Freeze-in and freeze-out of sterile neutrino dark matter

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Sydney-CPPC

based on work in collaboration with
Rupert Coy 2204.08795 (accepted by JCAP)

keV sterile neutrino dark matter

- Sterile neutrinos well motivated by neutrino masses
- keV sterile neutrino candidate for decaying dark matter
- Warm DM depending on mass and production mechanism

DM production

- (Resonant) neutrino oscillations
  Barbieri, Dolgov 1991; Enqvist, Kainulainen, Maalampi 1991; Dodeson, Widrow hep-ph/9303287; Shi, Fuller astro-ph/9810076;...
- Hidden decoupled sector
  Berezhiani, Mohapatra hep-ph/9505385; Berezhiani, Dolgov, Mohapatra hep-ph/9511221; Bezrukov, Hettmansperger, Lindner 0912.4415; Nemevsek, Senjanovic, Zhang 1205.0844; ...
- Real scalar decays
  Shaposhnikov, Tkachev hep-ph/0604236; Bezrukov, Gorbunov 0912.0390; Kusenko hep-ph/0609081; Kusenko, Petraki 0711.4646; Frigerio, Yaguna 1409.0659; Adulpravitchai, MS 1507.05694; Merle, Niro, Schmidt 1306.3996; Adulpravitchai, MS 1409.4330;...

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How about a complex scalar?

1602.04816

6.3.1 Decay in thermal equilibrium

Let us first analyze what happens if the parent particle S is in thermal equilibrium for all relevant temperatures. That can happen if the S-particle is strongly mixed with the neutral Higgs boson, so that all decay channels in SM particles are present and maintain it in thermal equilibrium until temperatures below its mass.

The scalar S can be either real or complex. If S acquires non-zero vacuum expectation value (VEV), then the interaction eq. (6.28) leads not only to the neutrino production, but generates also the Majorana masses for them, $M_1 = y\langle S\rangle$. In this case, and if S is complex, the model contains (pseudo) Nambu-Goldstone boson, called the Majoron [203, 734]. As a result, the sterile neutrinos may be not stable enough to form the DM because they decay into a Majoron, if it is lighter,[32] and an active neutrino. While this case is not interesting from the point of view of sterile neutrinos being the DM, the case of decaying sterile neutri-

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Complex scalar decay - model

SM + sterile neutrino N_R and complex scalar ϕ

$$\mathcal{L}_{\rm int} \supset -\frac{f}{2}\left(\phi N_R^T C N_R + \text{h.c.}\right) - \left(y_i^\nu \overline{L_i}\tilde{H} N_R + \text{h.c.}\right) + \lambda_\phi\left(|\phi|^2 - \frac{v_\phi^2}{2}\right)^2 + \kappa\left(|\phi|^2 - \frac{v_\phi^2}{2}\right)\left(H^\dagger H - \frac{v^2}{2}\right)$$

Lepton number: $N_R \sim 1$, $\phi \sim -2$

Symmetry breaking of lepton number

$$\phi(x) = \frac{v_\phi + \varphi(x)}{\sqrt{2}} e^{i\alpha(x)/v_\phi}$$

Local $B-L$ transformation

$$f \to e^{iQ_{B-L}^{(f)}\alpha(x)/2v_\phi} f$$

- Scalar φ
- pNGB (Majoron) α

$\Rightarrow$ explicit derivative couplings

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Interaction Lagrangian

Scalar interactions

$$\mathcal{L}_s = \left(\frac{\varphi}{v_\phi} + \frac{\varphi^2}{2v_\phi^2}\right) \partial_\mu \alpha \partial^\mu \alpha - V(h, \varphi)$$

Sterile neutrino interactions

$$\begin{aligned}\mathcal{L}_\nu = & -\frac{m_N}{2}\frac{\varphi}{v_\phi}\,\overline{n_{Mi}}\left[\mathrm{Re}(U_{Ni}U_{Nj}) - i\,\mathrm{Im}(U_{Ni}U_{Nj})\gamma_5\right] n_{Mj} \\ & -\frac{\partial_\mu \alpha}{4v_\phi}\,\overline{n_{Mi}}\gamma^\mu\gamma_5 n_{Mi} + g_Z Z_\mu J_Z^\mu + \left(g W_\mu^- J_W^{\mu -} + \mathrm{h.c.}\right)\end{aligned}$$

No tree-level flavour-changing couplings of the pNGB α

But flavour-changing charged and neutral currents

$$J_W^{\mu -} = \frac{U_{ij}}{\sqrt{2}}\,\overline{e_i}\gamma^\mu P_L n_{Mj} \qquad\qquad J_Z^\mu = \frac{1}{4}\sum_{\alpha=1}^{3} U_{\alpha i}^* U_{\alpha j}\overline{n_{Mi}}\gamma^\mu n_{Mj}$$

Experimental constraints

CMB constraint on $\nu - \nu$ scattering mediated by pNGB α

$$v_\phi \gtrsim 0.7\mathrm{MeV}(m_\nu/1\mathrm{eV})$$

Forastieri,Lattanzi, Natoli 1904.07810

DM decay from flavour violating interactions

DM lifetime > age of universe

- Fastest decay
  $N \to \nu Z(\to \nu\nu)$
  $\theta^2 \lesssim 3 \times 10^{-4}(10\mathrm{keV}/m_N)^5$

  Pal, Wolfenstein (1982); Barger, Phillips hep-ph/9503295
- $N \to \nu\varphi(\to \nu\nu)$
- Tree-level $N \to \nu\varphi(\to \alpha\alpha)$
- Loop-level $N \to \nu\alpha$

X-ray observations $N \to \nu\gamma$

- mediated by W boson at loop level

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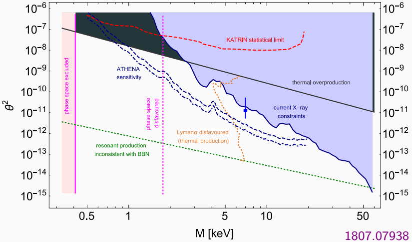

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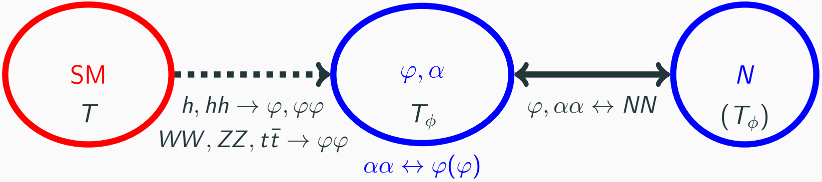
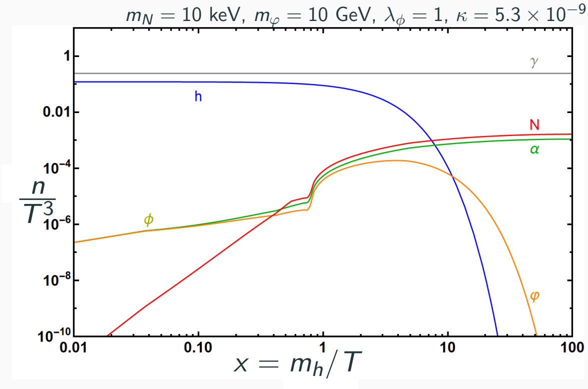
Sterile neutrino production – main idea





no active-sterile mixing

$$\mathcal{L} \supset -V(h, \varphi)$$

$$\left(\frac{\varphi}{v_\phi} + \frac{\varphi^2}{2v_\phi^2}\right) \partial_\mu \alpha \partial^\mu \alpha$$

$$-\frac{m_N}{2}\frac{\varphi}{v_\phi}\overline{N}N$$

$$-\frac{\partial_\mu \alpha}{4v_\phi}\overline{N}\gamma^\mu\gamma_5 N$$

At $T = 1$ MeV

$N_{\rm eff} = 1.2 \times 10^{-3}\left[\frac{T_\phi}{0.1\,T}\right]^4$

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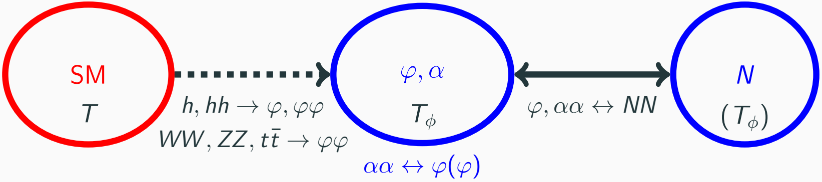

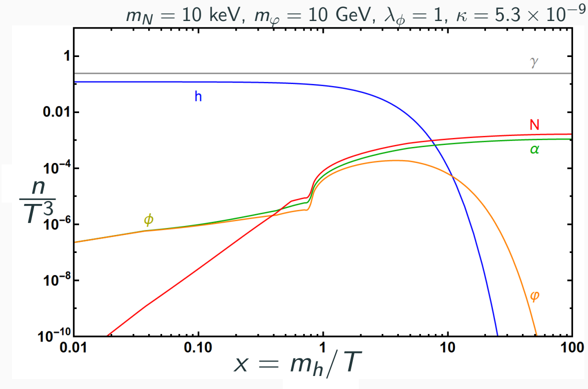

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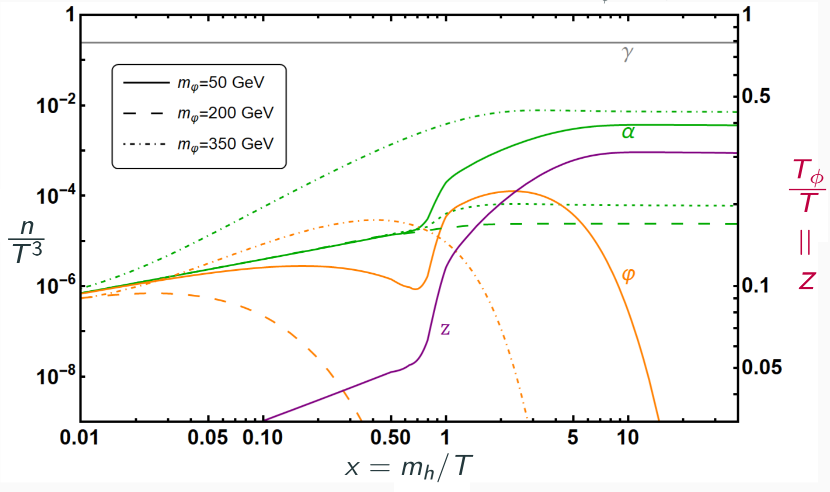
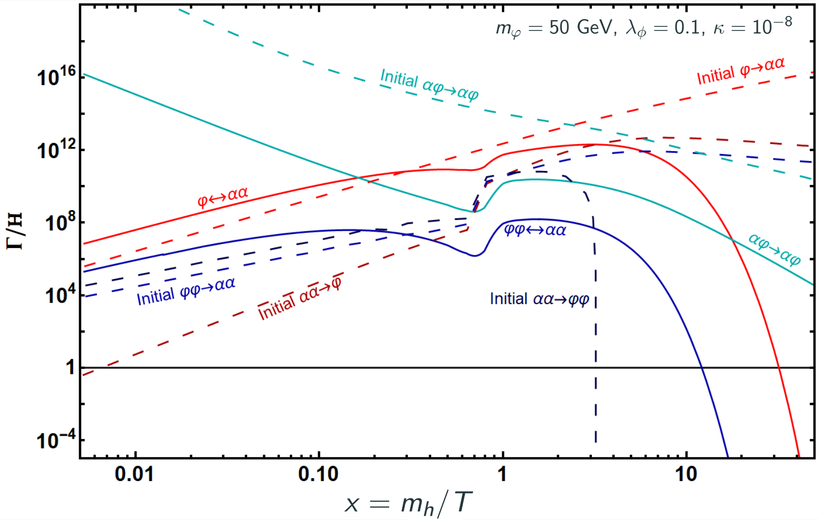
Sterile neutrino production

- energy transfer to dark sector $\frac{d(\rho_{\rm dark} a^4)}{dt} = C[\mathrm{SM} \to \phi]$
- 3 different regimes, depending on m_φ / m_h

$\lambda_\phi = 0.1,\ \kappa = 10^{-8}$

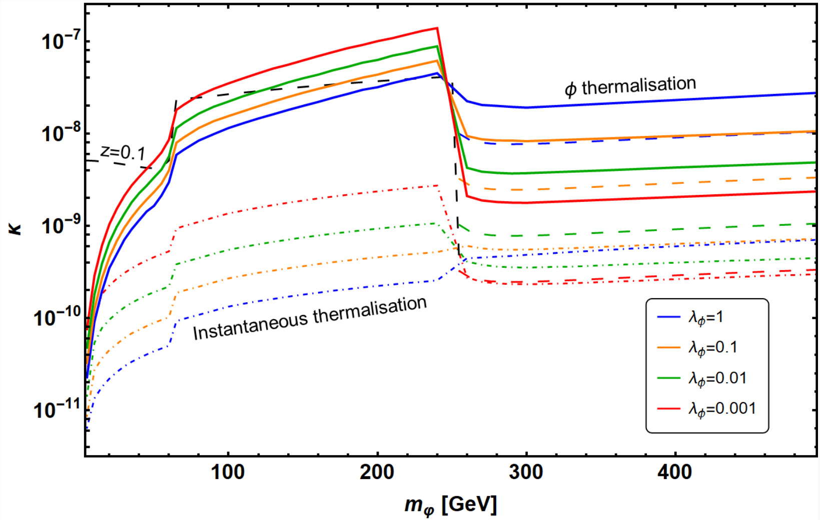


Thermalisation of dark scalar sector



- kinetic (α) and chem. (α, φ) equil.: $\langle \Gamma(\alpha\alpha \leftrightarrow \varphi(\varphi)) \rangle_\alpha > H$
- kinetic (φ) equil.: relaxation rate $x_\varphi^{-1} \langle \Gamma(\alpha\varphi \leftrightarrow \alpha\varphi) \rangle_\varphi > H$

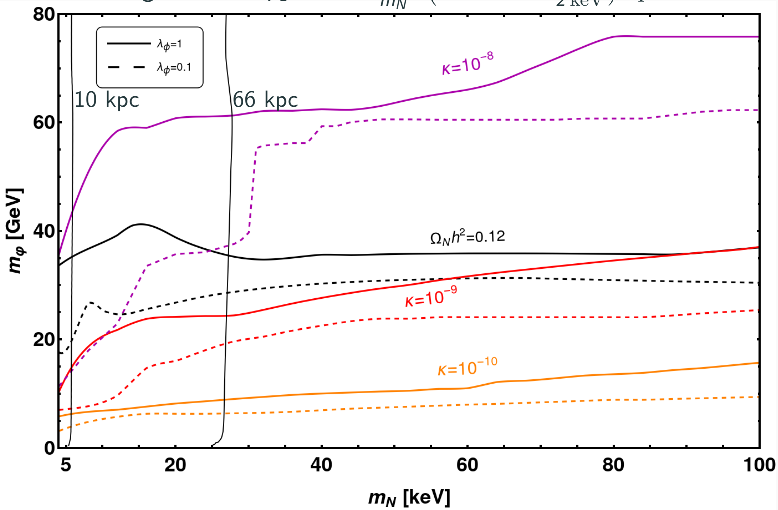
Thermalisation of dark scalar sector - results



- observed DM abundance for $z \simeq 0.1$
- Thermalisation if (a) $\Gamma > H$ preceeded by $\Gamma_{\text{initial}} > H$ and in addition (b) more than 80% of ϕ produced

Thermalisation of keV sterile neutrinos - results

free-streaming horizon $\lambda_{FS} \simeq 366 \frac{z\,\mathrm{keV}}{m_N} \left(7.299 + \ln \frac{m_N}{z\,\mathrm{keV}}\right) \mathrm{kpc}$



- Thermalization achieved below lines of constant κ (coloured)
- constant DM abundance (black)

Summary and conclusions

keV sterile neutrino with complex scalar is viable DM scenario

pNGB may thermalise dark sector

both warm and cold DM possible

The Dark Side of the Universe

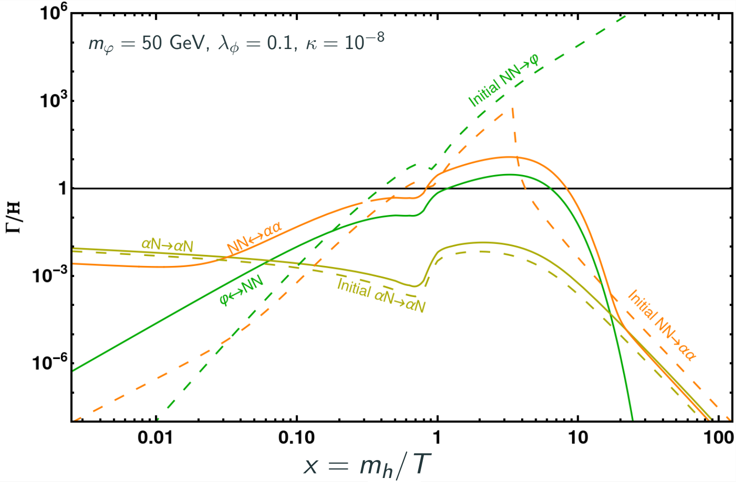
DSU2022

5-9 December 2022

https://indico.cern.ch/event/1107937

Backup slides

Thermalisation of keV sterile neutrinos



- φ, α in kinetic and chemical equilibrium
- kin. and chemical equil. $\langle\Gamma(\varphi \leftrightarrow NN)\rangle_N, \langle\Gamma(\alpha\alpha \leftrightarrow NN)\rangle_N > H$
- kinetic equilibrium $\langle\Gamma(\alpha N \leftrightarrow \alpha N)\rangle_N > H$