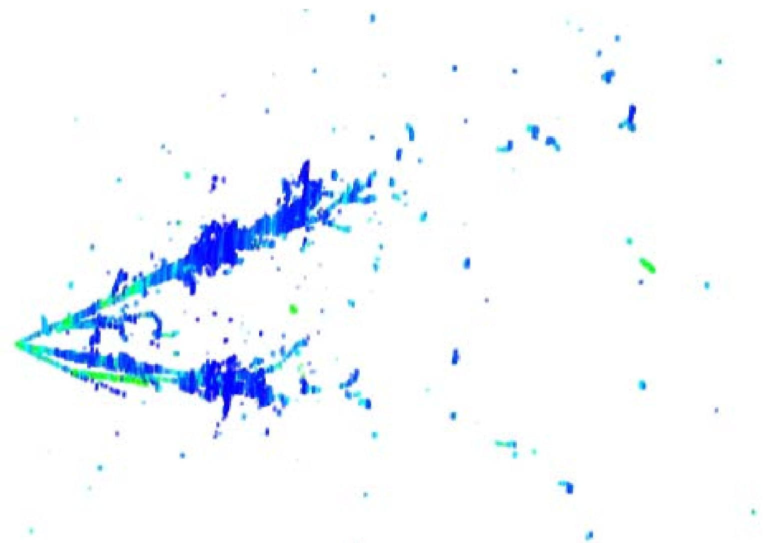
Development of LArTPC for Neutrino Physics

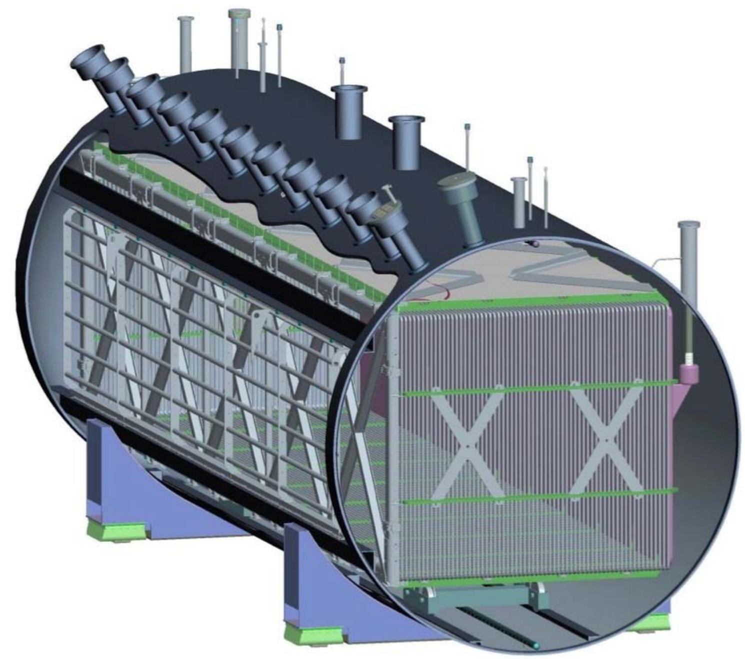
Xin Qian

BNL



Outline

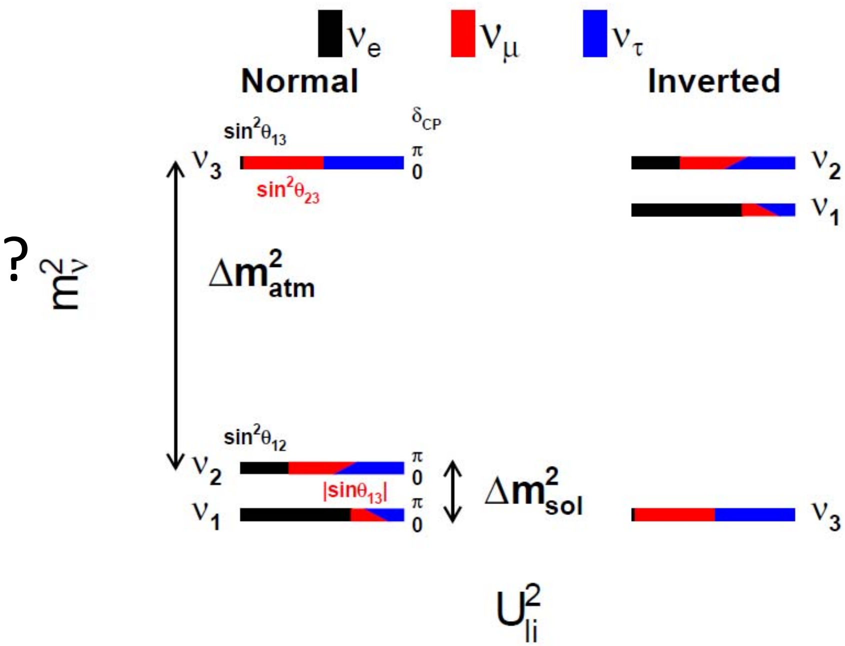
- LArTPCs for Neutrino Physics
- Principle of LArTPC
  - LArTPC Signal Processing
  - Wire-Cell Tomographic Event Reconstruction
  - Optimization of LArTPCs
- Summary



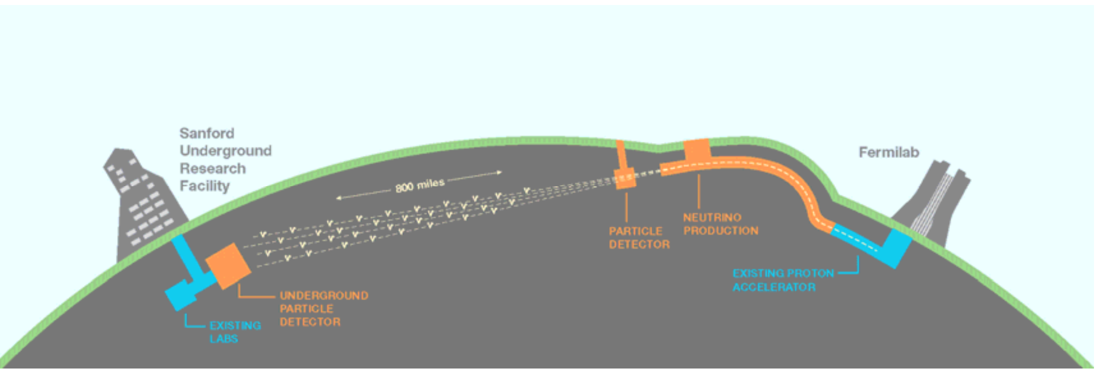
MicroBooNE LArTPC

Big Questions in Neutrino Physics?

- Are neutrinos responsible for the large matter anti-matter asymmetry?
- What's the neutrino mass hierarchy?
- Are neutrino Dirac or Majorana particles?
- What is the neutrino mass?
- Are there sterile neutrinos?
- …

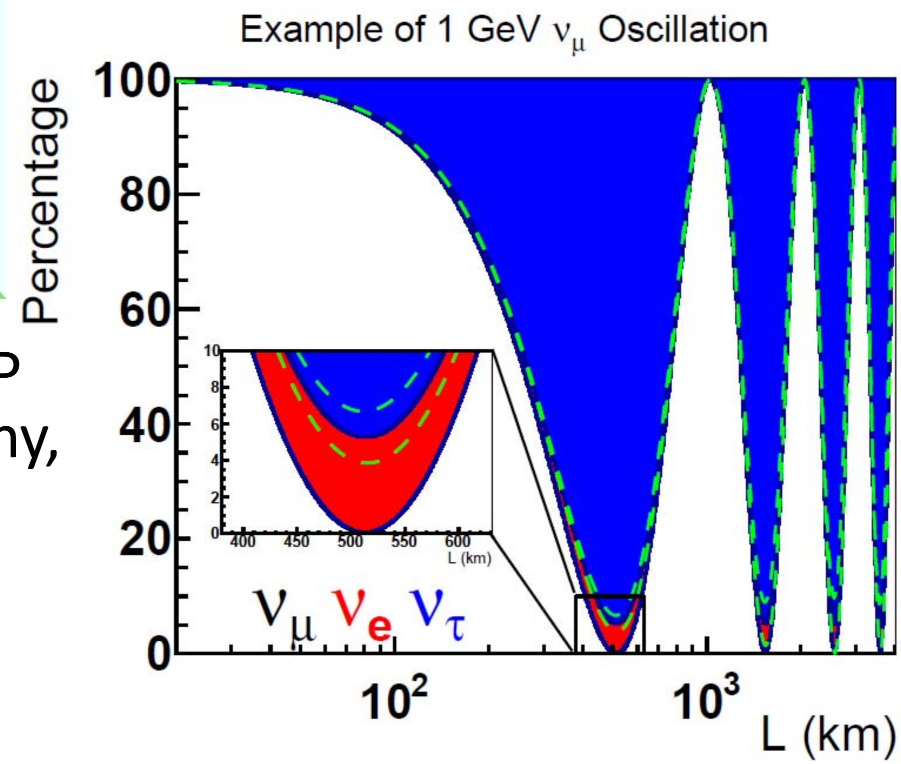


Deep Underground Neutrino Experiment (DUNE)



- DUNE is designed to search for new CP violation, determine the mass hierarchy, test the unitarity of PMNS matrix through precision measurement of (anti)ν_μ→(anti)ν_e

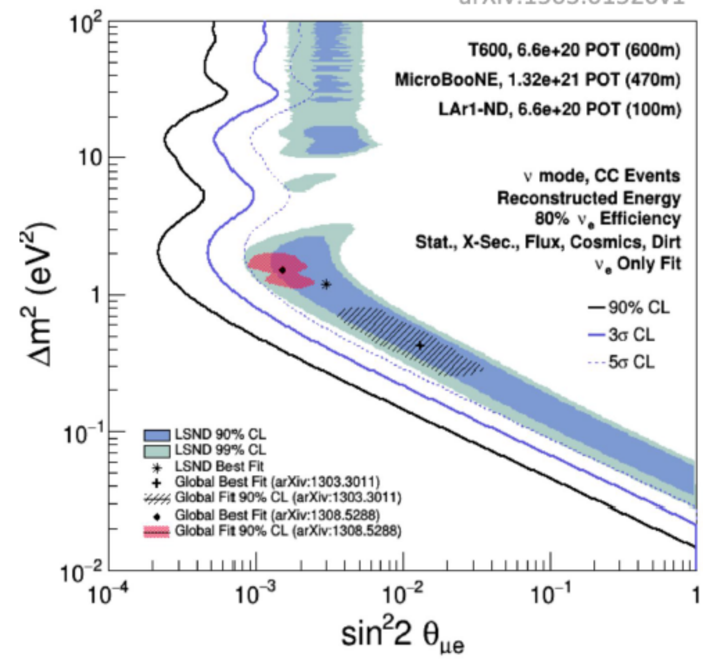
- Also search for proton decay and detect supernova neutrinos

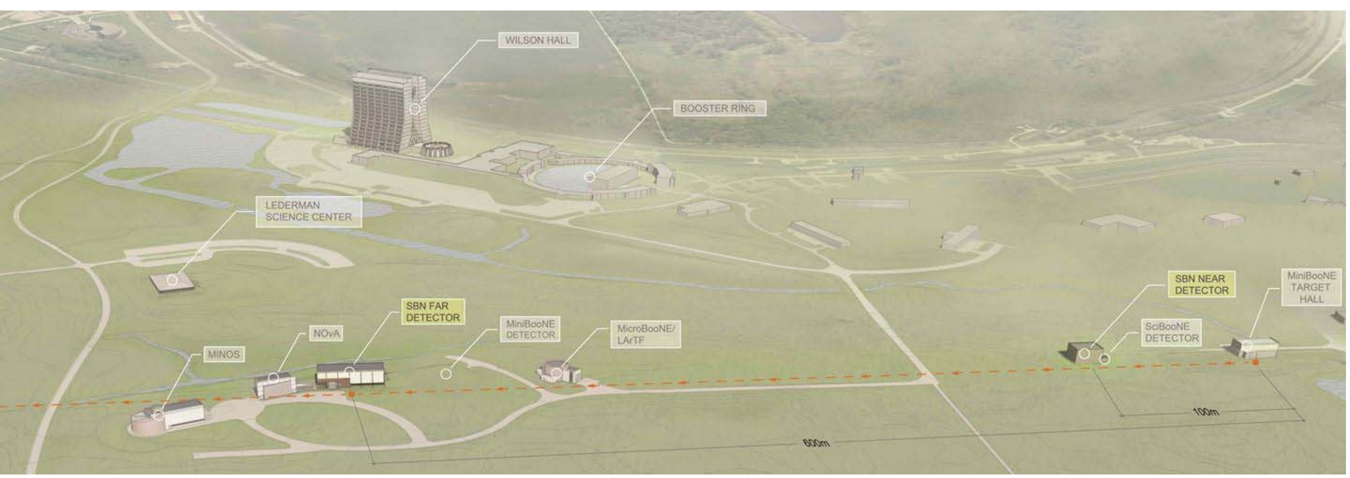


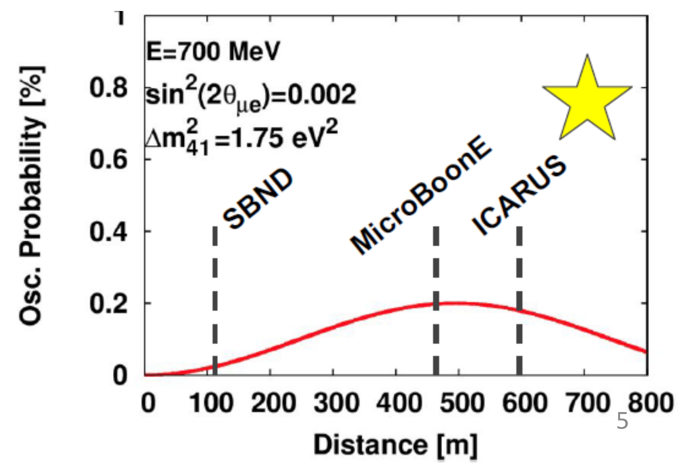
Short-Baseline Neutrino Program

- Search for light sterile neutrino through search for anomalous $\nu_\mu \rightarrow \nu_e$ oscillation motivated by LSND and MiniBooNE anomalies

arXiv:1503.01520v1

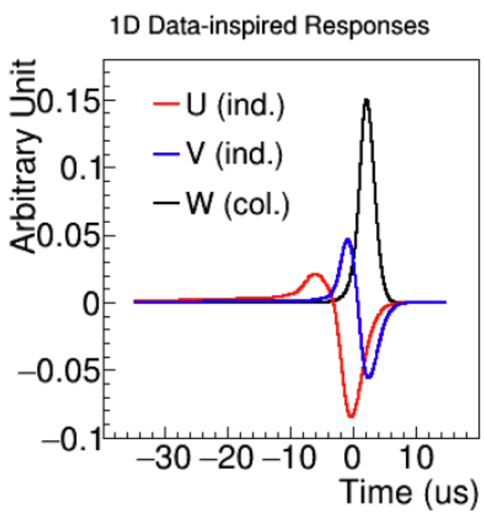


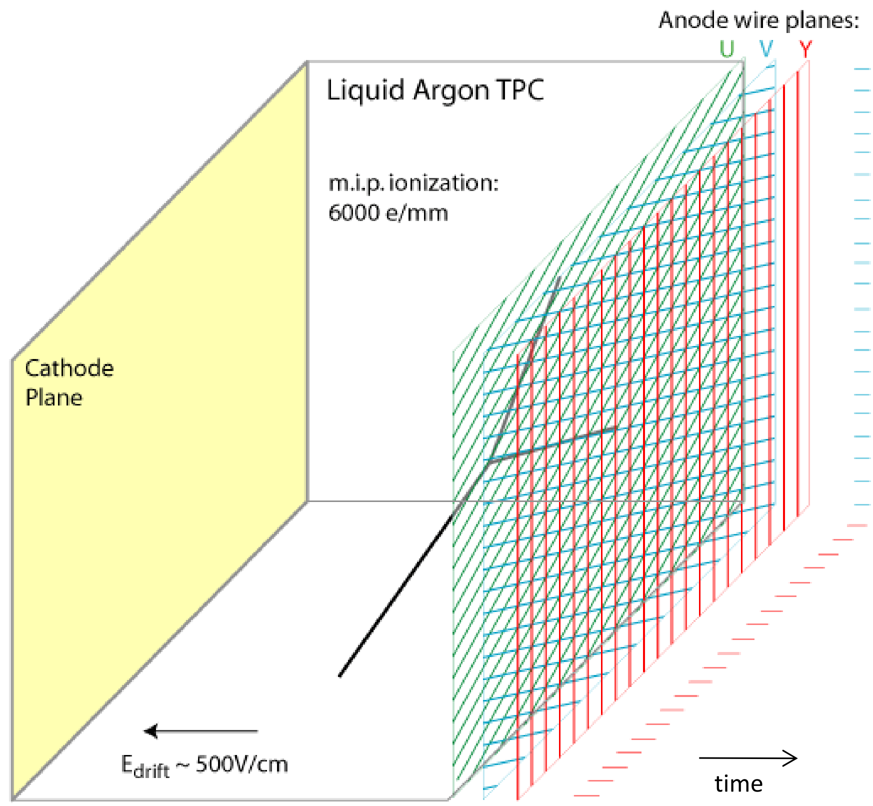




Principle of Single-Phase Liquid Argon Time Projection Chamber (LArTPC)

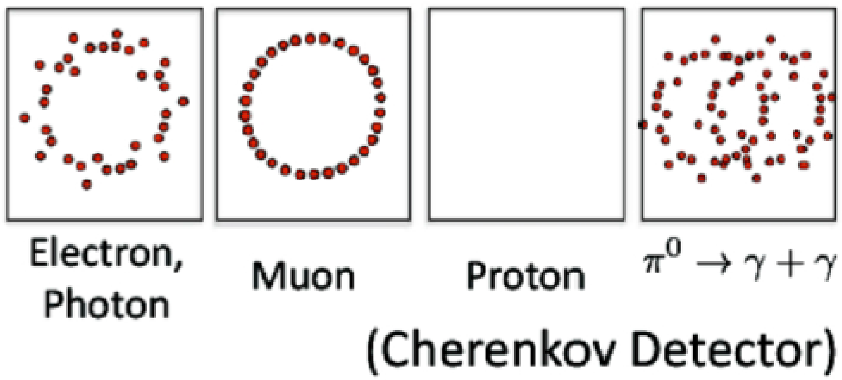
- LArTPC has mm scale position resolution with multiple 1D wire readouts
- Energy deposition and topology can be used to do PID
- Ar: the most abundant noble gas



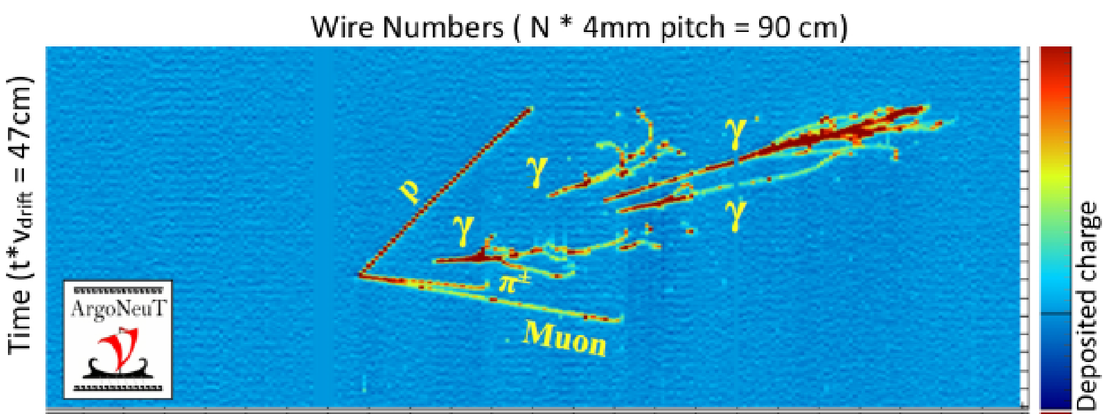


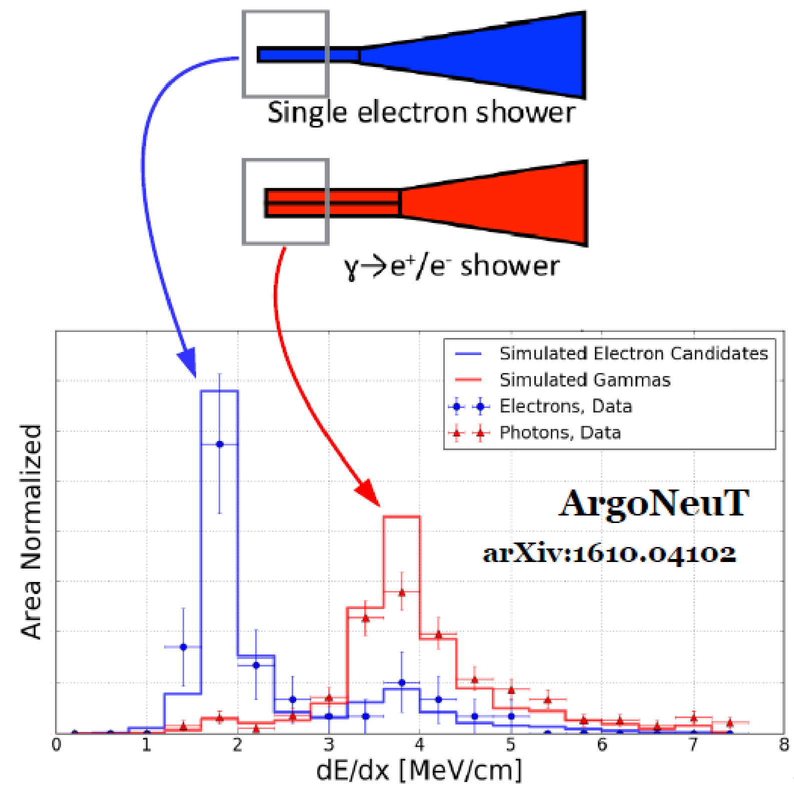
Drift velocity 1.6 km/s → several ms drift time

Unique e/γ separation in LArTPC



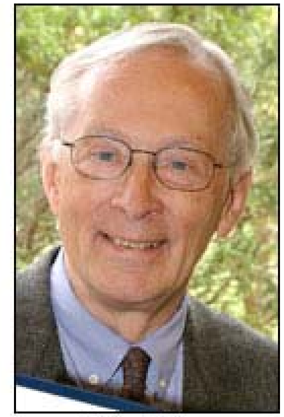
- Gap Identification + dE/dx for LArTPC

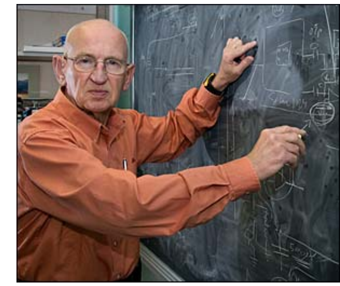


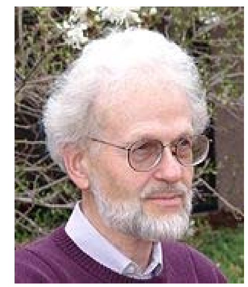


Early History of the Development of LArTPC

- W. Willis and V. Radeka, Liquid argon ionization chambers as total absorption detector, NIMA 120:221 (1974)
- D. R. Nygren, The Time Projection Chamber: A New 4π Detector for Charged Particles. eConf. C740805:58 (1974)
- H. H. Chen et al. A Neutrino detector sensitive to rare process. I. A study of neutrino electron reactions. FNAL-Proposal-0496 (1976)
- C. Rubbia, The liquid argon time projection chamber: a new concept for neutrino detector, CERN-EP/77-08 (1977)


William Willis

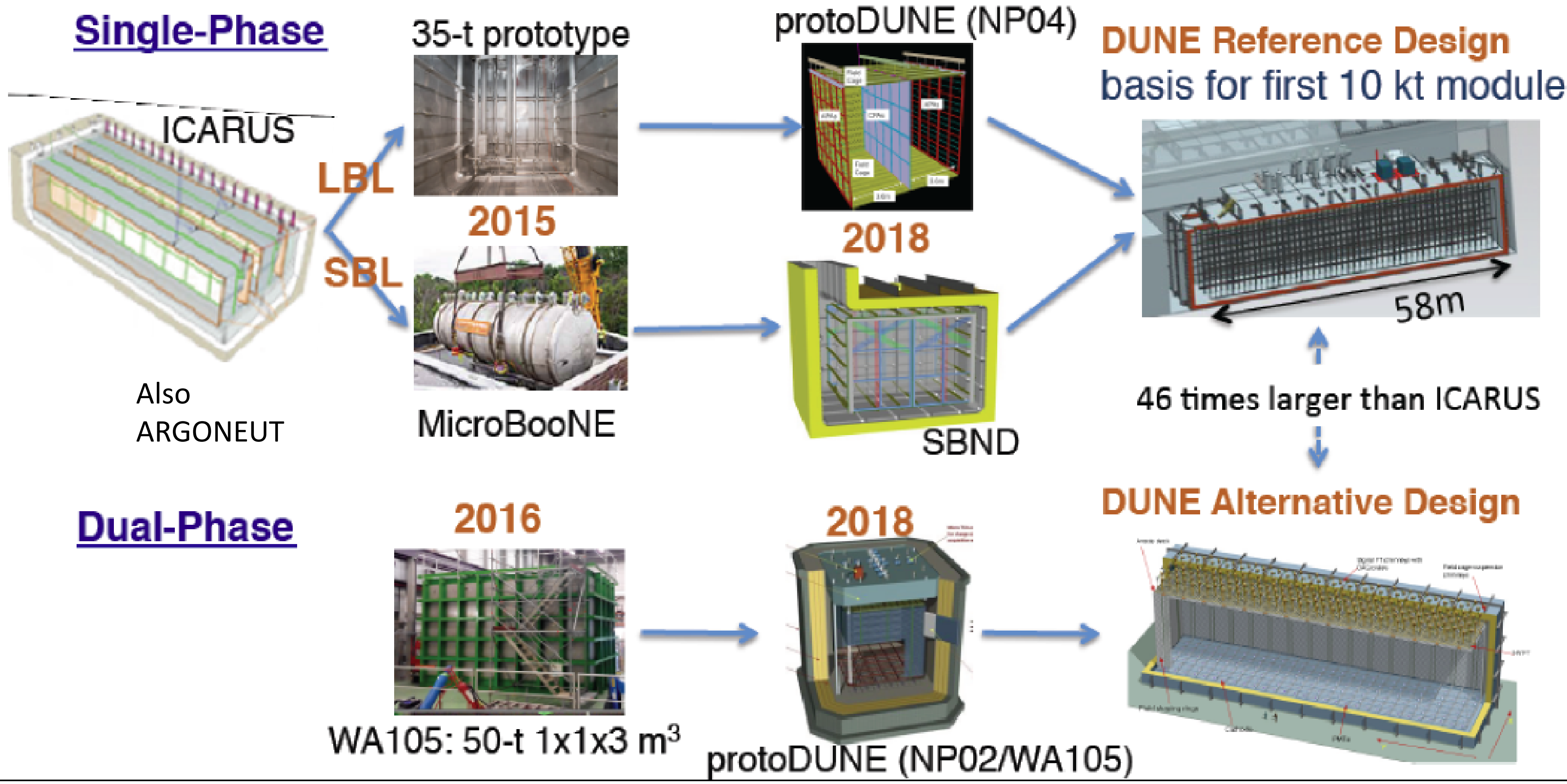

V. Radeka


D. R. Nygren

H. H. Chen


C. Rubbia

History of the Development of LArTPC



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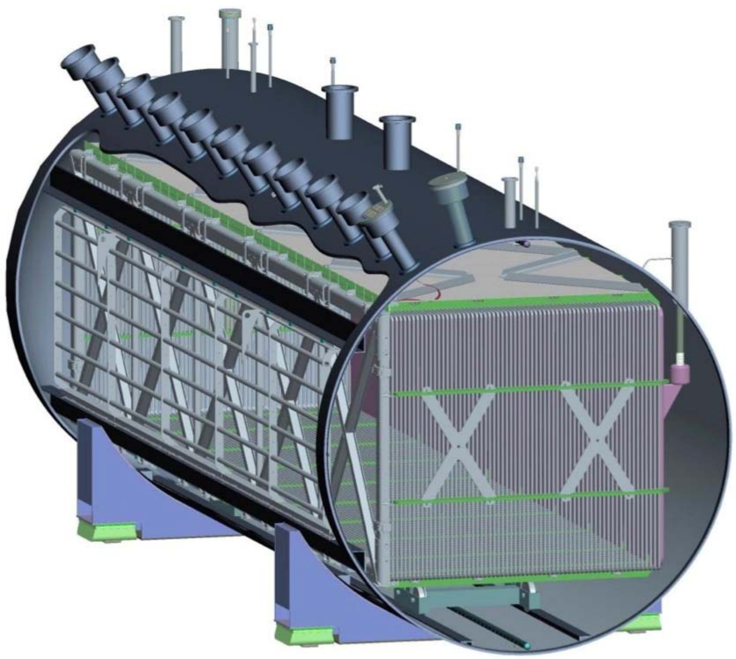
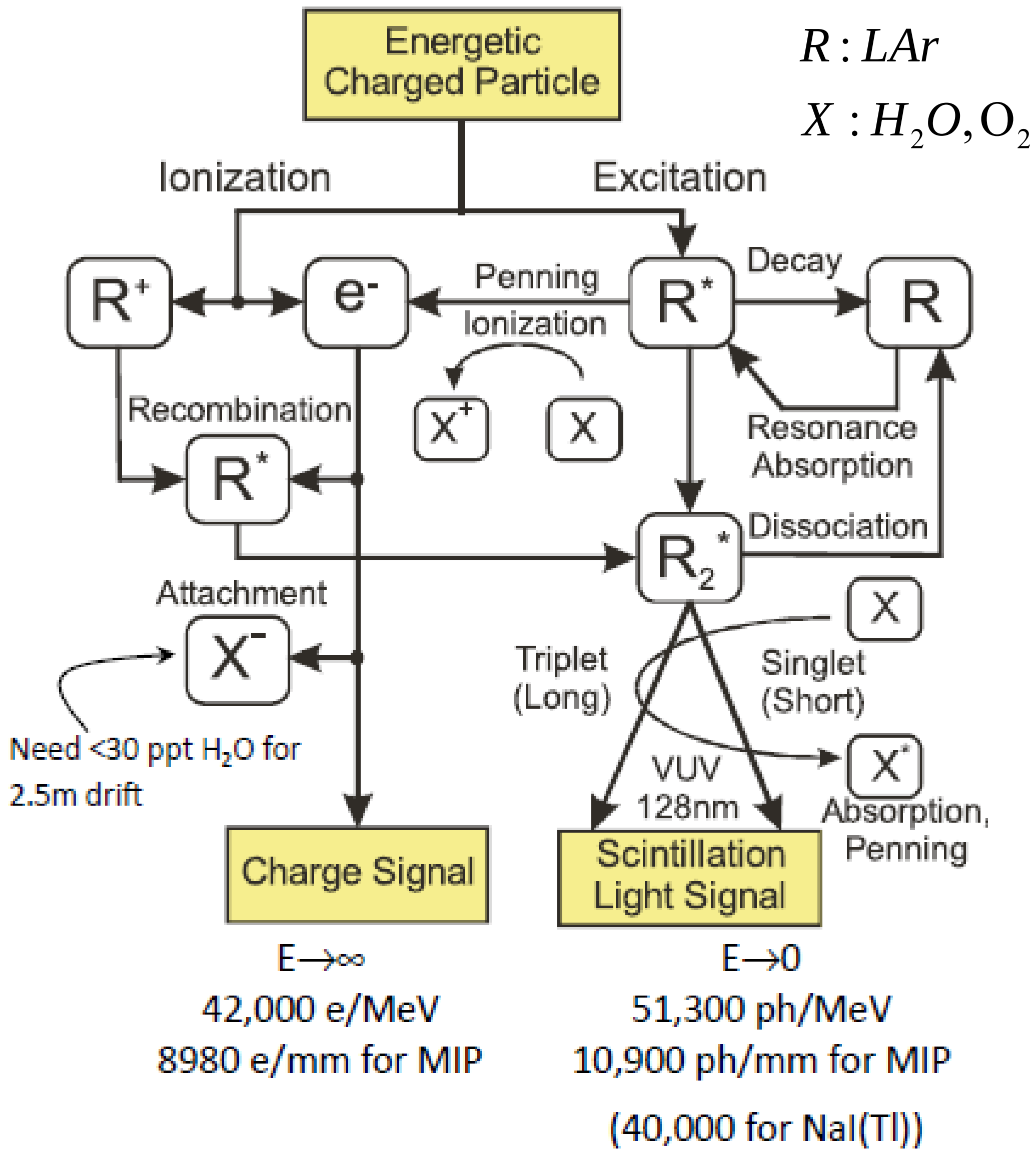


MicroBooNE LArTPC



Charge Particle going through LAr

- Ionization signal is very small

$$\frac{1.8\,\mathrm{MeV}/\mathrm{cm}}{23.6\ \mathrm{eV}} \times (0.3\ \mathrm{cm}) \times 0.7 \times 0.85 \sim 13600\ \mathrm{e}^-$$

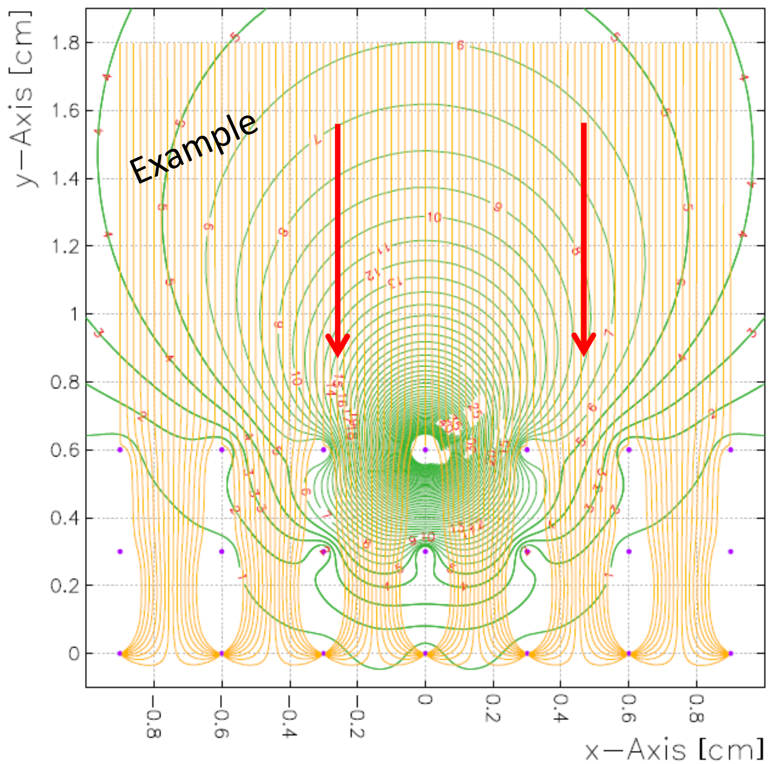
Energy deposition — Wire pitch — Recombination — Attenuation due to attachment

- Ultra pure LAr (~ ppb O_2 and ppt H_2O) is needed as $O(10^{12})$ collisions every second for an electron

Single-Phase TPC Signal Formation

Number of ionized electrons
↓ Field Response
Signal on Wire Plane
↓ Electronic Response
Signal to be digitized by ADC
↓ (Charge Extraction)
Number of ionized electrons

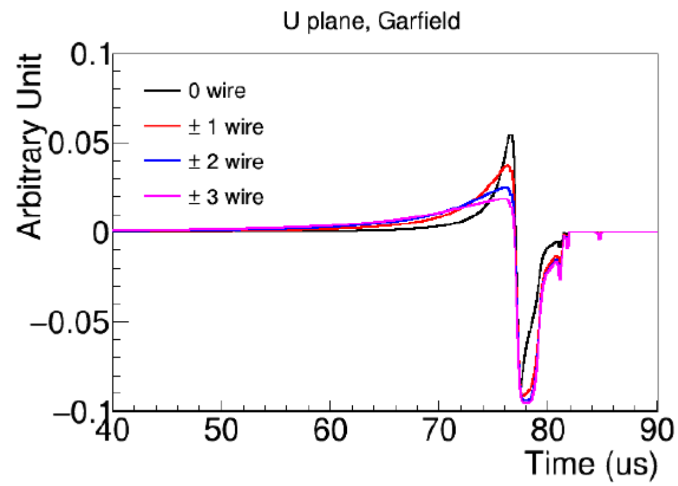
Weighting Potential of a U Wire



Shockley–Ramo theorem

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

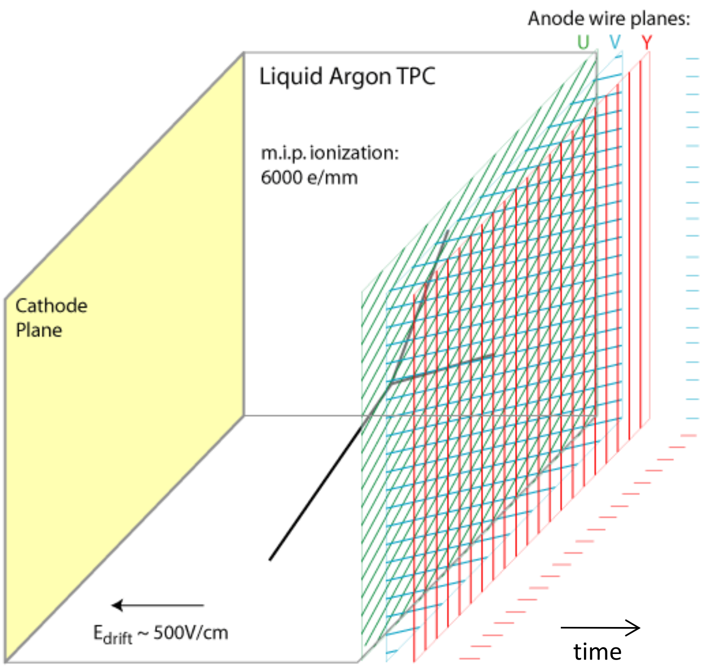
v_q: velocity
E_w: weighting field
q: charge



- Induction plane signal strongly depends on the local charge distribution, collection plane signal is much simpler

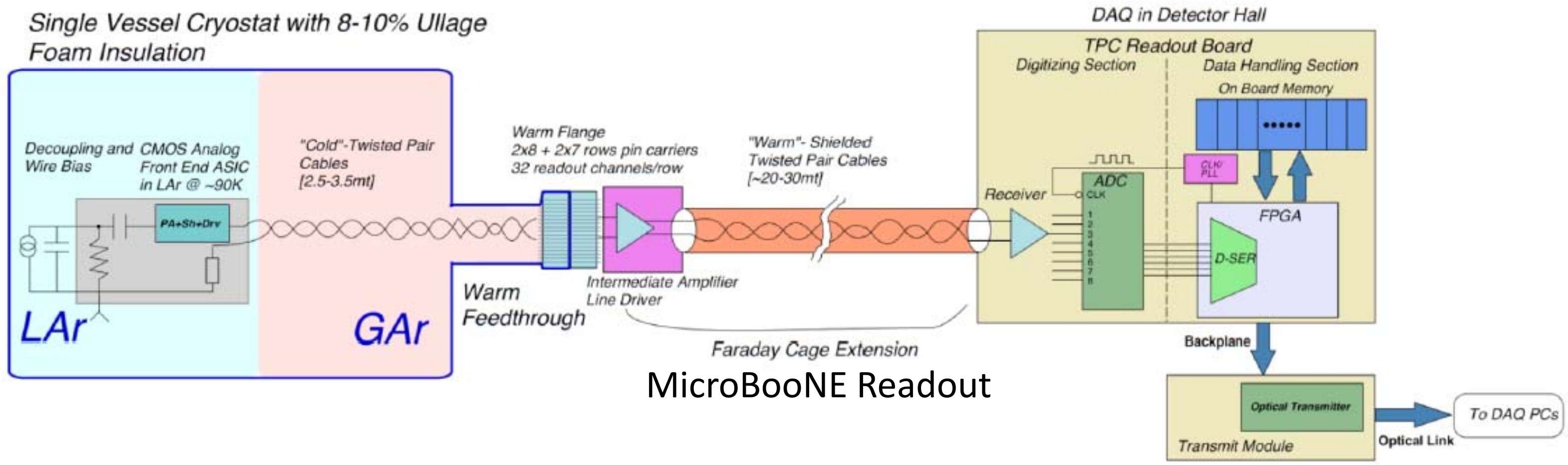
Challenges in LArTPC Signal

- Wire/strip readout is essential!
  - Power consumption of pixel readout in LAr is 1-2 orders higher than what we can handle
  - 40 kton detector → cost of pixel readout
    - MicroBooNE (60 tons)
      8256 wires vs. 3 million pixel readout
  - Important to have induction wire planes in addition to the collection wire plane



- There is no electron amplification inside LAr
  - Signal is very small ~10s k electrons
  - Cold electronics is essential to minimize electronics noise considering large wire capacitance

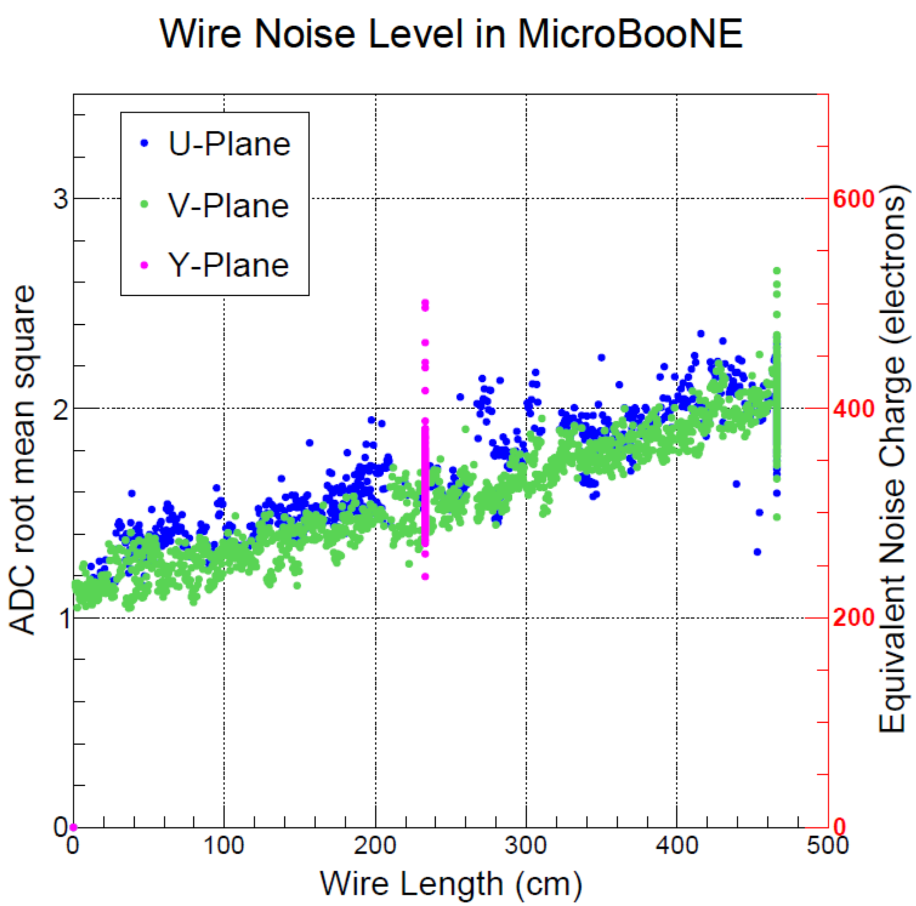
Enabling Technology: Cold Electronics

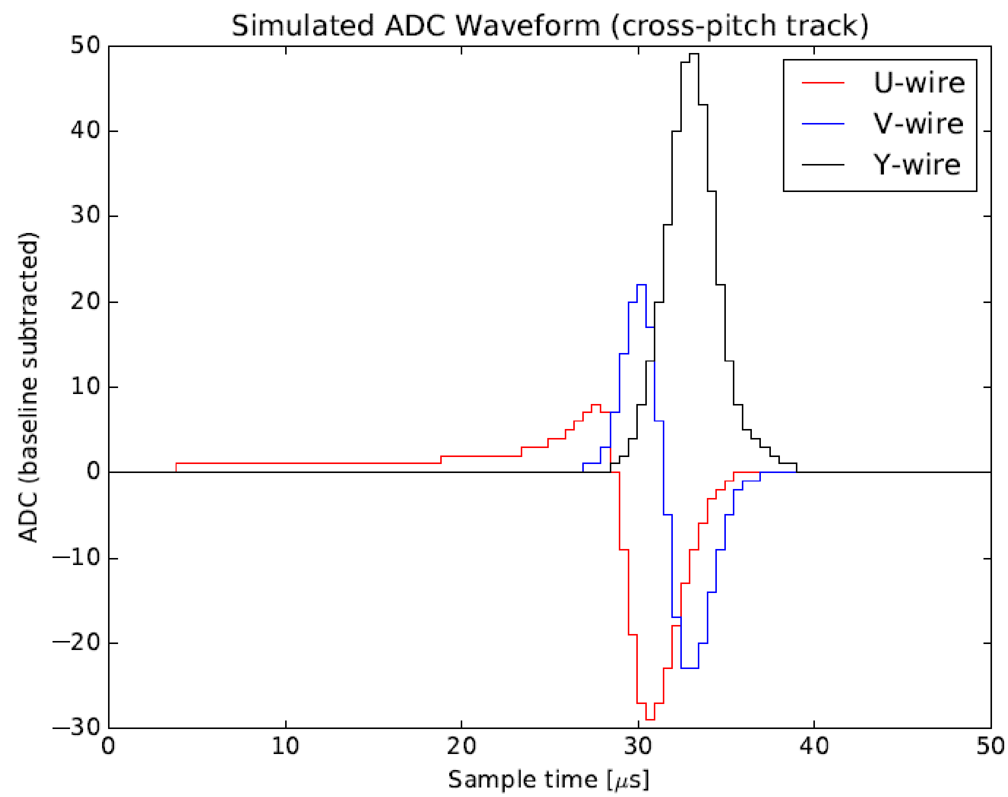


MicroBooNE Readout

- Placing the preamplifier inside LAr significantly reduced the electronics noise
  - 5-6 times comparing to past warm electronics (10:1 → 60:1 MIP peak-to-noise ratio in the collection)
  - Significantly improve the performance of induction wire plane

Cold Electronics Performance in MicroBooNE





TPC Signal Processing → Recover Ionization Electrons

Time domain

$$M(t_0) = \int_t R(t - t_0) \cdot S(t) \cdot dt$$

↓ Fourier transformation

$$M(\omega) = R(\omega) \cdot S(\omega)$$

Frequency domain

↓

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

↓

Back to time domain $S(t)$ Anti-Fourier transformation

- Signal processing is based on deconvolution technique
  - $O(N^3)$ matrix inversion is achieved through a $O(N \log N)$ fast Fourier transformation
- General good for collection plane signals
- Not good for induction plane signals due to lack of universal average response function

2-D Deconvolution

$$M_i(t_0) = \int_t \left(R_0(t - t_0) \cdot S_i(t) + R_1(t - t_0) \cdot S_{i+1}(t) + \ldots \right) \cdot dt$$

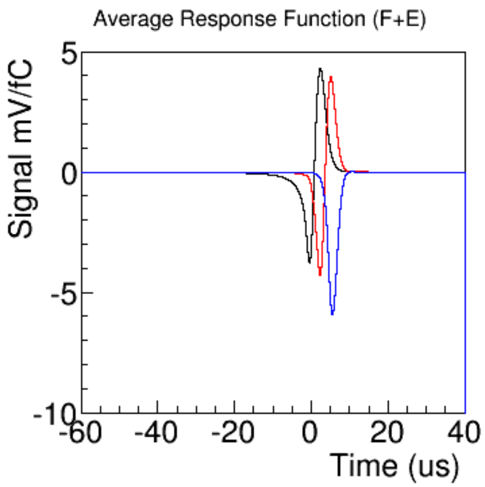
$$M_i(\omega) = R_0(\omega) \cdot S_i(\omega) + R_1(\omega) \cdot S_{i+1}(\omega) + \ldots$$

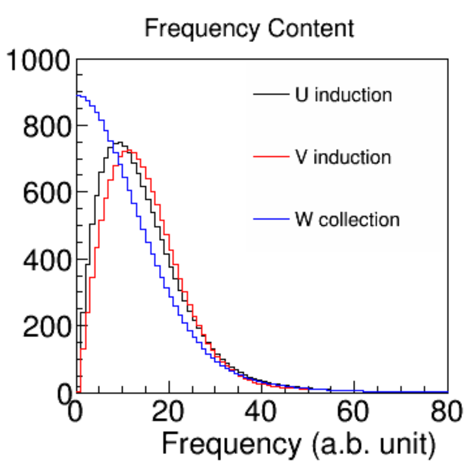
$$\begin{pmatrix} M_1(\omega) \\ M_2(\omega) \\ \ldots \\ M_{n-1}(\omega) \\ M_n(\omega) \end{pmatrix} = \begin{pmatrix} R_0(\omega) & R_1(\omega) & \ldots & R_{n-2}(\omega) & R_{n-1}(\omega) \\ R_1(\omega) & R_0(\omega) & \ldots & R_{n-3}(\omega) & R_{n-2}(\omega) \\ \ldots & \ldots & \ldots & \ldots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

- With induced signals, the signal is still linear sum of direct signal and induced signal
  - R_1 represents the induced signal from i+1th wire signal to ith wire
  - S_i and S_{i+1} are not directly related

The inversion of matrix R can again be done with deconvolution through 2-D FFT

Just 2D deconvolution will not be enough → ROI + Adaptive Baseline

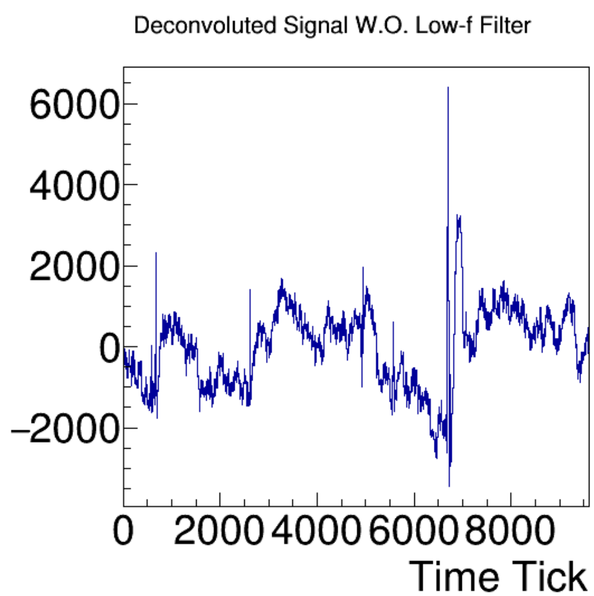




- The bi-polar nature of induction signal amplify the low-frequency noise during deconvolution

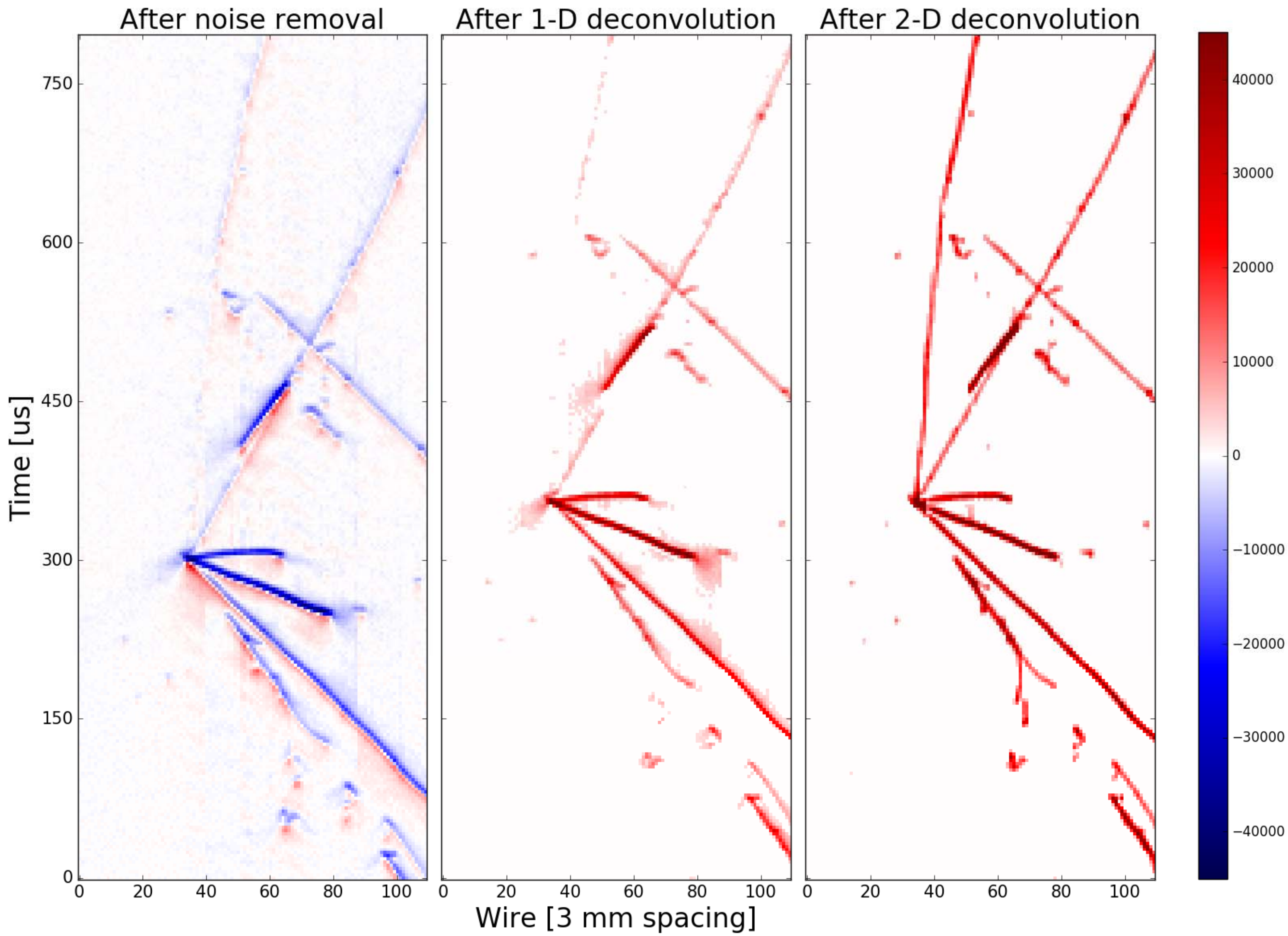
$$S(\omega) = \frac{M(\omega)}{R(\omega)} \cdot F(\omega)$$

- One can improve the situation through ROI and baseline correction



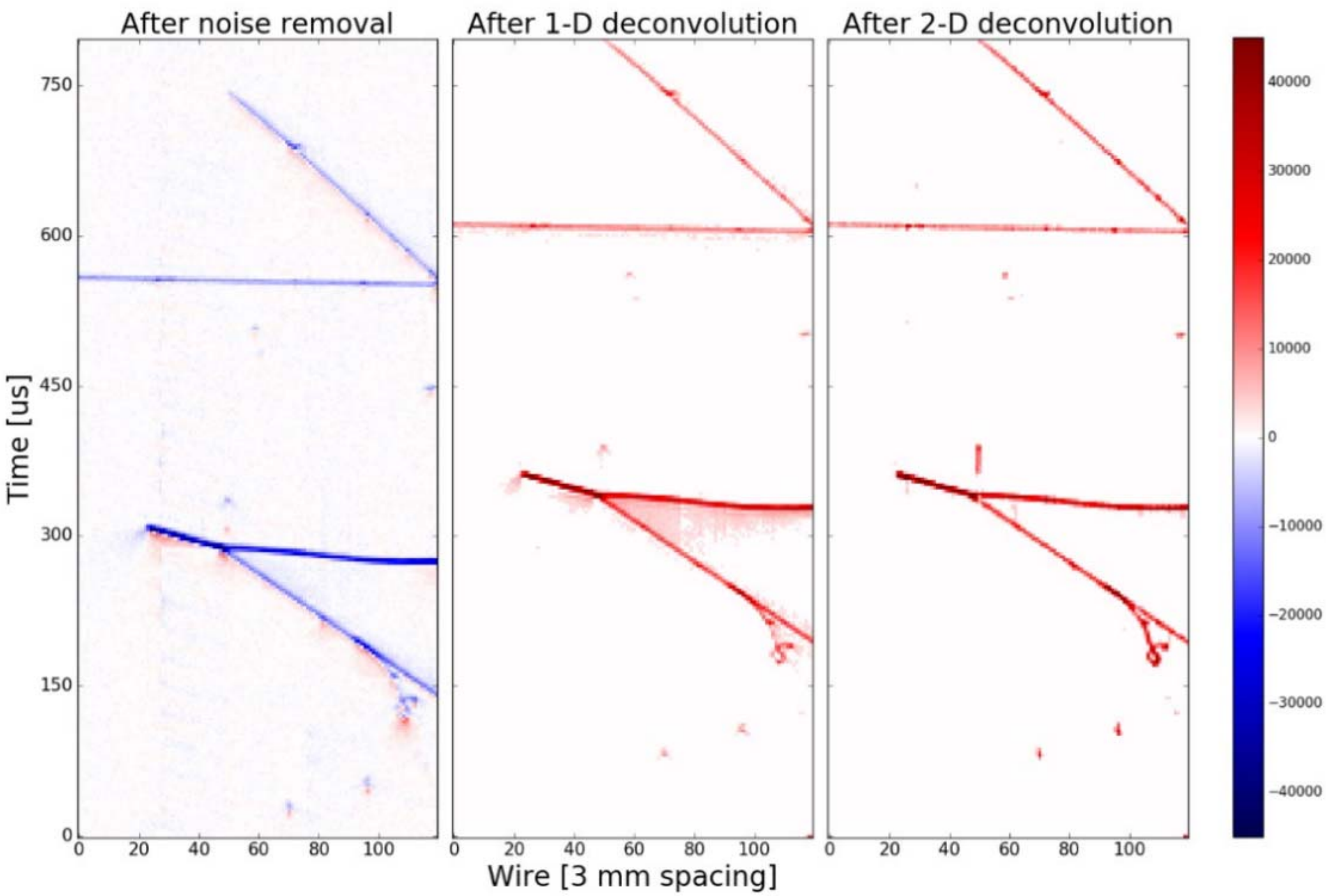
- Given N time bins with 2 MHz digitization frequency, the lowest freq (above 0) is 2/N MHz
- Obviously not sensitive to noise < 2/N MHz

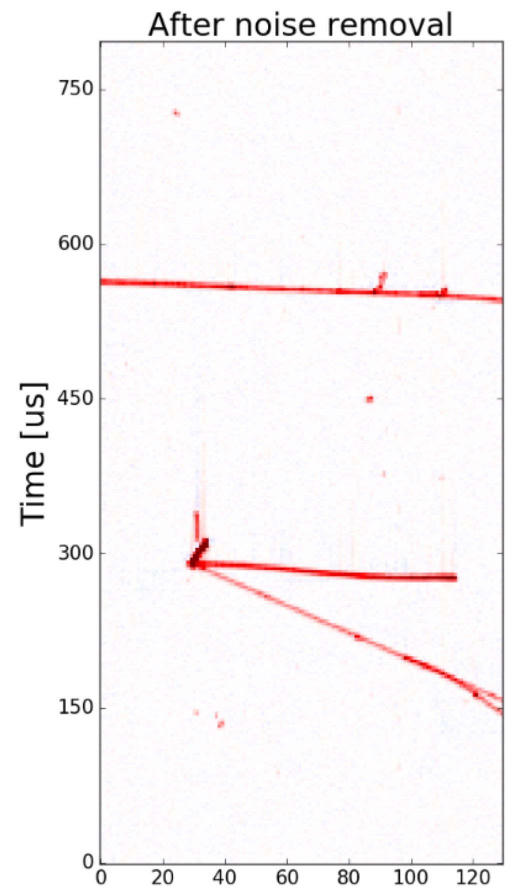
- 200 bins → 10 kHz


After noise removal
After 1-D deconvolution
After 2-D deconvolution
Time [us]
Wire [3 mm spacing]
0
150
300
450
600
750
0
20
40
60
80
100
40000
30000
20000
10000
0
−10000
−20000
−30000
−40000

Induction U plane

Collection plane





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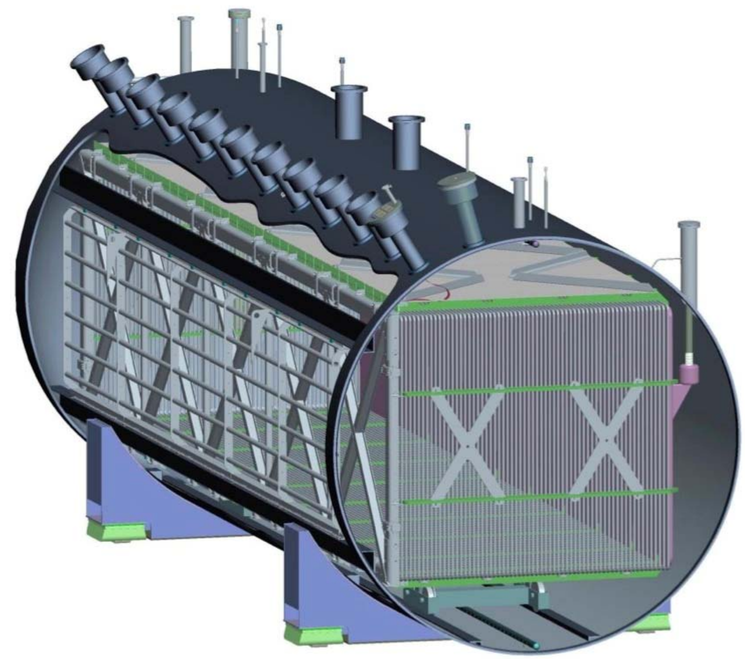
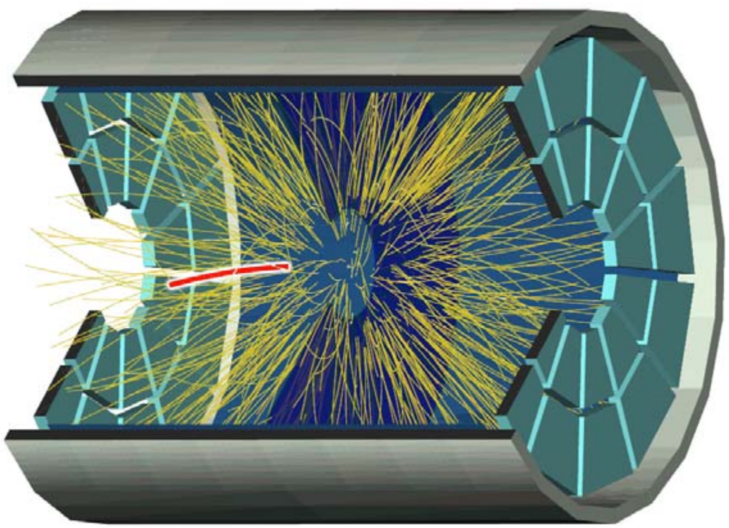
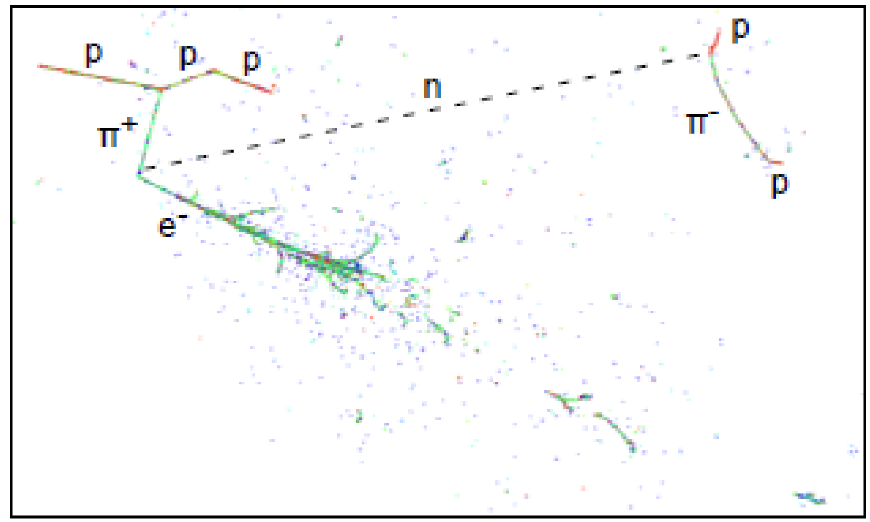


MicroBooNE LArTPC

Challenges of Event Reconstruction in LArTPCs

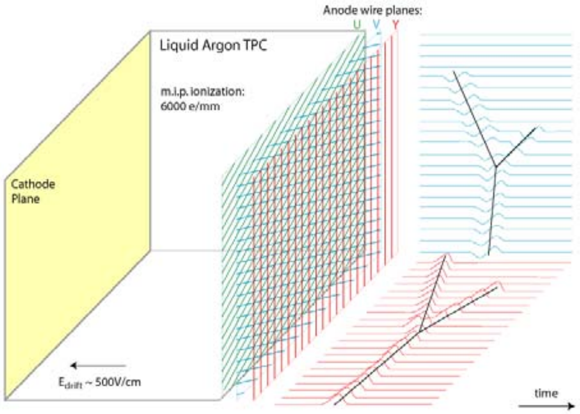
- Event topology:
  - Tracks, showers, unknown vertex in LArTPCs
  - Simple tracks in collider's gas TPCs

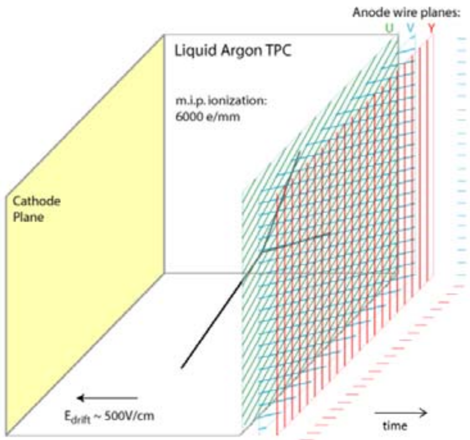




- Wire vs. Pixel readout
  - Large LArTPCs has to use wire readout due to **power consumption** of electronics and **costs**
  - Puedo-3D detector

2D matching → 3D





Wire-Cell Approach

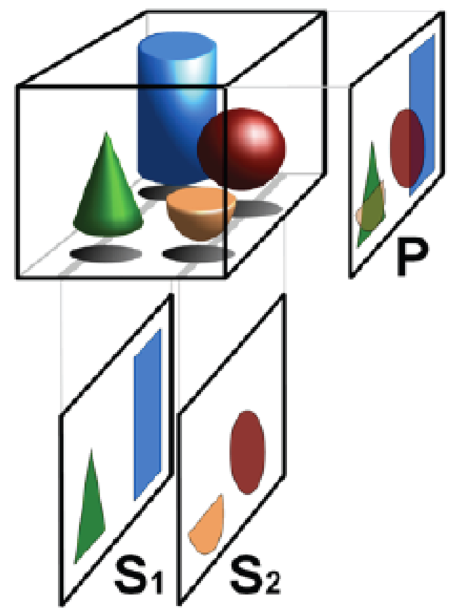
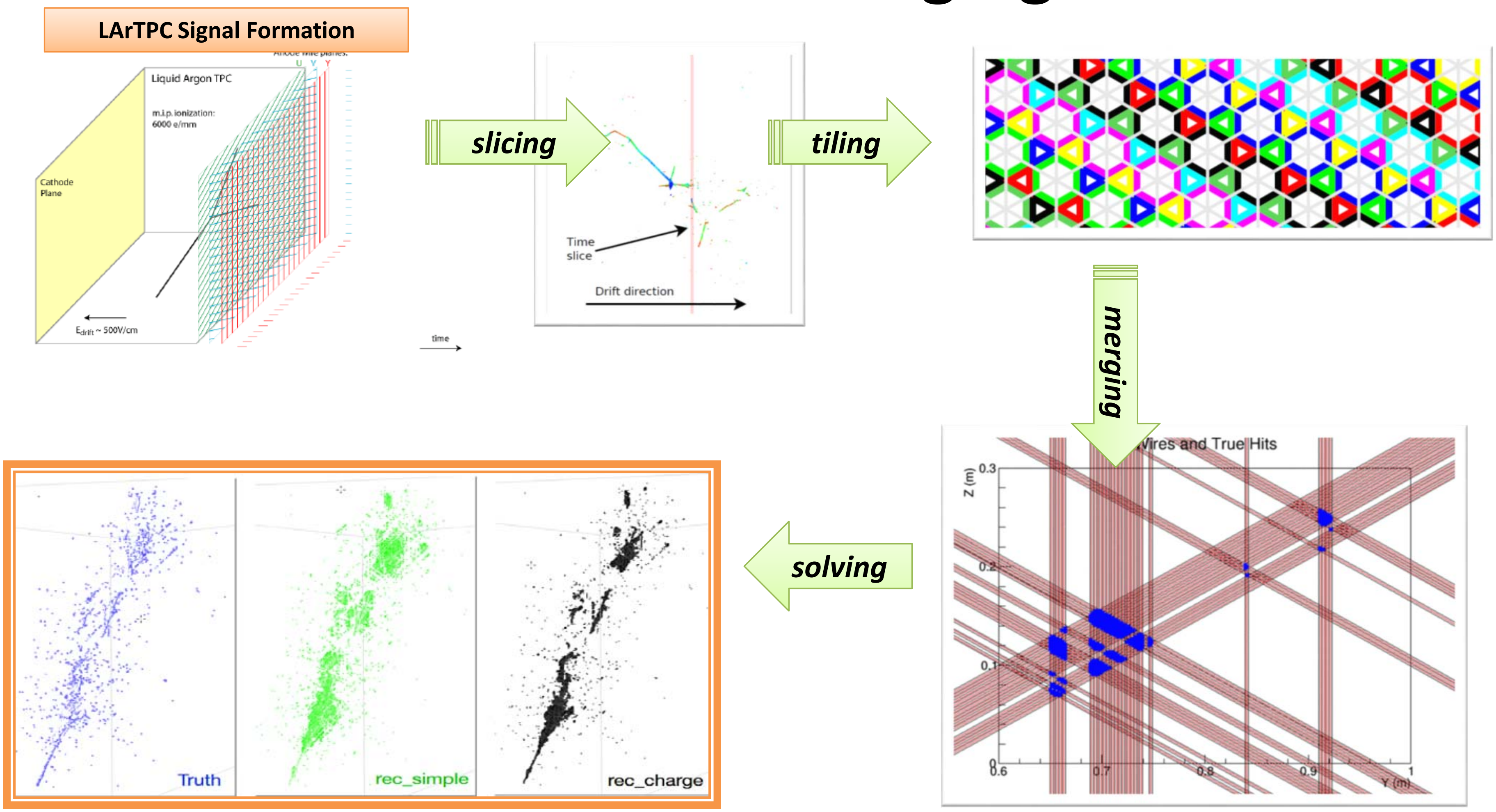


Fig.1:Basic principle of tomography: superposition free tomographic cross sections S1 and S2 compared with the projected image P

https://en.wikipedia.org/wiki/Tomography

Wire-Cell Imaging

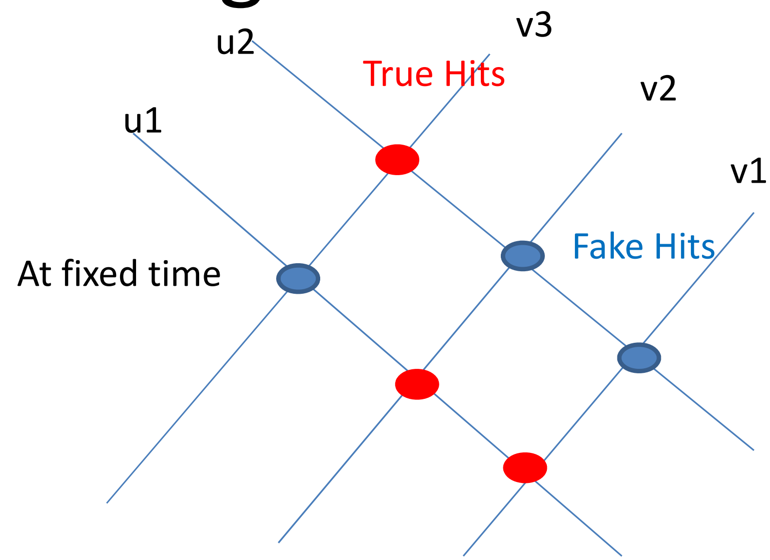


Solving for Images

$$\chi^2 = (\mathrm{B}\cdot \mathrm{W} - G\cdot C)^T V_{BW}^{-1} (\mathrm{B}\cdot \mathrm{W} - G\cdot C)$$

$$\frac{\partial \chi^2}{\partial C} = 0 \rightarrow C = (\mathrm{G}^T V_{BW}^{-1} \mathrm{G})^{-1} G^T V_{BW}^{-1} BW$$

- C: charge in each (merged) cell
- G: Geometry matrix connecting cells and wires
- W: charge in each single wire
- B: Geometry matrix connecting merged wires and single wires
- V_{BW}: Covariance matrix describing uncertainty in wire charge



- Use two-plane as an example
- Red points are true hits
- Blue ones are fake hits

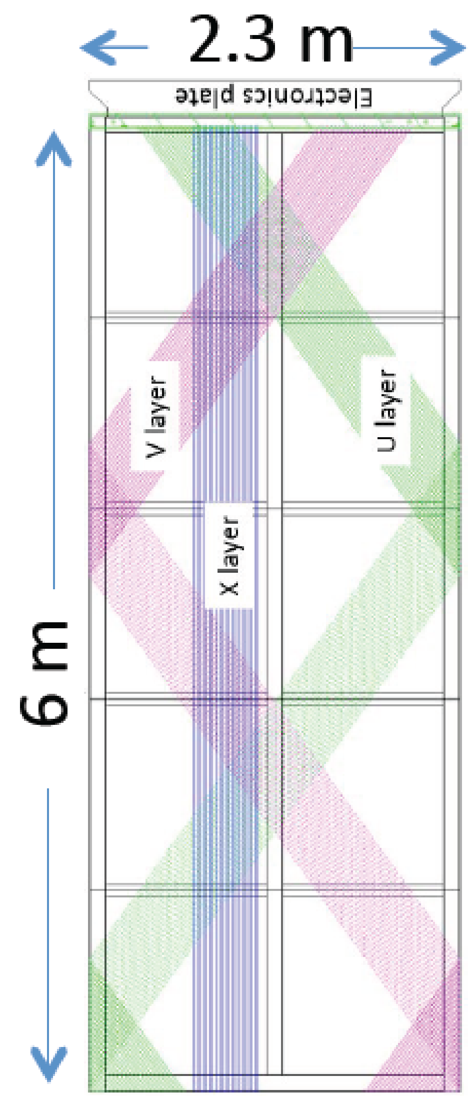
$$W = G \cdot C$$

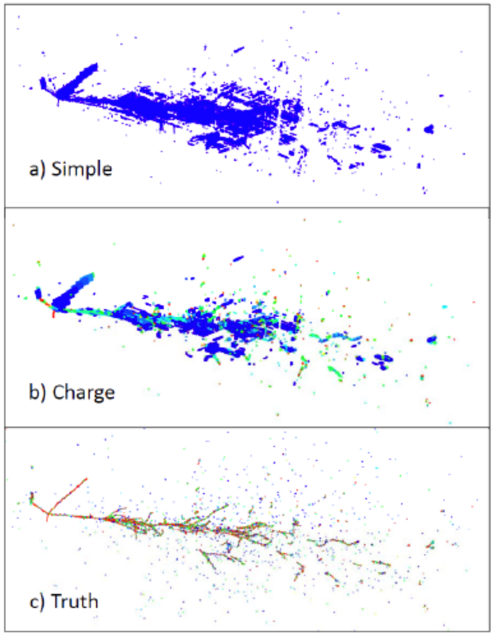
Same formulism for Wrapped Wire

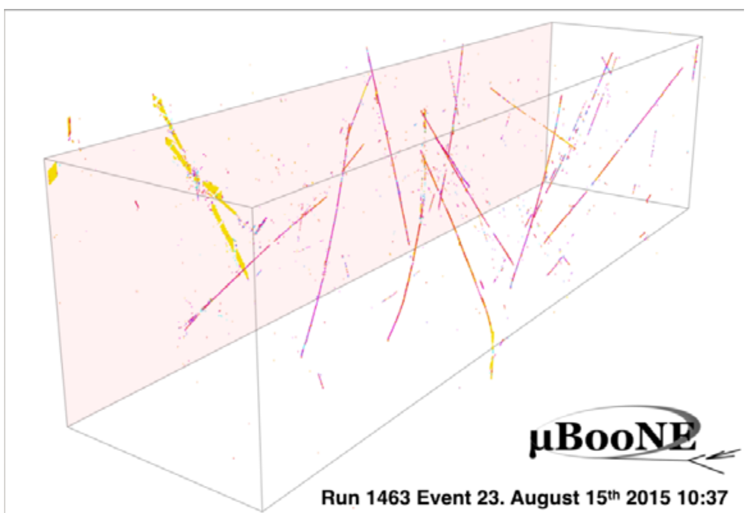
$$\chi^2 = (\mathrm{B} \cdot \mathrm{W} - G \cdot C)^T V_{BW}^{-1} (\mathrm{B} \cdot \mathrm{W} - G \cdot C)$$

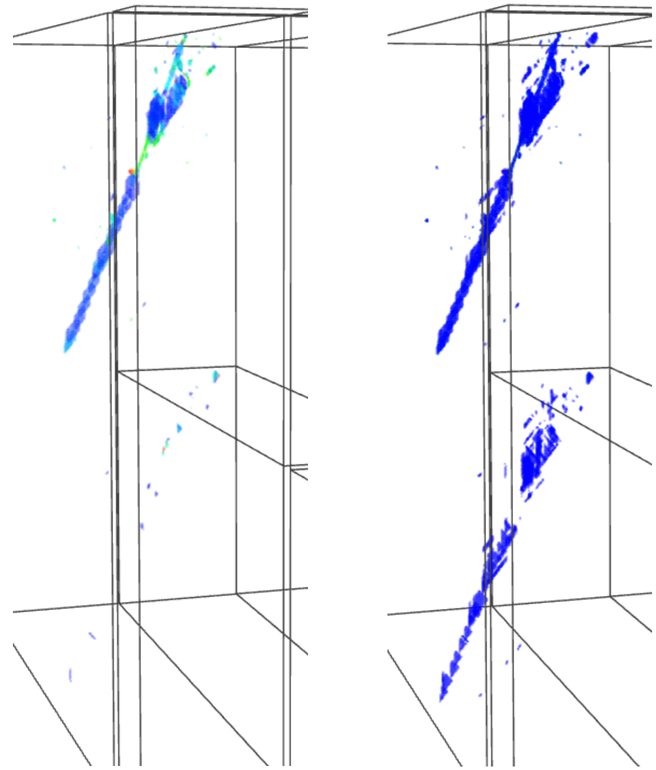
$$C = (\mathrm{G}^T V_{BW}^{-1} \mathrm{G})^{-1} G^T V_{BW}^{-1} BW$$

- C: charge in each (merged) cell
- G: Geometry matrix connecting cells and **channels**
- W: charge in each single **channel**
- B: Geometry matrix connecting merged **channels** and single **channels**
- V_{BW}: Covariance matrix describing uncertainty in **channel** charge









With Charge

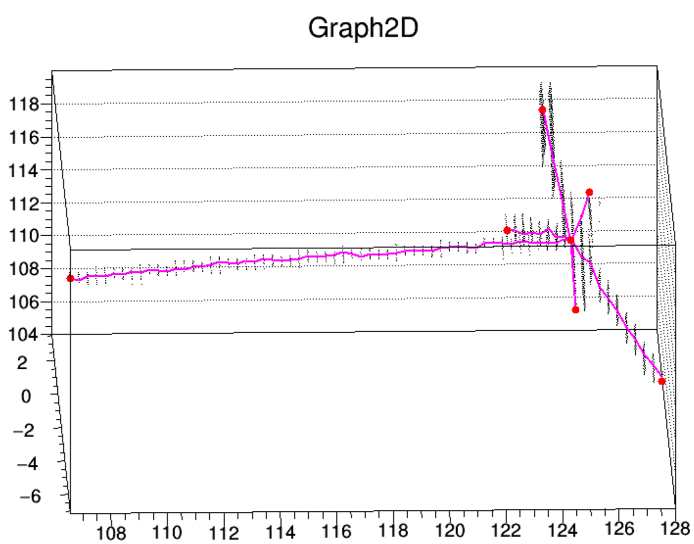
Without Charge

More 3D events can be found at
http://www.phy.bnl.gov/wire-cell/bee/
Bee: interactive 3D display

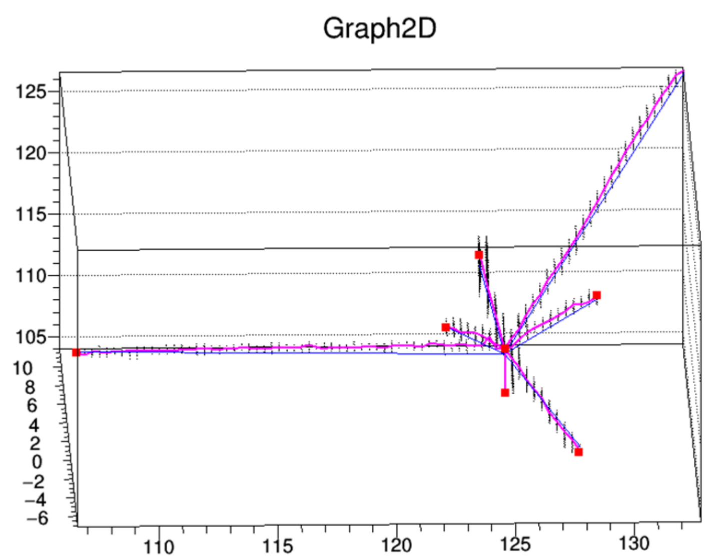
Connectivity information

- Use the connectivity information to choose the optimal imaging solution
  – Penalty term added in χ^2

Without Connectivity



With Connectivity



Strategy Comparison

2D Matching

- Start with 2D (time+wire x 3)
- 2D pattern recognition
  - Particle track/cluster information
- Matching 2D patterns into 3D objects
  - **Time** information (start/end of clusters)
  - **Geometry** information
  - Some **charge** information to remove ambiguities in matching

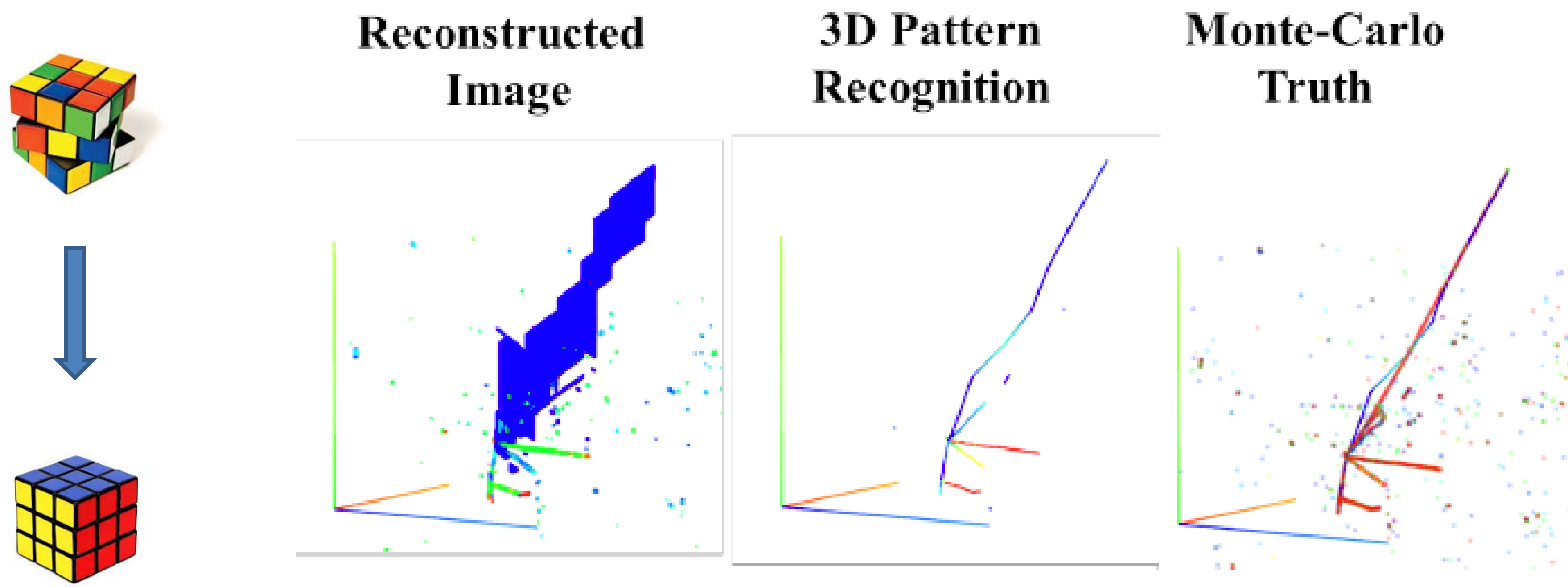
Each approach uses the same set information in different order!

3D Tomography

- Start with 2D (wire+wire+wire at fixed time slice)
- 2D image reconstruction
  - **Explicit Time + Geometry + Charge** information
  - Some connectivity information can be used
- 3D image reconstruction
  - Straight forward
- 3D pattern recognition
  - Particle track/cluster information (tracks, showers)

Wire-Cell Pattern Recognition (under developing)

- Given the 3D images, pattern recognition is performed with the track and shower hypotheses



- Operations are all “local” i.e. Hough transformation, Crawler, Vertex fitting/merging …
- Too many different topologies → many corner cases

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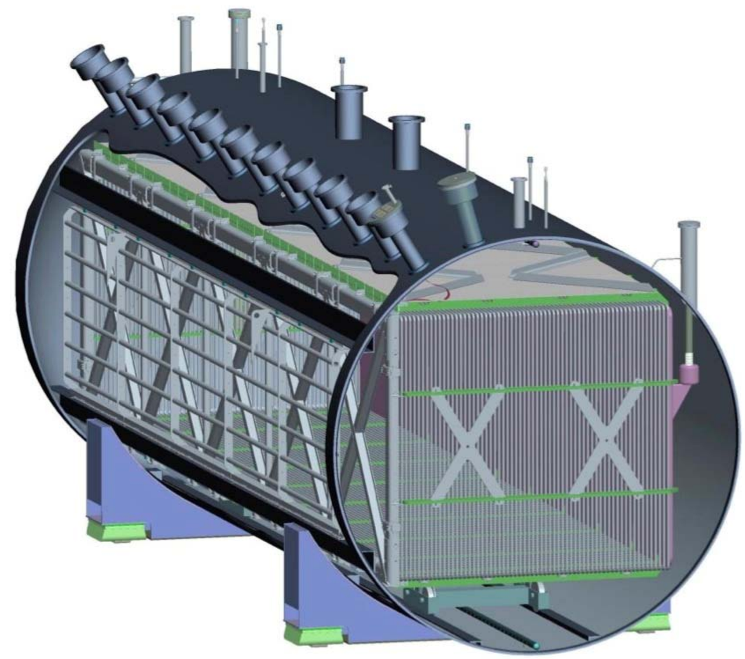
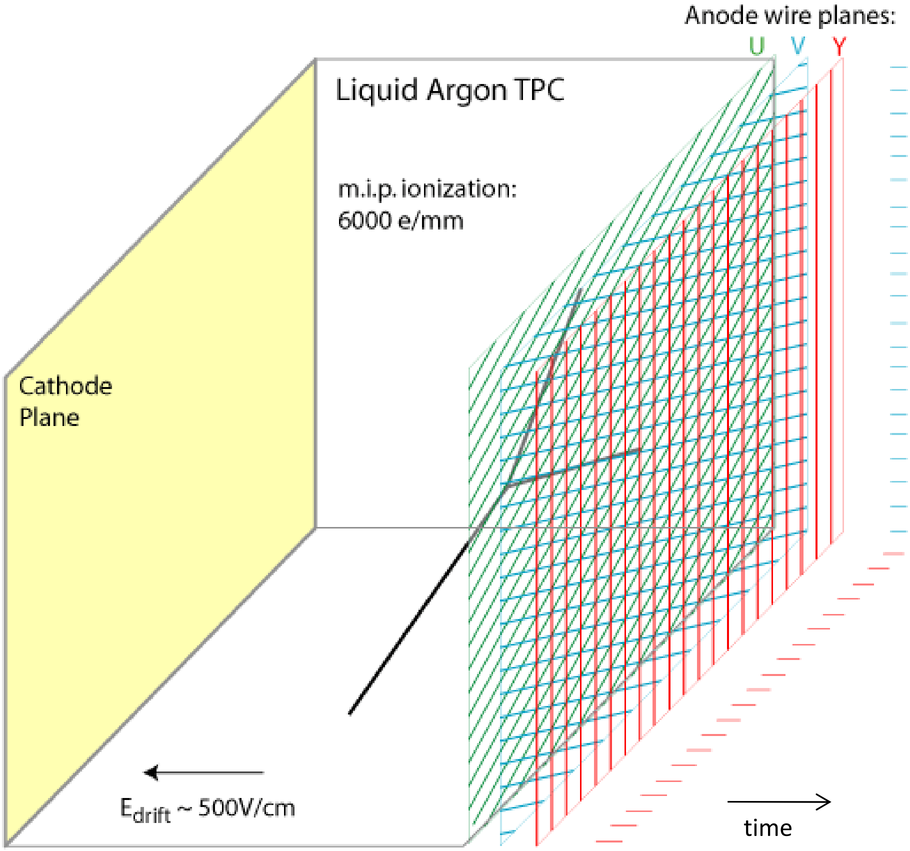


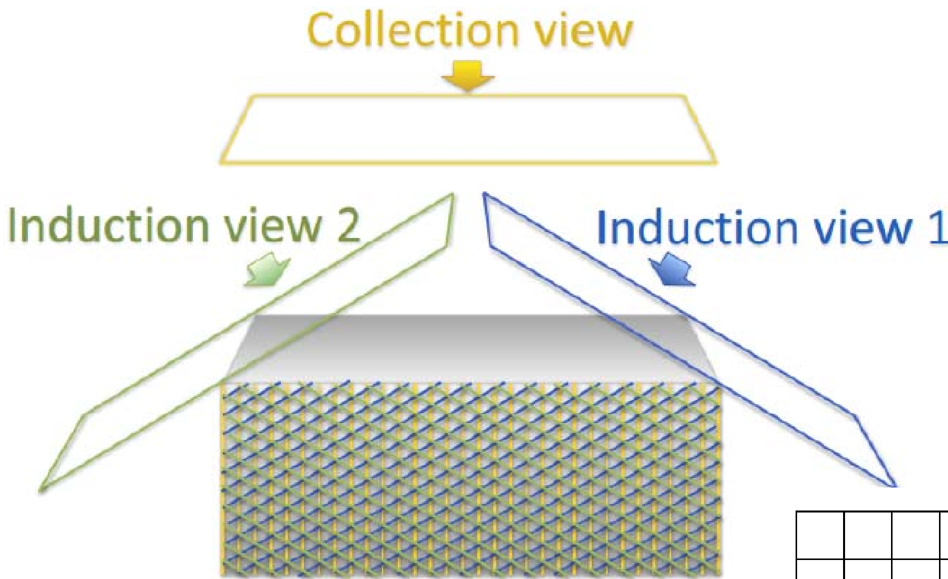
MicroBooNE LArTPC

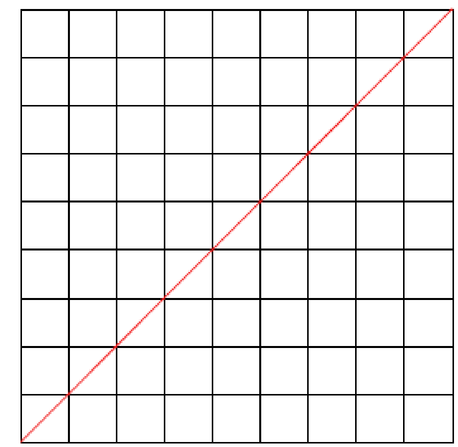
Information from LArTPC

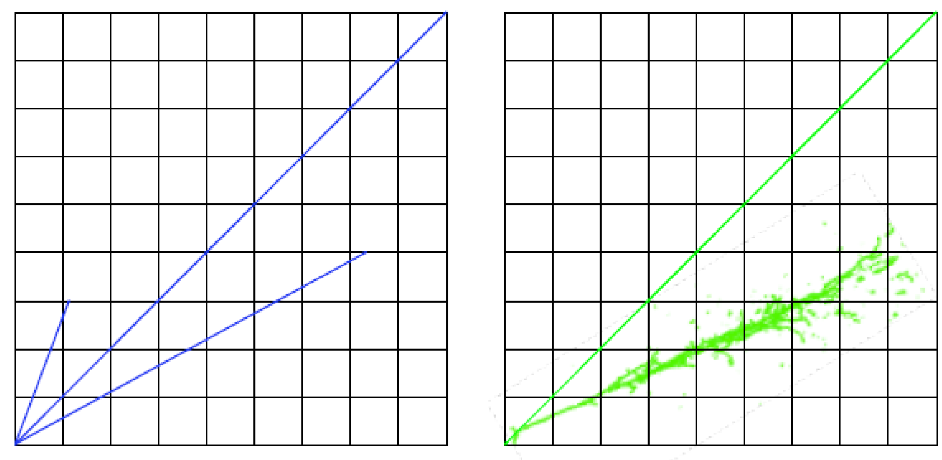


- Time information: when ionization electrons arrive (drift distance)
- Geometry information: which wires are fired (transverse position)
- Charge information: how many ionization electrons (energy deposition)

Limited Geometry information for Wire Readout

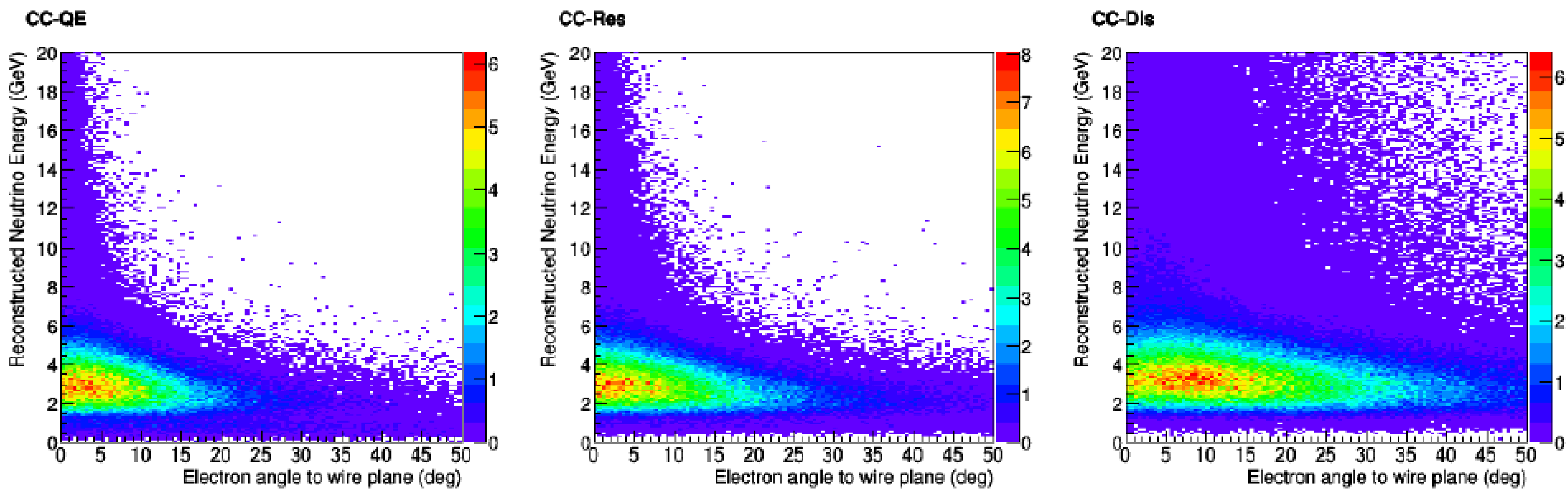


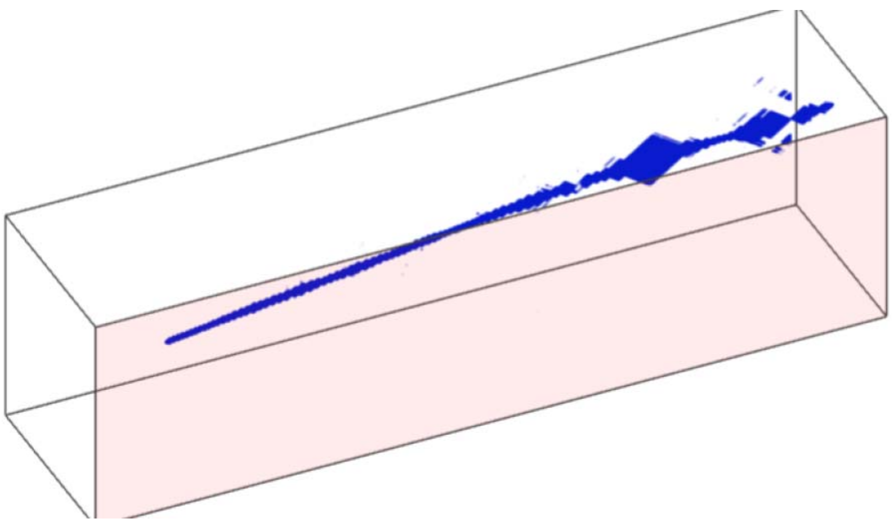




- Due to the wire readout, the geometry information is not as robust as the time information

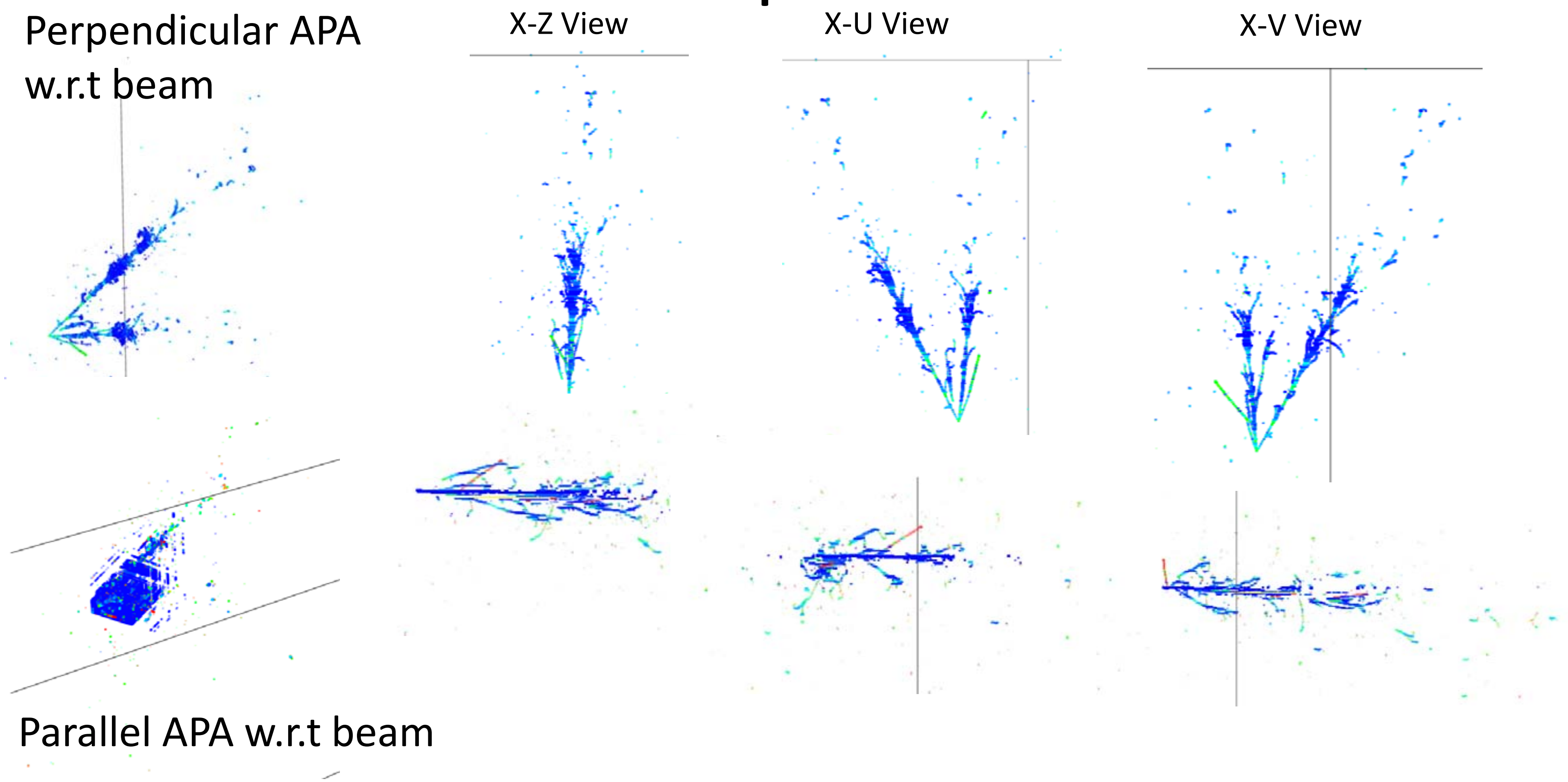
Default: Parallel TPC Orientation





- Current TPC orientation is parallel to the neutrino beam direction leading to less time information, but more geometry information
- Can we turn TPC orientation 90 degrees?

Parallel vs. Perpendicular APA

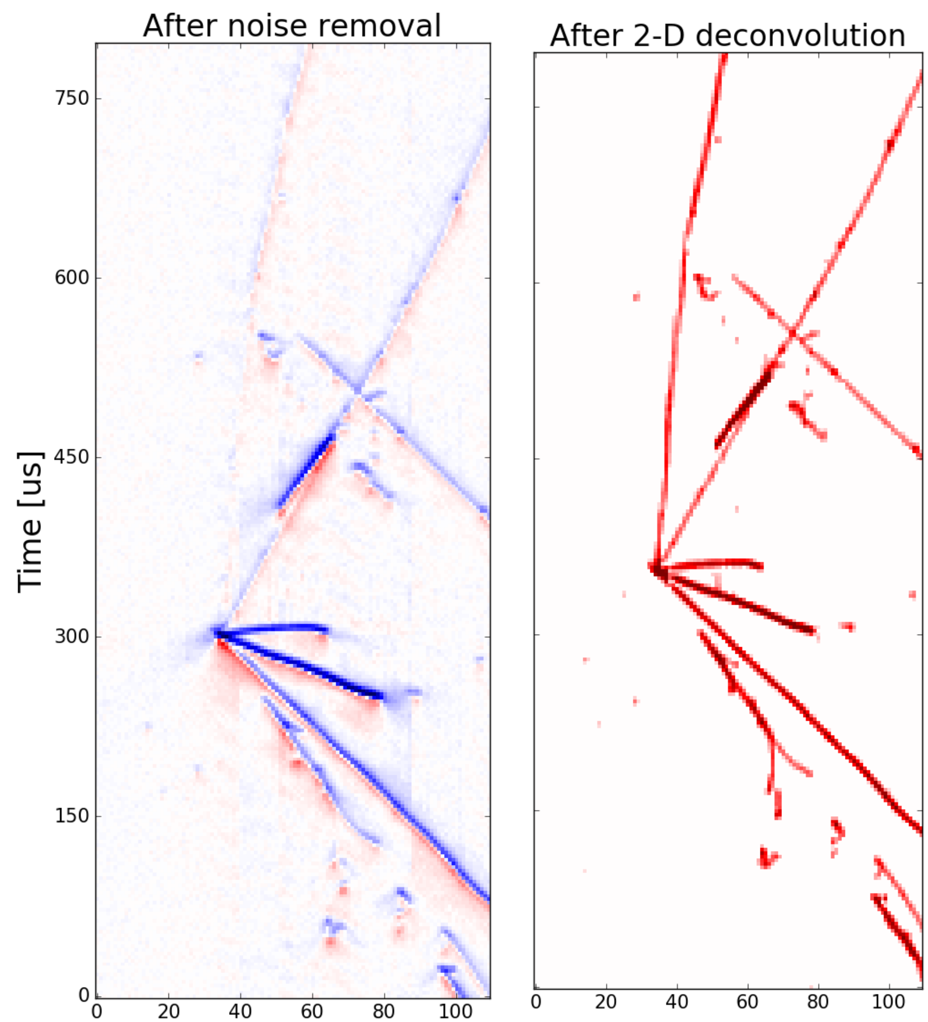


- Perpendicular APA → fewer hit wires + more times info → less ambiguities
- Parallel APA → easier situation for induction plane signal processing

Parallel vs. Perpendicular APA

	Longitudinal (Drift)	Transverse
Digitization length	0.8 mm	3-5 mm
Diffusion (σ)	<1.7 mm	<2.4 mm
Electronics Shaping (σ)	1.3 mm	N/A
Field Response Function	~1.1 mm	3-5 mm

- Better resolution in the drift direction
- Perpendicular APA expects a better e/gamma separation with better gap identification and dE/dx resolution
- <u>Induction signal processing is the key!</u>

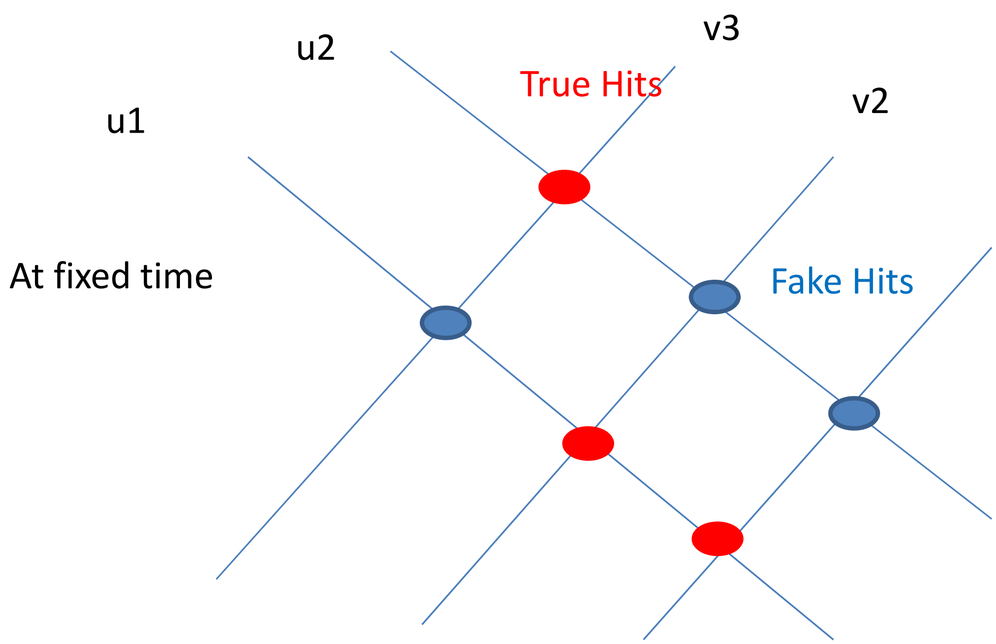


Parallel vs. Perpendicular TPC

	CC-QE	CC-Res	CC-DIS	Total Signal	Vertex-overlapping Bkgd.	Displaced-overlapping Bkgd.
Events	175.2	254.1	371.8	801.1		
Parallel TPC						
$\theta_h, \theta_e < 2.5^o$	2.5 (1.4%)	4.4 (1.7%)	6.3 (1.6%)	13.2 (1.6%)	15.5 (1.9%)	21.6 (2.7%)
$\theta_h, \theta_e < 5.0^o$	7.0 (3.9%)	16.2 (6.3%)	22.5 (5.6%)	45.6 (5.4%)	52.9 (6.6%)	95.1 (11.9%)
$\theta_h, \theta_e < 7.5^o$	12.1 (6.8%)	32.5 (12.6%)	45.7 (11.3%)	90.3 (10.8%)	103.5 (12.9%)	189.4 (23.6%)
Perpendicular TPC						
$\theta_h, \theta_e < 2.5^o$	0.0 (0.0%)	0.1 (0.0%)	0.2 (0.1%)	0.3 (0.0%)	1.6 (0.2%)	1.6 (0.2%)
$\theta_h, \theta_e < 5.0^o$	0.0 (0.0%)	0.2 (0.1%)	0.9 (0.2%)	1.1 (0.1%)	5.8 (0.7%)	6.0 (0.7%)
$\theta_h, \theta_e < 7.5^o$	0.1 (0.0%)	0.5 (0.2%)	1.8 (0.5%)	2.4 (0.3%)	12.1 (1.5%)	13.9 (1.7%)

- Significant background reduction is expected for perpendicular TPC → increased physics sensitivity

Four Wire Planes: Reduction of Ambiguities

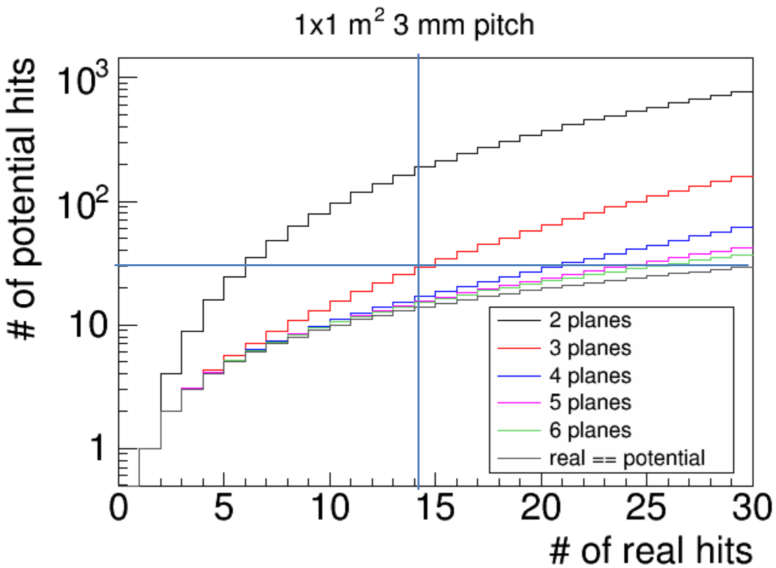


- Ambiguities can be evaluated by comparing the "# of real hits" and the "# of potential hits"

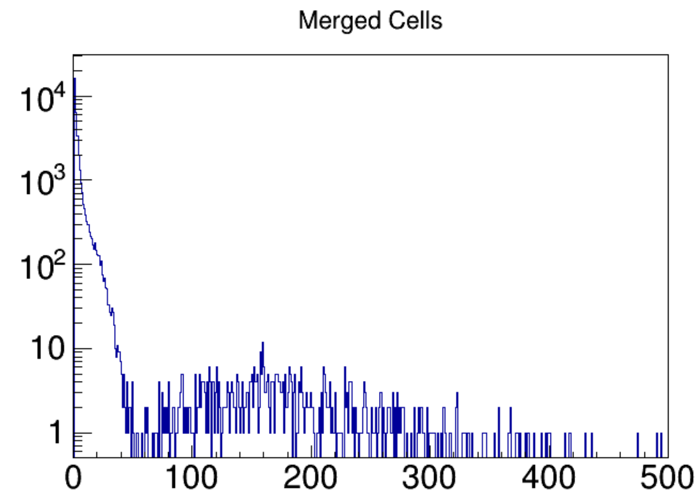
- Take two-plane as an example
  - 3 real hits
  - 6 potential hits (each has two fired wires going through them)

- Ambiguities can be reduced with Connectivity, Charge, Recognized Pattern information
  - These tools are powerful, but not yet robust enough
  - It is much desired to have less ambiguities to start with

Four Wire Planes: Reduction of Ambiguities



Toy MC, a hit only fire one wire in a plane



Number of potential hits for ν_e CC events in DUNE for the default configuration

- **Three-plane setting is much better than two-plane setting, the latter has two much ambiguities**
- **Four-plane setting can significantly reduce the ambiguities, especially when things are busy**

Robustness Against Dead Channels

- In reality, it is highly unlikely to have 100% good channels for a 10 kt detector
- Let's assume "p" is the efficiency of a single plane, the given "n" number of planes, the volume efficiency can be estimated as $\varepsilon_n = p^n$
- The efficiency can be higher if less planes are required

$$\varepsilon_{n-1} = p^n + n \cdot (1-p) \cdot p^{n-1}$$

- However, the cost of higher efficiency is an increase of ambiguities (i.e. fake hits)

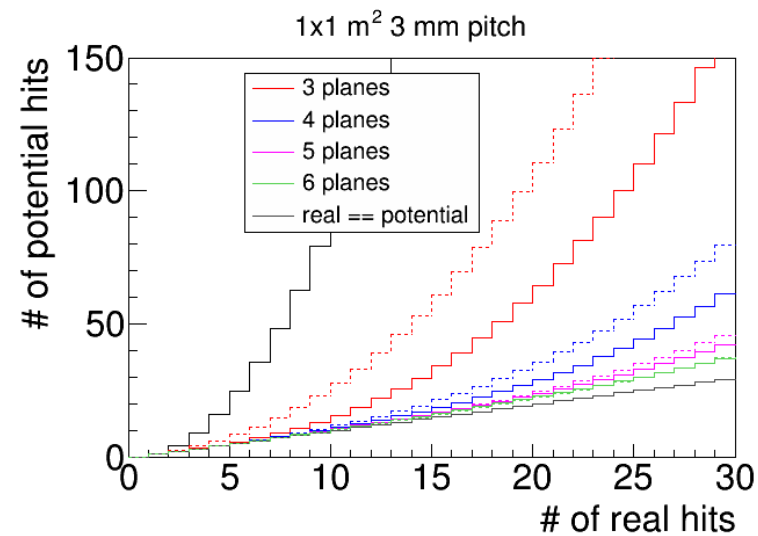
$$\left(F_n + (1-p) \cdot \mathrm{n} \cdot \left(F_{n-1} - F_n \right) \right) \cdot \varepsilon_{n-1}$$

Original fake hits at "n" planes

Increase of fake hits due to dead channel, leaked from fake hits at "n-1" planes, n different "n-1" planes

Overall reduction in efficiency

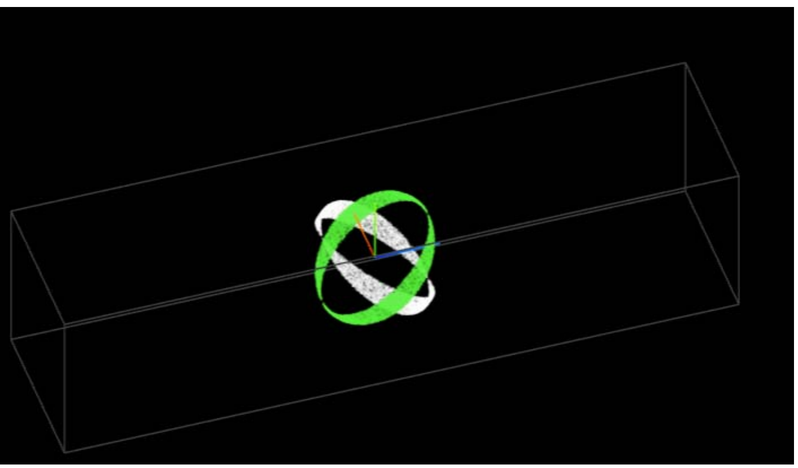
	1% (n/n-1)	5%
3-plane	97% / 99.97%	85.7% / 99.2%
4-plane	96% / 99.94%	81.5% / 98.6%



5% dead wires for dotted lines

ROI finder in TPC Induction Signal Processing

- The developed ROI finder is very complicated, and uses the connectivity information and also cut off at ~ O(100) us
- Some part of the phase space will be lost …
  - http://www.phy.bnl.gov/wire-cell/bee/set/pps/event/0/?theme=light

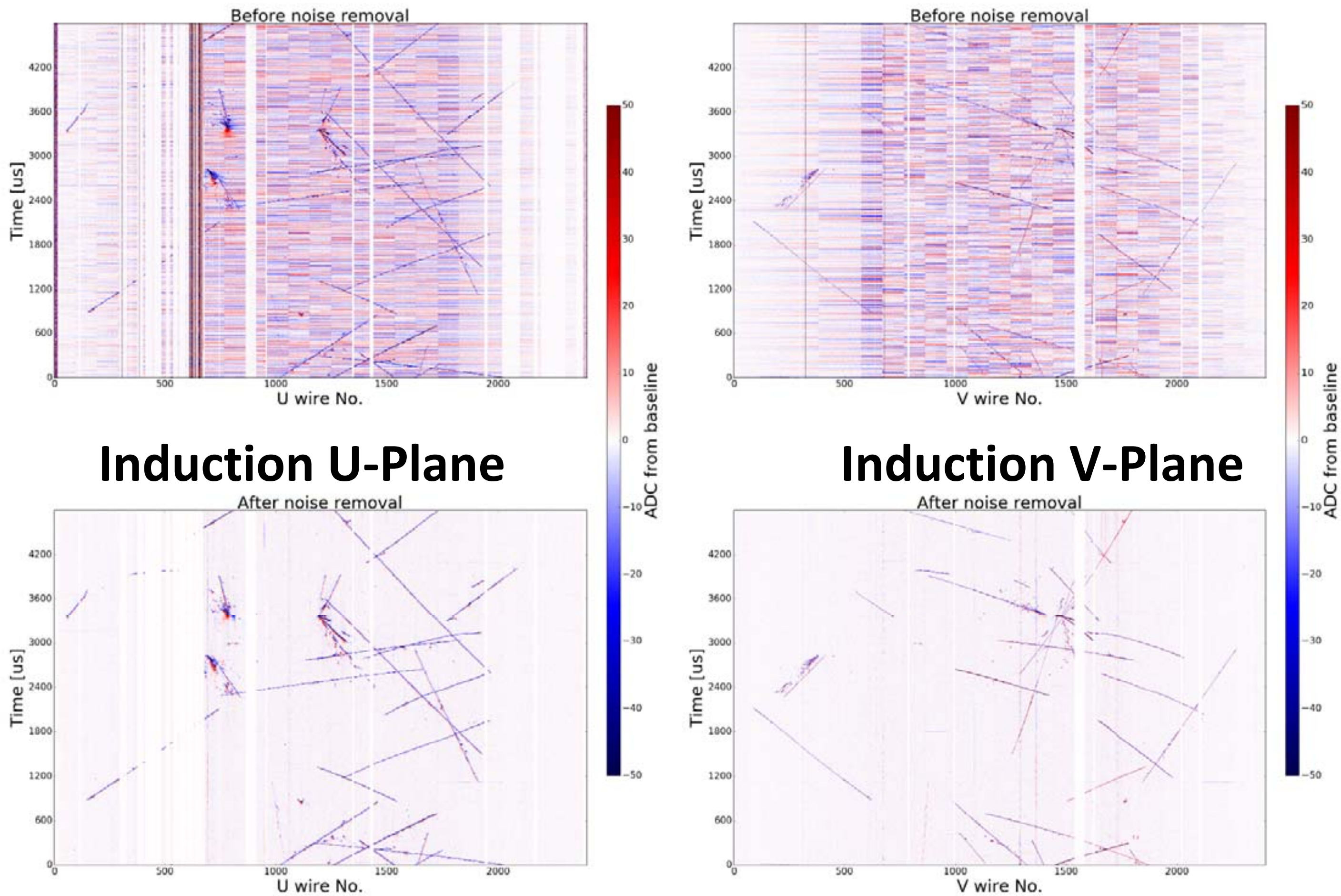


- Each band is for one induction wire plane
- Adding one more plane (4 wire planes) will largely reduce these regions (other benefits not covered here)
- ROI finder would rely on the other three planes' tight ROI

Summary

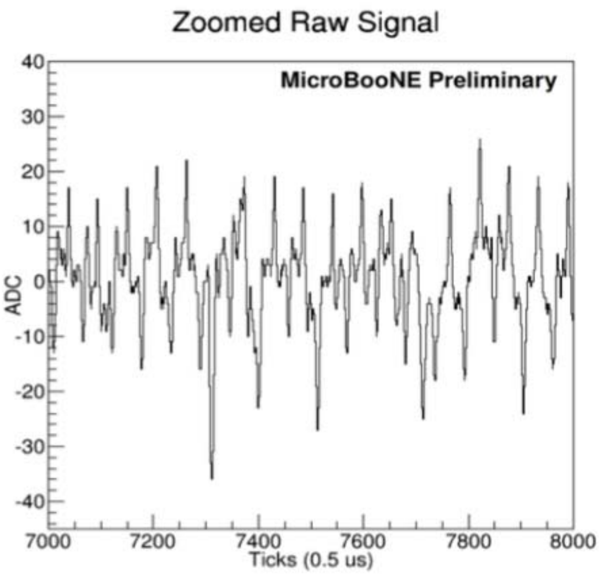
- Significant progresses have been made in the TPC signal processing and event reconstruction
  - 2D deconvolution + Wire-Cell Tomographic Reconstruction
  - Challenges still remains in achieving low electronic noises and high-quality automated event reconstruction
- Lots of room available to improve the LArTPC design and performance for DUNE’s four 10 kt modules
  - Perpendicular TPC orientation, four wire planes …
- LArTPC technology may hold the key to many major discoveries:
  - Lepontic CP violation, neutrino mass ordering, proton decay, sterile neutrinos …
- Exciting program in the next decades

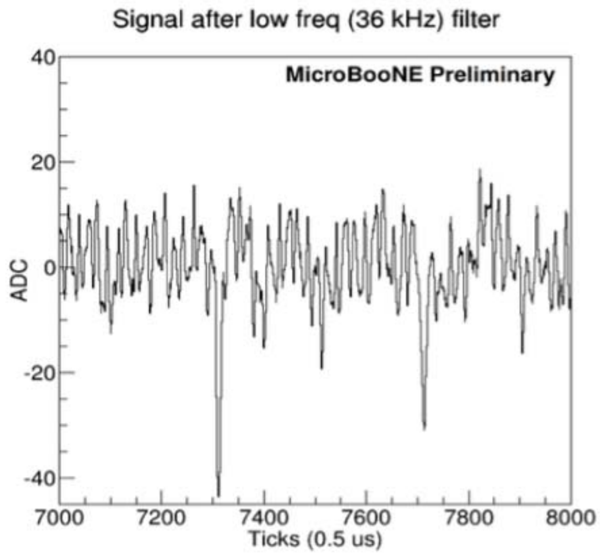
Before and After Excess Noise Filter



MicroBooNE
preliminary

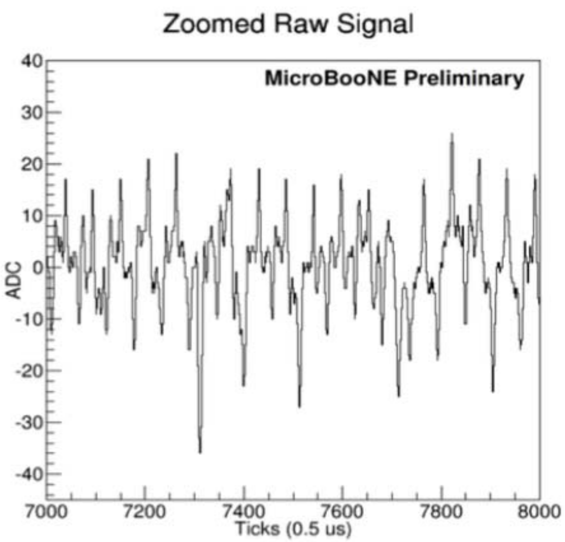
Excess noises are observed and have to be filtered

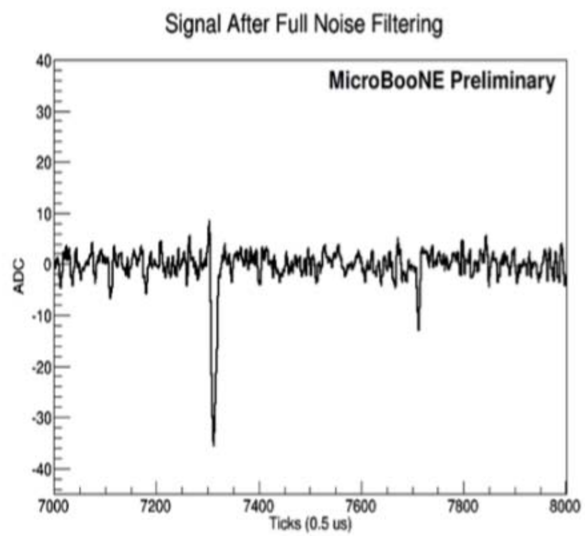




Induction U-Plane Channel

This harmonic noise filtered out directly in the frequency domain (noise in the drift high voltage)





Coherent noise subtraction for the regulator noise (power supply to the preamp)

MicroBooNE preliminary

Excess Noise Removed via Hardware Fix

MicroBooNE
preliminary