Exploring Novel Dark Matter-Neutrino Connection

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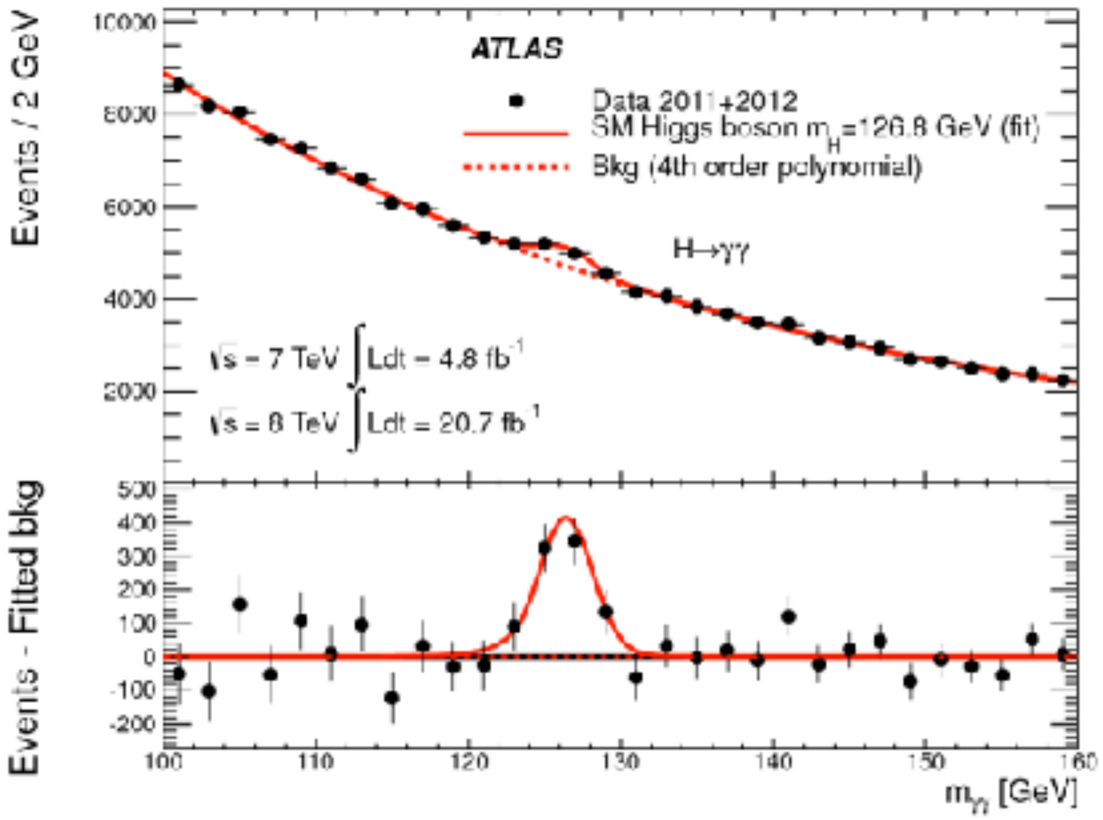
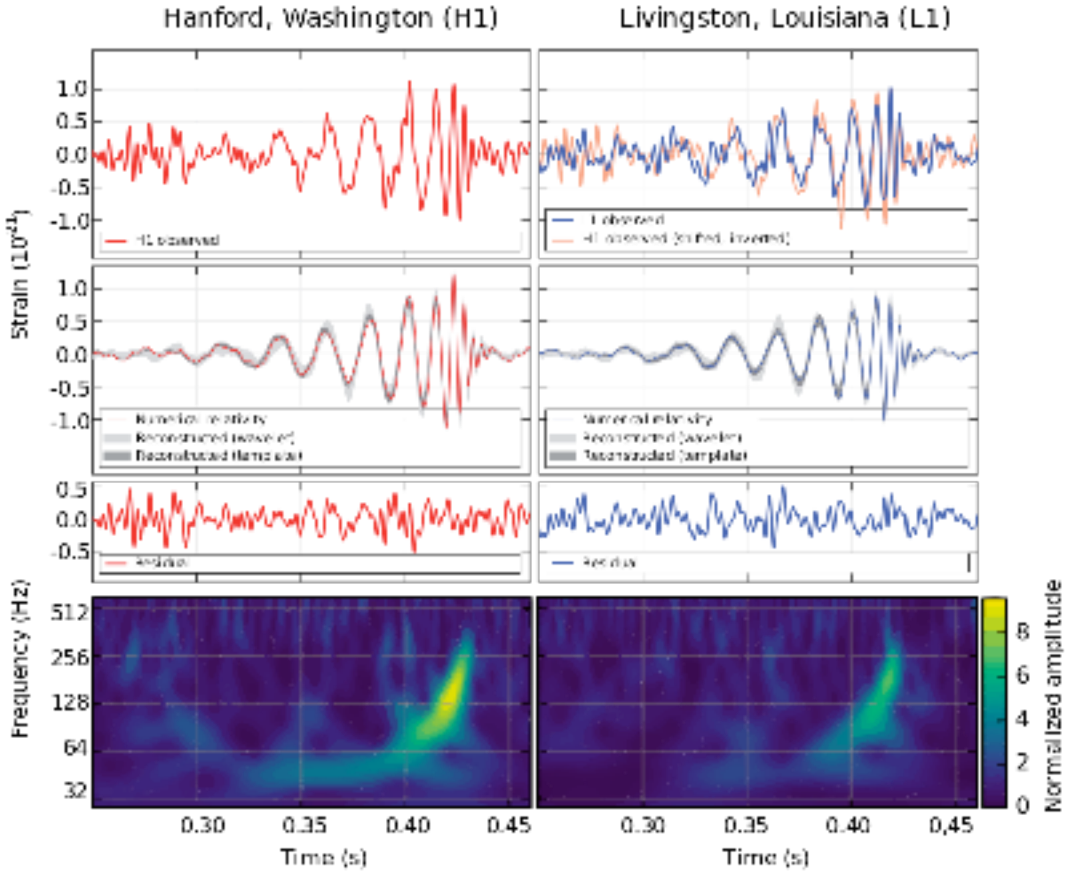
Recent Milestones





Discovery of the Higgs boson (2012)

Discovery of gravitational waves (2015)

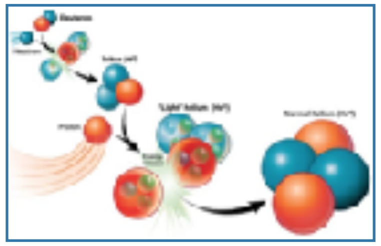
Nobel Prize (2013)

Nobel Prize (2017)

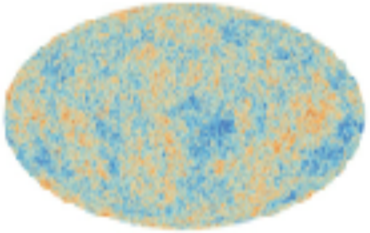
Standard Model completed!

Einstein's gravity still works!

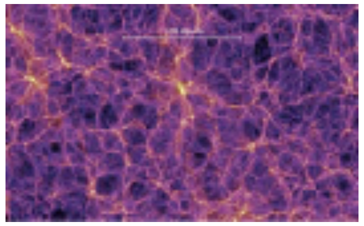
Recipe for Our Universe



Big-bang nucleosynthesis



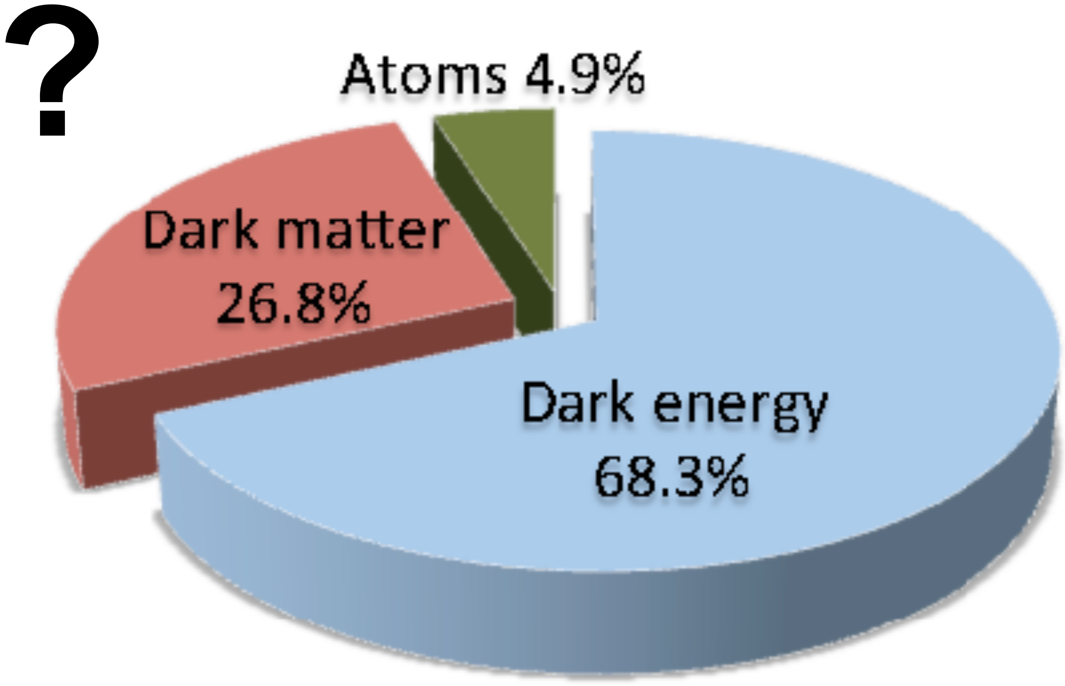
Distribution of light



Distribution of baryons

Standard candles

?



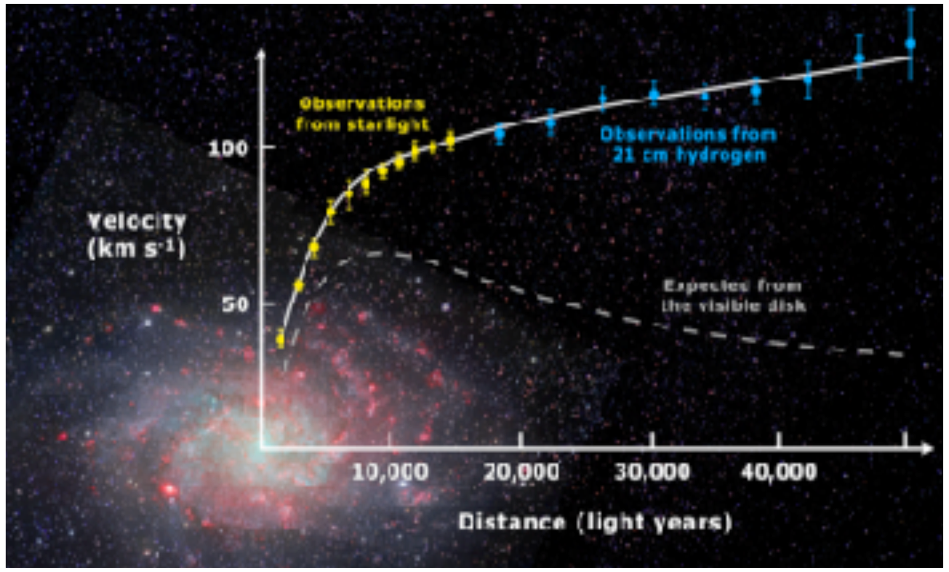
Today's energy budget

Rich Evidence for Dark Matter

1930s

2000s

1970s



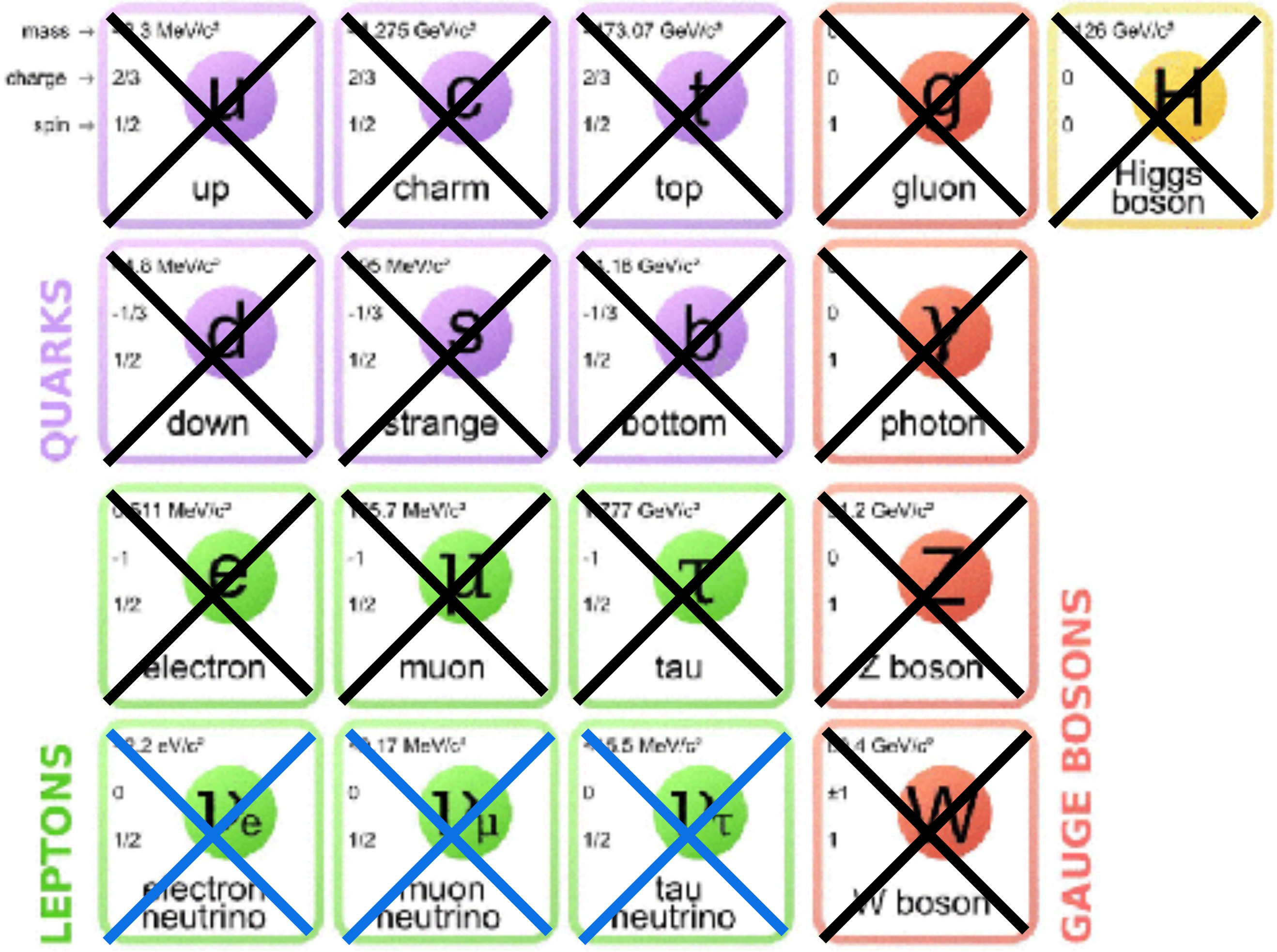
$F \neq ma$

Stuff gravitating
light cannot see!

What Have We Learned

- Wide mass range 10^{-20} eV to 10^{4} $M_\odot$
- Stable, or cosmologically long-lived
- Cold, or not very relativistic recently
- Less collisional than atoms
- Its relic abundance has been measured.

How Standard Model Fails



No electric charge or color

Long lived enough

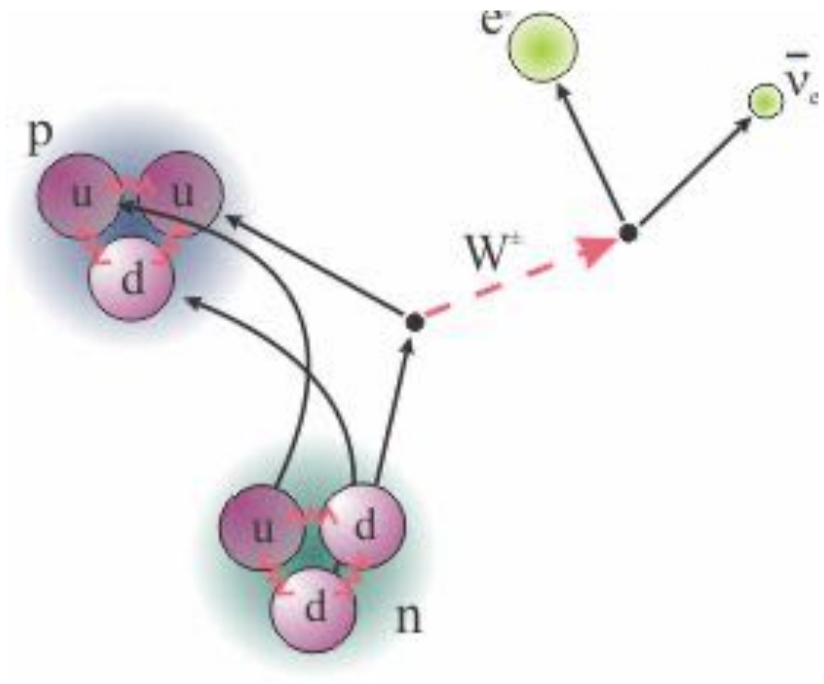
Has mass

Finally: neutrinos too light

Neutrino

Neutrinos are members of the Standard Model, only participate in weak interaction. There are three flavors of neutrinos.

Neutrino was first introduced to balance momentum conservation in neutron decay.



1930s

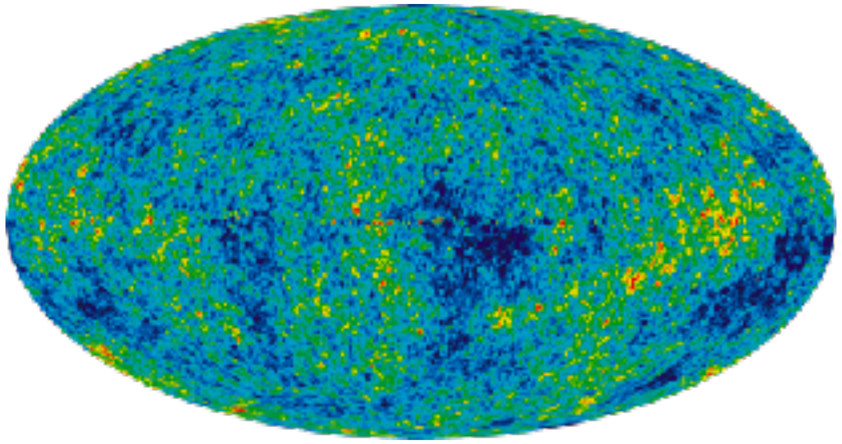
Tremaine-Gunn Bound

Argument based on Fermi statistics: lower limit on fermion dark matter mass set by dwarf galaxies.

$$m_{1/2} \gtrsim \text{keV}$$

(Upper bound on SM neutrino mass < 1.1 eV from KATRIN, tritium β decay)

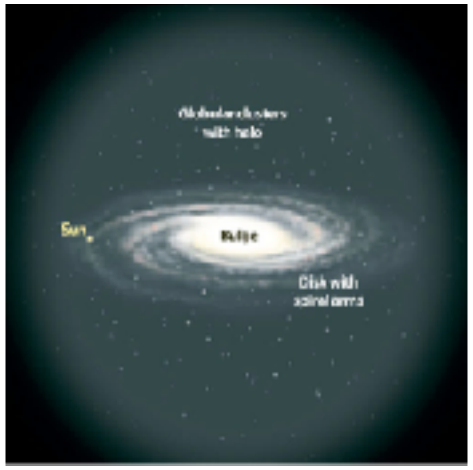
Dark Matter-Neutrino Similarity

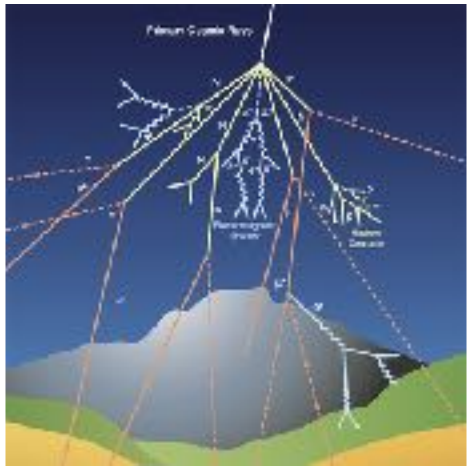


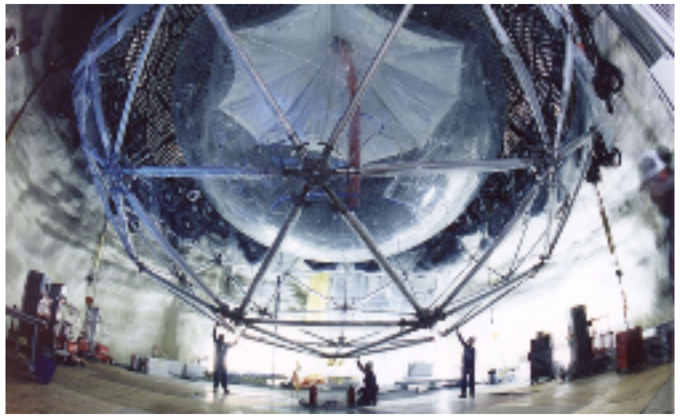
Both are remnants of Big-Bang

*Neutrinos almost pass the dark matter test, except for being too light

Both are everywhere around us







Both are not easy to detect.

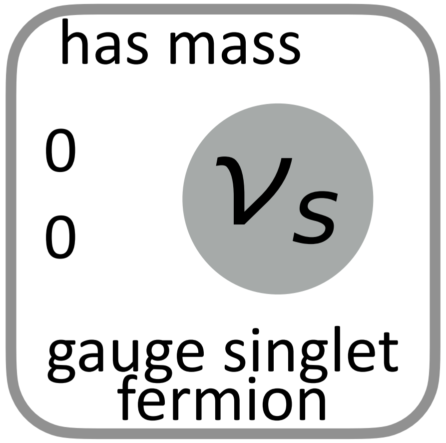
Dark Matter-Neutrino Connections

Useful starting point that has borne many fruits:

this talk

- **WIMP:** dark matter as a heavy copy of neutrino.
- **Sterile neutrino dark matter:** dark matter and neutrino are part of each other.
- **Neutrino portal dark sector:** more theory structures on the dark side.
- **More theoretical connections:** e.g. can dark matter address origin of neutrino mass?
- **Novel signals:** look dark matter in neutrino detectors, and vice versa.

Sterile Neutrino Dark Matter

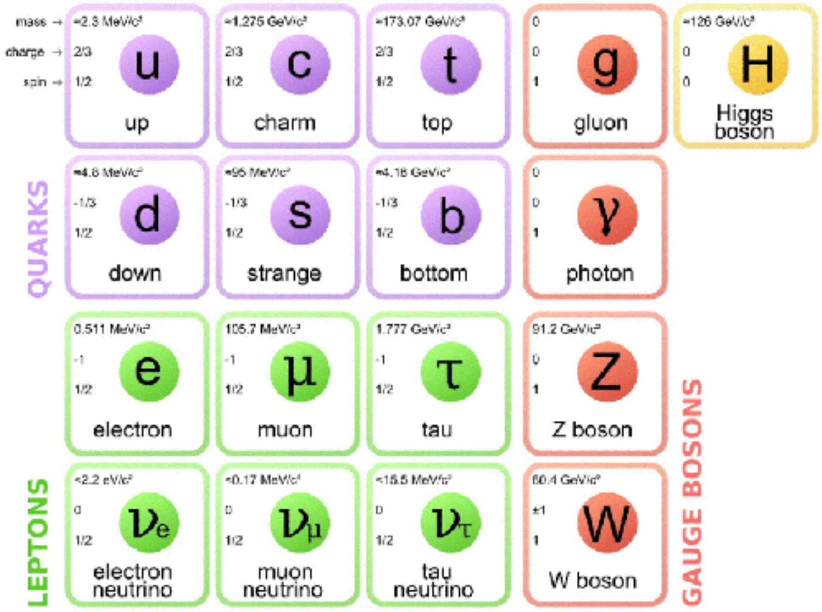

has mass

0

0

ν_s

gauge singlet fermion



ν_s features a mixing with the active neutrinos $\nu_\alpha \quad (\alpha = e, \mu, \tau)$

$$|\nu_4\rangle = \sin\theta\,|\nu_\alpha\rangle + \cos\theta\,|\nu_s\rangle$$

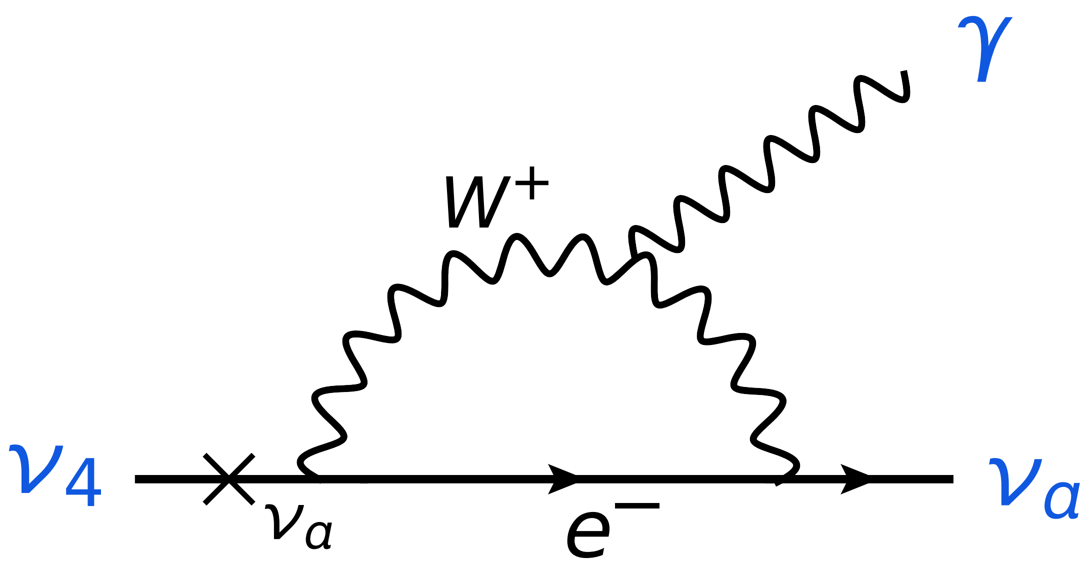
$$|\nu_1\rangle = \cos\theta\,|\nu_\alpha\rangle - \sin\theta\,|\nu_s\rangle$$

mass eigenstates,
physical

Flavor eigenstates

It Can Decay Into Photon

Very simple dark matter model: only two parameters, and not even a symmetry thus dark matter is not strictly stable.



Dark matter longevity attributed to small mass and mixing angle.

Thermal History not Allowed

How about thermalizing ν_4 with SM particles in early universe, just like active neutrinos?

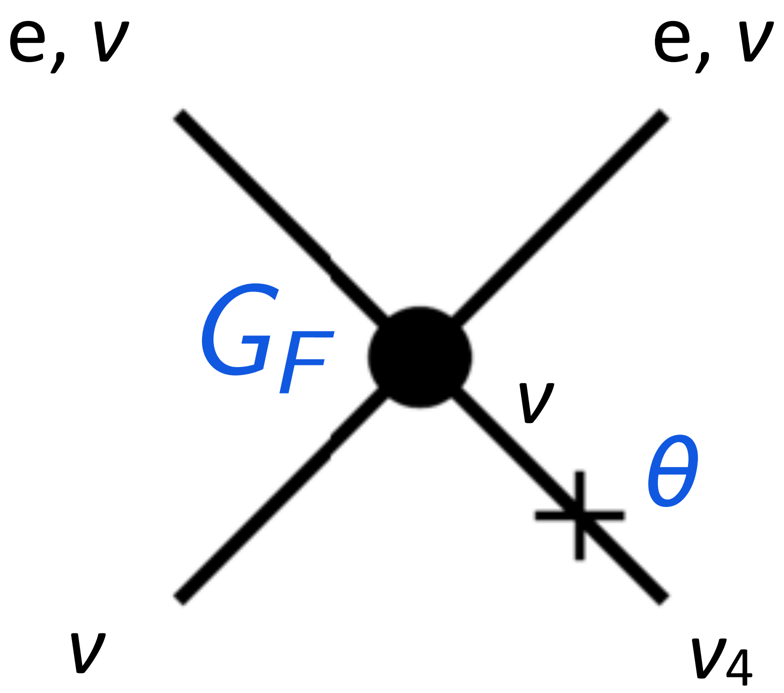
Not an option — will produce way too much dark matter.

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

Successful cosmology requires $\Omega_4 = 0.268$.

Must be produced in a non-thermal way with a small $\theta << 1$.

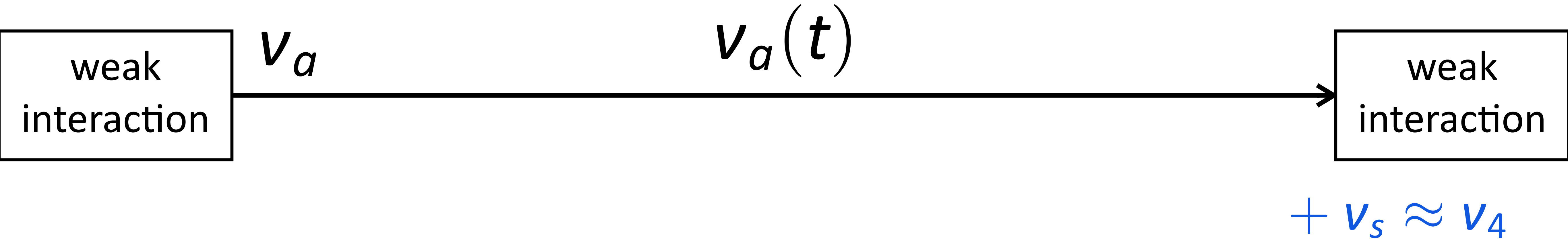
Dodelson-Widrow Mechanism



Tiny mixing angle ϑ controls the relic density.

hep-ph/9303287, PRL

Neutrino Oscillation in Early Universe



weak interaction

ν_a

$\nu_a(t)$

weak interaction

$+\,\nu_s \approx \nu_4$

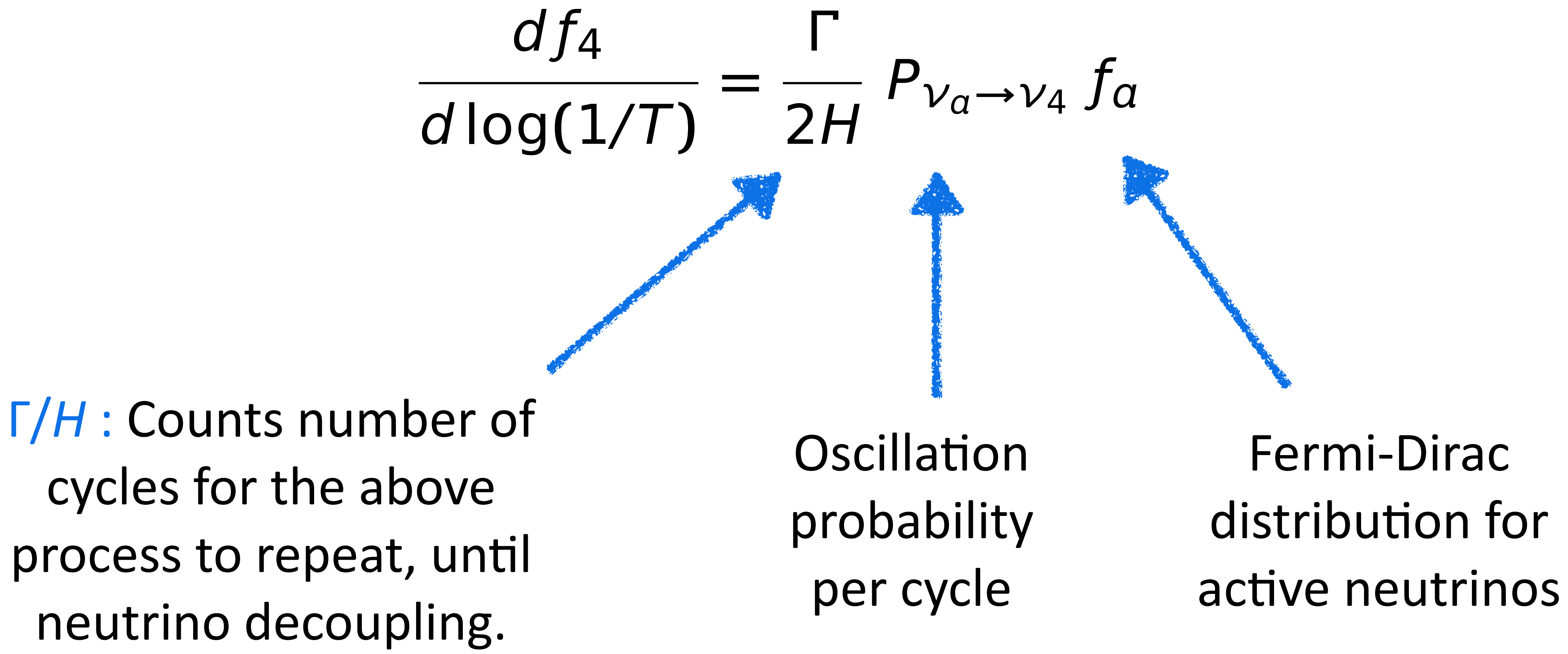
Two time scales:

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

In between, active-sterile neutrino oscillation occurs.

Dark Matter Production Rate

Rate equation for active neutrinos to turn into dark matter



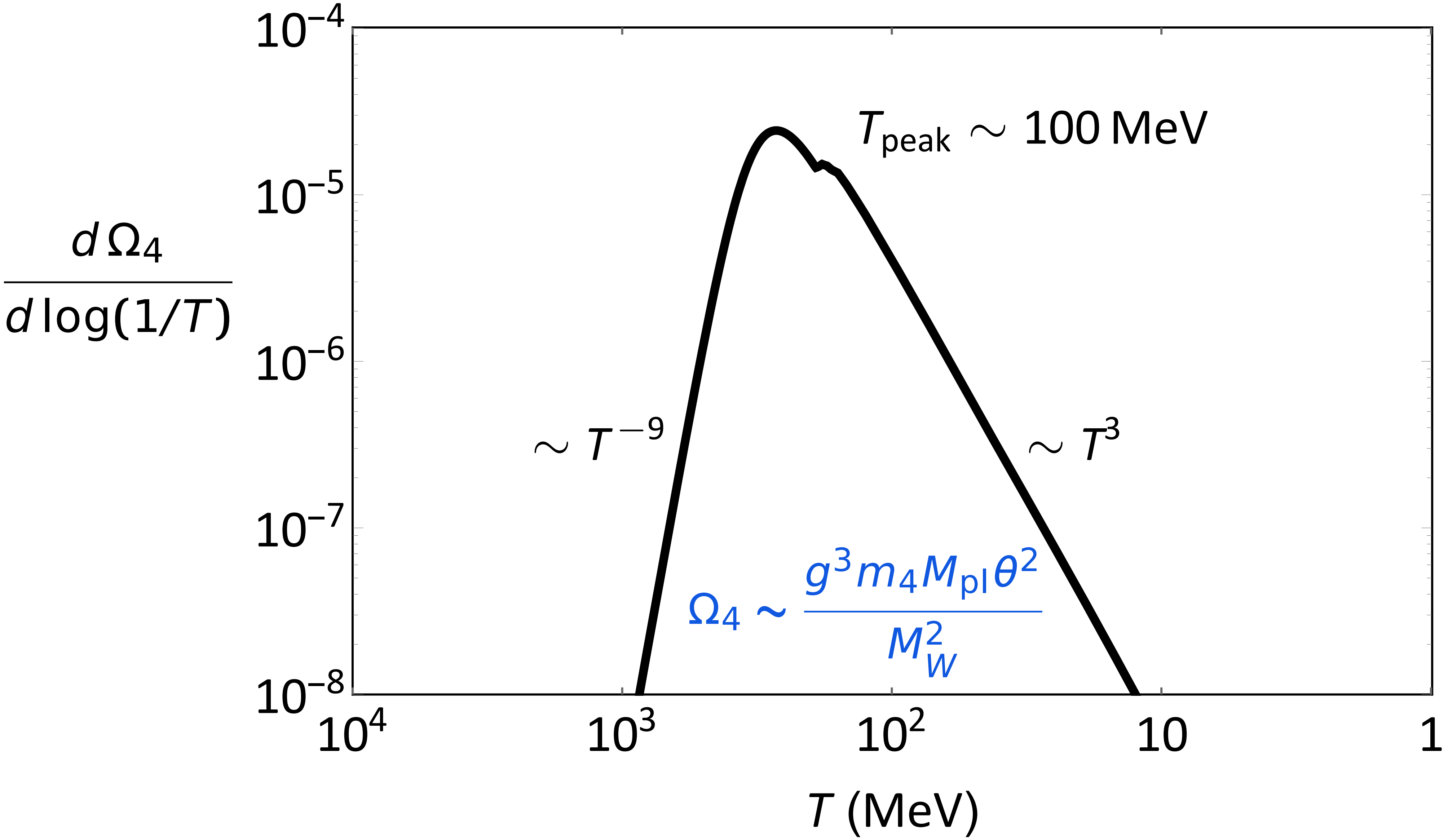
$$\frac{d f_4}{d \log(1/T)} = \frac{\Gamma}{2H} P_{\nu_a \to \nu_4} f_a$$

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

Oscillation probability per cycle

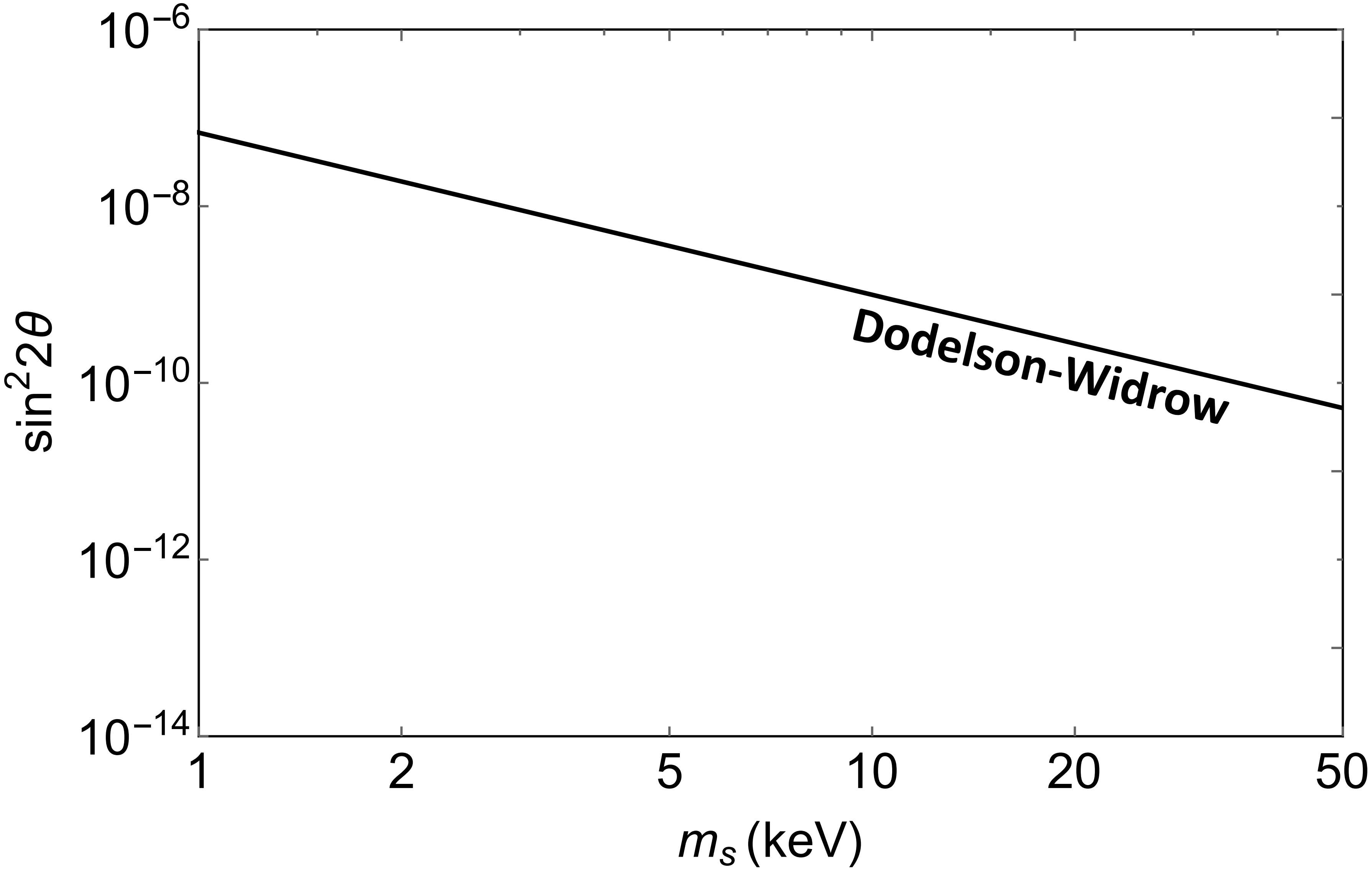
Fermi-Dirac distribution for active neutrinos

Production Epoch

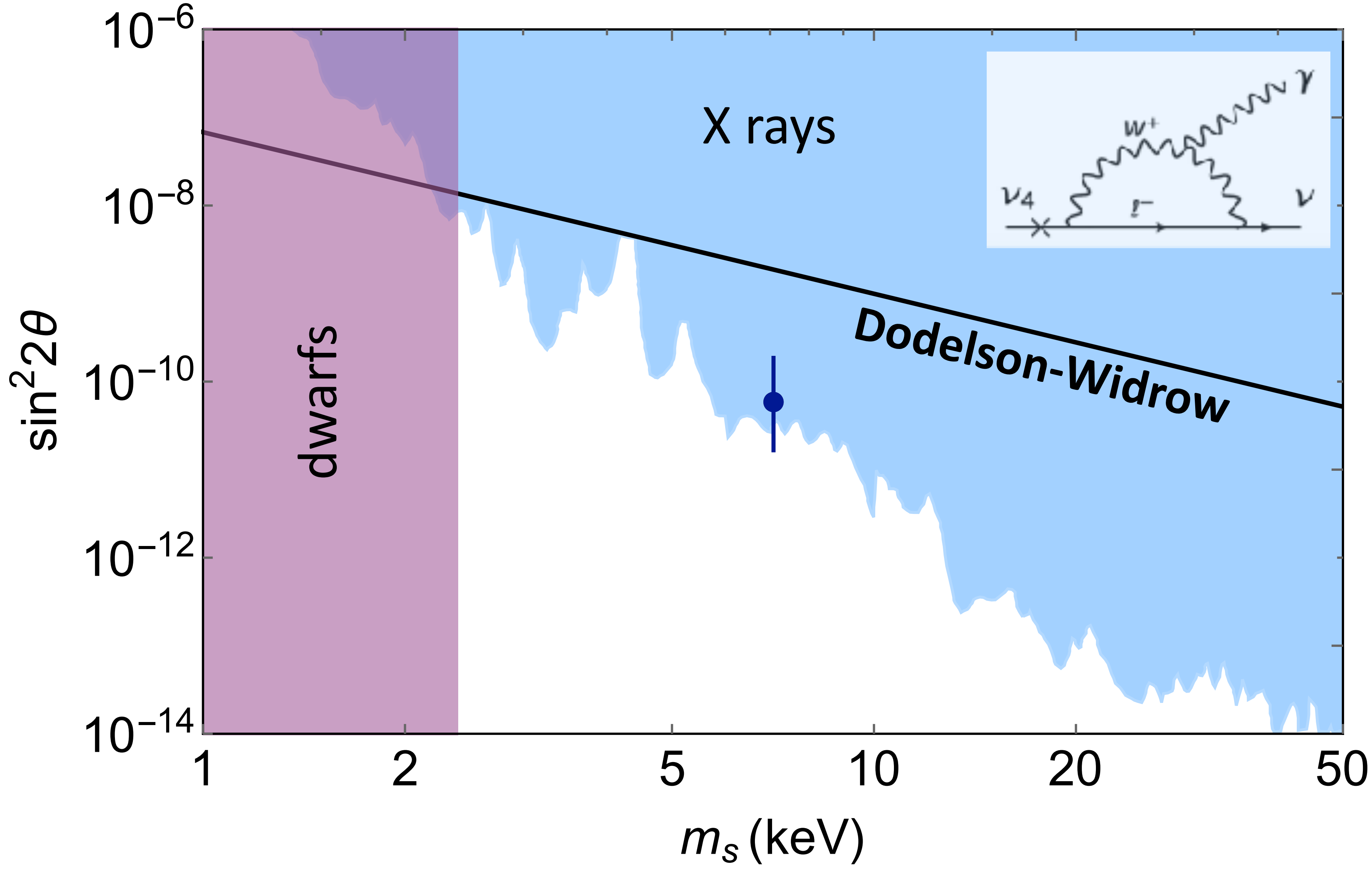


time →

Parameter Space for Relic



Tantalizing Puzzle



Abazajian (1705.01837, Physics Reports)

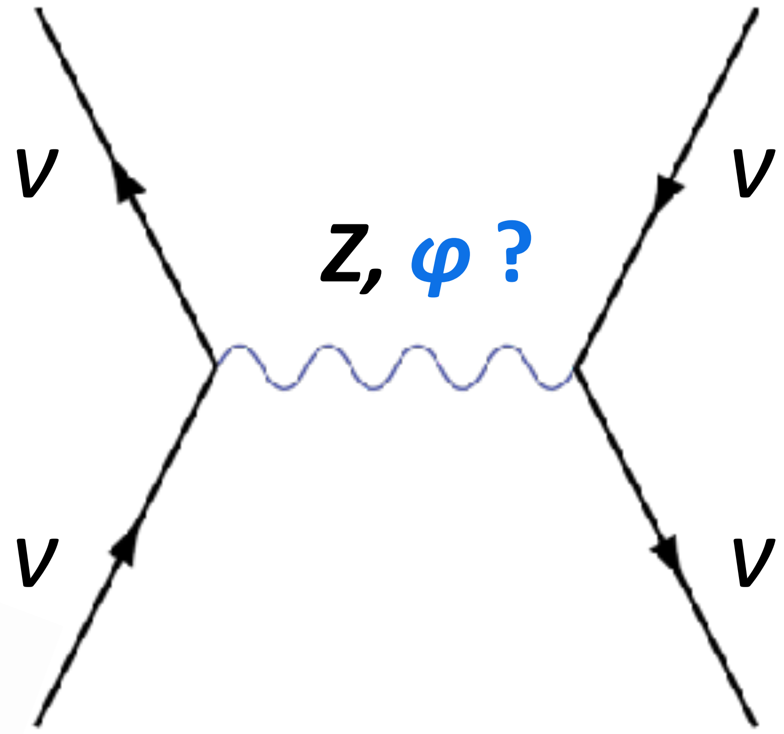
A Simple Idea

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

Intuition: compensate smaller mixing with larger reaction rate.

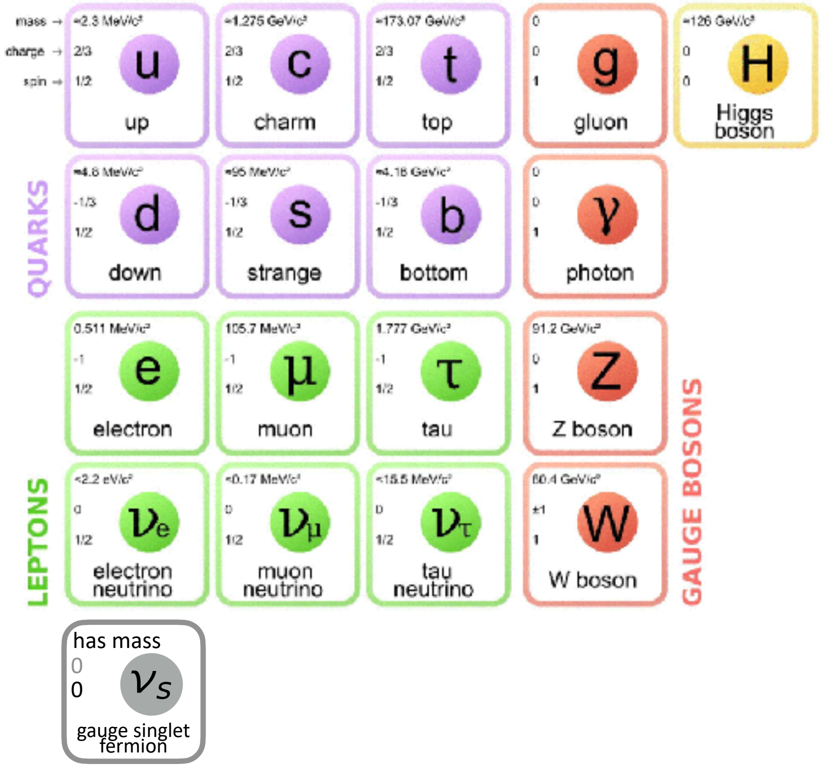
Beyond Standard Model neutrino interactions with other known particles (e.g. electron) already tightly constrained — resort to neutrino self-interactions.

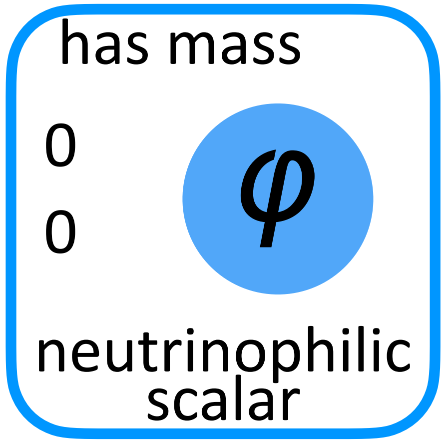
Neutrino Self Interaction



Never directly measured. There is large room for neutrino self interaction to be much stronger.

Scalar Particle Couples to Neutrinos





has mass

0

0

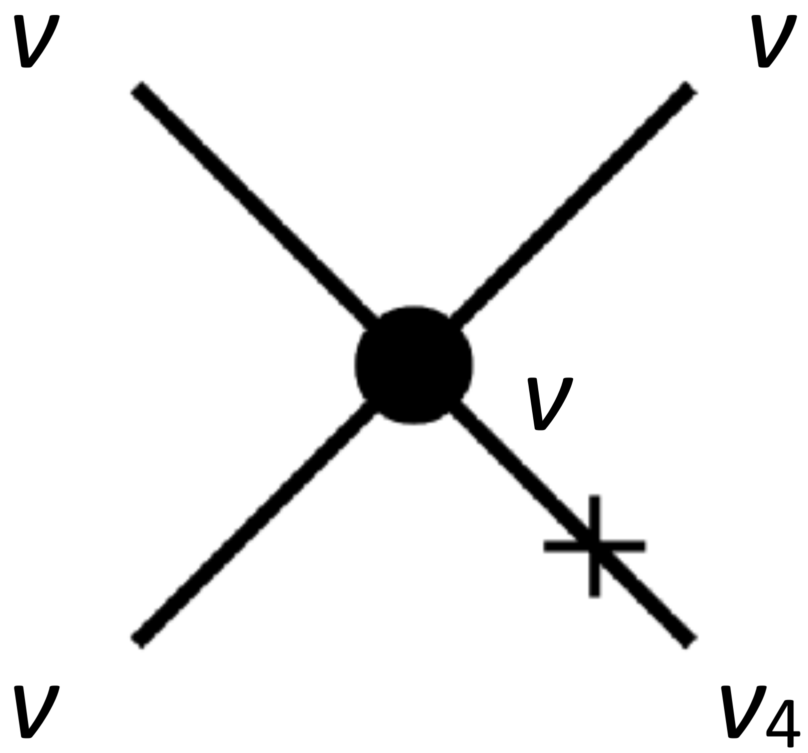
φ

neutrinophilic scalar

New Lagrangian for interaction (low energy effective coupling)

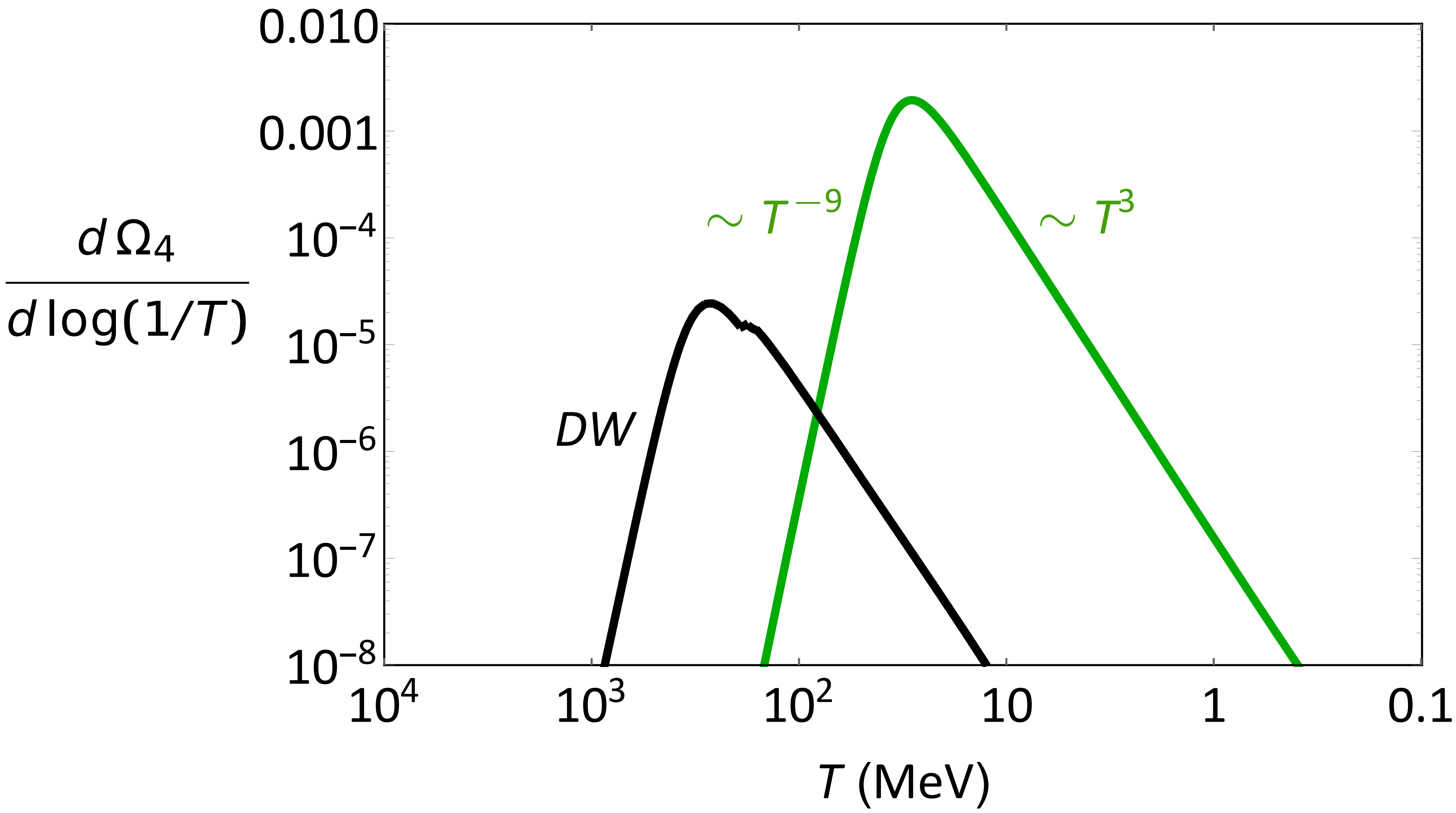
$$\mathcal{L}_{\text{int}} = \lambda \nu \nu \varphi + \text{h.c.}$$

Case of Heavy Mediator



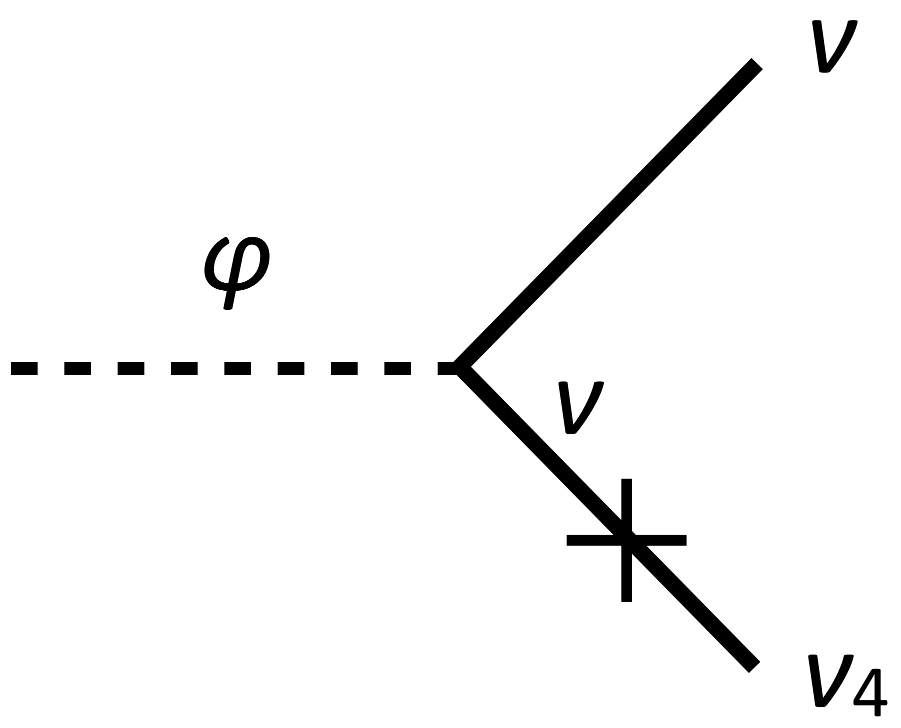
Similar to weak boson exchange case.

Case of Heavy Mediator



Similar parametrical dependence: $\Omega_4 \propto \frac{\lambda^3}{m_\varphi^2} \gg \frac{g^3}{M_W^2}$

Case of Light Mediator

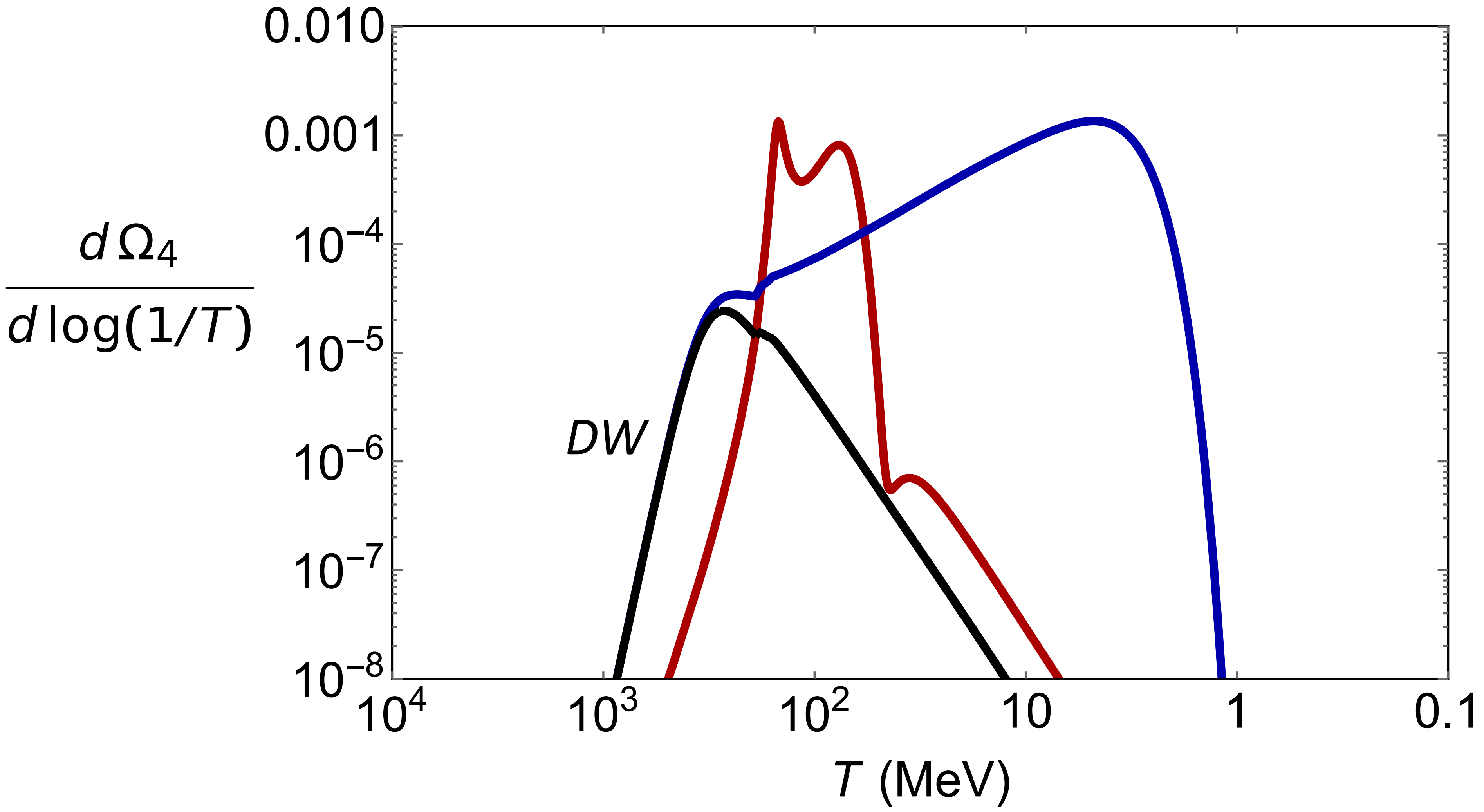


When $T > m_\varphi$, φ exists in thermal bath, decays to ν_4.

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

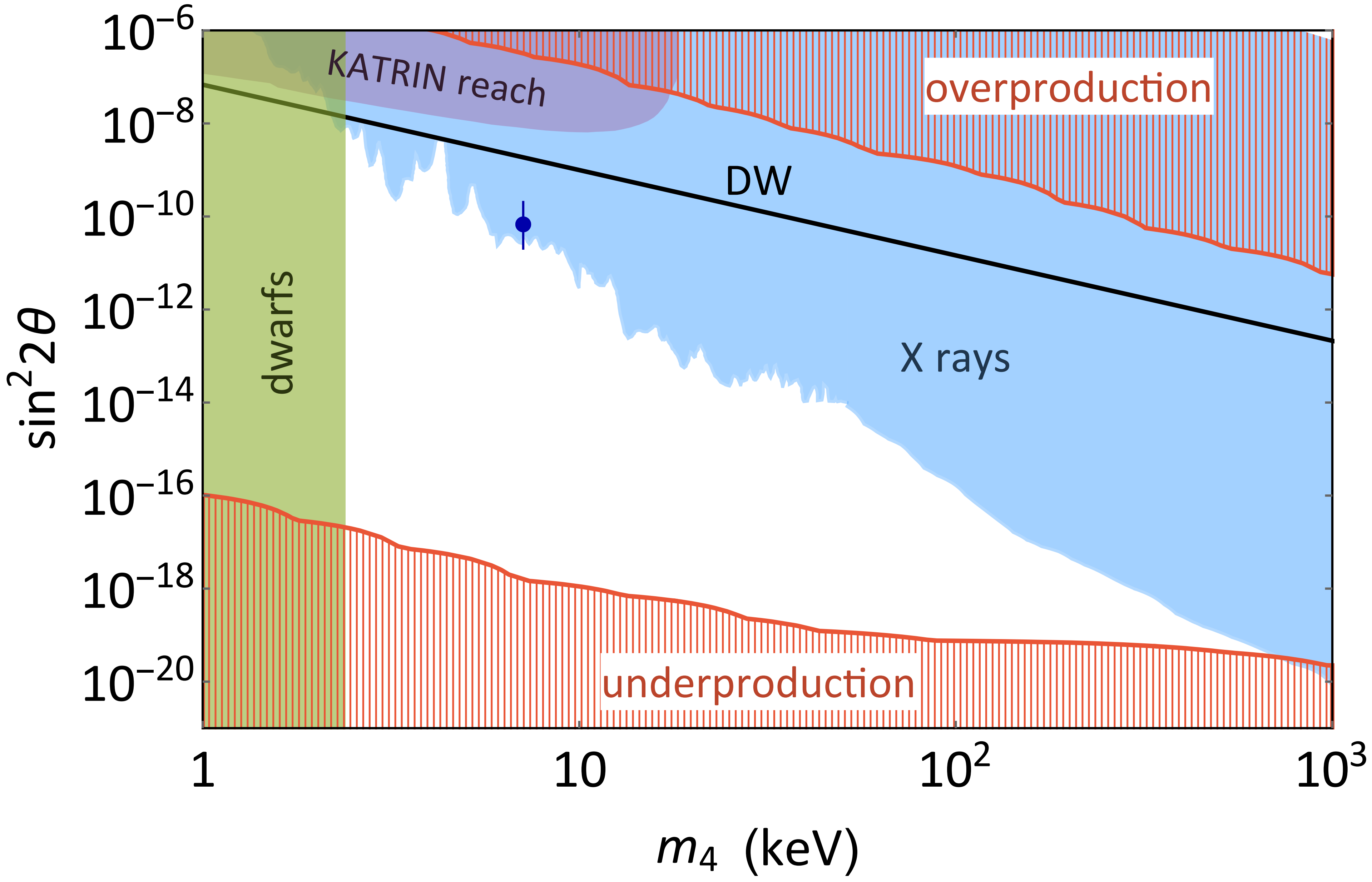
Opens up new production channels.

Case of Light Mediator



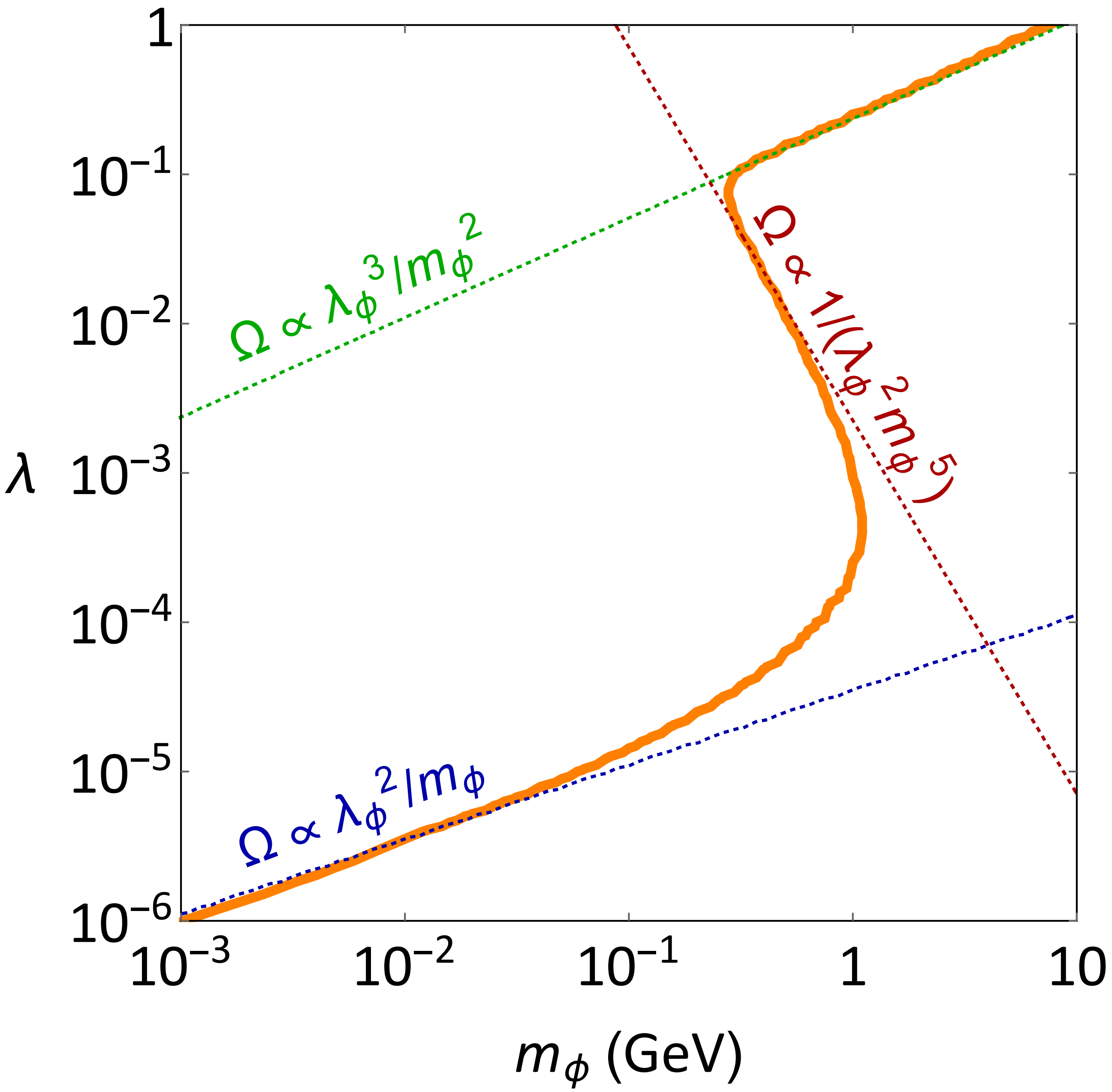
φ can be light and allow for new scenarios in early universe.

Open Up Viable Window



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

Well Motivated Target



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

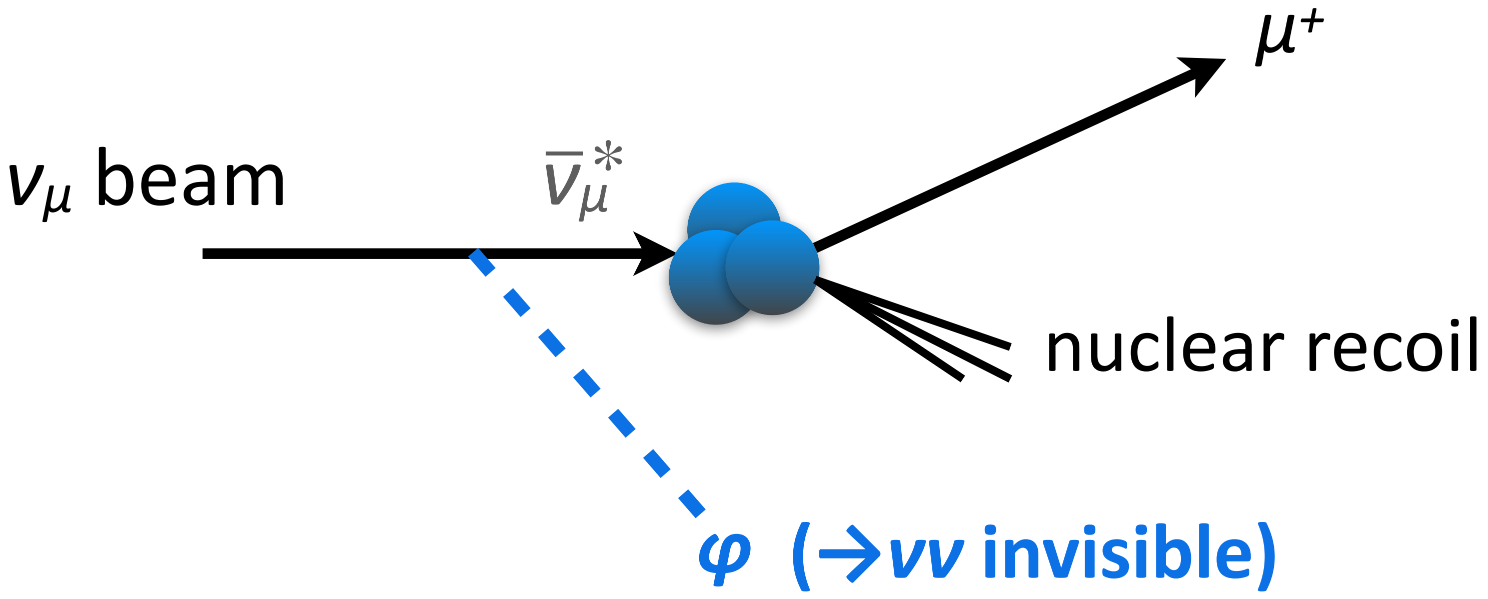
m_4=7.1 keV

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

Rich Experimental Probes

- **Particle physics:** meson, Z, Higgs boson decays; missing energy search in neutrino beam experiments; double beta decay.
- **Astrophysics:** core-collapse supernovae.
- **Cosmology:** nucleosynthesis, CMB, Lyman-α, 21 cm cosmology.

Mono-Neutrino Signal



Novel signatures:

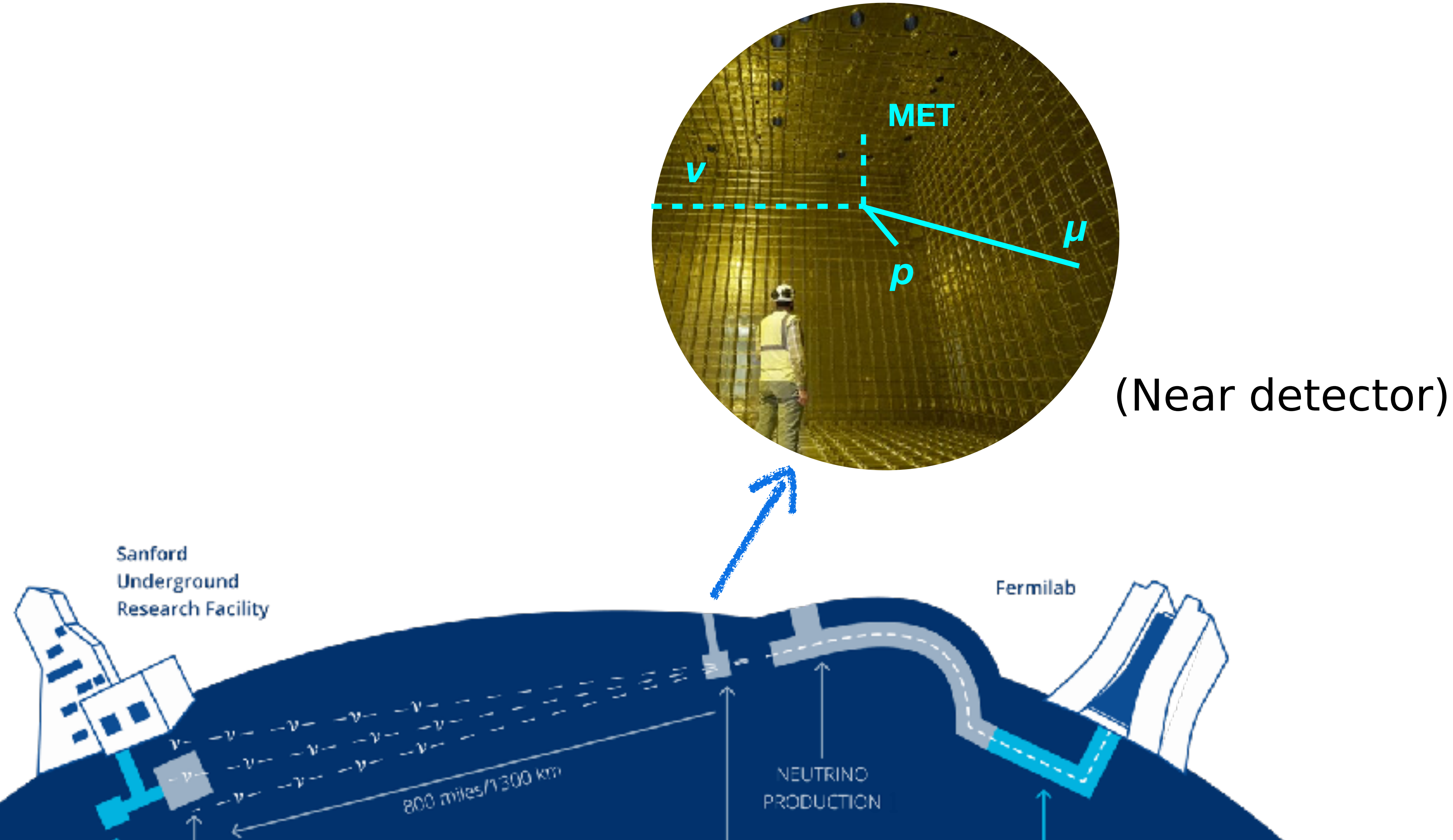
- Large missing transverse momentum p_T
- "Wrong-sign" outgoing muon

Kelly, YZ (1901.01259, PRD)

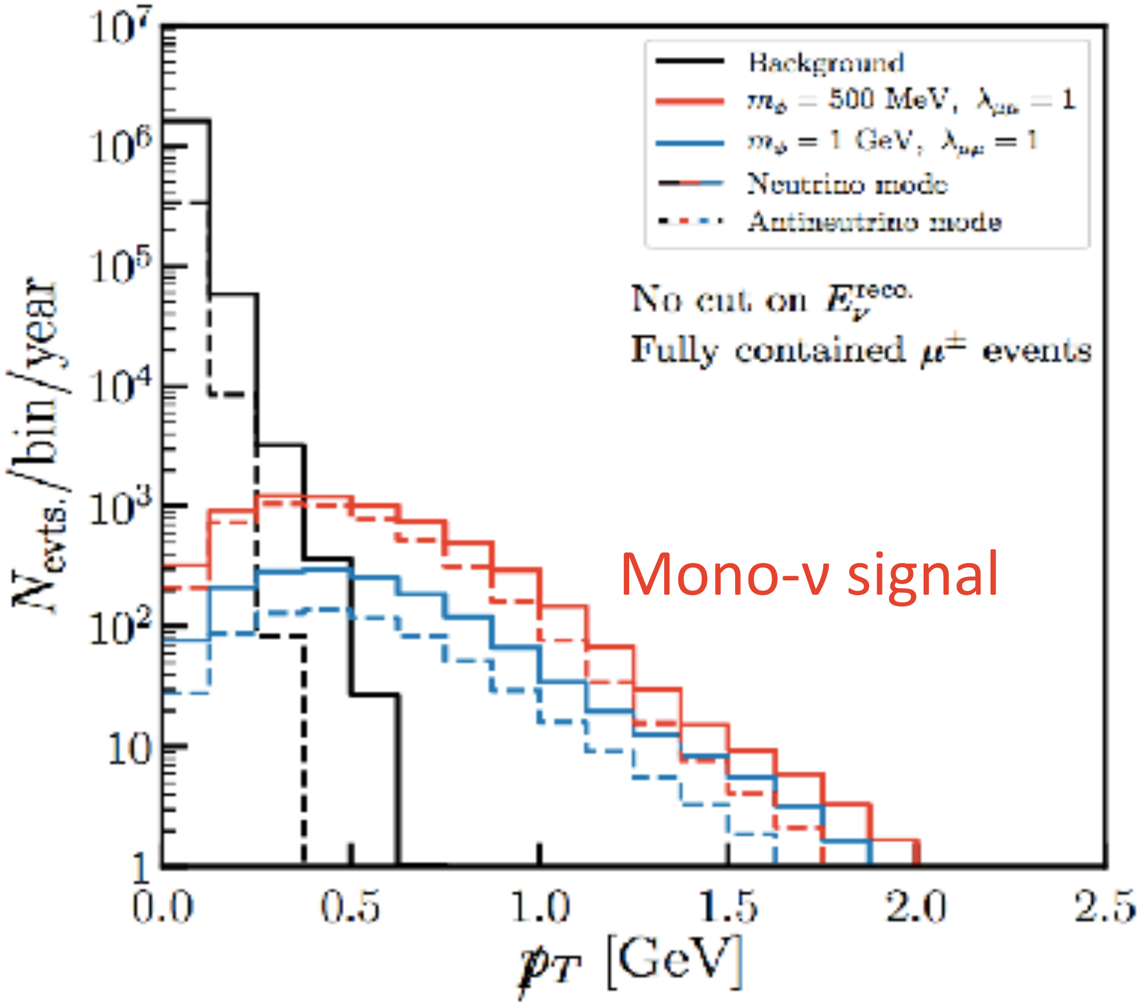
DUNE

Intense neutrino beam (GeV scale) strikes on the near detectors(s).

Liquid argon: excellent particle ID and energy resolution capability.



Missing Transverse Momentum



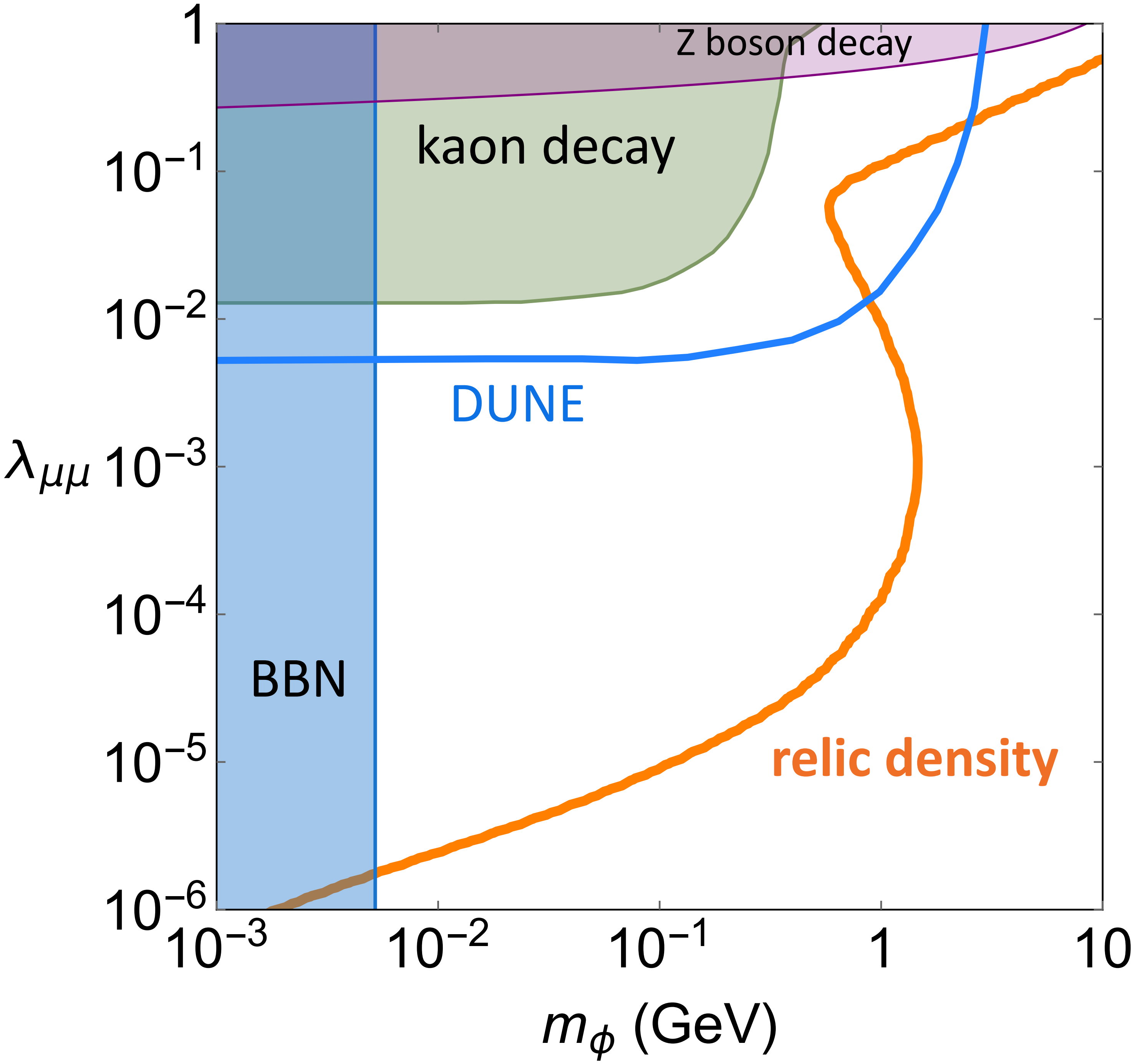
Mono-ν signal

Kelly, YZ (1901.01259)

Theorists' estimate, nucleon level simulation, smearing based on DUNE CDR (2015)

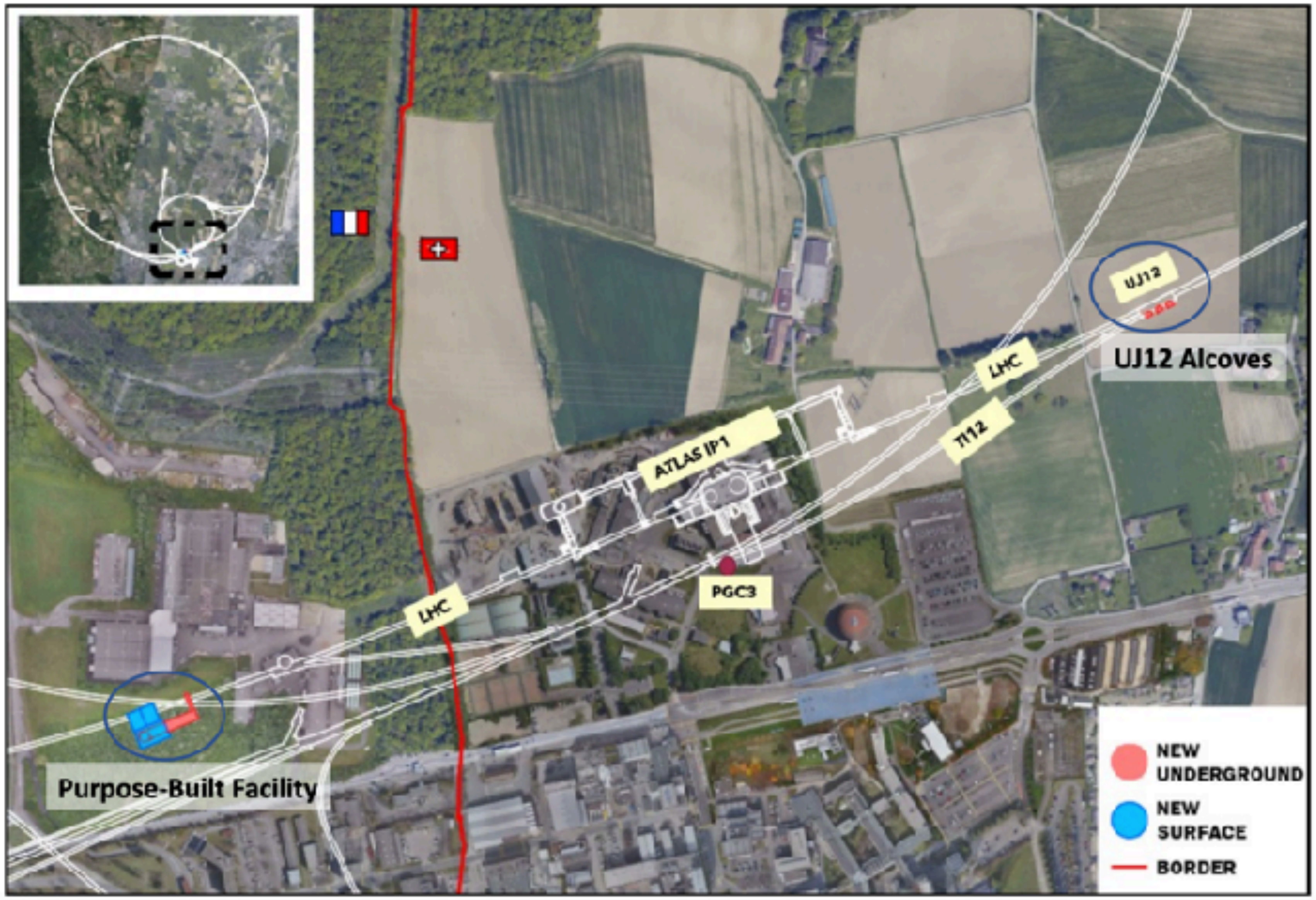
$$3\%/\sqrt{E_{\text{muon}}[\text{GeV}]},\ 20\%/\sqrt{E_{\text{proton}}[\text{GeV}]},\ 40\%/\sqrt{E_{\text{neutron}}[\text{GeV}]}$$

Coverage



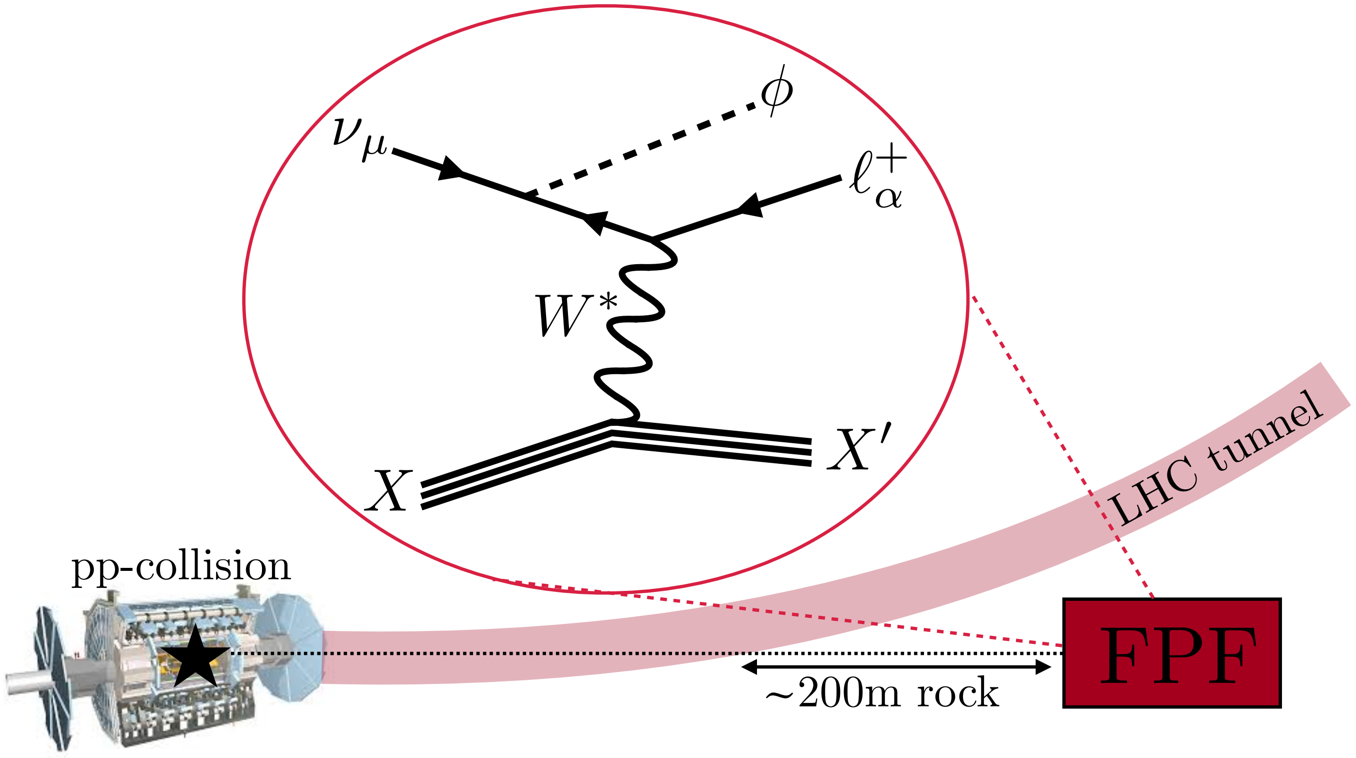
Kelly, YZ (1901.01259, PRD)

LHC Forward Physics Facility



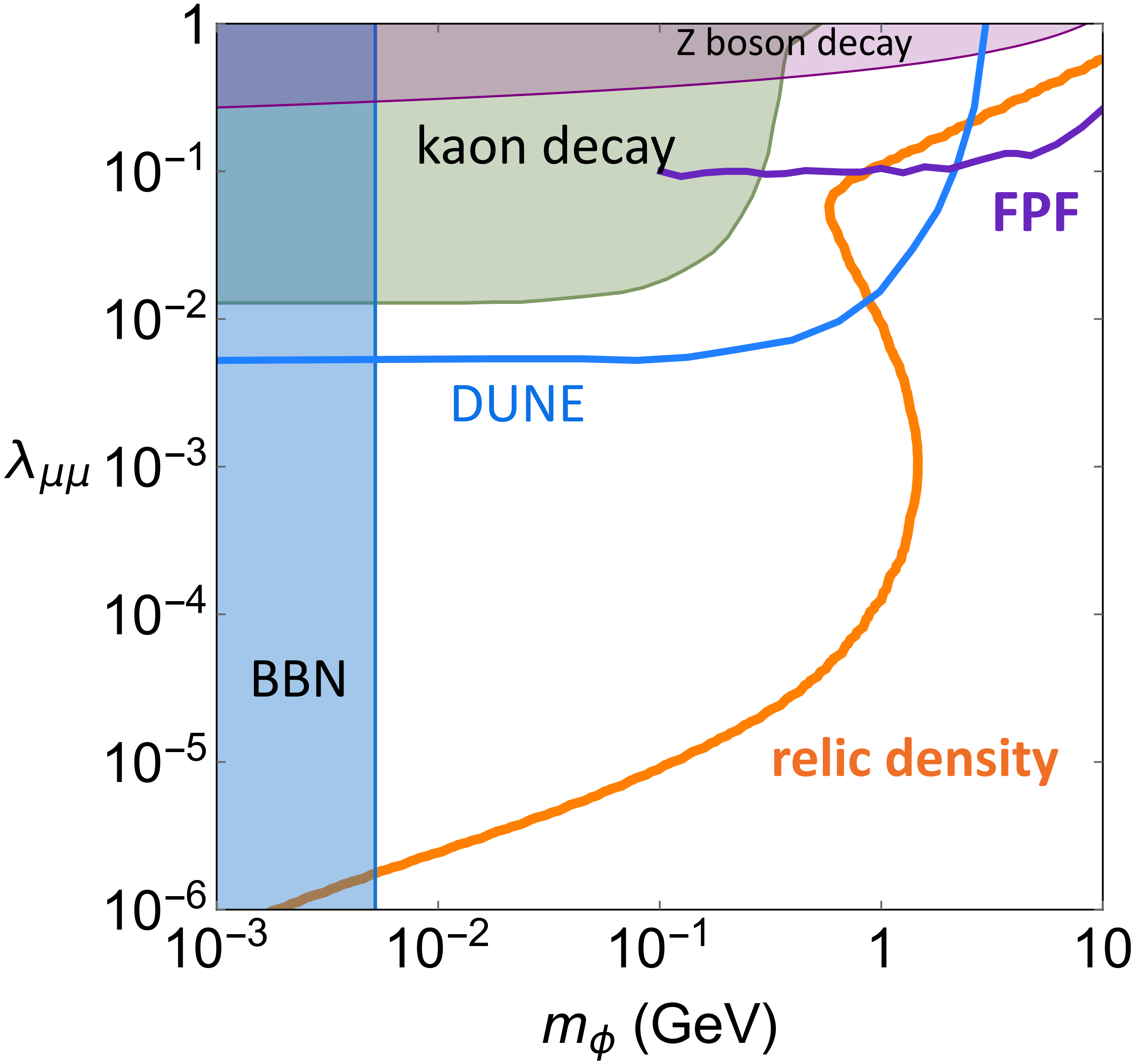
FPF paper (2109.10905)

LHC Forward Physics Facility



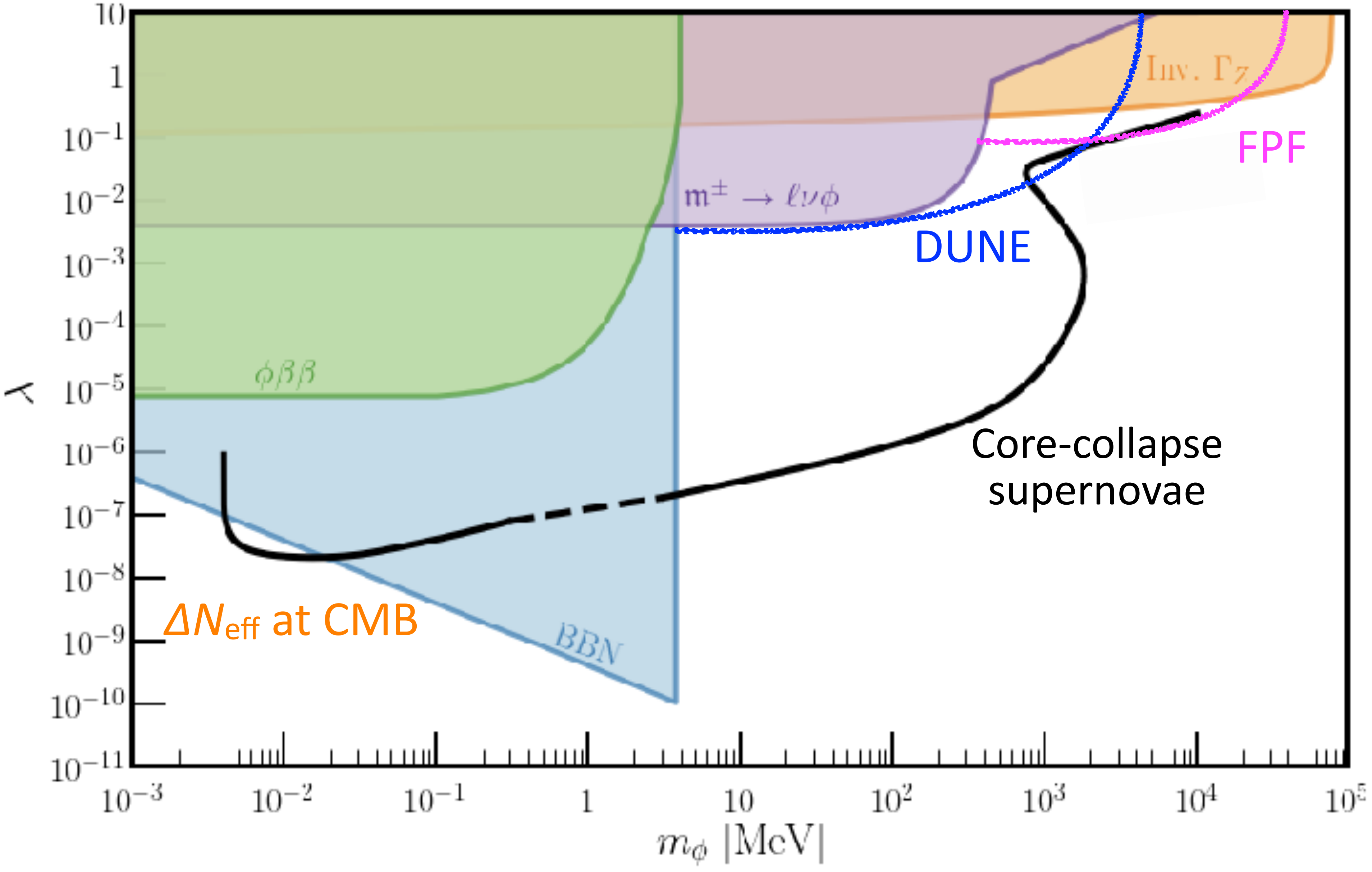
- Higher energy neutrinos (hundreds of GeV)
- DIS: less hadronic uncertainties

Coverage



Kelly, Kling, Tuckler, YZ (2111.05868)

The Big Picture



Kelly, Sen, YZ (2111.05868, PRL)

Conclusion

Mysteries in dark matter and neutrinos makes it inspiring to speculate on their potential connections — open question with a number of interesting avenues.

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!