Reviving keV sterile neutrino Dark Matter

produced by thermal freeze-out through dynamical Yukawa couplings

Based on 2207.11269 and 2004.12904

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Motivation

Based on 2207.11269 and 2004.12904

SM Extension by 3 sterile neutrinos is a great idea (see νMSM hep-ph/0503065)

$$-\mathcal{L} \supset \bar{L}\,\underbrace{Y_\nu\,\tilde{\phi}}_{m_D}\,\nu_R + \frac{1}{2}\overline{\nu_R^c}\,M_R\,\nu_R + \mathrm{h.c.}$$

Light neutrino masses through Type I Seesaw mechanism

Warm Dark Matter with keV mass

Leptogenesis

What about the production mechanism and stability?

Sterile neutrinos as a DM candidate

Production:

- Non-resonant oscillations (Dodelson-Widrow)
- Resonant oscillation - requires Lepton number asymmetry (Shi-Fuller)
- (Decay from heavier particles - many in the literature)

Sterile neutrinos as a DM candidate

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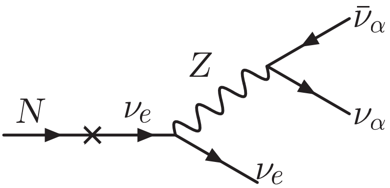
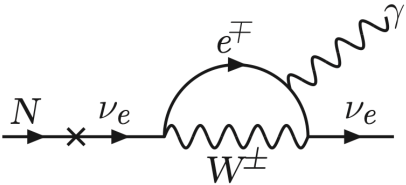
Longevity: Sterile neutrinos are not stable!





Challenge: Balance θ for successful production & longtime stability.

Sterile neutrinos as a DM candidate

The lightest sterile state N_1 is DM

The loop decay is easy to detect: monochromatic photon with $E = M_1/2$

$$\Gamma_{N\to\gamma\nu} \propto \theta_1^2 \left(\frac{M_1}{\mathrm{keV}}\right)^5 \mathrm{s}^{-1}$$

$$\theta_1^2 = \sum_{\alpha=e,\mu,\tau} \frac{|(m_D)_{\alpha 1}|^2}{M_1^2}$$

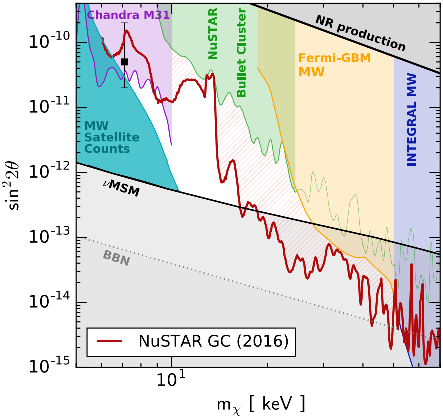


Figure: K. Perez et al. 1609.00667

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Suspicious line at $M_1 = 7.1\,\mathrm{keV}$
Dodelson-widrow: excluded
Shi-Fuller: strongly constrained
New production mechanism needed!

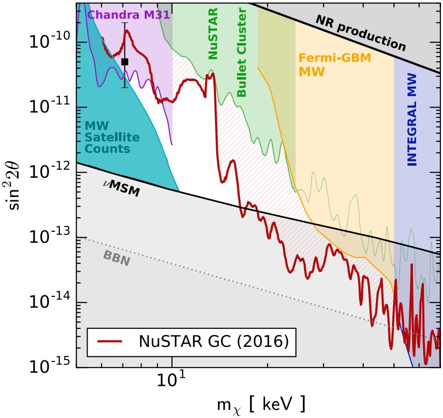


Figure: K. Perez et al. 1609.00667

The main idea: WIMP inspiration

WIMPs are in thermal equilibrium:

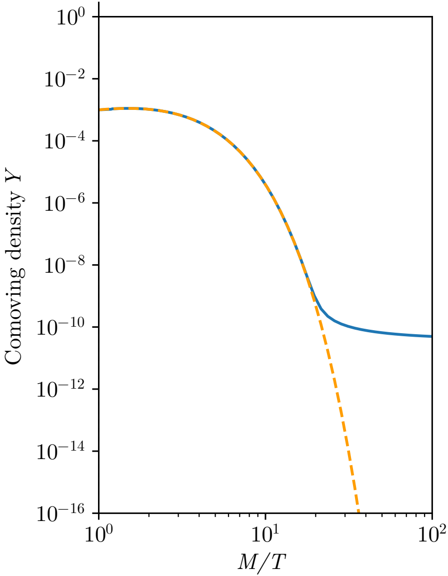
Interaction rate $\Gamma_\chi > H$.

WIMP density $= n_{\rm eq}(T)$

Universe expands and cools:

WIMPs drop out of eq.: $\Gamma_\chi < H$,

WIMP density freezes-out!



The main idea: Freeze-out for sterile neutrinos

Use effectively dynamic neutrino Yukawa coupling

$$Y^\nu \sim \begin{cases} \mathcal{O}(1): & \text{at early times} \Rightarrow \text{thermal equilibrium} \\ \ll 1: & \text{at late times} \Rightarrow \text{freeze-out} \end{cases}$$

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Implementation?

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Implementation? $\rightarrow$ e.g. embedement in **Froggatt-Nielsen Model**:

Add Flavour symmetry $U(1)_{\mathrm{FN}}$ and scalar field flavon Θ.

Field	L_i	E_{R_j}	N_k	Θ	ϕ
Charge	q_{L_i}	q_{R_j}	q_{N_k}	-1	0

$$Y_{ij}\,\overline{f_L}_i\,\phi\,f_{R\,j} \longrightarrow Y_{ij}\,\overline{f_L}_i\,\phi\,f_{R\,j}\,\left(\frac{\langle\Theta\rangle}{\Lambda_{\mathrm{FN}}}\right)^{q_{L,i}+q_{R,j}}$$

Implementing varying Yukawa couplings

- Within a FN model, the relevant part of the leptonic Lagrangian is

$$-\mathcal{L}_{\text{eff}} \supset \bar{L}_i \, Y^e_{ij} \, \phi \, E_{R\,j} \, \left(\frac{\langle\Theta\rangle}{\Lambda_{\text{FN}}}\right)^{q_{\bar{L}i}+q_{Rj}} + \bar{L}_i \, Y^\nu_{ij} \, \tilde{\phi} \, \nu_{Rj} \, \left(\frac{\langle\Theta\rangle}{\Lambda_{\text{FN}}}\right)^{q_{\bar{L}i}+q_{Nj}}$$

$$+ \frac{1}{2}\overline{\nu^c_{Ri}} \, (M_N)_{ij} \, \nu_{Rj} \, \left(\frac{\langle\Theta\rangle}{\Lambda_{\text{FN}}}\right)^{q_{Ni}+q_{Nj}} + \text{h.c.}$$

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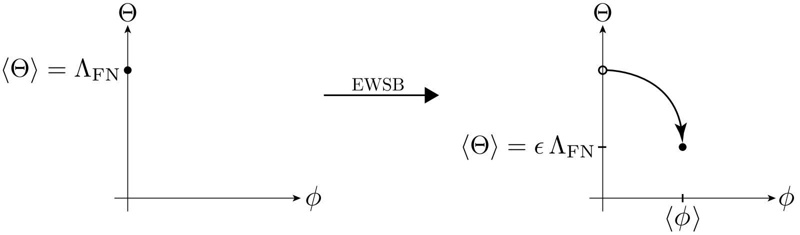
- At the EWPT the potential finds a new minimum in field space: (see 1608.03254)



Implementing varying Yukawa couplings

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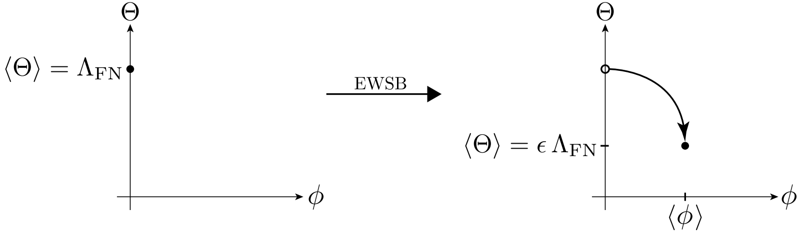

$$(Y^\nu_{\rm eff})_{ij} = (Y^\nu)_{ij}\,\left(\frac{\langle\Theta\rangle}{\Lambda_{\rm FN}}\right)^{q_{\bar{L}_i}+q_{N_j}} = \begin{cases} (Y^\nu)_{ij}, & \text{for} \quad T > T_c \\ (Y^\nu)_{ij}\,\epsilon^{\,q_{\bar{L}_i}+q_{N_j}}, & \text{for} \quad T < T_c \end{cases},$$

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At $T = T_c$ the Yukawa interactions get suppressed by powers of $\epsilon < 1$,
$\Rightarrow \Gamma$ gets suddenly suppressed
$\Rightarrow$ decoupling/freeze-out is induced while also ensuring longevity!

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Not only the Yukawas vary, the Majorana mass matrix varies too:

The early mass:	$(\tilde{M})_{jk} = (M_N)_{jk},$	for	$T > T_c$
The late mass:	$(M)_{jk} = (M_N)_{jk}\,\epsilon^{q_{Nj}+q_{Nk}},$	for	$T < T_c$

This affects DM production...

Sterile Neutrino Dark Matter production by freeze-out

$$\Omega_{\mathrm{DM}} = \frac{s_0\, y_{\mathrm{fo}}\, M_{\mathrm{DM}}}{\rho_{\mathrm{crit}}}, \quad \text{with} \quad y_{\mathrm{fo}}(T_c, m) \propto \left(\frac{m}{T_c}\right)^{3/2} e^{-m/T_c}$$

$M_{\mathrm{DM}} \to$ late mass M $\qquad$ $m \to$ early mass $\tilde{M}$

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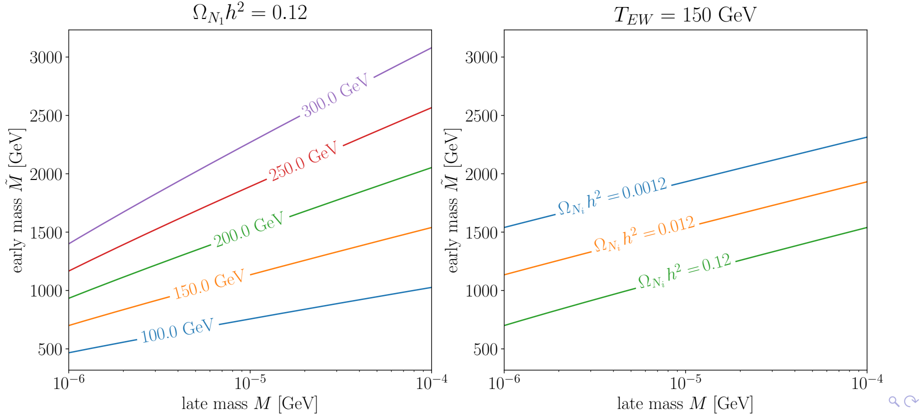


Towards a concrete FN realization

Formulate a concrete FN model for the leptonic sector + RH neutrinos such that:

1. there is one RH neutrino is a viable, long-lived DM candidate with keV mass
2. the lepton mass hierarchy is explained or at least alleviated
3. the small neutrino masses arise by FN & seesaw suppression
4. the PMNS matrix is recovered

Specify FN charges and couplings/coefficients close to $\mathcal{O}(1)$.

Here we choose $\epsilon = \left(\frac{\langle\Theta\rangle}{\Lambda_{\rm FN}}\right)_{T<T_c} = 0.1$

Towards a concrete FN realization

For successful keV Dark Matter production:
With the unsuppressed (early) Majorana mass matrix $\tilde{M} = \Lambda_M \, Y^N$

$$Y^N \sim \mathcal{O}(1), \qquad \Lambda_M = 10^4 \, \mathrm{GeV},$$
$$q_N = \{q_{N_1}, q_{N_2}, q_{N_3}\} = \{\mathbf{4},\ \mathbf{4},\ \mathbf{4}\} \ \text{(or } \{5,\ 4,\ 4\}\text{)}$$

For neutrino masses, oscillation data and lepton flavour hierarchy:
Use Casas-Ibarra parametrization, assuming normal ordering

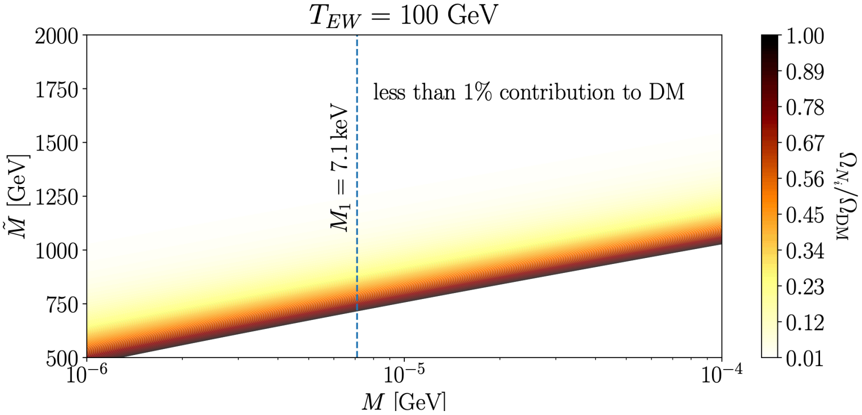
$$q_L = \{q_{L_e}, q_{L_\mu}, q_{L_\tau}\} = \{7,\ 7,\ 7\}, \qquad Y^\nu \sim \mathcal{O}(0.01 - 1)$$
$$q_E = \{q_{R_e}, q_{R_\mu}, q_{R_\tau}\} = \{-3,\ -4,\ -4\}, \qquad Y^E \sim \mathcal{O}(1)$$

For Dark Matter cosmological longevity:
Use Casas-Ibarra parametrization, $m_D = i \, V^\star \sqrt{m_\nu^d} \, R \sqrt{M}$,
scan over the free params. in the arbitrary orthogonal matrix R.

Towards a concrete FN realization: the Majorana sector

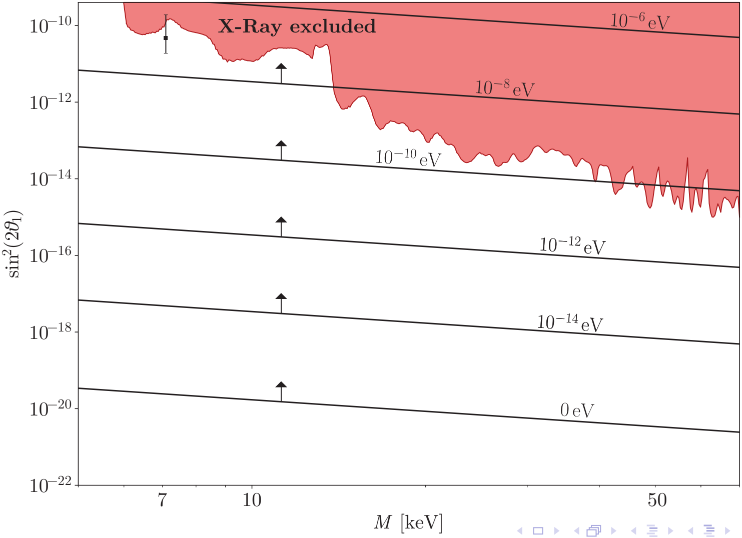
Choose e.g. the eigenvalues for successful DM genesis

$$M^d = \mathrm{diag}(7.1,\, 20,\, 30)\,\mathrm{keV} \Rightarrow \tilde{M}^d = \mathrm{diag}(0.71,\, 2,\, 3)\,\mathrm{TeV}$$



Towards a concrete FN realization: the Majorana sector

DM stability depends on the mass of the lightest active neutrino m_1



Conclusions

- Varying neutrino Yukawa couplings in the early Universe, from large to tiny, can enable DM sterile neutrino production via freeze-out, similar to WIMPs
- If the late time suppression of the Yukawa couplings is drastic enough, X-Ray bounds can be evaded
- The implementation through the embedment of the seesaw sterile neutrinos in a Froggatt-Nielsen model allows to simultaneously explain the active neutrino masses and alleviates the flavour hierarchy in the lepton sector

look for 2207.11269

More details?

The origin of neutrino masses: the neutrino seesaw

Add (three) heavy Majorana SM-singlet neutrinos

$$-\mathcal{L} \supset \bar{L}\, \underbrace{Y_\nu\, \tilde{\phi}}_{m_D}\, \nu_R + \frac{1}{2}\overline{\nu_R^c}\, M_R\, \nu_R + \text{h.c.},$$

$$-\mathcal{L}_{\nu,\text{mass}} = \frac{1}{2}\,\overline{\nu_{\mathcal{M}}^c}\, \mathcal{M}_\nu\, \nu_{\mathcal{M}} + \text{h.c.} = \frac{1}{2}\,\overline{\nu_{\mathcal{M}}^c} \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \nu_{\mathcal{M}} + \text{h.c.},$$

$\mathcal{M}'_\nu = \text{diag}(m_\nu,\, M_N),$ and if $m_D \ll M_R,$ then

$$m_\nu \approx m_D\, M_R^{-1}\, m_D^T, \qquad M_N \approx M_R.$$

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$$m_\nu \approx m_D\, M_R^{-1}\, m_D^T, \qquad M_N \approx M_R.$$

The lightest sterile neutrino **could be** a good DM candidate!
The sterile-active mixing $\theta \sim m_D\, M_R^{-1}$.

Towards a concrete FN realization

Defining

$$Q_N = \mathrm{diag}(\epsilon^{q_{N_1}}, \epsilon^{q_{N_2}}, \epsilon^{q_{N_3}}), Q_{\bar{L}} = \mathrm{diag}(\epsilon^{q_{\bar{L}_e}}, \epsilon^{q_{\bar{L}_\mu}}, \epsilon^{q_{\bar{L}_\tau}}), \quad \& \quad Q_E,$$
$$M = \Lambda_M\, Q_N\, Y^N\, Q_N, \quad m_D = v\, Q_L\, Y^\nu\, Q_N, \quad m_E = v\, Q_L\, Y^E\, Q_E.$$

We need Y^E, Y^ν, $Y^N \sim \mathcal{O}(1)$.

We need to investigate M, m_D, m_E separately.

Towards a concrete FN realization: the Majorana sector

The early and late Majorana mass matrices

$$\tilde{M} = \Lambda_M \, Y^N, \quad M = \Lambda_M \, Q_N \, Y^N \, Q_N$$

For right abundance, the early Majorana mass $\tilde{M} = \Lambda_M \, Y^N \sim 10^4 \, \mathrm{GeV}$.

Since we need $Y^N \sim \mathcal{O}(1)$ it follows that $\Lambda_M = 10^4 \, \mathrm{GeV}$.

Aiming to have sterile neutrinos with late mass eigenvalues in keV range:

$$10^{-6} \, \mathrm{GeV} \sim M = \Lambda_M \, Q_N \, Y^N \, Q_N \rightsquigarrow \epsilon^{q_{N_i} + q_{N_j}} \sim 10^{-9}$$

suggesting $q_N = \{q_{N_1}, q_{N_2}, q_{N_3}\} = \{\mathbf{4}, \ \mathbf{4}, \ \mathbf{4}\}$ (or $= \{5, \ 4, \ 4\}$)

Then, $\tilde{M}$ and M are proportional and have the same eigenbasis $\tilde{U} = U$, and their diagonalized versions are related by $\tilde{M}^d = \epsilon^8 \, M^d$

Towards a concrete FN realization

The neutrino Dirac mass matrix

Redevire the Casas-Ibarra param. for non-diagonal Majorana matrix

$$m_D = Q_{\bar{L}}\, Y^\nu\, Q_N = i\, V^\star \sqrt{m_\nu^d}\, R\, \tilde{U} \sqrt{\tilde{M}^d}\, \tilde{U}^T\, Q_N,$$

- If m_E was diagonal, V would just be the PMNS matrix. Here $m_E^d = W_L^\dagger\, m_E\, W_R$ and $V_{\text{PMNS}} = W_L^\dagger\, V$
- $m_\nu^d = \text{diag}(m_1, m_2, m_3)$ contains the light neutrino eigenmasses. Assume massless ν_1 and normal ordering: $m_1 = 0\,\text{eV},\ m_2 = 8.7 \times 10^{-3}\,\text{eV},\ m_3 = 5 \times 10^{-2}\,\text{eV}$
- R is an arbitrary orthogonal matrix
- After choosing $\tilde{M}^d$ we generate a random $\tilde{U}$
- Dimensional analysis gives us $Q_L = \text{diag}(\epsilon^7, \epsilon^7, \epsilon^7)$

Towards a concrete FN realization

$$Q_{\bar{L}}\, Y^{\nu} = i\, V^{\star} \sqrt{m_{\nu}^{d}}\, R\, \tilde{U} \sqrt{\tilde{M}^{d}}\, \tilde{U}^{T}$$

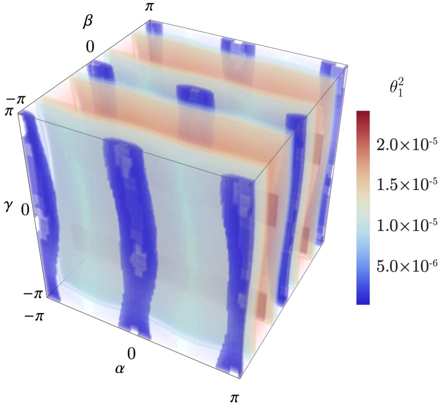
The freedom to choose Y^{ν} is in the 3 free parameters of R.
Parametrize $R_x(\alpha)\, R_y(\beta)\, R_z(\gamma)$

Gen.	L_i	E_{R_j}	N_k
1	7	-3	4 or 5
2	7	-4	4
3	7	-4	4

Towards a concrete FN realization: the Majorana sector

Finding the minimum of θ_1^2 by varying R

Parametrize $R = R_x(\alpha)\, R_y(\beta)\, R_z(\gamma)$



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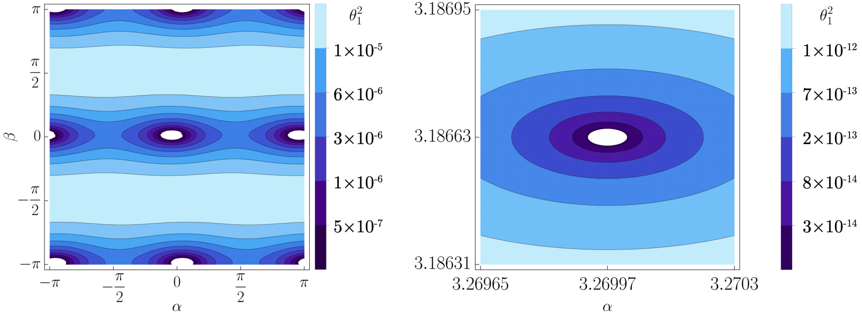

that's it for now