Signal Processing in SBND with WireCell

NuFACT 2023 (08/25/2023)

Avinay Bhat, on behalf of the SBND Collaboration

SBN Program at Fermilab

Goals of SBN(D)

- Definitive goals of the SBN(D) Program at Fermilab are:
    - To investigate the source of the MiniBooNE ‘Low Energy Excess’
    - Discovery or exclusion of ~1 eV^2 sterile neutrinos, a region motivated by MiniBooNE
    - High precision study of ν_μ-Ar and ν_e-Ar interactions using both BNB and NuMI neutrino beams
    - Conduct BSM physics searches.

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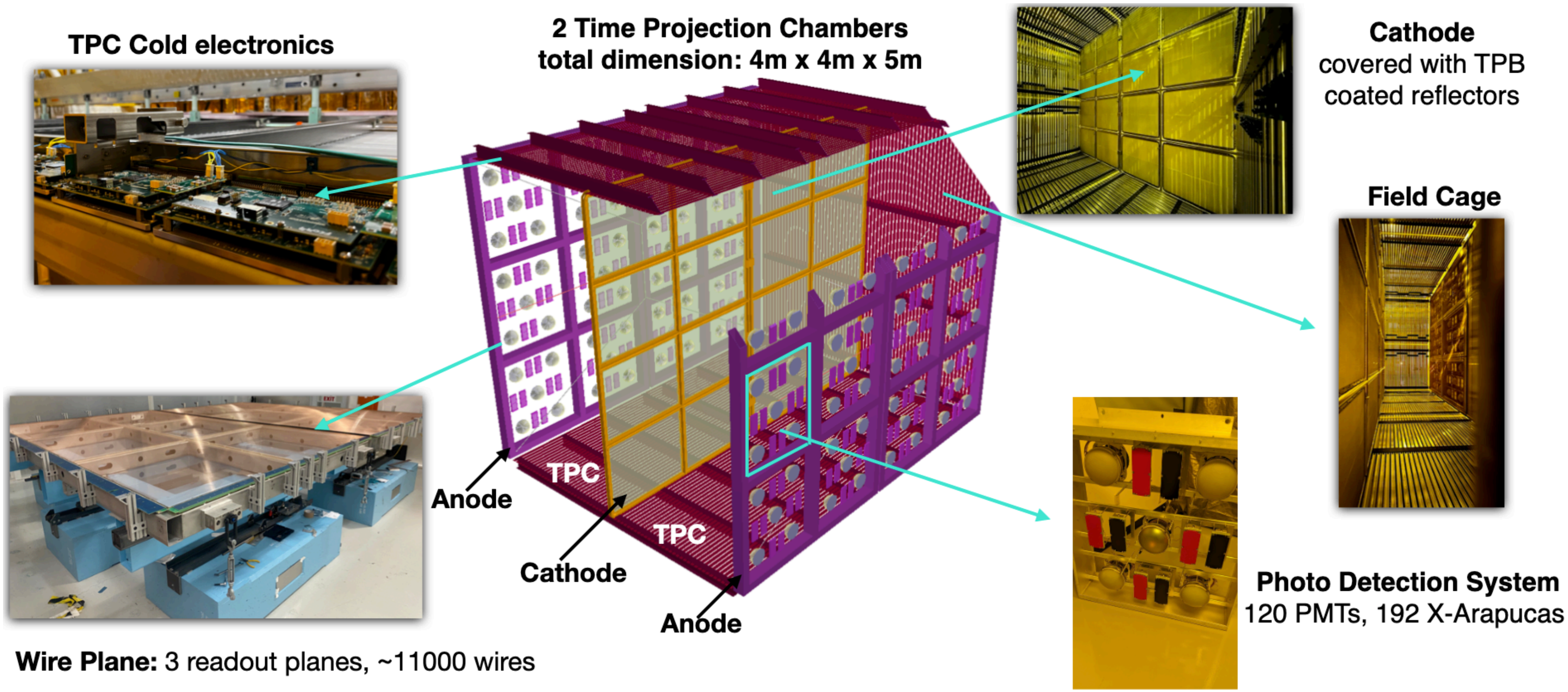
Status of the Short-Baseline Near Detector at Fermilab
Diana Patricia Mendez
Building 28
Aug 22, 2023, 2:00 PM

Neutrino Interaction Measurement Capabilities of the SBND Experiment
Andrew Furmanski, Vishvas Pandey
Building 28
Aug 25, 2023, 2:30 PM

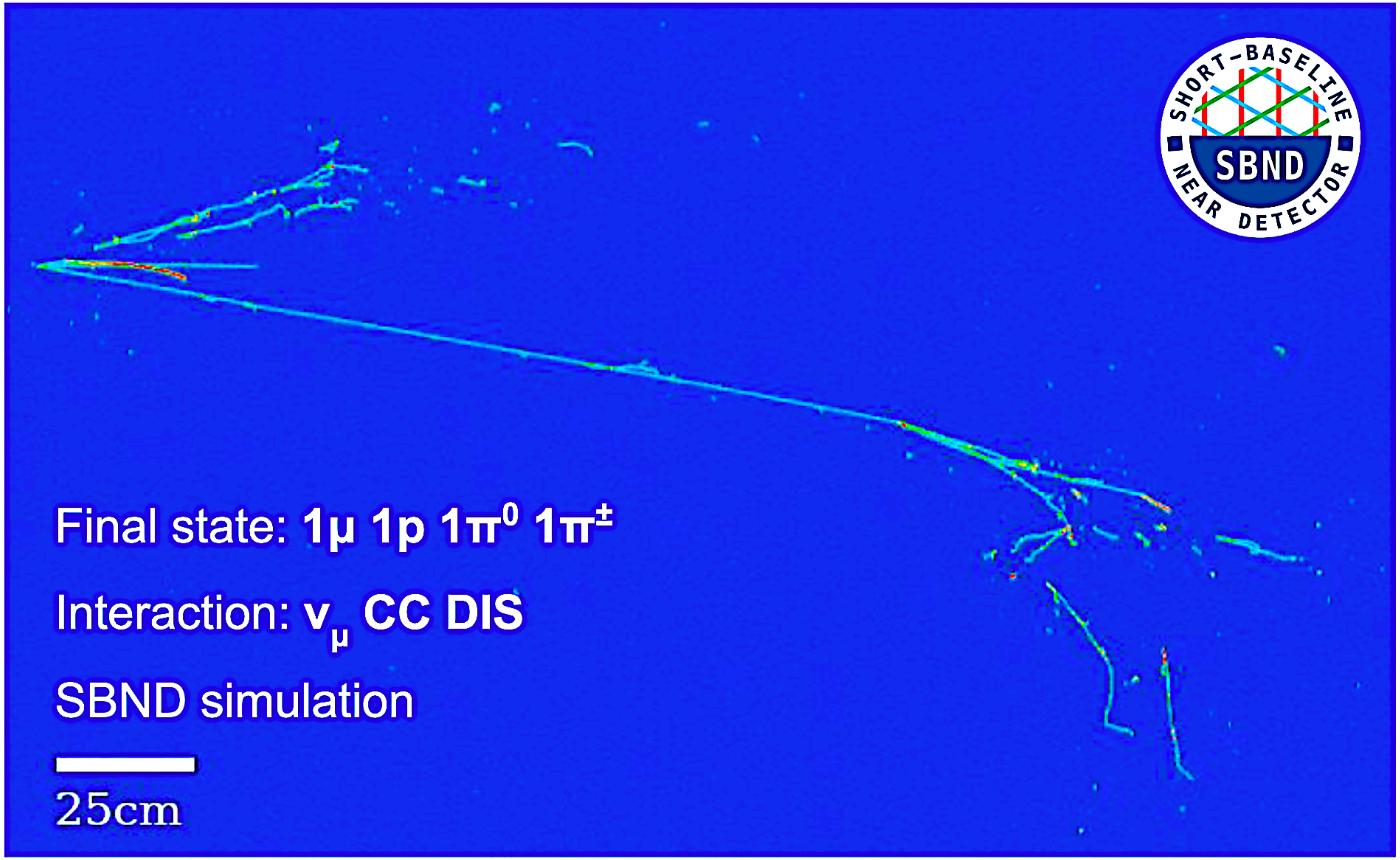
Beyond the Standard Model Searches with the Short Baseline Near Detector
Xiao Luo
Building 28
Aug 25, 2023, 6:06 PM

Studying Neutrino-Nucleus Interactions at SBND with Muon Neutrino Charged-Current Events with no Pions in the Final State
Mun Jung Jung

SBN Near Detector

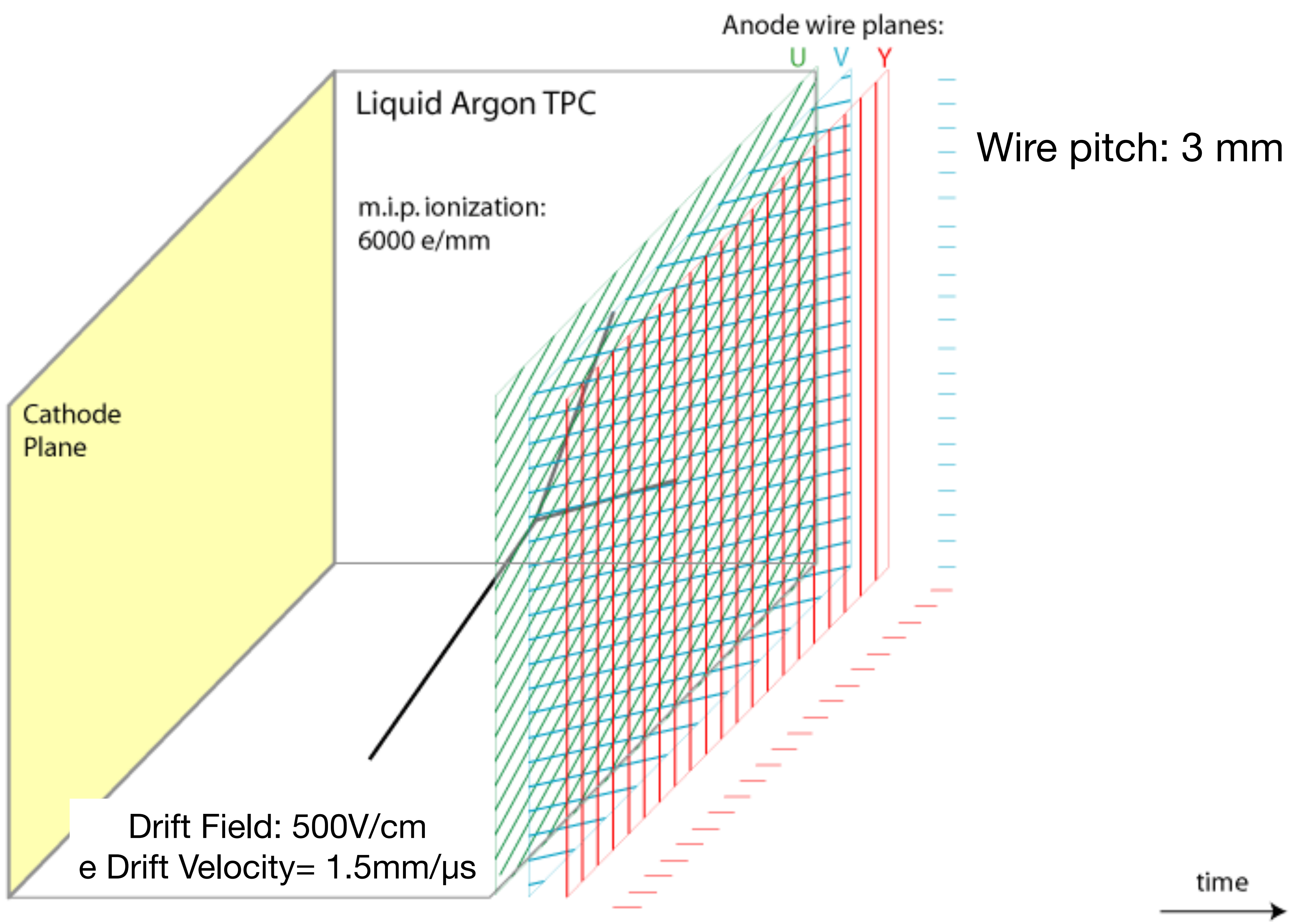


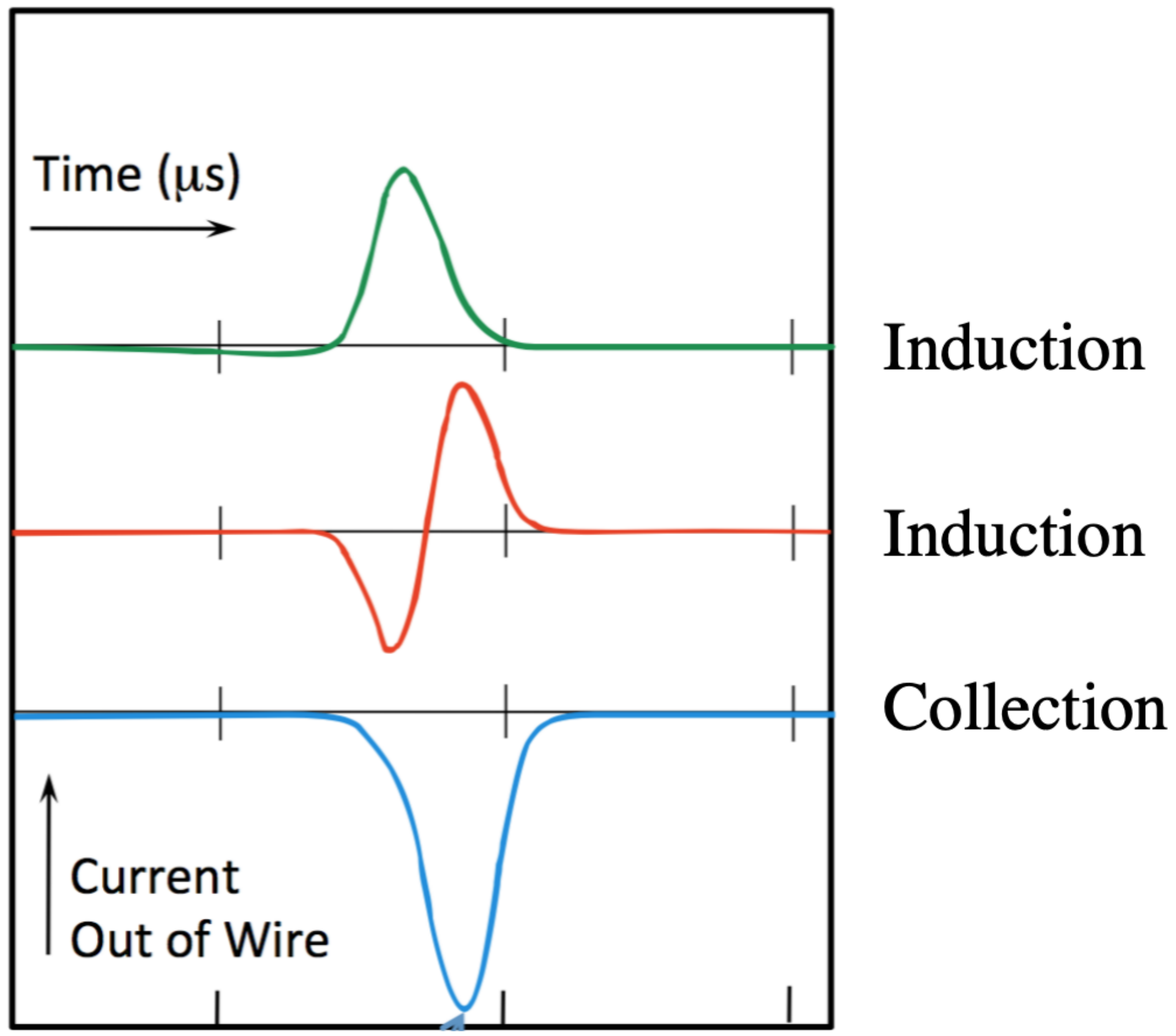
SBND Event Display



https://lar.bnl.gov/home/img/signal.gif

LArTPC Technology (Single Phase)





Time propagation of signal across three wire planes

Three wire planes sense the induced current signal

WireCell Signal Processing

- Signal Formation in SBND LArTPC
- Signal Processing and Optimization
- Future Outlook and Summary

Signal Formation

- Signal formation is the overall series of steps from creation of ionization electrons to the eventual ADC waveform information

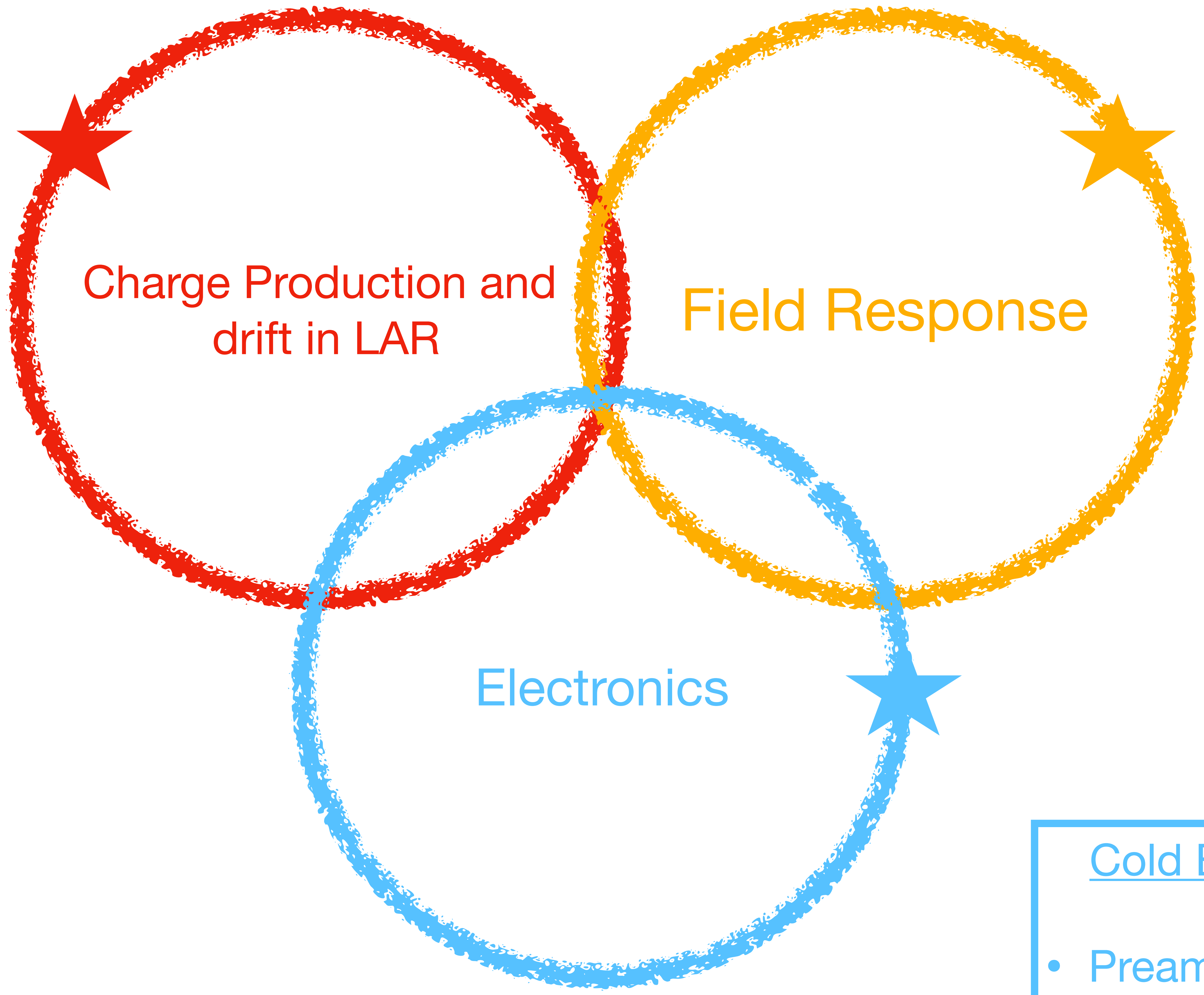
Signal Formation

<u>Production</u>

- Ionization
- Recombination

<u>Drift</u>

- Diffusion
- Attachment or absorption



<u>Long Range Effect</u>

- Time
- Wire

<u>Cold Electronics</u>

- Preamplifier
- RC Filter
- ADC

Signal Formation

Charge Production and drift in LAR

Signal Formation

<u>Production</u>

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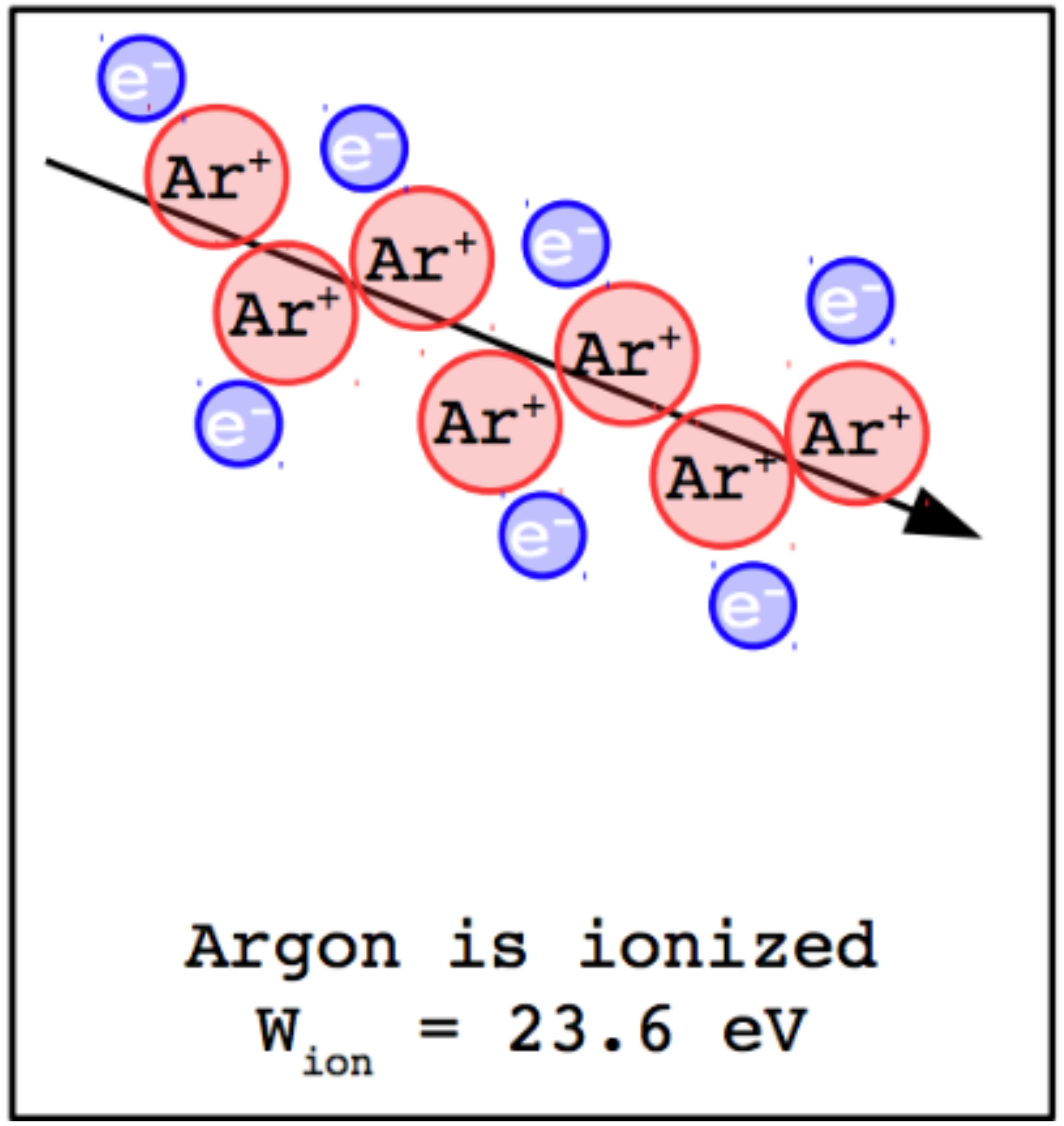
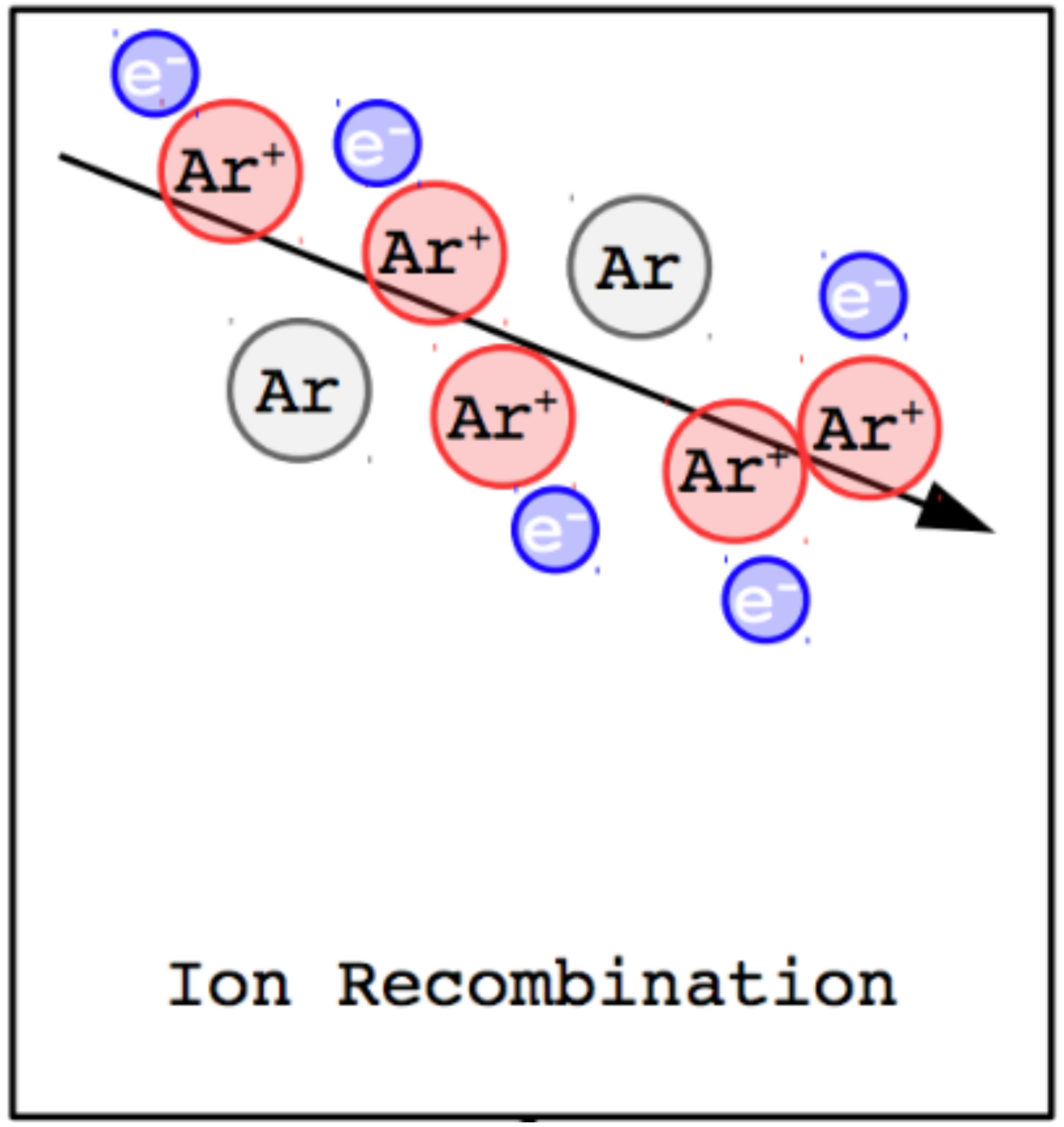
Signal Formation—Ionization



Ionization of Ar atom by incident particle

Charge Production and drift in LAR

Signal Formation — Recombination

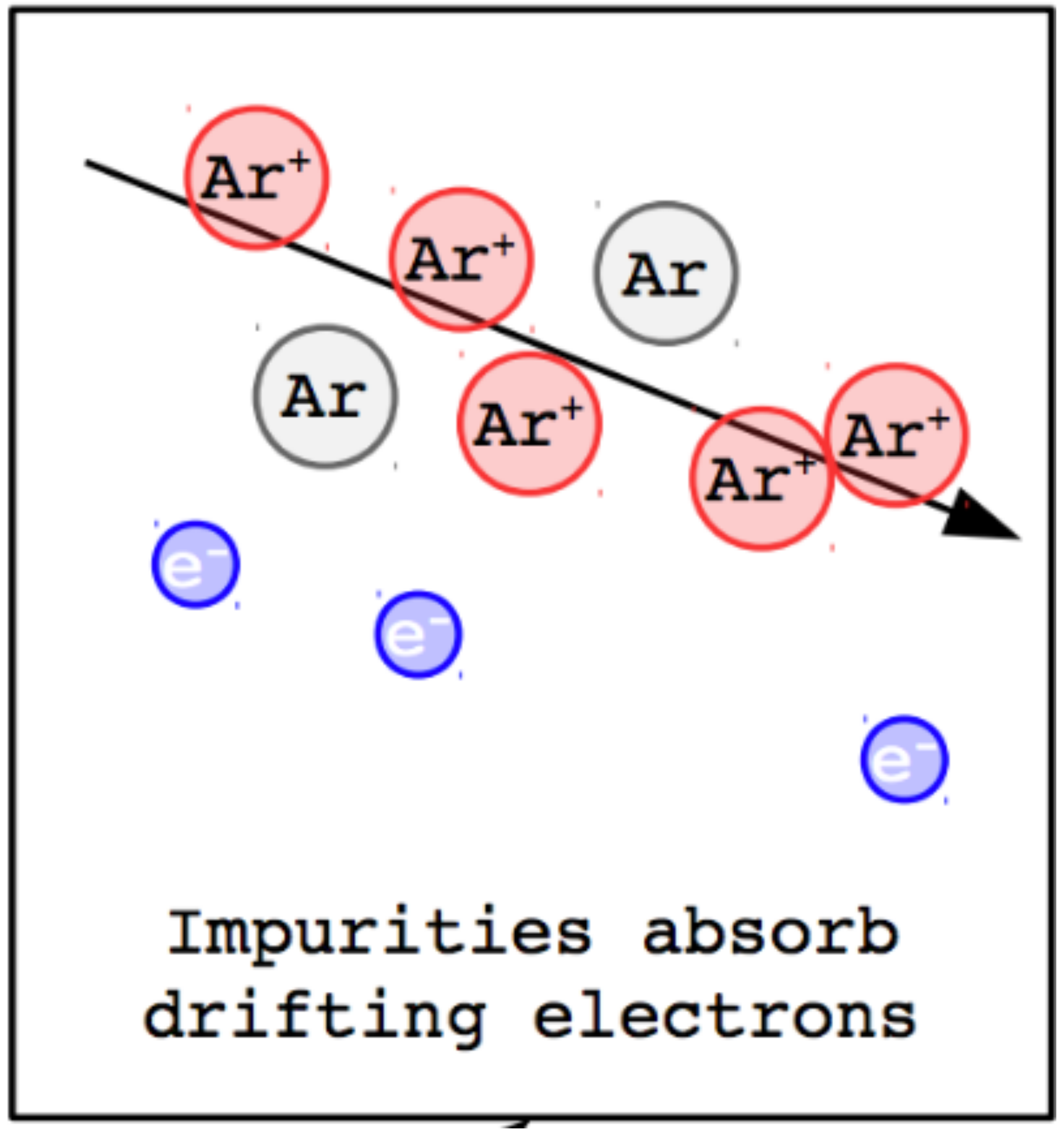


Recombination is binding of a free (or continuum) electron to a positive ion.

$$R = \frac{dQ/dX}{dE/dX}$$

$R \cong$ 70% @87K, 500V/cm

Signal Formation—Attachment

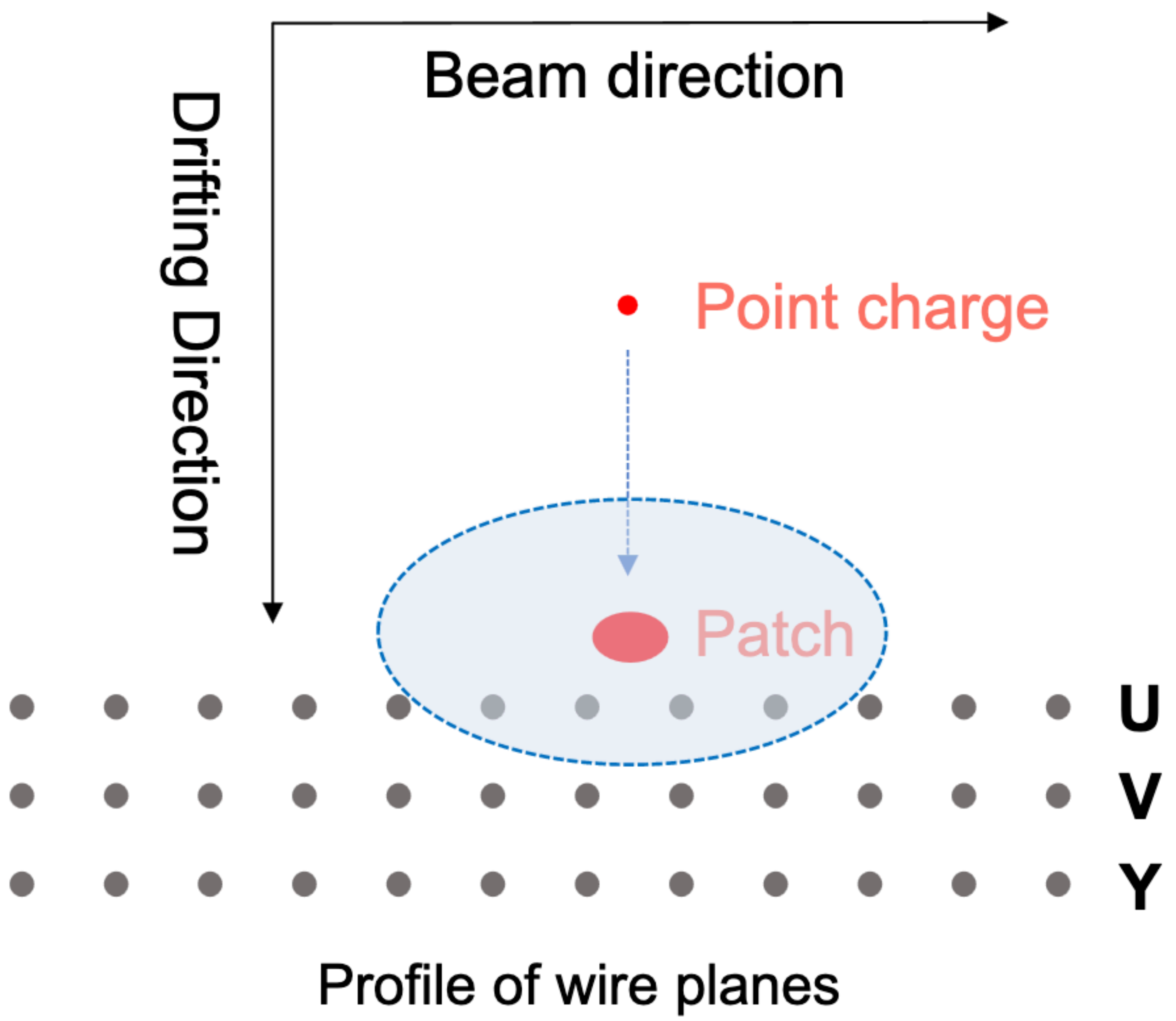


Attachment is the binding of a free (unbound) electron to an atom or molecule.

$L = \exp(\frac{-t}{\tau})$, where τ is defined as electron lifetime

For high purity Ar, values of τ can be as high as ~18ms (MicroBooNE)

Signal Formation — Diffusion



Roughly a 3D **Gaussian diffusion**
$\sigma_{\parallel}$ (longitudinal) ~ 1.0 us @1 m drifting
$\sigma_{\perp}$ (transverse) ~ 1.5 mm @1 m drifting

$$\sigma \propto \sqrt{D_{drift}}$$

The effects of diffusion are generally very small, especially in comparison with long-range wire induction field response

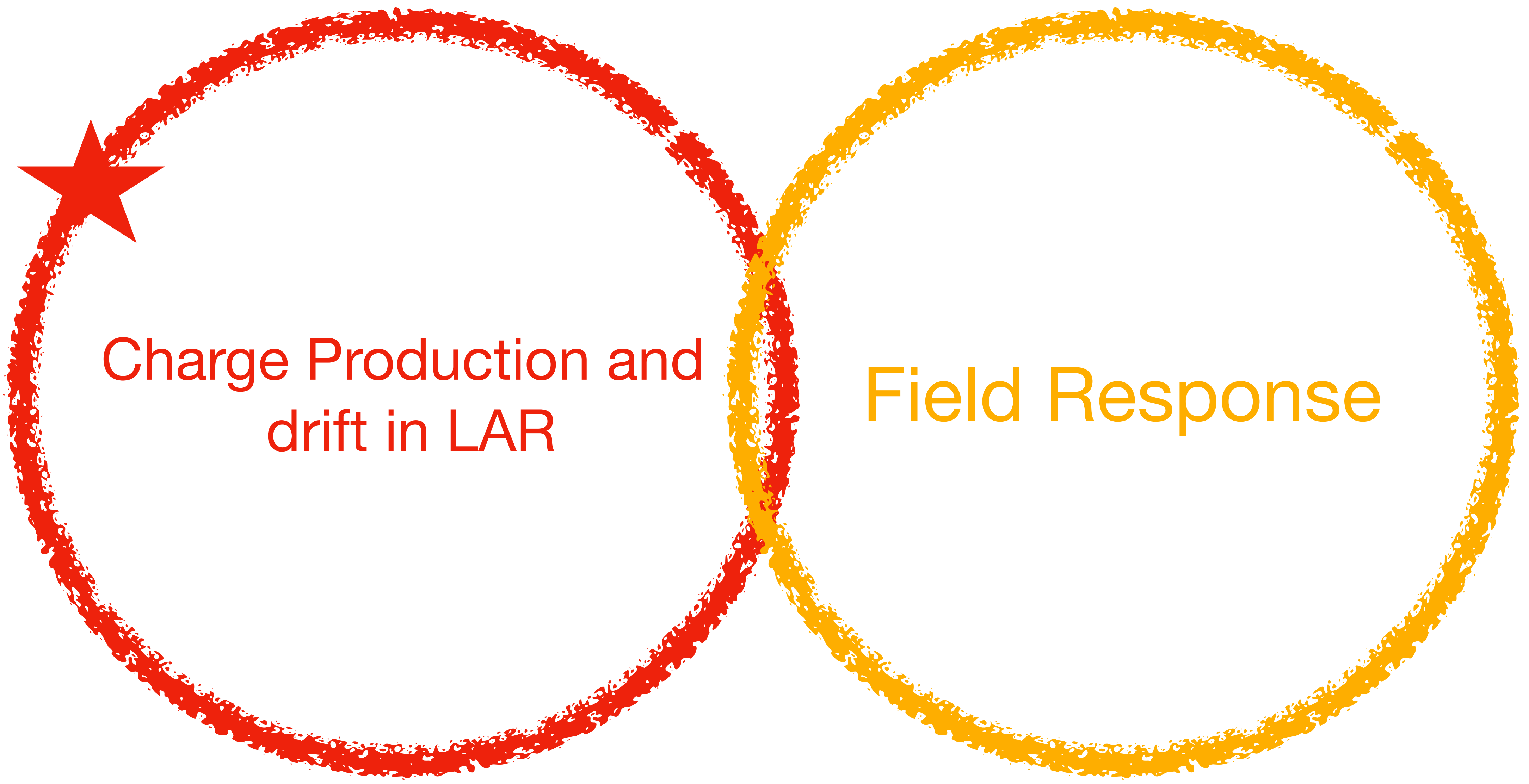
Signal Formation

Production

- Ionization
- Recombination

Drift

- Diffusion
- Attachment or absorption



Signal Formation

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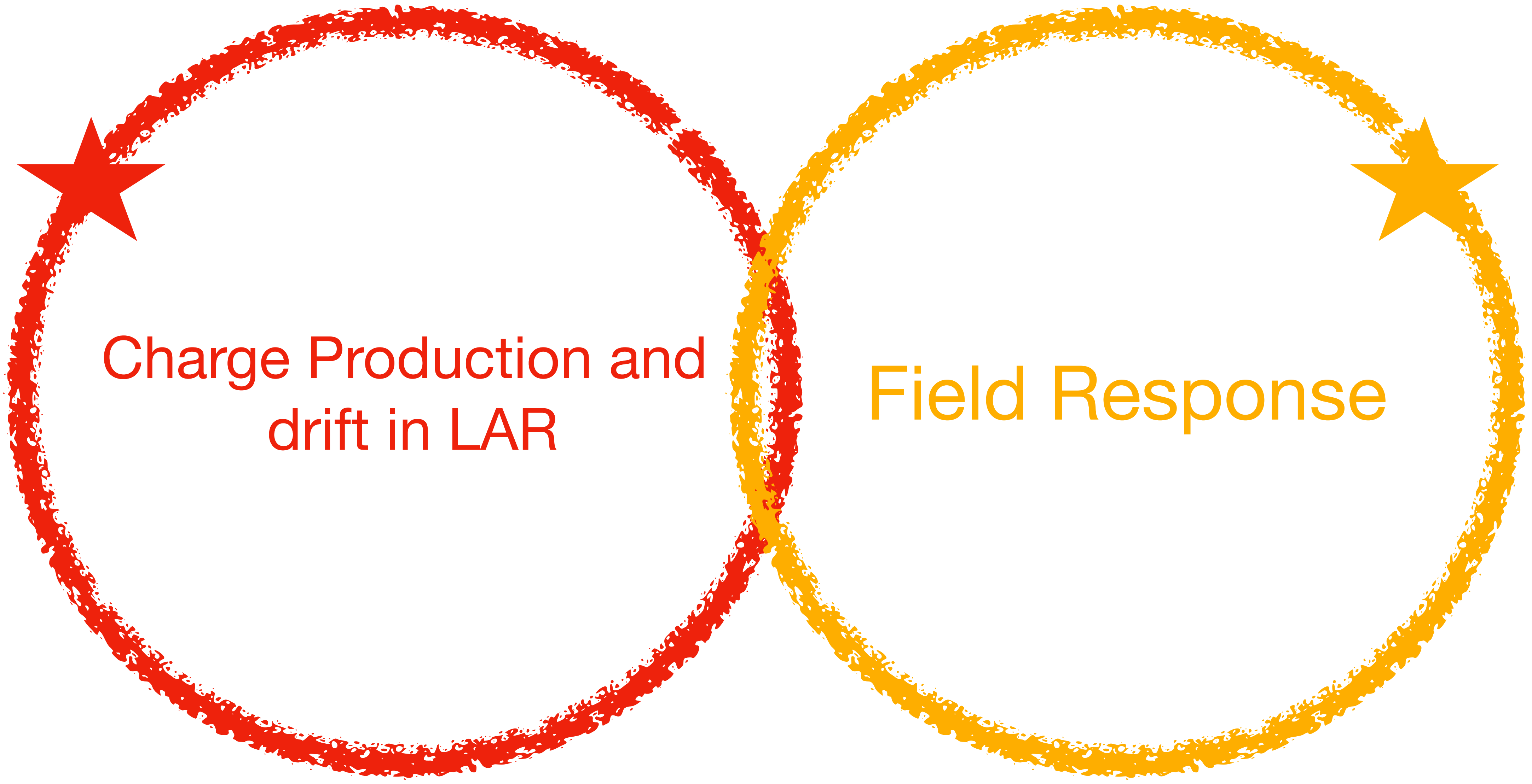


<u>Long Range Effect</u>

- Time
- Wire

C. Adams et al, 2018 JINST 13 P07006

Signal Formation —Field Response

- When ionization electrons drift past the initial two induction wire planes toward the final collection wire plane, current is induced on nearby wires. We refer to the induced current on one wire due to a single electron charge as the field response function.

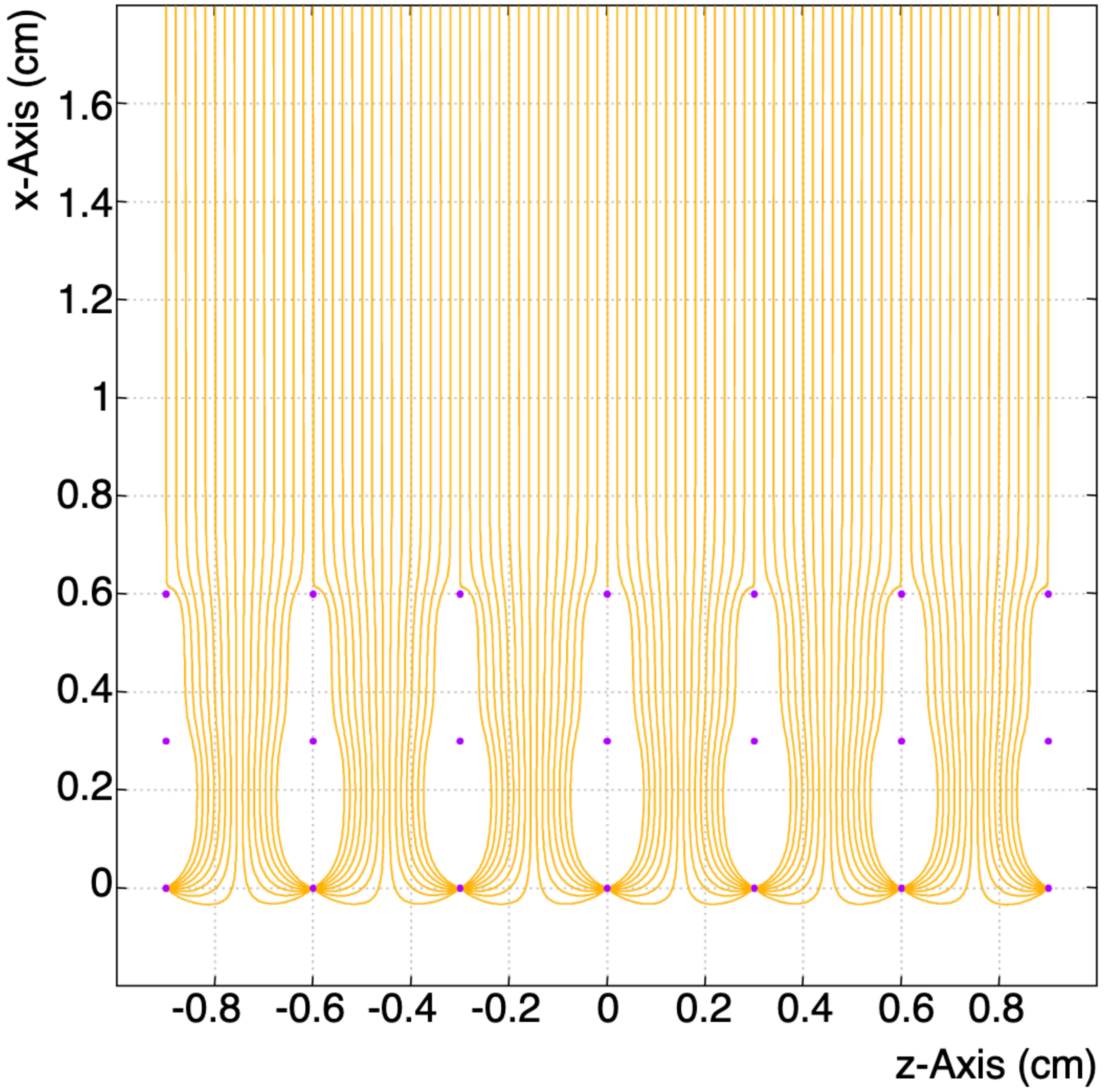
- The principle of current induction is given by Ramo's theorem

$$i = -q\vec{E}_w \cdot \vec{v}_q$$

  - where $\mathbf{E}_w$ is the weighting potential at a given wire
  - and $\mathbf{V}_q$ is the drift velocity of the charge at the given location

- Garfield program is used to calculate the field response functions

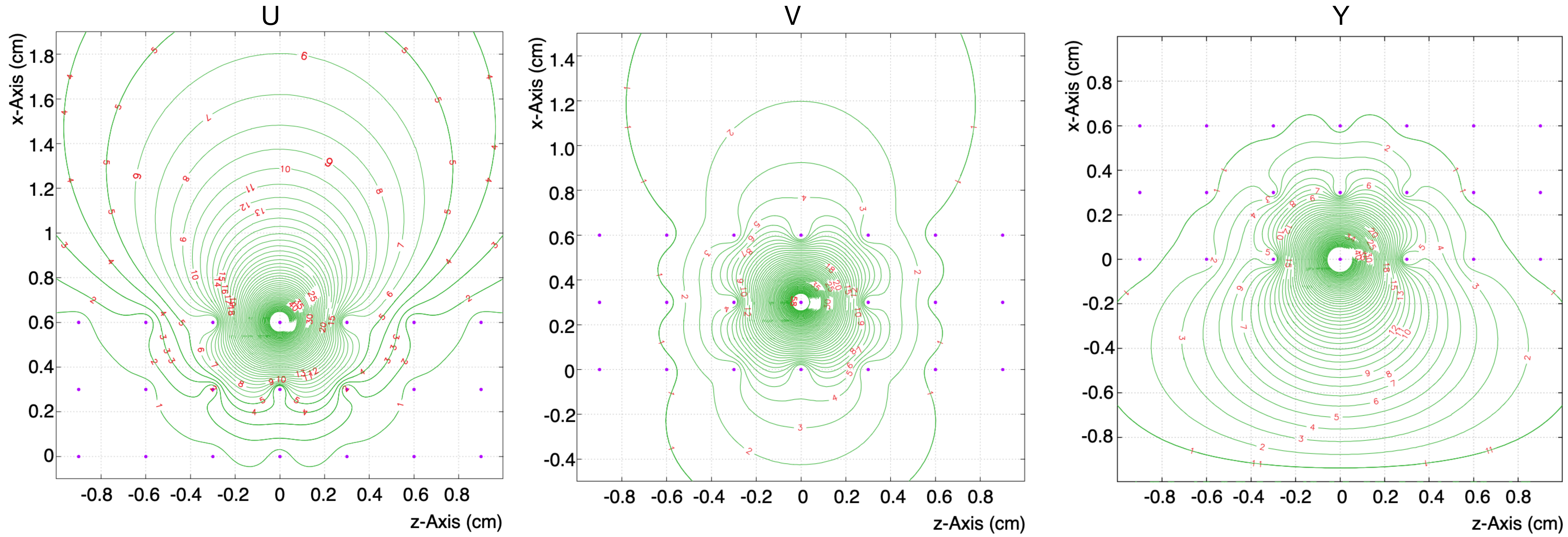
- Long range induction current is also induced on nearby wires



Demonstration of electron drift paths in the applied electric field

C. Adams et al, 2018 JINST 13 P07006

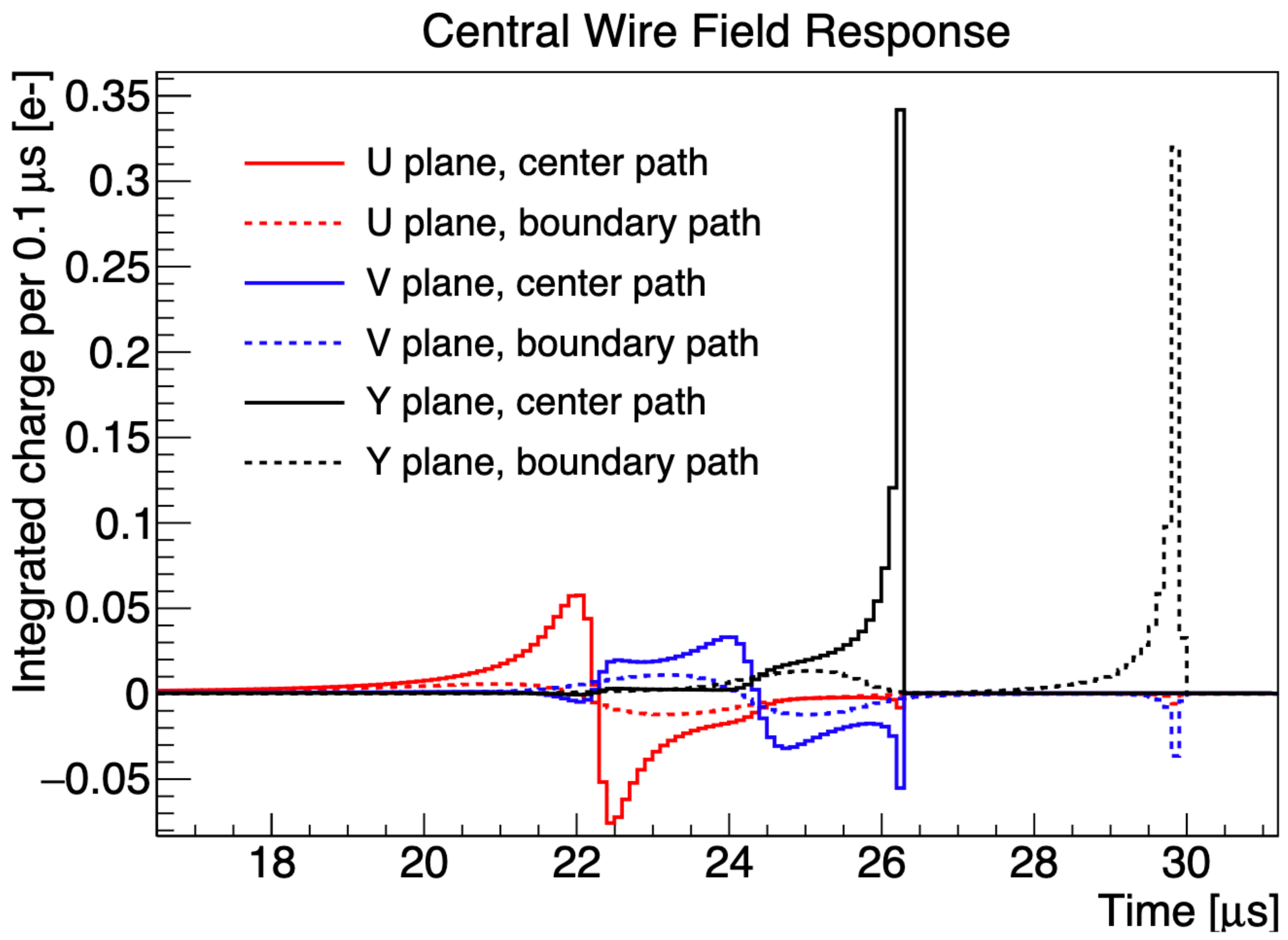
Signal Formation — Field Response



Weighting potentials on individual wires of the 2D LArTPC model, using the Garfield program.

C. Adams et al, 2018 JINST 13 P07006

Signal Formation — Field response shape



Field response generally weaker at the boundary

Field responses (induced-current) from various paths of one drifting ionization electron for the three wire planes.

Signal Formation

Production

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Drift

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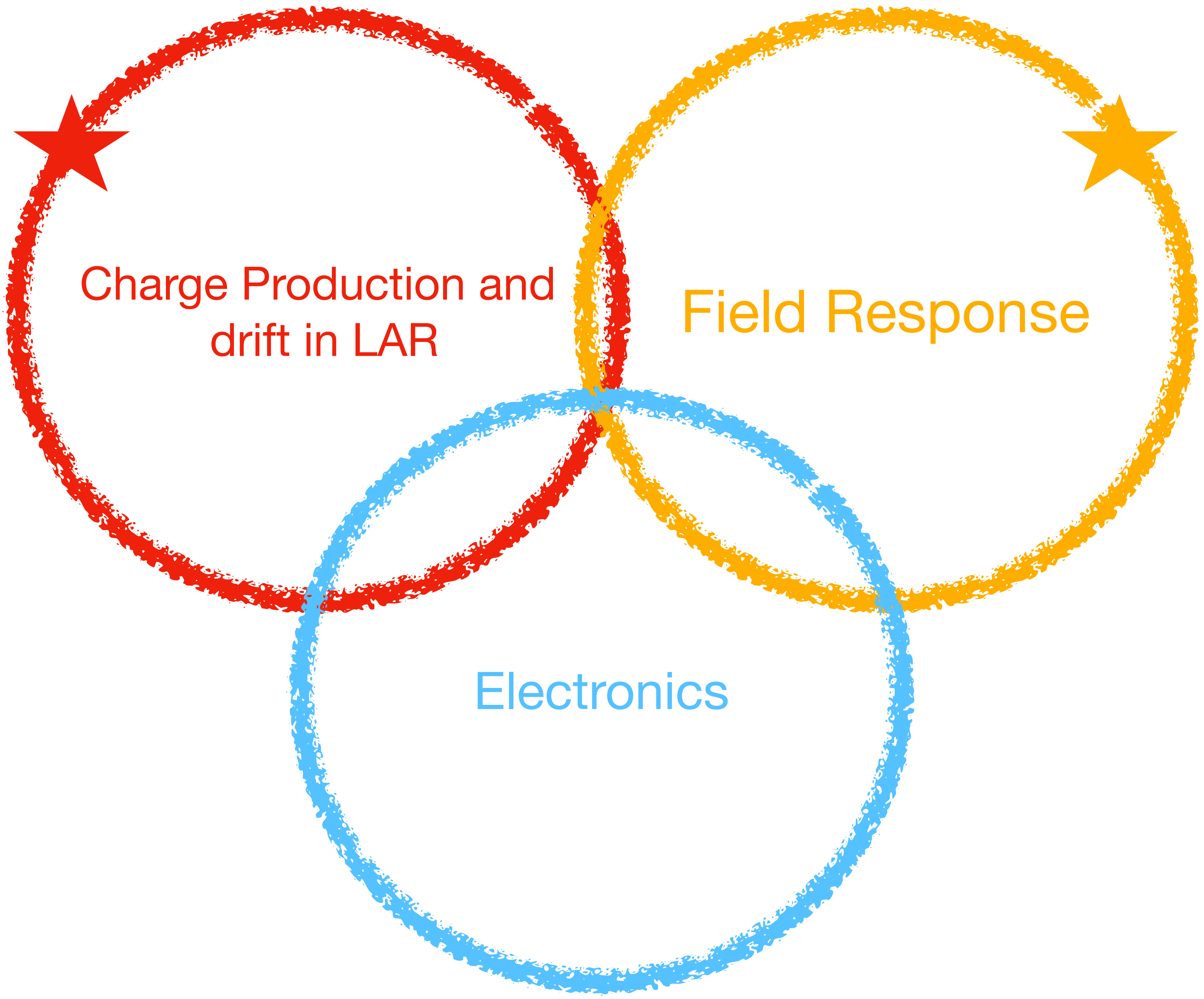
- Attachment or absorption



Long Range Effect

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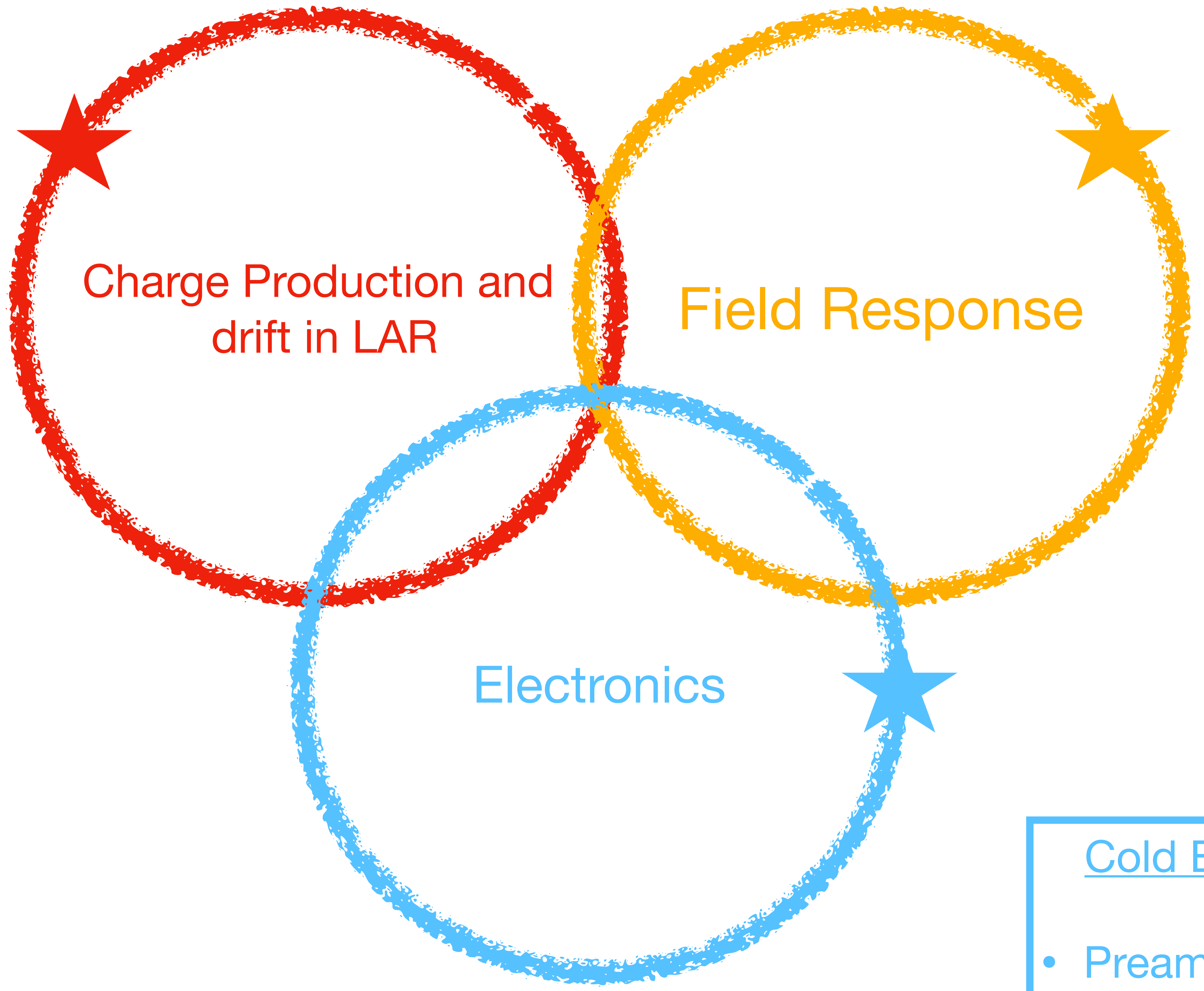


Long Range Effect

- Time
- Wire

Cold Electronics

- Preamplifier
- RC Filter
- ADC

arXiv:1910.06434

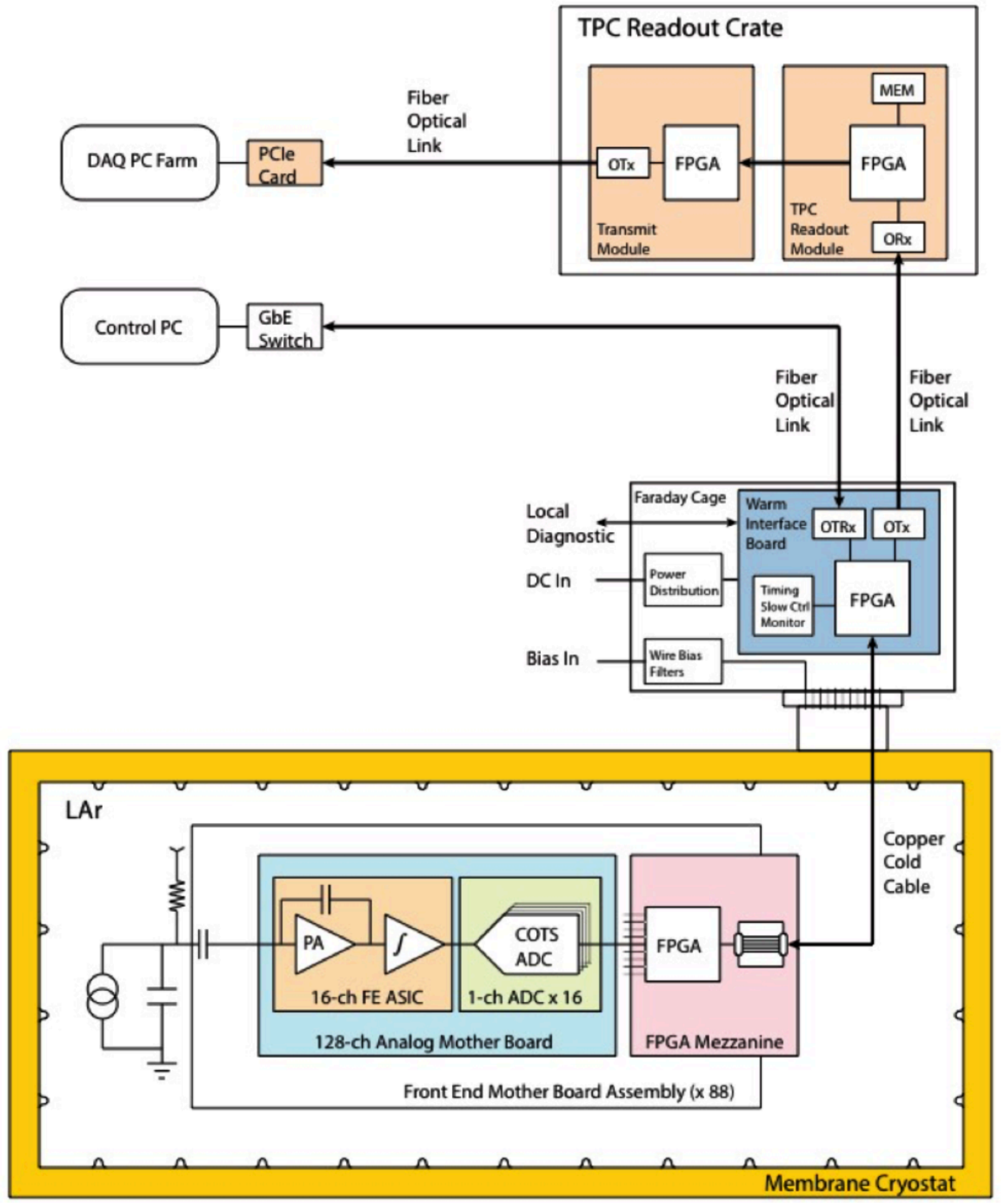
Signal Formation— Cold Electronics

There is no electron amplification inside LAr.

—Signal is very small ~10s k electrons

— Cold electronics is essential to minimize electronics noise considering large wire capacitance

—Significantly improves the performance of induction wire plane



TPC Readout Electronics

Warm Interface Electronics

Cold Electronics

Diagram of SBND TPC readout electronics.

arXiv:1910.06434

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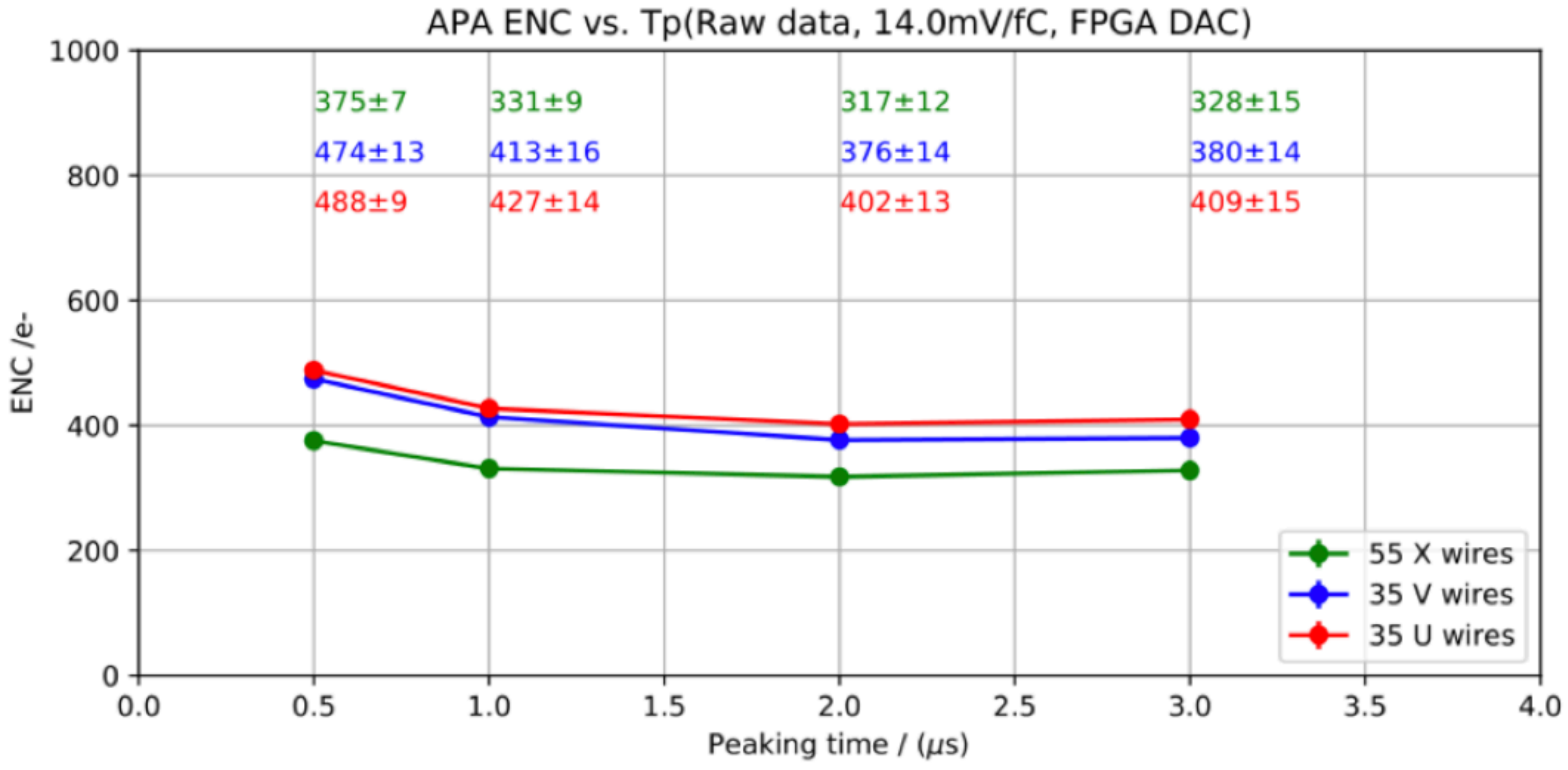
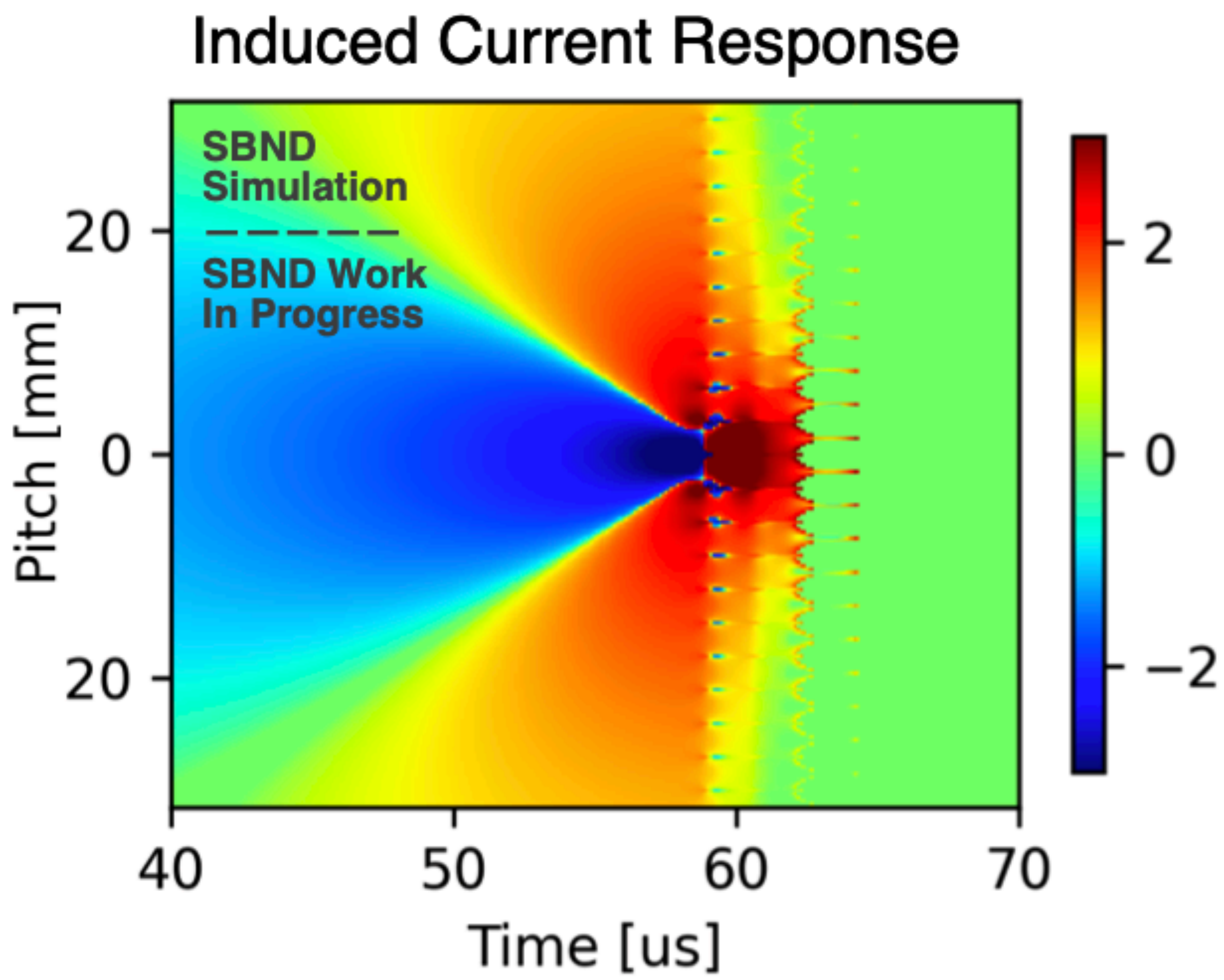
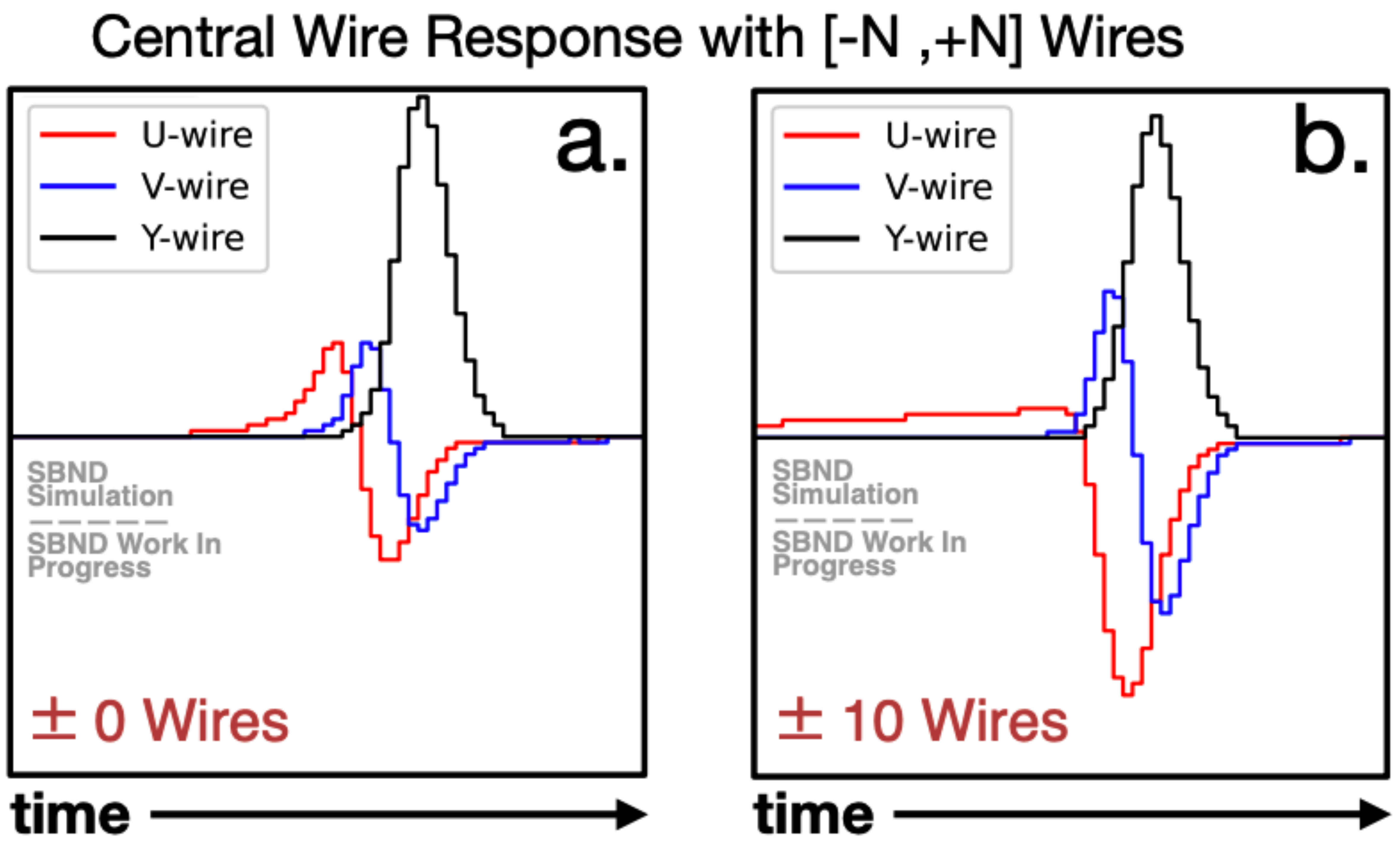


ENC measurement for SBND wire planes

Signal Formation — Response over wires



Position-averaged convolved field and electronics response for the U plane in SBND.



Central wire response function for a single electron including

(a) no neighboring wires or

(b) [-10, +10] neighboring wires

WireCell Signal Processing

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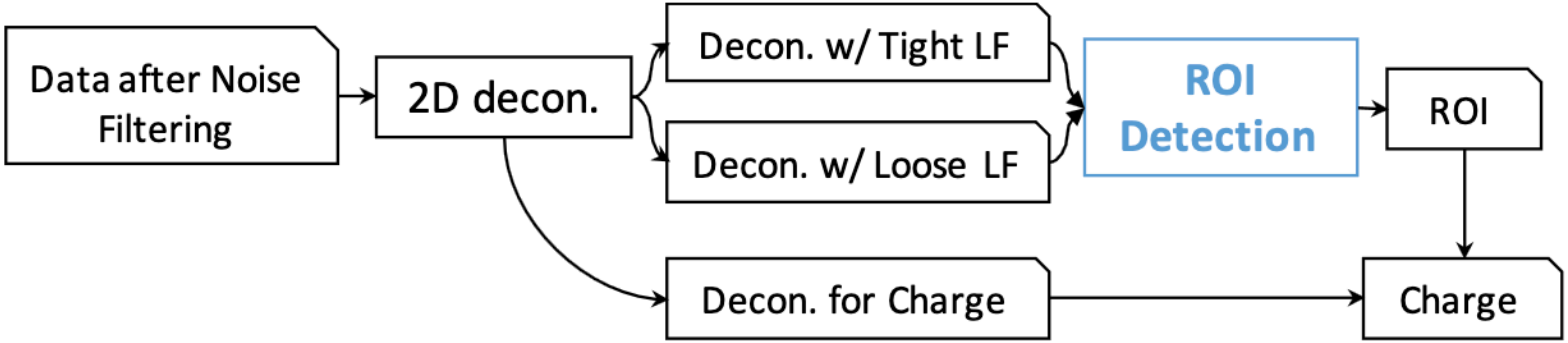
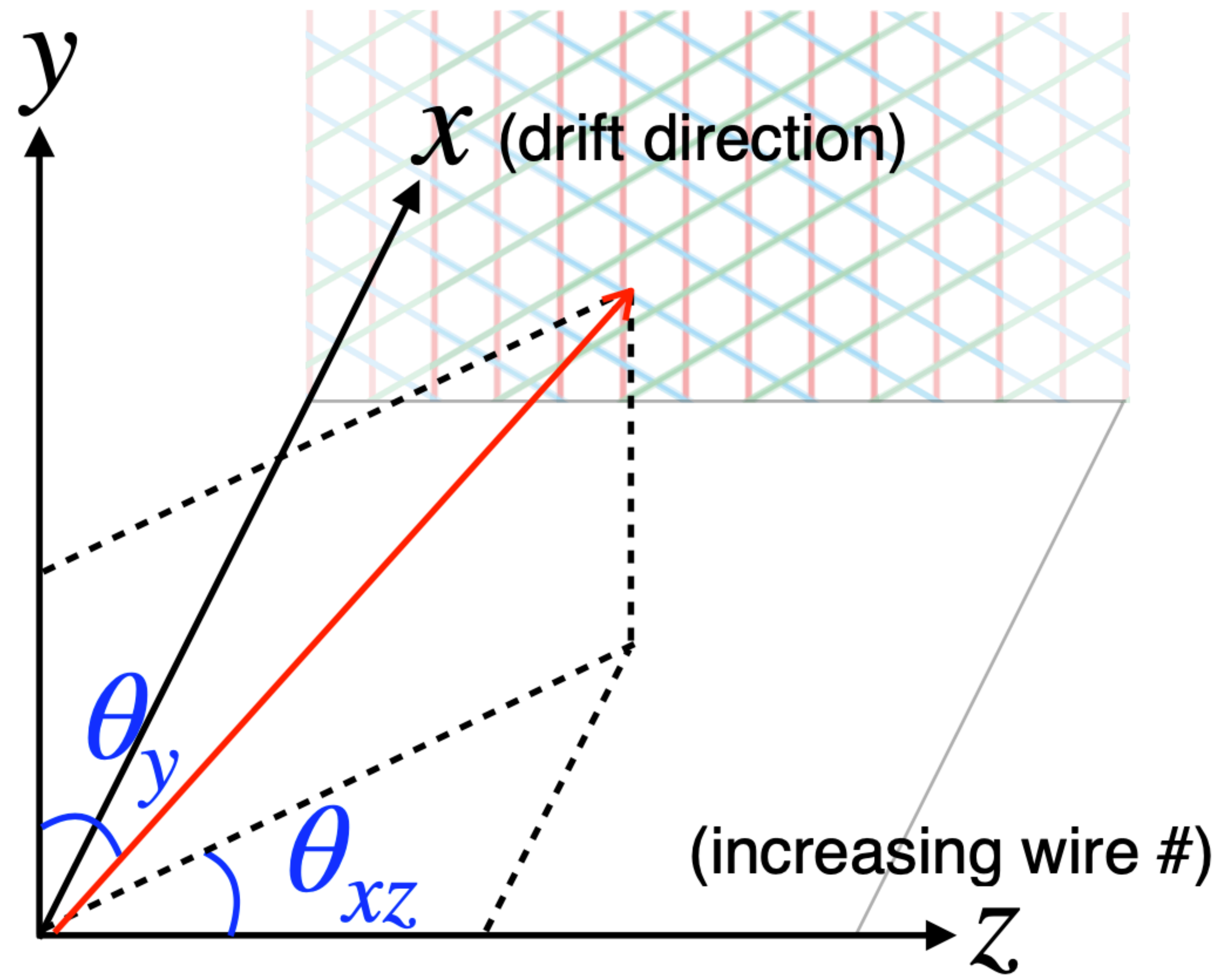
WireCell Signal Processing

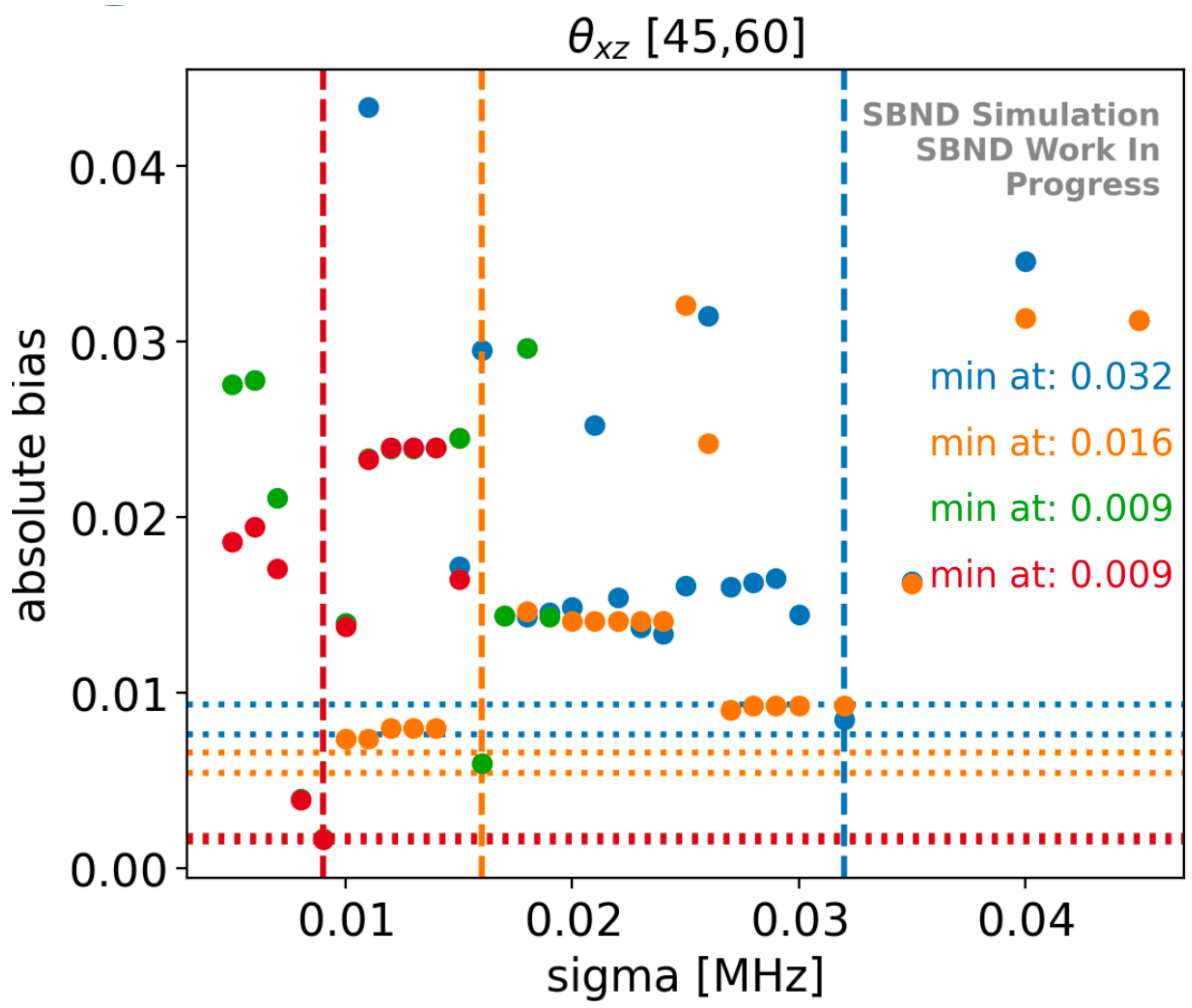


- The goal of (ROI) detection technique is to define a region in the time domain to contain the distribution of ionization electrons.
- Significantly reduces low-frequency noise, increasing the signal-to-noise ratio
- To maximize the signal-to-noise ratio, the ROI in the time domain should be as small as possible

Signal Processing Optimization in SBND

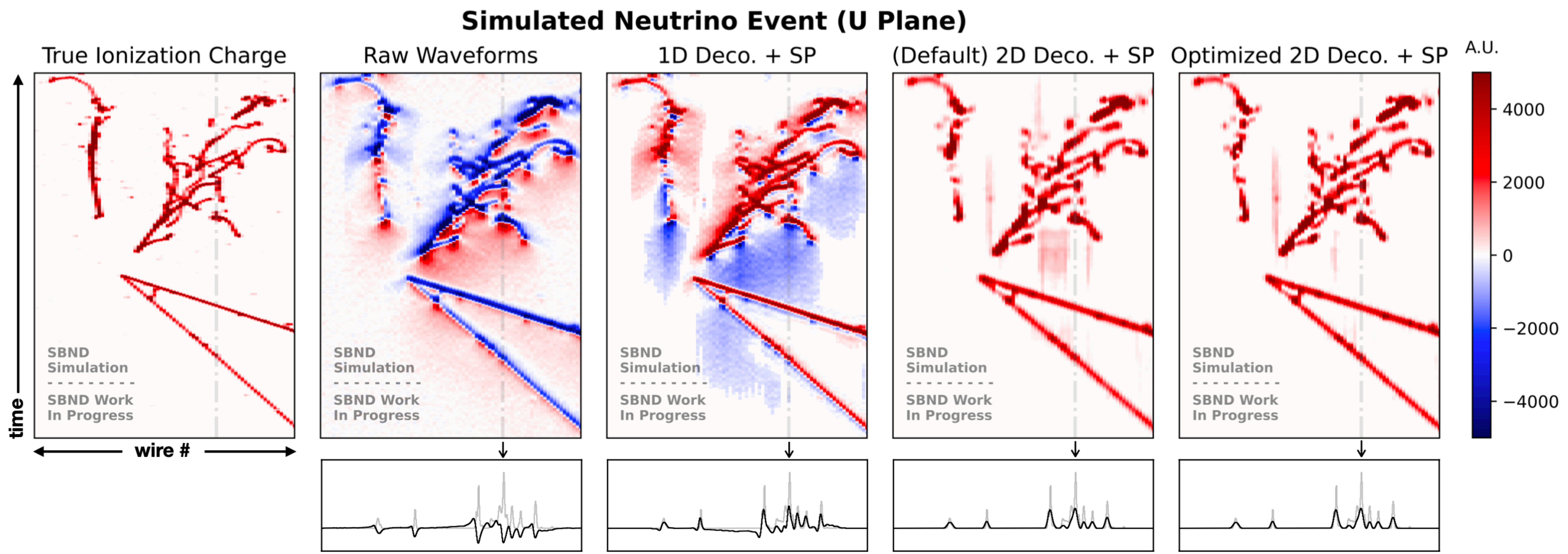


Geometric coordinates and angles. The θ_{xz} angle of the ionization affects the signal shape on the wires.



Absolute bias as a function of tight LF filter parameters in $\theta_{xz} \in [45,60]$

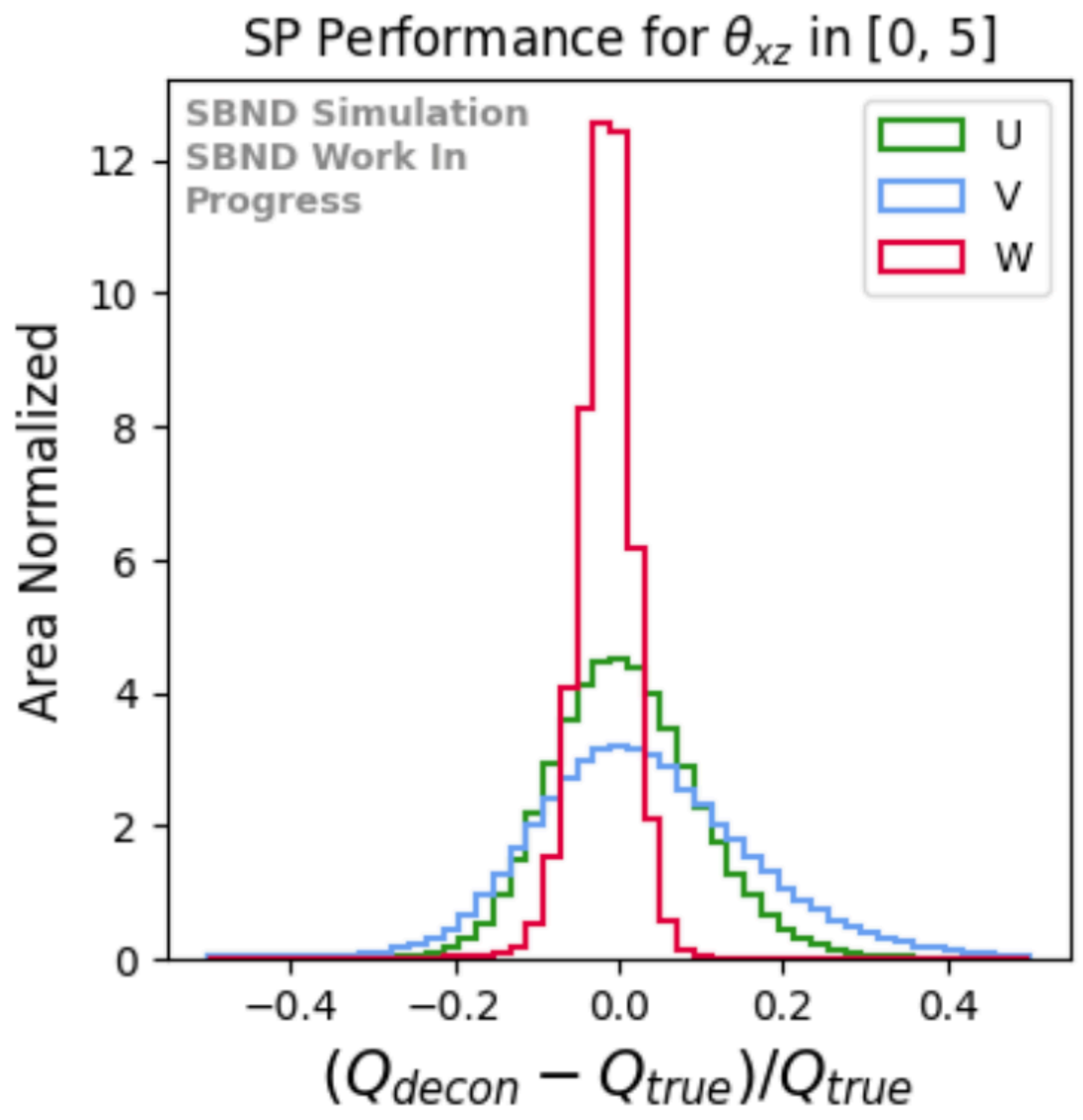
Signal Processing Optimization in SBND



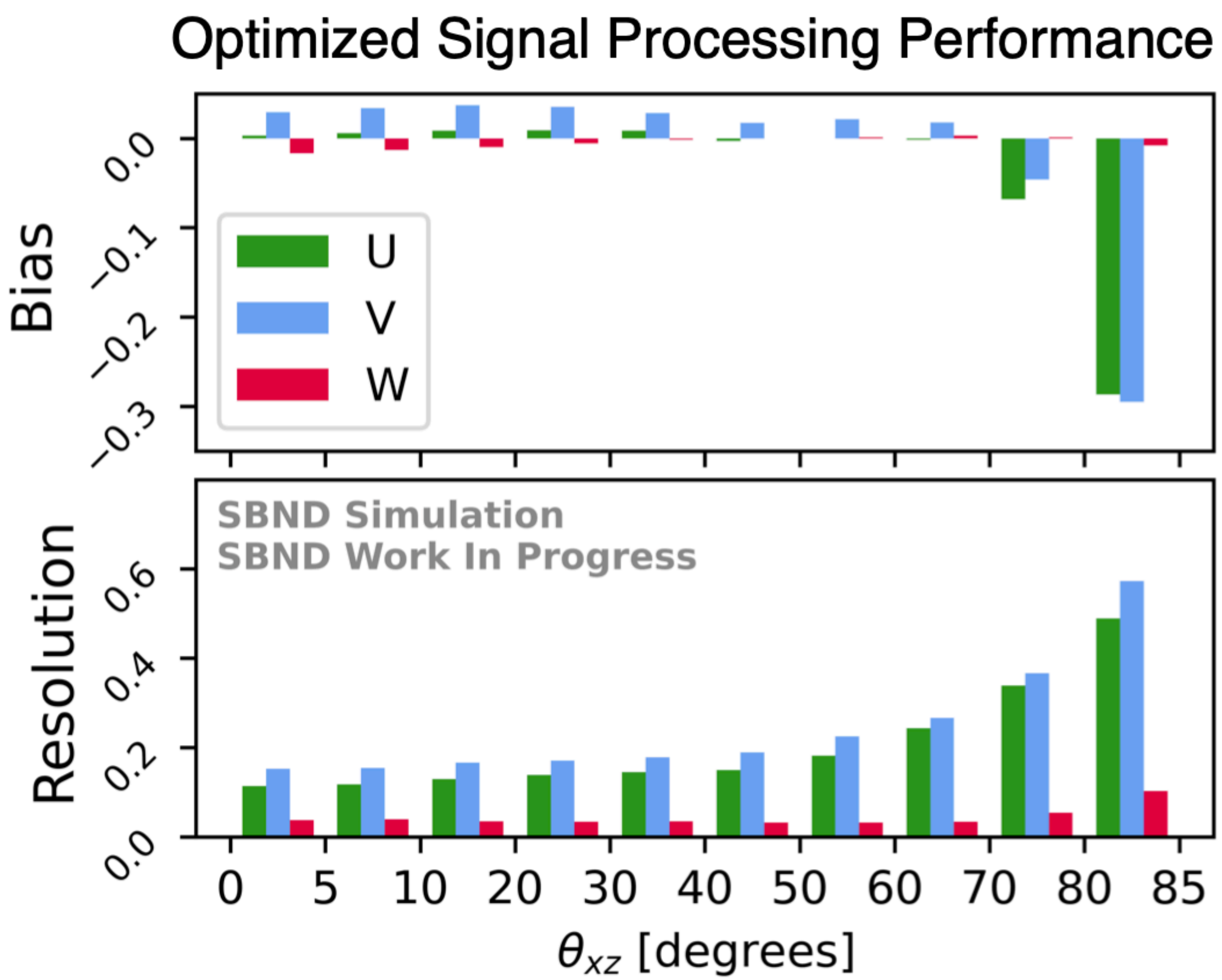
Comparison of true, raw, and deconvolved waveforms with corresponding 2D event displays.

The unphysical negative features of the 1D deco. are visible, as well as the improved “shadow" removal of the optimized 2D deco.

Signal Processing Optimization in SBND



Fractional charge difference distribution for $\theta_{xz} \in [0,5]$



Bias and resolution of charge extraction using optimal SP filter values for all angular bins.

Multithreading for Signal Processing

Time/evt [seconds]	two-step workflow	single step (w/ raw)	single step (no raw)
gpmv	31.08 | 46.68	80.13	74.61
grid	53.12 | 48.95	82.23	80.46

VmPeak [MB]	two-step workflow	single step (w/ raw)	single step (no raw)
gpmv	3050.70 | 3111.84	3511.78	3416.85
grid	2840.71 | 3047.73	3399.26	3253.52

VmHWM [MB]	two-step workflow	single step (w/ raw)	single step (no raw)
gpmv	1627.08 | 1779.73	2093.58	1997.06
grid	1511.52 | 1735.80	2061.24	1929.47

Incremental file size w/ Wire-Cell [MB]	two-step workflow	single step (w/ raw)	single step (no raw)
grid	+217.33 | +20.44	+237.77	+52
gpvm	same	same	same

- On the computing power side of things, we have implemented multithreading to significantly improve the time required to process the signal response for each event as well as save memory.

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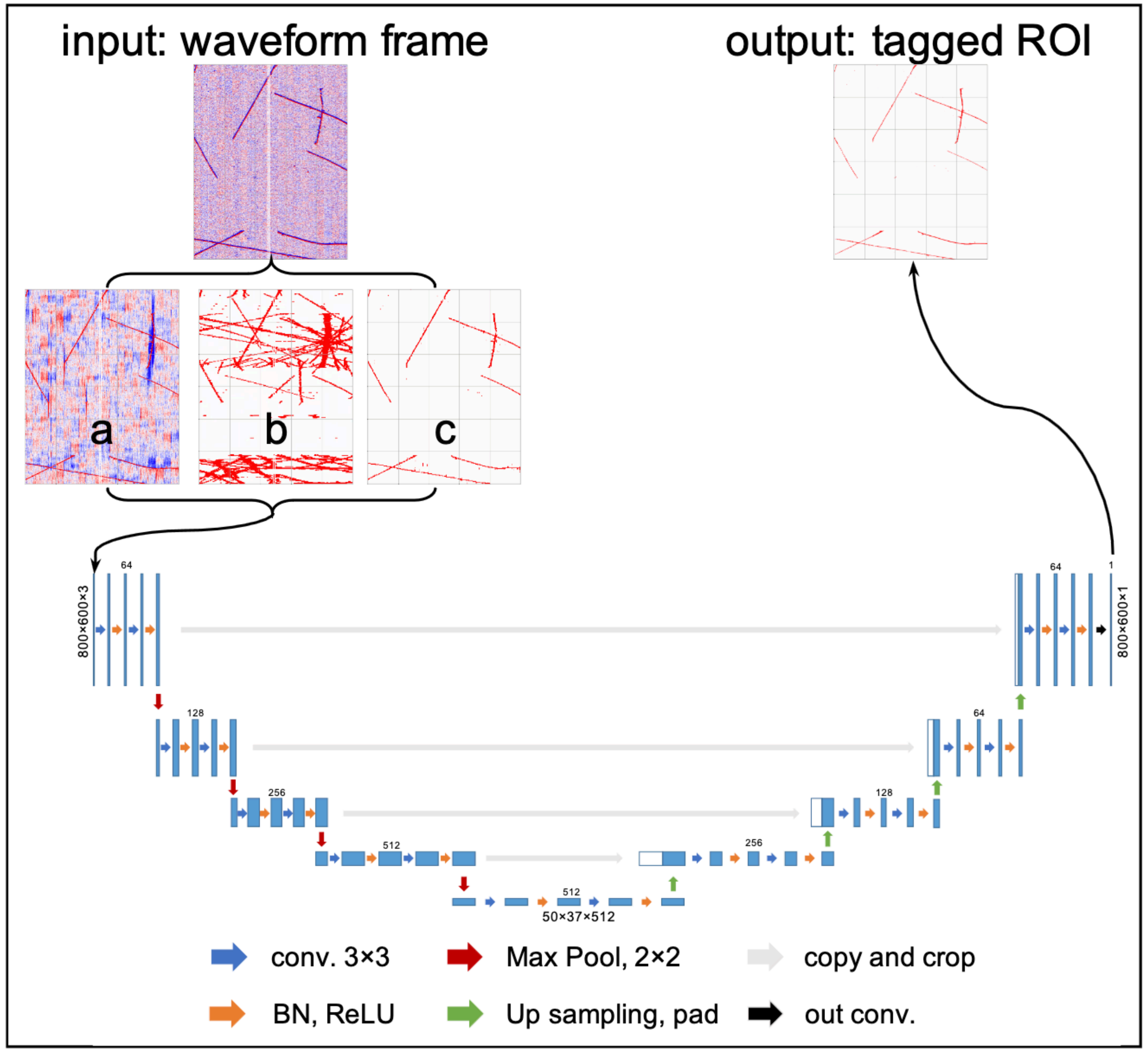
DNNs for Improving Signal Processing

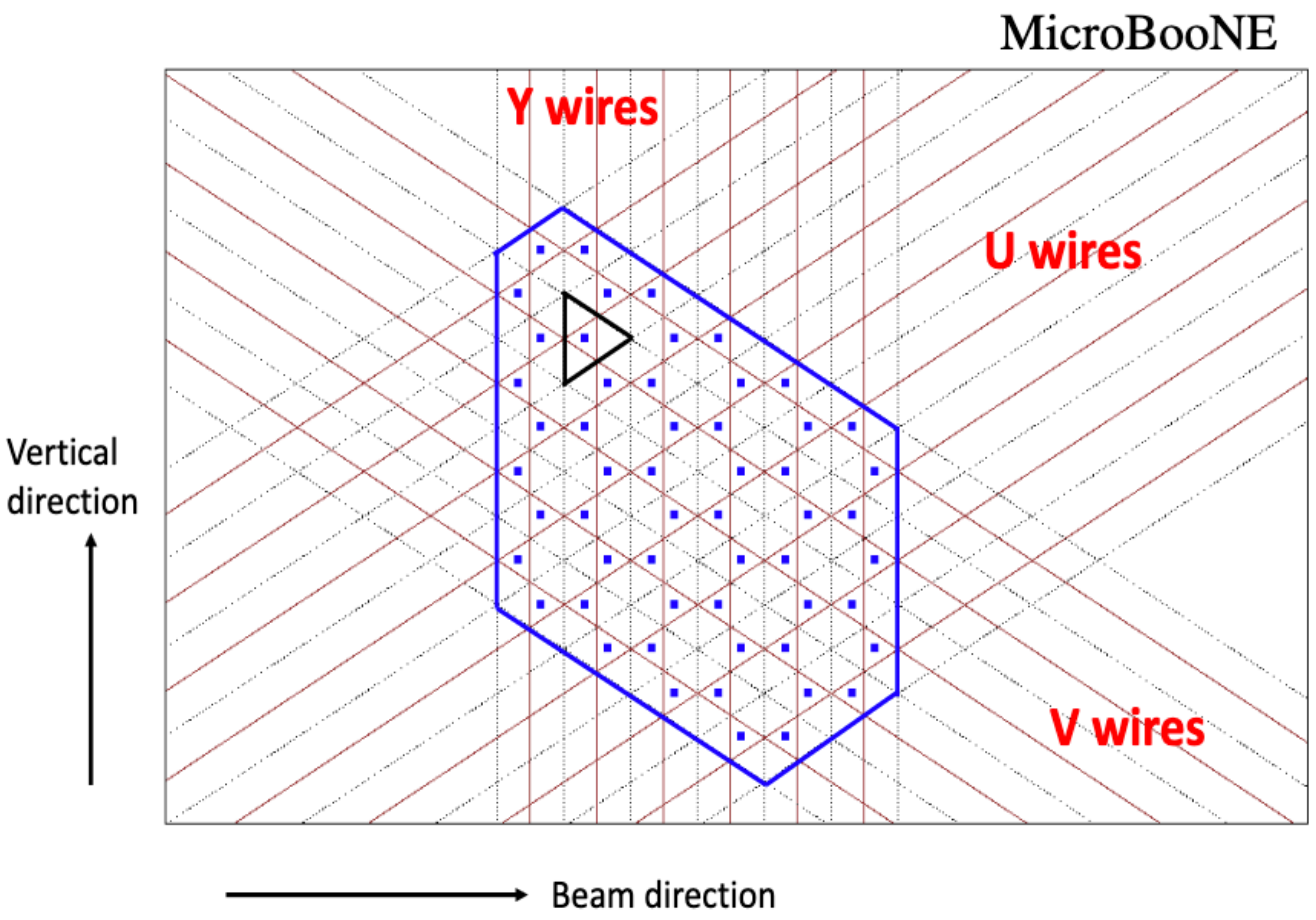


U-Net architecture

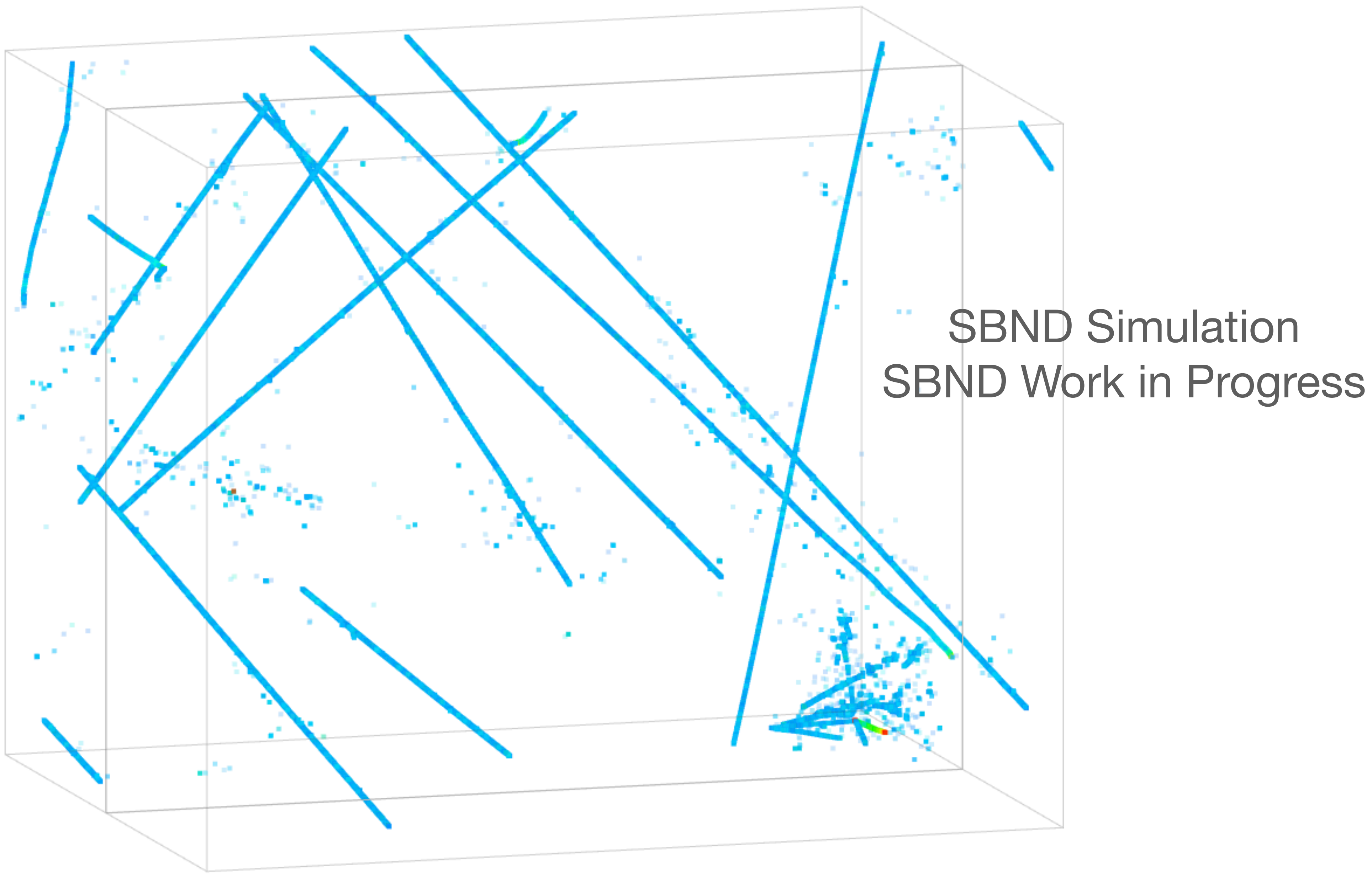
- Intermediate 2D images are generated from original raw waveform images.
- Deconvolved signals from a loose low-frequency filter (a)
- Multi plane matching using 2 planes (MP2) (b)
- Multi plane matching using 3 planes (MP3) (c)
- Output is a single channel 2D image labeling each pixel as signal or not.

JINST 16 P06043

Wire-Cell 3D Imaging



3D Image



https://www.phy.bnl.gov/twister/bee/set/f215e454-7c61-4088-b756-71ff78af3761/event/0/

3D Image

Summary

- It is important to understand all the constituent steps in signal formation to be able to recover all the charge via signal processing.
- Significant progresses have been made in the SBND TPC signal processing and optimization
- Further improvements utilizing DNN ROI finding will significantly improve signal processing performance. Ongoing work in 3-D Imaging. We also plan on utilizing lowered thresholds to protect the blip-like MeV scale energy topologies.
- Will further optimize signal processing with SBND commissioning data, to be taken by this year end. Stay tuned !

Thanks !

Backup Slides

Outline

- Fermilab SBN Program and SBN Near Detector (SBND)
- SBND Physics, Technology and Goals
- Signal Formation in SBND LArTPC
- Signal Processing and Optimization
- Future Outlook and Summary

SBN Program at Fermilab

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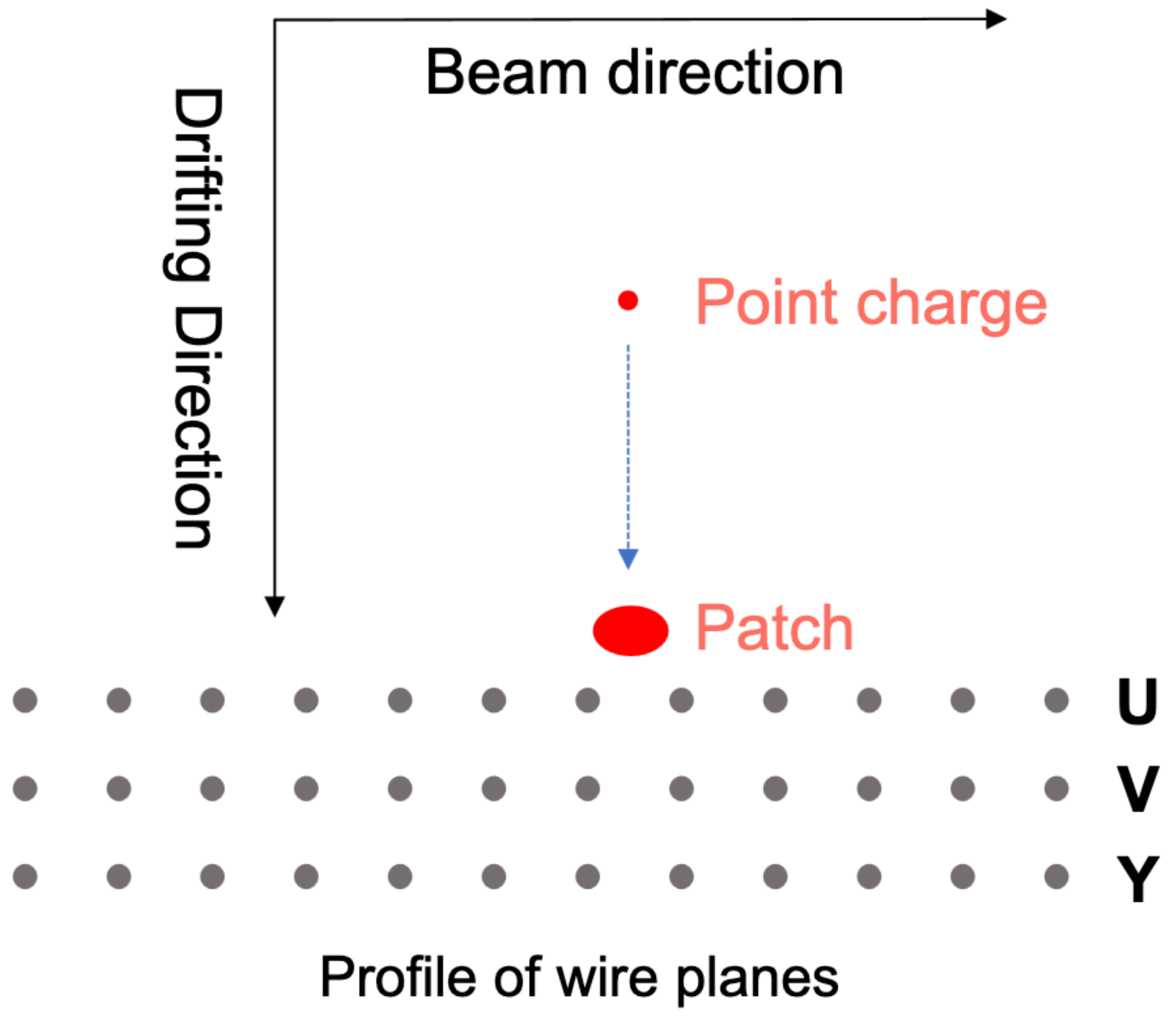
Signal Formation — Diffusion

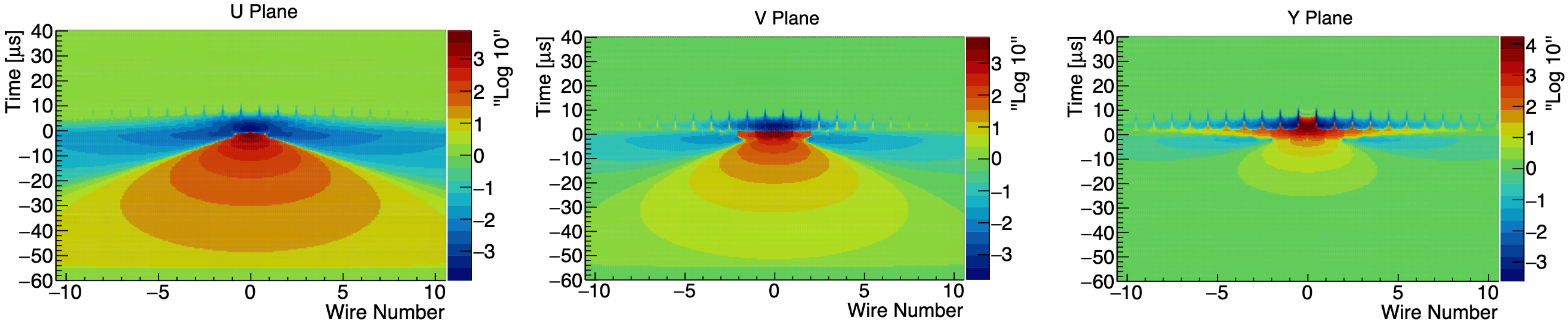


Charge Production and drift in LAR

As charge drifts in the direction of the electric field, it changes from point charge to a patch undergoing both longitudinal as well as transverse diffusion, in time and wire dimension respectively.

C. Adams et al, 2018 JINST 13 P07006

Signal Formation —Field Response



The overall response functions after convolving the field response function and an electronics response function