Snowmass 2021 Rare&Precision Frontier (RF6): Dark Matter Production at Intensity-Frontier Experiments

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Dark matter particles can be observably produced at intensity-frontier experiments,* and opportunities in the next decade will explore important parameter space motivated by thermal DM models, the dark sector paradigm, and anomalies in data.

* includes: forward LHC searches, LHCb, FASER, etc – focusing on the low-pair-mass, high-intensity region.

Outline of this Talk

Summary of Big Idea 1 Whitepaper

- Scope, Outline, and Process
- Executive Summary Message
- Figures

Discussion

Process

Dec 2020: "Big Idea" **whitepaper scopes formulated** in town-hall meetings pre-pause.

Jan 20: **town hall meeting on Big Idea 1 WP** & survey of interest in helping with writing and plots + reached out to some additional authors to request contributions

April: Complete **draft circulated** on RF6 slack channel for feedback

May: **Community discussion** at Cincinnati rare frontier meeting and follow-up virtual meeting. Key outcomes for BI1:

- Simplified sensitivity plot for executive summary
- Request from RF conveners to include a "thermal targets at accelerators and in DD" plot
- Offline feedback on wording about specific experiments
- Comments on role of theory added to Exec Summary and Road Ahead

Revised WP circulated June 29 & posted to arxiv July 1

- One feedback on wording about specific experiments

Exec. Summ	Context/motivation — accelerator production — opportunities
Introduction	Thermal origin cosmology, WIMPs vs. LDM, portals to SM
Approaches	Missing Mass/Energy/Momentum [colliders & fixed targets] Re-scattering signals Semi-visible signals
Models & Frameworks	Thermal production milestones Vector portal (& param variation) Other vectors Scalar mediators Neutrino portal Non-minimal DM Millicharges
Discussion & Road Ahead	Experimental synergy, connections to other RF/frontiers, complementarity to other DM searches…

Executive Summary

6-page "Executive Summary" in Big Idea 1 paper
→ section of RF6 Topical Group report

- Context and Motivation
- Accelerator Production of Light DM
- Science Opportunities and Road Ahead

} Summarize the main points and key figures

Further compressed to 2/3 page in introduction of RF6 Topical Group report.

Executive Summary – Context and Motivation

Dark matter is sharp evidence for BSM physics

The range of DM candidates is immense, but observed abundance + a thermal production scenario define a natural goalpoast.

Lots of community interest in light DM, which keeps many simple features of WIMPs but extends to new mass range and poses different experimental challenges & opportunities. Light DM models rely on light force carriers coupling weakly to SM – and theoretically motivated small couplings are well aligned with what's needed for freeze-out!

Executive Summary – Accelerator Production of Light DM

Laboratory production of Light DM by intensity-frontier experiments — including dedicated fixed-target experiments, small forward detectors, and flavor factories — **has emerged as an essential strategy for exploring light DM**. These experiments are **optimized for intensity, instrumentation precision, and/or background rejection rather than energy reach.**

Classification of strategies:

- *Missing energy, momementum, or mass searches* use kinematics of visible particles recoiling from DM production + veto on SM products
- *Re-scattering experiments* search for DM and/or millicharges via subsequent scattering in a forward detector
- *Semi-visible searches* leverage the possibility of metastable dark sector resonances – often motivated by specific models of DM cosmology – that decay into a combination of DM and visible SM particles.

Executive Summary – Accelerator Production of Light DM

Mimicking Big Bang Dark Matter Production at Accelerators

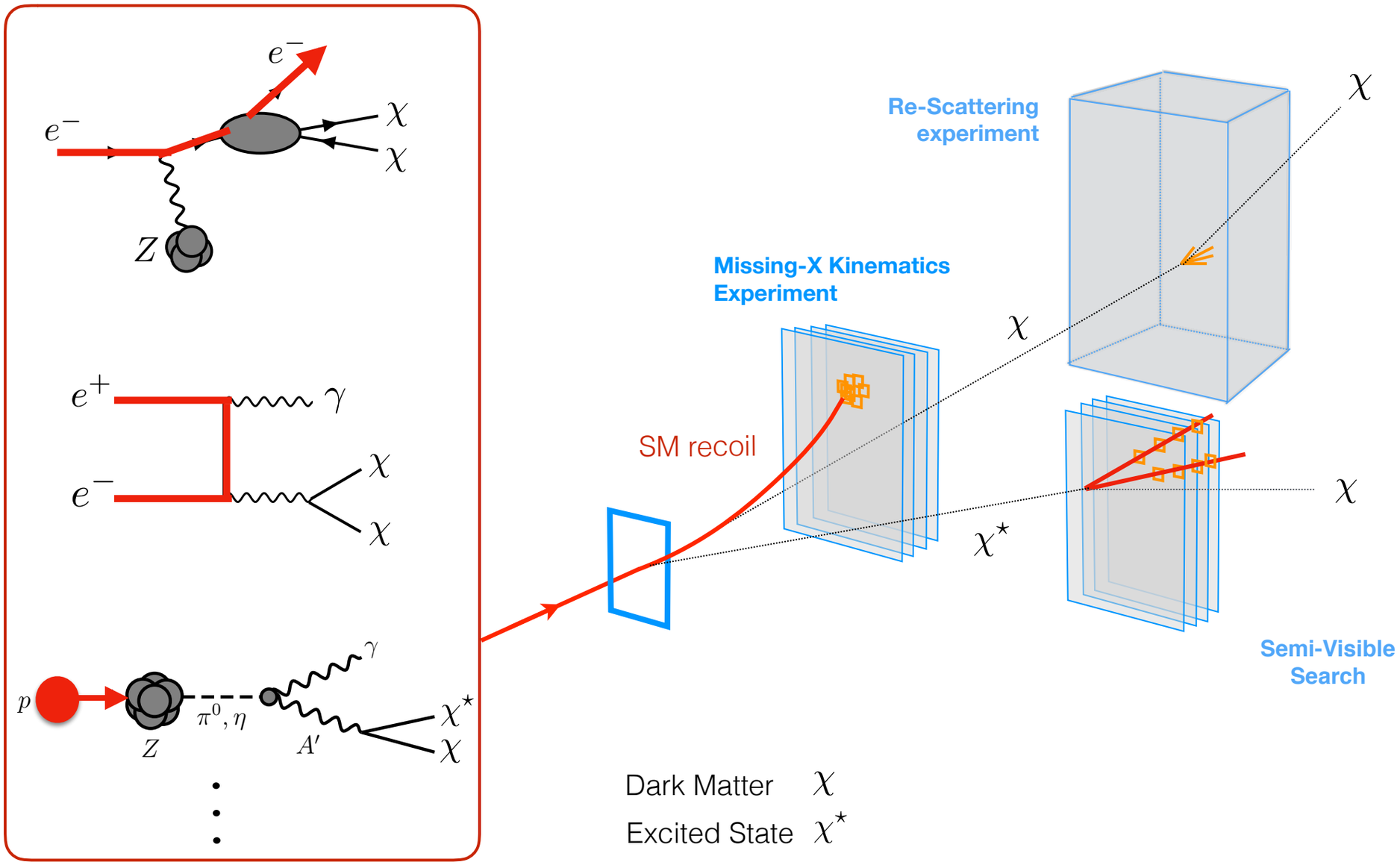


FIG. 1: Illustration of representative DM production mechanisms (left) and (right) the concepts for detecting DM production via, clockwise from left, missing X, re-scattering, and semi-visible detection strategies.

Executive Summary – Accelerator Production of Light DM

Complementarity with low-threshold DD:

- Probe different properties (particle properties @accel, combination w/ cosmic abundance at DD)
- Explore different kinematics (v<<c in DD, v~c at accel)
  - Low-threshold DD has enhanced sensitivity to Coulombic scattering as in light-mediator freeze-in)
  - Accelerators are optimal for discovery of DM with suppressed interactions at low velocity, including freeze-out through dark photon with generic spin/mass structure.
- Where both are effective (e.g. elastic scalar thermal freeze-out), exciting opportunities for combined characterization of a signal

Executive Summary – Accelerator Production of Light DM

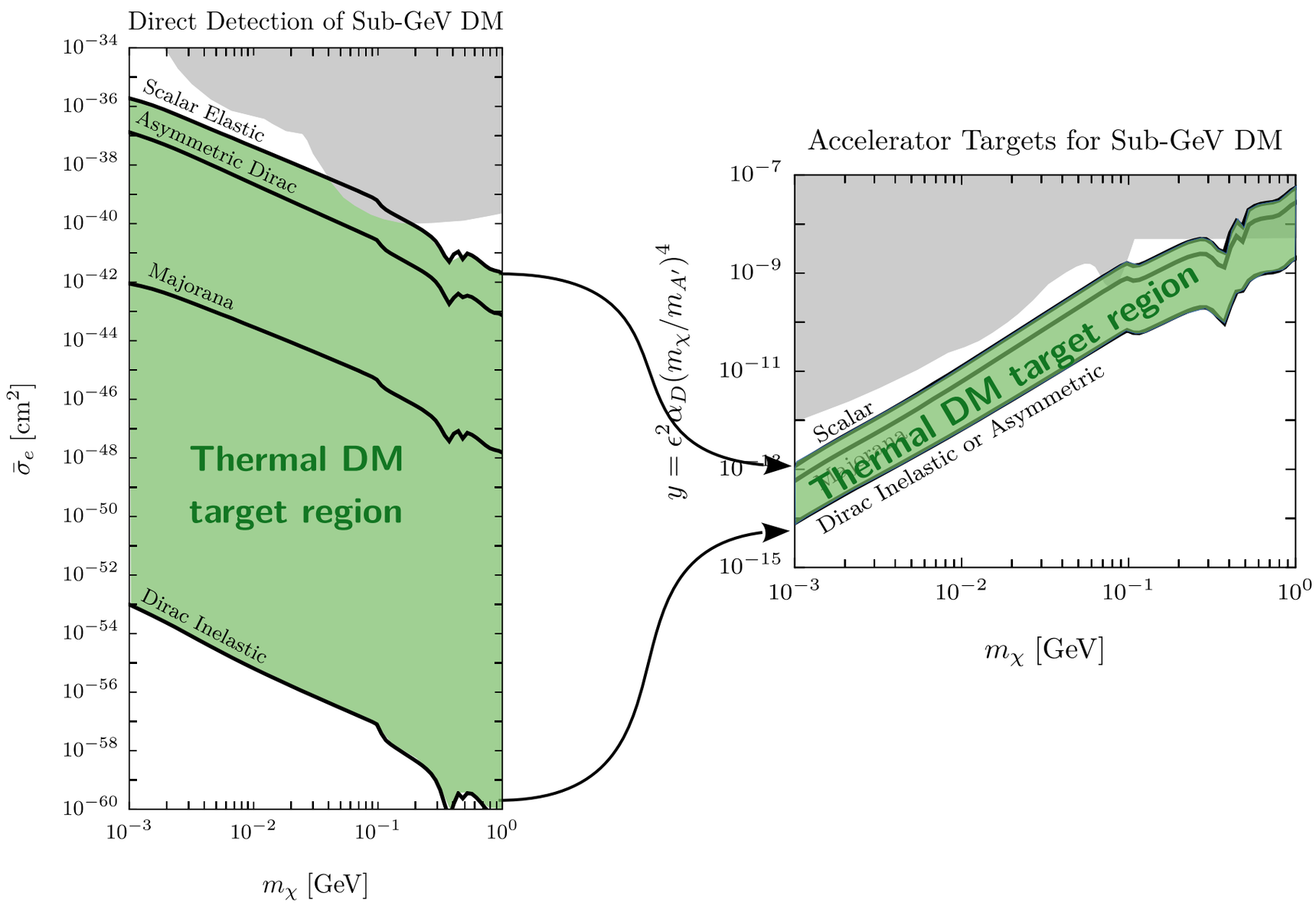


FIG. 2: Comparison of sub-GeV DM thermal production targets in the direct detection plane in terms of the electron cross section (left) and on the accelerator plane in terms of the variable y (right). Since accelerator production mimics the relativistic kinematics of the early universe, the corresponding signal strength is never suppressed by velocity, spin, or small degrees of inelasticity, so the targets are closer to experimentally accessible regions of parameter space. Note, however, that direct detection sensitivity has a complementary enhancement for DM candidates with Coulombic interactions, which are enhanced at low velocity.

Executive Summary – Science Opportunities and Road Ahead

- Key goal over last decade: broadly exploring DM models in the MeV to GeV mass range.
- **Two big takeaways:**
  - **DMNI and data analysis efforts achieve something important to the community.**
  - **There is strong motivation to go beyond DMNI, even *within* the focus on DM production.**

DMNI and data analysis efforts achieve something important:

- Thermal freeze-out via *s*-channel dark photon is key benchmark model; identified as high priority milestone by Dark Matter New Initiatives BRN

- DMNI funding will enable CCM and LDMX – mainly sensitive to DM below 1/2 GeV
- Complemented by Belle II for ~GeV DM masses
- Together, sensitive to benchmark/milestones (see figure) and robust to many variations

Executive Summary – Science Opportunities and Road Ahead

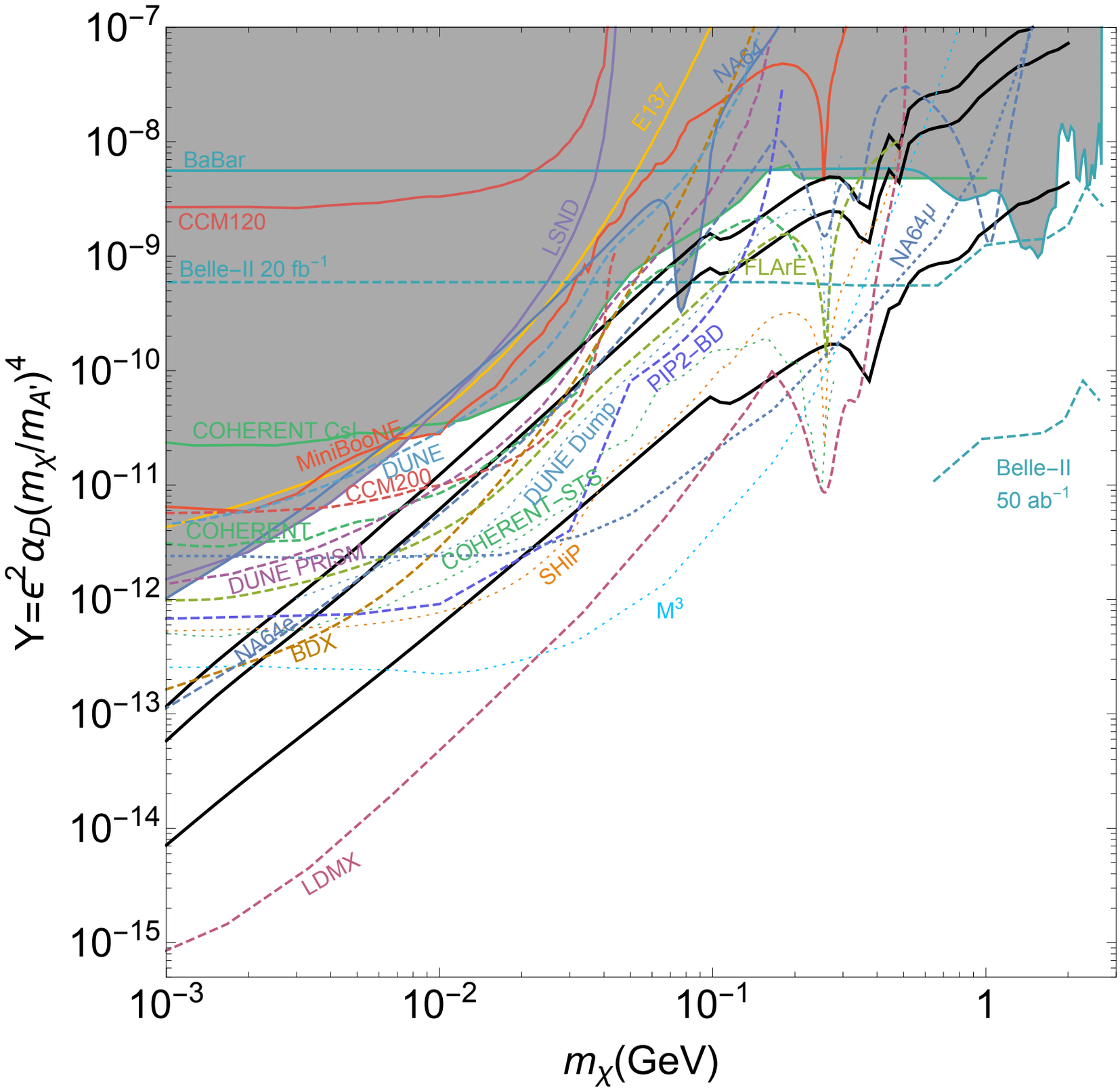
There is strong motivation to go beyond DMNI, even *within* the focus on DM production:

- Within s-channel dark photon like freeze-out picture:
  - Complementary techniques assure robust program & measurement opportunities
  - generalizations of thermal freeze-out preferentially coupled to heavy leptons or baryons over electrons

- Beyond s-channel dark photon like picture:
  - Models with meta-stable dark particles (semi-visible)
  - Neutrino portal annihilation
  - Millicharged particles

- Finally, emphasize importance of theory.

Executive Summary – Science Opportunities and Road Ahead



Plot style presented at Cincinnati and in body of text (Fig. 5a).

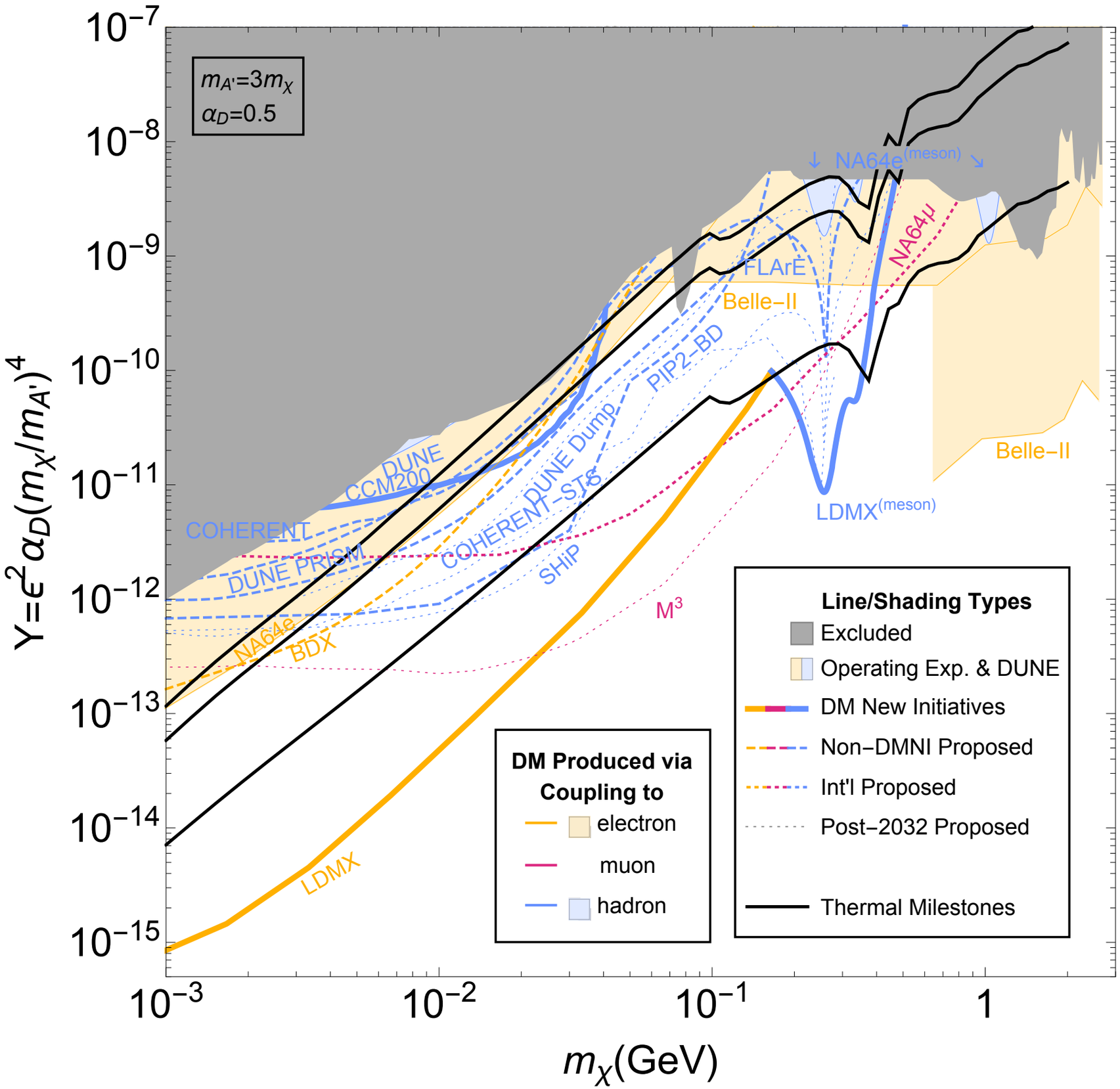
Several iterations of community feedback: Visually simplify, while supporting

(a) overall RF6 narrative of 3 stages (analyses at ongoing/planned experiments, DMNI experiments, future iterations)

(b) scientific importance of US opportunities relative to international program

(c) value of probing non-electron couplings

Executive Summary – Science Opportunities and Road Ahead



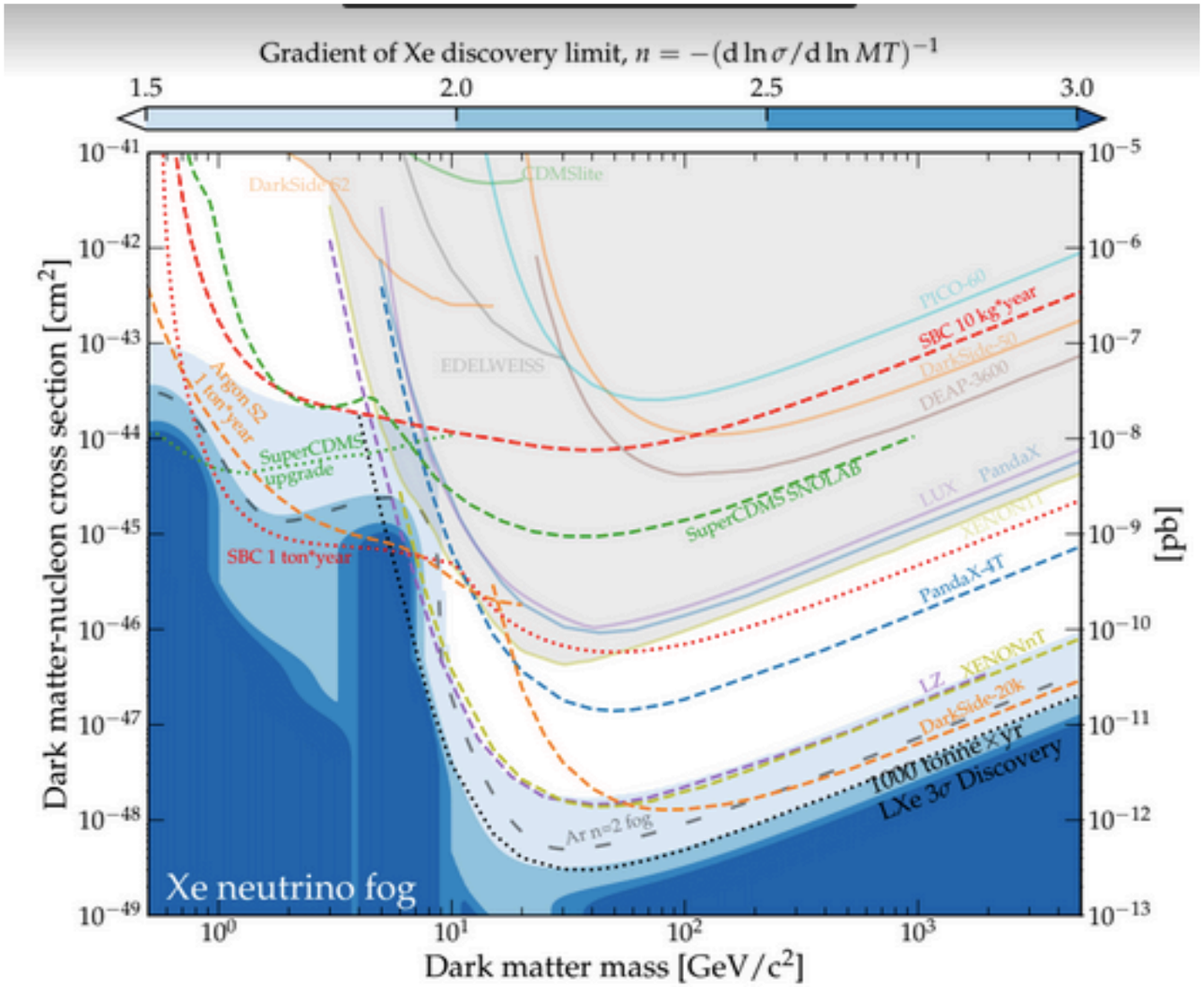
Shading/line format encode (a), (b) from last slide.

Color encodes (c)

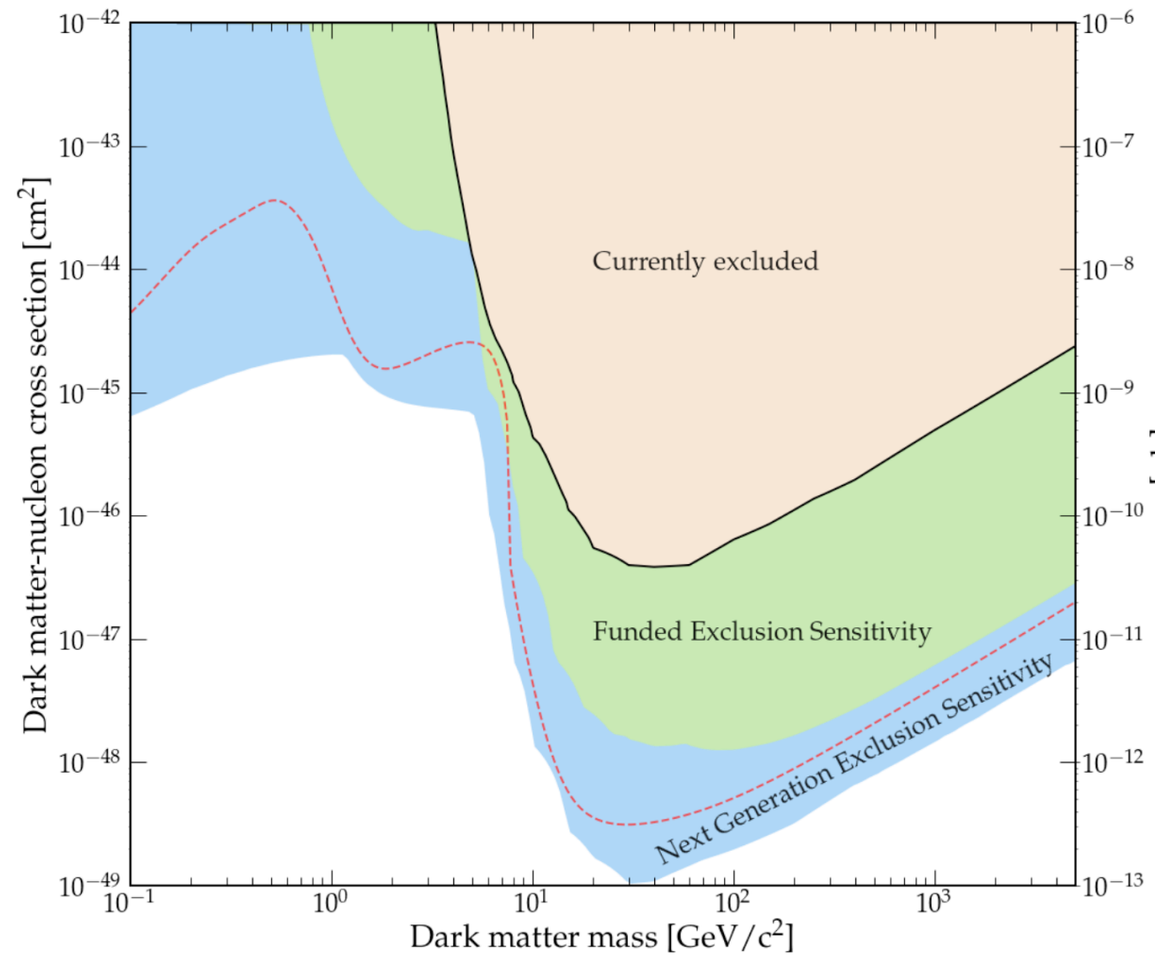
In slack discussion, decided to add experiment names all curves.

Personal take: We've struggled in the past to help agencies see past the large # of individual proposals. This is ok, but on the "busy" end of exec summary plots. Do we simplify further? (e.g. removing all names? grouping like curves? suppressing nuance?)

For comparison…



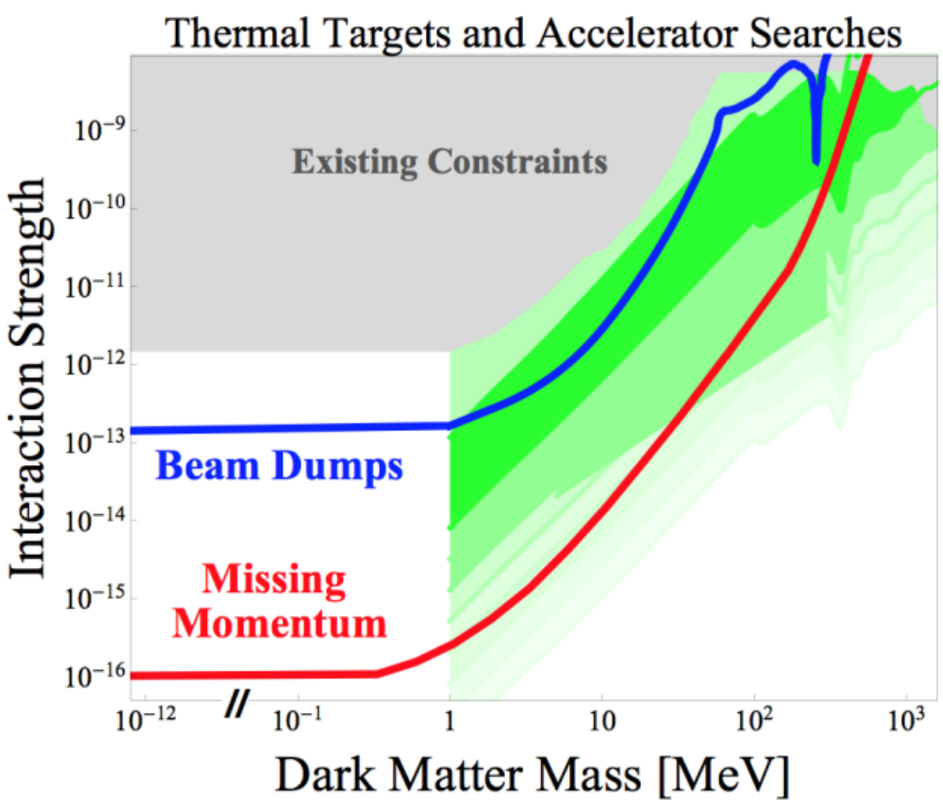
WIMP sensitivity plot from CF1 report 1st draft

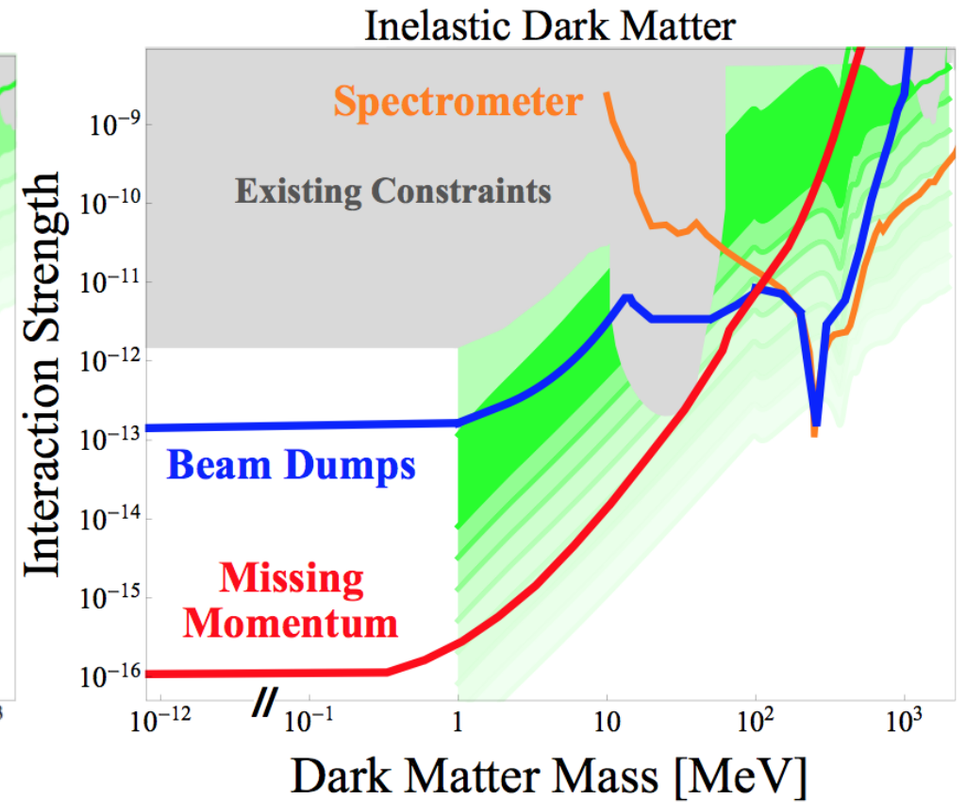


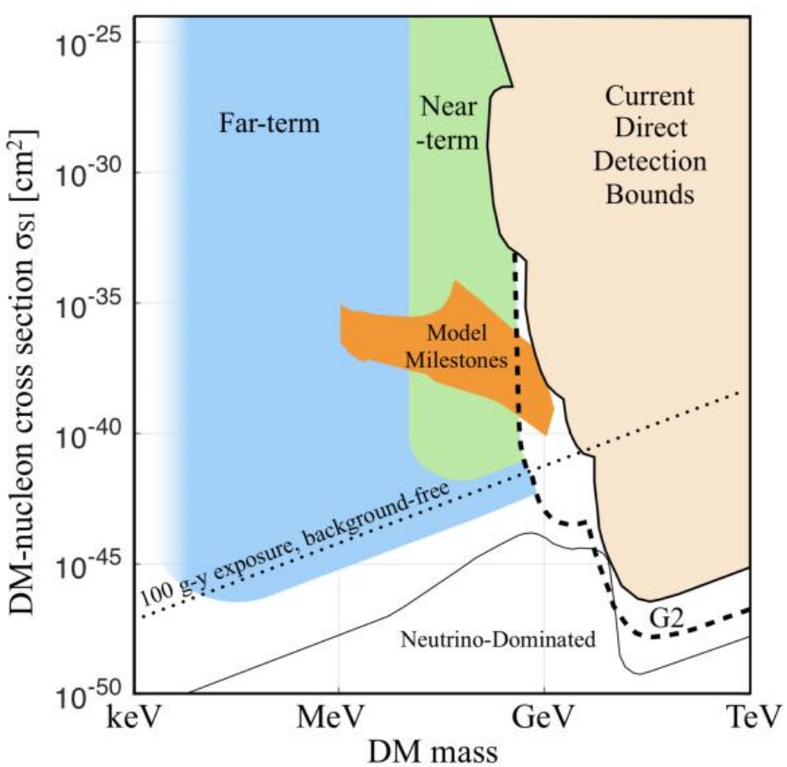
Proposed refinement for 2nd draft (highly preliminary – ongoing Slack discussion)

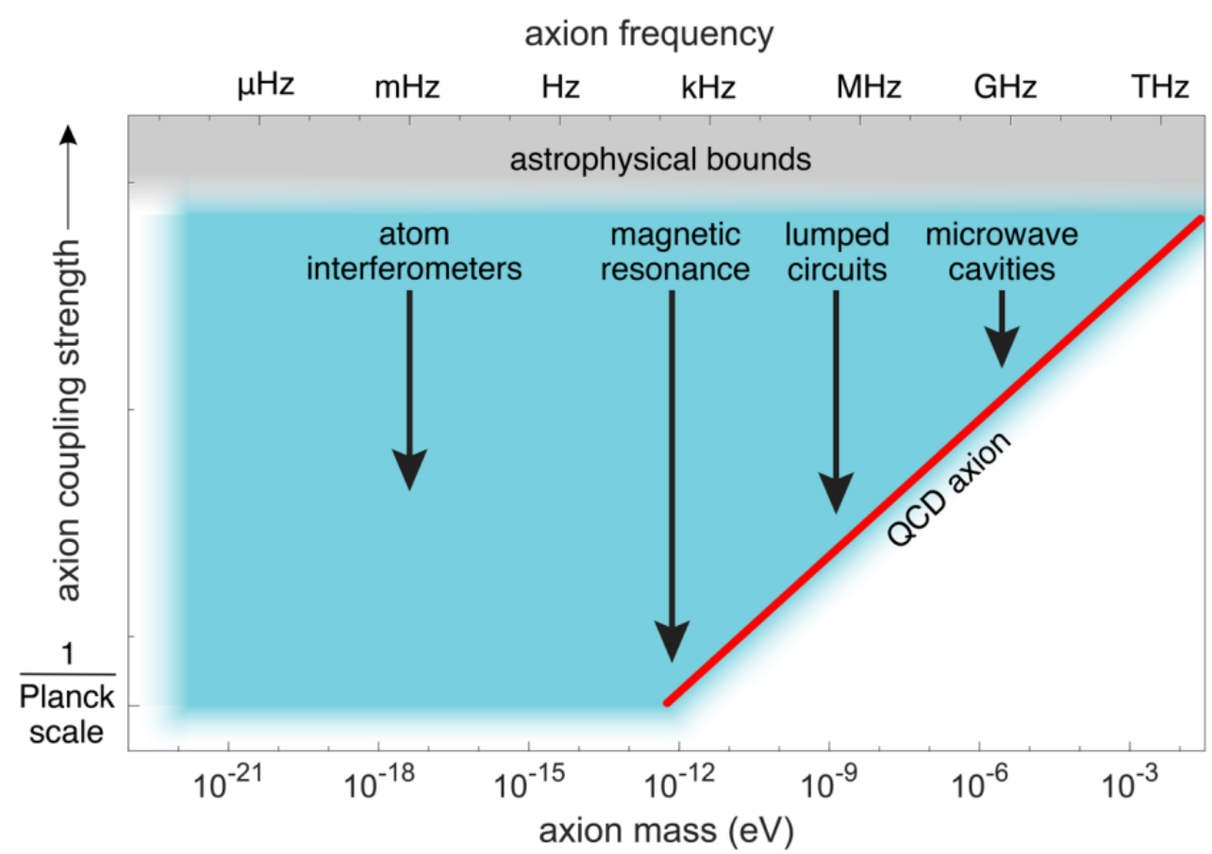
For comparison…

2018 BRN report









Executive Summary – Ultra-short summary

2/3 page summary in the RF6 topical group report

Big Idea 1: Dark matter production at intensity-frontier experiments

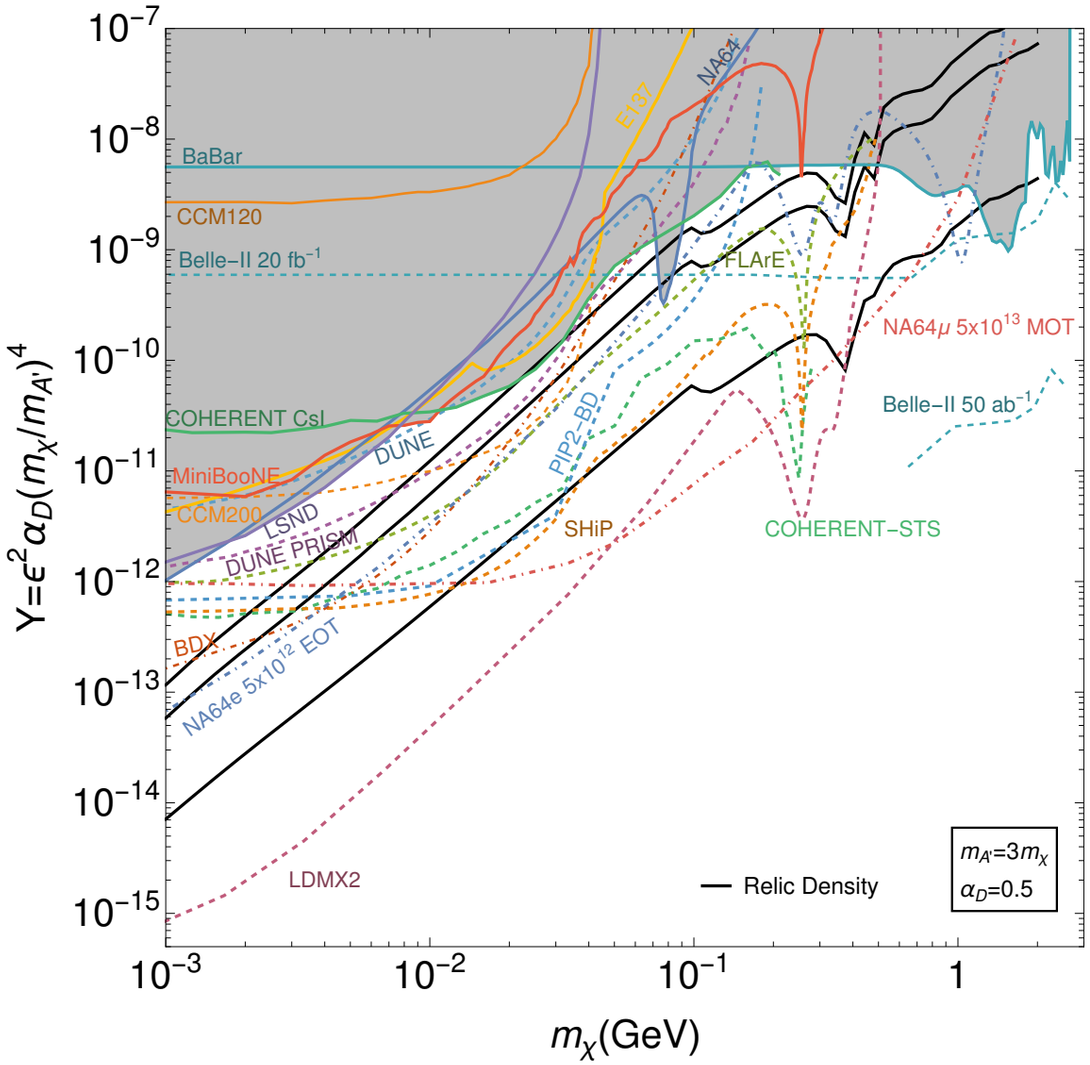
As discussed above, matter from a dark sector is an attractive DM candidate. Indeed, thermal freeze-out of light DM (below the proton mass) requires DM interactions through a light force carrier with feeble SM couplings, which arise naturally in a dark sector. Taken together, these arguments motivate an exciting program to search for light DM by producing it at intensity-frontier experiments.

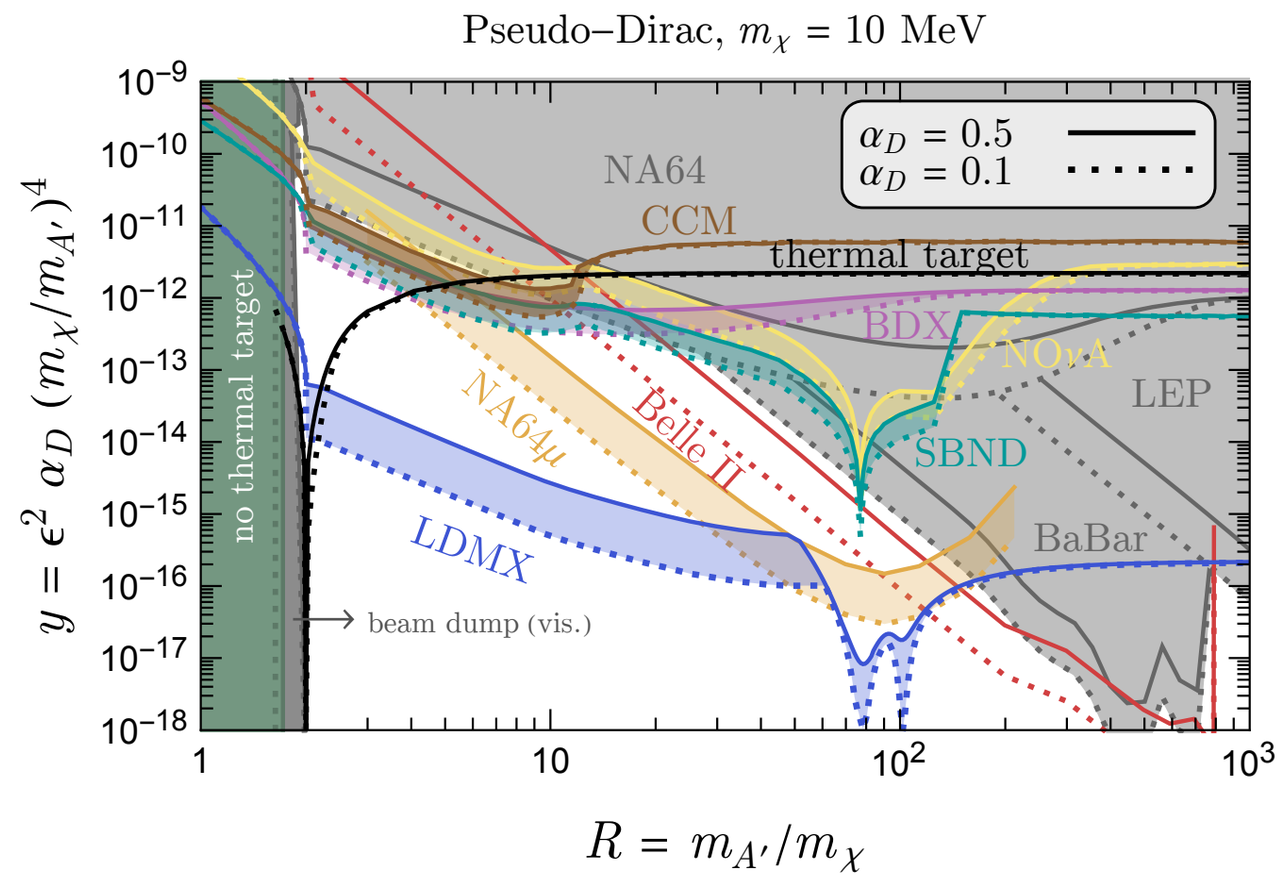
A particularly exciting opportunity is presented by the vector portal, where the simplest models of thermal freeze-out relate the cosmological abundance of DM to the signals expected at accelerator-based experiments, defining a sharp and high-priority milestone in DM interaction strength as a function of its mass. This milestone (illustrated by the black diagonal lines in Fig. 2) is not yet experimentally constrained over most of the MeV-to-GeV mass range. However, at interaction strengths 10 to 1000 times smaller than those presently explored, it is within reach of next-generation experiments.

Accelerator-based production of DM particles can be observed at intensity-frontier experiments, including dedicated fixed-target experiments, small forward detectors, and flavor factories. Three categories of search strategy, with complementary sensitivity, are employed: (i) inferring missing energy, momentum, or mass; (ii) detecting re-scattering of DM particles in downstream detectors; (iii) observing semi-visible signatures of metastable dark-sector particles.

In the next decade, the primary goal will be to explore parameter space motivated by thermal DM models, the dark-sector paradigm, and anomalies in data. Figure 2 shows that the milestone highlighted above—full exploration of the range of interaction strengths compatible with light DM thermal freeze-out via the simplest mechanism of s-channel annihilation to SM particles mediated by a dark photon (black diagonal lines in Fig. 2)—is achievable by near-future experiments. While for this one goal many future experiments seem redundant, the use of multiple complementary techniques is important: (i) to probe a broader class of thermal freeze-out models, such as those where a mediator, unlike the dark photon, does not couple to electrons; (ii) to test models where meta-stable particles in the dark sector play important roles in DM cosmology and enable new discovery techniques; (iii) to explore neutrino portal annihilation, which has qualitatively different experimental signals. These opportunities are highlighted and examined in more detail in Sec. 2 of this report and in a dedicated Snowmass white paper [2].

Plots from Main Body – Science Opportunities and Road Ahead

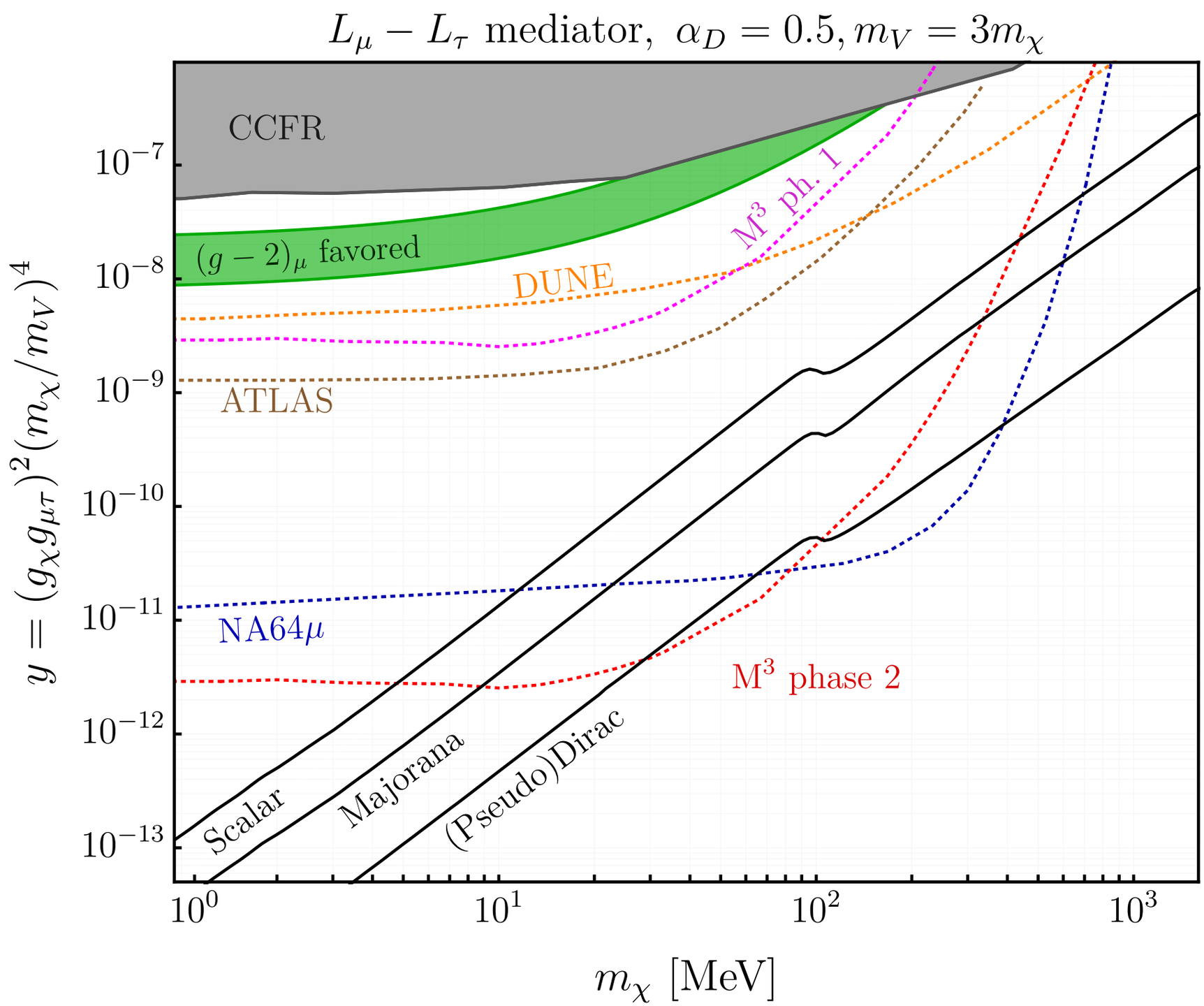




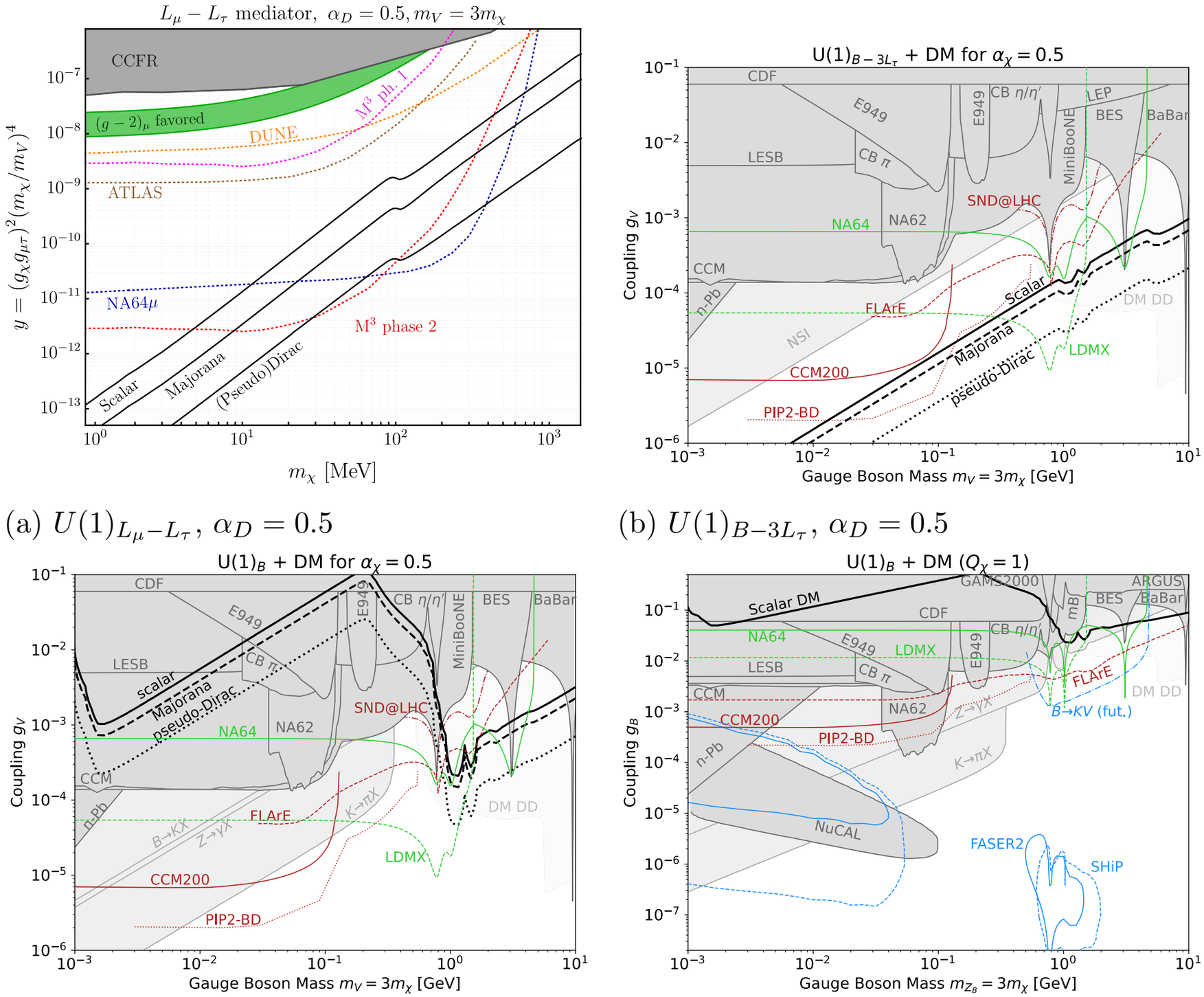
5a – same content as exec summary, but focus more on identifying each experiment (unique colors) and democratize line styles.

5b – parameter variation: varying DM to dark photon mass ratio, α_D

DM via anomaly free U(1) interactions



DM via anomaly-free and anomalous U(1) interactions



(a) $U(1)_{L_\mu - L_\tau}$, $\alpha_D = 0.5$ (b) $U(1)_{B-3L_\tau}$, $\alpha_D = 0.5$

(c) $U(1)_B^{(*)}$, $\alpha_D = 0.5$ (d) $U(1)_B^{(*)}$, $\alpha_D = \alpha_B$

FIG. 6: Thermal targets for several examples of a mediator V coupled to SM global symmetries. In the top four panels, we choose the conventional benchmark mass

Higgs Mixed Scalars

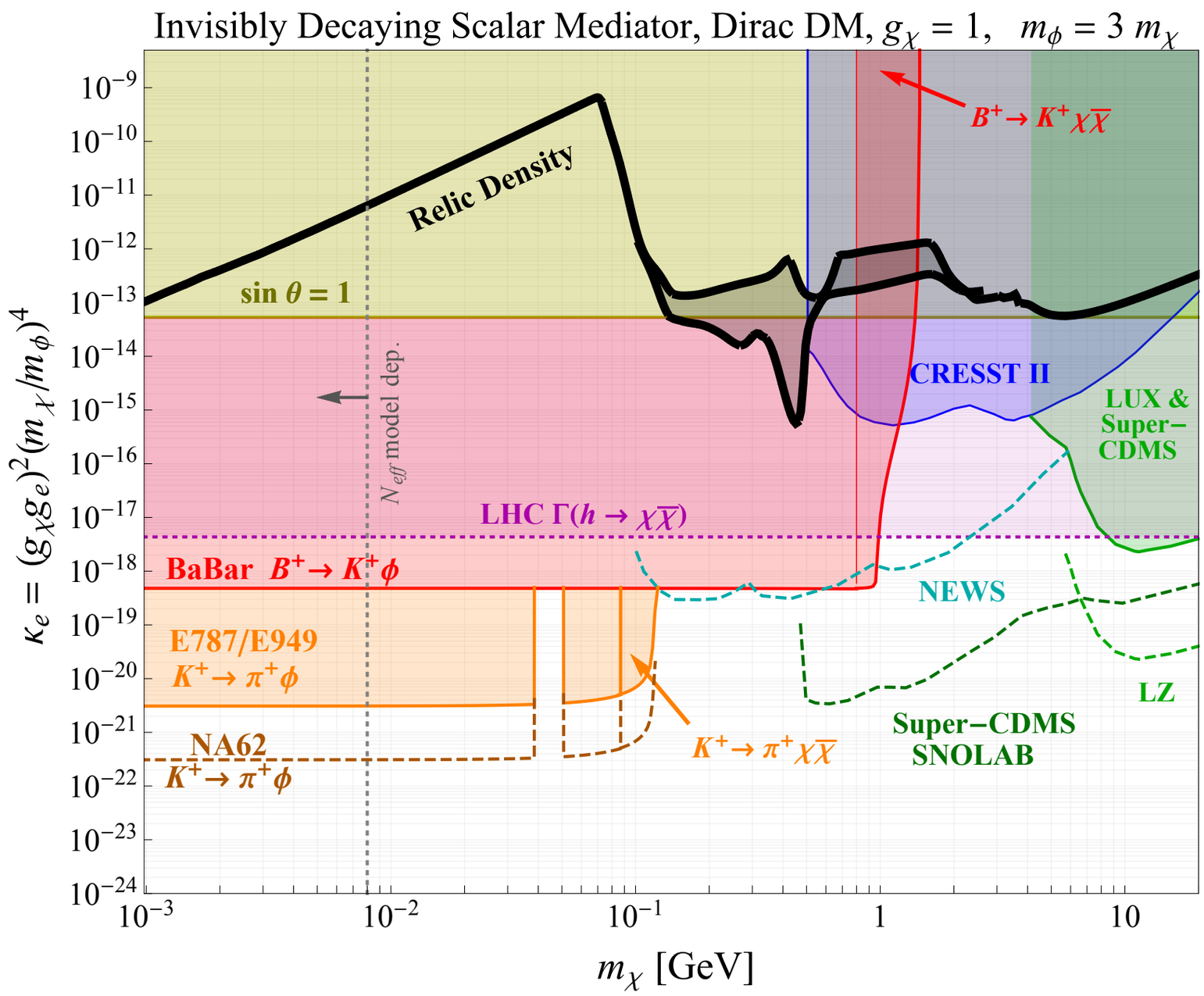


FIG. 7: Direct annihilation to SM particles through a light Higgs-mixed scalar [59]

Flavor Specific Scalars

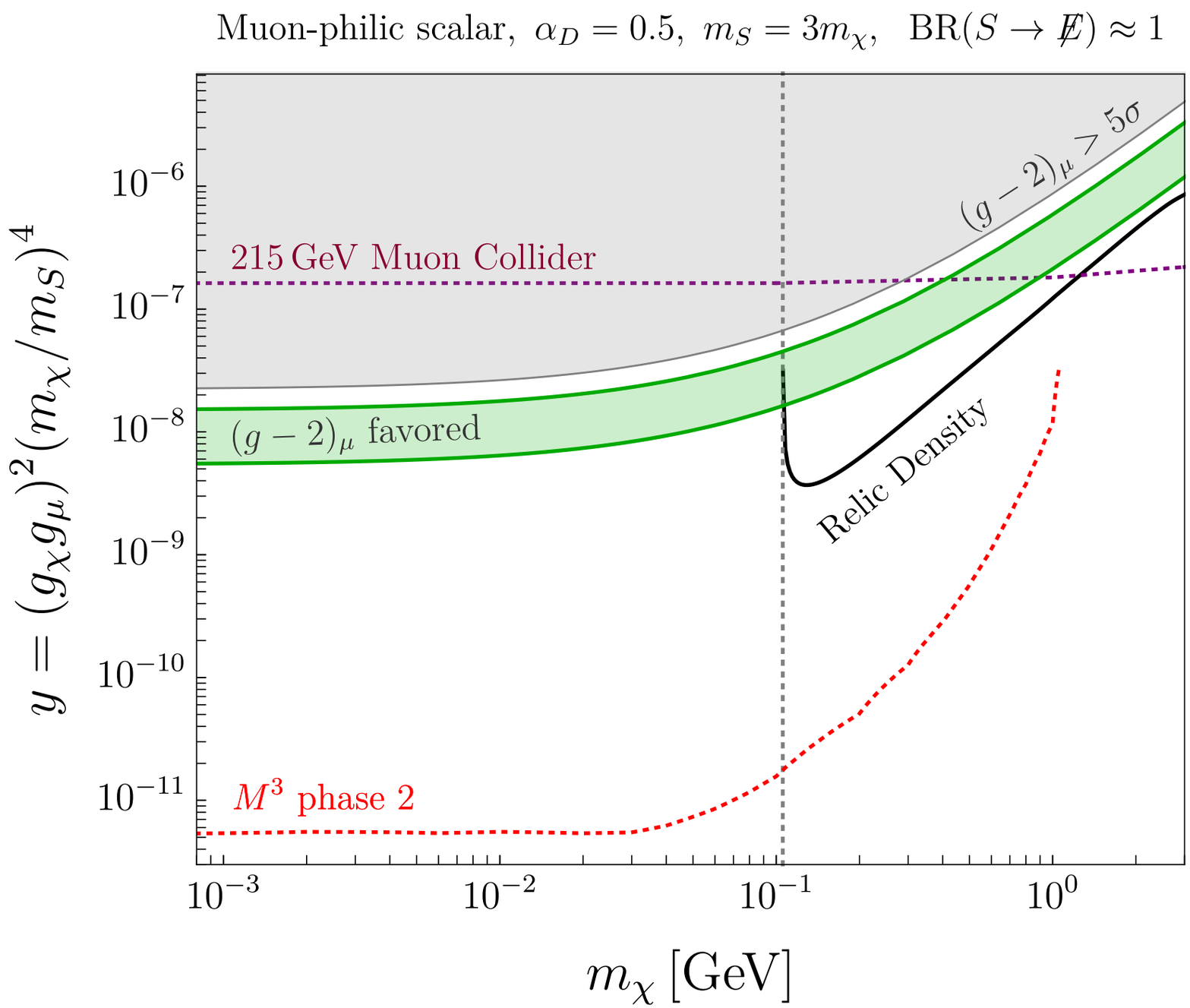
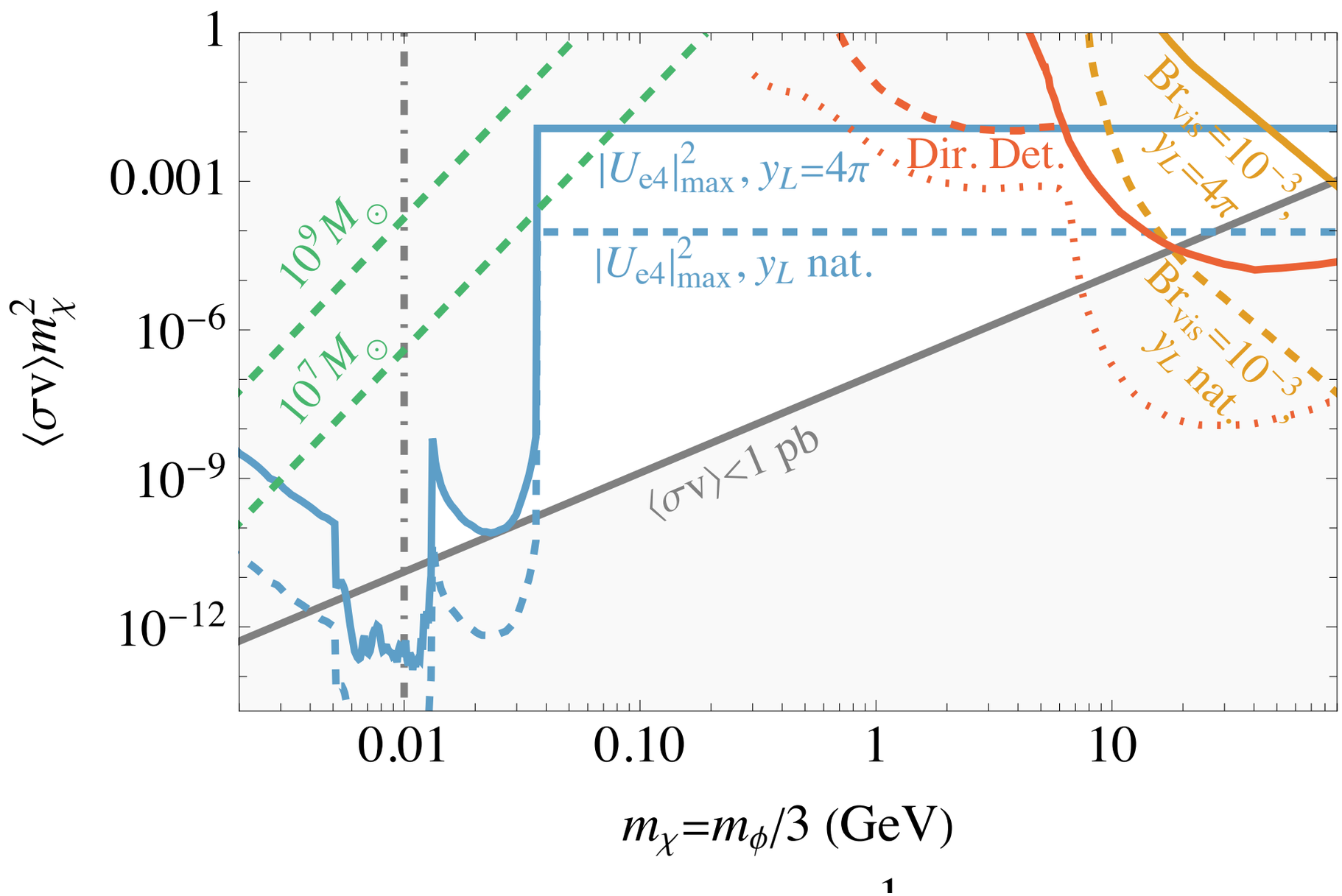


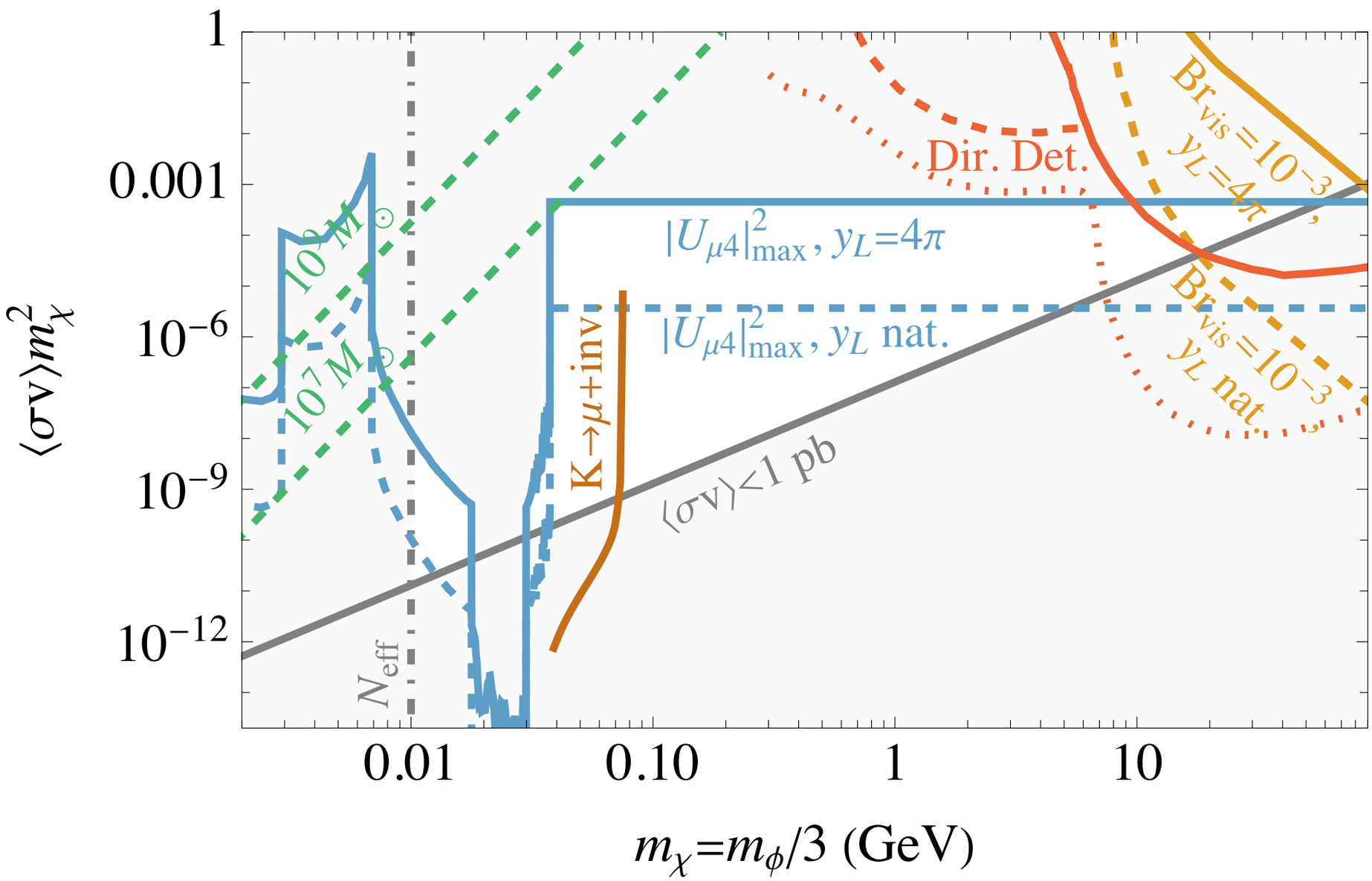
FIG. 8: Flavor Specific Scalar mediators couplings to muons. This model is one of only two viable scenarios for resolving the $(g-2)_\mu$ anomaly via SM singlet particles below the GeV scale [62]; the other option is gauged $L_\mu - L_\tau$ shown in Fig. 6.

Neutrino Portal



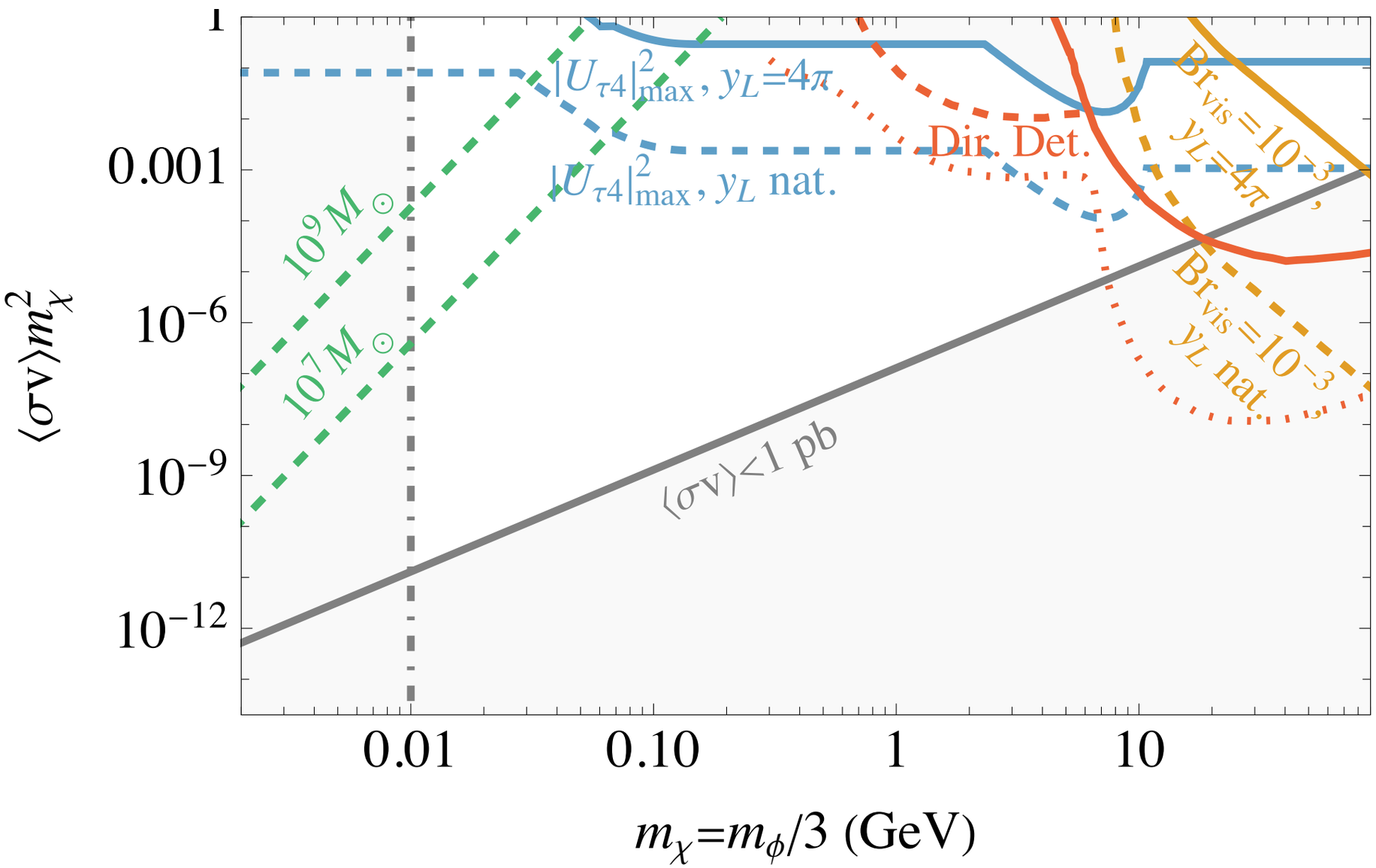
t-channel annihilation, electron flavor mixing

Neutrino Portal



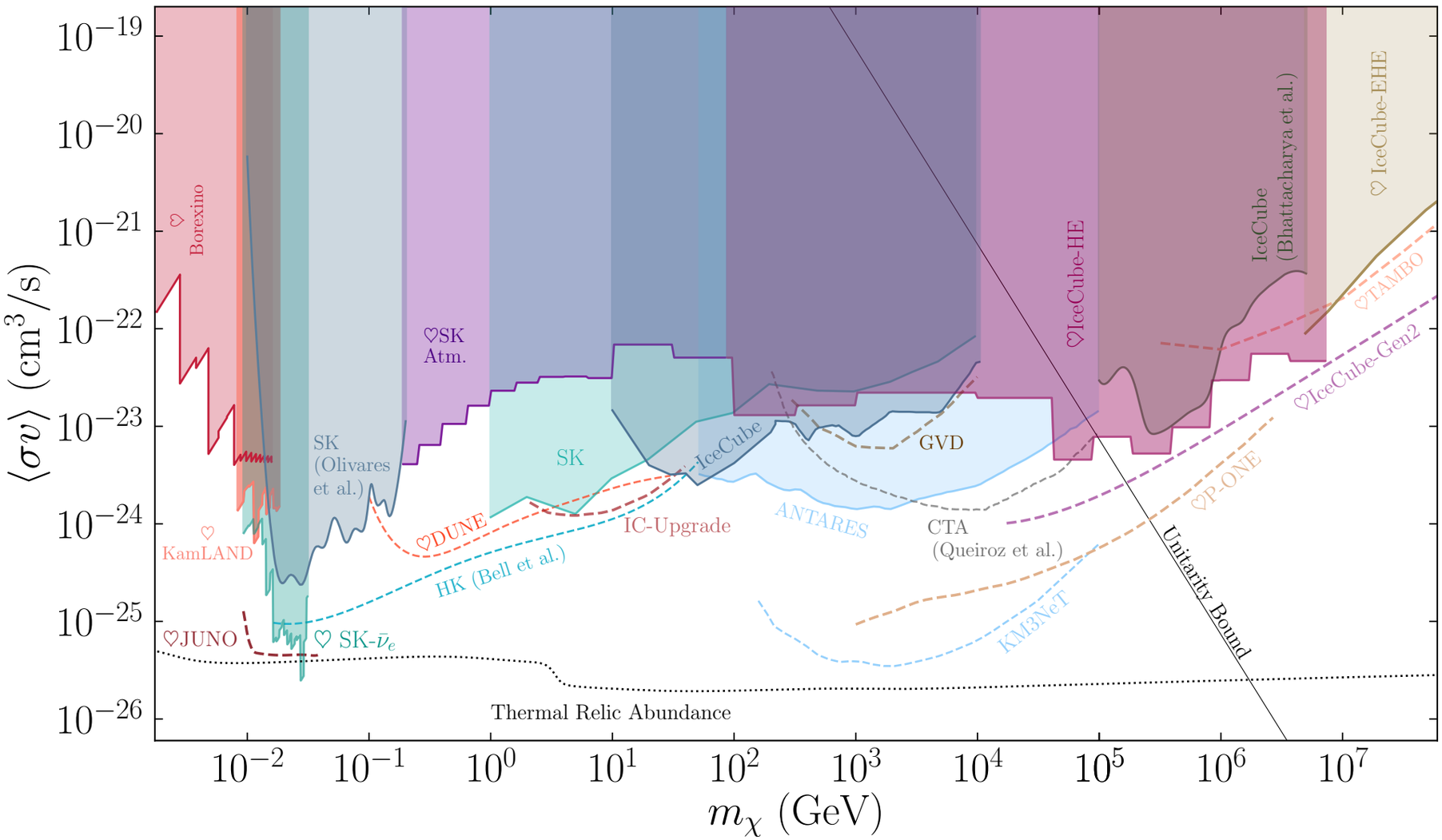
t-channel annihilation, muon flavor mixing

Neutrino Portal



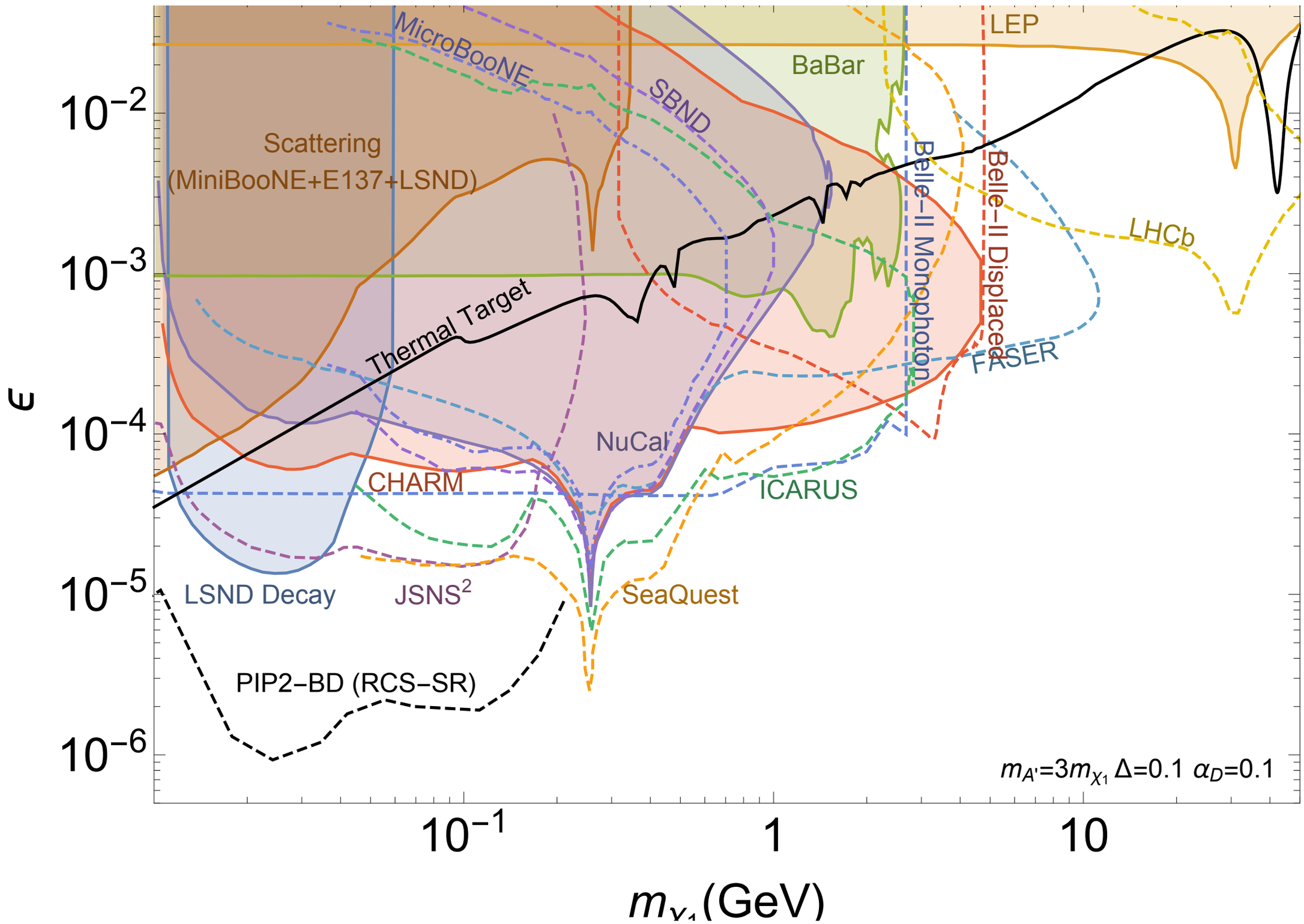
t-channel annihilation, tau flavor mixing

Neutrino Portal

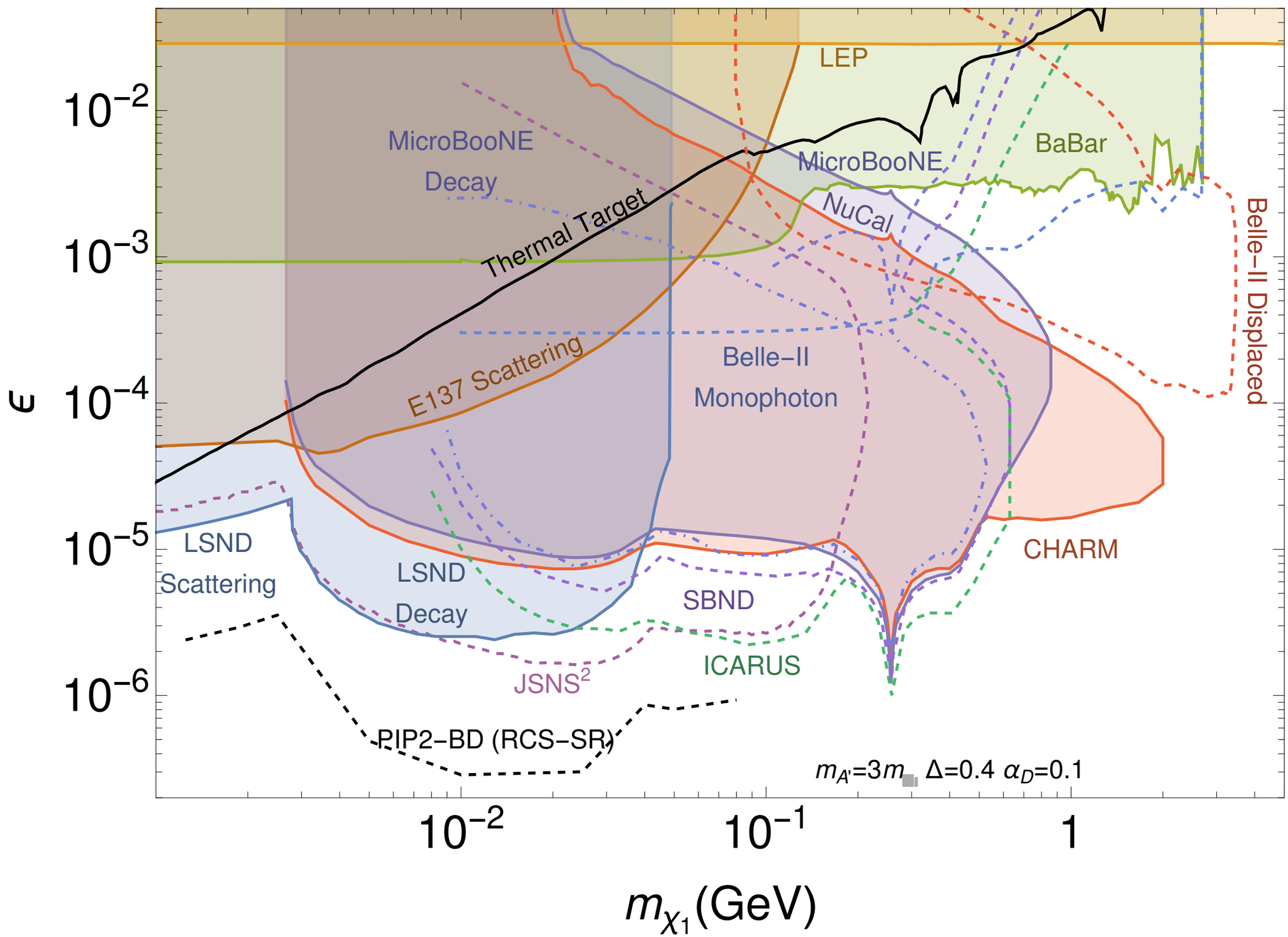


s-channel annihilation, tau flavor mixing

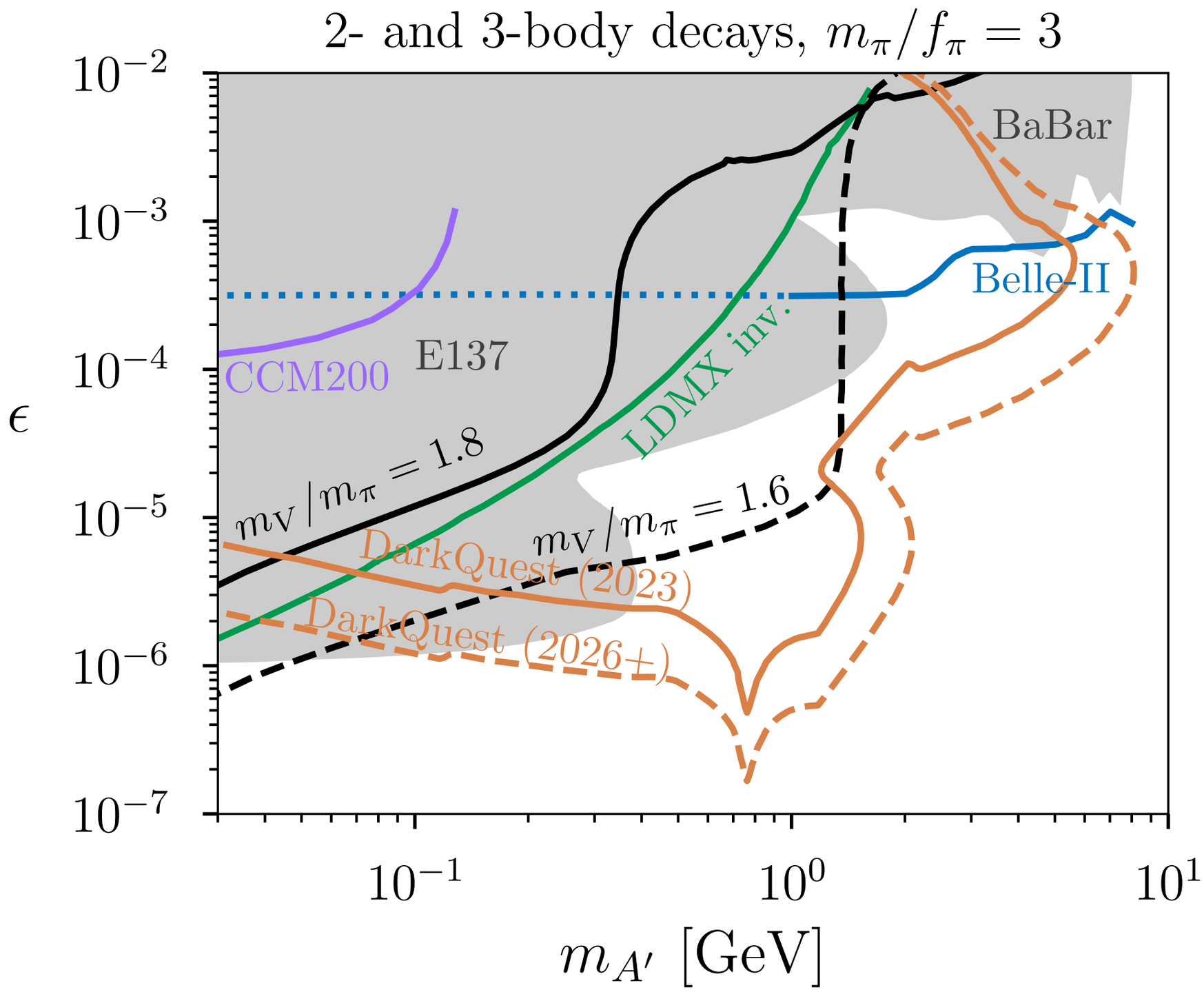
DM Semi-Visible Signals



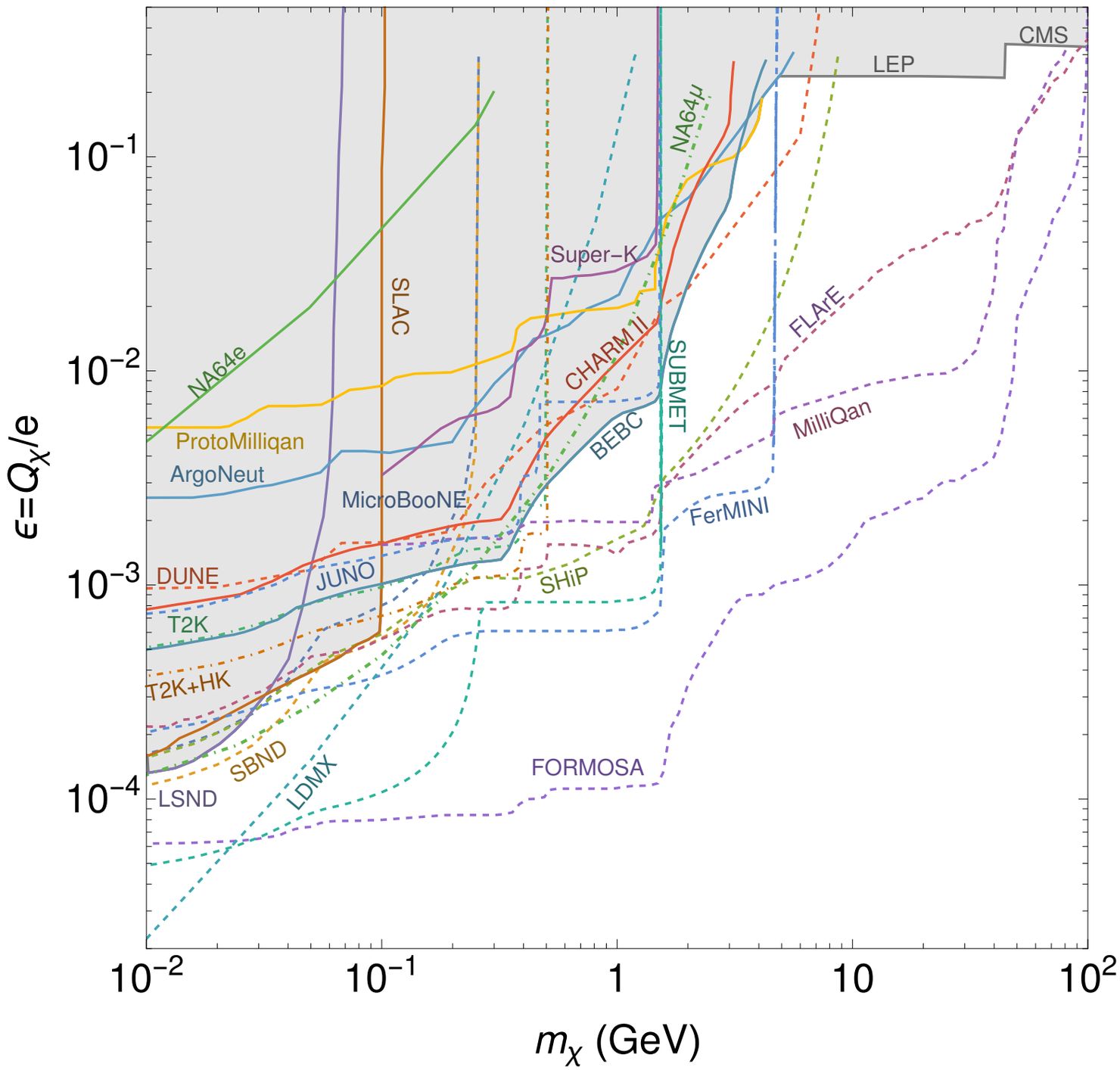
DM Semi-Visible Signals



DM Semi-Visible Signals



Millicharged Particles



Discussion …