Wire-Cell TPC Responses, Simulation, Signal Processing and Implications for Vertical Drift Designs

Brett Viren and Andrea Scarpelli

January 14, 2021

Topics

- Concepts governing simulation, noise filtering, signal processing.
- Requirements and progression of LArTPC detector response models.
- Performance of Wire-Cell Toolkit's implementations for wire detectors.
- Challenges for 2-view strips+holes and performance of Wire-Cell Toolkit with 50-L detector data.
- Implications of 3-view strips+holes design choices.

Conceptual LArTPC Simulation

Real detector (and its simulation) produces an event via a **convolution** of:

- $\mathcal{S}$ an **ionization charge distribution** ("signal") with
- $\mathcal{R}$ a **detector response** to drifting electrons, plus
- $\mathcal{N}$ all non-signal related "**noise**", producing
- $\mathcal{M}$ a **measurement** (eg ADC waveforms on channels).

$$\mathcal{M}_x = \mathcal{N}_x + \mathcal{R}_x \circledast \mathcal{S}_x$$

With $x =$ "*det*" (real detector) or "*sim*" (detector simulation).

knowns $\mathcal{M}_{det}$, $\mathcal{M}_{sim}$, $\mathcal{S}_{sim}$ and $\mathcal{N}_{sim}$ (modeled), $\mathcal{R}_{sim}$ (but imperfect).

unknowns $\mathcal{R}_{det}$, $\mathcal{S}_{det}$ and $\mathcal{N}_{det}$.

Conceptual LArTPC Noise Filtering

Noise filtering is a transformation F_{nf} on the measurement:

$$\mathcal{M}_x \rightarrow \mathcal{M}'_x = F_{nf}(\mathcal{M}_x)$$

designed to strongly remove **excess** or **external** noise and potentially reduce **inherent noise** leaving residual noise n_x:

$$F_{nf}(\mathcal{N}_x) \rightarrow n_x \ll \mathcal{N}_x$$

while attempting to leave the signal term approximately invariant:

$$F_{nf}(\mathcal{R}_x \circledast \mathcal{S}_x) \approx \mathcal{R}_x \circledast \mathcal{S}_x$$

Conceptual LArTPC Signal Processing

Signal processing attempts to recover a good approximation of $\mathcal{S}_x$ from $\mathcal{M}_x$.

It uses a **deconvolution** of the measure with a response and with added filters F_{sp} to further suppress the residual noise term.

$$\mathcal{S}'_x = F_{sp} \circledast \mathcal{R}_{sp}^{-1} \circledast \mathcal{M}_x, x \in \{sim, det\}$$

We may not use the detailed $\mathcal{R}_{sim}$ here as it is in terms of the detailed, inaccessible "true" signal coordinates so we use an **average** $\mathcal{R}_{sp}$ (ie, per-channel vs sample time matching $\mathcal{M}_x$).

Note: for **induction channels**, $\mathcal{R}_{sp}^{-1}$ diverges at DC, thus **amplifies residual, low-frequency noise**. To counter, F_{sp} includes special algorithmic high-pass "filters" called *signal region of interest* (signal-ROI) and *local baseline correction*.

Conceptual LArTPC Responses

We then must **choose** $\mathcal{R}_{sim}$ and $\mathcal{R}_{sp}$ and wish to minimize the **per-event difference** between SP and "true" ionization signal in the *sim*:

$$|\mathcal{S}'_{sim} - \mathcal{S}_{sim}|$$

and simultaneously minimize an **ensemble difference** between SP signal over similar samples from *det* and *sim*:

$$| < \mathcal{S}'_{det} > - < \mathcal{S}'_{sim} > |$$

This obviously implies we want:

$$\mathcal{R}_{det} \approx \mathcal{R}_{sim} \sim \mathcal{R}_{sp}$$

IOW, we want $\mathcal{R}_{sim}$ as **close to reality as computational power allows** and $\mathcal{R}_{sp}$ as **close to reality tempered by our limited basis of measurement** $\mathcal{M}$ (ie, channel-level info).

Historical Progress of Response Sophistication

$$\mathcal{R}^{1D} \rightarrow \mathcal{R}^{2D} \rightarrow \mathcal{R}^{2.5D} \stackrel{?}{\rightarrow} \mathcal{R}^{3D}$$

LArSoft $\rightarrow$ Wire-Cell Toolkit (with wires) $\rightarrow$ WCT (with strips+holes) $\rightarrow$???

1D response model: $\mathcal{R}^{1D}(x)$

- Response depends on 1D coordinate (drift direction).
- Sim and SP assume current only in wire nearest to drifting electron.

Pros:

- Computationally fast and algorithmically easy.
- Still available for use in LArSoft SP and sim.
- For sim, strongly minimizes: $|\mathcal{S}'_{sim} - \mathcal{S}_{sim}| \approx 0$

Cons:

- For sim, the $|\mathcal{S}'_{sim} - \mathcal{S}_{sim}| \approx 0$ minimum is "too perfect".
- For data, avg SP signal differences $| < \mathcal{S}'_{det} > - < \mathcal{S}'_{sim} > |$ are large.
  - The "long range induction" effects can not be ignored.
  - MicroBooNE data demonstrated this model is too simplistic.
    - ★ will give examples

Wire-Cell 2D response model: $\mathcal{R}^{2D}(x, \rho)$

- Response depends on 2D coords (drift + pitch directions).
- May induce current on range of nearby wires (1 ± 10) or strips (1 ± 5).
- Response varies w/in one wire/strip region (10 sub-pitch bins).
- Average sim over wire to get SP: $\mathcal{R}^{2D}_{sp}(x) = \frac{1}{N} \sum_{\rho} \mathcal{R}^{2D}_{sim}(x, \rho)$

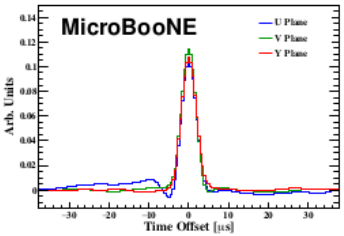
Pros:

- Well minimizes both $|\mathcal{S}'_{sim} - \mathcal{S}_{sim}|$ and $| < \mathcal{S}'_{det} > - < \mathcal{S}'_{sim} > |$.
- Validated, optimized implementation in Wire-Cell Toolkit.
  - Now established as default in most LArSoft uses.
- Works well even with geometries that are not actually 2D.
  - But, note a coming *caveat*.

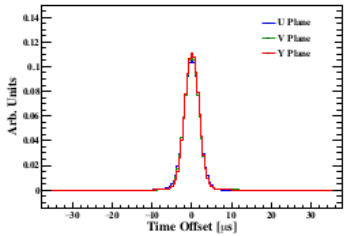
Cons:

- Field response calculations more difficult than 1D, but reasonable.
- Sim and sigproc algorithms more complex, somewhat slower than 1D.
- The more 3D the geometry $\Rightarrow$ more imperfections in 2D model.
  - Particularly not suited for **strips + holes** (more on this coming)

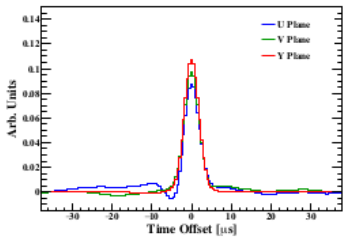
1D SP *vs* Wire-Cell 2D SP on MicroBooNE *det* data



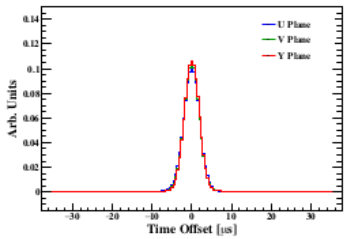
(a) 1D deconvolution, $5° < \theta_{xz} < 15°$.



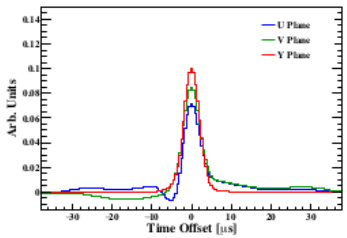
(b) 2D deconvolution, $5° < \theta_{xz} < 15°$.



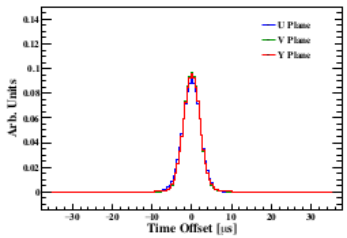
(c) 1D deconvolution, $15° < \theta_{xz} < 30°$.



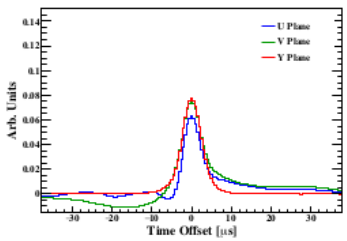
(d) 2D deconvolution, $15° < \theta_{xz} < 30°$.



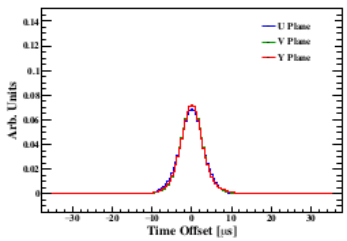
(e) 1D deconvolution, $30° < \theta_{xz} < 50°$.



(f) 2D deconvolution, $30° < \theta_{xz} < 50°$.



(g) 1D deconvolution, $50° < \theta_{xz} < 70°$.



(h) 2D deconvolution, $50° < \theta_{xz} < 70°$.

Plotted: $\mathcal{S}'^{1D}_{det}$ and $\mathcal{S}'^{2D}_{det}$ average reconstructed ionization signal *vs* sample time for ensemble of tracks in four angle bins.

2D Wire-Cell signal processing is able to correctly recover identical **average** track signal $\mathcal{S}'^{2D}_{det}$ **independently on each wire plane**.

Ionization Electron Signal Processing in Single Phsae LArTPCs II. Data/ Simulation Comparison and Performance in MicroBooNE MicroBooNE Collaboration arXiv:1804.02583, JINST 13, P07007 (2018).

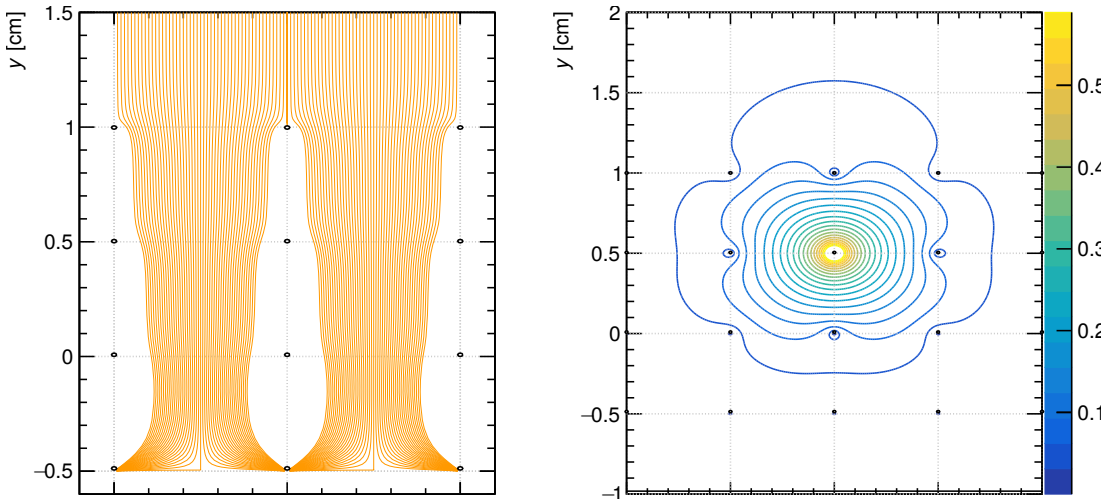
The Test Metric Caveat

Sensitive to **response averages over space**.

- Demonstrates WCT $\mathcal{R}^{2D}$ **good on average** for SP(*sim*) $\approx$ SP(*det*).
  - Does control for **3D direction**, important variation for SP efficiency!
- May not be sensitive to **imperfect detailed variations** in $\mathcal{R}^{2D}_{sim,sp}$
  - Eg, is there SP(*sim*) $\neq$ SP(*det*) bias/resolution at specific locations?
  - Particularly strip+holes have large variations along strip direction.
    - ★ (will show)
- Examples of more **precise metrics** to apply in future *det* vs *sim*:
  - Signal matching between planes with ^{39}Ar or other "blips".
  - Detailed comparison of dE/dX with tracks from full 3D reco.

2D Field Response Calculations - Wires

- In 2D, wires are **infinite, parallel and uniform**, and there are **no edge effects**.
- 126 drift paths per plane: 1 ± 10 wires, 6 "impact positions" per wire at $\frac{1}{10}^{th}$ pitch, exploit translation and mirror symmetries.
- Pre convolve field and electronics response, 10 MHz $\rightarrow$ 200 2 MHz samples per FR function.



2D (x, ρ) drift paths and example U-wire weighting field for ProtoDUNE-SP calculated by drifires/Garfield++ (we are migrating from the venerable GARFIELD).

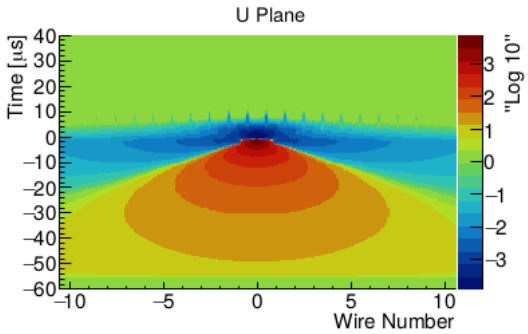
Instantaneous induced current: $I(t_i) = q\vec{W}(\vec{r}_i) \cdot \vec{v}(\vec{r}_i); \vec{r}_i = \vec{r}(t_i); t_i = t_0 + i\Delta t$

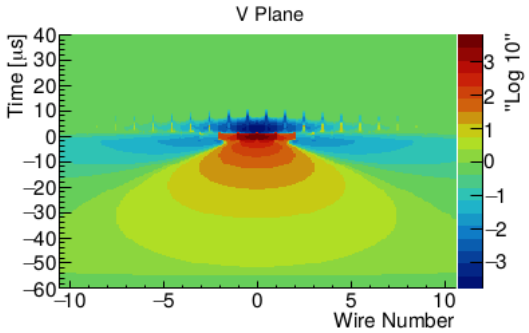
- $\vec{W}$: *weighting field* is $\vec{E}$-field with conductor-of-interest at 1V, all else at 0V.
- $\vec{v}$: drift velocity along path $\vec{r}$ calculated from LAr physics and solving for applied $\vec{E}$-field.
- q: an infinitesimal element from the distribution of drifted ionization electrons at the start of a drift path.

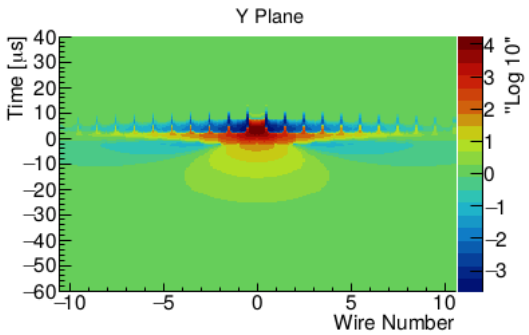
Wire-Cell 2D response for MicroBooNE

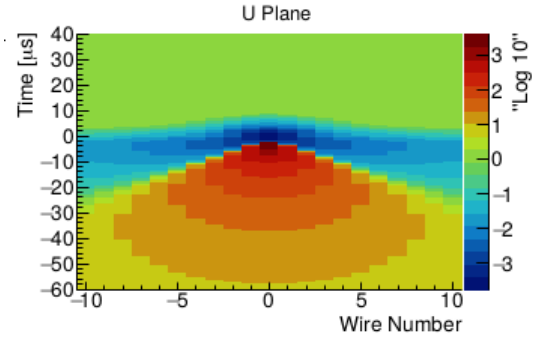
$\mathcal{R}^{2D}_{sim}(x, \rho)$
(drift vs impact position)

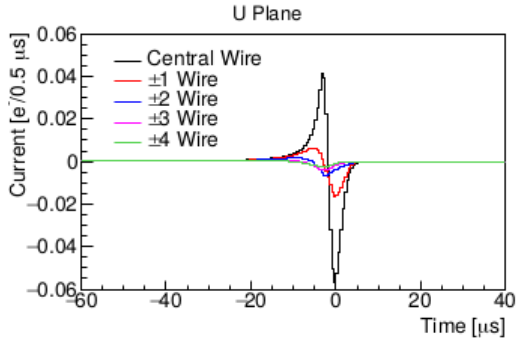
$\mathcal{R}^{2D}_{sp}(x)$
(drift vs wire region + select wire regions)

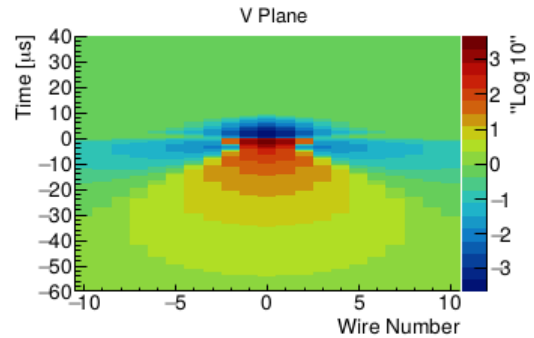


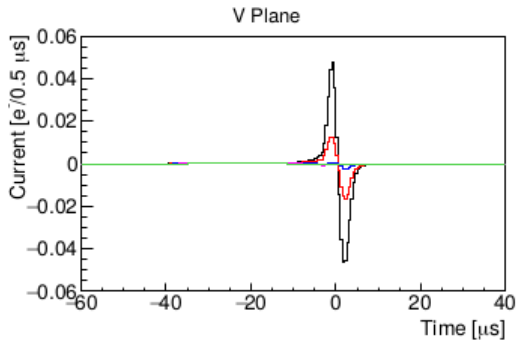


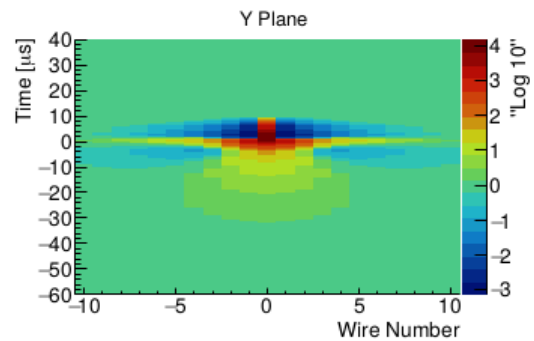


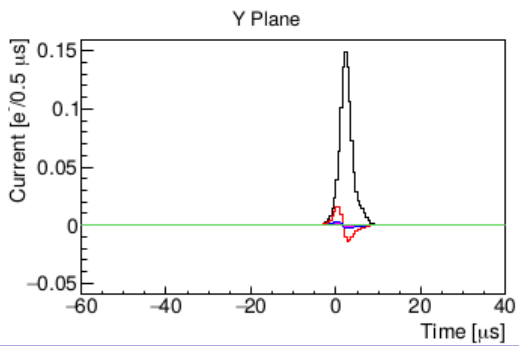






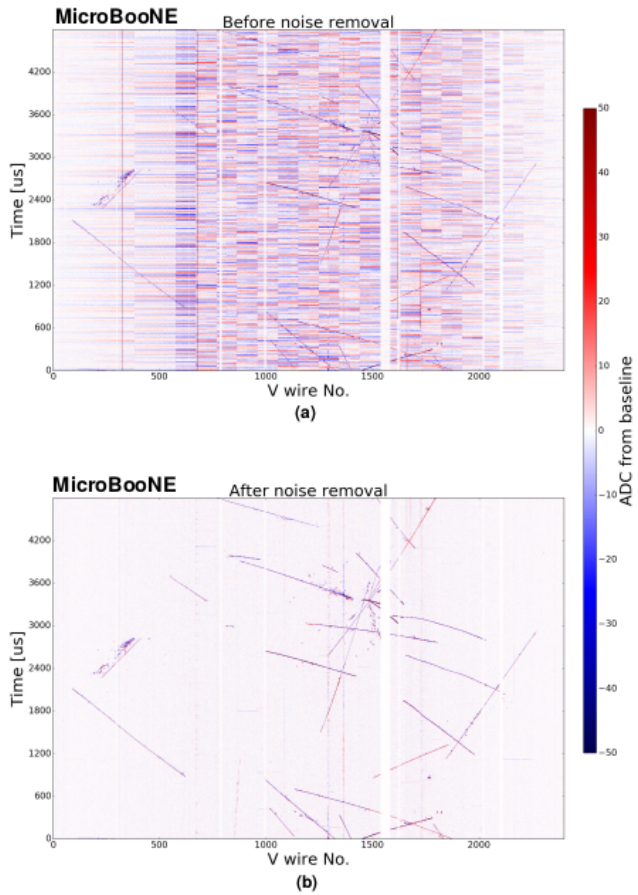




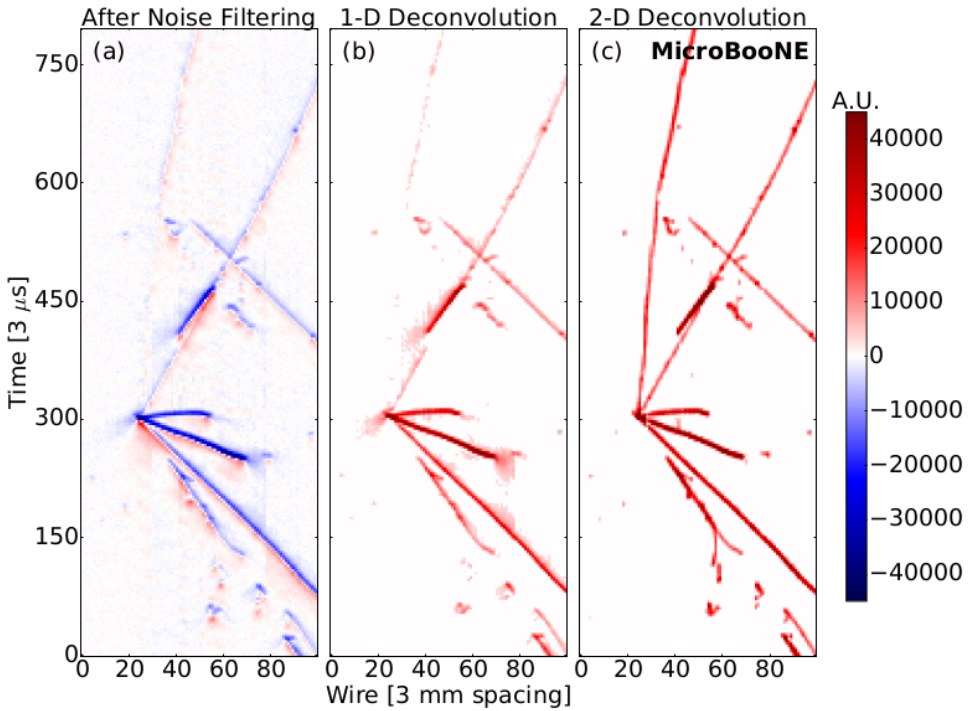


More Wire-Cell NF/SP performance on MicroBooNE

Wire-Cell software **noise filter** applied to MicroBooNE data event.



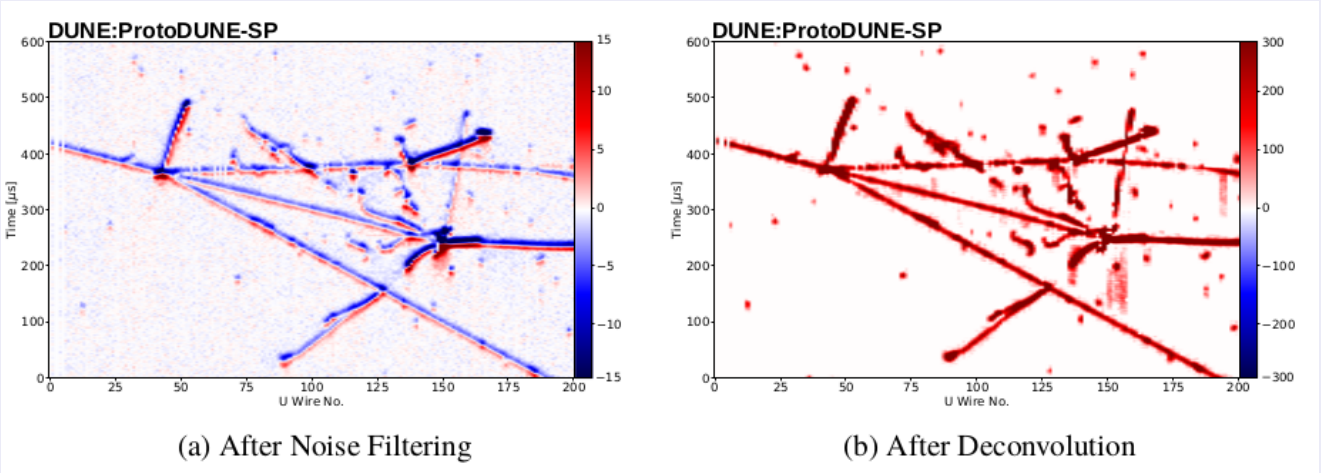
Signal processing on MicroBooNE data event:
(a) noise filtered, (b) 1D and (c) Wire-Cell 2D



Ionization Electron Signal Processing in Single Phase LArTPCs I. Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation MicroBooNE Collaboration arXiv:1802.08709, JINST 13, P07006 (2018).

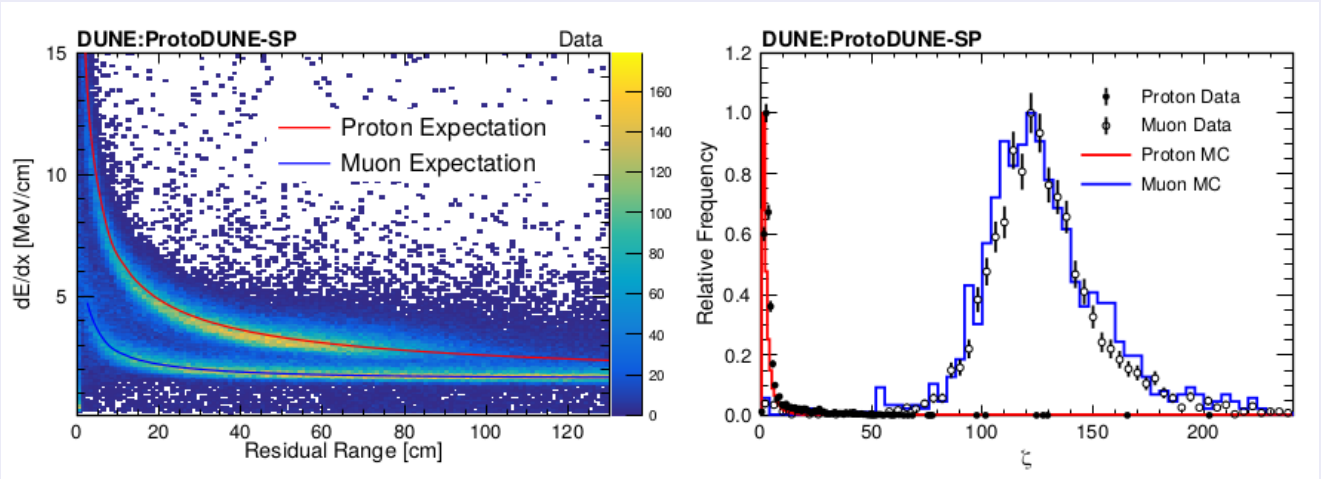
Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC MicroBooNE Collaboration arXiv:1705.07341, JINST 12 P08003 (2017).

Wire-Cell signal processing on ProtoDUNE-SP data



(a) After Noise Filtering (b) After Deconvolution

Wire-Cell simulation/data comparison dE/dX for μ and P on PDSP



First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform. arXiv:2007.06722, JINST 15 (2020) P12004.

Challenges of strips+holes for $\mathcal{R}$

Strips+holes strongly violate 2D model

- **non-parallel strips between the planes**
  - (a "feature" shared with wires)
- **non-uniform along their length**.

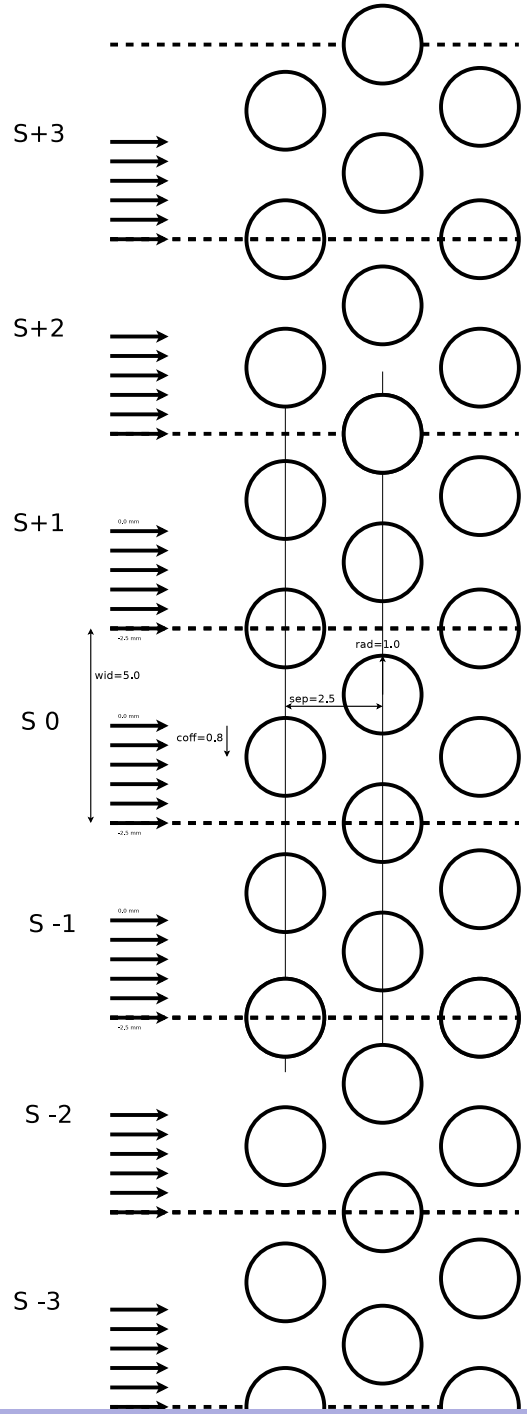
Extra challenges:

- ind/col hole patterns differ between strips-in-plane and strips-across-planes
- hole-pattern has some finite *repetition distance*
  - 2-hole distance for 50-L's 2 views,
  - longer for the 3-view designs (will show *eg*).

Small bonus: fields drop faster with strips than wires

- 1 ± 10 wires $\rightarrow 1 \pm 5$ strips.

50-L detector collection stips+holes $\longrightarrow$



2.5D model for strips+holes $\mathcal{R}^{2.5D} \rightarrow \mathcal{R}^{2D}_{sim,sp}$

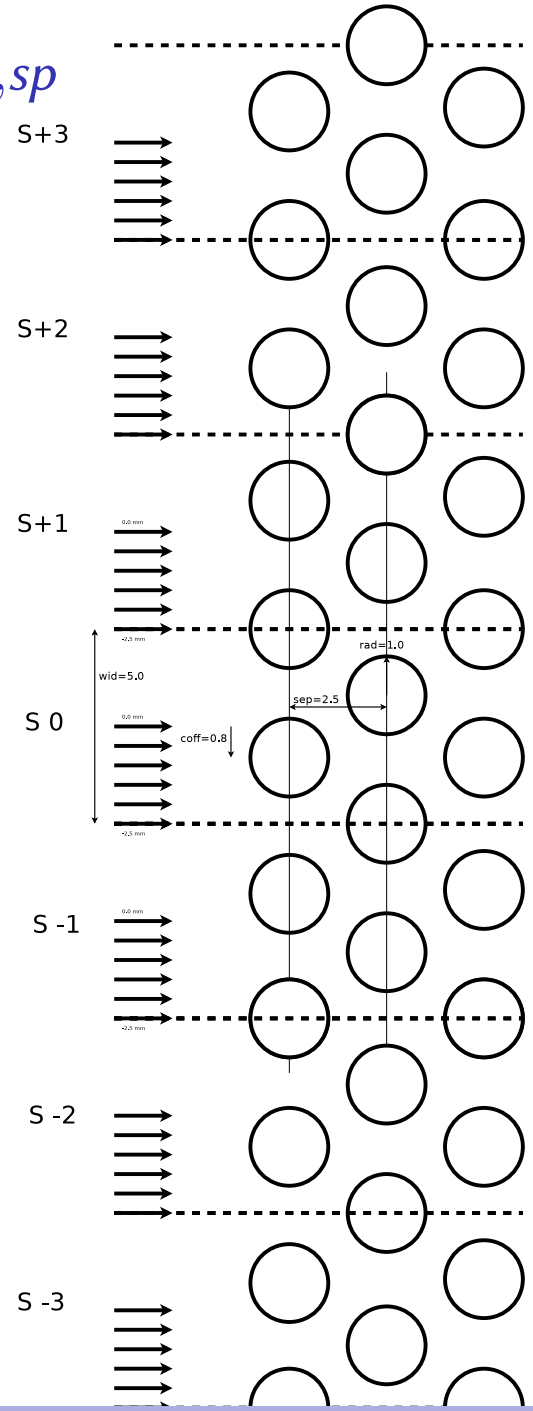
"2.5D" trick

- Construct "slices" across strips spanning the *pattern repetition distance*.
- Each slices defines an $\mathcal{R}^{2D}$ problem domain.
- Calculate per-slice $\mathcal{R}^{2D}_{slice}$, **average** over slices to get $\mathcal{R}^{2D}_{sim,sp}$

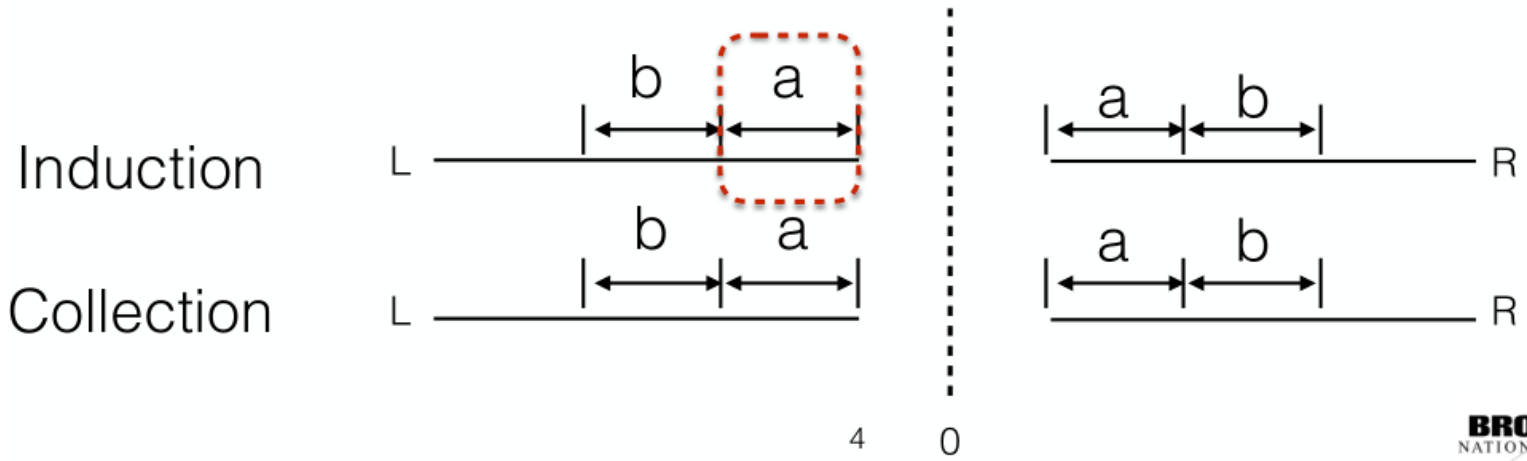
Calculating the $\mathcal{R}^{2D}_{slice}$'s brings new problems:

- how best to define slices?
  - we chose diameter-crossing slices
- how many slices are needed?
  - we chose two slices for 50-L, "skewed" will need more.
- how to exploit symmetry to reduce calculation?
  - next slides.
- **how wrong** is this?
  - initial **average** checks (recall *caveat*) with 50-L look good.
  - longer hole *pattern repetition distance* is worrisome.

Chosen slices shown as vertical lines $\longrightarrow$



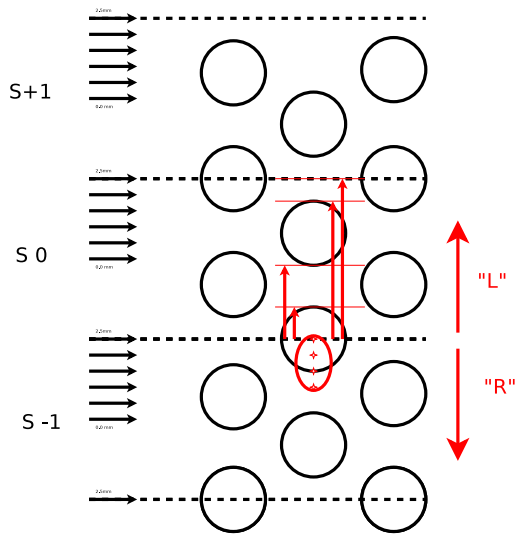
The 2.5D trick applied to GARFIELD



GARFIELD setup for 2D single-hole (Yichen Li)

Clever work-around to limitations of 2D and GARFIELD:

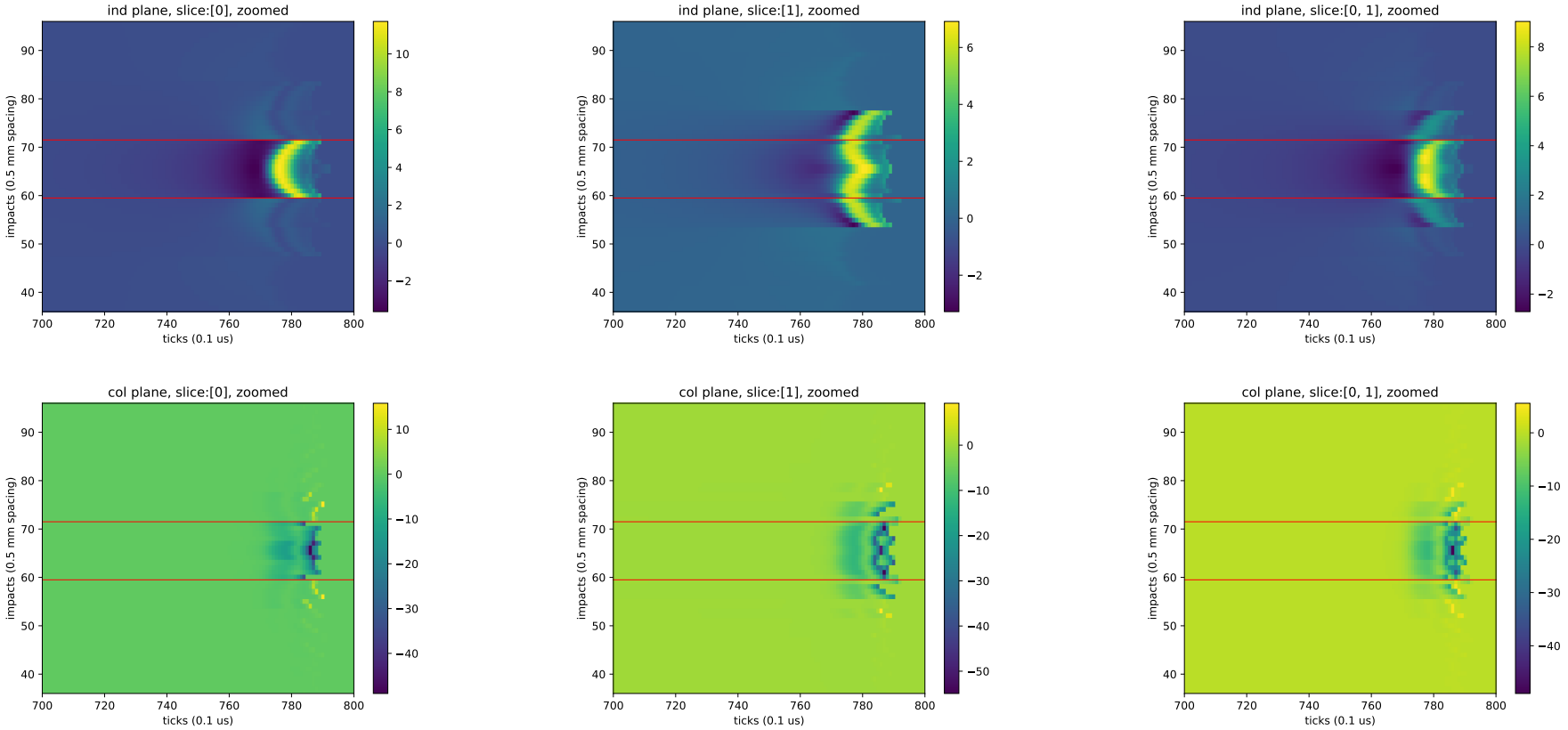
- **Single-hole**, 2D geometry with strips constructed as array of hundreds of "**micro wire**" sensing conductors
  - the L/R and A/B blocks work around some GARFIELD technical limits.
- Manual labor intensive post processing
  - Catalog maps of drift paths on slice to single-hole geometry.
  - Catalog micro wire selection criteria for each drift path.
  - Longer the hole pattern repetition distance ⇒ more the effort.



50-L detector's $\mathcal{R}^{2.5D} \rightarrow \mathcal{R}^{2D}_{sim}$

Given the cataloging and GARFIELD "micro-wire" responses, the PCBro (PCB anode readout) package processes and averages the per-slice responses to produce WCT-compatible $\mathcal{R}^{2D}_{sim,sp}$.

(induction plane, slices 0, 1 and average)
(collection plane, slices 0, 1 and average)



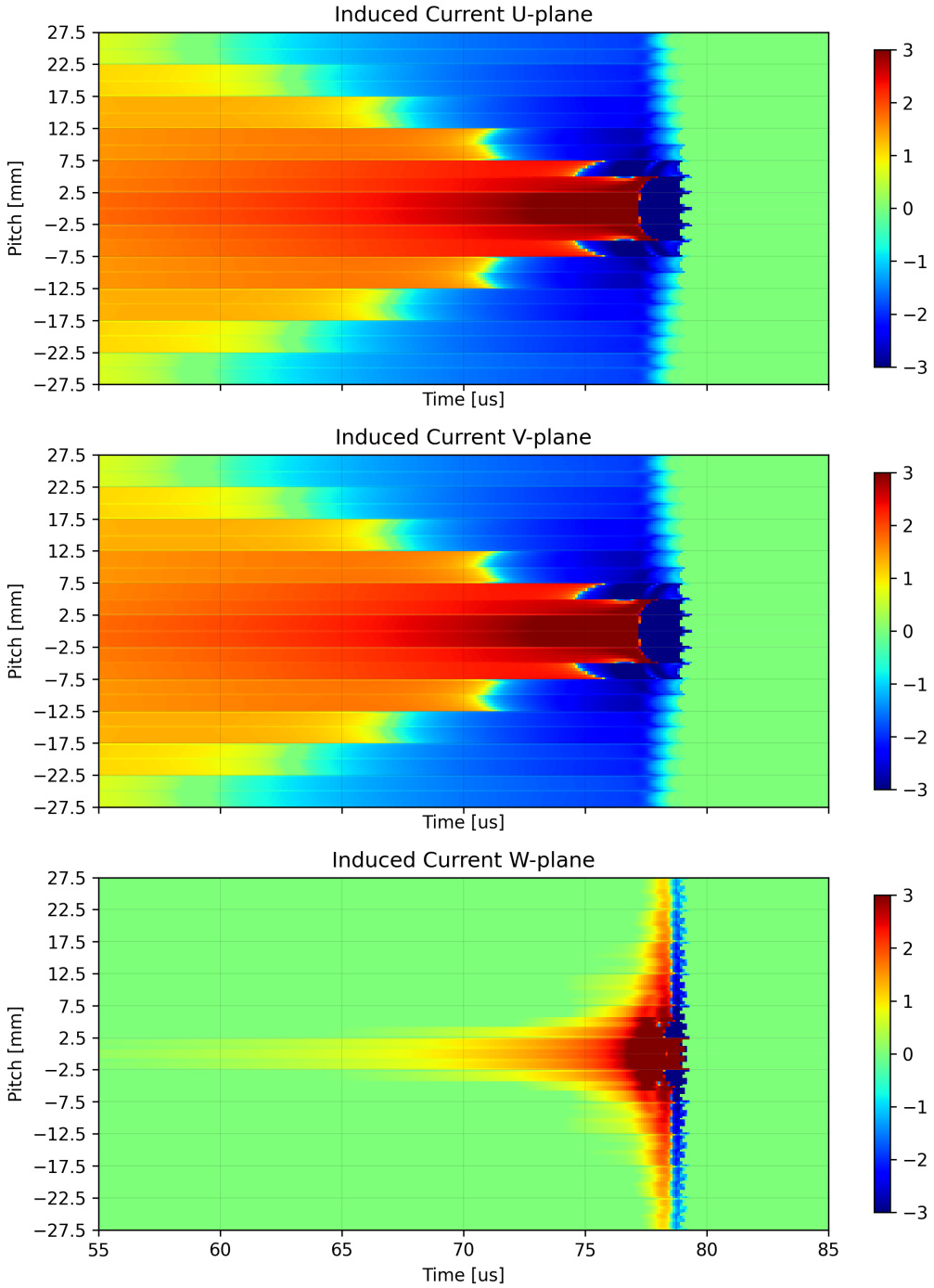
Slice 1 Slice 2 Slices 1 + 2

Next 3 slides

Better view tails with "$\pm\log 10$" scale for 50-L's $\mathcal{R}^{2D}_{sim}$.
Each slide shows a slice-average or a specific slice:

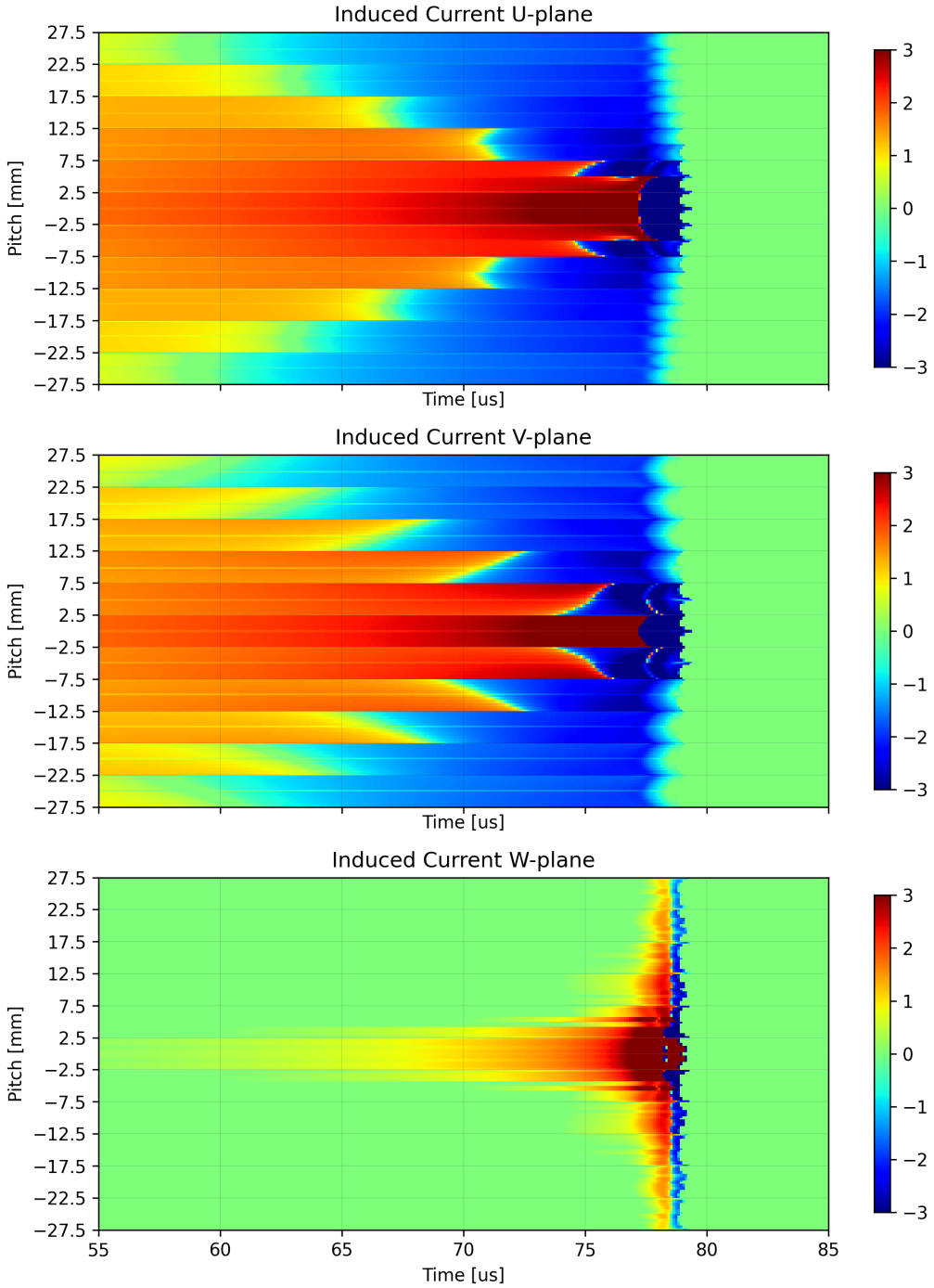
1. average over both slices
2. highlight slice 0
3. highlight slice 1

50-L detector only has 2-views: induction + collection.
The "U" and "V" labels indicate different forms for the **induction** plane info.
The "W" is always the **collection** plane info.



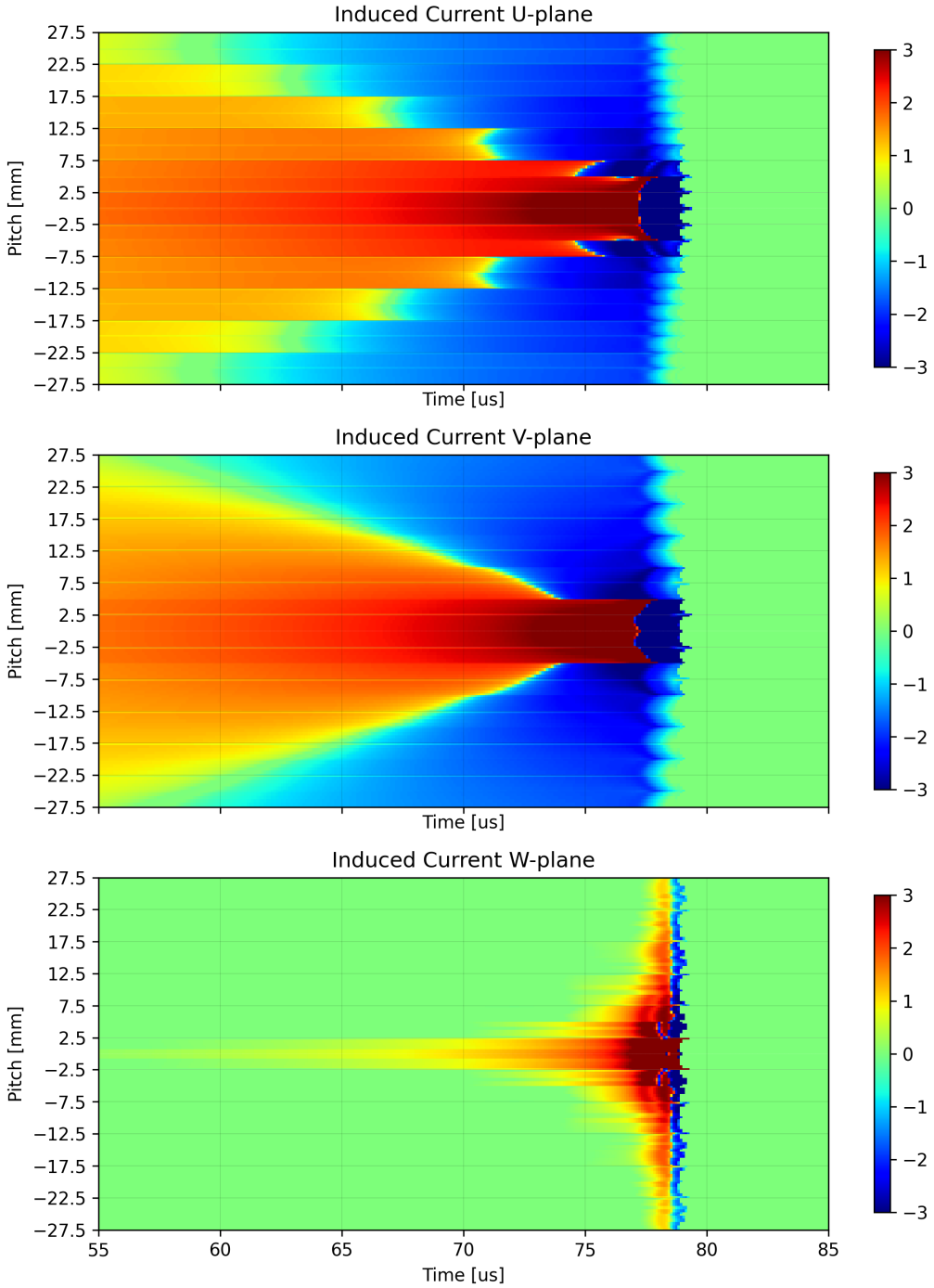
50-L $\mathcal{R}^{2D}_{sim}$

1. U is average over the two induction slices.
2. V is average over the two induction slices.
   - (the two are identical)
3. W is average over the two collection slices.



50-L $\mathcal{R}^{2D}_{sim}$

1. U is average over both induction slices
2. V is induction slice 0
3. W is collection slice 0



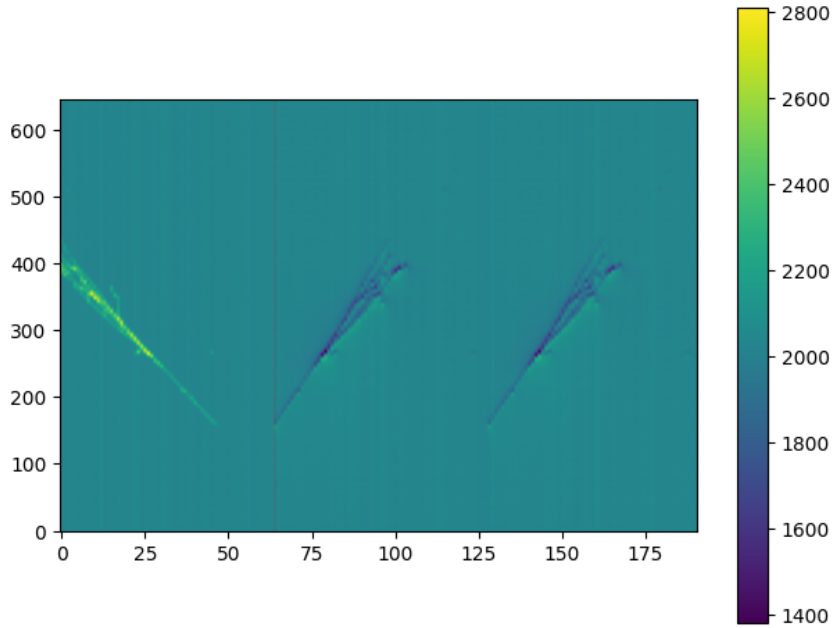
50-L $\mathcal{R}^{2D}_{sim}$

1. U is average over both induction slices
2. V is induction slice 1
3. W is collection slice 1

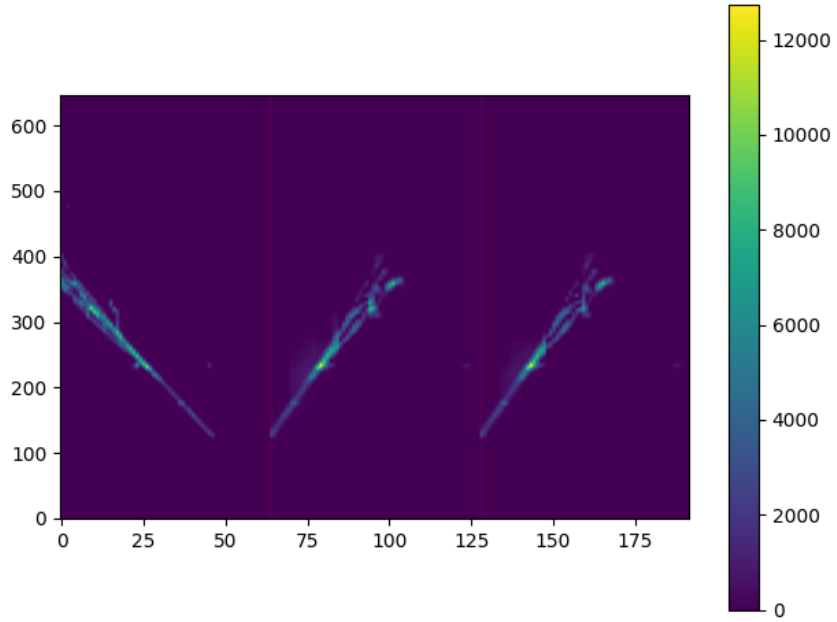
50-L raw data and WCT sigproc with $\mathcal{R}_{sp}^{2.5D}$

The PCBro package also provides a 50-L raw data decoder and hooks to run **Wire-Cell Toolkit signal processing** on 50-L data.

50-L raw data event
PCBro data decoder



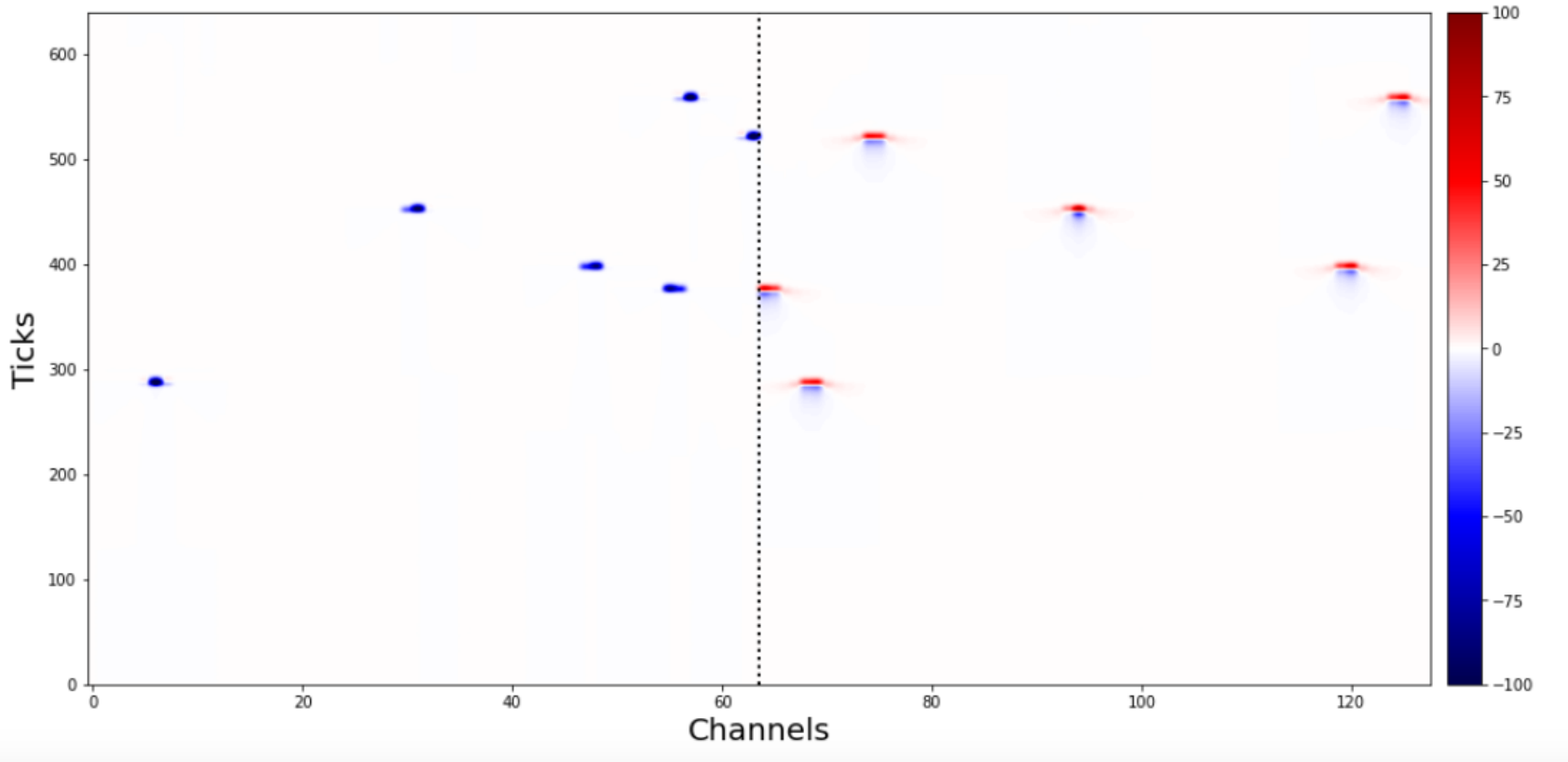
Same event after **Wire-Cell signal processing**



Note, the "**double induction**" plane is merely duplicate to fit nominal WCT assumptions of 3 planes.
The PCBro package uses this "extra" plane to test different field responses in the same job.
In production processing, we need not waste CPU on the duplication.

50-L WCT simulation of ^{39}Ar "blips"

Andrea Scarpelli
collection plane | induction plane



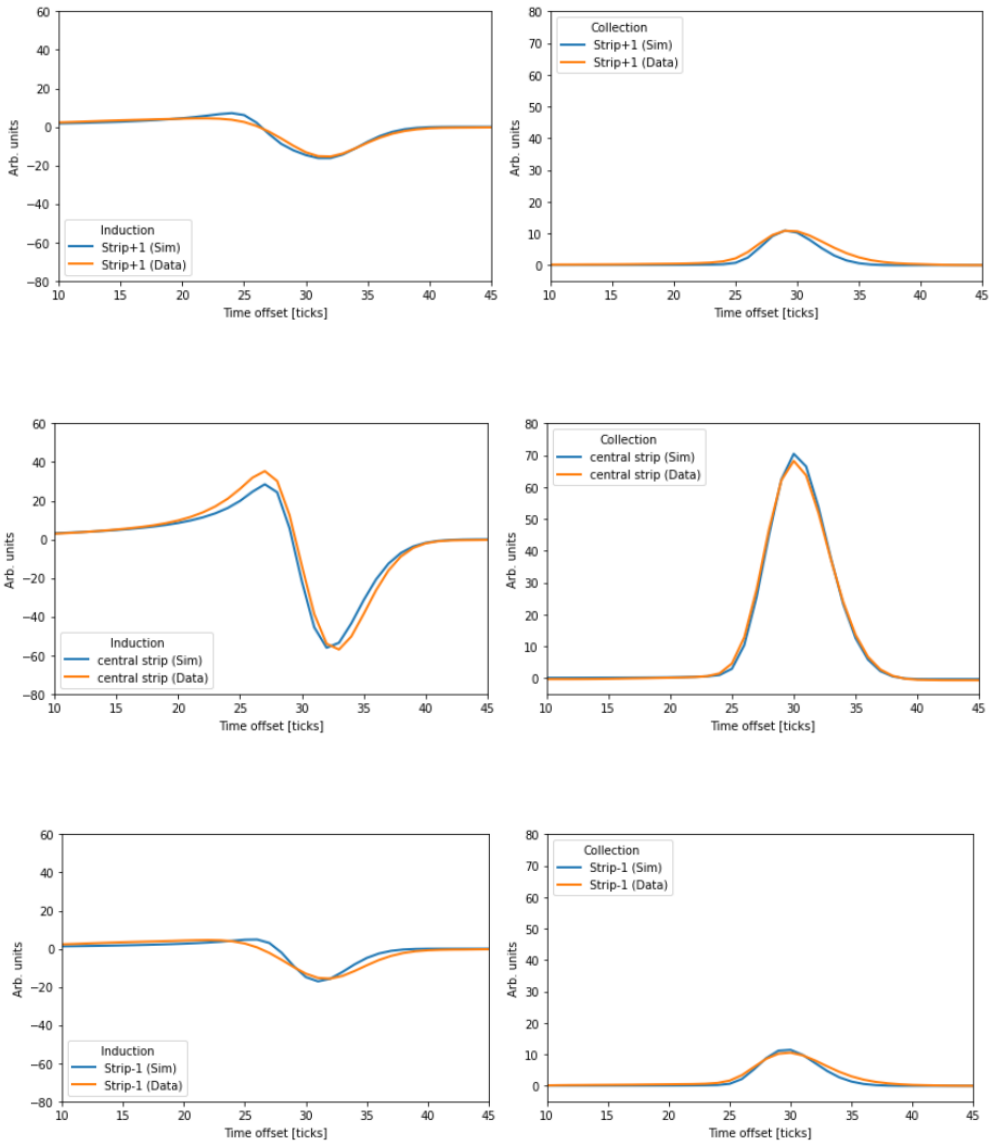
Samples ^{39}Ar energy spectrum scanned from arXiv:1705.05726v1.

50-L data / WCT sim comparison - ^{39}Ar “blips”

Andrea Scarpelli and Serhan Tufanli

average raw waveforms

50-L data (orange) and Wire-Cell 2D sim (blue) using a 2-slice $\mathcal{R}^{2.5D}$.
Separated by induction (left) and collection (right) planes and for central strip (middle) and central ± 1 strips (top/bottom).



50-L data/sim checks t.b.d.

Other sources:

- 1 MeV e- Bismuth source "blips".
- MIP tracks in different direction bins.

Address "Test Metric Caveat" with more precise *det vs sim* comparisons:

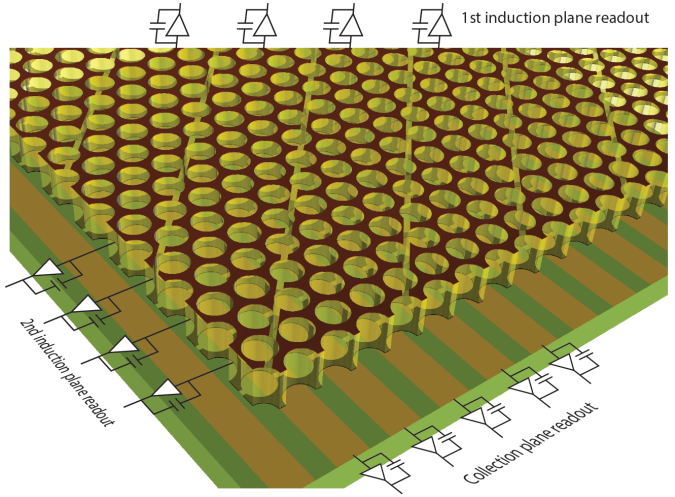
- SP ind/col ratio for "blips", ideally $= 1.0$
- Invariant values (eg, raw ind waveform integral $= 0.0$)
- Raw waveforms from "blips" as $f(\rho)$?

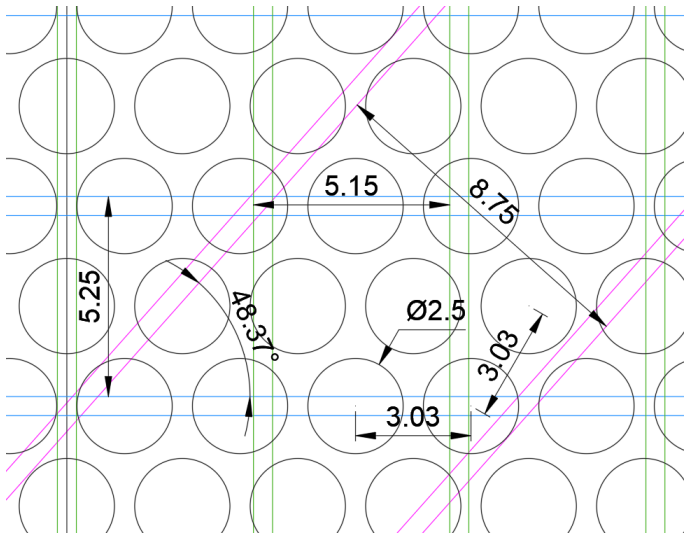
Skewed hole pattern: 2.5D? 2.7D?

50-L: **average** tests look good for $\mathcal{R}_{sim}^{2.5D}$, **eyeballing** SP event display looks good for $\mathcal{R}_{sp}^{2.5D}$.
But, 50-L has fairly **regular hole pattern**.
New worry: 3-view's "diagonal" strip with "skewed" hole pattern. $\longrightarrow$

- May need $N > 2$ slice average: "2.7D … 2.9D"
  - Have scheme to produce **data-driven optimal weighting** of slices. Non-trivial, but there if we need it.
- Strip angle such that **no slice** goes only through hole diameters.
  - Further biasing of the "2.x D" approach?
- Even with 3D, prefer to maximize regularity of patterns.

$\therefore$ **Design wish**: rectangular 2-plane or isosceles/hexagonal 3-plane!



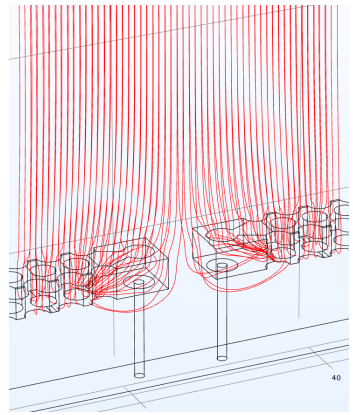


From Bo's presentation at the recent DUNE collab call

So, why not $\mathcal{R}^{3D}$?

Some work in 3D exists.

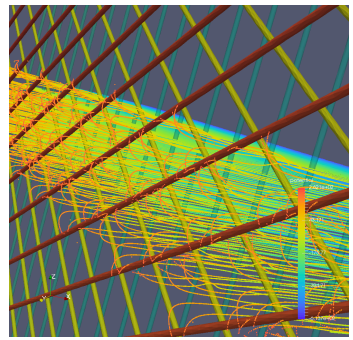
- Mostly for "near by" fields or "far fields" but for **wires**.
- Far field 2D calculation takes **minutes-hours**, 3D calculations take **hours-days** (using BEM, effectively impossible with FEM).
- Strips+holes need finer meshing $\Rightarrow$ more processing (than wires).
- Longer hole repetition distance $\Rightarrow$ more processing (than 50-L).



From Bo's talk again

And, given $\mathcal{R}^{3D}$ sim must contend with an explosion of data.

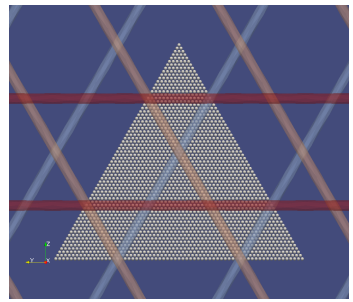
- $\mathcal{R}_{sim}$ **drift paths per plane** (some estimate/guesses)
  - 2D wires: 126.
  - 2.5D strips: O(100) for 50L, O(1,000) for skewed hole pattern
    - ★ but at least results in "standard" $\mathcal{R}^{2D}_{sim,sp}$!
  - 3D: O(50,000), and worse: **old simulation must be thrown out**.



LARF

3D simulation

- Same concepts as 2D sim, but need all new algorithms/code.
- 2D sim exploits 10-way interlacing across common, wire-relative impact positions in order to use 2D FFT + 10-way sum for fast convolution.
  - How to even apply this trick in 3D? More variety along the strip direction will increase interlacing $\Rightarrow$ harder/slower calculation.



Summary and some next steps

- Wire-Cell's use of $\mathcal{R}^{2D}_{sim,sp}$ improves over $\mathcal{R}^{1D}$ as demonstrated with MicroBooNE and ProtoDUNE.
- The $\mathcal{R}^{2.5D}$ trick brings Wire-Cell support to 50-L strips+holes det.
  - Eyeball SP event display and average raw waveform tests look okay.
  - These **average** test metrics may hide some variational problems.
- Unclear if "2.5D" trick can be pushed to designs with more variability.
  - Will need test detector data to confirm.
- 2D or 3D $\mathcal{R}$ calculations prefer regularity.
  - **rectangular 2-view** and **isosceles/hexagonal 3-plane** designs, please!
- Continue developing and applying test metrics
  - Focus on **precise tests** to check for **variational problems**.
  - If found, will first look into pushing on "2.5D" to more slices.
  - Hold off on 3D as last resort due to effort required.
- We continue to improve support in Wire-Cell Toolkit for strip+hole test detectors and for the eventual DUNE VD module(s)!

FIN