Neutrino Oscillations and light Dark Matter searches with the MiniBooNE experiment
Alexis A. Aguilar-Arévalo (ICN-UNAM) (for the MiniBooNE collaboration)
Outline

- LSND and MiniBooNE
- Experiment description
- Oscillations results (\(\nu_e, \bar{\nu}_e\) appearance)
- Light Dark Matter search in a proton beam
- Future plans
- Conclusions
MiniBooNE motivation: LSND

- LSND Experiment (Los Alamos, 1993-1998)
- Excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam: $\text{Excess} = 87.9 \pm 22.4 \pm 6$ (3.8σ)
- Source is Pion decay at rest: $\pi^+ \rightarrow \mu^+ + \nu_\mu$, $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$
  
  $\nu_e$ signal: Cherenkov light from $e^+$ with delayed $n$ capture (2.2 MeV $\gamma$)
- Interpreted as 2ν oscillations: $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$
  (equivalent to 3+1 model) $= (0.245 \pm 0.067 \pm 0.045)\%$

In conflict with other osc. exp's if only 3 ν's.
Mini-Booster Neutrino Experiment

- L/E similar to LSND
  MiniBooNE ~500 m /~500 MeV
  LSND ~30m / 30 MeV

- Horn focused neutrino beam (p+Be)
  **Horn increases nu/nubar flux by ~6**
  Polarity → neutrinos or anti-neutrinos

- Cherenkov Detector
  800 ton mineral oil
Mini-Booster Neutrino Experiment

- Booster
- Horn/target
- Decay tunnel
- Absorber
- Dirt
- Detector

π + ν → ν e ñ

- Primary beam
- Secondary beam (protons)
- Tertiary beam (mesons)
- Neutrinos

~800ton mineral oil (CH₂) Cherenkov detector
12 m diameter, 1280 inner PMTs, 240 veto PMTs
541 m from target

Veto
Predicted neutrino flux (MC)

<table>
<thead>
<tr>
<th>Neutrino mode:</th>
<th>Anti-neutrino mode:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$</td>
<td>$\nu_\mu$ (WS)</td>
</tr>
<tr>
<td>93.6 %</td>
<td>15.7 % (WS)</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>$\bar{\nu}_\mu$</td>
</tr>
<tr>
<td>5.86 % (WS)</td>
<td>83.7 %</td>
</tr>
<tr>
<td>$\nu_e + \bar{\nu}_e$</td>
<td>$\nu_e + \bar{\nu}_e$</td>
</tr>
<tr>
<td>0.57 %</td>
<td>0.6 % WS: &quot;wrong sign&quot;</td>
</tr>
</tbody>
</table>

Neutrino mode $E_{\text{avg}} \sim 0.8$ GeV

\[ \begin{array}{c}
\phi \left( \text{1/cm}^2 \text{cm}^2 \text{POT/50 MeV} \right) \\
\text{(a)} \\
\end{array} \]

Antineutrino mode $E_{\text{avg}} \sim 0.6$ GeV

\[ \begin{array}{c}
\phi \left( \text{1/cm}^2 \text{cm}^2 \text{POT/50 MeV} \right) \\
\text{(b)} \\
\end{array} \]

Run time
- 3 years 8 months in neutrino mode ($6.4 \times 10^{20}$ POT)
- 5 years in antineutrino mode ($11.2 \times 10^{20}$ POT)

Alexis A. Aguilar-Arévalo (ICN-UNAM)
Events in MiniBooNE

- Identification based on timing and event topology. (Cher+Scint light)
- Neutrino cross sections from NUANCE event generator.

**neutrino mode**

- NC EL
  - PRD 82, 092005 (2010)

**antineutrino mode**

- CC π^+
  - PRL 103, 081801 (2009)
  - PRD 83, 052007 (2011)

Have measured cross sections of 90% of all the Interactions in MiniBooNE.

**QE**: Most relevant for oscillations analysis

**NCE**: Most relevant for MB Dark Matter search
CCQE and NCE events

CCQE: Charged-Current Quasi-Elastic
Single $\mu$ events + decay $e$

$$E_{v}^{QE} = \frac{2M_{n}E_{E} - [M_{n}^{2} + m_{\mu}^{2} - M_{p}^{2}]}{2[M_{n}^{2} - E_{\mu} + p_{\mu}/\cos\theta_{\mu}]}$$

NCE: Neutral-Current Elastic
Low hits activity with no $\mu$ or $\pi$

$$E_{rec} = \text{sum of charges from all PMTs /event}$$

PRL 100, 032301 (2008)
PRD 81, 092005 (2010); PRD 88, 032001 (2013)

PRD 82, 092005 (2010)
Oscillation analysis: Strategy

- Start with a beam composed primarily by $\nu_\mu$ ($\bar{\nu}_\mu$).
- Measure the $\nu_e$ ($\bar{\nu}_e$) present in the beam, using CCQE evts.
- Interpret a $\nu_e$ ($\bar{\nu}_e$) excess as oscillations $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$).

All major bkgd's constrained by data or in-situ measurements.

Similar backgrounds in neutrino and anti-neutrino modes.
Final oscillations ($\nu_e$ app.) results

Excess (200-1250 MeV): 78.4 ± 28.5 (2.8 $\sigma$)

Excess (200-1250 MeV): 162.0 ± 47.8 (3.4 $\sigma$)

(200-1250 MeV):

- $\chi^2/ndf$ (bf) = 5/7
- Prob(bf) = 66%

- $\chi^2/ndf$ (null) = 16.6/8.9
- Prob(null) = 5.4%

(200-1250 MeV):

- $\chi^2/ndf$ (bf) = 13.2/6.8
- Prob(bf) = 6.1%

- $\chi^2/ndf$ (null) = 22.8/8.8
- Prob(null) = 0.5%
3+2 model

- Allows CP violation effects.
- Better fit to MiniBooNE excess shape.
- Better fit to world data (see e.g. arXiv:1207.4765 for recent global fits)

Other global fits:
- C. Giunti (arXiv:1311.1335) → Different approach, different conclusions.
What we know about the low-E excess

- Not quite the same in nu/antinu modes
- Not a stat fluctuation
- Unlikely to be intrinsic $\nu_e$, small bkg at low E
- NC $\pi^0$ background dominates
  - Heavily constrained by NC $\pi^0$ in situ measurement
- Region where single $\gamma$ can contribute
- MB ties $\Delta \rightarrow N\gamma$ expected rate to be 1% of measured NC $\pi^0$ rate
  - Number of theory calculations for various single $\gamma$ processes:
    - Jenkins & Goldman, arXiv:0906.0984
    - Serot & Zhang, arXiv:1011.5913
  - All find total cross section within 20% of MB $\sim 5 \times 10^{-42} \text{cm}^2/N$
  - Would need nearly 300% change

MicroBooNE (LAr) experiment will study this excess
MiniBooNE+ (+Scint) can do complimentary studies.
\( \nu_\mu \) & \( \bar{\nu}_\mu \) disappearance

Not yet observed at short baselines.

MiniBooNE+SciBooNE performed joint \( \nu_\mu \) & \( \bar{\nu}_\mu \) disappearance searches obtaining null results.

These results are in tension with appearance evidence from LSND and MB- \( \bar{\nu} \).
(expect 5 -10\% \( \nu_\mu \), \( \bar{\nu}_\mu \) disappearance).

Including the disappearance results in global fits (3+1, 3+2, 3+3) with LSND+MB data → tension btwn appearance and disappearance data sets.
Light Dark Matter Search

- Recent theoretical work highlights light (sub-GeV) WIMP's as viable DM candidates
  

- Idea: *relativistic WIMP beam + well understood neutrino detector.*

- MiniBooNE is pioneering in this type or DM search.
Light Dark Matter

• A minimal extension to the Standard Model: Secluded U(1)' sector with weak admixture to photons (SB<1GeV)

\[
\mathcal{L}_{V,\chi} = |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} V_{\mu\nu}^2 + \frac{1}{2} m_V^2 V_\mu V_\mu + \kappa V_{\mu\nu} F^{\mu\nu} + \ldots
\]

\[D_\mu = \partial_\mu - ie'V_\mu, \quad e' = \sqrt{4\pi\alpha'}\]

4 parameters: \(m_\chi, m_V, \kappa, \alpha'\)


• New mediators increase annihilation cross section of the dark matter to give the correct relic density. Also mediate interactions with the SM

• Mediator with mass \(O(10^{-10^3} \text{ MeV})\) can alleviate \((g-2)_\mu\ 3\sigma\) discrepancy (theo vs. exp).

M. Pospelov, Phys. Rev. D 80, 095002 (2009)
A minimal extension to the Standard Model:  
Secluded U(1)’ sector with weak admixture to photons (SB<1GeV)

\[ \mathcal{L}_{V,\chi} = |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} V_{\mu\nu}^2 + \frac{1}{2} m_V^2 V_\mu^2 + \kappa V_{\mu\nu} F_{\mu\nu} + \ldots \]

Proton beam

\[ \pi^+ \to \mu^+ \nu_\mu \quad \mu^+ \to e^+ \nu_e \bar{\nu}_\mu \]

\[ p + p(n) \to V^* \to \bar{\chi} \chi \]

\[ \pi^0, \eta \to V \gamma \to \bar{\chi} \chi \gamma \]

\[ \chi + e \to \chi + e \]

\[ \chi + N \to \chi + N \]

Dark Matter production/detection

- (anti)neutrino running → DM beam accompanying $\bar{\nu}$ (\nu) beam
- Beam off-target running → neutrino background reduction by factor~70!

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**Be target**

8.9 GeV

RWM

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WIPMs travel ~540 m

Coaxial cable delivers RWM timing signal

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**Be target**

8.9 GeV

Fe dump

50 m

Timing info useful.
MiniBooNE: WIMP search

Neutrino mode Result: 
νNCE analysis 6.4E20 POT

Beam off target expectation

Assuming: $M_V = 300$ MeV, $\alpha' = \alpha$

Outlook of Light WIMP searches:
Stage 1: Operate in tandem with existing experiments.
Stage 2: Dedicated searches with existing (future) neutrino exps.
Stage 3: Dedicated experiments for Light WIMP searches.
Add scintillator to MiniBooNE oil:

Increase capability to tag neutron captures:

\[ n + {}^{12}\text{C} \rightarrow {}^{12}\text{C}^* \rightarrow \gamma(2.2\text{MeV}) \]

Current n-tag → 5 PMTs hit
MB+ Scintillator→ 25 PMTs (reconstructible!)

Primary goal: Study MB Low-E excesses

Do a \( \nu_\mu \rightarrow \nu_e + \text{“n-tag” oscillations} \) search

Excess is CCQE → No excess in MB+
Excess due to NC processes → Excess persists

Complimentary to MicroBooNE

Other studies: \( \Delta s \ldots \)
Conclusions

● MiniBooNE (2002-2012) collected $$(6.46_{(\nu)} + 11.27_{(\bar{\nu})} + 0.055_{(bm-off-tgt)}) \times 10^{20} \text{ POT.}$$

● In the energy range 200-1250 MeV, MiniBooNE observes:
  ➔ Antineutrino mode excess (2.8\(\sigma\)): compatible with LSND signal.
  ➔ Neutrino mode excess (3.4\(\sigma\)): marginally compatible with LSND.

● Combined \(\nu_e, \bar{\nu}_e\) fits show tension within a simple 2-\(\nu\) oscillation model.
  ➔ Some theoretical ideas exist to alleviate tension (arXiv:1211.1523).
  ➔ Much better fit achieved with 3+2 model.

  ➔ Developed analysis with \(\nu\)-mode data and produced a limit. Working on other data sets (\(\bar{\nu}\)-mode, small beam-off-tgt run).
  ➔ Test run with 0.35e20 POT: can probe part of the region relevant for \((g-2)_\mu\) anomaly. Needed to develop longer plan for a dedicated search.
  ➔ A novel way to Search for Dark Matter!

Thank you!
Backup Slides
Experiment progress (10 yr run)

Booster protons delivered to MiniBooNE target

1st $\nu_e$ app. Result $(5.58E20)$ (2007)

$\nu_e$ app. Update $(6.46E20)$ (2009)

$\bar{\nu}_e$ app. Result $(3.39E20)$ (2009)

$\nu_e$ app. Update $(5.66E20)$ (2010)

$\nu_e$, $\bar{\nu}_e$ app. update $(6.46E20)$ $(11.27E20)$ (2013)

$\bar{\nu}_e$ app. update $8.58E20$ (2011)

Period with 1 & 2 absorbers at 25 m taken into account
Detector calibration

Tracker system

15% E resolution at 53 MeV

Michel electrons

δm~20%

π⁰

Michel electron distribution (absolute calibration)

π⁰ photon energies

Tracker & Cubes

Through-going cosmics

Visible energy range of oscillation signal
Signal selection, $\nu_e$ appearance

Identical in neutrino and anti-neutrino analyses.

- **The Pre-cuts:**
  - No late time activity, removes $\mu$ decay e's, cuts $\sim 80\%$ of $\nu_\mu$ CCQE events.
  - Veto Hits <6, contained & not cosmic ray.
  - Tank Hits >200 & $E_{\text{vis}}$ > 140 MeV, removes NC elastic bkgds. And remaining $\mu$ decay e's
  - Radius < 500 cm, far enough from PMT's to avoid hard to model region.
  - R-to-Wallbackward cut, removes bkgds from beam interacting outside of detector.

Aimed at selecting $\nu_e$-CCQE events

$$\nu_e + n \rightarrow e^- + p$$

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
Signal selection, $\nu_e$ appearance

- Form charge ($Q$) and time ($T$) PDF's, and fit for track parameters under 3 hypotheses:
  1. Track is from electron
  2. Track is from Muon
  3. Two tracks from $\gamma$'s from $\pi^0$ decay

- Apply energy-dependent cuts on $L(e/\mu)$, $L(e/\pi)$ and $\pi^0$ mass to search for single electron events.

- Plot events passing cuts as a function of reconstructed energy and fit for two neutrino oscillations.
Oscillation analysis: method

Combined fit to $\nu_e$ & $\nu_\mu$ data

- For each bin $i$:
  \[ \Delta_i = N_i^{\text{DATA}} - N_i^{\text{MC}} \]

- Scan in $\Delta m^2$ & $\sin^2 2\theta$ to calculate
  \[-2 \ln(\mathcal{L}) \text{ over } \nu_e \text{ & } \nu_\mu \text{ bins} \]

\[-2 \ln(\mathcal{L}) = \Delta M^{-1} \Delta^T + \ln(|M|) \]

- Error matrix $M$ includes systematic errors for $\nu_e$ & $\nu_\mu$ and correlations.
  \[ M = M_{\text{om}} + M_{\text{Xsec}} + M_{\text{flux}} + M_{\pi^0} + M_{\text{dirt}} + M_{K^0} + M_{\text{beam}} + \ldots \]

- Large $\nu_\mu$ sample constrains many of the uncertainties.

The $\nu_\mu$ sample works as a near detector.
Improvements in 2013 publication

- In situ measurement of WS contamination in anti-$\nu$ beam
  $\nu_\mu$-CCQE angular fit and constraint from $CC\pi^+$ rate ... agree w/expectation (Phys.Rev.D81 072005 (2011)).

- New constraint from SciBooNE experiment on intrinsic $\nu_e$ from K+.
  Found production to be 0.85+-0.12 relative to prediction.
  Consistent with prior assessment of 1.00 +-0.30.
  Leading error on K+ bkgd becomes ~20% error from cross section.

- Higher statistics for all MC samples $\rightarrow$ reduced fluctuations in error matrices.

- Added new error matrix for intrinsic $\nu_e$ from K-.

- Improved smoothing algorithm that was being used to assess systematics due to discriminator thresholds and PMT response.

- Applied $Q^2$ reweighing to $CC\pi^+$ events based on internal MB measurement.

**Main improvement:** Doubling of anti-$\nu$ mode statistics $5.66E20$ POT $\rightarrow 11.3E20$ POT.
  $\Rightarrow$ higher stats. for anti-$\nu_e$ appearance
  $\Rightarrow$ and samples used for constraints
Final result with neutrinos

6.46E20 POT neutrino mode

- Excess (200-1250 MeV): $146.3 \pm 28.4 \pm 40.2$
- Tension between fits in the two regions.
  → May be reduced by taking into account multi-nucleon knock-outs (M. Martini et al. arXiv:1211.1523)

<table>
<thead>
<tr>
<th>$\nu$ mode</th>
<th>$E &gt; 200$ MeV</th>
<th>$E &gt; 475$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$(null)</td>
<td>22.81</td>
<td>6.35</td>
</tr>
<tr>
<td>Prob(null)</td>
<td>0.5%</td>
<td>36.6%</td>
</tr>
<tr>
<td>$\chi^2$(bf)</td>
<td>13.24</td>
<td>3.73</td>
</tr>
<tr>
<td>Prob(bf)</td>
<td>6.12%</td>
<td>42.0%</td>
</tr>
</tbody>
</table>

arxiv:1207.4809
Final result with anti-neutrinos

**11.27E20 POT anti-neutrino mode**

- Excess (200-1250 MeV): $78.2 \pm 20.0 \pm 23.4$
- No tension between fits in two energy regions
- Caveat: WS $\nu_\mu$ assumed not to oscillate

<table>
<thead>
<tr>
<th>anti-$\nu$ mode</th>
<th>E &gt; 200 MeV</th>
<th>E &gt; 475 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$(null)</td>
<td>16.6</td>
<td>7.8</td>
</tr>
<tr>
<td>Prob(null)</td>
<td>5.4%</td>
<td>24.6%</td>
</tr>
<tr>
<td>$\chi^2$(bf)</td>
<td>4.8</td>
<td>3.3</td>
</tr>
<tr>
<td>Prob(bf)</td>
<td>67.1%</td>
<td>49.2%</td>
</tr>
</tbody>
</table>
Simultaneous 3+1 fit to $\nu$ and anti-$\nu$ data

- WS accounted for properly
- Construction of correlated systematic error matrix
- E>200 MeV BF preferred at 3.6 $\sigma$ over null.

Simultaneous fit (E>200 MeV) with fully-correlated systematic to entire MB neutrino and anti-neutrino data

<table>
<thead>
<tr>
<th></th>
<th>E &gt; 200 MeV</th>
<th>E &gt; 475 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$ (null)</td>
<td>42.53</td>
<td>12.87</td>
</tr>
<tr>
<td>Prob (null)</td>
<td>0.1%</td>
<td>35.8%</td>
</tr>
<tr>
<td>$\chi^2$ (bf)</td>
<td>24.72</td>
<td>10.67</td>
</tr>
<tr>
<td>Prob (bf)</td>
<td>6.7%</td>
<td>35.8%</td>
</tr>
</tbody>
</table>

Total Excess: 240.3 +/- 34.5 +/- 52.6
Sterile neutrinos, 3+1, 3+2

- 3+1 and 3+2 models with sterile nu's can fit the data.

\[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2\theta \sin^2(1.27 \Delta m^2 \text{L/E}) \]

\[ + 4 |U_{e4}|^2 |U_{\mu4}|^2 \sin(1.27 \Delta m^2_{41} \text{L/E}) \]

\[ + 4 |U_{e5}| |U_{\mu4}| |U_{e5}| |U_{\mu5}| \sin(1.27 \Delta m^2_{41} \text{L/E}) \]

\[ + 4 |U_{e4}| |U_{\mu4}| |U_{e5}| |U_{\mu5}| \cos(1.27 \Delta m^2_{54} \text{L/E} \pm \varphi_{45}) \]

More parameters. Can fit shape difference btwn nu antinu
Dark Matter Search: Analysis

- Builds on robustness of NCE analysis
- MiniBooNE WIMP signal prediction:
  - rates from model
  - efficiency corrected
  - extrapolated to MiniBooNE POT
- \( \chi^2 \) minimization → sensitivity & limits
  - Exploits shape difference
  - Parameters: \( \kappa \) vs \( M_\chi \)
  - for fixed Vector mass \( M_V = 300 \) MeV

\[
\chi^2 (M_\chi, \kappa) = \sum_{i=1}^{n} \sum_{j=1}^{n} \left[ T_{i}^{MC} (M_\chi, \kappa) - T_{i}^{Data} \right] (M_{i,j}^{tot})^{-1} \left[ T_{j}^{MC} (M_\chi, \kappa) - T_{j}^{Data} \right]
\]

The total error matrix

Timing information can be useful.

WIMPS travel much slower than c.

MiniBooNE Time resolution: few ns.
MiniBooNE: Beam-off-target mode

WIMP-nucleon scattering capabilities

Outlook of Light WIMP searches:

Stage 1: Operate in tandem with existing experiments.
Stage 2: Dedicated searches with existing (future) neutrino exps.
Stage 3: Dedicated experiments for Light WIMP searches.