

# Extremely weak and super-efficient production of keV sterile neutrino: phase transition and induced parametric resonance creation

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- 1 Non-resonant production
- 2 Phase transition in hidden sector
- 3 Feebly interacting scalar field

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

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

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

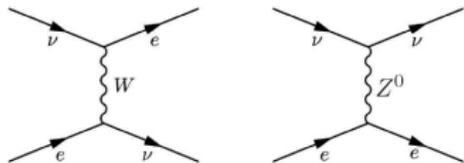
Sterile neutrino production rate  $\nu_\alpha \rightarrow \nu_s$

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

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

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

# Boltzmann equation: $\nu_e \rightarrow \nu_s$



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

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

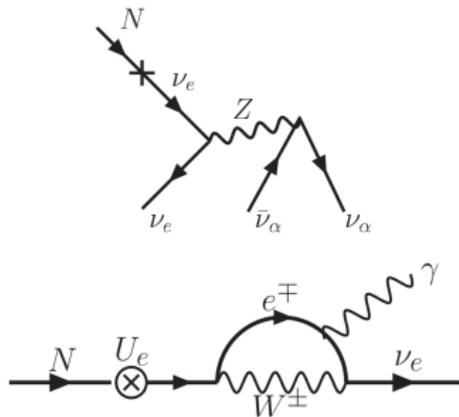
$$-HT \left. \frac{\partial f_s}{\partial T} \right|_{y=\text{const}} = \frac{\sin^2(2\theta_m) \Gamma_e}{4} (f_d - f_s)$$

Dodelson-Widrow scenario

$$\langle\langle p \rangle\rangle = 3.15T$$

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

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



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

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

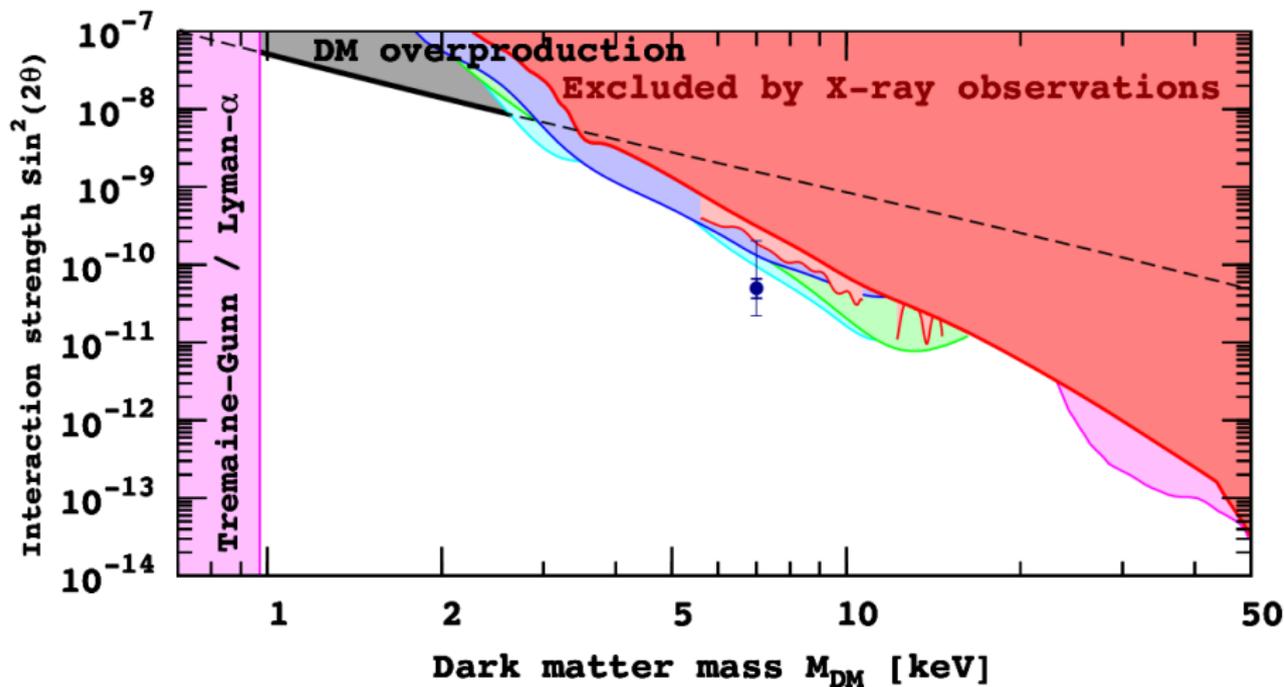
$$\Gamma_{\nu_s \rightarrow \gamma \nu_e} = \frac{9\alpha G_F^2}{256 \cdot 4\pi^4} \sin^2(2\theta) m_s^5$$

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

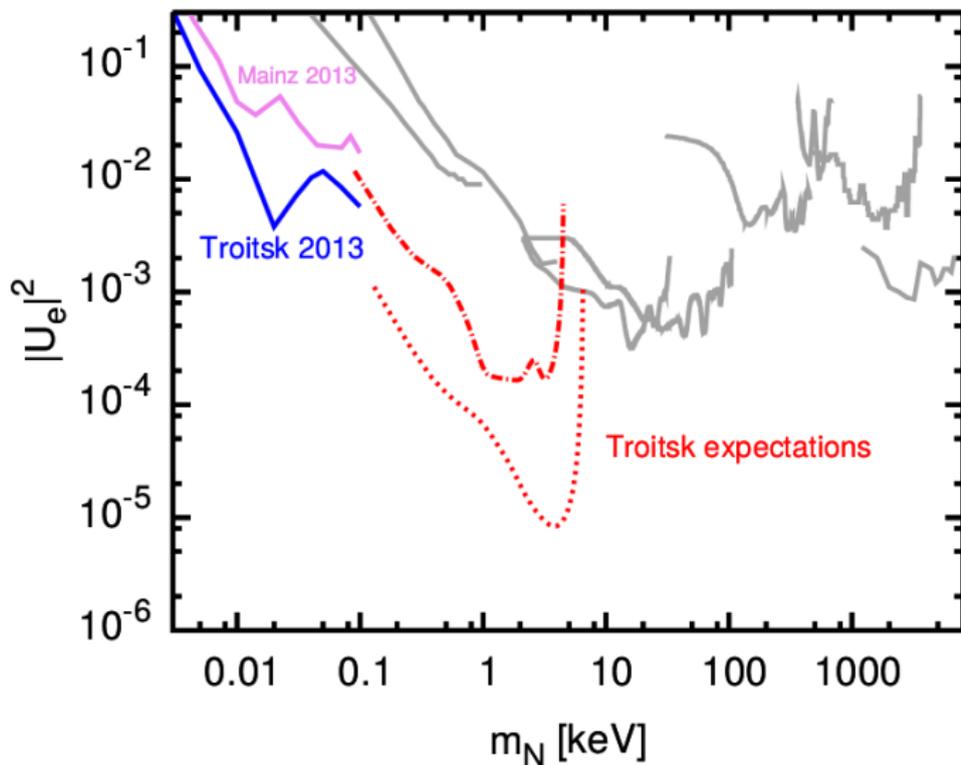
## Abundance of sterile neutrinos today

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

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



# Direct searches: "Troitsk nu-mass" spectrometer



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# Instant phase transition at $T_{h,c} = \xi T_c$

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

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

Oscillations at  $T < T_c < 130 \text{ MeV} (M/\text{keV})^{1/3}$

$$\langle\langle p \rangle\rangle = 4.1T$$

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

Admixture of right-handed  $\nu_s$  at  $T > T_c$

$$\langle\langle p \rangle\rangle = 1.28T$$

$$\frac{f_{N,\text{in}}}{f_e} \simeq \frac{m_D^2}{4y^2 T_c^2} \rightarrow \frac{0.25 \times 10^{-6} \theta^2}{y^2} \left( \frac{M}{\text{keV}} \right)^2 \left( \frac{\text{MeV}}{T_c} \right)^2$$

## Overall abundance of $\nu_s$ today

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

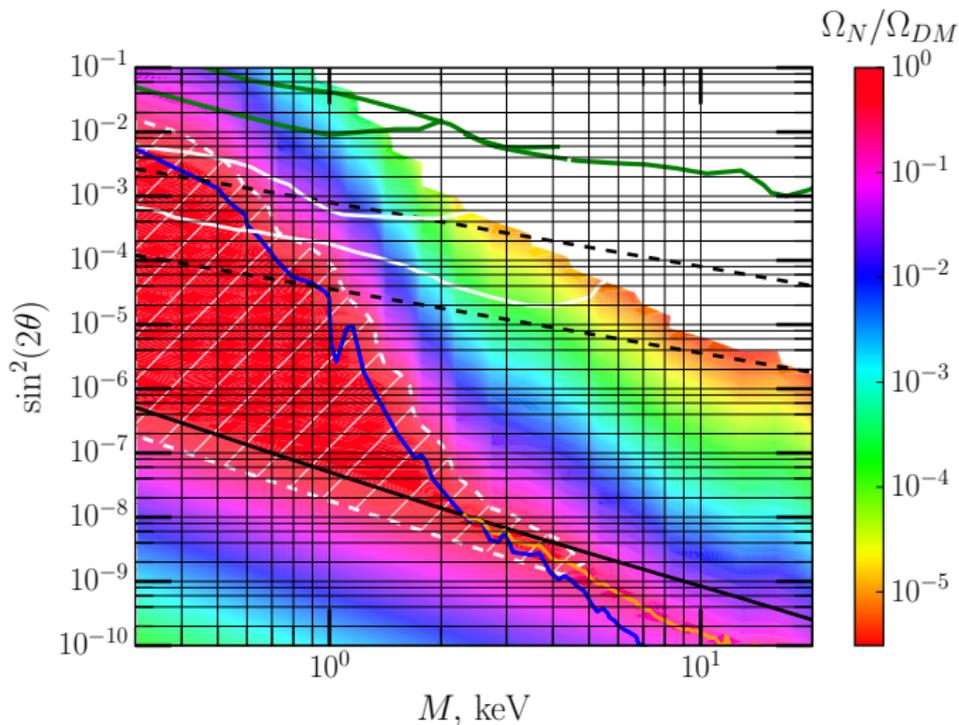
$$h^2\Omega_{N,\text{in}} \simeq 10^{-6}\theta^2 \left(\frac{M}{\text{keV}}\right)^3 \left(\frac{\text{MeV}}{T_c}\right)^2$$

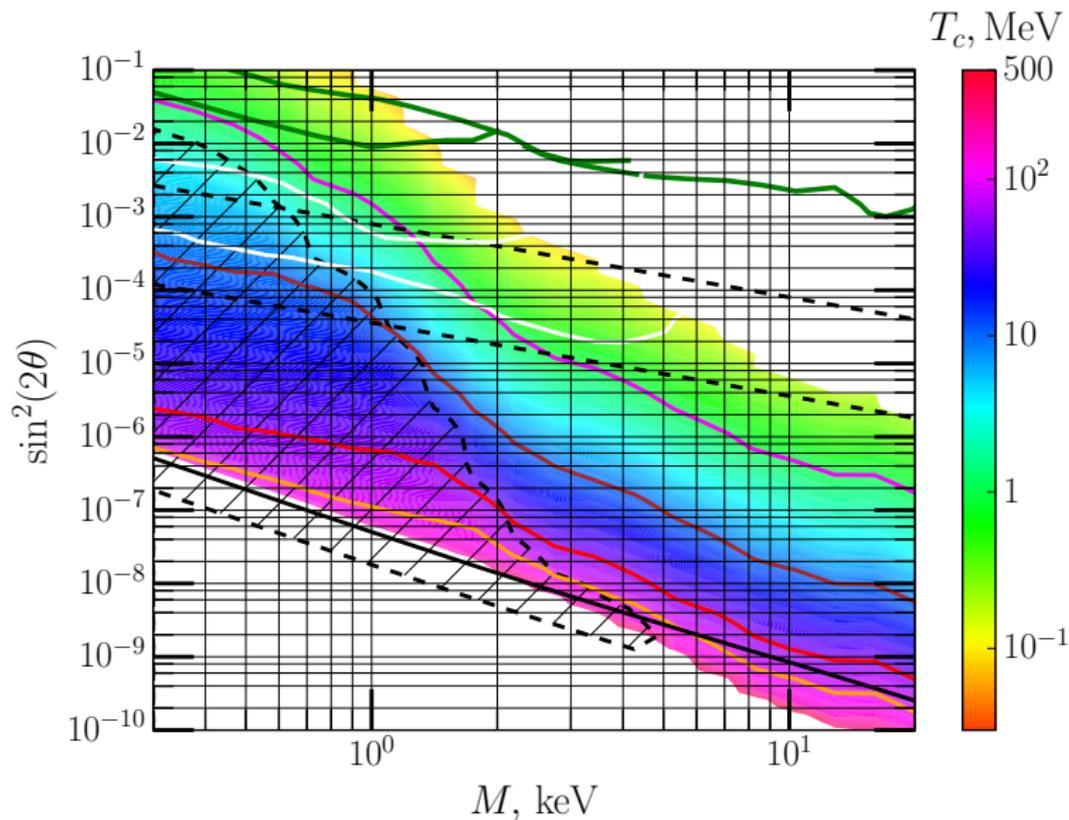
$$T_{c,\text{min}} \simeq 0.05 \text{ MeV} \left(\frac{M}{\text{keV}}\right)^{2/5}$$

## Minimal number of sterile neutrinos today

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

$$0.01 \text{ eV} \approx \sqrt{\Delta m_{sol}^2} < m_a < \sum m_\nu \approx 0.2 \text{ eV} \text{ [Planck+BAO]}$$





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

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

Hubble friction regime:

$$m_\phi < H$$

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

Oscillating field regime:

$$m_\phi > H$$

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

## Background evolution and quantum stability

$$\rho_{\phi,0} = \frac{1}{2}m_\phi^2\phi_i^2 \frac{h_0 T_0^3}{h_{\text{osc}} T_{\text{osc}}^3} \quad \text{where} \quad T_{\text{osc}} = \frac{T_0}{\Omega_{\text{rad}}^{1/4}} \left(\frac{m_\phi}{H_0}\right)^{1/2}$$

$$\frac{f^4\phi_i^4}{32\pi^2} \ll \frac{1}{2}m_\phi^2\phi_i^2 \quad (\text{feebly interacting})$$

$$\Delta_0 \equiv 2\beta(z + \sin mt)^2 \quad \beta \equiv \frac{M_A^2}{4p} \quad z \equiv \frac{M}{M_A}$$

$$i \frac{\partial}{\partial t} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} = \frac{\Delta_0}{2} \begin{pmatrix} -\cos 2\theta(t) & \sin 2\theta(t) \\ \sin 2\theta(t) & \cos 2\theta(t) \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$$

$$y_1(t) = A_{\nu_a \rightarrow \nu_a} = \langle \psi_a | \psi(t) \rangle$$

$$y_2(t) = A_{\nu_a \rightarrow \nu_s} = \langle \psi_s | \psi(t) \rangle$$

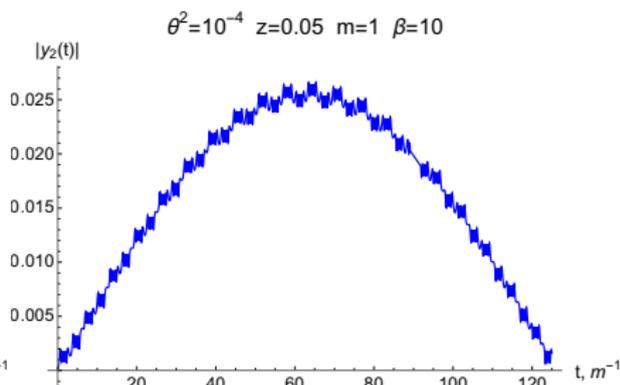
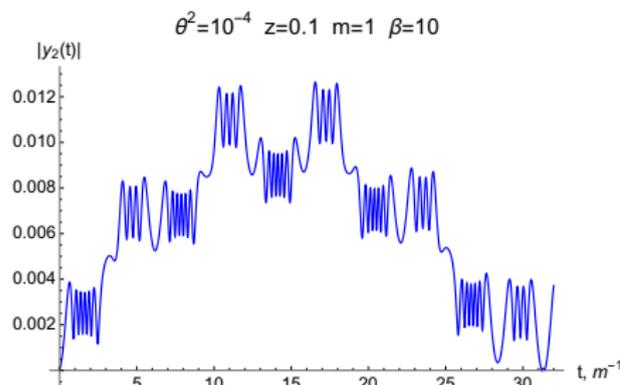
$$\begin{cases} \frac{\partial y_1(t)}{\partial t} = -2i\beta z \theta_0 (z + \sin mt) e^{-2i\beta \int_0^t (z + \sin m\zeta)^2 d\zeta} y_2(t) \\ \frac{\partial y_2(t)}{\partial t} = -2i\beta z \theta_0 (z + \sin mt) e^{2i\beta \int_0^t (z + \sin m\zeta)^2 d\zeta} y_1(t) \end{cases}$$

## Assumptions

$$\sin \theta(t) \approx \frac{m_D}{M_{\text{tot}}} = \frac{\theta_0 z}{z + \sin mt} \ll 1 \quad \left| \frac{\dot{\theta}(t)}{\Delta_0} \right| \ll 1$$

$$y_1(0) = 1 \quad y_2(0) = 1$$

$$\frac{\partial^2 y_2(t)}{\partial t^2} - \frac{\partial y_2(t)}{\partial t} \left[ 2i\beta(z + \sin mt)^2 + \frac{m \cos mt}{z + \sin mt} \right] + 4y_2(t)\beta^2 z^2 \theta_0^2 (z + \sin mt)^2 = 0$$

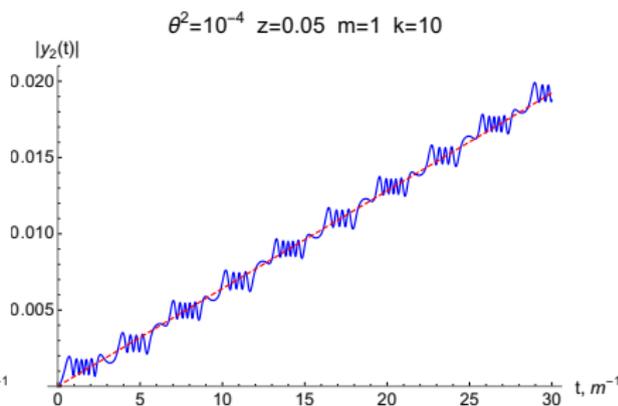
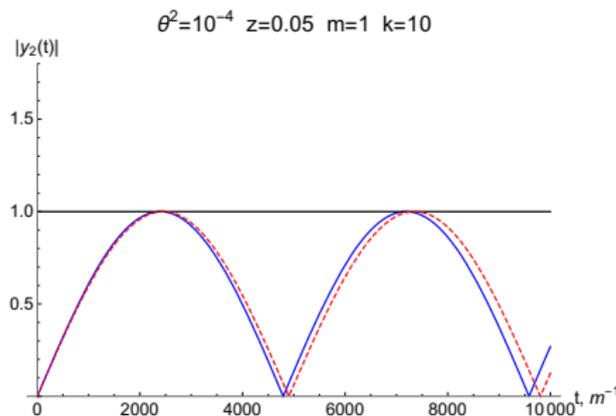


$$y_2(0) = 0 \quad \frac{\partial y_2}{\partial t}(0) = -2i\beta z^2 \theta_0$$

## Resonance condition

$$k \equiv \frac{\beta(1 + 2z^2)}{m} \in \mathbb{Z}$$

$$y_{2,\text{res}}(t_1) \approx \sin \left[ 2z\theta_0 \left( \frac{\beta}{12m} \right)^{1/3} \sqrt{3} \Gamma \left( \frac{2}{3} \right) \frac{mt_1}{\pi} C_k \right], \quad C_k = \begin{cases} |\sin 4zk| & \text{for even } k \\ |\cos 4zk| & \text{for odd } k \end{cases}$$



$$y_k \equiv \frac{p_k}{T} = \frac{M_A^2}{4Tmk} \sim T^2$$

$$\Delta y_k = \frac{\omega_{\text{res}}}{k} y_k$$

## Slow resonance transition

$$\delta t_k = \Delta y_k \left( \frac{dy_k}{dt} \right)^{-1} \gg \omega_{\text{res}}^{-1} \Rightarrow \frac{\omega_{\text{res}}^2}{mH} \frac{1}{2k} \gg 1$$

## Small plasma effect

$$\frac{\omega_{\text{res}}}{\Gamma_A} \gg 1 \quad \text{where} \quad \Gamma_A \equiv 1.27 \times y_k \times G_F^2 T^5$$

$$\omega_{\text{res}} \approx 2zm\theta_0 \left( \frac{\beta}{12m} \right)^{1/3} \sqrt{3} \Gamma \left( \frac{2}{3} \right) \times \left( \frac{2}{\pi} \right) \begin{cases} |\sin 4zk| & \text{for even } k \\ |\cos 4zk| & \text{for odd } k \end{cases}$$

- **Phase transition** allows to alleviate different cosmological and astrophysical bounds by shifting the onset of oscillations to later times.

keV sterile neutrino with mixing  $\theta^2 \sim 10^{-5} - 10^{-3}$  is still alive!

## keV sterile neutrinos with large mixing

- naturally explain small masses of active neutrinos within different hierarchies via the See-Saw mechanism
- solve the small-scale problems of cold DM
- are not able to compose all DM today in the light of the bounds from structure formation in the Lyman- $\alpha$  forest ( $M > 8$  keV) and from phase space density ( $M > 5.7$  keV)
- **Feebly interacting scalar field** provides the induced parametric resonance which ensures super-efficient production of keV sterile neutrinos

keV sterile neutrino with mixing  $\theta^2 \ll 10^{-8} - 10^{-7}$  can still produce all DM!

## keV sterile neutrinos with extremely small mixing

- can compose all DM today in parametric resonance
- alleviate structure formation constraints since  $y_{k,\max} \approx 0.5$  is necessary to produce all DM. It also helps to address the small-scale problems of cold DM.

Thank you for your attention

# Expectations of the KATRIN

