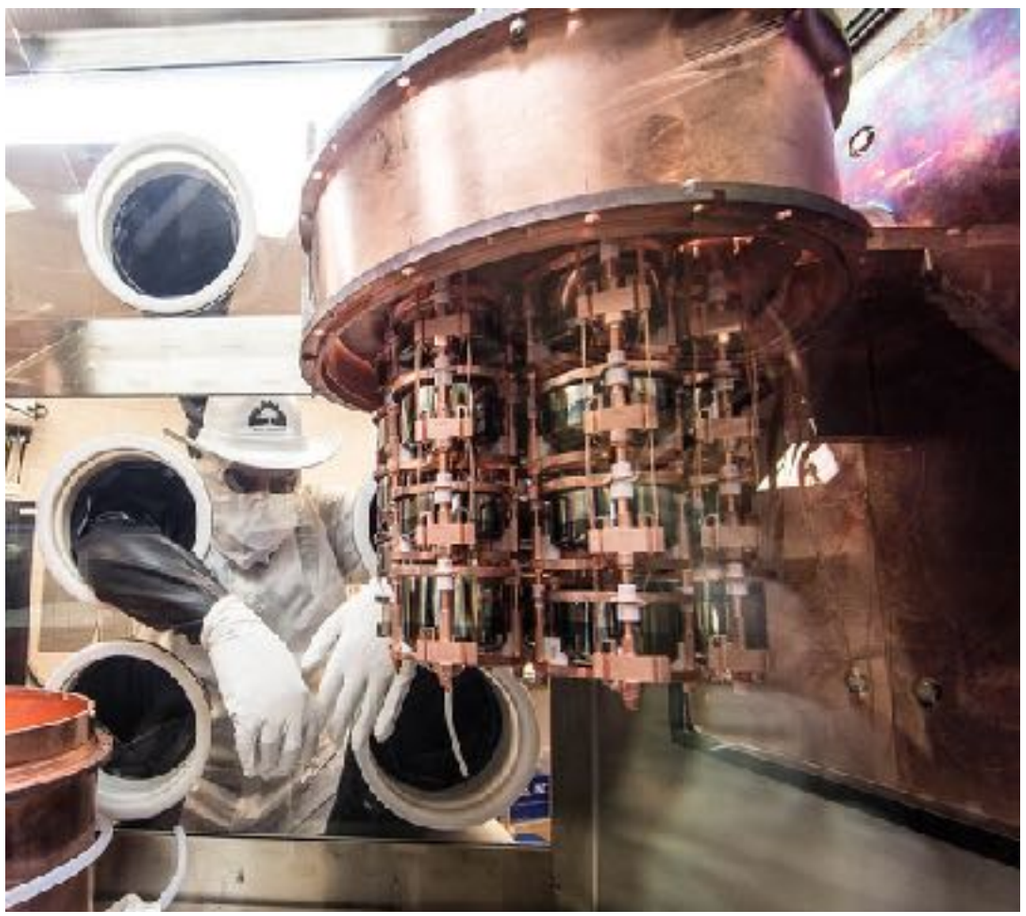
Precise Modeling of PPC Signals

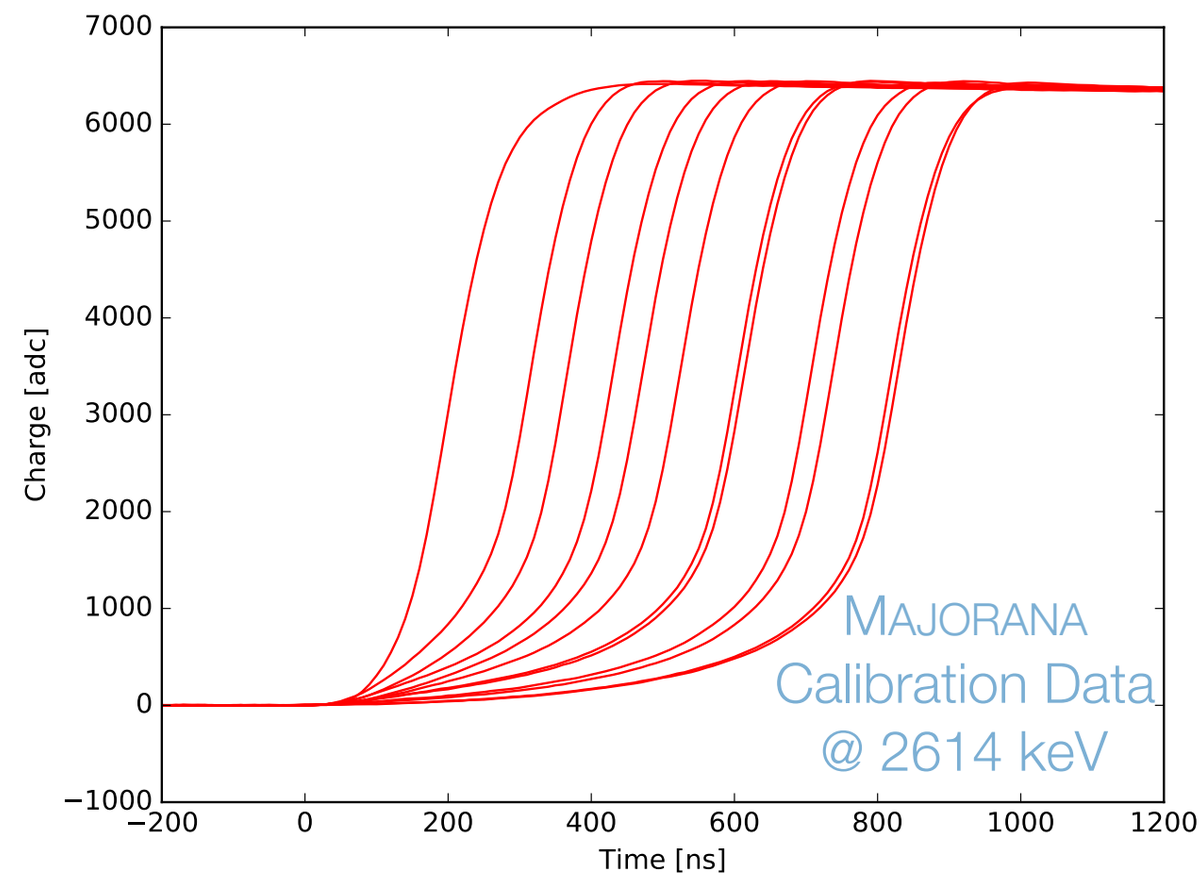
Ben Shanks
ORNL

“Deep” Learning

Work has been done as part of MAJORANA DEMONSTRATOR.

- PPC detectors (enriched, manufactured by ORTEC)





Goal: understanding signal shape as well as possible with eye toward maximizing extraction of information

Model Components

Component	Dependencies
Weighting Potential	Crystal geometry
Electric Field	Crystal geometry; impurities
Drift velocity	Mobility (crystal specific); electric field
Electronics shaping	Electronics chain
Energy deposition	—

Weighting Potential and Electric Field

Similar calculations:

- WP: solve the Laplace equation given electrode configuration
- EF: solve Poisson equation (includes charge from impurities)

Has to be done numerically. Two options:

- Custom-built numerical relaxation on a grid (*fieldgen)*
- Open-source PDE solver using finite element mesh method (*FEniCS*)

In either case, answer is discretized: calculating field at arbitrary point requires interpolation

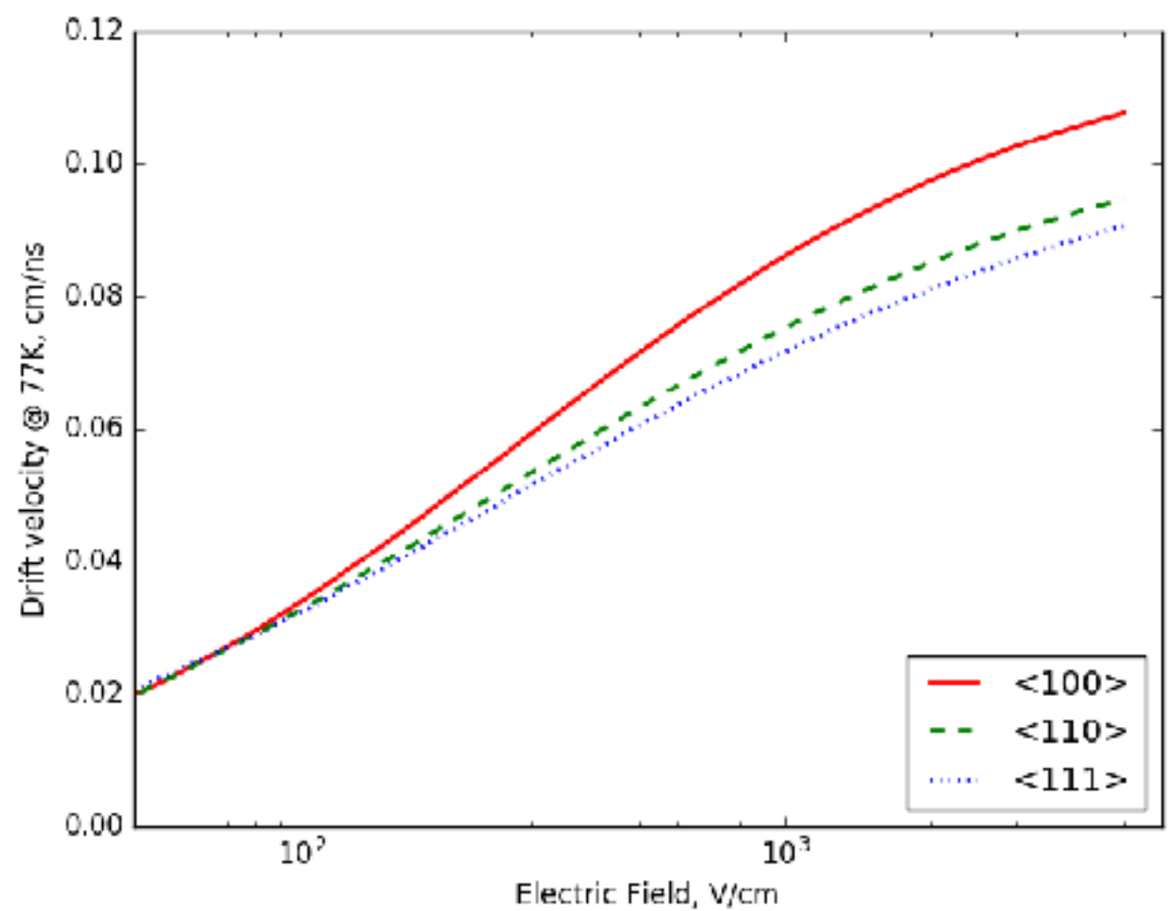
http://radware.phy.ornl.gov/MJ/mjd_siggen/

https://fenicsproject.org/

Carrier Velocity

Both hole and electron velocities are:

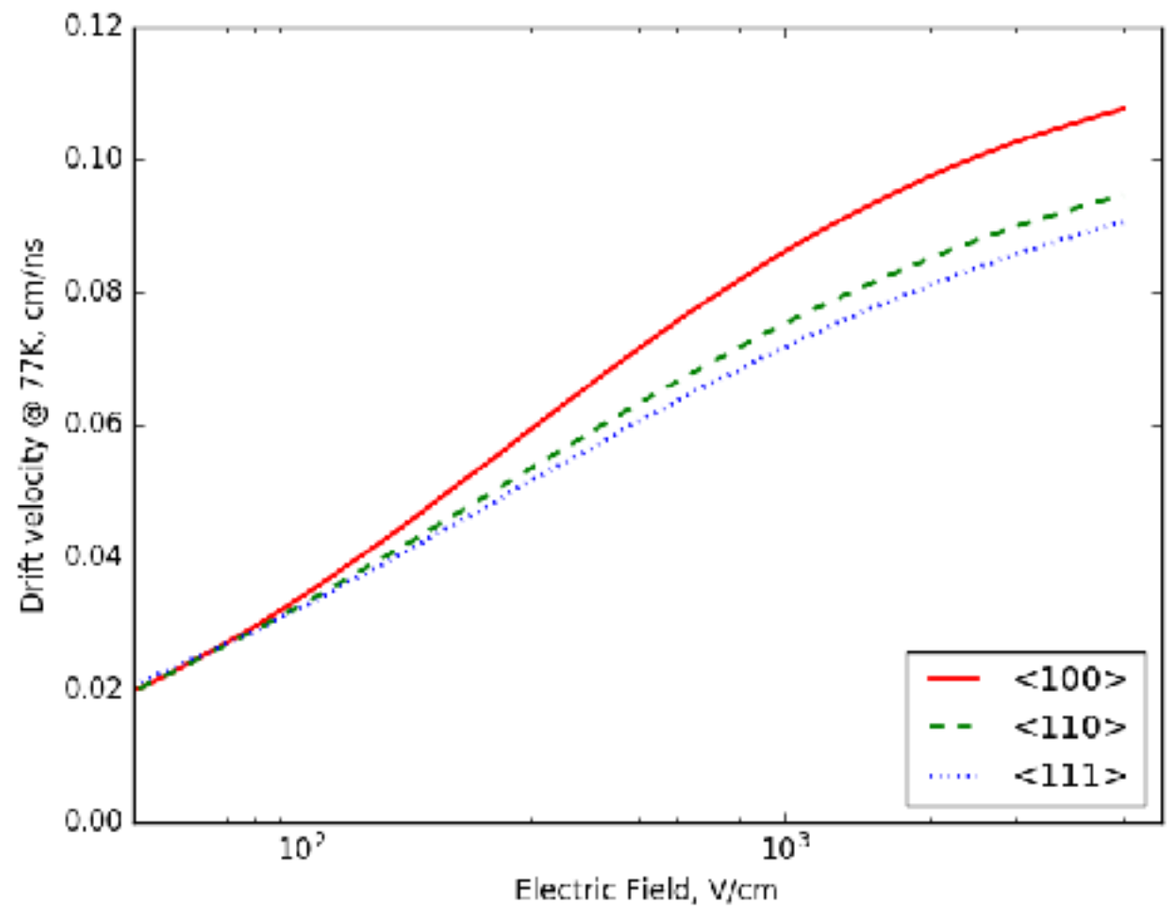
- Linear at low field
- Saturate at high field (due to scattering)
- Anisotropic between crystallographic axes (due to multi valleyed conduction band)



Carrier Velocity

Standard Parameterization along any given axis:

$$v = \frac{\mu_0 E}{(1 + (E/E_0)^\beta)^{1/\beta}}$$



Carrier Velocity

Velocity curves depend sensitively on crystal temperature, and can vary between crystals due to differences in impurities

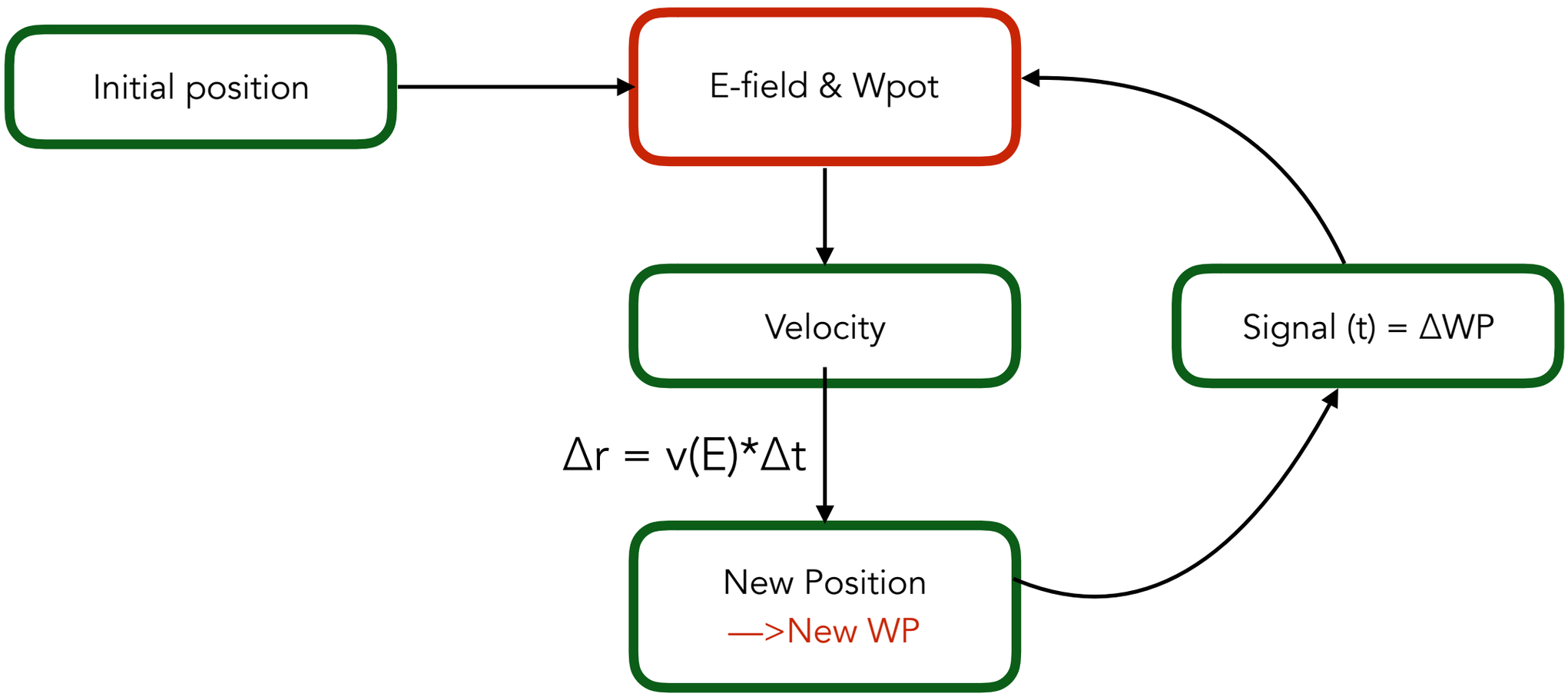
Approach: parameterize along fast (<100>) and slow (<111>) axes; use band structure to calculate velocity between axes

Electrons: Mihailescu NIM A 447

Holes: Bruyneel NIM A 569

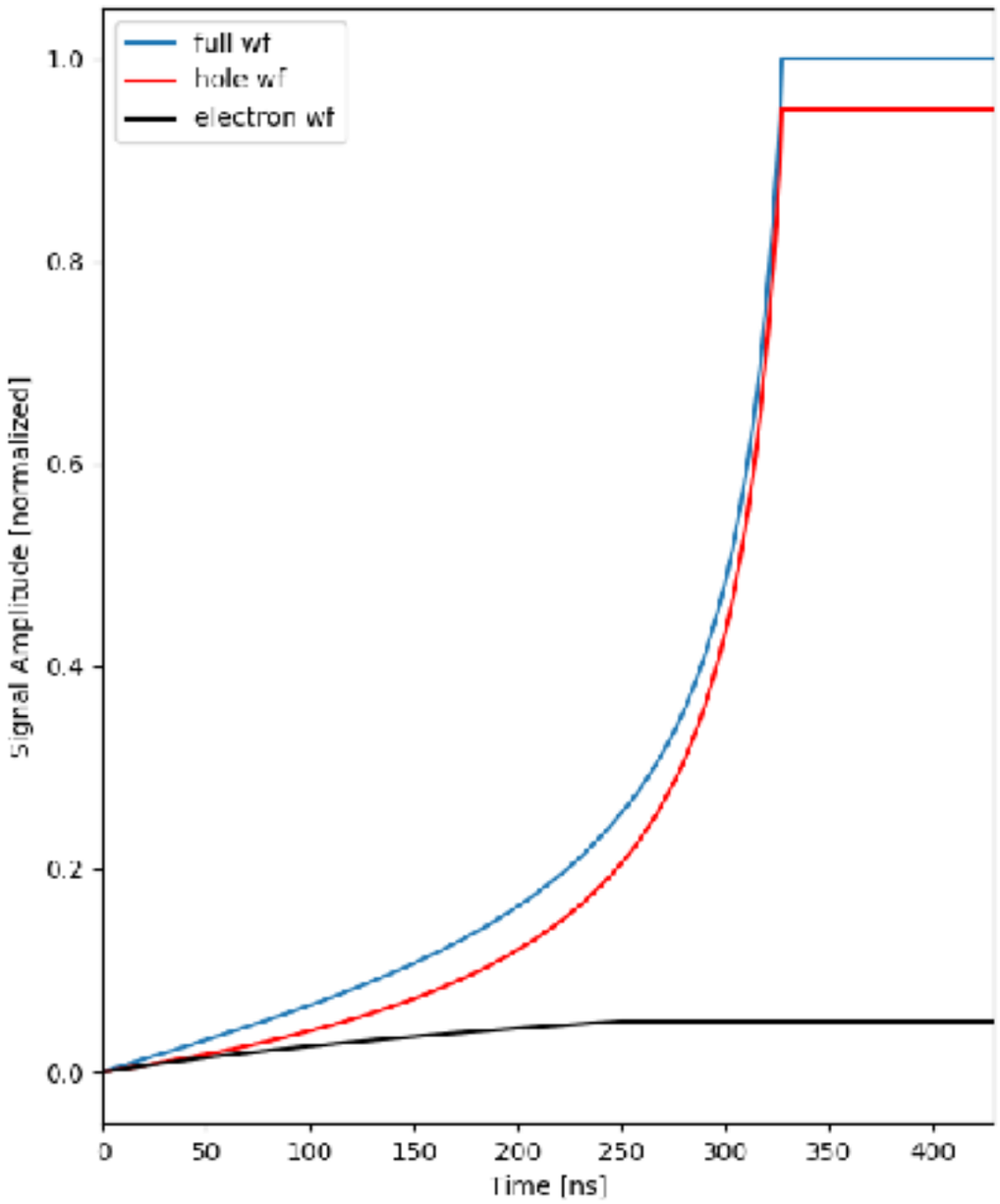
Waveform Calculation

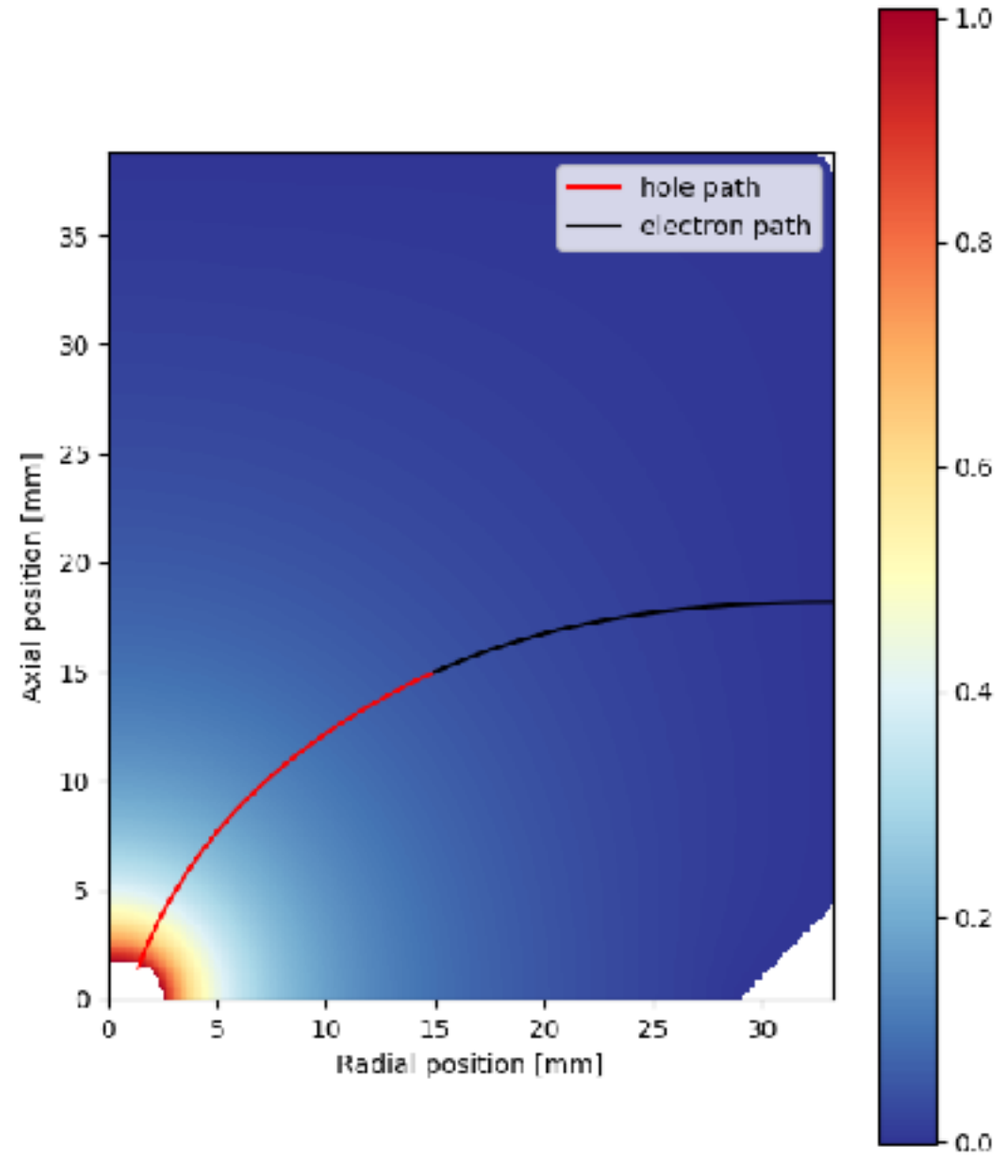
for a point-like event, ignoring electronics effects



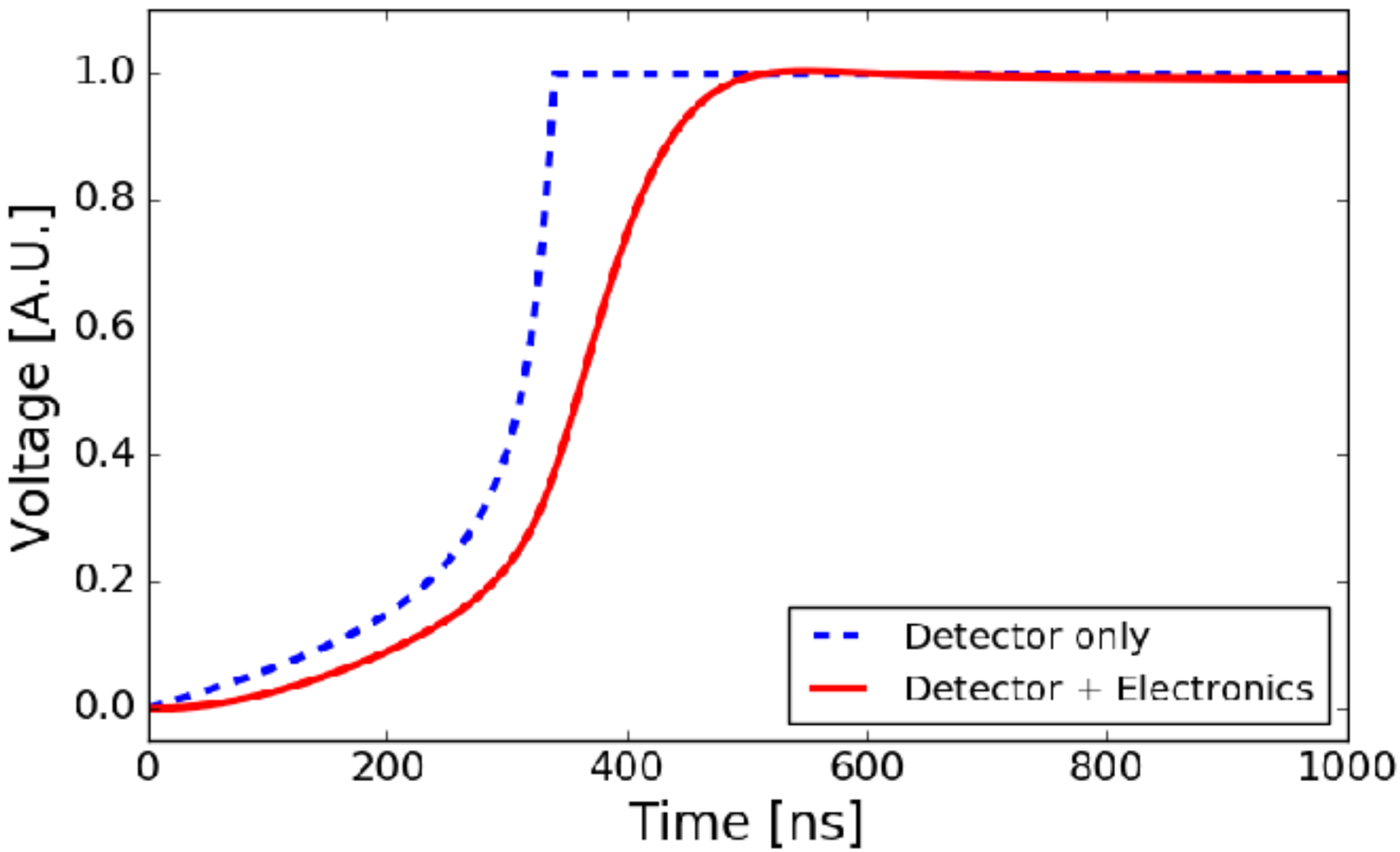
Siggen: http://radware.phy.ornl.gov/MJ/mjd_siggen/

Calculated Waveform





MJD Electronics

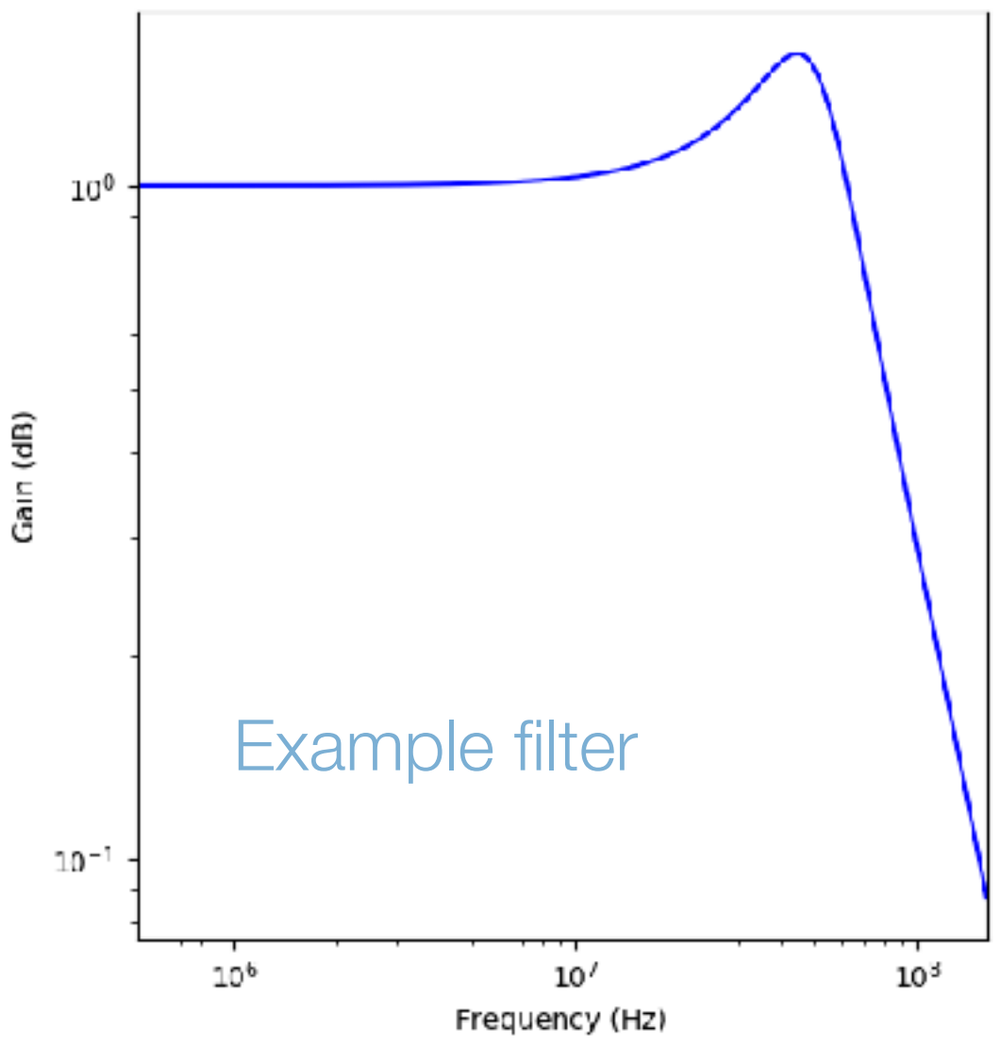


Electronics shaping is particularly significant for MJD waveforms due to long feedback loop (~100 ns rise time increase!)

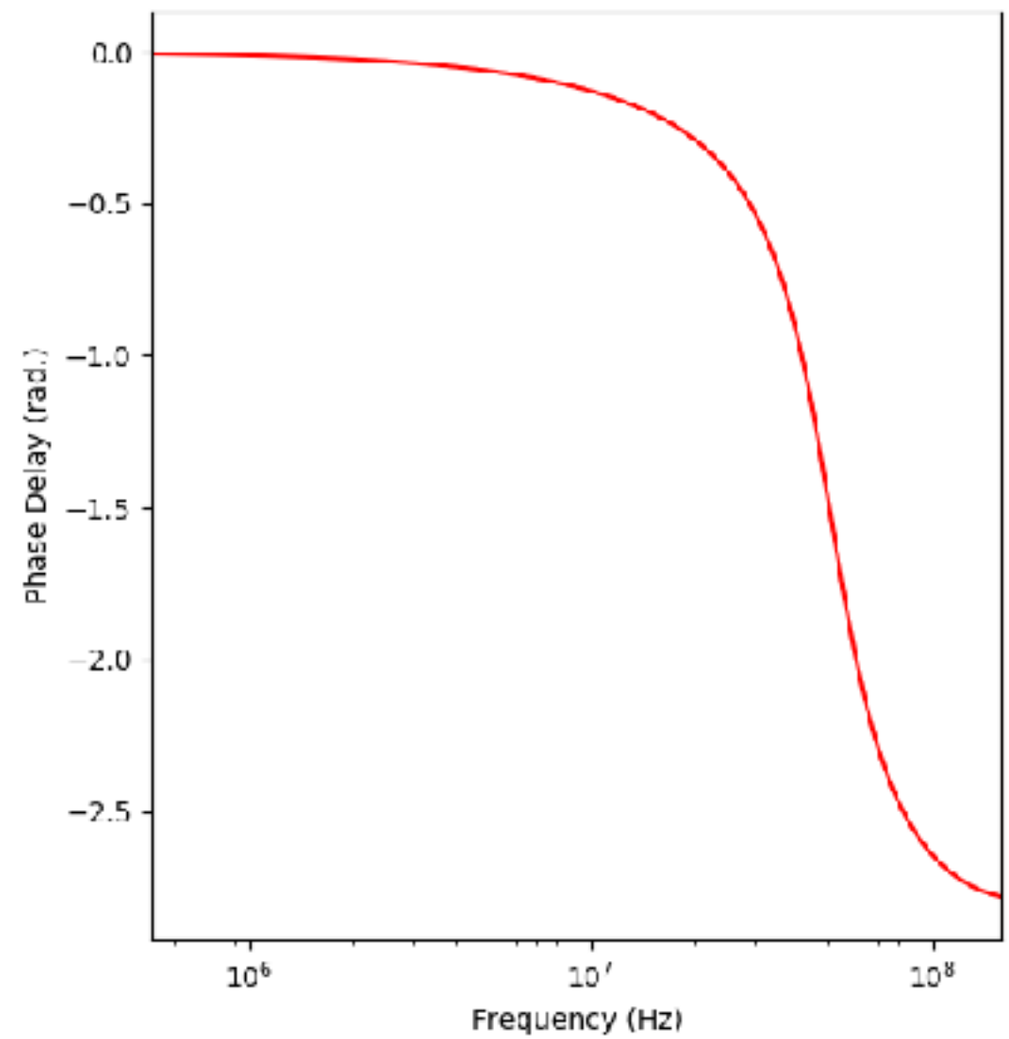
Modeling electronics signal

Response dictated by gain and delay as function of frequency

Gain

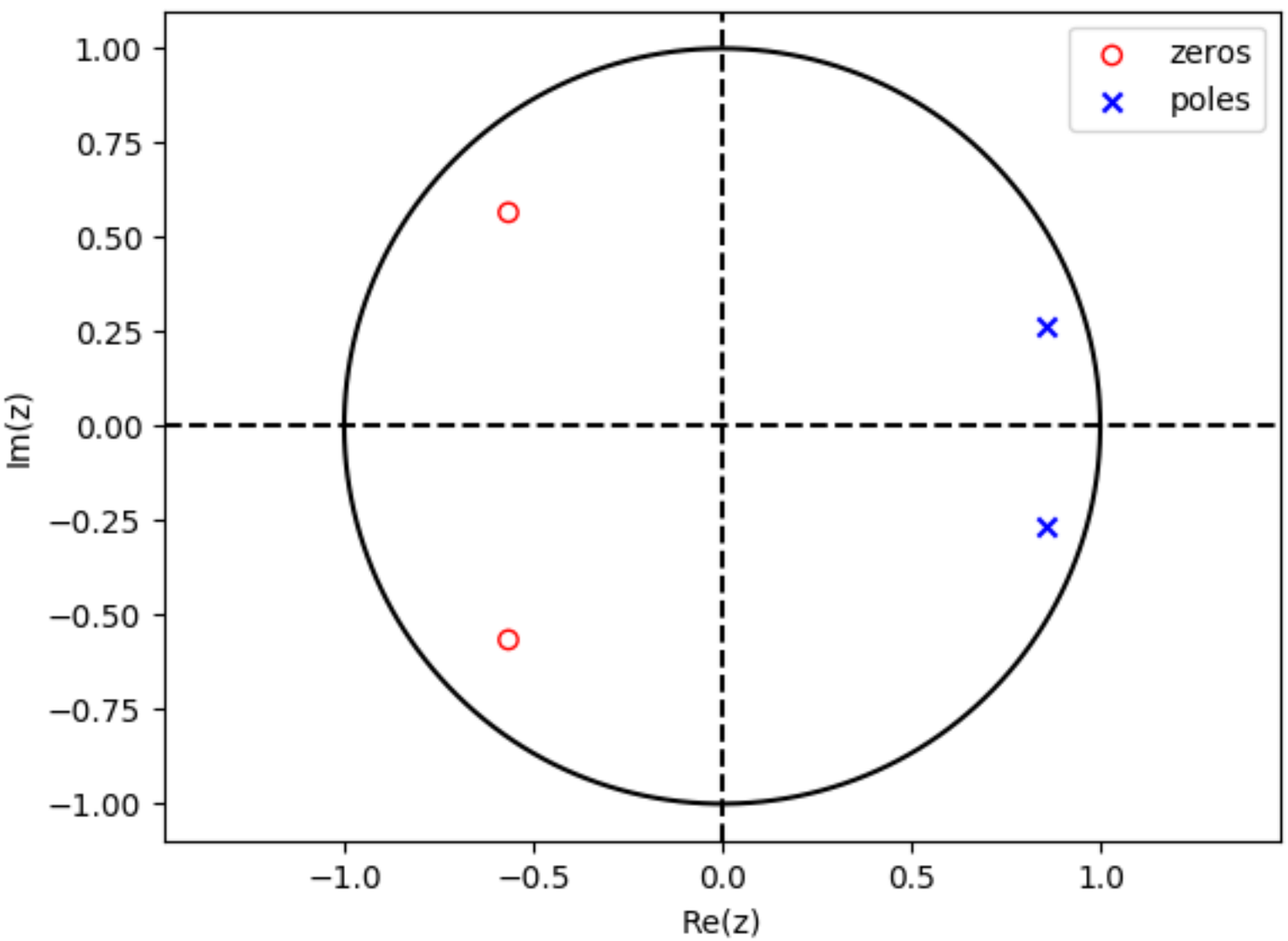


Delay



Modeling electronics signal

Parameterized as a digital filter in frequency space by a *pole-zero* representation

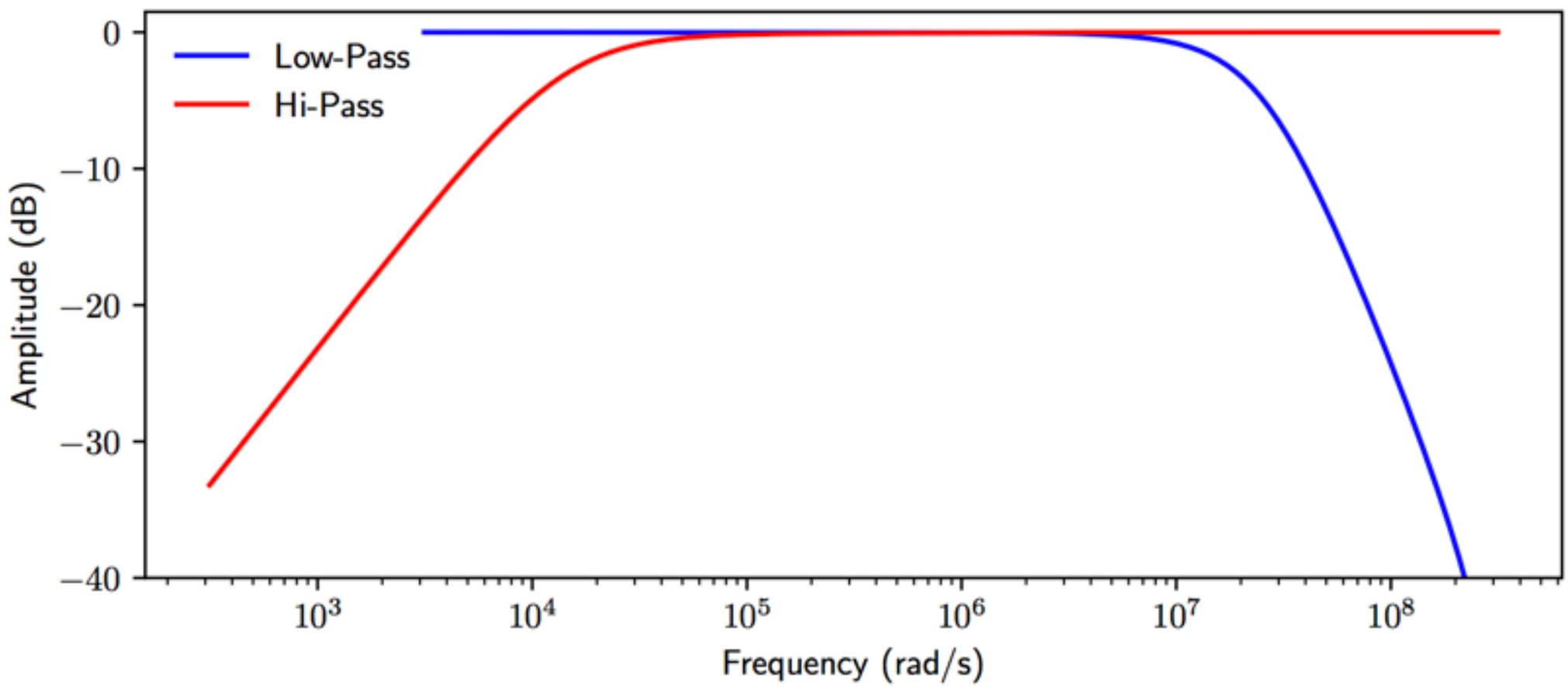


$$H(z) = \frac{(z-s)(z-s^\dagger)}{(z-p)(z-p^\dagger)}$$

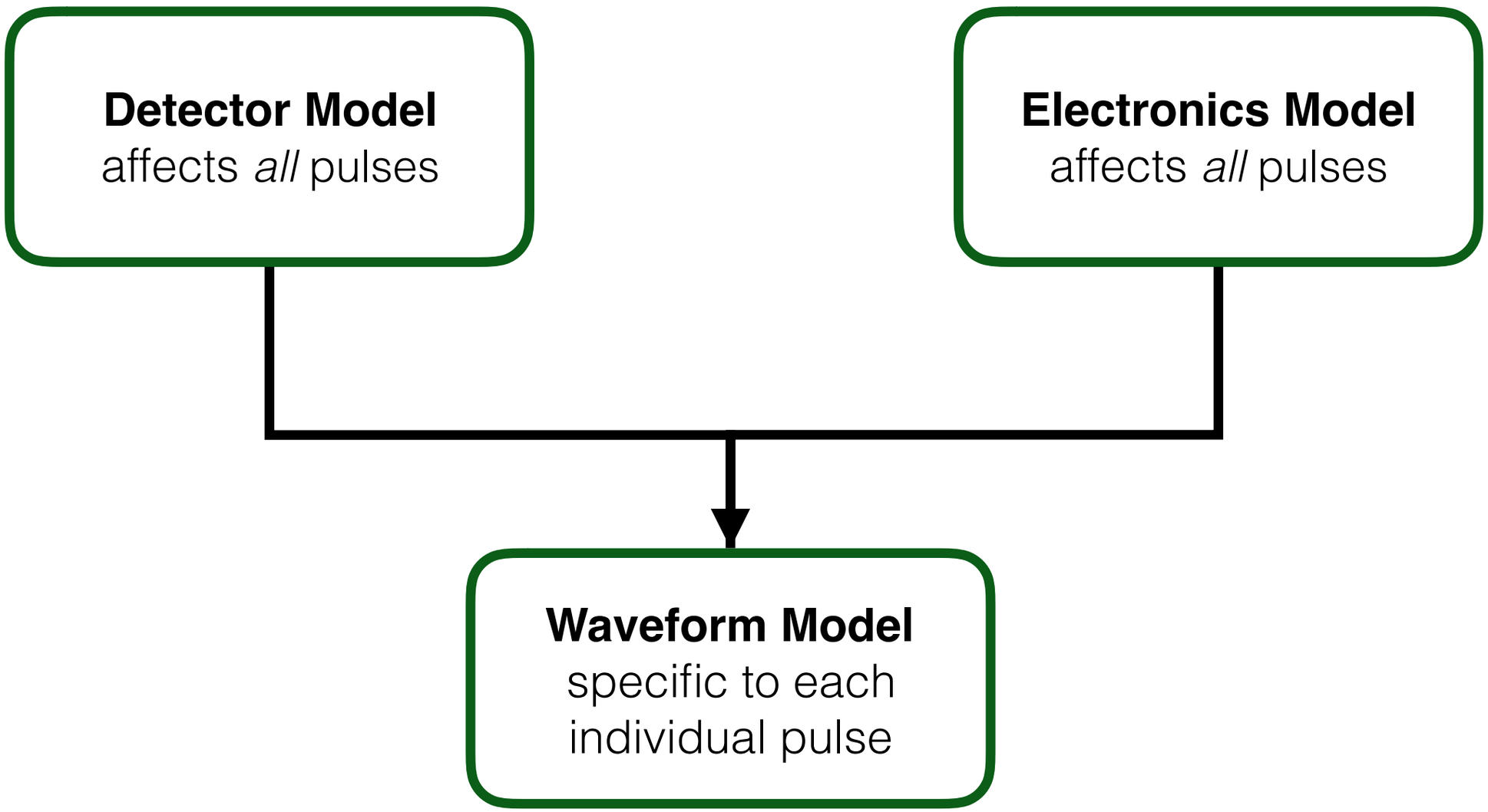
Modeling electronics signal

For MJD signals, we use two cascaded filters

Lowpass~ hi-frequency attenuation from preamp
Highpass~ RC-decay from capacitive couplings



Total Model Overview



Total Model Overview

Waveform	Detector	Electronics
Position (r,phi,z)	Hole Mobilities (x6)	Preamp response (x2)
Energy	Impurity Profile (x2)	RC Decay (x2)
Charge cloud size		
Waveform align time		
Total: 6 params	**8 params**	**6 params**

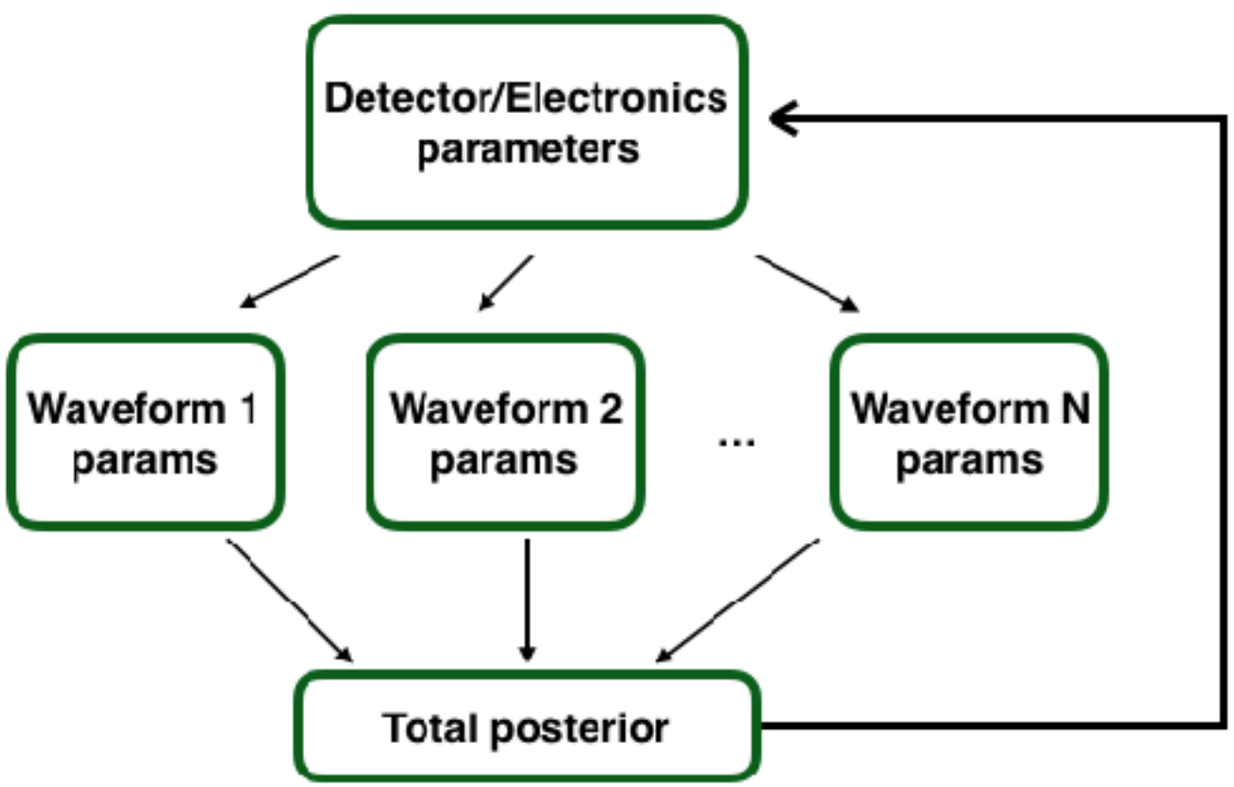
Assumptions
Detector geometry
Operating voltage
Axial-only, linear impurity gradient
Spherical Gaussian charge cloud
Flat baseline, pre-removed
Electron mobility

Uncertainties in each of the input parameters: how to optimize?

Learning from Waveforms

Question: can we use the waveforms we measure to optimize the parameters?

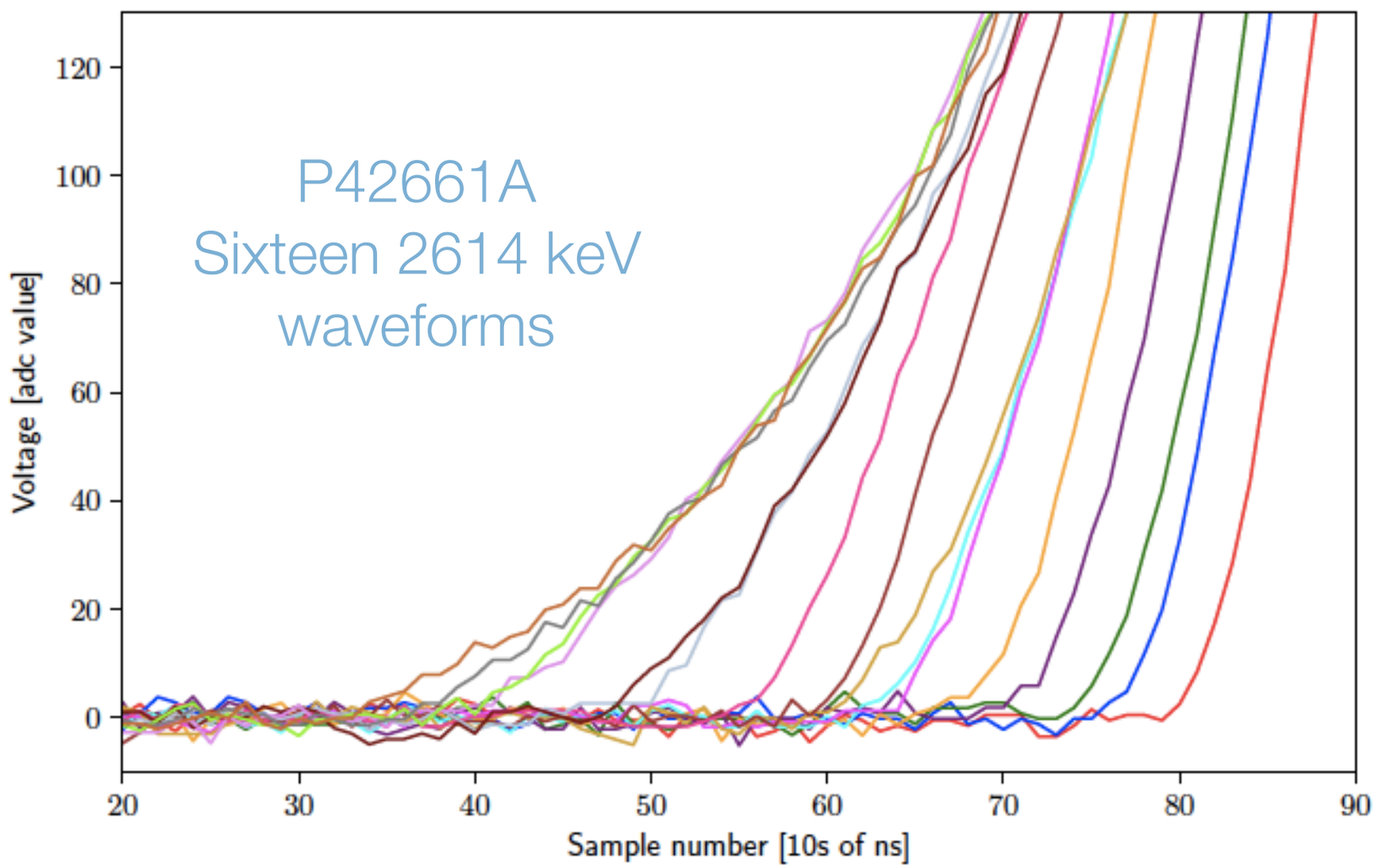
Technique: Fit a set of “training” waveforms, in a way that pools information from each individual waveform to learn as much as possible about the detector



Bayesian Model

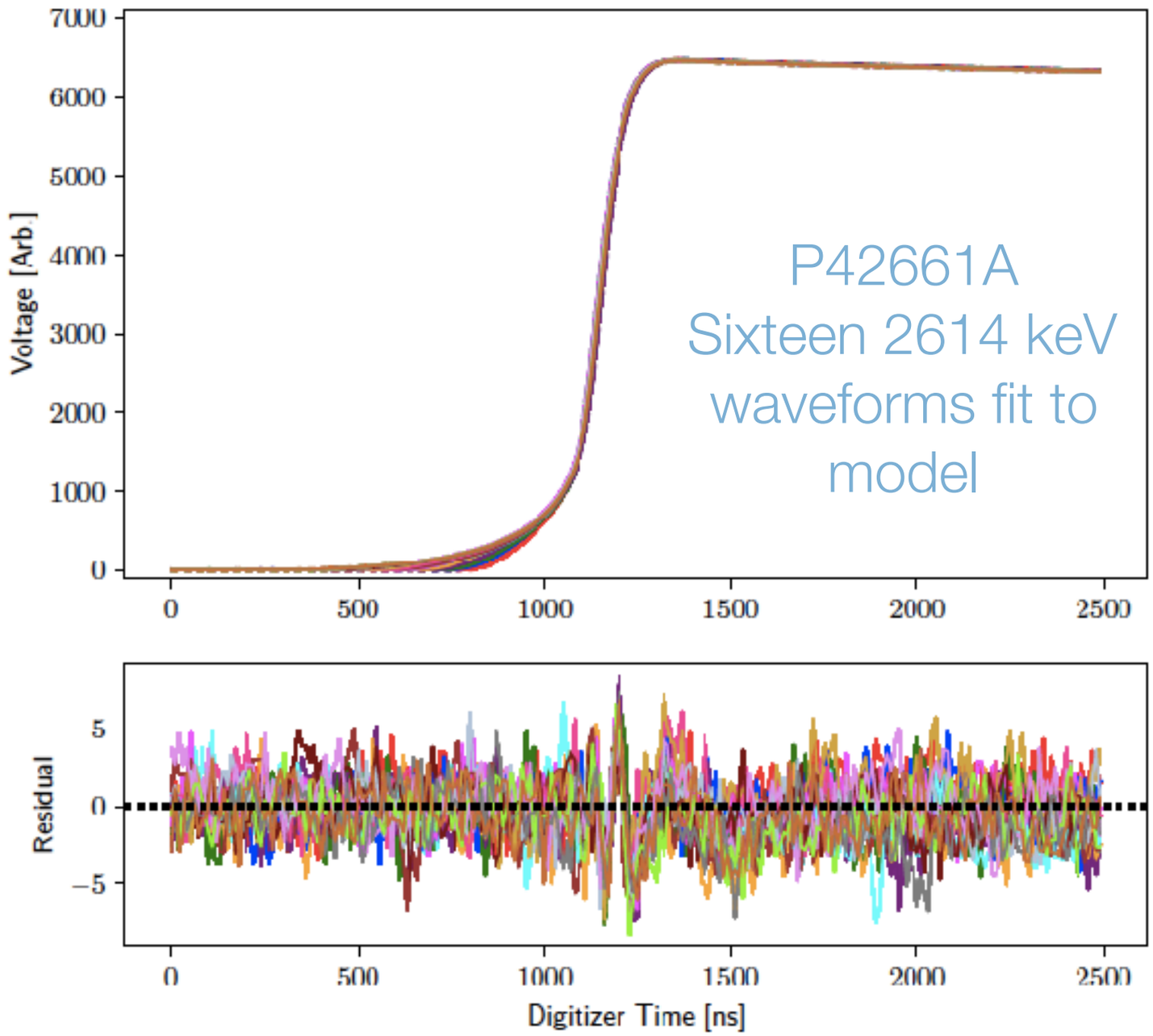
Fit done with MCMC
(Diffusive Nested Sampler)

Training Performance



Choose well-behaved waveforms with a variety of drift times to sample across the detector

Fit Performance

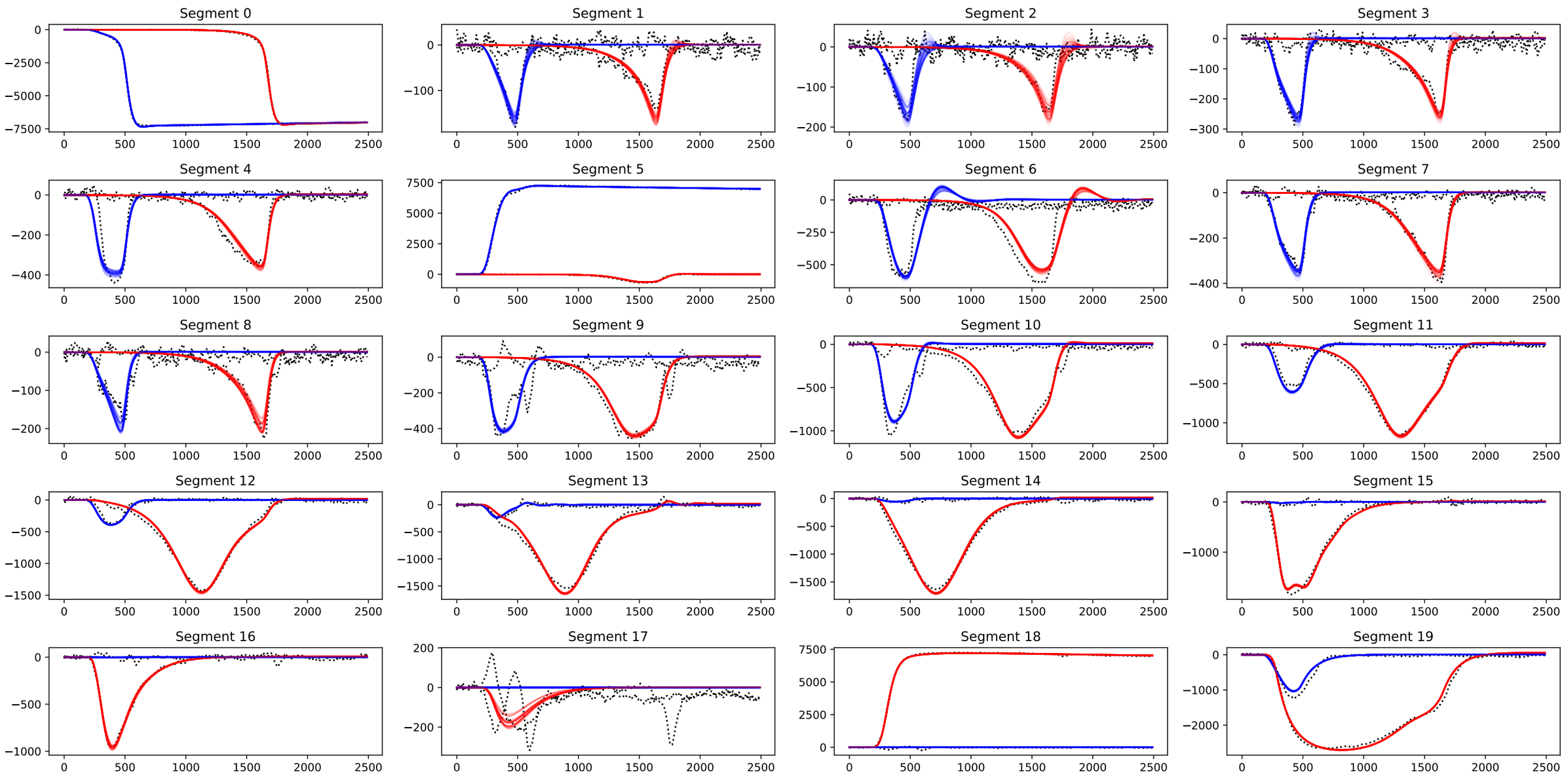


Residuals from across the detector are ~ part per thousand

(But the coherent residual structure indicates model can be improved)

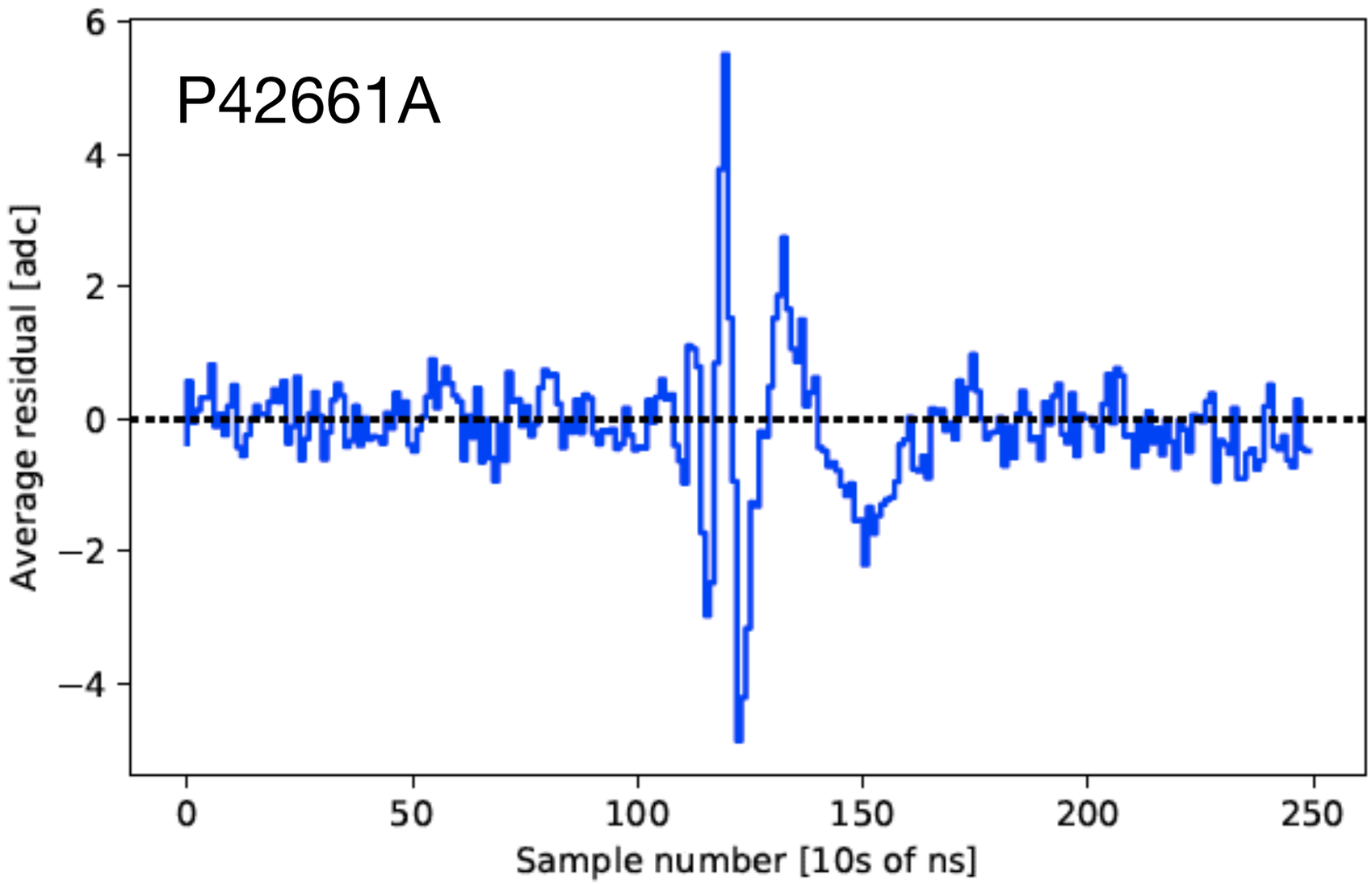
Segmented Detectors

n-type inverted coaxial point contact detector



Backup

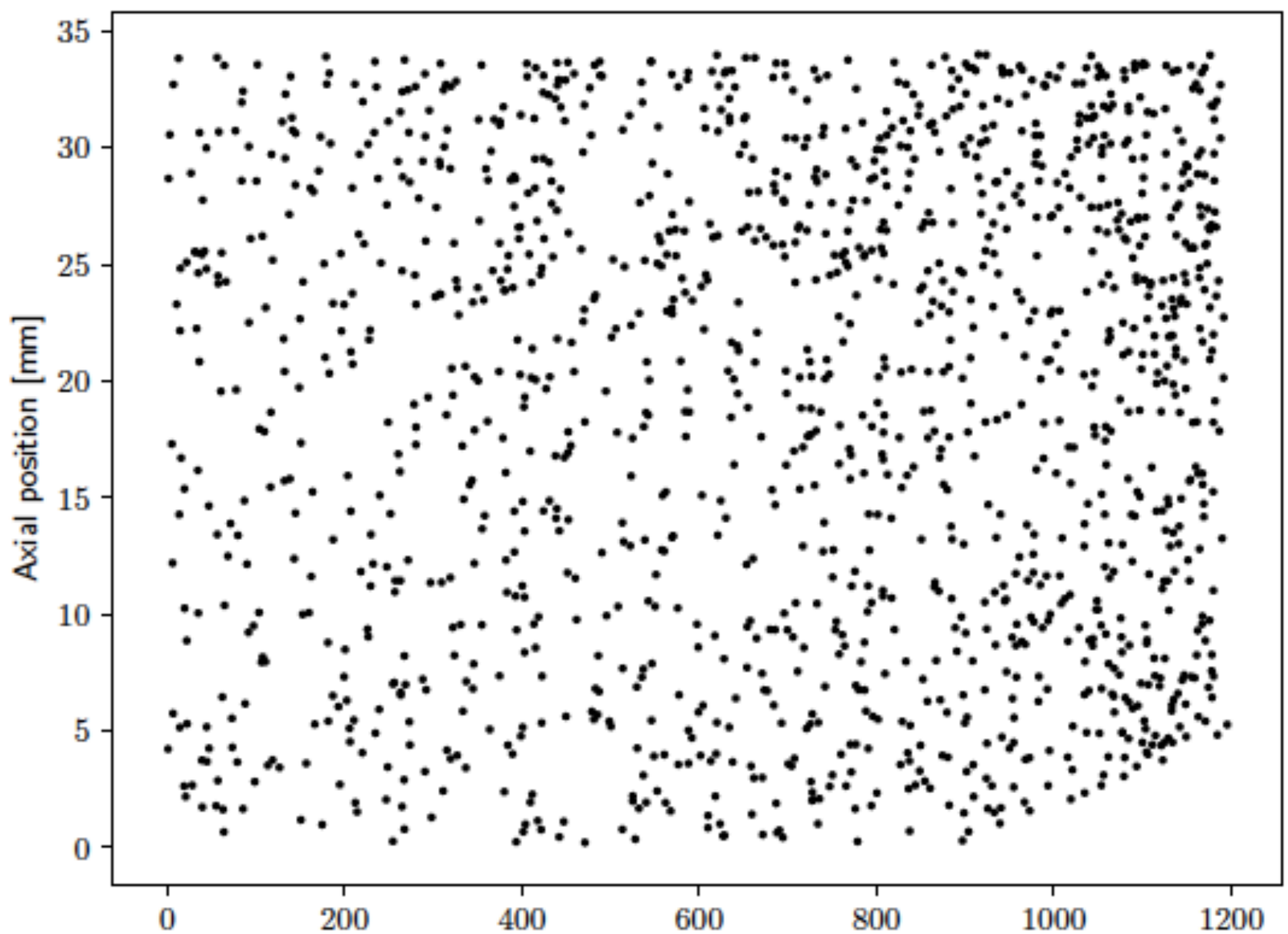
Mean of Residuals



“The wiggle” — Fast and slow components

Expected Position

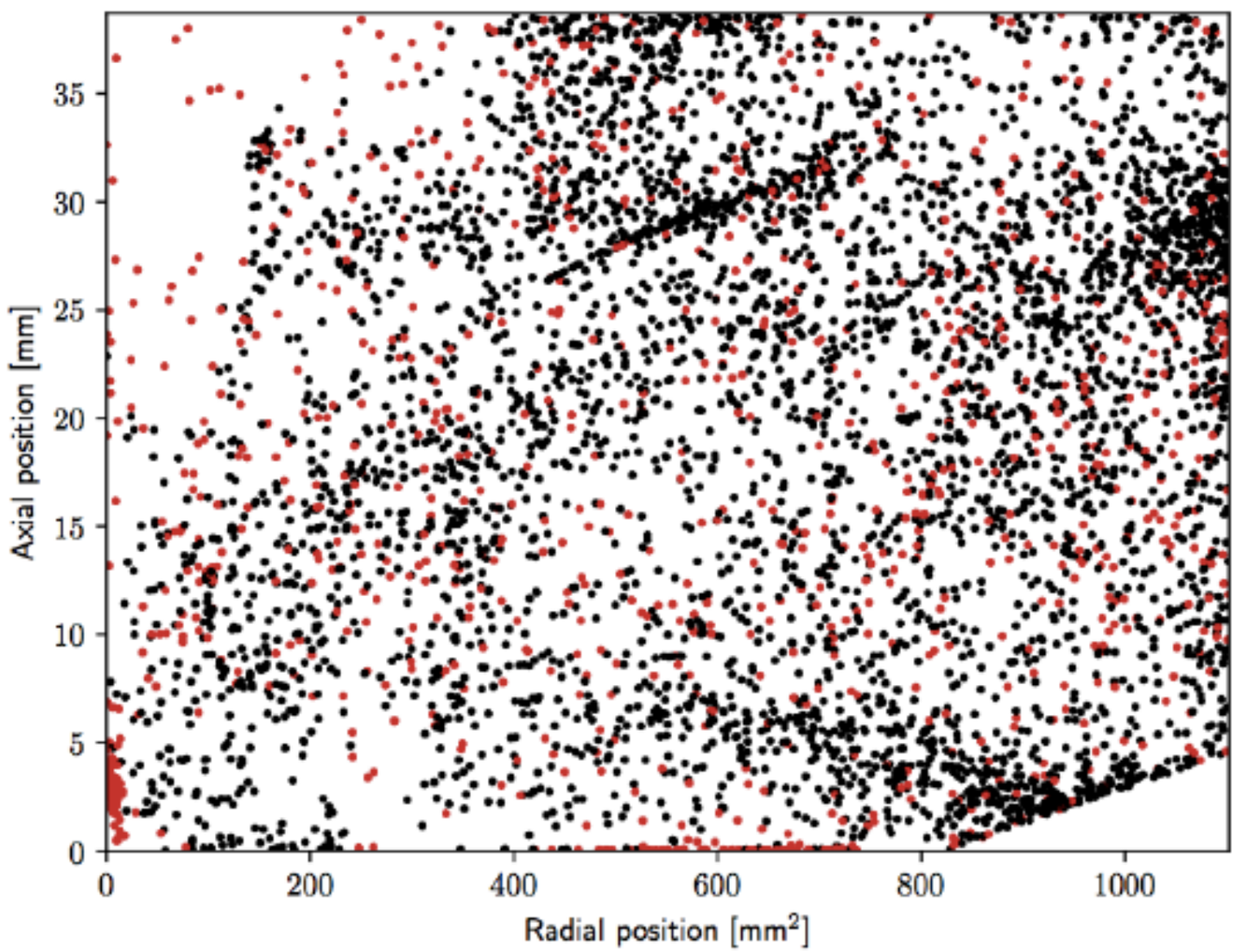
Simulation prediction of position of DEP Events



Estimating Position

Reconstructed position of DEP Events in P42575A

Able to sample the full detector fairly well

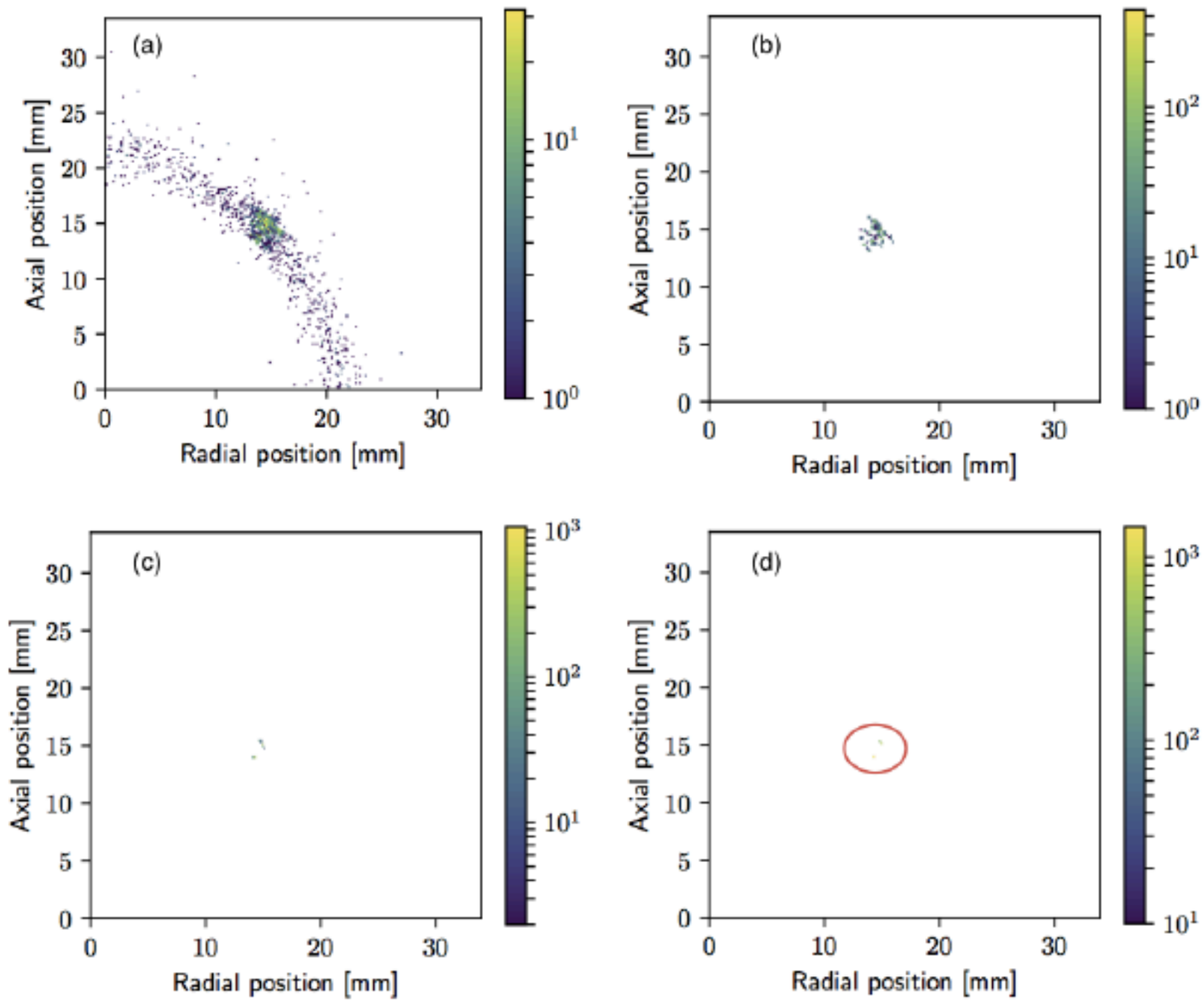


Pass cut

Fail cut

Estimating Position

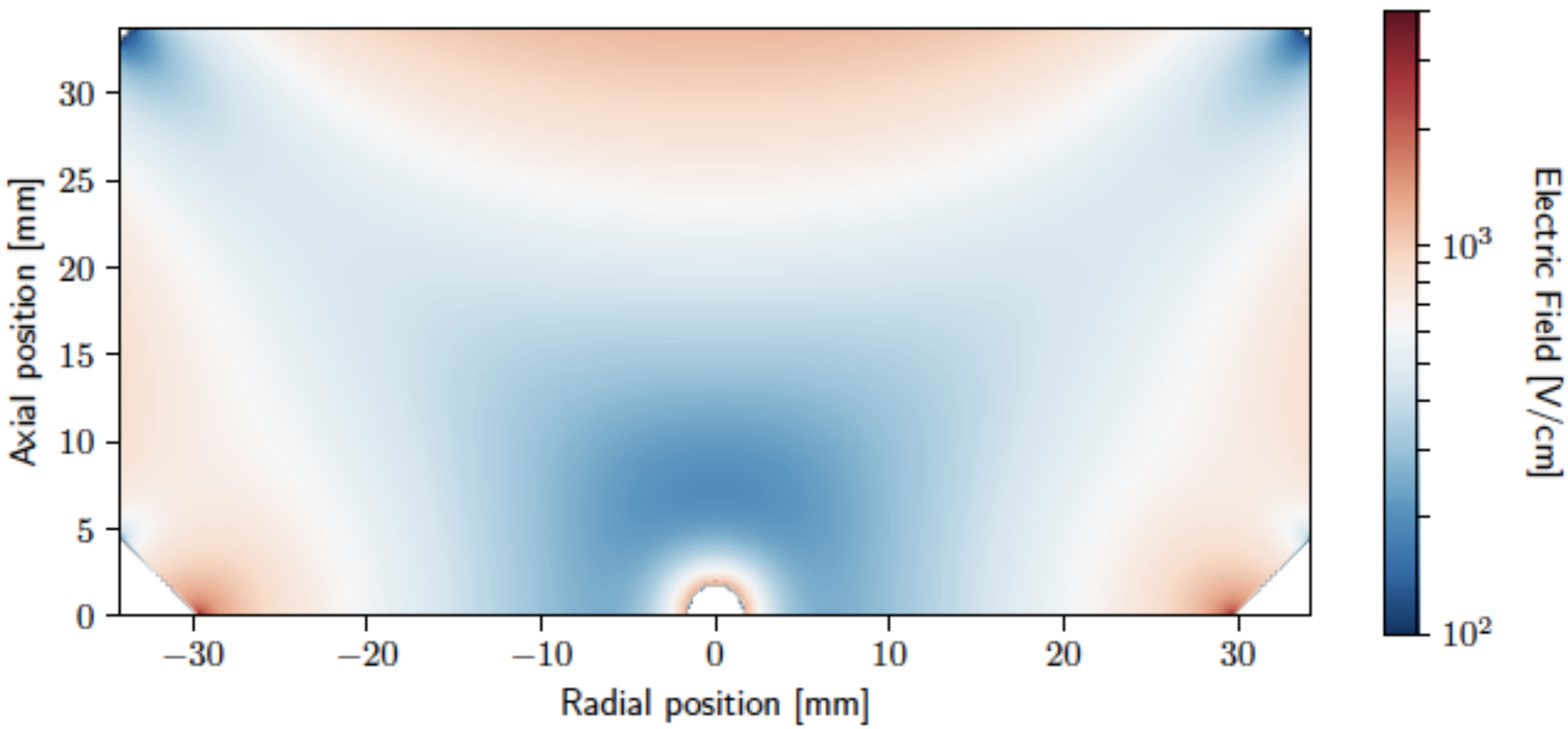
Our ultimate ability to estimate position is limited by model



The chain was run for 680,000 saved steps. Each plot shows a histogram of chain values for position over a different slice of the iteration number:
(a) steps 1,000 - 7,700;
(b) 7,700 - 14,400;
(c) 14,400 - 21,100;
(d) 21,100 - 27,800.

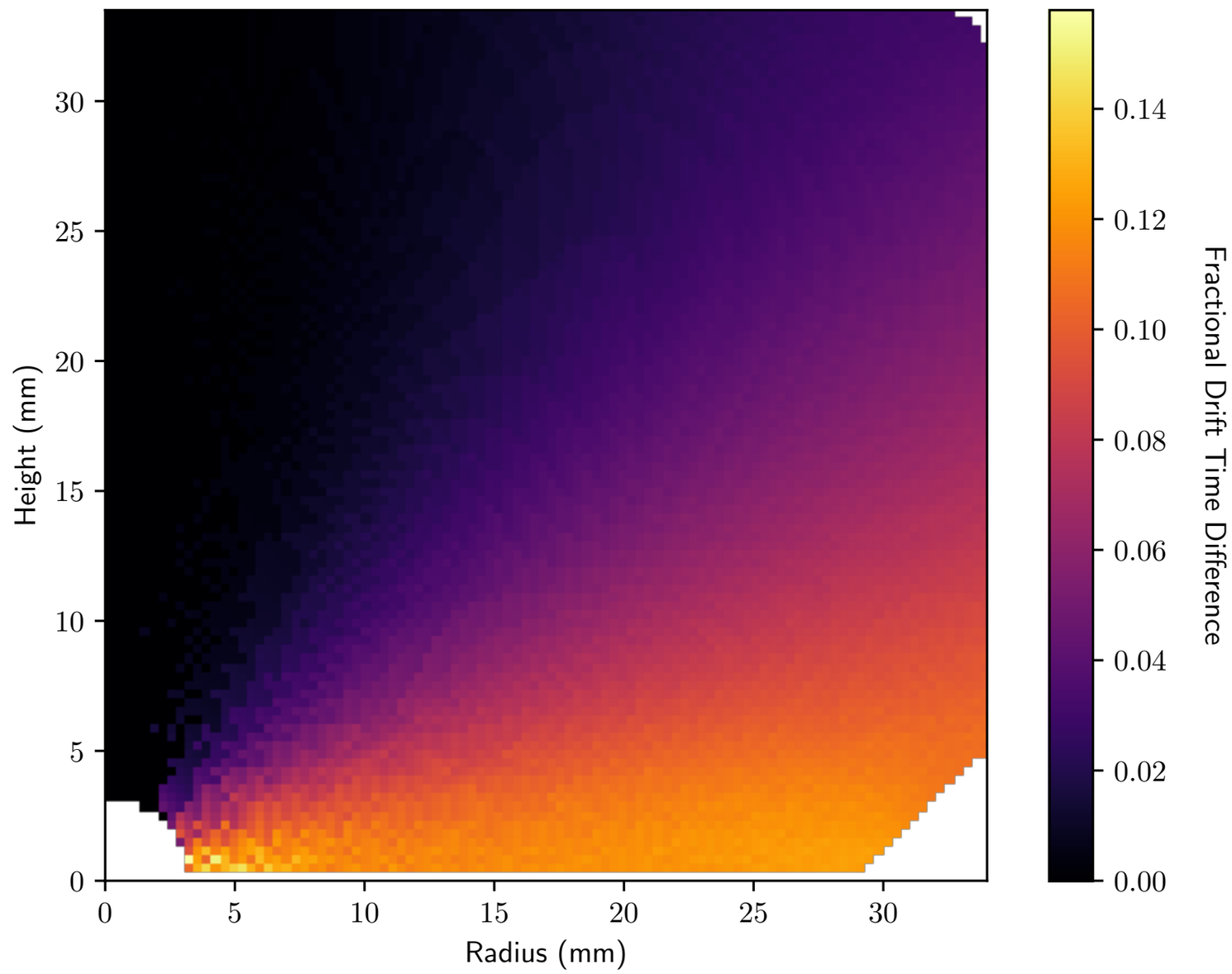
Electric Field

E-field in DEMONSTRATOR enriched detector



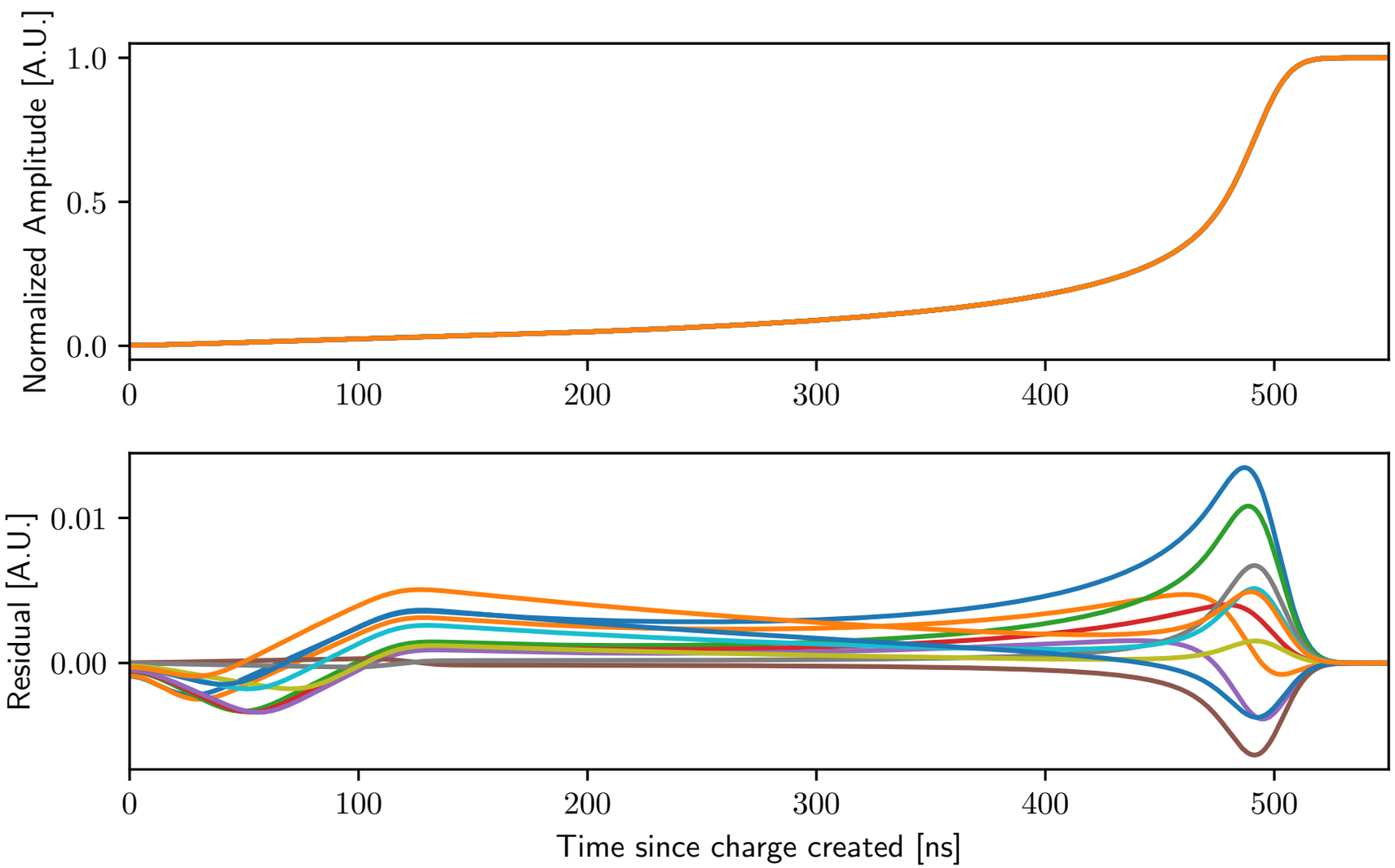
Azimuthal Sensitivity

Difference in rise time between <100> and <110> as a function of position



Position Sensitivity

Difference in waveforms between events on the 500 ns isochrone: part per hundred (all on <100> axis)



Notes on digital filters

Order of filter given by number of zeros and poles

- First order filter is purely real; second+ order is complex
- Every pole/zero must have a complex conjugate because the filter has to be symmetric about its nyquist frequency (top half of the unit circle represents frequencies up to the nyquist frequency, bottom half is frequencies from nyquist to sampling frequency)

Low -vs- hi-pass:

- Pure low-pass: zeros are at z=-1
- Pure hi-pass: zeros are at z=+1

Gain:

- Gain given by H(z) at z=1 (correponds to t->infinity)