Search for light dark matter at MiniBoone

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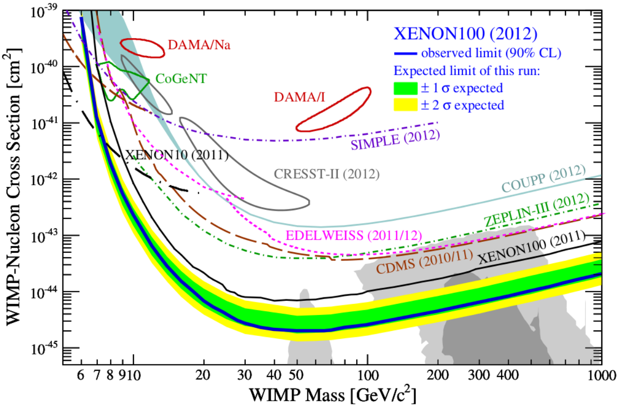
Theoretical Perspectives on New Physics at the Intensity Frontier

[P. dN, M. Pospelov & A. Ritz '11, arXiv: 1107.4580 [hep-ph]]
[P. dN, D. McKeen & A. Ritz '12, arXiv: 1205.3499 [hep-ph]]
[B. Batell, P. dN, D. McKeen, M. Pospelov, A. Ritz '14, arXiv: 1405.7049 [hep-ph]]

Motivation

Experimental limits for WIMP-Nucleon cross section

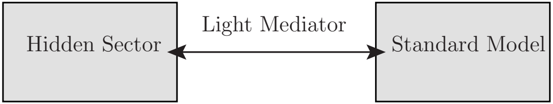


[XENON Collaboration 2012, arXiv:1207.5988 [astro-ph]]

A Low Mass Dark Matter Scenario

The primary constraint on low mass thermal relic model building is the effect on cosmology of a new particle produced copiously in the early universe.

- If annihilation to SM states in the early universe is too weak, too much dark matter is produced in the early universe.
  - Introducing a light particle to mediate interactions between dark sector and SM can enhance the annihilation rate.



- Too large an annihilation rate at later times would have been observed through annihilation signals or its effect on the cosmological history of the universe.
  - Choosing a **scalar dark matter candidate** and a **vector mediator particle** results in a velocity suppressed annihilation rate, reducing these signals.

Kinetic Mixing

Dark sector containing scalar DM χ and vector mediator V, with $m_V > 2m_\chi$.

$$\mathcal{L} = |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} V_{\mu\nu}^2 + \frac{1}{2} m_V^2 V_\mu^2 - \frac{\kappa}{2} V_{\mu\nu} F^{\mu\nu} + \dots$$

$$D_\mu = \partial_\mu - ie' V_\mu$$

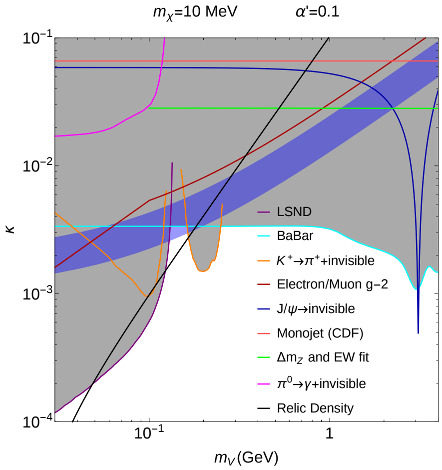
V interacts with SM through kinetic mixing with the photon.

$$\mathcal{L} \supset -e\kappa V_\mu J^\mu_{EM}$$

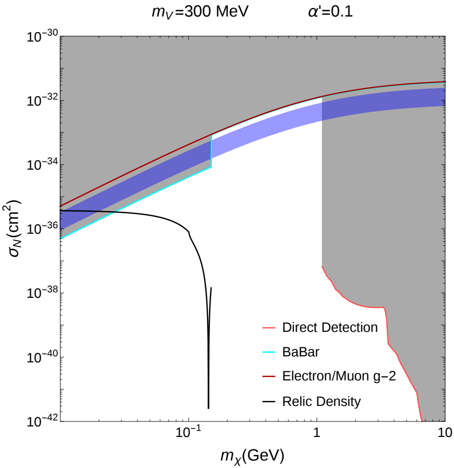
Four free parameters: m_χ, m_V, κ, and e'.

- Set $\frac{e'^2}{4\pi} = \alpha' = 0.1$ for convenience.
- Scenario is weakly constrained by direct and indirect dark matter searches, but constraints from collider physics are improving.

Scenario Parameter Space - Kinetic Mixing



Dark force parameter space



Direct detection parameter space

Baryonic Coupling Scenario

Dark sector containing scalar DM χ and vector mediator V, with $m_V > 2m_\chi$.

$$\mathcal{L} = |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} V_{\mu\nu}^2 + \frac{1}{2} m_V^2 V_\mu^2 + g_B V_\mu J_B^\mu - \frac{\kappa}{2} V_{\mu\nu} F^{\mu\nu} + \ldots$$

$$D_\mu = \partial_\mu - i g_B q_B V_\mu = \partial_\mu - i e' V_\mu$$

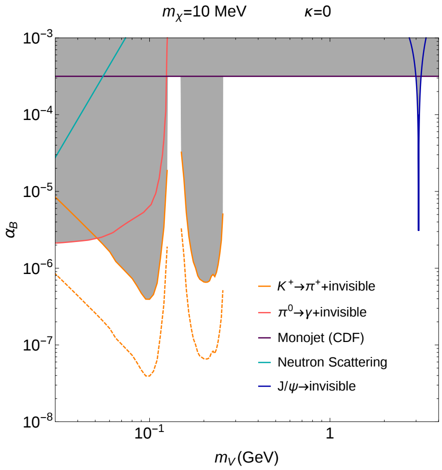
Dark vector mediator interacts with SM through kinetic mixing with the photon, coupling to the baryonic current, or some combination of the two.

$$\mathcal{L} \supset V_\mu \left(g_B J_B^\mu - \kappa e J_{EM}^\mu \right)$$

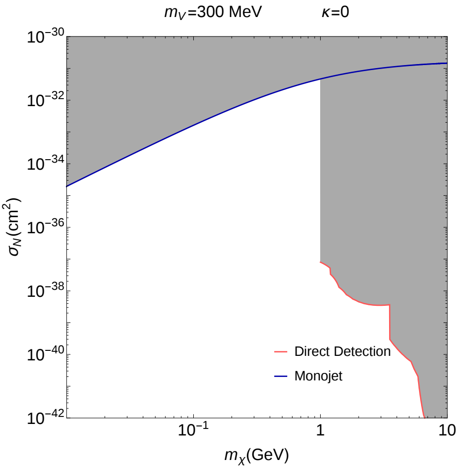
Five free parameters: m_χ, m_V, κ, g_B and e'.

- We will consider the regime where baryonic coupling dominates, and set $\kappa = 0$.
- $e'^2 = 4\pi\alpha_B$ when we add coupling to baryons.

Scenario Parameter Space - Baryonic Vector

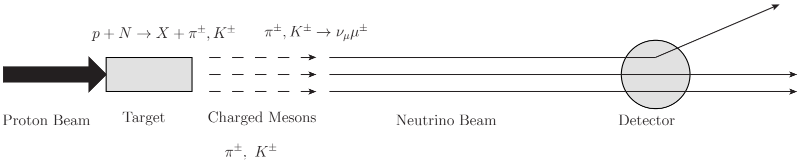


Dark force parameter space



Direct detection parameter space

Fixed Target Neutrino Experiments

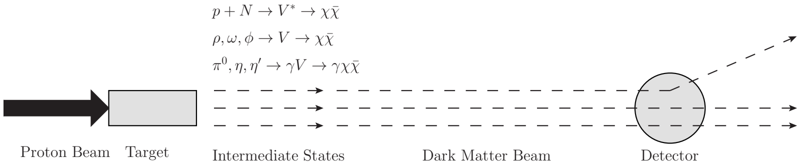


- Experiments impact a target with $\sim 10^{20} - 10^{22}$ protons to produce a high intensity neutrino beam.
  - Neutrinos produced from decays of charged mesons propagating through subsequent decay volume.
  - Can select for neutrino or antineutrino beams through the use of magnetic focusing horns.
- Non-neutrinos are removed from the beam before it reaches the detector to reduce background.
- Several fixed target neutrino experiments were investigated, including: LSND, MiniBooNE, T2K.

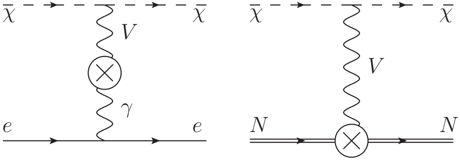
Dark Matter Beams

Production of a dark matter beam through:

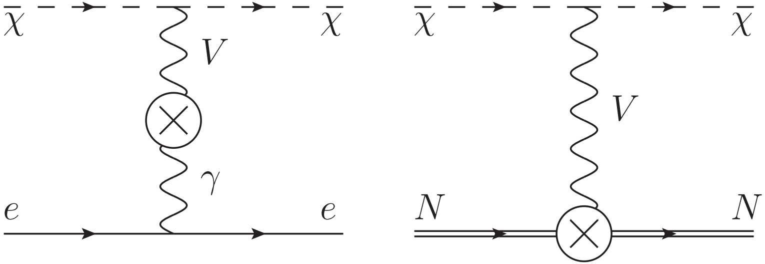
- Radiative decays of pseudoscalar mesons: π^0, η, η'.
- Coupling to vector mesons: ρ, ω, ϕ.
- Direct parton-level production: $p + N \to V^* \to \chi\bar{\chi}$



Detection through NCE scattering off electrons or nucleons. Very similar to neutrino NCE scattering.



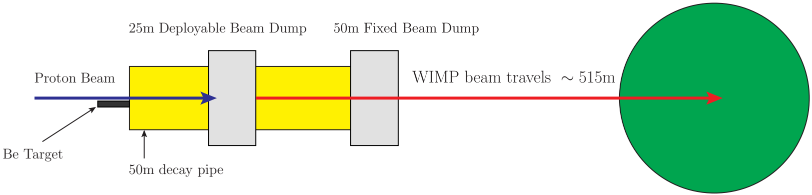
Detecting Dark Matter with Neutrino Detectors



- In the most straightforward analyses, without special timing or energy cuts, dark matter signal manifests as neutral-current-like elastic scattering events in excess of those expected from neutrinos.
  - For our analyses, neutrino events are the background. Need to generate a significant number of excess events to obtain useful sensitivity.
- Interaction channel chosen for analysis of each experiment dependent on backgrounds and the neutral-current elastic scattering analyses published.

Reducing the Neutrino Background

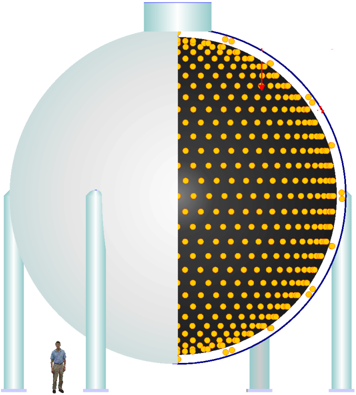
- Sensitivity can be improved by either reducing the number of neutrinos reaching the detector, or by differentiating between likely neutrino and dark matter events.
  - Timing Cuts - DM beam takes longer to reach the detector than neutrino beam.
  - Energy Cuts - DM energy distribution peaks at a higher energy than the neutrino distribution.
- Off-Target/Beam Dump runs
  - Can dramatically decrease the neutrino flux by sending a proton beam directly into the beam dump, while leaving DM flux largely unchanged.
  - MiniBooNE has been running in beam dump mode for much of the last year. [arXiv:1211.2258v1, with Richard Van de Water] .



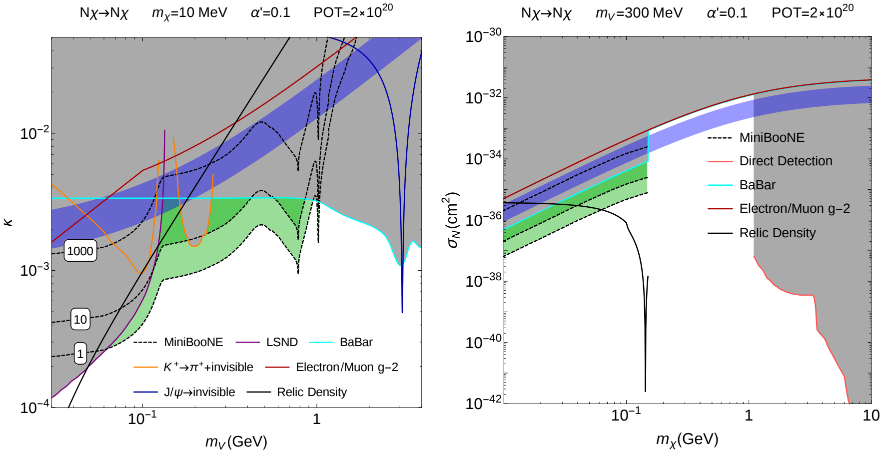
The MiniBooNE Experiment

- Located at Fermilab.
- Operated in neutrino mode from 2002 to 2012, delivering nearly 2×10^{21} protons delivered to its beryllium target.
- Target is followed by a 50 meter decay region and iron beam dump.
- Uses an 800 ton mineral oil Cerenkov detector, located 541 meters from the target.
- Operated in beam dump mode from November 8, 2013 to September 5, 2014, collecting 2×10^{20} POT.

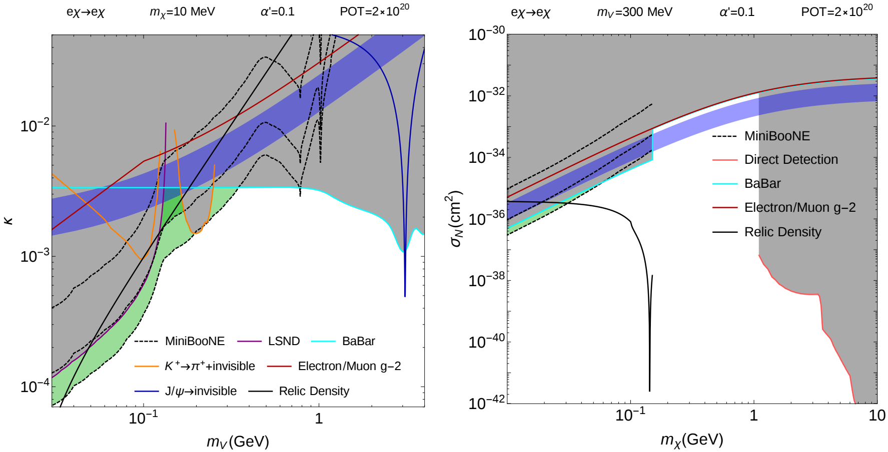
MiniBooNE Detector



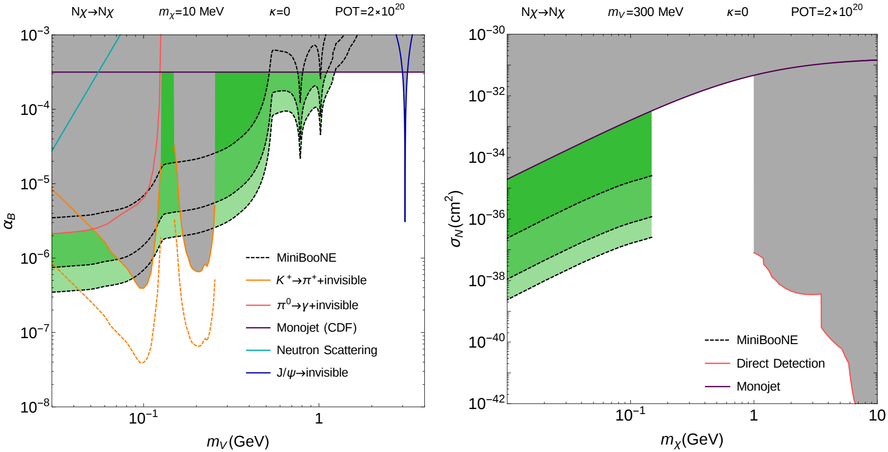
MiniBooNE Kinetic Mixing - $\chi N \to \chi N$



MiniBooNE Kinetic Mixing - $\chi e \to \chi e$



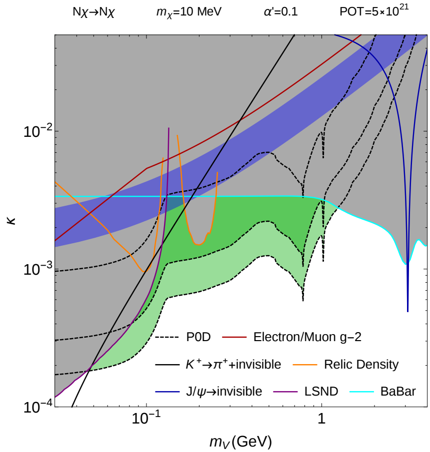
MiniBooNE Baryonic Vector

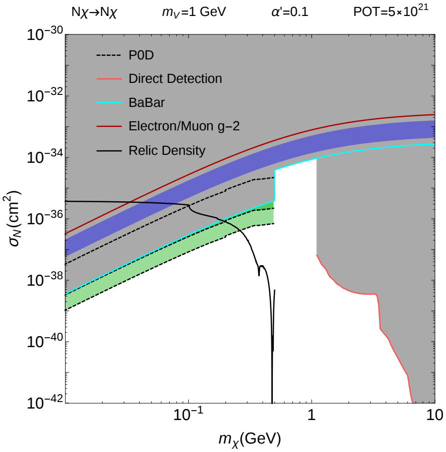


T2K

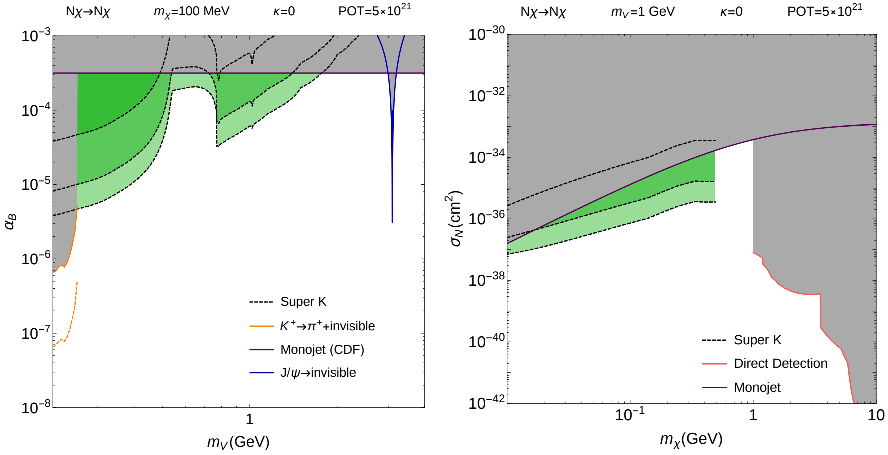
- Long baseline fixed-target neutrino experiment .
- Expects to deliver $> 5 \times 10^{21}$ 30 GeV protons on target.
- Utilizes a multi-component near detector, ND280, and a 50 ton water Cerenkov far detector, Super-K.
  - Both detectors are 2.5 degrees off-axis to better select for specific neutrino energies.
  - ND280 is 280 m from the target, while Super-K is 295 km from the target.

T2K P0D Kinetic Mixing





T2K Super-K Baryonic Vector



Summary

- Thermal relic WIMP 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.
  - While new limits are being placed on the parameter space, a great deal of viable parameter space remains unconstrained. Electron fixed target experiments could reduce this further.

    [see i.e. arXiv:1307.6554 [hep-ph], arXiv:1403.6826 [hep-ph], arXiv:1406.3028]
  - Variants on this model, such as a baryonically coupled $U(1)_B$ vector boson, can escape many of these new constraints.
- Fixed Target Neutrino Facilities possess good sensitivity to these hidden-sector scenarios.
  - Capable of probing regions of the hidden-sector parameter space currently inaccessible to other techniques.
- Running a Fixed Target Neutrino Experiment in an off target mode could provide new sensitivity, while requiring far fewer POT.
  - A test of this approach is being conducted by the MiniBooNE experiment.

Acknowledgements

The work of Patrick deNiverville was funded in part by NSERC Canada.

Choosing a Portal

For $m_V > 2m_\chi$

- **U(1)′ Mediator - Vector Portal**
  - **Fermionic DM** - s-wave annihilation and an increased dark matter number density due to the low dark matter mass results in a visible distortion of the CMB. Also leads to a more visible signal from galactic center. [Padmanabhan & Finkbeiner et al '05; Slatyer et al '08]
  - **Scalar DM** - p-wave annihilation allows this scenario to be viable for small κ, as the annihilation rate is suppressed by an additional factor of v. A small v heavily suppresses the dark matter annihilation rate.
- **Scalar Mediator - Higgs Portal**
  - **Scalar DM** - s-wave annihilation excludes this scenario for the reasons given previously.
  - **Fermionic DM** - p-wave annihilation renders this model viable. However, fermionic DM requires a large mixing, which could affect B decays. [Bird, Kowalewski & Pospelov 2006]

Dark Matter Beams - Production Channel Cross Sections