Prospects of closing the window of sterile neutrino dark matter

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OAC, Chania, Crete, Greece
Standard Model: Major Problems

Gauge fields (interactions): $\gamma, W^\pm, Z, g$

Three generations of matter: $L = (\nu_L, e_L), e_R; Q = (u_L, d_L), d_R, u_R$

- Describes
  - all experiments dealing with electroweak and strong interactions

- Does not describe
  - Neutrino oscillations
  - Dark matter ($\Omega_{DM}$)
  - Baryon asymmetry ($\Omega_B$)
  - Inflationary stage

- Neutrino oscillations
- Dark matter ($\Omega_{DM}$)
- Baryon asymmetry ($\Omega_B$)
- Inflationary stage

Only direct evidence for New Physics

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Neutrino oscillations: masses and mixing angles

Solar $2 \times 2$ “subsector”

Atmospheric $2 \times 2$ “subsector”

$\Delta m^2$ [eV$^2$]

$10^{-3}$

$10^{-6}$

$10^{-9}$

$10^{-4}$

$10^{-2}$

$10^{0}$

$10^{2}$

$\tan^2 \theta$

$\sin^2 2 \theta_{13} \approx 0.08$

$0.6$ $0.7$ $0.8$ $0.9$ $1$

$0.6$ $0.7$ $0.8$ $0.9$ $1$

$1.0$

$1.5$

$2.0$

$2.5$

$3.0$

$3.5$

$4.0$

$| \Delta m^2 | (10^{-3} eV^2)$

$0.008$ eV

$0.05$ eV

http://hitoshi.berkeley.edu/neutrino/

DAYA-BAY, RENO, T2K:

$\sin^2 2 \theta_{13} \approx 0.08$

arXiv:0806.2237

$m_1 > 0.008$ eV

$m_2 > 0.05$ eV

Prospects of closing the window of sterile neutrino dark matter

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Physics behind the neutrino oscillations is still elusive

- nature of neutrino mass (Dirac vs Majorana)
- neutrino mass hierarchy
- $CP$-violation
- relevance for the matter-antimatter asymmetry
- neutrino anomalies
  - LSND $\rightarrow$ MiniBooNE
  - SAGE & GALLEX (gallium anomaly)
  - reactor antineutrinos $\rightarrow$ DANSS, NEUTRINO-4
  - do not fit to $3\nu$
Sterile neutrinos: NEW ingredients

One of the optional physics beyond the SM:

sterile: new fermions uncharged under the SM gauge group
neutrino: explain observed oscillations by mixing with SM (active) neutrinos

Attractive features:

- possible to achieve within renormalizable theory
- only $N = 2$ Majorana neutrinos needed
- baryon asymmetry via leptogenesis
- dark matter (with $N \geq 3$ at least)
- light(?) sterile neutrinos might be responsible for neutrino anomalies...?
Sterile neutrinos: the simplest model

Three Generations of Matter (Fermions) spin $\frac{1}{2}$

<table>
<thead>
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<th>Mass</th>
<th>Charge</th>
<th>Name</th>
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<tbody>
<tr>
<td>$2.4 \text{ MeV}$</td>
<td>$\frac{2}{3}$</td>
<td>$u$ (up)</td>
</tr>
<tr>
<td>$1.27 \text{ GeV}$</td>
<td>$\frac{2}{3}$</td>
<td>$c$ (charm)</td>
</tr>
<tr>
<td>$171.2 \text{ GeV}$</td>
<td>$\frac{2}{3}$</td>
<td>$t$ (top)</td>
</tr>
<tr>
<td>$4.8 \text{ MeV}$</td>
<td>$-\frac{1}{3}$</td>
<td>$d$ (down)</td>
</tr>
<tr>
<td>$104 \text{ MeV}$</td>
<td>$-\frac{1}{3}$</td>
<td>$s$ (strange)</td>
</tr>
<tr>
<td>$4.2 \text{ GeV}$</td>
<td>$-\frac{1}{3}$</td>
<td>$b$ (bottom)</td>
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<tr>
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<tbody>
<tr>
<td>$0.511 \text{ MeV}$</td>
<td>$-1$</td>
<td>$e$ (electron)</td>
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<tr>
<td>$105.7 \text{ MeV}$</td>
<td>$-1$</td>
<td>$\mu$ (muon)</td>
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<tr>
<td>$1.777 \text{ GeV}$</td>
<td>$-1$</td>
<td>$\tau$ (tau)</td>
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<tr>
<th>Mass</th>
<th>Charge</th>
<th>Name</th>
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<tbody>
<tr>
<td>$&lt;0.0001 \text{ eV}$</td>
<td>$0$</td>
<td>$\nu_e$ (electron neutrino)</td>
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<tr>
<td>$\sim 0.01 \text{ eV}$</td>
<td>$0$</td>
<td>$\nu_\mu$ (muon neutrino)</td>
</tr>
<tr>
<td>$\sim 0.04 \text{ eV}$</td>
<td>$0$</td>
<td>$\nu_\tau$ (tau neutrino)</td>
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<tbody>
<tr>
<td>$91.2 \text{ GeV}$</td>
<td>$0$</td>
<td>$Z^0$ (weak force)</td>
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<tr>
<td>$&gt;114 \text{ GeV}$</td>
<td>$0$</td>
<td>$H$ (Higgs boson)</td>
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</tbody>
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<th>Charge</th>
<th>Name</th>
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</thead>
<tbody>
<tr>
<td>$80.4 \text{ GeV}$</td>
<td>$\pm 1$</td>
<td>$W^\pm$ (weak force)</td>
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</tbody>
</table>

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Seesaw mechanism: $M_N \gg 1$ eV

With $m_{\text{active}} \lesssim 1$ eV we work in the seesaw (type I) regime:

$$\mathcal{L}_N = \bar{N} i \gamma \eta N - f \bar{L}_e \tilde{H} N - \frac{M_N}{2} \bar{N}^c N + \text{h.c.}$$

Higgs gains $\langle H \rangle = v/\sqrt{2}$ and then

$$\psi_N = \frac{1}{2} \begin{pmatrix} \bar{N}_c \\ \eta \end{pmatrix} \begin{pmatrix} 0 & v \frac{f}{\sqrt{2}} \\ v \frac{f}{\sqrt{2}} & M_N \end{pmatrix} \begin{pmatrix} \nu_e \\ N \end{pmatrix} + \text{h.c.}$$

For a hierarchy $M_N \gg M_D \equiv \nu \frac{f}{\sqrt{2}}$ we have

flavor state $\nu_e = U \nu_1 + \theta N$ with $U \approx 1$ and

active-sterile mixing: $\theta = \frac{M_D}{M_N} = \frac{v f}{2M_N} \ll 1$

and mass eigenvalues

$\approx M_N$ and $-m_{\text{active}} = \theta^2 M_N \ll M_N$
Violation of $L$, $C$ and $CP$ symmetries

\[ \mathcal{L}_N = \overline{N} i \partial \tau N - f \overline{L}_e H N - \frac{M_N}{2} \overline{N}^c N + \text{h.c.} \]

- $f = 0 \quad \rightarrow \quad$ free fermion, no need to call 'sterile'
- $M_N = 0 \quad \rightarrow \quad$ $N$ and $\nu$ form pure Dirac neutrino, the most boring case, worth than we have with the Higgs boson one may refuse to call it 'new physics'
- $f \neq 0, \quad M_N \neq 0 \quad \rightarrow \quad$ introduces new massive parameter, violates lepton symmetry $L$
  (and $C$- and $CP$-symmetry with several $N$'s)
Seesaw mechanism: $M_N \gg 1$ eV

With $m_{\text{active}} \lesssim 1$ eV we work in the seesaw (type I) regime:

$$\mathcal{L}_N = \overline{N}_I i \mathcal{D} N_I - f_{\alpha I} \overline{L}_\alpha \tilde{H} N_I - \frac{M_{N I}}{2} \overline{N}_I^c N_I + \text{h.c.}$$

When Higgs gains $\langle H \rangle = v/\sqrt{2}$ we get in neutrino sector

$$\mathcal{V}_N = \frac{1}{2} \left( \overline{v}_1, \ldots, \overline{N}_1 \right)^T \begin{pmatrix} 0 & v \hat{f} \sqrt{2} \\ v \hat{f}^T \sqrt{2} & \hat{M}_N \end{pmatrix} \left( v_1, \ldots, v_1 \right) + \text{h.c.}$$

Then for $M_N \gg \hat{M}^D = v \hat{f} \sqrt{2}$ we find the eigenvalues:

$$\simeq \hat{M}_N \quad \text{and} \quad \hat{M}^\nu = - (\hat{M}^D)^T \frac{1}{\hat{M}_N} \hat{M}^D \propto f^2 \frac{v^2}{M_N} \ll M_N$$

Mixings: flavor state $\nu_\alpha = U_{\alpha i} v_i + \theta_{\alpha I} N_I$

- active-active mixing: $U^\dagger \hat{M}^\nu U = \text{diag} (m_1, m_2, m_3)$
- active-sterile mixing: $\theta_{\alpha I} = \frac{(M^D)^T_{\alpha I}}{M_I} \propto \hat{f}^T \frac{v}{M_N} \ll 1$
Sterile neutrino: a vast region of mass

Within the seesaw paradigm, as far as

$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

Any set

(mass scale $M_N$, Yukawa coupling $f$)

is viable

And with special tuning or symmetry larger (but not smaller) mixing

is viable

$$\hat{m}_a \sim \hat{f}^T \frac{1}{\hat{M}_N} \hat{f} v^2$$
Dark Matter properties from cosmology: $p = 0$

(If) particles:

1. (almost) electrically neutral
2. (almost) collisionless
3. stable on cosmological time-scale
   
   requires new (almost) conserved quantum number
4. produced in the early Universe at $T > 10 \text{ eV}$
5. all matter inhomogeneities (perturbations) are adiabatic:

$$\delta \left( \frac{n_B}{n_{DM}} \right) = \delta \left( \frac{n_B}{n_{\gamma}} \right) = \delta \left( \frac{n_\nu}{n_{\gamma}} \right) = 0$$
Sterile neutrino: well-motivated keV-mass Dark Matter

- massive fermions giving mass to active neutrino through mixing (seesaw)

\[ m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N \]

- unstable, \( N \rightarrow \nu \nu \nu \) is always open but exceeding the age of the Universe if (applicable for \( M_N < M_W \))

\[ \tau_{N \rightarrow 3\nu} \sim \frac{1}{G_F^2 M_N^5 \theta^2_{\alpha N}} \implies \theta^2 < 1.5 \times 10^{-7} \left( \frac{50 \text{ keV}}{M_N} \right)^5 \]

- with seesaw constraint \( m_a \sim \theta^2 M_N \)

\[ \tau_{N \rightarrow 3\nu} \sim \frac{1}{G_F^2 M_N^4 m_\nu} \sim 10^{11} \text{ yr} \left( \frac{10 \text{ keV}}{M_N} \right)^4 \]
Sterile neutrino: indirect searches

\[ m_a \sim \frac{f^2 \nu^2}{M_N^2} M_N \sim \theta^2 M_N \]

- unstable, but exceeding the age of the Universe if

\[ \frac{\theta^2}{3 \times 10^{-3}} < \left( \frac{10 \text{ keV}}{M_N} \right)^5 \]

- DM sterile neutrinos can be searched at X-ray telescopes because of two-body radiative decay give limits in absence of the feature a narrow line \( \frac{\delta E_\gamma}{E_\gamma} \sim \nu \sim 10^{-3} \)

at photon frequency \( E_\gamma = \frac{M_N}{2} \)

\[ \frac{\theta^2}{10^{-11}} \lesssim \left( \frac{10 \text{ keV}}{M_N} \right)^4 \]

\[ \text{FLUX}_{\gamma} \propto \Gamma_N \rho_N / M_N \ldots \]
Can seesaw neutrino serve as DM?

X-ray limits (roughly)

\[
\frac{\theta^2}{10^{-11}} \lesssim \left( \frac{10 \text{ keV}}{M_N} \right)^4
\]

see-saw relation

\[
\frac{\theta^2}{10^{-5}} \sim \left( \frac{m_a}{0.1 \text{ eV}} \right) \left( \frac{10 \text{ keV}}{M_N} \right)
\]

one order down

\[
\frac{\theta^2}{10^{-7}} \lesssim \left( \frac{1 \text{ keV}}{M_N} \right)^4
\]

\[
\frac{\theta^2}{10^{-4}} \sim \left( \frac{m_a}{0.1 \text{ eV}} \right) \left( \frac{1 \text{ keV}}{M_N} \right)
\]

How light can be this dark matter?
Galactic Dark Matter

X-ray limits (roughly)

$$\frac{\theta^2}{10^{-7}} \lesssim \left( \frac{1 \text{ keV}}{M_N} \right)^4$$

see-saw relation

$$\frac{\theta^2}{10^{-4}} \sim \left( \frac{m_a}{0.1 \text{ eV}} \right) \left( \frac{1 \text{ keV}}{M_N} \right)$$

Pauli blocking for fermions in a dwarf galaxy:

$$M_X \gtrsim 750 \text{ eV}$$

$$f(p, x) = \frac{\rho_x(x)}{M_X} \cdot \frac{1}{\left( \sqrt{2\pi M_X v_X} \right)^3} \cdot e^{-\frac{p^2}{2M_X^2v_X^2}} \bigg|_{p=0} \leq \frac{g_X}{(2\pi)^3}$$

DM sterile neutrino cannot contribute much to neutrino masses
Refined constraint for DM: phase space density

after decoupling $f_i = f_i(\kappa) = \text{const}$ and defines psd, which remains intact due to the Liouville theorem even in galaxies with inhomogeneous distribution in space.

course grained phase space density:

$$f(\kappa, \mathbf{x}, t) \leq \max_\kappa f_i(\kappa)$$

observation:

$$Q = \frac{\rho}{\langle v_\parallel^2 \rangle^{3/2}} = Q \cdot 1 \frac{M_\odot/\text{pc}^3}{(\text{km/s})^3} = \left(5 \cdot 10^{-3} - 2 \cdot 10^{-2}\right) \frac{M_\odot/\text{pc}^3}{(\text{km/s})^3}.$$

$$Q \simeq 3^{3/2} \frac{\rho_{DM}}{\langle v_{DM}^2 \rangle^{3/2}} = 3^{3/2} m^4 \frac{n}{\langle P^2 \rangle^{3/2}} = 3^{3/2} m^4 f(P, \mathbf{x}).$$

$$m^4 \gtrsim \frac{Q}{3^{3/2} \max f_i}$$

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Matter perturbations are adiabatic: \( \delta(n_B/n_{DM}) = 0 \)

- CMB is isotropic, but “up to corrections, of course…”
  - Earth movement with respect to CMB
    \[ \Delta T_{\text{dipole}} \sim 10^{-3} \]
  - More complex anisotropy:
    \[ \Delta T \sim 10^{-4} \]

- There were matter inhomogeneities \( \Delta \rho/\rho \sim \Delta T/T \) at the stage of recombination \( (e + \rho \rightarrow \gamma + H^+) \)
  - Jeans instability in the system of gravitating particles at rest \( \Rightarrow \Delta \rho/\rho \uparrow \) galaxies (CDM halos)
  - \( \Delta \rho_{DM}/\rho_{DM} \sim a \sim 1/T \) from \( T = 0.8 \text{ eV} \),
    while \( \Delta \rho_B/\rho_B \sim a \sim 1/T \) only after recombination \( T = 0.25 \text{ eV} \)
    - without DM total growth factor would be 1100
      not enough to explain structures!

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Sterile neutrinos produced in plasma...

typical momenta are

\[ \frac{p_X}{M_X} \propto \frac{a_d}{a} \sim \frac{3T}{M_X} \left( \frac{g^*_\ast(T)}{g^*_\ast(T_d)} \right)^{1/3} \]

at RD/MD transition (equality) their velocities are

\[ v \sim \frac{T}{1\,\text{eV}} \frac{1\,\text{keV}}{M_X} \sim 10^{-3} \]

Warm Dark Matter:
all inhomogeneities of sizes smaller than (roughly)

\[ l = v \times t_{\text{Universe}} \]

are smoothed out due to free streaming

it allows to test the model
Tesing with satellite counting. . .

Heavy (CDM-like)  Light (WDM-like)

\[
\left( \frac{dN_{obj}}{d\ln M} \right)_{WDM} / \left( \frac{dN_{obj}}{d\ln M} \right)_{CDM}
\]

\[
\log_{10} \frac{M}{M_{\odot}}
\]
Production in oscillations

\[ \frac{\partial}{\partial t} f_s(t, p) - H_p \frac{\partial}{\partial p} f_s(t, p) = \frac{1}{2} \Gamma_\alpha P(\nu_\alpha \to \nu_s) f_\alpha(t, p). \]

\( \Gamma_\alpha \propto G_F^2 T^4 E \) is the weak interaction rate in plasma

\[ P(\nu_\alpha \to \nu_s) = \sin^2 2\theta^\text{mat}_\alpha \cdot \sin^2 \left( \frac{t}{2t^\text{mat}_\alpha} \right), \]

\[ t^\text{mat}_\alpha = \frac{t^\text{vac}_\alpha}{\sqrt{\sin^2 2\theta_\alpha + (\cos 2\theta_\alpha - V_{\alpha\alpha} \cdot t^\text{vac}_\alpha)^2}}, \]

\[ \sin 2\theta^\text{mat}_\alpha = \frac{t^\text{mat}_\alpha}{t^\text{vac}_\alpha} \cdot \sin 2\theta_\alpha, \quad t^\text{vac}_\alpha = \frac{2E}{M_N^2} \]

sign of the effective plasma potential matters:

- \( V_{\alpha\alpha} < 0 \) \( \implies \) mixing gets suppressed \( \implies \) \( V_{\alpha\alpha} \sim #G_F^2 T^4 E \)
- \( V_{\alpha\alpha} > 0 \) \( \implies \) amplification via resonance \( \implies \) \( V_{\alpha\alpha} \sim #G_F T^2 \mu_{L\alpha} \)
Most recent result of NuSTAR

1908.09037, see also XMM-Newton 2102.02207

$m_x$ [keV]

$\sin^2 2\theta$

MW Sat. Counts

Suzaku

Fermi-GBM + INTEGRAL

BBN Limit (Resonant Production)

Chandra + XMM

Counts

NuSTAR

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+ INTEGRAL

MW Sat.
eROSITA (0.2-10 keV), ART-XC (4-30 keV)
Prospects of closing the window of sterile neutrino dark matter

Chandra and XMM
Suzaku
Fermi-GBM and Integral

MW SC

BBN Limit

eROSITA
eROSITA + ART-XC
ART-XC

$\sin^2(2\theta)$ vs. $m_s$ [keV]

$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
$10^{-14}$
Prospects of closing the window of sterile neutrino dark matter
More robust, but less sensitive

1505.07829, V. Barinov, R. Burenin, D.G., R. Krivonos

4 yr eROSITA, CC perfect DM map

- $\ell = 10^1 - 10^4$
- $\ell = 10^2 - 10^4$ (baseline)
- $\ell = 10^3 - 10^4$
- $\nu_s < 10^{13} M_\odot$

Interaction strength, $\sin^2 2\theta$ vs. Dark matter mass, $m_s$ [keV]

- Too much DM
- Excluded by X-ray
- Too little DM

My 95 C.L. ART-XC

My 95 C.L. Constraints (eRosita)
Closing sterile neutrino DM? ... in a minimal variant

situation changes with just 1 new d.o.f. $\phi \bar{N}^{c} N$

- reopen large mixings with $\Omega_{N} < \Omega_{DM}$ (part of DM)
  to avoid $X$-ray bounds:
  $$\theta_{X-ray}^2 = \theta_{\alpha I}^2 \frac{\Omega_{N}}{\Omega_{DM}}$$
  
- direct searches: Troitsk, KATRIN can be seesaw neutrino

- small mixing: dominant DM
  testing with future telescopes

- reopen small masses with $\nu_{N} \ll \nu_{WDM}$,
  e.g. cold sterile neutrino

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Conclusions

- sterile neutrino DM implies one massless active neutrino (with $N = 3$ sterile neutrino seesaw)
- we can fully explore the model with new X-ray data (e.g. on board of SRG)
- more dwarf galaxies observed around us
- progress in checking BBN predictions
- much larger room with new ingredients in the sterile sector
Searches for DM are deep inside the forbidden region.
Larger mixing: Suppression of production

Form only a fraction of DM !!

\[ P(\nu_\alpha \rightarrow \nu_s) = \sin^2 2\theta^\text{mat}_\alpha \cdot \sin^2 \left( \frac{t}{2t^\text{mat}_\alpha} \right), \quad \sin 2\theta^\text{mat}_\alpha = \frac{t^\text{mat}_\alpha}{t^\text{vac}_\alpha} \cdot \sin 2\theta_\alpha, \]

\[ t^\text{mat}_\alpha = \frac{t^\text{vac}_\alpha}{\sqrt{\sin^2 2\theta_\alpha + (\cos 2\theta_\alpha - V_{\alpha\alpha} \cdot t^\text{vac}_\alpha)^2}}, \quad t^\text{vac}_\alpha = \frac{2E}{M_N^2} \]

Most efficient production occurs at (DW)

\[ T_{\text{max}} \approx 133 \text{ MeV} \left( \frac{1 \text{ keV}}{M_N} \right)^{1/3} \]

It is suppressed if \( T_{\text{reh}} \ll T_{\text{max}} \)

Suppression of cosmological production

Add more ingredients e.g.

$$\bar{L}HN + M_N \tilde{N}^c N \rightarrow \bar{L}HN + \phi \tilde{N}^c N$$

Scalar? Majoron? (lepton symmetry)

$$P(\nu_\alpha \rightarrow \nu_s) = \sin^2 2\theta^\text{mat}_\alpha \cdot \sin^2 \left( \frac{t}{2t^\text{mat}_\alpha} \right), \quad \sin 2\theta^\text{mat}_\alpha = \frac{t^\text{mat}_\alpha}{t^\text{vac}_\alpha} \cdot \sin 2\theta_\alpha,$$

$$t^\text{mat}_\alpha = \frac{t^\text{vac}_\alpha}{\sqrt{\sin^2 2\theta_\alpha + (\cos 2\theta_\alpha - V_{\alpha\alpha} \cdot t^\text{vac}_\alpha)^2}}, \quad t^\text{vac}_\alpha = \frac{2E}{M^2_N}.$$

Coupling to scalar can change the effective neutrino Hamiltonian in the primordial plasma

$$\begin{pmatrix} V_{\alpha\alpha} & M_D \\ M_D & V_{NN} + M_N \end{pmatrix}$$
Suppression of production with $\phi \tilde{N}^c N$

- strong coupling to scalar or Majoron, which decreases the active-sterile mixing in primordial plasma
  
  $\phi \tilde{N}N \rightarrow G \tilde{N}N \tilde{N} \rightarrow V_{NN}$

- homogeneous $\phi = \phi(t)$ makes sterile neutrino mass changing in cosmology, which suppresses the early-time oscillations

  $\phi(t)NN \rightarrow M_N = M_N(t) = M_N(T)$

- sterile neutrinos are massless in the early Universe
- sterile neutrinos are superheavy in the early Universe
Massless in the early Universe

\[ \mathcal{L} = \frac{1}{2} g^{\mu \nu} \partial_\mu \phi \partial_\mu \phi - V(\phi) + \frac{f}{2} \phi \bar{N}^c N + \text{h.c.} \]

with a hidden sector... to make the phase transition:

\[
\begin{align*}
T > T_c & \implies \langle \phi \rangle = 0, \quad M_N = 0 \\
T < T_c & \implies \langle \phi \rangle = v_\phi, \quad M_N = f v_\phi
\end{align*}
\]

So the neutrino is pure Dirac fermion at the beginning...

The production in oscillations will be suppressed, if

\[ T_c < T_{\text{max}} \approx 133 \text{ MeV} \left( \frac{1 \text{ keV}}{M_N} \right)^{1/3} \]

there is always a chirality flip contribution \( \propto M_D^2 / E^2 \)

similar for \( \langle \phi \rangle \neq 0 \) disappearing later...
Results: large mixing is allowed for details see 1705.02184

Important:

1. seesaw light sterile neutrino (dashed lines: $m_a \sim 0.008 - 0.2$ eV)
2. can be directly tested !! (between green and white lines)
3. Warm, so most probably only a part of DM

$m_a \sim \theta^2 M_N$
Sterile neutrinos: a part of dark matter

$P(k) [(\text{Mpc}/h)^3]$

$\Lambda$CDM

$f_{\text{ncdm}} = 0.05 \ m_{\text{ncdm}} = 1.5 \text{ eV}$

$f_{\text{ncdm}} = 0.25 \ m_{\text{ncdm}} = 10^3 \text{ eV}$

SDSSDR11

$\log_{10} m_{\text{ncdm}} / \text{eV}$

$N_{\text{sat}} \simeq 160$

$N_{\text{sat}} \simeq 60$

$\frac{dN_{\text{sat}}}{d\ln M}$

$M [\text{M}_\odot / h]$
The oscillating scalar field

\[ \mathcal{L} = \frac{1}{2} g^{\mu \nu} \partial_\mu \phi \partial_\mu \phi - \frac{1}{2} m_\phi^2 \phi^2 + \frac{f}{2} \phi \bar{N}^c N + \text{h.c.} \]

homogeneous scalar field in FLRW expanding Universe

\[ \ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0 \]

two-stage evolution:

\[ m_\phi < H(t) \implies \phi = \phi_i = \text{const} \]
\[ m_\phi > H(t) \implies p = \langle E_k \rangle - \langle E_p \rangle = 0, \quad \rho \sim m_\phi^2 \phi^2 \propto 1/a^3 \]

- At \( m_\phi < H(t) \) sterile neutrino mass is \( M = M_N + f\phi_i \gg M_N \)
- At present sterile neutrino mass is \( M_N \sim 1 \text{ keV} \)
- If at \( m_\phi > H(t) \) sterile neutrinos are nonrelativistic most time, \( m_\phi = H_{\text{osc}} = \frac{T_{\text{osc}}^2}{M_{\text{Pl}}} \)

\[ M(t) = M_N + f\phi_i \frac{T^3}{T_{\text{osc}}^3} > T \]
Subtleties with Effective neutrino mass

\[ M_{N_{i/3}} = 3T \]

\[ M_N = 3T \]

\[ 3T_c \]

\[ M \]

\[ M_{N_i} \]

\( T_f \)

\( T_c \)

\( T_{osc} \)

\( M_{N_{i/3}} \)

\[ - \rho_\phi > \rho_N, \text{ so the scalar is DM} \]

or, in case of rapid production, must account for the backreaction

\[ \text{Yukawas induce } \lambda \phi^4 \sim f^4/(16\pi^2)\phi^4 \text{ which may dominate instead} \]

\[ \text{Both } L_{osc} \text{ and } \theta_{eff} \text{ change with } M(t), \text{ which oscillates} !! \]

very complicated system: three oscillators with time-dependent couplings
sterile neutrino mass

\[ M(t) = M_N + f\phi(t) = M_N + f\phi_i \frac{T^3}{T_{osc}} \cos(m\phi t) \]

1) sometimes crosses zero, which allows for sterile neutrino production by a 'slow' oscillator \( m\phi \ll M_N \) with large amplitude
the produced sterile neutrinos are almost at rest Cold Dark Matter
avoiding limits from structure formation
avoiding X-ray limits with tiny mixing angle

2) Both \( L_{osc} \) and \( \theta_{eff} \) change with \( M(t) \), which oscillates !!
very complicated system: three oscillators with time-dependent couplings resonance
cool
Allowed regions for each mechanism

\[
\sin^2(2\theta_0) = 10^{-5} \quad M_0 = 1 \text{ keV}
\]

- \( m_\phi < 2M_N \)
- \( \Gamma_{\phi \to \nu\nu} < \ldots \)
- \( \rho_{\phi} + \rho_N \leq \rho_{DM} \)

\( \Omega_N \gtrsim \Omega_\phi \)
\( \Omega_N < \Omega_\phi \)
Another option: coupling to light inflaton

Non-resonant production (active-sterile mixing) is ruled out

Resonant production (lepton asymmetry) requires $\Delta M_{2,3} \lesssim 10^{-16} \text{ GeV}$

[arXiv:0804.4542, 0901.0011, 1006.4008]

Dark Matter production from inflaton decays in plasma at $T \sim m_\chi$

$M_{N_I} \overline{N}_i^{c} N_i \leftrightarrow f_i X \overline{N}_i N_i$

Can be “naturally” Warm ($250 \text{ MeV} < m_\chi < 1.8 \text{ GeV}$)

$M_1 \lesssim 15 \times \left( \frac{m_\chi}{300 \text{ MeV}} \right) \text{ keV}$

M. Shaposhnikov, I. Tkachev (2006)

Limits form SN

Energy transfer

Energy loss

$\eta = 0$

$\Omega_s h^2 = 0.1$

Sterile Neutrino Mass (keV)

sin$^2 (2\theta)$

$10^{-12}$ $10^{-10}$ $10^{-8}$ $10^{-6}$ $10^{-4}$ $10^{-2}$ $1$ 0.1

Energy transfer

Energy loss

$\eta = 0$

$\Omega_s h^2 = 0.1$

Sterile Neutrino Mass (keV)

sin$^2 (2\theta)$

$10^{-12}$ $10^{-10}$ $10^{-8}$ $10^{-6}$ $10^{-4}$ $10^{-2}$ $1$ 0.1

$100\%$

$1\%$

$10\%$

$\sin^2 2\theta$

Sterile Neutrino Mass (keV)

$10^{-12}$ $10^{-10}$ $10^{-8}$ $10^{-6}$ $10^{-4}$ $10^{-2}$ $1$ 0.1

$100\%$

$1\%$

$10\%$

$\sin^2 2\theta$

Sterile Neutrino Mass (keV)