MOCa 2021

Sterile Neutrino Dark Matter and Self-Interactions

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and work in progress

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

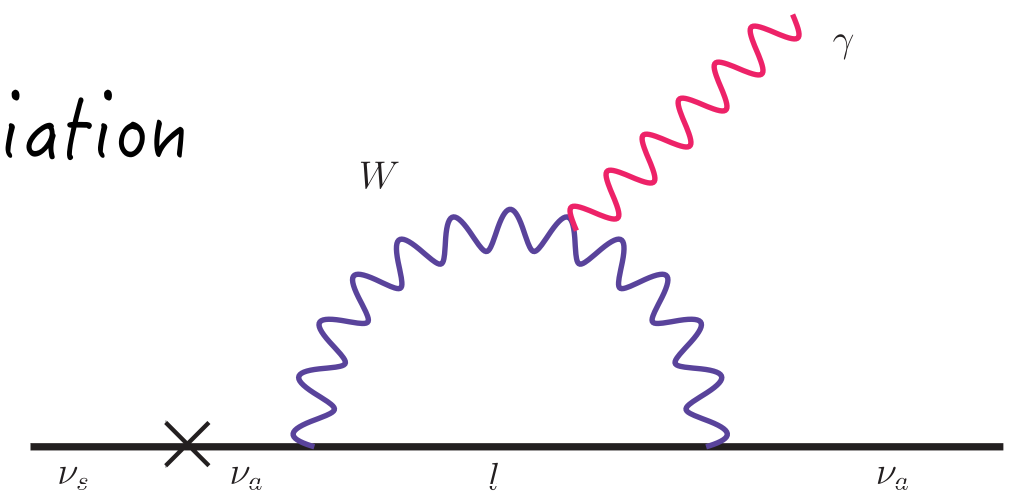
Sterile Neutrino as Dark Matter

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

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), …

How to produce it?

Two (among several) proposals:

Dodelson-Widrow (1994)

Shi-Fuller (1999)

For a review: Abazajian (2017)

Dodelson-Widrow Mechanism

Dodelson & Widrow (1994)

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

In SM: $V_T \sim T^5$

$\Gamma \sim T^5$

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

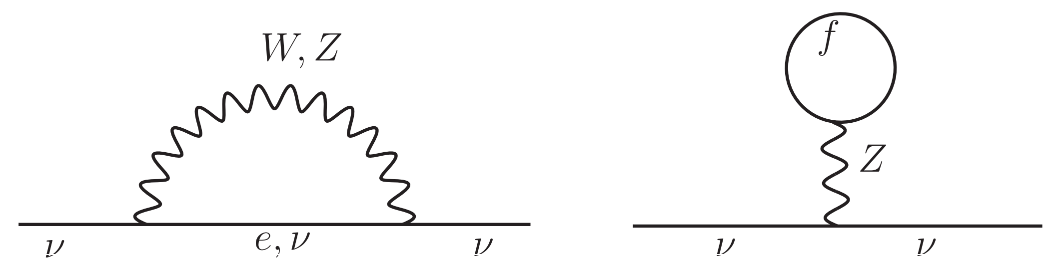
$$\sin^2 2\theta_{\rm eff} \simeq \frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + (\Gamma/2)^2 + (\Delta \cos 2\theta - V_T)^2}$$

$\Delta = m_s^2/2E$

Thermal potential

Quantum Zeno effect (damping)

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



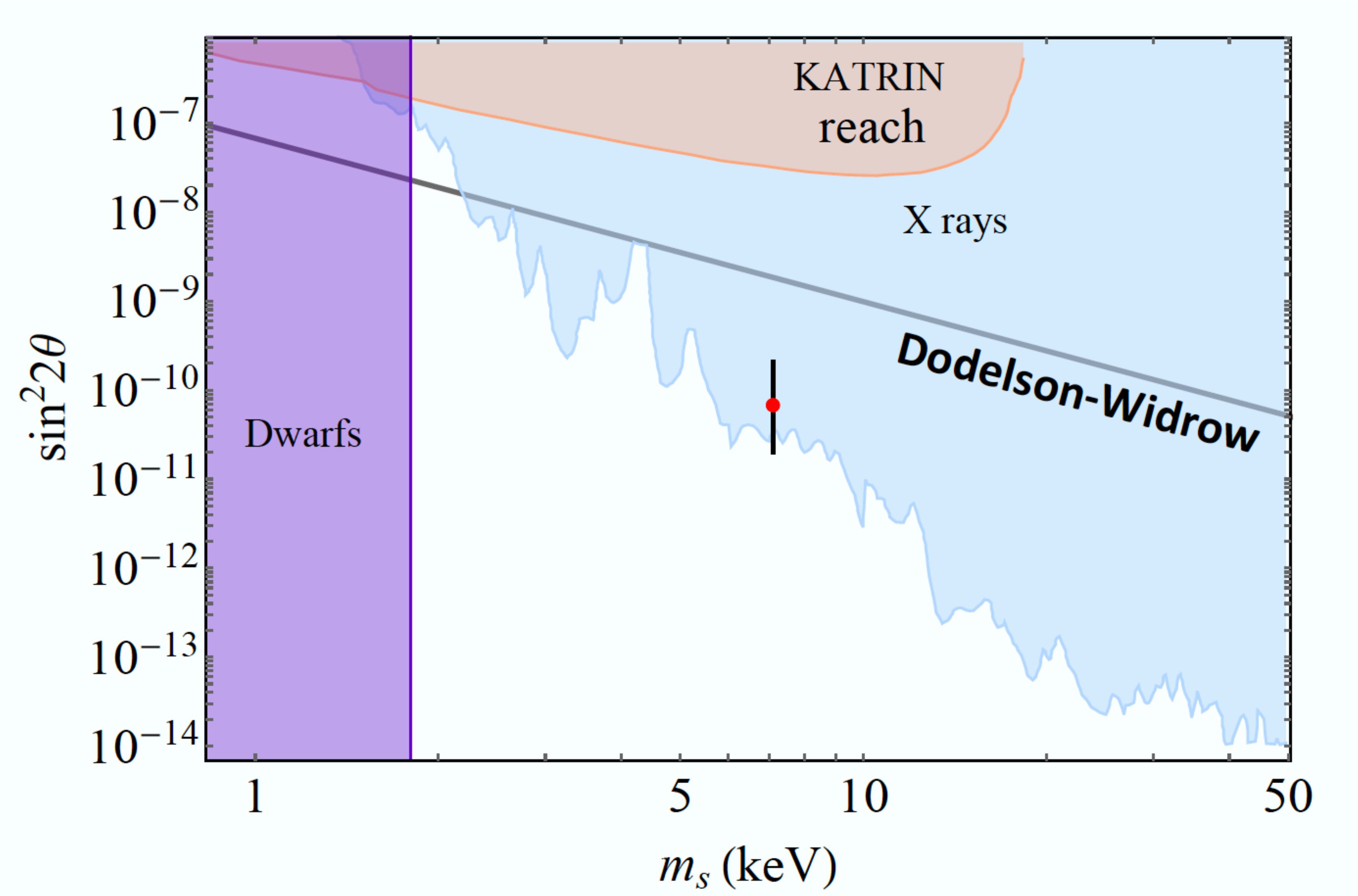
Result: A non-thermal abundance of sterile neutrinos by solving the Boltzmann equation

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

$z = \mathrm{MeV}/T$

Dodelson-Widrow Mechanism

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



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

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

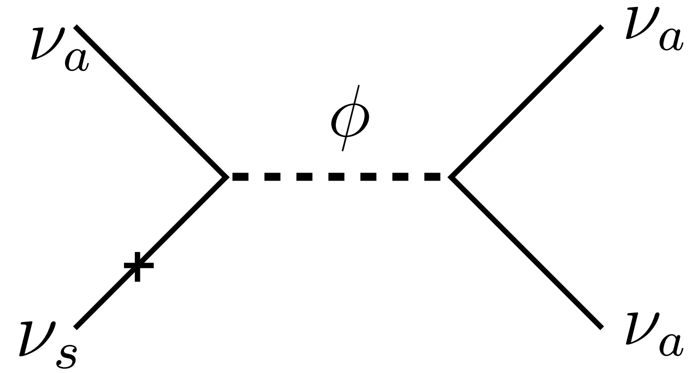
Sterile neutrino self-interactions!

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

Dodelson-Widrow Mechanism + new neutrino self-interactions

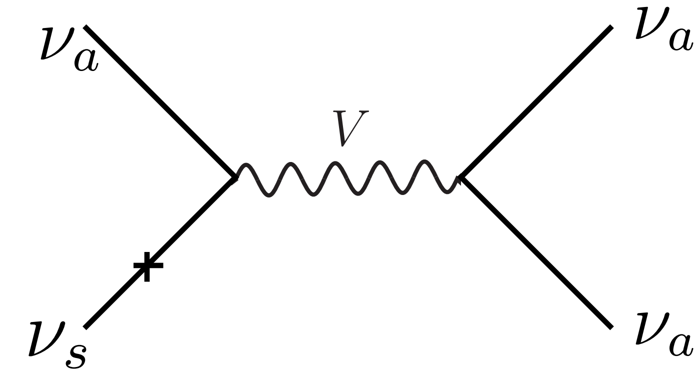
De Gouvêa, Sen, Tangarife & Zhang PRL (2020)
Kelly, Sen, Tangarife & Zhang PRD (2020)

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



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

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



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

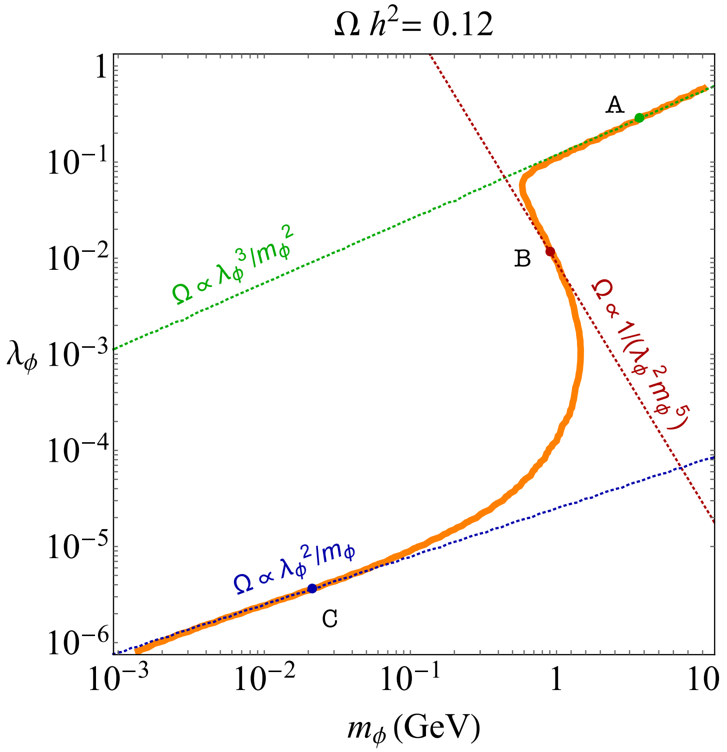
$$\frac{d\, f_{\nu_4}(x,z)}{d \ln z} = \frac{\Gamma}{4H} \sin^2 2\theta_{\rm eff}\, f_\nu(x)$$

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

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



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

Three useful timescales:

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

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

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

Case A:

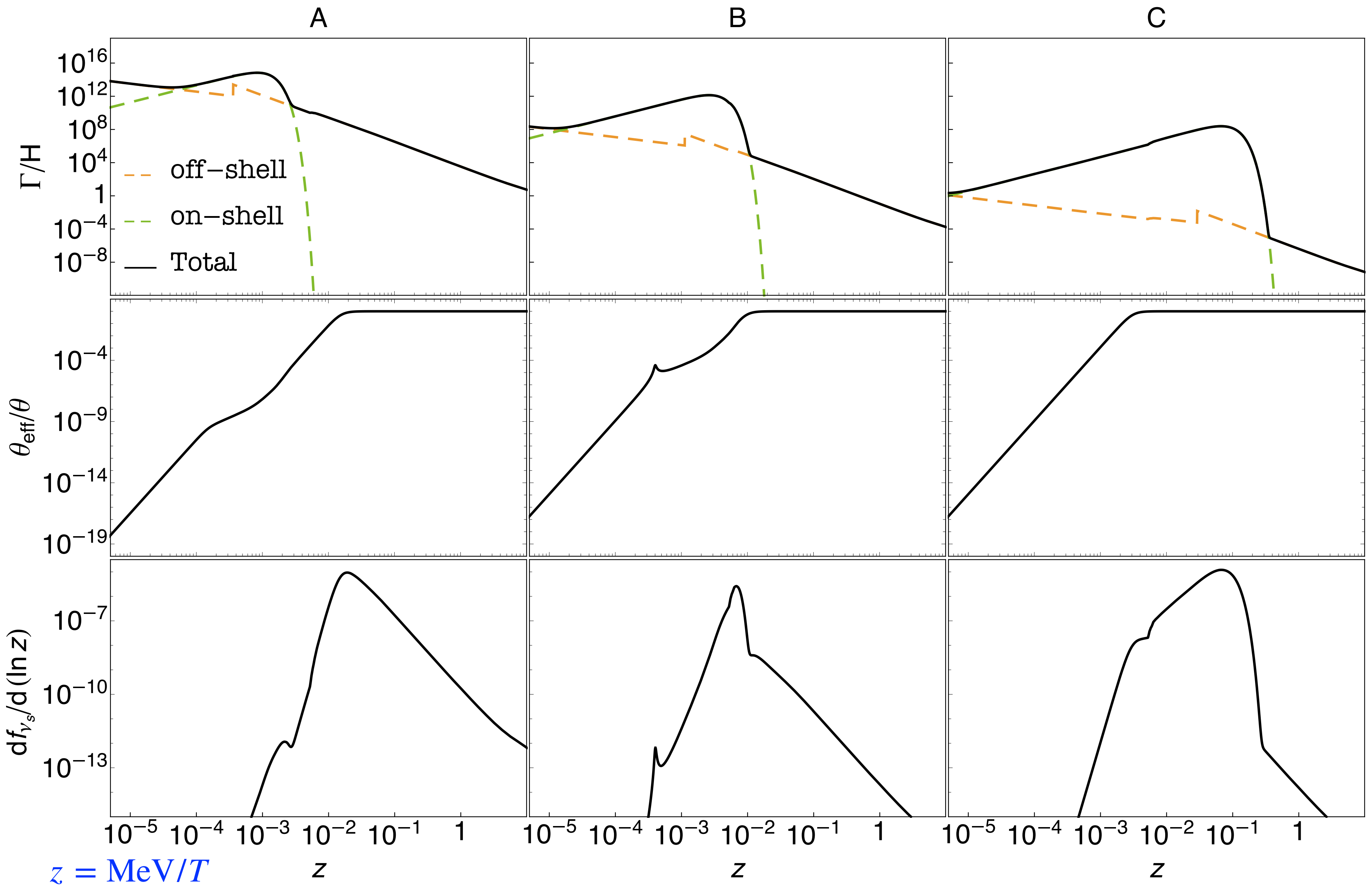
$z_2 < z_1 < z_0$

Case B:

$z_2 \sim z_1 < z_0$

Case C:

$z_1 < z_2 < z_0$



$z = \text{MeV}/T$

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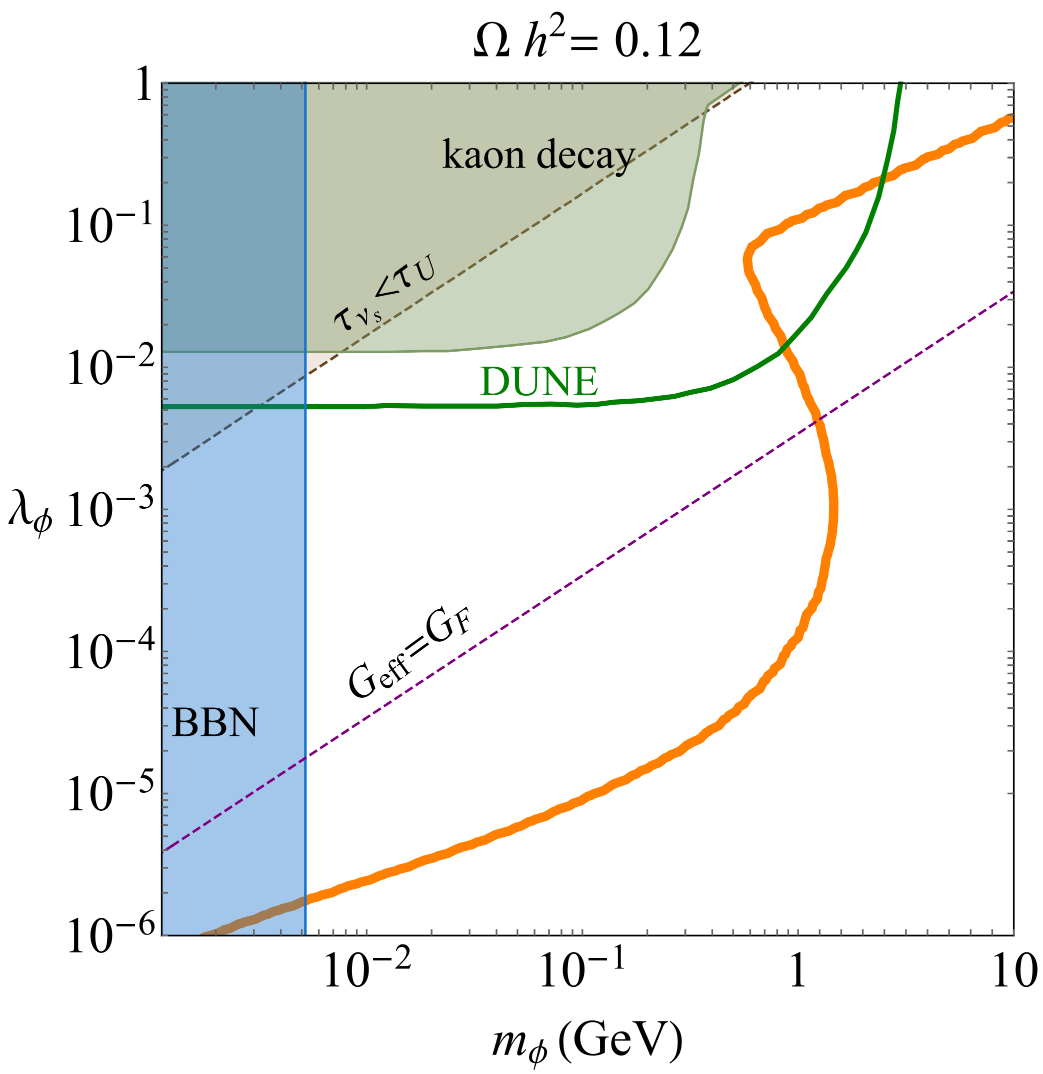
Current and future constraints



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

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

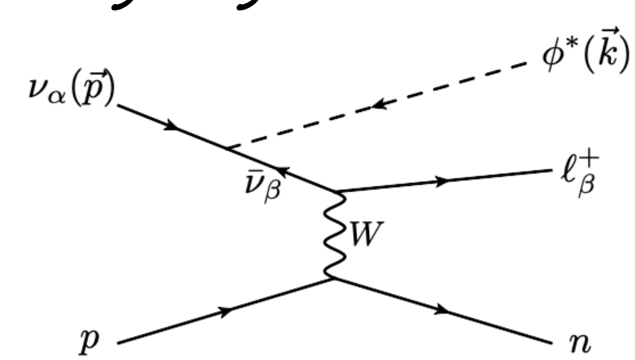
$\mathrm{Br}(K^- \to \mu^- + 3\nu) < 10^{-6}$

BBN bounds on light d.o.f.s

Expected sensitivity of DUNE:

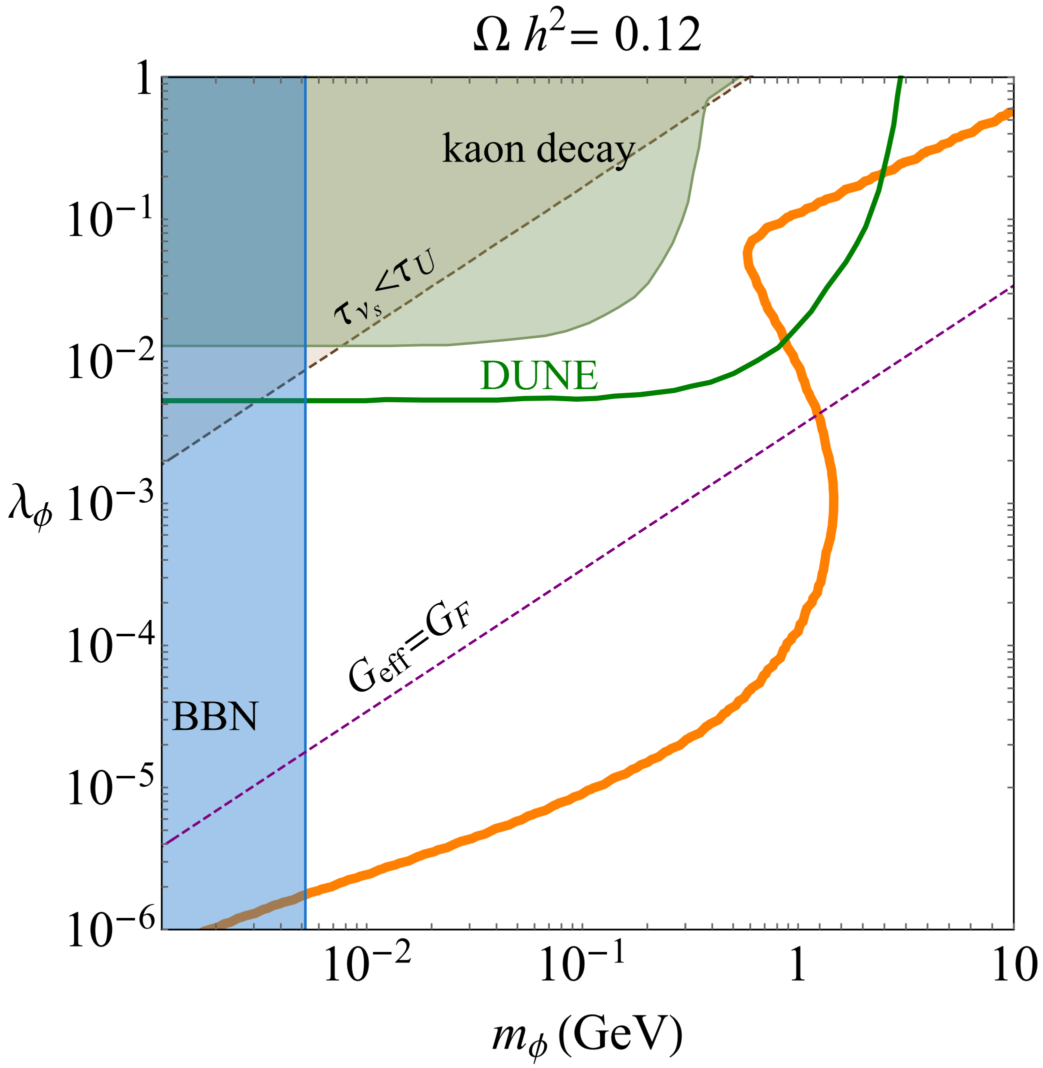
Look for the "wrong-sign muon"

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

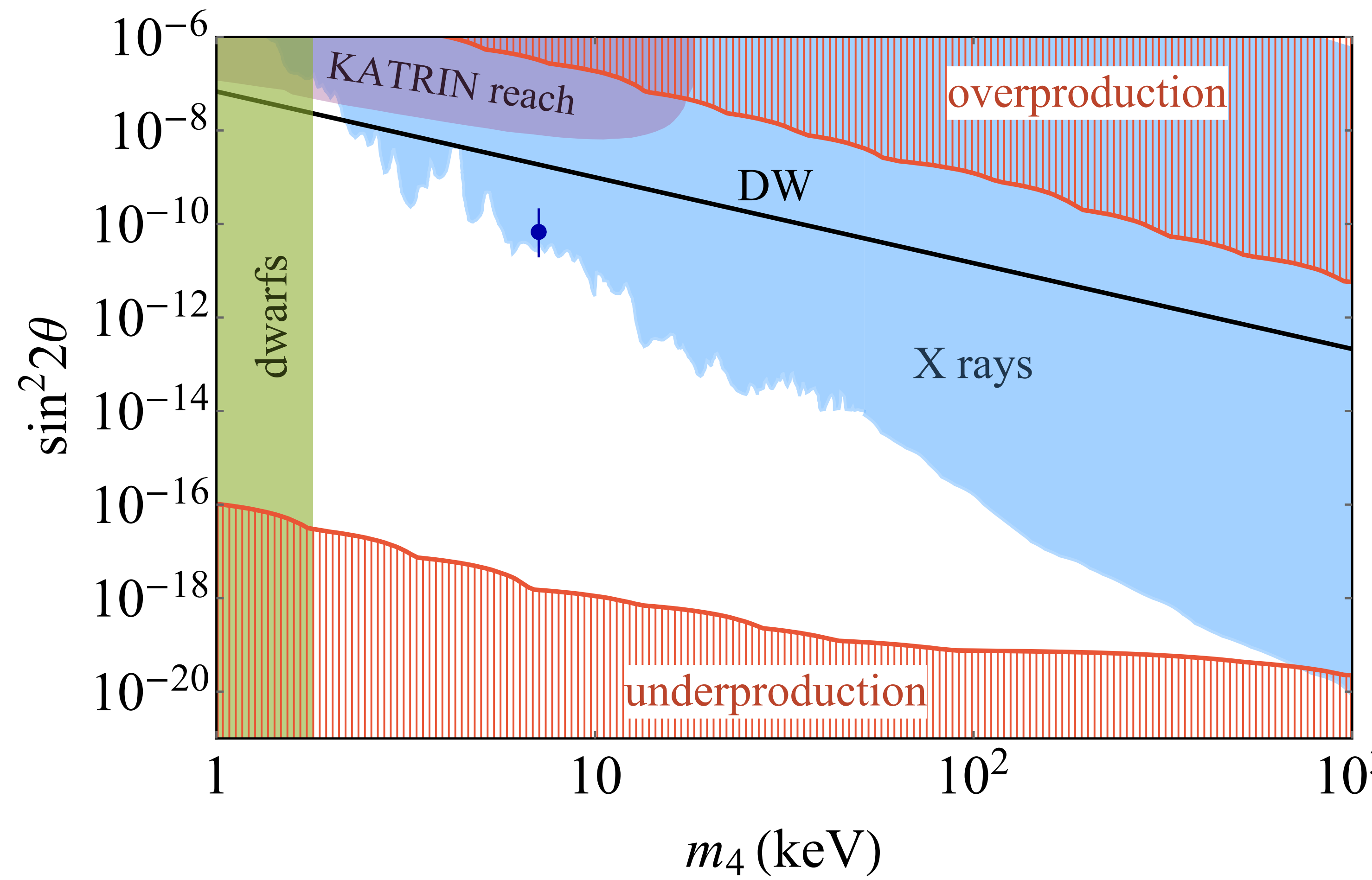


Berryman, de Gouvêa, Kelly & Zhang (2018)
Blinov, Kelly, Krnjaic & McDermott (2019)
Kelly & Zhang (2019)

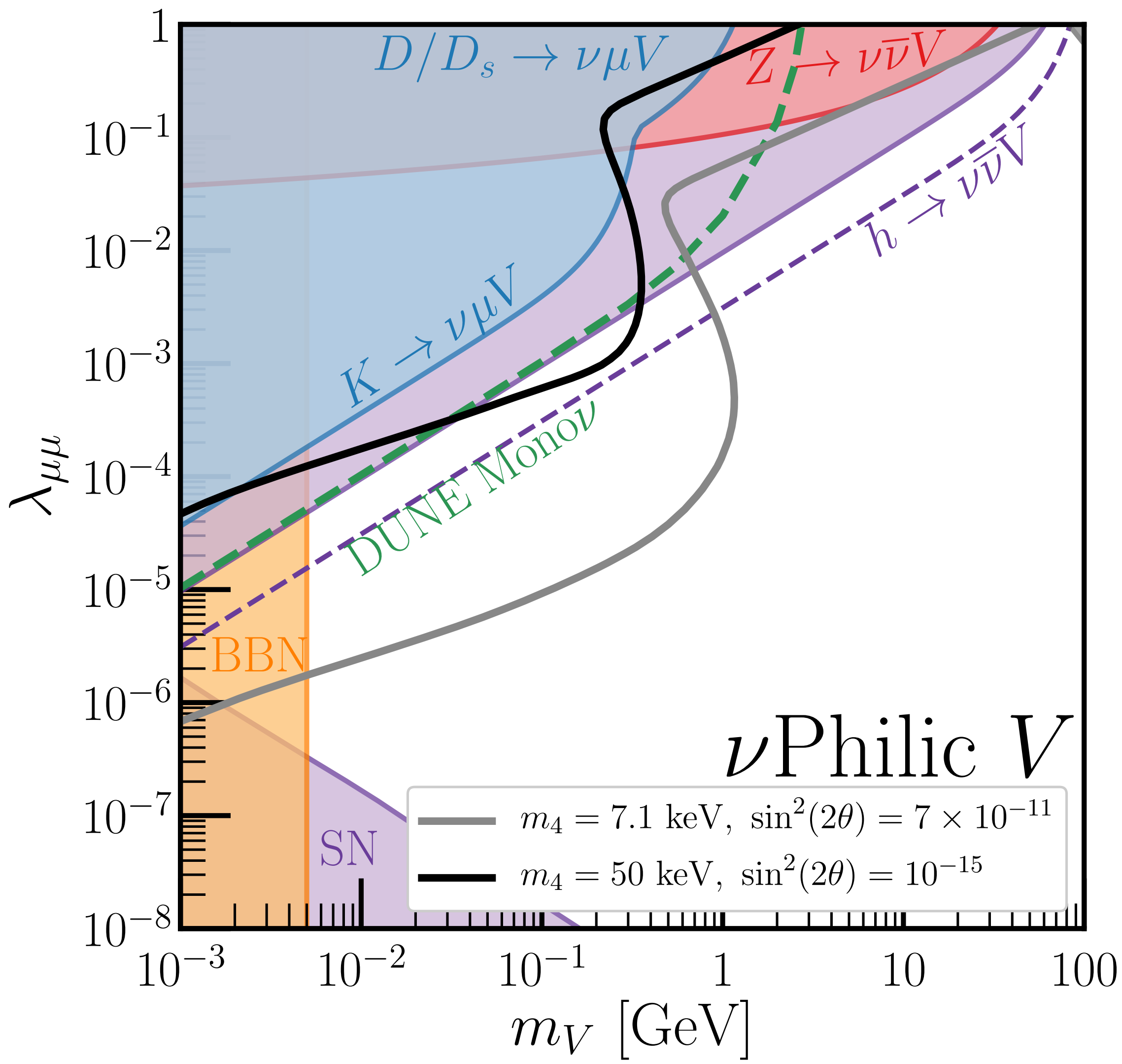
Current and future constraints



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



Current and future constraints: Neutrinophilic $U'(1)$



$$\mathcal{L} \supset \sum_{\alpha,\beta=e,\mu,\tau} \frac{(\overline{L}_\alpha i\sigma_2 H^*)\gamma_\mu (H^T i\sigma_2 L_\beta) V^\mu}{\Lambda^2_{\alpha\beta}}$$

A new Higgs invisible decay: $h \to \nu_\mu \bar{\nu}_\mu V$

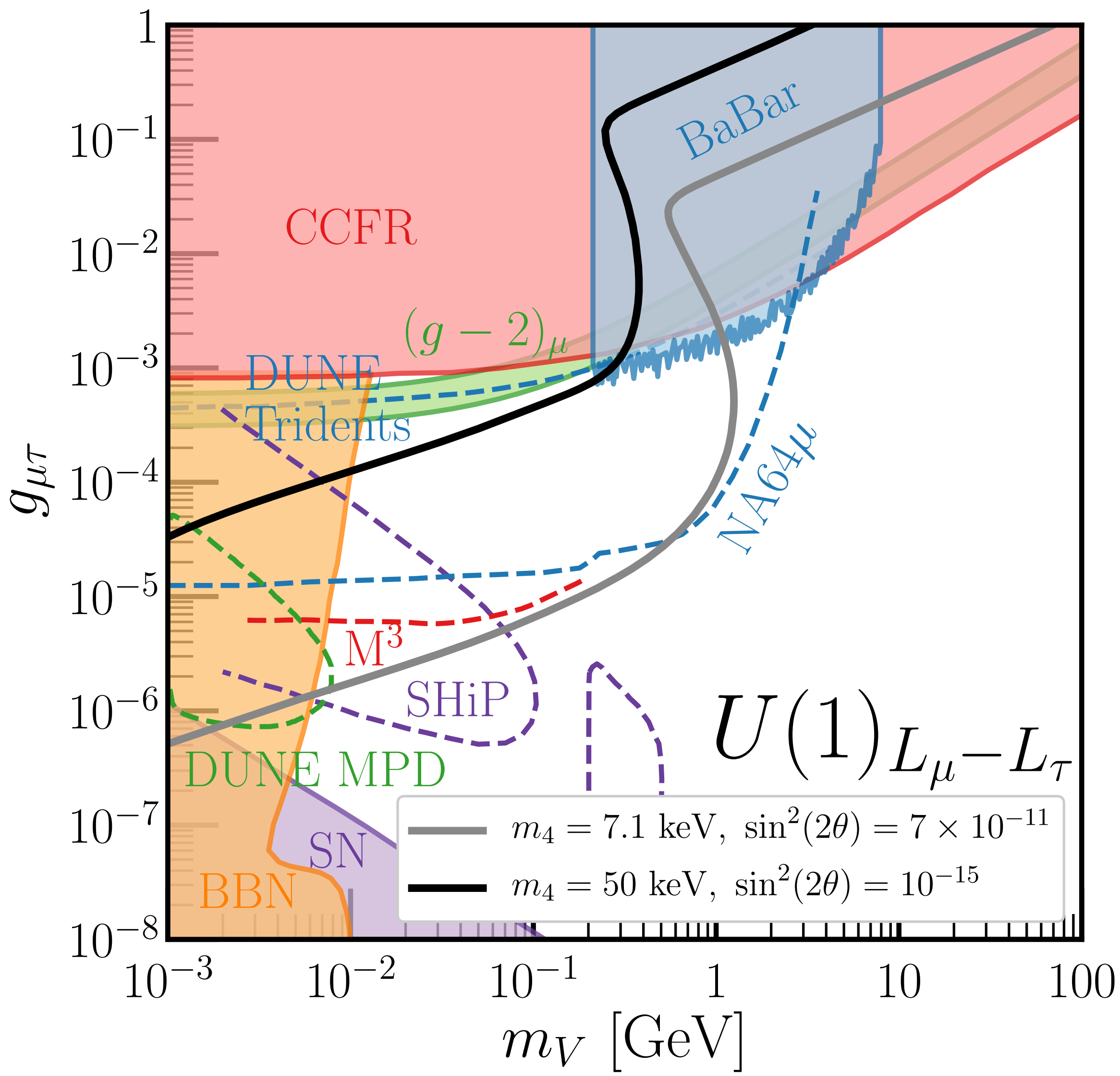
$\mathrm{Br}(H \to \text{invisible}) < 24\%$ Current HLC (purple)

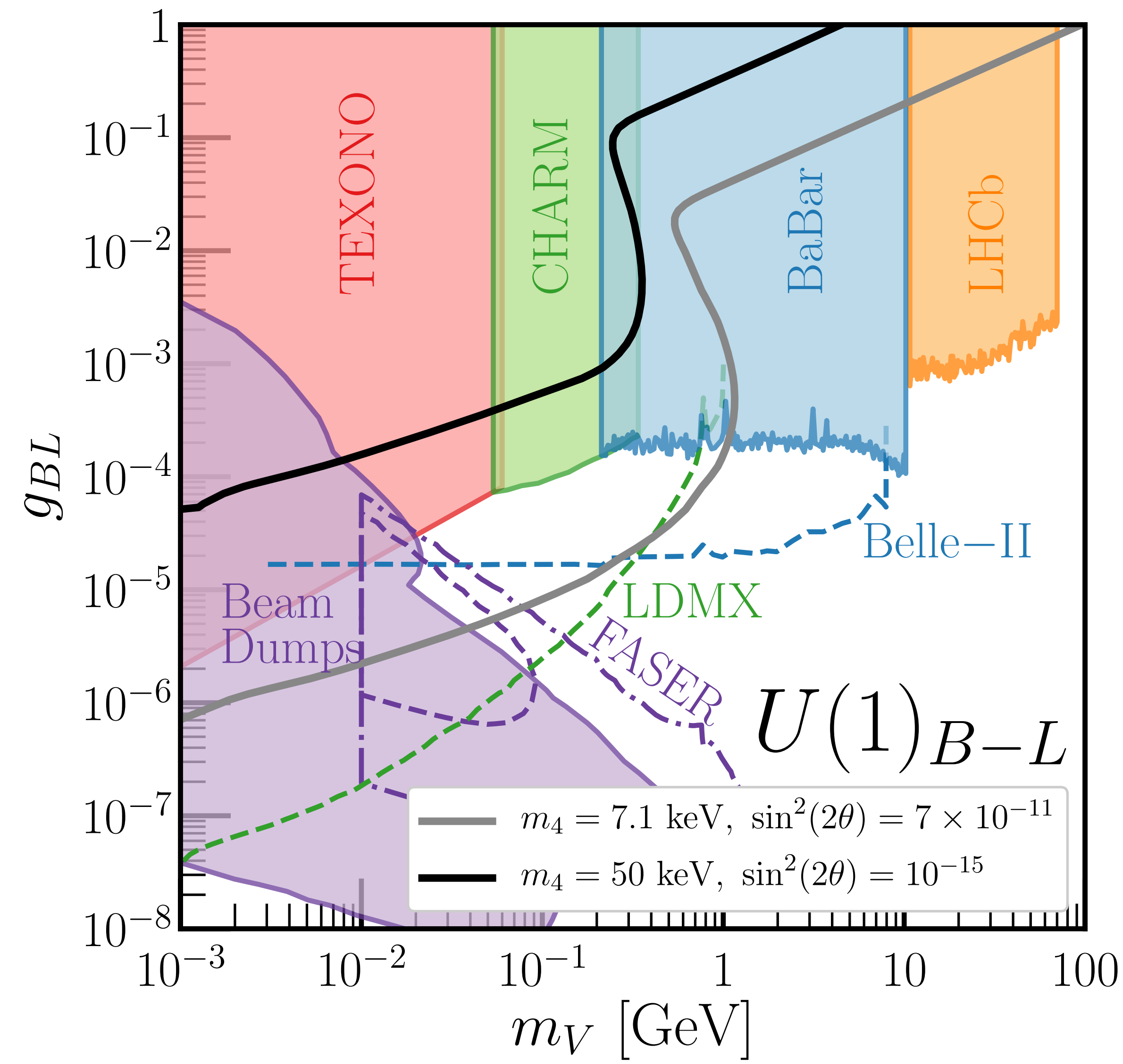
$\mathrm{Br}(H \to \text{invisible}) < 2.5\%$ Future HL- HLC

In $\nu_\mu n \to V \mu^- p^+$, the emission of a light vector has a longitudinal enhancement ~ E^2/m_V^2

DUNE (5 yrs)

Current and future constraints: $U(1)_{L_\mu - L_\tau}$ and $U(1)_{B-L}$





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

Small-scale structure "problems" have motivated the possibility that DM particles self-interact with $\sigma_{\rm DM}/m_{\rm DM} \sim 1\,{\rm cm}^2/{\rm g}$ e.g. Kanplinghat, Tulin, Yu (2015), …

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 Johns & Fuller (2019) for heavy-mediator case

Dodelson-Widrow Mechanism + new DM self-interactions

Sen, Tangarife & Zhang, in preparation

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

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

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

$$\Gamma_s = 2\times\int\frac{d^3\vec{q}_1}{(2\pi)^3}\sigma_s v_{\rm M} f_{22}(q_1)$$

If $\Gamma_s > H$

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

(pseudo) chemical potential

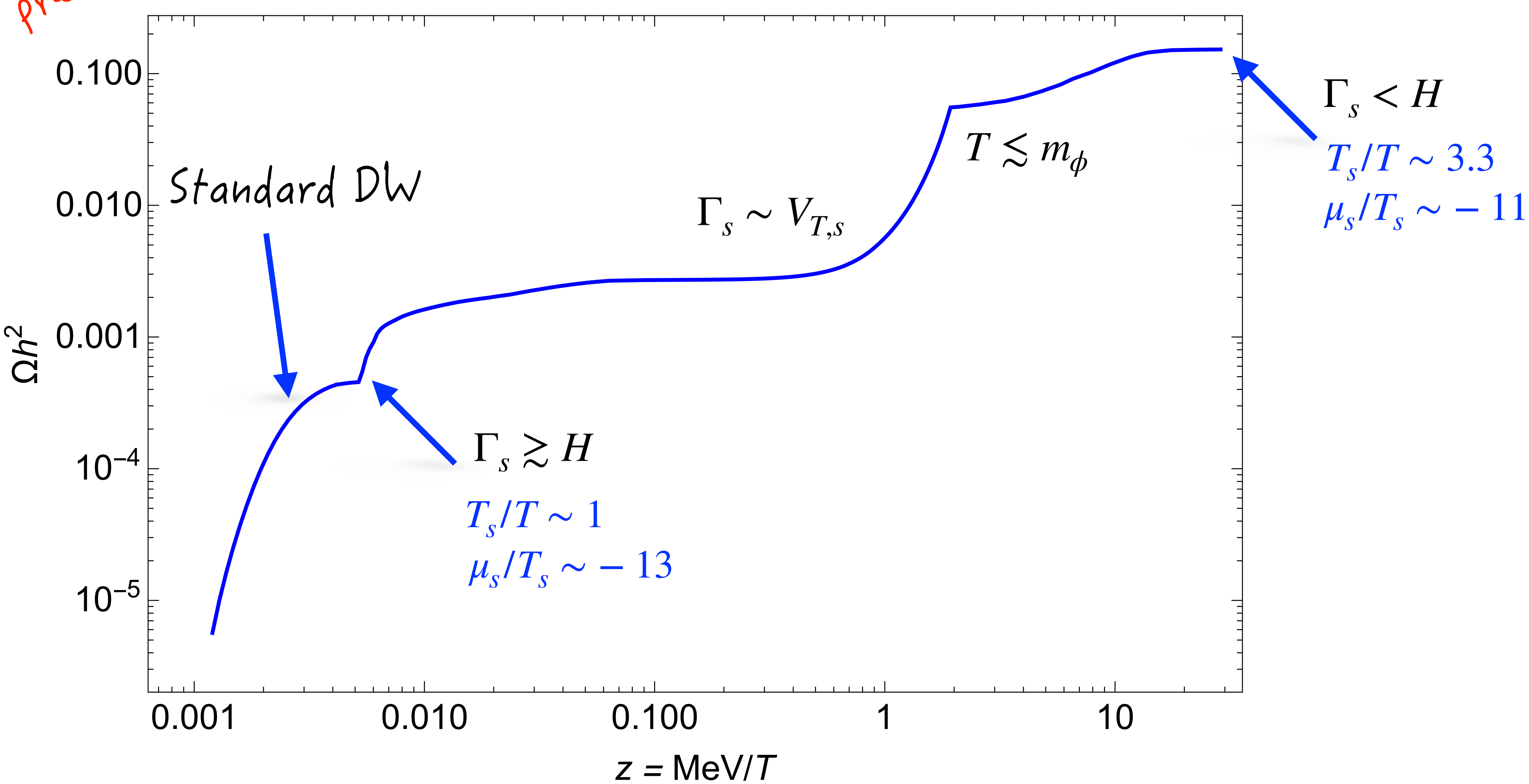
dark temperature

Dodelson-Widrow Mechanism + new DM self-interactions

Sen, Tangarife & Zhang, in preparation

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

VERY preliminary



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.

This model can be probed in upcoming neutrino and collider experiments such as DUNE, SHiP, NA64-μ, and HL-LHC.

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

Thank you!