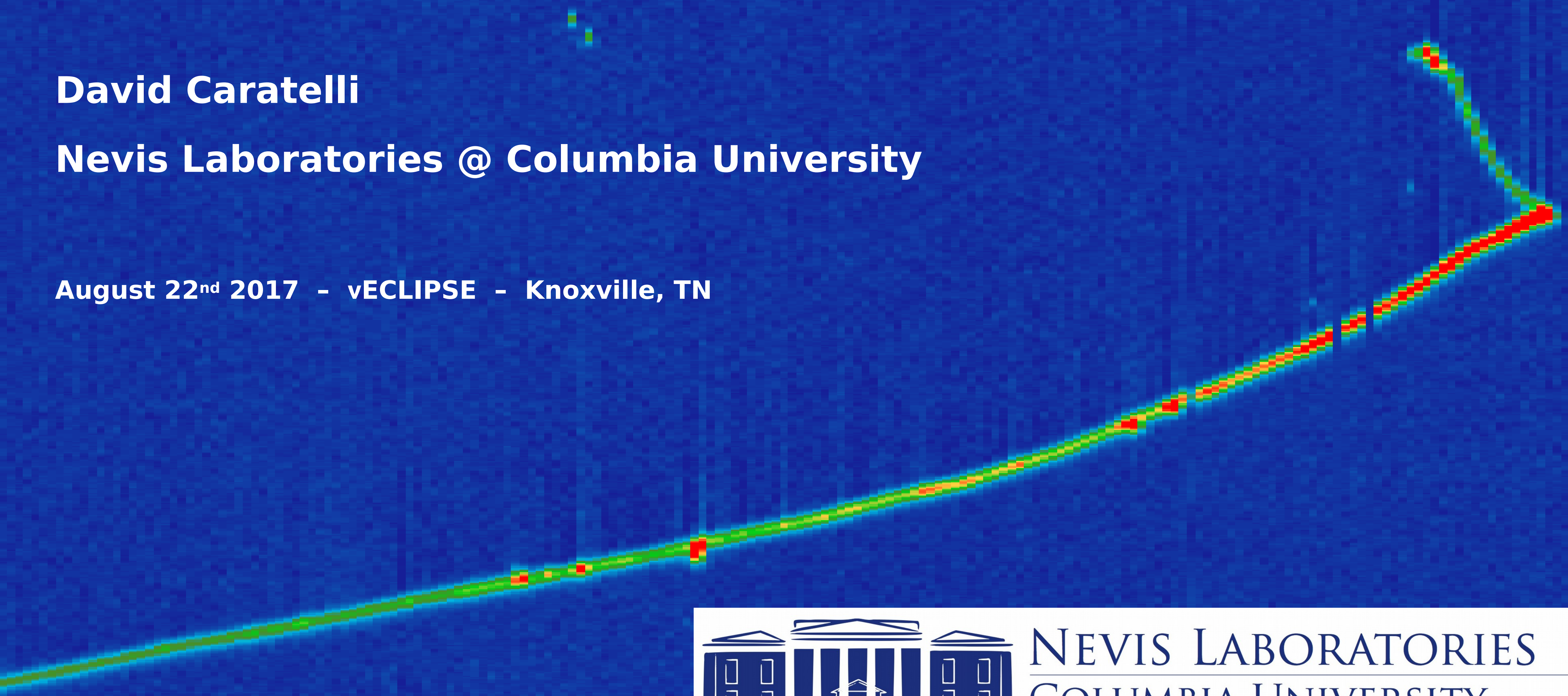
Low Energy Electron Reconstruction with MicroBooNE's LArTPC



David Caratelli

Nevis Laboratories @ Columbia University

August 22nd 2017 – νECLIPSE – Knoxville, TN

Outline

- MicroBooNE and LAr-TPCs, potential for physics at $\mathcal{O}$(10 MeV).
- Reconstructing low energy electrons in MicroBooNE.
- Going to even lower energies.

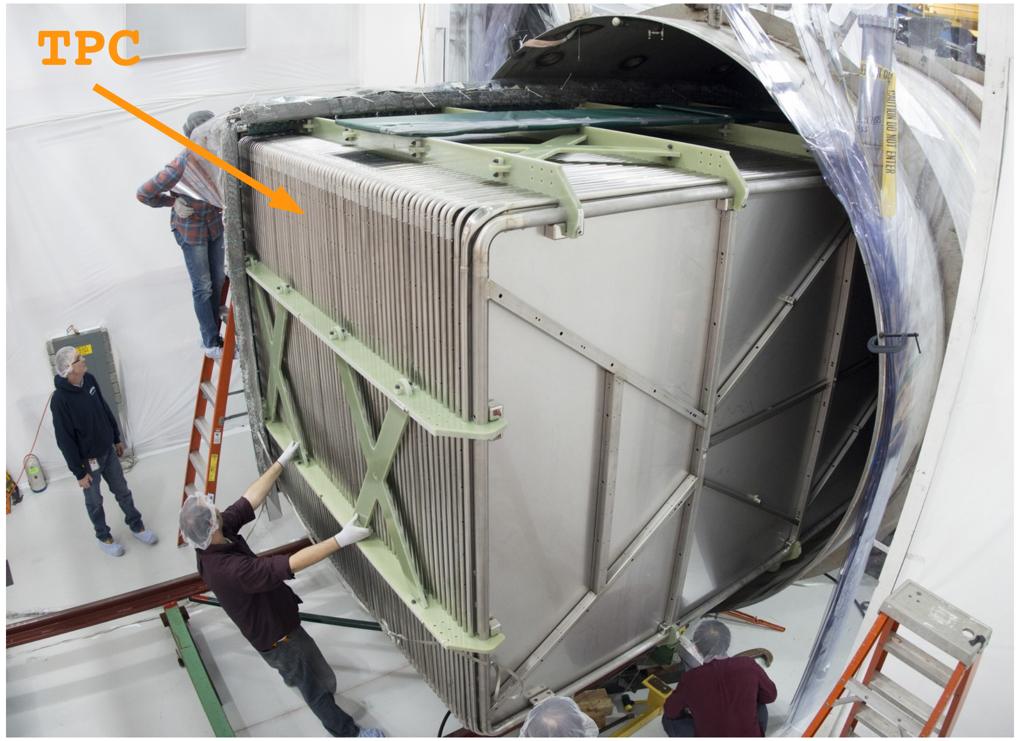
The MicroBooNE Experiment

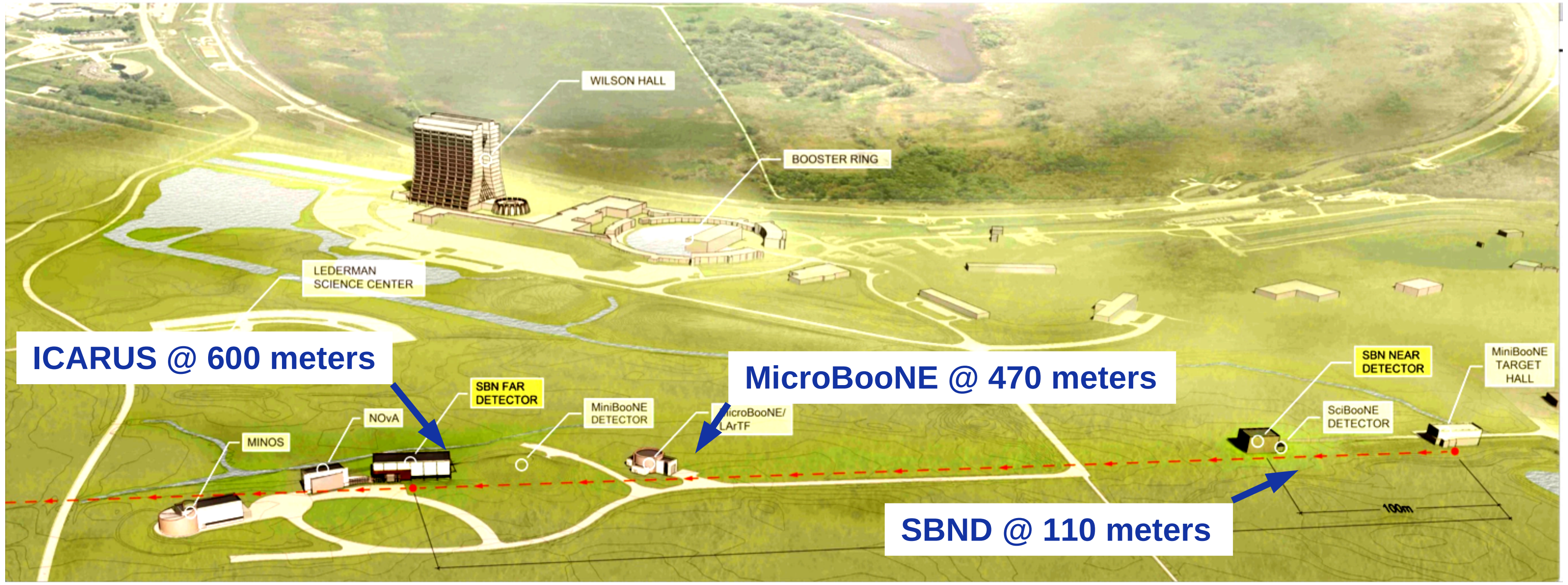
Neutrino experiment at Fermilab sitting on the Booster Neutrino Beamline O(1 GeV) ν_μ beam.

Taking data since fall ‘15.

Investigate MiniBooNE’s excess of low energy electron-like neutrino events below 500 MeV. Neutrino oscillations?

First of 3 detectors in the Short Baseline Neutrino program studying potential neutrino oscillations at 1 eV^2.

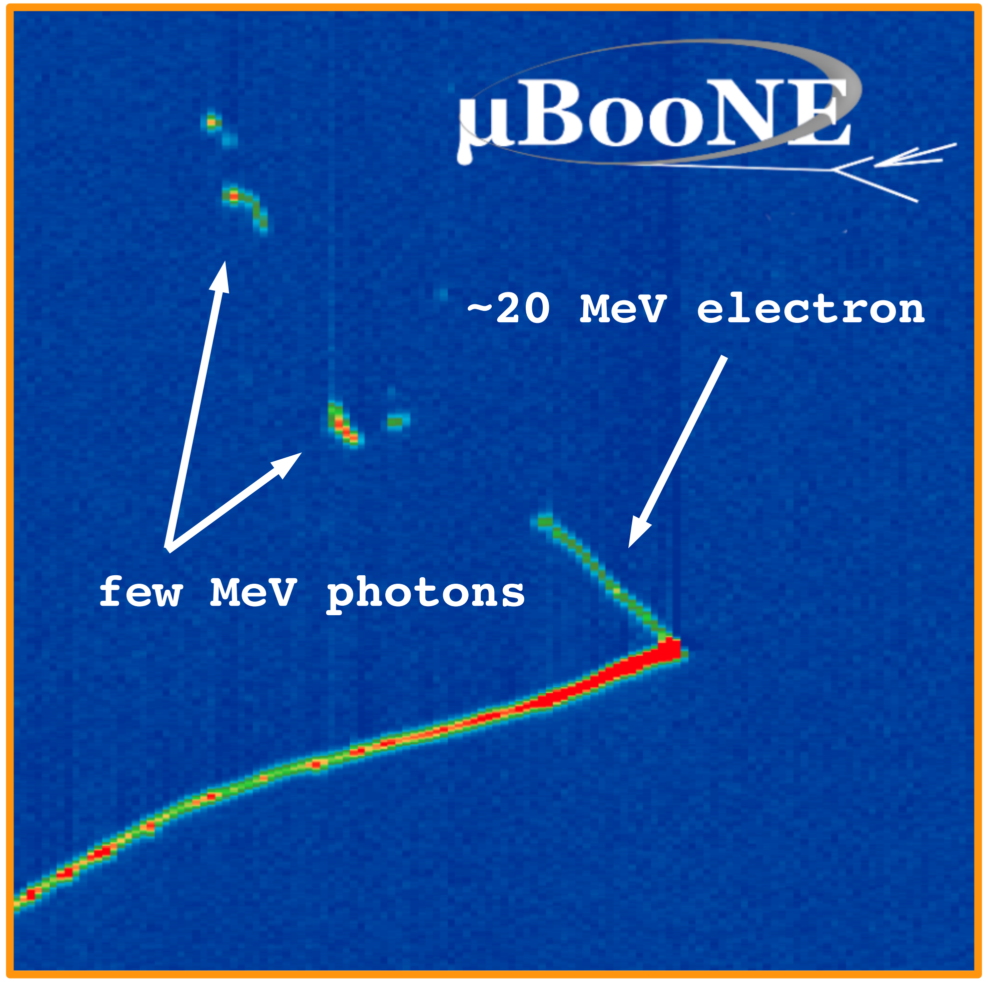


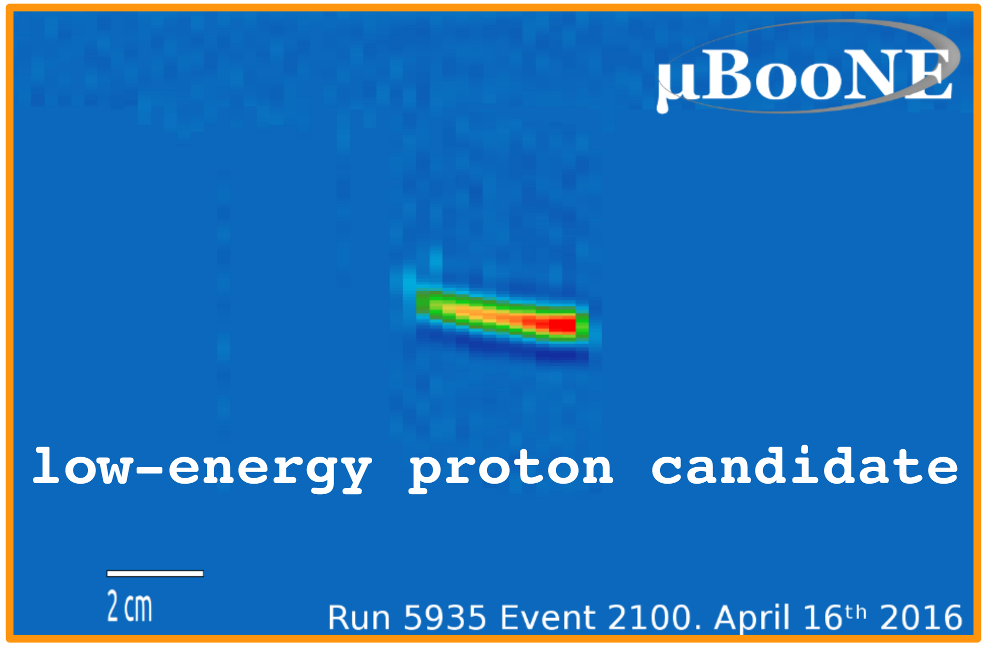


What does a LAr-TPC have to offer at low energy?

3 mm wire spacing → good spatial resolution.

Pre-amplifiers in cold argon → high signal-to-noise.





See MicroBooNE note on NC elastic events
www-microboone.fnal.gov/publications/publicnotes/
MICROBOONE-NOTE-1025-PUB.pdf

Low detection thresholds and "fully-active" fine grained detector → contributions to neutrino physics at tens of MeV energies in large-scale LAr-TPCs.

Physics Motivation

Supenova Neutrino Burst:

- 5-50 MeV neutrinos.
- 100 ν_e interactions / kiloton mass.

Visible channels:

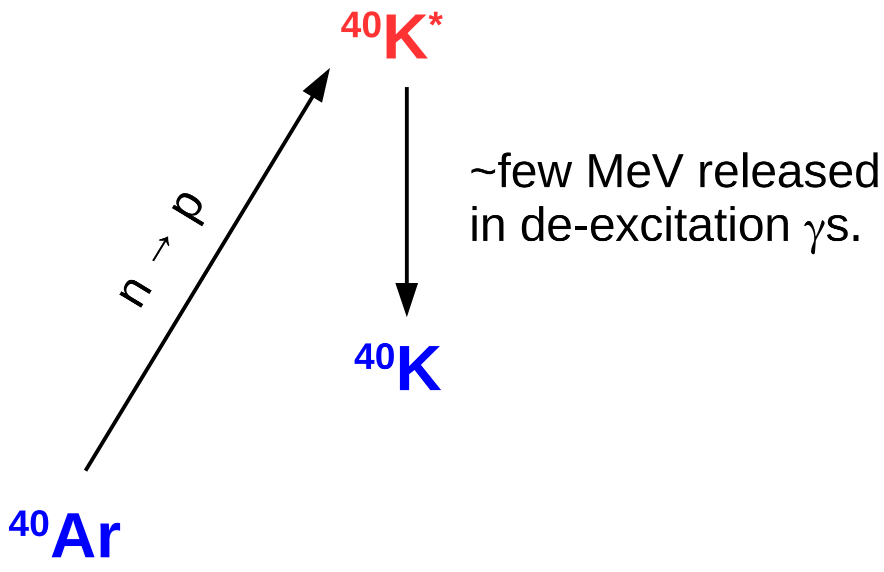
$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ ⟶ CC: Largest statistics. ${}^{40}K^* \rightarrow \gamma \rightarrow e$

$\bar{\nu}_e + {}^{40}Ar \rightarrow e^- + {}^{40}Cl^*$ ⟶ CC: Lower xsec

$\nu_x + e^- \rightarrow \nu_x + e^-$ ⟶ NC: All ν species. Good directionality

Relevant Questions:

- How to identify low energy electrons?
- What about de-excitation photons?
- What resolution / efficiency is needed to reach physics goals?



Other interesting physics:

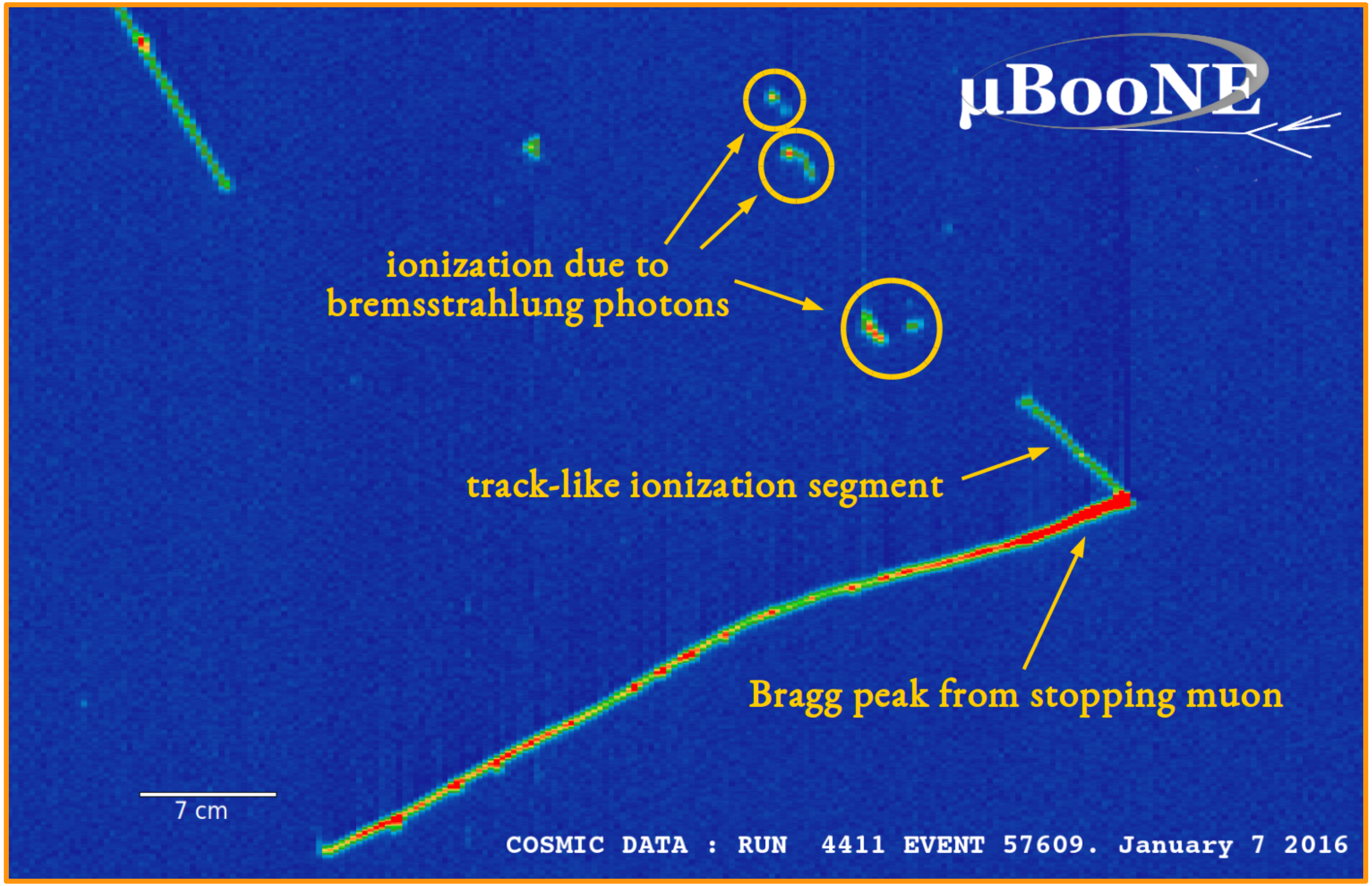
- neutrinos from stopped pion beam.
- cross-sections at low energies.
- Solar neutrinos.

<u>This talk: what are the challenges of reconstructing electrons in this energy range? With what energy resolution?</u>

“Michel Electron Reconstruction Using Cosmic-Ray Data from the MicroBooNE LArTPC”

arXiv:1704.02927 accepted for publication in JINST

What do Michel electrons look like?



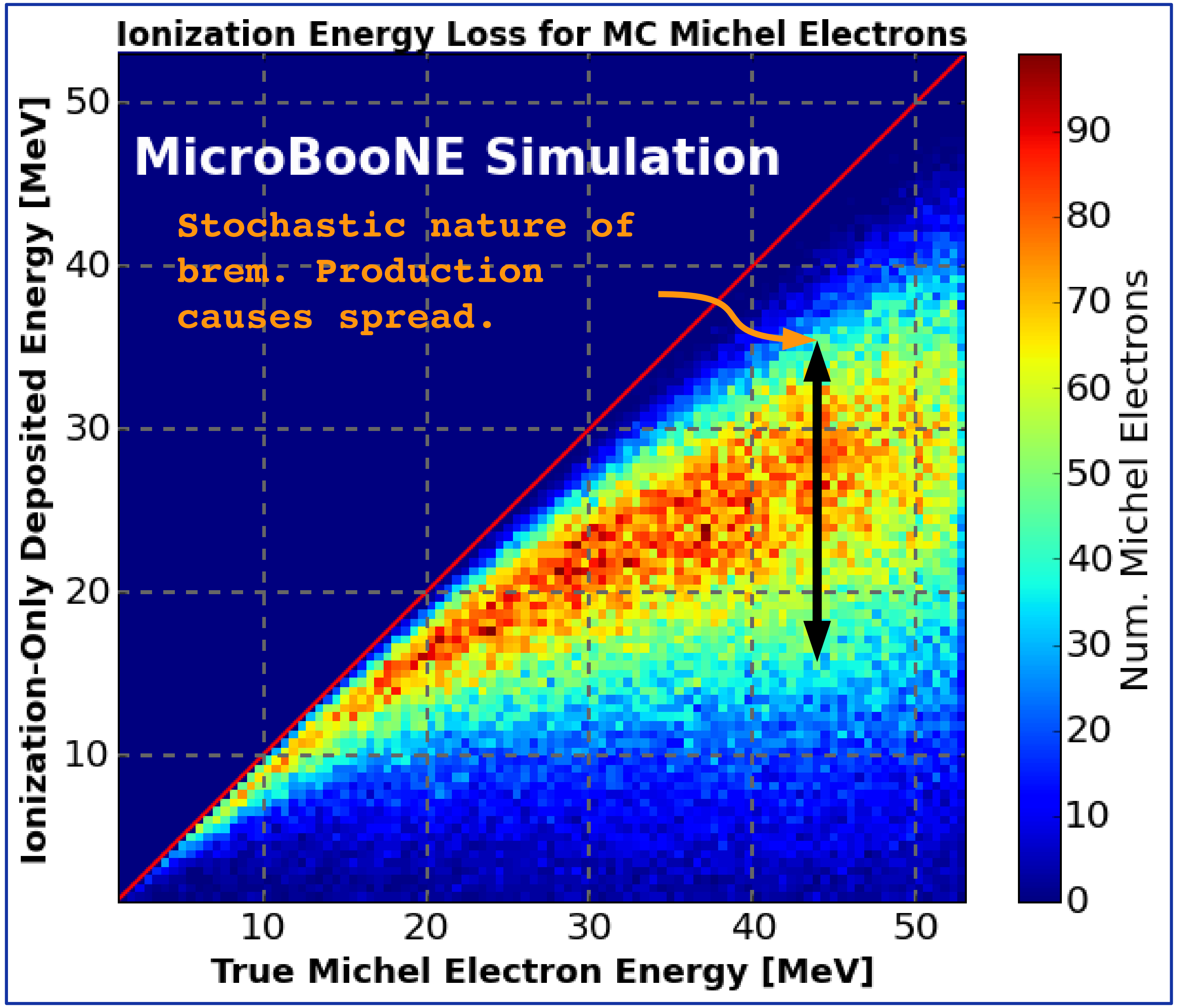
Michel electrons : impact of radiative energy loss

Similar contributions to energy loss from bremsstrahlung photons and ionization.

→ Complex topology.

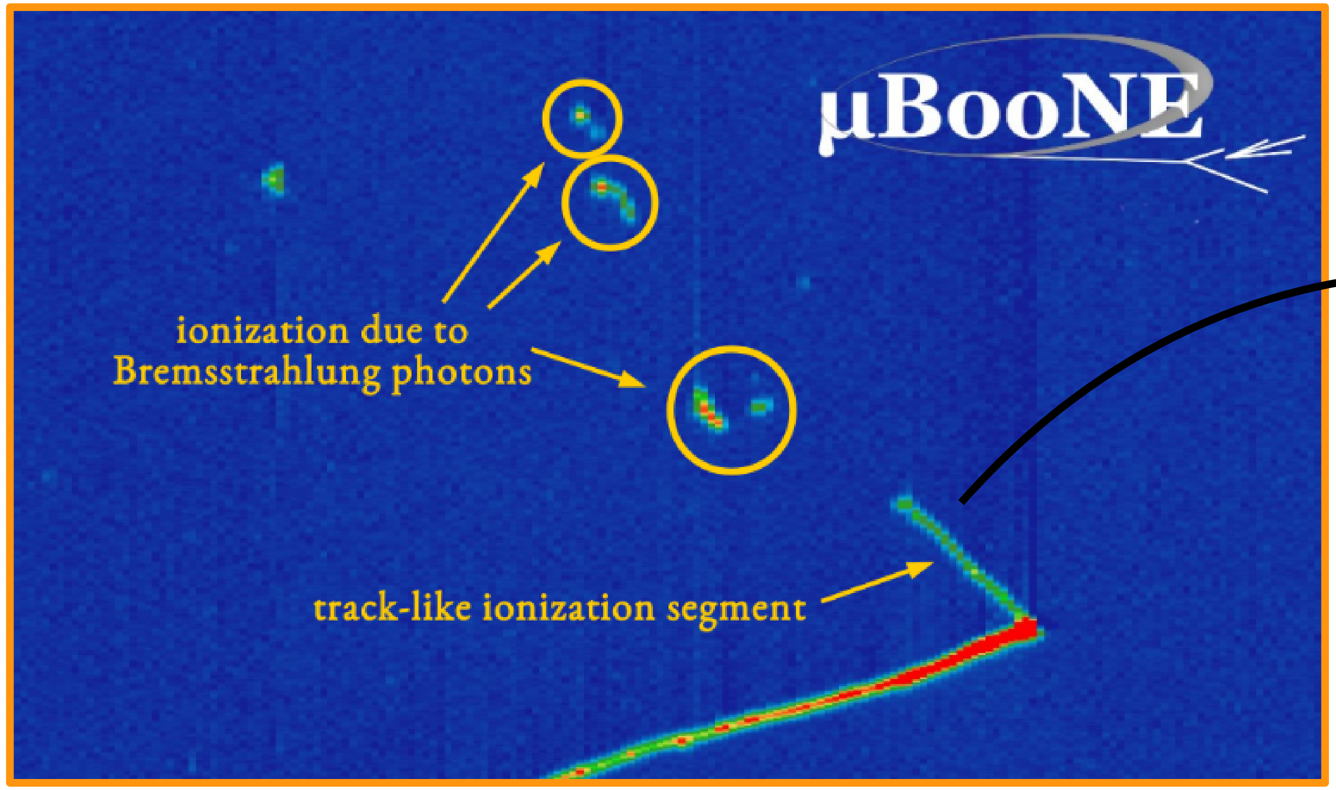
Stochastic nature of bremsstrahlung photon production:

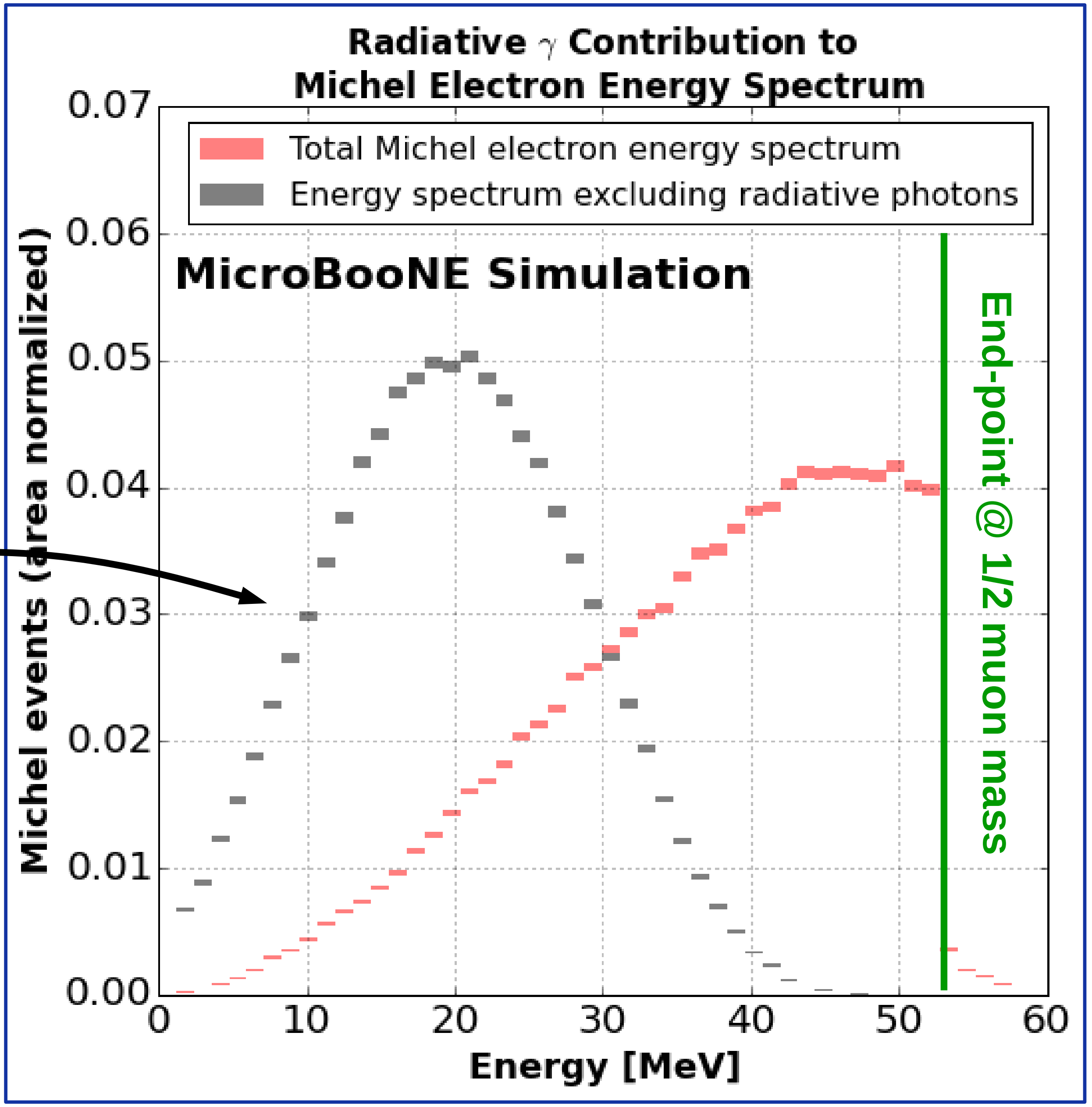
→ "Ionization-only" energy not sufficient for good energy resolution.



Michel electrons : impact of radiative energy loss

Missing energy from radiative photons has a significant impact on the Michel energy spectrum.



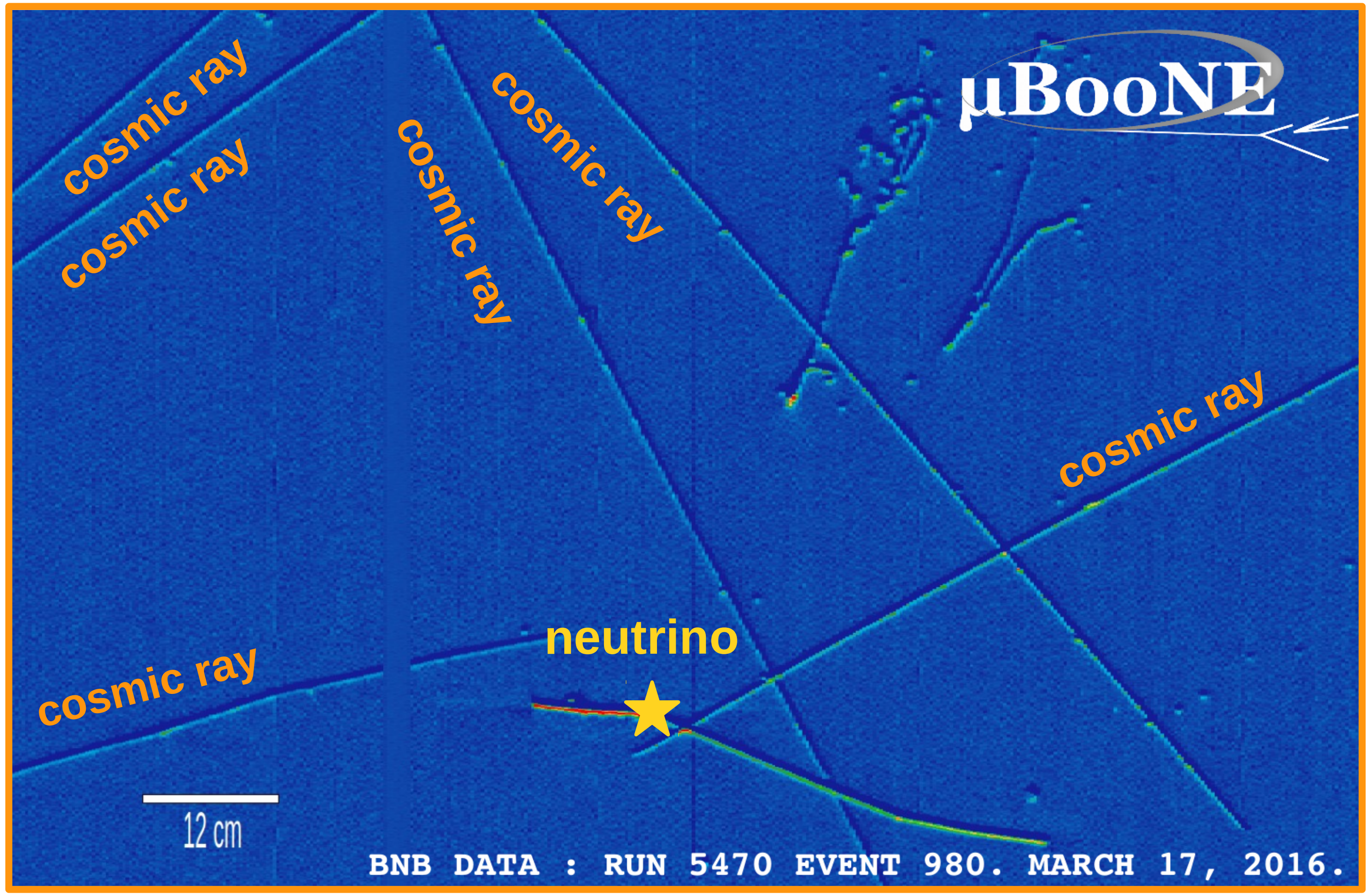


Challenges to Reconstruction

Radiative photons are challenging to identify because:

1) few MeV gammas require low detection threshold.

2) Hard to collect all far-reaching gammas, especially in a “busy” detector with pileup from cosmic-rays.

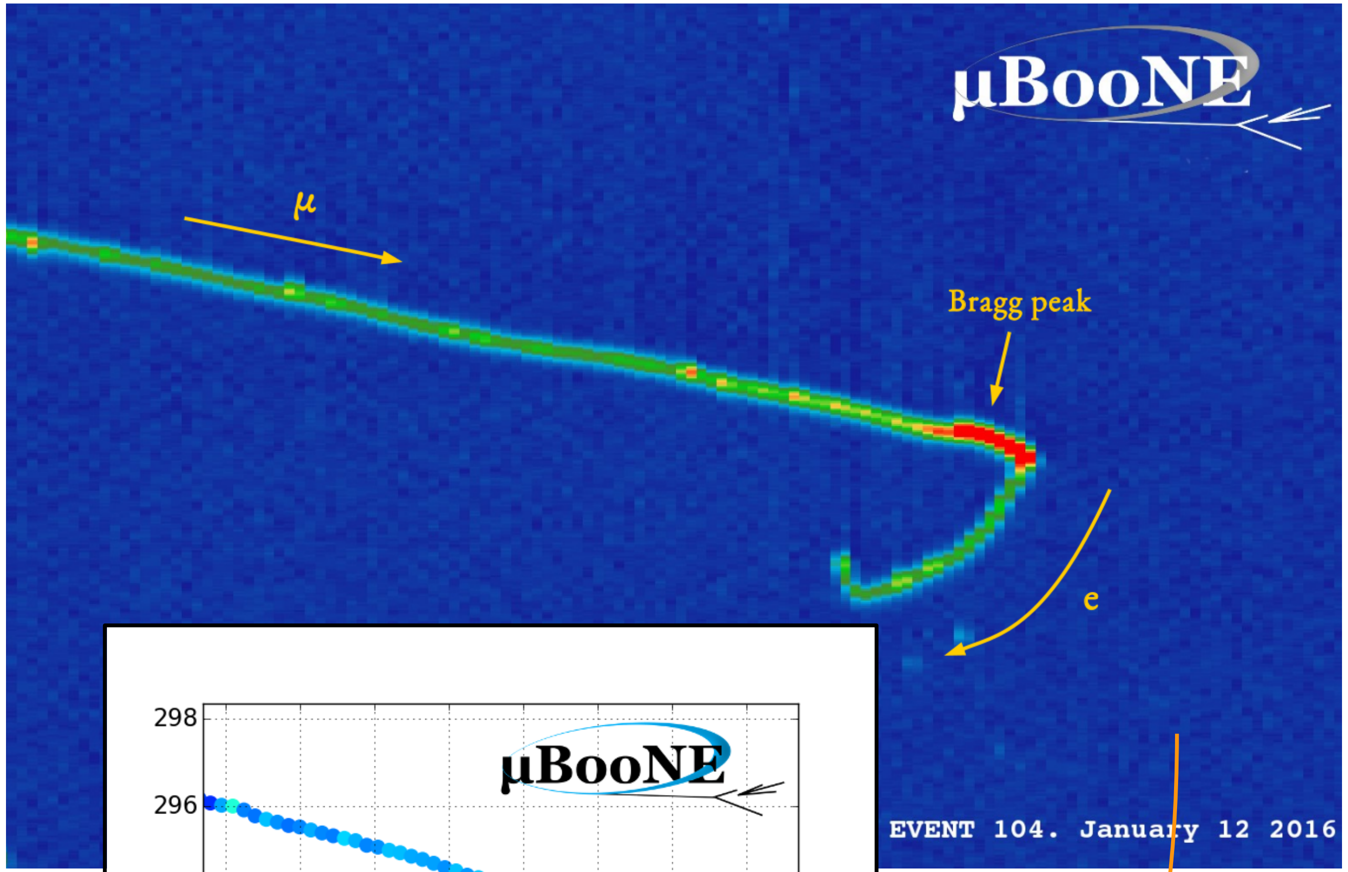


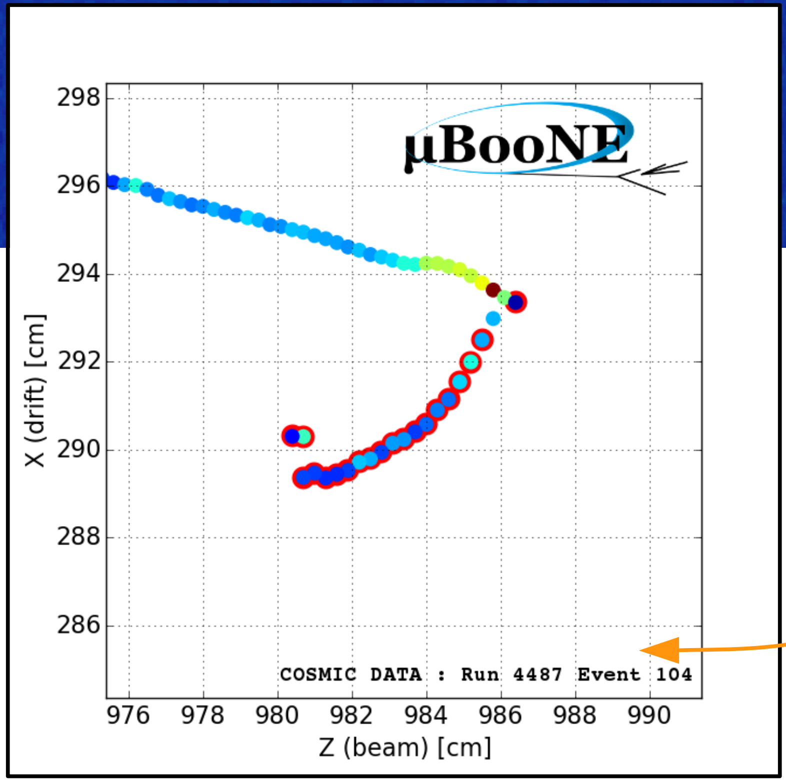
“long exposure” image due to slow electron drift → many cosmic-ray tracks overlap neutrino image in surface detector.

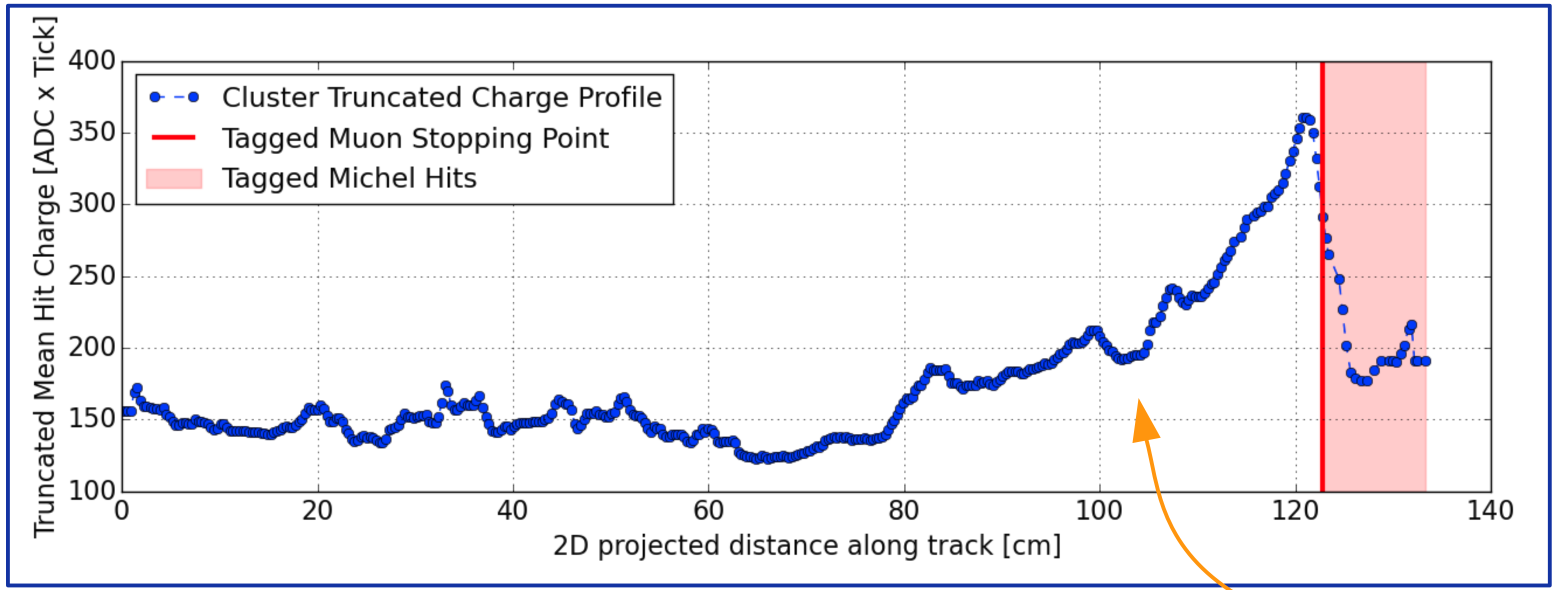
Michel electrons : reconstruction

Analysis relies on 2D reconstruction which identifies Bragg peak and electron "kink" from collection-plane image.

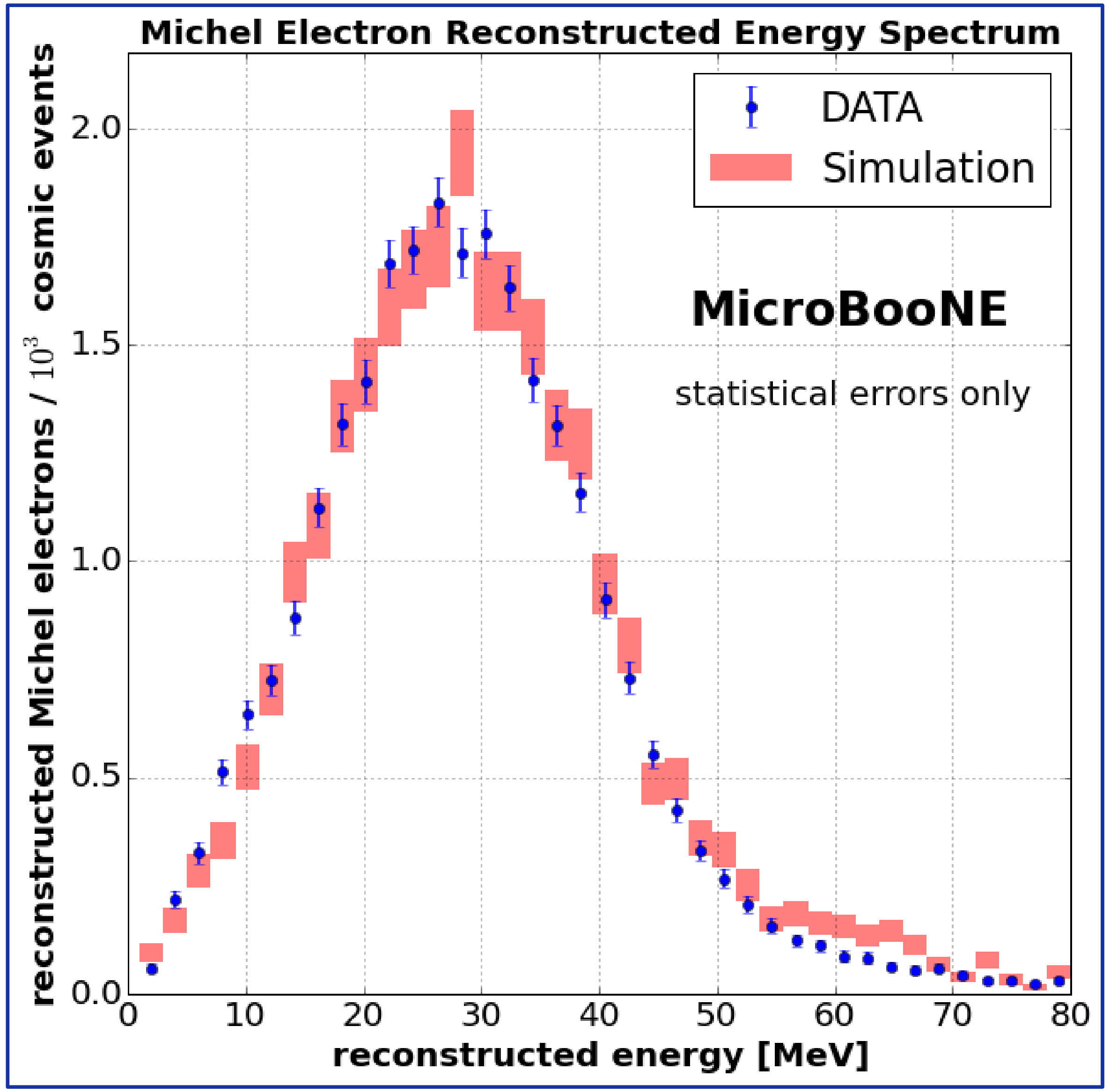
Tag bremsstrahlung photons up to 80 cm from decay, avoid cosmic accidentals.

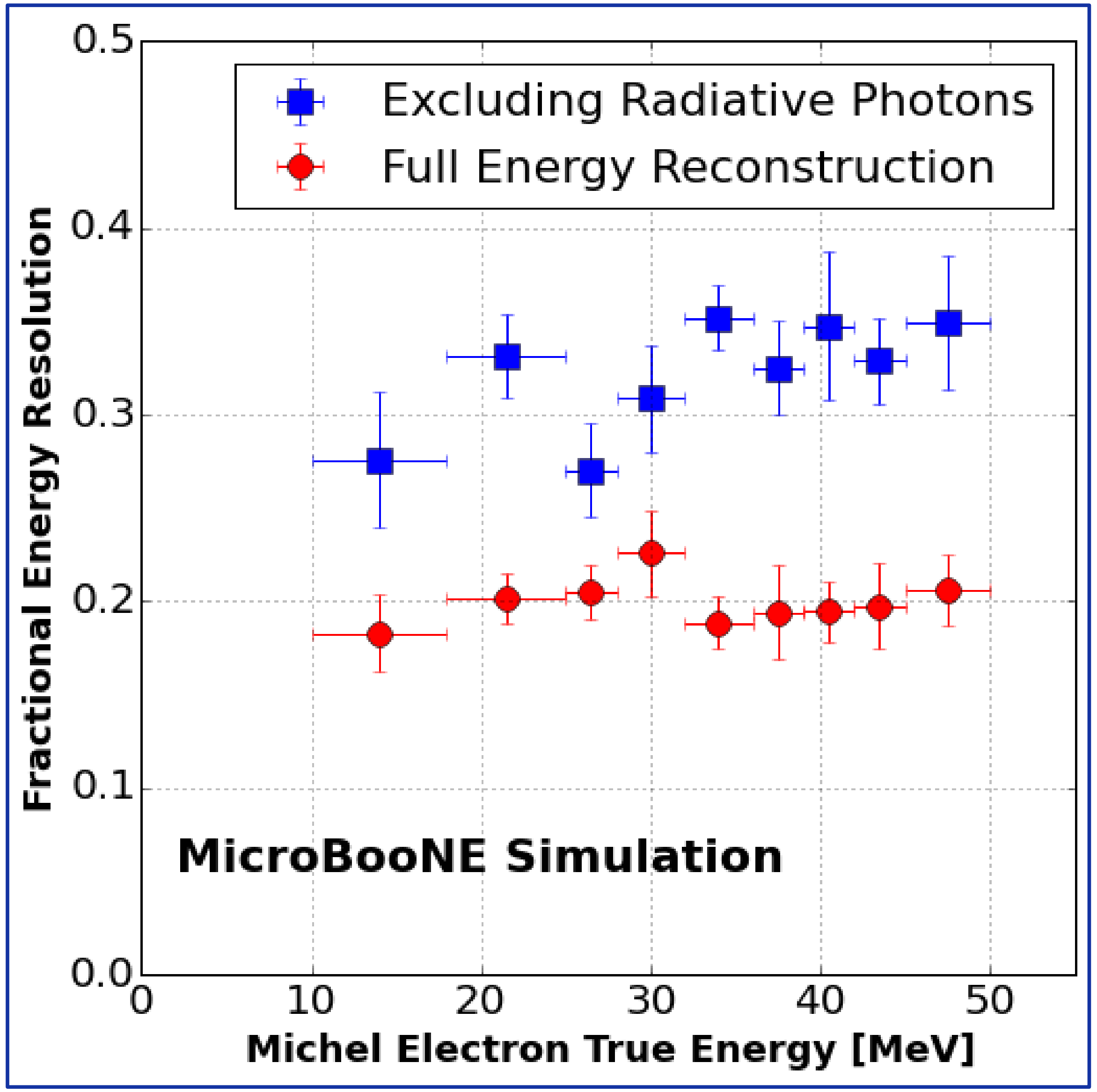






Reconstruction Performance





Above: attempt to tag radiative photons. Reconstructed spectrum still shows bias.

Attempting to recover radiative photons improves energy reconstruction.

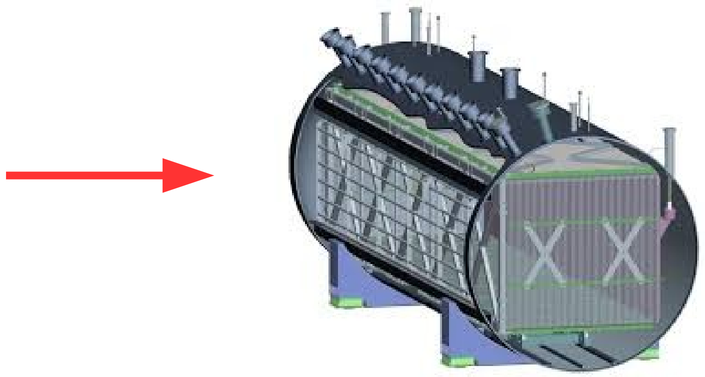
Challenges to non-beam physics

No beam trigger → require 100% live-time.

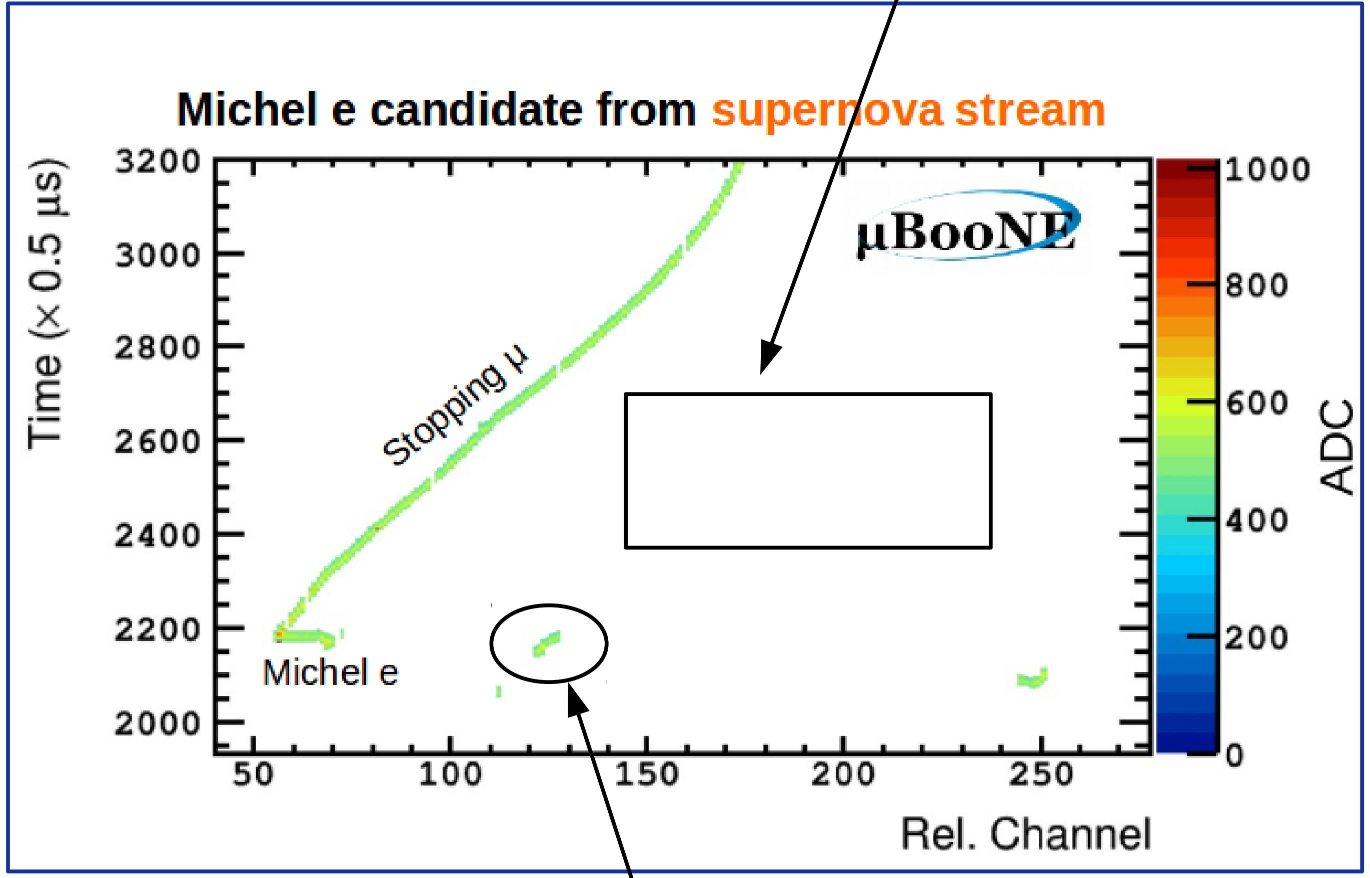
TPC challenge: large data-volumes.

- 30 GB / sec @ MicroBooNE
- 5 TB / sec @ DUNE

Solution: MicroBooNE employs *dynamic zero-suppression* to reduce data-volume while remaining sensitive to supernova physics.



empty baseline region zero-suppressed



Candidate Michel electron from MicroBooNE's continuous-readout data-stream.

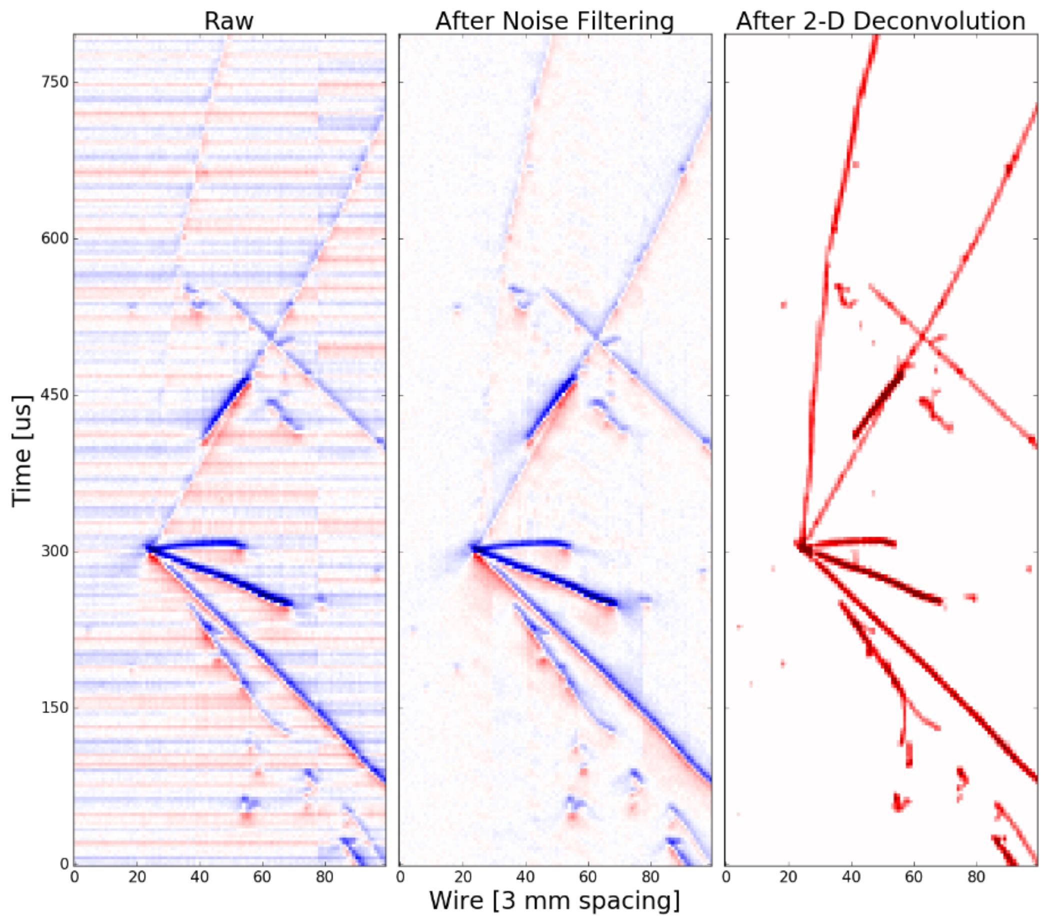
Charge from muon, Michel e⁻, and ~few MeV brem. Photons saved

Moving Forward

Lowering detection thresholds

Significant advances in signal-processing over the past year. Signal-to-noise: > 30 on collection-plane.

"*Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC*", JINST (**12**), 2017. [arXiv:1705.07341]



Pattern Recognition

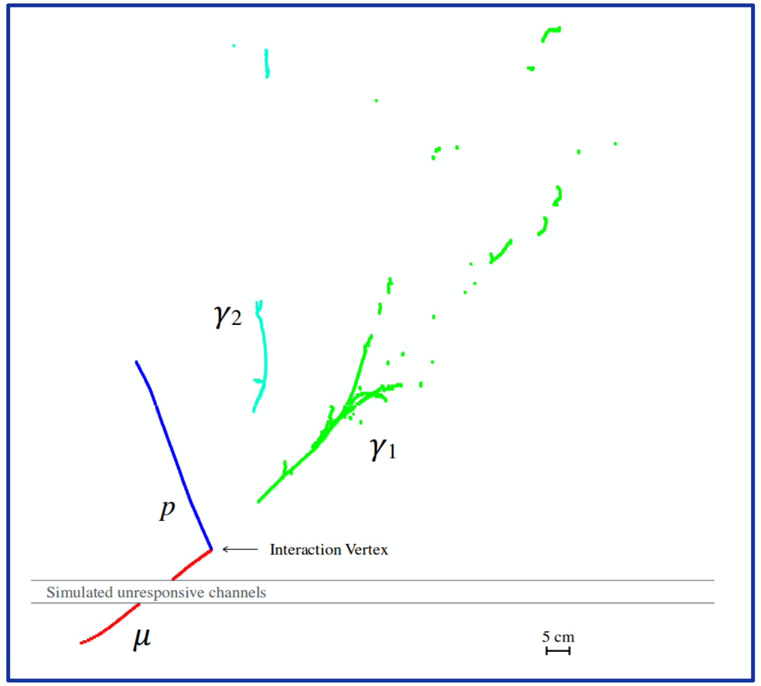
MicroBooNE is leading the development of sophisticated techniques to face the challenges of reconstructing complex topologies in surface LArTPCs.

Multiple approaches to pattern-recognition:

"*Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber*", JINST (12), 2017. [arXiv:1611.05531]

"*The Pandora multi-algorithm approach to automated pattern recognition of Cosmic-ray muon and neutrino events in the MicroBooNE detector*" [arXiv:1708.03135]

Wire-Cell:
http://www.phy.bnl.gov/wire-cell/



Michel electrons : summary

– First fully-automated reconstruction of EM activity in LAr-TPC neutrino detector.

  – Interesting energy range in terms of electron energy loss and topology.

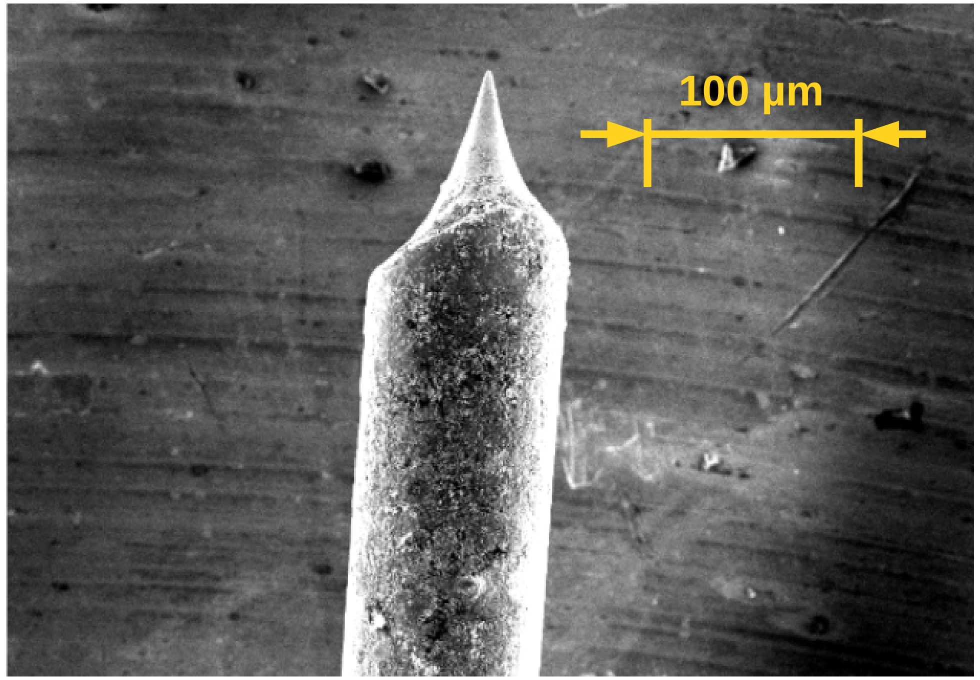
– Main challenge to reconstruction are low energy, far-reaching bremsstrahlung photons.

  – Photon tagging has significant impact on energy resolution, even with current simple 2D reconstruction technique.

– Significant work from MicroBooNE over the past year which will benefit low-energy physics potential of Lar-TPC:

  – Hardware/signal processing to improve signal-to-noise + advanced pattern recognition reconstruction techniques.
  – Full 3D reconstruction as input to pattern-recognition → improved performance.

Going even further?



Current large-scale LAr-TPCs aim for tens of MeV detection thresholds.

Lower thresholds → Dark Matter and CEvNS physics.

Limitation: electronics signal-to-noise.

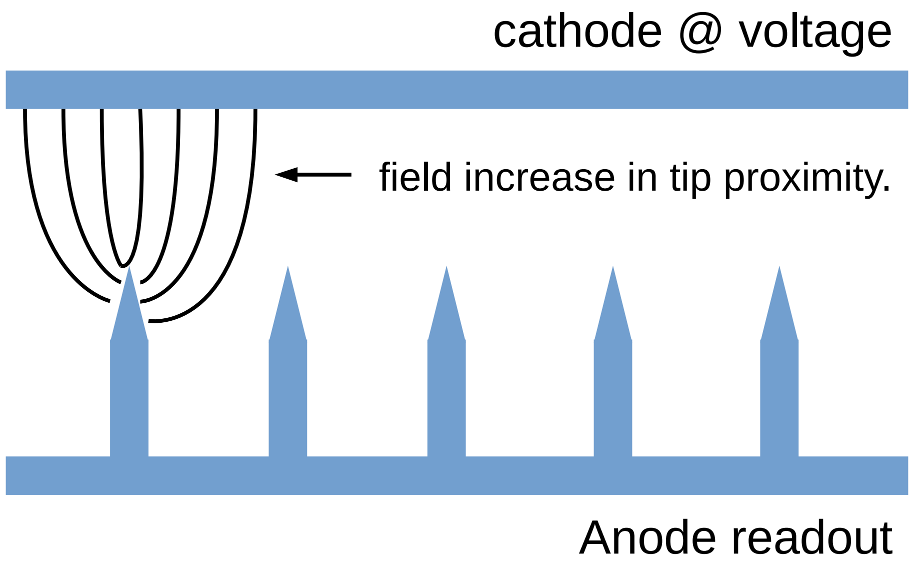
Solutions:

1) dual-phase (DarkSide dual-phase Lar-TPC)

2) charge amplification in liquid phase → **LArCADe**[1] R&D effort at Fermilab, led by Angela Fava.

Needles @ anode with locally strong E-field to induce charge-multiplication.

End goal: micro-strip readout.



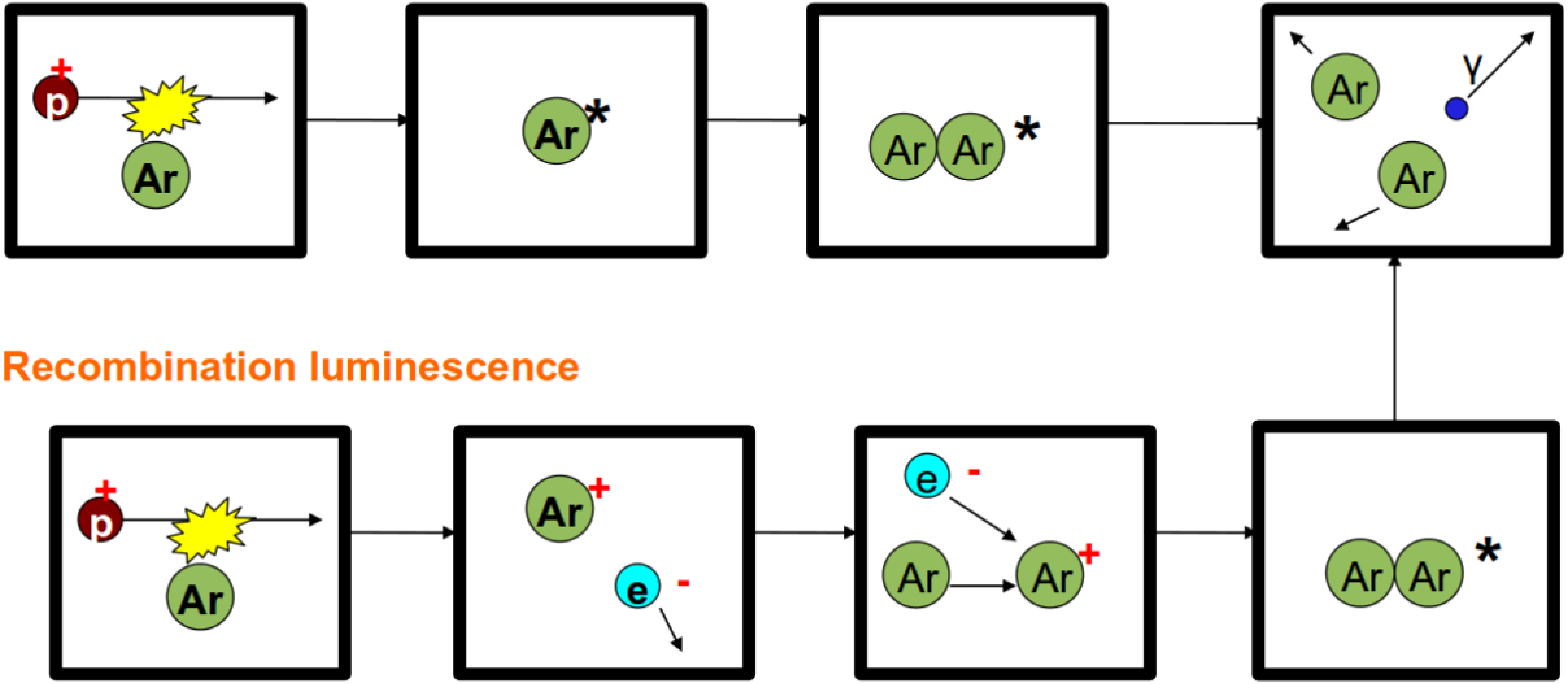
[1]http://ldrd.fnal.gov/subdir/FNAL-LDRD-2017-011-D1.pdf

Thank you

Backup

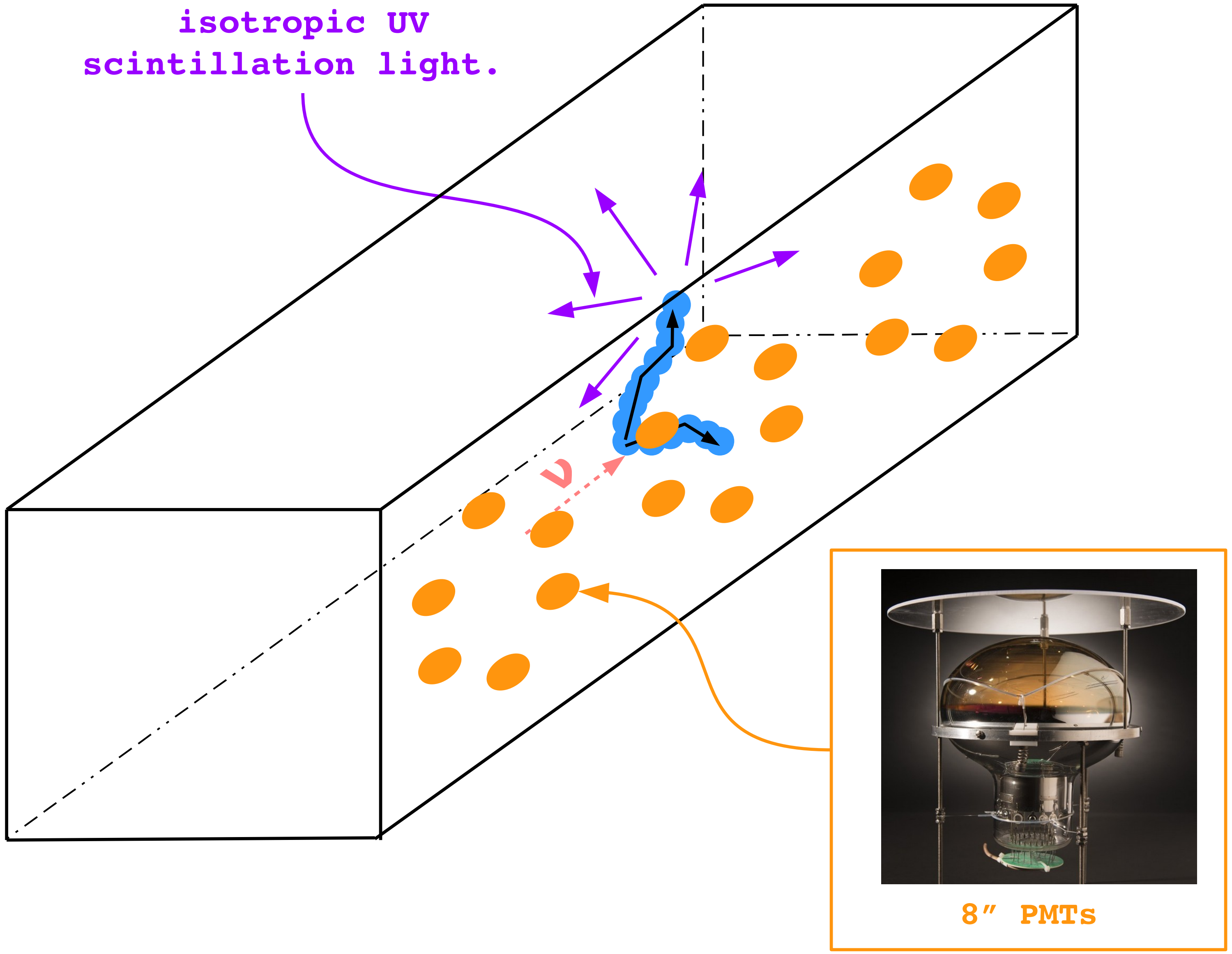
Self-trapped exciton luminescence

Recombination luminescence



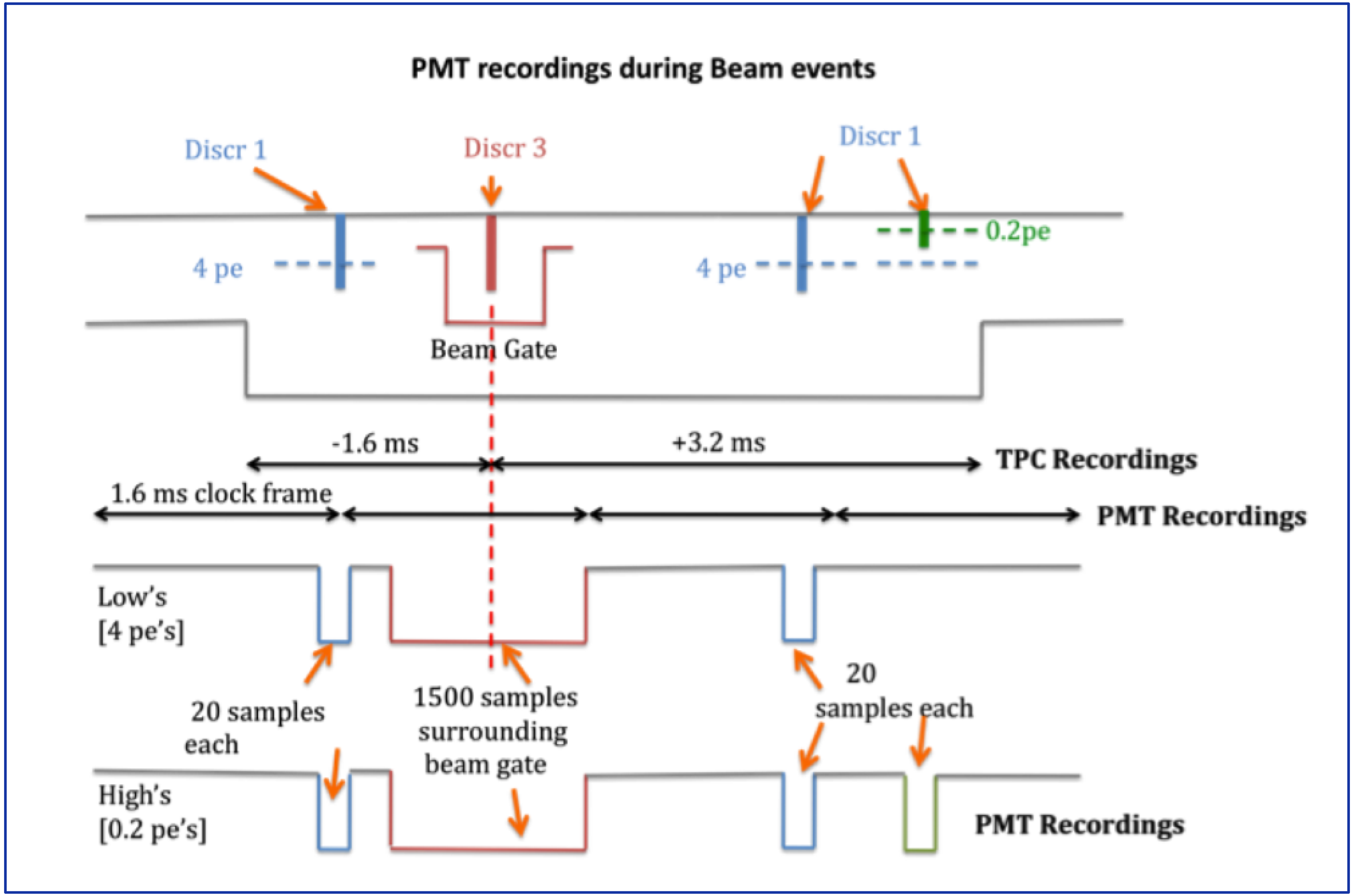
Ben Jones @ Univ. Texas, Arlington

LArTPC Working Principle : MicroBooNE



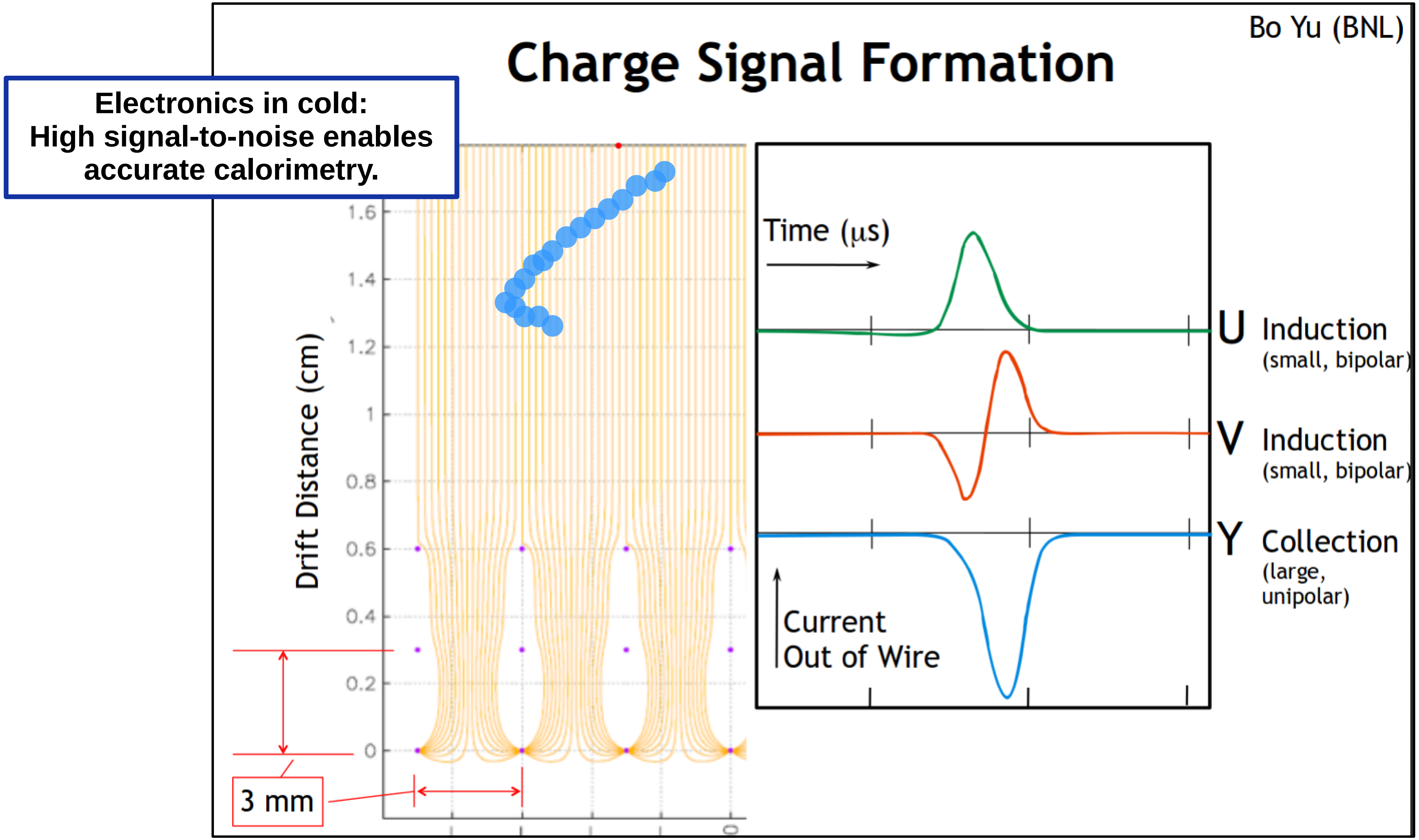
Looking inside cryostat, before TPC inserted

MicroBooNE Readout Electronics "timeline"

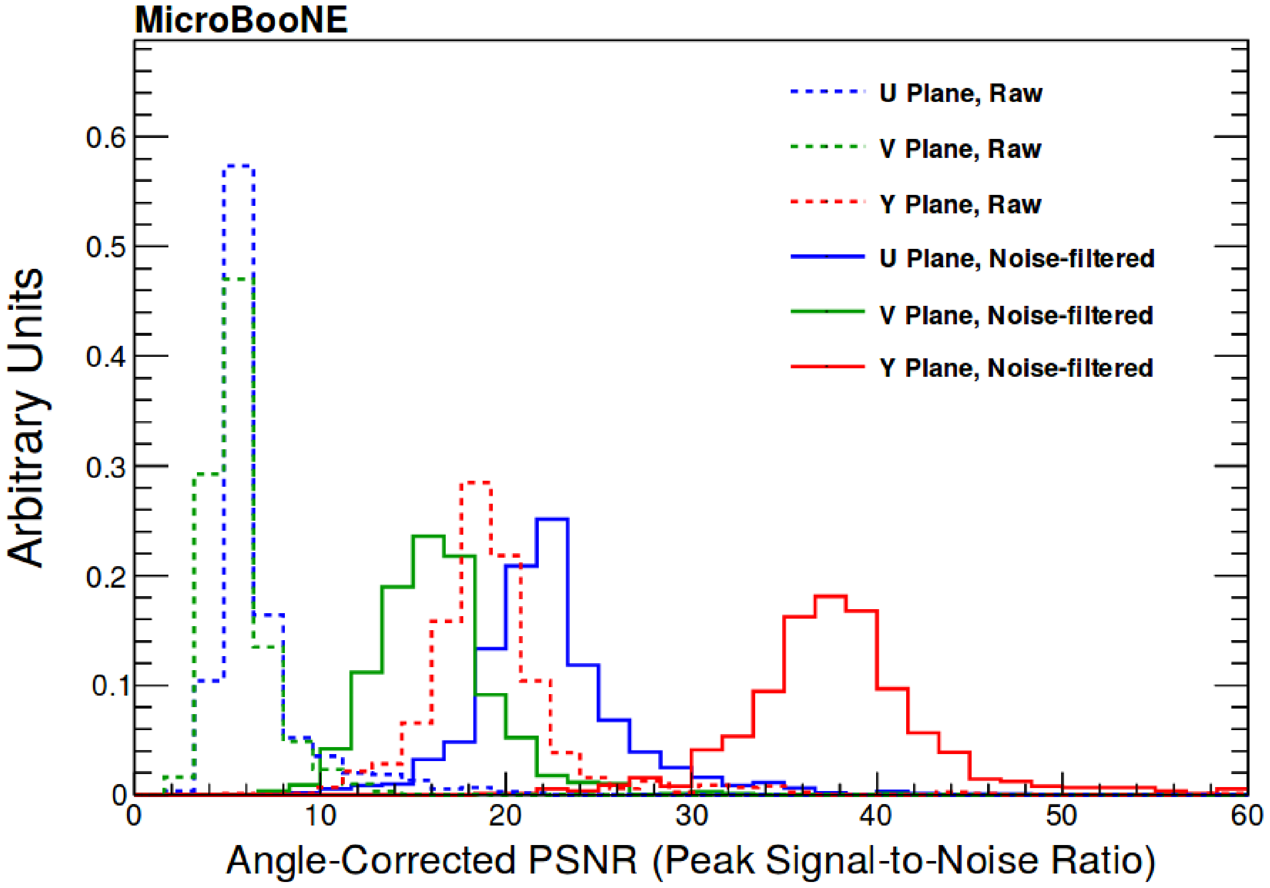


ArXiv:1308.3446v1 – D. Kaleko @ Columbia

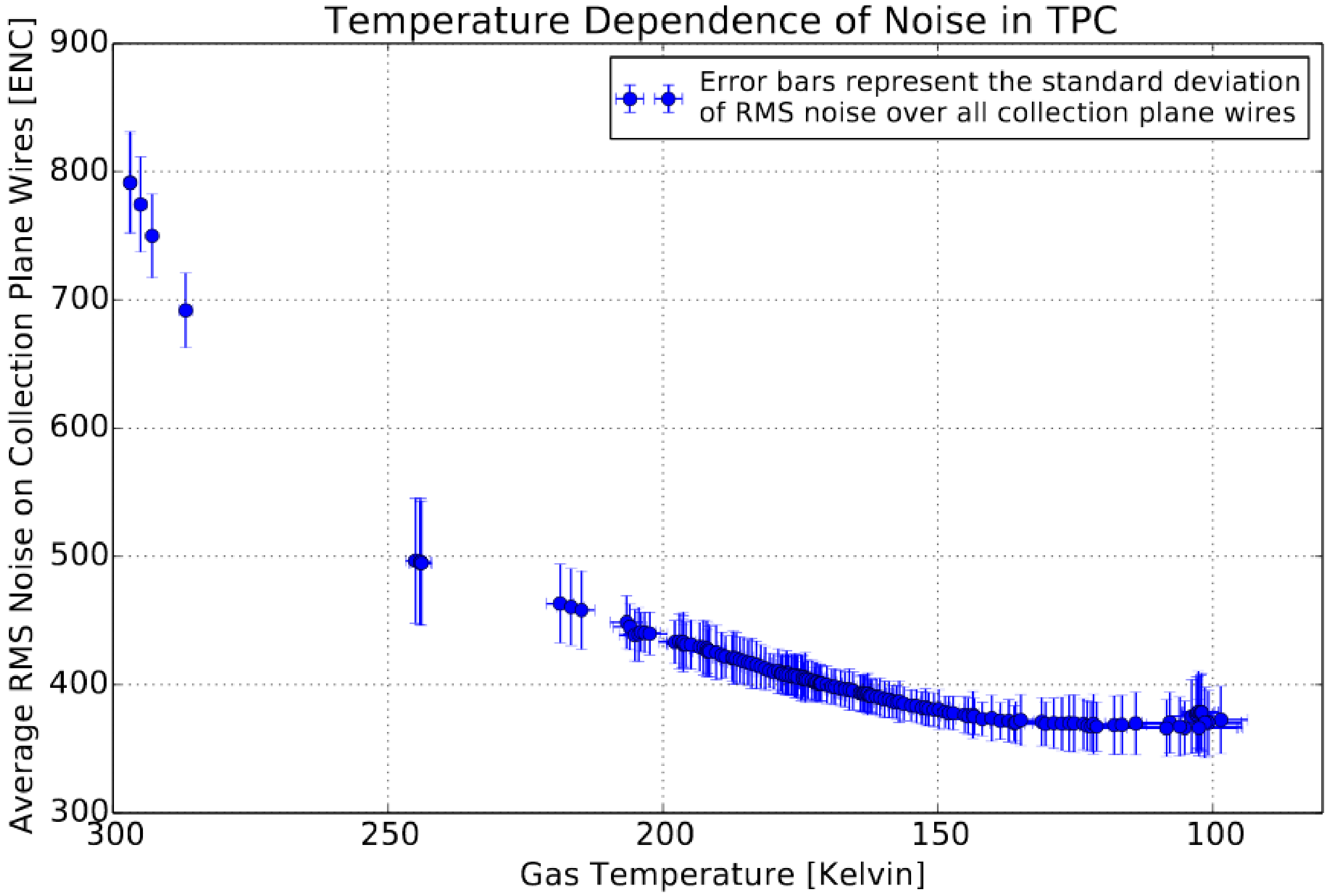
LArTPC Working Principle : MicroBooNE



"Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC", JINST (12), 2017



"Noise Dependence on Temperature and LAr Fill Level in the MicroBooNE Time Projection Chamber"
https://www-microboone.fnal.gov/publications/publicnotes/MICROBOONE-NOTE-1001-TECH.pdf



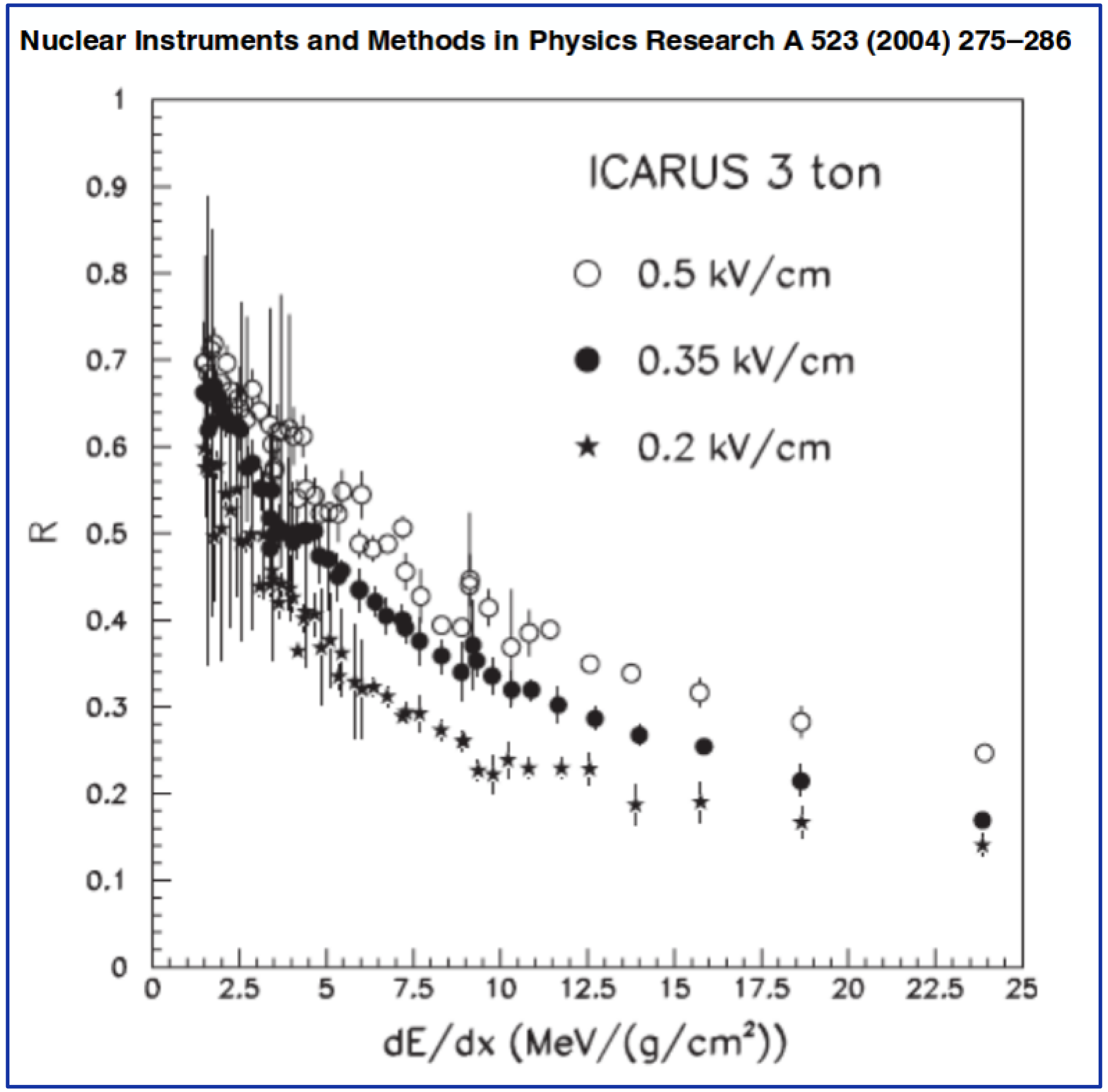
Recombination

$$\mathscr{R}_{\text{ICARUS}} = \frac{A_B}{1 + k_B \cdot (dE/dx)/\mathscr{E}}$$

Box model

$$dE/dx = \frac{dQ/dx}{A_B/W_{ion} - k_B \cdot (dQ/dx)/\mathscr{E}}.$$

Birks model



Recombination depends on density of Ar^+ and e^-.

Affected by:

- dE/dx (more energy deposition per unit distance → larger ion density → more recombination)
- E-field strength: determined timescale at which Ar^+ / e^- drift away from each other.

For electrons / photons much smaller variation in dE/dx vs. energy compared to muons/protons/pions.

→ significant effect, but ~constant.

Space Charge

Positive ions in LAr drift at 10^{-3} the speed of electrons.

→ “space-charge” buildup in TPC.

Effect leads to distortions in electric field.

Local variations in E field In turn affect:

- Local drift speed → spatial “wiggles”
- Field magnitude → recomb. Effect.

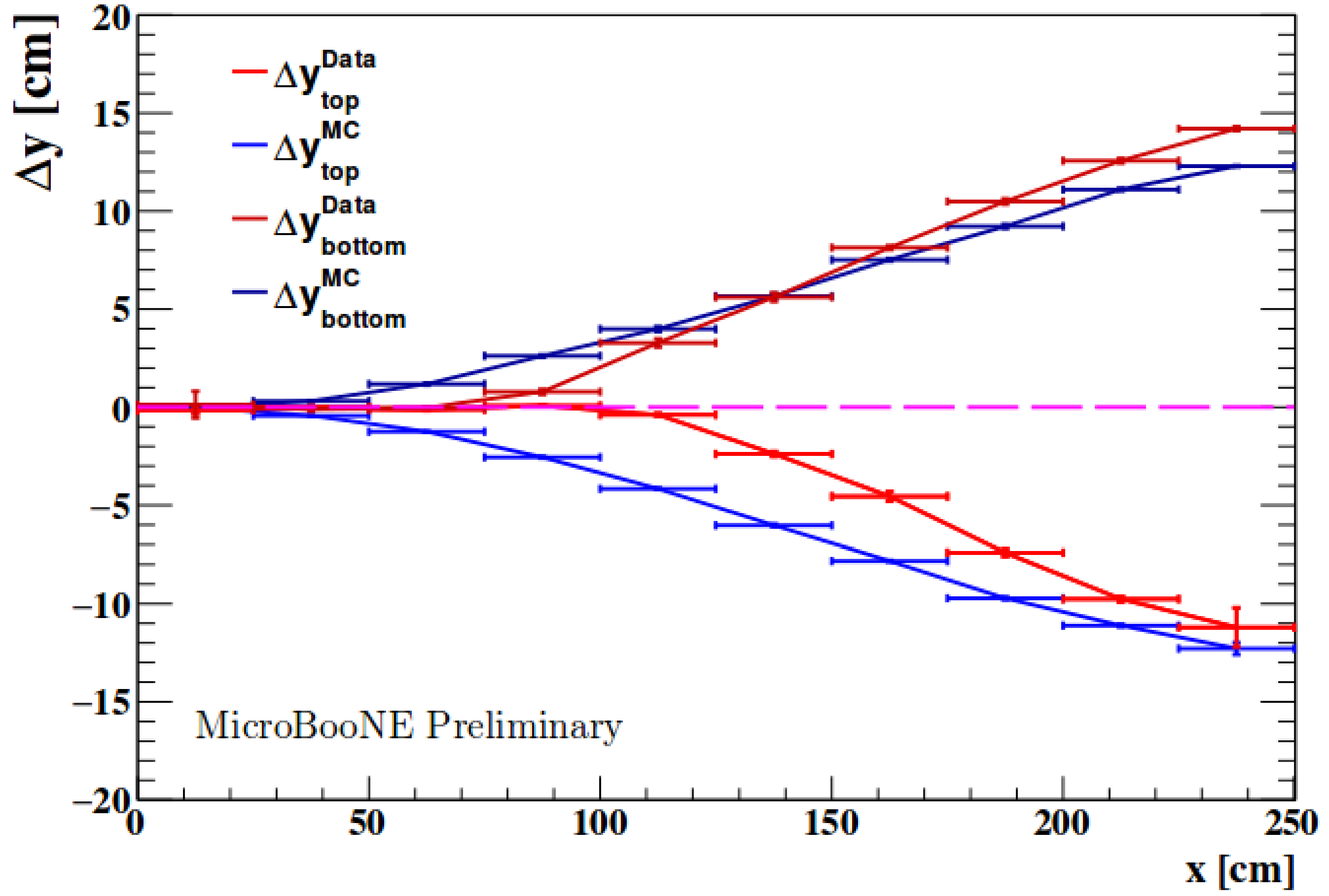
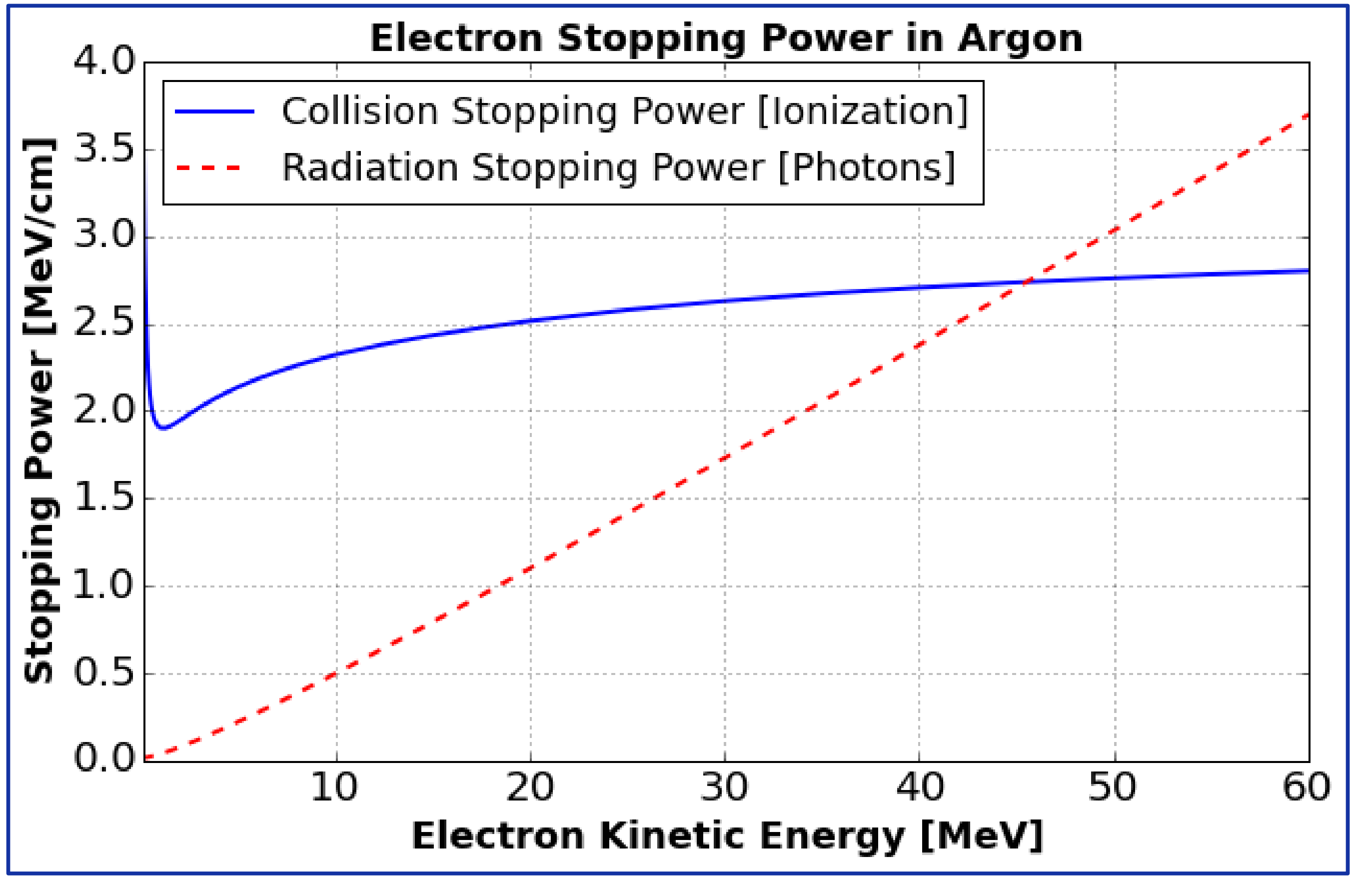
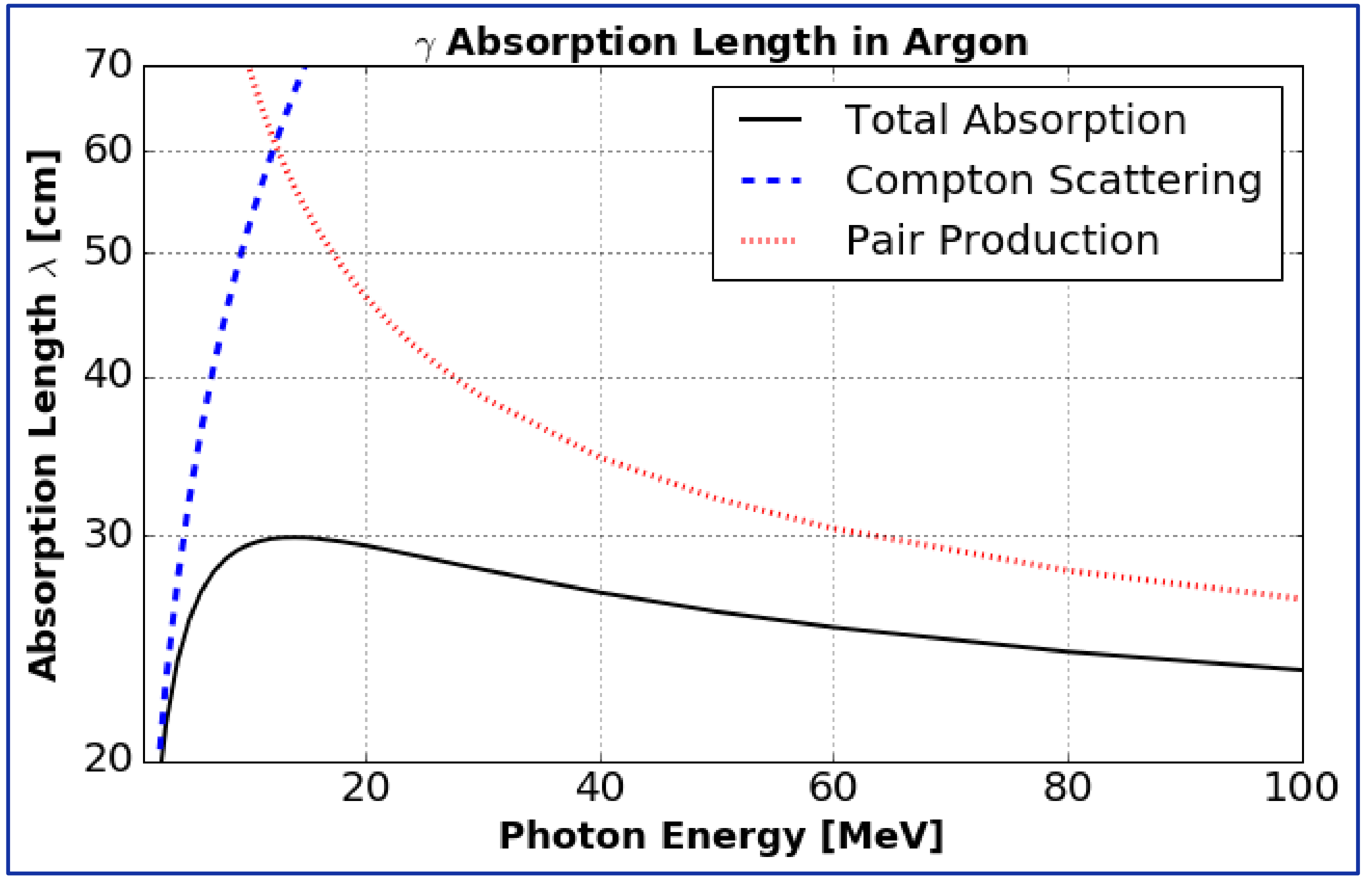


Figure 9: Predicted/measured SCE distortions as a function of the drift coordinate at both the top and bottom of the TPC, comparing data to MC. The magenta dashed line represents the offsets expected if there were no SCE in the detector.

Source: Study of Space Charge Effects in MicroBooNE:
http://www-microboone.fnal.gov/publications/publicnotes/MICROBOONE-NOTE-1018-PUB.pdf

EM activity in LAr : a summary



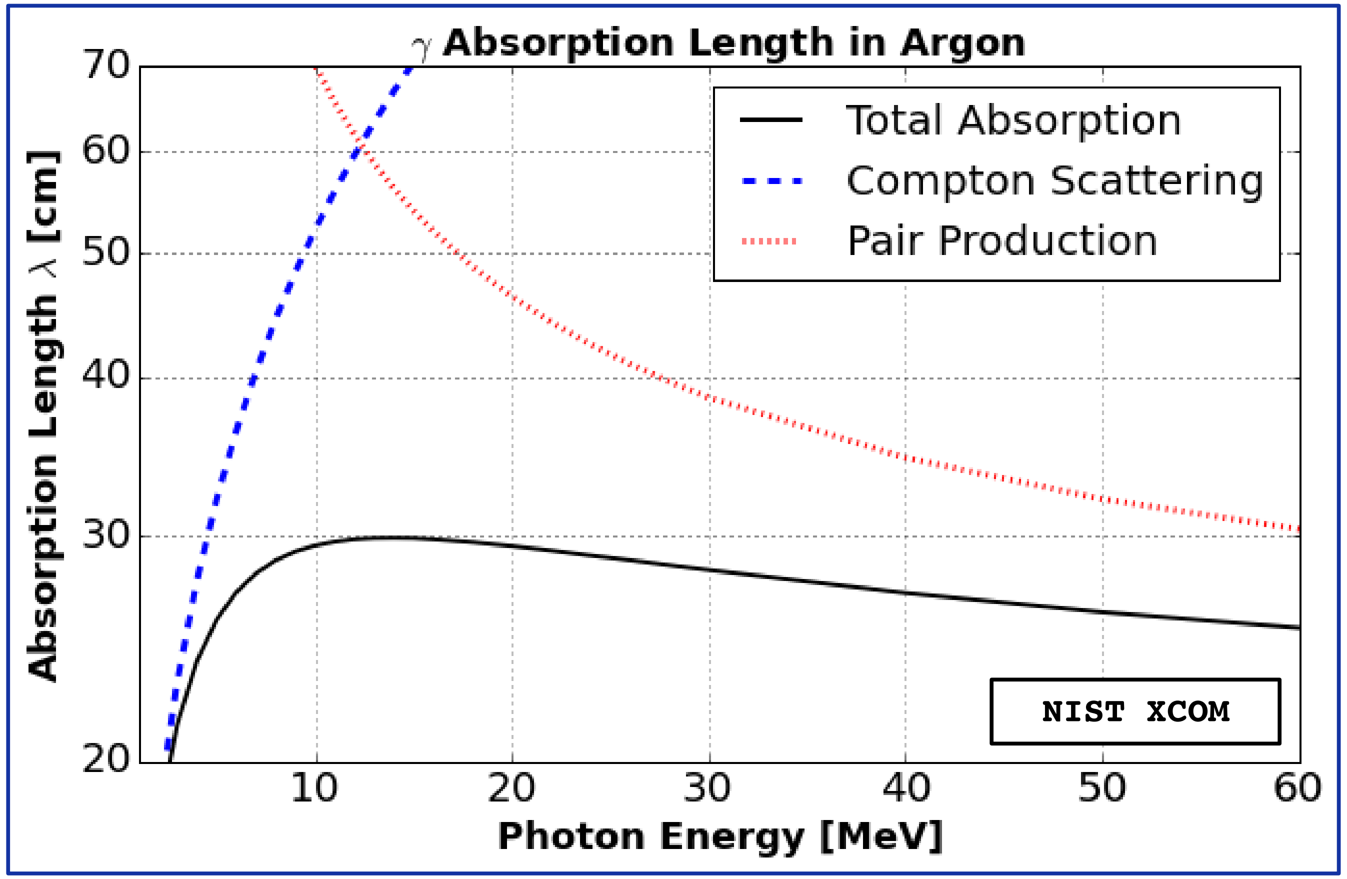


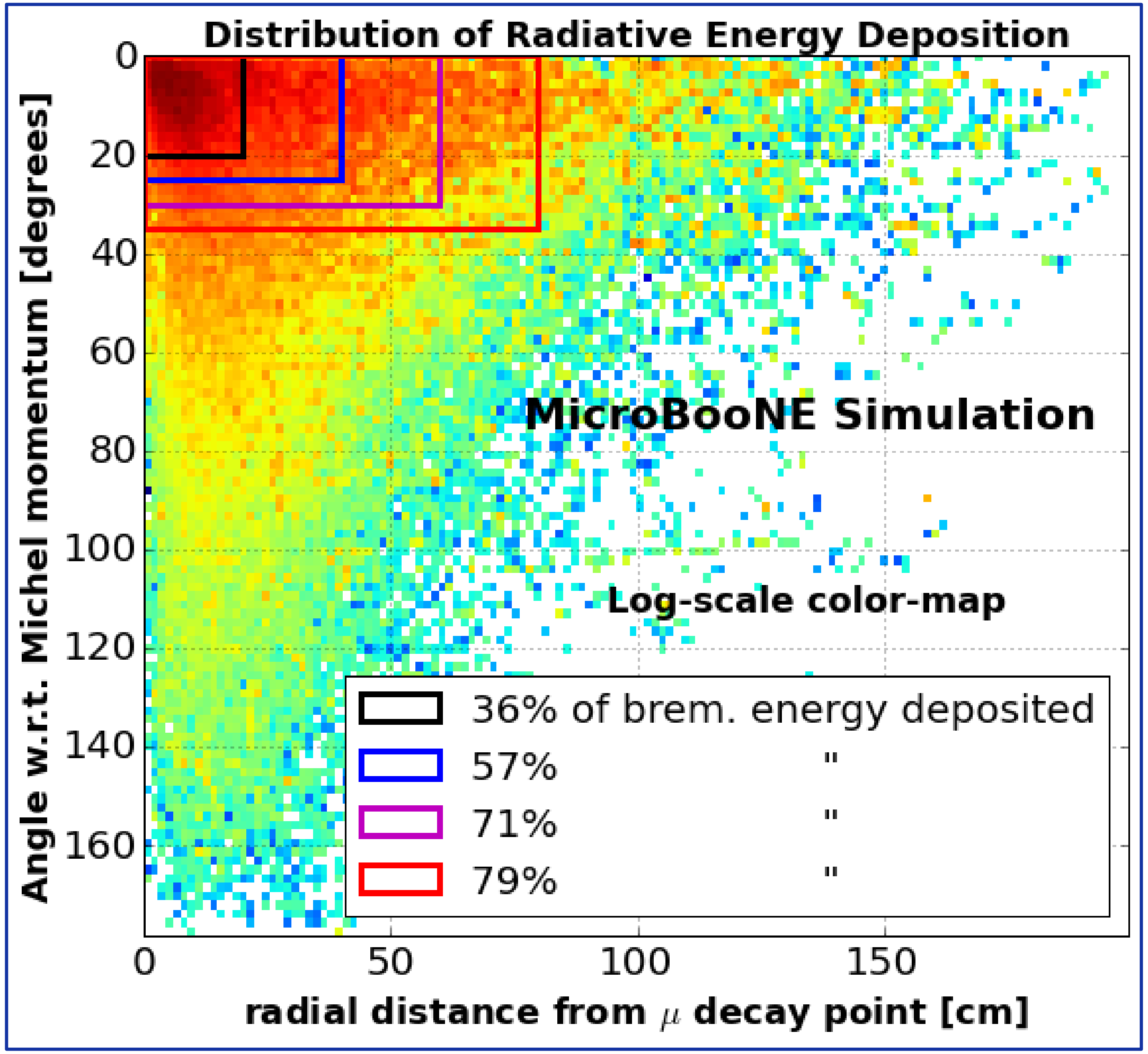
Two things to note:

1) Energy loss process depends significantly on energy. At lower energies (<100 MeV) significant contribution from primary ionization. Electron/photon not very “shower-like”.

2) Radiative photons can travel tens of cm before depositing their energy in TPC.

Michel electrons : Radiative Photons





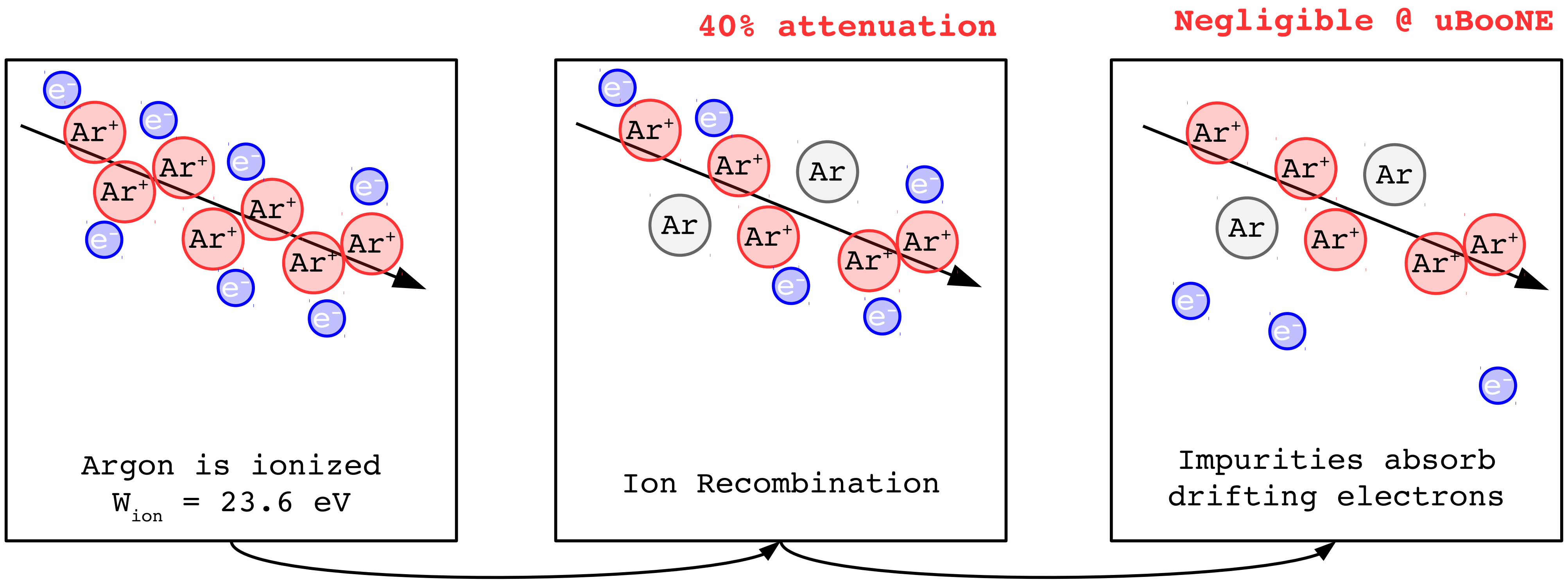
To recover radiative photons need to extend the search for charge tens of cm away from muon stopping point.

This presents challenges, especially for a surface detector with “dense” accidental cosmic activity.

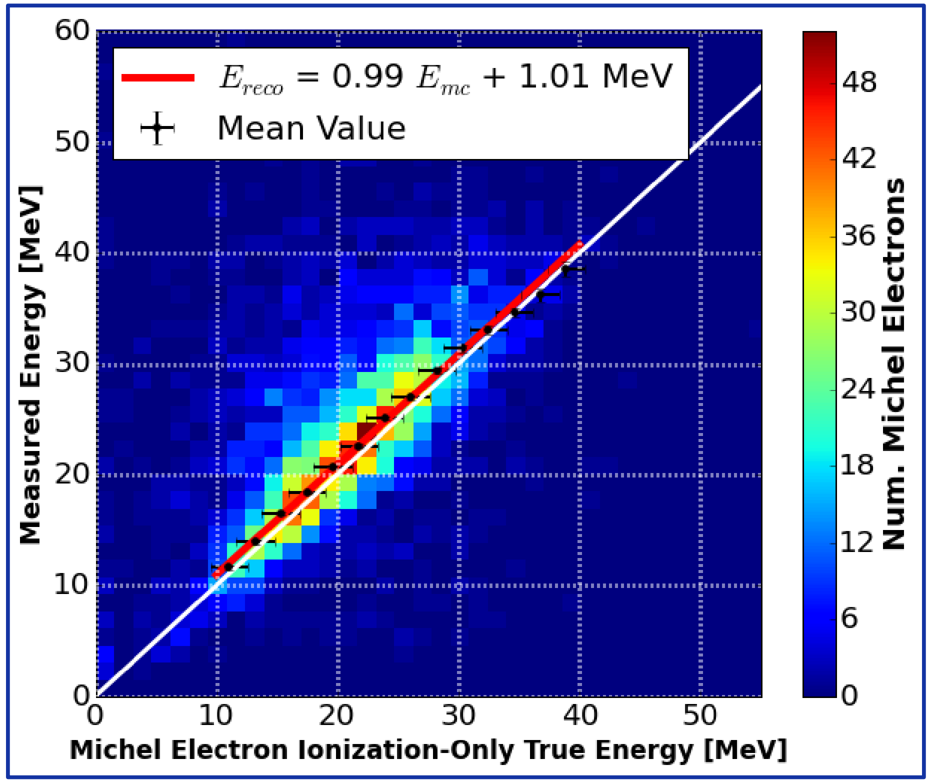
Calorimetric Energy Reconstruction

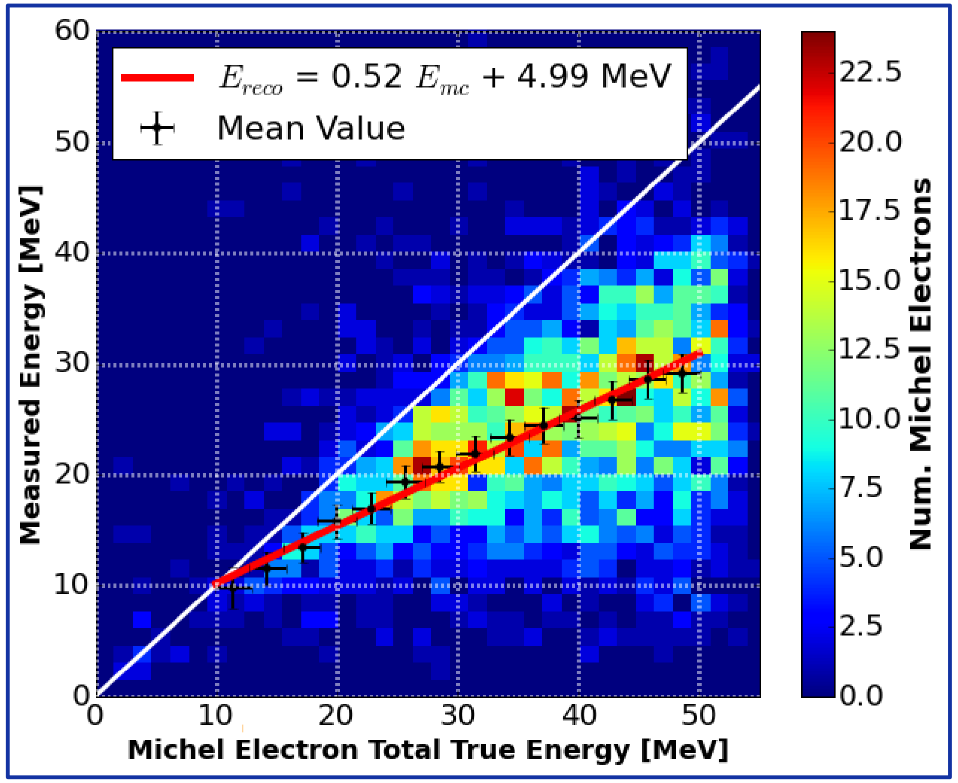
1) Integrate charge associated to tagged Michel electron hits.

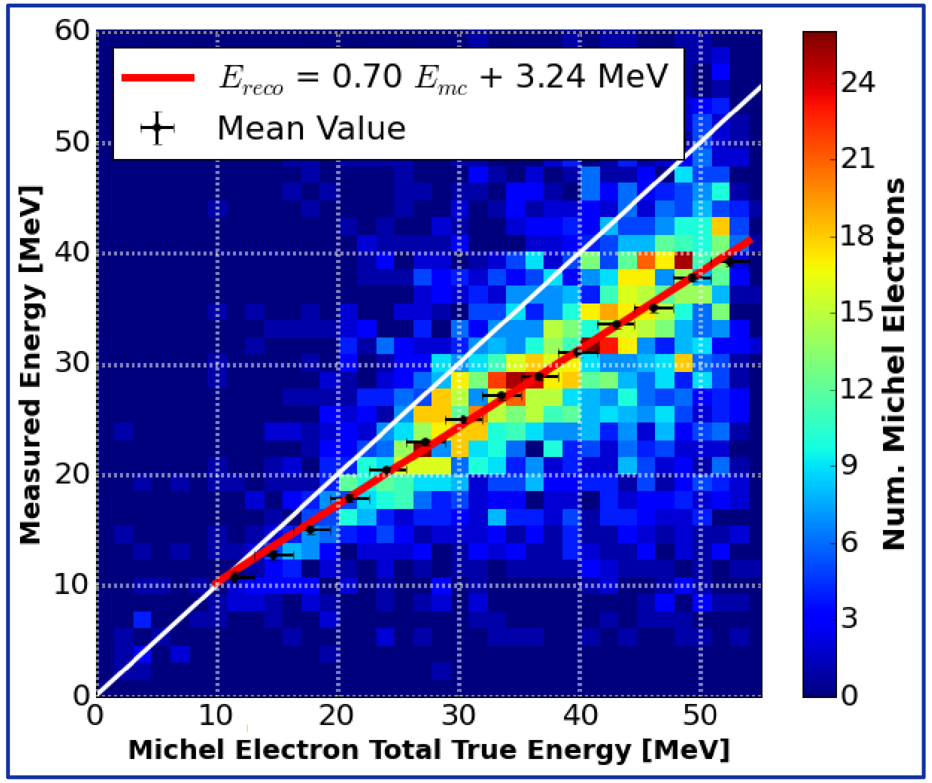
2) Account for processes affecting energy loss and signal formation in MicroBooNE's TPC:

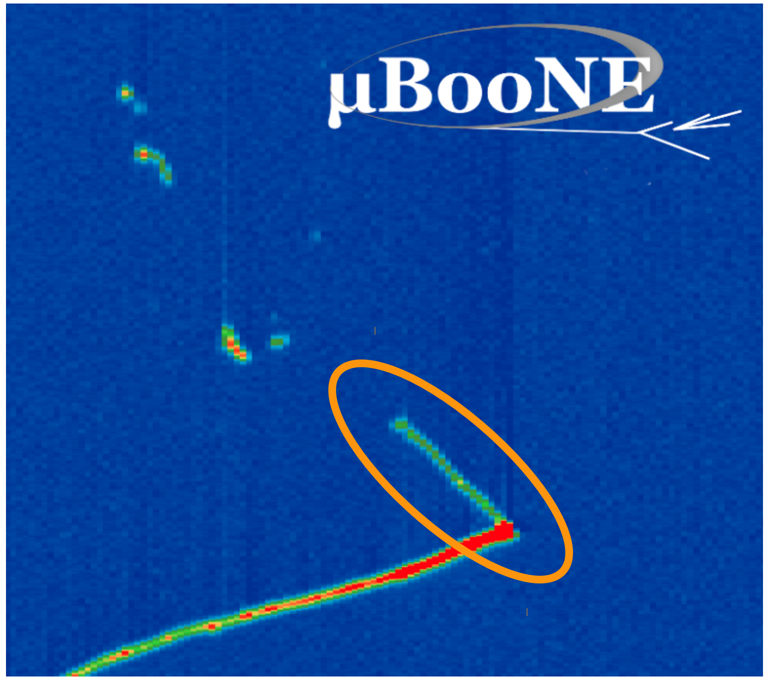


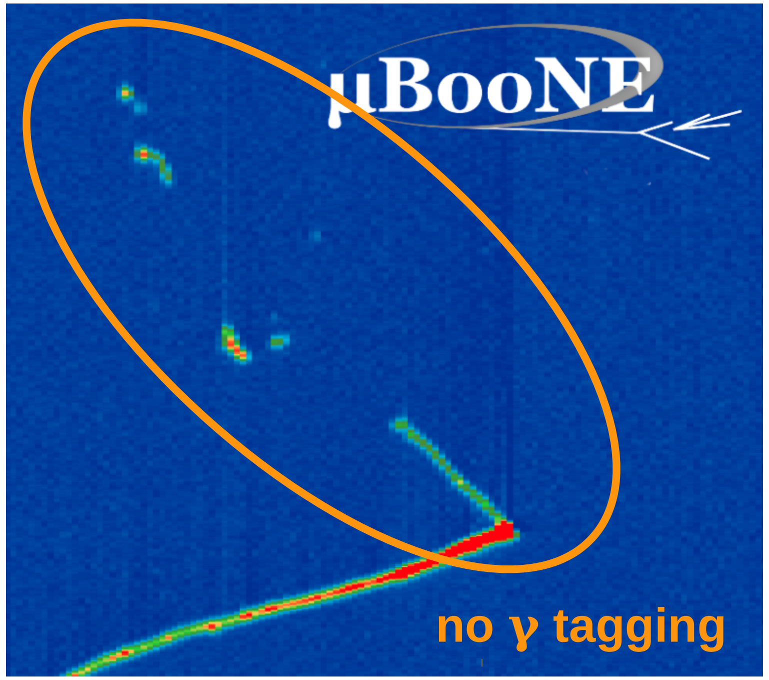
Michel electrons : Monte Carlo energy resolution studies.

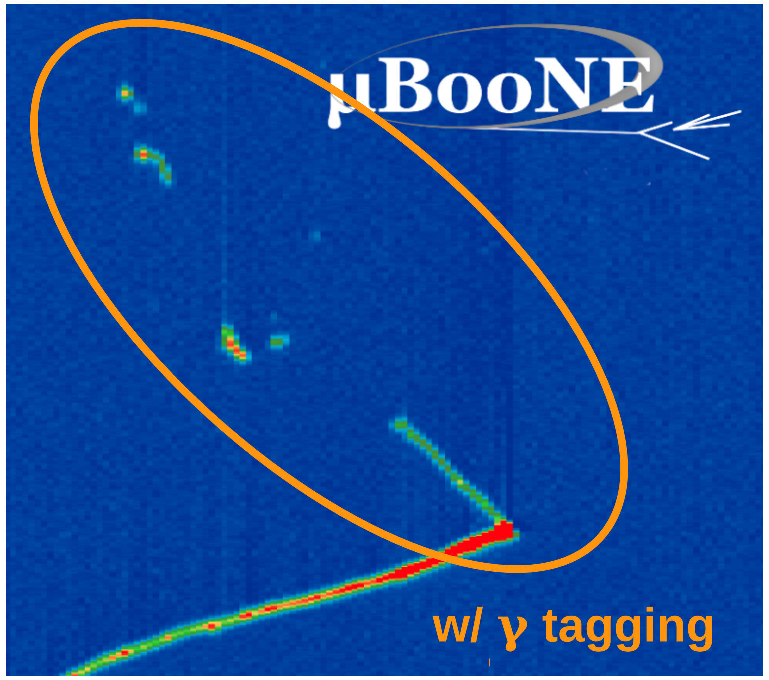




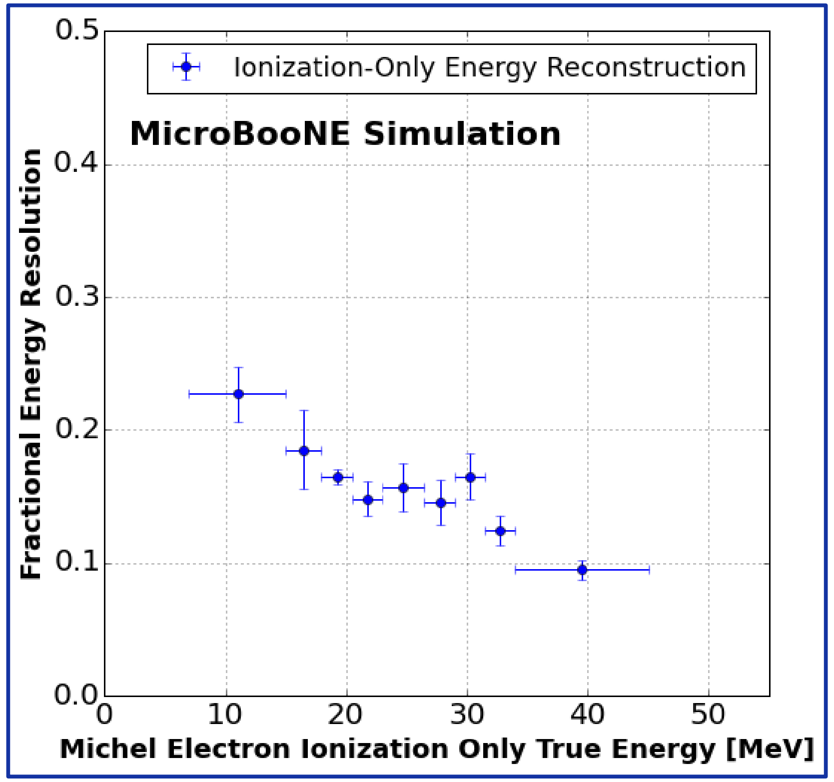


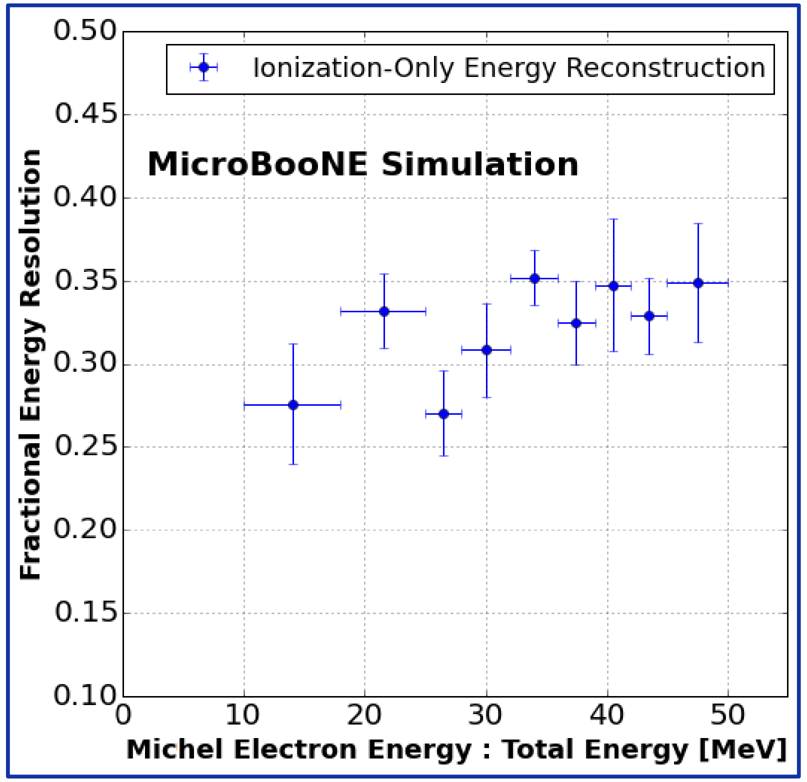


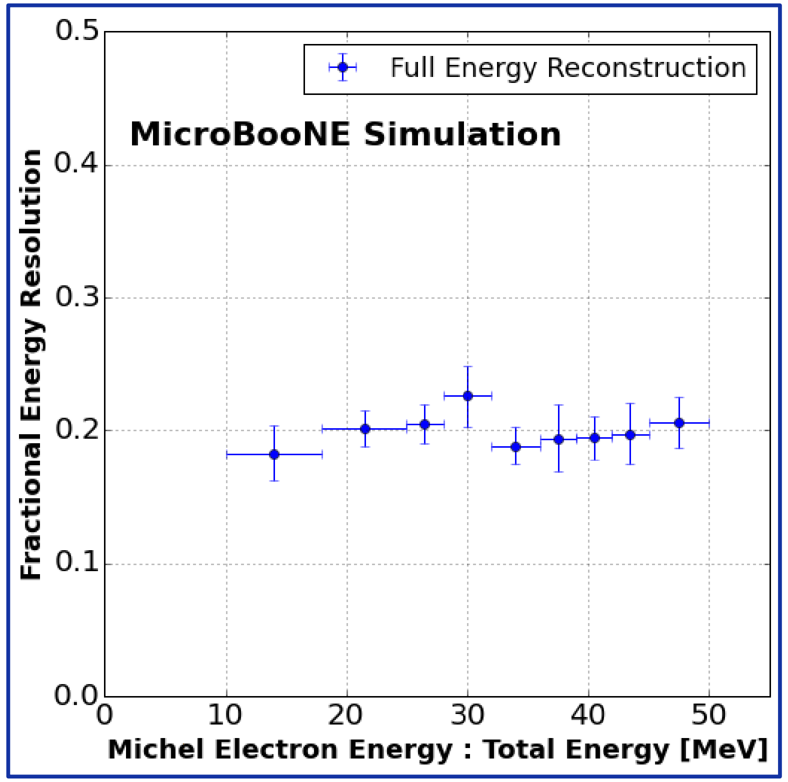


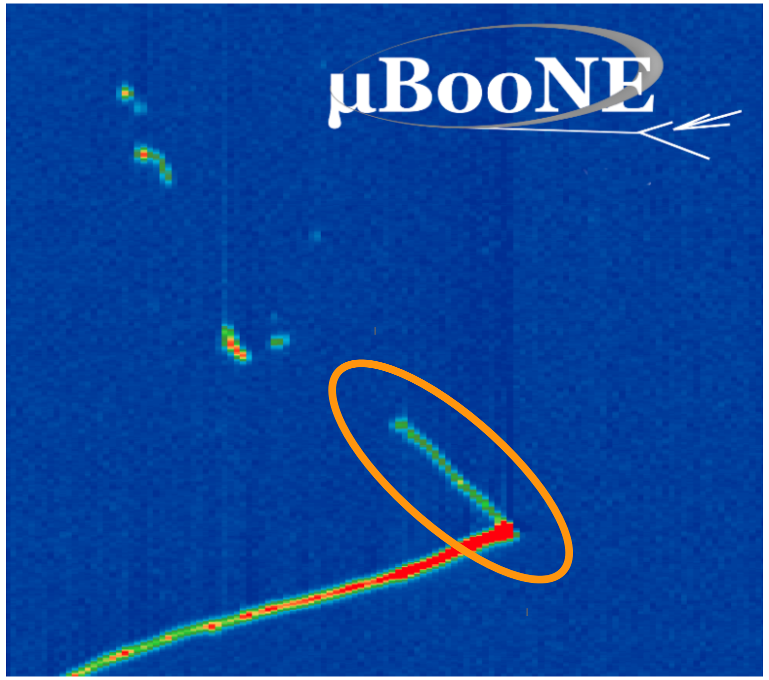


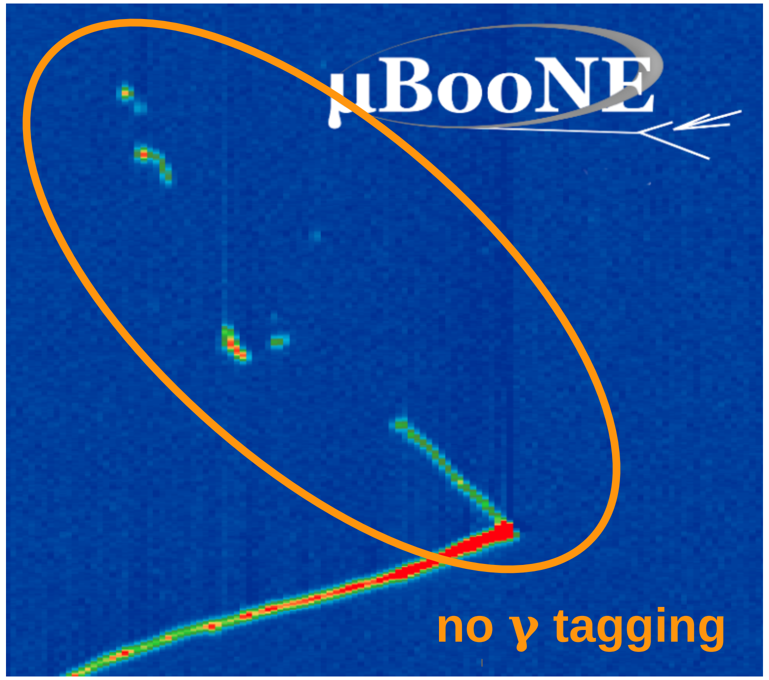
Michel electrons : Monte Carlo energy resolution studies.

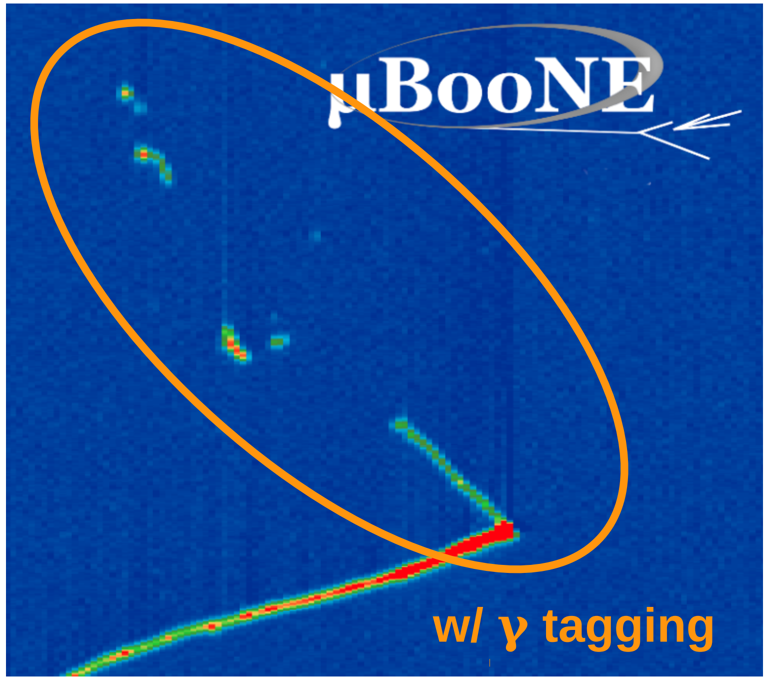








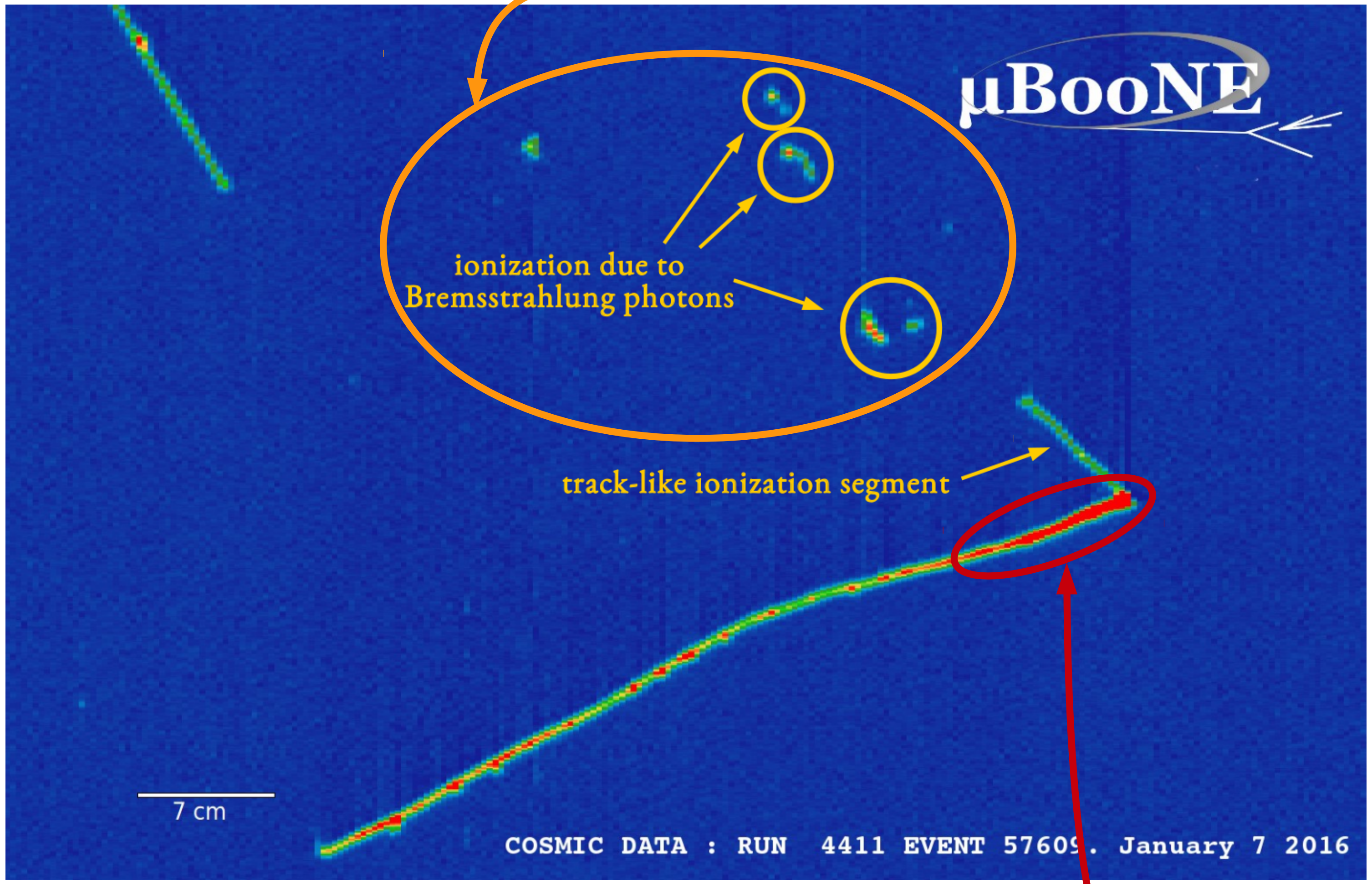


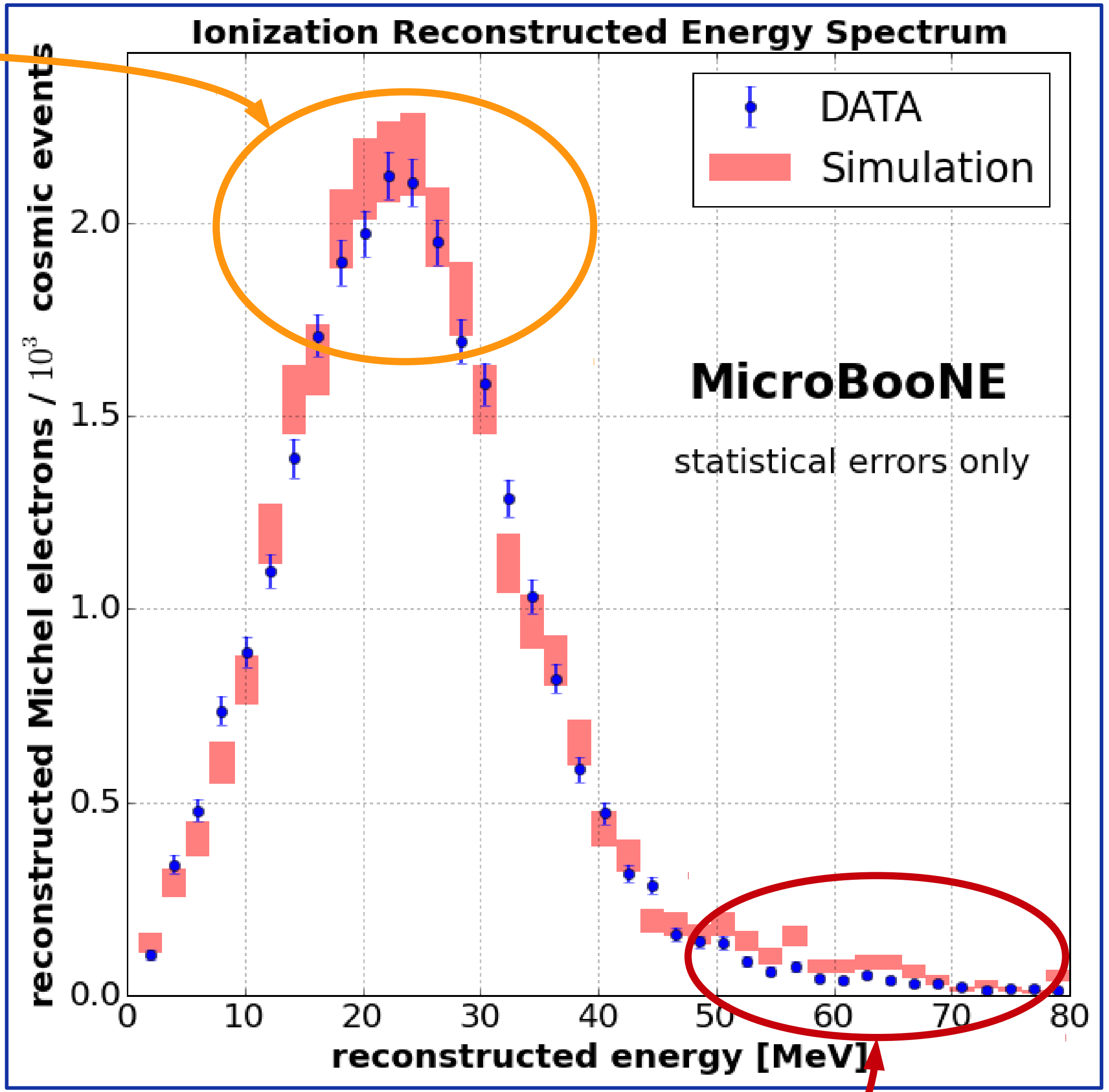


Michel electrons : Energy Reconstruction

David Caratelli @ Columbia University

Exclusion of radiative photons causes shift in spectrum.





Muon Bragg peak can contaminate clustered Michel energy

Michel Electrons : Purity and Resolution