Future Dark Matter Searches at the Fermilab Short Baseline Neutrino Experimental Program

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How To Look For Dark Matter

Collider Production
- Can cover most of mass range
- Signal is lack of a signal (Missing $E_T$)

Annihilation
- Energetic particle/antiparticle signals
- Also gamma rays (e.g., 511 keV)

Scattering
- Galactic halo DM scatters in detector
- Very low energy deposits
Where Are We With Direct Searches?

“WIMP Miracle”

- Electroweak scale masses (∼100 GeV) and cross sections (10^{-38} cm^2) give correct relic abundances
- Conflicting claims, mostly ruled out phase space
- A rich dark sector easily bypasses “miracle”

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The Short Baseline Neutrino Program

- Suite of 3 liquid argon LAr time-projection chambers (TPCs) to search for sterile neutrino oscillations on the Fermilab Booster Neutrino Beamline (BNB)

The Short Baseline Neutrino Program

- **MicroBooNE** 170 ton LAr, 32 × 8” PMTs, 8250-wire TPC
- Operates 470 m from BNB neutrino production target
- Has been operating since late-2015

The Short Baseline Neutrino Program

- **ICARUS T-600** 2 × 300 ton LAr TPCs (600 ton total volume)
- Has operated at CERN from 2010-2014; move to FNAL in 2017
- Will operate at 700 m from BNB target

1. ICARUS website. [http://icarus.lngs.infn.it](http://icarus.lngs.infn.it).
The Short Baseline Neutrino Program

- **SBND (formerly LAr1-ND)** 260 ton LAr (112 ton active volume)
- Design being finalized; 120 × 8” PMTs (similar to MicroBooNE)
- Will operate at 110 m from BNB target

\[1\text{SBND website. http://sbn-nd.fnal.gov.}\]
How a TPC Works in a Nutshell

- Particle interaction creates ionization tracks (or points)
- Externally applied electric field drifts free ionized charge at (millisecond per meter) scale velocities
- Fine array of induction and collection wires collect 2D signal
- Light flash in photon detection system sets $t_0 \rightarrow 3D$ reconstruction
LAr Performance

- LAr TPCs offer unprecedented separation of tracks from vertices
- dE/dx particle ID for an EM shower
  - LOW dE/dx $\rightarrow$ single $e^+/e^-$
  - HIGH dE/dx $\rightarrow$ $e^+e^-$ pair from converted photon
- TPC can measure vertex / track separation
- Identify converting gamma ray or a candidate neutral particle decay

![Graph showing dE/dx distribution for different particle types]

**Event displays and $e^-\gamma$ separation**

- Energy loss for 0.5 – 4.5 GeV $e'$s and $\gamma$'s
- Uses dE/dx and event topology to distinguish $e'$s from gammas
OK, Great! More Reasons for LAr?!

- Very long ionized electron drift lengths for scalable, large TPCs (read: DUNE)
- High scintillation output with easily separable short / long lifetimes
  - Scintillation is fast enough to approach ns-level timing resolution
- "Easy" to purify
- Low-energy $^{39}\text{Ar}$ beta decay is only significant radio-impurity
- Relatively abundant and inexpensive (compared to LXe)
  - LAr and water (and maybe organic scintillator) are only technologies scalable to 10-100 kton scale
- The ability to construct large-scale, fine-grained tracking TPCs for a full 3D reconstruction and particle identification through $dE/dx$ is a game changing opportunity for rare searches
LAr is No Panacea

- Millisecond drift times present serious problems correlating to BNB
- BNB pulse width is 1.6 \( \mu \)s; Constructed of 81X 20 ns RF “buckets”
- Prompt scintillation is our only hope

Proposed SBND photon detection system elements (120 PMTs total)
Minimal Vector Portal Model
An Initial Motivator

- Extends the familiar dark photon concept; new lighter mediator bypasses Lee-Weinberg bound to allow adequate DM annihilation
- U(1) vector mediator kinematically mixed
- Requires 4 parameters: $m_\chi$, $m_\nu$, $\kappa$, $g'$

\[ \frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu} \]

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Dark Matter Beam and Detector

• High-energy production and scattering detection

\[ \begin{align*}
\chi \leftarrow \chi^\dagger & \rightarrow \chi \\
\bar{f} & \rightarrow f \\
\gamma & \rightarrow \chi \\
\pi^0, \eta & \rightarrow \chi \end{align*} \]

Production

\[ \begin{align*}
\chi & \rightarrow \chi \\
\gamma & \rightarrow \chi \\
\pi^0, \eta & \rightarrow \chi \end{align*} \]

Detection

Neutrino Backgrounds
A Lesson from MiniBooNE

- Consider nucleon elastic scattering

\[ \chi \rightarrow N \]

- Same as $\nu$ NC elastic

$\rightarrow \text{MUST SUPPRESS } \nu$

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Neutrino Backgrounds
A Lesson from MiniBooNE

- Consider nucleon elastic scattering

\[ N + \nu \rightarrow N + \nu \]

- Same as $\nu$ NC elastic
  \[ \rightarrow \text{MUST SUPPRESS } \nu \]

MiniBooNE Antineutrino Data Set with DM Models and Efficiencies

Looking for signal excess over neutrino (and other) “backgrounds”

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The Booster Neutrino Beamline (BNB)

- 8.9 GeV Booster protons to BNB endstation (or Main Injector)

- At BNB, protons strike Be target (1.8 radiation lengths)

- Typical operation: $2 \times 10^{20}$ protons on target (POT) per year
How To Suppress $\nu$ and Produce $\chi$

- $\nu_\mu$ from $\pi^+$ don’t let “escape” into air, absorb them in material

- $\chi$ from $\pi^0, \eta$: short lifetimes ($\tau \sim 10^{-16}$ s) $\rightarrow$ decays before absorption in material

- Bypass Be target, hit steel beam stop

- Neutrino flux suppression factors of 1/44 demonstrated by MiniBooNE (see R. Tayloe talk about MiniBooNE)

Beam “off-target” to 50 m beamstop
Our Primary Sensitivity

- A “beam” of dark matter traveling through meters of dirt requires invisible decays
  \[ m_V > 2m_\chi \]

- Want final state of \( V \) decays to prefer pairs of \( \chi \)s
  \[ V \rightarrow \chi\chi^\dagger \]

- SM final state suppression

- Minimal vector portal model initially motivated run

- Not the only viable model (e.g. leptophobic dark matter)

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# SBN and MiniBooNE Signal Estimates

- For all configurations, assume 50 m beam dump, $2 \times 10^{20}$ POT

<table>
<thead>
<tr>
<th></th>
<th>MiniBooNE</th>
<th>MicroBooNE</th>
<th>SBND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from 50m Dump (m)</td>
<td>500</td>
<td>420</td>
<td>50</td>
</tr>
<tr>
<td>Analysis Fiducial Mass (tons)</td>
<td>450</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>Efficiency (N or e⁻)</td>
<td>30%</td>
<td>60%</td>
<td>60%</td>
</tr>
<tr>
<td>Approximate scaling¹</td>
<td>1.0</td>
<td>0.38</td>
<td>17.7</td>
</tr>
<tr>
<td><strong>DM-N signal²</strong></td>
<td>1,326</td>
<td>503</td>
<td>23,500</td>
</tr>
<tr>
<td><strong>ν-N elastic background³</strong></td>
<td>406+/-80</td>
<td>40</td>
<td>2,500</td>
</tr>
<tr>
<td><strong>DM-e⁻ signal²</strong></td>
<td>4.8</td>
<td>1.8</td>
<td>85.0</td>
</tr>
<tr>
<td><strong>ν-e⁻ elastic background³</strong></td>
<td>~0.6</td>
<td>&lt; 0.1</td>
<td>~10</td>
</tr>
</tbody>
</table>

¹Sensitivity plots contain other scaling factors, e.g., $1/r^2$ distance scaling, energy, etc.
²Assume $M_\chi = 50$ MeV, and $\sigma = 8 \times 10^{-36}$ cm².
³Contains beamdump neutrino flux suppression 1/44, POT, efficiency, and $\cos \theta_{e\text{-beam}} > 0.98$ cut
Signal Sensitivity DM-N ($2 \times 10^{20}$ POT)
Cross Section vs. DM Mass

- **MiniBooNE**
- **MicroBooNE**
- **SBND**

$N_X \rightarrow N_X \; m_V = 300 \text{ MeV} \; \alpha' = 0.1 \; \text{POT} \sim 2 \times 10^{20}$

1-10 events
10-100 events
100-1000 events

- **Signal** sensitivity only $\rightarrow$ background and systematics ignored
Signal Sensitivity DM-N (2 × 10^{20} POT) 
Mixing Strength vs. Vector Mediator Mass

- **MiniBooNE**

- **MicroBooNE**

- **SBND**

1-10 events  
10-100 events  
100-1000 events

- **Signal** sensitivity only → background and systematics ignored
Signal Sensitivity DM-e\(^{-}\) (2 \(\times\) 10\(^{20}\) POT)

Cross Section vs. DM Mass

**MiniBooNE**

- \(\alpha' = 0.1\)
- \(m_N = 300\) MeV
- \(\alpha' = 0.1\)
- \(POT \sim 2 \times 10^{20}\)

**MicroBooNE**

- \(\alpha' = 0.1\)
- \(POT = 2 \times 10^{20}\)

**SBND**

- \(\alpha' = 0.1\)
- \(POT = 2 \times 10^{20}\)

- **Signal** sensitivity only \(\rightarrow\) background and systematics ignored

- 1-10 events
- 10-100 events
- 100-1000 events
Signal Sensitivity DM-e⁻ (2 × 10^{20} POT)  
Mixing Strength vs. Vector Mediator Mass

**MiniBooNE**

![Graph showing signal sensitivity for MiniBooNE with 1-10 events, 10-100 events, and 100-1000 events highlighted.]

**MicroBooNE**

![Graph showing signal sensitivity for MicroBooNE with 1-10 events, 10-100 events, and 100-1000 events highlighted.]

**SBND**

![Graph showing signal sensitivity for SBND with 1-10 events, 10-100 events, and 100-1000 events highlighted.]

- **Signal** sensitivity only → background and systematics ignored

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New Mexico State University  
All About Discovery!  
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4/28/16  
R.L. Cooper - SLAC Dark Sector Workshop  
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Dark Matter Propagation Time

- $\chi$ is massive so travels the 500 m slower than $c$ ($m_\chi = 120$ MeV, $E = 1.5$ GeV $\rightarrow$ 6 ns delay over 500 m drift)

- SBND drift is 50 m, sensitive to higher mass dark matter; complementary

- Beam – 81 RF bunches

- MiniBooNE has prompt Cherenkov timing response and excellent PMT coverage

- Is LAr scintillation and PMT coverage sufficient for ns-scale resolution in SBN?
Beam-Related "Dirt" Backgrounds

- Neutrons produced in surrounding rock by beam neutrinos can penetrate deep within detector
- Background not subtractable
- SciBath is 80 L liquid scintillator neutron tracking detector
- Proven record for measuring neutrons backgrounds at BNB (e.g., SciBooNE near SBND site, results forthcoming)
Future Improvements in Beam Dump

- Future DM search must reduce neutrino backgrounds
- Current beam dump goes through 50 m of air.
- A thick iron target could significantly reduce the neutrino flux relative to the DM production
- $1/r^2$ DM flux reduction, but significant S/B increase
Conclusions

• MiniBooNE has paved the way for Light Mass Dark Matter searches at the Fermilab BNB → a new proton beam dump result

• The Short Baseline Program is approved and will build SBND and ICARUS near and far detectors to complement MicroBooNE

• SBN will use a trio of LAr TPCs with unprecedented 3D track reconstruction and EM shower particle ID

• SBND (in particular) has a high sensitivity to DM-Nucleon and DM-electron elastic scattering channels

• Fast timing resolution is one of the major challenges
BACKUPS
Beampipe Survey with FRED

- **FRED**: Finding Radiation Evidence in the Decay pipe

- Visual and magnetic field survey → no anomalies
Current Limits

Invisible

- $m_V > 2m_\chi$

- Final state $V$ decays prefer to go to pairs of $\chi$s

$$V \rightarrow \chi\chi^\dagger$$

- SM final states suppressed

- We need these for $\chi$ beams

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Current Limits

Visible

• \( m_V > 2m_\chi \)

• Final state \( V \) decays are visible SM model particles, e.g.,

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

• Can’t produce pairs of \( \chi \)s