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PRD 101 (2020) 11, 116006

and work in progress

Sterile Neutrino Dark Matter and Self-Interactions

Walter Tangarife

with

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LOYOLA UNIVERSITY CHICAGO

Preparing people to lead extraordinary lives

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Can we produce enough sterile neutrino DM in the early universe?

Sterile Neutrino as Dark Matter

Fourth mass eigenstate: $\nu_4 = \nu_s \cos\theta + \nu_a \sin\theta \approx \nu_s$

The mixing angle is small and the sterile neutrino never reaches thermal equilibrium with the primordial plasma

For a review: Abazajian (2017)
Dasgupta & Kopp (2021)

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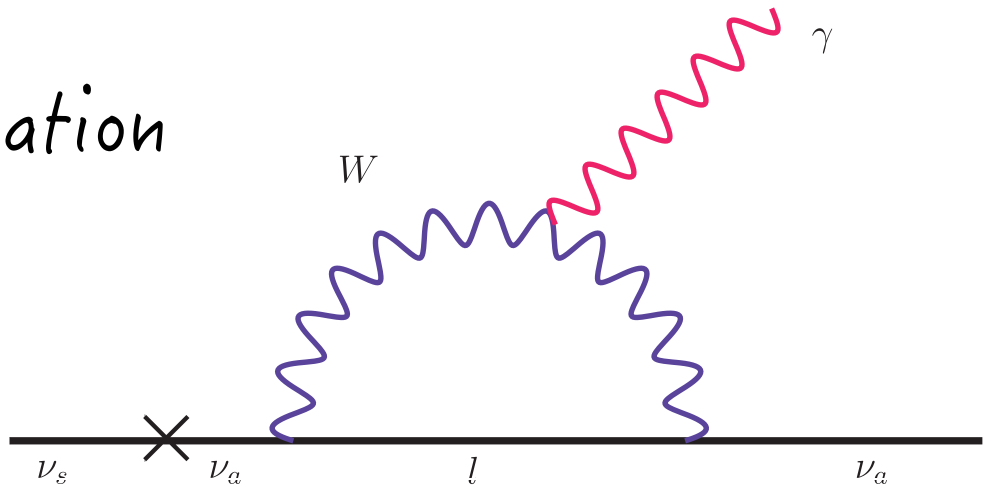
It can be detected through decay into radiation

$$\Gamma \sim 10^{-28}\mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{7\times 10^{-11}} \right) \left(\frac{m_s}{7\ \mathrm{keV}} \right)^5$$



e.g. Pal & Wolfenstein (1982),
Abazajian, Fuller & Tucker (2001), …

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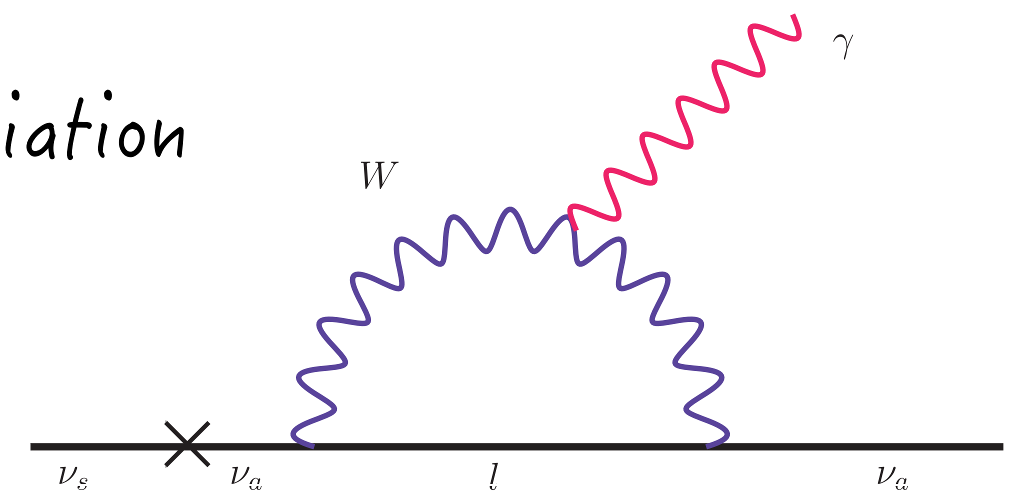

e.g. Pal & Wolfenstein (1982),
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How to produce it?

Two (among several) proposals:

Dodelson-Widrow (1994)

Shi-Fuller (1999)

For a review: Abazajian (2017)
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Sterile Neutrino as Dark Matter

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How to produce it?

In the early universe, an active neutrino can oscillate to a sterile neutrino, with probability

Dodelson-Widrow Mechanism

Dodelson & Widrow (1994)

$$\sin^2 2\theta_{\rm eff} \simeq \frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + (\Gamma/2)^2 + (\Delta \cos 2\theta - V_T)^2}$$

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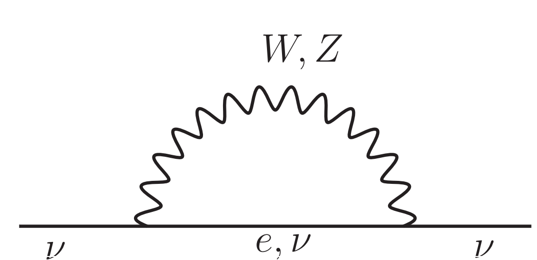
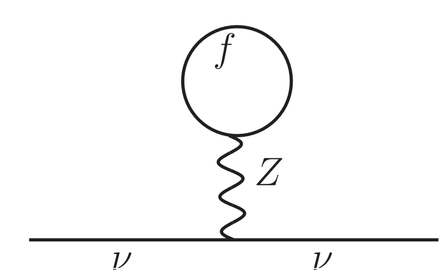
$\Delta = m_s^2/2E$

Quantum Zeno effect (damping)

Thermal potential

$$\Gamma_V(E,T) = 2\int \frac{d^3\vec{p}'}{(2\pi)^3}\, f_\nu(E',T)\, \sigma_{\text{tot}}(\vec{p},\vec{p}')\, v_{\text{rel}}$$





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Result: A non-thermal abundance of sterile neutrinos by solving the Boltzmann equation

$$\frac{d\, f_{\nu_4}(x,z)}{d \ln z} = \frac{\Gamma}{4H}\, \sin^2 2\theta_{\rm eff}\, f_\nu(x)$$

$z = \mathrm{MeV}/T$

$x = E/T$

$\Delta = m_s^2/2E$

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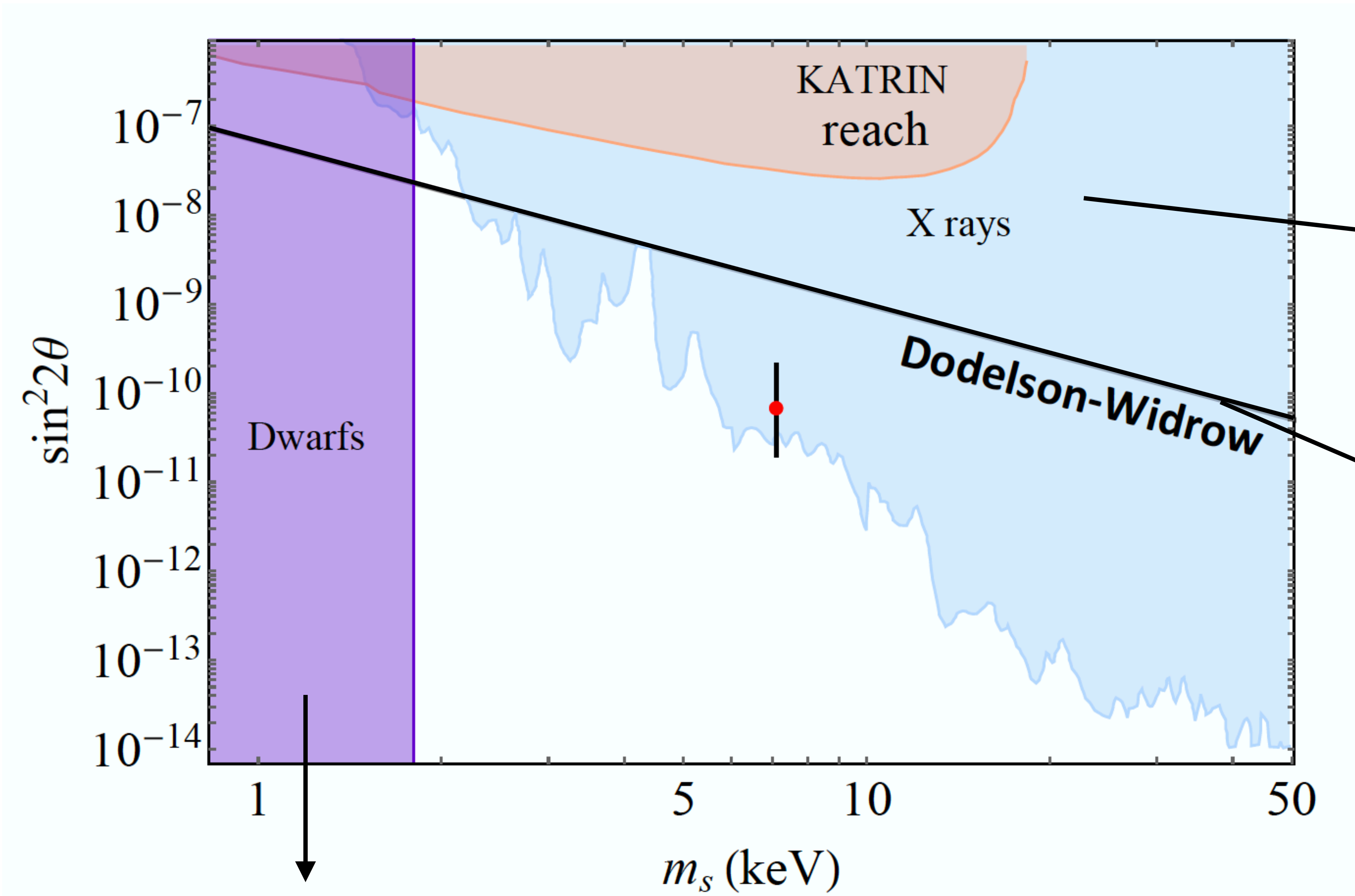
In SM: $V_T \sim T^5$

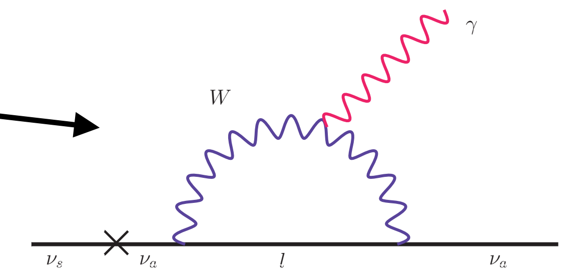
$\Gamma \sim T^5$ $\longrightarrow$ Production rate peaks at $T \sim 108\,\mathrm{MeV}\left(\frac{m_s}{\mathrm{keV}}\right)^{1/3}$

$\Delta \sim T^{-1}$

Dodelson-Widrow Mechanism

Ruled out by X-ray experiments and phase-space considerations





$$\Omega_s h^2 = 0.12$$

Phase space restrictions (Tremaine– Gunn)

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Dodelson-Widrow Mechanism

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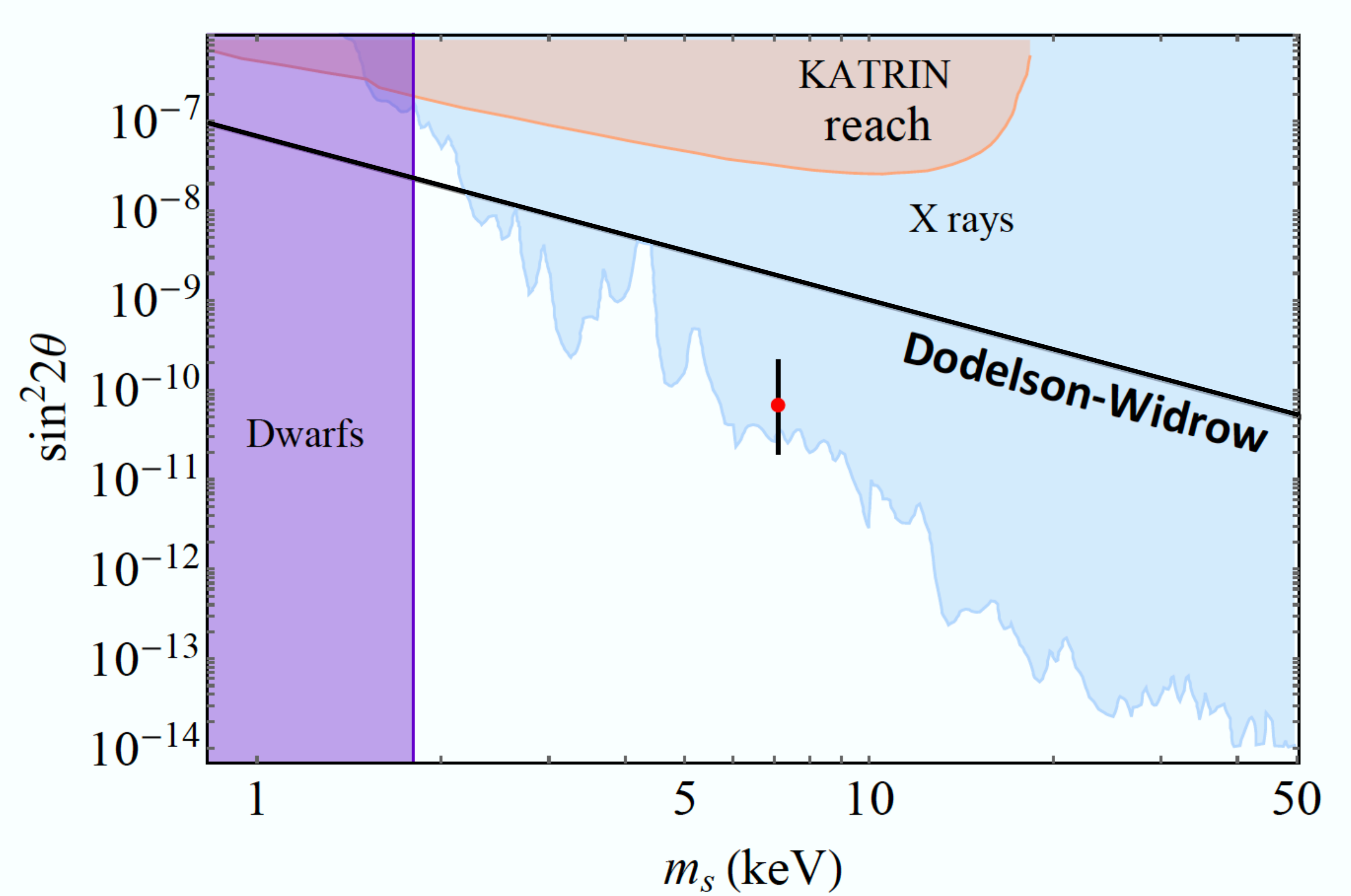

How to generate enough sterile neutrino DM within the allowed region?

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Add self-interactions!

How to generate enough sterile neutrino DM within the allowed region?

Add self-interactions!

Active neutrino self-interactions!

- Enhancement in interaction rate
- Sterile sector remains out of equilibrium

Sterile neutrino self-interactions!

- Self-interacting dark matter
- Sterile sector acquires a ``dark temperature''

Dodelson-Widrow Mechanism + new neutrino self-interactions

De Gouvêa, Sen, Tangarife & Zhang PRL (2020)
Kelly, Sen, Tangarife & Zhang PRD (2020)

Dodelson-Widrow Mechanism + new neutrino self-interactions

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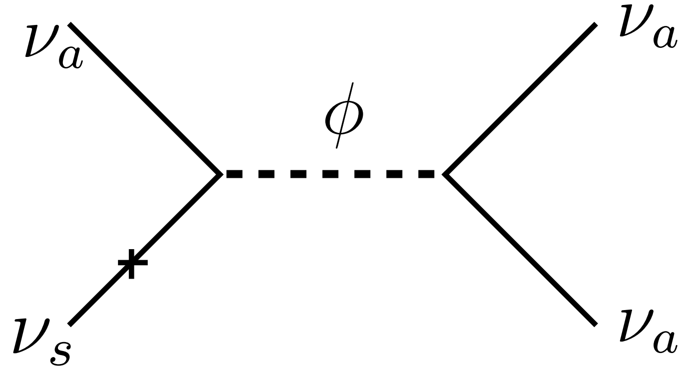
$$\mathcal{L} \supset \frac{\lambda_\phi}{2}\nu_a\nu_a\phi + \mathrm{h.c.}$$



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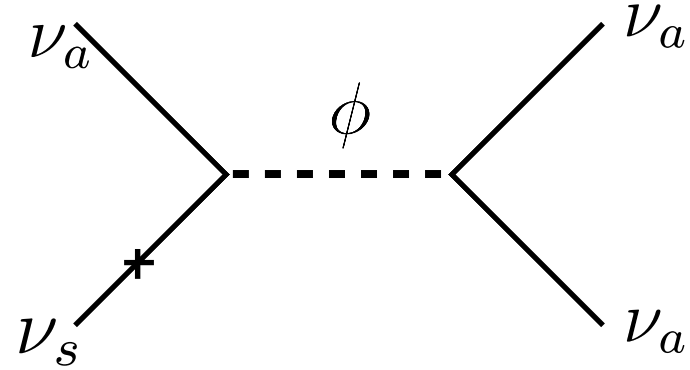
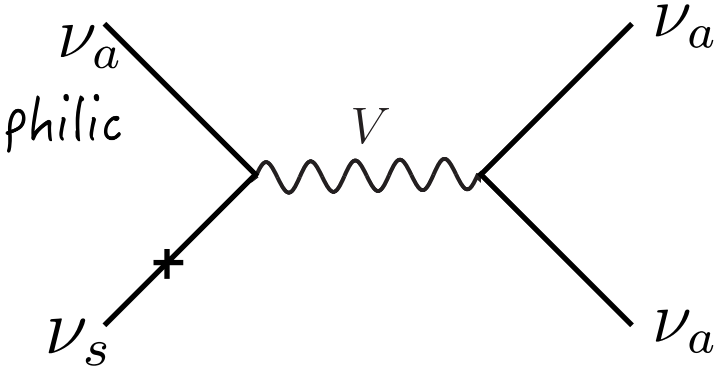


$$\mathcal{L} \supset \lambda_{\alpha\beta}\bar{\nu}_\alpha\gamma^\mu\nu_\beta V_\mu$$

$U'(1)$ neutrinophilic
$U(1)_{L_\mu - L_\tau}$
$U(1)_{B-L}$



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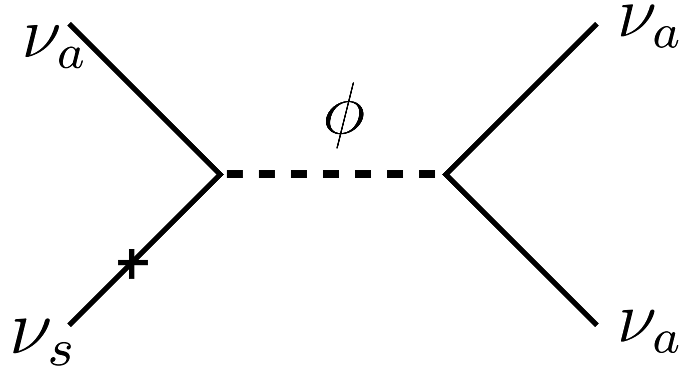

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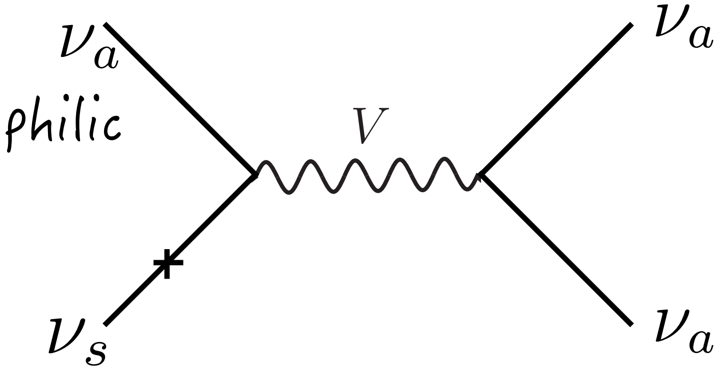


It can enhance the interaction rate while keeping a small mixing angle

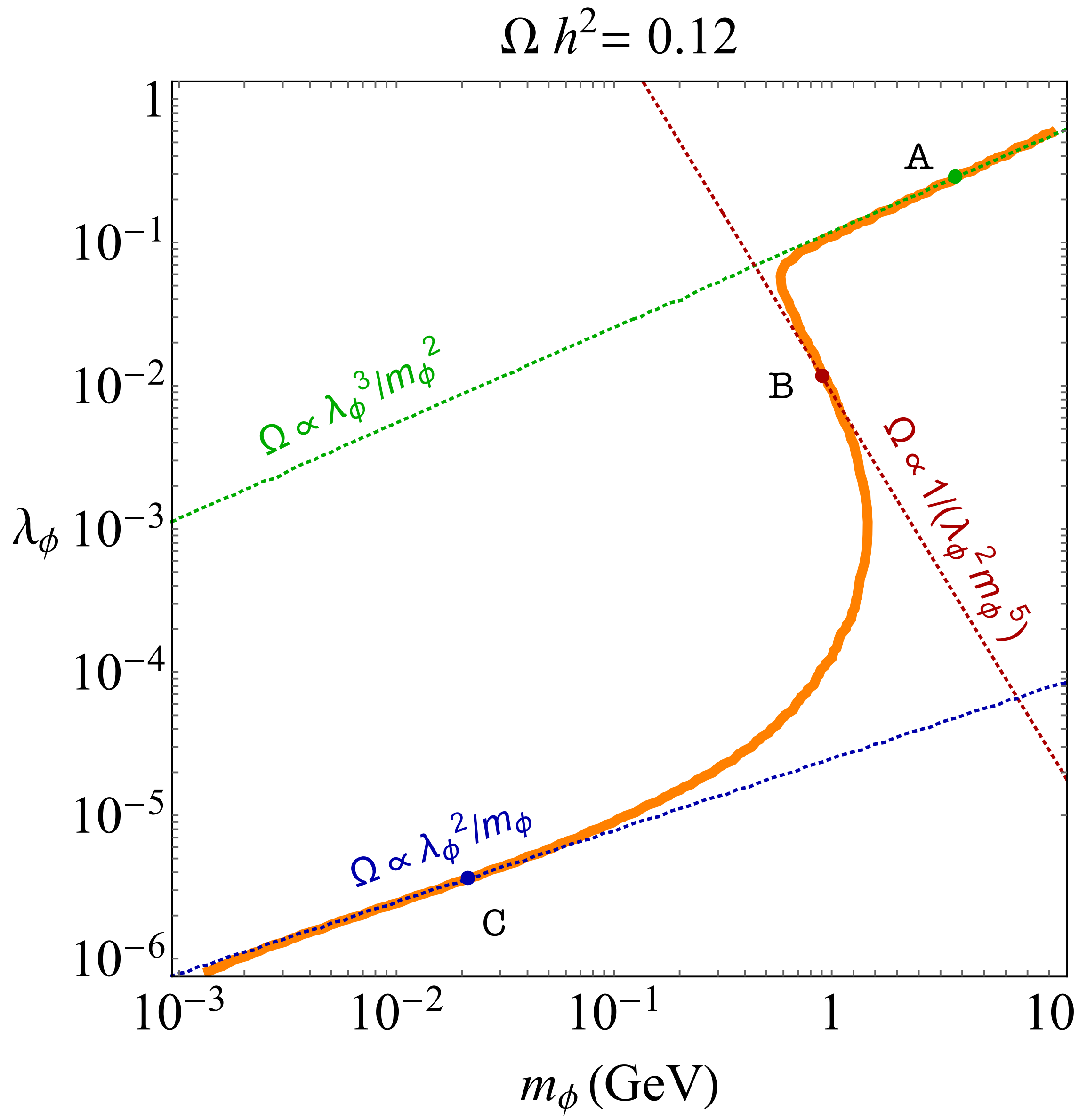
$$\frac{d\, f_{\nu_4}(x,z)}{d\ln z} = \frac{\Gamma}{4H}\sin^2 2\theta_{\text{eff}}\, f_\nu(x)$$

$$\sin^2 2\theta_{\text{eff}} \simeq \frac{\Delta^2\sin^2 2\theta}{\Delta^2\sin^2 2\theta + (\Gamma/2)^2 + (\Delta\cos 2\theta - V_T)^2}$$

The new interaction also contributes to the thermal potential V_T

Similar works Koop et al. (2014), Mirizzi et al. (2015), Friedland et al. (2016), Johns et al. (2019), …

Sterile neutrino relic density



$$m_{\nu_s} = 7.1\,\mathrm{keV},\ \ sin^2 2\theta = 7\times 10^{-11}$$

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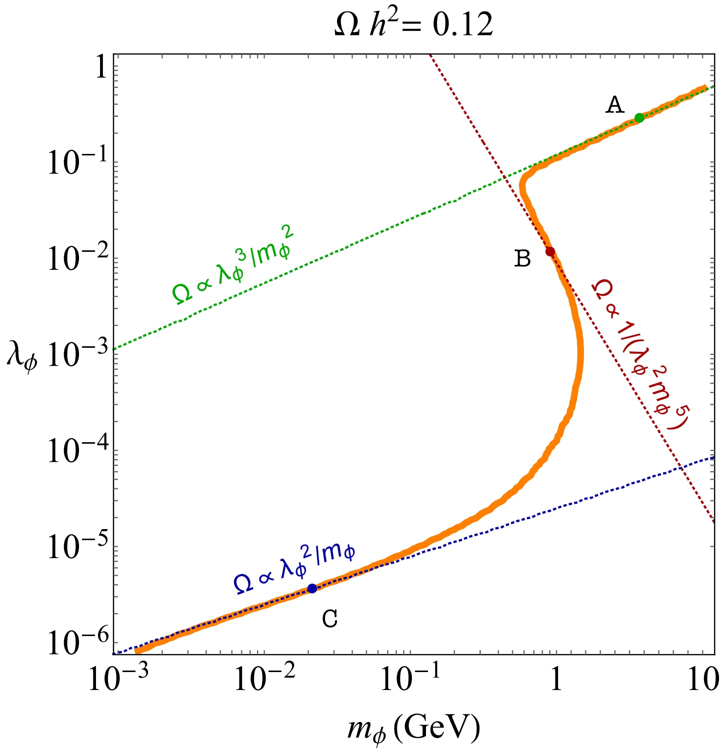


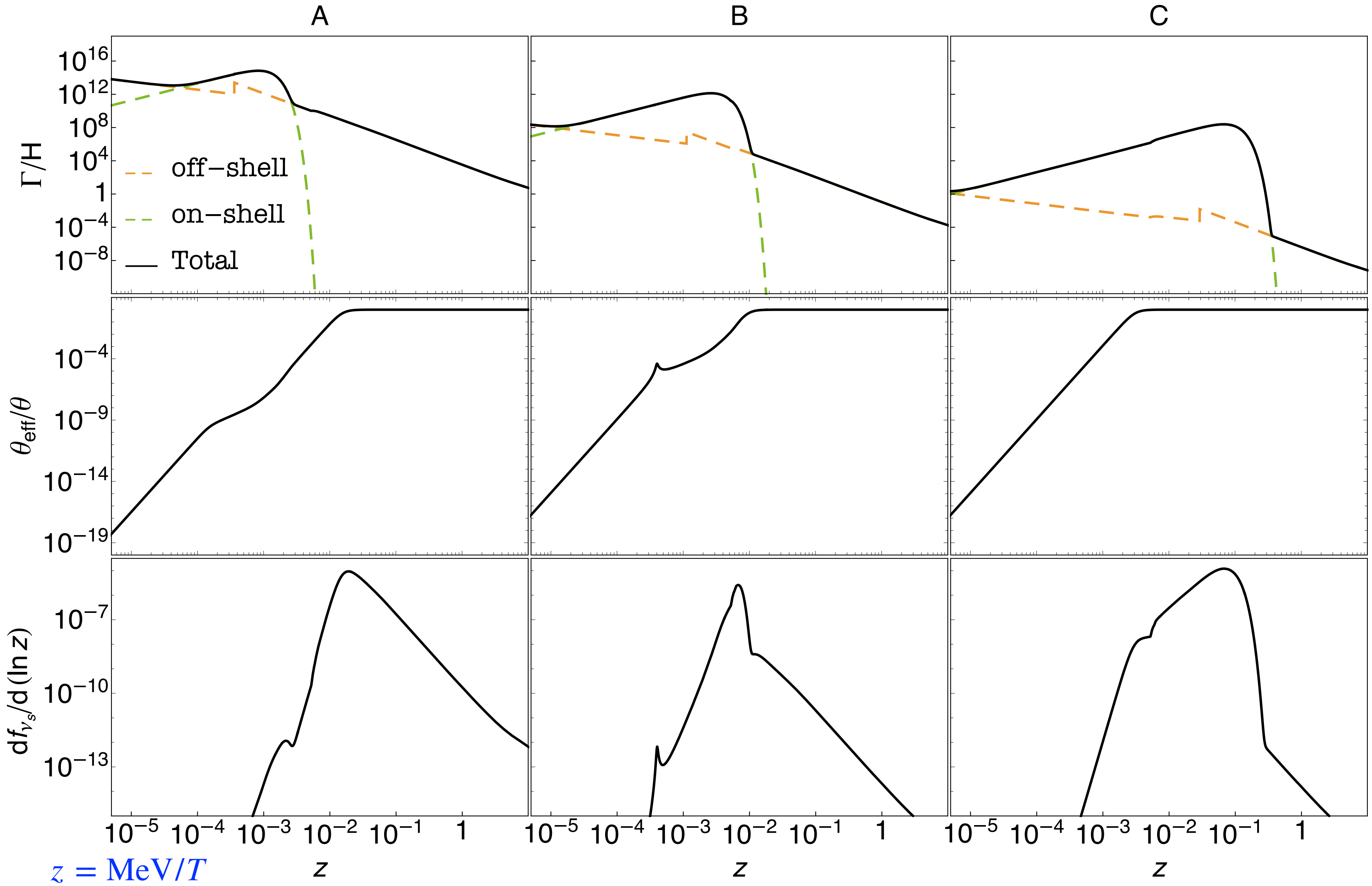
$m_{\nu_s} = 7.1\,\mathrm{keV},\ sin^2 2\theta = 7 \times 10^{-11}$

Three useful timescales:

z_0: When $\Gamma/H = 1$.

z_1: When $\Delta \simeq \mathrm{Max}\{|V_T|, \Gamma_a\}$.

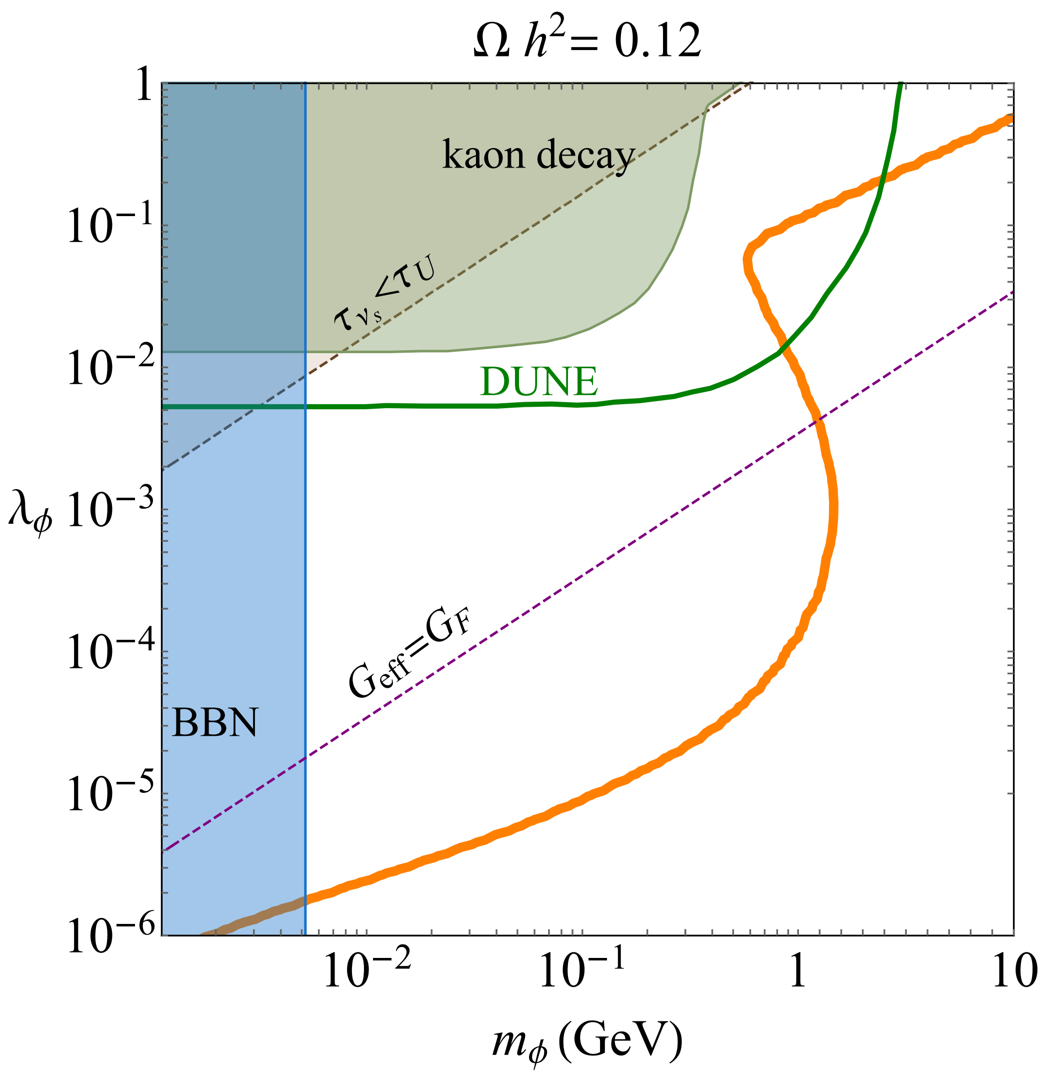
$z_2 = \mathrm{MeV}/m_\phi$.



$z = \mathrm{MeV}/T$

$z_2 < z_1 < z_0$ $z_2 \sim z_1 < z_0$ $z_1 < z_2 < z_0$

Current and future constraints



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Bounds from $K^- \to \mu^- \nu_\mu \phi,\ \phi \to \nu\nu$

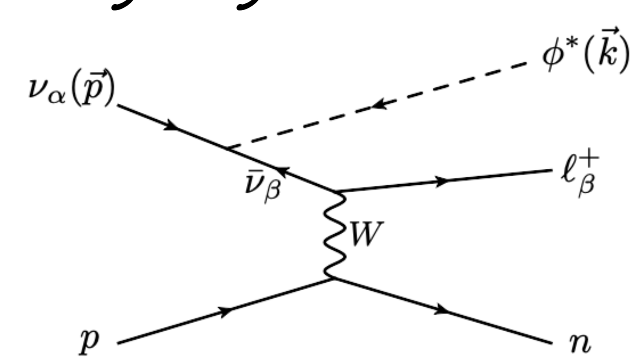
$\mathrm{Br}(K^- \to \mu^- + 3\nu) < 10^{-6}$

BBN bounds on light d.o.f.s

Expected sensitivity of DUNE:

Look for the "wrong-sign muon"

$\nu_\mu N \to \mu^+ N' \phi$.

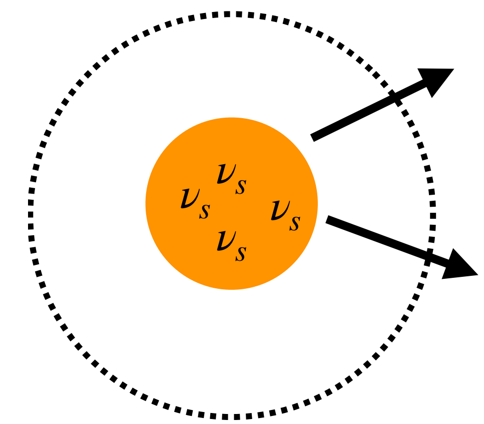


Berryman, de Gouvêa, Kelly & Zhang (2018)
Blinov, Kelly, Krnjaic & McDermott (2019)
Kelly & Zhang (2019)

Constraints from supernovae

Chen, Sen, Tucker, Tangarife & Zhang, JCAP 11 (2022) 014

~99% of the binding energy of the SN is released in neutrinos

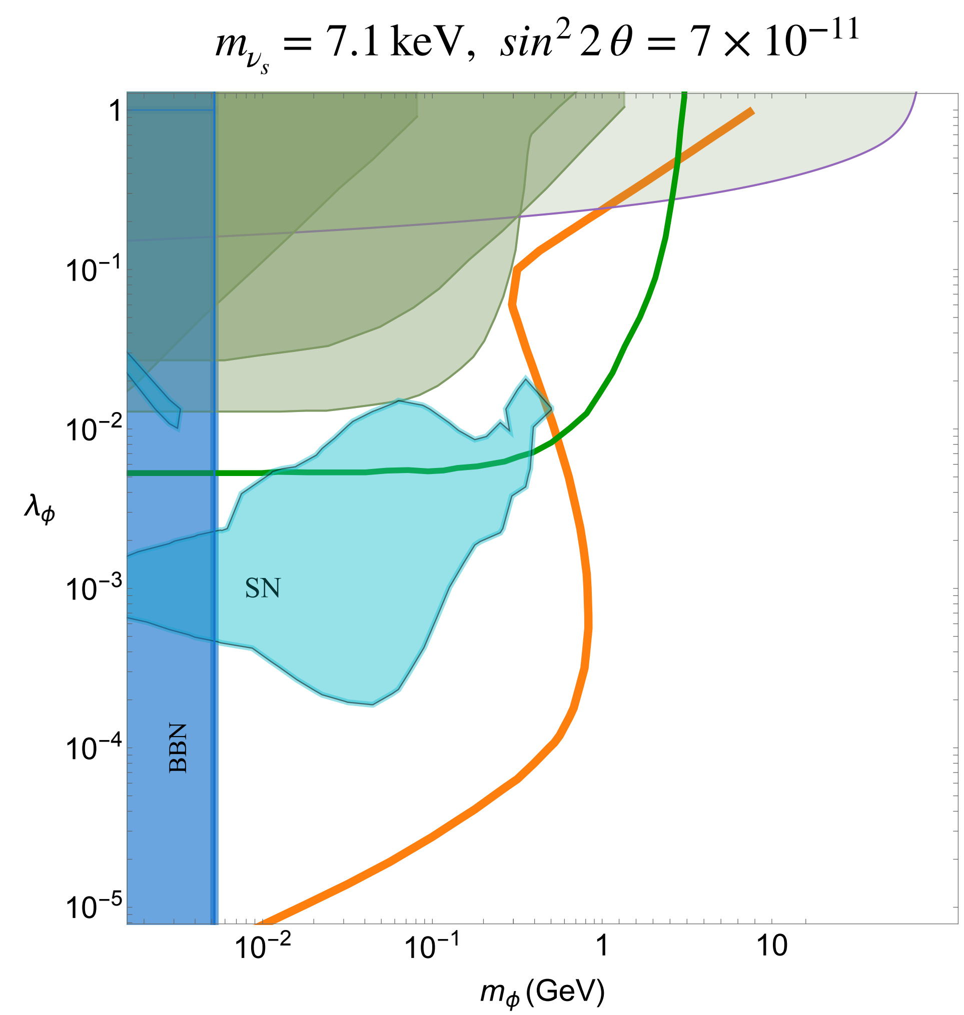


The outgoing neutrino burst should carry enough energy from the collapsed core ti re-energize the shockwave. This sets a bound on the energy carried away by sterile neutrinos

$$\sin^2 2\theta_{\rm eff}(E,r) = \frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + \Gamma(E,r)^2 + (\Delta\cos 2\theta - V(E,r))^2}$$

We need $L \lesssim 10^{53}\,\mathrm{erg/s}$

Raffelt (1996)



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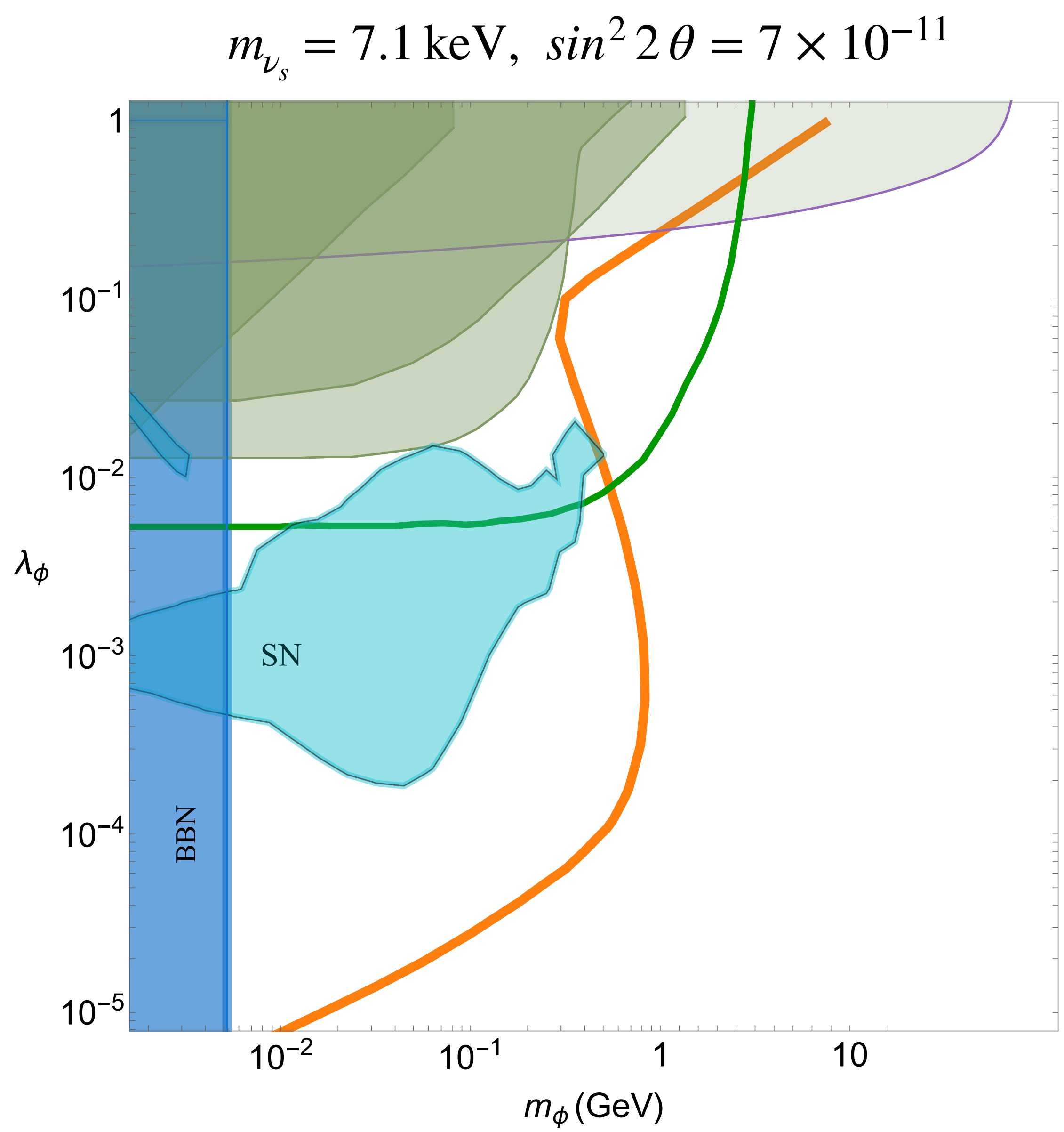

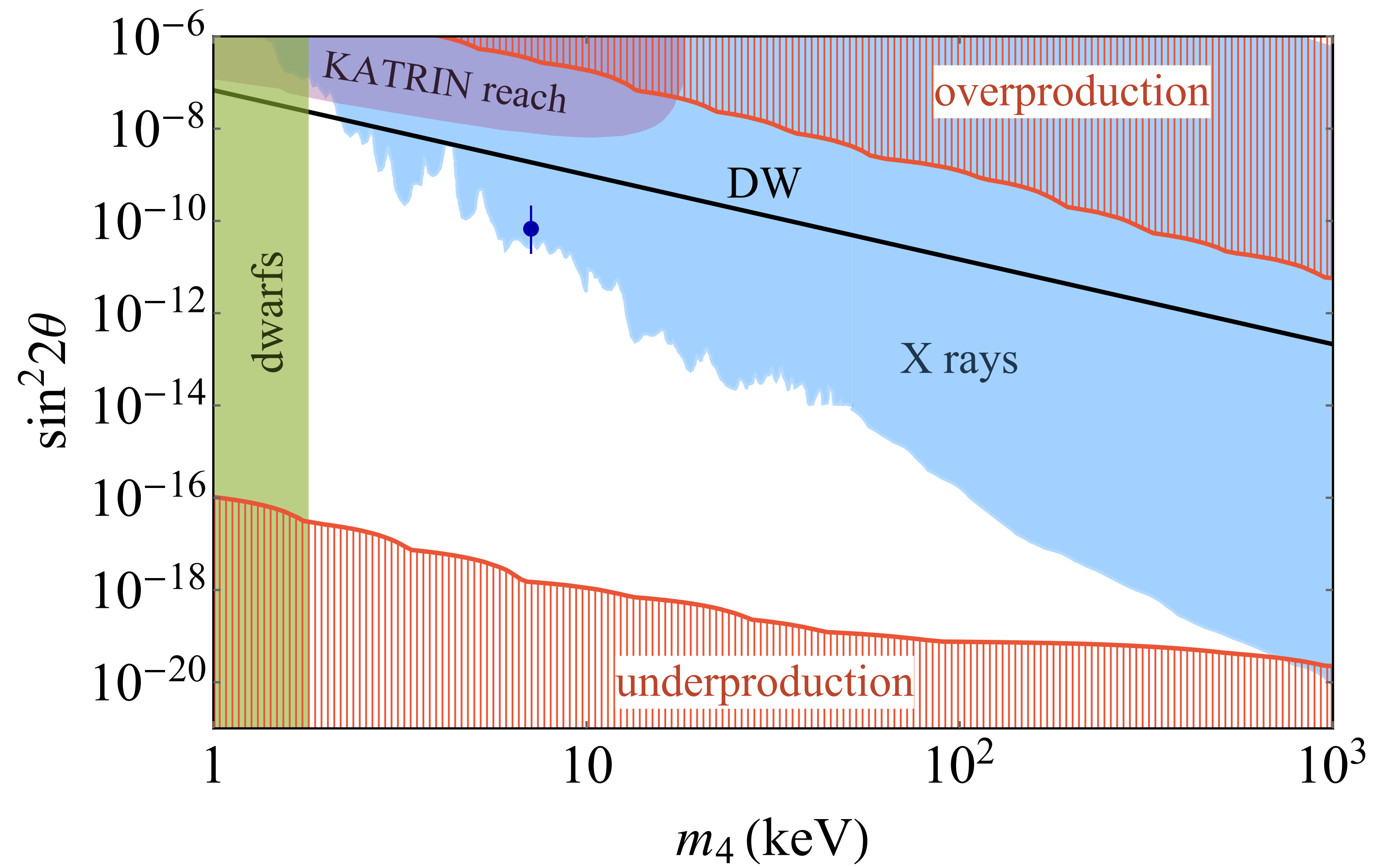

Dodelson-Widrow Mechanism + new DM self-interactions

Sen, Tangarife & Zhang, in preparation

Move the self-interaction to the sterile neutrino sector (light mediator)

Work in progress

See also Bringmann et al. (2022) for similar work

See Johns & Fuller (2019) for heavy-mediator case

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Work in progress

So that I can go back to Pollica!

The self-interaction will lead to a thermalized hidden sector. We want to explore the effect of this new interaction on the sterile neutrino DM production.

See also Bringmann et al. (2022) for similar work

See Johns & Fuller (2019) for heavy-mediator case

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We need to use the density-matrix formalism $\rho \equiv \langle\psi|\hat{\rho}|\psi\rangle = \begin{pmatrix} f_{11} & f_{12} \\ f_{21} & f_{22} \end{pmatrix}$

Work in progress

$$H\frac{\partial f_{11}}{\partial \log z} = \frac{i}{2}\Delta\sin(2\theta)(f_{12} - f_{21}) \ ,$$
$$H\frac{\partial f_{12}}{\partial \log z} = \frac{i}{2}\left[\Delta\sin(2\theta)(f_{11} - f_{22}) + 2(\Delta\cos(2\theta) - V_T)f_{12}\right] - (\Gamma_a + \Gamma_s)f_{12}/2 \ ,$$
$$H\frac{\partial f_{21}}{\partial \log z} = -\frac{i}{2}\left[\Delta\sin(2\theta)(f_{11} - f_{22}) + 2(\Delta\cos(2\theta) - V_T)f_{21}\right] - (\Gamma_a + \Gamma_s)f_{21}/2 \ ,$$
$$H\frac{\partial f_{22}}{\partial \log z} = -\frac{i}{2}\Delta\sin(2\theta)(f_{12} - f_{21}) \ .$$

$$\Gamma_s = 2 \times \int \frac{d^3\vec{q_1}}{(2\pi)^3}\sigma_s v_{\mathrm{M}} f_{22}(q_1)$$

$$\Delta = m_s^2/2E$$

$$z = \mathrm{MeV}/T$$

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Work in progress

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$$\Delta = m_s^2/2E$$

$$z = \mathrm{MeV}/T$$

If $\Gamma_s > H$

the sterile neutrino develops an equilibrium distribution function $f_{22} = \dfrac{1}{1 + e^{(E - \mu_s)/T_s}}$

chemical potential

dark temperature

Dodelson-Widrow Mechanism + new DM self-interactions

Sen, Tangarife & Zhang, in preparation

Move the self-interaction to the sterile neutrino sector (light mediator)

$$\frac{1}{2\pi^2}\int E^2 dE f_{22}(E) = \frac{1}{2\pi^2}\int \frac{E^2 dE}{1+e^{(E-\mu_s)/T_s}} = -\frac{T_s^3}{\pi^2}\mathrm{Li}_3(-e^{\mu_s/T_s})$$

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Work in progress

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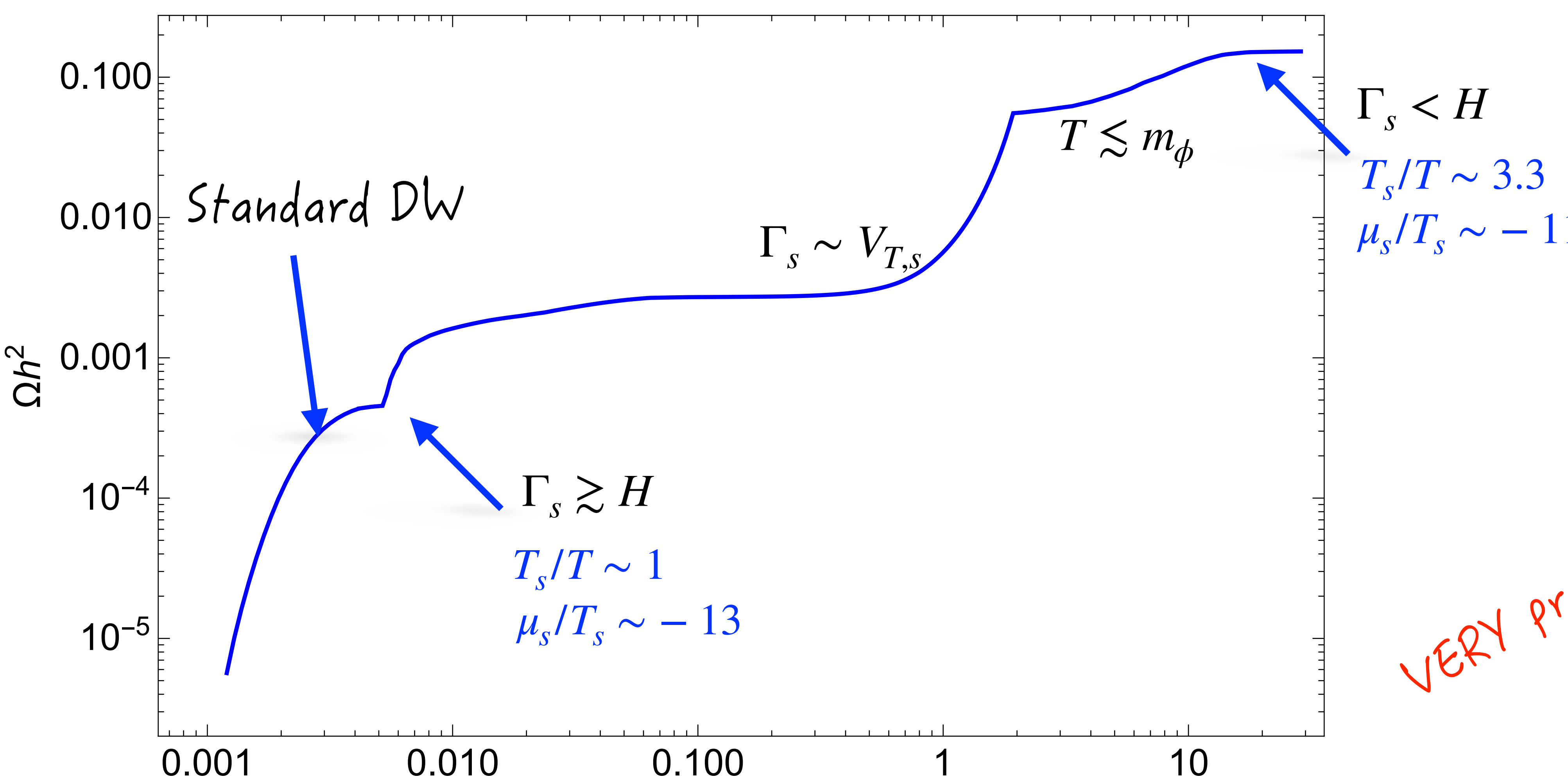
$$m_{\nu_s} = 7\,\mathrm{keV} \qquad \theta = 6\times 10^{-7} \qquad m_\phi = 1\,\mathrm{MeV} \quad \lambda_\phi = 10^{-2}$$

Work in progress



VERY preliminary

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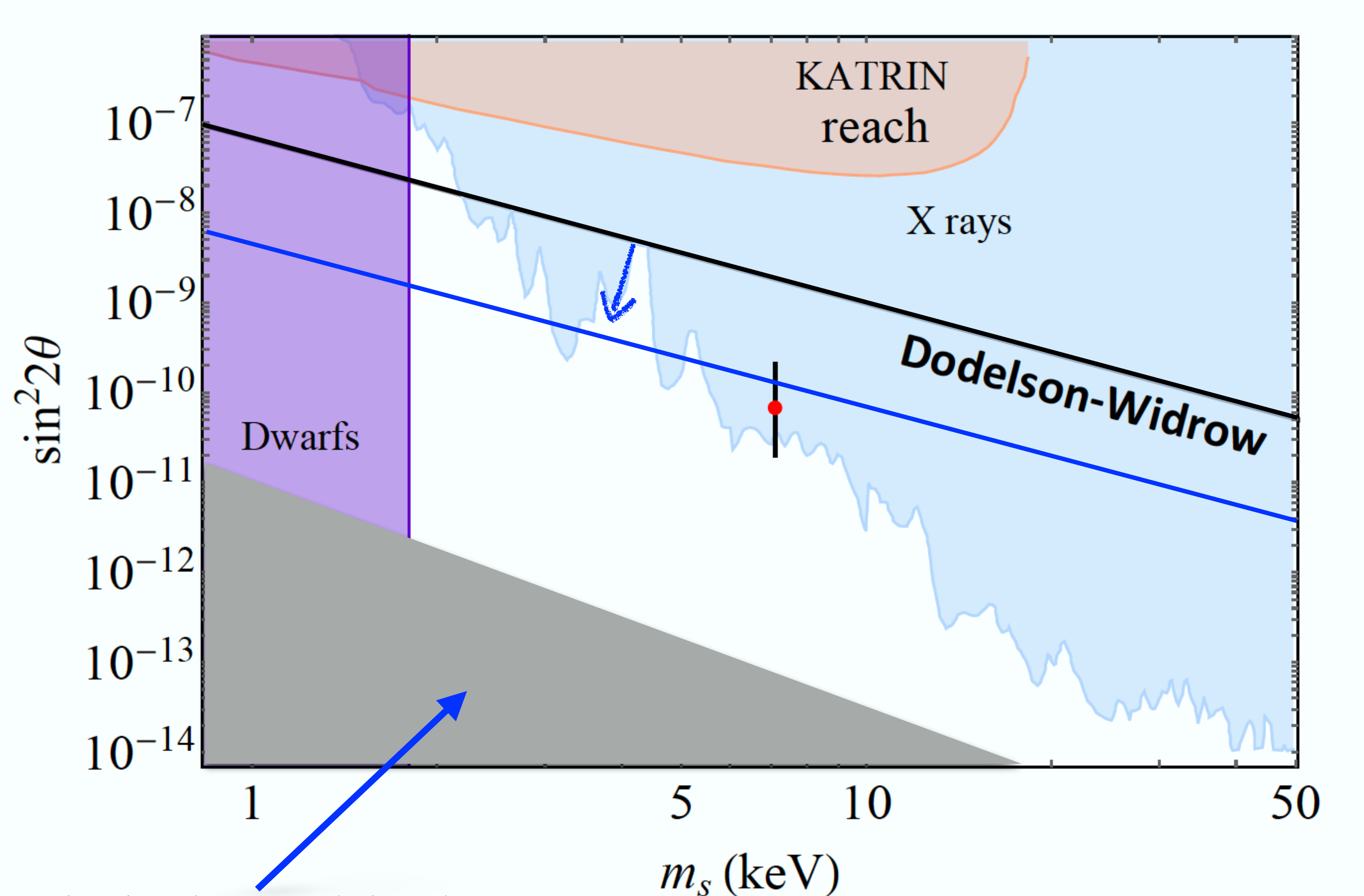

$m_\phi = 1$ MeV

$\lambda_\phi = 10^{-2}$

No dark thermal bath

Can we produce enough sterile neutrino DM in the early universe?

Yes! Sterile neutrinos can be produced non-thermally from active-neutrino oscillations.

A new interaction, via a scalar or a vector, for the active neutrinos helps alleviate tensions with the Dodelson-Widrow mechanism.

The case of self-interacting sterile neutrinos could be an attractive scenario of SIDM. This is currently being explored.

Thank you!