DUNE Single Phase Signal Processing

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The International Workshop on Next Generation Nucleon Decay and Neutrino Detectors

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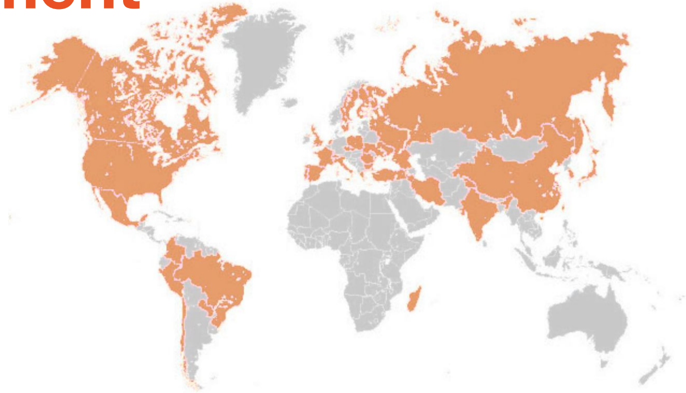
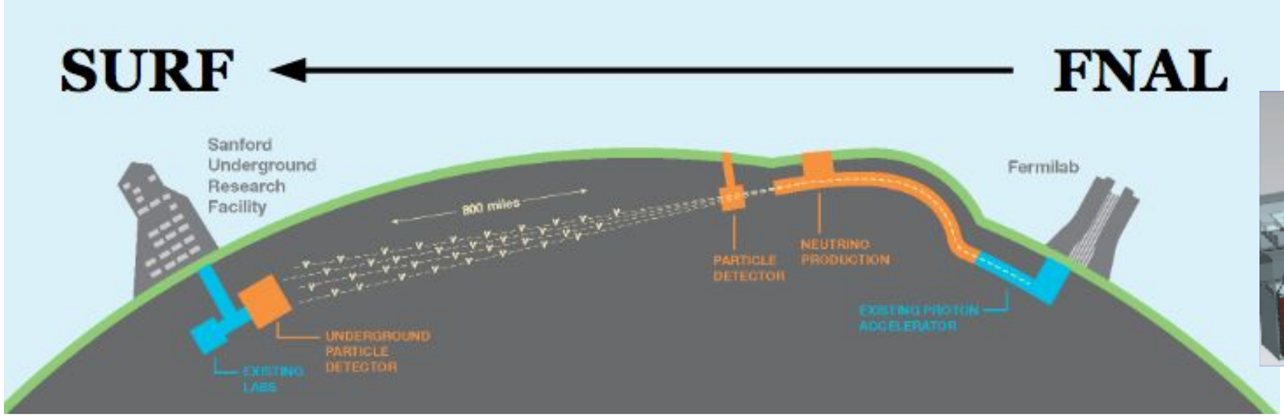
COLORADO STATE UNIVERSITY

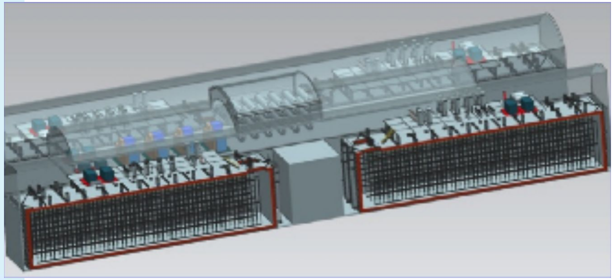
DUNE

Deep Underground Neutrino Experiment



- Long baseline (1300 km) accelerator neutrino experiment spanning between Chicago and South Dakota
- Large (40 kt) LArTPC far detector plus near detector
- Far detector deep (1.5 km) underground at Homestake Mine
  - Four 10-kt fiducial mass modules
  - Two planned types: single phase (LAr only) and dual phase (LAr + GAr)
- Physics goals: ν oscillations (mass ordering, δ_{CP}, θ_{23}, θ_{13}), baryon number violation (e.g. nucleon decay), supernova burst neutrinos

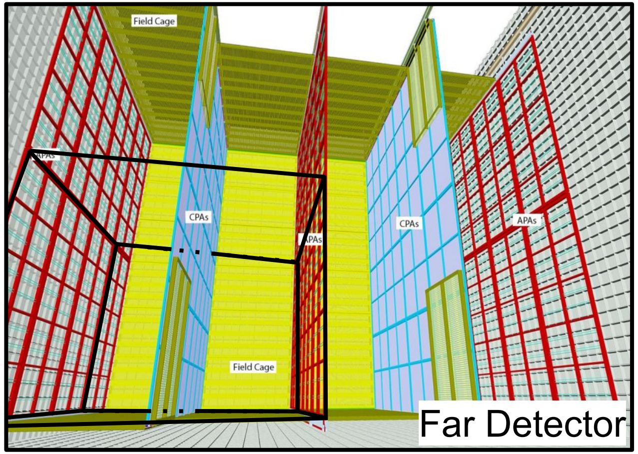


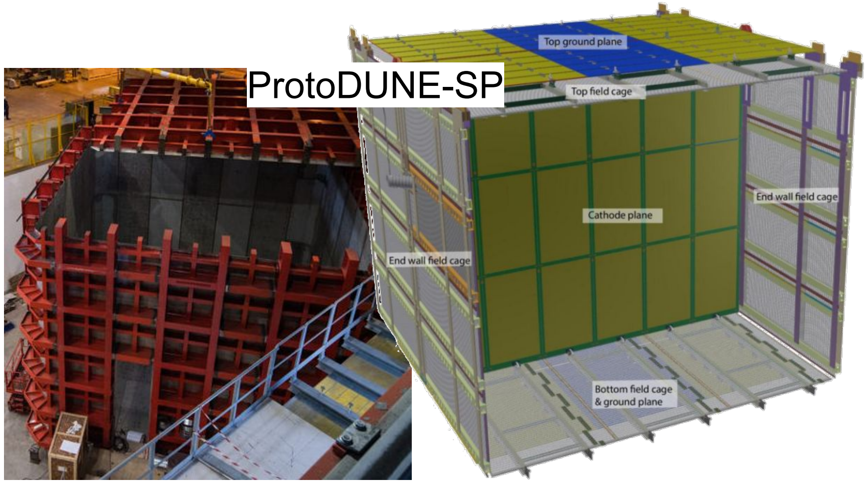


DUNE Collaboration FERMILAB-DESIGN-2018-02

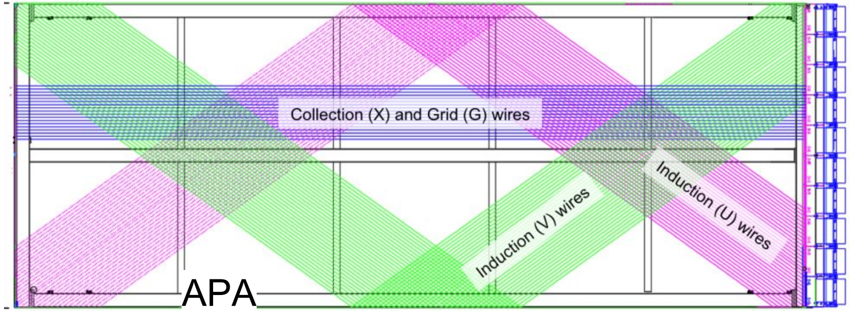
ProtoDUNE Single Phase

- Test of single-phase far detector technology
- Contains 6 modular drift cells
  - 3.6 m drift length
  - Suspended Anode (APA) and Cathode (CPA) Plane Assemblies
  - Wrapped wires form induction planes
  - ~ 5mm wire pitch
  - 500 V/cm drift electric field

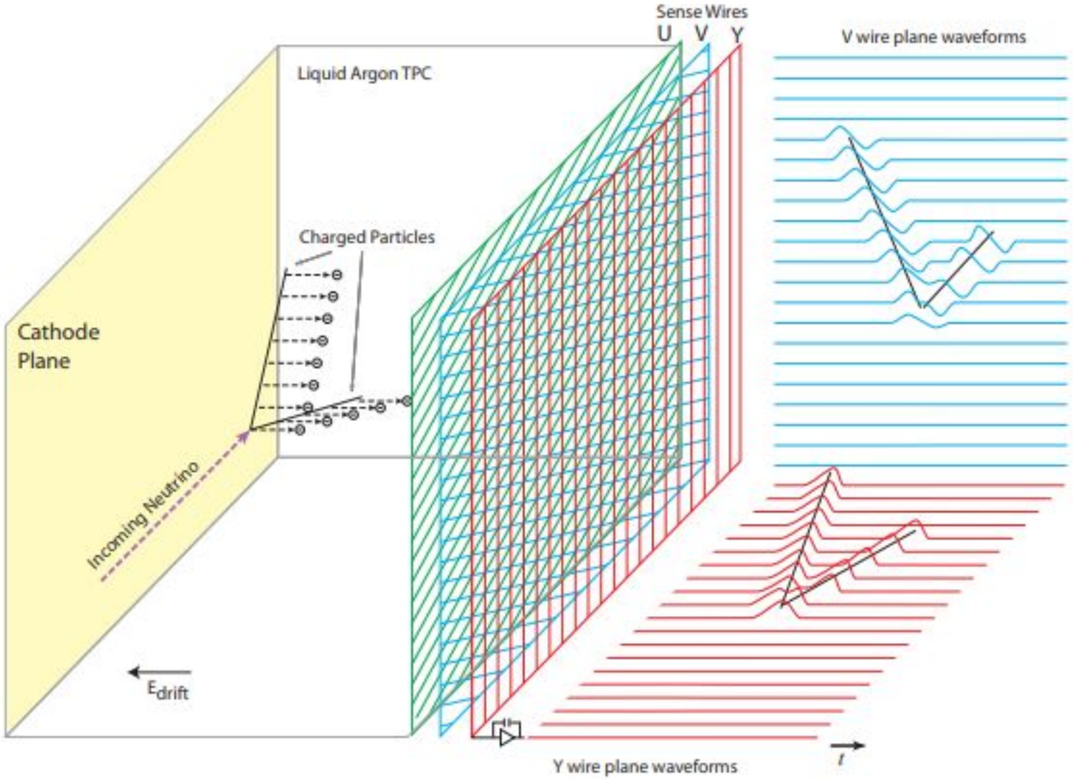




DUNE Collaboration, FERMILAB-DESIGN-2017-02
DUNE Collaboration, FERMILAB-DESIGN-2018-03



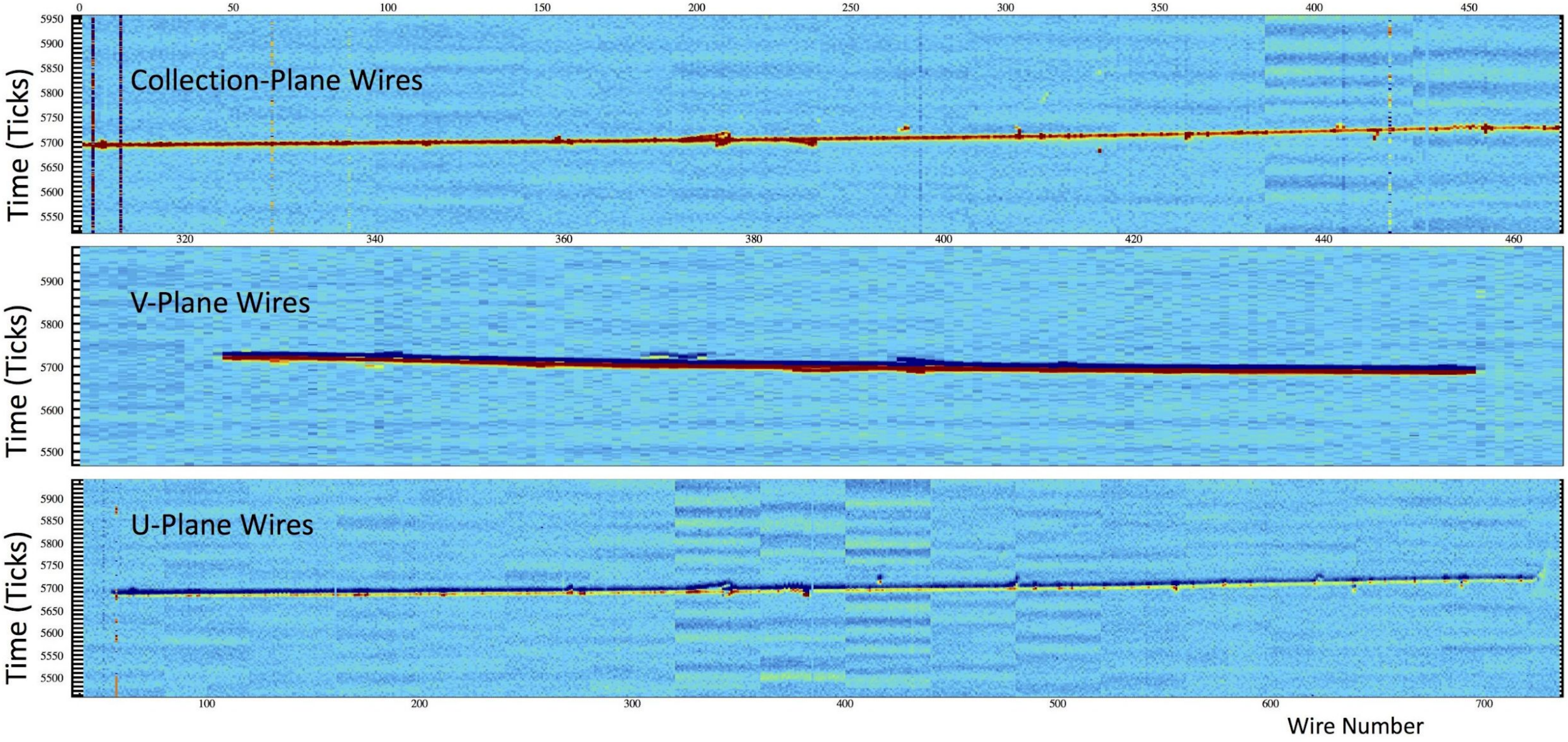
LArTPC Signal Formation



MicroBooNE collaboration, JINST 13, P07006 (2018)

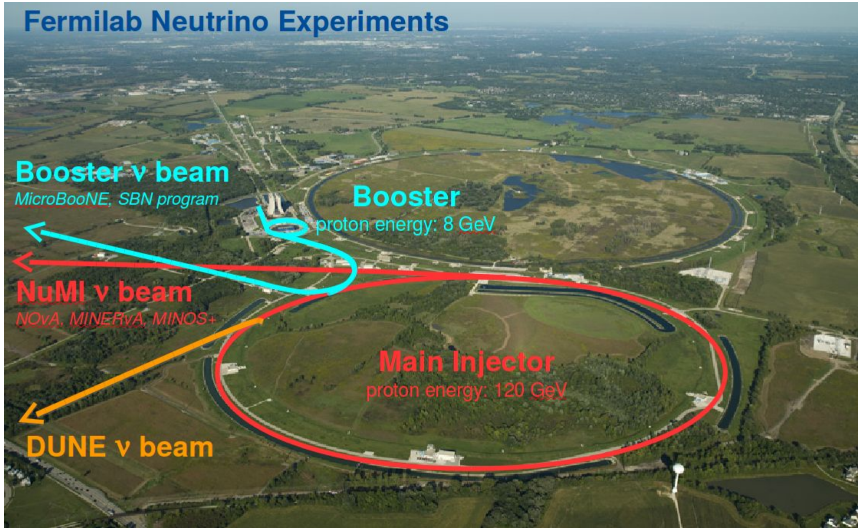
- Charged particles in LAr lead to ionization electrons
  - Initial loss due to recombination
- Electrons drift towards anode plane
  - Drift is affected by space charge, electron lifetime, diffusion (transverse and longitudinal)
- Ionization signal measured by two induction planes and one collection plane

ProtoDUNE-SP Event Display - First Data!

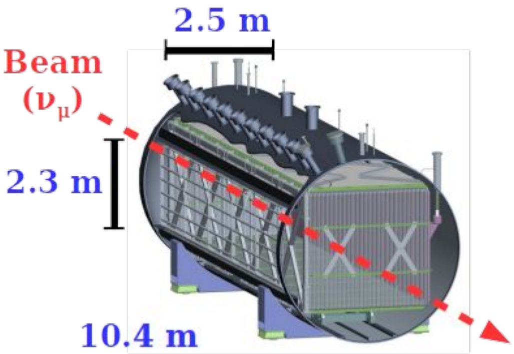


MicroBooNE

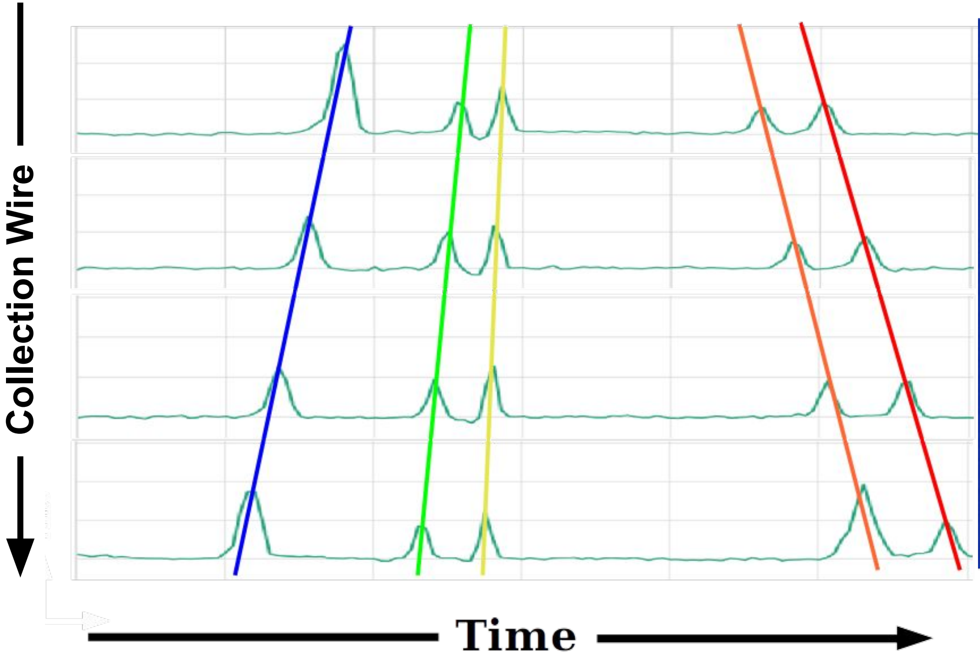
- Single-Phase LArTPC running since 2015
    - 85 ton active mass
    - Largest active LArTPC in US
- Located at Fermi National Accelerator Laboratory in the Booster Neutrino Beam

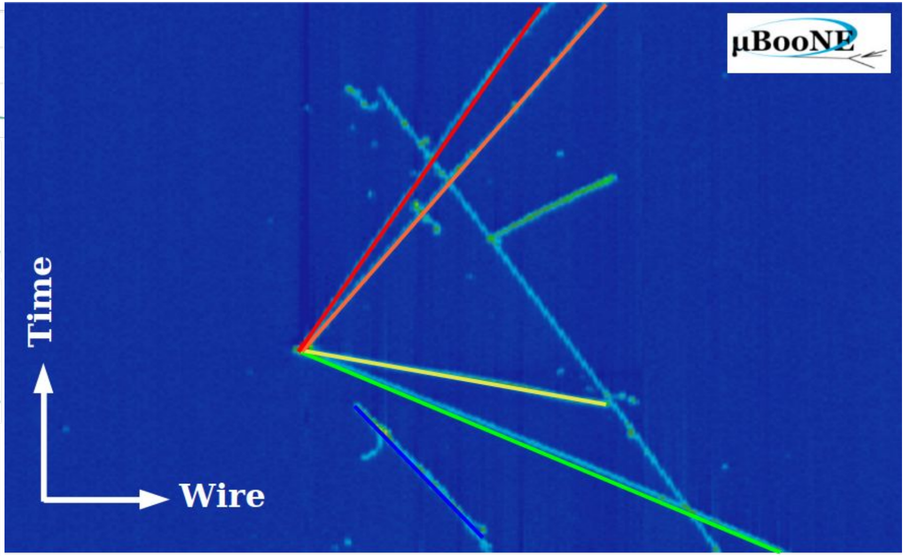


- Provides R&D and a test facility for DUNE
    - Very similar detector technology and signal readout / processing
    - Smaller wire pitch (3mm)
    - Lower drift electric field (273 V/cm)
    - No grid plane before first induction plane
    - Induction plane wire lengths vary
- MicroBooNE experience can be used to improve signal-to-noise at DUNE!



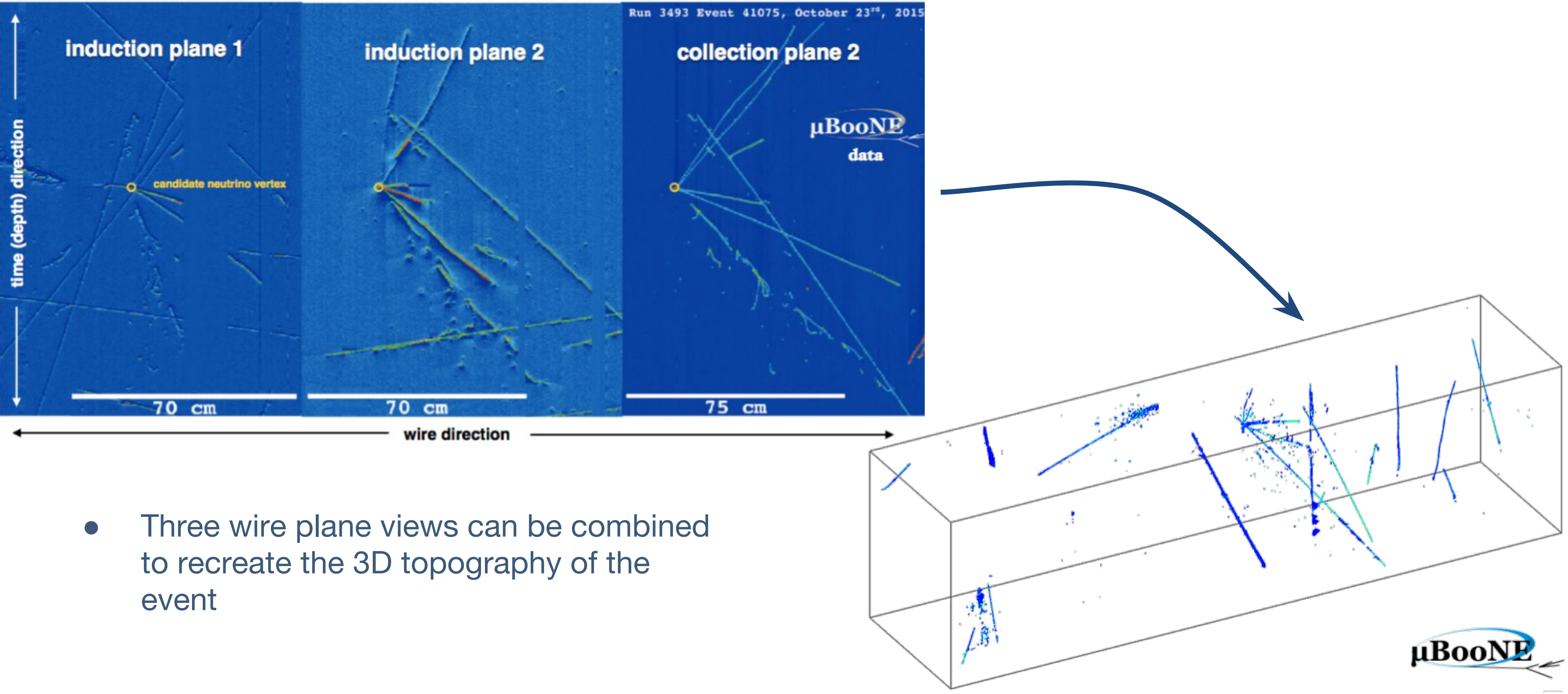
Raw Waveforms





- Raw waveform output results in bubble-chamber-like images with high spatial resolution and calorimetric information

3D Event Reconstruction



- Three wire plane views can be combined to recreate the 3D topography of the event

Signal Formation - Wire and Electronics Responses

Number of Ionized Electrons

Field Response

Signal on Wire Plane

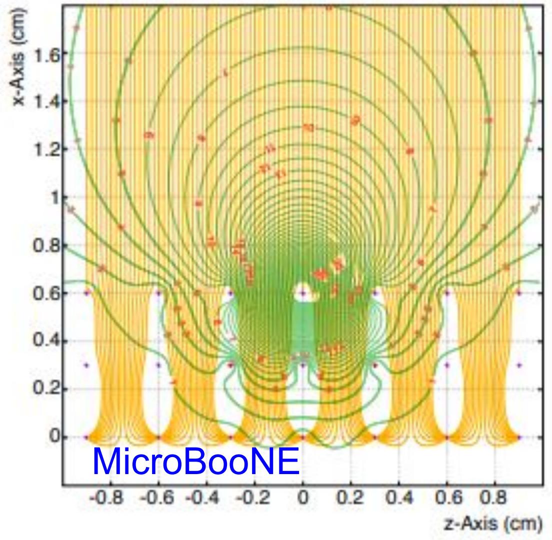
Electronics Response

Signal to be Digitized by ADC

Signal Deconvolution and Calibration

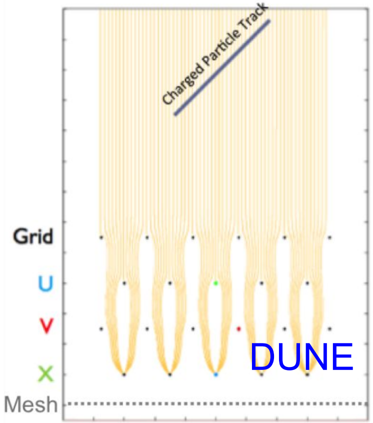
Number of Ionized Electrons

$$i = -q\vec{E}_w \cdot \vec{v}_q$$

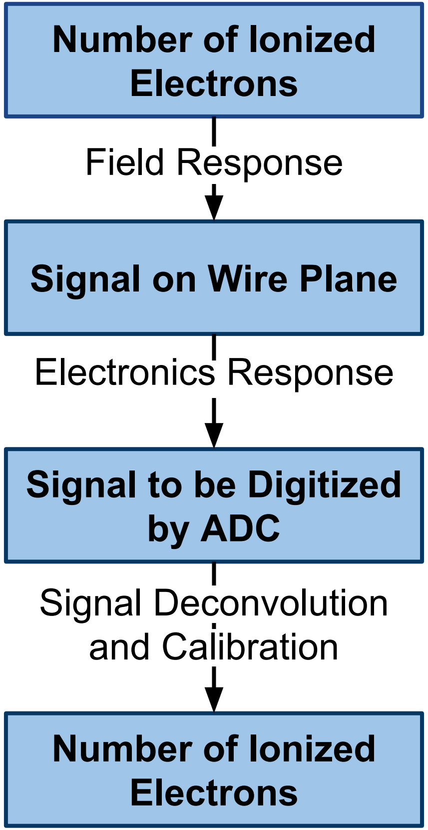


MicroBooNE collaboration, JINST 13, P07006 (2018)
MicroBooNE collaboration, JINST 13, P07007 (2018)

- Current on a wire (wire response) determined by Shockley-Ramo's theorem
  - Weighting potential calculated using 2D Garfield simulation
- Account for long-range effects by including induced charge on neighboring wires (± 10 wires)



Signal Formation - Wire and Electronics Responses



Number of Ionized Electrons

Field Response

Signal on Wire Plane

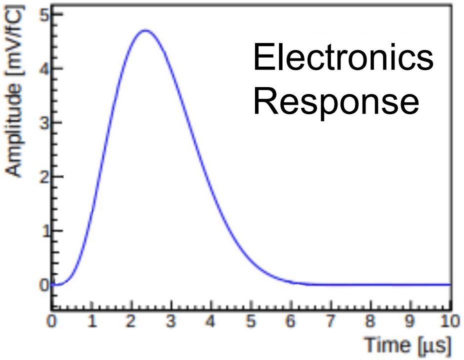
Electronics Response

Signal to be Digitized by ADC

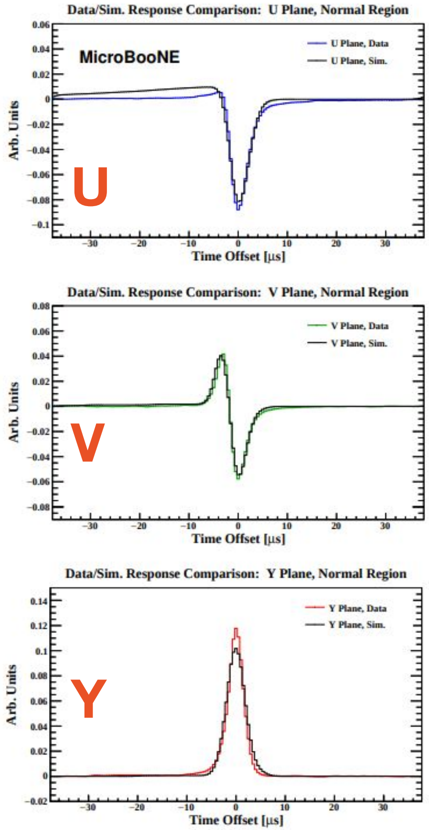
Signal Deconvolution and Calibration

Number of Ionized Electrons

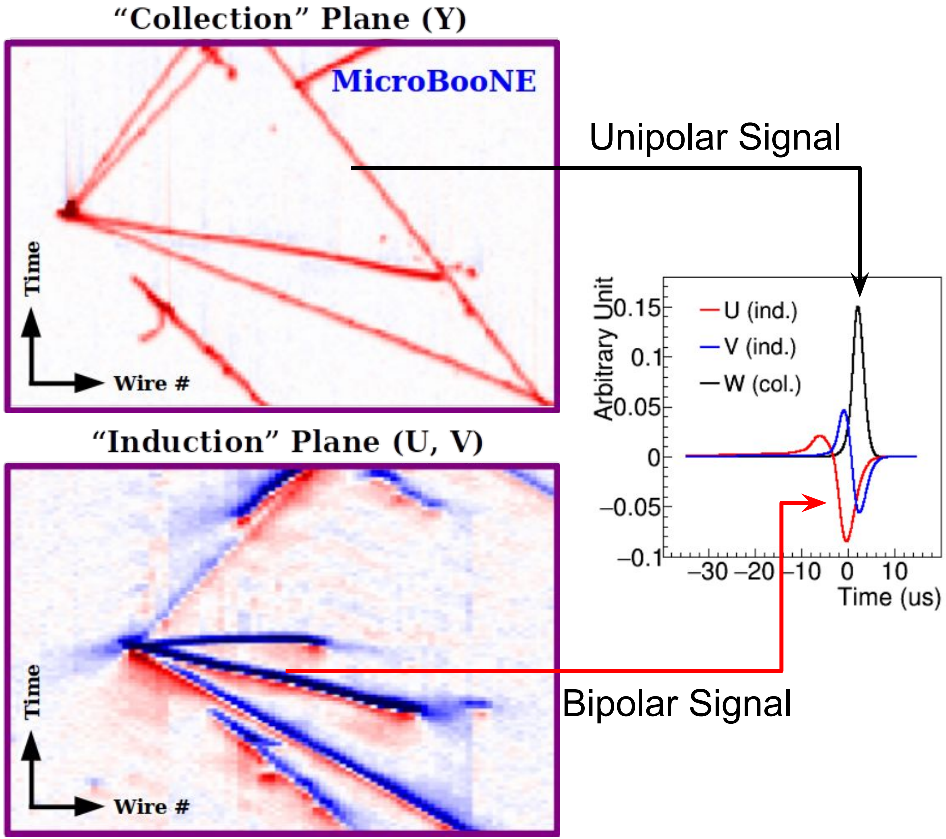
- Electronics response determined by pre-amplifier
  - Approximates response of triangle with equal rise and fall times
- Induction planes have bipolar signals
- Collection plane has unipolar signals
- DUNE grid shields U plane → looks more like V plane



MicroBooNE collaboration, JINST 13, P07006 (2018)
MicroBooNE collaboration, JINST 13, P07007 (2018)

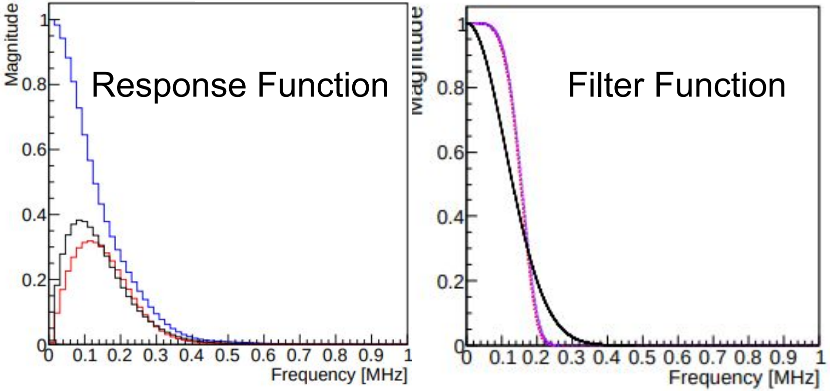


Signal Deconvolution



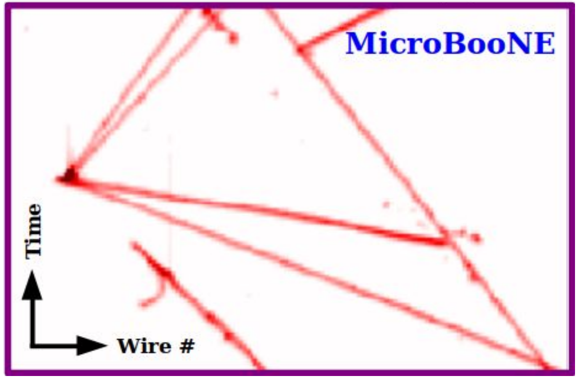
- Necessary to accurately locate ionization signals and determine charge
- Removes detector response, R(ω)
- Includes filter function, F(ω), to mitigate high frequency noise influence
  - Uses Wiener or Gaussian filter function

$$F(\omega) = \frac{\overline{R^2(\omega)S^2(\omega)}}{\overline{R^2(\omega)S^2(\omega)} + \overline{N^2(\omega)}}$$

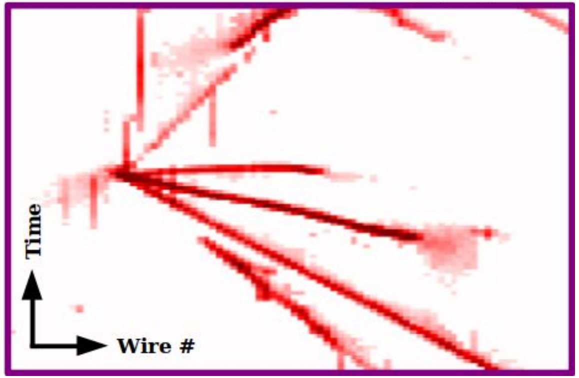


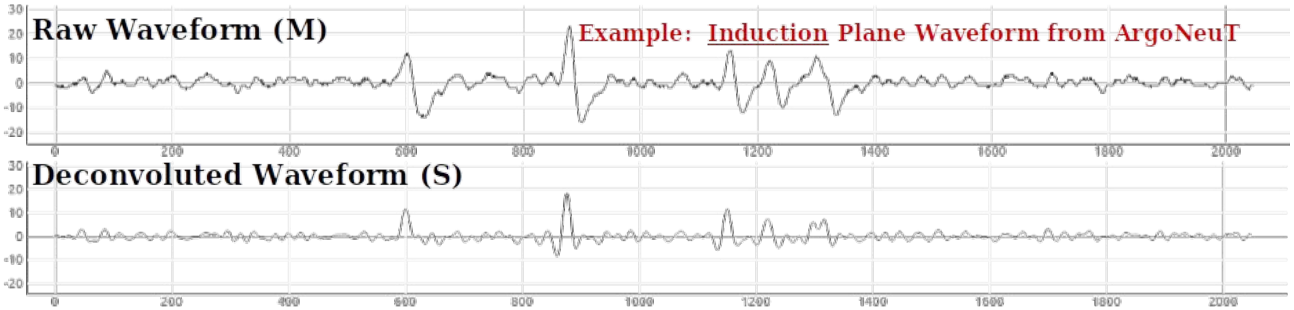
Signal Deconvolution - 1D

“Collection” Plane (Y)



“Induction” Plane (U, V)





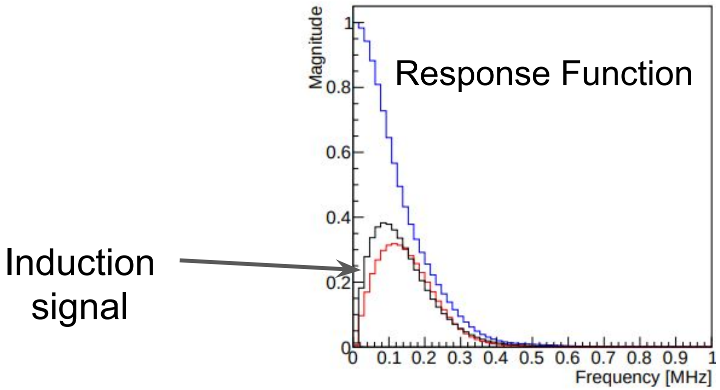
- Only considers the measured signal on a single wire with respect to time
  - Ignores induced charge on neighboring wires
- Assumes response is independent of ionization electron topology
  - Tracks nearly perpendicular to the wire plane reconstruct poorly

$$S(\omega) = \frac{M(\omega)}{R(\omega)} \cdot F(\omega)$$

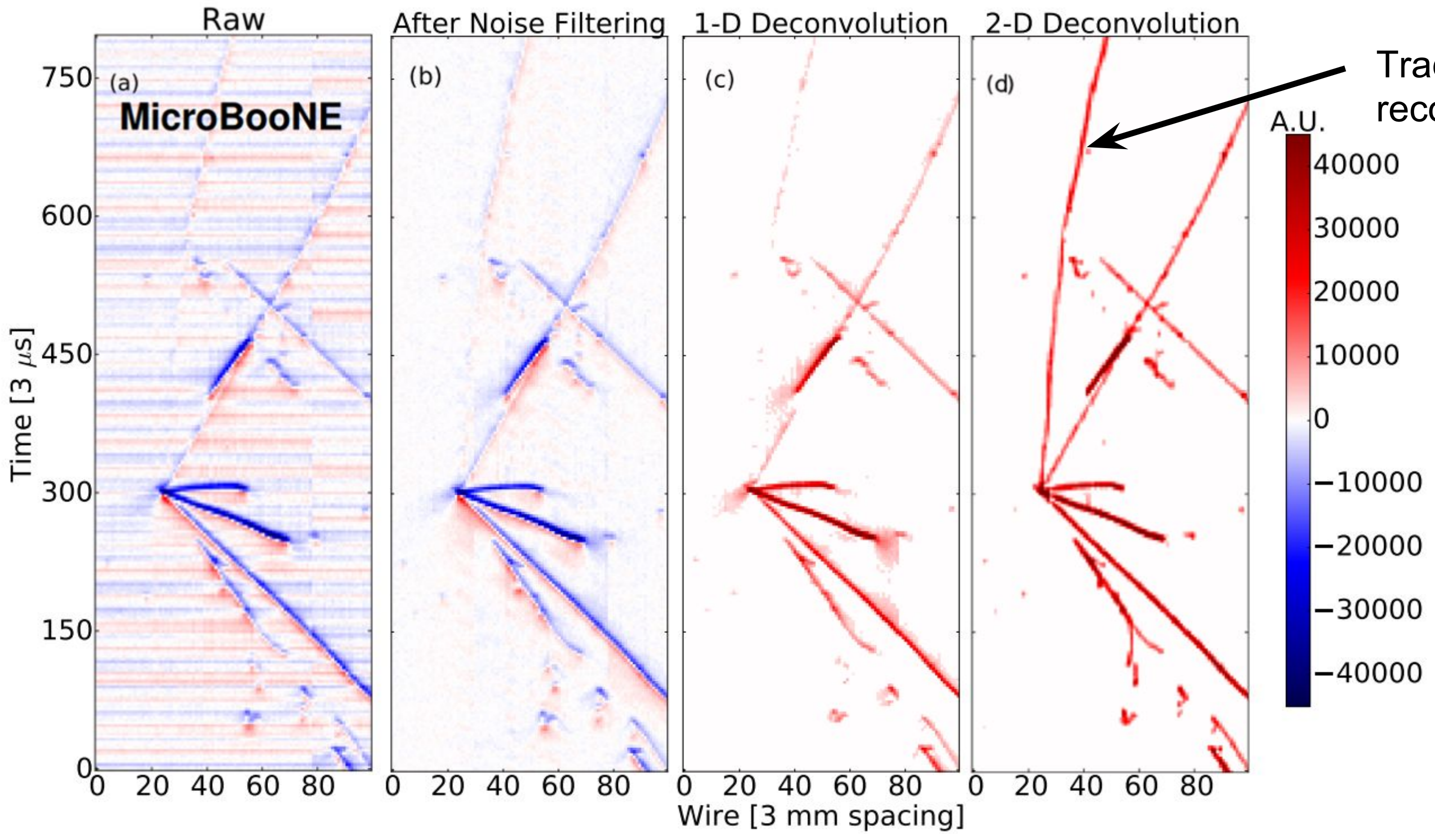
Signal Deconvolution - 2D and ROI Finding

- Uses both timing and wire information to determine charge and track position
    - Accounts for induced charge on neighboring wires
- Low-frequency noise amplified for induction signal
    - Use ROI-finding algorithm to suppress noise
        - ROI = **R**egion **o**f **I**nterest
    - ROIs determined from loose and tight low-frequency filters

$$\begin{pmatrix} M_1(\omega) \\ M_2(\omega) \\ \vdots \\ M_{n-1}(\omega) \\ M_n(\omega) \end{pmatrix} = \begin{pmatrix} R_0(\omega) & R_1(\omega) & \ldots & R_{n-2}(\omega) & R_{n-1}(\omega) \\ R_1(\omega) & R_0(\omega) & \ldots & R_{n-3}(\omega) & R_{n-2}(\omega) \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ R_{n-2}(\omega) & R_{n-3}(\omega) & \ldots & R_0(\omega) & R_1(\omega) \\ R_{n-1}(\omega) & R_{n-2}(\omega) & \ldots & R_1(\omega) & R_0(\omega) \end{pmatrix} \cdot \begin{pmatrix} S_1(\omega) \\ S_2(\omega) \\ \vdots \\ S_{n-1}(\omega) \\ S_n(\omega) \end{pmatrix}$$



Signal Deconvolution Comparison

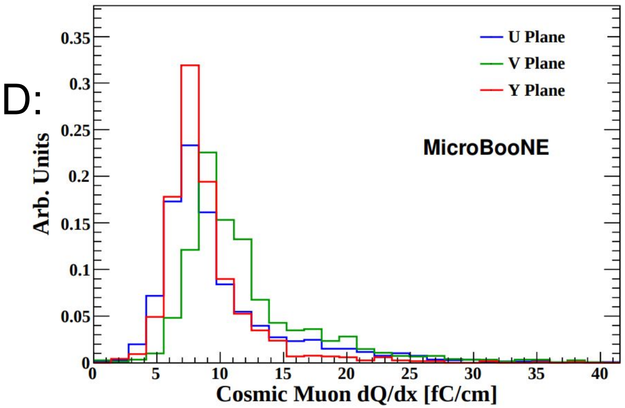


Track recovered!

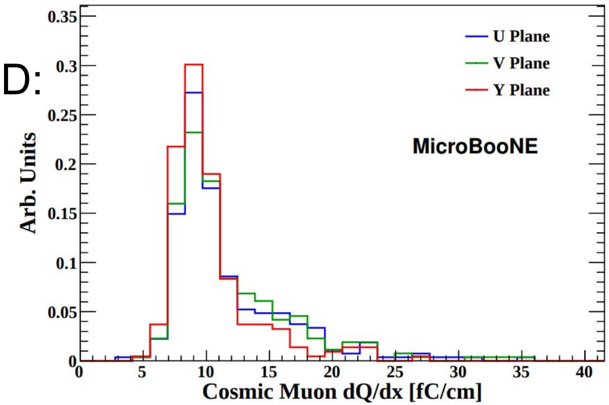
Performance of Signal Processing at MicroBooNE

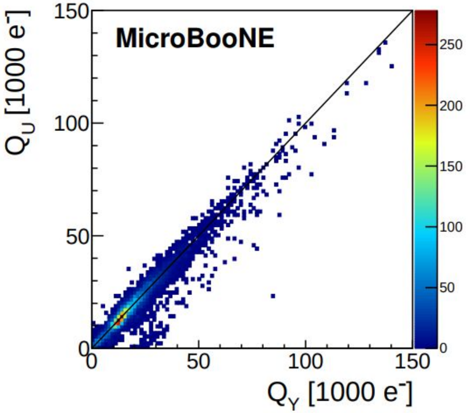
- Full signal processing chain allows for cross-plane charge matching
- Ionization charge extracted from (bipolar) induction plane signal
- 2D deconvolution performs better than 1D deconvolution
- Remaining mismatch due to electronics noise, non-ideal wires, inaccurate field responses in deconvolution

1D:

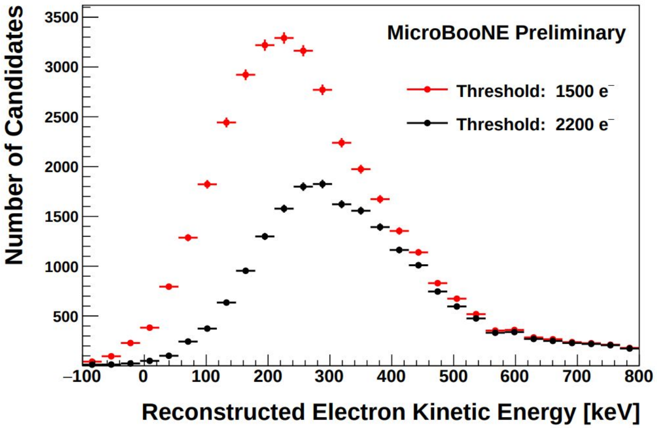


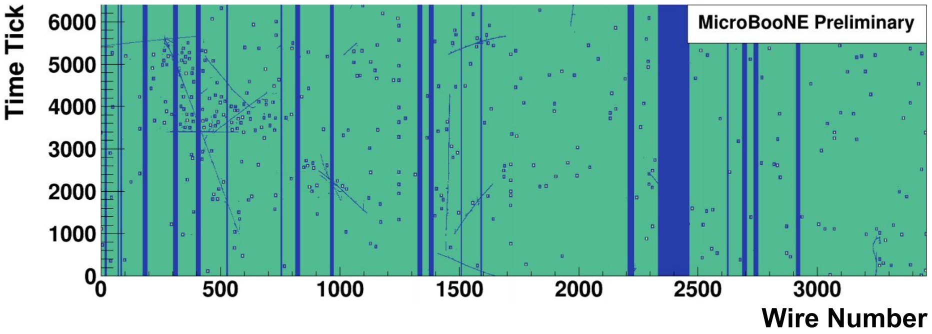
2D:





^{39}Ar Beta Decays



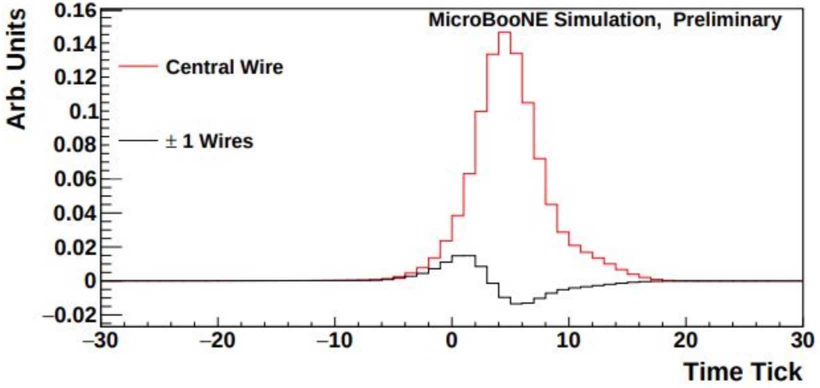


- Uniformly-distributed, point-like decays with low end-point energy (565 keV)
  - Energy scale relevant for supernova neutrinos
- Point-like activity useful for measuring wire response
  - Spans only a few wires: good approximation of impulse response (after accounting for diffusion)
  - Can measure wire-to-wire variations

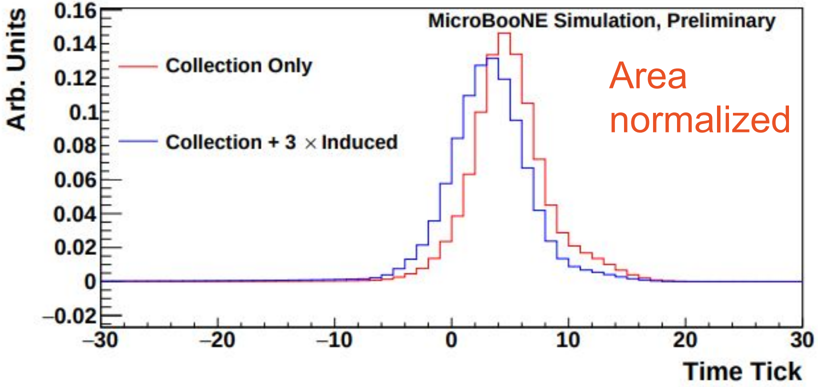
MicroBooNE Collaboration, MICROBOONE-NOTE-1050-PUB

^{39}Ar - A Case Study for Signal Shape

All charge collected on central wire:



Some charge collected on side wires:

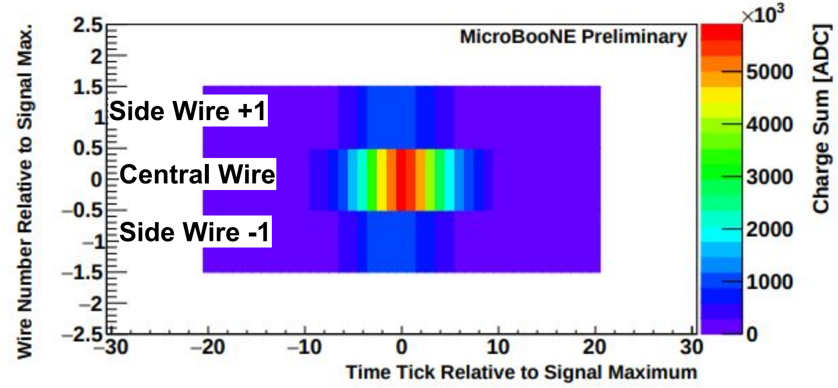


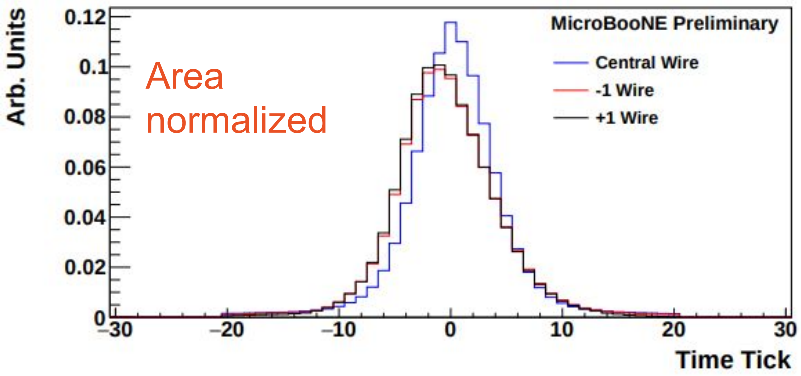
Area normalized

- Some collection and induction on same wire:
    - Shifts peak forward in time
    - Does not change total charge (bipolar signal integrates to zero)

^{39}Ar - A Case Study for Signal Shape

- Averaged waveforms show shift forward in time for side wires
    - Side wire response includes both induction (bipolar) and collection (unipolar) components
- Study of averaged waveforms of ^{39}Ar decays
    - Study focused on collection-plane wires only
    - Measured using 1000 MicroBooNE data events corresponding to ~292,000 ^{39}Ar decays
    - Averaged over topology and drift-dependent effects
- Induction response on collection plane should not be ignored in signal processing!





Area normalized

Conclusions

- Single-phase LArTPCs at DUNE far detector require dedicated signal processing chain to locate ionization electrons and reconstruct charge information
- Three-wire-plane readout allows for 3D event reconstruction and precise calorimetry
- MicroBooNE has enabled development of signal processing techniques for next-generation LArTPC experiments such as DUNE
  - 2D deconvolution includes long-range effects from induced charge on neighboring wires
  - Point-like activity such as ^{39}Ar beta decays can be used to measure wire response
- Next step: exercise these signal processing techniques at ProtoDUNE-SP

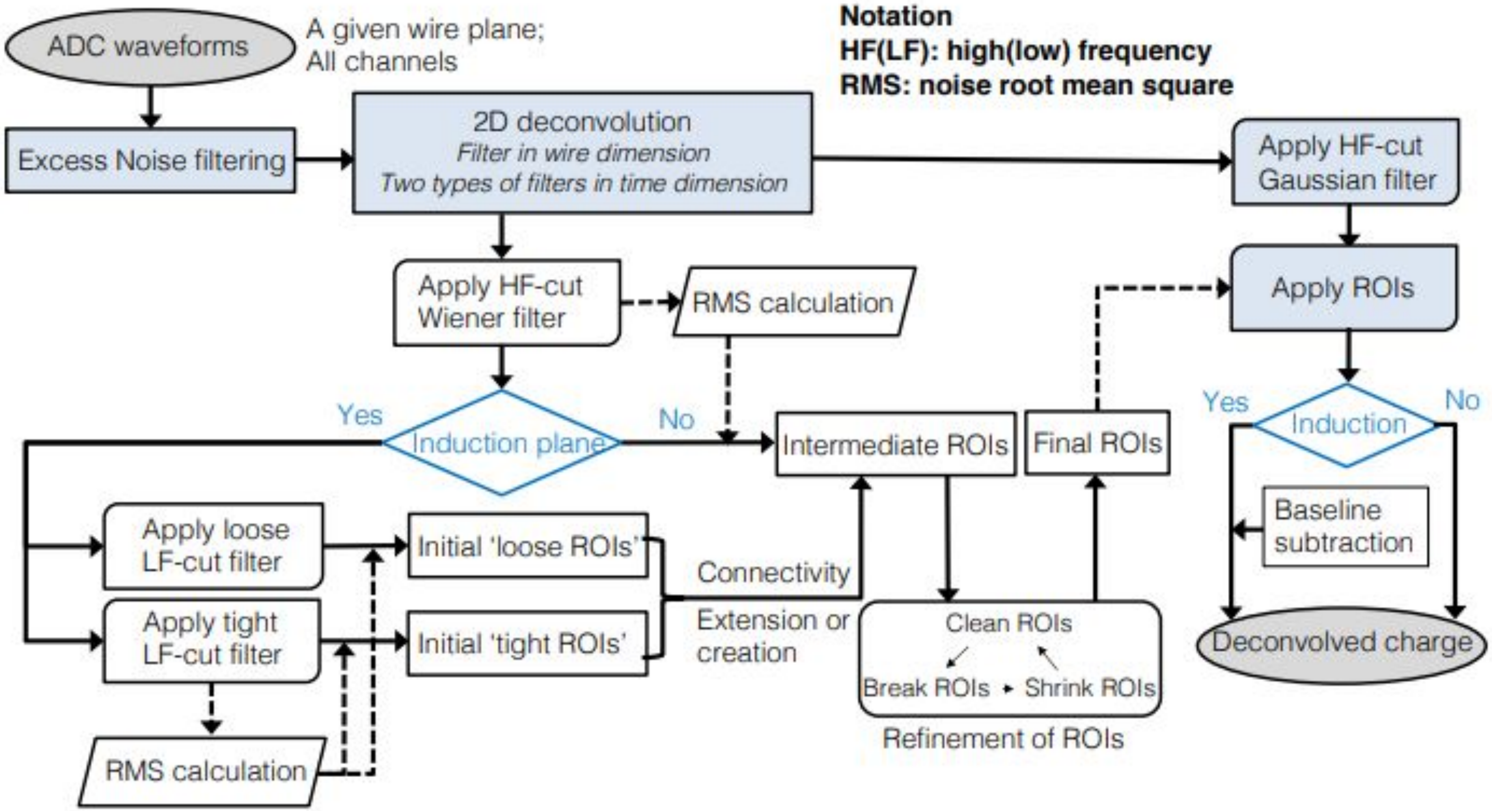
Thank you!

References Used for Figures

1. DUNE Collaboration, “The DUNE Far Detector Interim Design Report Volume 1: Physics, Technology, and Strategies”, FERMILAB-DESIGN-2018-02
2. DUNE Collaboration, “The DUNE Far Detector Interim Design Report Volume 2: Single-Phase Module”, FERMILAB-DESIGN-2018-03
3. DUNE Collaboration, “The Single-Phase ProtoDUNE Technical Design Report”, FERMILAB-DESIGN-2017-02
4. MicroBooNE collaboration, “Ionization Electron Signal Processing in Single Phase LAr TPCs I: Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation”, JINST 13, P07006 (2018)
5. MicroBooNE collaboration, “Ionization Electron Signal Processing in Single Phase LAr TPCs II: Data/Simulation Comparison and Performance in MicroBooNE”, JINST 13, P07007 (2018)
6. MicroBooNE Collaboration, “Study of Reconstructed ^{39}Ar Beta Decays at the MicroBooNE Detector”, MICROBOONE-NOTE-1050-PUB

Backup Slides

ROI-Finding Algorithm



Notation
HF(LF): high(low) frequency
RMS: noise root mean square