Seesaw Light Dark Matter from Higgs Decay

in memory of Eileen (1949-2022)

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Thomas and Lillian Ma Garden Study Atrium


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Proud Anteater parents and grandparents
ANTEATERS
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Contents

- Introduction
- Are There Truly Massless Fermions?
- U(1) Gauge Symmetry with Special Fermions
- Seesaw Dark Matter Type I
- Seesaw Dark Matter Type III
- Freeze-In Dark Matter from Higgs Decay
- Concluding Remarks

Introduction

1930: Pauli postulated the neutrino.

2023: We know there are 3 neutrinos $\nu_{1,2,3}$ with measured Δm^2_{21}, Δm^2_{32}, θ_{12}, θ_{13}, θ_{23}, and δ_{CP}.

1933: Zwicky postulated dark matter.

2023: Direct detection of dark matter is still negative, but already excluding a large region of parameter space, i.e. mass versus interaction strength with nuclei.

Neutrinos are elusive, but dark matter is more so. Perhaps the reason is similar, as suggested in arXiv:2304.00184.

Are There Truly Massless Fermions?

Once upon a time (which most of you would not remember), before the advent of 't Hooft (renormalizable spontaneously broken non-Abelian gauge theory), neutrinos were generally believed to be massless. This notion persisted for a little while longer because in the minimal renormalizable Lagrangian of the standard model (SM), with just the one Higgs doublet $\Phi = (\phi^+, \phi^0)$, the neutrino has no mass term. It appears only in a left-handed doublet $(\nu, l)_L$ and the N_R singlet is not mandatory.

However, it was soon realized that the dim-5 term (Weinberg:1979)

$$\mathcal{L}_5 = \frac{(\nu_L \phi^0 - l_L \phi^+)^2}{2\Lambda} + H.c.$$

implies that

$$m_\nu = \frac{\langle \phi^0 \rangle^2}{\Lambda} > 1.26 \times 10^{-5}\ \mathrm{eV}$$

for $\Lambda < 2.4 \times 10^{18}$ GeV (the reduced Planck mass).

1979: Seesaw mechanism with N_R yields $m_\nu = m_D^2/m_R$.

U(1) Gauge Symmetry with Special Fermions

Consider a set of chiral (left-handed) fermions ψ_i with charges q_i under U(1), then the resulting renormalizable field theory is free of anomalies if

$$\sum_i q_i = 0, \qquad \sum q_i{}^3 = 0.$$

The simplest realization is $q_1 = 1$, $q_2 = -1$, so that $\psi_1\psi_2$ is a Dirac mass term, and the theory is quantum electrodynamics.

Consider now 7 ψ_i with charges $1, 2, 2, -3, -3, -3, 4$. Since $1 + 2(2) + 3(-3) + 4 = 0$ and $1 + 2(8) + 3(-27) + 64 = 0$, this is an anomaly-free theory with a massless gauge boson and 7 massless fermions.

Add now a scalar singlet χ with unit charge, then the gauge U(1) symmetry is spontaneously broken with $\langle\chi\rangle \neq 0$. It also links $\psi_i\psi_j$ with $q_i + q_j = 1$ or -1, i.e. $2 + (-3) = -1$ and $4 + (-3) = 1$, resulting in 3 Dirac fermions. The remaining fermion (call it S_L) of charge (1) is massless like the neutrino.

However, the dim-5 term again appears:

$$\mathcal{L}_5 = \frac{(S_L \bar{\chi})^2}{2\Lambda} + H.c.$$

This tells us that a seesaw mass for S_L is available, and the anchor heavy fermion may well be N_R which is neutral with respect to the SM as well as this U(1). In some sense, S_L is a sterile neutrino and it mixes indirectly (in 3 steps) with the active neutrinos through N_R, 4 copies of which are required for 3 massive neutrinos and 1 massive S_L. Unlike the usual sterile neutrino, S_L has gauge interactions.

Seesaw Dark Matter Type I

fermion/scalar	$SU(2)_L$	$U(1)_Y$	$U(1)_D$
$L_L = (\nu, l)_L$	2	$-1/2$	0
l_R	1	-1	0
N_R	1	0	0
$\Phi = (\phi^+, \phi^0)$	2	1/2	0
S_L	1	0	1
χ^0	1	0	1

$\mathcal{L}_Y = f_N \overline{N_R}(\nu_L \phi^0 - l_L \phi^+) + f_\chi \overline{S_L} N_R \chi^0$ implies
$\theta_{SN} = f_\chi v_1/m_N = \sqrt{m_S/m_N}$, just as $\theta_{\nu N} = \sqrt{m_\nu/m_N}$.

$$V_1 = -\mu_0^2\Phi^\dagger\Phi - \mu_1^2|\chi|^2 + \frac{1}{2}\lambda_0(\Phi^\dagger\Phi)^2 + \frac{1}{2}\lambda_1|\chi|^4 + \lambda_{01}(\Phi^\dagger\Phi)|\chi|^2.$$

$$\begin{pmatrix} v_0^2 \\ v_1^2 \end{pmatrix} = \frac{1}{\lambda_0\lambda_1 - \lambda_{01}^2}\begin{pmatrix} \lambda_1 & -\lambda_{01} \\ -\lambda_{01} & \lambda_0 \end{pmatrix}\begin{pmatrix} \mu_0^2 \\ \mu_1^2 \end{pmatrix}.$$

Only $\sqrt{2}Re(\phi^0)$ and $\sqrt{2}Re(\chi^0)$ are physical scalars with

$$\mathcal{M}_{\phi\chi}^2 = \begin{pmatrix} 2\lambda_0 v_0^2 & 2\lambda_{01}v_0v_1 \\ 2\lambda_{01}v_0v_1 & 2\lambda_1 v_1^2 \end{pmatrix}.$$

The mixing $\theta_{\phi\chi} \simeq \lambda_{01}v_0/\lambda_1 v_1$ is assumed small.

Seesaw Dark Matter Type III

fermion/scalar	$SU(2)_L$	$U(1)_Y$	$U(1)_D$
$L_L = (\nu, l)_L$	2	$-1/2$	0
l_R	1	-1	0
$(\Sigma^+, \Sigma^0, \Sigma^-)_R$	3	0	0
$\Phi = (\phi^+, \phi^0)$	2	1/2	0
S_L	1	0	1
χ^0	1	0	1
(ρ^+, ρ^0, ρ^-)	3	0	1

$\mathcal{L}_Y = f_\Sigma(\overline{\Sigma_R^+}\nu_L\phi^+ + \overline{\Sigma_R^0}(\nu_L\phi^0 + l_L\phi^+)/\sqrt{2} + \overline{\Sigma_R^-}l_L\phi^0) + f_\rho\overline{S_L}(\Sigma_R^+\rho^- - \Sigma_R^0\rho^0 + \Sigma_R^-\rho^+)$ implies $\theta_{S\Sigma} = \sqrt{m_S/m_\Sigma}$ as expected.

$$V_2 = V_1 + m_2^2\rho^\dagger\rho + \frac{1}{2}\lambda_2(\rho^\dagger\rho)^2 + \lambda_{02}(\Phi^\dagger\Phi)(\rho^\dagger\rho)$$
$$+\lambda_{12}|\chi|^2(\rho^\dagger\rho) + [\lambda_{012}\chi^\dagger\Phi^\dagger(\vec{\sigma}\cdot\vec{\rho})\Phi + H.c.].$$

$m_2^2 >> \mu_{0,1}^2$ implies $v_2 \simeq \lambda_{012}v_1v_0^2/m_2^2 = 3.68$ GeV for $M_W = 80.4335 \pm 0.0094$ GeV [CDF: 2022].

Spanning $\sqrt{2}Re(\phi^0, \chi^0, \rho^0)$,

$$\mathcal{M}^2_{\phi\chi\rho} = \begin{pmatrix} 2\lambda_0 v_0^2 & 2\lambda_{01} v_0 v_1 & -2\lambda_{012} v_0 v_1 \\ 2\lambda_{01} v_0 v_1 & 2\lambda_1 v_1^2 & -\lambda_{012} v_0^2 \\ -2\lambda_{012} v_0 v_1 & -\lambda_{012} v_0^2 & m_2^2 \end{pmatrix}.$$

Hence

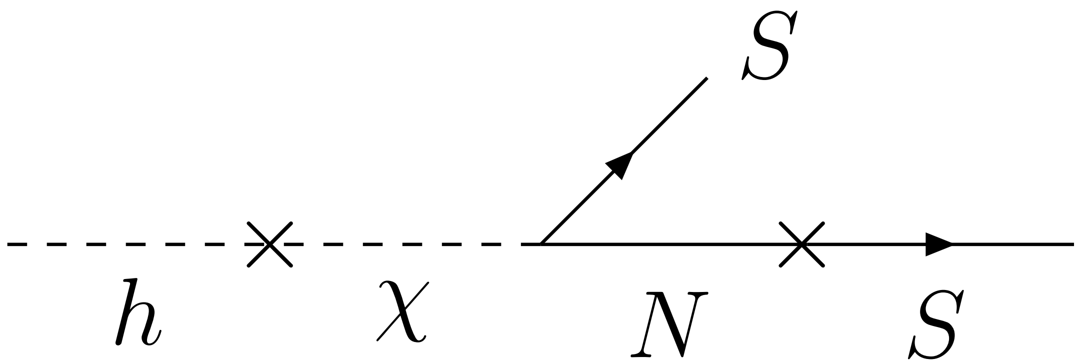
$$\theta_{\phi\rho} \simeq \frac{-2\lambda_{012} v_0 v_1}{m_2^2} \simeq \frac{-2v_2}{v_0}.$$

Neutrino mixing with the heavy triplet anchor $\theta_{\nu\Sigma} \simeq \sqrt{m_\nu/m_\Sigma}$ as expected.

Freeze-In Dark Matter from Higgs Decay

The dark matter candidate in this proposal is S_L. It has a seesaw mass in analogy to that of the neutrino, through the heavy fermion anchor N_R or Σ_R. It interacts with χ and N_R, or ρ and Σ_R, as well as the $U(1)_D$ gauge boson, all of which are assumed heavy.

If the reheat temperature of the Universe is above the electroweak scale, but well below m_D, m_χ, m_ρ (with m_N, m_Σ much heavier), then S_L is produced only through Higgs decay.


S
h
χ
N
S

The effective coupling is

$$f_h = f_\chi \theta_{\phi\chi} \theta_{SN} = \frac{2\lambda_{01} v_0 m_S}{m_\chi^2}.$$

The decay rate of $h \to SS + \bar{S}\bar{S}$ is

$$\Gamma_h = \frac{f_h^2 m_h}{8\pi} \sqrt{1 - 4r^2}(1 - 2r^2),$$

where $r = m_S/m_h$. Arcadi/Covi(2013): The correct relic abundance is obtained if $f_h \sim 10^{-12} r^{-1/2}$. Consider for example $m_\chi = 1$ TeV, $\lambda_{01} = 0.01$, then $m_S = 0.22$ MeV.

Replacing χ with ρ^0 and N with Σ^0,

$$f_h = f_\rho \theta_{\phi\rho} \theta_{S\Sigma} = \frac{2m_S}{v_0}.$$

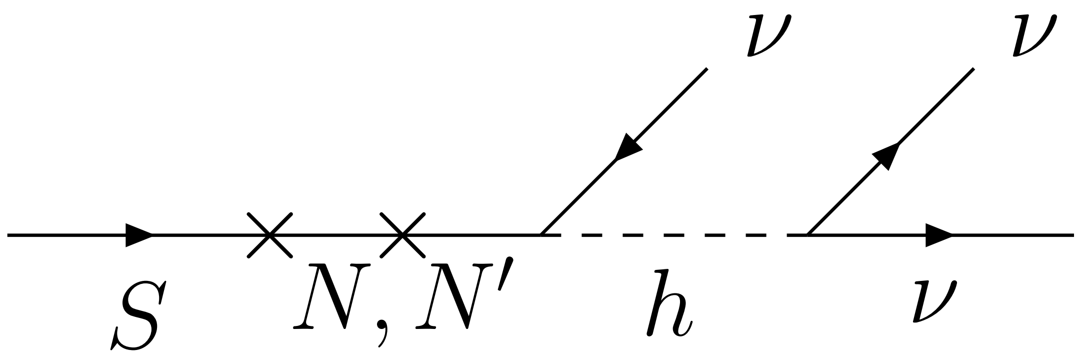
This uniquely determines $m_S = 1$ keV.

Consider now $\nu - S$ mixing. One possible dim-5 term

$$\mathcal{L}_5 = \frac{(\nu\phi^0 - l\phi^+)(S\bar{\chi})}{\Lambda} + H.c.$$

comes from the 4×4 N_R mass matrix.

Hence S is not stable and must decay.


ν
ν
S
N, N'
h
ν

The effective four-fermion coupling for $S \to \bar{\nu}\nu\nu$ is

$$G_S = \sqrt{\frac{m_S}{m_N}} \theta_{NN'} \frac{\sqrt{m_\nu m_{N'}}}{v_0} \frac{1}{m_h^2} \frac{m_\nu}{v_0}.$$

For $m_S = 0.22$ MeV, $m_\nu = 0.1$ eV, $m_N \sim m_{N'}$, $\theta_{NN'} = 0.1$, $G_S \sim 3.1 \times 10^{-27}\ \mathrm{GeV}^{-2}$.

The decay rate of $S \to \bar{\nu}\nu\nu + \bar{\nu}\bar{\nu}\bar{\nu}$ is

$$\Gamma_S = \frac{G_S^2 m_S^5}{48(4\pi)^3}.$$

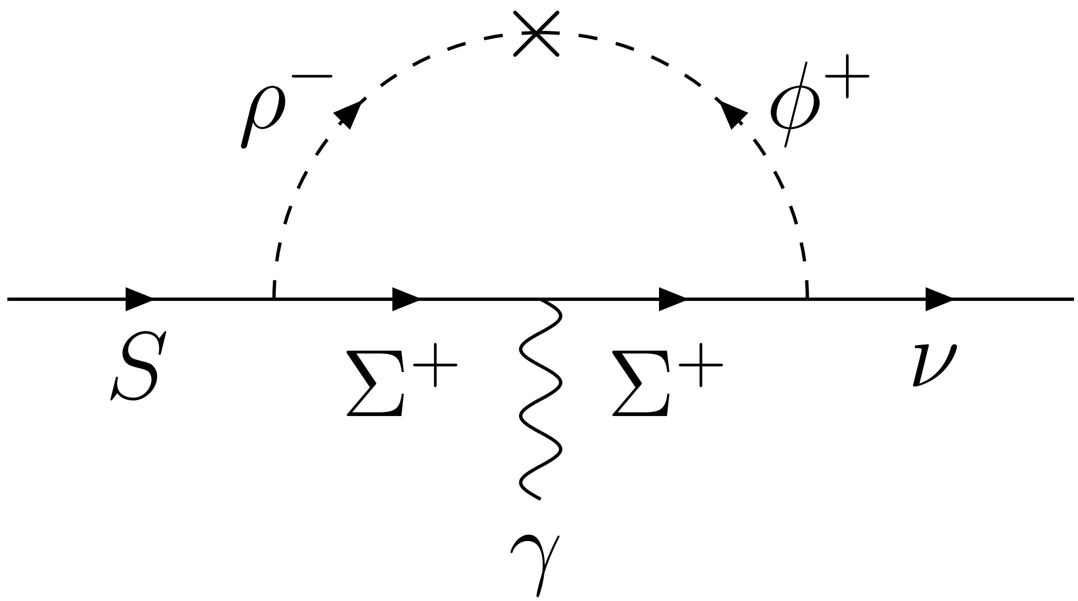
Hence $\tau_S \sim 1.2 \times 10^{52}\ \mathrm{s} = 3.8 \times 10^{44}$ y.

In the SM, the decay $\nu_i \to \nu_j \gamma$ is possible because there is a loop involving charged particles, i.e. the $W^\pm$ gauge bosons and the charged leptons. Here $S \to \nu\gamma$ occurs only through $\nu - S$ mixing in the case of N_R, so its rate is suppressed.

However, Σ_R^+ and $(\rho/\phi)^\pm$ allow

$$\Gamma_S = \frac{\alpha (f_\rho f_\Sigma v_2)^2 m_S^5}{(24\pi^2 v_0)^2 m_\Sigma^4}.$$

For $m_S = 1$ keV and $m_\Sigma/\sqrt{f_\rho f_\Sigma} \sim 10^9$ GeV,
$\tau_S \sim 10^{52}\ \mathrm{s}$.


ρ^-
ϕ^+
S
Σ^+
Σ^+
ν
γ

Back to the 3 Dirac fermions with $U(1)_D$ charges $(-3,-3,-3)$ paired with $(2,2,4)$. They possess an accidental unbroken global U(1) symmetry at the Lagrangian level, and the lightest (call it ψ) could be a dark matter candidate. However the dim-5 term

$$\mathcal{L}_5 = \frac{\psi S \chi \chi}{2\Lambda} + H.c.$$

breaks this global symmetry for Λ at the Planck scale and allows the decay $\psi \to Sh$ with $f_\psi = v_1 \theta_{\phi\chi}/\Lambda_{Pl}$. The decay rate is $\Gamma_\psi = f_\psi^2 m_\psi / 8\pi$.

Let $\lambda_{01}/\lambda_1 = 0.1$, $\Lambda_{Pl} = 2.4 \times 10^{18}$ GeV, then Calmet/Kuipers(2021): $m_\psi > 1$ TeV implies $\tau_\psi < 3 \times 10^8$ s.

Hence quantum gravity rules out ψ as a dark matter candidate. This argument has the same origin as that against massless particles, and applies to all global and discrete dark symmetries and tends to favor

light dark matter!

Concluding Remarks

The notion is put forward that dark matter S is light and has a seesaw origin akin to that of neutrinos. In fact they share the same heavy fermion anchors, either singlets N_R or triplets $(\Sigma^+, \Sigma^0, \Sigma^-)_R$. The connecting scalars are different. For neutrinos it is the usual SM Higgs doublet (ϕ^+, ϕ^0). For dark matter, a dark $U(1)_D$ gauge symmetry is invoked and the connecting scalar is an SM singlet χ or triplet (ρ^+, ρ^0, ρ^-).
The latter allows an explanation of the W mass shift observed by CDF.

Assuming the reheat temperature of the Universe is above m_h but well below all the new particles except of course S, the relic abundance of S is through the freeze-in mechanism from Higgs decay. It is shown that in the case of N_R, the typical mass range of m_S is around 0.22 MeV, whereas in the case of Σ_R it is uniquely determined at 1 keV. In either case, they are not absolutely stable, but with lifetimes many orders of magnitude greater than the age of the Universe. The former decays to 3 neutrinos and the latter to neutrino + photon.