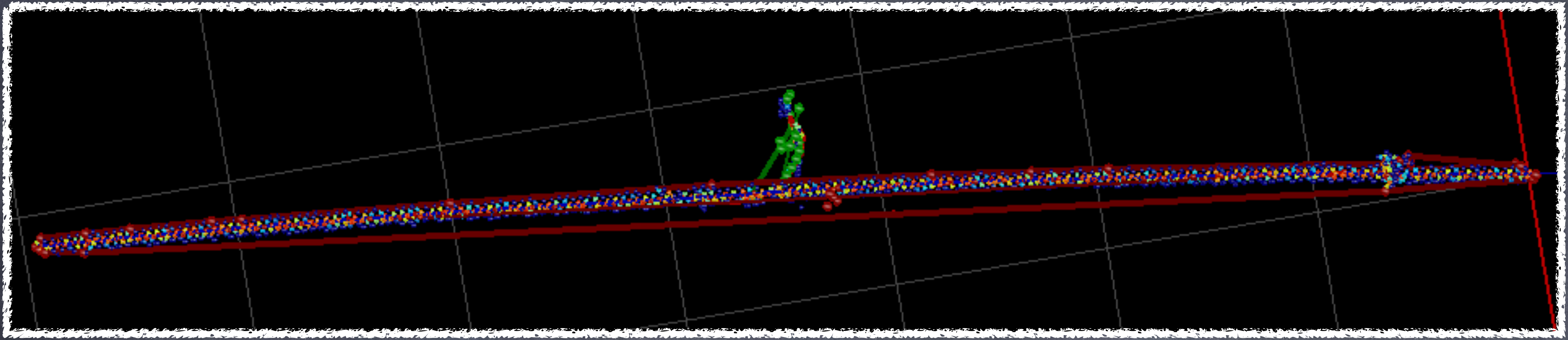

Building 3D Space Points in Liquid Argon Time Projection Chambers

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Exa.TrkX Kickoff Meeting

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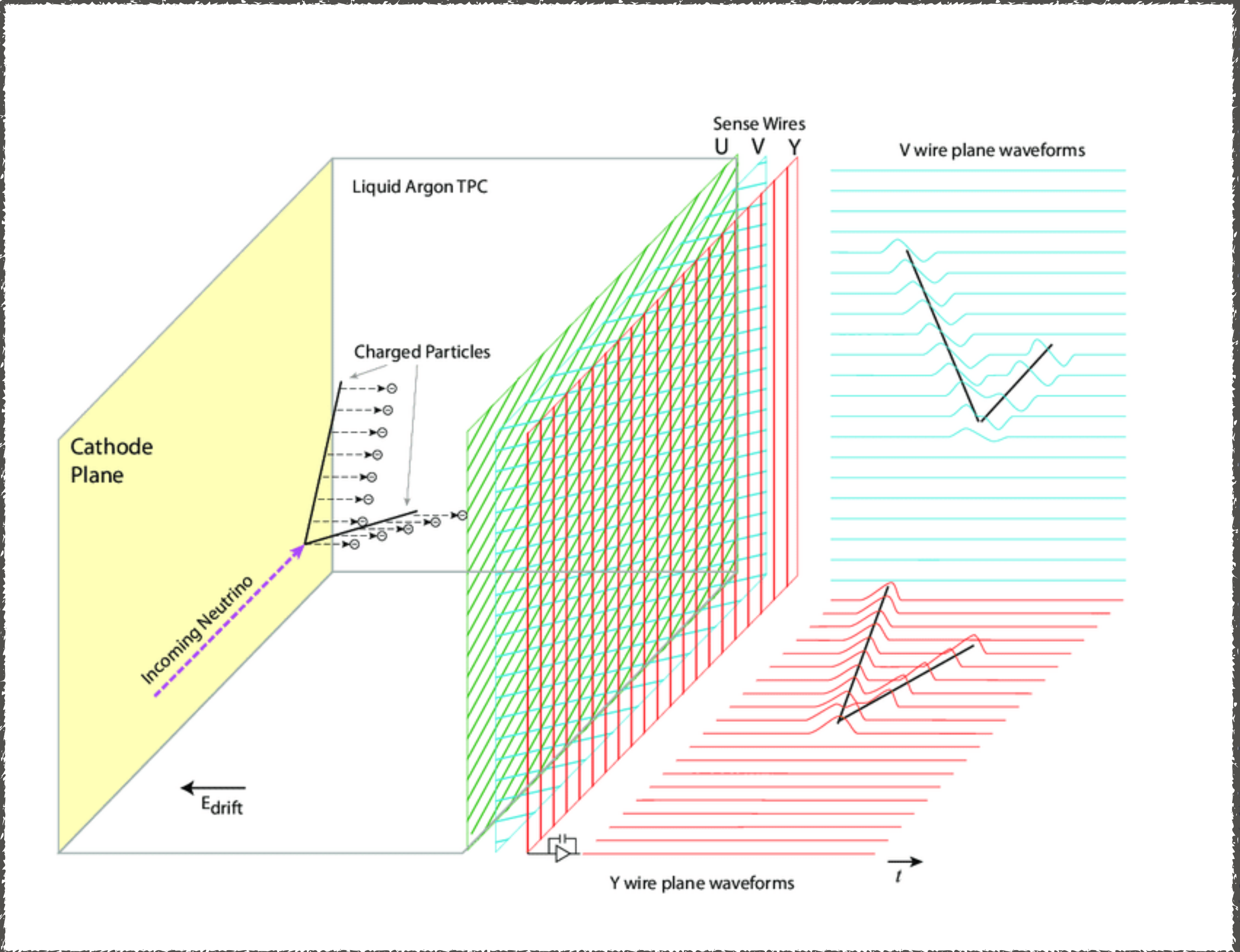
Overview

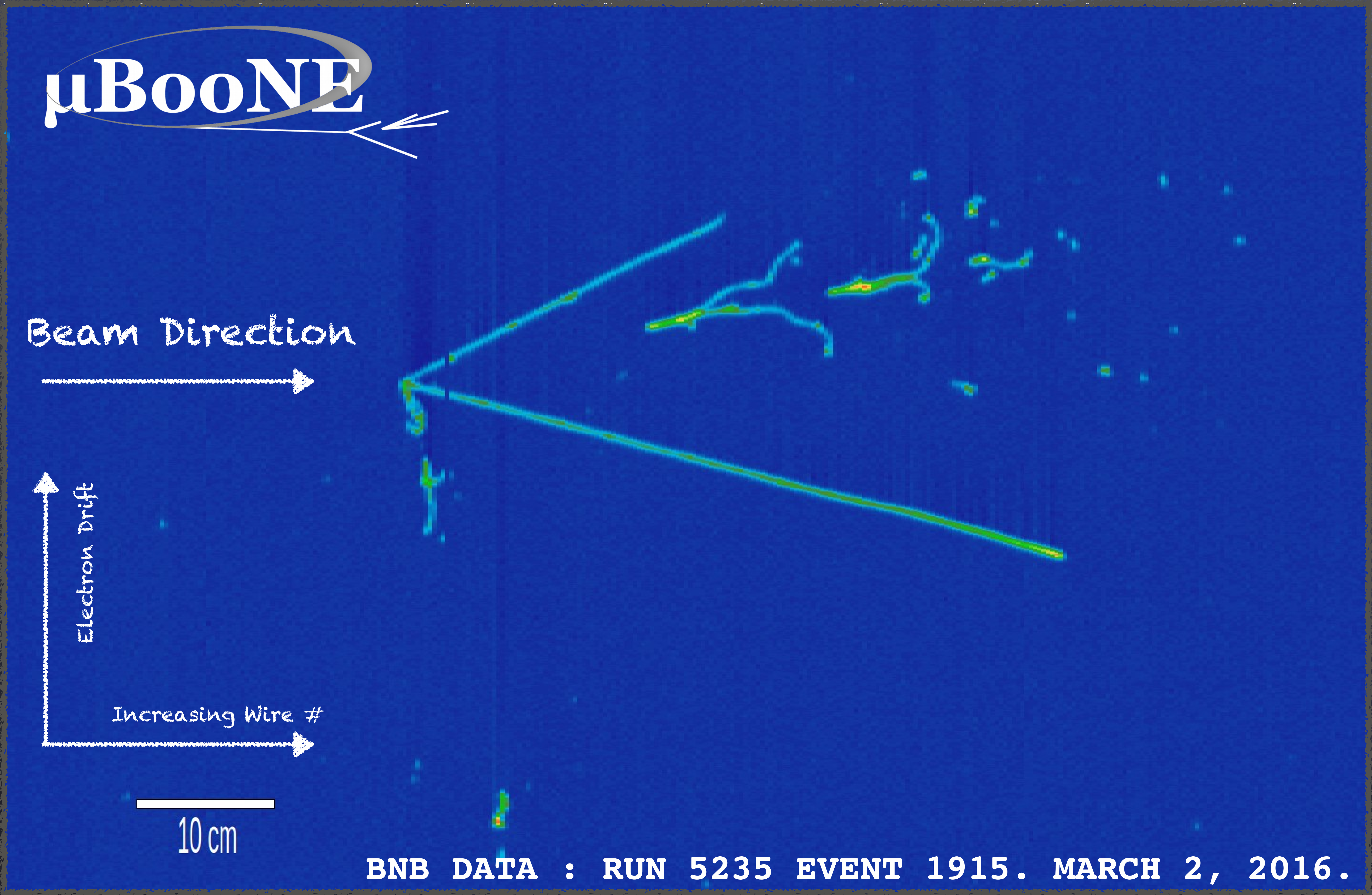
- Overall Goal: True 3D Reconstruction of events in Liquid Argon Time Projection Chambers
  - First Step is the creation of 3D Space Points from 2D information
  - Hopefully this sets the stage for Kazu/Taritree
- Plan for this presentation:
  - Introduction to how 3D Space Points are formed in wire readout Liquid Argon Time Projection Chambers (LArTPC)
    - Will try to illustrate the pitfalls
    - You will naturally conclude that machine learning techniques are perfect for solving this problem
  - Assume little to no familiarity with LArTPCs so will give a brief introduction

Single Phase LAr TPC



- Typical Dimensions
  - Drift 1.5-2.5 m
  - Vertical 1.5-2.5 m
  - Length ~10 m
- Drift Field 500 V/cm
  - v ~1.5 mm/us
  - Exposure time on order of ms
  - Electronics sample rate ~0.5 us
- Wire orientations 60°
- Also instrumented to detect light emitted during the ionization

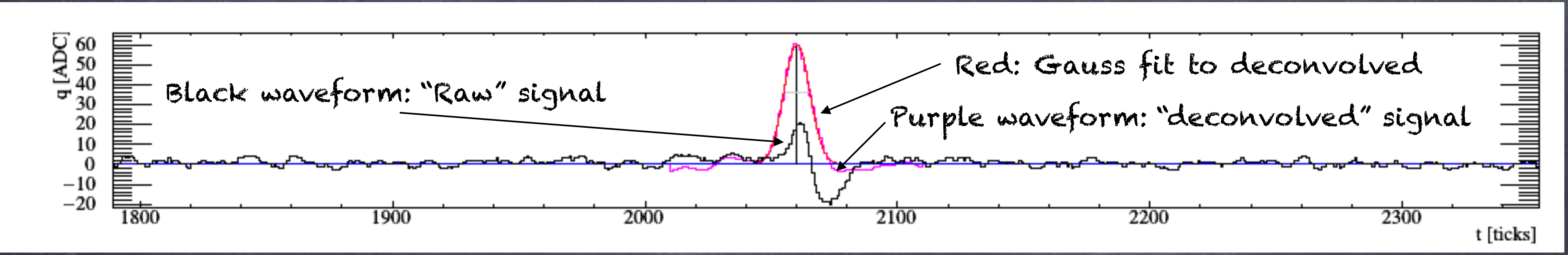
MicroBooNE: 170 tons, SBND: 220 tons, ICARUS: 760 tons, ProtoDUNE: 800 tons


μBooNE
Beam Direction
Electron Drift
Increasing Wire #
10 cm
BNB DATA : RUN 5235 EVENT 1915. MARCH 2, 2016.

"Hit" Based Reconstruction

"Raw" waveforms for induction planes are bipolar, for the collection plane they will be unipolar

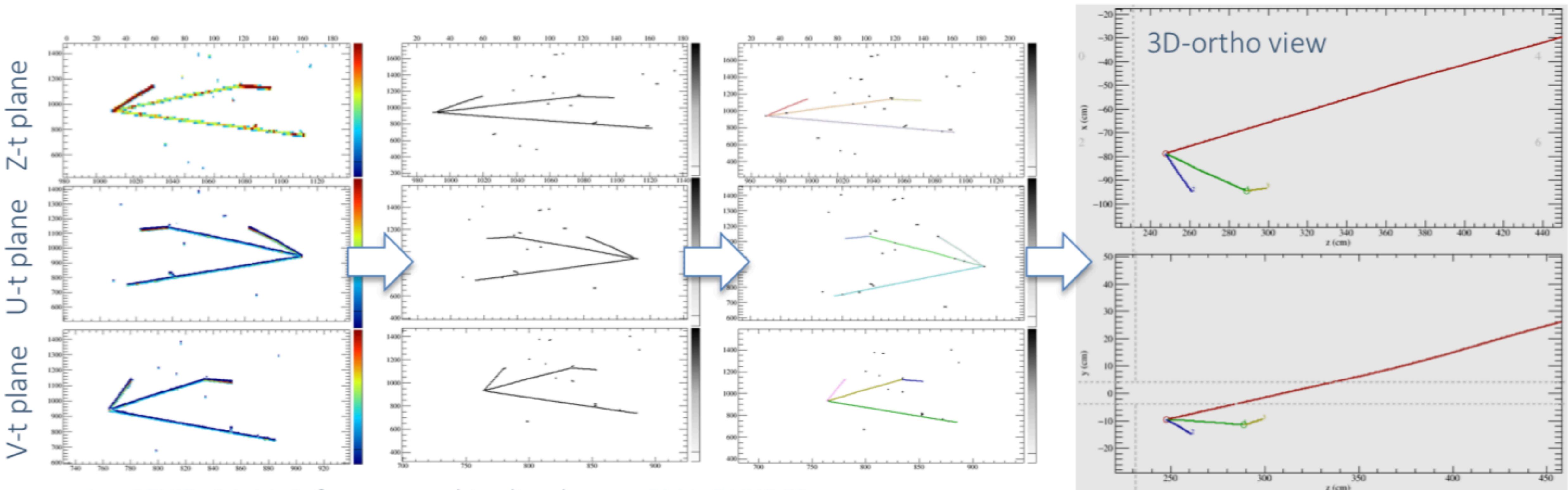
Example of a typical signal from the middle induction layer



- Signal processing uses a deconvolution procedure to recover gaussian shaped unipolar waveforms.
- A subsequent algorithm identifies and fits "hits", returning peak time, width and deposited charge

"Classic" Event Reconstruction

2D ADC → 2D hits → 2D objects → 3D structures → PID & energy

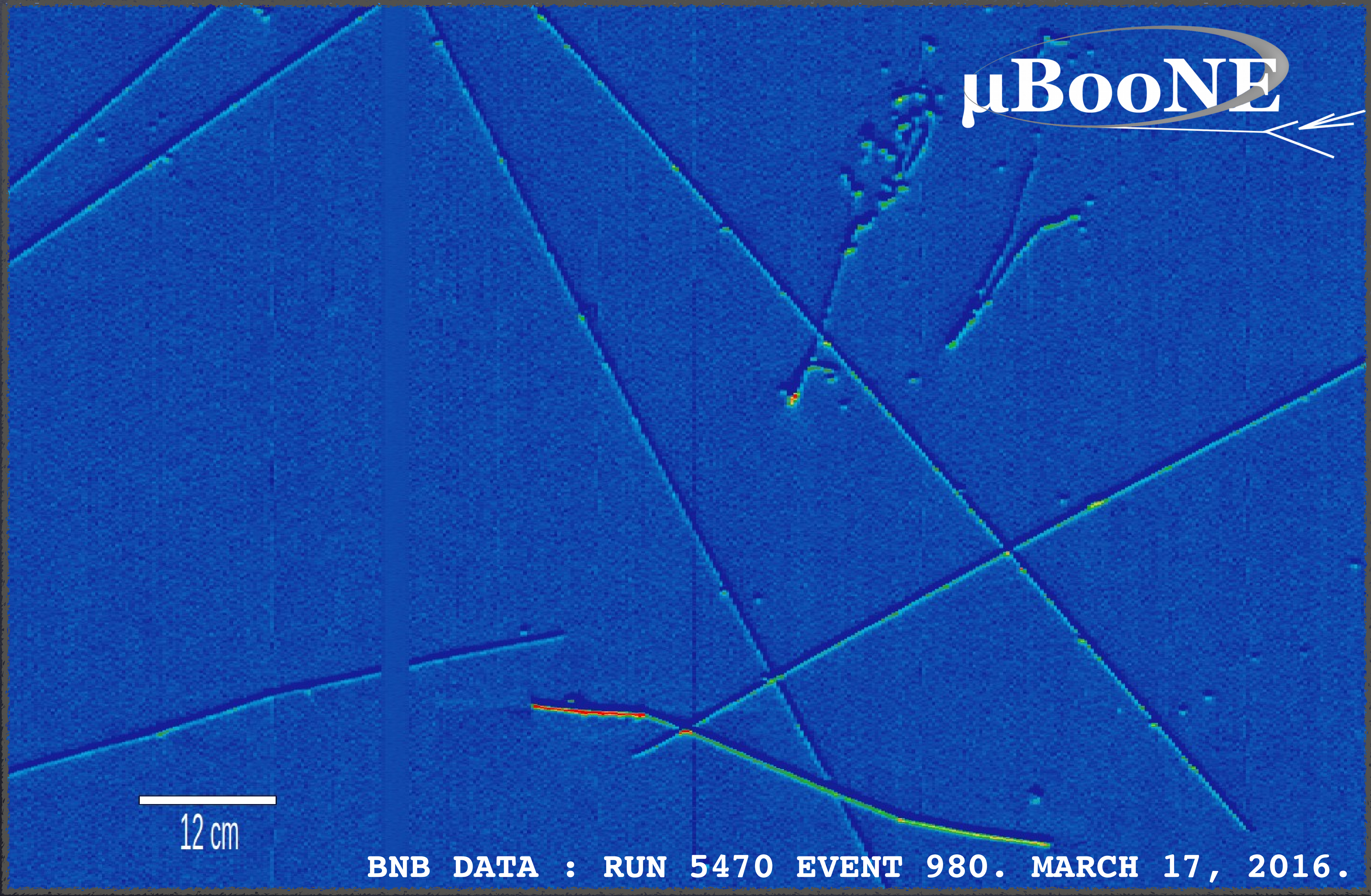


sim: GENIE+G4+LArSoft, reco: gaushit + linecluster + PMA, DUNE FD geometry

Here: trivial topology for illustration, all tracks/vertices correct, but LArTPC can be hard!

- dense medium – multiple scattering, secondary interactions
- **unlike colliders:** no fixed interaction location, no hits ordering, no event direction in non-beam physics
- „special" orientations in LArTPC: isochronous, along drift, along readout wire
- difficult pattern recognition of low energy and/or multiple EM cascades
- **long chain of pattern reco / 3D reco algorithms prone to inefficiency accumulation**

Slide by Robert Sulej - Connecting The Dots 2017


μBooNE
12 cm
BNB DATA : RUN 5470 EVENT 980. MARCH 17, 2016.

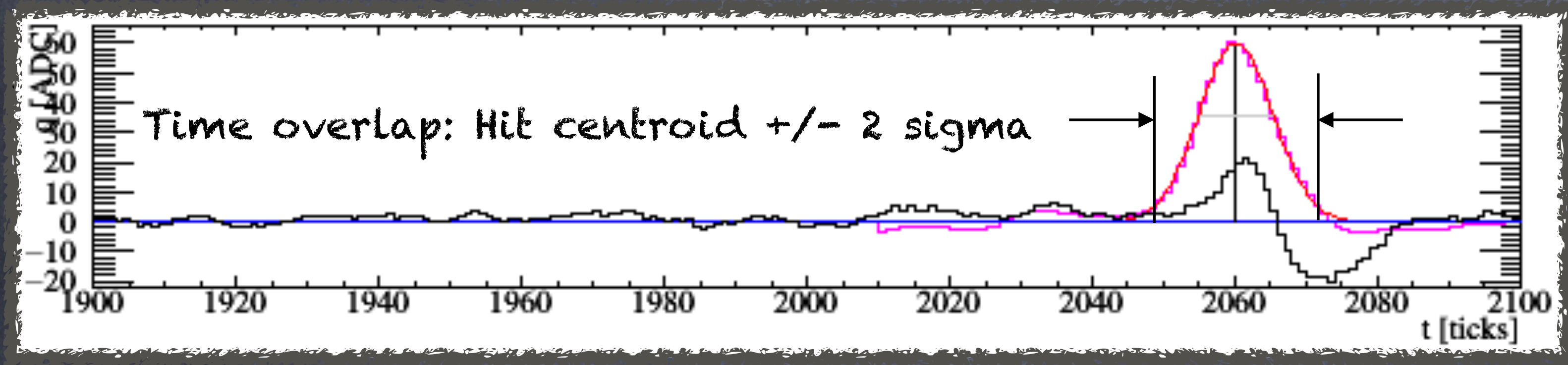
3D Space Point Building

- Alternative to 2D feature matching reconstruction is to first create 3D Space Points and then utilize 3D reconstruction algorithms
  - The problem here is in dealing with the ambiguous combinations of 2D hits that lead to "ghost" 3D Space Points
- Give brief overview of two methods:
  - The first approach aims to create all possible Space Points with goal of maximizing efficiency at the expense of purity
  - The second approach attempts to only build "correct" Space Points with the goal of better purity at the expense of efficiency

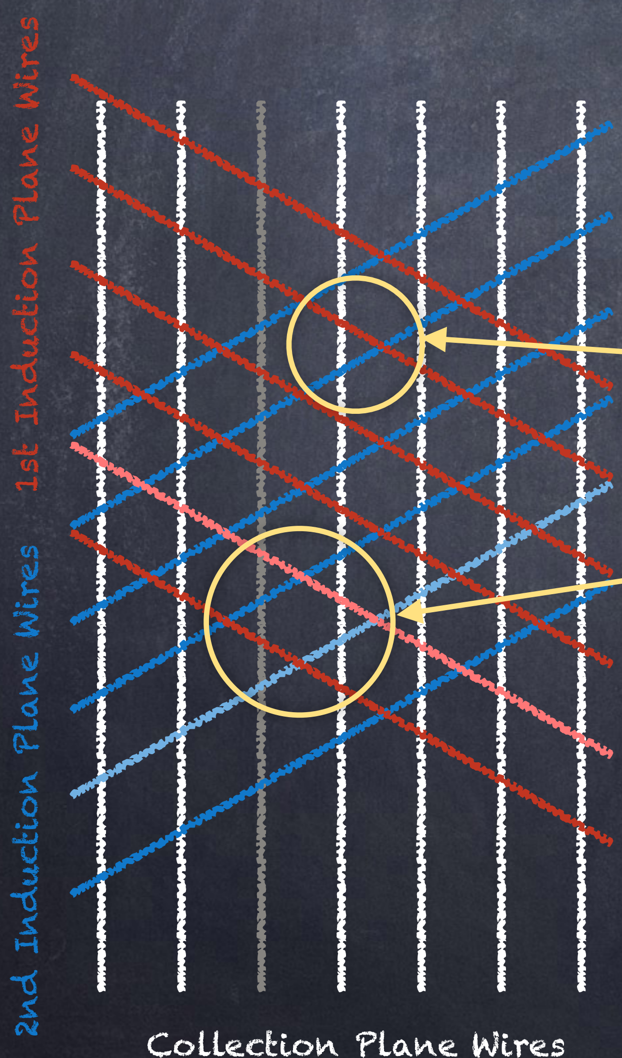
Simple Space Points

- Driving philosophy is that one builds and keeps space points from all "allowed" combinations of individual 2D hits
  - Want high efficiency for "true" space points, willing to accept to accept some level of "ghost" space points to achieve goal
    - In fact, one has to accept that there are always ambiguous combinations
  - Assume 3D level algorithms will resolve allowed ambiguities
- The approach is simple, the work is in handling the combinatorics

"Allowed" Combinations



First criteria: Hits must overlap in time



Second Criteria: Wires "intersect" forming a "minimum size triangle"

Allowed intersection

Non Allowed intersection

Given the typical width of a hit there are still plenty of combinations that will satisfy the second criteria: Ghost Points

Some Obvious Problems

- Creating space points depends critically on the 2D hit finding efficiency and quality
  - Missing 2D hits will result in either missing space points -or- (worse) the wrong space points
  - Obviously, the 2D hit finding depends critically on the signal processing
  - Dead/sick/noisy channels also lead to missing hits
- Building the "correct" space points from 2D hits also requires understanding inter-plane timing offsets

The Obvious Pathologies

- Isochronous tracks
  - Large numbers of 2D hits will agree in time and have good values for the metric above.
  - Generally, once the hits start to have a separation on the order of the average width then the quality metric starts to have value in sorting these out
- Distorted waveforms
  - Primarily an issue for track trajectories parallel to the drift direction - creates long pulse trains on a small number of wires
  - Also an issue when track trajectory is parallel to the wire orientation in a given sense plane
- Can we define a metric to help identify these cases?

Space Point Quality Metric

$$\tau_{pull,n} = \frac{(t_n - t_{ave})}{\sqrt{\sigma_n^2 - \sigma_{ave}^2}}$$

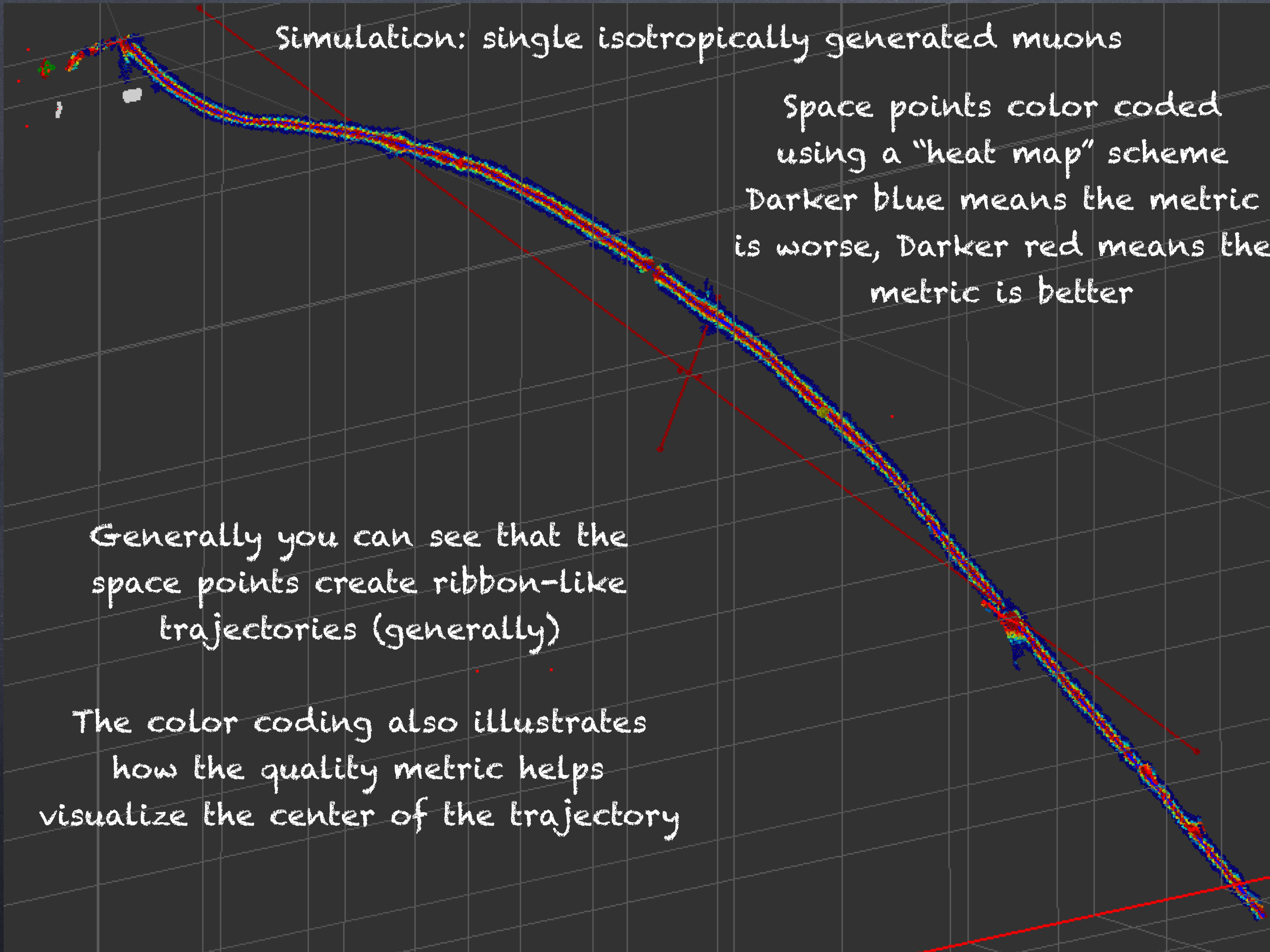
$$\chi^2 = \sum_n \tau_{pull,n}^2$$

- Build a quality metric which can be useful in the downstream reconstruction:
  - First compute weighted average time of the three 2D hits, using this and the widths of the hits, form the sum of the squares of the "pulls" of the three hits
  - Can reject those with outright "bad" chi-square values
  - Can be very useful in downstream disambiguation

Example Displays

- Following example event displays utilize the ICARUS TPC simulation/reconstruction
  - Space point finding works with other TPCs
    - Currently also used in MicroBooNE and ProtoDUNE
    - ICARUS is a more interesting example because it is a multi-Cryostat and mulit-TPC detector
- In the 3D event displays, space points are color coded according to the previously described metric
  - Using a "heat map" - better values of metric are at the red end of the spectrum, worse at the blue end

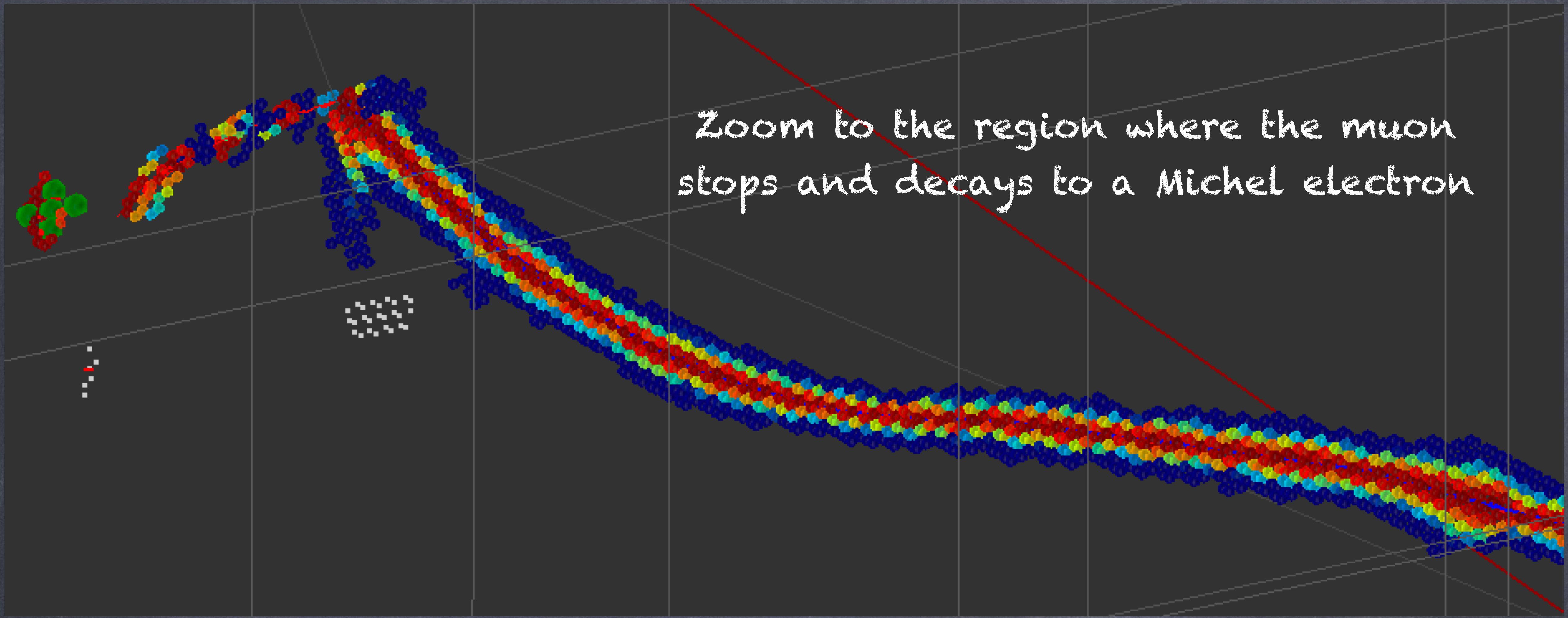
Simulation: single isotropically generated muons



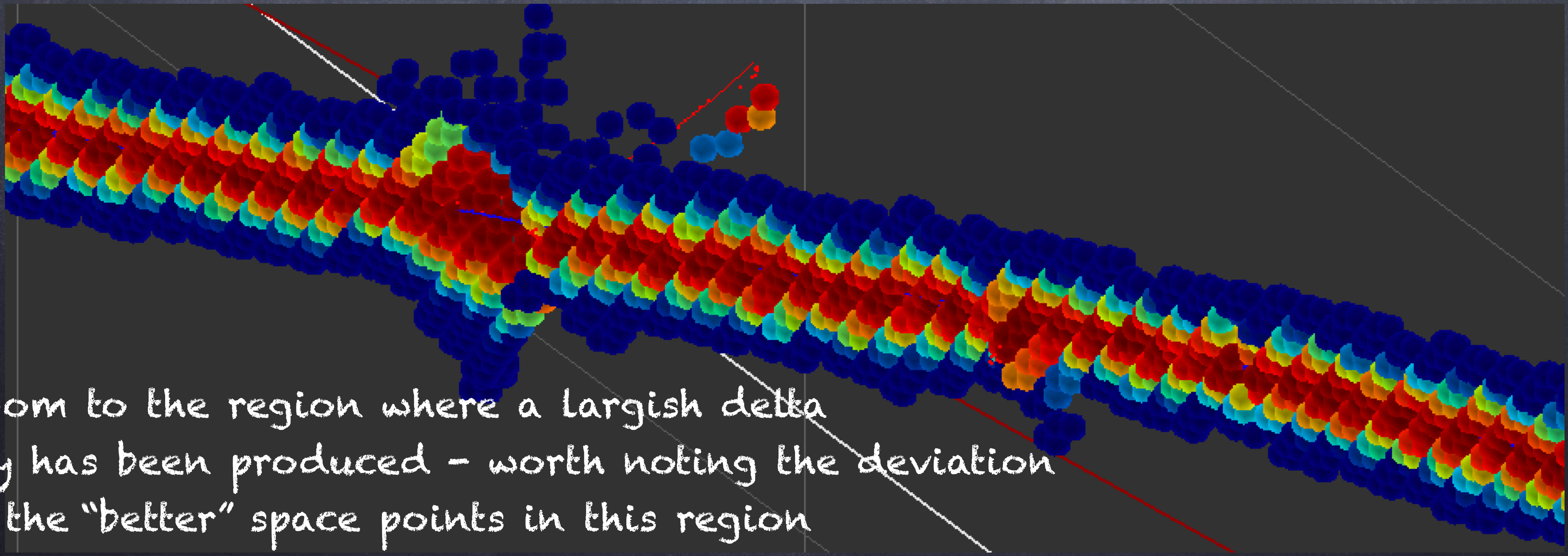
Space points color coded using a “heat map” scheme Darker blue means the metric is worse, Darker red means the metric is better

Generally you can see that the space points create ribbon-like trajectories (generally)

The color coding also illustrates how the quality metric helps visualize the center of the trajectory



Zoom to the region where the muon stops and decays to a Michel electron



Zoom to the region where a largish delta ray has been produced - worth noting the deviation in the "better" space points in this region

Space Point Solver

- Developed by Chris Backhouse ~Spring/Summer 2017
- Goal here is to prefer building of space points from the correct combinations of 2D hits - aim to reduce the ghost point combinations
    - Starting point similar to the simple approach - form all "allowed" combinations
    - Then try to resolve ambiguous space points using the charge information of the hits
        - Assume the collection plane charges have the "true" deposition at that time and position
        - Employ a minimization technique to distribute this charge among the matched induction plane hits
- Originally motivated by a similar technique developed at Brookhaven using pixel info instead of hits - "WireCell"

Resolving Ambiguities

$$\text{minimize } \chi^2 = \sum_i^{\text{iwires}} \left(q_i - \sum_j^{\text{sites}} T_{ij} p_j \right)^2$$

q_i = charge observed in the i^{th} induction hit
T_{ij} = 0 or 1, does site j contribute to hit i?
p_j = charge predicted at site j

$$\text{subject to } p_j > 0 \text{ for all } j \text{ and } \sum_j^{\text{sites}} U_{jk} p_j = Q_k \text{ for all } k$$

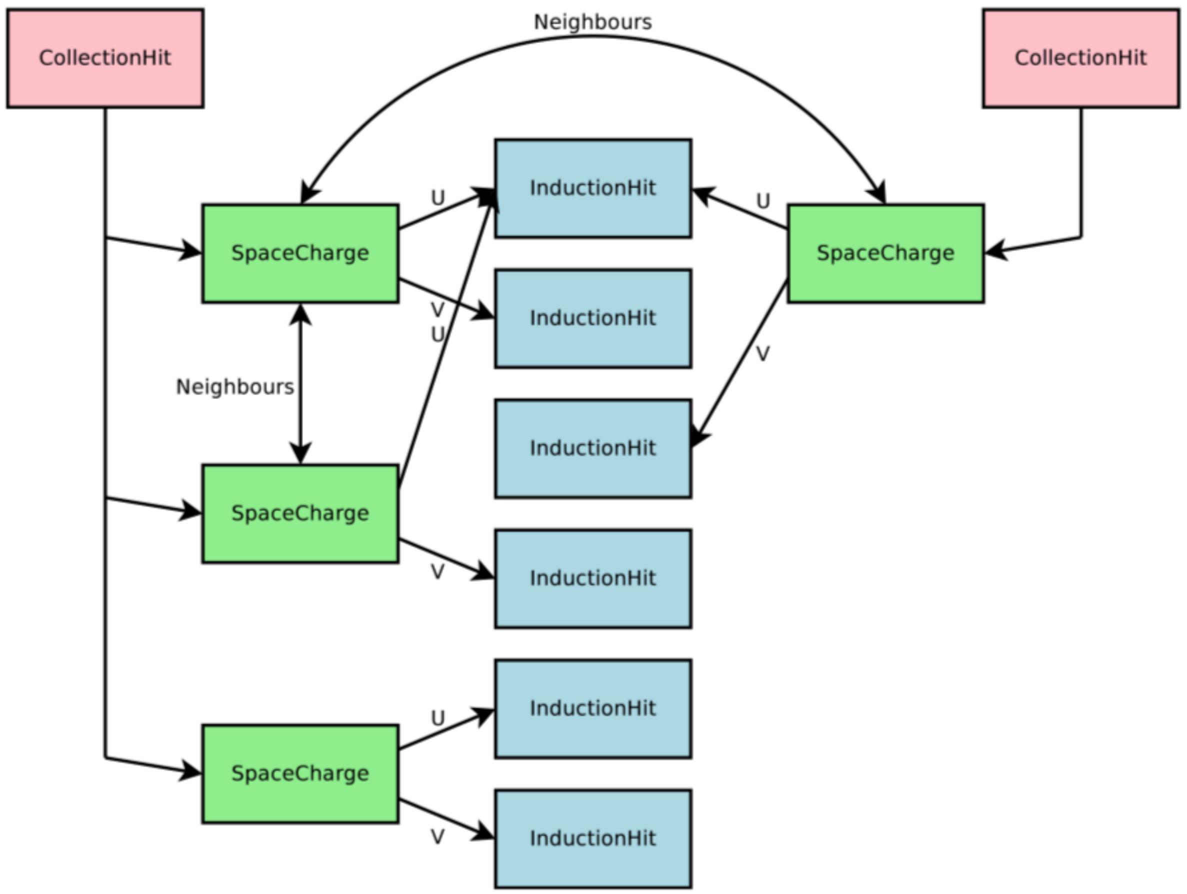
U_{jk} = 0 or 1 – does site j contribute to collection wire k?
Q_k = total charge in the k^{th} collection hit to be distributed

Further Improvement

- Remaining freedom while maintaining a convex problem, add terms

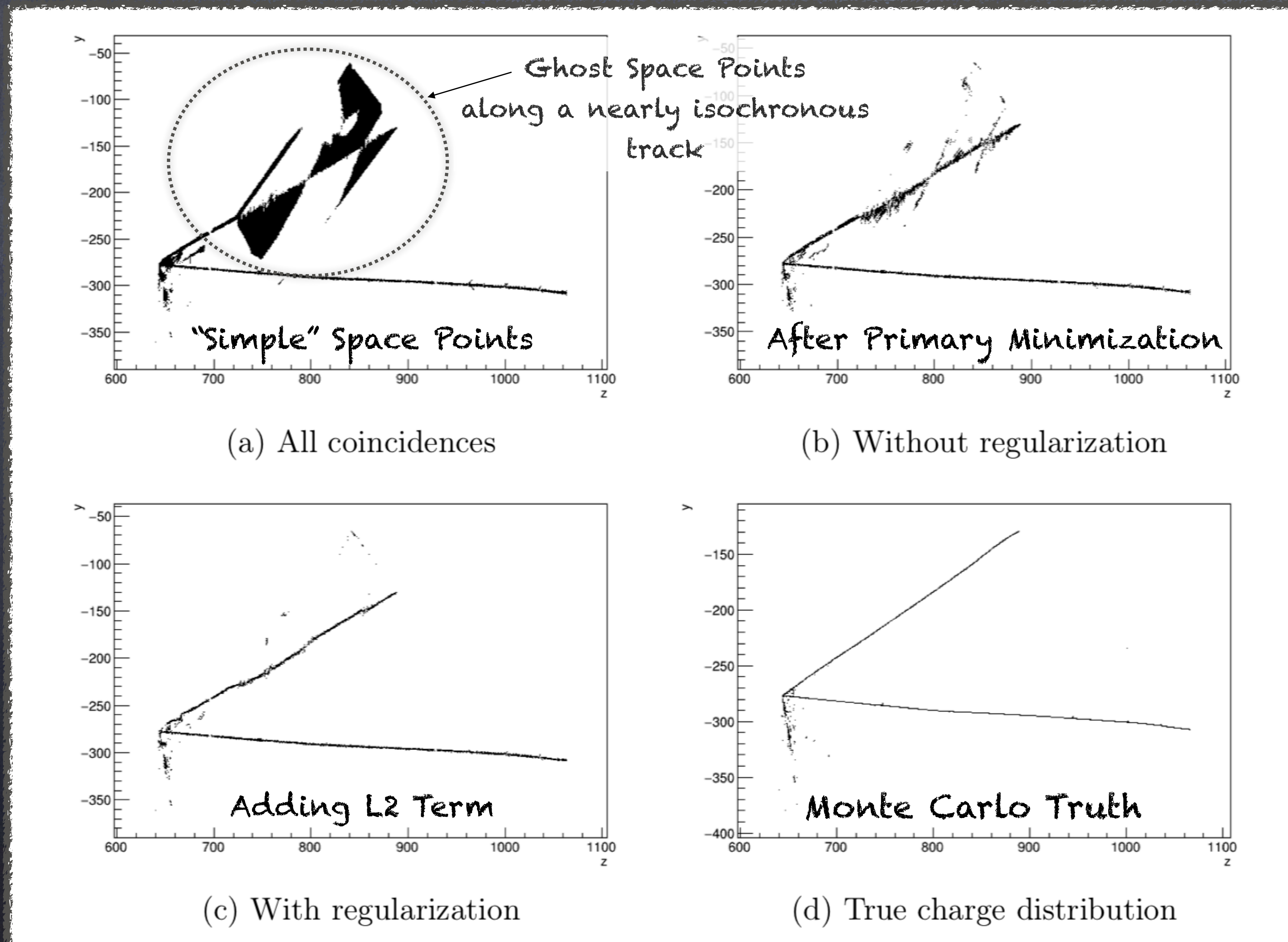
$$\chi^2 \to \chi^2 - \sum_{ij}^{\text{sites}} V_{ij} p_i p_j$$

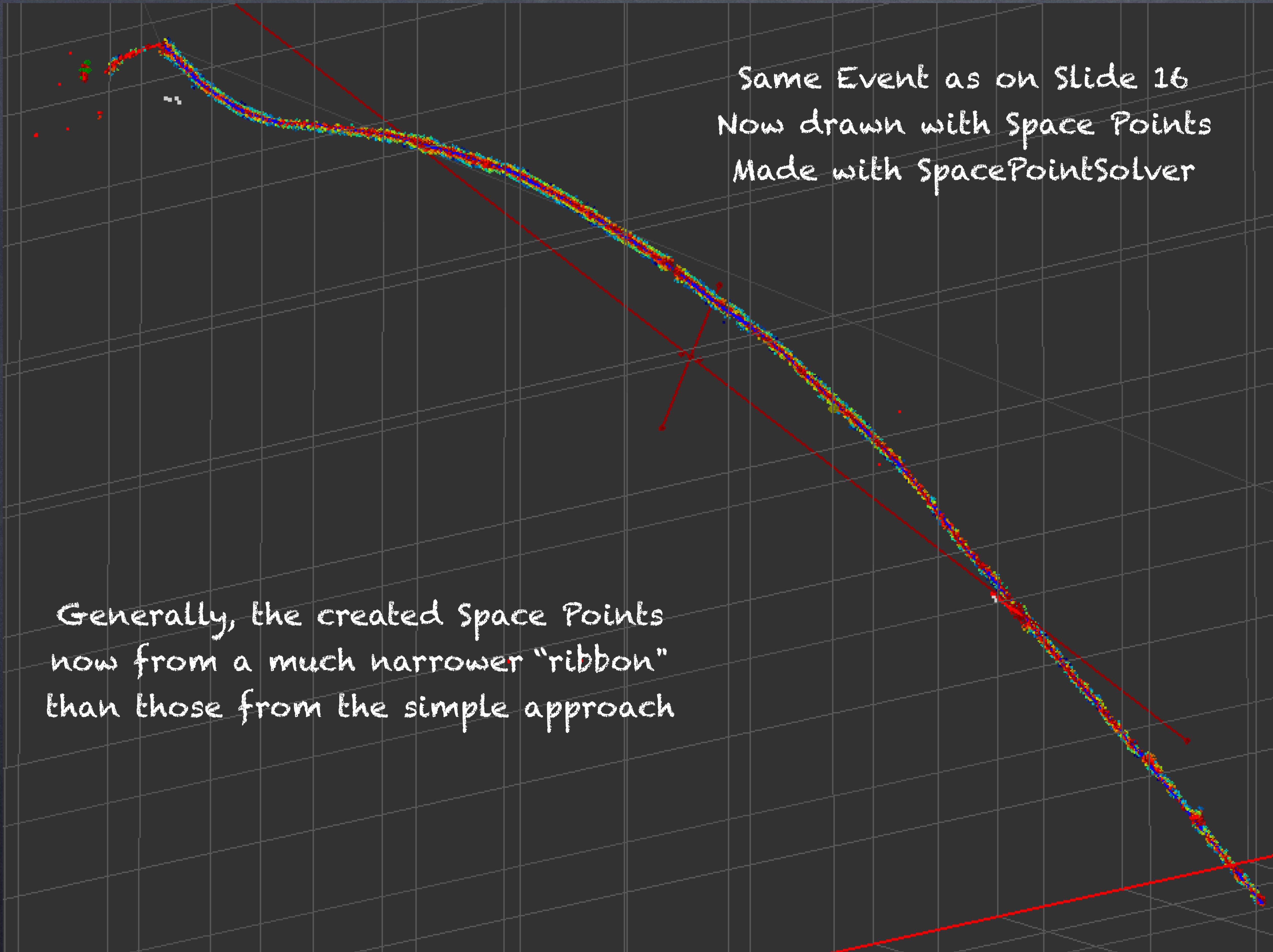
- A term like $\sum_i p_i$ has no effect due to overall charge conservation
- V_{ii} terms amount to L2 regularization – prefer one large hit to two small ones



- Pick $V_{ij} = 0.15e^{-r_{ij}/2\text{cm}}$ arbitrarily
- Rewards proximity of charges
- Overall strength set by trial and error

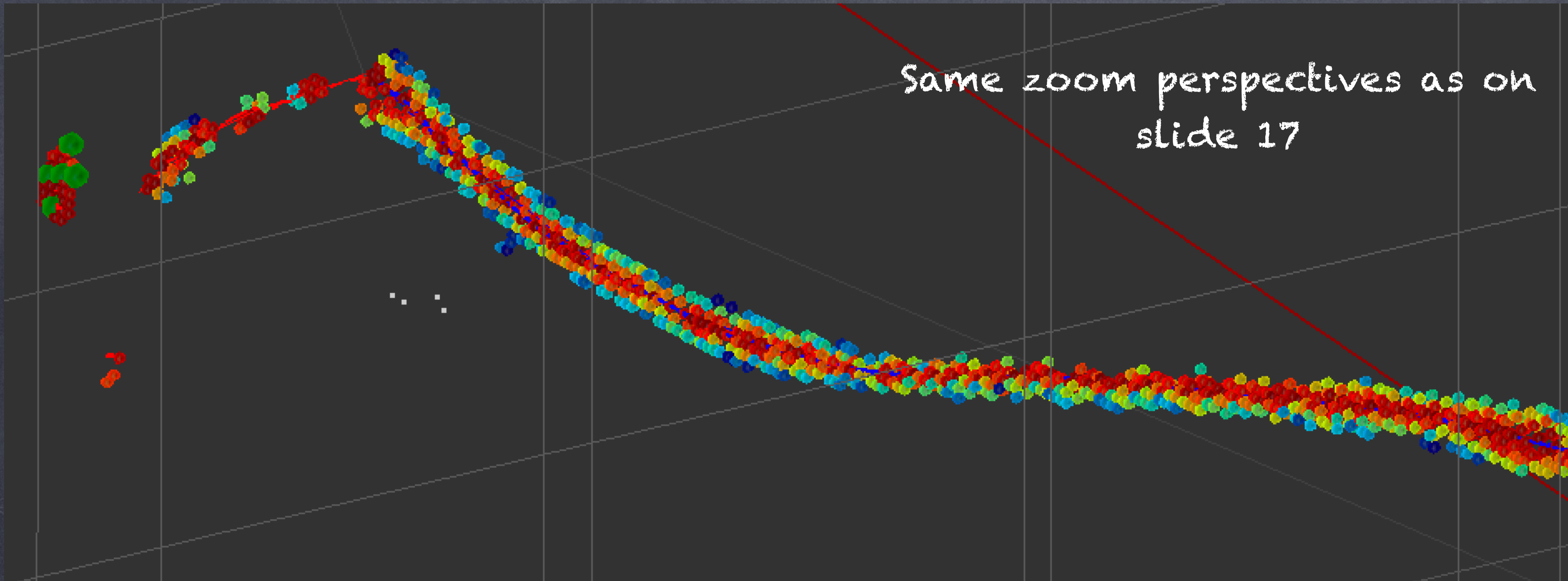
Nice example event with a nearly isochronous track to illustrate the impact of the minimization and regularization



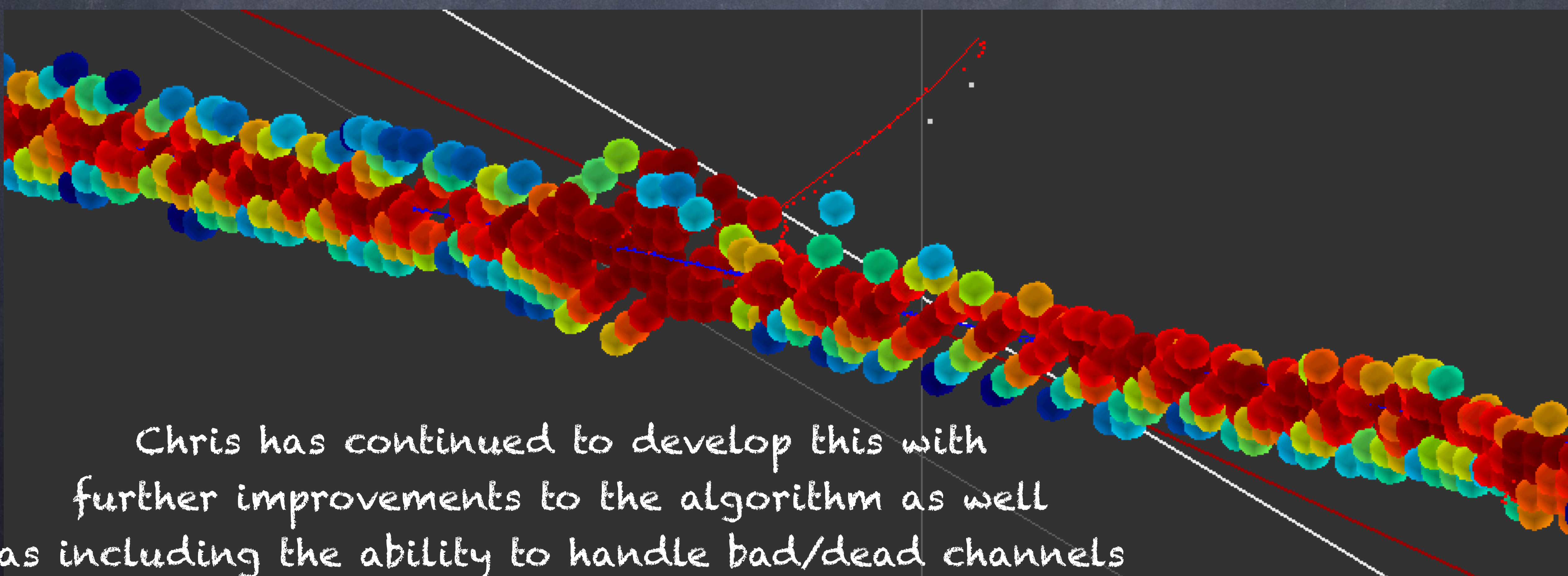


Same Event as on Slide 16
Now drawn with Space Points
Made with SpacePointSolver

Generally, the created Space Points now from a much narrower "ribbon" than those from the simple approach



Same zoom perspectives as on slide 17



Chris has continued to develop this with further improvements to the algorithm as well as including the ability to handle bad/dead channels

Space Point Summary

- Building Space Points using only reconstructed hit information is not problem free
  - Ghost points arise due to the finite width of reconstructed hits, the problem gets worse as tracks become isochronous
- The best strategy for reducing ambiguous Space Points requires "more" information than at hand when constructing them
- Machine Learning techniques Should be better suited to solving this problem
  - In this case it is best to have high efficiency at the expense of purity when building the Space Points