Sterile neutrino production in presence of non-standard self interactions

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Introduction

Aim

Study the effect of **Non-Standard neutrino Self-Interactions (NSSIs)** on non-resonant production of **sterile neutrino dark matter** in a model independent EFT framework.

Result

- Self-interactions can enhance or suppress sterile neutrino production depending on the NSSI strength
- Thus, DW mechanism can evade astrophysical constraints or move closer to experimental sensitivities.

Overview

Dodelson-Widrow Mechanism

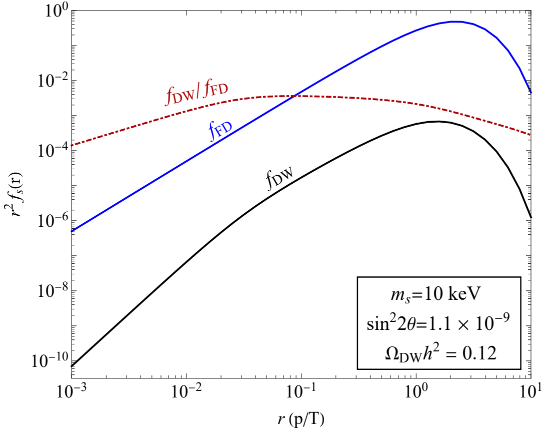
Dodelson-Widrow Mechanism

- Most generic sterile neutrino production mechanism
- Introduced by Dodelson and Widrow in 1994

  (Dodelson & Widrow, Sterile neutrinos as dark matter, PRL 72 (1994))
- Assumptions:
  - Lepton symmetric universe ($\mathcal{L}^{\alpha} = 0$)
    $\Rightarrow$ Non-resonant production
  - Negligible initial abundance of sterile neutrinos
    $\Rightarrow$ Sterile neutrino never reaches equilibrium with the plasma
- Freeze-in production of sterile neutrino dark matter via active-sterile transition

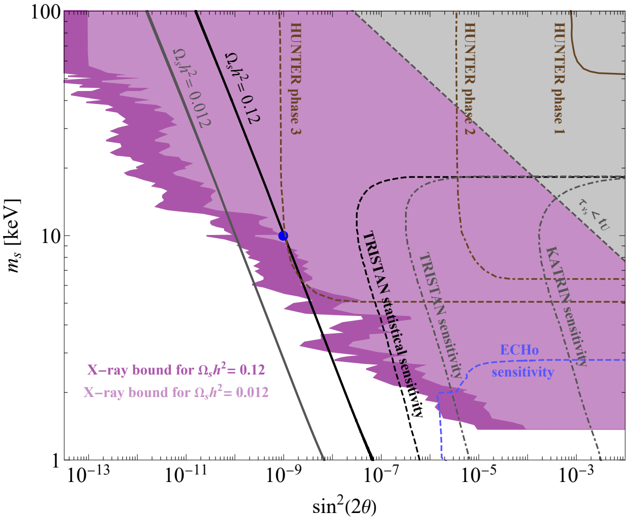
Standard Dodelson-Widrow mechanism

- Solving semi-classical Boltzmann equation from QKE Abazajian, Fuller, & Patel, PRD 64 (2001), 023501



Sterile neutrino distribution function

Standard Dodelson-Widrow mechanism



Relic Abundance parameter space

Standard Dodelson-Widrow mechanism

Standard Dodelson-Widrow scneario:

- produces a non-thermal momentum distribution
- parameter space is almost closed by astrophysical constraints
- cannot be reached by present neutrino experiments
- can be modified by non-zero lepton asymmetry!
  (Shi-Fuller mechanism)
  requires large lepton asymmetry ($\mathcal{L}^\alpha \sim 10^{-4} \gg \eta_B$)
- How can we modify DW parameter space without lepton asymmetry?
  Non-standard interactions involving active neutrinos!

Non-Standard Self-Interactions (NSSIs)

Non-Standard Self-Interactions (NSSIs)

- We introduce active neutrino self-interactions
- Previously works have been done for Dirac neutrinos with scalar (De Gouvêa, Sen, Tangarife, & Zhang, PRL 124 (2020) 8, 081802) and vector (Kelly, Sen, Tangarife, & Zhang, PRD 101 (2020) 11, 115031) mediators
- In this work: NSSI as an EFT framework with Majorana active neutrinos.
  $\Rightarrow$ Allows us to carry out model independent study
  However, limits us to heavy mediators ($m_\phi >$ few GeVs)
- Motivated from experiments to focus on electron neutrinos.

Non-Standard Self-Interactions (NSSIs)

- Starting with a Yukawa-like interaction,

$$\mathcal{L}_{\rm int} \supset \lambda_\phi \bar{\nu}\mathcal{O}\nu\phi + \text{h.c.} \tag{1}$$

NSSI Lagrangian

$$\mathcal{L}_j = \frac{G_\phi}{\sqrt{2}}\left[(\bar{\nu}\mathcal{O}_j\nu)(\bar{\nu}\bar{\mathcal{O}}_j\nu) - (\bar{\nu}\mathcal{O}_j\nu)\frac{\square}{m_\phi^2}(\bar{\nu}\bar{\mathcal{O}}_j\nu)\right] \tag{2}$$

$$= \frac{G_F\epsilon_j}{\sqrt{2}}\left[(\bar{\nu}\mathcal{O}_j\nu)(\bar{\nu}\bar{\mathcal{O}}_j\nu) - (\bar{\nu}\mathcal{O}_j\nu)\frac{\square}{m_\phi^2}(\bar{\nu}\bar{\mathcal{O}}_j\nu)\right], \tag{3}$$

where

$$G_\phi = \frac{\sqrt{2}\lambda_\phi^2}{m_\phi^2} = G_F\epsilon_j, \qquad \mathcal{O}_j, \bar{\mathcal{O}}_j = \left\{\mathbb{I}, \gamma^\mu, i\gamma^5, \gamma^\mu\gamma^5, \sigma^{\mu\nu}\right\}$$

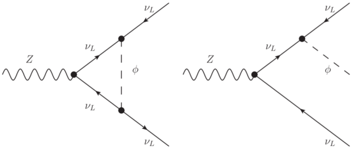
Non-Standard Self-Interactions (NSSIs)

We consider

- only flavour diagonal NSSIs $\Rightarrow \epsilon > 0$
- neutrinos to be Majorana
  $\Rightarrow$ No vector (γ^μ) or tensor ($\sigma^{\mu\nu}$) interactions possible
  $\Rightarrow$ Possible NSSIs: scalar ($\mathbb{I}$), pseudoscalar ($i\gamma^5$), axial-vector ($\gamma^\mu\gamma^5$)

Constraints on NSSI strength

- Only relevant limit from Z-boson decay at one-loop level (Bilenky & Santamaria (1999). *Secret* neutrino interactions.)
- For Dirac neutrinos with vector NSSI:



$$|\epsilon| \lesssim 2$$

- Cancellation of NSSI couplings among different neutrino flavours

$$\Rightarrow \qquad |\epsilon| \lesssim 250$$

- We assume bounds of similar order can be applied for other NSSIs
- In this work,

$$0.1 \leq \epsilon_{\text{NSSI}} \leq 100$$

Modified Boltzmann equation

- The Boltzmann equation

$$\frac{\partial}{\partial t} f_s(p,t) - Hp\frac{\partial}{\partial p} f_s(p,t) \approx \frac{1}{4} h(p,T)\left[f_\alpha(p,t) - f_s(p,t)\right] \tag{4}$$

where

$$h(p,T) = \frac{\Gamma_{\rm total}(p,T)\Delta^2(p)\sin^2 2\theta}{\Delta^2(p)\sin^2 2\theta + \left(\frac{\Gamma_{\rm total}(p,T)}{2}\right)^2 + \left[\Delta(p)\cos 2\theta - \mathcal{V}_{\rm total}(p,T)\right]^2}$$

modifies with

$$\Gamma_{\rm total}(p,T) = \Gamma_{\rm SM}(p,T) + \Gamma_{\rm NSSI}(p,T)$$
$$\mathcal{V}_{\rm total}(p,T) = \mathcal{V}_{\rm SM}(p,T) + \mathcal{V}_{\rm NSSI}(p,T)$$

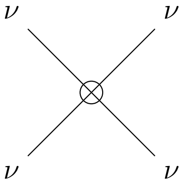
NSSI rate Γ_{NSSI}

Majorana Feynman rules with $\mathcal{L}_{\mathrm{NSSI}}$ gives

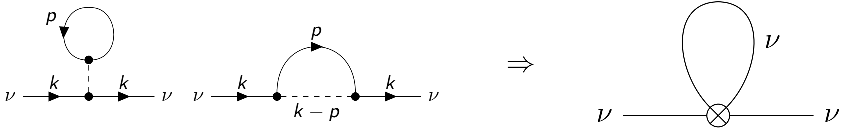
$$\textbf{Scalar NSSI:} \quad \Gamma_S(p,T) = \frac{7\pi G_F^2 \epsilon_S^2}{180}\, p\, T^4 \ , \tag{5}$$

$$\textbf{Pseudoscalar NSSI:} \quad \Gamma_P(p,T) = \frac{7\pi G_F^2 \epsilon_P^2}{180}\, p\, T^4 \ , \tag{6}$$

$$\textbf{Axial vector NSSI:} \quad \Gamma_A(p,T) = \frac{7\pi G_F^2 \epsilon_A^2}{135}\, p\, T^4 \ . \tag{7}$$



NSSI thermal potential $\mathcal{V}_{\mathrm{NSSI}}$



Scalar NSSI:

$$\mathcal{V}_{\mathrm{S}} = -\frac{8\sqrt{2}G_F\,\epsilon_S}{3m_\phi^2}\cdot\omega\cdot\left(n_\nu\left\langle E_\nu\right\rangle + n_{\bar{\nu}}\left\langle E_{\bar{\nu}}\right\rangle\right) = -\frac{7\sqrt{2}\pi^2 G_F\,\epsilon_S}{45m_\phi^2}\epsilon_S\cdot p\,T^4\ , \quad (8)$$

Axial vector NSSI:

$$\mathcal{V}_{\mathrm{A}} = -\frac{16\sqrt{2}G_F\,\epsilon_A}{3m_\phi^2}\cdot\omega\cdot\left(n_\nu\left\langle E_\nu\right\rangle + n_{\bar{\nu}}\left\langle E_{\bar{\nu}}\right\rangle\right) = -\frac{14\sqrt{2}\pi^2 G_F\,\epsilon_A}{45m_\phi^2}\cdot p\,T^4\ , \quad (9)$$

Pseudoscalar NSSI:

$$\mathcal{V}_{\mathrm{P}} = -\frac{8\sqrt{2}G_F\,\epsilon_P}{3m_\phi^2}\cdot\omega\cdot\left(n_\nu\left\langle E_\nu\right\rangle + n_{\bar{\nu}}\left\langle E_{\bar{\nu}}\right\rangle\right) = -\frac{7\sqrt{2}\pi^2 G_F\,\epsilon_P}{45m_\phi^2}\cdot p\,T^4\ . \quad (10)$$

Non-Standard Self-Interactions (NSSIs)

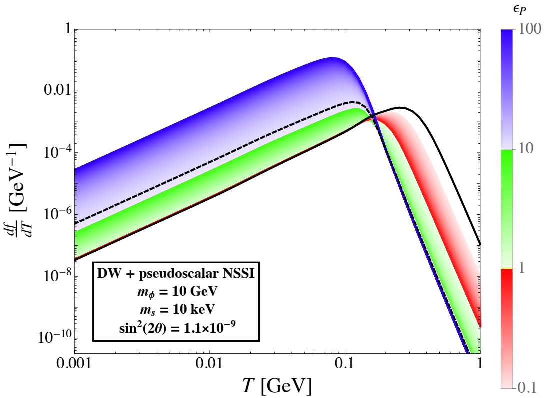
- All possible NSSIs give similar results
- Scalar and pseudoscalar NSSIs are indistinguishable from an EFT perspective
- Two parameters: NSSI strength ϵ, mediator mass m_ϕ
- $\Gamma_{\mathrm{NSSI}} \propto \epsilon^2, \quad \mathcal{V}_{\mathrm{NSSI}} \propto \epsilon$
- Higher order EFT is essential for thermal potential calculations
- EFT treatment is justified if production temperatures are small compared to mediator masses

$$T \ll m_\phi$$

- Standard DW mechanism peaks at $T \sim 133\,(m_s/\mathrm{keV})^{\frac{1}{3}}\,\mathrm{MeV}$
- We take three mediator masses $m_\phi = 10$ GeV, 50 GeV, 100 GeV.

Results and Discussion

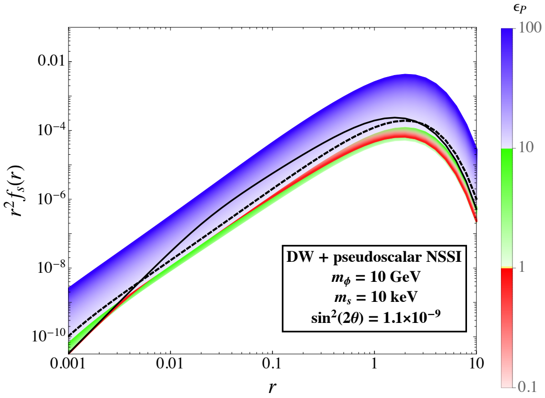
Differential production rate



Black line: Standard DW case, Dashed black line: NSSI case with
$\Omega_s h^2 = \Omega_{\rm DM} h^2 = 0.12$

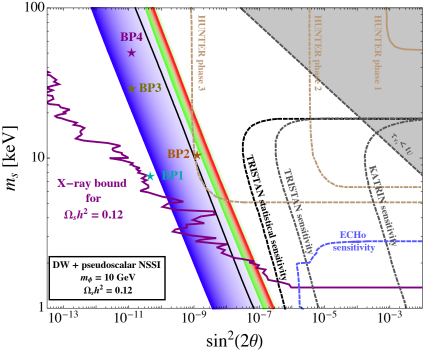
- peak temperature $T_{\rm peak} \sim 100$ MeV
  $\Rightarrow$ if $m_\phi >$ few GeV, EFT framework valid!

Sterile neutrino distribution function

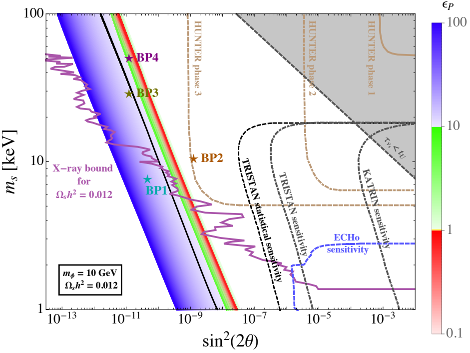


Black line: Standard DW case, Dashed black line: NSSI case with $\Omega_s\, h^2 = \Omega_{\rm DM}\, h^2 = 0.12$

Relic abundance paramter space for $m_\phi = 10$ GeV

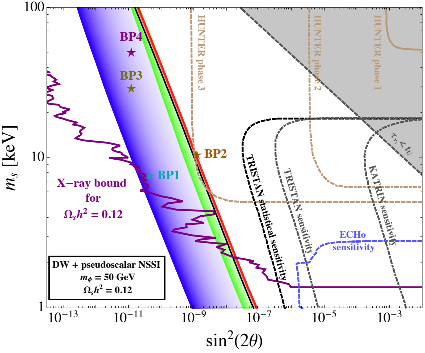


$\Omega_s\, h^2 = 0.12$

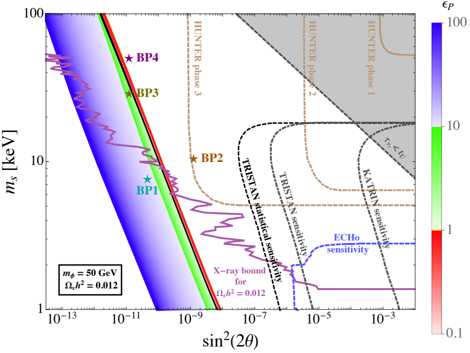


$\Omega_s\, h^2 = 0.012$

Relic abundance paramter space for $m_\phi = 50$ GeV

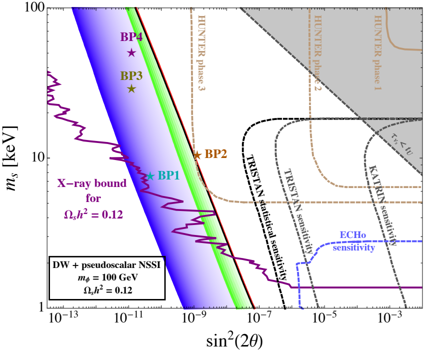


$\Omega_s\, h^2 = 0.12$

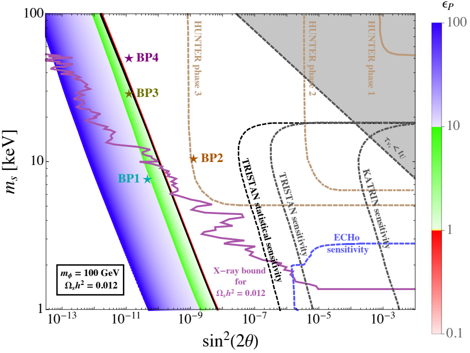


$\Omega_s\, h^2 = 0.012$

Relic abundance paramter space for $m_\phi = 100$ GeV



$\Omega_s\, h^2 = 0.12$



$\Omega_s\, h^2 = 0.012$

DW parameter space in presence of NSSIs

In presence of NSSIs,

- sterile neutrino production
  - suppressed for smaller values of $\epsilon \sim 0.1 - 10$
  - enhanced for larger values of $\epsilon \sim 10 - 100$
- mediator masses have less effect as $m_\phi \gg M_{W,Z}$
- parameter space widens and reachable by phase 3 of HUNTER
- X-ray constraints still strong, but better than standard DW scenario

Free streaming length

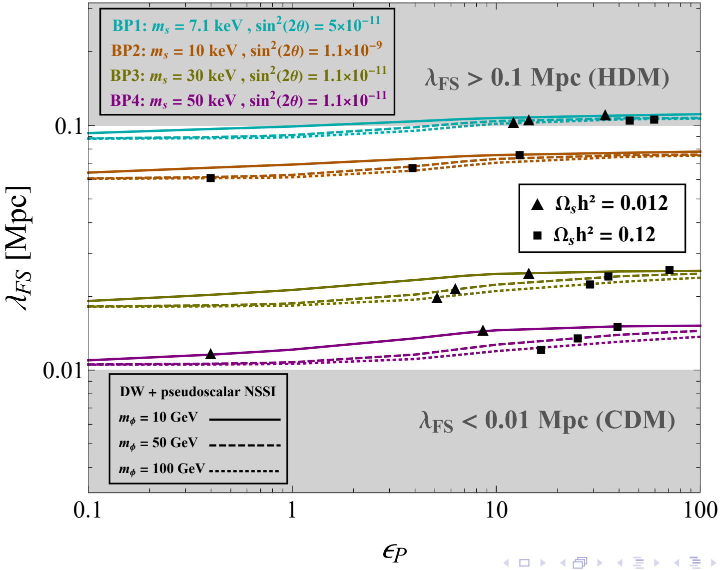
Dark matter can be classified according to free streaming length as:

- Hot Dark Matter : $\lambda_{\rm FS} > 0.1$ Mpc,
- Warm Dark Matter : $0.01\ \rm{Mpc} < \lambda_{\rm FS} < 0.1$ Mpc,
- Cold Dark Matter : $\lambda_{\rm FS} < 0.01$ Mpc.

$$\lambda_{\rm FS} = \int_0^{t_0} \frac{\langle v(t)\rangle}{a(t)} dt \simeq 1.2 \text{ Mpc} \left(\frac{\text{keV}}{m_s}\right) \frac{\langle p/T\rangle}{3.15}, \tag{11}$$

- A check whether NSSIs are compatible with structure formation

Free streaming length



Free streaming length

- NSSIs have limited influence on free streaming length
- sterile neutrinos produced with $m_s \sim 10 - 50$ keV are "warm dark matter"

Summary

In this work, we demonstrated that

- Non-standard neutrino self-interactions can modify standard Dodelson-Widrow mechanism and improve testability in future experiments such as HUNTER
- NSSIs are compatible with structure formation and have little influence on free streaming length
- EFT analysis of dark matter production needs to include momentum-dependent terms in Lagrangian to get correct temperature dependence.

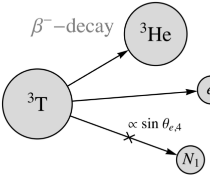
Thanks for your attention!

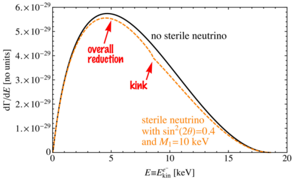
Questions?

Backup

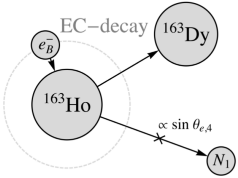
Experimental searches for sterile neutrino dark matter

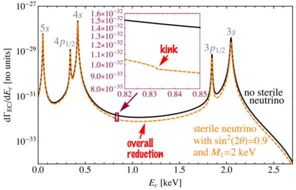
- Single beta decay
  E.g., KATRIN, TRISTAN
  (Q-value $= 18.6$ keV)





- Electron Capture
  E.g., ECHo
  (Q-value $= 2.833$ keV), HUNTER
  (future experiment, $m_s = 7 - 300$ keV detectable)





Images from A Merle, Sterile neutrino dark matter, Morgan & Claypool Publishers (2017)

Boltzmann equation

- Semi-classical Boltzmann equation from QKE Abazajian, Fuller, & Patel, PRD 64 (2001), 023501

$$\frac{\partial}{\partial t} f_s(p,t) - Hp\frac{\partial}{\partial p} f_s(p,t) \approx \frac{\Gamma_\alpha(p,t)}{2} \cdot \langle P_m\left(\nu_\alpha \to \nu_s; p, t\right)\rangle \cdot \left[f_\alpha(p,t) - f_s(p,t)\right] \quad (12)$$

$$\frac{\partial}{\partial t} f_s(p,t) - Hp\frac{\partial}{\partial p} f_s(p,t) \approx \frac{1}{4} h(p,T)\left[f_\alpha(p,t) - f_s(p,t)\right] \quad (13)$$

where

$$h(p,T) = \frac{\Gamma_\alpha(p,T)\Delta^2(p)\sin^2 2\theta}{\Delta^2(p)\sin^2 2\theta + \left(\frac{\Gamma_\alpha(p,T)}{2}\right)^2 + \left[\Delta(p)\cos 2\theta - \mathcal{V}_\alpha(p,T)\right]^2}$$

contains the details of Dodelson-Widrow mechanism.

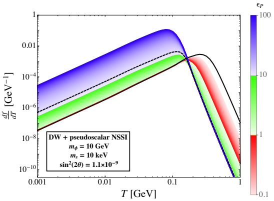
Boltzmann equation

$$\begin{aligned} f_\alpha(p,t) &= \text{active neutrino momentum distribution}, \\ f_s(p,t) &= \text{sterile neutrino momentum distribution}, \\ H(t) &= \text{Hubble constant}, \\ \theta &= \text{active-sterile mixing angle in vacuum}, \\ \Gamma_\alpha &= \text{active neutrino interaction rate}, \\ \mathcal{V}_\alpha &= \text{active neutrino effective potential}, \\ \Delta(p) &= \frac{\Delta m_{as}^2}{2p} \approx \frac{m_s^2}{2p} \end{aligned}$$

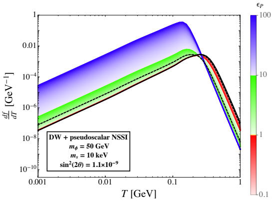
Differential production rate

$$\frac{df_s}{dT} = \sqrt{\frac{90}{8\pi^3}} \frac{M_{\rm Pl}}{\sqrt{g_{*s}(T)}\,T^3} \left(1 + \frac{T g'_{*s}(T)}{3 g_{*s}(T)}\right) \cdot h\left(p_{\rm redshift}, T\right) \frac{1}{\exp\left(\frac{p_{\rm redshift}}{T}\right) + 1} \quad (14)$$

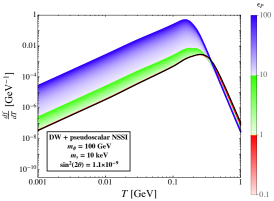
where $p_{\rm redshift} = p(T_f)\frac{T}{T_f}\left(\frac{g_{*s}(T)}{g_{*s}(T_f)}\right)^{1/3}$



(a) $m_\phi = 10$ GeV



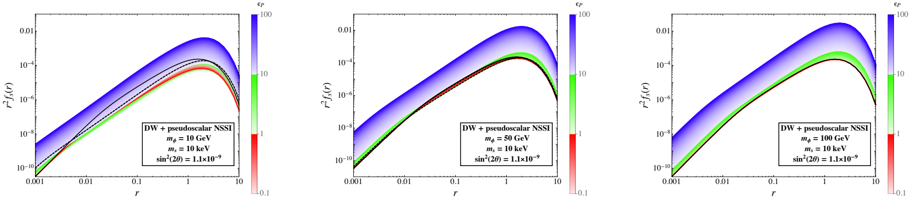
(b) $m_\phi = 50$ GeV



(c) $m_\phi = 100$ GeV

Sterile neutrino distribution function

$$
f_s(p_f, T_f) = \int_{T_i}^{T_f} \sqrt{\frac{90}{8\pi^3}} \frac{M_{\rm Pl}}{\sqrt{g_{*s}(T)}\,T^3} \left(1 + \frac{T g'_{*s}(T)}{3 g_{*s}(T)}\right) \cdot h\left(p_{\rm redshift}, T\right) \frac{1}{\exp\left(\frac{p_{\rm redshift}}{T}\right) + 1} dT \ , \quad (15)
$$



(a) $m_\phi = 10$ GeV **(b)** $m_\phi = 50$ GeV **(c)** $m_\phi = 100$ GeV

The End