Novel Neutrino Self-interaction Can Save Sterile Neutrino Dark Matter

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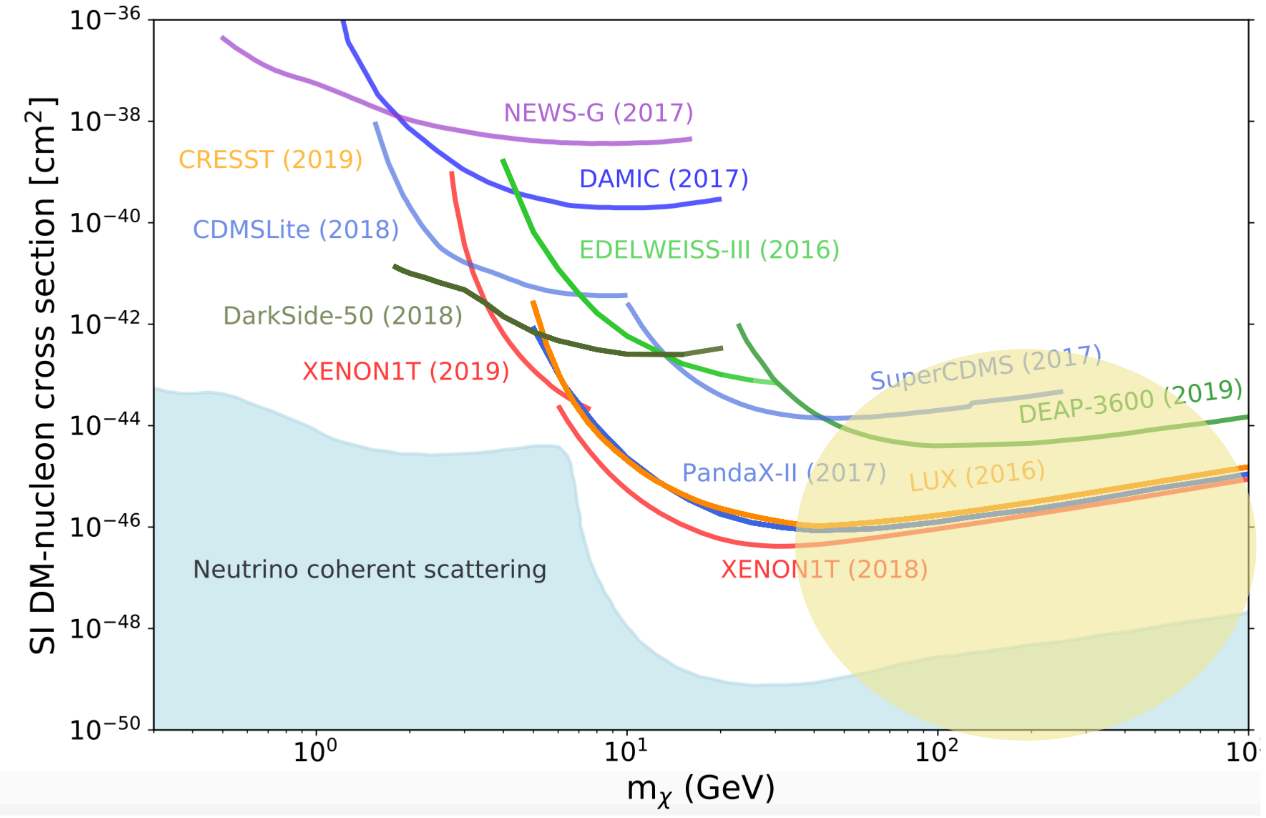
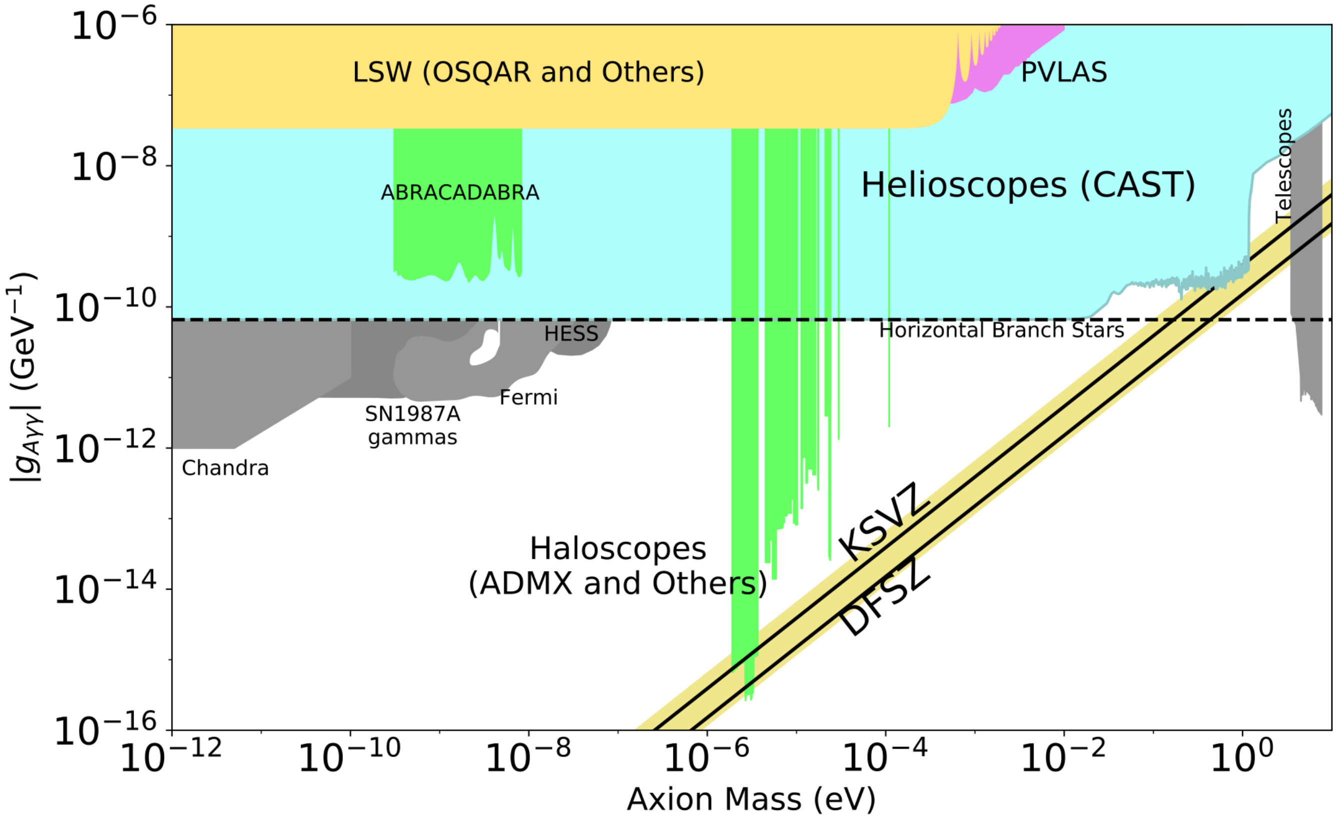
2024 Mitchell Conference on Collider, Dark Matter, and Neutrino Physics, Texas A&M University

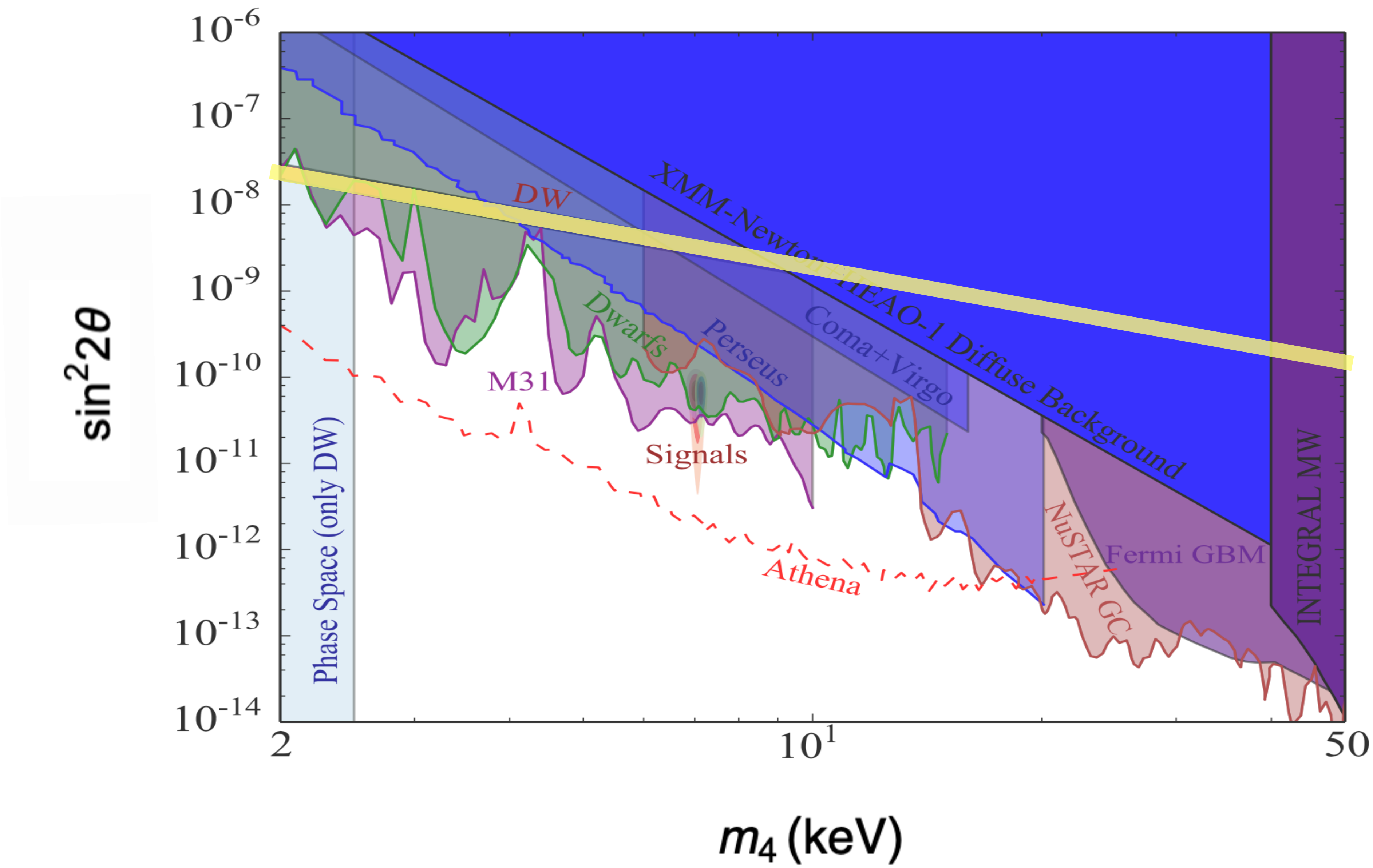
WIMP and Axion





Some dark matter candidates still live well.

Sterile Neutrino: game over?



Abazajian (Physics Reports 2017)

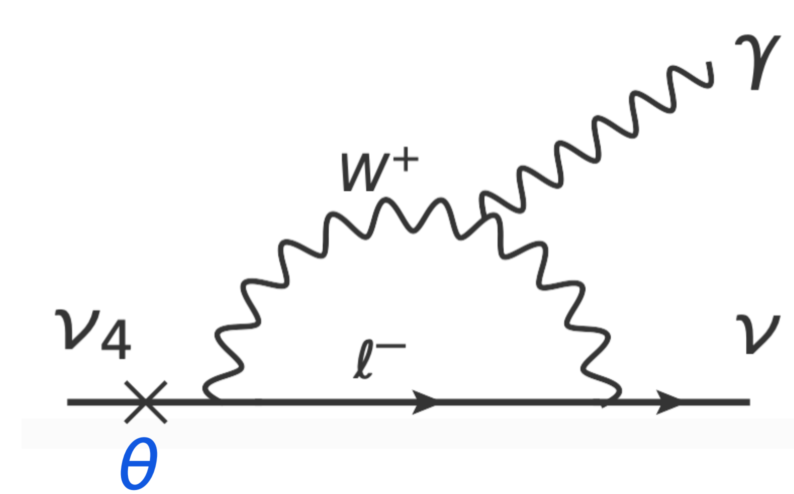
Sterile Neutrino

Introduce a gauge singlet fermion, mix it with SM neutrinos

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

Flavour eigenstates: ν_a active, weakly interacting, ν_s has no other interactions. θ is active-sterile neutrino mixing in the vacuum.

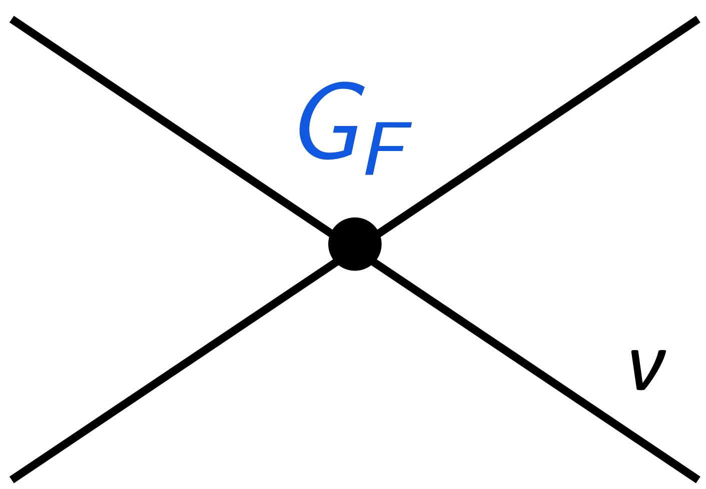
Very simple: only two parameters.

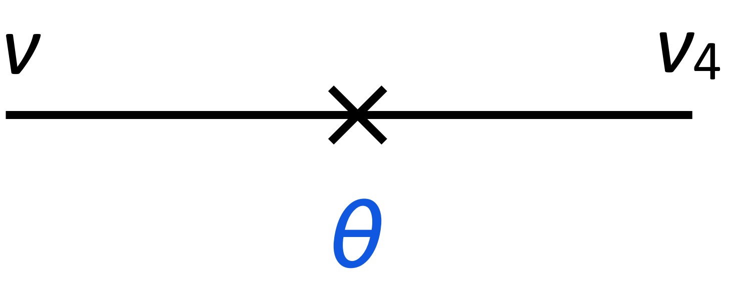


Dodelson-Widrow Mechanism

DM production via neutrino oscillation in the early universe.

Two important ingredients:



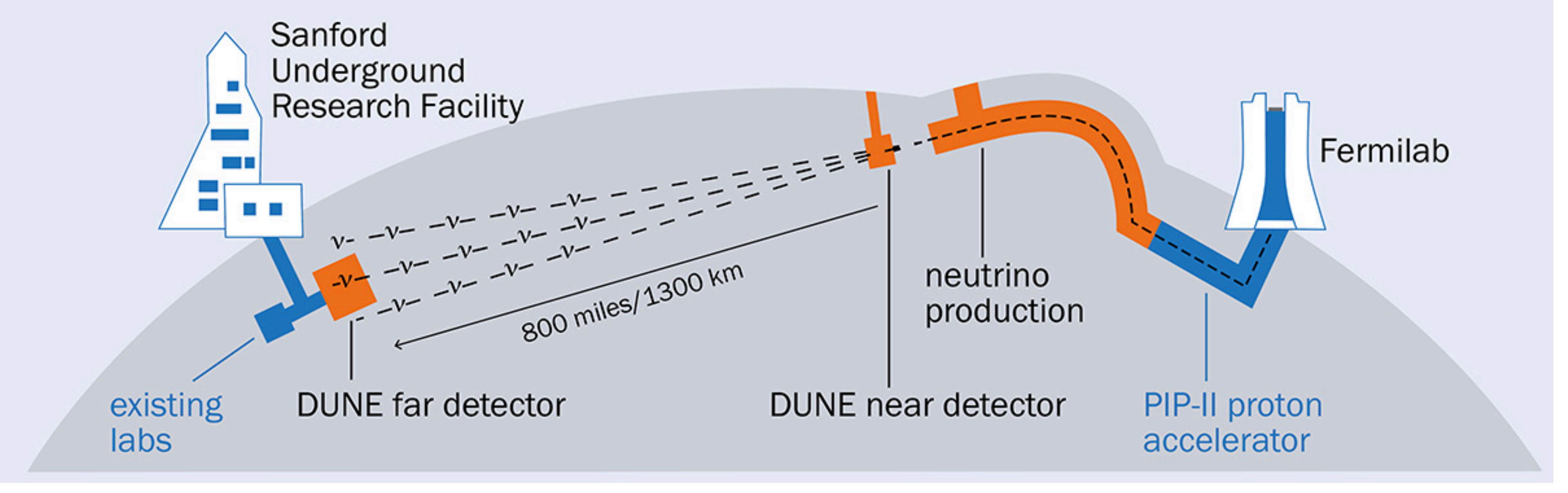


Dodelson, Widrow (PRL 1994)

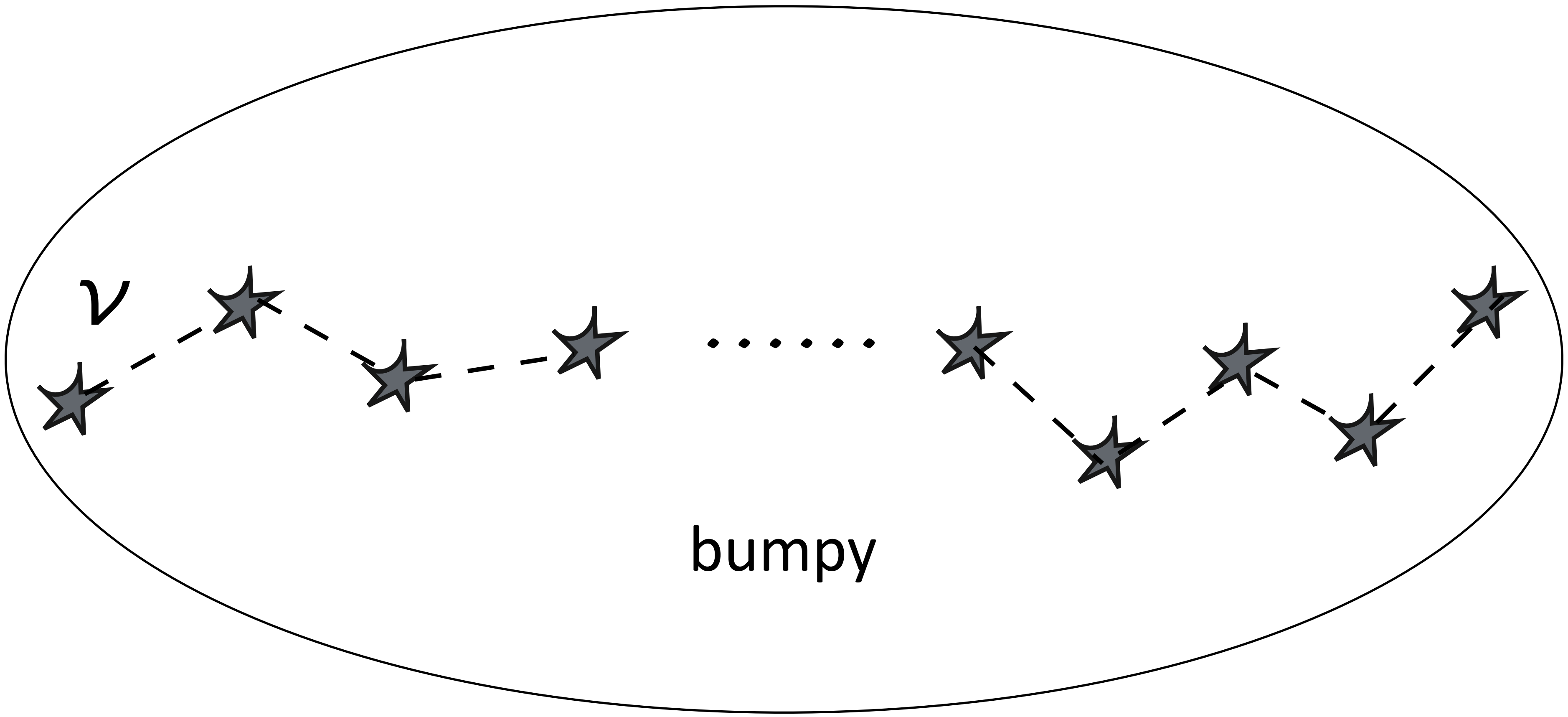
Neutrino Oscillation Phenomenon

Flavour conversion among active neutrinos flavours can happen.

For example:

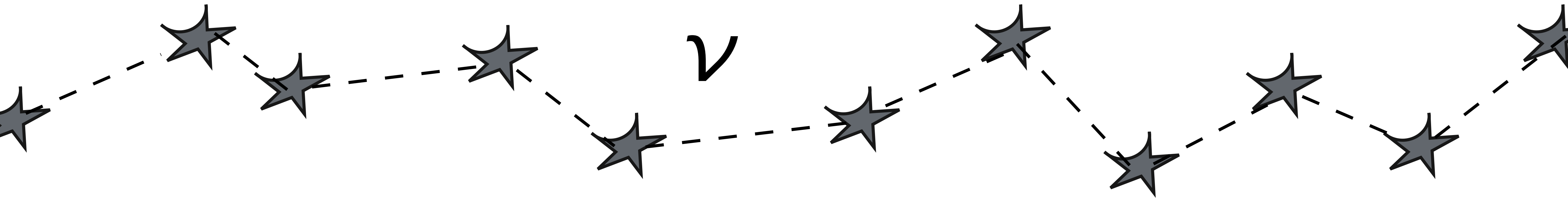


Neutrinos in Early Universe



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

Collisional Oscillation



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

Active-sterile neutrino oscillation between two weak interactions.

$$\frac{df_4}{d\log(1/T)} = \frac{\Gamma}{4H}\, P_{\nu_\alpha \to \nu_s}\, f_\alpha$$

Oscillation Probability

Active-to-sterile, on each baseline:

$$P_{\nu_a \to \nu_s} = \frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + \qquad + (\Delta \cos 2\theta - V_T)^2}$$

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

θ : vacuum mixing angle

V_T : high temperature potential energy

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

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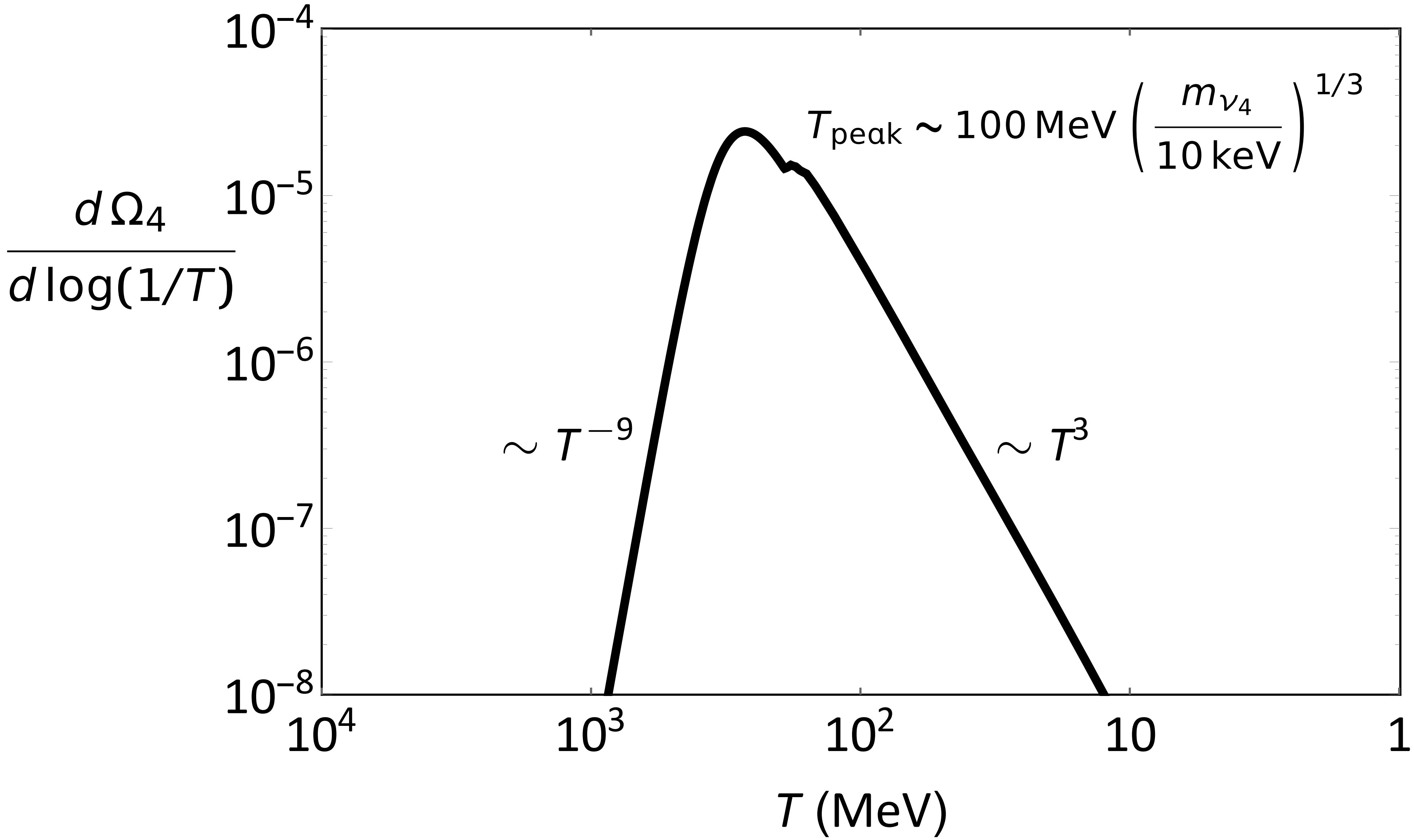
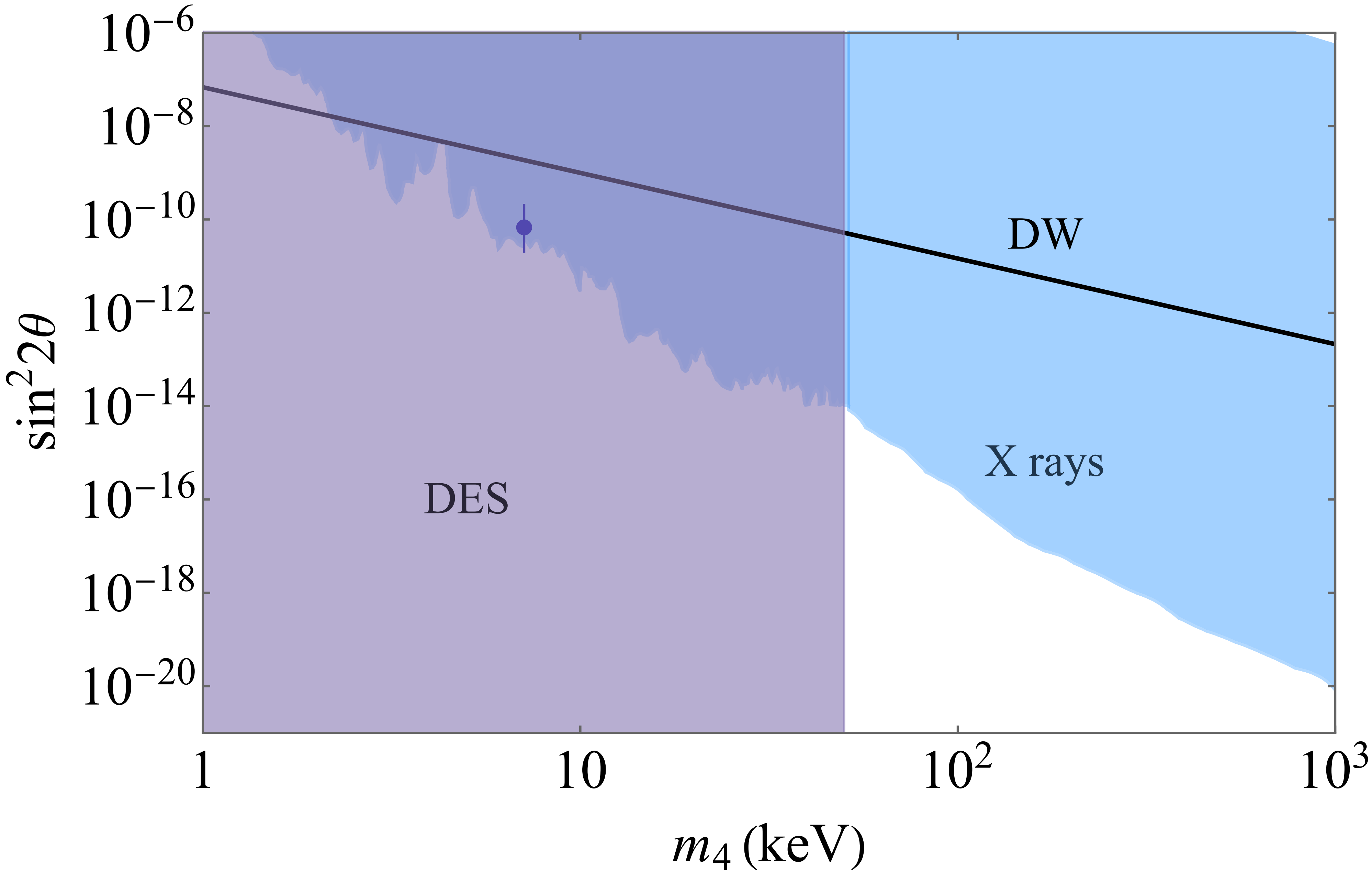
Quantum Zeno effect due to scatterings in early universe plasma.

Production Time Window

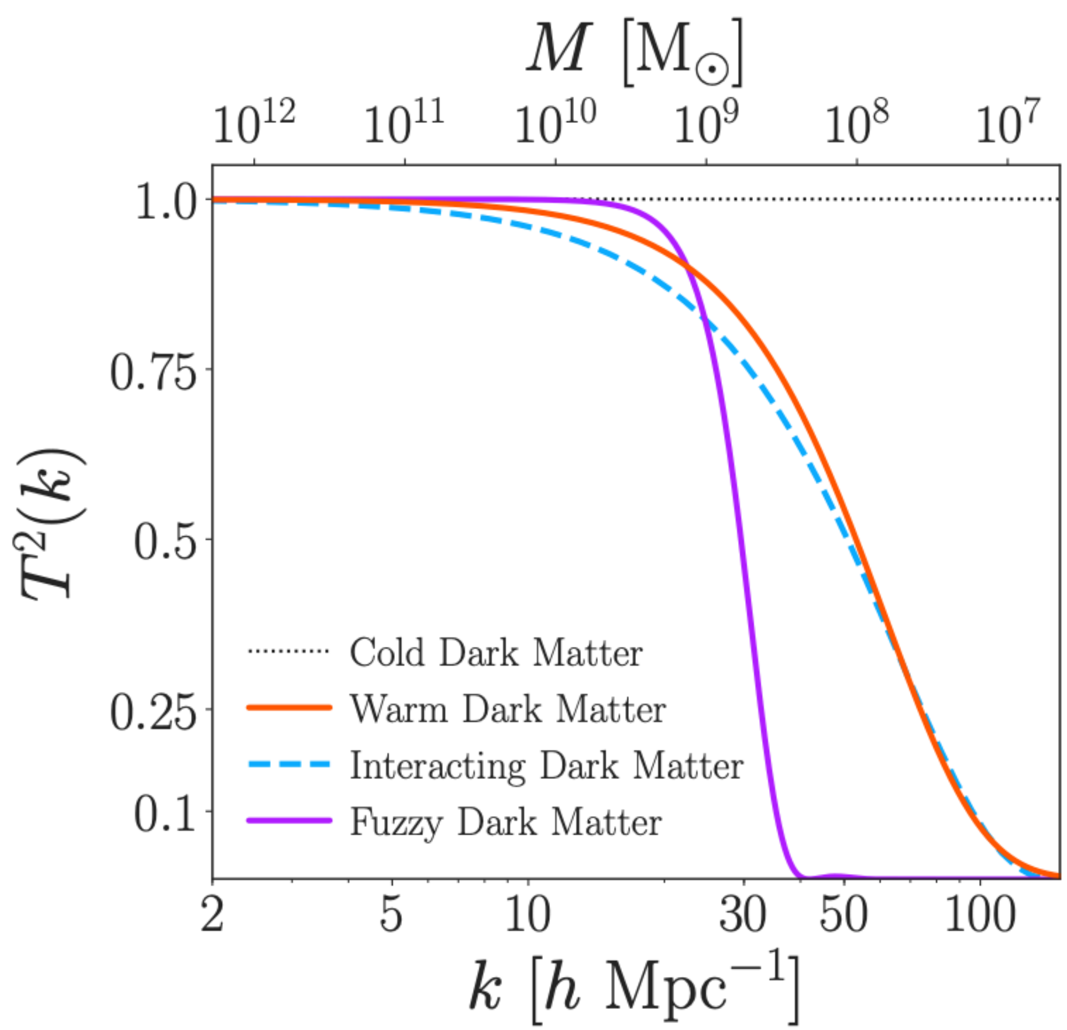


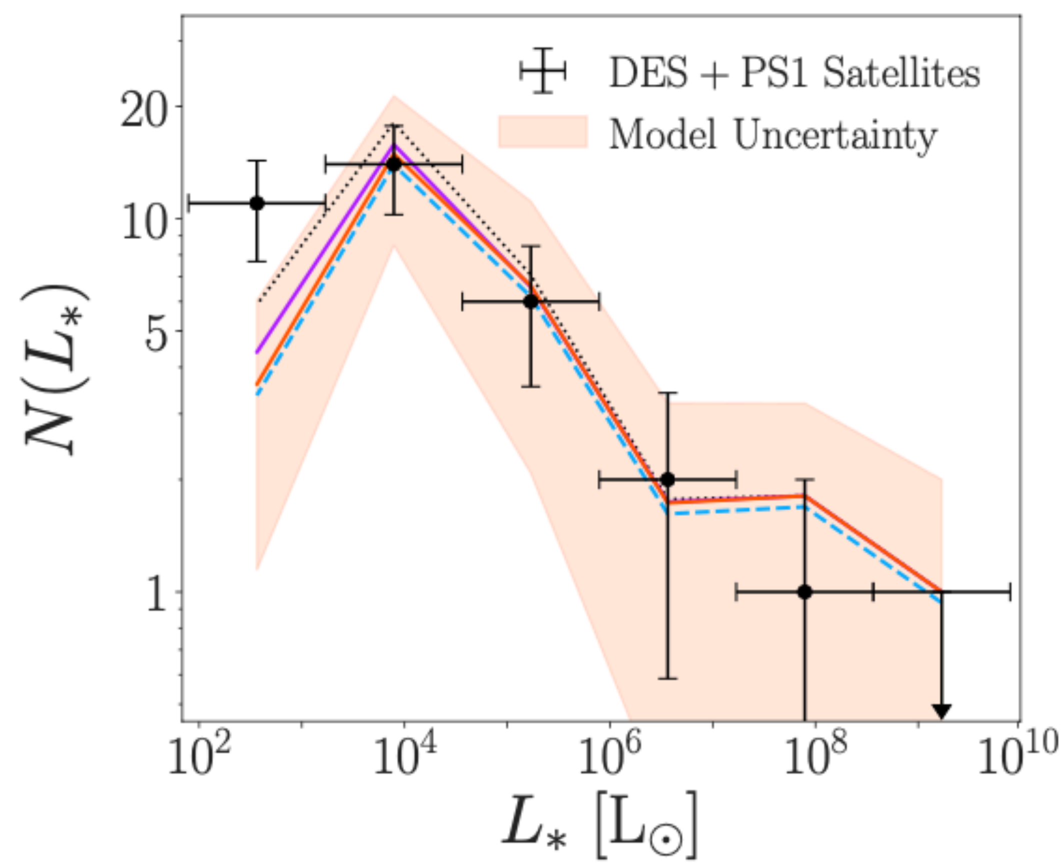
Dodelson, Widrow (PRL 1994)

Dark Matter Relic versus Constraints



DES limit: ultra-faint MW dwarfs





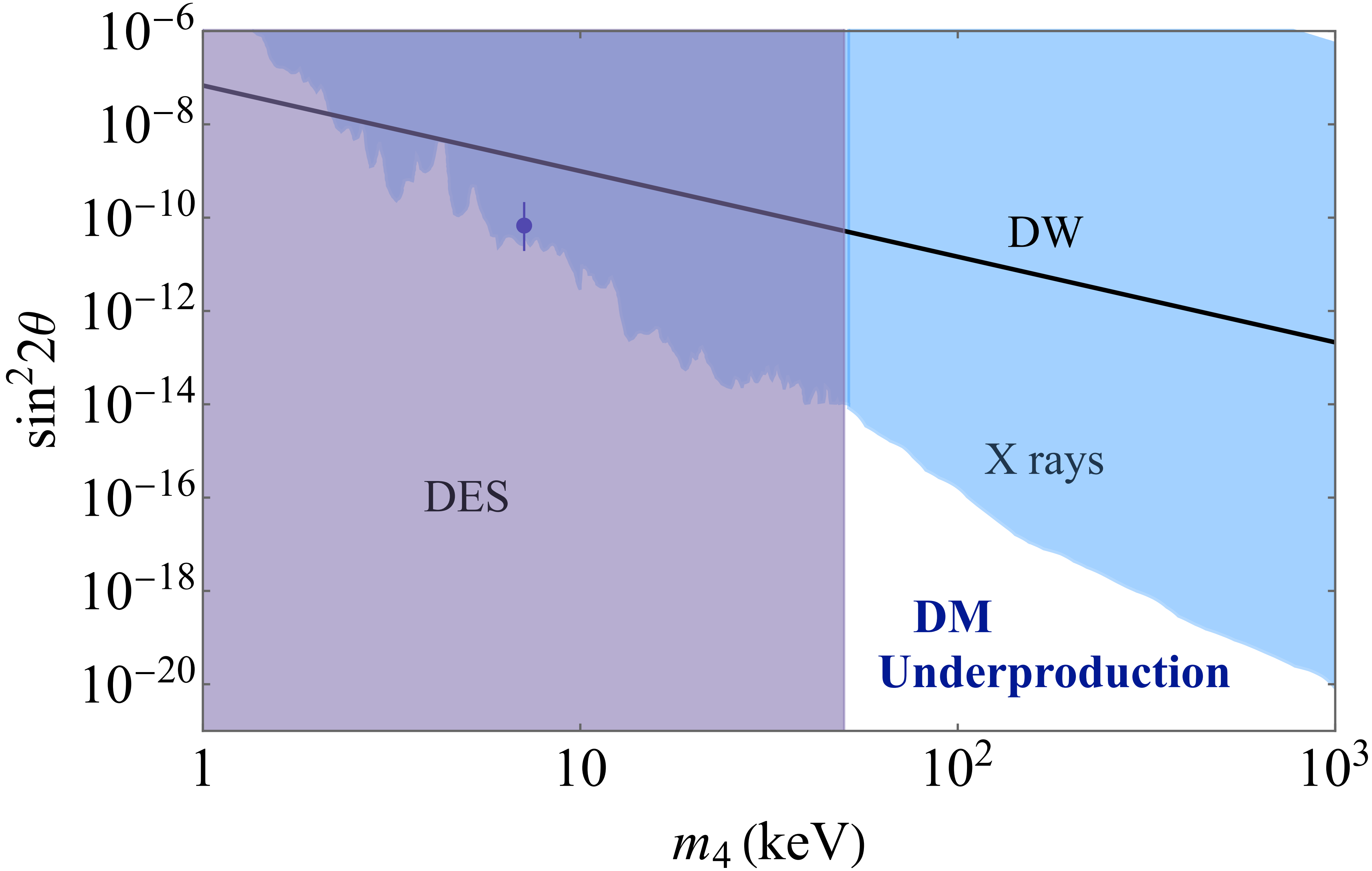
DM free streaming suppresses matter power spectrum at large k.

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

Nadler et al, DES collaboration (PRL 2021)

m_4 > 92 keV, combine w. Lyman-α and lensing, Zelko et al (PRL 2022)

D-W Mechanism Firmly Excluded



Caveats

1) assumed ν_4 comprises 100% dark matter

2) assumed no/little particle-antiparticle asymmetries

3) assumed no DM population at very early times

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The strong interplay hold for ν_4 as O(1) fraction of all the DM.
We keep the standard high.

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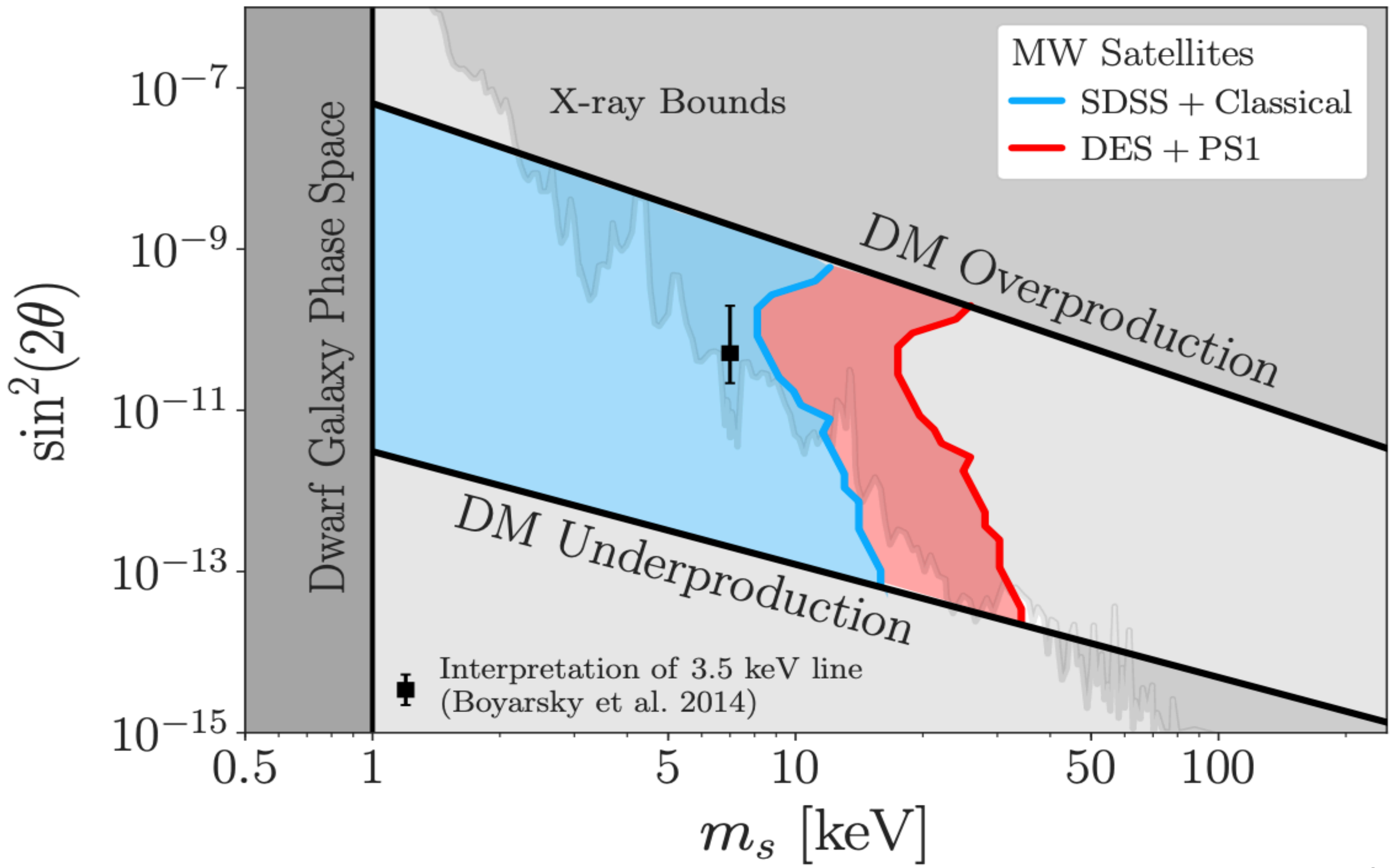

Shi, Fuller (PRL 1999)

Nadler et al, DES collaboration (PRL 2021)

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High scale physics could modify initial abundance.

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Puzzle: does any oscillation mechanism work at all to account for sterile neutrino dark matter relic?

A Simple Idea

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

Intuition: compensate smaller mixing with larger reaction rate.

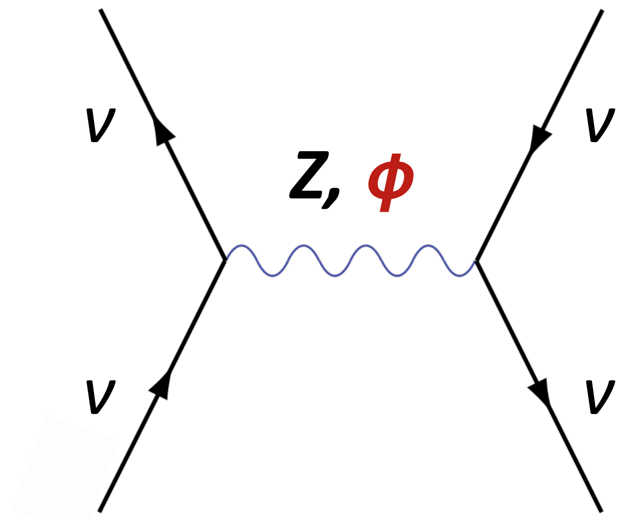
Requirement: new physics enhances Γ but without introducing additional contribution to DM radiative decay rate.

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

A Simple Model

Neutrinophilic mediator

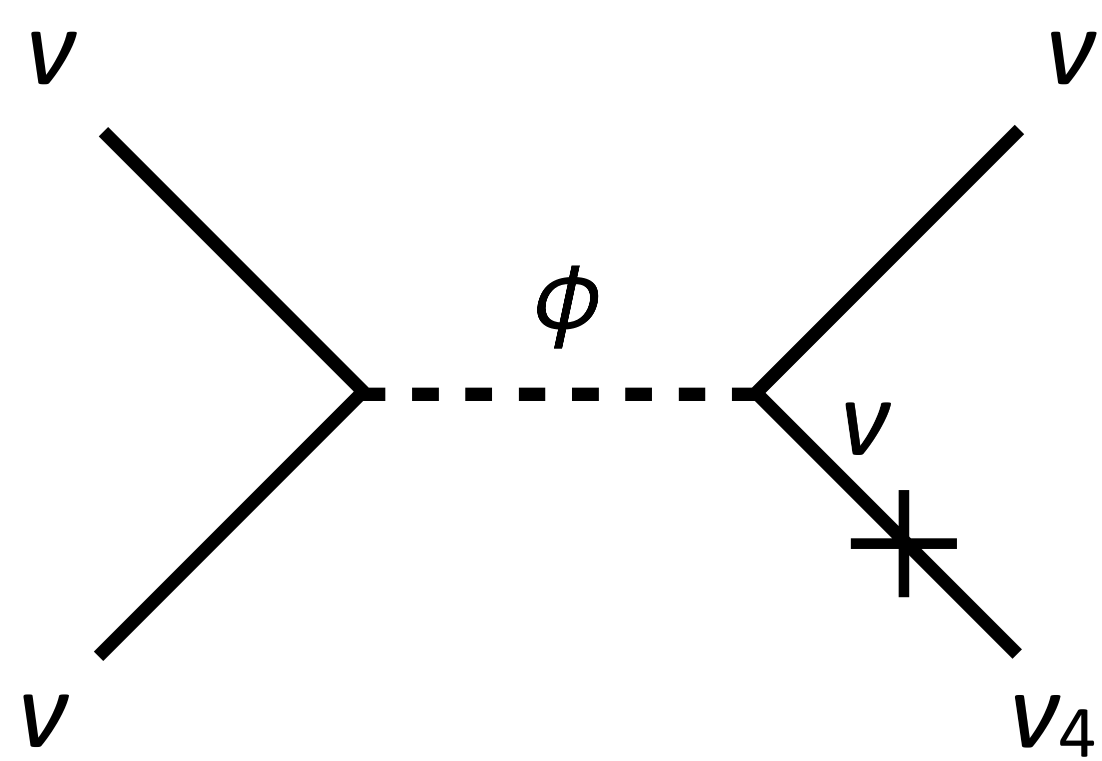
$$\mathcal{L}_{\text{int}} = \frac{(LH)^2}{\Lambda^2}\phi \xrightarrow{\text{EWSB}} \lambda\nu^2\phi$$



ϕ can be a complex or real scalar, SM singlet, light.

PS: in case ϕ is the Majoron, coupling λ is proportional to neutrino mass matrix and $1/F$. (F: lepton number breaking scale)

More Powerful Engine for DM Production

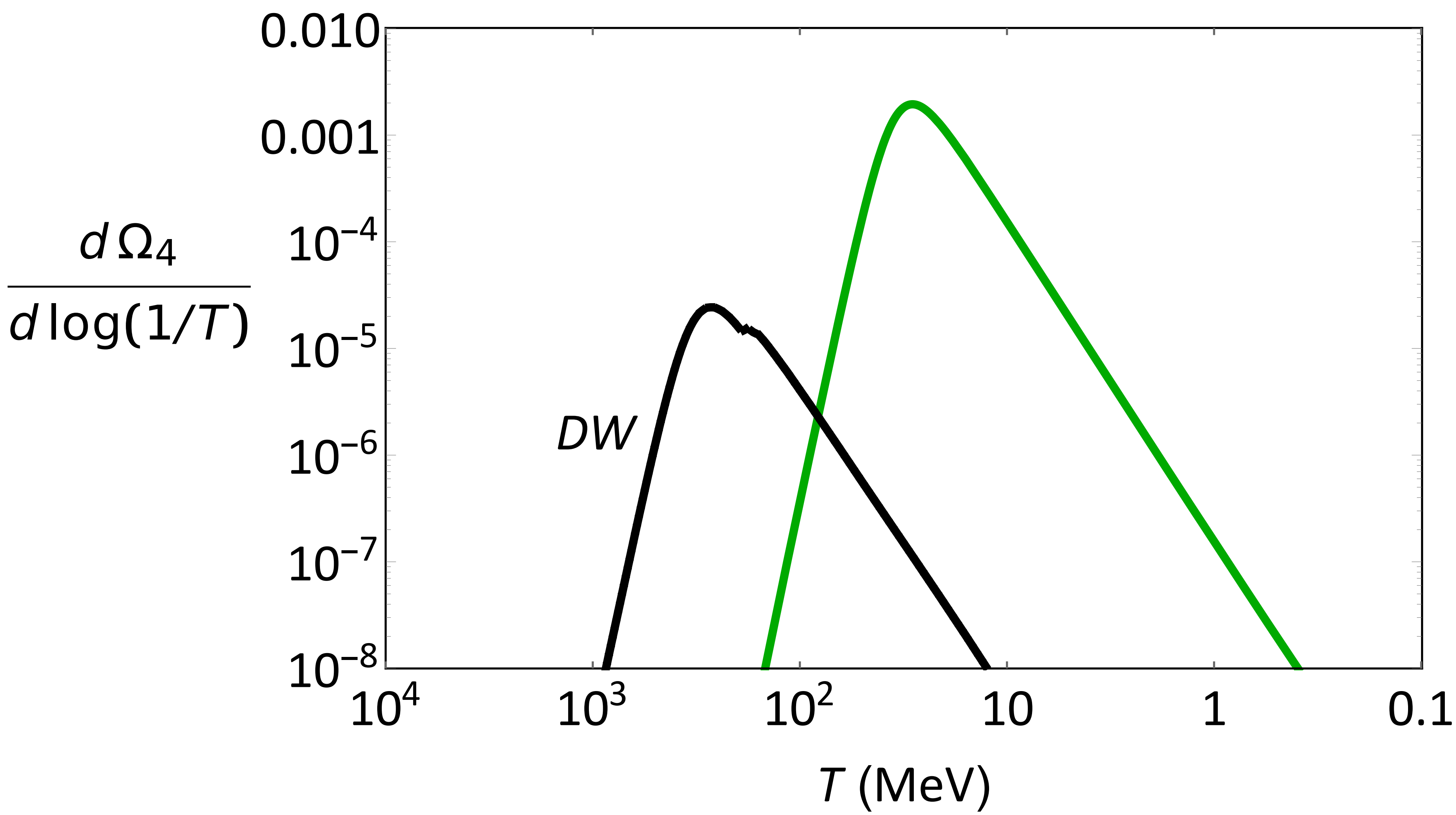


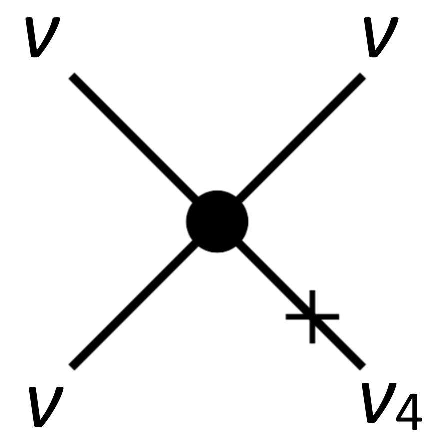
After ν decouples from weak interaction, still talk to themselves, keeps the production of dark matter effective.

de Gouvêa, Sen, Tangarife, YZ (PRL 2020)

Heavy Mediator Scenario

(Copy Dodelson & Windrow)

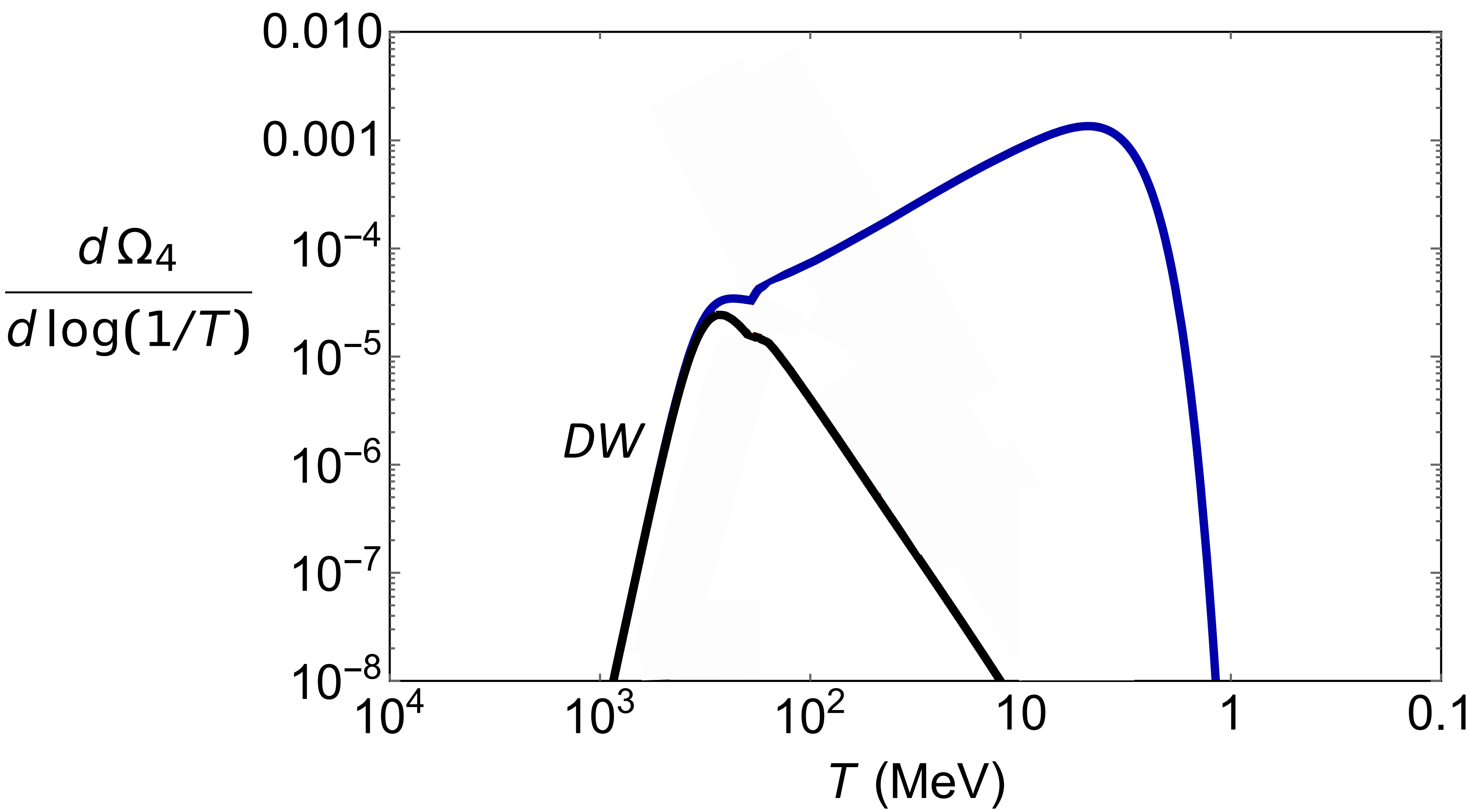


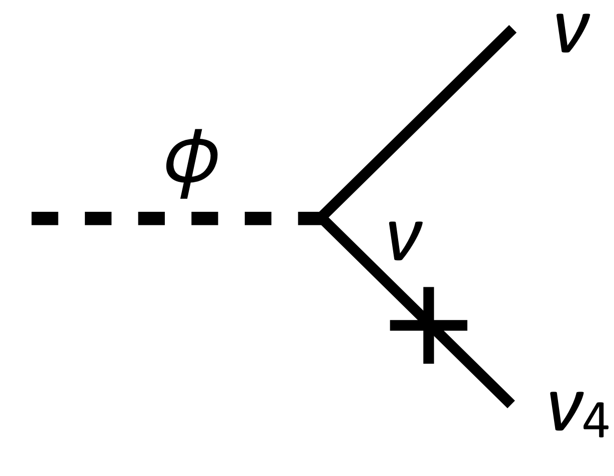


Final relic density: $\Omega_4 \propto \frac{\lambda^3}{m_\varphi^2} \gg \frac{g^3}{M_W^2}$

Light Mediator Scenario

(New production scenario: $\theta_{\text{eff}} \approx \theta$)





When $T>m_\phi$, ϕ can thermalize, on-shell contribution dominates the $\nu\nu \rightarrow \nu\nu_4$ scattering. Effectively, ϕ decays to ν_4.

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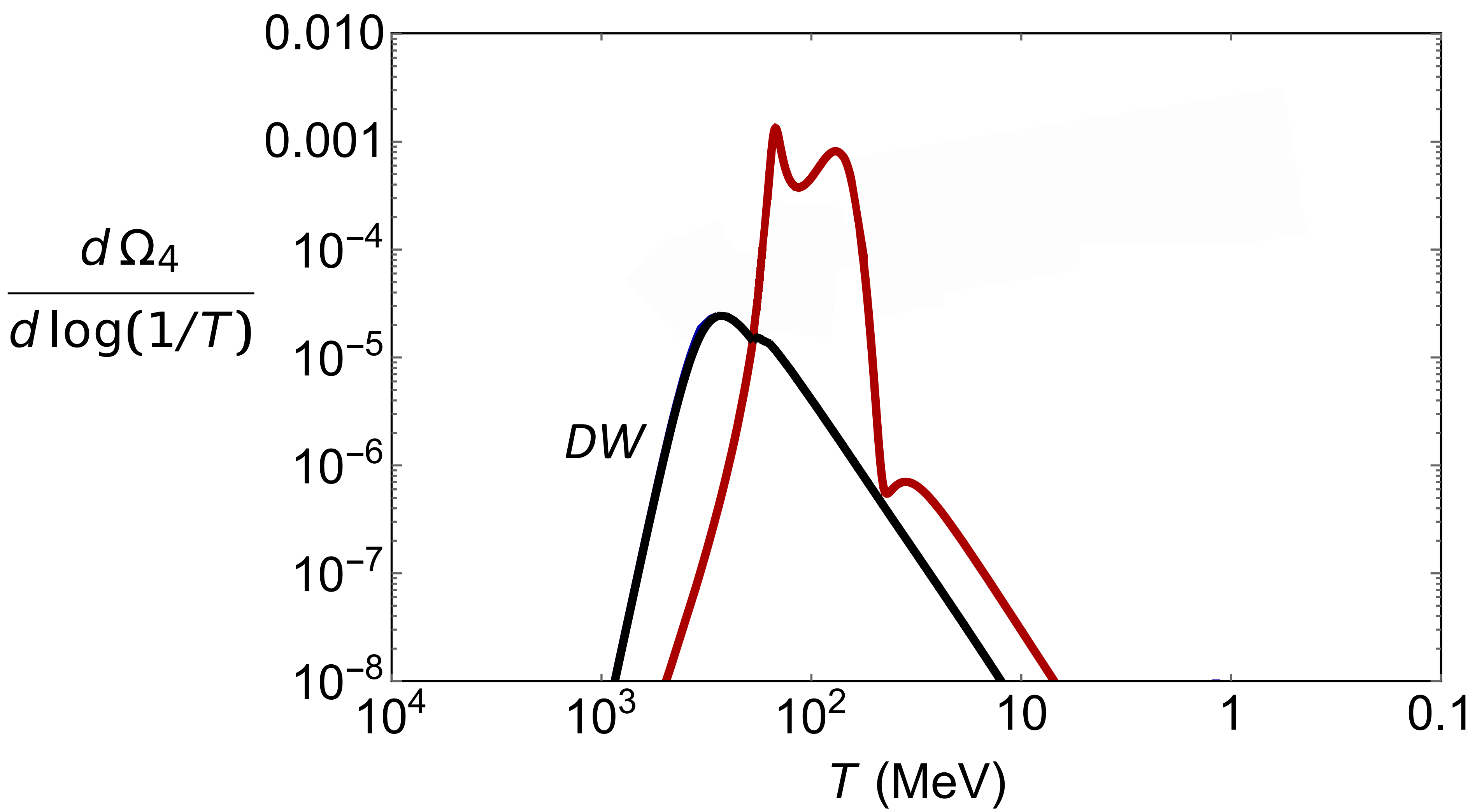

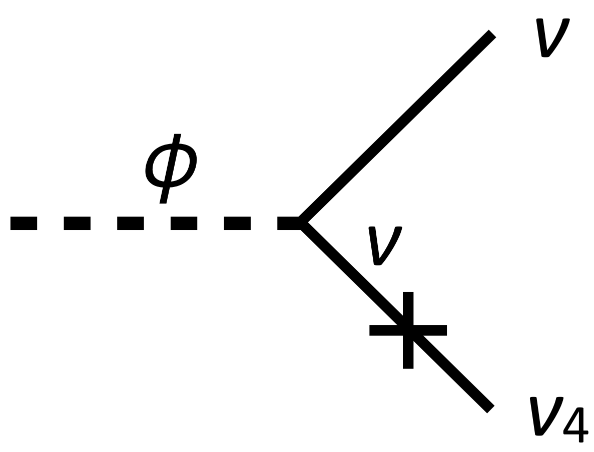

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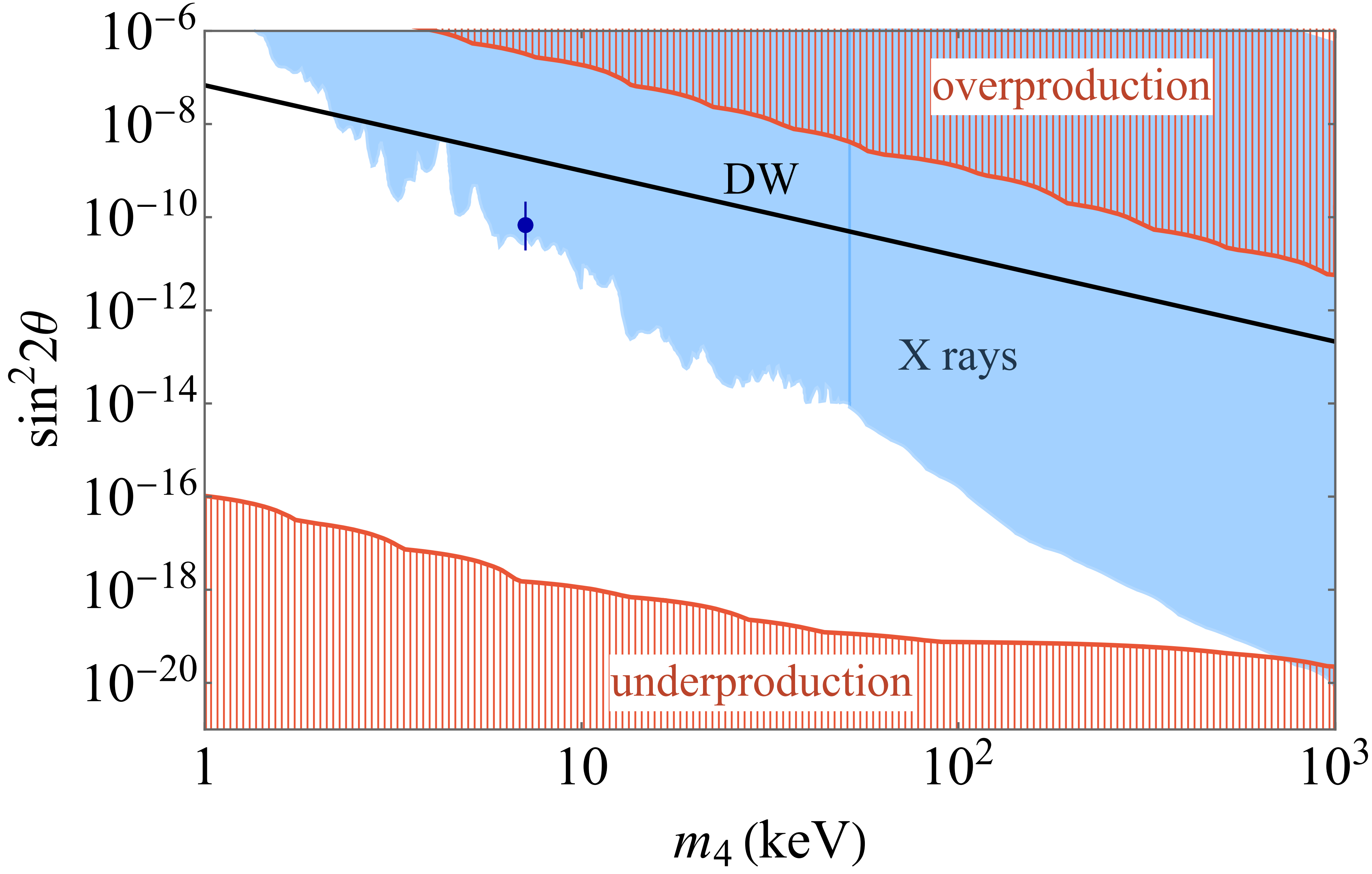
Open up Wide Parameter Space



de Gouvêa, Sen, Tangarife, YZ (PRL 2020)

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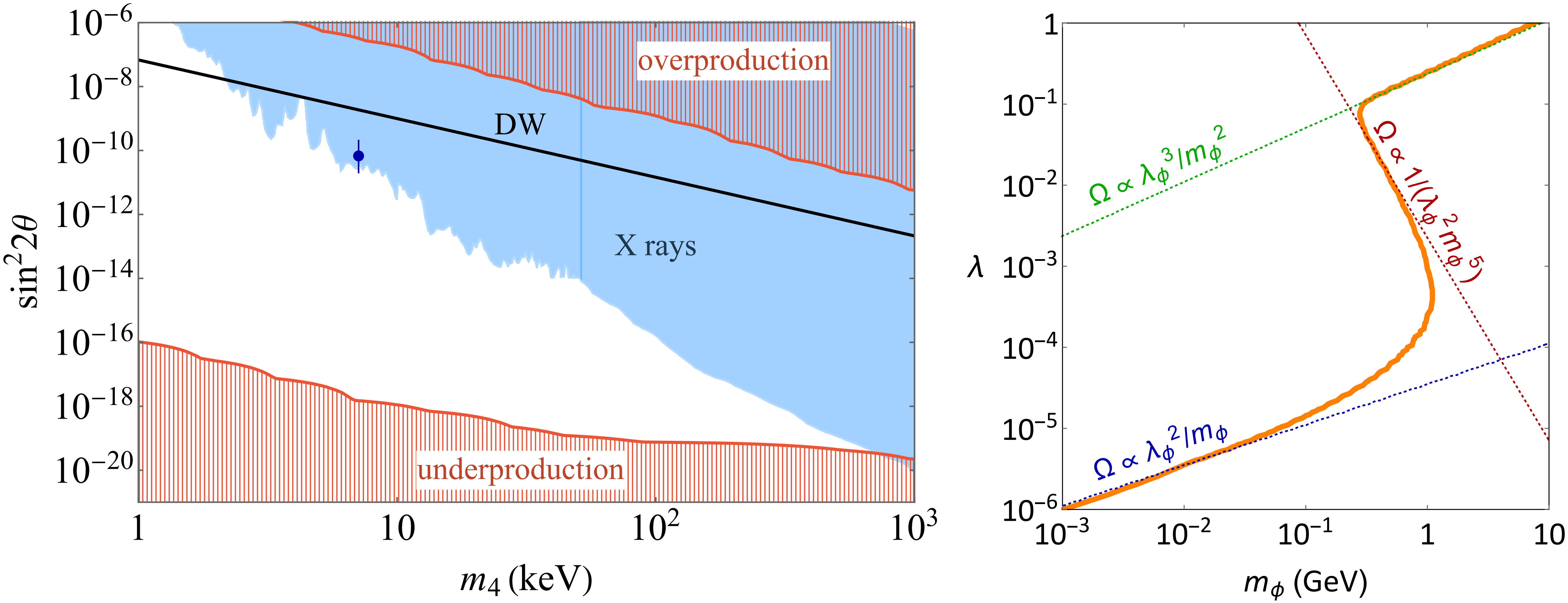

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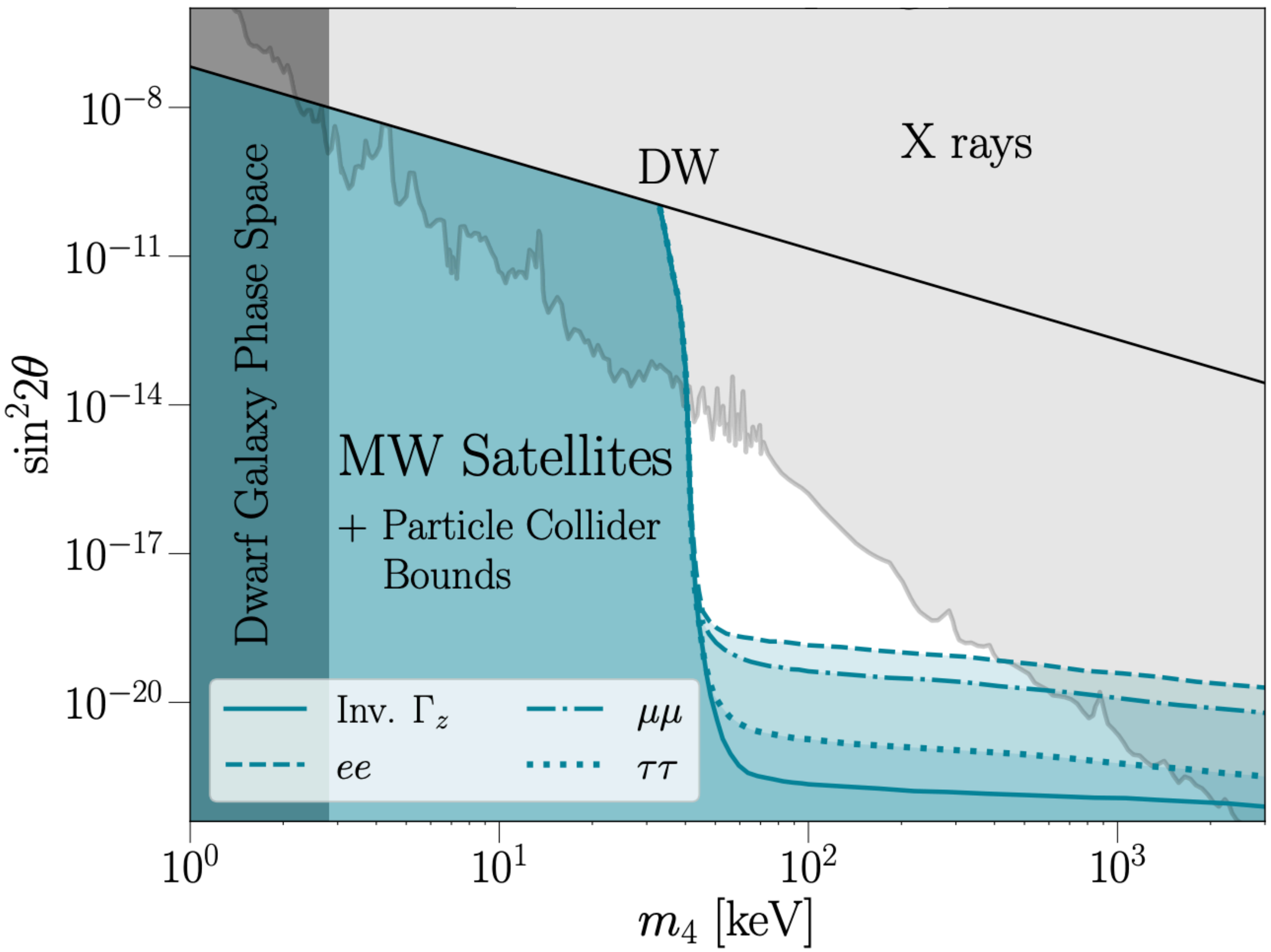
Include Small Scale Structure Limit (DES)



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

An, Gluscevic, Nadler, YZ (APJL 2023)

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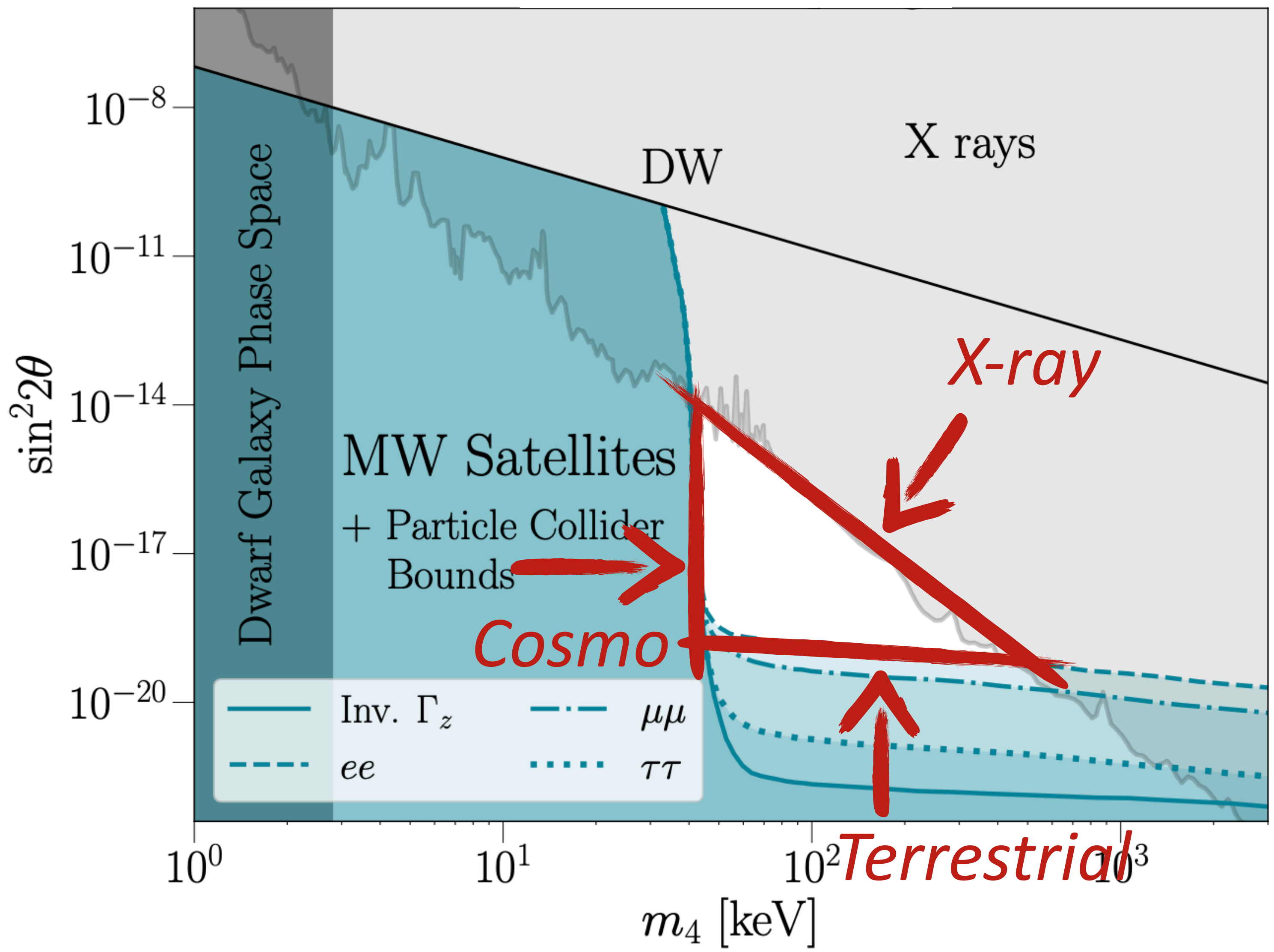

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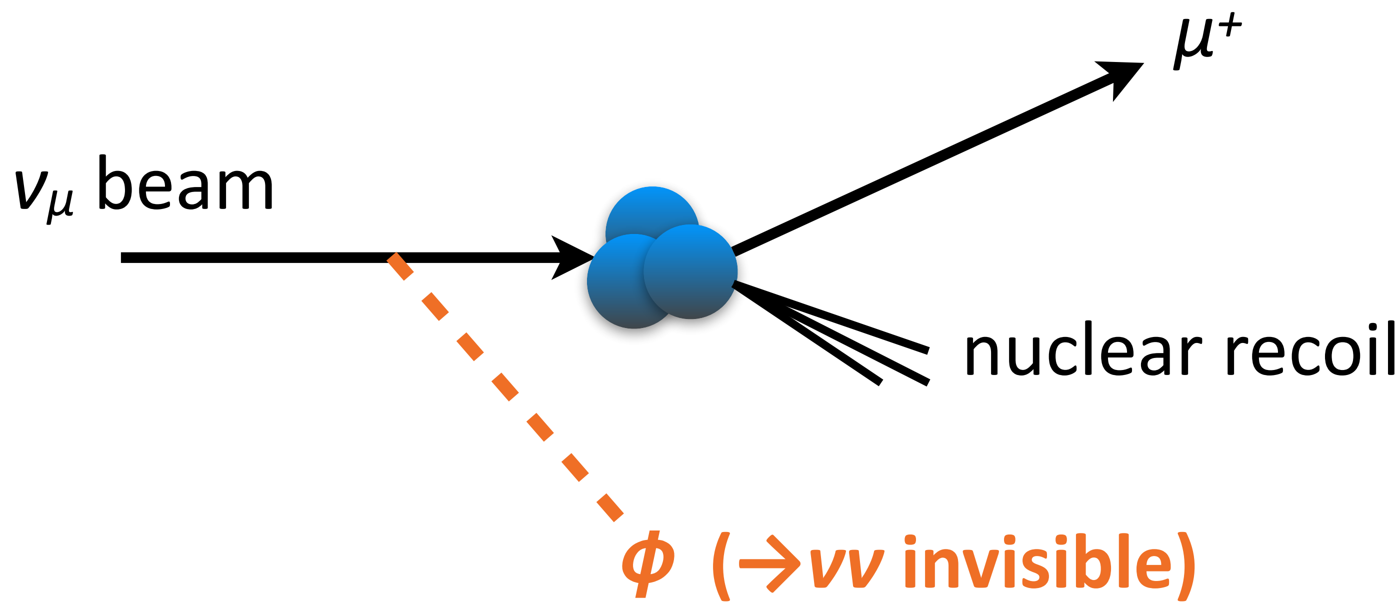
Mono-Neutrino Signal

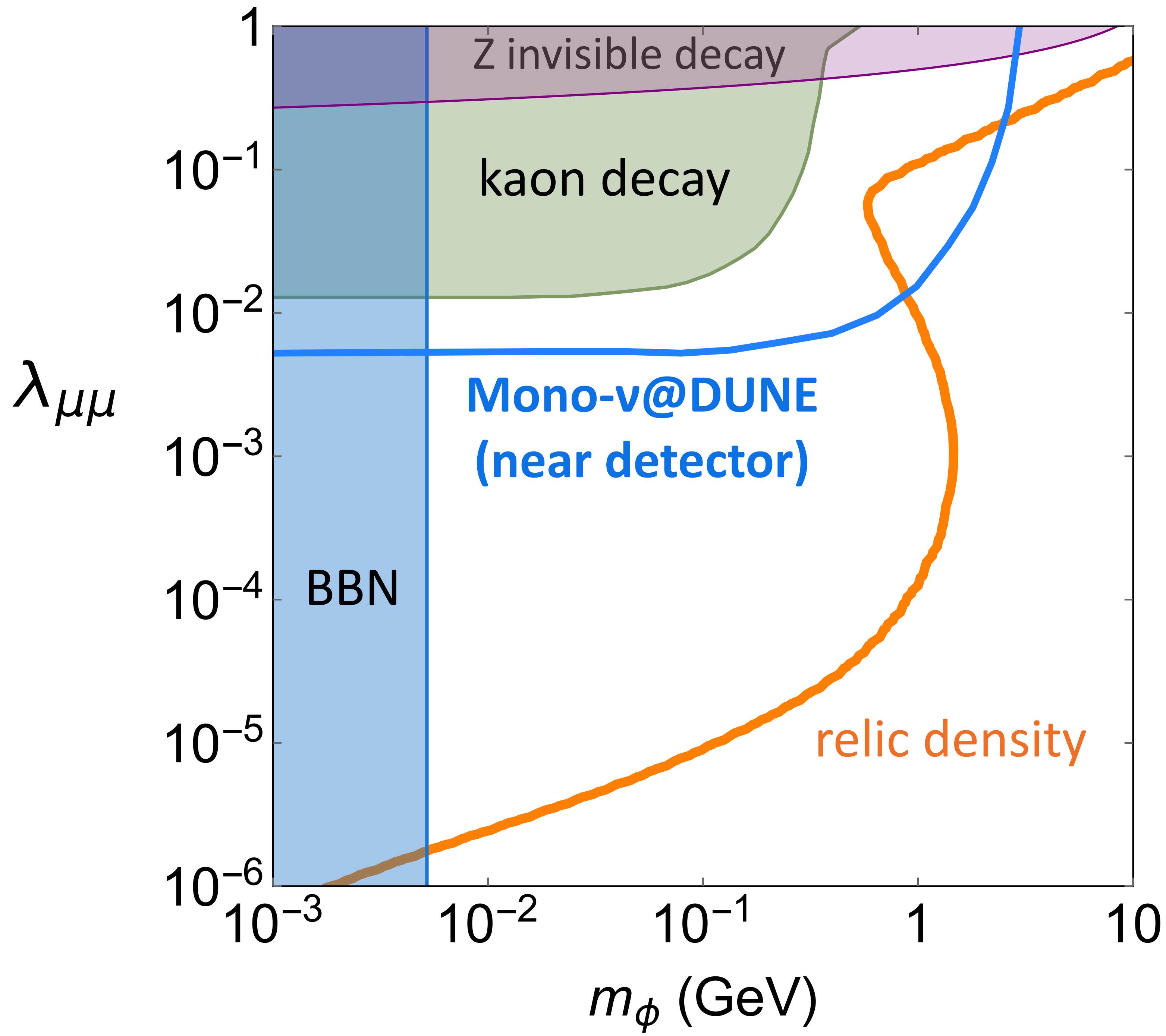


Beamstrahlung process: $\nu_\mu+N\rightarrow\mu^++N'+\phi$, features

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

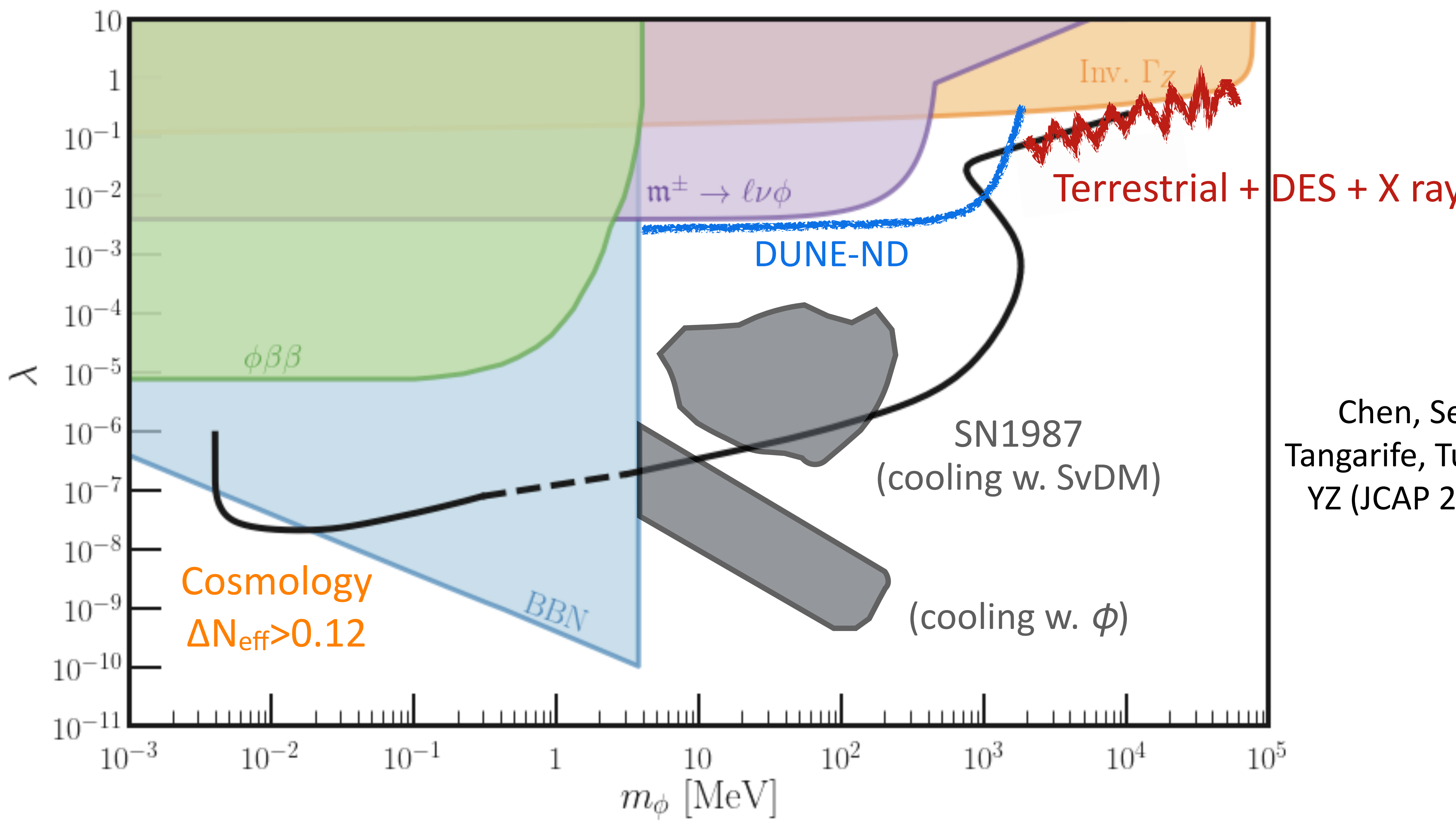
Kelly, YZ (PRD 2019)

Useful Probe of Relic Target



Kelly, YZ (PRD 2019)

The Big Picture



Chen, Sen, Tangarife, Tuckler, YZ (JCAP 2022)

Blinov, Bustamante, Kelly, YZ, et al (PDU 2023) Snowmass 2021 whitepaper

Conclusion

There is a novel connection between origin of sterile neutrino dark matter and active neutrino self-interactions.

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

Thanks!