universität freiburg

Boosting the production of sterile neutrino dark matter with self-interactions

María Dias

Based on arXiv: 2307.15565

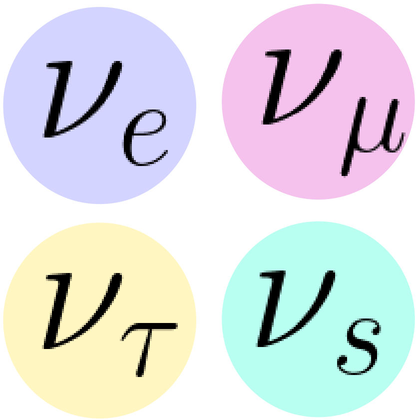
In collaboration with:
Stefan Vogl

SUSY 2024, Madrid

Sterile neutrinos as dark matter

What are sterile neutrinos?

- Singlets under the SM gauge group



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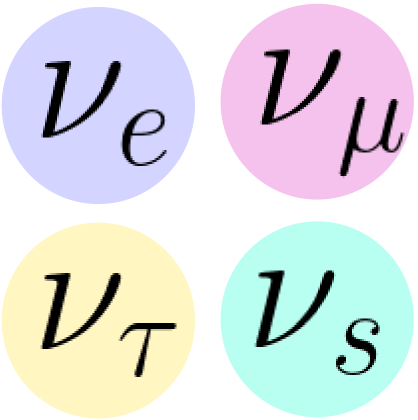

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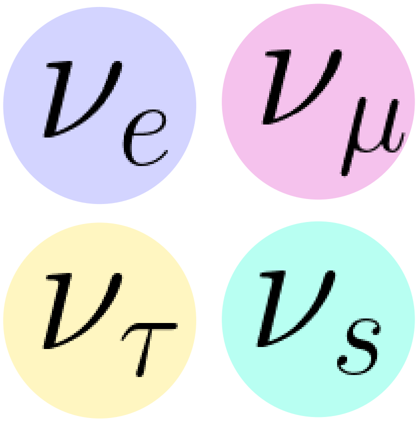

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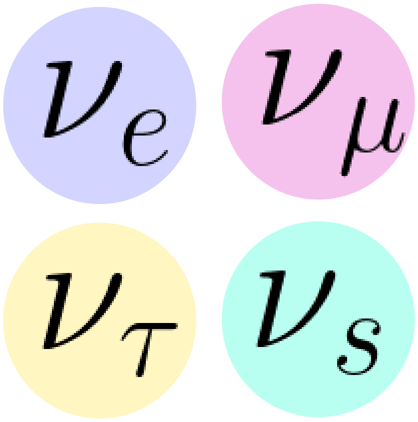

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How to extend DW?

Self-interactions

Johns and Fuller 1903.08296
Bringmann et al. 2206.10630

$$\mathcal{L}_{\rm int} = y\ \bar{\nu}_s \nu_s \phi.$$

Production of sterile neutrinos

The evolution of the phase-space density of sterile neutrinos is given by the Boltzmann equation

$$\frac{\partial f_s}{\partial t} - Hp\frac{\partial f_s}{\partial p} = \frac{\Gamma_t}{4}\left(\frac{\omega^2 \sin^2(2\theta)}{\omega^2 \sin^2(2\theta) + \frac{\Gamma_t^2}{4} + [\omega\cos(2\theta) - V_{\text{eff}}]^2}\right)[f_a - f_s] + \mathcal{C}_s$$

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Active's distribution function

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Vacuum oscillation frequency $\sim \frac{{m_s}^2}{2p}$

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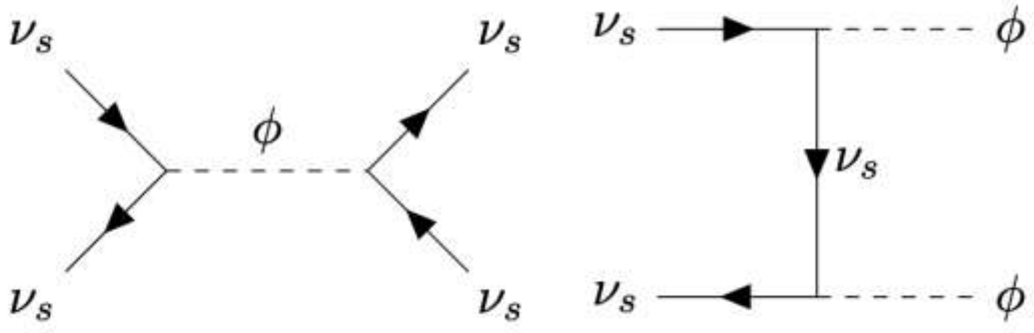
Vacuum mixing angle

Total rate

Active's distribution function

Sterile-sterile scattering processes

$$\Gamma_t = \Gamma_a + \Gamma_s$$



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Sterile's distribution function

Hubble's rate

Vacuum oscillation frequency $\sim \frac{{m_s}^2}{2p}$

Vacuum mixing angle

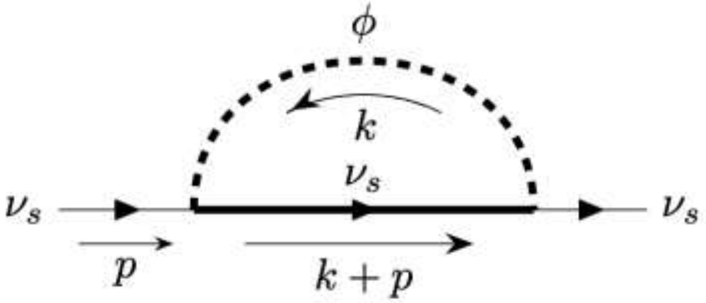
Total rate

Effective potential

Active's distribution function

Sterile-sterile scattering processes

$$V_{\text{eff}} = V_a - V_s$$



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Transition Probability

$$\langle P_m(\nu_a \leftrightarrow \nu_s)\rangle$$

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$$\sin^2(2\theta_m)$$

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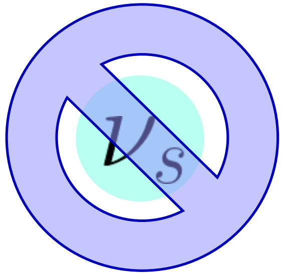
System is damped

few MeV

Intermediate temperatures

few GeV



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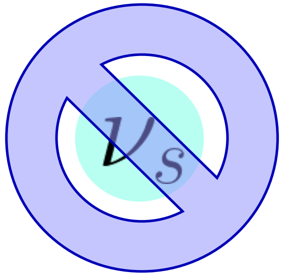

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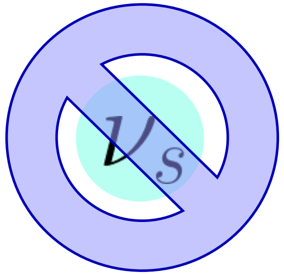

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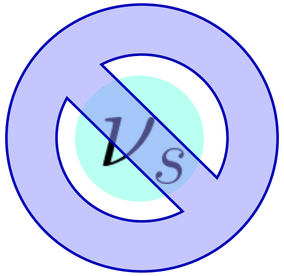

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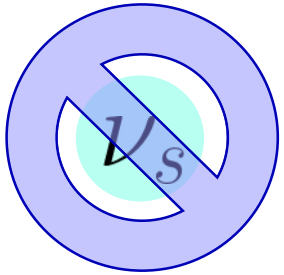

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1 **DW production** $\xrightarrow{\text{Initial condition}}$ 2 **Neutrino-neutrino scattering**

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m_s θ m_ϕ y

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- The mass of the sterile neutrinos

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- The mass of the sterile neutrinos
- The mixing angle

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The are four parameters controlling the behavior of the system

- The mass of the sterile neutrinos
- The mixing angle
- The mass of the mediator

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The are four parameters controlling the behavior of the system

- The mass of the sterile neutrinos
- The mixing angle
- The mass of the mediator
- The size of the Yukawa coupling

Production regimes

m_s θ m_ϕ y

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The are four parameters controlling the behavior of the system

- The mass of the sterile neutrinos
- The mixing angle
- The mass of the mediator →
- The size of the Yukawa coupling

$$m_\phi \gg T \quad \Big| \quad \boxed{V_s < 0}$$

$$m_\phi \ll T \quad \Big| \quad V_s > 0$$

Thermalization of the system

What role does the sterile collision term play?

$$\frac{\partial f_s}{\partial t} - Hp\frac{\partial f_s}{\partial p} = \frac{\Gamma_t}{4}\left(\frac{\omega^2 \sin^2(2\theta)}{\omega^2 \sin^2(2\theta) + \frac{\Gamma_t^2}{4} + [\omega\cos(2\theta) - V_{\text{eff}}]^2}\right)[f_a - f_s] + \mathcal{C}_s$$

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$$\boxed{\Gamma_{\nu_s\nu_s\leftrightarrow\phi\phi}\, f_s \left(1 - \frac{f_s^2}{f_{\text{eq}}^2}\right)}$$

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- C_s tries to drive the system towards equilibrium

$$\boxed{\Gamma_{\nu_s\nu_s\leftrightarrow\phi\phi}\, f_s\left(1 - \frac{f_s^2}{f_{\text{eq}}^2}\right)}$$

Thermalization of the system

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$$\frac{\partial f_s}{\partial t} - Hp\frac{\partial f_s}{\partial p} = \frac{\Gamma_t}{4}\left(\frac{\omega^2 \sin^2(2\theta)}{\omega^2 \sin^2(2\theta) + \frac{\Gamma_t^2}{4} + [\omega \cos(2\theta) - V_{\text{eff}}]^2}\right)[f_a - f_s] + \mathcal{C}_s$$

$$\Gamma_{\nu_s\nu_s\leftrightarrow\phi\phi}\, f_s \left(1 - \frac{f_s^2}{f_{\text{eq}}^2}\right)$$

- C_s tries to drive the system towards equilibrium
- The process $\nu_s\nu_s \leftrightarrow \phi\phi$ essentially results in $2\nu_s \longrightarrow 4\nu_s$ upon the decay of ϕ

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$$\Gamma_{\nu_s\nu_s\leftrightarrow\phi\phi}\, f_s\left(1 - \frac{f_s^2}{f_{\text{eq}}^2}\right)$$

The process stops itself

Thermalization of the system

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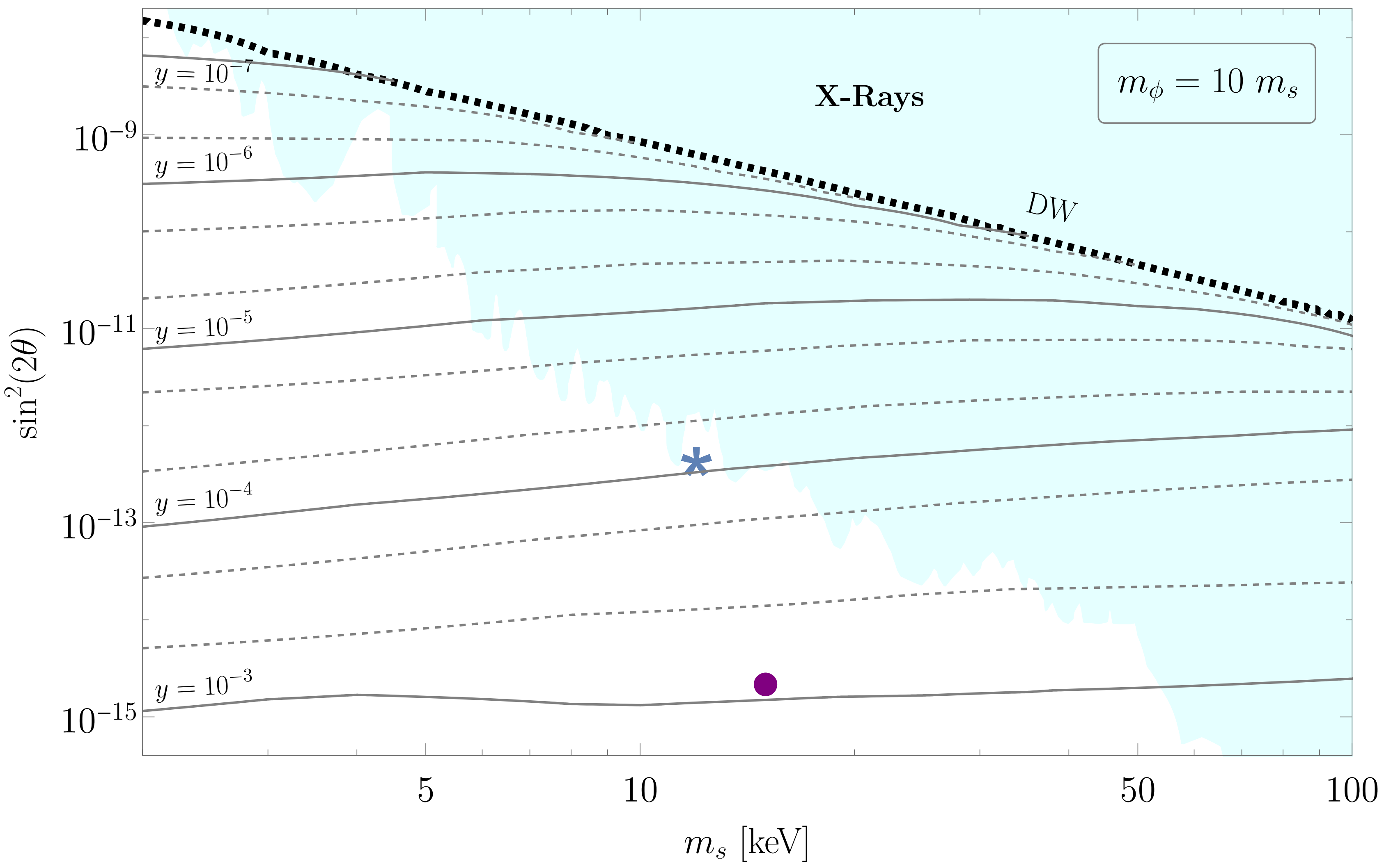
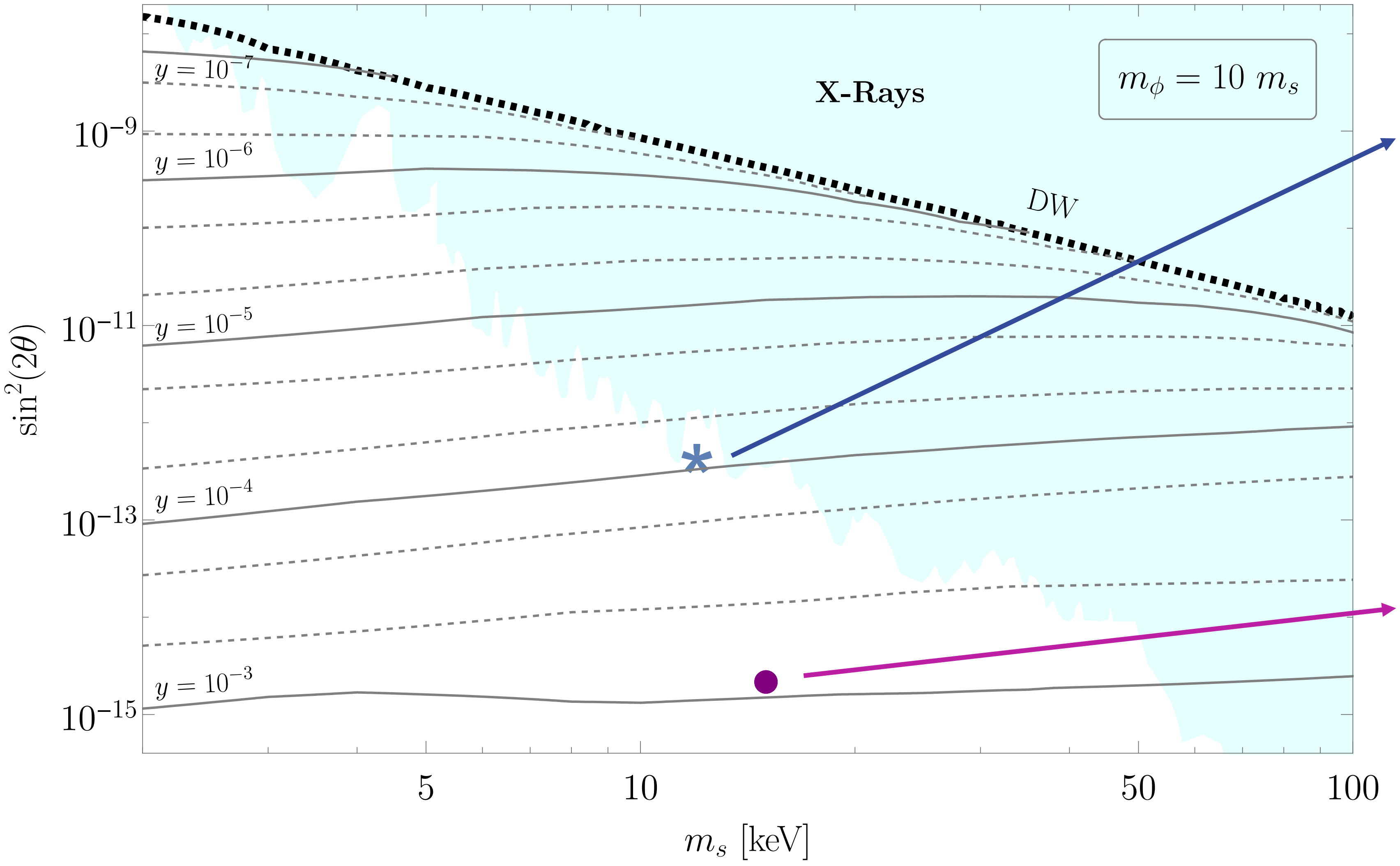
Only important for low and intermediate mediator masses

The parameter space



The parameter space



m_s	$\sin^2(2\theta)$
12 keV	$5\ x\ 10^{-13}$

m_s	$\sin^2(2\theta)$
15 keV	$2.16\ x\ 10^{-15}$

One heavy-mediator benchmark

m_s	m_ϕ	y	$\sin^2(2\theta)$
12 keV	1.5 GeV	$6.92\ x\ 10^{-2}$	$5\ x\ 10^{-13}$

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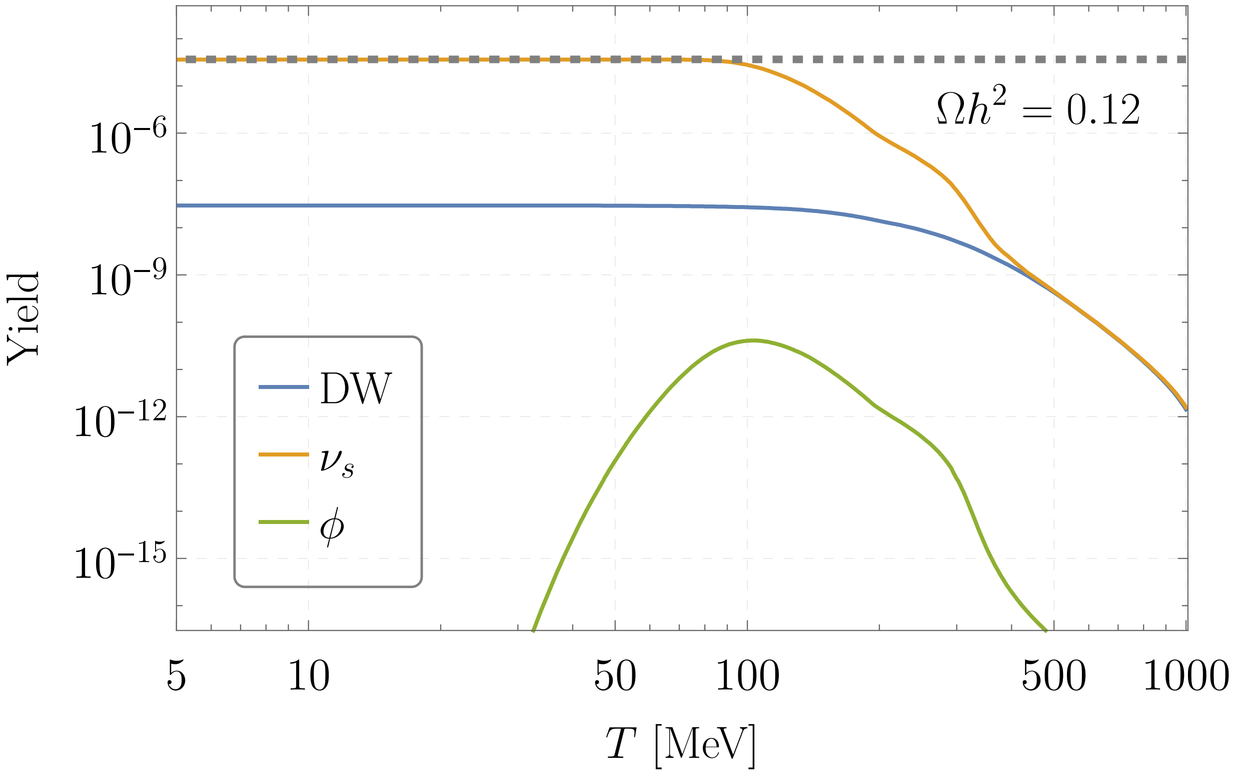

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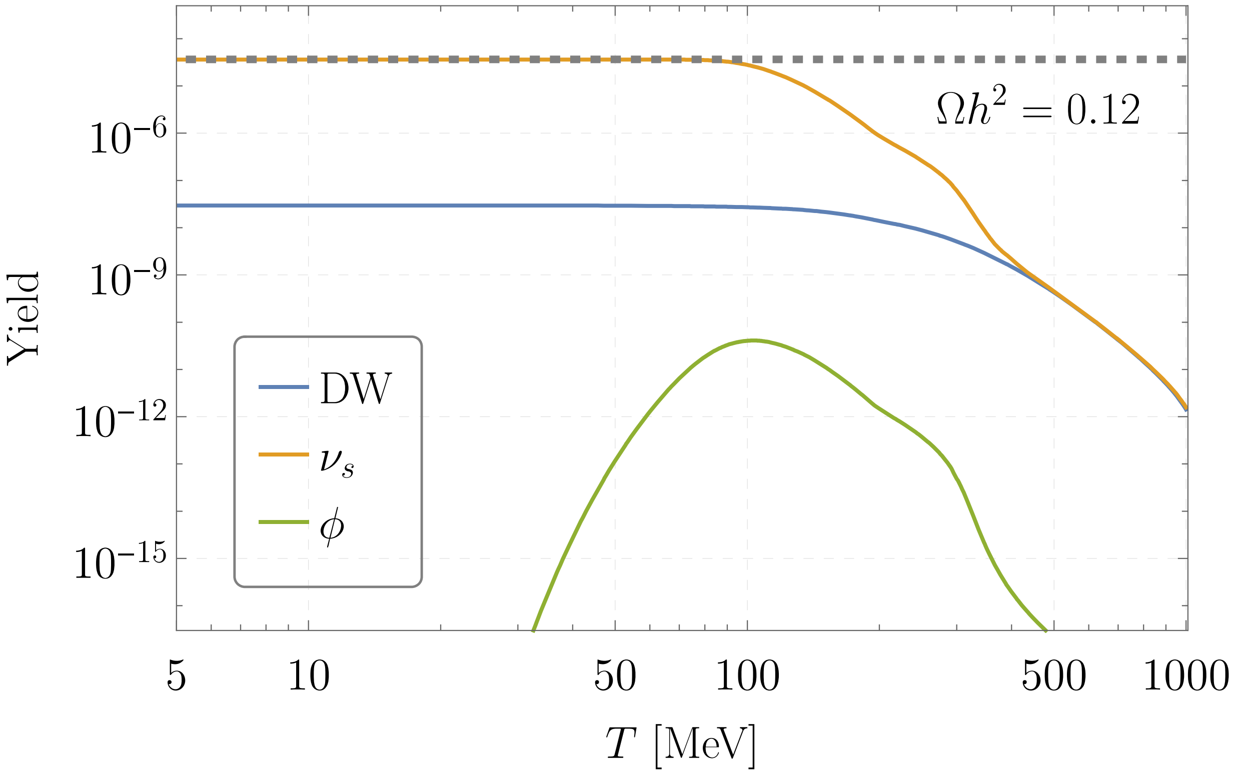

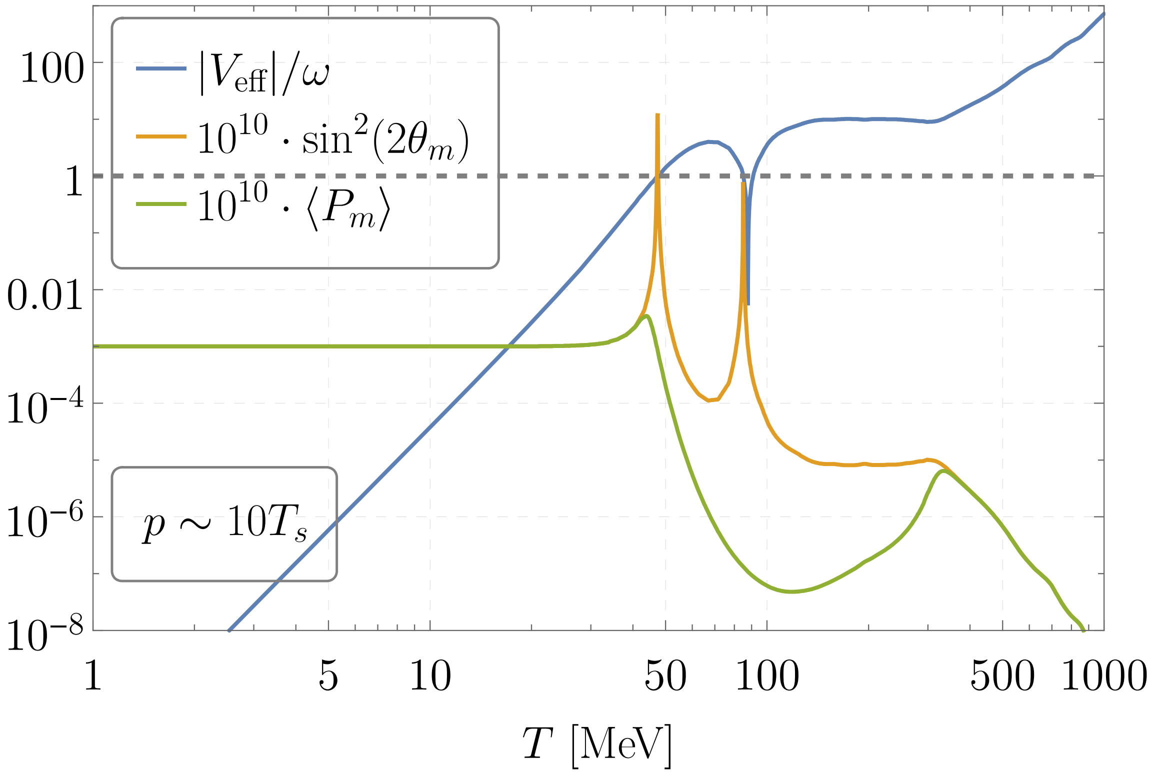

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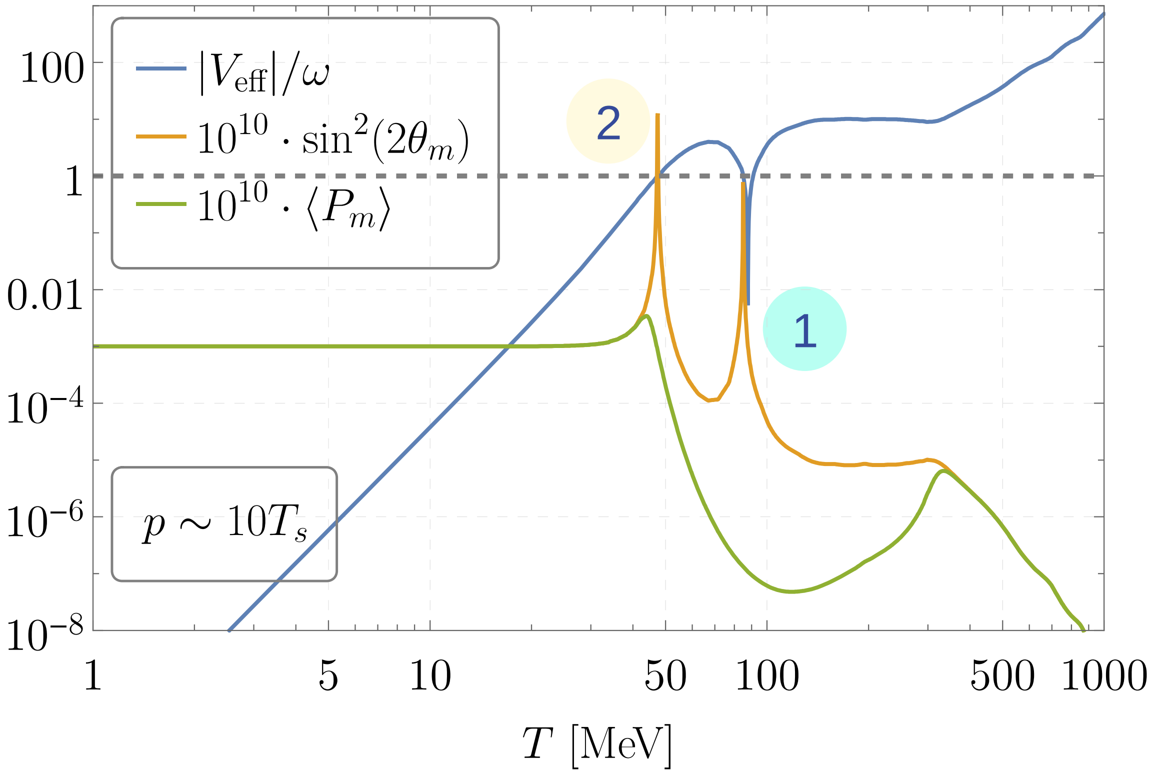
➡ $\omega\cos(2\theta) - V_a + V_s \approx 0$



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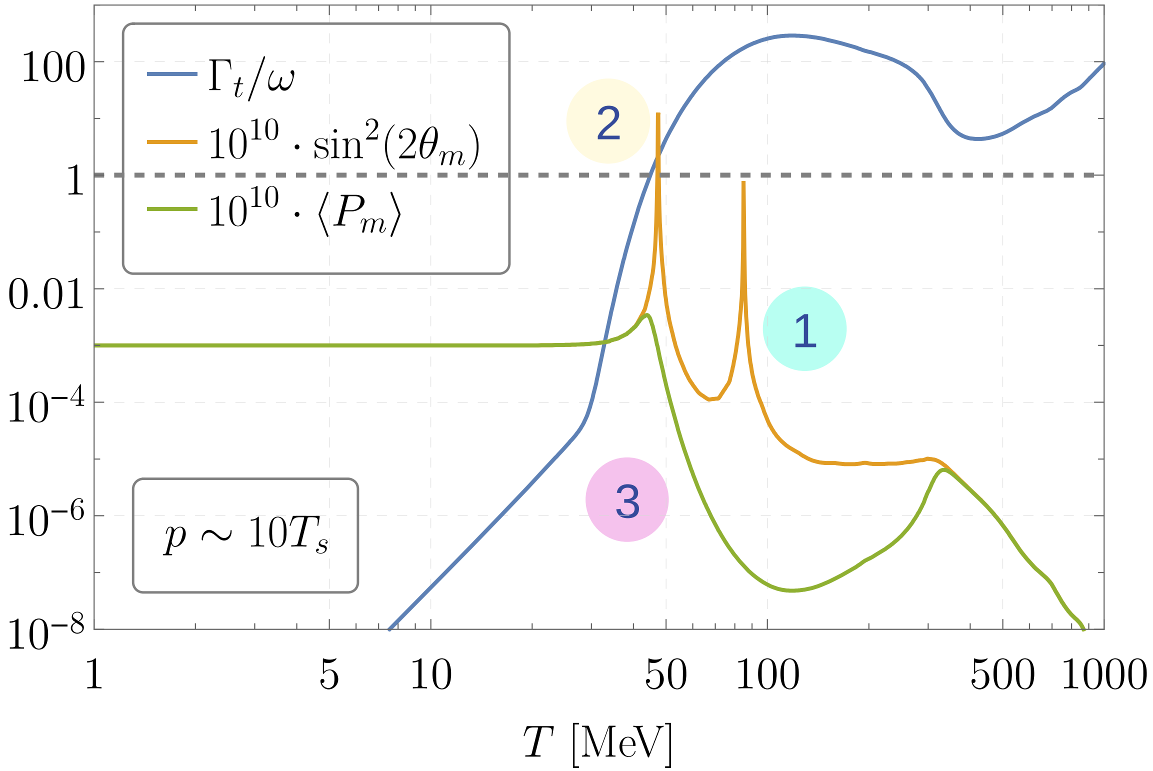
$$\omega\cos(2\theta) - V_a + V_s \approx 0$$

3 The resonances are regulated by quantum damping

$$\frac{\partial f_s}{\partial t} - Hp\frac{\partial f_s}{\partial p} \sim \frac{\omega^2\sin^2(2\theta)}{\Gamma_t}[f_a - f_s] + \mathcal{C}_s$$



A benchmark with partial thermalization

m_s	m_ϕ	y	$\sin^2(2\theta)$
15 keV	150 keV	$9\ x\ 10^{-4}$	$2.16\ x\ 10^{-15}$

For lighter mediator masses, we expect the # changing processes to be important

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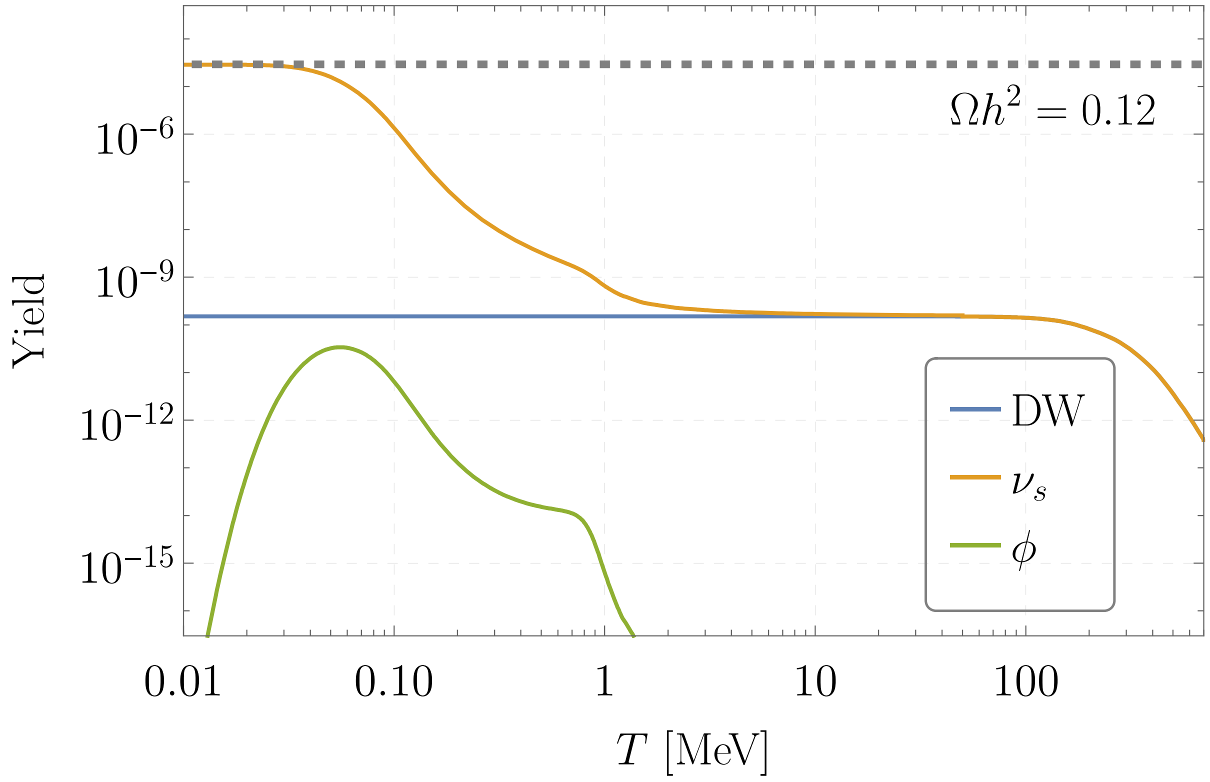

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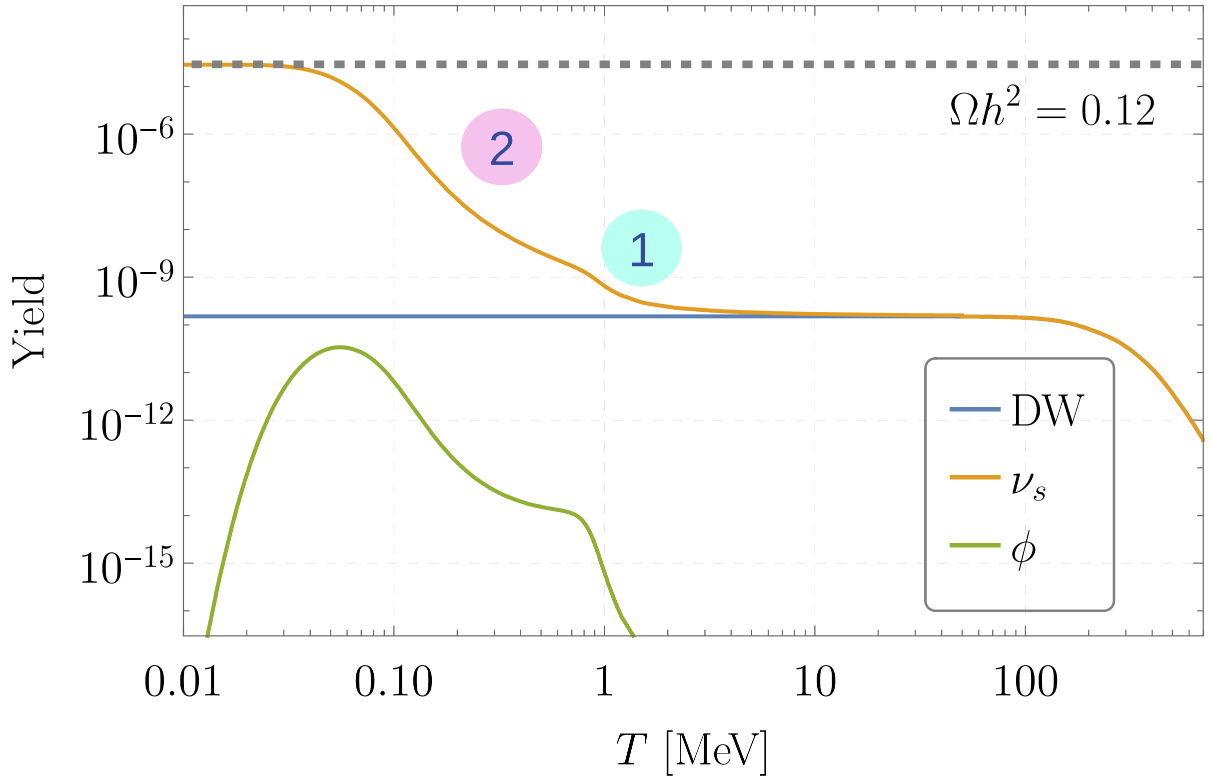

1 # changing processes

$$\nu_s \nu_s \rightarrow \phi\phi \rightarrow 4\nu_s$$

2 Neutrino-neutrino scattering

$$\nu_s \nu_s \rightarrow \nu_s \nu_s$$

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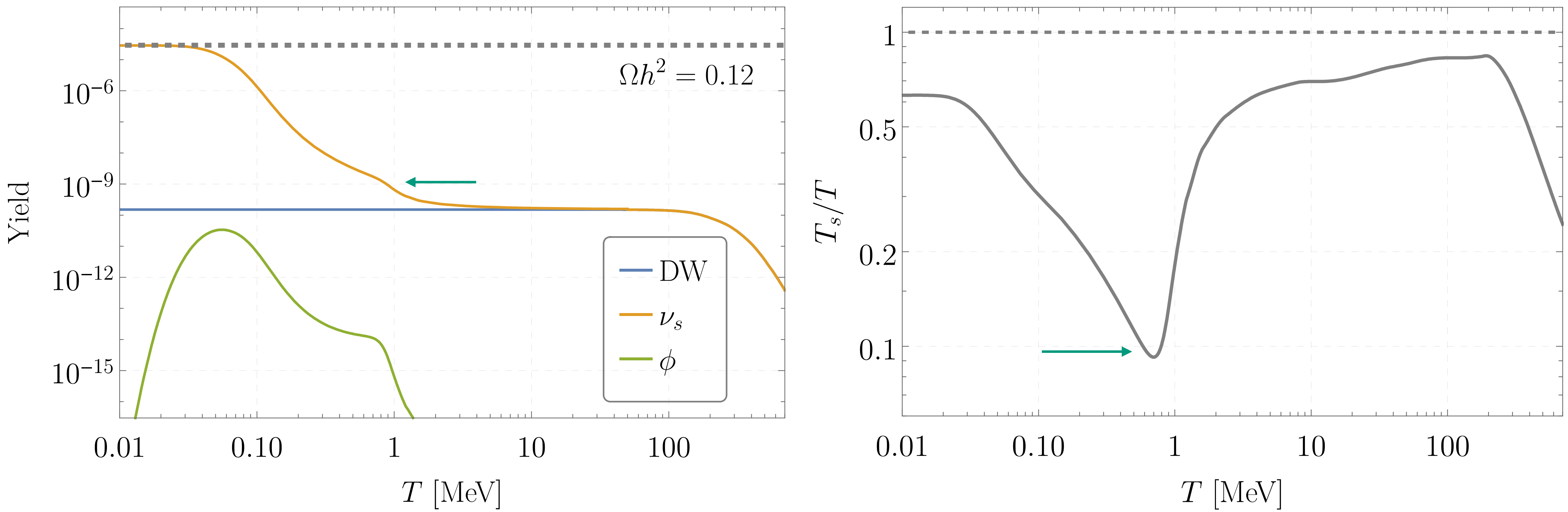


Overview of production regimes

$m_\phi \lesssim 100 \text{ MeV}$

- Simplified Boltzmann equation
- Initial DW production

Bringmann et al. 2206.10630

$800 \text{ MeV} \lesssim m_\phi \lesssim 3 \text{ GeV}$

- Full Boltzmann equation
- Regulated resonances

This work 2307.15565

$100 \text{ MeV} \lesssim m_\phi \lesssim 800 \text{ MeV}$

- Full Boltzmann equation
- Quantum damping

This work 2307.15565

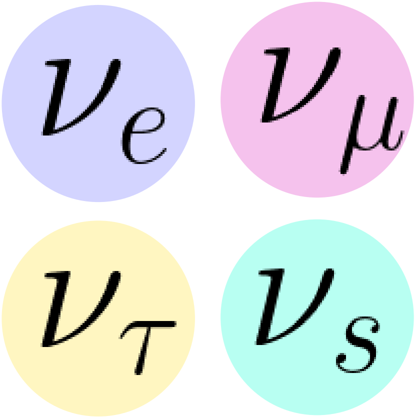
$m_\phi \gtrsim 3 \text{ GeV}$

- Non-regulated resonances
- Runaway production

Johns and Fuller 1903.08296

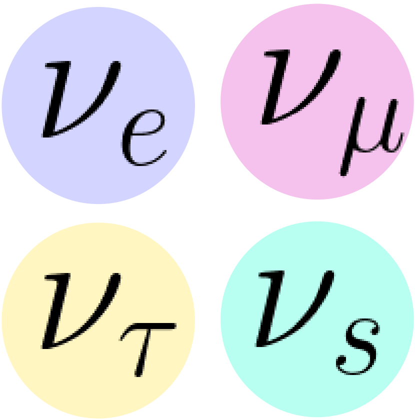
Conclusions

- Sterile neutrinos are attractive BSM candidates



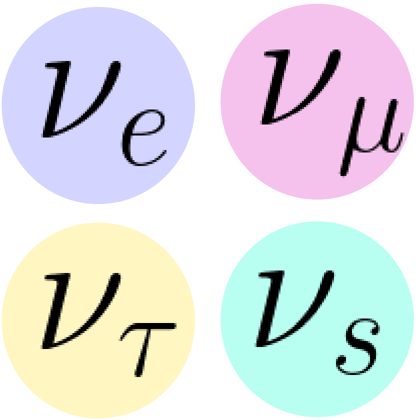
Conclusions

- Sterile neutrinos are attractive BSM candidates
- The canonical DW mechanism is mostly excluded



Conclusions

- Sterile neutrinos are attractive BSM candidates
- The canonical DW mechanism is mostly excluded
- Self-interactions among the sterile neutrinos can open new portions of parameter space



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Thank you for your attention

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Backup

Observational Constraints

- **X-ray searches**

- The decay of sterile neutrinos into an active neutrino and a photon is phenomenologically important

$$\Gamma_{\nu_s \to \nu_a \gamma} \sim \left(\frac{\sin^2(2\theta)}{10^{-8}}\right)\left(\frac{m_s}{1\ \mathrm{keV}}\right)^5$$

For keV sterile neutrinos, the resultant photon is in the X-ray band

can be searched for by current and future X-ray telescopes

Upper limit on the mixing angle

No signal

- NuStar
- Integral
- XMM-Newton
- Others…

Observational constraints

Structure formation

- Sterile neutrinos are produced (and decouple) while still relativistic.
- They resemble warm dark Matter (WDM)

Smearing out of structures on scales smaller than the neutrino's free streaming length

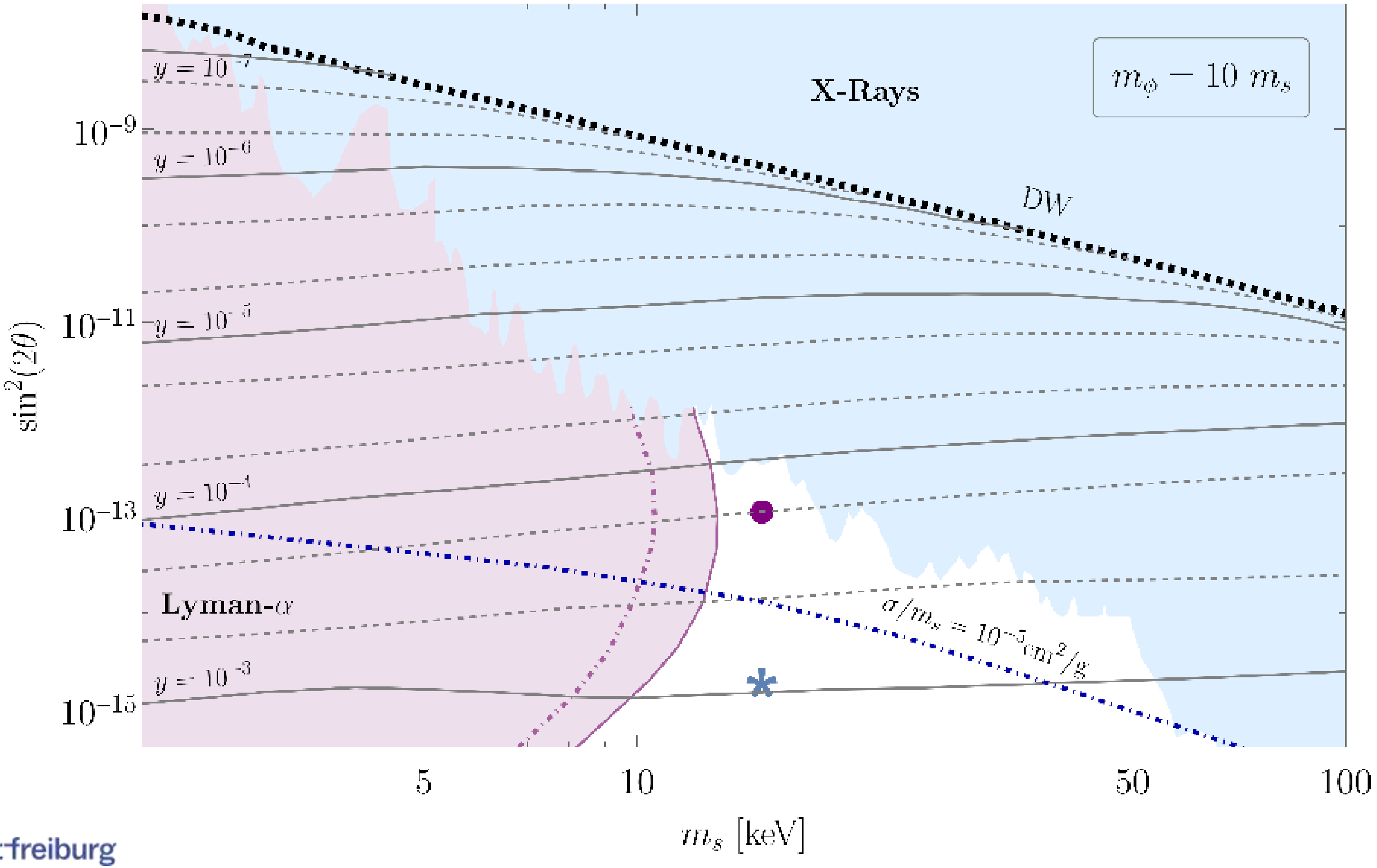
- How far can the DM particles travel before they collapse?

ν_s

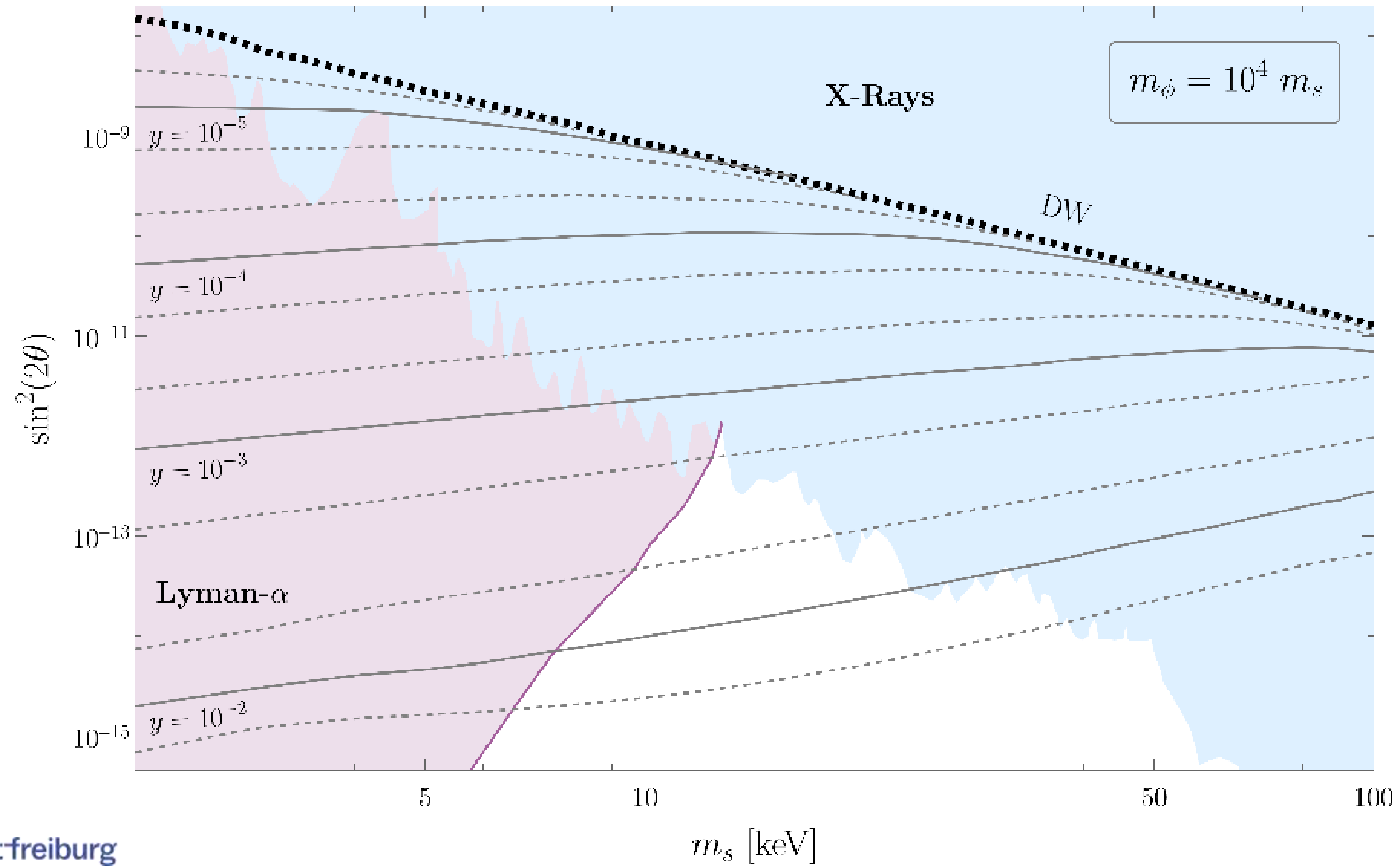
Lyman-α forest observations → **Lower limit on the mass of the sterile neutrinos**

ν_s ν_s ν_s

The light parameter space



The heavy parameter space



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The rates

The rates are computed in the following way

$$\Gamma_{\nu_s\nu_s\leftrightarrow kk} = \frac{1}{2E_1}\int \mathrm{d}\Pi_2\mathrm{d}\Pi_3\mathrm{d}\Pi_4(2\pi)^4\delta^4(p_i - p_f)|\mathcal{M}|^2_{\nu_s\nu_s\leftrightarrow kk}|f_s$$

The nine integrals can usually be reduced to two integrals that must be solved numerically

$$\Gamma_{\nu_s\nu_s\leftrightarrow\nu_s\nu_s} = \begin{cases} \frac{3y^4T_s^2}{2\pi^3 p}e^{\frac{\mu}{T_s}} + \frac{y^2T_s m_\phi^2}{2\pi p^2}e^{-\frac{m_\phi^2}{4pT_s}+\frac{\mu}{T_s}} & pT_s > \frac{3m_\phi^2}{2\sqrt{10}} \\ \frac{20y^4pT_s^4}{3\pi^3 m_\phi^4}e^{\frac{\mu}{T_s}} + \frac{y^2T_s m_\phi^2}{2\pi p^2}e^{-\frac{m_\phi^2}{4pT_s}+\frac{\mu}{T_s}} & pT_s \leq \frac{3m_\phi^2}{2\sqrt{10}} \end{cases}$$

The potential

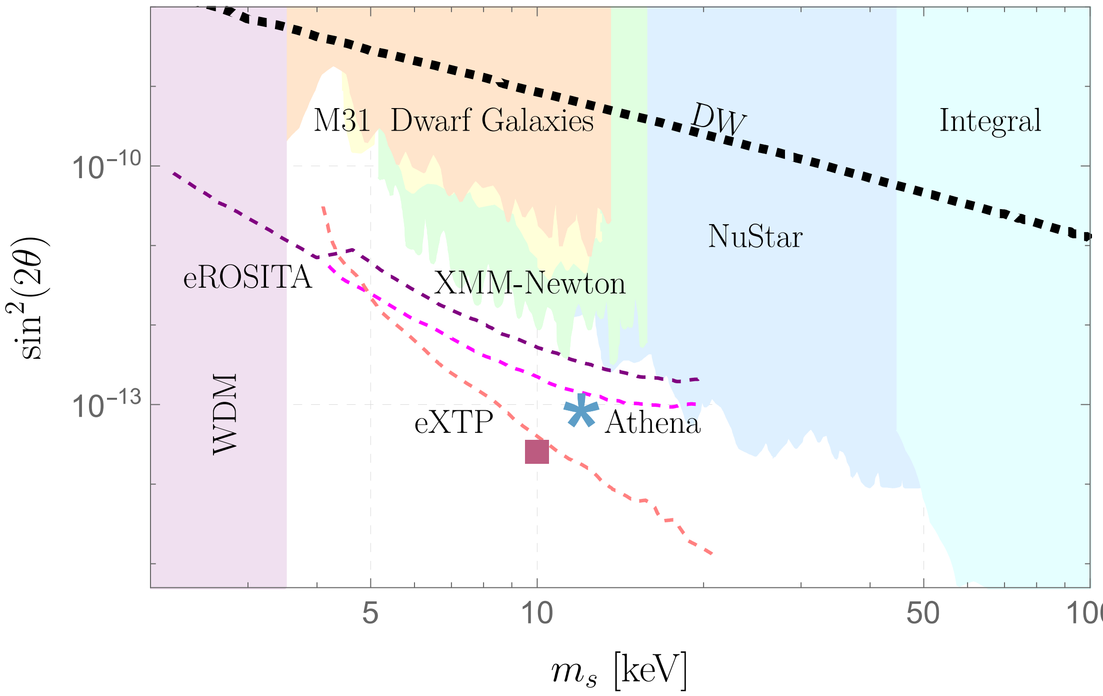
The potential modifies the dispersion relation of the SN

$$E = |\mathbf{p}| + \frac{m^2}{2|\mathbf{p}|} + V_{\text{eff}}$$

In the limiting cases the potential takes the form

$$V_s(p) = \begin{cases} \frac{y^2 T_s^2}{2\pi^2 p} e^{\frac{\mu_s}{T_s}} & T_s \gg m_\phi \\ -\frac{16 y^2 p T_s^4}{\pi^2 m_\phi^4} e^{\frac{\mu_s}{T_s}} & T_s \ll m_\phi \end{cases}$$

The parameter space



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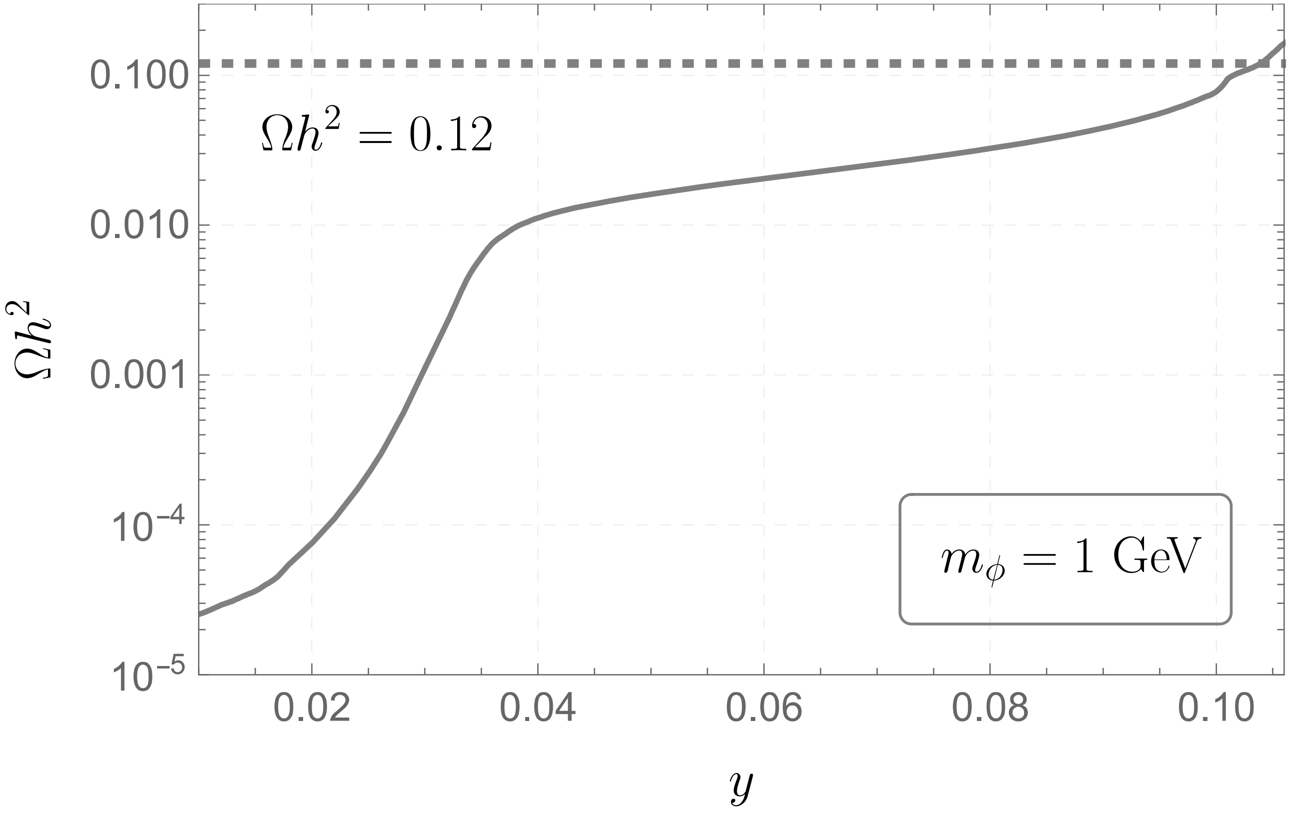

A heavy mediator implies a relatively large Yukawa