LArTPC: From Raw Data to 3D reconstruction

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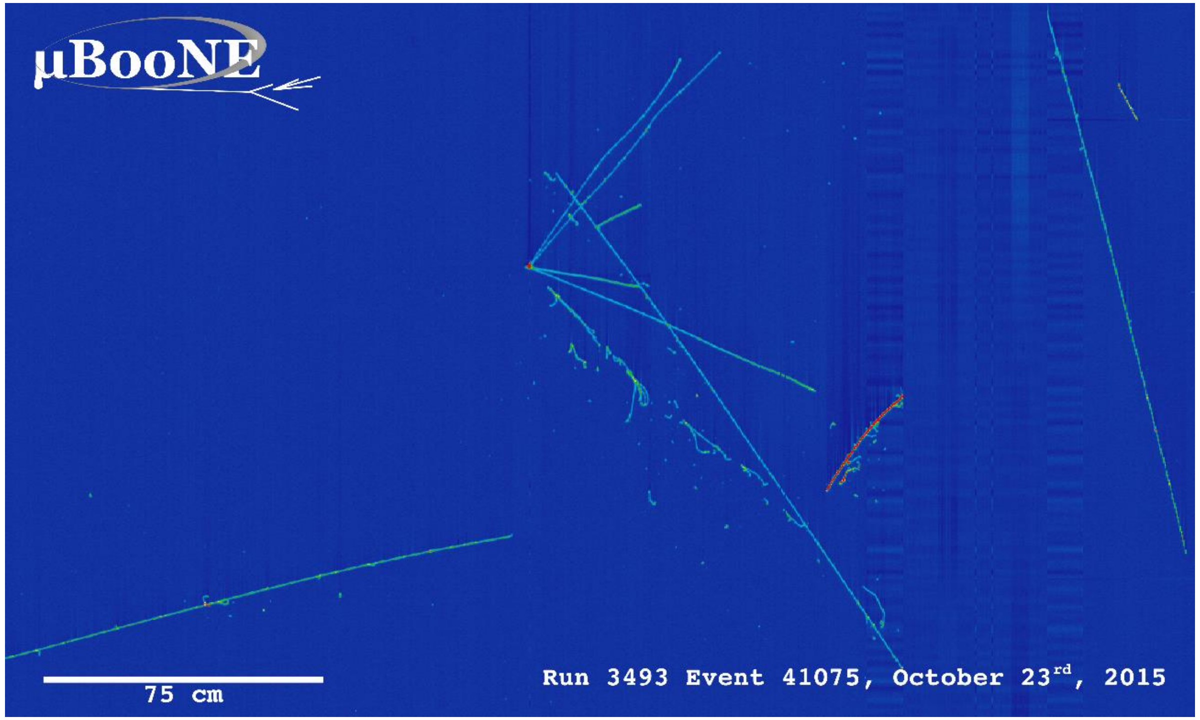
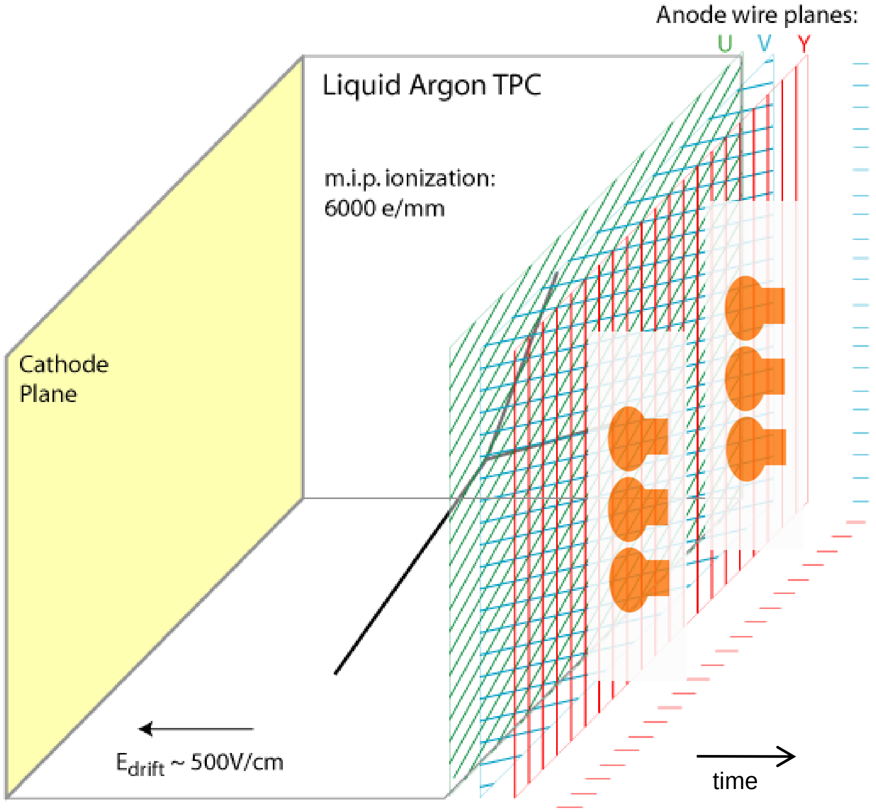
Liquid Argon Time Projection Chamber (LArTPC)

- ~mm scale position resolution in 3D

From Bo Yu (BNL)

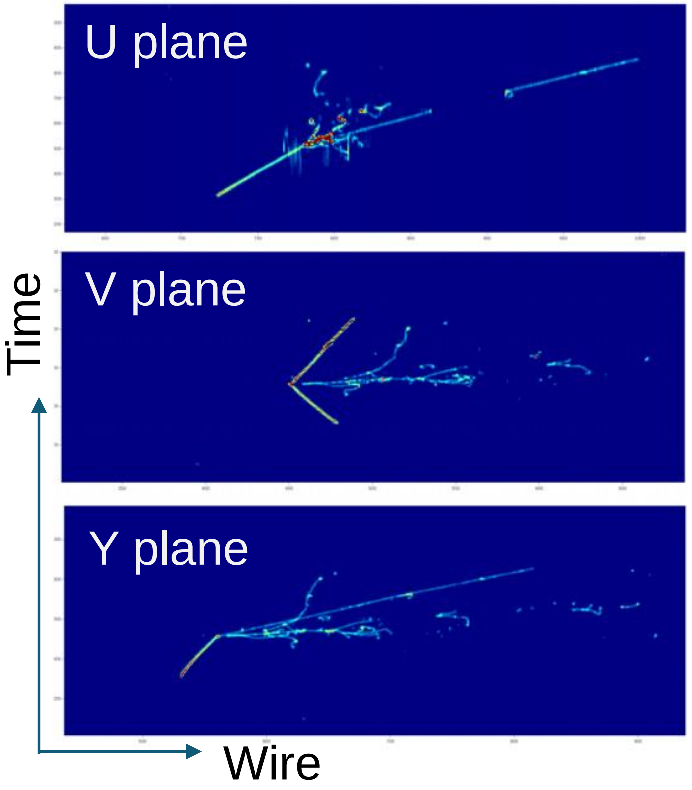


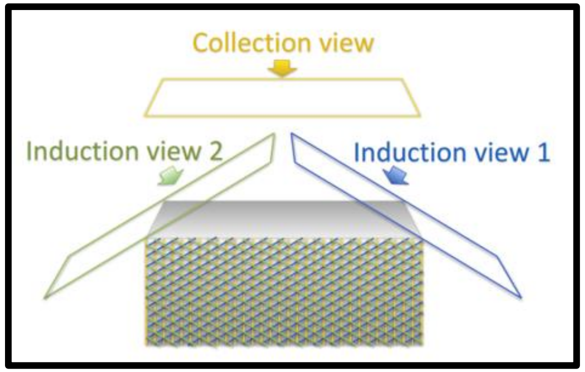


drift speed 1.6 m / milisec
wire pitch 3 mm

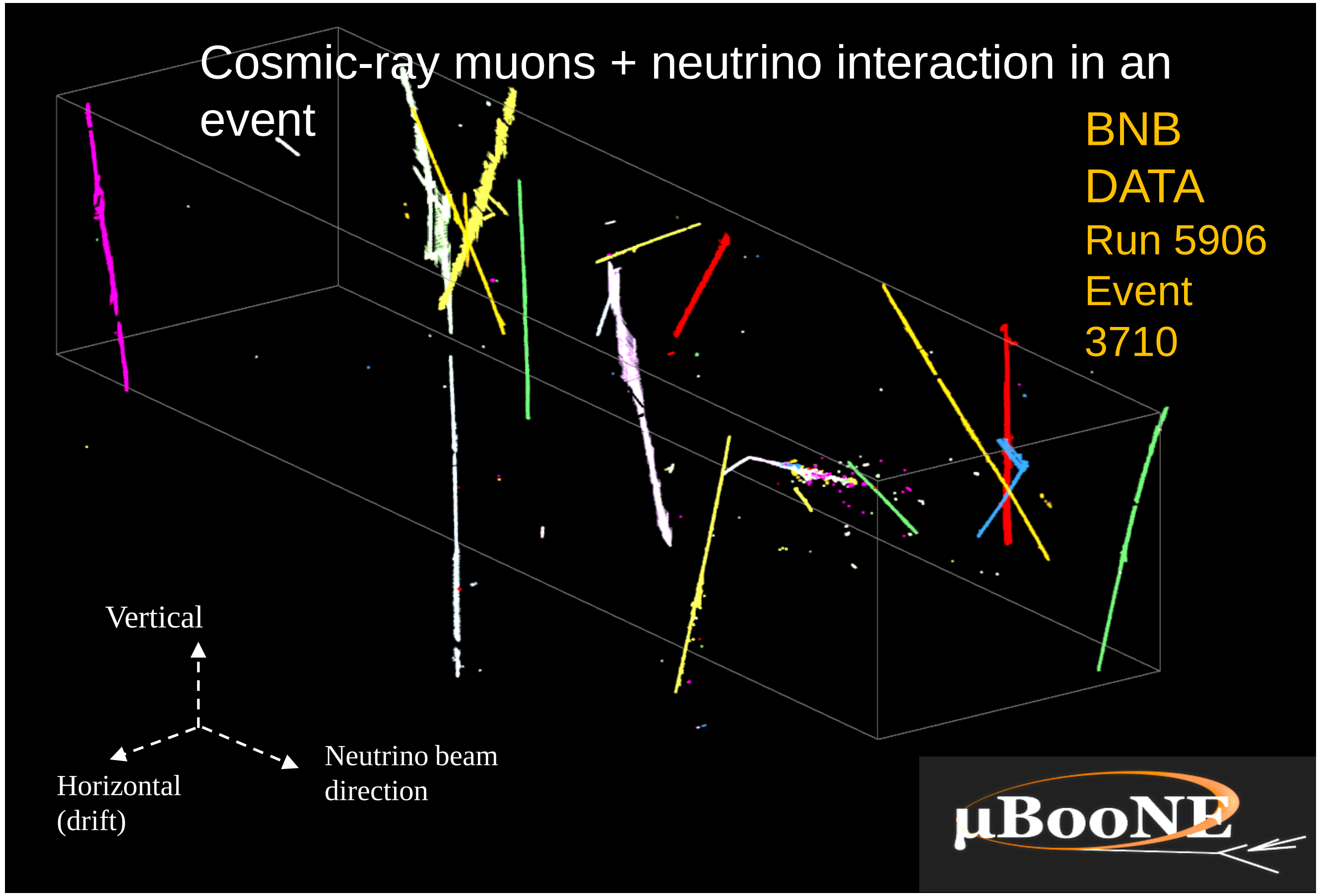
Wire-Cell Event Reconstruction

Three time-versus-wire views



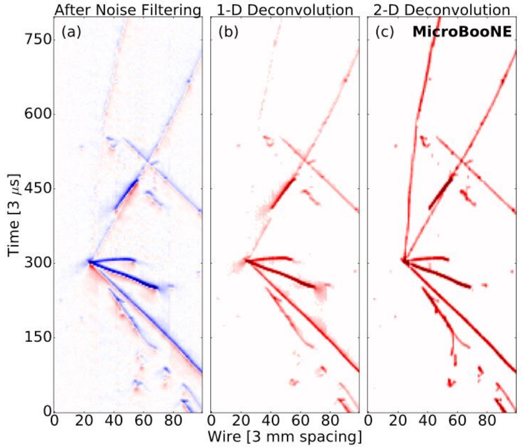


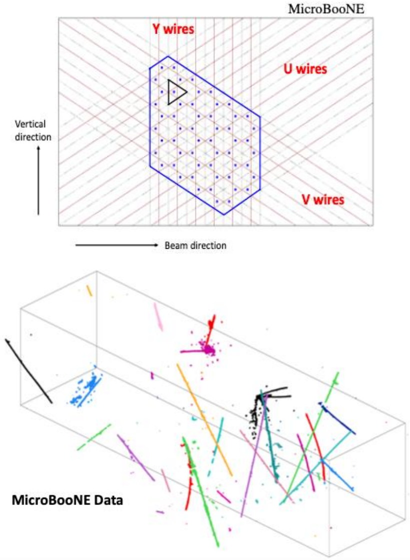
3D imaging, clustering

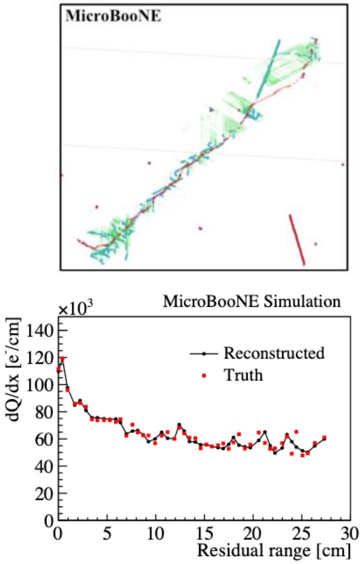


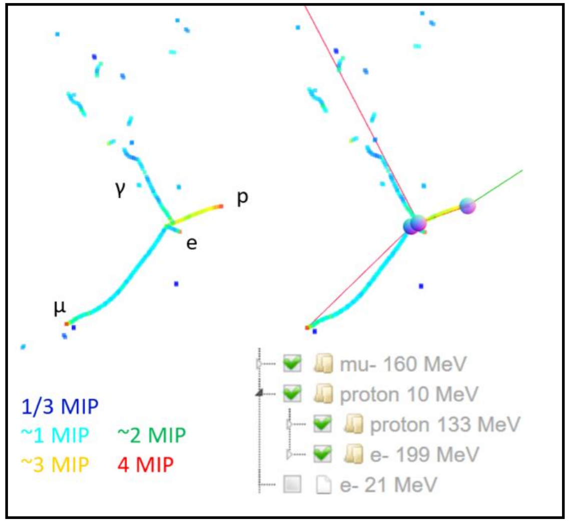
Wire-Cell Event Reconstruction

TPC simulation noise filtering signal processing	3D imaging clustering charge-light matching	3D trajectory & dQ/dx fitting cosmic muon tagger	multi-track fitting DL-3D vertexing particle identification









JINST 12 P08003 (2017)
JINST 13 P07006 (2018)
JINST 13 P07007 (2018)
JINST 16 P01036 (2020)

JINST 13 P05032 (2018)
JINST 16 P06043 (2021)

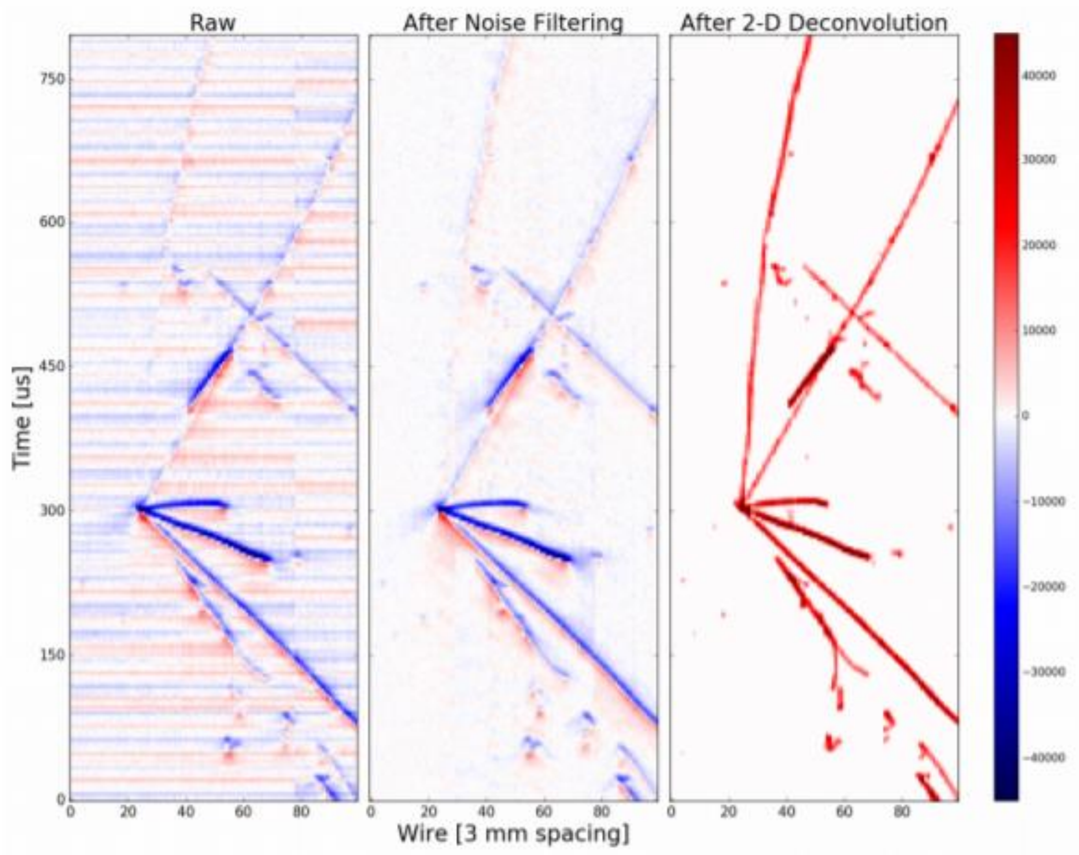
Phys. Rev. Applied 15 064071 (2021)
arXiv:2012.07928

JINST 17 P01037 (2022)

Wire-Cell Low Level Signal Processing

- Noise filtering
  - Single-frequency white noise
  - Coherent noise
- Signal deconvolution
  - Remove “field response” and “electronic response”

$$M(x',t') = \int_{-\infty}^{\infty}\int_{-x_0}^{x_0} R(x-x',t-t')S(x,t)\,dx\,dt$$



Online display:
http://lar.bnl.gov/magnify/

Digital Signal Processing

- Fundamental theory of linear time-invariant (LTI) system:
  - Any LTI system can be characterized entirely by a single function called the system's **impulse response**

$$y = Ax$$

- y: measured discrete-time signal
- x: the (unknown) true signal
- A:Response matrix

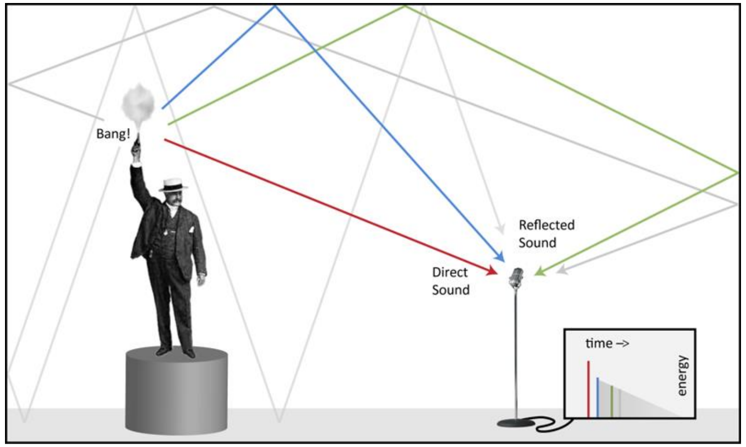
$$x(t) \longrightarrow \boxed{h(t)} \longrightarrow y(t) = h(t) * x(t)$$

$$= \int_{-\infty}^{\infty} h(t-\tau)x(\tau)d\tau$$

digitize

Impulse response

Room
acoustic
response



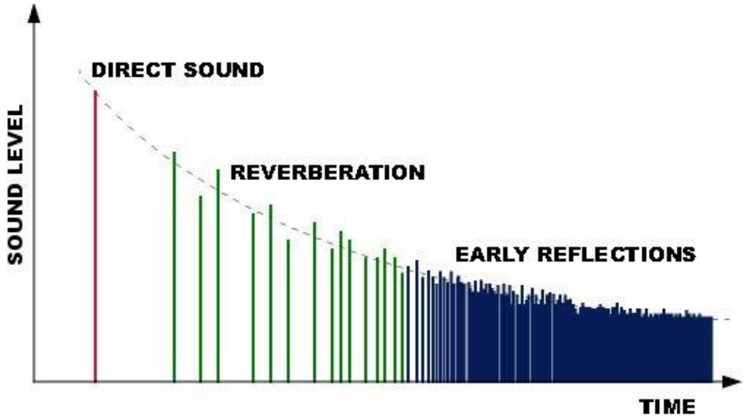
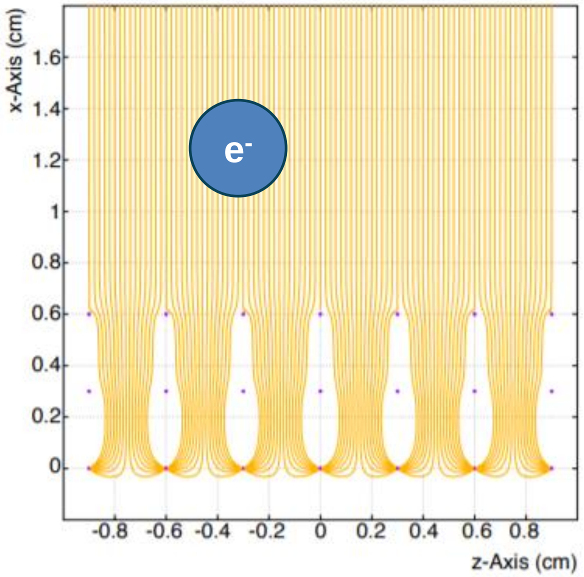
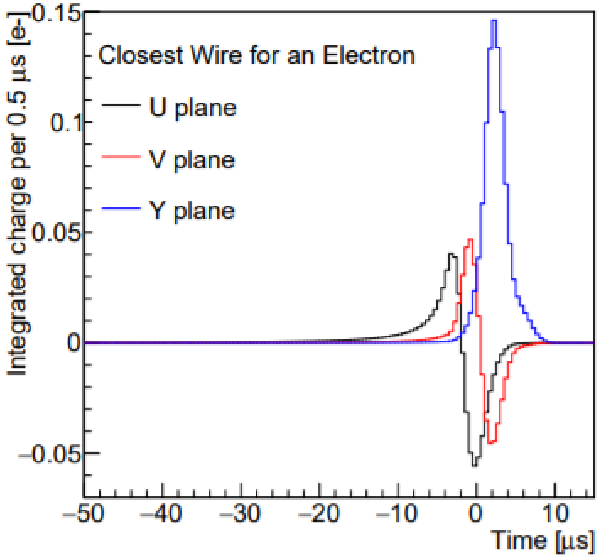


Image credit: www.prosoundweb.com

$h(t)$

LArTPC
field + electronic
response

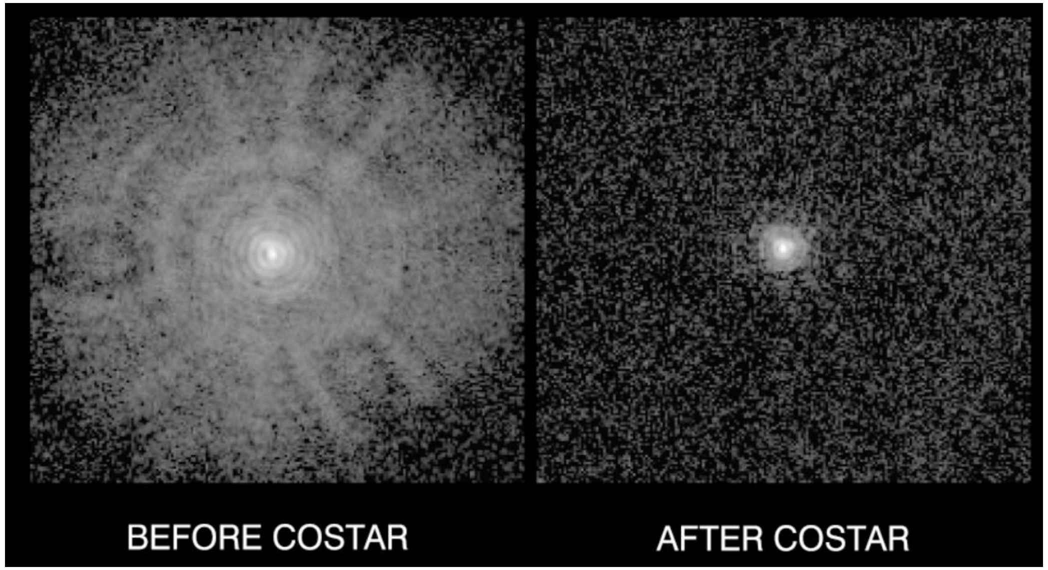




JINST 13 P07007 (2018)

2D Impulse response

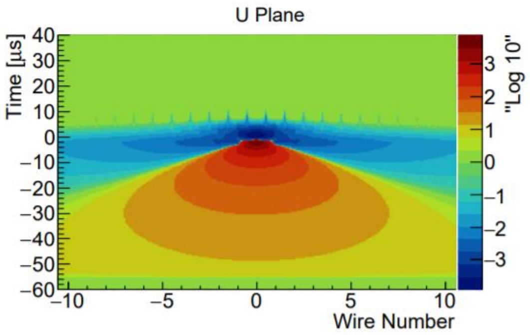
Camera optical response

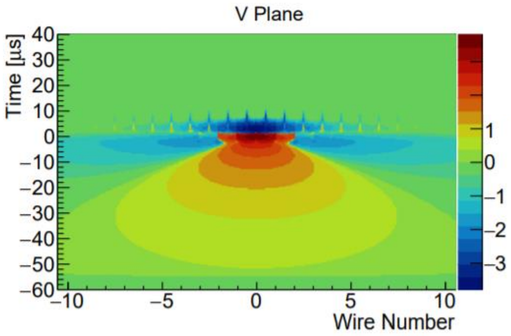


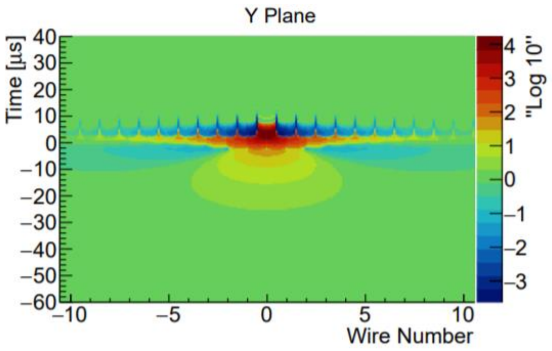
Hubble telescope impulse response (Image credit: http://web.mit.edu)

$$h(x, y)$$

LArTPC 2D response:
y: t * drift velocity
x: wire number * pitch







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Change of Basis

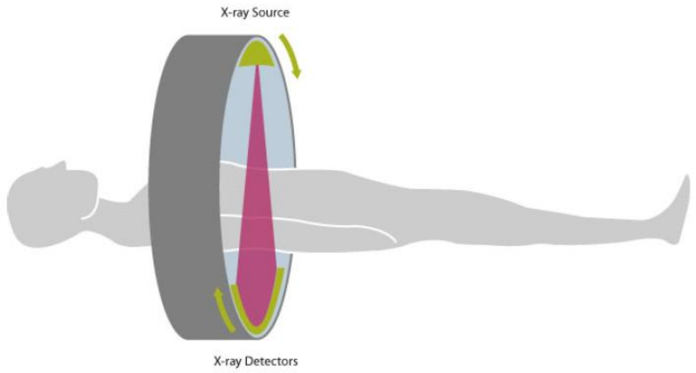
$$\begin{pmatrix} & \cdots & \\ \vdots & \ddots & \vdots \\ & \cdots & \end{pmatrix}$$

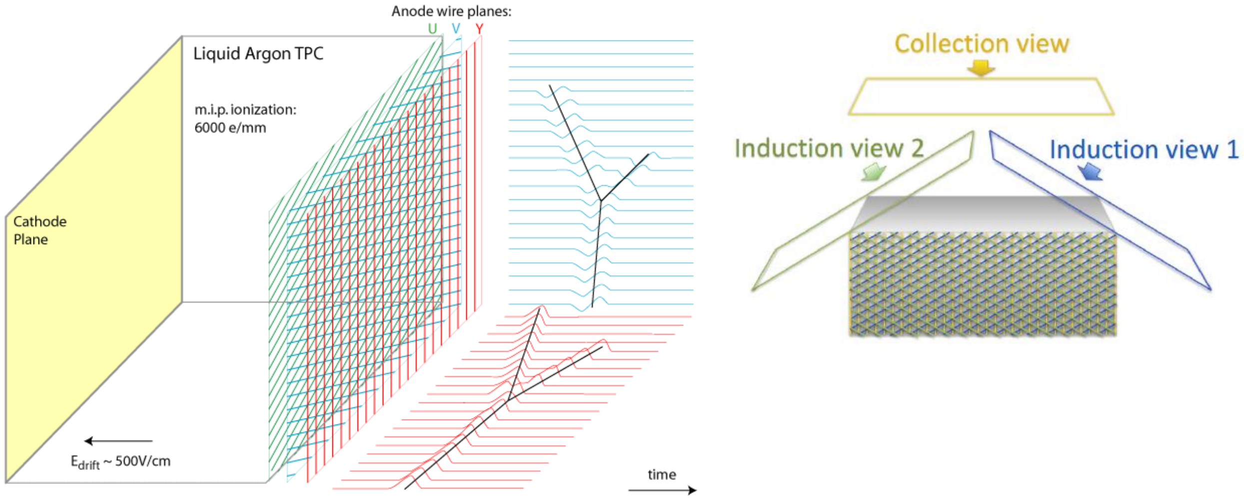
$$\begin{tikzcd}
\text{Time Domain} & x(t,w) \arrow[r] & \boxed{h(t,w)} \arrow[r] \arrow[d, "\text{DFT}"] & y(t,w) = h(t,w) * x(t,w) \arrow[d, "\text{DFT}"] \\
\text{Frequency Domain} & X(f,s) \arrow[r] \arrow[u, "\text{IDFT.}"] & \boxed{H(f,s)} \arrow[r] & Y(f,s) = H(f,s) \cdot X(f,s)
\end{tikzcd}$$

$$\begin{pmatrix} \lambda_1 & & \\ & \ddots & \\ & & \lambda_n \end{pmatrix}$$

- Discrete Fourier Transform;
  - Convolution -> multiplication: matrix diagonalization
  - FFT algorithm: $O(N^2) \rightarrow O(N \log N)$: fast computation
  - Frequency-domain filters: reduce noise, regularize fluctuations

Wire-cell Tomographic Reconstruction





- CAT Scan
  - Detector (x-ray generator/receiver) moves across the object (body)
  - Axial projections (~180) by detector rotation
  - Cross section can be reconstructed at each position along detector movement

- LArTPC
  - Objects (ionizing electrons) move across detectors (wire planes)
  - Axial projections (~3) by wire orientation
  - Cross section can be reconstructed at each time slice along electron drift

Construct Linear Equations

$$y = Ax$$

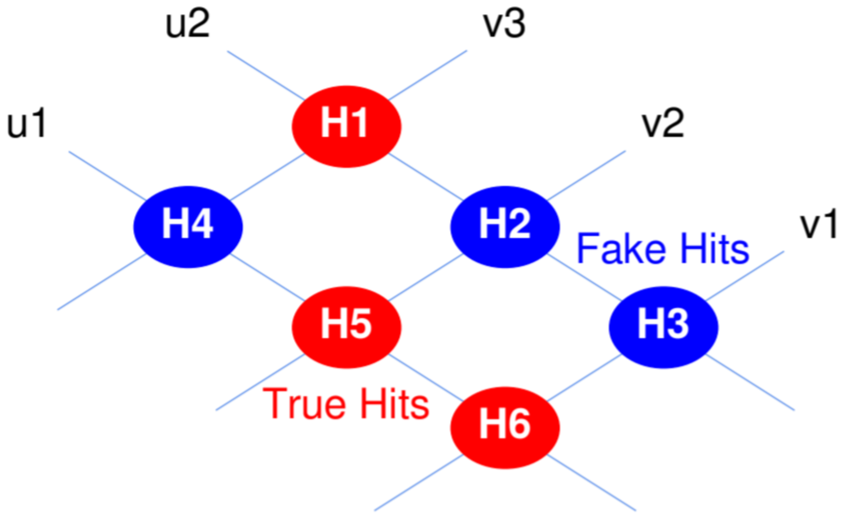
$$\begin{pmatrix} u1 \\ u2 \\ v1 \\ v2 \\ v3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} H1 \\ H2 \\ H3 \\ H4 \\ H5 \\ H6 \end{pmatrix}$$

y: measured charge signal on each wire

x: the (unknown) true charge deposition in each possible cell

A: bi-adjacency matrix connecting wires and cells (determined solely by wire geometry)

Use two planes as an illustration



At one time slice

Desired Solution

$$x = \begin{pmatrix} H1 \\ 0 \\ 0 \\ 0 \\ H5 \\ H6 \end{pmatrix}$$

Solve underdetermined linear problem: regularization

- Previous example has 6 unknowns, 5 equations: under-determined system

$$x = \boxed{(A^T V^{-1} A)}^{-1} A^T V^{-1} \cdot y$$

non-invertible, 2 zero-eigenvalues out of 6.

- Adding constraints: find the sparsest solution (applies to most physics events): L0-regularization

minimize $\|x\|_0$, subject to: $y = Ax$

(L0-norm: number non-zero elements)

NP-hard!

Procedure

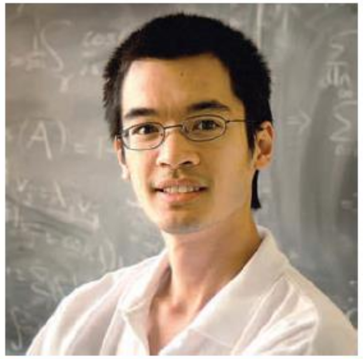
- Remove unknowns until equations can be solved, then find the best solution with the minimum χ^2
- a combinatorial problem
  - 2 out of 6: 15 combinations
  - 10 out of 40: 0.8 billion combinations

Compressed Sensing (L1-regularization)

- Breakthrough: mathematical proof that L0 problem can be well approximated by the L1 problem (Compressed Sensing, *Candes, Romberg, and Tao, 2005*.)

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

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



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

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

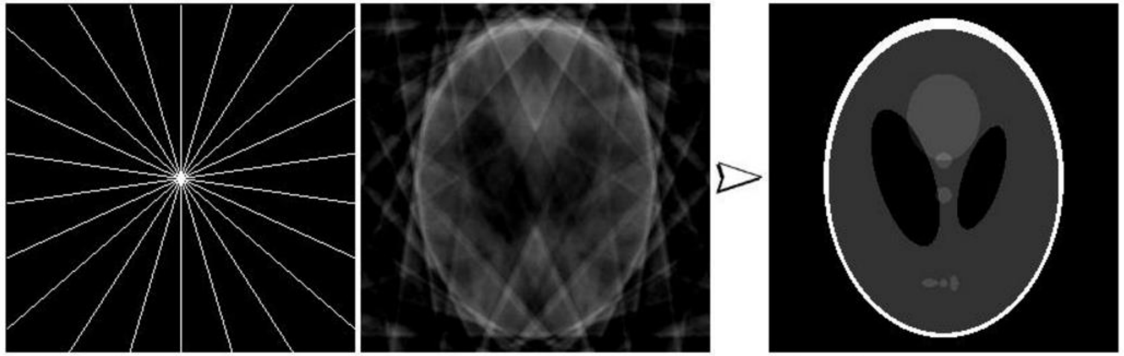
minimize $||x||_1$, subject to: $y = Ax$

(L1-norm: sum of absolute values of the elements)

Or, equivalently, minimize

$$\chi^2 = (y - Ax)^T \cdot V^{-1} \cdot (y - Ax) + \lambda||x||_1$$

Sparse projections: 11 radial lines



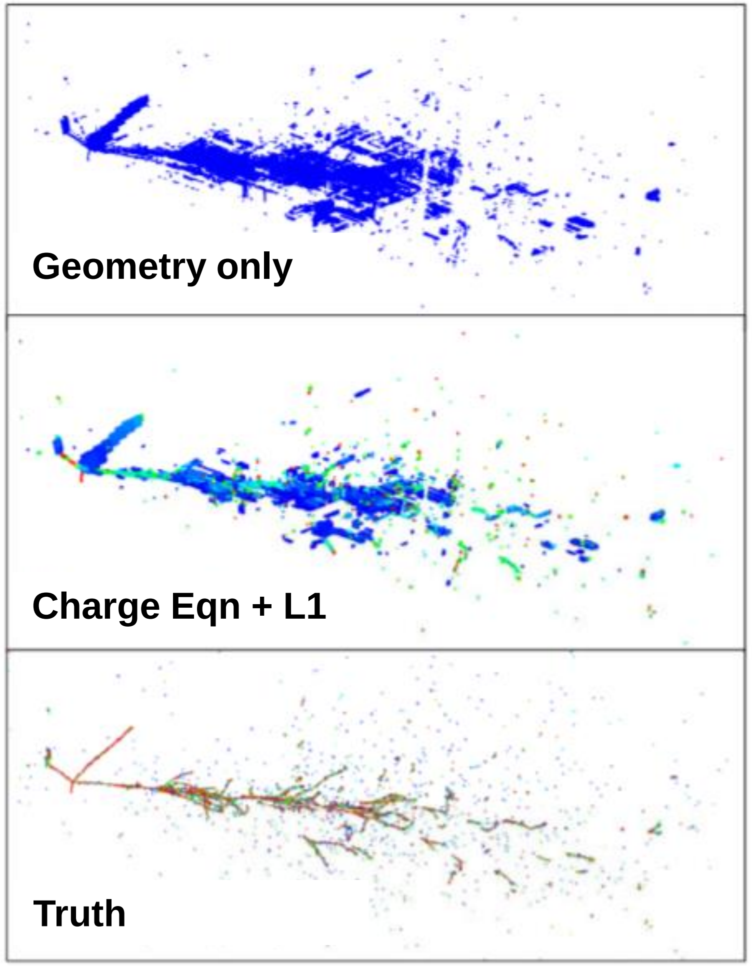
available portion of the spectrum (11 radial lines)

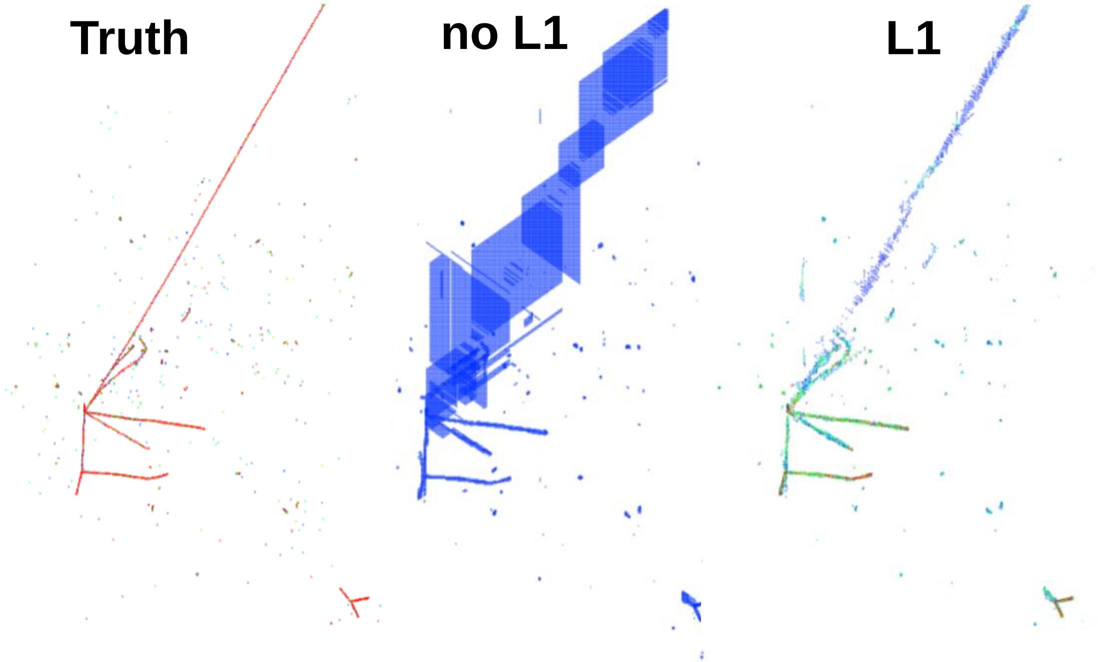
Back-projection estimate

Estimate after convergence (exact reconstruction)

Tomography: reconstruct image with far less projections

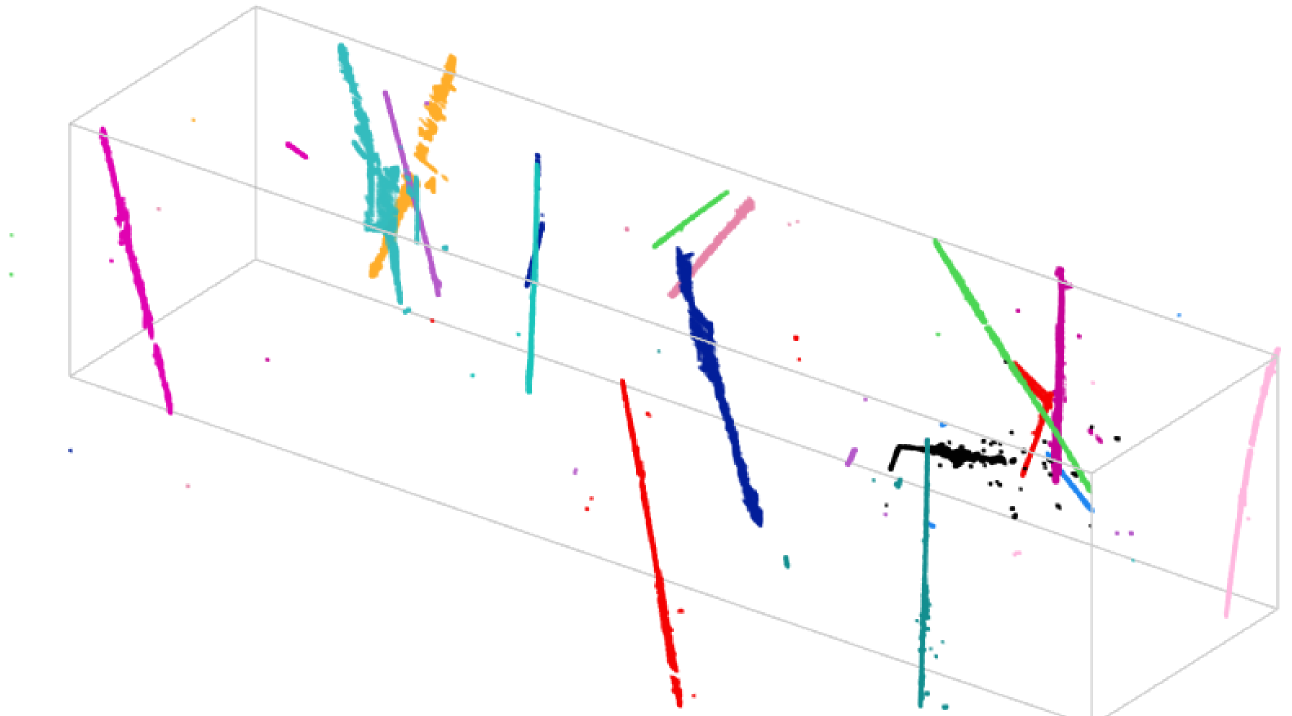
Performance in Wire-Cell





- Typically, ~tens of seconds to reconstruct the whole 3D image (originally a few hours)

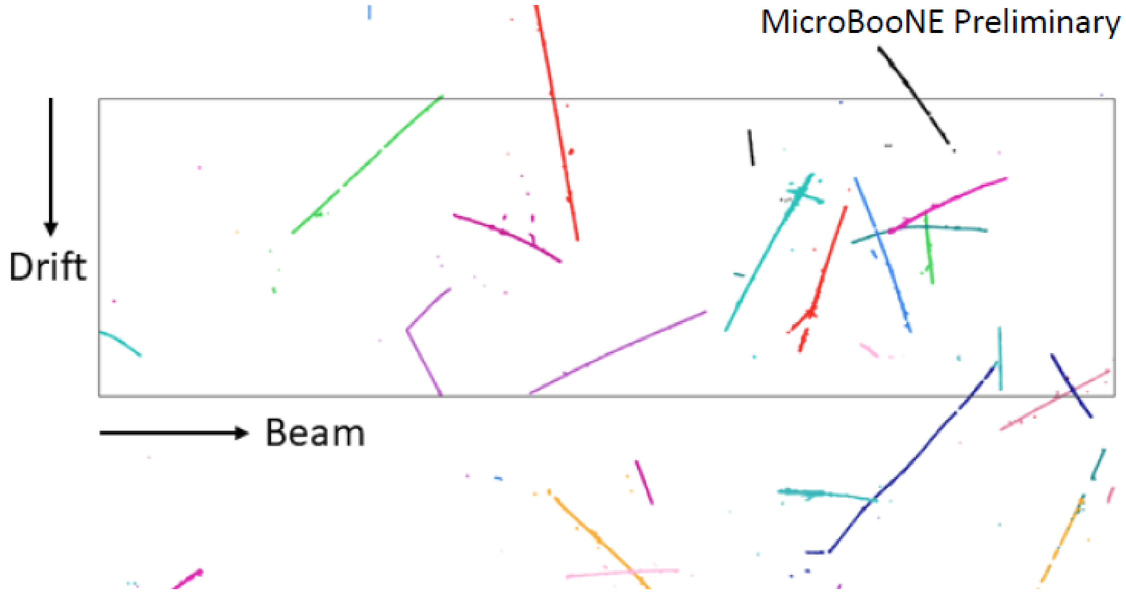
JINST 13, P05032 (2018)

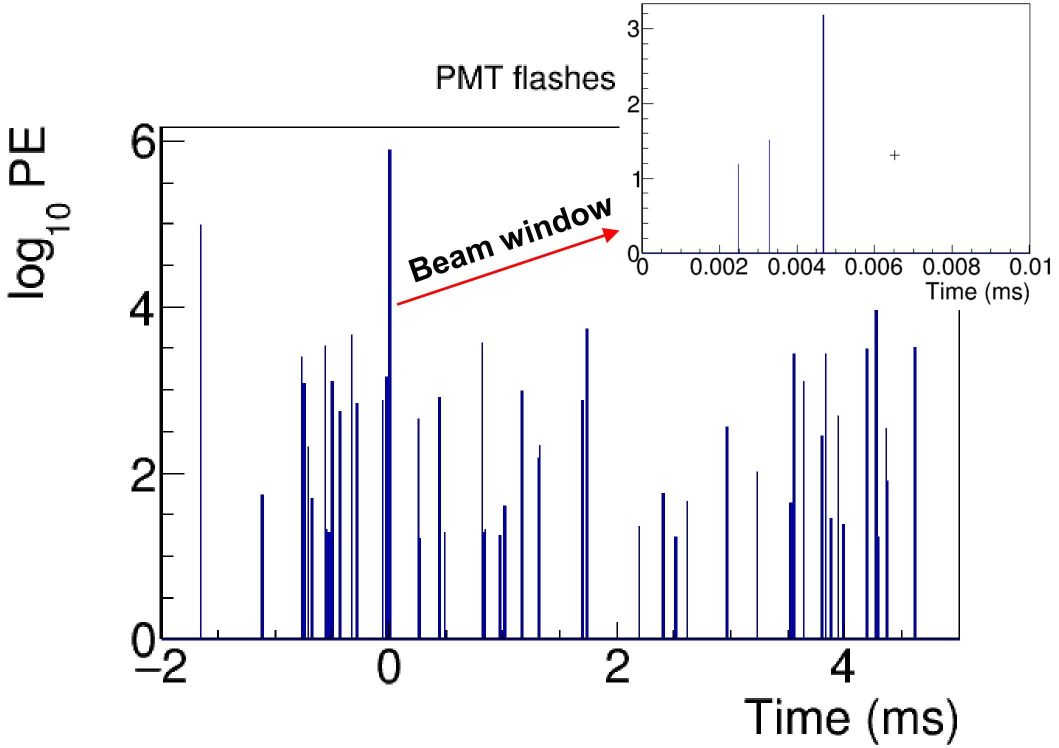


An example MicroBooNE event after 3D reconstruction

Finding Neutrino Interaction

4.8 ms drift window



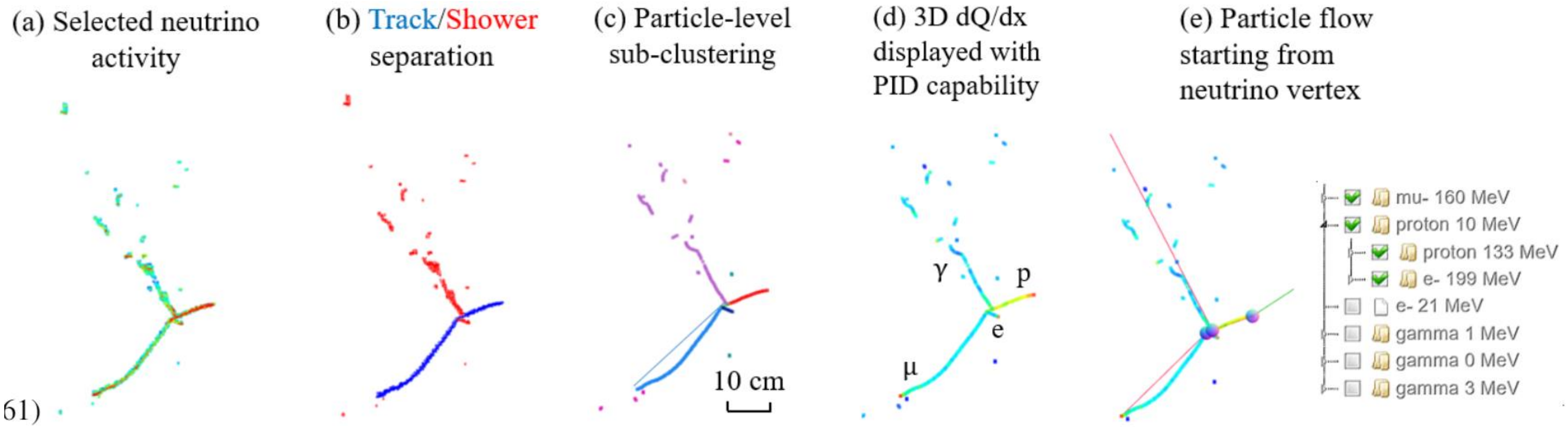


20-30 TPC activities

40-50 PMT activities

- ❑ 3D Cluster based on proximity (kd-tree)
- ❑ associate the light flash to the corresponding TPC cluster based on light pattern

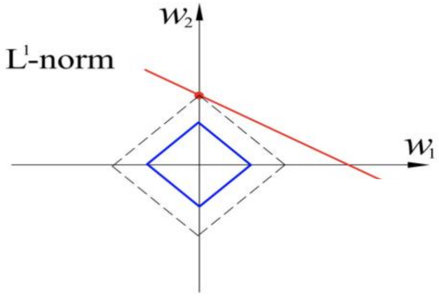
3D Pattern Recognition

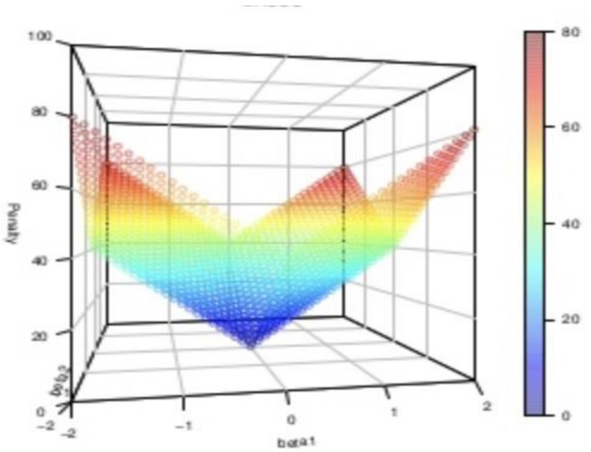


- ❑ Categorize neutrino interaction type
- ❑ Reconstruct neutrino energy

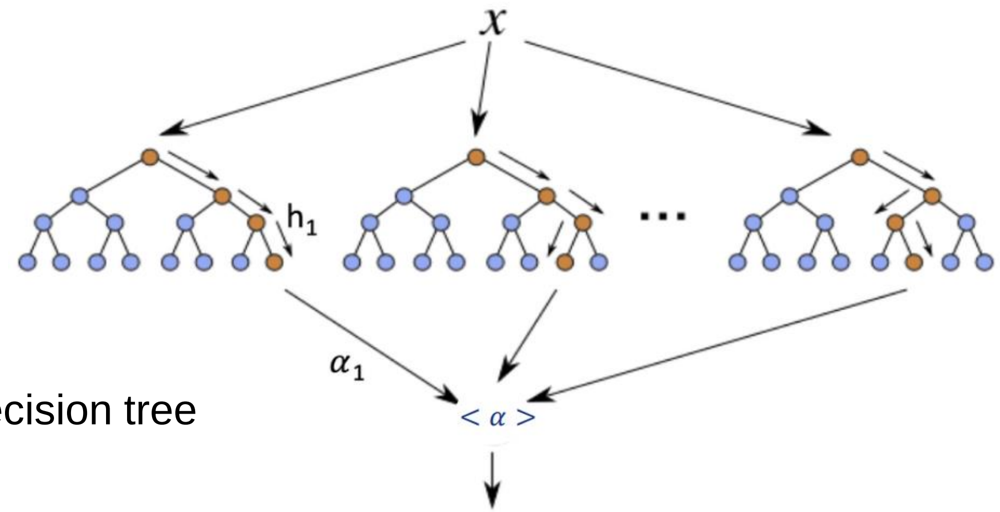
Math and Machine Learning in LArTPC analysis

Various mathematical and machining learning techniques to further improve the reconstruction and event selection

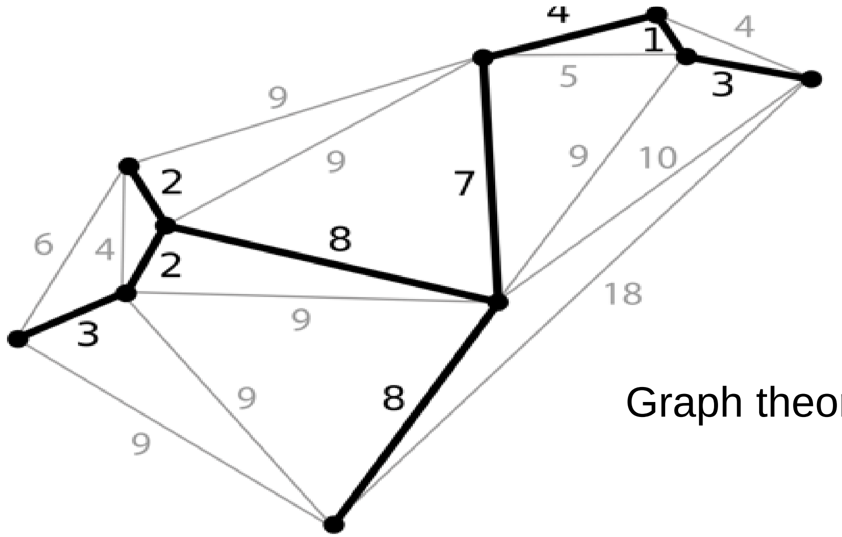




L1 regularization
(Lasso regression)



Boost decision tree



Graph theory

Deep-learning
neural network