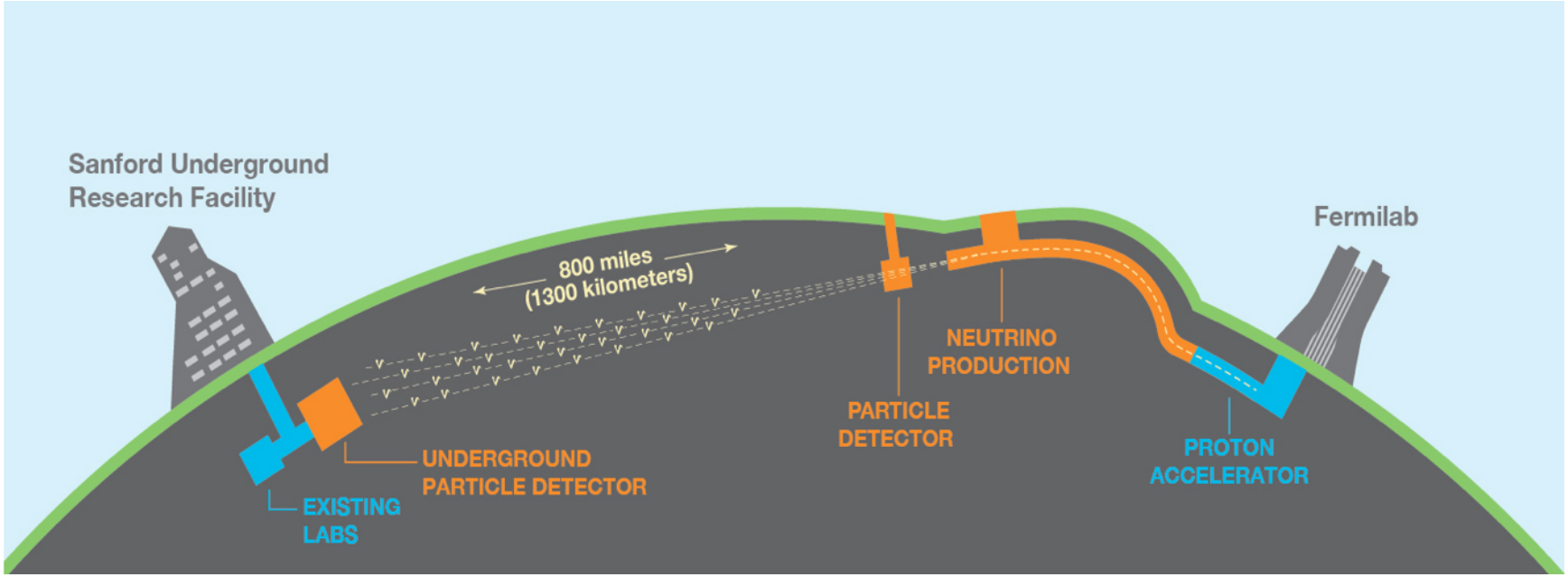
# Recent progress on wire-cell tomographic reconstruction for LArTPC

Hanyu WEI for the DUNE Collaboration
Brookhaven National Lab

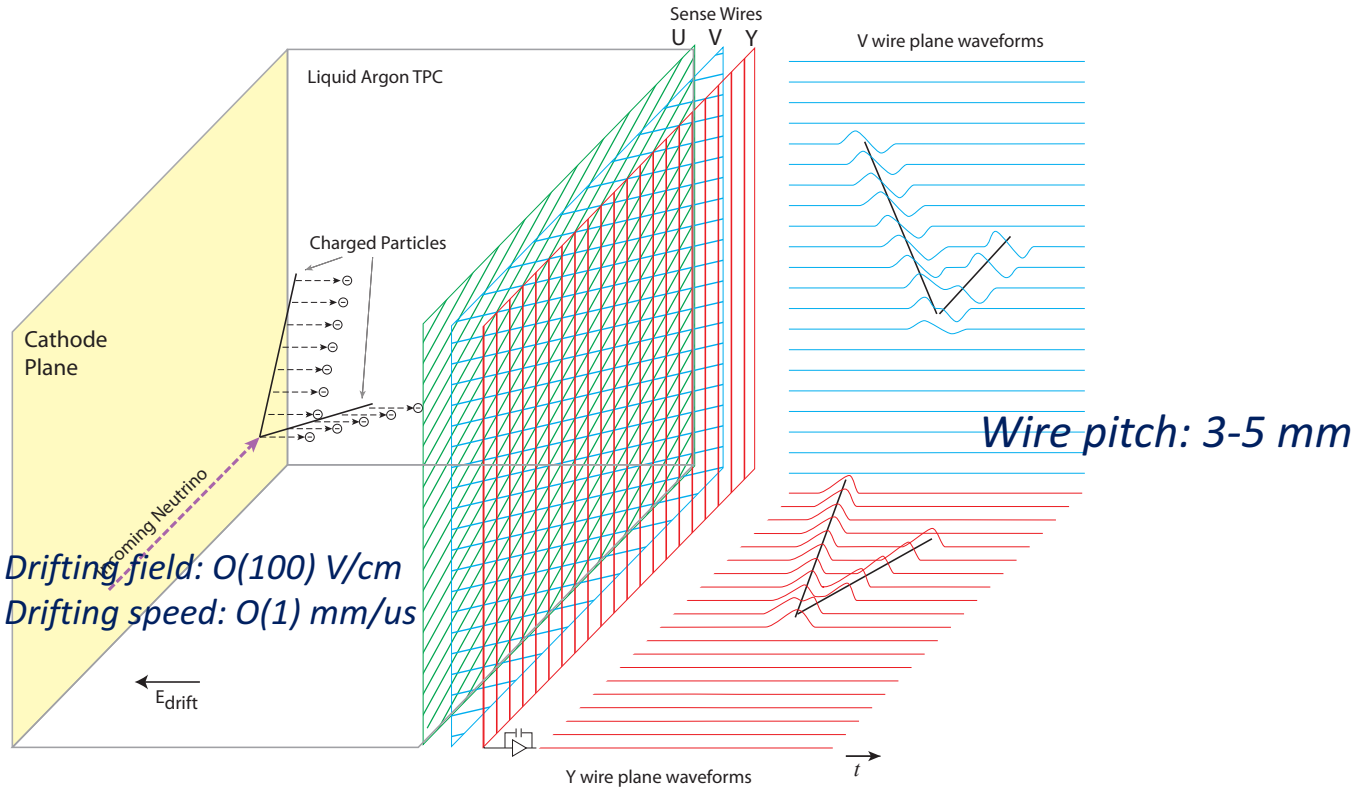
July 31, 2017

# Deep Underground Neutrino Experiment (DUNE)




- Aiming for groundbreaking discoveries that can help unravel the mysteries of the origin and evolution of the matter by studying the neutrino oscillations and other phenomena.
- 1300 kilometers downstream, large far detector using LArTPC

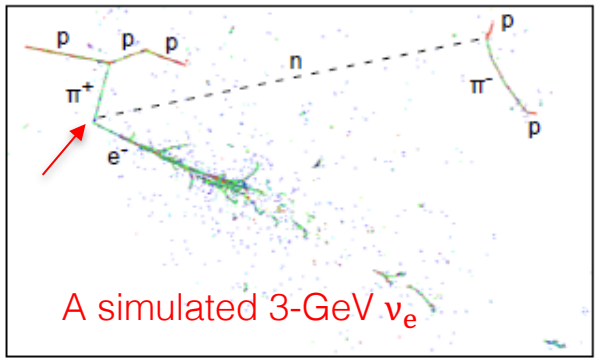
# Liquid Argon Time Projection Chamber



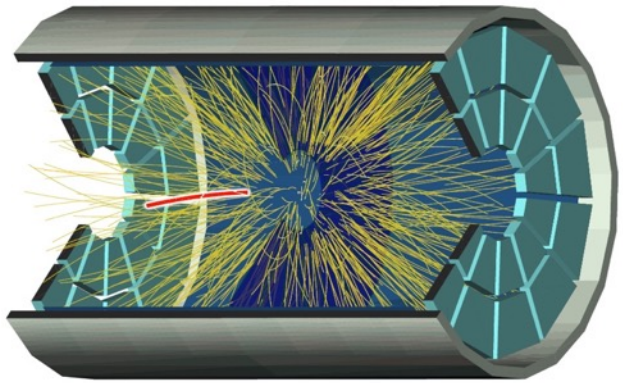

- ✓ Ionized electrons in LAr drift to sense wires [*drifting distance*]
- ✓ Three wire planes: two induction planes, one collection planes, different angles, *mm* wire pitch [*3* × 1D *projection/view*]
- ✓ Photon sensor to record scintillation light [*start time*]

# Event Reconstruction in LArTPC

- 3D reconstruction with excellent spatial resolution
- Challenges:
  - Tracks, showers, unknown vertex in LArTPC




v.s.



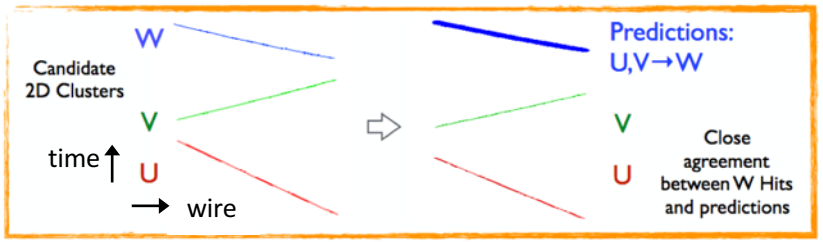
  - Wire readout (intrinsic ambiguity)
    - Cold electronics power consumption in LAr and cost
    - Lose information of where the charge along the wire (pixel $n^2 \rightarrow 3 \cdot n$ wire) , a *pseudo-2D position* + 1D time

# Review of existing approaches

Signal Processing
(charge extraction)

2D pattern recognition
(Time + Wire) for each plane

Matching 2D patterns into 3D
Time, geometry, charge, etc.

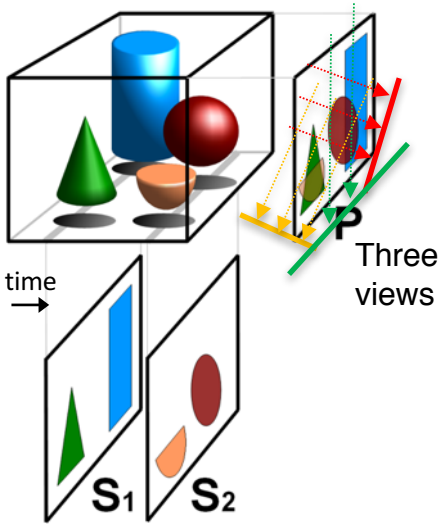



LineCluster, Pandora, PMA, DL, etc.

Tomography
(wire at a given time slice) ×
3 views/planes

2D imaging
Geometry, charge, connectivity, etc.

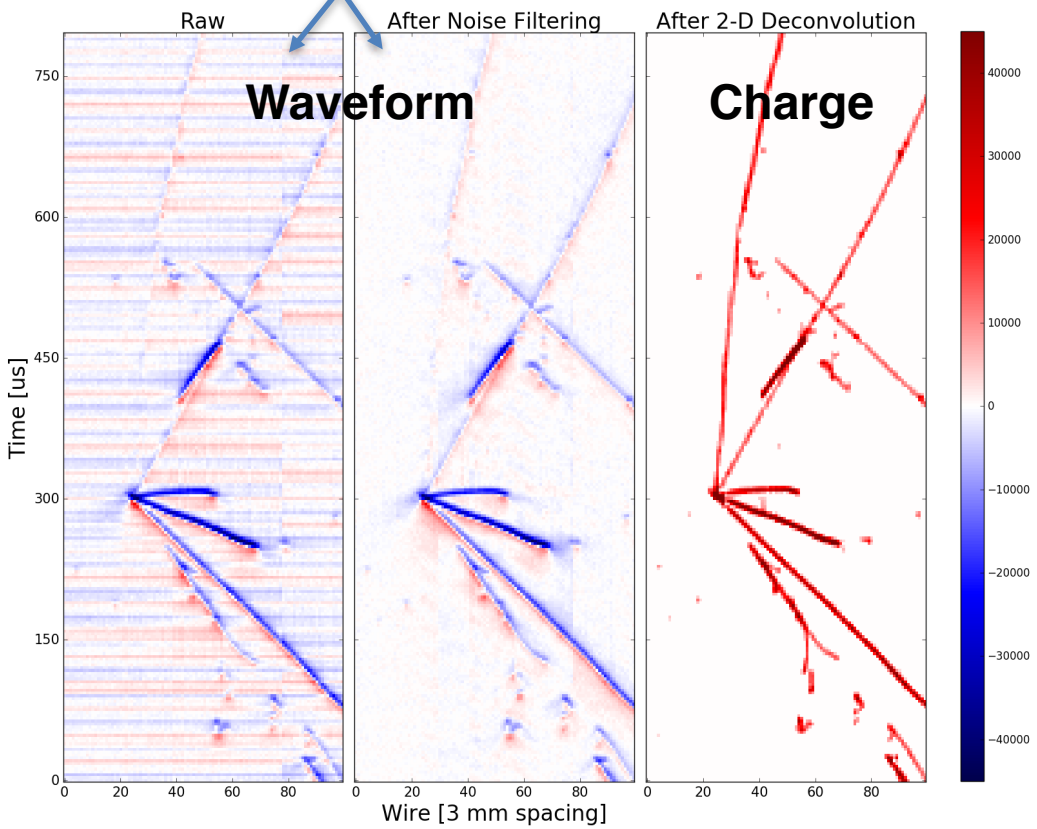
3D imaging
Time
+
3D pattern
recognition



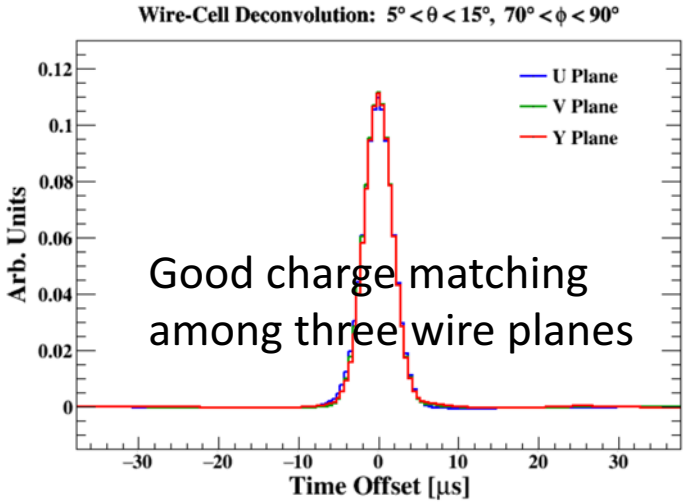

Each approach uses
the same information in different order/way.

# Wire-cell Signal Processing

*"Noise Characterization and Filtering in the MicroBooNE TPC", MicroBooNE collaboration, accepted by JINST, on arXiv: 1705.07341*




*U plane, MicroBooNE event 41075, Run 3493*

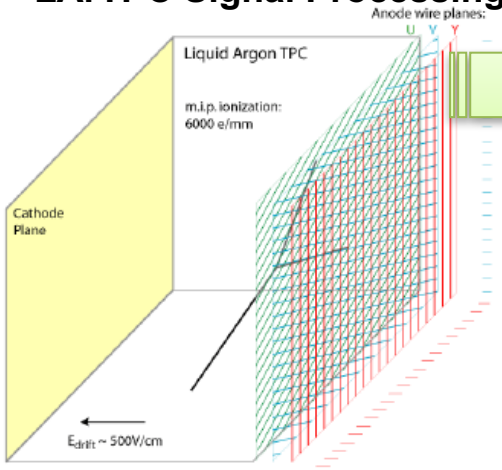



***See B. Kirby's talk, J. Joshi and B. Russell's posters***

- Extract ionized charge from LArTPC (noise removal, 2D decon, ROI, etc)
- Basic for wire-cell event reconstruction

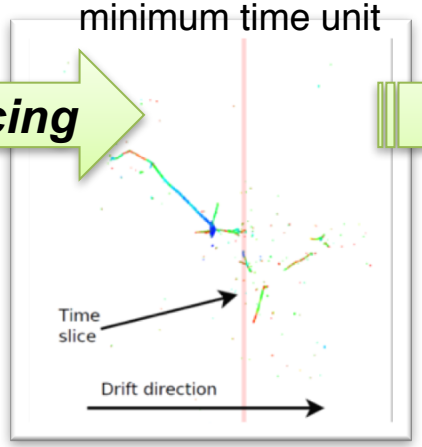
# Wire-cell Tomographic reconstruction

**LArTPC Signal Processing**



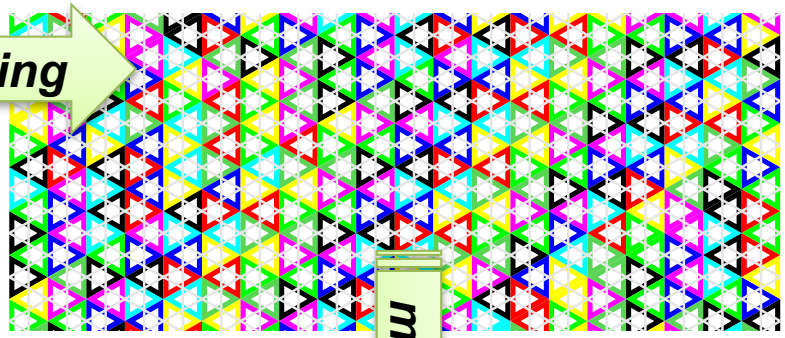

***slicing***

minimum time unit

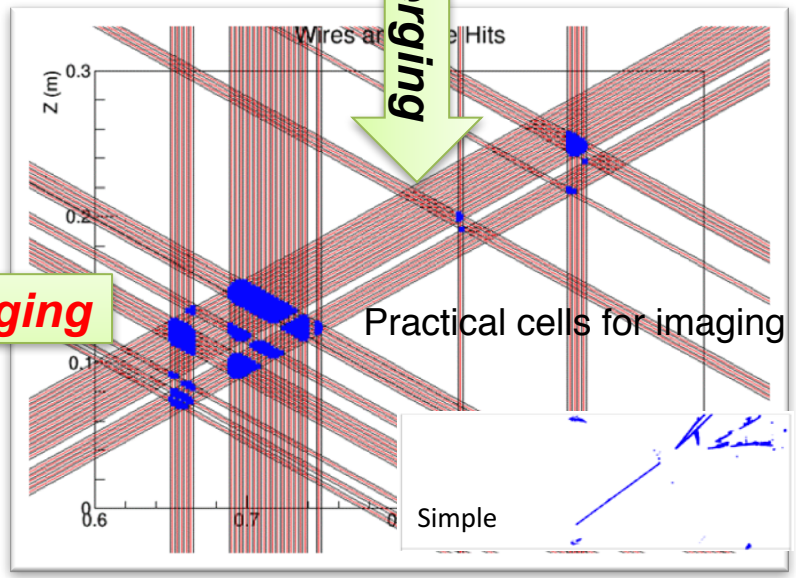



***tiling***

Create cells from wires

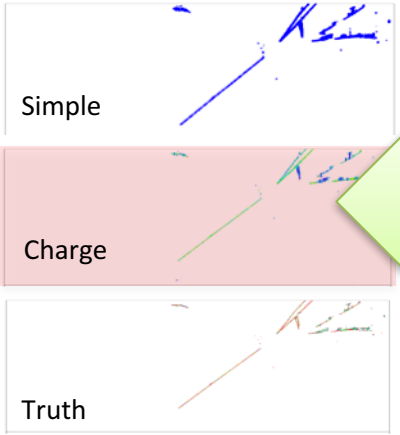


***merging***

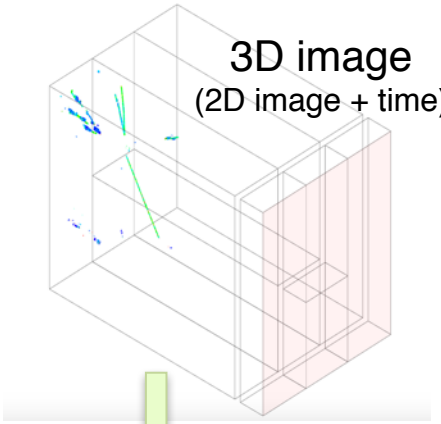



Practical cells for imaging

***Imaging***




2D image



3D image
(2D image + time)

***3D pattern recognition***

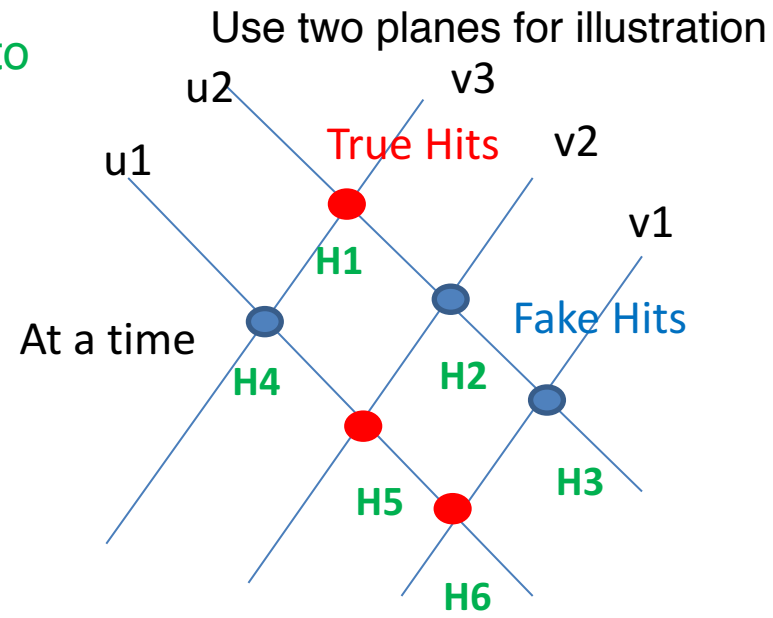
# Construct linear equation for imaging

Measured charges on wires

True charge hits to be solved

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

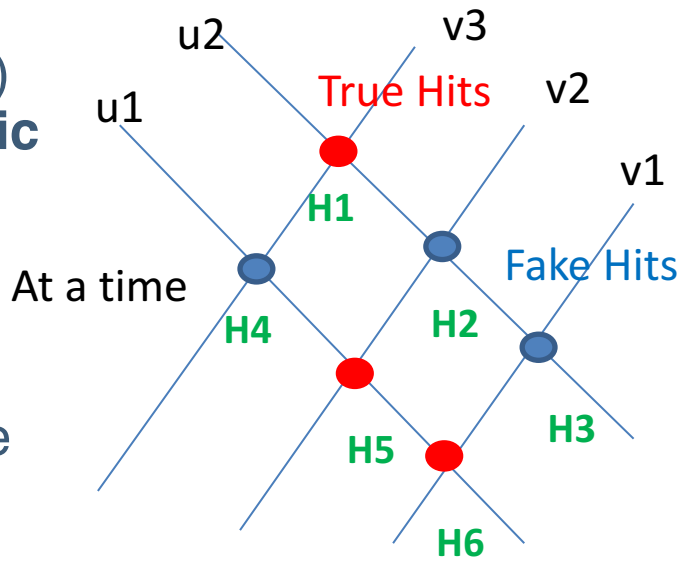
Matrix determined by geometry




- **Same charge in a voxel measured 3 times by wires on three planes**
- In practice, minimizing $\chi^2 = \left(B \cdot \vec{W} - G \cdot \vec{C}\right)^T V^{-1} \left(B \cdot \vec{W} - G \cdot \vec{C}\right)$
  - *W*: recon charge in single wire [**signal processing**], *B*: geometry matrix connecting single wire to merged wires [**merging**]
  - *C*: charge in merged cells [**to be solved**], *G*: geometry matrix connecting merged cells to merged wires [**tilling**]
- Easy to extend to wrapped wire case

# Solving for imaging (1)

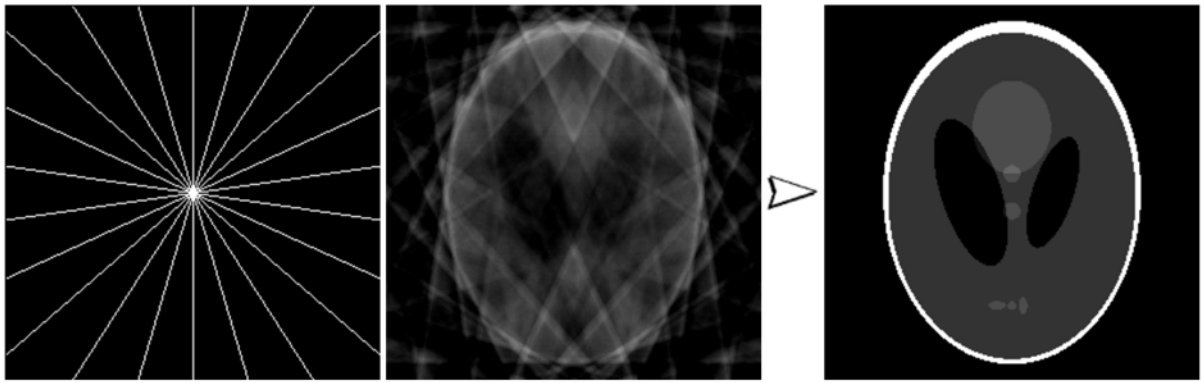
- Underdetermined linear equation
  - More unknowns (charge hits to be solved) than knowns (measured in wires) [**intrinsic ambiguity of wire readout**]
- Solutions can be found assuming/regarding **sparse** signal
  - LArTPC signal is typically sparse in space
  - Most of the charge hits are fake
  - Remove unknowns until solutions can be achieved and pick up the best one
- Issues
  - **Combinatorial** removal of unknowns, unrealistic number, NP-hard for computing




1) *5 knowns, 6 unknowns*
2) *Assuming one fake hit*
3) *6 ways to remove one unknown*
4) *Pick up the best one, e.g.* $\chi^2$

# Solving for imaging (2.0)

- Compressed sensing
  - a signal processing technique for efficiently reconstructing ***sparse*** signal, by finding solutions to ***underdetermined linear systems***
  - E.g. tomography with sparse projections http://www.cs.tut.fi/~comsens/



available portion of the spectrum (11 radial lines) | Back-projection estimate | Estimate after convergence (exact reconstruction)

- Important definition
  - L*p*-norm of a vector $\boldsymbol{x}$: $\|x\|_p = (\Sigma|x|^p)^{1/p}$
  - L0-norm is the number of non-zero elements of vector $\boldsymbol{x}$
  - L1-norm is the sum of absolute value of elements of vector $\boldsymbol{x}$

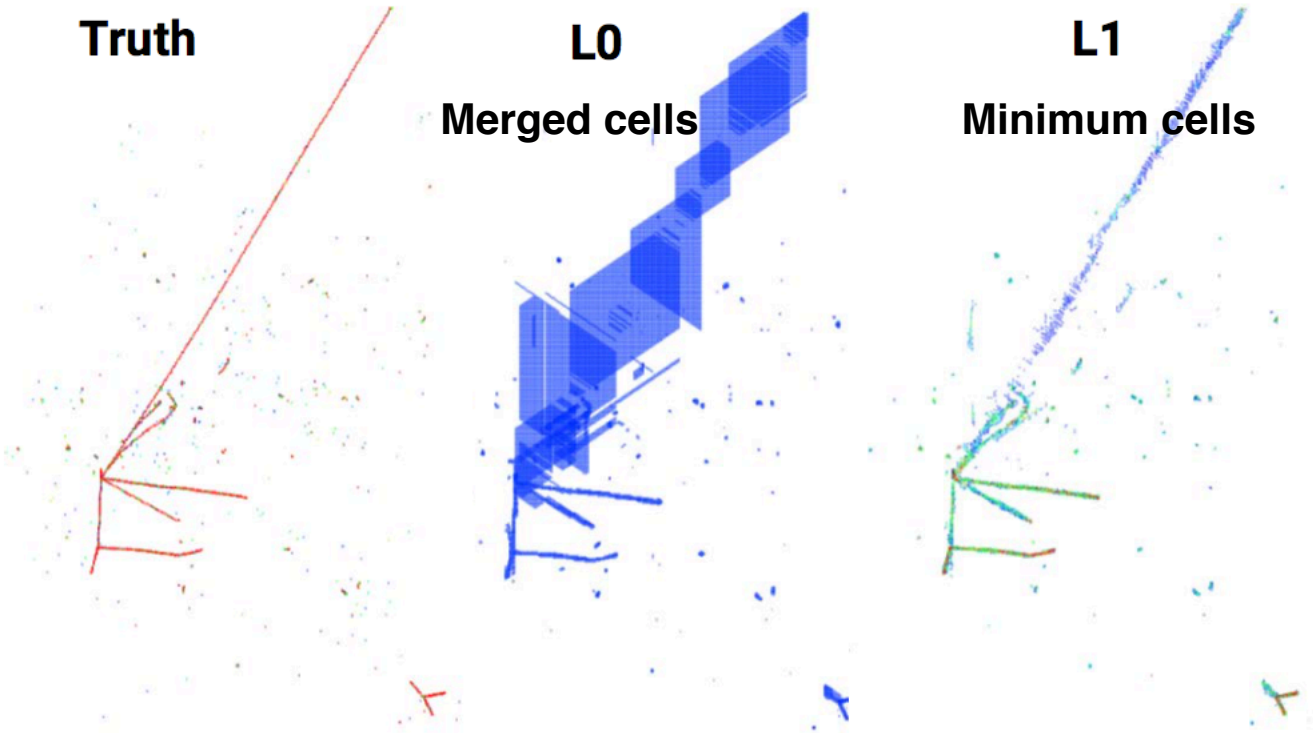
# Solving for imaging (2.1)

- L0-regularization problem
  - Minimize L0-norm of vector $x$ [***sparse***], subject to $y = Ax$ [***underdetermined***]
  - Equivalent to minimize $\chi^2 = (y - Ax)^2 + \lambda \|x\|_0$
  - Solving linear equation of ***wire-cell imaging*** is a L0-regularization problem.
- L1-regularization problem
  - Minimize $\chi^2 = (y - Ax)^2 + \lambda \|x\|_1$
  - **Well approximate (in most cases exactly recover) L0-regularization problem [apply to wire-cell imaging]**
  - **Irrelevant variables to exactly ZERO [sparse]**
  - **Convex, local minimum = global minimum [fast algorithms]**
  - Regularization parameter $\lambda$ needs tuning according to data/MC, but has a non-sensitive region yielding similar/optimal results

*Candes, Romberg, and Tao, "Stable Signal Recovery from Incomplete and Inaccurate Measurements" [arXiv:math/0503006]*

A fast way to find the unique sparse solution using the so-called ***L1-regularized minimization***

# Solving for imaging (2.2)




Test of principle in wire-cell

http://www.phy.bnl.gov/wire-cell/bee/set/d6323cd5-80e1-4721-9671-9c7c95c29e36/event/0/

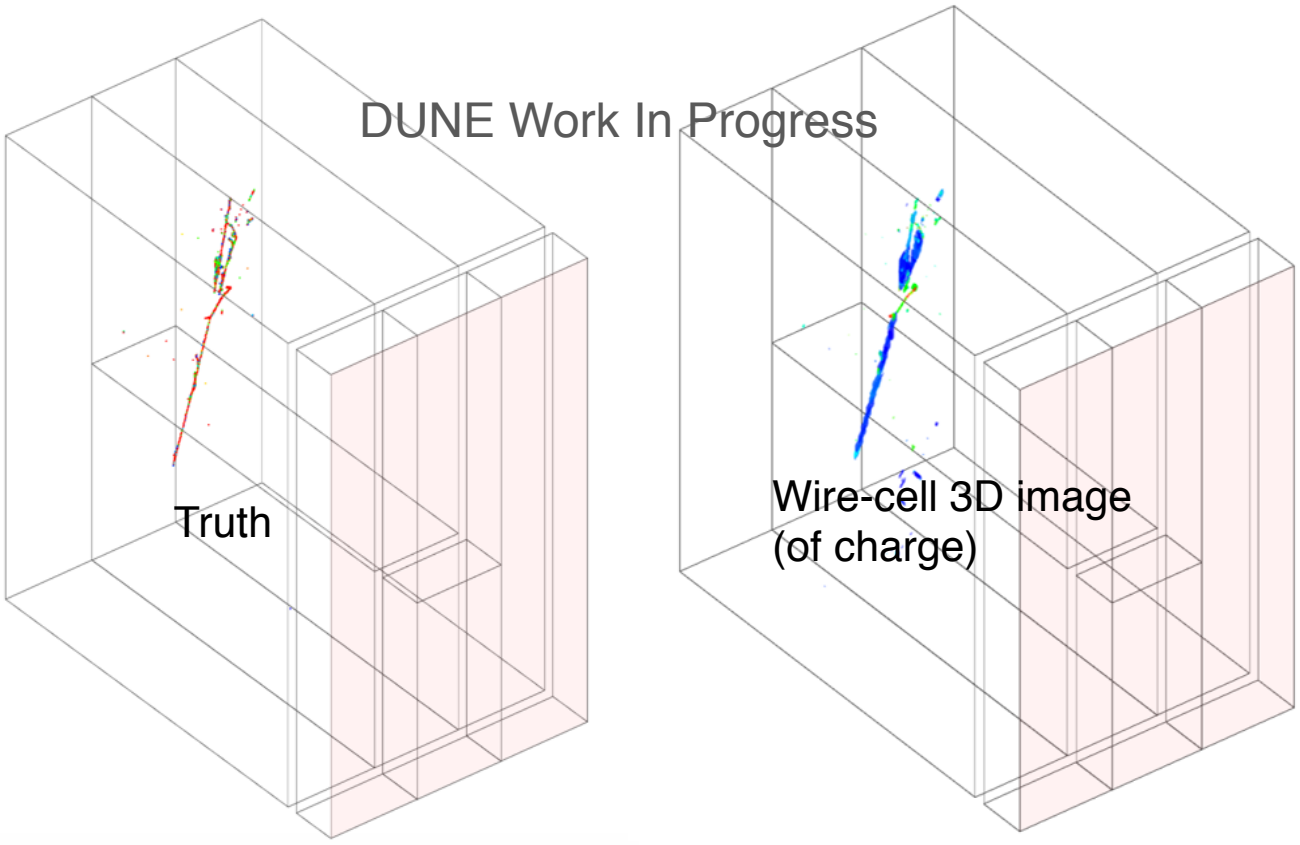
- ***Half a minute*** (***v.s. a few hours***) to reconstruct the whole 3D image
- Matrix can be as large as 10K × 1K (e.g., without merging)
- Space/time unit (precision) can be improved

# Solving for imaging (3)

- Simple math description (basic $\chi^2$) considering ***time, geometry, charge,*** plus regularized term (***sparsity***) and additional penalty terms for other purposes, e.g. ***systematics***, ***positivity***
- A 'best' solution using the information we have and absolutely lose information to recover the 'true'
- Use L0-regularization at present
- L1-regularization to solve the imaging problem
  - Breakthrough for wire-cell imaging
  - Implementation of L1-regularization in wire-cell near completion

# Example of wire-cell 3D images

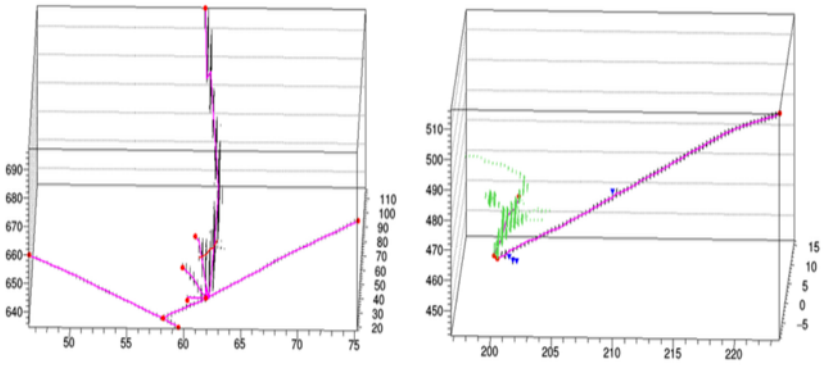
Simulation
DUNE 35t
2GeV $\pi^-$
wrapped wires




*http://www.phy.bnl.gov/wire-cell/bee/*
*Bee: interactive web-based 3D display (Chao Zhang, Brett Viren, etc.)*

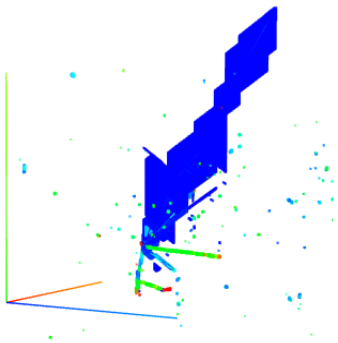
# Wire-cell pattern recognition

- Very preliminary pattern recognition
  - Clustering based on 3D images of charge cells
  - Track and vertex identification
  - Shower identification (not finished)

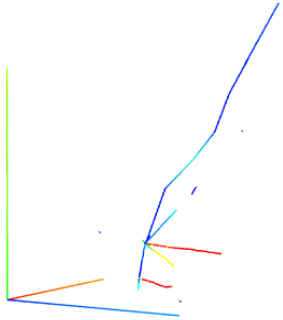


Red vertices, magenta tracks, green showers, blue short tracks

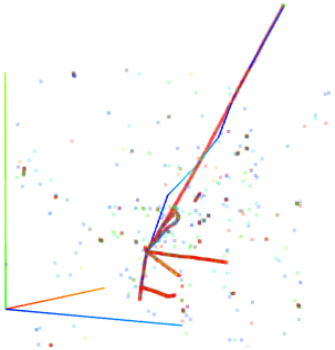
Reconstructed Image



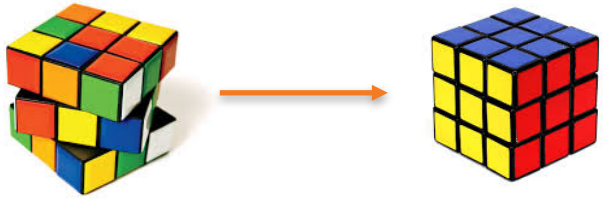
3D Pattern Recognition



Monte-Carlo Truth



- ✓ *Operations are all "local" i.e. Hough transformation, Crawler, Vertex fitting/merging …*
- ✓ *Many topologies/corner cases*



# Summary

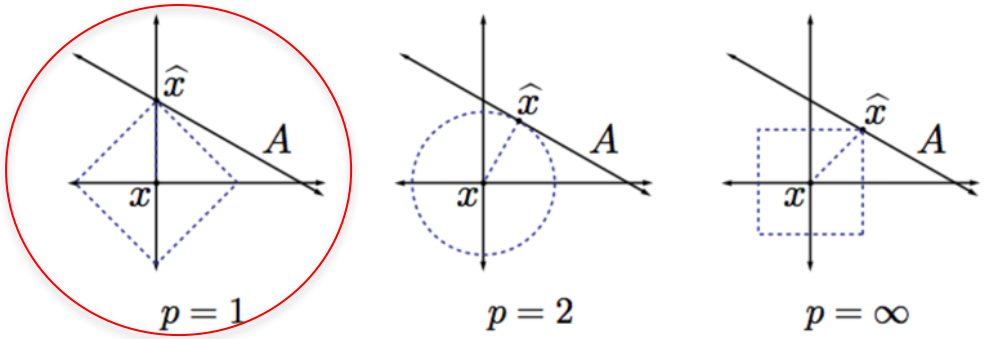
- Wire-cell ***tomographic*** event reconstruction for LArTPC is in good shape
  - Charge matching among wire planes demonstrated in uBooNE
  - Breakthrough of 3D imaging using L1-regularization
  - Use all the robust information (time, geometry, charge, sparsity, positivity, etc.) to do the imaging and evaluated by a single number $\chi^2$, a major step towards the automated reconstruction
  - Pattern recognition separated with 3D imaging, under rapid development
- Related tools/techniques
  - Bee: interactive web-based 3D event display http://www.phy.bnl.gov/wire-cell/bee/, in progress to implement "human-directed" event reconstruction associated with wire-cell 3D pattern recognition
  - Wire-cell toolkit https://github.com/WireCell/ (also include full TPC simulation, signal processing, etc.)

# Backup

# Illustration of L1-regularization

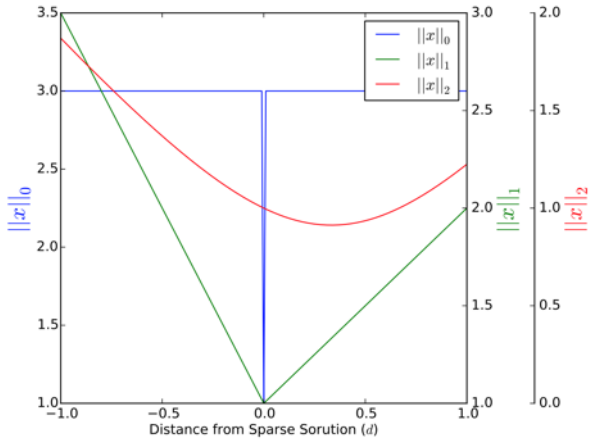
*http://statweb.stanford.edu/~markad/publications/ddek-chapter1-2011.pdf*

- ✓ **Approximate L0**
- ✓ **Sparse**




Best approximation of a point in $\mathbb{R}^2$ by a one-dimensional subspace using $l_p$ norms

- ✓ **Approximate L0**
- ✓ **Convex (fast algorithm)**




*http://stemblab.github.io/intuitive-cs/*

Norm evaluated along solution
Green: L1-norm