An Accelerator-Produced, Sub-GeV Dark Matter Search with the MiniBooNE Neutrino Detector

Robert Cooper

http://neutrino.indiana.edu/rlcooper
Outline

• The Evidence for Dark Matter

• A Model for Sub-GeV Dark Matter

• The MiniBooNE Detector and Its Sensitivity

• Dark Matter Beams and Neutrino Contamination

• Current Analysis and Preliminary Results

• Upcoming work and conclusions

dark matter
http://www.particlezoo.net/
THE EVIDENCE FOR DARK MATTER
Historical Postulation of Dark Matter

- Fritz Zwicky applied virial theorem to Coma cluster\(^1\)

- Visible matter cannot explain rotational velocities of the cluster

- Order 100 times more matter unseen → Dark Matter

Modern Validations: Galaxy Rotation

• Rotational velocity a distance $r$ from center is

$$v = \sqrt{\frac{GM(r)}{r}}$$

where $M(r)$ is contained mass

• Visible mass implies a falling rotational velocity, *but*...

• Rotational velocity appears flat

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Modern Validations: CMB

- Precision cosmic microwave background temperature anisotropy measurements
- COBE, WMAP, Planck satellites
- Planck collaboration uses multi-parameter fit to extract dark energy, dark matter, etc. of universe\(^1\)

Modern Validations: Large Structure

- Numerical $N$-body simulations require dark matter model\(^1\)

- Bottom-up scenarios favored from vanilla cold dark matter models (in favor of top-down from hot dark matter)

\(^1\)http://cosmicweb.uchicago.edu/filaments.html
Modern Validations: Gravity Lensing

- Weak gravitational lensing can map mass distribution
- Chandra X-Ray observatory mapped Bullet Cluster
- Strong evidence for dark matter rather than modified gravitation

\(^1\)Images from Wikipedia
What We Know About Dark Matter

- Annihilate with cross section $\langle \sigma v \rangle$ against Hubble expansion
- Freezes-out relic abundance
- Energy density today $\rho_{DM} = n_{DM} M_{DM} \approx 0.3 \text{ GeV/cm}^3$
- Local galactic velocity $v \approx 220 \text{ km/s} \approx 10^{-3}c$

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Possible Models For Dark Matter?

Neutrinos

- They exist
- Not enough mass and relativistic → hot dark matter
- Prefers top-down structure
- Sterile neutrinos have other cosmological constraints → possible cold dark matter

---

Possible Models For Dark Matter?

**Neutrinos**

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- Sterile neutrinos have other cosmological constraints $\rightarrow$ possible cold dark matter

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Possible Models For Dark Matter?

Axions

- Introduced to solve strong-CP problem, but have low mass < 0.01 eV

Supersymmetry Candidates

- Neutralino
- Sneutrino
- Axino…

Etc…

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} \text{ cm}^2) give correct relic abundances

• Conflicting claims, mostly ruled out phase space

• A rich dark sector easily bypasses “miracle”

Why Not Sub-GeV Dark Matter?

• Lee-Weinberg bound: \( M_\chi > O(1 \text{ GeV}) \) presumes weak annihilation rate \( \sim \frac{M_\chi^2}{M_Z^4} \) which is too low

• New forces and force carriers \( \rightarrow \) viable light thermal relic
  1. Mediate SM interactions to a dark sector
  2. Open up annihilation channels – circumventing L-W bound

Minimal Vector Portal Model

- Postulated to solve excess 511 keV $\gamma$s from central galaxy bulge $\rightarrow$ extends more familiar dark photon concept

- U(1) vector mediator kinematically mixed

- Requires 4 parameters: $m_\chi$, $m_V$, $\kappa$, $g'$

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

\[ \alpha' = \frac{g'^2}{4\pi} \]

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Dark Matter Beam and Detector

• High-energy production and scattering detection

Our Primary Sensitivity

- To create a “beam” of dark matter traveling 500 m in dirt, require 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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MINIBOONE DETECTOR
The MiniBooNE Detector

- 12 m spherical detector with 800 tons pure mineral oil (CH$_2$)
- Cherenkov response with some scintillation from trace fluors
- Inner signal region 1280×8” PMTs
  Outer veto region 240×8” PMTs
  (10% photocathode coverage)
- Detector is very well characterized

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The MiniBooNE Detector

- Run for over 10 years
- 11 oscillation papers
- 14 cross section and flux papers
- Relevant to this work
  - NC elastic $\nu$-mode ($6.7 \times 10^{20}$ POT)
  - NC elastic $\bar{\nu}$-mode ($11.5 \times 10^{20}$ POT)
- 19 Ph.D. Theses

1 See our website for a list of all publications. http://www-boone.fnal.gov/
Particle IDentification

Nucleon PID
• Slow scintillation, very little Cherenkov
• Poorer energy resolution p - 20%, n – 30%

Electron PID
• Mostly Cherenkov but shape is important
• $e/\mu$ – fuzzy/sharp ring
• $\pi^0$ – 2 rings $\rightarrow$ degeneracy
• $e\chi$ collision forward peaked $\rightarrow$ another cut
## Previous Beam Dump / Fixed Target Experiments – Proton Beams

<table>
<thead>
<tr>
<th>Experiment</th>
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<th>approx. Date</th>
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1Table by R.T. Thornton, Indiana University Nuclear Physics Seminar, Nov. 21, 2014

7/14/15  

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Dark Matter Exclusion Plots

**Nucleon – DM**

- 1-10 events
- 10-100 events

\[ \text{N}_\chi \to \text{N}_\chi \quad m_V = 300 \text{ MeV} \quad \alpha' = 0.1 \quad \text{POT} = 1.75 \times 10^{20} \]

**Electron – DM**

- 100-1000 events

\[ \text{e}_\chi \to \text{e}_\chi \quad m_V = 300 \text{ MeV} \quad \alpha' = 0.1 \quad \text{POT} = 1.75 \times 10^{20} \]
Vector Portal Exclusion Plots

**Nucleon – DM**
- $N_{\chi} \rightarrow N_{\chi}$, $m_{\chi} = 10$ MeV, $\alpha' = 0.1$, $POT = 1.75 \times 10^{20}$
- 1-10 events
- 10-100 events

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- $e_{\chi} \rightarrow e_{\chi}$, $m_{\chi} = 10$ MeV, $\alpha' = 0.1$, $POT = 1.75 \times 10^{20}$
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7/14/15
What Is Expected In MiniBooNE?

- Consider nucleon elastic scattering

- Same as $\nu$ NC elastic scattering

\[ \rightarrow \text{MUST SUPPRESS } \nu \]

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What Is Expected In MiniBooNE?

- Consider nucleon elastic scattering

\[ \chi \rightarrow N \]

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

With Detector Efficiency

Benchmark Theory III

Production and Interaction

- Production mechanisms in beam dumps
  \[ e^- (p) \rightarrow e^- (p) \]
  \[ \chi \chi^\dagger \rightarrow \pi^0, \eta \]

- \chi \chi \chi \chi^\dagger \text{interactions in detector}

Nucleon-Dark Matter yN-DM)

Electron-Dark Matter ye-DM)

\[ \text{Similar to } \nu \text{ neutral current elastic scattering } y_{\nu\mathrm{NC}e} \]

\[ \nu \text{ NCE data with total error} \]

\[ M_\chi = 100 \text{ MeV } \kappa = 0.005 \]

\[ M_\chi = 75 \text{ MeV } \kappa = 0.0075 \]

\[ M_\chi = 50 \text{ MeV } \kappa = 0.01 \]

\[ M_\chi = 20 \text{ MeV } \kappa = 0.015 \]

<table>
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<th>no. of events</th>
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<table>
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<th>nucleon energy (MeV)</th>
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What Is Expected In MiniBooNE?

- Consider nucleon elastic scattering

\[
\chi \rightarrow \nu N \rightarrow \chi
\]

- Same as \( \nu \) NC elastic \( \rightarrow \text{MUST SUPPRESS} \ \nu \)

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

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7/14/15

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What Is Expected In MiniBooNE?

- Consider nucleon elastic scattering
  
  $\chi \rightarrow N$  

- Same as $\nu$ NC elastic  
  $\rightarrow$ MUST SUPPRESS $\nu$

With production, cross section, and efficiency: most sensitive region is 35-250 MeV nucleons

DARK MATTER FROM BNB
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
The Booster Neutrino Beamline (BNB)

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In MiniBooNE this works because pion production target is small.

Pions escape and can decay in flight.
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) → decays before absorption in material
- Bypass Be target, hit steel beam stop
- $\pi^0$ production in Fe and Be similar

Beam “off-target” to 50 m beamstop
Off-Target vs. On-Target Monte Carlo

- Neutrino-mode horn-on for on-target MC
- flux-weighted MC suppression ~40 \( \rightarrow \) CCQE data ~50
- Better beamline MC

\[ \nu_\mu \rightarrow W^\pm \rightarrow \mu^- \]

\[ ^{12}\text{C} \rightarrow \pi X \]

---

Off-Target vs. On-Target Monte Carlo

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![Diagram of neutrino interactions]

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\[ \nu_\mu \rightarrow W^{\pm} \rightarrow \mu^- \]

\[ ^{12}\text{C} \rightarrow p + X \]

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\(^1\text{A.A. Aguilar-Arevalo et al., Phys. Rev. D79} \ (2009) \ 072002. \ arXiv:0806.1449 \ [hep-ex] \)
Beampipe Survey with FRED

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

- Visual and magnetic field survey → no anomalies
Event Selection Cuts

- 1 Track (single recoil) in beam timing window
- Event is centralized contained
  - No activity in veto
  - Fiducialized inner tank
- Signal above hits and visible energy threshold
- PID: Nucleon or electron
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)

- Beam – 81 RF bunches

- Can correlate events to a particular bunch
  $\delta t \sim 1.5$ ns Cherenkov ($e_\chi$)
  $\delta t \sim 4.2$ ns Scintillation ($N_\chi$)

- Provides more sensitivity to dark matter parameter space
Preliminary Results (3.19×10^{19} POT)

- Total 1.86×10^{20} POT in 10 month run
- Semi-blind: open analysis of 17% of data
- Beam unrelated biggest contribution (measured in strobe)
- Anticipate ~10% systematic uncertainty

<table>
<thead>
<tr>
<th># events</th>
<th>error</th>
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<td>$\nu_{\text{det}}$</td>
<td>88.8</td>
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<tr>
<td>$N_{\text{BUB}}$</td>
<td>113.24</td>
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<tr>
<td>Total Bkg</td>
<td>206.35</td>
<td>15%(sys.)</td>
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<tr>
<td>Data</td>
<td>196</td>
<td>7.1%(stat.)</td>
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</tbody>
</table>

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Preliminary Results (3.19×10^{19} POT)

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UPCOMING WORK AND CONCLUSIONS
Conclusions

• MiniBooNE has collected $1.86 \times 10^{20}$ POT in beam-off-target configuration to search for sub-GeV dark matter

• Beam-off-target suppresses neutrino backgrounds $\rightarrow$ beam uncorrelated backgrounds dominant

• First of its kind, proton beam dump to a large neutrino detector $\rightarrow$ an extremely well characterized detector!

• N-DM analysis will be completed soon $\rightarrow$ e-DM and inelastic $\pi^0$ channels are underway
Thank You!

A Proposal to Search for Dark Matter with MiniBooNE
Submitted to the FNAL PAC Dec 16, 2013

The MiniBooNE Collaboration
R. Dharmapalan, & I. Stancu
University of Alabama, Tuscaloosa, AL 35487
R. A. Johnson, & D.A. Wickremasinghe
University of Cincinnati, Cincinnati, OH 45221
R. Carr, G. Karagiorgi, & M. H. Shaevitz
Columbia University, New York, NY 10027
M. Badhik, B.C. Brown, F.G. Garcia, R. Ford, T. Koblaric, W. Marsh
Fermi National Accelerator Laboratory, Batavia, IL 60510
J. Grange, & H. Ray
University of Florida, Gainesville, FL 32611
R. Cooper, R. Taylor, & R. Thornton
Indiana University, Bloomington, IN 47405
G. T. Garvey, L. Green, W. Huesnitz, W. Ketchum, Q. Liu, W. C. Louis, B. B. Mills,
Los Alamos National Laboratory, Los Alamos, NM 87545
B. P. Roe
University of Michigan, Ann Arbor, MI 48109
A. A. Aguilar-Arevalo, & I. L. de Icaza Astiz
Instituto de Ciencias Nucleares, Universidad Nacional Autonoma de Mexico, D.F. Mexico
P. Nienaber
Saint Mary's University of Minnesota, Winona, MN 55987
T. Katori
Queen Mary University of London, London, E1 4NS, UK
C. Mariani
Virginia Tech, Blacksburg, VA 24061
The Theory Collaboration
B. Batell
University of Chicago, Chicago, IL, 60637

The Theory Collaboration (Continued)
P. deNiverville, M. Pospelov, & A. Ritz
University of Victoria, Victoria, BC, V8P 5C2
D. McKeen
University of Washington, Seattle, WA, 98195

1A.A. Aguilar-Arevalo et al. arXiv:1211.2258 [hep-ex]
BACKUPS
## Previous Beam Dump / Fixed Target Experiments – Electron Beams

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1. Table by R.T. Thornton, Indiana University Nuclear Physics Seminar, Nov. 21, 2014

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Current Limits

Invisible

- $m_V > 2m_\chi$

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

  $$V \rightarrow \chi\bar{\chi}$$

- SM final states suppressed

- We need these for $\chi$ beams

---

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 a pair of \( \chi \)s

---

Energy Spectrum Reconstruction

- Previous neutrino running important for spectrum reconstruction


Energy Spectrum Reconstruction

- CCQE is a “standard candle” to fix new cross sections against

\[ \frac{\sigma_{\nu \text{ NC elastic}}}{\sigma_{\nu \text{ CCQE}}} = \frac{d\sigma_{\nu \text{ NC elastic}}}{dQ^2} / \frac{d\sigma_{\nu \text{ CCQE}}}{dQ^2} \]

\[ \frac{\sigma_{\bar{\nu} \text{ NC elastic}}}{\sigma_{\bar{\nu} \text{ CCQE}}} = \frac{d\sigma_{\bar{\nu} \text{ NC elastic}}}{dQ^2} / \frac{d\sigma_{\bar{\nu} \text{ CCQE}}}{dQ^2} \]

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