Searching for Light Dark Matter with Fixed Target Neutrino Experiments

Patrick deNiverville

IBS Workshop on Prospects of Particle Physics and Cosmology

[PdN, M. Pospelov, A. Ritz 2011, arXiv:1107.4580 [hep-ph],arXiv:1505.07805 [hep-ph]]
[PdN, D. McKeen, A. Ritz 2012, arXiv:1205.3499 [hep-ph]]
[B. Batell, PdN, D. McKeen, M. Pospelov, A. Ritz 2014, arXiv:1405.7049 [hep-ph]]
[C. Chen, PdN, M. Pospelov, A. Ritz, arXiv:1609.01770]
[MiniBooNE Collaboration, arXiv:1807.06137]

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Dark Matter - A Brief Review

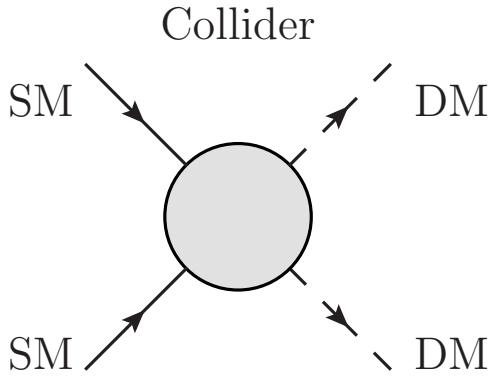
What is known:

- A source of hidden mass/matter.
- Abundance: 84% of the matter density, 26% of the energy density.
- Non-relativistic.
- Very long lived, interacts with Standard Model very weakly, self-interactions are rare.
- Weakly Interacting Massive Particle (WIMP) is a common paradigm.

This says very little about its particle nature. Still do not know:

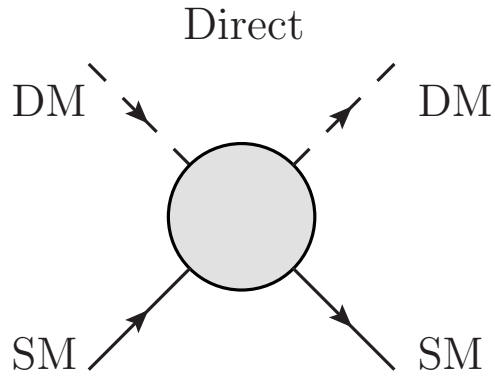
- Mass.
- Interactions with Standard Model matter.
  - So far have only observed its presence through gravitational interactions with SM particles.
  - May only interact gravitationally with the SM.

Searching for Dark Matter



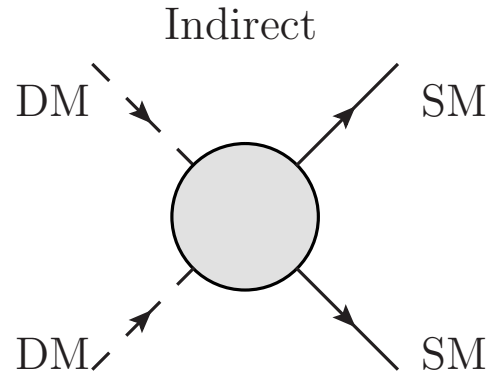
Produce dark matter in high energy collisions, search for missing energy.

Experiments: LHC, Tevatron



Build detectors deep underground and search for scatterings between cosmic dark matter and nuclei or electrons.

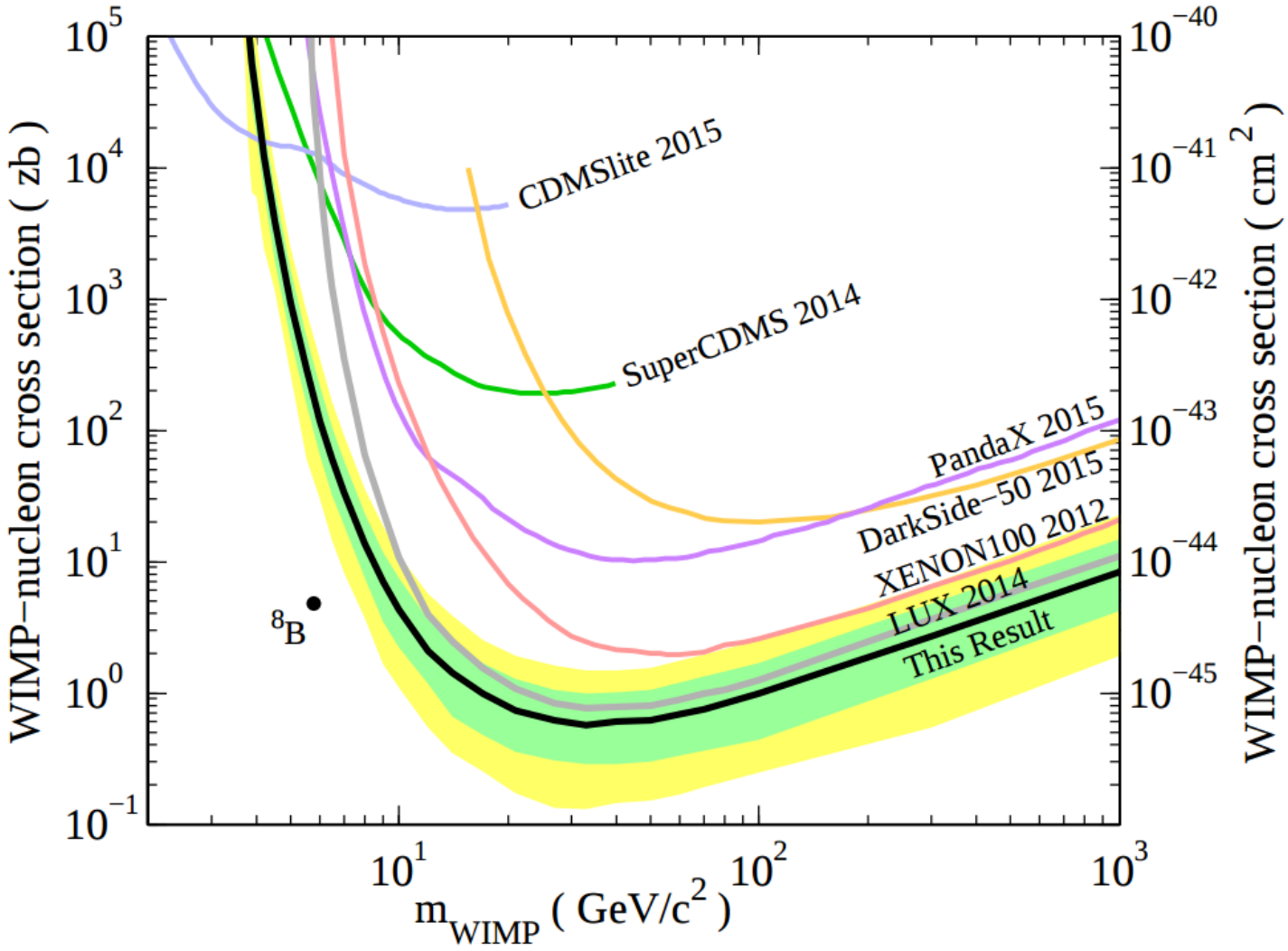
Experiments: XENON10/100/1T, DAMIC, (Super-)CDMS(-lite), CRESST, DAMA/LIBRA, LUX



Use earth and space based telescopes to search for signals (photons or cosmic rays) from cosmic dark matter decays and annihilations.

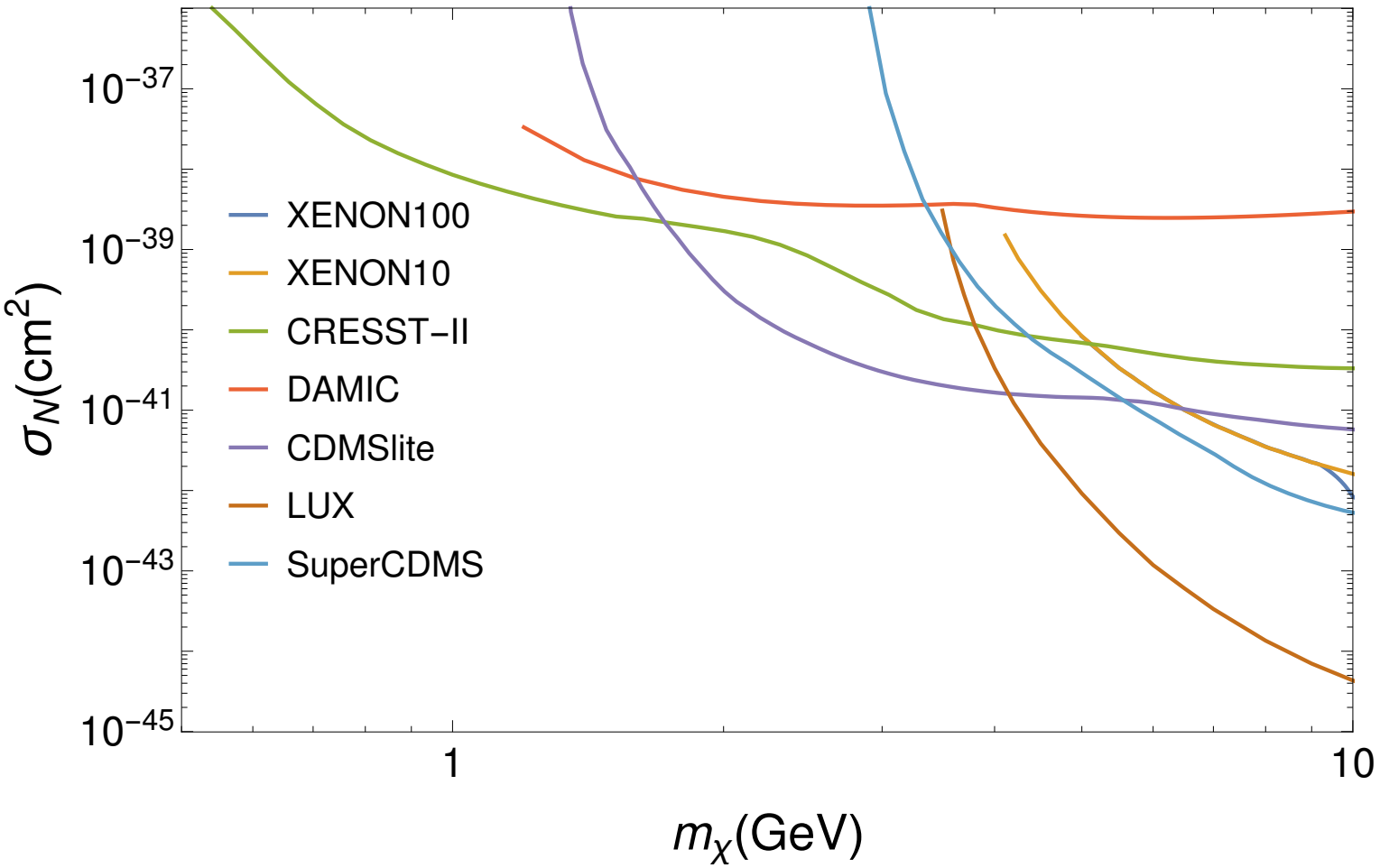
Experiments: INTEGRAL, PAMELA, AMS-2, ATIC, HESS, FERMI, IceCube

Direct Searches



[LUX Collaboration (2016), [arXiv:1512.03506]]

Direct Searches



Thermal Relic Dark Matter

One of the simplest WIMP dark matter production mechanisms is that of the thermal relic. Dark matter is a relic left over from early universe, before Big Bang Nucleosynthesis.

- While $T \gg m_{\mathrm{DM}}$, dark matter in thermal equilibrium with early universe.
- As T decreases, production becomes less efficient, and n_{DM} declines.
- Annihilation rate is suppressed, as it is proportional to n_{DM}^2. Dark matter is further diluted by the expansion of the universe.
- Annihilation ceases to have a major effect on the number density, and the dark matter freezes out.

Scenario is insensitive to initial conditions of the universe. We can relate the annihilation cross section to the observed dark matter abundance

$$\frac{\Omega_{DM}}{\Omega_{\mathrm{matter}}} \sim \frac{1\mathrm{pbn}}{\langle \sigma v \rangle_{\mathrm{fo}}}$$

Lee-Weinberg Bound and Thermal Relics

The Lee-Weinberg bound tells us that for $m_{\mathrm{DM}} <$ few GeV that annihilates via SM mediators with weak scale mass, the dark matter annihilation rate is too small and a thermal relic is overproduced in the early universe,

$$\frac{\Omega_{\mathrm{DM}}}{\Omega_{\mathrm{matter}}} > 1.$$

This bound can be circumvented by introducing new light mediators that allow new dark matter annihilation channels.

Dark matter candidates in these scenarios could potentially be created at low energies. We will be particularly interested in the regime where $m_{\mathrm{DM}} < m_{\mathrm{Mediator}}$.

Hidden Sector Dark Matter with Kinetic Mixing

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{1}{2}m_V^2 V_\mu^2 + \epsilon V_\nu \partial_\mu F_{\mu\nu} + |(\partial_\mu - e' V_\mu)\chi|^2 - m_\chi^2 |\chi|^2 + \mathcal{L}_{h'}$$

- Scalar DM candidate χ charged under $U(1)'$. V (commonly called A' or Dark Photon) is the gauge boson of $U(1)'$ symmetry.
- Four model parameters:
  - m_V, m_χ, ϵ and α'
- V can be produced through kinetic mixing with γ at $\mathcal{O}(\epsilon^2)$.
  - For $2m_\chi < m_V$, Br$(V \to \chi\bar{\chi}) \sim 1$ and V decay is prompt. For $2m_\chi > m_V$, Br$(V \to \mathrm{SM}) \sim 1$.
- We set $U(1)'$ coupling strength $\alpha' = 0.5$.
  - Largest possible value without significant running in coupling [Davoudiasl'15, 1502.07383] .
- Thermal relic.
  - $\sigma(\chi\bar{\chi} \to l\bar{l}) \propto \epsilon^2 \alpha' \left(\frac{m_\chi}{m_V}\right)^4$

Experimental Constraints

Cosmological:

- Big Bang Nucleosynthesis - So long as $m_{\rm DM} > 1 - 2$ MeV, freeze-out occurs before BBN [Serpico & Raffelt '04, Jedamzik & Pospelov '09] .
- Cosmic Microwave Background - Annihilation through p-wave, has little effect [Padmanabhan & Finkbeiner et al '05; Slatyer et al '08] .

Particle Physics:

- $V \to l^+ l^-$ - Weak so long as Br$(V \to 2\chi) \sim 1$, holds for most of parameter space of interest. [Bjorken et al. '09; Batell et al '09; Reece & Wang '09; MAMI '11, APEX '11, BaBar'12, ...]

Direct Dark Matter Detection:

- DAMIC, LUX, CDMS(lite), CRESST-II, XENON10/100/1T...
- DM-electron scattering can reach lower dark matter masses [Essig'17, arXiv:1703.00910]

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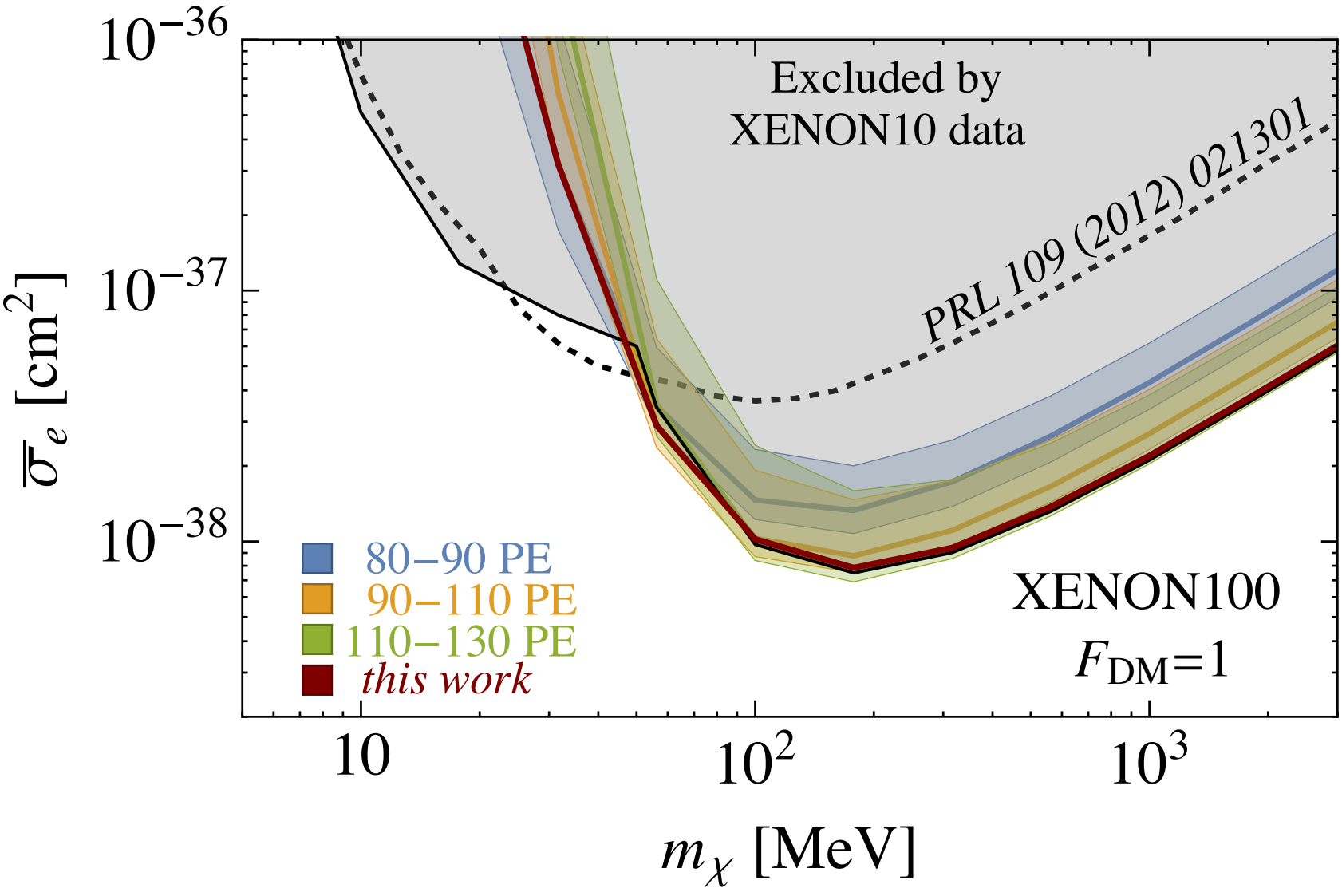
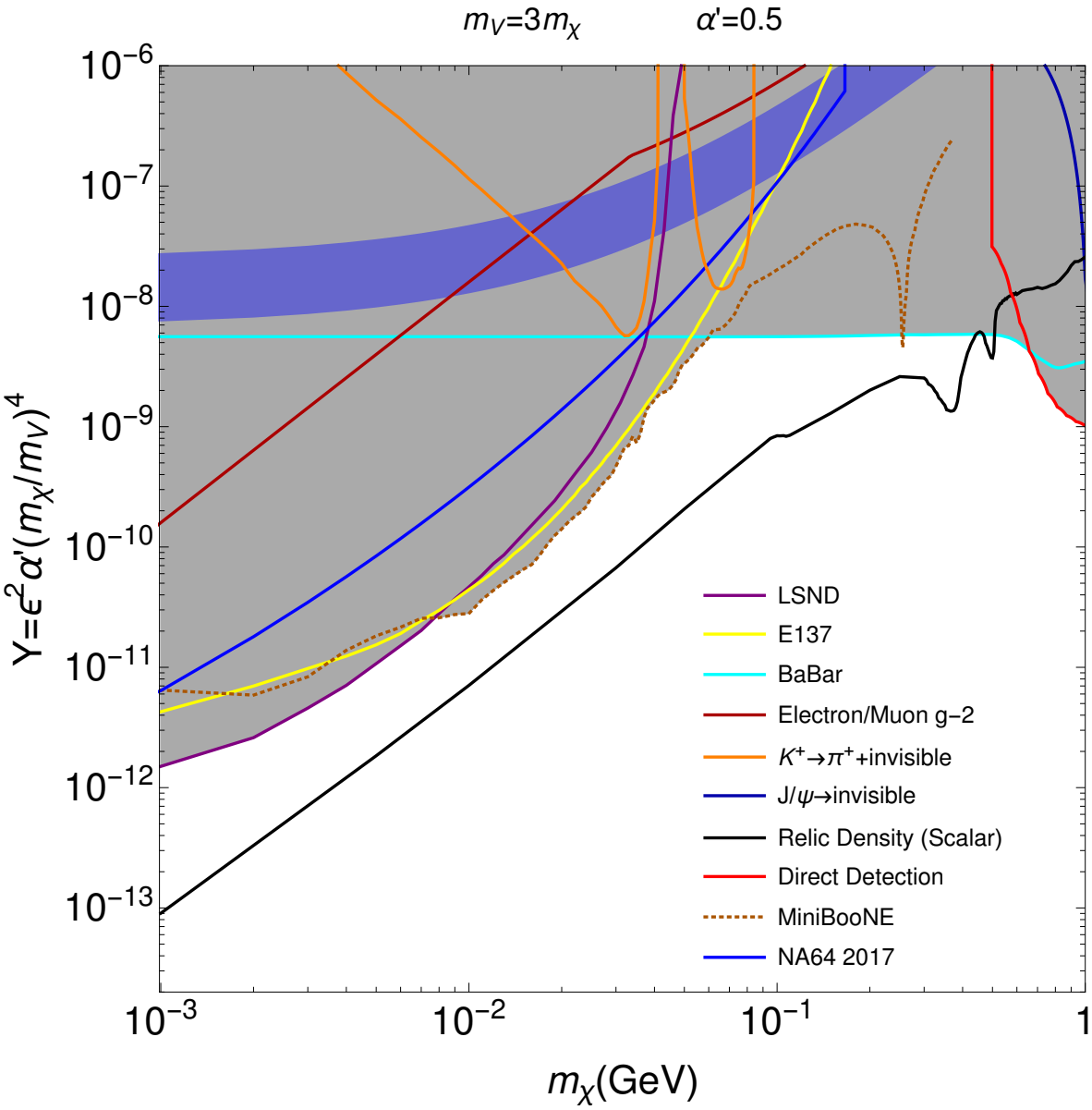
Direct Detection: DM-electron scattering



[Essig'17, arXiv:1703.00910]

Kinetic Mixing Parameter Space



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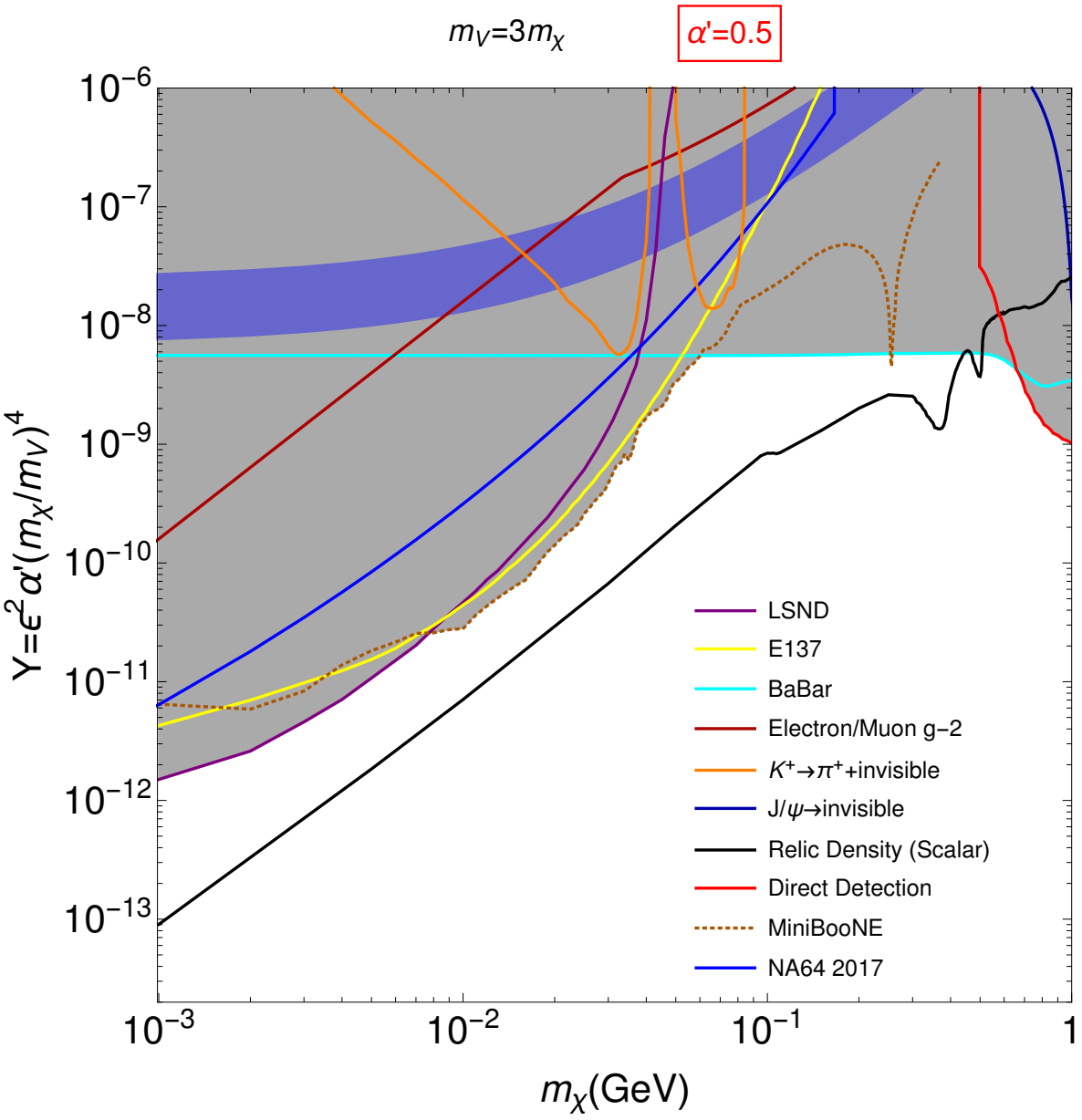

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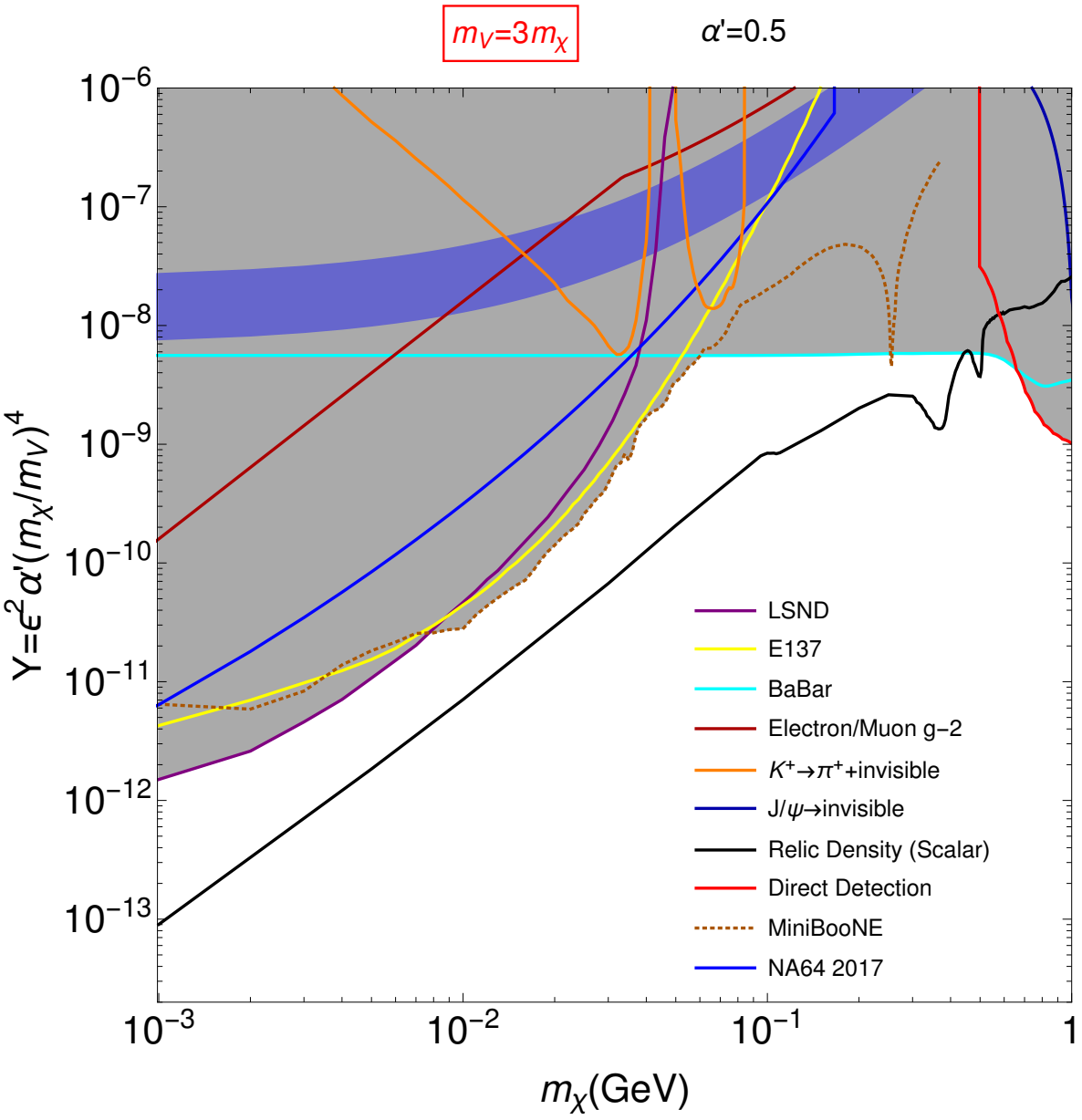

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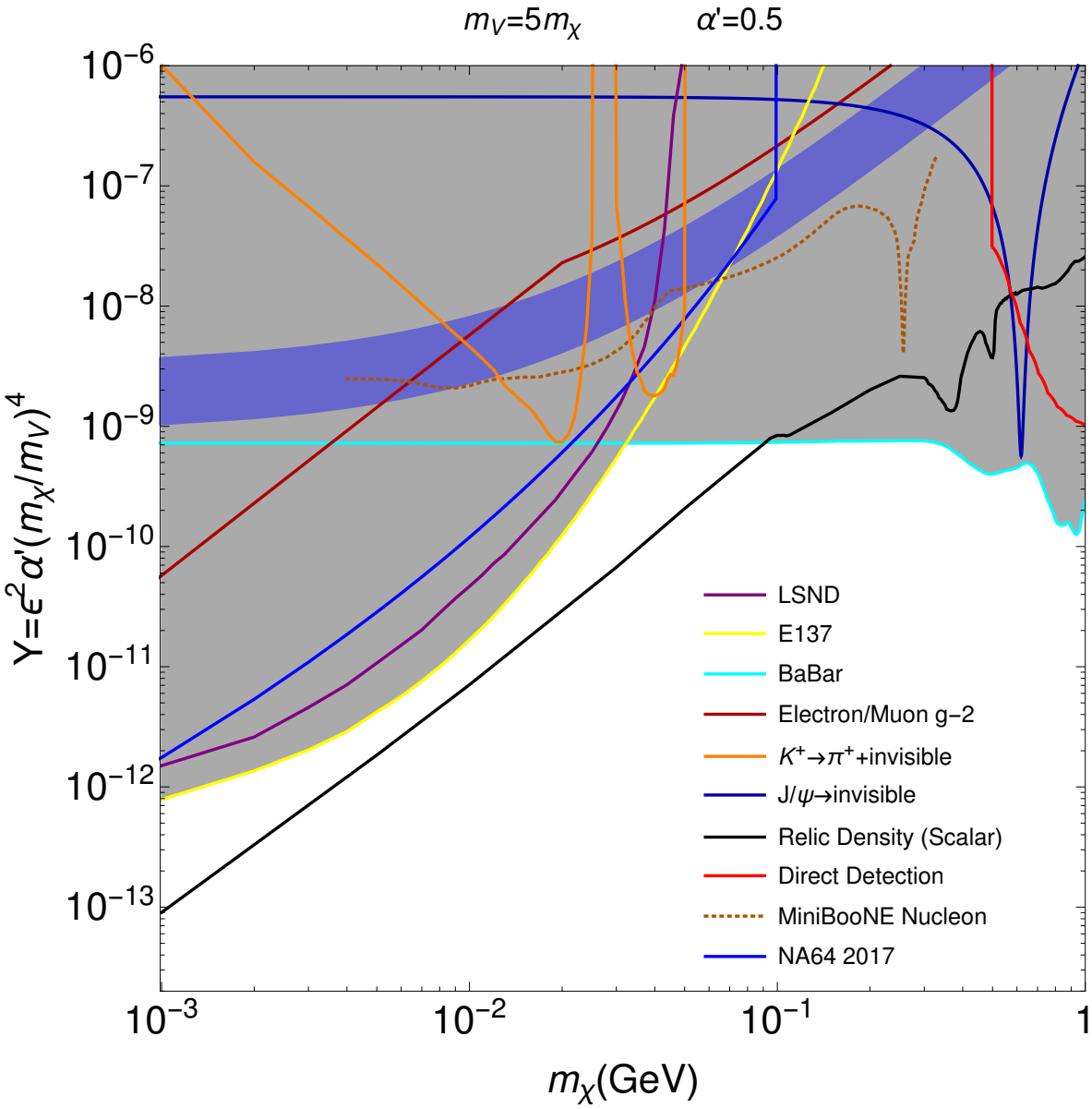

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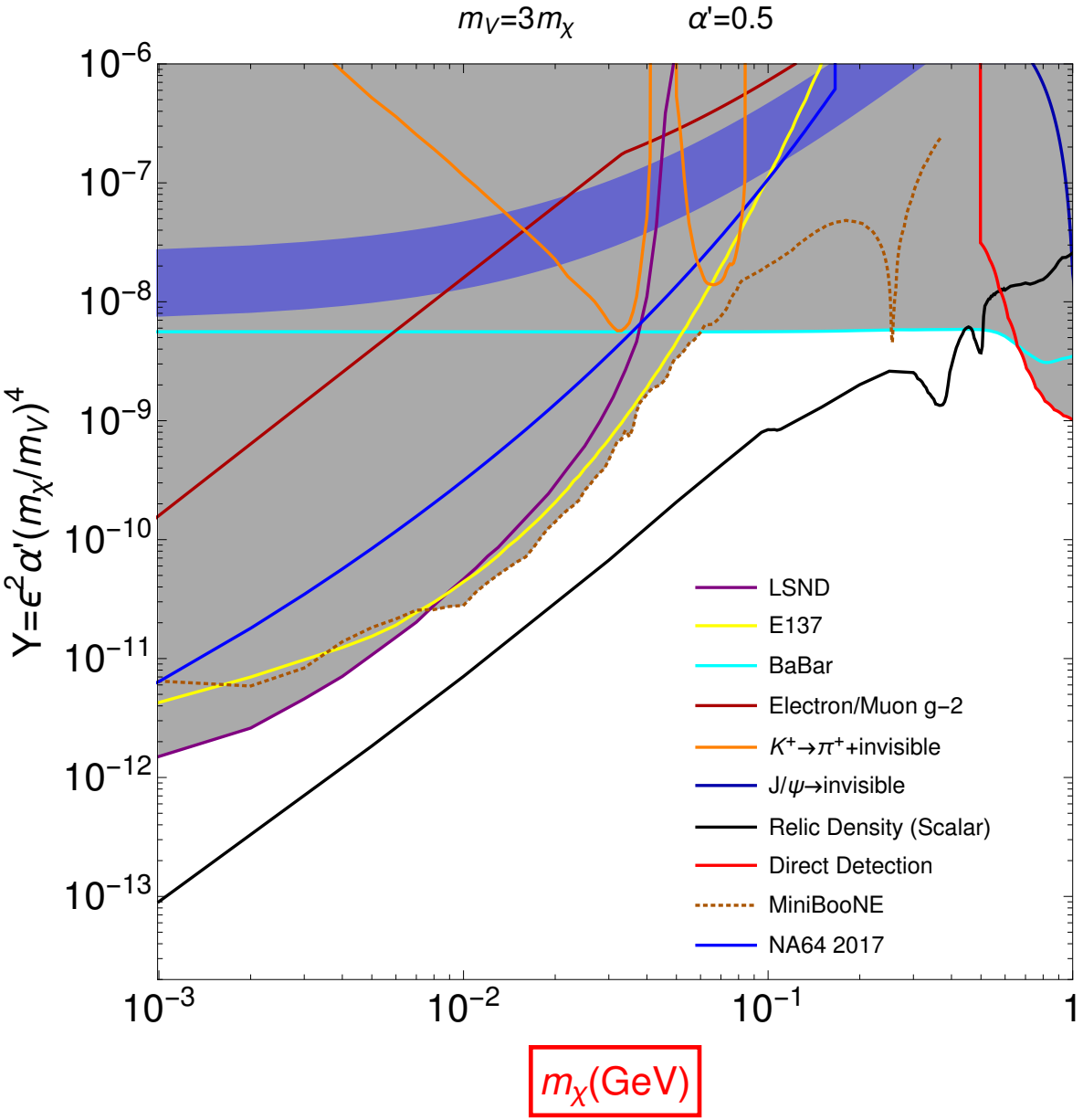

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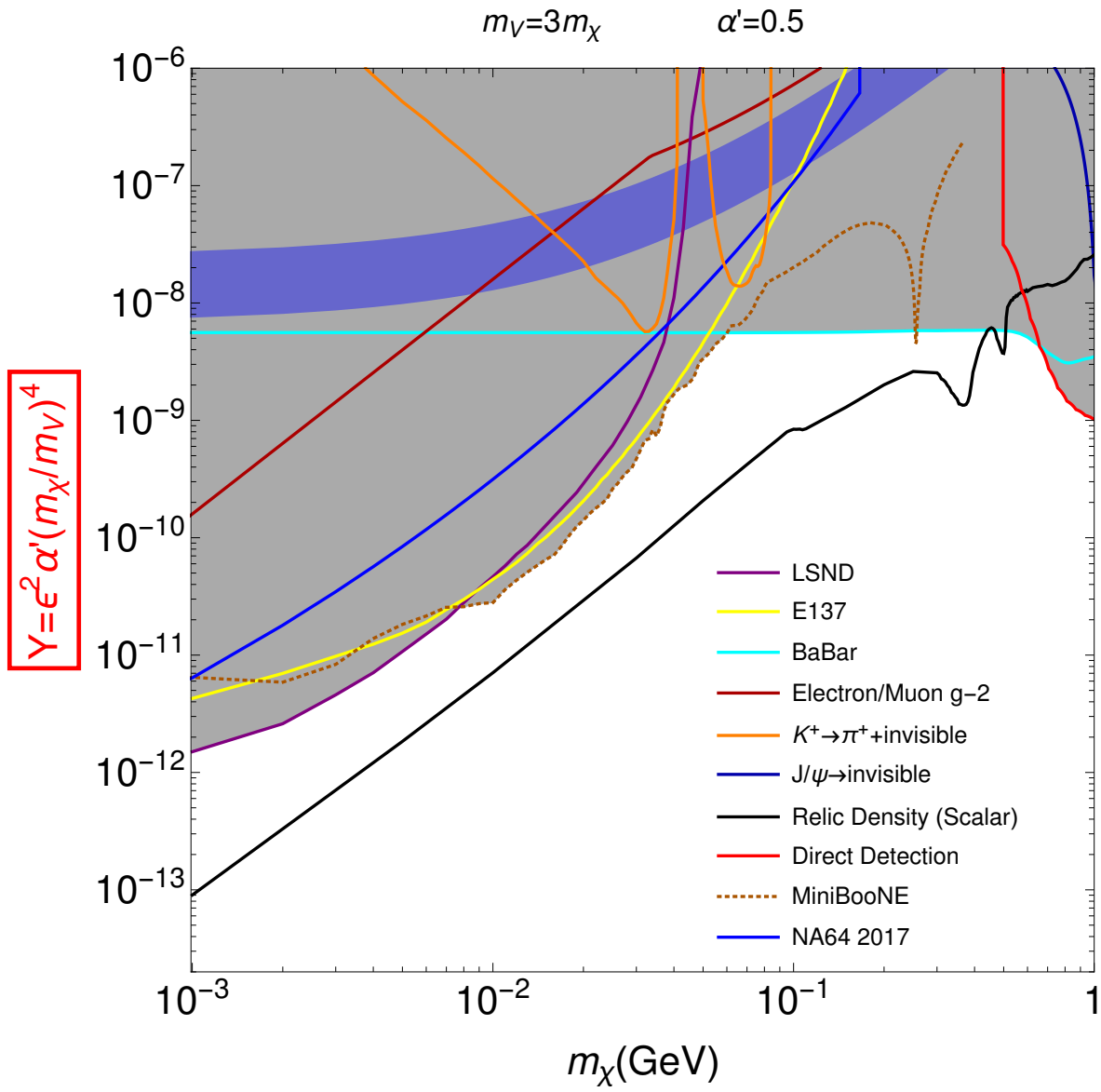
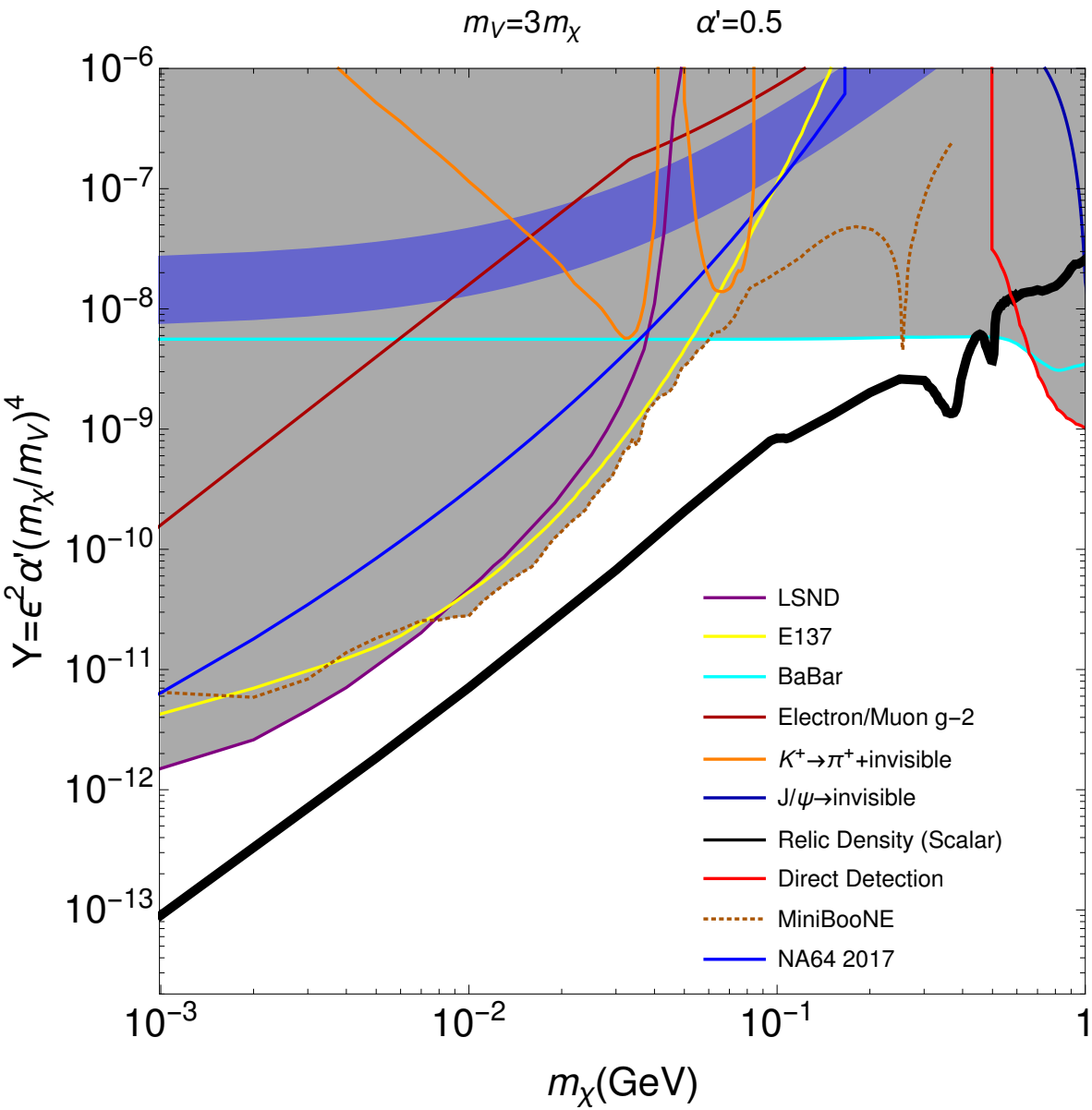


Kinetic Mixing Parameter Space - Relic Density



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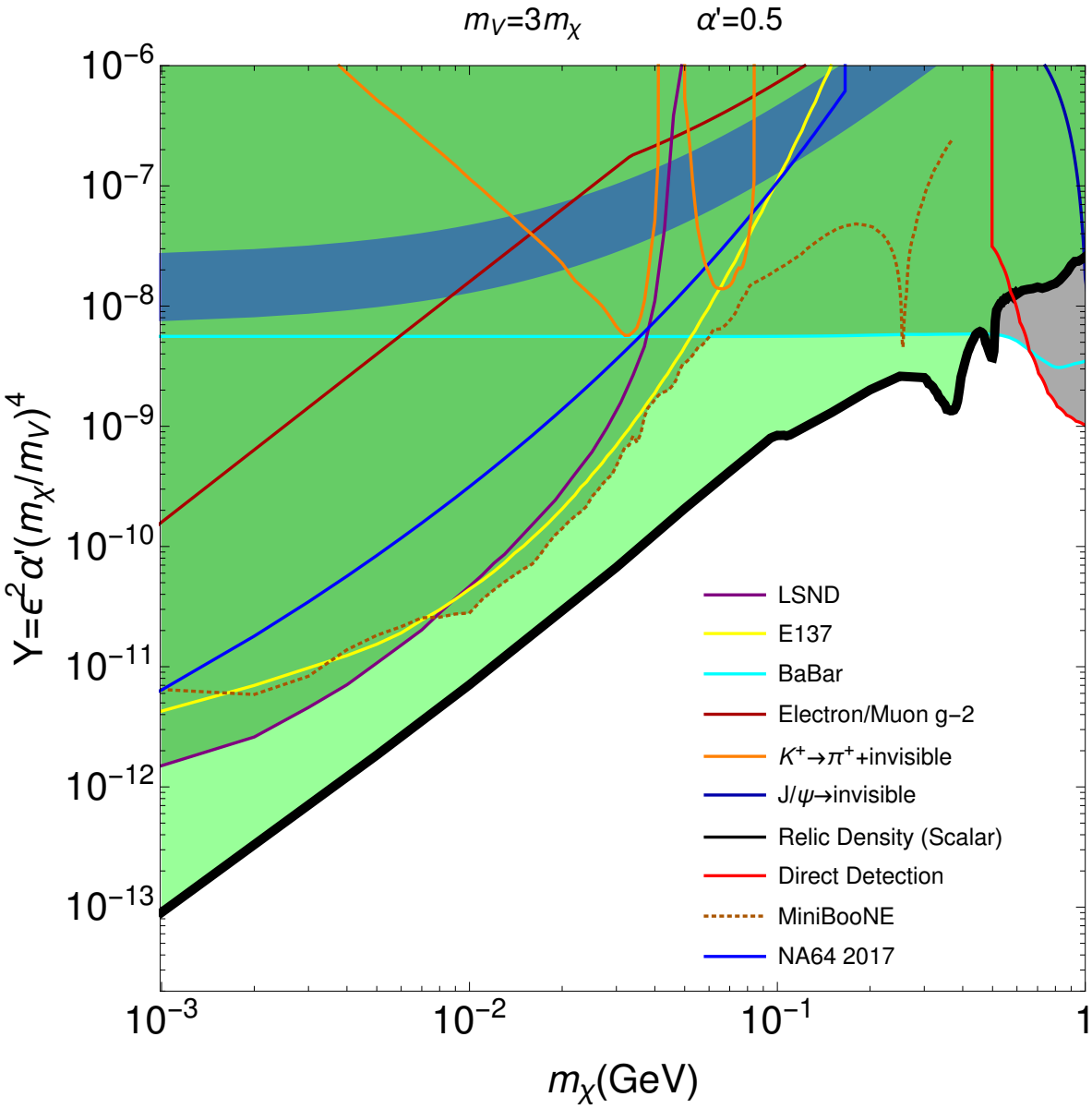

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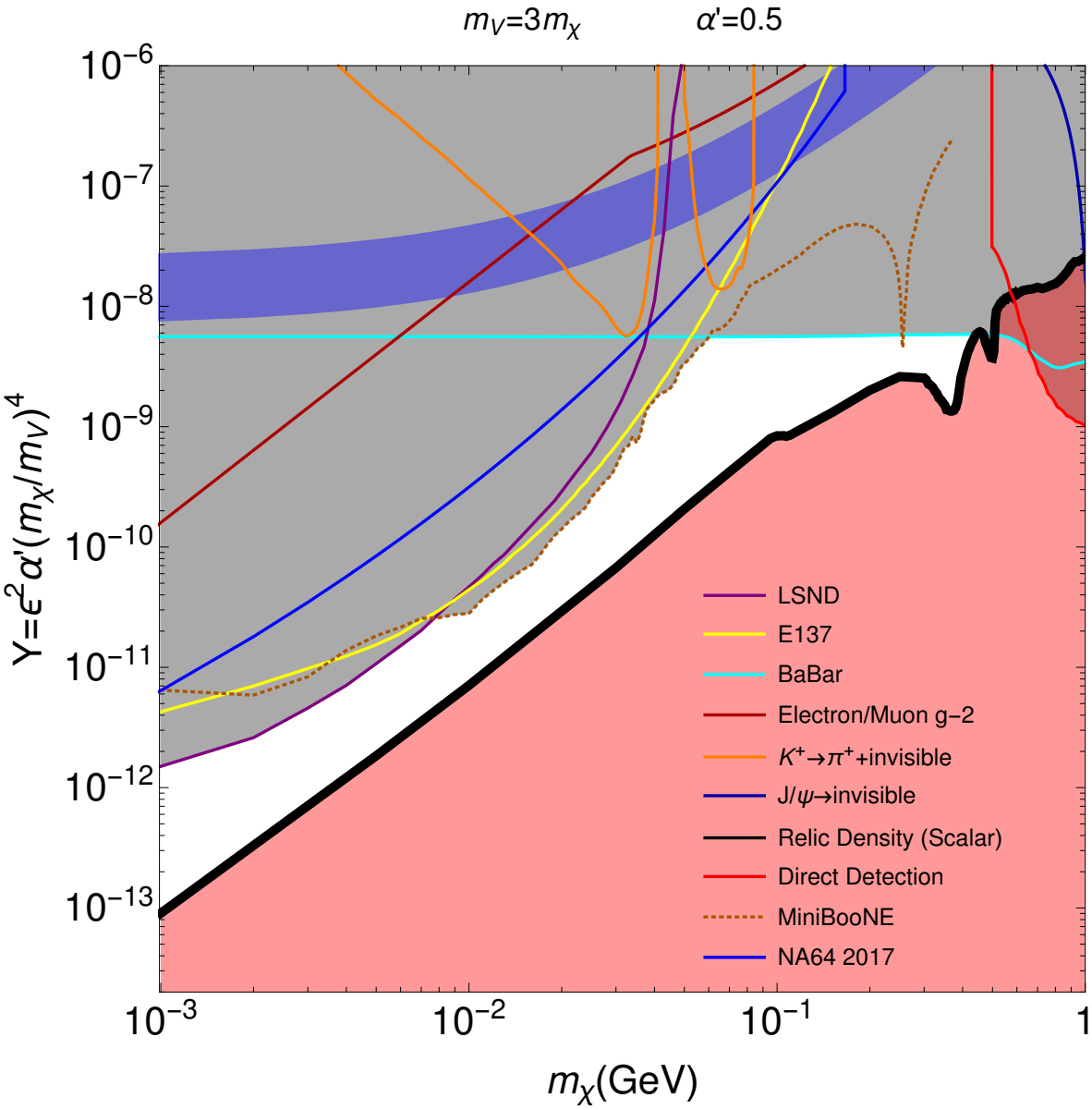
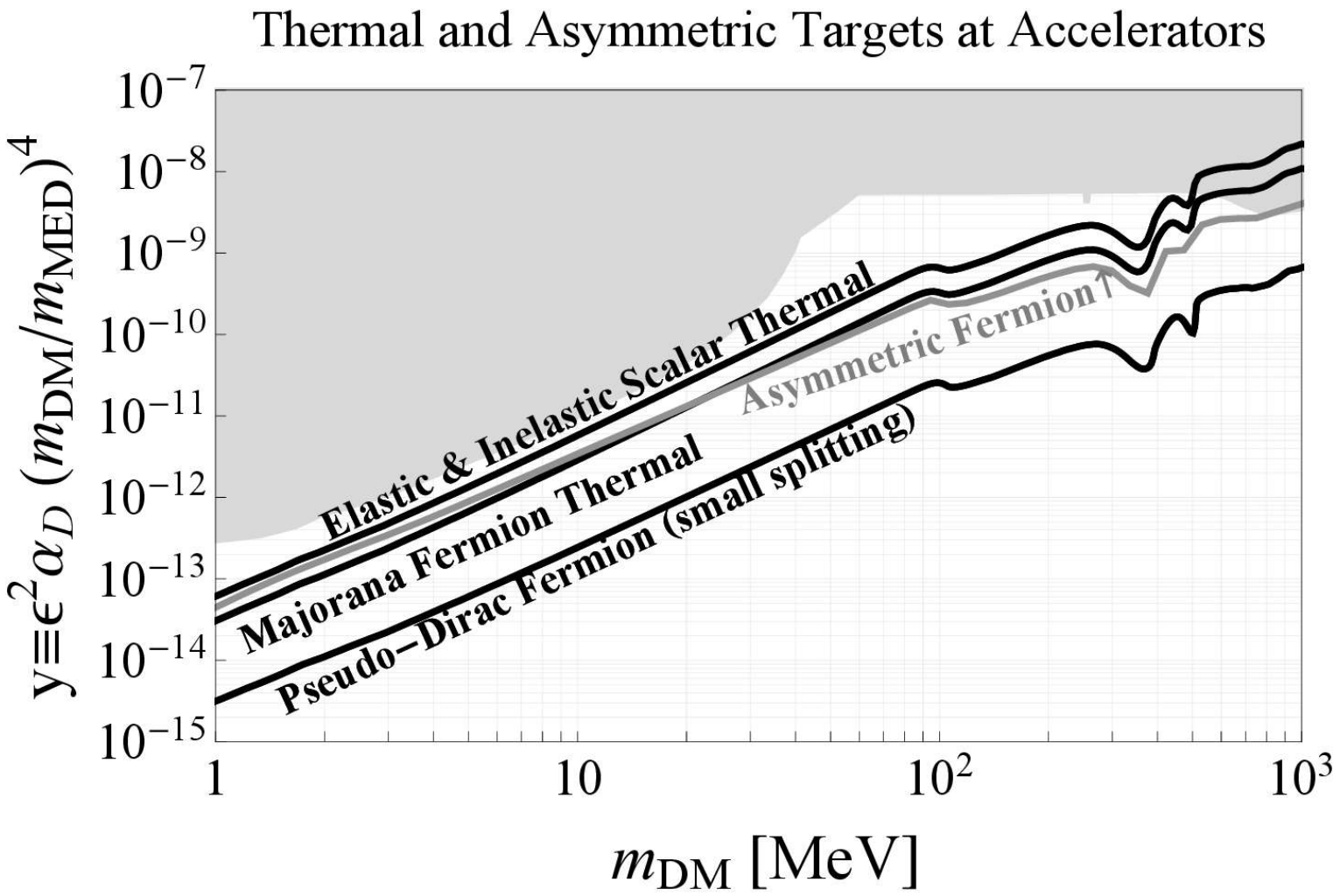
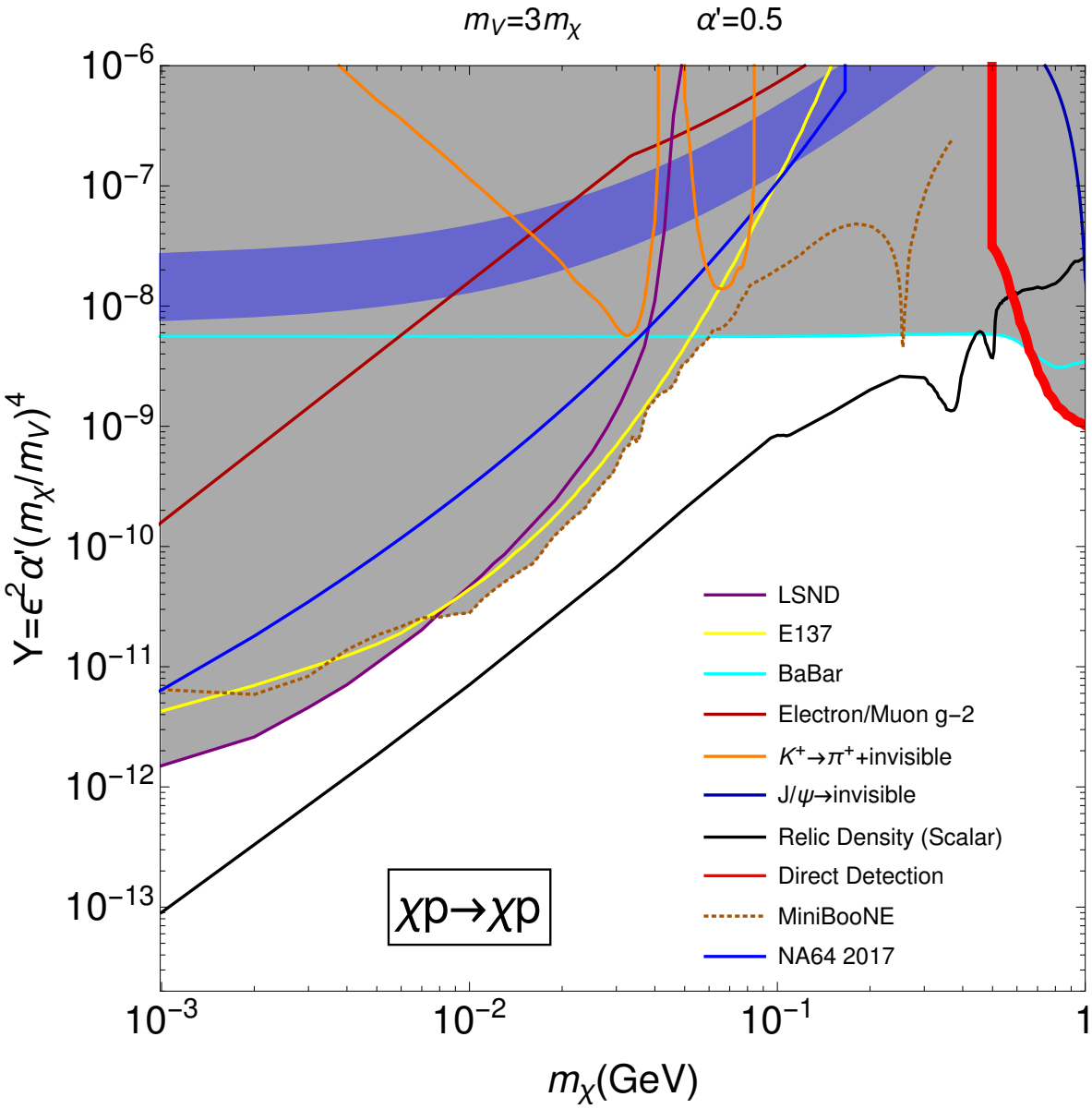


Relic Density Variations

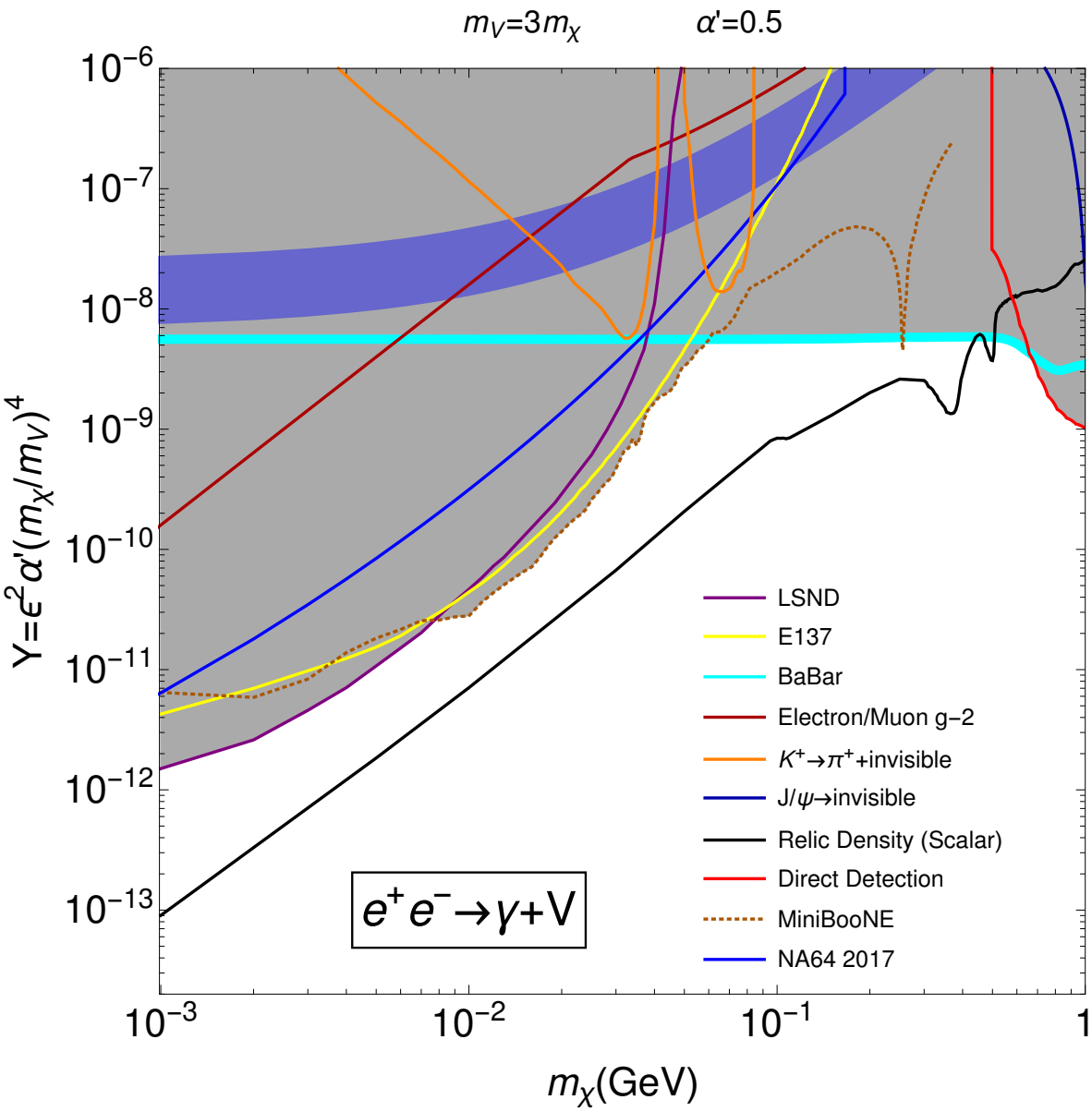


[US Cosmic Vision 2017 arXiv:1707.04591]

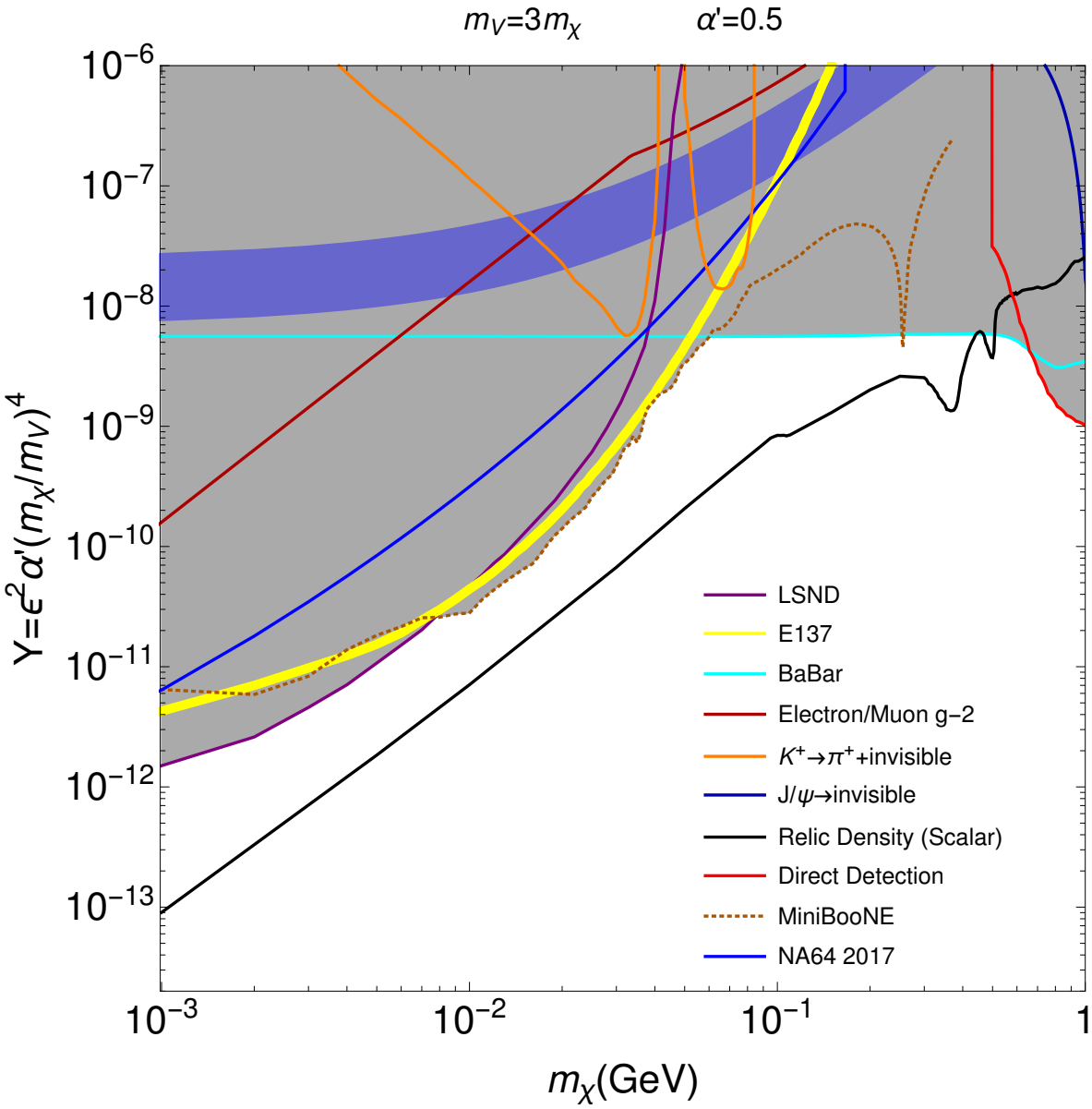
Kinetic Mixing Parameter Space - Direct Detection



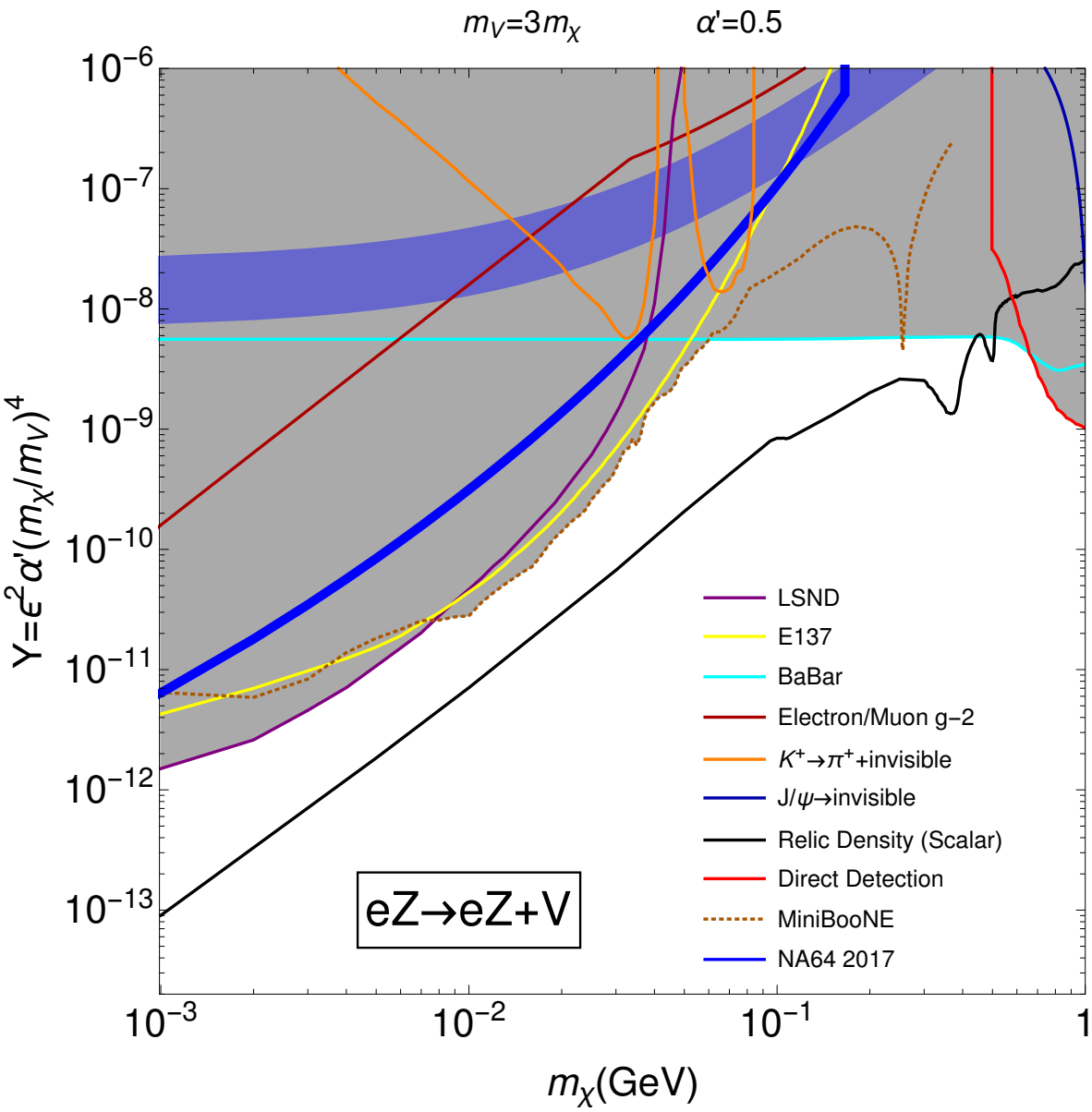
Kinetic Mixing Parameter Space - BaBar



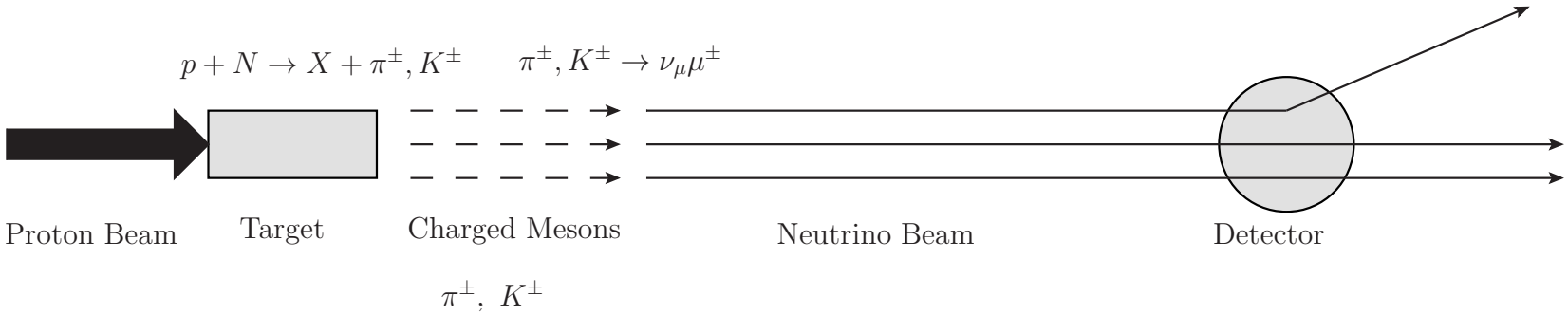
Kinetic Mixing Parameter Space - E137



Kinetic Mixing Parameter Space - NA64



Fixed Target Neutrino Experiments

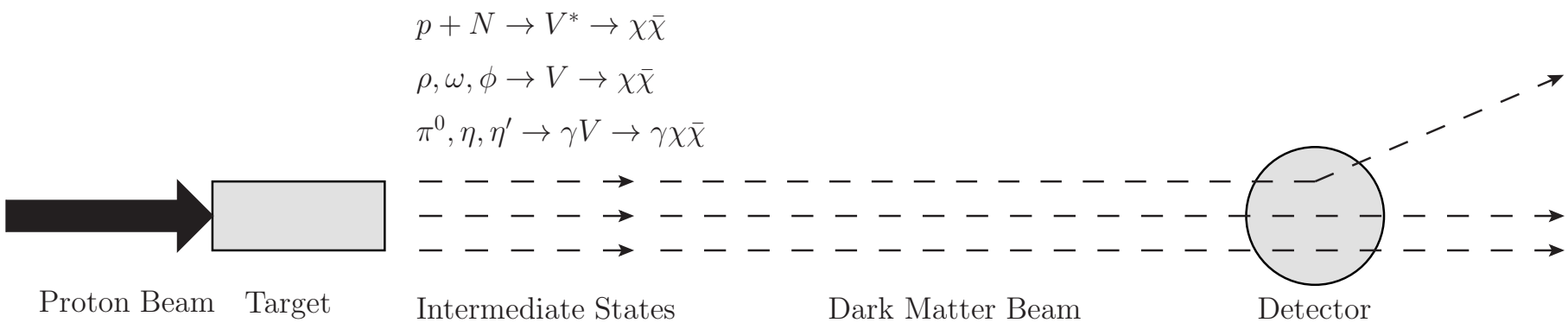


- Experiments impact a target with $\sim 10^{20} - 10^{22}$ protons to produce a high intensity neutrino beam.
  - Neutrinos produced from decays of charged mesons.
  - Can select for neutrino or antineutrino beams through the use of magnetic focusing horns.
- Non-neutrinos are removed from the beam before it reaches the detector to reduce background.

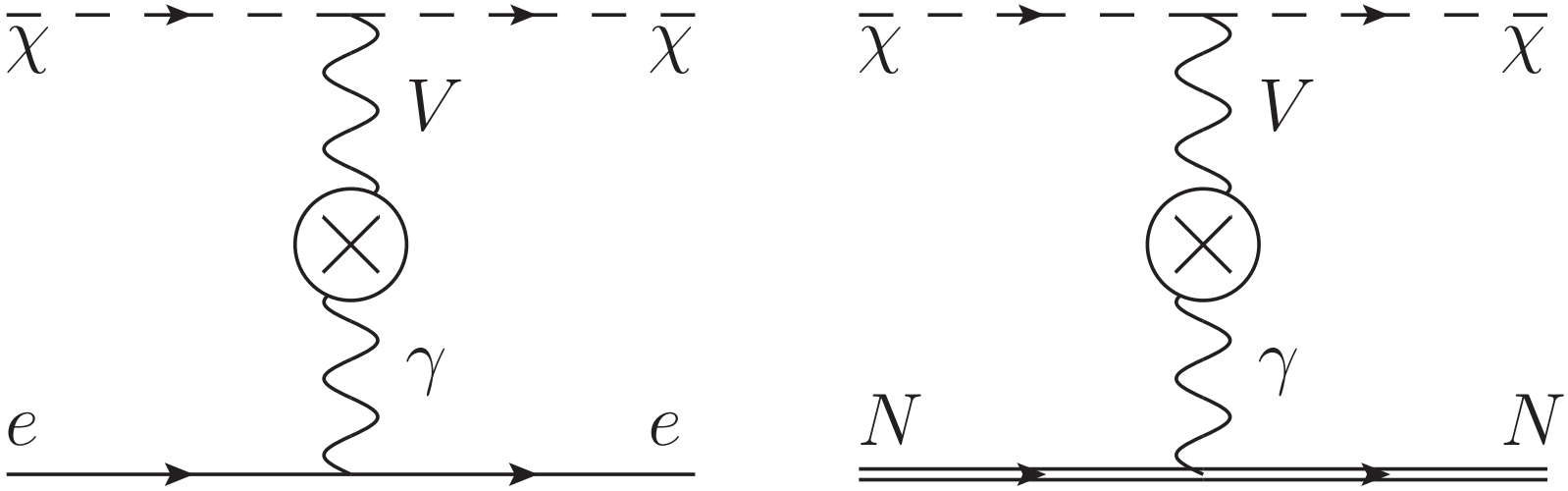
Production of a Dark Matter Beam

Combine Collider (production) and Direct (detection) search strategies to find light dark matter at FTNEs.

- Production of a dark matter beam could occur through many channels:
  - Radiative decays of pseudoscalar mesons: π^0, η, η'.
  - Bremsstrahlung: $p \to p + V^*$.
- Dark matter production is prompt, so it can benefit from any timing structure in the beam.
- Dark matter propagation may be delayed relative to that of neutrinos, and could appear as out-of-time events.

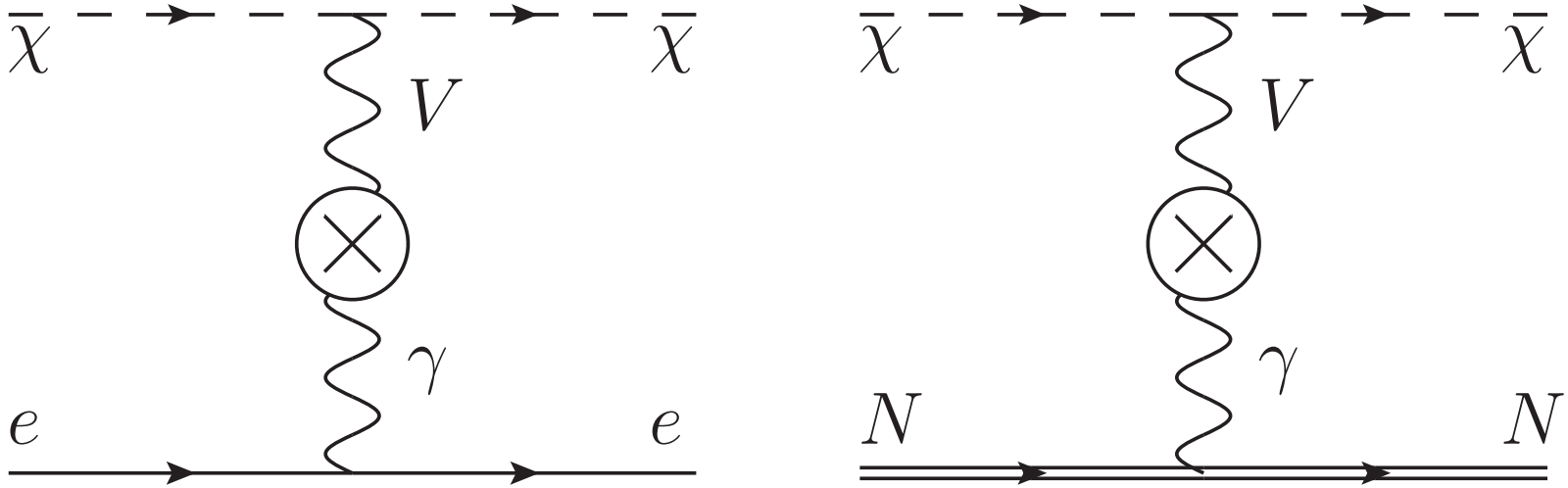


Detecting Low Mass Dark Matter - Elastic Scattering



- We can search for hidden sector dark matter through its interactions with nucleons or electrons.
- Dark matter scattering signature resembles NCE (neutral current elastic) ν scattering.
- A simple counting experiment is possible, but may fail to generate a significant signal above the neutrino signal and other backgrounds without very large POT.
- $\sigma_{\chi N, e \to \chi N, e} \propto \epsilon^2 \alpha' \alpha$

Detecting Low Mass Dark Matter - Elastic Scattering



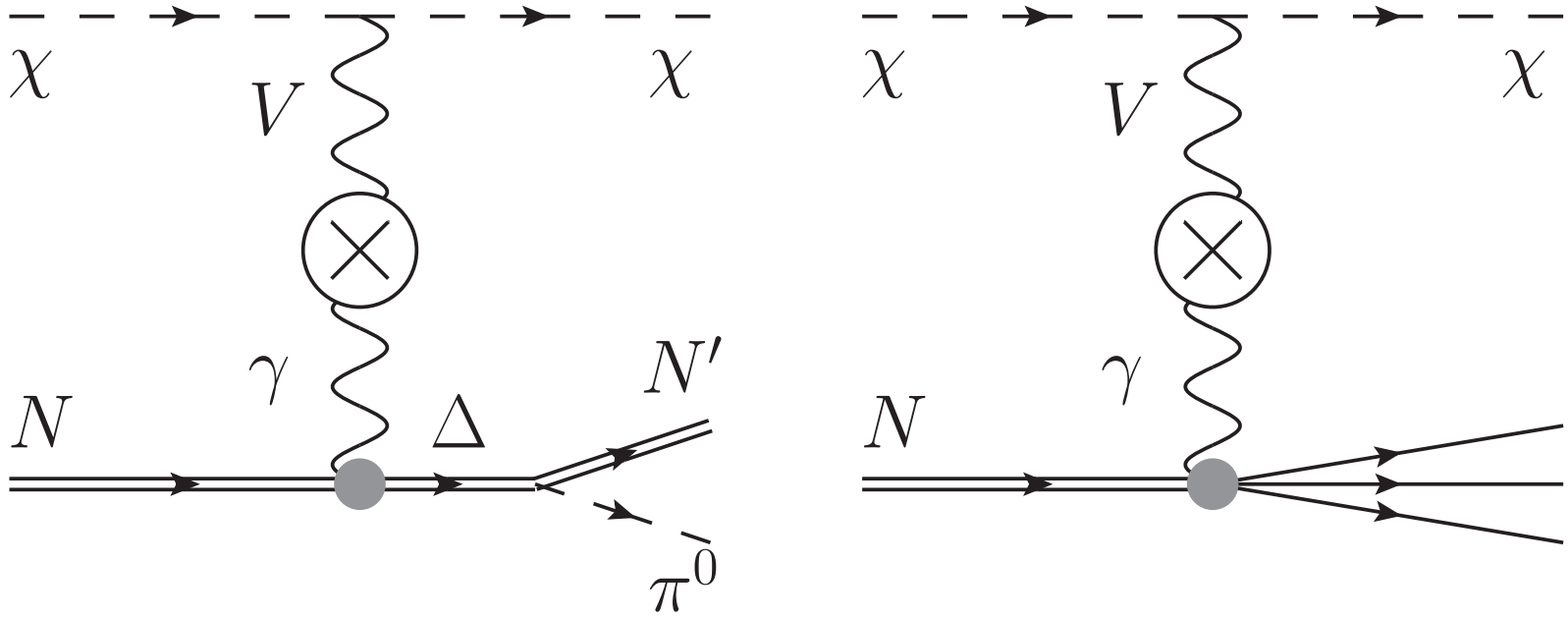
Electron Scattering

- Electron scattering can be very peaked in the forward direction, angle cuts can dramatically reduce background.

Coherent scattering

- Future coherent neutrino nucleon scattering experiments could have greatly enhanced sensitivity to dark matter scattering.
- $\sigma_{\chi Z \to \chi Z} \propto Z^2 F_{\mathrm{Helm}}(q^2)$.
- Switch to incoherent scattering for $q^2 > (50\ \mathrm{MeV})^2$.

Detecting Low Mass Dark Matter - Inelastic Scattering



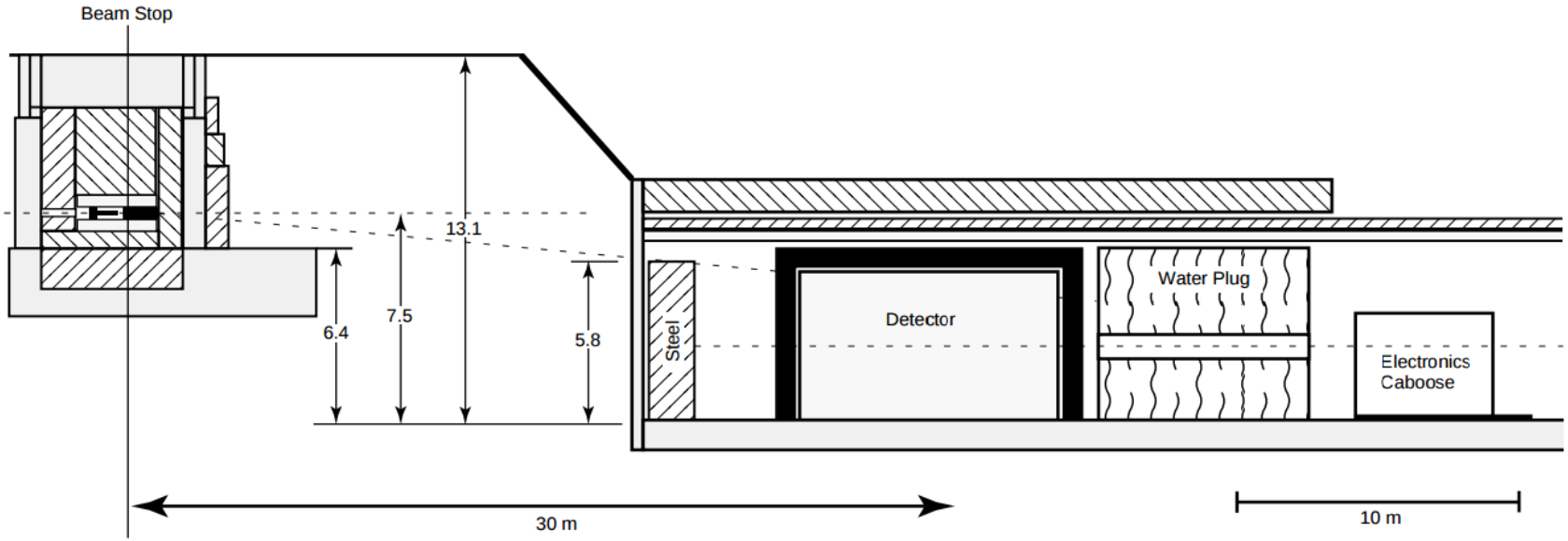
DM induced inelastic π^0 production

- Smaller cross section than NCE Nucleon-DM scattering, but expect lower backgrounds.
- Energy distribution very similar to neutrino induced production. Angular distribution may differ?

Deep Inelastic Scattering

- Fairly basic treatment, no modeling of end state.

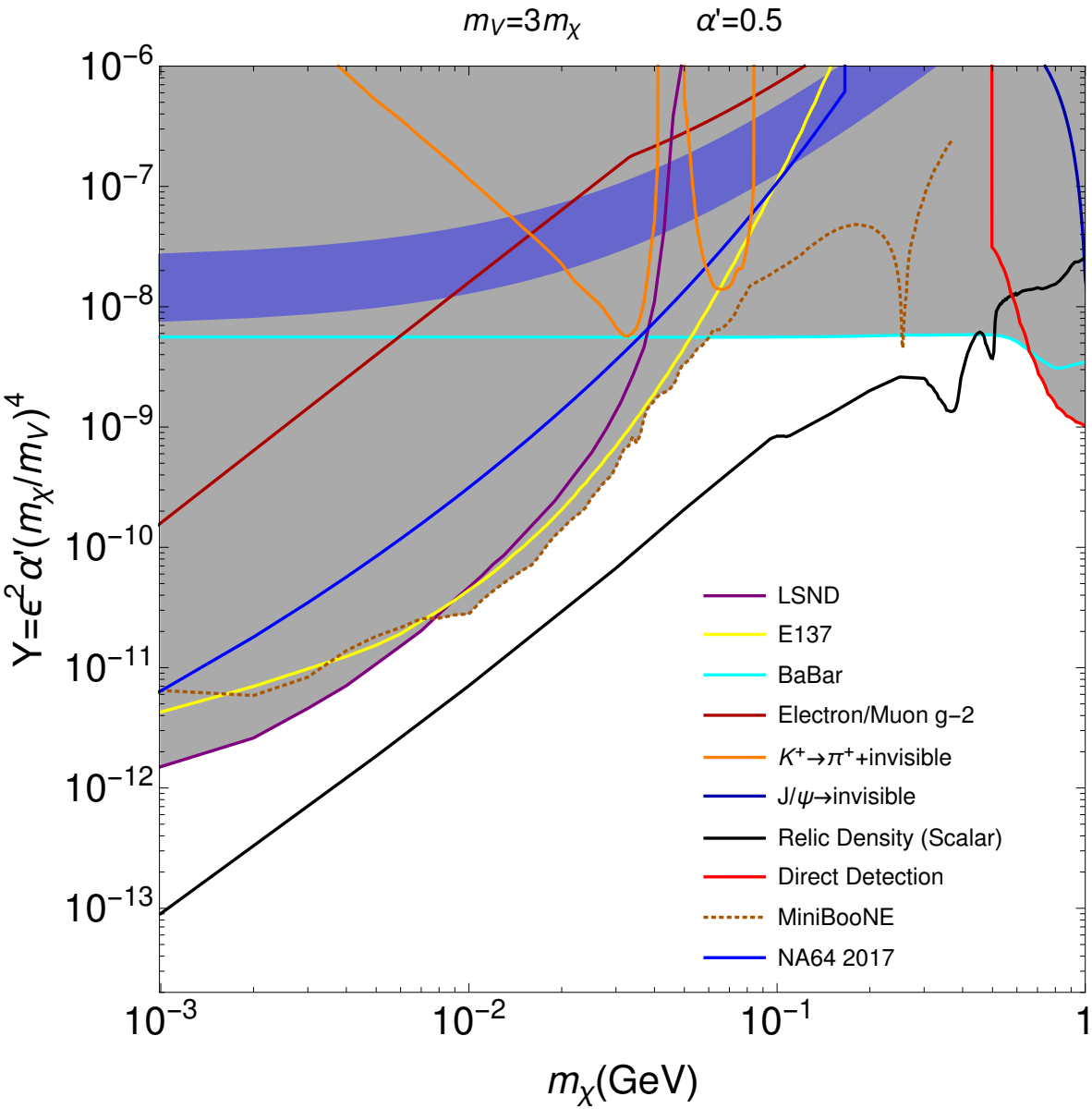
Fixed Target Neutrino Experiments - LSND



[Athanassopoulos, C. arXiv:nucl-ex/9605002]

- 1.8×10^{23} POT with 800 MeV beam, operating from 1993 to 1998.
- Signal from $\pi^0 \to V^{(*)}\gamma \to \gamma\chi\bar{\chi}$.
- Burman-Smith π^+ distribution used to estimate π^0 distribution [LA-11502-MS http://www.osti.gov/scitech/servlets/purl/6167579]
- Limit with a counting experiment: Observed 55 non-standard scattering events [[LSND Collaboration] 2001, arXiv:hep-ex/0101039] . We cut on 110, to account for uncertainties in π^0 production.
- Off-shell calculation performed by [Y. Kahn, et al., arXiv:1411.1055 [hep-ph]]

Kinetic Mixing Parameter Space - LSND

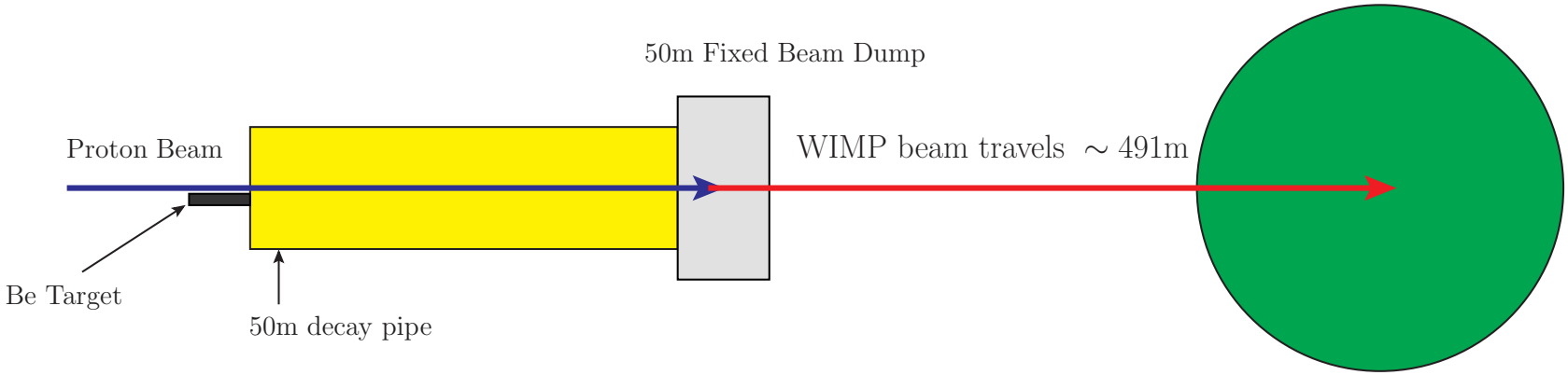


Cut on 110 NCE electron-DM scattering events.

MiniBooNE Neutrino Run

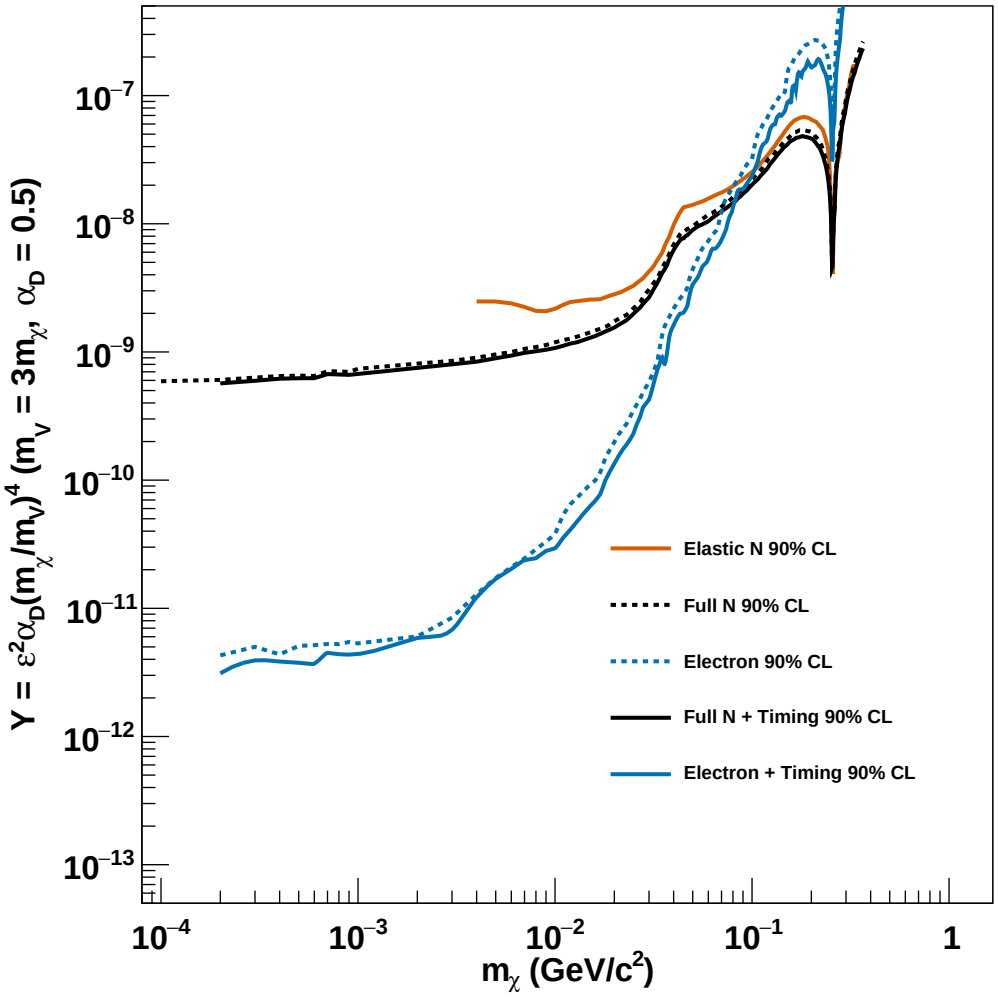
- 650 tonne mineral oil Detector located 541 meters from a beryllium production target.
- Charged pions decay into neutrinos in a 50 meter decay volume following the target.
- Magnetic focusing horns select for neutrino or antineutrinos.
- Collected 1.6×10^{21} POT with 8.9 GeV energy.
- Likely to be large neutrino backgrounds $\mathcal{O}(1000)$ without harsh cuts to discriminate between dark matter and neutrino scattering events.

MiniBooNE Beam Dump Run



- Rather than using the target, direct beam into 50m steel beam absorber.
  - Reduce background by reducing total number of neutrinos produced.
  - Neutrino background should drop by factor of 50.
  - Can further reduce background for $m_\chi > 100\,\text{MeV}$ by considering timing.
- Collected 1.89×10^{20} POT with 8.9 GeV energy.
- Analysis of nucleon signal completed.
  - Was weaker than initial estimates expected.
- Analysis of electron dark matter scattering signal recently completed.

MiniBooNE limits



[MiniBooNE Collaboration '18 arXiv:1807.06137]

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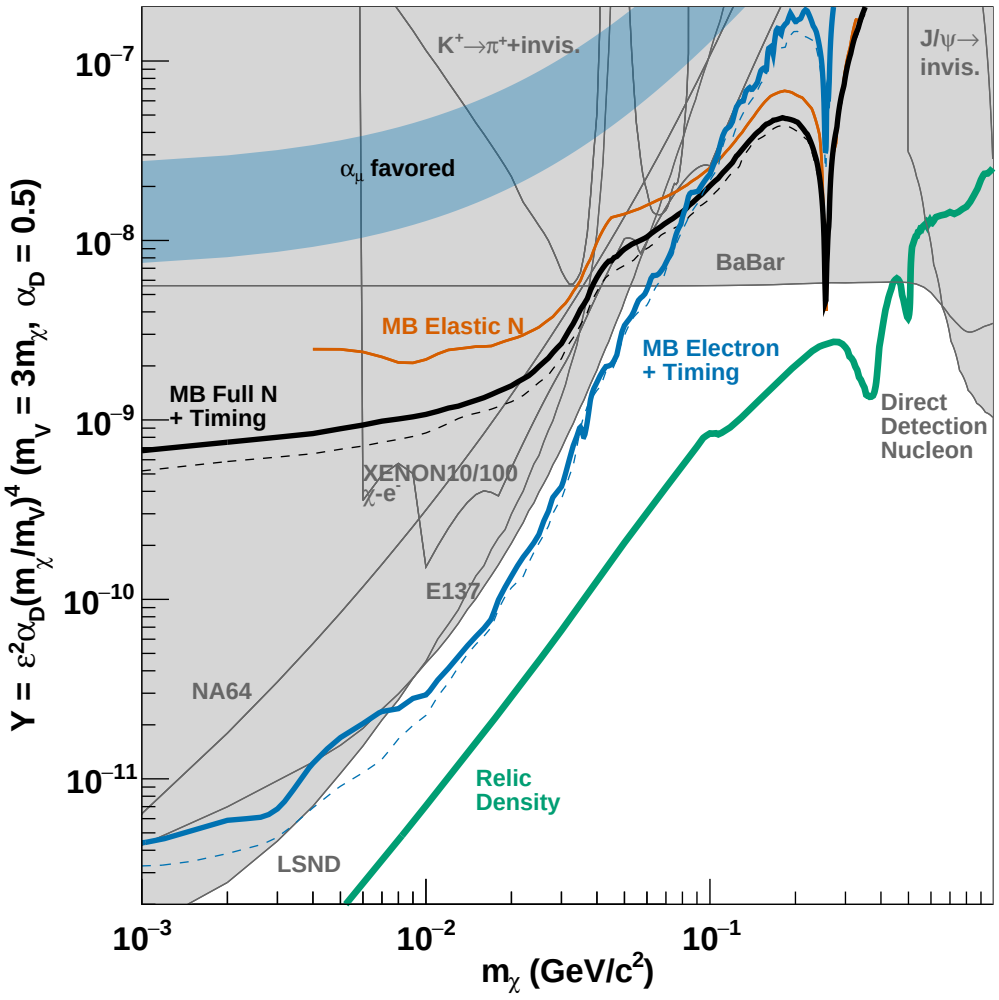

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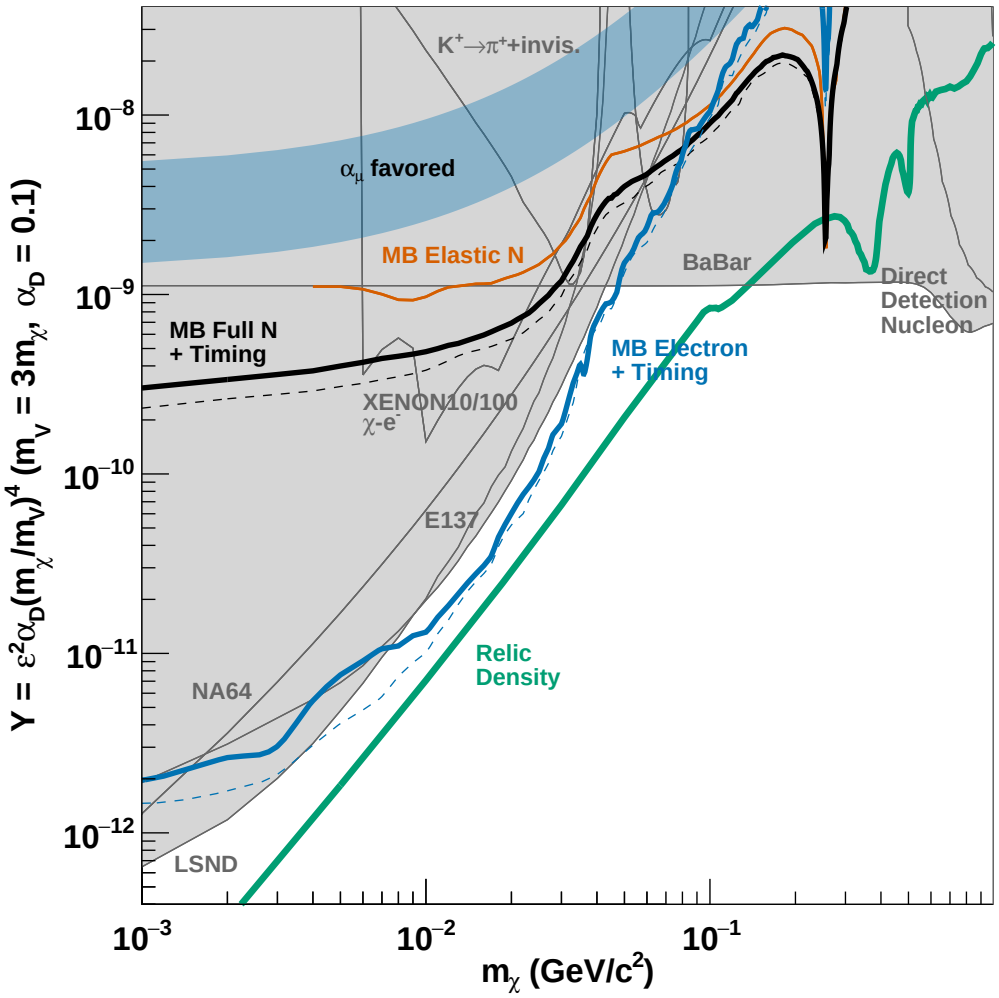

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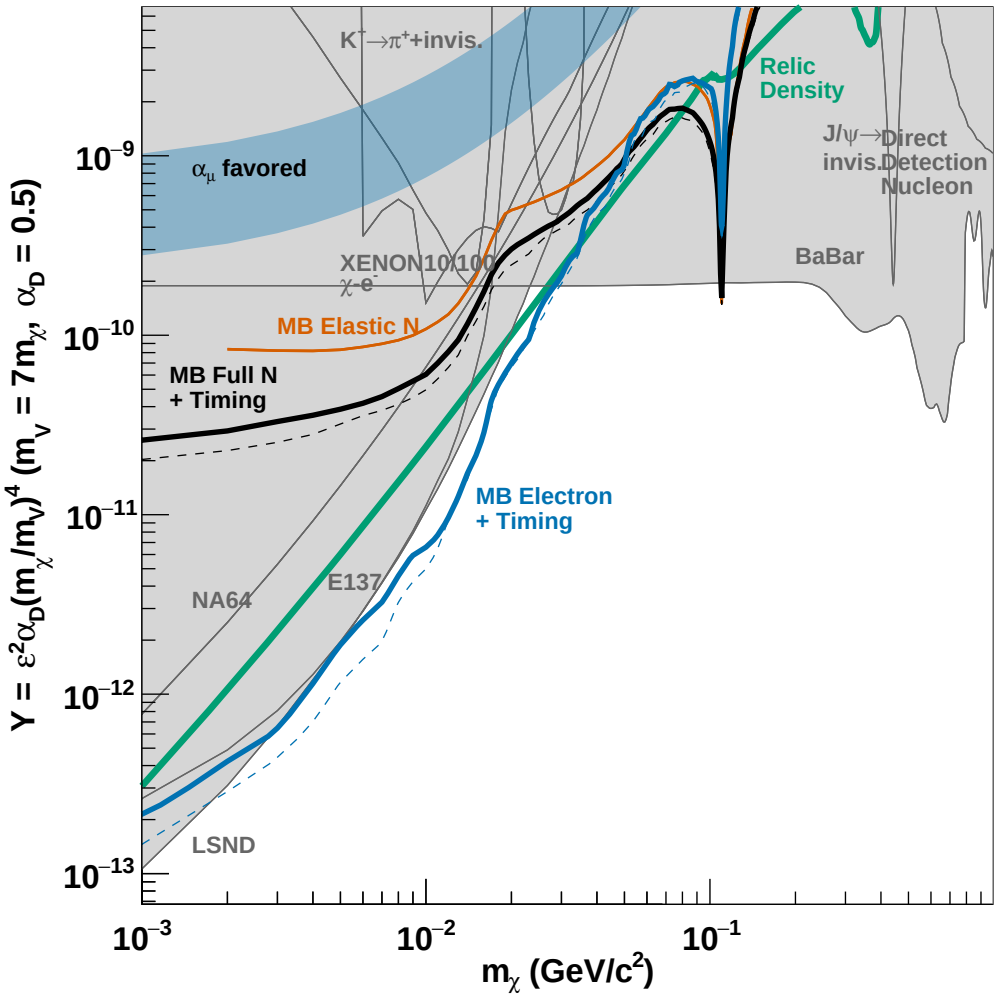


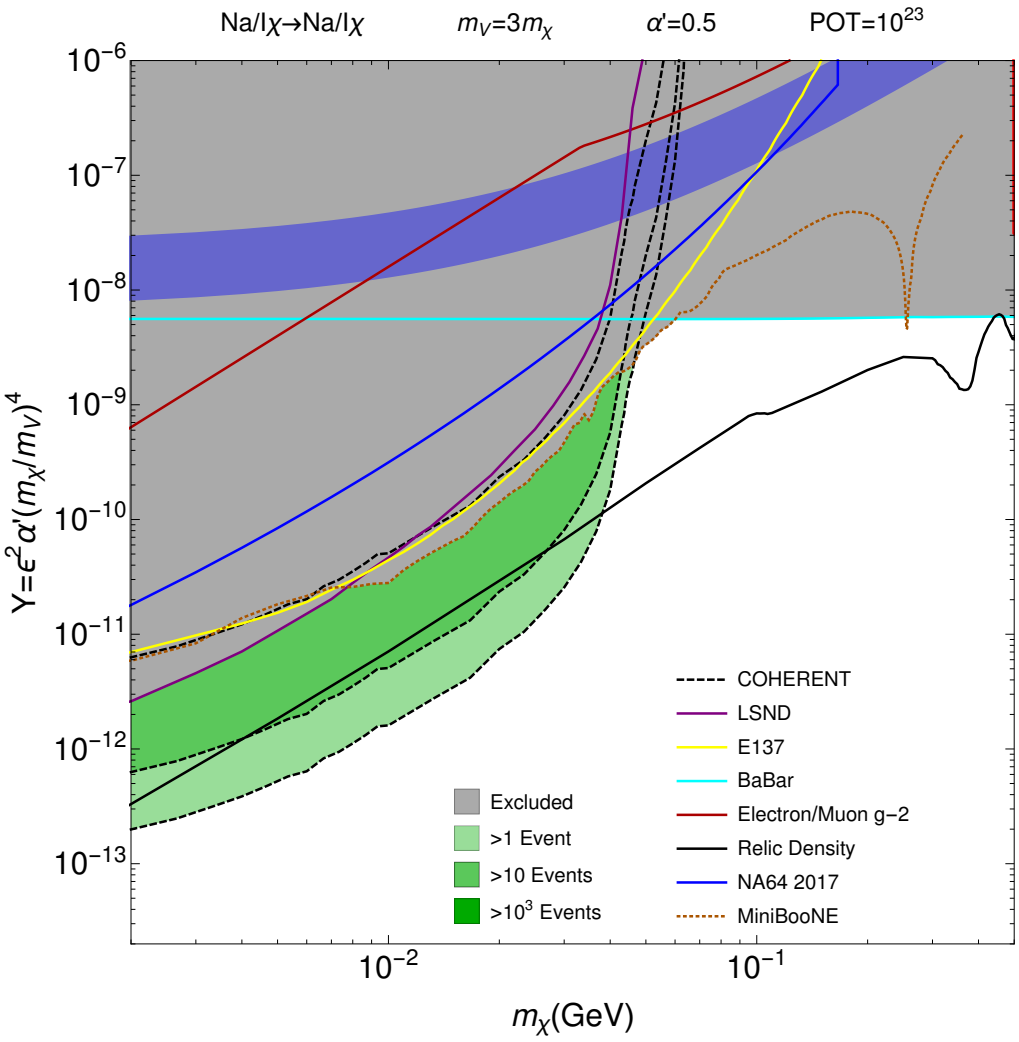
[MiniBooNE Collaboration '18 arXiv:1807.06137]

CEνNS - COHERENT

Proposed experiments that impact a low energy proton beam to study Coherent Elastic Neutrino Nucleus Scattering (CEνNS) by studying neutrinos produced from at-rest decays of charged pions. Most interested in COHERENT (SNS):

- Currently testing multiple multi-kilogram detectors.
- Phase III experiment calls for a ton-scale detector.
- We consider 1 ton of Na/I located 30 meters from the target, 90° relative to the beamline.
- $\sim 10^{23}$ POT (protons on target) per year with 1 GeV kinetic energy.
- Dark matter production is prompt.

COHERENT - ton-scale projections



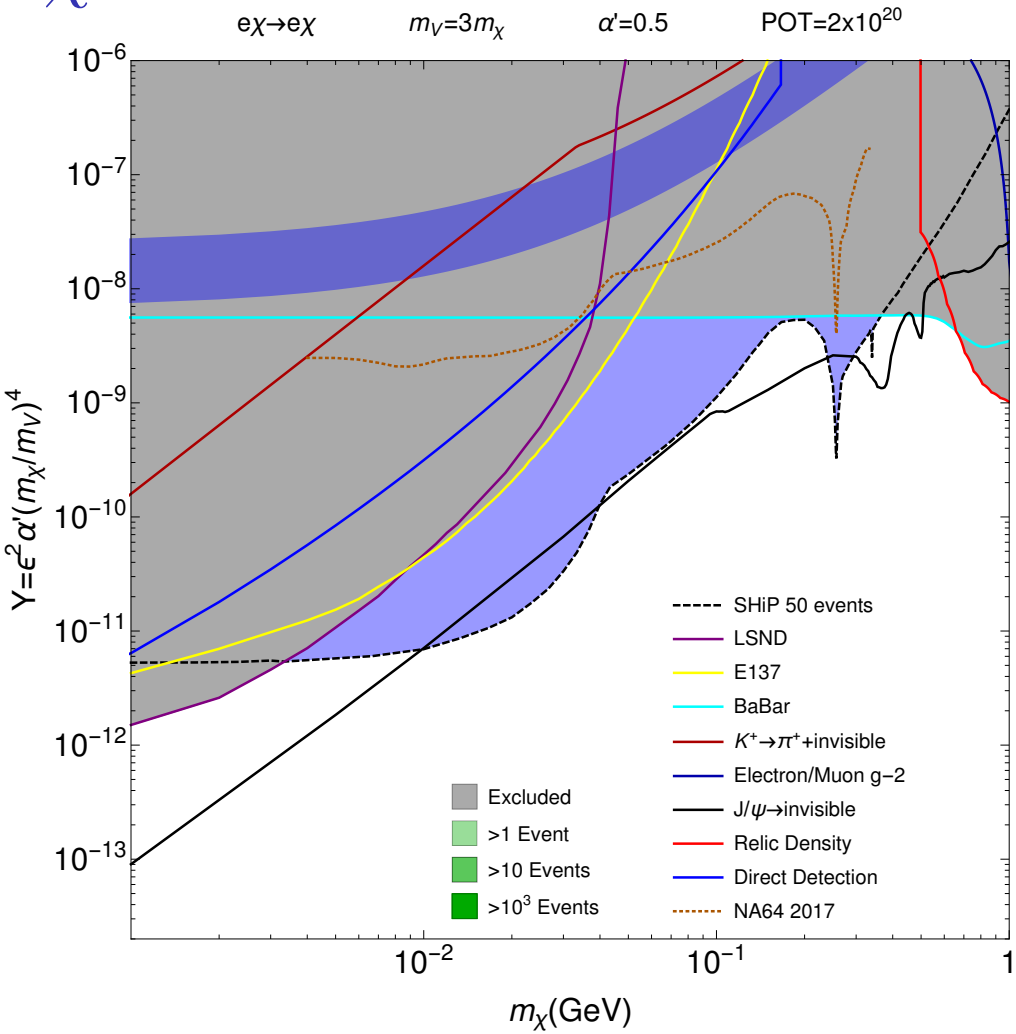
$E_{\text{recoil}} > 16$ keV to remove prompt Neutrinos

SHiP

Search for Hidden Particles

- Proposed beam dump experiment with sensitivity to a wide variety of hidden sector scenarios.
- 400 GeV proton beam from the SPS.
- Projections made for 2×10^{20} POT with 10 ton neutrino detector located 100 m from the target.
  - Current plans place it at 50 m from the target. Larger background likely.
- Neutral Current DM-electron scattering is highly peaked in the forward direction. Cutting on very forward scattering can remove most other projected backgrounds.
- Thanks to Walter Bonivento for background estimates/cuts.

SHiP - $e\chi \to e\chi$



- Electron Energy $\in [2, 20]$ GeV.
- Electron Scattering Angle $\in [10, 20]$ mrad.
- ~ 300 background events expected in this energy and angle window.
- Could make exclusion with $2 \times \sqrt{300} \approx 30$ events

Summary

- Thermal relic particles with a sub-GeV mass and interactions mediated by a light U(1)$'$ vector boson provides a viable dark matter candidate.
- This candidate escapes many of the best limits imposed by standard direct, indirect and collider searches.
- Counting experiment with LSND and MiniBooNE's DM-Electron scattering analysis provide the best constraint on a large range of dark matter masses.
- Proposed CEνNS experiments like COHERENT, and beam dump experiments like SHiP possess novel sensitivity to light dark matter scenarios, and can search much of the remaining parameter space during regular operations.
- Simple variations on the benchmark scenario, such as a leptophobic or inelastic dark matter, possess different sets of constraints, and can also be targeted by hadron experiments.

Experimental Constraints

Cosmological:

- Big Bang Nucleosynthesis - So long as $m_{\mathrm{DM}} > 1 - 2$ MeV, freeze-out occurs before BBN [Serpico & Raffelt '04, Jedamzik & Pospelov '09] .
- Cosmic Microwave Background - Annihilation through p-wave, has little effect [Padmanabhan & Finkbeiner et al '05; Slatyer et al '08] .
- N_{eff} - WIMP must be more massive than a few MeV, exact limit in literature unclear. [Boehm, Dolan & McCabe arXiv:1303.6270]

Particle Physics:

- Lepton $g - 2$ - Affects the value of $g - 2$. Strongest at low mass, but weakens with increasing mass [Fayet; Pospelov '08] .
  - Can also bring theoretical value of muon $g - 2$ into closer agreement with experimental value.
- Missing energy in rare decays.
  - Sensitivity to low m_V provided by π, K decays. [E949]
  - Need to use J/ψ, $\Upsilon(1S)$ decays for higher masses of m_V. [BESII'08, BaBar'09, Fayet'09]

Experimental Constraints

More Particle Physics:

- Monophoton search at BaBar, provides strongest constraint at high masses [Essig '13 arXiv:1309.5084, BaBar '17 arXiv:1702.03327] .
  - This could be improved dramatically by future e^+e^- colliders (Belle-II).
- Electron beam dump experiments, provide some of the strongest limits at low energies.
  - E137 [Batell '14 arXiv:1406.2698] , NA64 [NA64 Collaboration '17, arXiv:1710.00971] .
- Proton Beam Dumps and Fixed Target Experiments.
  - Neutral current elastic scattering at LSND [PdN '11, LSND Collaboration '01 arXiv:hep-ex/0101039, Y. Kahn 2014, arXiv:1411.1055] .
  - NCE electron and nucleon scattering, as well as inelastic nucleon scattering at MiniBooNE [MiniBooNE Collaboration arXiv:1807.06137] .

Experimental Constraints

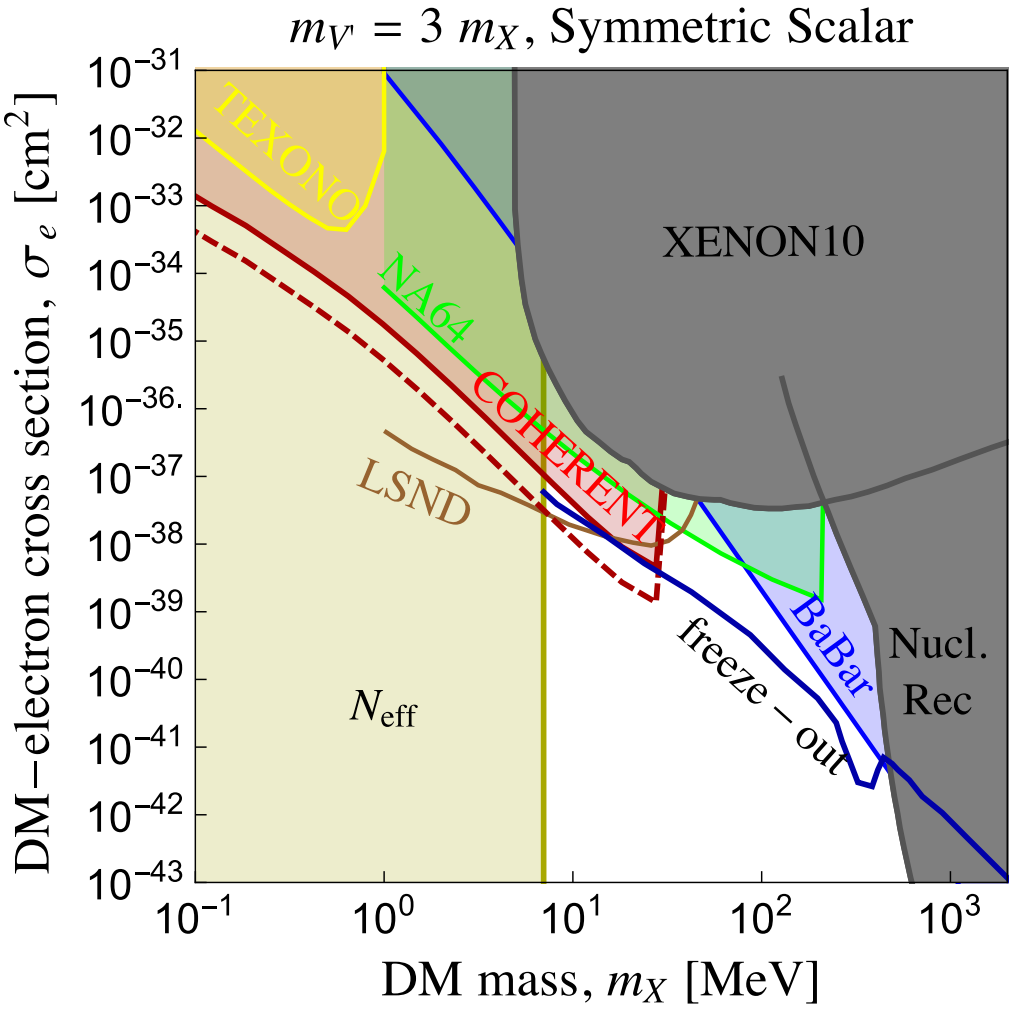
Even More Particle Physics Constraints:

- $V \to l^+ l^-$ - Weak so long as Br$(V \to 2\chi) \sim 1$, holds for most of parameter space of interest. [Bjorken et al. '09; Batell et al '09; Reece & Wang '09; MAMI '11, APEX '11, BaBar'12, ...]

Direct Dark Matter Detection:

- DM-Nucleon scattering -DAMIC, LUX, CDMS(lite), CRESST-II, XENON10/100/1T...
- DM-electron scattering - Reaches lower dark matter masses that Nucleon scattering [Essig'17, arXiv:1703.00910] .

COHERENT - 17 kg CsI



[Ge & Shoemaker '17 arXiv:1710:10889]

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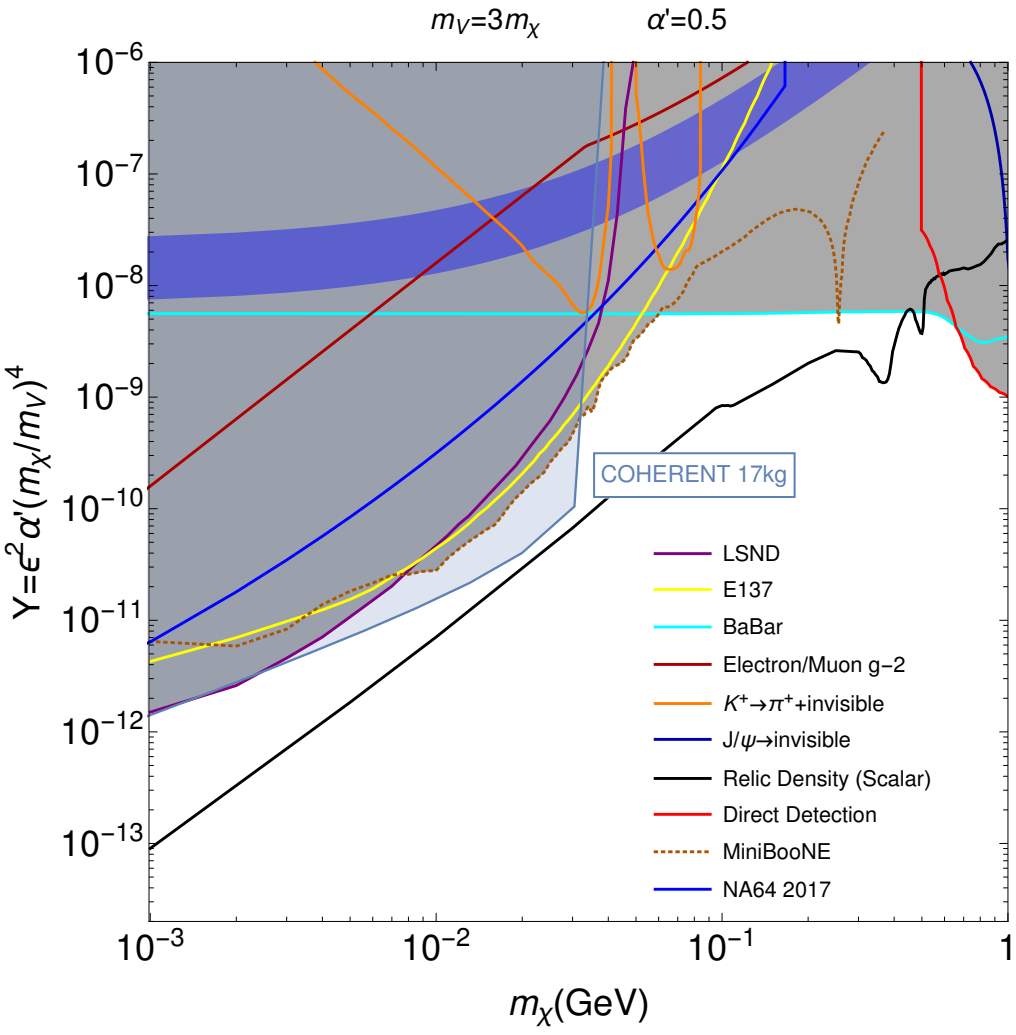

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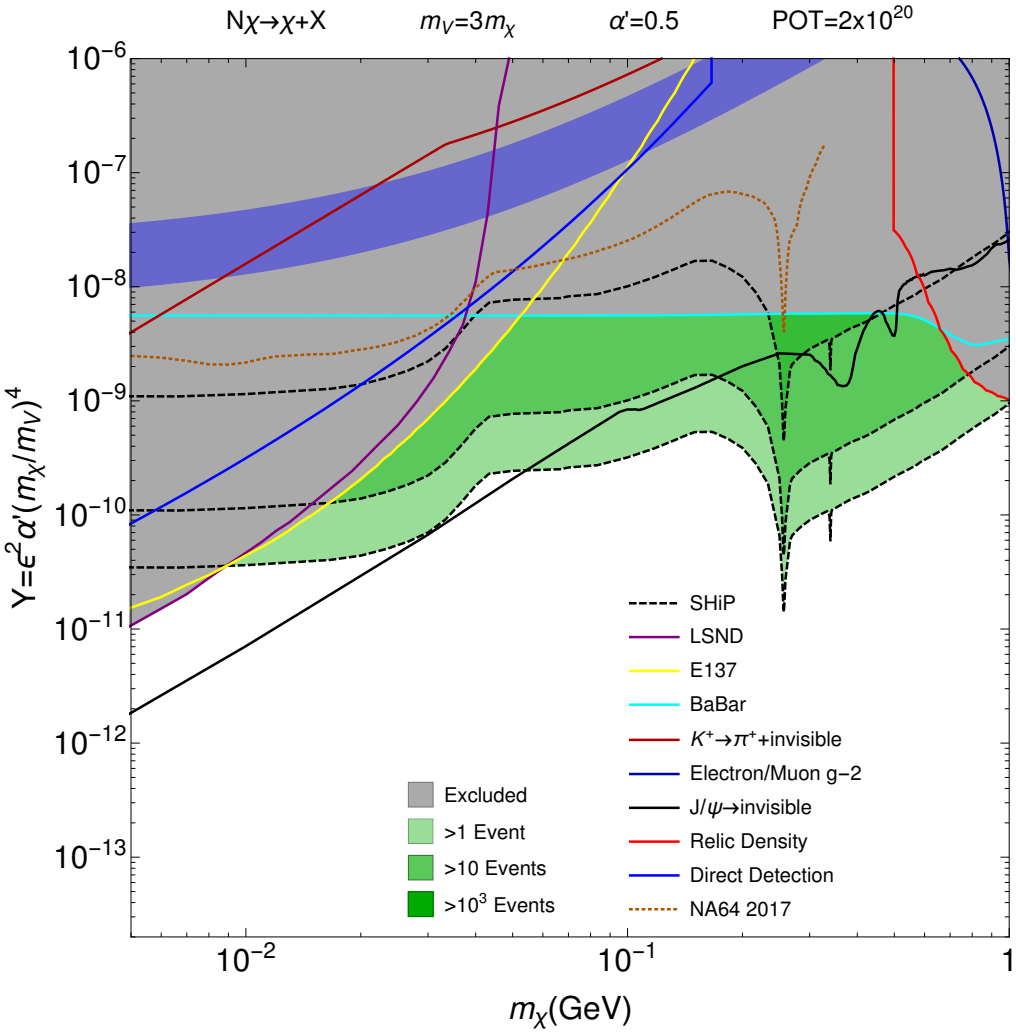
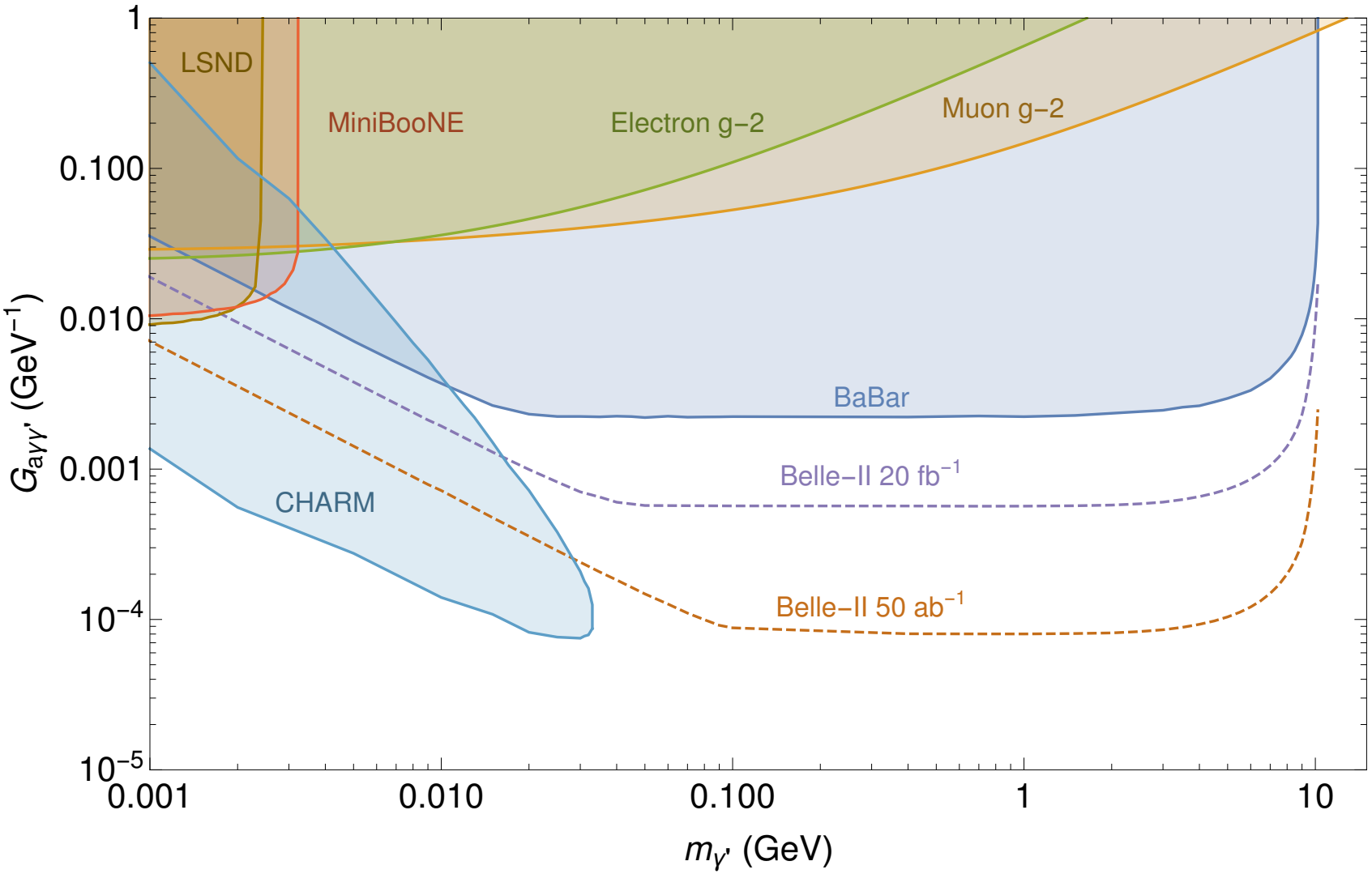
SHiP - Deep Inelastic Scattering



- Very large neutrino backgrounds expected, $\mathrm{few} \times 10^5$.
- Could be dramatically improved by differentiation between neutrino and DM induced DIS.

Searching for the Dark Axion Scenario