Probing Neutrino Portal Dark Matter: From Colliders to Supernovae

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Dark Interactions: New Perspectives for Theory and Experiment
November 16, 2022

Based on:
arXiv:2111.05868 w/ K. J. Kelly, F. Kling, and Y. Zhang
arXiv:2207.14300 w/ Y. Cheng, M. Sen, W. Tangarife, and Y. Zhang

A Neutrinophilic Scalar Mediator

- Introduce a scalar field ϕ of mass m_ϕ that mediates *self interactions among SM neutrinos*

$$\mathscr{L} \supset \frac{1}{2}\lambda_{\alpha\beta}\nu_\alpha\nu_\beta\phi + h.c.$$

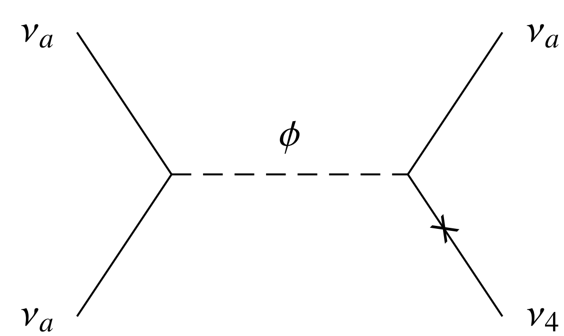
J. Berryman, A. de Gouvea, K.J. Kelly, Y. Zhang arXiv:1802.00009

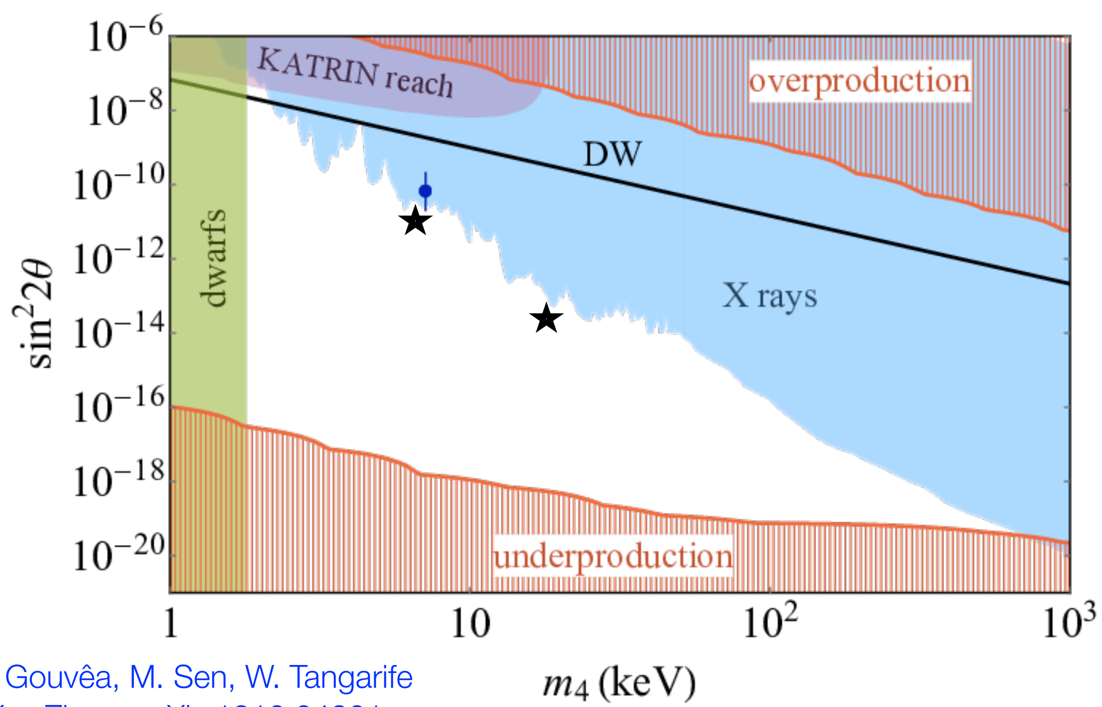
K. J. Kelly and Y. Zhang arXiv:1901.01259

- Can be larger than weak interactions. *New neutrino self-interaction can revive sterile neutrino DM!*

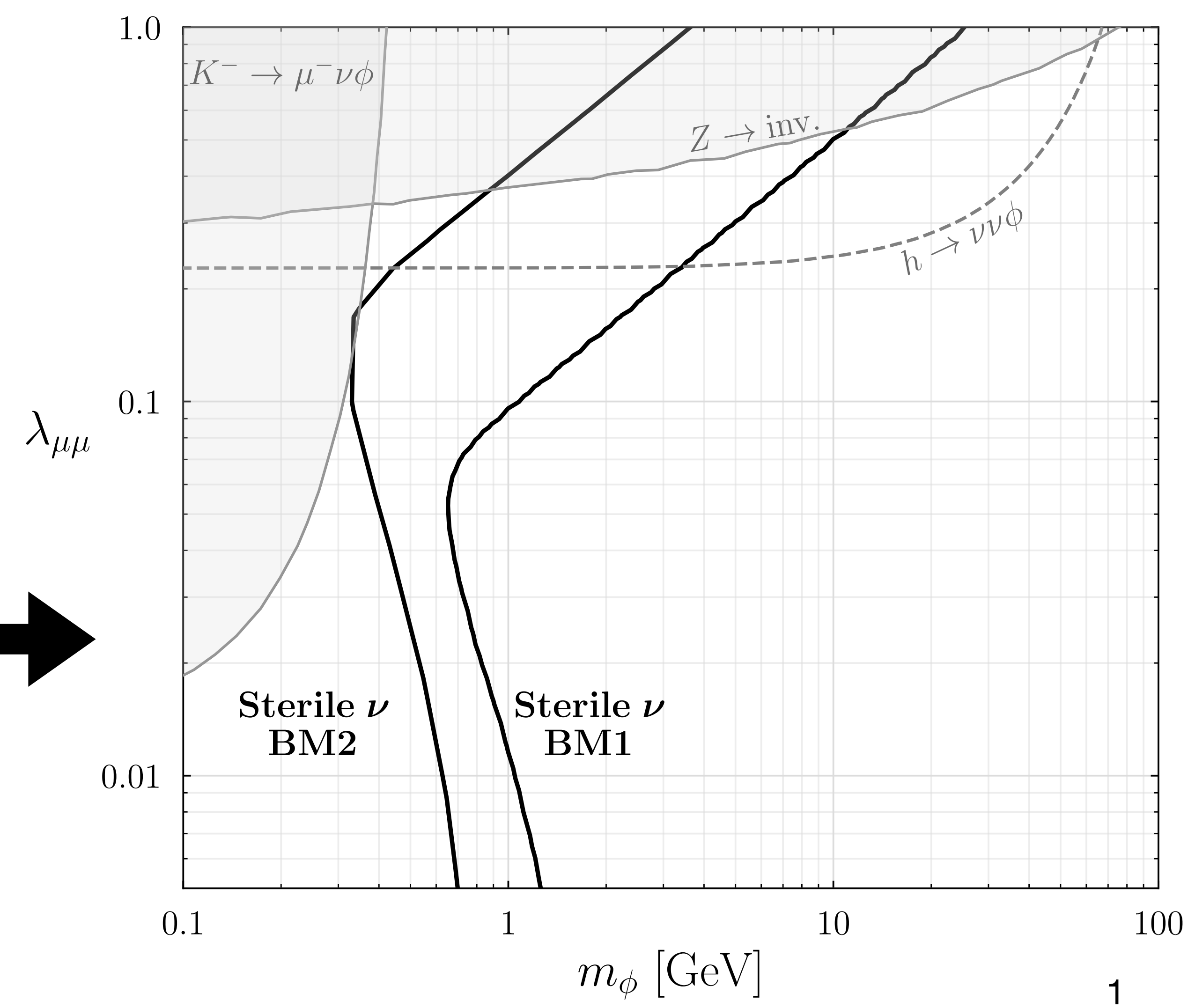
$$\nu_4 = \nu_s \cos\theta + \nu_a \sin\theta$$

$$\Omega_4 \sim \Gamma \sin^2 2\theta$$



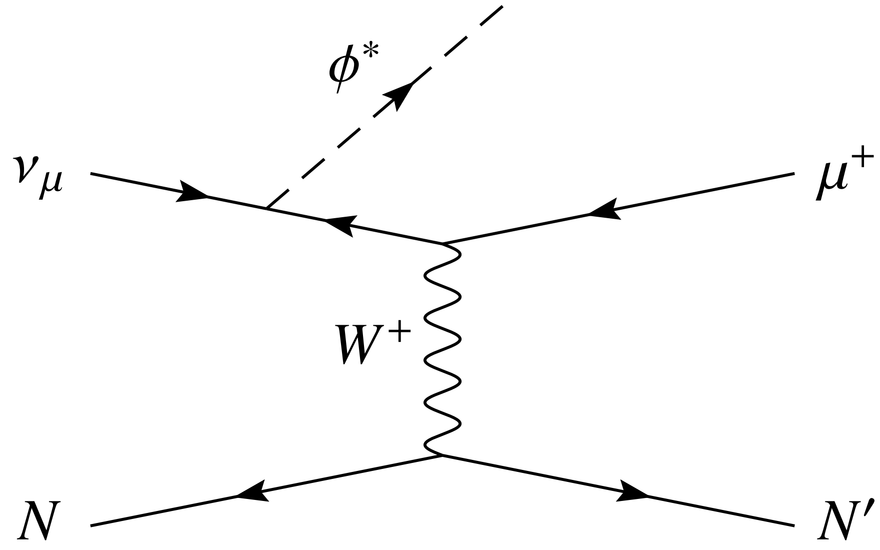


A. de Gouvêa, M. Sen, W. Tangarife and Yue Zhang arXiv:1910.04901



The Mono-neutrino Signature

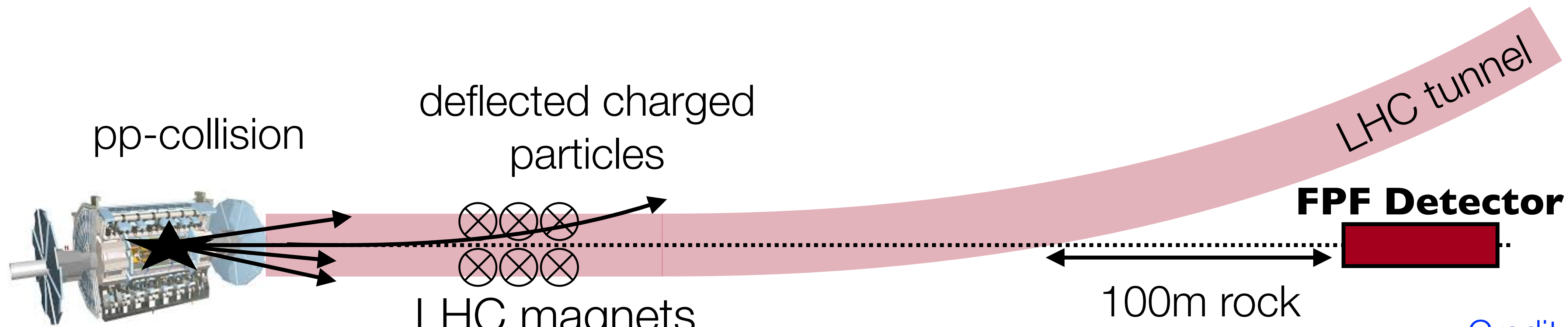
- Incoming neutrino radiates a scalar particle and then converts to a muon via CC interactions K. J. Kelly and Y. Zhang arXiv:1901.01259



- **Missing transverse momentum** carried away by ϕ
  - Similar in spirit to mono-X searches at the LHC, missing transverse momentum technique @ LDMX
- Neutrino facilities are excellent to probe this signature!

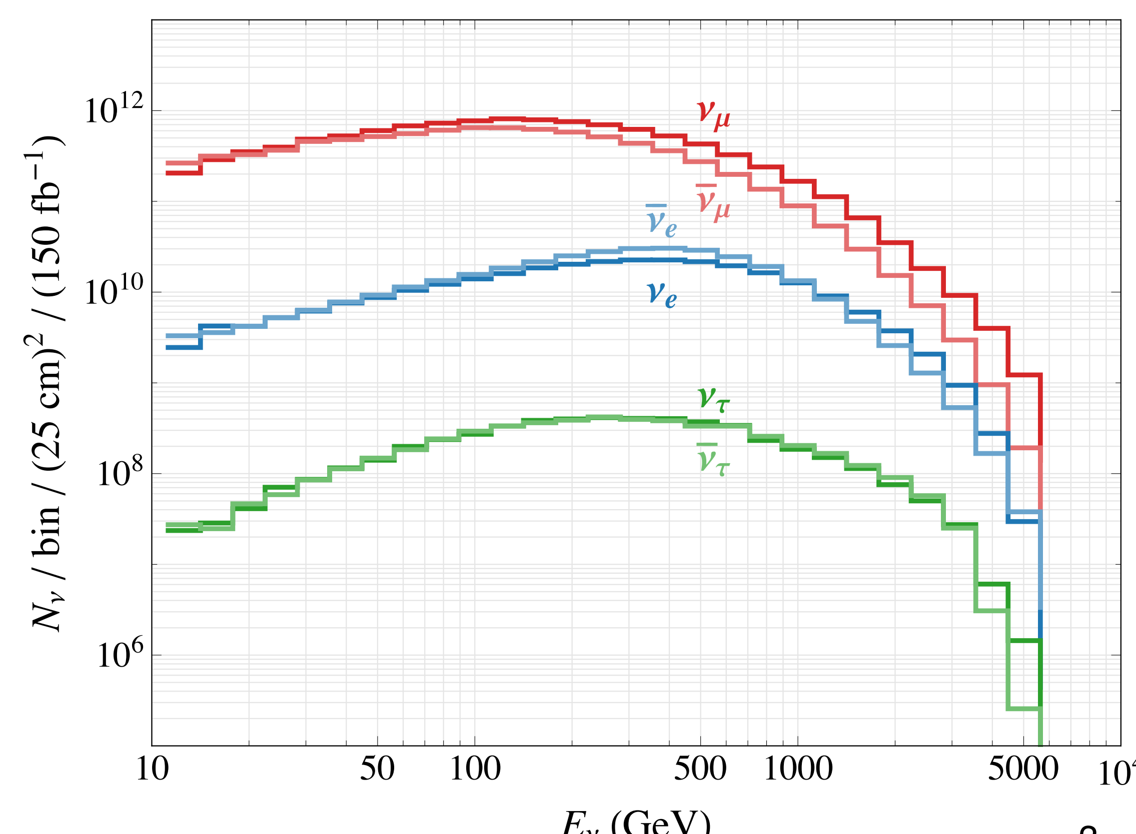
LHC Forward Physics Facility

- A proposal to explore SM and BSM physics in the far forward region of LHC detectors



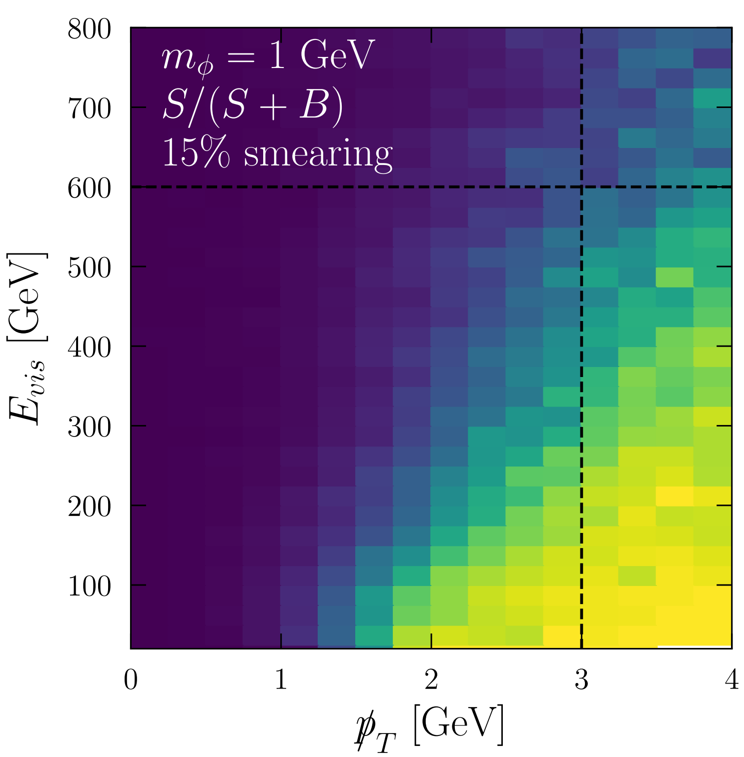
Credit: Felix Kling

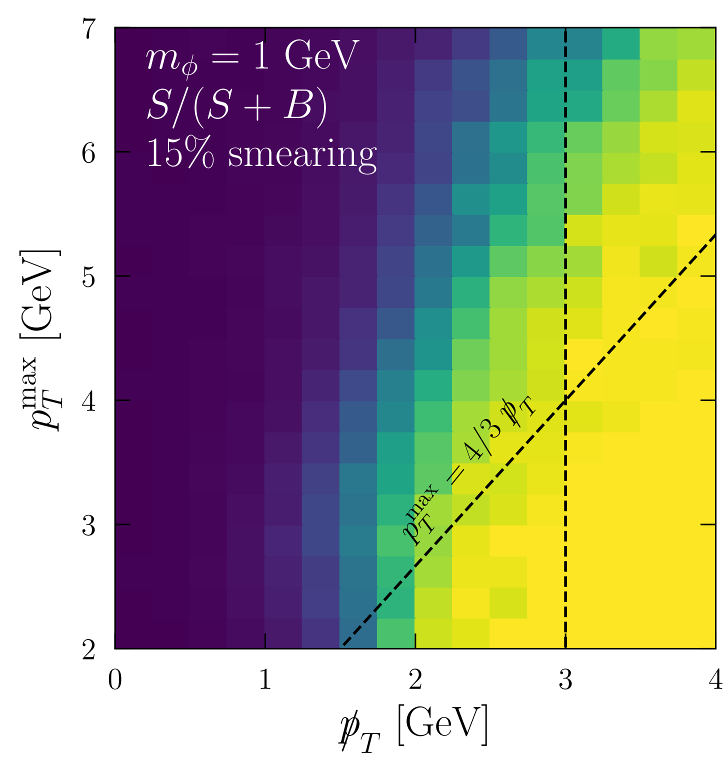
- Flux of high energy neutrinos can be used to probe our model!
- Advantages of LHC neutrinos:
  - High energy neutrinos can probe higher scalar masses
  - Neutrino scattering is DIS → smaller uncertainties



Analysis Strategy

- Focus on argon detector, which has excellent energy/momentum resolution B. Batell, J. Feng, S. Trojanowski arXiv:2101.10338
- Parton-level event generation. Assume 5% muon momentum resolution, 15% hadron momentum resolution.
- **Relevant observables:**
  - **Missing transverse momentum** $\not{p}_T$
  - **Total energy of all visible final states** E_{vis}
  - **Highest transverse momentum of visible final state objects** p_T^{max}





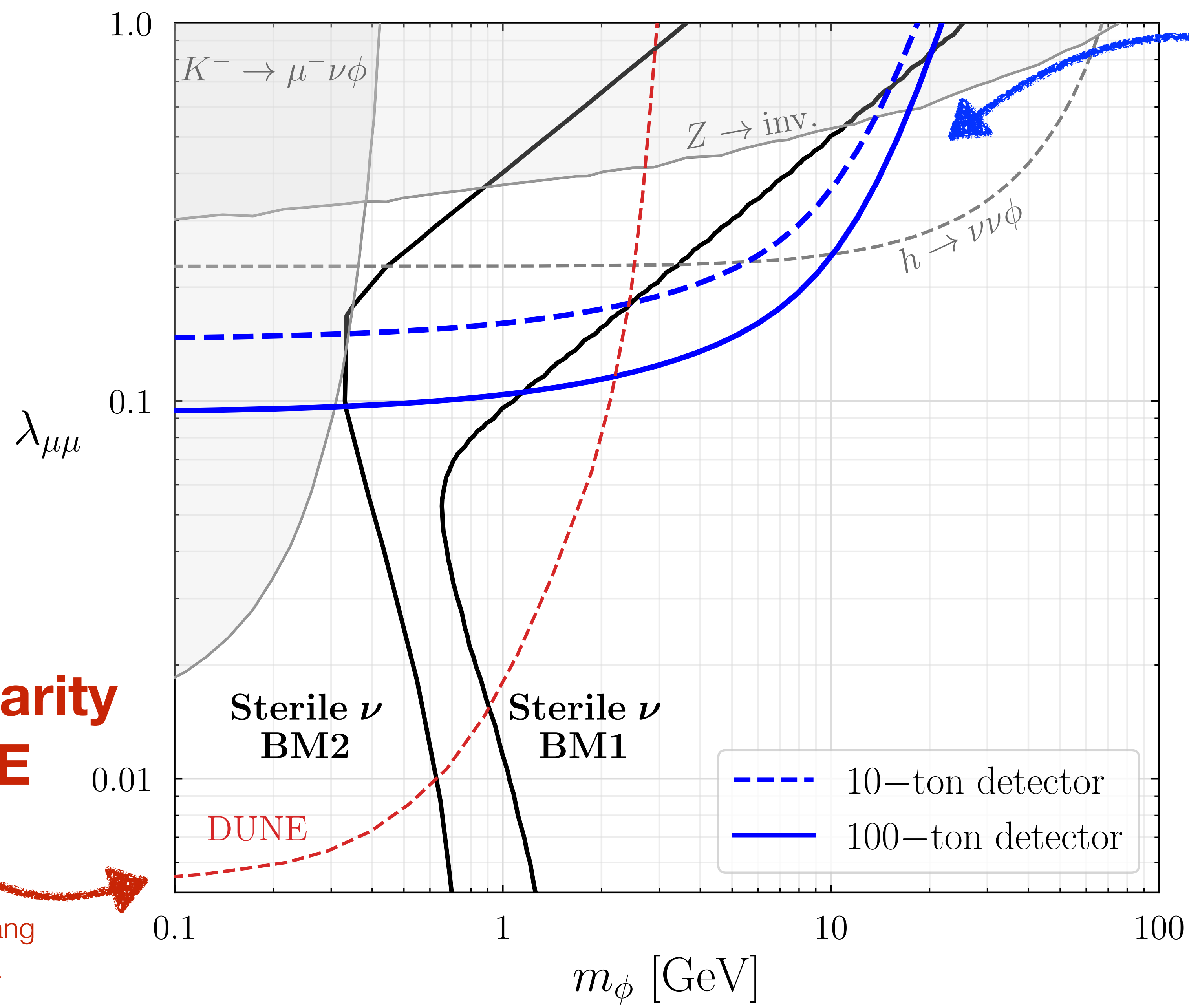
Cut Flow

	$\nu_\mu + \overline{\nu}_\mu$ CC	$m_\phi = 1$ GeV
$E_{\text{vis.}} < 600$ GeV	61%	76%
$\not{p}_T > 3$ GeV	0.2%	26%
$p_T^{\max} < \frac{4}{3}\not{p}_T$	10^{-5}	15%

Significant reduction in bkg. *from missing transverse momentum cut*!

Reach of the Forward Physics Facility

- Feed relevant observables into a neural network to determine an optimal cut on $S/\sqrt{B}$ to maximize the sensitivity.

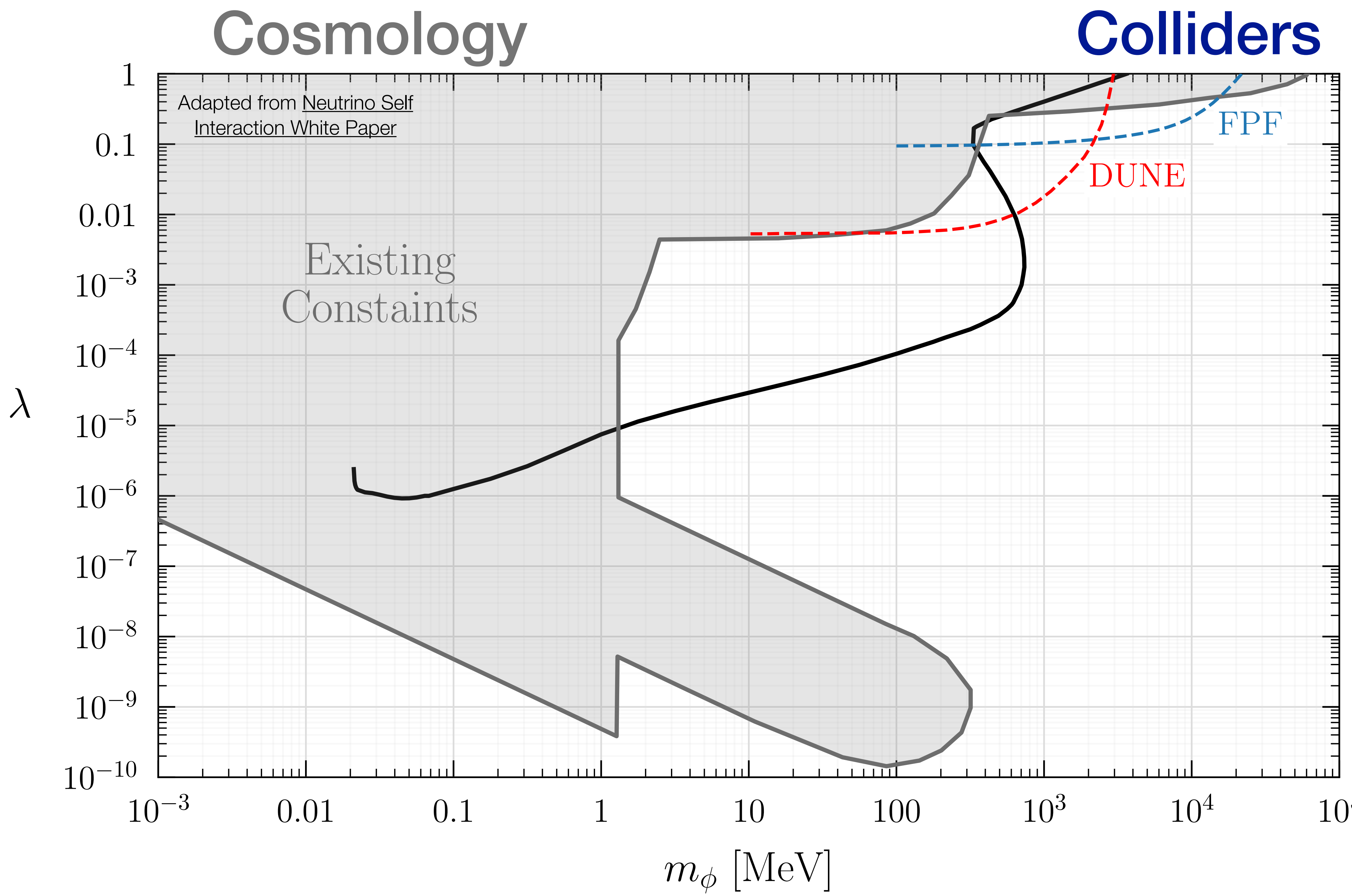


Importance of higher energy!

Complementarity with DUNE

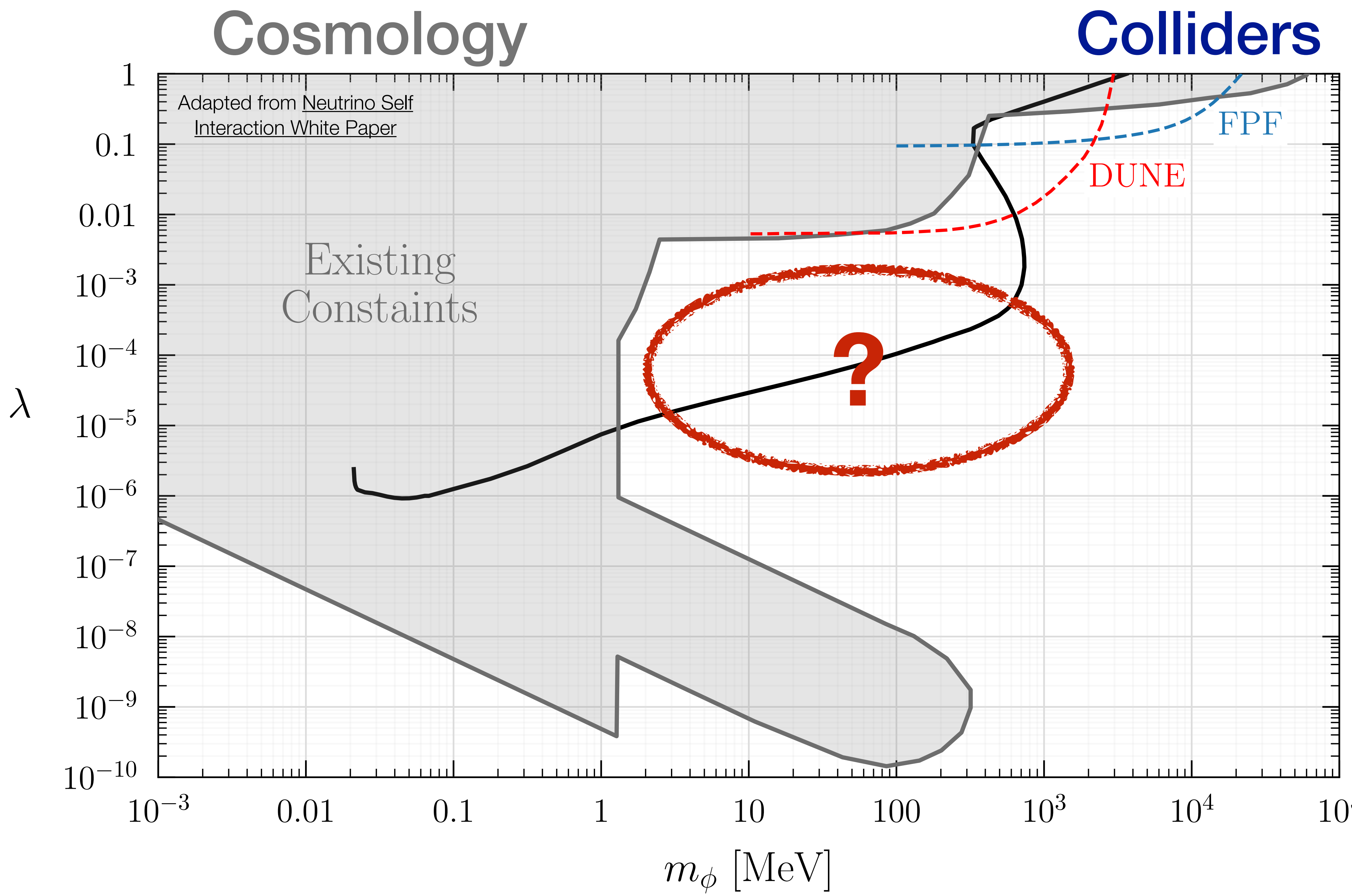
K. J. Kelly and Y. Zhang
arXiv:1901.01259

Big Picture



Cosmology
Colliders
Adapted from Neutrino Self
Interaction White Paper
Existing
Constaints
FPF
DUNE
1
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
λ
10^{-3}
0.01
0.1
1
10
100
10^{3}
10^{4}
10^{5}
m_ϕ [MeV]

Big Picture



Cosmology
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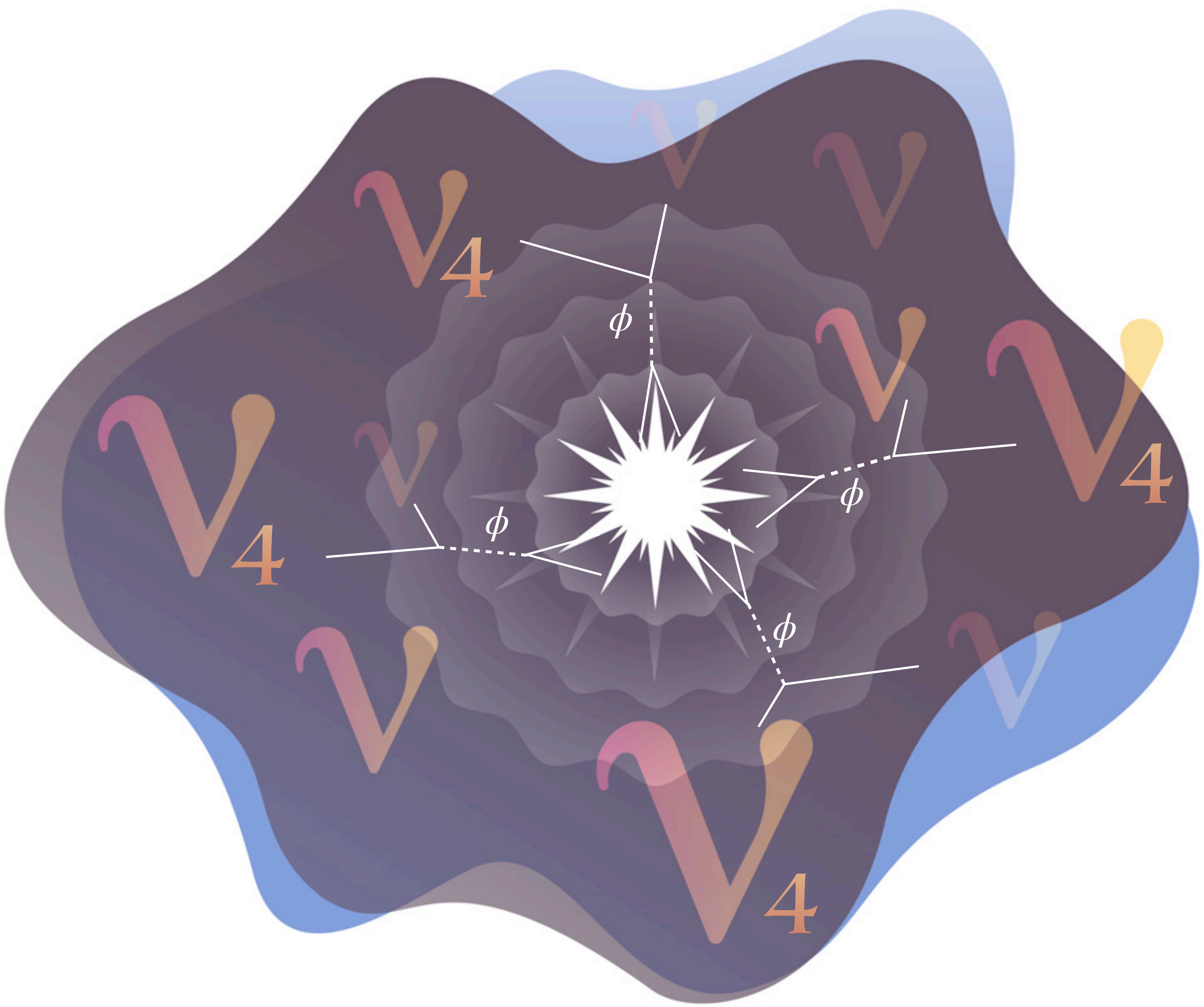
1
10
100
10^3
10^4
10^5
m_ϕ [MeV]

Sterile Neutrino Production in Supernova

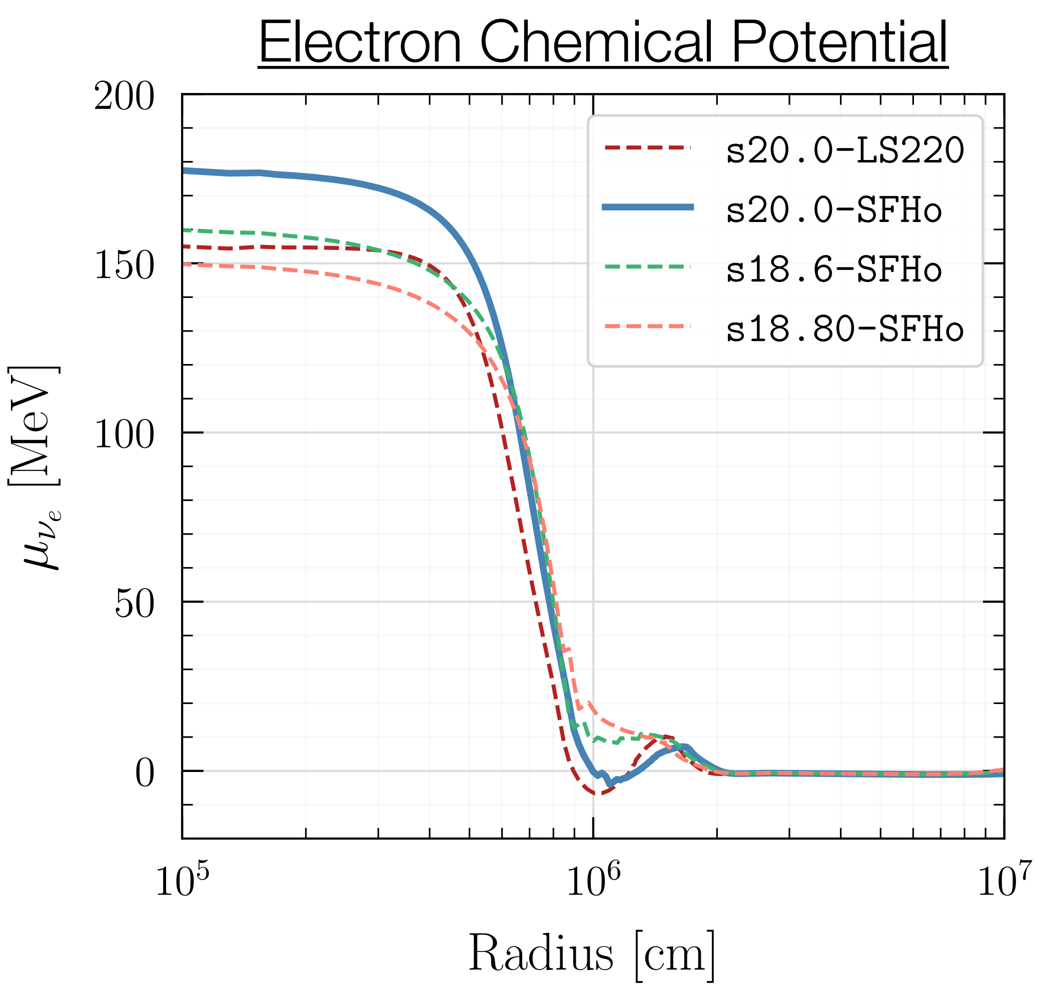
- Supernovae — another neutrino dense environment
- Same process that generates SνDM relic abundance in early universe produces SνDM in the supernova → excessive supernova cooling!

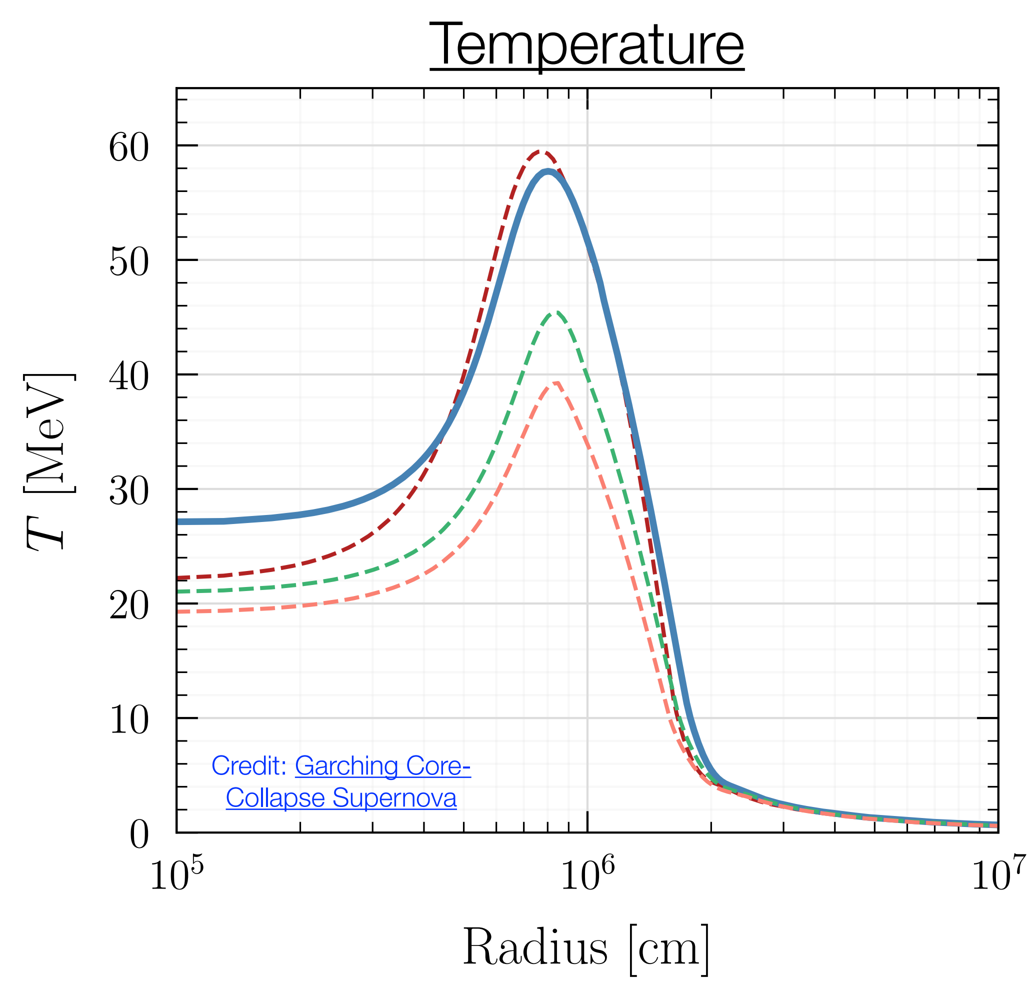


Adapted from Fermilab

Cooling Rate Calculation: A Sketch

- **Step 1: Get supernova profile** $\mu_\nu(r), T(r), \rho(r), Y_e(r)$





- $\mu_{\nu_e}/T > 1 \rightarrow$ Fermi-Dirac Distributions are not exponentially suppressed! Enhanced cooling rate $\mu \neq 0 \rightarrow$ probe smaller couplings!
- $T_{SN} \sim 60$ MeV $\rightarrow$ can probe m_ϕ of 1 MeV up to few 100s of MeV. Exactly where we are missing probes!

Cooling Rate Calculation: A Sketch

- **Step 2: Calculate active-sterile neutrino mixing in matter**

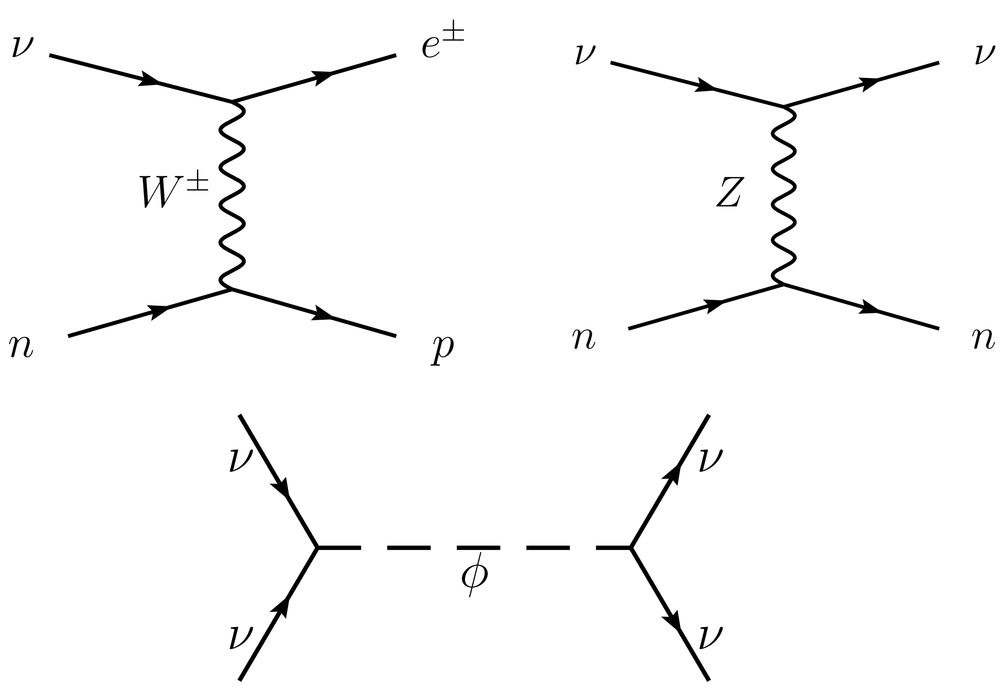
$$\sin^2(2\theta_{eff}) = \frac{\Delta^2 \sin^2(2\theta)}{\Delta^2 \sin^2(2\theta) + \Gamma^2 + (\Delta \cos(2\theta) - V)^2}$$

Interaction Rate

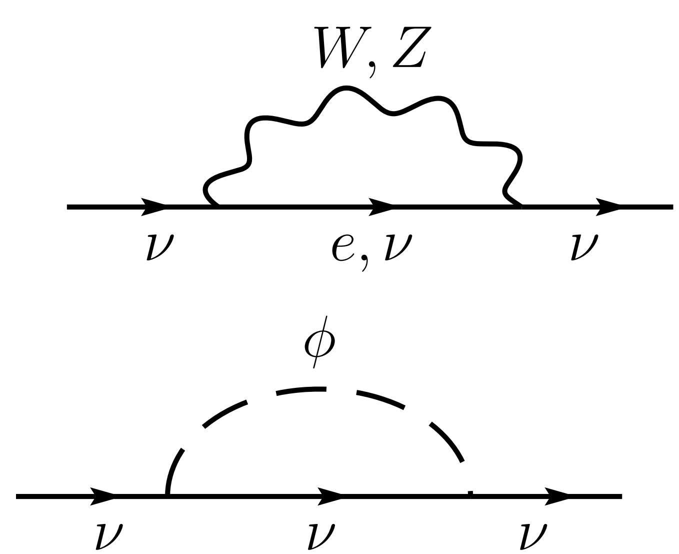
$$\Gamma = \Gamma_{weak} + \Gamma_{\phi}$$

Effective Potential

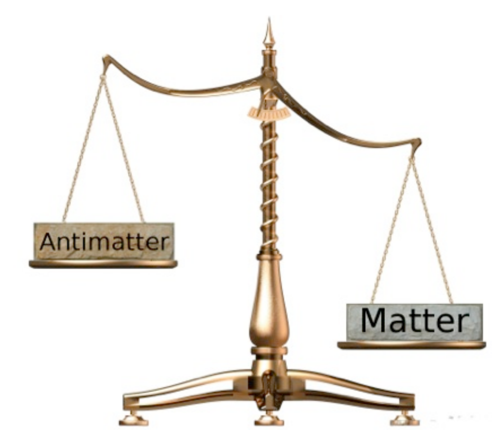
$$V = V_{weak} + V_{\phi}$$



Thermal potential



Matter asymmetries



Cooling Rate Calculation: A Sketch

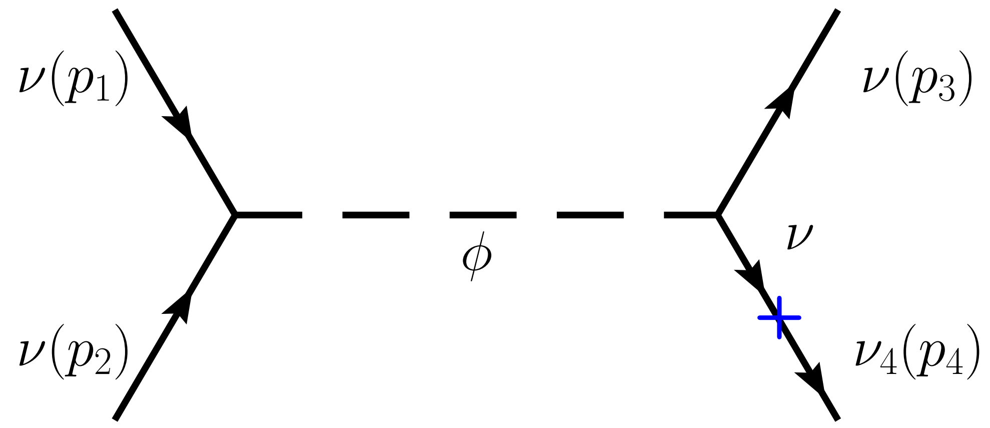
- **Step 3: Optical depth, or ν_4 energy loss due to scattering**

$$\tau = \int_r^\infty dr\ sin^2(2\theta_{eff})\ \Gamma(E, r)$$

Interaction Rate

$$\Gamma = \Gamma_{weak} + \Gamma_\phi$$

- **Step 4: Sterile neutrino production matrix element**



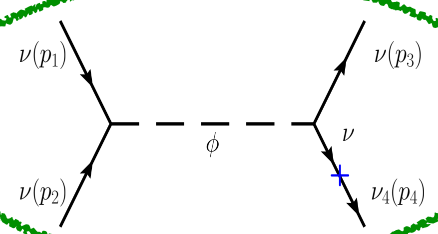
$$|\mathcal{M}|^2 = 32\pi^2\lambda^2\, m_\phi^2\, \delta(s - m_\phi^2) \sin^2\theta_{\rm eff}(r, E_4)$$

- **Step 4.5: Profit**

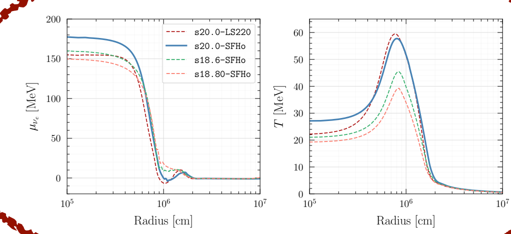
Cooling Rate Calculation: A Sketch

- **Step 5: Put everything together to calculate the luminosity**

SνDM production



SN Profile



$$L = \frac{\lambda^2 m_\phi^2}{4\pi^2} \int_0^{4R_c} r^2 dr \int_0^\infty dE_1 f(E_1, r) \int_{m_\phi^2/(4E_1)}^\infty dE_2 f(E_2, r) \frac{1}{\sqrt{(E_1+E_2)^2 - m_\phi^2}}$$

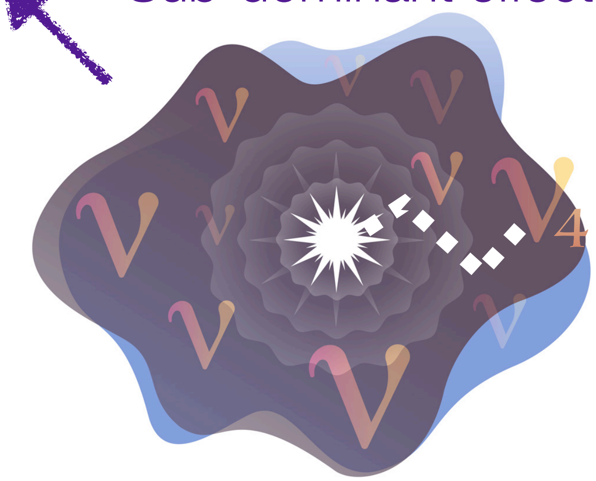
$$\times \int_{\frac{1}{2}\left(E_1+E_2-\sqrt{(E_1+E_2)^2-m_\phi^2}\right)}^{\frac{1}{2}\left(E_1+E_2+\sqrt{(E_1+E_2)^2-m_\phi^2}\right)} dE_4 \sin^2\theta_{\rm eff}(r, E_4)\, E_4\, e^{-\tau(E_4, r)}$$

Re-absorption.
Sub-dominant effect

Matter effects

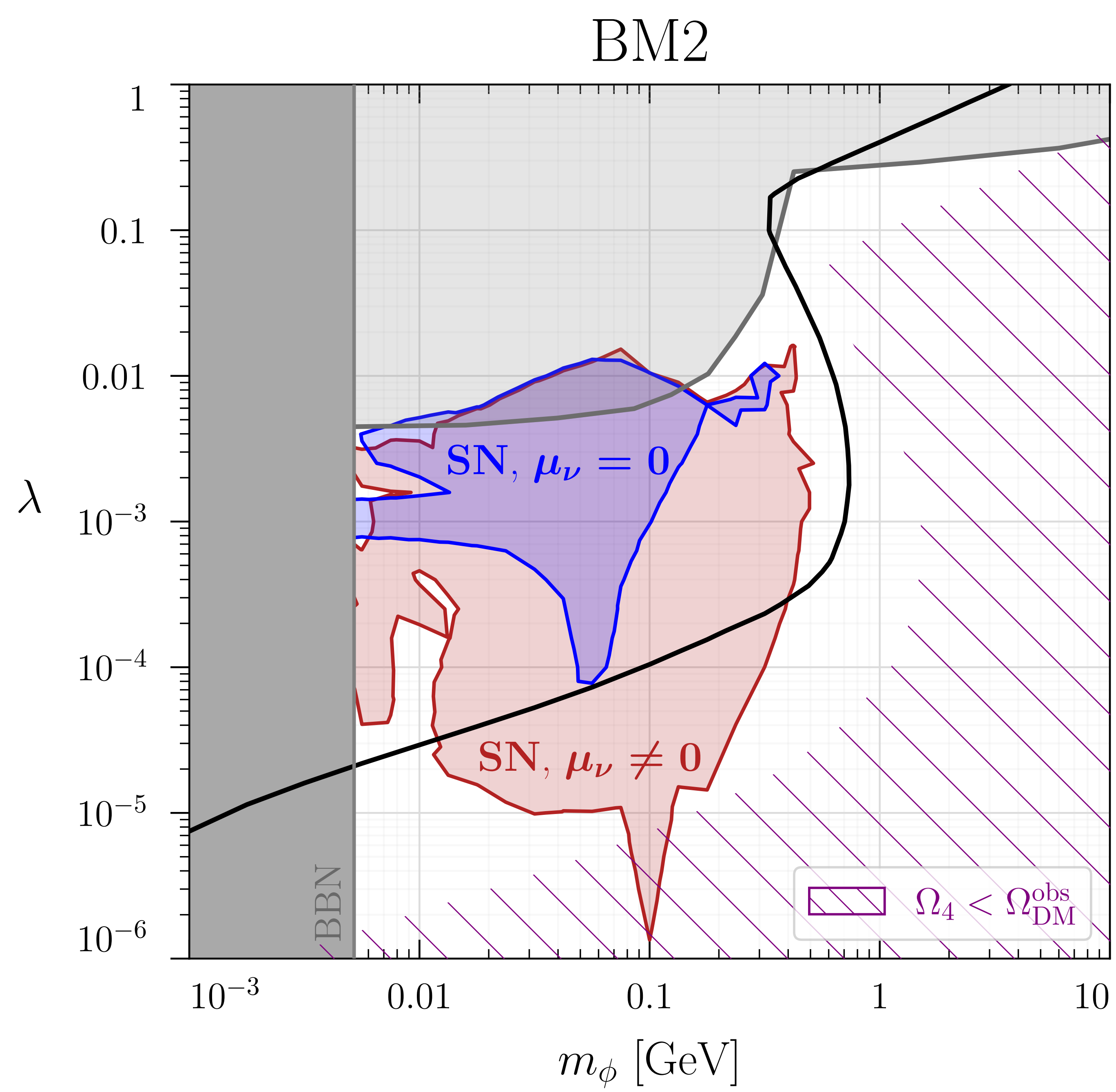
ν ——×—— ν_4

$\Gamma(E, r),\ V(E, r)$

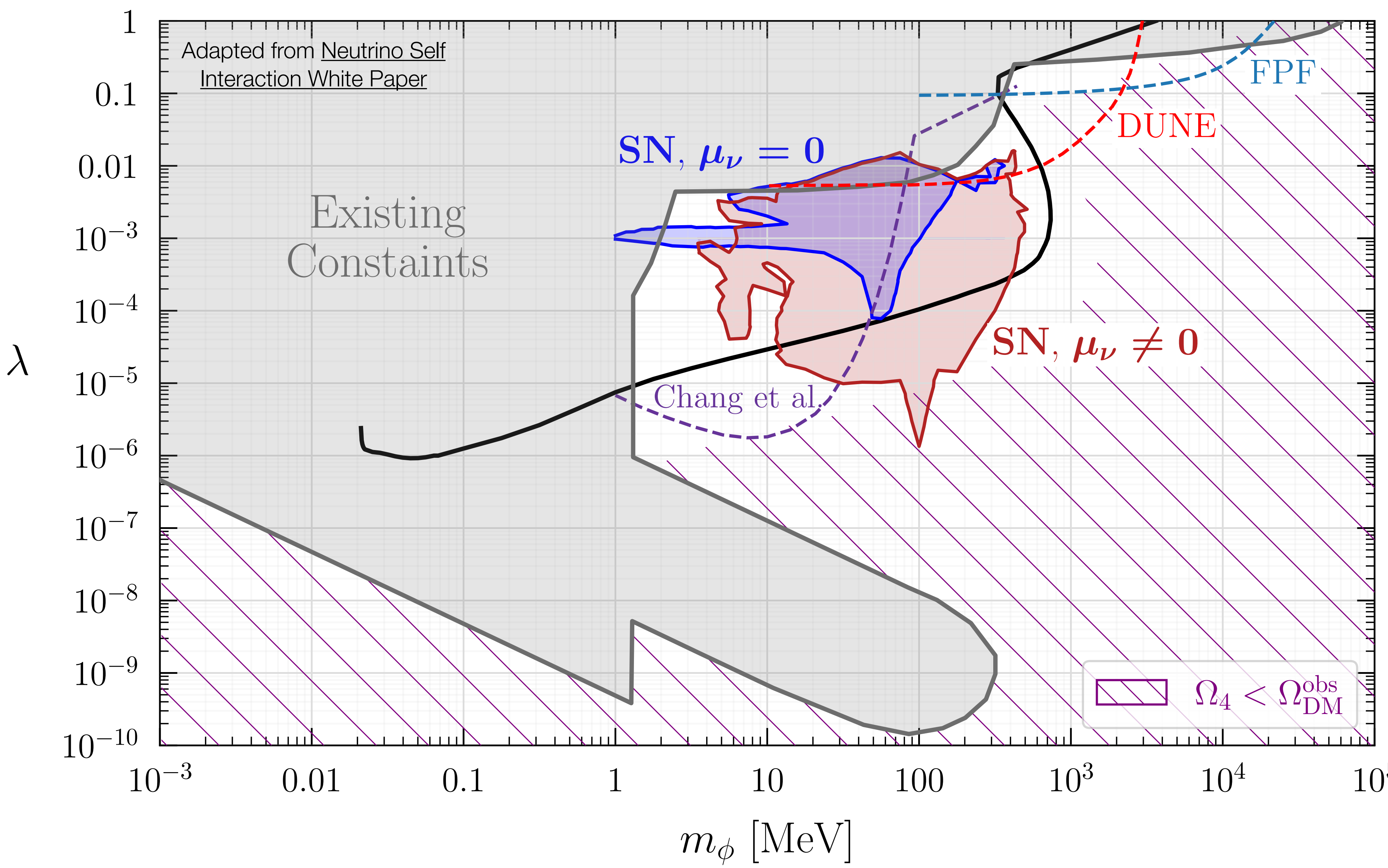


Supernova Cooling Bounds

- Observations of SN1987 bound the emission luminosity to be $L \lesssim 3 \times 10^{52}$ ergs/s

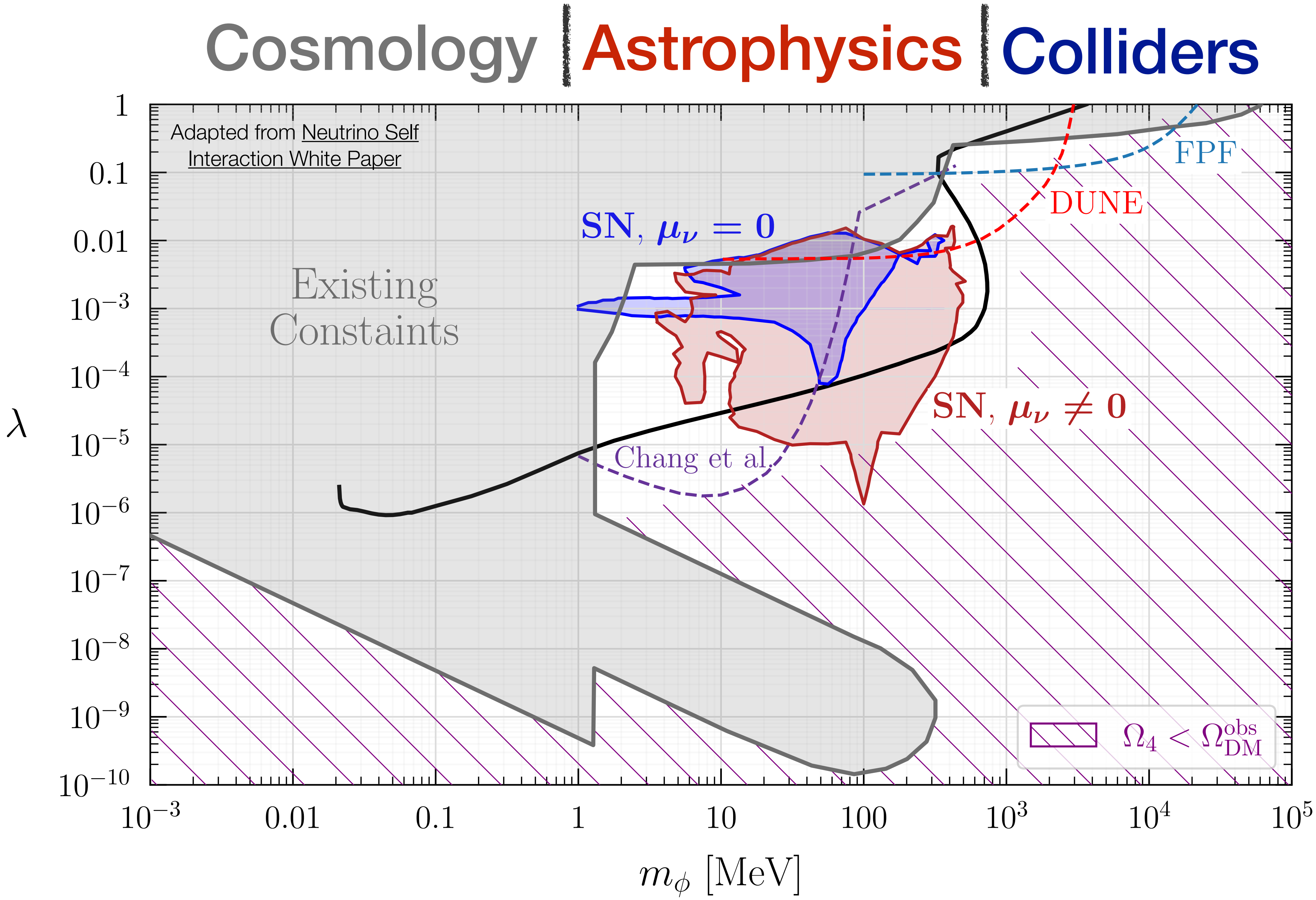


Big Picture



Adapted from Neutrino Self Interaction White Paper
Existing Constaints
SN, $\mu_\nu = 0$
SN, $\mu_\nu \neq 0$
Chang et al.
DUNE
FPF
$\Omega_4 < \Omega_{DM}^{obs}$
λ
m_ϕ [MeV]
1
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-3}
0.01
0.1
1
10
100
10^3
10^4
10^5

Big Picture



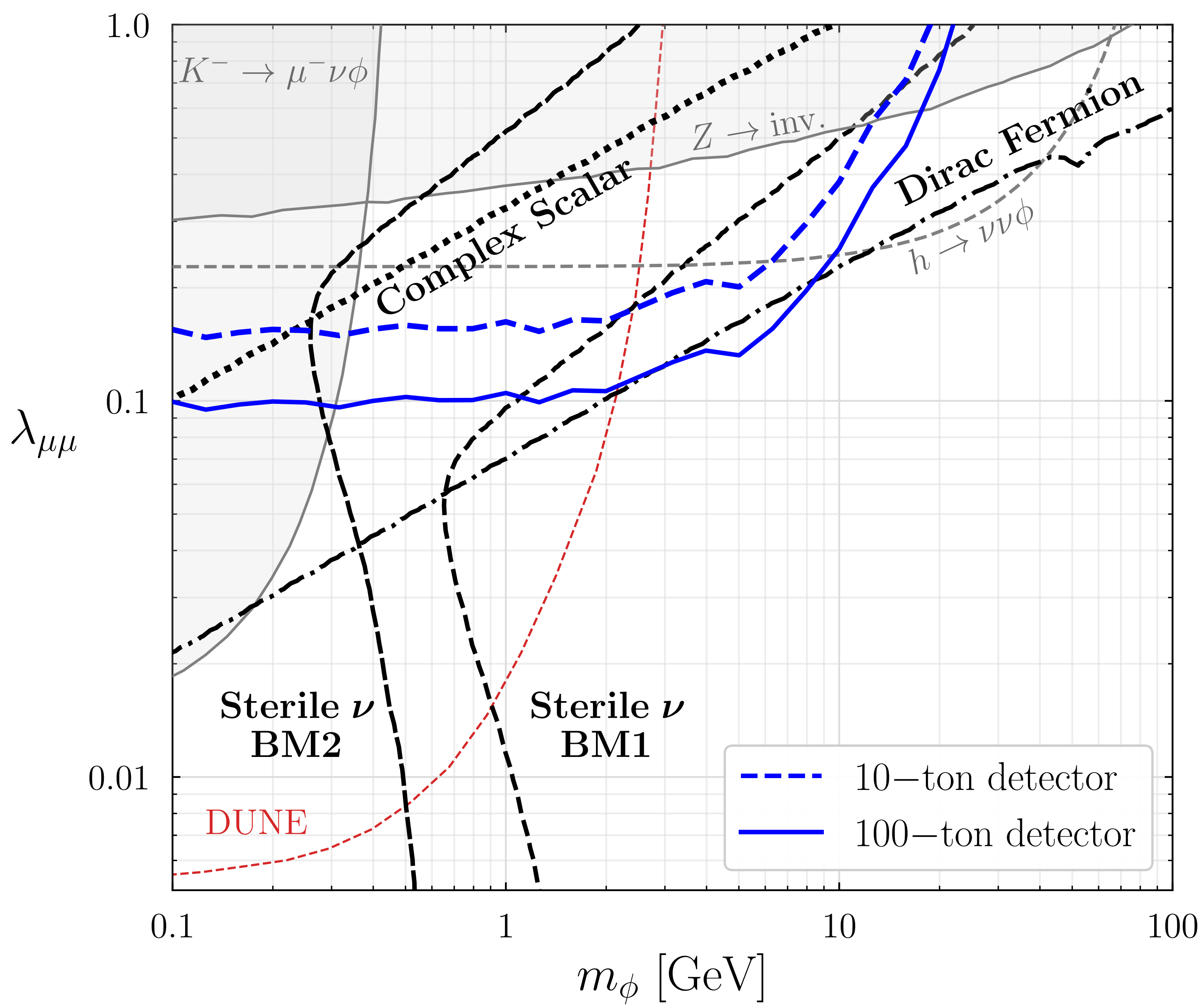
Great complementarity between different probes of neutrinophilic DM!

Thanks!
Questions?

Back up

FPF Reach: Thermal Dark Matter Targets

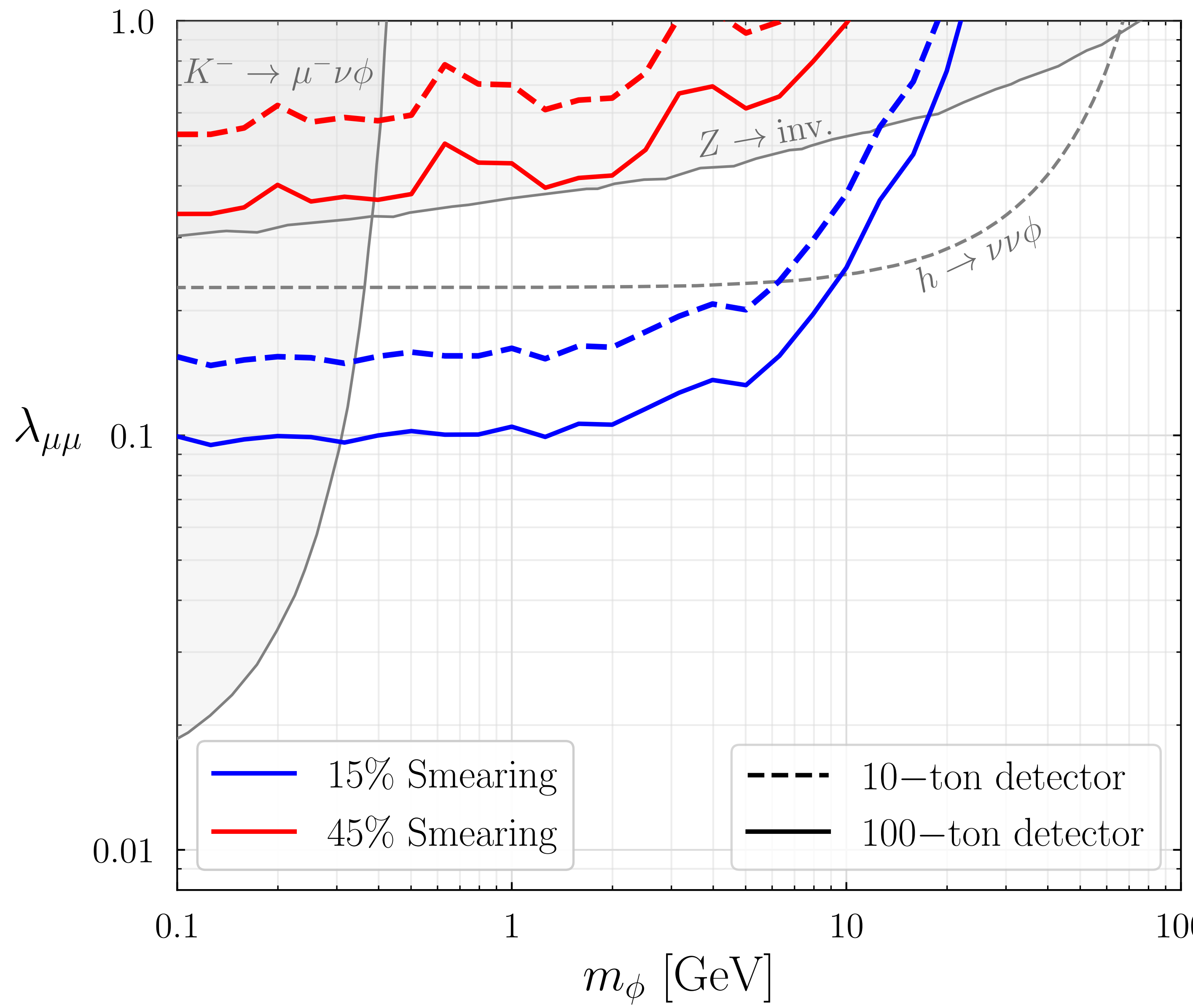
- The neutrinophilic scalar ϕ can also be a mediator to thermal DM



FPF Reach: Effect of Momentum Smearing

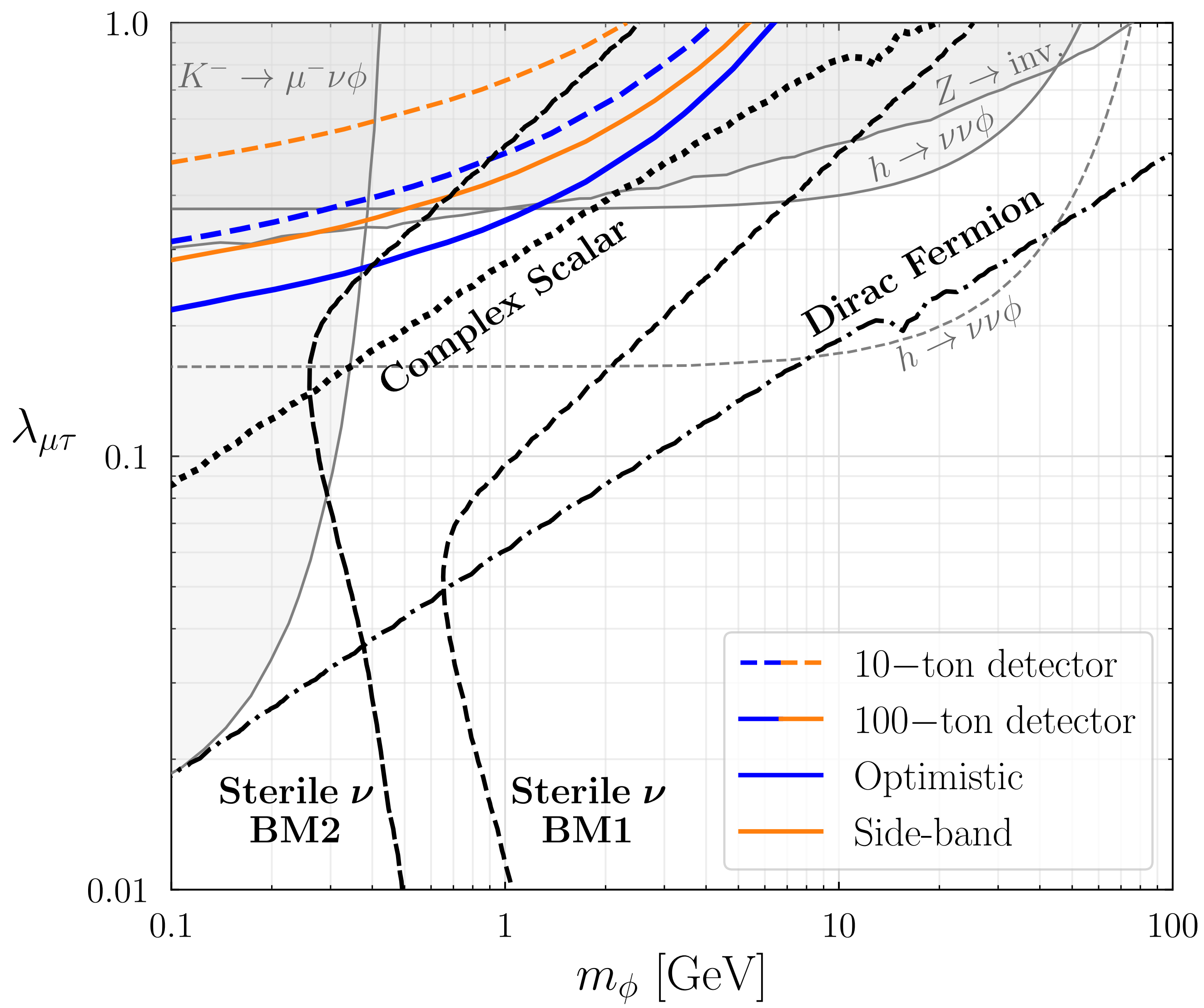
45% smearing on hadron momentum

15% smearing on hadron momentum

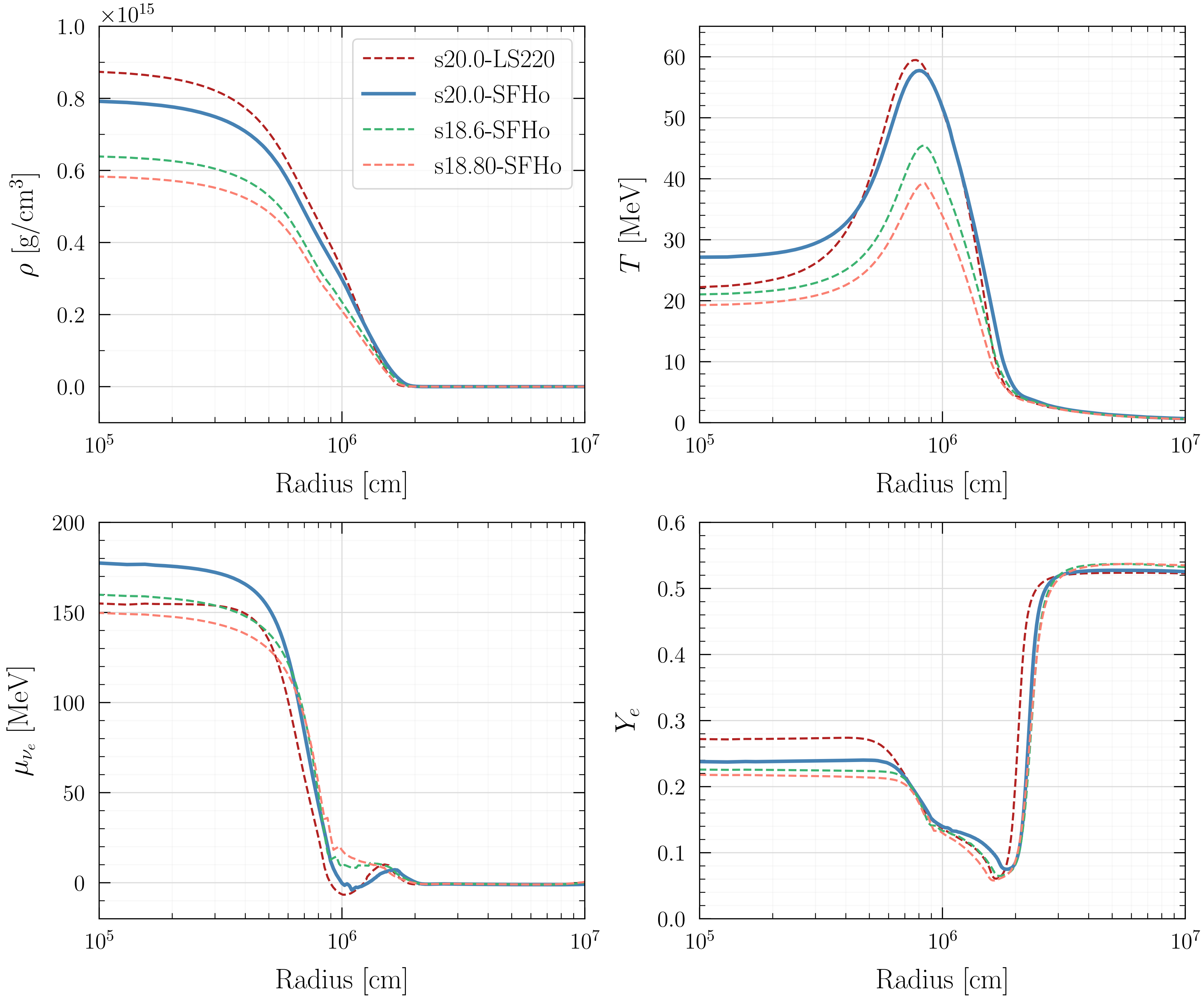


FPF Reach: Final State Tau Leptons

- For $\lambda_{\mu\tau} \neq 0$, the signal is a tau + $\not{p}_T$ coming from a muon-neutrino beam.
- Only $\mathcal{O}(100)$ tau neutrinos are expected to interact with the detector. The signal will result in an excess of tau events compared to the SM.
- Simple analysis: count the number of signal events with a tau in the final state



Supernova Profile



λ Dependence of Relevant Quantities