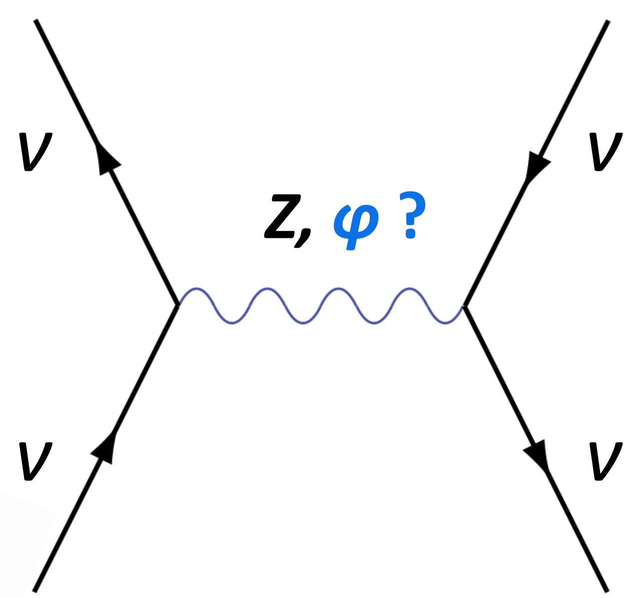
Novel Neutrino Self-interaction Motivations and Opportunities

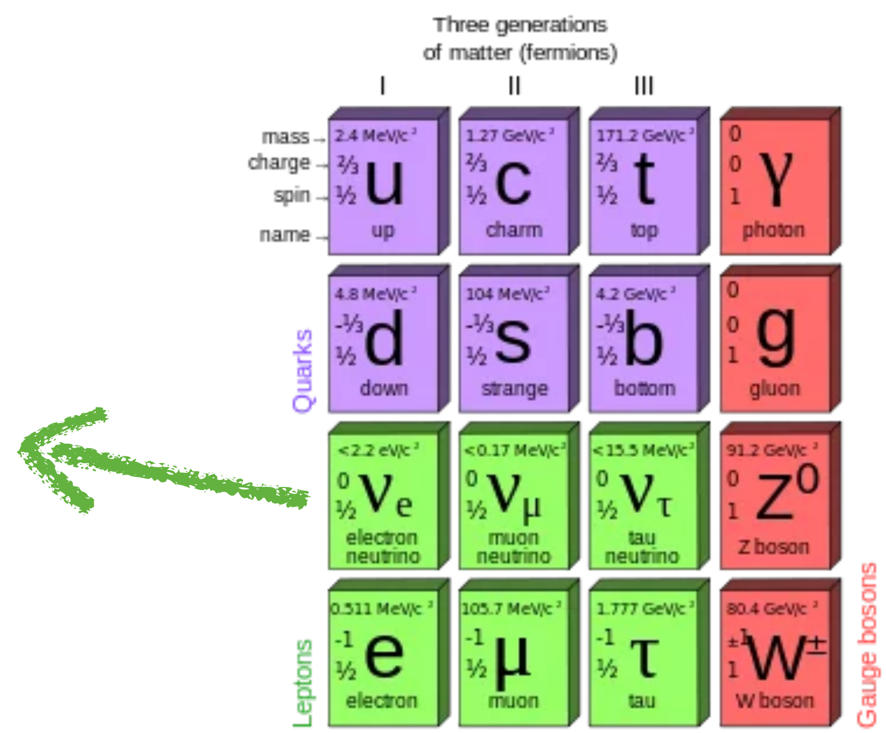
Yue Zhang

Carleton University

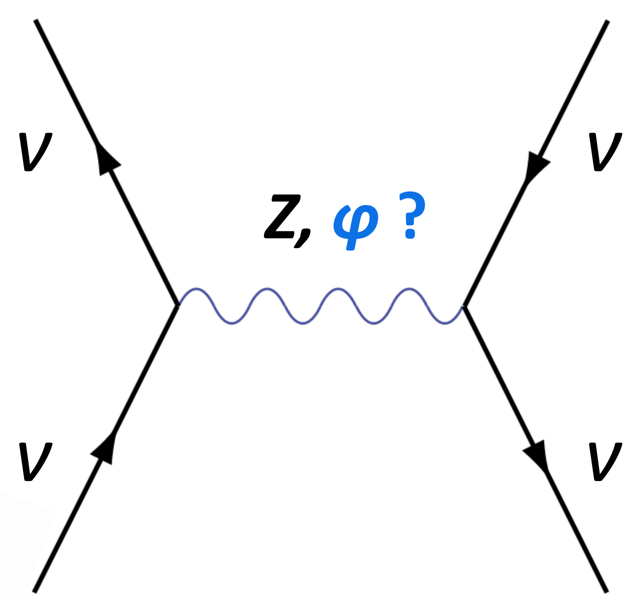
The Frontier of Particle Physics:
Exploring Muons, Quantum Science and the Cosmos
YITP Kyoto 2025

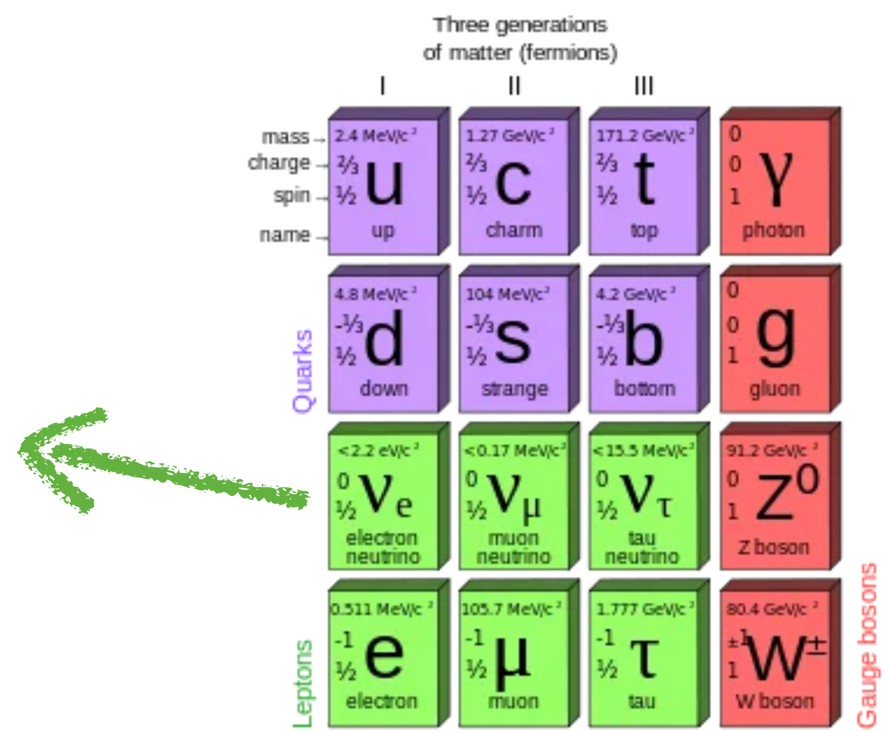
Neutrino Self Interaction





Neutrino Self Interaction





Zνν coupling at LEP is an indirect measurement.

Allowed to be much stronger than in the SM.

Humans have not built *νν* collider to measure $\sigma_{\nu\nu\to\nu\nu}$ yet.

Neutrino Collisions in the Sky

In ΛCDM model, neutrinos decouple around MeV temperature, afterwards free stream through the universe.

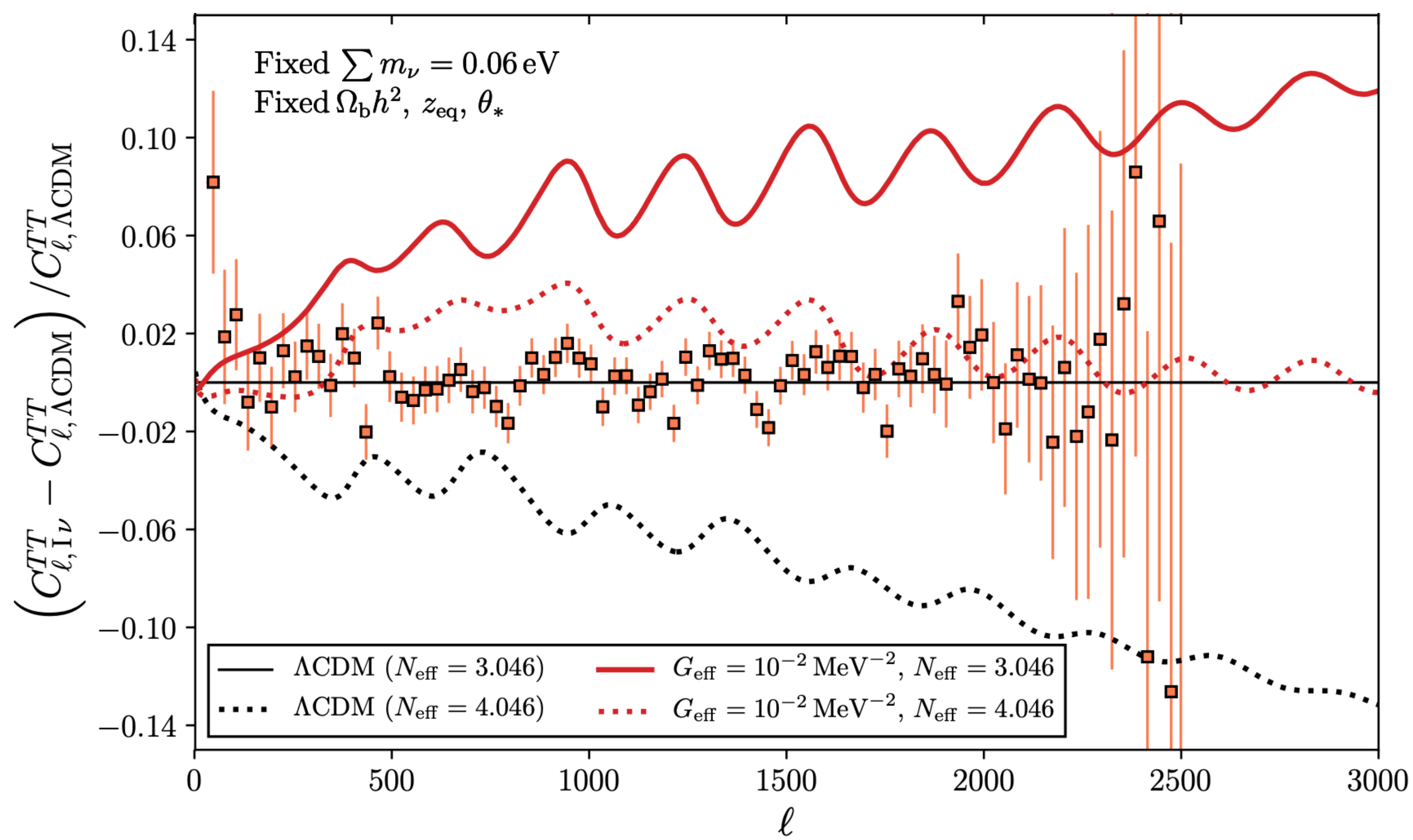
Stronger self-interaction delays the onset of free streaming.

Notable implications:

- Hint from existing cosmological data (brief).
- Close connection to the origin of sterile neutrino DM.
- Back to Earth, opportunities for future experimental tests.

Motivation from the Hubble "Tension"

more anisotropic



self-interaction

ΛCDM

add both

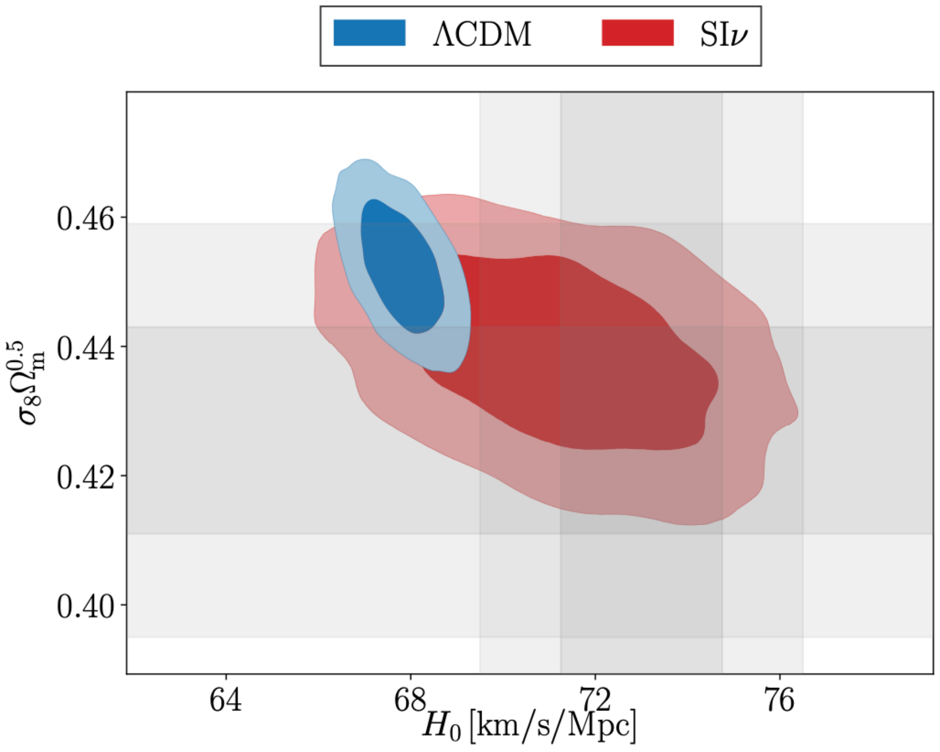
$N_{\rm eff}$=4

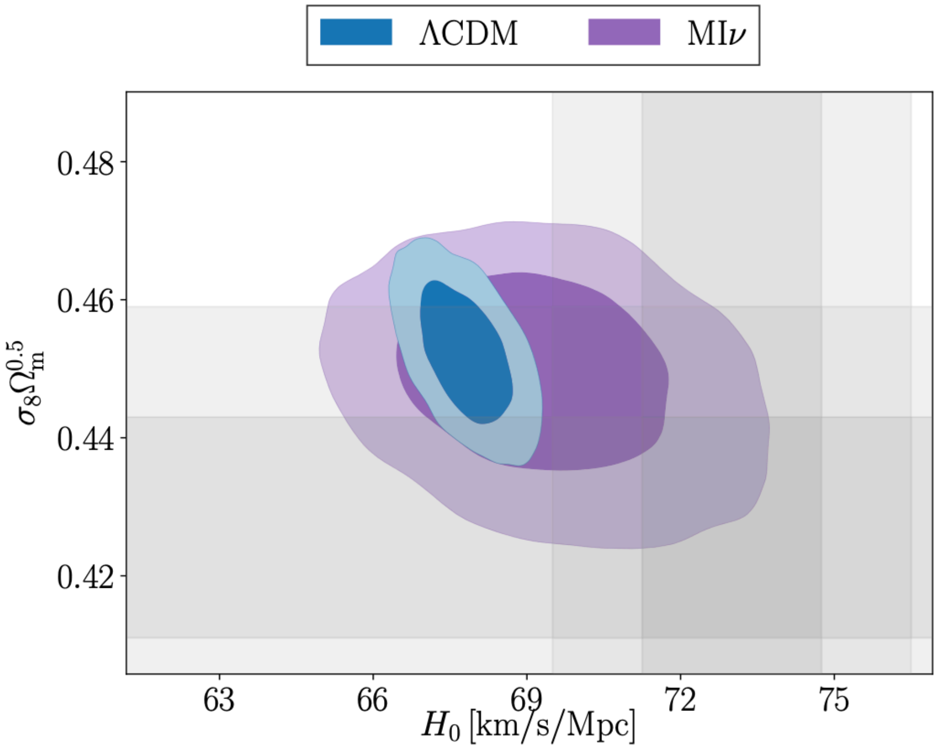
more uniform

$$\Gamma_{\nu\nu\to\nu\nu} \sim G_{\rm eff}^2 T^5$$

Kreisch, Cyr-Racine, Dore, 1902.00534

A Stone for Two Birds





Kreisch, Cyr-Racine, Dore, 1902.00534

Self-interaction decoupling temperature

$$\textbf{SI}\nu: \quad G_{\rm eff} \simeq (5\,{\rm MeV})^{-2} \quad \longrightarrow \quad T_{\rm dec} \simeq 0.5{\rm eV}$$

$$\textbf{MI}\nu: \quad G_{\rm eff} \simeq (100\,{\rm MeV})^{-2} \quad \longrightarrow \quad T_{\rm dec} \simeq 20{\rm eV}$$

Hot Topic

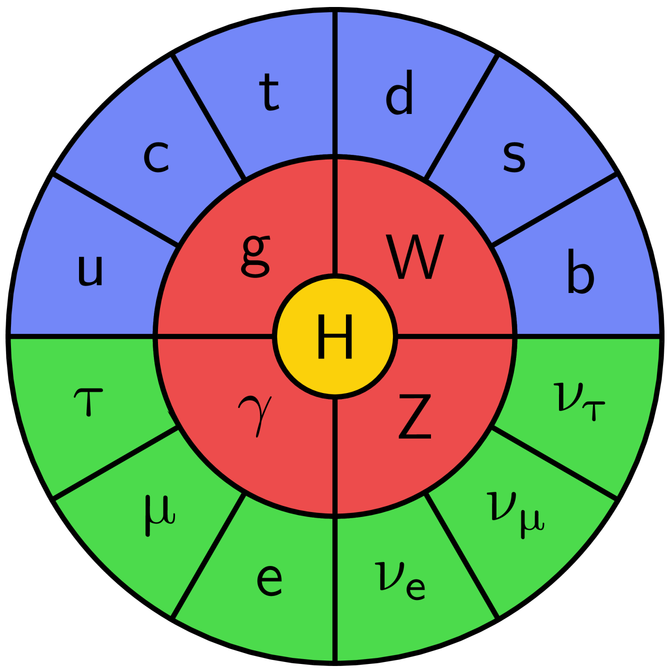
Numerous analyses of existing data (incomplete list):

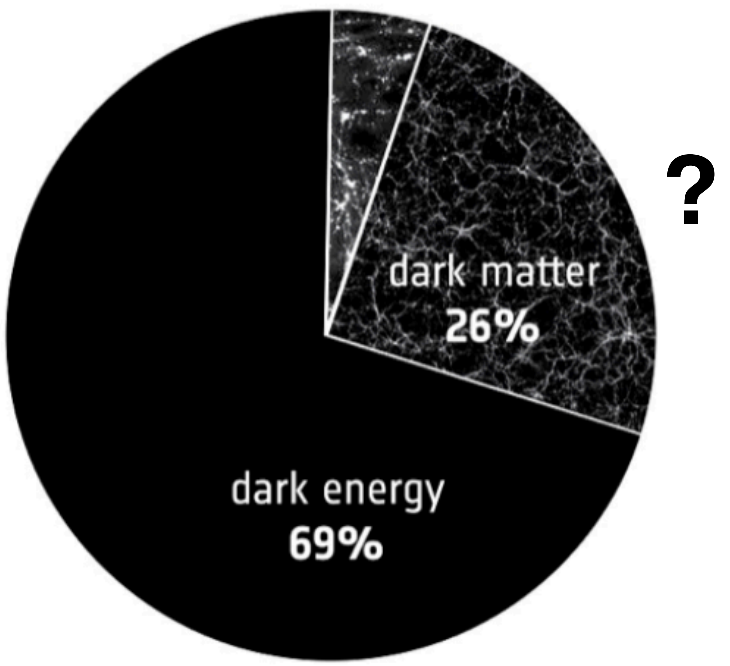
Kreisch, Cyr-Racine, Dore, 1902.00534; Das, Ghosh, 2011.12315; Hannestad, Tram, 2012.07519; Brinckmann, Chang, LoVerde, 2012.11830; Kreisch et al, 2207.03164; Das, Ghosh, 2303.08843; Camarena, Cyr-Racine, Houghteling, 2309.03941; He, An, Ivanov, Gluscevic, 2309.03956; Camarena, Cyr-Racine, 2403.05496; Pal, Samanta, Pal, 2409.03712; Racco, Zhang, Zheng, 2412.04959

Evidence of neutrino self-interaction much stronger than in SM, even without addressing the "Hubble tension" i.e. keeping N_{eff}=3.

Will soon learn better, from upcoming cosmological data, ACT, DESI, LSST, Euclid, CMS-S4, Spec-S5 …

Connection to Dark Matter





Sterile Neutrino as Dark Matter

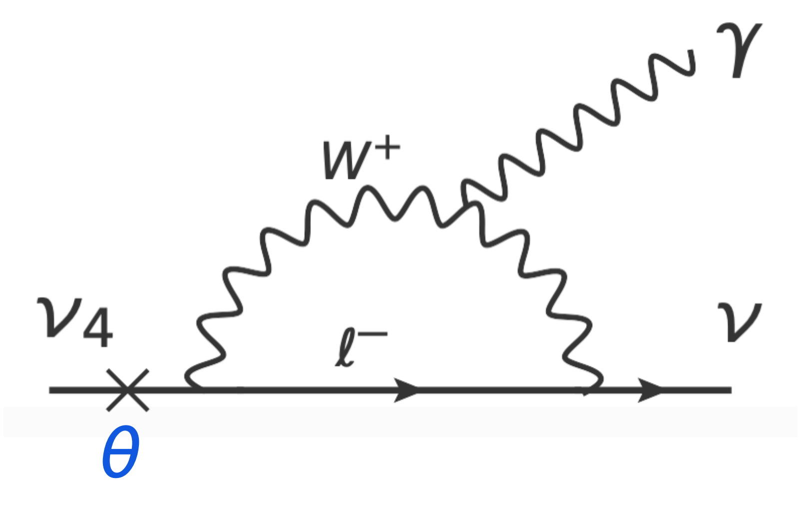
Introduce a gauge singlet fermion ν_s, mix it with SM neutrinos ν_a

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

ν_4 physical mass eigenstate. θ is active-sterile mixing in vacuum, θ is tiny & irrelevant for light neutrino mass generation.

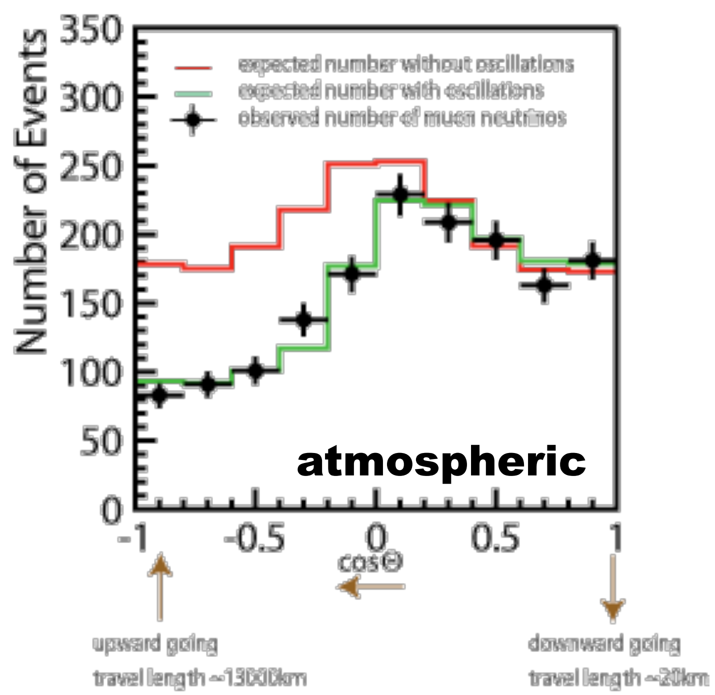
Useful benchmark for warm dark matter analyses in cosmology.

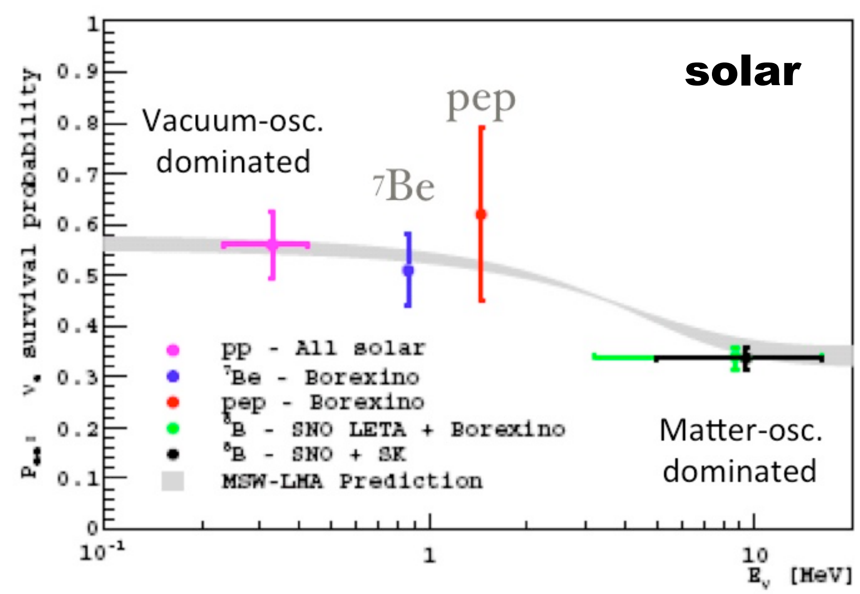
Very simple: only two parameters.



Neutrino Oscillation Phenomena

Success stories

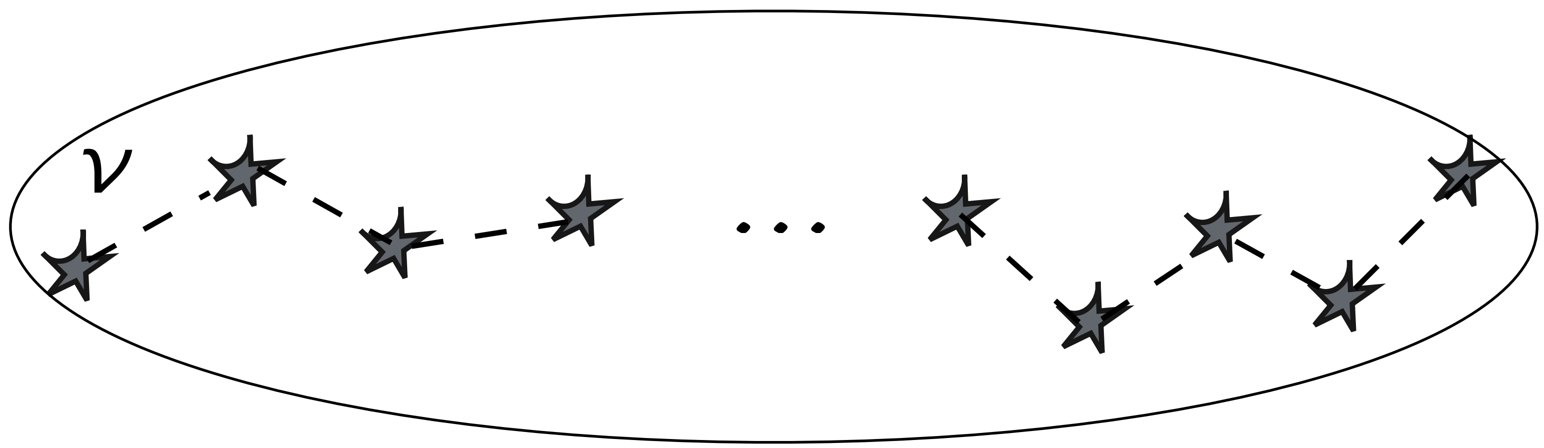




Dark matter from active-sterile neutrino oscillation in early universe?

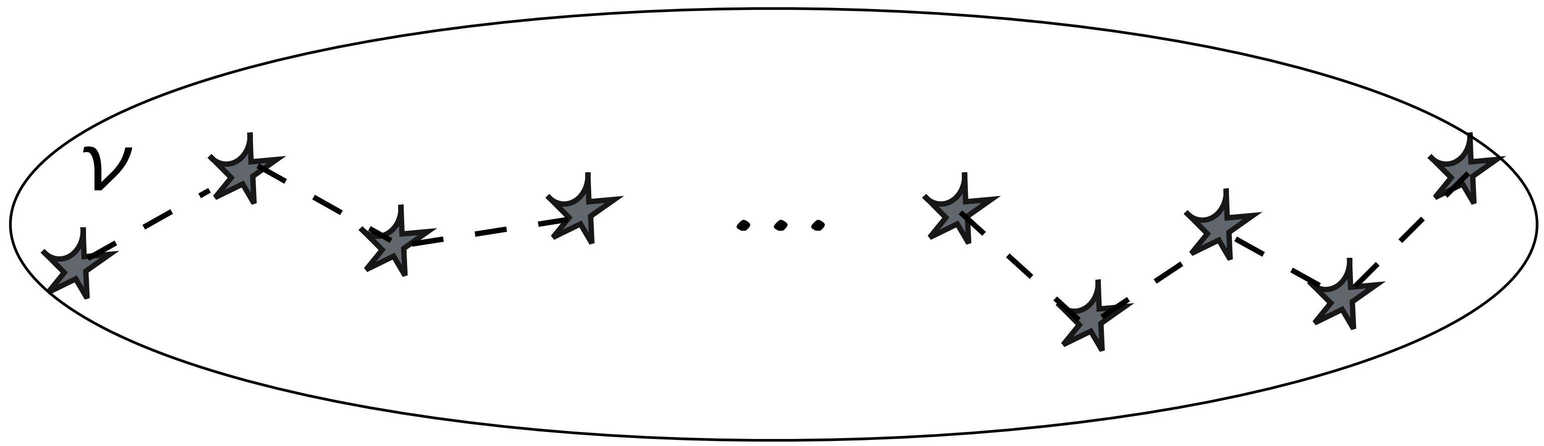
e.g. Dodelson-Widrow mechanism.

Neutrino in Early Universe



$T \sim 100\,\text{MeV}, \quad H^{-1} \sim 100\,\text{km}, \quad l_{\text{mean free path}} < 1\,\text{m}$

DM Production Rate



Many oscillation baselines: $\Gamma/H >> 1$ before decoupling.

Active-sterile oscillation can take place on every baseline.

$$\frac{df_4}{d\log(1/T)} = \frac{\Gamma}{4H} P_{\nu_a \to \nu_s} f_a$$

Oscillation Probability

On each baseline:

$$P_{\nu_a \to \nu_s} = \frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + \qquad + (\Delta \cos 2\theta - V)^2} \equiv \sin^2 2\theta_{\text{eff}}$$

$\Delta \sim m_4^2/E$: energy difference in vacuum

θ : vacuum mixing angle

V_T : high temperature potential energy

Wolfenstein, 1978; Notzold, Raffelt, 1988

Oscillation Probability

On each baseline:

$$P_{\nu_a \to \nu_s} = \frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + \Gamma^2/4 + (\Delta \cos 2\theta - V)^2} \equiv \sin^2 2\theta_{\rm eff}$$

$\Delta \sim m_4^2/E$: energy difference in vacuum

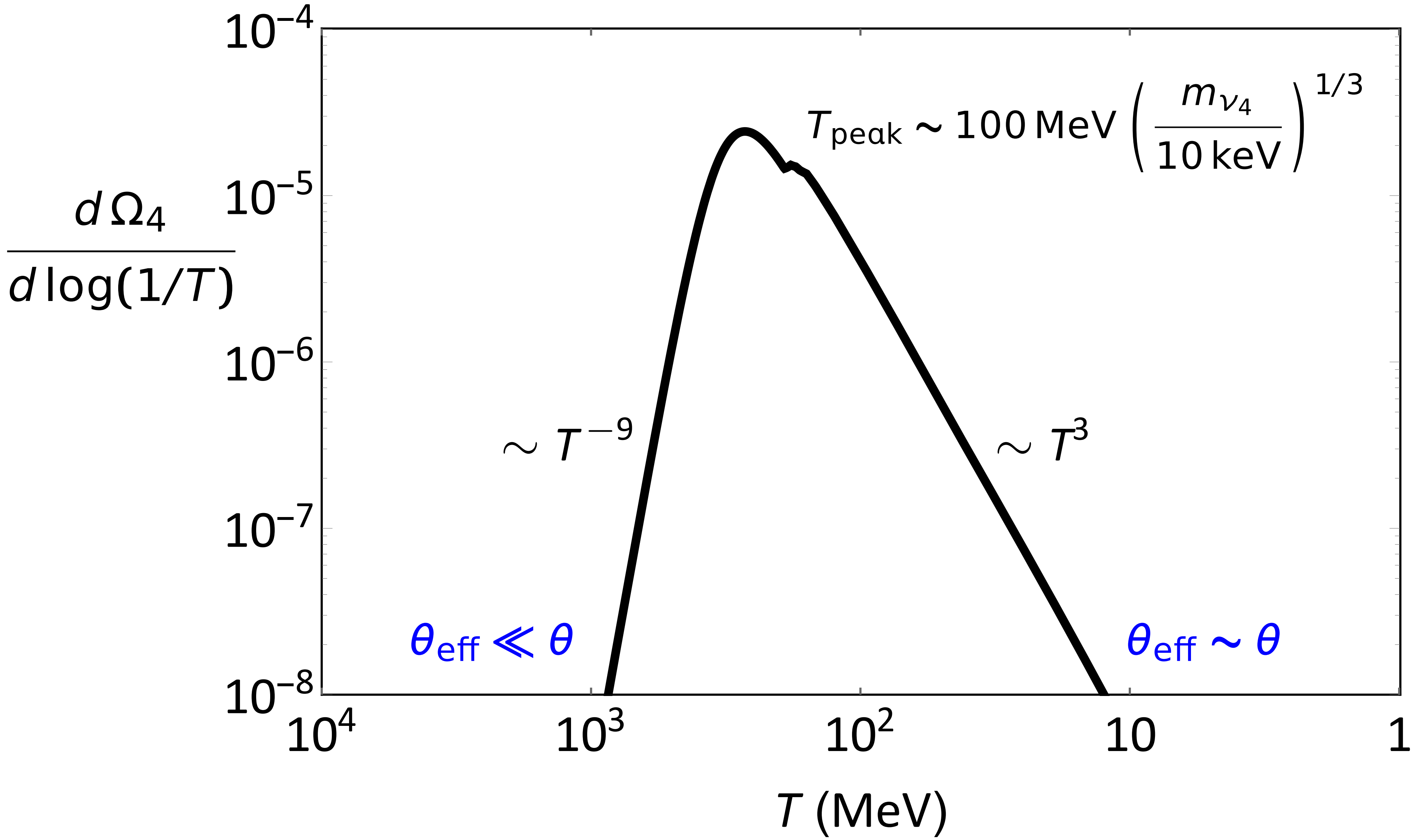
θ : vacuum mixing angle

V_T : high temperature potential energy

Hard scatterings (quantum Zeno effect)

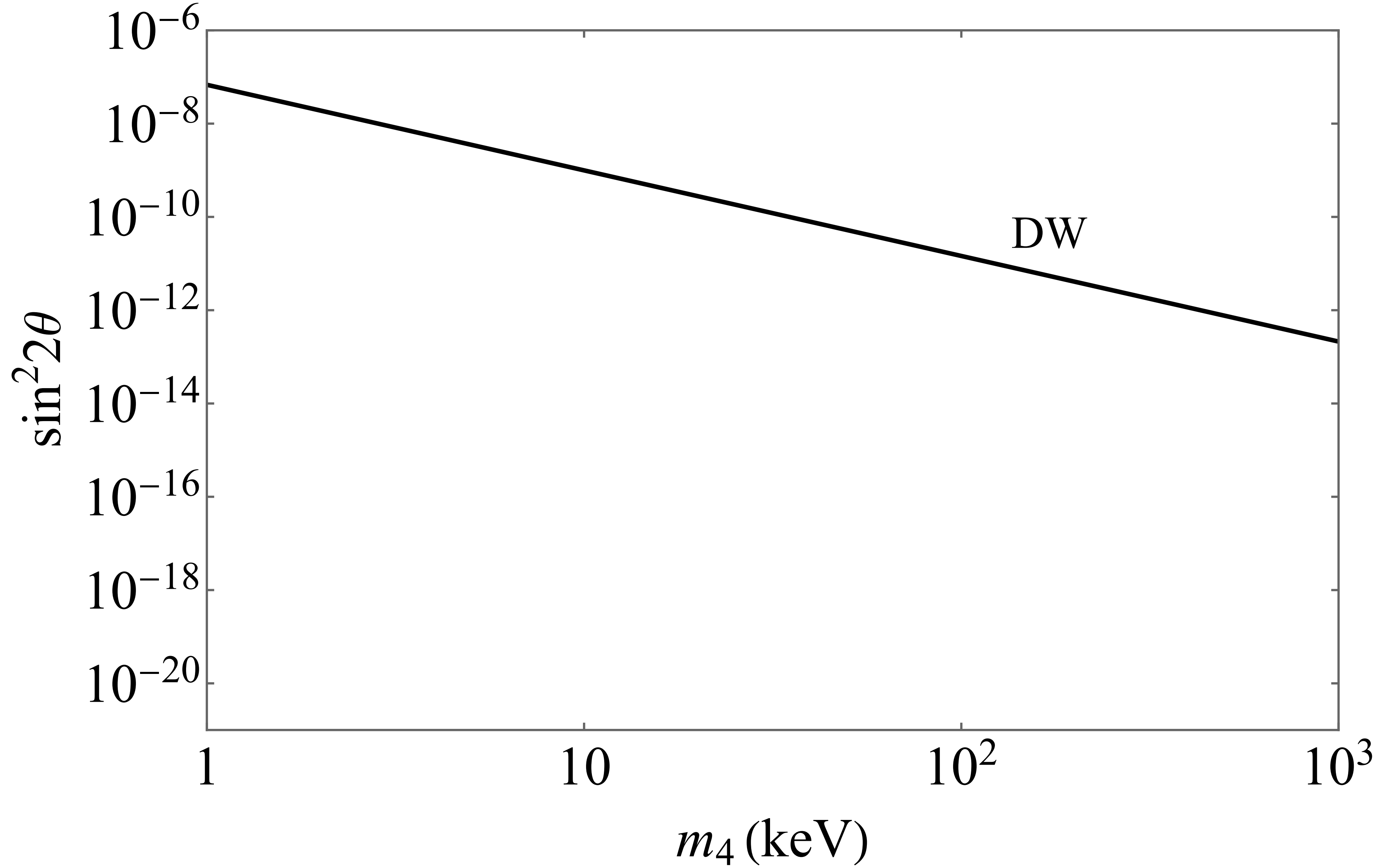
Wolfenstein, 1978; Notzold, Raffelt, 1988

Dodelson-Widrow Mechanism



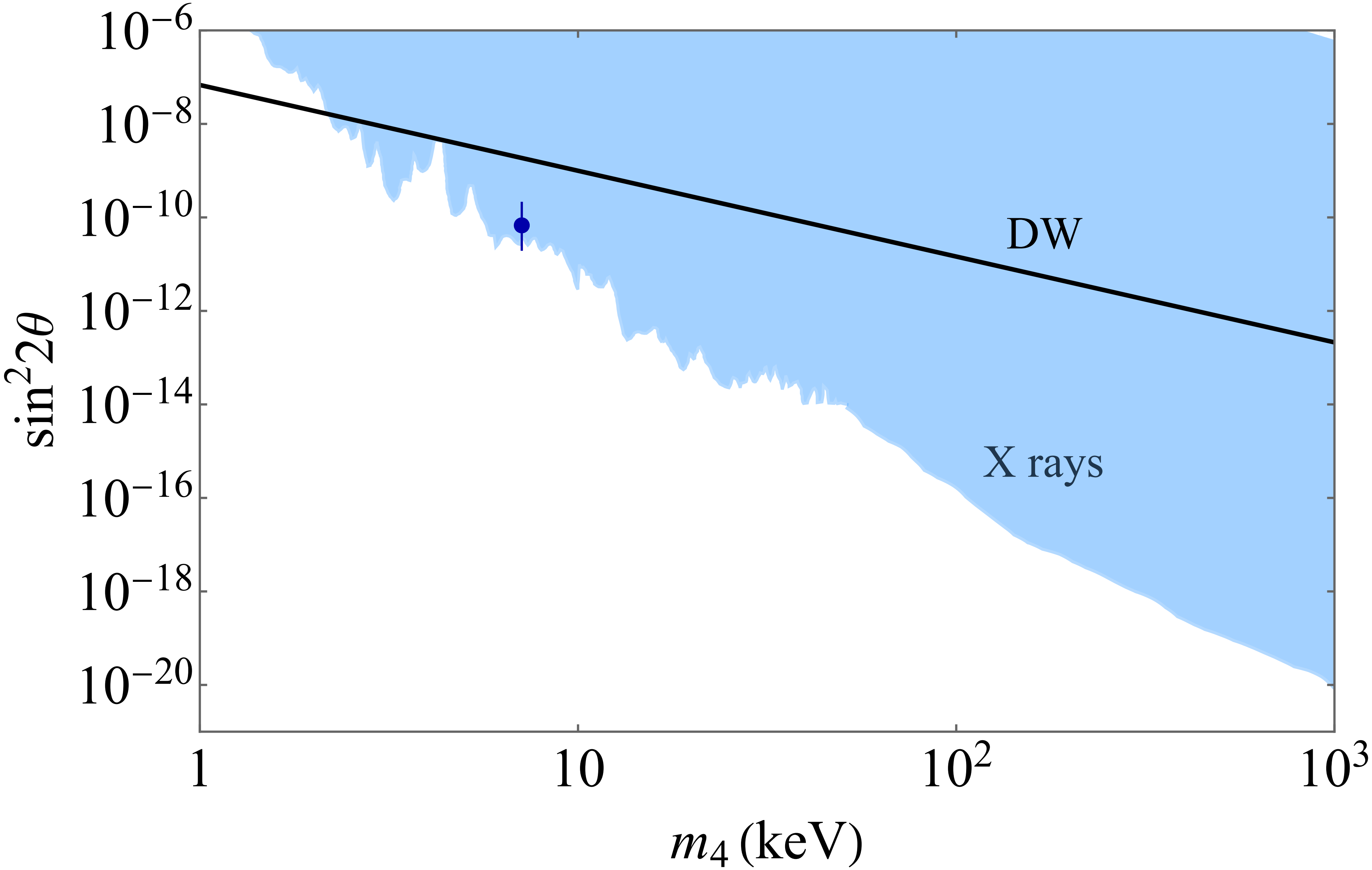
Dodelson, Widrow, hep-ph/9303287

Dodelson-Widrow Mechanism



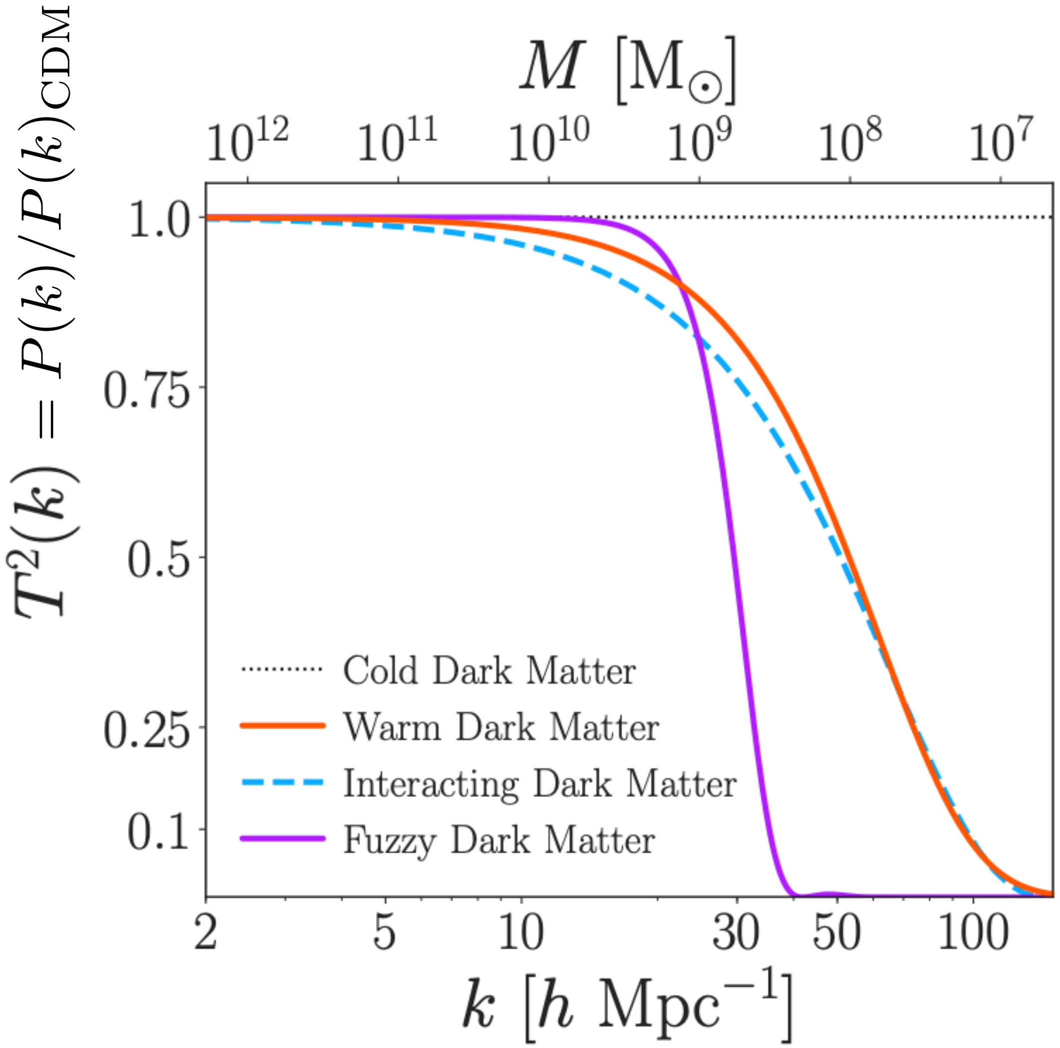
Dodelson, Widrow, hep-ph/9303287

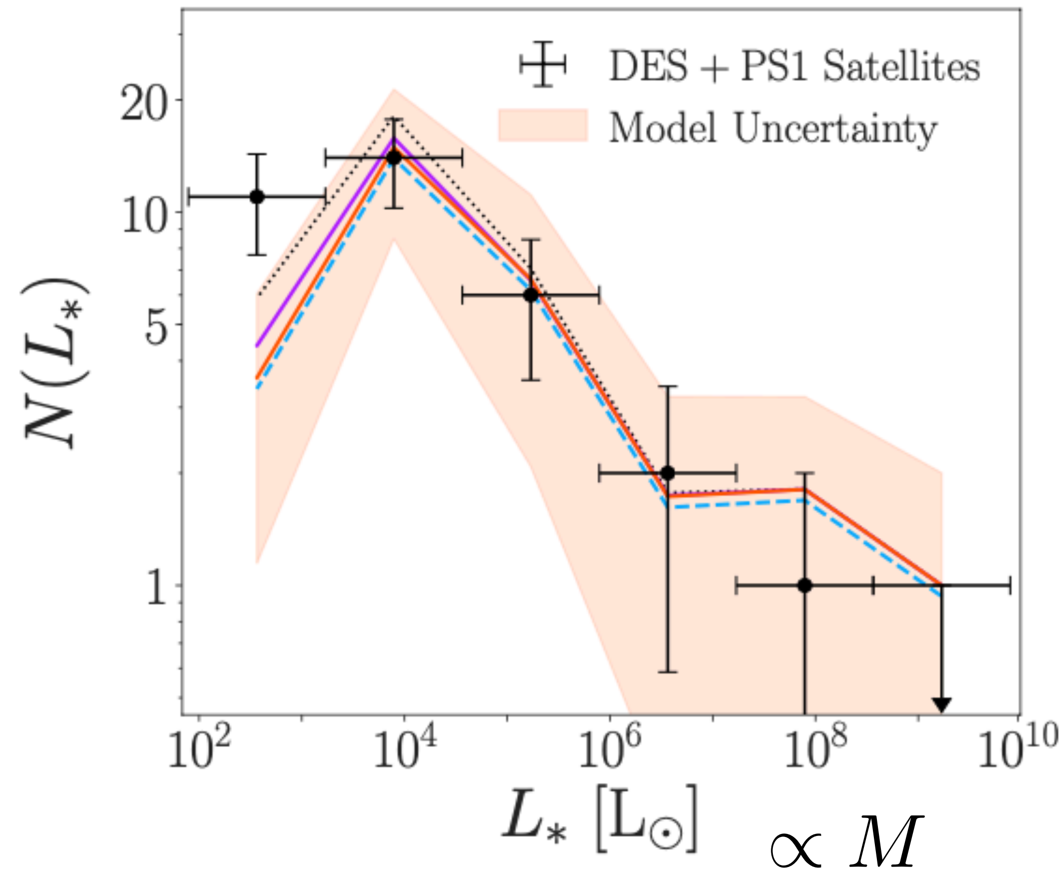
X-Ray Line Search Limits



Abazajian, 1705.01837

DES limit: ultra-faint MW dwarfs



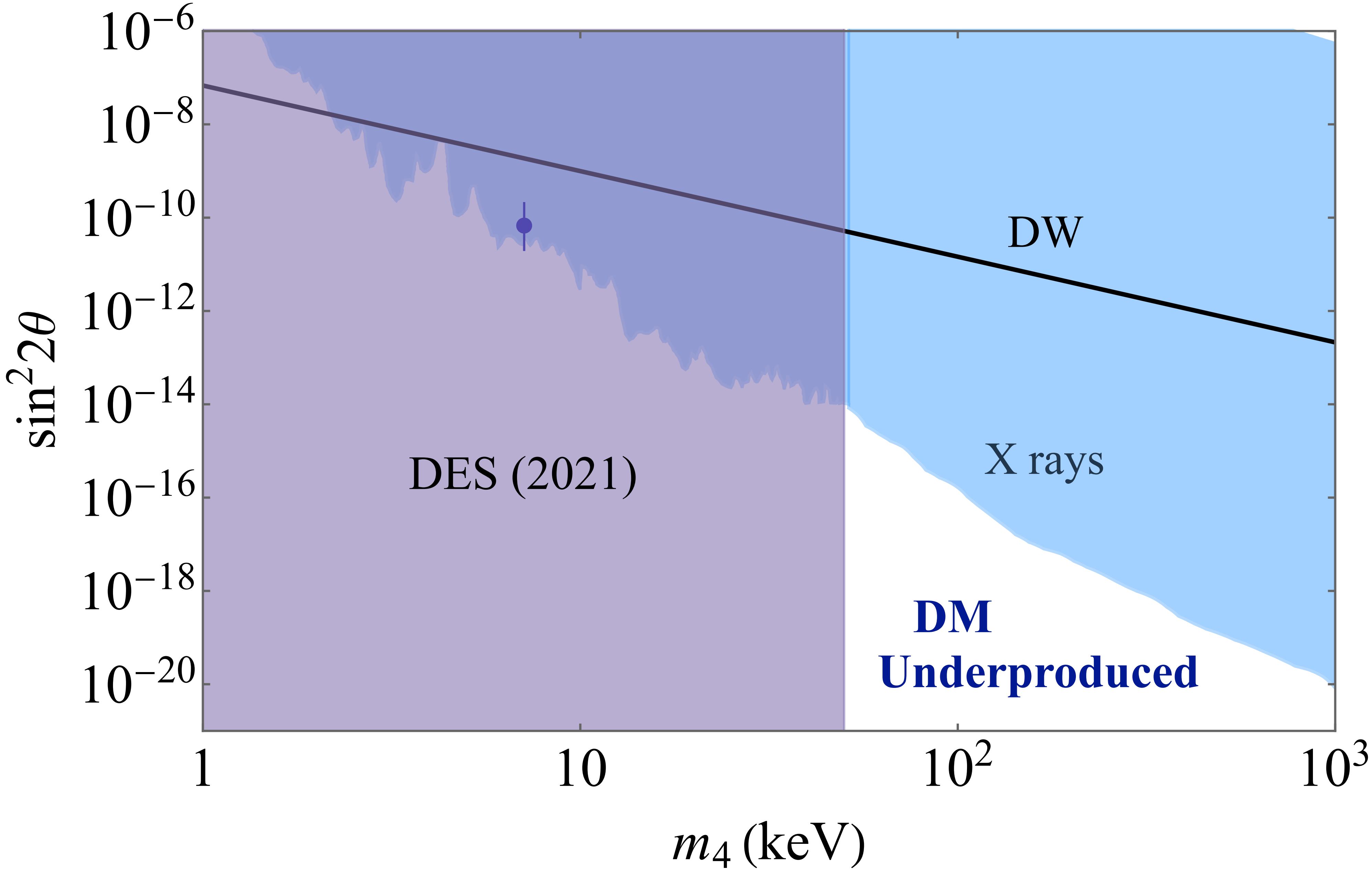


DM free streaming suppresses matter power spectrum at large k.

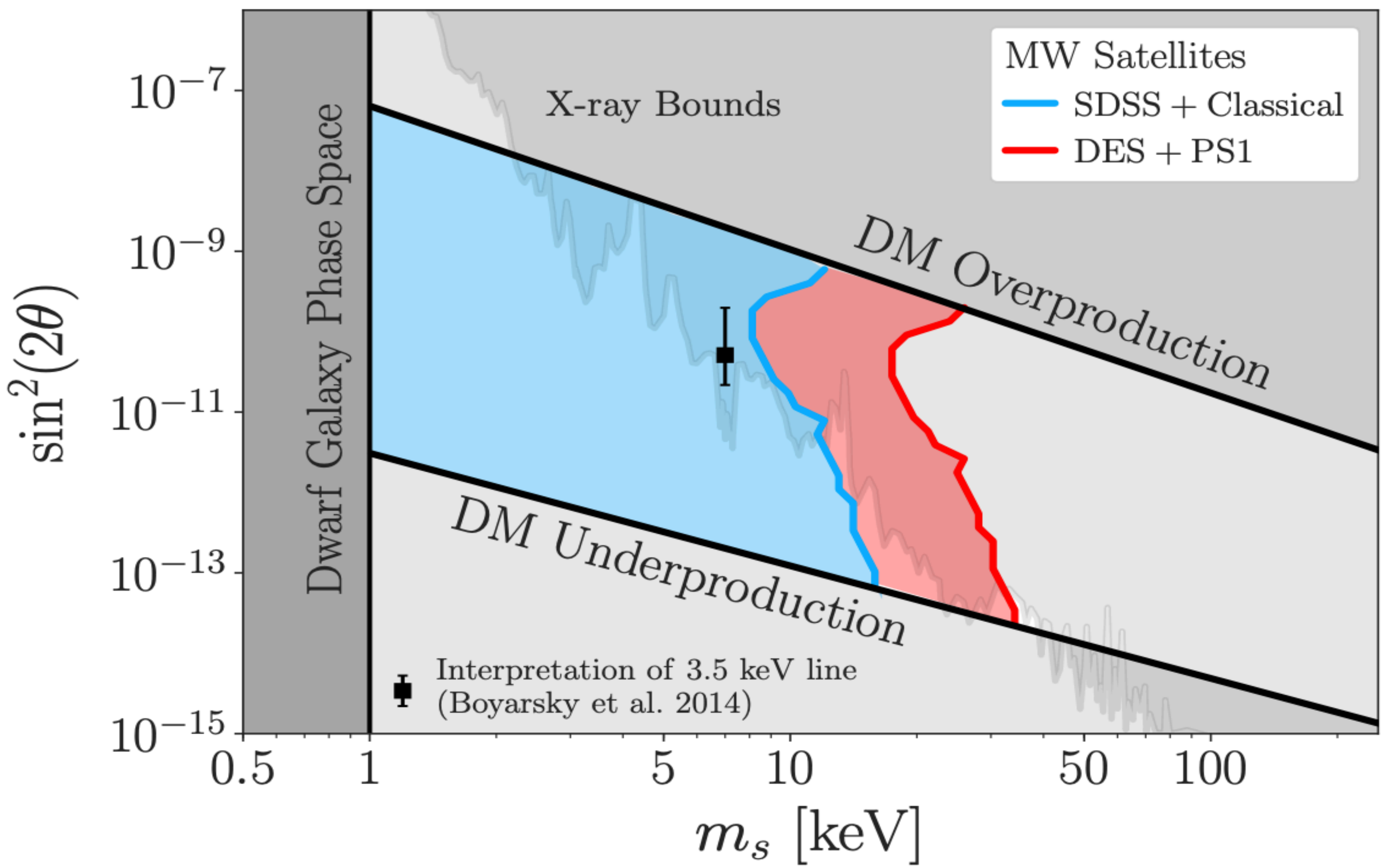
$\Rightarrow m_4 > 50\,\text{keV}$

DES collaboration, 2008.00022

D-W Mechanism Firmly Excluded



Lepton Asymmetry Cannot Save



Shi, Fuller, astro-ph/9810076; DES collaboration, 2008.00022

A Useful Question

Does any oscillation mechanism for SvDM work at all?

… that will continue to guide astro and cosmo probes,

& offer new opportunities for terrestrial probes.

A Simple Idea

$$\Omega_4 \propto [\text{weak interaction rate}] \times \sin^2 2\theta$$

~~weak~~ total

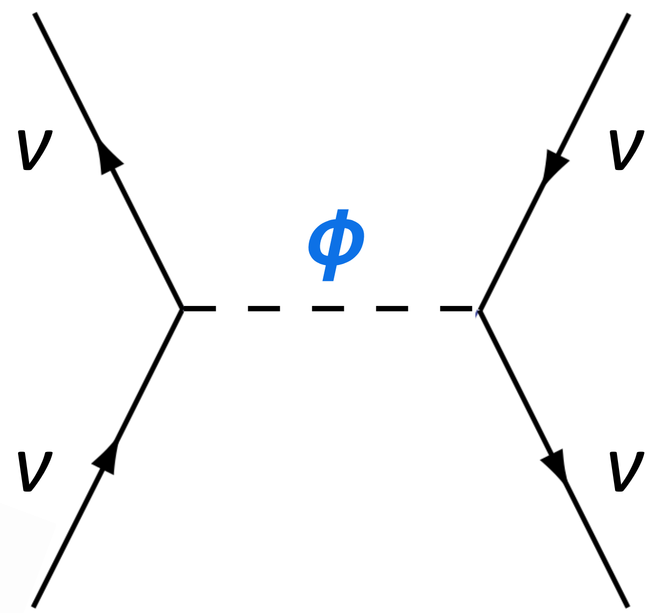
Intuition: compensate smaller mixing with larger reaction rate.

Rule of game: new physics enhances Γ but without introducing additional contribution to DM radiative decay rate.

Particles in early universe plasma T~100 MeV: *e, μ, u, d, γ, ν*

↑

A Simple Model



$$\mathcal{L}_{\text{int}} = \lambda \nu^2 \phi + \text{h.c.}$$

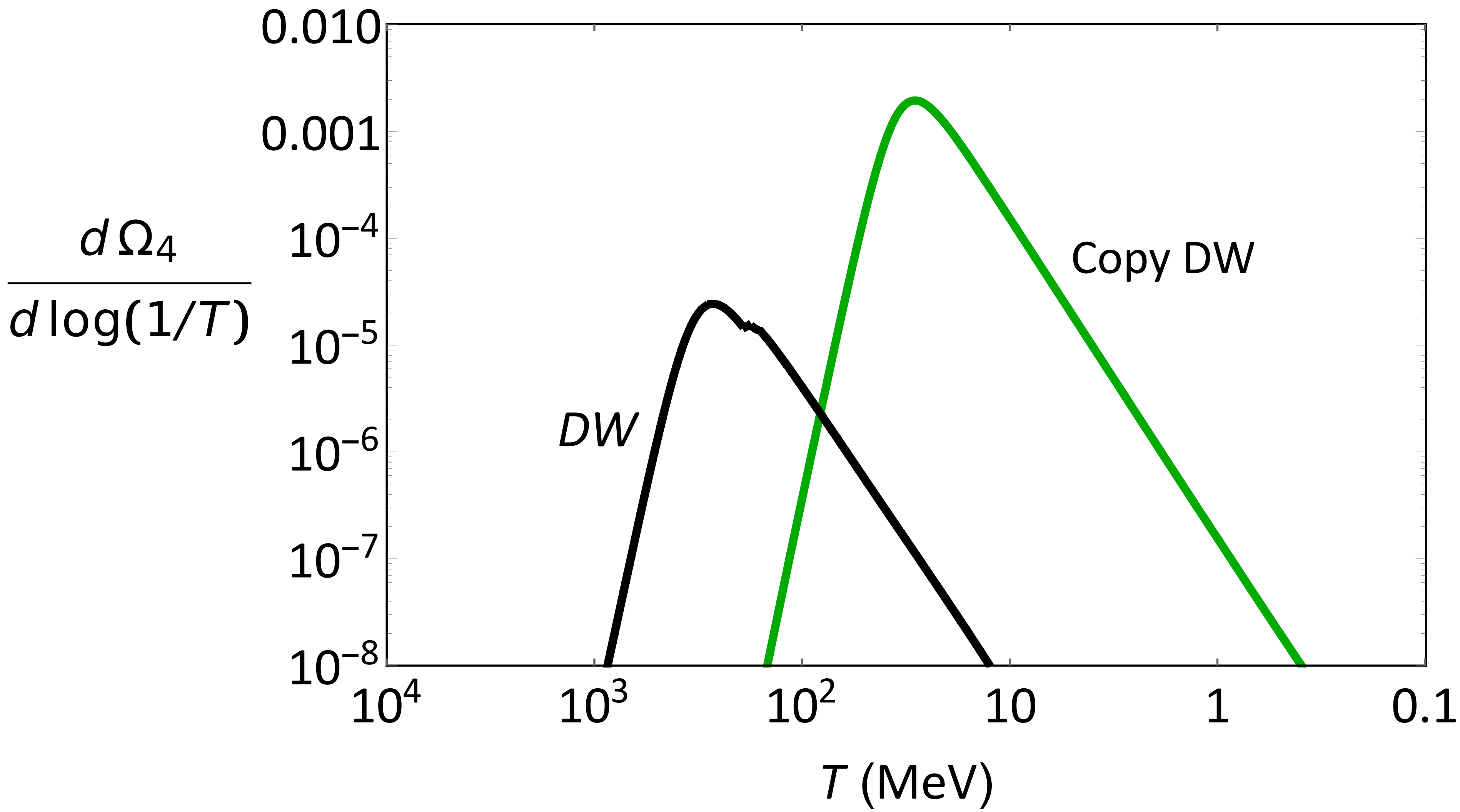
$$= \lambda \overline{\nu^c} \mathbb{P}_L \nu \phi + \text{h.c.}$$

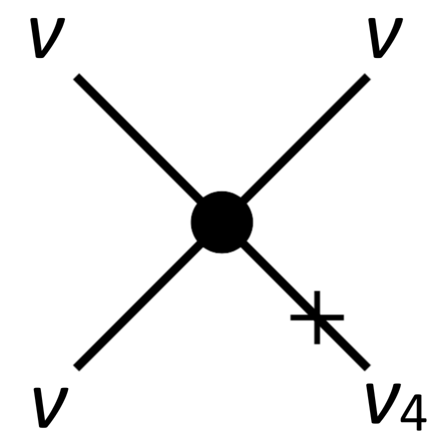
ϕ is a complex or real scalar, SM singlet, light, has no VEV.

Hold on to your curiosity about gauge invariance.

Self-interaction effectively creates more baselines for active-sterile oscillation to take place in the early universe.

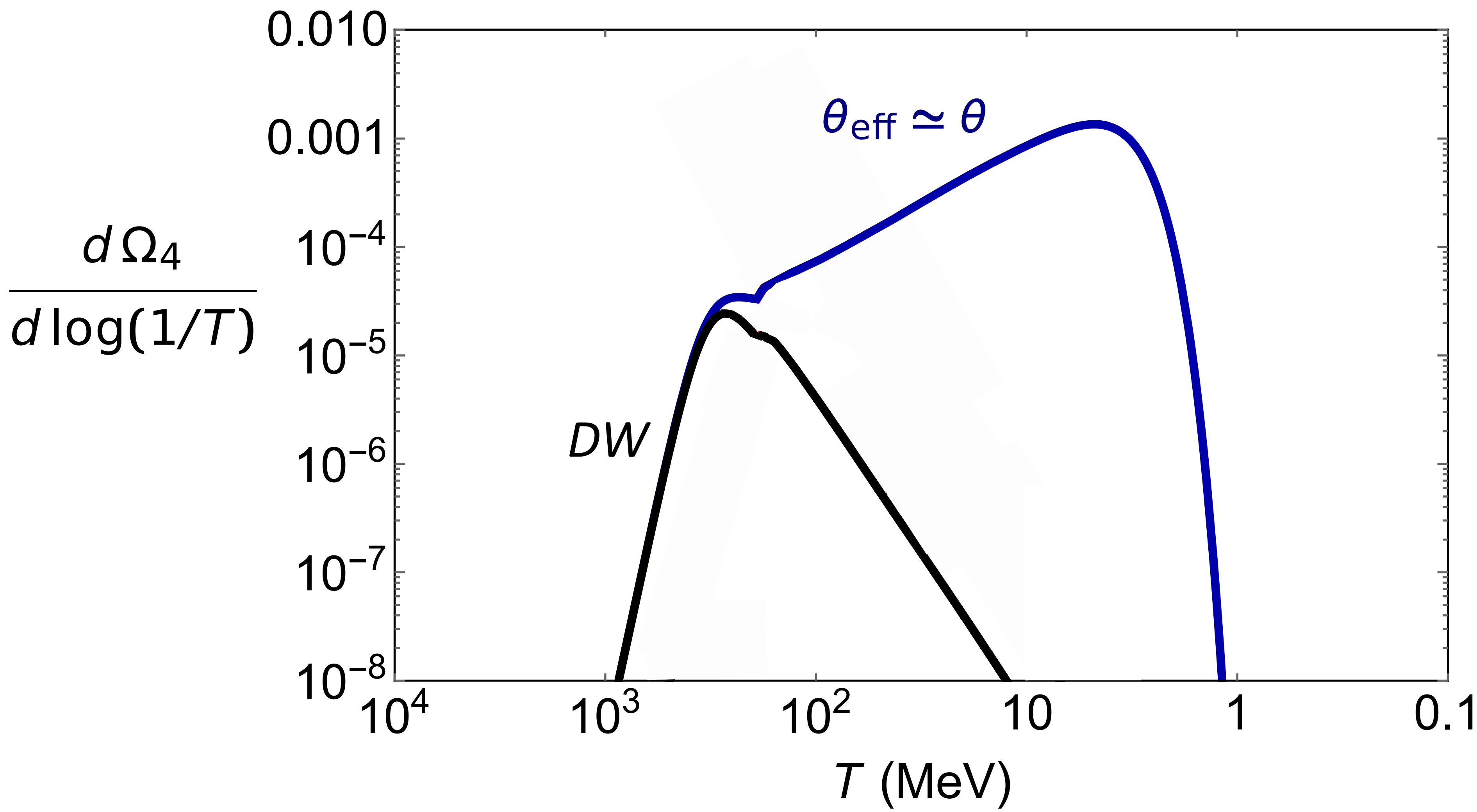
Heavy Mediator Scenario

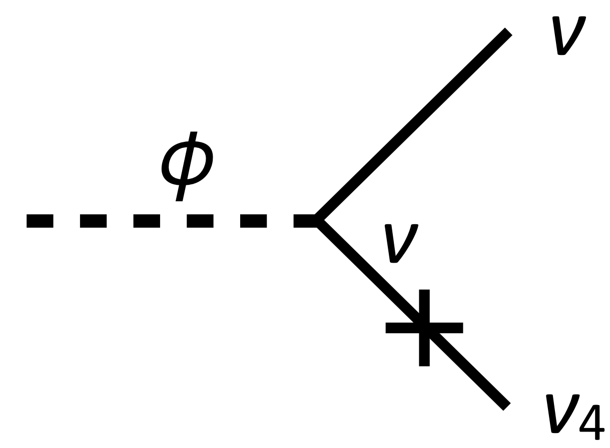




Final relic density: $\Omega_4 \propto \frac{\lambda^3}{m_\varphi^2} \gg \frac{g^3}{M_W^2}$

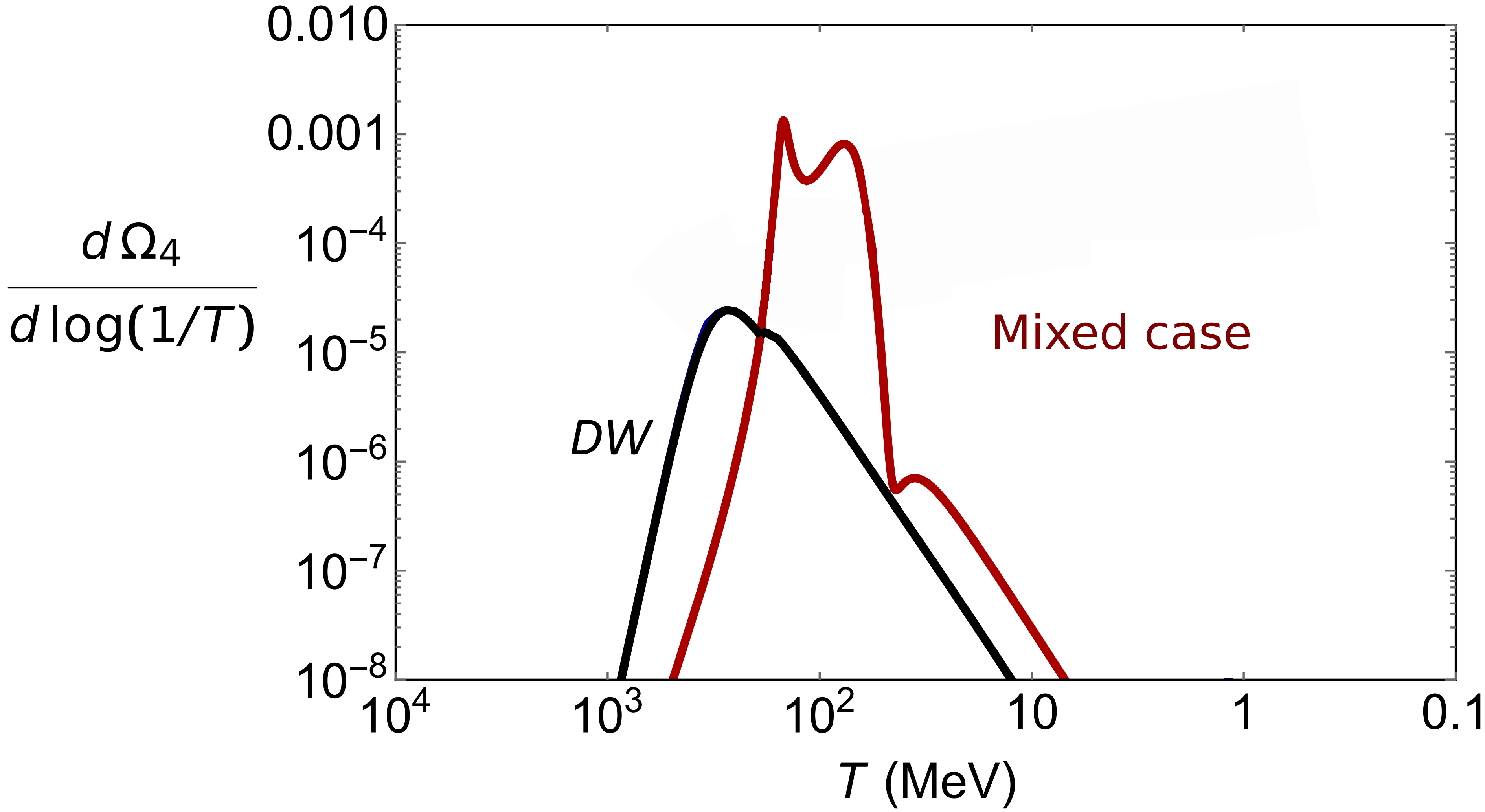
Light Mediator Scenario

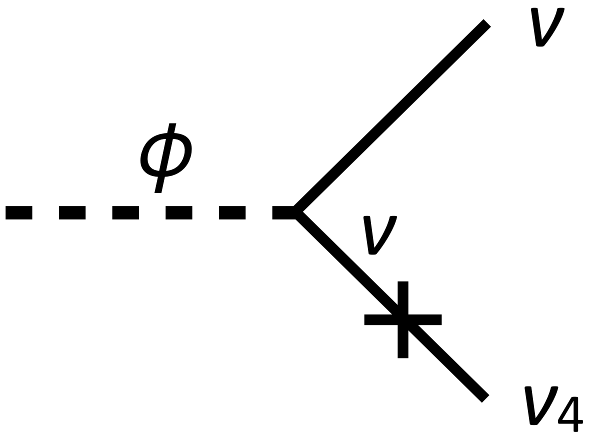




When $T > m_\phi$, neutrino scattering dominated by on-shell ϕ

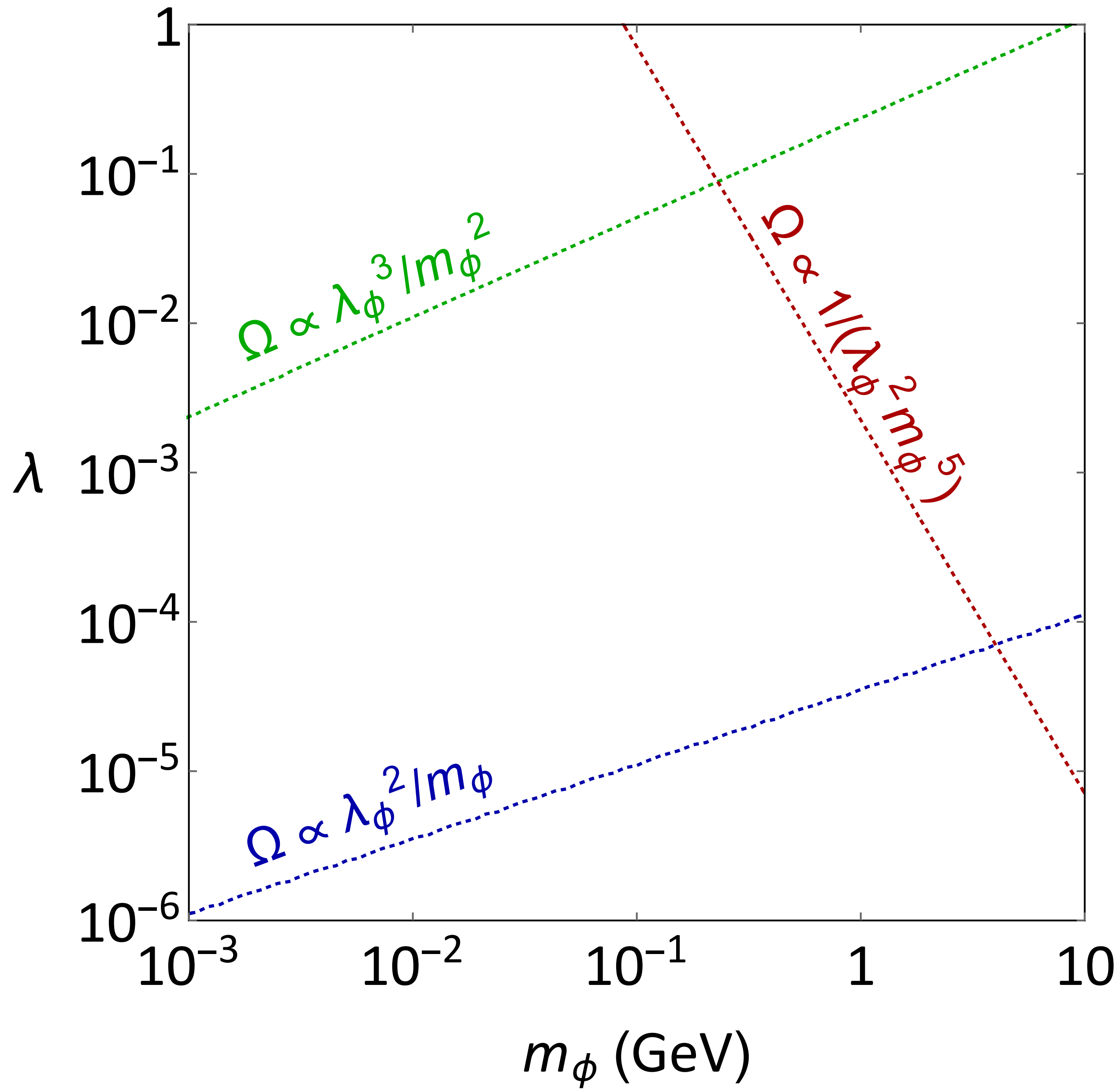
Light Mediator Scenario





When $T>m_\phi$, neutrino scattering dominated by on-shell ϕ

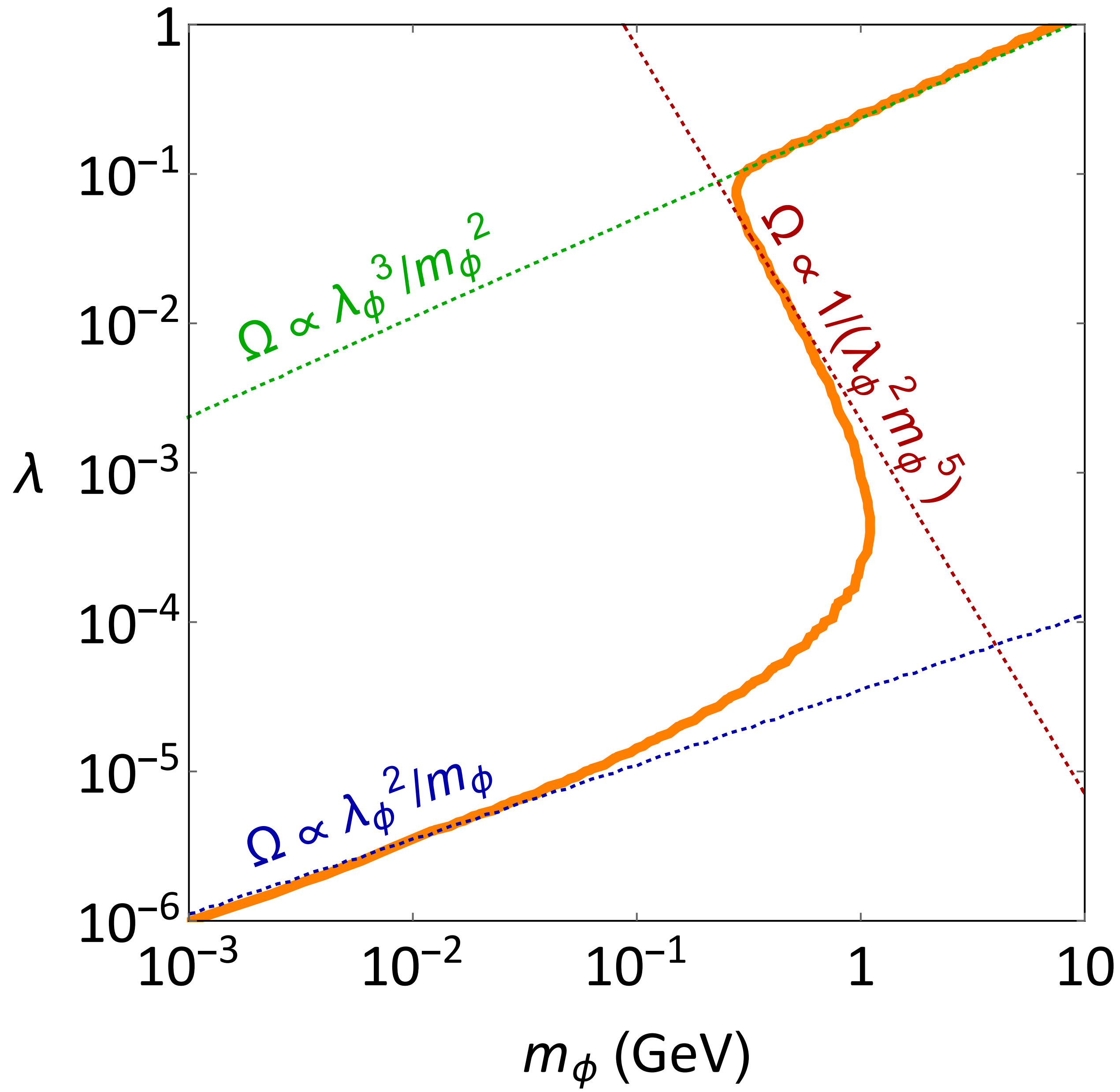
Three Regimes



hold θ and m_4 fixed

de Gouvêa, Sen, Tangarife, YZ, 1910.04901

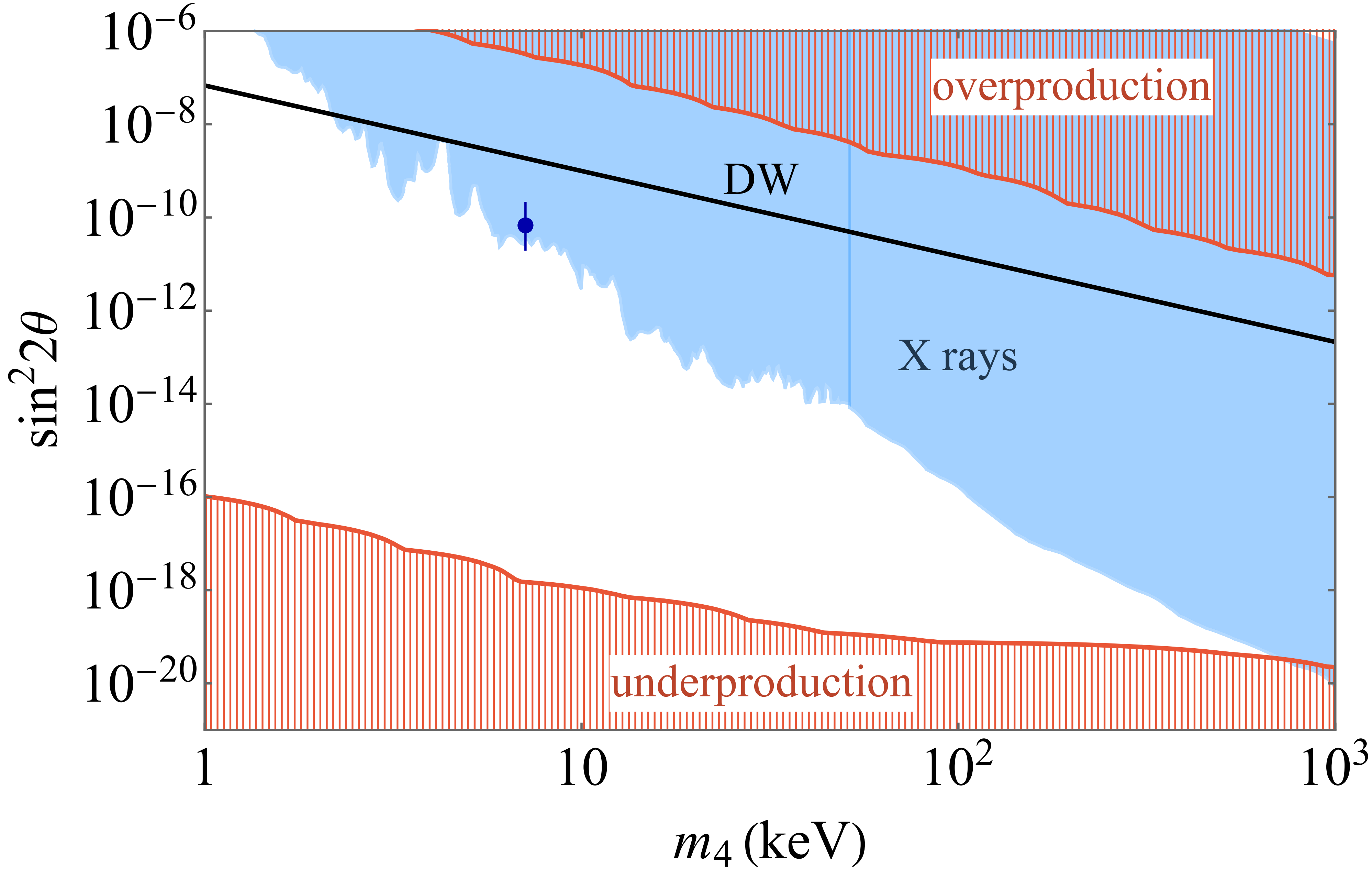
Numerical Result



Varying θ and m_4, S shape curve sweeps across the plane

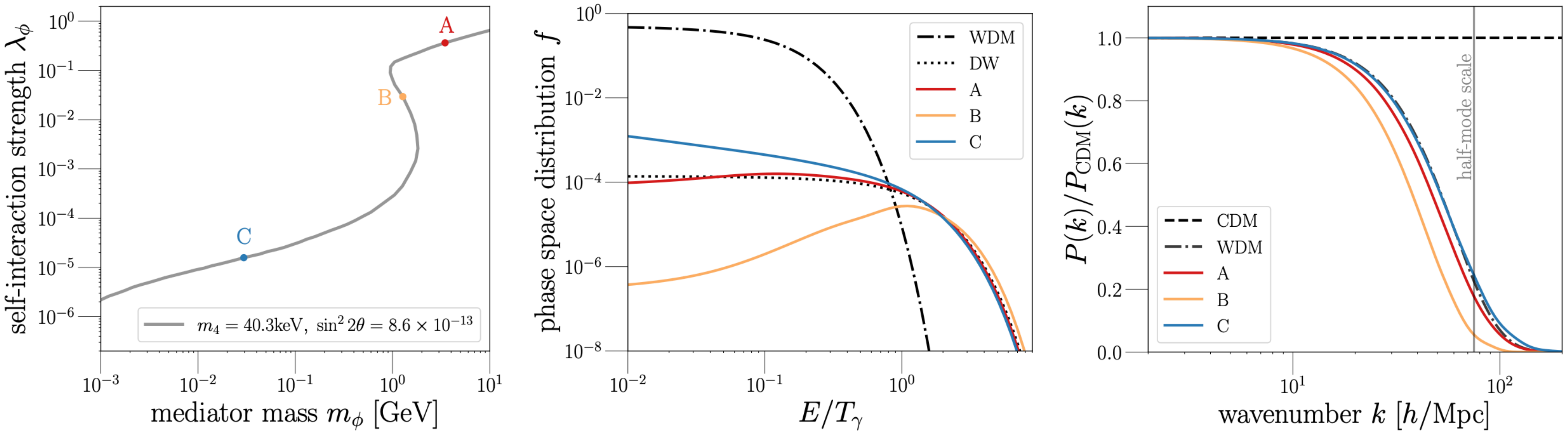
de Gouvêa, Sen, Tangarife, YZ, 1910.04901

Open up Wide Parameter Space



de Gouvêa, Sen, Tangarife, YZ, 1910.04901

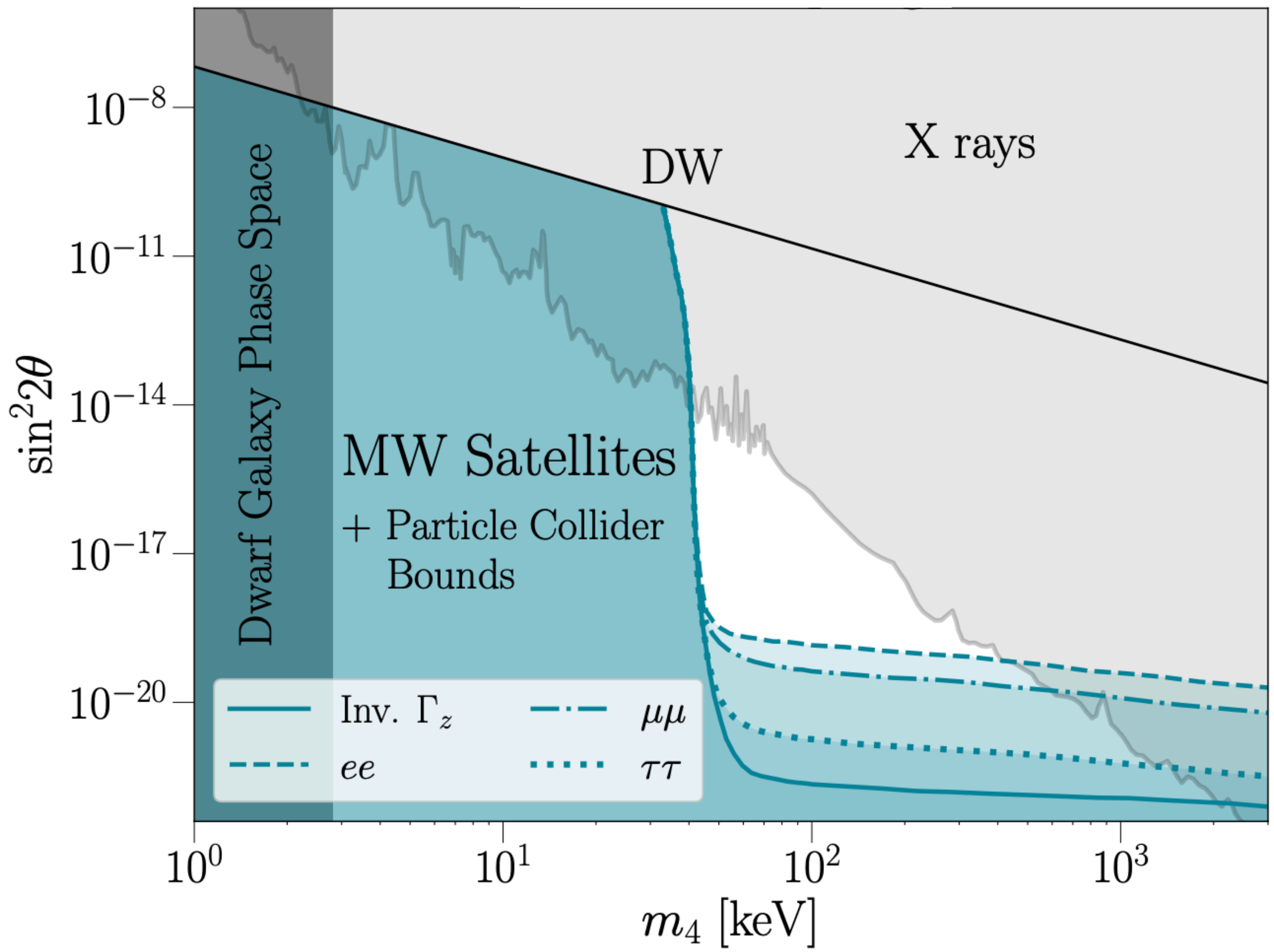
What about the DES Constraint?



Each model point predicts a DM phase space distribution.

An, Gluscevic, Nadler, YZ, 2301.08299

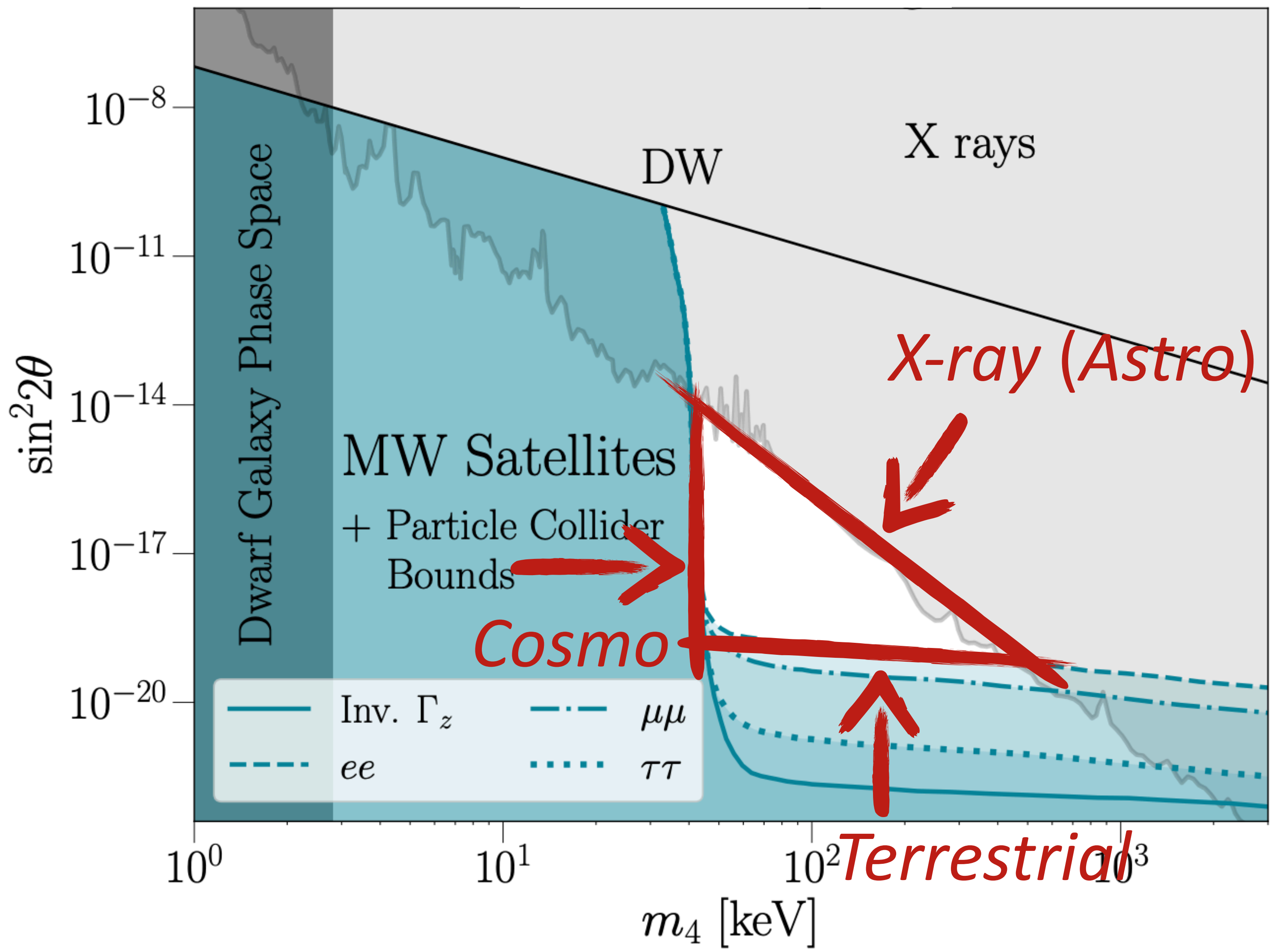
νSI Can Save Sterile Neutrino DM



Lower bound on sterile neutrino dark matter mass, $m_4 > 37.4$ keV.

An, Gluscevic, Nadler, YZ, 2301.08299

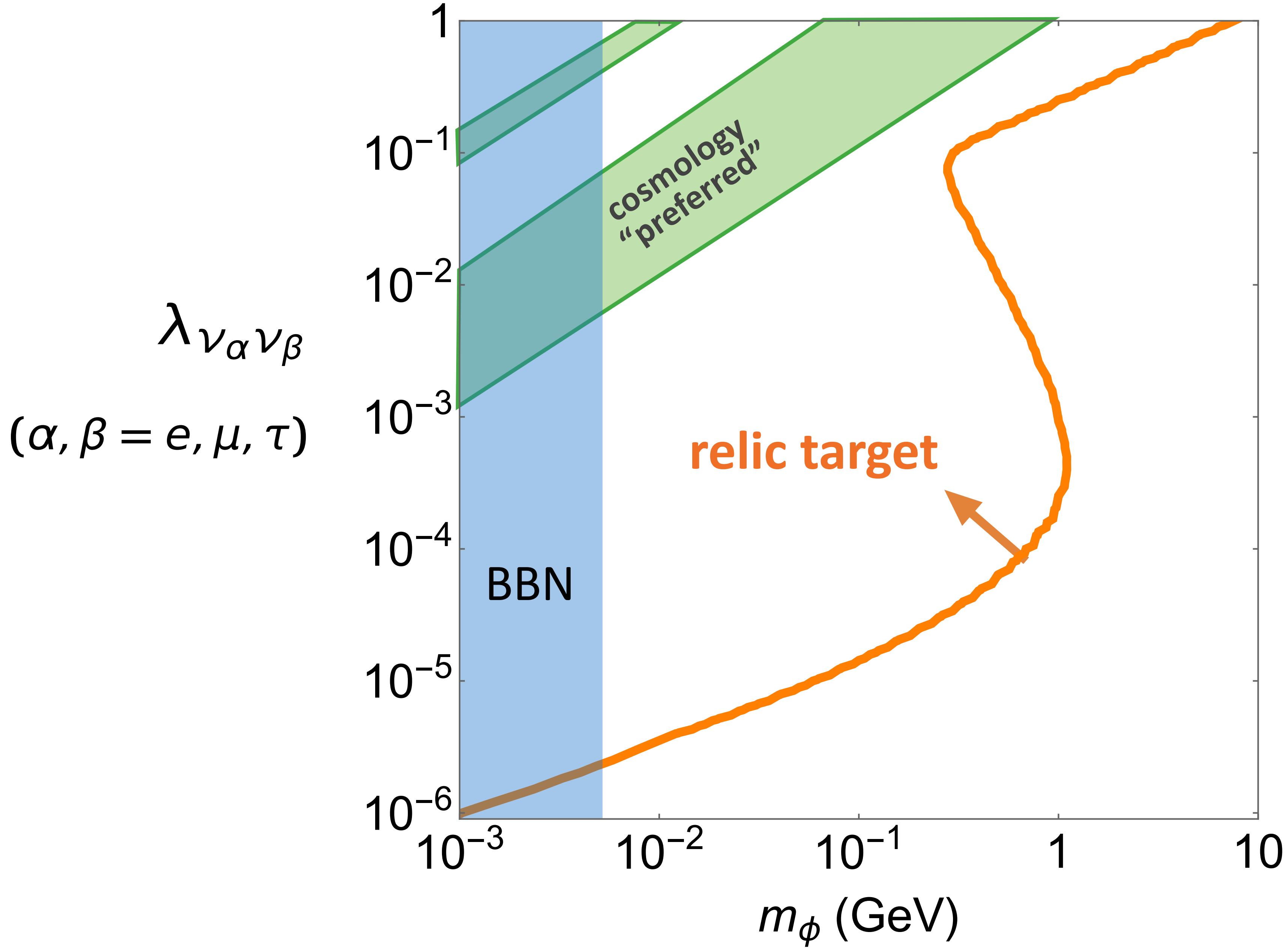
vSI Can Save Sterile Neutrino DM



Lower bound on sterile neutrino dark matter mass, $m_4 > 37.4$ keV.

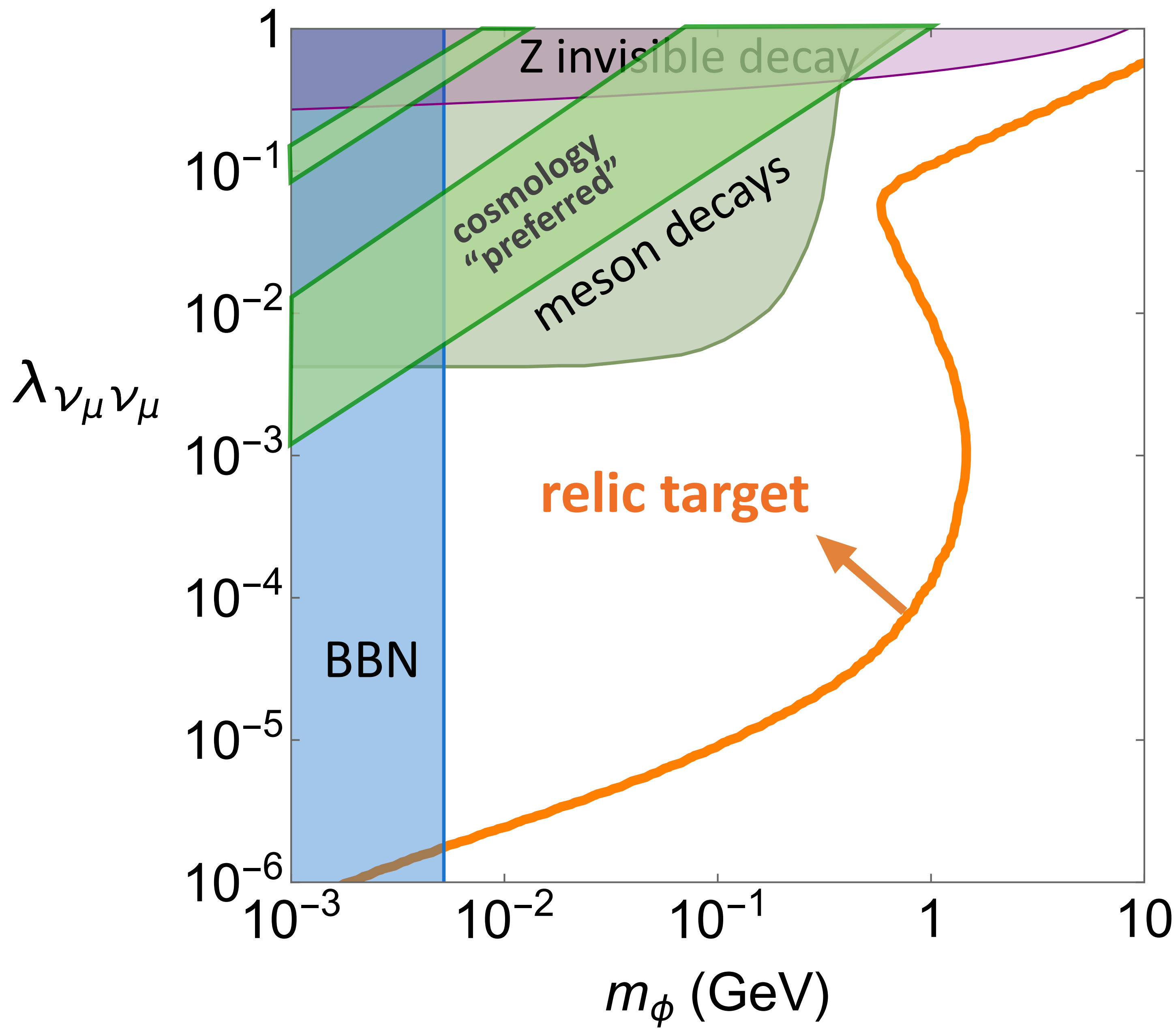
An, Gluscevic, Nadler, YZ, 2301.08299

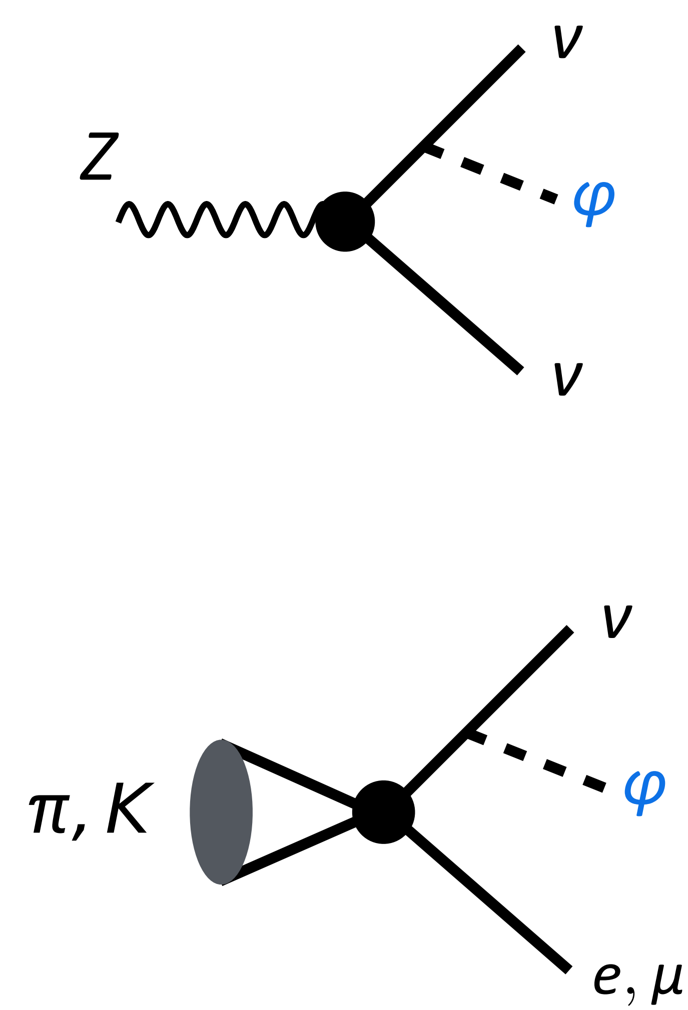
νSI Targets



$\lambda_{\nu_\alpha \nu_\beta}$
$(\alpha, \beta = e, \mu, \tau)$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-3}
10^{-2}
10^{-1}
1
10
m_ϕ (GeV)
cosmology "preferred"
relic target
BBN

Known Limits

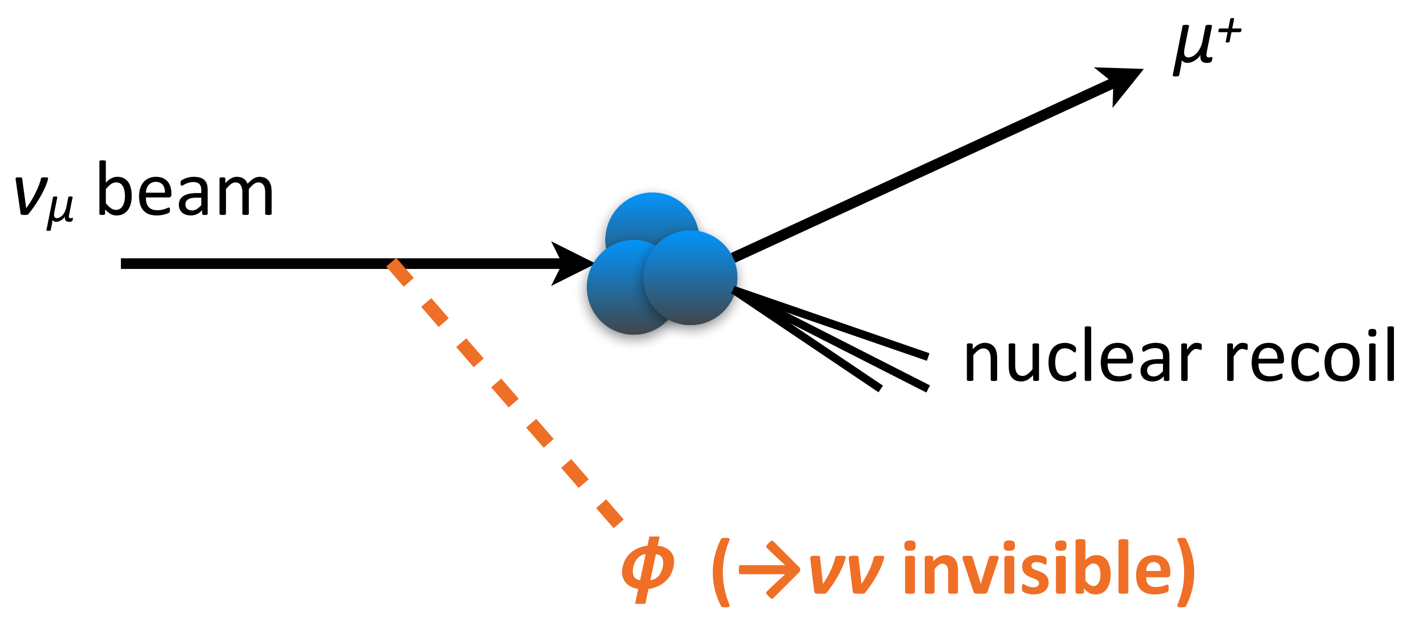




Barger, Keung, Pakvasa, 1982

Heintze et al, 1979; PIENU, 2020; NA62, 2021

Mono-Neutrino Signal

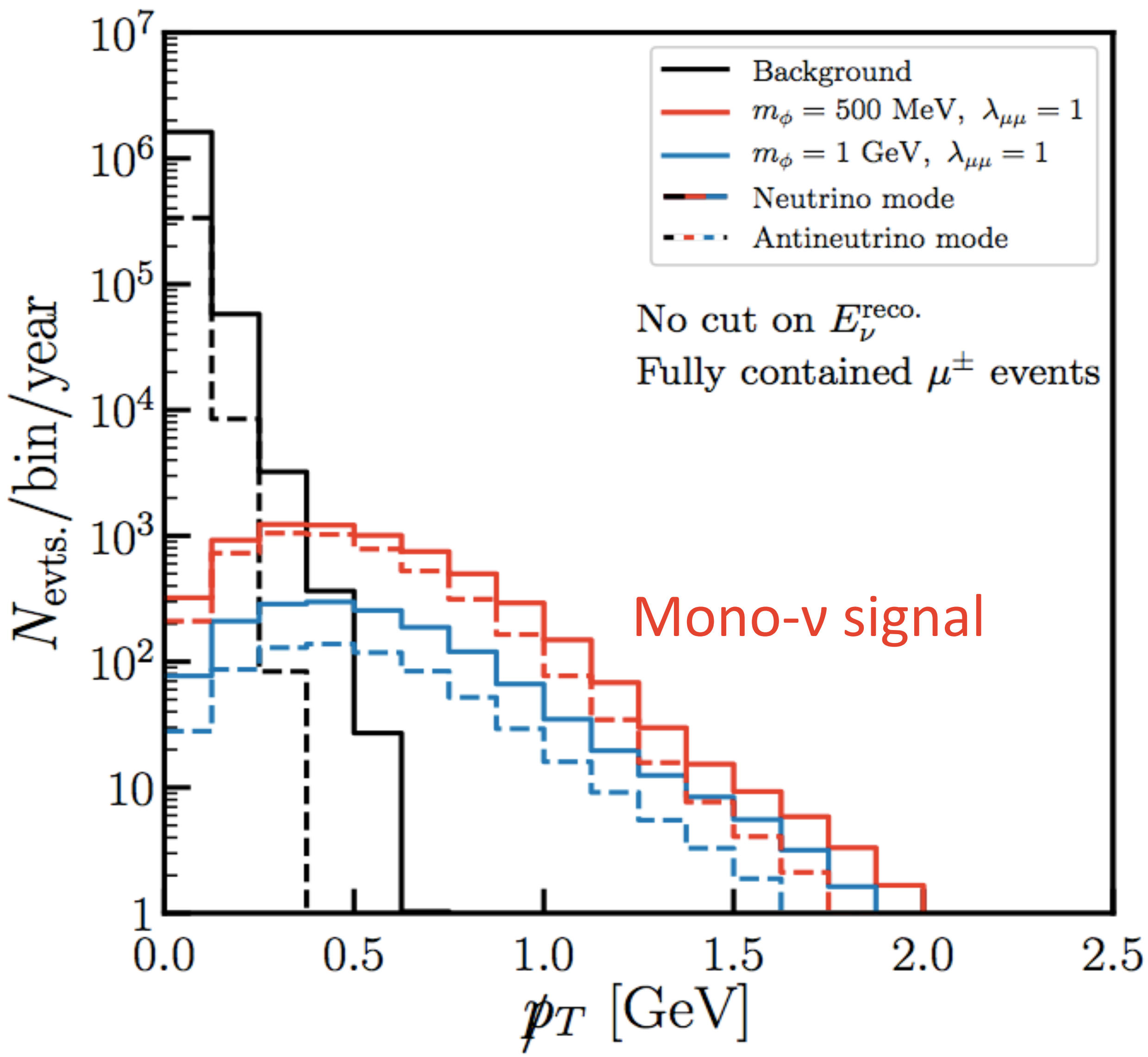


Beamstrahlung process: $\nu_\mu + N \rightarrow \mu^+ + N' + \phi$, features

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

Kelly, YZ, 1901.01259

Theorists' Simulation

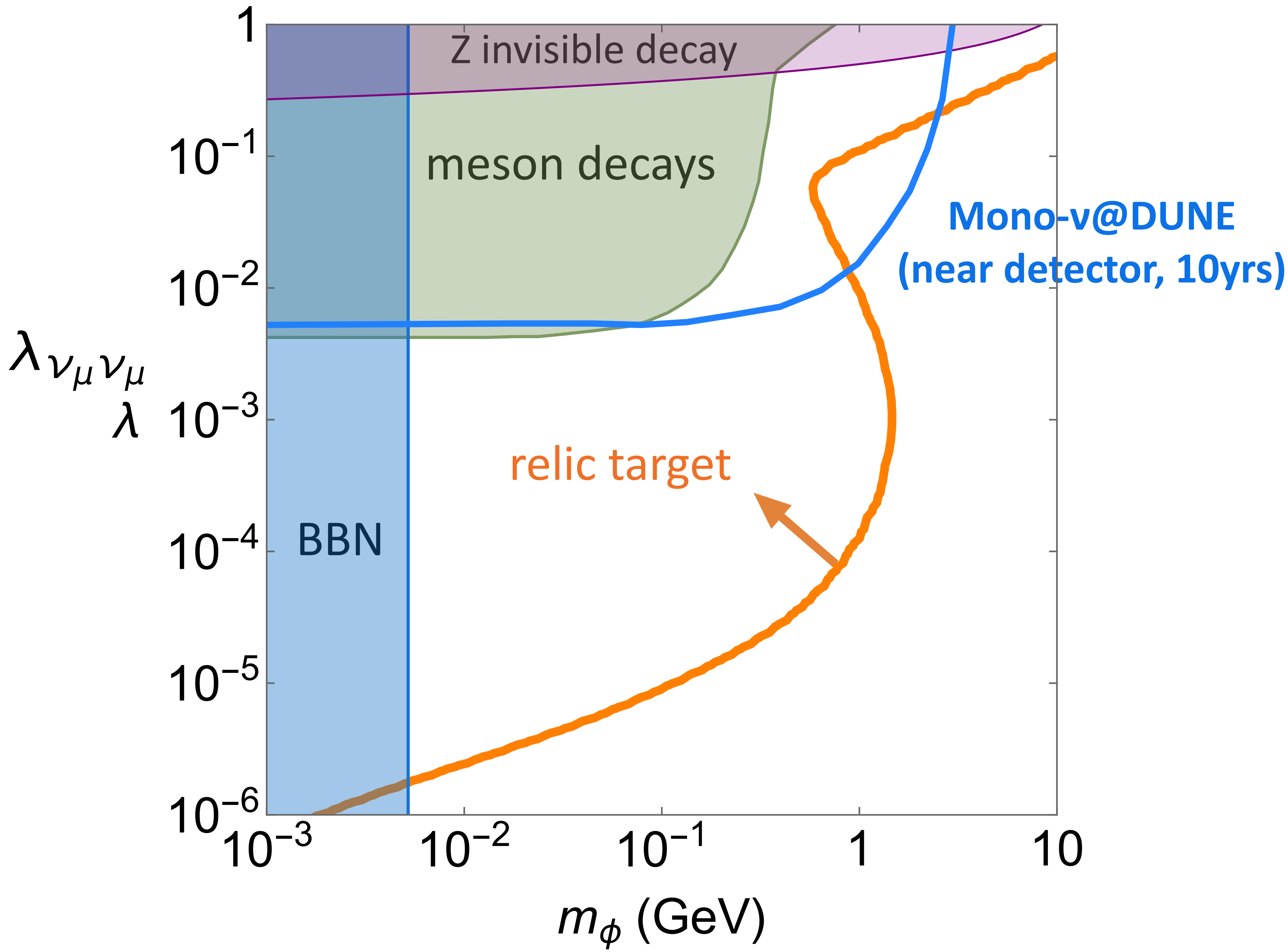


Nucleon level simulation, smearing

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

DUNE CDR, 2015

Useful Probe of Relic Target



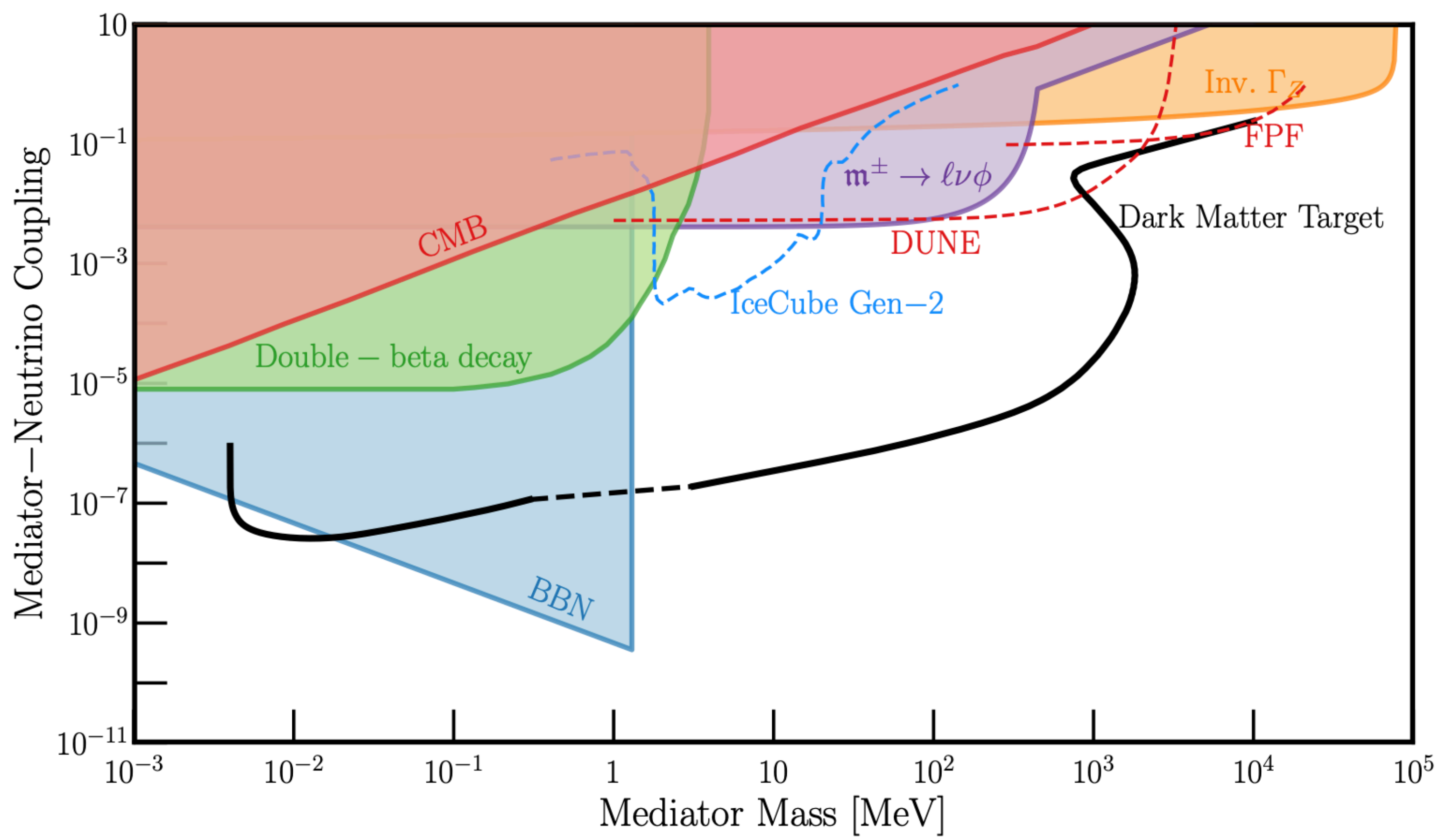
Kelly, YZ, 1901.01259

More ideas to explore νSI, see

Neutrino Self-Interactions: A White Paper

Editors: Nikita Blinov, Mauricio Bustamante, Kevin J. Kelly, Yue Zhang

Jeffrey M. Berryman,[1,2] Nikita Blinov,[3] Vedran Brdar,[4,5] Thejs Brinckmann,[6,7] Mauricio Bustamante,[8] Francis-Yan Cyr-Racine,[9] Anirban Das,[10] André de Gouvêa,[5] Peter B. Denton,[11] P. S. Bhupal Dev,[12] Bhaskar Dutta,[13] Ivan Esteban,[14,15] Damiano Fiorillo,[8,16,17] Martina Gerbino,[7] Subhajit Ghosh,[18] Tathagata Ghosh,[19] Evan Grohs,[20] Tao Han,[21] Steen Hannestad,[22] Matheus Hostert,[23,24] Patrick Huber,[25] Jeffrey Hyde,[26,27] Kevin J. Kelly,[4,28] Felix Kling,[29] Zhen Liu,[24] Massimiliano Lattanzi,[7] Marilena Loverde,[30] Sujata Pandey,[31] Ninetta Saviano,[17,32] Manibrata Sen,[33] Ian M. Shoemaker,[25] Walter Tangarife,[34] Yongchao Zhang,[35] Yue Zhang[36]



Issue of Gauge Invariance

Neutrinophilic scalar interaction can arise from a dimension-6 operator. Higgs VEV projects out neutrinos from doublet.

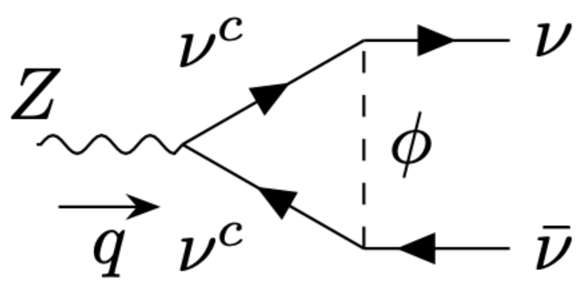
$$\lambda \nu^2 \phi \quad \leftarrow \quad \frac{(LH)^2 \phi}{\Lambda^2}$$

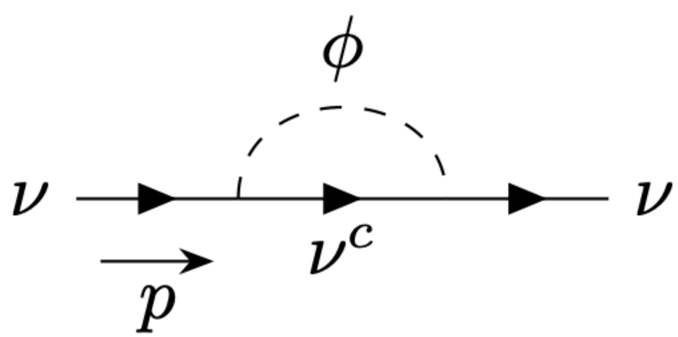
Good enough for exploring low-energy, tree-level processes well below the EW scale.

But issue of gauge invariance would strike again at loop level.

Of phenomenological relevance for $\lambda \sim \mathcal{O}(1)$.

Radiative Correction to EW Couplings





$$\delta g_Z(q^2, m_\phi^2) = g_Z^0 \left(\Gamma_{Z\nu\bar{\nu}}(q^2, m_\phi^2) + \frac{\partial \Sigma_\nu(p, m_\phi^2)}{\partial \not{p}} \right)$$

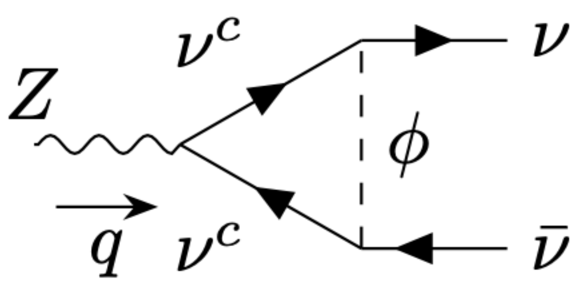
$$\delta g_W(m_\phi^2) = g_W^0 \frac{1}{2} \frac{\partial \Sigma_\nu(p, m_\phi^2)}{\partial \not{p}}$$

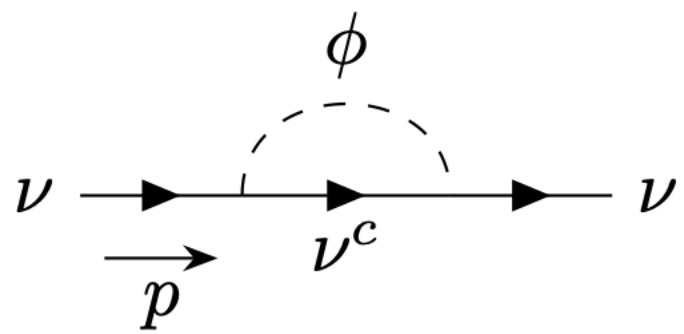
At one loop level, $Z\nu\bar{\nu}, W\ell\nu$ couplings are UV divergent.

Unlike regular Yukawa, ϕ interaction turns neutrino into anti-neutrino — extra minus sign from $Z\nu^c\bar{\nu}^c$ vertex.

YZ, 2411.05070

Radiative Correction to EW Couplings





$$\delta g_Z(q^2, m_\phi^2) = g_Z^0 \left(\Gamma_{Z\nu\bar{\nu}}(q^2, m_\phi^2) + \frac{\partial \Sigma_\nu(p, m_\phi^2)}{\partial \not{p}} \right)$$

$$\delta g_W(m_\phi^2) = g_W^0 \frac{1}{2} \frac{\partial \Sigma_\nu(p, m_\phi^2)}{\partial \not{p}}$$

At one loop level, $Z\nu\bar{\nu}, W\ell\nu$ couplings are UV divergent.

Unlike regular Yukawa, ϕ interaction turns neutrino into anti-neutrino — extra minus sign from $Z\nu^c\bar{\nu}^c$ vertex.

But finiteness implied by Ward identity!

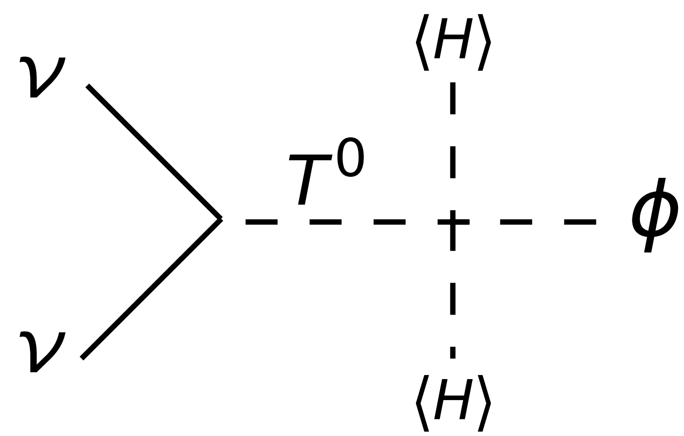
YZ, 2411.05070

Gauge Invariant UV Completion

Concrete example, introduce SU(2) triplet scalar T, hyper charge 2

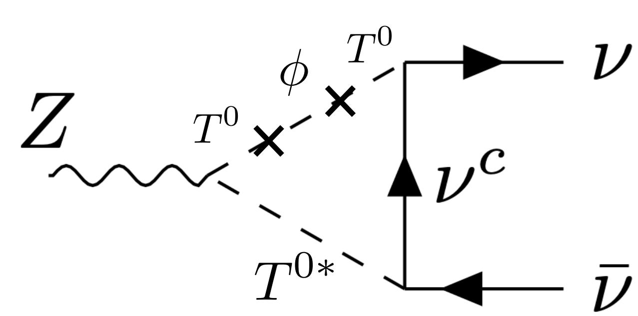
$$\mathcal{L}_{\rm UV} = y_1 \bar{L}^c T L + y_2 H^T T^\dagger H \phi + \text{h.c}$$

$\nu\nu\phi$ interaction from:



$$\Rightarrow \quad \frac{(LH)^2\phi}{\Lambda^2}$$

Additional loop diagram from T-ϕ mixing that saves the day to render UV divergence cancellation.



Generic Form of Couplings

If ϕ is the only BSM state below EW scale, one-loop form factor is completely fixed by Ward identity and decoupling theorem.

$$g_Z(q^2, m_\phi^2, M^2) = g_Z^0 - \frac{g_Z^0|\lambda|^2}{32\pi^2}\left\{\ln\frac{M^2}{m_\phi^2} + 2\int dxdy\left[\ln\left(\frac{M^2}{(1-x-y)m_\phi^2 - xyq^2}\right) + \frac{xyq^2}{(1-x-y)m_\phi^2 - xyq^2}\right] + c_Z\right\}$$

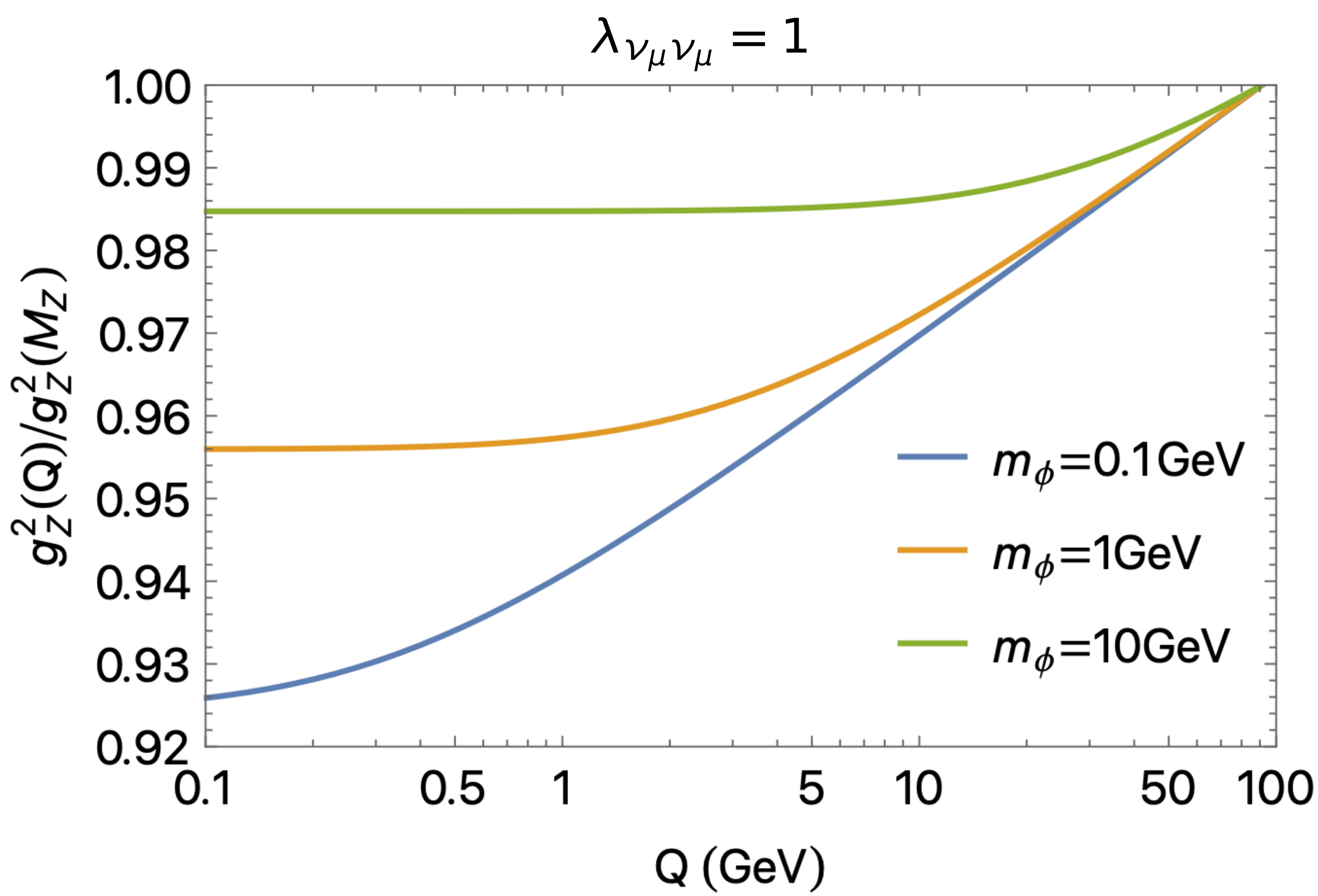
$$g_W(m_\phi^2, M^2) = g_W^0 - \frac{g_W^0|\lambda|^2}{64\pi^2}\left(\ln\frac{M^2}{m_\phi^2} + c_W\right)$$

$$+\mathcal{O}\left(\frac{1}{M}\right)$$

$c_Z = -3/2$, $c_W = 0$ for the triplet extention, M is triplet mass.

YZ, 2411.05070

Neutral Current: Q Dependence



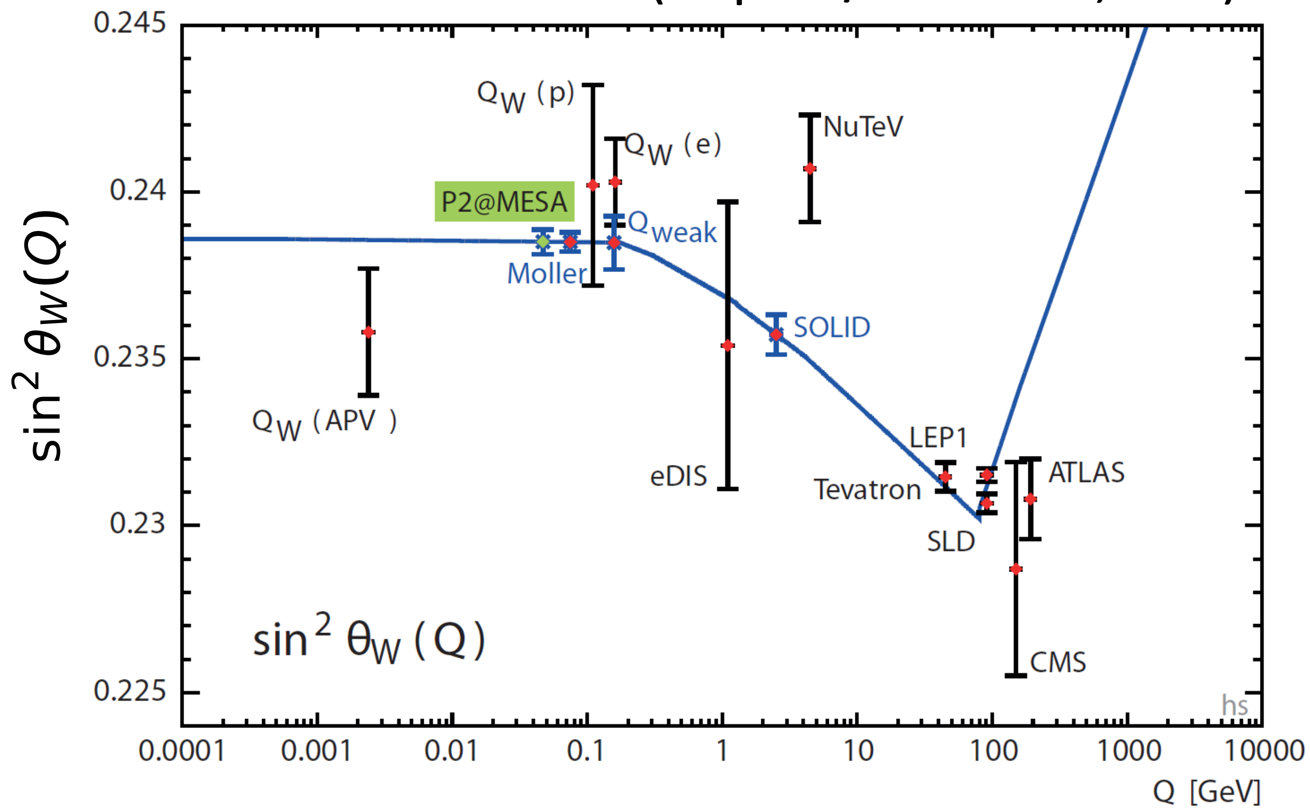
$Q = \sqrt{-q^2}$

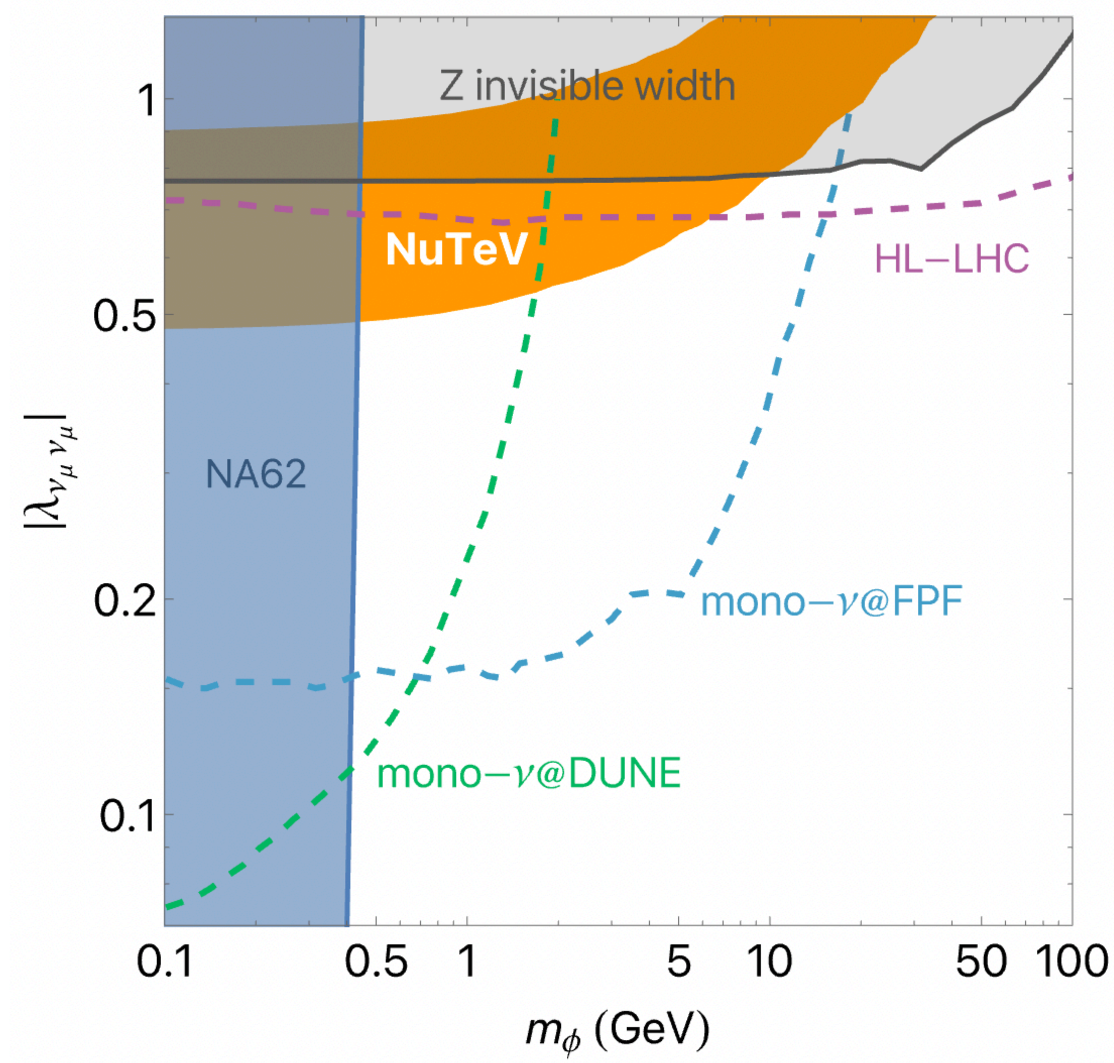
Q dependence thanks to separation of scales between M and m_ϕ

YZ, 2411.05070

Connection to NuTeV "Anomaly"

Zeller et al (hep-ex/0110059, PRL)





NuTeV saw a deficit in neutral to charged-current event ratio

$$R \sim g_Z^2(Q^2)\left[1 - 2\sin^2\theta_W(Q)\right]$$

YZ, 2411.05070

Break the Degeneracy

CEvNS:

$$\sigma_{\nu N} \sim g_Z^2(Q^2) \sin^4 \theta_W(Q)$$

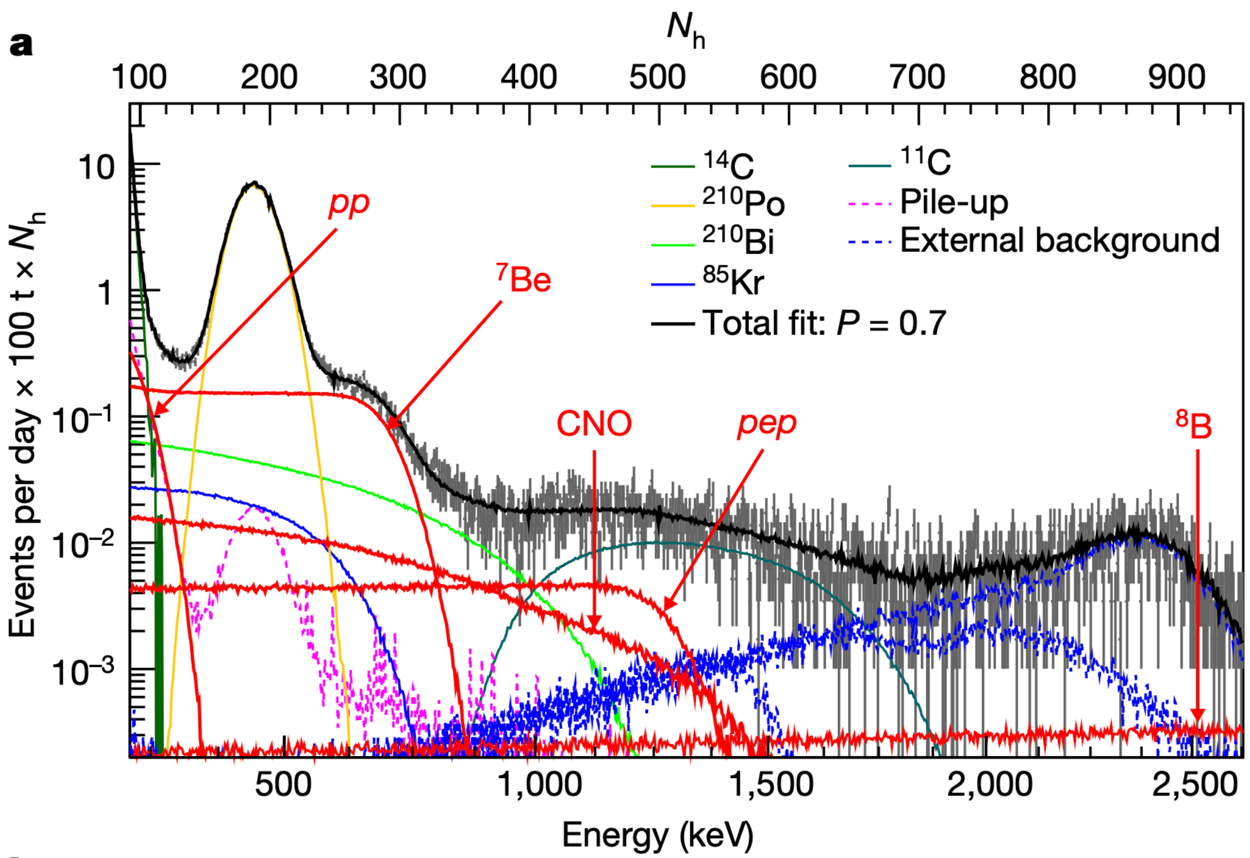
Neutrino/antineutrino-electron scattering:

$$\sigma_{\nu_\mu e} \sim g_Z^2(Q^2) \left[3 - 12 \sin^2 \theta_W(Q) + 16 \sin^4 \theta_W(Q)\right]$$
$$\sigma_{\bar{\nu}_\mu e} \sim g_Z^2(Q^2) \left[1 - 4 \sin^2 \theta_W(Q) + 16 \sin^4 \theta_W(Q)\right]$$

It is possible to disentangle the Q dependences in $Z\nu\bar{\nu}$ coupling and the weak mixing angle.

YZ, 2411.05070

vSI versus Solar Neutrino Flux



BOREXINO Collaboration, 2020

Measured ^{7}Be neutrino flux:

$$(4.99 \pm 0.11^{+0.06}_{-0.08}) \times 10^9$$

Standard solar model prediction:

$$4.93 \times (1 \pm 6\%) \times 10^9$$

Percent level measurement of flux is sensitive to $\nu\nu\phi$ coupling in the range 0.1-1, & apply to all flavours.

S. Foroughi-Abari, YZ, in progress

Conclusion

Neutrino self-interaction much stronger than in the SM is well motivated: cosmo data, origin of dark matter abundance.

Not so elusive in the presence of a neutrinophilic mediator below the electroweak scale.

Rich opportunities for testing such a hypothesis with upcoming cosmological and terrestrial experiments.

Thanks!