Sterile neutrino dark matter from scalar decay

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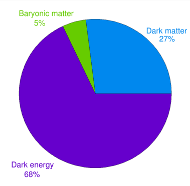
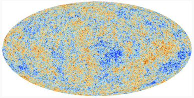
The University of New South Wales Sydney
Sydney-CPPC

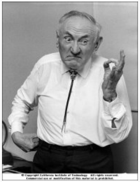
based on work in collaboration with
Rupert Coy JCAP 08 (2022) 070 [2204.08795]
Adisorn Adulpravitchai JHEP 01 (2015) 006 [1409.4330]
Adisorn Adulpravitchai JHEP 12 (2015) 023 [1507.05694]

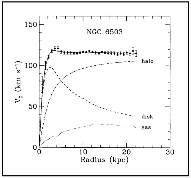
Dark Matter

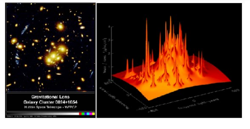
- Virial theorem $\left(\frac{1}{2}\left\langle v^2\right\rangle = \frac{GM}{R}\right)$ applied to COMA cluster (F.Zwicky 1933)
- Galactic rotation curves $[\mathcal{O}(10s)\mathrm{kpc}]$
- Gravitational lensing $[< \mathcal{O}(200)\mathrm{kpc}]$
- Bullet cluster (X-ray + grav. lensing)
- Cosmic microwave background
  Large scale structure
- ...





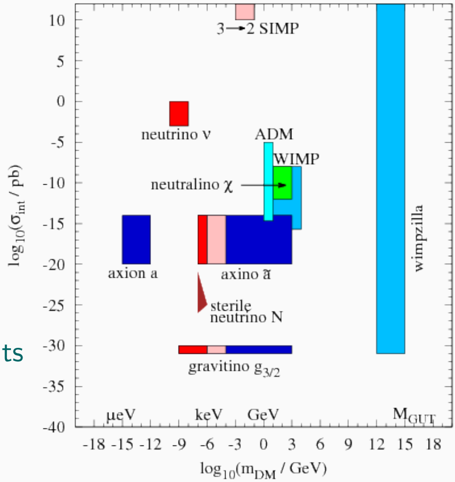






Properties of Dark Matter

- Lifetime larger than age of universe
- Relic density Planck 1807.06209
  $\Omega_{dm}h^2 = 0.120 \pm 0.001$
- Structure formation
  $\Rightarrow$ DM sufficiently cold
- Not excluded by direct or indirect searches
- Compatible with constraints on self-interactions



1407.0017

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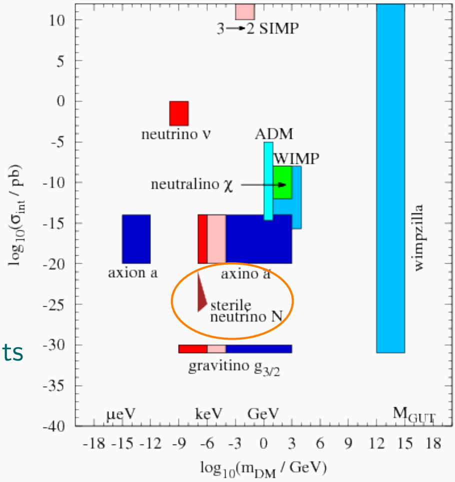
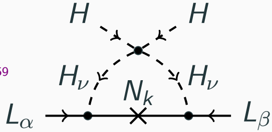


1407.0017

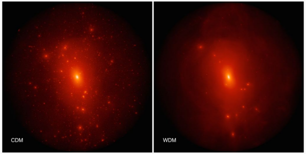
keV sterile neutrinos

Well motivated via their link to neutrino masses

- keV sterile neutrino in seesaw model
  mixing with active neutrinos $\Rightarrow$ Decaying DM
- Fermionic DM in radiative seesaw Ma hep-ph/0601225
  Stable DM
  produced via freeze-in Molinaro, Yaguna, Zapata 1405.1259



Warm dark matter candidate



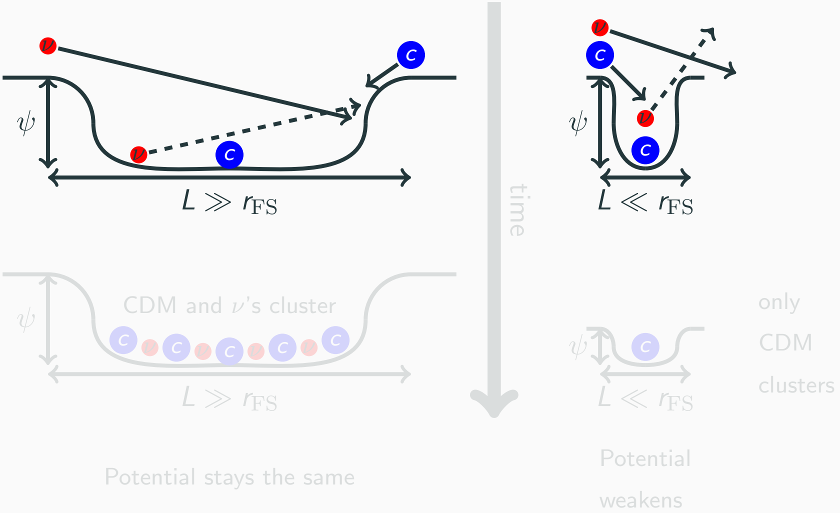
may wash out structure
at small scales
$\Rightarrow$ ease small-scale structure issues

Lovell et al. 1104.2929

Suppression of small scale structure

Size of astrophysical object: L

Free-streaming scale: $r_{\mathrm{FS}} = \int_{t_i}^{t_0} \frac{\langle v(t) \rangle}{a(t)} dt$



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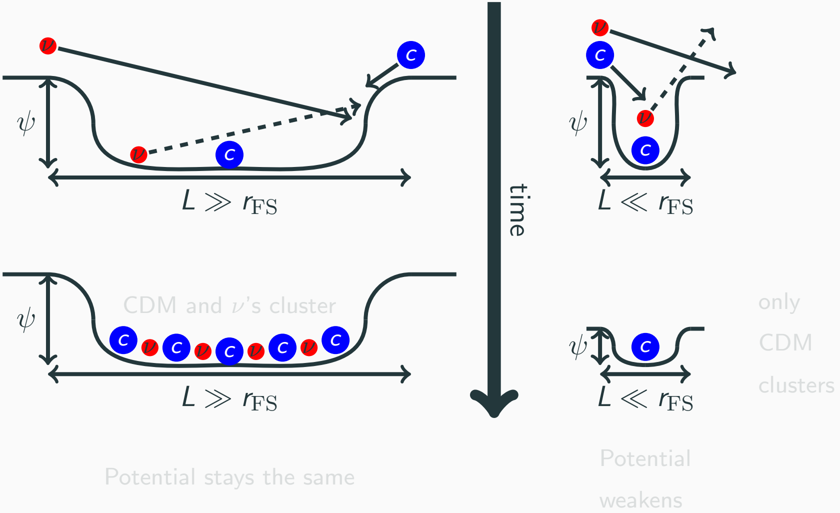

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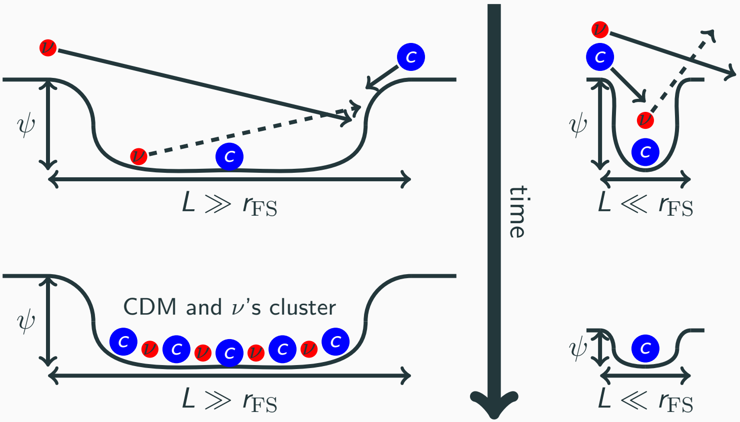
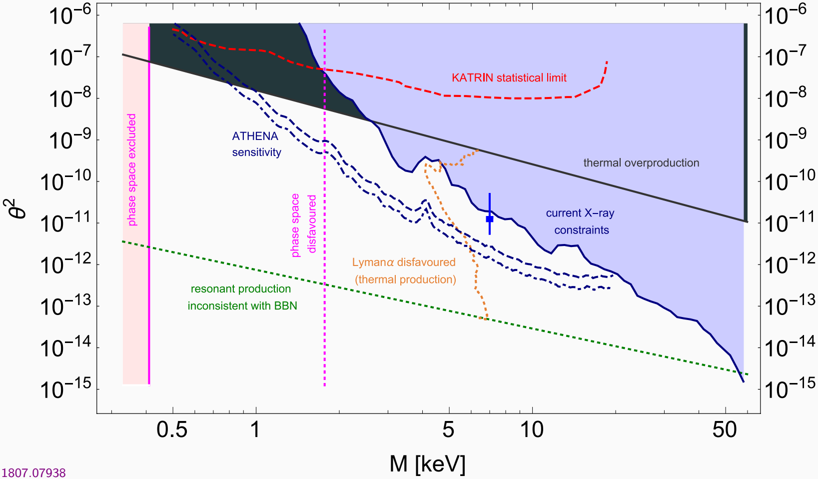


only CDM clusters

Potential stays the same

Potential weakens

Constraints



1807.07938

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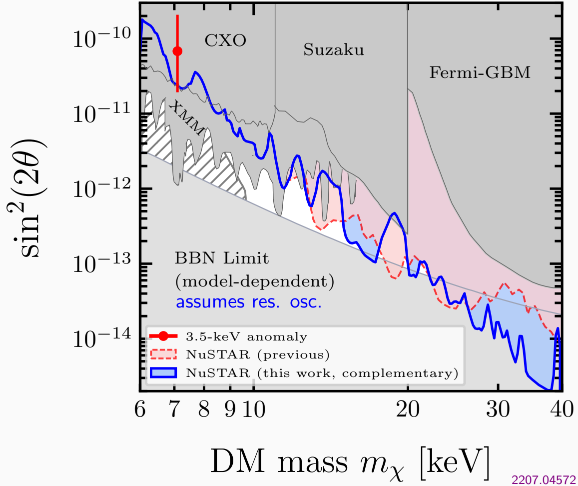

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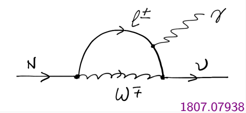
X-ray observations



1807.07938

Grey-hatched: Structure formation constraints

$$\Gamma = \frac{9\alpha G_F^2 m_N^5}{1024\pi^4}\sin^2(2\theta) = 5.5\times10^{-22}\left(\frac{m_N}{\mathrm{keV}}\right)^5 \mathrm{s}^{-1}$$

Sterile Neutrino DM Production

Neutrino oscillations Barbieri, Dolgov 1991; Enqvist, Kainulainen, Maalampi 1991

- Non-resonant oscillations – Dodelson-Widrow mechanism
  Dodeson, Widrow hep-ph/9303287
- Resonant oscillations – Shi-Fuller mechanism Shi, Fuller astro-ph/9810076

Thermal production

- Hidden decoupled (mirror) sector
  Berezhiani, Mohapatra hep-ph/9505385; Berezhiani, Dolgov, Mohapatra hep-ph/9511221
- New gauge interaction and entropy dilution
  Bezrukov, Hettmansperger, Lindner 0912.4415; Nemevsek, Senjanovic, Zhang 1205.0844

Scalar decays **[if via same coupling as oscillations typically subdominant]**

- Inflaton decay Shaposhnikov, Tkachev hep-ph/0604236; Bezrukov, Gorbunov 0912.0390
- In thermal equilibrium
  Kusenko hep-ph/0609081; Kusenko, Petraki 0711.4646; Frigerio, Yaguna 1409.0659; Adulpravitchai, MS 1507.05694
- Out of thermal equilibrium Merle, Niro, Schmidt 1306.3996; Adulpravitchai, MS 1409.4330
- Complex scalar decay Coy, MS 2204.08795

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Real scalar:
out-of-equilibrium decay [1409.4330]

Model

- New particles: sterile neutrino N and real scalar ϕ

- Lagrangian [discrete Z_4 lepton number with charges $L(1)$, $N(-1)$, $\phi(2)$]

$$-\Delta\mathcal{L} = -\frac{\kappa}{2} H^\dagger H \phi^2 + \left[y^\nu LHN + \frac{f}{2}\phi N^2 + \mathrm{h.c.} \right]$$

- Effective scalar interaction after EWSB $[\langle H \rangle = \begin{pmatrix} 0 & v \end{pmatrix}^T$ and $\phi = v_\phi + \varphi]$

$$\Delta V(h, \varphi) = \kappa \left(\frac{h^2 \varphi^2}{4} + \frac{v}{\sqrt{2}} h \varphi^2 \right)$$

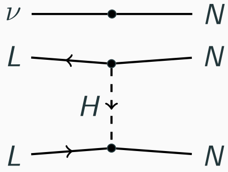
- Neutrino mixing: $\propto \frac{y^\nu v}{f v_\phi} \ll 1$

- Sterile neutrino DM production
    - φ in thermal equilibrium $[\kappa$ sizeable$]$ Petraki, Kusenko 0711.4646
    - φ frozen in $[\kappa \ll 1]$ Merle, Niro, Schmidt 1306.3996; Adulpravitchai, MS 1409.4330

See also Merle, Totzauer 1502.01011; König, Merle, Totzauer 1609.01289

Sterile Neutrino DM Production

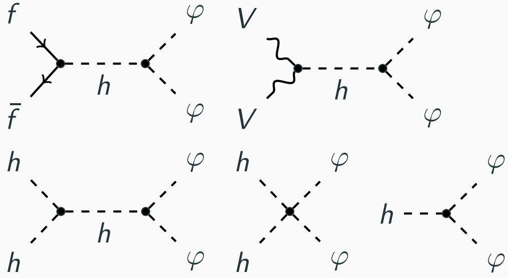
SM$\rightarrow N$



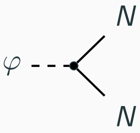
Dominantly two step production

SM $\xrightarrow{1}$ φ $\xrightarrow{2}$ N

SM $\rightarrow \varphi$



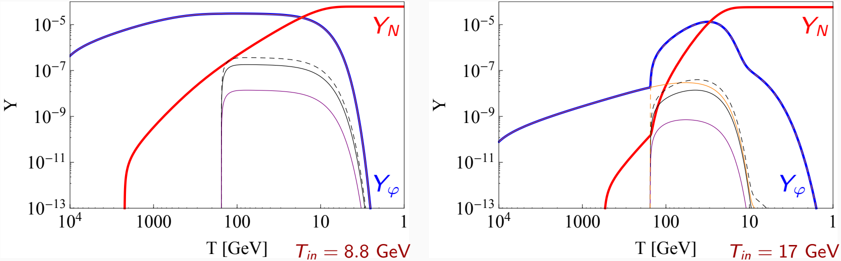
$\varphi \rightarrow N$



Several approximations:
$g_* = \mathrm{const}$,
no finite T effects, . . .

Dark Matter Abundance [1409.4330]

$m_\varphi = 500\mathrm{GeV};\ \kappa = 2.7 \cdot 10^{-7}$ $m_\varphi = 30\mathrm{GeV};\ \kappa = 3.7 \cdot 10^{-9}$



Higgs annihilation solid (decay dashed), ZZ (solid), WW (dashed); $t\bar{t}$

$m_N = 7.1$ keV; $\lambda_\phi = 0.5$

Dark matter abundance [$\Omega_{\mathrm{DM}} h^2 \simeq 0.120 \pm 0.001$ Planck1807.06209]

$$\Omega_N \simeq \frac{m_N\, Y_N^\infty s(T_0)}{\rho_c}$$

Higgs decays dominant contribution when kinematically accessible

Suppression of Small Scale Structure

- Free streaming horizon e.g. Boyarsky, Lesgourges, Ruchayskiy, Viel 0812.0010

$$r_{FS} \simeq \int_{t_d}^{t_0} \frac{\langle v(t)\rangle}{a(t)} dt = \int_{t_d}^{t_{nr}} \frac{1}{a(t)} dt + \int_{t_{nr}}^{t_{eq}} \frac{\langle v(t)\rangle}{a(t)} dt + \int_{t_{eq}}^{t_0} \frac{\langle v(t)\rangle}{a(t)} dt$$

t_d decay time; t_{eq} time of matter-radiation equality; t_0 today

Hasenkamp, Kersten 1212.4160; Merle, Niro, Schmidt 1306.3996; Adulpravitchai, MS 1409.4330

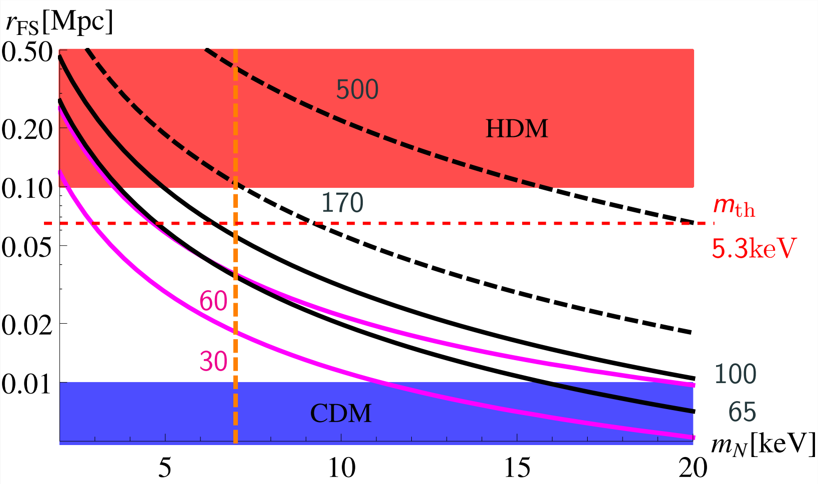
- Average velocity

$$\langle v(t)\rangle = \begin{cases} 1 & \text{for } t < t_{nr} \\ \frac{\langle p\rangle}{m_N} & \text{for } t > t_{nr} \end{cases}$$

- Sterile neutrino become non-relativistic at time t_{nr} with

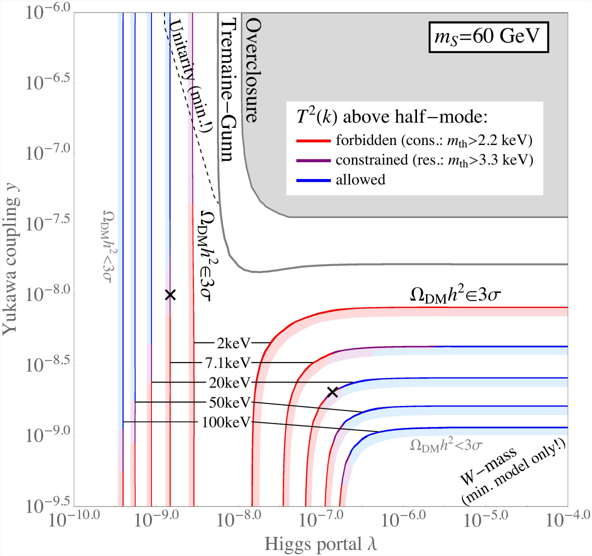
$$m_N = \langle p(T_{nr})\rangle \simeq \frac{\sqrt{\pi}}{2} T_{nr} \quad \Rightarrow \quad t_{nr} \simeq \frac{\pi}{16} \frac{m_\varphi^2}{m_N^2} \left(\frac{g_*^s(T_0)}{g_*^s(T_{in})}\right)^{2/3} t_{in}$$

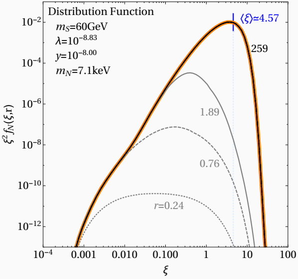
Free-Streaming Horizon $\quad r_{FS} \simeq \frac{\sqrt{t_{eq} t_{nr}}}{a_{eq}} \left(5 + \ln \frac{t_{eq}}{t_{nr}}\right)$



$$r_{FS} \simeq 0.366 \frac{z\,\mathrm{keV}}{m_{\rm th}} \left(7.299 + \ln \frac{m_{\rm th}}{z\,\mathrm{keV}}\right) \mathrm{Mpc} \qquad \text{with} \quad z = \frac{T_{\rm dm}}{T}$$

Full calculation of distribution functions [1609.01289]





$$r = \frac{m_\varphi}{T}$$

$$\xi = \left(\frac{g_s(T_0)}{g_s(T)}\right)^{1/3} \frac{p}{T}$$

Features due to EWPT

Real scalar decay:
in thermal equilibrium [1507.05694]

Neutrinophillic Two-Higgs Doublet Model [1507.05694]

- New particles odd under Z_2

  Sterile neutrino $N \to -N$

  Second Higgs doublet $H_\nu \to -H_\nu$

- Lagrangian

$$-\mathcal{L}_N = y_{LN} L H_\nu N + \frac{1}{2} m_N N\, N + \mathrm{h.\,c.}$$

- Scalar potential

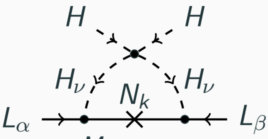
$$V = \mu_\nu^2 H_\nu^\dagger H_\nu + \frac{\lambda_2}{2}(H_\nu^\dagger H_\nu)^2$$
$$+ \lambda_3 H^\dagger H\, H_\nu^\dagger H_\nu + \lambda_4 |H^\dagger H_\nu|^2 + \frac{\lambda_5}{2}[(H^\dagger H_\nu)^2 + \mathrm{h.\,c.}]$$

- Scalar particle masses $m_{kk}^2 = \mu_\nu^2 + (\lambda_3 + \lambda_4)\, v^2$

$$m_{k,K^0}^2 = m_{kk}^2 \pm \lambda_5 v^2 \qquad m_{K^\pm}^2 = m_{kk}^2 - \lambda_4 v^2$$

Neutrino Mass

Radiative seesaw Ma hep-ph/0601225; Molinaro, Yaguna, Zapata 1405.1259



- H_ν does not obtain VEV
- Radiative neutrino mass generation

$$m_\nu \simeq 10^{-2}\mathrm{eV}\left(\frac{\lambda_5 y_{2,3}^2}{10^{-11}}\right) \times \begin{cases} \left(\frac{1\mathrm{TeV}}{M_{2,3}}\right) & m_{kk} \ll M_{2,3} \\ \left(\frac{1\mathrm{TeV}}{m_{kk}}\right)\left(\frac{M_{2,3}}{m_{kk}}\right) & m_{kk} \gg M_{2,3} \end{cases}$$

- keV sterile neutrino does not (significantly) contribute
- Sterile neutrino is stable

Naturally small seesaw Ma hep-ph/0011121; Haba, Ishida, Takahashi 1407.6827

- Soft-breaking term $V_{\mathrm{soft}} = \mu_{12}^2 H^\dagger H_\nu + \mathrm{h.c.}$

$\Rightarrow$ Induced VEV $\frac{\langle H_\nu \rangle}{v} = \frac{\mathrm{Re}(\mu_{12}^2)}{m_k^2} + i\frac{\mathrm{Im}(\mu_{12}^2)}{m_{K^0}^2}$

- Active-sterile mixing $\theta_\alpha \simeq \frac{y_{LN,\alpha}\langle H_\nu \rangle}{m_N}$

$\Rightarrow$ Possible X-ray line signal

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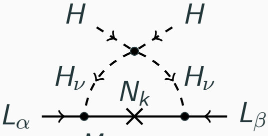

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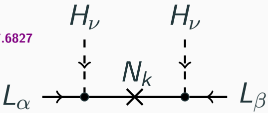

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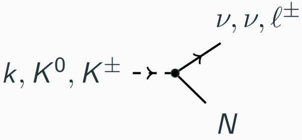
Scalar decay



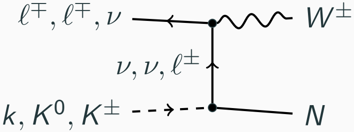
- Dominating for $T \lesssim m_{kk}$
- One daughter has Fermi-Dirac distribution

$\Rightarrow$ Pauli-blocking

Scattering

- Scattering suppressed for $T \lesssim m_{kk}$
- Neglected in analytic study

$\Rightarrow$ Freeze-in IR dominated



Derived analytic solution to Boltzmann equation

Finite temperature corrections neglected among other approximations.

See Drewes, Kang 1510.05646 for finite temperature corrections

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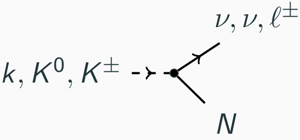

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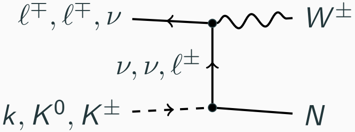

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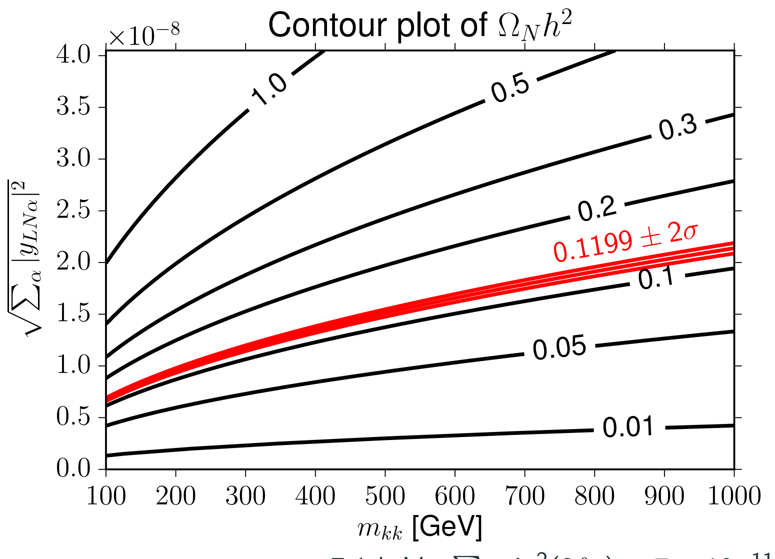
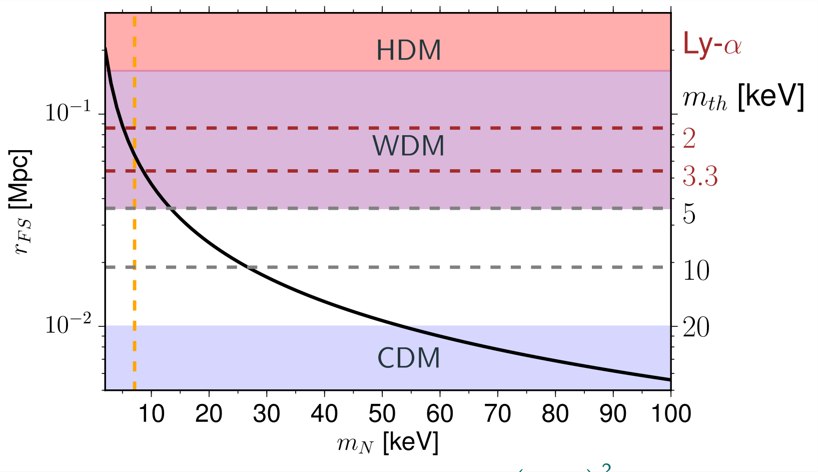
Dark Matter Abundance



$m_N = 7.1$ keV, $\sum_\alpha \sin^2(2\theta_\alpha) \simeq 7 \times 10^{-11}$

Contribution from non-resonant oscillations negligible

Free-Streaming Horizon

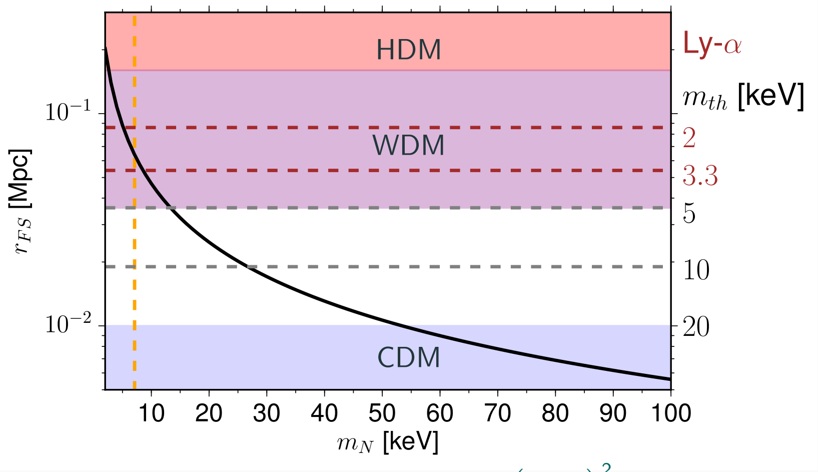


$$m_N = \langle p(T_{nr}) \rangle \simeq 2.46\, T_{nr} \quad \Rightarrow \quad t_{nr} \simeq 1500\mathrm{s} \left(\frac{10\mathrm{keV}}{m_N} \right)^2$$

$$\Rightarrow r_{FS} = \frac{\sqrt{t_{eq} t_{nr}}}{a_{eq}} \left(5 + \ln \frac{t_{eq}}{t_{nr}} \right) \simeq 0.047\, \mathrm{Mpc} \left(\frac{10\mathrm{keV}}{m_N} \right)$$

$$1\mathrm{keV} < m_{th} < 5\mathrm{keV} \Rightarrow 2.5\,\mathrm{keV} \lesssim m_N \lesssim 13\,\mathrm{keV}$$

Free-Streaming Horizon

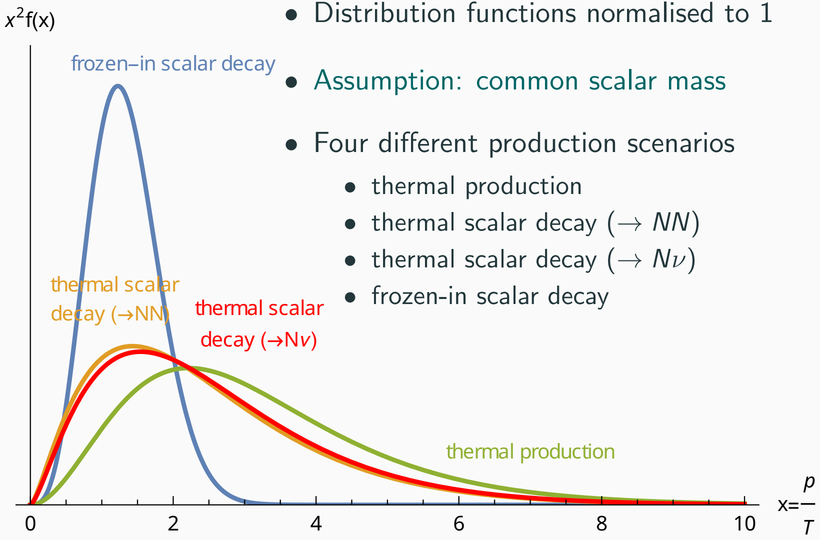


$$m_N = \langle p(T_{nr}) \rangle \simeq 2.46\, T_{nr} \quad \Rightarrow \quad t_{nr} \simeq 1500\mathrm{s} \left(\frac{10\mathrm{keV}}{m_N}\right)^2$$

$$\Rightarrow r_{FS} = \frac{\sqrt{t_{eq} t_{nr}}}{a_{eq}} \left(5 + \ln \frac{t_{eq}}{t_{nr}}\right) \simeq 0.047\,\mathrm{Mpc} \left(\frac{10\mathrm{keV}}{m_N}\right)$$

$$1\mathrm{keV} < m_{th} < 5\mathrm{keV} \Rightarrow 2.5\,\mathrm{keV} \lesssim m_N \lesssim 13\,\mathrm{keV}$$

How cold is sterile neutrino DM?



- Distribution functions normalised to 1
- Assumption: common scalar mass
- Four different production scenarios
  - thermal production
  - thermal scalar decay ($\rightarrow NN$)
  - thermal scalar decay ($\rightarrow N\nu$)
  - frozen-in scalar decay

Complex scalar decay: thermalised [2204.08795]

Complex scalar decay - model

SM + sterile neutrino N_R and complex scalar ϕ

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

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

Symmetry breaking of lepton number

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

Scalar φ, pNGB (Majoron) α

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

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Sterile neutrino interactions

Local $B-L$ transformation

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

$\Rightarrow$ explicit derivative couplings

$$\mathcal{L}_\nu = -\frac{m_N}{2}\frac{\varphi}{v_\phi}\,\overline{n_{Mi}}\left[\mathrm{Re}(U_{Ni}U_{Nj}) - i\mathrm{Im}(U_{Ni}U_{Nj})\gamma_5\right] n_{Mj}$$
$$-\frac{\partial_\mu\alpha}{4v_\phi}\,\overline{n_{Mi}}\gamma^\mu\gamma_5 n_{Mj}(U^\dagger P U)_{ij} + g_Z Z_\mu J^\mu_Z + \left(g W^-_\mu J^{\mu -}_W + \mathrm{h.c.}\right)$$

Flavour-changing charged and neutral currents

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

with $P = \mathrm{diag}(1,1,1,-1)$ and the mixing matrix U, $\hat{n}_{M\alpha} = U n_{Mi}$

$\Rightarrow$ Dominant sterile neutrino decay $N \to \nu\alpha$ with $(U^\dagger P U)_{\nu N} \sim 2\theta$

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: $N \to \nu\alpha$
  $\sin^2(2\theta) \lesssim 10^{-25} \frac{v_\phi}{\mathrm{GeV}} \left(\frac{10\mathrm{keV}}{m_N}\right)^3$
- $N \to \nu Z(\to \nu\nu)$
  $\sin^2(2\theta) \lesssim 1.2 \times 10^{-3} \left(\frac{10\mathrm{keV}}{m_N}\right)^5$

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

X-ray observations $N \to \nu\gamma$
via W boson loop

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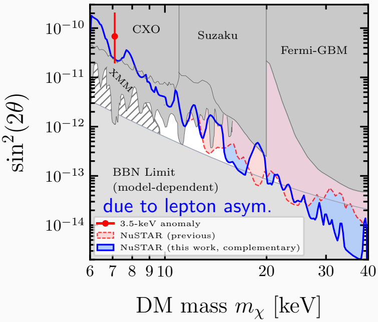
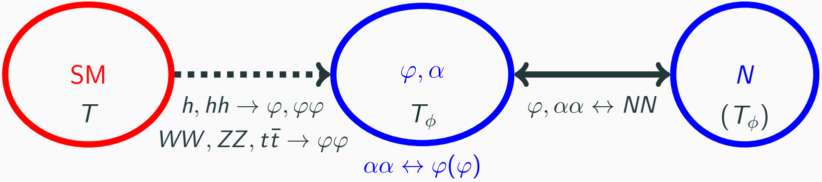
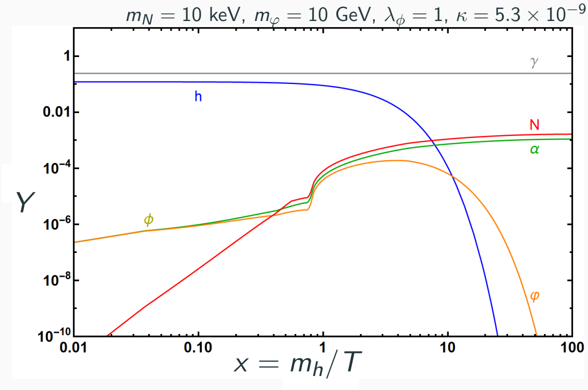


2207.04572

Sterile neutrino production – main idea





no active-sterile mixing

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

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

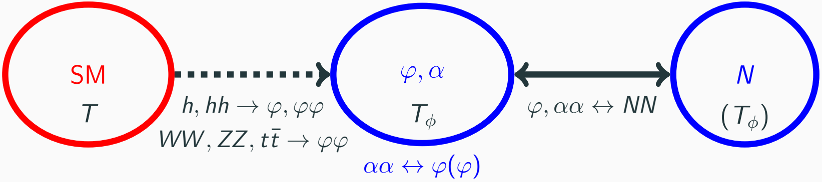
$$-\frac{m_N}{2}\frac{\varphi}{v_\phi}\overline{N}N$$

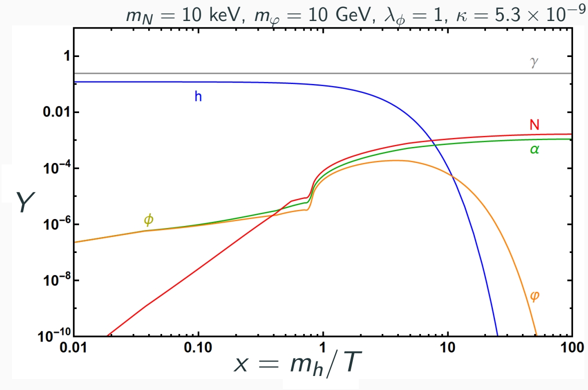
$$-\frac{\partial_\mu\alpha}{4v_\phi}\overline{N}\gamma^\mu\gamma_5 N$$

At $T = 1$ MeV

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

Sterile neutrino production – main idea





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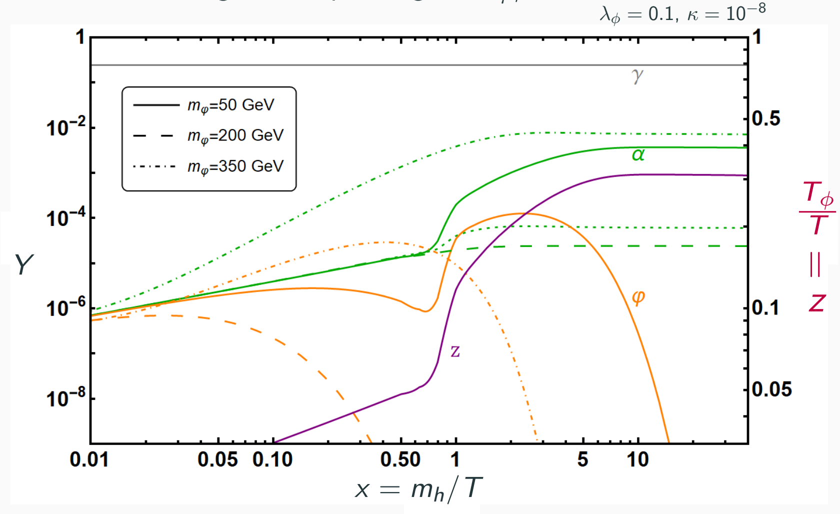
At $T = 1$ MeV

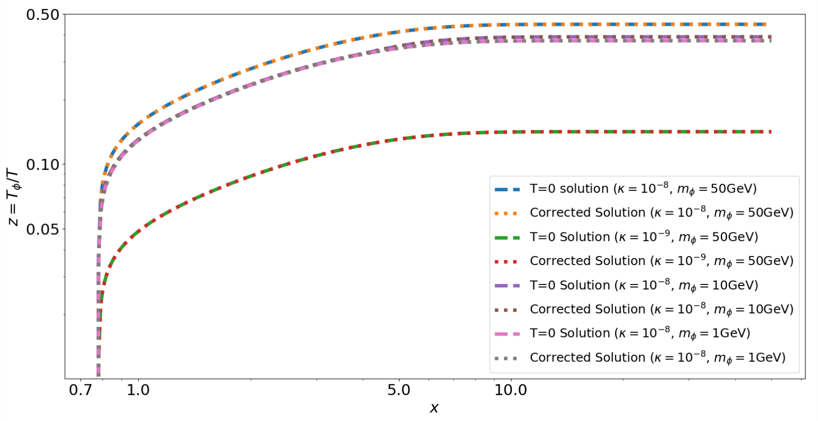
$N_{\rm eff} = 1.2 \times 10^{-3}\left[\frac{T_\phi}{0.1\,T}\right]^4$

Sterile neutrino production – scalar sector

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

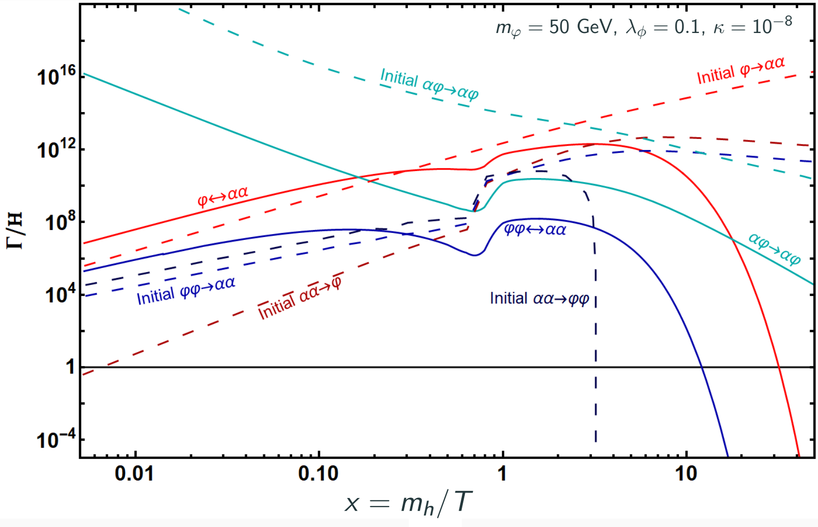


Thermal corrections



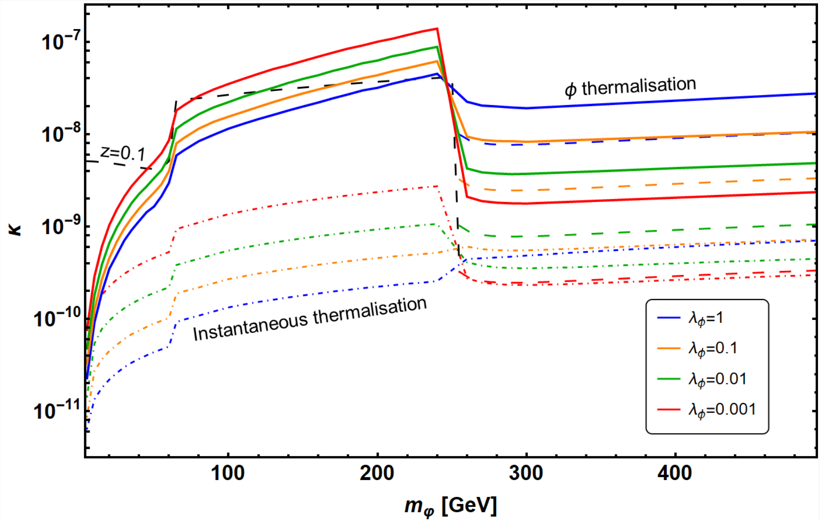
- Thermal corrections dominantly due to thermal scalar masses
- only relevant for temperatures close to critical temperature
- corrections generally $\lesssim 2\%$

Thermalisation of dark scalar sector



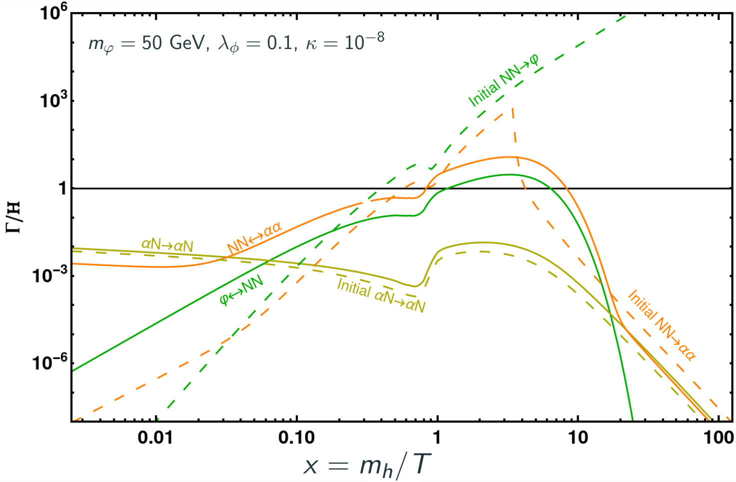
- kinetic (α) and chem. (α, φ) equil.: $\langle \Gamma(\alpha\alpha \leftrightarrow \varphi(\varphi)) \rangle_\alpha > H$
- kinetic (φ) equil.: relaxation rate $x_\varphi^{-1} \langle \Gamma(\alpha\varphi \leftrightarrow \alpha\varphi) \rangle_\varphi > H$

Thermalisation of dark scalar sector - results



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

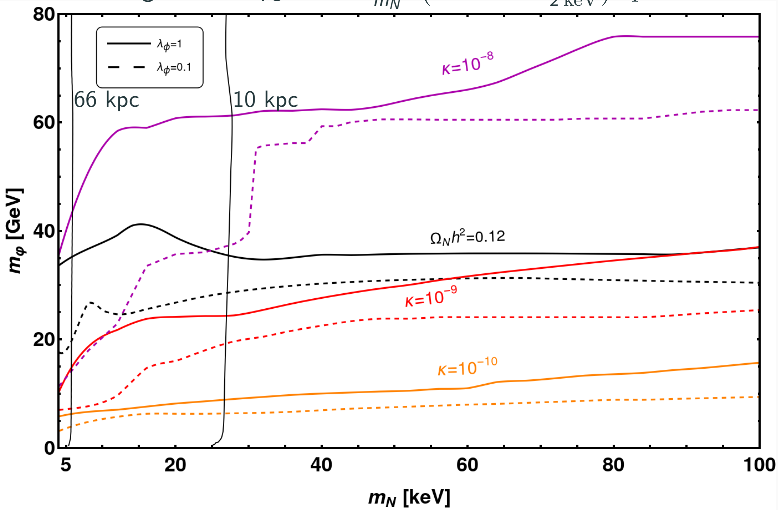
Thermalisation of keV sterile neutrinos



- 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 $\langle\Gamma(\alpha N \leftrightarrow \alpha N)\rangle_N > H$

Thermalisation of keV sterile neutrinos - results

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



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

Summary: Take-home messages

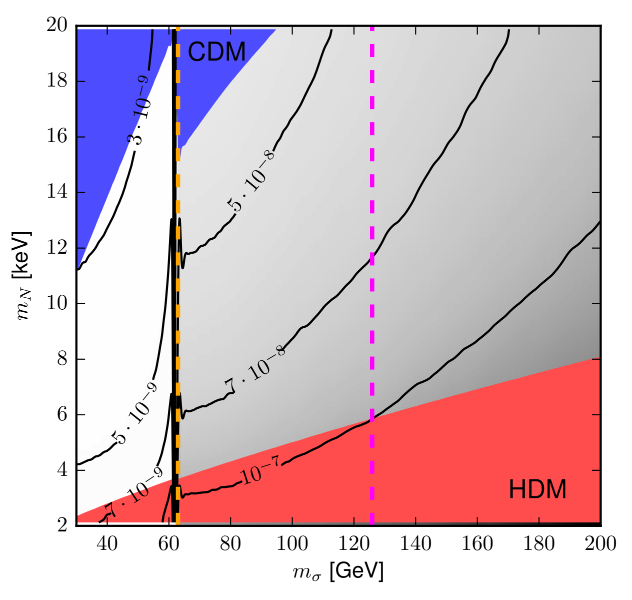
keV sterile neutrino from scalar decay is viable DM scenario

DM distribution (and thus free-streaming horizon) sensitive to production mechanism

pNGB in case of complex scalar may thermalise dark sector

Backup slides

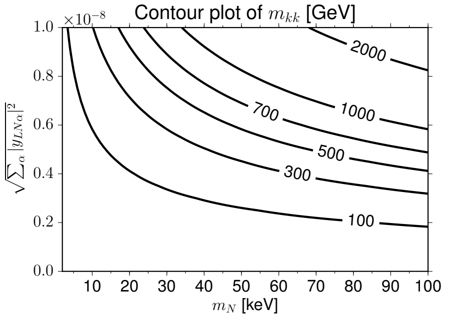
Real scalar - Higgs portal coupling [1409.4330]

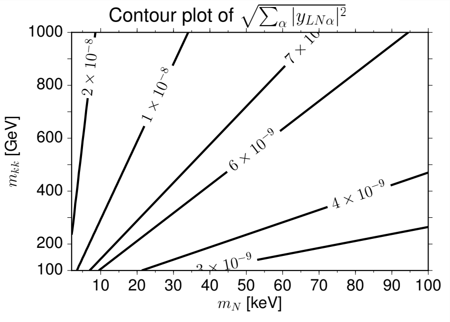


CDM: $r_{FS} \leq 10$ kpc

HDM: $r_{FS} \geq 100$ kpc

Dark Matter Abundance II



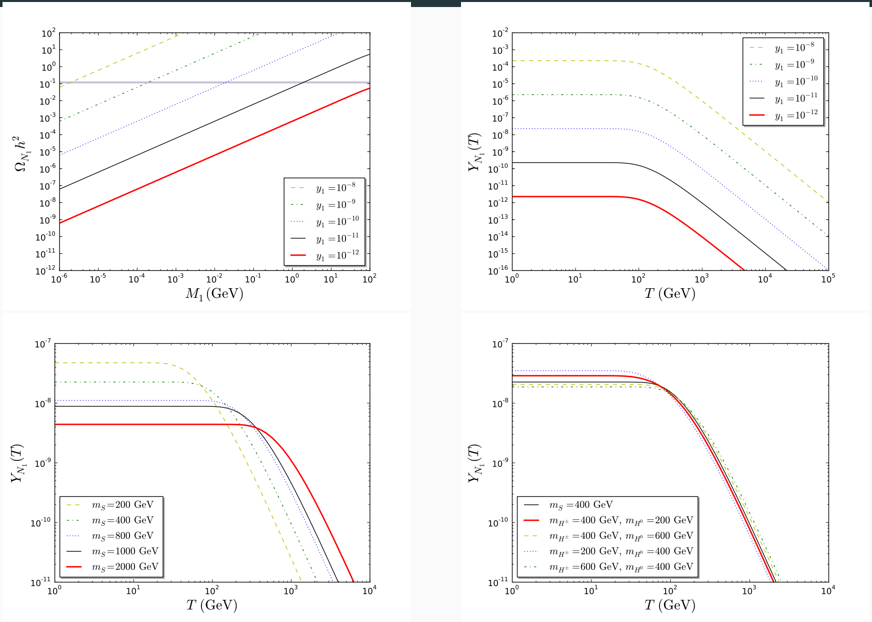


DM abundance

$$\Omega_N h^2 \simeq 3.5 \times 10^{15} \frac{m_N}{10\mathrm{keV}} \frac{100\mathrm{GeV}}{m_{kk}} \sum_\alpha |y_{LN,\alpha}|^2$$

$\Rightarrow$ Yukawa couplings $\sim 10^{-8}$ for scalars at TeV scale

Dark Matter Abundance [Pauli blocking neglected]



study of fermionic FIMP DM in radiative seesaw model Molinaro, Yaguna, Zapata 1405.1259