Viable production mechanism of keV sterile neutrino with large mixing angle

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Overview

1. Non-resonant production
2. Phase transition in the hidden sector
3. Feebly interacting scalar
   - $\epsilon_\phi \approx 1$
   - $\epsilon_\phi = 1/2$

Overview

Neutrino oscillations in matter

$$\Delta_0 = \frac{2E}{\Delta m^2} \approx \frac{2E}{m_s^2}$$

$$\Delta_m = \Delta_0 \sqrt{\sin^2(2\theta_0) + (\cos(2\theta_0) - V_\alpha/\Delta_0)^2}$$

$$\sin^2(2\theta_m) = \frac{\sin^2(2\theta_0)}{\sin^2(2\theta_0) + (\cos(2\theta_0) - V_\alpha/\Delta_0)^2}$$

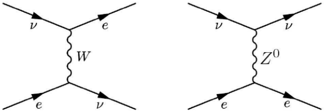
The sterile neutrino production rate $\nu_\alpha \to \nu_s$

$$\Gamma_{\nu_\alpha \to \nu_s} = \frac{\langle \sin^2(\frac{t}{2t_m}) \sin^2(2\theta_m) \rangle_{t_{coll}}}{2t_{coll}} = \frac{1}{2} sin^2(2\theta_m) \frac{\Gamma_\alpha}{2}$$

$$t_m \ll t_{coll} \ll t_{exp} \Leftrightarrow \Delta_m \gg \Gamma_\alpha \gg H$$

$$\frac{|\dot{\theta}_m|}{\Delta_m} \ll 1$$

The Boltzmann equation: $\nu_e \to \nu_s$



$$\Gamma_e \approx 1.27 \cdot G_F^2 y T^5$$

$$V_e \approx -\frac{14 G_F y T^5}{45\alpha_w}(2+\cos^2\theta_W)$$

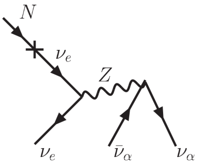
$$-HT\left.\frac{\partial f_s}{\partial T}\right|_{y=\mathrm{const}} = \frac{\sin^2(2\theta_m)\Gamma_e}{4}(f_d - f_s)$$

The Dodelson-Widrow formula $\langle\langle p\rangle\rangle = 3.15\,T$

$$\frac{f_s}{f_d} = \frac{2.9}{\sqrt{g_*}}\left(\frac{\theta^2}{10^{-6}}\right)\left(\frac{m_s}{1\,\mathrm{keV}}\right)\int_x^\infty \frac{y\,dx'}{(1+y^2x'^2)^2} \to \frac{2.9}{\sqrt{g_*}}\left(\frac{\theta^2}{10^{-6}}\right)\left(\frac{m_s}{1\,\mathrm{keV}}\right)\frac{\pi}{4}$$

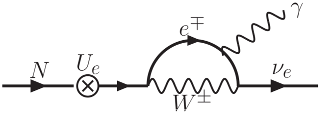
$$x \equiv 148\left(\frac{1\,\mathrm{keV}}{m_s}\right)\left(\frac{T}{1\,\mathrm{GeV}}\right)^3 \qquad y \equiv \frac{E}{T}$$

Cosmological bounds



$$\Gamma_{\nu_s \to 3\nu} = \frac{G_F^2 m_s^5}{96\pi^3} \sin^2\theta$$

$$\theta^2 < 1.1 \cdot 10^{-7} \left(\frac{50\ \text{keV}}{m_s}\right)^5$$



$$\Gamma_{\nu_s \to \gamma\nu_e} = \frac{9\alpha G_F^2}{256 \cdot 4\pi^4} \sin^2(2\theta) m_s^5$$

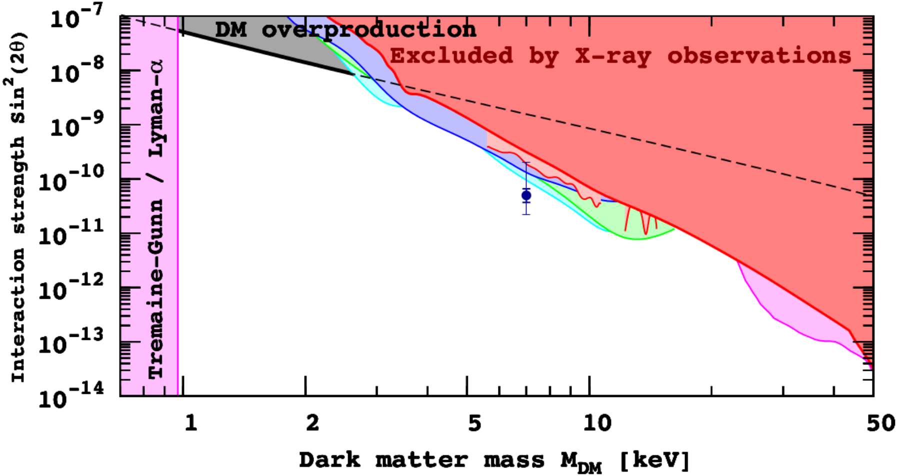
$$\Omega_s \sin^2(2\theta) \lesssim 3 \cdot 10^{-5} \left(\frac{1\ \text{keV}}{m_s}\right)^5$$

The abundance of sterile neutrinos today

$$n_s(T_{\nu,0}) = 2 \cdot \left[\int_0^\infty f_s(y, \frac{m_s}{y}) 4\pi y^2 dy\right] \cdot \frac{4}{11} T_0^3 ,$$

$$\Omega_s h^2 = \frac{m_s n_s}{\rho_c / h^2} = \frac{1}{10.5} \left(\frac{m_s}{1\ \text{keV}}\right) \left(\frac{n_s}{1\ \text{cm}^{-3}}\right) < \Omega_{dm} h^2 \approx 0.12$$

Experimental bounds on $\theta_{\alpha s}$



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An instant phase transition at $T_{h,c} = \xi T_c$

$$\mathcal{L} = \frac{f}{2}\phi \bar{N}^c N + \text{h.c.} + \mathcal{L}_{DS}(\phi)$$

$$\langle\langle\phi\rangle\rangle|_{T_h > \xi T_c} = 0, \qquad M = 0$$
$$\langle\langle\phi\rangle\rangle|_{T_h < \xi T_c} = v_\phi, \qquad M = f v_\phi$$

Oscillations $\nu_s \to \nu_e$ in $T < T_c$ $\quad \langle\langle p\rangle\rangle = 4.1\,T$

$$\frac{f_N}{f_e} = \frac{2.9}{g_*^{1/2}}\left(\frac{\theta^2}{10^{-6}}\right)\left(\frac{M}{\text{keV}}\right)\int_x^{x_c}\frac{y\,dx'}{(1+y^2x'^2)^2} \to 0.13\theta^2\left(\frac{10.75}{g_*}\right)^{1/2}\left(\frac{T_c}{\text{MeV}}\right)^3 y$$

The admixture of right handed ν_s to ν_e in $T > T_c$ $\quad \langle\langle p\rangle\rangle = 1.28\,T$

$$\frac{f_{N,\text{in}}}{f_e} \simeq \frac{m_D^2}{4y^2T_c^2} \to \frac{0.25\times10^{-6}\theta^2}{y^2}\left(\frac{M}{\text{keV}}\right)^2\left(\frac{\text{MeV}}{T_c}\right)^2$$

The overall abundance of ν_s today

$$h^2\Omega_{N,\mathrm{osc}} \approx 4.3 \times \theta^2 \left(\frac{10.75}{g_*}\right)^{1/2} \left(\frac{T_c}{\mathrm{MeV}}\right)^3 \left(\frac{M}{\mathrm{keV}}\right)$$

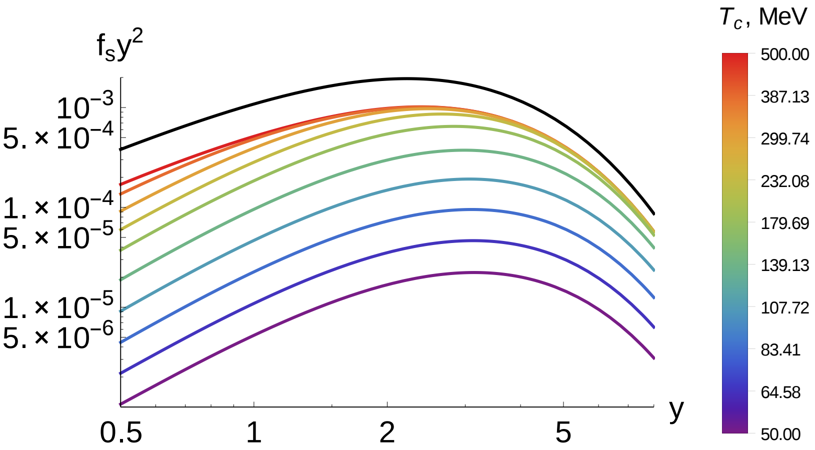
$$h^2\Omega_{N,\mathrm{in}} \simeq 10^{-6}\theta^2 \left(\frac{M}{\mathrm{keV}}\right)^3 \left(\frac{\mathrm{MeV}}{T_c}\right)^2$$

$$T_{c,\mathrm{min}} \simeq 0.05\,\mathrm{MeV} \left(\frac{M}{\mathrm{keV}}\right)^{2/5}$$

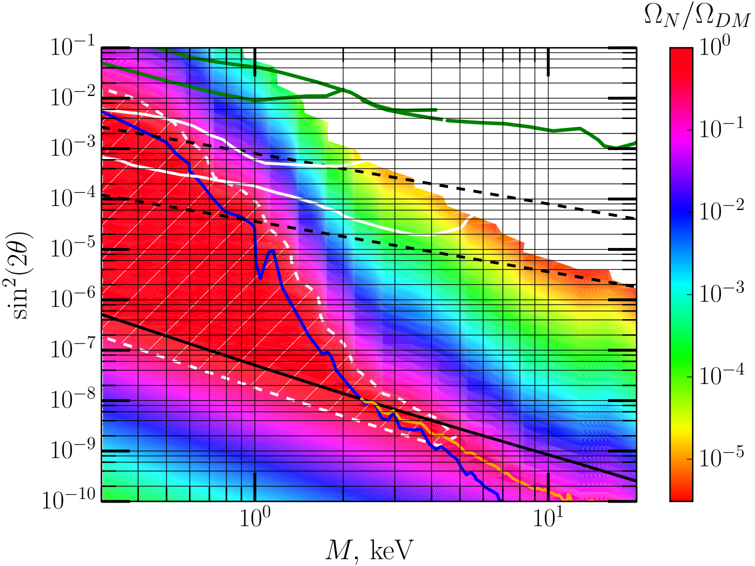
The absolute minimum of sterile neutrino abundance today

$$h^2\Omega_{N,\mathrm{min}} \simeq h^2\Omega_{N,\mathrm{osc}} + h^2\Omega_{N,\mathrm{in}} \simeq 0.9 \times 10^{-3}\theta^2 \left(\frac{M}{\mathrm{keV}}\right)^{11/5}$$

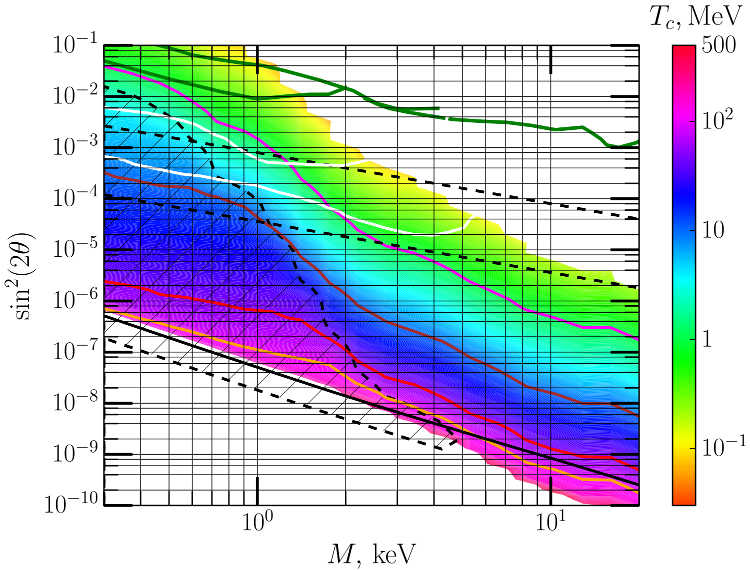
The momentum distribution of ν_s [F.Bezrukov et. al,2017]



The numerical results for Ω_N/Ω_{dm} [F.Bezrukov et. al,2017]



The numerical results for $T_{c,\max}$ [F.Bezrukov et. al,2017]



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Phenomenology of the dark sector

$$\mathcal{L} = i\bar{N}\hat{\partial}N + \frac{M}{2}\bar{N}^c N + y_\nu H \bar{\nu}_a N + \frac{f}{2}\phi \bar{N}^c N + \text{h.c.} + \mathcal{L}_{DS}(\phi)$$

$$\mathcal{L}_{DS} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2$$

Hubble friction regime:

$$m_\phi < H$$

$$\phi_i \sim M_{Pl}, \quad M_{N,i} = f\phi_i$$

Oscillating field regime:

$$m_\phi > H$$

$$|\phi| \propto a^{-3/2}, \quad M_N = M_{N,i}\left(\frac{a_i}{a}\right)^{3/2}$$

The scalar setup

$$\rho_{\phi,0} = \frac{1}{2}m_\phi^2\phi_i^2\left(\frac{T_0}{T_{\rm osc}}\right)^3 \quad \text{where} \quad T_{osc} = \frac{T_0}{\Omega_{rad}^{1/4}}\left(\frac{m_\phi}{H_0}\right)^{1/2}$$

$$\epsilon_\phi \equiv \frac{\rho_{\phi,0}}{\Omega_{DM}\rho_c} \leqslant 1$$

The main assumptions

The condition $f\phi_0 < M$ can be consistent with $T_{\rm osc} > 100\,{\rm eV}$ which allows sterile neutrinos to compose all dark matter today!

$$\left(\frac{T_{\rm osc}}{100\,{\rm eV}}\right)\left(\frac{2.73\,{\rm K}}{T_0}\right) \gtrsim \left(\frac{M_i}{1\,{\rm TeV}}\right)^{2/3}\left(\frac{1\,{\rm keV}}{M}\right)^{2/3}$$

Assumptions.

- $M_{N,i} > T_{EW}$ suppresses the active-sterile oscillations in the region $T \lesssim T_{EW}$.
- $m_\phi < 2M$ forbids the perturbative decay $\phi \to NN$ kinematically.
- $m_\phi \gtrsim (1-2)\times 10^{-21}\,{\rm eV}$ is consistent with the Ly-α clumping.
- For $m_\phi > m_{sol} \approx 0.01\,{\rm eV}$ we require $\frac{\Gamma_{\phi\to\nu_a\nu_a}}{H_0} \equiv \theta^4 \times \frac{f^2}{16\pi}\frac{m_\phi}{H_0} \ll 1$.

Different production mechanisms

$T > T_{EW}$: generation by thermal Higgs boson decay

$$\frac{\Gamma_{H\to\nu_a N}}{H} \simeq \frac{y_\nu^2}{16\pi}\frac{T}{H} \ll 1$$

$T_* < T < T_{\rm osc}$: nonperturbative production until $f|\phi| = M$

$$n_N \simeq \frac{2}{6\,\pi^2}\,(Mm_\phi)^{3/2} \qquad \rho_N(T_*) = \frac{M}{3\,\pi^2}\,(Mm_\phi)^{3/2} \qquad \text{where } T_* = T_{osc}\left(\frac{M}{M_{N,i}}\right)^{2/3}$$

$$h^2\Omega_{N,\phi} = \frac{\rho_N(T_*)}{\rho_c/h^2}\left(\frac{T_0}{T_*}\right)^3 \simeq 0.21 \times \left(\frac{f}{0.1}\right)^2\sqrt{\frac{M}{1\text{ keV}}}\sqrt{\frac{0.01\text{ eV}}{m_\phi}} \times \epsilon_\phi \times \Omega_{DM}h^2$$

$M < T < T_c$: oscillations from active neutrinos

$$h^2\Omega_{N,osc} \simeq 4.3 \times \theta^2\left(\frac{10.75}{g_*}\right)^{1/2}\left(\frac{T_c}{\text{MeV}}\right)^3\left(\frac{M}{\text{keV}}\right) \qquad \text{where } T_c = T_{osc}\left(\frac{T_{osc}}{M_{N,i}}\right)^2$$

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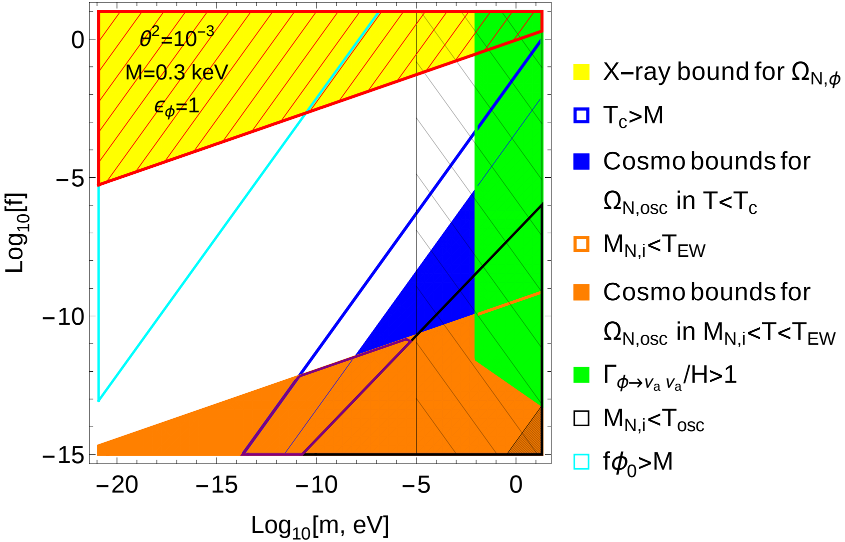
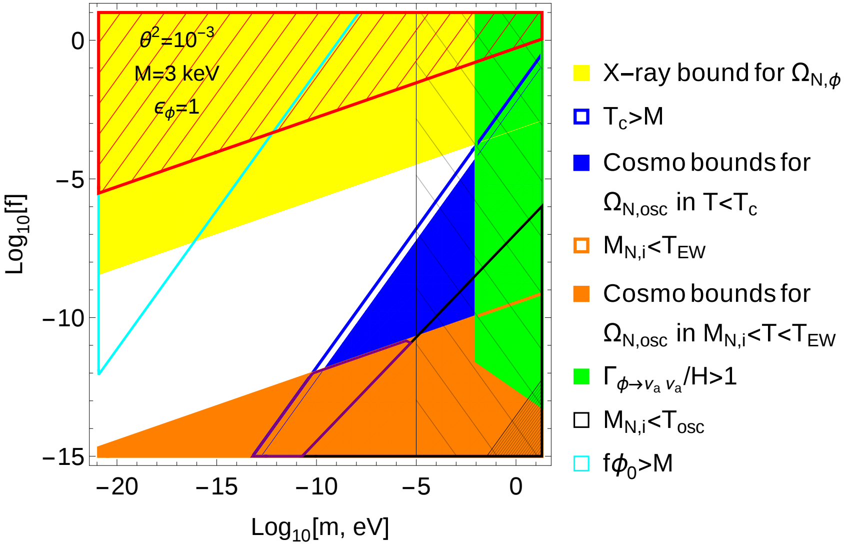
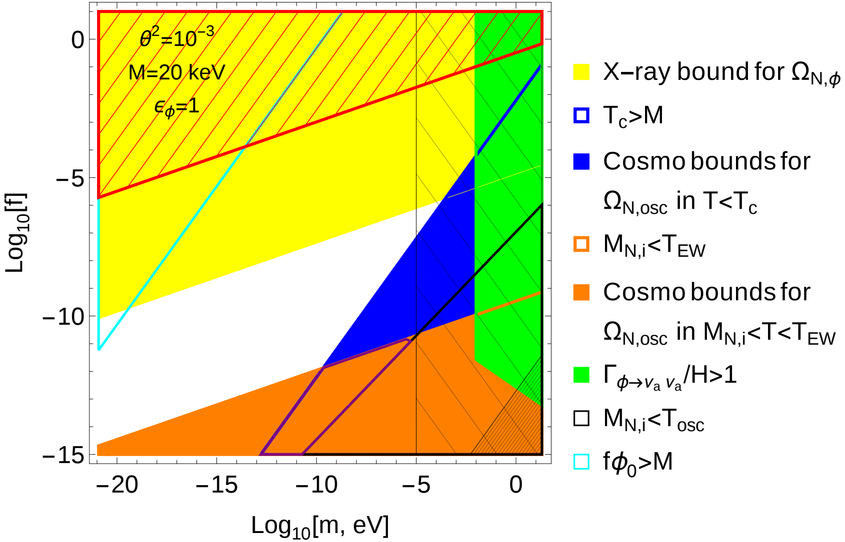
$\theta^2 = 10^{-3}$, $M = 0.3$ keV, $\epsilon_\phi = 1$



$\theta^2 = 10^{-3}$, $M = 3\,\mathrm{keV}$, $\epsilon_\phi = 1$



$\theta^2 = 10^{-3}$, $M = 20\,\text{keV}$, $\epsilon_\phi = 1$



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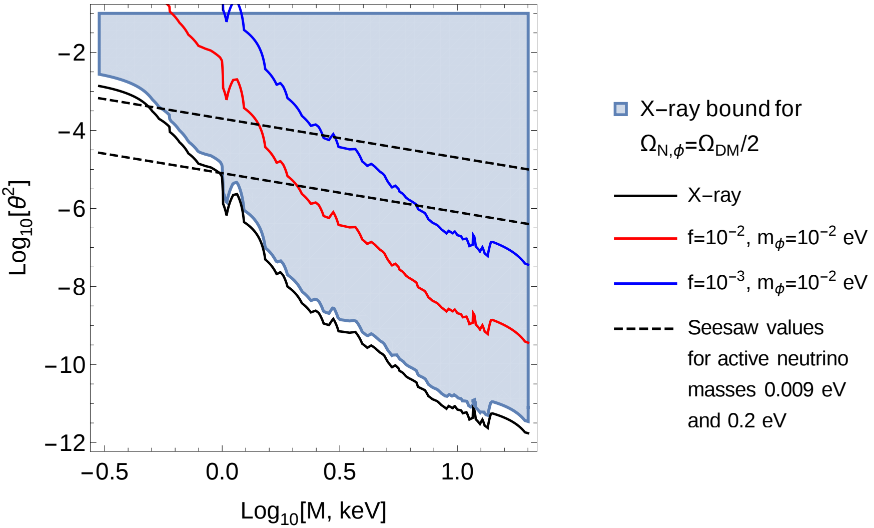
$\epsilon_\phi = 1/2,\ f = 0.2\left(\frac{m_\phi}{0.01\ \text{eV}}\right)^{1/4}\left(\frac{1\ \text{keV}}{M}\right)^{1/4}$

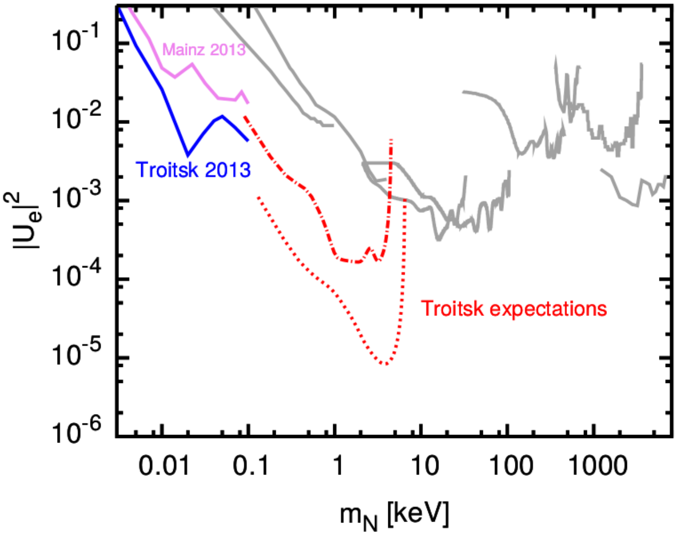


Conclusion

- The model with phase transition let us simply alleviate different cosmological and astrophysical bounds by shifting the onset of oscillations to later times.
- The model with the feebly interacting scalar is able to suppress the sterile neutrino production in the early Universe to the level which makes the direct laboratory searches the strongest ones in the scalar dominated Universe.
- Super-cool sterile neutrinos produced by the oscillating background contributing significantly to DM help to escape the bounds of $M > 8\,\text{keV}$ from the structure formation in the Lyman-α forest and of $M > 5.7\,\text{keV}$ from phase space density.
- keV sterile neutrinos can naturally explain small masses of active neutrinos within different hierarchies via the See-Saw mechanism.

Thank you for your attention

Bounds from the "Troitsk nu-mass" spectrometer



Expectations of the KATRIN