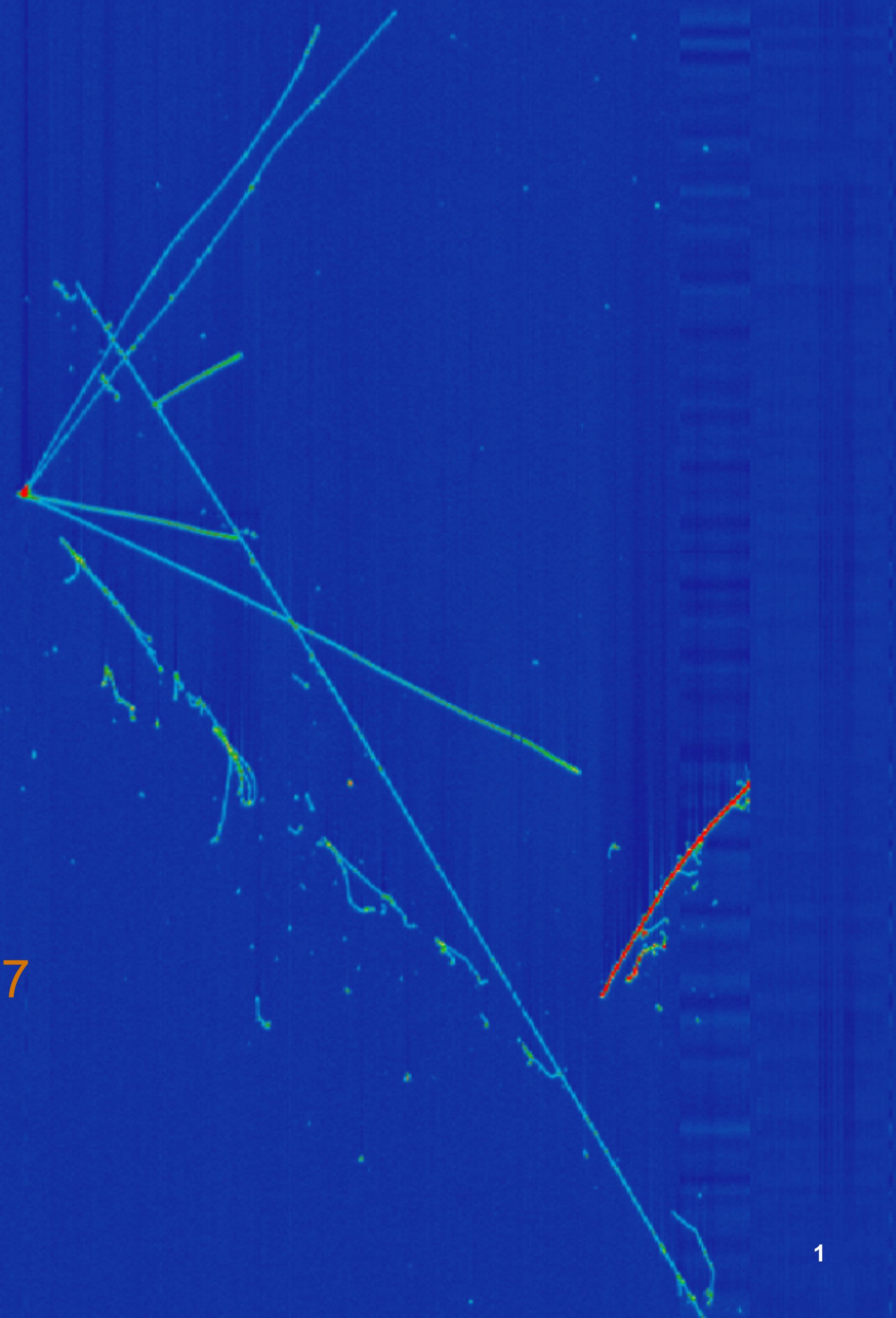
μBooNE

MicroBooNE Results

ERIC CHURCH, PNNL
LAKE LOUISE WINTER INSTITUTE 2017



Pacific Northwest NATIONAL LABORATORY

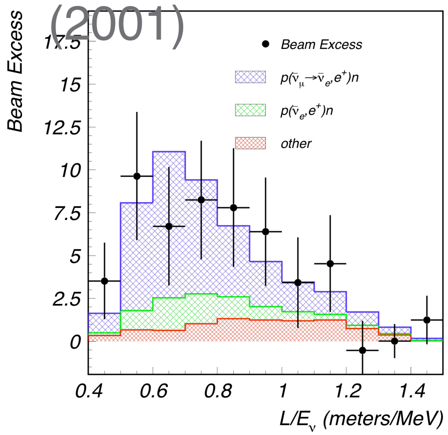
Short-Baseline Neutrino Anomalies

μBooNE

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

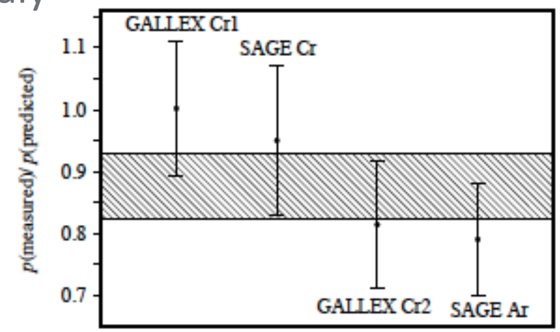
LSND

A. Aguilar et al., Phys. Rev. D 64, 112007, (2001)

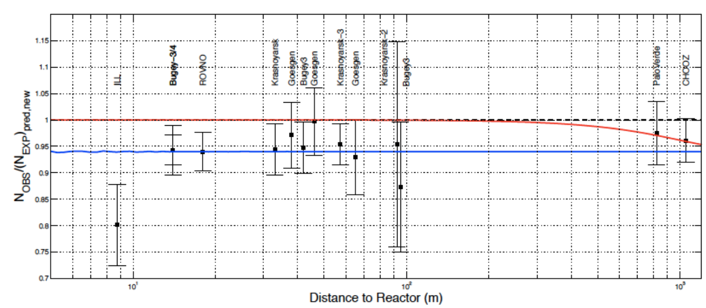


Gallium anomaly

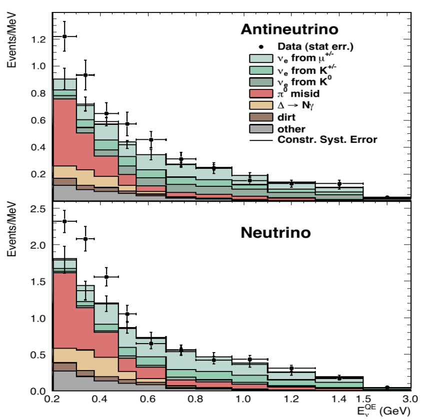
SAGE, Phys. Rev. C 73 (2006) 045805



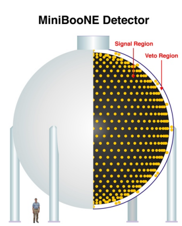
Reactor "anomaly"



G. Mention et al., Phys.Rev.D83:073006,2011



Excess mostly at Low energy in ν and $\bar{\nu}$.

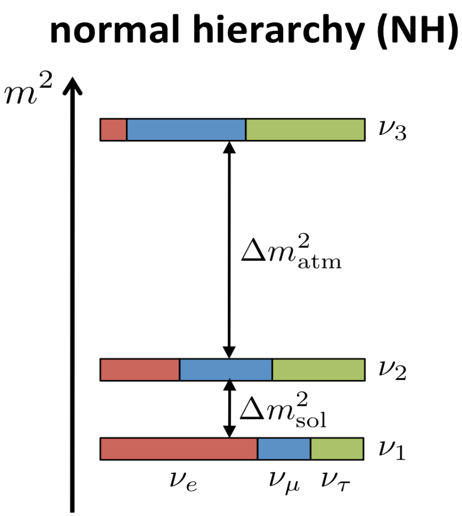


MiniBooNE
Phys. Rev. Lett. 110, 161801 (2013)
Combined analysis:
240.3 +/- 62.9 3.8σ

LLWI2017

All of this *could* be explained by a 4th "sterile" neutrino ~1 eV^2.

If real, 4 neutrinos are required, however



Phys. Rept. 427, 257 (2006)

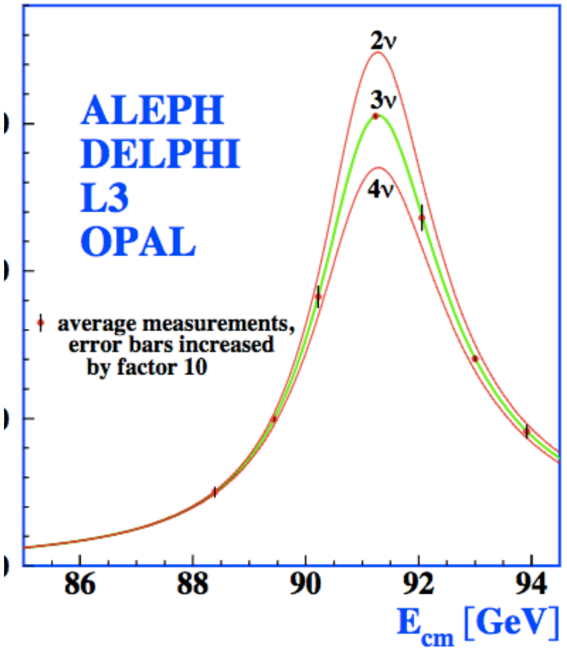


Figure 1.13: Measurements of the hadron production cross-section around the Z resonance. The curves indicate the predicted cross-section for two, three and four neutrino species with SM couplings and negligible mass.

… and the 4^{th} one must be "sterile"

US Particle Physics Prioritization Report

μBooNE

Pacific Northwest NATIONAL LABORATORY

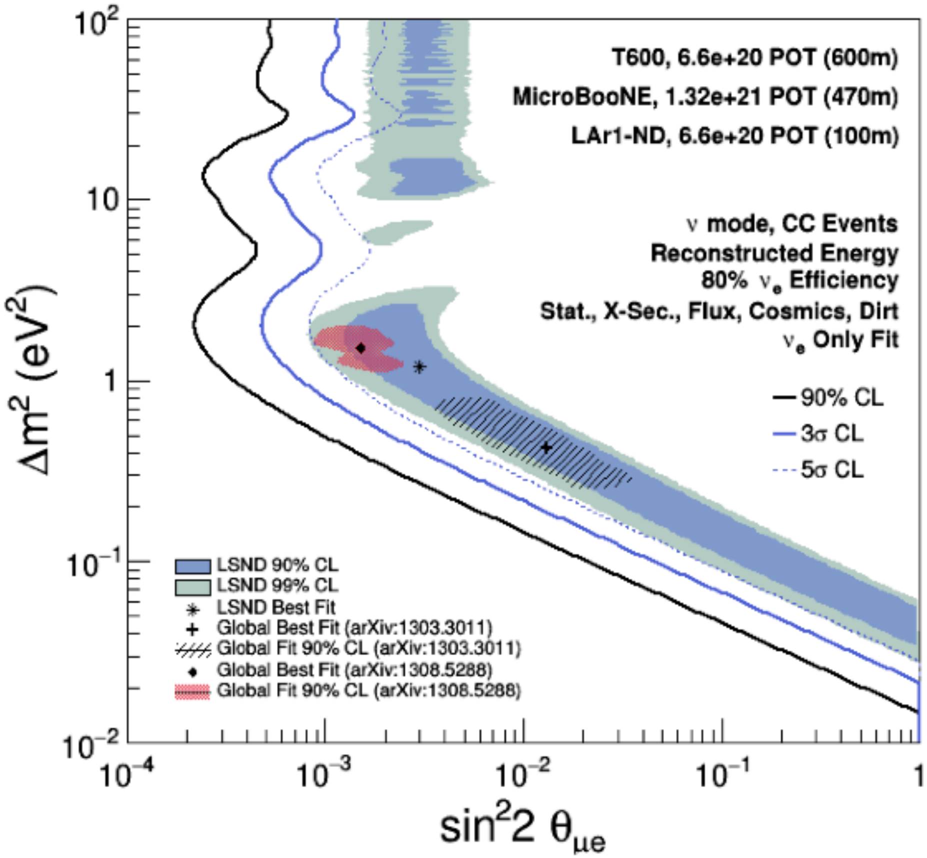
Proudly Operated by **Battelle** *Since 1965*

Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

P5 Report, May 2014

Recommendation 15: Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab.

Full 3-detector SBN program after ~3 years (2021)

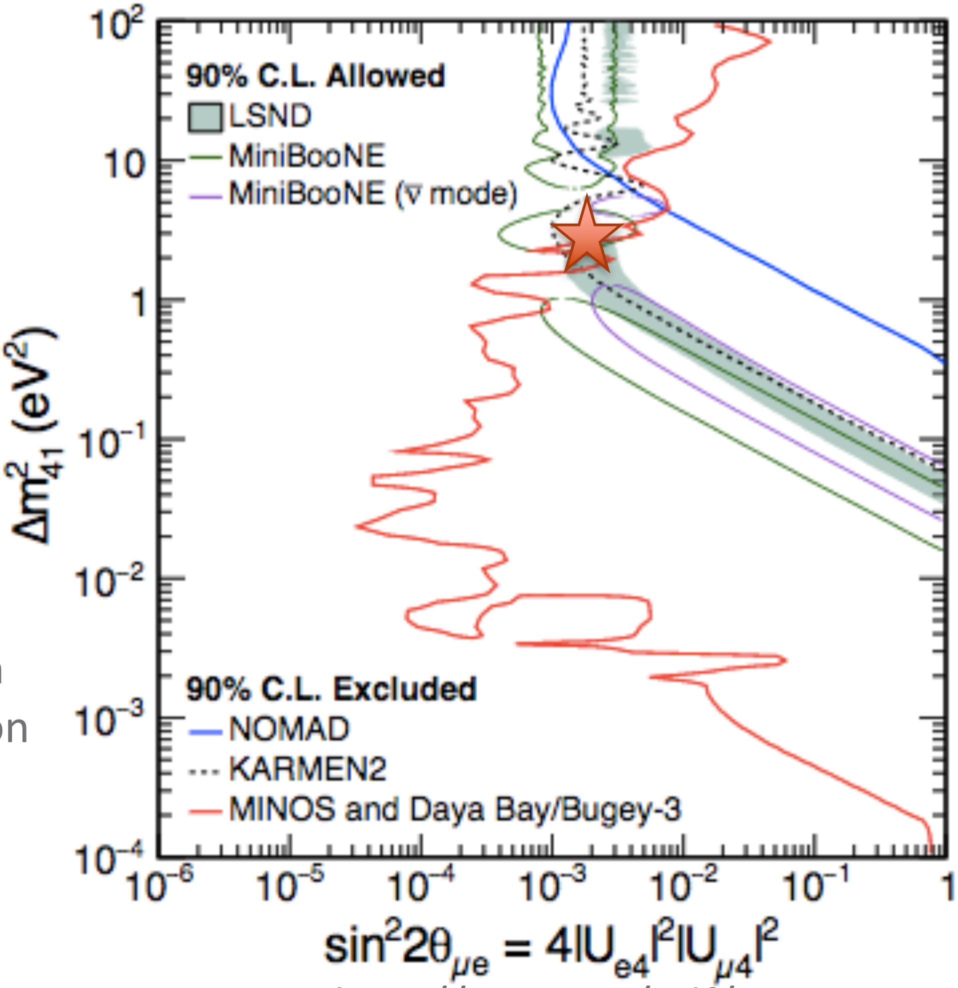


Parameter space significantly reduced

… but global best fit is at 1.75 eV^2 w. $\Delta\chi^2$/ndf ~ 12

arxiv: 1607.00011

Shown In the “3+1” model which allows to compare LSND/MiniBooNE to muon neutrino disappearance results



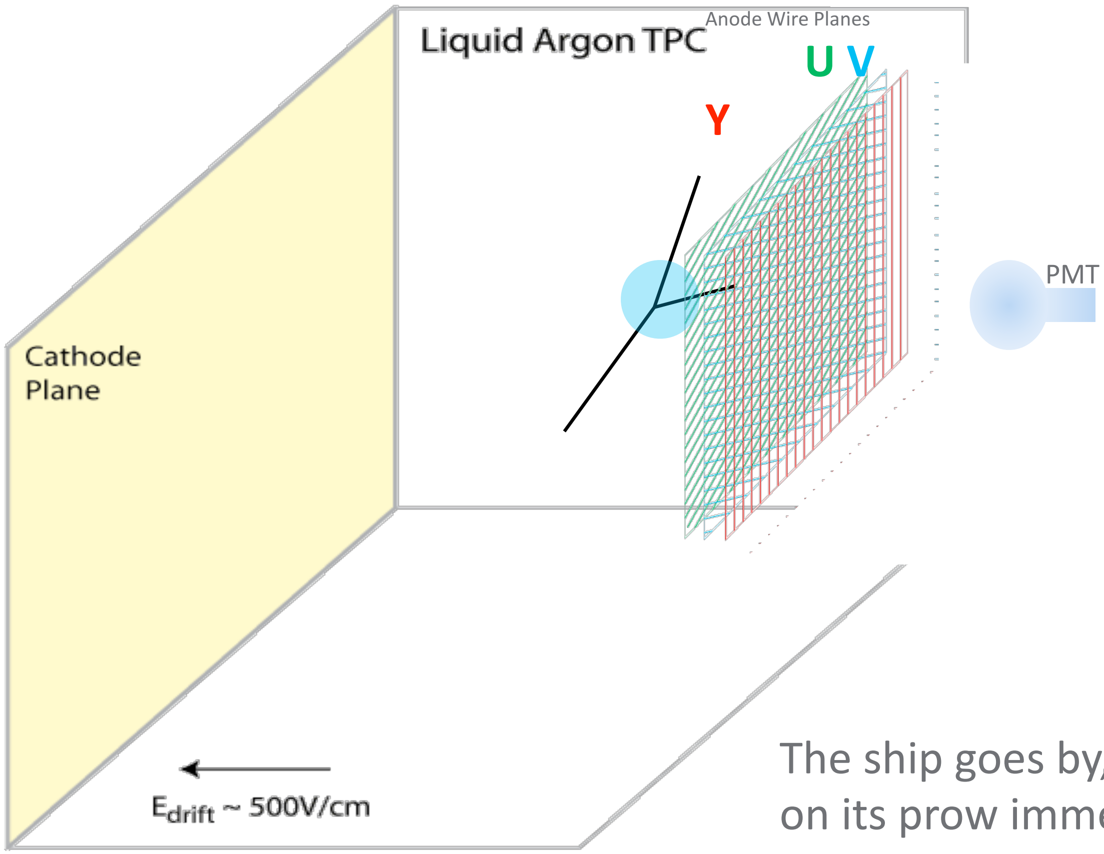
MINOS+ http://arxiv.org/pdf/1607.01177.pdf

Ice Cube has new results that similarly cast serious doubt on the sterile neutrino explanation Of LSND/miniBooNE results.

Topic at hand: Why LArTPCs?

- Charged particles ionize the medium through which they pass
  - If you can keep atoms from re-combining and drift them to an anode via application of a not-so-unreasonably large electric field you might hope to capture a (projection of) their 3-dimensional track.
    - With sufficient such projections (2) you can reconstruct the 3d track.
  - Further, can do calorimetry and particle ID if dE/dx is distinct by particle species
    - Can hope to distinguish between e^{-}s and γs
    - And between muons and electrons and protons and maybe kaons. Pions look just like muons, sadly.
  - Further still, photons may be liberated and can be detected to aid in t_0 and PID
- **Liquid nobles have above properties**.
  - They are not so hard to cool to liquid state
  - Argon, in particular, is “cheap” -- $1k/tonne
  - Its radiation length is 14cm, its hadronic interaction length is 90cm.

LArTPC detector working mechanics



Light detection is for determining t_0 to first order.

The ship goes by, and you see the light on its prow immediately (10 nsec). The waves lap on shore much later (~1 msec).

US-based LArTPC Program

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*

Yale TPC

Location: Yale University
Active volume: 0.002 ton
operational: 2007

Bo

Location: Fermilab
Active volume: 0.02 ton
operational 2008

ArgoNeuT

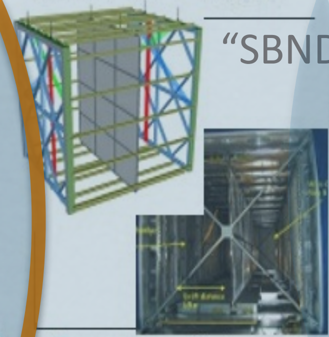
Location: Fermilab
Active volume: 0.3 ton
operational: 2008
First neutrinos: June 2009

MicroBooNE

Location Fermilab
Active volume: 0.1 kton
Operational: 2014

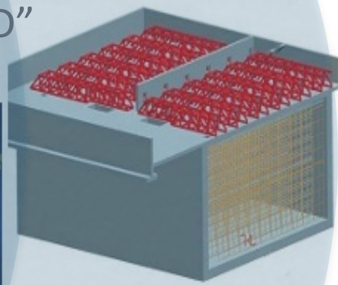
SBN @ FNAL

"SBND"



Location: Fermilab
Active volume: 0.05 + 0.6 kton
Construction start: 2017

DUNE



Location: Homestake
Active volume: 35 kton
Construction start 202?

Luke

Location: Fermilab
Purpose: materials test st
Operational: since 2008

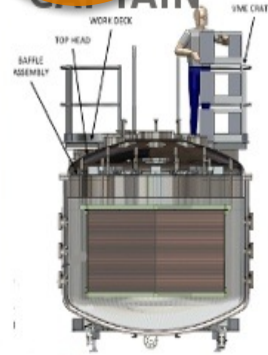
LAPD

Location: Fermilab
Purpose: LAr purity demo
Operational: 2011

LArIAT

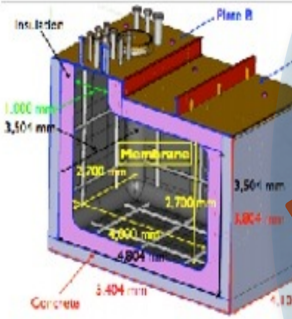
Location: Fermilab
Purpose: LArTPC calibration
Operational: 2014 (phase 1)

CAPTAIN



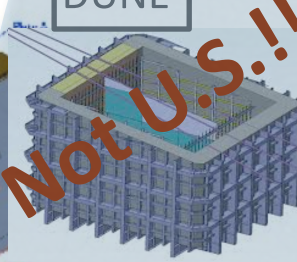
Location: LANL
Purpose: LArTPC calibration
Operational: 2014

LBNE 35 Ton



Location: Fermilab
Purpose: purity demo
Operational: 2013

proto DUNE



Not U.S.!!

CER N
770 ton
2018

MicroBooNE in a slide

μBooNE

Pacific Northwest NATIONAL LABORATORY

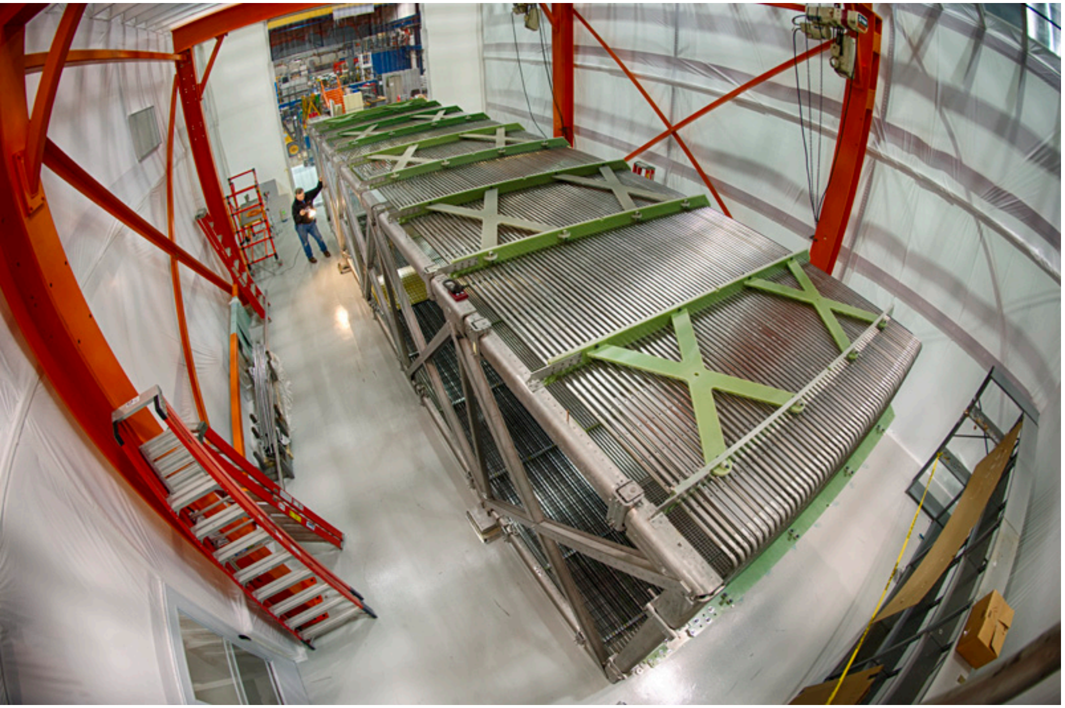
Proudly Operated by **Battelle** *Since 1965*

- The First large liquid argon time projection chamber (LArTPC) in the US
  - 89 tonnes LAr
  - One TPC: 2.3mx2.5mx10.4m
    - 8192 wires
      - 3 planes
      - 3mm separation of wires, 3mm between planes
    - 32 PMTs + 4 scintillator bars + PMTs
  - Sits in Fermilab's Booster Neutrino Beam
  - Short baseline: 470m from beam target/horn

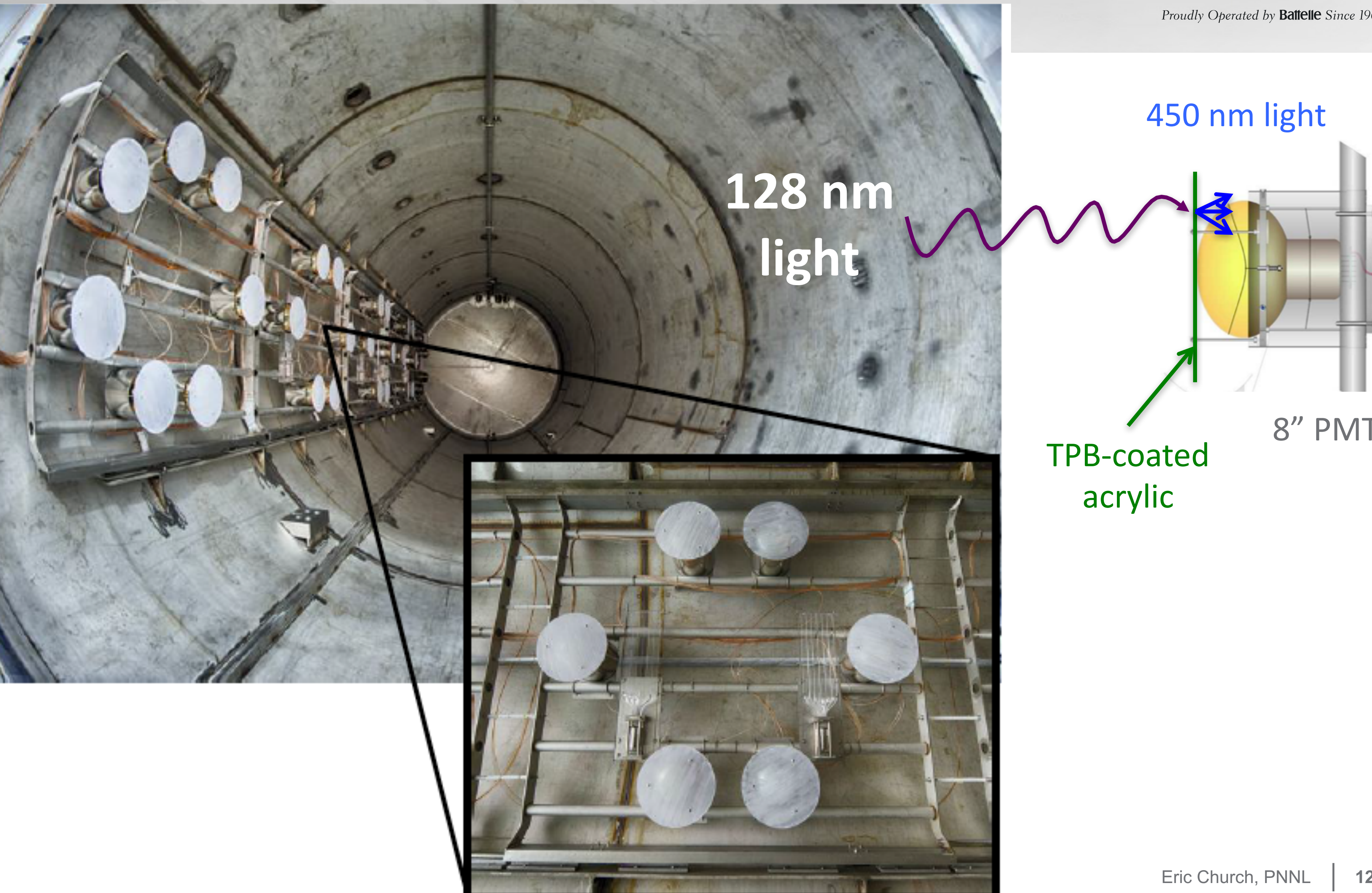
MicroBooNE In assembly hall

µBooNE

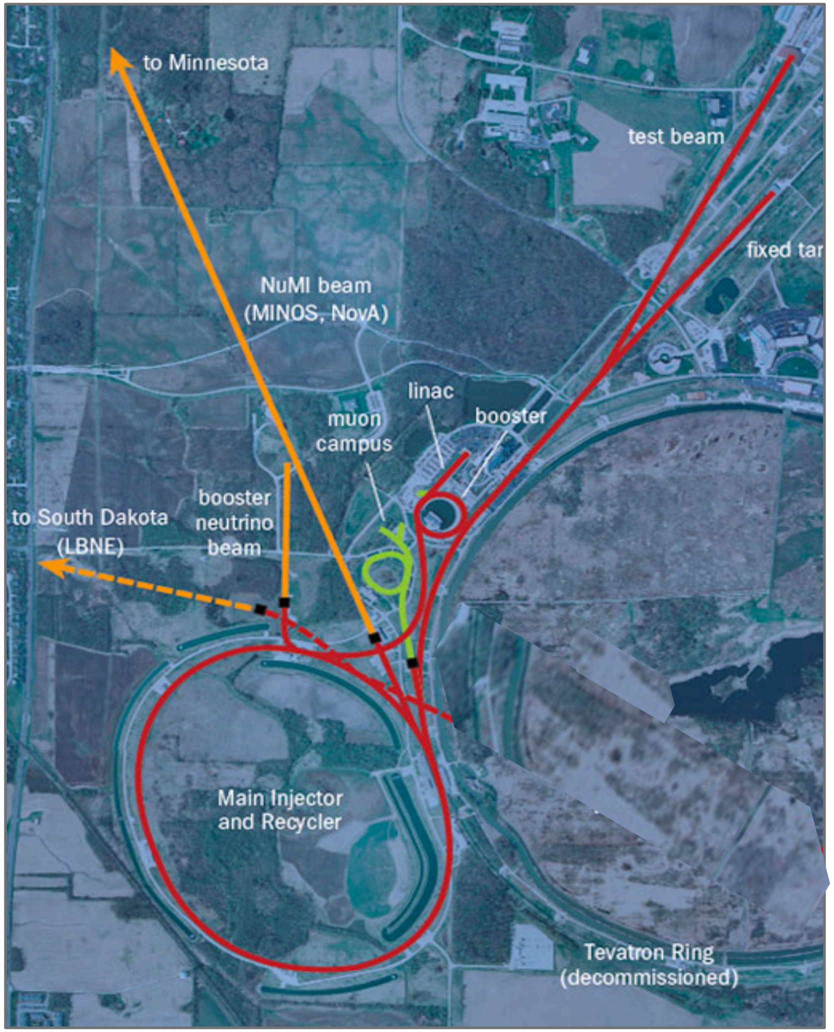
Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*

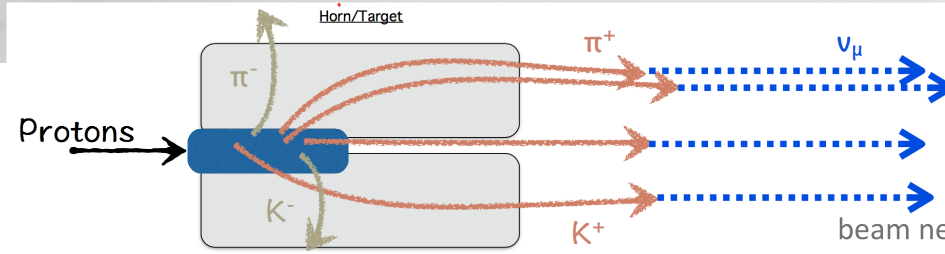


MicroBooNE Photon Detection

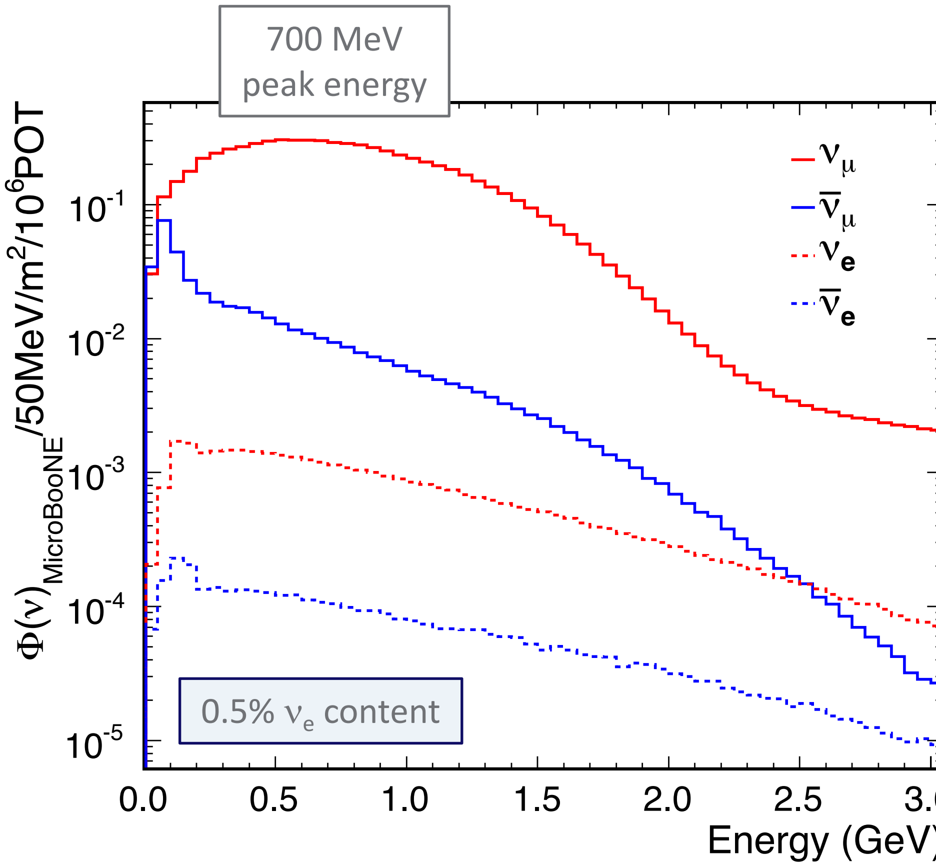


The Booster Neutrino Beam





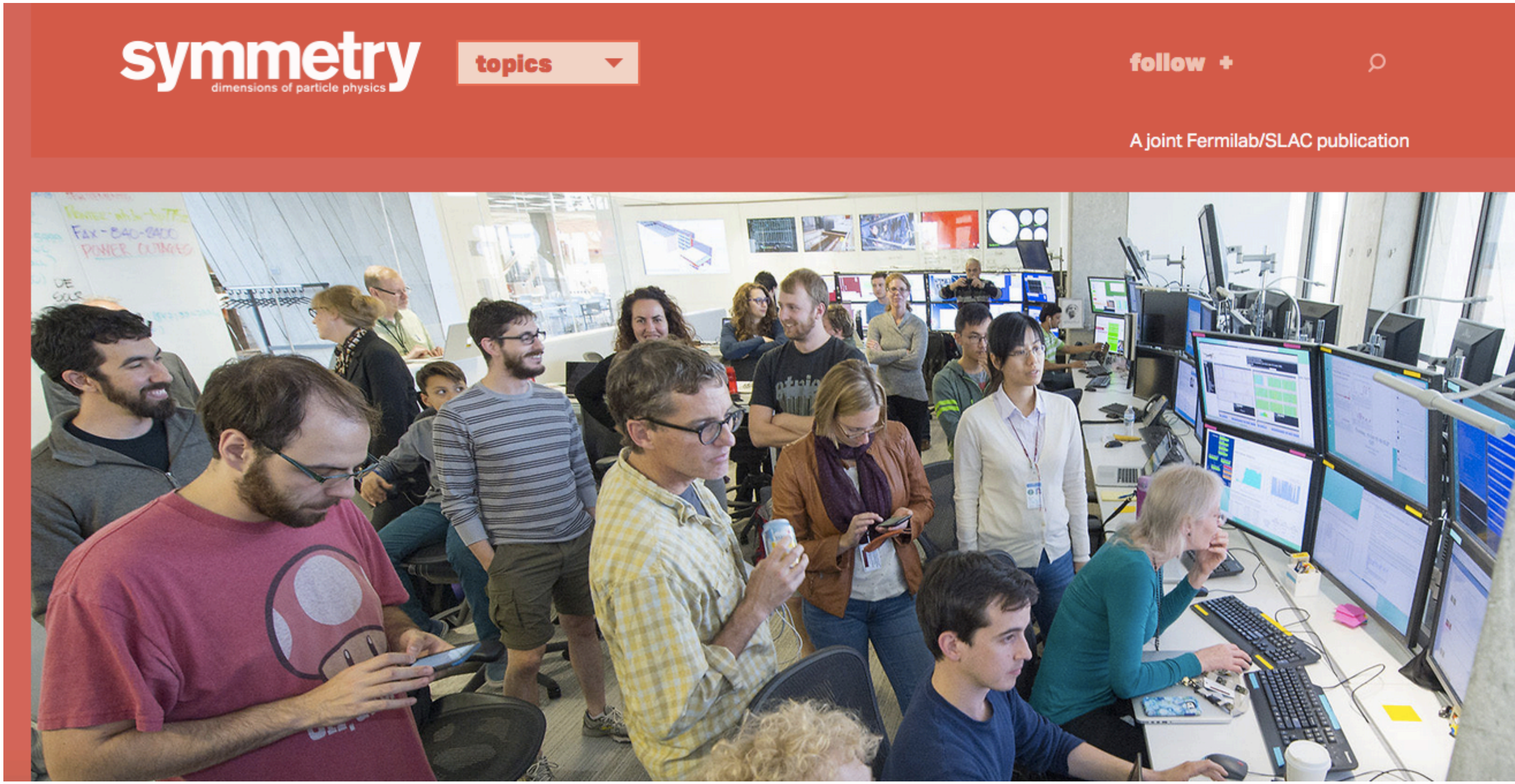
beam near the surface, parallel



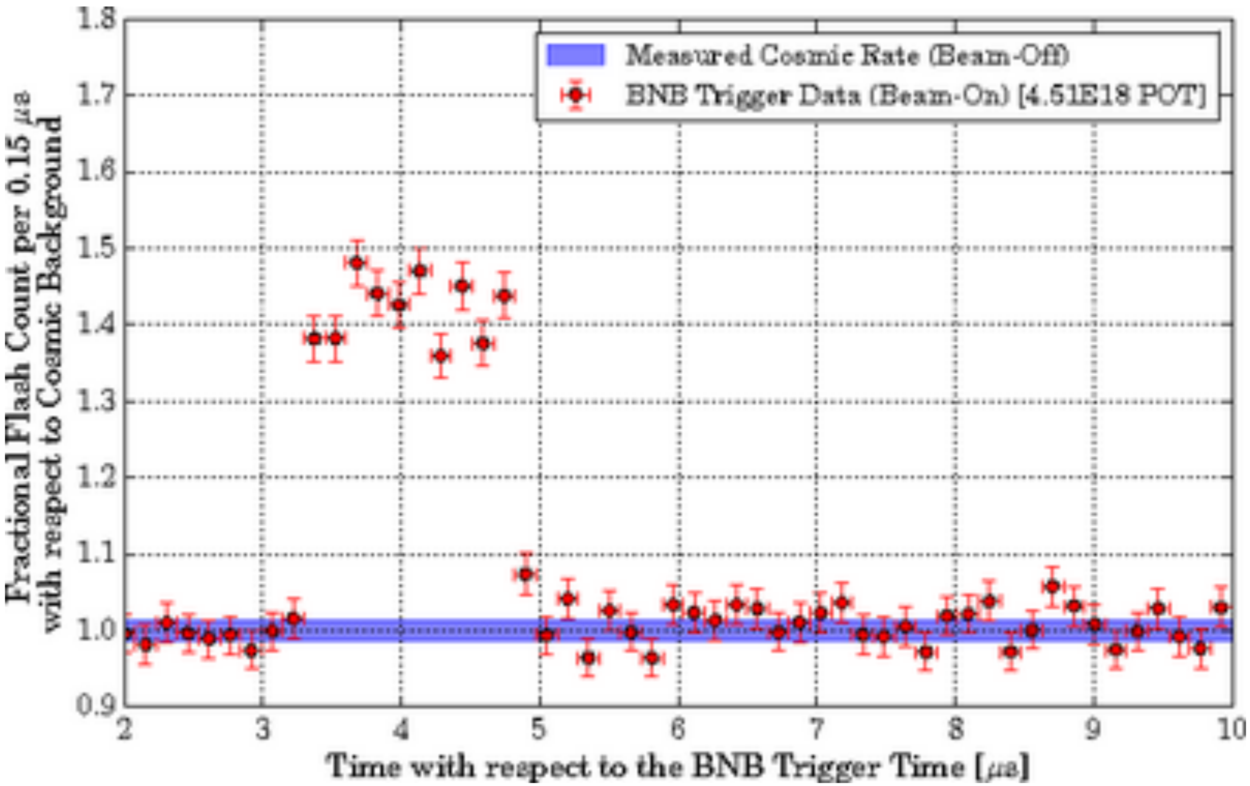
October 15, 2015: First MicroBooNE neutrinos

µBooNE

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*



Arrival time – neutrinos!



This excess in the 1.6 musec BNB beam spill window can only be due to neutrinos.

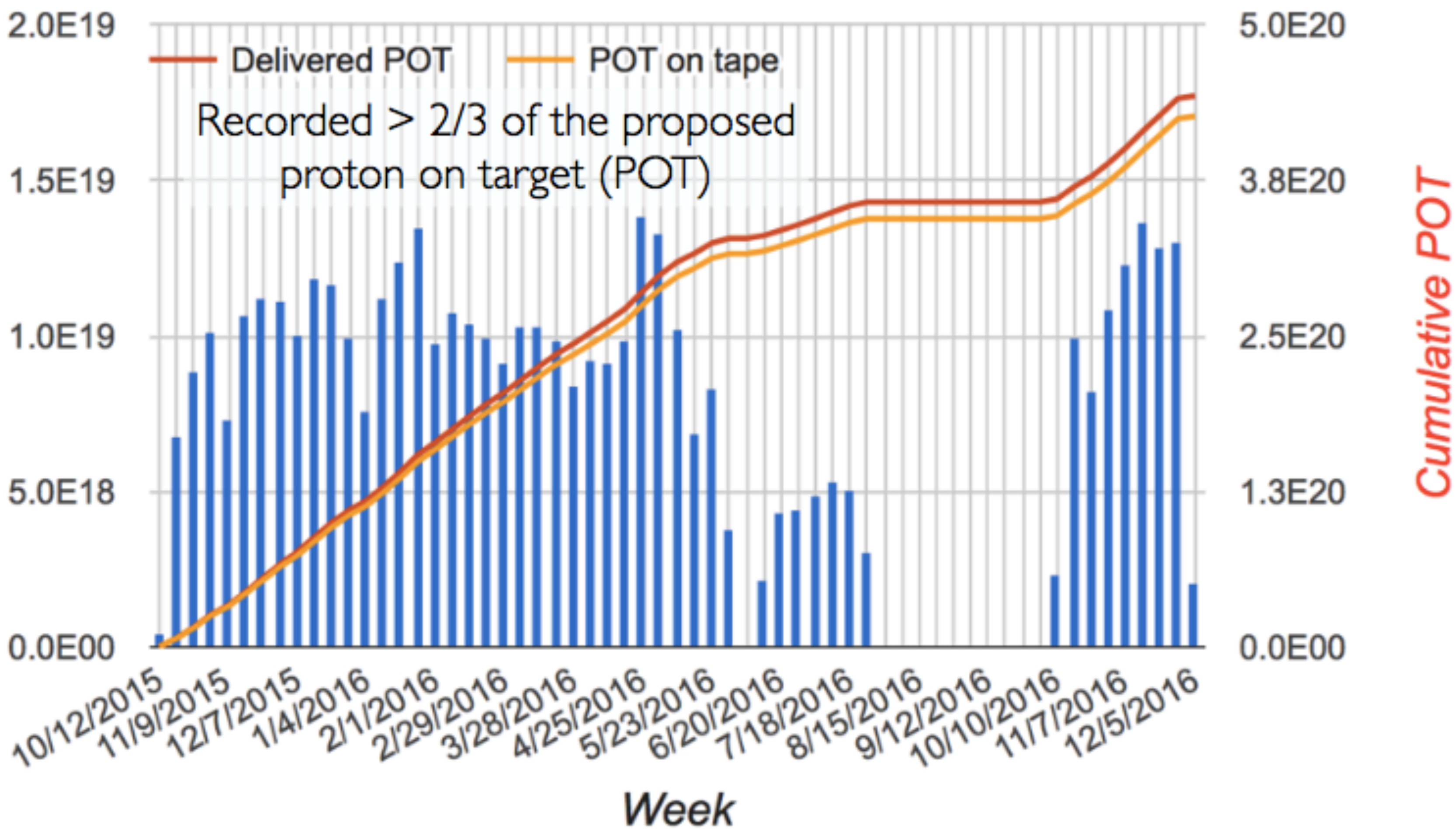
First Neutrino Events!

more images here: http://www-microboone.fnal.gov/first-neutrinos/index.html

Events selected by automatic reconstruction! -- a big deal

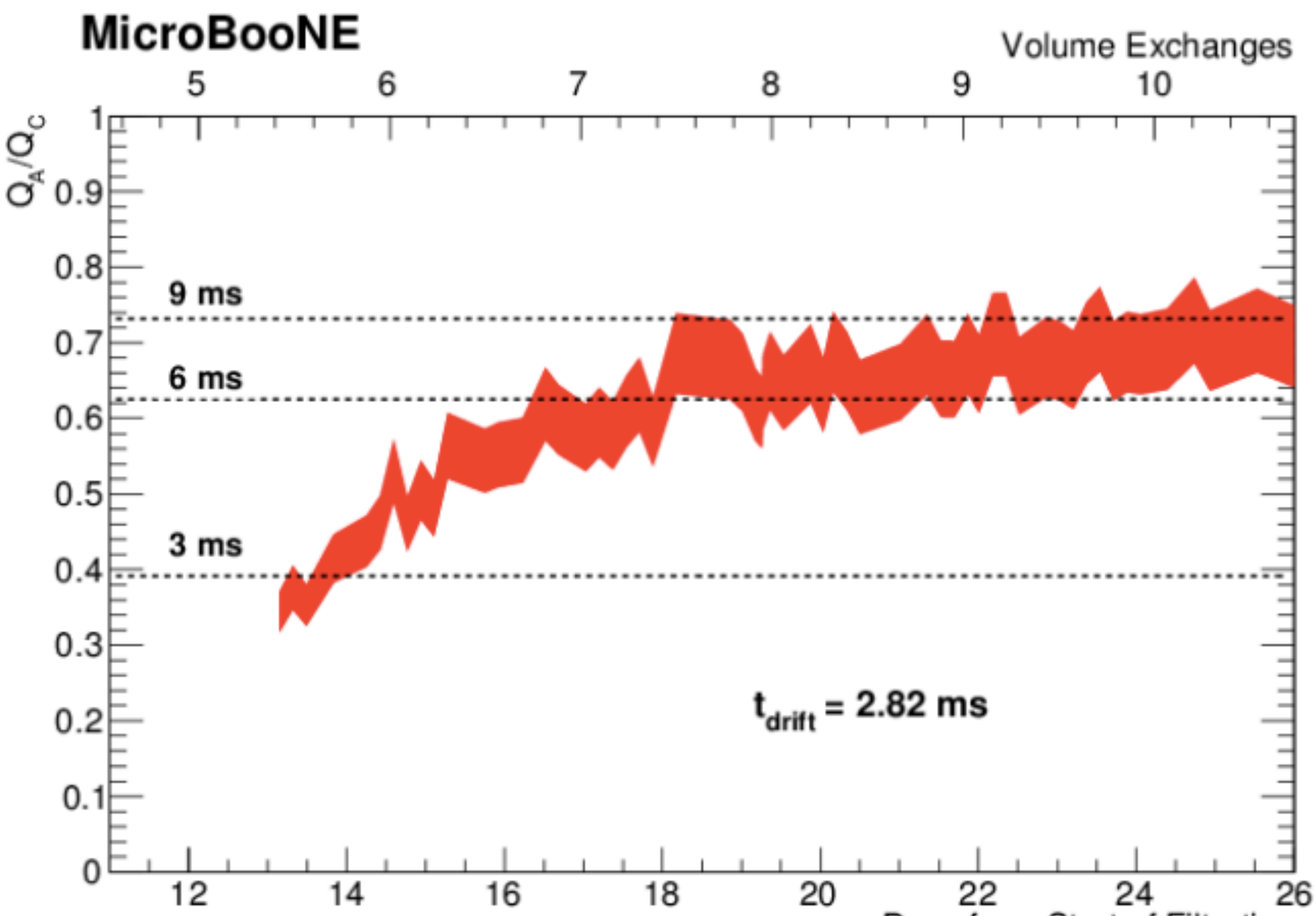
Performance

POT Already have 2/3 of the 6E20 scheduled. Over 97% Uptime!



Electron Lifetime

http://www-microboone.fnal.gov/publications/publicnotes/MICROBOONE-NOTE-1003-PUB.pdf



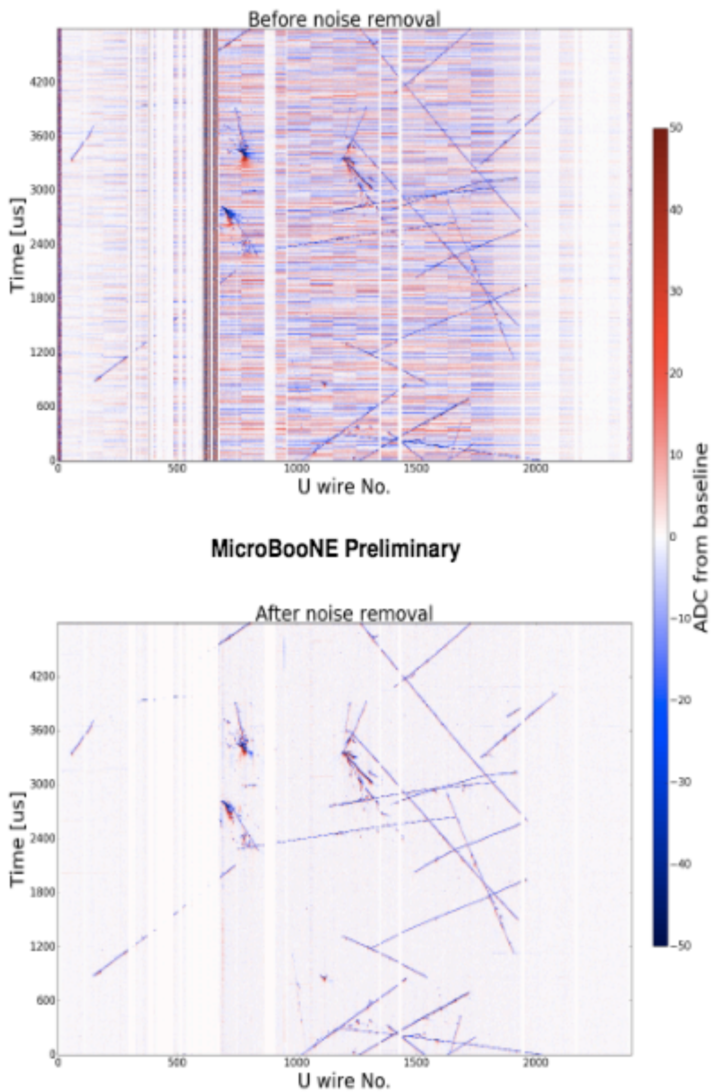
Noise removal from raw signals

μBooNE

Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle *Since 1965*

http://www-microboone.fnal.gov/publications/publicnotes/MICROBOONE-NOTE-1016-PUB.pdf



"U" plane shown for one event.

TABLE 3. Summary of the observed TPC noise in MicroBooNE. The estimated contribution to the total ENC for the longest wires in each plane is presented in the 4th column.

Noise	Frequency range	Plane Impacted [a]	ENC in e- (Plane)	Possible Source
Burst	~ 900 kHz	U , V, Y	negligible [b] at 2 μs shaping time	Field pick-up on wires (?)
Single frequency	~ 36 kHz	U , V	920 (U), 380 (V), 0 (Y)	HV Supply
Single frequency	~ 108 kHz	U	750 (U), 0 (V), 0 (Y)	HV Supply
ASIC saturation	< 20 Hz	U, V, Y	unknown [c]	Wire motion (?)
Regulator	< 50 kHz	U, V, Y	1030 (U), 1300 (V), 550 (Y)	LV regulators
Cold ASIC			430(U), 420 (V), 330 (Y)	Design spec
Total			1600 (U), 1400 (V), 660 (Y)	

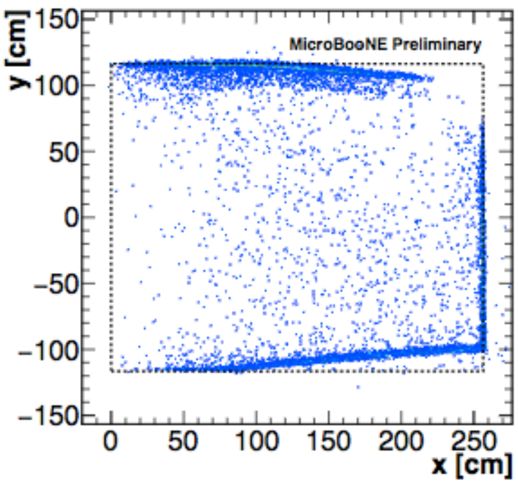
[a] Bad channels identified in Sec. 2.5 are excluded from noise studies.
[b] As described in Sec. 2.2, this noise is largely suppressed after choosing 2μs shaping time. The bursts of this noise are intermittent (non-stationary) with amplitude varying in time
[c] It is hard to quantify ENC associated with ASIC saturation without studying effect of microphonics in details which is beyond the scope of this document.

Spacecharge: distortion of track end points

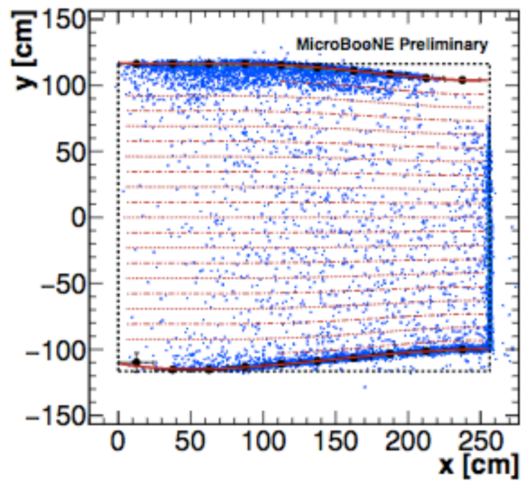
μBooNE

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*

http://www-microboone.fnal.gov/publications/publicnotes/MICROBOONE-NOTE-1018-PUB.pdf

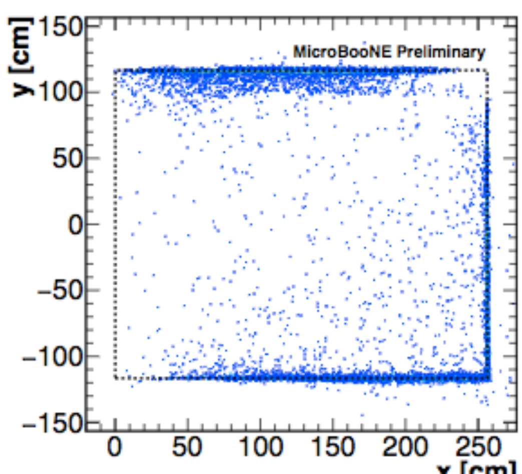


(a) Before SCE correction



(b) Fit of the data points

Corrected:



Distortion of drift field due to an accumulation of positive ions at the cathode from continuous exposure to cosmics.

Stopped cosmic muons: measured Michel spectrum

http://www-microboone.fnal.gov/publications/publicnotes/MICROBOONE-NOTE-1008-PUB.pdf

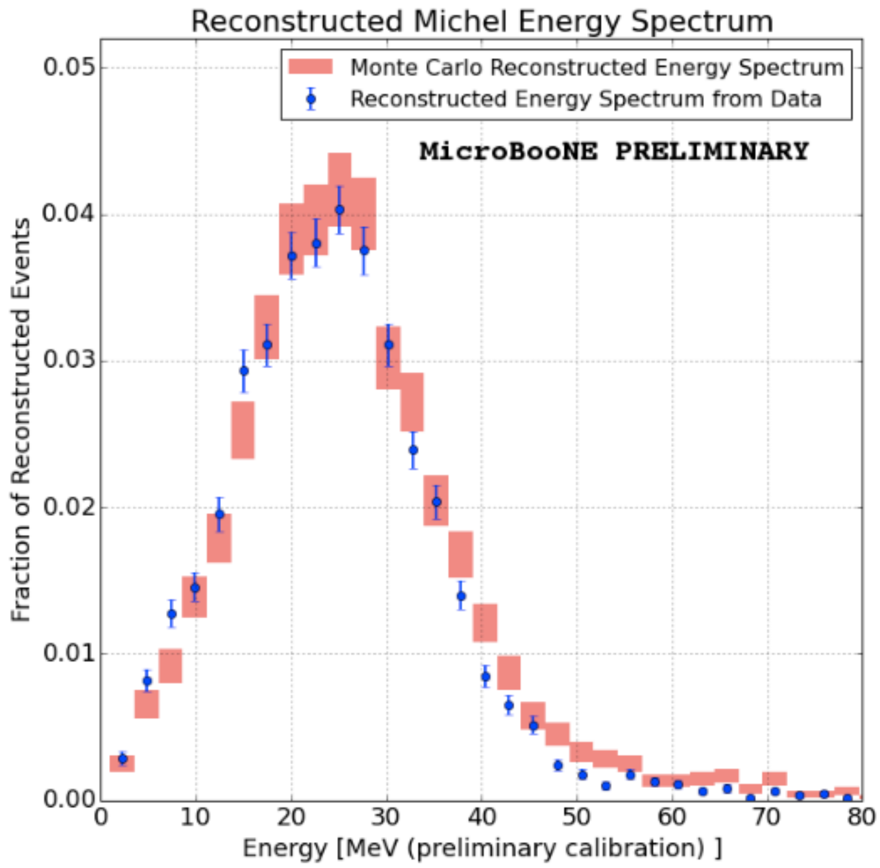


Figure 13: Reconstructed Energy spectrum from cosmic data (blue data points) overlayed on the energy spectrum reconstructed from Monte Carlo (red bands) following the same procedure as for the data. Each curve is area normalized to one. Error bars represent statistical uncertainties only.

Two papers in JINST imminently

Design and Construction of the MicroBooNE Detector

MicroBooNE Collaboration: R. Acciarri, C. Adams, R. An, A. Aparicio, S. Aponte, J. Asaadi, M. Auger, N. Ayoub, L. Bagby, B. Baller, R. Barger, G. Barr, M. Bass, F. Bay, K. Biery, M. Bishai, A. Blake, V. Bocean, D. Boehnlein, V. D. Bogert, T. Bolton, L. Bugel, C. Callahan, L. Camilleri, D. Caratelli, B. Carls, R. Castillo Fernandez, F. Cavanna, S. Chappa, H. Chen, K. Chen, C.Y. Chi, C. S. Chiu, E. Church, D. Cianci, G. H. Collin, J. M. Conrad, M. Convery, J. Cornele, P. Cowan, J. I. Crespo-Anadon, G. Crutcher, C. Darve, R. Davis, M. Del Tutto, D. Devitt, S. Duffin, S. Dytman, B. Eberly, A. Ereditato, D. Erickson, L. Escudero Sanchez, J. Esquivel, S. Farooq, J. Farrell, D. Featherston, B. T. Fleming, W. Foreman, A. P. Furmanski, V. Genty, M. Geynisman, D. Goeldi, B. Goff, S. Gollapinni, N. Graf, et al. (174 additional authors not shown)

(Submitted on 17 Dec 2016 (v1), last revised 17 Jan 2017 (this version, v2))

Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber

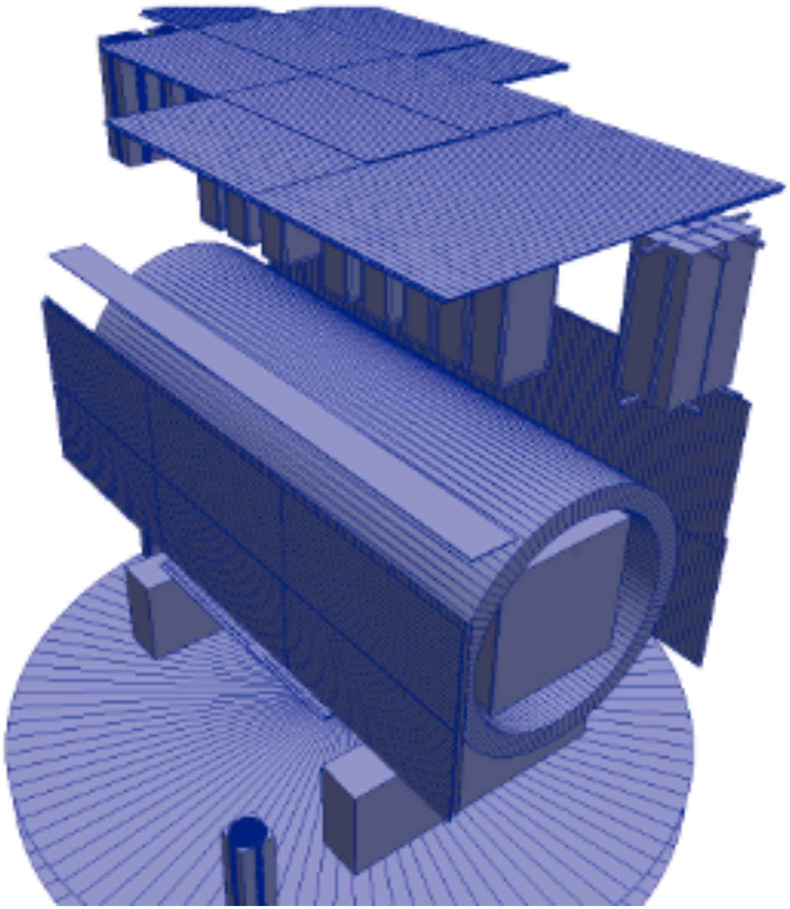
MicroBooNE collaboration: R. Acciarri, C. Adams, R. An, J. Asaadi, M. Auger, L. Bagby, B. Baller, G. Barr, M. Bass, F. Bay, M. Bishai, A. Blake, T. Bolton, L. Bugel, L. Camilleri, D. Caratelli, B. Carls, R. Castillo Fernandez, F. Cavanna, H. Chen, E. Church, D. Cianci, G. H. Collin, J. M. Conrad, M. Convery, J. I. Crespo-Anadón, M. Del Tutto, D. Devitt, S. Dytman, B. Eberly, A. Ereditato, L. Escudero Sanchez, J. Esquivel, B. T. Fleming, W. Foreman, A. P. Furmanski, G. T. Garvey, V. Genty, D. Goeldi, S. Gollapinni, N. Graf, E. Gramellini, H. Greenlee, R. Grosso, R. Guenette, A. Hackenburg, P. Hamilton, O. Hen, J. Hewes, C. Hill, J. Ho, G. Horton-Smith, C. James, J. Jan de Vries, C.-M. Jen, L. Jiang, R. A. Johnson, B. J. P. Jones, J. Joshi, H. Jostlein, D. Kaleko, G. Karagiorgi, W. Ketchum, et al. (75 additional authors not shown)

(Submitted on 17 Nov 2016)

Deep Learning is a particularly active area at PNNL

Coming: Cosmic Ray Tagger commissioning in next half-year

The CRT will greatly reduce MicroBooNE's most pernicious background: beam unrelated cosmics



Actual detector hall CRT wall

Conclusions

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*

μBooNE

- LArTPCs offer unparalleled event fidelity as well as calorimetry and particle ID
- They will be used in the SBN program to go after the would-be sterile neutrino
  - MicroBooNE running now
    - Detector understood
    - Producing physics results
      - www-microboone.fnal.gov/publications/publicnotes
- MicroBooNE is a key DUNE technology demonstrator
  - 40+ kTon LArTPC will be used in the large, international LBN program at DUNE to investigate CP violation and neutrino mass hierarchy, …. Nucleon decay, supernovae neutrinos, atmospheric neutrinos, ….
- Certainly much more to come from MicroBooNE: cross-sections and the flagship neutrino oscillation results. Stay tuned

7 cm

COSMIC DATA : RUN 455 EVENT 18489. January 9, 2016, 9:21

Backup

Past LArTPCs

- Icarus at LNGS, Italy!
  - **NOT** U.S.!, but we owe a large debt to this program
  - 600 tonnes, proved the LArTPC technology

- ArgoNeuT at FNAL in the NuMI beam
  - 0.2 tonne
  - A program of cross-section measurements

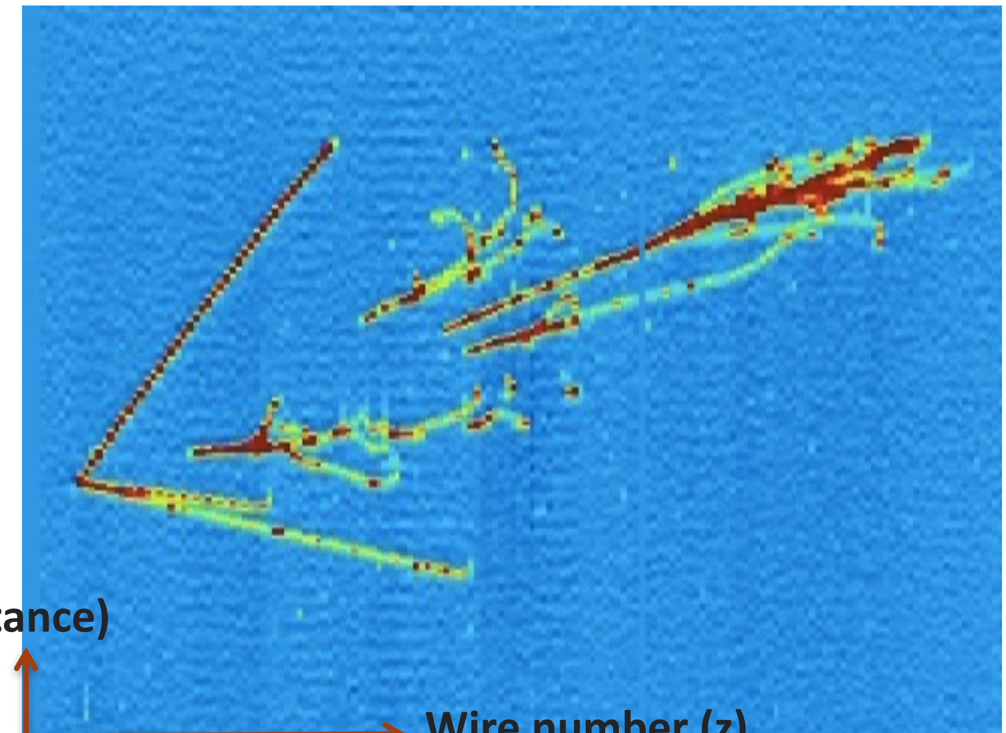
- Other small demonstrators at FNAL (not in a ν beam)
  - LUKE at Yale
  - TallBo
  - Liquid Ar Purity Demonstrator

US-Based LArTPCs: early proof of principle

Unparalleled fidelity: image resolution and calorimetry.

ArgoNeuT (Collection Plane)

~40cmx40cm



Likely:
$\nu_\mu \to \mu p \pi^0 \pi^0$

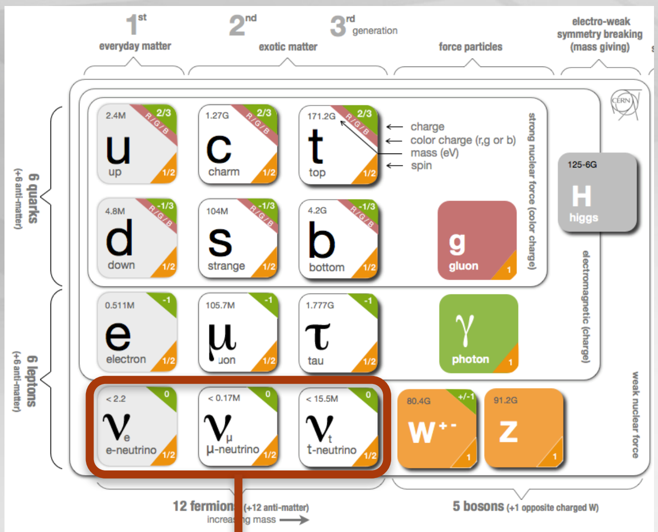
The red indicates higher energy deposition, as from a proton, or an EM shower.

Future

- The Short Baseline Program at FNAL, 2018-2021
  - MicroBooNE
  - SBND
  - Icarus!
    - What?! That is so 2008.
    - Yes, it's being transported to FNAL next year and resuscitated!

- The Long Baseline Program at FNAL and Sanford (South Dakota) 2023-?
  - The FNAL Near Detector
    - Likely, the province of the Indian government
    - May not in fact be a LArTPC
  - And Far Detector, DUNE, at Sanford lab in SD
    - US-INFN-UK, others combo
  - ~$1.3 billion USD

Neutrino Masses and Mixing



$$|\nu_\alpha\rangle \rightarrow |\nu(L)\rangle = \sum_i U^*_{\alpha i} e^{-i(m_i^2/2E)L}$$

Weak flavor α at production point

After traveling a distance L, some probability to be a different flavor β

Neutrino Mixing Matrix

Flavor states participating in standard weak interactions

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino mass states of mass m_i

PMNS matrix

Neutrino Masses and Mixing

Parameterize in a form analogous to the CKM matrix for quarks and factorize:

3 mixing angles and 1 CP-violating phase

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric, accel, DUNE — Reactor, accelerator, DUNE — solar

2-neutrino mixing:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\,\Delta m_{ij}^2 \frac{L}{E}\right)$$

θ = *mixing angle*

$\Delta m_{ij}^2 \equiv m_j^2 - m_i^2$

L = neutrino path length

E = neutrino energy

A Really Beautiful Experimental History

Mass Found in Elusive Particle; Universe May Never Be the Same

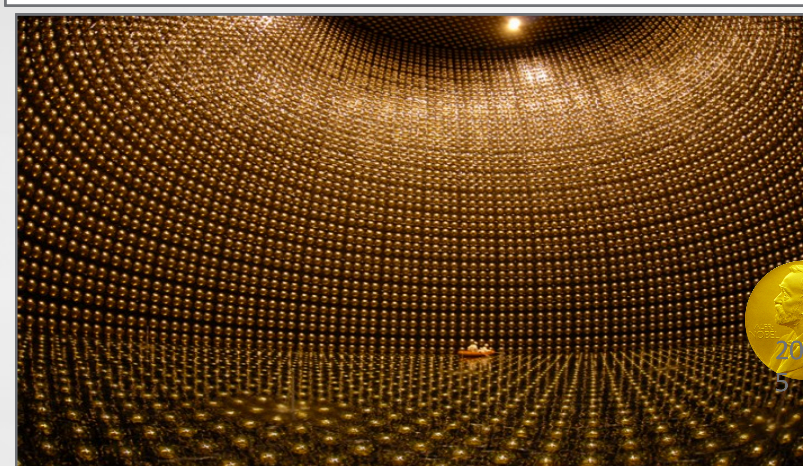
By MALCOLM W. BROWNE
Published: June 5, 1998

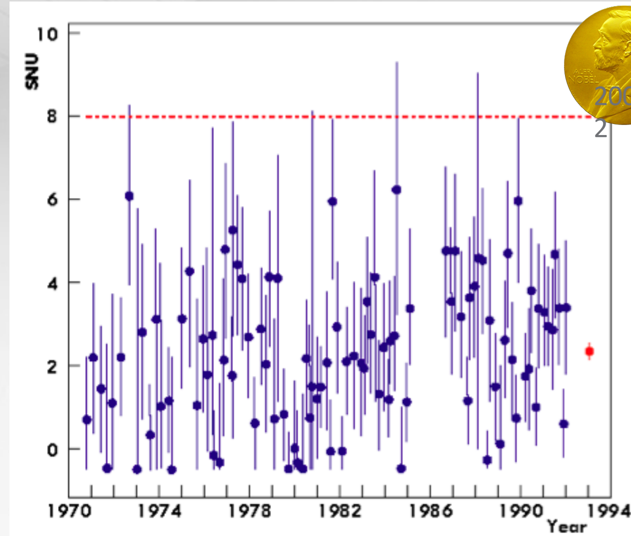
Atmospheric neutrinos at Super-Kamiokande

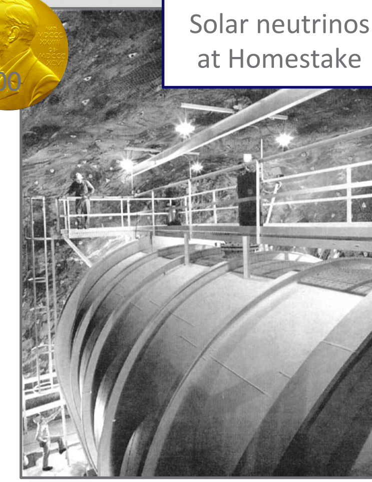
TAKAYAMA, Japan, Friday, June 5— In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that a significant part of the mass of the universe might be in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter, the Standard Model.

NY Times link

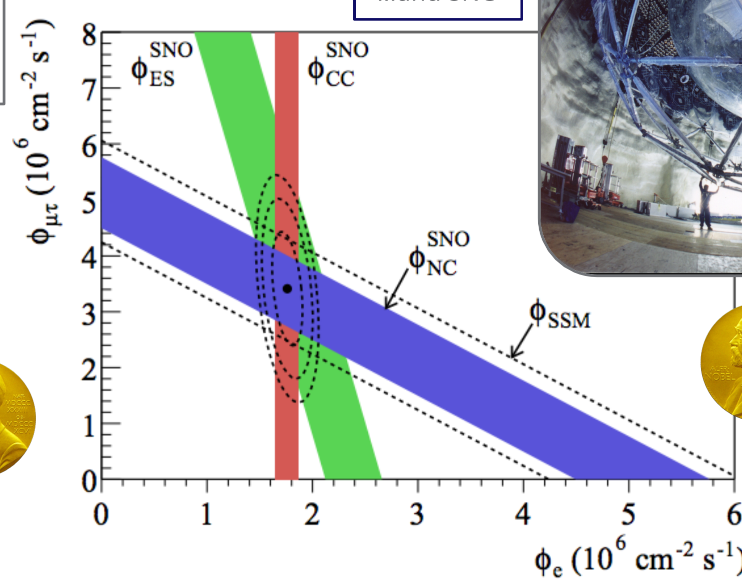


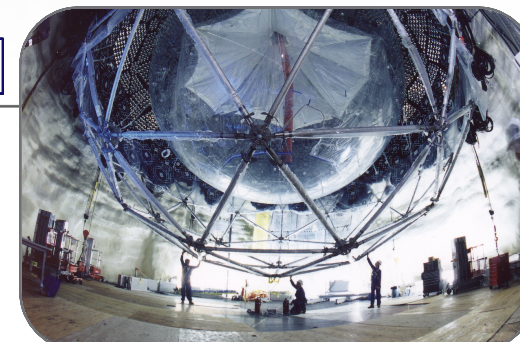




Solar neutrinos at Homestake

...and SNO

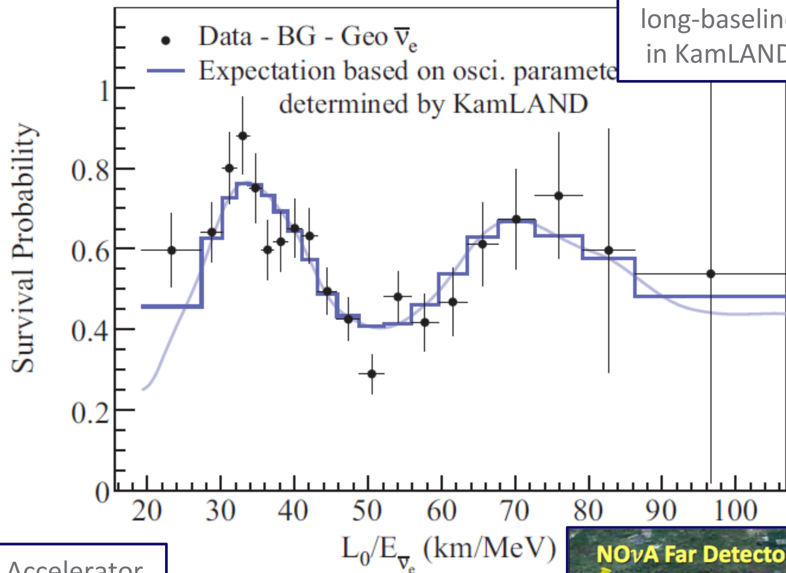


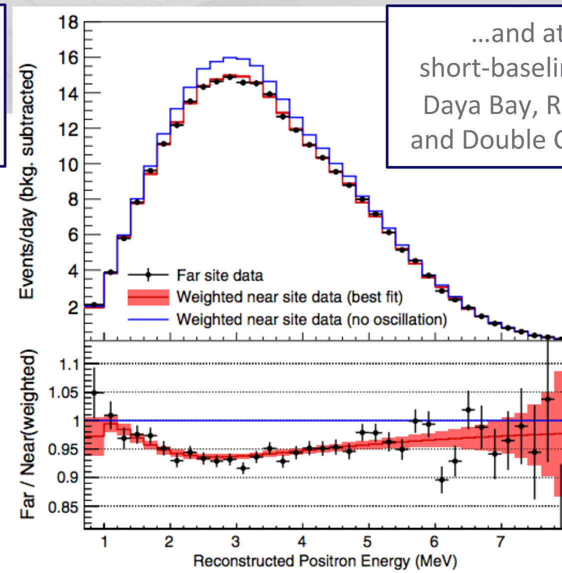


A Really Beautiful Experimental History

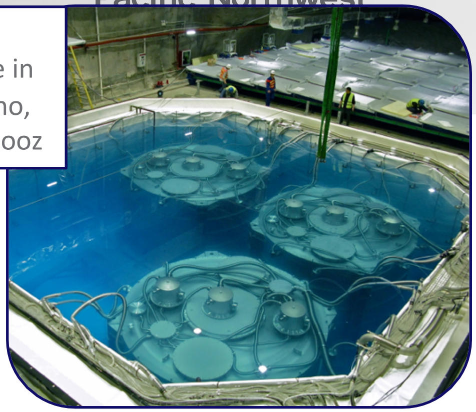
Pacific Northwest

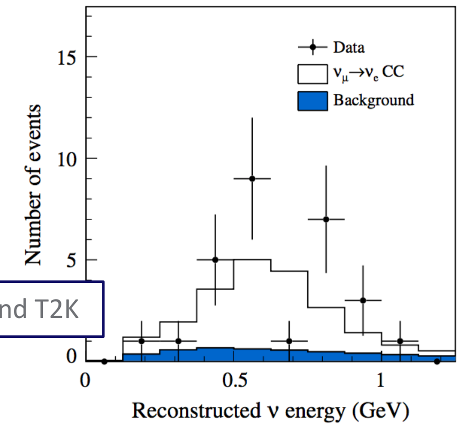
Reactor neutrinos at long-baseline in KamLAND





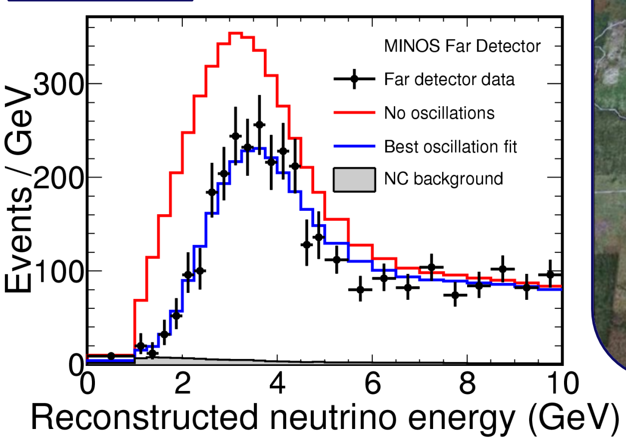
...and at short-baseline in Daya Bay, Reno, and Double Chooz

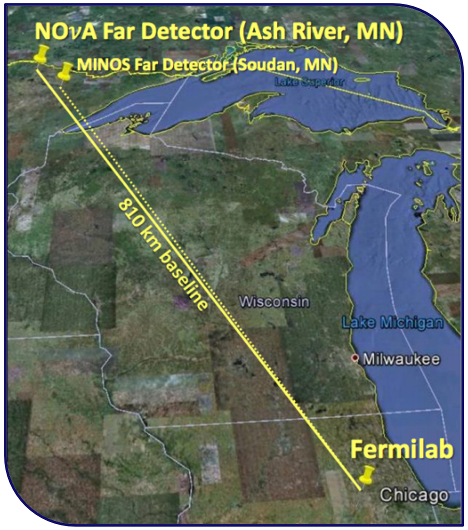




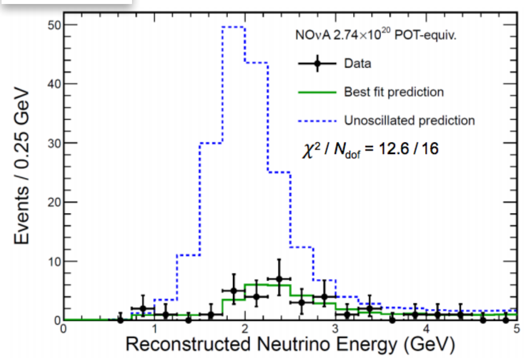
...and T2K

Accelerator neutrinos at MINOS





...and now at NOvA



$\nu_\mu \to \nu_e$ appearance!

The Three-Detector SBN Program

Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton