Wire-Cell Project
– towards Precision Reconstruction in Liquid Argon TPC

Haiwang Yu (BNL)
for the Wire-Cell team

Brookhaven Forum 2019, Sep. 26, 2019

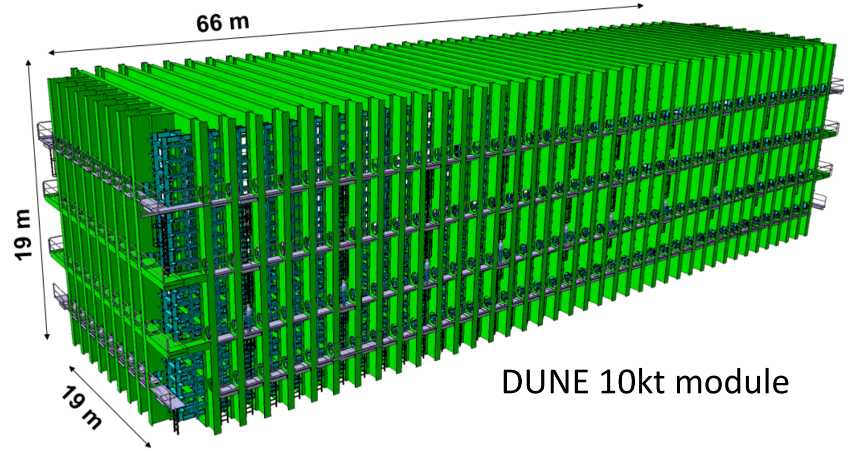
Wire-Cell

BROOKHAVEN NATIONAL LABORATORY

Principle of Liquid Argon Time Projection Chamber (LArTPC)

LArTPC

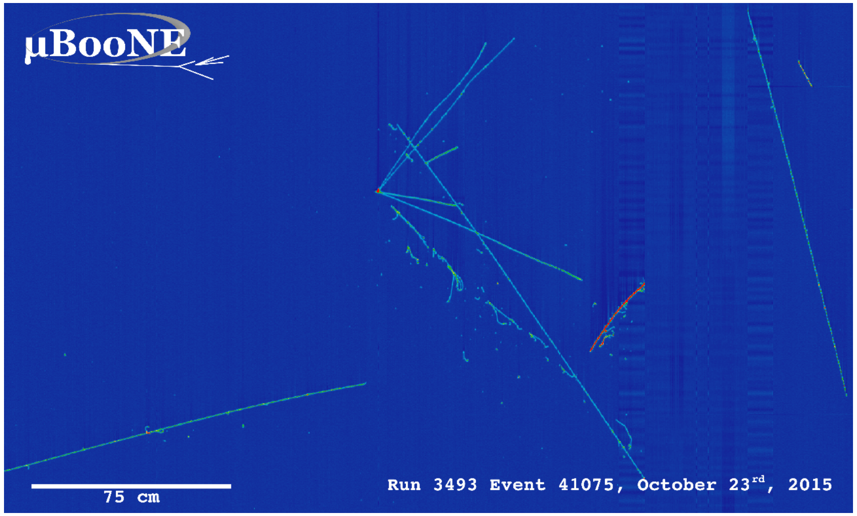
- dense ~ 1000 higher interaction prob. than gas TPC
- noble gas - low electron absorption – efficiency
- abundant scintillation – timing
- relatively inexpensive – large-scale



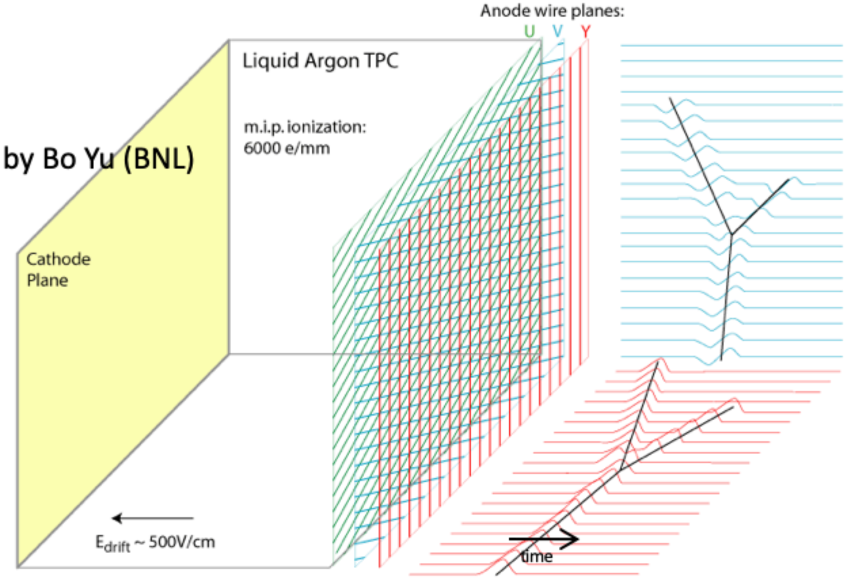
DUNE 10kt module

Usually use wire readout at large scale – heat, cost

- ~mm resolution
- fully active



Made by Bo Yu (BNL)

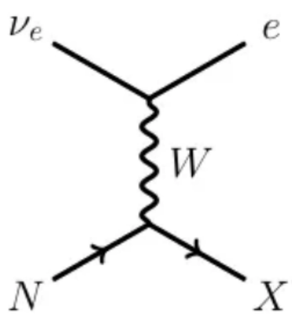


Drift velocity 1.6 km/s → several ms drift time

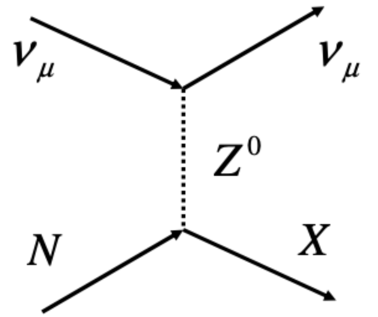
Unique capability to identify ν_e charge-current interactions in LArTPC

One key of ν_e detection is e/γ separation

- Detached shower vertex
- Large dE/dx

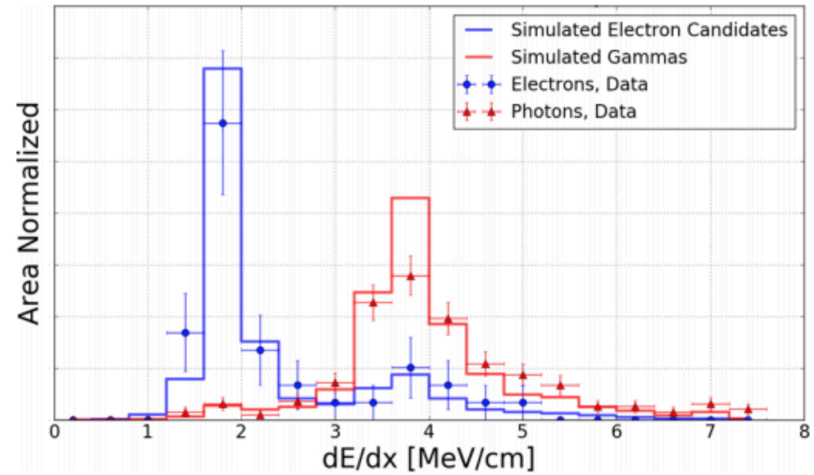


Charged current (CC)

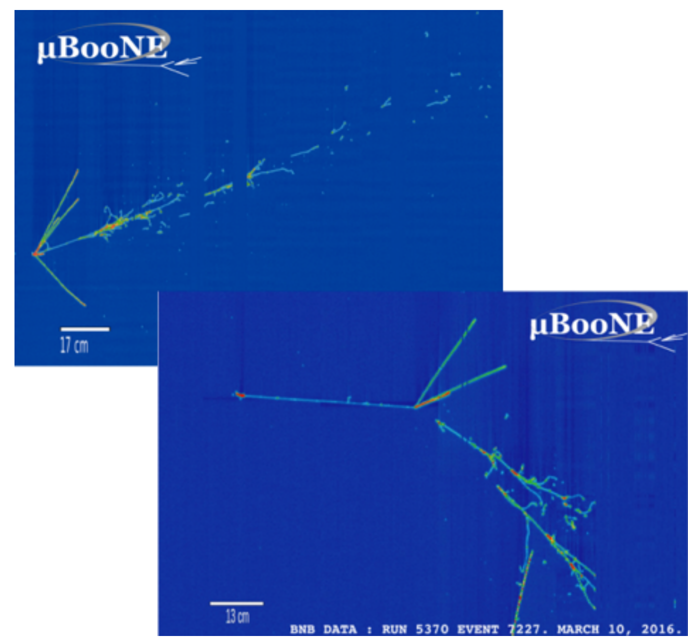


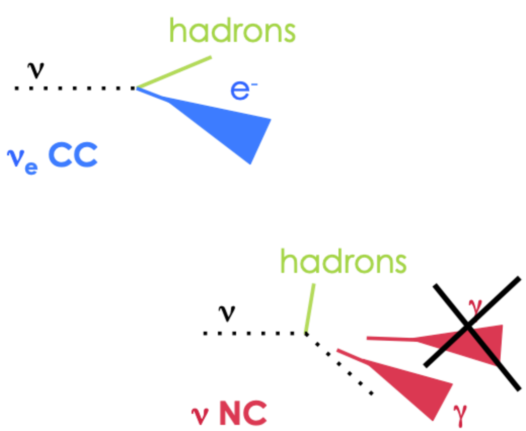
Neutral current (NC)

ArgoNeuT Phys. Rev. D 95, 072005 (2017)

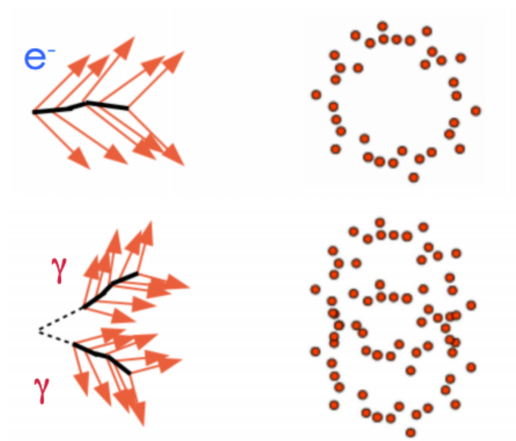


LArTPC





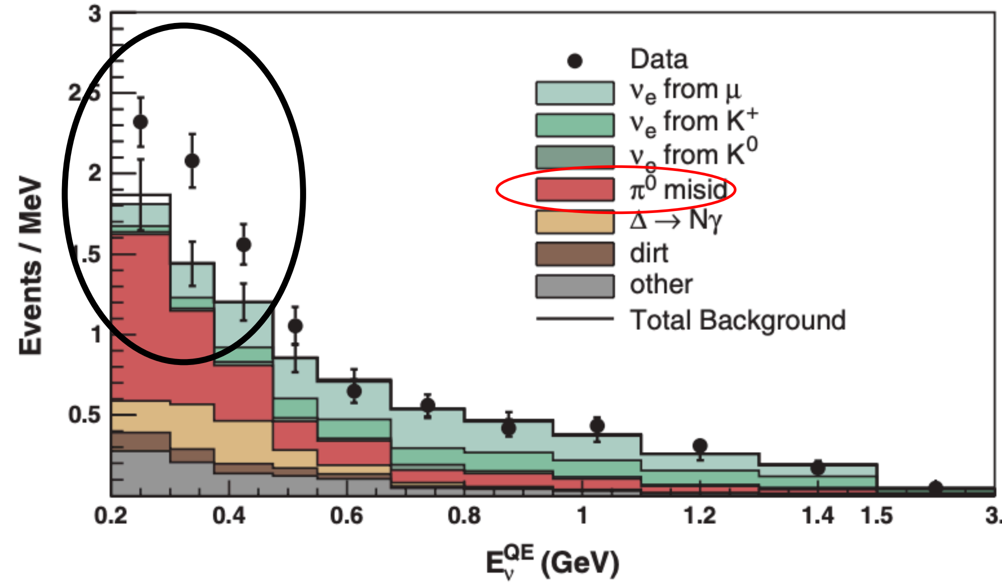
Cherenkov detector



G. Karagiorgi:
https://crunch.ikp.physik.tu-darmstadt.de/erice/2017/sec/talks/friday/karagiorgi.pdf

Short-Baseline Neutrino Program

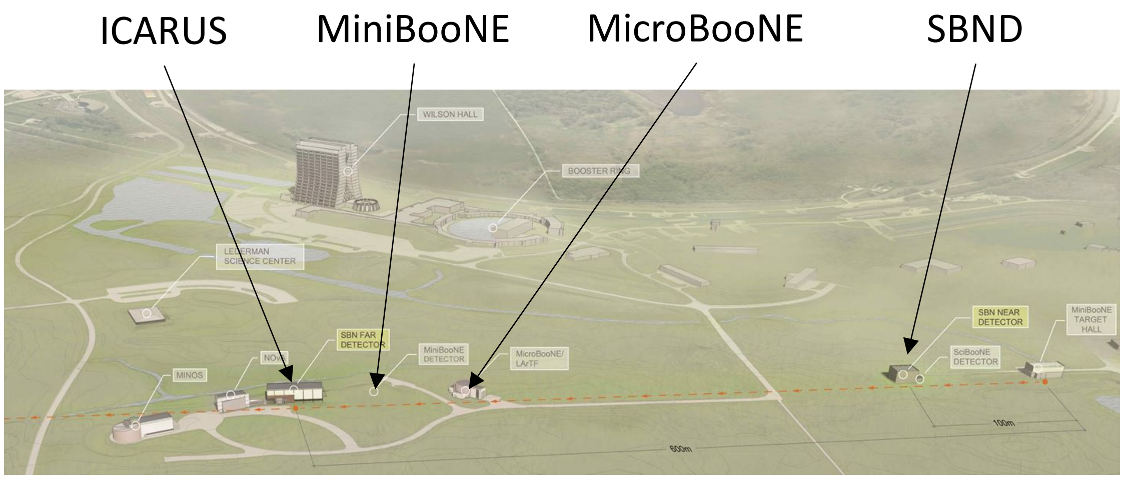
MiniBooNE, PRL 102, 101802 (2009)
anomalous low energy excess

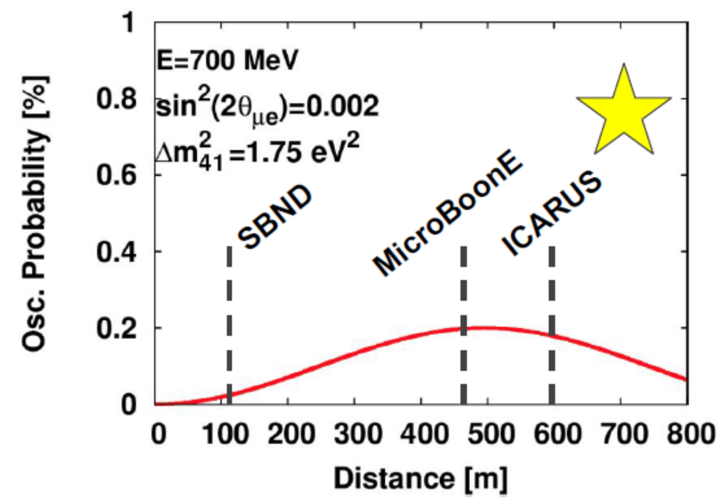


Unexpected electron-like event excess at low energy observed in LSND and MiniBooNE

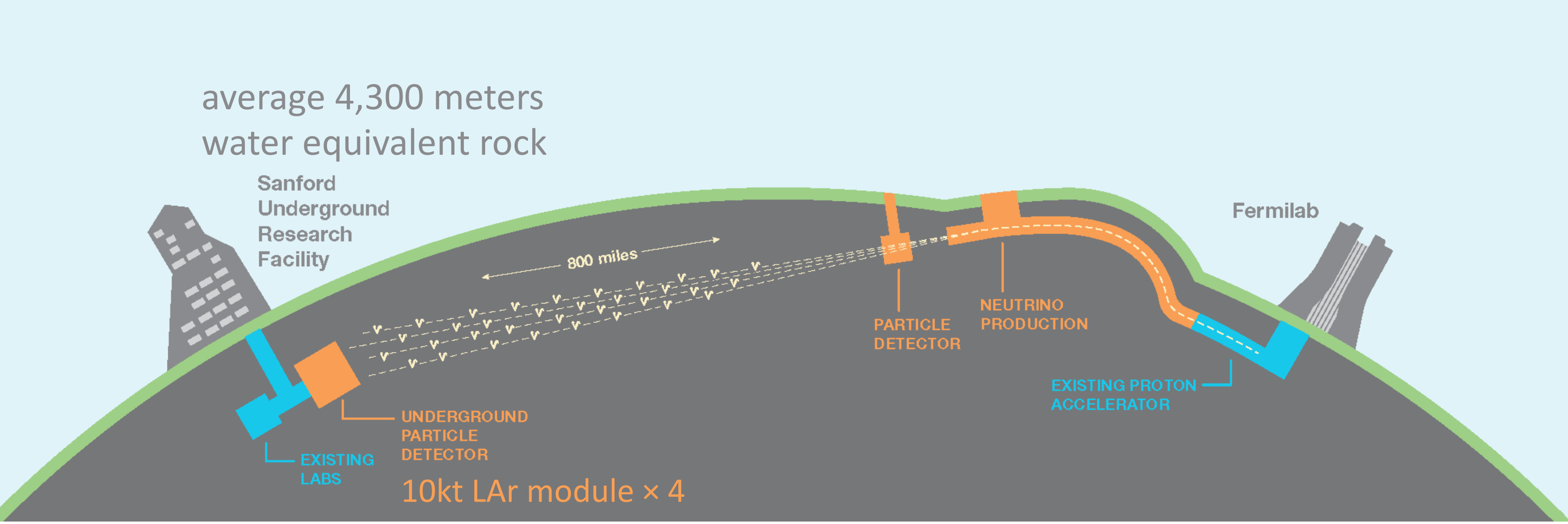
- light sterile neutrino(s)?
- electron-like or photon-like?

$\Longrightarrow$ SBN Program with LArTPC!





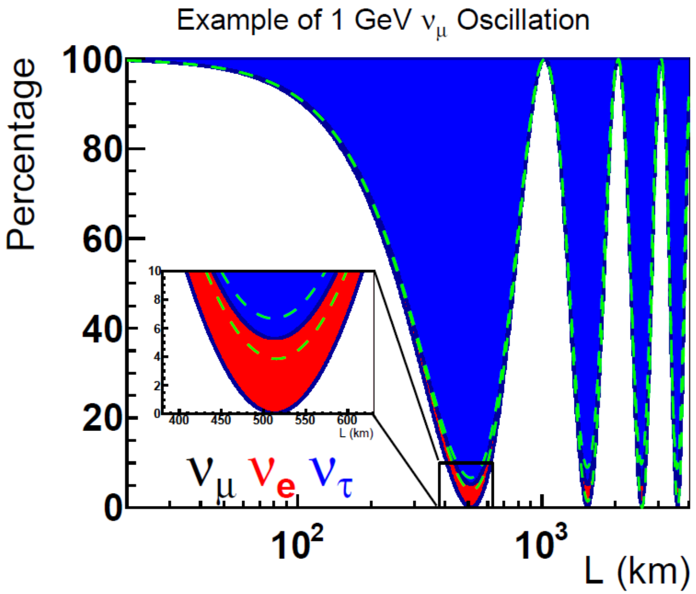
Deep Underground Neutrino Experiment (DUNE)



Through precision measurement of **(anti)ν_μ→(anti)ν_e oscillation**

- search for leptonic CP violation
- determine mass hierarchy
- test the unitarity of PMNS matrix through

More in DUNE TDR, arxiv:1807.10334



Hardware effort in BNL: Cold Electronics

Placing the preamplifier inside LAr significantly reduced the electronics noise

- 5-6 times compared to past warm electronics → **60:1** MIP peak-to-noise ratio in the collection
- Significantly improve the performance of induction wire plane → **An enabling technology**

Cold electronics for "Giant" Liquid Argon Time Projection Chambers

Veljko Radeka[1*], Hucheng Chen[1], Grzegorz Deptuch[2], Gianluigi De Geronimo[1], Francesco Lanni[1], Shaorui Li[1], Neena Nambiar[1], Sergio Rescia[1], Craig Thorn[1], Ray Yarema[2], Bo Yu[1]

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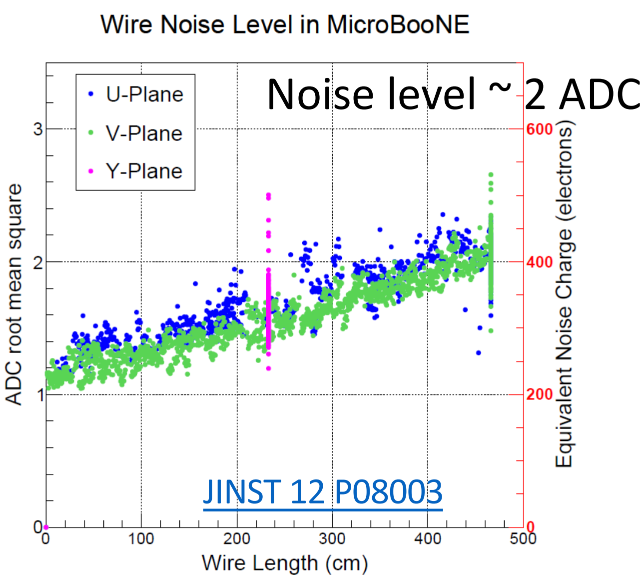
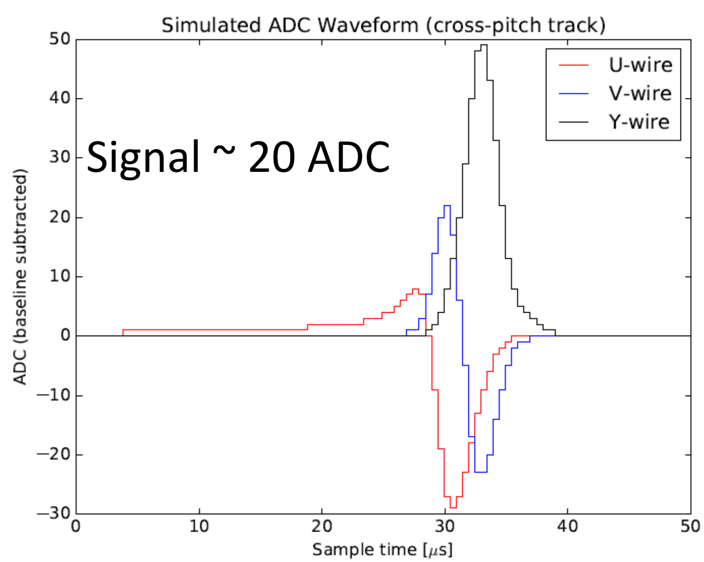
[2] Fermi National Laboratory,

[*]Correspondence, e-mail: radeka@bnl.gov

Abstract. The choice between cold and warm electronics (inside or outside the cryostat) in very large LAr TPCs (>5-10 ktons) is not an electronics issue, but it is rather a major cryostat design issue. This is because the location of the signal processing electronics has a direct and far reaching effect on the cryostat design, an indirect effect on the TPC electrode design (sense wire spacing, wire length and drift distance), and a significant effect on the TPC performance. All these factors weigh so overwhelmingly in favor of the cold electronics that it remains an optimal solution for very large TPCs. In this paper signal and noise considerations are summarized, the concept of the readout chain is described, and the guidelines for design of CMOS circuits for operation in liquid argon (at ~89 K) are discussed.

1st International Workshop towards the Giant Liquid Argon Charge Imaging Experiment (2011)



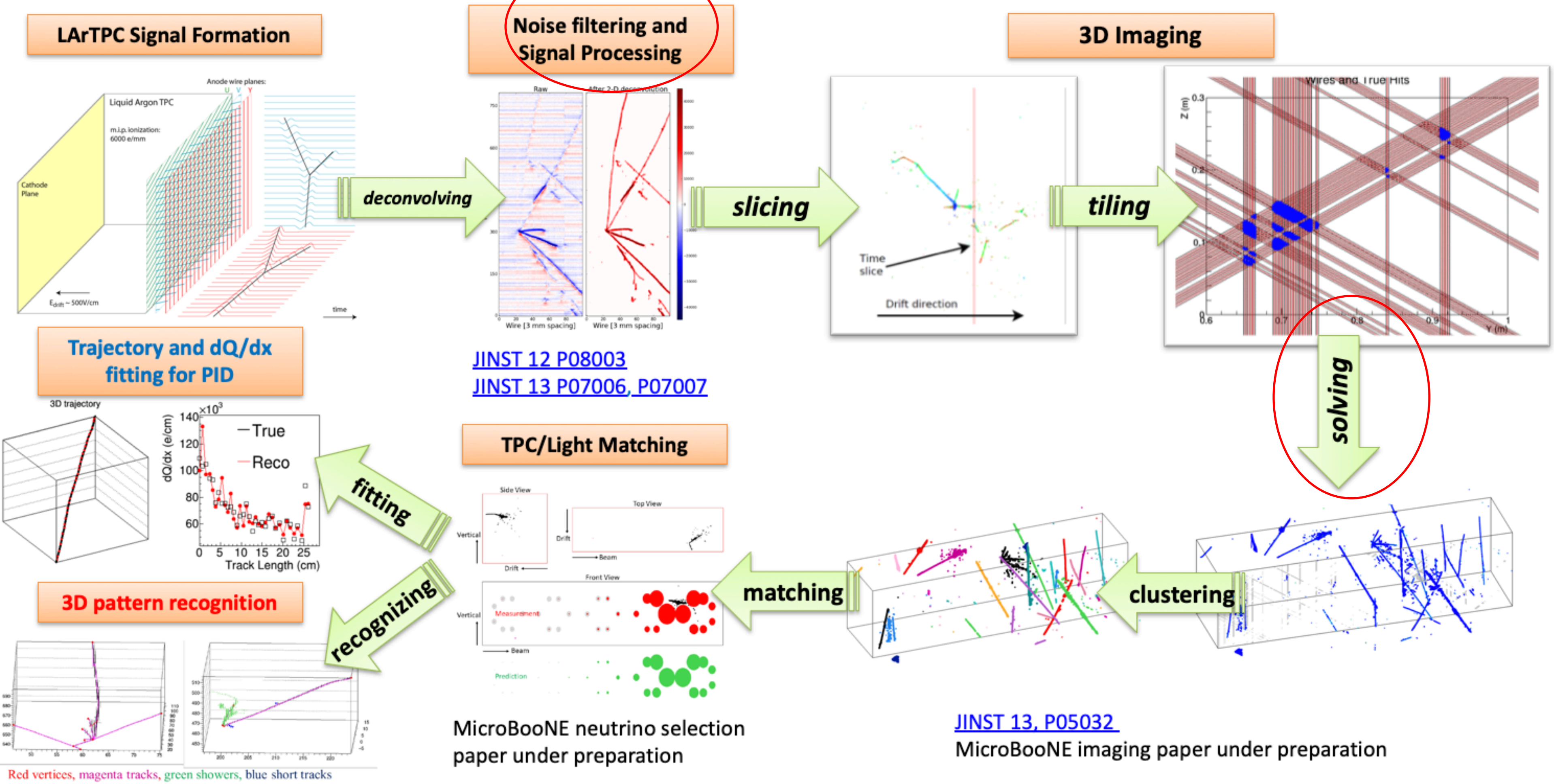


Software: Wire-Cell - Tomographic LArTPC Reconstruction

- Form 2D blobs for each time slice – Wire-Cell
- Reconstructed 3D clusters first – **no pattern assumption**
  - Charge, sparsity information used to resolve ambiguity
- Interactive pattern recognition with 3D objects

Wire-Cell

https://lar.bnl.gov/wire-cell/



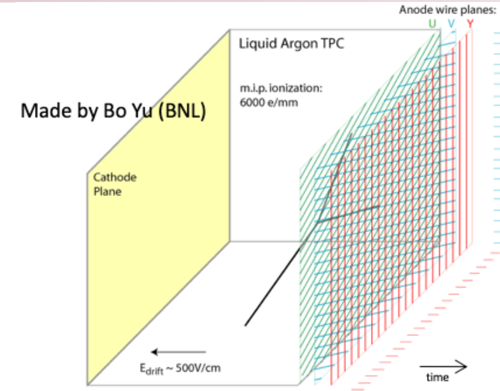
JINST 12 P08003
JINST 13 P07006, P07007

MicroBooNE neutrino selection paper under preparation

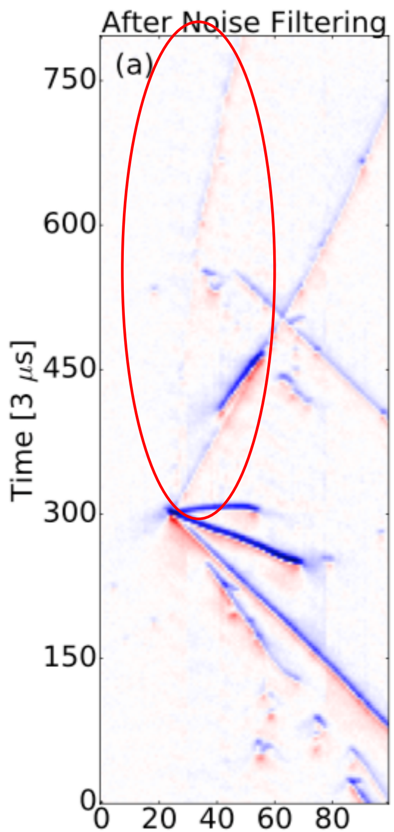
JINST 13, P05032
MicroBooNE imaging paper under preparation

Prolonged Tracks - Challenges for Signal Processing

- Collection plane – unipolar signal – only 1
- Induction plane – bipolar signal – several
- Prolonged track – canceling – weak signal – harder to reconstruct

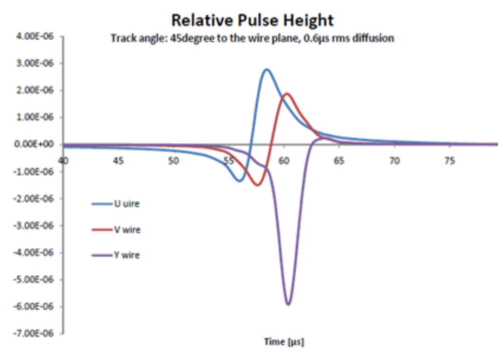


Prolonged track

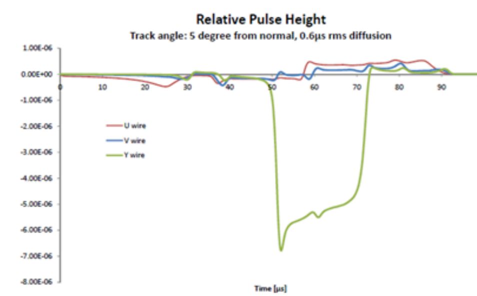


JINST 13 P07006 (2018)

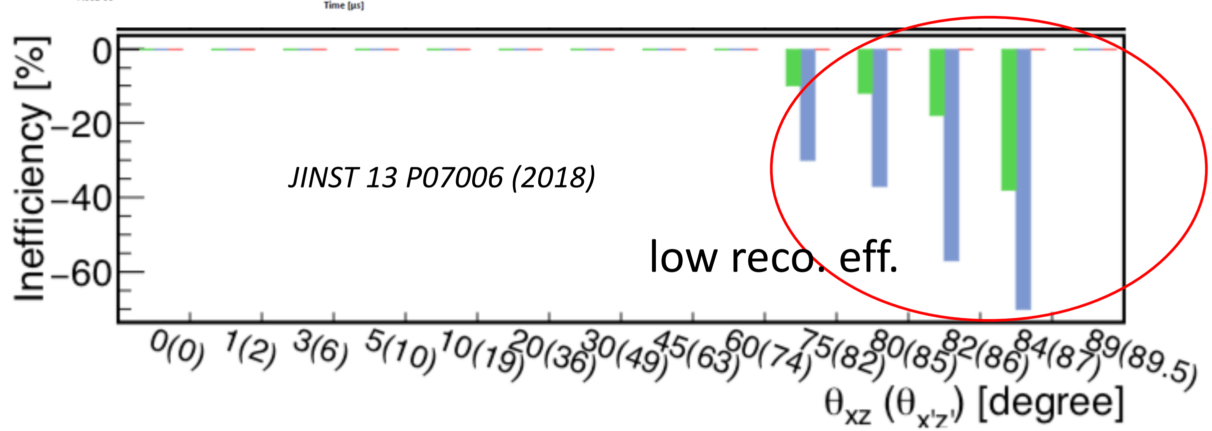
45 degrees



85 degrees



small induction signal

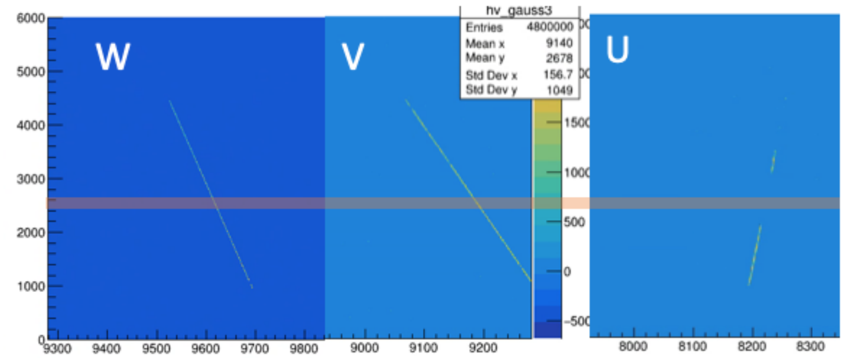


Multi-plane Signal Processing (mp-sp)

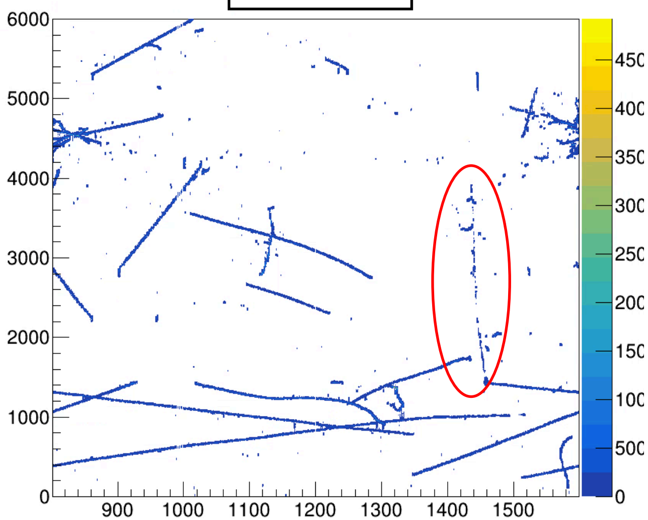
Signal processing using information from multi wire plane

- Utilizing the redundancy of wire planes
- Initial test on ProtoDUNE data looks promising!

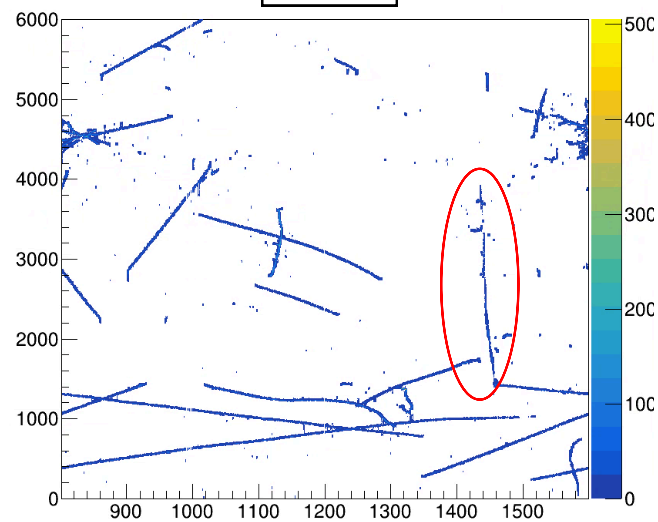
1 track from 3 planes



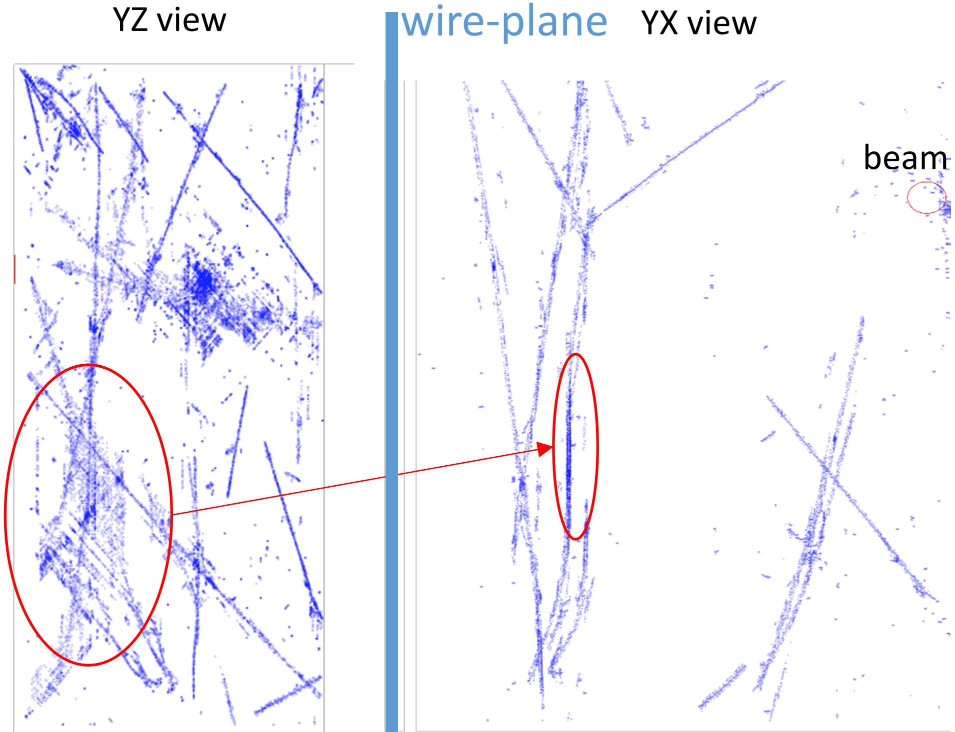
no mp-sp



mp-sp



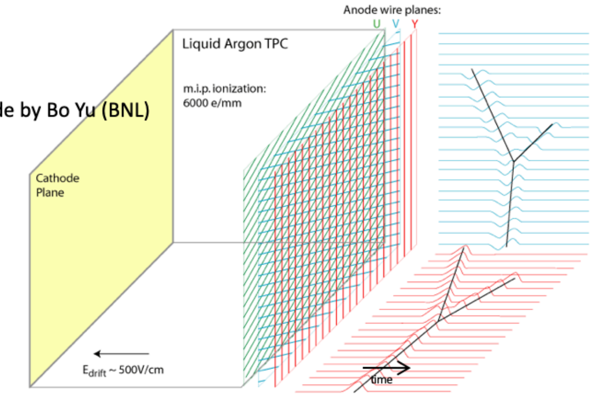
Isochronous Tracks - Ambiguity in Solving



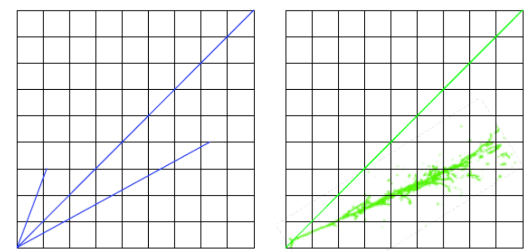
[Bee Event Display](#)by Chao Zhang

Charges arrive at same time for Isochronous tracks

Made by Bo Yu (BNL)



causing ambiguity



Isochronous tracks – tracks parallel to the wire plane

- Not enough time information to resolve truth crossings
- Extra information needed to solve the ambiguity – Charge!

Solving - Underdetermined Linear System

Use two-plane as an example

measured charges on wires

true charges to be solved

$$\begin{pmatrix} u1 \\ u2 \\ v1 \\ v2 \\ v3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & a & a & a \\ a & a & a & 0 & 0 & 0 \\ 0 & 0 & a & 0 & 0 & a \\ 0 & a & 0 & 0 & a & 0 \\ a & 0 & 0 & a & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} H_1 \\ H_2 \\ H_3 \\ H_4 \\ H_5 \\ H_6 \end{pmatrix}$$

Matrix determined by geometry

(a=1)

$y = Ax$

charge ~ 3N, but 2D coordinate ~ N^2
- Underdetermined Linear System

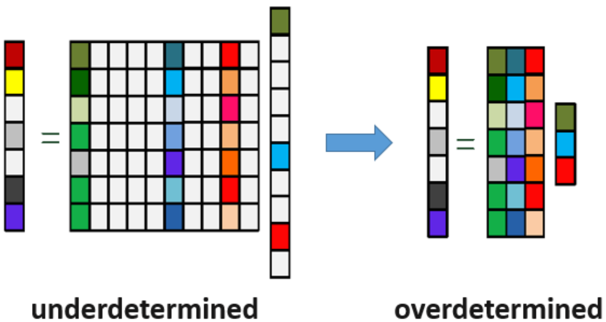
If we assumes signal is sparse - compressed sensing (L0 regularization)

- Remove unknowns (assuming zero) until the equations solvable
- Pick the best solution (smallest χ^2)

L0 reg. Minimize $\chi^2 = (y - A \cdot x)^2 + \lambda \cdot \sum_i |x_i|^0$

- computational hard

compressed sensing



https://commons.wikimedia.org/wiki/File:Compressed_Sensing.png

Compressed Sensing with L1 regularization

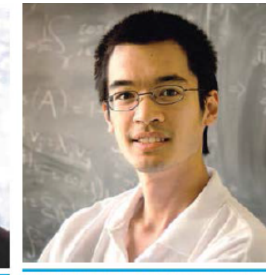
A breakthrough comes from the proof that L0 problem can be well approximated by the L1 regularization

Candes, Romberg, and Tao, "Stable Signal Recovery from Incomplete and Inaccurate Measurements"

https://arxiv.org/abs/math/0503066

Emmanuel Candes. *(Photo courtesy of Emmanuel Candes.)*

Justin Romberg. *(Photo courtesy of Justin Romberg.)*



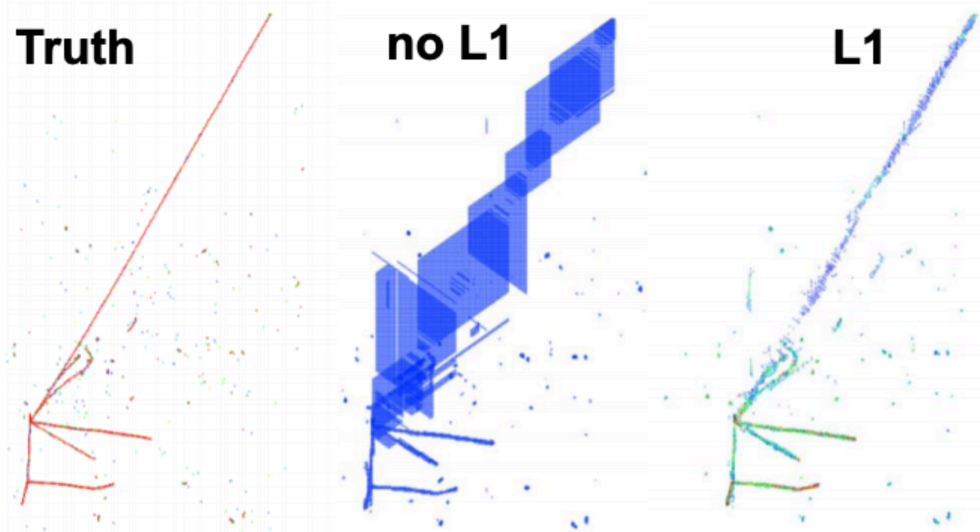
Terence Tao. *(Photo courtesy of Reed Hutchinson/UCLA.)*

$$\chi^2 = (y - A \cdot x)^2 + \lambda \cdot \sum |x_i|^0$$

$$\Rightarrow \quad \chi^2 = (y - A \cdot x)^2 + \lambda \cdot \sum_i |x_i|^1$$

much faster

Hours of computing time with L0 → tens of seconds of computing time with L1

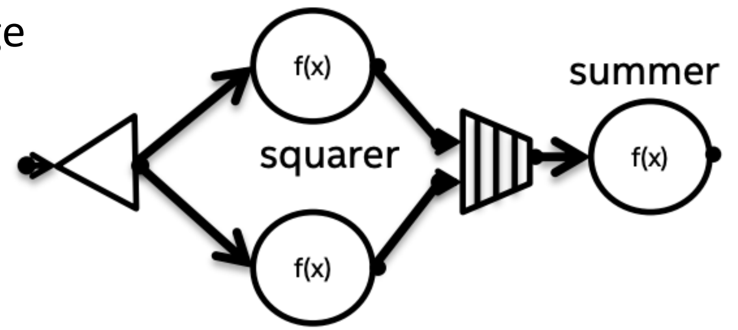


Wire-Cell Framework - Dataflow Programing (DFP)

Parallelization in HEP computing

- Large single event size
- Relative small memory/core in HTC node configuration
- Memory sharing in MT – reduce per core memory usage

Directed Acyclic Graph



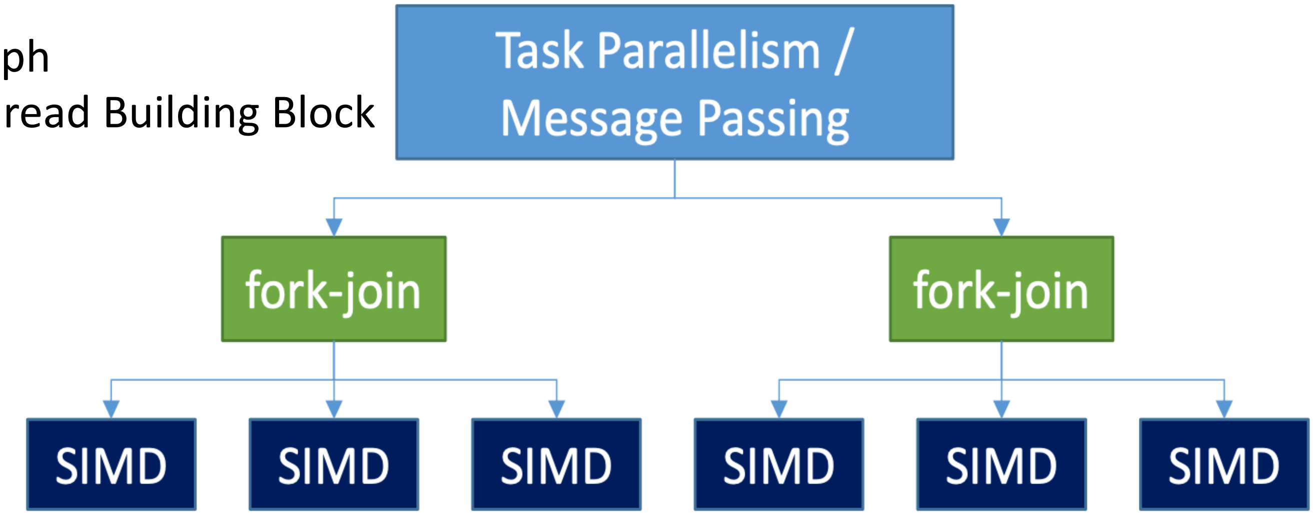
Wire-Cell used Dataflow Programing paradigm

- job as directed acyclic graph (DAG)
- Node – processing task
- edge – data flow
- compatible with task parallelism execution engine

TBB flow graph
TBB: Intel Thread Building Block

OpenMP

Intel SSE



https://indico.cern.ch/event/673615/sessions/254930/attachments/1567622/2471316/Programming_with_TBB_Flow_Graph.pdf

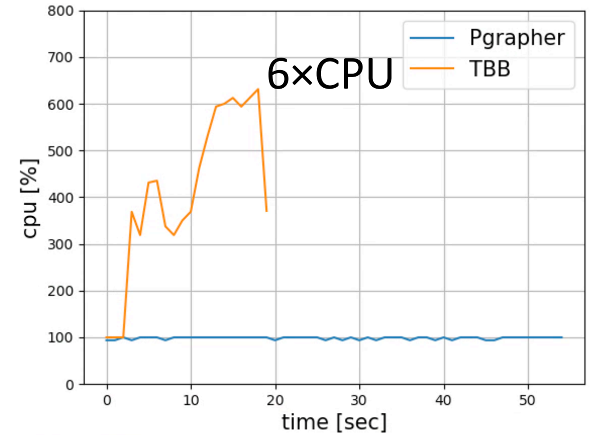
Multithreading example with TBB engine

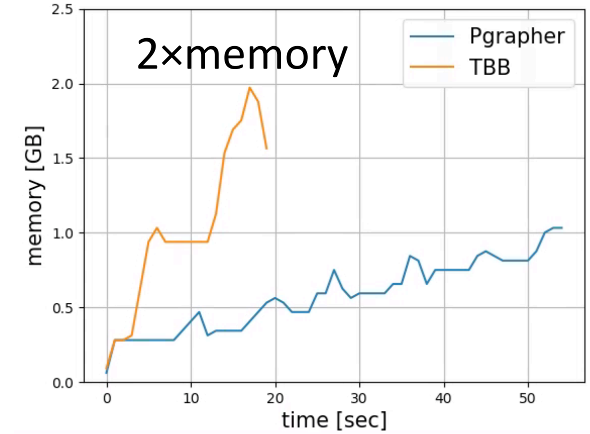
Execution engines in Wire-Cell

- single thread (ST) – *Pgrapher* – used in MicroBooNE, ProtoDUNE
- multi thread (MT) – *TbbFlow* – based on Intel Thread Building Block (TBB) – under dev

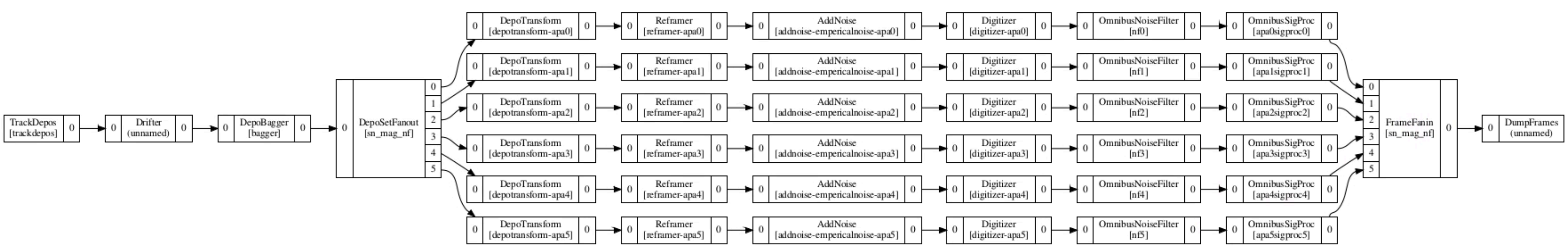
Tested with "simulation – noise filtering (NF) - signal processing (SP)" chain

- runs 3 times faster than ST mode (*Pgrapher*)
- max mem. × time ~ 2/3 of ST





visualization of a Wire-Cell graph



Summary

Wire-Cell is an open source project mainly targeting LArTPC reconstruction

- DFP framework – MT at higher level
- algorithms for LArTPC reco.
- more

Wire-Cell is now being used in MicroBooNE and ProtoDUNE experiment

More development under way towards fully automated precision LArTPC reconstruction

More at: https://lar.bnl.gov/wire-cell/

Backups

Wire-Cell

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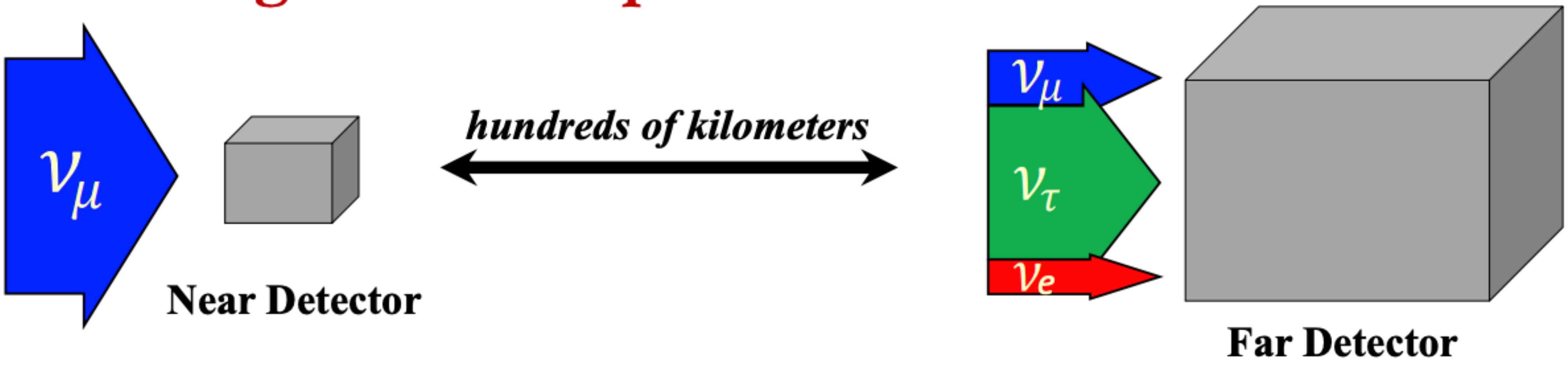
Why Argon

Why LAr?	He	Ne	Ar	Kr	Xe
Atomic Number	2	10	18	36	54
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120	165
Density [g/cm³]	0.125	1.2	1.4	2.4	3
Radiation Length [cm]	755.2	24	14	4.9	2.8
dE/dx [MeV/cm]	0.24	1.4	2.1	3	3.8
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000
Scintillation λ [nm]	80	78	128	150	175
Cost ($/kg)	52	330	5	330	1200

LAr combines abundant signal (ionization/scintillation), good dielectric, low diffusions, and low cost http://lar.bnl.gov/properties/

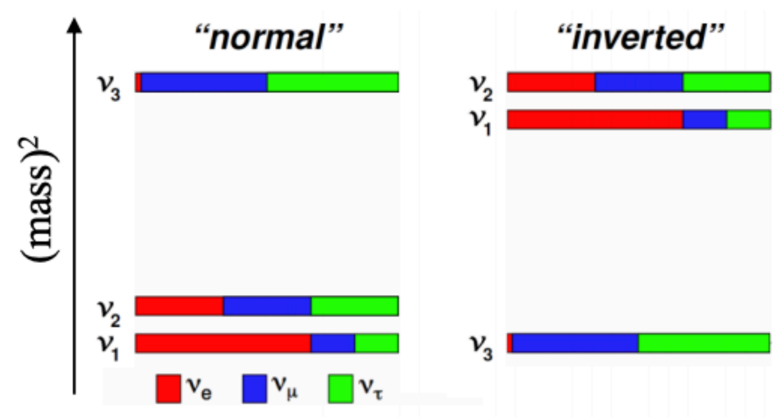
Generic long-baseline experiment



ν_e appearance:

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23}\ \sin^2 2\theta_{13}\ \sin^2(\Delta m^2_{32} L/4E)$$

...plus ***potentially large CPv*** *and*
matter effect* *modifications!*

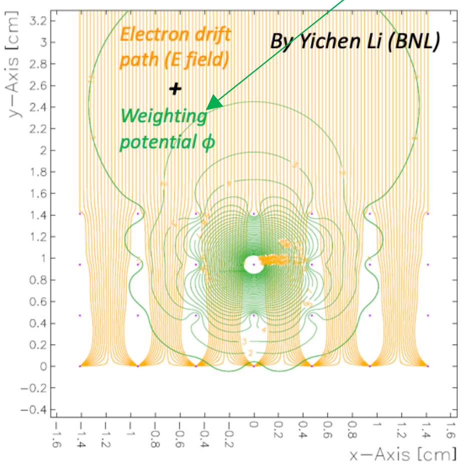


* ν_e see different potential than $\nu_{\mu,\tau}$ when propagating through matter (here, the earth)
⇒ a hierarchy-dependent effect

https://indico.cern.ch/event/645835/contributions/2777693/attachments/1590918/2517686/20180129_np-th-cern-dune_patterson.pdf

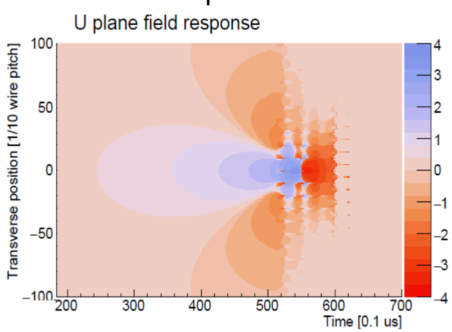
WireCell Detector Response Simulation

Ramo's theorem
$i = e\vec{v} \cdot \vec{E}_v = e\vec{v} \cdot (-\nabla\phi)$



Garfield, a drift-chamber simulation program User's Guide, Veenhof, R. (1993)

2D field response



Hanyu Wei' talk, DUNE collab. meeting May 2019

Response matrix:

- Field response from Garfield simulation
- Electronic response

2D convolution – realized by FFT and IFFT

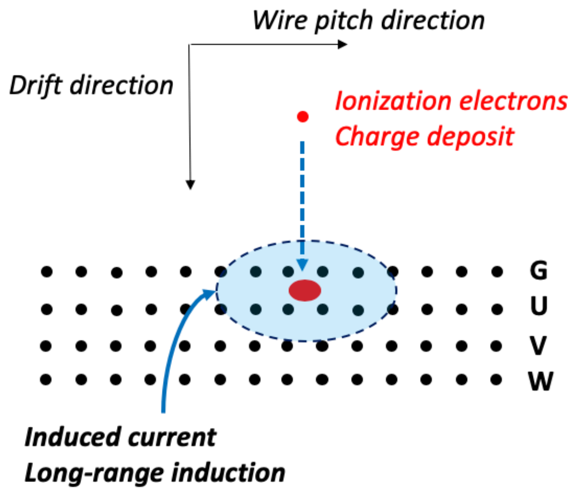
Add inherent electronics noise

- M. Diwan. *Basic mathematics of random noise part ½*

Refer: *JINST 13 P07006 (2018)*

2D Conv.

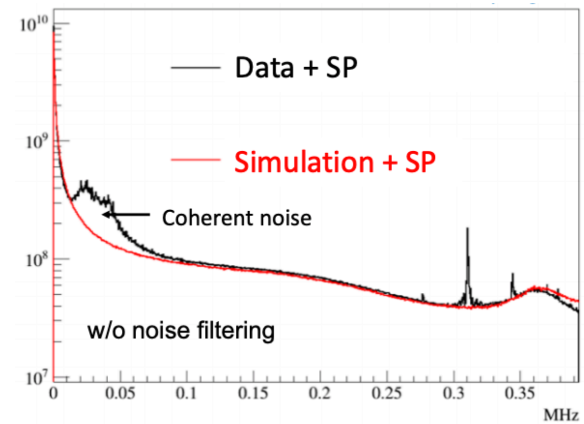
$$M(t',x') = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} R(t,t',x,x') \cdot S(t,x)dtdx$$



Hanyu Wei' talk, DUNE collab. meeting May 2019

Noise simulation

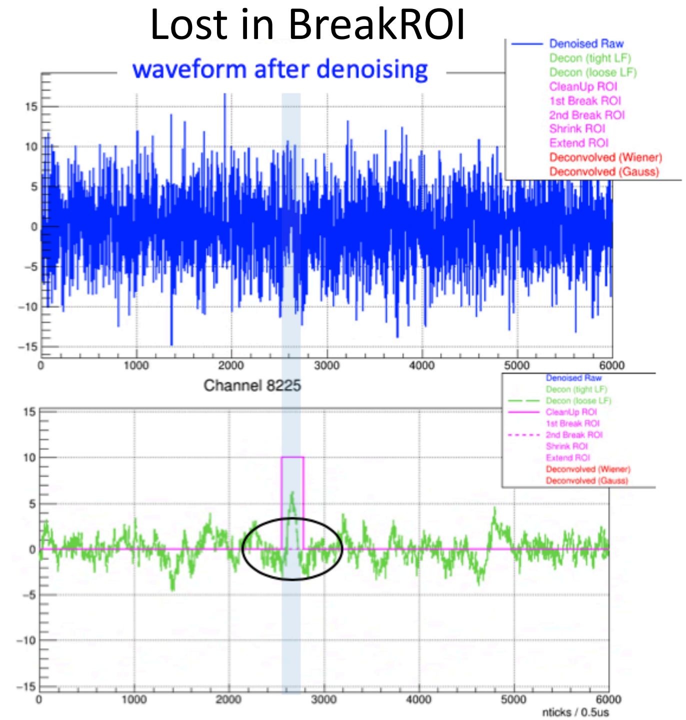
- Input: frequency spectrum of the noise from real data
- In freq-domain, any type of inherent noise is in general a high-dimension random walk in complex plane.
    - The amplitude follows Rayleigh distribution
    - The phase follows uniform in 0-2pi
    - Additivity (sum up all sources of noise)



by Wenqiang Gu in Hanyu Wei' talk, DUNE collab. meeting May 2019

Lost in BreakROI

- Weak signal in raw waveform
- With proper filter, signal could be enhanced after 2D deconvolution
- Due to the LF nature of the signal, some of the ROIs are lost after ‘BreakROI’ step

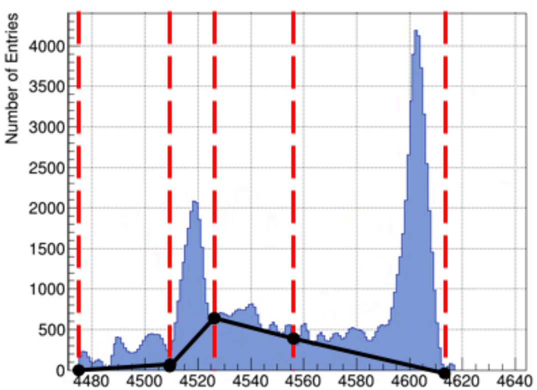


BreakROI

deconvoluted waveform

Peak/valley finding

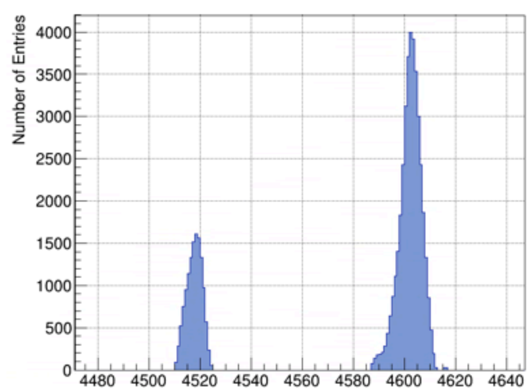
Baseline subtraction



BreakROI

- Baseline subtraction
- thresholding

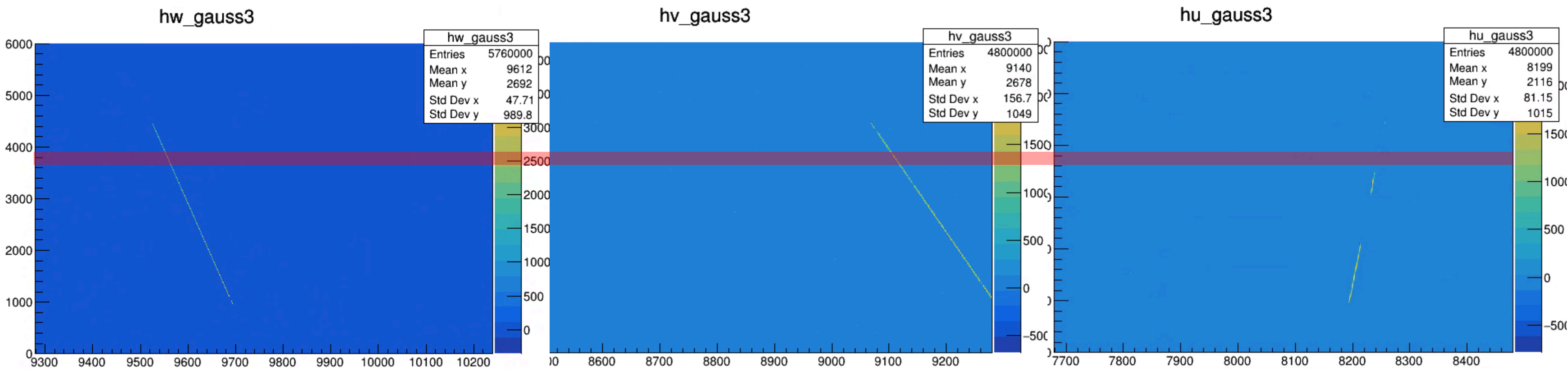
SP result



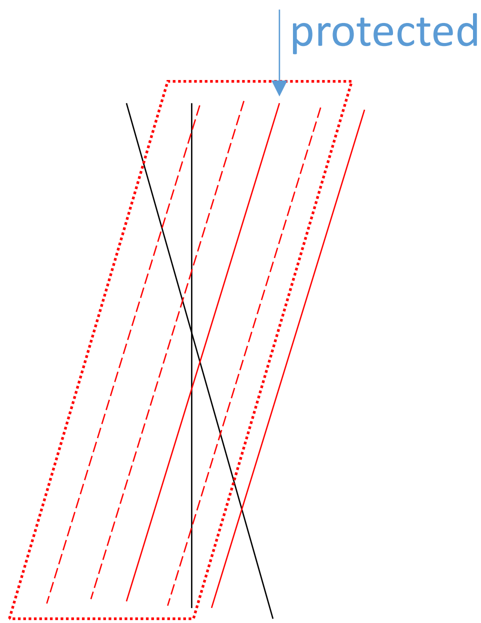
Using multi-plane information to enhance prolonged track reco.

proposed by Xin Qian

1, make time slices



2, Matching active (with ROI) wires in multiple planes



3, mark matched ROIs as 'protected'

active wire in the time-slice :

ref. plane, target plane

in-active wire in the time-slice