# Probing Neutrinophilic Dark Matter: From Colliders to Supernovae

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TRIUMF & Simon Fraser University

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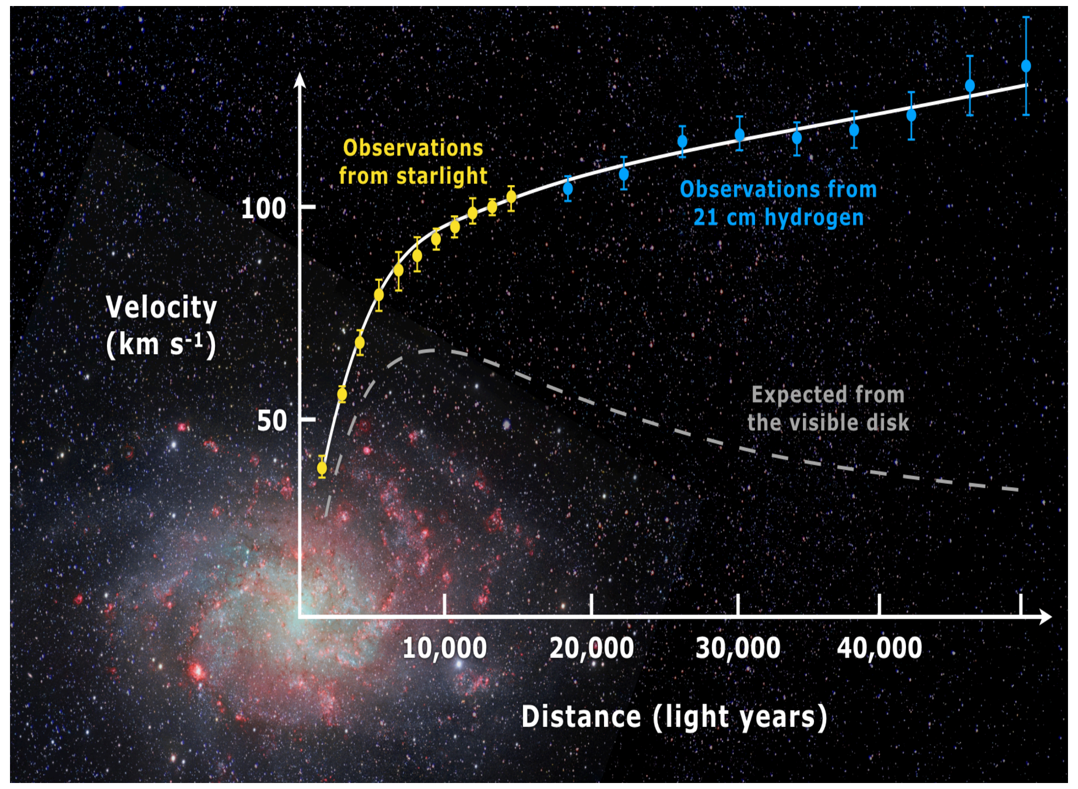
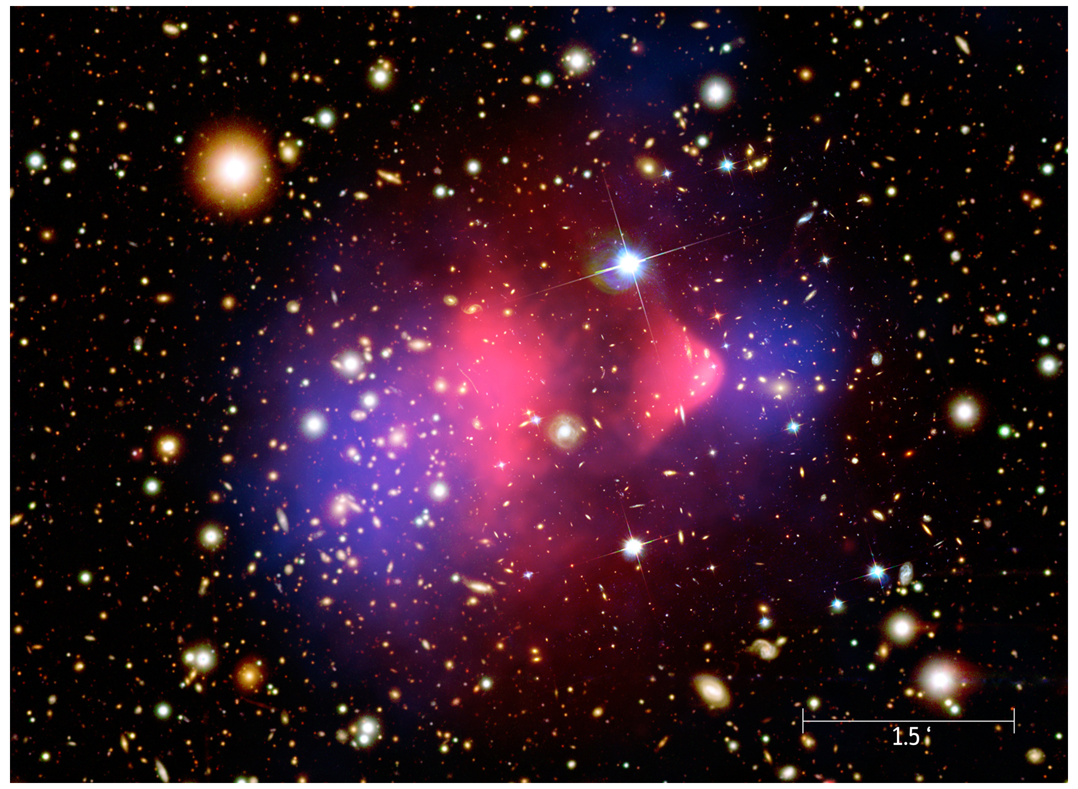
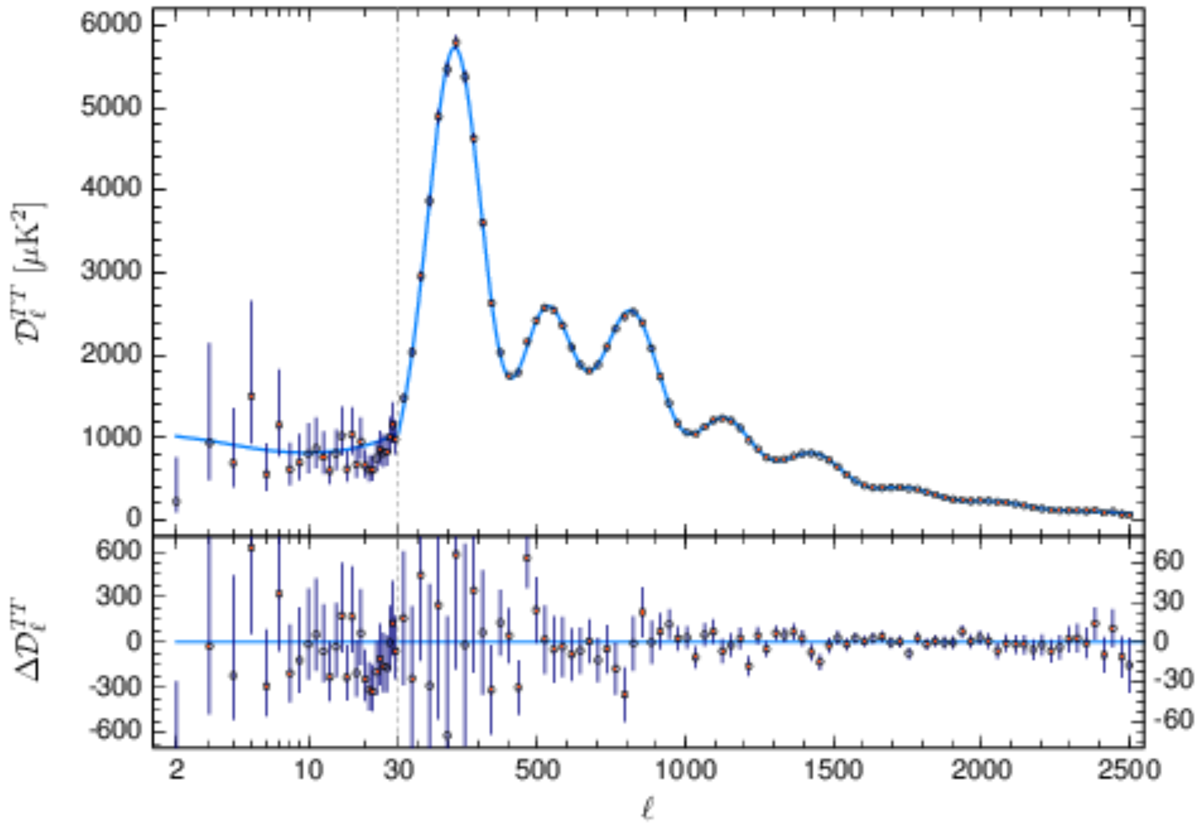
# Evidence for Dark Matter



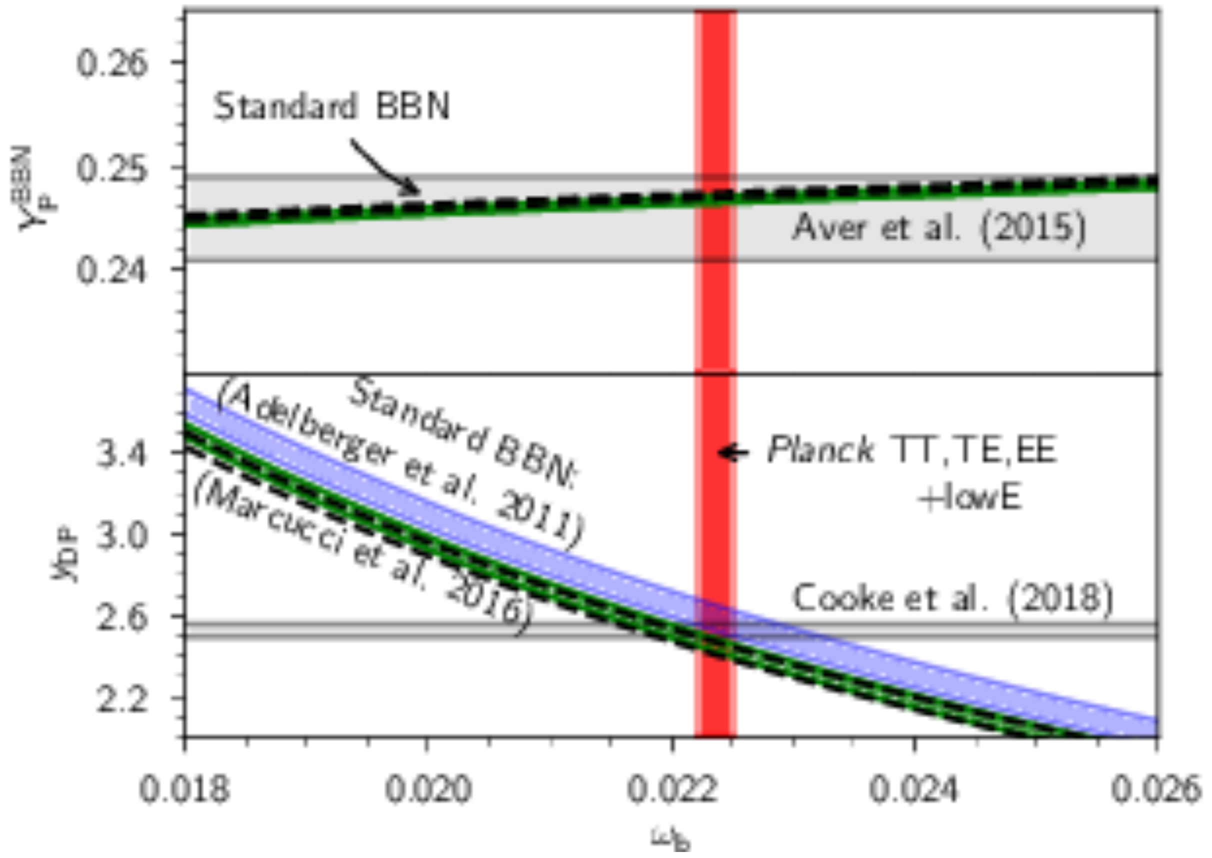
**Galaxy rotation curves**



**Gravitational Lensing**



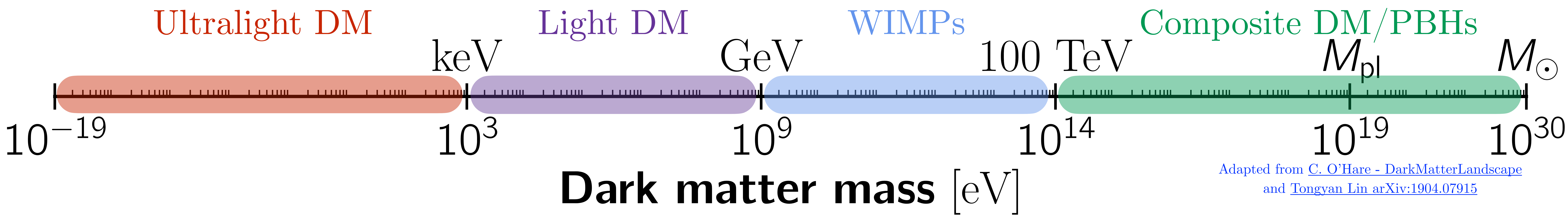
**CMB**



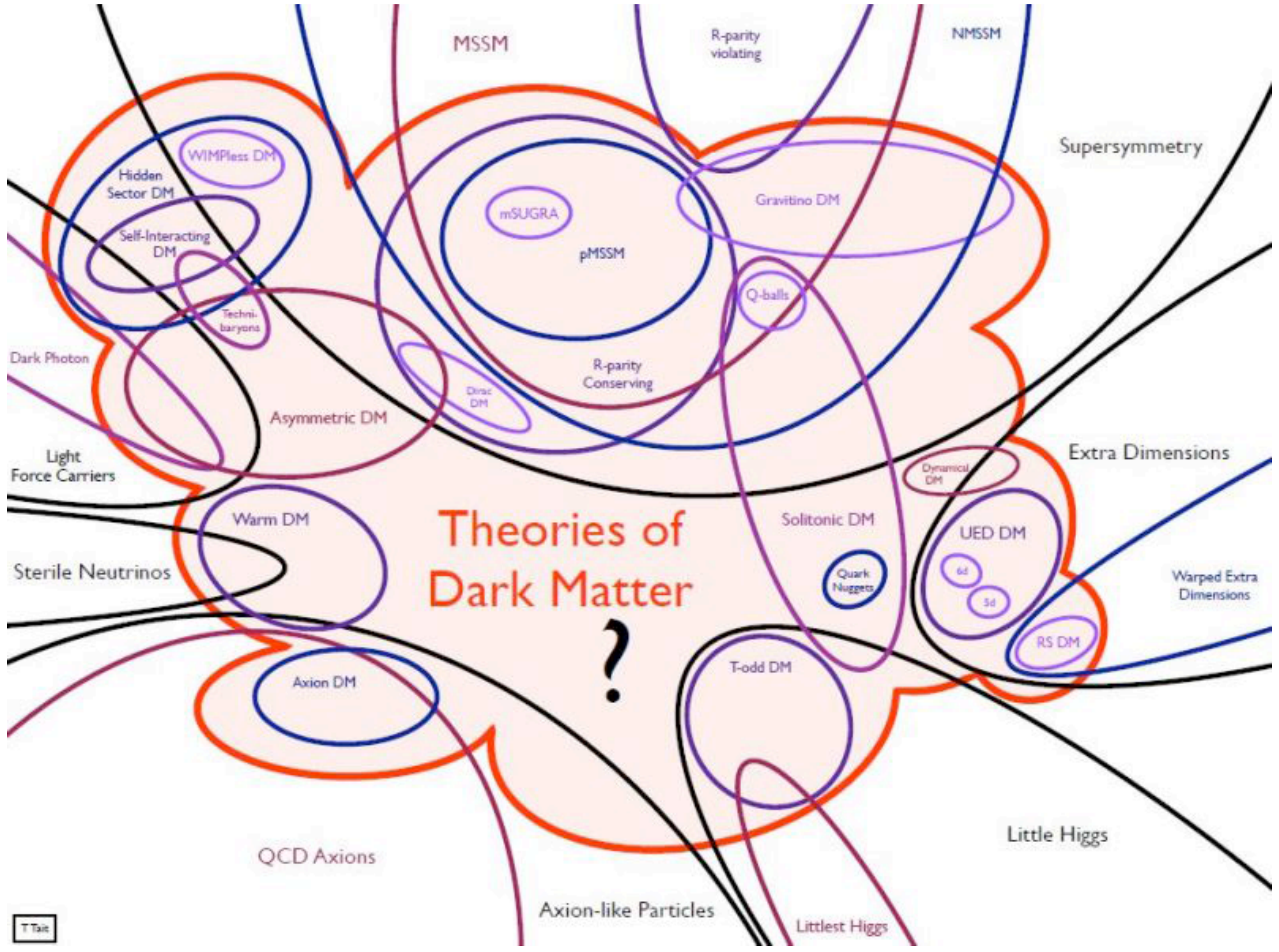
**BBN**

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

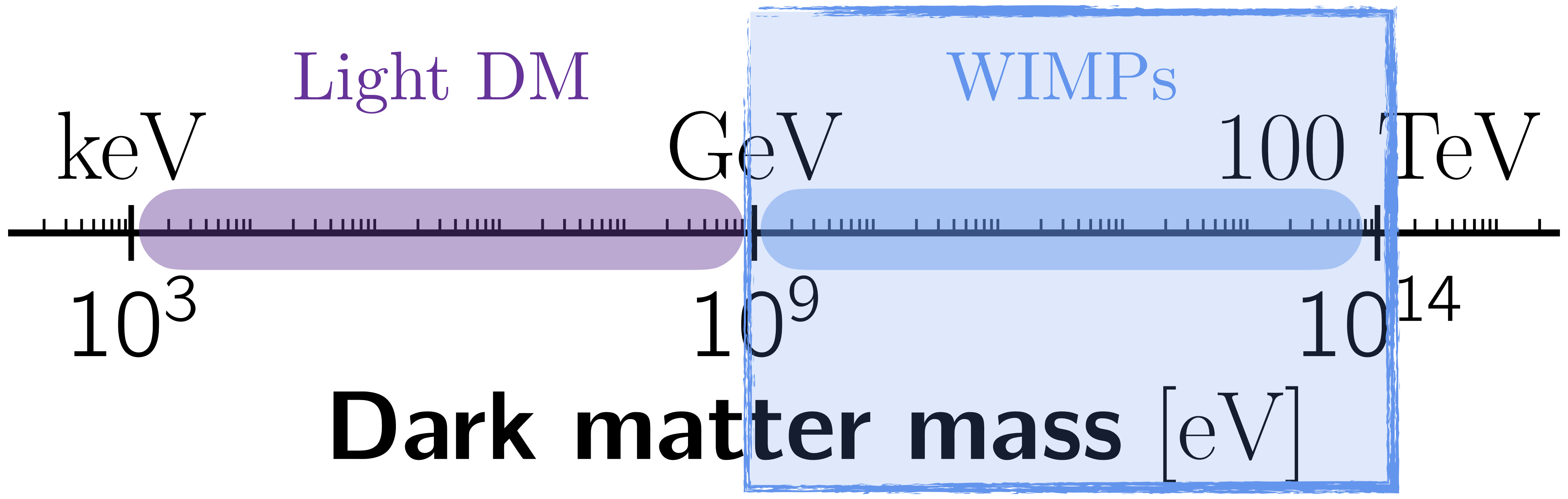
# What even is DM?



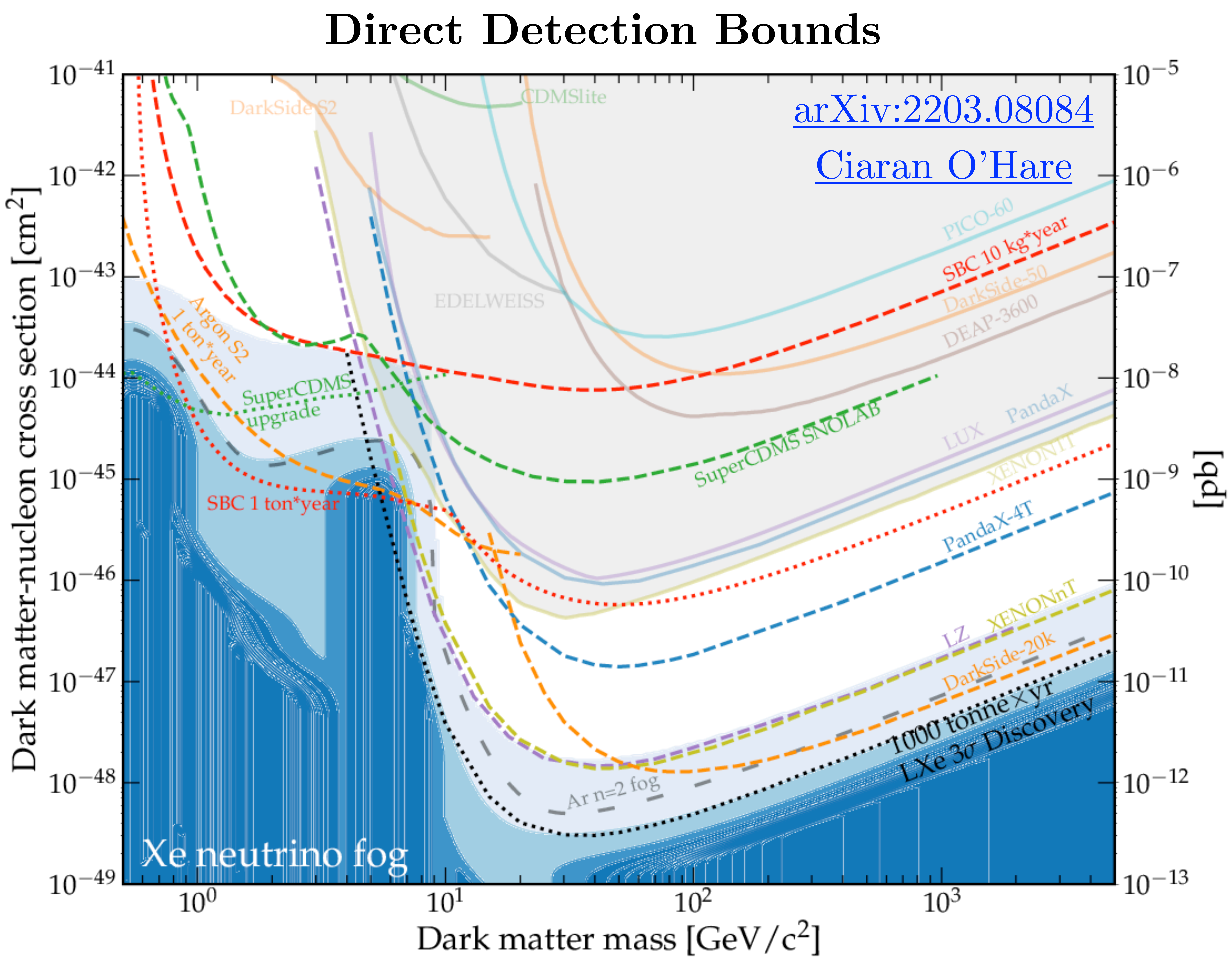
Adapted from C. O'Hare - DarkMatterLandscape
and Tongyan Lin arXiv:1904.07915



# Weakly Interacting Massive Particles



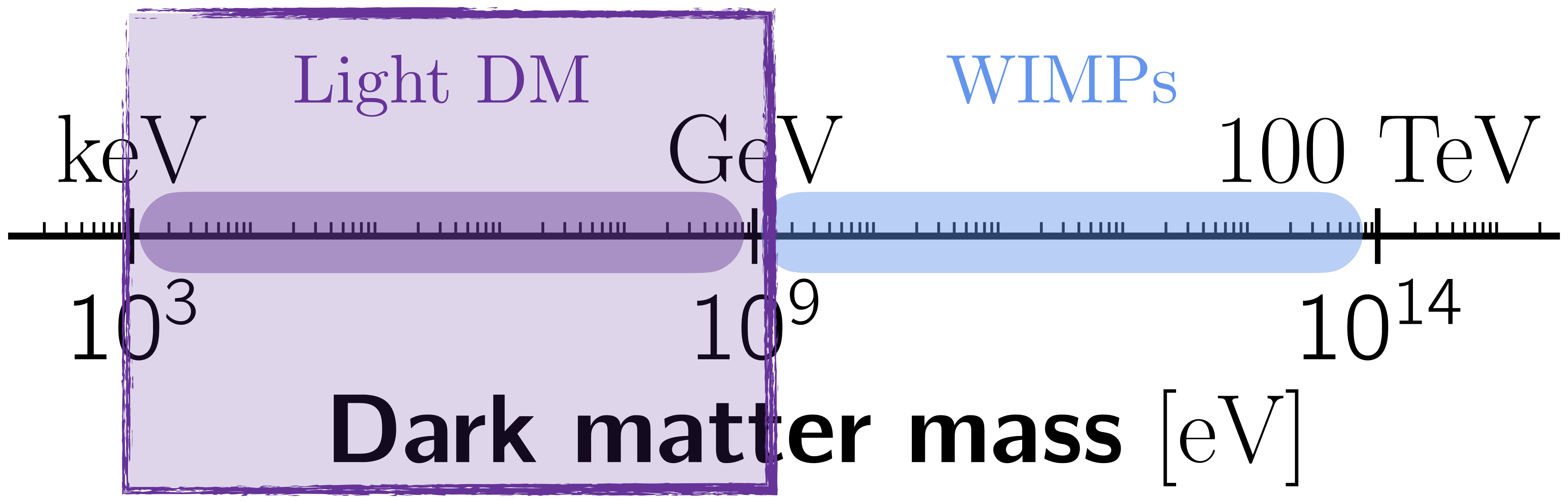
- Traditional idea - *DM is a thermal relic*
- Direct detection bounds are becoming very constraining. Push to smaller couplings. *How to get beyond the neutrino floor?*
- *Alternative: go to lower masses where there are weaker bounds*

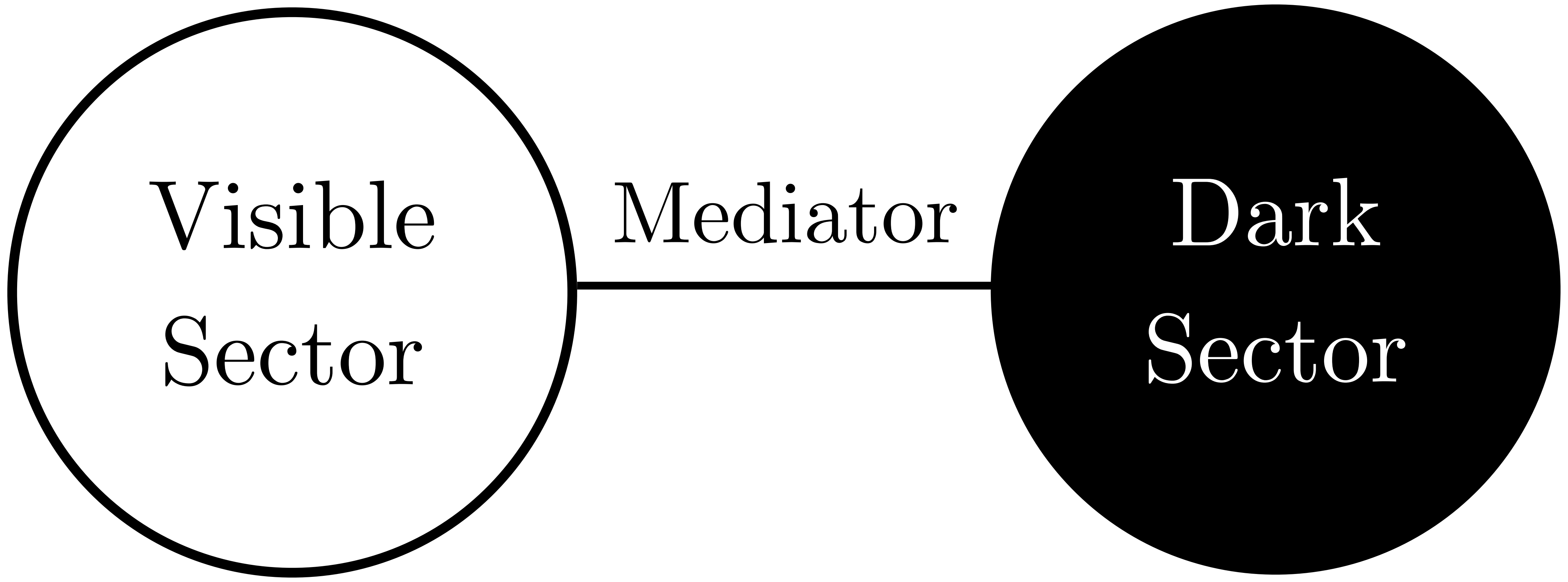

**Direct Detection Bounds**

arXiv:2203.08084

Ciaran O'Hare

# Light Dark Matter and Dark Sectors



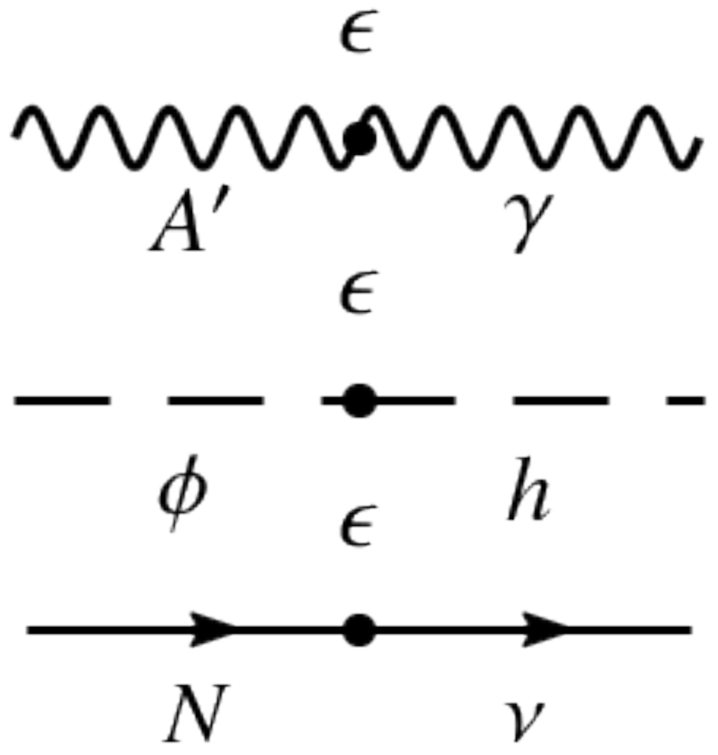


- Lee-Weinberg bound → light thermal DM requires **new light mediators**
- Light mediators must be **SM singlets** → **portal models**
- **Dark sectors** = DM + mediator + other SM singlet particles

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

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

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



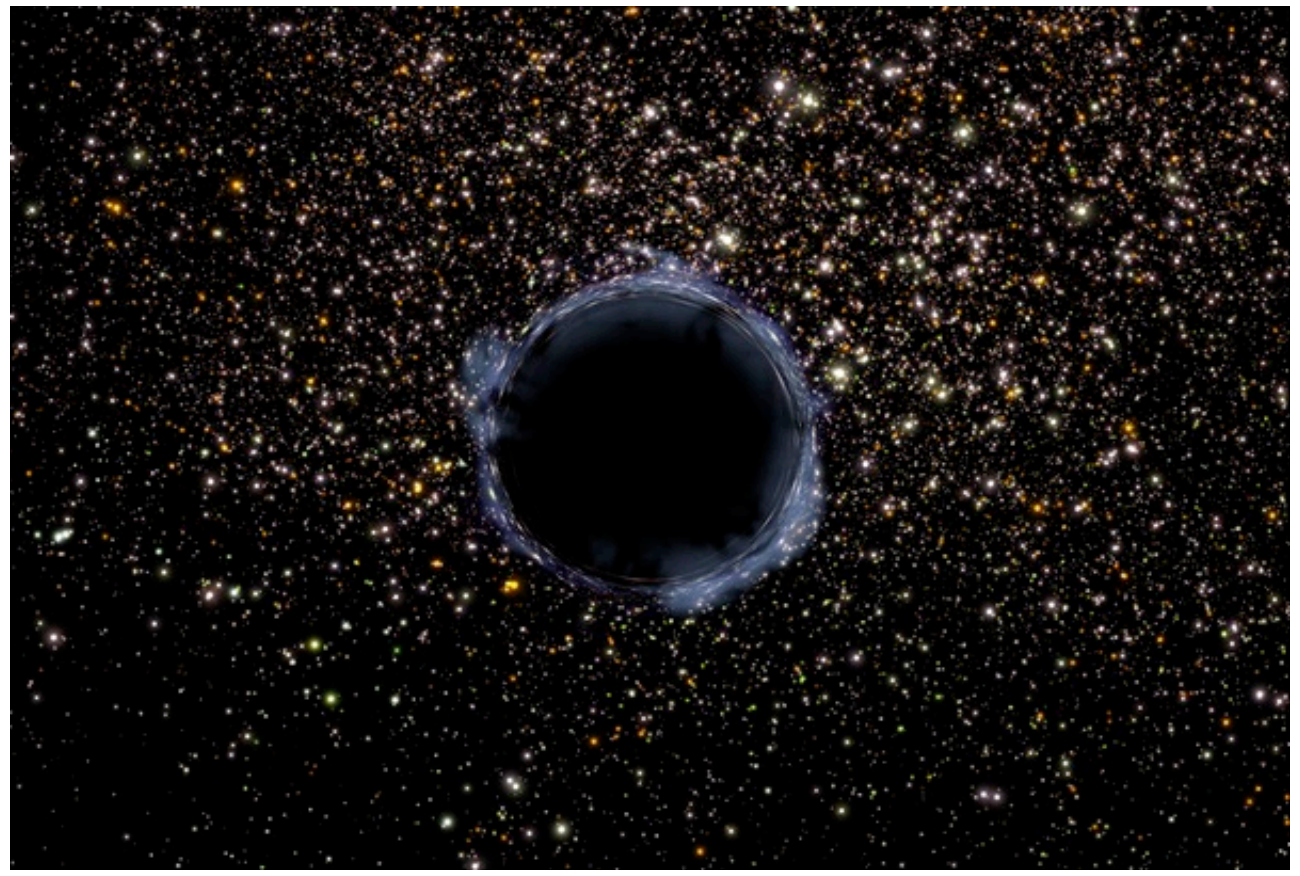
# Non-Thermal DM Candidates

Axions

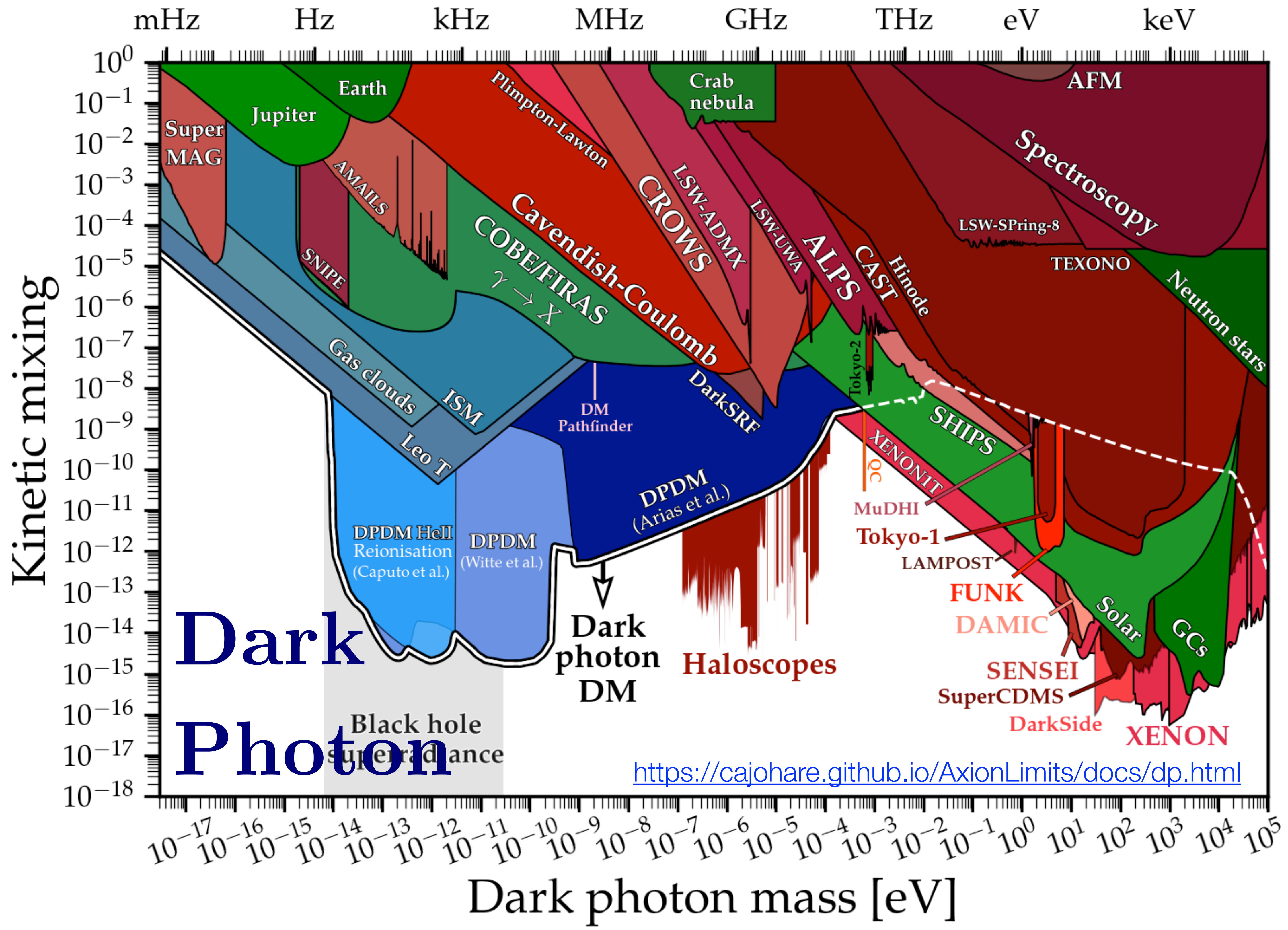
Composite/Heavy DM

Ultra-light/wave DM

Primordial Black Holes



# Experimental Results

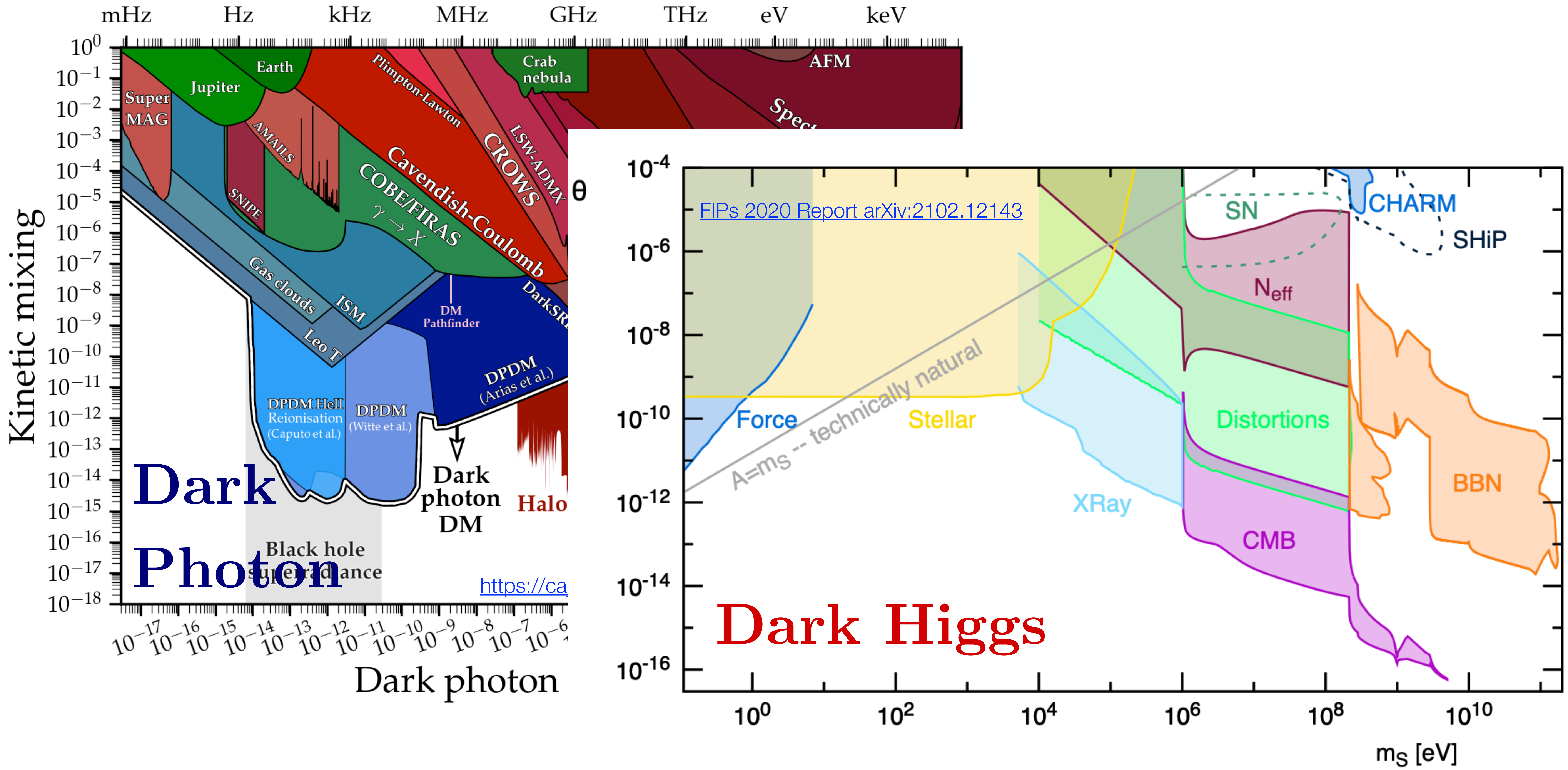


**Dark Photon**

https://cajohare.github.io/AxionLimits/docs/dp.html

FIPs 2020 Report arXiv:2102.12143

# Experimental Results



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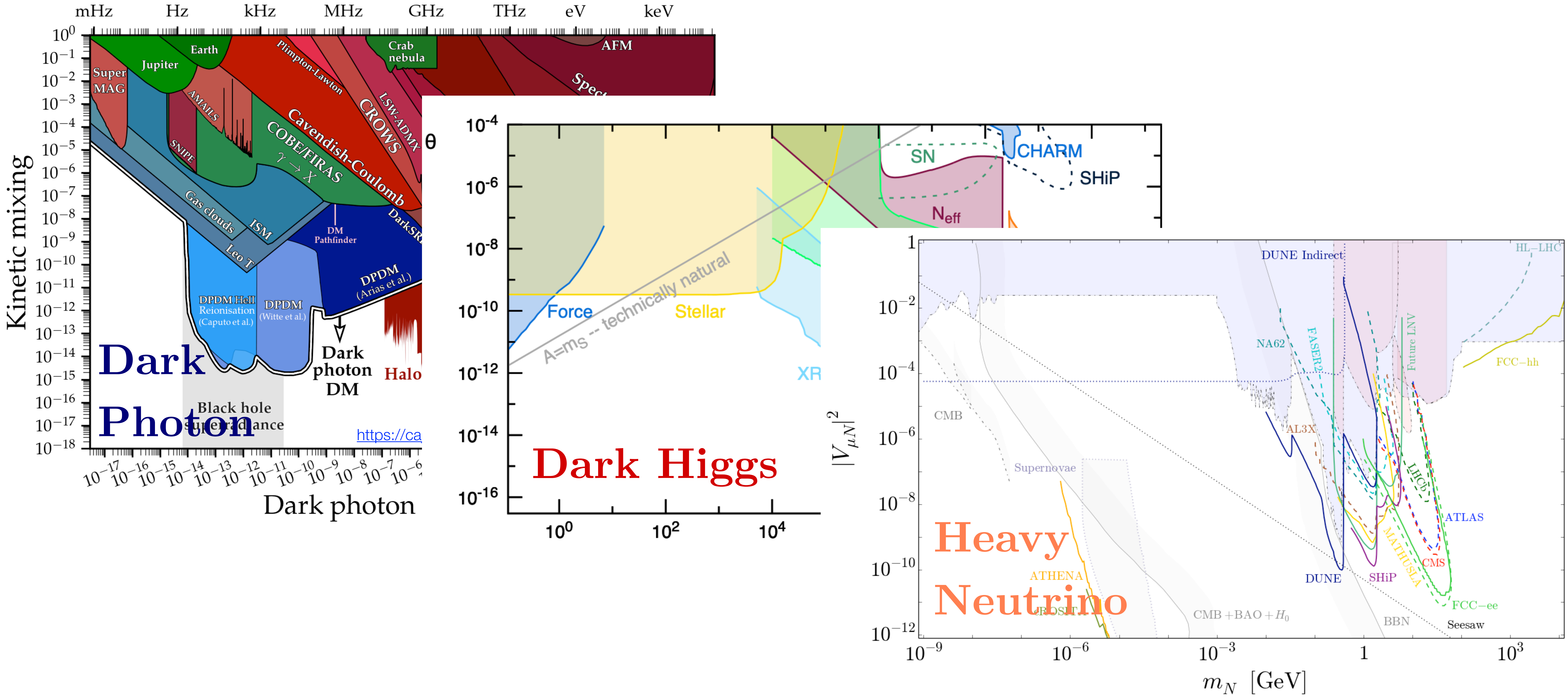
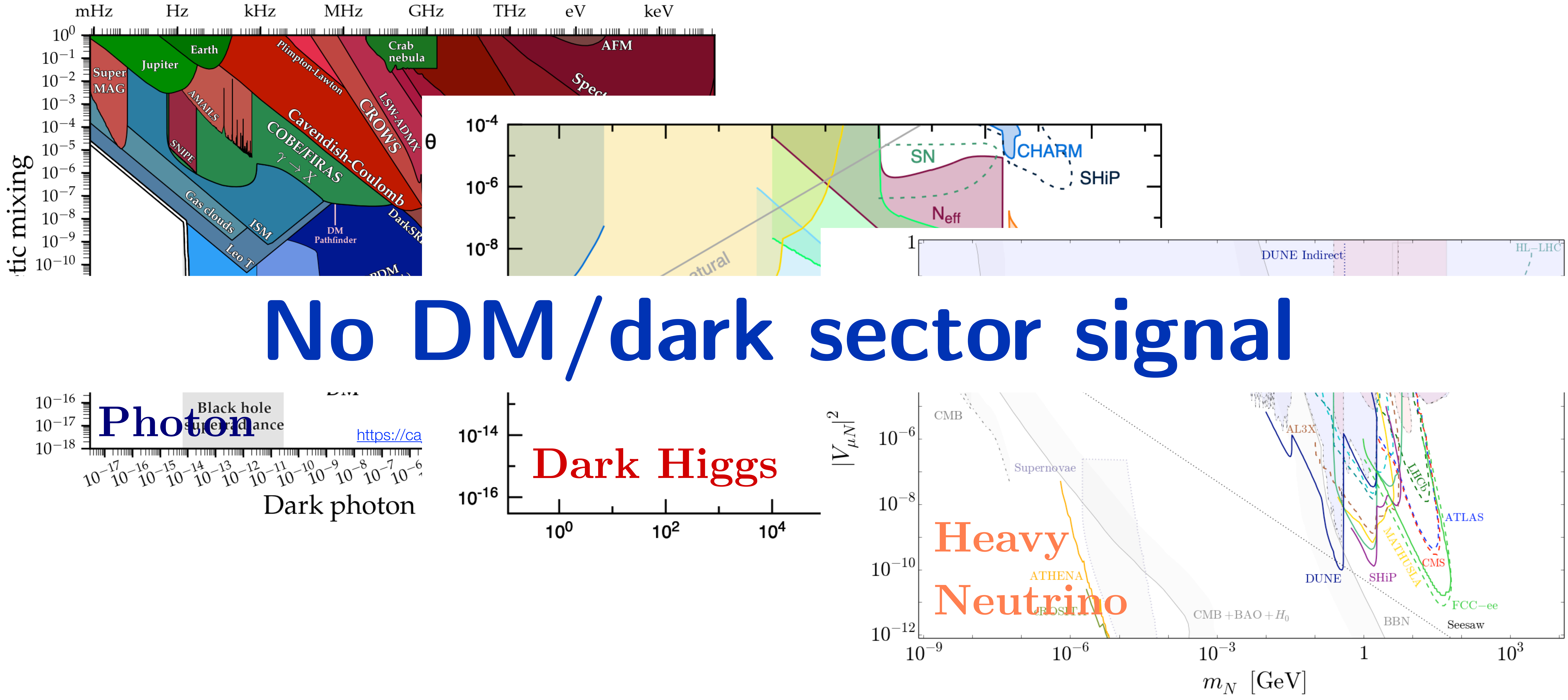


**Dark Photon**

**Dark Higgs**

**Heavy Neutrino**

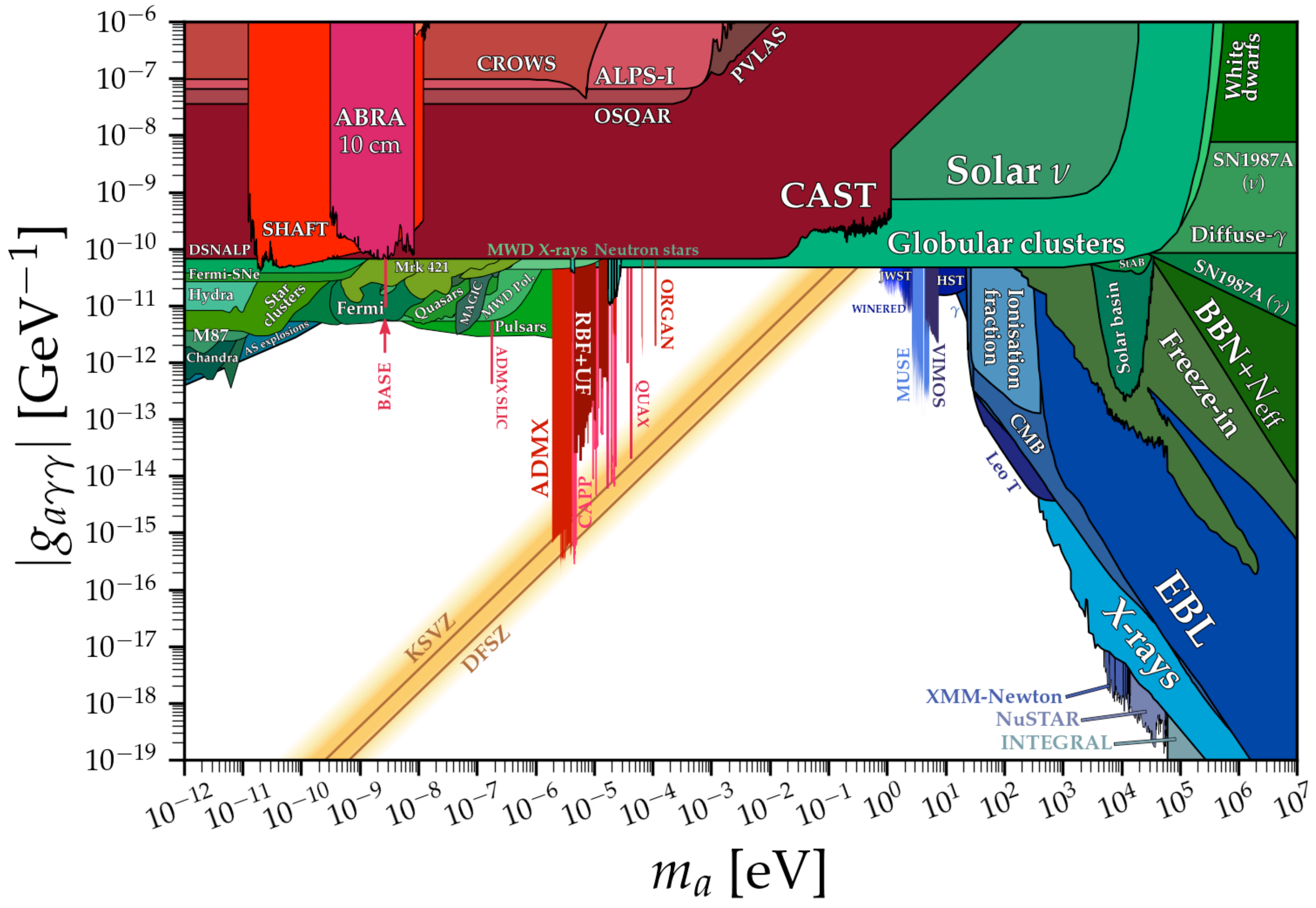
# Experimental Results



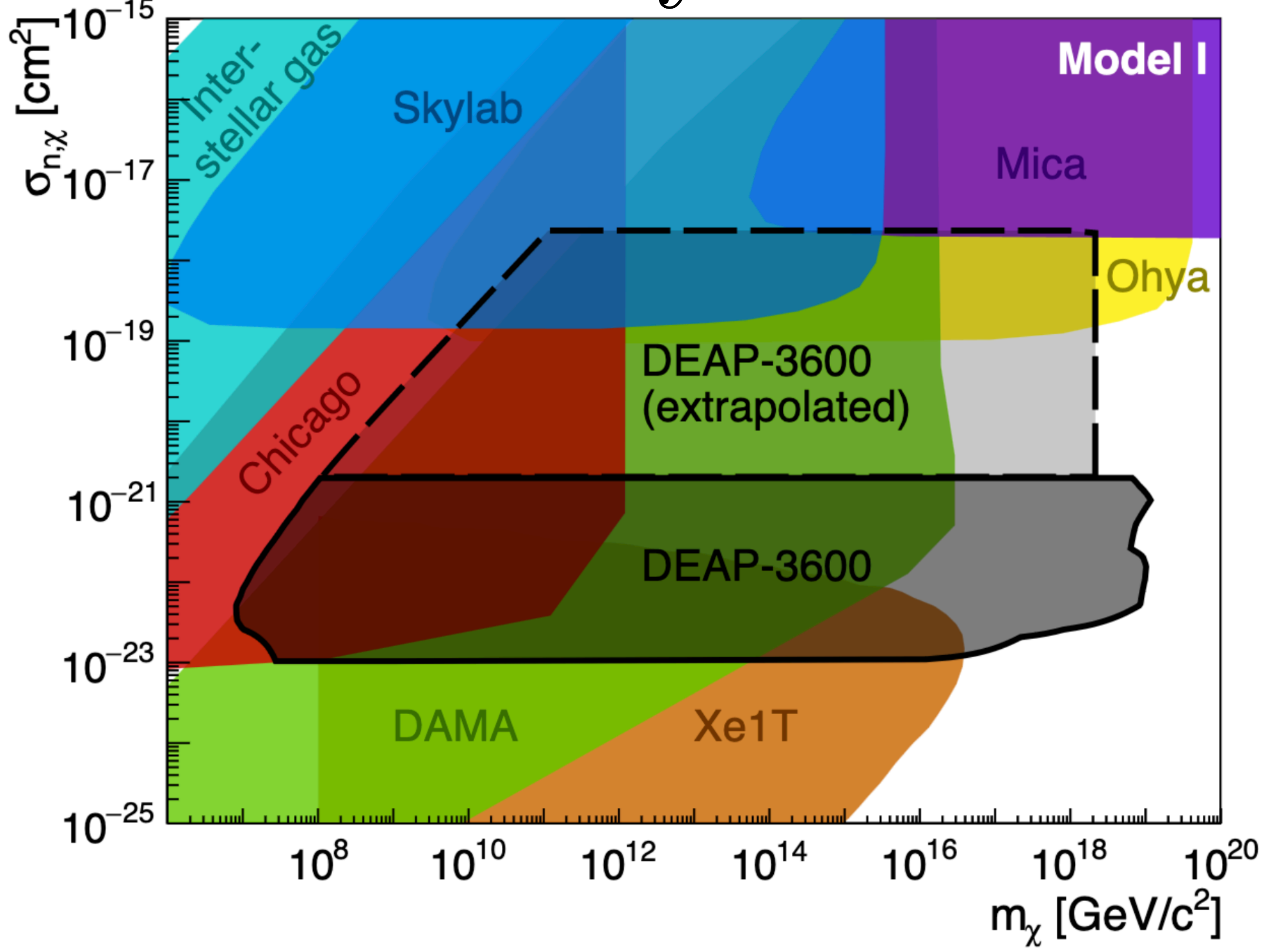
**No DM/dark sector signal**

# Experimental Results

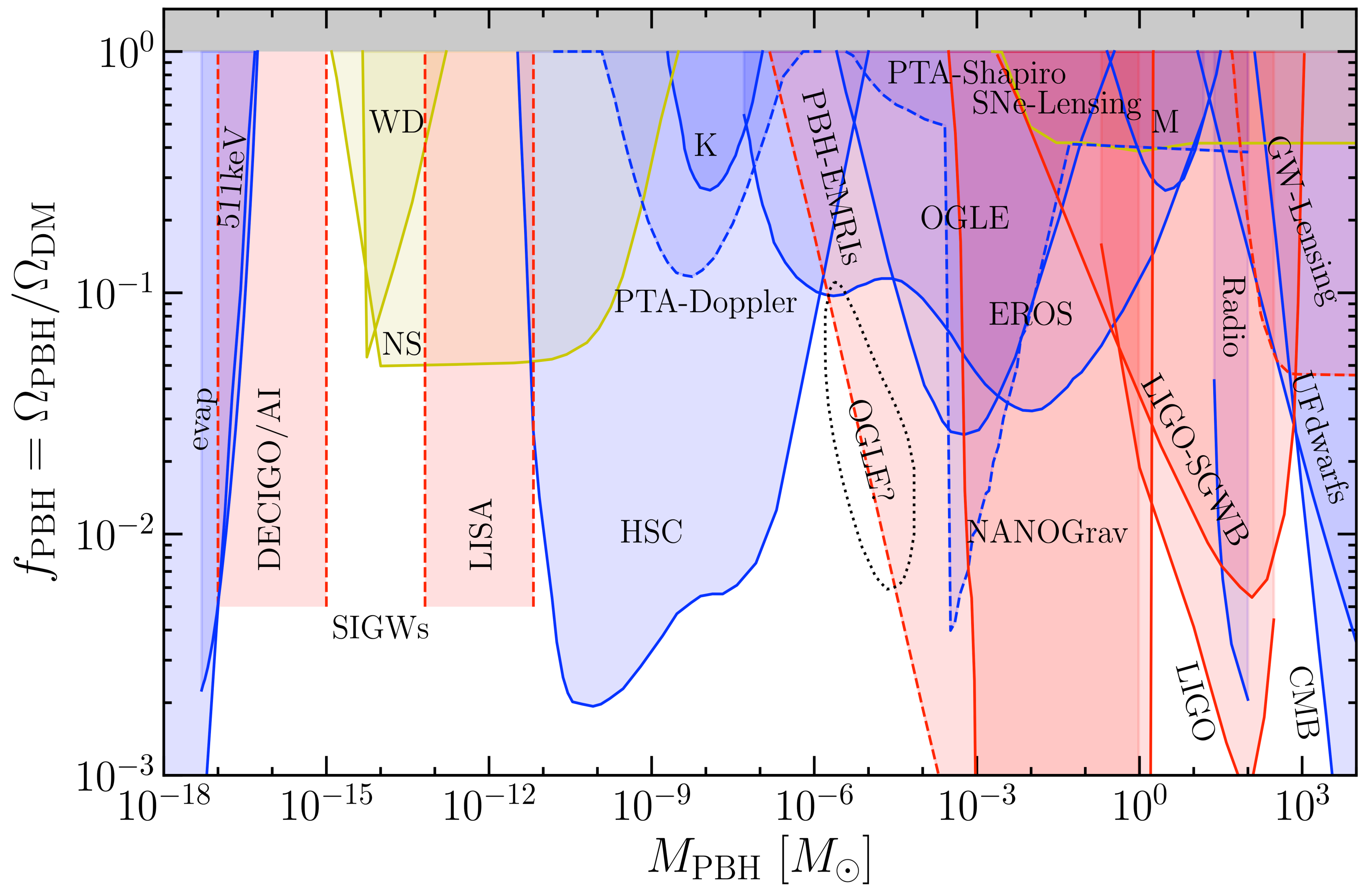
## Axions



## Heavy DM



## PBHs



**No DM/dark sector signal**

# Next steps?

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

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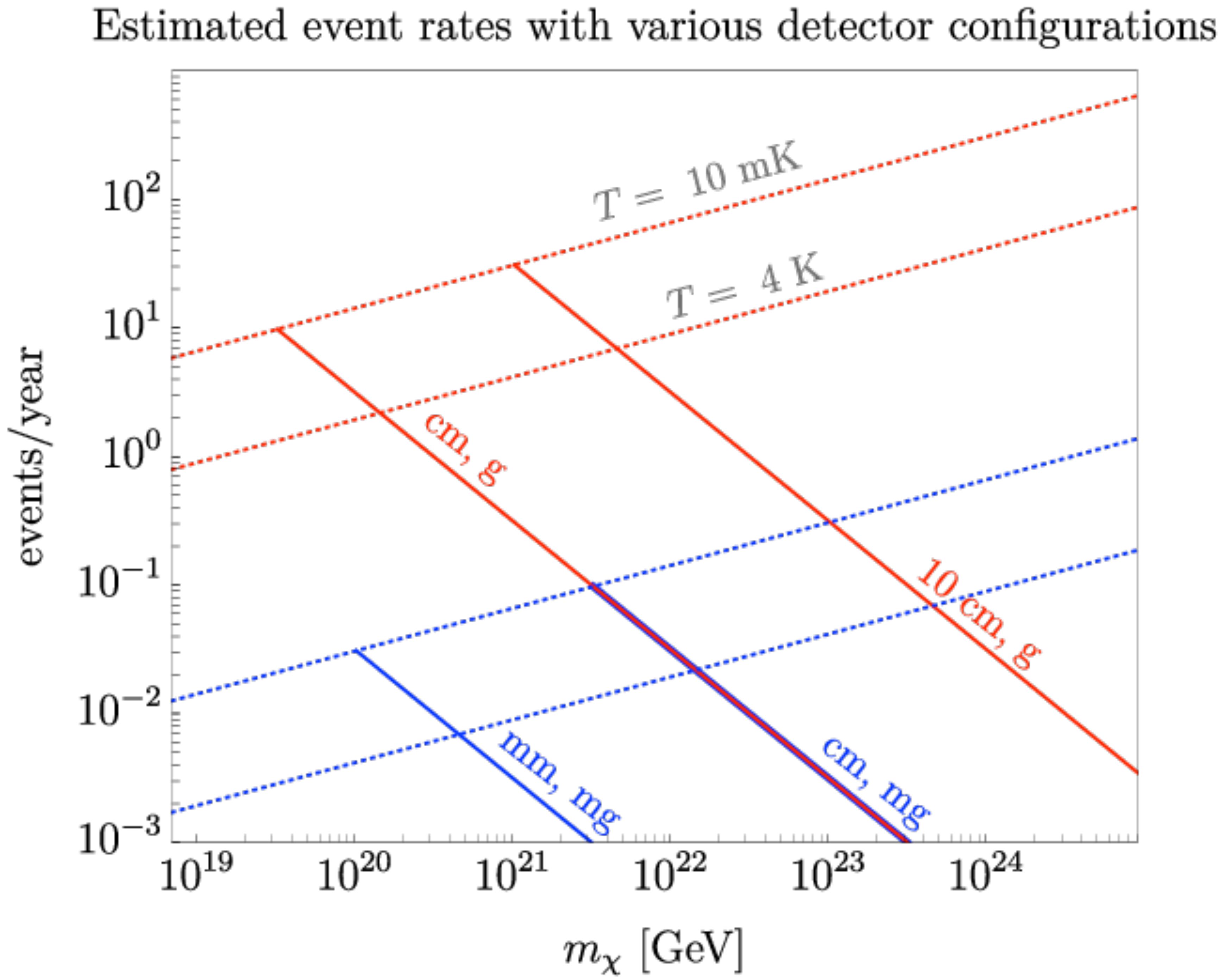
**The Windchime Project: Gravitational Detection of Dark Matter in the Laboratory**

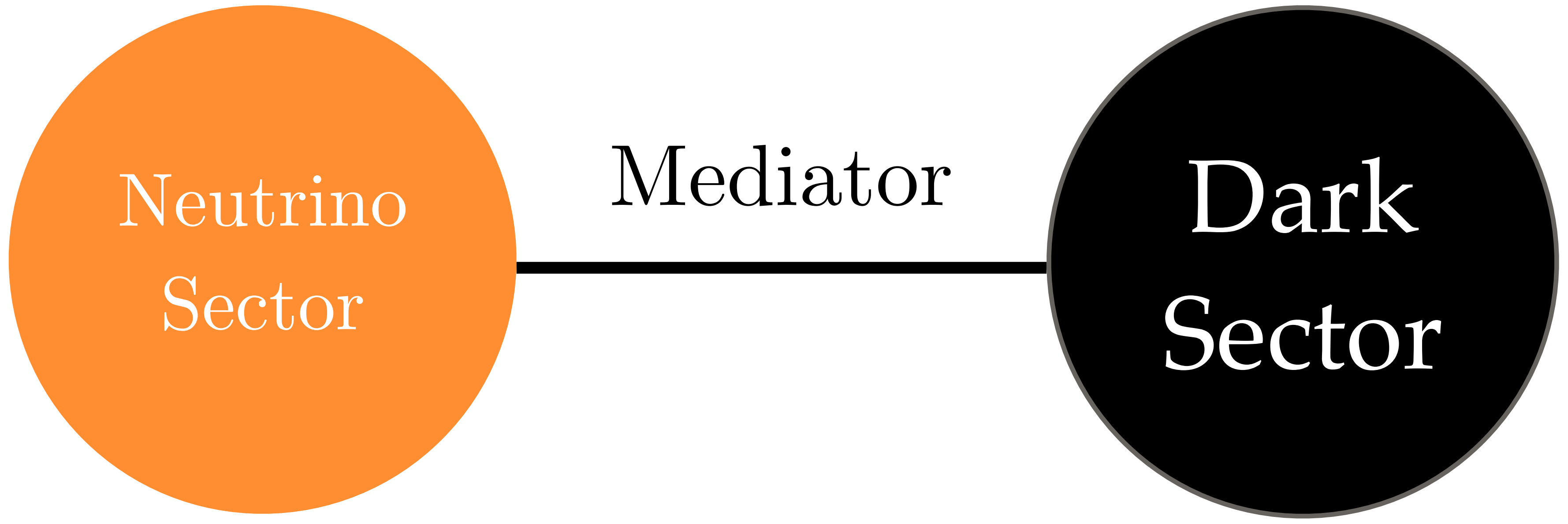
**Small window where this could work so we better hope that DM has this mass!**



# Next steps?

- No dark matter signal has been observed. 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, electrons, protons). *What if DM is more elusive than we thought? What if DM only interacts with neutrinos?*



Neutrino Sector

Mediator

Dark Sector

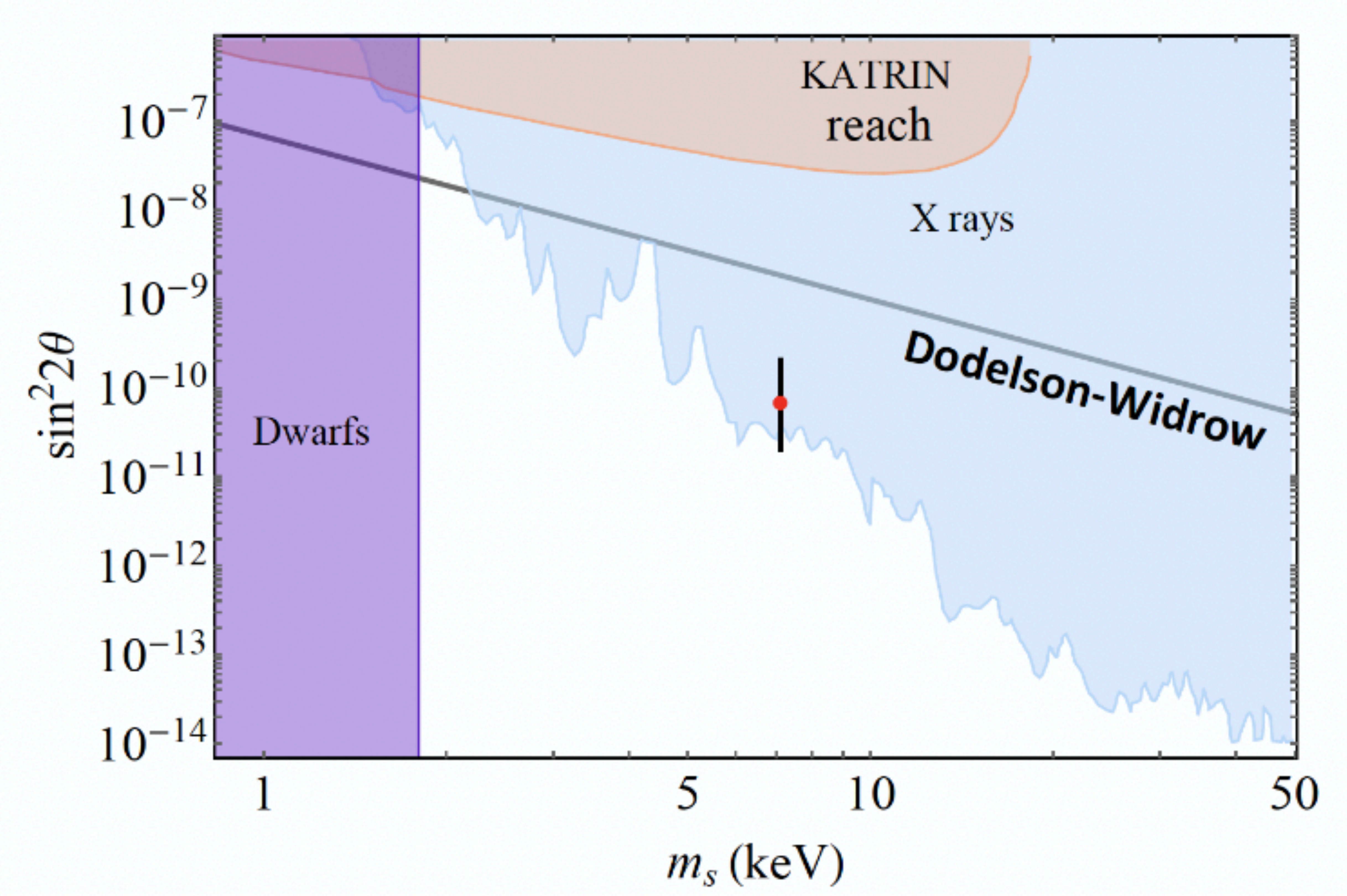
# Sterile Neutrino Dark Matter

- 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 Dodelson-Widrow Mechanism

- Indirect detection via one-loop decay $\nu_s \to \nu_a \gamma$ with X-ray line at $E_\gamma = m_4/2$



S$\nu$DM is almost completely excluded.
Can we save Dodelson-Widrow?

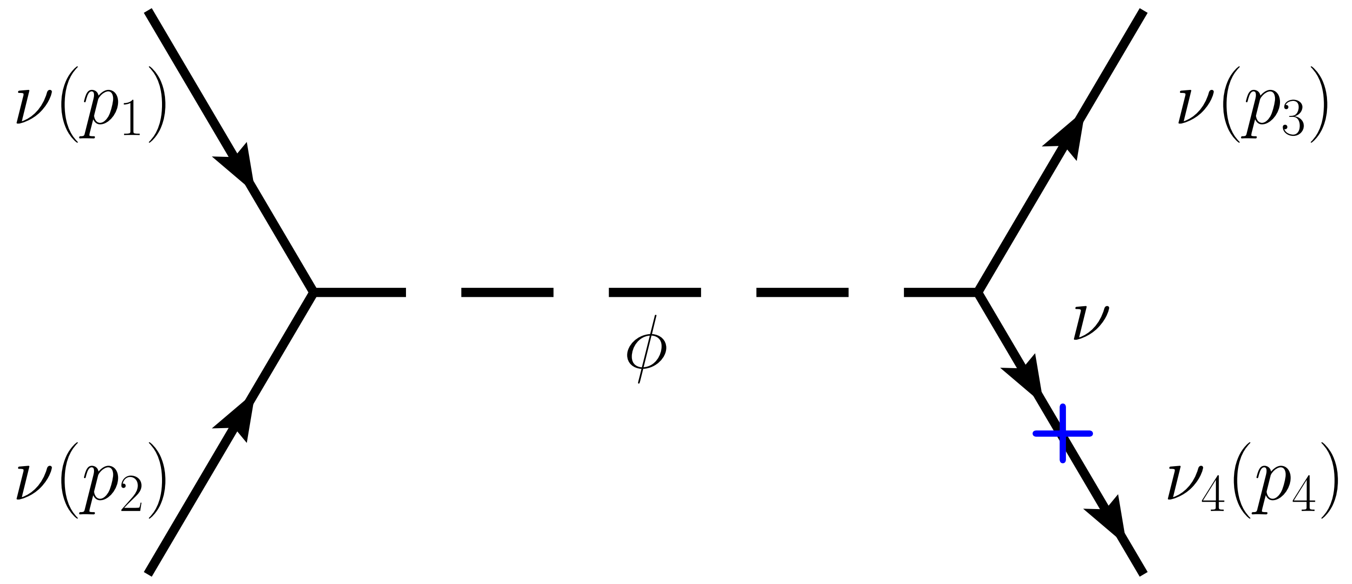
# A Neutrinophilic Scalar Mediator

- 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 $\phi$ of mass $m_\phi$ that mediates *new self interactions among SM neutrinos.*

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

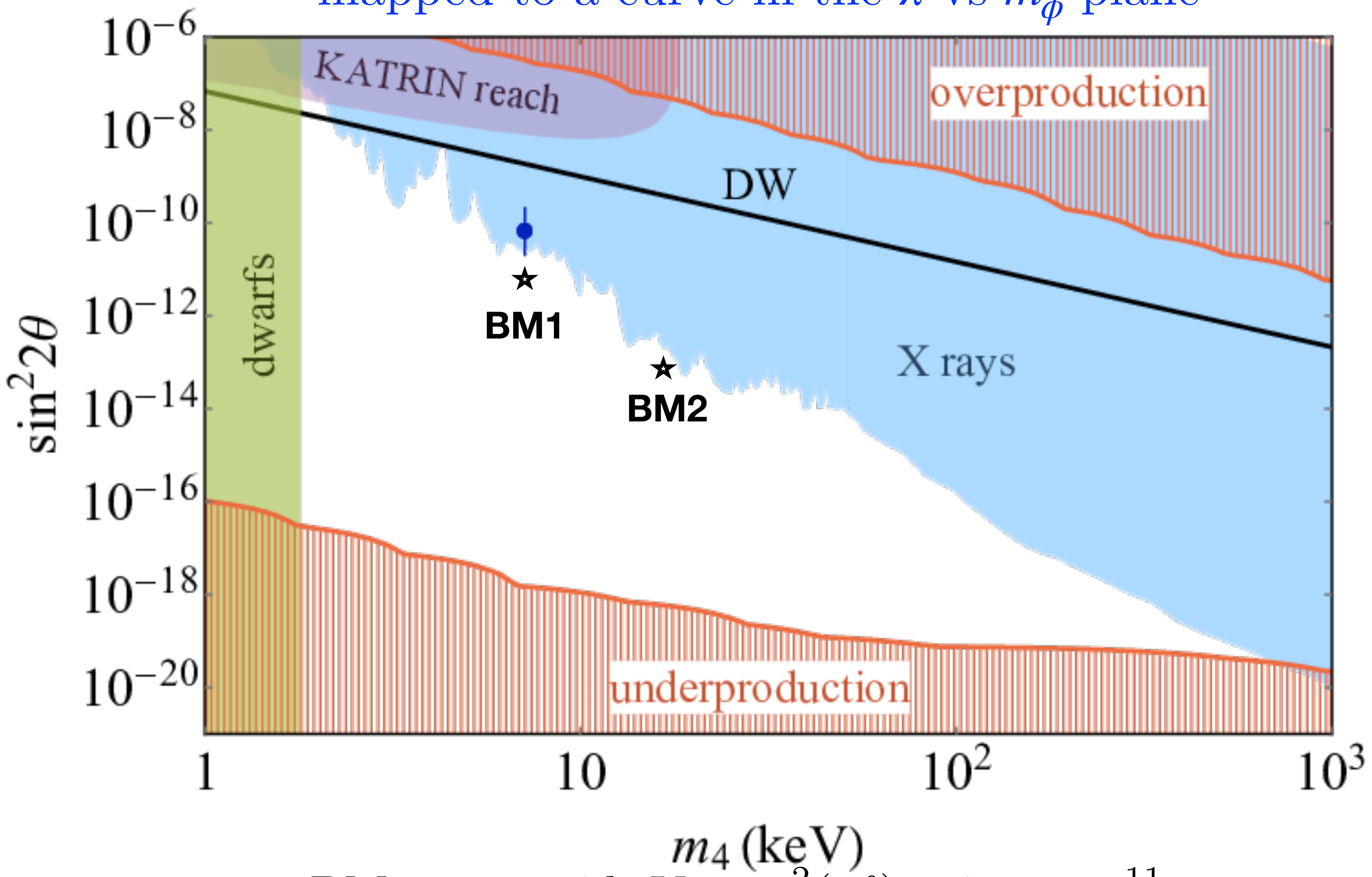


Larger rate than the weak interactions keeps SM neutrinos in contact for a longer period of time to build up the DM abundance!

# A Neutrinophilic Scalar Mediator

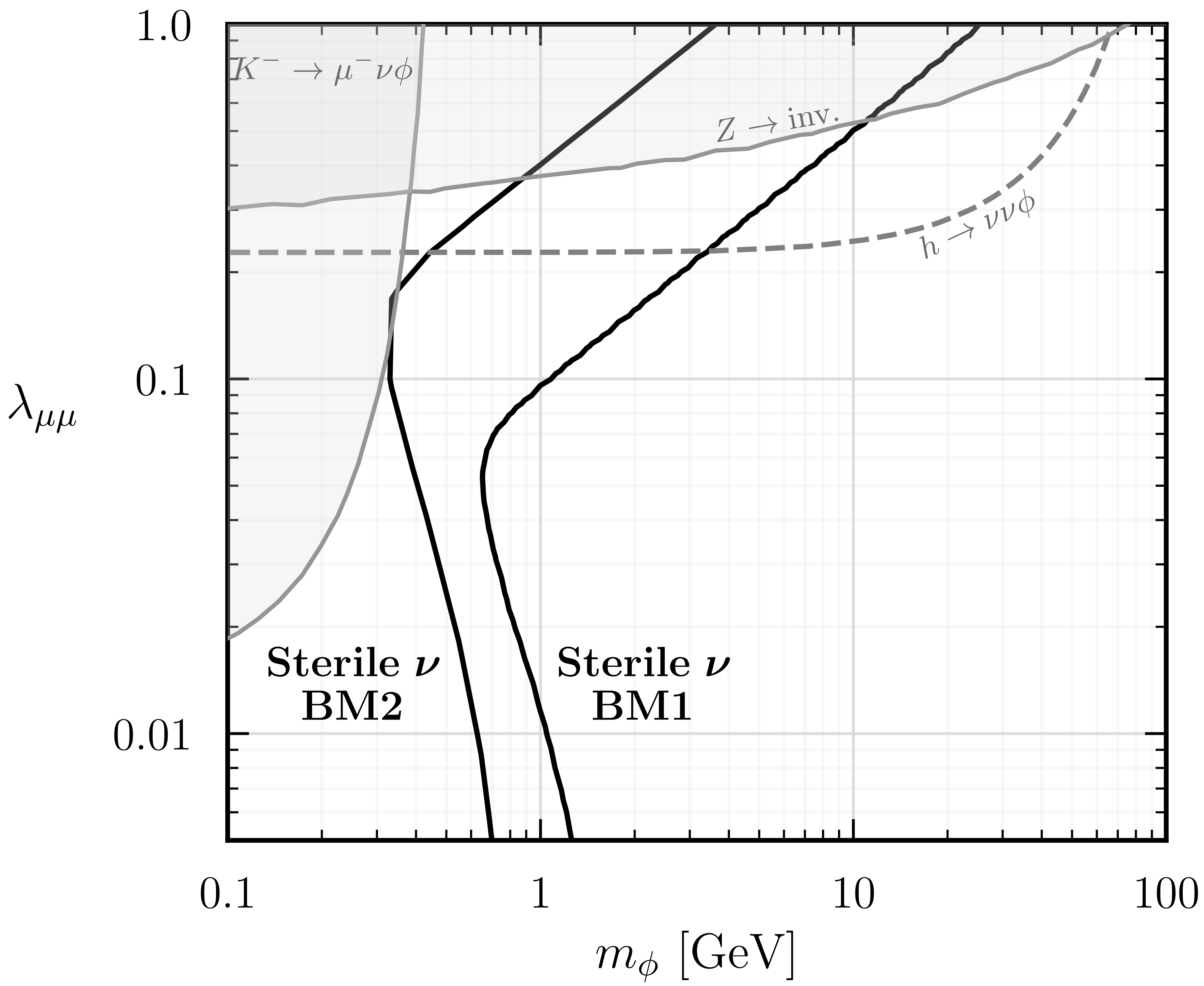
- New production mode → don't have to live on DW line!

Any point in this parameter space can be mapped to a curve in the $\lambda$ vs $m_\phi$ plane



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

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



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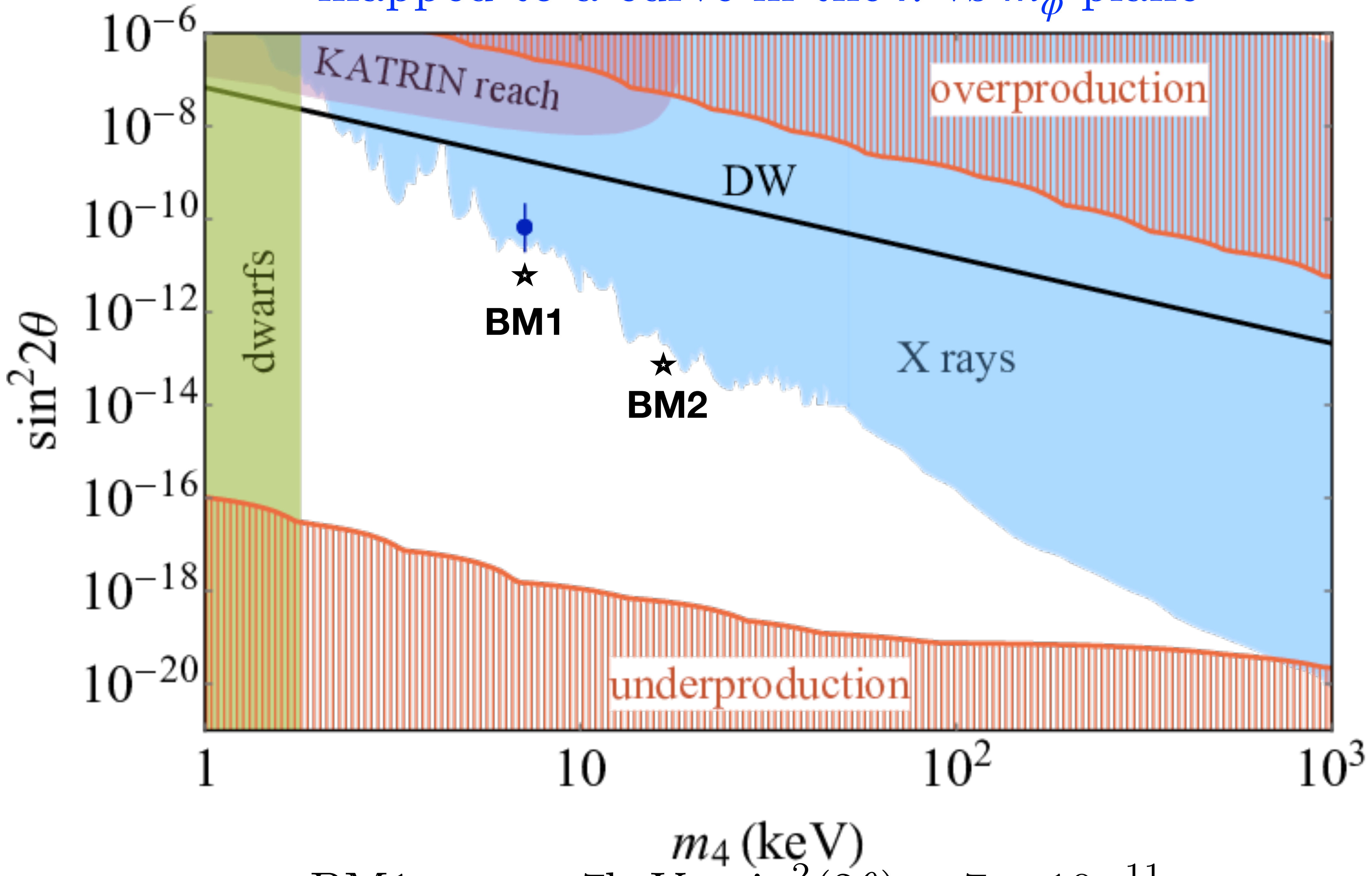

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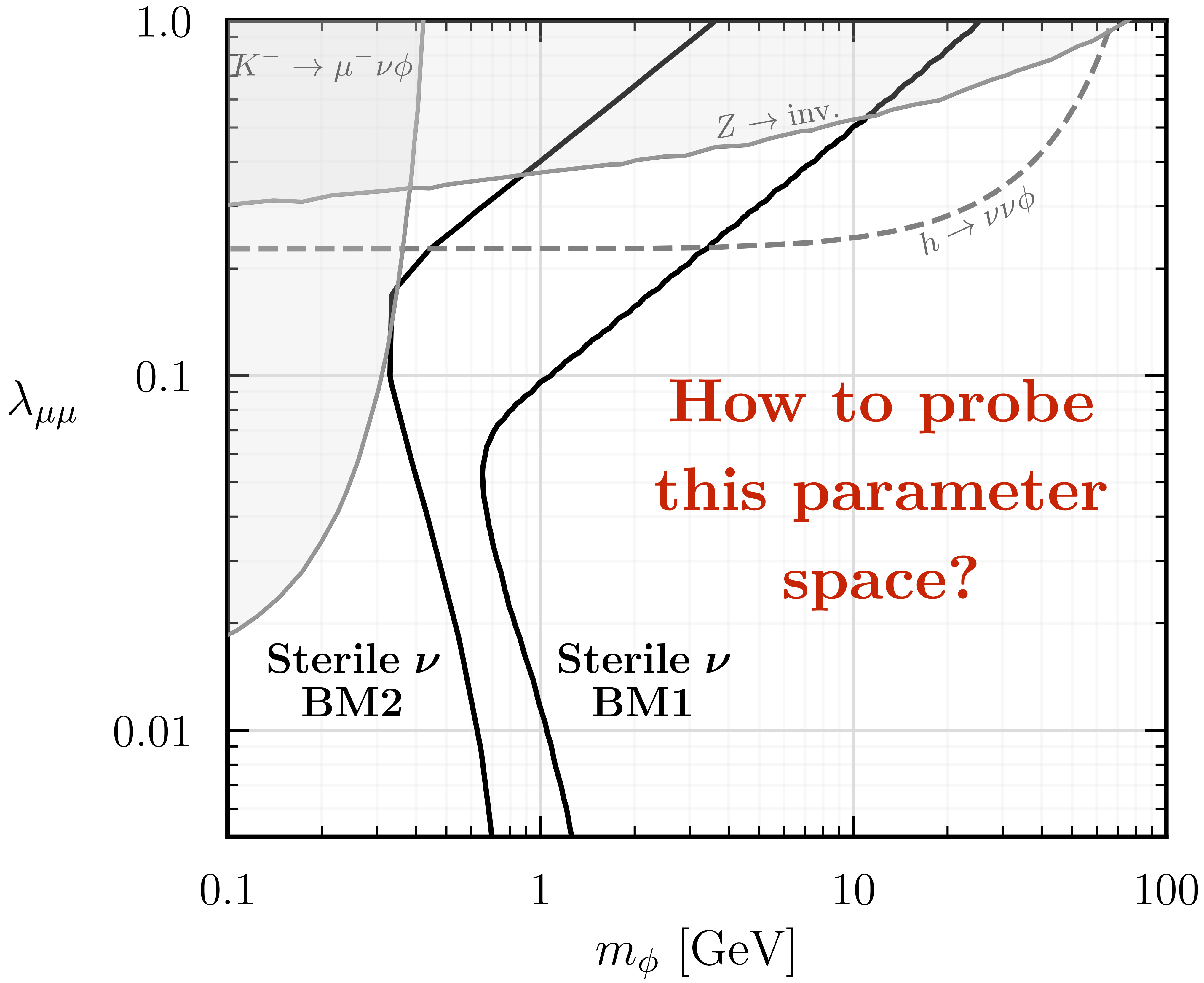
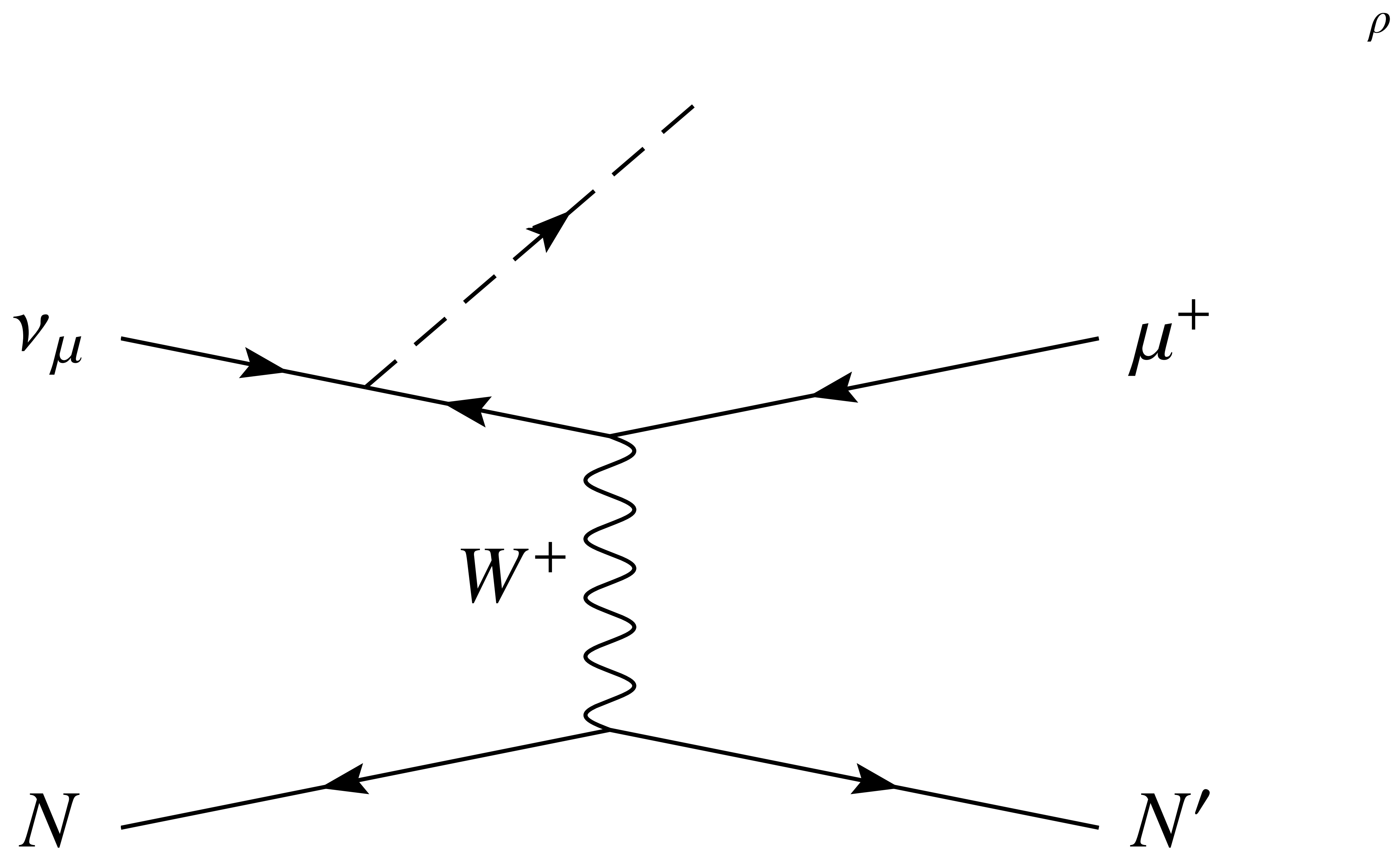


How to probe this parameter space?

# The Mono-neutrino Signature

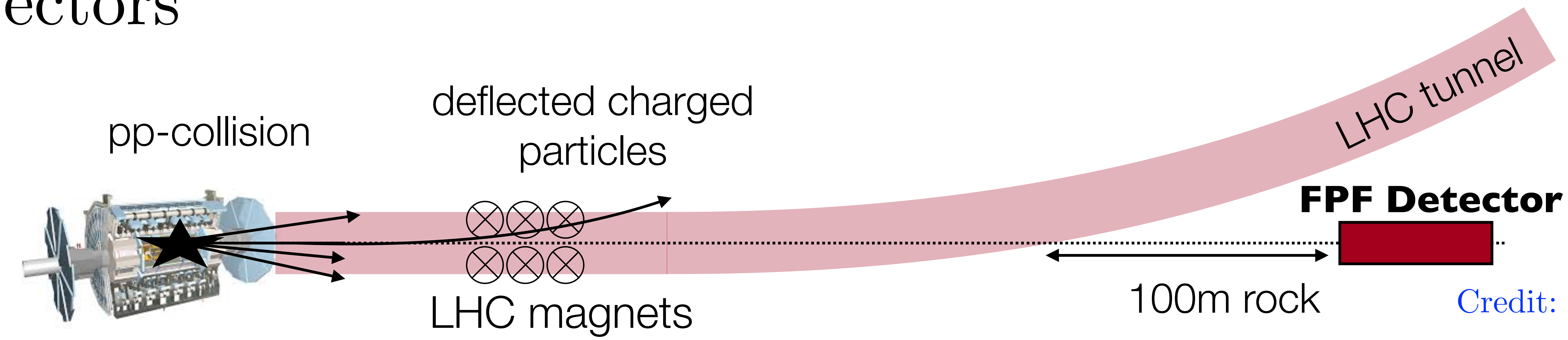
- Unique signature due to the neutrinophilic nature of the mediator: incoming neutrino radiates a scalar particle and then converts to a muon via CC interactions. K. J. Kelly and Y. Zhang [arXiv:1901.01259](arXiv:1901.01259)



- Observable: **Missing transverse momentum** carried away by $\phi$
    - 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



pp-collision

deflected charged particles

LHC tunnel

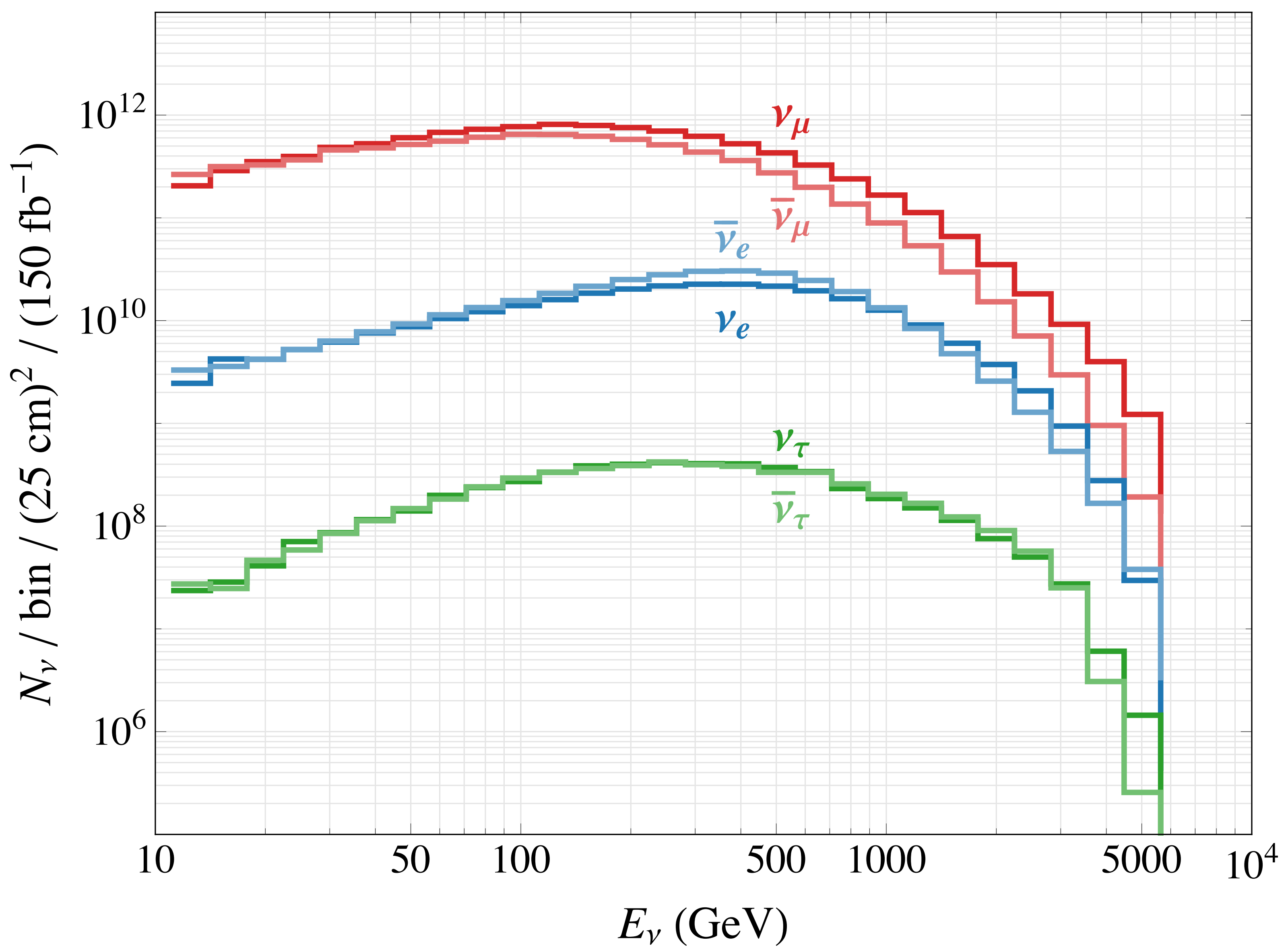
FPF Detector

LHC magnets

100m rock

Credit: Felix Kling

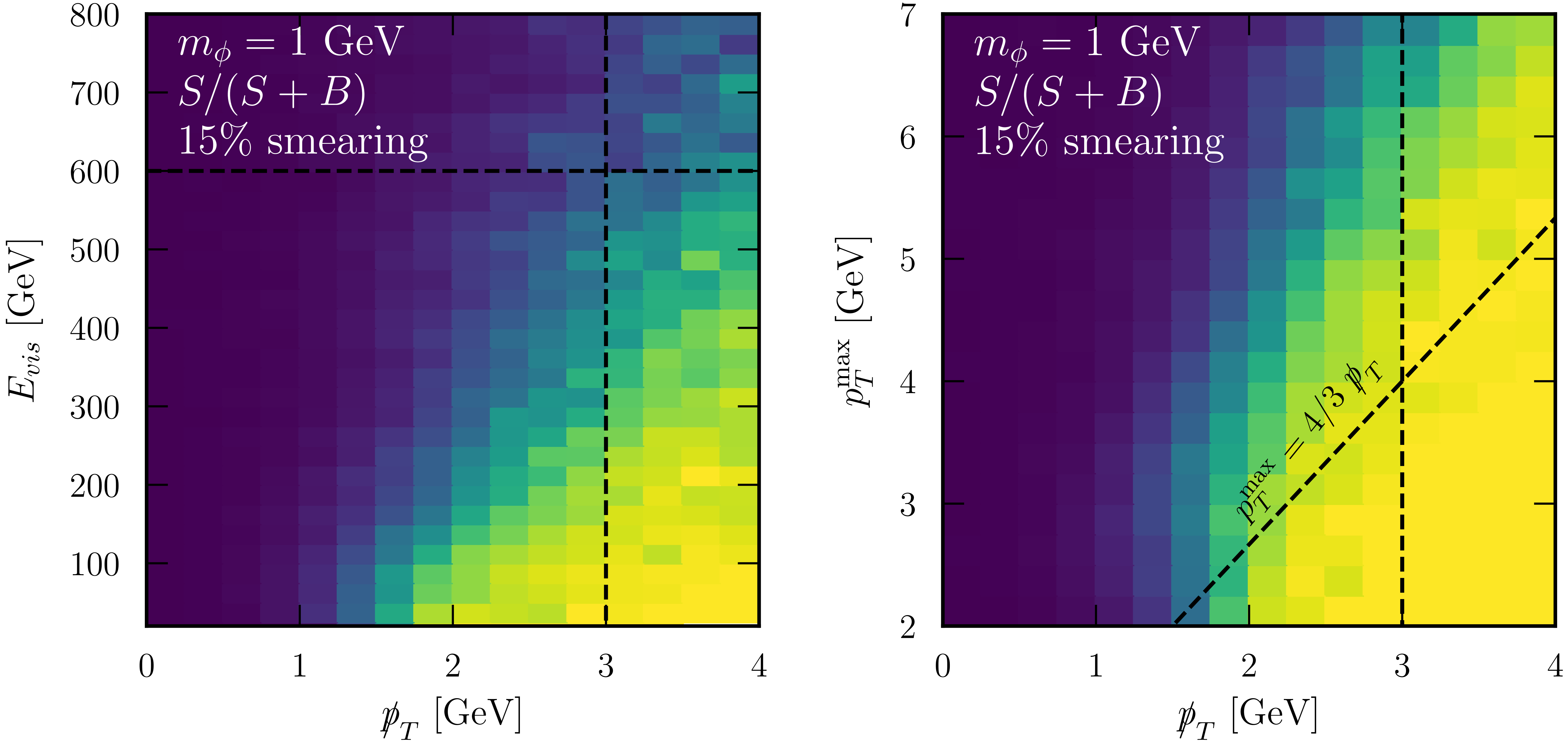
- Flux of high energy neutrinos can be used to probe our model!
- Advantages of LHC neutrinos:
  - High energy neutrinos can probe higher scalar masses
  - Neutrino scattering is DIS → smaller uncertainties



# Analysis Strategy

- 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 $p_T^{max}$

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



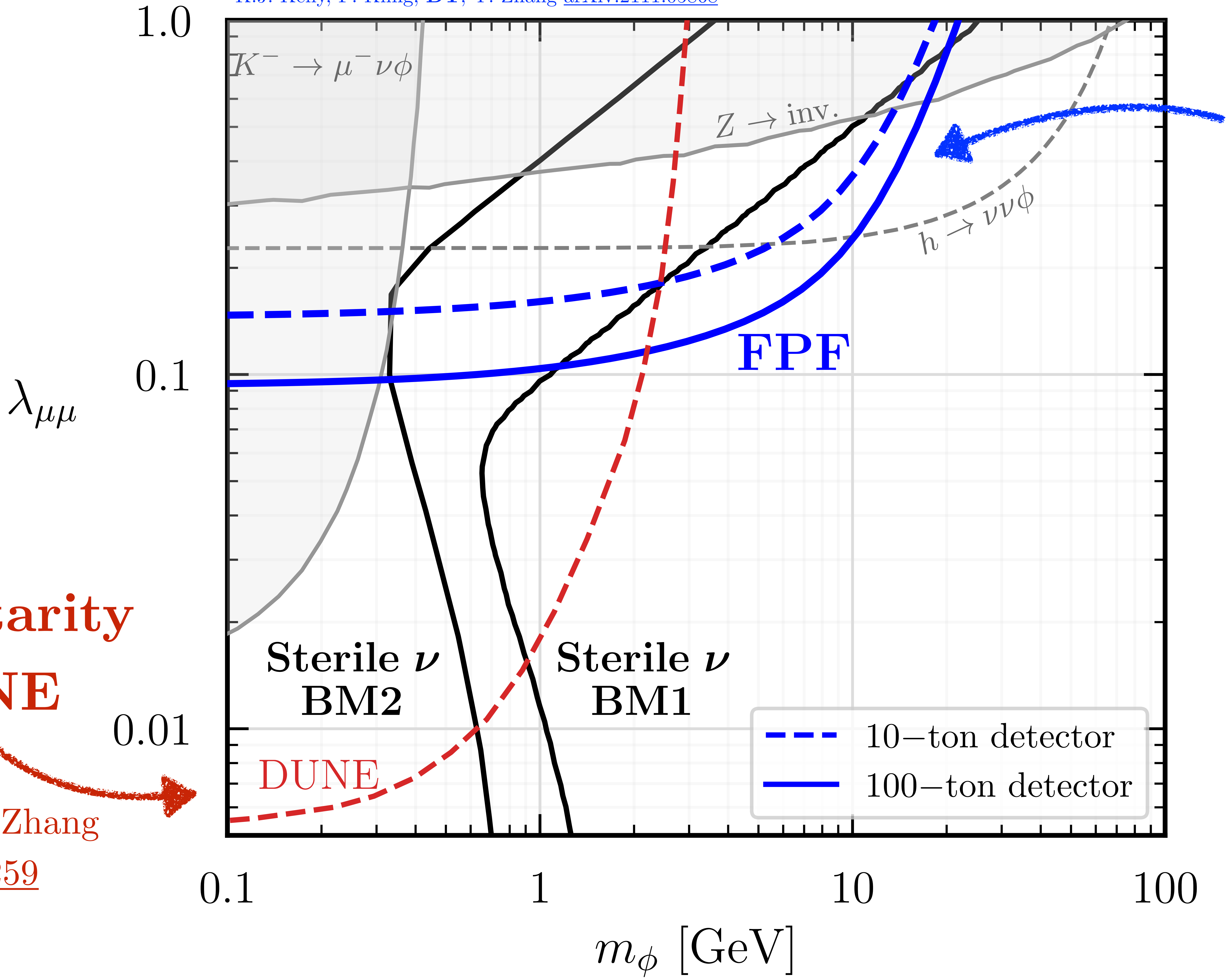
## Cut and Count

| | $\nu_\mu + \overline{\nu}_\mu$ 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***!

# FPF Reach: Sterile Neutrinos

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



**Importance of higher energy!**

**Complementarity with DUNE**

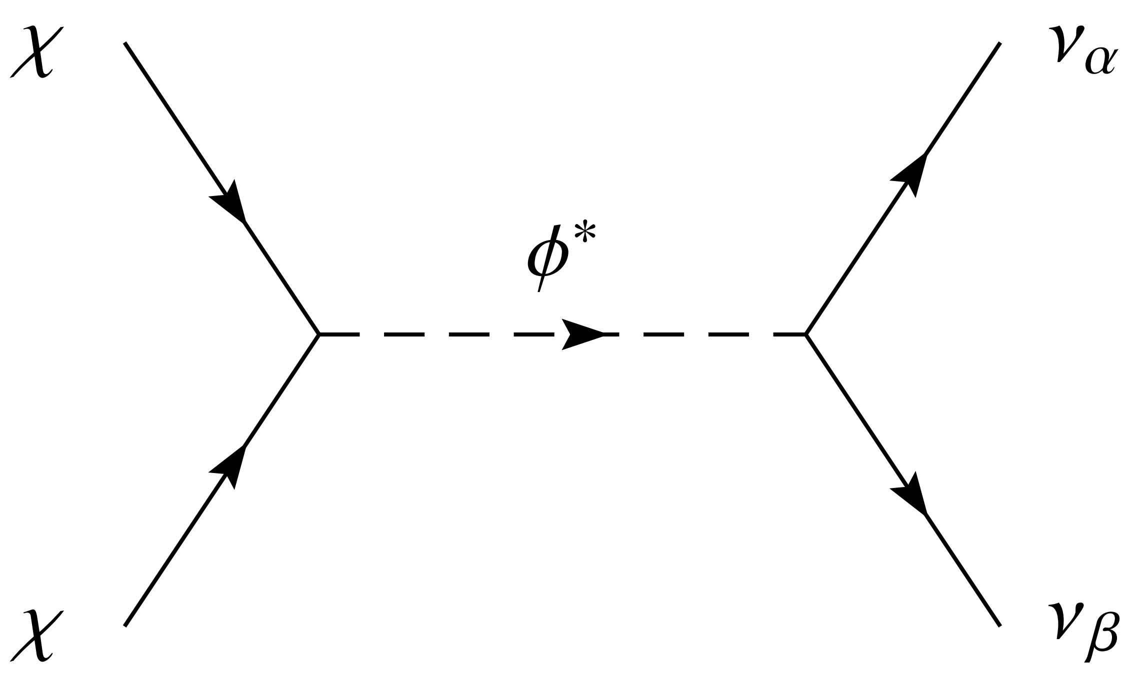
K. J. Kelly and Y. Zhang arXiv:1901.01259

# FPF Reach: Thermal DM

- The neutrinophilic scalar $\phi$ can also be a mediator to thermal DM

## Fermion DM

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



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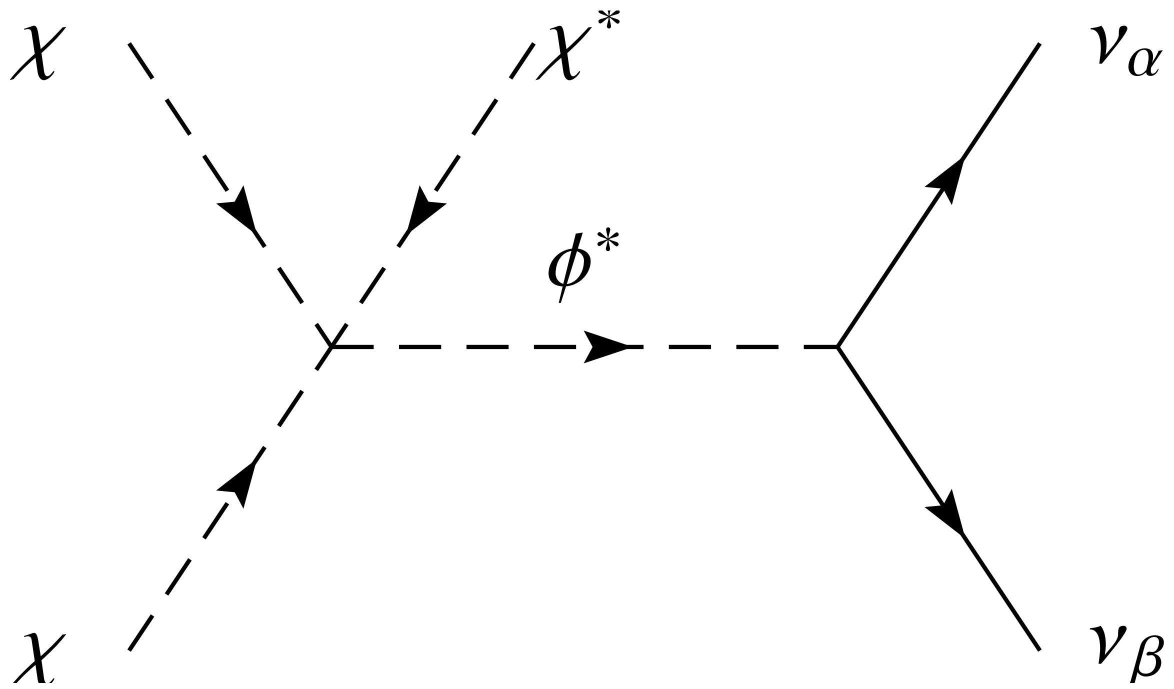
## Scalar DM

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



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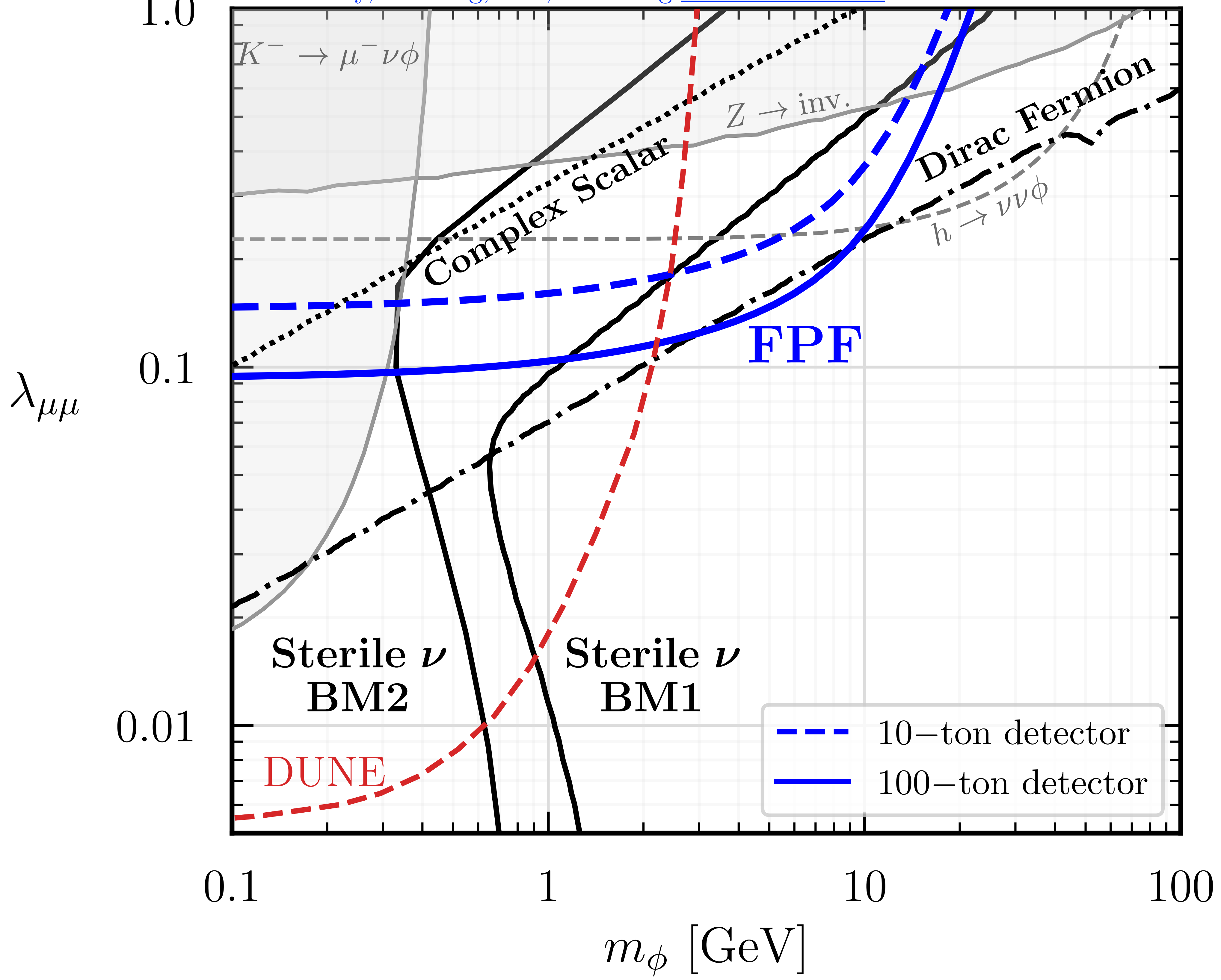
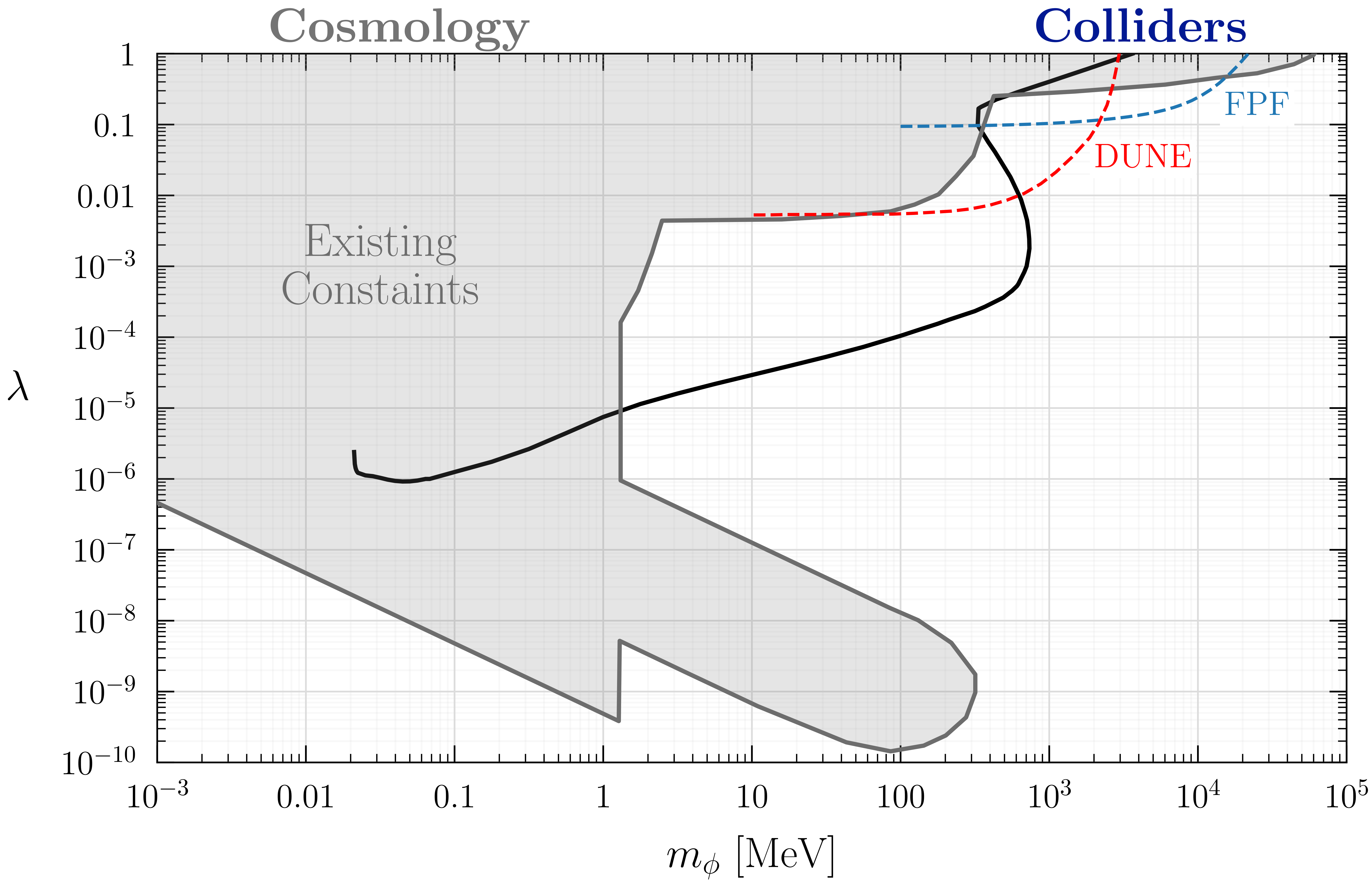


# Big Picture


**Cosmology**
**Colliders**
1
0.1
0.01
$10^{-3}$
$10^{-4}$
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$\lambda$
Existing
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FPF
DUNE
$10^{-3}$
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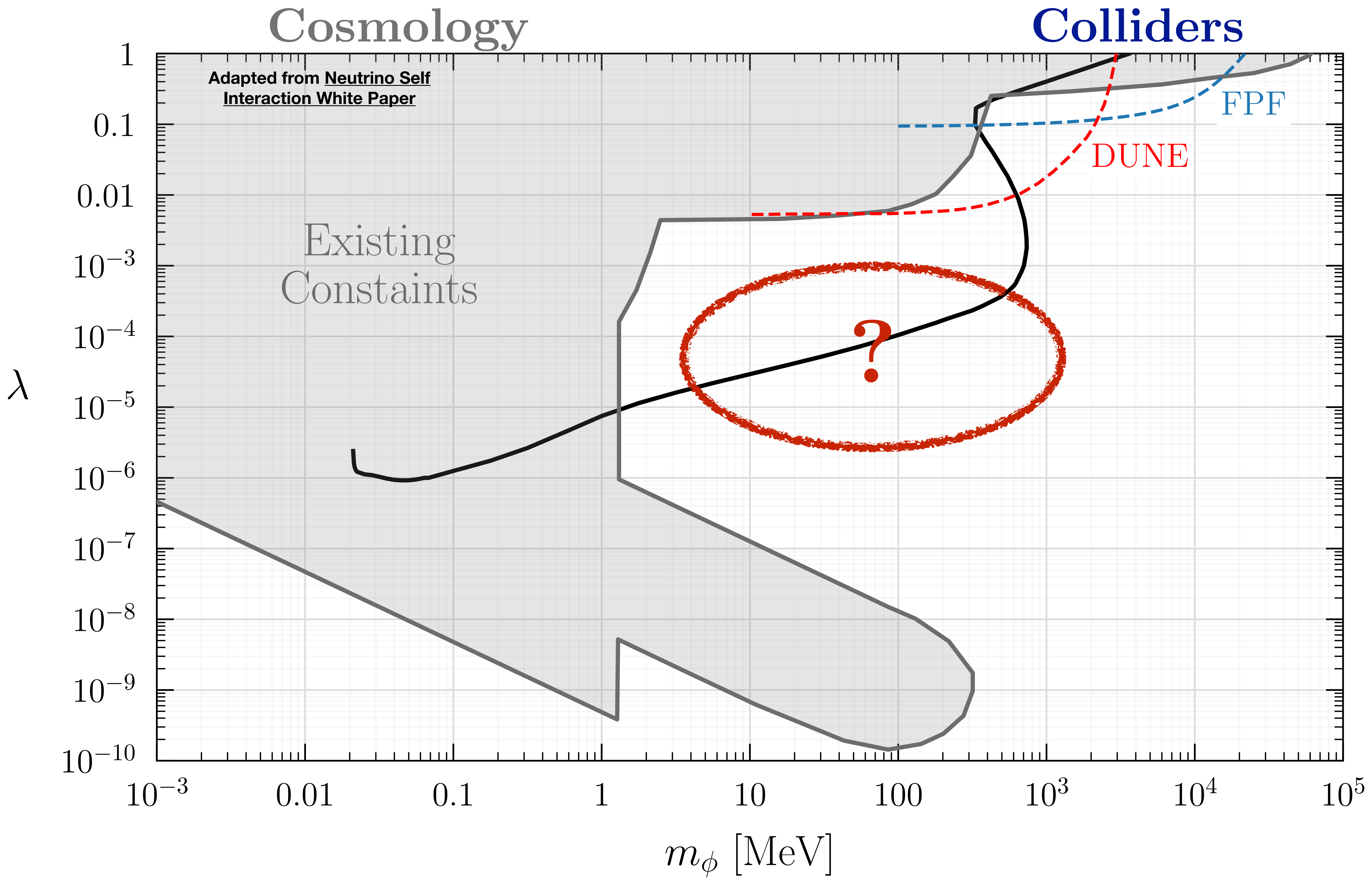
0.1
1
10
100
$10^{3}$
$10^{4}$
$10^{5}$
$m_\phi$ [MeV]

# Big Picture


Cosmology
Colliders
Adapted from Neutrino Self Interaction White Paper
Existing Constaints
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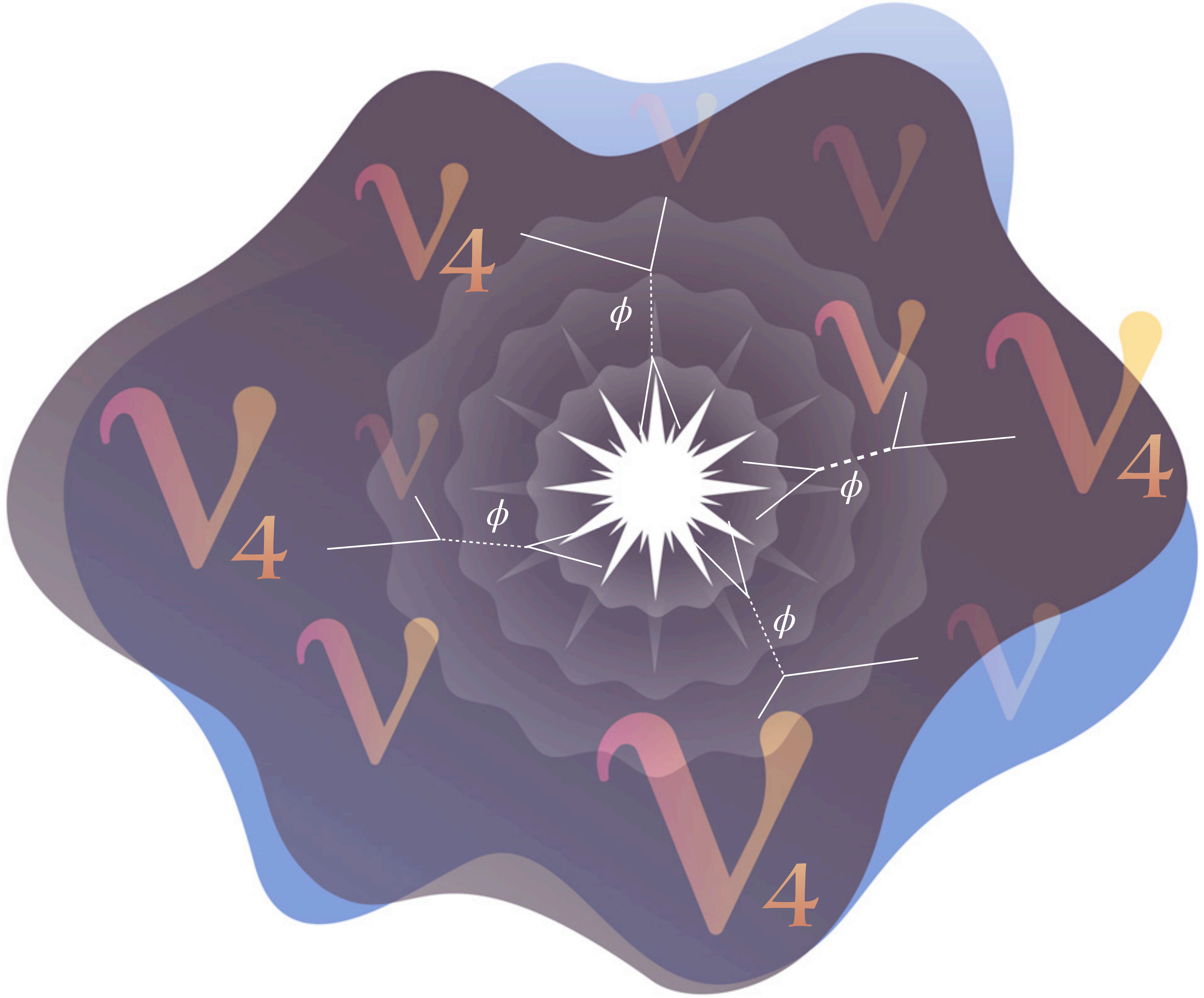
$10^{-3}$
0.01
0.1
1
10
100
$10^3$
$10^4$
$10^5$
$m_\phi$ [MeV]

# Supernovae

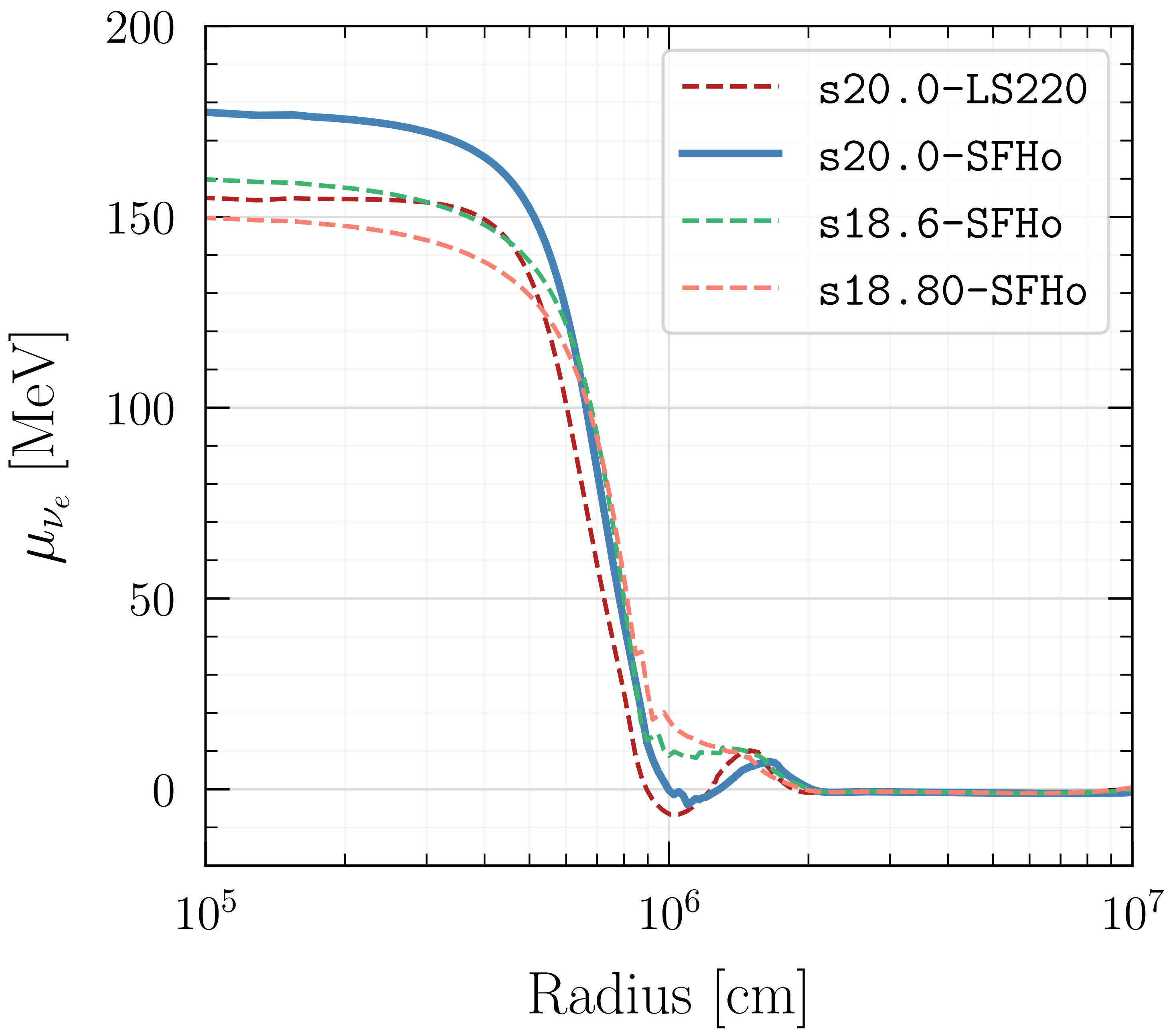
- Another neutrino dense environment!
- Same process that generates S$\nu$DM relic abundance in early universe produces S$\nu$DM in the supernova → excessive supernova cooling!

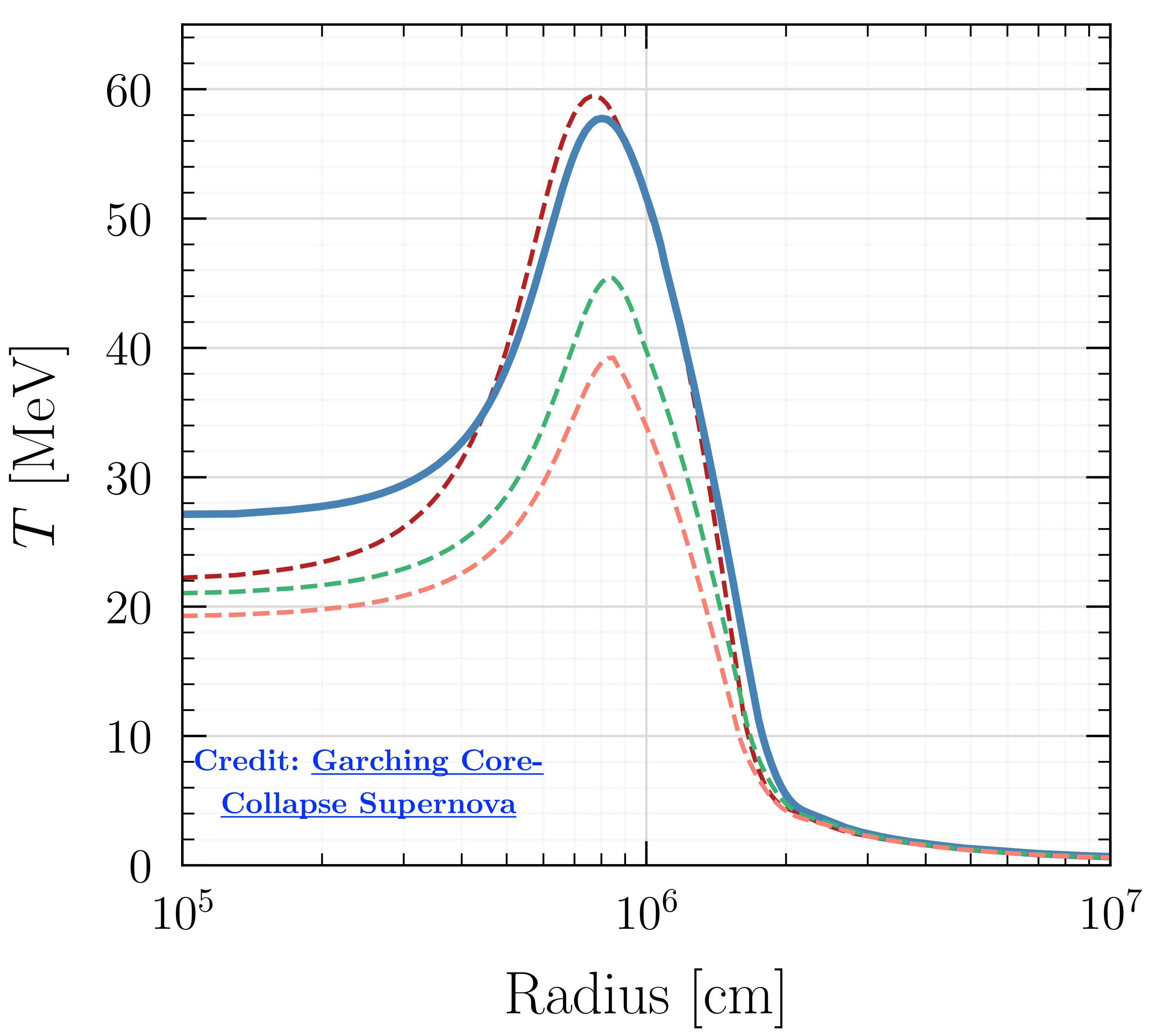


Adapted from Fermilab

# Cooling Rate Calculation: A Sketch

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


**Electron Chemical Potential**


**Temperature**

Credit: Garching Core-Collapse Supernova

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

# Cooling Rate Calculation: A Sketch

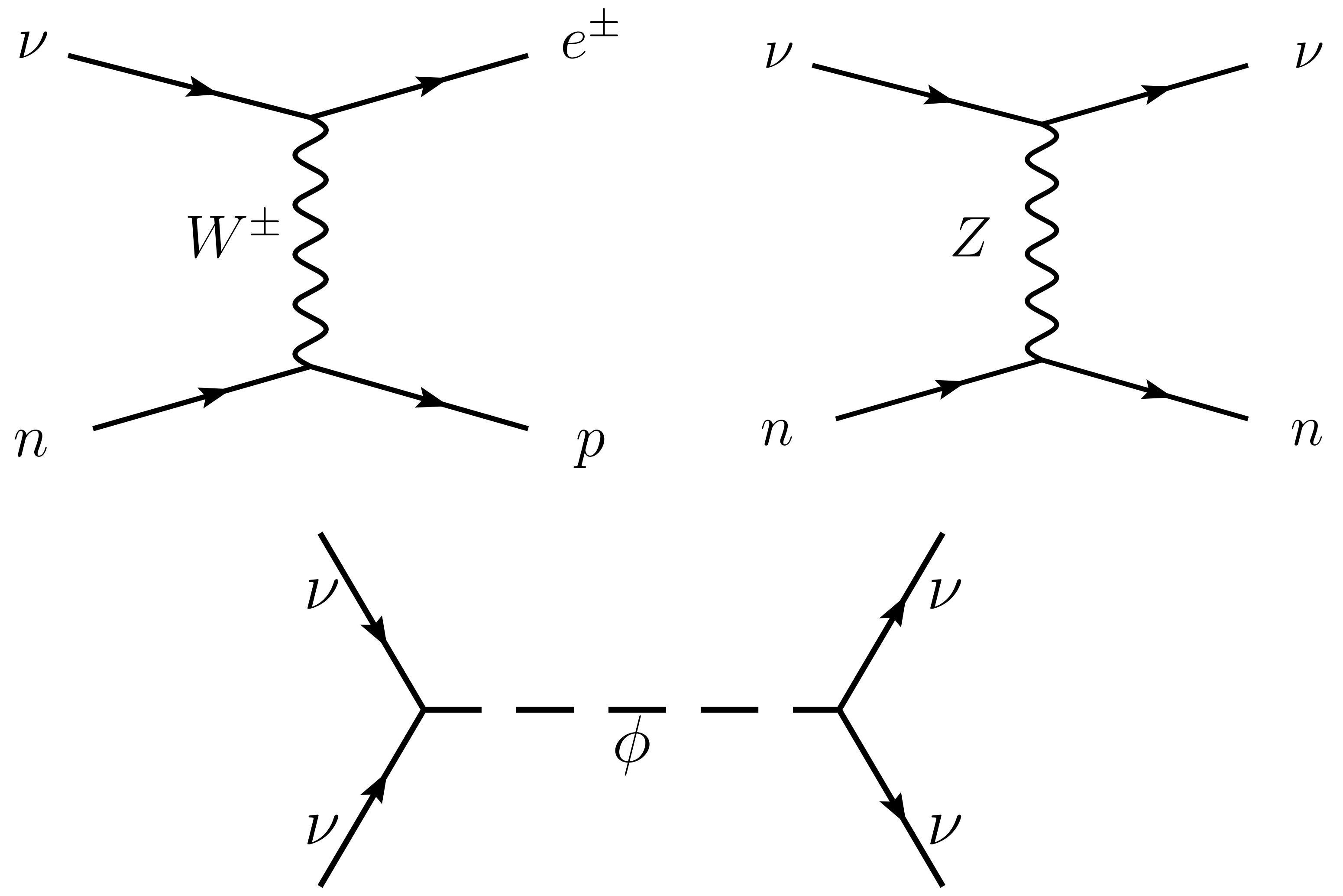
- **Step 2: Calculate active-sterile neutrino mixing in matter**

**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**

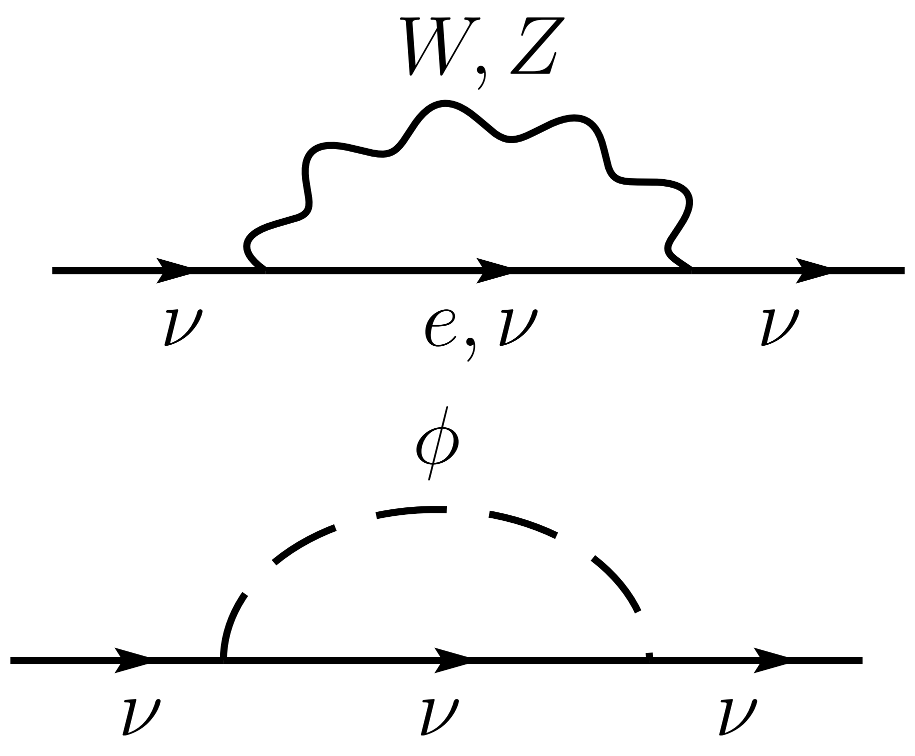
$$\Gamma = \Gamma_{weak} + \Gamma_{\phi}$$



**Effective Potential**

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

**Thermal potential**



**Matter asymmetries**

# Cooling Rate Calculation: A Sketch

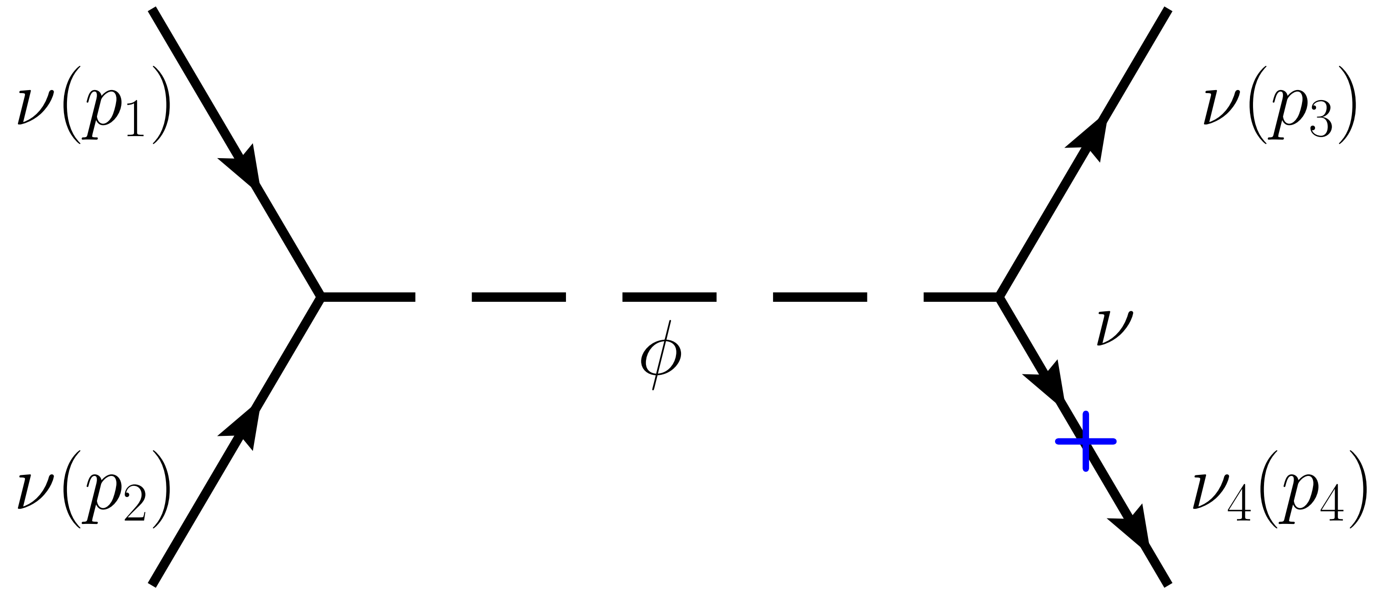
- **Step 3: Optical depth, or $\nu_4$ energy loss due to scattering**

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

**Interaction Rate**

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

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



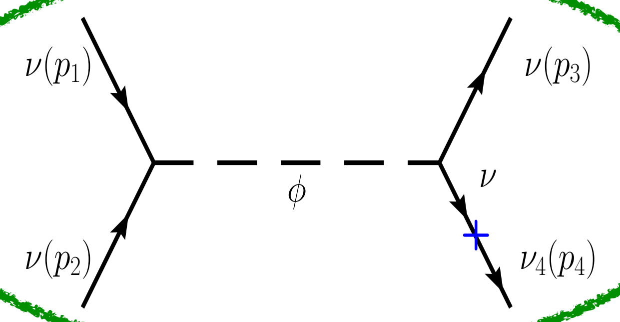
$$|\mathcal{M}|^2 = 32\pi^2\lambda^2\, m_\phi^2\, \delta(s - m_\phi^2)\, \sin^2\theta_{\rm eff}(r, E_4)$$

- **Step 4.5: Profit**

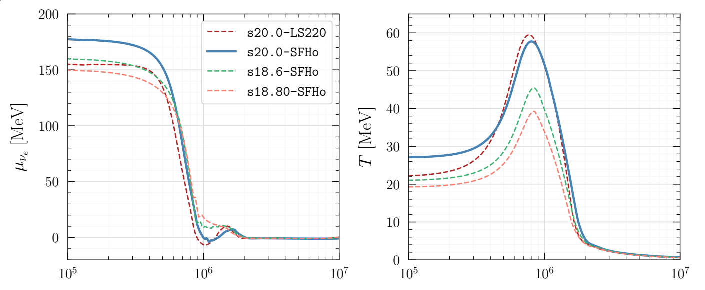
# Cooling Rate Calculation: A Sketch

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

**S$\nu$DM production**



**SN Profile**

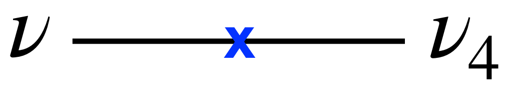


$$L = \frac{\lambda^2 m_\phi^2}{4\pi^2} \int_0^{4R_c} r^2 dr \int_0^\infty dE_1 f(E_1, r) \int_{m_\phi^2/(4E_1)}^\infty dE_2 f(E_2, r) \frac{1}{\sqrt{(E_1+E_2)^2 - m_\phi^2}}$$

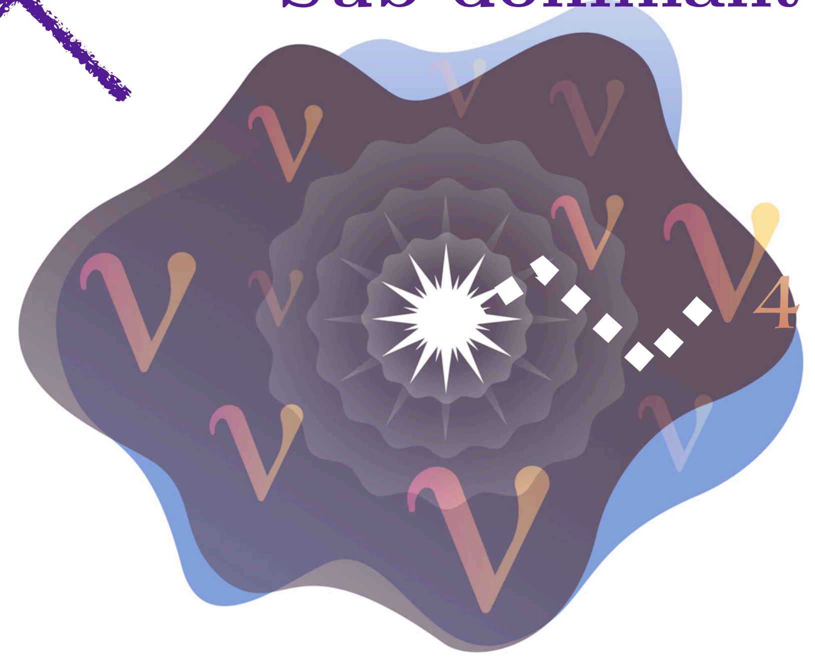
$$\times \int_{\frac{1}{2}\left(E_1+E_2-\sqrt{(E_1+E_2)^2-m_\phi^2}\right)}^{\frac{1}{2}\left(E_1+E_2+\sqrt{(E_1+E_2)^2-m_\phi^2}\right)} dE_4 \sin^2\theta_{\text{eff}}(r, E_4)\, E_4\, e^{-\tau(E_4, r)}$$

**Re-absorption.**
**Sub-dominant effect**

**Matter effects**

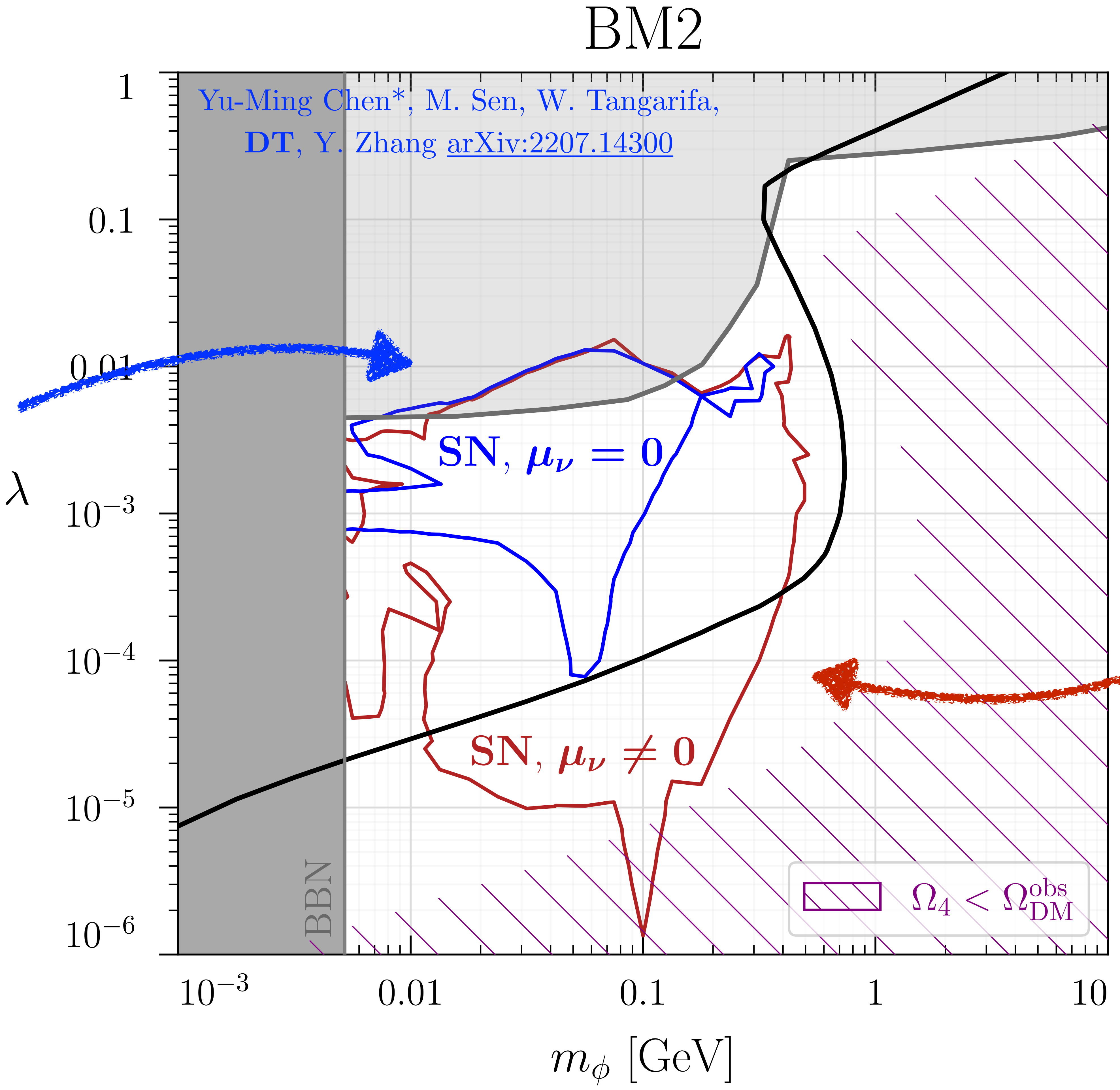


$\Gamma(E, r)$, $V(E, r)$



# Supernova Cooling Bounds

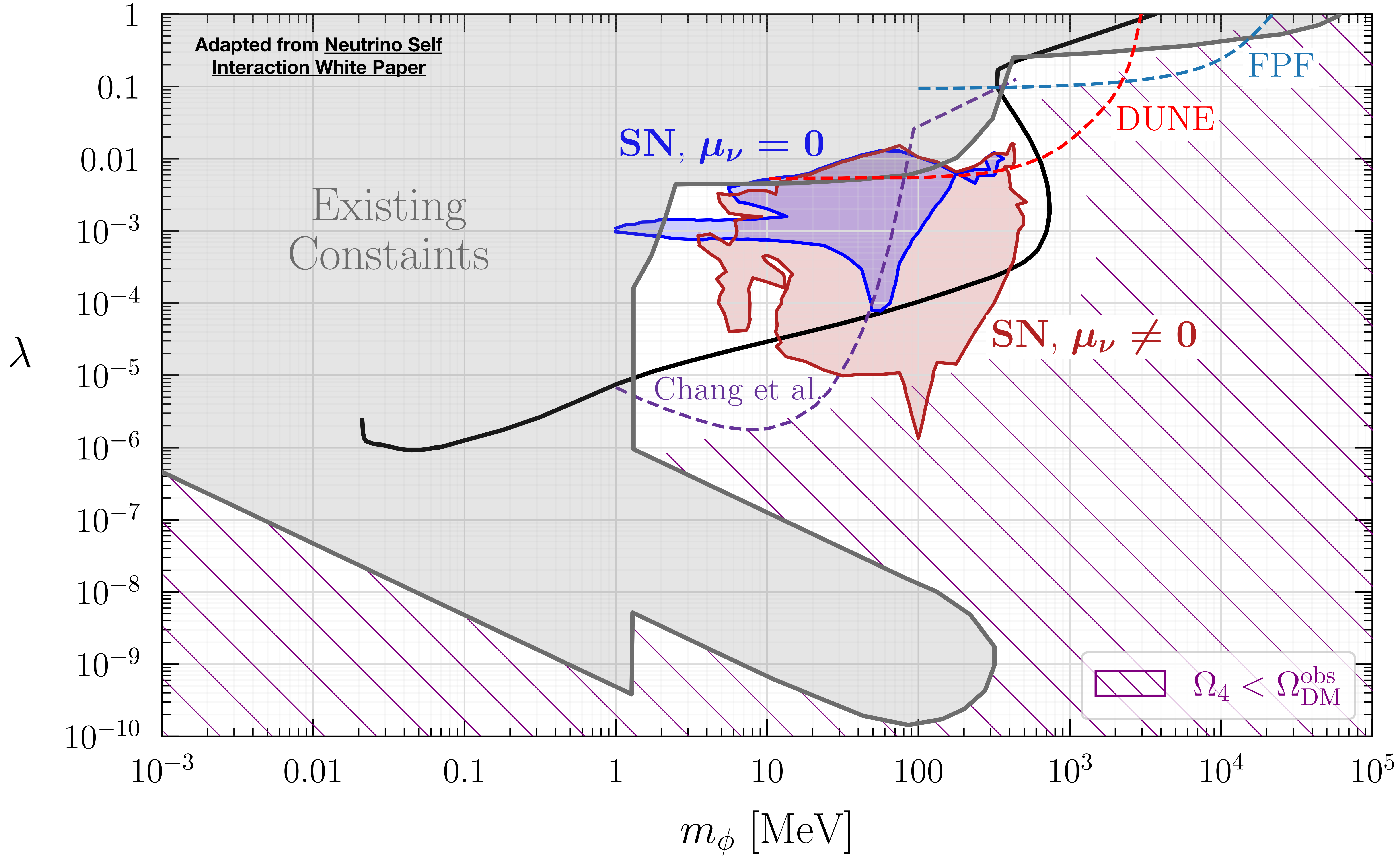
- Observations of SN1987 bound the emission luminosity to be $L \lesssim 3 \times 10^{52}$ ergs/s



Zero chemical potential

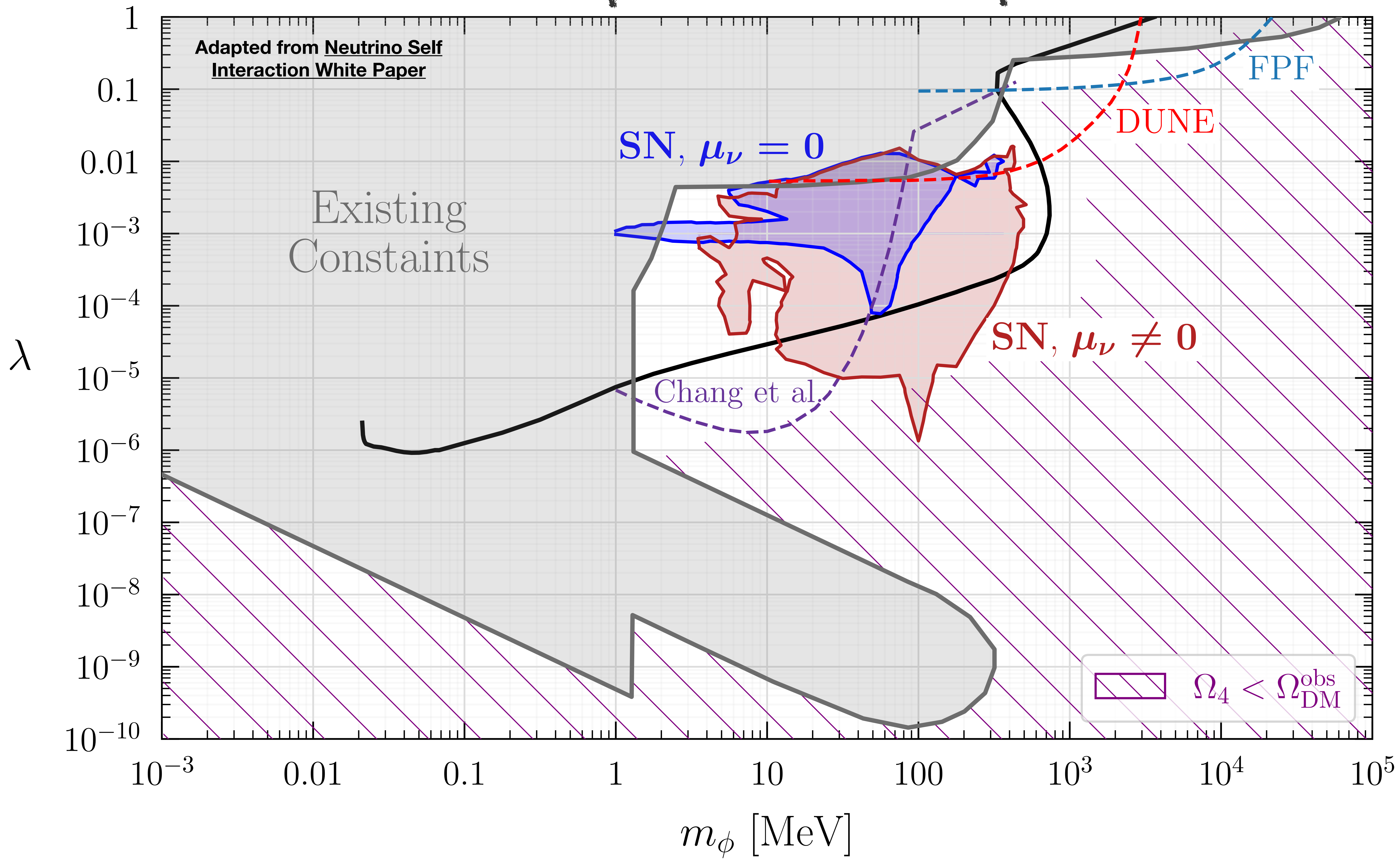
Non-zero chemical potential

# 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
$\Omega_4 < \Omega_{\rm DM}^{\rm obs}$
$\lambda$
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
$10^3$
$10^4$
$10^5$
$m_\phi$ [MeV]

# Big Picture

**Cosmology** | **Astrophysics** | **Colliders**


Adapted from Neutrino Self Interaction White Paper

**Great complementarity between different probes of neutrinophilic DM!**

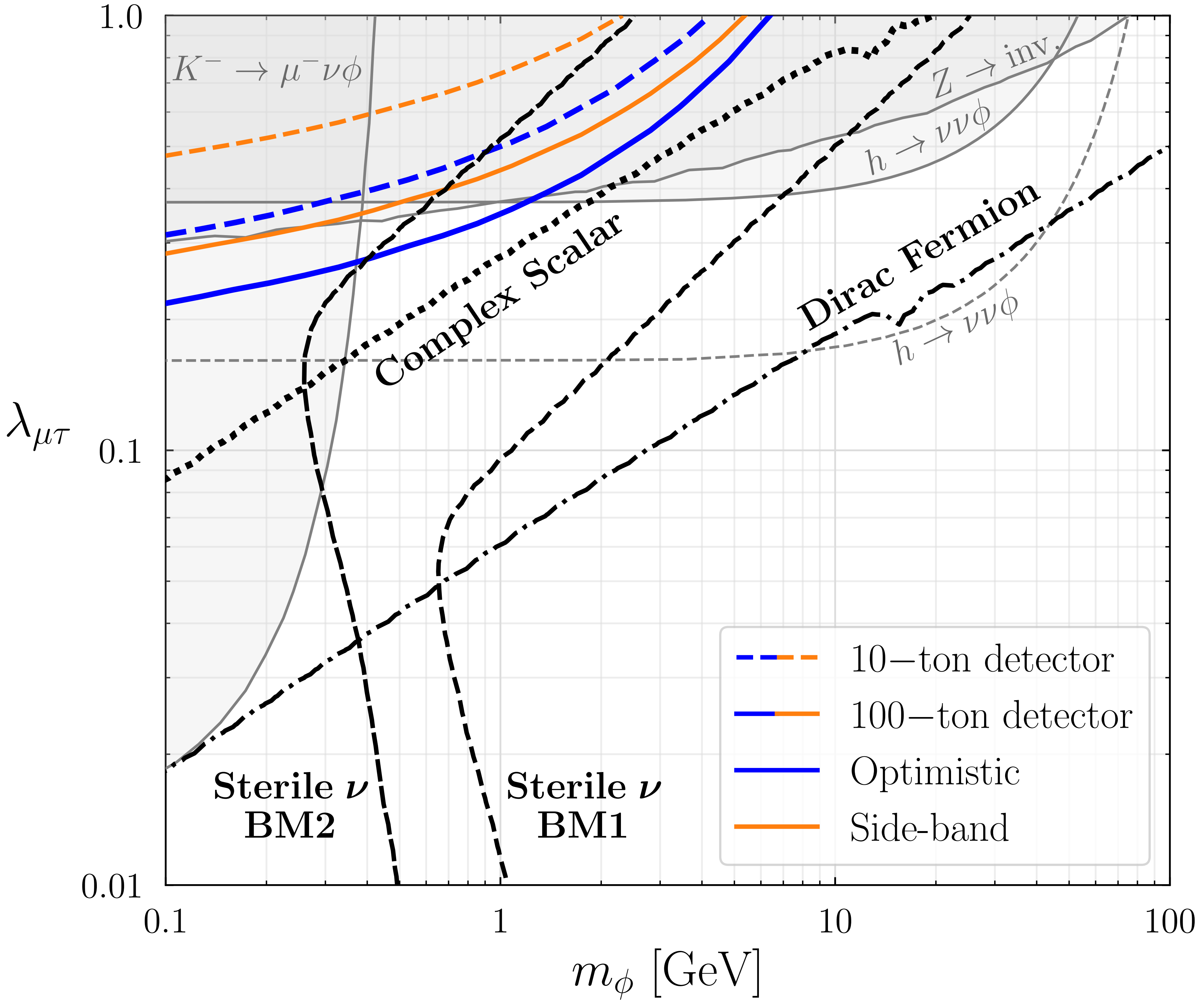
Thanks!

Questions?

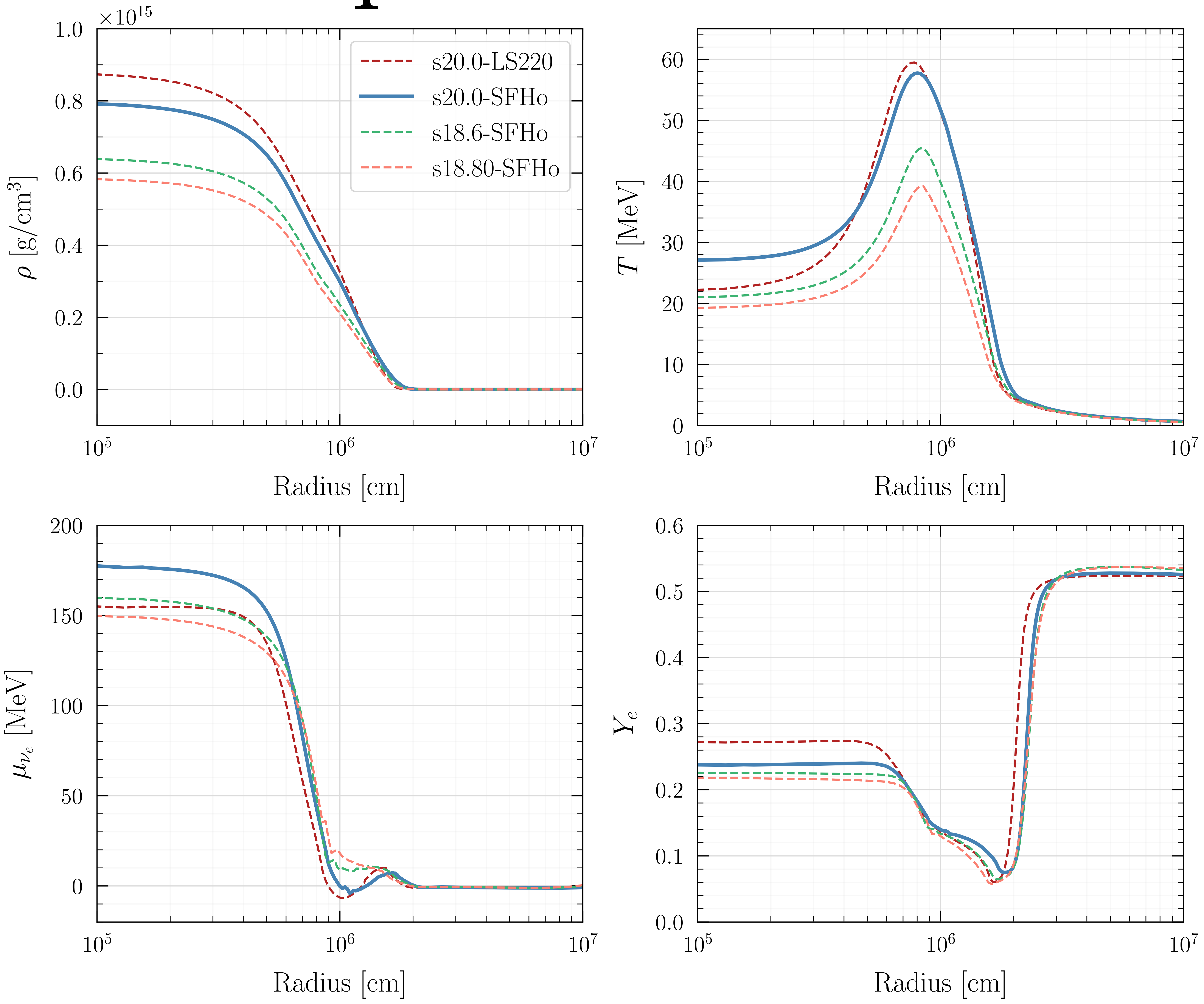
# Back up

# 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



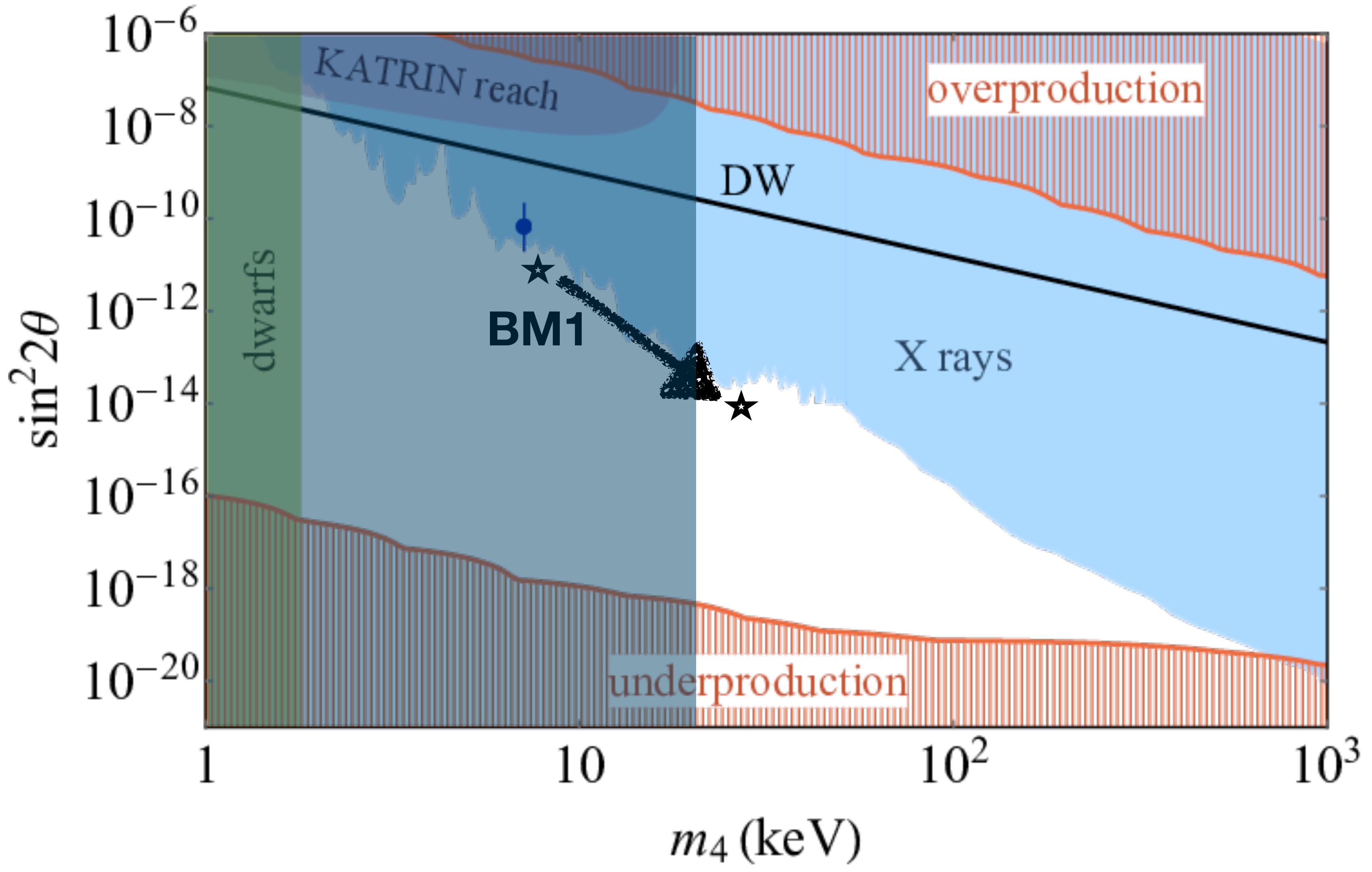
# Supernova Profile



# 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 $\lambda$.**
**Run into existing constraints.**
**See arXiv:2301.08299**