Dodelson-Widrow and Self-Interacting Neutrino

Yue Zhang

Carleton University

TRIUMF Theory workshop 2020

Based on: 1910.04901 and 1901.01259

Dark Matter Is?

Not known the rule of game yet.

Old suspects not convicted: naturalness, simplicity …

New moves being tried, e.g. multipurpose/new detectors …

Relic density is perhaps a useful guiding principle, in spite of variations of early universe.

I will to discuss some new prospects of an old candidate.

Dark Matter Is?

Symmetry magazine

Sterile Neutrino Dark Matter

Introduce to SM a gauge singlet fermion, mix it with neutrinos

$$\nu_4 = \cos\vartheta\, \nu_s + \sin\vartheta\, \nu_a$$

Flavor eigenstates: ν_a active, weakly interacting, ν_s pure singlet.

ϑ is vacuum mixing angle.

Relic Density

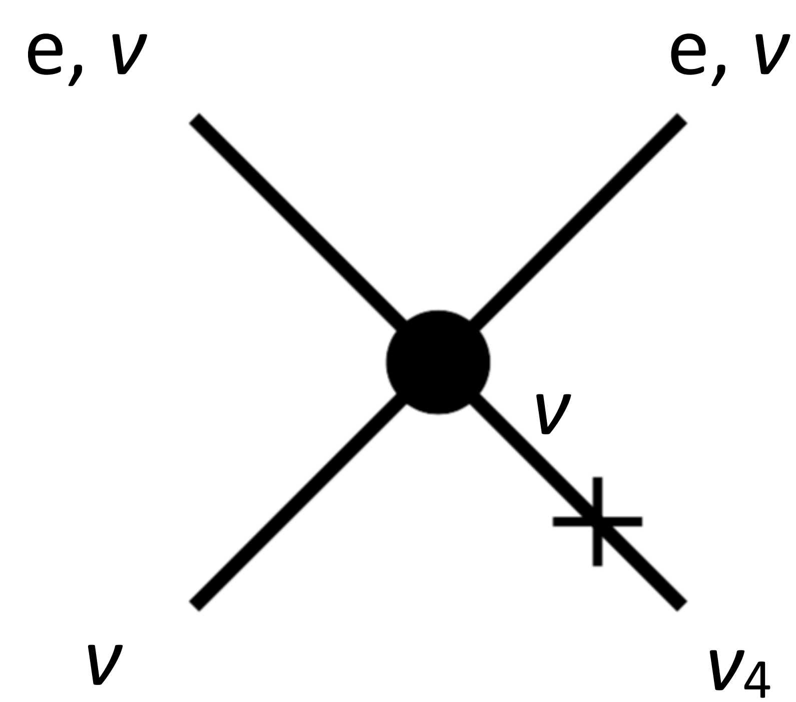
Fully thermalizing ν_4 with SM sector overclose the universe:

$$\Omega_{\nu_4} \sim 10 \left(\frac{m_{\nu_4}}{\text{keV}} \right)$$

ν_4 heavier than keV from dwarf galaxies (Tremaine, Gunn 1979).

Must be produced in a non-thermal way with a small ϑ << 1.

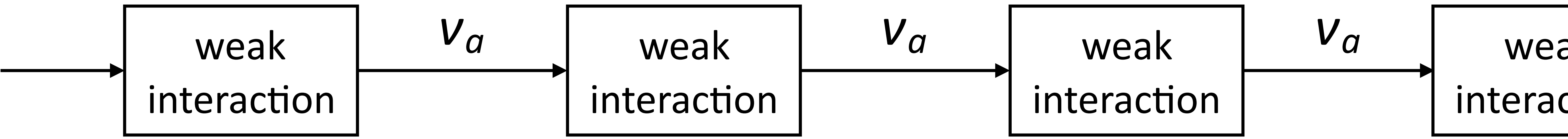
Dodelson-Widrow Mechanism



Tiny mixing angle ϑ controls the relic density.

hep-ph/9303287

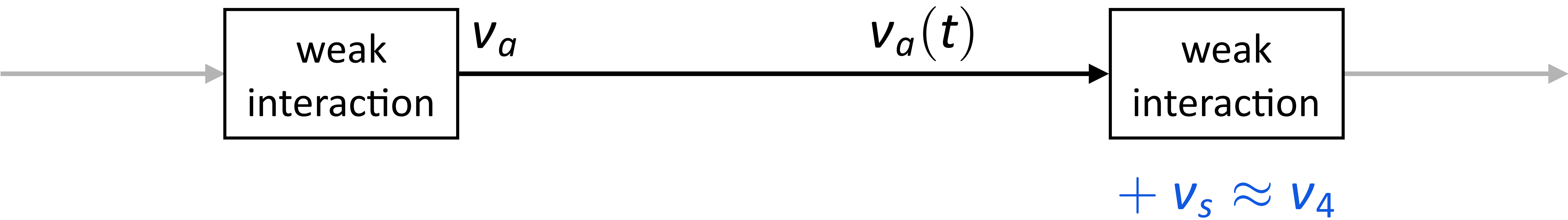
Neutrinos in Early Universe



In a thermal bath:

Neutrino after produced remains a coherent state until destroyed

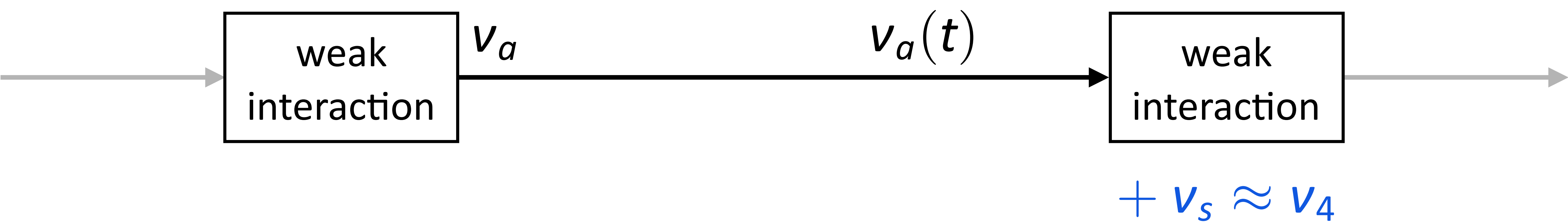
Neutrino Oscillation



In vacuum

$$P_{\nu_a \to \nu_4} = \sin^2 2\vartheta \sin^2\left(\frac{m_4^2 - m_1^2}{2E} t\right)$$

Neutrino Oscillation in Early Universe

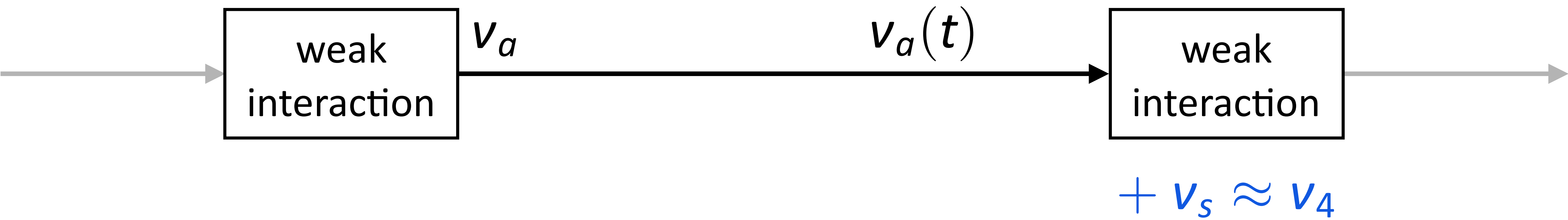


Include matter effect

$$P_{\nu_a \to \nu_4} = \frac{\Delta^2 \sin^2 2\vartheta}{\Delta^2 \sin^2 2\vartheta + (\Delta \cos 2\vartheta - V_T)^2} \sin^2 [(E_4 - E_1)t]$$

$$\Delta = (m_4^2 - m_1^2)/(2E)$$

Neutrino Oscillation in Early Universe



Frequent interactions (damping after t > 1/Γ)

$$P_{\nu_a \to \nu_4} = \frac{\Delta^2 \sin^2 2\vartheta}{\Delta^2 \sin^2 2\vartheta + \Gamma^2/4 + (\Delta \cos 2\vartheta - V_T)^2}$$

Boltzmann Equation

$$T\frac{df_{\nu_4}}{dT} = \frac{\Gamma}{4H}\frac{\Delta^2 \sin^2 2\vartheta}{\Delta^2 \sin^2 2\vartheta + \Gamma^2/4 + (\Delta \cos 2\vartheta - V_T)^2} f_{\nu_\alpha}$$

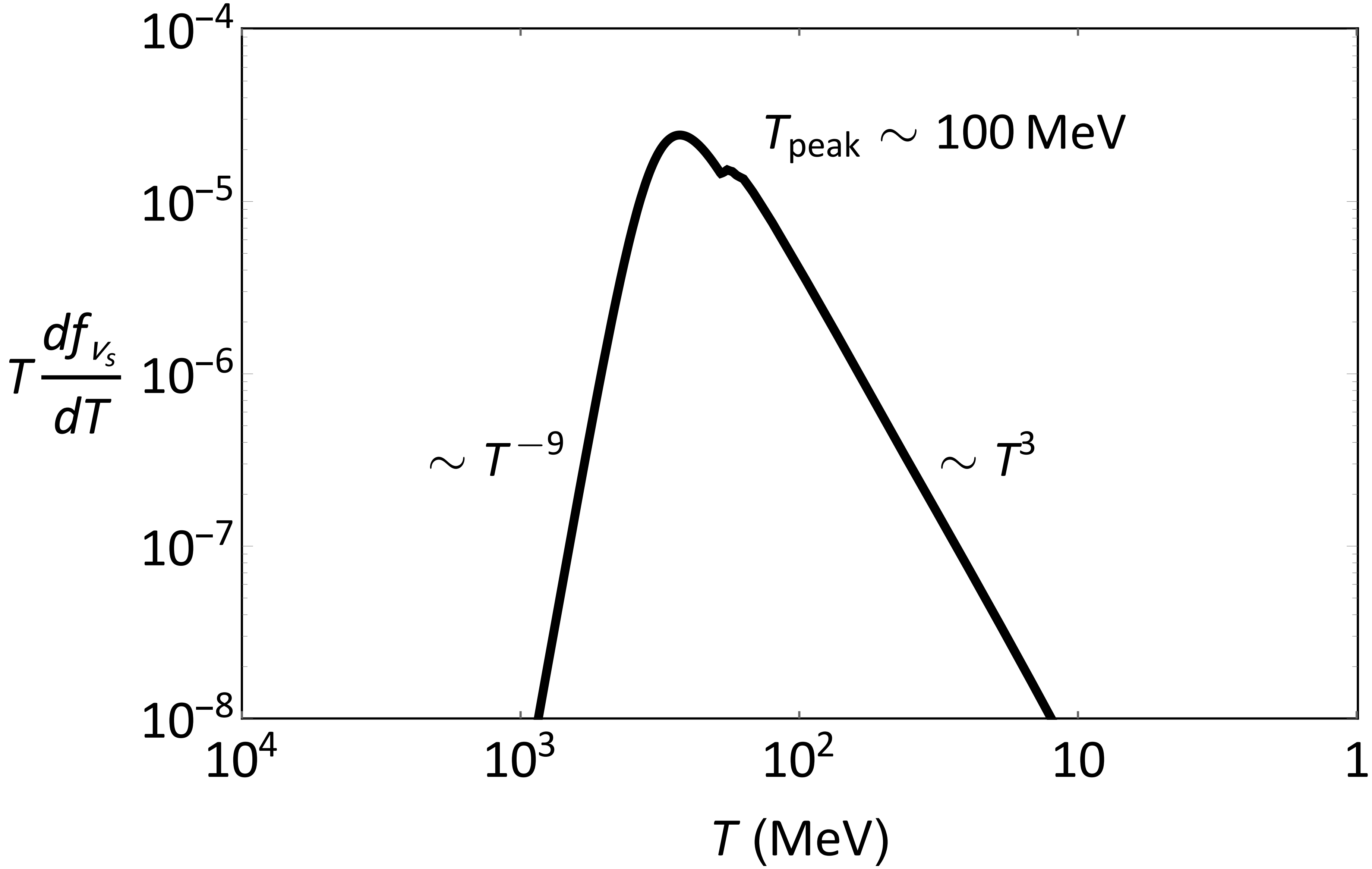
Boltzmann Equation

$$T\frac{df_{\nu_4}}{dT} = \frac{\Gamma}{4H}\frac{\Delta^2 \sin^2 2\vartheta}{\Delta^2 \sin^2 2\vartheta + \Gamma^2/4 + (\Delta \cos 2\vartheta - V_T)^2} f_{\nu_a}$$

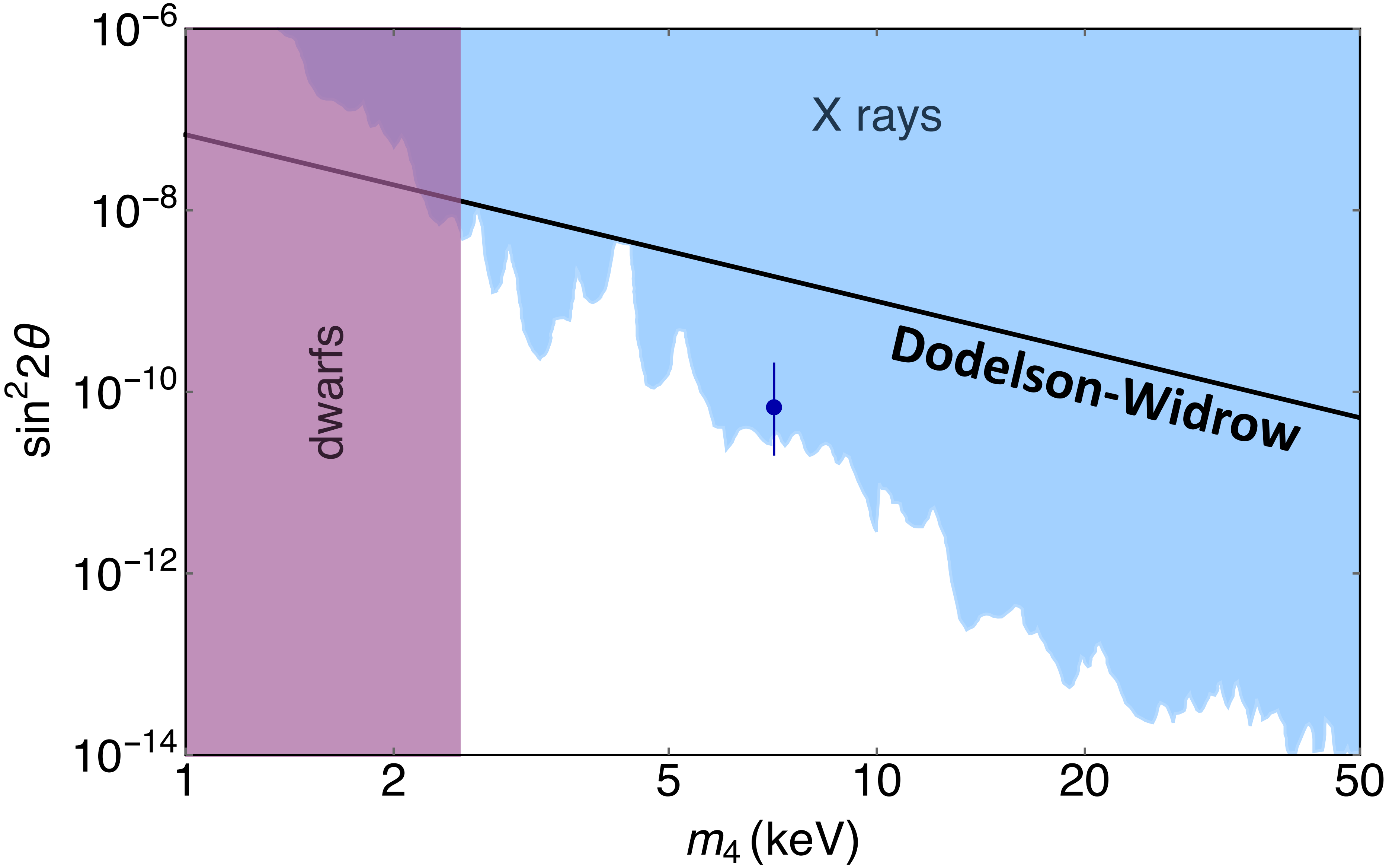
>>1 in early universe, production and oscillations occur for many times until SM neutrinos decouple.

If too early, strong suppression in $P_{\nu_a \to \nu_4}$ (denominator).

Production Time Window



Severely Constrained



Abazajian (1705.01837)

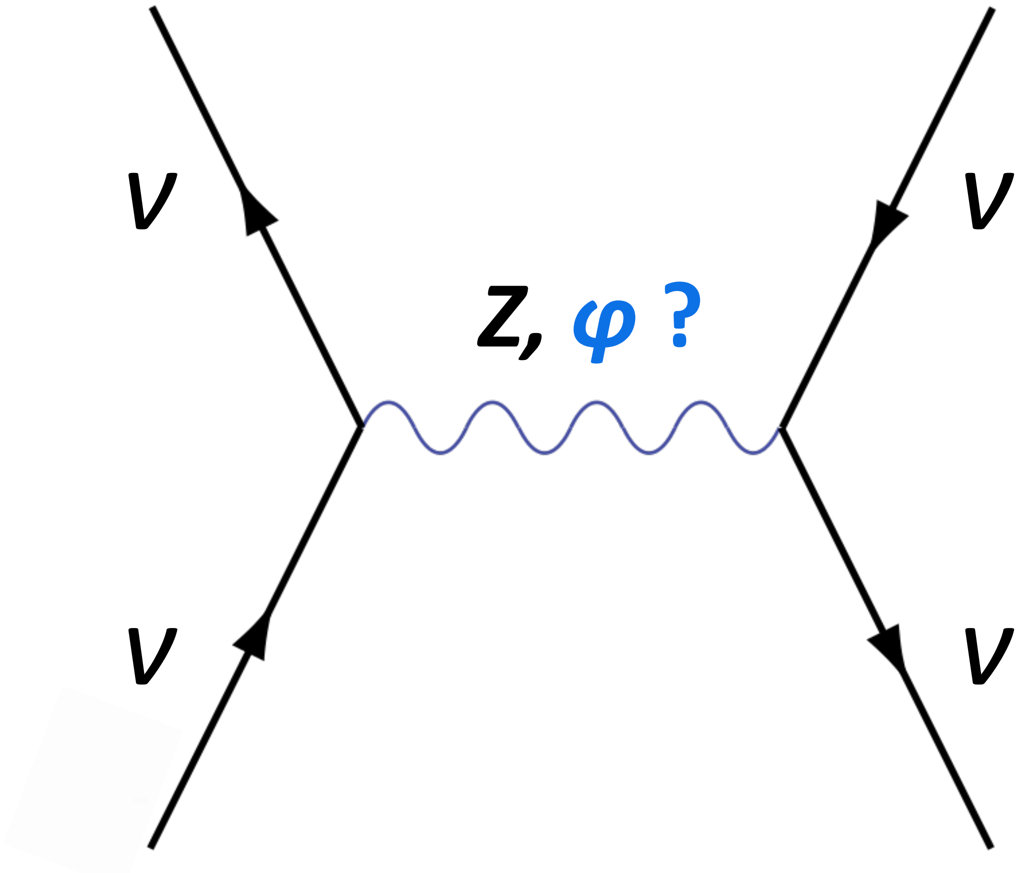
Reconcile Such Tension

$$T\frac{df_{\nu_4}}{dT} = \frac{\Gamma}{4H}\frac{\Delta^2 \sin^2 2\vartheta}{\Delta^2 \sin^2 2\vartheta + \Gamma^2/4 + (\Delta \cos 2\vartheta - V_T)^2} f_{\nu_a}$$

Intuition: compensate smaller mixing with larger reaction rate.

Γ in SM includes neutrino interacting with electron, muon, quark, and **itself**.

Neutrino Self Interactions



Never directly measured. Allowed to be much stronger.

Zνν coupling at LEP is an indirect measurement.

A Model

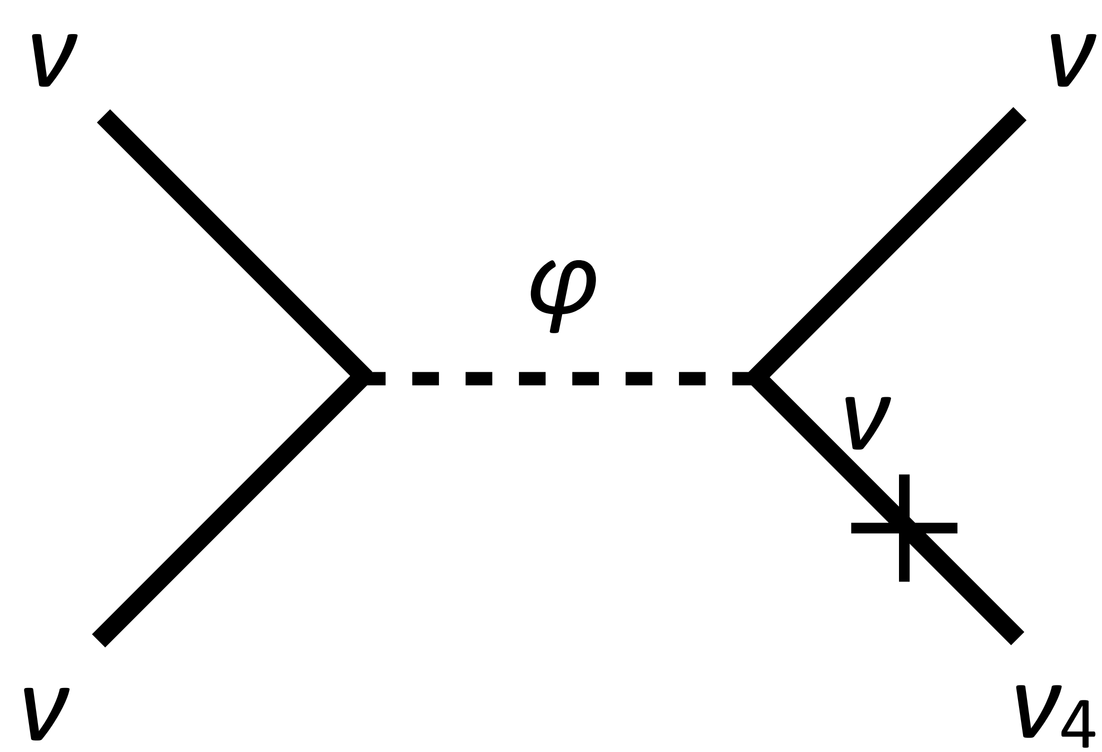
Add to Standard Model

$$\mathcal{L}_{\text{int}} = \frac{(LH)^2}{\Lambda^2}\varphi \xrightarrow{\text{EWSB}} \lambda v^2 \varphi$$

φ is a complex scalar, SM singlet, light.

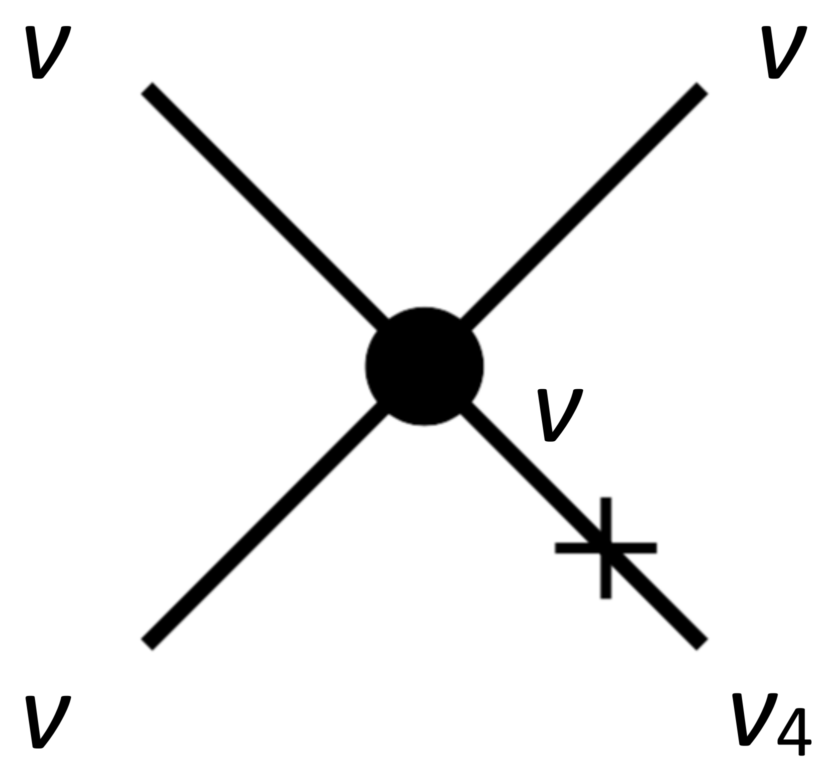
Its zero or small VEV (related to neutrino mass) can be protected by lepton number.

New Interaction Helps Dark Matter

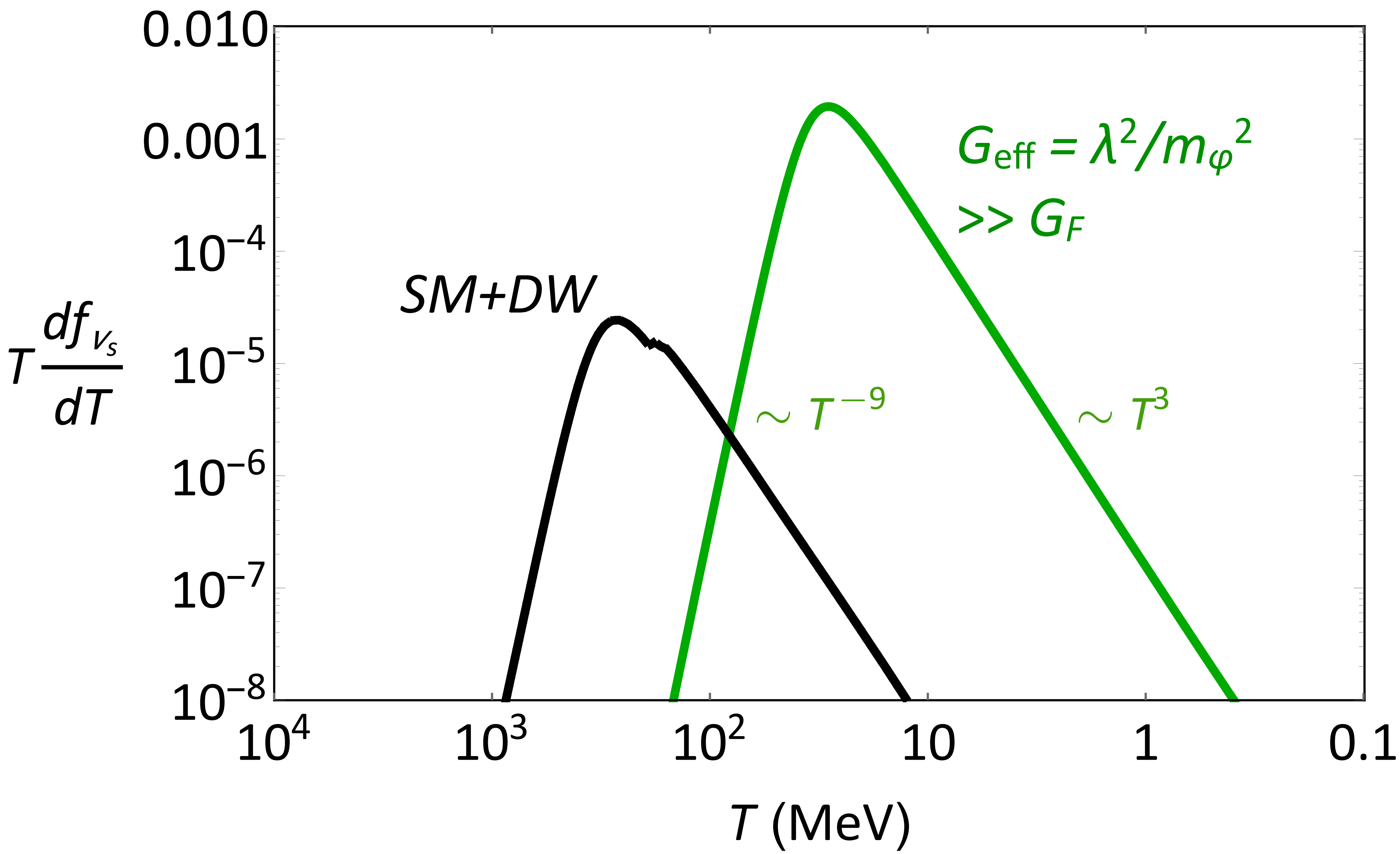


de Gouvêa, Sen, Tangarife, YZ (1910.04901, PRL)

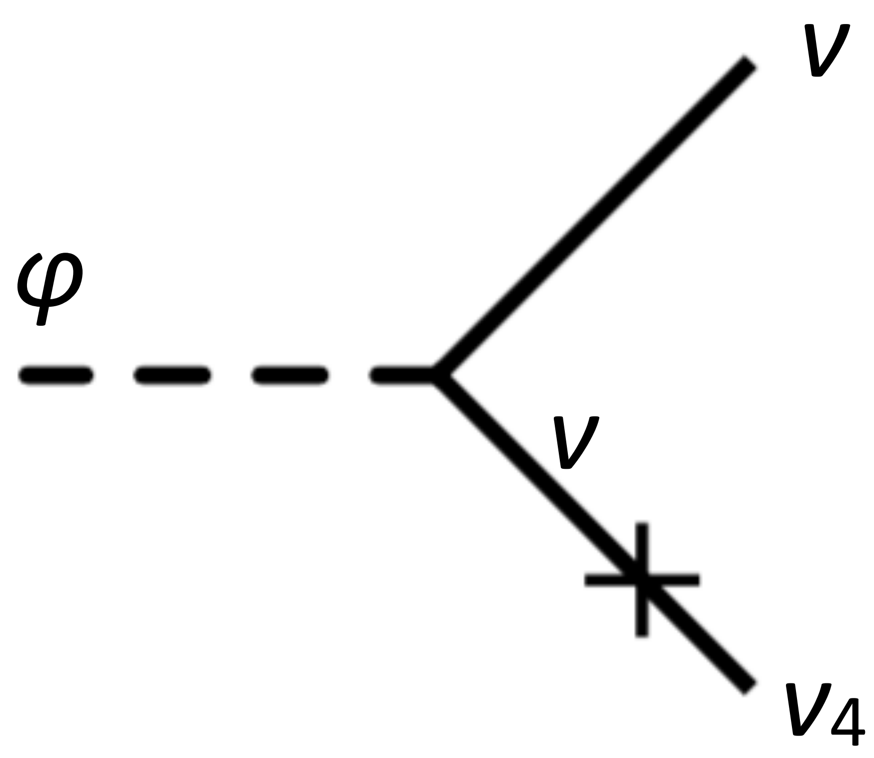
Case of Heavy Mediator



Case of Heavy Mediator



Case of Light Mediator

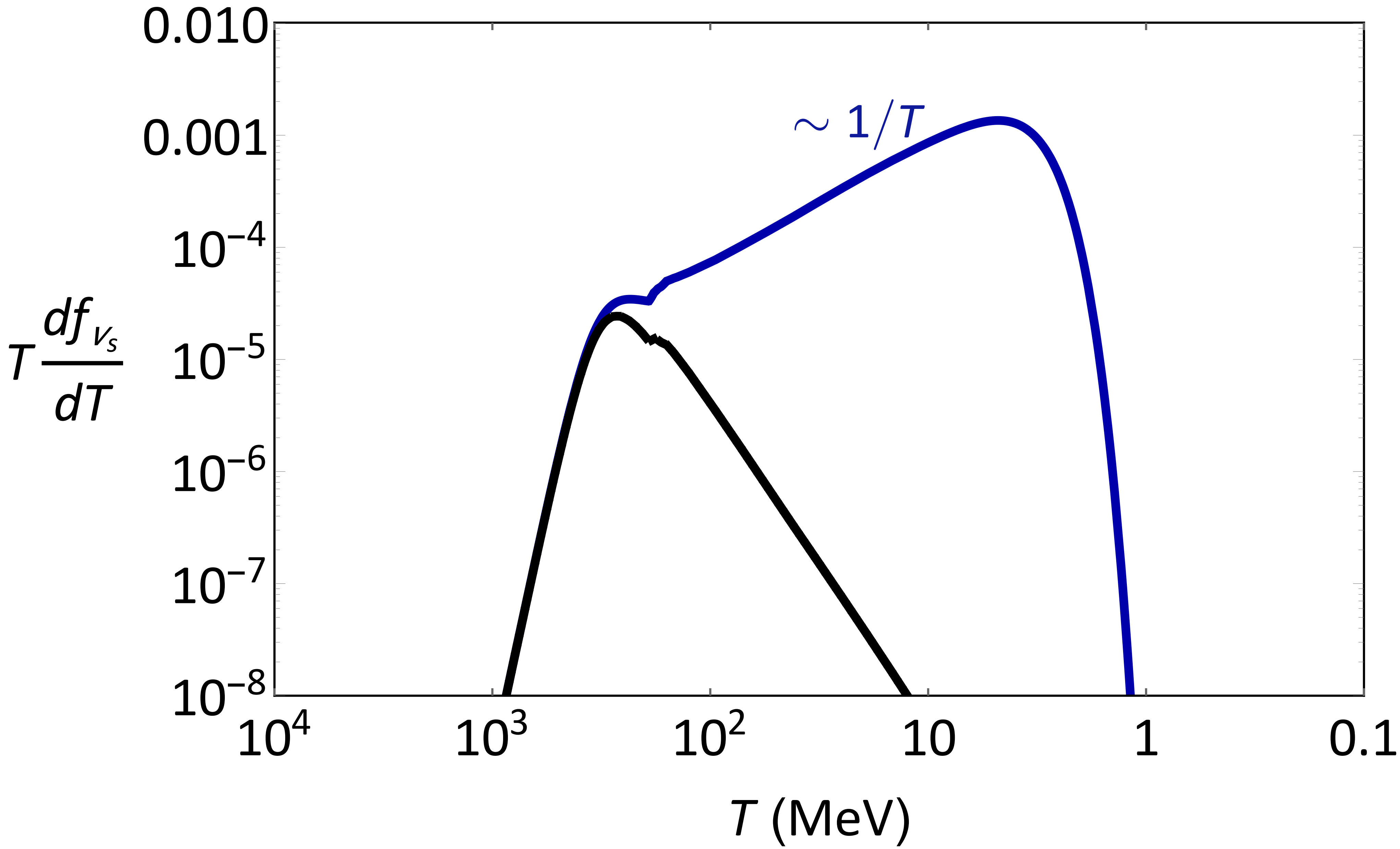


When $T>m_\varphi$, φ exists in plasma, decays and inverse decays.

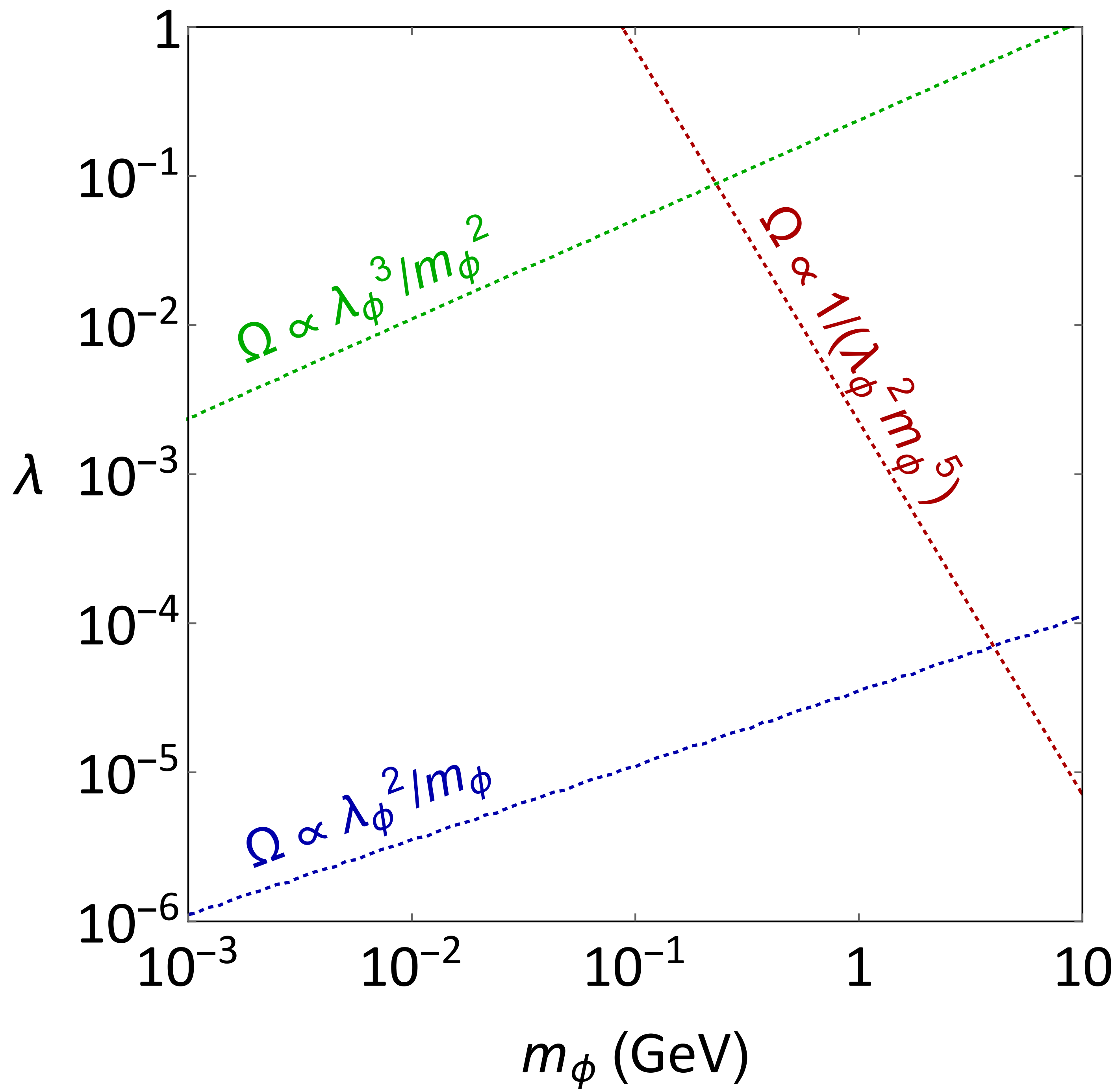
$\Gamma_{\text{decay}} \sim \lambda^2$, more important than scattering for $\lambda << 1$.

Opens up new parameter space.

Case of Light Mediator



Three Regimes

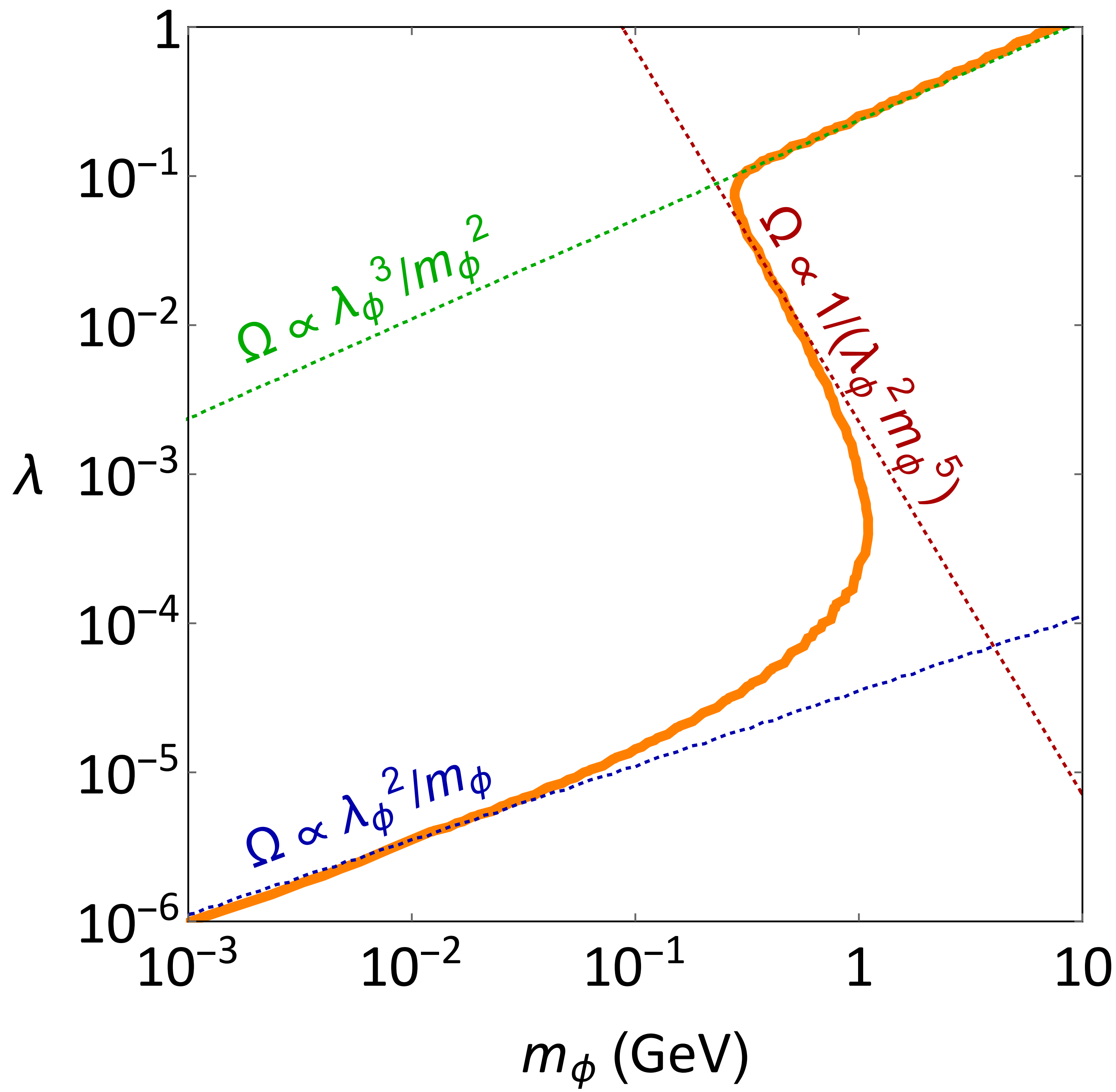


Green: heavy φ, $\nu\nu \rightarrow \nu\nu_s$ scattering.

Red: light φ decay, temperature suppressed $\vartheta(T)$.

Blue: light φ decay, $\vartheta(T) \simeq$ vacuum ϑ.

Numerical Result

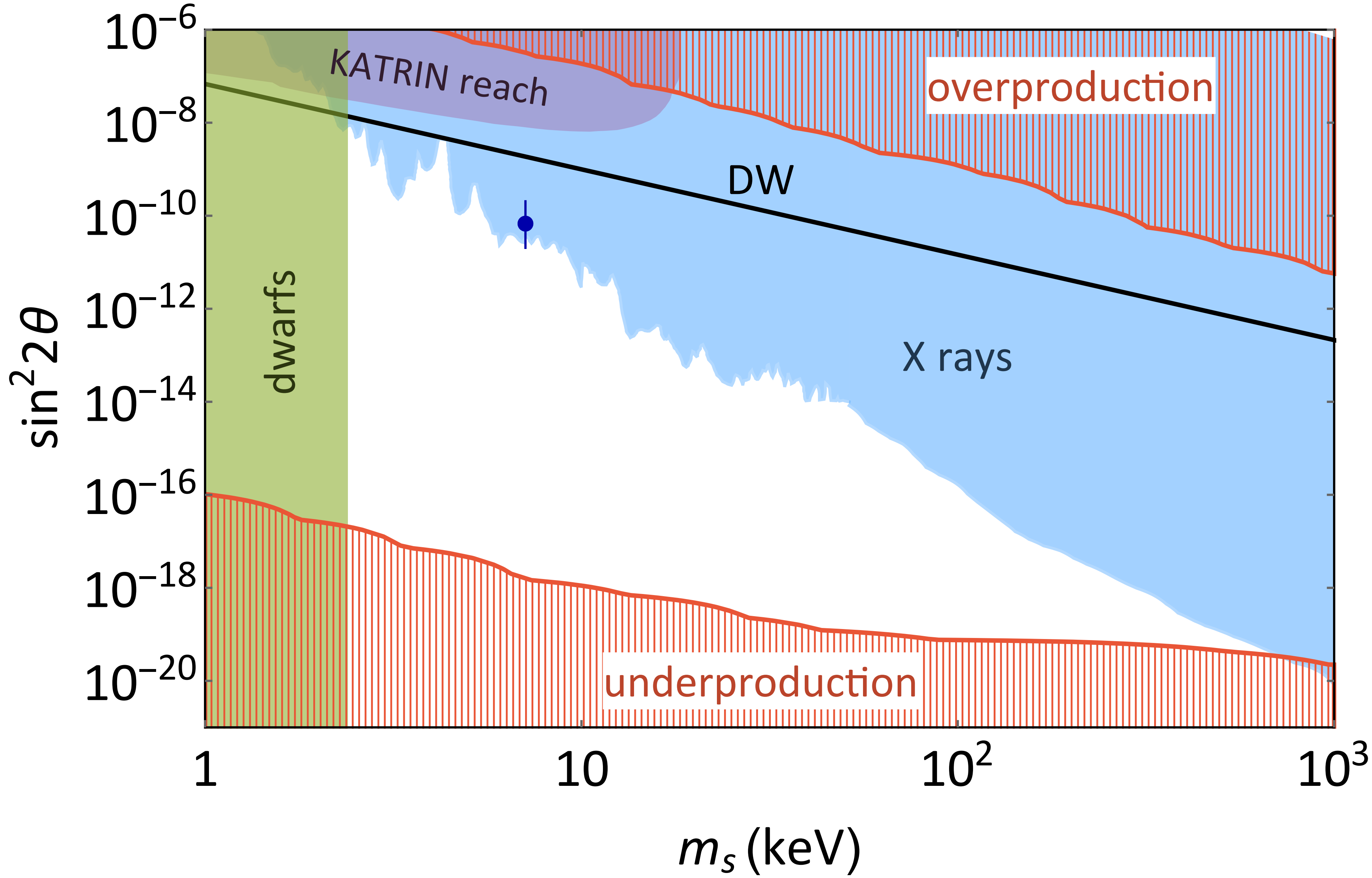


$\sin^2 2\vartheta = 7\text{x}10^{-11}$

m_4=7.1 keV

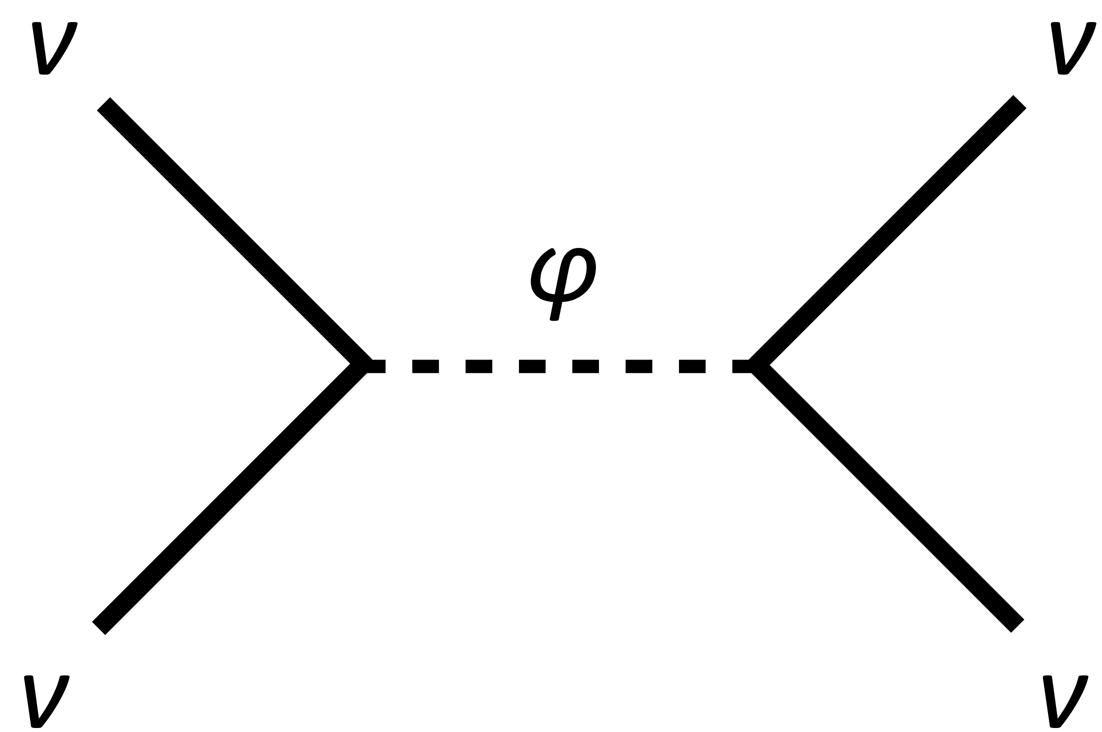
de Gouvêa, Sen, Tangarife, YZ (1910.04901, PRL)

Wide Relic Density Window

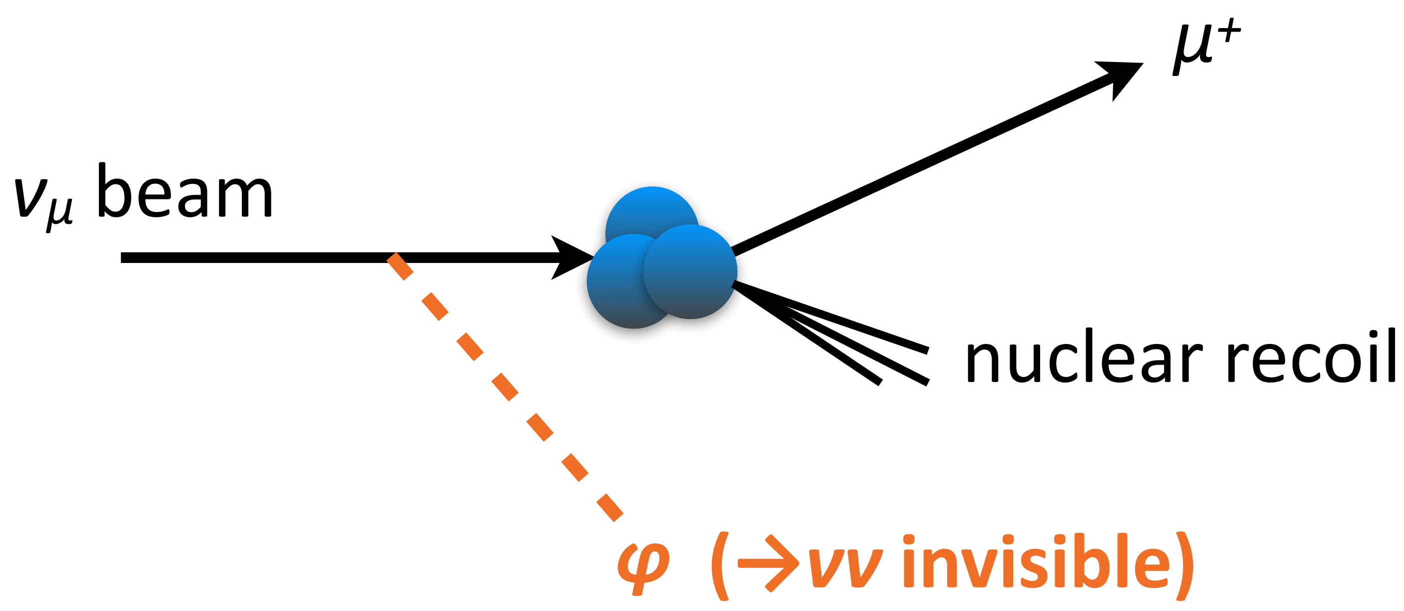


de Gouvêa, Sen, Tangarife, YZ (1910.04901, PRL)

Testing the New Interaction



Mono-Neutrino Signal

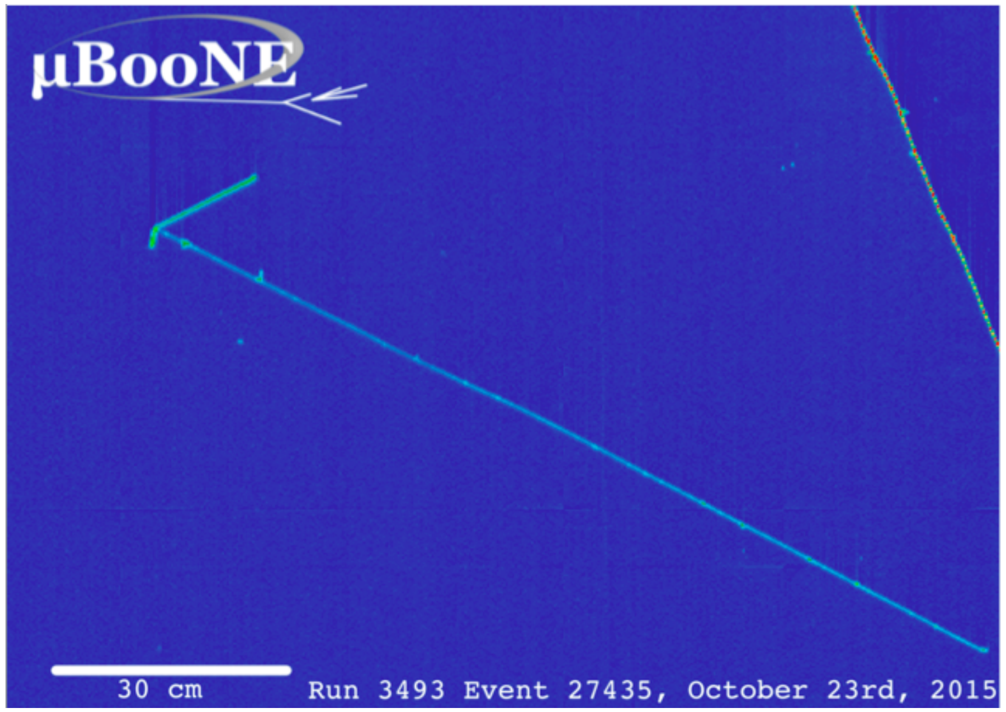


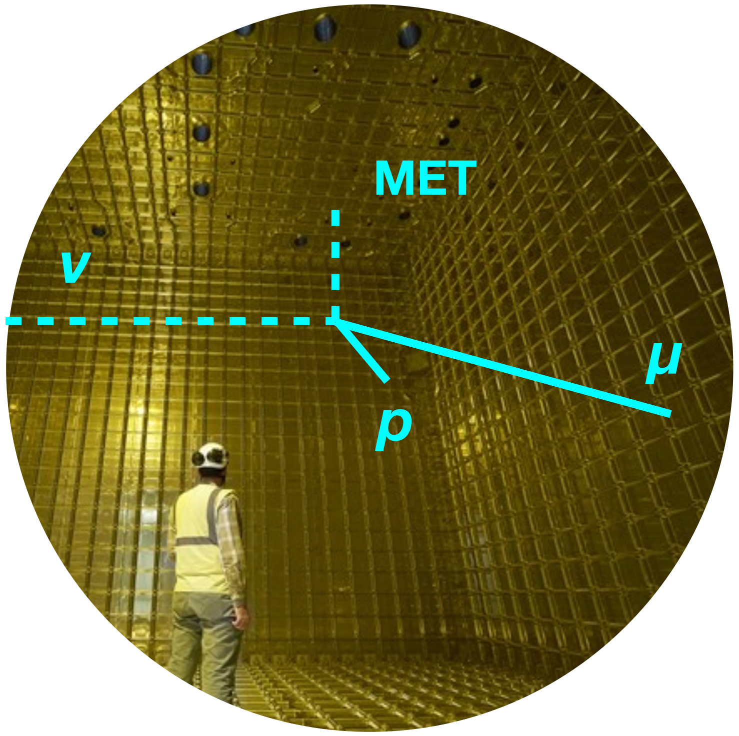
Signal process: $\nu_\mu+N\rightarrow\mu^++N'+\varphi$, characterized by:

- Missing transverse momentum p_T
- "Wrong-sign" outgoing muon

Kelly, YZ (1901.01259, PRD)

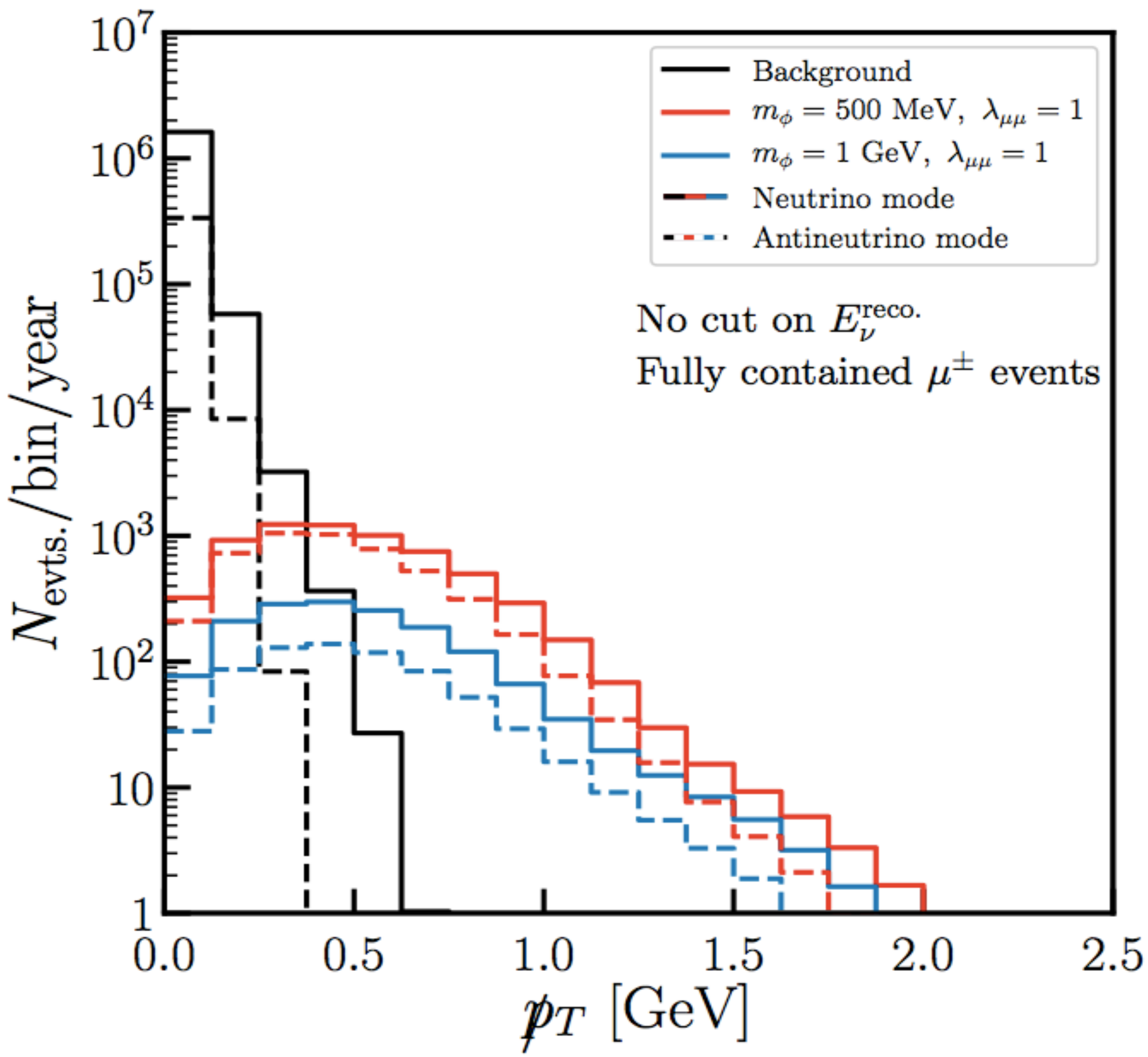
New Prospects With Argon





Excellent particle ID and energy resolution capabilities: reconstruct both final state muon and nucleon — hunt for events with sizeable missing transverse momentum.

Theorists' Simulation



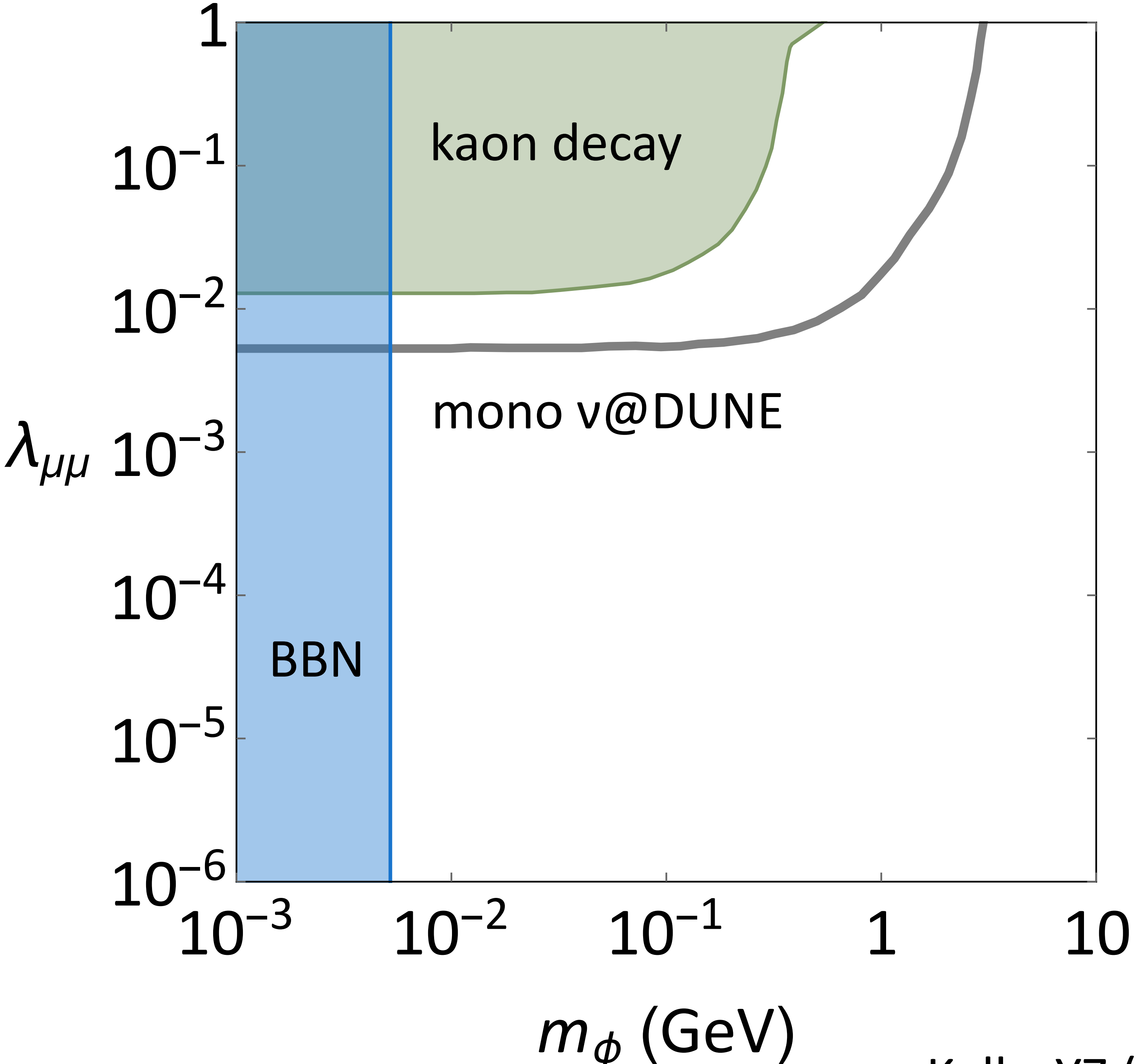
Kevin Kelly, YZ
(1901.01259, PRD)

Nucleon level simulation, smearing

$$3\%/\sqrt{E_{\rm muon}[{\rm GeV}]},\ 20\%/\sqrt{E_{\rm proton}[{\rm GeV}]},\ 40\%/\sqrt{E_{\rm neutron}[{\rm GeV}]}$$

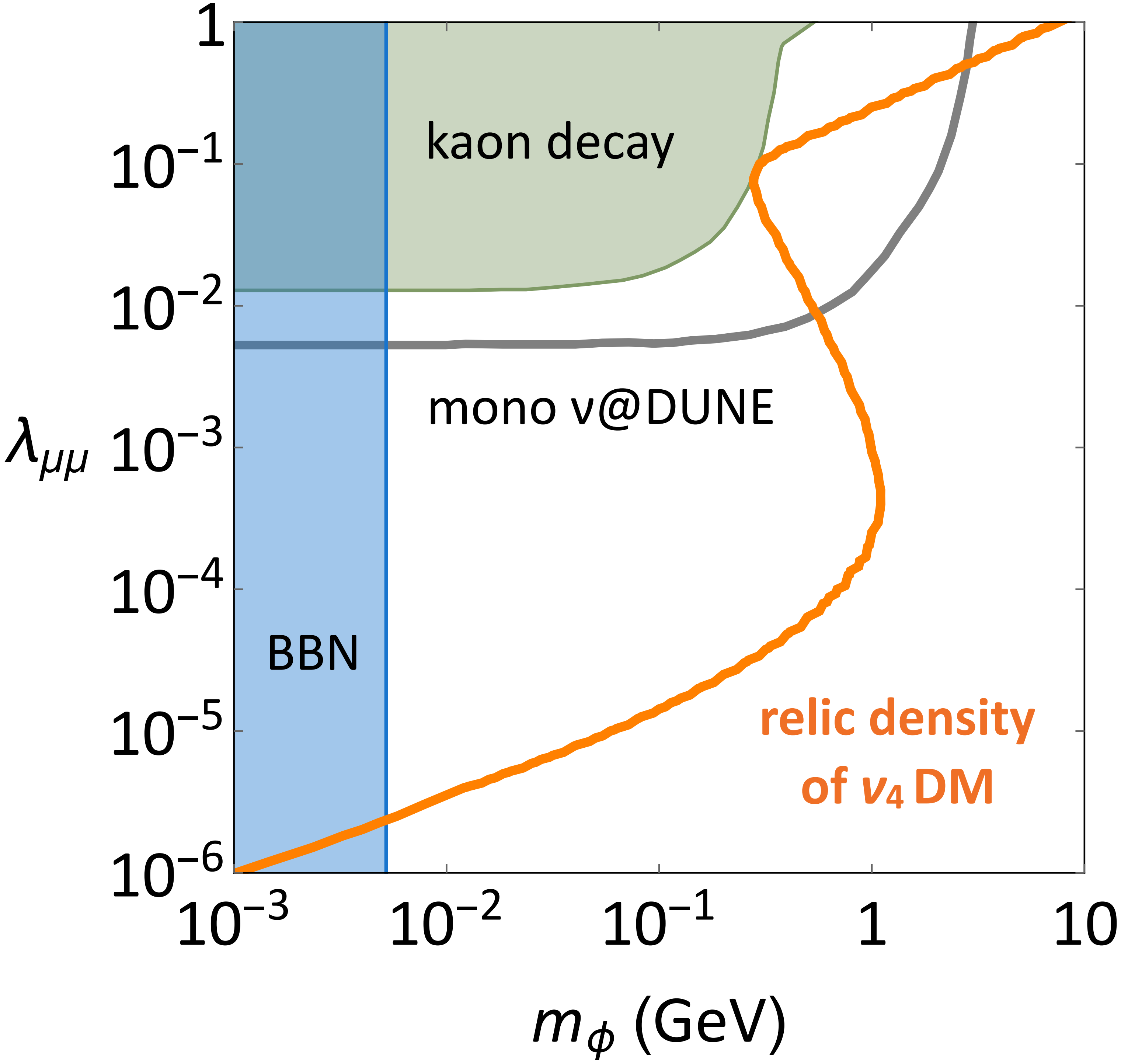
DUNE CDR (2015)

Expected DUNE Coverage



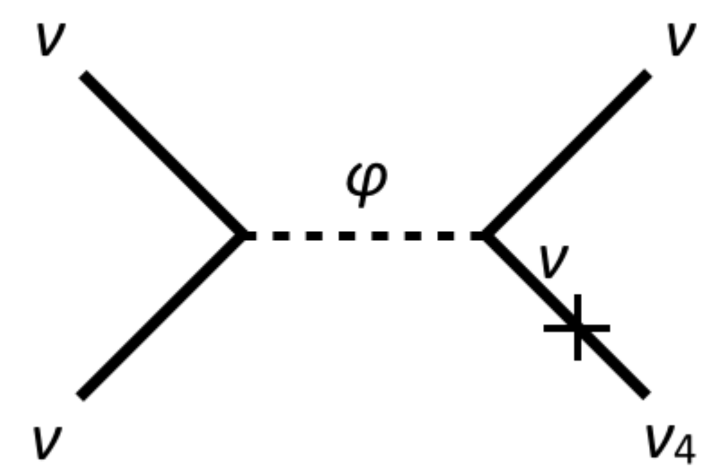
Kelly, YZ (1901.01259, PRD)

All Together



New Target for Direct Detection

KeV sterile neutrino dark matter (ν_4) decays into active neutrinos with keV energy.



Suitable to be detected at dark matter direct detection experiments looking for electron recoils, $E_R \sim m_{\nu_4}{}^2/m_e$.

New interaction allows dark matter to decay much faster.

Decaying dark matter in our galaxy could produce a large flux of keV neutrinos well above that of solar neutrinos.

with Maíra Dutra, in progress

Summary

It is amusing to show that new neutrino self interaction can impact (help) the relic density of dark matter.

I present a viable model of self-interacting neutrinos with a new light mediator (neutrinophilic).

"Mono-neutrino" signal at neutrino beam experiments, and new opportunity at direct detection experiments.

Summary

It is amusing to show that new neutrino self interaction can impact (help) the relic density of dark matter.

I present a viable model of self-interacting neutrinos with a new light mediator (neutrinophilic).

“Mono-neutrino” signal at neutrino beam experiments, and new opportunity at direct detection experiments.

thanks!