Probing Neutrinophilic Dark Matter: From Colliders to Supernovae

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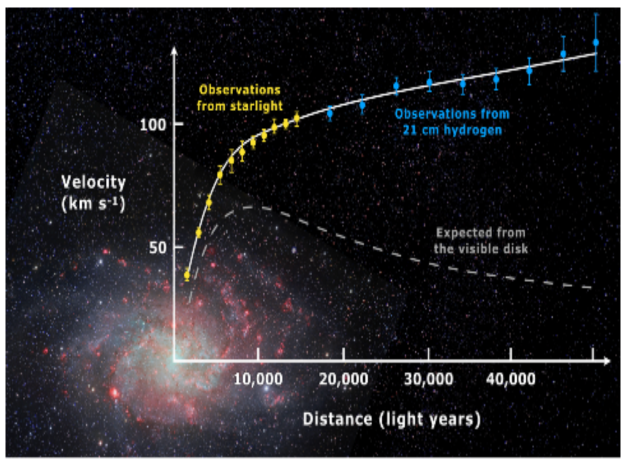
Neutrinos in Cosmology and Astrophysics
TRIUMF
March 8, 2024

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

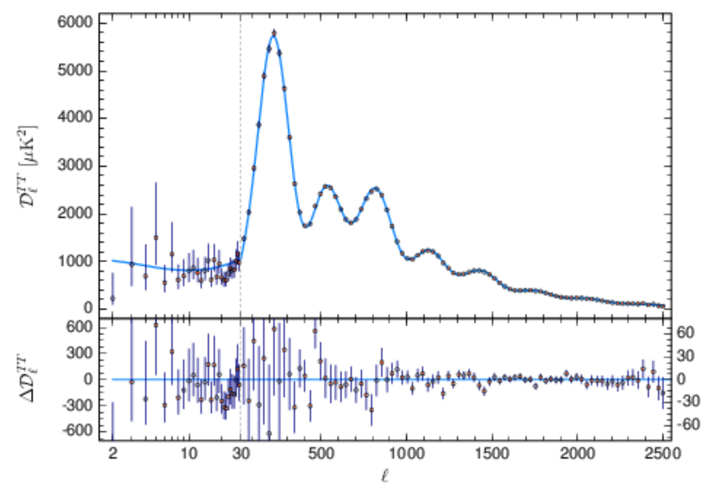
Evidence for Dark Matter

- Dark matter exists! Lots of cosmo/astro evidence.

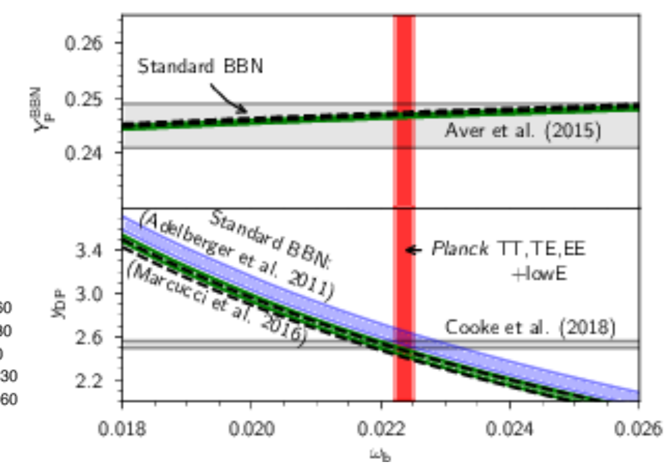


Galaxy rotation curves

Gravitational Lensing/Cluster Collisions



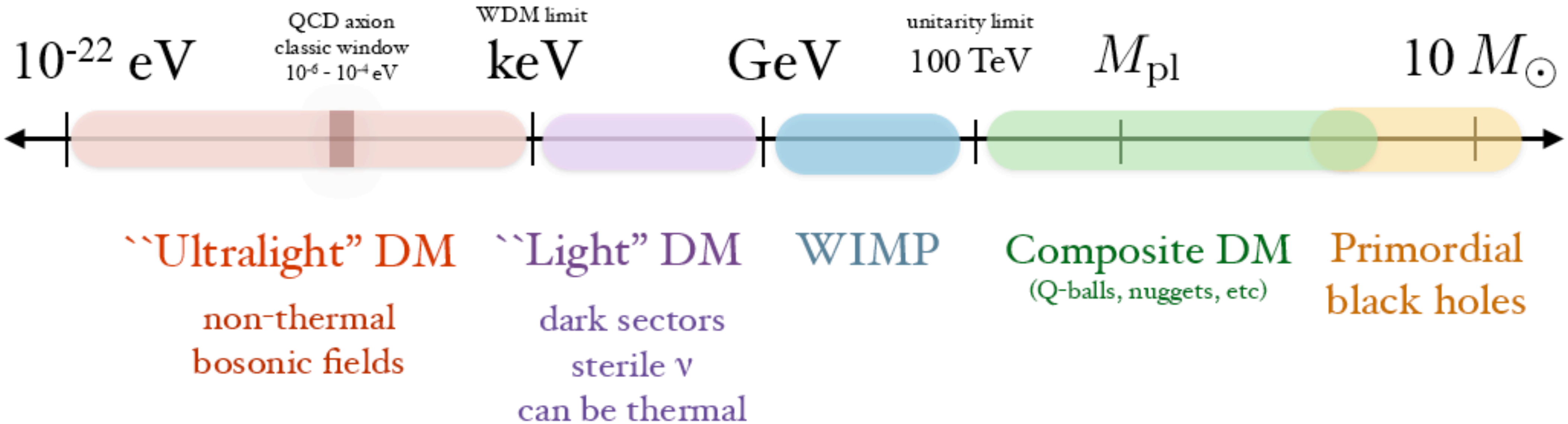
CMB

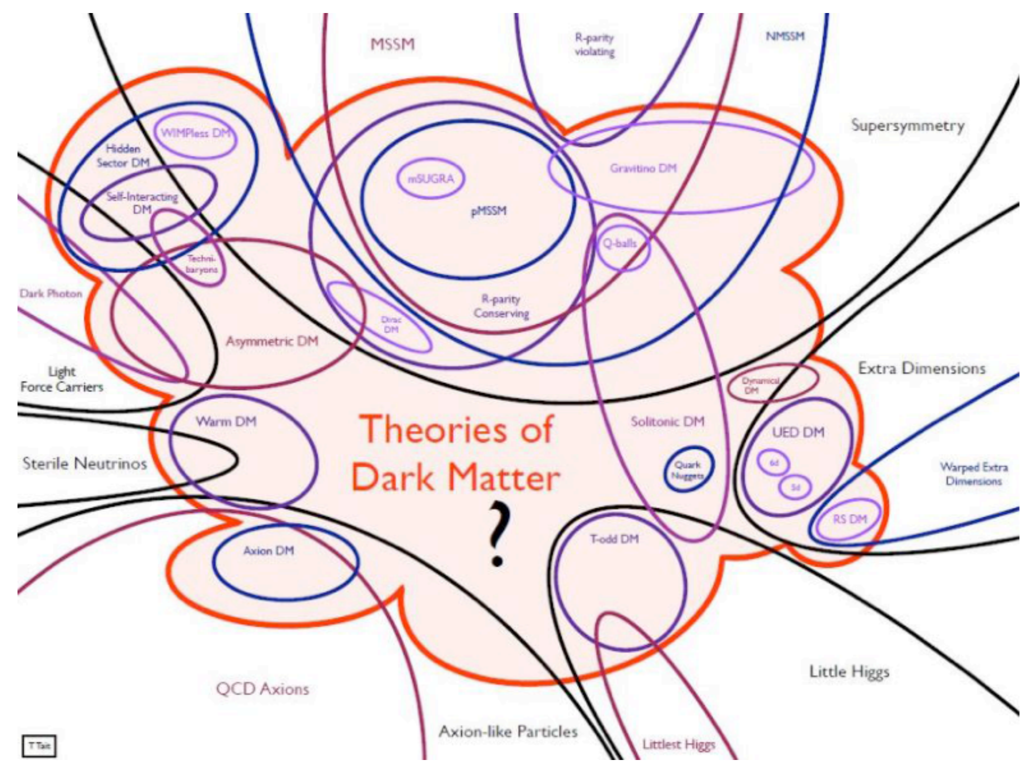


BBN

These observations tell us only about the macroscopic properties of DM. How can we probe the *microscopic* properties i.e. mass, non-gravitational interactions?

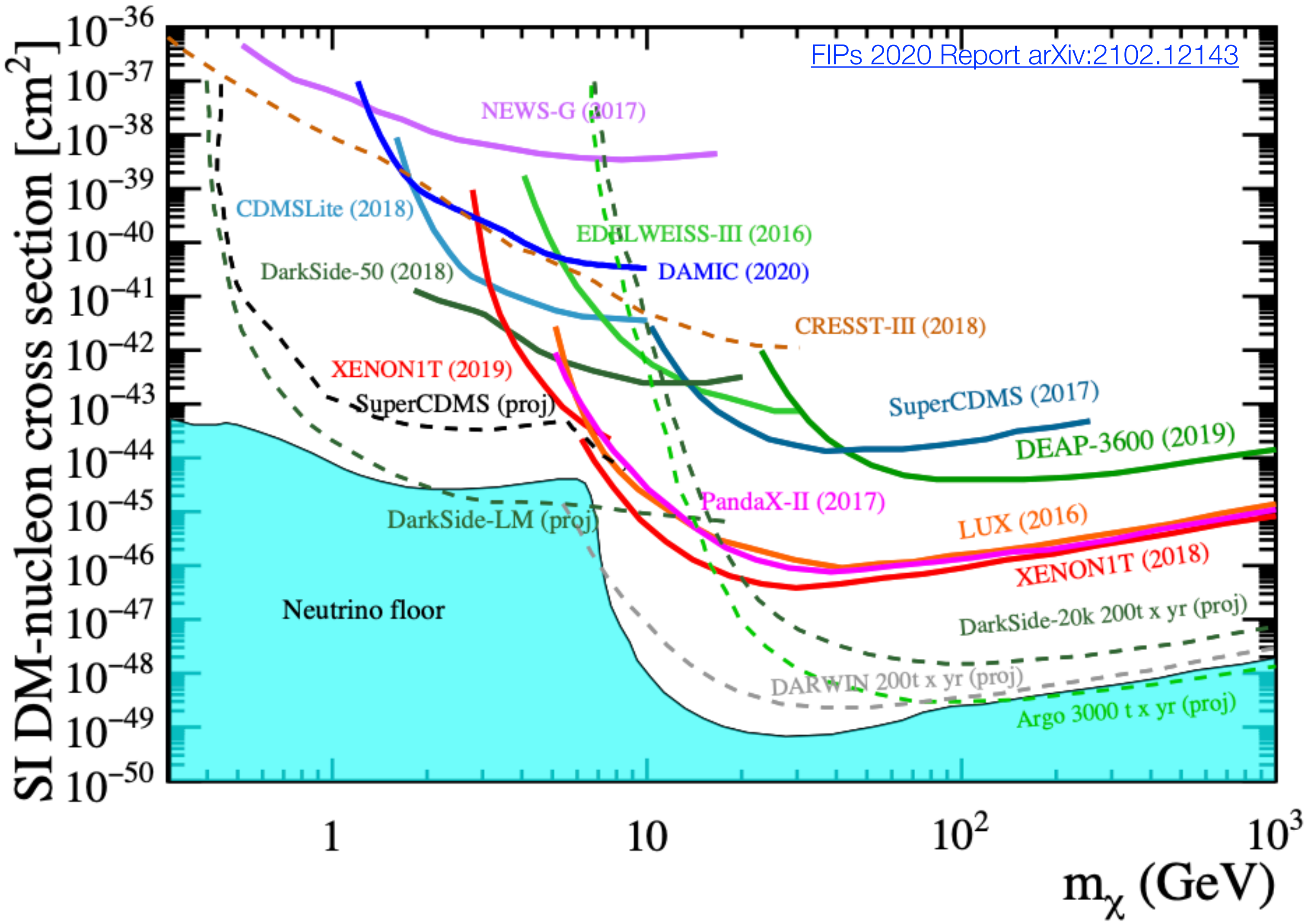
What even is DM?





WIMPs

- Traditional idea: DM is a thermal relic from the early universe.
- WIMP Miracle: Weakly interactive massive particles (WIMPs) with 10s of GeV to TeV masses and EW interactions
- Direct detection experiments are setting stronger and stronger limits on WIMPs



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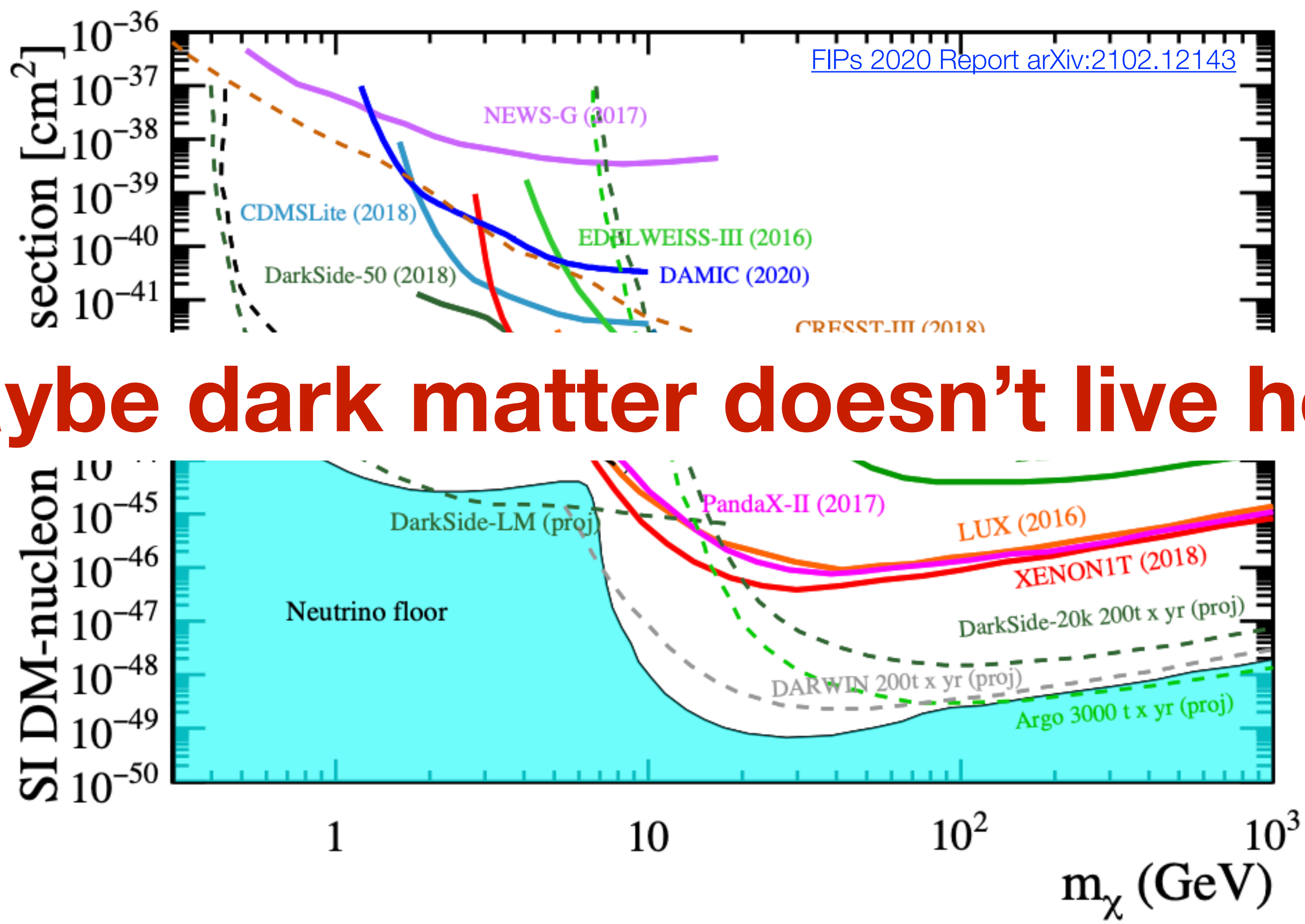


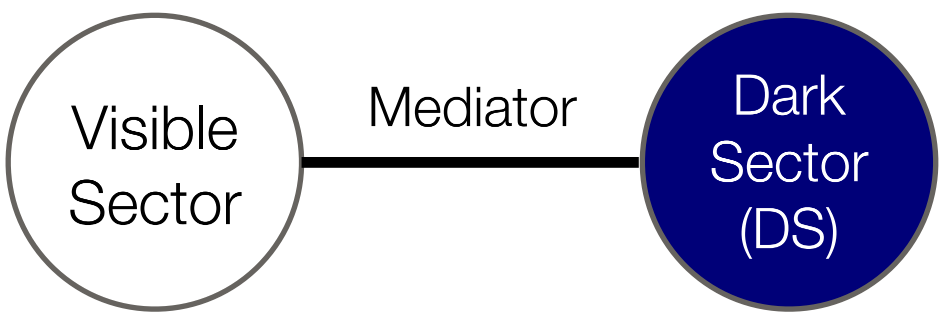
Maybe dark matter doesn’t live here?

Beyond the WIMP Paradigm

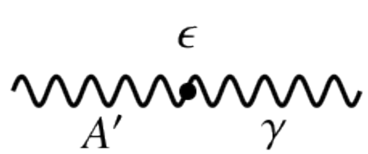
- Strong direct detection constraints on WIMPs and no SUSY seen at the LHC motivates going *beyond the WIMP paradigm*

Light Thermal DM/Dark Sectors

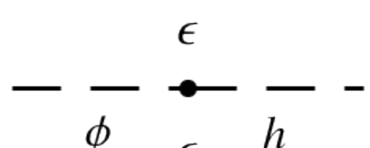
Lee-Weinberg bound → Light thermal DM requires **light new particles**



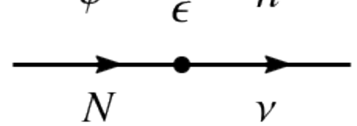
1. Dark Photon: $\epsilon F^{\mu\nu} F'_{\mu\nu}$



2. Dark Higgs: $\epsilon |h|^2 |s|^2$



3. Heavy Neutrino: $\epsilon \ell h N$



Non-thermal Dark matter

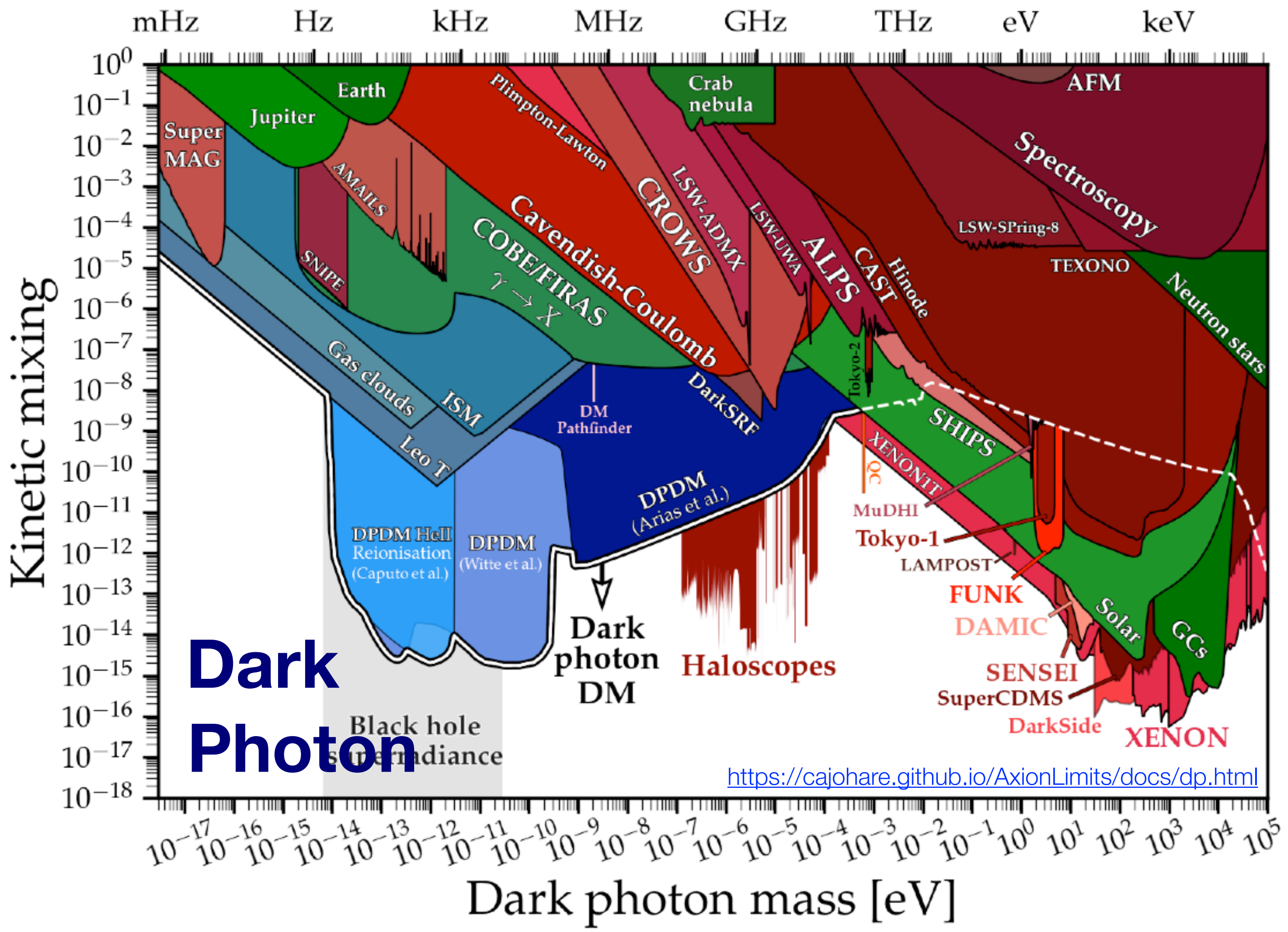
Axions

Primordial Black Holes

Ultra-light/Wave Dark Matter

Composite Dark Matter

(Very) Incomplete List of Experimental Limits



Dark Photon

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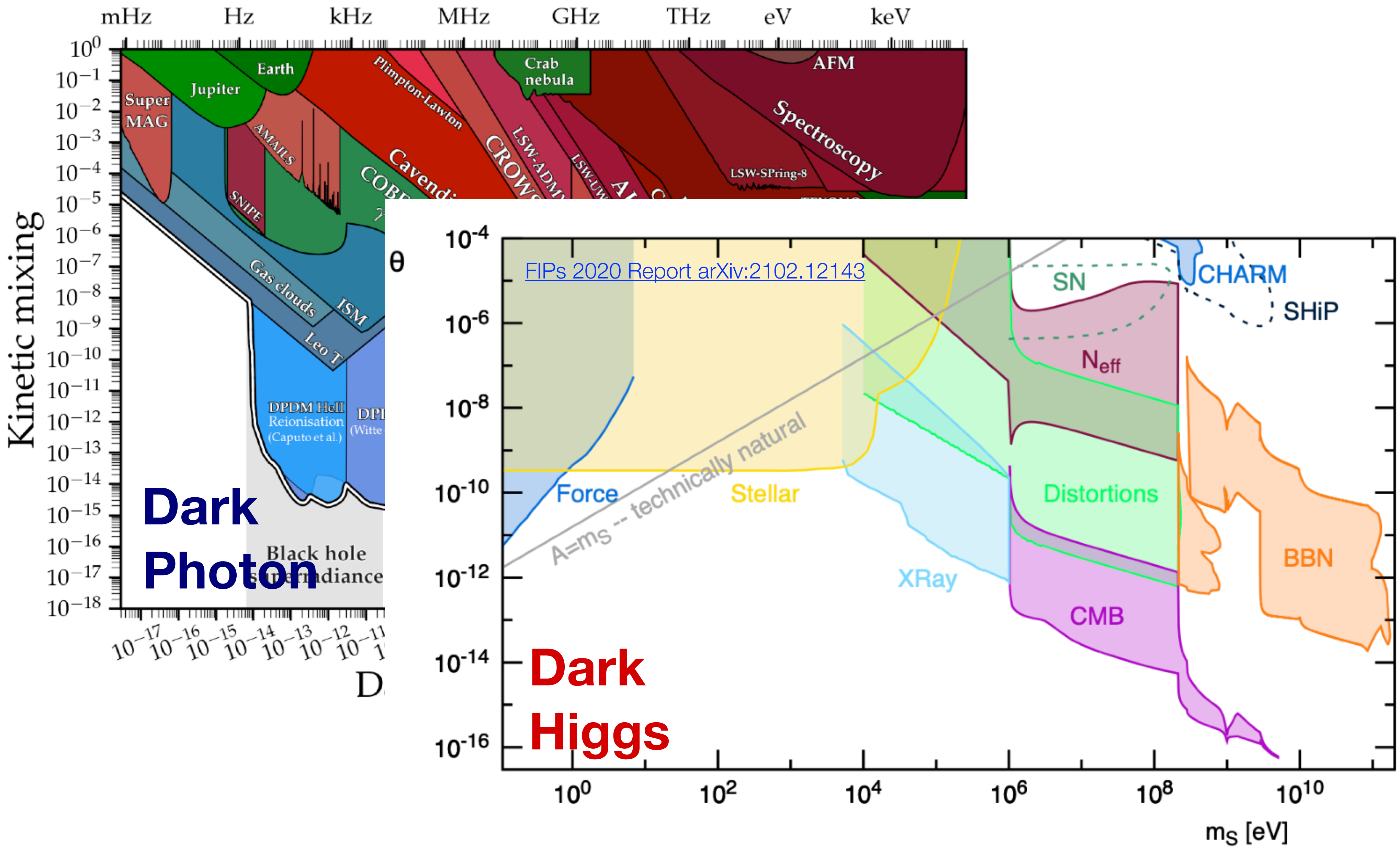

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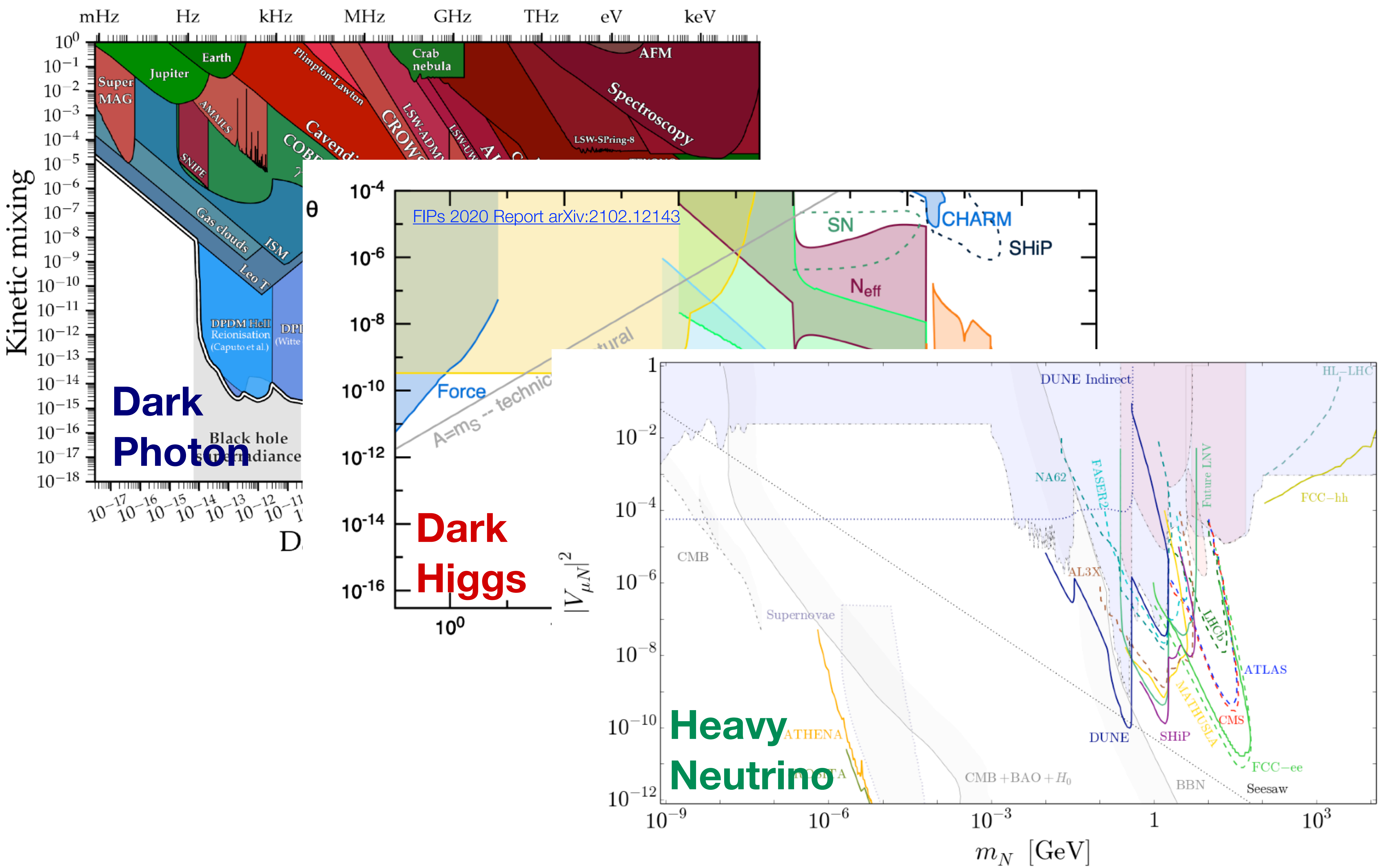

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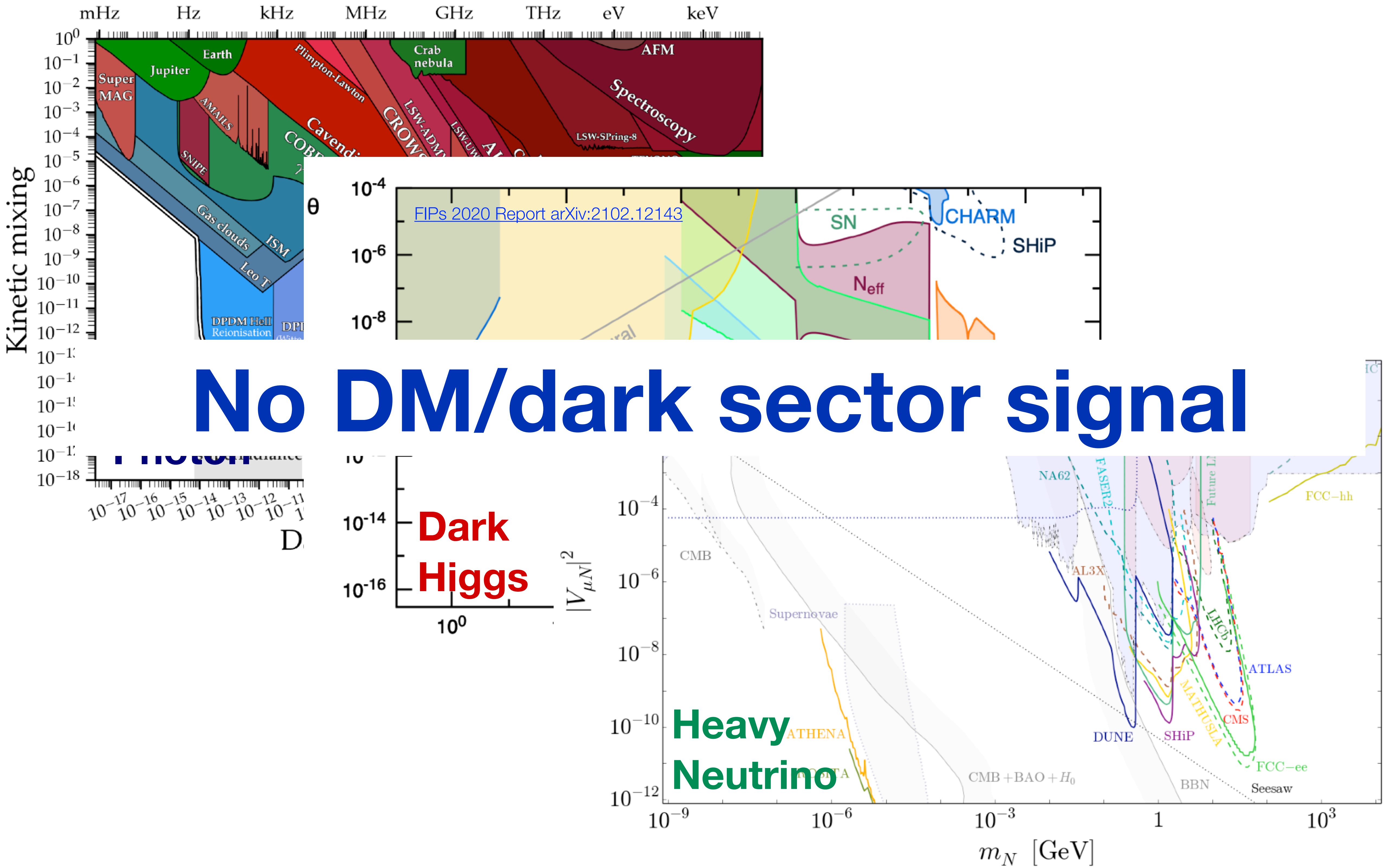
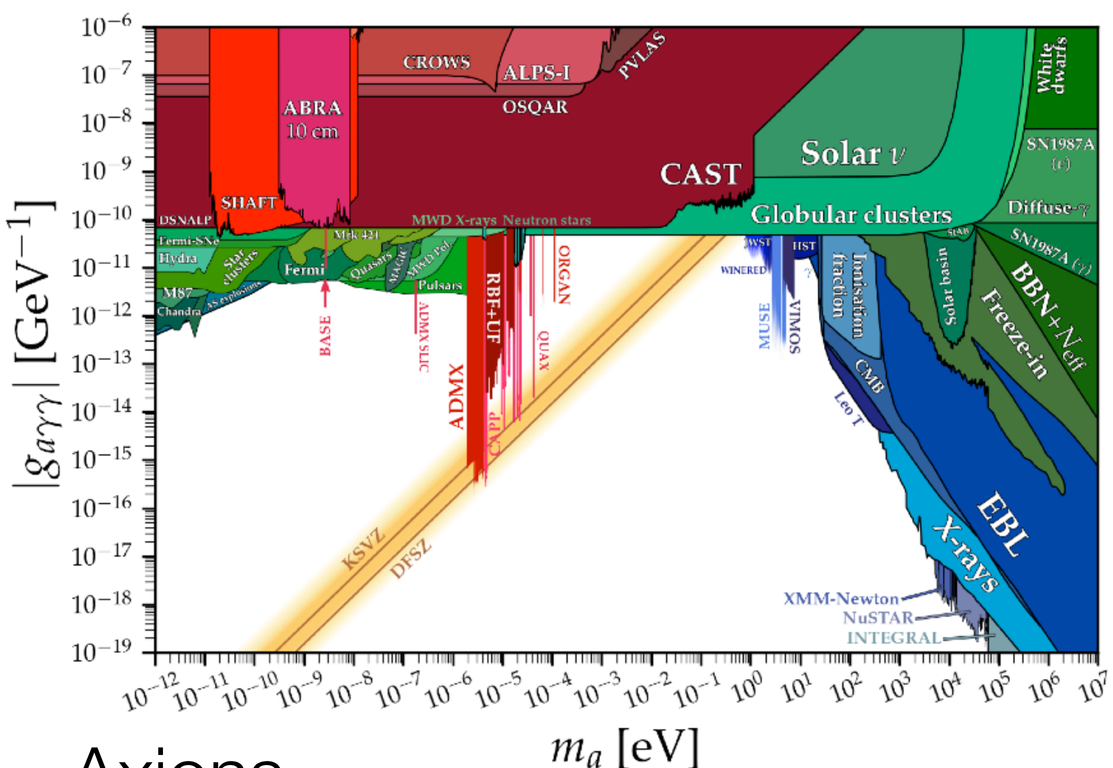
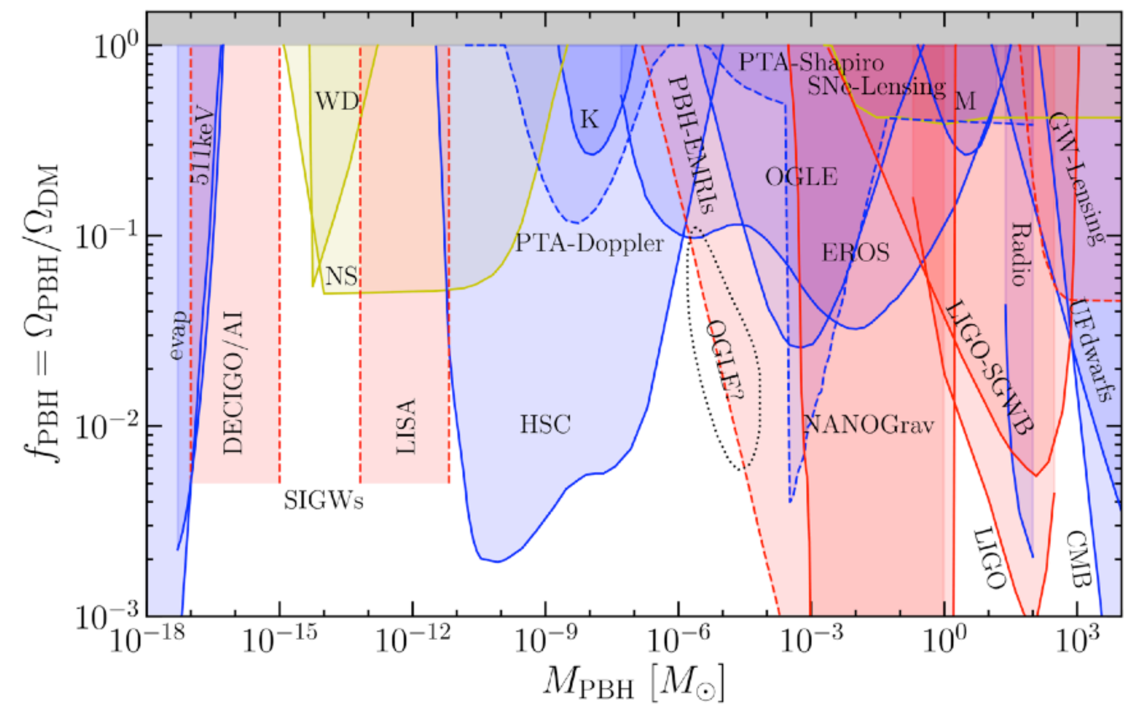


No DM/dark sector signal

(Very) Incomplete List of Experimental Limits

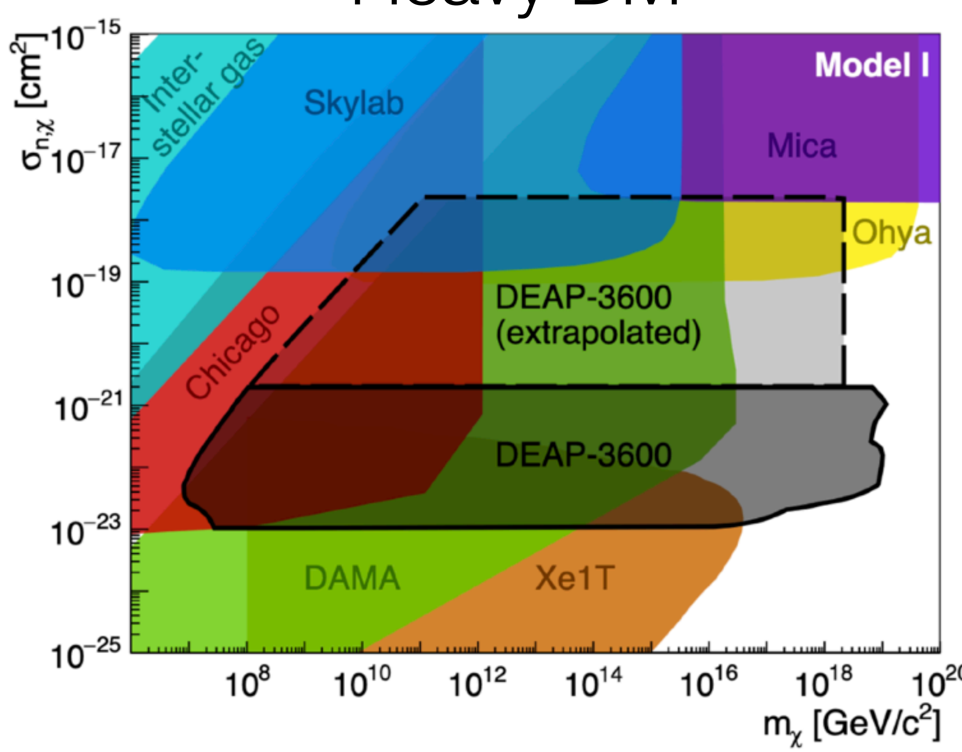


Axions



PBHs

Heavy DM



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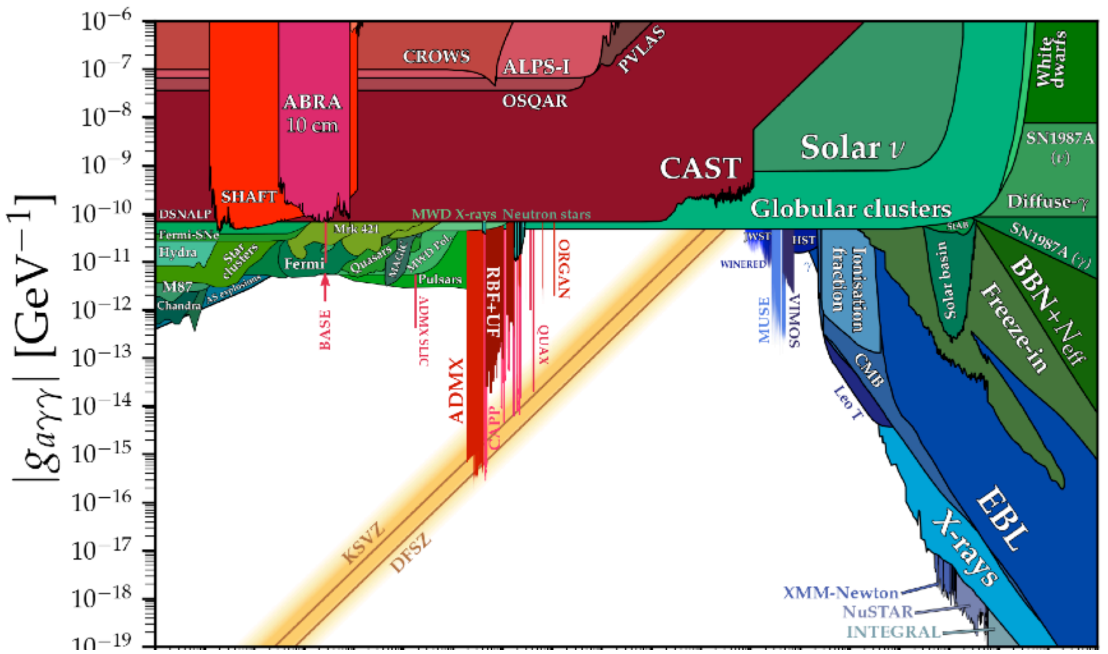

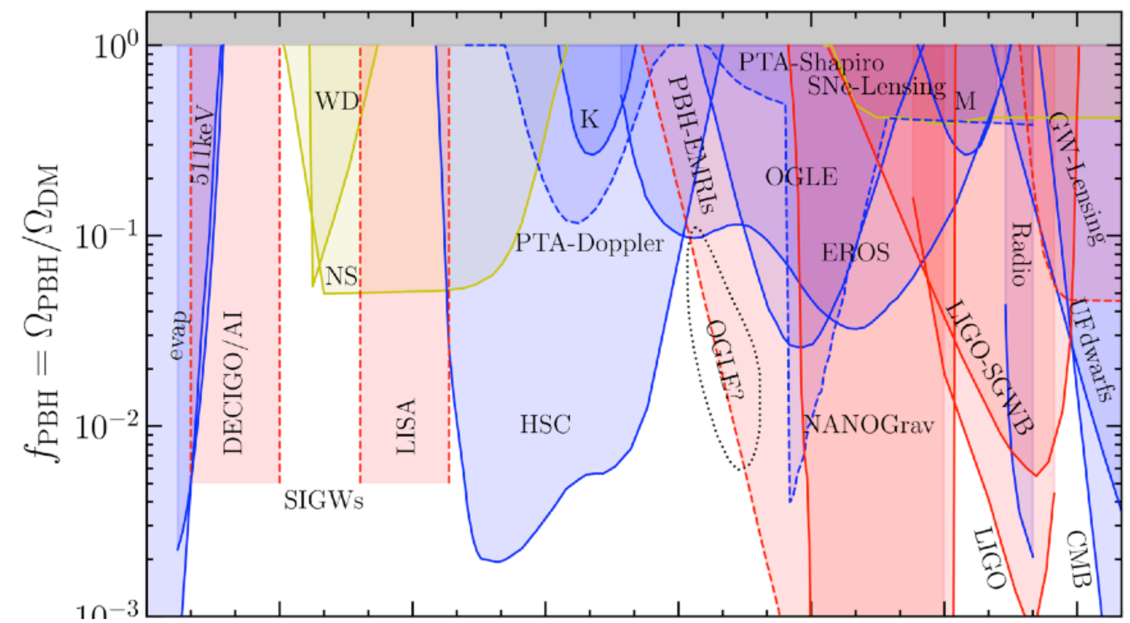

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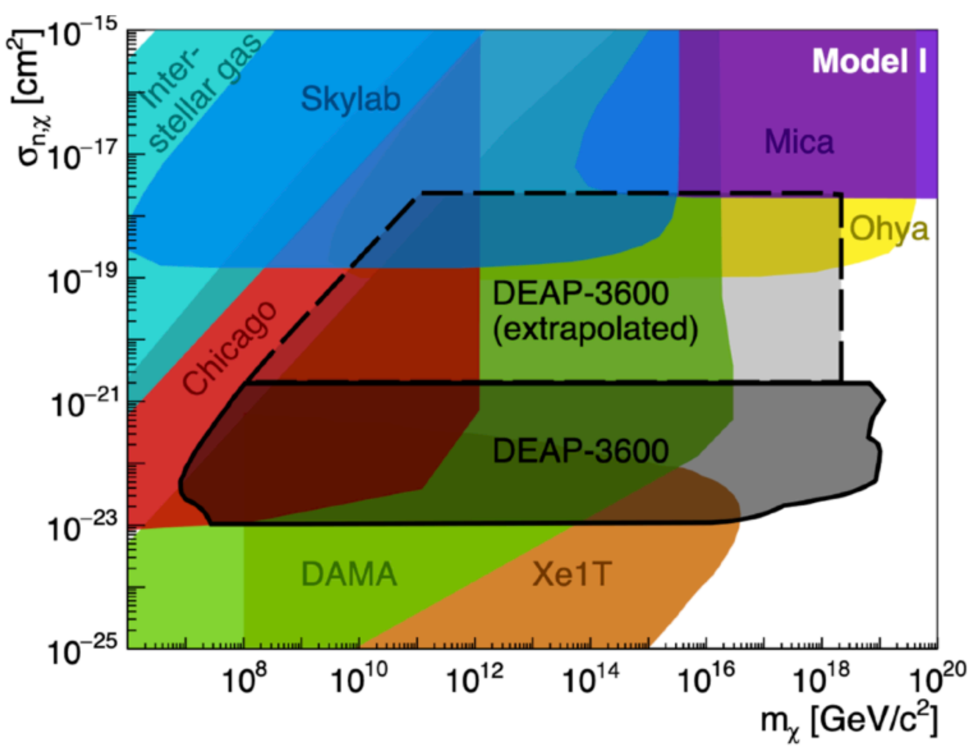
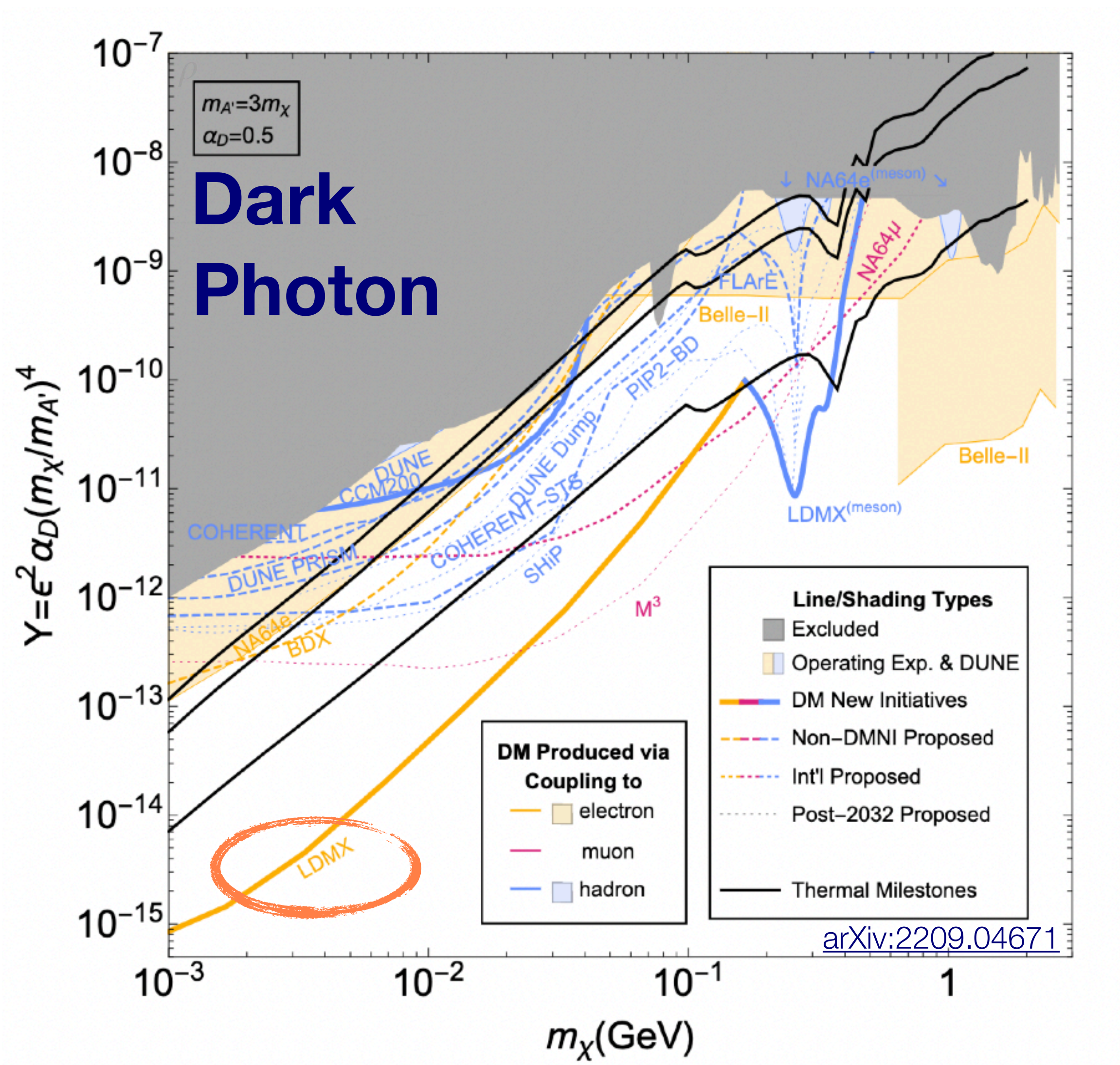
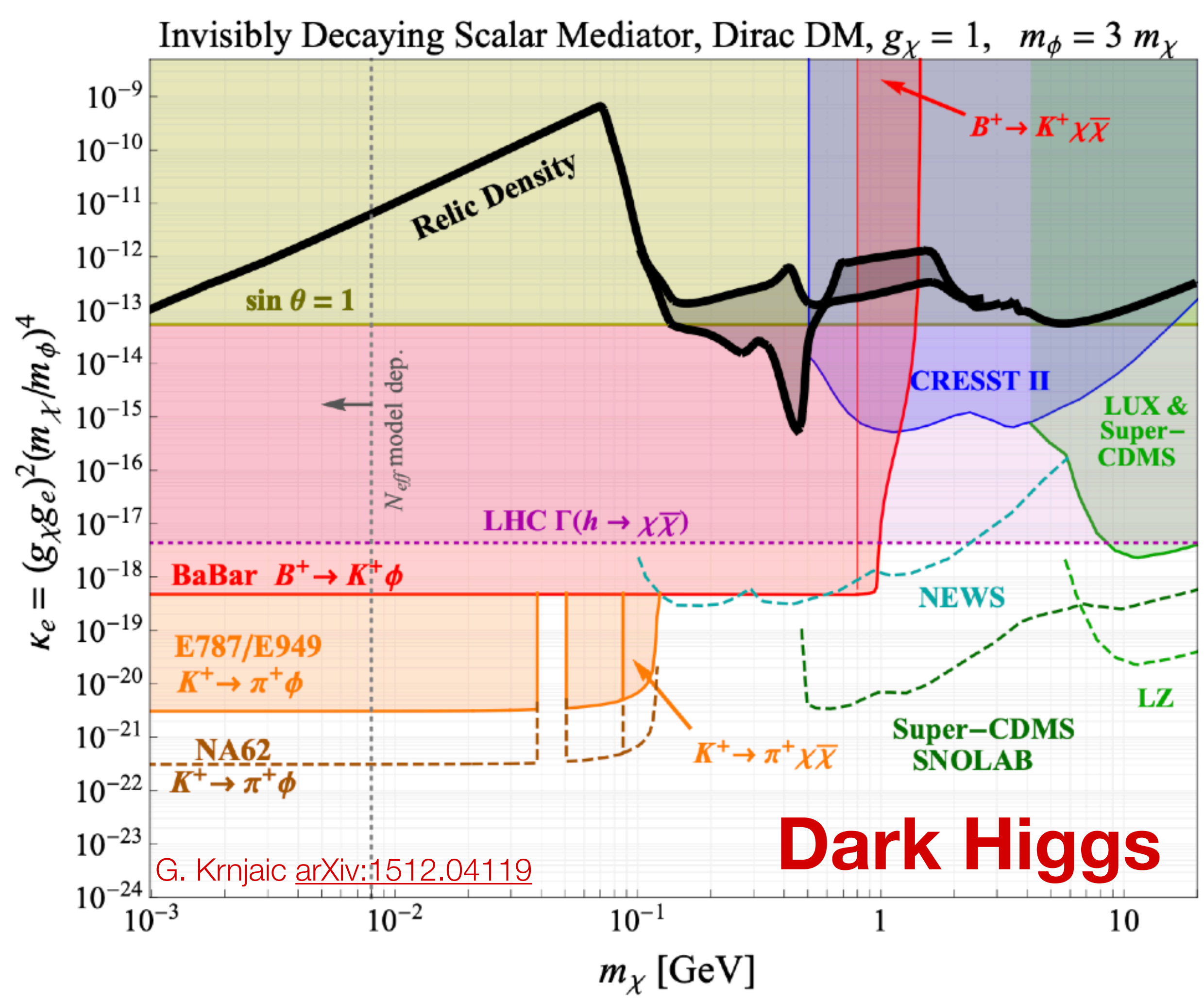


Connections to Dark Matter

- Maybe we should look for invisible signals



Light Dark Matter eXperiment (LDMX) is projected to rule out thermal DM via dark photon portal



Thermal DM completely excluded

Next steps?

- No dark matter signal has been observed. Why? Where do we go from here?

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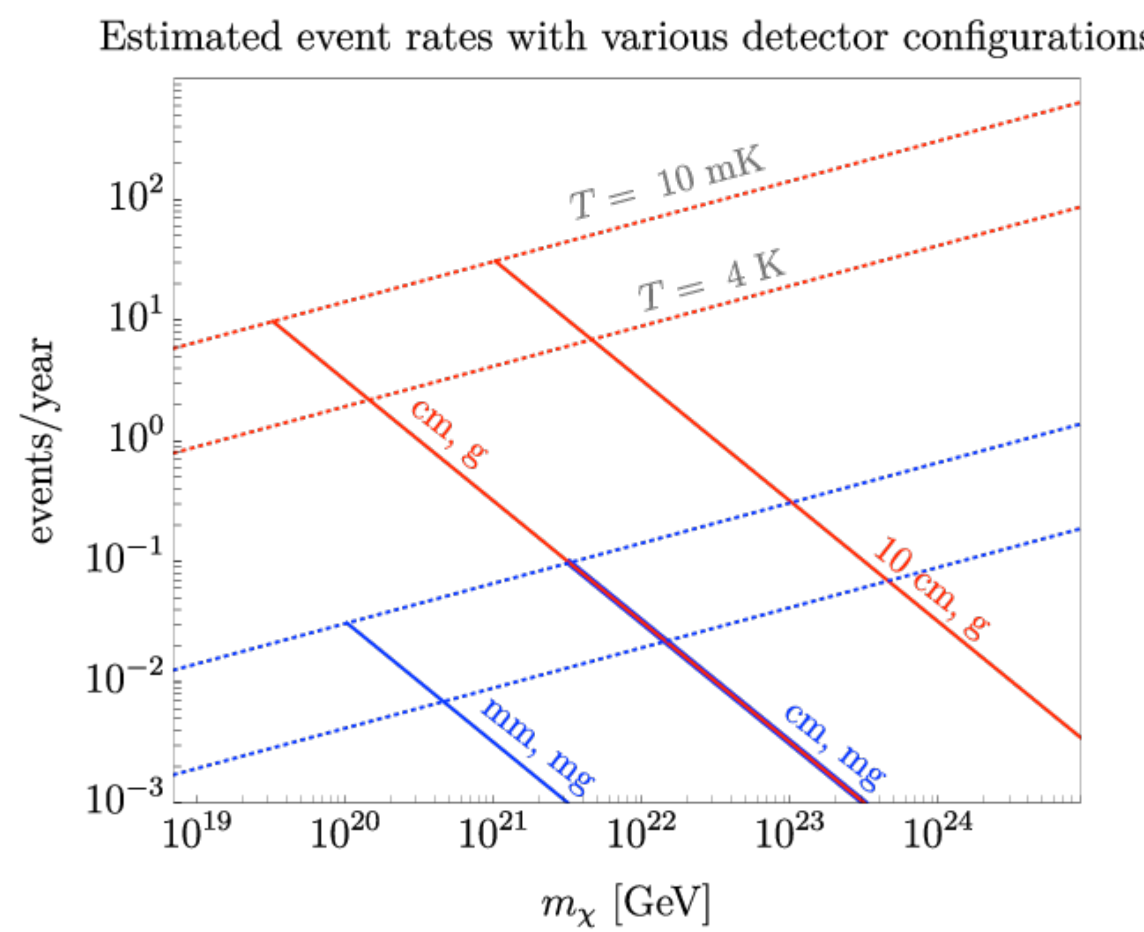
The Windchime Project: Gravitational Detection of Dark Matter in the Laboratory

Small window where this could work so we better hope that DM has this mass!



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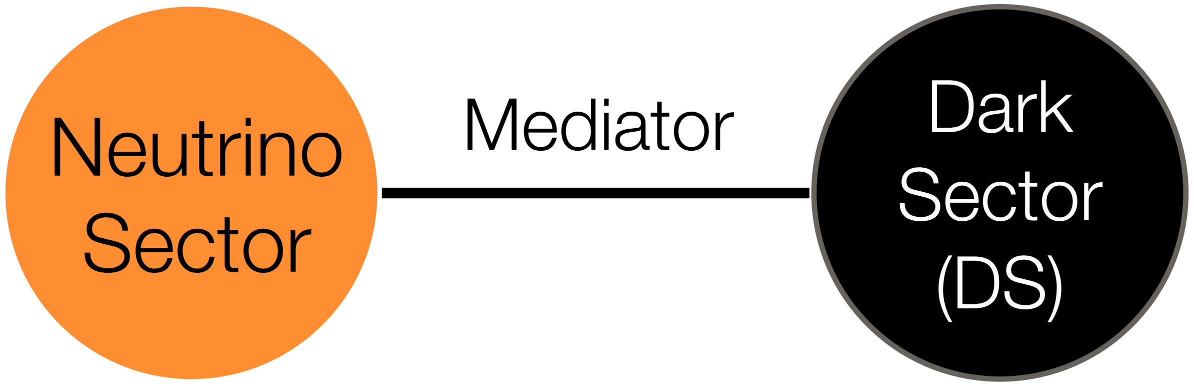
- No dark matter signal has been observed. Why? Where do we go from here?

1. *Maximally Optimistic option:* We need to build all the experiments.
2. *Maximally Pessimistic option:* dark matter has no non-gravitational interactions.
3. Searches for DM assume that DM interacts with visible stuff (e.g. photons, electron, protons). ***What if DM is more elusive than we thought?***



Topic of this talk: Neutrinophilic Dark Matter

Motivations for Neutrino Self-Interactions

- Neutrinos are mysterious! Self-interactions have never been directly measured → new particles can introduce new self-interactions that are larger than the SM self-interactions.
- Other motivations:
  - Models with new neutrino self-interactions can also generate neutrino masses
  - New neutrino self-interactions frequently appear in gauge extensions of the SM (though not purely neutrinophilic)
  - ***New particle = mediator to dark matter/dark sector***

Prototype: Sterile Neutrino Dark Matter

- keV-scale singlet fermion that mixes only with the SM neutrinos

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

- Sterile neutrino produced via active-sterile neutrino oscillations in weak interactions → Dodelson-Widrow Mechanism
- Indirect detection via one-loop decay $\nu_s \to \nu_a \gamma$ with X-ray line at $E_\gamma = m_4/2$

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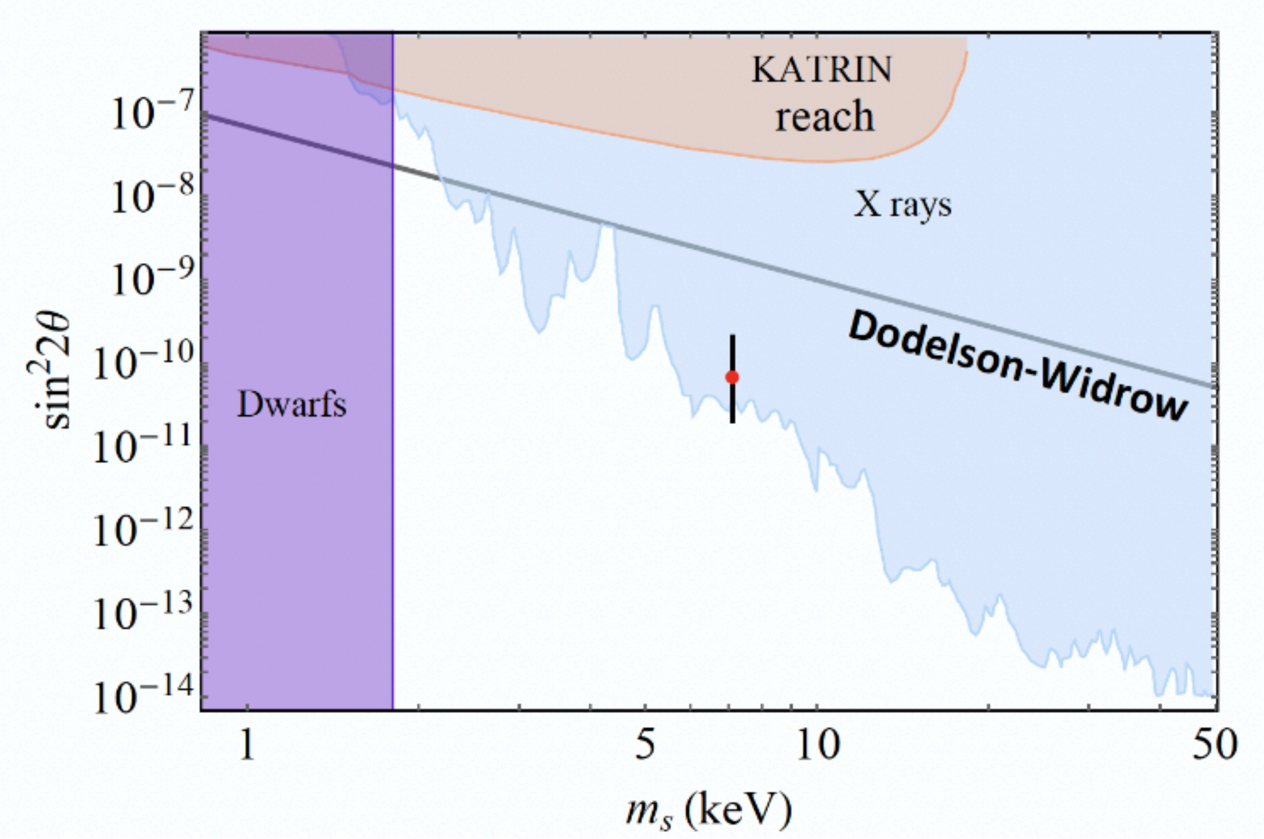


SνDM is almost completely excluded. Can we save Dodelson-Widrow?

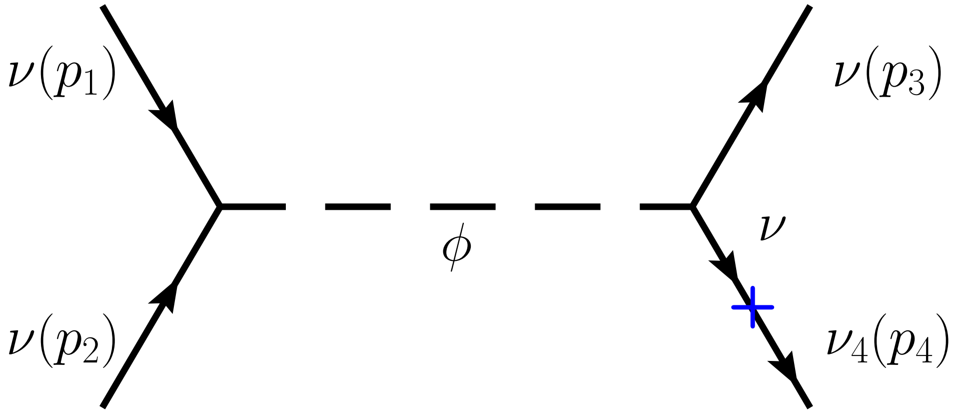
A Neutrinophilic Scalar Mediator

- Schematically, the sterile neutrino relic abundance is

$$\Omega \sim \Gamma \times \sin^2(2\theta)$$

- If $\Gamma = \Gamma_W$, then a large angle is required → X-ray constraints.
- Smaller mixing angle by increasing the interaction rate? Yes! Introduce a scalar field ϕ of mass m_ϕ that mediates *new self interactions among SM neutrinos.*

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

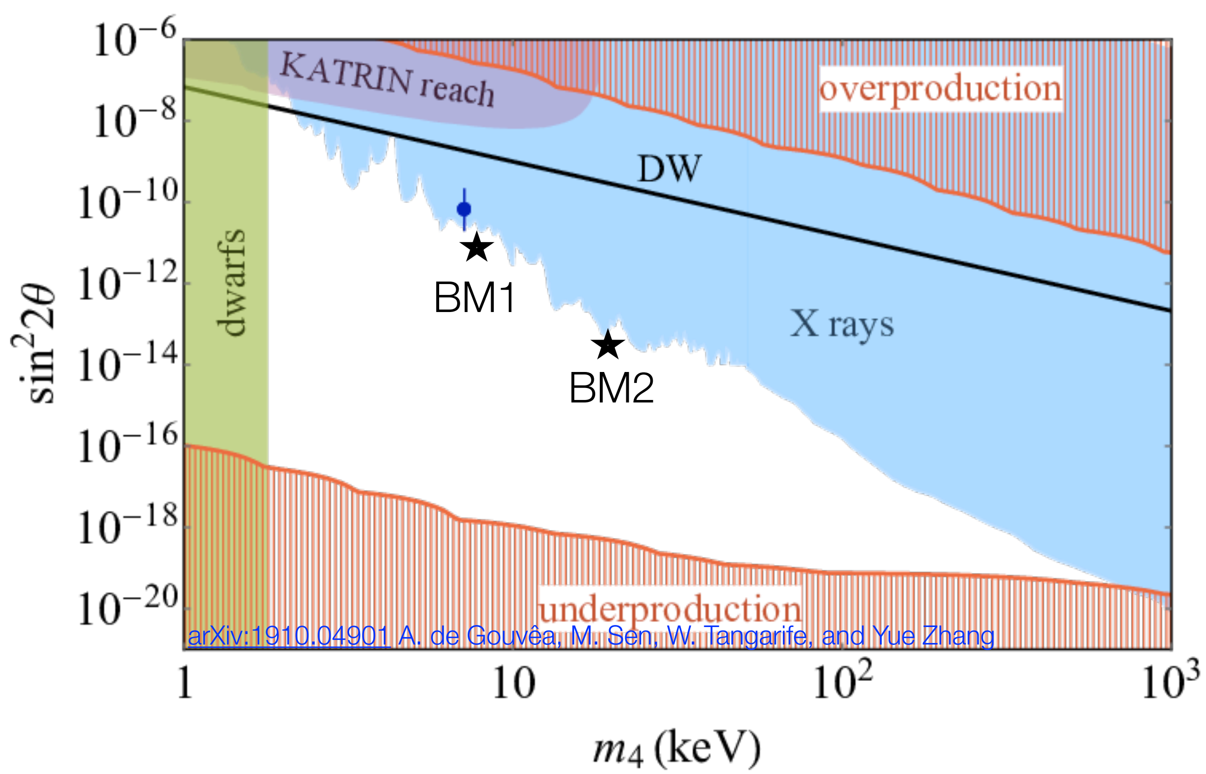


Larger rate than the weak interactions keeps SM neutrinos in contact for a longer period of time to build up the DM abundance!

A Neutrinophilic Scalar Mediator

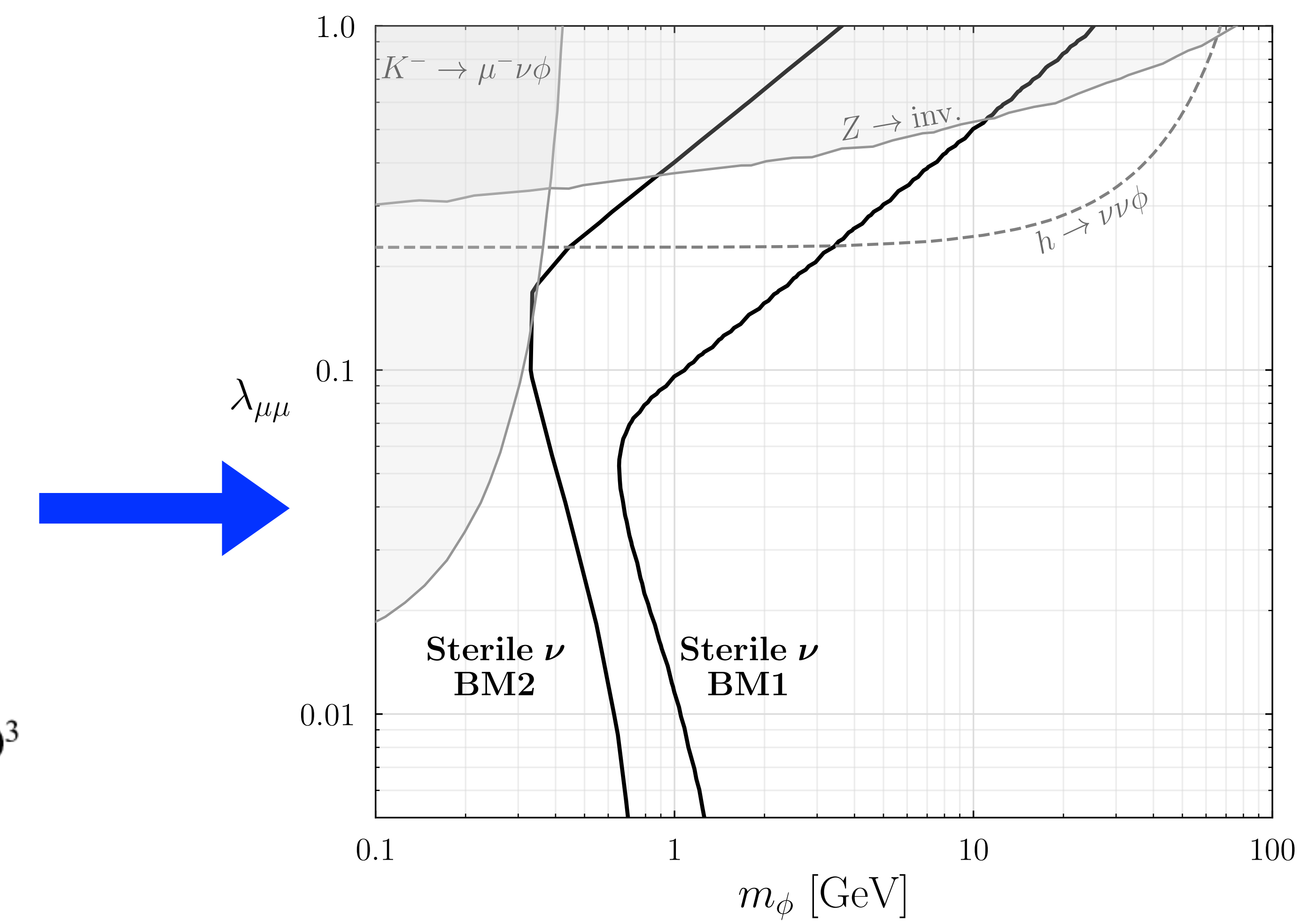
- New production mode for SνDM via neutrinophilic mediator opens up a wide window for the DM relic abundance. Don't have to live on DW line.

Any point in this parameter space can be mapped to a curve in the λ vs m_ϕ plane



$$\text{BM1} : m_4 = 7\text{keV}, \ \ \sin^2(2\theta) = 7 \times 10^{-11}$$

$$\text{BM2} : m_4 = 21\text{keV}, \ \ \sin^2(2\theta) = 1.4 \times 10^{-13}$$



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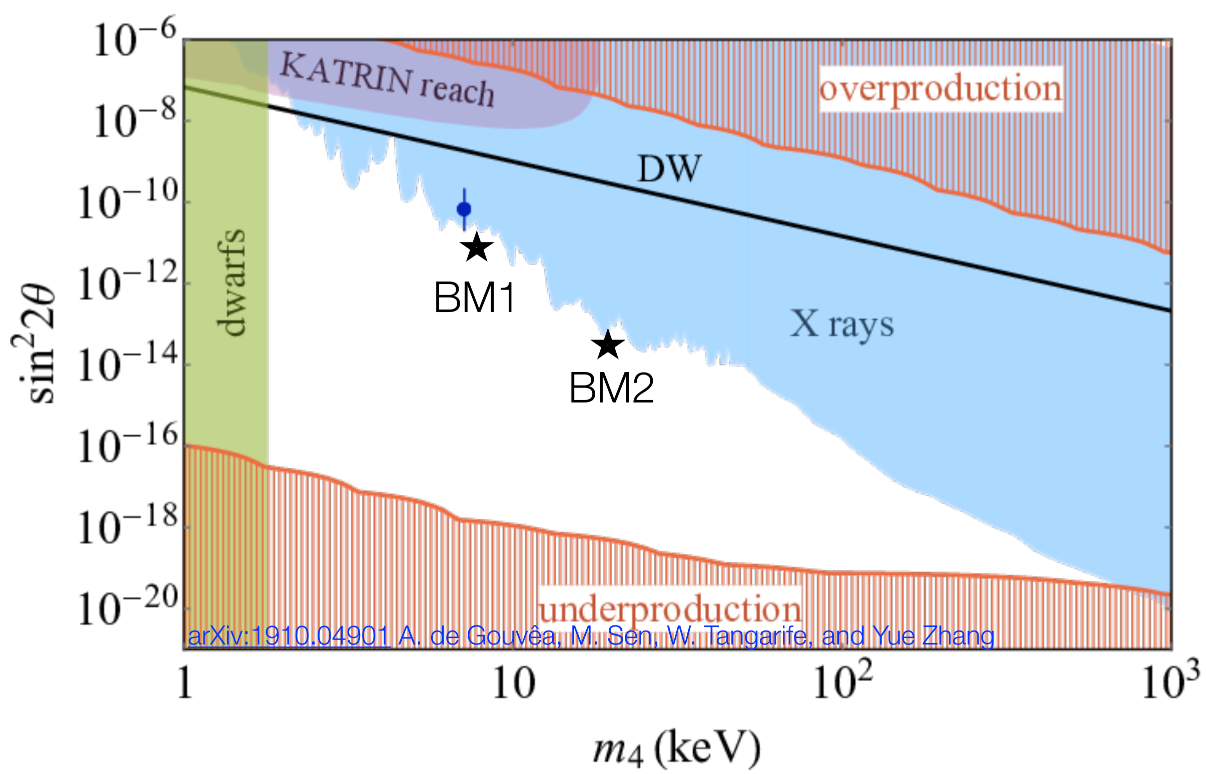

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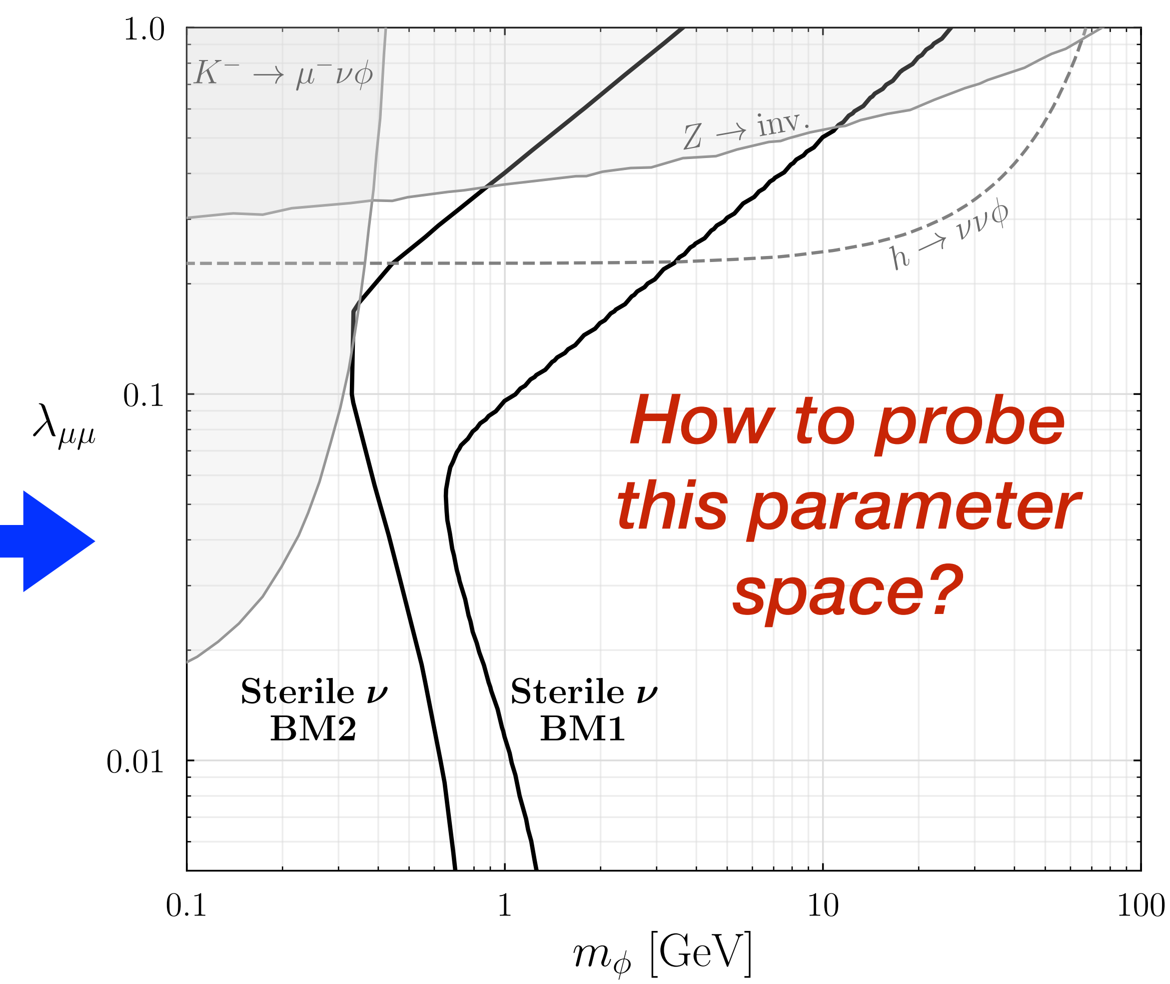
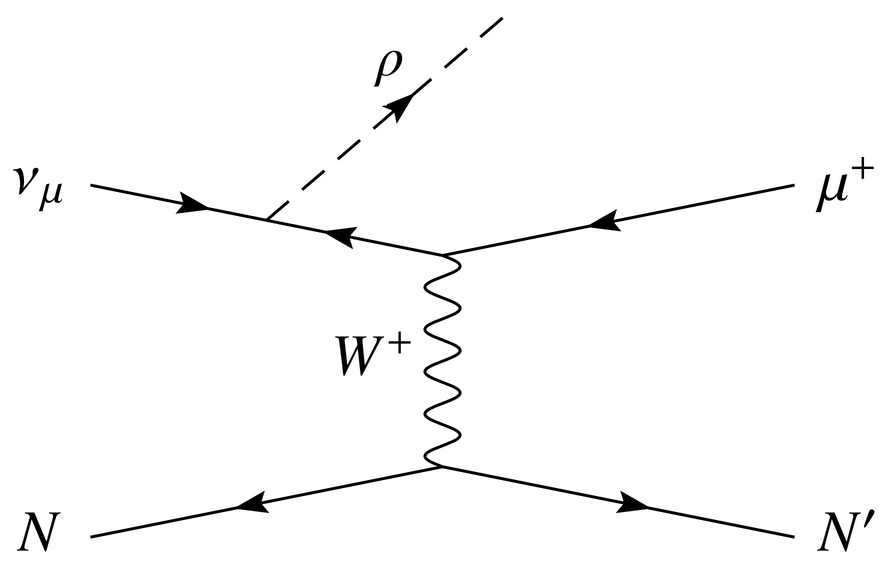


The Mono-neutrino Signature

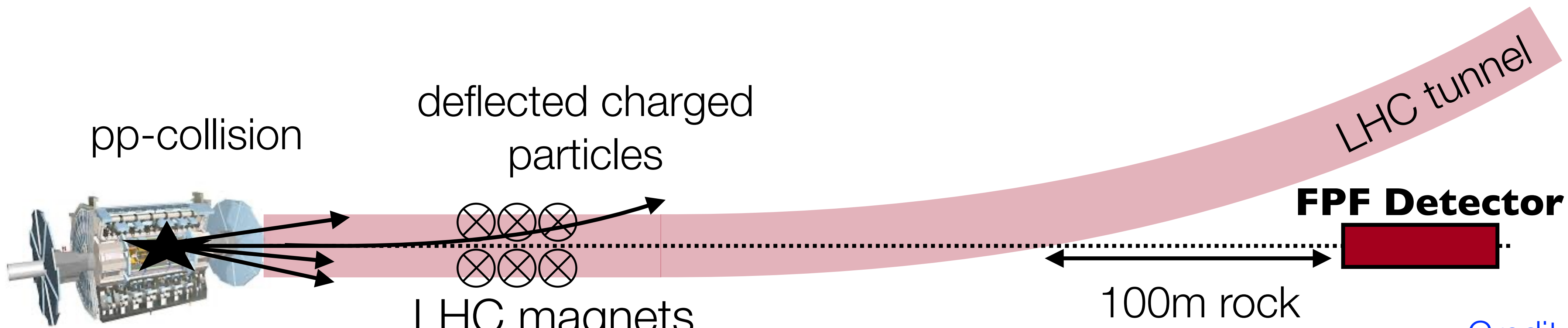
- Unique signature due to the neutrinophilic nature of the mediator: Incoming neutrino radiates a scalar particle and then converts to a muon via CC interactions K. J. Kelly and Y. Zhang arXiv:1901.01259



- Observable: **Missing transverse momentum** carried away by ϕ
  - Similar in spirit to mono-X searches at the LHC, missing transverse momentum technique @ LDMX/DarkLight
- High energy/intensity neutrino environments are excellent to probe this signature!

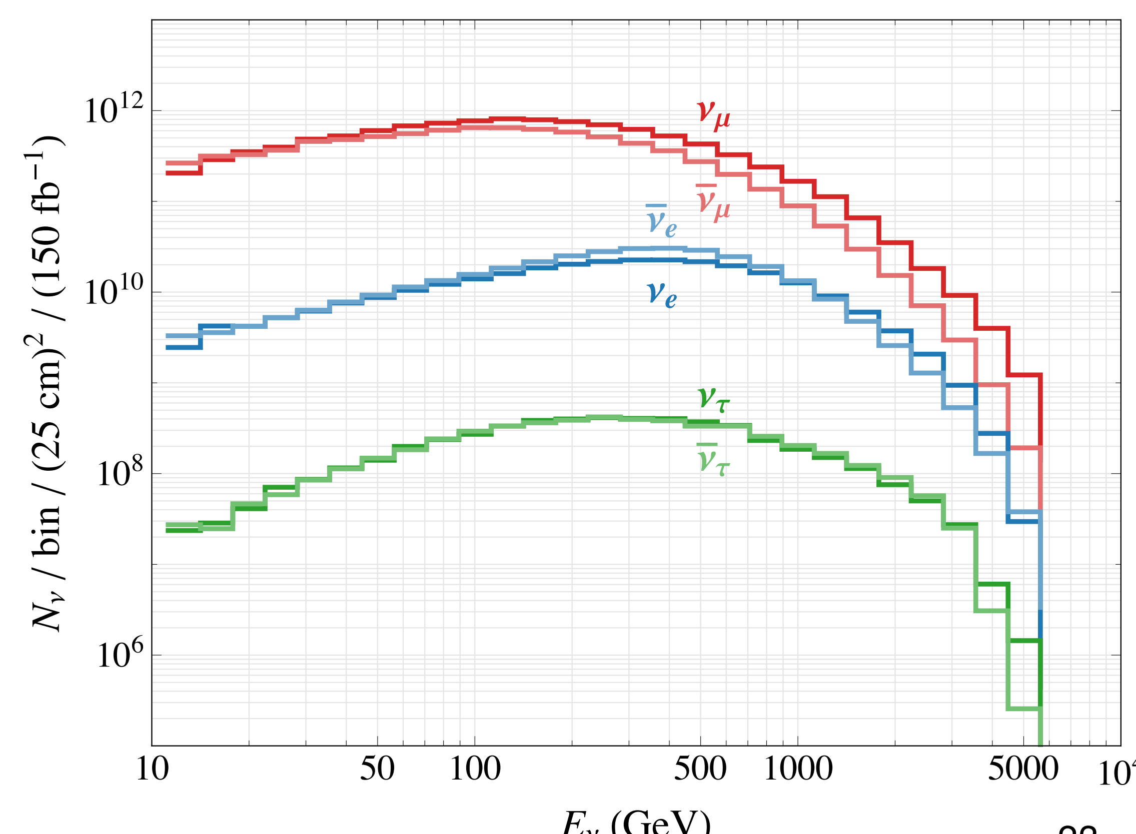
LHC Forward Physics Facility

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



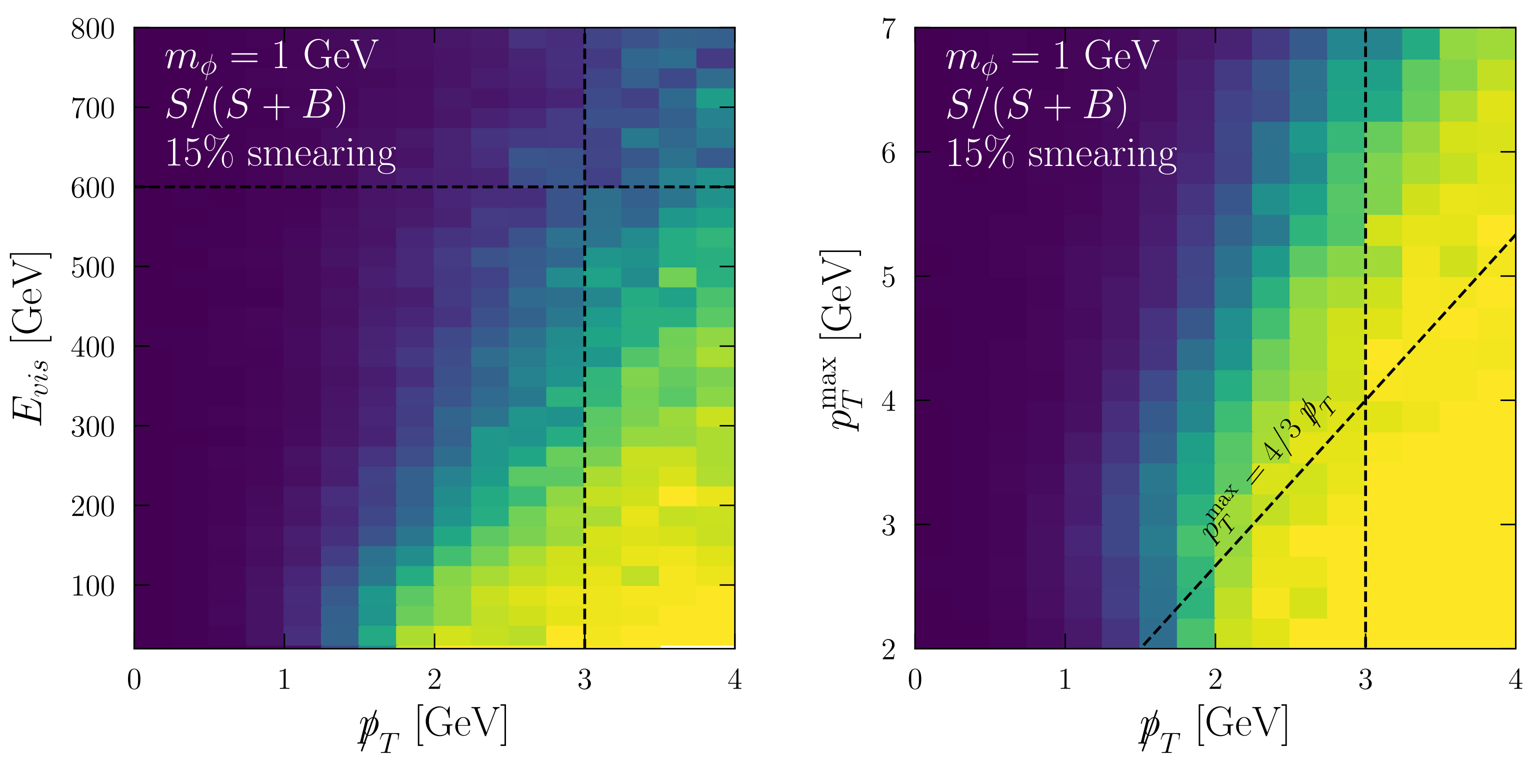
Credit: Felix Kling

- 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
$E_{\rm vis.} < 600$ GeV	61%	76%
$\not{p}_T > 3$ GeV	0.2%	26%
$p_T^{\rm max} < \frac{4}{3}\not{p}_T$	10^{-5}	15%

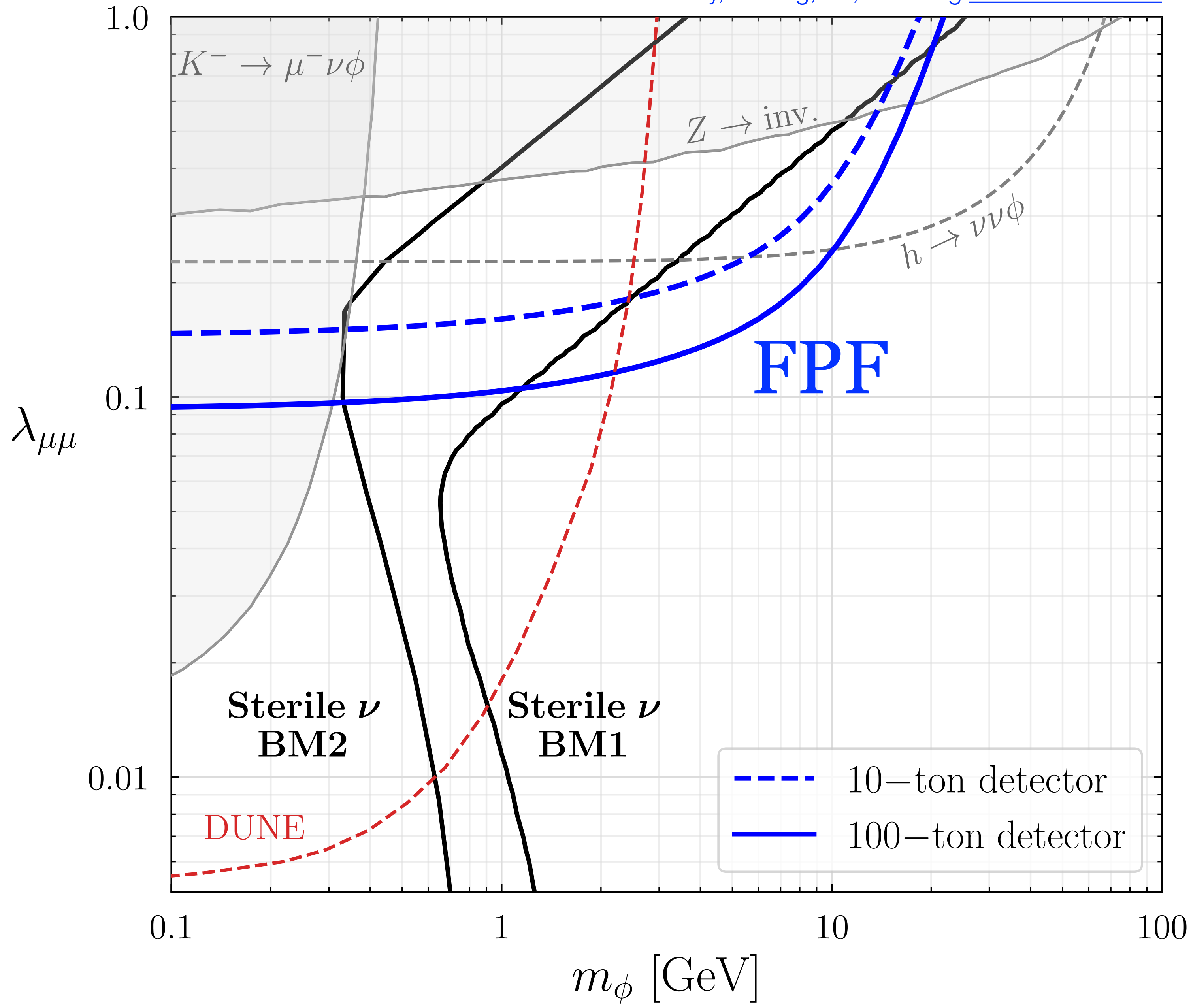
Significant reduction in bkg. *from missing transverse momentum cut*!

K.J. Kelly, F. Kling, DT, Y. Zhang arXiv:2111.05868

Reach of the Forward Physics Facility

- Feed relevant observables into a neural network to optimize the analysis

K.J. Kelly, F. Kling, DT, Y. Zhang arXiv:2111.05868



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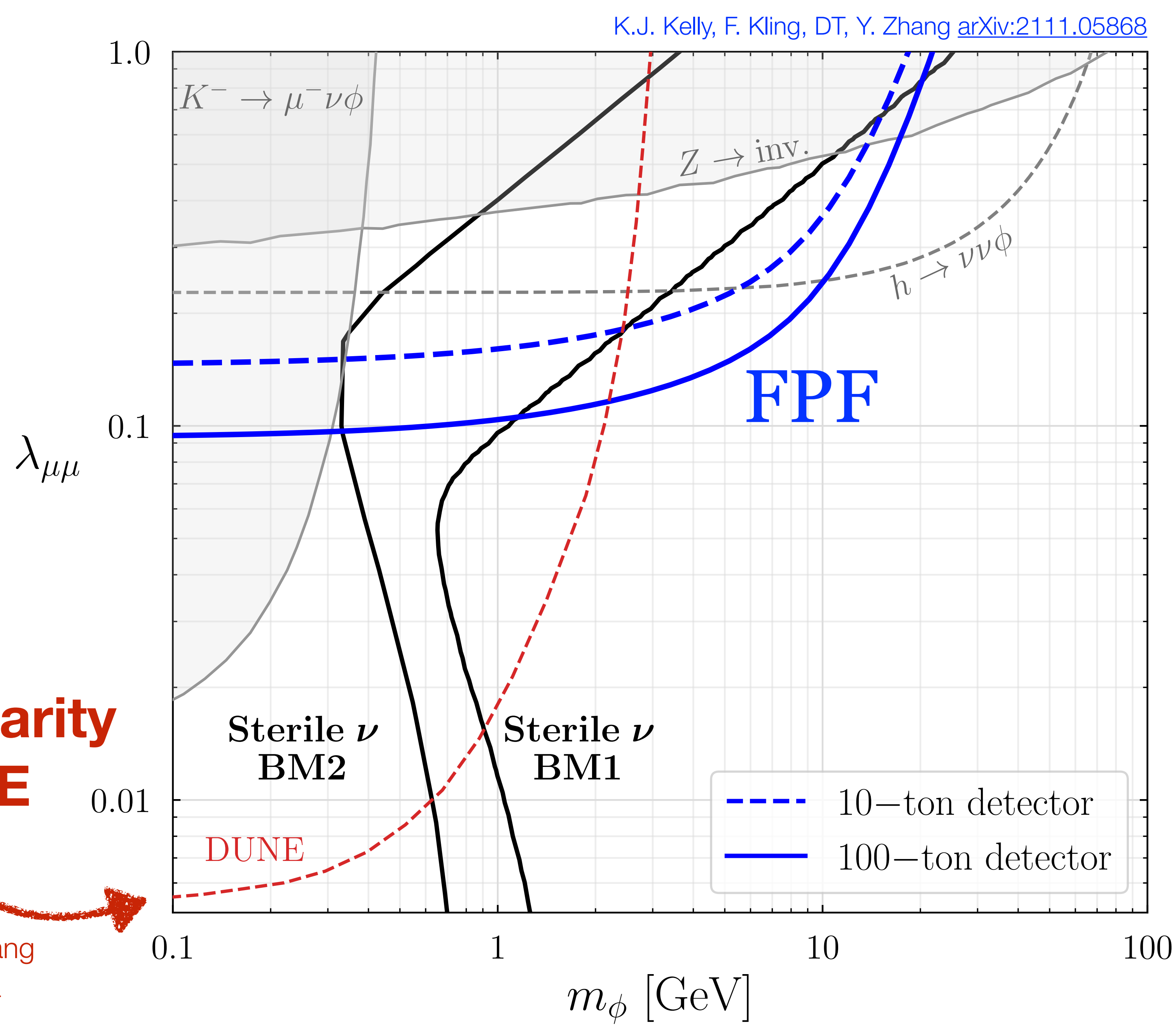

Complementarity with DUNE

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

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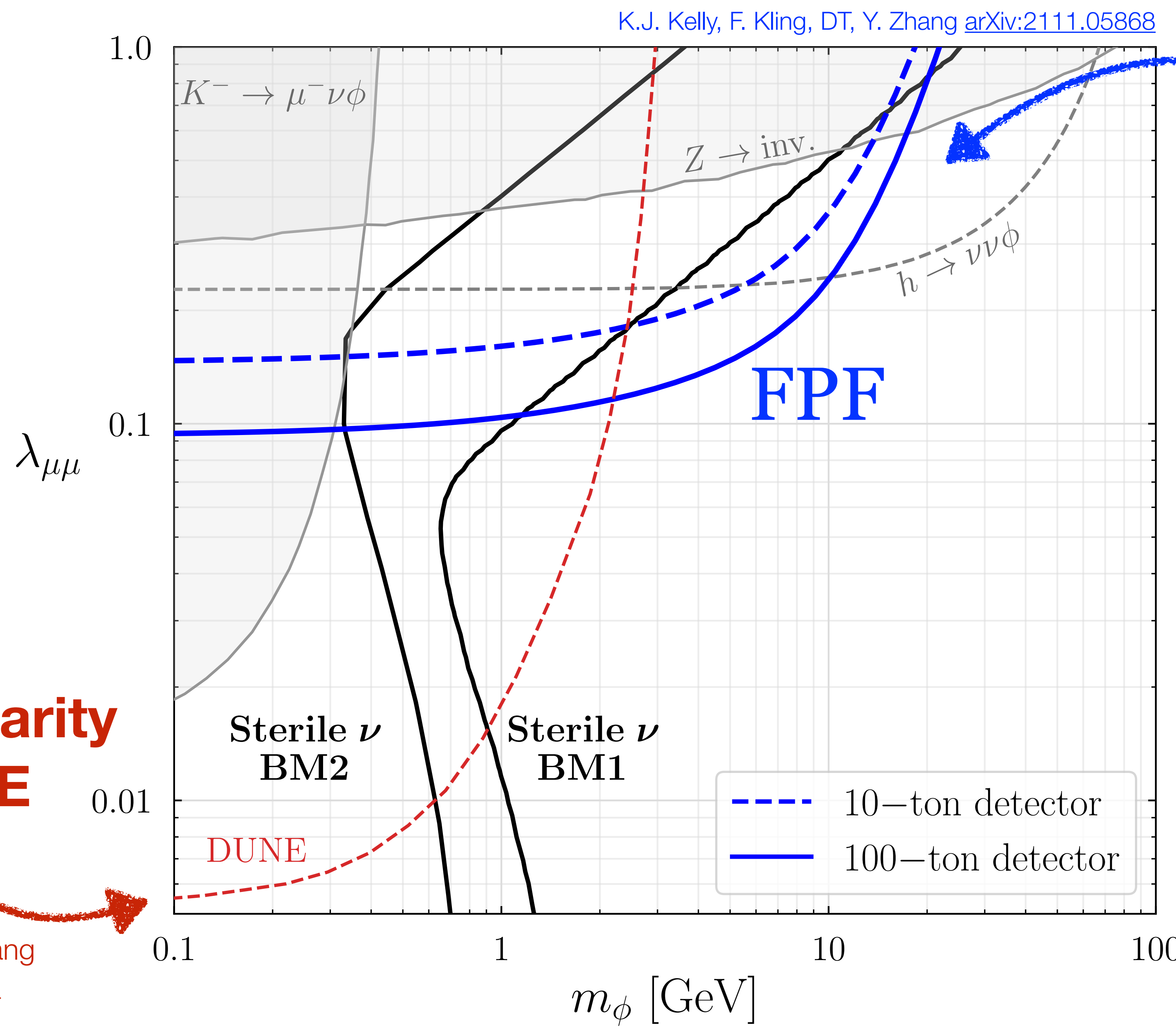


Importance of higher energy!

Complementarity with DUNE

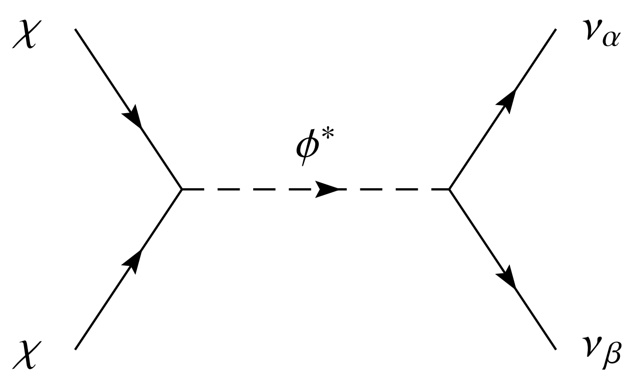
K. J. Kelly and Y. Zhang arXiv:1901.01259

FPF Reach: Thermal Dark Matter Targets

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

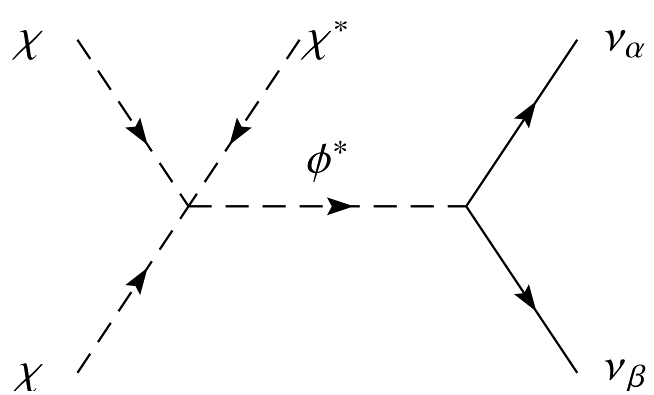
Fermion DM

$$\mathscr{L}_\chi = \frac{1}{2} y_\chi \bar{\chi}\chi\phi + h.c.$$

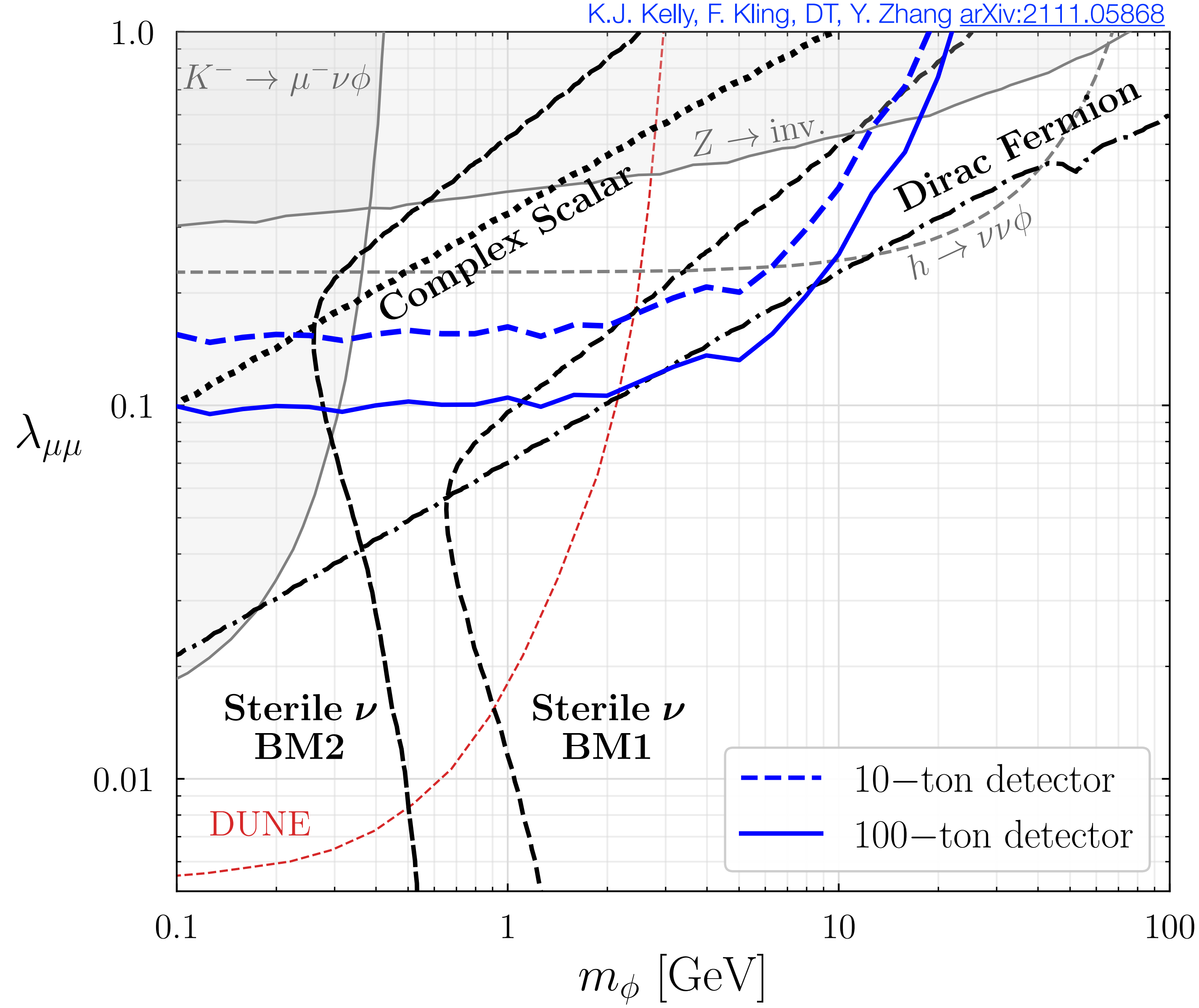


Scalar DM

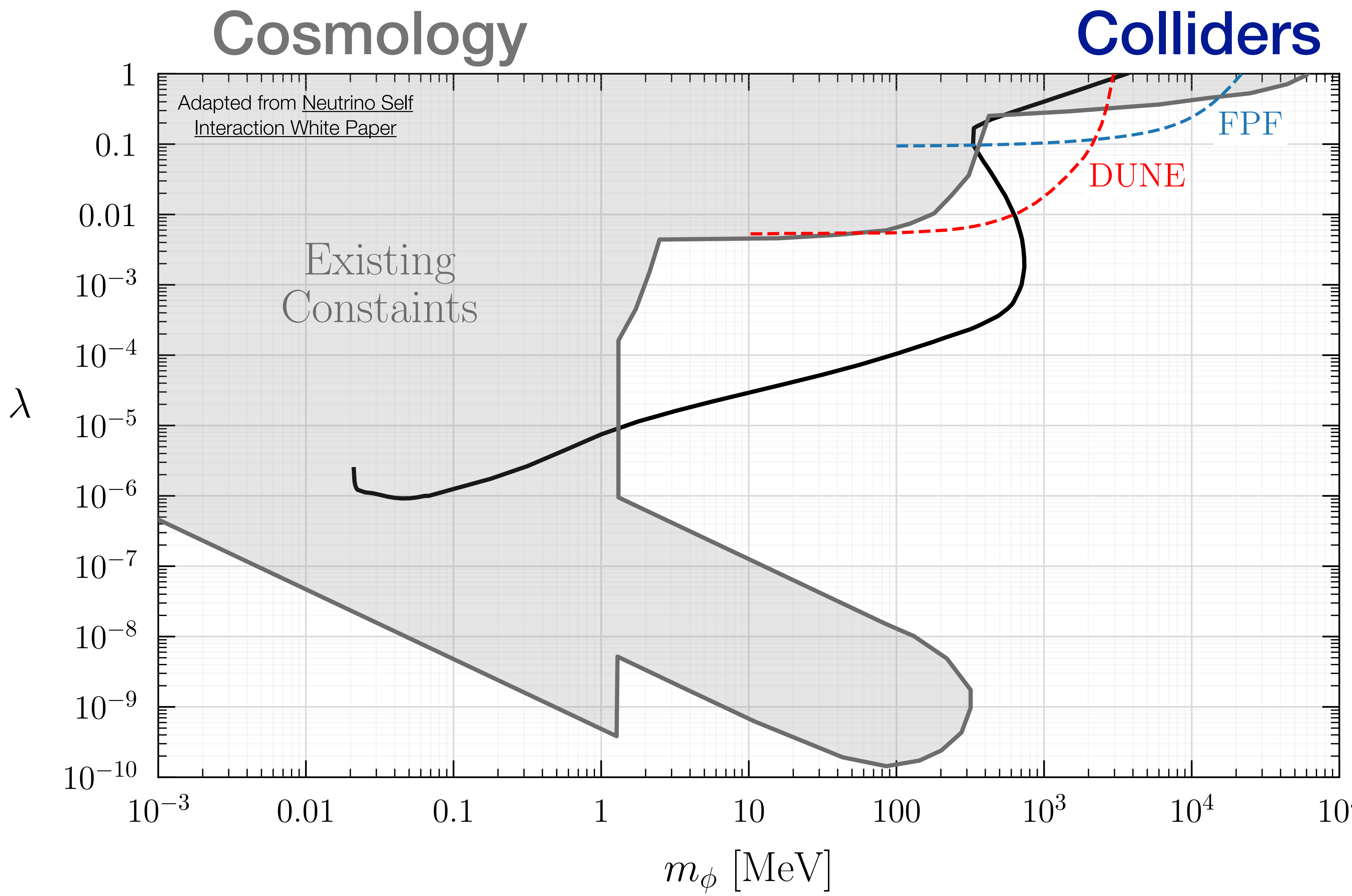
$$\mathscr{L}_\chi = \frac{1}{6} y_\chi \chi^3\phi + h.c.$$



K.J. Kelly, F. Kling, DT, Y. Zhang arXiv:2111.05868



Big Picture



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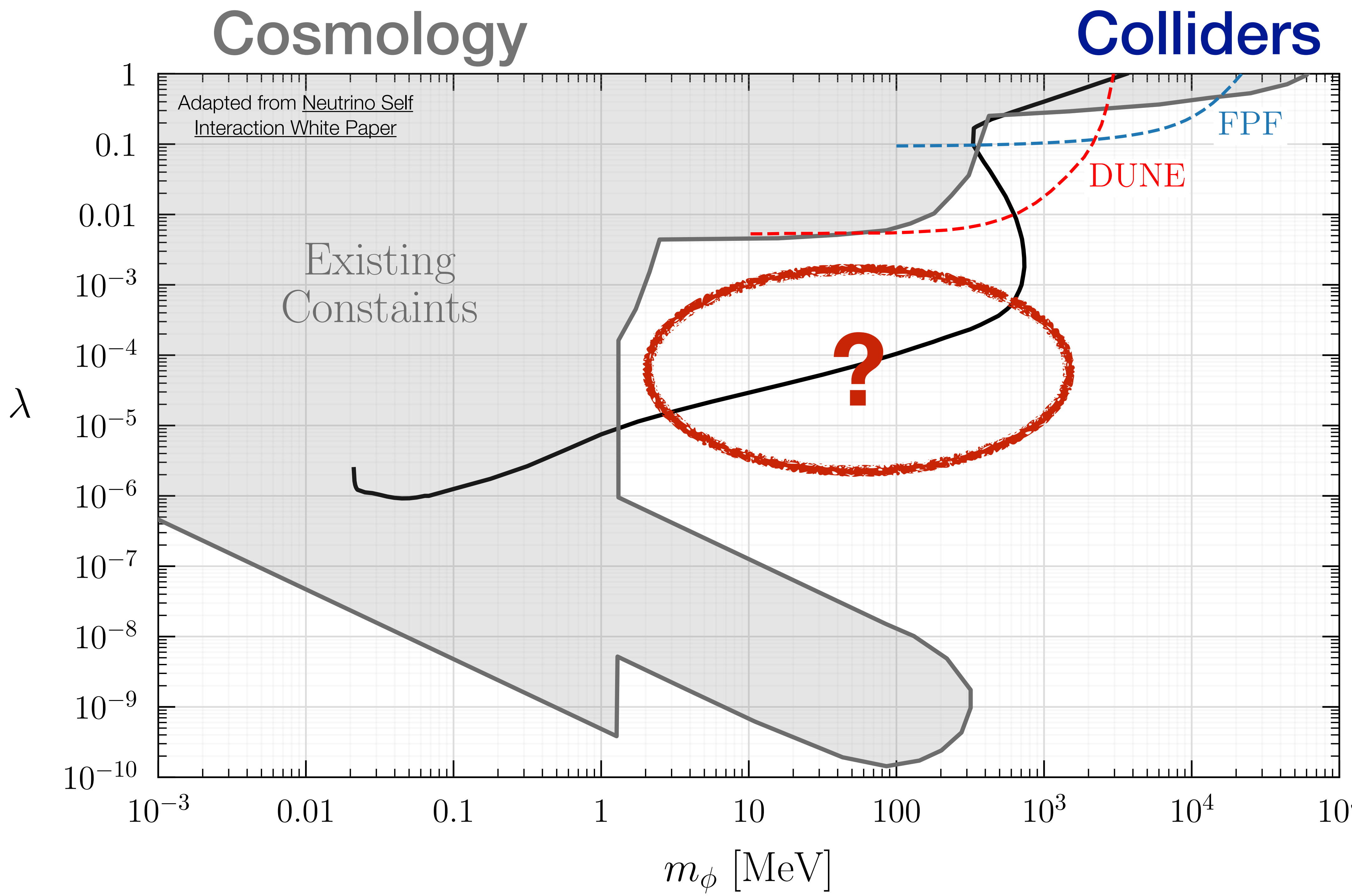
10^3
10^4
10^5
m_ϕ [MeV]

Big Picture



Cosmology
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Existing Constaints
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10^{-10}
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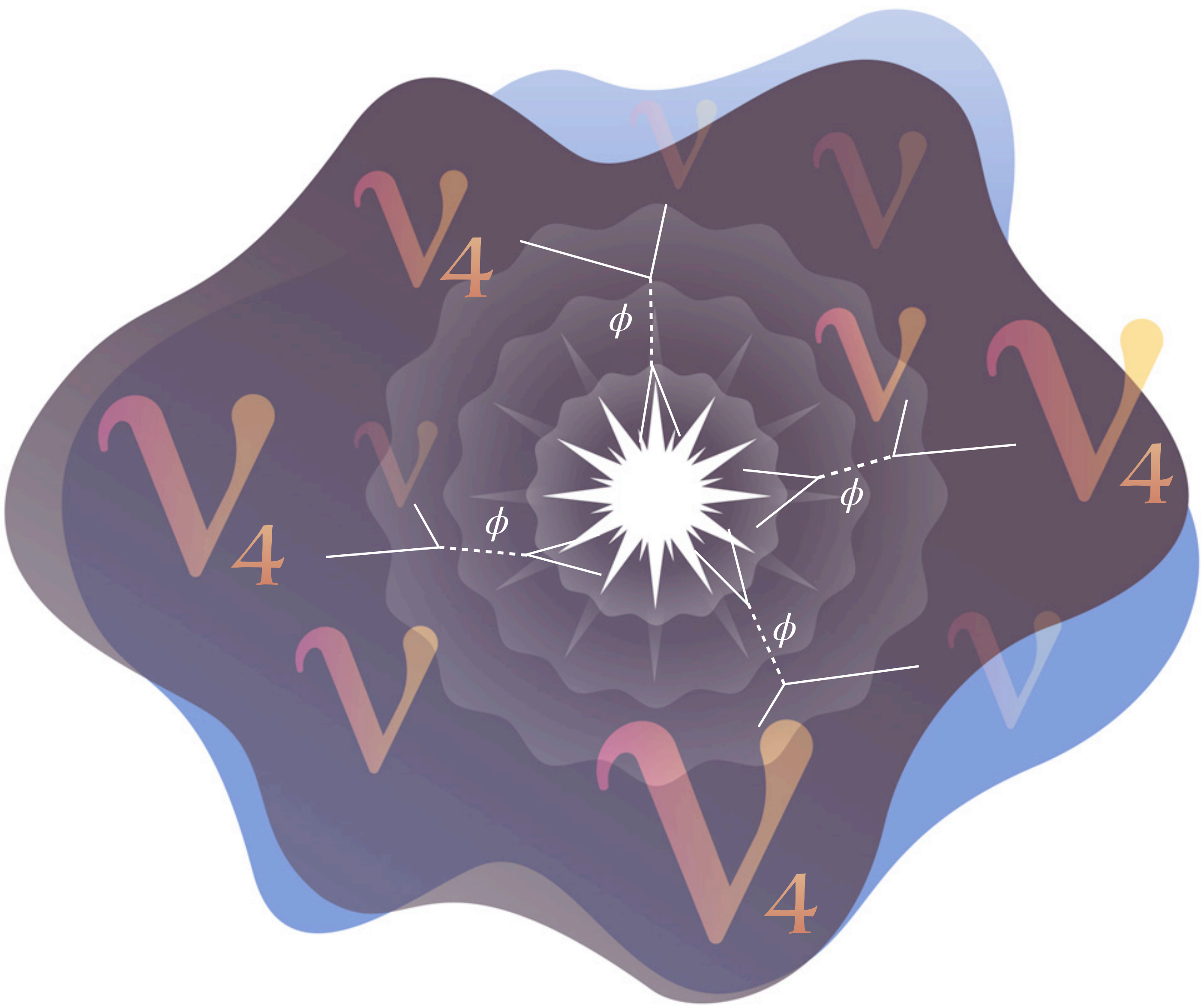
0.01
0.1
1
10
100
10^3
10^4
10^5
m_ϕ [MeV]

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!

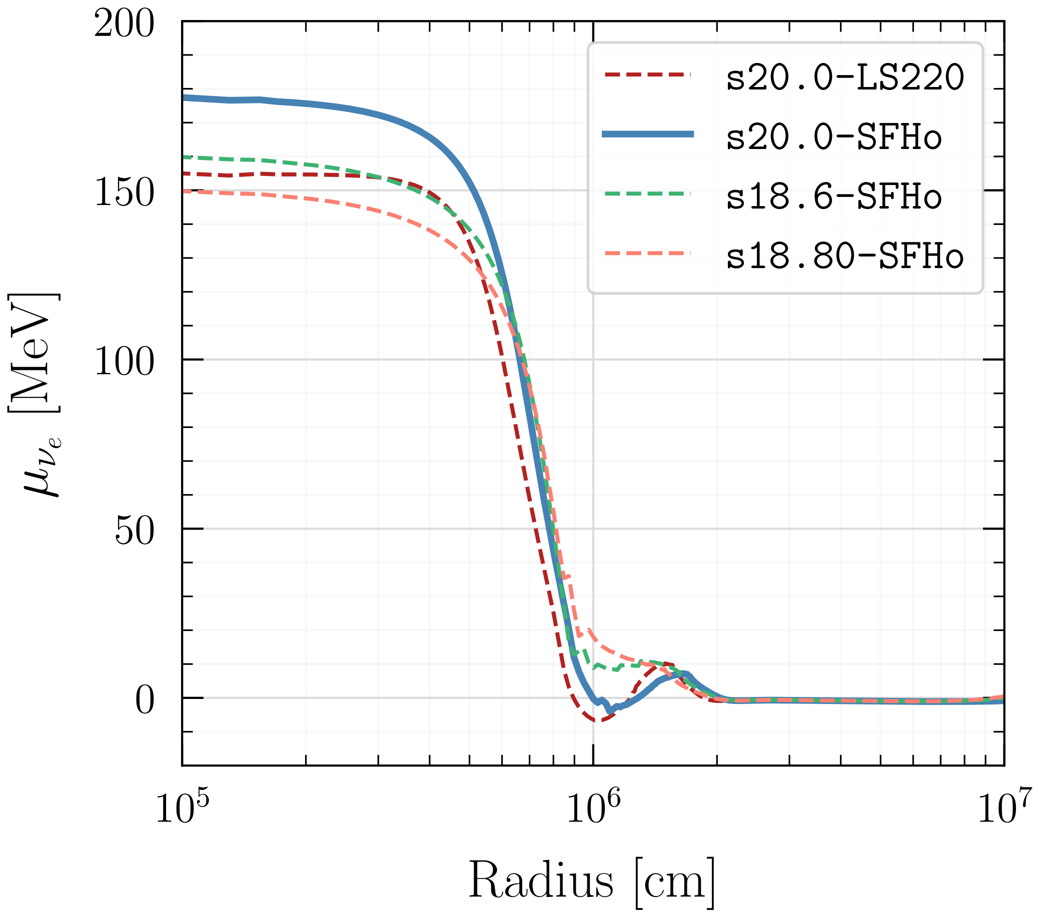


Adapted from Fermilab

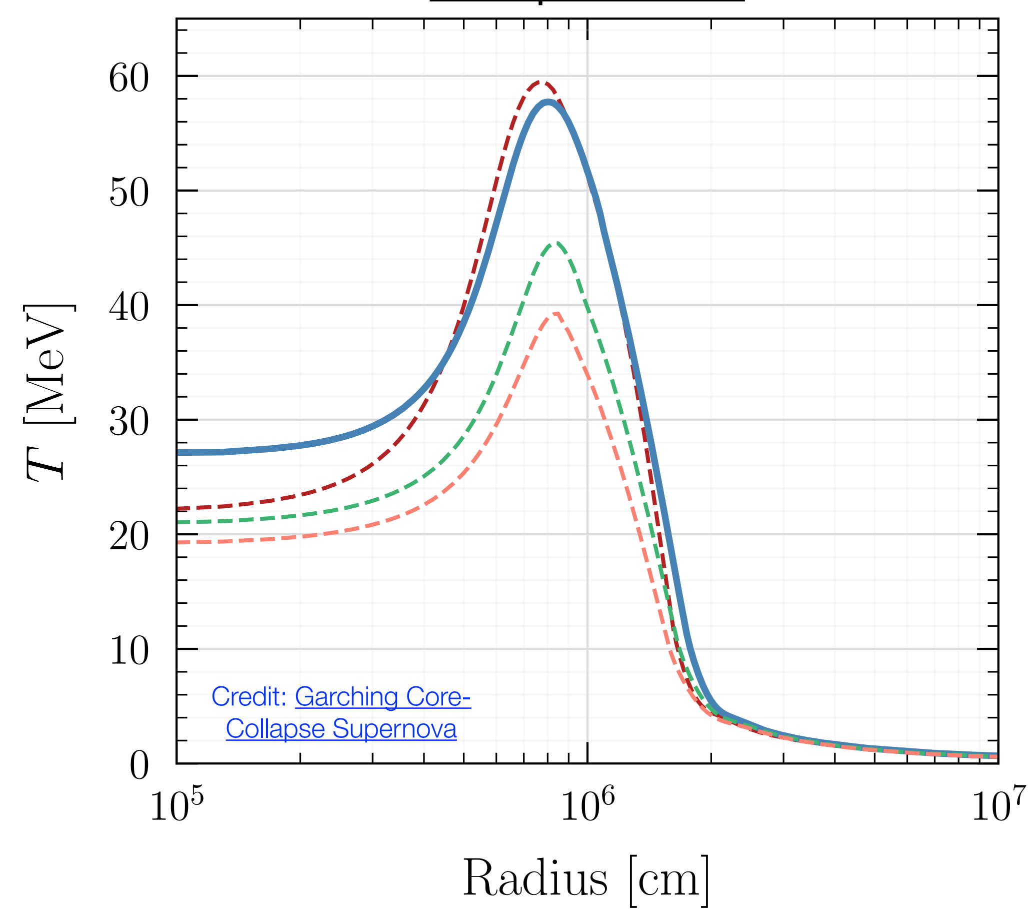
Cooling Rate Calculation: A Sketch

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

Electron Chemical Potential



Temperature



- $\mu_{\nu_e}/T > 1 \rightarrow$ 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**

Vacuum Mixing Angle

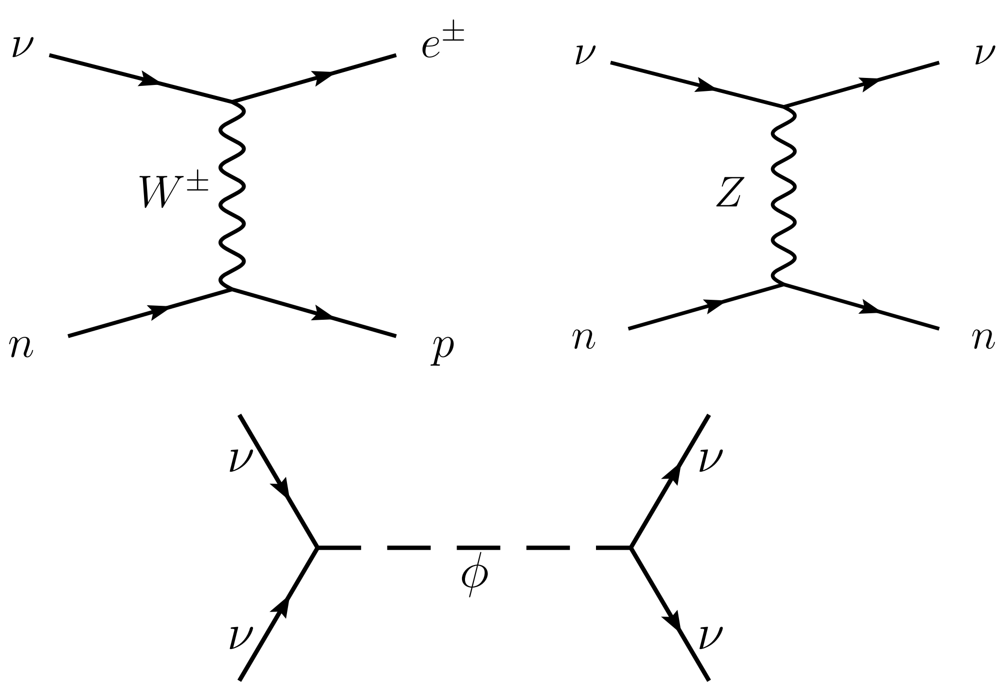
$$\sin^2(2\theta_{eff}) = \frac{\Delta^2 \sin^2(2\theta)}{\Delta^2 \sin^2(2\theta) + \Gamma^2 + (\Delta \cos(2\theta) - V)^2}$$

Interaction Rate

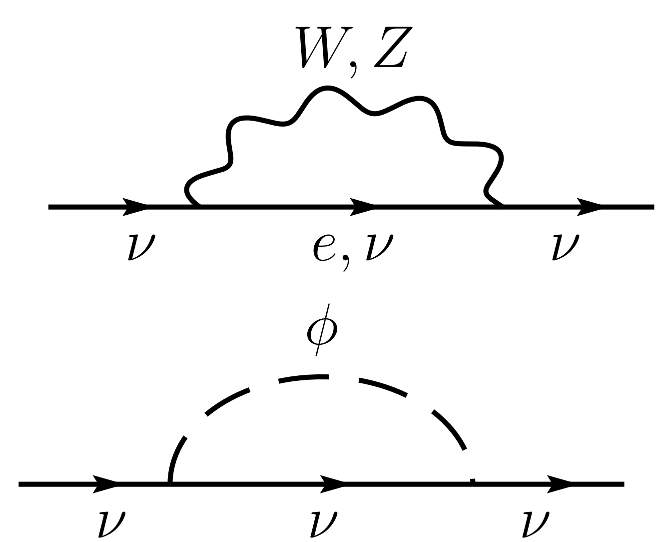
$$\Gamma = \Gamma_{weak} + \Gamma_{\phi}$$

Effective Potential

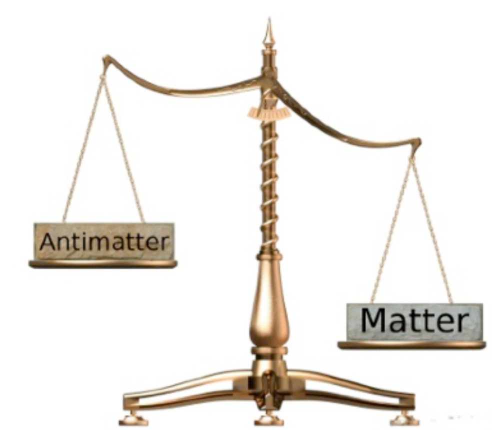
$$V = V_{weak} + V_{\phi}$$



Thermal potential



Matter asymmetries



Cooling Rate Calculation: A Sketch

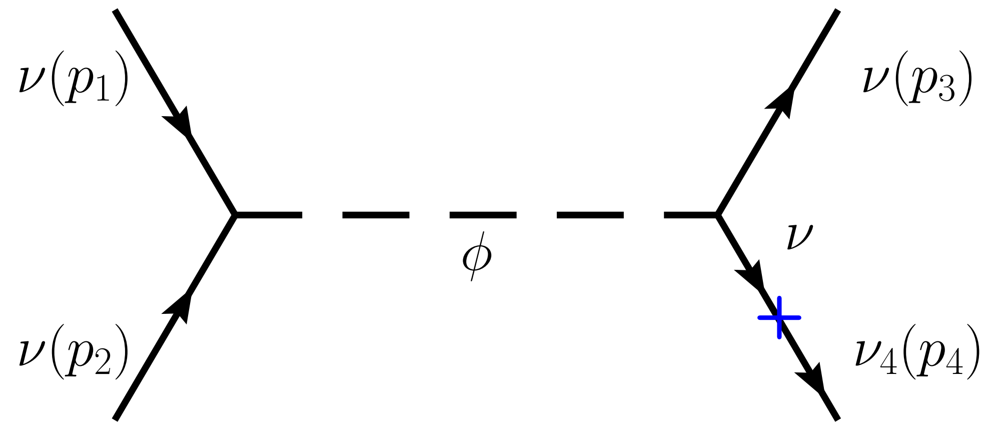
- **Step 3: Optical depth, or ν_4 energy loss due to scattering**

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

Interaction Rate

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

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



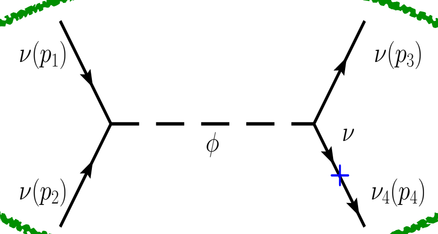
$$|\mathcal{M}|^2 = 32\pi^2\lambda^2\, m_\phi^2\, \delta(s - m_\phi^2)\, \sin^2\theta_{\rm eff}(r, E_4)$$

- **Step 4.5: Profit**

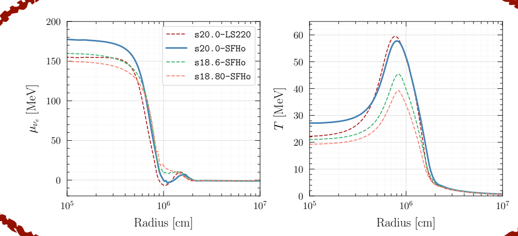
Cooling Rate Calculation: A Sketch

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

SνDM production



SN Profile



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

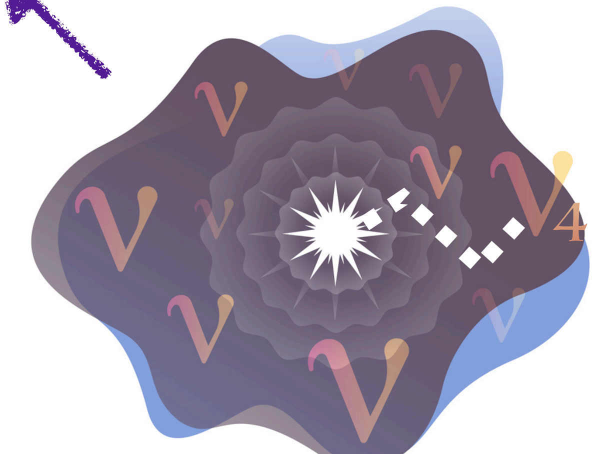
$$\times \int_{\frac{1}{2}\left(E_1+E_2-\sqrt{(E_1+E_2)^2-m_\phi^2}\right)}^{\frac{1}{2}\left(E_1+E_2+\sqrt{(E_1+E_2)^2-m_\phi^2}\right)} dE_4 \sin^2\theta_{\rm eff}(r, E_4)\, E_4\, e^{-\tau(E_4, r)}$$

Re-absorption.
Sub-dominant effect

Matter effects

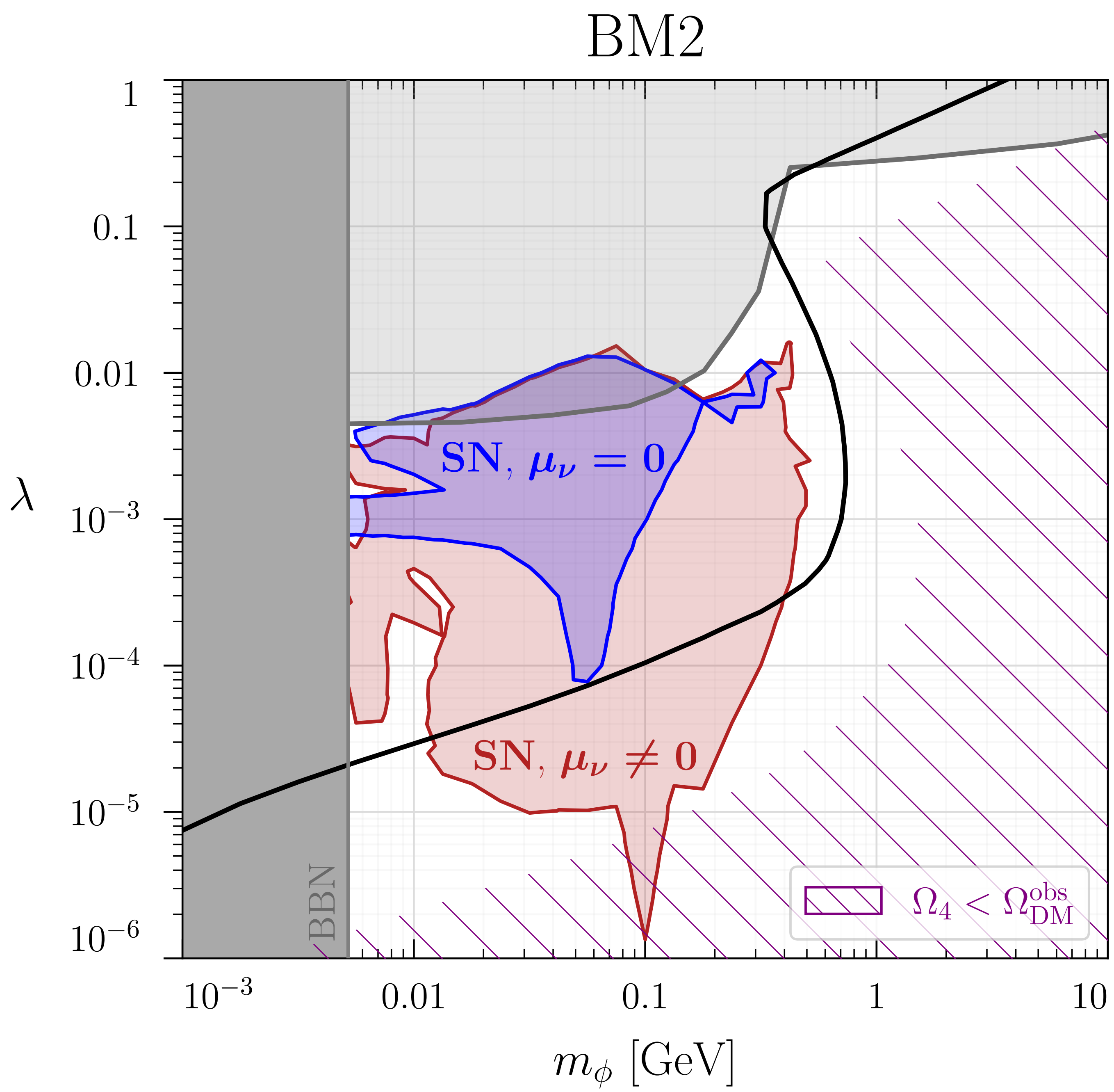
ν —×— ν_4

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

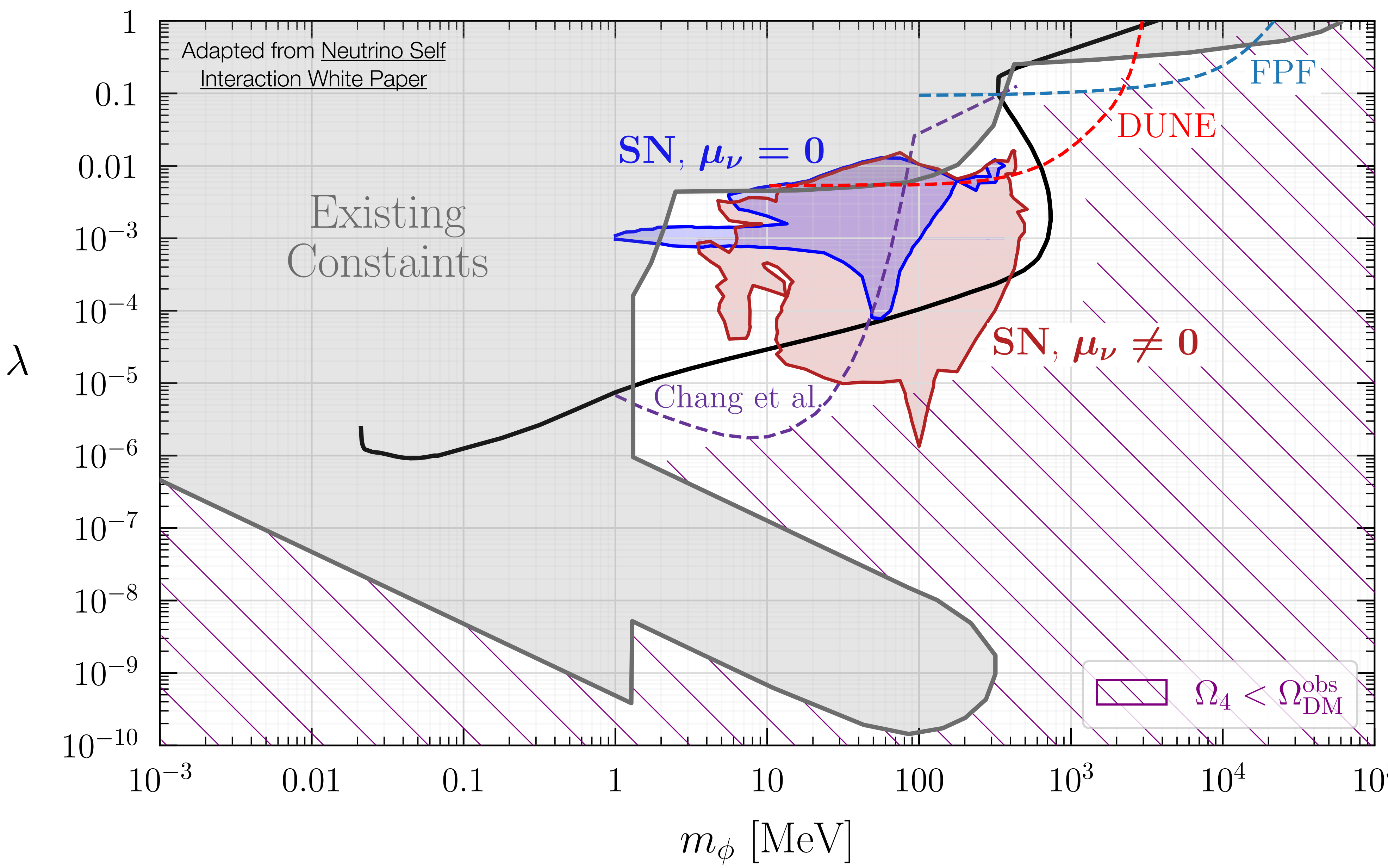


Supernova Cooling Bounds

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

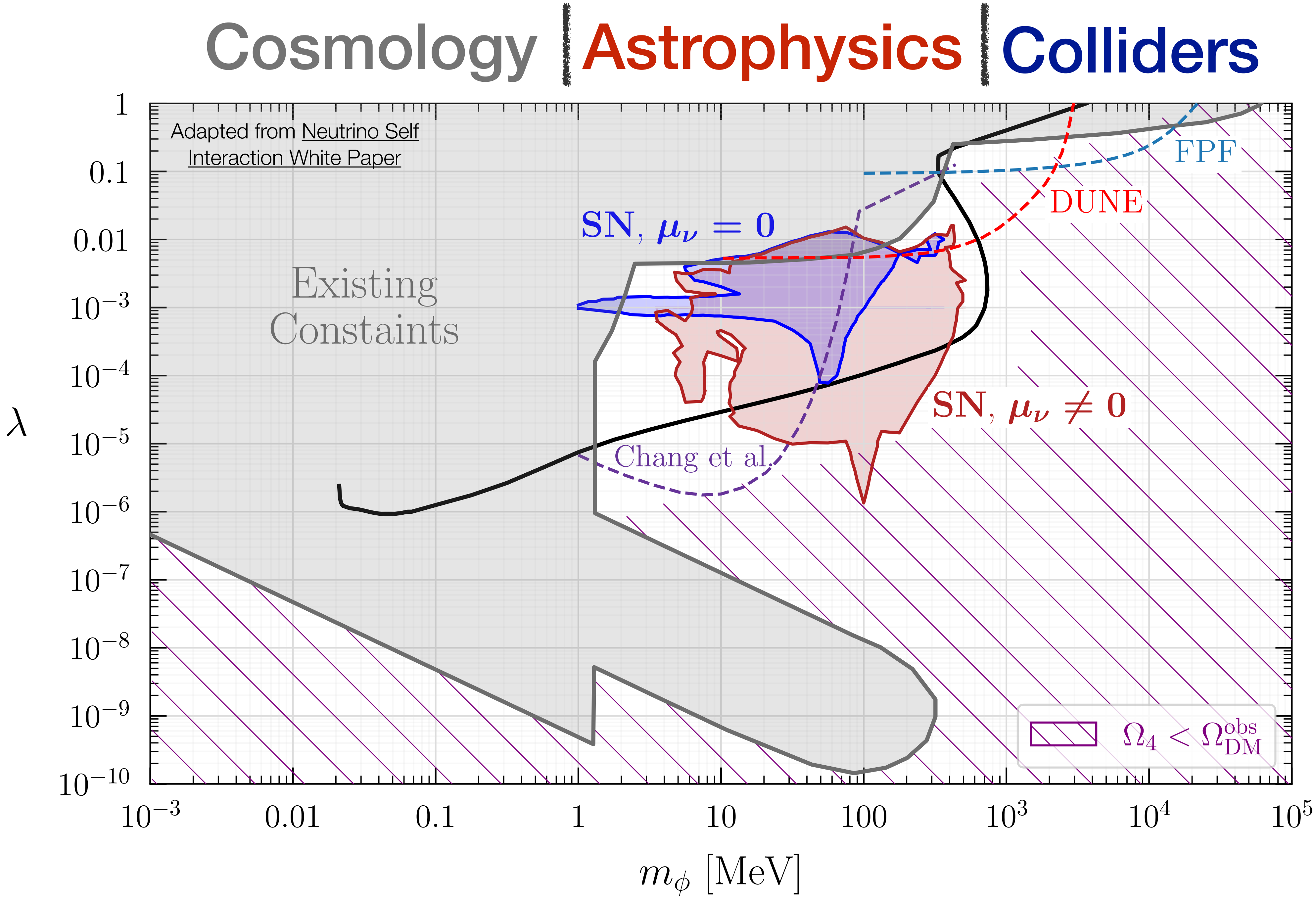


Big Picture



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



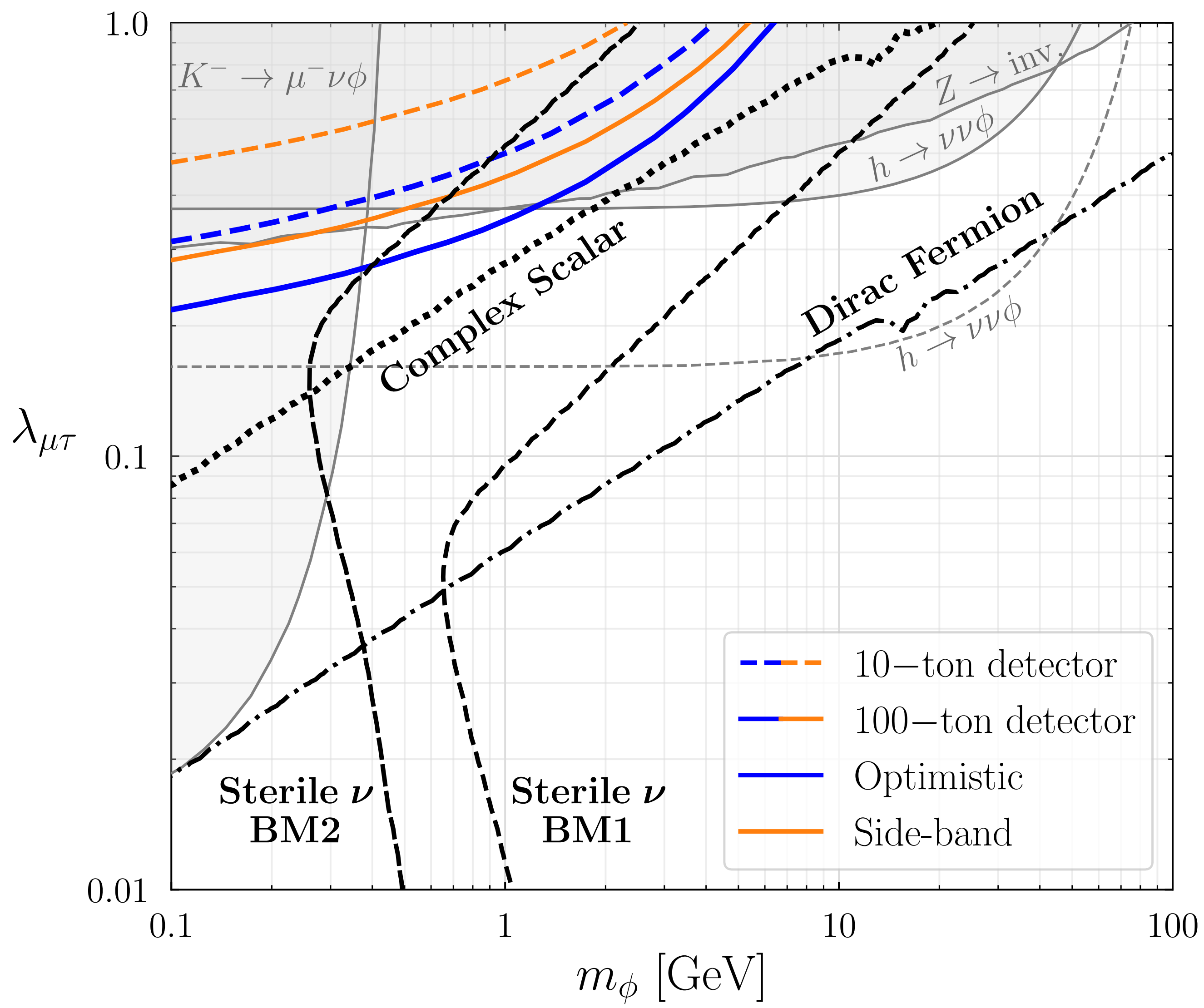
Great complementarity between different probes of neutrinophilic DM!

Thanks!
Questions?

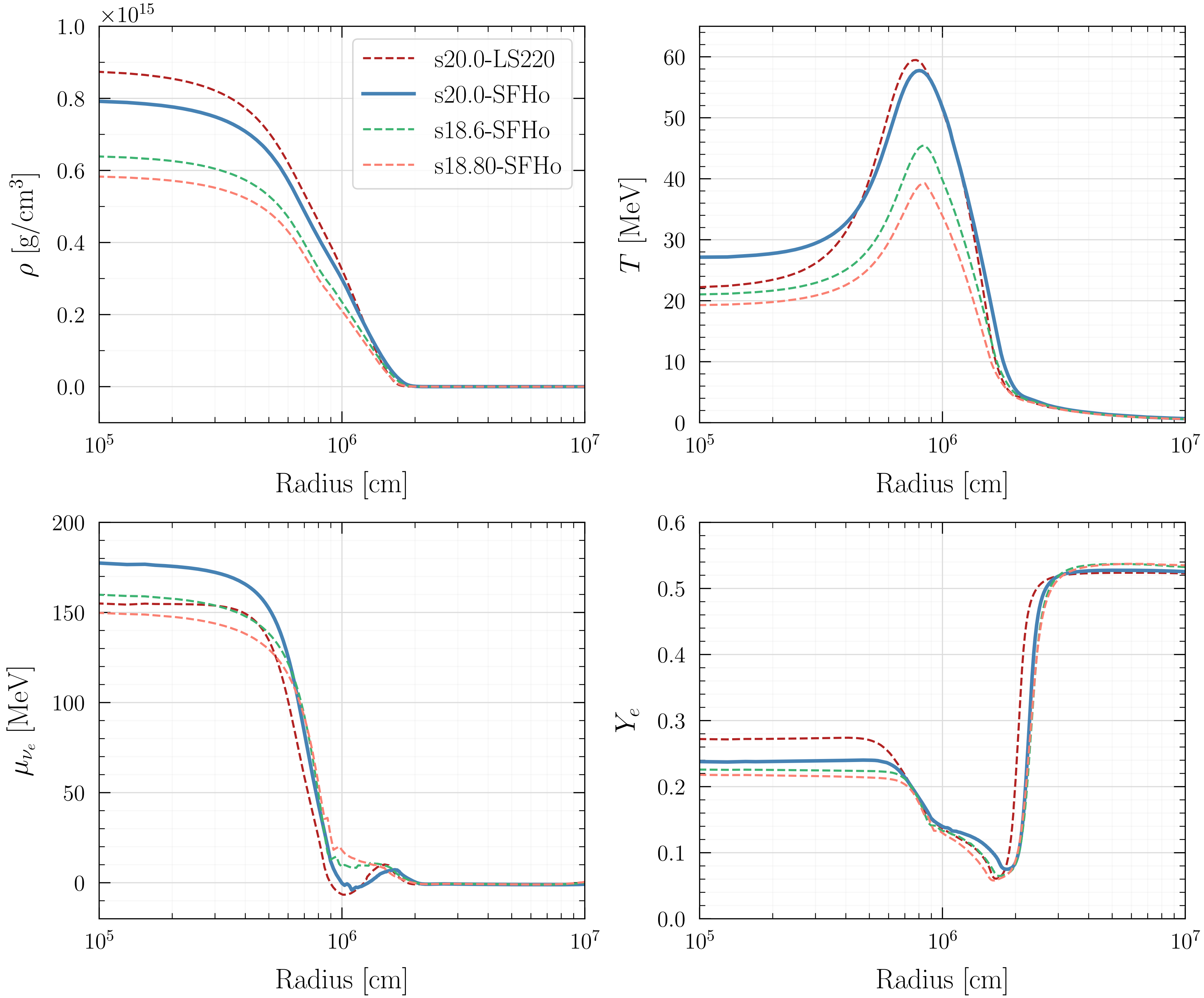
Back up

FPF Reach: Final State Tau Leptons

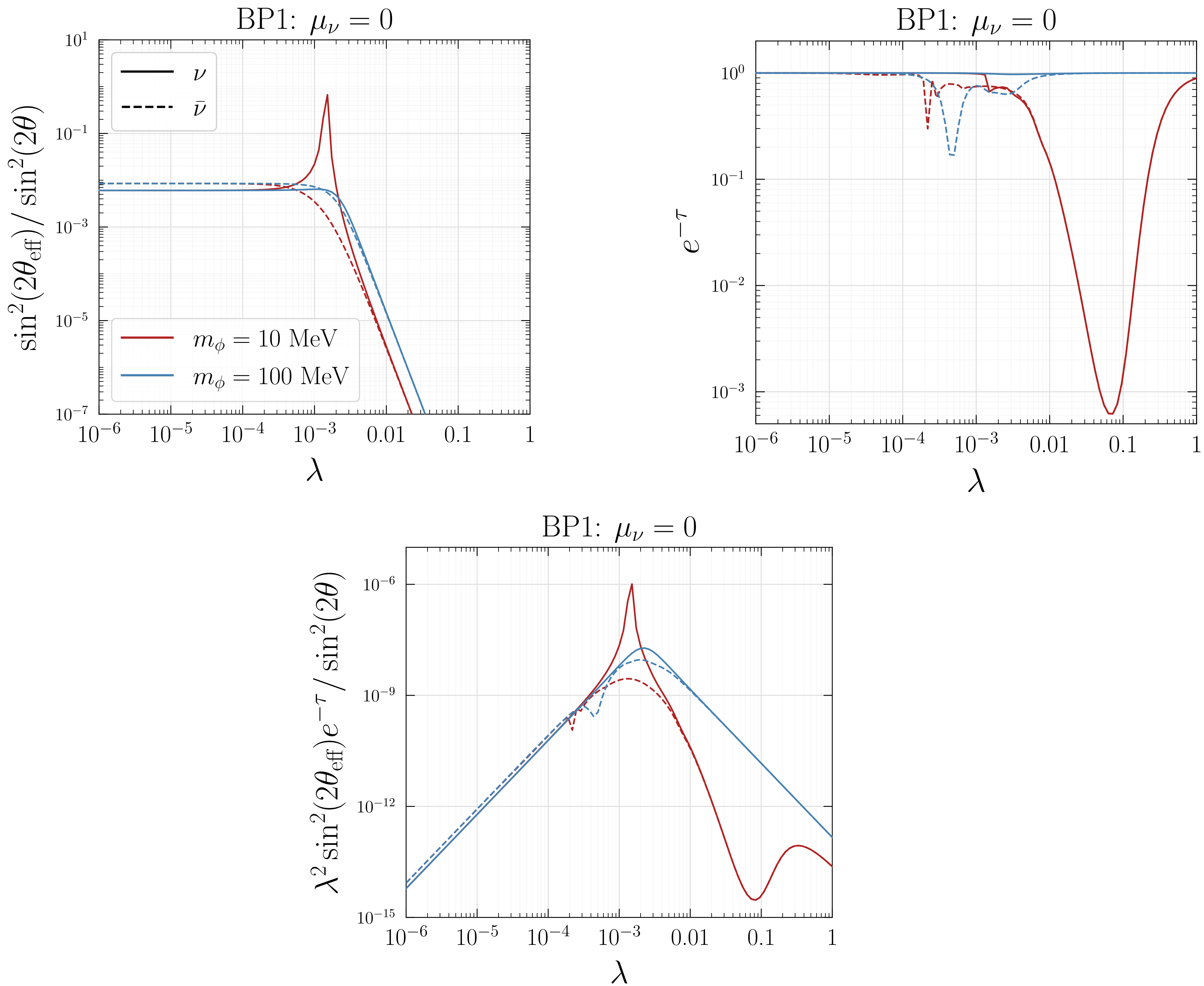
- For $\lambda_{\mu\tau} \neq 0$, the signal is a tau + $\not{p}_T$ coming from a muon-neutrino beam.
- Only $\mathcal{O}(100)$ tau neutrinos are expected to interact with the detector. The signal will result in an excess of tau events compared to the SM.
- Simple analysis: count the number of signal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



Supernova Profile



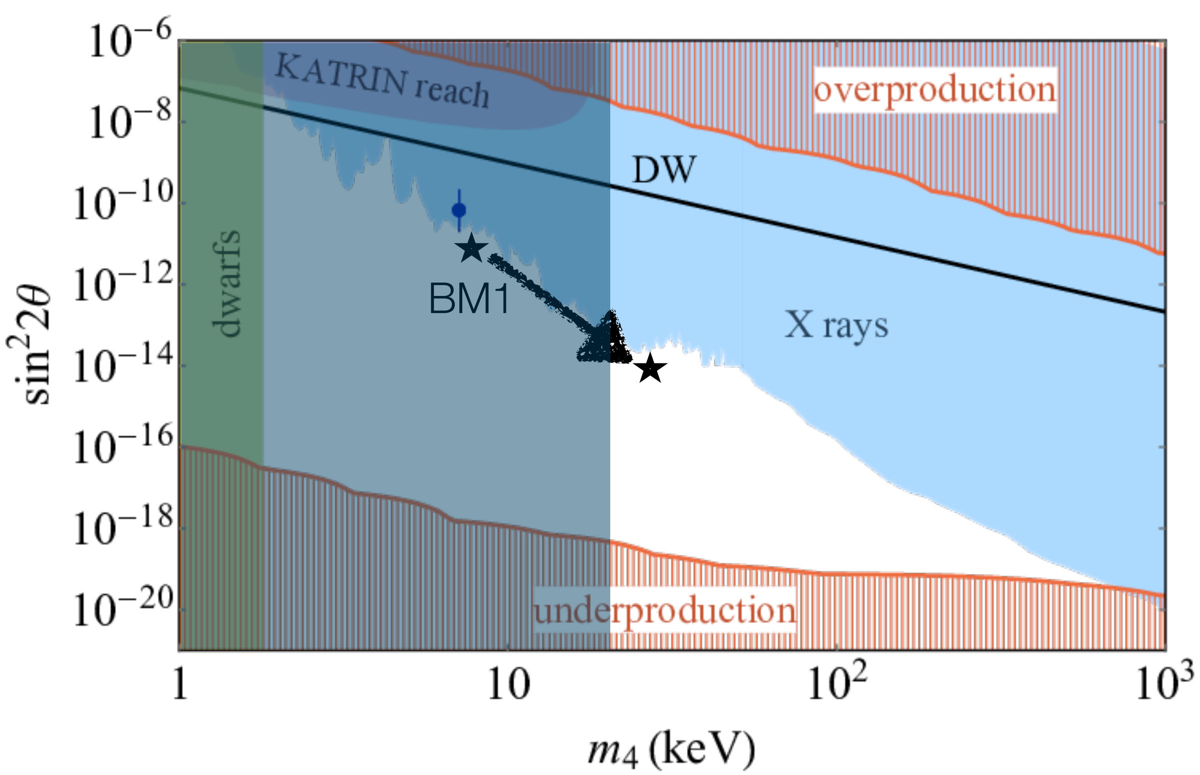
λ Dependence of Relevant Quantities

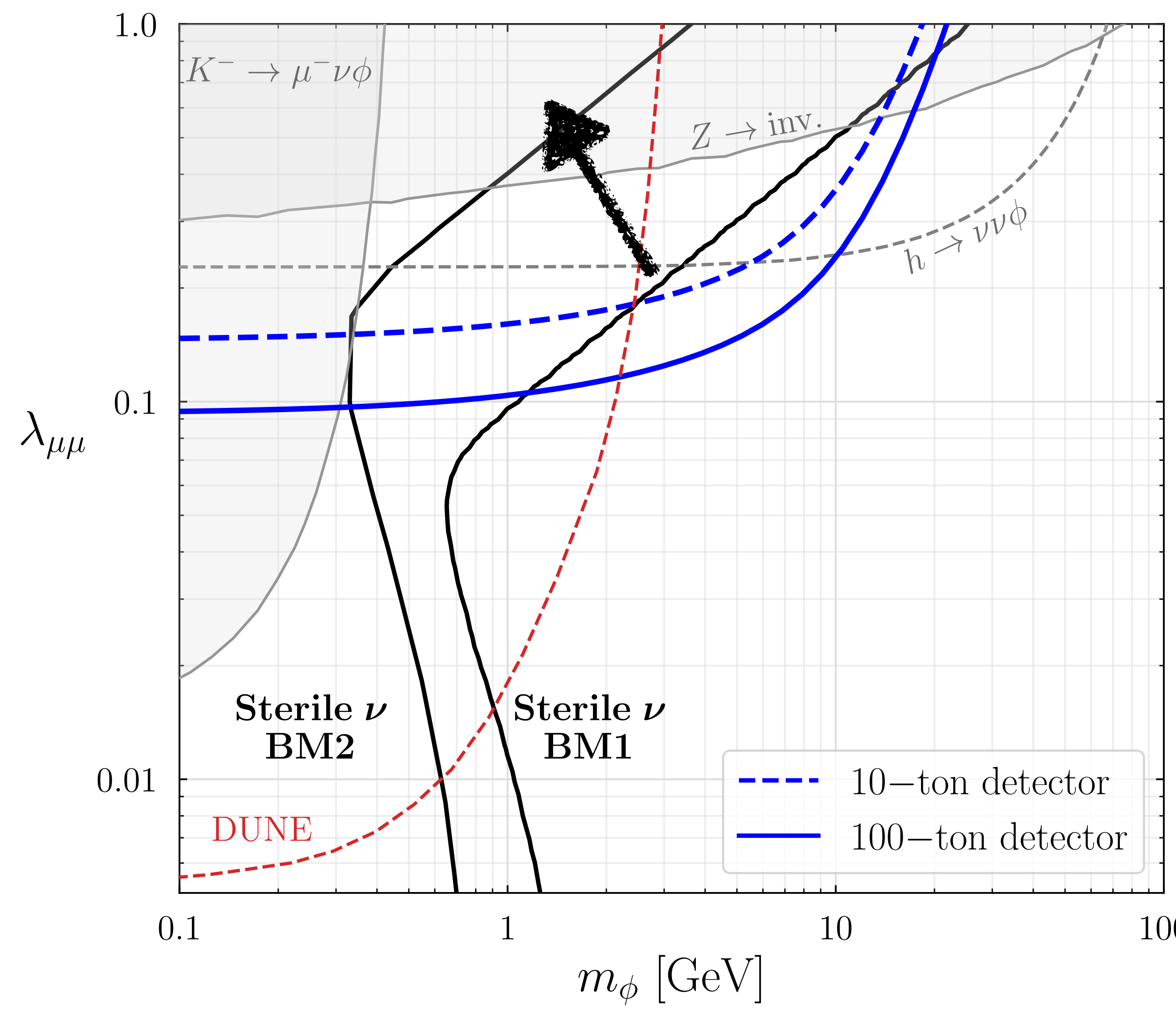


Constraints from MW Dwarf Galaxies

- Spoiler alert: There is a lower limit on sterile neutrino dark matter mass in the presence of a neutrinophilic scalar mediator!

$$\Omega \sim \Gamma \times \sin^2(2\theta)$$





Smaller mixing → larger λ. Run into existing constraints. See Yue's talk for more details