A Hybrid 3D/2D Field Response Calculation for Liquid Argon Detectors with PCB Based Anode

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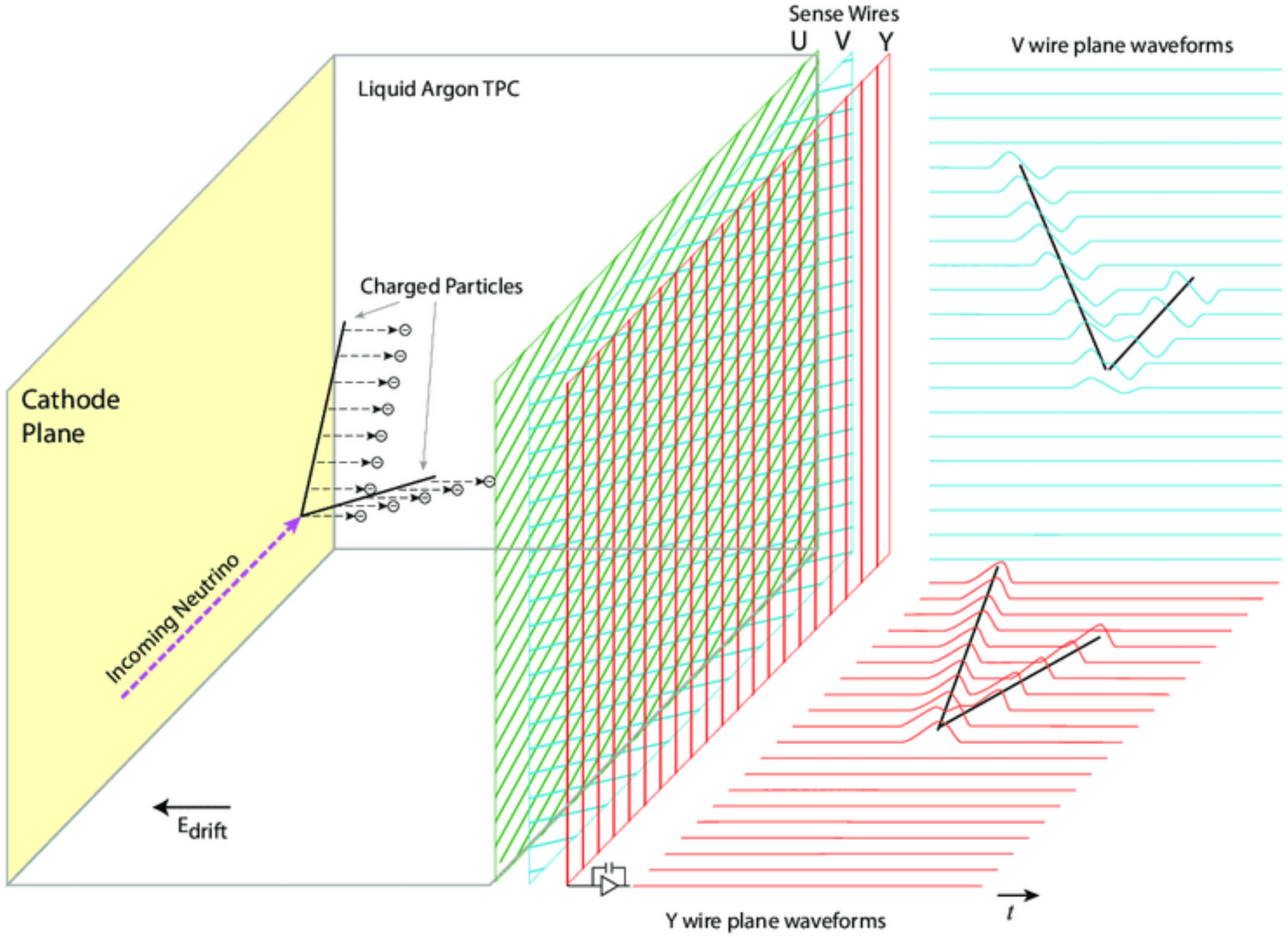
Liquid Argon TPC

- LArTPC is the chosen detector technology for DUNE to search for leptonic CP and to determine the neutrino mass hierarchy

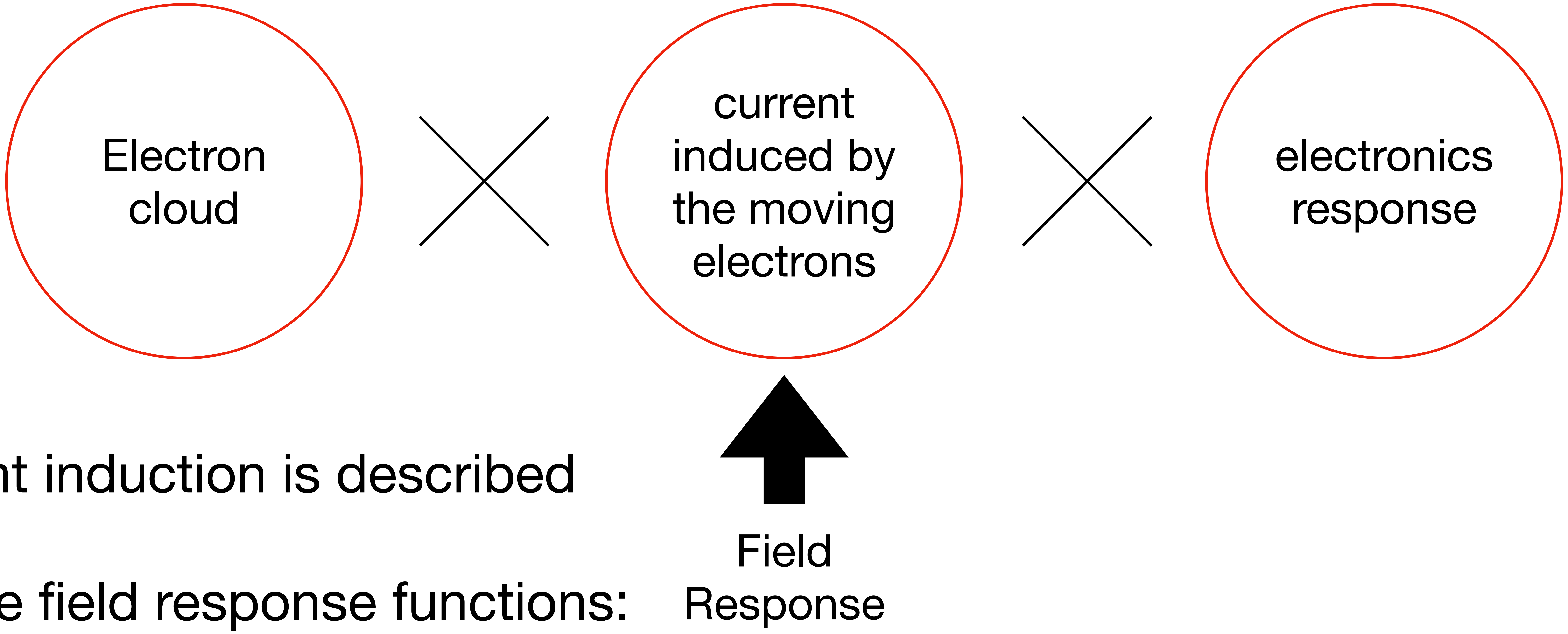
- Basic Idea:
  - Apply an electric field
  - Drift ionization electrons towards planes of wires
  - Detect and reconstruct deposited charge
  - Reconstruct track images on each anode plane => get 3D picture of the event

- Major Requirement:
  - Understand detector signal to correctly reconstruct charge



Field Response Function

Detector Signal =



- The principle of current induction is described by Ramo's theorem
- Stages to calculate the field response functions:
  - Electron drift field
  - Electron drift paths/velocities
  - Ramo Weighting field
- The field response function depends on:
  - anode plane design
  - applied nominal drift field
  - per plane bias voltages

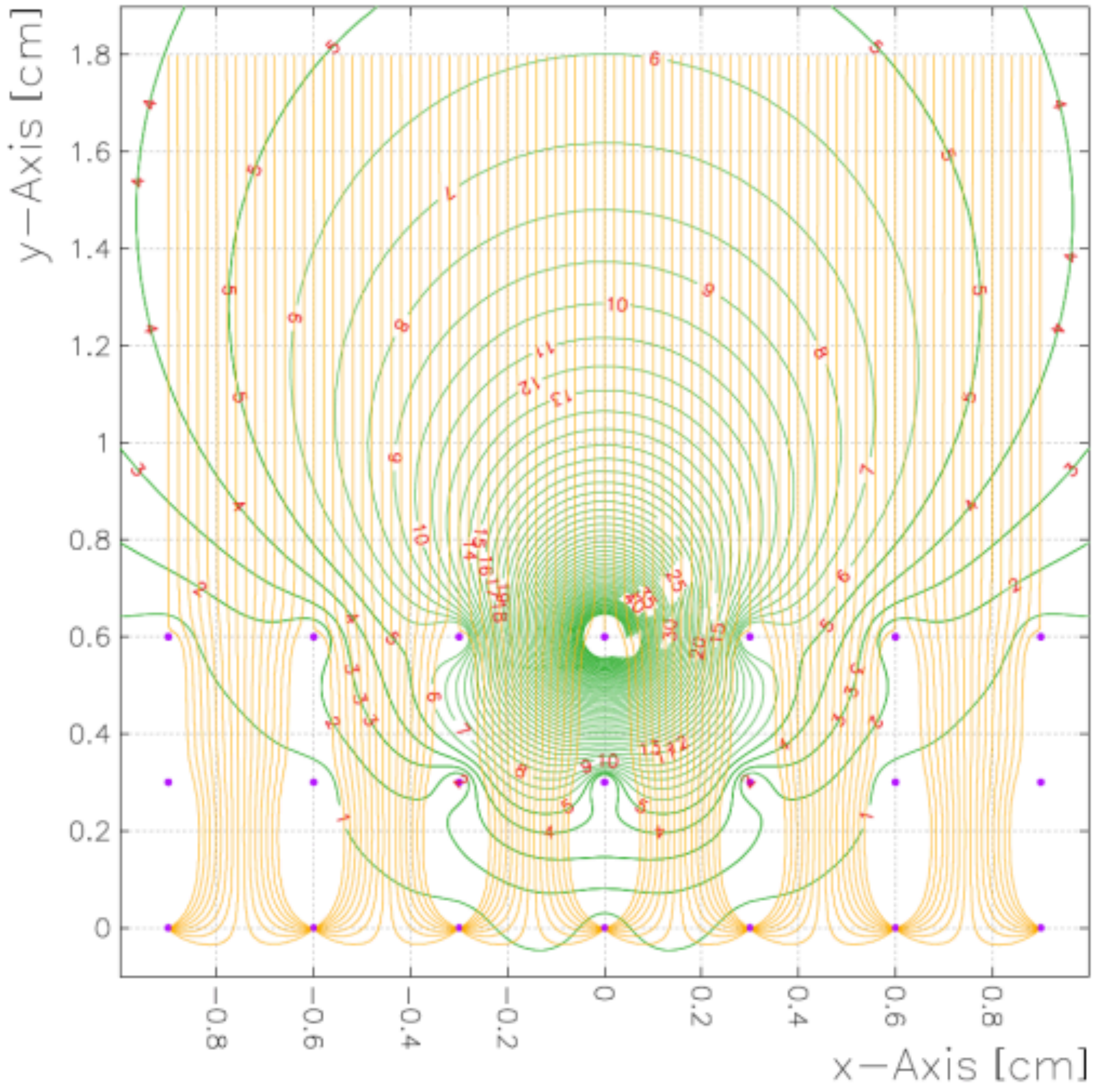
Ramo theorem

$$i = -e \times \vec{v} \times \vec{E_w}$$

Field Response for Wires

- Most of recent experiments (MicroBooNE, ICARUS, SBND) utilize wire-based anodes
- Design also proposed for first 10kT module for DUNE far detector, and used in ProtoDUNE prototypes
- 2D field response calculation for wire-based anodes assumes wires to be infinite along the wire direction
- 2D calculations are typically done via GARFIELD for 21 wires to capture long range induction effects

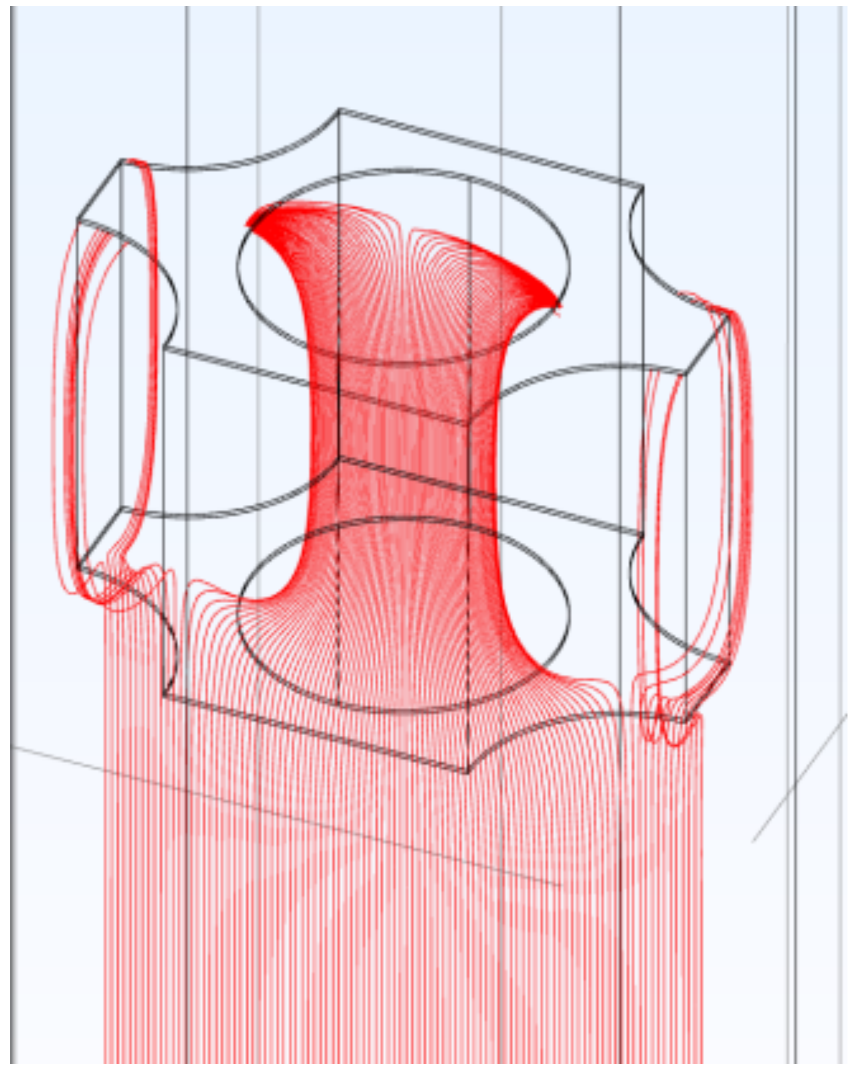
Weighting field(green) and electron drift paths(yellow) for 3 Wire planes*



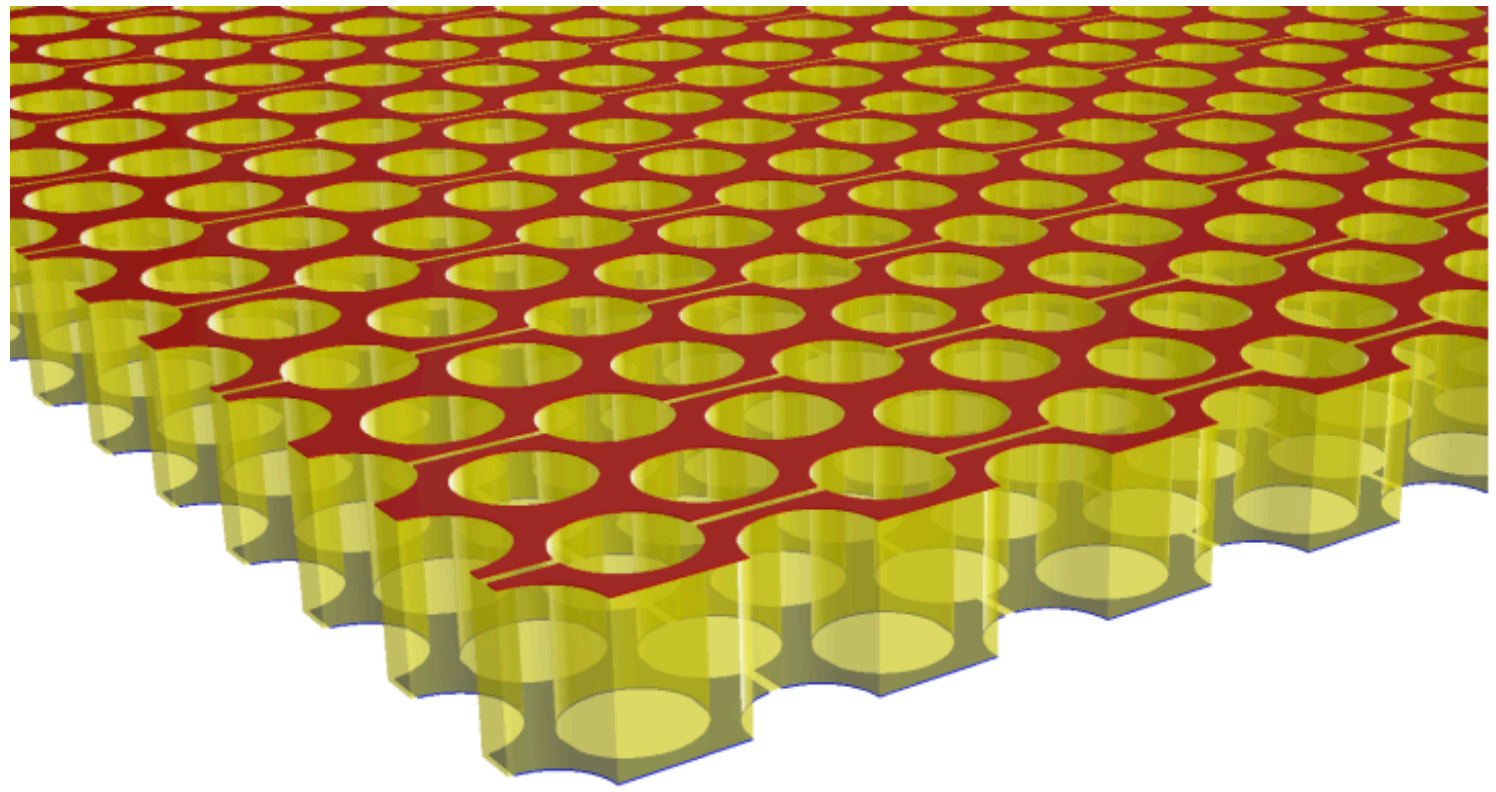
Adams, C., et al. "Ionization electron signal processing in single phase LArTPCs. Part I. Algorithm Description and quantitative evaluation with MicroBooNE simulation." *Journal of Instrumentation* 13.07 (2018): P07006.

Field Response for PCB

Electron drift paths(red) inside PCB hole



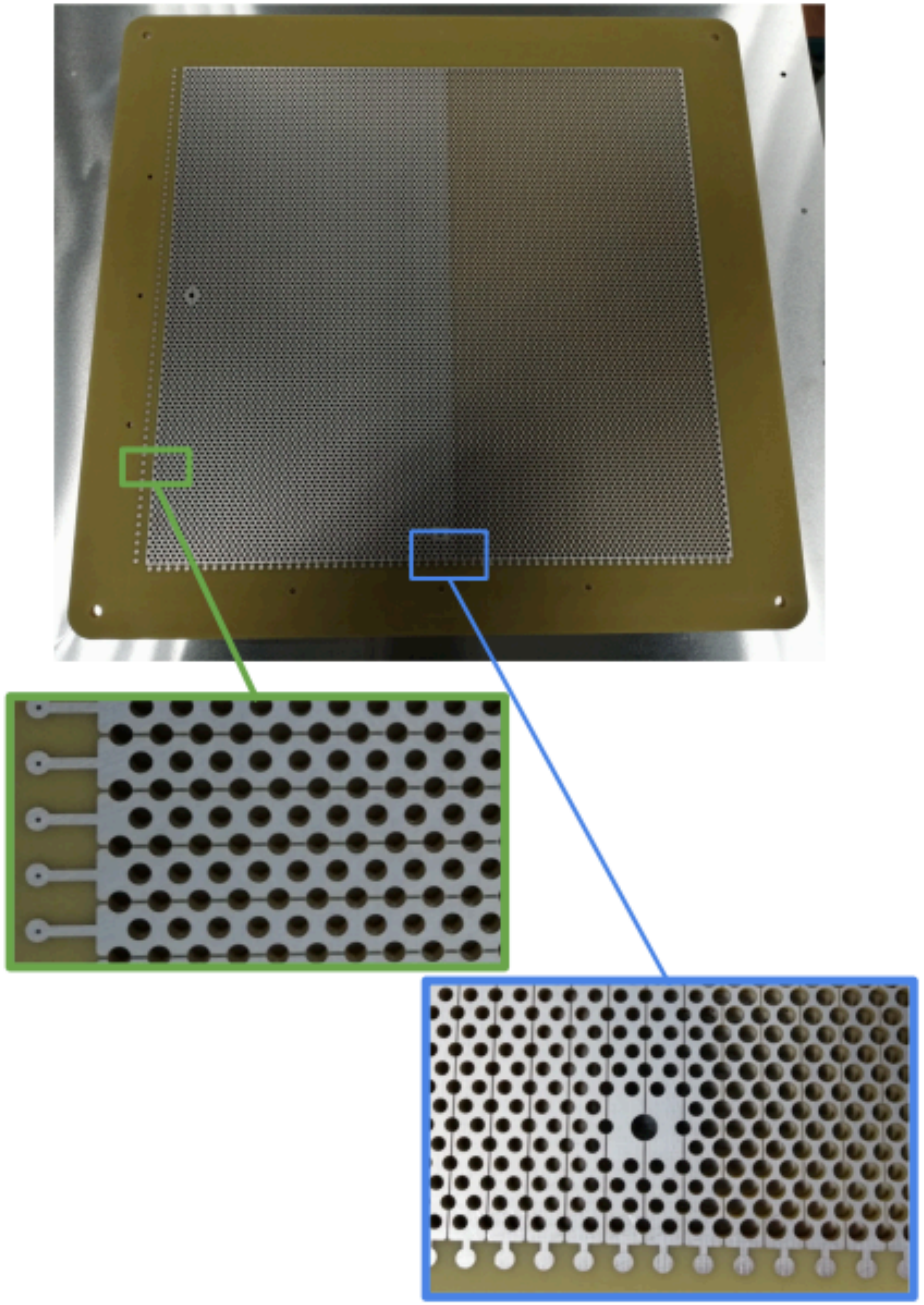
- Printed circuit board (PCB) anode chosen for second 10kT module for DUNE far detector and is used in running prototypes
- PCB anode have specific hole patterns drilled in them, making it essential to precisely model the electron's behavior inside the holes
- 3D field response calculation is essential for PCB-based anodes
- Several packages, such as COMSOL can be used
    - Such simulation is accurate but computationally intensive, particularly in modeling the long-range effects (needs a sizable simulated volume!)
- The Goal:
    - Make fast, precise, and easy to use package (https://github.com/brettviren/pochoir)



https: //edms.cern.ch/ui/file/2429382/1/VERTICAL_SINGLE_PHASE_LARTPC_Draft_1.pdf

CERN 50-L Prototype

- CERN 50-L prototype is LArTPC and a part of Single-Phase Vertical Drift Technology test for the DUNE experiment* (we use configurations and data from May 26th, 2020);
- Detector specification:
  - Uniform drift field of 500 V/cm
  - LAr temperature ~ 87.5 K
- Anode specification:
  - 32 cm × 32 cm × 3.2 mm two-layer PCB plate
  - Induction layer voltage 0V, collection layer voltage 2 kV
  - Two hole configurations : 2 and 2.5 mm diameter
  - Strip width (pitch): 5 mm



https://edms.cern.ch/ui/file/ 2619631/1/ Vertical_Single_Phase_FD_Technology_CDR.pdf.

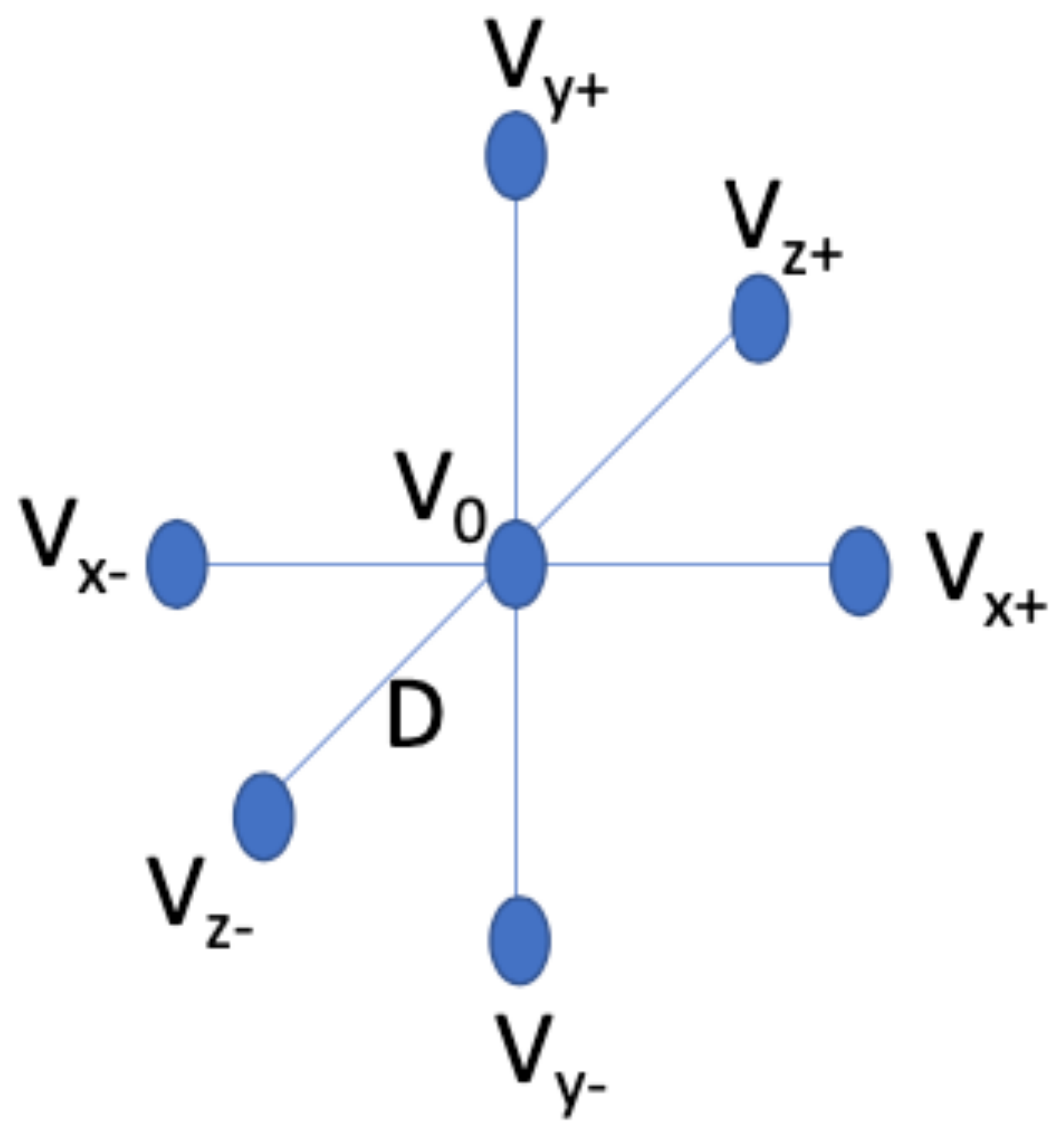
Electric Field Calculation

Iteratively solved for whole simulated volume

- Solve 1st Maxwell equation ($\nabla E = 0$) on a 3D lattice both for the drift field and the weighting field using Finite Difference Method (FDM)

$$\frac{\partial E}{\partial x} + \frac{\partial E}{\partial y} + \frac{\partial E}{\partial z} = 0 \Rightarrow \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = 0 \Rightarrow V_0 = \frac{(V_{x+} + V_{x-} + V_{y+} + V_{y-} + V_{z+} + V_{z-})}{6}$$

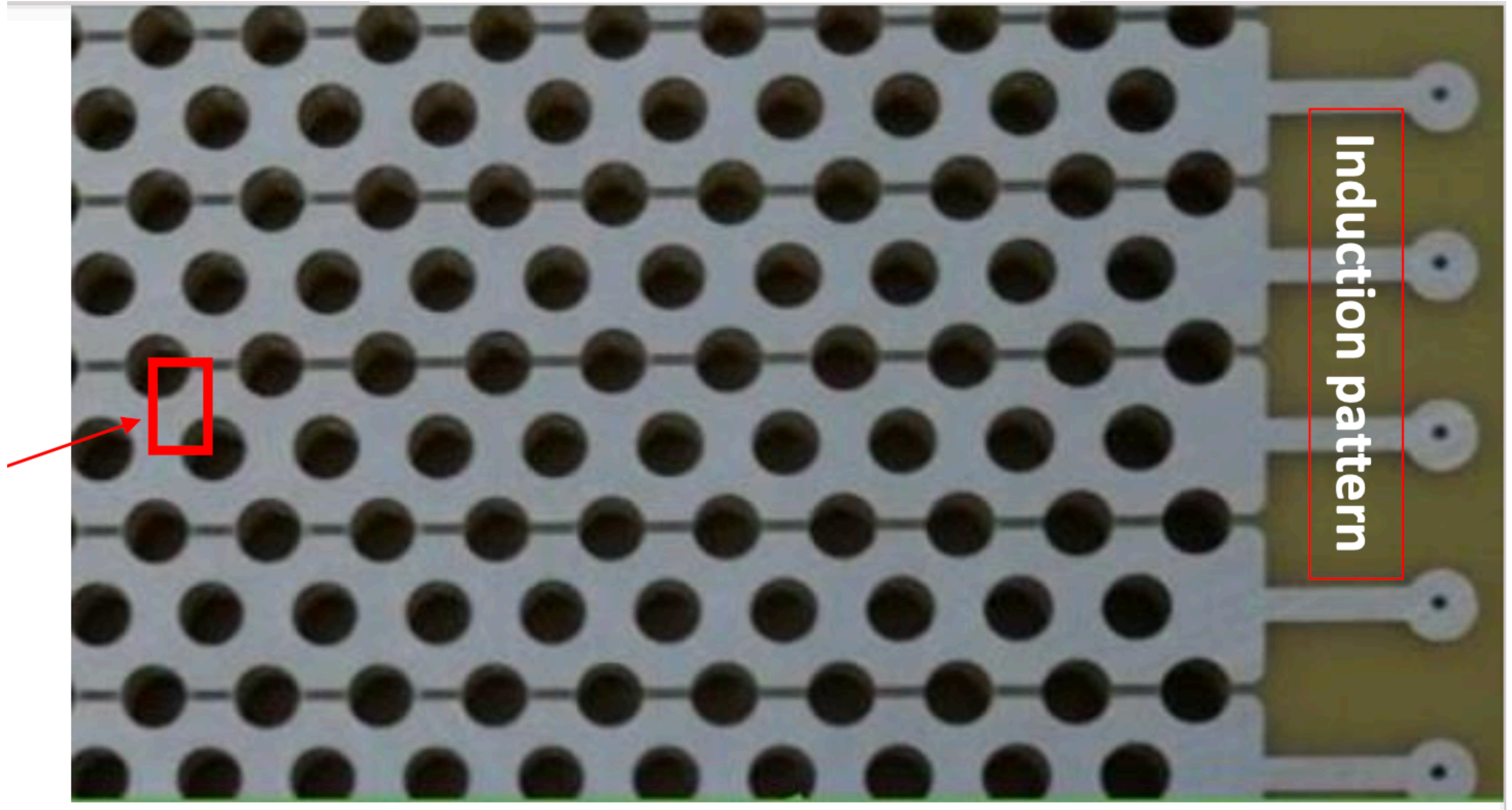
- New approach to minimize computing time:
  - Use python matrix calculation
  - Use python GPU-based tensors
  - Utilize PCB symmetries volume for 3D drift field calculation
  - Combine 3D and 2D Ramo weighting field calculation:
    - Do 3D calculation for smaller number of strips
    - Switch to 2D calculation at the boundaries



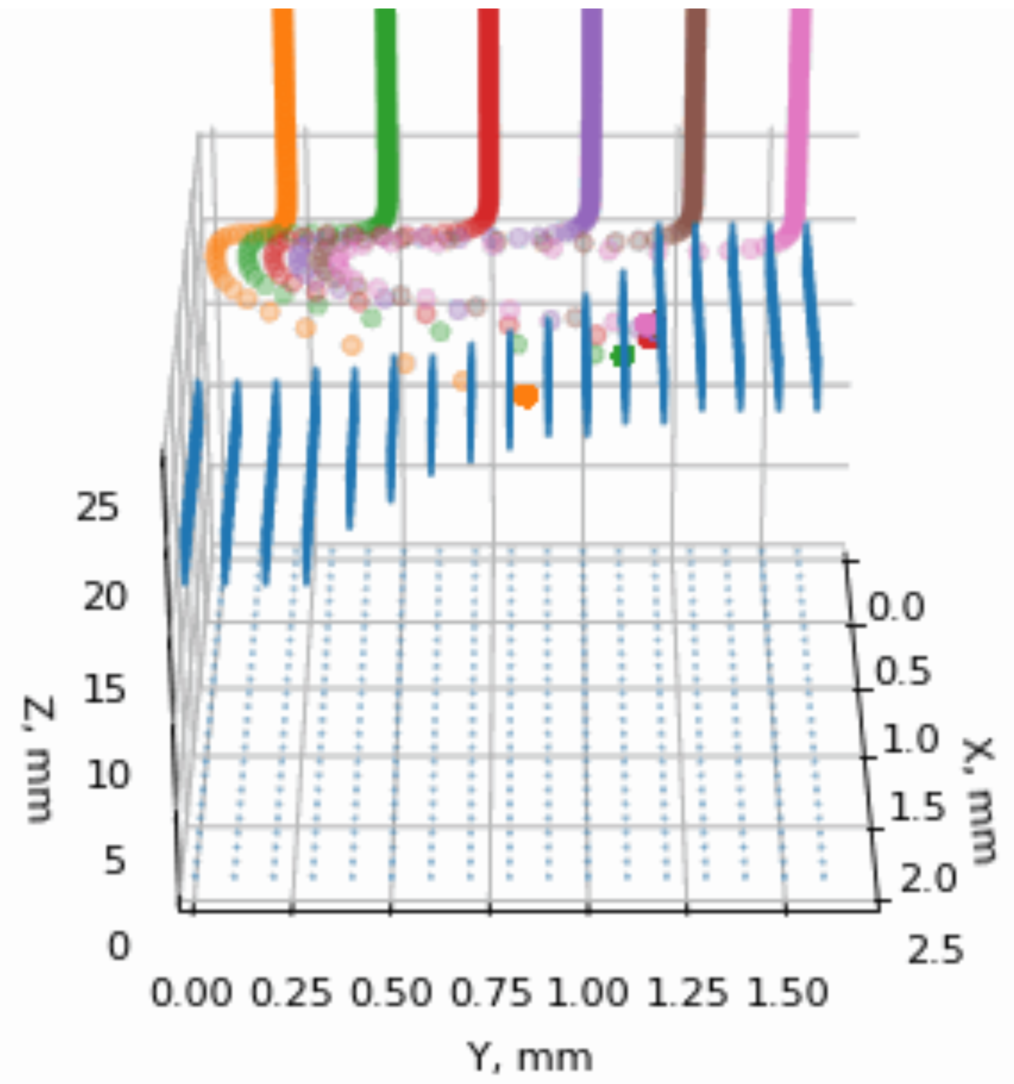
Drift Velocity Calculation (3D)

- Choose a minimal symmetry volume to speed up calculation by asserting a periodic boundary condition:
  - Quarter of pcb strip (Area 2.5mm x 1.67mm) with hole diameter ~2.5 mm;
- Calculate 3D drift field using FDM
- Drift Velocity is calculated : $v = \mu \times E$, $\mu = \mu(E, T)$ - electron mobility
- Result:
  - Calculation gives ~1.6 mm/us in the volume at nominal 500 V/cm drift field which matches expectations.

Induction plane hole pattern

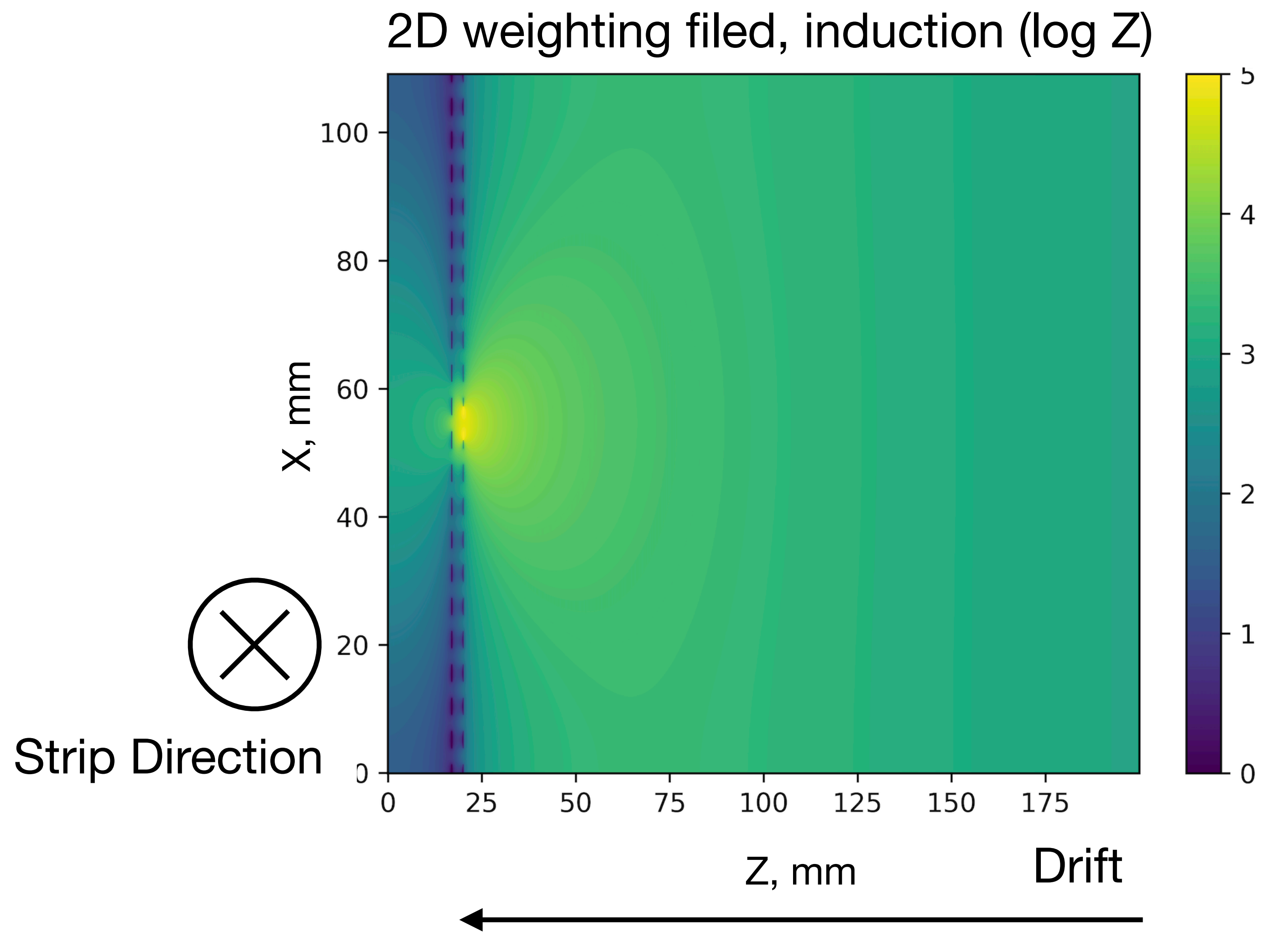


Example electron Drift Paths



Ramo Weighting Field Calculation

- Ramo weighting field calculation: middle strip at 1 V, all other electrodes at 0 V
- Broad domain coverage to capture long range effects
- Calculate full volume in 2D (21 strip x 200 mm drift)



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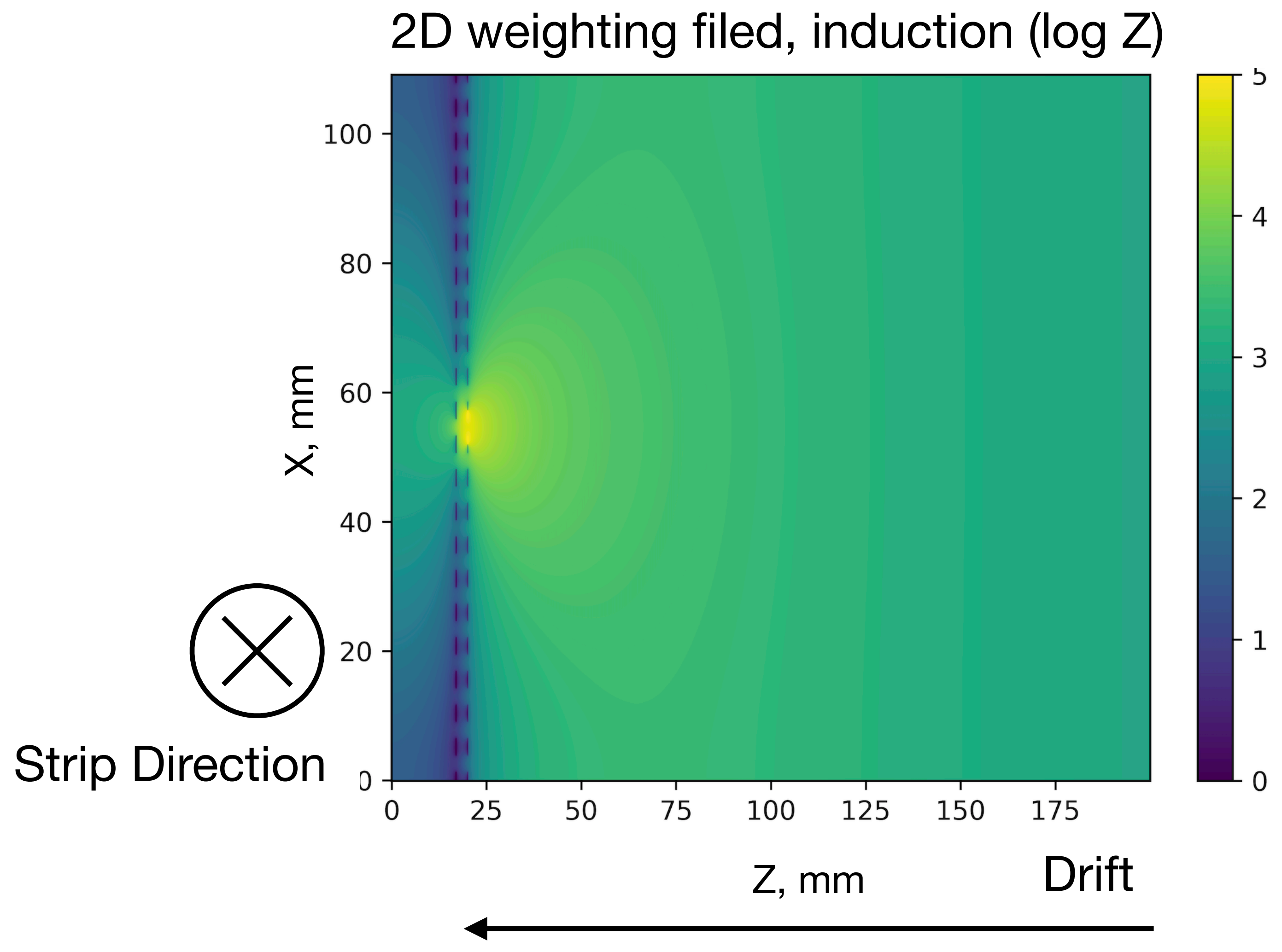
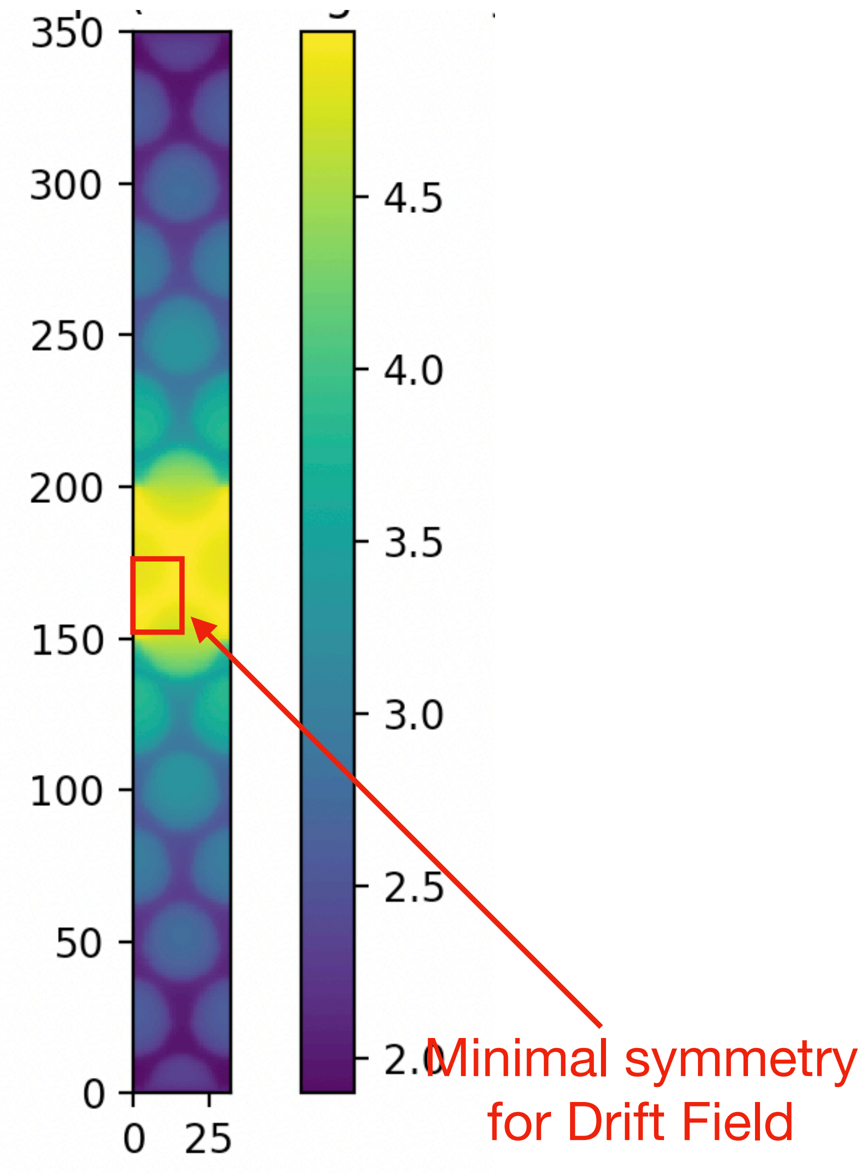
  - 3D geometry effects are more local than broad 2D effects
  - Use 2D solution as boundary condition in 3D calculation



3D Geometry_slice along Z



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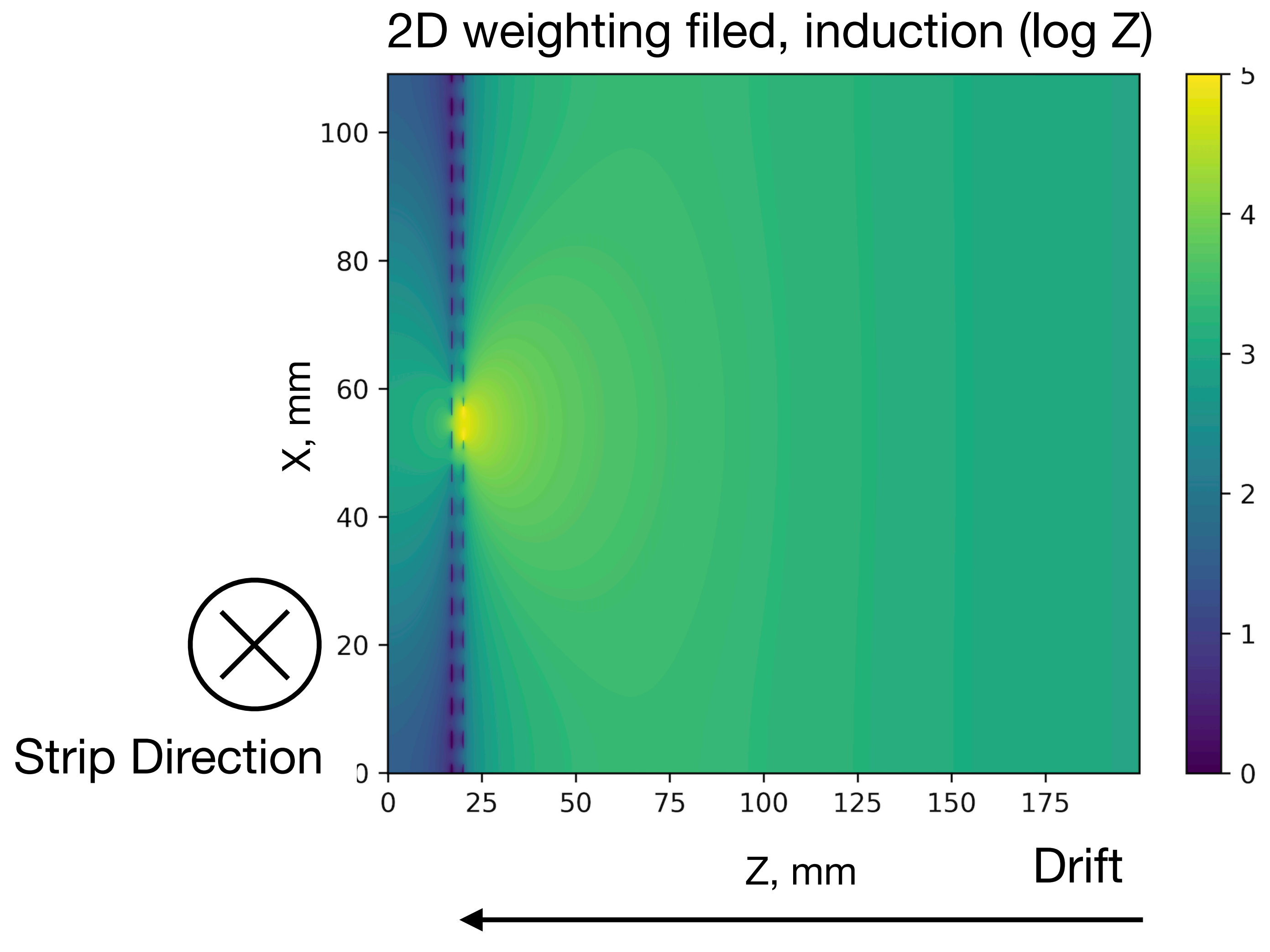
- Combine 3D and 2D solution



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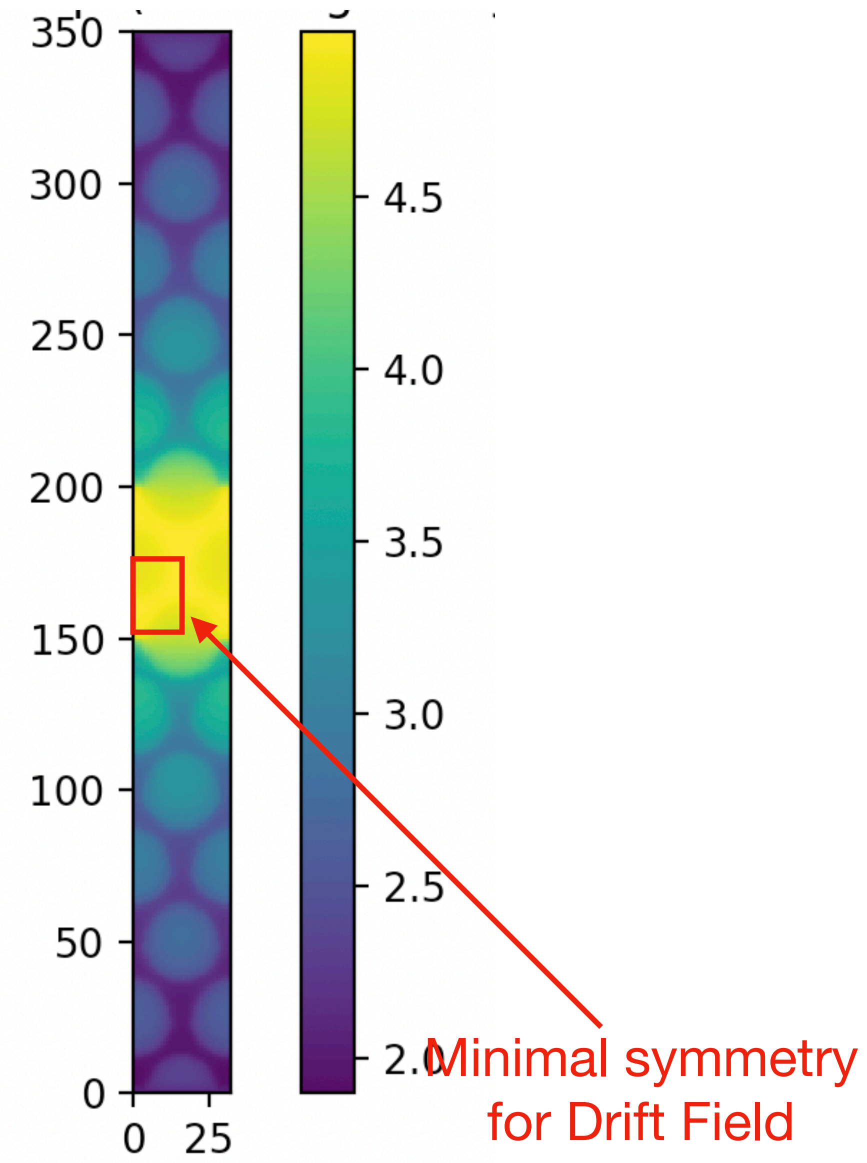
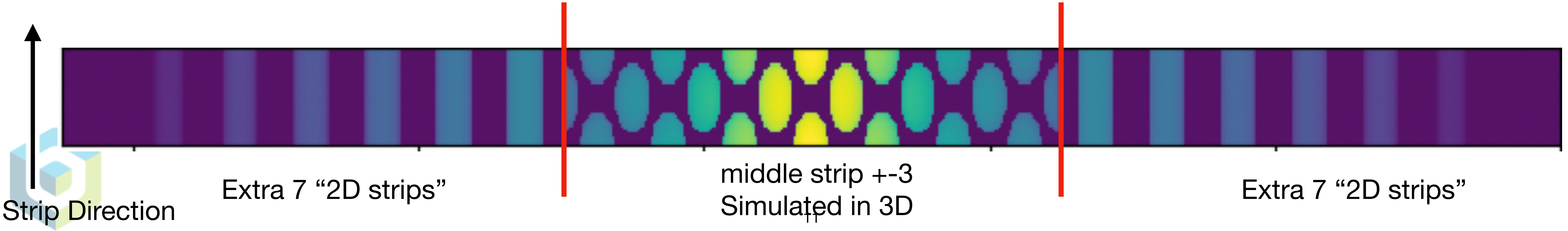
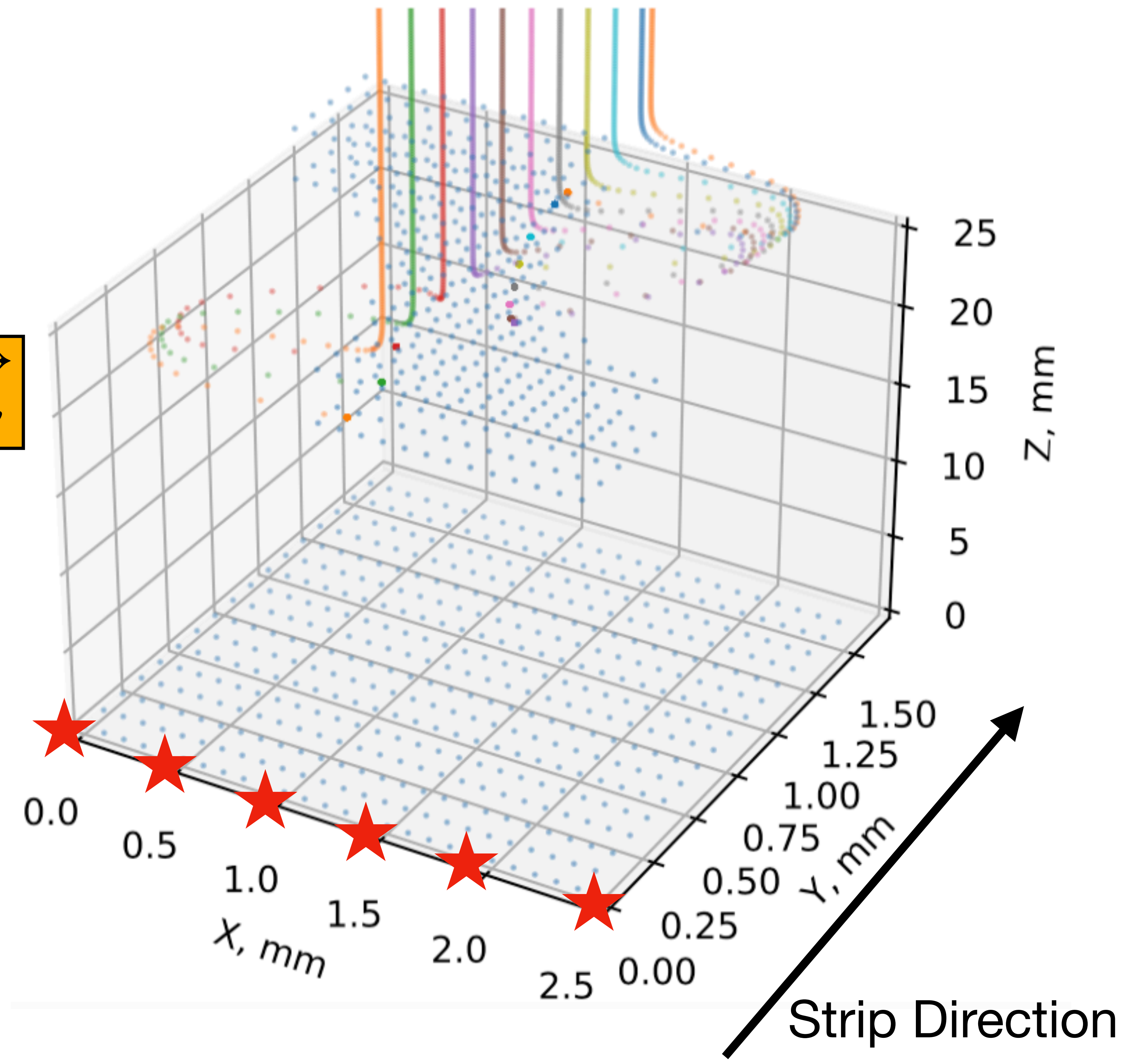


Slice of weighting field along drift (log color scale)



Field Response Calculation Summary

- Simulations using Finite Difference Method simulations:
    - 3D drift field -> electron drift paths/velocities
    - 3D weighting field for 7 strips in the middle + 2D weighting field for the rest (total 21 strip)
- Induced current calculated using Ramo's theorem $i = -e \times \overrightarrow{v} \times \overrightarrow{E_w}$
- Induced current is provided for future state-of-art WireCell 2D simulation/deconvolution* at six location perpendicular to the strip directions (★):
    - First location is between the strips, last is in the middle of the strip, and other 4 are with equal distance between them
    - Each location is an average of 11 paths along the strip direction

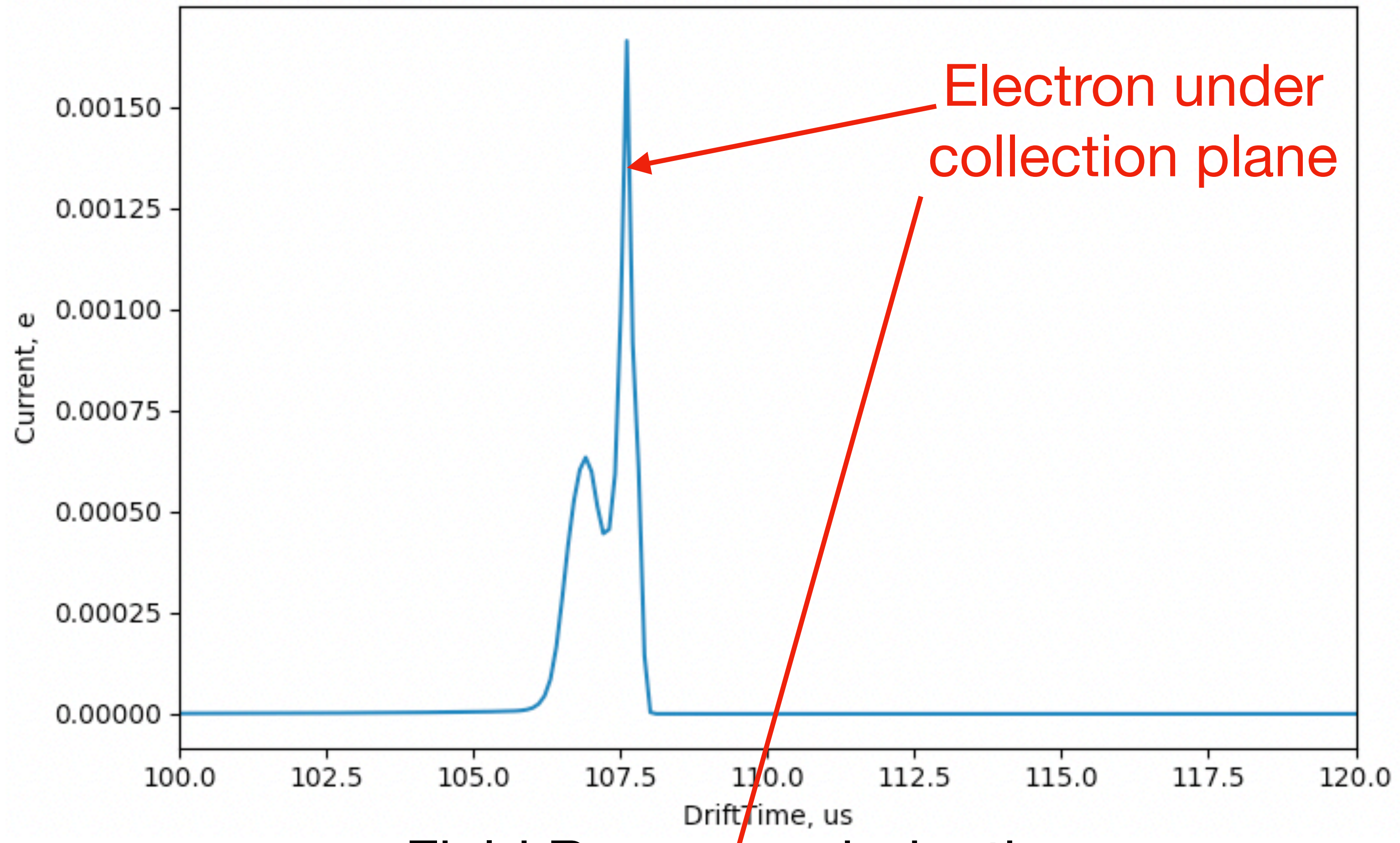


https://wirecell.bnl.gov/.

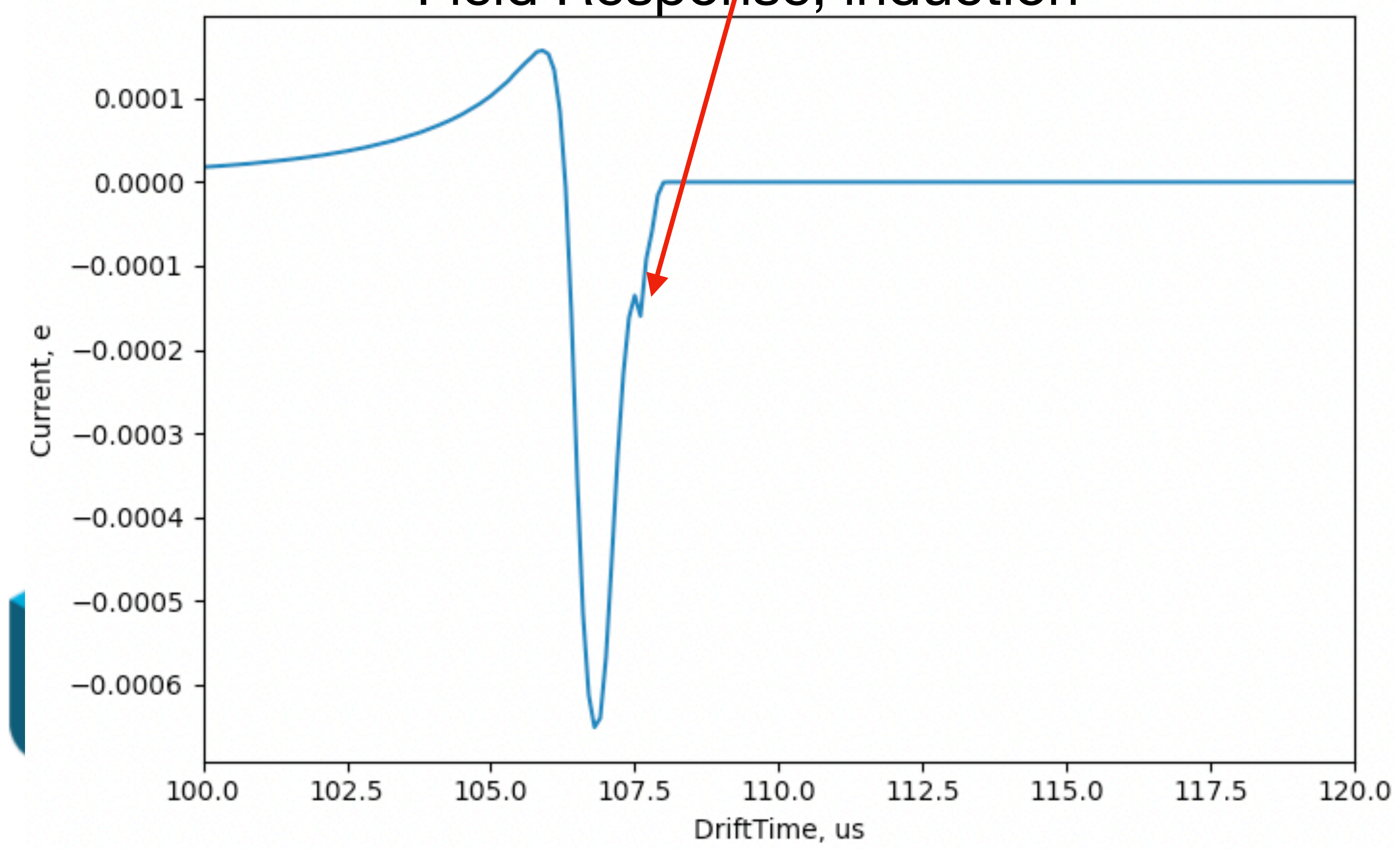
Induced Current and Elec. response convolution

Example of averaged along the strip induced current

Field Response, collection

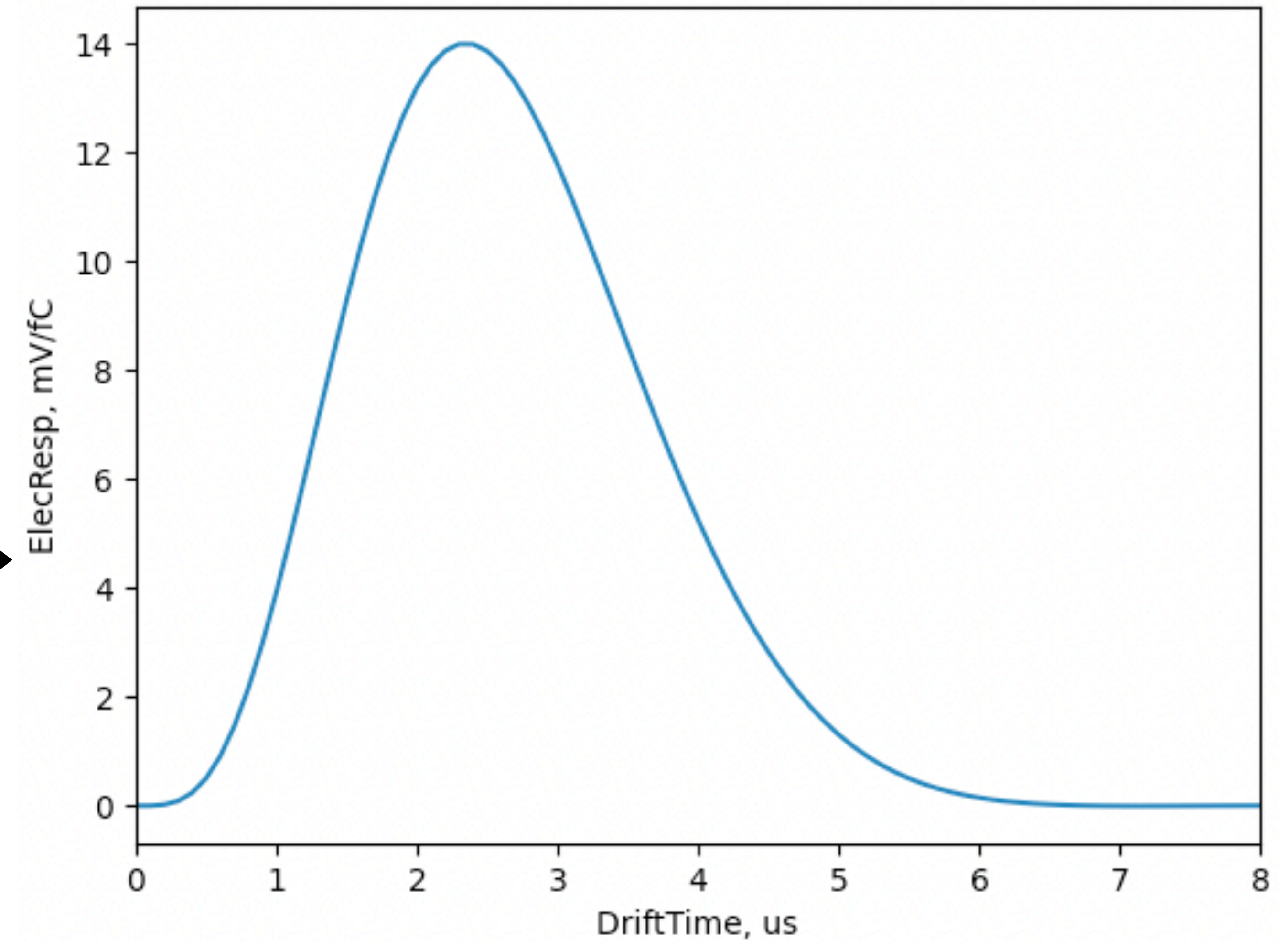


Field Response, induction



BNL cold electronics response function* (gain 14 mV/fC, shaping 2 us)

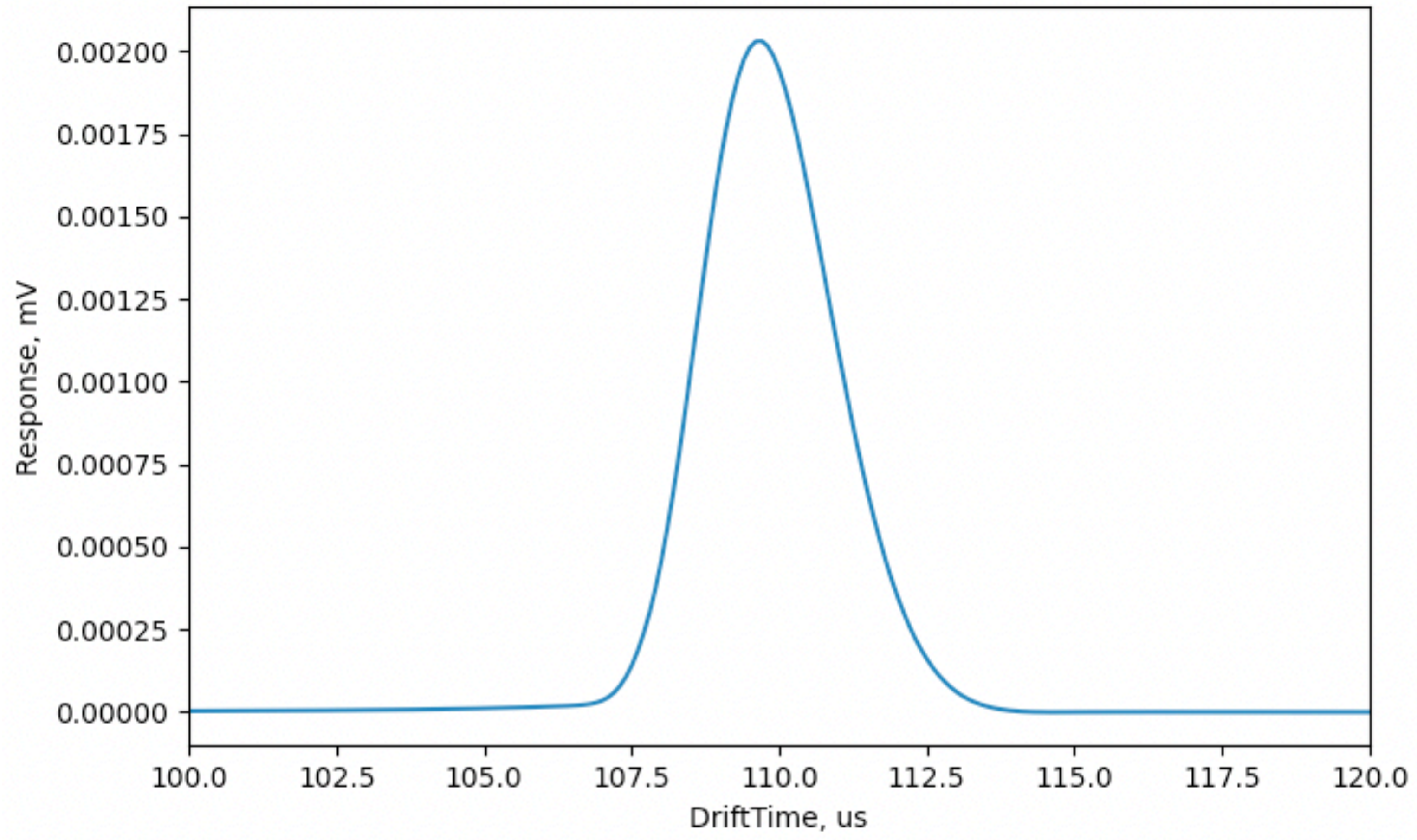
Electronics Response



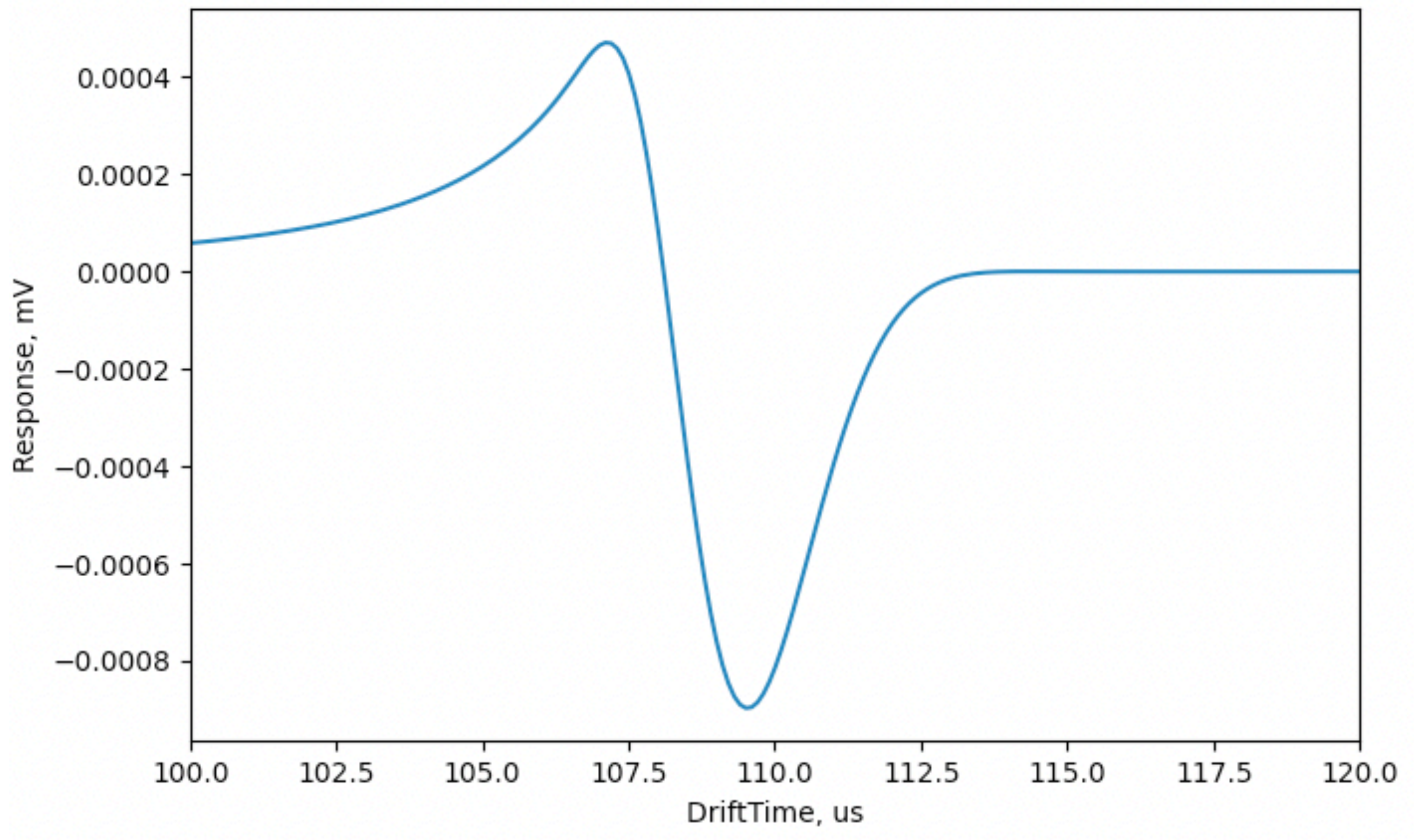
Chen, Hucheng, et al.
"Readout electronics for the MicroBooNE LAr TPC, with CMOS front end at 89K."
Journal of Instrumentation 7.12 (2012): C12004.

Convolution of induced current with electronics repose

Convolved response, induction



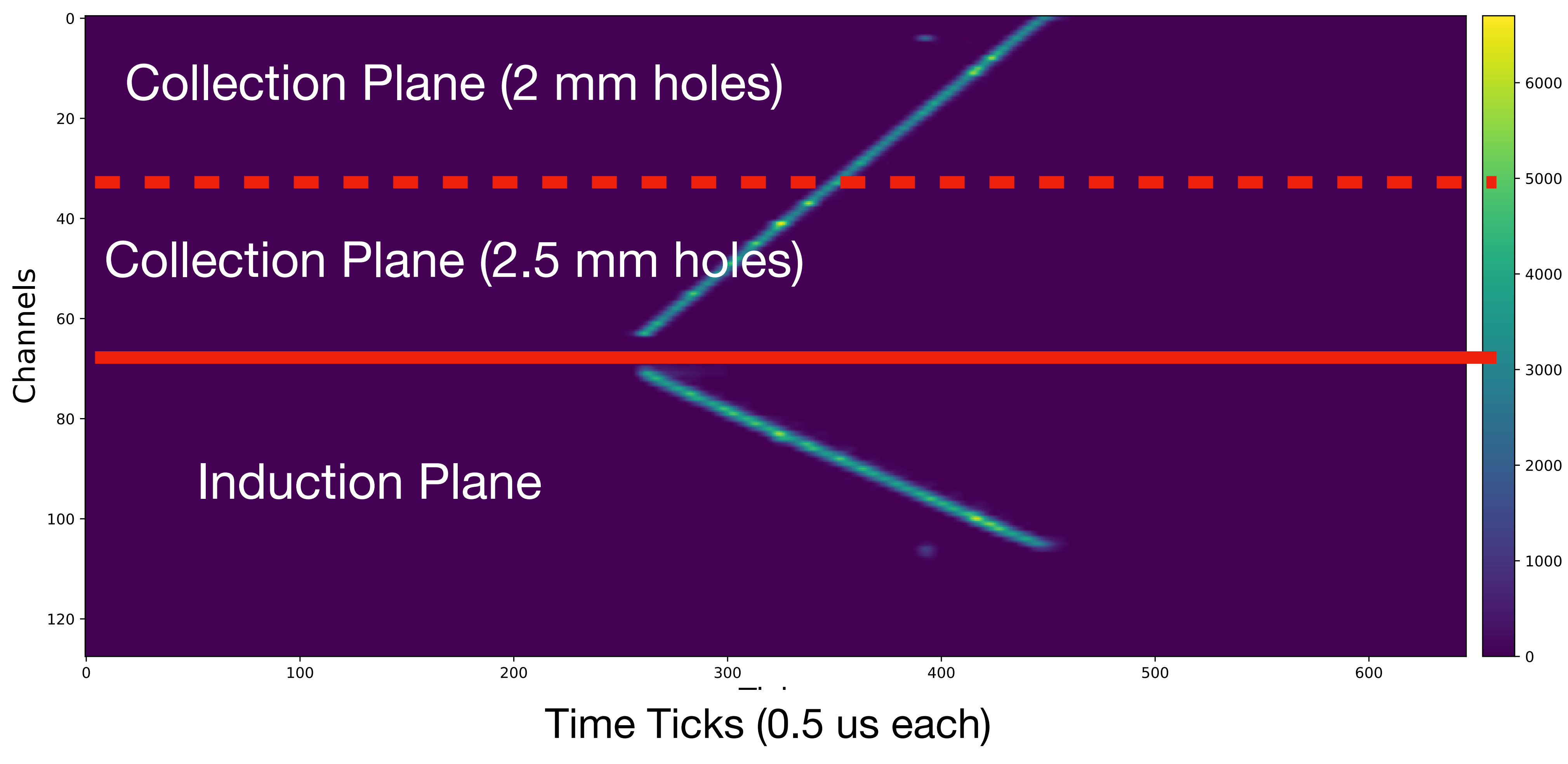
Convolved response, induction



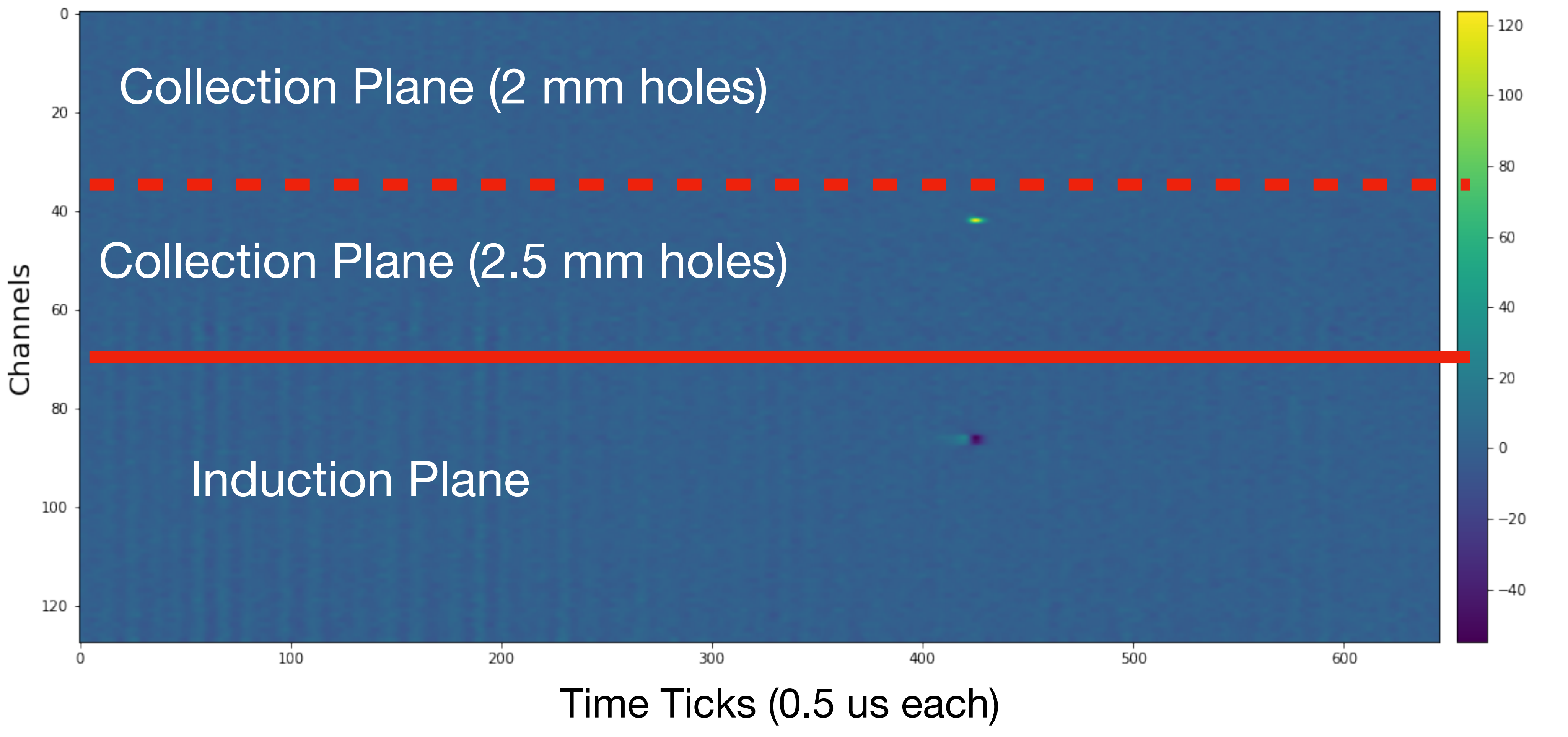
Field Response Validation

- Validation with cosmic muons:
  - Simulate tracks with similar topologies/energy as observed in data
  - Compare the raw shape (before signal processing) of the induced signal seen by the real and simulated detectors
  - Look at deconvolved charge on each anode plane.
    - Total reconstructed charge for induction and collection plane between data and simulation
    - Charge seen by induction and collection plane exclusively with data
- Validation with Ar39 beta decay events:
  - Approximately a point source in the detector, well-known energy spectrum.
  - Perform studies sensitive to charge position inside a single strip:
    - Effect of hole size on field response
    - Variation of the field response along the strip

Data Track after 2D deconvolution

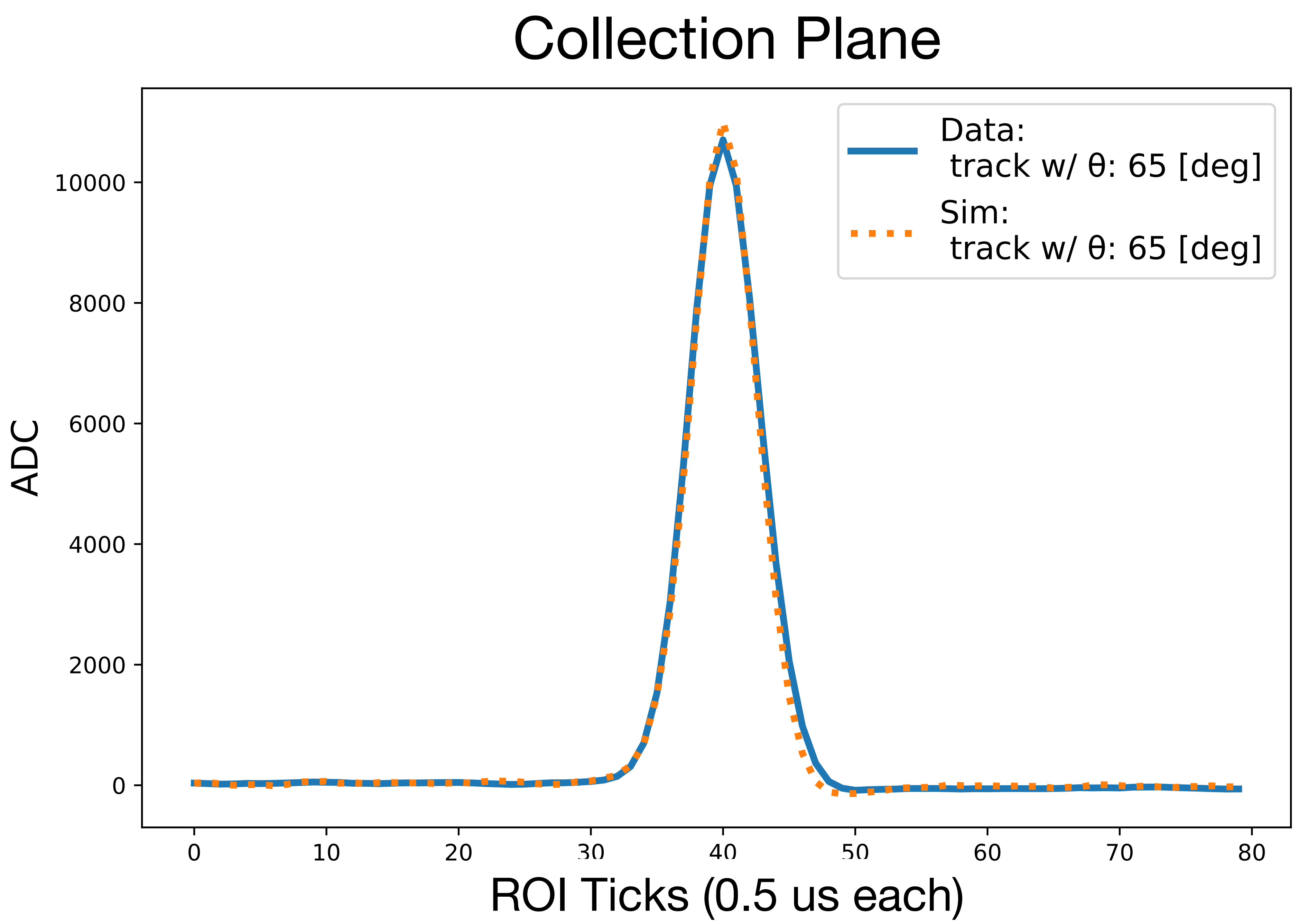


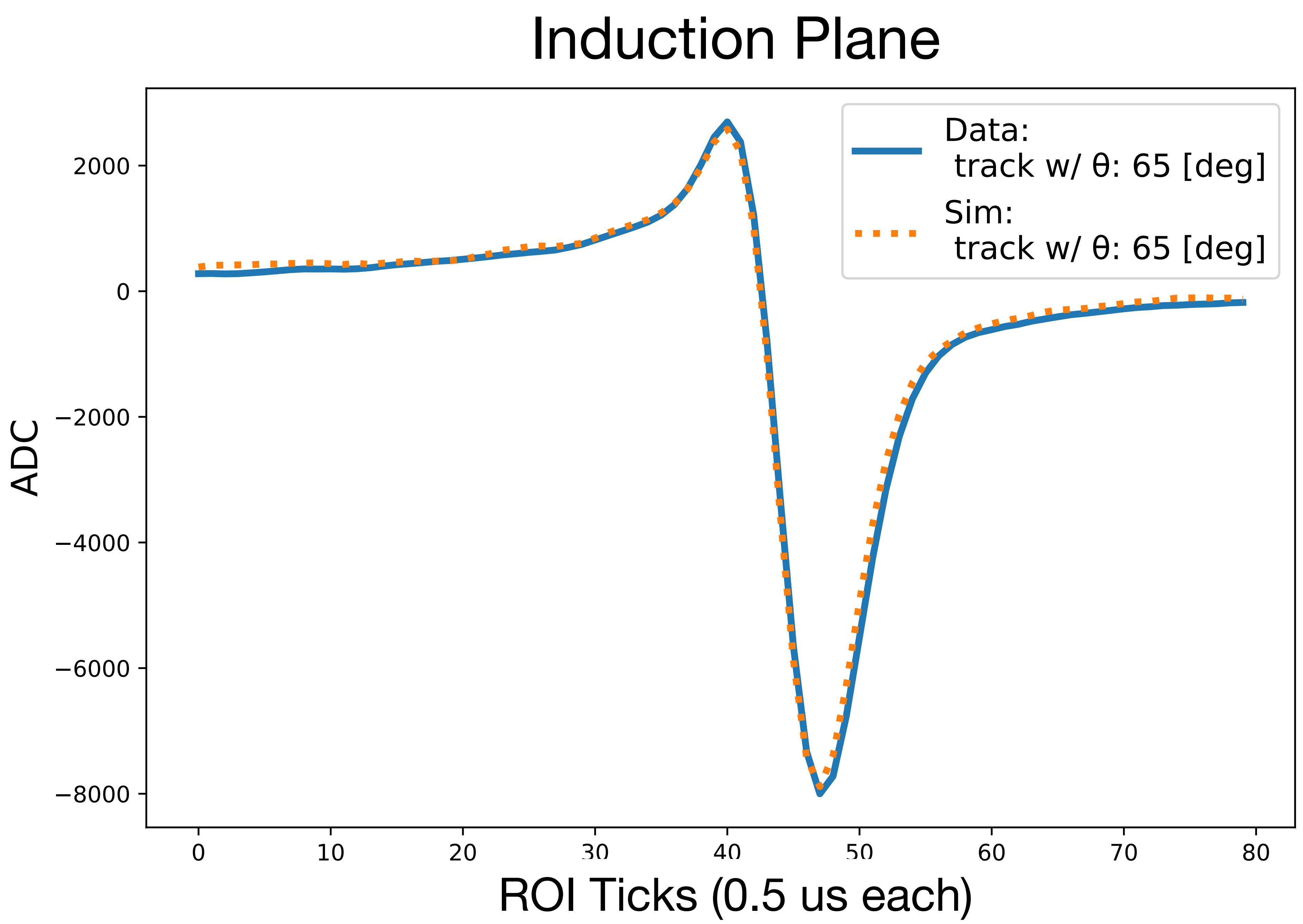
Example of Ar39 event



Raw Waveform Comparison Data/Sim (cosmic tracks)

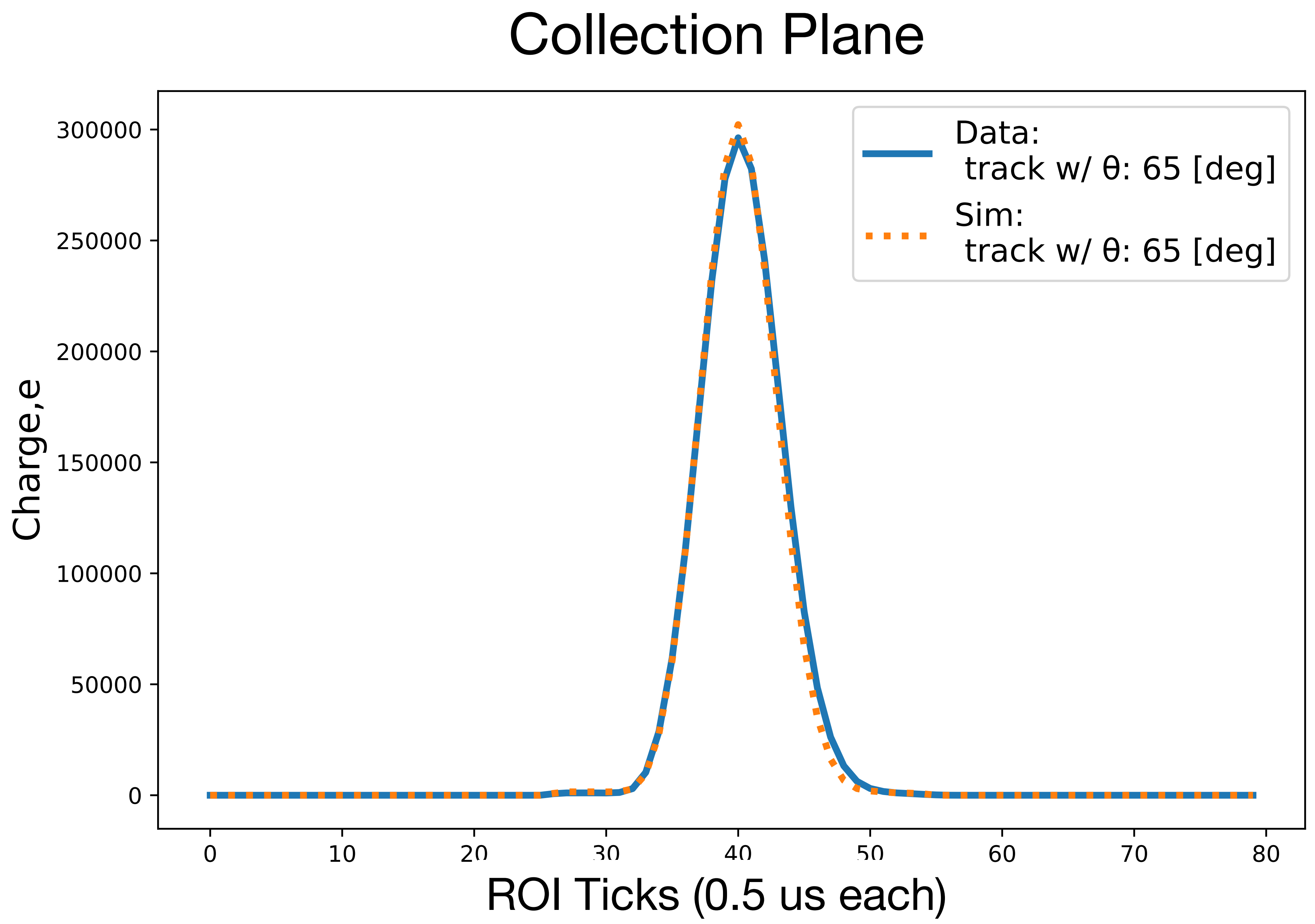
- Compare raw waveforms for selected track (before signal processing)
- For each track: sum waveforms for all channels, aligned by positive peak
- Plots are independently area normalized
- Consistent with expectation!

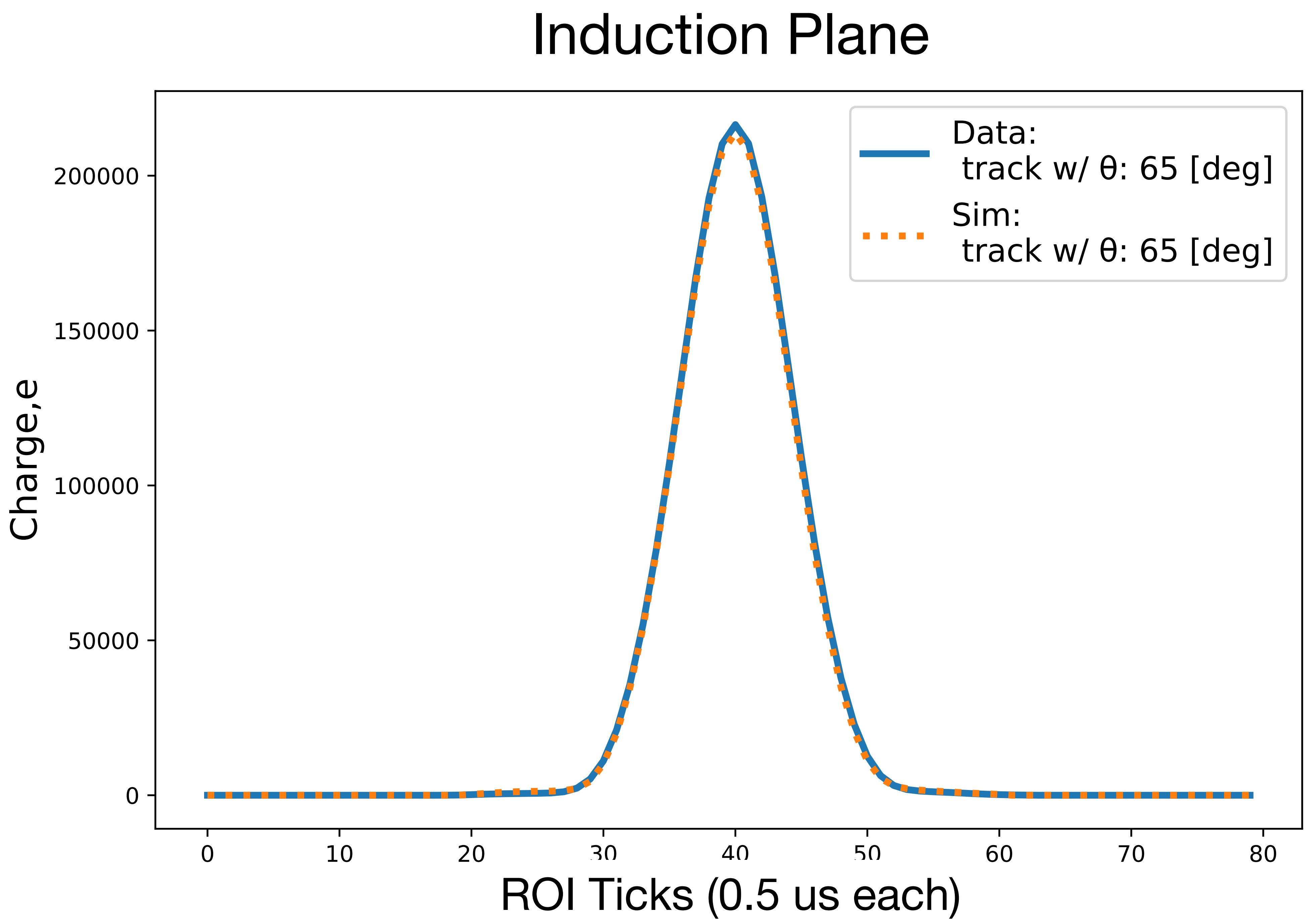




Reconstructed Charge Comparison Data/Sim (cosmic track)

- Compare reconstructed charge for selected track
- For each track: sum charges for all channels, aligned by positive peak
- Plots are independently area normalized
- Consistent with expectation!

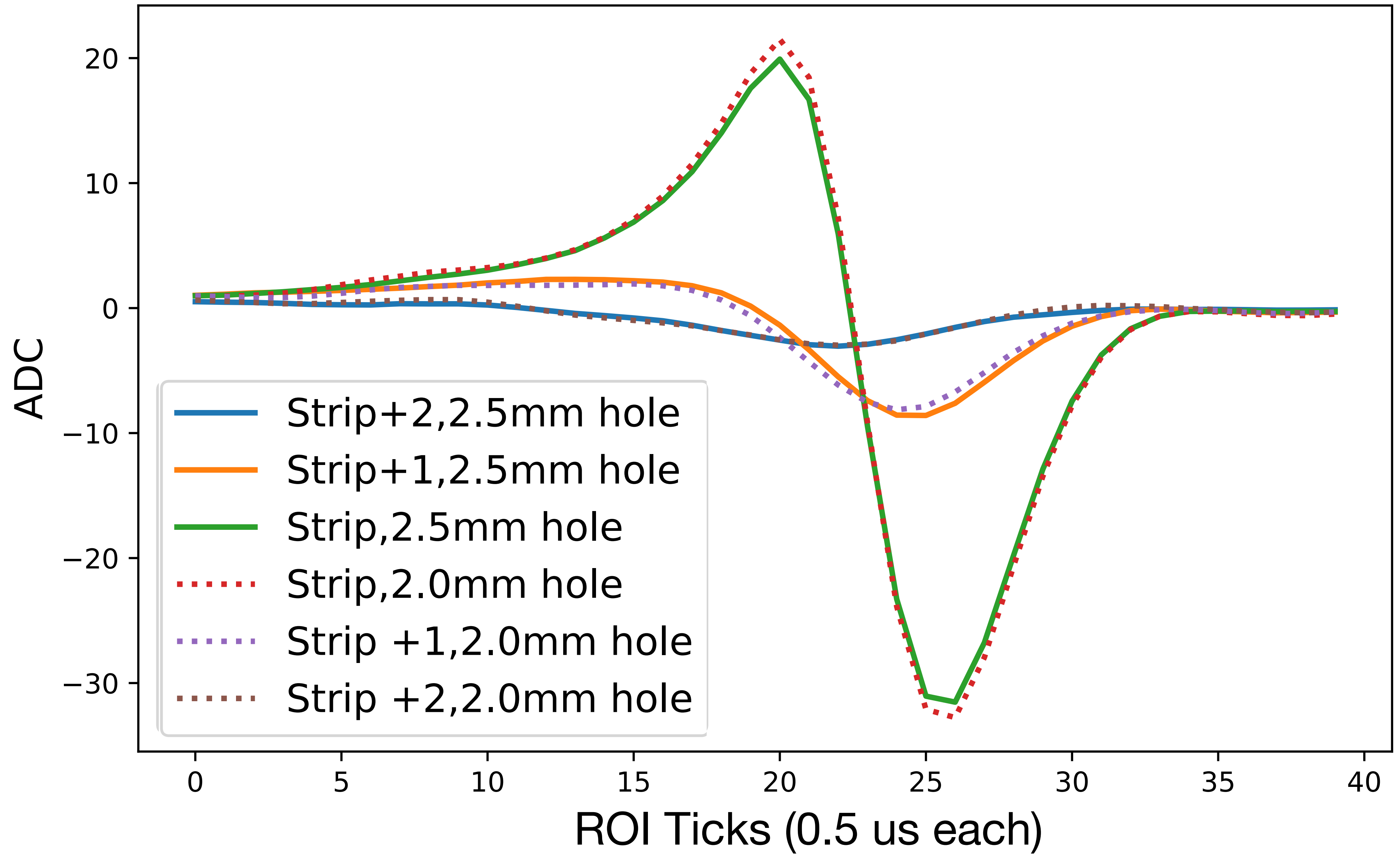




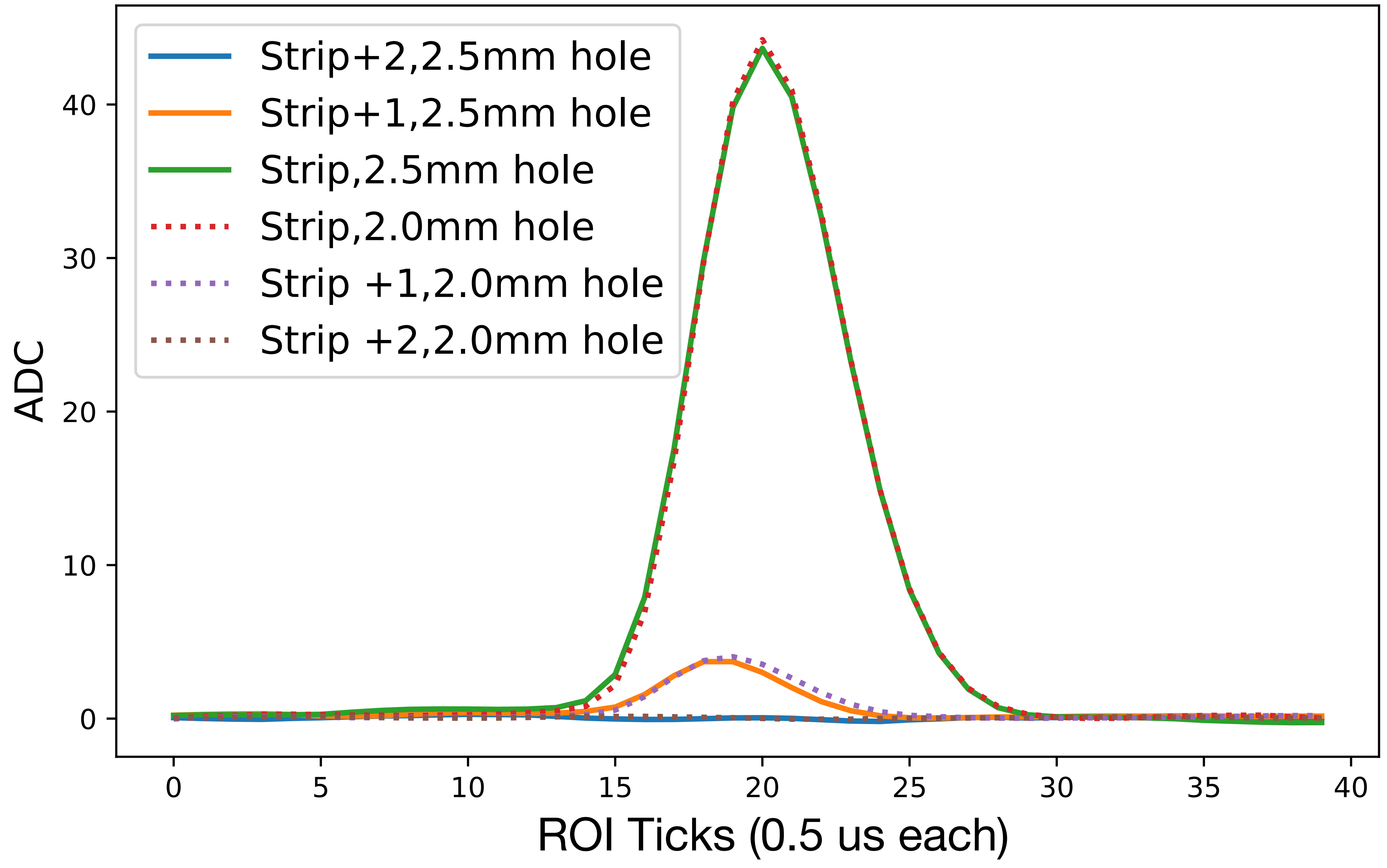
Compare FR for Large/Small Holes (Data Ar39 Events)

- Ar39 events are approximately a point source
- Select Ar39 events separately for 2 and 2.5 mm holes
- Check raw response function for different hole configurations
- The difference in FR for induction plane ~3%; sub 1% for collection plane

Induction Plane

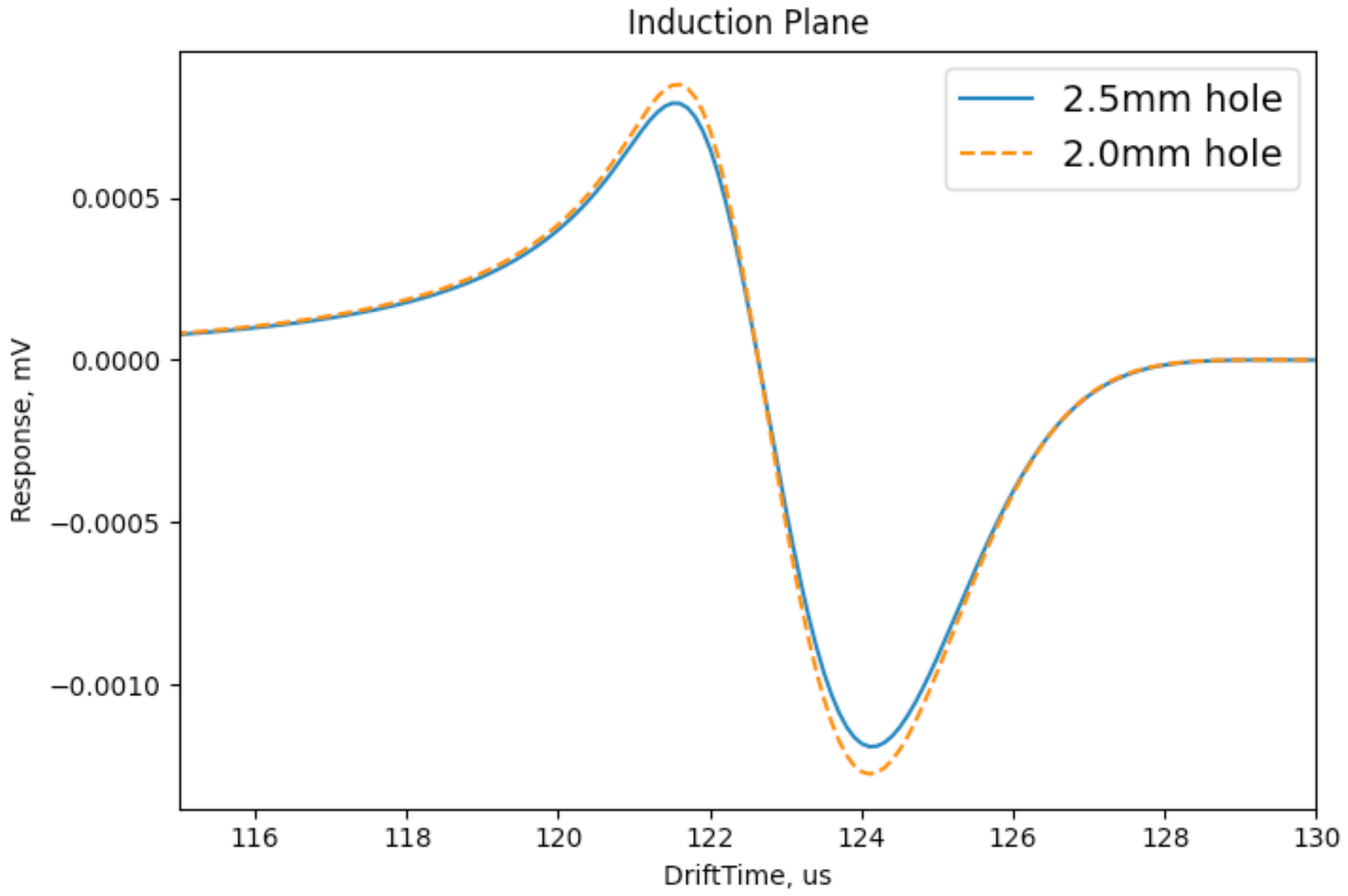


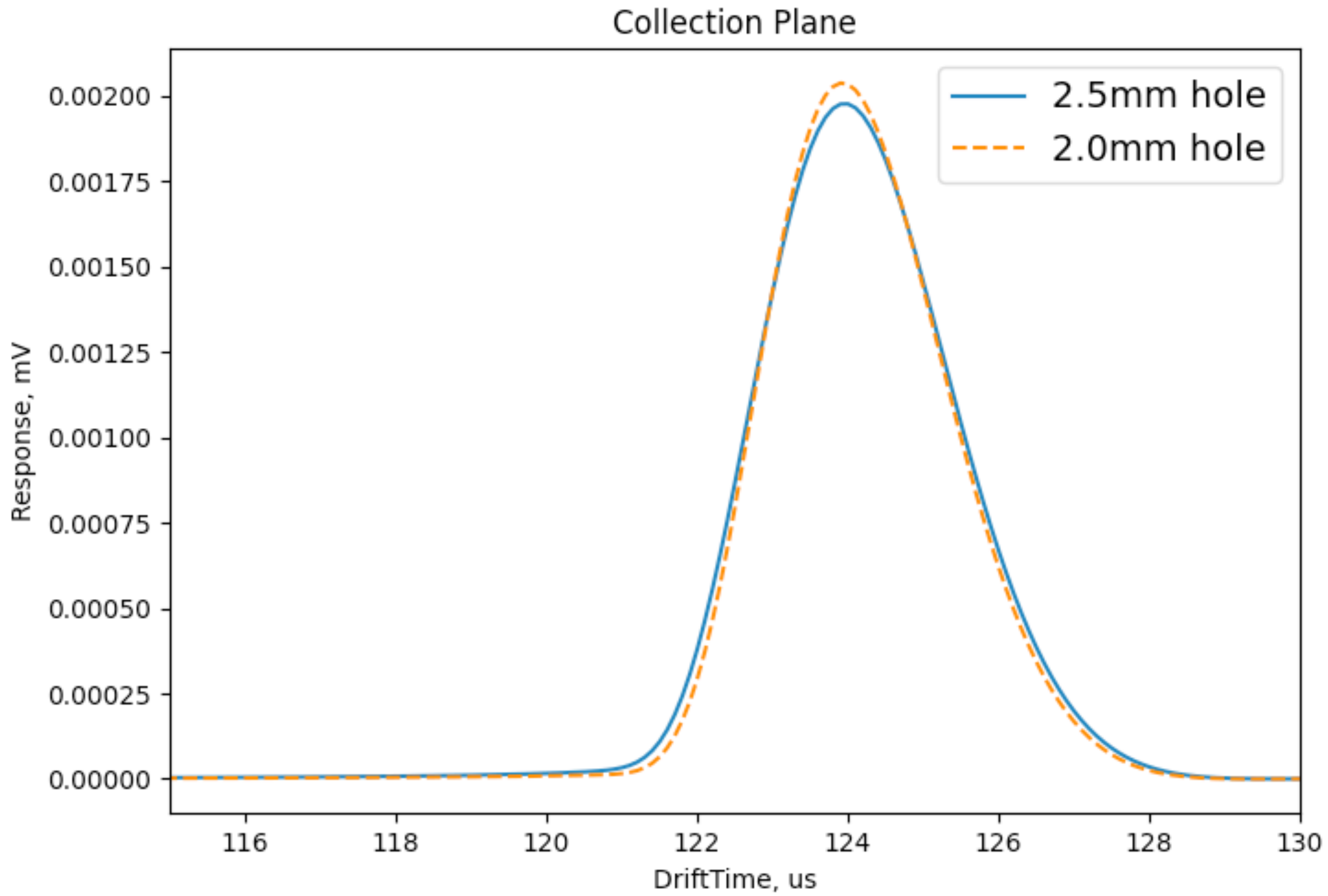
Collection Plane



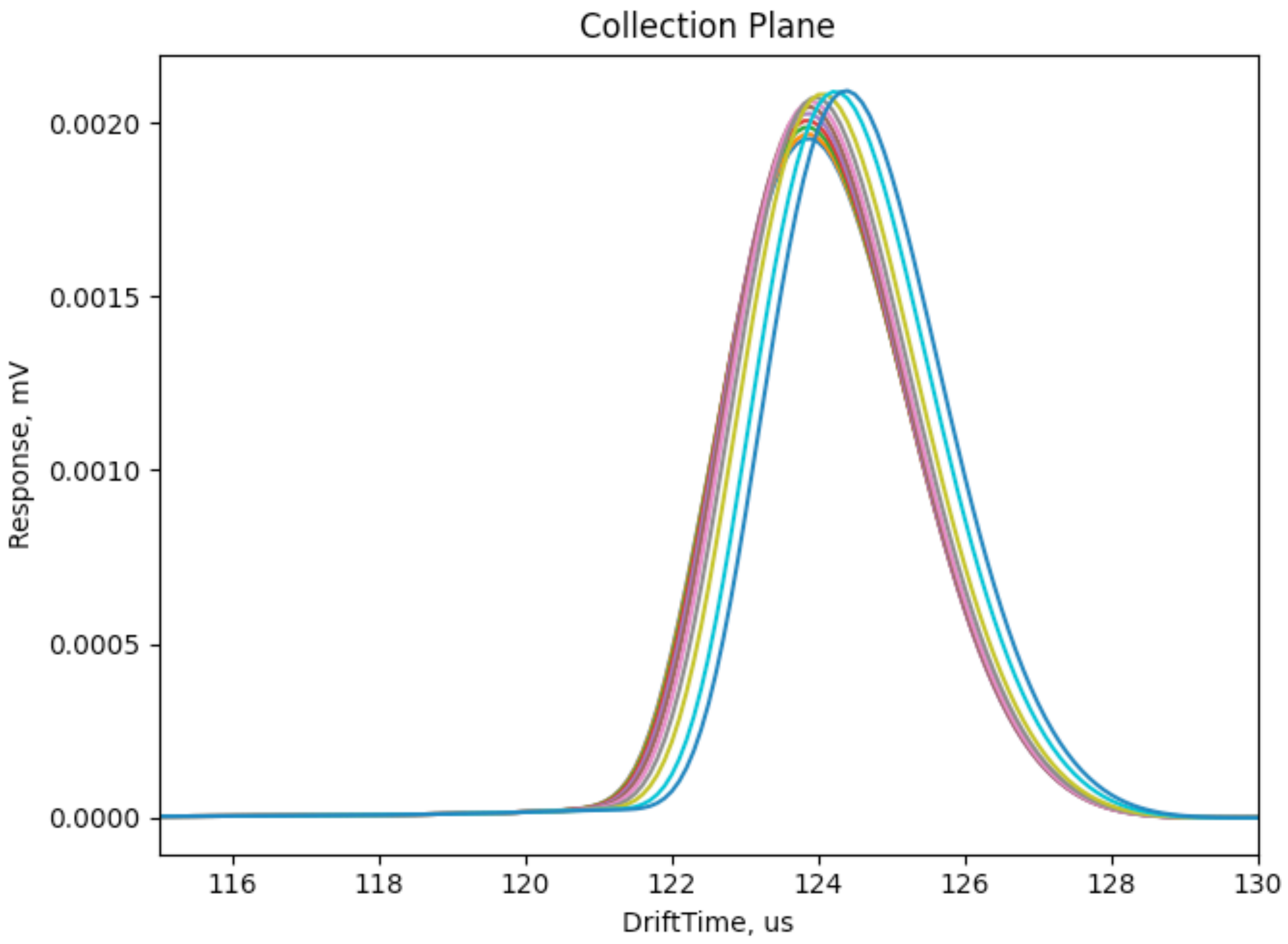
Compare FR for large/small holes for simulation

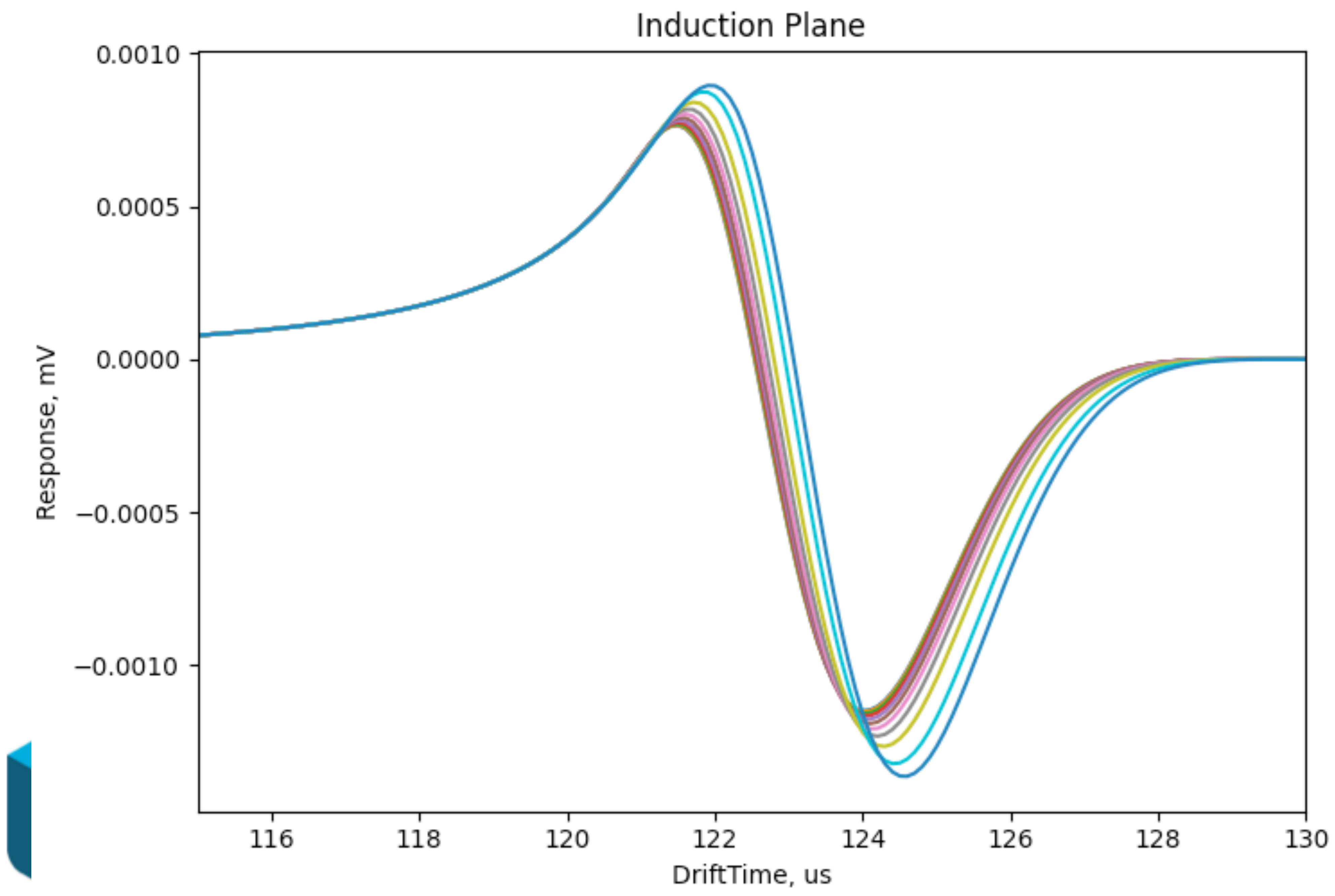
- Check if simulation sees the effect of hole size
- Simulate field response for 2 and 2.5 mm holes and convolve it with cold electronics response function
- The observed difference for induction plane ~4% and ~2% for collection



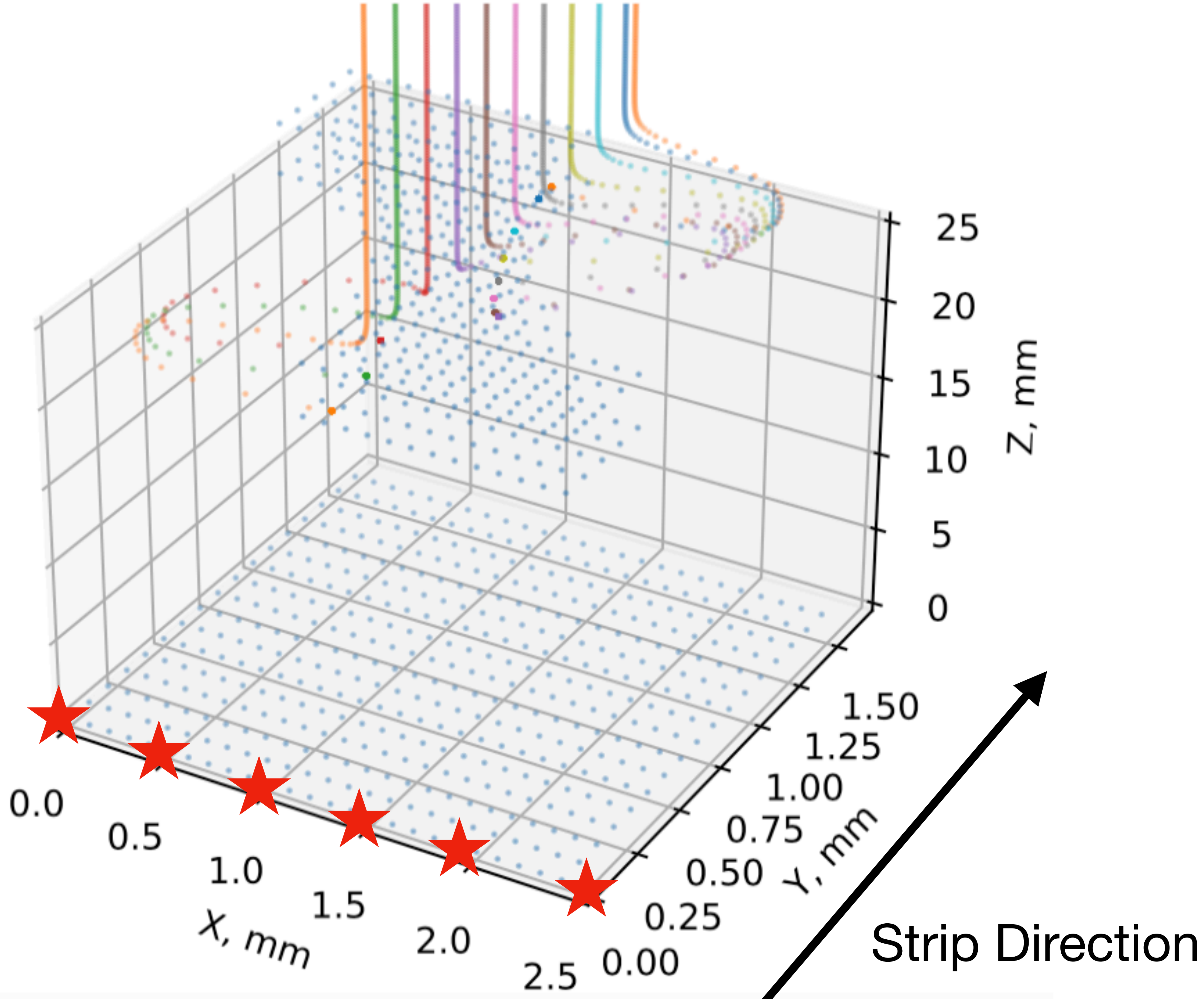


Field Response Variation Along the Strip (Simulation)





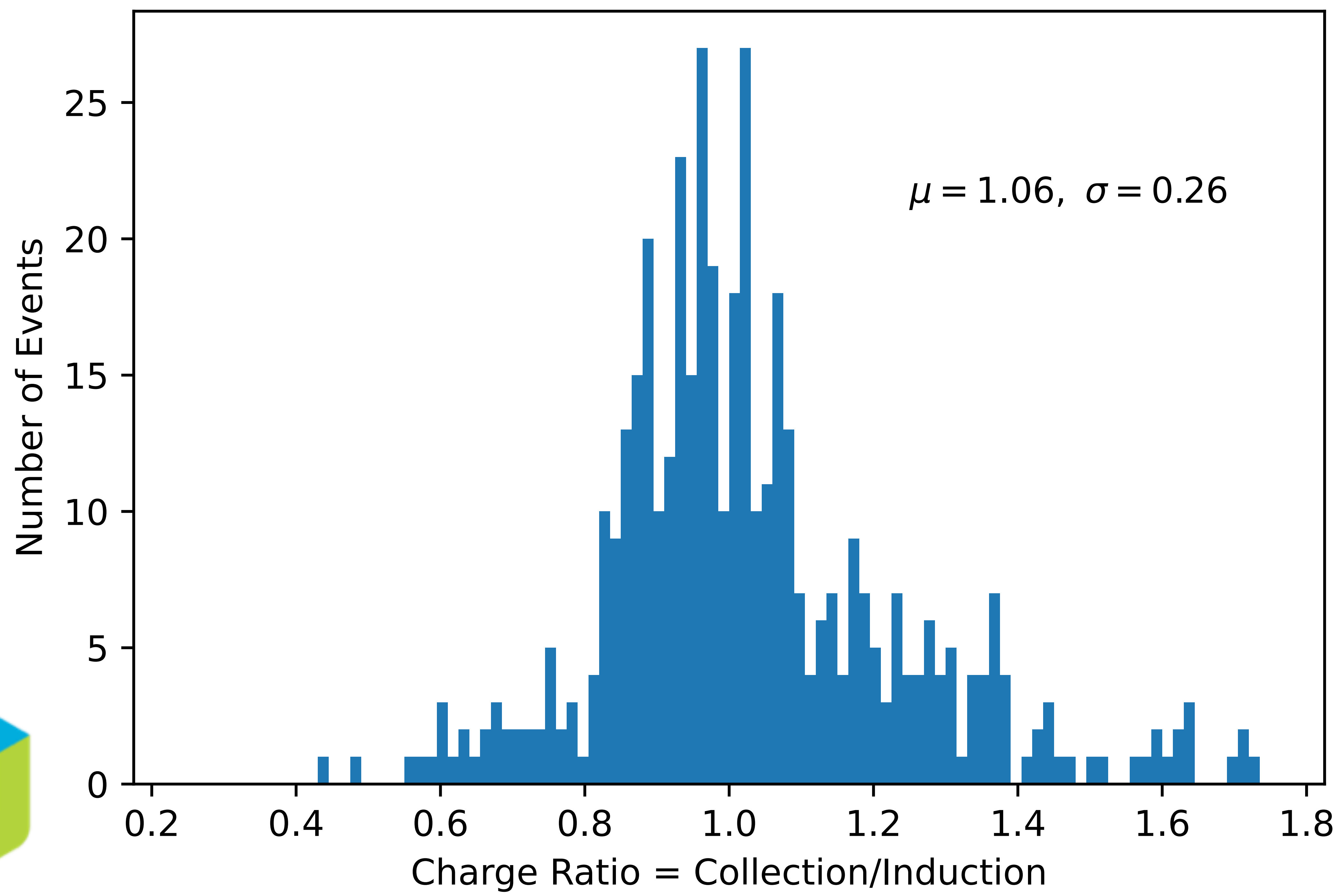
- Plots: field response convolved with elec. response along the strip (paths end up in different holes)
- To get field response for simulation we average across these paths
- Collection variation ~4%, Induction ~23%



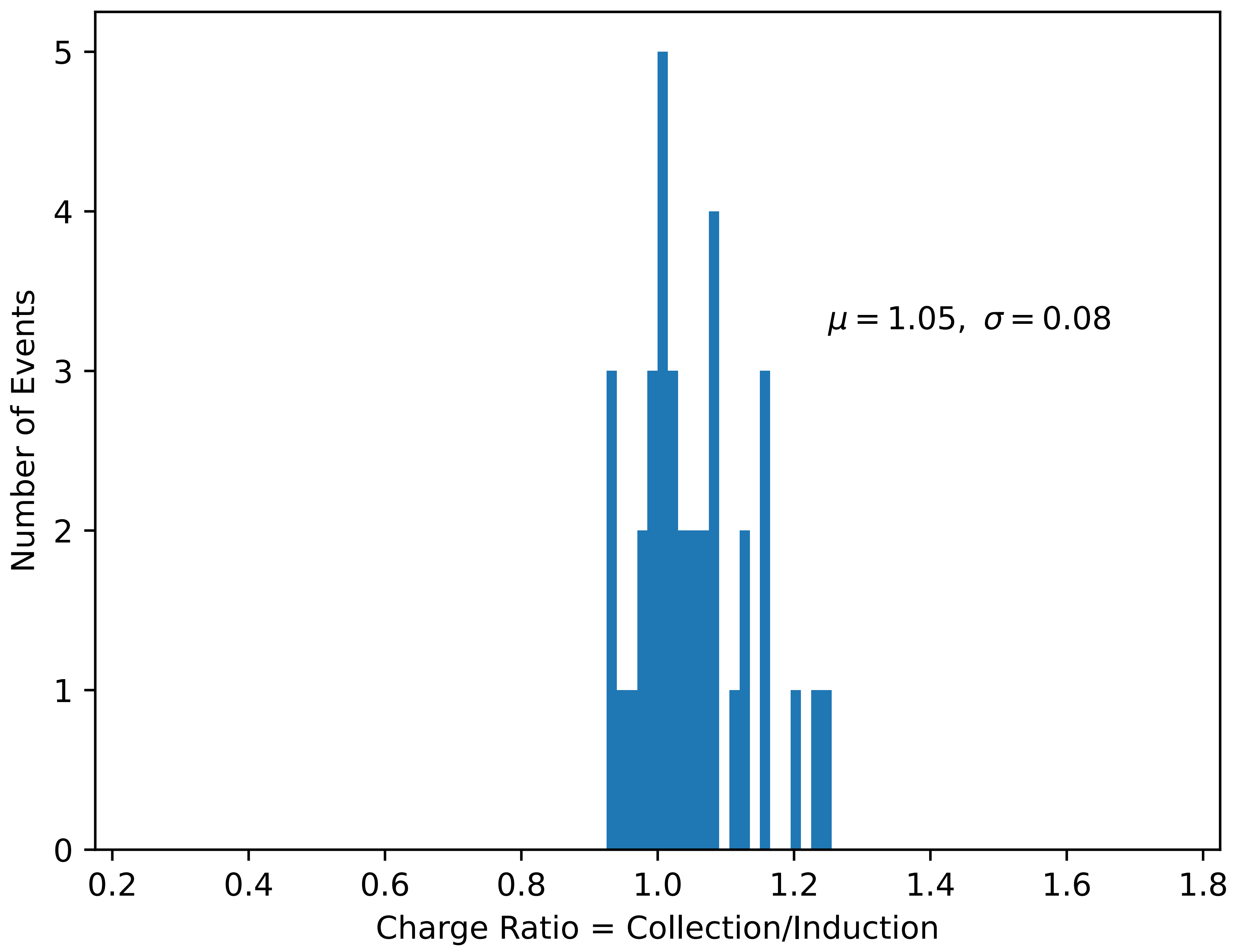
Collection/Induction Reconstructed Charge (Data)

- Compare total charge on collection and induction planes for Ar39 events and for cosmic tracks (Data only)
- Simple selection based on number of strips with signal
- Both Ar39 and cosmic tracks show variation in charge observed by induction and collection planes:
  - Possible source is variation of field response along the strip

Ar39



Cosmic Tracks



Summary

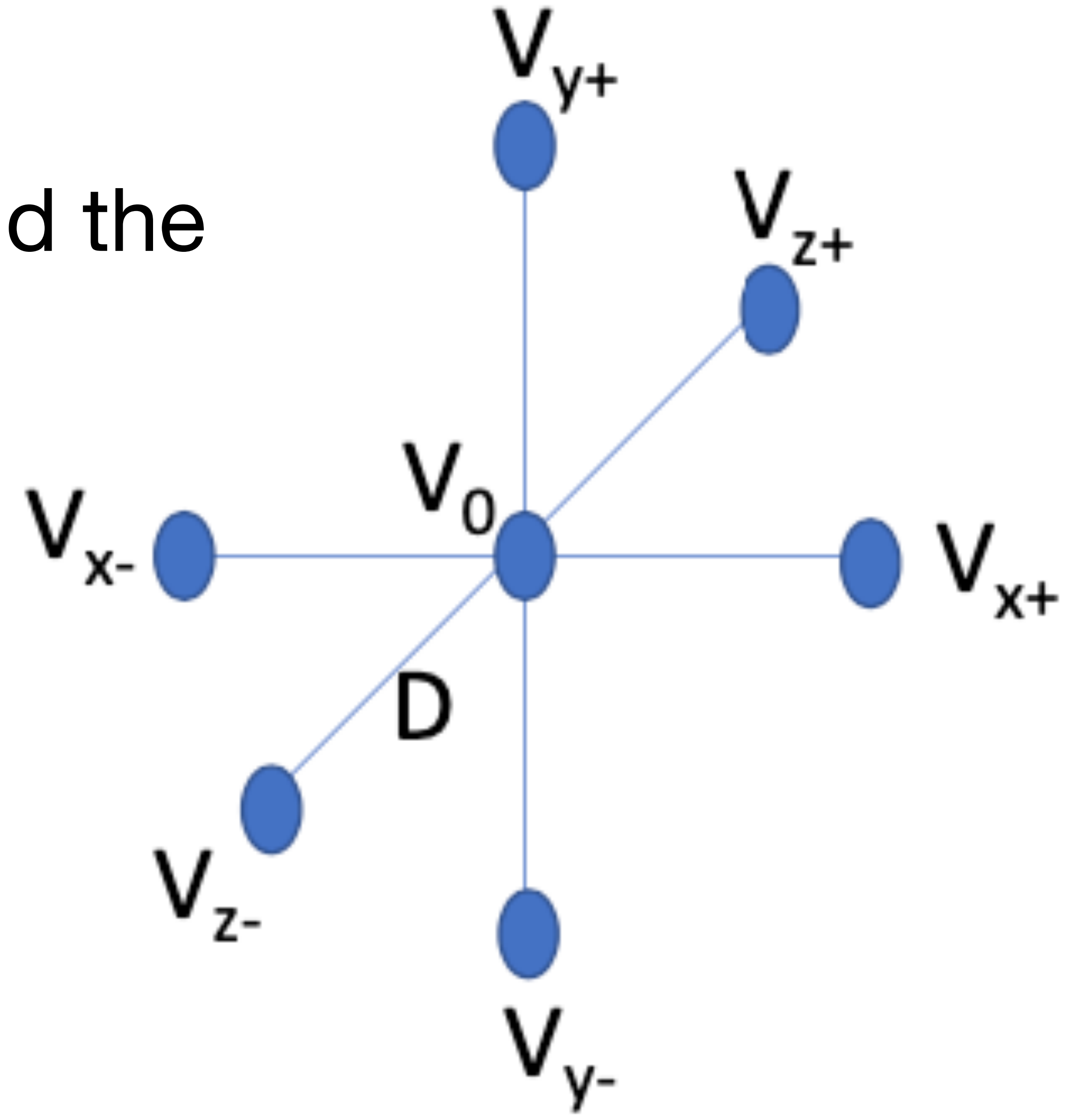
- We designed fast, precise, and easy to use hybrid 3D/2D field response simulation for PCB-based anodes (https://github.com/brettviren/pochoir)
- We compared the simulation against the data from the CERN 50-L prototype detector => **Good Agreement!** (sub 5%)
- Using the simulation, we showed the existence of response variation along a strip because of the hole pattern :
  - Effect possibly seen in data for Ar39 and for cosmic tracks
- Future:
  - The difference between data and simulation may be significant, particularly for AI/ML approaches
  - There are several possible ways to address it:
    - The averaging procedure can be improved to reduce field response uncertainty
    - New ways of 3D detector simulation and iterative reconstruction techniques can be explored to account for observed effects properly

backup

Electric Field Calculation

- Solve 1st Maxwell equation ($\nabla E = 0$) on a 3D lattice both for the drift field and the weighting field (collection/indiction) using Finite Difference Method (FDM)

$$\frac{\partial E}{\partial x} + \frac{\partial E}{\partial y} + \frac{\partial E}{\partial z} = 0 \qquad \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = 0$$



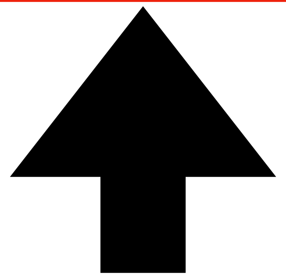
- Solving on 3D grid with grid spacing D:

$$\frac{\partial^2 V}{\partial x^2} = \frac{((V_{x+} - V_0) - (V_0 - V_{x-}))}{D^2}$$

$$\frac{\partial^2 V}{\partial y^2} = \frac{((V_{y+} - V_0) - (V_0 - V_{y-}))}{D^2}$$

$$\frac{\partial^2 V}{\partial z^2} = \frac{((V_{z+} - V_0) - (V_0 - V_{z-}))}{D^2}$$

$$V_0 = \frac{(V_{x+} + V_{x-} + V_{y+} + V_{y-} + V_{z+} + V_{z-})}{6}$$



Can be iteratively solved for whole simulated volume

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = \frac{(V_{x+} + V_{x-} + V_{y+} + V_{y-} + V_{z+} + V_{z-} - 6V_0)}{D^2} = 0$$

FDM Calculation

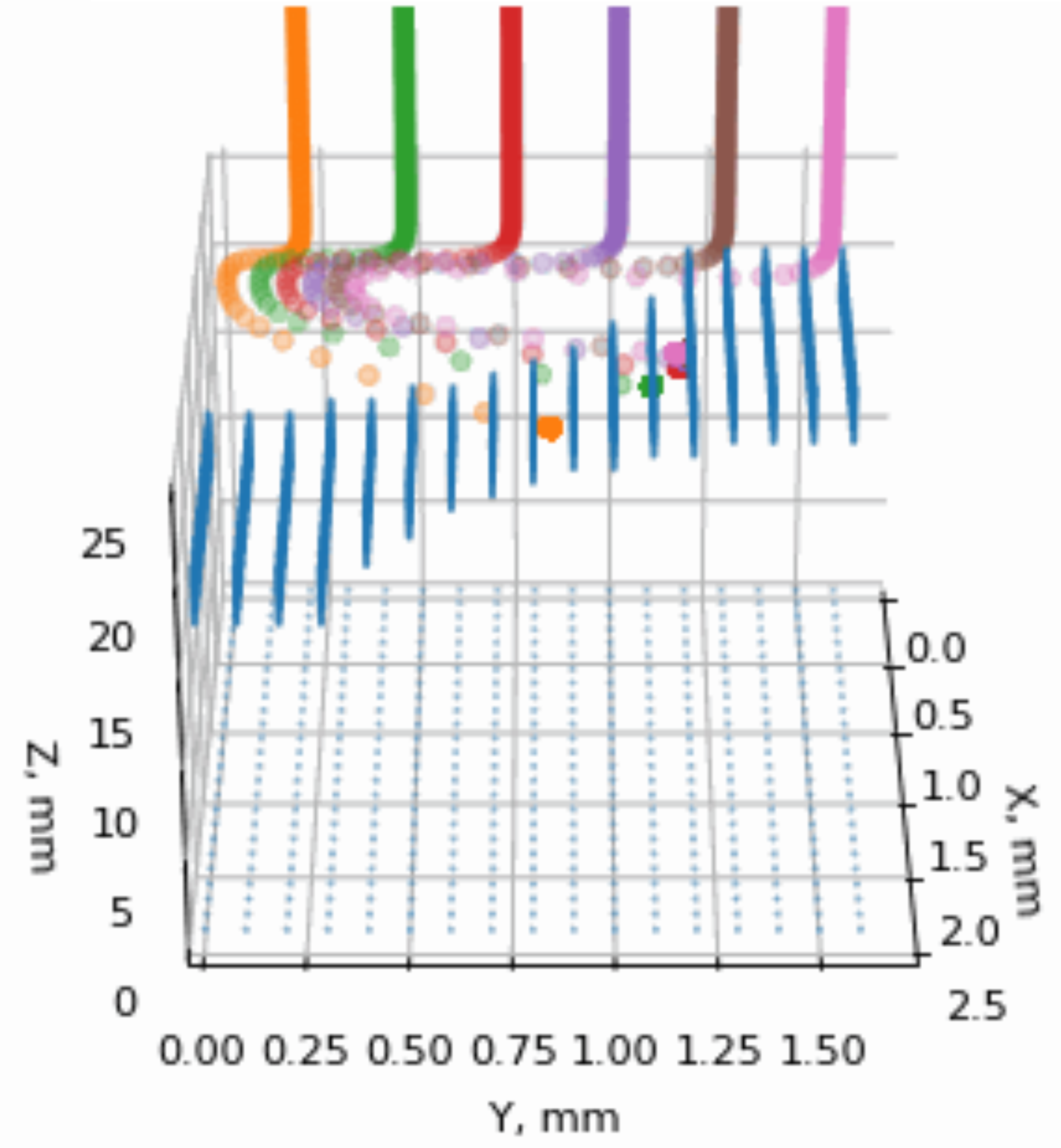
- Total of 3 FDM simulations:
  - 3D drift field
  - 2D weighting field
  - 3D weighting field (with 2D case as boundary condition)
- FDM need on two inputs:
  - Number of steps to cover all volume
  - Number of epochs to do the solution refinement (optional)
- Number of steps for weighting field is set very high and can be reduced to speed up the calculation

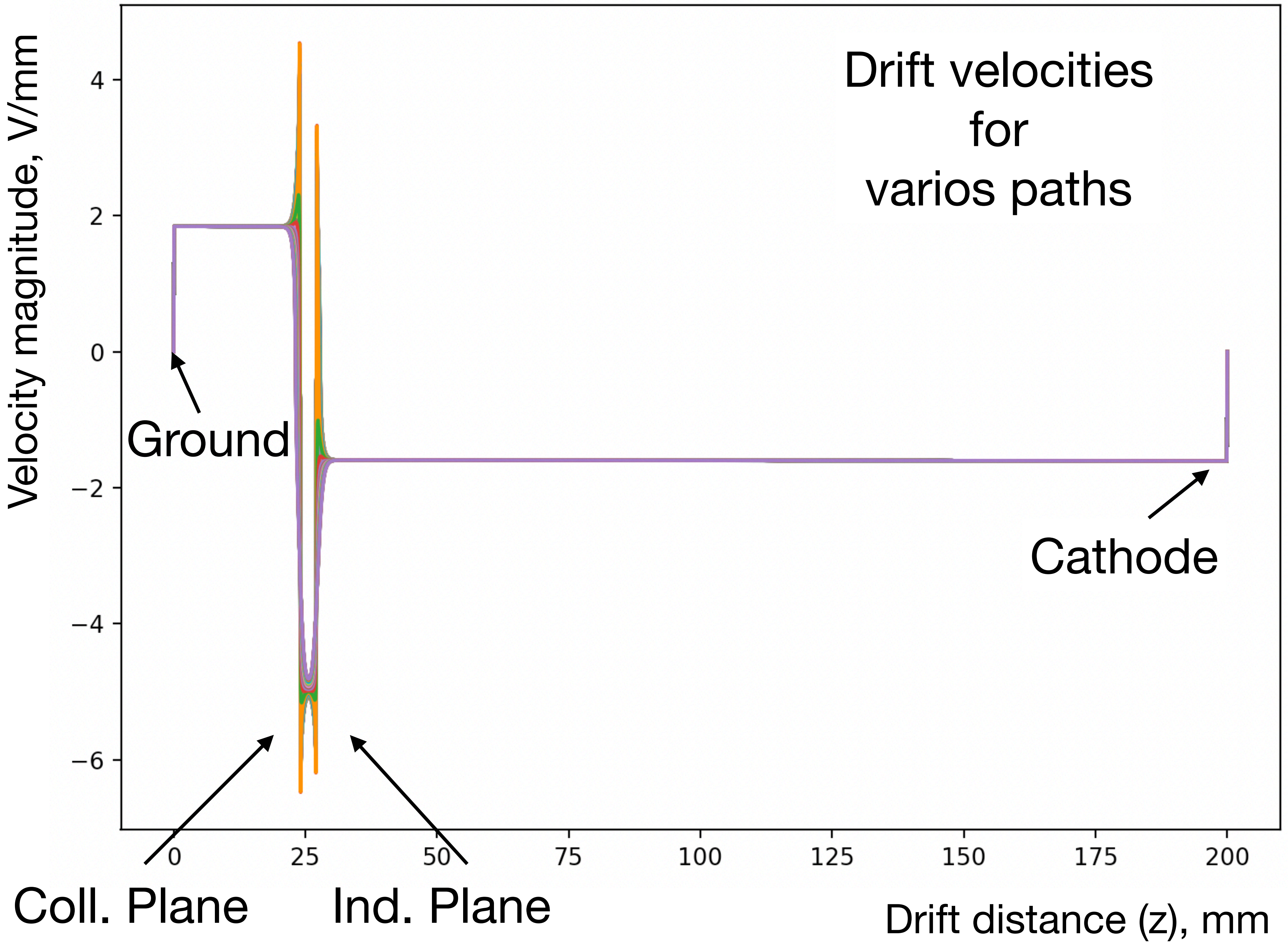
Grid Points (# of epochs/steps)	**GPU (PyTorch tensors)**
3D drift: 25x17x2000 (2ep,5000000 steps)	~60min
2D weighting: 1092x2000 (2ep,5000000 steps)	~90min
3D weighting: 350x34x2000 (1ep,5000000 steps)	~890min

Drift Paths/Velocities

- Drift Velocity is calculated : $v = \mu \times E$, $\mu = \mu(E, T)$ - electron mobility;
- Uniform ~1.6 V/mm velocity through the drift volume (expected for chosen detector configurations)
- Drift paths are calculated using Runge-Kutta implementation in scipy (cover drift distance with 0.1us step);
- Example : choose paths to check behavior near the volume boundary and near PCB;
- Starting less than 0.05mm from the boundary makes electron to go out of boundaries.

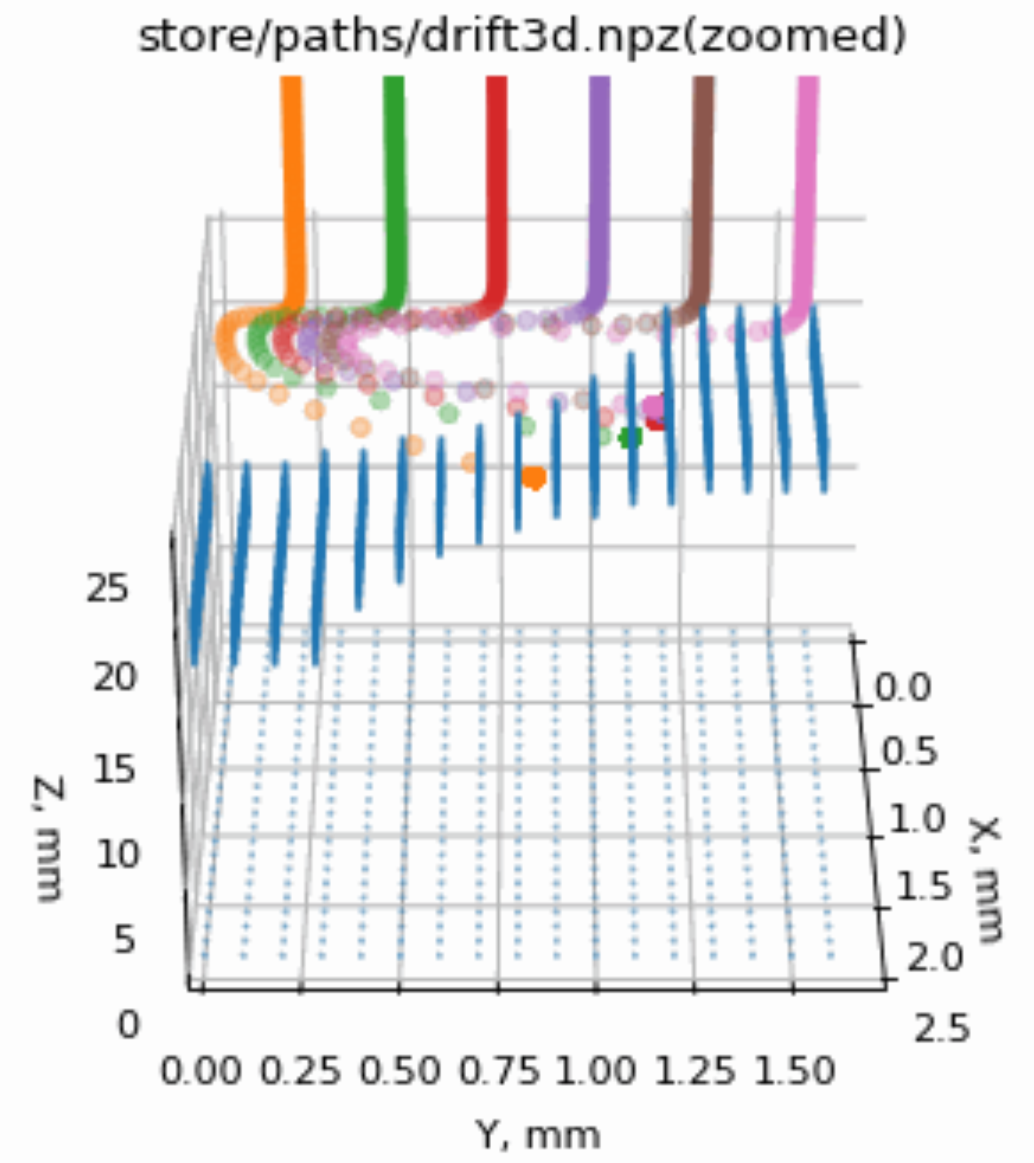
Example electron Drift Paths

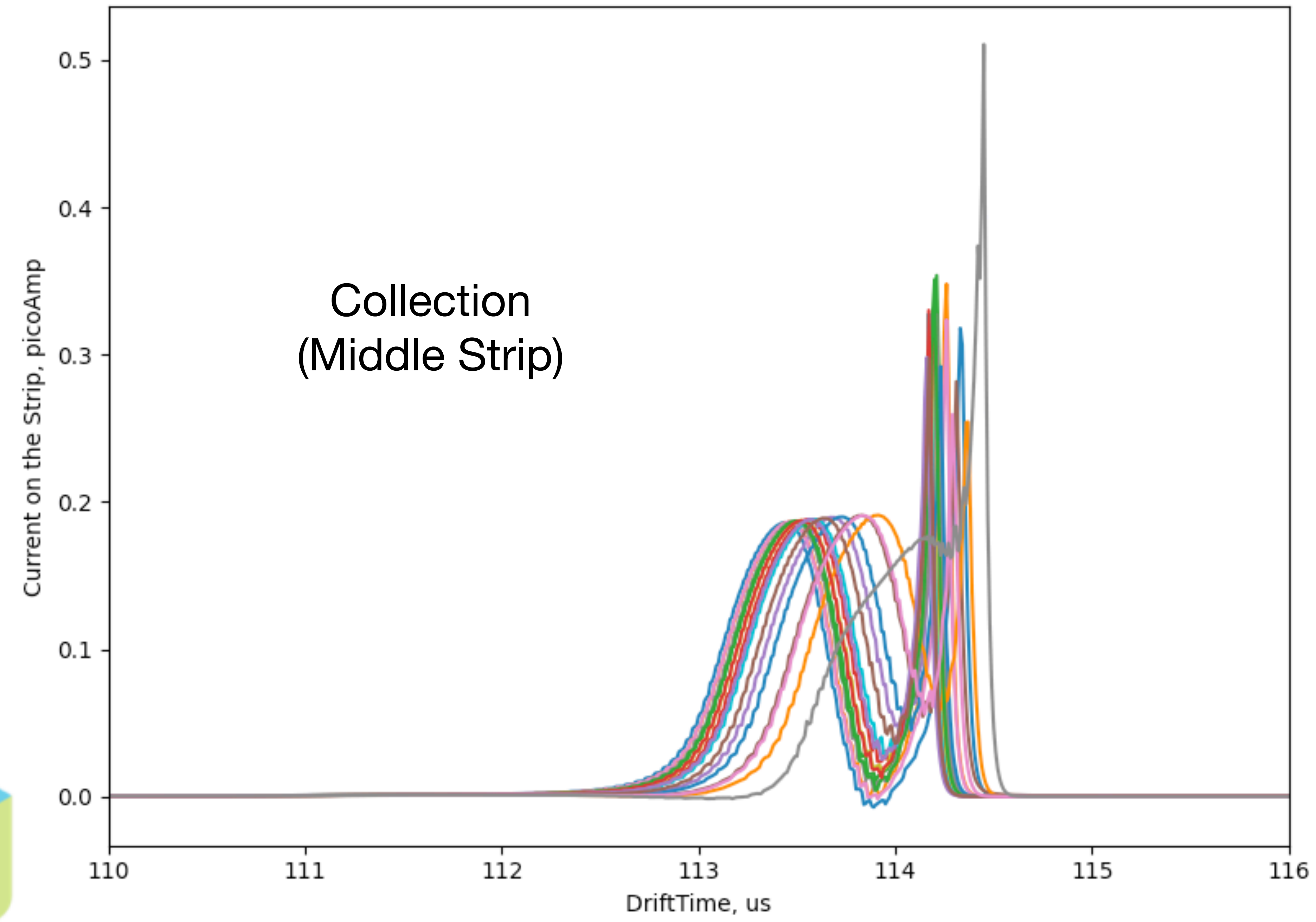


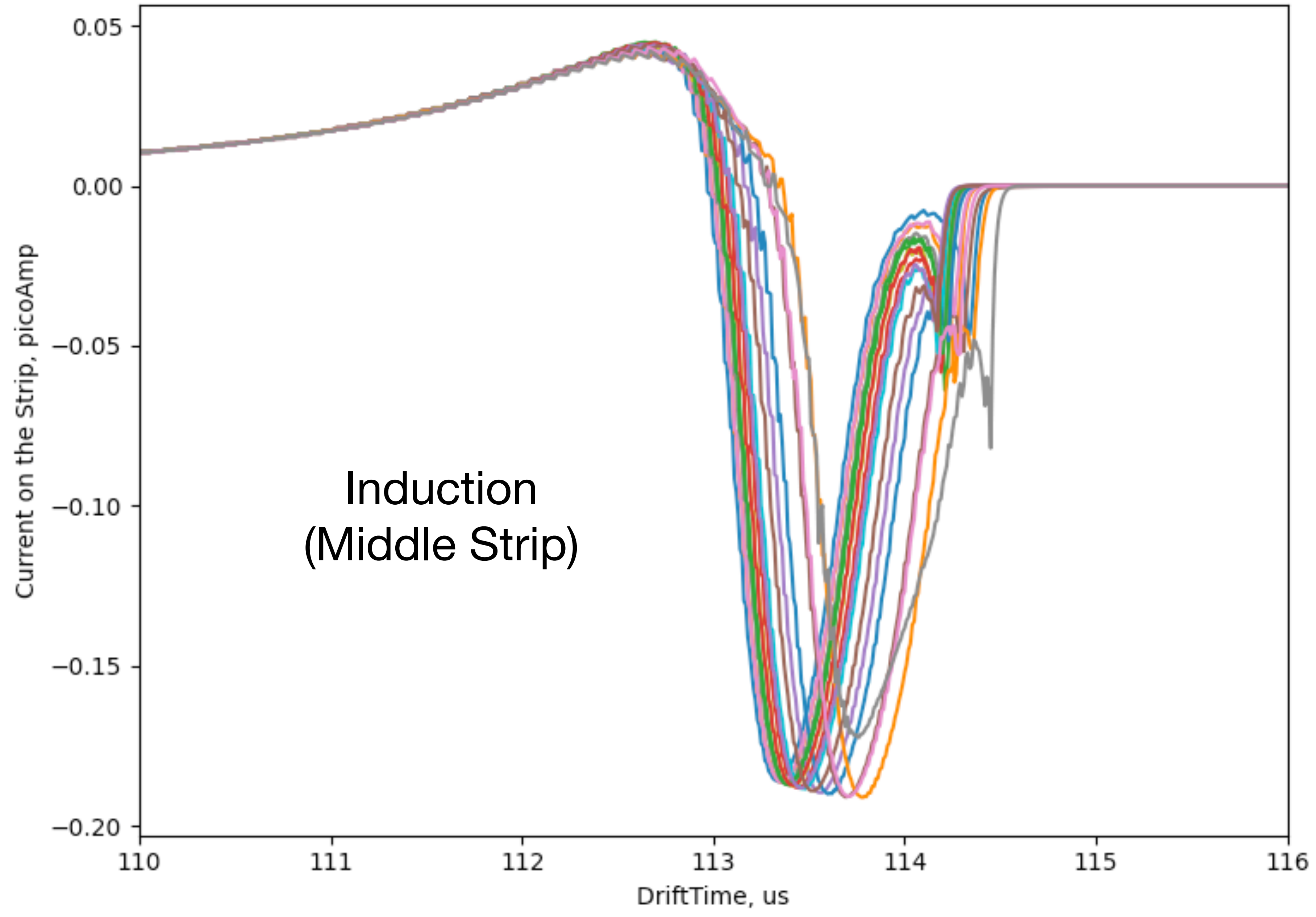


Induced current/Charge

- Total charge simulated ~1e
- Check total charge induced on collection plane always ~ 0.999

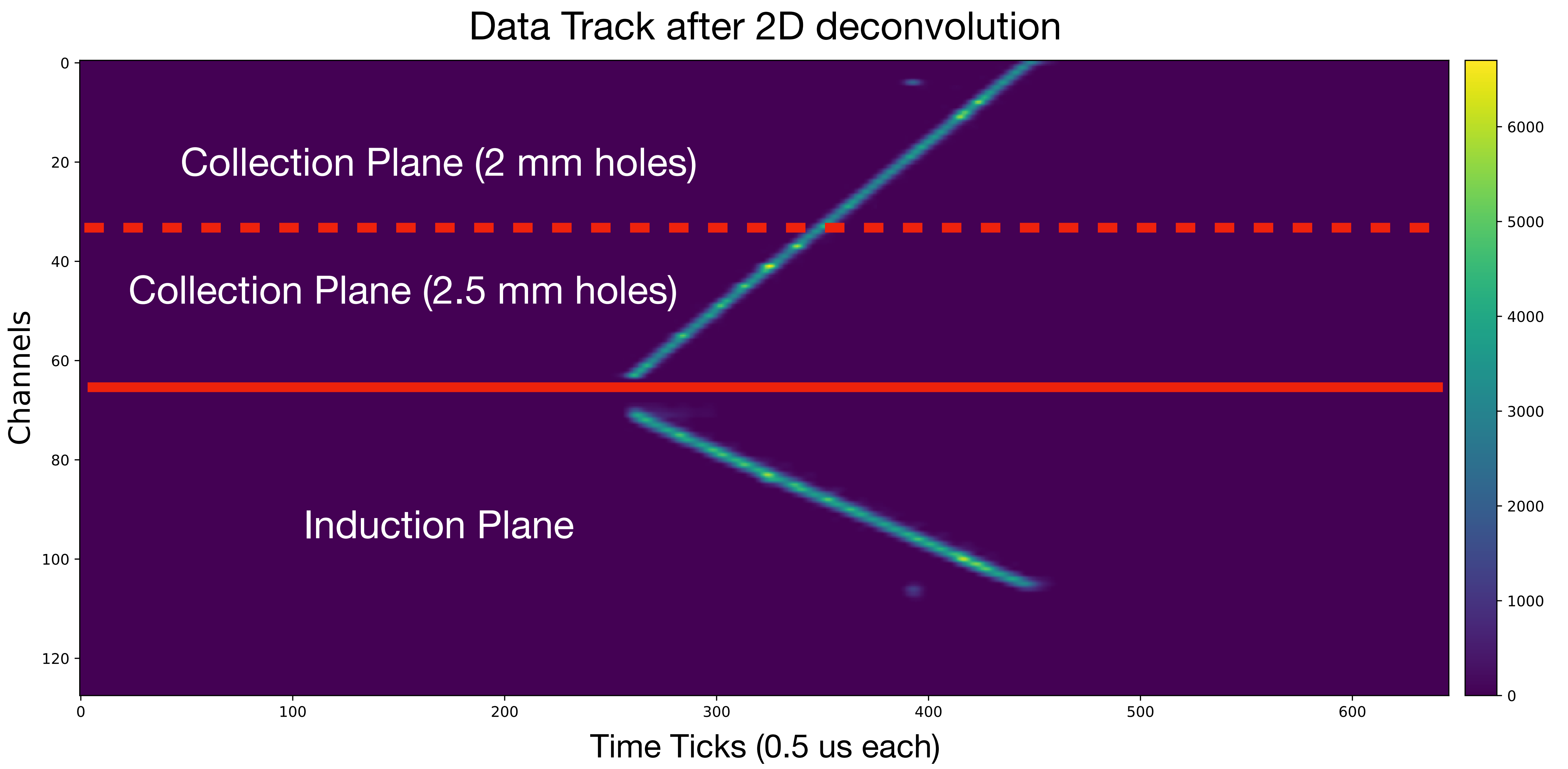


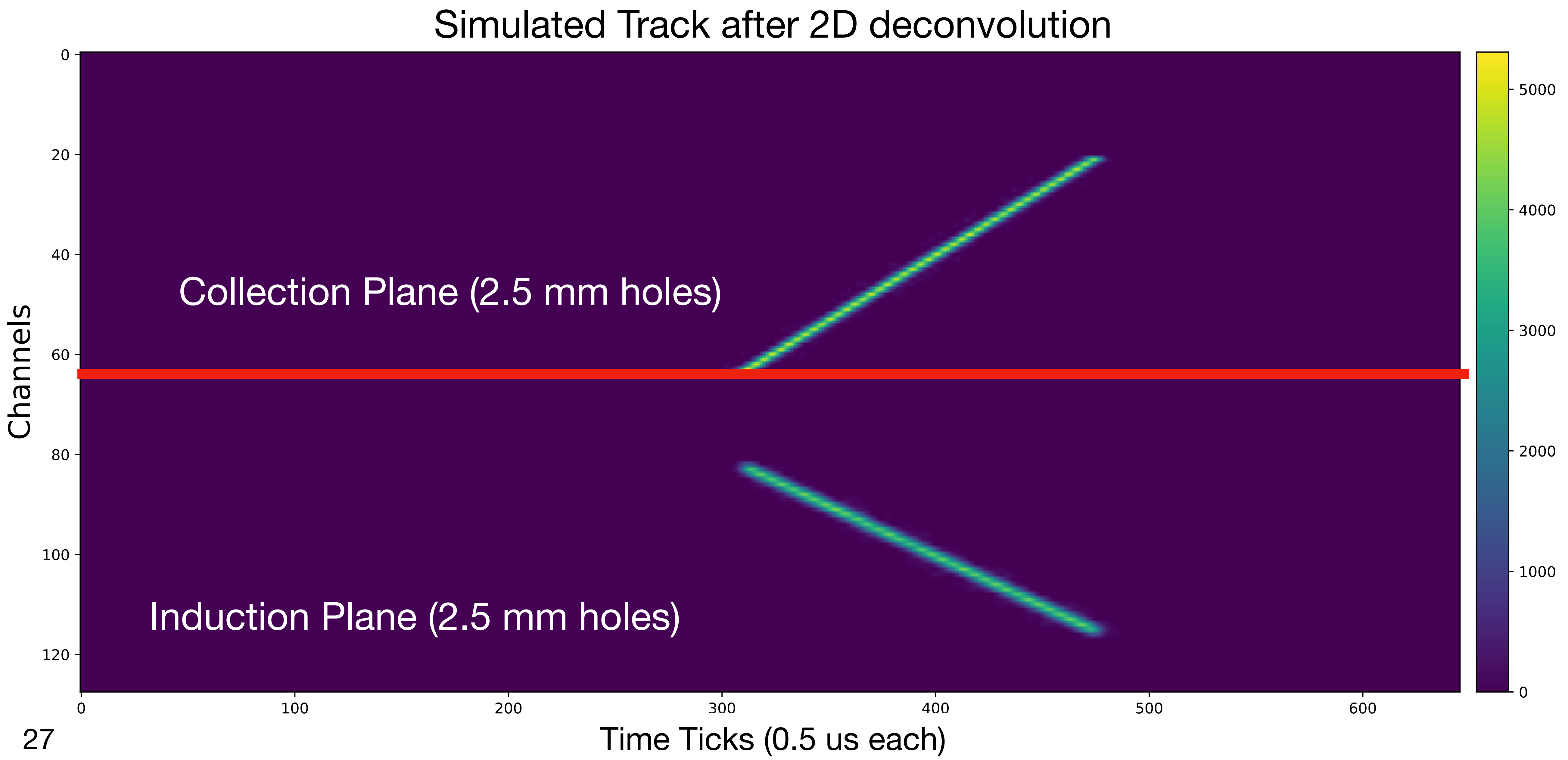




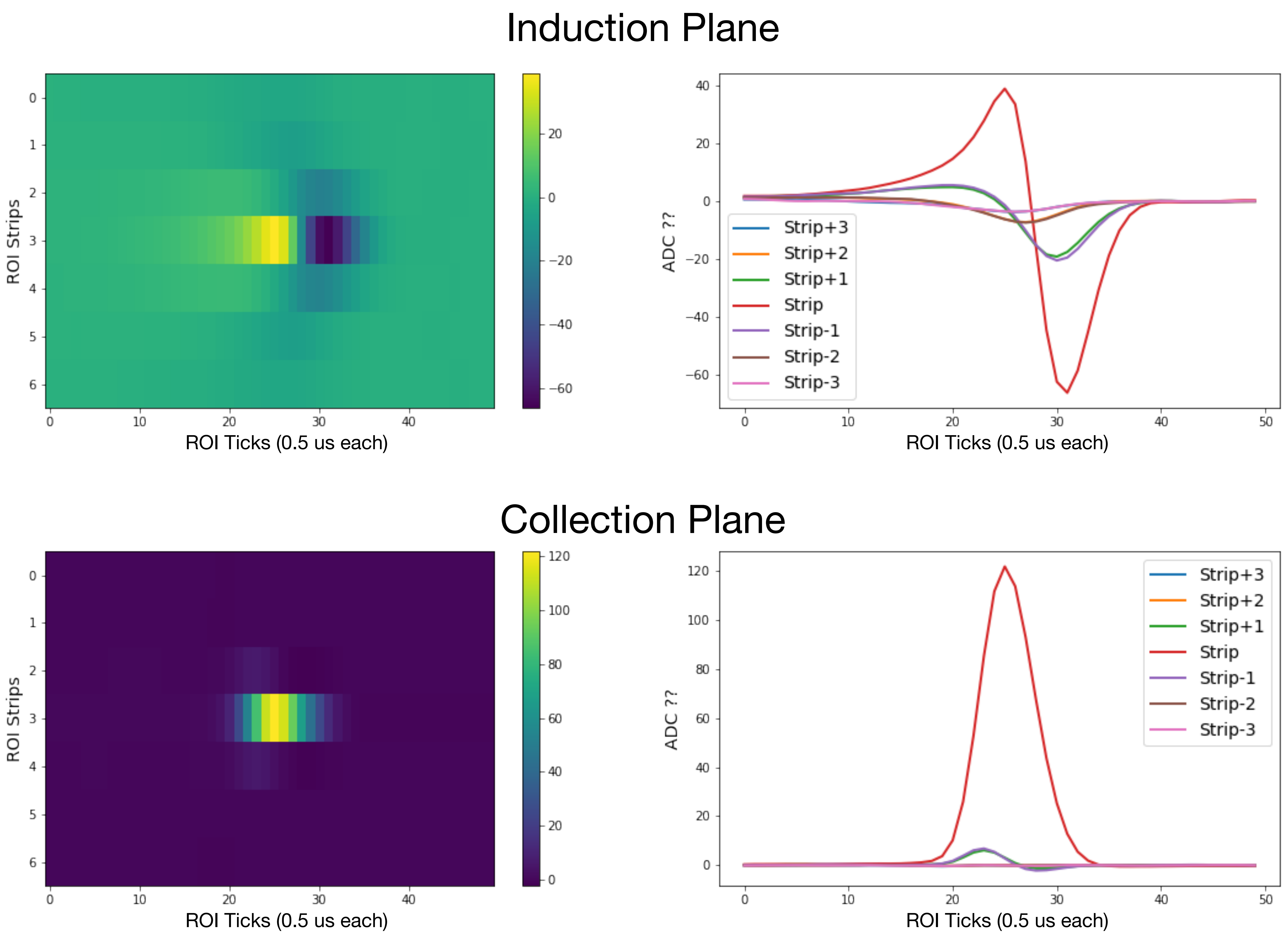
Cosmic track

- Select track from the data and simulate one with similar angle;
- At the moment track for data is selected without any cuts on region with particular hole size;
- Simulated track has 2.5 MeV/cm energy deposition.





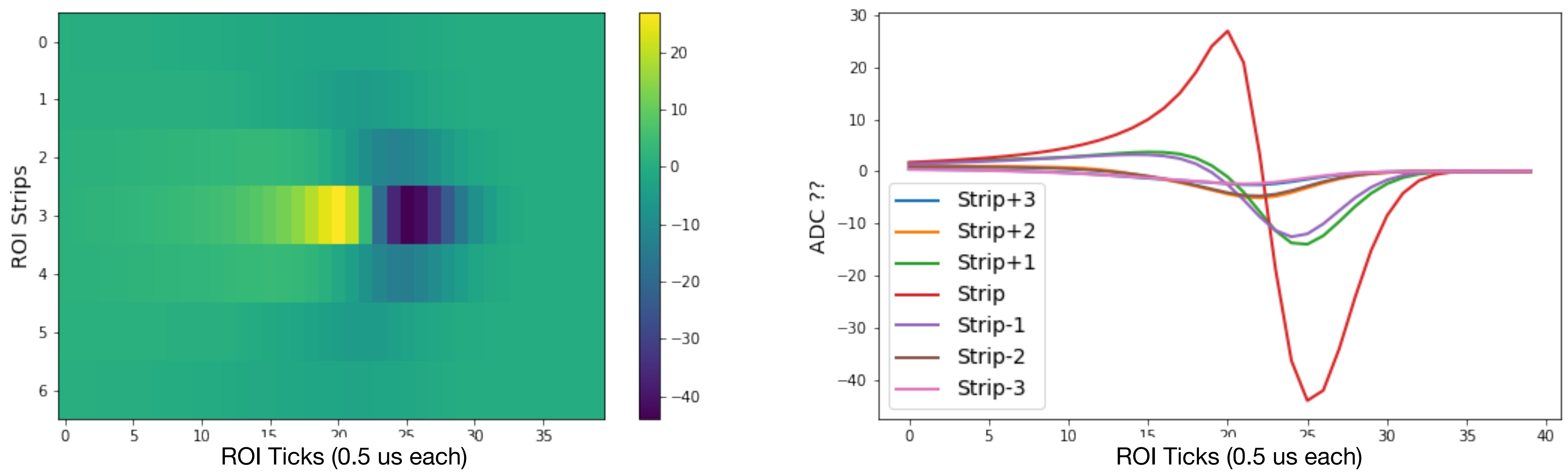
Ar39 event selection (Data)



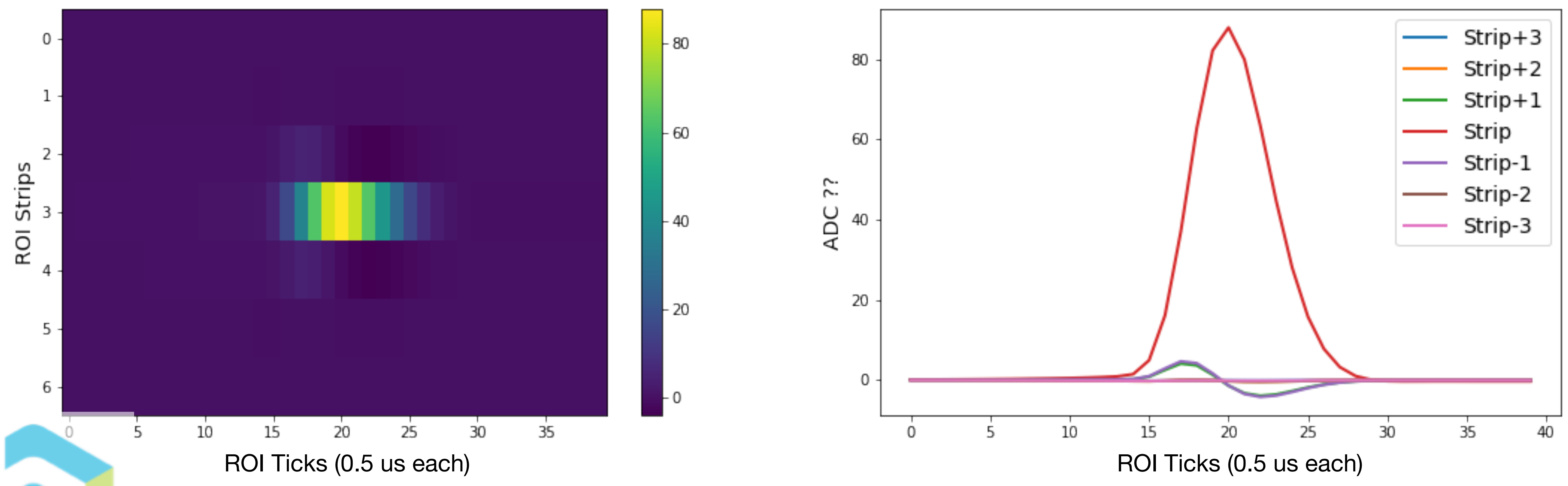
- Select events with peak > 70 ADC above baseline on collection plane;
- Take into account only channels 32:64 on collection plane (hole diameter of 2.5mm) or channels 0:32 for 2mm holes;
- Select ROI as Middle strip +-3 strips and time of the peak +-25 time ticks (0.5 us each);
- Average across ~700 events.

Simulation : Ar39 events

Induction Plane



Collection Plane



- Diffusion : Transverse 8.8cm^2/s ; Longit. 4cm^2/s
- Elec lifetime 9 us
- Hole size 2.5mm
- Select events with peak > 70 ADC above baseline on collection plane
- Select ROI as Middle strip +-3 strips and time of the peak +-25 time ticks
- Average across ~60 events

Compare reconstructed charge between planes

- Use reconstructed charge from data only (with field response calculated for 2.5 mm holes);
- Beginning and end edges match well between two planes;
- Total ratio (Coll/Ind) = 0.968
- Average ratio for 2.5 mm holes= 0.9785
- Average ratio for 2 mm holes = 0.9591