Wire Cell Reconstruction Method and Software Library
for Liquid Argon Time Projection Chambers

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BROOKHAVEN
NATIONAL LABORATORY

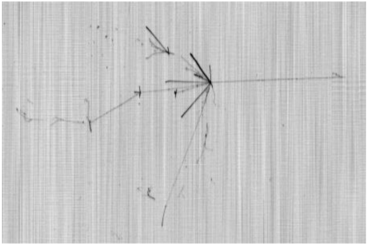
Connecting The Dots 2016

Outline

LArTPC Experiments - ICARUS

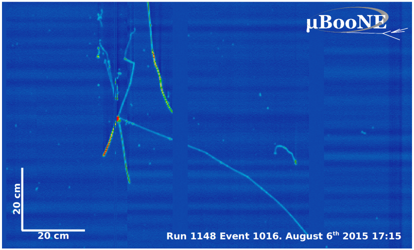
The origin of LArTPC technology for Neutrinos: C. Rubbia, 1977 led to **ICARUS, the first, large-scale LArTPC**.

- $2\times$ 300 t modules.
- Took data in the Gran Sasso tunnel, Italy from CERN neutrino beam.
- Moving to Fermilab as part of the **Short-Baseline Neutrino** Program.



LArTPC Experiments - MicroBooNE

Recently started taking ν-data at Fermilab!

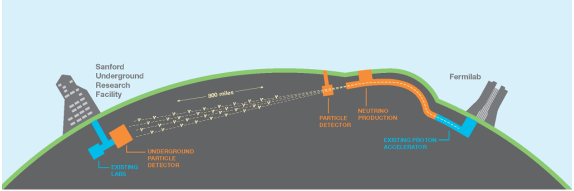


- 85 ton fiducial mass.
- 8256 channels
- 3 mm wire pitch.
- Investigate:
  - low energy excess puzzle
  - sterile-ν search
  - ν-Ar cross sections

MicroBooNE is the initial test bed for Wire Cell reconstruction.

LArTPC Experiments - DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

"International **mega-science** project"



Three stages of DUNE LArTPC detectors:

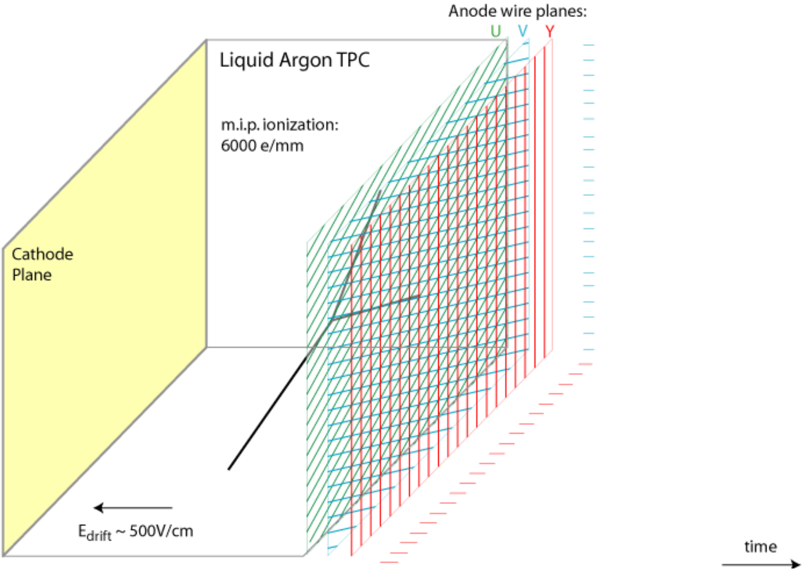
1. "**35ton**" prototype (at FNAL), just started operating, cosmic-μ exposure.
2. Full-scale "**protoDUNE**" (at CERN) 2017/2018 with π, K, p beam tests.
3. Full "**DUNE**" far detector underground in South Dakota ~2025.
    - At least **10 kt** of single-phase LAr, 3-plane, wire readout: 5 mm wire pitch, **375K channels**.
    - Total of **40 kt fiducial mass** in **4 separate cryostats**, different technologies possible for each module.

LArTPC with Wire Readout - Basics Principles

- Charged particles produce tracks of ionized LAr
- Electrons drift in an applied electric field
  - Eg: E = 500 V/cm, $v_{\text{drift}} = 1.6\,\text{mm}/\mu\text{s}$
- Charge drifts past 3 parallel wire planes (3-5 mm pitch)
  - 2 induction planes with bipolar signals.
  - 1 collection plane with monopolar signals.
- Digitize wire signal waveforms (2 MHz, 12 bits)
- Deconvolve detector response and apply noise filter.
- Optical system gives prompt T_0 from scintillation light.

→ Gives **three independent measures** of each element of drifting charge as **three, 2D views** (in **wire vs time**) which **multiplex the two transverse dimensions**.

(animation by Bo Yu →)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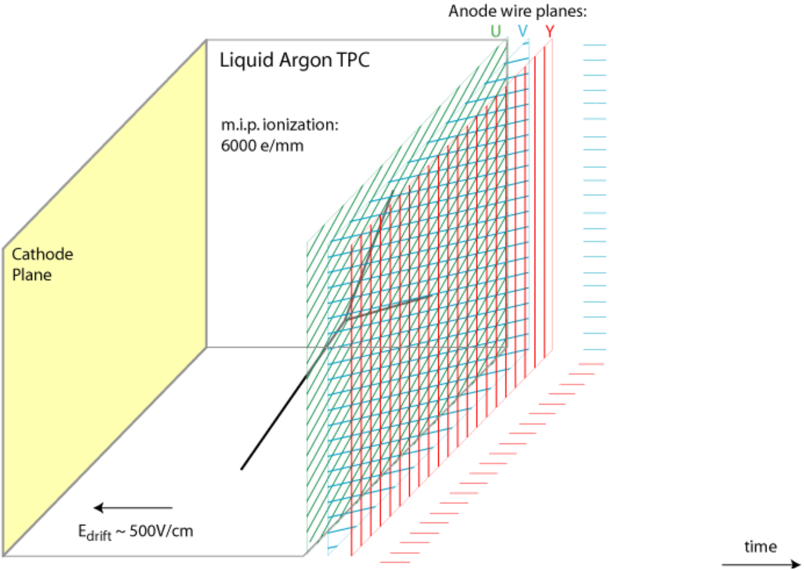
U V Y
Liquid Argon TPC
m.i.p. ionization:
6000 e/mm
Cathode
Plane
E drift ~ 500V/cm
time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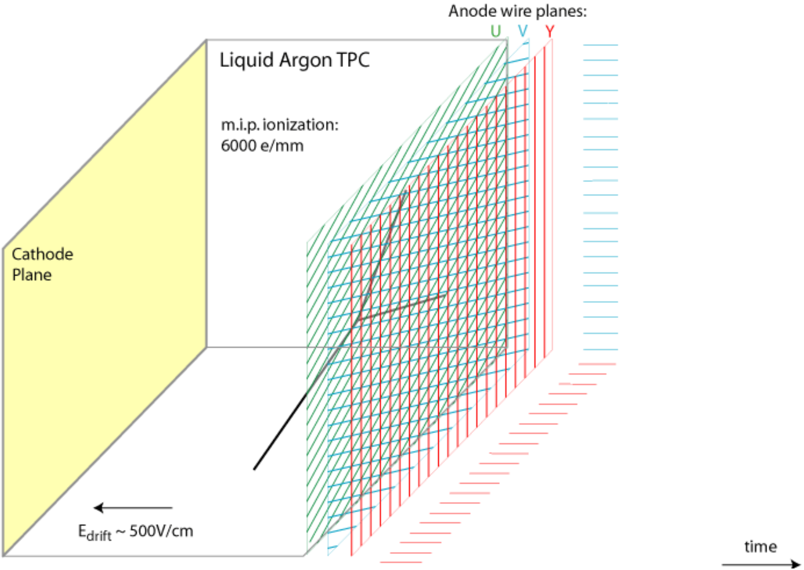
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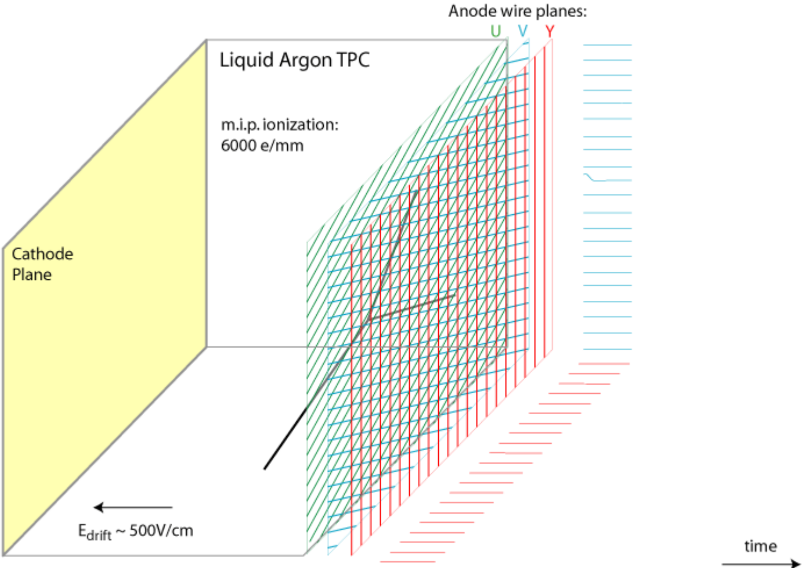
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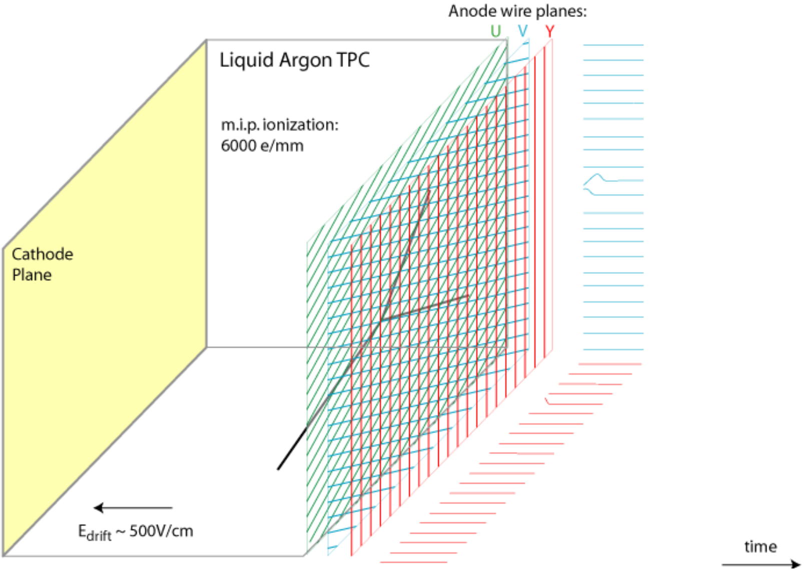
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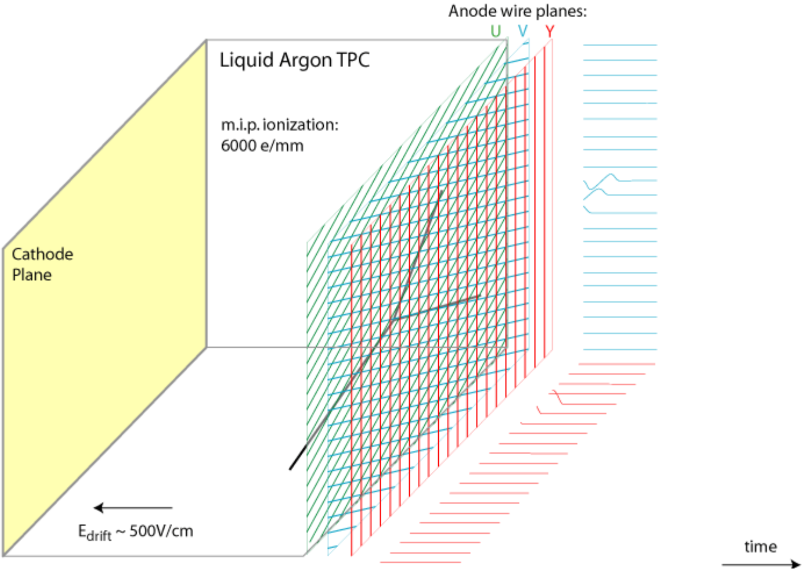
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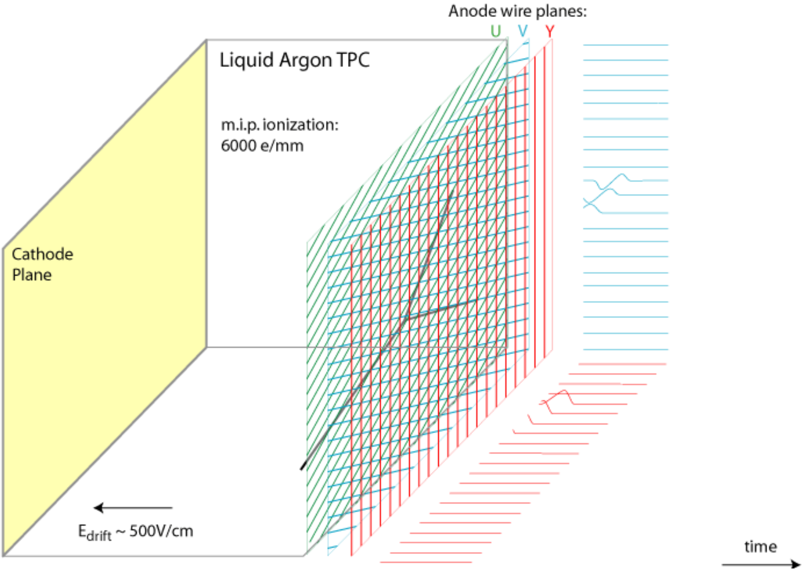
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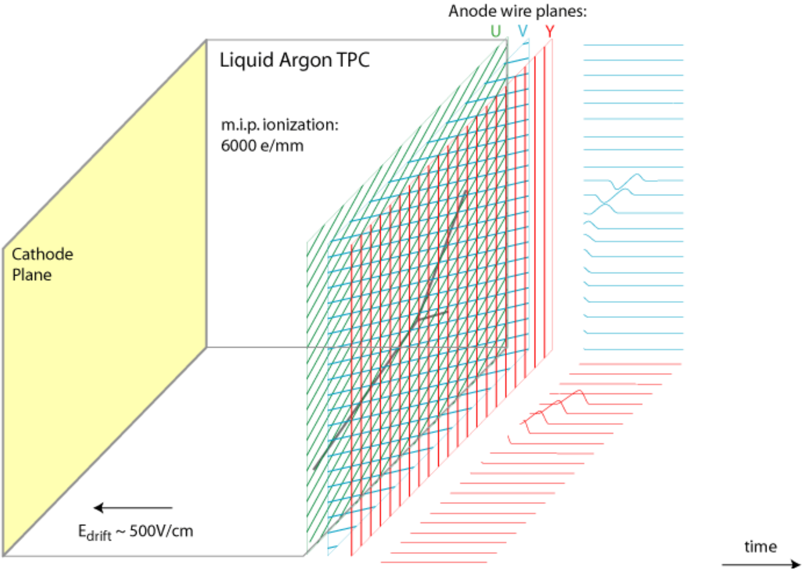
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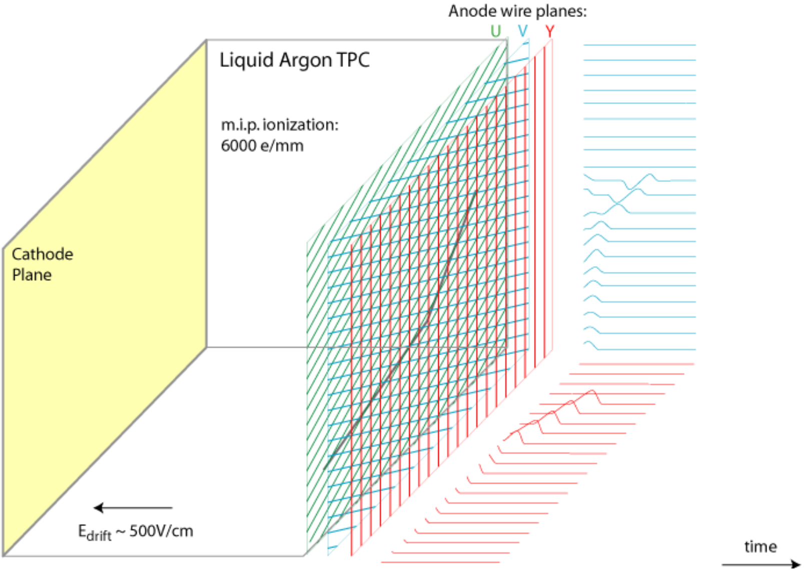
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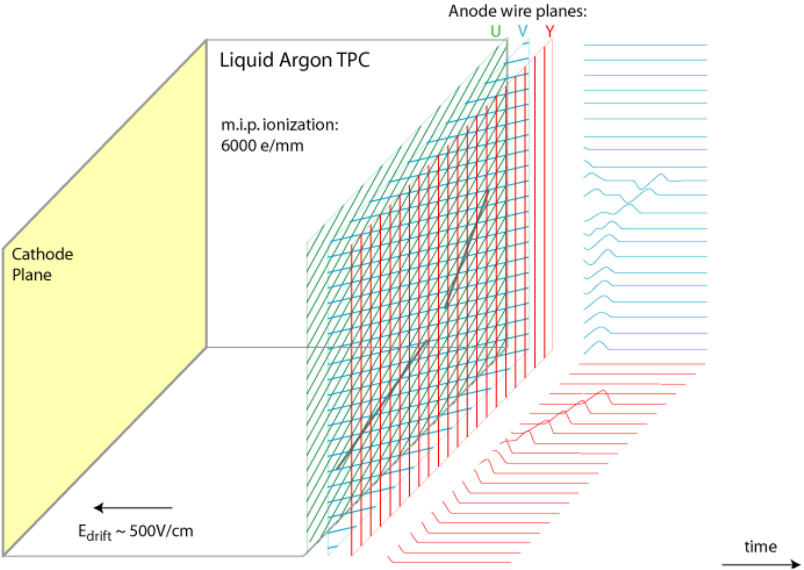
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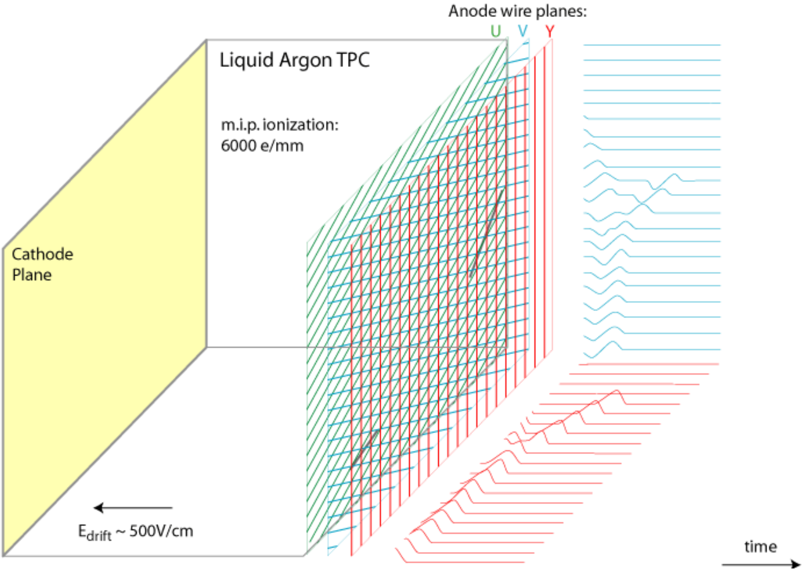
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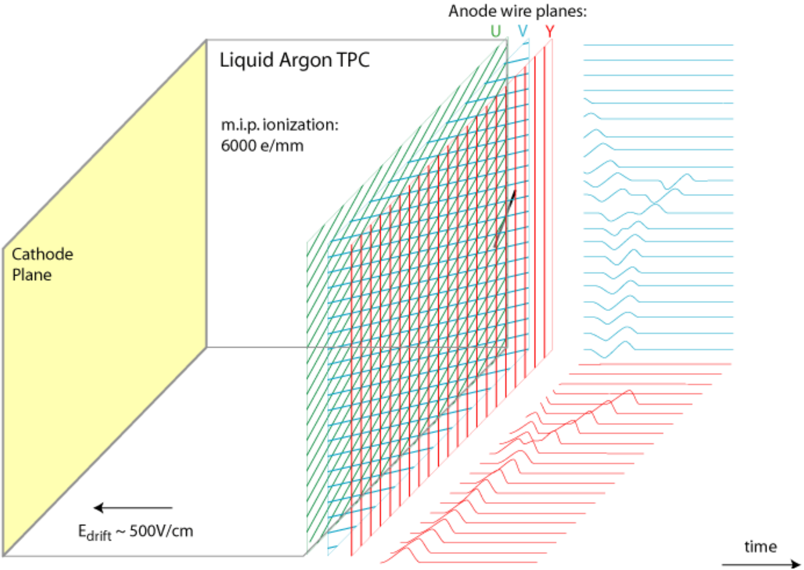

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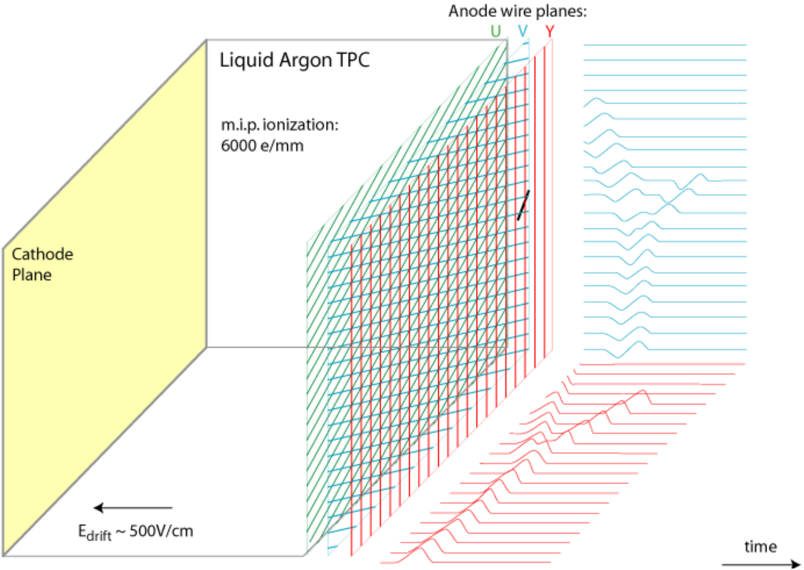
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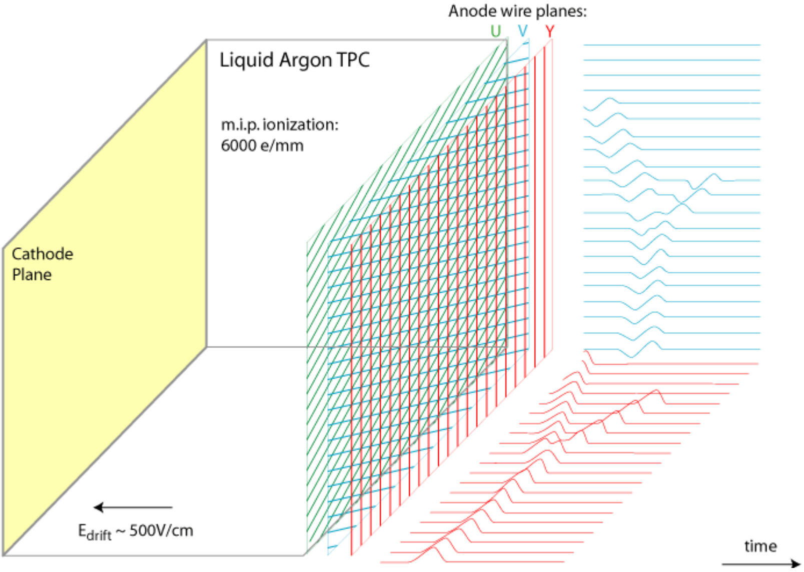
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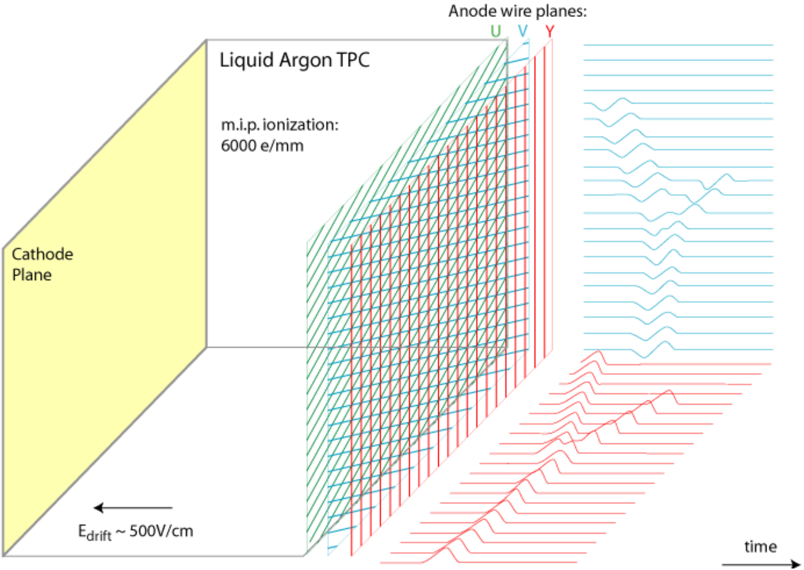

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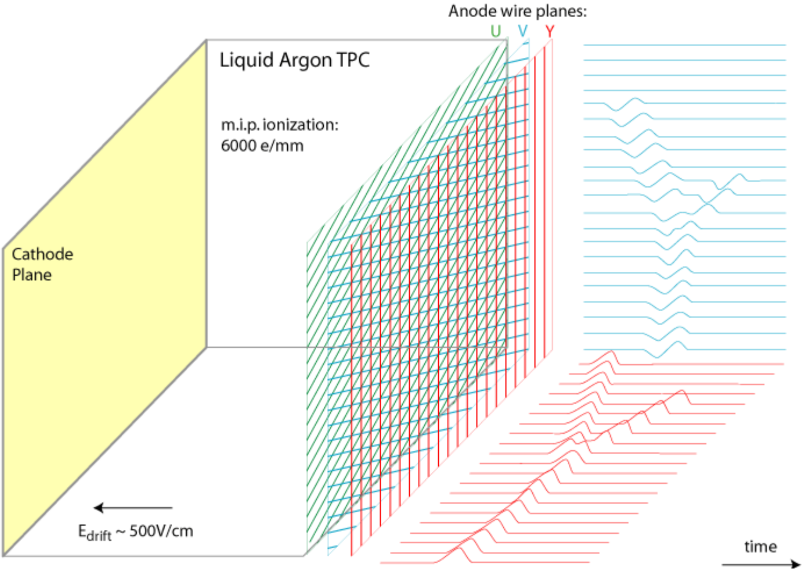
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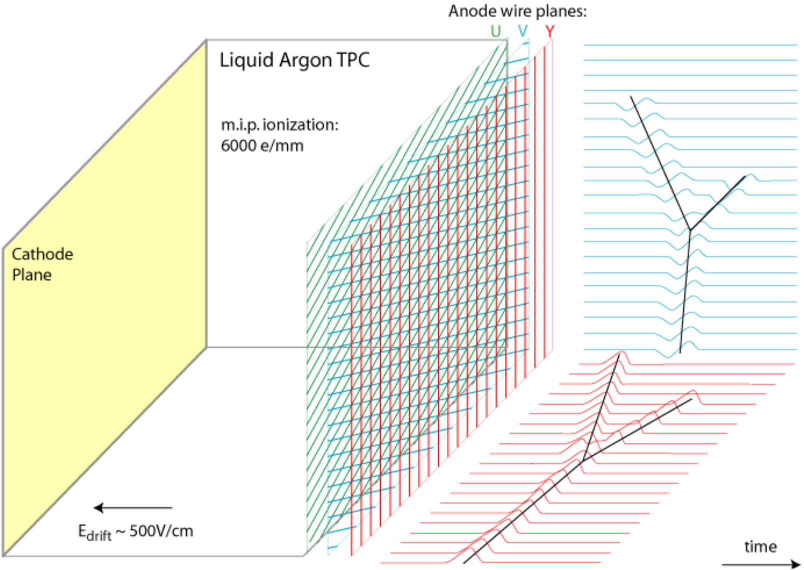
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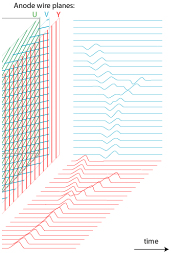
LArTPC Data

LArTPC can produce **huge quantities** of **high-resolution** data from **large detector volumes**:

- 10^4 – 10^6 channels
- 2MHz @ 12 bit waveform digitization
- each "event" spans several milliseconds



Two general DAQ readout strategies:

Full Stream: read out entire waveform (**MicroBooNE**)

- **30GB/s in 120 MB "events"**.
- DUNE at FS would produce 5 TB/s in 25 GB "events"!

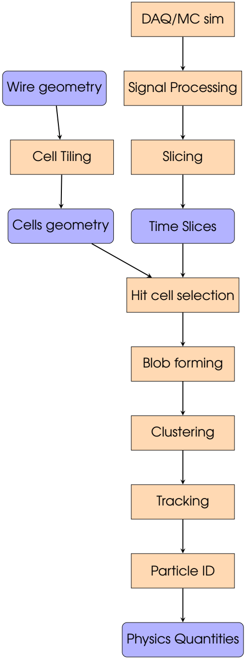
Zero Supression: only save waveform parts with significant activity (**DUNE**)

- Threshold chosen based on noise (E_{thesh} ~0.1 MeV/wire)
- 2.5 MB/event → **100's TB/year**
- requires rejection of natural ^{39}Ar decay @ **50 PB/year**

Wire Cell Reconstruction Method

Four main parts:

1. Data Preparation
   - Deconvolve **detector response and filter noise**.
   - Construct **wire** geometry and associated **cells**.
   - Form **time slices** across all wire signal waveforms.
2. Imaging of Activity
   - The heart of the Wire Cell technique.
   - Identify regions ("**cells**") in each time slice that likely contain the drifted charge.
3. Pattern Recognition
   - **Cluster** imaged activity in space and time slices.
   - **Categorize** patterns as track, shower, etc.
4. Physics Quantities
   - Determine particle ID and kinematics of tracks/showers.



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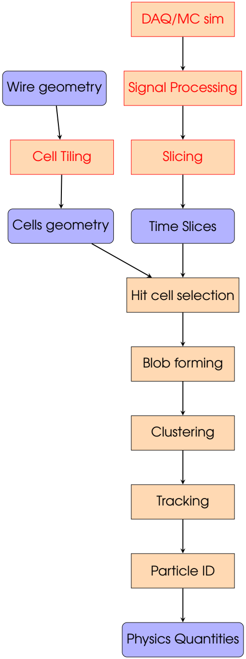

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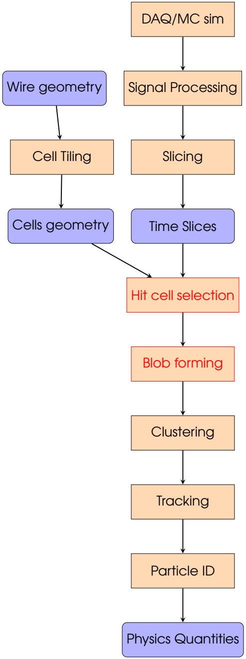

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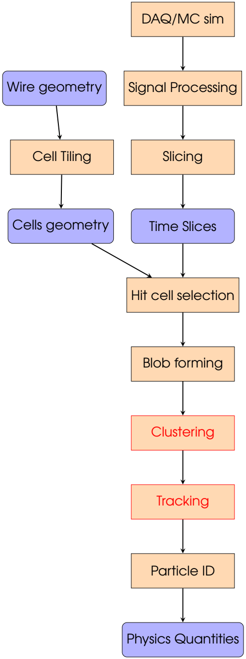

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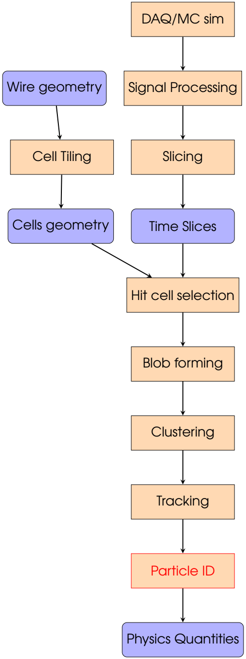
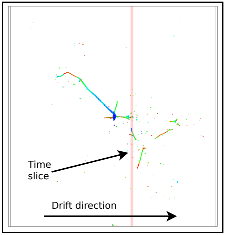
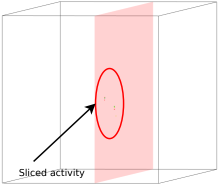
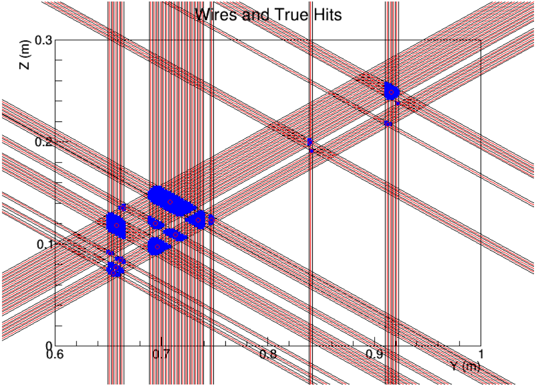


Time Slicing





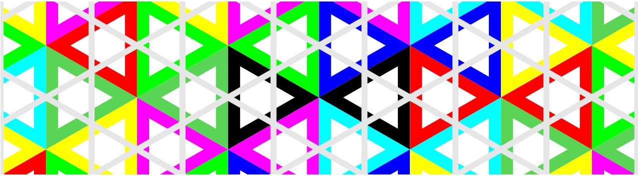
Focus on one **time slice** along a plane transverse to the drift.



- Slice duration is chosen to **match electronics shaping time**: combine 4 FADC "ticks" = 2 μs.
- Select wires above threshold in the slice.
- Identify regions near triple-wire overlap as potential "cells" holding drifted charge in that **time slice**.

Tiling

Zoom in on the wires and their associated (constructed) cells.



MicroBooNE geometry, grey wires, colored cells.

- Try to localize drifted charge into 2D bins or "cells" in the plane transverse to the electron drift direction.
- Each cell covers region near the approximate **triple-crossing of one wire from each plane**.
- Pattern determined by **pitch**, **angle** and **phase** of wire planes.

MicroBooNE	regular isosceles triangles of fixed size.
DUNE	variety of polygons with a spectrum of sizes.

The heart of the Wire Cell concept: if all three **wires** are above threshold in a **time slice**, the associated **cell** *likely* contains some **drifted charge**.

Ideal Solution

In a **perfect detector**, simply invert matrix equation:

$$\vec{w} = \mathbf{G}\vec{c}$$

- $\vec{w}$ measured charge on **wires** (in time slice)
- $\vec{c}$ expected charge o n **cells** (in time slice)
- $\mathbf{G}$ fixed wire-cell **connection** matrix (geometry)

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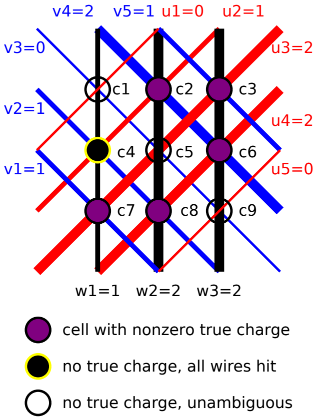
G fixed wire-cell **connection** matrix (geometry)

In a **real detector**:

- **Solution is often ambiguous** ($N_{wires} < N_{cells}$)
  - CT scanners have 100s of views in each slice, not just 3!
- **Uncertainty in charge measurements** ($\vec{w}$)
  - Environmental, electronic and thermal noise.
  - Statistical uncertainty due to digitization.
  - Systematic uncertainties from deconvolution.

Ambiguities - Example Hit Pattern

Zoom in on $5 \times 5 \times 3$ wires:



Cartoon of activity in one time slice:

- 9 cells and their associated wires.
- wires: color=plane, thickness=charge
- purple shows true drifted charge

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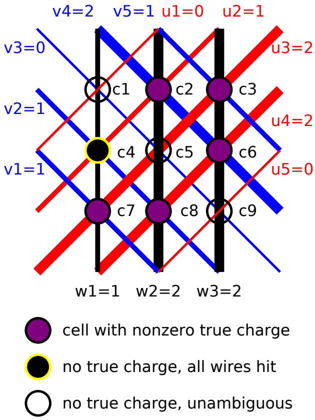

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Good wire v3 measures no charge, ∴ all its cells must **not** be hit.

Bad wires hit by charge in **c2**, **c7** and **c8** induce "ghost" at **c4**.

Ambiguous multiple cells measured by same wire. How much charge is in **c6**???

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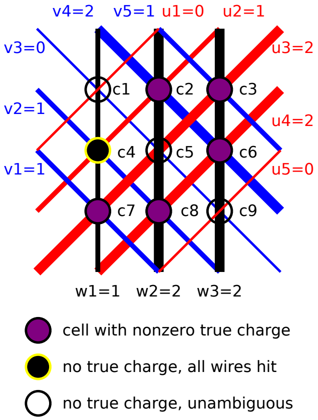

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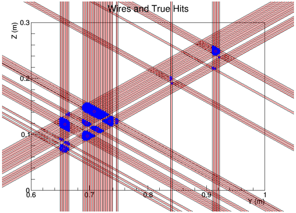
⇒Fight ambiguity by reducing number of unknowns!

Blobs

Reduce matrix size and (try to) **remove ambiguity** by exploiting knowledge of cell-nearest-neighbors.



cells $\rightarrow$ blobs
wires $\rightarrow$ merged wires

Same basic problem to solve:

$$\vec{w_b} = \mathbf{G_{wb}} \vec{b}$$

- **Sometimes** gives more favorable numerology: $N_{blob} \lesssim N_{w_b}$
- **But not always!** some $\mathbf{G_{wb}}$ can still not be inverted.

$\rightarrow$ And, we still haven't taken into account **uncertainty**.

Charge Measurement Uncertainty

Can form:

$$\chi^2 = (\vec{w}_{meas} - \vec{w}_{exp})^{\intercal}\mathbf{V}^{-1}(\vec{w}_{meas} - \vec{w}_{exp})$$

$\vec{w}_{meas}$ measured (merged) wire charges (in a slice)

$\vec{w}_{exp}$ expected wire charge ($\vec{w}_{exp} = \vec{w}_b = \mathbf{G_{wb}}\vec{b}$)

$\mathbf{V}$ wire charge uncertainty covariance matrix

Minimization over blob charges is equivalent to matrix inversion and gives:

$$\vec{b} = (\mathbf{G}^{\intercal}\mathbf{V}\mathbf{G})^{-1}\mathbf{G}^{\intercal}\mathbf{V}^{-1}\mathbf{B}\vec{w}_{meas}$$

$\mathbf{B}$ matrix connects “merged” wires to individual wires (per slice).

Reminder: only works if $N_{blob} < N_{w_b}$!

Remaining Ambiguities

Even after forming **blobs** sometimes still some **time slices** with:

$$N_{blob} > N_{w_b}$$

$\Rightarrow$ **zero-value eigenvalues**, remaining ambiguity.

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$$N_{blob} > N_{w_b}$$

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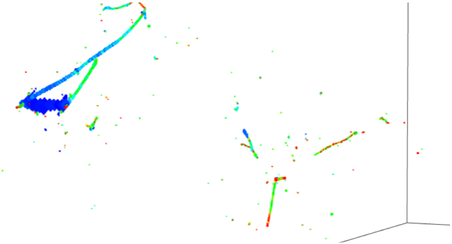
- Try removing **blobs in combinations**: 2, 3, ... until all **eigenvalues are nonzero**
- **Combinatorics** $\Rightarrow$ **hugely time consuming!**
    - Algorithm optimization and shortcuts employed.
    - Still, some time slices can take $\sim$hours.

  $\Rightarrow$ We are looking into exploiting GPUs.
- For now, if no solution is found after fixed number of iterations $\Rightarrow$ give up on time slice....

The Payoff: imaged 3 GeV ν_e interaction

True energy depositions.



Wire Cell Imaging.

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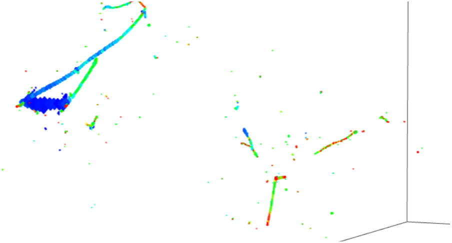

Wire Cell Imaging.

- **Excellent imaging** of major features and isolated activity.
  - → a static 2D view doesn't do it justice! Follow link to view it online.

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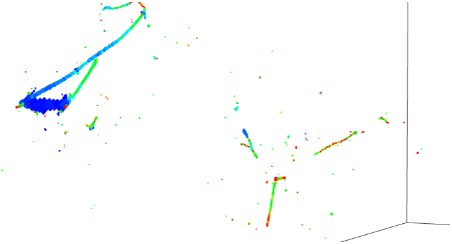

Wire Cell Imaging.

- **Excellent imaging** of major features and isolated activity.
  - → a static 2D view doesn't do it justice! Follow link to view it online.
- **Residual ambiguity** seen as wide blue patches.
  - → **Inherent problem of tomography using low number of viewing angles**
  - → Will pursue an **iterative** approach: constrain ambiguous regions after reconstructing the good parts to the kinematics-level.

Post-imaging Pattern Recognition

1. **cluster** together blobs contiguous in space and time (slice).
2. **track** straight line through a cluster.
3. **categorize** track fit solutions/failures.

Some initial, coarse categories:

- track: cluster is well characterized by the track.
- shower: cluster consistent with an EM/hadronic shower.
- short: cluster appears to be a "short track" (eg, δ-ray).
- undefined: no well-suited categorization.

- This is an **active area of development** for Wire Cell.
- Plan for **semi-automated, hand-scanning** to **map out problem space**.
- Maybe a problem suited for **machine learning**?

LArTPC Detectors

Wire Cell Technique

Wire Cell Software
- Bee Display
- Prototype
- Toolkit

Wire Cell Software Ecosystem

The software is composed into three main parts:

- **visualization** the “Bee” web application (Chao Zhang)
- **prototype** reconstruction algorithms, initial proof of principle (Xin Qian)
- **toolkit** production process, parallelism and basis for long-term development (bv)

Bee: an interactive 3D visualization system

Select features:

- **Web browser-based** 3D event display,
- Shows variety of reconstructed and “true” information.
- Implemented in **JavaScript/WebGL** (**Django** backend).
- Simple **JSON** data file format,
  - drag-and-drop user file uploads.

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Bee 2.0 in development

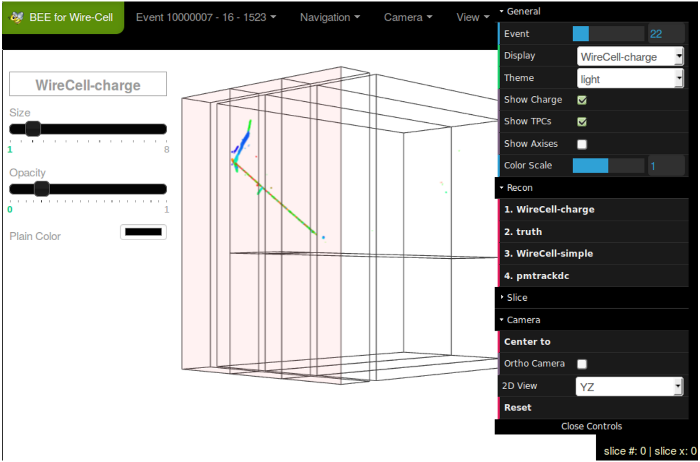
→ **semi-automated, human-guided** pattern recognition.

→ collect and replay human decisions.

→ look for **low-hanging fruit to automate**.

→ maybe feed into machine learning?

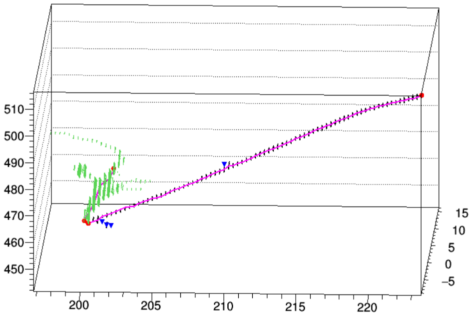
Bee Screenshot



Try it yourself: `http://www.phy.bnl.gov/wire-cell/bee/`

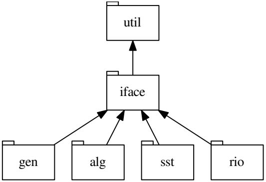
Wire Cell Working Prototype

- **Very successful proof of principle!**
- Currently **leads the state of the art** in LArTPC reconstruction techniques.



Example result showing imaging + pattern recognition. Colors indicate identified tracks and showers.

Wire Cell Toolkit



Address compromises made in the name of rapid prototyping

- Modular **packaging and build** system (waf).
- Comprehensive **API** via abstract interface classes.
- Mindful of **dependencies**, external and internal.
- Built-in wire and cell **geometry descriptions** or load from file.
- Includes simple **LArTPC detector simulation**.
- Rewriten implementations of **prototype algorithms**.
- **Data Flow Programming** execution model with **abstracted DFP engine**.

Just now becoming available but with some work still to do.

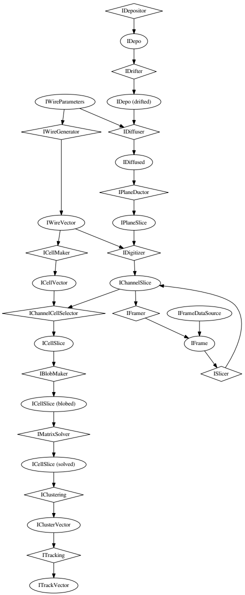
Wire Cell Execution Model

The toolkit supports **data flow programming** paradigm

- Design influenced by VisTrails and others.
- Data flows through a **graph** made from:

  vertices: **computational units** (algorithms)
  edges: **data queues** of a given type

- Streamed processing minimizes RAM usage.
- High-level "graph programming" in user config.
- **Thread-safe queues ⇒ parallel processing.**
- Abstract graph execution machinery.
  - Intel TBB provides reference implementation.



One possible Wire Cell flow.

Summary

- The **Wire Cell working prototype LArTPC reconstruction** method and software has been developed.
  - already producing some of the **world's best results**,
  - technical and performance improvements on-going.
- The **Bee interactive 3D event visualization** application has been developed
  - critical for understanding LArTPC and developing Wire Cell
  - plans to evolve to "human-directed automated reconstruction" system.
- The **Wire Cell Toolkit** for LArTPC reconstruction becoming available.
  - Basis for long term development including investigations into parallel processing.

We expect Wire Cell requires wading into the **new waters** (for us) of parallel processing, hardware acceleration, computing science and mathematics.

$\rightarrow$ **Expert suggestions, help and collaboration are most welcome!**

Wire Cell on the web

- home page:
  http://www.phy.bnl.gov/wire-cell/
- Bee entry page:
  http://www.phy.bnl.gov/wire-cell/bee/
- prototype user manual:
  http://bnlif.github.io/wire-cell-docs/
- prototype repositories:
  https://github.com/BNLIF
- toolkit user manual:
  http://wirecell.github.io/wire-cell-docs/
- toolkit code reference:
  http://www.phy.bnl.gov/wire-cell/doxy/html/
- toolkit repositories:
  https://github.com/WireCell