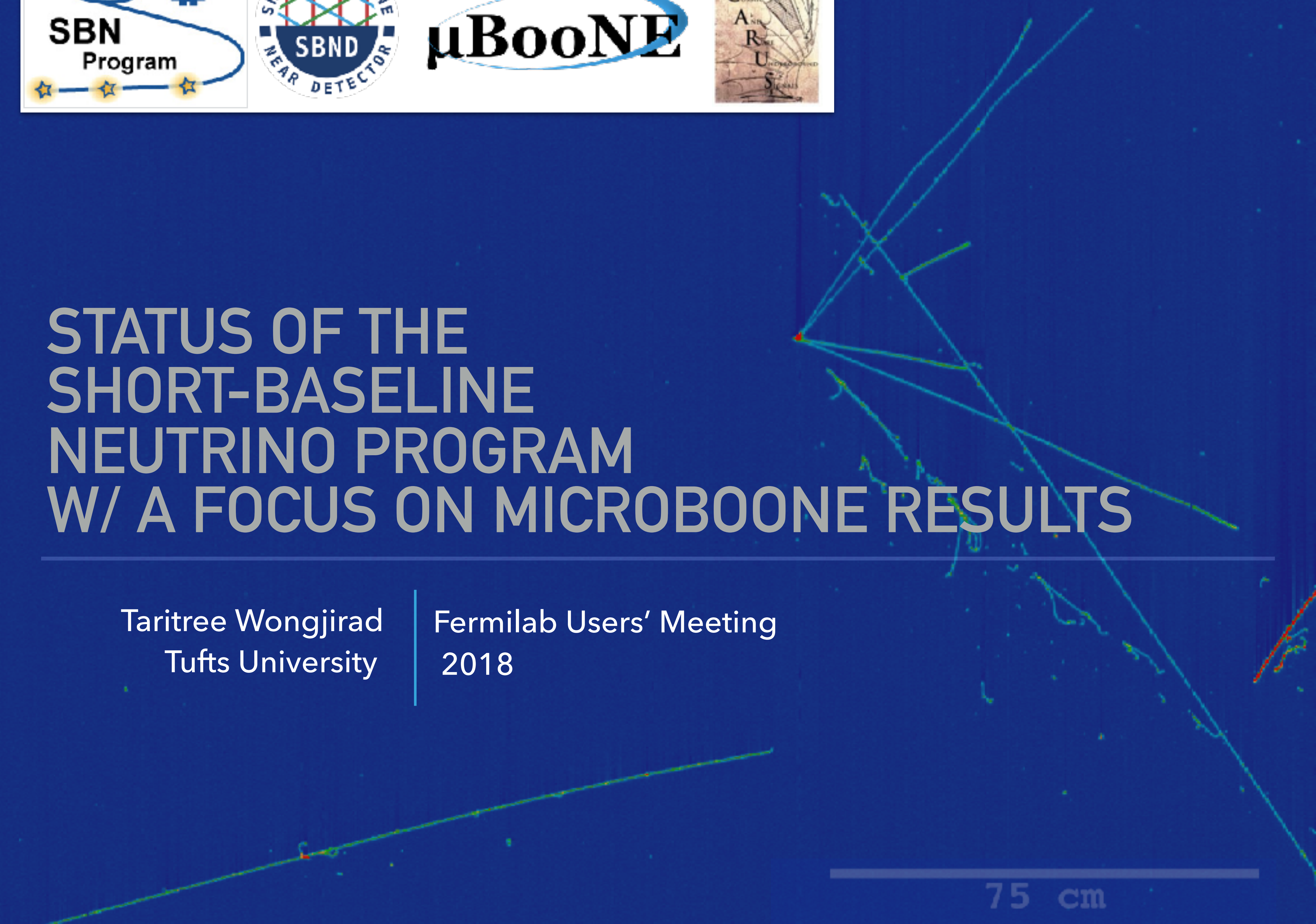
Run 3493 Event 41075, Oct. 23rd, 2015



STATUS OF THE SHORT-BASELINE NEUTRINO PROGRAM W/ A FOCUS ON MICROBOONE RESULTS

Taritree Wongjirad
Tufts University

Fermilab Users' Meeting
2018

Exciting time to be working on SBN

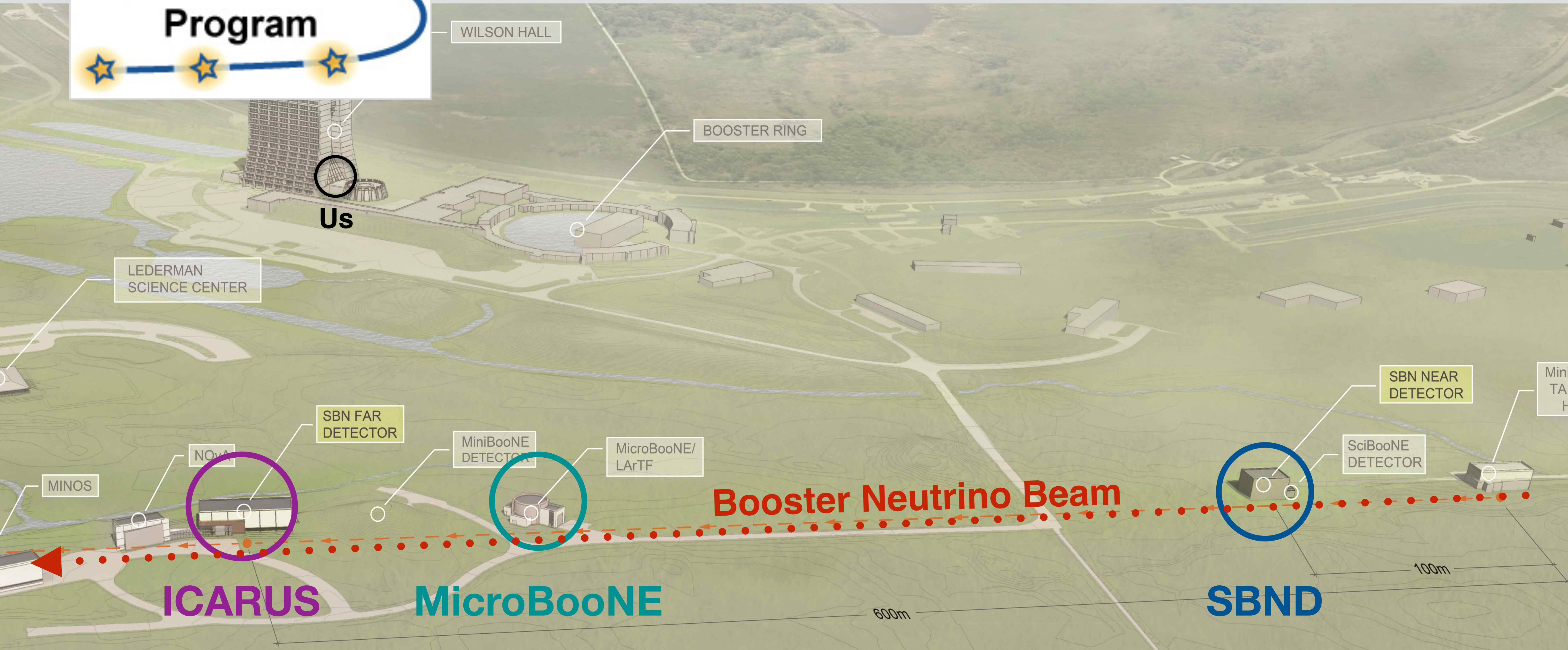
After Neutrino 18, the goals of Short Baseline Neutrino (SBN) program continue to be very relevant to the field

- Investigation of the sterile neutrino anomaly
  - New results from ν_e-appearance and $\bar{\nu}_e$-disappearance do not yet exclude the global best fit
  - Strong tension remains between channels, especially with ν_μ-disappearance
- Help further understanding of argon-nucleus cross sections
- R&D in hardware, reconstruction, calibration, data analysis techniques for LArTPCs relevant for future LArTPC experiments like DUNE

Outline

- Brief overview of the Short Baseline Neutrino program
- Status of ICARUS/SBND
- Focus will be on recent results from MicroBooNE, the first detector to be taking data

Three LArTPCs in the BNB



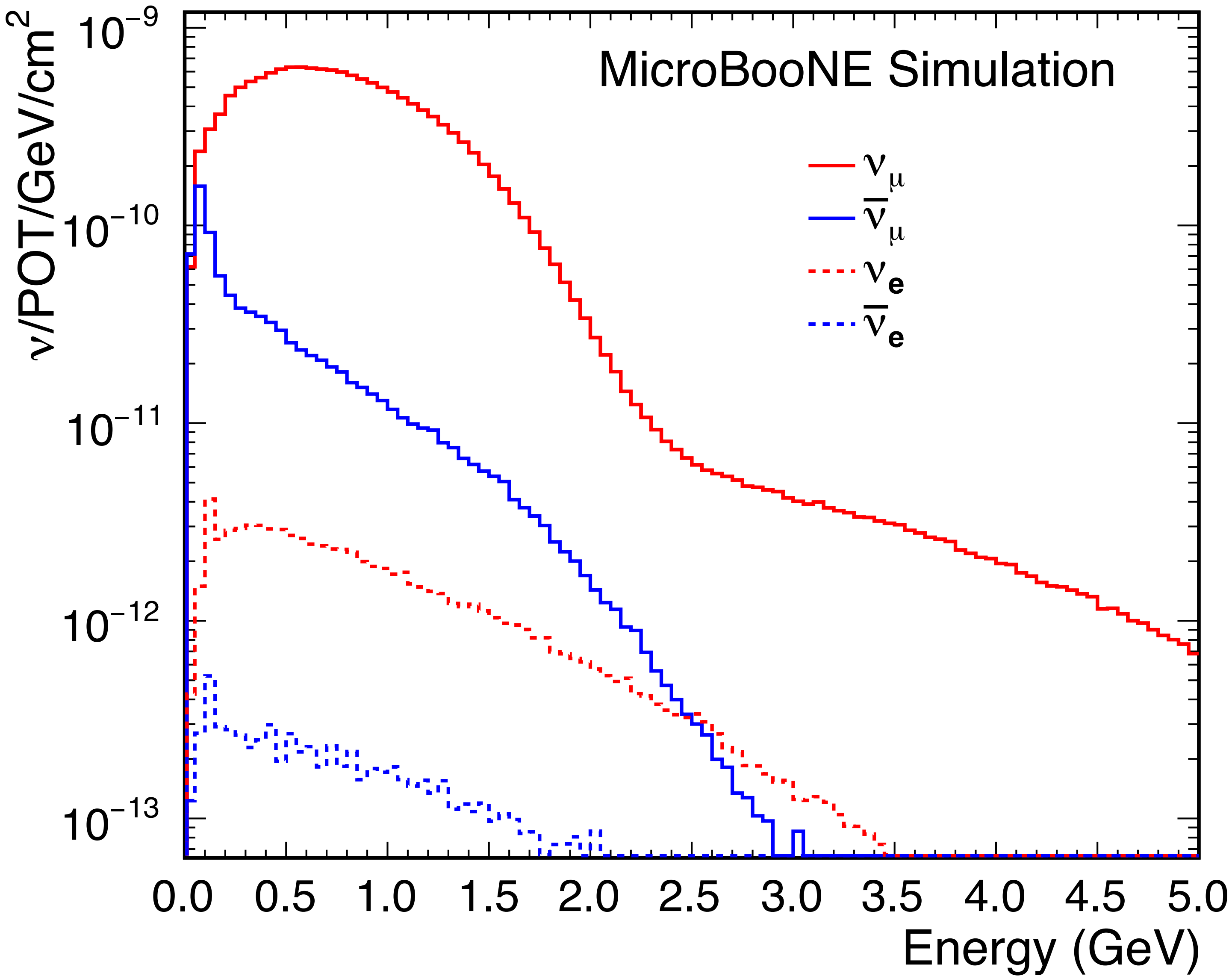
ICARUS
L = 600 m
M = 476 ton

μBooNE
L = 470 m
M = 85 ton

SBND
L = 110 m
M = 112 ton

The Booster Neutrino Beam (BNB) Flux

absolute flux through MicroBooNE active volume TPC



- BNB flux has a lower energy relative to NuMI
- Average 800 MeV
- Intrinsic ν_e about 0.5%

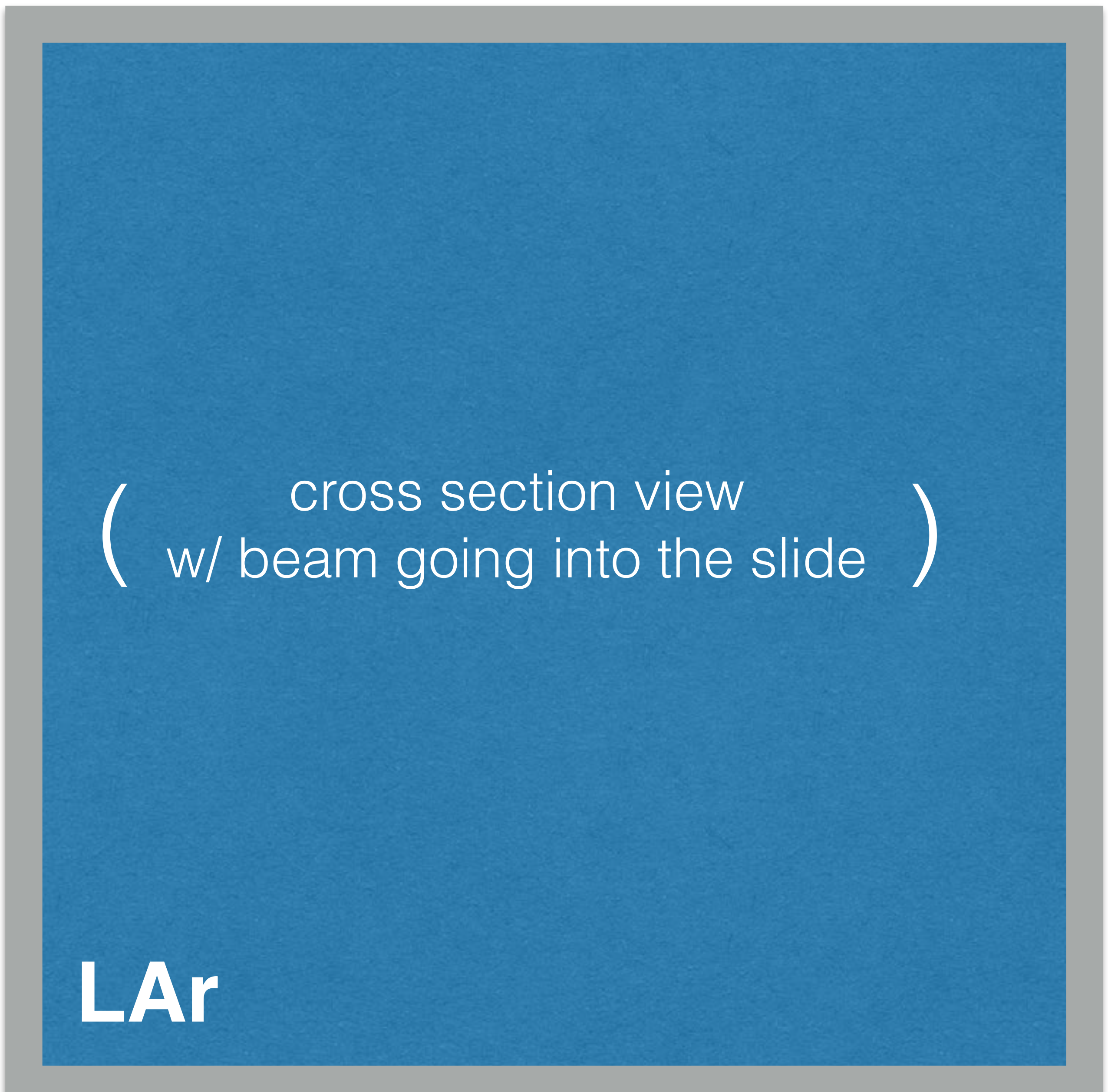
from Public Note: MicroBooNE-1031-PUB

LArTPCs

How to build and operate a liquid argon time-projection chamber

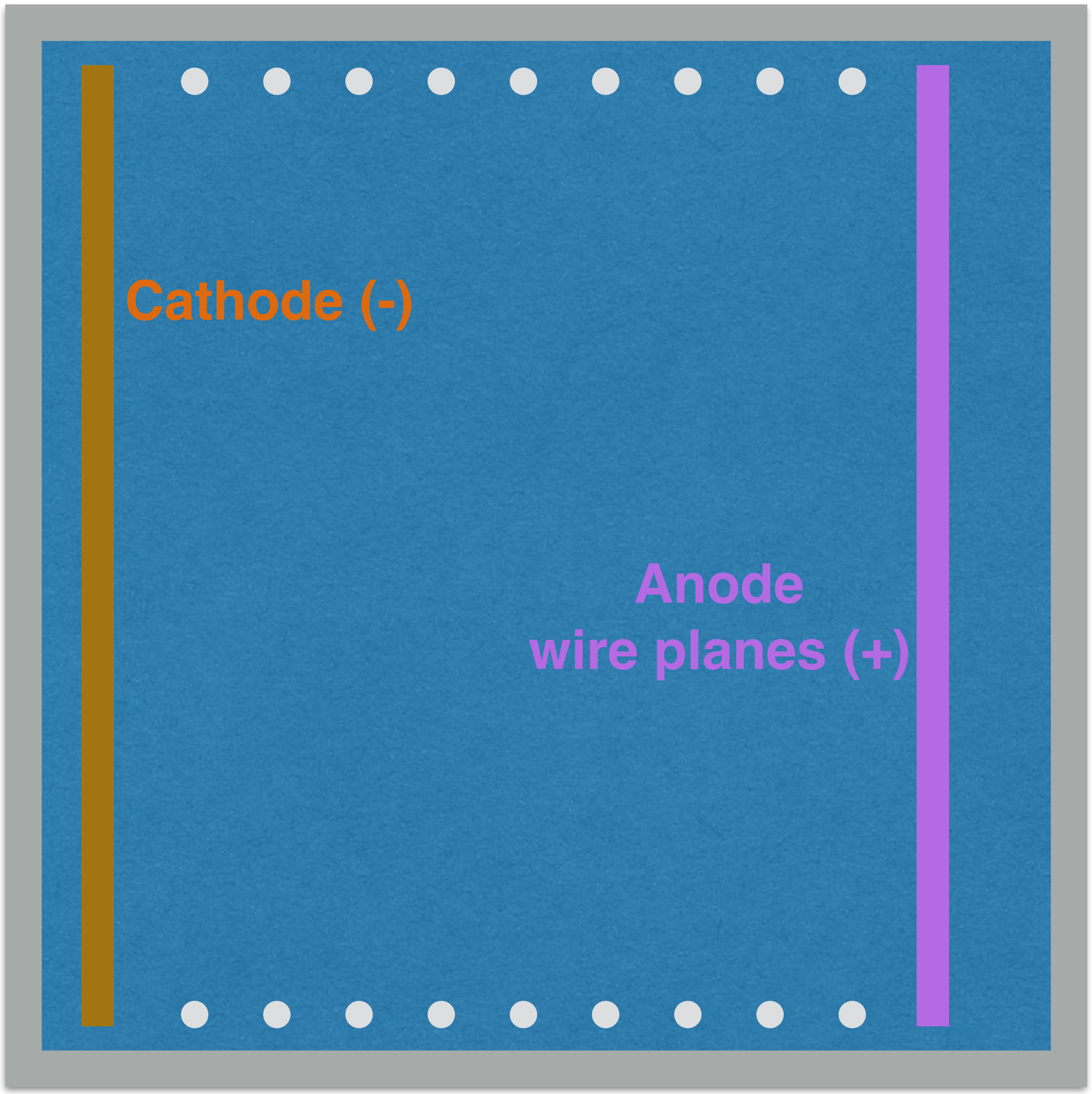
LArTPC Operation

Start with cryostat filled w/ LAr

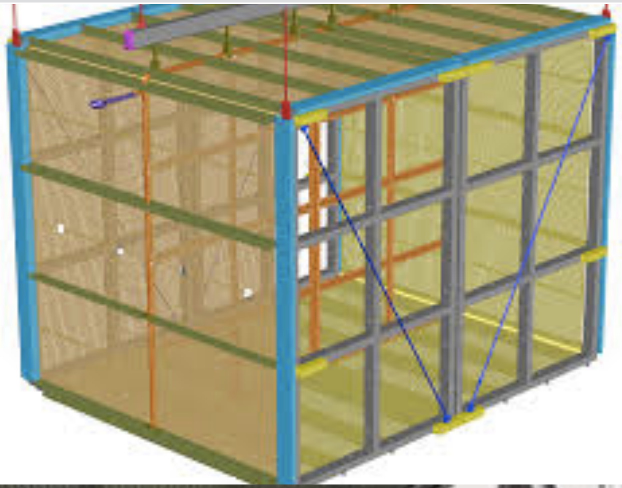


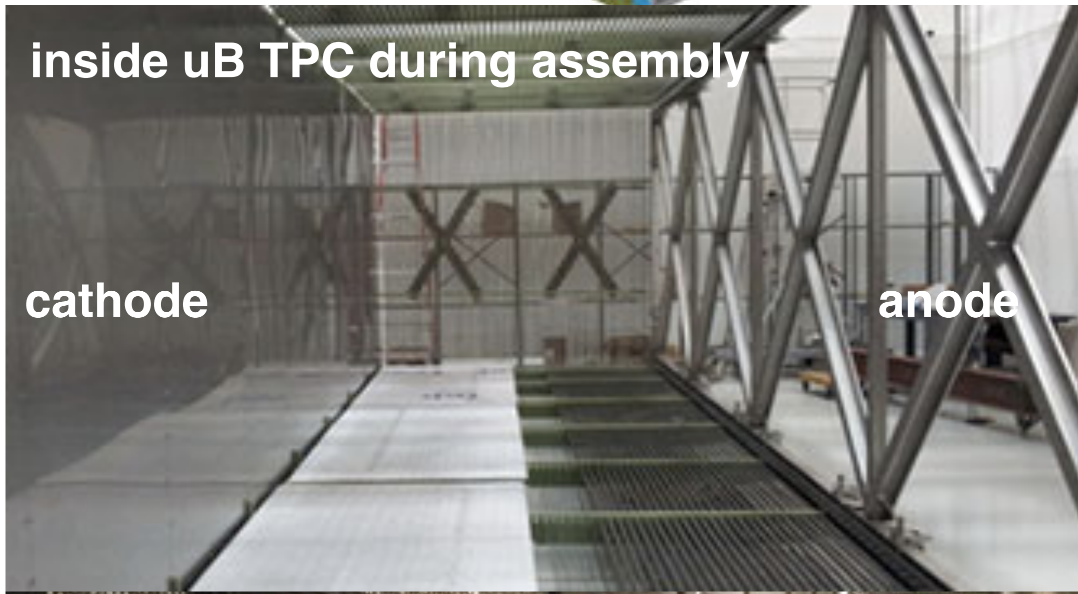
LArTPC Operation

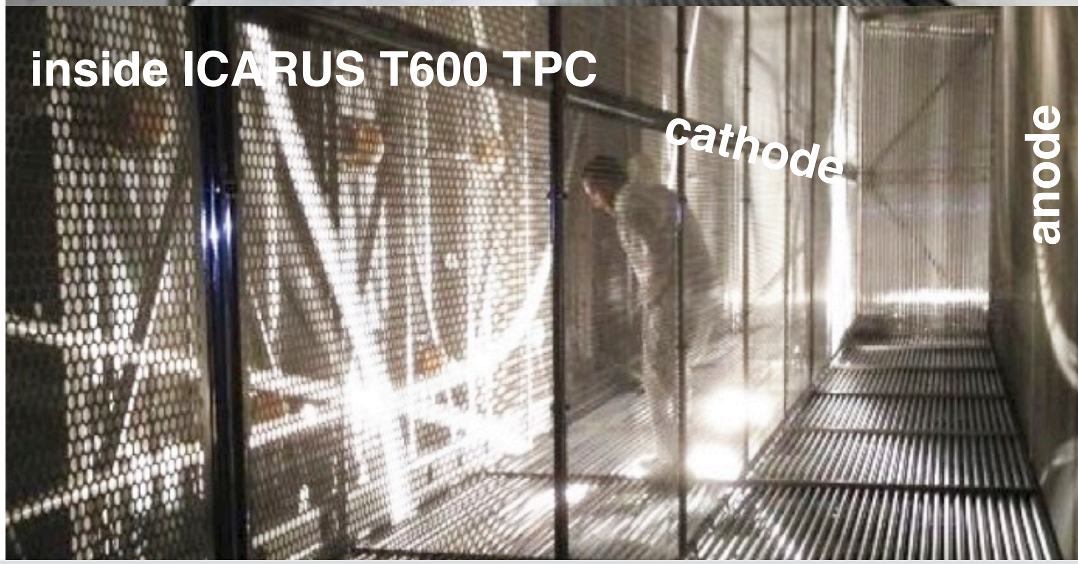
Insert a TPC



SBND using the DUNE TPC design

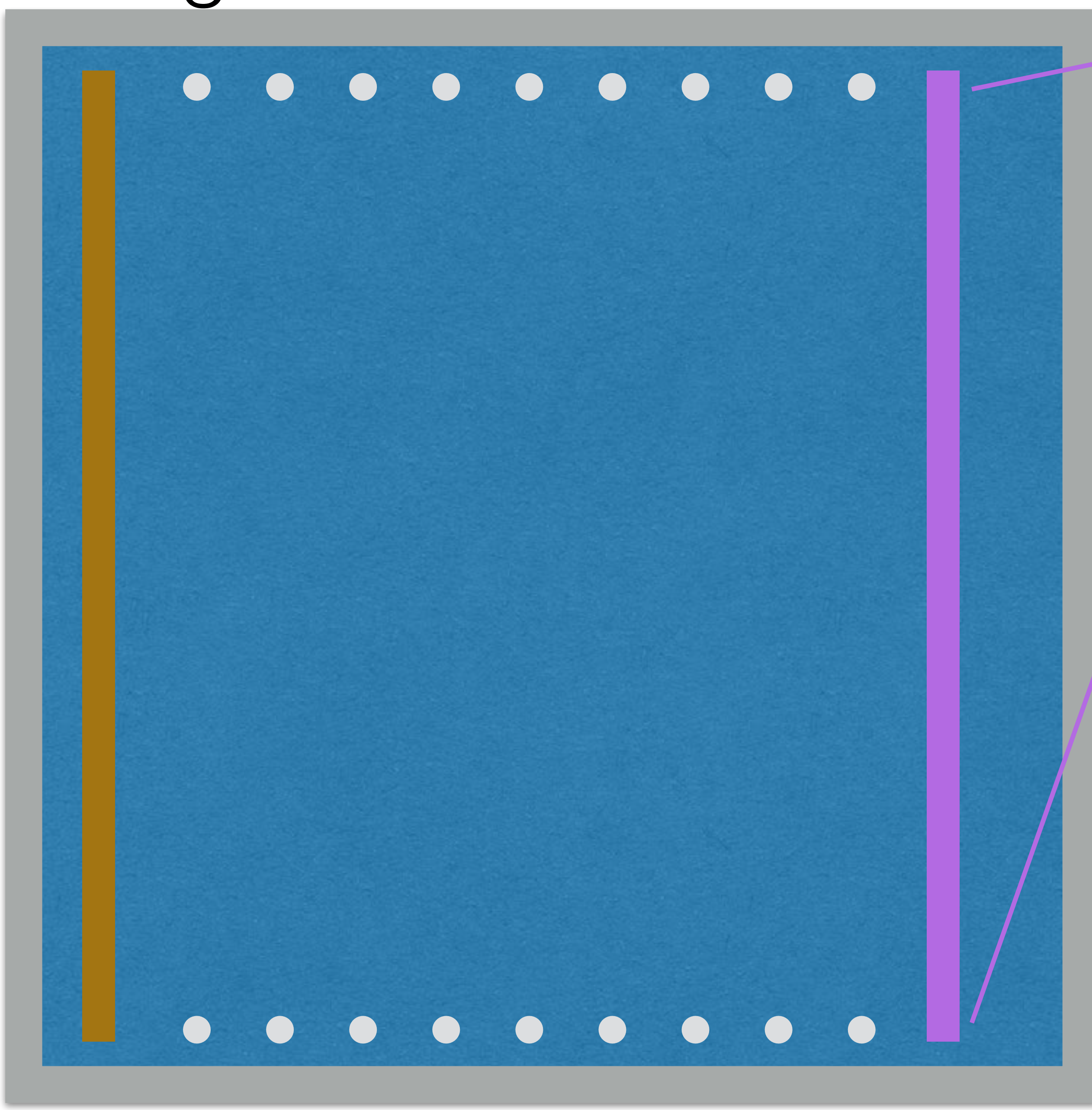






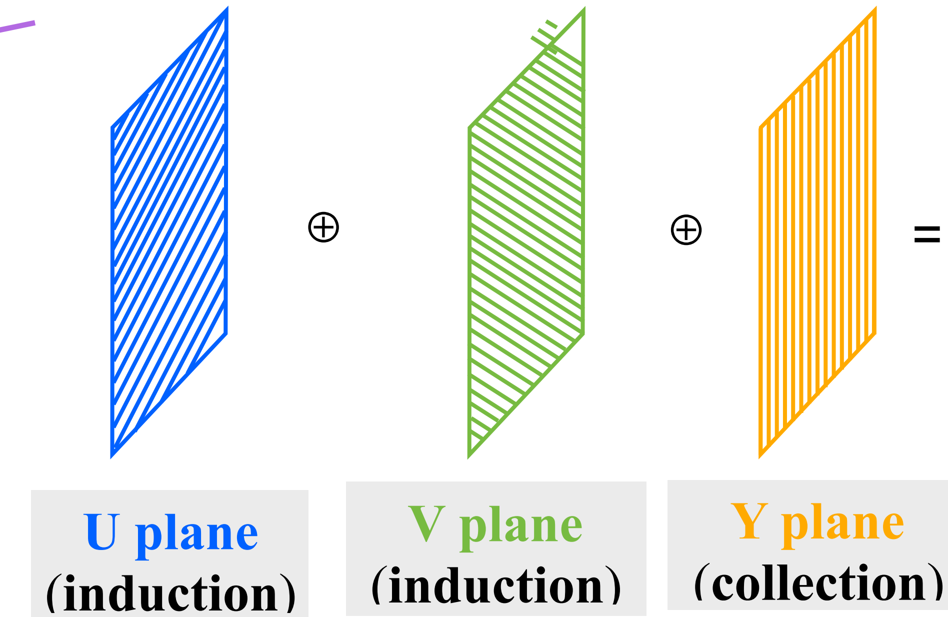
LArTPC Operation

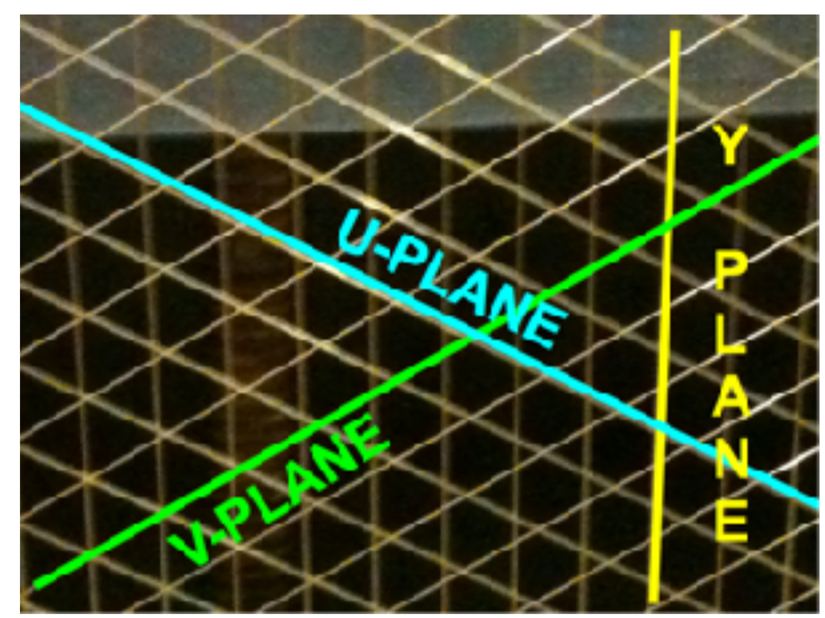
Anode consists of several charge-sensitive sense-wires



Three Wire Planes

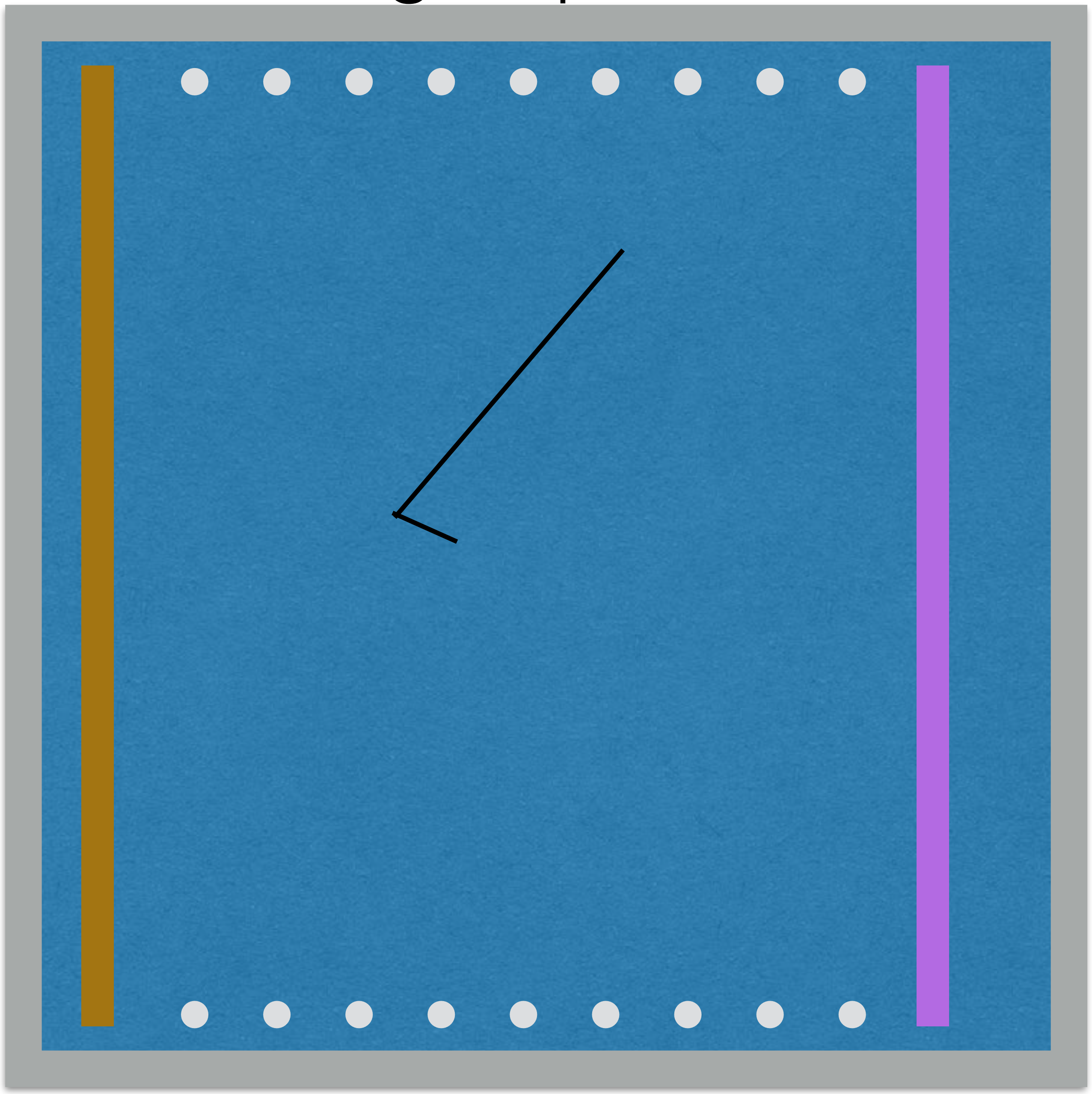
(using MicroBooNE as example)





LArTPC Operation

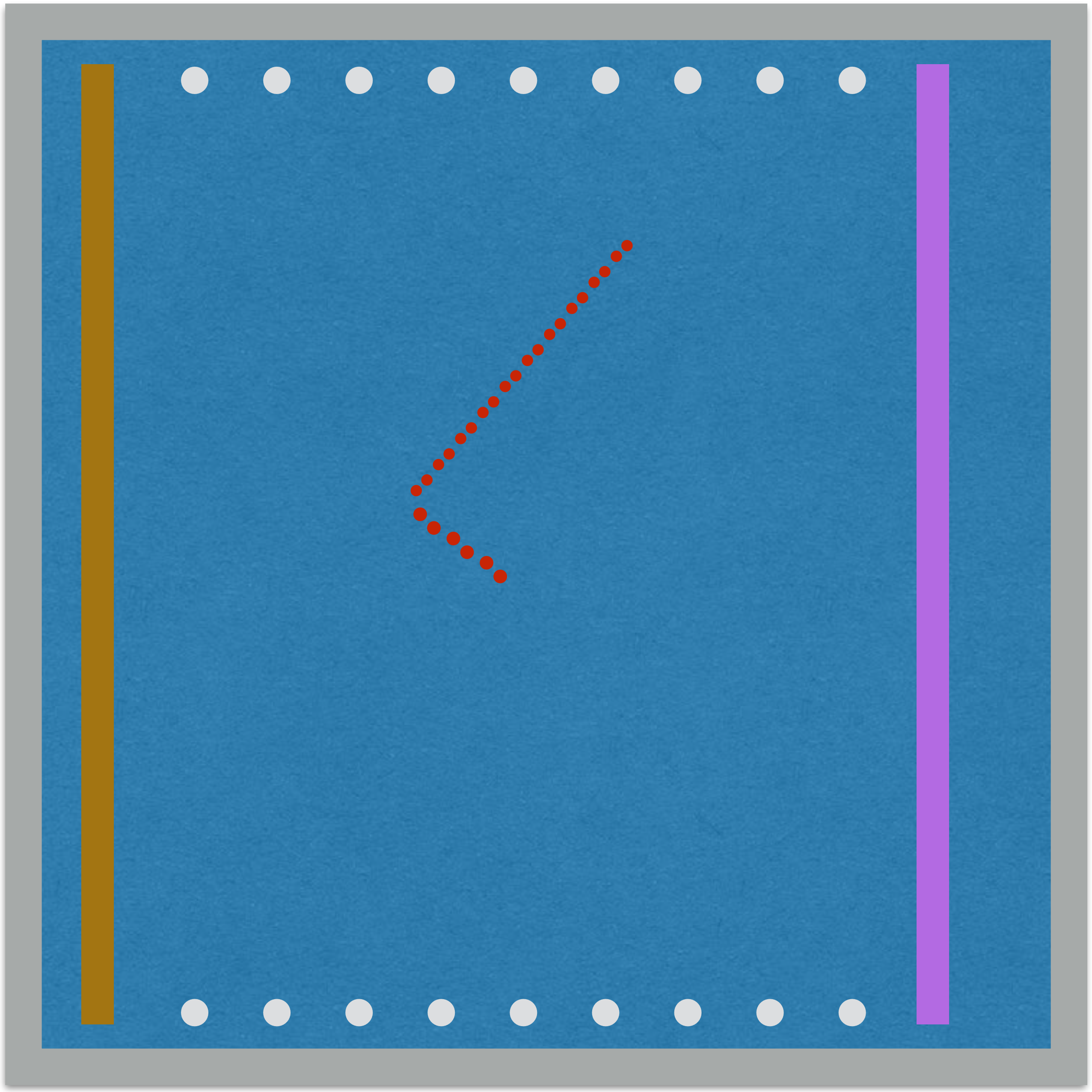
interaction produces
charged particles



LArTPC Operation

liberates ionization electrons

(and argon ions, not shown)



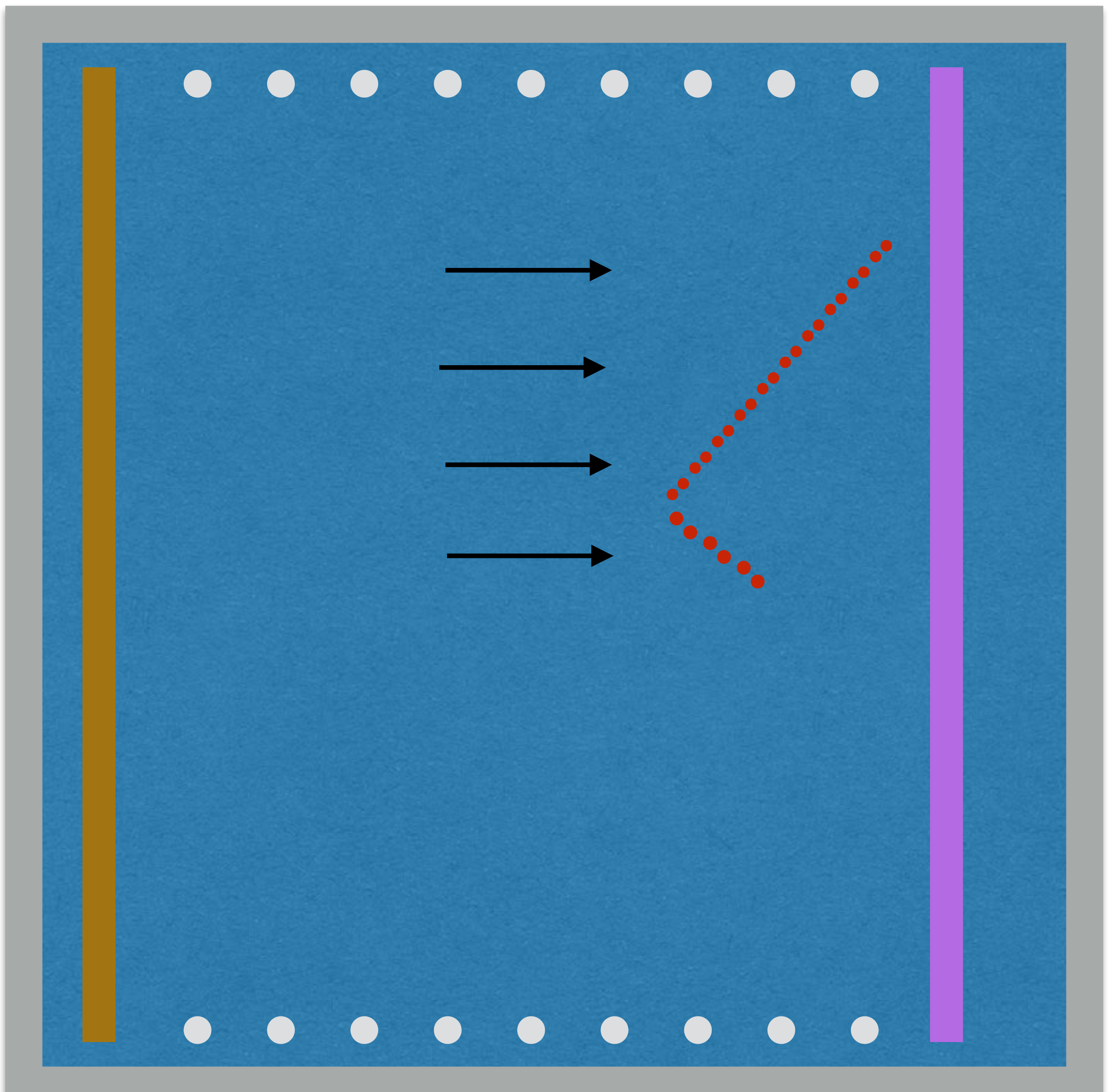
deposited energy also produces scintillation photons
(not shown in cartoon)

within nanoseconds photons collected by detectors placed behind the anode wires

light signal important for timing

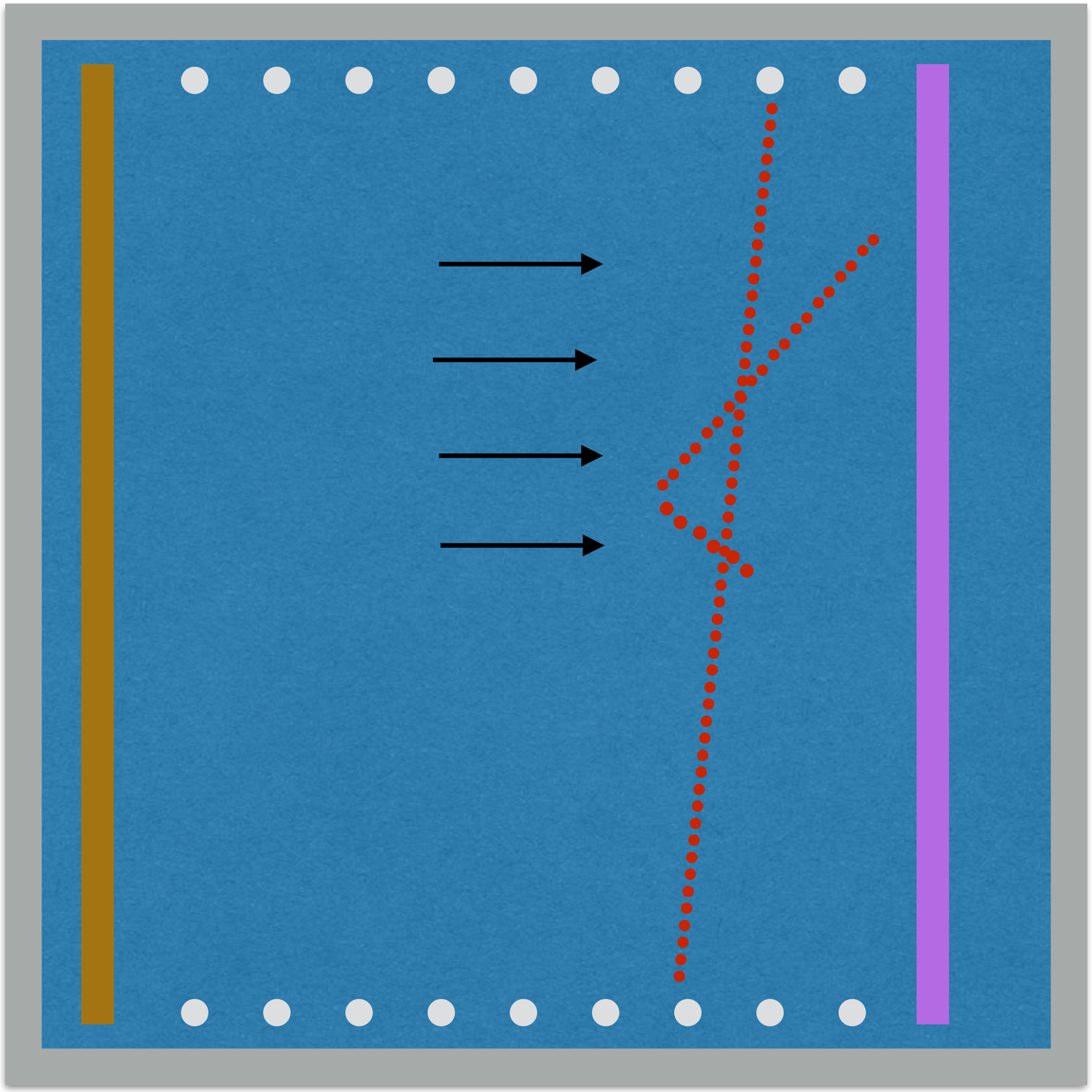
LArTPC Operation

ionization follows field to anode



LArTPC Operation

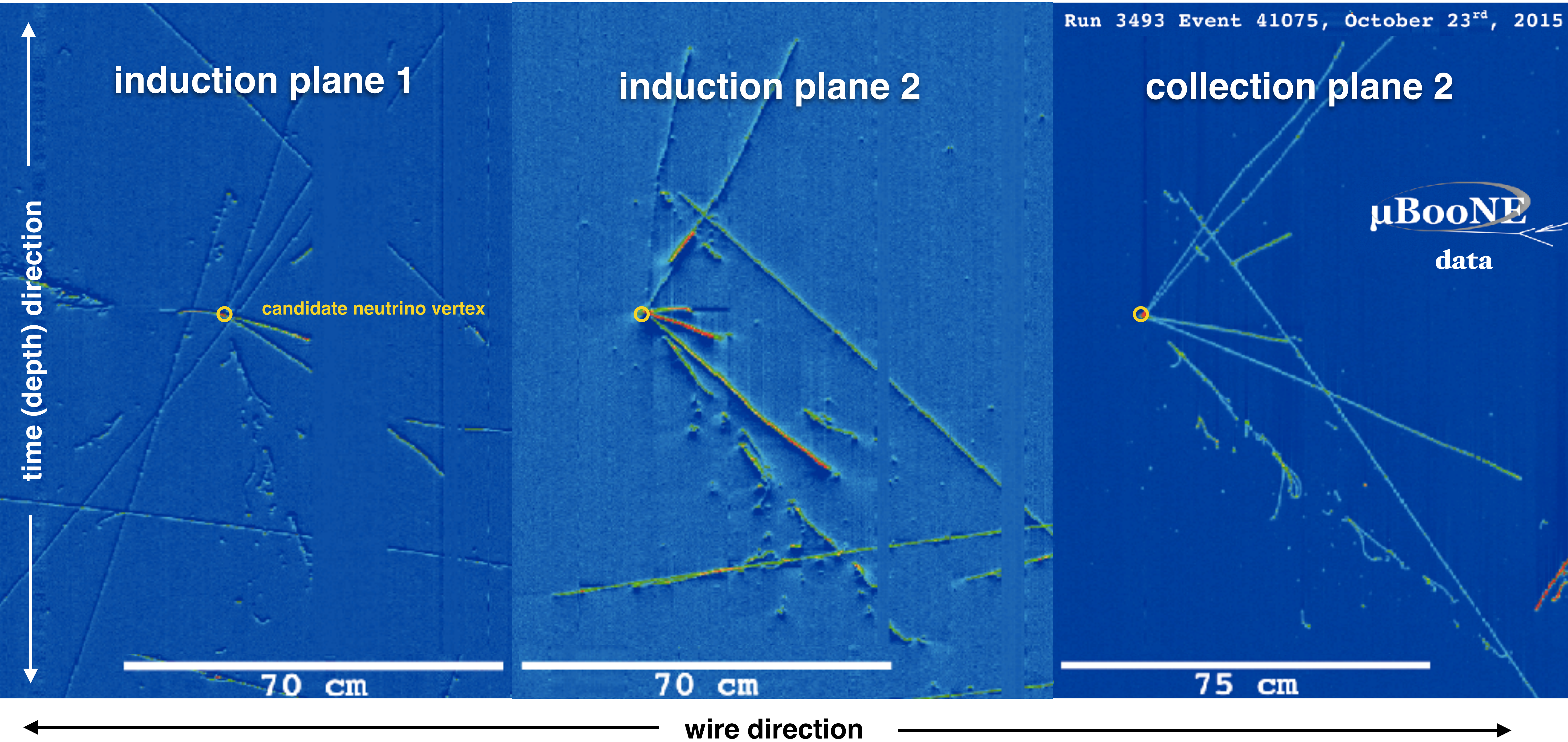
drift is relatively slow (e.g. ~2.3 ms from cathode to anode in uB)



during that time cosmic particles, mainly muons, will also create tracks of ionization

LArTPC Operation

ionization drifts past (induction) or collects on (collection) wire planes. each provides 2D view of same event



The SBN program

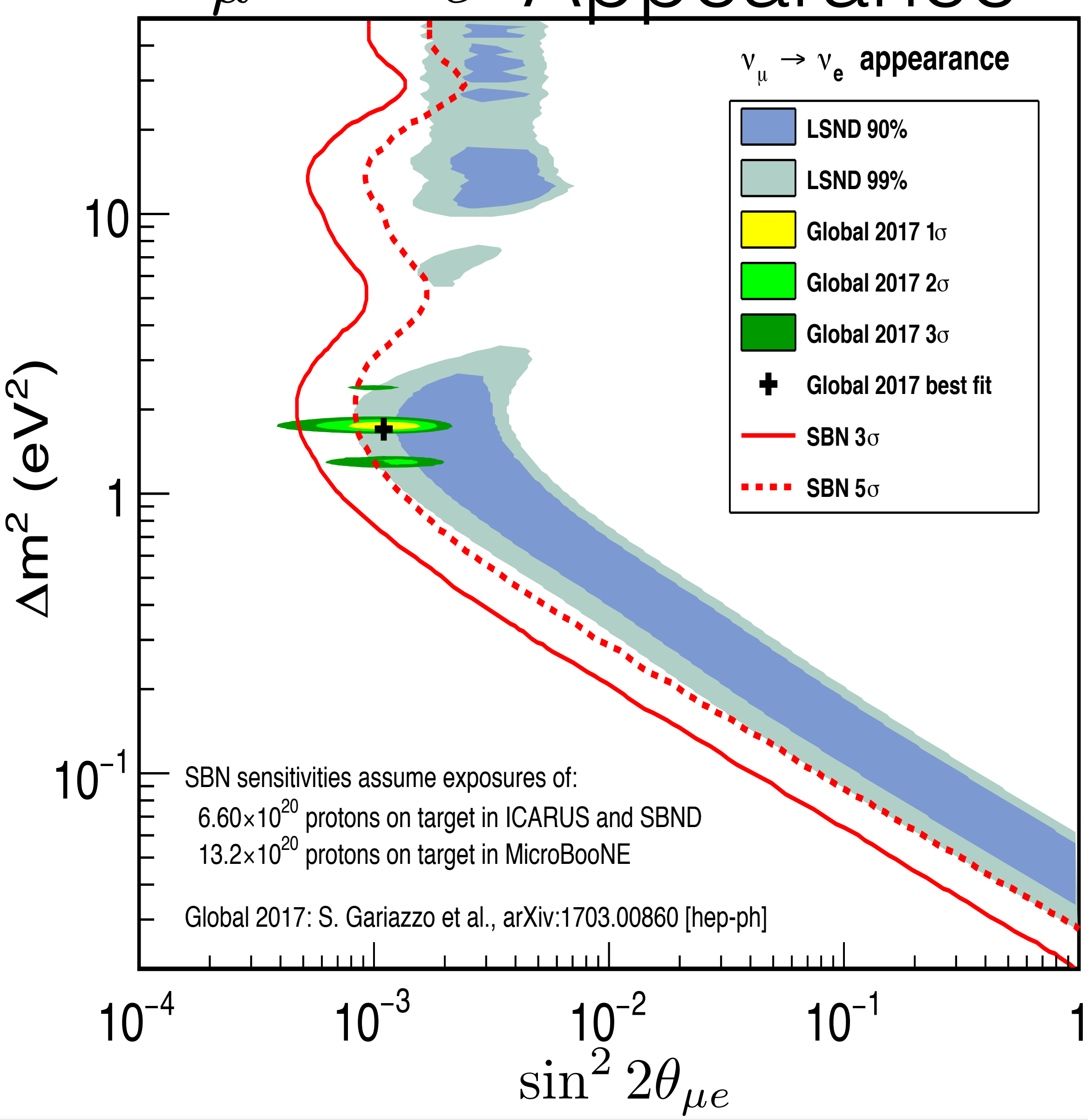
- Program proceeding in two stages
- MicroBooNE (phase 1) investigation of MiniBooNE anomaly
  - Currently taking data
  - Search for presence (or not) of excess
  - Is it electron-like or photon-like?
- ICARUS/SBND (phase 2) definite search for sterile neutrinos where near and far detectors reduce the influence of beam and cross section systematics

Sensitivity

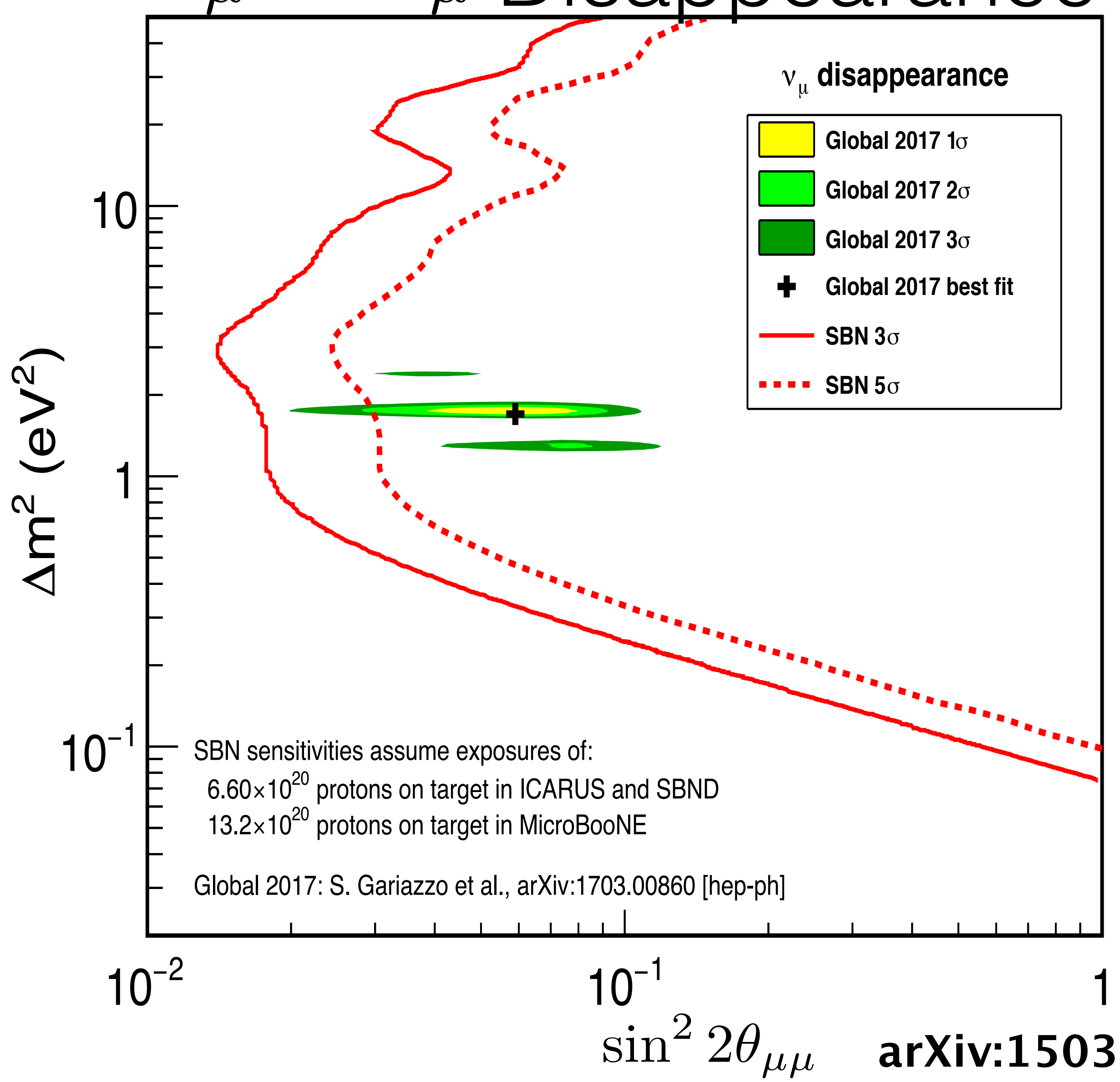
- Reach of full program
  - SBND/ICARUS (6.6e20 POT ~ 3 years)
  - MicroBooNE (13.2e20 POT ~ 6 years)

Appearance and disappearance tested in one program

$\nu_\mu \rightarrow \nu_e$ Appearance



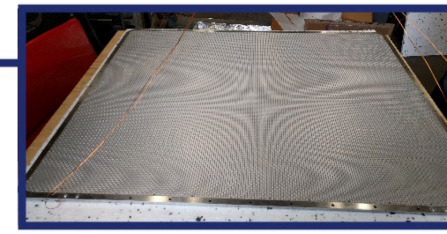
$\nu_\mu \rightarrow \nu_\mu$ Disappearance



arXiv:1503.01520

Status: SBND

- Detector construction underway!
- Planned data taking 2020

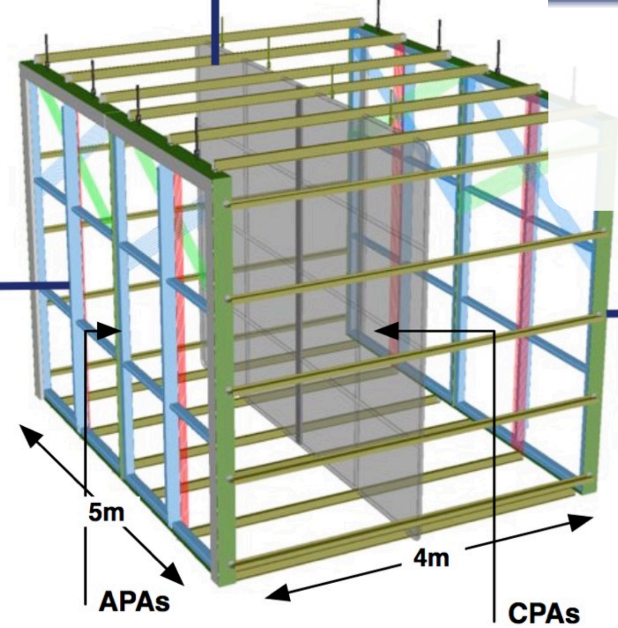


Foils

- CPA will be fitted with TPB coated reflector foils.
- Shifts UV Ar scintillation light to visible.

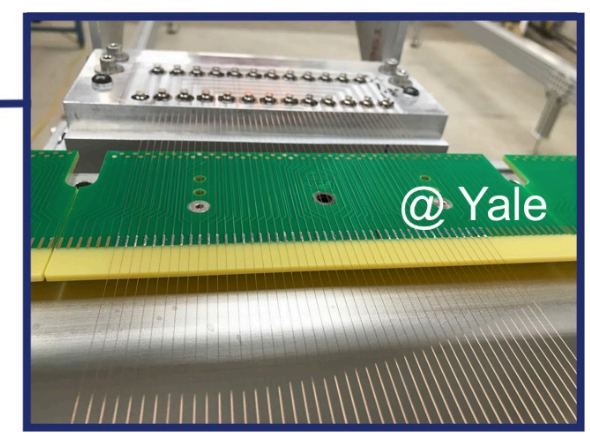
CPA

- Frame constructed.
- Shipping to Fermilab.



APA

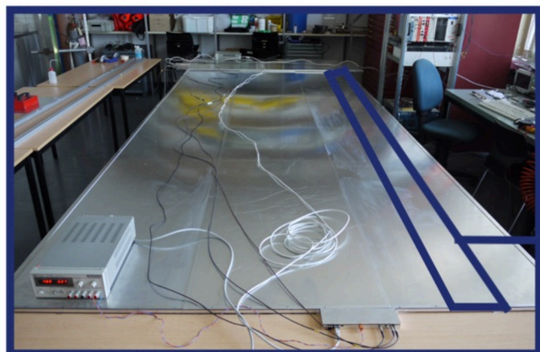
- Frames constructed.
- Wiring in progress.

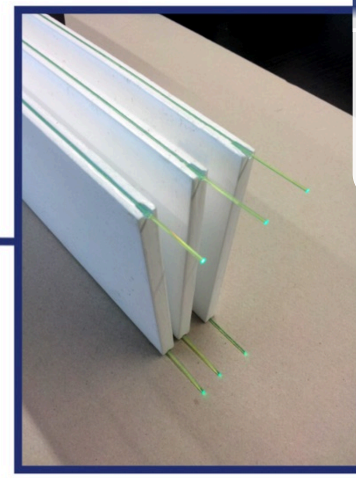


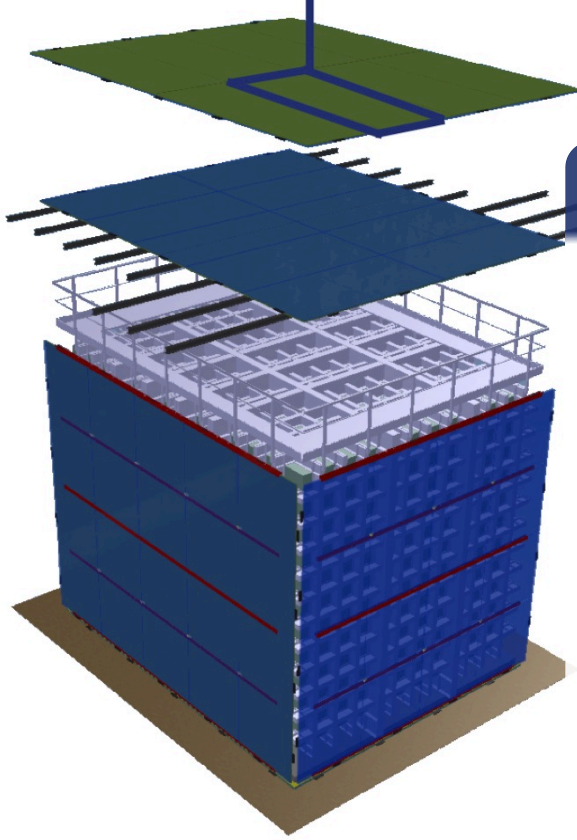
see Tom Brook's New Perspectives Talk for more info

Status: SBND

- Detector construction underway!
- Planned data taking 2020





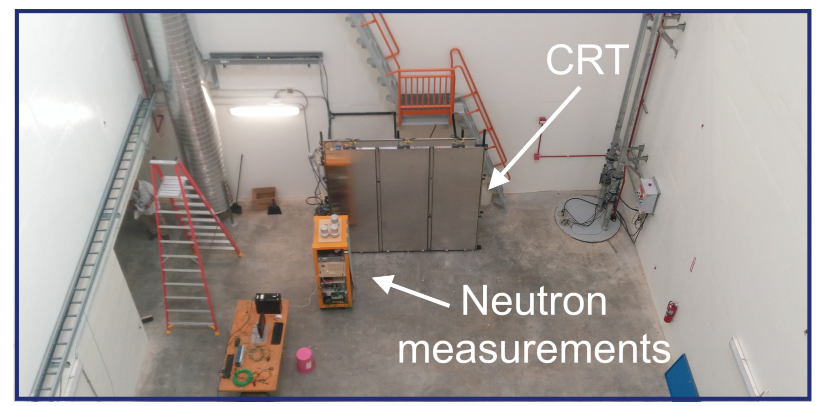


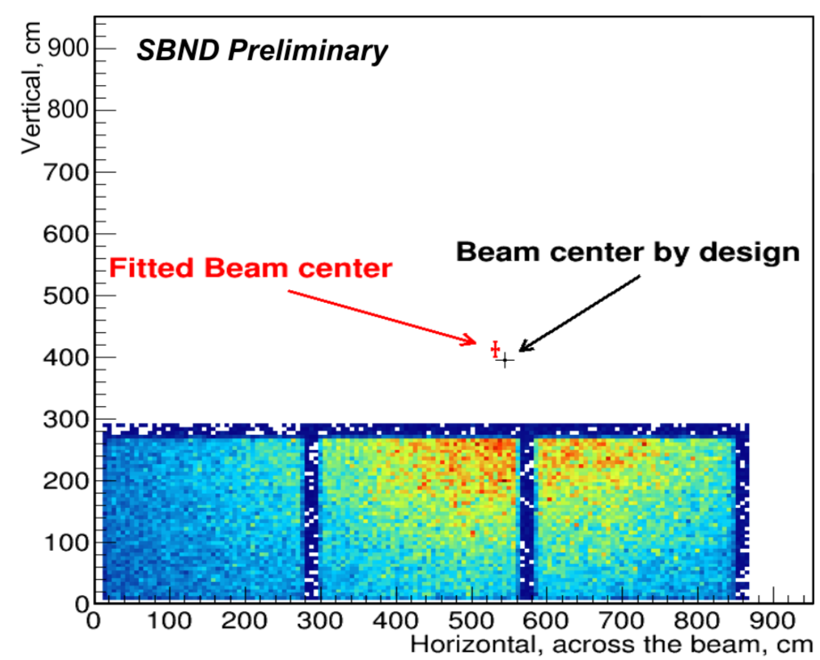
CRT

- Production in full swing.
- Several modules delivered to Fermilab.
- Beam measurements underway in SBND pit.

Neutron background

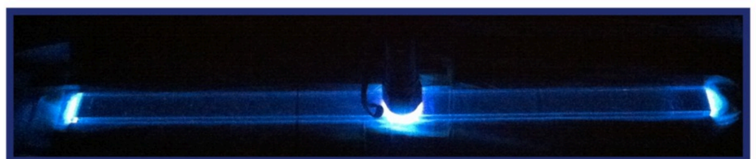
- Taking measurements with portable liquid scintillator neutron detector.





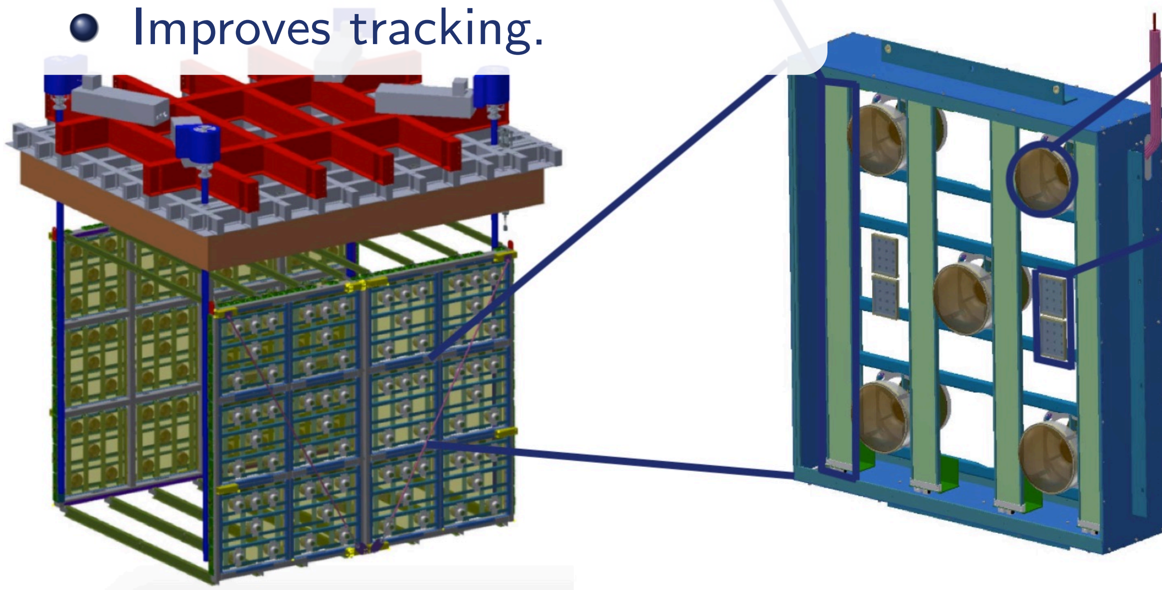
Status: SBND

- SBND performing R&D with candidate DUNE technologies
- E.g. Photon detection system will test candidate several candidate technologies



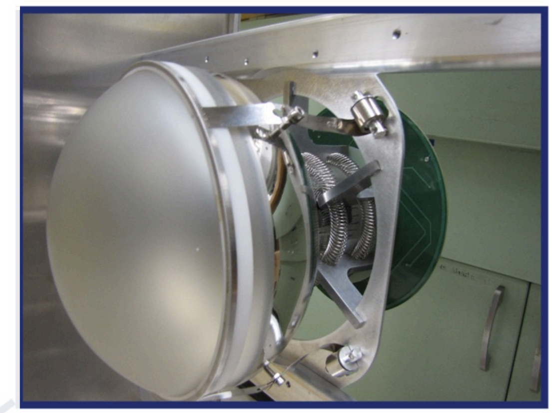
Light bars

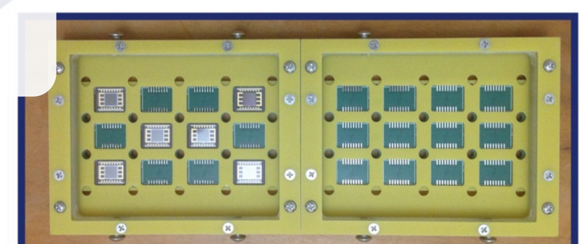
- Acrylic bars dip-coated with TPB coupled to SiPMS.
- Only sensitive to UV.
- Improves tracking.



PMTs

- 120 8" Hamamatsu PMTs (96 TPB coated).
- Mounts being fabricated.
- Preparing for full system test.





ARAPUCAs

- Trap photons with highly reflective internal surface.
- Detect with SiPMS.
- Prototypes under construction.

Status: ICARUS

- Detector construction underway
- TPC arrived last summer
- Warm vessel completed
- Cold shield recently installed
- Cosmic Ray Tagger being installed and tested
- Detector installation will begin next month (July)
- Data taking planned for 2019!

TPC arrive on-site (July 2017)

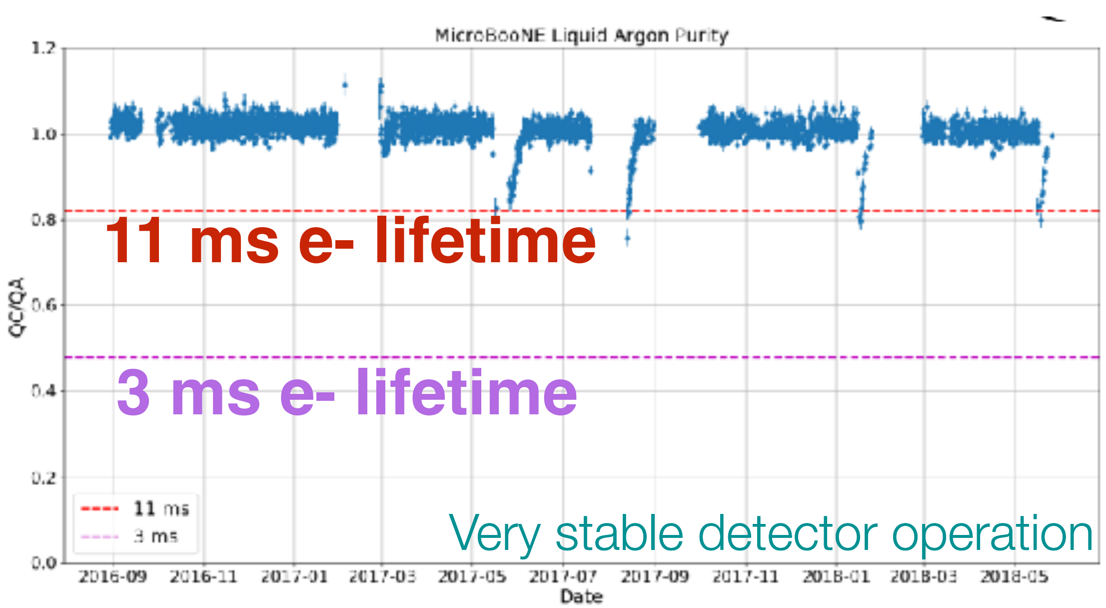
MicroBooNE Operations

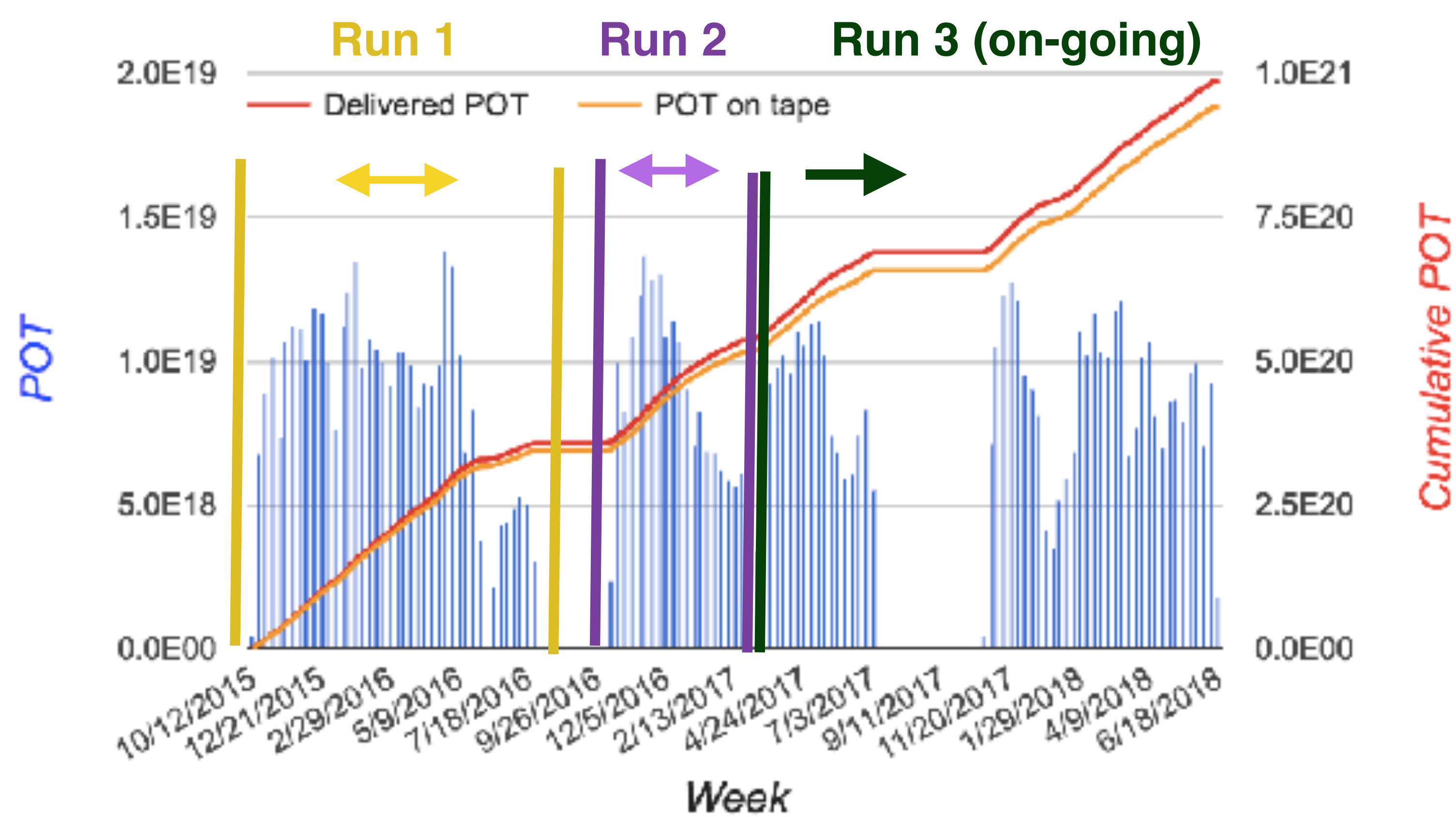
- Detector operating stably
- >95% DAQ up-time
- 9.4E20 POT collected currently

Run 1	-
Run 2	New service boards
Run 3	Full Cosmic Ray Tagger

Results shown today from portions of Run 1

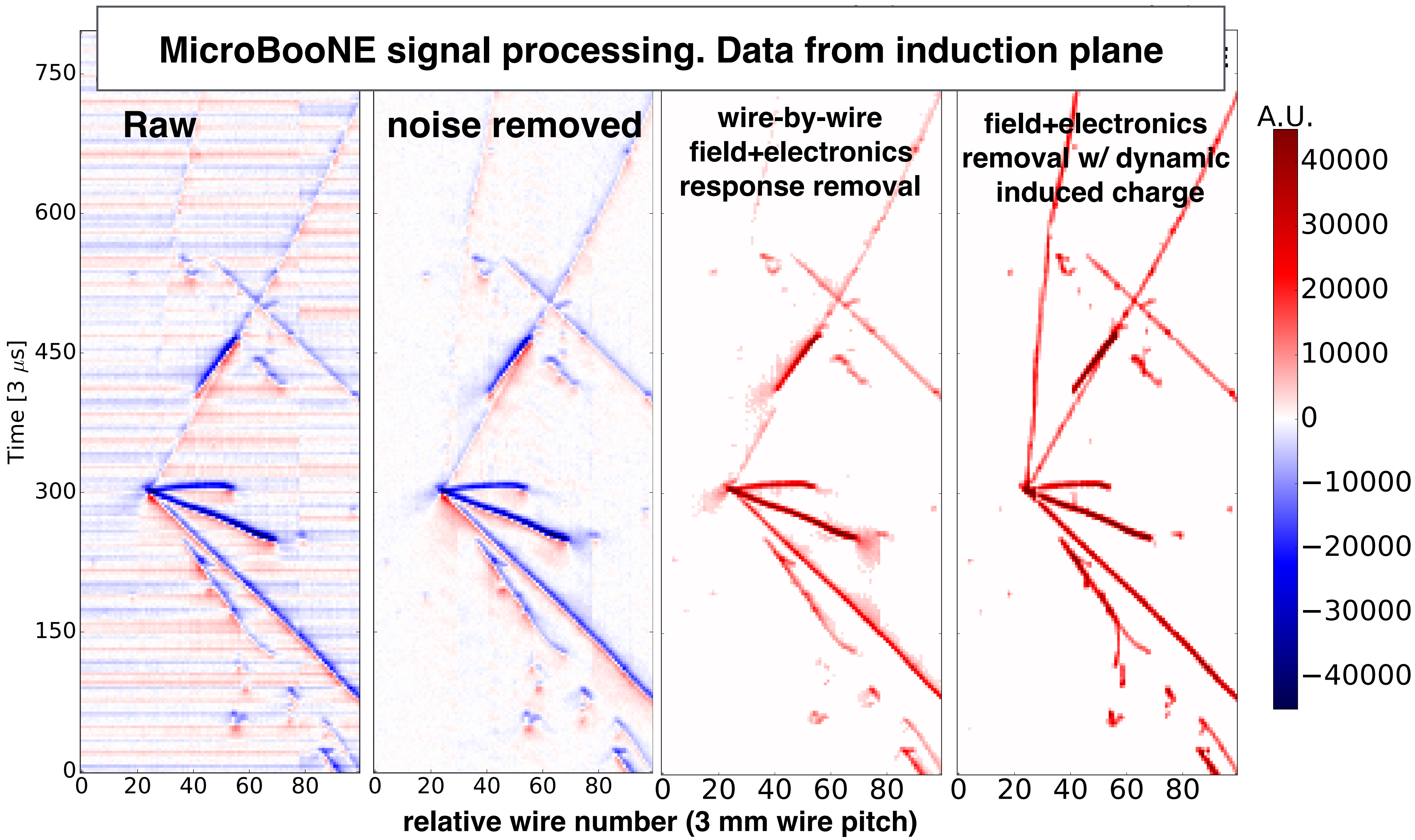
purity vs. time





Detector Response

- Improvements to noise characterization+filtering plus wire response modeling leading to more accurate MC and measurements of charge deposition in data



A cloud of ionization produces signals on several adjacent wires

Properly accounting for this helps better true position and amount of ionization than past method

Enables accurate calorimetric information in all three planes -- improves induction planes in particular

"Ion. Electron Signal Proc. in Single Phase LAr TPCs II: Data/Simulation Comparison and Performance in MicroBooNE", arXiv:1804.02583, Accepted by JINST
"Ion. Electron Signal Proc. in Single Phase LAr TPCs I: Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation", arXiv:1802.08709, Accepted by JINST

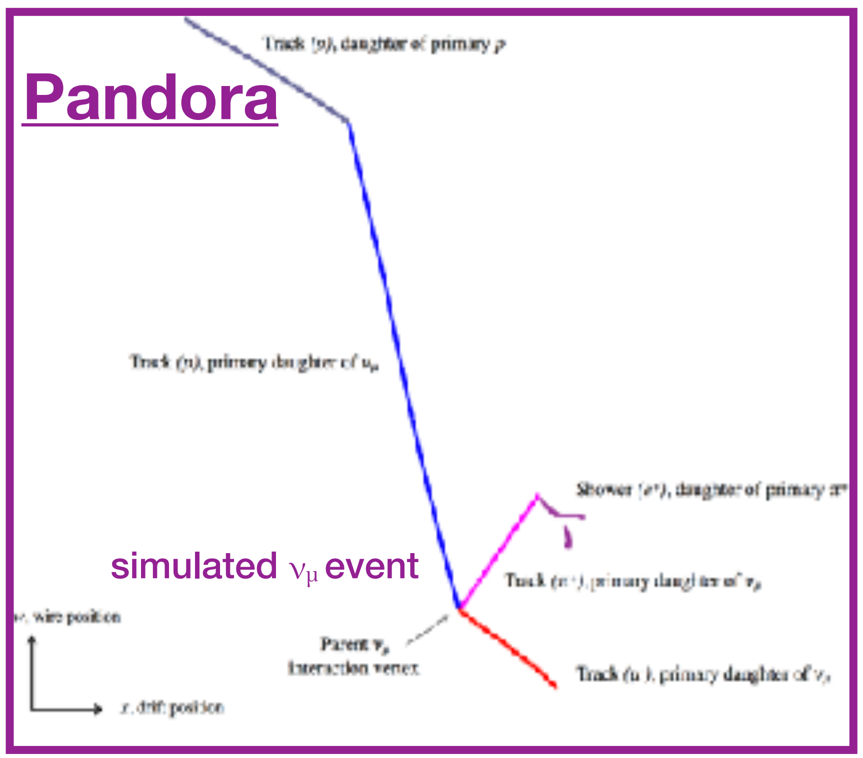
Reconstruction

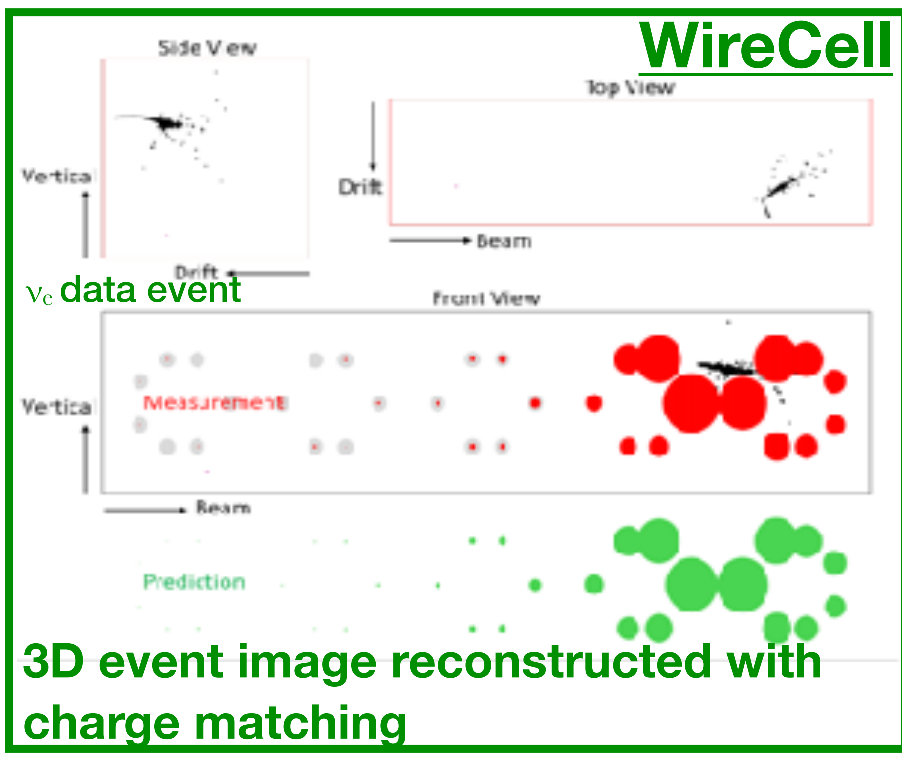
- Several independent reconstruction methods taking very different approaches
- Having independent analyses with different code-bases and approaches will provide valuable cross-checks

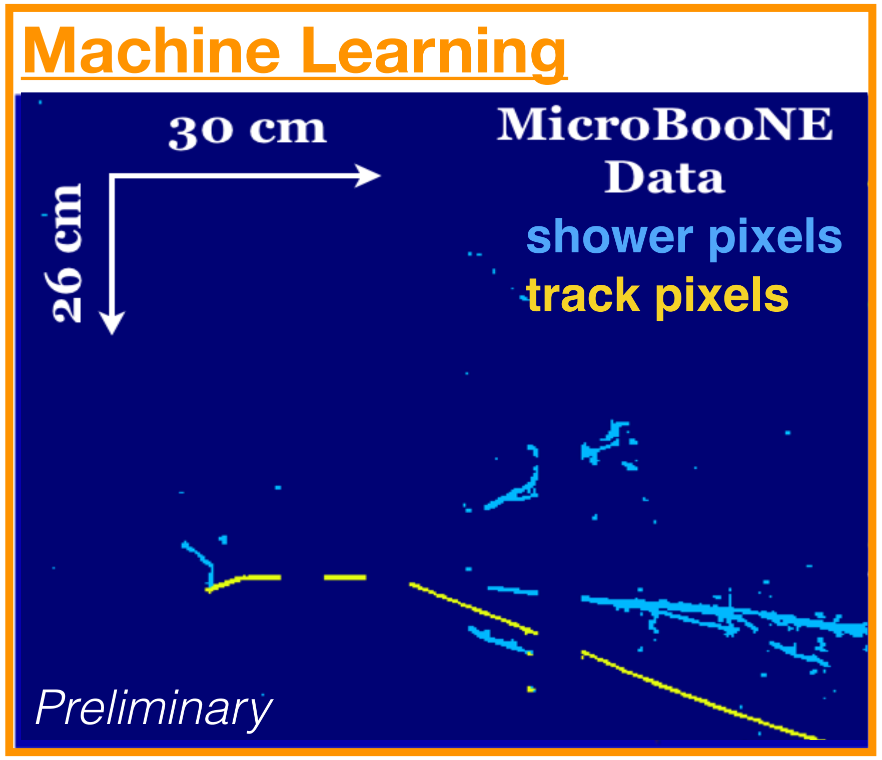
Starts w/ 2D patterns to get **3D recon**. Widely used by LArTPC community

Use tomographic approach to turn 2D charge info. into 3D charge. Start w/ 3D earlier

Employ recent computer vision advances







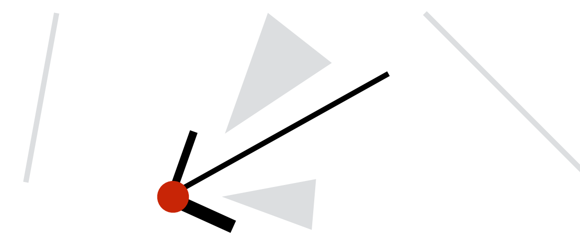
"The Pandora Multi-Algorithm Approach to Automated Pattern Recognition of Cosmic Ray Muon and Neutrino Events in the MicroBooNE Detector", Eur. Phys. J. C78, 1, 82 (2018)"

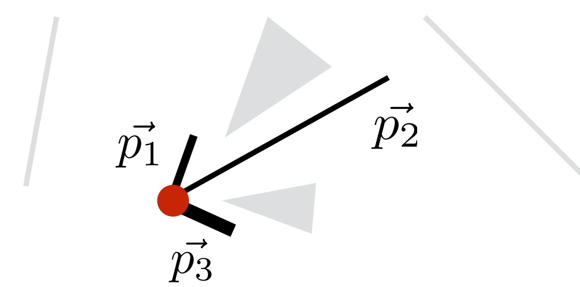
"Three-dimensional Imaging for LArTPCs", JINST 13 05 P05032 (2018)
Public Note: MICROBOONE-1040-PUB

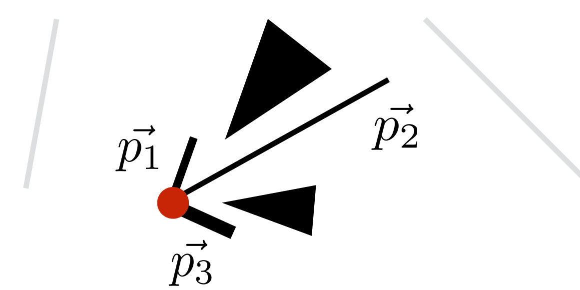
"Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber", JINST 12, P03011 (2017)

Analysis Roadmap

- Employing available reconstructed quantities in a staged manner
  - Locate neutrino **vertex** and count number of attached **charged tracks**: first test of interaction and flux models
  - Reconstruct **kinematics** of individual tracks: inclusive ν_μ-CC cross section
  - Reconstruct **showers** associated to inclusive ν_μ CC vertices: ν_μ-CC $\boldsymbol{\pi}^0$ cross section
- Producing physics while building reconstruction and analysis for the low-energy excess search



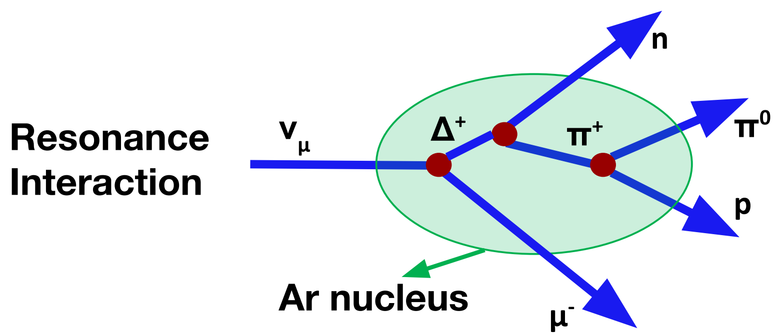




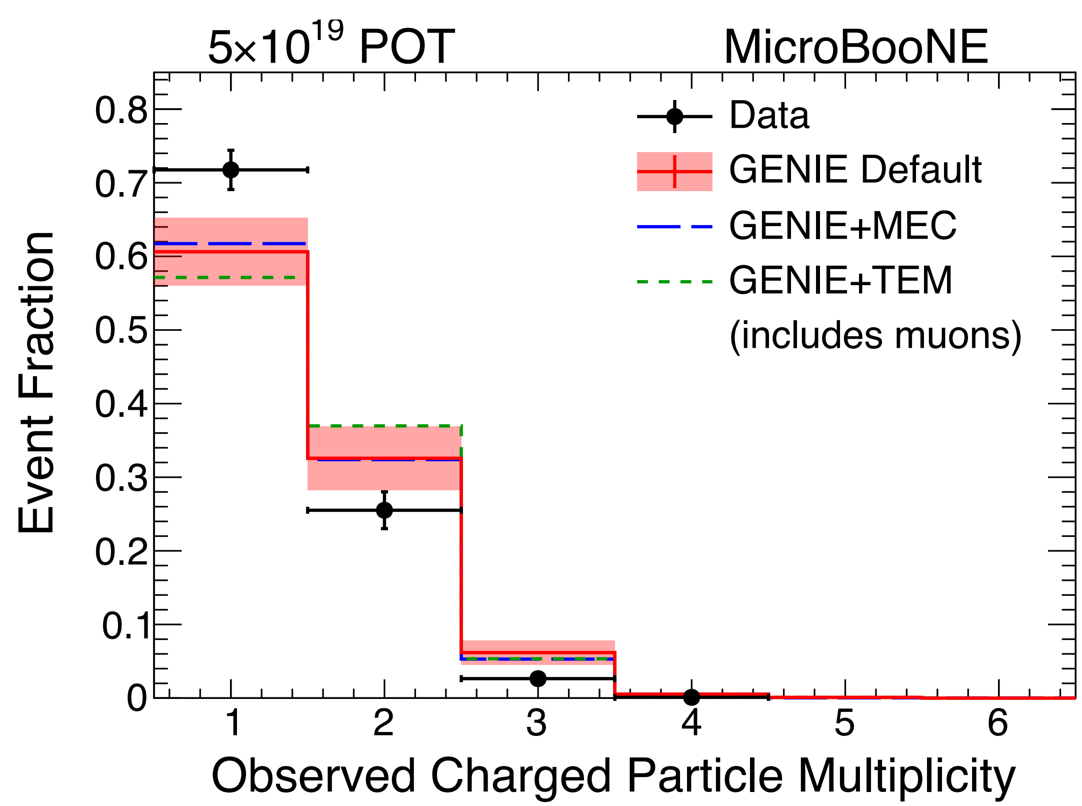
Charged particle multiplicity

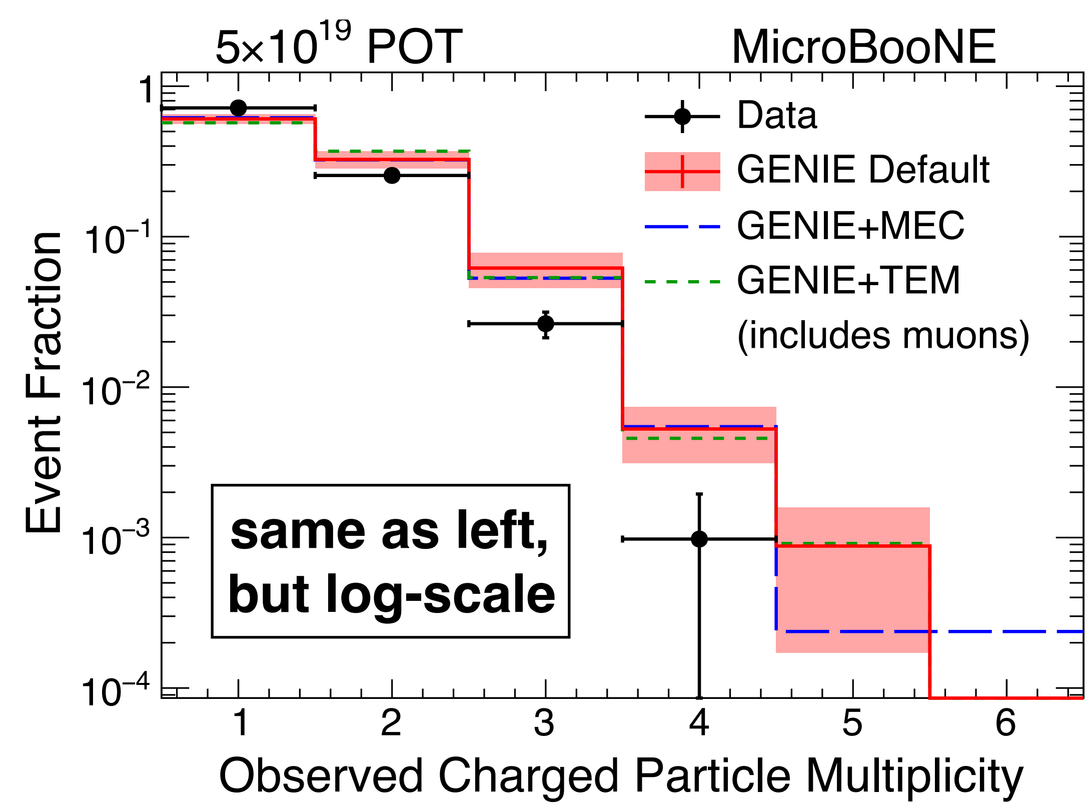
- Our first physics result!
- CPM distribution used to test nuclear models in generator
- Data lower than expectation at high multiplicities

Example of neutrino interaction with CPM = 2



"Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions", arXiv:1805.06887, submitted to PRD (2018)

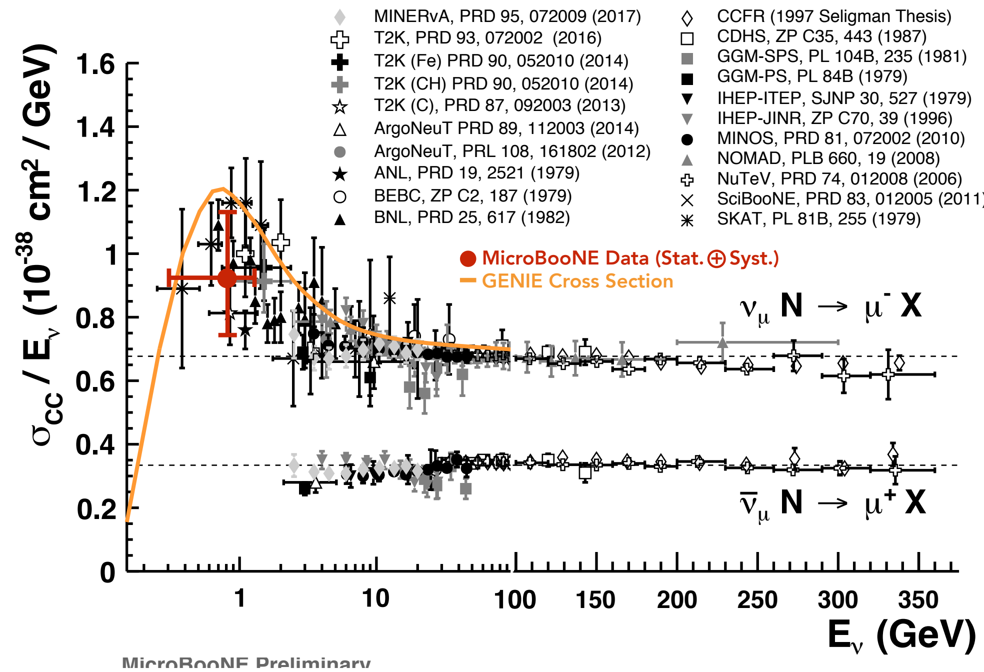


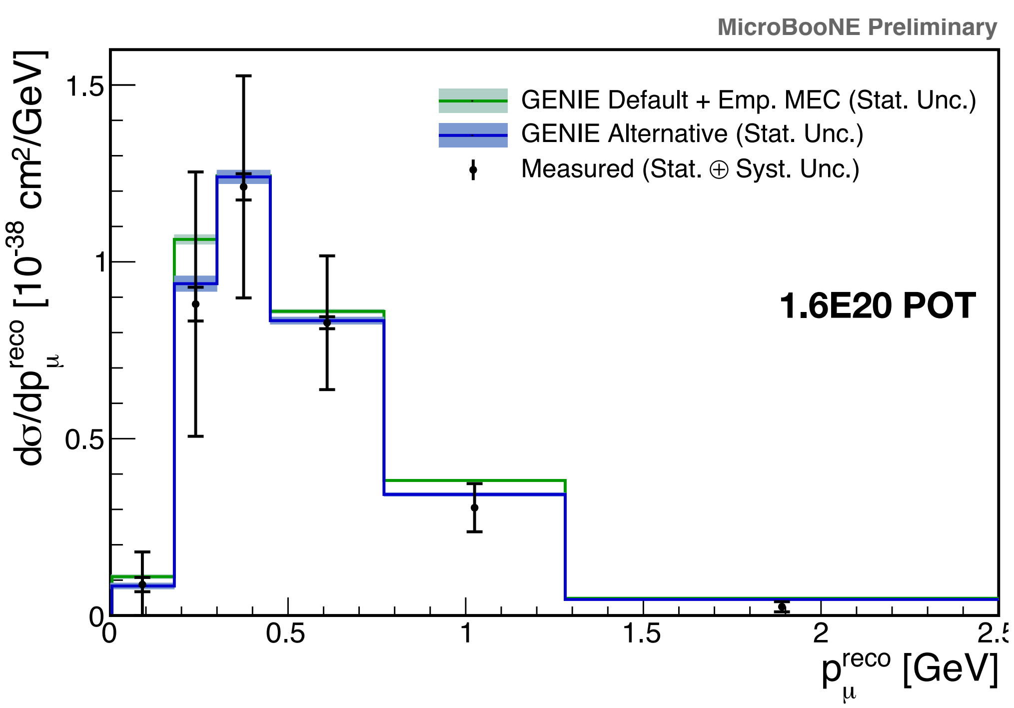


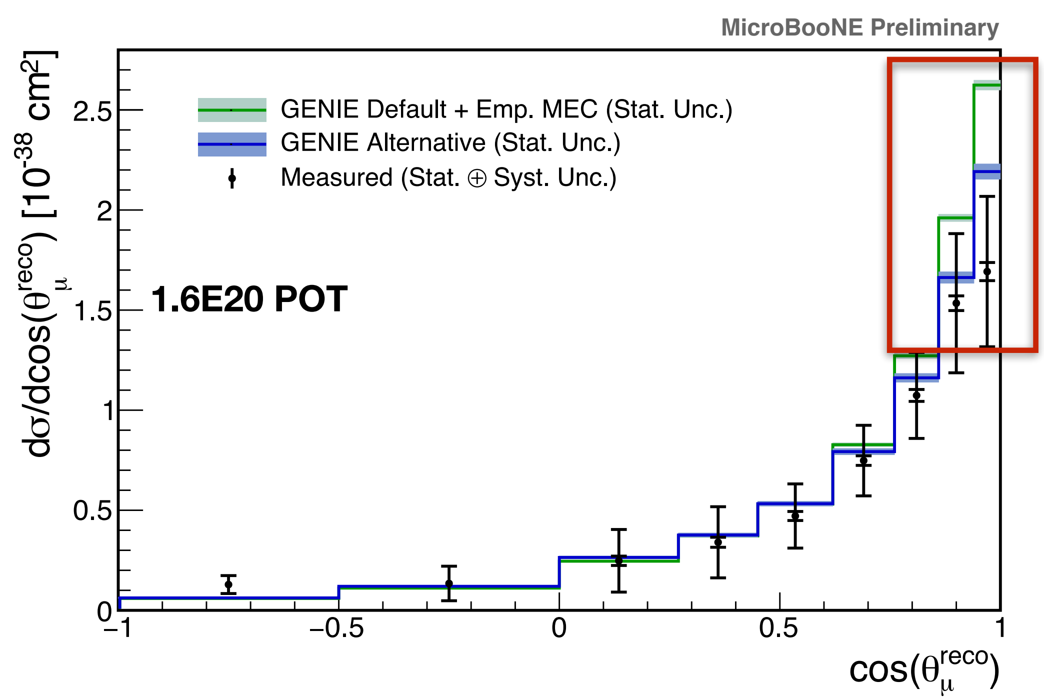
Inclusive ν_μ-CC Cross section

- inclusive ν_μ-CC differential cross section
- Comparison to GENIE with different model choices
- First comparisons for Argon at low energies (<1 GeV)

Public Note: MICROBOONE-NOTE-1045-PUB, 2018







forward bin a handle for investigating nuclear effects

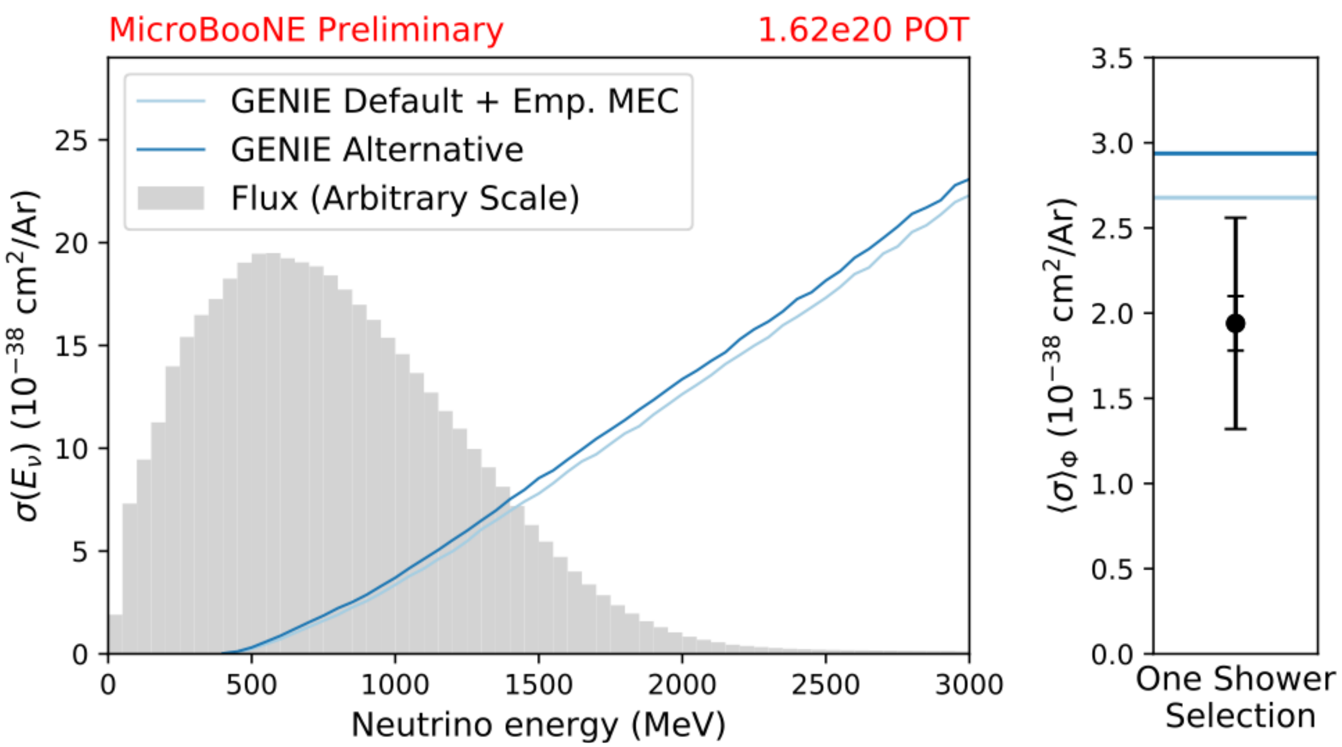
Double-differential cross section coming soon!

ν_μ-CC π^0

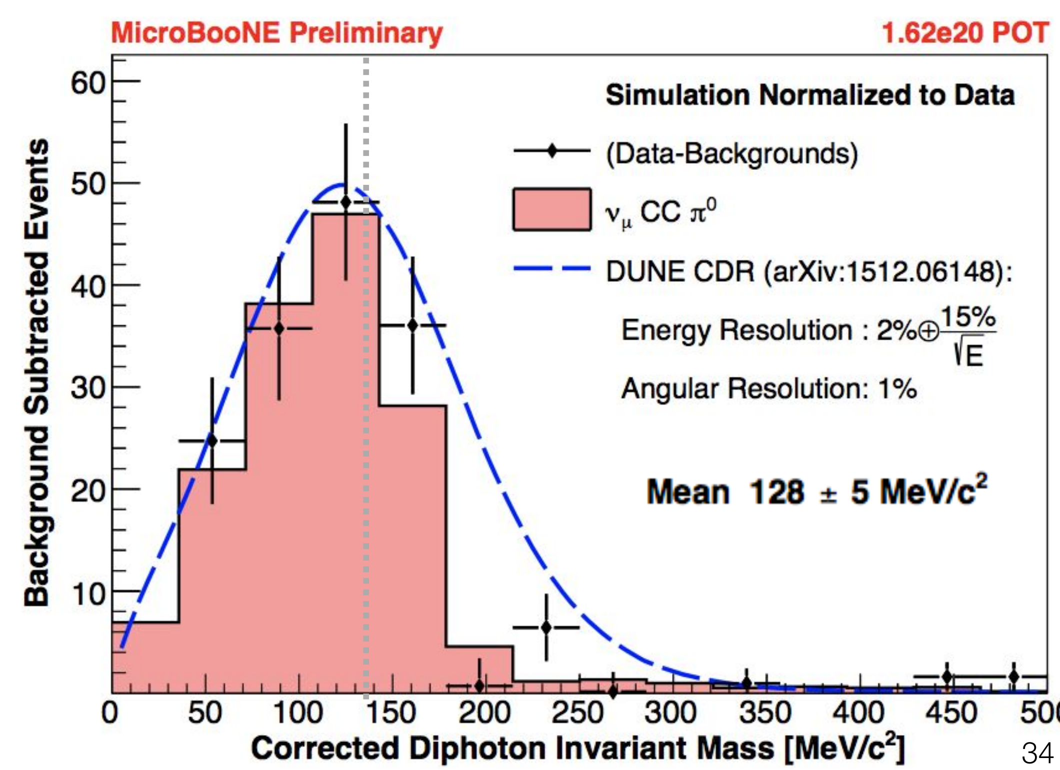
- Measurement requires crucial components to low-energy excess analysis
    - Shower reconstruction and validation of shower resolution
    - First ν_μ-CC π^0 measurement on argon

Flux integrated cross section

$$\left\langle \sigma^{\nu_\mu CC\pi^0} \right\rangle_\Phi = (1.94 \pm 0.16[\text{stat.}] \pm 0.60\text{syst.}) \times 10^{-38}\,\frac{\text{cm}^2}{\text{Ar}}$$



Two-photon invariant mass



Public Note: MICROBOONE-NOTE-1032-PUB, 2018

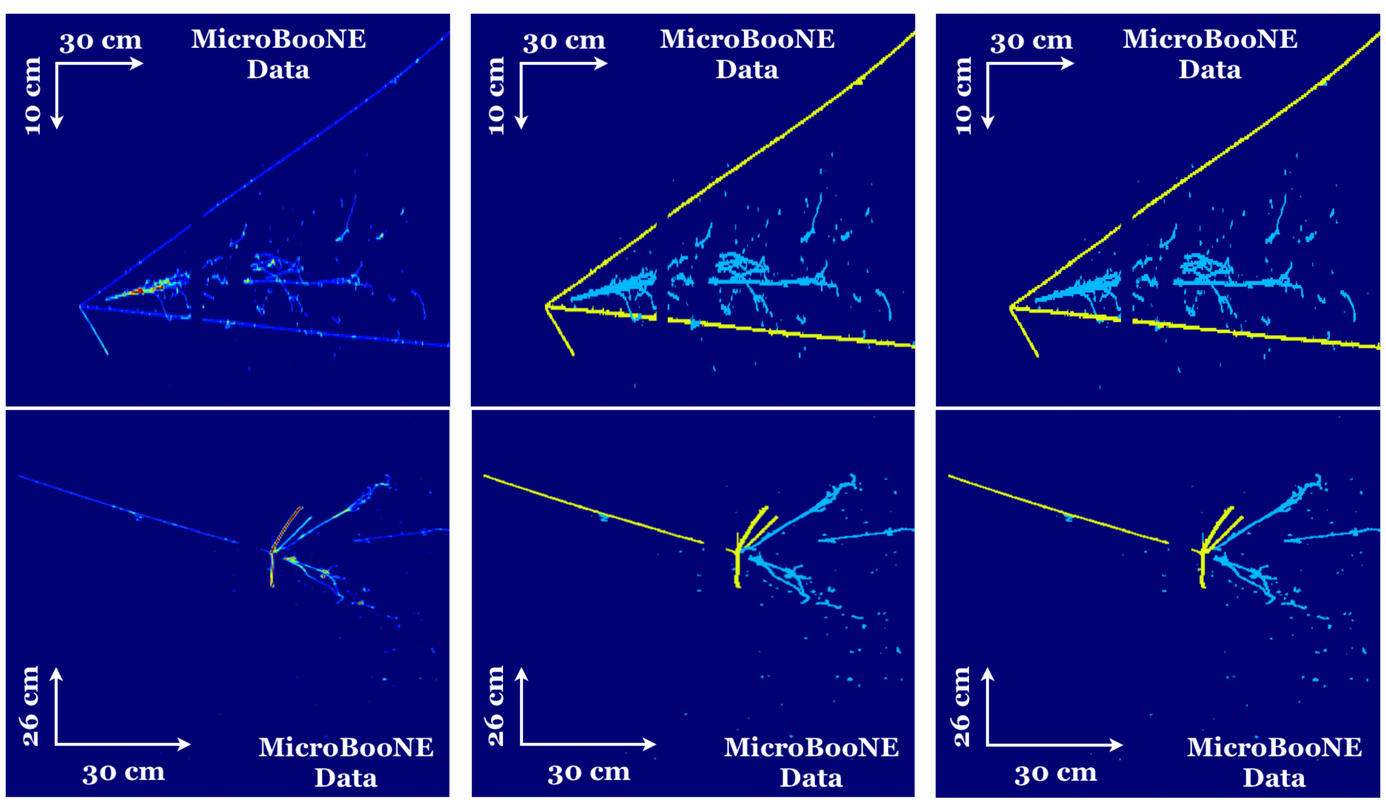
Next steps: higher statistics analysis leading to differential cross-section

DL on data

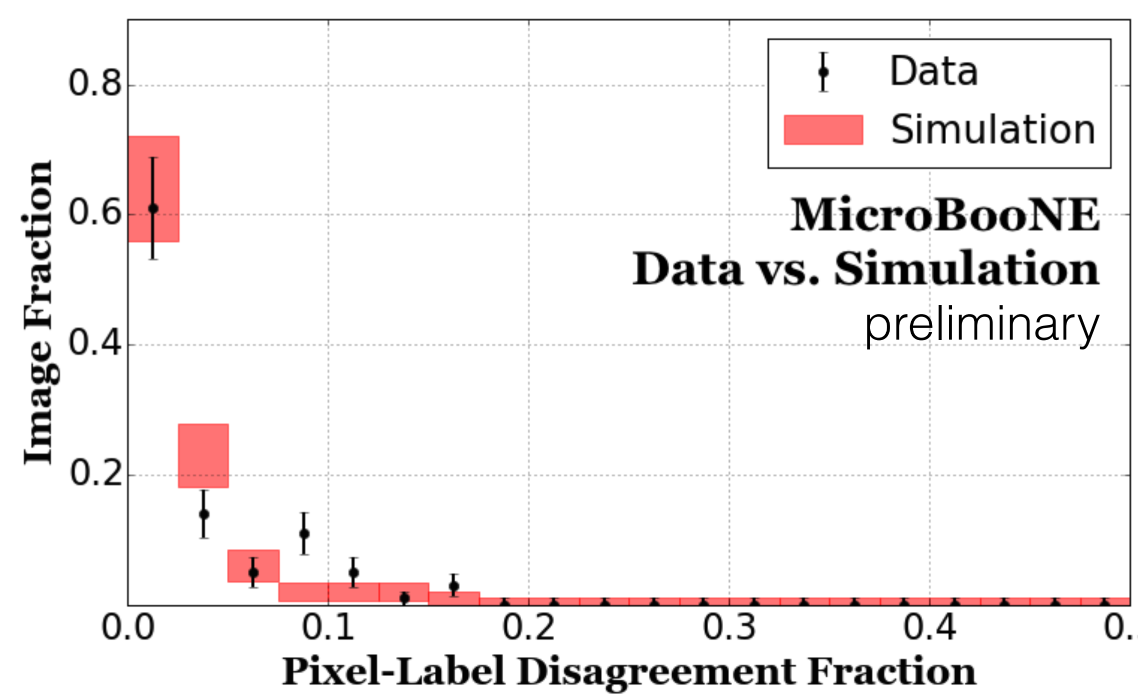
- **Next-gen. reconstruction tools coming on-line soon from all techniques**
- Example: pixel-labeling of MicroBooNE images on data using a deep convolutional neural network
- DL-techniques showing promise for DUNE reconstruction
- MicroBooNE provides the opportunity to establish that these techniques work on LArTPC data, despite being trained on MC

Study on ν_μ-CC π^0 *data* events

raw image | human labeled | machine labeled



disagreement between human and machine



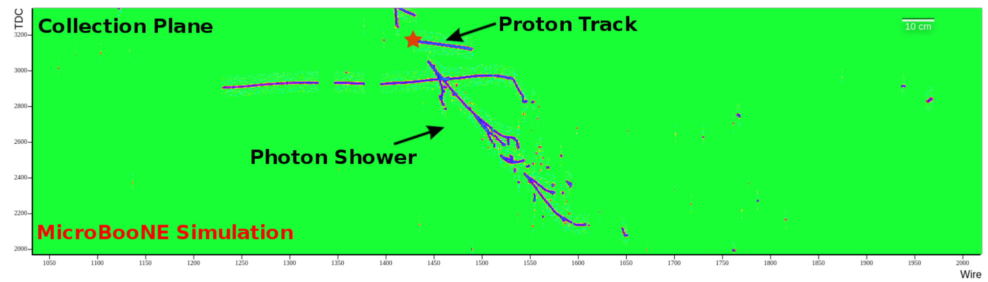
preliminary: publication coming very soon!

Building to Low Energy Excess

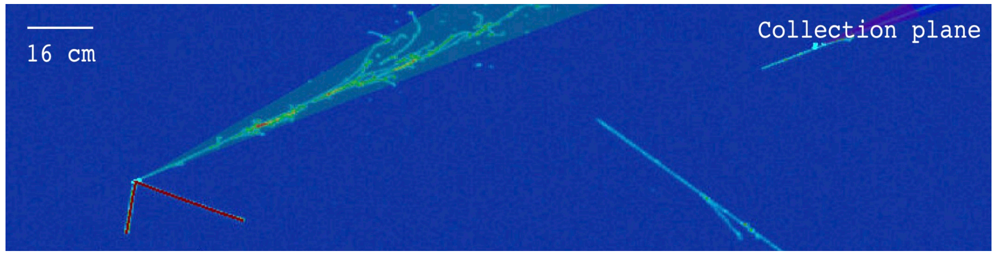
Have built a foundation from which to investigate the excess using different tools and channels

Such approaches important to test different possible explanations of the excess, *not just* sterile neutrinos

These are current analyses, but more to come



Example of reconstructed photon signal MC event



Example of reconstructed nue signal MC event

1γ+1p

1γ+0p

1e+Np | 1e+1p | 1e + X

Automated Reconstruction Tools

Pandora | Deep Learning | Wire Cell | and more…

calibrations

wire response understanding and modeling

Stable operation of both detector and beam

Summary

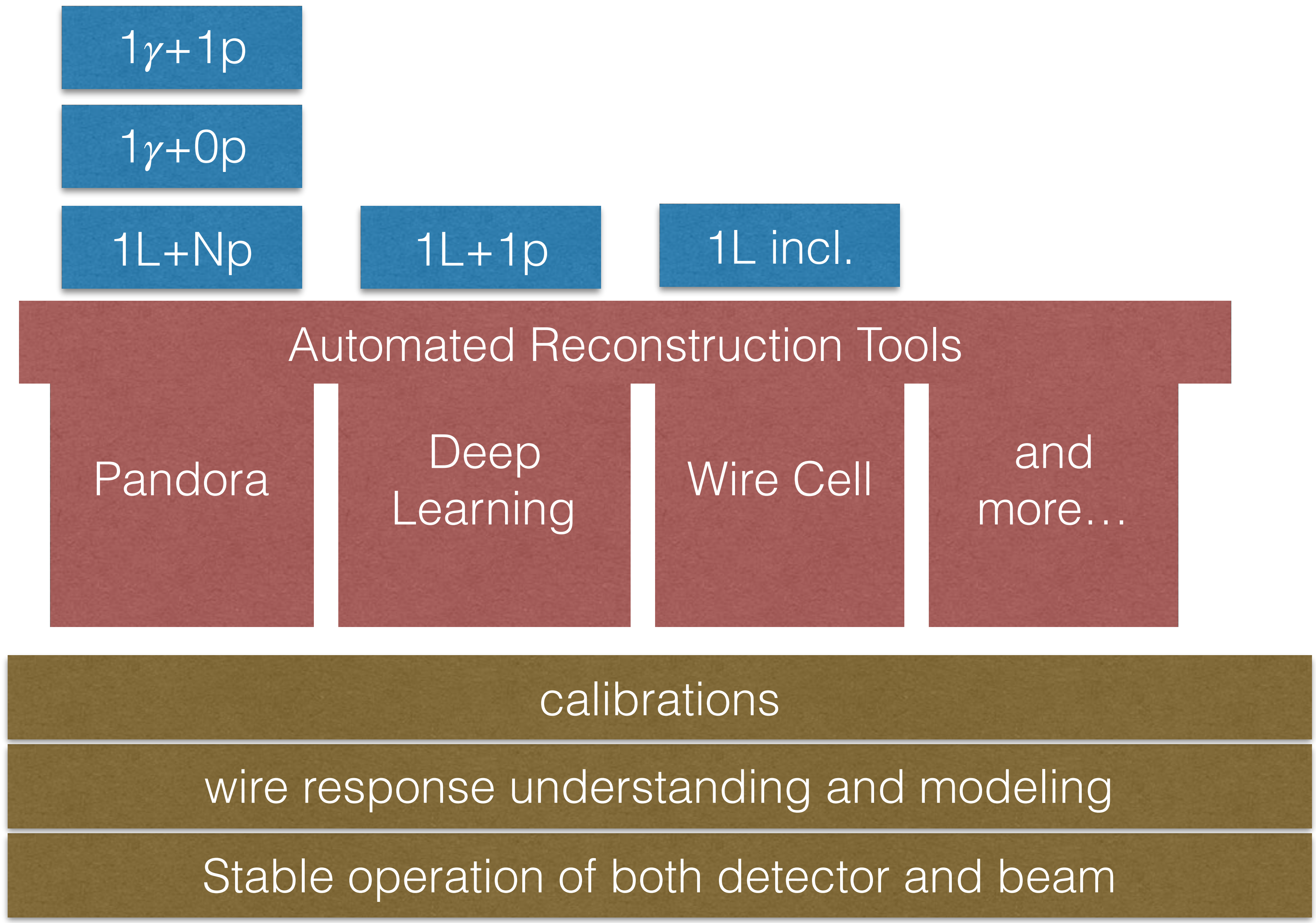
- MicroBooNE, the first phase of the SBN program, has built a solid foundation from which it has put out first results with many more on the way
- MicroBooNE has developed our first fully automated nue and single photon selections, some with independent techniques, and are addressing the improvements needed for the low-energy excess search
- SBN progressing towards phase 2: ICARUS and SBND detector construction on-going with full three detector data taking by 2020

Backups

More on MicroBooNE

Building to Low Energy Excess

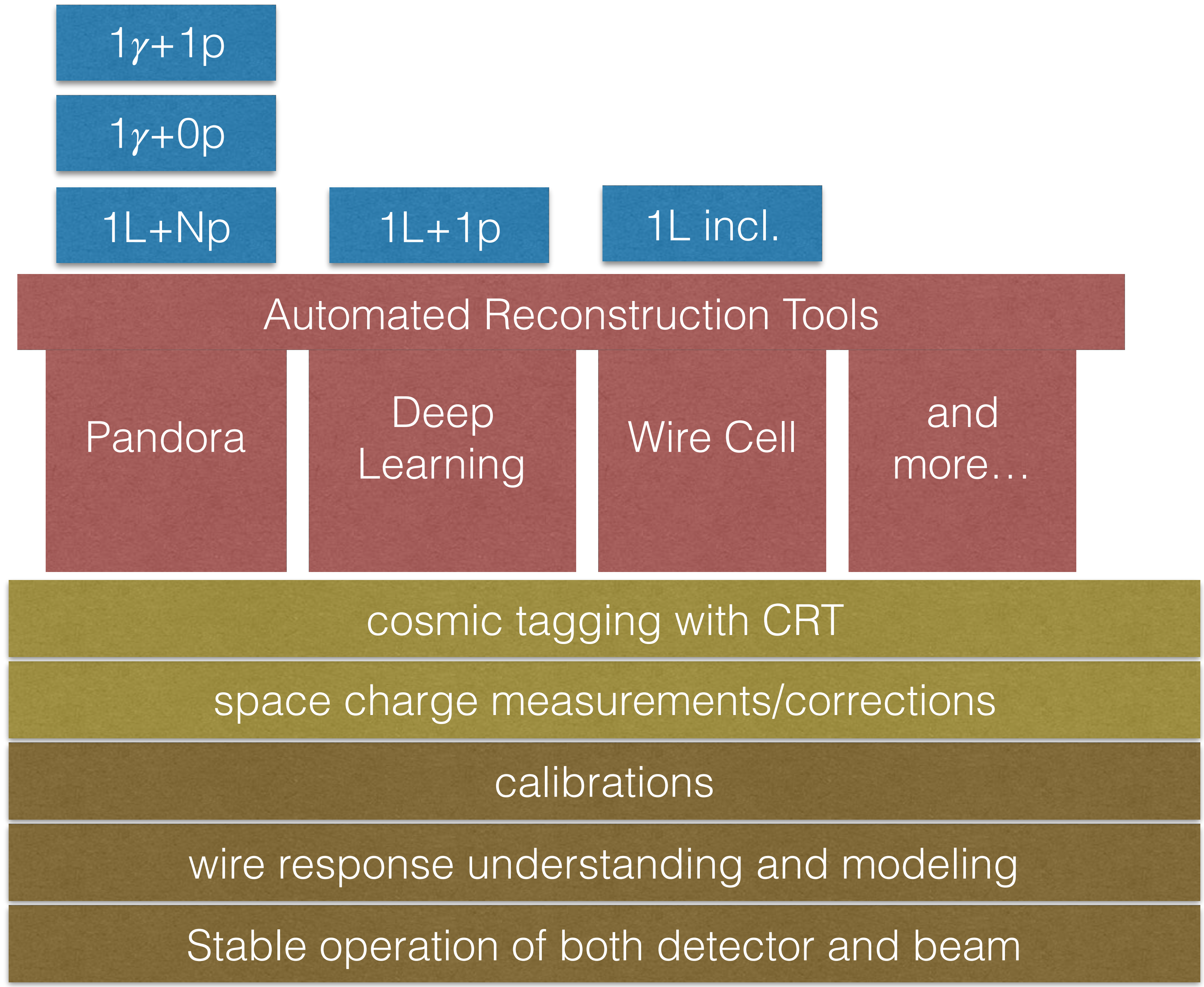
<u>Taking a blind approach</u>



These tools have been building on a small sample of data which cannot provide significant indication

NuMI sample recorded: provides sample of electron neutrinos to validate with

Building to Low Energy Excess

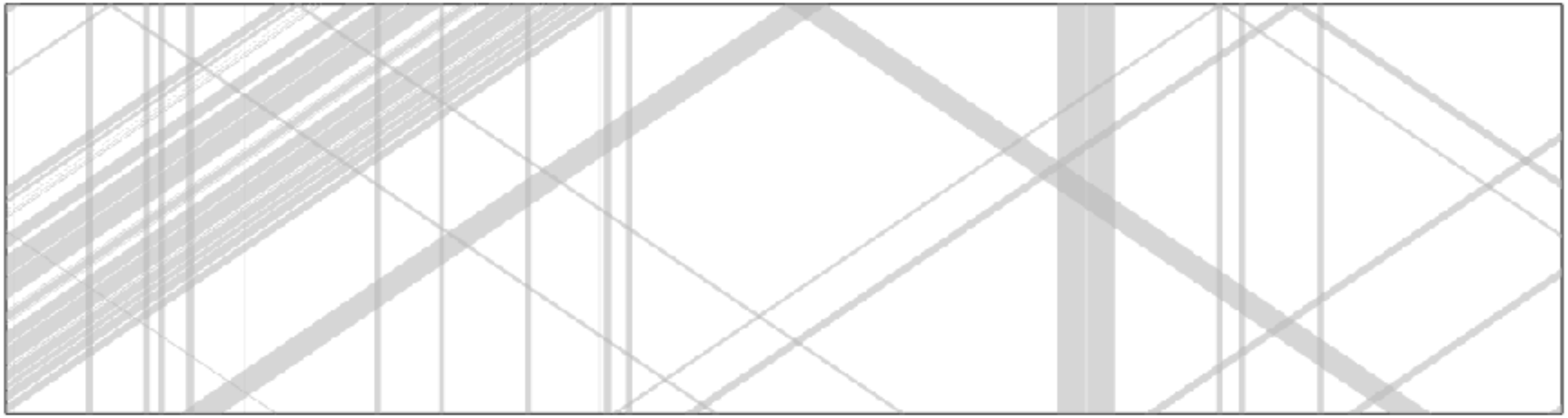


<u>Adding Improvements to foundation as well</u>

CRT data will be incorporated to assist in cosmic removal

measurements of space charge will improve current model

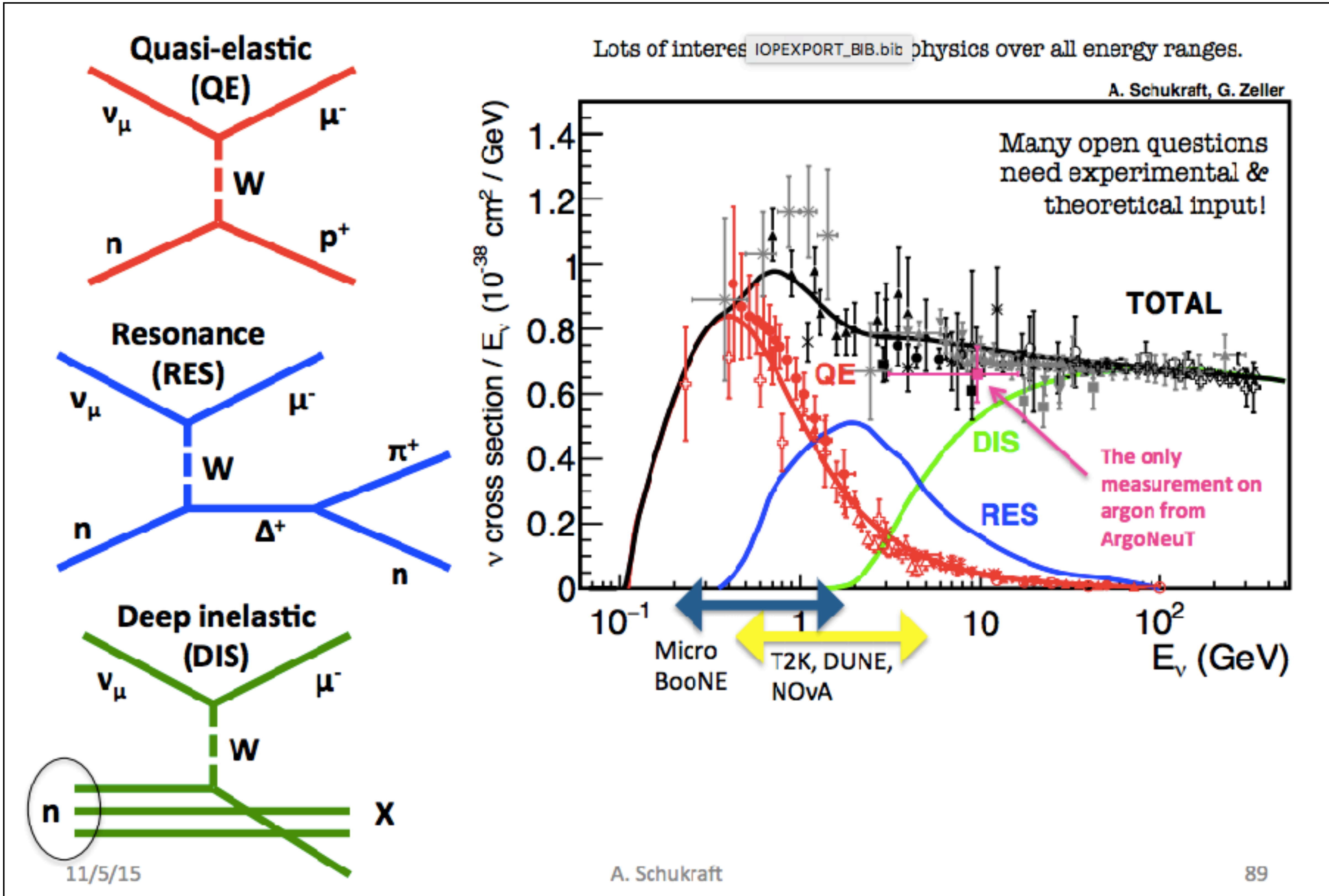
Good wire coverage



All unresponsive wires on all three planes (~10%)

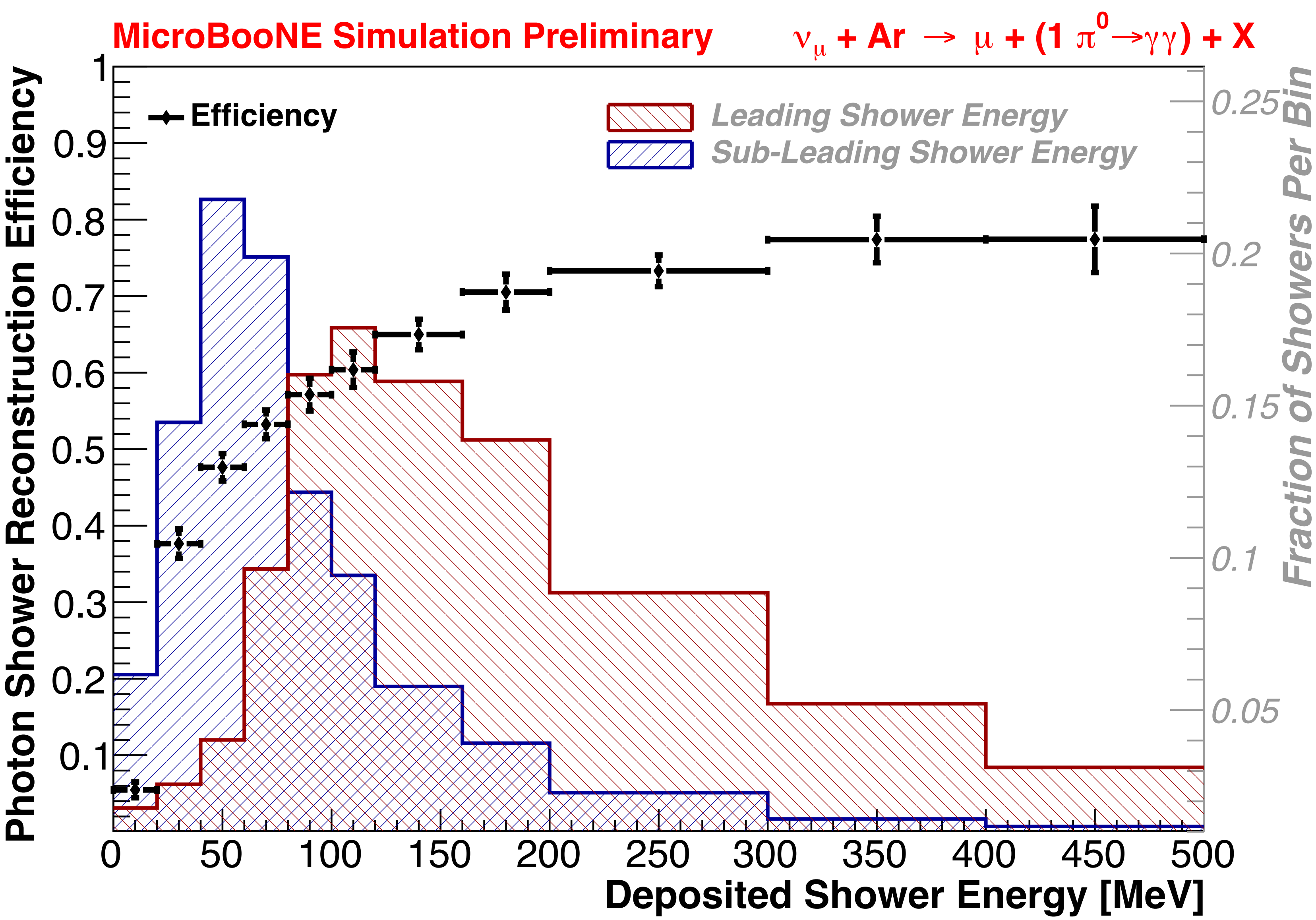
All unresponsive wires with no redundancy (~3%)

Neutrino Interactions with Nucleons



CCPi0

CCpi0 backups



Collected Neutrino 18 Results

Neutrino 18: Sterile Summary

Summary 25

- Anomalies in $\nu_e \to \nu_e$ disappearance and $\nu_\mu \to \nu_e$ appearance experiments point towards conversion mechanisms beyond the well-established 3ν oscillation paradigm;
- each of these anomalies can be **individually** explained by sterile neutrinos;
- sterile neutrinos still succeed in simultaneously explaining groups of anomalies **sharing the same oscillation channel**. However some problem arises:
  - $\nu_e \to \nu_e$ disappearance data face issues with flux normalization and the 5 MeV bump, as well as small tensions in reactor vs gallium and "rates" vs DANSS/NEOS;
  - $\nu_\mu \to \nu_e$ appearance data show an excess in low-E neutrino data, which is not so manifest in antineutrino data.
- in contrast, no anomaly is found in any $\nu_\mu \to \nu_\mu$ disappearance data set;

$\Rightarrow$ sterile neutrino models **fail to simultaneously account** for **all** the $\nu_e \to \nu_e$ data, the $\nu_\mu \to \nu_e$ data and the $\nu_\mu \to \nu_\mu$ data. This conclusion is robust;

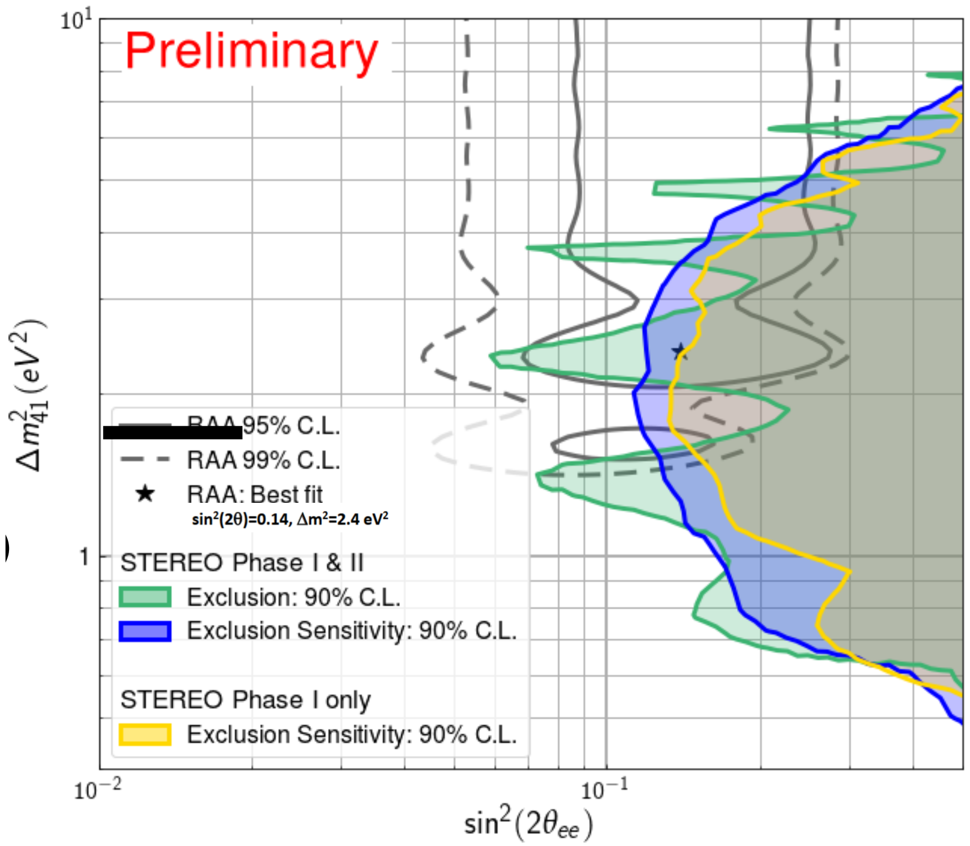
- if the $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_e$ anomalies are confirmed, and the $\nu_\mu \to \nu_\mu$ bounds are not refuted, new physics will be needed. Such new physics may well involve extra sterile neutrinos, but together with something else (or some "unusual" neutrino property).

Michele Maltoni <michele.maltoni@csic.es> NEUTRINO 2018, 8/06/2018

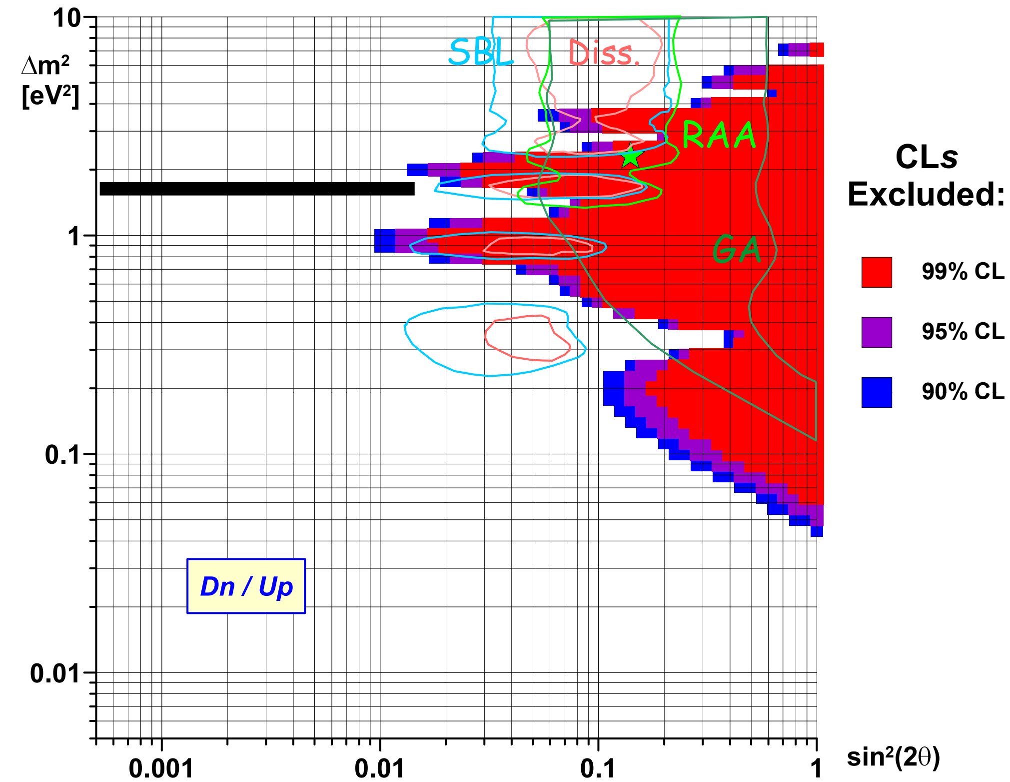
https://zenodo.org/record/1287015#.WyKcxRJKjOQ

Neutrino 18: Reactor Results

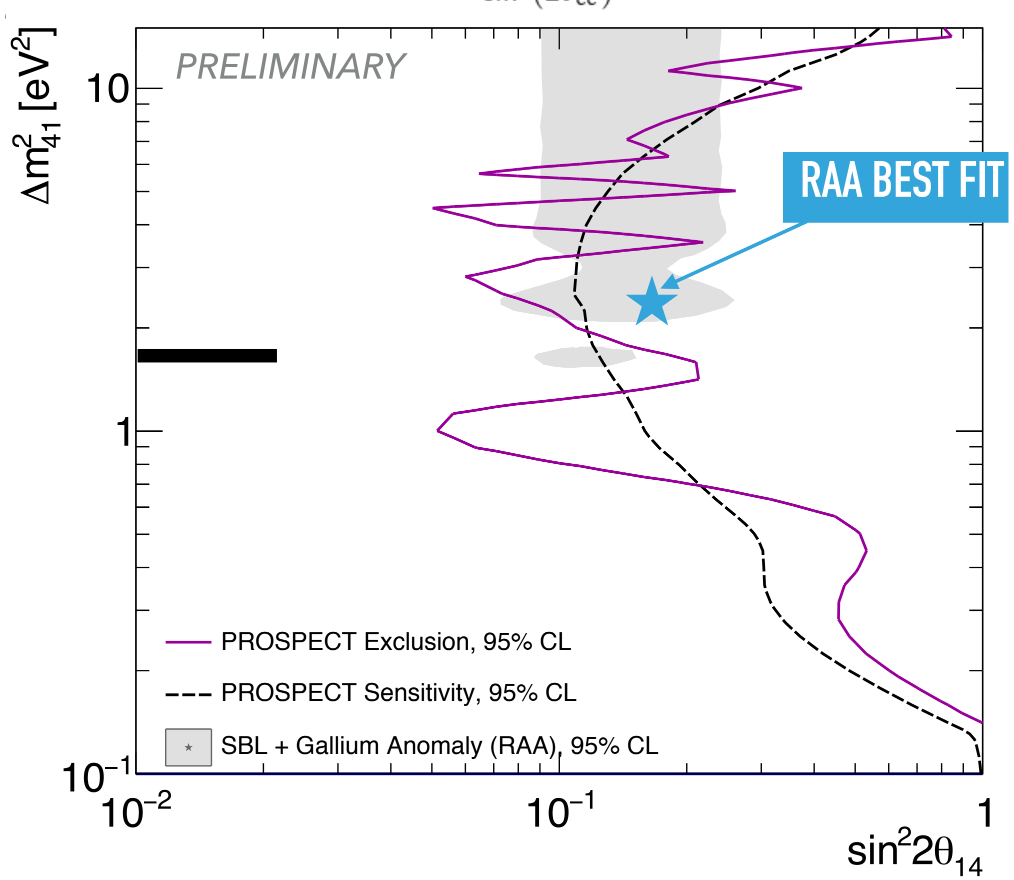
STEREO



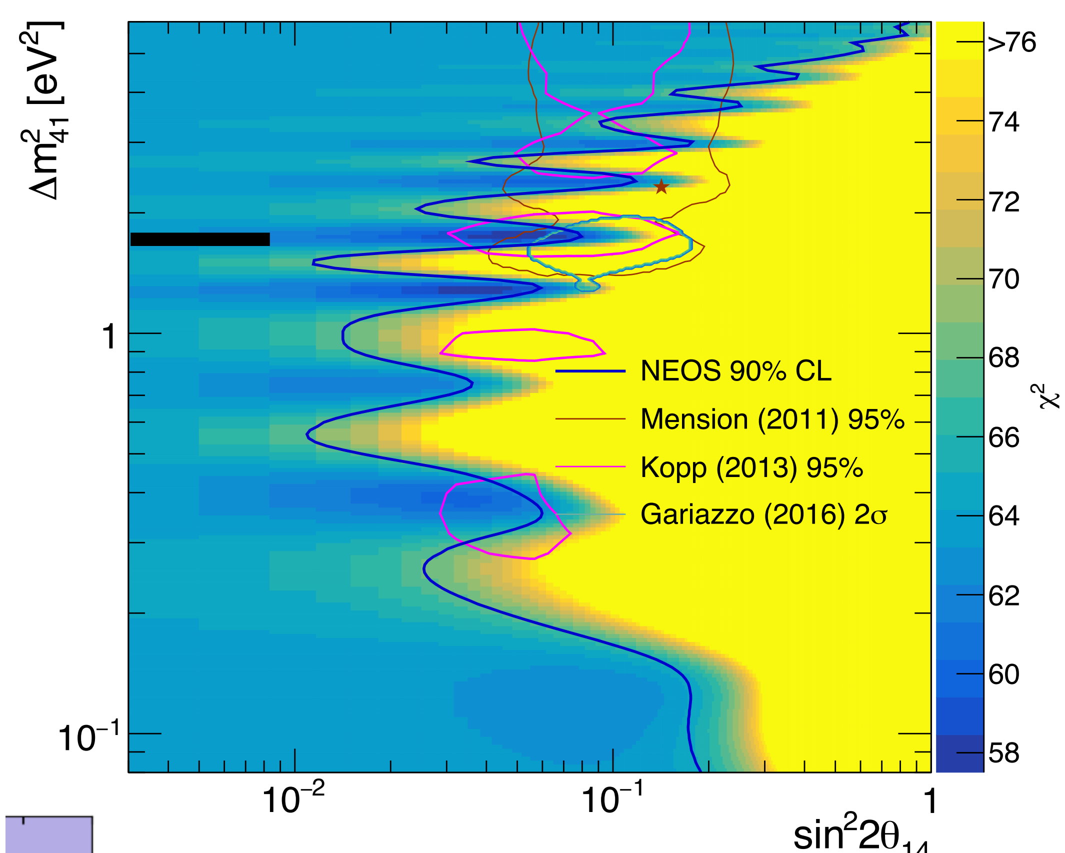
DANSS



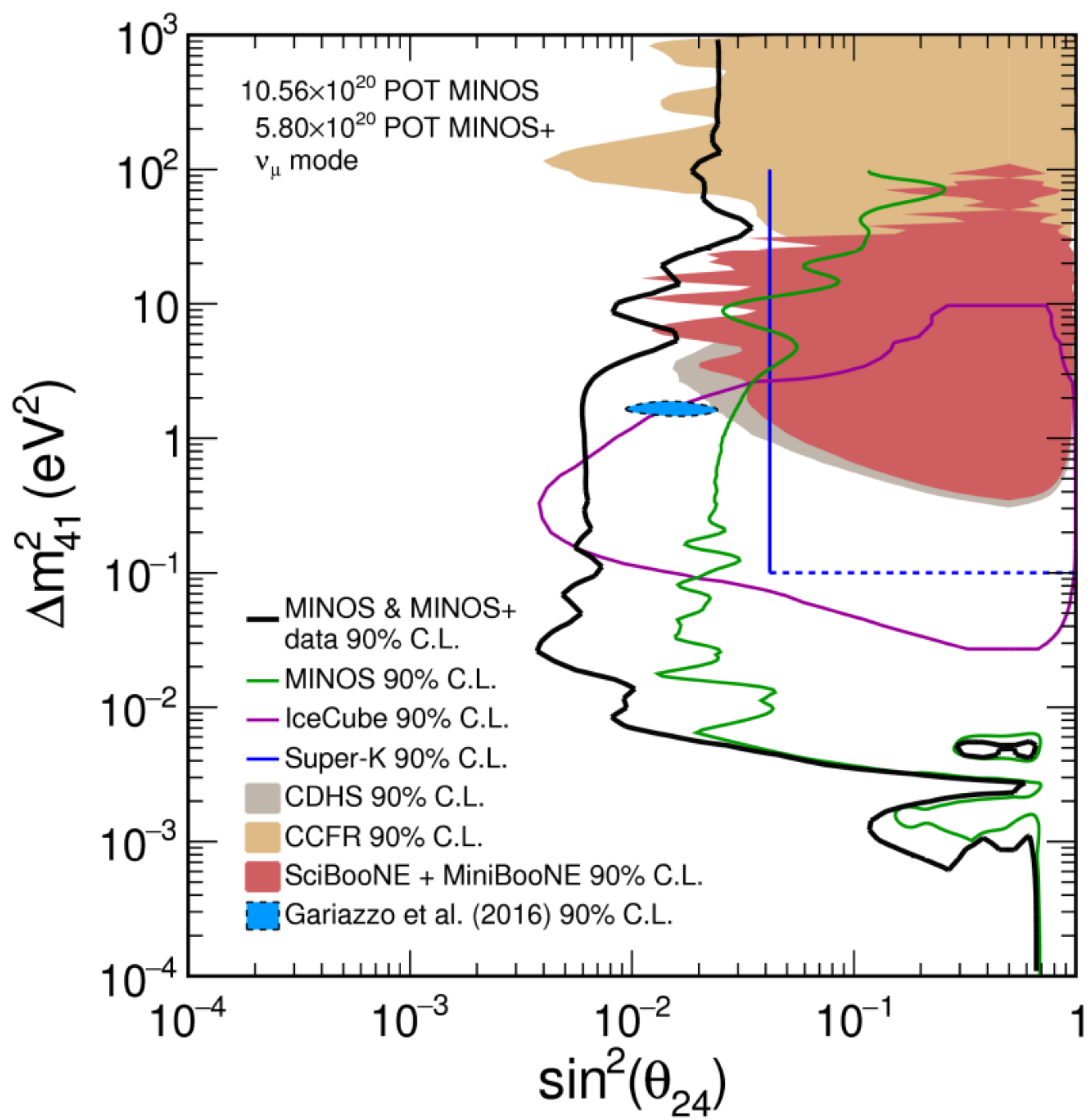
PROSPECT



NEOS

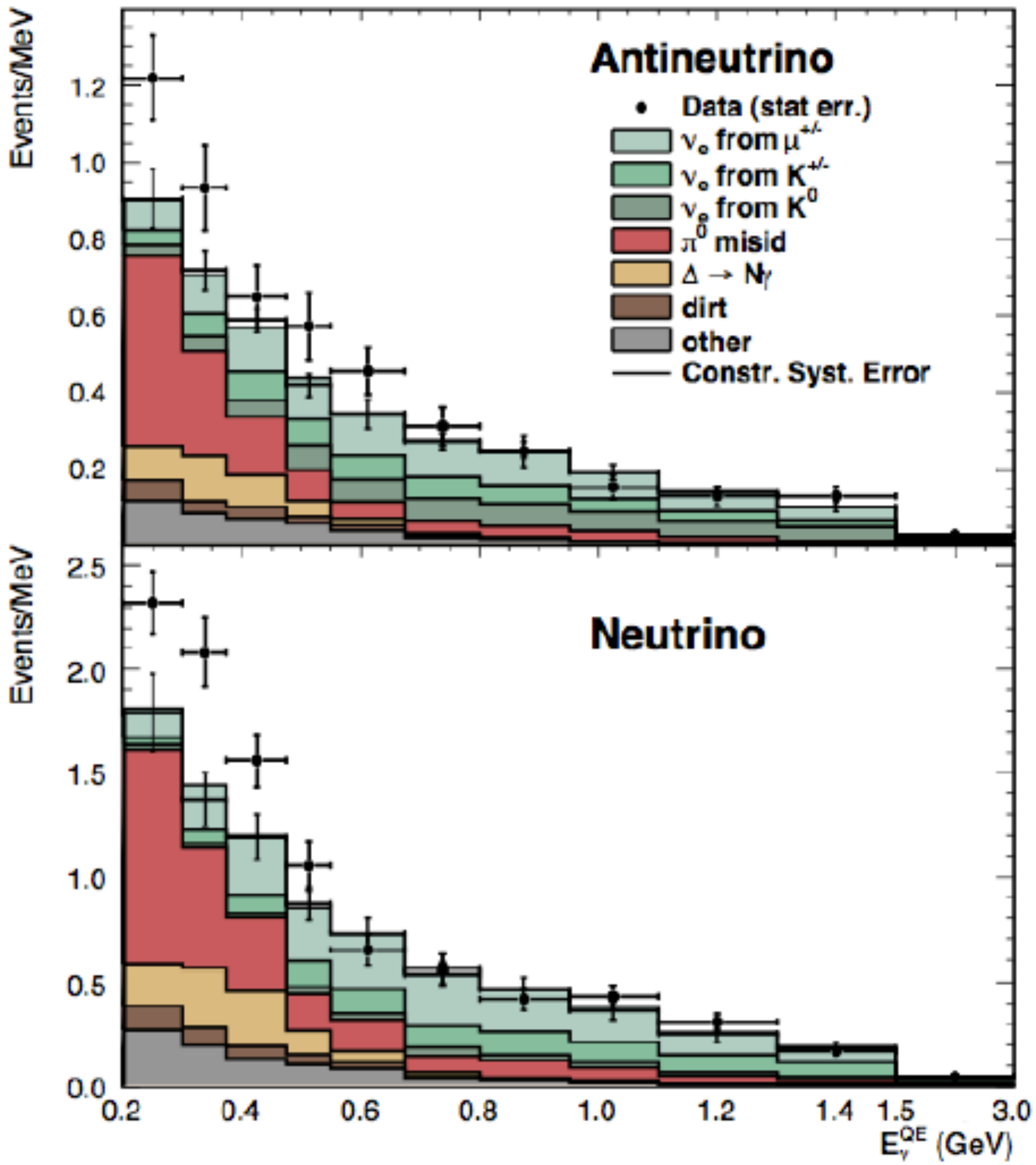


Neutrino 18: MINOS+

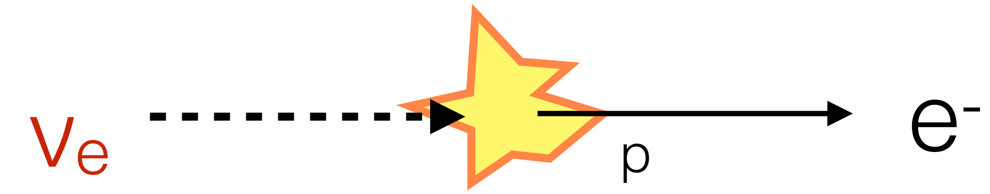


MINIBOONE EXCESS BACKUPS

MiniBoonE Low Energy Excess

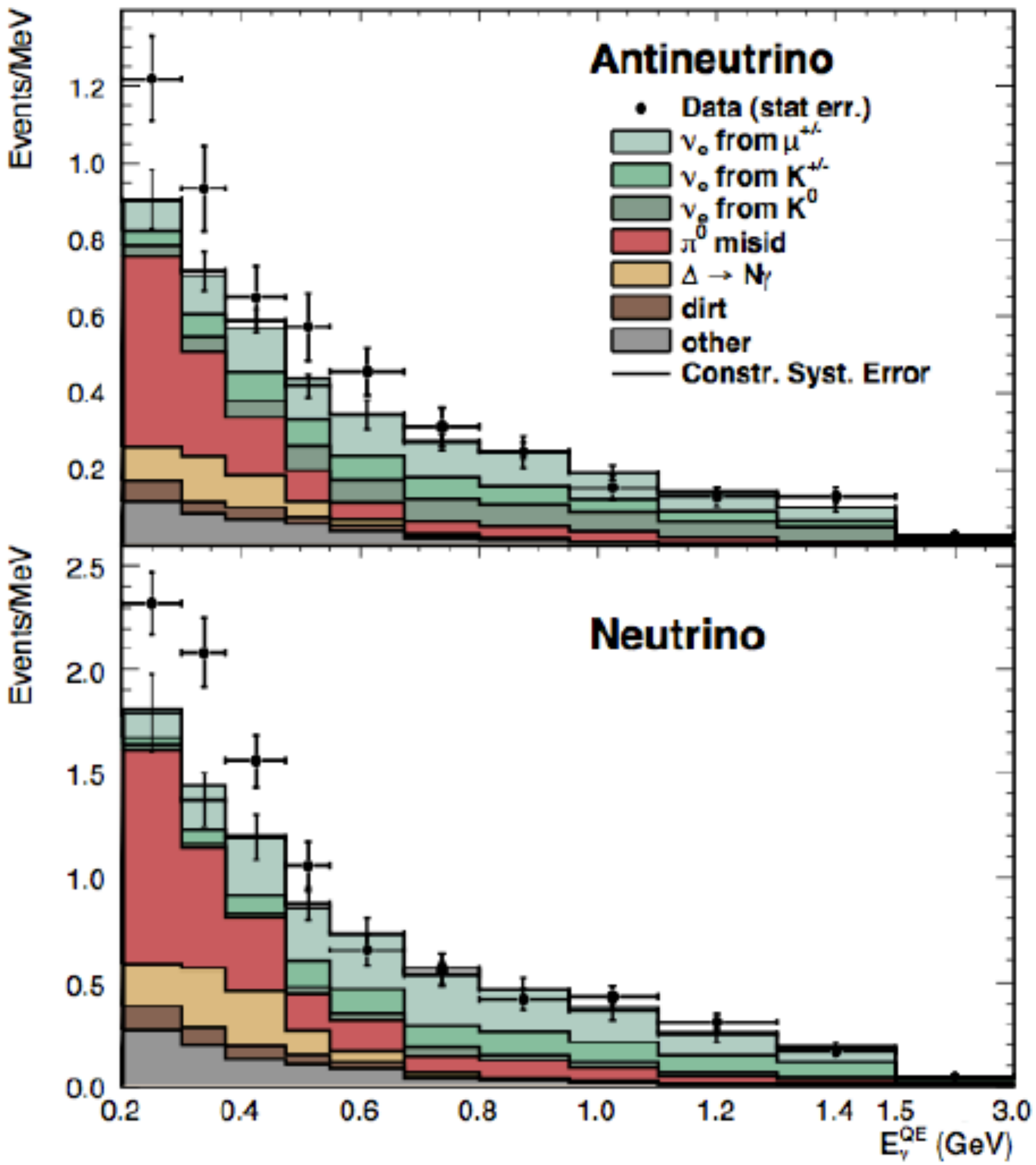


Phys. Rev. Lett. 110, 161801 (2013)

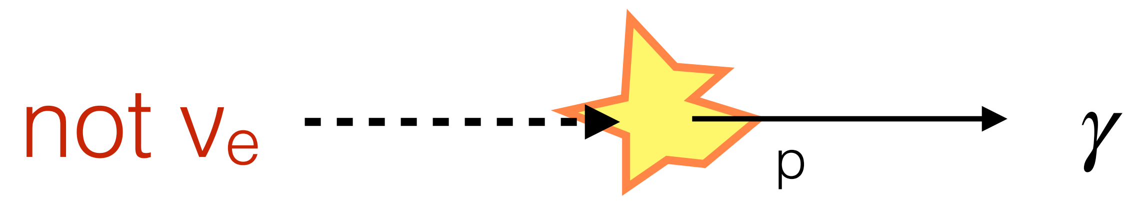


- MiniBooNE saw an excess of (anti-)electron neutrino events at low energy
- Potential explanation:
  - Neutrino oscillations, but at this distance (500 m) incompatible with previous measurements like Super-K
  - possible explanation are ***sterile neutrinos!***

MiniBoonE Low Energy Excess



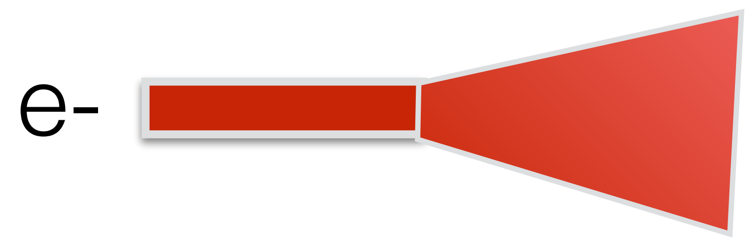
Phys. Rev. Lett. 110, 161801 (2013)



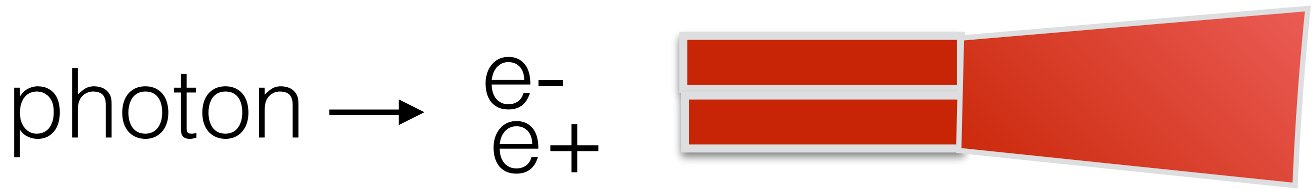
- Other possibilities for the excess
    - due to mis-id backgrounds, such as photons coming from some un-modeled neutrino process
- Need a detector that can distinguish photon vs. electrons and potentially address these other issues

Photons versus Electrons in LArTPCs

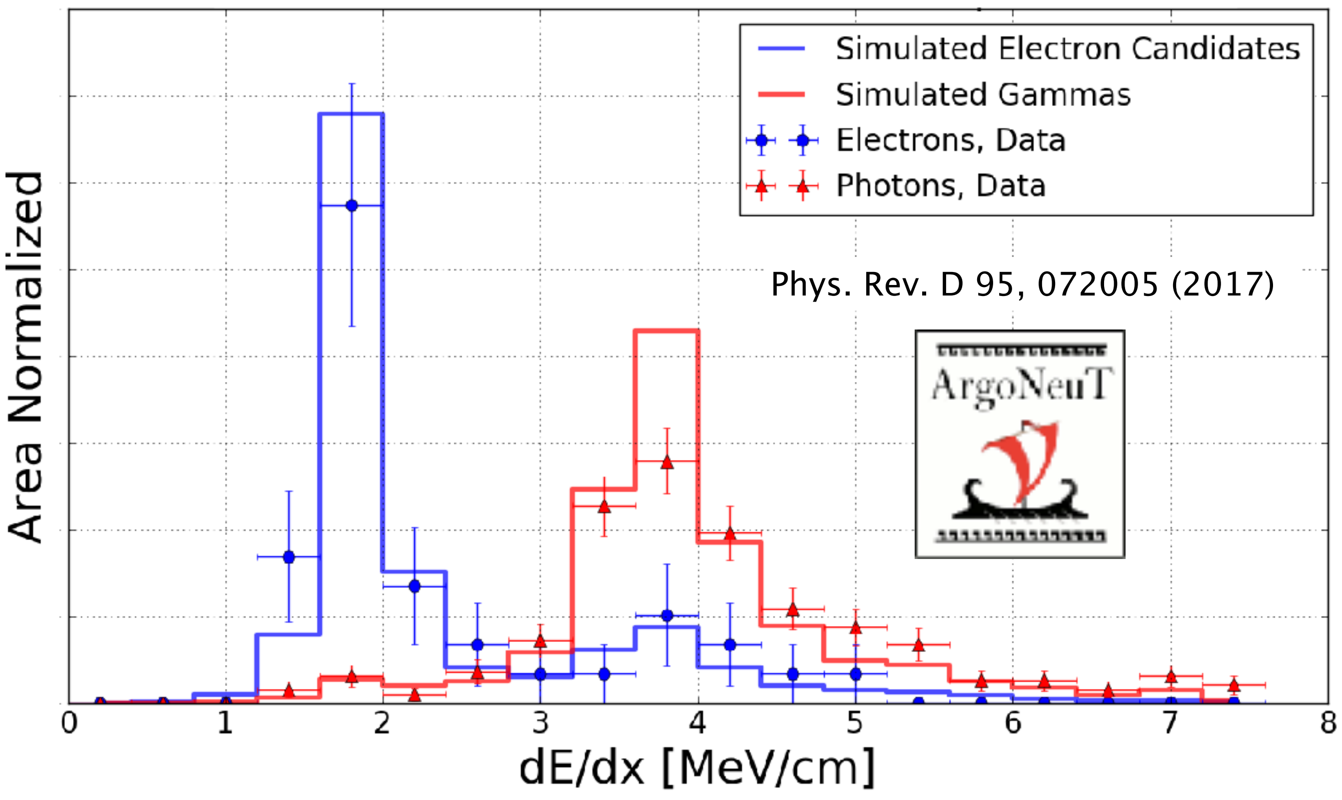
Electron leaves one unit of charge near start of shower



Photon converts (much of the time), leaves two unit of charge

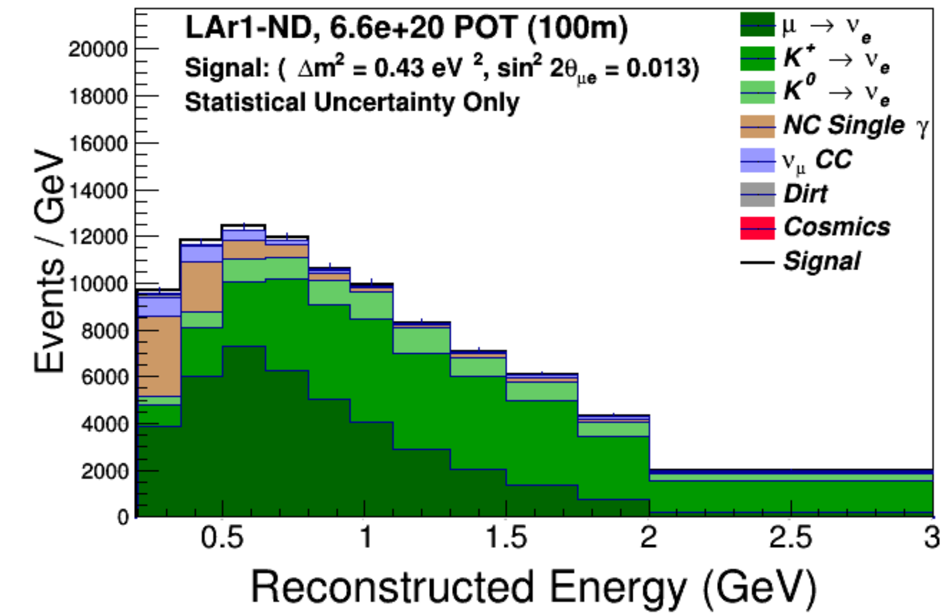


Demonstration of handle in the ArgoNeuT Detector

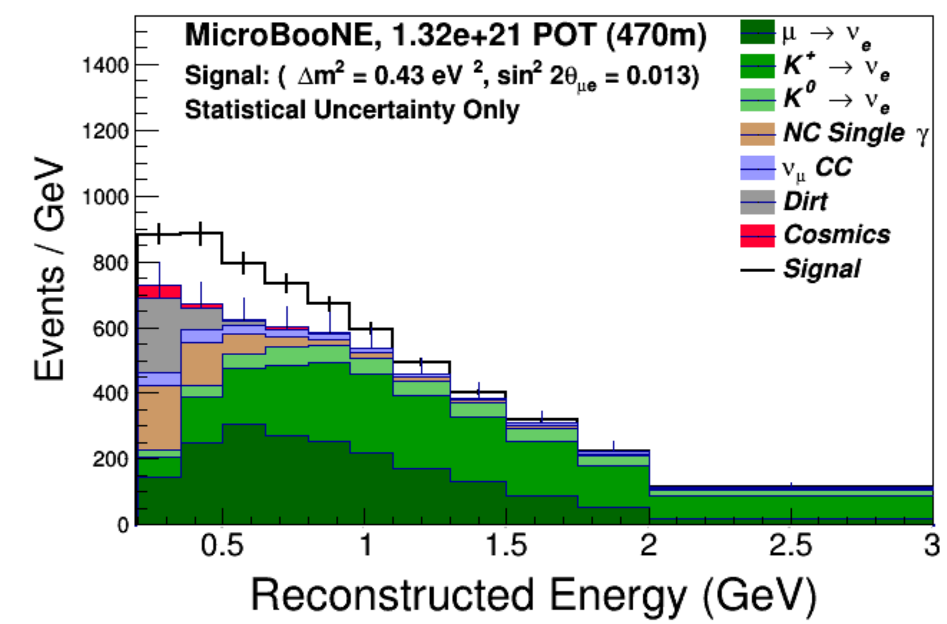


SBN BACKUPS

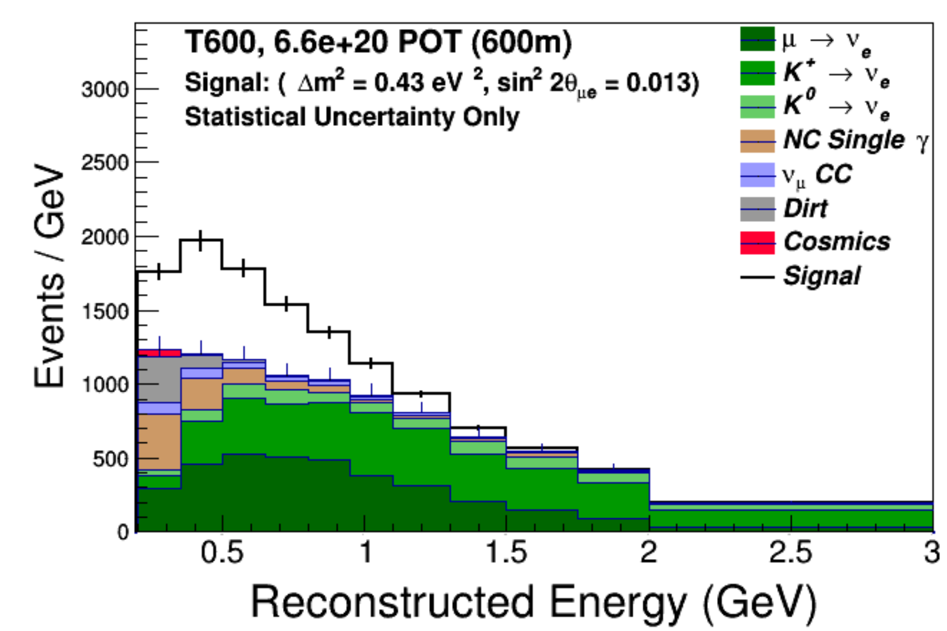
Rate



LAr1-ND, 6.6e+20 POT (100m)
Signal: (Δm² = 0.43 eV ², sin² 2θ_μe = 0.013)
Statistical Uncertainty Only
μ → ν_e
K⁺ → ν_e
K⁰ → ν_e
NC Single γ
ν_μ CC
Dirt
Cosmics
Signal
Events / GeV
Reconstructed Energy (GeV)



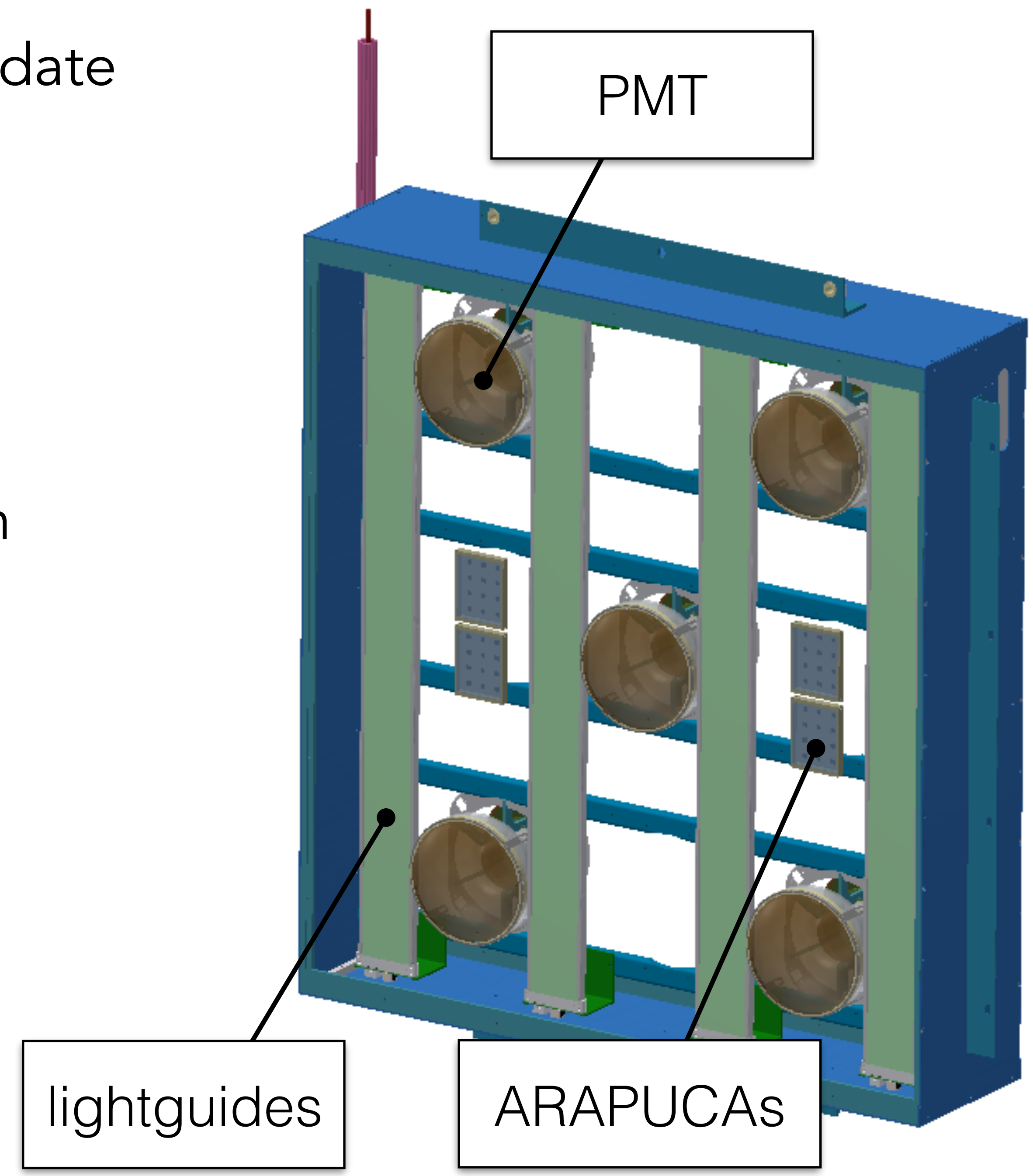
MicroBooNE, 1.32e+21 POT (470m)
Signal: (Δm² = 0.43 eV ², sin² 2θ_μe = 0.013)
Statistical Uncertainty Only
μ → ν_e
K⁺ → ν_e
K⁰ → ν_e
NC Single γ
ν_μ CC
Dirt
Cosmics
Signal
Events / GeV
Reconstructed Energy (GeV)



T600, 6.6e+20 POT (600m)
Signal: (Δm² = 0.43 eV ², sin² 2θ_μe = 0.013)
Statistical Uncertainty Only
μ → ν_e
K⁺ → ν_e
K⁰ → ν_e
NC Single γ
ν_μ CC
Dirt
Cosmics
Signal
Events / GeV
Reconstructed Energy (GeV)

Status: SBND

- SBND performing R&D with candidate DUNE technologies
- E.g. Photon detection system will test candidate several candidate technologies
- operating side-by-side
    - PMT system (uB and ICARAUS-like) serves as reference to well-known system
    - Light-guide bars
    - ARAPUCAS
    - Reflecting foils to increase light-yield



DL BACKUPS

ConvNets In a Slide

- ConvNets work by finding complex, hierarchal features to represent abstract information in images
- Begin with image pixels (layer 1)
- Start by applying convolutions of simple patterns (layer 2)
- Find groups of patterns by applying convolution on feature maps (layer 3)
- Repeat
- Eventually patterns of patterns can be identified as faces (layer 4)