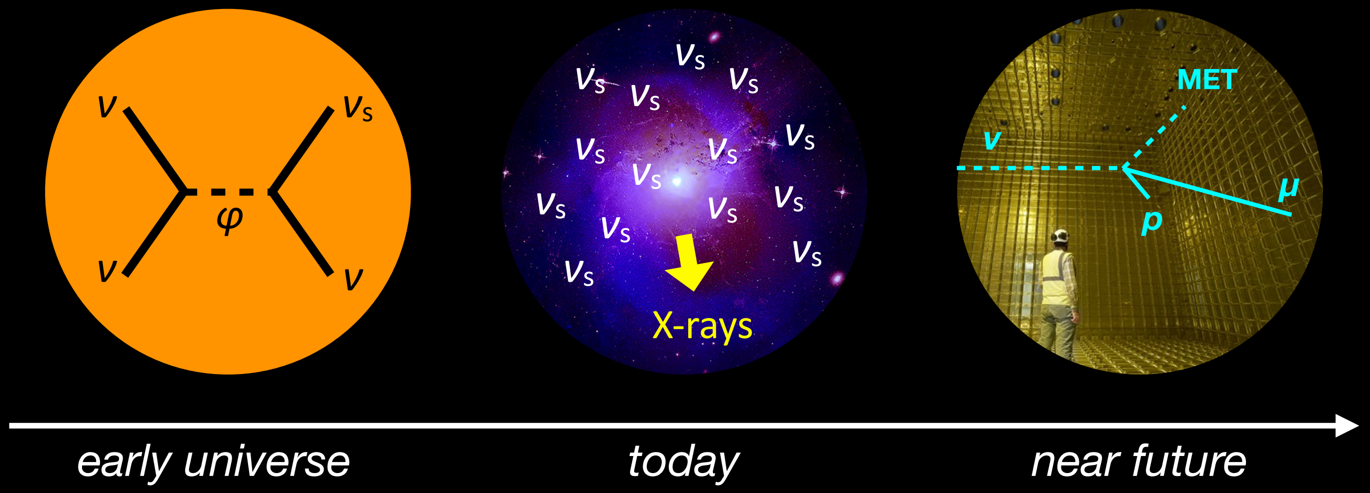

Sterile Neutrino Dark Matter via Secret Neutrino Interactions

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LOYOLA
UNIVERSITY CHICAGO
Preparing people to lead extraordinary lives

with André de Gouvêa, Kevin Kelly, Manibrata Sen, and Yue Zhang

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PRD 101 (2020) 11, 115031, arXiv:2005.03681

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

Motivation

Neutrino Non-Standard Interactions

Cosmology

Indirect Detection Aspects of Hidden Sector Dark

Dark Matter

Direct Probes of the Matter Effect in Neutrino Oscillations

Opportunities and signatures of non-minimal Heavy Neutral Leptons

NuSte: Global Light Sterile Neutrino Fits

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

Astrophysics

Ultralight dark matter and neutrinos

Dark Sector Studies With Neutrino Beams

Large Extra-Dimension Searches

Neutrino mass

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

Non-Unitarity of the neutrino mixing matrix

Short-Baseline anomalies

Testing quasi-Dirac leptogenesis through neutrino oscillations

THREE STERILE NEUTRINOS IN E6

Leptogenesis

Neutrino Decay as a Solution to the Short-Baseline Anomalies

For a review: Abazajian (2017)

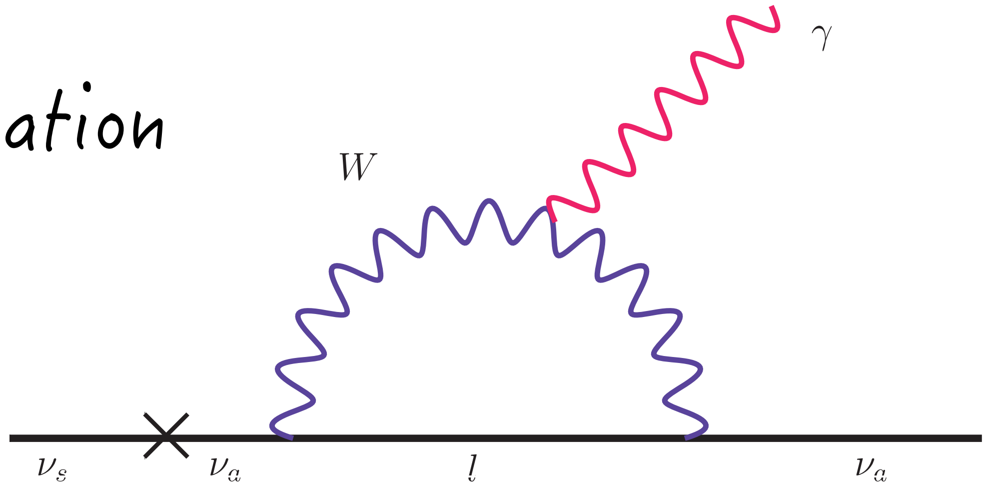
Sterile Neutrino as Dark Matter

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

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



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

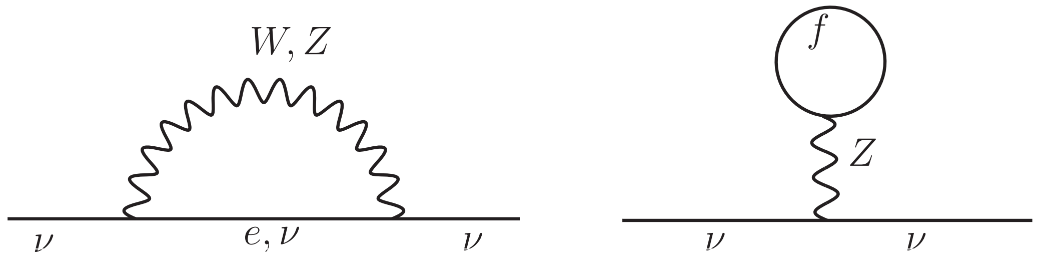
$$\sin^2 2\theta_{\rm eff} \simeq \frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + (\Gamma/2)^2 + (\Delta \cos 2\theta - V_T)^2}$$

$\Delta = m_s^2/2E$

Thermal potential

Quantum Zeno effect (damping)

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



Dodelson-Widrow Mechanism

Dodelson & Widrow (1994)

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

In SM: $V_T \sim T^5$

$\Gamma \sim T^5$

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

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

$\Delta = m_s^2/2E$

Thermal potential

Quantum Zeno effect (damping)

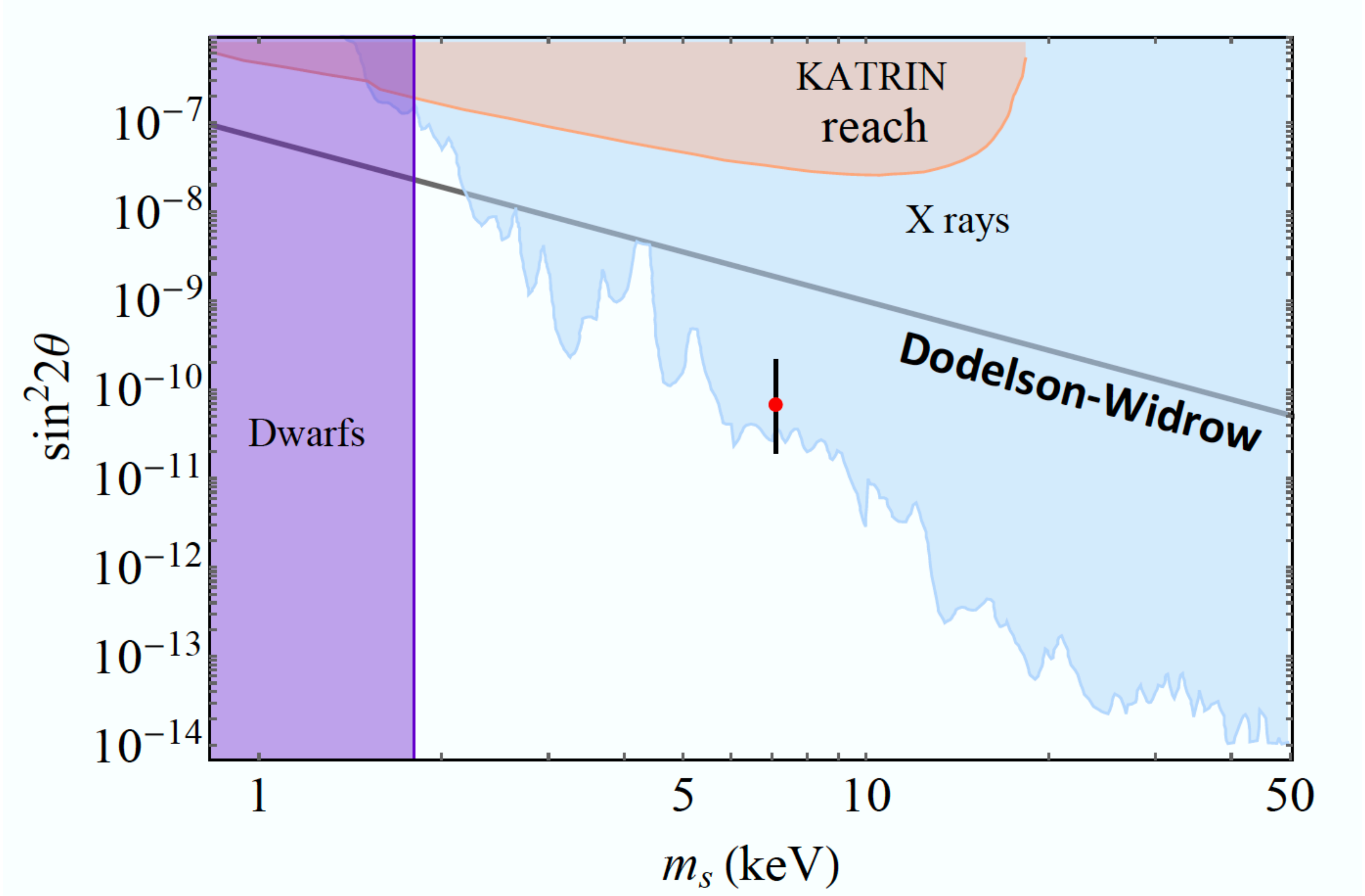
Result: A non-thermal abundance of sterile neutrinos by solving the Boltzmann equation

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

$z = \text{MeV}/T$

Dodelson-Widrow Mechanism

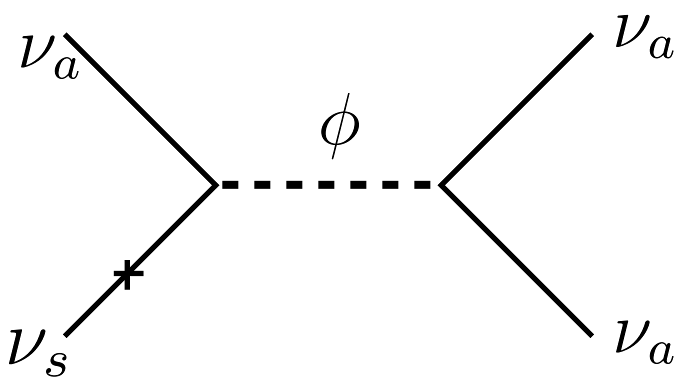
Ruled out by X-ray experiments and phase-space considerations



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

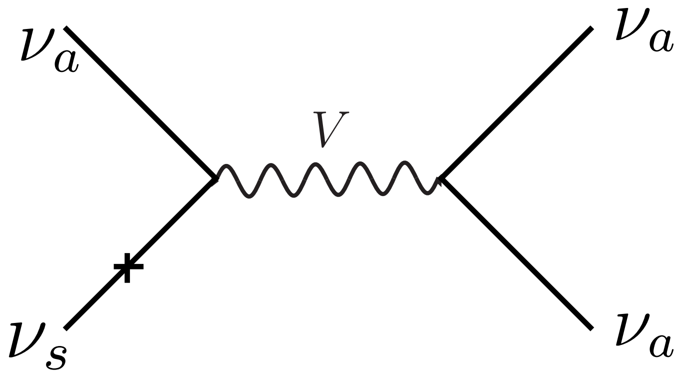
Dodelson-Widrow Mechanism + new neutrino self-interactions

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



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

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



Kelly, Sen, Tangarife & Zhang PRD (2020)

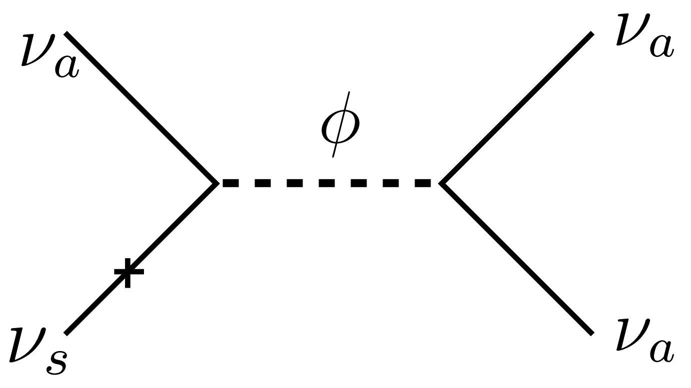
$U'(1)$ neutrinophilic

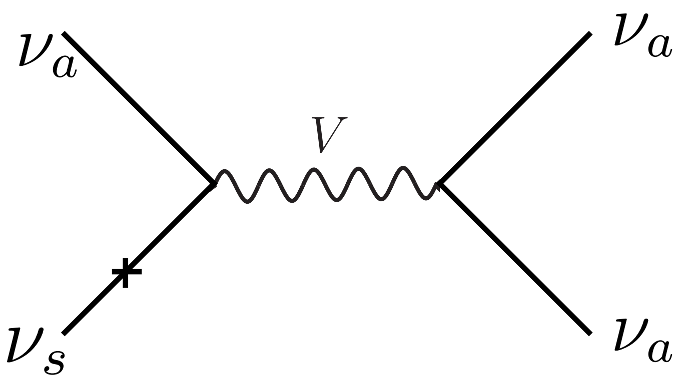
$U(1)_{L_\mu - L_\tau}$

$U(1)_{B-L}$

Dodelson-Widrow Mechanism + new neutrino self-interactions

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





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

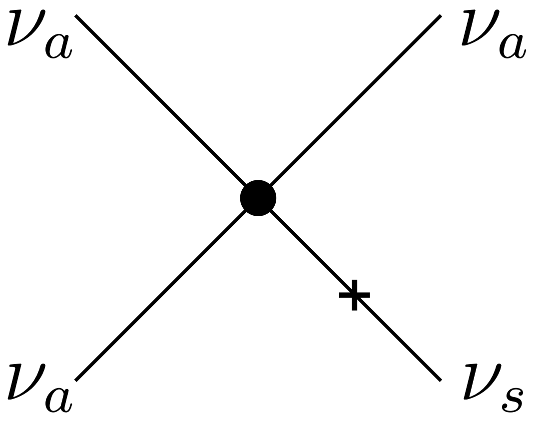
$$\frac{d\, f_{\nu_4}(x,z)}{d\ln z} = \frac{\Gamma}{4H}\sin^2 2\theta_{\rm eff}\, f_\nu(x)$$

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

The new interaction also contributes to the thermal potential V_T

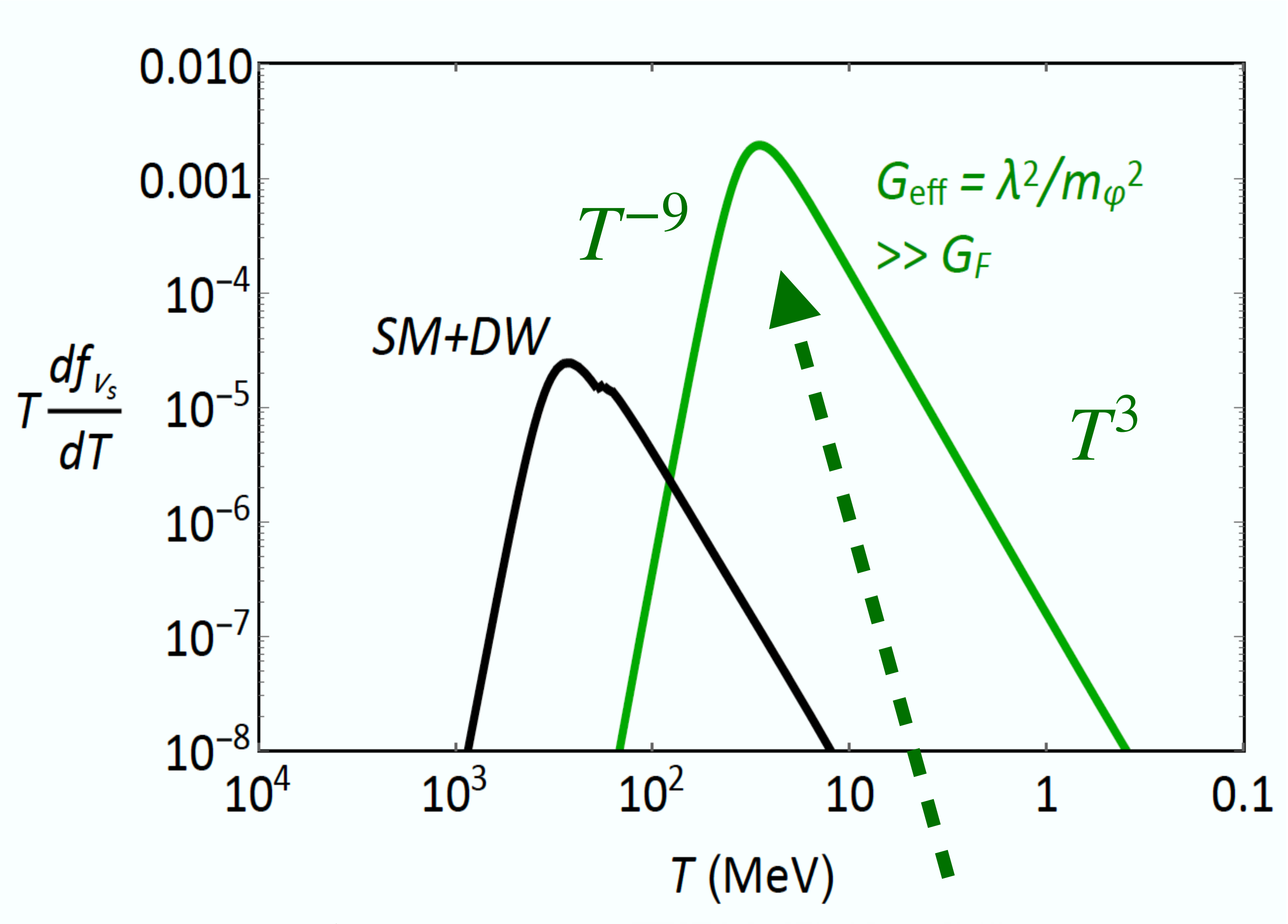
Similar works Koop et al. (2014), Mirizzi et al. (2015), Friedland et al. (2016), Johns et al. (2019), …

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



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

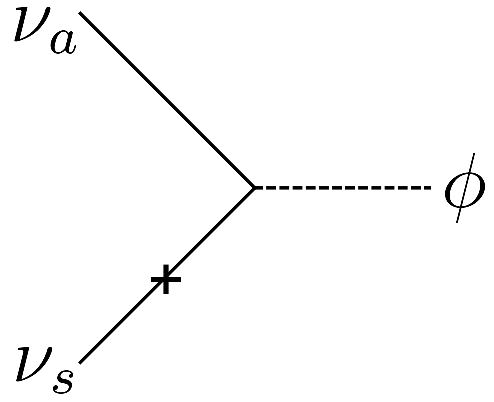
Compare to SM+DW



Production peaks at a lower temperature

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

The mediator can be produced on-shell in the plasma



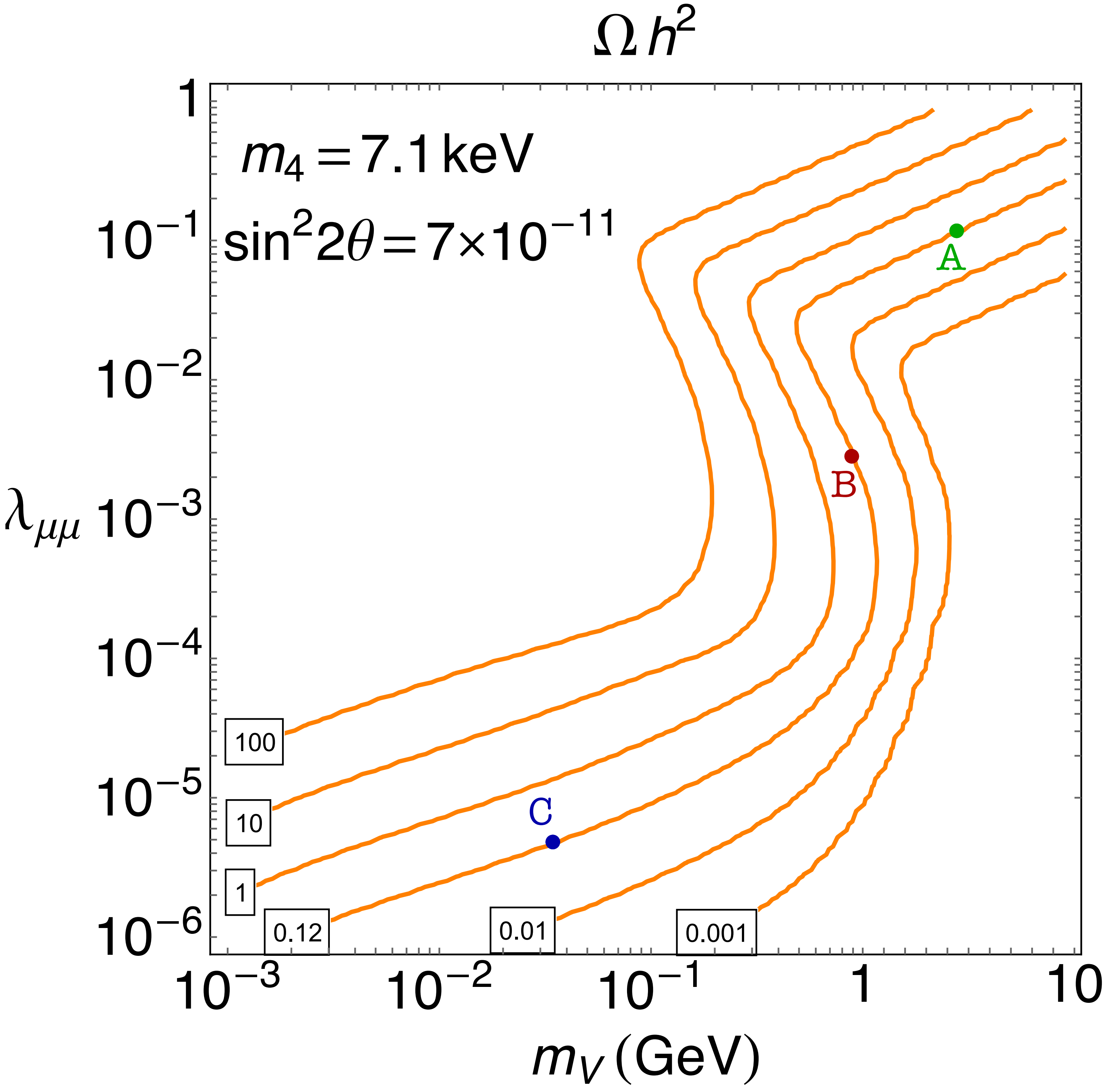
$$\Gamma \sim V_T \sim \frac{\lambda_\phi^2 T^2}{E}$$

A positive thermal potential allows for a resonance in

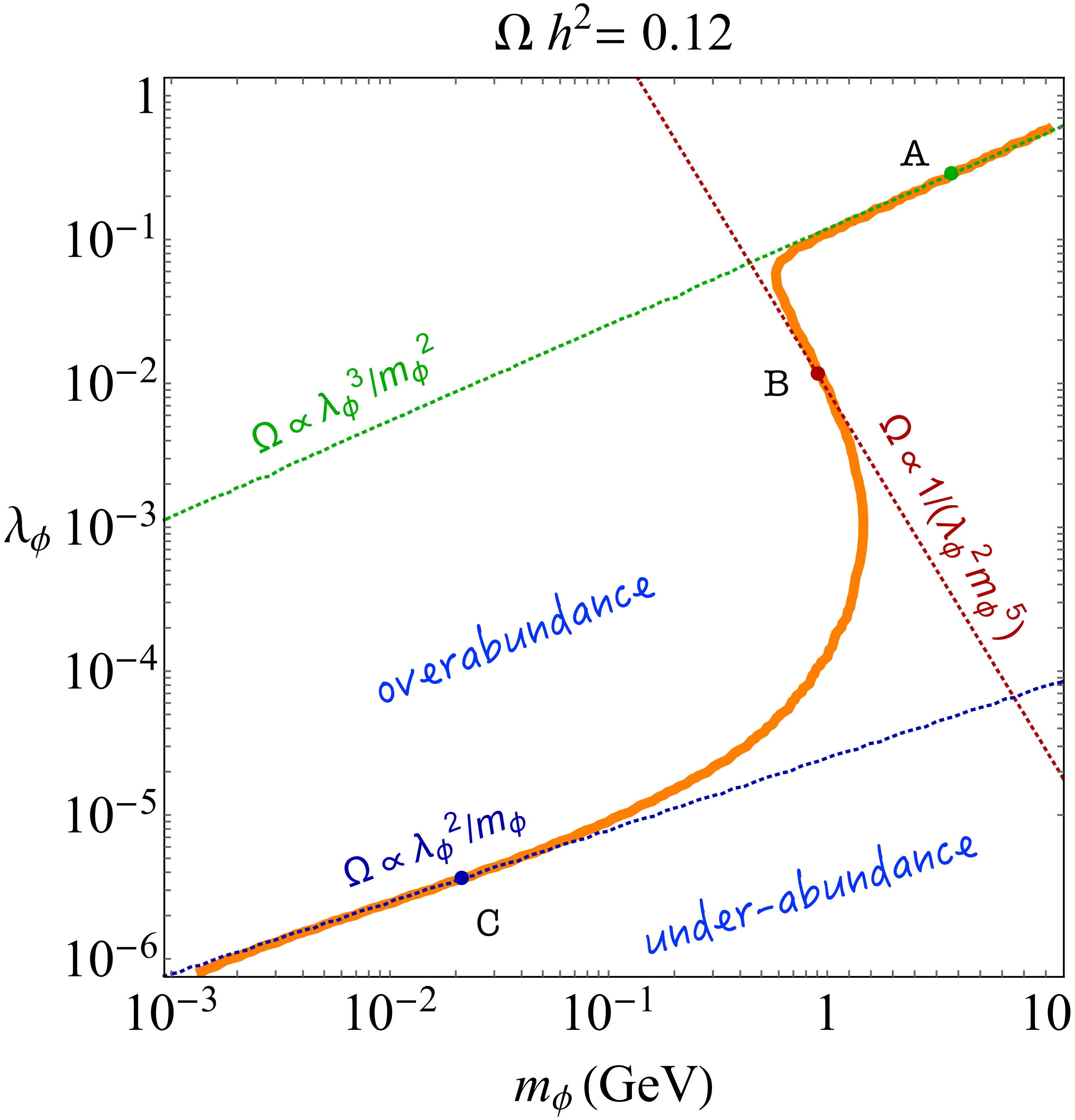
$$\sin^2 2\theta_{\rm eff} \simeq \frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + (\Gamma/2)^2 + (\Delta \cos 2\theta - V_T)^2}$$

Now let's proceed to integrate the Boltzmann equation

Sterile neutrino relic density

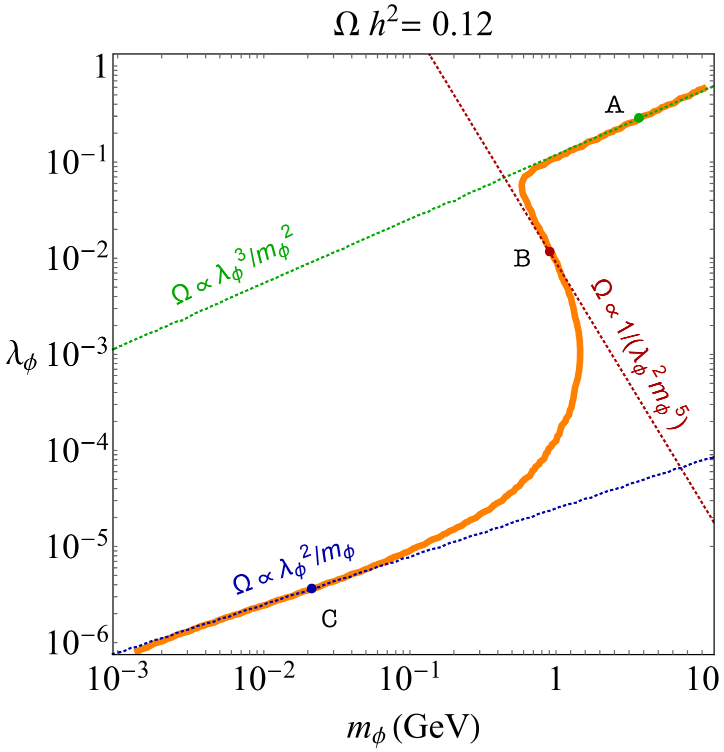


Sterile neutrino relic density



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

Sterile neutrino relic density



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

Three useful timescales:

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

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

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

Case A:

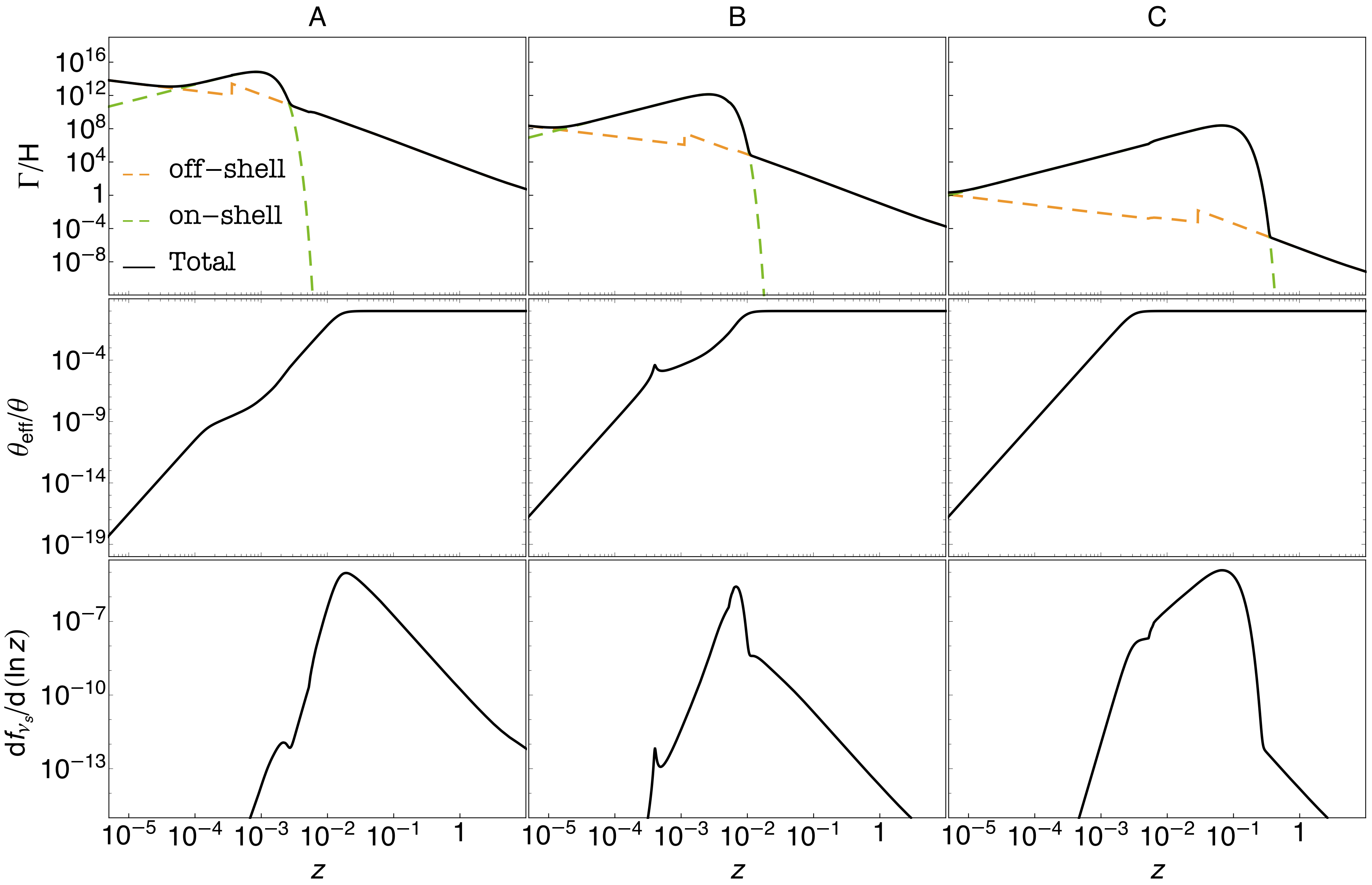
$z_2 < z_1 < z_0$

Case B:

$z_2 \sim z_1 < z_0$

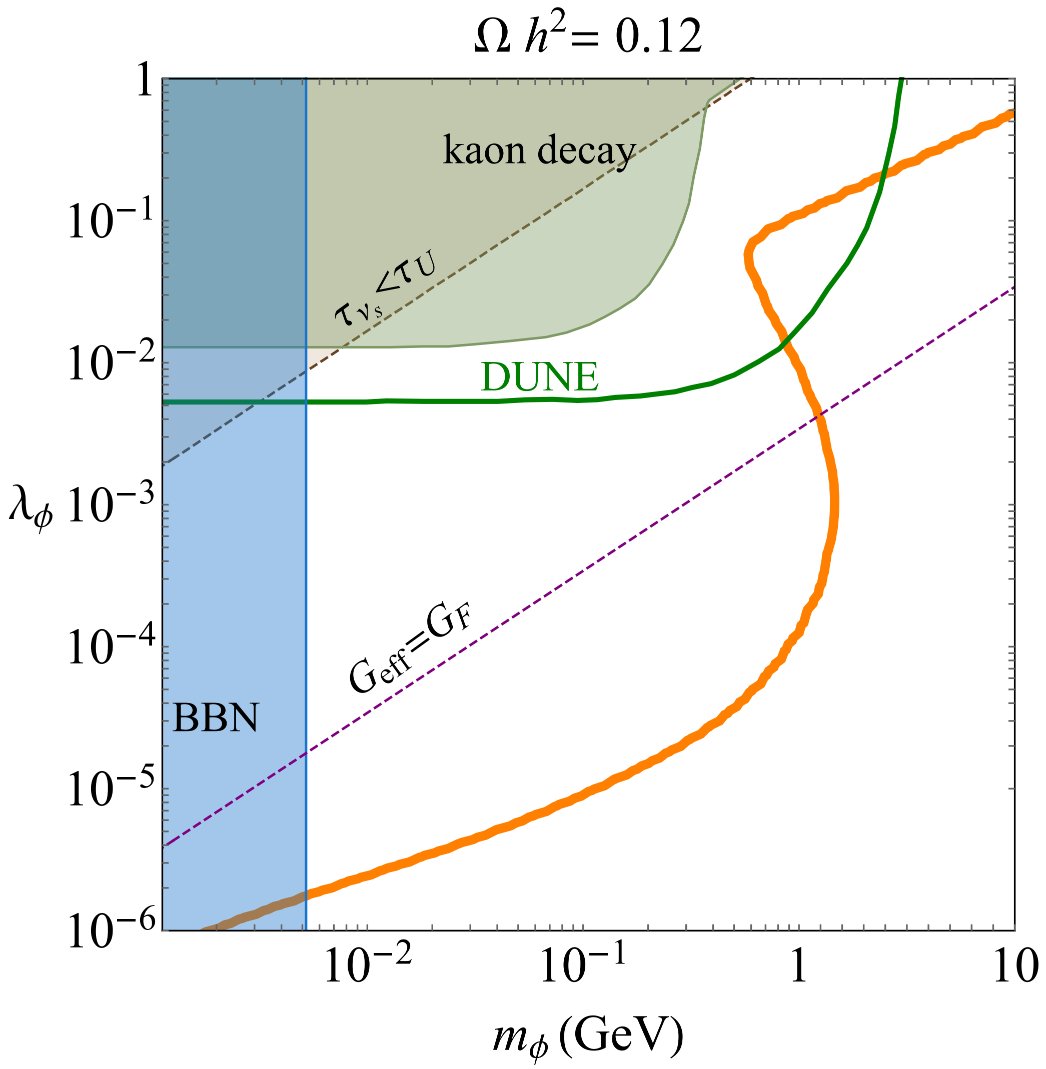
Case C:

$z_1 < z_2 < z_0$



$z = \mathrm{MeV}/T$

Current and future constraints: Scalar mediator



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

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

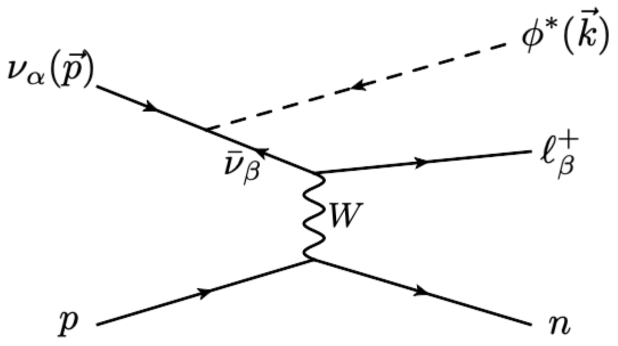
$\text{Br}(K^- \to \mu^- + 3\nu) < 10^{-6}$

BBN bounds on light d.o.f.s

Expected sensitivity of DUNE:

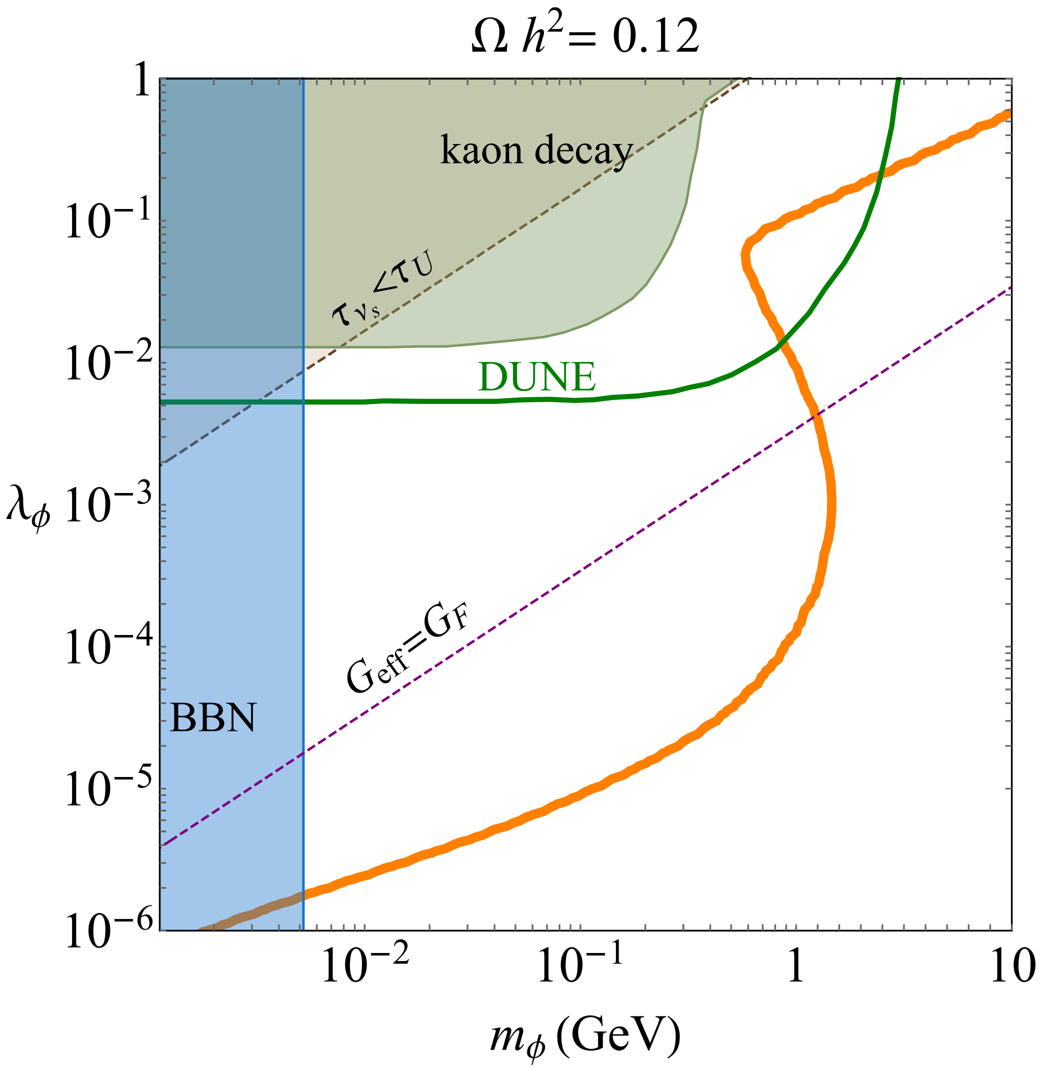
Look for the "wrong-sign muon"

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

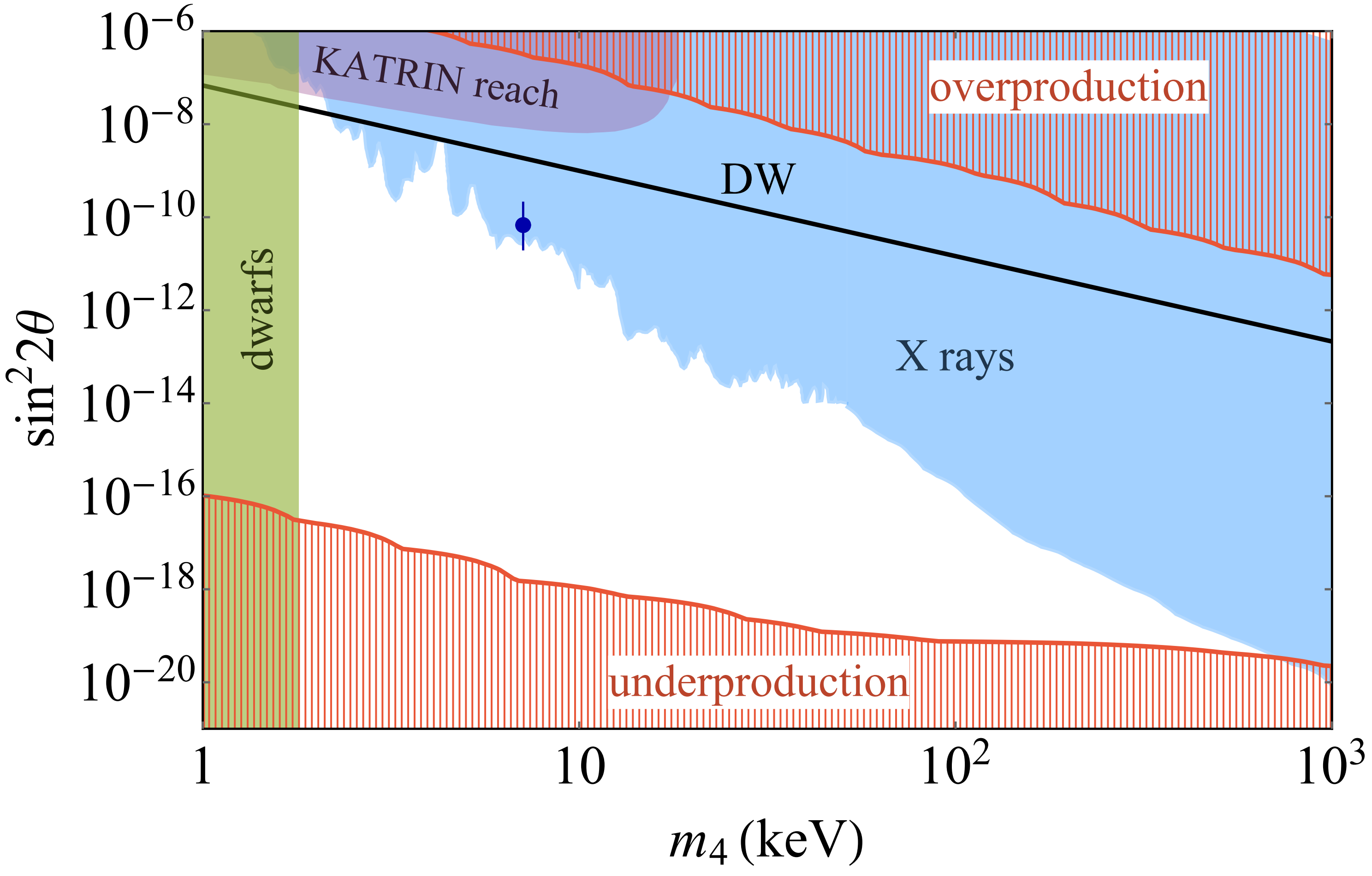


Berryman, de Gouvêa, Kelly & Zhang (2018)
Blinov, Kelly, Krnjaic & McDermott (2019)
Kelly & Zhang (2019)

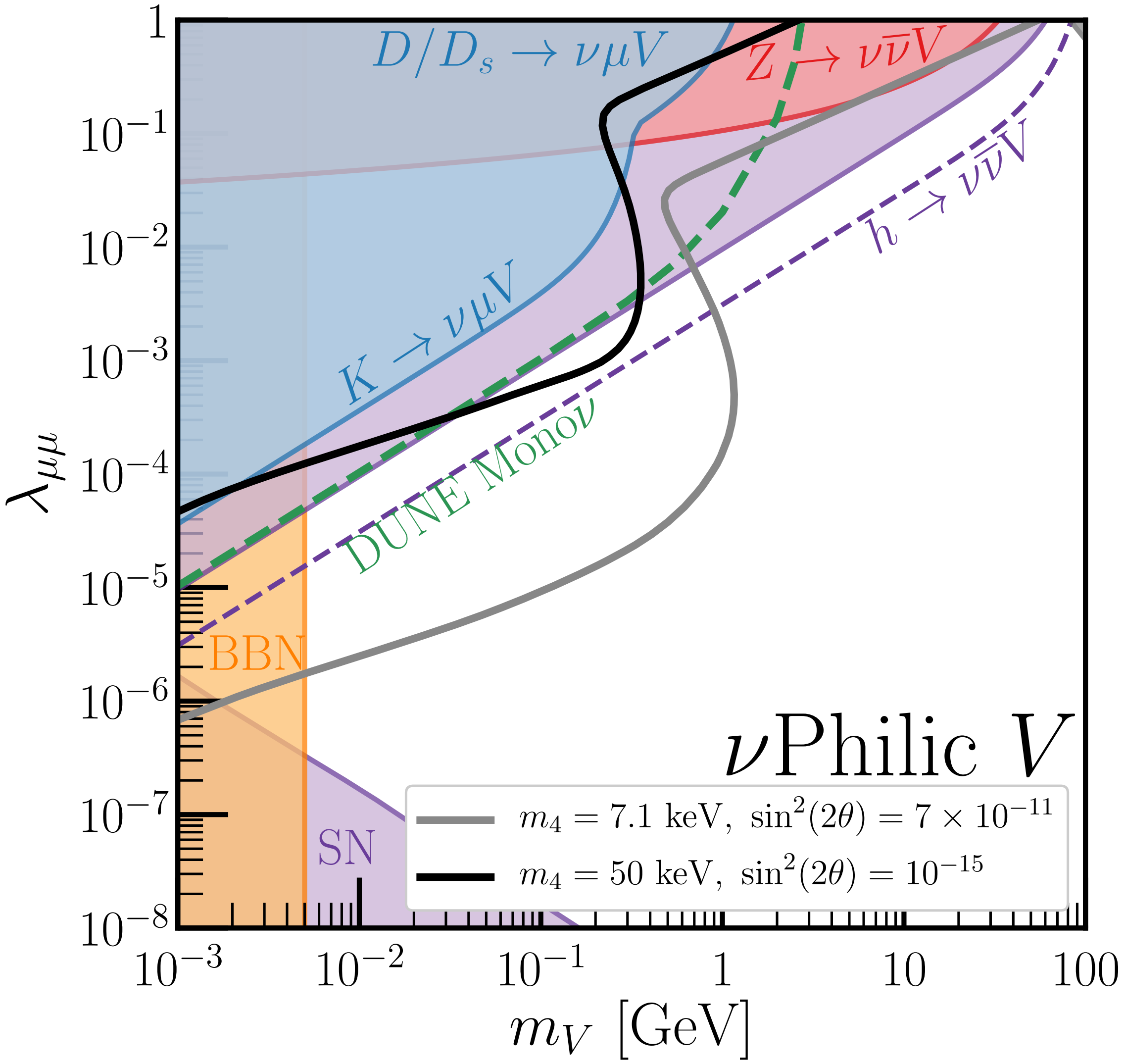
Current and future constraints: Scalar mediator



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



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

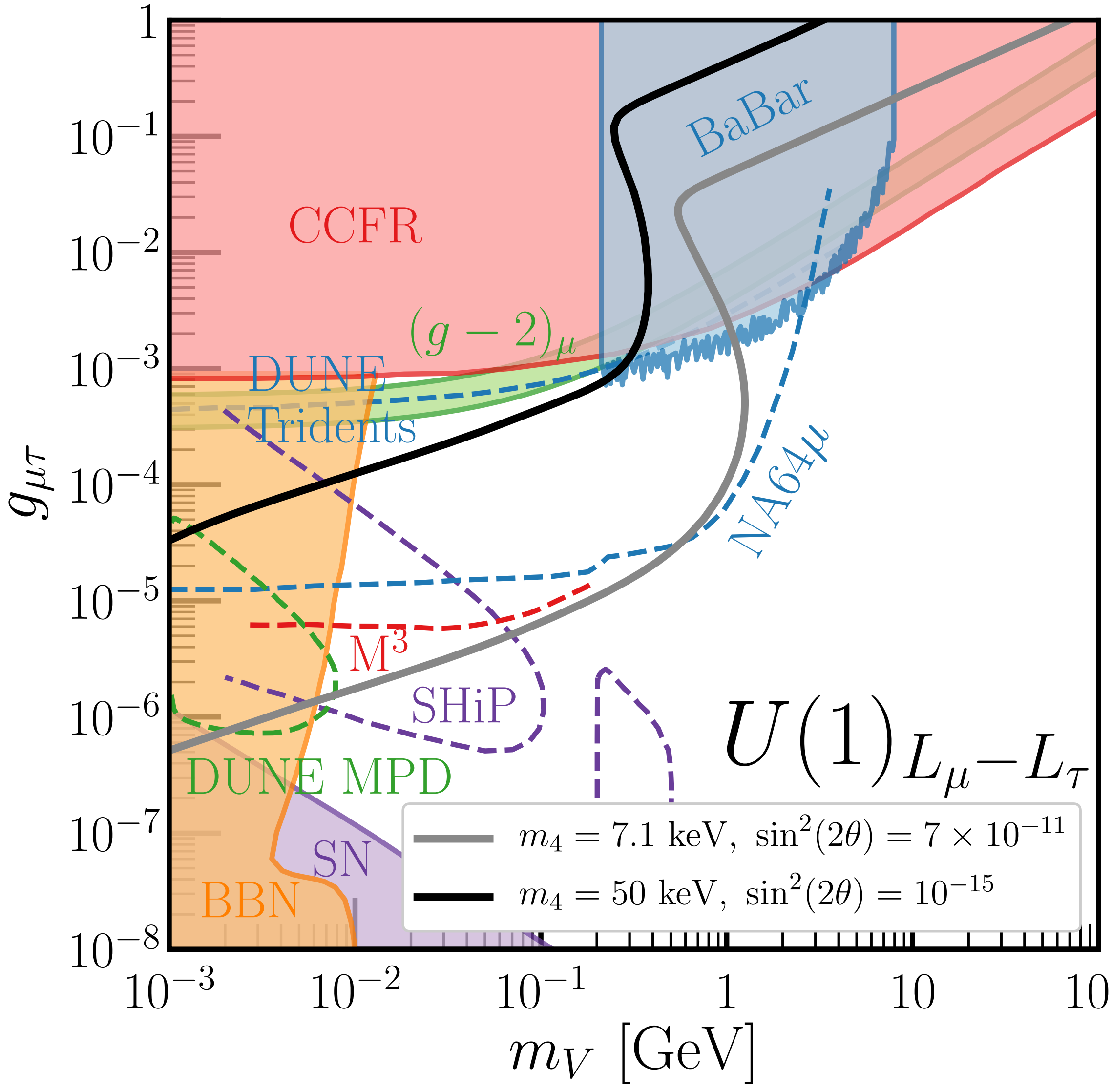
$\mathrm{Br}(H \to \text{invisible}) < 24\%$ Current HLC (purple)

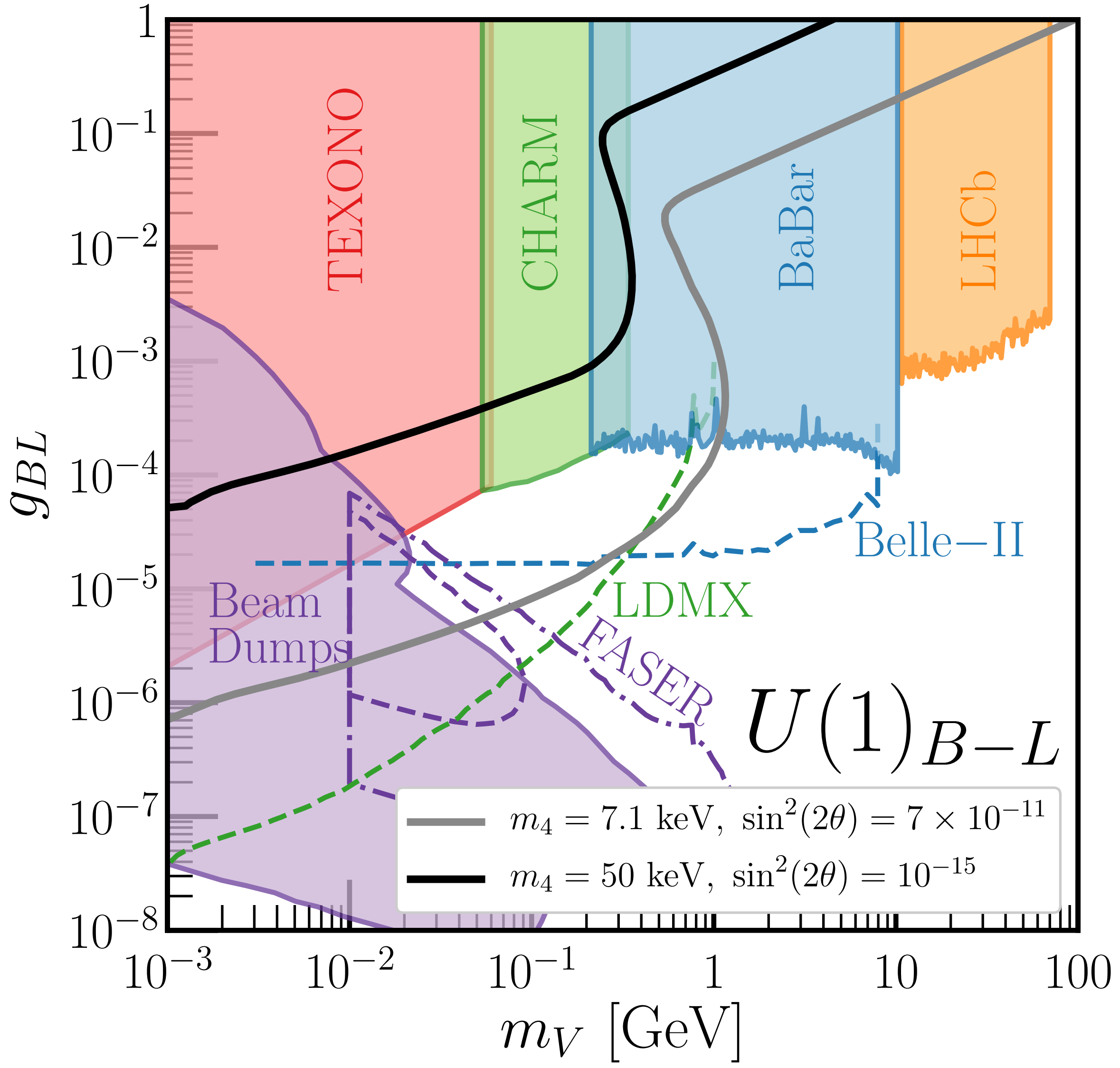
$\mathrm{Br}(H \to \text{invisible}) < 2.5\%$ Future HL- HLC

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 $U(1)_{B-L}$





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.

Gracias!