A novel method for event reconstruction in Liquid Argon Time Projection Chamber

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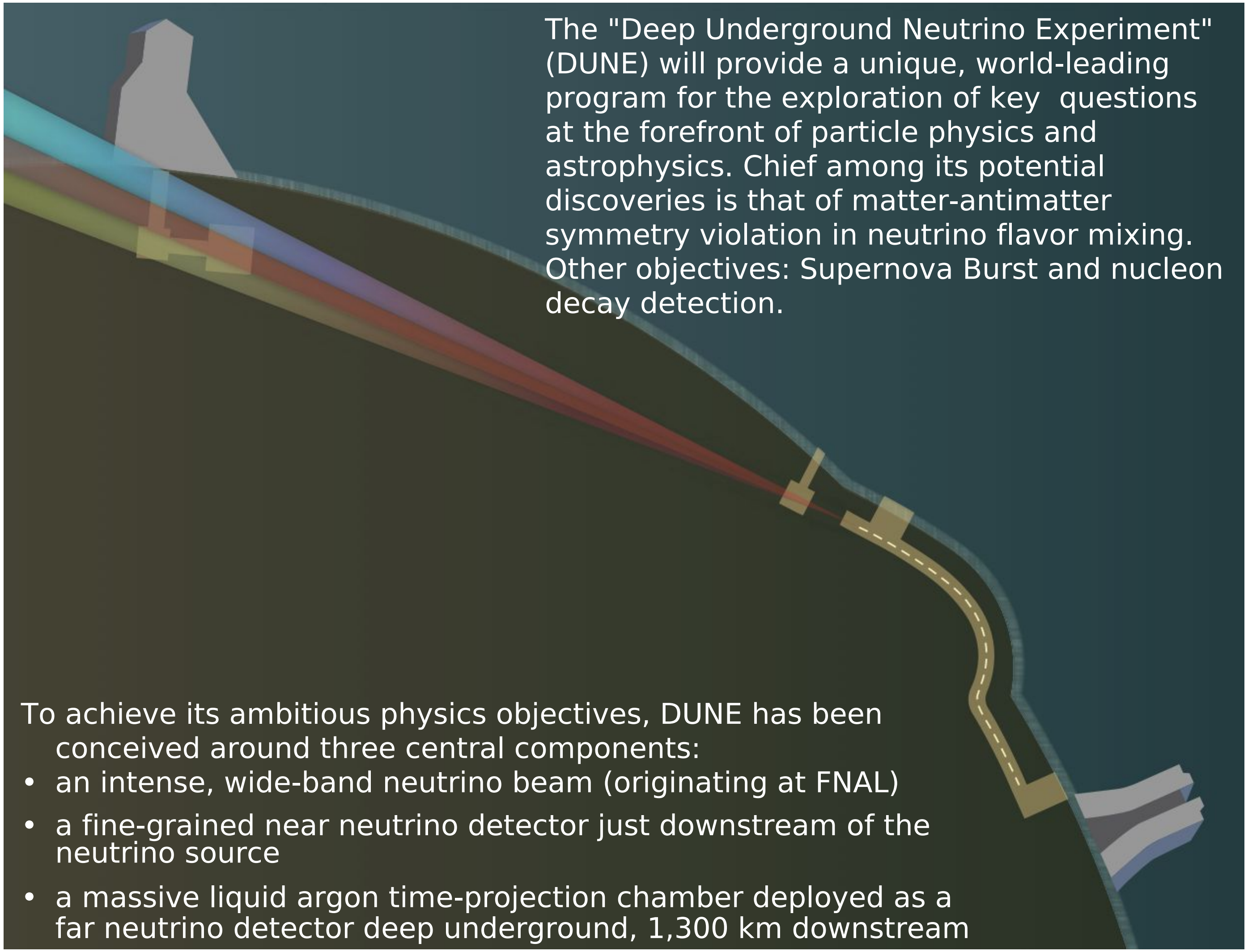
Overview

- Single-Phase Liquid Argon Time Projection Chamber (LArTPC) has become the instrument of choice in the recent generation of Intensity Frontier (IF) experiments. Readout principles and other characteristics set this type of detector apart from "traditional" TPCs used in collider experiments, and there is a different set challenges with regards to event reconstruction in these devices.
- Event reconstruction will be one of the main factors which determine performace of future IF experiments such as DUNE (a brief overview of which is included in this presentation).
- Principles of operation of the Liquid Argon Time Projection Chamber will be discussed briefly.
- TPC with wire sensors: wire readout and its analogy to tomographic projection technique.
- "Wirecell" method of solving the inverse problem utilizing a few techniques from tomography.

DUNE

http://www.dunescience.org/



The "Deep Underground Neutrino Experiment" (DUNE) will provide a unique, world-leading program for the exploration of key questions at the forefront of particle physics and astrophysics. Chief among its potential discoveries is that of matter-antimatter symmetry violation in neutrino flavor mixing. Other objectives: Supernova Burst and nucleon decay detection.

To achieve its ambitious physics objectives, DUNE has been conceived around three central components:

- an intense, wide-band neutrino beam (originating at FNAL)
- a fine-grained near neutrino detector just downstream of the neutrino source
- a massive liquid argon time-projection chamber deployed as a far neutrino detector deep underground, 1,300 km downstream

DUNE: the Primary Science Program

- precision measurements of the parameters that govern $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations with the goal of

  – measuring the charge-parity (CP) violating phase δ_{CP} — where a value differing from zero or π would represent the discovery of CP-violation in the leptonic sector, providing a possible explanation for the matter-antimatter asymmetry in the universe;

  – determining the neutrino mass ordering (the sign of $\Delta m^2_{31} \equiv m^2_3 - m^2_1$), often referred to as the neutrino *mass hierarchy*;

  – precision tests of the three-flavor neutrino oscillation paradigm through studies of muon neutrino disappearance and electron neutrino appearance in both ν_μ and $\overline{\nu}_\mu$ beams, including the measurement of the mixing angle θ_{23} and the determination of the octant in which this angle lies;

- search for proton decay in several important decay modes, for example $p \rightarrow K^+\overline{\nu}$, where the observation of proton decay would represent a ground-breaking discovery in physics, providing a portal to Grand Unification of the forces;

- detection and measurement of the ν_e flux from a core-collapse supernova within our galaxy, should any occur during the lifetime of the DUNE experiment.

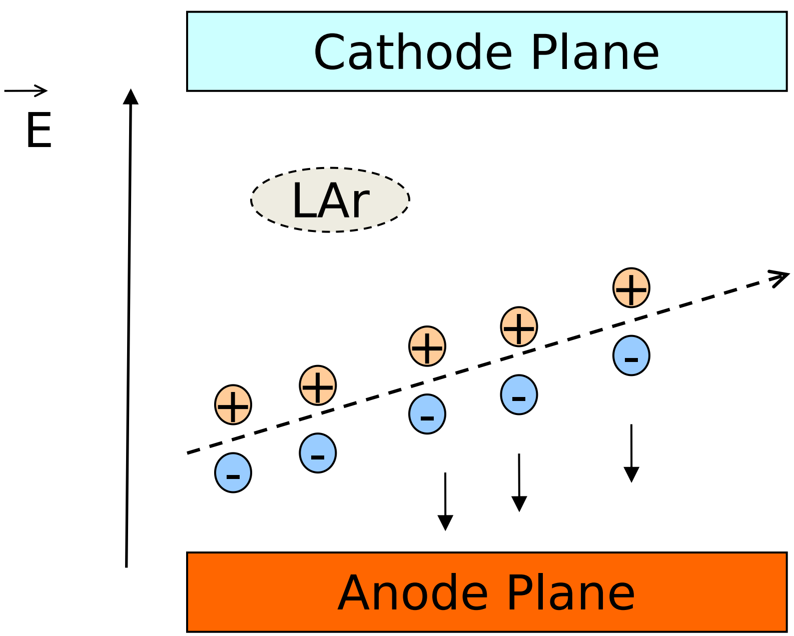
also see backup slides

Primary Science Program as the driver for detector technology selection

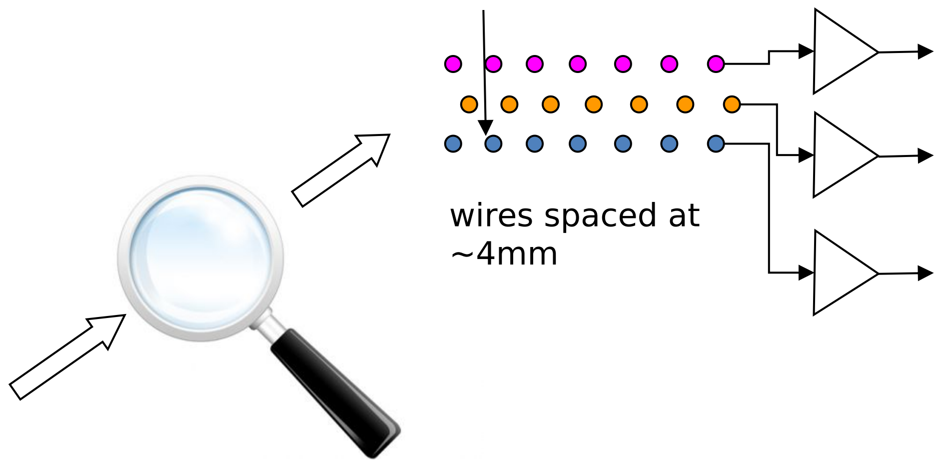
- To fullfil the DUNE science program the Far Detector must have good tracking capability over an extended volume (in fact a very large volume).
- Precise measurement of ionization charge is essential for dE/dx for PID purposes and total energy determination.
- The detector must be capable of recording and reconstructing ionization patterns ranging from a single MeV scale to multi-GeV events.
- Since oftentime tracks must be reconstructed in presence of nearby showers, imaging capability is essentially a must.
- Liquid Argon Time Projection Chamber has the potential to meet these requirements. However, event reconstruction is still a challenge and meeting this challenge was motivation for work presented here.

Single-Phase LArTPC

- Currently state-of-the-art technology for Intensity Frontier experiments (ICARUS, μBooNE etc).
- Liquid Argon serves as both the target and the sensitive medium, for tracking and calorimetry
- LArTPC is essentially an ionization chamber with multiple sets of electrodes.
- Due to the large scale of modern devices, for channel count to be realistic, these TPCs do not utilize pads but wires to detect signals from ionization charge drifting in Liquid Argon.
- Planar arrays of sensor wires are grouped in the anode assembly, including two "induction planes" with wires at a **stereo angle**, and the collection plane.
- Two coordinates (in the plane) are determined via stereo projections on three planes, and the third (along the drift) via the time measurement.
- There is a potential for excellent spatial and charge resolution due to small wire pitch and ADC time resolution.



Two "induction planes" with wires at a stereo angle, and the collection plane: each wire connected to a single amplifier



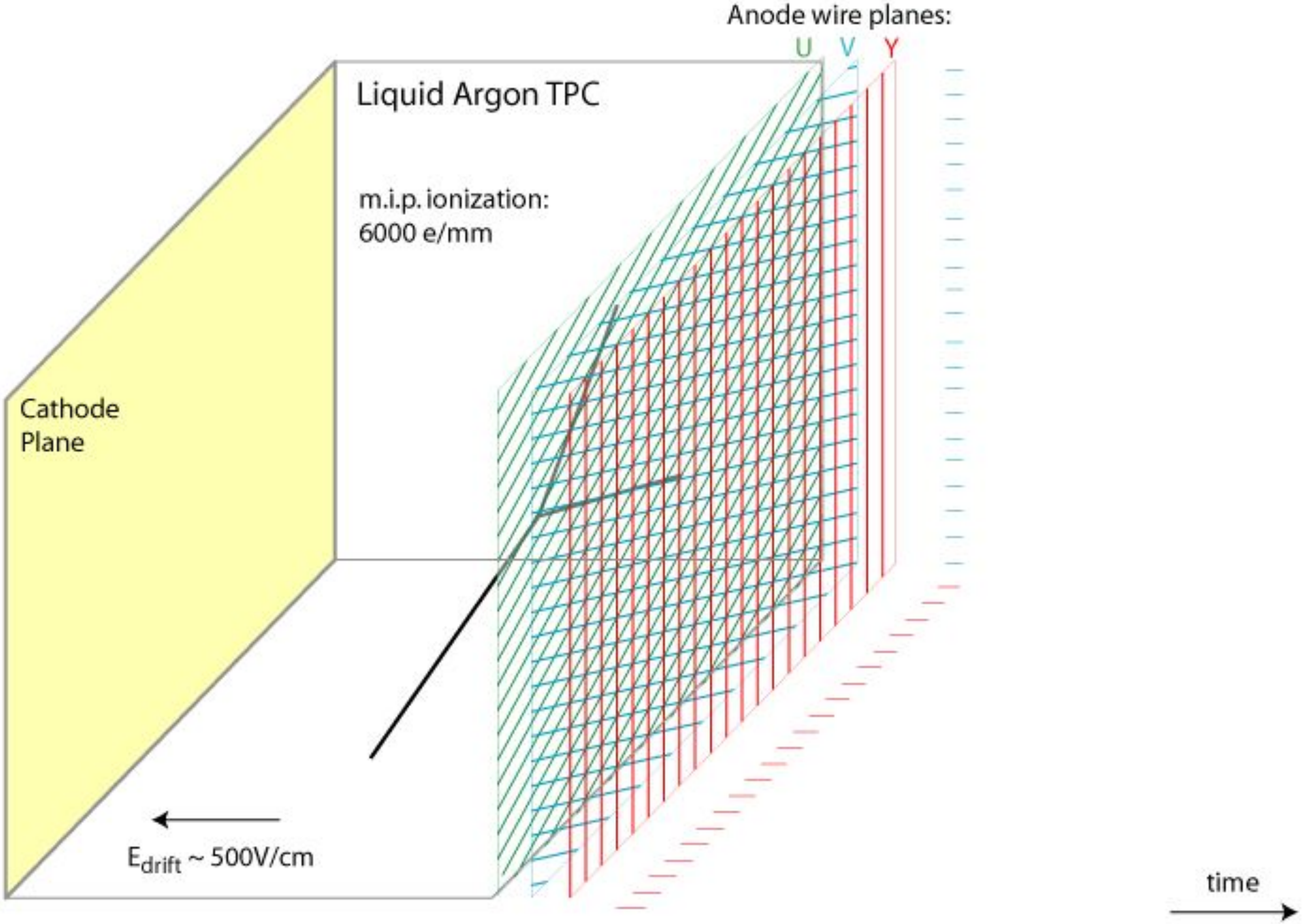
LArTPC Anode Plane Assembly

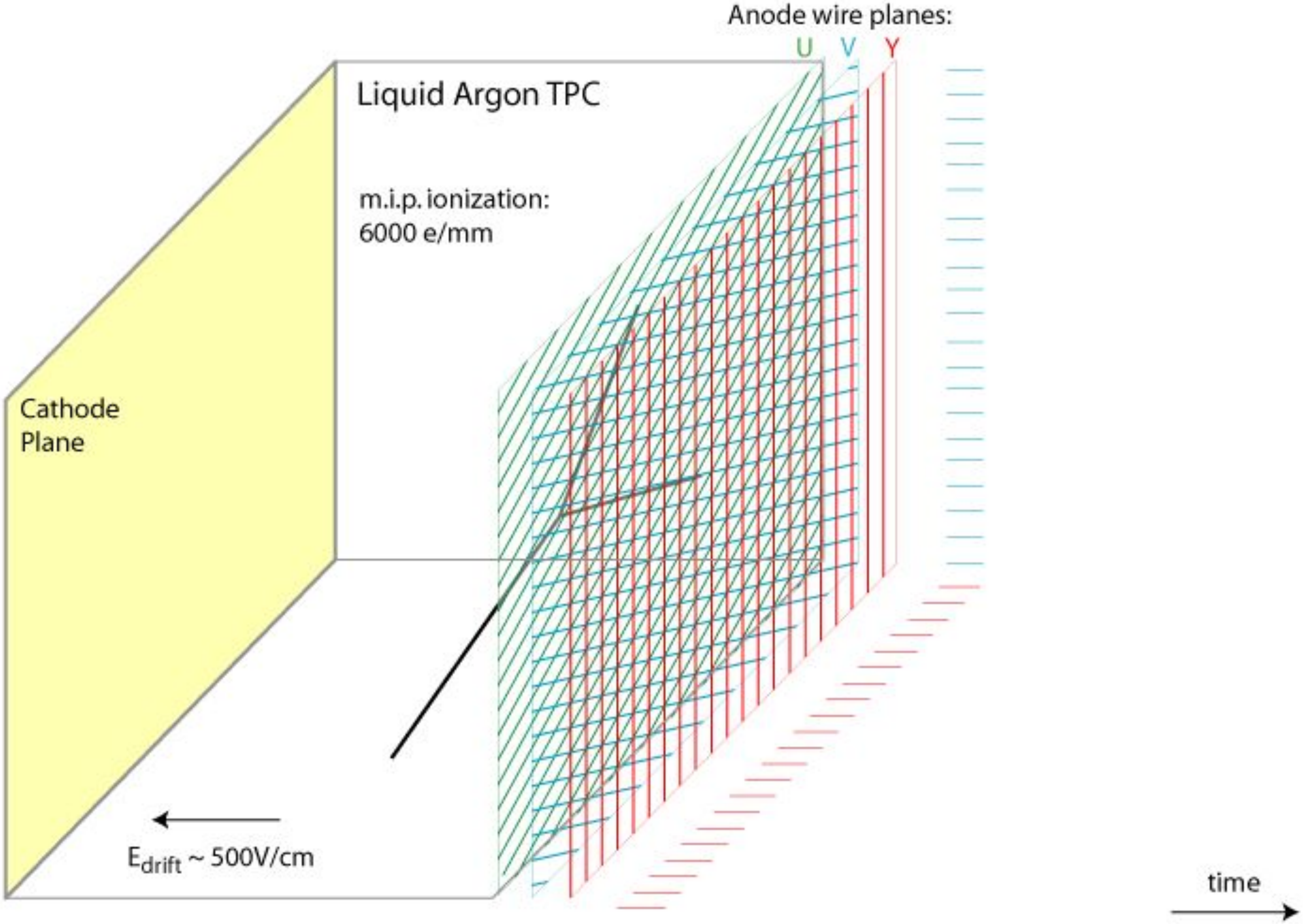
- Wires are supported by a tubular steel frame
- A prototype frame for the Anode Plane Assembly (APA):

DUNE prototype (35t)

- View of Anode Plane Assemblies installed inside the cryostat (prototype).
- Right image shows the field cage.

Following slides are an animated representation of the concept of operation of a TPC with wire-plane based readout.

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m.i.p. ionization:
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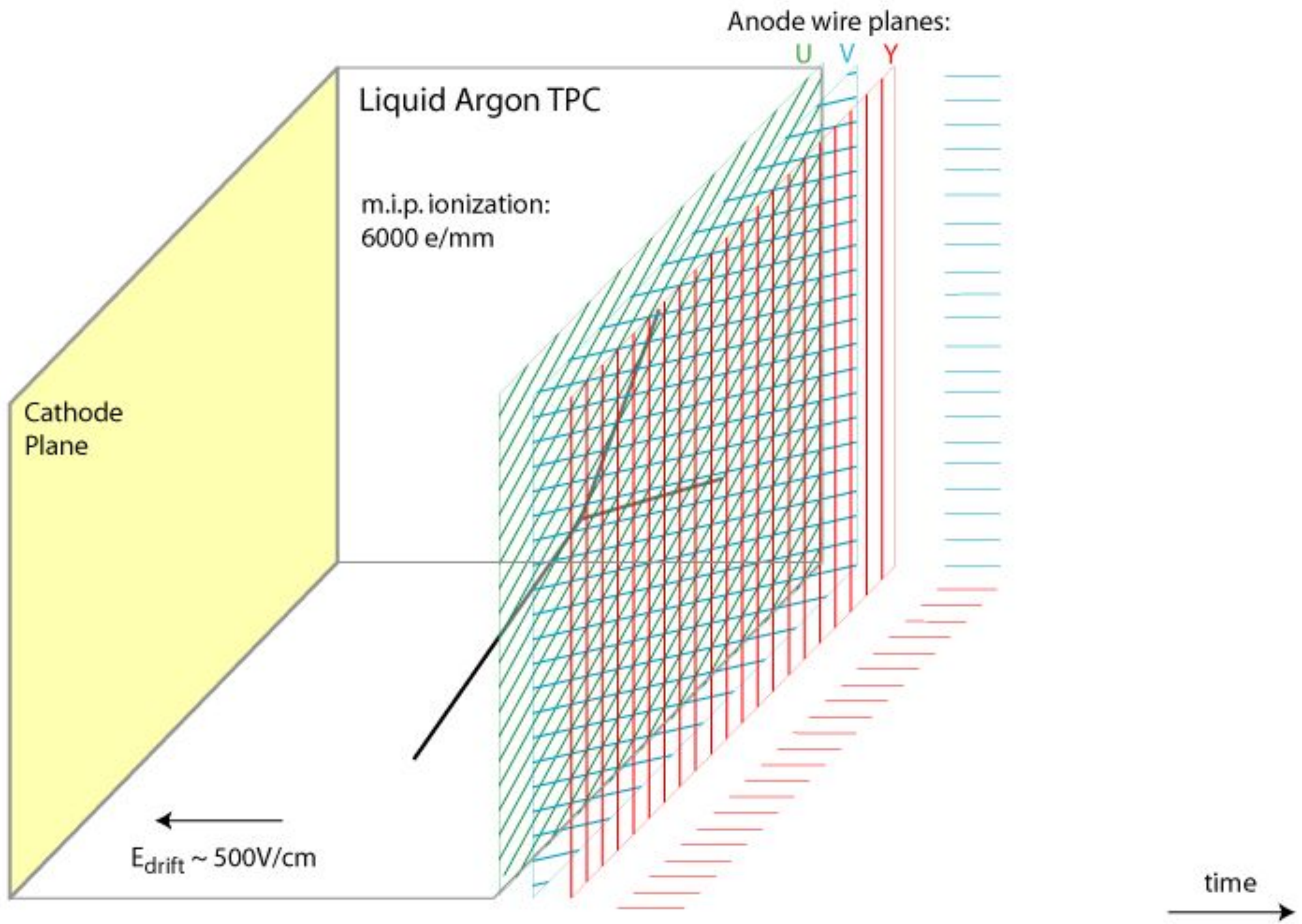
Plane
E_{drift} ~ 500V/cm
time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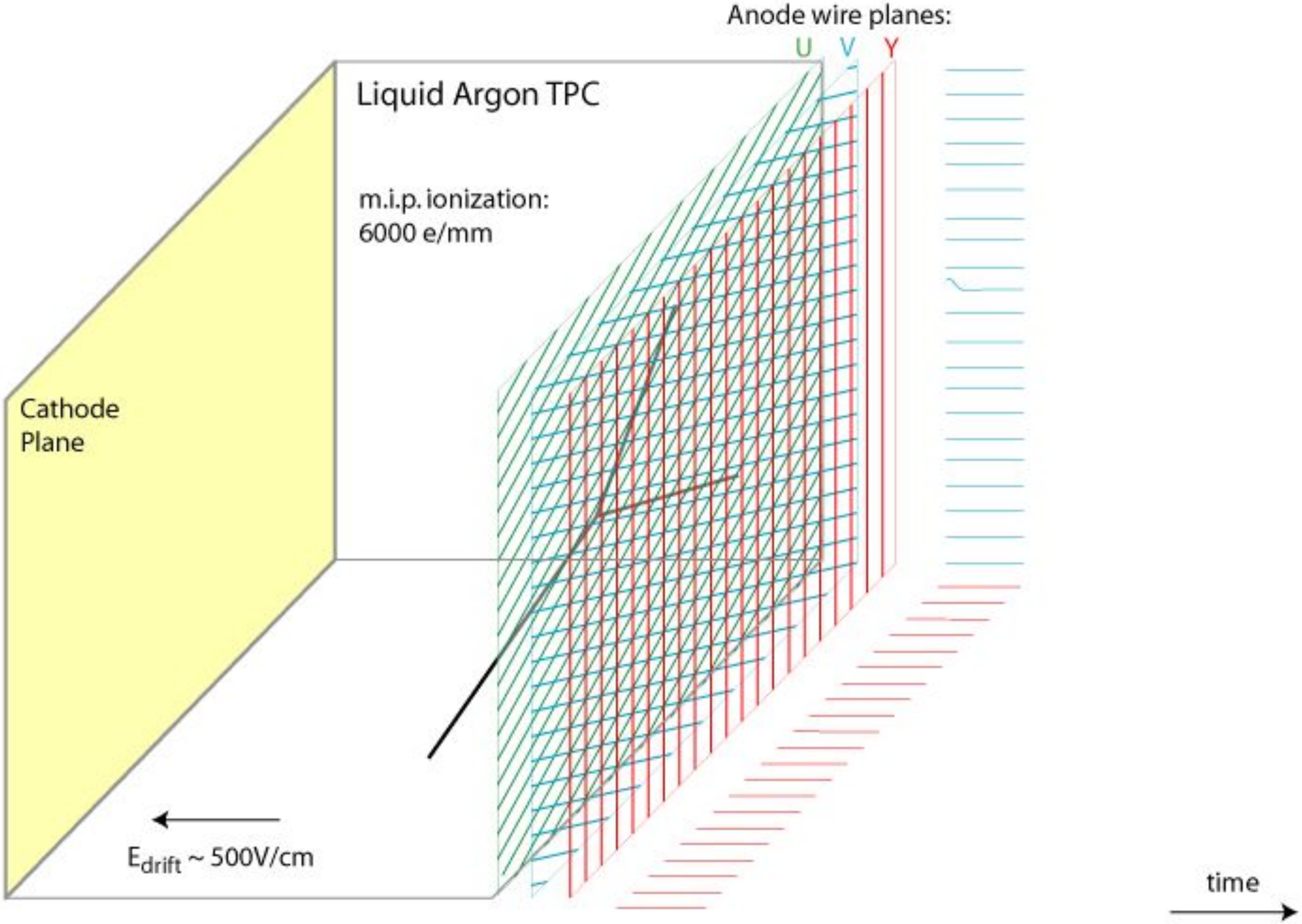
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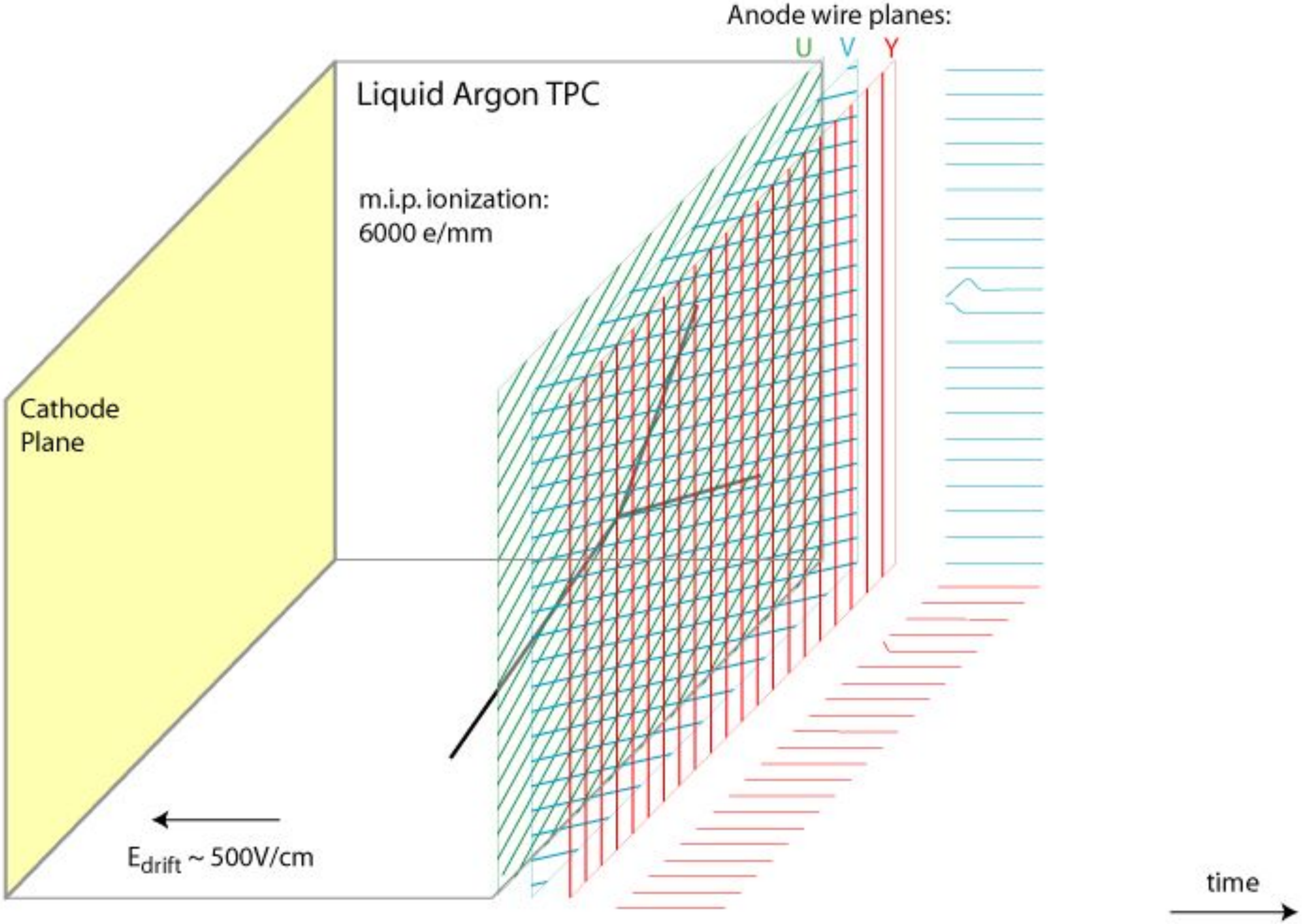
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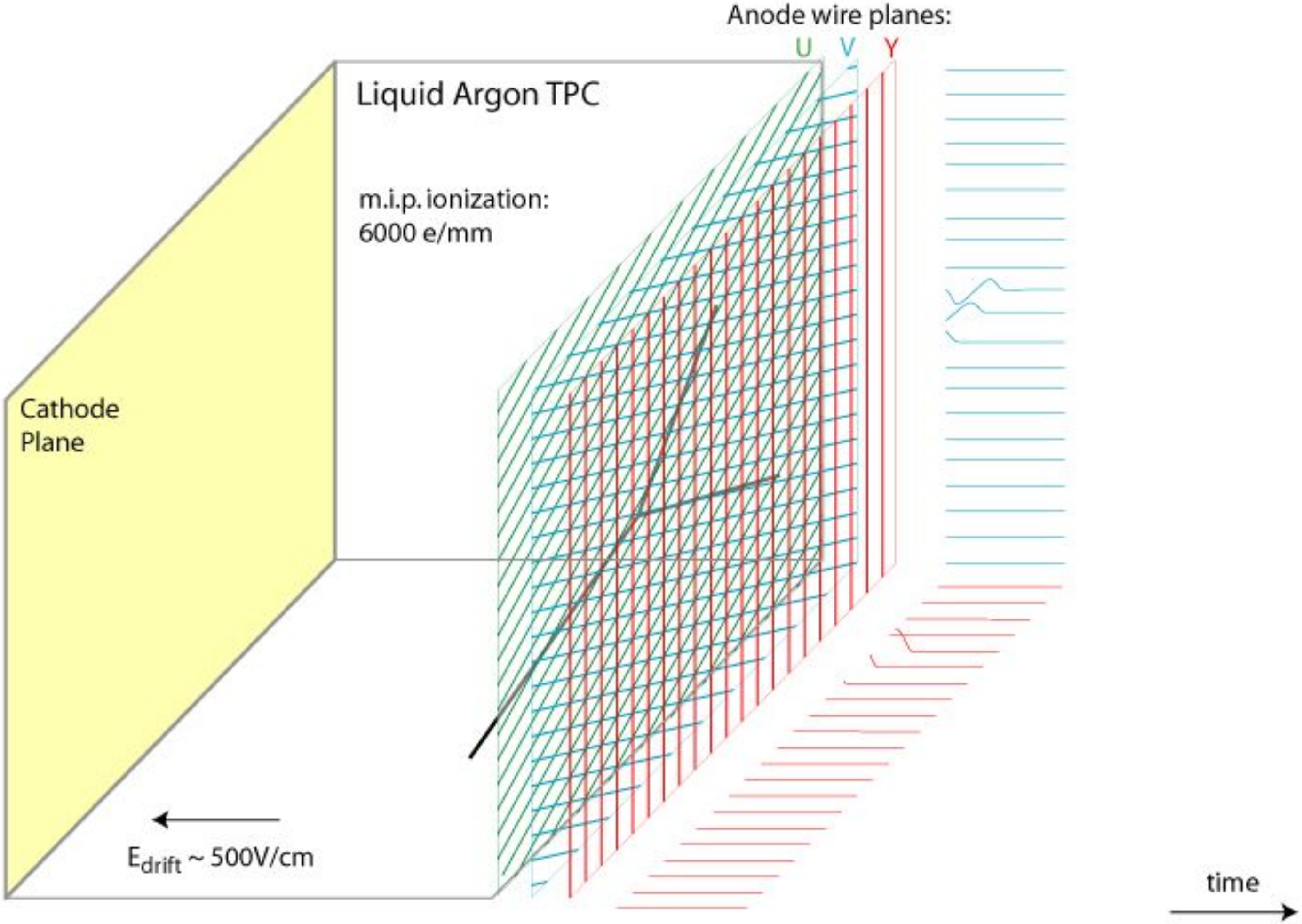
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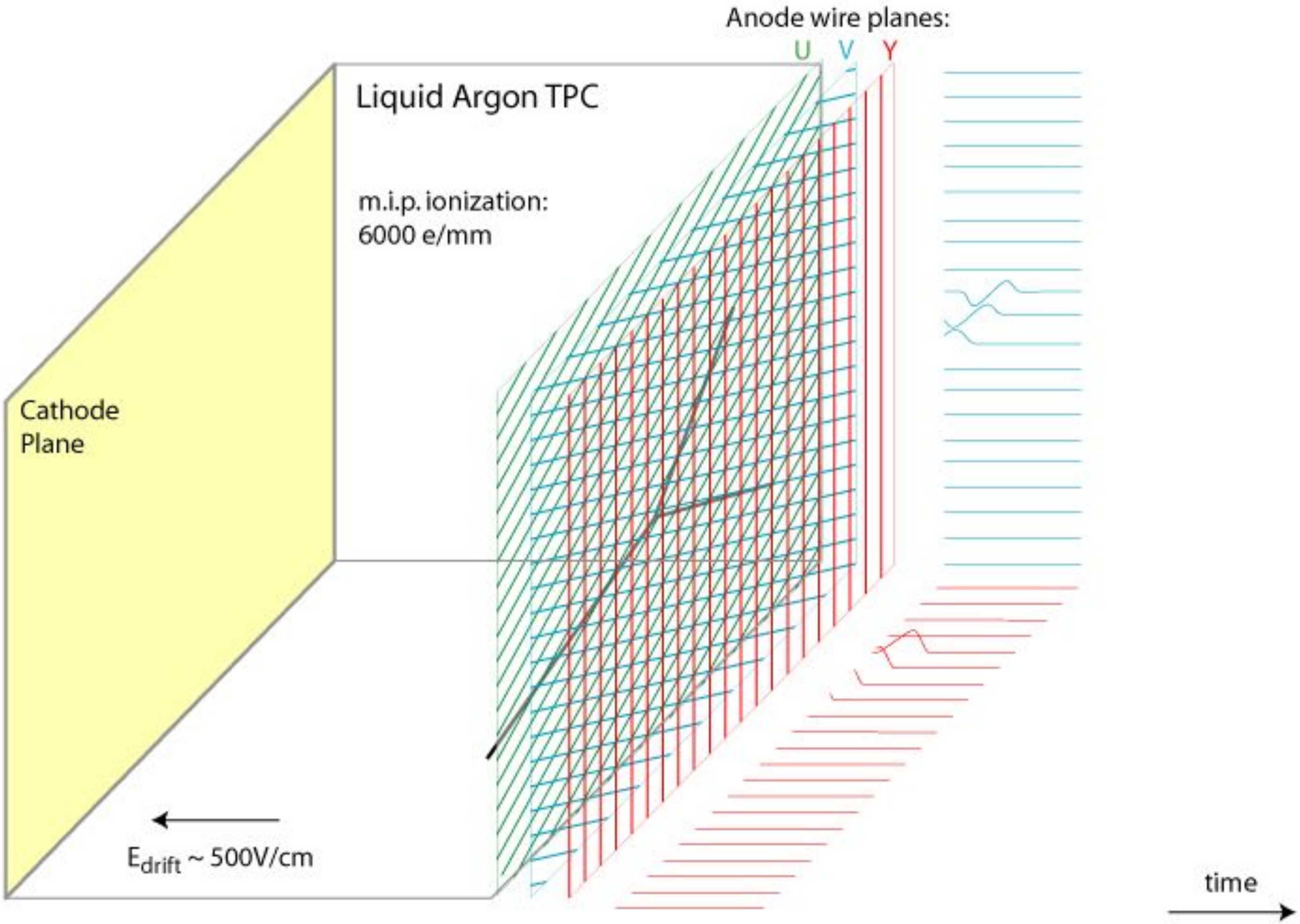
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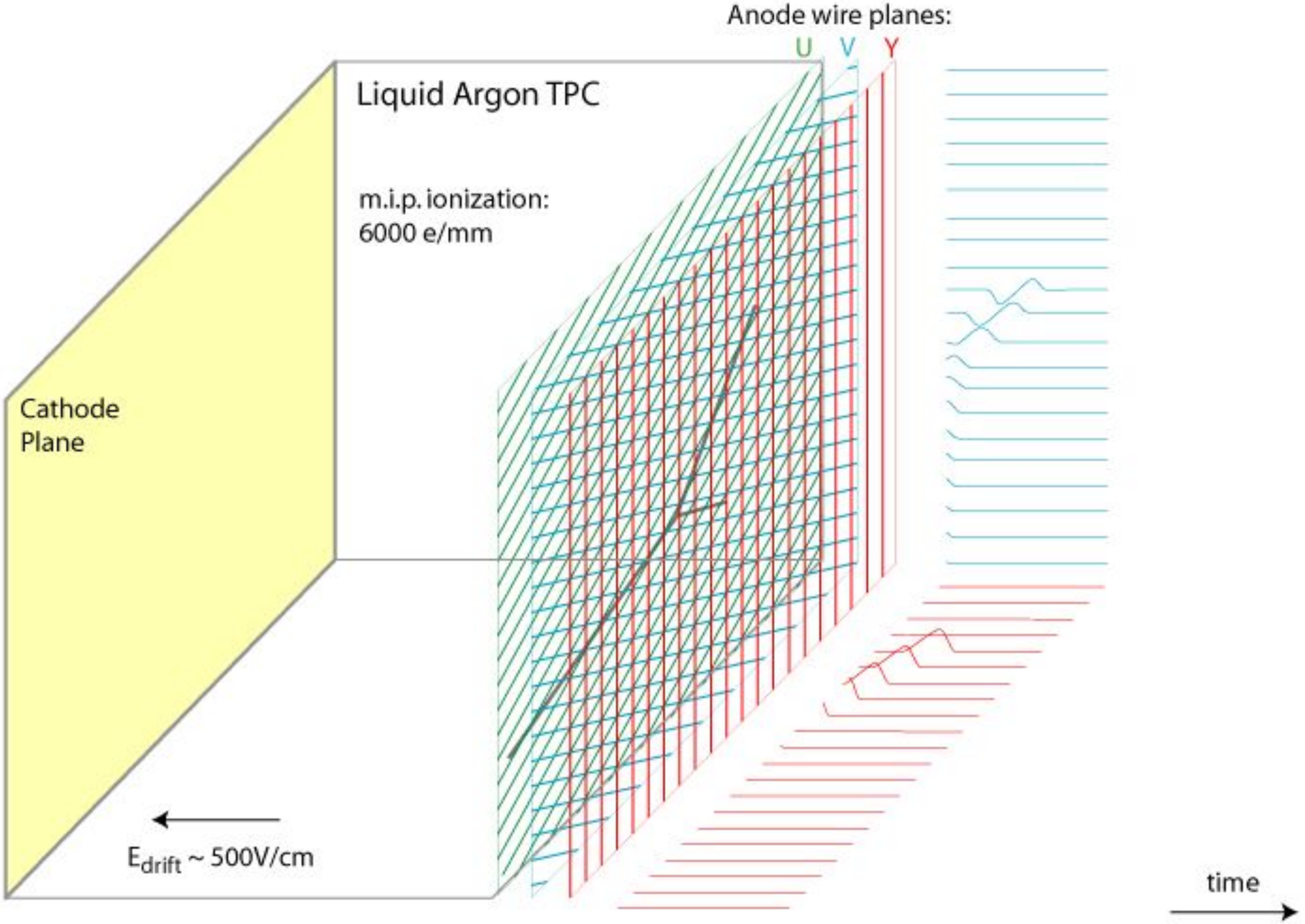
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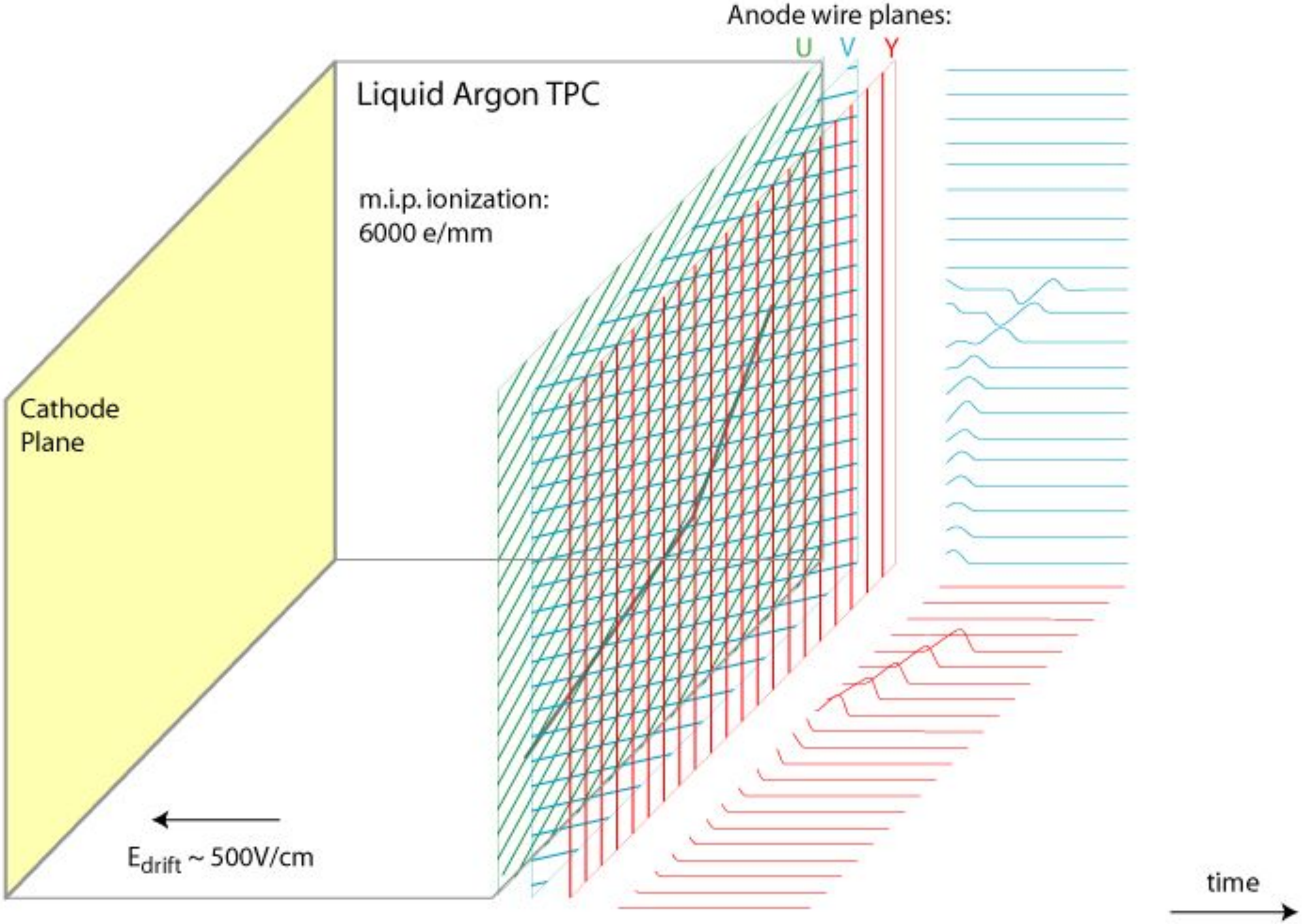
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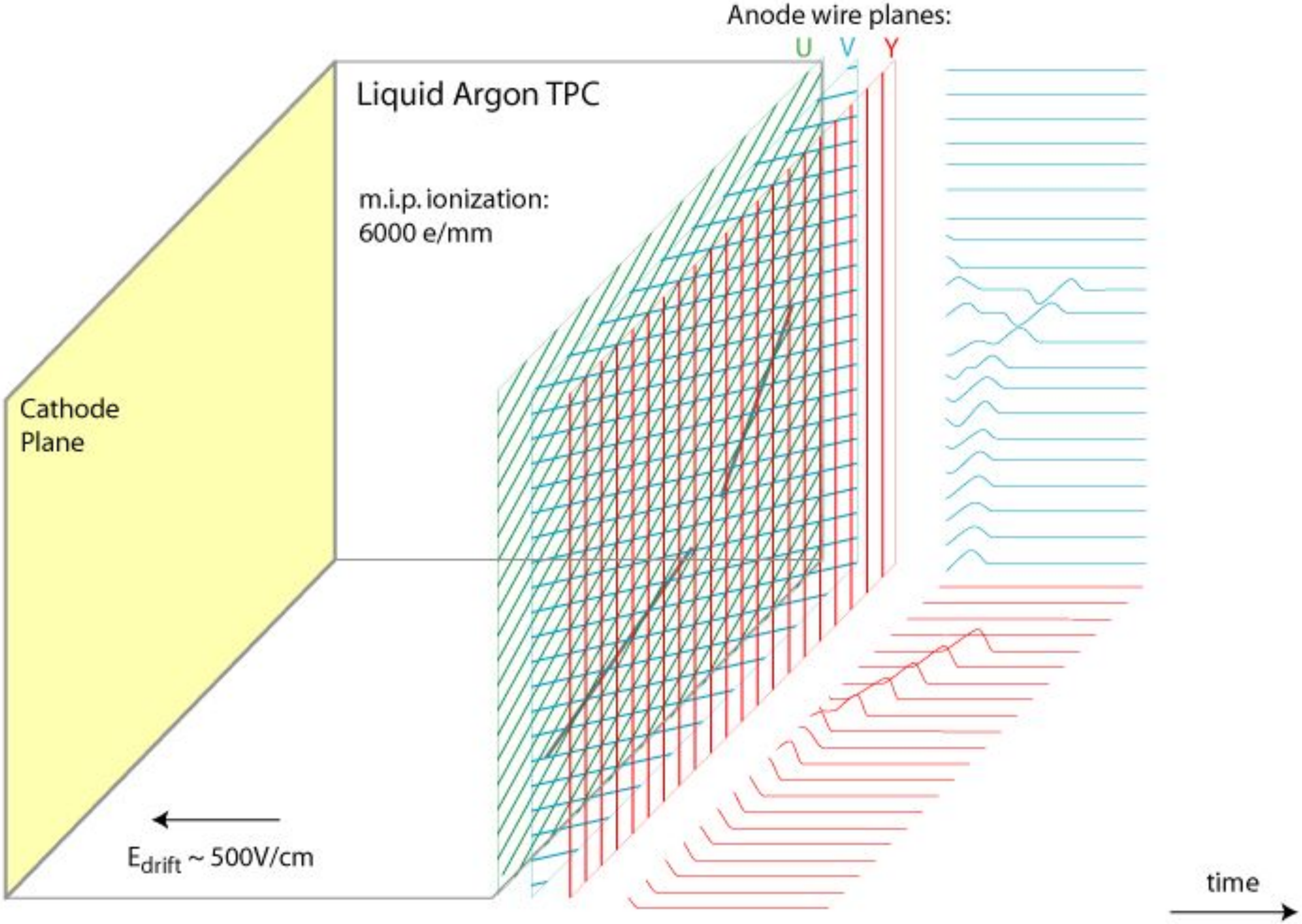
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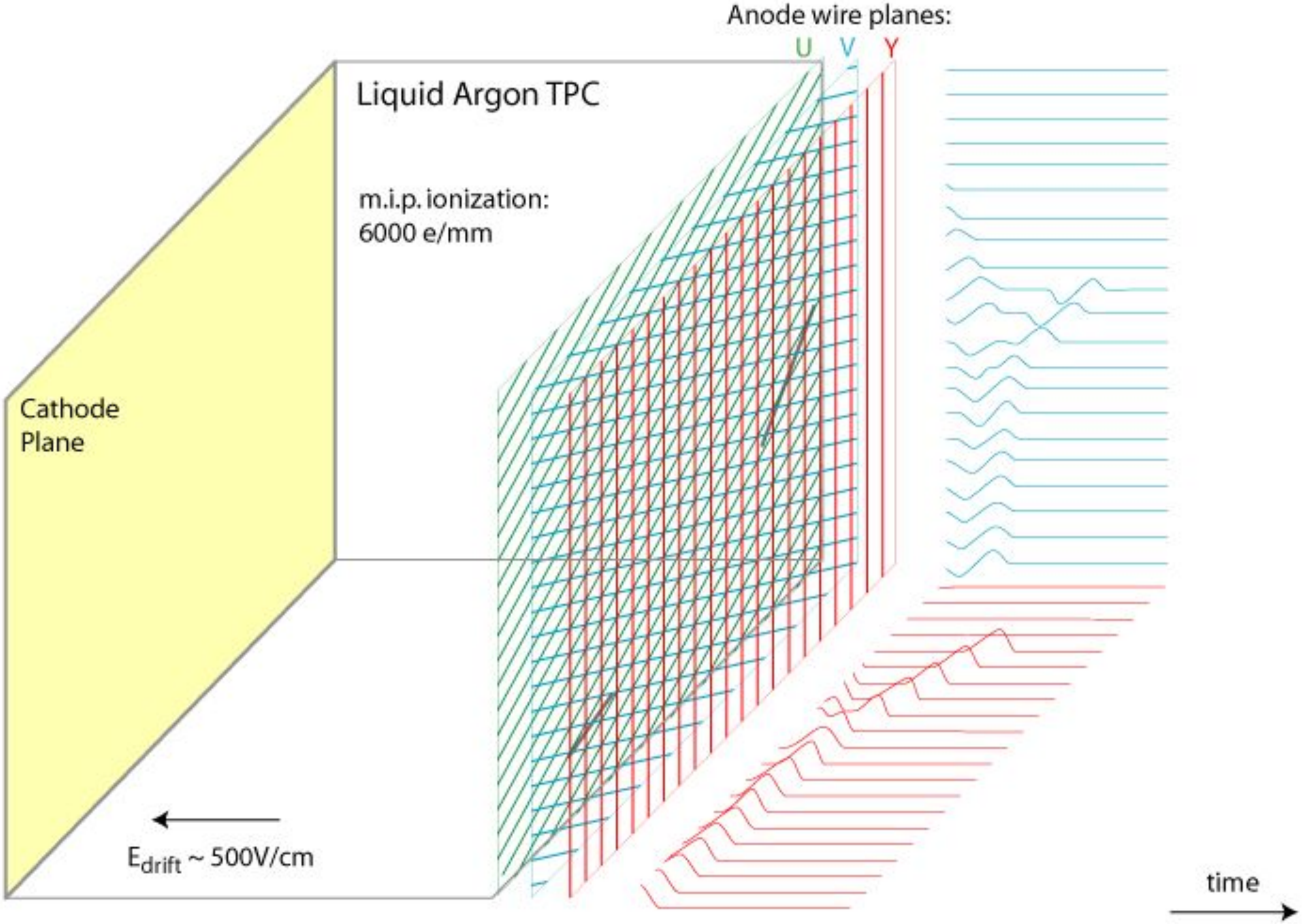
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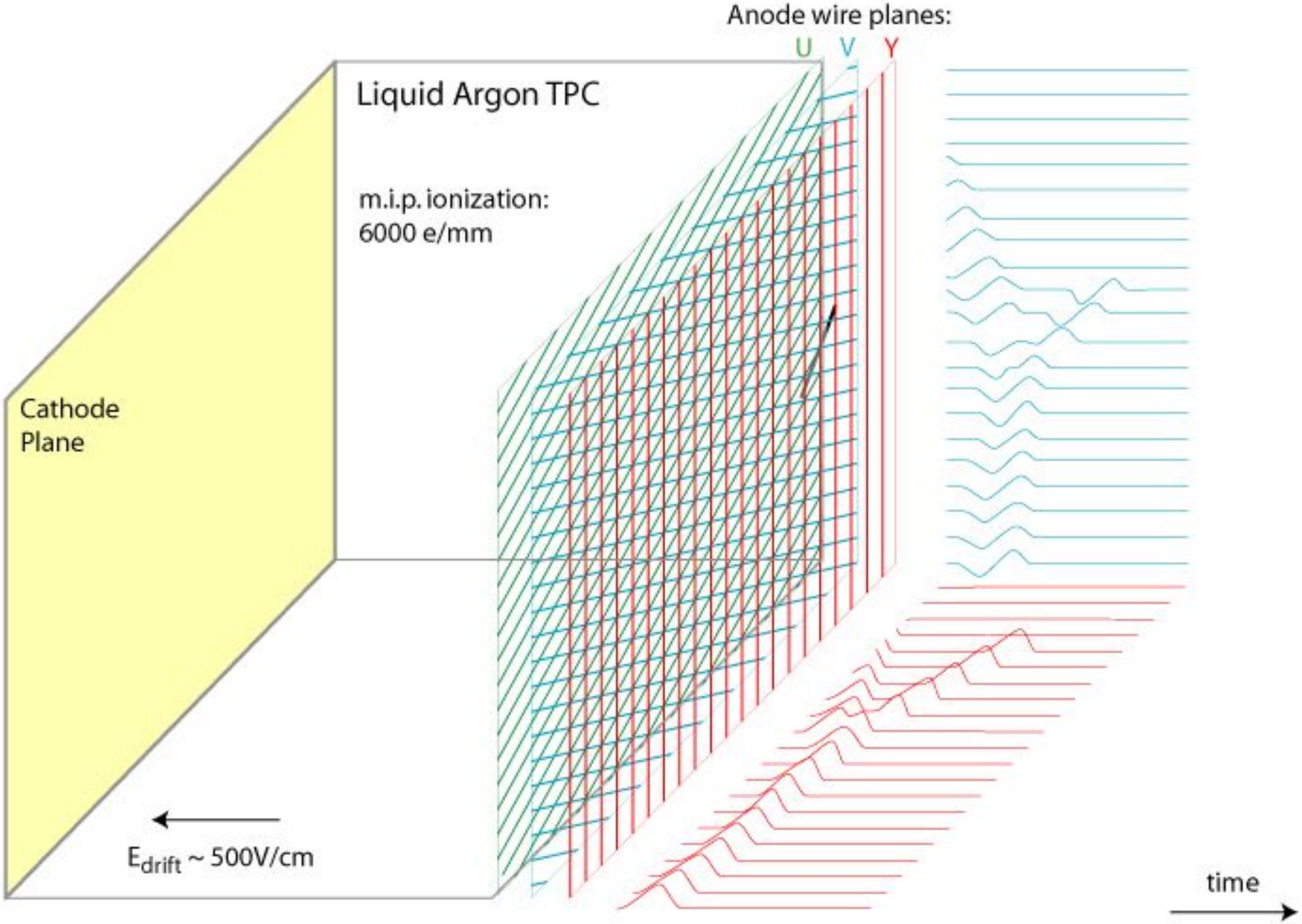
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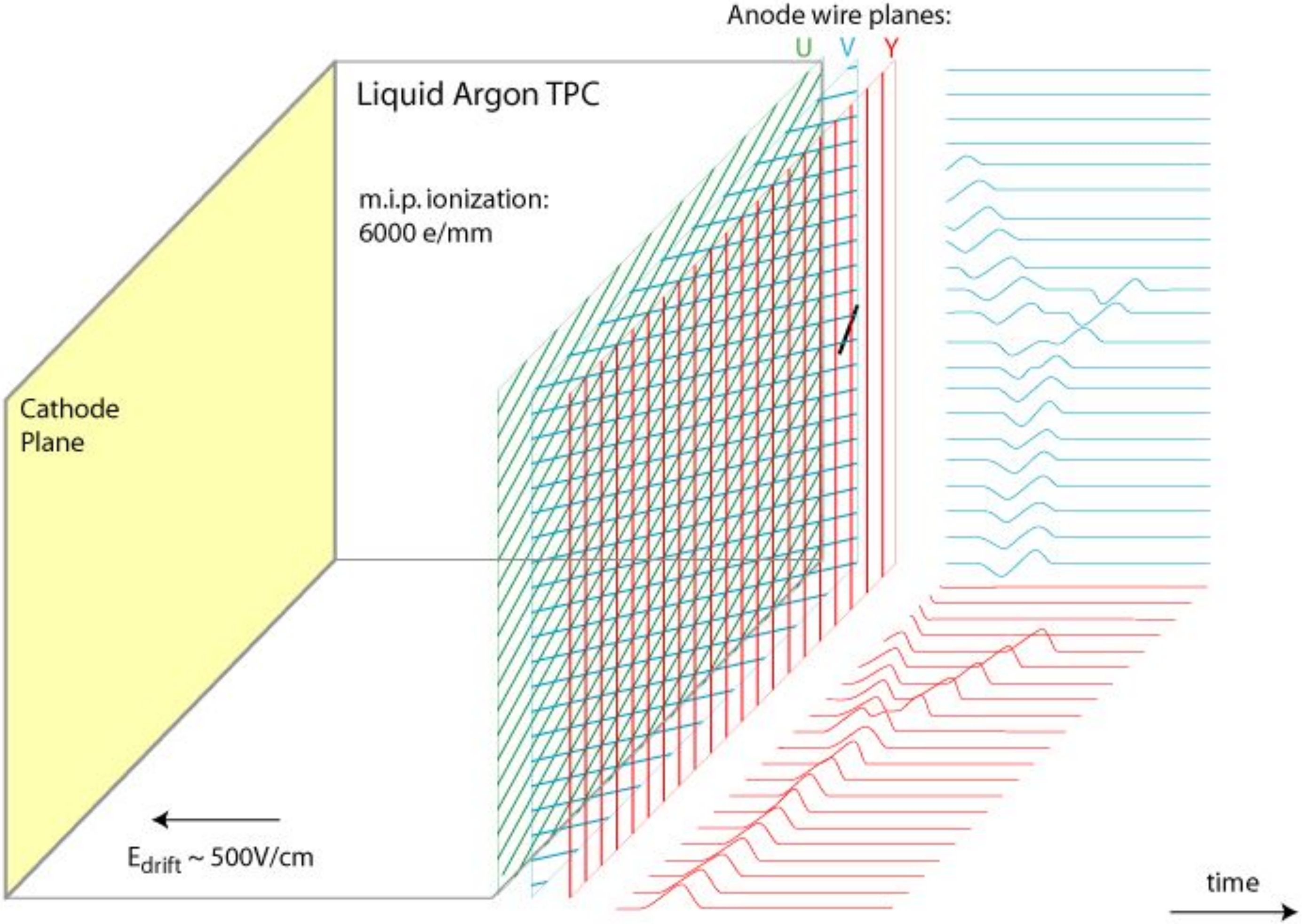
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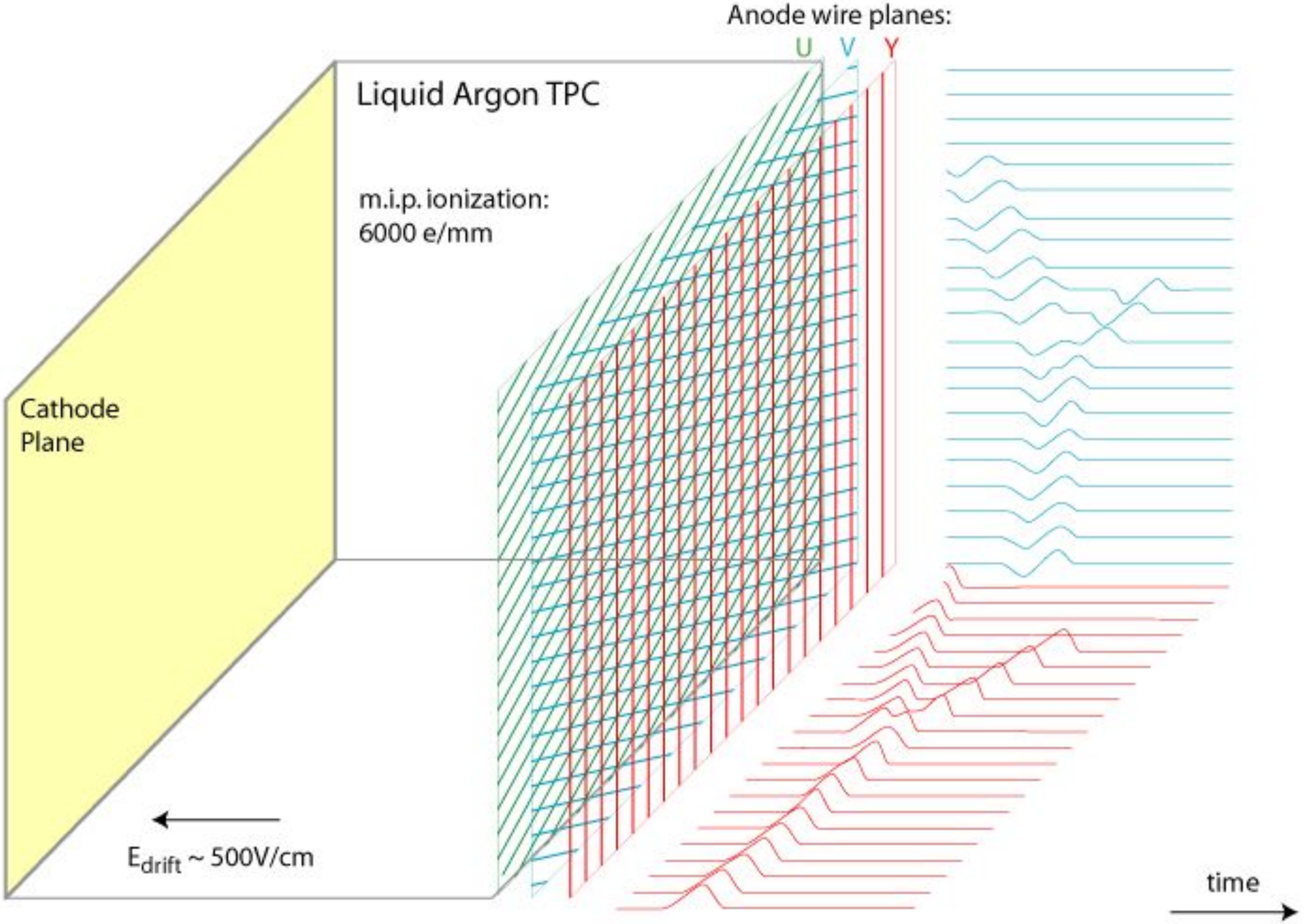
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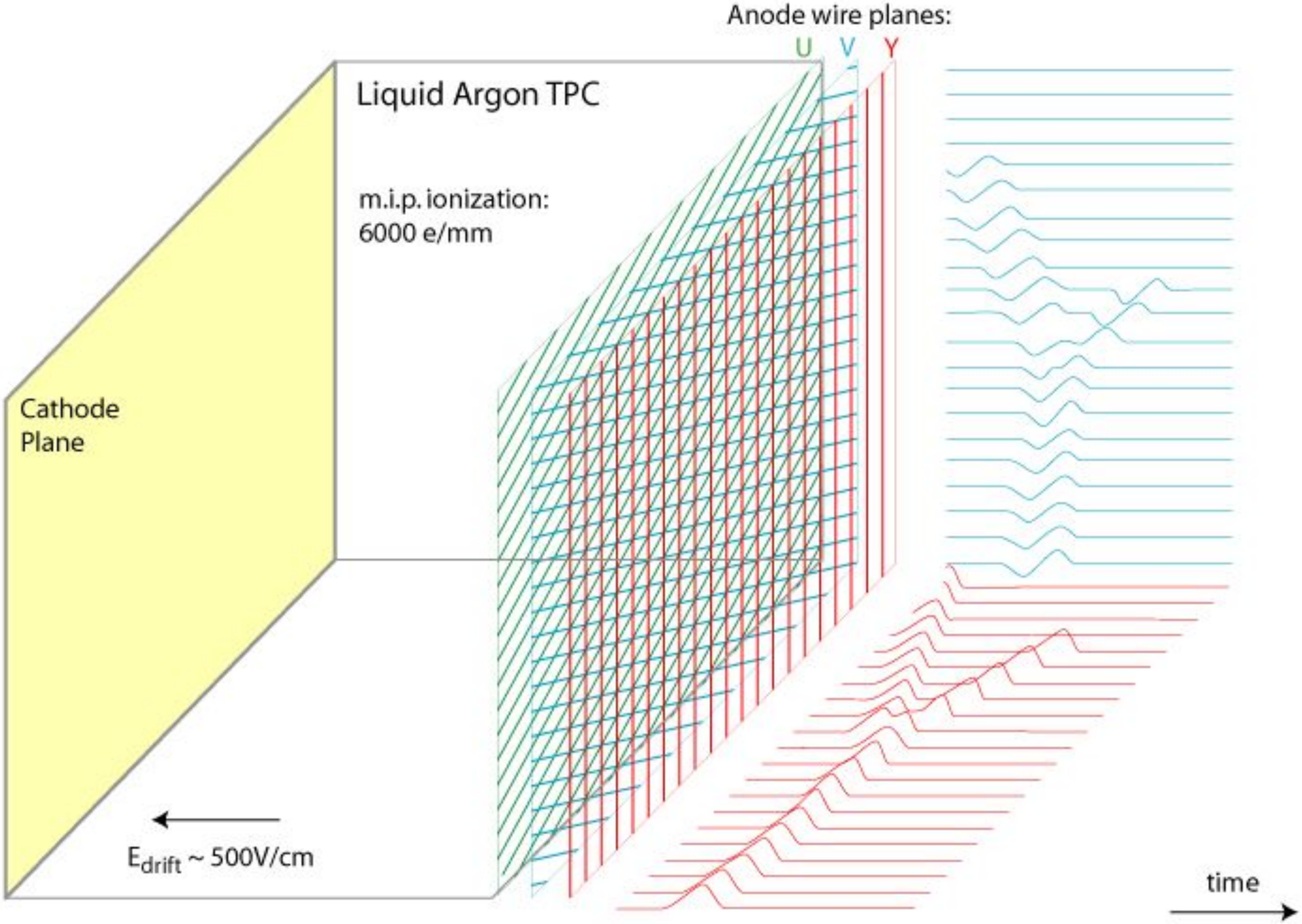
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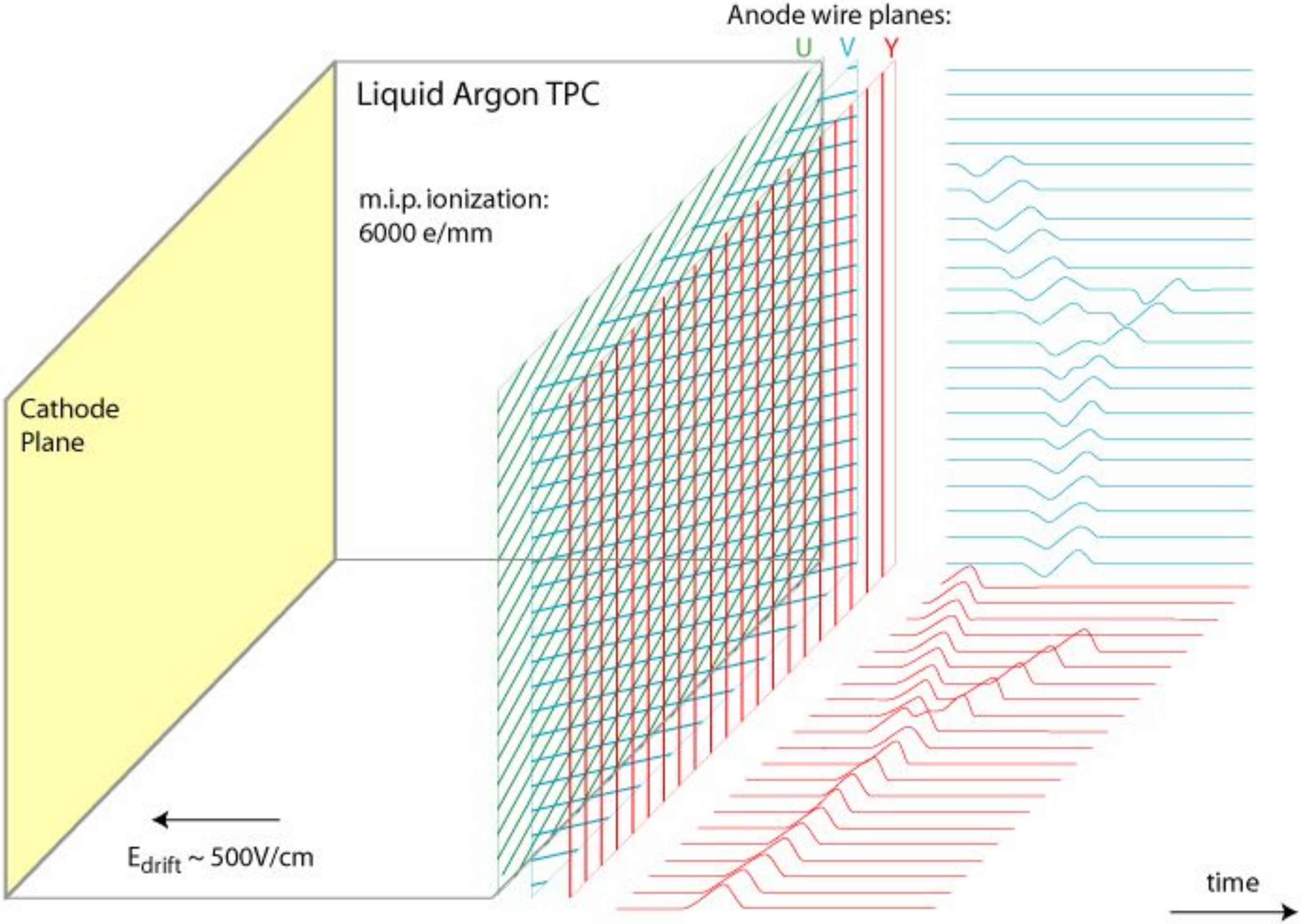
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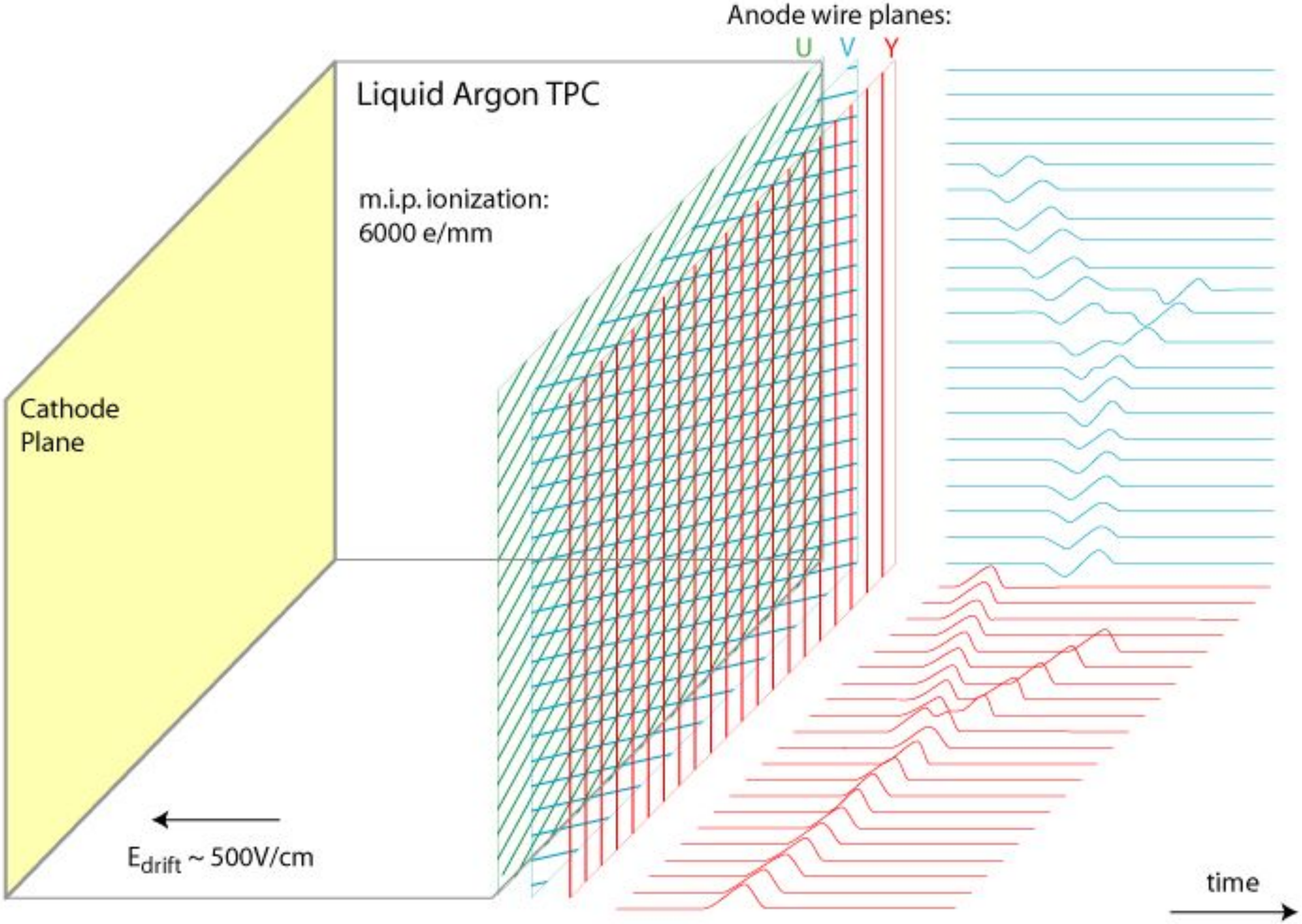
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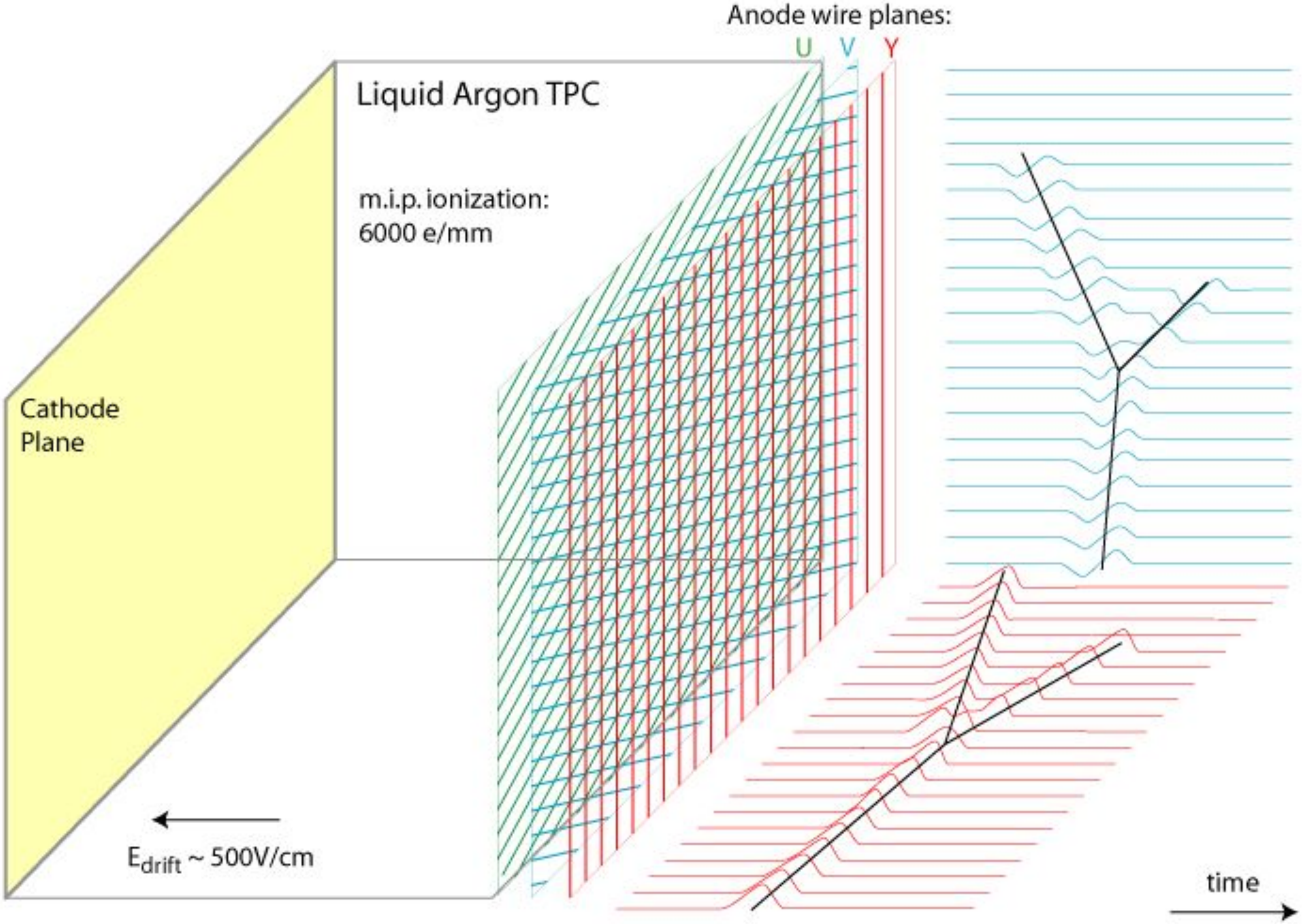
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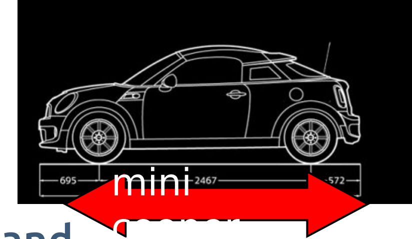
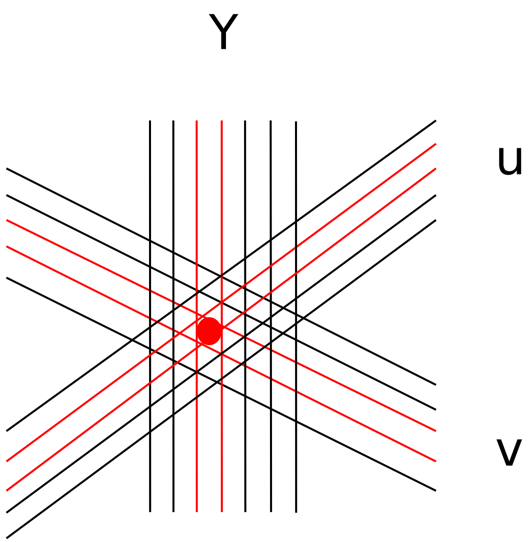
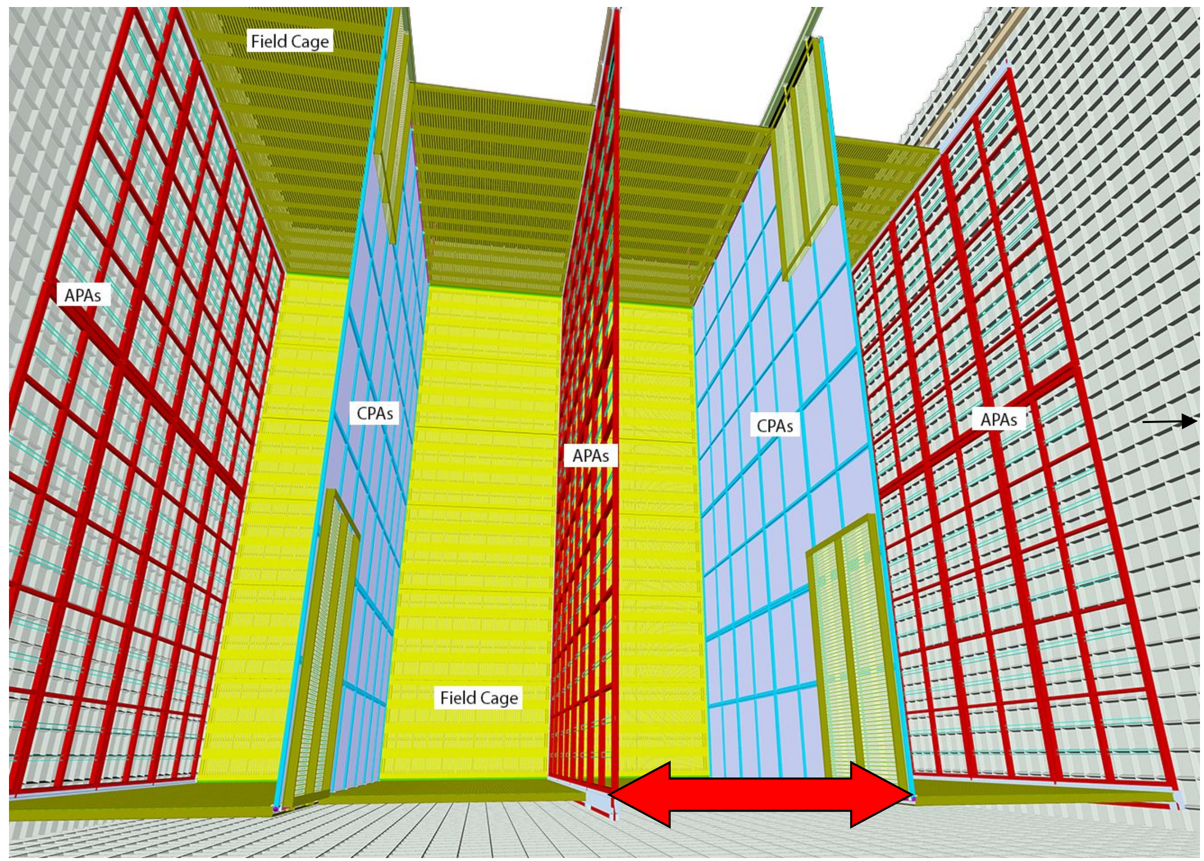
DUNE LArTPC design



- Anode Plane Assemblies (APA) each containing two induction planes and one collection plane, wires at stereo angles - interspersed with Cathode Plane Assemblies (CPA).
- 3.6m drift distance



Drift direction view: three wire planes.
“u” and “v” are induction planes.
The dot represents a localized charge.



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DUNE

DUNE LArTPC: signals to be detected

- Beam neutrinos:
  - appearance of ν_e and anti-ν_e
  - e/γ separation cobmined with high efficiency is key
- Cosmic ray muons
- Atmospheric neutrinos
- Potentially…
  - Supernova Burst neutrinos ("SNB")
    - time scale of the burst: O(10s)
    - events per kiloton: O(100)
  - Nucleon Decay
- Background radioactivity (e.g. ^{39}Ar)

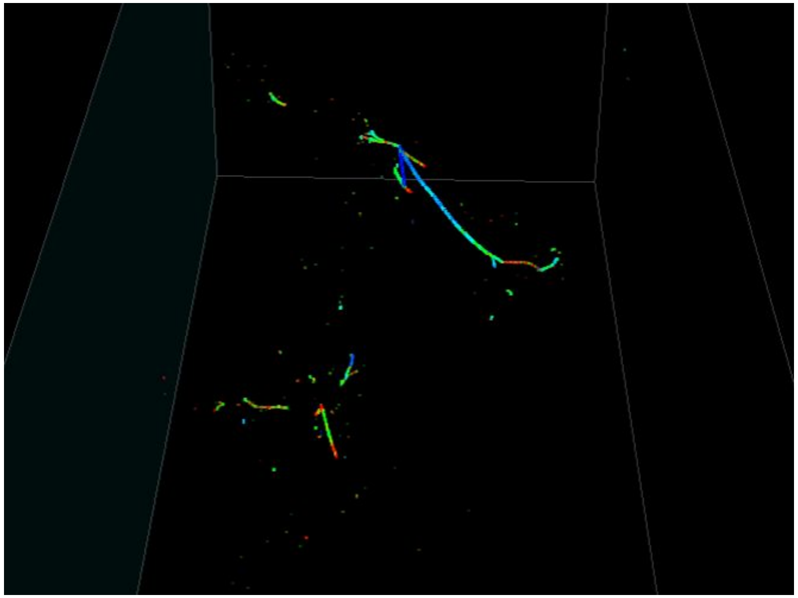
- Different signatures and energy scales of the phenomena under study require thorough design of online systems and of DUNE data flow in general.
- Events can be quite complex (cascades, decays etc).
- Accurate measurement of charge is essential for physics performance (energy, PID via dE/dx etc).

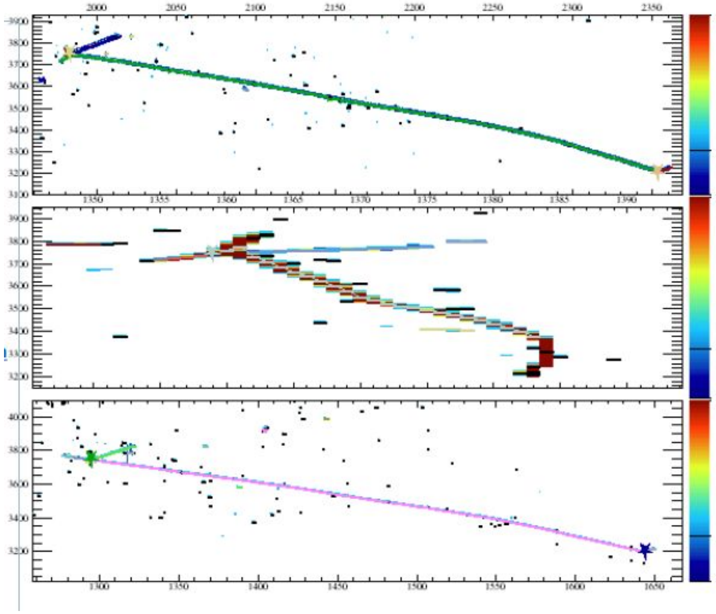
LArTPC vs "conventional" TPCs

- Majority of gas-filled TPCs used in experiments over the past decades utilized MWPC with pad readout, which makes 2D imaging in each time bin relatively straightforward.
- Large scale of modern IF experiments (such as DUNE with its 40kt fiducial volume) precludes pad readout because of prohibitively high channel count and associated power consumption and dissipation, as well as cost. LArTPC is instrumented with wires, which means less information is available for reconstruction.
- IF experiments do not have apriori constraints on the vertex position (such as in collider experiment where the interaction diamond is well known).
- Magnetic field vs no magnetic field.
- TPCs used in collider experiments are combined with other detectors such as inner tracker and external calorimeter, and so for example measuring showers is not its primary function. With LArTPC for IF experiments, the instrument has few (if any) auxiliary detectors and must provide correct identification and measurement of secondary interactions in its volume, and yield precision measurement of dE/dx as well as calorimetry in same device.
- High efficiency of track and shower reconstruction is crucial to reach the science goals of DUNE.
- Beam nearly parallel to the wire planes poses additional challenge.
- Considerable range of energies and momenta needs to be measured accurately in the same detector.

What are we looking at in LArTPC?

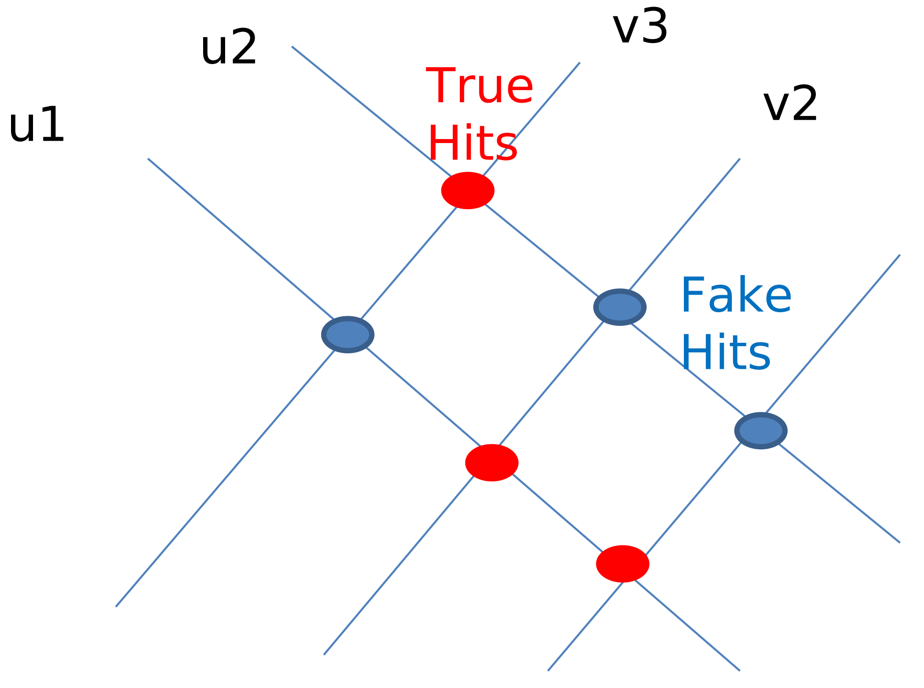
- One of the challenges in reconstruction is that interaction patterns we are dealing with contain features of different scale and complexity, and energies differ by orders of magnitude (from MeV to GeV range).
- "Traditional" approach to reconstruction is to start by exploiting continuity of objects in time (drift time). For example, time vs wire number pairs can be created, resulting in 2D track candidates, then an attempt is made to match them in 3D. Inspired by tracking methods used in HEP. Charge information is not used in initial steps of reconstruction. In some methods, hypotheses about the pattern being recognized are tried early on, before a 3D image is formed, which could lead to biases.





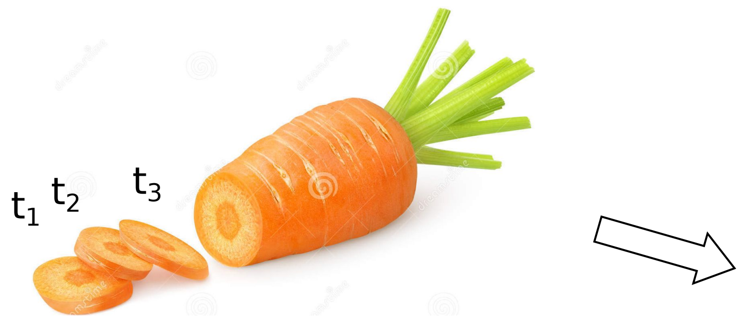
Reconstruction challenges: wire readout

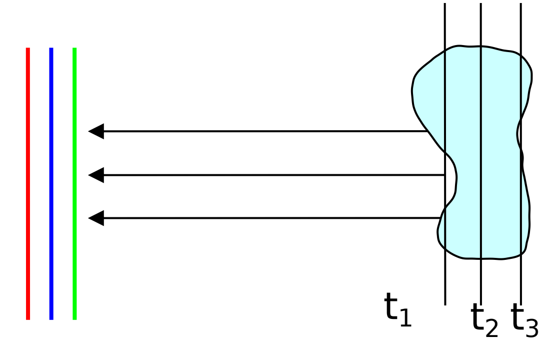
In a single time slice, reconstruction of multiple hits detected on the wires are subject to a well known problem in experimental HEP: the "ghost hits", a feature of many strip and multiwire detectors.



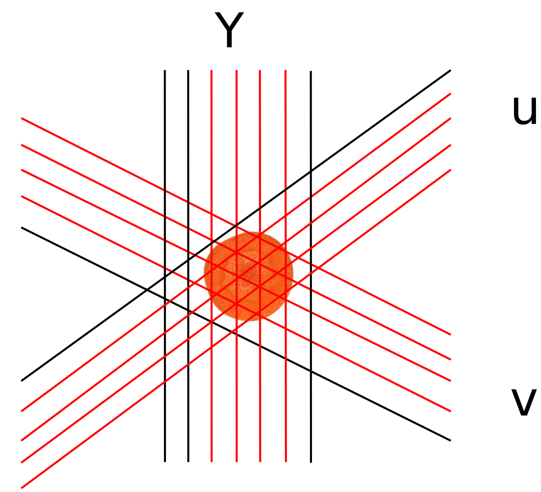
A closer look at the wire-plane readout

- DUNE TPC wire-plane readout has a useful feature - ***same*** drifting charge is measured not once, but three times, and in different geometric projections.
- Due to the finite frequency of the ADC clock the 3D object being measured becomes a set of 2D slices - in each time bin.





Side view: three wire planes (u,v,Y) and the direction of electron drift



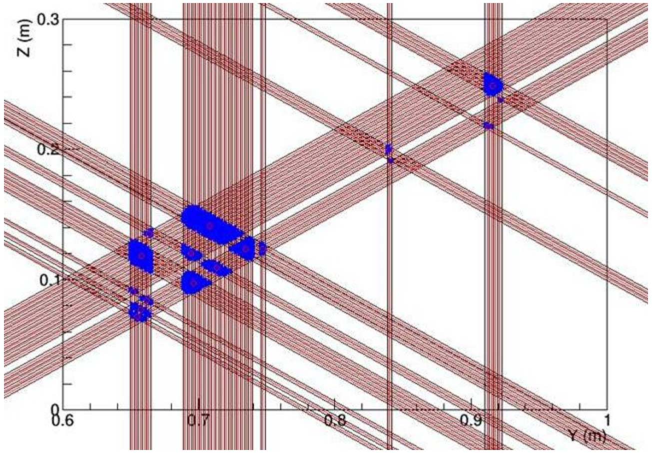
Drift direction view: three wire planes. The carrot slice represents charge measured in a single time bin.

- Charge collected on each wire in a given time bin is effectively a line integral of the charge density of the 2D slice.
- There is therefore a compelling analogy between this TPC measurement technique and Computed absorption Tomography with Multiplanar Reconstruction, albeit with a small number of projection angles (3).

Motivations for the tomography approach

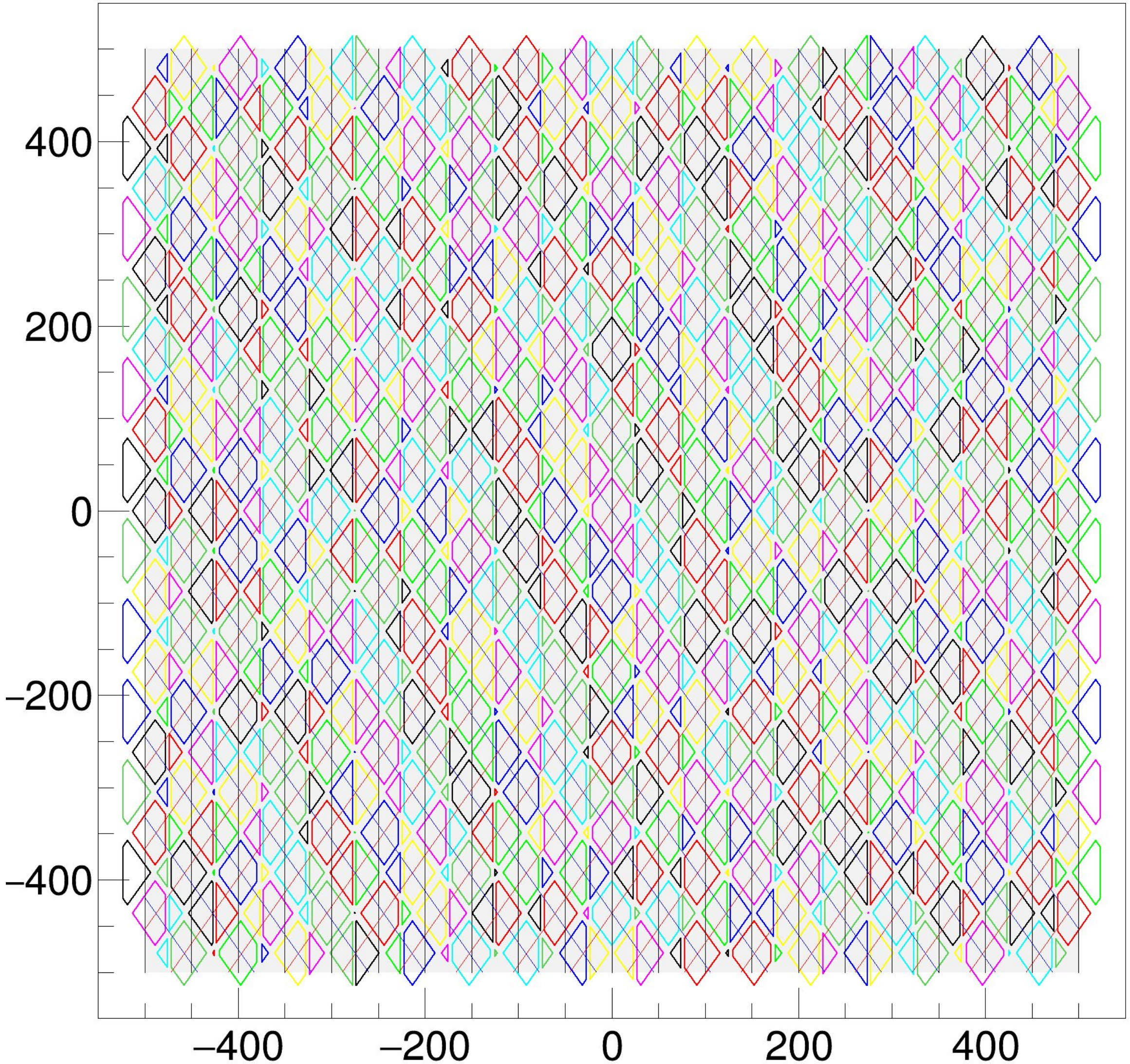
Approaching the wire-plane readout of LArTPC as a tomography problem has a number of potential advanteges over existing methods:

- "Traditional" time-vs-wire methods often put emphasis on trying hypothesis early on (track, shower, etc), which does not describe equally well all cases. Tomography approach does not have this limitation - having a 3D model of the event before most of pattern recognition is done means having more information and less bias. Potentially opens possibilities for machine learning methods of image analysis.
- It opens the possibility to explore existing techniques and mathematical methods for 3D imaging developed in other disciplines.
- Measurement of charge which is crucial for the TPC physics performance becomes an integral part of the event reconstruction



Reconstruction can now be formally described as an inverse problem in 2D, in the plane perpendicular to the drift direction. The main challenge in solving this problem is that it is underdetermined with just 3 projection angles.

"Wire Cell"

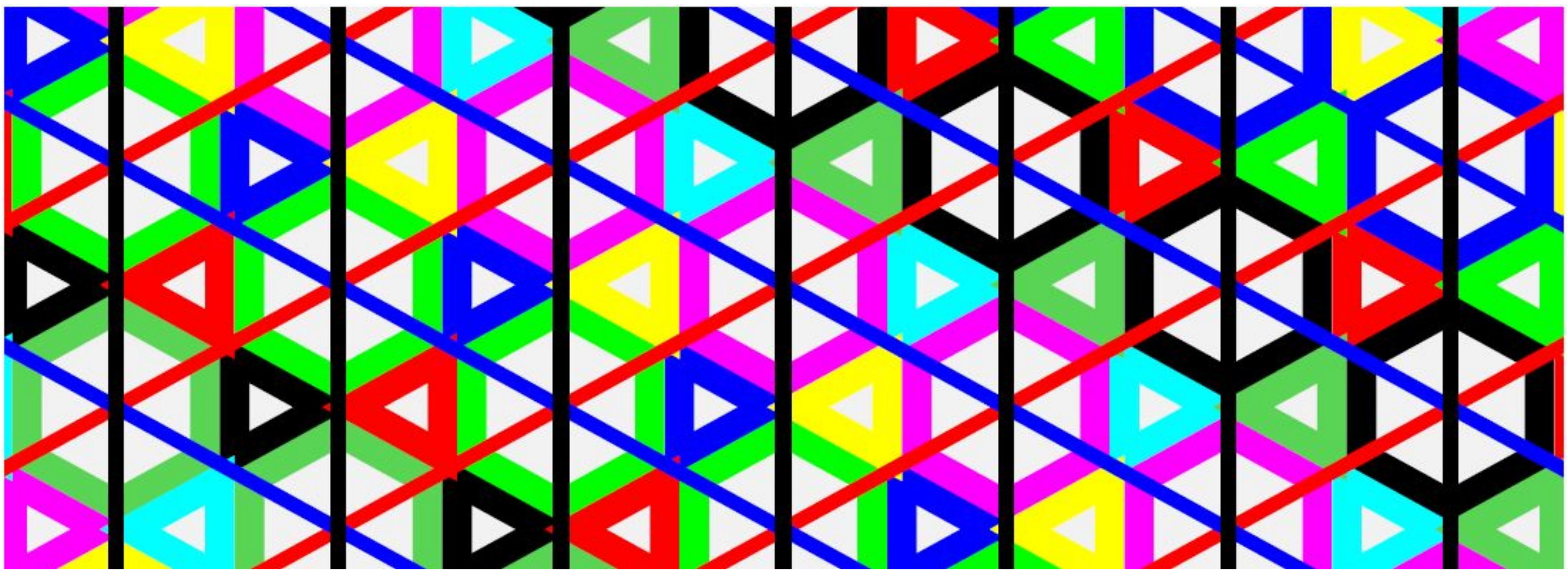


Wire Cell: comparison to CT

- Since the total charge on a sensor wire corresponds to a linear integral of charge density along the length of the electrode, an analogy can be drawn between a single wire and an individual X-ray beam in absorption tomography.
- Having discrete time bins which contain information about a slice of the measured object makes Multiplanar Reconstruction an attractive choice (i.e. a 3D model of object is built by "gluing together" reconstructed 2D slices). This, again, is a common technique in CT and it is adopted in Wire Cell.
- In CT, a common approach is to voxelize the volume in which reconstruction is being done, with the goal of estimating absorbance in each voxel. In Multiplanar Reconstruction this leads to introduction of pixels in 2D slices. In Wirecell, this is accomplished by tesselation (tiling) of 2D space in each time bin.
- Challenge with TPC readout: with N wires, the number of degrees of freedom scales $\sim N^2$, while the number of inputs scales as $\sim N$. This is analogous to sparse data tomography.
- There are many tomography methods and not of them are well suited for solving the LArTPC reconstruction problem. The Wire Cell method utilizes the Markov Chain Monte Carlo Algorithm combined with regularization, both approaches known in CT industry.

Example of tesselation of sensor wire plane (based on μBooNE geometry)

- There is more than one way to "tile" a 2D object for purposes of tomographic reconstruction. Optimal algorithms are being investigated. Below is an illustration of tesselation used in reconstruction of μBooNE events.

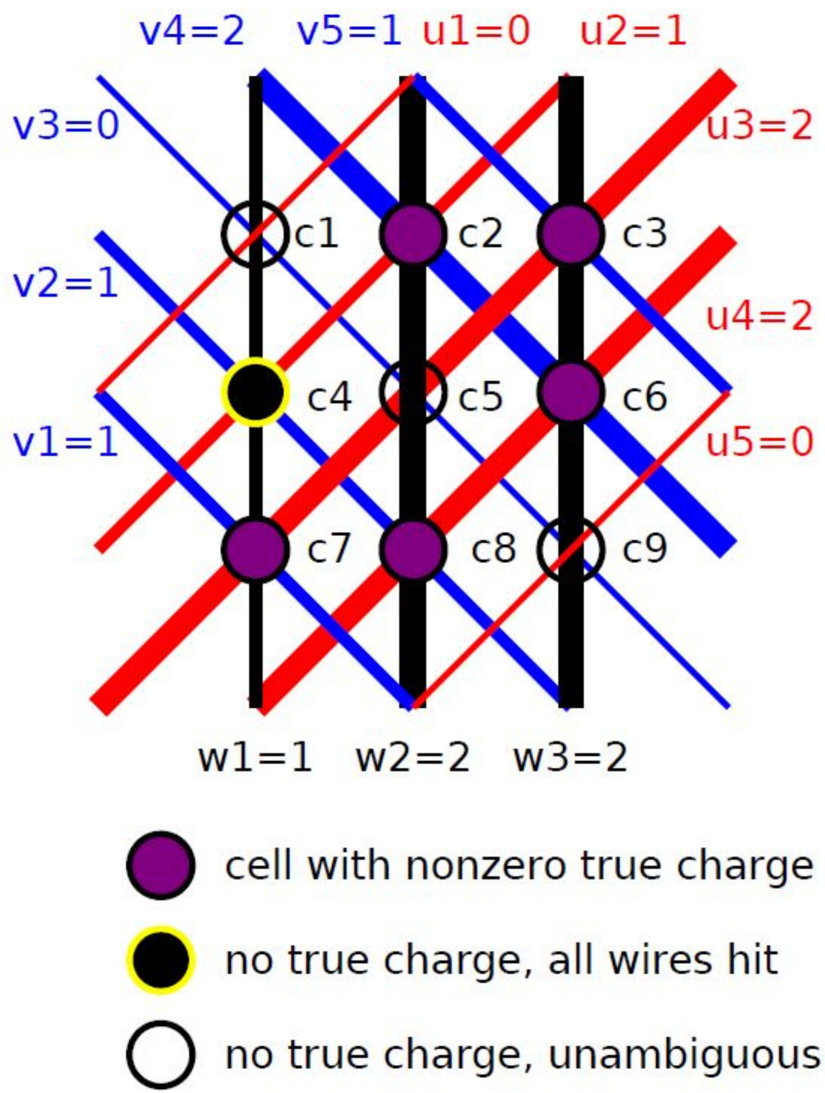


Wire vs Cell ambiguity

- With tiling complete, the 2D plane can now be considered as an array of discrete cells.
- Charges present in cells and signals registered on wires can be considered as vectors related via an adjacency matrix:

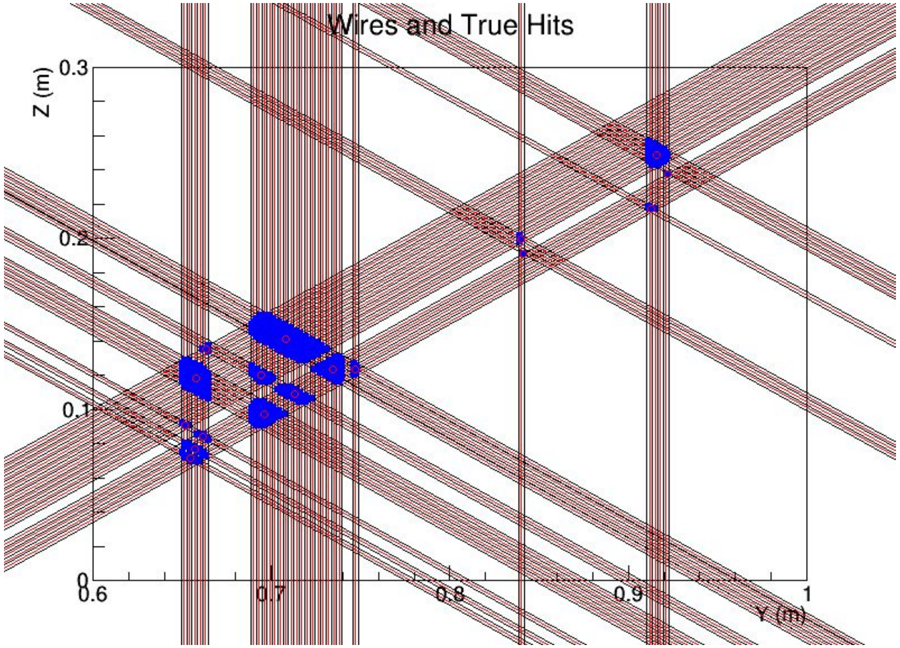
$$w = Gc$$

- Classic inverse problem - have wire information but really need cell information.
- Solve by matrix inversion?
- The matrix is defined by the geometry but in general, it can't be inverted. In general, there are more cells than wires. The problem is often underdetermined (ill-posed).



Wire Cell: merging cells as regularization tool

- Wire Cell algorithm includes regularization to reduce the number of unknowns in order to ultimately solve the inverse problem.
- Adjacent cells with non-zero charge are likely to be associated with a localized ionization pattern. For example, a track inclined with respect to the wire plane will "light up" a group of adjacent cells.
- For that reason, groups of adjacent cells can be formed, in the process called "merging". Likewise, the wires associated with these groups can be merged as well reducing number of dimensions in the problem.



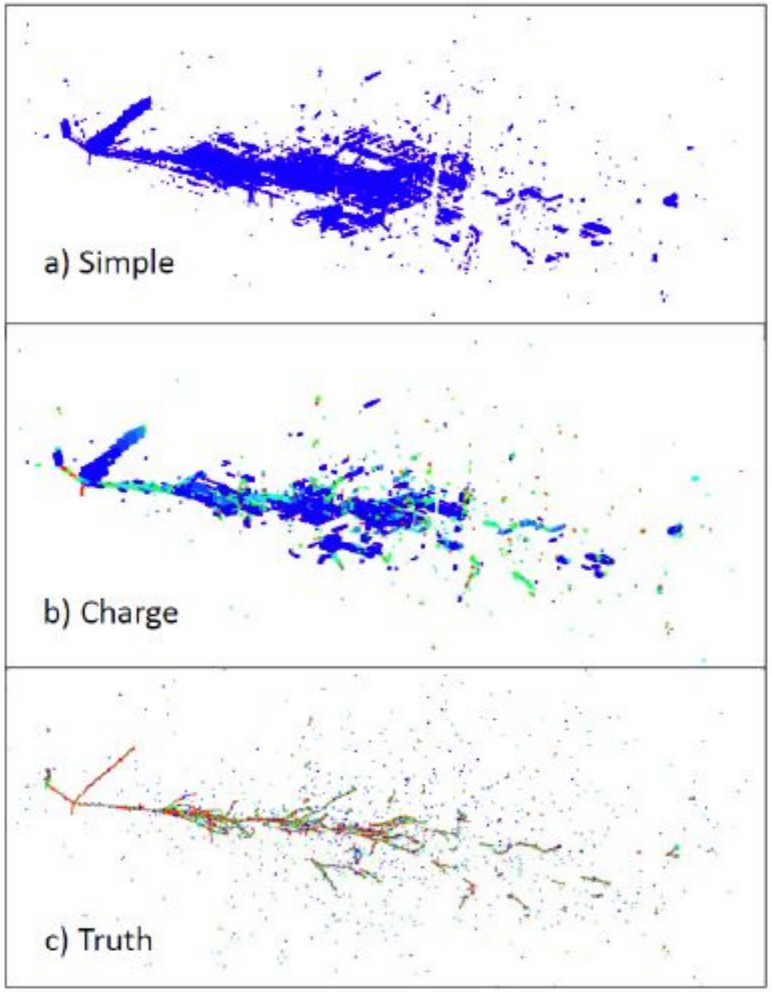
Wire Cell: the method

- The problem can then formulated as minimizing the residual $||w_{expected} - w_{observed}||$ over cells and wires.
- Assuming:
  - W_m is a vector merged wires (signals)
  - C_m is a vector of merged cells
  - G is the "geometry matrix" mapping merged cells to merged wires
  - V is covariance matrix (which can be approximated as a diagonal for now)

  the quantity to be minimized can be written as $x^2 = (W_m - G*C_m)^T V^{-1} (W_m - G*C_m)$
- The phase space being probed is the set of merged cells included in the computation.
- Secondary regularization is possible since one can introduce a penalty term in the x^2 by interrogating adjacent time bins (continuity hypothesis) - whether a merged cell is found in the vicinity of point in the next time bin or not. This approach must be tuned with heuristics since it works better for some hypotheses than another - for example, for particle tracks compared to EM showers.
- Markov Chain MC: eliminate cells, update matrices and recompute x^2. Compare to see if there is an improvement. Repeat. Solve for C.
- Combine the results of 2D imaging in each slice to obtain a 3D voxelized representation of the event.
- Do pattern recognition (e.g. track vs shower): more details below.

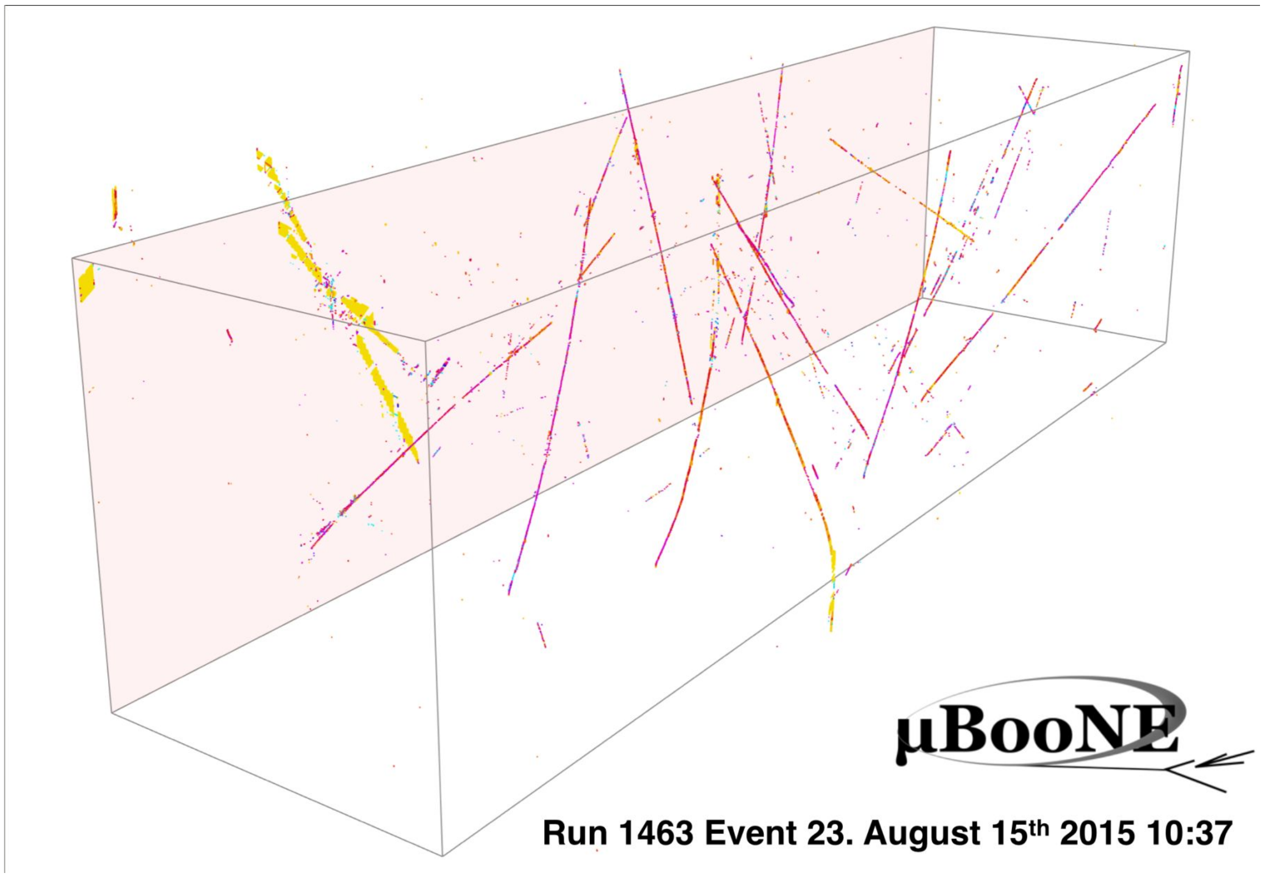
Wire Cell reconstruction example
(Simple hit finder, charge info, MC truth)

Wire Cell reconstruction



Wire Cell: example with real data

- Wire Cell is currently being tested using real data collected in the μBooNE experiment at FNAL (preliminary).



Performance

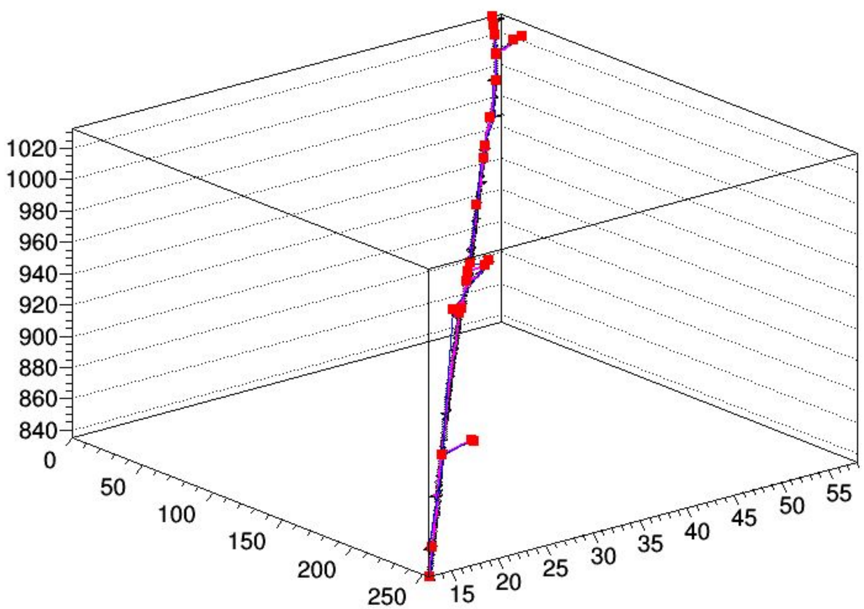
- Wire Cell uses Markov Chain MC to minimize x^2 and it's a CPU-intensive procedure due to essentially combinatorial growth of the number of candidate cells to be tried out with a number of inputs.
- On an average CPU, it currently takes O(1) hours to reconstruct a typical event.
- Need to understand how this method can be improved.
- Potential application of parallel/MPI/GPU technologies.

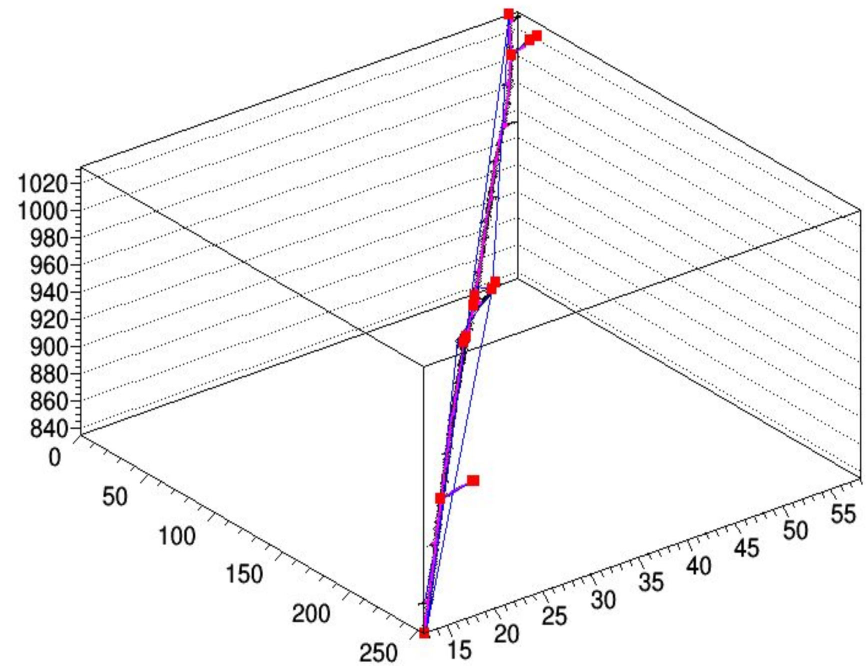
Pattern Recognition

- Pattern recognition is the stage in reconstruction where 3D voxels have been identified using the technique described in previous slides, corresponding voxel charge has been calculated and this information is used to identify physics objects and ultimately extract details of the interaction being observed.
- 3D clustering:
  - connectivity in 3D helps identify candidate tracks not parallel to the wire plane
- A few methods are under investigation including Hough transform, as well as tools already in use in DUNE (e.g. Pandora toolkit).
- In general, pattern recognition is hard due to difficult event topologies (cf. EM shower overlaying single tracks).
- Since liquid argon is a dense medium, extra care is required when reconstructing tracks with "kinks" (point of large scattering angle along the track). Track segments need to be properly stitched together.
- Recently started exploring machine-learning techniques, in particular with neural networks.

Pattern Recognition: track merging

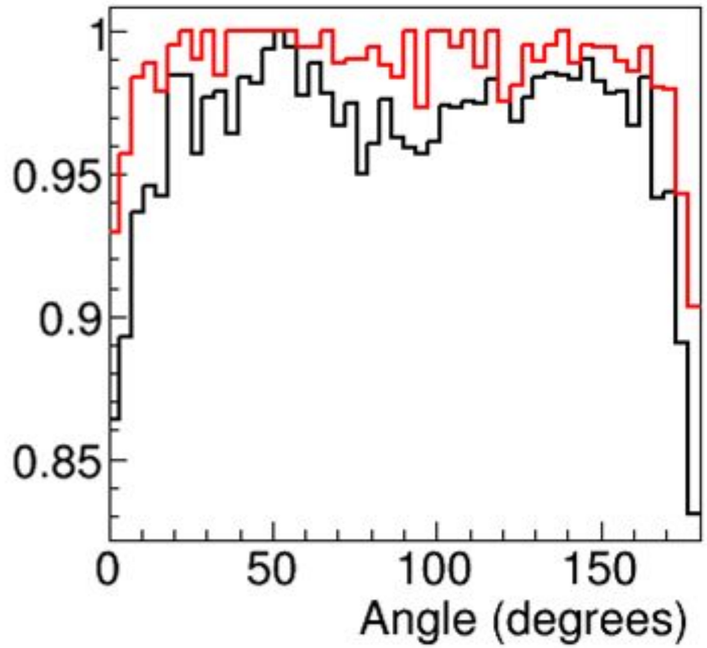
- An improved algorithm combines track segments: fragmented track shown on the left is recombined as shown on the right.





Reconstruction Efficiency

- Tracks parallel to wire plane are a difficult case to handle for any reconstruction algorithm since one dimension (time) is collapsed. Plotted below is efficiency for muon track as a function of angle between the track and the wire plane, for two different selection criteria.

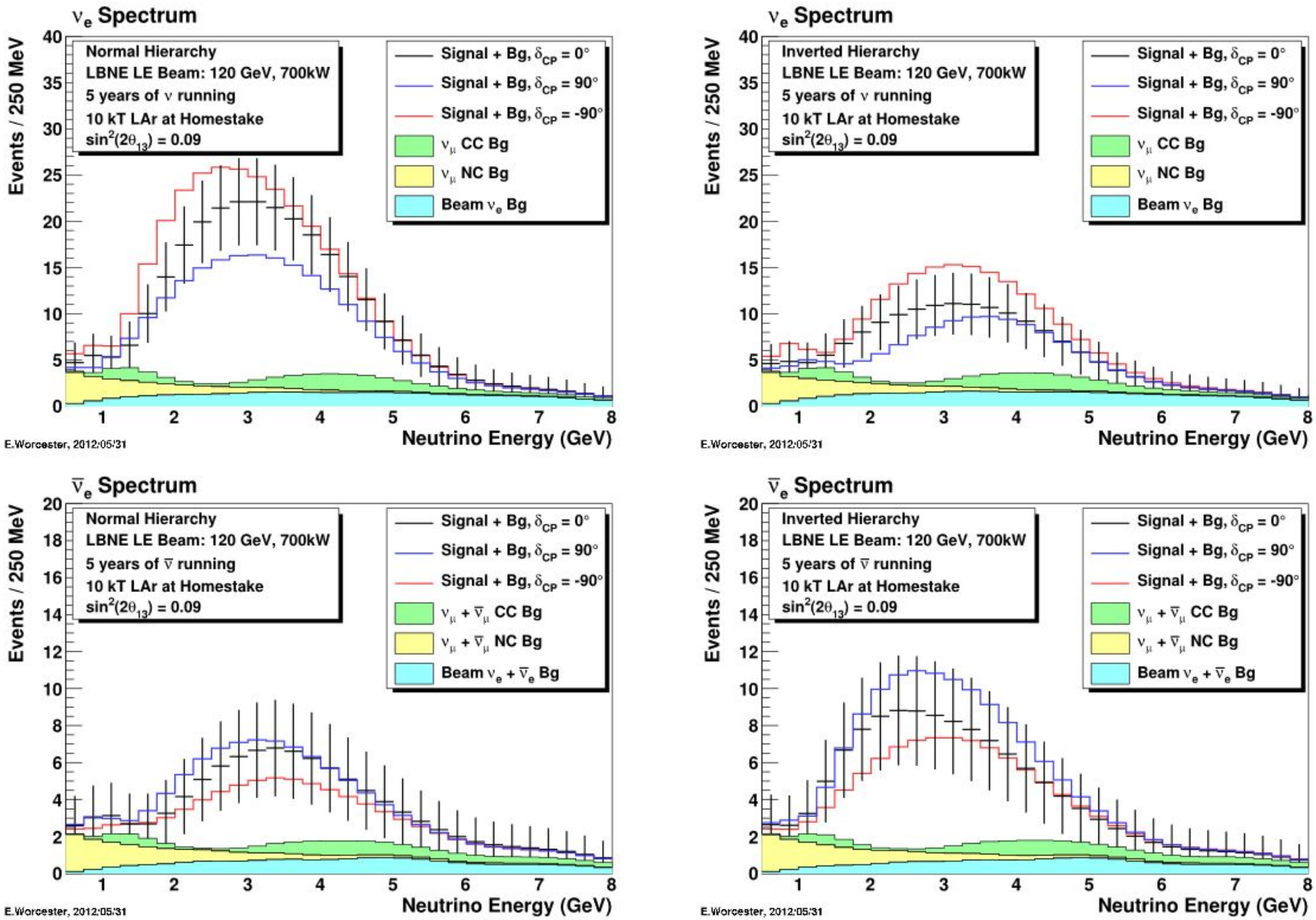


Summary

- The large-scale Liquid Argon TPCs designed for the current and future generations of Intensity Frontier experiments have different characteristics compared to Time Projection Chambers used in collider experiments, regarding both readout method and the scope of measurements (e.g. it's both a fine-grained tracker and a calorimeter).
- First generation of reconstruction software for LArTPC was influenced by methods borrowed from tracking detectors in HEP.
- It has been realized that the unique feature of LArTPC such as one being designed for DUNE is that same drifting charge is measured three times by three separate sets of sensor wires, which creates a close analogy to the sparse angle tomography method.
- The Wire Cell method is using a few approaches from the tomography domain: voxelization of the object, imaging in individual 2D slices using Markov Chain MC, and multiplanar reconstruction of the 3D object.
- Initial tests have been performed with Monte Carlo data and also with real data coming from the μBooNE experiment at FNAL.
- The method is still very much work in progress, initial estimates indicate efficiency of track reconstruction in excess of 90%. This will need a careful study as it depends on event topology and detector parameters.
- Wire Cell may benefit from application of parallel computing techniques (accelerators, GPUs etc).

Backup slides

ν spectra in the Far Detector (an example of simulation)



Supernova Burst: ν spectra and detection modes