

Searching for Light Dark Matter with Fixed Target Experiments

Patrick deNiverville

Magnificent CE ν NS 2019

[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]

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.

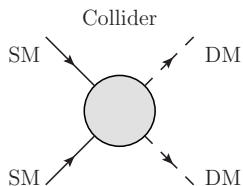
Hidden Sector Dark Matter with Kinetic Mixing

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

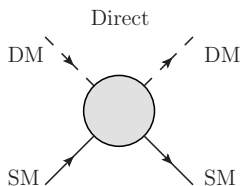
- ▶ Sub-GeV scalar DM candidate χ charged under $U(1)'$. The A' (I will sometimes call it a V) is the gauge boson of $U(1)'$ symmetry.
- ▶ Four model parameters:
 - ▶ $m_{A'}$, m_{χ} , ϵ and α_D (often labelled α')
- ▶ A' can be produced through kinetic mixing with γ at $\mathcal{O}(\epsilon^2)$.
 - ▶ For $2m_{\chi} < m_{A'}$, $\text{Br}(A' \rightarrow \chi\bar{\chi}) \sim 1$ and A' decay is prompt.
 - ▶ For $2m_{\chi} > m_{A'}$, $\text{Br}(V \rightarrow \text{SM}) \sim 1$.
- ▶ We set $U(1)'$ coupling strength $\alpha_D = 0.5$.
 - ▶ Largest possible value without significant running in coupling [Davoudiasl'15, 1502.07383] .
- ▶ Thermal relic.

- ▶ $\sigma(\chi\bar{\chi} \rightarrow l\bar{l}) \propto \epsilon^2 \alpha_D \left(\frac{m_{\chi}}{m_{A'}}\right)^4$

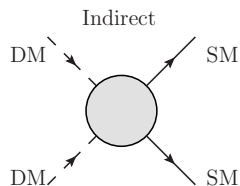
Searching for Dark Matter



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

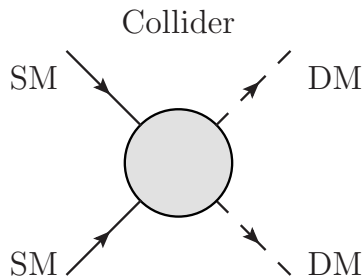


Build detectors deep underground and search for scatterings between cosmic dark matter and nuclei or electrons.

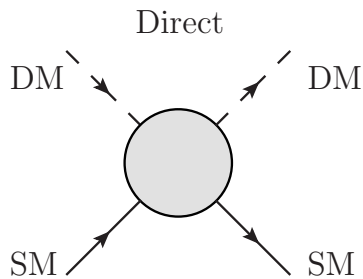


Use earth and space based telescopes to search for signals (photons or cosmic rays) from cosmic dark matter decays and annihilations.

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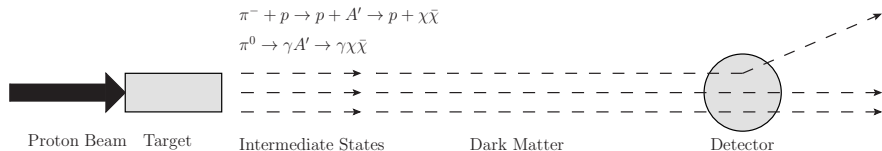


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Production of Dark Matter at a CE ν NS experiments

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

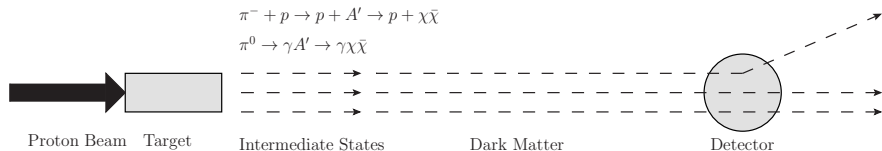
- ▶ Production of dark matter could occur through many channels. Relevant channels at low energies include:
 - ▶ Radiative decays of $\pi^0 \rightarrow \gamma A'^*$.
 - ▶ Radiative π^- capture: $p + N \rightarrow \pi^-$, $\pi^- + p \rightarrow n + A'^*$.
 - ▶ BR $\sim 40\%$ on protons, but drops to a few % for larger nuclei.
See [Pospelov, Tsai, 1706.00424] and [Chiang '89] .



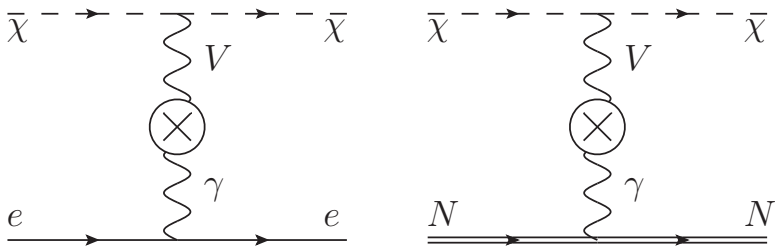
Production of Dark Matter at CE ν NS experiments

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

- ▶ Timing provides an important handle on the hidden sector signal:
 - ▶ Dark matter production is prompt, so it can benefit from any timing structure in the beam.
 - ▶ Dark matter arrives at the detector before delayed neutrino signals or other backgrounds.
 - ▶ Significant advantage to short bunches.

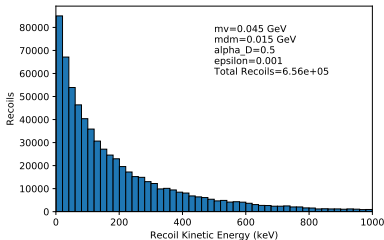
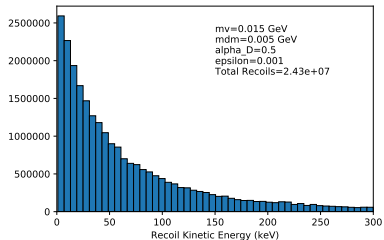


Detecting Low Mass Dark Matter - Elastic Scattering



- ▶ 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.
- ▶ $\sigma_{\chi N, e \rightarrow \chi N, e} \propto \epsilon^2 \alpha' \alpha$

Detecting Low Mass Dark Matter - Coherent Scattering



- ▶ Example plots made with 800 MeV proton beam, scattering on Argon.
- ▶ $\sigma_{\chi Z \rightarrow \chi Z} \propto Z^2 F_{\text{Helm}}(q^2)$.
- ▶ High-recoil tail of scattering distribution grows with the mass of the dark matter.
- ▶ Decline in overall event rate due in large part to decline in scattering cross section with increasing mass rather than production rate.
- ▶ Switch to incoherent scattering for $q^2 > (50 \text{ MeV})^2$.

Experimental Constraints

Cosmological:

- ▶ **Big Bang Nucleosynthesis** - So long as $m_{\text{DM}} > 1 - 2 \text{ MeV}$, 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:

- ▶ $A' \rightarrow l^+l^-$ - Weak so long as $\text{Br}(A' \rightarrow 2\chi) \sim 1$, 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, (Super)CDMS(lite), CRESST-II, CRESST-III, XENON10/100/1T...
- ▶ DM-electron scattering can reach lower dark matter masses [Essig'17, arXiv:1703.00910]

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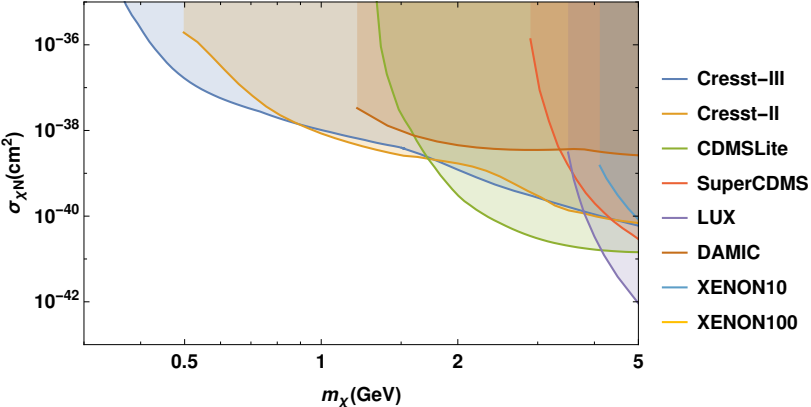
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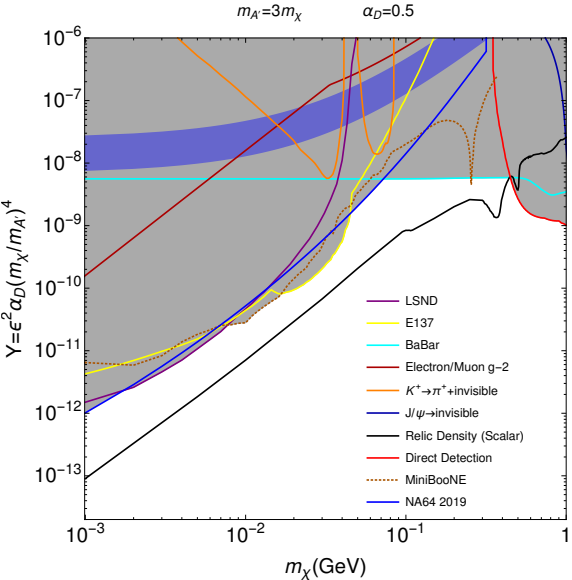
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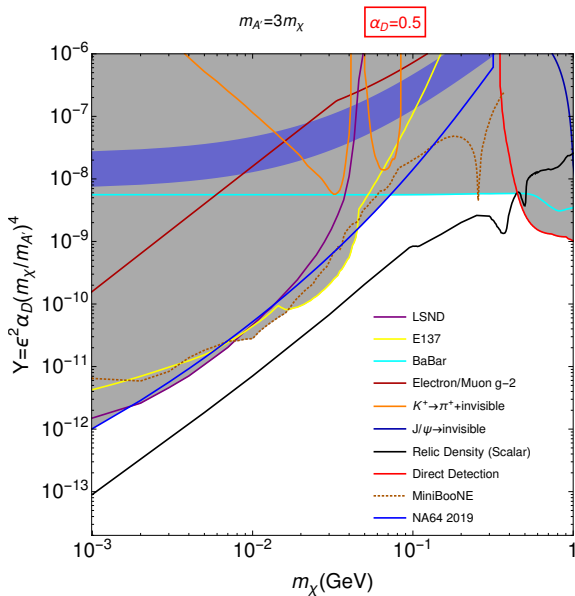
Direct Searches



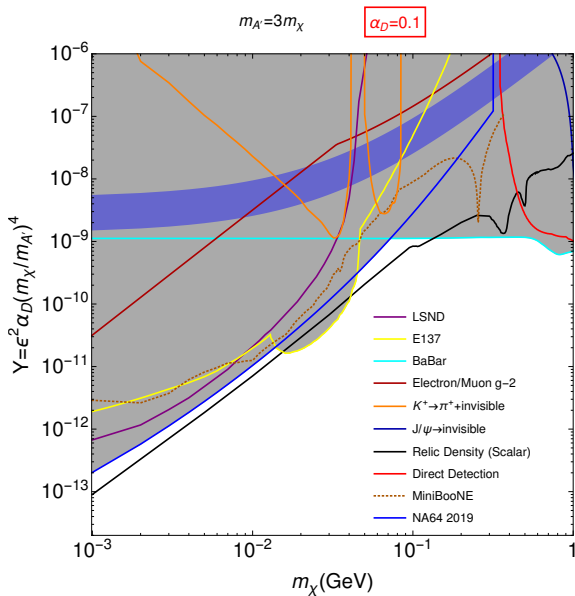
Kinetic Mixing Parameter Space



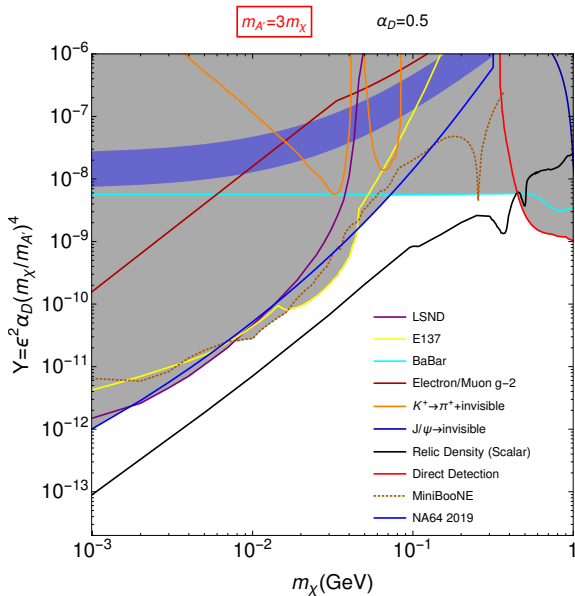
Kinetic Mixing Parameter Space



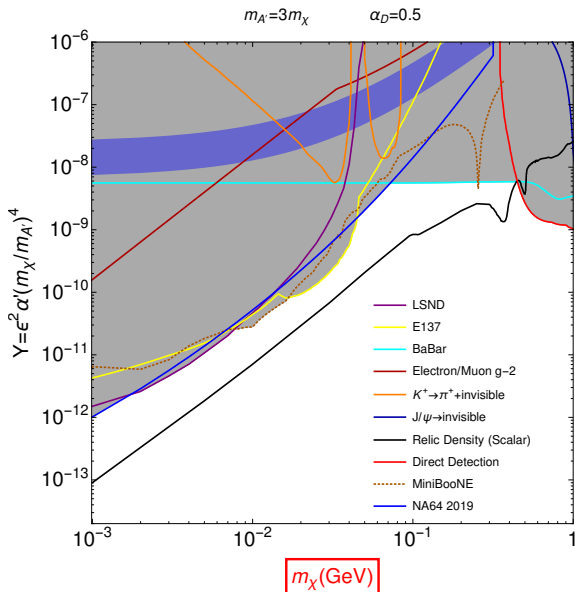
Kinetic Mixing Parameter Space



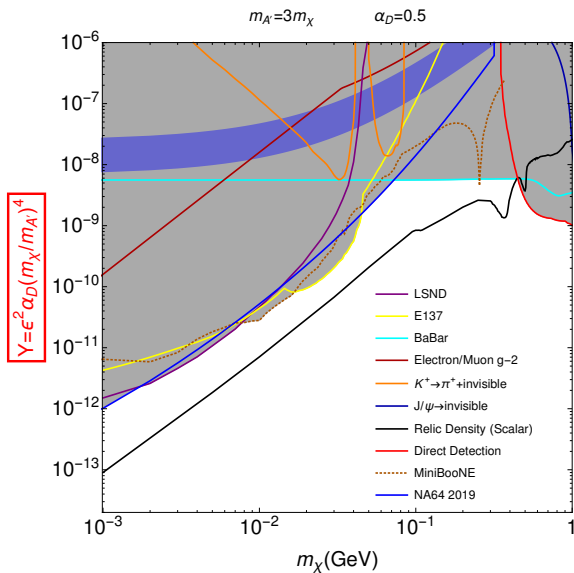
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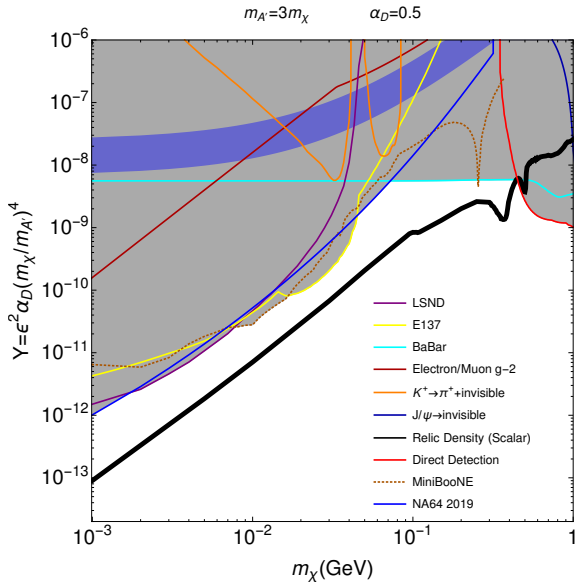
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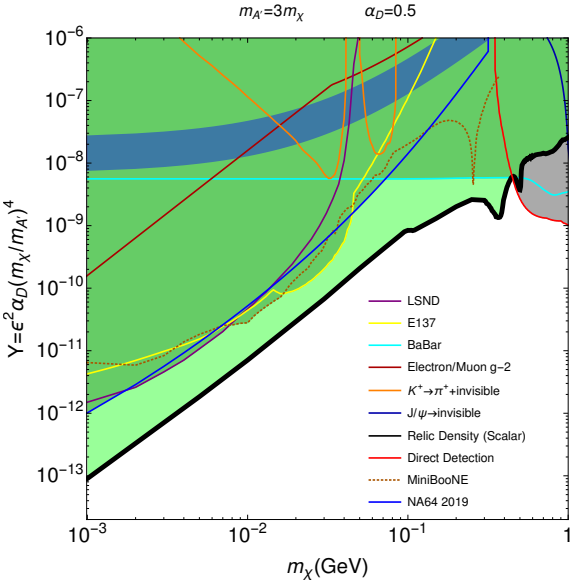
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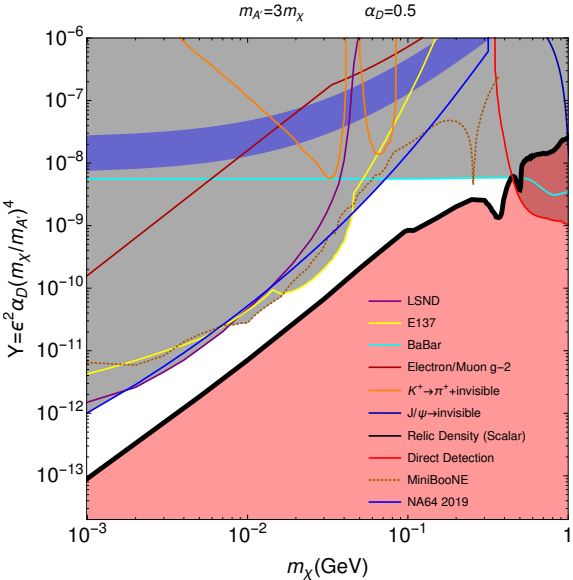
Kinetic Mixing Parameter Space - Relic Density



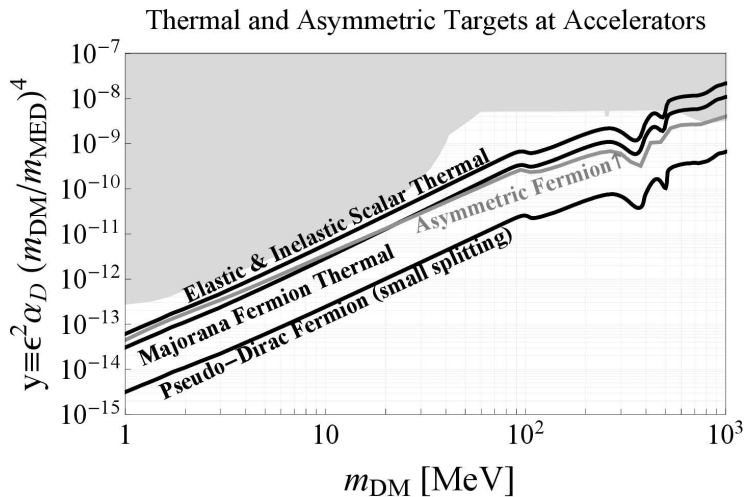
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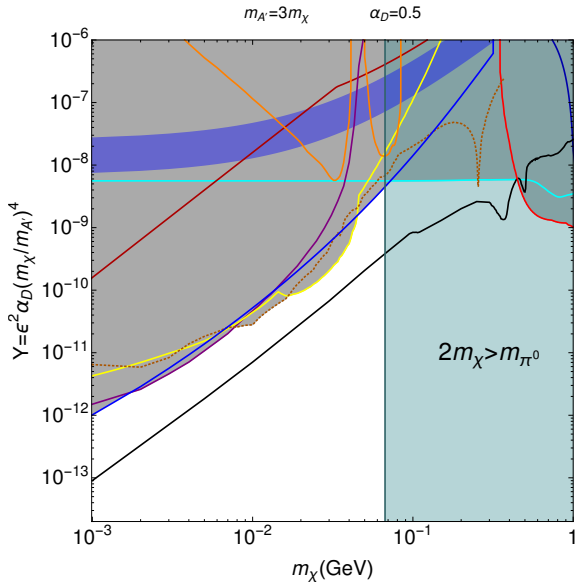


Relic Density Variations

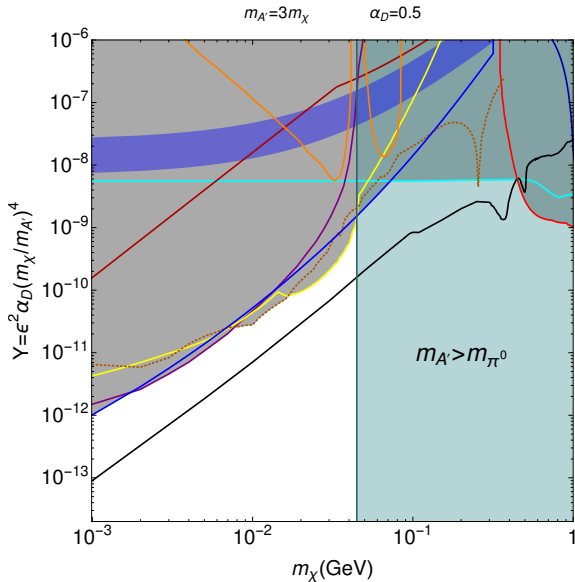


[US Cosmic Vision 2017 arXiv:1707.04591]

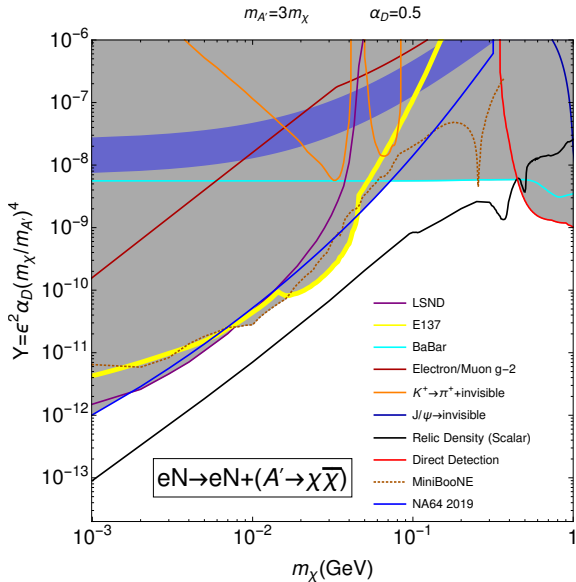
Kinetic Mixing Parameter Space - CE ν NS Reach



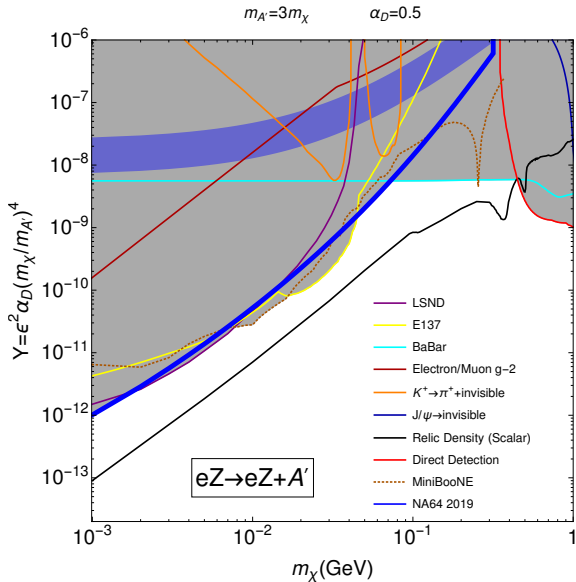
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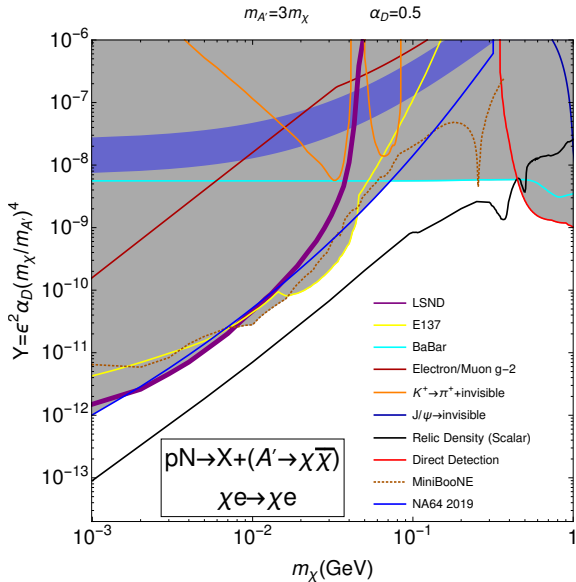
Kinetic Mixing Parameter Space - E137



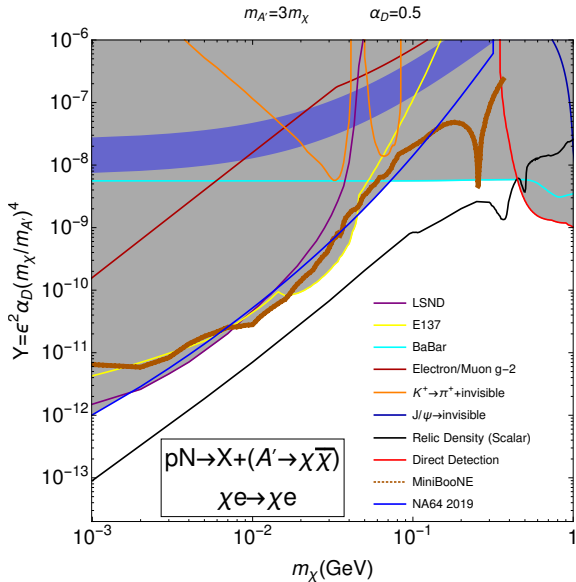
Kinetic Mixing Parameter Space - NA64



Kinetic Mixing Parameter Space - LSND

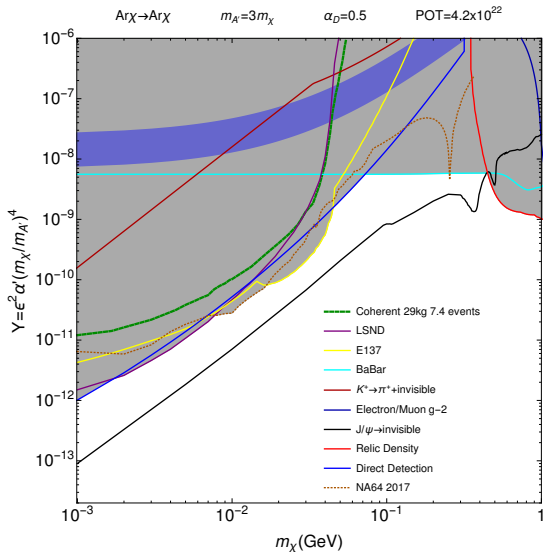


Kinetic Mixing Parameter Space - MiniBooNE



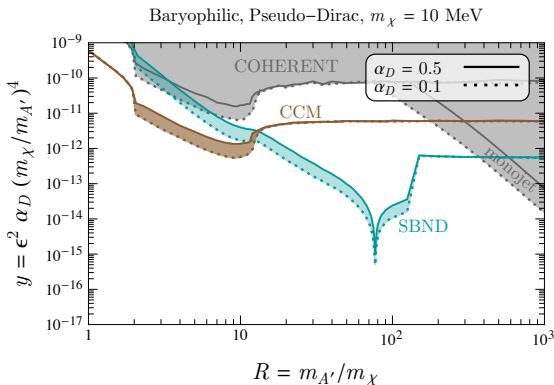
COHERENT 29kg LAr Engineering Run

- ▶ Detector located 28.3 meters from target at large angle.
- ▶ Predicted 112 ± 30 background events, observed 126 ± 15
- ▶ Placed a 1σ upper limit of 7.4 coherent neutrino-nucleus scattering events.
- ▶ Plotted 7.4 events from light dark matter scenario.



[COHERENT arXiv:1909.05913]

Looking only at Hadronic Couplings...

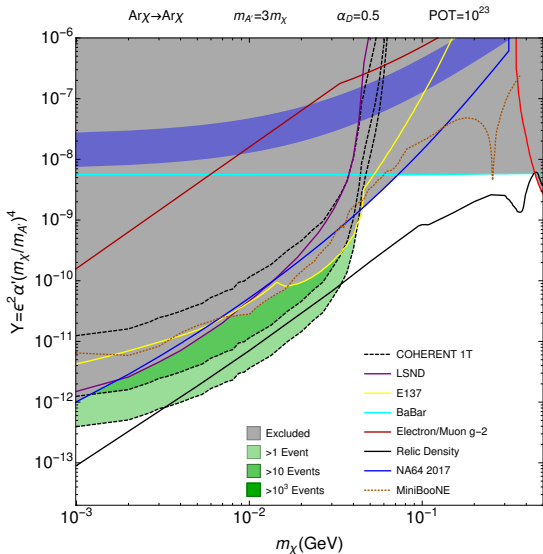


[A. Berlin, PDN, P. Schuster, A. Ritz, N. Toro arXiv:1911.XXXXX]

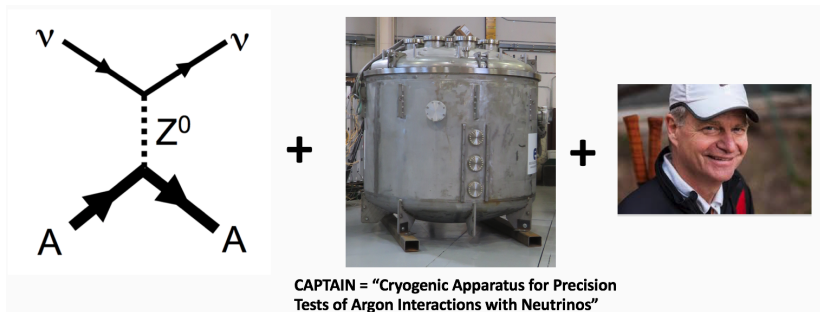
Caveat: Models without lepton-couplings tend to have many other strong constraints (see arXiv:1705.06726), may not be a good thermal relic, plot generated for easy rescaling.

COHERENT 1T

- ▶ Scaling up to a possible 1T detector.
- ▶ Would require reduction in background, but does have significant potential reach.
- ▶ COHERENT may be able to take significantly more than 10^{23} POT, which would dramatically improve its potential reach.



Coherent CAPTAIN-Mills (CCM)



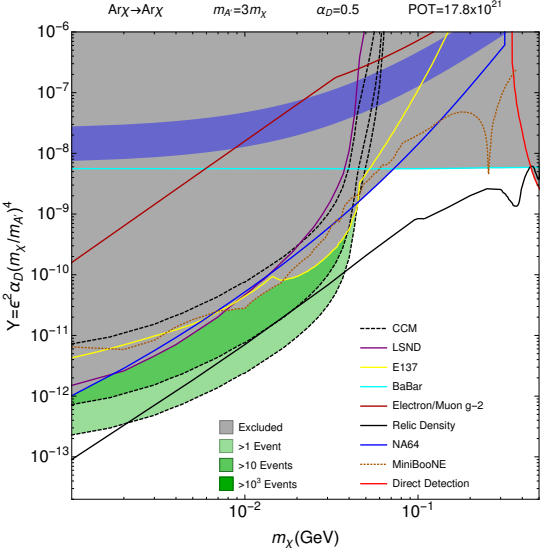
The image contains three main components arranged horizontally. On the left is a Feynman diagram showing a neutrino (ν) and an Argon nucleus (A) interacting via a Z^0 boson. The neutrino and nucleus are shown as incoming particles from the left, and the neutrino and nucleus are shown as outgoing particles to the right. A dashed line labeled Z^0 connects the two vertices. In the center is a photograph of the CAPTAIN apparatus, a large, cylindrical, stainless steel cryogenic vessel. On the right is a portrait of Edward Dunton, a man wearing a white cap and a dark jacket.

CAPTAIN = "Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos"

- ▶ 7 tons of Liquid Argon with 3 tons of veto.
- ▶ Located at Los Alamos National Laboratory.
 - ▶ 800 MeV proton beam.
- ▶ As with COHERENT, located $> 90^\circ$ off-axis.
- ▶ See Edward Dunton's talk on Sunday for more details.

Dark Matter at CCM

- ▶ Simulation performed for 10T LAr located 20 meters from stopped pion source.
- ▶ Shielding is still being assembled, backgrounds not yet well known.
- ▶ Timing is an excellent tool for reducing background, but may be challenging.



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 strong constraints, though now surpassed by NA64.
- ▶ Proposed $CE\nu NS$ experiments like COHERENT and CCM are well placed to search for $\mathcal{O}(10 \text{ MeV})$ dark matter candidates.
- ▶ 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 proton beam experiments.