Sterile neutrino dark matter

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Particle, Nuclear, Astroparticle Physics and Cosmology

UCM, Madrid, Spain
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 (PHENO)
  - Neutrino oscillations
  - Dark matter ($\Omega_{DM}$)
  - Baryon asymmetry ($\Omega_B$)
  - Inflationary stage

- Does not describe (THEORY)
  - Dark energy ($\Omega_\Lambda$)
  - Strong CP-problem
  - Gauge hierarchy
  - Quantum gravity

Only direct evidence for New Physics ???

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Neutrino oscillations: masses and mixing angles

**Solar 2 × 2 “subsector”**

- **CI 95%**
- **KamLAND 95%**
- **SNO 95%**
- **Super-K 95%**
- **Ga 95%**

**Atmospheric 2 × 2 “subsector”**

- **MINOS 90%**
- **MINOS 68%**
- **MINOS best oscillation fit**
- **Super-K 90%**
- **Super-K L/E 90%**
- **K2K 90%**

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

\[ m_1 > 0.008 \text{ eV} \]

**DAYA-BAY, RENO, T2K:** \[ \sin^2 2\theta_{13} \approx 0.08 \]

\[ m_2 > 0.05 \text{ eV} \]
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 → MiniBooNE
  - SAGE & GALLEX (gallium anomaly)
  - reactor antineutrinos → DANSS, NEUTRINO-4

neutrino anomalies do not fit to 3ν
Phenomenological problems of the Standard Model

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

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  - Neutrino oscillations: active neutrino masses via mixing
  - Dark matter ($\Omega_{DM}$): sterile neutrino as DM
  - Baryon asymmetry: leptogenesis via sterile neutrino decays or oscillations

- Sterile neutrinos explain the oscillations
- and (add to) the cosmological problems
Phenomenological problems of the Standard Model

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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...?

Disappointing feature:

Major part of parameter space is UNTESTABLE
### Sterile neutrinos: the simplest model

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

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#### Leptons

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<tr>
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<td>tau</td>
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#### Bosons (Forces) spin 1

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<td>( \sim 10 \text{ keV} )</td>
<td>( \sim 1 \text{ GeV} )</td>
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<tr>
<td>name</td>
<td>sterile neutrino</td>
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#### Bosons (Forces) spin 0

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<td>( &gt;114 \text{ GeV} )</td>
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<tr>
<td>name</td>
<td>Z</td>
<td>H</td>
<td>W</td>
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#### Higgs boson

| mass  | \( \sim 10 \text{ keV} \) | \( \sim \text{ GeV} \) | \( \sim \text{ GeV} \) |
| name  | sterile neutrino | sterile neutrino | sterile neutrino |

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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:

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

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

$$\psi_N = \frac{1}{2} \begin{pmatrix} \bar{v}_e, \bar{N}^c \end{pmatrix} \begin{pmatrix} 0 & v \frac{f}{\sqrt{2}} \\ v \frac{f}{\sqrt{2}} & M_N \end{pmatrix} \begin{pmatrix} v_e \\ N \end{pmatrix} + \text{h.c.}$$

For a hierarchy $M_N \gg M_D \equiv v \frac{f}{\sqrt{2}}$ 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

$$\approx M_N \quad \text{and} \quad -m_{\text{active}} = \theta^2 M_N \ll M_N$$
Seesaw mechanism: $M_N \gg 1 \text{ eV}$

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

$$\mathcal{L}_N = \bar{N}_i i \tilde{\partial} N_i - f_{\alpha i} \bar{L}_\alpha \tilde{H} N_i - \frac{M_{N_i}}{2} \bar{N}_i^c N_i + \text{h.c.} \quad (1)$$

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

$$\nu_N = \frac{1}{2} \left( \bar{v}_1, \ldots, \bar{N}_1^c, \ldots \right) \left( \begin{array}{c} 0 \\ -v \sqrt{2} \hat{f}^T \\ \hat{M}_N \end{array} \right) \left( \nu_1, \ldots, N_1, \ldots \right)^T + \text{h.c.} \quad (2)$$

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

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

Mixings: flavor state $\nu_\alpha = U_{\alpha i} \nu_i + \theta_{\alpha i} N_i$

- active-active mixing: $U^\dagger \hat{M}^\nu U = \text{diag} \left( m_1, m_2, m_3 \right)$
- 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 tunning 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. stable on cosmological time-scale
   requires new (almost) conserved quantum number
2. produced in the early Universe at \( T > 100 \text{ eV} \)
3. nonrelativistic particles long before RD/MD-transition (\( T = 0.8 \text{ eV} \))
   (either Cold or Warm, \( \nu_{RD/MD} \lesssim 10^{-3} \))
   Otherwise no small-size structures, like dwarf galaxies:
   smoothed out by free streaming

If were in thermal equilibrium:
4. (almost) collisionless
5. (almost) electrically neutral
6. 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

\(\text{applicable for } M_N < M_W \)

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

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

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

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

- 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 \((\delta E_\gamma/E_\gamma \sim \nu \sim 10^{-3})\)
  - at photon frequency \(E_\gamma = M_N/2\)

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

\[ F_\gamma \propto \Gamma_N \rho_N / M_N \ldots \]
Can seesaw neutrino serve as DM?

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

one order down

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

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

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

How light can be this dark matter?
Dark Matter Particle Properties

1. **stable** on cosmological time-scale
2. **nonrelativistic** long before RD/MD-transition (either Cold or Warm, \( \nu_{RD/MD} \lesssim 10^{-3} \), \( M_X \gtrsim 1 \text{keV} \) for thermal production)
3. (almost) collisionless
4. (almost) electrically neutral

Pauli blocking for fermions in a galaxy: \( M_X \gtrsim 750 \text{ eV} \)

\[
f(p, x) = \frac{\rho_x(x)}{M_x} \cdot \frac{1}{\left(\sqrt{2\pi} M_x v_x\right)^3} \cdot e^{-\frac{p^2}{2M_x^2 v_x^2}} \bigg|_{p=0} \leq \frac{g_x}{(2\pi)^3}
\]
Decoupling of relativistic Dark Matter

Assumptions

1. DM particles are in equilibrium in plasma
2. DM decouple from plasma at temperature \( T_d \gtrsim M_X \), so they are relativistic (e.g. neutrino)

\[
n_X(T_d) = g_X \cdot \left( \frac{\zeta(3)}{\pi^2} \right) \cdot T_d^3
\]

Later on useful

\[
n_X a^3 = \text{const}, \quad sa^3 = \text{const} \quad \Rightarrow \quad \frac{n_X}{s} = \text{const} = \# \frac{g_X}{g^*(T_d)}
\]

DM particle mass \( M_X \) fixes \( \Omega_X \):

\[
\Omega_X = \frac{M_X \cdot n_{X,0}}{\rho_c} = \frac{M_X \cdot s_0}{\rho_c} \frac{n}{s} \approx 0.2 \times \frac{M_X}{100 \text{ eV}} \left( \frac{g_X}{2} \right) \cdot \left( \frac{100}{g^*(T_d)} \right)
\]

– NO thermal sterile neutrino DM !!

Pauli blocking prevents fermionic DM
Stable neutrino Dark Matter

Matter perturbations

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

- There were matter inhomogeneities $$\Delta \rho / \rho \sim \Delta T / T$$ at the stage of recombination ($e + p \rightarrow \gamma + H^*$) → Jeans instability in the system of gravitating particles at rest $$\Rightarrow$$ $$\Delta \rho / \rho \uparrow$$ galaxies (CDM halos)

- $$\Delta \rho_{\text{DM}} / \rho_{\text{DM}} \propto a \propto 1 / T$$ from $$T = 0.8 \text{ eV}$$, while $$\Delta \rho_{\text{B}} / \rho_{\text{B}} \propto a \propto 1 / T$$ only after recombination $$T = 0.25 \text{ eV}$$
  without DM total growth factor would be 1100 not enough to explain structures!
Sterile neutrinos produced in plasma...

\[ \Omega_N < \Omega_X = \frac{M_X \cdot n_{X,0}}{\rho_c} = \frac{M_X \cdot s_0}{\rho_c} \frac{n}{s} \approx 0.2 \times \frac{M_X}{100 \text{ eV}} \left( \frac{g_X}{2} \right) \cdot \left( \frac{100}{g_*(T_d)} \right) \]

typical momenta are

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

at RD/MD transition (equality) their velocities are

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

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, but also...
CDM Problems at small-scales . . . ?

- NFW profile fits nicely DM in galaxy clusters: $\rho \propto r^{-1}(r + r_c)^{-2}$
- Dwarf galaxy density profiles: $\rho_M(r) \propto r^{-(0.5-1.5)}$ cusp

Most DM-dominated objects

Cores observed (?)

5 Clusters in the Fornax dSph

![Graph showing density profiles of different dwarf galaxies and clusters over time.](image-url)
CDM Problems with small structures . . . ?

- Missing satellites: \( \frac{dN_{\text{obj}}}{d \ln M} \propto \frac{1}{M} \) no-scale 100 instead of 1000
- “Too big to fail” problem
- Solved (?) by Warm Dark Matter (sterile neutrino, gravitino) free-streaming

\[
\left( \frac{dN_{\text{obj}}}{d \ln M} \right)_{\text{WDM}} / \left( \frac{dN_{\text{obj}}}{d \ln M} \right)_{\text{CDM}}
\]
Refined constraint for DM: phase space density

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

course grained phase space density:

\[
f(\kappa, x, t) \leq \max_\kappa f_i(\kappa)
\]

observation:

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

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

\[
m^4 \gtrsim \frac{Q}{3^{3/2} \max f_i}
\]
Sterile neutrino production in the early Universe

1. before the EW transition, $T > T_{EW}$

$$H \rightarrow L + N, \quad \frac{\Gamma_{H \rightarrow \nu_a N}}{H} \simeq \frac{f_{\nu}^2}{16\pi} \frac{T}{H} \ll 1,$$

2. after the EW transition, $T < T_{EW}$

- r.h. neutrino production in scatterings
  $$\nu_L + X \rightarrow N_R + Y, \quad \Gamma \propto \frac{M_D^2}{T^2}$$

- sterile neutrino production in oscillations
Neutrino matter effect: asymmetry

Mikheev–Smirnov–Wolfenstein effect

\[ P(e^\nu \rightarrow e^\nu) \]

\begin{align*}
\mathcal{L} &= -2\sqrt{2}G_F \bar{v}_e\gamma^\mu e \cdot \bar{e}\gamma^\mu v_e \\
\langle \langle \bar{e}_k \gamma^0_{kl} e_l \rangle \rangle &= \langle \langle e^\dagger e \rangle \rangle = n_e, \\
\langle \langle \bar{e}_k \gamma^i_{kl} e_l \rangle \rangle &= 0. \\
\langle \langle e_k \bar{e}_l \rangle \rangle &= -\frac{1}{4} \gamma^0_{kl} \cdot n_e \\
\end{align*}

Fermi charged currents

only matter, no currents

Fermi interaction gives

\[ \mathcal{L}_{eff} = -\sqrt{2}G_F n_e \bar{v}_e \gamma^0 v_e. \]

effective potential

\[ i\gamma^0 \partial_0 \rightarrow i\gamma^0 \partial_0 - \sqrt{2}G_F n_e \gamma^0, \]

\[ i\partial_0 - V, \text{ with } V = \sqrt{2}G_F n_e \]

competes with

\[ H_{eff} = \Delta m^2 / 2E \]

(BOREXINO)
Production in oscillations

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

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

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

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

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

The sign of the effective plasma potential matters:

\( V_{\alpha\alpha} < 0 \implies \text{mixing gets suppressed} \)

\( V_{\alpha\alpha} > 0 \implies \text{amplification via resonance} \)
DM from oscillations: (DW & ShF)

$$(\cos 2\theta_{\alpha} - V_{\alpha\alpha} \cdot t_{\alpha}^{\text{vac}})^2$$

non-resonant:

$$V_{\alpha\alpha} \sim -\# G_F^2 T^4 E$$

resonant production in the lepton asymmetric plasma

$$V_{\alpha\alpha} \sim +\# G_F T^2 \mu_{L\alpha}$$

BAU-DM relation?

$$\ldots \Omega_B \sim \Omega_{DM}$$

1601.07553
Sterile neutrino spectra from oscillations

Sterile neutrino Dark Matter

non-resonant production:

thermal-shape spectrum

both models imply Warm DM, \( \nu_{EQ} \sim 10^{-3} \),

Free Streaming at scales \( L \lesssim \nu_{EQ}/H_{EQ} \to \)

no such structures

\[
\nu = \frac{\langle p \rangle}{m} = 3.15 \left( \frac{T}{m} \right) \left( \frac{g_\ast.0}{g_\ast} \right)^{1/3}
\]

1601.07553

1611.00005

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Sterile neutrino dark matter

10.10.2019, Vth-R-I-Congress 25/45
Refined constraint for DM: phase space density

for non-resonance production

\[ m \gtrsim 6 \, \text{keV} \cdot \left( \frac{0.2}{\Omega_{DM}} \right)^{1/3} \left( \frac{\Omega}{5 \cdot 10^{-3}} \right)^{1/3} \left( \frac{g_*(T_d)}{43/4} \right)^{1/3}, \]

and about 3-6 keV for resonant one


F. Bezrukov, D.G. (work in progress)
Sterile neutrino Dark Matter

... present searches

- (not a seesaw $\theta^2 \sim 10^{-5}(10\text{ keV}/M_N)$)
- upper limits on mixing: from X-ray searches
- lower limits on mass: from structure formation

$\lambda_{FS} \sim 1\text{ Mpc} \times \frac{\text{keV}}{M_N} \frac{\langle \rho_N \rangle}{\langle \rho_\nu \rangle}$

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Most recent result of NuSTAR

![Graph showing the most recent result of NuSTAR compared to other experiments like Suzaku, Fermi-GBM, and INTEGRAL. The graph plots sin^2(2θ) on the y-axis against m_χ [keV] on the x-axis. The BBN Limit (Resonant Production) is shown as a horizontal line.]
5 years ago: Dark Matter decay observed in X-ray?

Stacking signals from many galaxies, especially Perseus cluster, then Andromeda

1402.2301, 1402.4119
Closing sterile neutrino DM? … in a minimal variant

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

- 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
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.

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

Scalar? Majoron?
(lepton symmetry)

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

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

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

\[ \phi NN \rightarrow G\tilde{N}N\tilde{N} \rightarrow V_{NN} \]

e.g. L.Bento, Z.Berezhiani (2001)

- 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:

$$T > T_c \implies \langle \phi \rangle = 0, \quad M_N = 0$$

$$T < T_c \implies \langle \phi \rangle = v_\phi, \quad M_N = f v_\phi$$

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: \( m_a \sim 0.008 - 0.2 \text{ eV} \))
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

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

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

$N_{\text{sat}} \approx 60$
The oscillating scalar field

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

homogeneous scalar field in FLRW expanding Universe

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

two-stage evolution:

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

- 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, \( m_\phi = H_{\text{osc}} = \frac{T^2_{\text{osc}}}{M_{Pl}} \)

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

- \( \rho_\phi > \rho_N \), so the scalar is DM

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

- Yukawas induce \( \lambda \phi^4 \sim f^4/(16\pi^2)\phi^4 \) which may dominate instead

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

very complicated system: three oscillators with time-dependent couplings
Cool and Cold sterile neutrinos

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 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 !! resonance very complicated system: three oscillators with time-dependent couplings cool

![Graphs showing oscillations and mixing angles](image-url)
Allowed regions for each mechanism

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

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

Other options: e.g. coupling to light inflaton

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

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

arXiv:0804.4542, 0901.0011, 1006.4008

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

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

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)

In a realistic model...

The possible issues to be studied

- Other degrees of freedom: Majoron from a complex field
  contribution to production?
- Other interactions: e.g. $\phi^4$ induced by Yukawas
  change of production?
- Scalar field dominating in the early Universe?
  Decaying or diminishing in the late Universe?
- Back reaction: $\bar{NN}$ shifts $\langle \phi \rangle$ in plasma
Summary on sterile neutrinos

- Most economic explanation of neutrino oscillations within renormalizable approach: 2-3 Majorana neutrinos enough
- One more neutrino can serve as (naturally Warm) dark matter
  - this specia does not explain oscillations!
- there are allowed mechanisms of DM sterile neutrino productions
- DM searches with X-ray telescopes: ART-X, eROSITA of Spektr-RG
Backup slides
Limits form SN

\[
\sin^2(2\theta) = \frac{\text{Energy loss}}{\text{Energy transfer}}
\]

\[
\Omega_s h^2 = 0.1
\]

\[
\eta = 0
\]
A sketch of model parameter space

\[ M, \text{ keV} \]

\[ \sin^2 2\theta \]

\[ 0, 1: \text{allowed even w/o scalar field} \]

\[ 2: \text{scalar helps to avoid X-ray bound and make } \Omega_N = \Omega_{DM}, \text{ but free-streaming...} \]

\[ 3, 4: \Omega_N \text{ is determined by X-ray bound} \]
DM from Heavy scalar (Majoron?) decay

$\tau H(T = M/3) \equiv \frac{1}{18} \frac{1}{\Lambda}$

$\chi = \frac{\rho}{T} \left( \frac{g_*(T_*)}{g_*(T)} \right)^{1/3}$
Leptogenesis in $2 + 1$ scheme: $0\nu2\beta$ decay region

Inverse hierarchy

$m_{\text{eff}} [10^{-2} \text{eV}]$

$M_N [\text{MeV}]$

Inverse hierarchy

Dmitry Gorbunov (INR)
Sterile neutrino dark matter
10.10.2019, Vth-R-I-Congress
\( \nu \text{MSM} \) parameter space with resonant DM

![Graph showing the parameter space for \( \nu \text{MSM} \) with resonant DM](image)

L. Canetti, M. Drewes, M. Shaposhnikov 1204.3902
Sterile neutrino mass scale: $\hat{M}_\nu = -v^2 \hat{f}^T \hat{M}_N^{-1} \hat{f}$

NB: With fine tuning in $\hat{M}_N$ and $\hat{f}$ we can get a hierarchy in sterile neutrino masses, and 1 keV and even 1 eV sterile neutrinos

$L_e - L_\mu - L_\tau$ or discrete symmetries

Froggatt-Nielsen mechanism

Extended seesaw

Seesaw diagram
Sterile neutrino lagrangian

Most general renormalizable with \(2(3\ldots)\) right-handed neutrinos \(N_l\)

\[
\mathcal{L}_N = \overline{N}_I i \partial \bar{\phi} N_I - f_{\alpha l} \overline{L}_\alpha \tilde{H} N_I - \frac{M_{N_l}}{2} \overline{N}_I^c N_I + h.c.
\]

Parameters to be determined from experiments

9(7): active neutrino sector
11: \(N = 2\) sterile neutrinos
( works if \(m_\nu = 0 \))
18: \(N = 3\) sterile neutrinos:

2 \(\Delta m_{ij}^2\): oscillation experiments
2: Majorana masses \(M_{N_l}\)

3 \(\theta_{ij}\): oscillation experiments
9: New Yukawa couplings \(f_{\alpha l}\) which form
15: New Yukawa couplings \(f_{\alpha l}\) which form

1 CP-phase: oscillation experiments
2: Dirac masses \(M^D = f \langle H \rangle\)
3: Dirac masses \(M^D = f \langle H \rangle\)
3+1: mixing angles
3+3: mixing angles

2(1) Majorana phases: \(0\nu ee, 0\nu\mu\mu\)
2+1: CP-violating phases
3+3: CP-violating phases

1(0) \(m_\nu\): \(^3H \rightarrow ^3He + e + \bar{\nu}_e, \) cosmology, \ldots
4 new parameters in total
3+3: CP-violating phases

Profit: can suggest why neutrinos are so light, \(m_\nu \sim 0.1 - 0.01\) eV
Sterile neutrino Dark Matter: ... gone?

A.Schneider (2016)

brown: MW satellite counts
green and yellow: Lyman-α production by inflaton