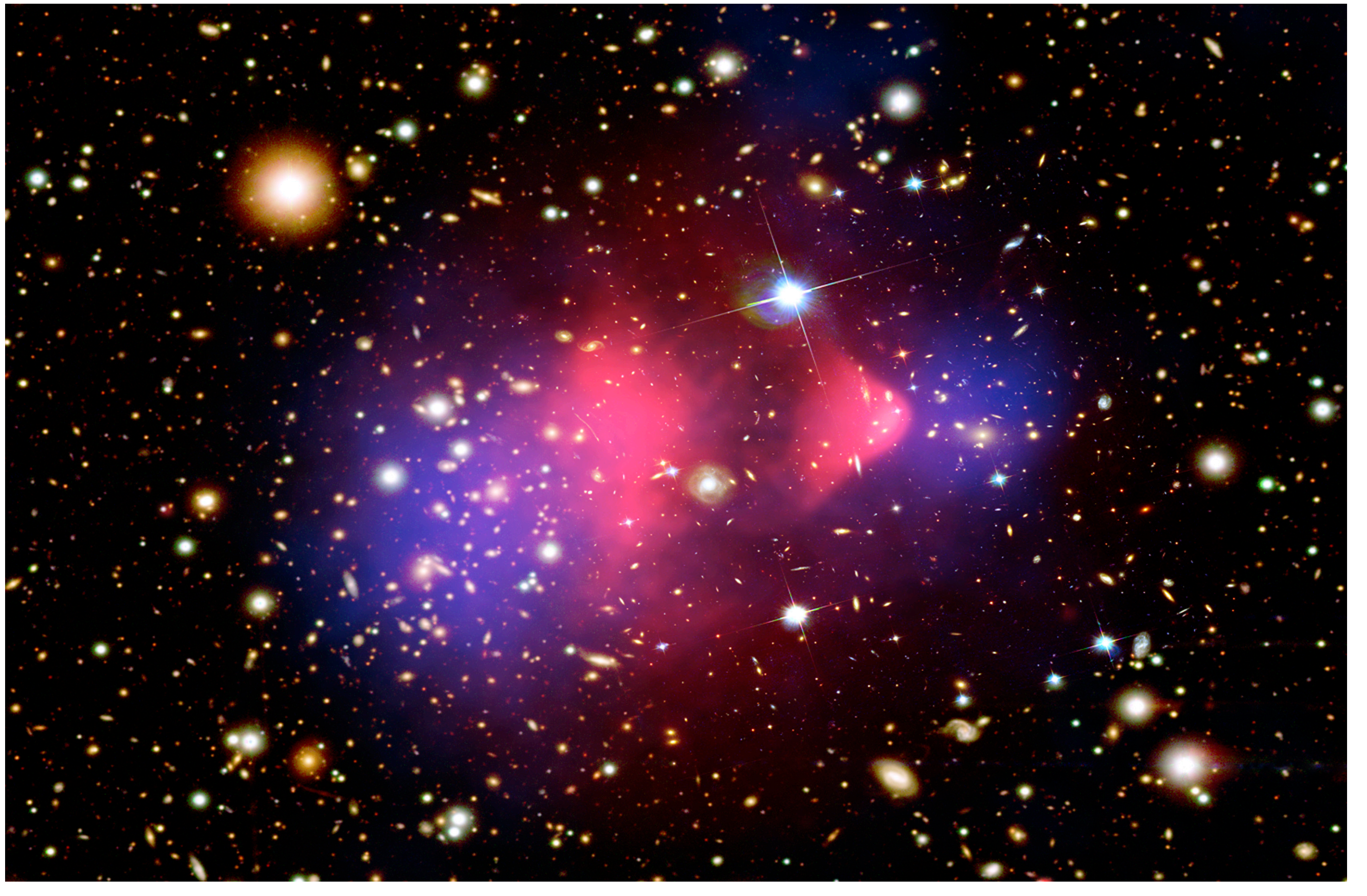
New Avenue to Sterile Neutrino Dark Matter

Yue Zhang

Carleton University

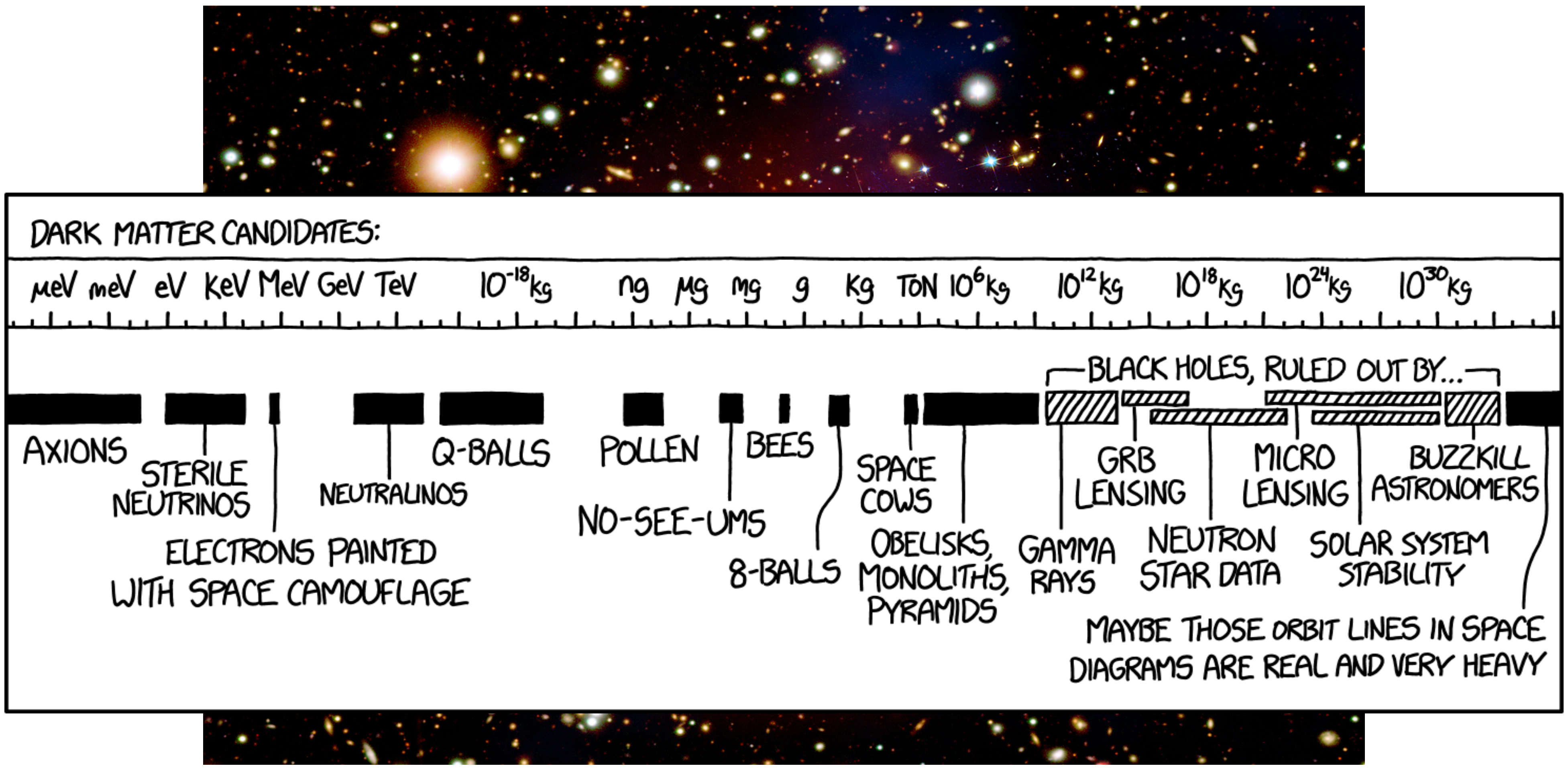
Seminar@IBS-CTPU 7 Apr 2021

Dark Matter Puzzle



$$F \neq ma$$

Dark Matter Puzzle



$$F \neq ma$$

Candidates

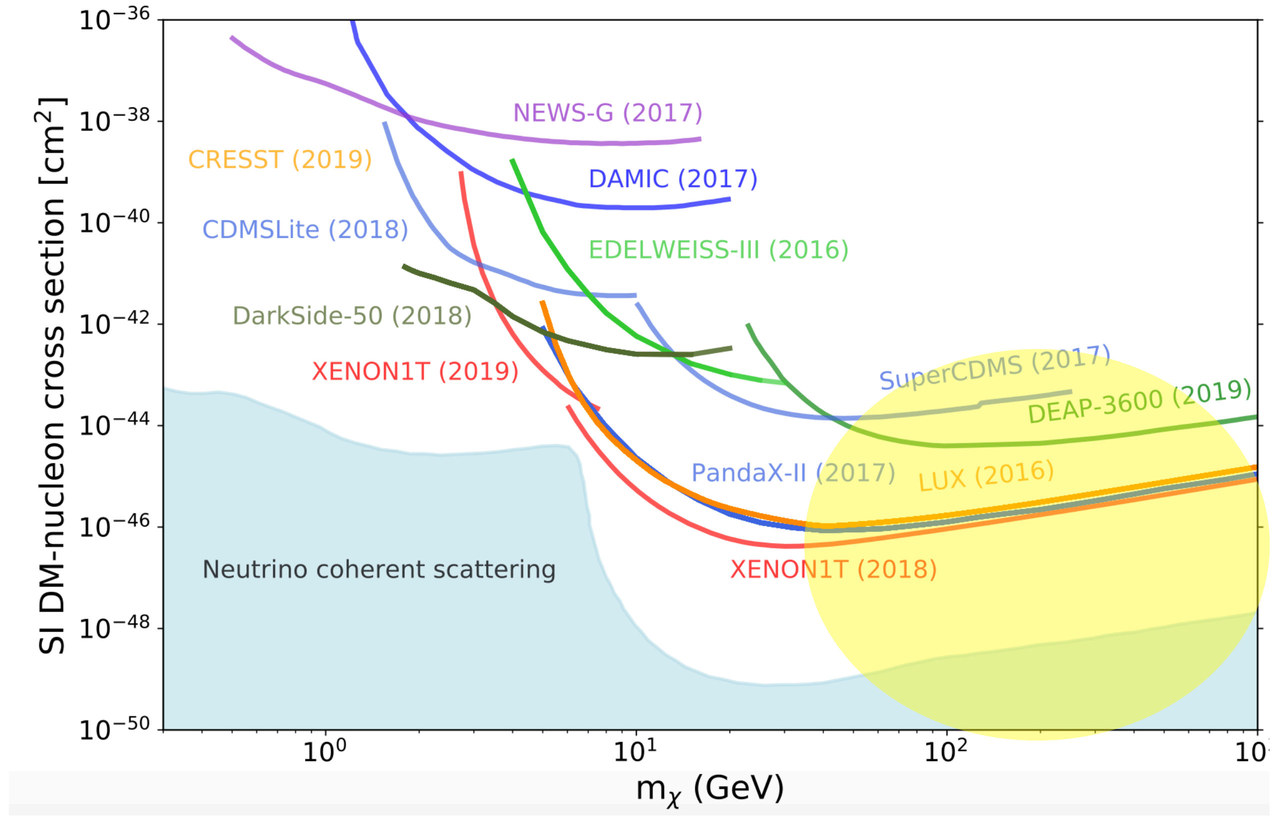
QCD axion

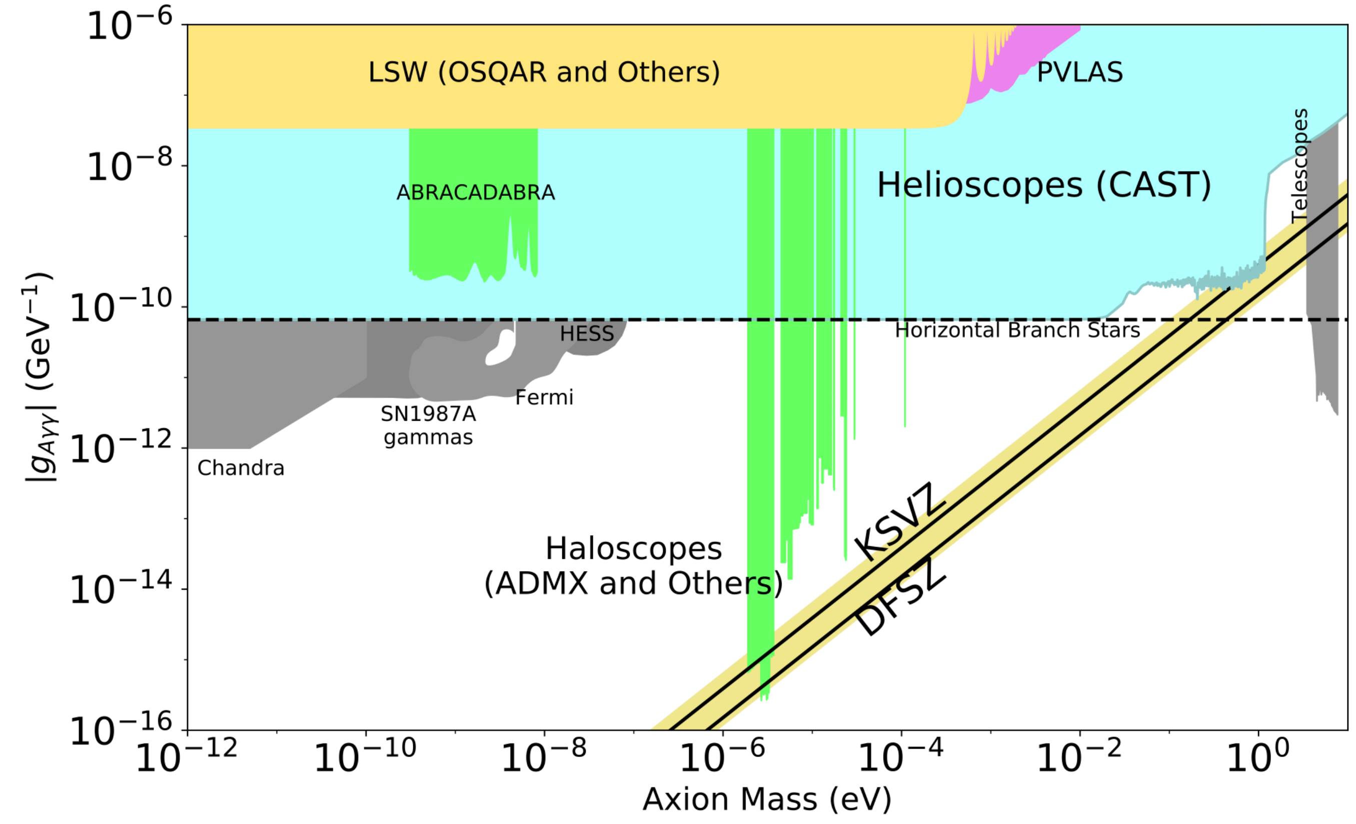
Sterile neutrino

WIMP

Relic abundance is a good guiding principle

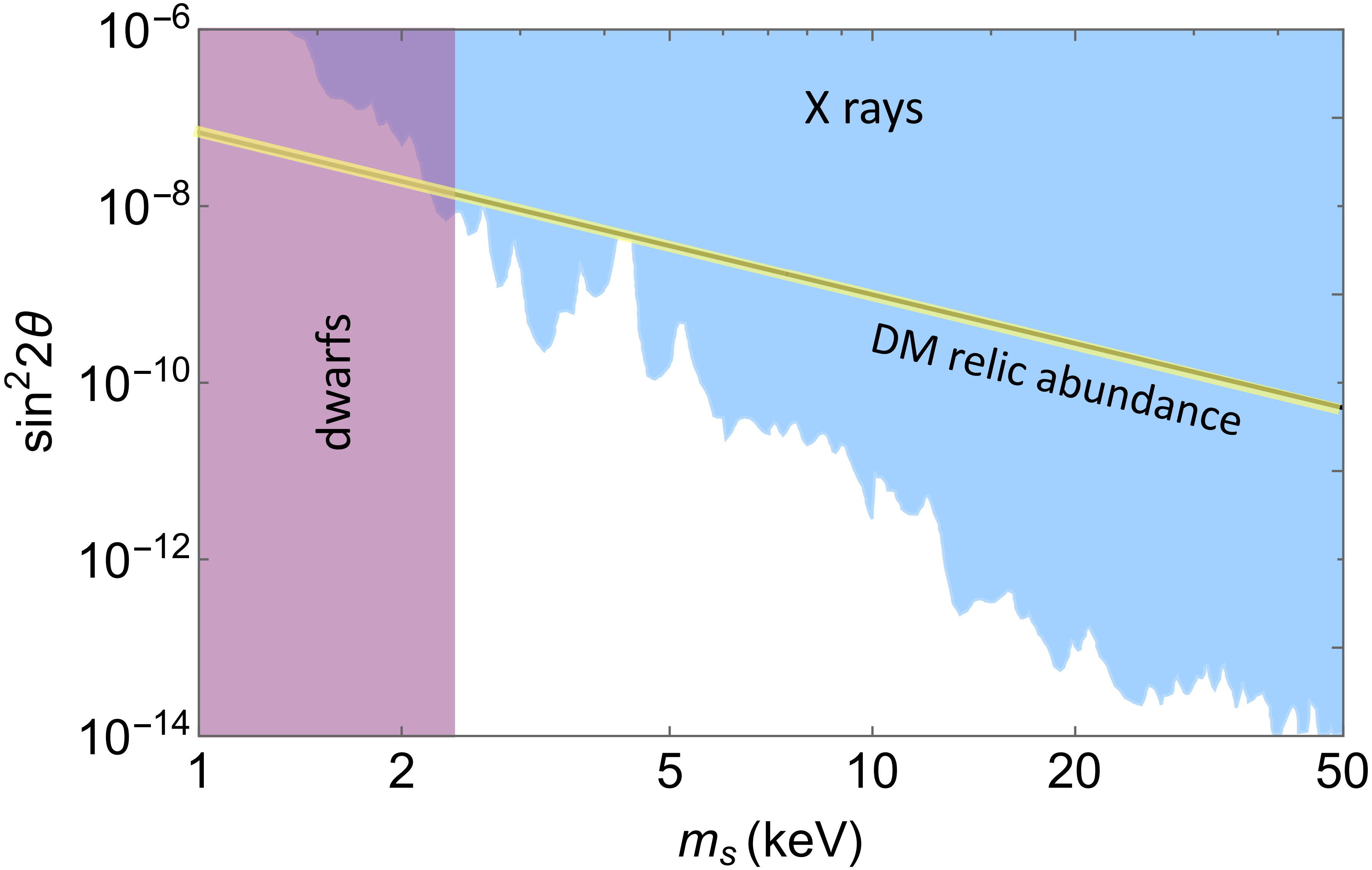
WIMP and Axion



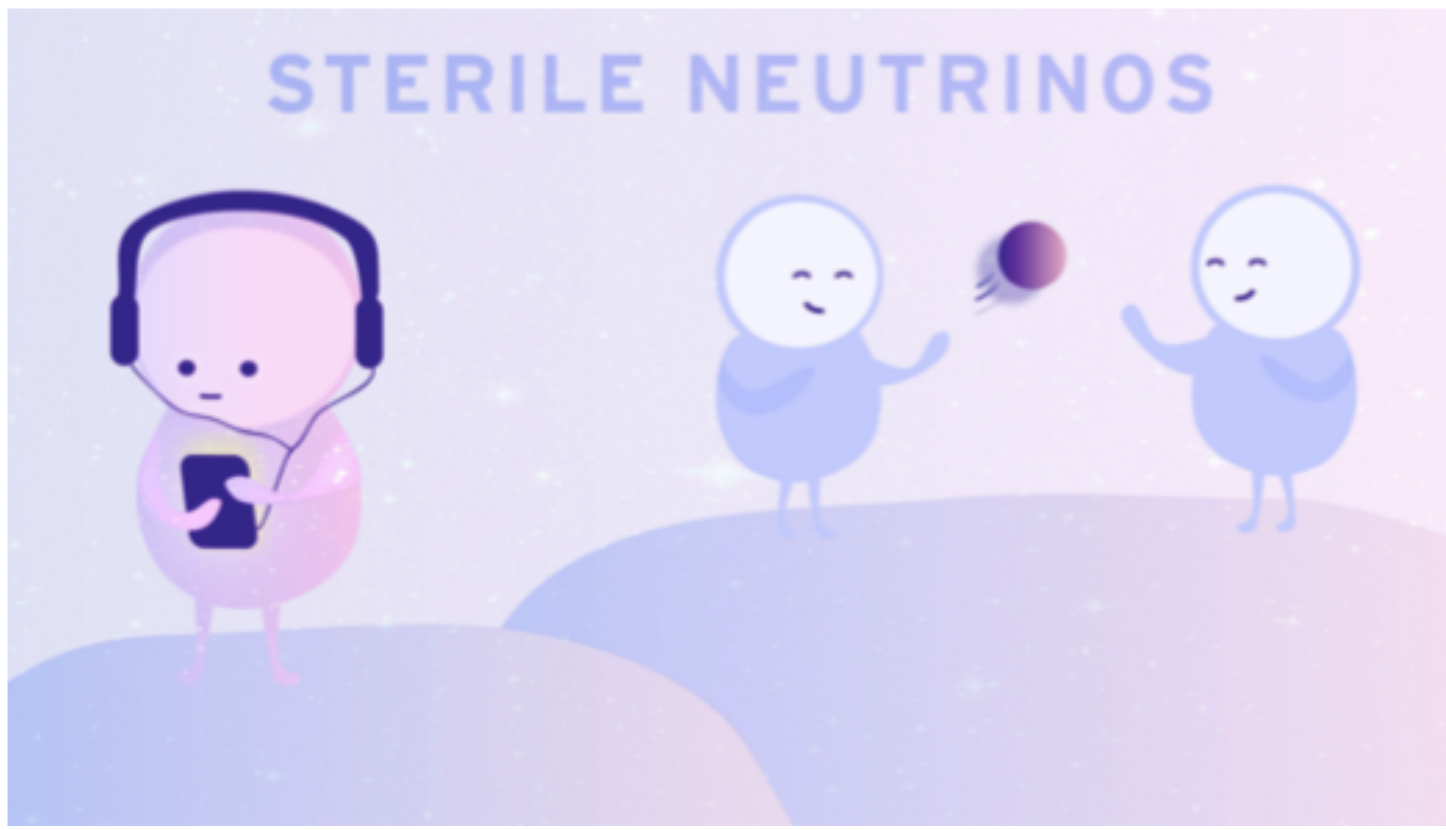


they still live well

Sterile Neutrino: in trouble?



Sterile Neutrino Dark Matter



Symmetry magazine

Sterile Neutrino Dark Matter

Introduce a gauge singlet fermion, mix it with SM neutrinos

$$\nu_4 = \cos\theta\ \nu_s + \sin\theta\ \nu_a$$

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

θ is vacuum mixing angle.

Relic Density

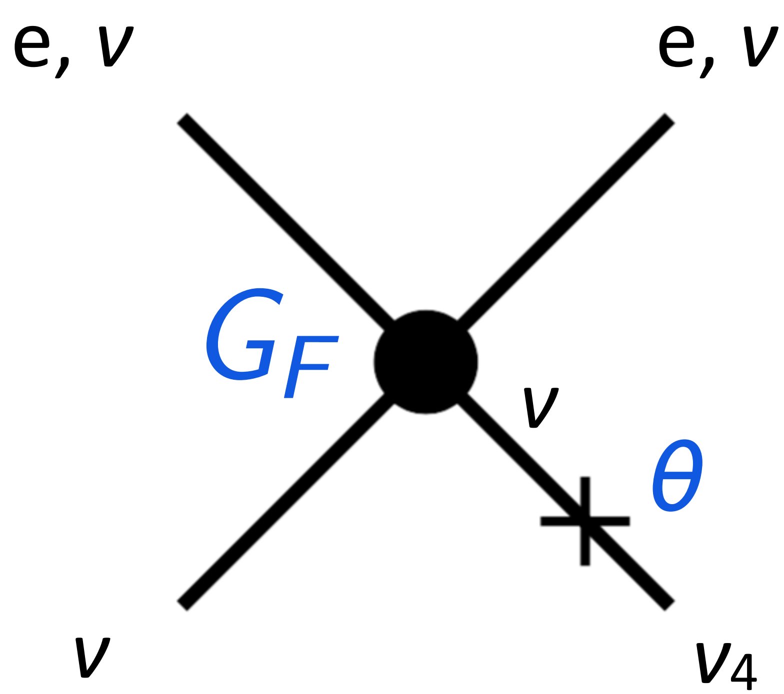
Fully thermalizing ν_4 with SM sector overclose the universe:

$$\Omega_4 \sim 10 \left(\frac{m_4}{\text{keV}} \right)$$

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

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

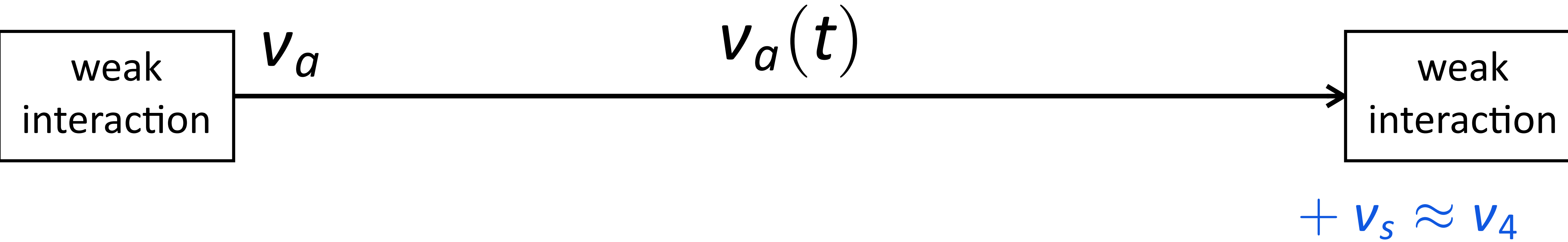
Dodelson-Widrow Mechanism



Tiny mixing angle ϑ controls the relic density.

hep-ph/9303287

Neutrino Oscillation in Early Universe



Two time scales:

In the thermal bath, neutrino after produced remains coherent state until destroyed.

In between, active-sterile neutrino oscillation occurs.

Probability in Each Cycle

$$P_{\nu_\alpha \to \nu_4} = \frac{1}{2} \sin^2 2\theta_{\text{eff}}$$
$$= \frac{1}{2} \frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + \Gamma^2/4 + (\Delta \cos\theta - V_T)^2}$$

V_T : Temperature creates a matter potential for active neutrinos.

$1/\Gamma^2$: Oscillation suppressed if interactions are too frequent.

$\Delta = (m_4^2 - m_1^2)/(2E) \sim \text{keV}^2/E$

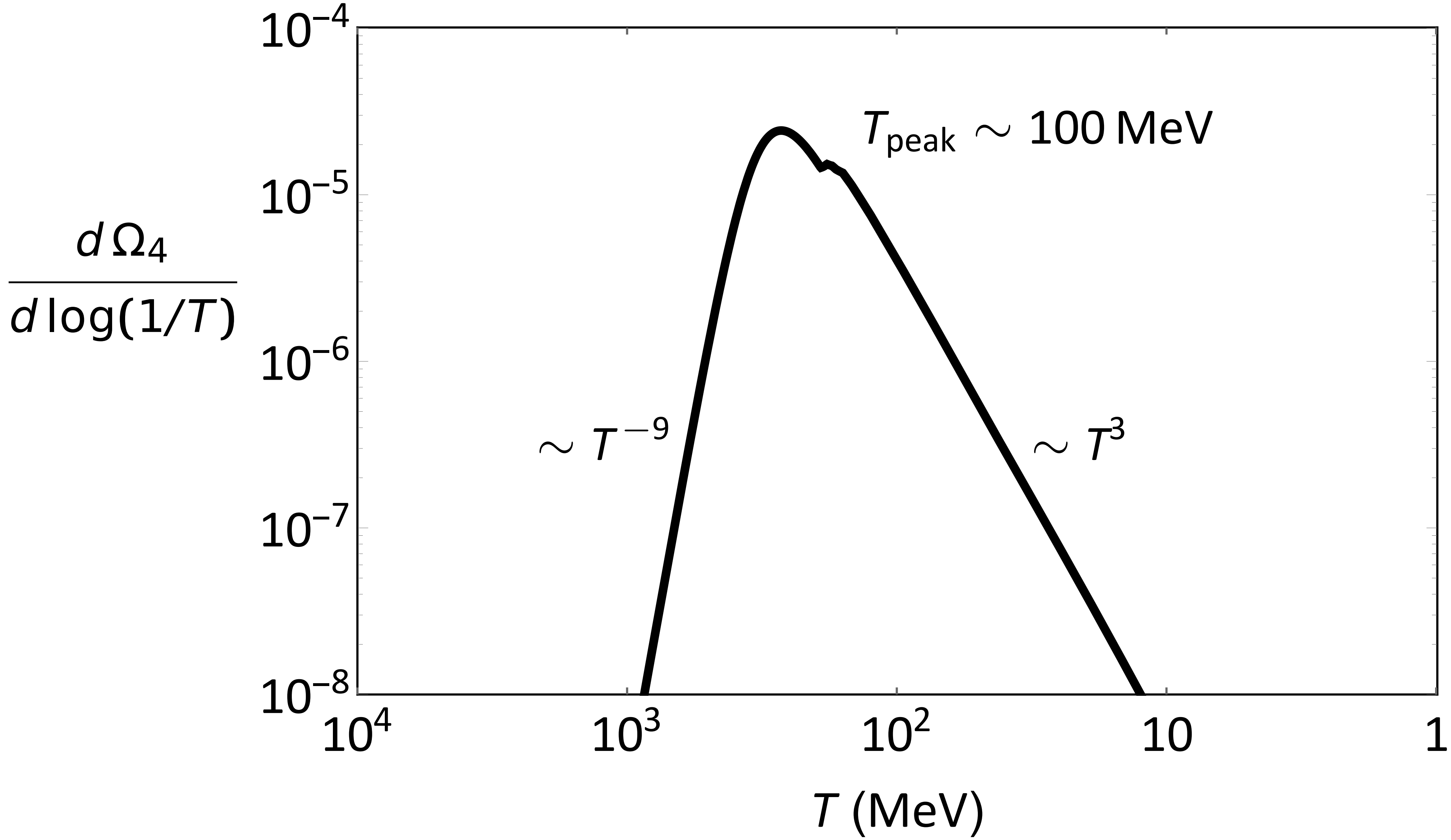
The Key Equation

$$\frac{d f_4}{d\log(1/T)} = \frac{\Gamma}{2H}\, P_{\nu_a \to \nu_4}\, f_a$$

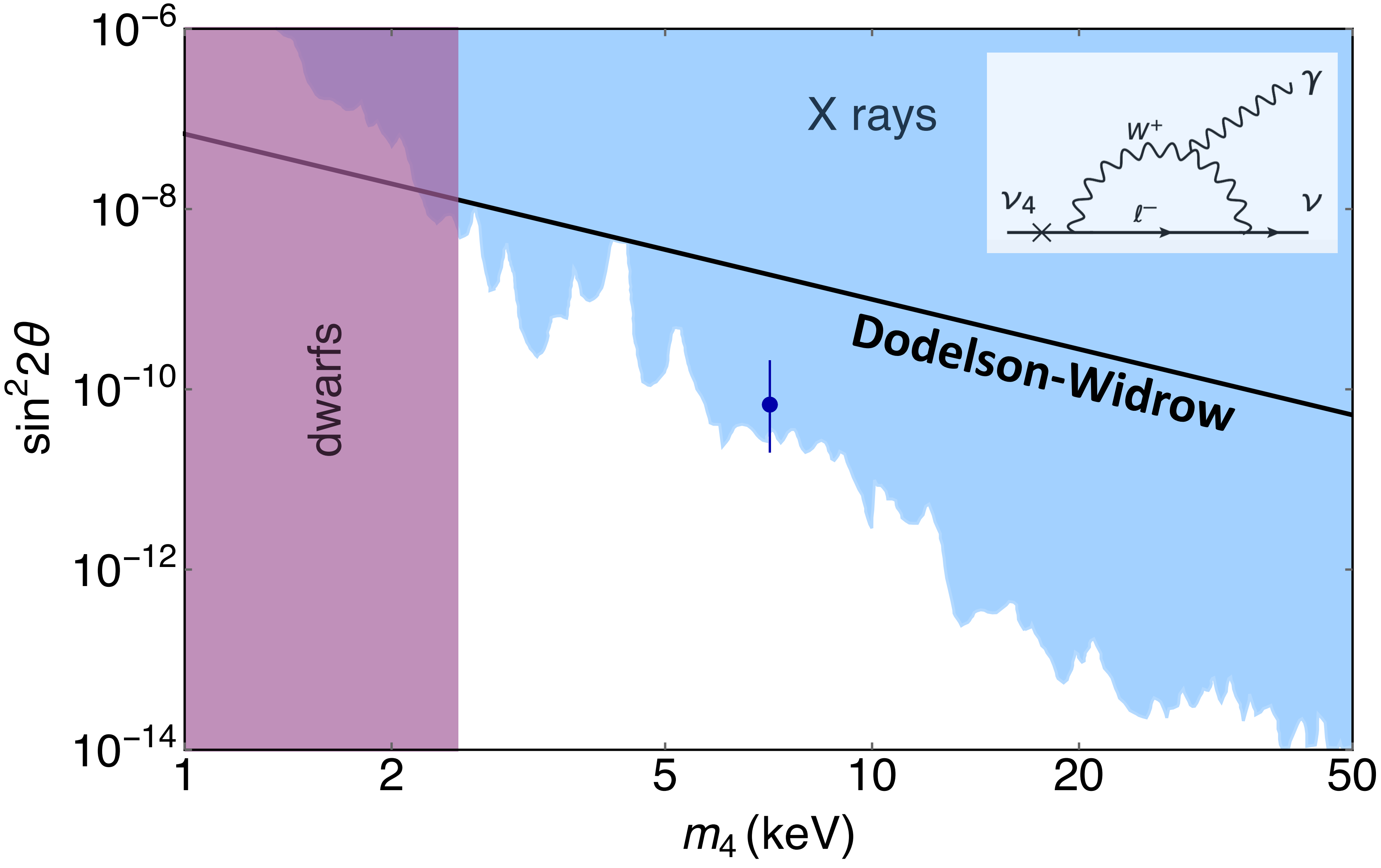
Γ/H : Counts number of cycles for the above process to repeat before neutrino decoupling.

At very high temperature, strong suppression from $1/\Gamma^2$ factor in probability. Dominantly produced around $T \sim 100$ MeV.

Production Time Window



Severely Constrained



Abazajian (1705.01837)

Tantalizing Puzzle

Primordial lepton number asymmetry (Fuller, Shi, astro-ph/9810076)

UV physics that modifies the initial condition (numerous proposals)

Here I am going to discuss a novel approach

- Simple
- Keeps the salient feature of Dodelson-Widrow (IR physics)
- Testable

Simple Idea

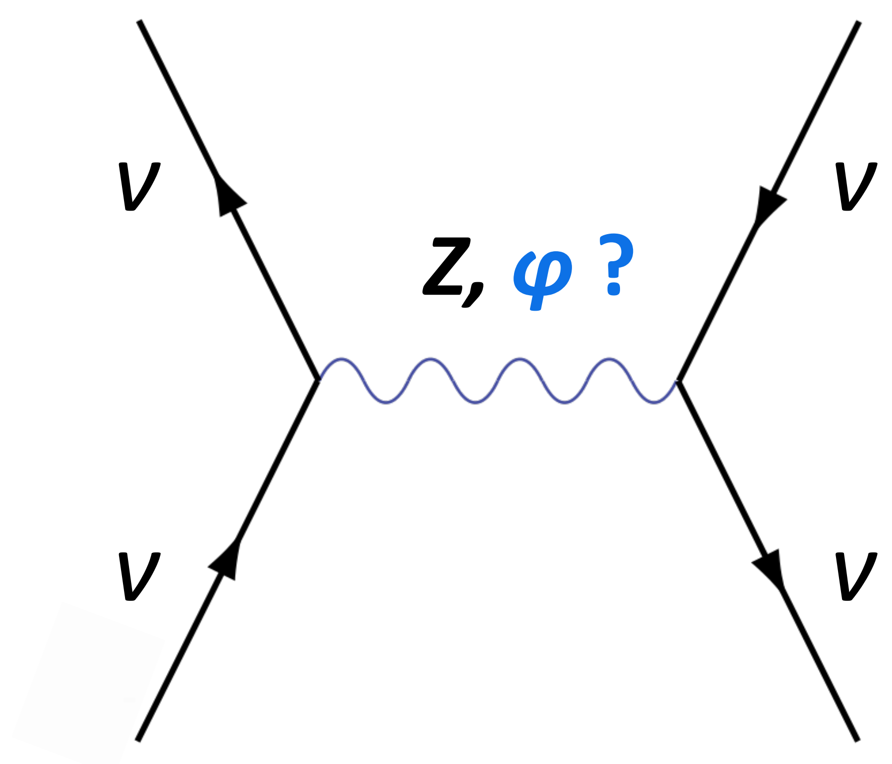
$$\Omega_4[\mathrm{DW}] \sim \Gamma_w \times \sin^2 2\theta$$

Γ_w given by weak interaction; X-ray constrains θ.

Intuition: compensate smaller mixing with larger reaction rate.

BSM neutrino interactions with known particles (e.g. electron, photon) are already tightly constrained.

Neutrino Self Interactions



Never directly measured. Allowed to be much stronger.

Zνν coupling at LEP is an indirect measurement.

Model with Scalar Mediator

Introduce a neutrino-philic scalar field

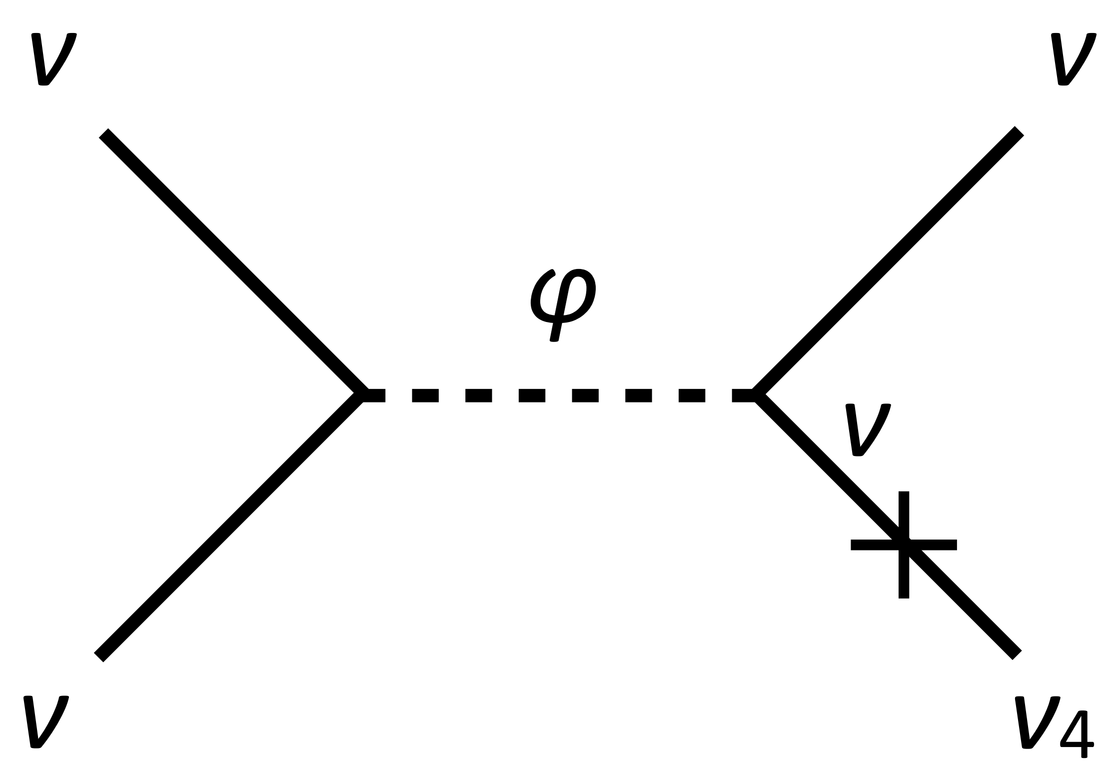
$$\mathcal{L}_{\text{int}} = \lambda \nu \nu \varphi + \text{h.c.}$$

φ is a complex or real scalar, SM singlet, light.

SM gauge invariance is respected if start with $(LH)^2 \varphi / \Lambda^2$.

If φ is the Majoron, coupling is set by neutrino mass divided by spontaneous lepton number breaking scale, $\lambda = M_\nu / F$.

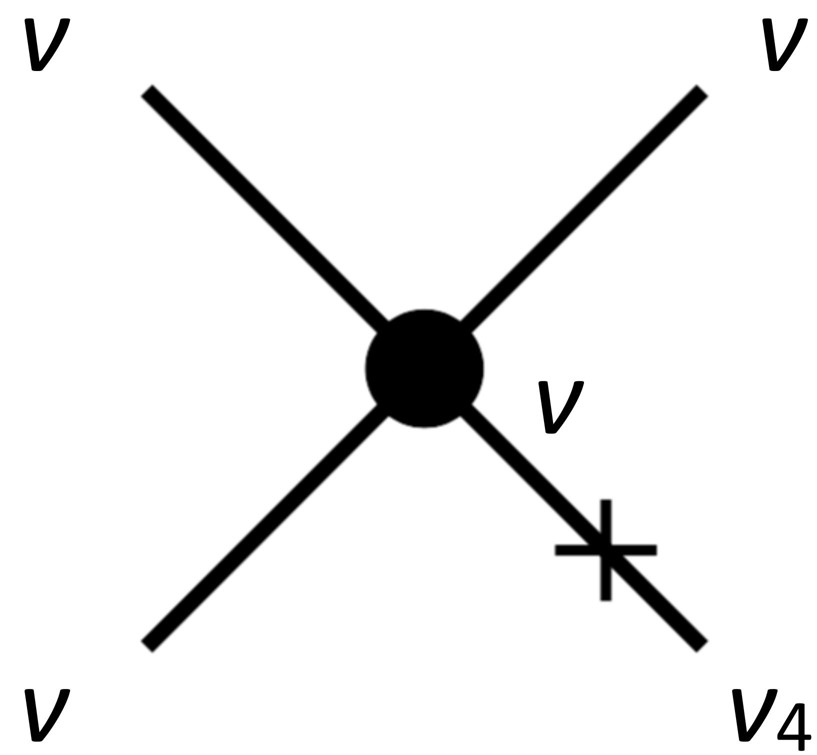
New DM Production Channel



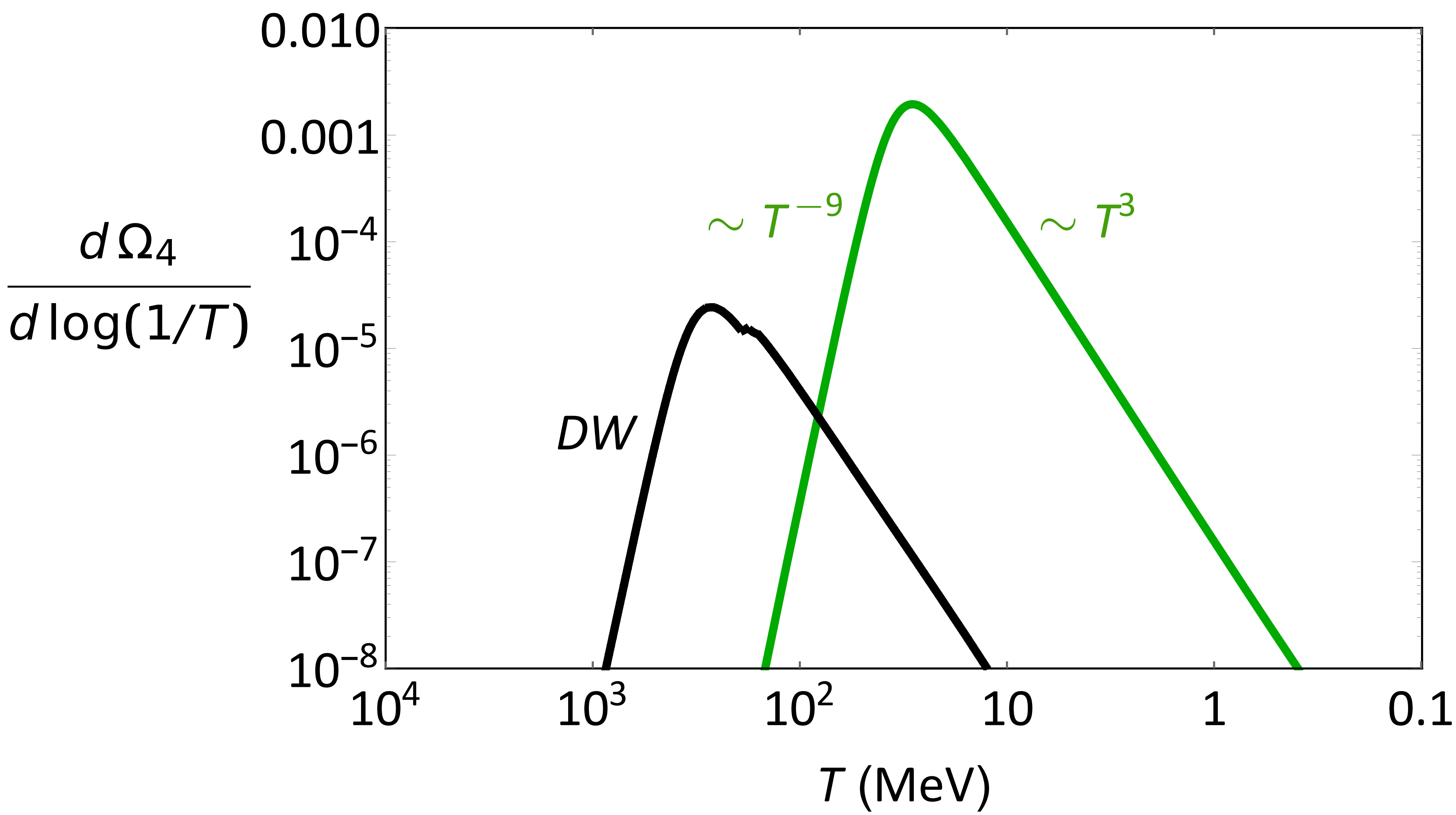
After ν decouples from weak interaction, still talk to themselves.

de Gouvêa, Sen, Tangarife, YZ (1910.04901)

Case of Heavy Mediator

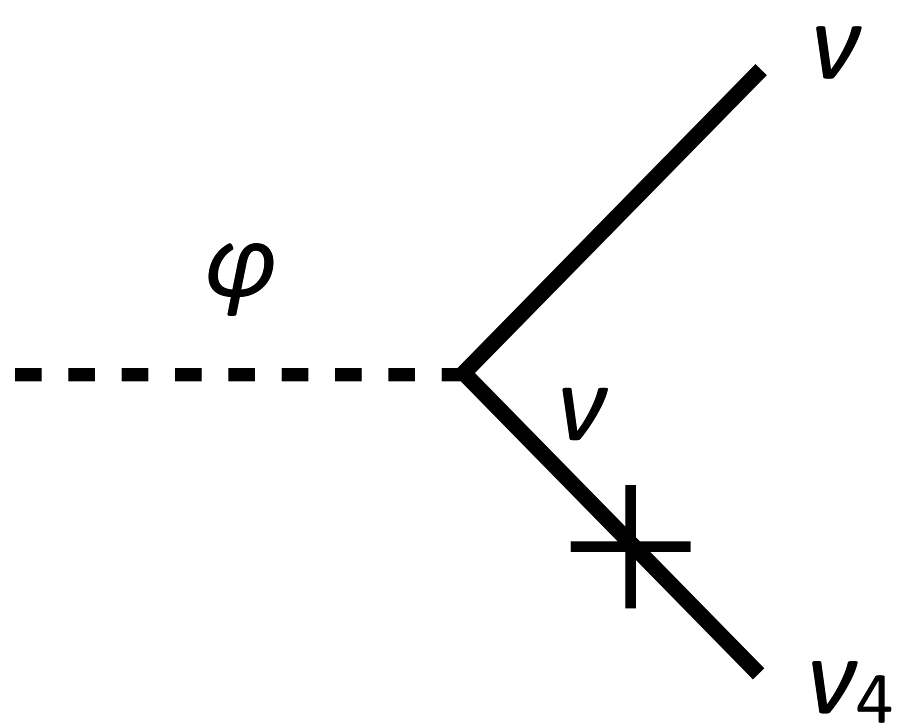


Case of Heavy Mediator



Final relic density: $\Omega_4 \propto \frac{\lambda^3}{m_\varphi^2} \gg \frac{g^3}{M_W^2}$

Case of Light Mediator

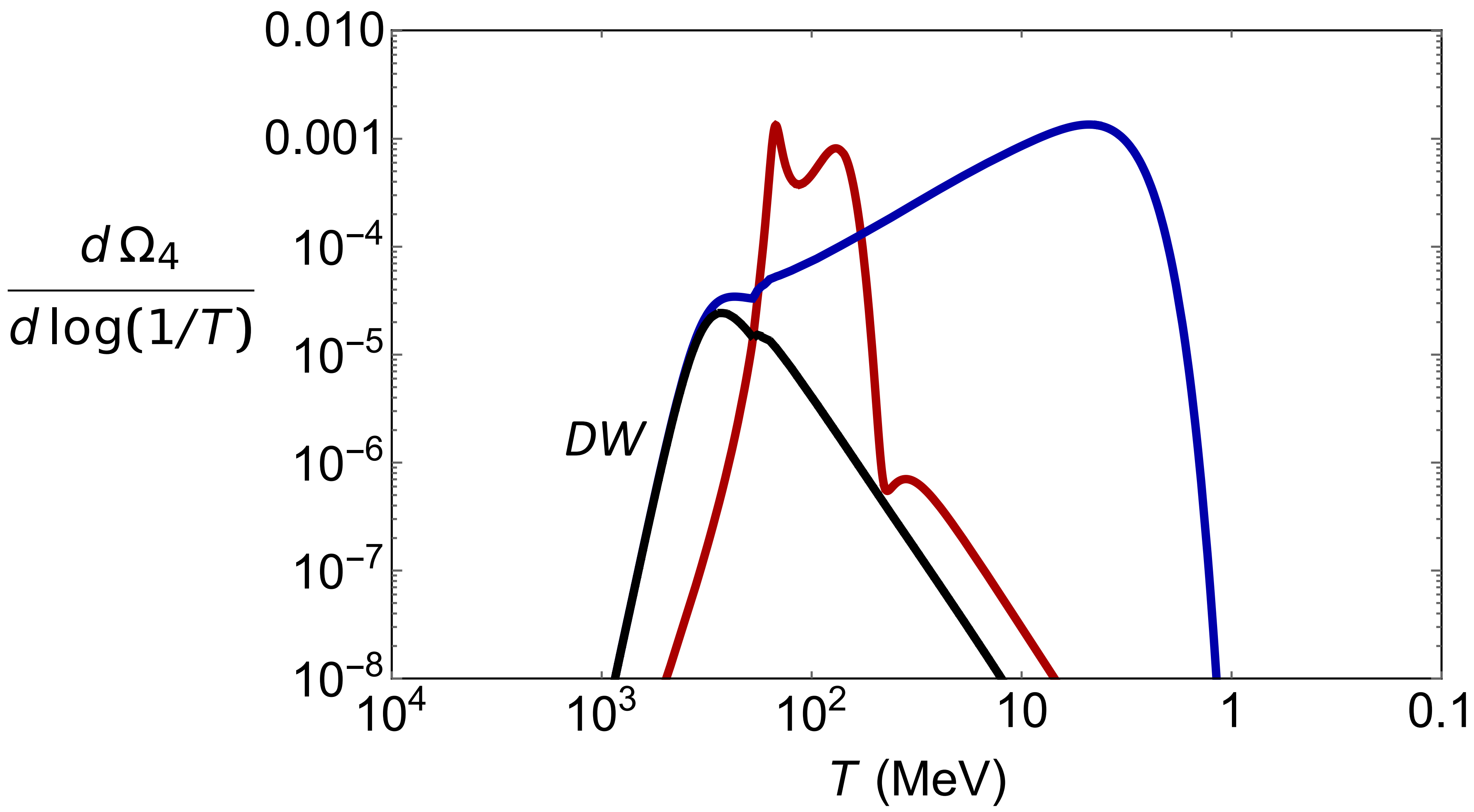


When $T>m_\varphi$, φ exists in thermal bath, decays to ν_4.

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

Opens up new parameter space.

Case of Light Mediator



Light φ with very weak coupling, or moderate coupling.

Three Regimes

As the universe cools: ϑ_{eff} relaxes to vacuum mixing ϑ;

φ eventually becomes heavy.

Three scenarios:

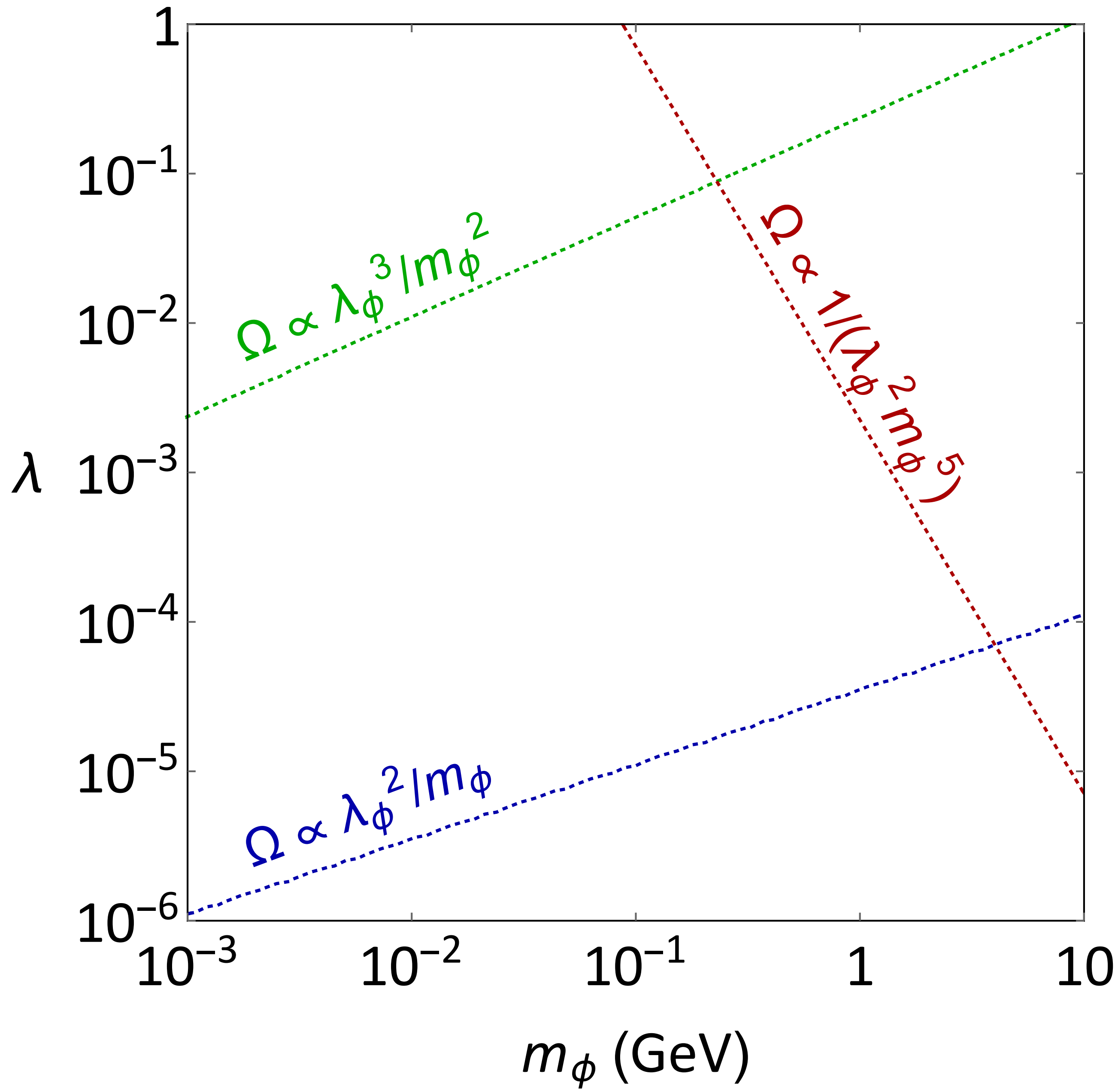
A. Production via $\nu\nu \rightarrow \nu\nu_4$ scattering with heavy φ exchange.

B. Production via light φ decay, $\vartheta_{\text{eff}} \simeq \vartheta$.

C. Production via light φ decay, while ϑ_{eff} still $\ll \vartheta$.

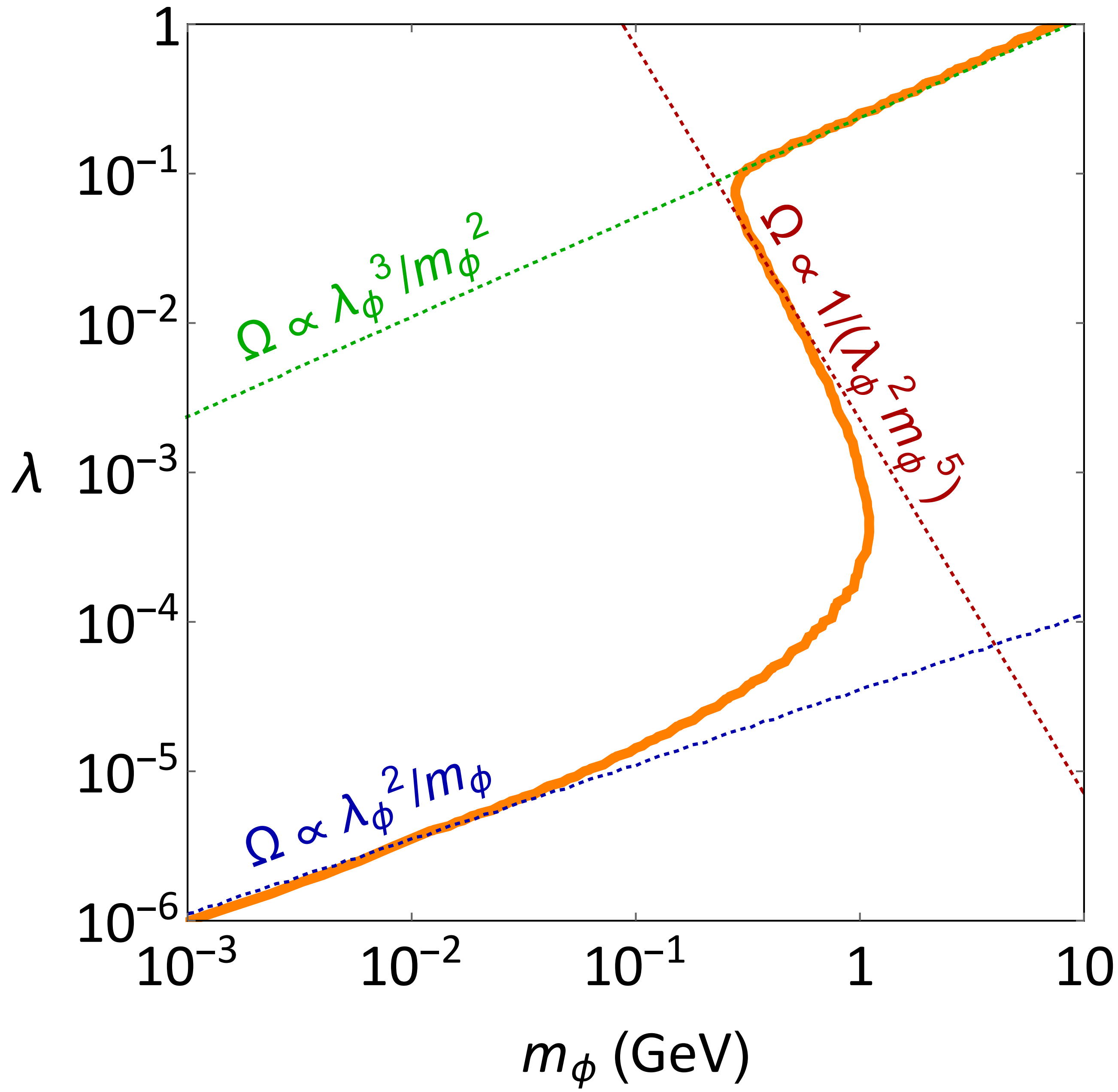
⇨ Lead to distinct parametrical dependences

Three Regimes



de Gouvêa, Sen, Tangarife, YZ (1910.04901)

Numerical Result

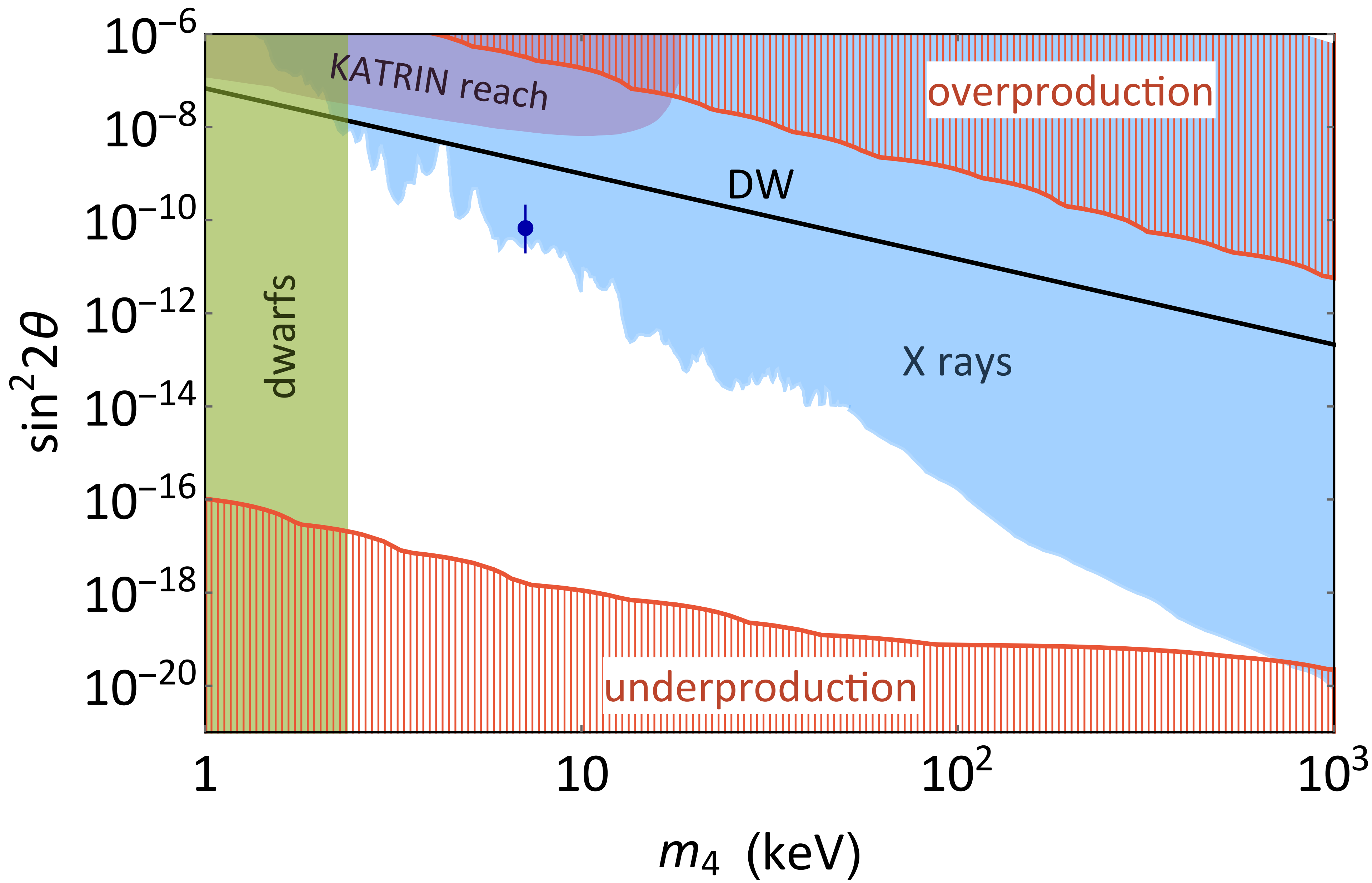


$\sin^2 2\vartheta = 7\times10^{-11}$

m_4=7.1 keV

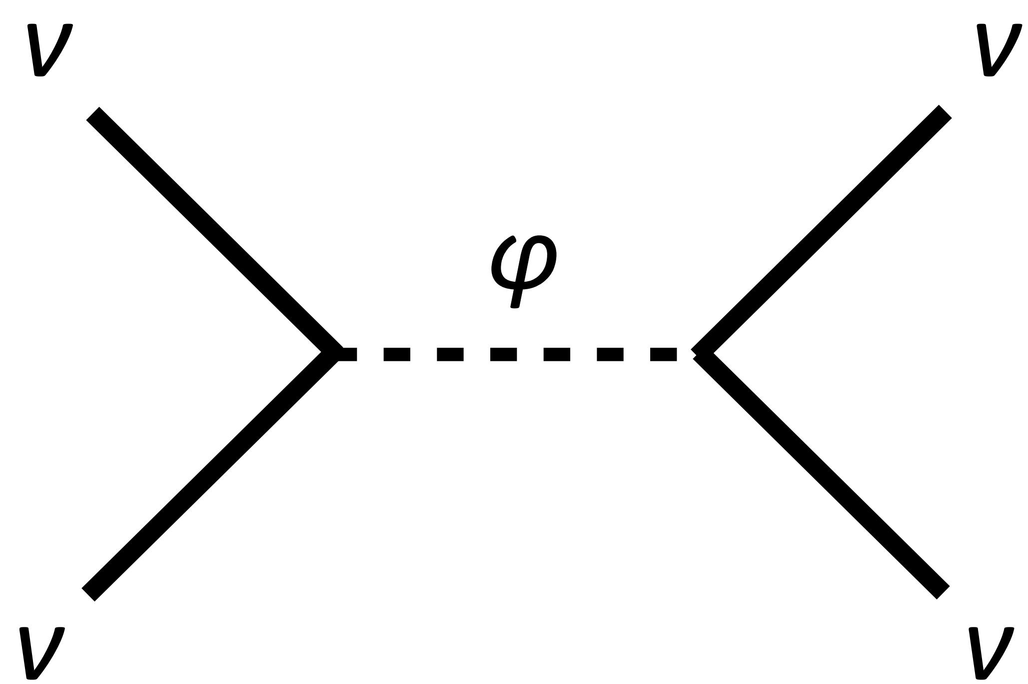
de Gouvêa, Sen, Tangarife, YZ (1910.04901)

Wide Window for Relic Density



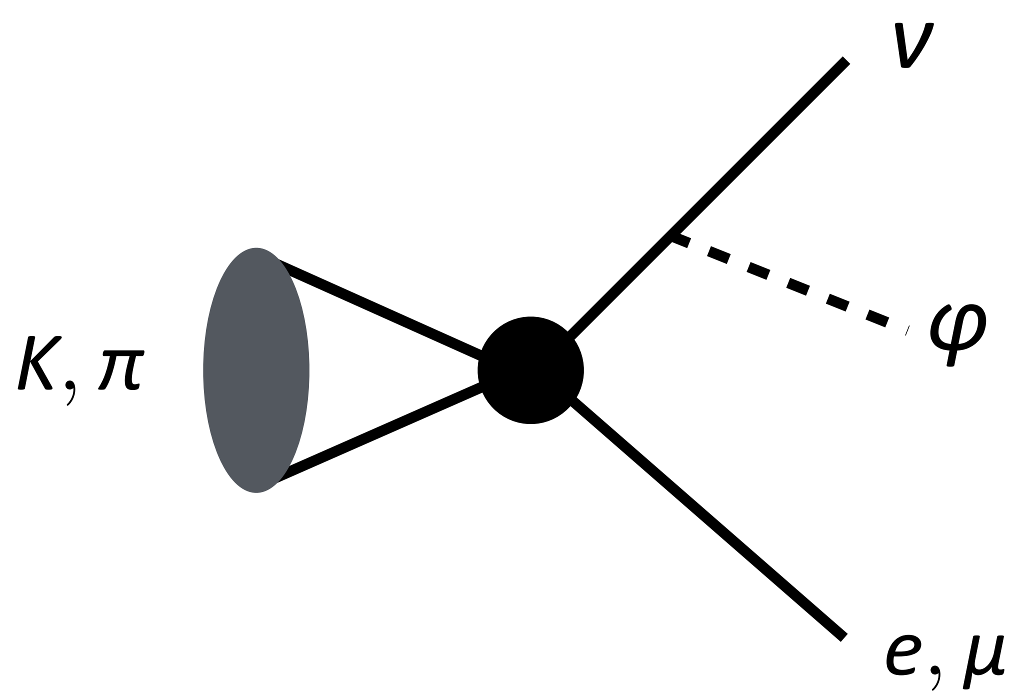
de Gouvêa, Sen, Tangarife, YZ (1910.04901)

Testing the New Interaction



First focus on φ mass between MeV and weak scale.

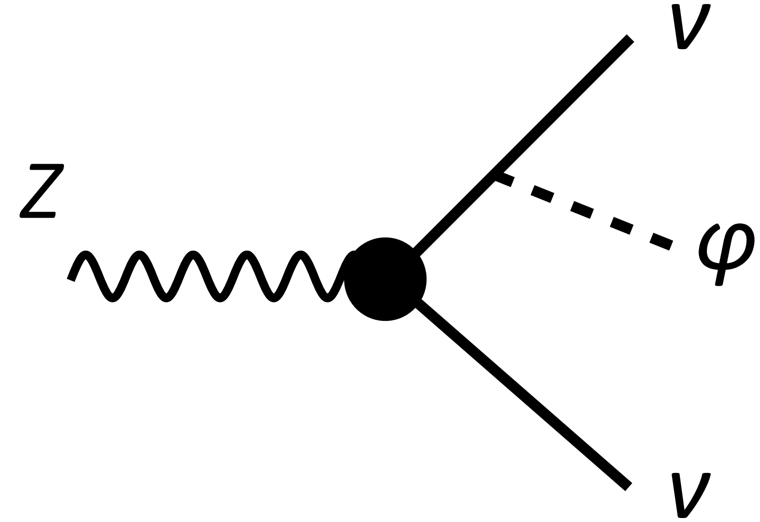
Charged Meson Decays

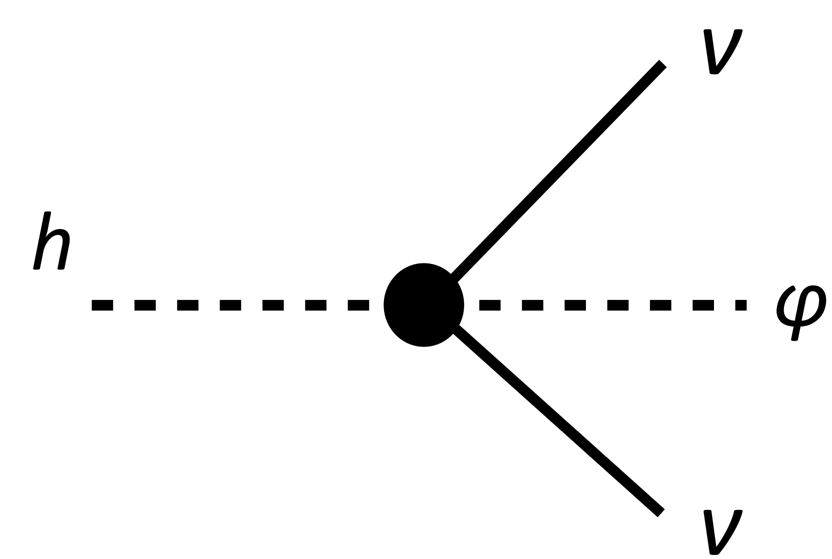


Distort energy of charged lepton, remove helicity suppression

Barger, Keung, Pakvasa (PRD 1982)
Pasquini, Perez (1511.01811)

Higgs and Z Invisible Decay

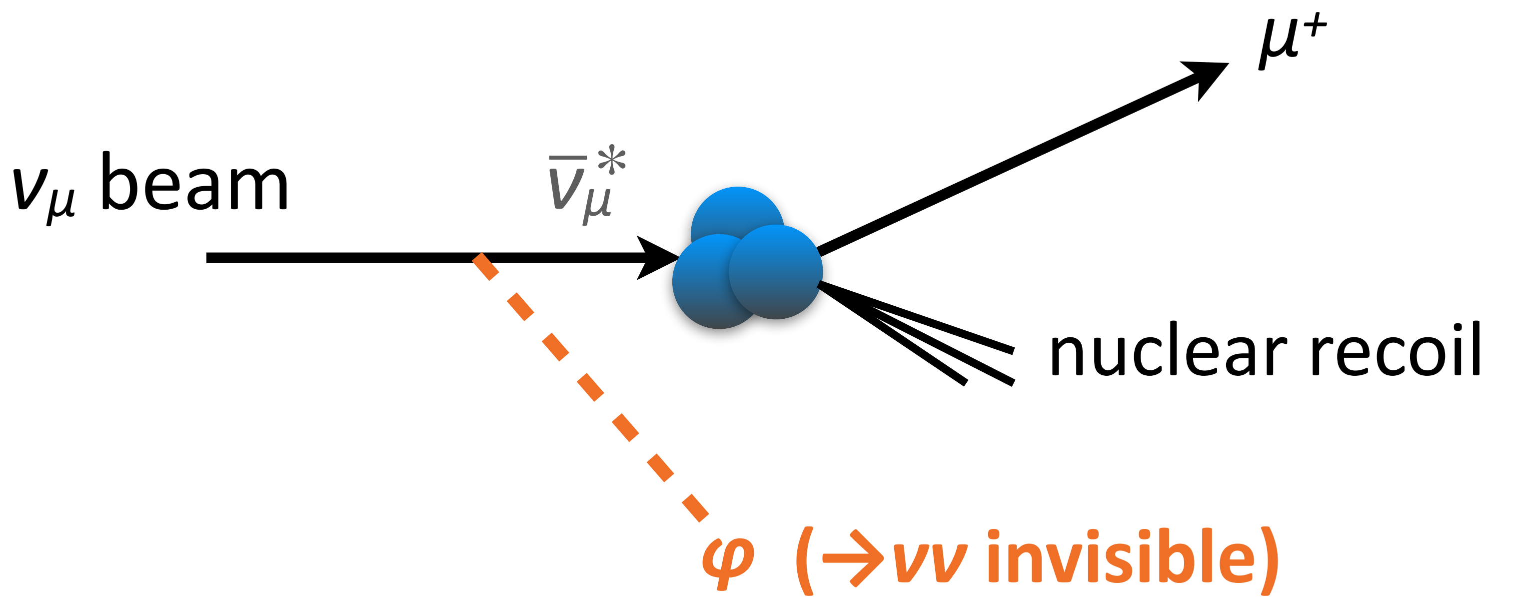




Starting from the gauge invariant operator $(LH)^2\varphi/\Lambda^2$

Brdar, Lindner, Vogl, Xu (2003.05339)
Berryman, de Gouvêa, Kelly, YZ (1802.00009)

Mono-Neutrino Signal



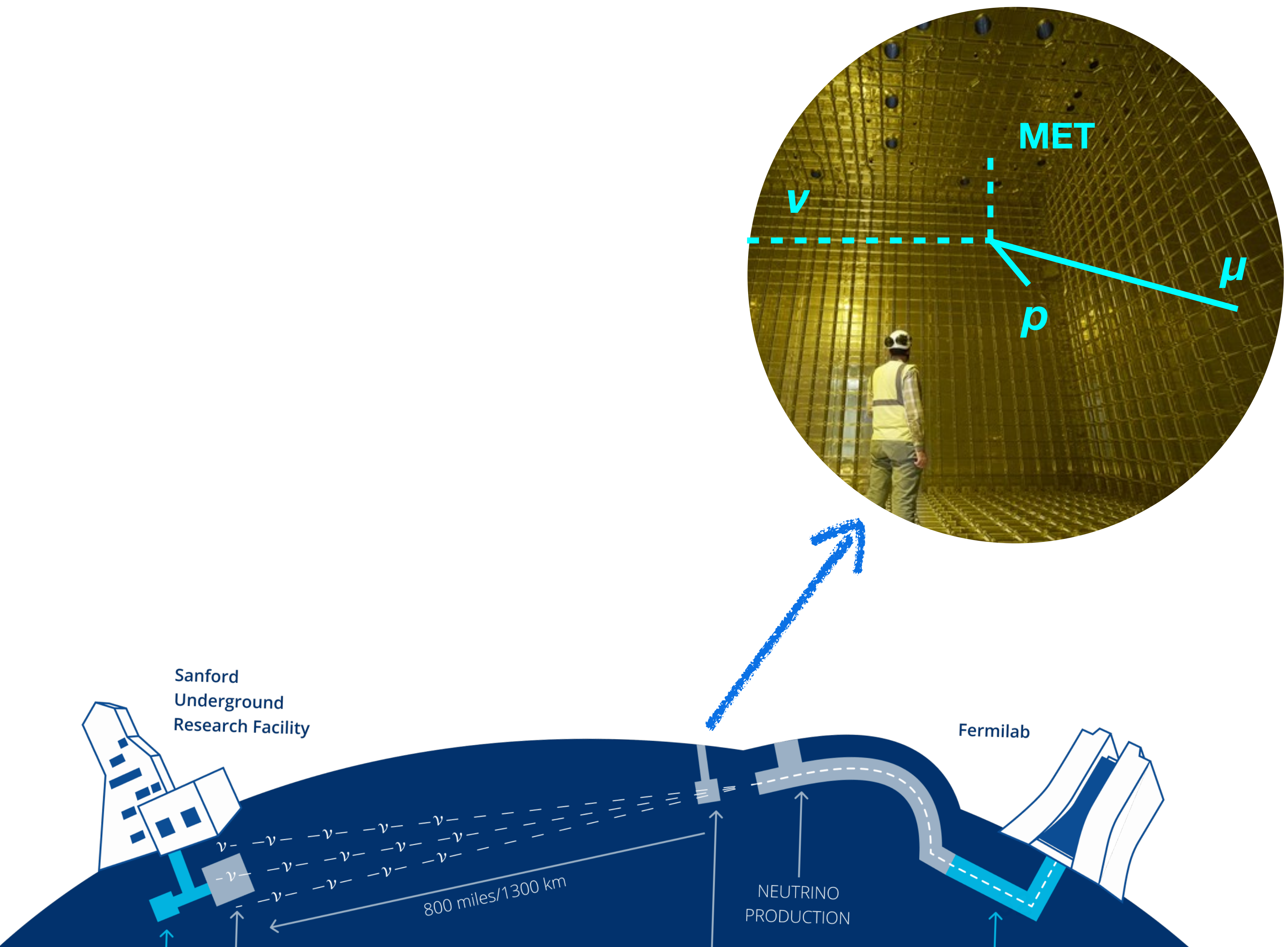
Beamstrahlung process: $\nu_\mu + N \to \mu^+ + N' + \varphi$, features

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

Kelly, YZ (1901.01259)

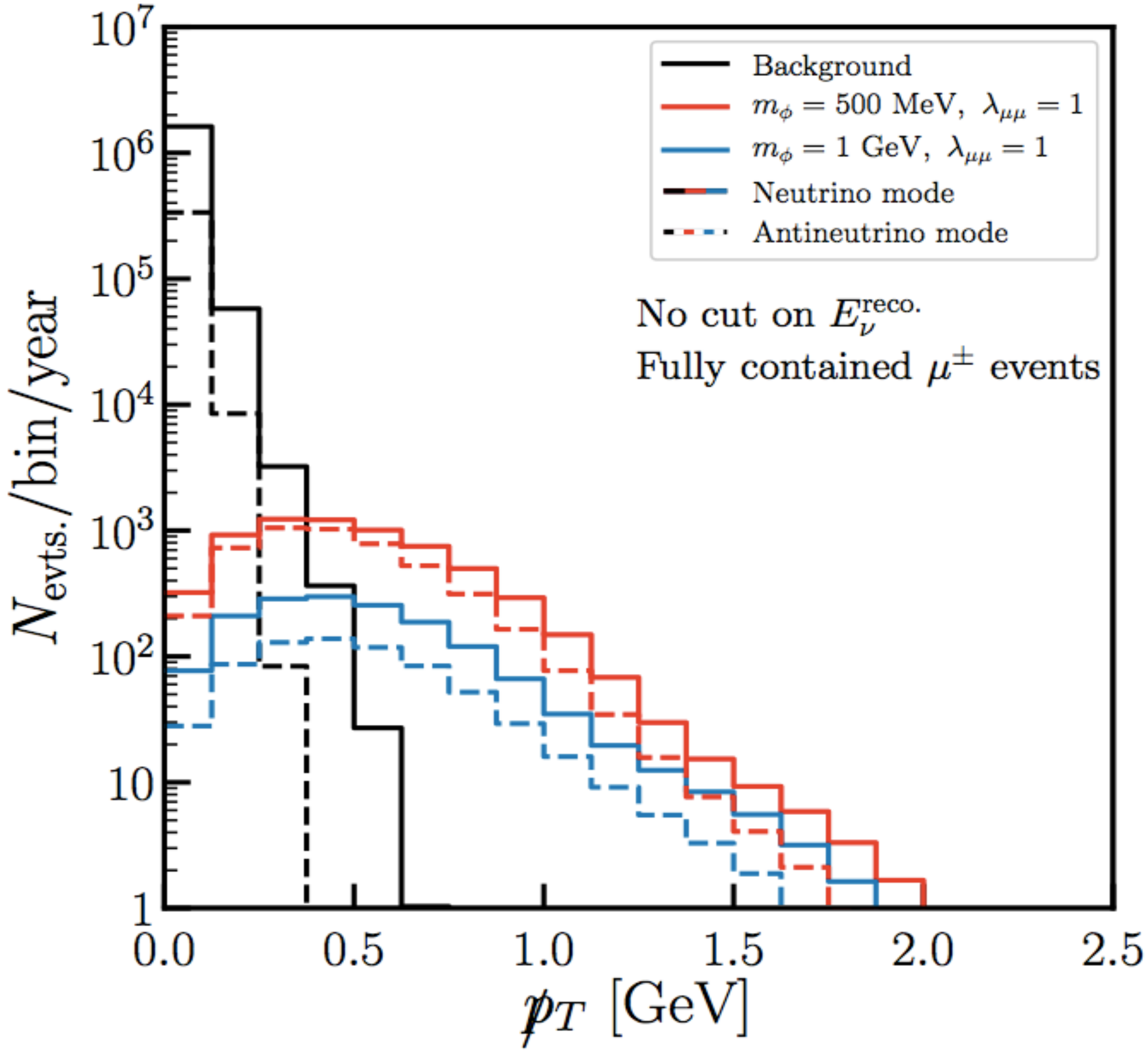
DUNE

Hunt events with large missing transverse momentum, using liquid argon detectors with excellent particle ID and energy resolution.



(Near detector)

Theorists' Simulation



$p_T \sim \sqrt{s} > \Lambda_{QCD}$

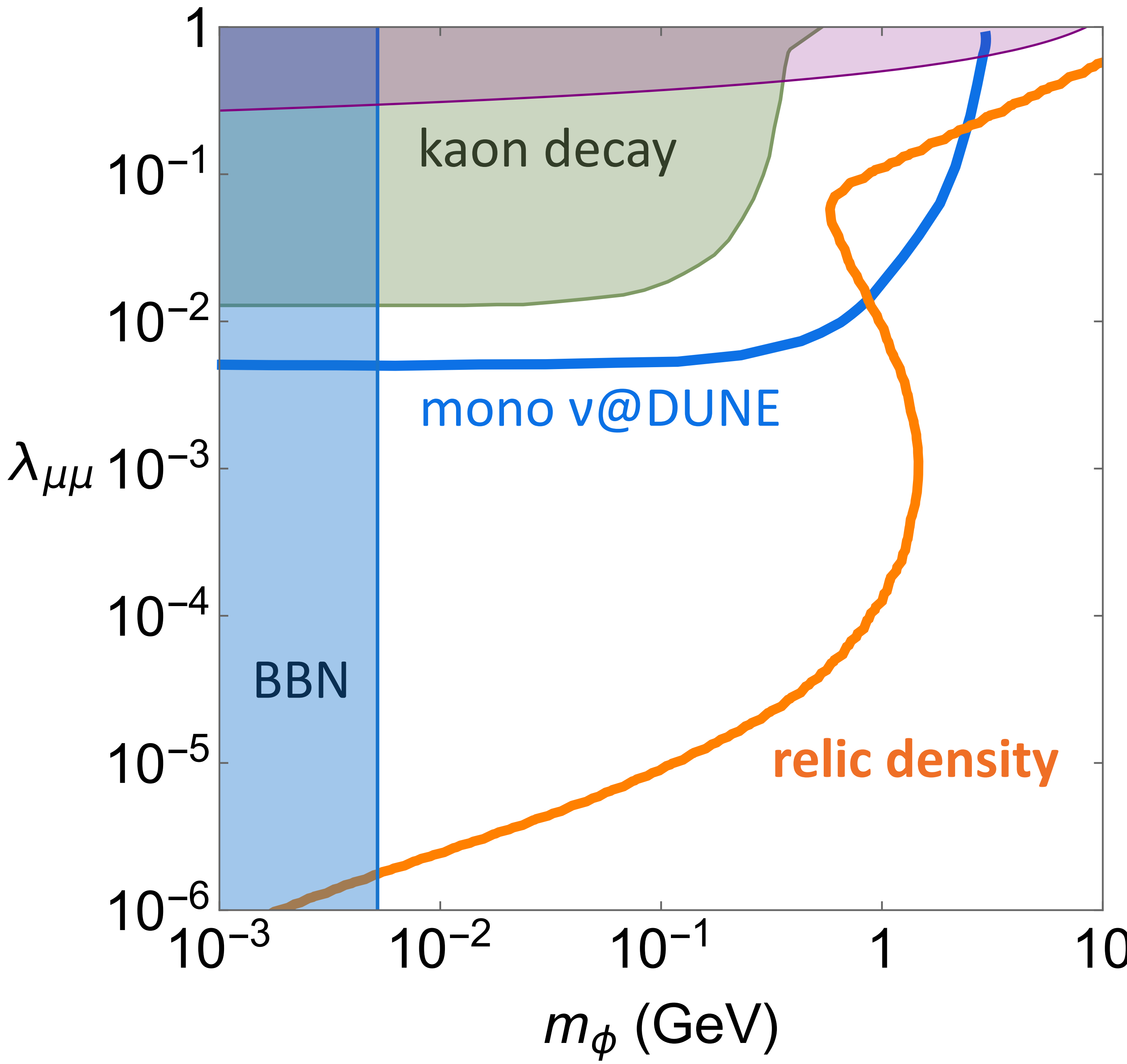
Kelly, YZ (1901.01259)

Nucleon level simulation, smearing

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

DUNE CDR (2015)

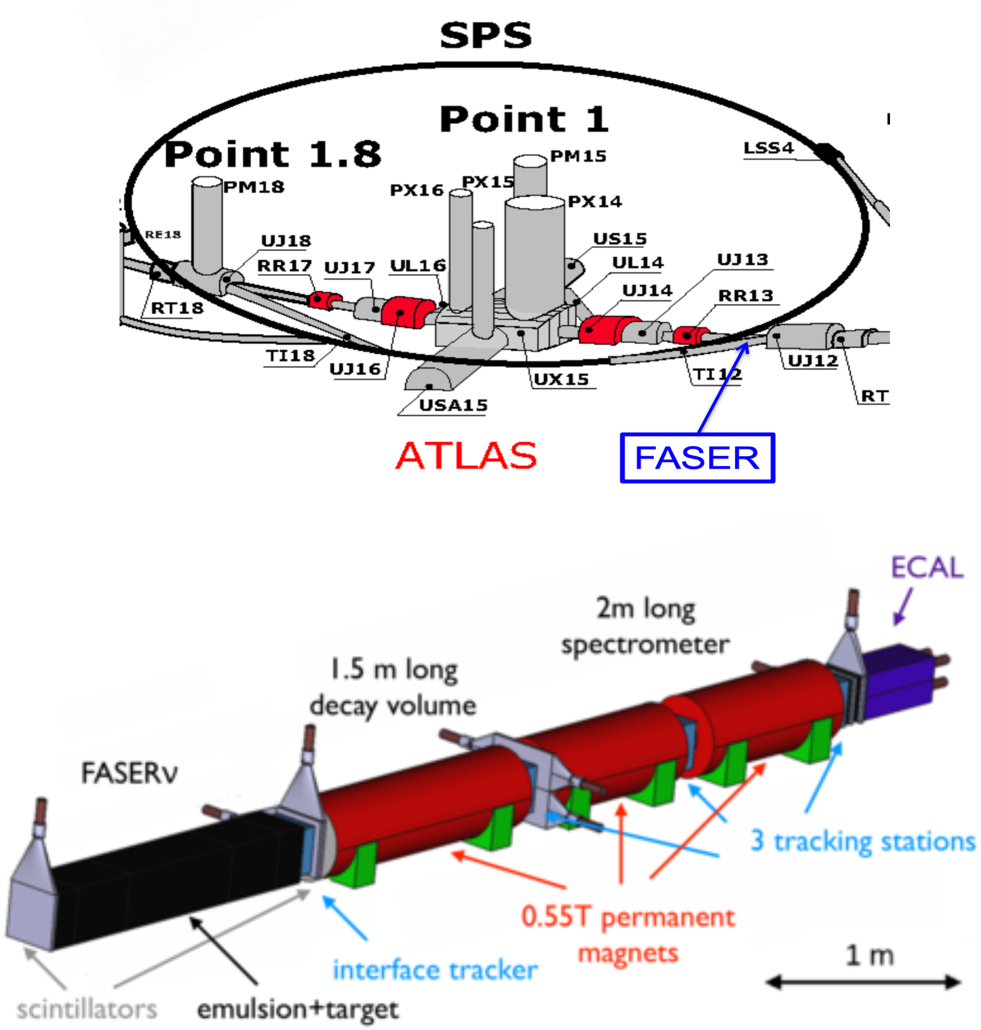
Coverage

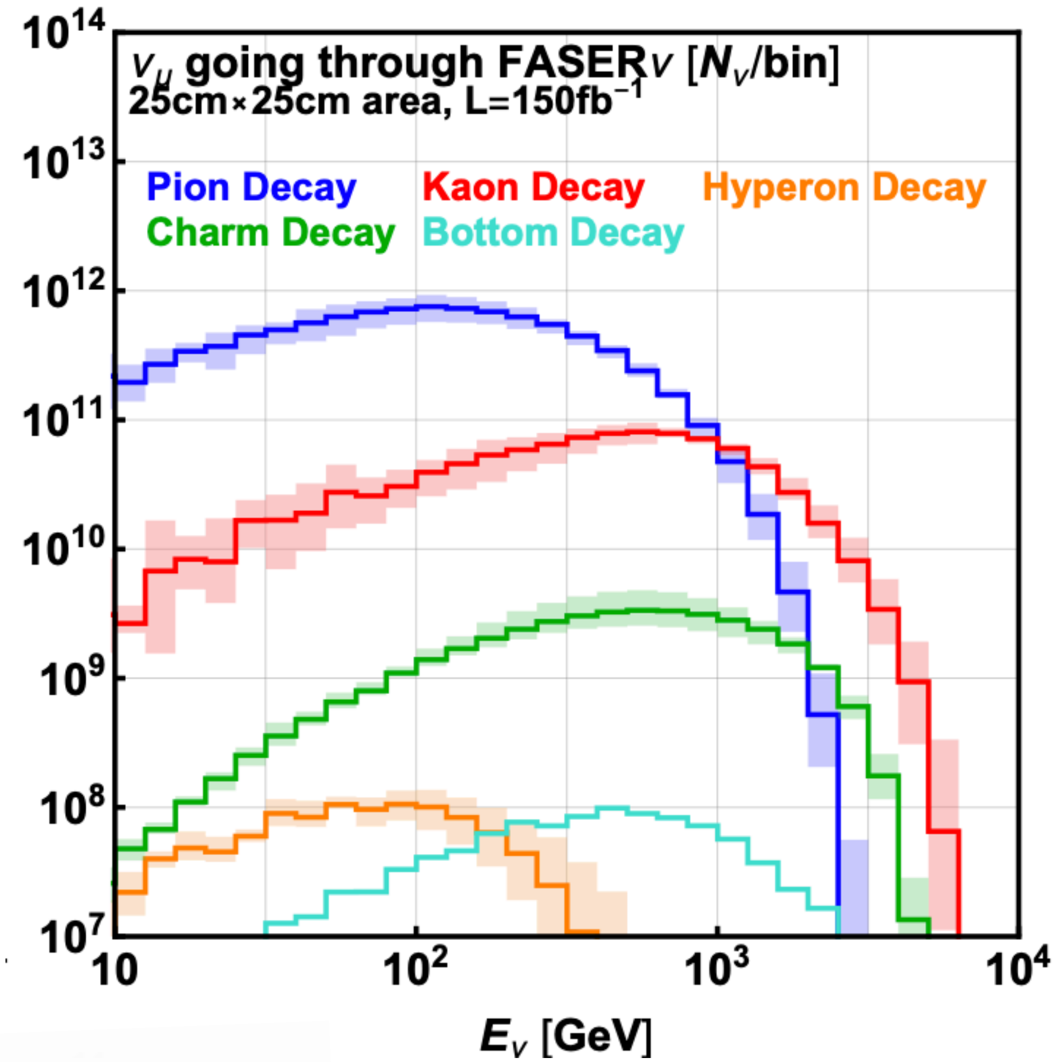


Kelly, YZ (1901.01259)

FASERν

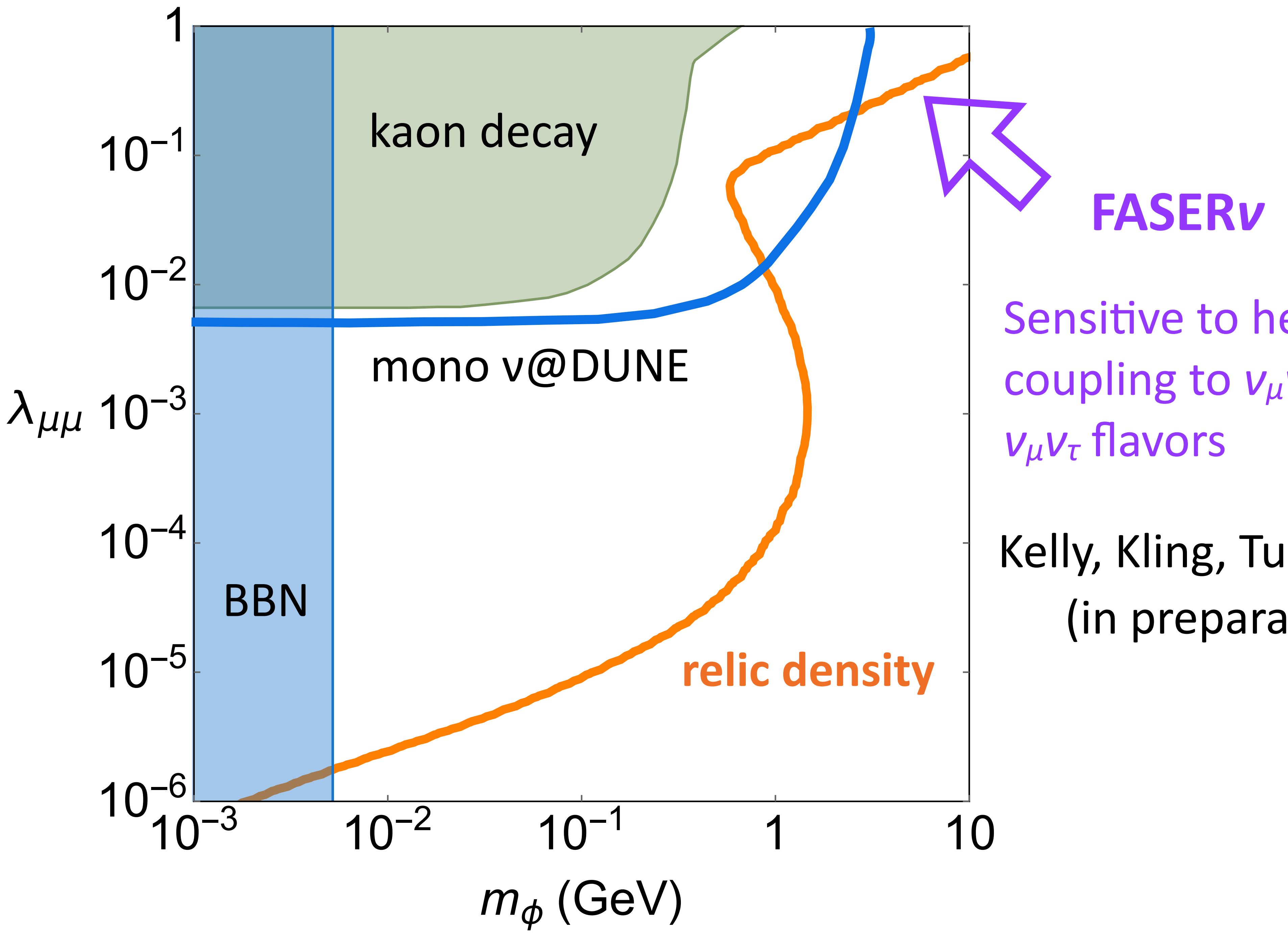
LHC delivers a high energy neutrino beam ($E_\nu \sim 100\,\mathrm{GeV}$) in the forward regions, less hadronic uncertainty.





FASER collaboration (1908.02310)

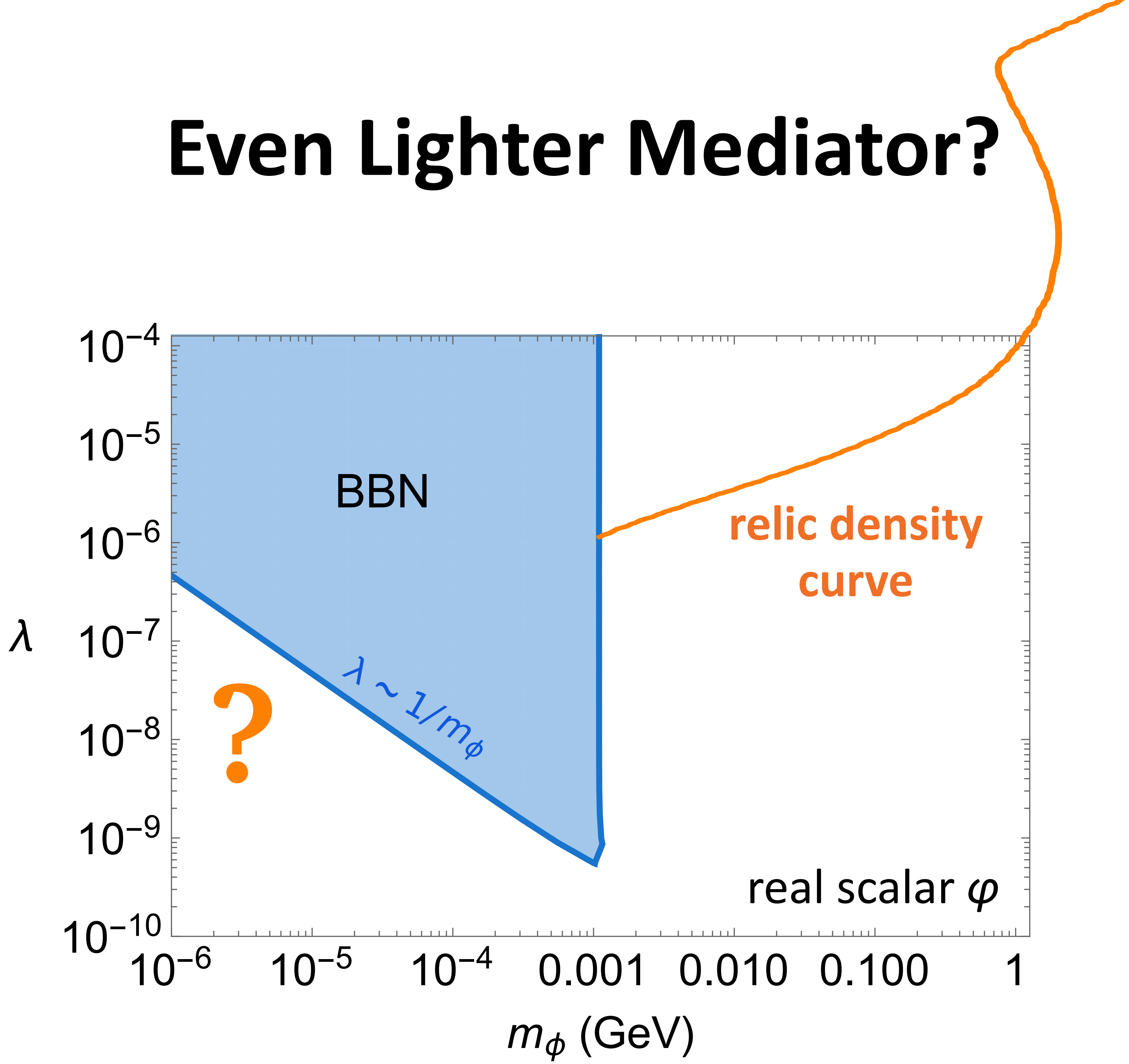
Coverage



Sensitive to heavier φ coupling to $\nu_\mu \nu_\mu$ and $\nu_\mu \nu_\tau$ flavors

Kelly, Kling, Tuckler, YZ (in preparation)

Even Lighter Mediator?



The wall of BBN constraint is not infinitely thick, $\Delta N_{\rm eff}^{\rm BBN} \lesssim 0.5\,.$

φ-ν Cosmology

The mediator φ has no abundance at very high temperatures, slowly freezes in. Fully thermalizes after BBN, with ν.

Kelly, Sen, YZ (2011.02487)

φ-ν Cosmology

The mediator φ has no abundance at very high temperatures, slowly freezes in. Fully thermalizes after BBN, with ν.

Once φ reaches equilibrium, previously discussed DM production mechanism (case B) applies, $\nu\nu \to$ on-shell $\varphi \to \nu\nu_4$

Kelly, Sen, YZ (2011.02487)

φ-ν Cosmology

The mediator φ has no abundance at very high temperatures, slowly freezes in. Fully thermalizes after BBN, with ν.

Once φ reaches equilibrium, previously discussed DM production mechanism (case B) applies, $\nu\nu \to$ on-shell $\varphi \to \nu\nu_4$

Kinematically, we need $m_\varphi > m_{\nu 4} >$ keV. Lower bound on m_φ .

Kelly, Sen, YZ (2011.02487)

φ-ν Cosmology

The mediator φ has no abundance at very high temperatures, slowly freezes in. Fully thermalizes after BBN, with ν.

Once φ reaches equilibrium, previously discussed DM production mechanism (case B) applies, $\nu\nu \rightarrow$ on-shell $\varphi \rightarrow \nu\nu_4$

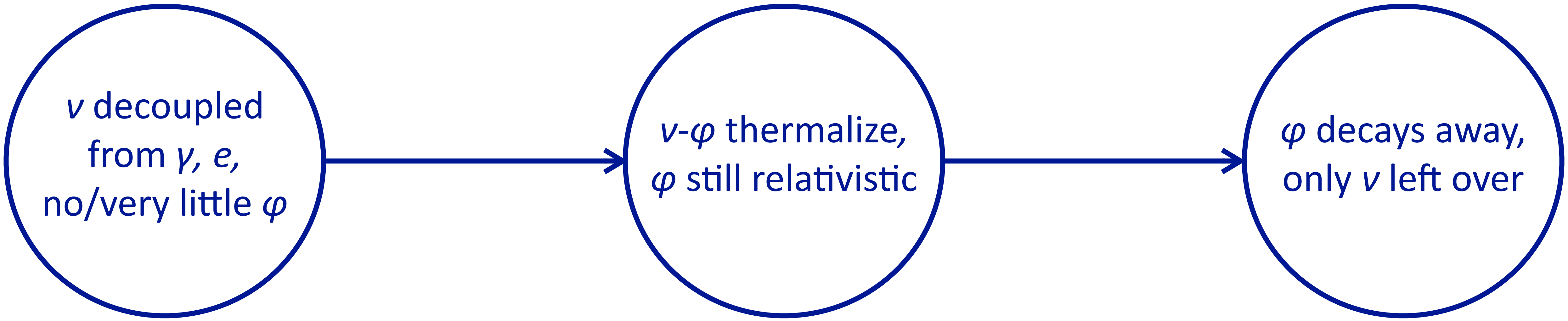
Kinematically, we need $m_\varphi > m_{\nu 4} >$ keV. Lower bound on m_φ .

φ decays away back to neutrinos when $T \ll m_\varphi$, well before CMB.

Kelly, Sen, YZ (2011.02487)

ΔN_{eff} at CMB

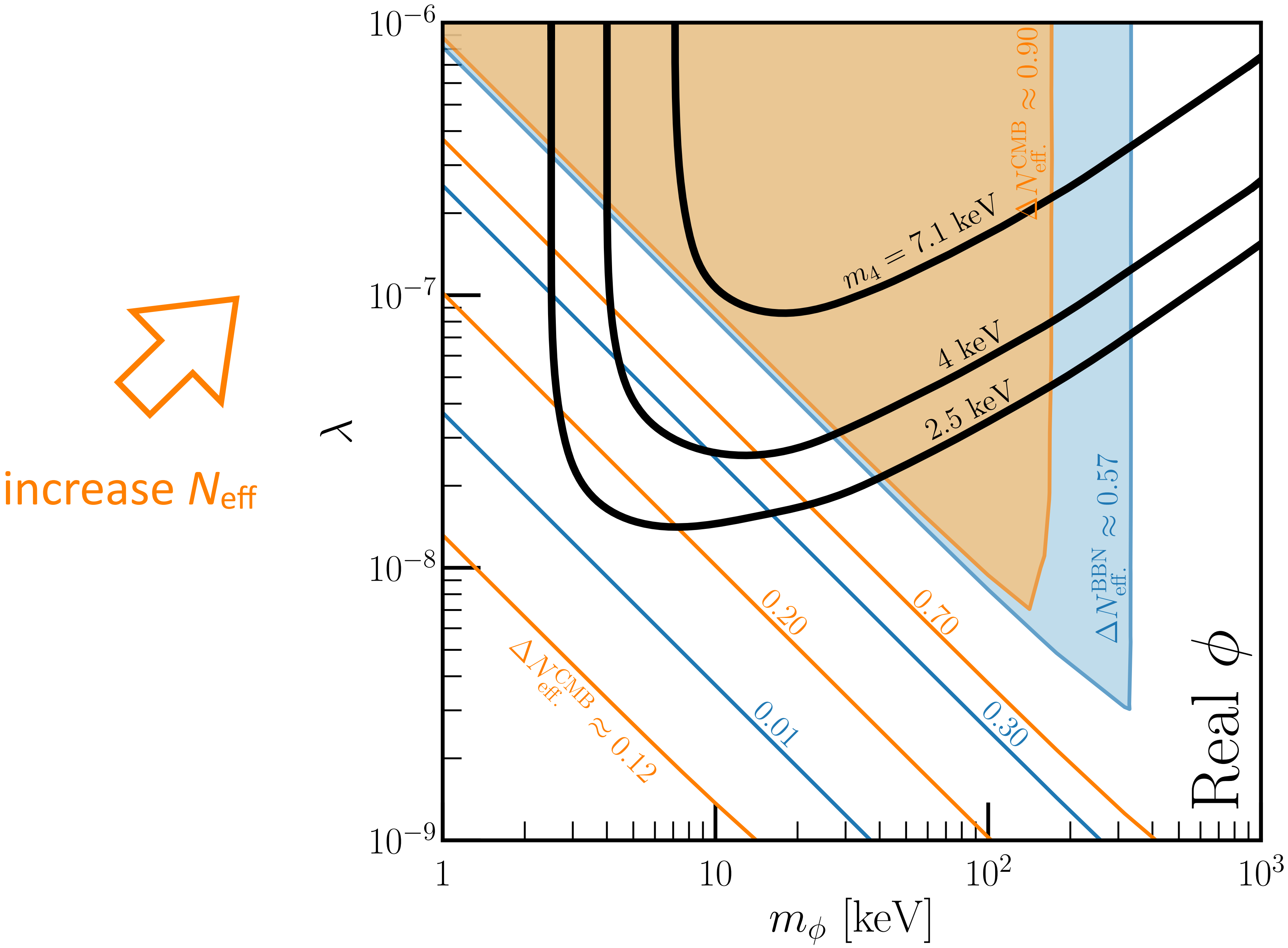
Thermal distribution of active neutrinos is nonstandard in the presence of the φ-ν interaction.



energy conserved,
entropy increases

entropy conserved,
energy increases

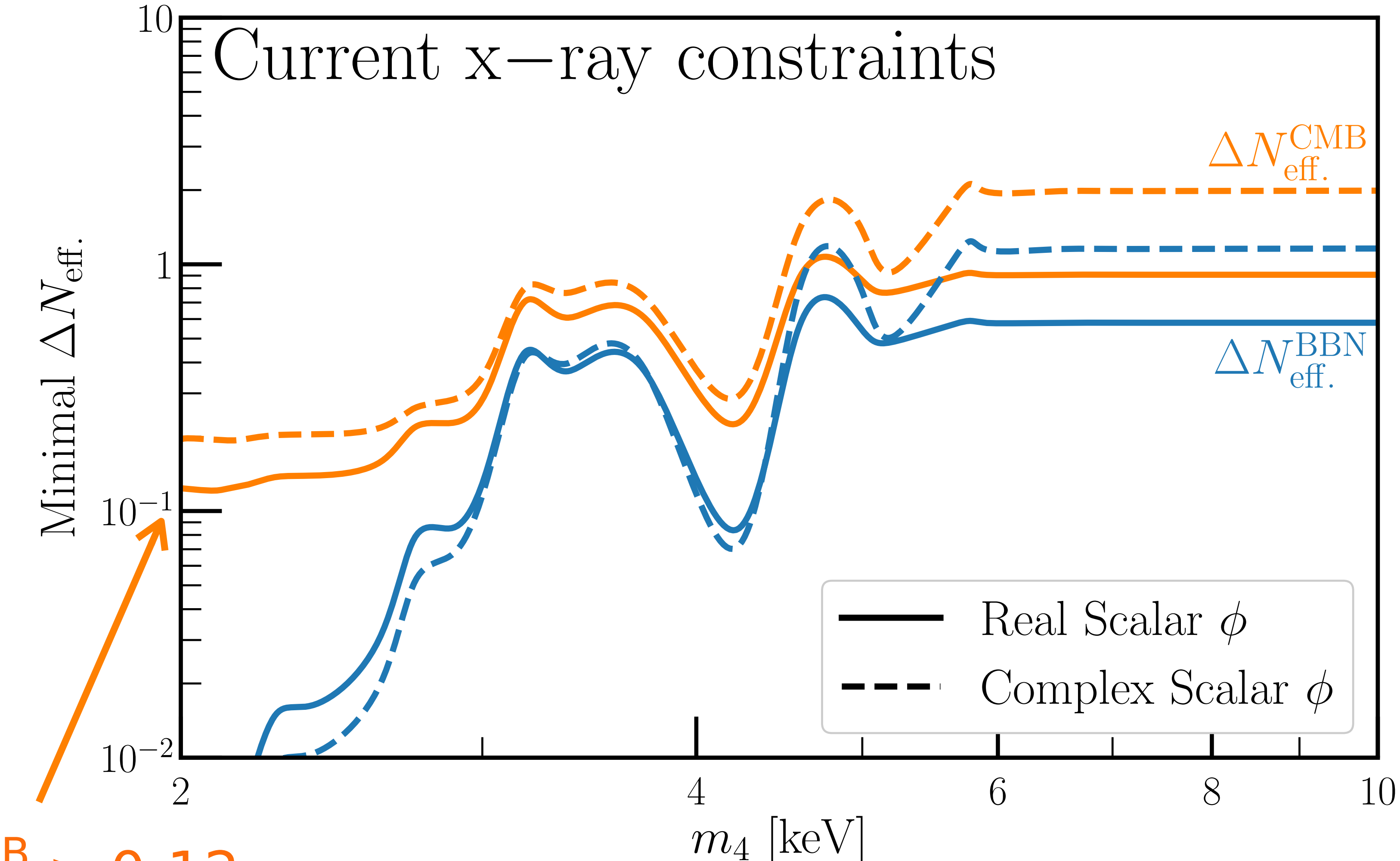
Lower Bound on ΔN_{eff}



For each mass, chose the largest experimentally allowed ϑ.

Kelly, Sen, YZ (2011.02487)

Indirect Detection and ΔN_{eff}

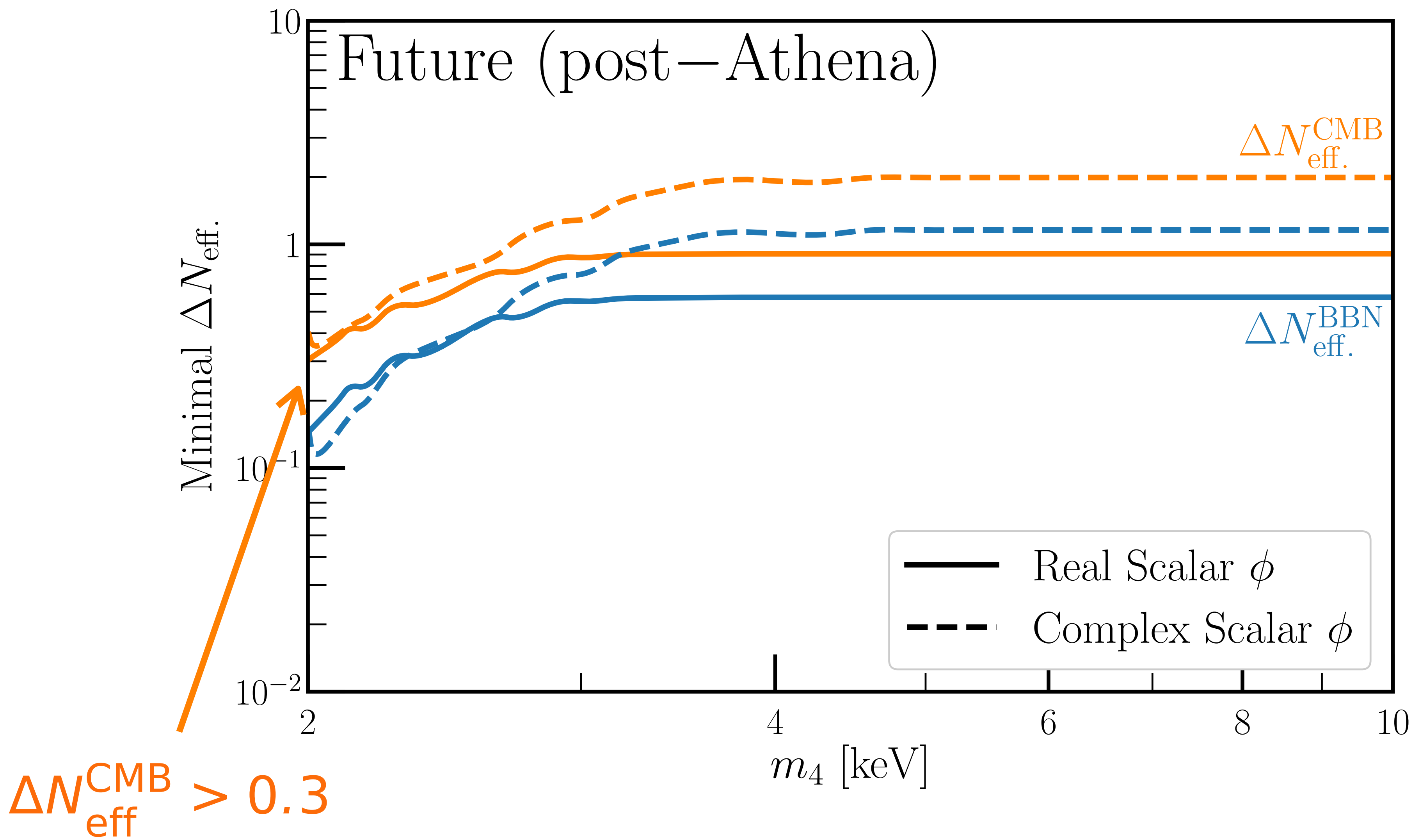


well-motivated target for CMB-S4

$\Delta N_{eff}^{CMB} > 0.12$

Kelly, Sen, YZ (2011.02487)

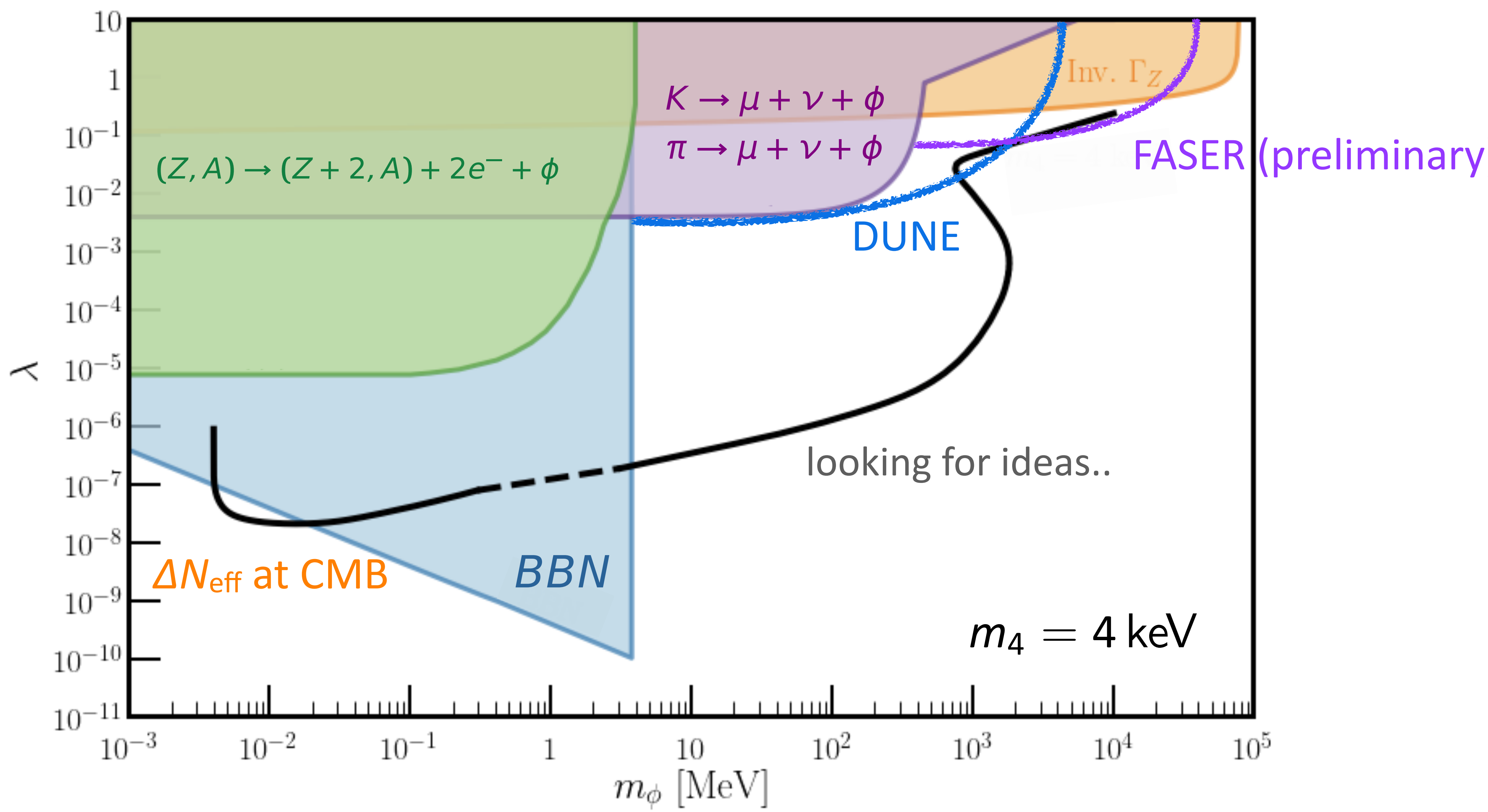
Indirect Detection and ΔN_{eff}



well-motivated target for CMB-S4

Kelly, Sen, YZ (2011.02487)

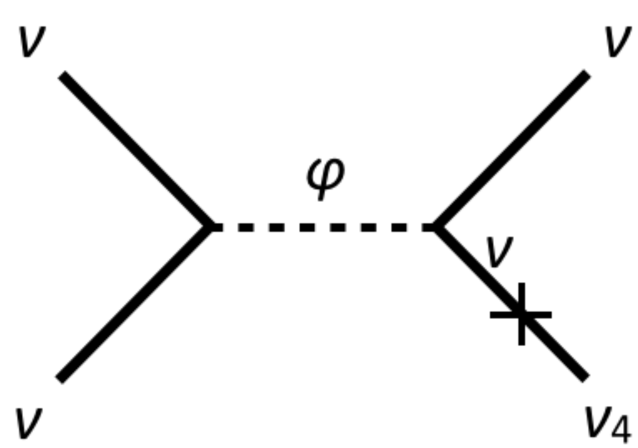
The Big Picture



Kelly, Sen, YZ (2011.02487)

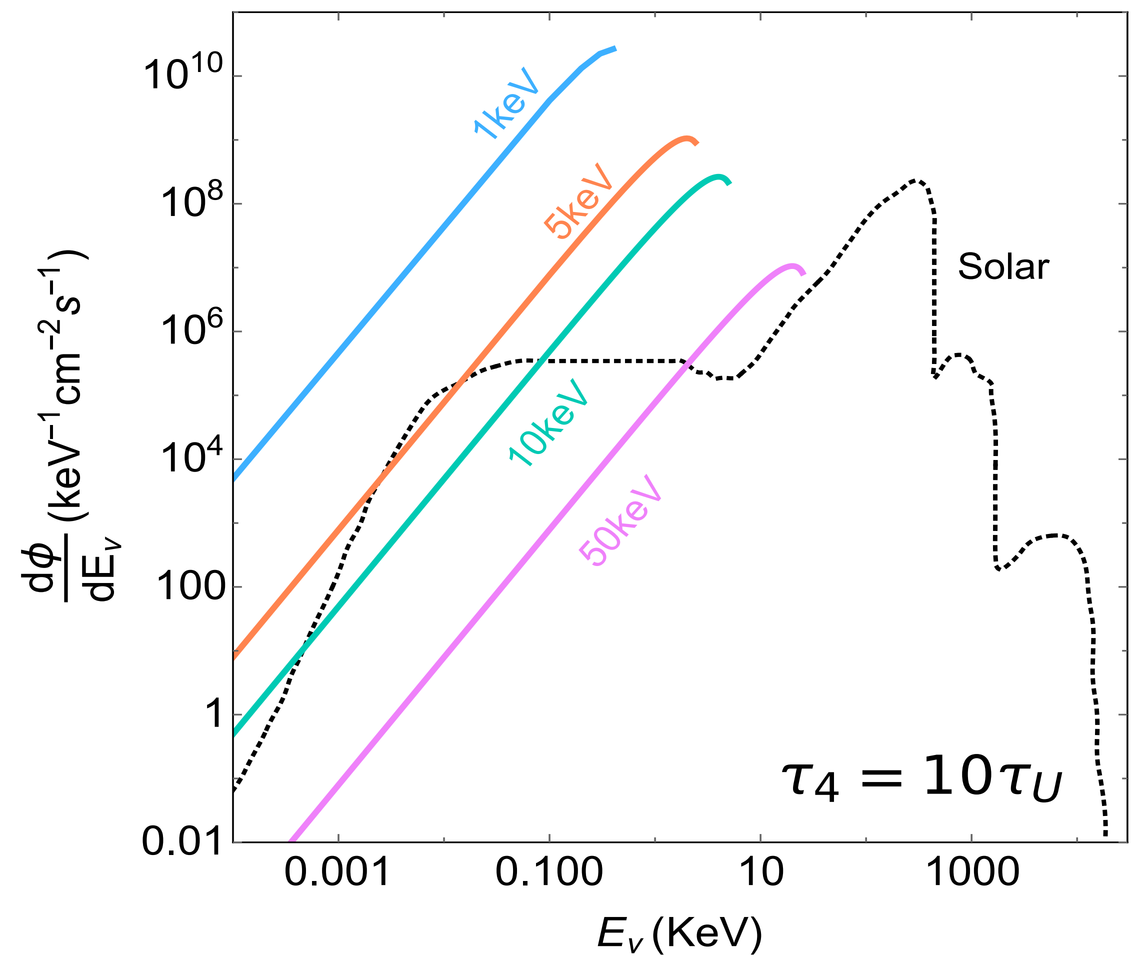
An Ultimate Test

Neutrinos from ν_4 DM decay: can verify both sterile neutrino as dark matter and neutrino self interaction.



$$\tau(\nu_4 \to 3\nu) \sim 10\,\tau_U \left(\frac{10^{-10}}{\sin^2 2\theta}\right)^2 \left(\frac{10\,\mathrm{keV}}{m_4}\right)^5 \times \left(\frac{10^{-3}}{\lambda}\right)^4 \left(\frac{m_\phi}{10\,\mathrm{MeV}}\right)^4$$

Neutrino flux from Milky Way galaxy



Dutra, Sen, YZ (in preparation)

Conclusion

It is amusing to show that neutrino self interactions have a novel impact on the origin of sterile neutrino dark matter.

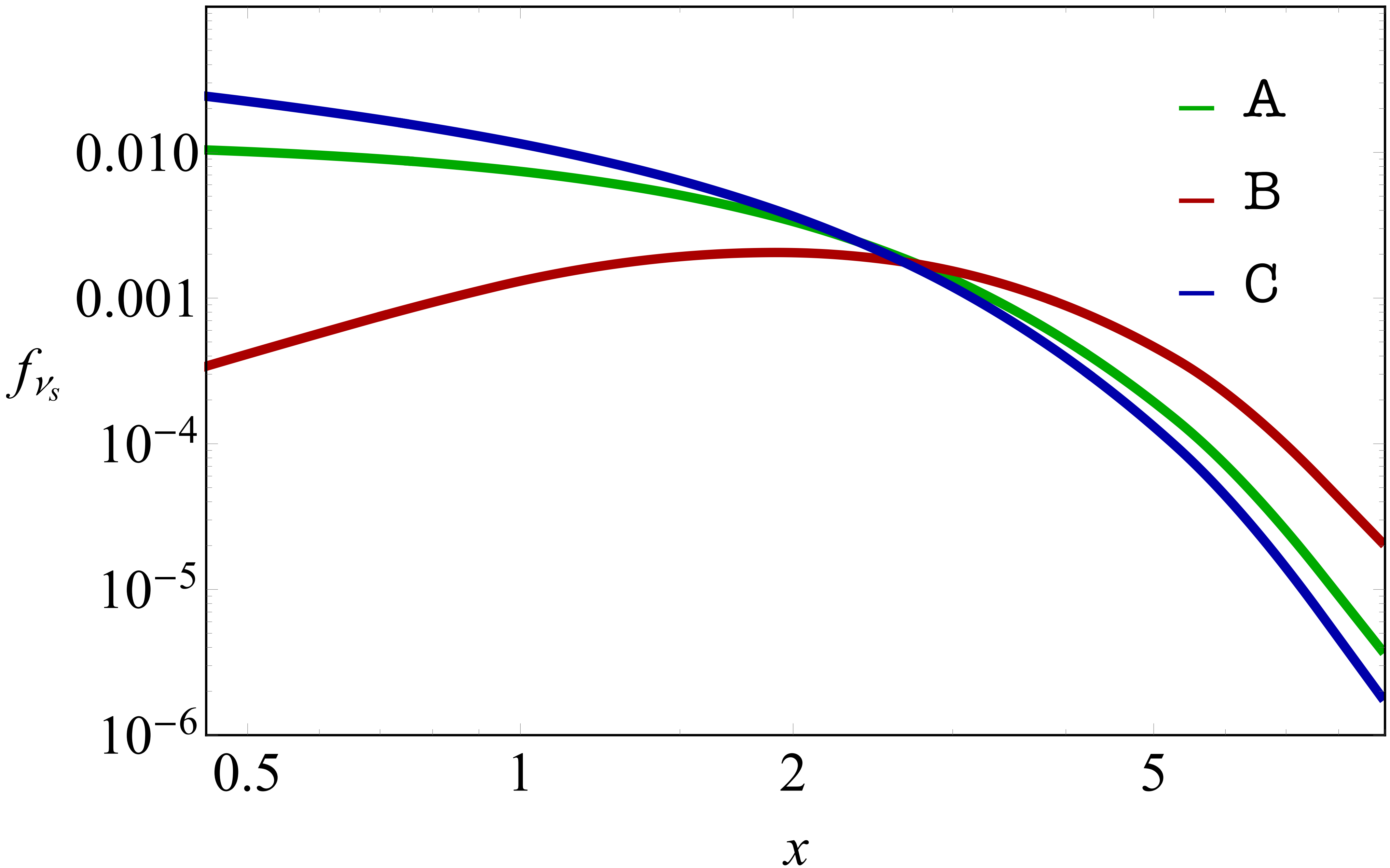
I present a simple model of self-interacting neutrinos via a neutrino-philic light scalar. (vector mediator also works.) Broad open parameter space relevant for dark matter.

Excitingly, a number of ways exist to test such a hypothesis with upcoming experiments, from laboratories to cosmos.

thanks!

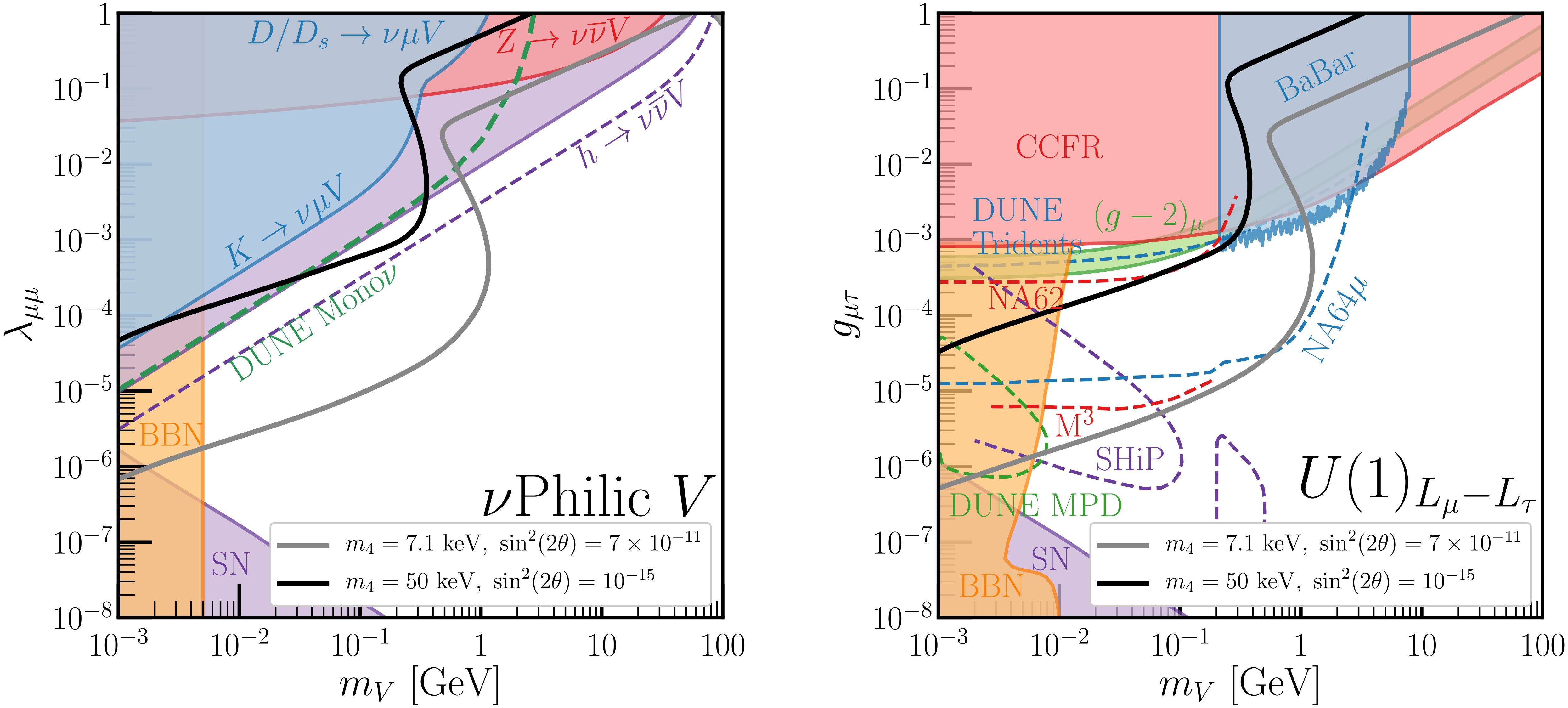
bonus

Energy Spectrum



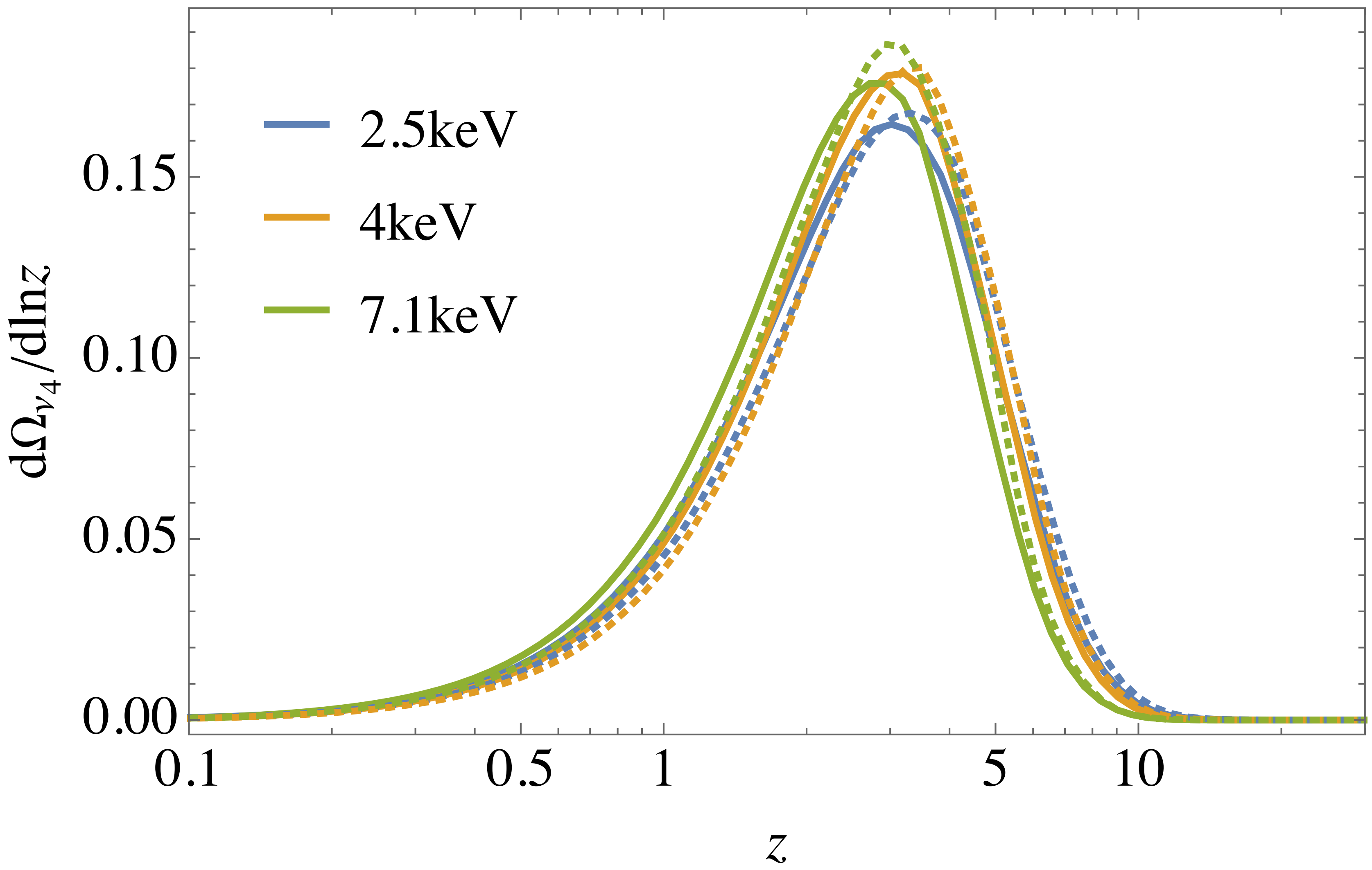
de Gouvêa, Sen, Tangarife, YZ (1910.04901)

Vector Mediator Case



Kelly, Sen, Tangarife, YZ (2005.03681)

Dominant Production Epoch



Kelly, Sen, YZ (2011.02487)