• Liquid Argon Time Projection Chambers (LArTPCs) are very attractive for neutrino physics.
• There is extensive experience with LArTPCs in Europe (see previous talk from ICARUS).
• In the U.S. there has recently been much activity in developing LArTPCs for future long-baseline neutrino experiments (LBNE).
• This talk will focus on LArTPCs of increasingly larger sizes that are being developed at Fermilab.

**LArTPC idea:** Ionization present in the aftermath of a neutrino interaction in liquid argon is drifted towards fine-grained readout wireplanes that are connected to low-noise electronics.
LArTPCs for Neutrinos

• Liquid argon provides a dense target for neutrino interactions, and ample ionization/scintillation for detection.

• Particle identification comes primarily from $dE/dx$ (energy deposited) along track.
  ‣ Wire spacing of a few millimeters combined with digital sampling provides fine-grained resolution
  ‣ Photons (2x MIP $dE/dx$) and Electrons (1x MIP $dE/dx$) can be cleanly separated
  ‣ Topological cuts can further improve photon/electron separation

• Ideal for $\nu_e$ appearance experiment
  ‣ Excellent signal (CC $\nu_e$) efficiency and background (NC $\pi^0$) rejection

• Beautiful, bubble-chamber like events!

ArgoNeuT Event

“appearance” signal

“appearance” background
Liquid Argon Activities at Fermilab

- Tremendous progress in LArTPC development in past few years at Fermilab.
- We are moving from pure R&D towards large detectors with great physics potential.

**Materials Test Stand**

- 2007
- 100% R&D
- 2007-

**Electronics Test Stand**

- 2008-

**2007-2008**

**ArgoNeuT**

**2007-2010**

**LAr Purity Demonstrator**

**2010-2013**

**MicroBooNE**

**2013-20??**

**LBNE**

**20??**

**20 Kilotons**

**20 Kilotons**

**100% Physics**

**20 Kilotons**

**20 Kilotons**

Ref:
2.) A system to test the effect of materials on electron drift lifetime in liquid argon and the effect of water Andrews et al, NIM A608:251-258 (2009)
ArgoNeuT is a test project at Fermilab to operate a LArTPC in a neutrino beam. Operated in NuMI beam at Fermilab, in front of MINOS near detector (for muon reconstruction).

Goals:

- Gain experience building/running LArTPCs in an underground setting.
- Accumulate neutrino/antineutrino events (1st time in the U.S., 1st time ever in a low-Energy beam).
- Develop simulation and reconstruction for LArTPCs, and compare MC with data.
### ArgoNeuT: Details

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cryostat Volume</strong></td>
<td>500 Liters</td>
</tr>
<tr>
<td><strong>TPC Volume</strong></td>
<td>175 Liters</td>
</tr>
<tr>
<td><strong># Electronic Channels</strong></td>
<td>480</td>
</tr>
<tr>
<td><strong>Wire Pitch</strong></td>
<td>4 mm</td>
</tr>
<tr>
<td><strong>Electronics Style (Temperature)</strong></td>
<td>JFET (293 K)</td>
</tr>
<tr>
<td><strong>Max. Drift Length (Time)</strong></td>
<td>0.5m (330μs)</td>
</tr>
<tr>
<td><strong>Light Collection</strong></td>
<td>None</td>
</tr>
</tbody>
</table>

Moving underground (lowering down 350 ft. shaft)

TPC outside of vacuum-insulated cryostat

---

**TPC Wire Orientations**

- ±60° wires
- ν beam

**Induction**

- Induction #1
- Induction #2

---
ArgoNeuT: NuMI Run

- ArgoNeuT acquired ~1.4E20 Protons On Target (P.O.T.), primarily in anti-neutrino mode
- Data is being used to develop techniques for reconstructing events in 3D
- Measuring dE/dx particle identification effectiveness using this data will be an important result
- We expect to obtain several cross-section measurements (e.g. CCQE)
- Essentially a “shift-free” detector once filled

### ArgoNeuT POT delivered and accumulated

<table>
<thead>
<tr>
<th>POT Delivered</th>
<th>POT Acquired</th>
</tr>
</thead>
<tbody>
<tr>
<td>ν-mode</td>
<td>ν̄-mode</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Failure and replacement of off-the-shelf cryocooler.

### Event Types and Counts

<table>
<thead>
<tr>
<th>Event Type</th>
<th># in 1.4×10^{20} POT</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\nu_\mu) CC</td>
<td>5110</td>
</tr>
<tr>
<td>(\bar{\nu}_\mu) CC</td>
<td>5490</td>
</tr>
<tr>
<td>(\nu_e) CC</td>
<td>142</td>
</tr>
<tr>
<td>NC</td>
<td>4266</td>
</tr>
</tbody>
</table>

Total Sample
First neutrino interactions in Liquid-Argon in U.S.!

Raw Data

Color is proportional to energy deposited

Pixel size: 4mm x 0.3mm

Drift Coordinate

t (ticks)

Induction Plane Wire

Collection Plane Wire

~1m

~0.5m
ArgoNeuT Neutrino Event

Pixel size: 4mm x 0.3mm

Raw Data
CCQE $\nu_e$ candidate

Electronics response is removed by Fourier Deconvolution
ArgoNeuT: Software

- Developing (automated) event reconstruction is critical.
- “LArSoft” is simulation/reconstruction/analysis code that can be used by future LAr experiments.
- Example: Different reconstruction techniques being developed...

**Hit Finding + Density-based clustering.**

**3D Reconstruction**

**Straight-line reconstruction using Hough Transform.**
ArgoNeuT: Analyzing Muons

3D Reconstructed muons from few hours of running.

Angular distribution...NuMI Beam is at -3°

“X-ray” of detector boundaries showing begin and end of each muon track

Working on publication to detail detector and analysis of large sample of muons in ArgoNeuT.
MicroBooNE

• MicroBooNE* is a LArTPC experiment that will operate in the on-axis Booster neutrino beam and off-axis NuMI neutrino beam on the surface at Fermilab.  
  • Combines timely physics with hardware R&D necessary for the evolution of LArTPCs.  
    ▶ MiniBooNE low-energy excess  
    ▶ Low-Energy Cross-Sections  
    ▶ Cold Electronics  
    ▶ Long-drift operation (strict demands on LAr purity)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryostat Volume</td>
<td>150 Tons</td>
</tr>
<tr>
<td>TPC Volume</td>
<td>90 Tons</td>
</tr>
<tr>
<td># Electronic Channels</td>
<td>~9000</td>
</tr>
<tr>
<td>Wire Pitch</td>
<td>3 mm</td>
</tr>
<tr>
<td>Electronics Style (Temp.)</td>
<td>JFET (120 K)</td>
</tr>
<tr>
<td>Max. Drift Length (Time)</td>
<td>2.5m (1.5ms)</td>
</tr>
<tr>
<td>Light Collection</td>
<td>~30 8” Hamamatsu PMTs</td>
</tr>
</tbody>
</table>

★ Stage 1 approval from Fermilab directorate in June 2008  
★ CD-0 (Mission Need) in October 2009  
★ CD-1 (reviewed early March)  
★ CD-2/CD-3a (Fall 2010)  
★ Turn On (2012-2013)

*See poster from Vassili Papavassiliou

MicroBooNE Experiment  
(DOE/NSF Supported)
MicroBooNE: Physics Goals

- Address the MiniBooNE\(^*\) low energy excess
  - Does MicroBooNE confirm the excess?
  - Utilize dE/dx + topology to determine if it is an electron-like or gamma-like process
- Low Energy Cross-Section Measurements (CCQE, NC \(\pi^0, \Delta \rightarrow N\gamma\), Photonuclear, ...)
- Study processes relevant for proton-decay searches in a large LArTPC
- Fully implement automated reconstruction (building on ArgoNeuT’s effort)

MiniBooNE \(\nu_e\) Appearance Result

- MiniBooNE Neutrino-Mode Excess
  - 200-300MeV: \(45.2\pm26.0\) events
  - 300-475MeV: \(83.7\pm24.5\) events

MicroBooNE will have \(>5\sigma\) significance for electron-like excess, \(>3.3\sigma\) for photon-like excess.

*See talks by: Richard Van deWater and Georgia Karagiorgi on Monday.

Refs:
• Deep Underground Science and Engineering Laboratory (DUSEL) at the Homestake Mine in South Dakota is the proposed home of future long-baseline far detectors.

• Long Baseline Neutrino Experiment (LBNE*) collaboration is working on beam+near-detector(s)+far-detector(s) configuration.

• Conceptual design for a ~20 kiloton LBNE LArTPC detector:
  ▶ “Membrane” style cryostat (used in Liquified Natural Gas shipping industry).
  ▶ Alternative design with vacuum-insulated modular-style cryostat is also being considered.
  ▶ Considering depths of 300, 800, and 4800 feet...(shallower depths allow possibility of drive-in access).

*LBNE Posters: R. Bradford, C. Mauger, S. Ouedraogo, M. Soderberg

Beam from Fermilab to DUSEL

“Membrane” Cryostat

*See talk by Bob Svoboda on Saturday.
Membrane-style cryostat anchored to rock walls

- Cathode and wire frames can be manufactured at a remote site and shipped to mine site.
- Wire frames contain all electronics, and can be tested in a LAr cryostat before transport into mine.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryostat Volume</td>
<td>25 kTons</td>
</tr>
<tr>
<td>TPC Fiducial Volume</td>
<td>16.8 kTons</td>
</tr>
<tr>
<td># Readout Wires</td>
<td>~645000 (128:1 MUX)</td>
</tr>
<tr>
<td>Wire Pitch</td>
<td>3 mm</td>
</tr>
<tr>
<td>Electronics Style (Temp.)</td>
<td>CMOS (87 K)</td>
</tr>
<tr>
<td>Max. Drift Length (Time)</td>
<td>2.5m (1.4ms)</td>
</tr>
<tr>
<td>Light Collection</td>
<td>TBD</td>
</tr>
</tbody>
</table>
• Preliminary sensitivity calculations for 100 kTon Water Cherenkov and 16.7 kTon LArTPC.
• Indicates a ~6:1 equivalence between Water:LAr

LArTPC Plots Assume:
- WBB design for LBNE
- 85% $\nu_e$ efficiency
- 5% background uncertainty

**Plots by J. Kopp**
Conclusion

- Liquid Argon detectors provide exceptional capabilities for neutrino physics, and a significant amount of development is occurring in the U.S.
- **ArgoNeuT** project recently completed run in NuMI tunnel.
  - Data analysis underway
  - Proposing a new run in the SciBooNE location
- **MicroBooNE** is next major U.S. LArTPC, and it will probe MiniBooNE Low-E excess, and further develop technology.
- **LBNE** LArTPC at DUSEL offers extraordinary physics opportunities.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Institutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>F. Cavanna</td>
<td>University of L'Aquila</td>
</tr>
<tr>
<td>A. Ereditato, S. Haug, B. Rossi, M. Weber</td>
<td>University of Bern</td>
</tr>
<tr>
<td>B. Baller, C. James, S. Fordes, G. Rameika, B. Rebel</td>
<td>Fermi National Accelerator Laboratory</td>
</tr>
<tr>
<td>M. Antonello, O. Palamara</td>
<td>Gran Sasso National Laboratory</td>
</tr>
<tr>
<td>T. Bolton, S. Farooq, G. Horton-Smith, D. McKee</td>
<td>Kansas State University</td>
</tr>
<tr>
<td>C. Bromberg, D. Edmunds, P. Laurens, B. Page</td>
<td>Michigan State University</td>
</tr>
<tr>
<td>K. Lang, R. Mehdiyev</td>
<td>The University of Texas at Austin</td>
</tr>
<tr>
<td>C. Anderson, B. Fleming, S. Linden, K. Partyka, M. Soderberg, J. Spitz</td>
<td>Yale University</td>
</tr>
</tbody>
</table>

New Collaborators for “Phase II”!

Thanks to:
BACK-UP SLIDES
• Neutrino interactions inside a TPC produce particles that ionize the argon as they travel (55k e⁻/cm).
• Ionization is drifted along E-field to wireplanes, consisting of wires spaced a few mm apart.
• Location of wires within a plane provides position measurements...multiple planes give independent views.
• Timing of wire pulse information is combined with drift speed to determine drift-direction coordinate.
• Scintillation light also present, can be collected by Photomultiplier Tubes and used in triggering.

Refs:
Why Noble Liquids for Neutrinos?

- Abundant ionization electrons and scintillation light can both be used for detection.
- If liquids are highly purified (<0.1 ppb), ionization can be drifted over long distances.
- Excellent dielectric properties accommodate very large voltages.
- Noble Liquids are dense, so they make a good target for neutrinos.
- **Argon** is relatively cheap and easy to obtain (1% of atmosphere).

---

### Properties of Noble Liquids and Water

<table>
<thead>
<tr>
<th></th>
<th>He</th>
<th>Ne</th>
<th>Ar</th>
<th>Kr</th>
<th>Xe</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling Point [K] @ 1 atm</td>
<td>4.2</td>
<td>27.1</td>
<td>87.3</td>
<td>120.0</td>
<td>165.0</td>
<td>373</td>
</tr>
<tr>
<td>Density [g/cm³]</td>
<td>0.125</td>
<td>1.2</td>
<td>1.4</td>
<td>2.4</td>
<td>3.0</td>
<td>1</td>
</tr>
<tr>
<td>Radiation Length [cm]</td>
<td>755.2</td>
<td>24.0</td>
<td>14.0</td>
<td>4.9</td>
<td>2.8</td>
<td>36.1</td>
</tr>
<tr>
<td>dE/dx [MeV/cm]</td>
<td>0.24</td>
<td>1.4</td>
<td>2.1</td>
<td>3.0</td>
<td>3.8</td>
<td>1.9</td>
</tr>
<tr>
<td>Scintillation [γ/MeV]</td>
<td>19,000</td>
<td>30,000</td>
<td>40,000</td>
<td>25,000</td>
<td>42,000</td>
<td></td>
</tr>
<tr>
<td>Scintillation λ [nm]</td>
<td>80</td>
<td>78</td>
<td>128</td>
<td>150</td>
<td>175</td>
<td></td>
</tr>
</tbody>
</table>
ArgoNeuT: Collaboration

F. Cavanna
*University of L’Aquila*

A. Ereditato, S. Haug, B. Rossi, M. Weber
*University of Bern*

B. Baller, C. James, S. Pordes, G. Rameika, B. Rebel
*Fermi National Accelerator Laboratory*

M. Antonello, O. Palamara
*Gran Sasso National Laboratory*

T. Bolton, S. Farooq, G. Horton-Smith, D. McKee
*Kansas State University*

C. Bromberg, D. Edmunds, P. Laurens, B. Page
*Michigan State University*

K. Lang, R. Mehdiyev
*The University of Texas at Austin*

*Yale University*

* = Spokesperson
MicroBooNE: Collaboration

V. Radeka, S. Rescia, J. Sondericker, C. Thorn, B. Yu
Brookhaven National Laboratory, Upton, NY

L. Camilleri, C. Mariani, B. Seligman, M. Shaevitz, W. Willis†
Columbia University, New York, NY

B. Baller, C. James, H. Jostlein, S. Pordes, G. Rameika, B. Rebel, R. Schmitt,
D. Schmitz, J. Wu, S. Zeller
Fermi National Accelerator Laboratory, Batavia, IL

T. Bolton, D. McKee, G. Horton-Smith
Kansas State University, Manhattan, Kansas

G. Garvey, J. Gonzales, B. Louis, C. Mauger, G. Mills, Z. Pavlovic,
R. Van de Water, H. White
Los Alamos National Laboratory, Los Alamos, NM

B. Barletta, L. Bugel, J. Conrad, G. Karagiorgi, T. Katori, H. Tanaka
Massachusetts Institute of Technology, Cambridge, MA

C. Bromberg, D. Edmunds
Michigan State University, Lansing, MI

K. McDonald, C. Lu, Q. He
Princeton University, Princeton, NJ

P. Nienaber
St. Mary’s University of Minnesota, Winona, MN

H. Wang
U.C.L.A., Los Angeles, CA

R. Johnson, A. Wickremasinghe
University of Cincinnati, Cincinnati, OH

S. Kopp, K. Lang
The University of Texas at Austin, Austin, TX

‡ = Spokesperson
† = Deputy Spokesperson

C. Anderson, B. Fleming†, S. Linden, K. Partyka, M. Soderberg, J. Spitz
Yale University, New Haven, CT