Searching for Light Dark Matter with Fixed Target Neutrino Experiments

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CAPP-CTPU-CUP Collaboration Meeting

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.

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

Collider

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

Experiments: LHC, Tevatron

Direct

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

Indirect

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

Direct Searches

$\sigma_N(\text{cm}^2) \times 10^{-41}$ vs $m_X(\text{GeV})$

- XENON100
- XENON10
- CRESST-II
- DAMIC
- CDMSlite
- LUX
- SuperCDMS
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 $T \gg m_{DM}$, 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

$$\frac{\Omega_{DM}}{\Omega_{\text{matter}}} \sim \frac{1\text{pbn}}{\langle \sigma v \rangle_{fo}}$$
Lee-Weinberg Bound and Thermal Relics

The Lee-Weinberg bound tells us that for $m_{DM} < \text{few GeV}$ 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,

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

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

![Diagram](Diagram)

Dark matter candidates in these scenarios could potentially be created at low energies. We will be particularly interested in the regime where $m_{DM} < m_{\text{Mediator}}$. 
Hidden Sector Dark Matter with Kinetic Mixing

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

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

Cosmological:

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

- $V \rightarrow l^+l^-$ - Weak so long as $\text{Br}(V \rightarrow 2\chi) \sim 1$, 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, 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 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]
Direct Detection: DM-electron scattering

[Essig'17, arXiv:1703.00910]
Kinetic Mixing Parameter Space

$m_v = 3m_\chi$  \( \alpha' = 0.5 \)

$Y = \epsilon^2 \alpha' (m_\chi/m_v)^4$

$m_\chi (\text{GeV})$

$10^{-3} - 10^{-1}$
Kinetic Mixing Parameter Space

\[ m_{V} = 3m_{\chi} \]

\[ \alpha' = 0.5 \]

\[ Y = \epsilon^2 \alpha'(m_{\chi}/m_{V})^4 \]

- LSND
- E137
- BaBar
- Electron/Muon g-2
- \( K^{+} \rightarrow \pi^{+}+\text{invisible} \)
- \( J/\psi \rightarrow \text{invisible} \)
- Relic Density (Scalar)
- Direct Detection
- MiniBooNE
- NA64 2017
Kinetic Mixing Parameter Space

\[ m_V = 3m_{\chi} \]

\[ \alpha' = 0.5 \]

\[ Y = \epsilon^2 \alpha'(m_{\chi}/m_V)^4 \]

\[ m_V = 3m_{\chi} \quad \alpha' = 0.5 \]

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\[ Y = \epsilon^2 \alpha'(m_{\chi}/m_V)^4 \]

\[ m_{\chi} \text{ (GeV)} \]

\[ 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 1 \]

\[ Y = \epsilon^2 \alpha'^4 \frac{m_{\chi}}{m_V} \]

\[ 10^{-13} \quad 10^{-12} \quad 10^{-11} \quad 10^{-10} \quad 10^{-9} \quad 10^{-8} \quad 10^{-7} \quad 10^{-6} \]
Kinetic Mixing Parameter Space

\[ Y = \epsilon^2 \alpha' \left( \frac{m_X}{m_V} \right)^4 \]

\[ m_V = 5m_X \]

\[ \alpha' = 0.5 \]

\[ m_X (\text{GeV}) \]

\[ Y \]

- LSND
- E137
- BaBar
- Electron/Muon g-2
- \( K^+ \rightarrow \pi^+ + \text{invisible} \)
- \( J/\psi \rightarrow \text{invisible} \)
- Relic Density (Scalar)
- Direct Detection
- MiniBooNE Nucleon
- NA64 2017

\[ 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 1 \]

\[ 10^{-13} \quad 10^{-12} \quad 10^{-11} \quad 10^{-10} \quad 10^{-9} \quad 10^{-8} \quad 10^{-7} \quad 10^{-6} \]
Kinetic Mixing Parameter Space

\[ m_V = 3m_\chi \]
\[ \alpha' = 0.5 \]

\[ Y = e^2 \alpha' (m_\chi / m_V)^4 \]

- LSND
- E137
- BaBar
- Electron/Muon g-2
- \( K^+ \rightarrow \pi^+ + \text{invisible} \)
- \( J/\psi \rightarrow \text{invisible} \)
- Relic Density (Scalar)
- Direct Detection
- MiniBooNE
- NA64 2017

\[ m_\chi (\text{GeV}) \]
Kinetic Mixing Parameter Space

\[ Y = \varepsilon^2 \alpha' \left( \frac{m_X}{m_V} \right)^4 \]

\[ m_V = 3m_X \quad \alpha' = 0.5 \]

- LSND
- E137
- BaBar
- Electron/Muon \( g-2 \)
- \( K^+ \rightarrow \pi^+ + \text{invisible} \)
- \( J/\psi \rightarrow \text{invisible} \)
- Relic Density (Scalar)
- Direct Detection
- MiniBooNE
- NA64 2017

\[ m_X \text{(GeV)} \]

\[ \varepsilon \text{ (}\text{GeV}\text{)} \]

\[ \alpha' \text{ (dimensionless)} \]
Kinetic Mixing Parameter Space - Relic Density

$m_{\nu} = 3m_{\chi}$

$\alpha' = 0.5$

$Y = \epsilon^2 \alpha' \left( \frac{m_{\chi}}{m_{\nu}} \right)^4$

$m_{\chi} (\text{GeV})$

$10^{-3}$ $10^{-2}$ $10^{-1}$ $10^0$

$10^{-11}$ $10^{-12}$ $10^{-13}$ $10^{-14}$ $10^{-15}$

$\text{LSND}$

$\text{E137}$

$\text{BaBar}$

$\text{Electron/Muon g-2}$

$K^+ \rightarrow \pi^+ + \text{invisible}$

$J/\psi \rightarrow \text{invisible}$

$\text{Relic Density (Scalar)}$

$\text{Direct Detection}$

$\text{MiniBooNE}$

$\text{NA64 2017}$
Kinetic Mixing Parameter Space - Relic Density

\[
Y = \epsilon^2 \alpha' \left( \frac{m_\chi}{m_V} \right)^4
\]

\[
m_V = 3m_\chi
\]

\[
\alpha' = 0.5
\]
Kinetic Mixing Parameter Space - Relic Density

$m_v = 3m_\chi$  \quad $\alpha' = 0.5$

$Y = \epsilon^2 \alpha' (m_\chi/m_v)^4$

$m_\chi (GeV)$

$10^{-3}$ $10^{-2}$ $10^{-1}$ $10^0$ $10^1$

$10^{-13}$ $10^{-12}$ $10^{-11}$ $10^{-10}$ $10^{-9}$ $10^{-8}$ $10^{-7}$ $10^{-6}$

- LSND
- E137
- BaBar
- Electron/Muon $g-2$
- $K^+ \rightarrow \pi^+ + \text{invisible}$
- $J/\psi \rightarrow \text{invisible}$
- Relic Density (Scalar)
- Direct Detection
- MiniBooNE
- NA64 2017
Relic Density Variations

Thermal and Asymmetric Targets at Accelerators

$y = \frac{\epsilon^2 \alpha_D}{(m_{DM}/m_{MED})^4}$

$m_{DM}$ [MeV]

Kinetic Mixing Parameter Space - Direct Detection

$m_y = 3m_\chi$  \( \alpha' = 0.5 \)

$Y = \varepsilon^2 \alpha' (m_\chi/m_y)^4$

$m_\chi (\text{GeV})$

\[ \chi_p \rightarrow \chi_p \]

LSND
E137
BaBar
Electron/Muon g--2
$K^+ \rightarrow \pi^+ + \text{invisible}$
$J/\psi \rightarrow \text{invisible}$
Relic Density (Scalar)
Direct Detection
MiniBooNE
NA64 2017
Kinetic Mixing Parameter Space - BaBar

\[ m_y = 3m_\chi \quad \alpha' = 0.5 \]

\[ Y = \varepsilon^2 \alpha' (m_\chi/m_V)^4 \]

\[ e^+ e^- \rightarrow \gamma + V \]

- LSND
- E137
- BaBar
- Electron/Muon g-2
- \( K^+ \rightarrow \pi^+ + \text{invisible} \)
- \( J/\psi \rightarrow \text{invisible} \)
- Relic Density (Scalar)
- Direct Detection
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\[ m_\chi (\text{GeV}) \]

\[ 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 1 \]
Kinetic Mixing Parameter Space - E137

\[ Y = \epsilon^2 \alpha' (m_\chi/m_V)^4 \]

\[ m_V = 3m_\chi \quad \alpha' = 0.5 \]

- LSND
- E137
- BaBar
- Electron/Muon g-2
- \( K^+ \rightarrow \pi^+ + \text{invisible} \)
- \( J/\psi \rightarrow \text{invisible} \)
- Relic Density (Scalar)
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\[ m_\chi (\text{GeV}) \]

\[ Y \]

10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 10^{0}
Fixed Target Neutrino Experiments

$\pi^\pm, K^\pm \rightarrow \nu_\mu \mu^\pm$

- 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: $\pi^0$, $\eta$, $\eta'$.  
- Radiative $\pi^-$ capture: $p + N \rightarrow \pi^-, \pi^- + p \rightarrow n + V^\ast$. Very relevant for low energy experiments.
- Direct parton-level production: $p + N \rightarrow V^\ast \rightarrow \chi\bar{\chi}$. Most relevant for high energy experiments.
- Bremsstrahlung: $p \rightarrow p + V^\ast$. 

$\pi^0, \eta, \eta' \rightarrow \gamma V \rightarrow \gamma \chi\bar{\chi}$  
$\rho, \omega, \phi \rightarrow V \rightarrow \chi\bar{\chi}$  
$\pi^0, \eta, \eta' \rightarrow \gamma V \rightarrow \gamma \chi\bar{\chi}$
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) $\nu$ 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.

- 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.

$$\sigma_{\chi N,e \rightarrow \chi N,e} \propto \epsilon^2 \alpha' \alpha$$
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.
  - $\sigma_{\chi Z \rightarrow \chi Z} \propto Z^2 F_{\text{Helm}}(q^2)$.
  - Switch to incoherent scattering for $q^2 > (50 \text{ MeV})^2$. 
DM induced inelastic $\pi^0$ 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.
1.8 × 10^{23} \text{ POT with 800 MeV beam, operating from 1993 to 1998.}

- Signal from $\pi^0 \rightarrow V(\ast)\gamma \rightarrow \gamma\chi\bar{\chi}$.
- Burman-Smith $\pi^+$ distribution used to estimate $\pi^0$ distribution
  \[\text{[LA-11502-MS http://www.osti.gov/scitech/servlets/purl/6167579]}\]
Cut on 110 NCE electron-DM scattering events.
MiniBooNE Neutrino Run

- 650 ton 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 $1.6 \times 10^{21}$ 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 $m_\chi > 100$ MeV by considering timing.
- Collected $1.89 \times 10^{20}$ 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

\[ Y = \varepsilon^2 \alpha_\theta \left( m / m_\nu \right)^2 \left( m_\nu = 3m_\chi, \alpha_\theta = 0.5 \right) \]

\[ D_\alpha, \chi = 3m_\nu V (m_4) V / m_\chi (m_\alpha^2 \varepsilon Y = 13) \]

MiniBooNE limits

MiniBooNE limits

MiniBooNE limits

Proposed experiments that impact a low energy proton beam to study Coherent Elastic Neutrino Nucleus Scattering (CE$\nu$NS) 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, $90^\circ$ relative to the beamline.
- $\sim 10^{23}$ POT (protons on target) per year with 1 GeV kinetic energy.
- Dark matter production is prompt.
\[ Y = e^2 \alpha' \left( \frac{m_\chi}{m_V} \right)^4 \]

\[ E_{\text{recoil}} > 16 \text{ keV to remove prompt Neutrinos} \]
COHERENT - 17 kg CsI

$m_{\nu} = 3 m_X$, Symmetric Scalar

COHERENT - 17 kg CsI

\[ Y = \epsilon^2 \alpha'(m_\chi/m_V)^4 \]

\[ m_V = 3m_\chi \]

\[ \alpha' = 0.5 \]

\[ m_\chi (\text{GeV}) \]

\[ Y \leq 10^{-13} \]

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 CE$\nu$NS 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

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- 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 $\pi, K$ decays. [E949]
  - Need to use $J/\psi, \Upsilon(1S)$ decays for higher masses of $m_V$. [BESII'08, BaBar’09, Fayet’09]
Experimental Constraints

More Particle Physics:

  - 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.
- Proton Beam Dumps and Fixed Target Experiments.
  - 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:

- \( V \rightarrow l^+ l^- \) - Weak so long as \( \text{Br}(V \rightarrow 2\chi) \sim 1 \), 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:

- DM-Nucleon scattering - DAMIC, LUX, CDMS(lite), CRESST-II, XENON10/100/1T...