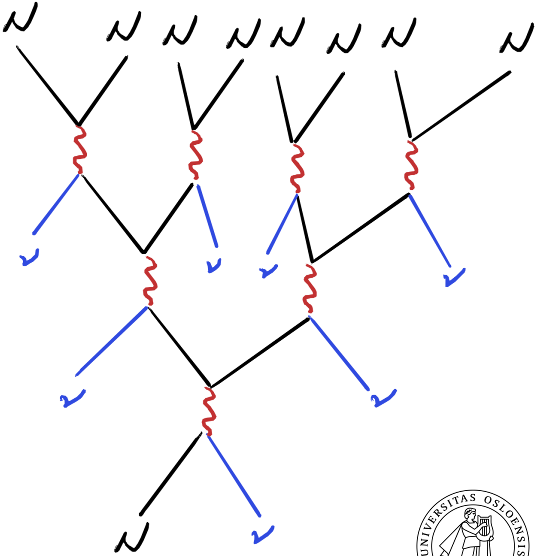
UNIVERSITY OF OSLO



Charged Sterile Neutrinos as Dark Matter

Halvor Melkild
halvor.melkild@fys.uio.no

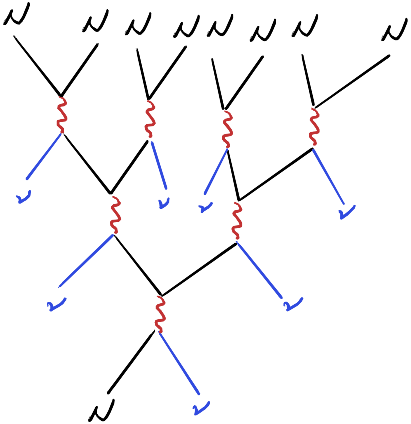
Work in progress with
A. Brekke, T. Bringmann, K. Schmidt-Hoberg

IDM2026, Zaragoza

01.06.2026

Outline

- keV scale sterile neutrinos as Dark Matter
- Charging sterile neutrinos
- Pandemic freeze-in production



Sterile neutrinos

Sterile neutrinos and neutrino mass

Neutrino masses can be generated by including a right-handed singlet, N_R,

$$\mathcal{L} \supset -\mathrm{i}\,\overline{\ell_\mathrm{L}}\tilde{H}Y_\mathrm{D}N_\mathrm{R} - \frac{1}{2}\overline{N^c_\mathrm{R}}M_\mathrm{M}N_\mathrm{R}$$

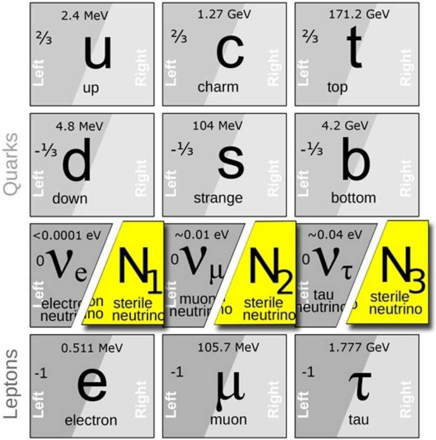
Seesaw mechanism:

$$\mathcal{L} \supseteq \frac{1}{2}\begin{pmatrix}\nu_\mathrm{L} & N_\mathrm{R}\end{pmatrix}\begin{pmatrix}0 & M_\mathrm{D}\\ M_\mathrm{D} & M_\mathrm{M}\end{pmatrix}\begin{pmatrix}\nu_\mathrm{L}\\ N_\mathrm{R}\end{pmatrix}$$

Assuming $M_\mathrm{D} \ll M_\mathrm{M}$

$$M_\nu \simeq M_\mathrm{D}\frac{1}{M_\mathrm{M}}M_\mathrm{D}$$

$$M_N \simeq M_\mathrm{M}$$



P. Minkowski, Phys. Lett. B. 67 (1977), R. N. Mohapatra, G. Senjanović, Phys. Rev. Lett. 44 (1980)

Sterile neutrinos and neutrino mass

Neutrino masses can be generated by including a right-handed singlet, N_{R},

$$\mathcal{L} \supset -\mathrm{i}\,\overline{\ell_{\mathrm{L}}}\tilde{H}Y_{\mathrm{D}}N_{\mathrm{R}} - \frac{1}{2}\overline{N_{\mathrm{R}}^{c}}M_{\mathrm{M}}N_{\mathrm{R}}$$

Seesaw mechanism:

$$\mathcal{L} \supseteq \frac{1}{2}\begin{pmatrix}\nu_{\mathrm{L}} & N_{\mathrm{R}}\end{pmatrix}\begin{pmatrix}0 & M_{\mathrm{D}} \\ M_{\mathrm{D}} & M_{\mathrm{M}}\end{pmatrix}\begin{pmatrix}\nu_{\mathrm{L}} \\ N_{\mathrm{R}}\end{pmatrix}$$

Assuming $M_{\mathrm{D}} \ll M_{\mathrm{M}}$

$$M_\nu \simeq M_{\mathrm{D}}\frac{1}{M_{\mathrm{M}}}M_{\mathrm{D}}$$

$$M_N \simeq M_{\mathrm{M}}$$

P. Minkowski, Phys. Lett. B. 67 (1977), R. N. Mohapatra, G. Senjanović, Phys. Rev. Lett. 44 (1980)

keV scale sterile neutrinos

Stable compared to age of the universe

$$\frac{\tau_N}{\tau_{\text{universe}}} \sim 10^{10}\left(\frac{10^{-8}}{\sin^2(2\theta)}\right)\left(\frac{1\,\text{keV}}{m_N}\right)^5$$

M. Drewes et al [1602.04816]

Tremaine-Gunn bound

- Pauli exclusion principle forbids N with masses below ~ 1 keV

S. Tremain, J. E. Gunn [Phys. Rev. Lett. 42, 407]

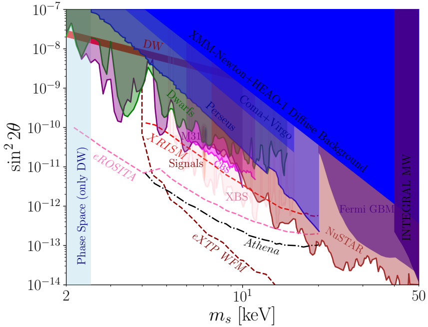
Dodelson-Widrow production

- Oscillations and scatterings with active neutrinos given by mixing angle, $\theta \simeq M_{\mathrm{D}}/M_{\mathrm{M}}$

$$m_N \sim 3.4 \times \left(\frac{10^{-8}}{\sin^2(2\theta)}\right)^{0.615} \text{keV}$$

S. Dodelson, L.M. Widrow [hep-ph/9303287]

M. Gerbino et al [2203.07377]



DW is ruled out by missing X-ray observations from decay.

Model building

What if we charge the sterile neutrino?

Let N be charged under a new $U(1)'$ symmetry:

1. Neutrino portal LHN_+ is not possible
2. Massless dark photon is constrained (e.g. BBN)

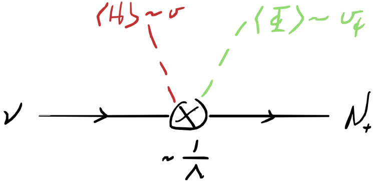
Both problems can be solved by breaking the symmetry with a new scalar, Φ.

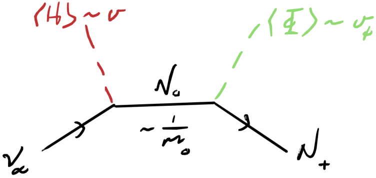
- Neutrino portal generated by dim-5 operator

$$\mathcal{L} \supset \frac{1}{\Lambda} \nu_\mathrm{L} \tilde{H} \Phi N_+$$

Obvious UV-completion: Add a totally neutral N_0

$$\mathcal{L} \supset -y_\alpha \overline{\nu_\mathrm{L}} \tilde{H} N_0 - y_+ \overline{N_0} \Phi N_+$$





Mass matrix

Anomaly cancellation requires a neutrino with opposite charge, N_-, giving a Dirac mass term

$$\mathcal{L} \supset m_\mathrm{D}(\overline{N_+} N_-^c + \overline{N_-^c} N_+)$$

The resulting mass matrix becomes

$$\begin{pmatrix} 0 & 0 & 0 & m_\alpha \\ 0 & 0 & m_\mathrm{D} & m_- \\ 0 & m_\mathrm{D} & 0 & m_+ \\ m_\alpha & m_- & m_+ & m_0 \end{pmatrix}$$

Considering mass hierarchy

$$m_\alpha, m_+ = m_- \lesssim m_\mathrm{D} \sim \mathcal{O}(\mathrm{keV}) \ll m_0$$

Physical masses:

$$m_\nu \simeq \frac{m_\alpha^2}{m_0}$$

$$m_{N_1} \simeq m_\mathrm{D} - \frac{2m_+^2}{m_0}$$

$$m_{N_2} = m_\mathrm{D}$$

$$m_{N_0} \simeq m_0$$

We assume m_0 big enough to integrate out N_0 .

Mixing angles with active neutrino:

$$\theta_{1\nu} \simeq \frac{m_\alpha m_+}{m_0 m_\mathrm{D}}$$

$$\theta_{0\nu} \simeq \frac{m_\alpha}{m_0}$$

Dark Matter production

Production mechanism

1. Initial abundance of N_1 is set by Dodelson-Widrow.

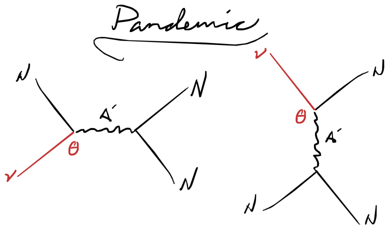
   T. Asaka, M. Laine, M. Shaposhnikov [hep-ph/0612182]

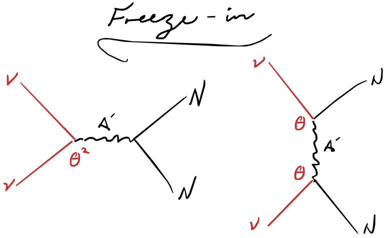
2. Dark sector thermalises through
   - $N_1 N_1 \leftrightarrow N_2 N_2$
   - $N_1 N_2 \leftrightarrow A'$

3. Further evolution governed by the Boltzmann eqs.

$$\frac{\mathrm{d}n}{\mathrm{d}t} + 3Hn = C_n$$

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + 3H(\rho + P) = C_\rho$$





Pandemic production

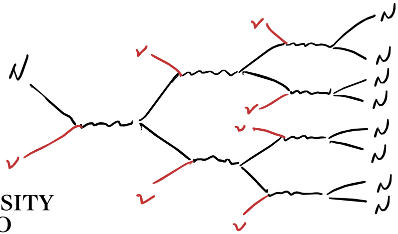
Boltzmann equation

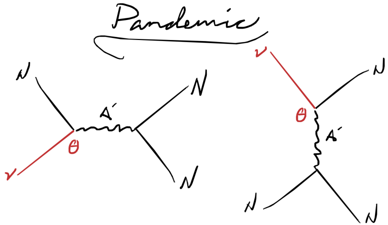
$$\frac{\dot{n}}{n} = (n_\nu^{\mathrm{eq}}\langle\sigma v\rangle - 3H)$$

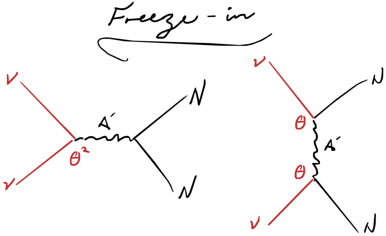
Exponential growth in n_N if

$$R \equiv \frac{n_\nu^{\mathrm{eq}}\langle\sigma v\rangle}{3H} \gtrsim 1$$

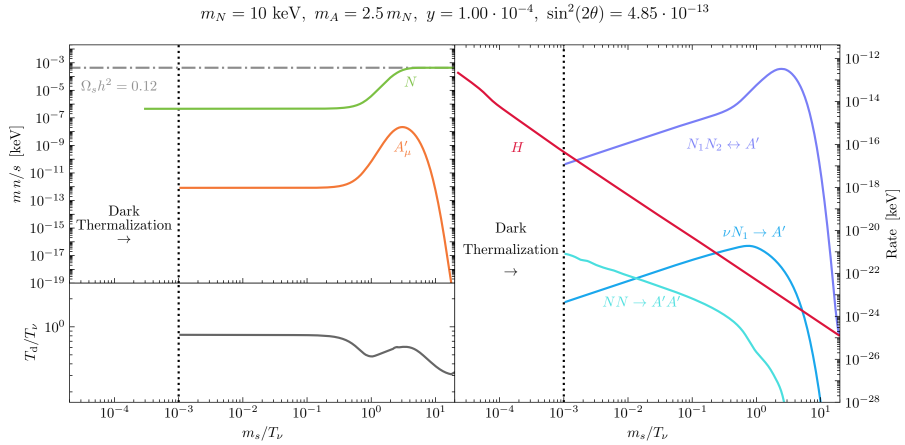
T. Bringmann et al [2103.16572]





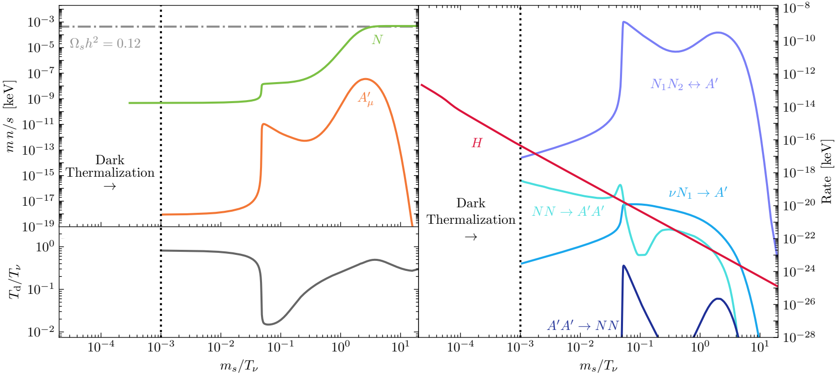


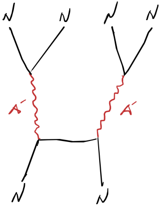
Pandemic production



Pandemic production

$m_N = 10$ keV, $m_A = 2.5\, m_N$, $y = 2.52 \cdot 10^{-3}$, $\sin^2(2\theta) = 5.00 \cdot 10^{-16}$

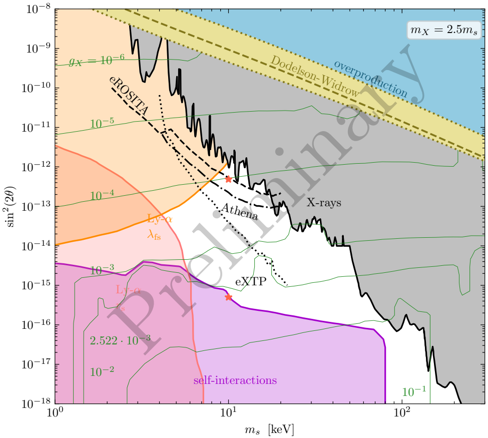




Preliminary results

Open parameter space is bounded from all sides

- X-ray searches constrain high masses and mixing angles
- Lyman-α constrain small masses
- Self-interactions constrain small mixing angles (need a too strong gauge coupling)

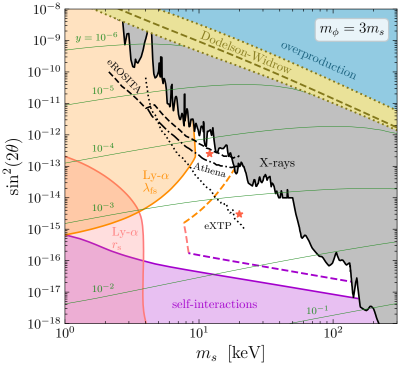


Warning: Don't trust lower right corner

UNIVERSITY OF OSLO

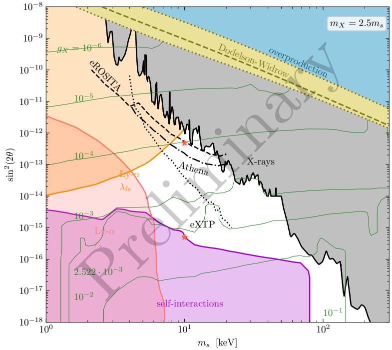
Comparison to scalar mediator

Scalar mediator



T. Bringmann et al [2206.10630]

Vector mediator

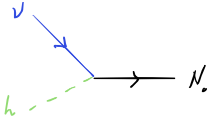


Warning: Don't trust lower right corner

Avenues to explore

We have assumed that N_0 can be integrated out. What if we can't?

$$
\begin{aligned}
\mathcal{L}^{\mathrm{DM,int}} = \;& \mathrm{i}\,\frac{g}{2}\overline{N_2}\gamma^\mu A'_\mu \left(N_1 + \sin\theta_{01} N_0 + \sin\theta_{1\nu}\mathrm{i}\gamma^5\nu\right) \\
& + y_\alpha \overline{\nu} h N_0 + y_\alpha \overline{N_1} h \left(\sin\theta_{01}\mathrm{i}\gamma^5\nu + \sin\theta_{1\nu} N_0\right) \\
& - y_+ \overline{N_1}\Phi \left(N_0 - \sin\theta_{01} N_1 + \sin\theta_{0\nu}\mathrm{i}\gamma^5\nu\right) + h.c.,
\end{aligned}
$$



- Freeze-in contribution from N_0 if $m_{N_0} \lesssim \mathcal{O}(T_{\mathrm{RH}})$
- Decays to Dark Sector particles, $N_0 \to N_1\Phi$

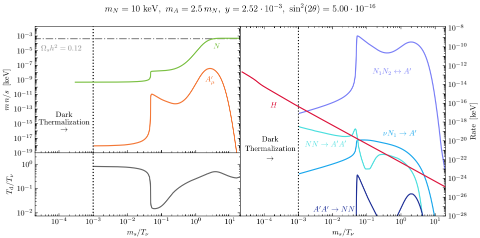
Neither process is suppressed

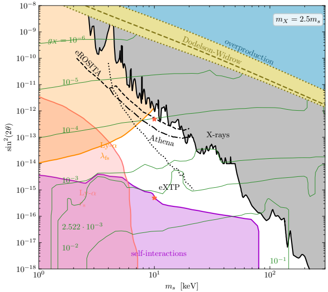
Need to include N and Φ in the numerical analysis!

Summary

- Sterile neutrinos is a well motivated extension of the SM
- Pandemic production gives the correct relic abundance
- Viable as DM for very specific parameter range

Motivation for further experimental searches for keV *Dark Matter in both X-ray and Lyman-α*





Thank you for the attention!

Backup

Lagrangian

$$
\begin{aligned}
\mathcal{L} \supset & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + (D_\mu\Phi)^*(D^\mu\Phi) - V(\Phi) \\
& + \mathrm{i}\,\overline{\nu_\mathrm{L}}\gamma_\mu D^\mu \nu_\mathrm{L} \\
& + \mathrm{i}\,\overline{\nu_\mathrm{R+}}\gamma_\mu D^\mu \nu_\mathrm{R+} + \mathrm{i}\,\overline{\nu_\mathrm{R-}}\gamma_\mu D^\mu \nu_\mathrm{R-} \\
& - \frac{1}{2}m_\mathrm{D}(\overline{\nu^c_\mathrm{R+}}\nu_\mathrm{R-} + \overline{\nu^c_\mathrm{R-}}\nu_\mathrm{R+}) \\
& + \mathrm{i}\,\overline{\nu_\mathrm{R0}}\gamma_\mu \partial^\mu \nu_\mathrm{R0} - \frac{1}{2}m_0\overline{\nu^c_\mathrm{R0}}\nu_\mathrm{R0} \\
& - y_\mathrm{D}\overline{\nu_\mathrm{L}}H\nu_\mathrm{R0} - y_1\overline{\nu^c_\mathrm{R+}}\Phi\nu_\mathrm{R0} - y_2\overline{\nu^c_\mathrm{R-}}\Phi^*\nu_\mathrm{R0} + h.c.,
\end{aligned}
$$

Mass eigenstates

$$
\begin{aligned}
N_0 &= \nu_0 + \sin\theta_0\,\nu_\alpha + \frac{m_M}{m_0}(\nu_+ + \nu_-)\\
N_1 &= \frac{1}{\sqrt{2}}\mathrm{i}\gamma^5(\nu_+ - \nu_-)\\
N_2 &= \frac{1}{\sqrt{2}}(\nu_+ + \nu_-) - \sqrt{2}\,\frac{m_M}{m_0}\nu_0 - \sin\theta_2\,\nu_\alpha\\
\nu &= \mathrm{i}\gamma^5\left(\nu_\alpha - \sin\theta_0\,\nu_0 + \frac{\sin\theta_2}{\sqrt{2}}(\nu_+ + \nu_-)\right)
\end{aligned}
$$

Solving the Boltzmann equation

Boltzmann equations for each species

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} + 3Hn_i = C_{n_i}$$
$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + 3H(\rho + P) = C_\rho$$

Assume N_1, N_2 and A' is in equilibrium

$$\mu_1 = \mu_2 = \frac{\mu_A}{2}$$

so we can simplify to one equation for the number density.

Initial conditions are fixed by DW production.

We assume kinetic equilibrium so the Dark Sector follows BE- and FD-distributions,

$$n(T_{\mathrm{DM}}, \mu_{\mathrm{DM}}), \qquad \rho(T_{\mathrm{DM}}, \mu_{\mathrm{DM}})$$

Having solved for number and energy density, we can invert to find

$$T_{\mathrm{DM}} = T_{\mathrm{DM}}(n, \rho),$$
$$\mu_{\mathrm{DM}} = \mu_{\mathrm{DM}}(n, \rho).$$

Halvor Melkild
E-mail: halvor.melkild@fys.uio.no
Charged Sterile Neutrinos as Dark Matter