}1} > 0,\ m_{\mathsf{a}2} > 0.009,\ m_{\mathsf{a}3} > 0.05\ \mathrm{eV}$$

$$m_{\mathsf{s}1} > 0,\ m_{\mathsf{s}2} > 0.009\,\theta_2^{-2},\ m_{\mathsf{s}3} > 0.05\,\theta_3^{-2}\ \mathrm{eV}$$

inverted

$$m_{\mathsf{a}1} \simeq m_{\mathsf{a}2} > 0.05,\ m_{\mathsf{a}3} > 0\ \mathrm{eV}$$

$$m_{\mathsf{s}1} > 0,\ m_{\mathsf{s}1} \simeq m_{\mathsf{s}1} > 0.05\,\theta^{-2}\ \mathrm{eV}$$

Fig: seesaw band

□ production

$$\ell_3 + \ell_4 \to \ell_2 + \nu_{\mathsf{s}},\ \bar\ell_3 + \bar\ell_4 \to \bar\ell_2 + \nu_{\mathsf{s}}$$

Dodelson & Widrow, Dolgov & Hansen

$$\left(\frac{\partial}{\partial_t} - \frac{\dot a}{a}\, p\, \frac{\partial}{\partial_p}\right) f_{\mathsf{s}}(p,t) \approx 2\sin^2\theta\, \frac{42}{\pi^3}\, G_{\mathsf{F}}^2\, T^4\, p\, f_{\mathsf{a}}(p,t)$$

cold electroweak baryogenesis

$T_{\mathsf{rh}} \approx \left(\frac{30}{\pi^2 g_*}\right)^{1/4} 100 = 43$ GeV, $g_* = 86.25$

$L \simeq B$, negligible lepton asymmetry

ν_{s}-production stops when the ν_{a}-decouple around $T \approx 3$ MeV

integrate: $T \propto a^{-1} \propto t^{-1/2}$

$$f_{\mathsf{a}}(p,t) = f(p/T), \quad f_{\mathsf{s}}(p,t) = c(t)(p/T)f(p/T)$$

$$\Rightarrow n_{\mathsf{s}} \approx \mathsf{cst}\, T_{\mathsf{rh}}^3\, \theta^2\, n_{\mathsf{a}} \approx 2.5 \times 10^{13}\, \theta^2\, n_a$$

if all dark matter is $\nu_{\rm s}$:

$$\Omega_{\rm a} = \frac{m_{\rm s} n_{\rm s}}{\rho_{\rm c}} = 0.3 \Rightarrow m_{\rm s} \approx 6 \times 10^{-13} \, (\theta^2)^{-1}$$

Abazajian, Fuller & Patel – Dolgov & Hansen: matter effects $\Rightarrow \theta \to 0$ as $T \gg 100$ MeV, $\Rightarrow m_{\rm s} \approx (0.35 - 0.13)(\theta^2)^{-1/2}$ (!)

Fig: out of seesaw band $\Rightarrow$ only lightest sterile possible

□ lifetime

$\nu_{\mathrm{s}} \to \nu_{\mathrm{a}j} + \nu_{\mathrm{a}k} + \nu_{\mathrm{a}l}$

$$\frac{1}{\tau} = \Gamma = 2\frac{\sin^2\theta\, G_{\mathrm{F}}^2\, m_{\mathrm{s}}^5}{192\pi^3}$$

$\tau > 10\,\mathrm{Gy} \Rightarrow m_{\mathrm{s}} \lesssim 2150\,(\theta^2)^{-1/5}$

other steriles should have decayed
e.g. $\tau_{\mathrm{other}} > 60\,\mathrm{s}$

Fig: $m_{\mathrm{s}} < 10^7 - 10^6$ eV, $m_{\mathrm{other}} > 10^{8.5}$ eV?

□ DEBRA

$\nu_s \to \nu_{ak} + \gamma$

$$\mathrm{br} = \frac{\Gamma_\gamma}{\Gamma} = \frac{27\alpha}{8\pi} \simeq \frac{1}{128}$$

differential energy flux

$$\frac{Ed^2F}{d\Omega dE} = \frac{\Gamma_\gamma}{4\pi}\frac{n_{s0}}{H_0}\left(\frac{E}{m_s/2}\right)^{3/2}$$
$$< \frac{1\,\mathrm{MeV}}{E}\,\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

$\Gamma_\gamma = \mathrm{cst}\, m_s^5\, \theta^2$, $n_{s0} = \Omega_s\, \rho_c/m_s$, $\Omega_s = 0.3$

$\Rightarrow m_s < 300\,(\theta^2)^{-1/5}$ eV*

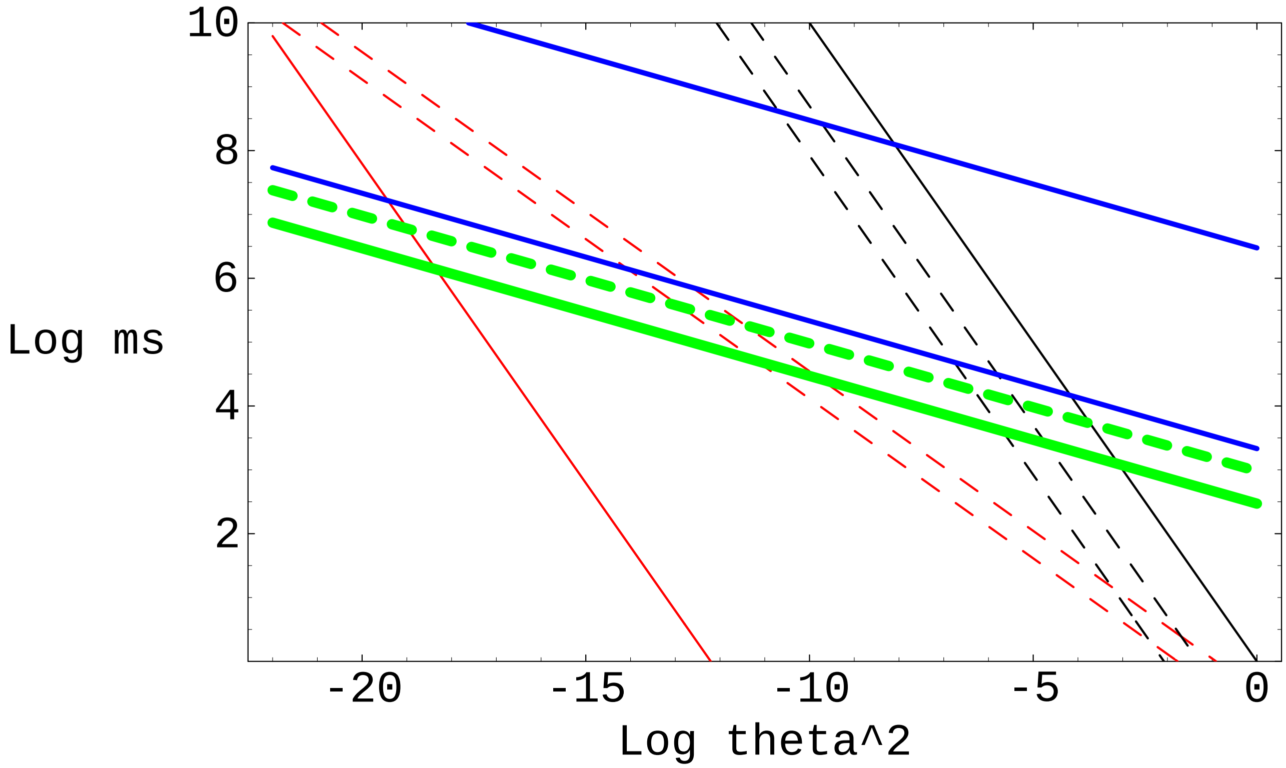
Fig: $m_s < 10^6 - 10^{5.5}$ eV

□ supernova $\theta^2 \lesssim 10^{-10}$

*) Dolgov & Hansen similar; Abazajian, Fuller & Patel: $m_s \approx 1000\,(\theta^2)^{-1/5}$ eV

constraints in $m_{\text{s}} - \theta^2$ plot:

$\text{Log}_{10}(m_{\text{s}}(\text{eV}))$ versus $\text{Log}_{10}(\theta^2)$



black: seesaw

red: production, $T_{\text{rh}} = 43$ GeV (full), Abazajian, Fuller & Patel, and Dolgov & Hansen (dashed)

blue: lifetime $\tau < 10$ Gy (lower), $\tau < 60$ s (upper)

green: DEBRA (full), Abazajian, Fuller & Patel (dashed)

Conclusion

- ESM, little seesaw, no prejudice

- sterile-neutrino dark matter and cold electroweak baryogenesis appear compatible
  $m_{\mathrm{s}} < 1$ MeV, other steriles much heavier

- m_{s} out of seesaw band

  $m_{\mathrm{a}} = m_{\mathrm{s}}\,\theta^2$, very light

  absolute masses

  $m_{\mathrm{a2}} \simeq 0.009$ eV, $m_{\mathrm{a3}} \simeq 0.05$ eV normal

  $m_{\mathrm{a1}} \simeq m_{\mathrm{a2}} \simeq 0.05$ eV inverted

- more analysis needed, matter effects