Sterile neutrino dark matter production

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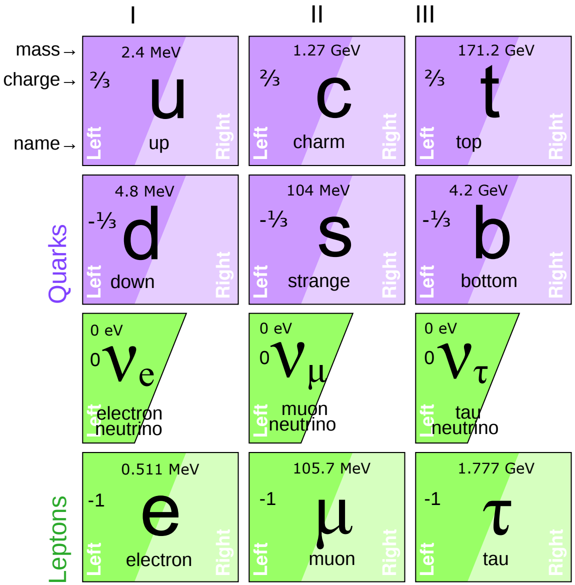
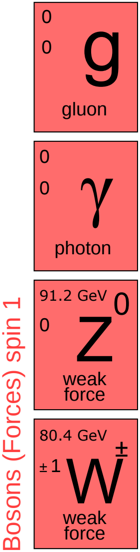
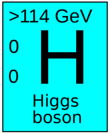
Three Generations
of Matter (Fermions) spin ½



The Matter generations
are indistinguishable by
electric
weak and
strong
forces



distinguishable
by gravity
and Yukawa
forces



spin 0

$m_H \approx 125\,\mathrm{GeV}$

Description of neutrino oscillations (I)

- Two bases: gauge $|\nu_\alpha\rangle$, $\alpha = e,\ \mu,\ \tau$ and mass $|\nu_i\rangle$, $i = 1, 2, 3$

$$|\nu_i\rangle = U_{\alpha i}|\nu_\alpha\rangle \qquad \text{with unitary PMNS } 3\times 3 \text{ matrix} \quad U_{\alpha i}$$

- Neutrino mass matrix is then

$$M_{\alpha\beta} = \langle\nu_\alpha|M|\nu_\beta\rangle = (UM^{(m)}U^\dagger)_{\alpha\beta}\ , \quad \text{where} \quad M^{(m)}_{ij} = m_i\delta_{ij}\ .$$

- Free neutrino evolution in time and space

$$|\nu_j(t)\rangle = \mathrm{e}^{-im_jt}|\nu_j(0)\rangle \quad \to \quad |\nu_j(t,L)\rangle = \mathrm{e}^{-i\left(E_jt-p_jL\right)}|\nu_j(0)\rangle\ ,$$

in ultrarelativistic case $\longrightarrow$ Hamiltonian

$$p_j = \sqrt{E^2 - m_j^2} = E - m_j^2/2E \quad \to \quad |\nu_j(L)\rangle = \mathrm{e}^{-i\frac{m_j^2}{2E}L}|\nu_j(0)\rangle\ .$$

Description of neutrino oscillations (II)

- Neutrino effective Hamiltonian

$$|\nu_j(L)\rangle = \mathrm{e}^{-i\frac{m_j^2}{2E}L}|\nu_j(0)\rangle \quad \to H_{eff} = \frac{M^2}{2E}$$

- Transition amplitude of neutrino ν_α to neutrino ν_β is

$$A(\alpha\to\beta) = \sum_j \langle\nu_\beta|\nu_j(L)\rangle\langle\nu_j(0)|\nu_\alpha\rangle = \sum_j \langle\nu_\beta|\nu_j\rangle \mathrm{e}^{-i\frac{m_j^2}{2E}L}\langle\nu_j|\nu_\alpha\rangle = \sum_j U_{\beta j}\mathrm{e}^{-i\frac{m_j^2}{2E}L}U^*_{\alpha j}$$

- and the transition probability $\Delta m_{ji}^2 \equiv m_j^2 - m_i^2$

$$P(\nu_\alpha\to\nu_\beta) = |A(\alpha\to\beta)|^2$$

$$= \delta_{\alpha\beta} - 4\sum_{j>i}\mathrm{Re}[U^*_{\alpha j}U_{\beta j}U_{\alpha i}U^*_{\beta i}]\sin^2\left(\frac{\Delta m_{ji}^2}{4E}L\right)$$

$$+2\sum_{j>i}\mathrm{Im}[U^*_{\alpha j}U_{\beta j}U_{\alpha i}U^*_{\beta i}]\sin\left(\frac{\Delta m_{ji}^2}{2E}L\right),$$

Description of neutrino oscillations (III)

- Two-neutrino oscillations: transition probability

$$P(\nu_\alpha \to \nu_{\beta\neq\alpha}) = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2}{4E}L\right) ,$$

- Two-neutrino oscillations: survival probability

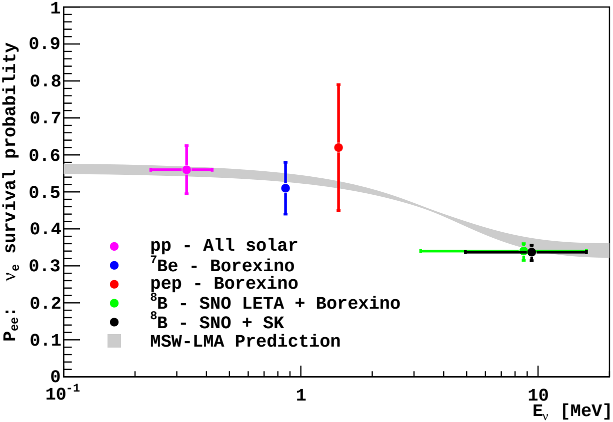
$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2}{4E}L\right)$$

- Oscillation length

$$L_{osc} = \frac{4\pi E}{\Delta m^2} = (2.5\ \mathrm{km}) \cdot \frac{E}{\mathrm{GeV}} \frac{\mathrm{eV}^2}{\Delta m^2}$$

Neutrino matter effect: asymmetry

Mikheev–Smirnov–Wolfenstein effect



BOREXINO measurements of solar neutrino flux

Fermi charged currents

$$\mathscr{L} = -2\sqrt{2}G_F \bar{\nu}_e \gamma^\mu e \cdot \bar{e}\gamma_\mu \nu_e$$

only matter, no currents

$$\langle\langle \bar{e}_k \gamma^0_{kl} e_l \rangle\rangle = \langle\langle e^\dagger e \rangle\rangle = n_e,$$

$$\langle\langle \bar{e}_k \gamma^i_{kl} e_l \rangle\rangle = 0.$$

$$\langle\langle e_k \bar{e}_l \rangle\rangle = -\frac{1}{4}\gamma^0_{kl} \cdot n_e$$

Fermi interaction gives

$$\mathscr{L}_{eff} = -\sqrt{2}G_F n_e \bar{\nu}_e \gamma^0 \nu_e.$$

$$i\gamma^0\partial_0 \to i\gamma^0\partial_0 - \sqrt{2}G_F n_e \gamma^0,$$

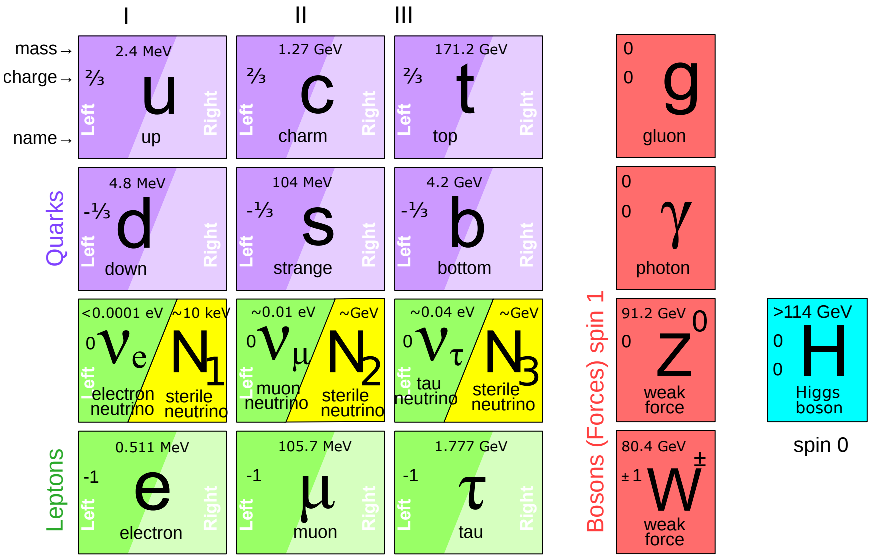
effective potential

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

competes with

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

Three Generations of Matter (Fermions) spin ½



Seesaw mechanism: $M_N \gg 1$ eV

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

$$\mathscr{L}_N = \overline{N} i \partial\!\!\!/ N - f \overline{L}_e^c \tilde{H} N - \frac{M_N}{2} \overline{N}^c N + \text{h.c.}$$

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

$$\mathscr{V}_N = \frac{1}{2} \left(\overline{\nu}_e \,, \overline{N}^c \right) \begin{pmatrix} 0 & v \frac{f}{\sqrt{2}} \\ v \frac{f}{\sqrt{2}} & M_N \end{pmatrix} \begin{pmatrix} \nu_e \\ N \end{pmatrix} + \text{h.c.}$$

For a hierarchy $M_N \gg M^D = v \frac{f}{\sqrt{2}}$ we have

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

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

and mass eigenvalues

$$\approx M_N \quad \text{and} \quad - m_{active} = \theta^2 M_N \lll M_N$$

Seesaw mechanism: $M_N \gg 1$ eV

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

$$\mathscr{L}_N = \overline{N}_I i\partial\!\!\!/ N_I - f_{\alpha I}\overline{L}^c_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2}\overline{N}^c_I N_I + \text{h.c.}$$

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

$$\mathscr{V}_N = \frac{1}{2}\left(\overline{\nu}_1, \ldots \overline{N}^c_1 \ldots\right)\begin{pmatrix} 0 & v\,\frac{\hat{f}}{\sqrt{2}} \\ v\,\frac{\hat{f}^T}{\sqrt{2}} & \hat{M}_N \end{pmatrix}\left(\nu_1, \ldots N_1 \ldots\right)^{\mathrm{T}} + \text{h.c.}$$

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

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

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

active-active mixing: $U^\dagger \hat{M}^\nu U = diag\,(m_1, m_2, m_3)$

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: 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, $N \to \nu\nu\nu$ is always open
  but exceeding the age of the Universe if

(applicable for $M_N < M_W$)

$$\theta^2 < 1.5 \times 10^{-7} \left(\frac{50\,\text{keV}}{M_N} \right)^5$$

- with seesaw constraint $m_a \sim \theta^2 M_N$

$$\tau_{N\to 3\nu} \sim 1/\left(G_F^2 M_N^5 \theta_{\alpha N}^2\right) \sim 1/\left(G_F^2 M_N^4 m_\nu\right) \sim 10^{11}\,\mathrm{yr}\,(10\,\mathrm{keV}/M_N)^4$$

Sterile neutrino: indirect searches

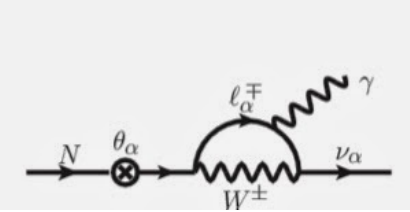
$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

- unstable, but exceeding the age of the Universe if

$$\frac{\theta^2}{3\times 10^{-3}} < \left(\frac{10\,\mathrm{keV}}{M_N}\right)^5$$

- DM sterile neutrinos can be searched at X-ray telescopes because of two-body radiative decay

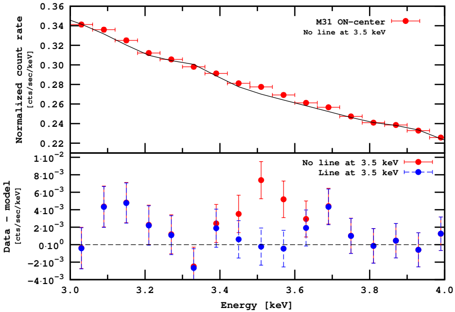
give limits in absence of the feature



a narrow line $(\delta E_\gamma / E_\gamma \sim v \sim 10^{-3})$
at photon frequency $E_\gamma = M_N/2$

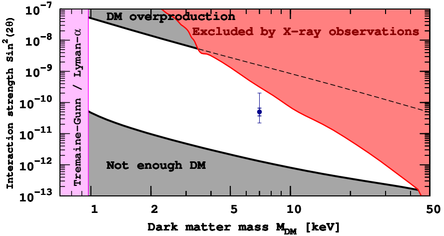
$$\frac{\theta^2}{10^{-11}} \lesssim \left(\frac{10\ \mathrm{keV}}{M_N}\right)^4$$

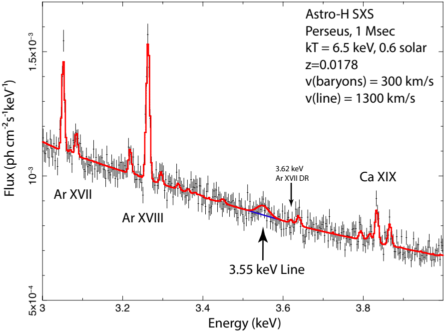
...3 years ago: Dark Matter decay observed in X-ray?



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

1402.2301, 1402.4119





Production in oscillations

$$\frac{\partial}{\partial t} f_s(t,\mathbf{p}) - H\mathbf{p}\,\frac{\partial}{\partial \mathbf{p}} f_s(t,\mathbf{p}) = \Gamma_\alpha\, P(\nu_\alpha \to \nu_s)\, f_\alpha(t,\mathbf{p})\,.$$

$\Gamma_\alpha \sim G_F^2 T^4 E$ is the weak interaction rate in plasma

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

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

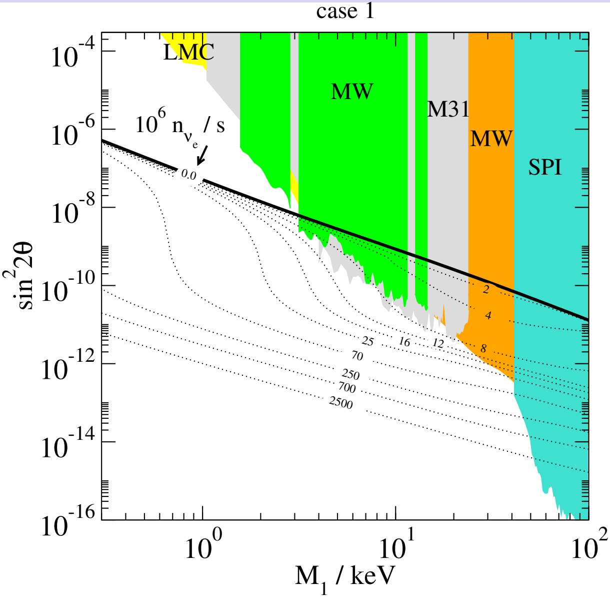
$$\sin 2\theta_\alpha^{\text{mat}} = \frac{t_\alpha^{\text{mat}}}{t_\alpha^{vac}}\cdot \sin 2\theta_\alpha\,, \quad t_\alpha^{vac} = \frac{2E}{M_N^2}$$

and effective plasma potential for active neutrinos

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

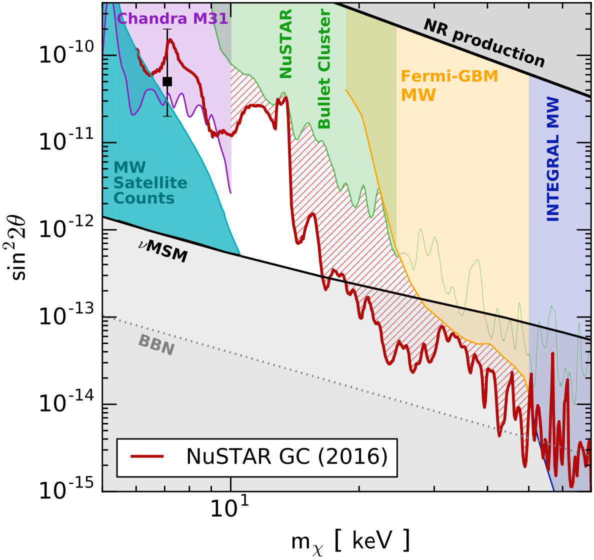
non-resonant and resonant production in the lepton asymmetric plasma

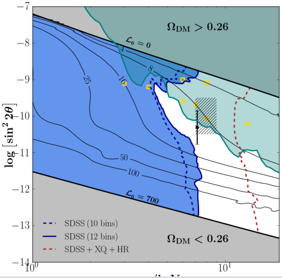
DM from oscillations



. . . present searches

1609.00667, 1706.03118





Production not by the mixing

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

Not seesaw neutrino!

M.Shaposhnikov, I.Tkachev (2006)

$$M_{N_I}\bar{N}_I^c N_I \leftrightarrow f_I X \bar{N}_I N_I$$

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

F.Bezrukov, D.G. (2009)

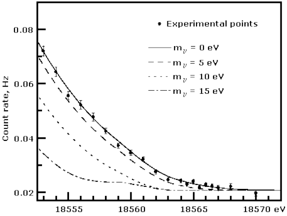
$$M_1 \lesssim 15 \times \left(\frac{m_\chi}{300\ \text{MeV}}\right)\ \text{keV}$$

or classical inflaton oscillations...

Not seesaw neutrino!

Direct searches for m_ν: cut in e-spectrum

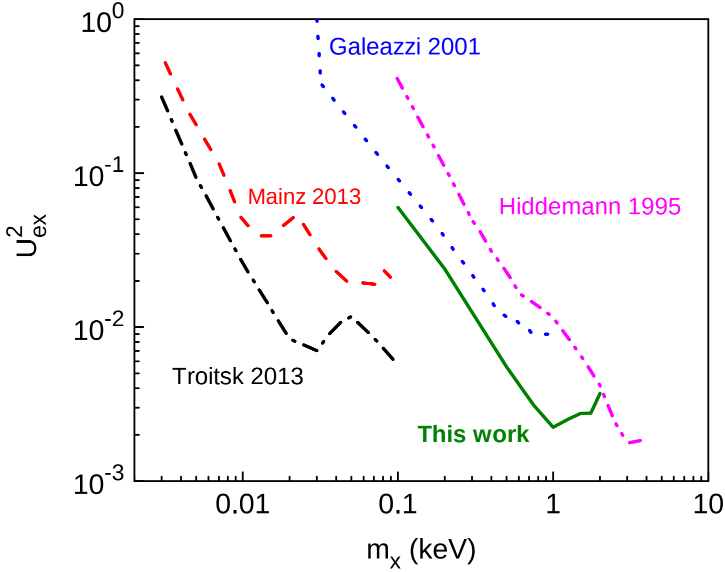
$$\mathrm{T} \to \ ^3\mathrm{He} \ + e + \bar{\nu}_e$$
$$(pnn) \to (ppn) + e + \bar{\nu}_e$$



INR RAS, 1990-2000 years: $m_{\bar{\nu}_e} \lesssim 2\,\mathrm{eV}$

the same technique for sterile neutrinos

Direct searches are deep inside the forbidden region



1703.10779

Direct searches are deep inside the forbidden region

Could they be of any use ?

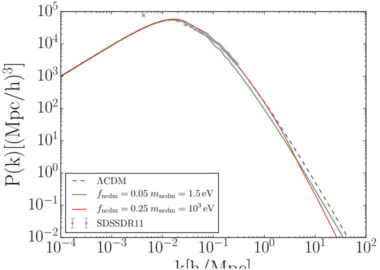
In a minimal scheme

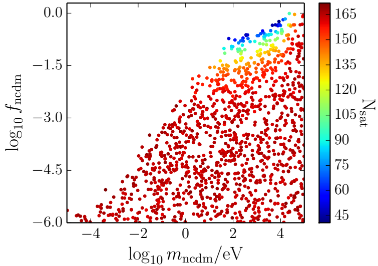
If Dark Matter no way to avoid X-ray bounds

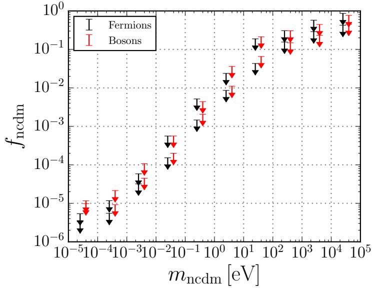
$$\theta^2_{X-ray} = \theta^2_{\alpha I}\,\frac{\Omega_N}{\Omega_{DM}}$$

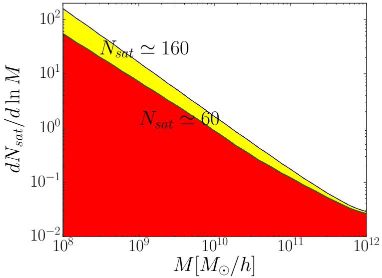
Sterile neutrinos: a part of dark matter

1701.03128









Suppression of cosmological production

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

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

Most efficient production occurs at

$$T_{crit} < T_{max} \approx 133\,\text{MeV}\left(\frac{1\,\text{keV}}{M_N}\right)^{1/3}$$

It is suppressed if $T_{reh} \ll T_{max}$

G.Gelmini, S.Palomares-Ruiz, S.Pascoli (2004)

Suppression of cosmological production

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

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

Add more ingredients e.g. Scalar? Majoron?

- strong coupling to scalar or Majoron, which decreases the active-sterile mixing in primordial plasma e.g. L.Bento, Z.Berezhiani (2001)
- varying sterile neutrino mass in cosmology, which suppresses the early-time oscillations F.Bezrukov, A.Chudaikin, D.G. (2017)
  - sterile neutrinos superheavy in the early Universe
  - sterile neutrinos massless in the early Universe

Superheavy in the early Universe

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

homogeneous scalar field in FLRW expanding Universe

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

two-stage evolution:

$$m_\phi < H(t) \quad \Longrightarrow \quad \phi = \phi_i = \text{const}$$

$$m_\phi > H(t) \quad \Longrightarrow \quad p = \langle E_k \rangle - \langle E_p \rangle = 0\,, \quad \rho \sim m_\phi^2 \phi^2 \propto 1/a^3$$

- 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 kept nonrelativistic, $\quad m_\phi = H_{osc} = \frac{T_{osc}^2}{M_{Pl}^*}$

$$M(t) = M_N + f\phi_i \frac{T^3}{T_{osc}^3} > T$$

production never happened

Only direct searches matter !!

Massless in the early Universe

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

And may be more scalar fields in the hidden sector. . . to make the phase transition:

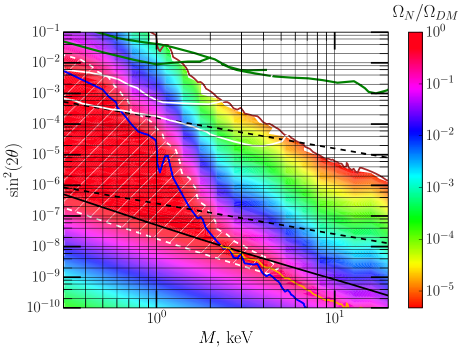
$$\begin{aligned} T > T_{crit} \quad &\Longrightarrow \quad \langle\phi\rangle = 0\,, \quad M_N = 0 \\ T < T_{crit} \quad &\Longrightarrow \quad \langle\phi\rangle = v_\phi\,, \quad M_N = f v_\phi \end{aligned}$$

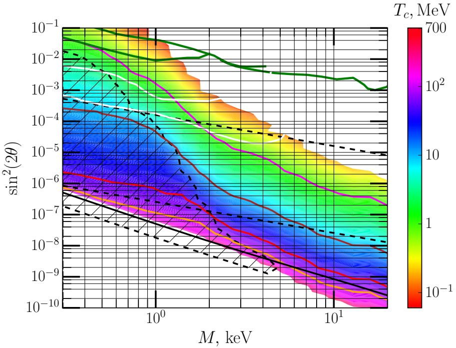
The production in oscillations will be suppressed, if

$$T_{crit} < T_{max} \approx 133\,\text{MeV} \left(\frac{1\,\text{keV}}{M_N}\right)^{1/3}$$

there is always contribution from left-right mixing, $\propto m_D^2/E^2$

Results for details see 1705.02184



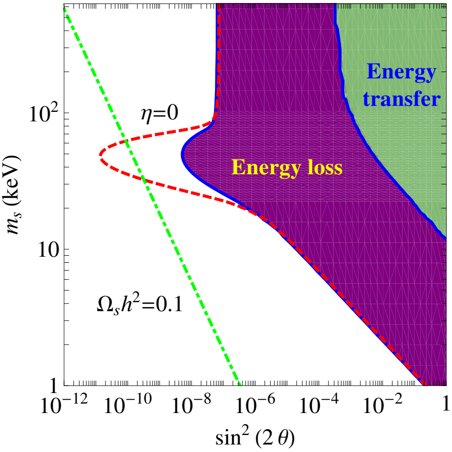


Summary and Outlook

- At moderate mixing DM production can be suppressed
- At small abundance ($\Omega_N < \Omega_{DM}$) direct searches can supersede those of X-ray satellites
- Direct tests of the seesaw prediction (Troitsk, KATRINE) become justified
- It is worth to study the resulting spectra in case of $\Omega_{DM} \simeq \Omega_N$
- Small masses are forbidden due to free-streaming
- Is it possible to make sterile neutrino DM in Superheavy case, where they are supercool, and form CDM. . . ? Yes
- Sterile neutrinos in SN explosion: many controversal results in literature even w/o hidden sector, but might compete with direct searches

Backup slides

Limits form SN



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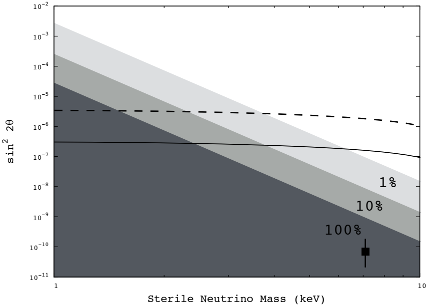

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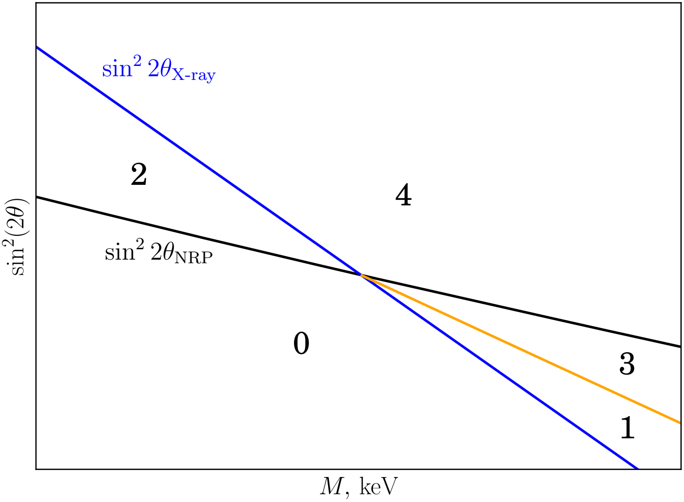
A sketch of model parameter space

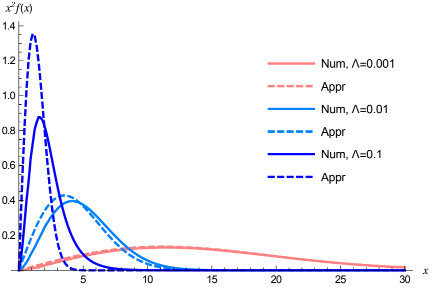


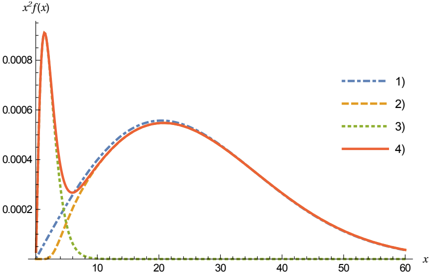
0,1: allowed even w/o scalar field

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

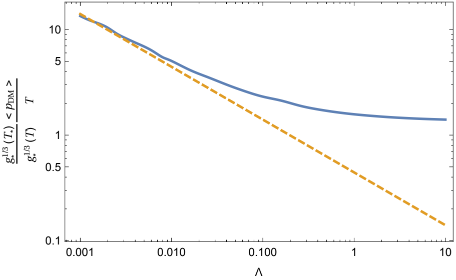
3,4: Ω_N is determined by X-ray bound

DM from Heavy scalar (Majoron?) decay





F.Bezrukov, D.G., 2014



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

$$x = \frac{p}{T}\left(\frac{g_*(T_*)}{g_*(T)}\right)^{1/3}$$

Decoupling of relativistic Dark Matter

Assumptions

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

$$n_X(T_d) = g_X \cdot \begin{pmatrix} 1 \\ \frac{3}{4} \end{pmatrix} \cdot \frac{\zeta(3)}{\pi^2}\, T_d^3$$

Later on

useful

$$n_X a^3 = \text{const}\,, \qquad s a^3 = \text{const} \qquad \Longrightarrow \qquad \frac{n_X}{s} = \text{const} = \# \frac{g_X}{g_*(T_d)}$$

DM particle mass M_X fixes Ω_X:

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

– NO heavy stable feebly coupled to SM particles !

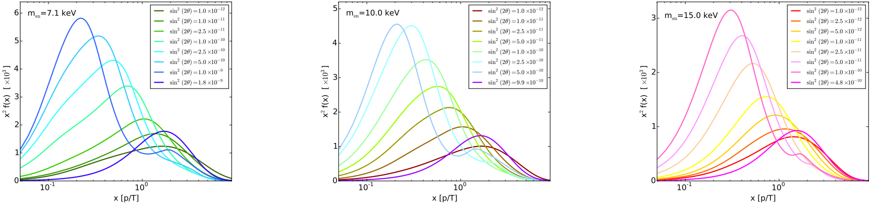
– NO realistic DM models:

Pauli blocking prevents fermionic DM

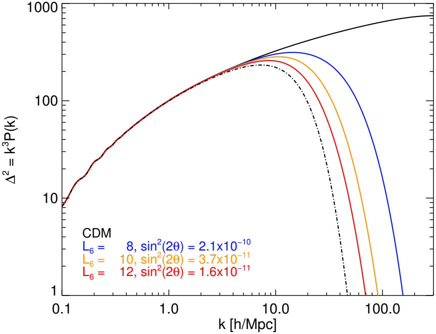
$$\frac{p_X}{M_X} \propto \frac{a_d}{a} \sim \frac{3T}{M_X}\left(\frac{g_*(T)}{g_*(T_d)}\right)^{1/3}$$

too energetic for the proper structure formation

Sterile neutrino spectra from resonant production



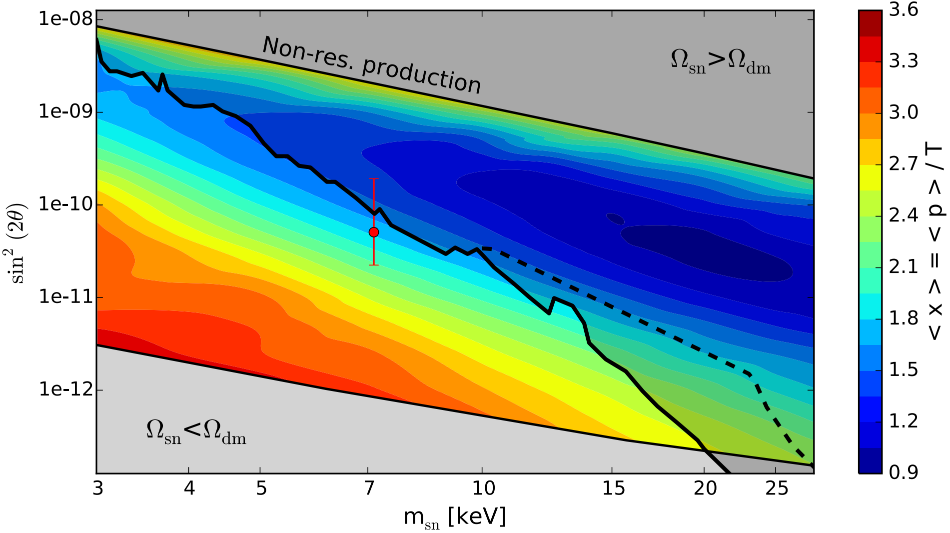
1601.07553



1611.00005

$$v = \frac{\langle p \rangle}{m} = 3.15\,\frac{T}{m}\left(\frac{g_{*,0}}{g_*}\right)^{1/3}$$

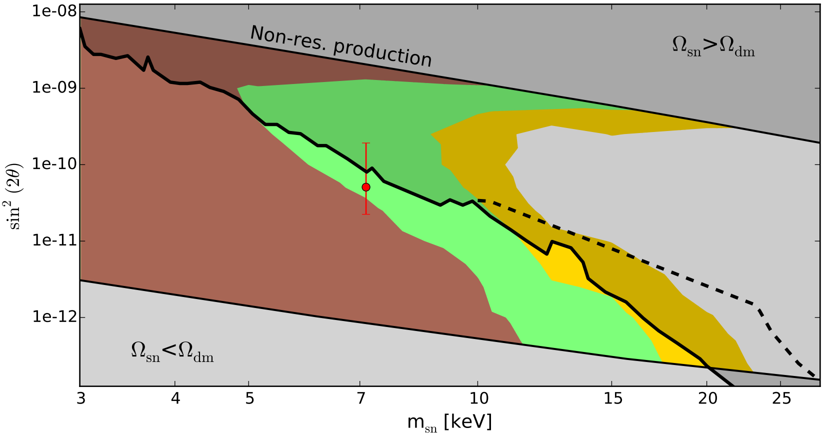
Sterile neutrino Dark Matter



A.Schneider (2016)

Sterile neutrino Dark Matter: ... gone?

A.Schneider (2016)



brown: MW satellite counts

green and yellow: Lyman-α

production by inflaton