Sterile Neutrino Dark Matter via Secret Neutrino Interactions

Walter Tangarife

Collaborators:
André de Gouvêa, Kevin Kelly,
Manibrata Sen, and Yue Zhang

PRL 124 (2020) 8, 081802
PRD 101 (2020) 11, 116006
and work in progress

LOYOLA UNIVERSITY CHICAGO
Preparing people to lead extraordinary lives

Supported by NSF grant No. PHY-2013052

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

Motivation

Dark Matter

Indirect Detection Aspects of Hidden Sector Dark

Opportunities and signatures of non-minimal Heavy Neutral Leptons

BSM Physics at the Electron Ion Collider: Searching for Heavy Neutral Leptons

Dark Sector Studies With Neutrino Beams

Cosmology

Neutrino Non-Standard Interactions

Direct Probes of the Matter Effect in Neutrino Oscillations

NuSte: Global Light Sterile Neutrino Fits

Astrophysics

Ultralight dark matter and neutrinos

Neutrino mass

Large Extra-Dimension Searches

Non-Unitarity of the neutrino mixing matrix

Short-Baseline anomalies

Exploration of a new model for neutrino oscillations using a kiloton-scale neutrino detector at the Advanced Instrumentation Testbed in Boulby England

Leptogenesis

Testing quasi-Dirac leptogenesis through neutrino oscillations

THREE STERILE NEUTRINOS IN E6

Neutrino Decay as a Solution to the Short-Baseline Anomalies

Carlos A. Argüelles - SnowMass NF02

For a review: Abazajian (2017)

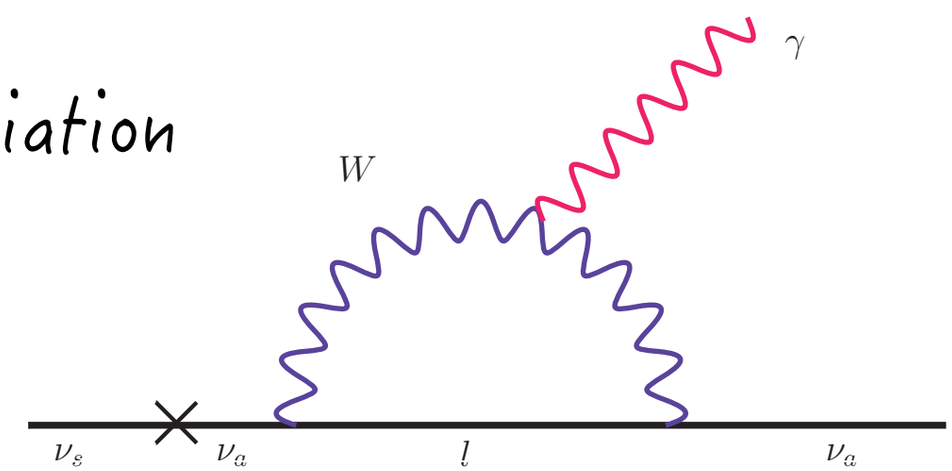
Sterile Neutrino as Dark Matter

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)

Dodelson-Widrow Mechanism

Dodelson & Widrow (1994)

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

In SM: $V_T \sim T^5$

$\Gamma \sim T^5$

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

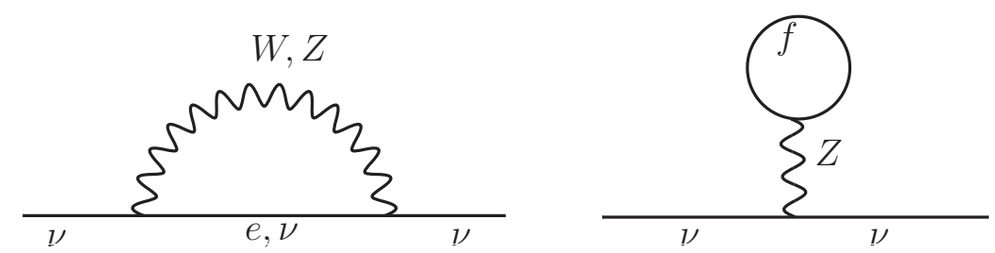
$$\sin^2 2\theta_{\rm eff} \simeq \frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + (\Gamma/2)^2 + (\Delta \cos 2\theta - V_T)^2}$$

$\Delta = m_s^2/2E$

Thermal potential

Quantum Zeno effect (damping)

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



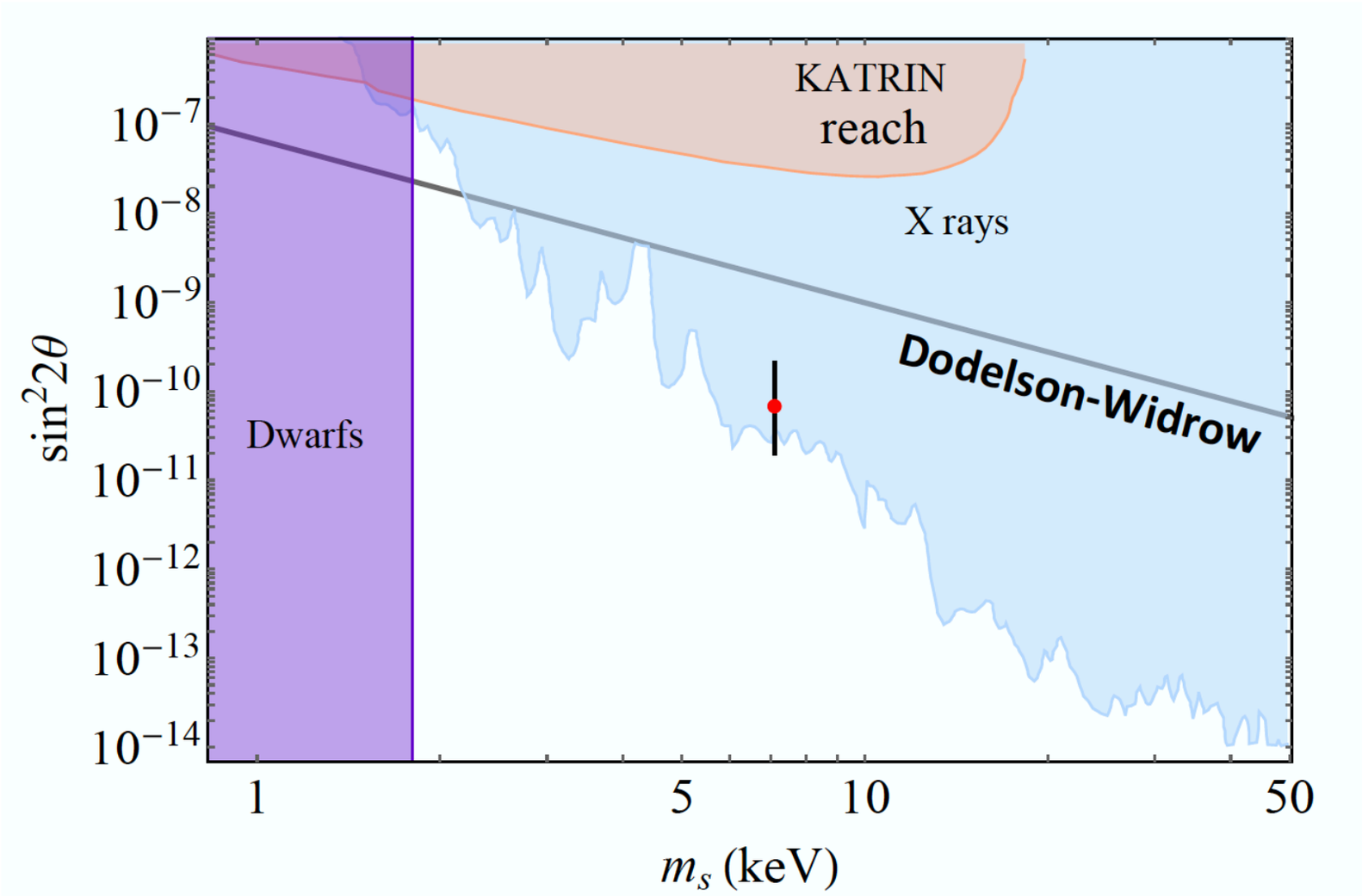
Result: A non-thermal abundance of sterile neutrinos by solving the Boltzmann equation

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

$z = \mathrm{MeV}/T$

Dodelson-Widrow Mechanism

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

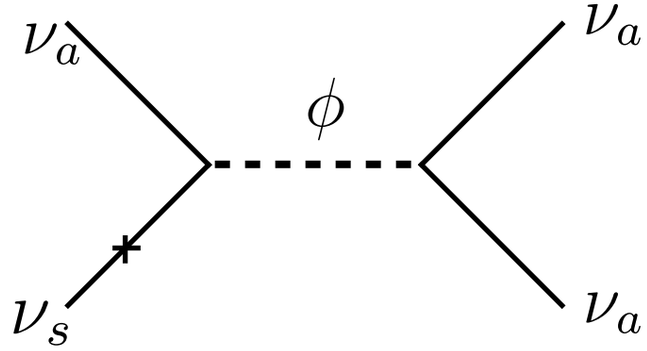


How to generate enough sterile neutrino DM within the allowed region?

Dodelson-Widrow Mechanism + new neutrino self-interactions

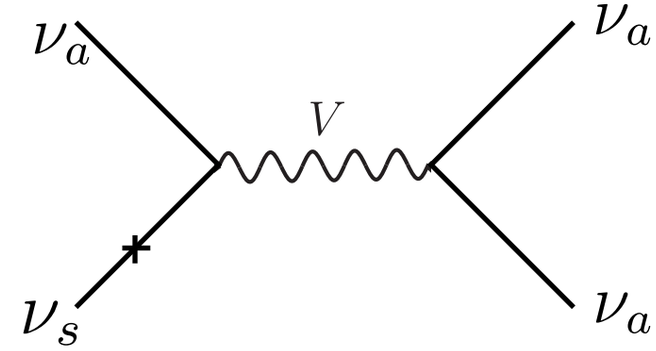
De Gouvêa, Sen, Tangarife & Zhang PRL (2020)
Kelly, Sen, Tangarife & Zhang PRD (2020)

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



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

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



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

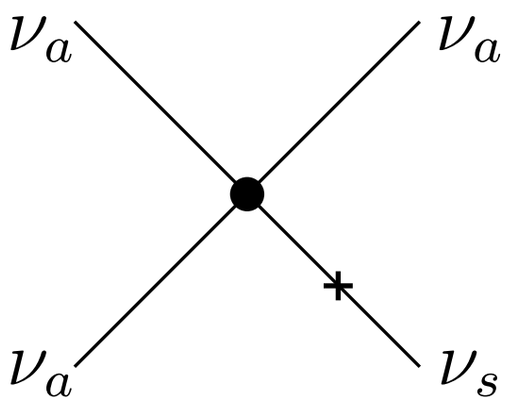
$$\frac{d\, f_{\nu_4}(x,z)}{d\ln z} = \frac{\Gamma}{4H}\,\sin^2 2\theta_{\text{eff}}\, f_\nu(x)$$

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

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), …

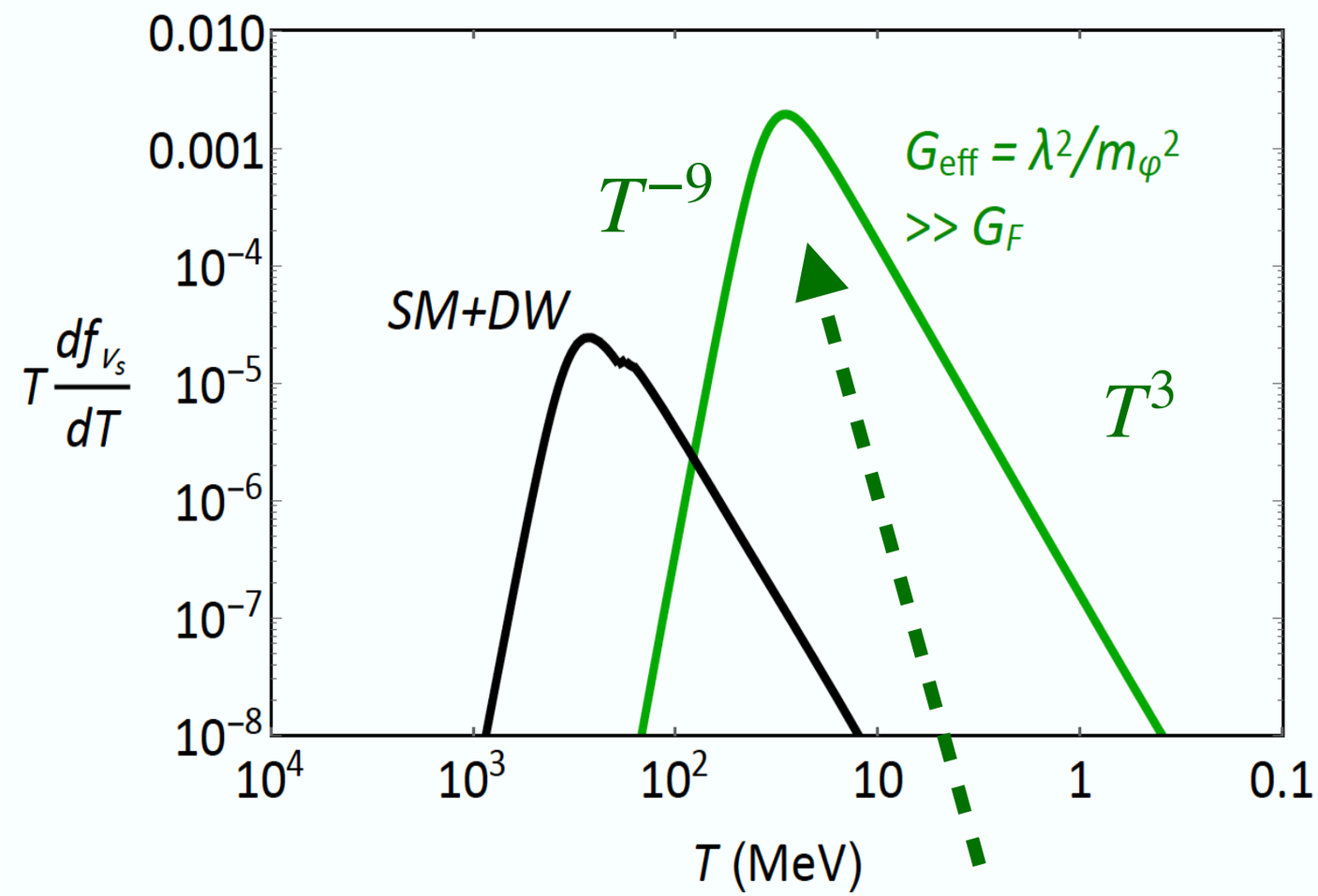
Heavy mediator limit: $m_\phi \gg T$



$$\Gamma \sim \frac{\lambda_\phi^4}{m_\phi^4} E T^4 \qquad V_T \sim -\frac{\lambda_\phi^2}{m_\phi^4} E T^4$$

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

Compare to SM+DW

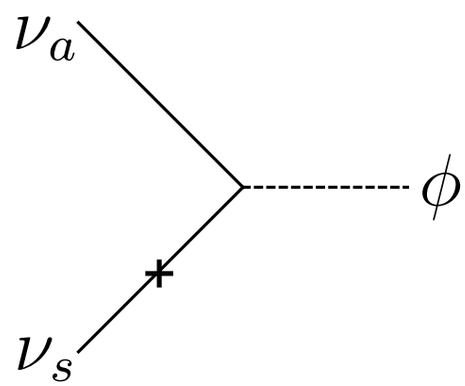


Production peaks at a lower temperature

Light mediator limit: $m_\phi \ll T$

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

The scalar can be produced on-shell in the plasma

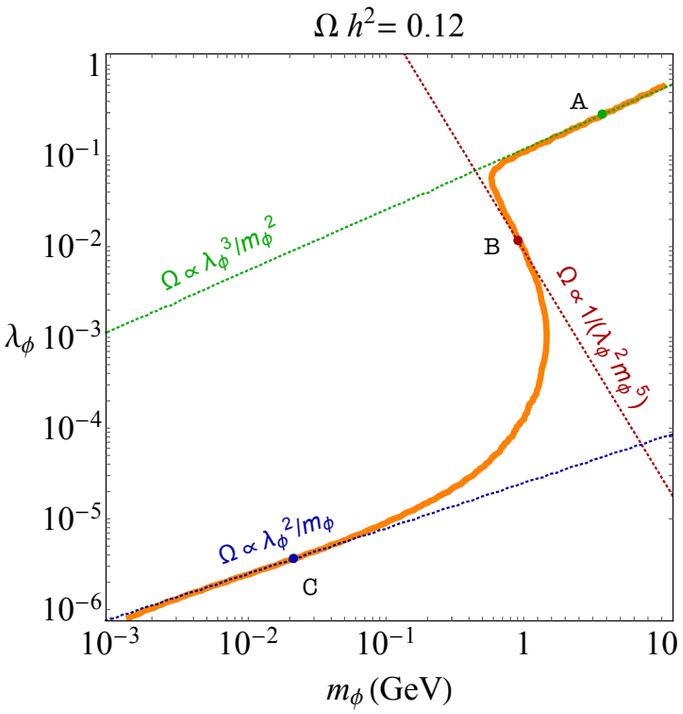


$$\Gamma \sim V_T \sim \frac{\lambda_\phi^2 T^2}{E}$$

A positive thermal potential allows for a resonance in

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

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:

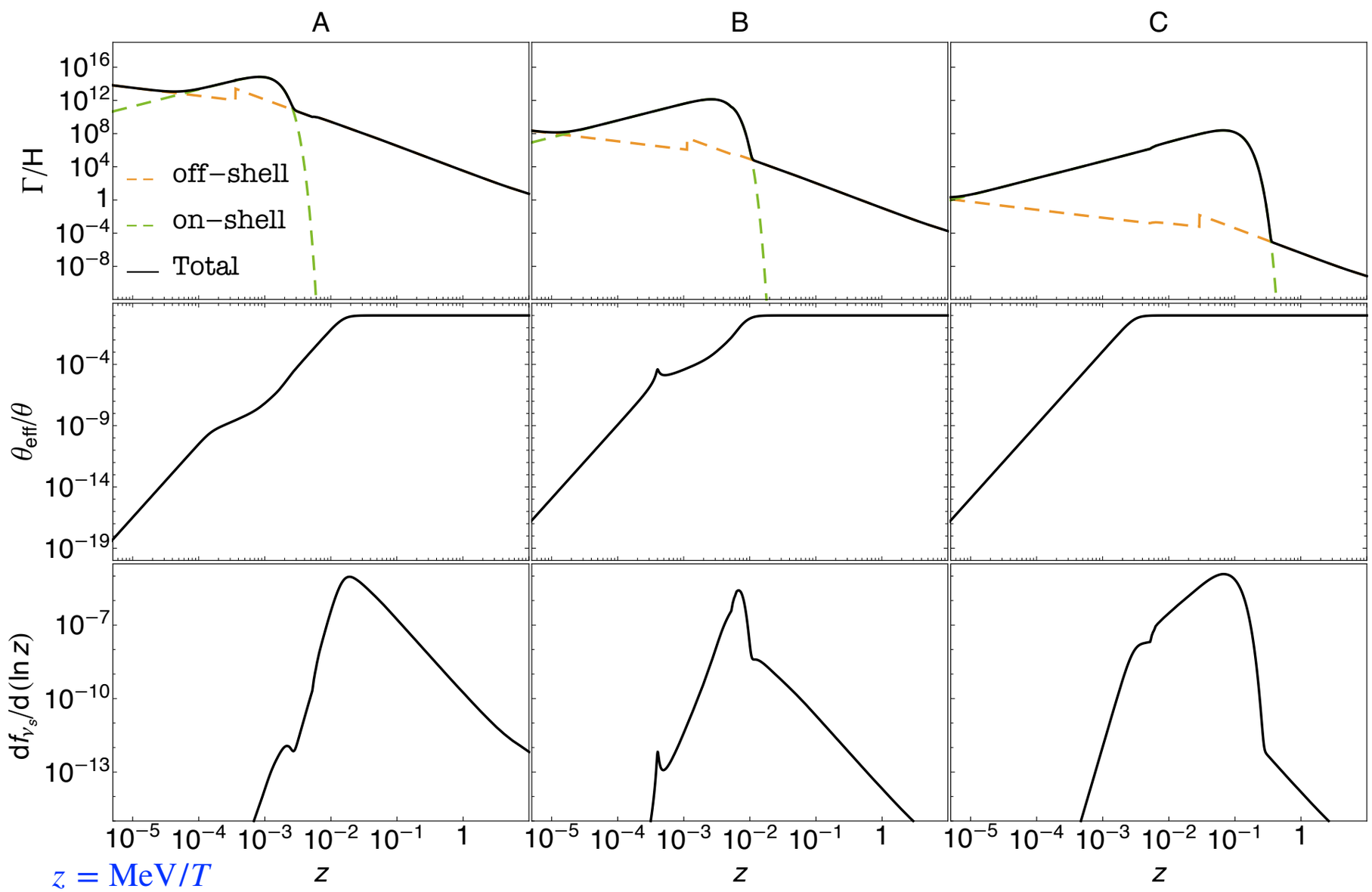
$z_2 < z_1 < z_0$

Case B:

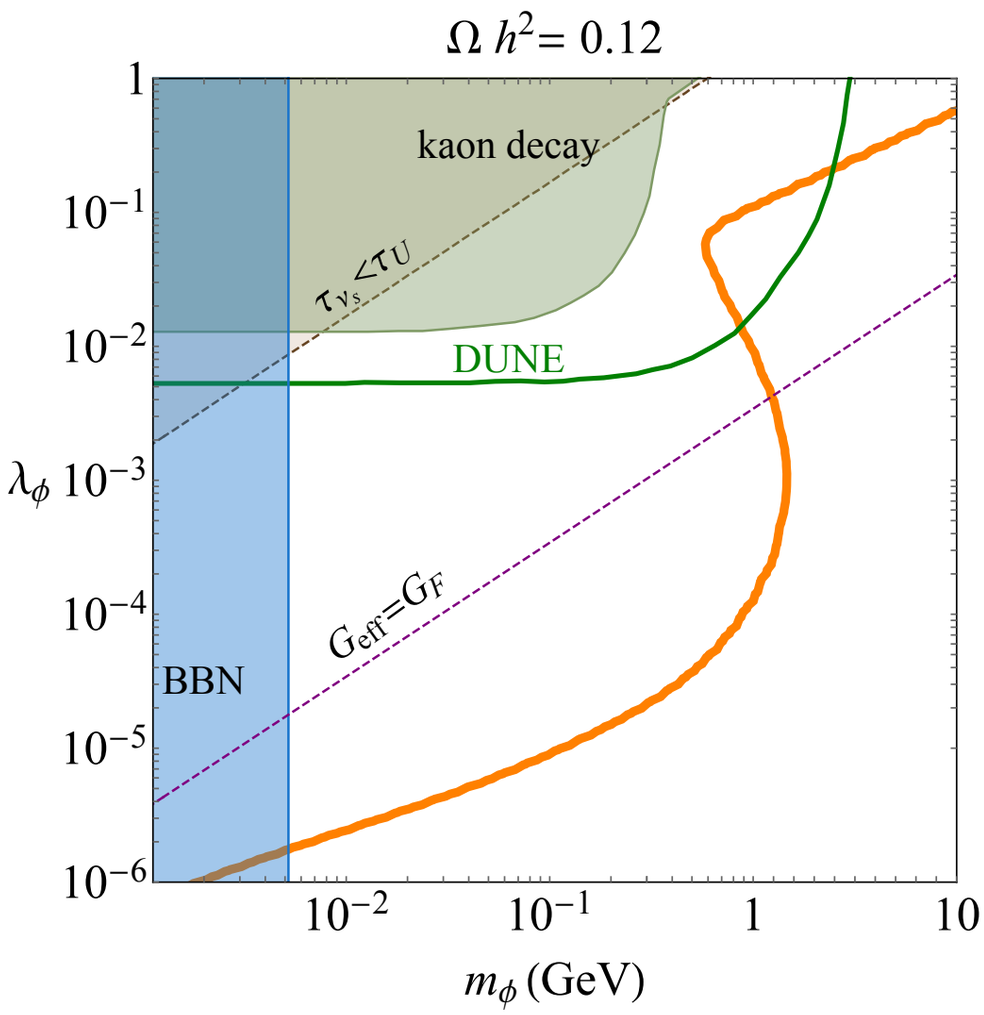
$z_2 \sim z_1 < z_0$

Case C:

$z_1 < z_2 < z_0$



Current and future constraints



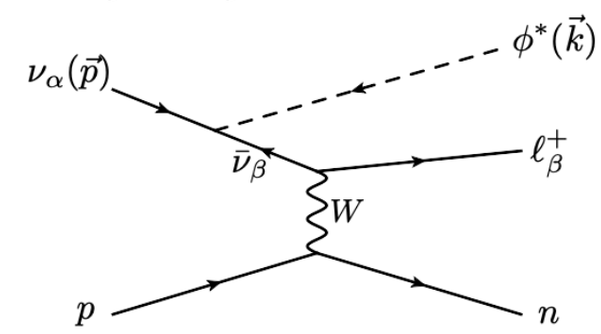
$m_{\nu_s} = 7.1\,\text{keV},\ \ sin^2 2\theta = 7 \times 10^{-11}$

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

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

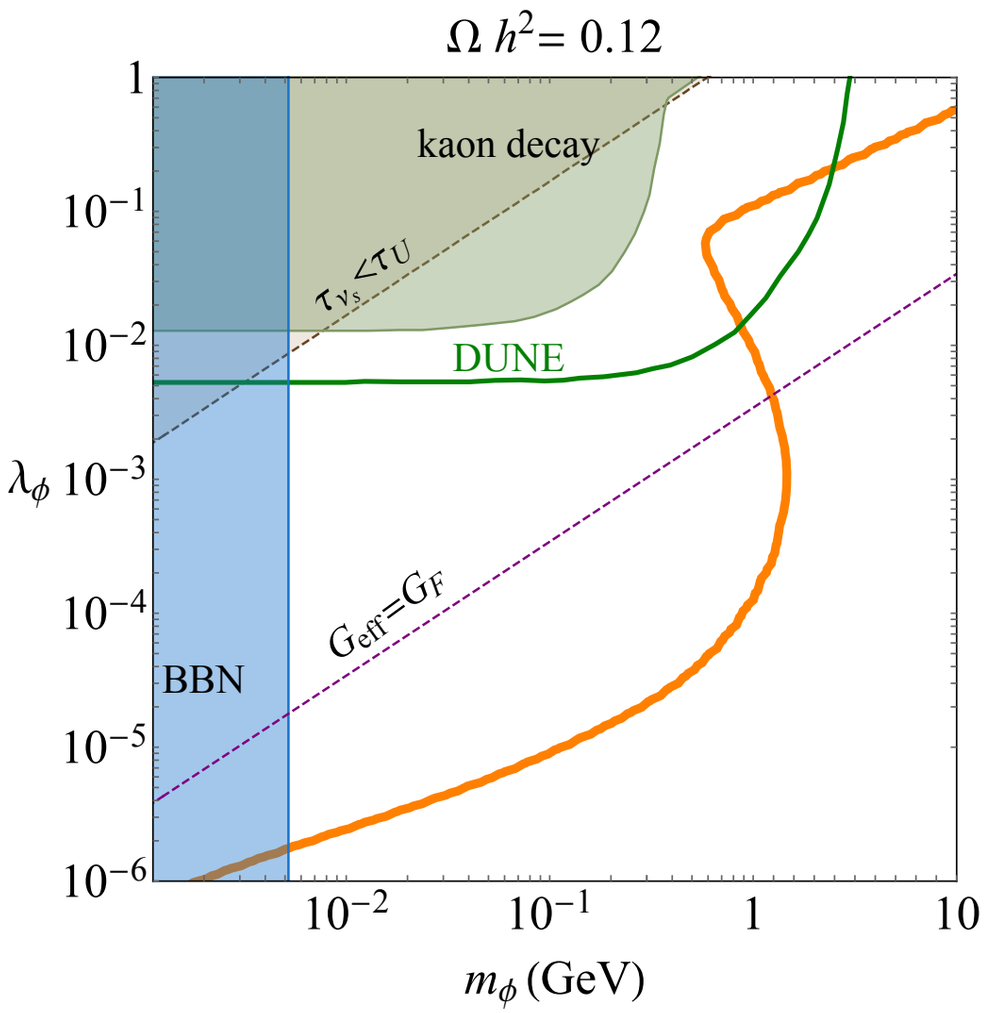
BBN bounds on light d.o.f.s

Expected sensitivity of DUNE:
Look for the "wrong-sign muon"
$\nu_\mu N \to \mu^+ N' \phi\,.$

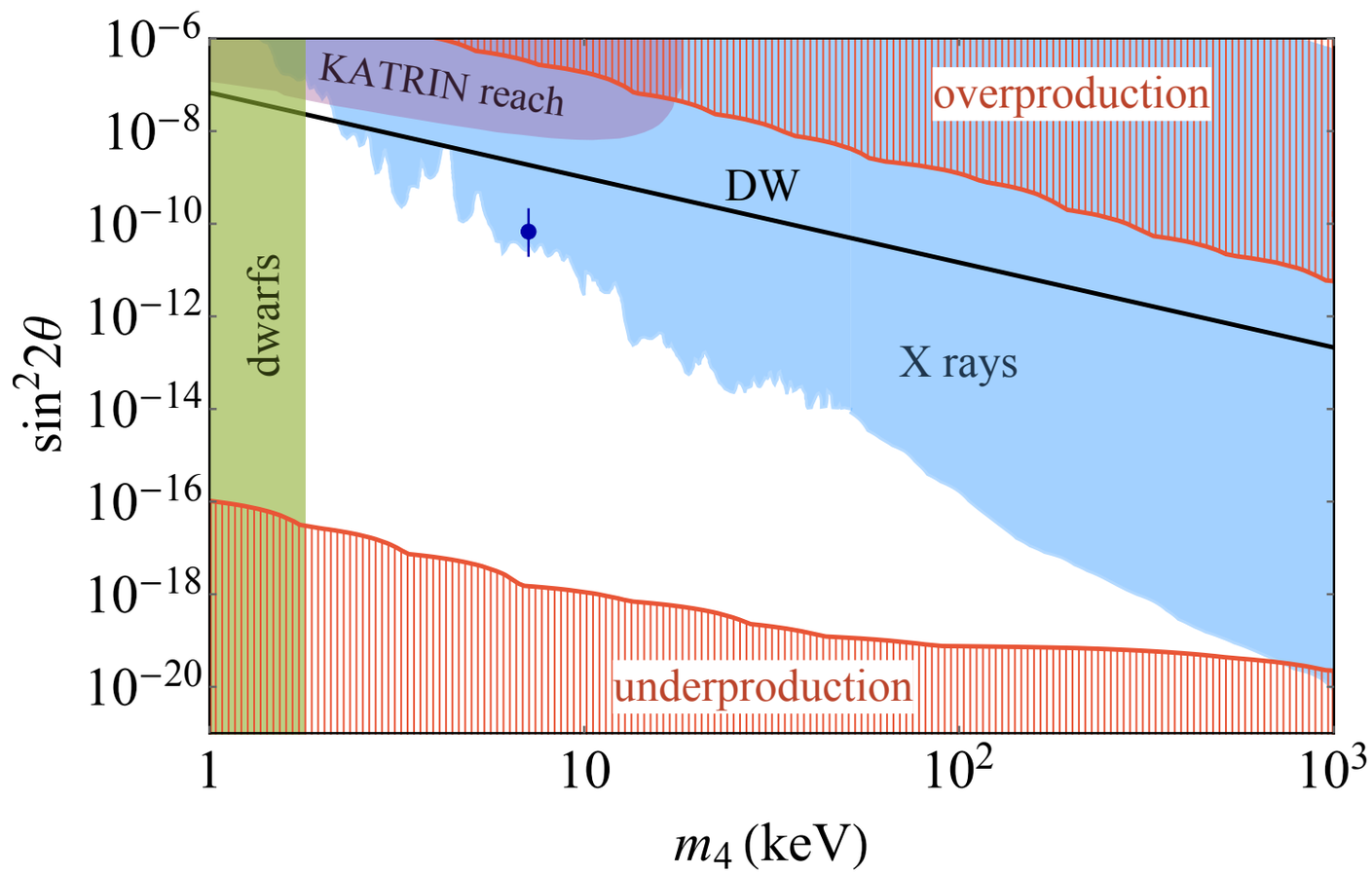


Berryman, de Gouvêa, Kelly & Zhang (2018)
Blinov, Kelly, Krnjaic & McDermott (2019)
Kelly & Zhang (2019)

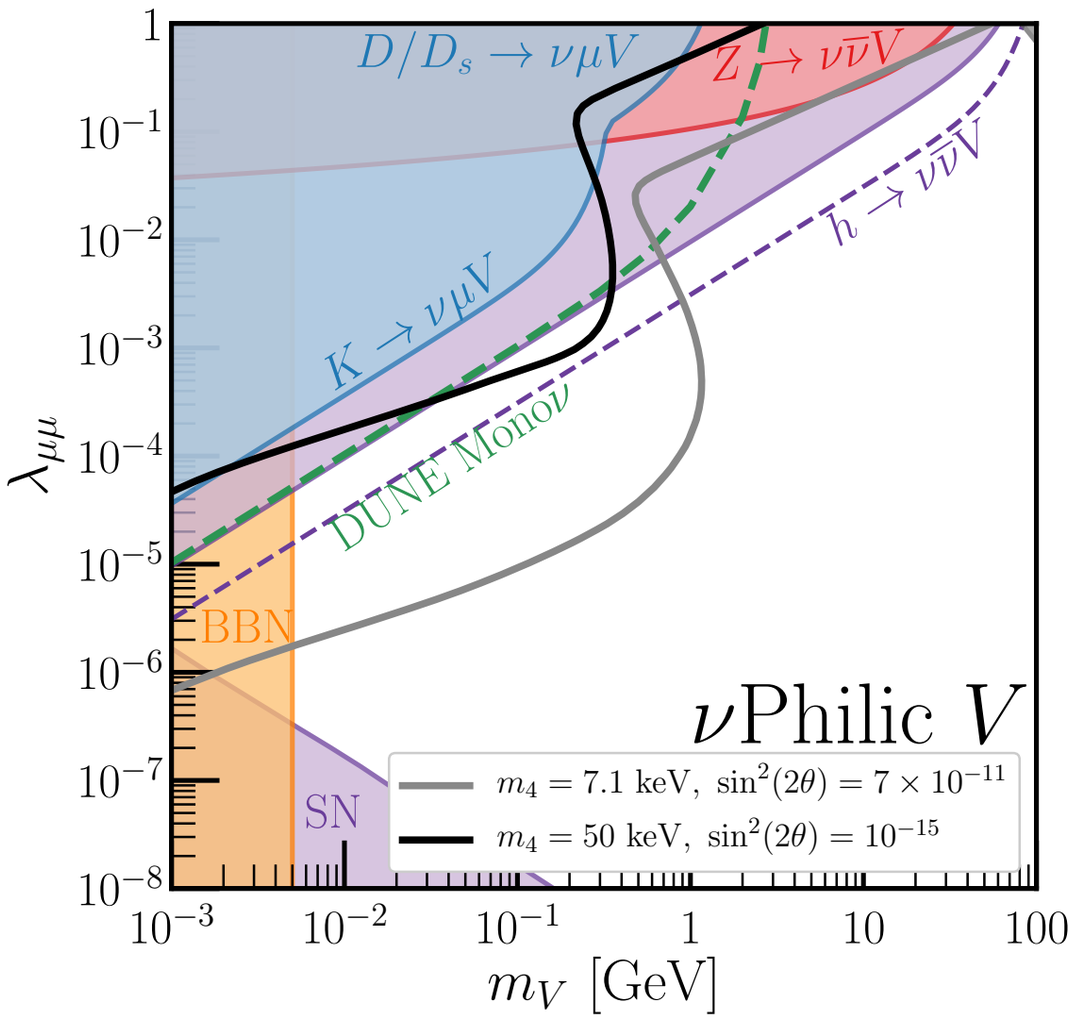
Current and future constraints



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



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: $h \to \nu_\mu \bar{\nu}_\mu V$

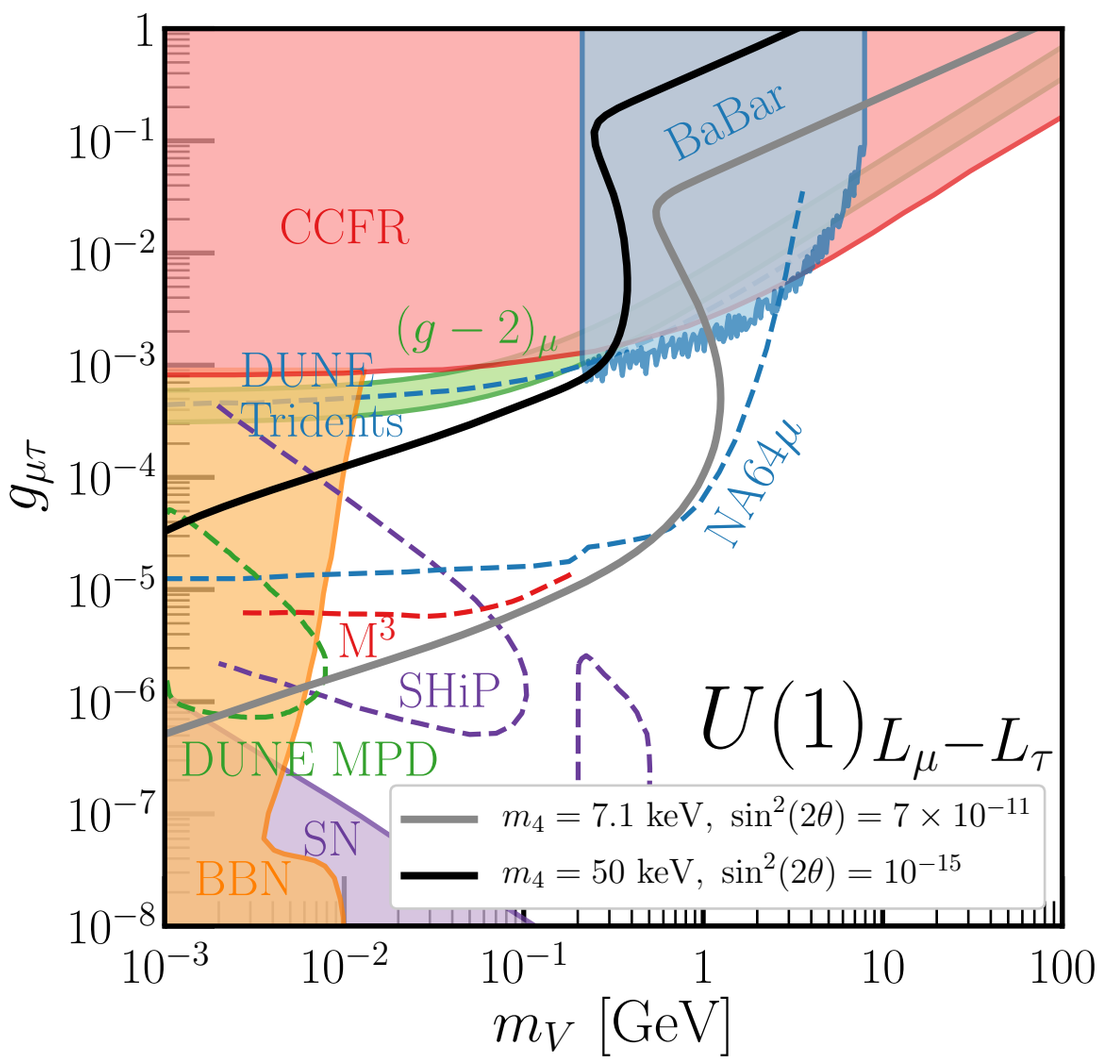
$\mathrm{Br}(H \to \mathrm{invisible}) < 24\%$ Current HLC (purple)

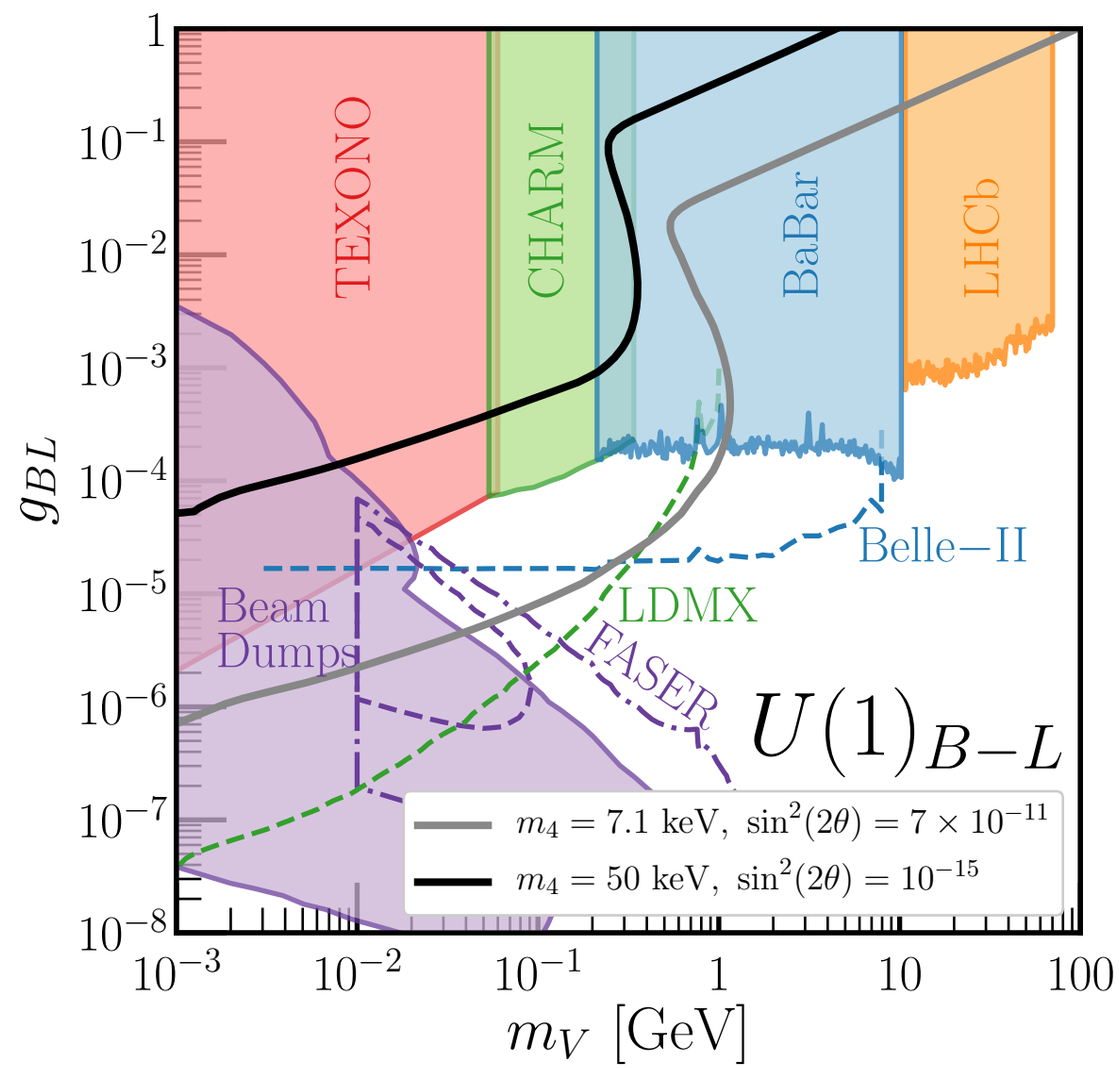
$\mathrm{Br}(H \to \mathrm{invisible}) < 2.5\%$ Future HL- HLC

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

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)

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

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

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

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.

Among the three gauge interactions that we studied, the $U(1)_{B-L}$ is the most strongly constrained and the neutrophilic vector is the least constrained.

The case of self-interacting sterile neutrinos is an attractive scenario of SIDM that's being currently explored

Thank you!