3-flavor Neutrino Oscillations: A well established phenomena

We have detected oscillations from

- Atmospheric
- Solar
- Accelerator
- Reactor

Experimentally confirmed that only three neutrinos couple to the Z boson

- Neutrinos oscillate and have tiny masses
- They come in 3 flavors in the SM
- Almost all of our results nicely fit the 3 neutrino Oscillation scenario
  - 2 mass splittings and 3 mixing angles

The measurement of \( \theta_{13} \approx 10^0 \) opened door to CP violation in the leptonic sector!

Experiments:

- Average measurements, error bars increased by factor 10
- LEP Experiments

\[ \text{E}_{\text{cm}} \text{ [GeV]} \]

\[ \sigma_{\text{had}} \text{ [nb]} \]

\[ m^2 \]

\( m_1^2 \)

\( m_2^2 \)

\( m_3^2 \)

atmospheric \( \sim 2 \times 10^{-3} \text{eV}^2 \)

solar \( \sim 7 \times 10^{-5} \text{eV}^2 \)
Still many profound unknowns

- Are there more than 3 neutrino flavors?  
  — do light sterile neutrinos exist?
- Is CP violated in the leptonic sector?  
  — understanding matter - anti-matter asymmetry?
- What is the Neutrino mass hierarchy?  
  — which neutrino is the lightest?

Several anomalies that don't fit in the 3 oscillation scenario:
A New Neutrino?

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Channel</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSND</td>
<td>DAR</td>
<td>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ CC</td>
<td>3.8σ</td>
</tr>
<tr>
<td>MiniBooNE</td>
<td>SBL accelerator</td>
<td>$\nu_\mu \rightarrow \nu_e$ CC</td>
<td>3.4σ</td>
</tr>
<tr>
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<td>SBL accelerator</td>
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</tr>
</tbody>
</table>

Still many profound unknowns

- Are there more than 3 neutrino flavors? — do light sterile neutrinos exist?
- Is CP violated in the leptonic sector? — understanding matter - anti-matter asymmetry?
- What is the Neutrino mass hierarchy? — which neutrino is the lightest?

### Short-Baseline Experiments (L~1 km)
- MicroBooNE, SBND, ICARUS,…

### Long-Baseline Experiments (L~1000 km)
- NOvA, DUNE, T2K,…

<table>
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<td>2.8(\sigma)</td>
</tr>
<tr>
<td>GALLEX/GADZU</td>
<td>Source - e capture</td>
<td>(\nu_e) disappearance</td>
<td>2.8(\sigma)</td>
</tr>
<tr>
<td>Reactors</td>
<td>Beta-decay</td>
<td>(\bar{\nu}_e) disappearance</td>
<td>3.0(\sigma)</td>
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</tbody>
</table>

Several anomalies that don’t fit A New Neutrino?
The MicroBooNE Experiment

Linac
Length: 150m
Proton Energy: 400 MeV

Booster (BNB)
Circumference: 468m
Proton Energy: 8 GeV

MicroBooNE
470 m baseline

› Short-Baseline Oscillation Experiment
› Located on the Booster Neutrino Beam (BNB) at Fermilab
The Short-Baseline Neutrino Program

- MicroBooNE is paving way for the three-detector SBN program to more definitively address the sterile neutrino question where we have existing hints
  - Well understood BNB beam
  - Same detector technologies, same beam = reduced systematics!
\( \nu_e \) Appearance Signal

(look for excess of \( \nu_e \) events)

Cannot measure the neutrino flavor directly, only through the outgoing lepton.

- Charged-current events typically signal events.
- Can use out-going lepton to tag neutrino flavor.

\( e/\gamma \) separation crucial for \( \nu_e \) appearance experiments!
The MicroBooNE LArTPC

- LArTPC = Liquid Argon Time Projection Chamber

- Surface-based, 89-ton active volume liquid argon

- One drift chamber
  - Cathode at -70kV
  - Drift at 2.56 m
  - E-field at 273 V/cm

- Three wire planes
  - 2 induction, 1 collection
  - 3 mm wire pitch
  - 3 mm wire plane spacing

- PMT and UV Laser System

- Collecting cosmic and neutrino data since Fall 2015
• Argon makes a desirable target (dense, abundant, …)
• Two signals: Ionization signal & Scintillation light
• Finely (mm-scale) segmented anode wires — excellent resolution!
• Bubble chamber quality images in HD!
• Technology allows for scalability — can build massive detectors
A neutrino event in MicroBooNE LArTPC

"Imaging" detectors
digitized Bubble chambers
with Calorimetry!
MicroBooNE Goals

- Protons
- Neutrinos
- Booster (BNB)

MicroBooNE 470m baseline

Investigate non-standard neutrino oscillations

high-statistics precision measurement of $\nu$-Ar in 1 GeV

Design example for future multi-kiloton detectors and develop automated reconstruction

(170 ton LAr)
High Resolution Detector

• **e/γ shower separation**: via both event topology and early dE/dx

• **Neutrino energy reconstruction, hadron kinematics come into play**
  • Fine grained tracking
  • event classification in terms of final state topology
  • Ability to reconstruct hadrons

Automated Proton Track Identification
Upgrades: Cosmic Ray Tagger System

- Plastic Scintillator Modules & SiPM readout
- Design & Construction paper under preparation for JINST
- Currently developing matching techniques between TPC and CRT

Completely installed and commissioned in March, 2017

85% coverage for through-going muons
MicroBooNE Operations

- TPC running stably since October 2015
- 97% beam uptime with full CRT since March 2017
- Accumulated more than 7.5E20 POT BNB data, 2.5E20 POT with CRT.

- Argon purity critical for LArTPC operation
- Electro-negative impurities (O$_2$ and H$_2$O) in argon can absorb drifting electrons
- Achieved 3 times the design goal for purity within 30 days of operation!
MicroBooNE Publications & Public Notes

7 Publications, 19 public notes (8 more in the pipeline)

Public Notes

<table>
<thead>
<tr>
<th>Date</th>
<th>Note</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>08/30/17</td>
<td>MICROBOONE-NOTE-1026-PUB</td>
<td>A Measurement of the Attenuation of Drifting Electrons in the MicroBooNE LArTPC</td>
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<tr>
<td>07/22/17</td>
<td>MICROBOONE-NOTE-1028-PUB</td>
<td>Establishing a Pure Sample of Side-Piercing Through-Going Cosmic-Ray Muons for LArTPC Calibration in MicroBooNE</td>
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<tr>
<td>06/04/17</td>
<td>MICROBOONE-NOTE-1024-PUB</td>
<td>Measurement of Reconstructed Charged Particle Multiplicities of Neutrino Interactions in MicroBooNE</td>
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<tr>
<td>01/26/17</td>
<td>MICROBOONE-NOTE-1025-PUB</td>
<td>Proton Track Identification in MicroBooNE Simulation for Neutral Current Elastic Events</td>
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<tr>
<td>11/29/16</td>
<td>MICROBOONE-NOTE-1018-PUB</td>
<td>Study of Space Charges in the LArTPC</td>
</tr>
<tr>
<td>07/04/16</td>
<td>MICROBOONE-NOTE-1017-PUB</td>
<td>A Method to Extract the TPC Wire Plane Position</td>
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<tr>
<td>07/04/16</td>
<td>MICROBOONE-NOTE-1016-PUB</td>
<td>Noise Characterization of TPC</td>
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<tr>
<td>07/04/16</td>
<td>MICROBOONE-NOTE-1015-PUB</td>
<td>The Pandora multi-pattern recognition software for MicroBooNE data</td>
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<tr>
<td>07/04/16</td>
<td>MICROBOONE-NOTE-1014-PUB</td>
<td>A Comparison of Cosmic Ray Events between MicroBooNE and FermiLab SCINT-160 Data</td>
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<tr>
<td>07/04/16</td>
<td>MICROBOONE-NOTE-1013-PUB</td>
<td>MicroBooNE Detector and tPC Performance for the SCINT-160 Data</td>
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<tr>
<td>07/04/16</td>
<td>MICROBOONE-NOTE-1012-PUB</td>
<td>Demonstration of the MicroBooNE Detector and tPC Performance for the SCINT-160 Data</td>
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<tr>
<td>07/04/16</td>
<td>MICROBOONE-NOTE-1011-PUB</td>
<td>Selection and kinematic analysis of high purity cosmic ray data for MicroBooNE data</td>
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<td>07/04/16</td>
<td>MICROBOONE-NOTE-1010-PUB</td>
<td>Selection and kinematic analysis of high purity cosmic ray data for MicroBooNE data</td>
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<tr>
<td>07/01/16</td>
<td>MICROBOONE-NOTE-1008-PUB</td>
<td>Michel Electron Reconstruction Using Cosmic Ray Data from the MicroBooNE LArTPC</td>
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<tr>
<td>05/03/16</td>
<td>MICROBOONE-NOTE-1006-PUB</td>
<td>Study Towards an Event Selection for Neutral Current Inclusive Single Pio Production in MicroBooNE</td>
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<tr>
<td>05/30/16</td>
<td>MICROBOONE-NOTE-1005-PUB</td>
<td>Cosmic Shielding Studies at MicroBooNE</td>
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<td>11/06/15</td>
<td>MICROBOONE-NOTE-1004-PUB</td>
<td>MC performance study for an early numu charged-current inclusive analysis with MicroBooNE</td>
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<tr>
<td>05/29/16</td>
<td>MICROBOONE-NOTE-1003-PUB</td>
<td>Measurement of the Electronegative Contaminants and Drift Electron Lifetime in the MicroBooNE Experiment</td>
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<tr>
<td>11/02/15</td>
<td>MICROBOONE-NOTE-1002-PUB</td>
<td>First neutrino interactions observed with the MicroBooNE Liquid-Argon TPC detector</td>
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<tr>
<td>08/28/15</td>
<td>MICROBOONE-NOTE-1001-TECH</td>
<td>Noise Dependence on Temperature and LAr Fill Level in the Liquid-Argon TPC</td>
</tr>
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</table>

Publications/Documents by the MicroBooNE Collaboration


Papers in all categories

- Construction & Operation
- Detector Physics
- Reconstruction Techniques
- Towards Cross-section Measurements
- Towards Oscillation Measurements
TPC Noise Filtering

• Several noise sources were identified and mitigated: both Hardware upgrades & Noise filtering techniques

• Peak Signal-to-Noise Ratio
  • > 16 (induction planes)
  • > 35 (collection plane)

Significantly lower noise levels achieved in a 100-ton scale LArTPC
Fully Automated Track Reconstruction

- Surface location = multiple cosmic tracks
- Developing and Testing our reconstruction & calibration on Cosmics
Space charge Effects

- Build up of slow moving Ar+ ions in the detector due to e.g. cosmic rays results in
  - 5 to 12% variation (drift) in E-field w.r.t. nominal
  - 5 cm (drift) and 12 to 15 cm (non-drift) spatial variation

First Measurement using tracks from a small **Muon Counter System (MuCS)** — limited angular coverage

- Data and MC reasonably agree in basic shape and normalization
- Measurements for the full TPC volume planned with laser & larger CRT
Electron Drift-lifetime & Argon purity

Measurement done using Anode-Cathode crossing Cosmic muons from data

- >18 ms electron lifetime!
- Maximum charge loss 12%
- *MicroBooNE Purification system is performing exceptionally well!*
- Space charge biggest systematic — will improve with future data measurements
Michel Electrons from Cosmic Data

- Physics Motivation
  - SuperNovae/Low-Energy Physics
  - Study detector response to low energy electrons (up to ~50 MeV)

- Complex Reconstruction
  - Reconstruction spectrum deficient due to escaping charge from radiative photons
  - 20% energy resolution

First study of radiative photons from tens-of-MeV electrons in LArTPC
The multi-kiloton LArTPC program critically depends on how much v-Ar cross-section knowledge we gain in the next few years.
First neutrino analysis: Charged Current $\nu_\mu$ inclusive

**Signature:** Look for a muon (plus anything) in the final state with an associated neutrino vertex

**Importance**
- First step towards a cross section measurement
- Will develop the reconstruction and systematics tools needed for final state topologies
- Lets you compare data between various experiments

- Fully automated reconstruction & event selection
- **Purity:** 60%
- **Acceptance x Efficiency:** 30%
  - Containment & Min. length cut for 1 track events
  - Cosmic backgrounds a challenge

<table>
<thead>
<tr>
<th></th>
<th>Before Selection</th>
<th>After Selection</th>
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</thead>
<tbody>
<tr>
<td>CCQE</td>
<td>60%</td>
<td>43%</td>
</tr>
<tr>
<td>RES</td>
<td>30%</td>
<td>42%</td>
</tr>
<tr>
<td>DIS</td>
<td>10%</td>
<td>14%</td>
</tr>
</tbody>
</table>

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Stat. only error shown

**MicroBooNE simulation preliminary**

- Quasi-elastic (QE)
- Resonance (RES)
- Deep inelastic (DIS)
CC $\nu_\mu$ inclusive event distributions

**Track Length (cm)**

- Data: Beam On - Beam Off
- Simulation:
  - selected $\nu_\mu$CC+bkgd
  - $\bar{\nu}_\mu$ bkgd
  - $\nu_\mu + \bar{\nu}_\mu$ bkgd
  - NC bkgd
  - Cosmic bkgd
  - $\nu_\mu$ CC true vertex Out of FV bkgd

**MicroBooNE preliminary**

$4.95 \times 10^{19}$ POT

Stat. only error shown
Building on CC $\nu_\mu$ inclusive analysis: Charged Particle Multiplicity

- Directly observable quantity
- Stringent test for $\nu$ event generators inclusively
- Compared charged particle multiplicity from data and different GENIE generator models

- Some under-prediction and over-prediction
- Future comparisons will involve more widely varying model predictions

First measurement of charged track multiplicity in $\nu_\mu$ CC interactions in Ar
Building on CC $\nu_\mu$ inclusive analysis: Charged Current $\pi^0$ events

Key sample towards developing low energy excess analysis

- Study shower reconstruction performance
- Energy calibration tests with $\pi^0$ mass peak
- NC $\pi^0$ background estimation

Currently working towards world’s first measurement of CC $\pi^0$ cross-section measurement on argon
Reconstruction & Particle ID

Muon tracking efficiency

JINST 12, P12030 (2017)

Deep Learning techniques


Pandora Pattern Recognition Algorithms

JINST 12, P03011 (2017)

Developing multiple approaches for the flagship oscillation analysis
Summary

• MicroBooNE is taking data stably since August 2015 and is continuously analyzing it at all levels

• Made enormous progress in understanding the detector and the technology

• Automatic Reconstruction algorithms Performing well and are continuously being improved

• Cosmic backgrounds being mitigated by the external large Cosmic Ray Tagger System

• Many more analyses in pipeline, Stay tuned for more exciting results from MicroBooNE soon!

• MicroBooNE is in an excellent place to address both technical and measurement challenges for both SBN and the multi-kiloton long-baseline DUNE program
Thank you!
Backup
High $\Delta m^2$ results: the MiniBooNE experiment

Same $L/E_\nu$ (~1m/MeV) as LSND – entirely different systematics and backgrounds than LSND

Water Cherenkov Detector

MiniBooNE excess

LSND excess

Subtract background from data

2.8$\sigma$ excess

3.4$\sigma$ excess

Data are consistent with anti-$\nu$ oscillations in the $0.01<\Delta m^2<1.0$ eV$^2$ range. Some overlap with LSND

Excess is only marginally compatible with a simple 2-$\nu$ oscillation formalism
What can MicroBooNE tell us about the MiniBooNE low-E excess?

MicroBooNE is capable of telling us whether the excess is electron-like or photon-like.

While MicroBooNE can address a critical piece of short-baseline puzzle, MicroBooNE by itself is not enough to explore the complete sterile neutrino oscillation parameter space.
SBN: $\nu_\mu \rightarrow \nu_e$ appearance sensitivity

The LSND 99% C.L. allowed region is covered at the $\geq 5\sigma$ level above $\Delta m^2 = 0.1$ eV$^2$. 
SBN: $\nu_\mu$ disappearance sensitivity

SBN can extend the search for muon neutrino disappearance an order of magnitude beyond the combined analysis of SciBooNE and MiniBooNE.

![Graph showing sensitivity](image)
Neutrino-Argon Interactions

Understanding $\nu$-N cross-sections over the energy range valid for short and long baseline experiments is vital for any oscillation measurement!

Neutrino-nucleus interactions

- Quasi-elastic (QE) $\nu_\mu \rightarrow \mu^-$: Target changes but no break up
- Resonance (RES) $\nu_\mu \rightarrow \pi^+$, $\nu_\mu \rightarrow \Delta^+$: Target goes into an excited state
- Deep inelastic (DIS) $\nu_\mu \rightarrow W^+ \rightarrow X$: Target nucleon breaks up!

Competitive physics processes and complicated nuclear effects in the 1 GeV range!
**Why Liquid Argon as nuclear target?**

- dense & Abundant (1% of atmosphere)
- easily ionizable (55,000 electrons/cm)
- highly scintillating (transparent to light produced)
- Pure argon results in high electron mobility => long drift lengths

### Table

<table>
<thead>
<tr>
<th></th>
<th>He</th>
<th>Ne</th>
<th>Ar</th>
<th>Kr</th>
<th>Xe</th>
<th>Water</th>
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<tbody>
<tr>
<td>Boiling Point [K] @ 1atm</td>
<td>4.2</td>
<td>27.1</td>
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<td>120.0</td>
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<td>Density [g/cm³]</td>
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<td>1.4</td>
<td>2.4</td>
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<td>Radiation Length [cm]</td>
<td>755.2</td>
<td>24.0</td>
<td>14.0</td>
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<td>dE/dx [MeV/cm]</td>
<td>0.24</td>
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<td>2.1</td>
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<td>1.9</td>
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<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>
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<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>

*credit: M. Soderberg*
Major R&D milestones from MicroBooNE

**Surge protection devices**
S. Gollapinni et al.,
JINST 9, T11004 (2014), JINST 9 P09002 (2014)

**Purity without evacuation**

**Successful design & installation of the 1st 100-ton scale TPC in the U.S.**
Typically expect signal to be induced on only one wire. But, in reality, nearby wires also see some signal.
Space Charge Measurement Improvements

- Space Charge Measurement being improved combining various calibration sources
  - UV Laser calibration data
  - Cosmic rays tagged using the larger CRT system

- Laser an ideal source to do 3D calibration for space charge

- Also need to understand how liquid argon flow impacts ion movement

MuCS vs CRT coverage

larger coverage of crossing muons from CRT
Pandora Reconstruction Performance

![Graphs showing reconstruction efficiency vs number of hits, true momentum, and angle.]
Pandora Reconstruction Performance

![Diagram of particle interactions]

<table>
<thead>
<tr>
<th>#Matched Particles</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3+</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>3.5%</td>
<td>95.1%</td>
<td>1.4%</td>
<td>0.0%</td>
</tr>
<tr>
<td>$p$</td>
<td>9.0%</td>
<td>86.8%</td>
<td>4.0%</td>
<td>0.3%</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>6.9%</td>
<td>80.9%</td>
<td>11.4%</td>
<td>0.8%</td>
</tr>
</tbody>
</table>

![Graphs showing reconstruction efficiency against number of hits, true momentum, and minimum angle]

MicroBooNE Simulation

$\nu_\mu + Ar \rightarrow \mu^- + p + \pi^+$

Reconstruction Efficiency

- $\mu$
- $p$
- $\pi^+$
Pandora Reconstruction Performance

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<th>3+</th>
</tr>
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<tr>
<td>$\mu$</td>
<td>3.7%</td>
<td>94.8%</td>
<td>1.5%</td>
<td>0.0%</td>
</tr>
<tr>
<td>$p$</td>
<td>9.9%</td>
<td>85.5%</td>
<td>4.3%</td>
<td>0.3%</td>
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<tr>
<td>$\gamma_1$</td>
<td>6.8%</td>
<td>88.0%</td>
<td>4.8%</td>
<td>0.4%</td>
</tr>
<tr>
<td>$\gamma_2$</td>
<td>29.9%</td>
<td>66.4%</td>
<td>3.6%</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

![Graphs showing reconstruction efficiency for different scenarios](image-url)

- MicroBooNE Simulation
- $\nu_\mu + Ar \rightarrow \mu^- + p + \pi^0$
- $\theta_{\gamma_1,\gamma_2}$ [radians]
Proton decay background

*Some GUT models explicitly break the baryon number symmetry predicting proton decay*

MicroBooNE is not big enough to study proton decay itself

– *But, MicroBooNE can study proton decay backgrounds for future experiments!*

Proton decay background

A cosmic muon interacts in a rock near the detector, produces a $K^0_L$ which then charge exchanges, $K^0_L p \rightarrow K^+ n = \text{looks like a } K^+ \text{ from proton decay if right energy (339 MeV/c)}$.

Decay mode of interest to MicroBooNE: $p \rightarrow K^+ \nu; K^+ \rightarrow \mu^+ \nu_\mu; \mu^+ \rightarrow e^+ \nu_e (\text{anti-} \nu_\mu)$

– the distinct dE/dx pattern enables study of this 3-fold decay mode
Supernovae neutrinos

A core-collapse supernova (SN) produces a burst of neutrinos of all flavors (in few-tens-of-MeV range)
→ physics of oscillations of SN neutrinos holds key astronomical phenomena

Water and liquid scintillator neutrino detectors,
→ primarily sensitive to electron anti-neutrinos
anti-$\nu_e + p \rightarrow n + e^+$ (inverse beta decay on free protons)

LArTPCs posses unique capability to detect SN electron neutrinos

1. CC$\nu_e$ capture of SN neutrinos on Ar
$\nu_e + Ar^{40}(18) \rightarrow K^{40}(19) + e^-$

Other processes:
2. Neutral current excitation of Ar$^{40}$
$\nu_{e,\mu,\tau} + Ar^{40}(18) \rightarrow Ar^{*40}(18) + \nu_{e,\mu,\tau}$

3. Elastic scattering off electron
$\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^-$
Supernovae neutrinos

Detection requires sensitivity to low-energy gammas (<50 MeV) and electrons

- CCν\textsubscript{e} capture on Ar can be tagged via
  the coincidence of emitted electron and accompanying de-excitation gamma cascade

Due to small size of MicroBooNE,

- will only see about 10-20 SN neutrinos
  in a duration of about 20 seconds
- A multi-kiloton detector (like LBNE) will be able to see a few hundred SN events!

Triggering on Supernovae events,

- MicroBooNE sits just below surface, too much cosmic traffic to have its own trigger!
- MicroBooNE will subscribe to SNEWS!