Dark Matter from Early Universe Neutrino Oscillation

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HET Seminar, Brookhaven National Laboratory

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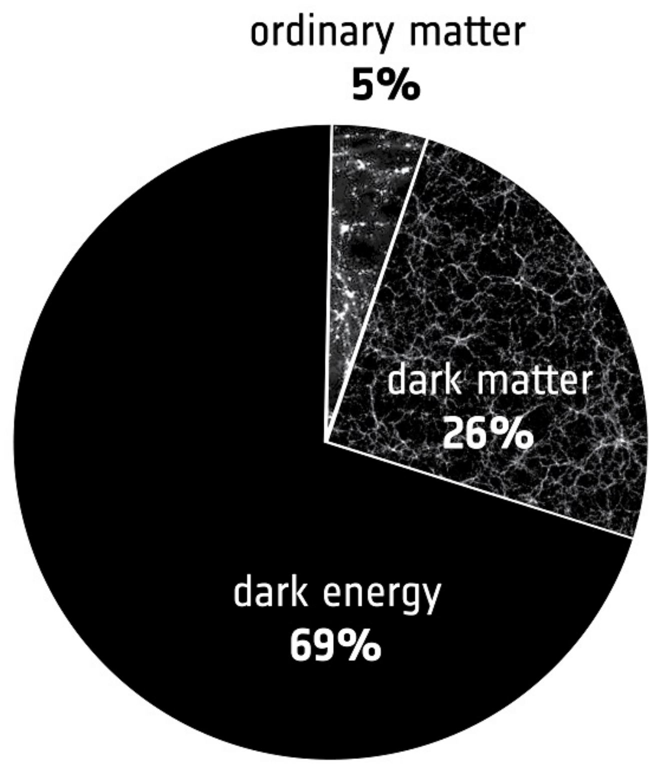
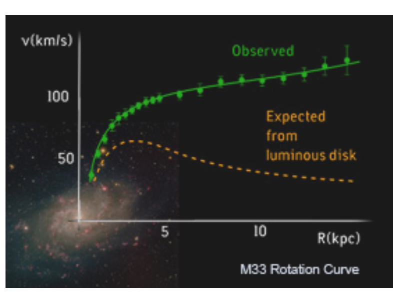
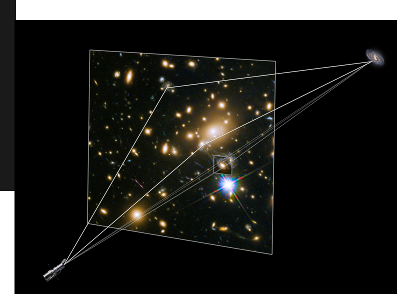
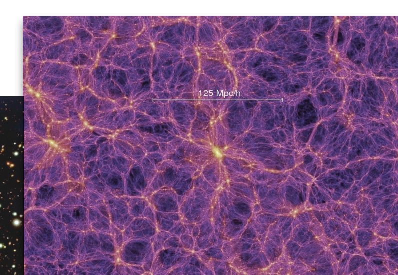
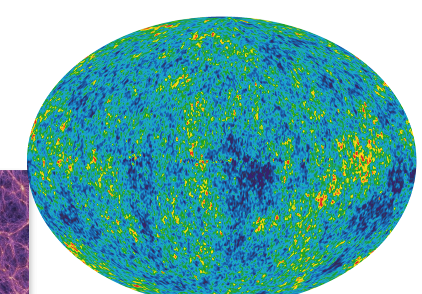
The Dark Matter Puzzle



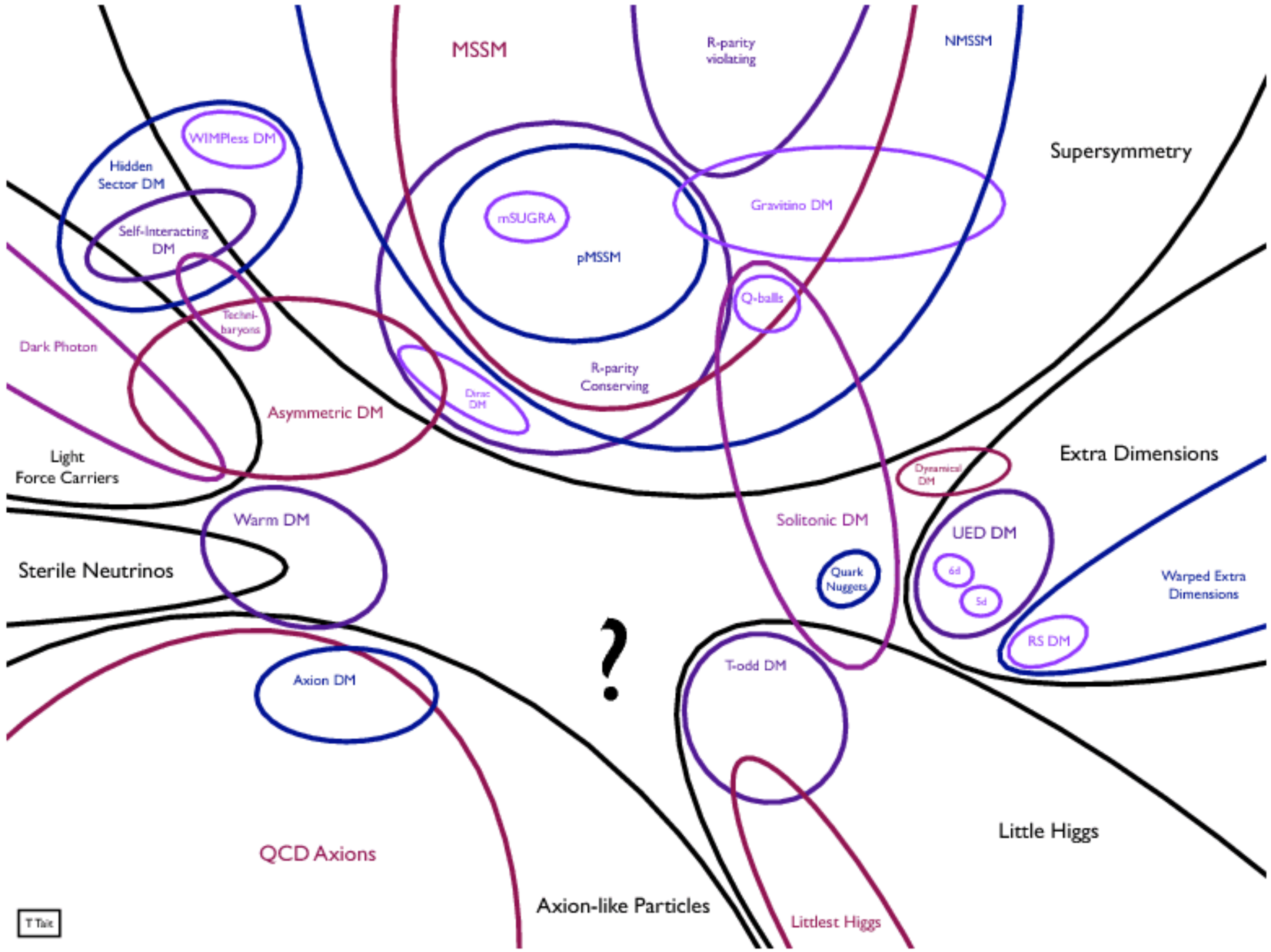








Particle Physics Theories



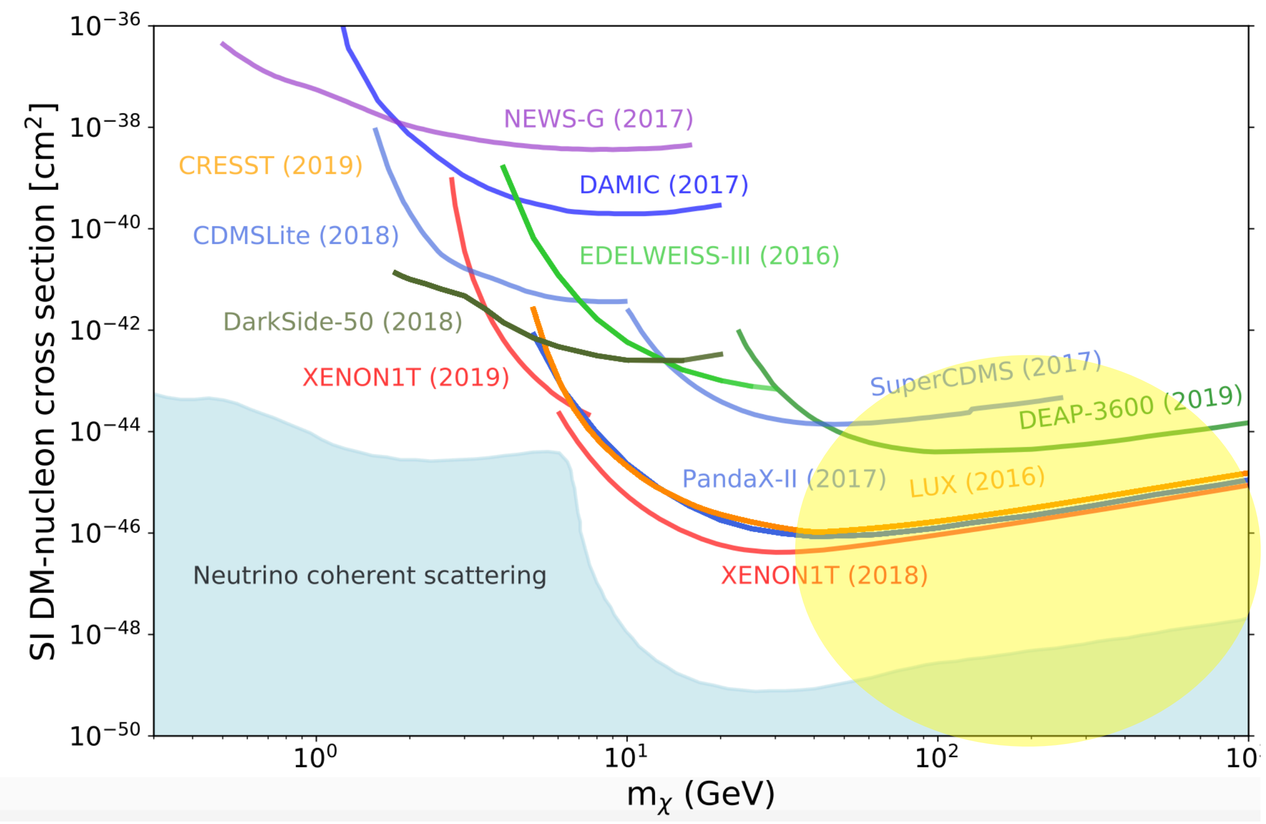
Opportunities

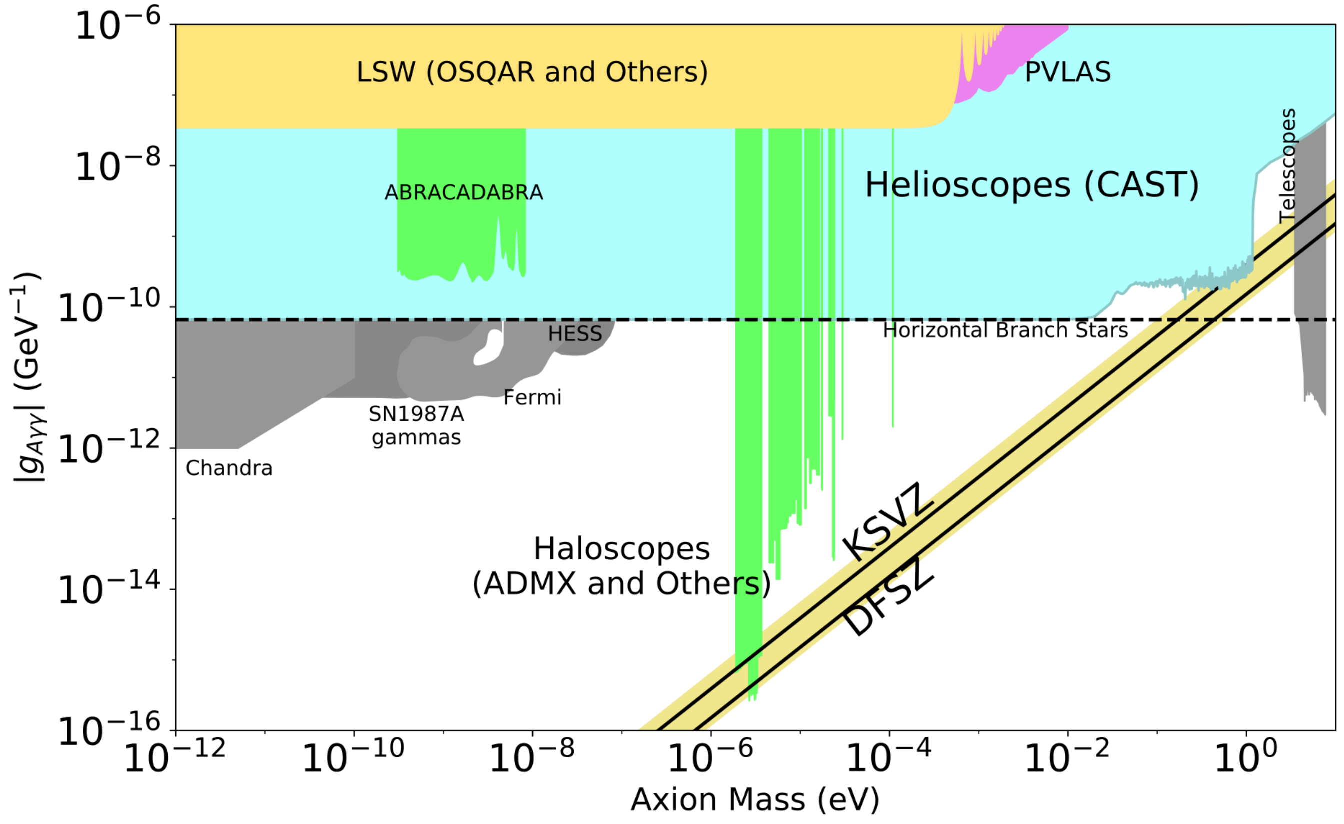
Dark matter theories not only explain a number (Ω=26%), often associate with predictions in DM properties and other signals.

Exciting time to work on this: extensive experimental program to test and distinguish the various hypotheses.

Crucial to combine measurements from all possible frontiers: cosmology, astrophysics, and particle physics.

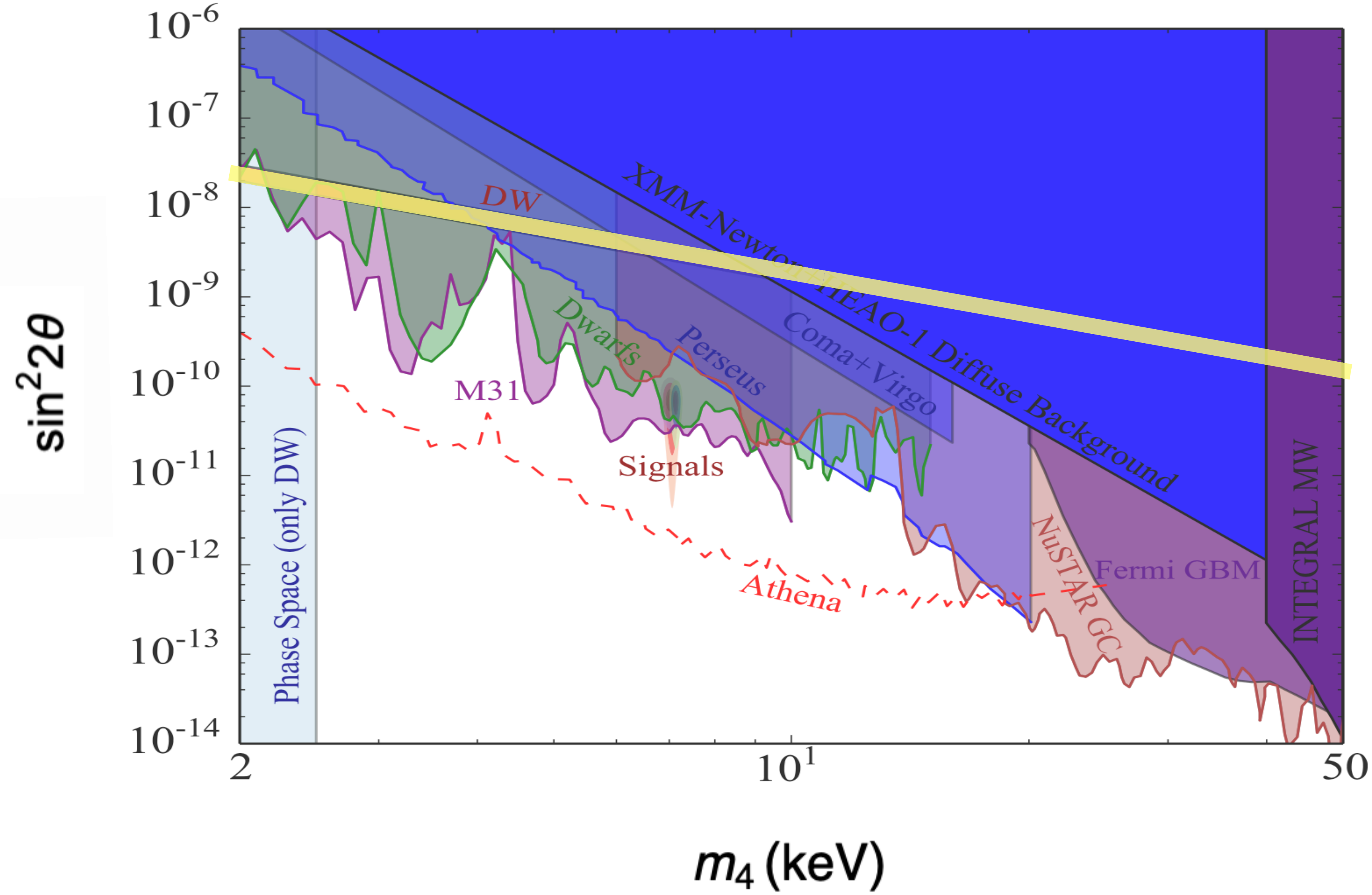
WIMP ('77) and Axion ('83)





Lots of searches, they still live well.

Sterile Neutrino ('93): in trouble?



Abazajian (1705.01837, Physics Reports)

Sterile Neutrino

Introduce a gauge singlet fermion, mix it with SM neutrinos

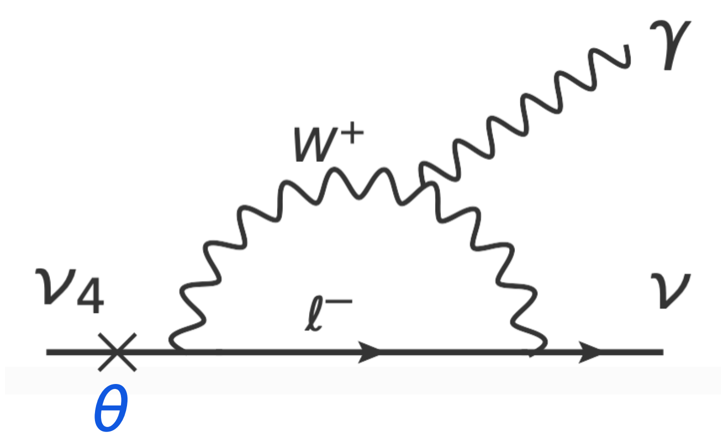
$$\nu_4 = \cos\theta\,\nu_s + \sin\theta\,\nu_a$$

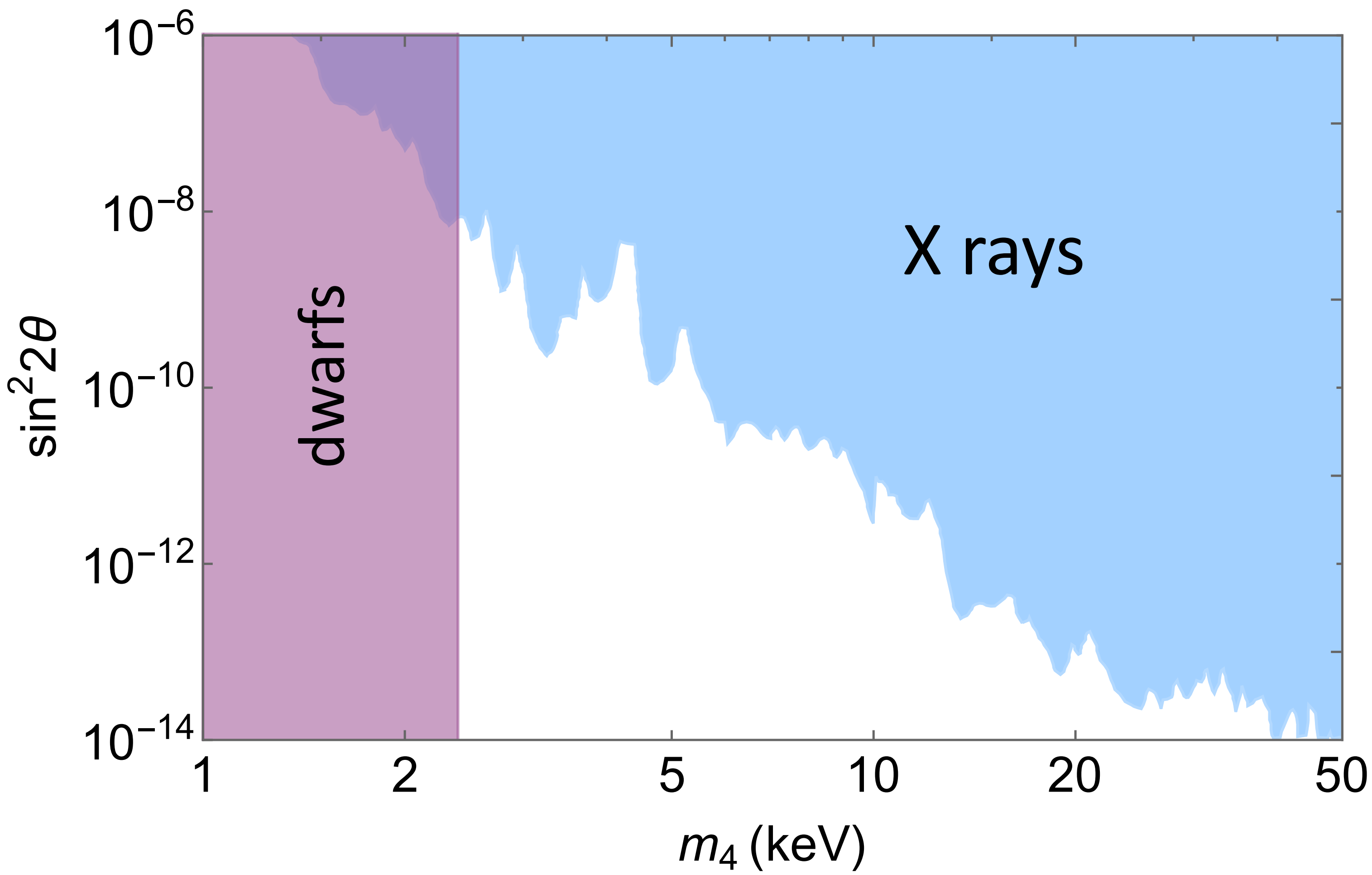
Flavor eigenstates: ν_a active, weakly interacting, ν_s pure singlet.

θ is vacuum mixing angle.

Minimal incarnation: a very simple two parameter model.

No Absolute Stability



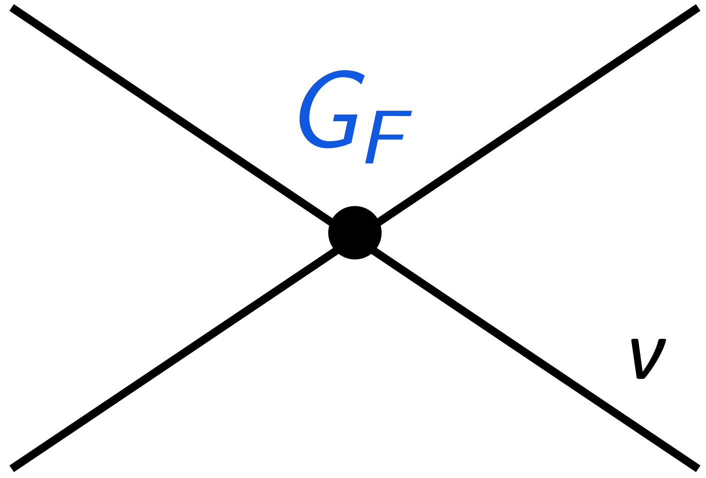


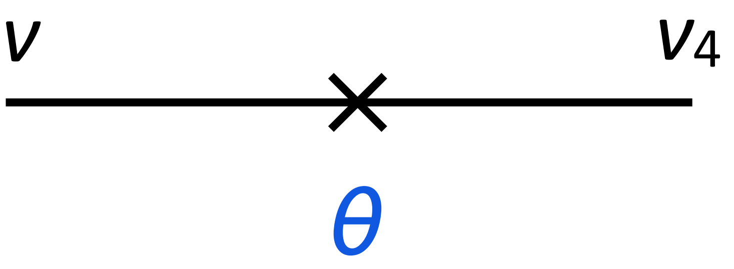
θ is constrained to be small — pointing to non thermal origins.

Assume 100% dark matter.

The Dodelson-Widrow Proposal

An elegant DM production mechanism via active-sterile neutrino oscillation in the early universe, assuming zero initial abundance. Two important ingredients:

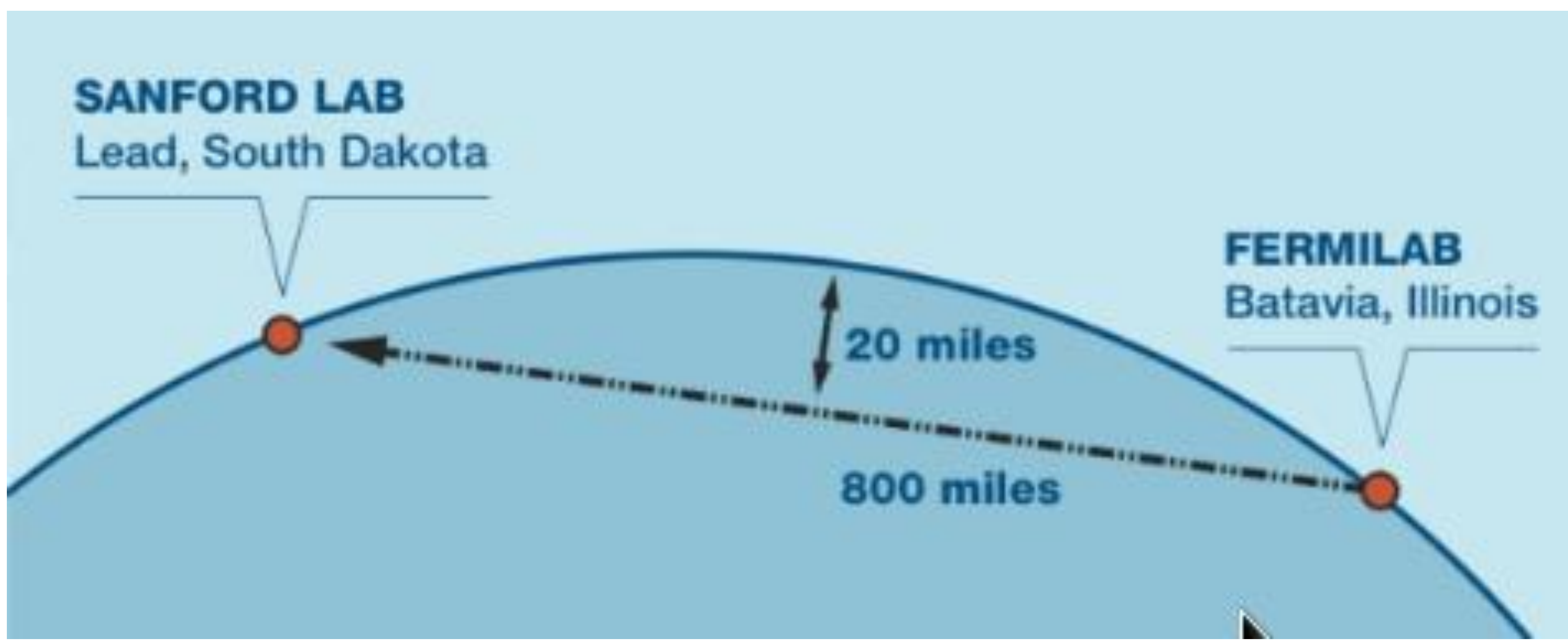




Dodelson, Widrow (hep-ph/9303287, PRL)

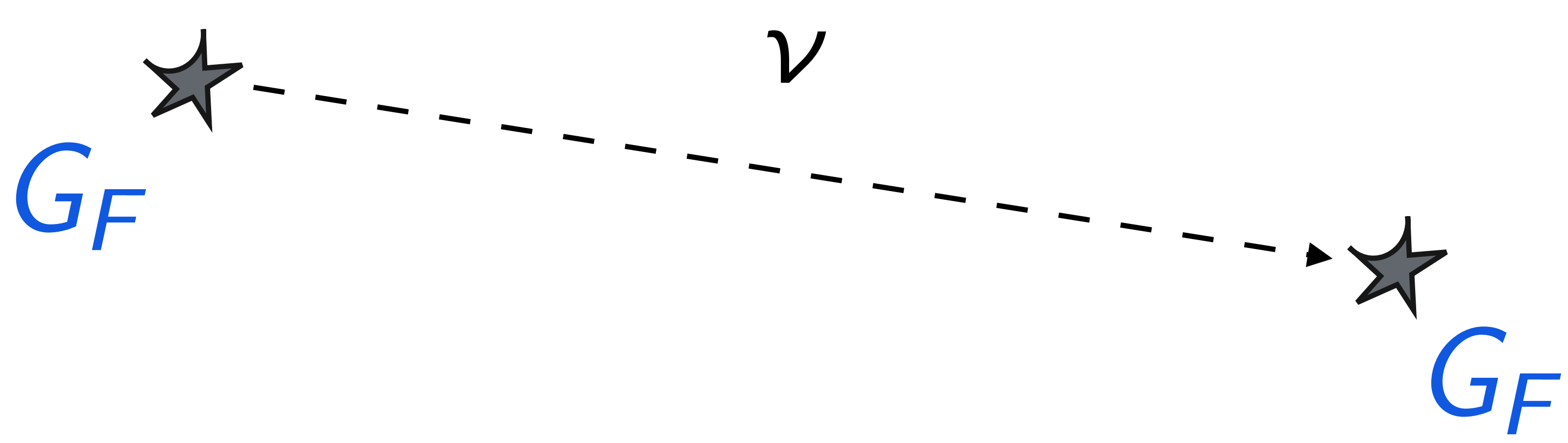
Neutrino Oscillation Experiments

A neutrino experiment currently under construction:



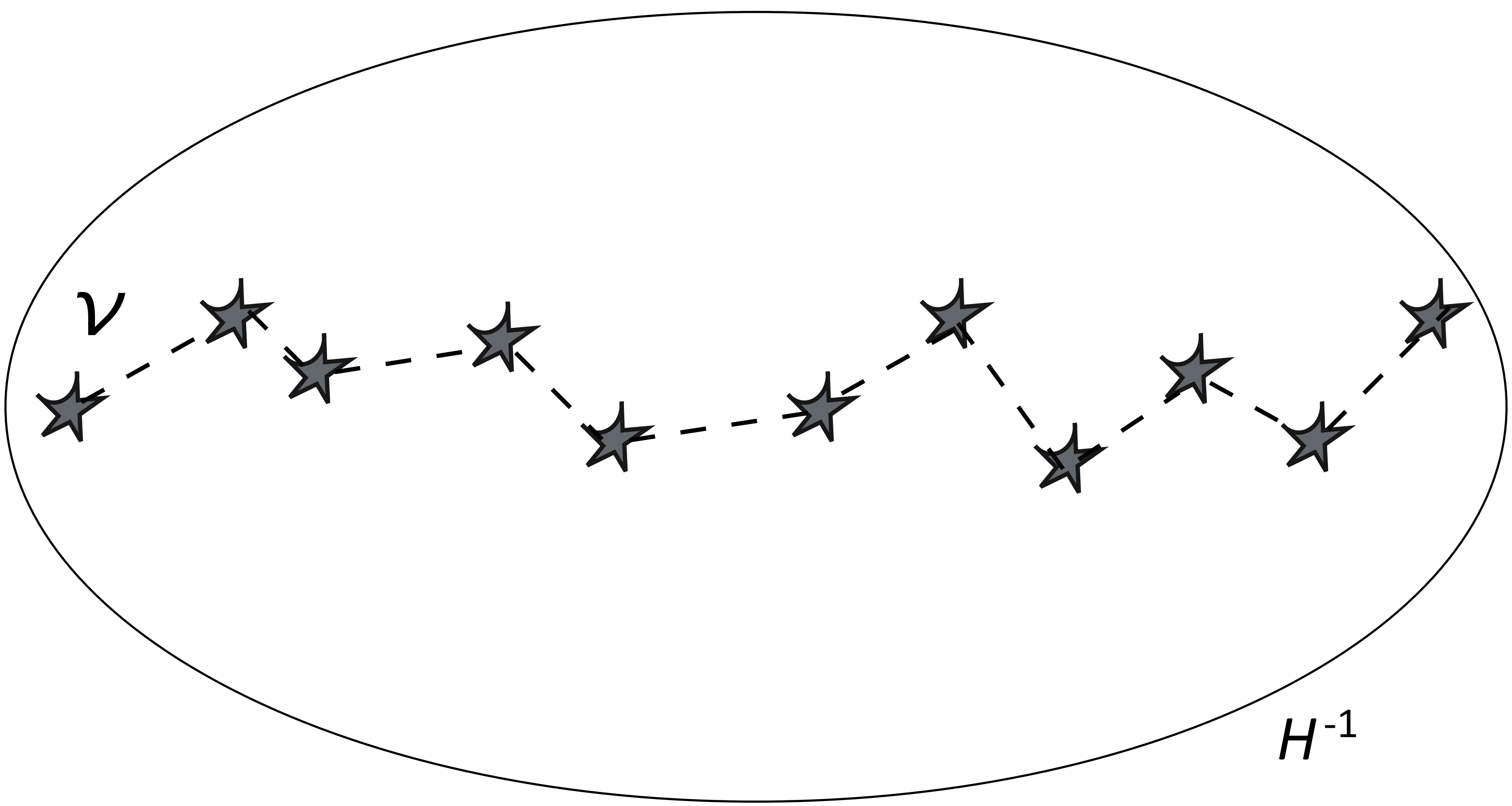
Neutrino Oscillation Experiments

Neutrinos free stream for hundreds of miles. Weak interaction at most occurs twice. Flavour conversion among active neutrinos.

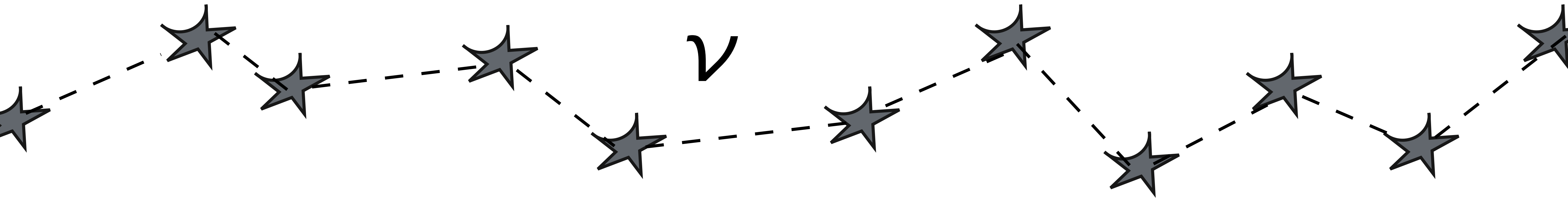


Neutrinos in Early Universe

At temperature T = 100 MeV. Size of universe H^{-1} ~ 10-100 miles, neutrino free-streaming length shorter than a meter.



Neutrinos in Early Universe

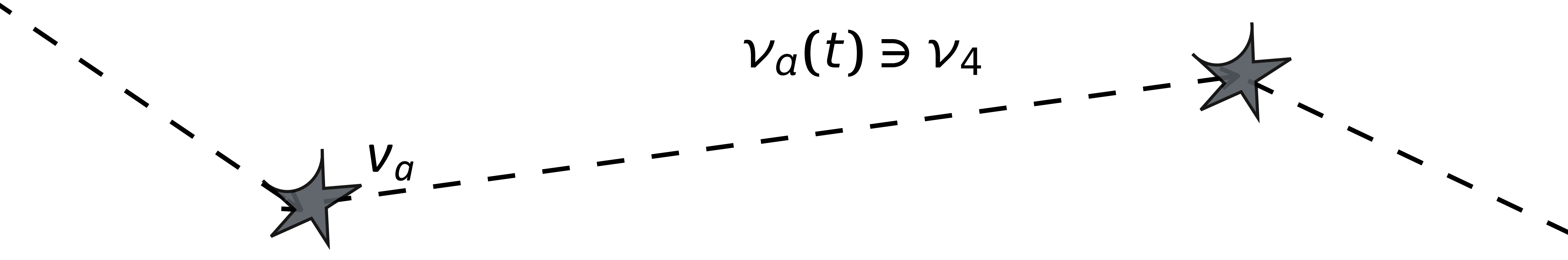


Interplay of two effects:

Active-sterile neutrino oscillation between two weak interactions.

Frequent weak interactions allow the oscillation to occur for many times: # oscillation baselines Γ/H >> 1 before decoupling.

Oscillation Probability



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

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

θ : vacuum mixing angle

V_T : high temperature potential energy

Note the $1/\Gamma^2$ terms in the denominator - quantum Zeno effect.

Boltzmann Equation

Phase space distribution

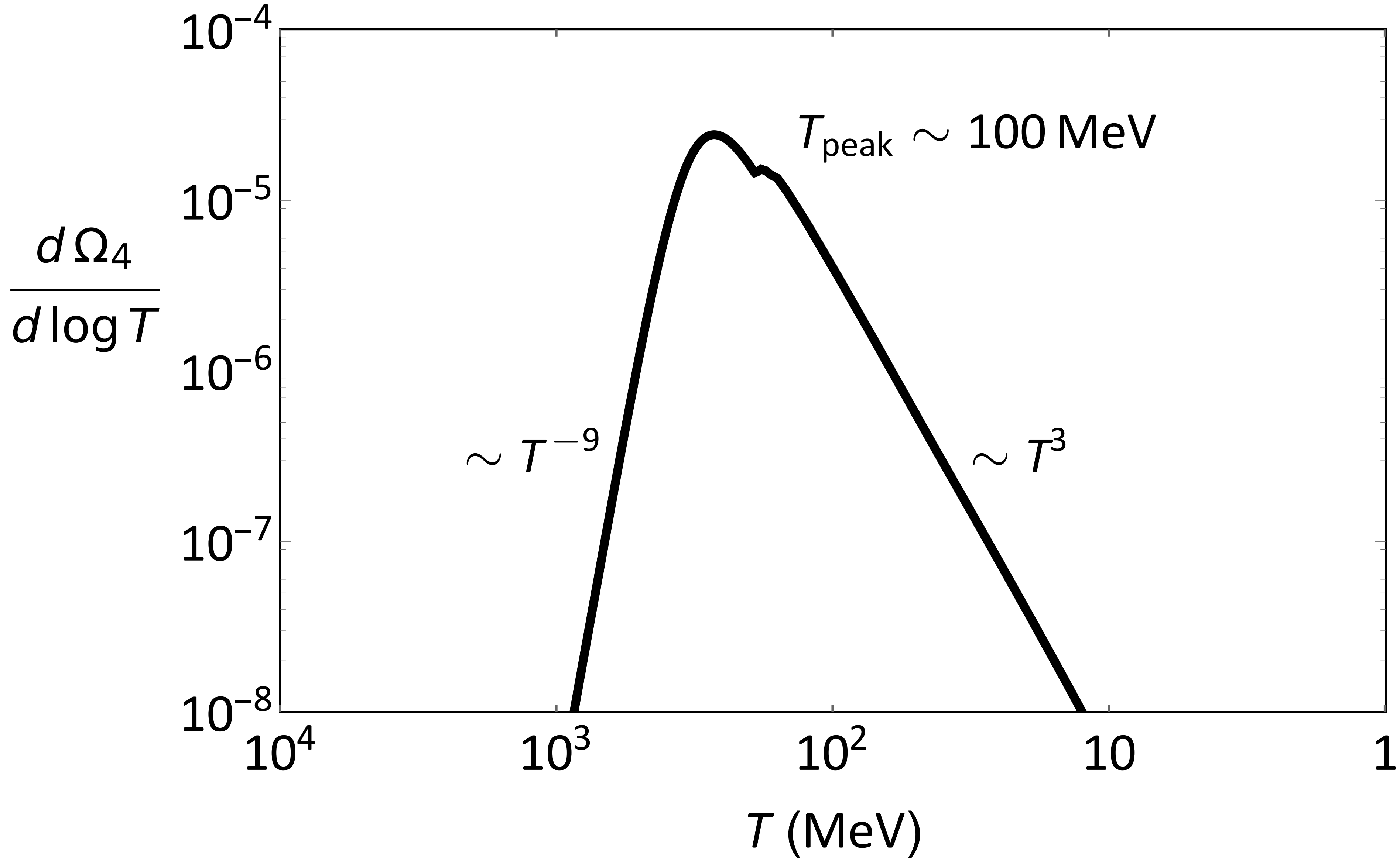
$$\frac{df_4}{d\log T} = \frac{\Gamma}{4H} P_{\nu_a \to \nu_4} f_a$$

Overall effect is not linear in Γ . (different from vanilla ``freeze in'')

Weak interaction rate $\Gamma \sim G_F{}^2 T^5$. Dark matter production rate suppressed at both very high and low temperatures.

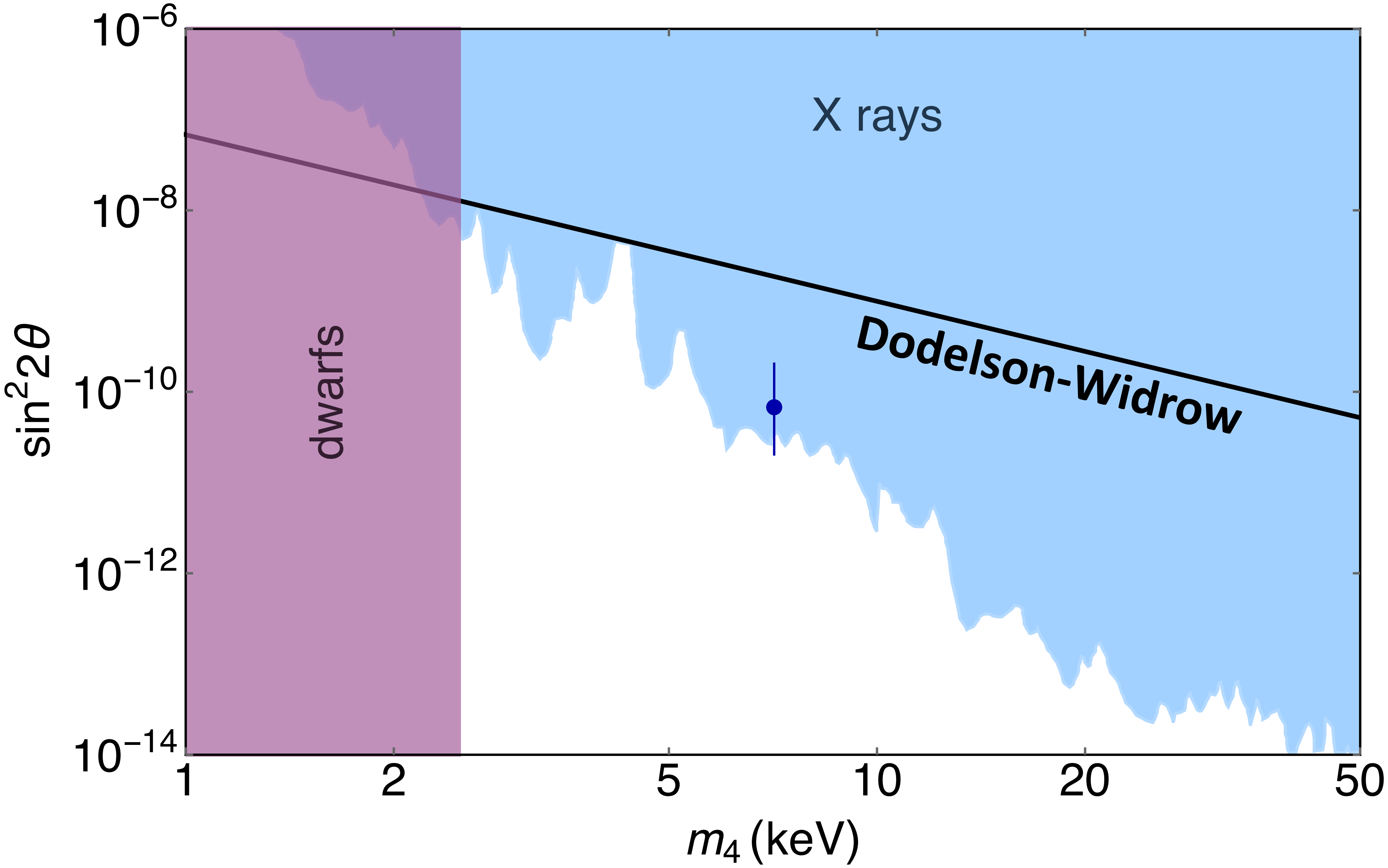
→ Sterile neutrino DM dominantly produced at $T \sim 100$ MeV.

Production Time Window



Dodelson, Widrow (hep-ph/9303287, PRL)

However, already excluded..



Assumptions: no DM population at very early times; no/little particle-antiparticle asymmetries

Lepton Asymmetric Universe?

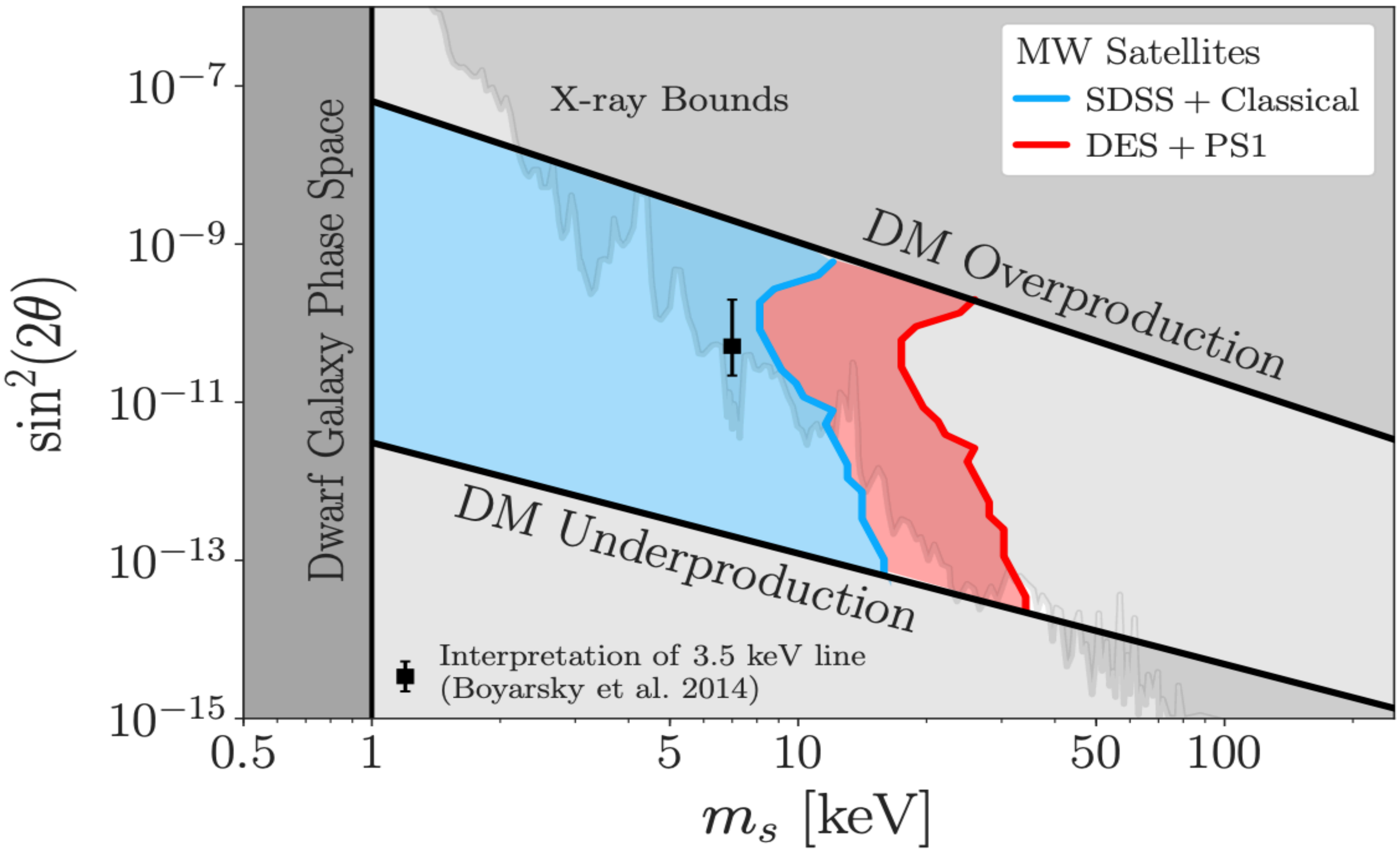
Shi and Fuller (astro-ph/9810076, PRL) suggested that a primordial lepton asymmetry can create a matter potential and trigger the MSW resonant† active-sterile neutrino (or anti-neutrino) conversion.

†Resonance does not occur for the Dodelson-Widrow case - thermal potential has the opposite sign.

For years, the Shi-Fuller mechanism served as the leading alternative production mechanism of sterile neutrino dark matter.

This possibility recently has been excluded by the DES collaboration.

DES Observes Ultra-faint Dwarfs



Lower bound on dark matter mass from # of ultra-faint dwarf galaxies.

DES Collaboration (2008.00022, PRL)

Ways Out?

A tantalizing puzzle calling for new theoretical ideas.

UV physics could contribute extra DM abundance. Totally different picture than just described: DM relic unrelated to θ; New physics scale often beyond the reach of collider experiments.

— Sound like surrendering.

Does any dark matter production mechanism via early universe neutrino oscillation work at all?

A Simple Idea

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

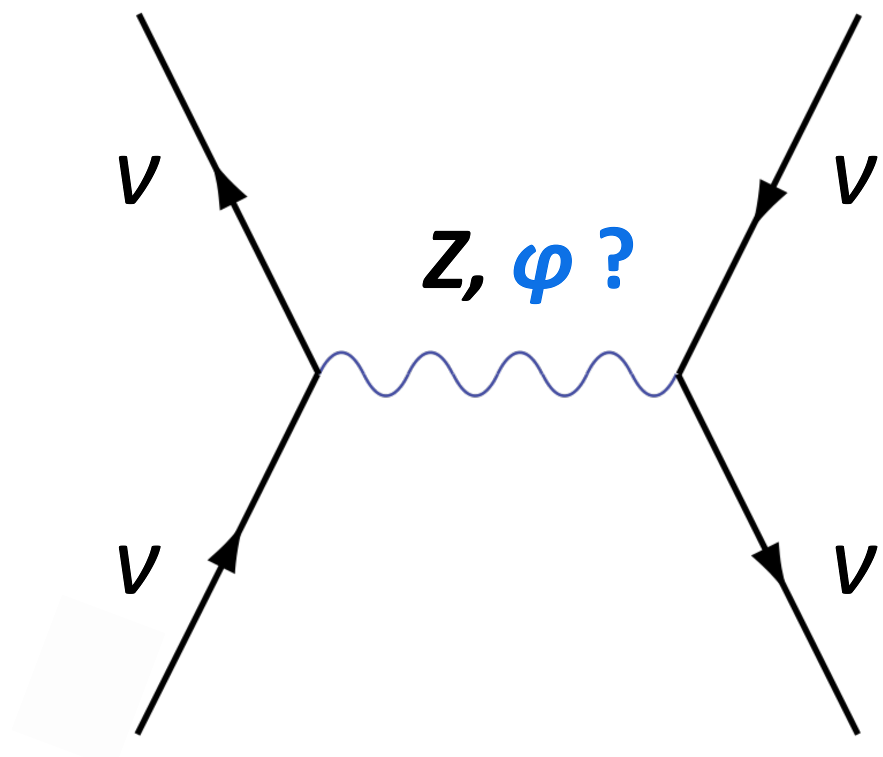
Intuition: compensate smaller mixing with larger reaction rate.

Requirement: new physics enhances Γ but without introducing additional DM radiative decay mode.

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

↑

Neutrino Self Interaction: Opportunities



Never directly measured. Allowed to be much stronger.

Zνν coupling at LEP is an indirect measurement.

A Simple Model

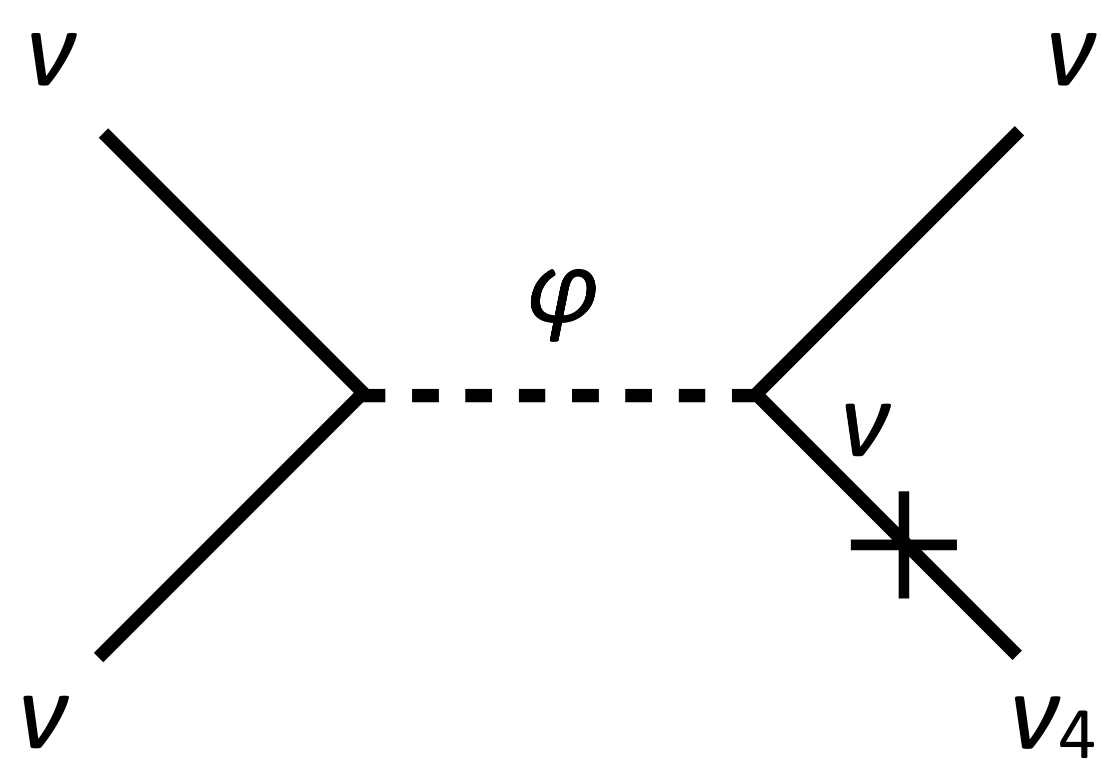
Add to Standard Model

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

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

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

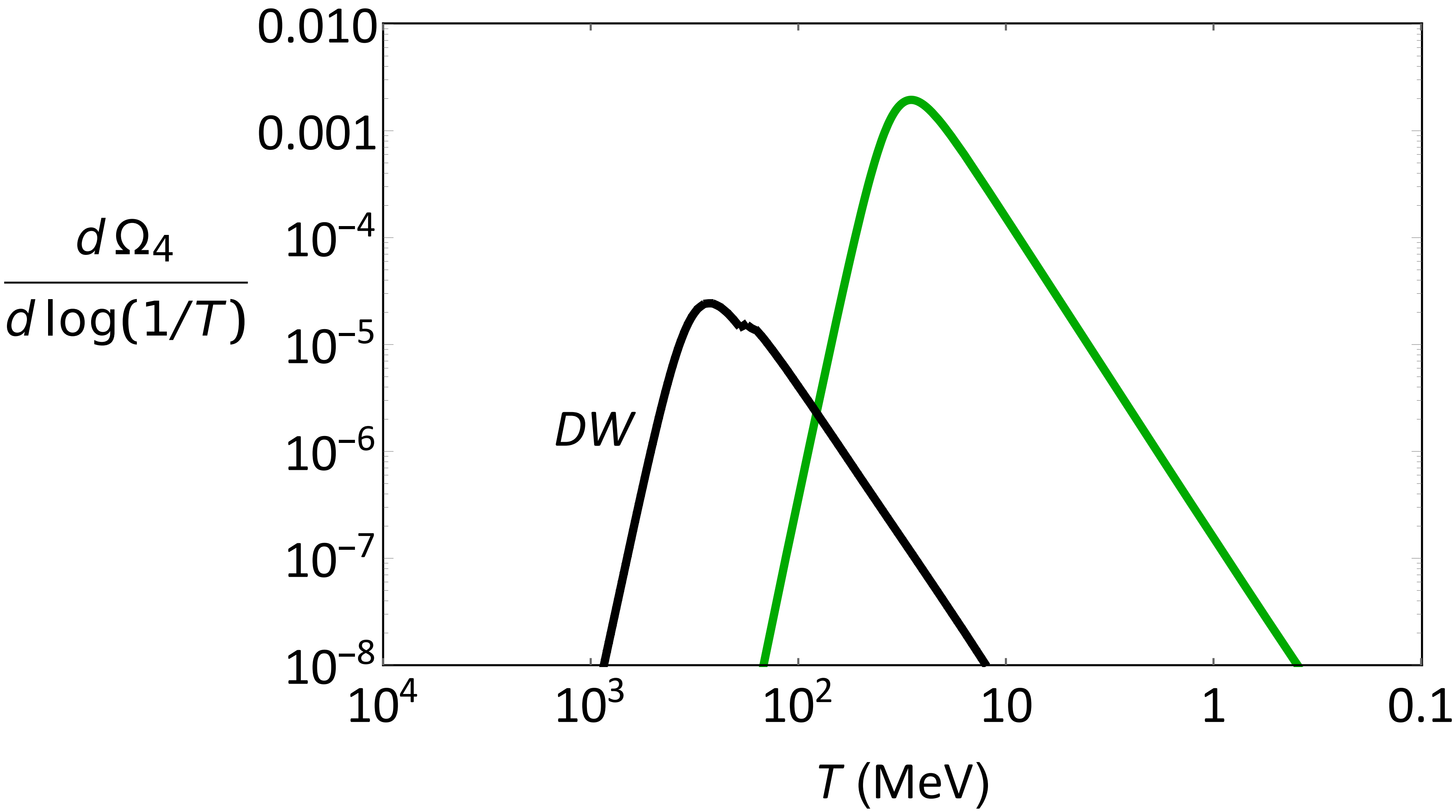
New Production Mechanism

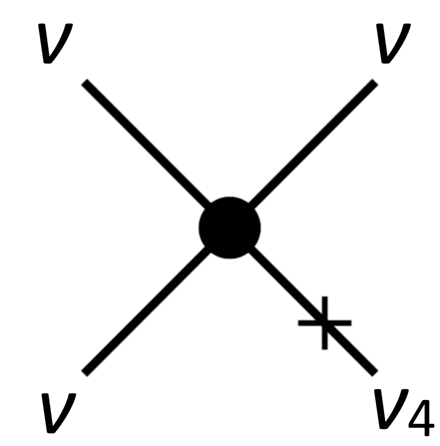


After *ν* decouples from weak interaction, still talk to themselves.

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

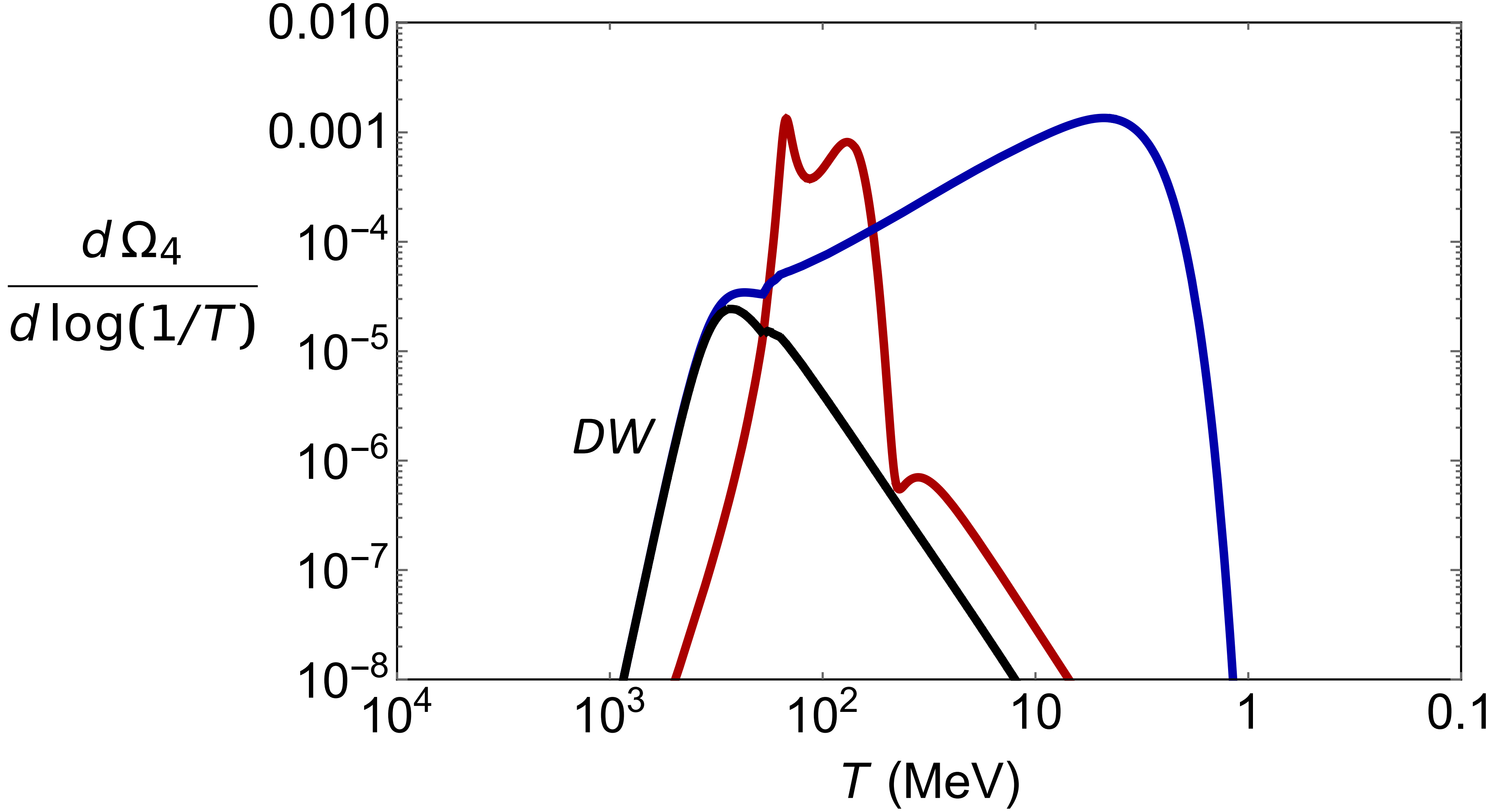
Heavy Mediator Scenario

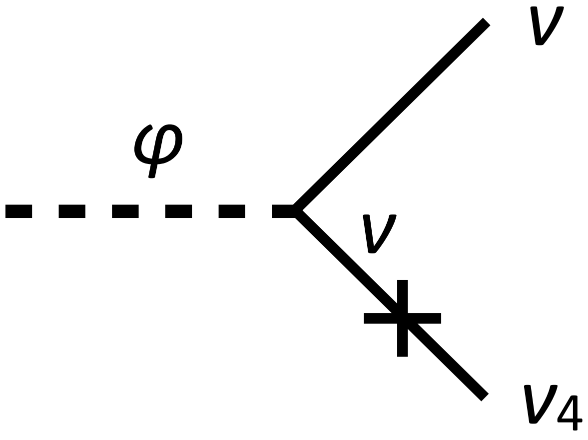




Final relic density: $\Omega_4 \propto \frac{\lambda^3}{m_\varphi^2} \gg \frac{g^3}{M_W^2}$

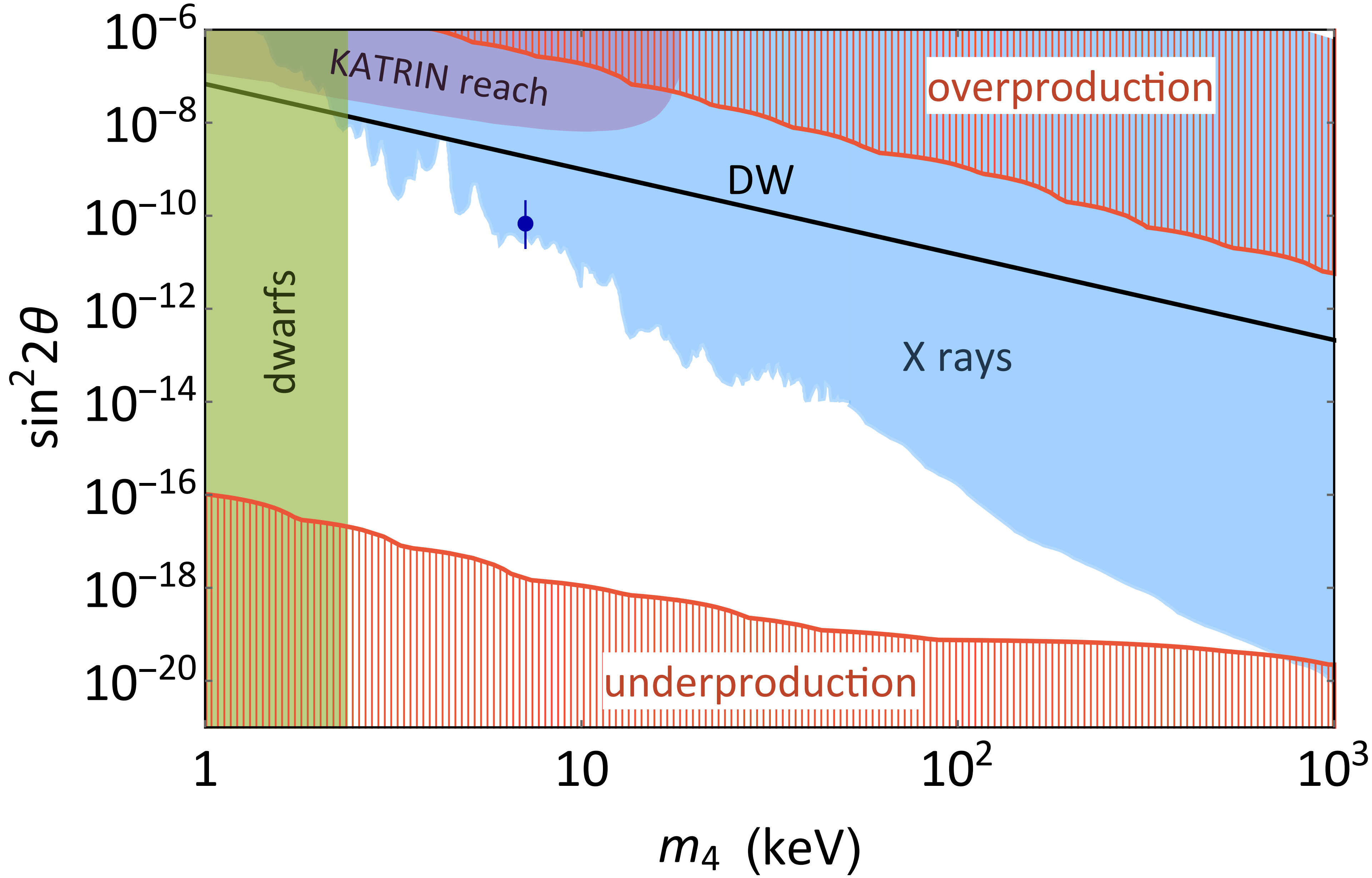
Light Mediator Scenario





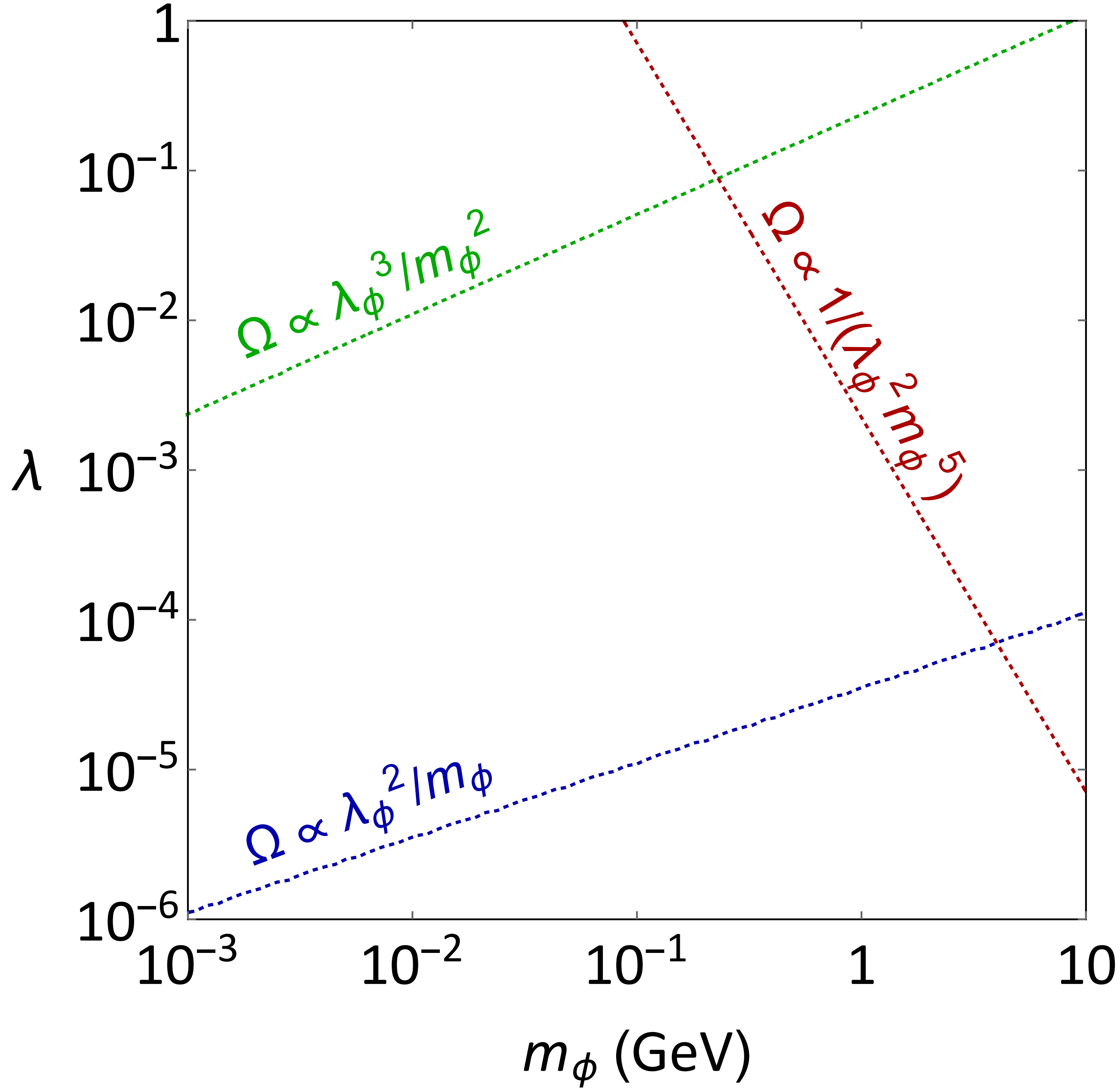
When $T>m_\varphi$, φ can thermalize, on-shell contribution dominates the $\nu\nu\rightarrow\nu\nu_4$ scattering. Effectively, φ decays to ν_4.

Opens Up Wide Window



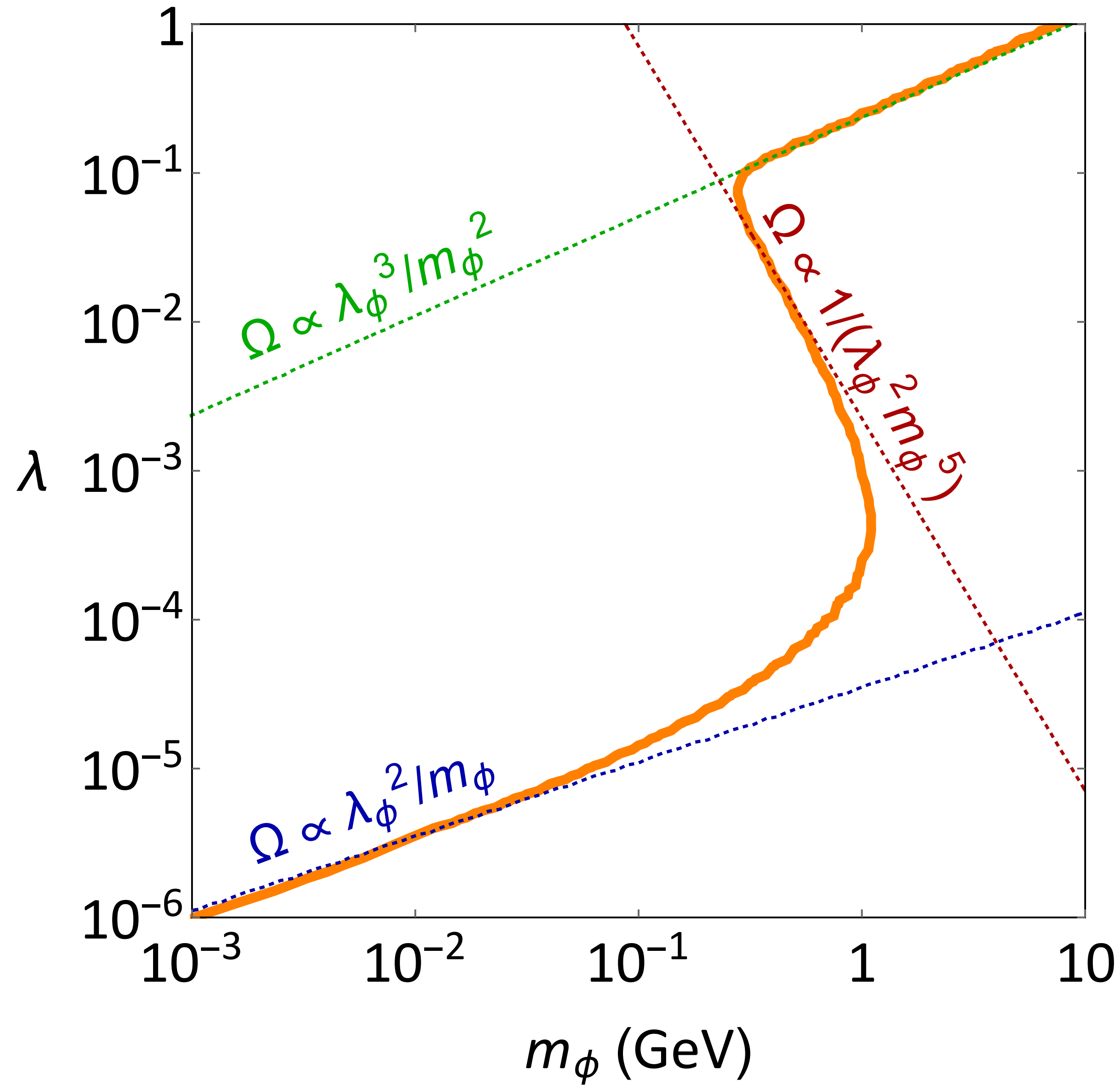
de Gouvêa, Sen, Tangarife, YZ (1910.04901, PRL)

Three Regimes



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

Numerical Result



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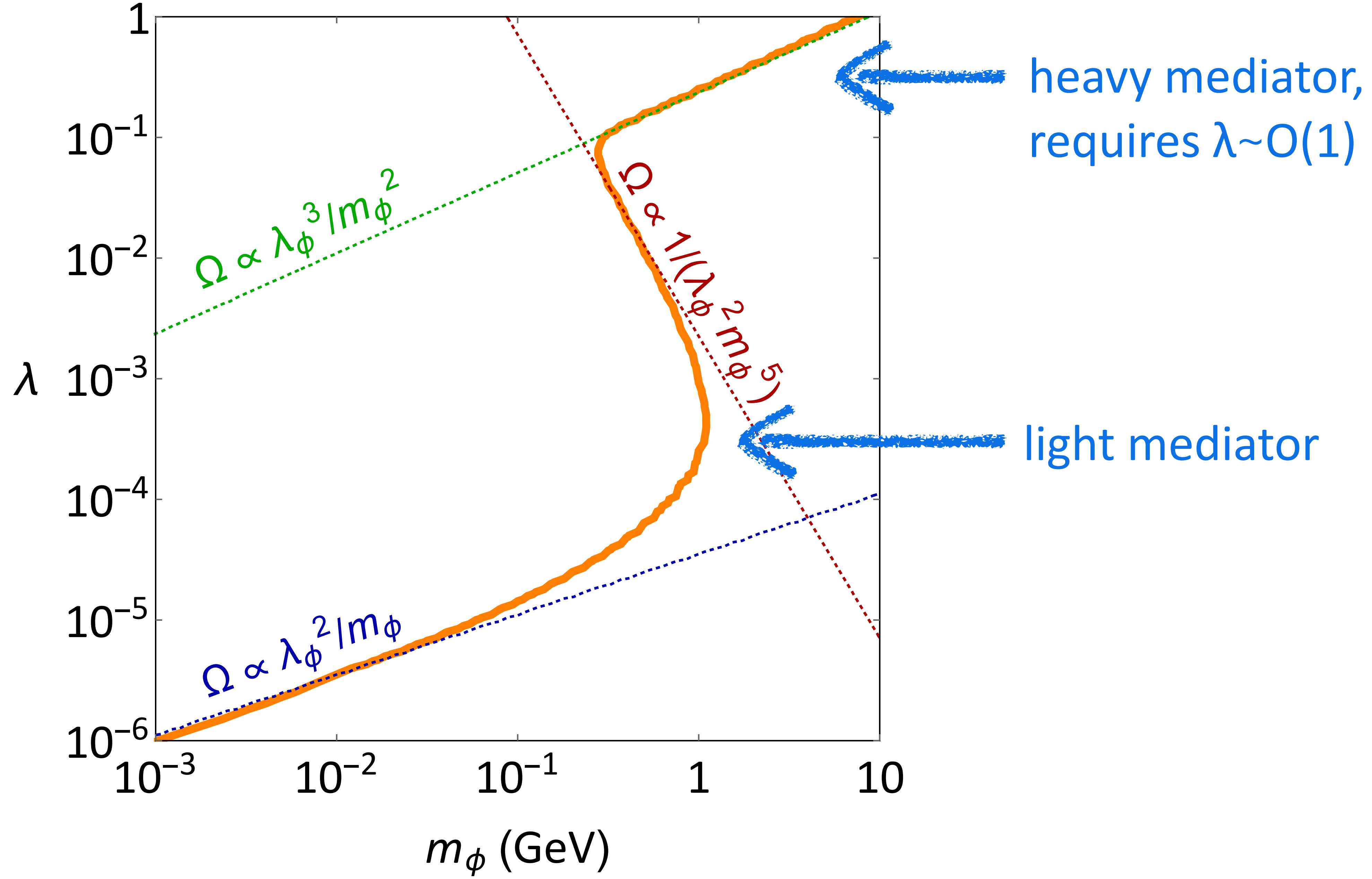
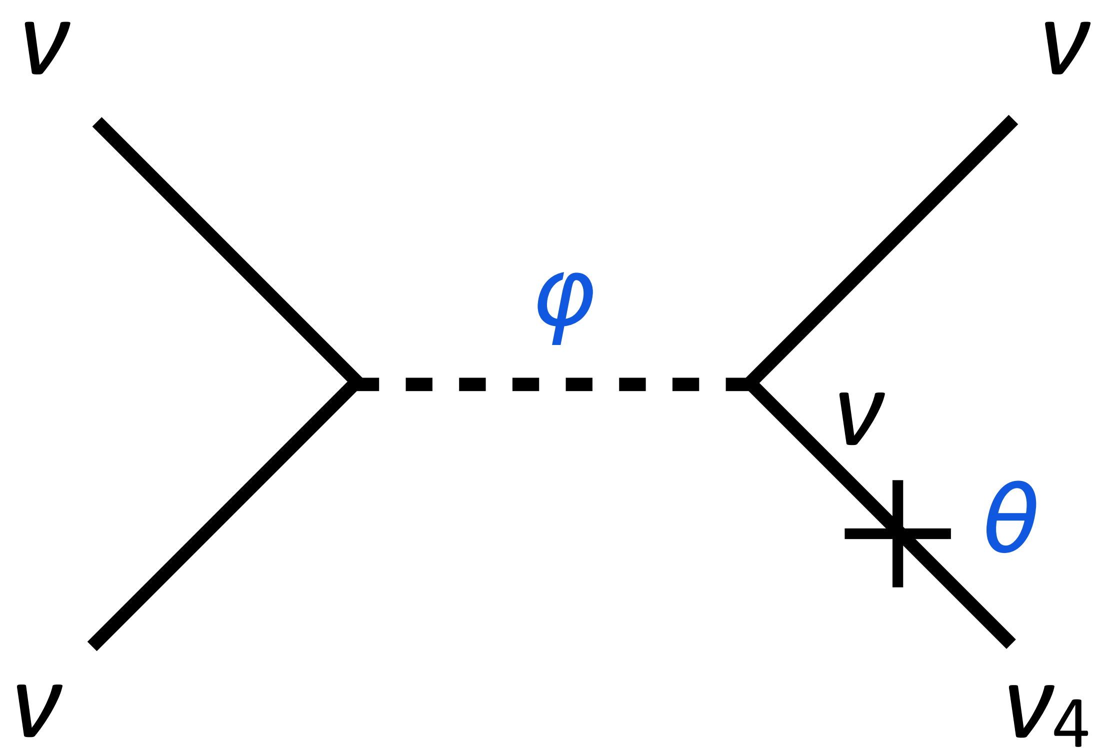
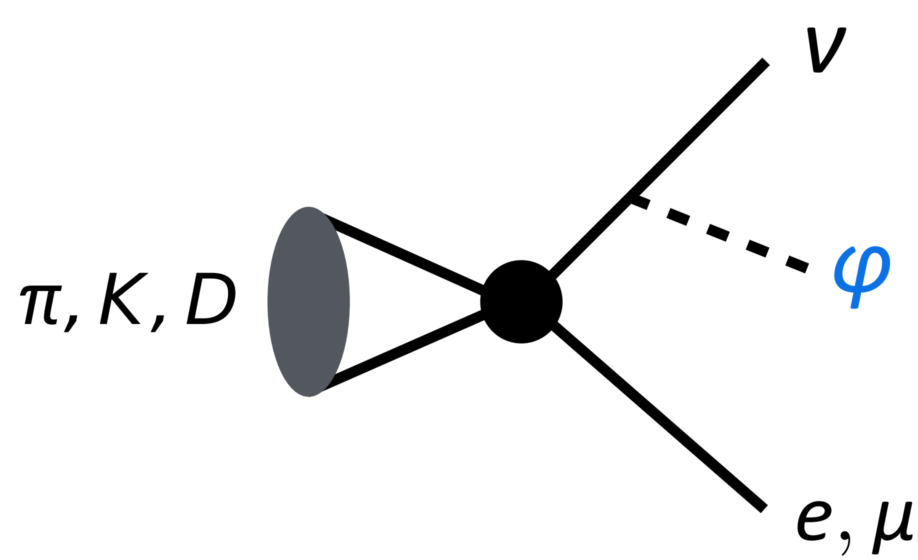


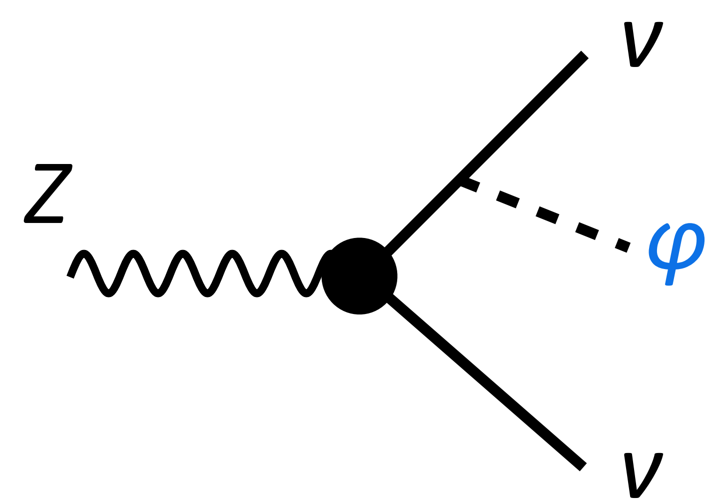
de Gouvêa, Sen, Tangarife, YZ (1910.04901, PRL)

Testing the Mechanism



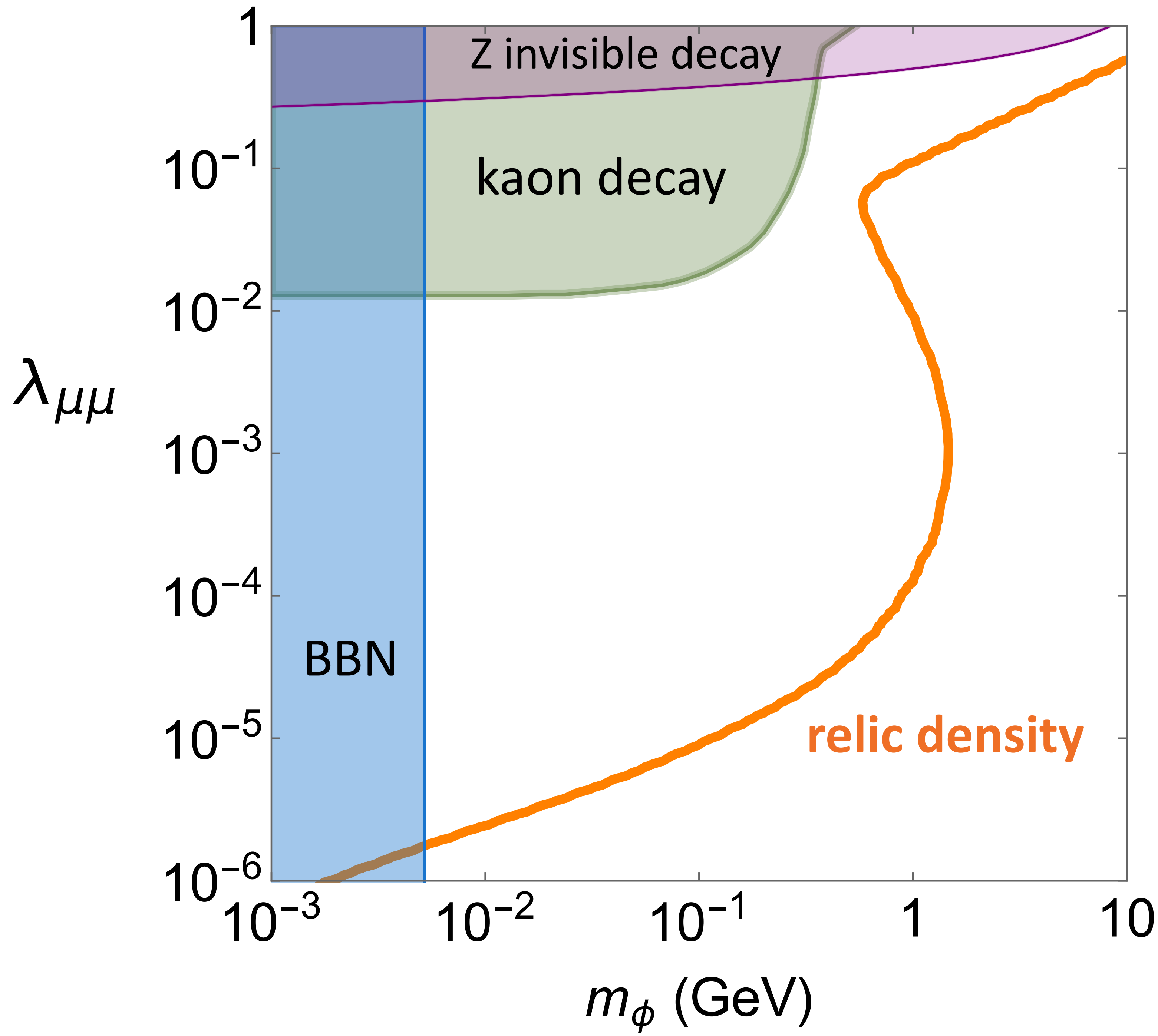
Known Particle Decays



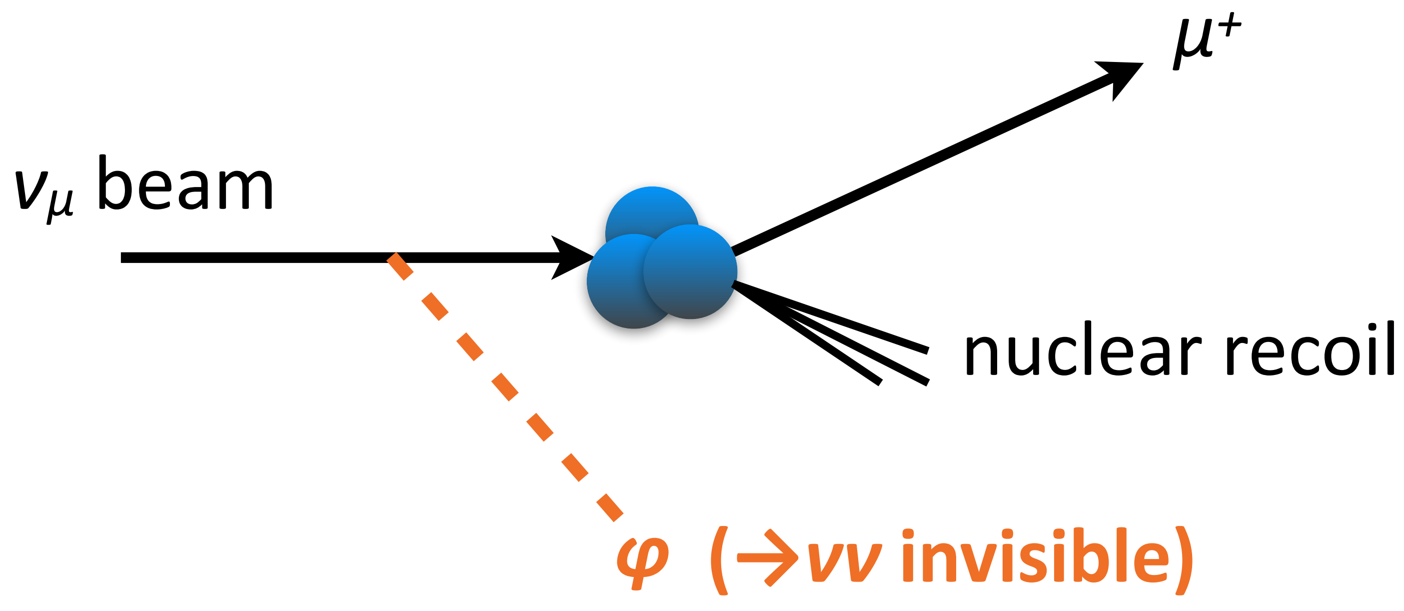


Barger, Keung, Pakvasa (1982, PRD)
PIENU (2020, PRD); NA62 (2021, PLB); Heintze et al (1979, NPB)

Known Limits



Mono-Neutrino Signal

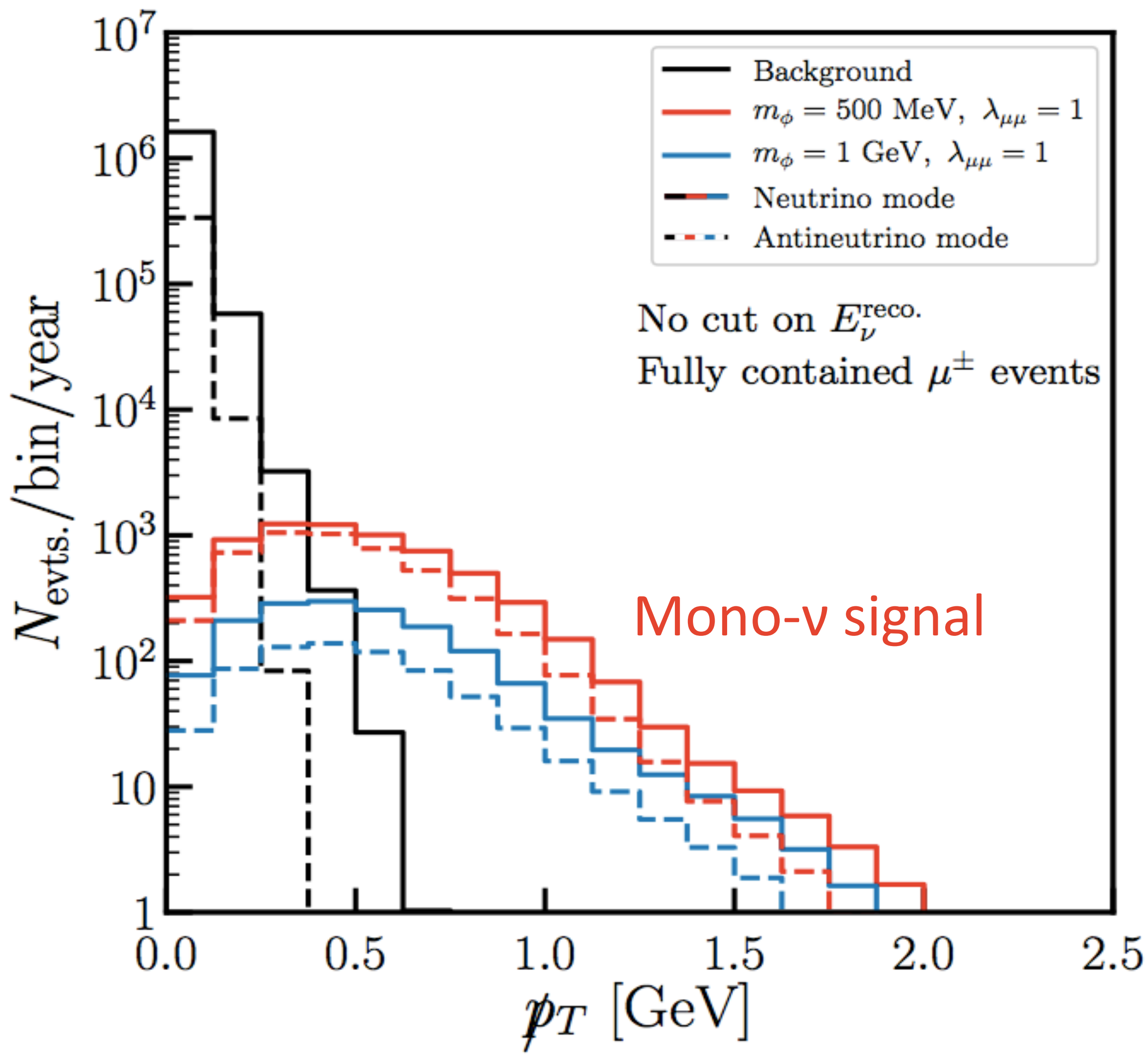


Beamstrahlung process: $\nu_\mu+N\rightarrow\mu^++N'+\varphi$, features

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

Kelly, YZ (1901.01259, PRD)

Theorists' Simulation

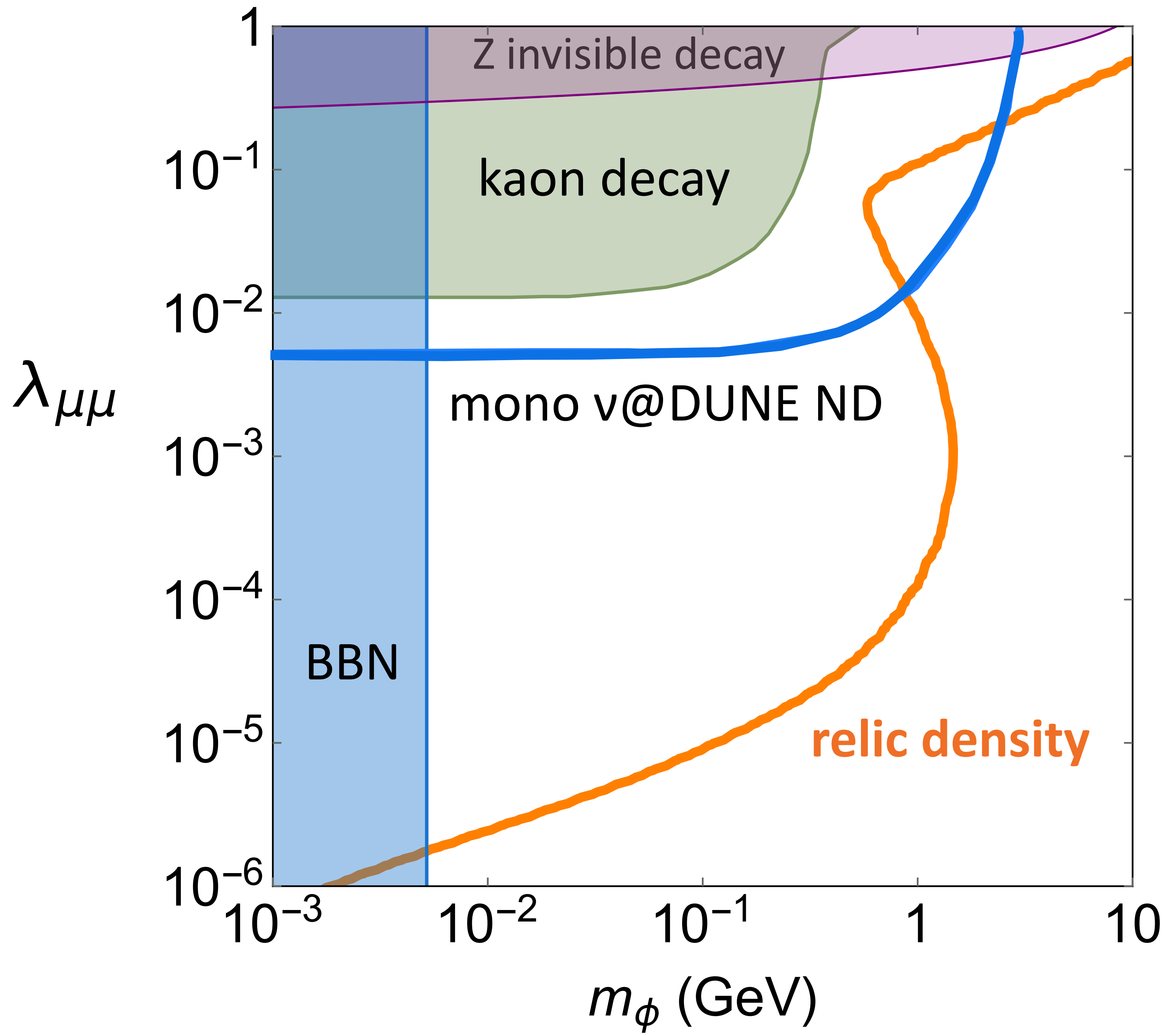


Nucleon level simulation, smearing

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

DUNE CDR (2015)

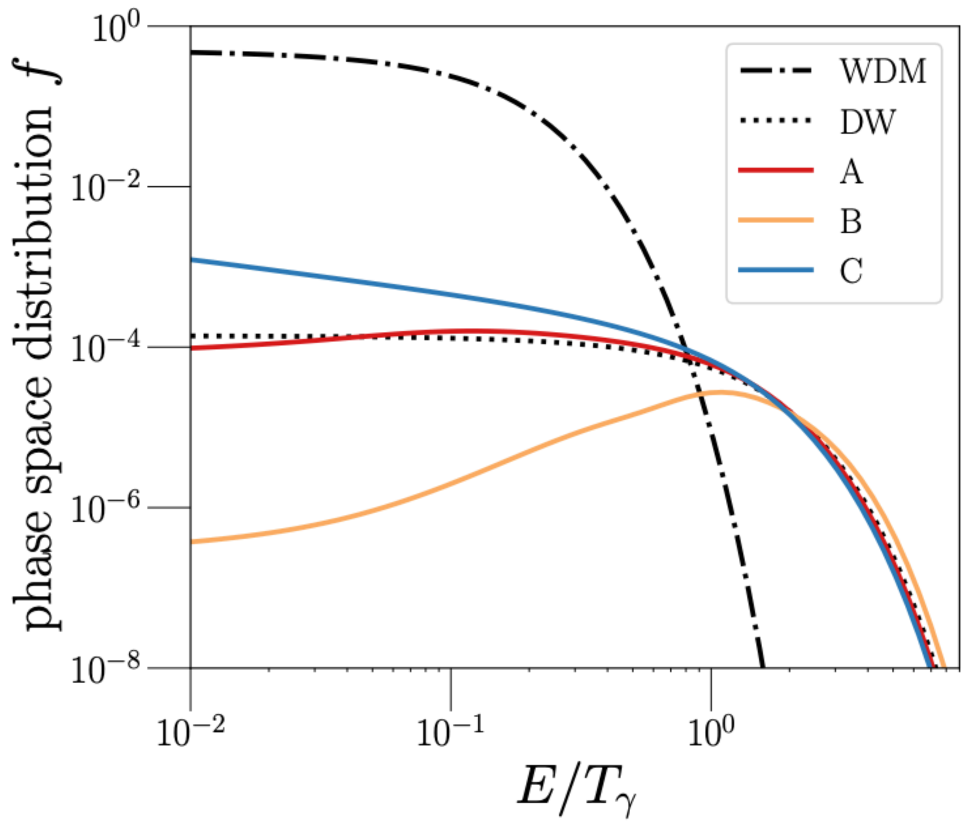
Neutrino Experiment Coverage

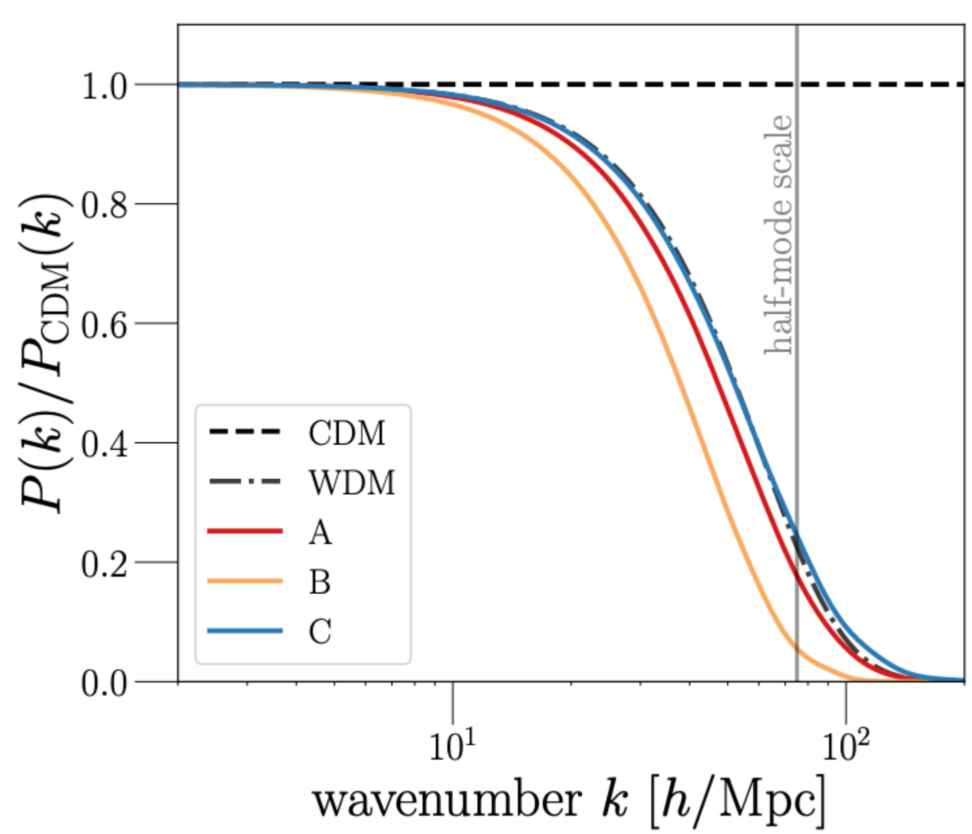


Kelly, YZ (1901.01259, PRD)

Combine with the DES Constraint

Each production scenario features a characteristic phase space distribution of dark matter. Damping scale in the matter power spectrum sensitive to sterile neutrino DM mass.





An, Gluscevic, Nadler, YZ (2301.08299)

Strong Interplay among Frontiers

DES: pushes DM to higher masses → X-ray: smaller mixing angles → Relic density $\Omega \propto \theta^2 \lambda^{2(3)}$ in turn requires larger couplings.

→ Neutrino self-interaction via a heavy mediator φ excluded.

An, Gluscevic, Nadler, YZ (2301.08299)

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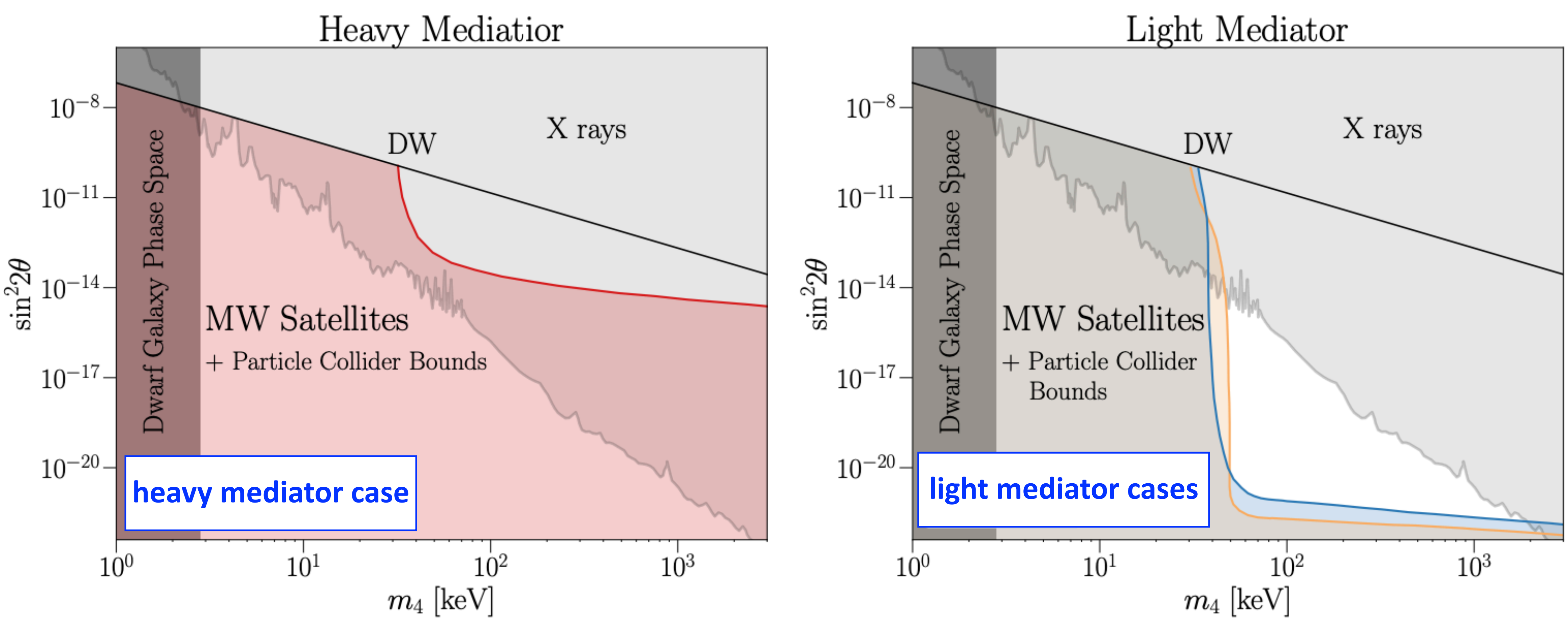
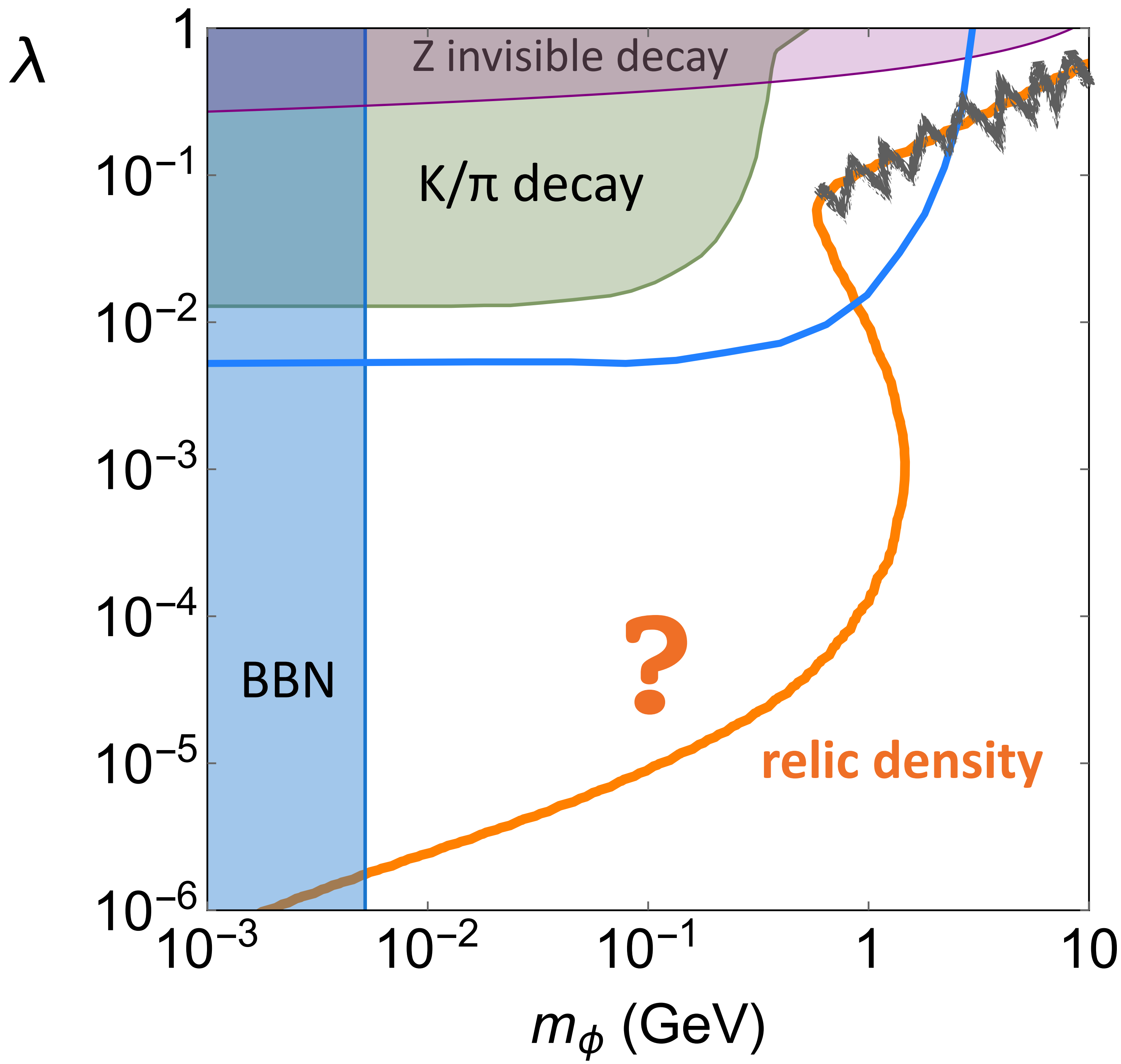
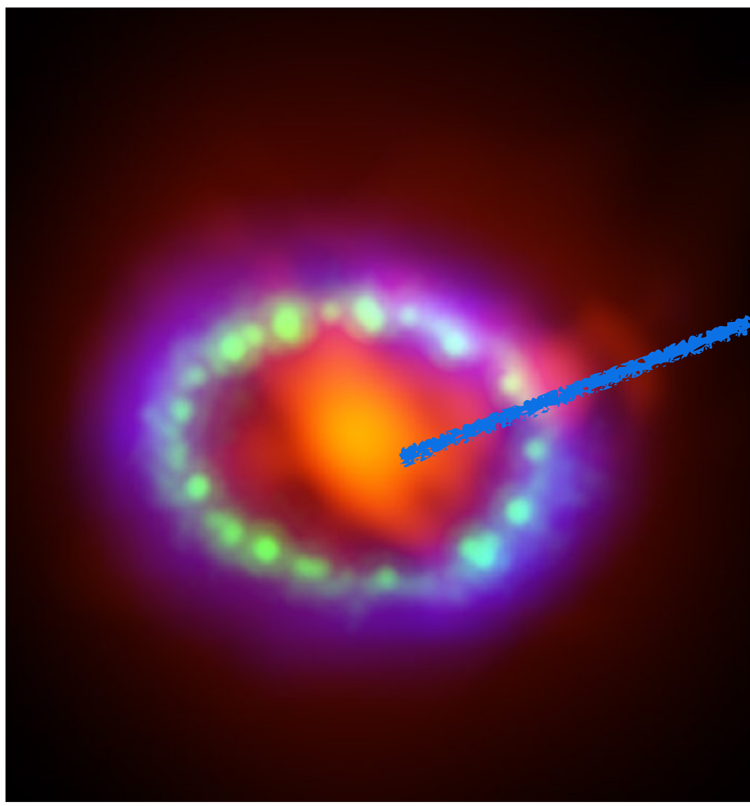


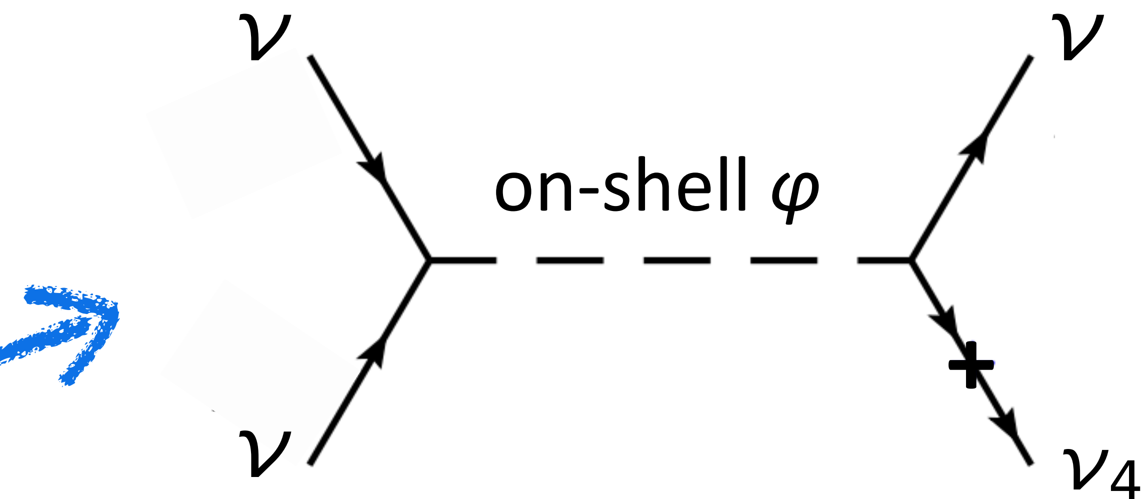
An, Gluscevic, Nadler, YZ (2301.08299)

Moving to Smaller Couplings



Core-collapse Supernova

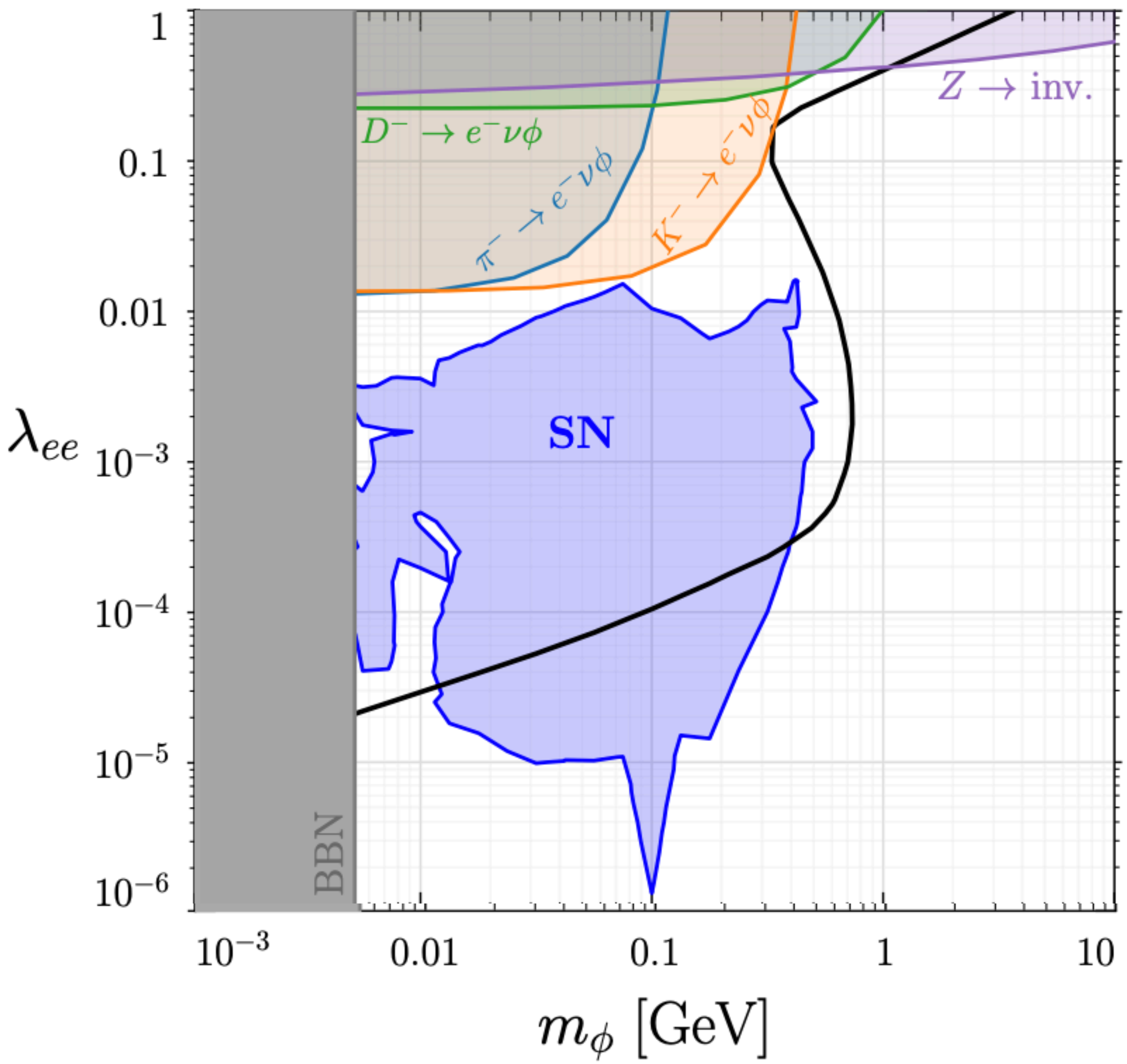




- Similar environment as early universe.
- Energy loss due to prompt decay $\varphi \to \nu\nu_4$ under the "neutrino sphere".
- Same fundamental process as dark matter production mechanism.

Sensitive to more weakly coupled φ

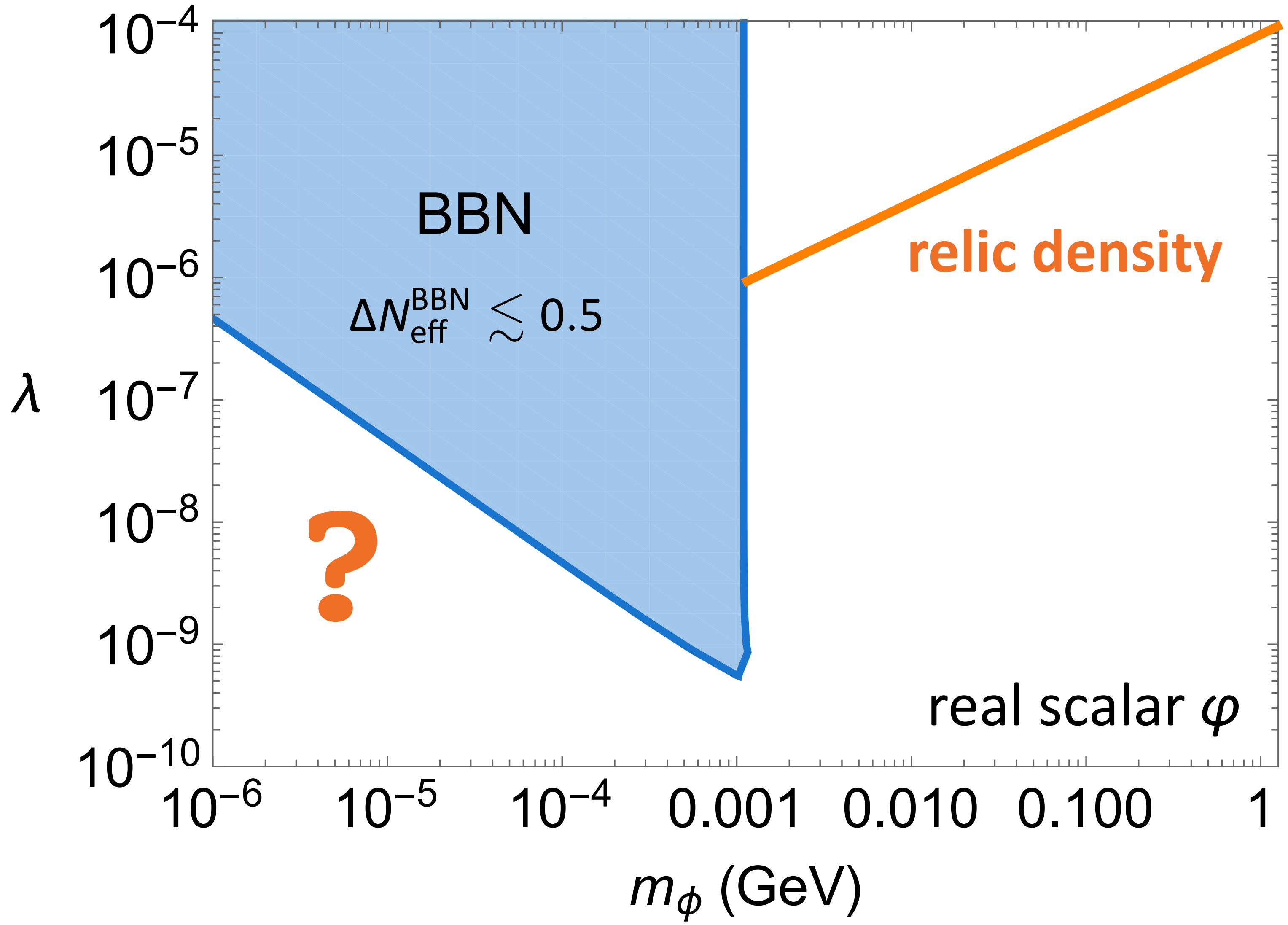
Constraint from SN 1987A



SN constraint most useful for ν_e flavour neutrino self interaction.

Chen, Sen, Tangarife, Tuckler, YZ (2207.14300, JCAP)

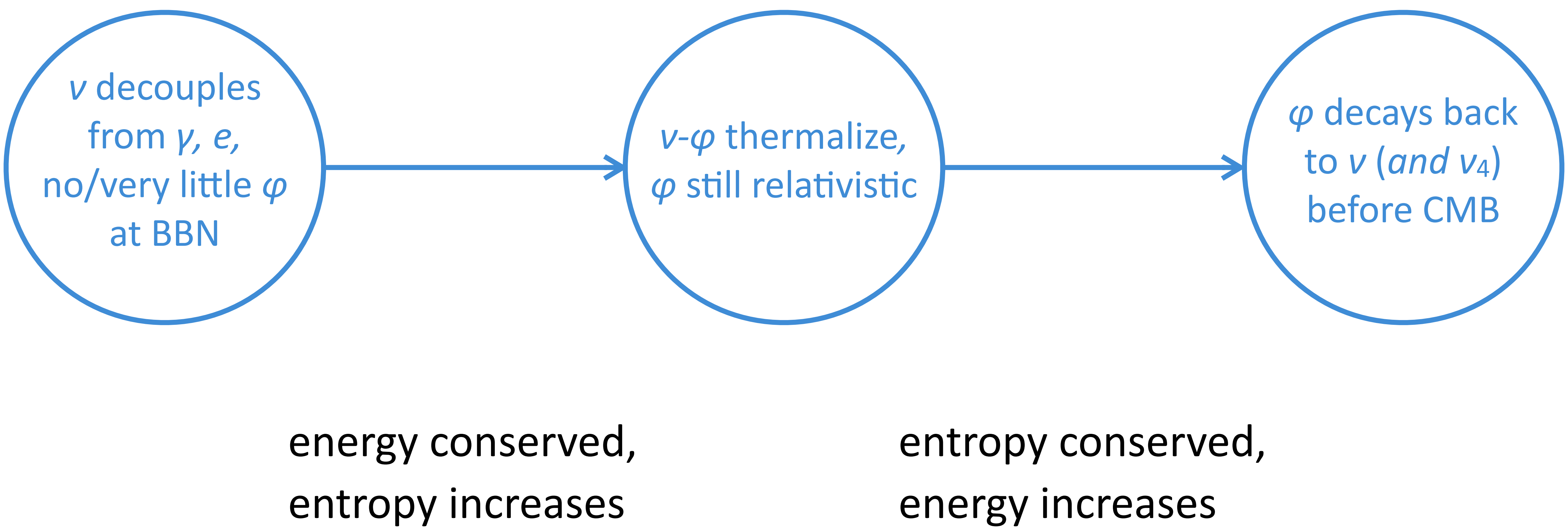
Lighter Mediator versus BBN



For dark matter production, φ must decay into $\nu + \nu_4$ → $m_\varphi > m_4$

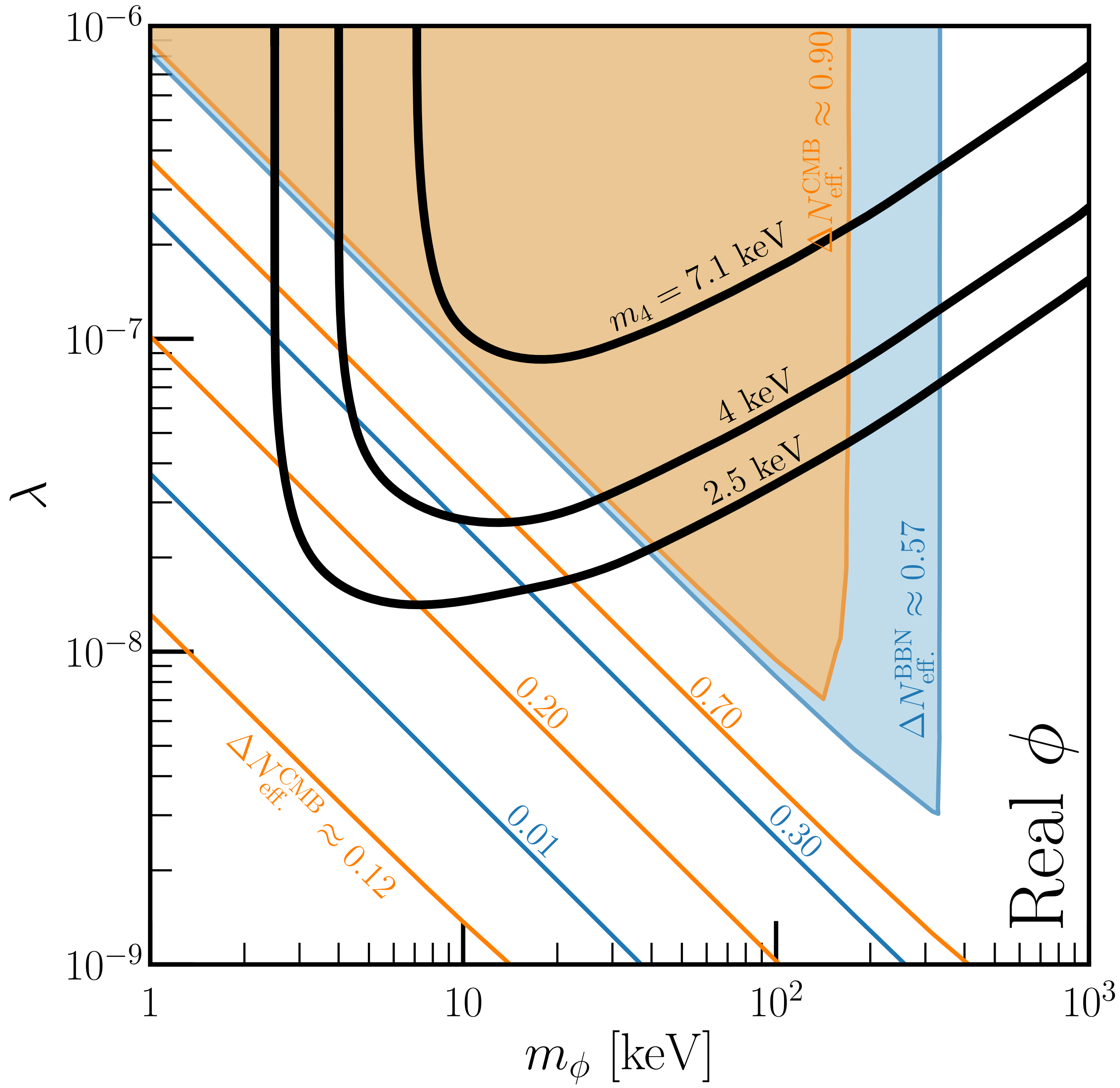
φ-ν Cosmology

The temporary existence of φ after neutrino decouples from the electron-photon plasma makes neutrino sector non-standard.



Net Contribution to ΔN_{eff}

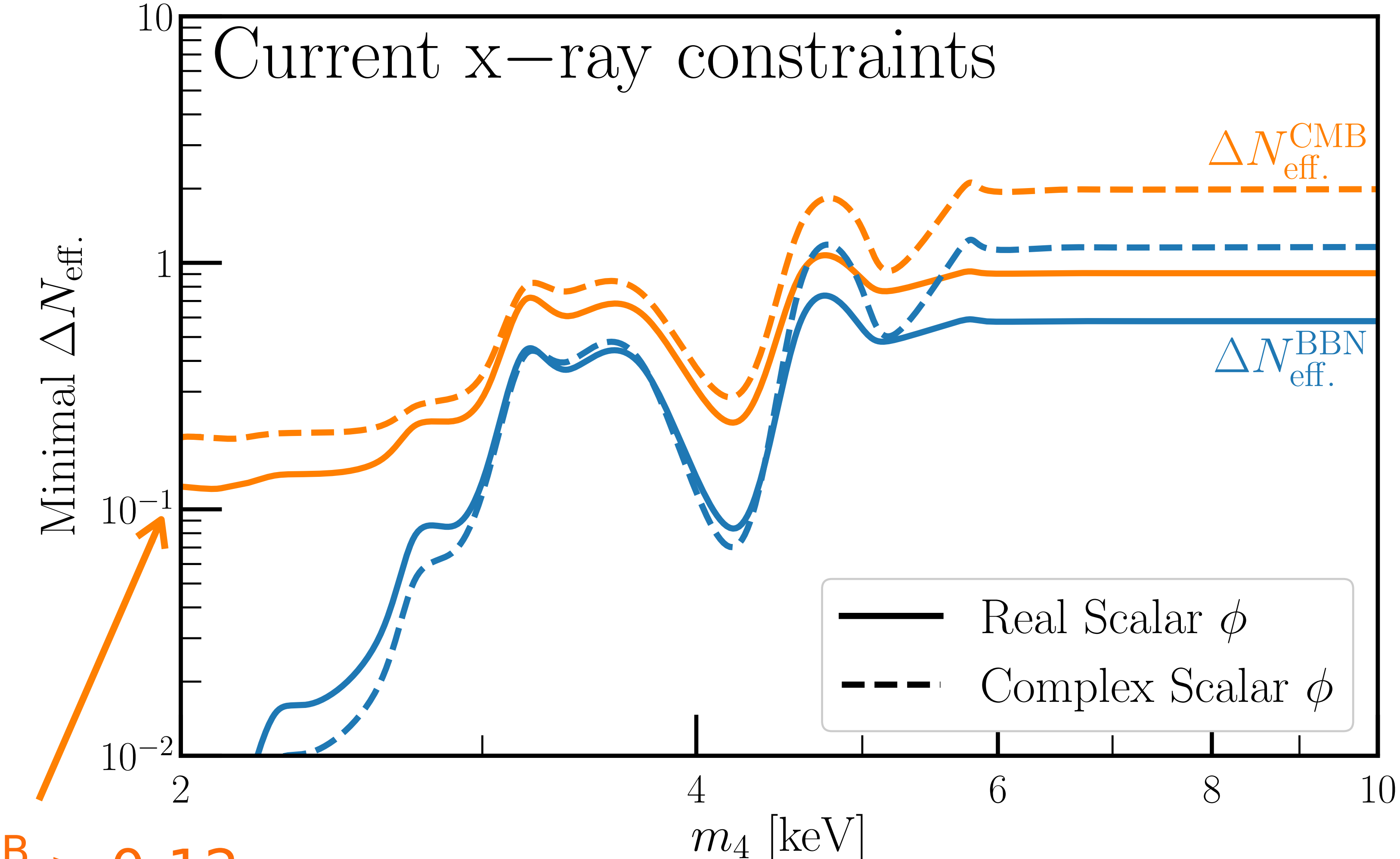
increase N_{eff}



For each mass, chose the largest experimentally allowed ϑ.

Kelly, Sen, YZ (2011.02487, PRL)

Indirect Detection and ΔN_{eff}

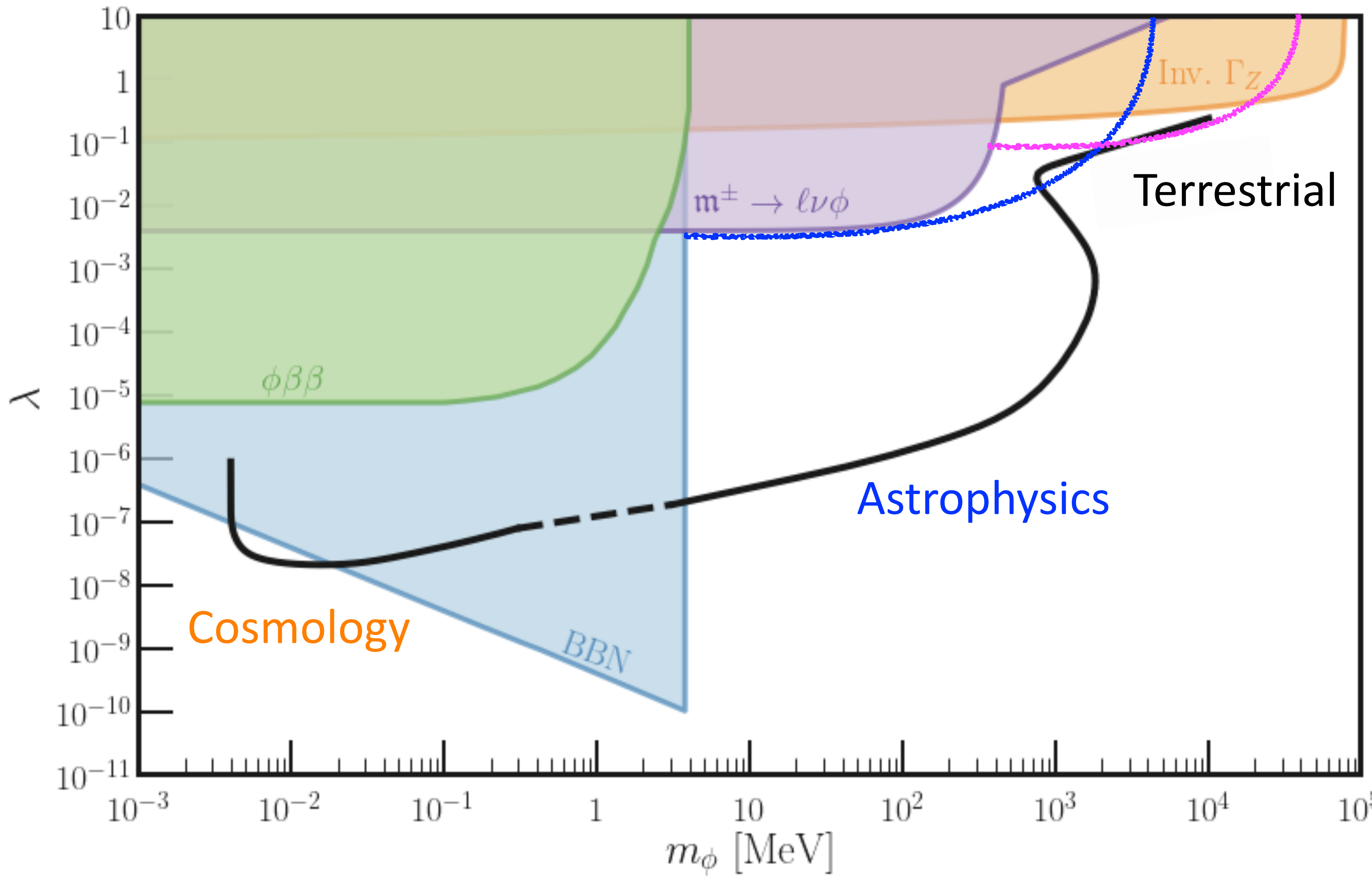


$\Delta N_{\rm eff}^{\rm CMB} > 0.12$

A well-motivated target for CMB-S4

Kelly, Sen, YZ (2011.02487, PRL)

Big Picture: Neutrino Self-interaction



Blinov, Bustamante, Kelly, YZ, et al (2203.01955, Snowmass whitepaper)

Conclusion

Dark matter and neutrino are both elusive members of the universe. This makes it inspiring to speculate on their potential connections.

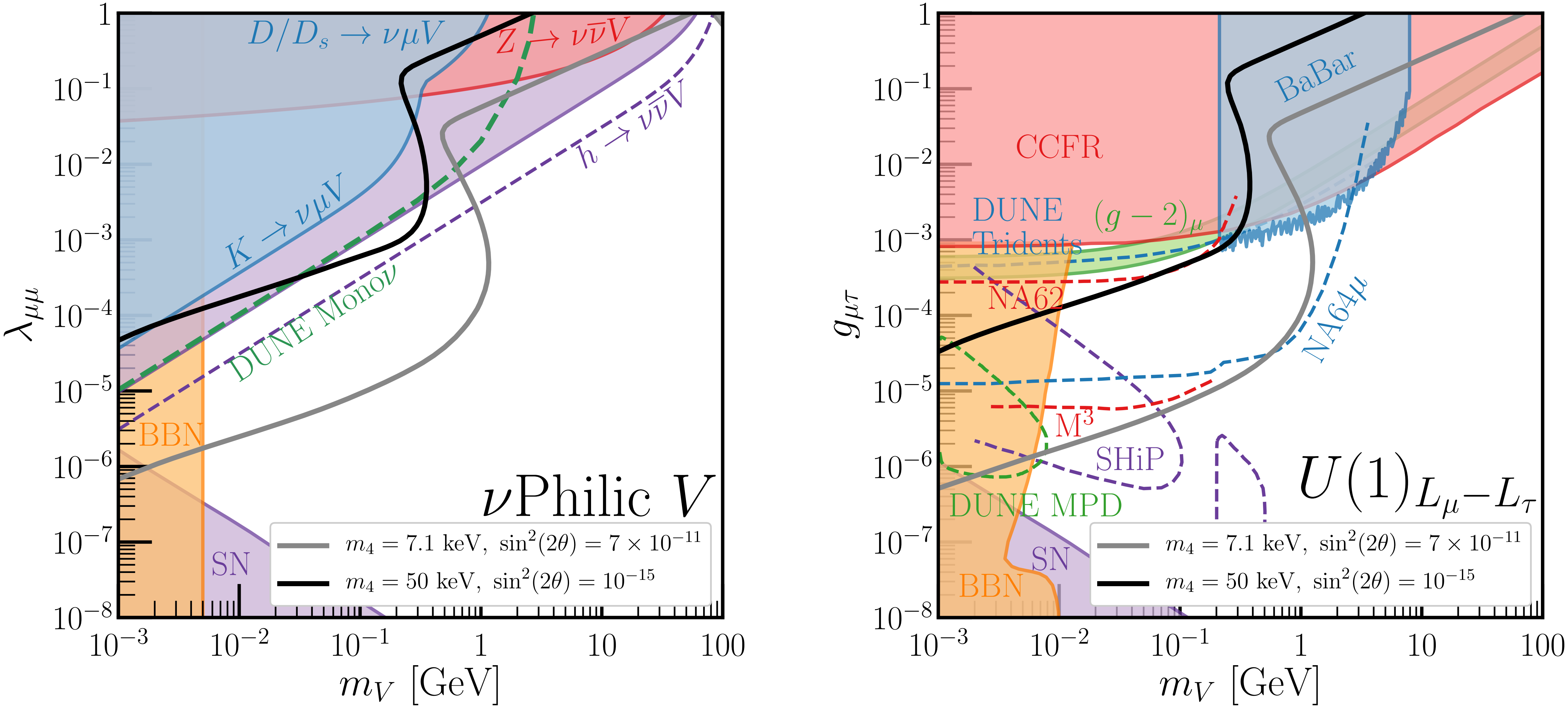
Neutrino self-interaction via light scalar can play instrumental role in the origin of sterile neutrino dark matter.

A number of ways for testing such a hypothesis with the upcoming particle physics and cosmology experiments.

Thanks!

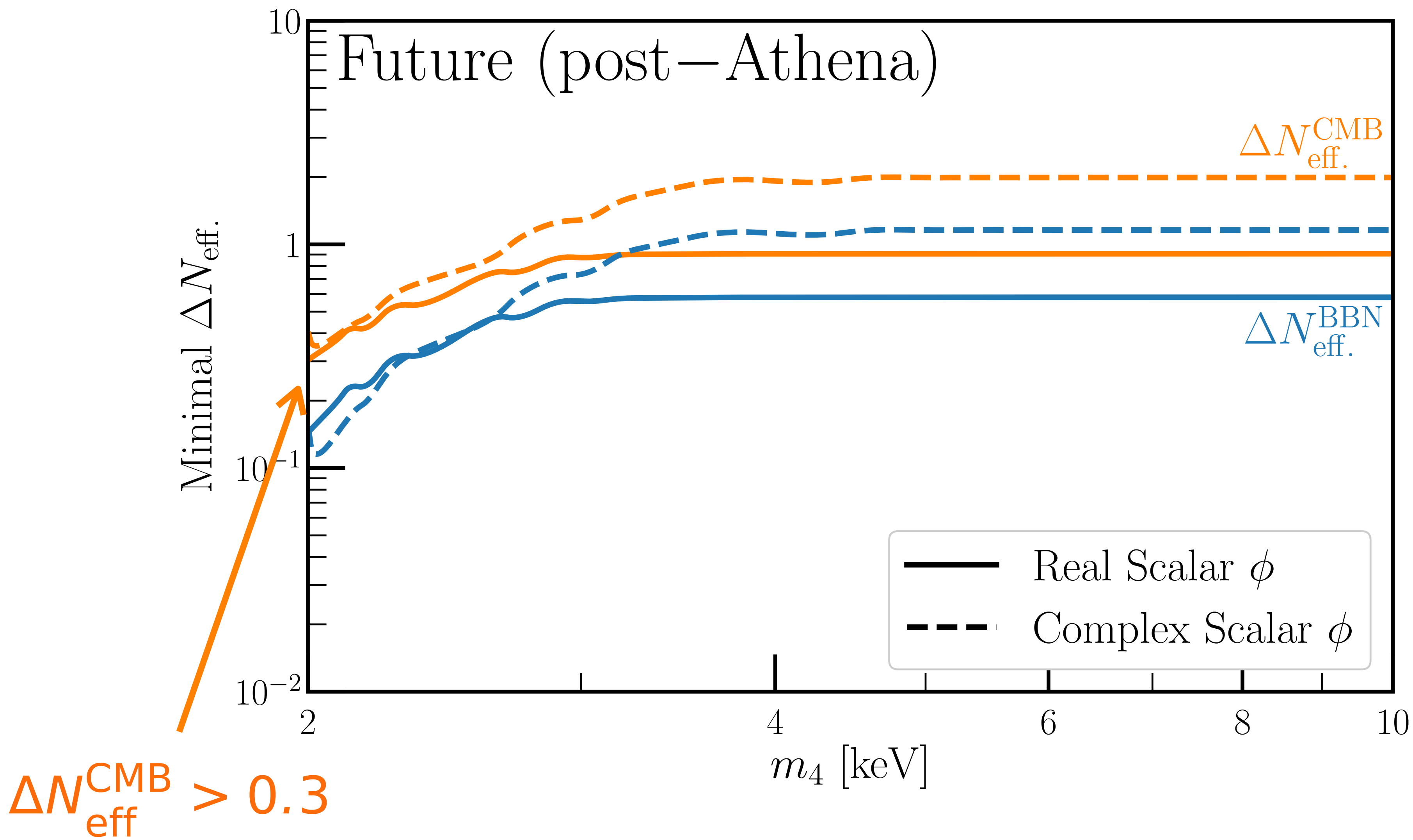
bonus

Vector Mediator Case



Kelly, Sen, Tangarife, YZ (2005.03681)

Indirect Detection and ΔN_{eff}

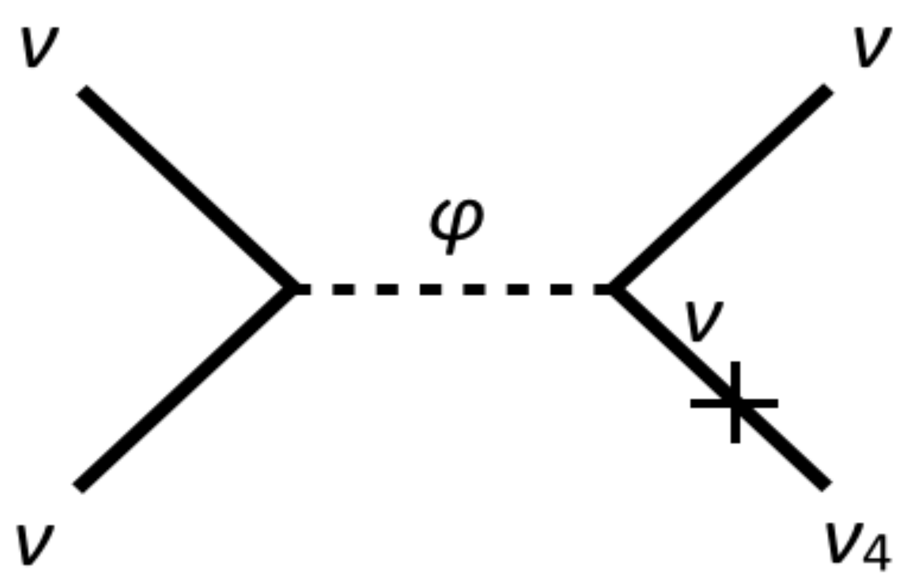


well-motivated target for CMB-S4

Kelly, Sen, YZ (2011.02487, PRL)

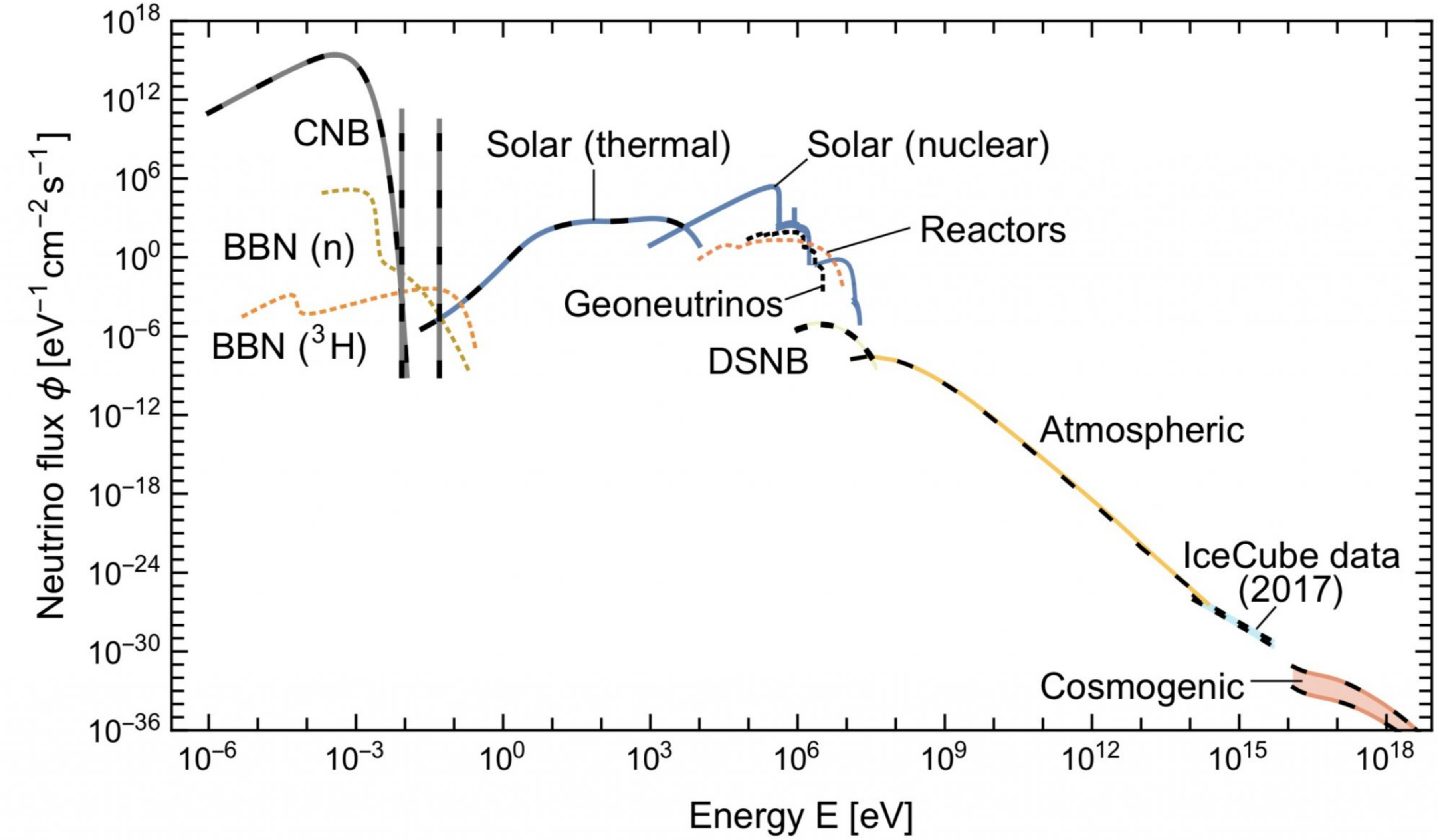
Dark Matter Decay to Neutrinos

Neutrinos from ν_4 DM decay: same Feynman diagram for dark matter production also makes it decay.



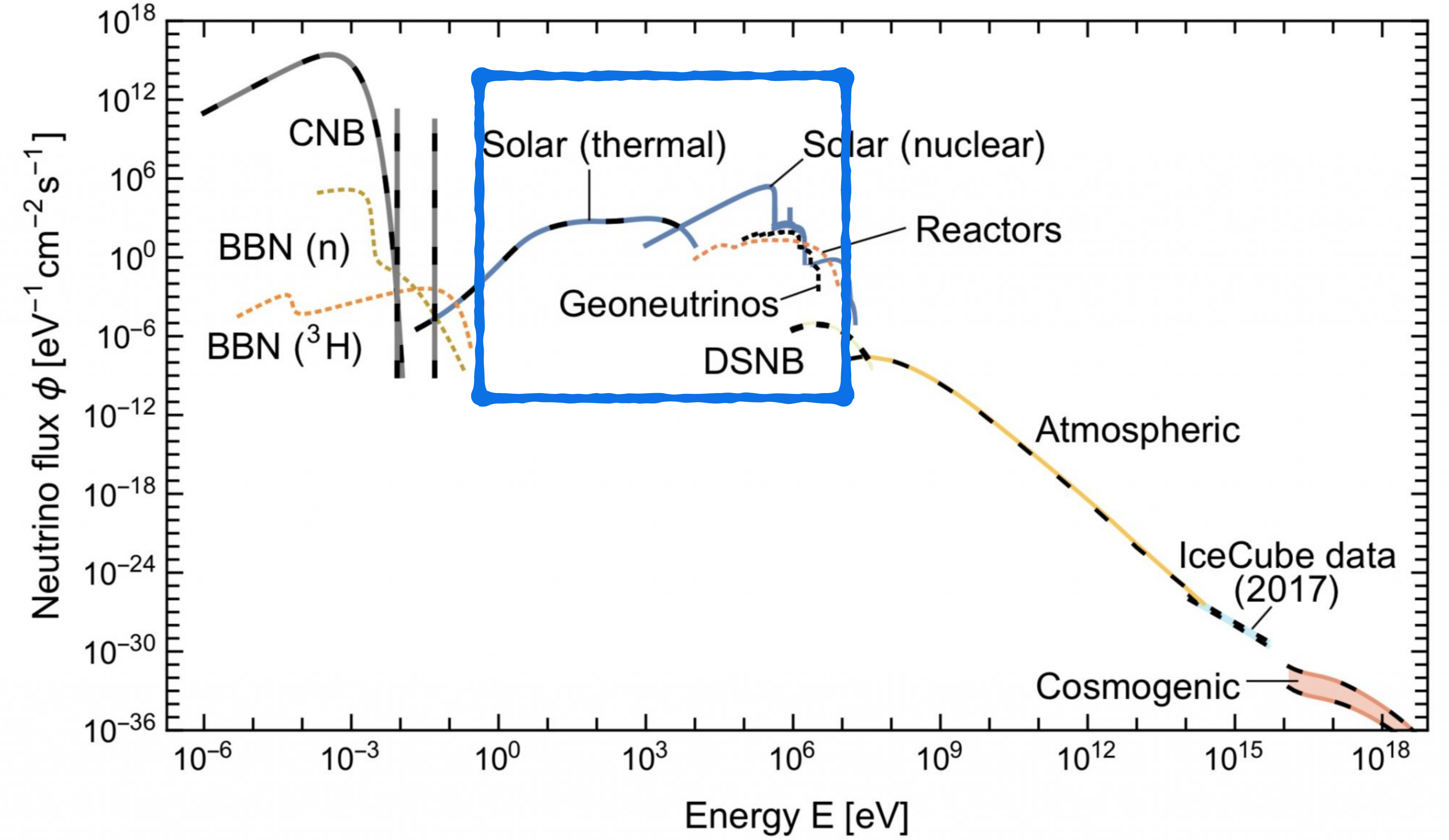
$$\tau(\nu_4 \to 3\nu) \sim 10\,\tau_U \left(\frac{10^{-10}}{\sin^2 2\theta}\right)^2 \left(\frac{10\,\mathrm{keV}}{m_4}\right)^5 \left(\frac{10^{-1}}{\lambda}\right)^4 \left(\frac{m_\phi}{1\,\mathrm{GeV}}\right)^4$$

Neutrino Spectrum at Earth



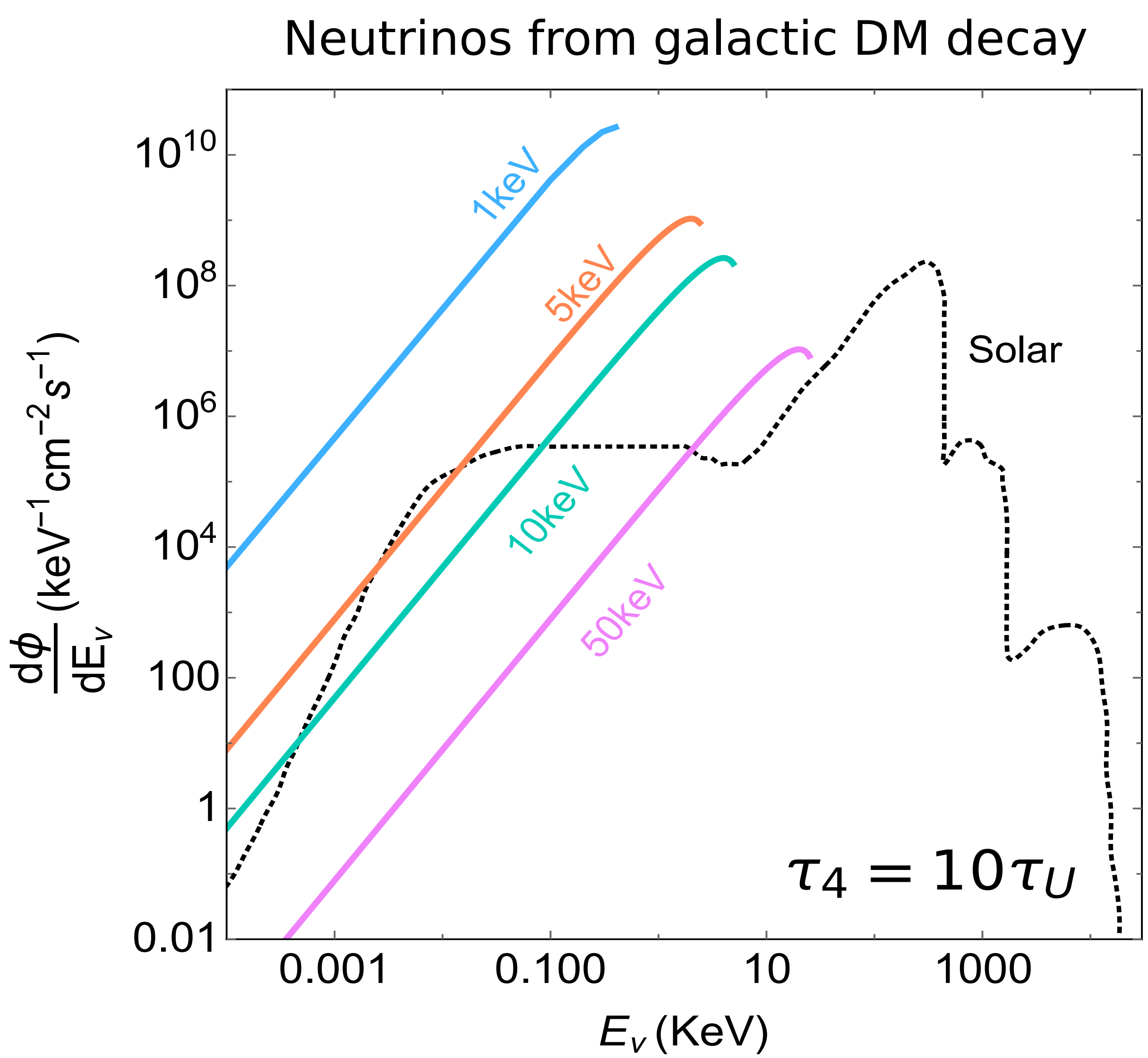
Vitagliano, Tamborra, Raffelt (1910.11878)

Neutrino Spectrum at Earth



Vitagliano, Tamborra, Raffelt (1910.11878)

Detecting keV Neutrinos



Clearly a crucial test of the dark matter production mechanism discussed here.

Can they be detected?

Neutrino-electron scattering in dark matter detectors?

[need very large detectors, e.g., DARWIN, ARGO]