end-to-end simulation of NCDs

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simulation overview: single unified application

event generators

- atmospheric neutrons
- AmBe calibration source

physics simulation

- pure geant4 simulation
- custom “standardNR” physics list for ion propagation (~10% agreement with SRIM)
- high-precision neutron physics

detector simulation

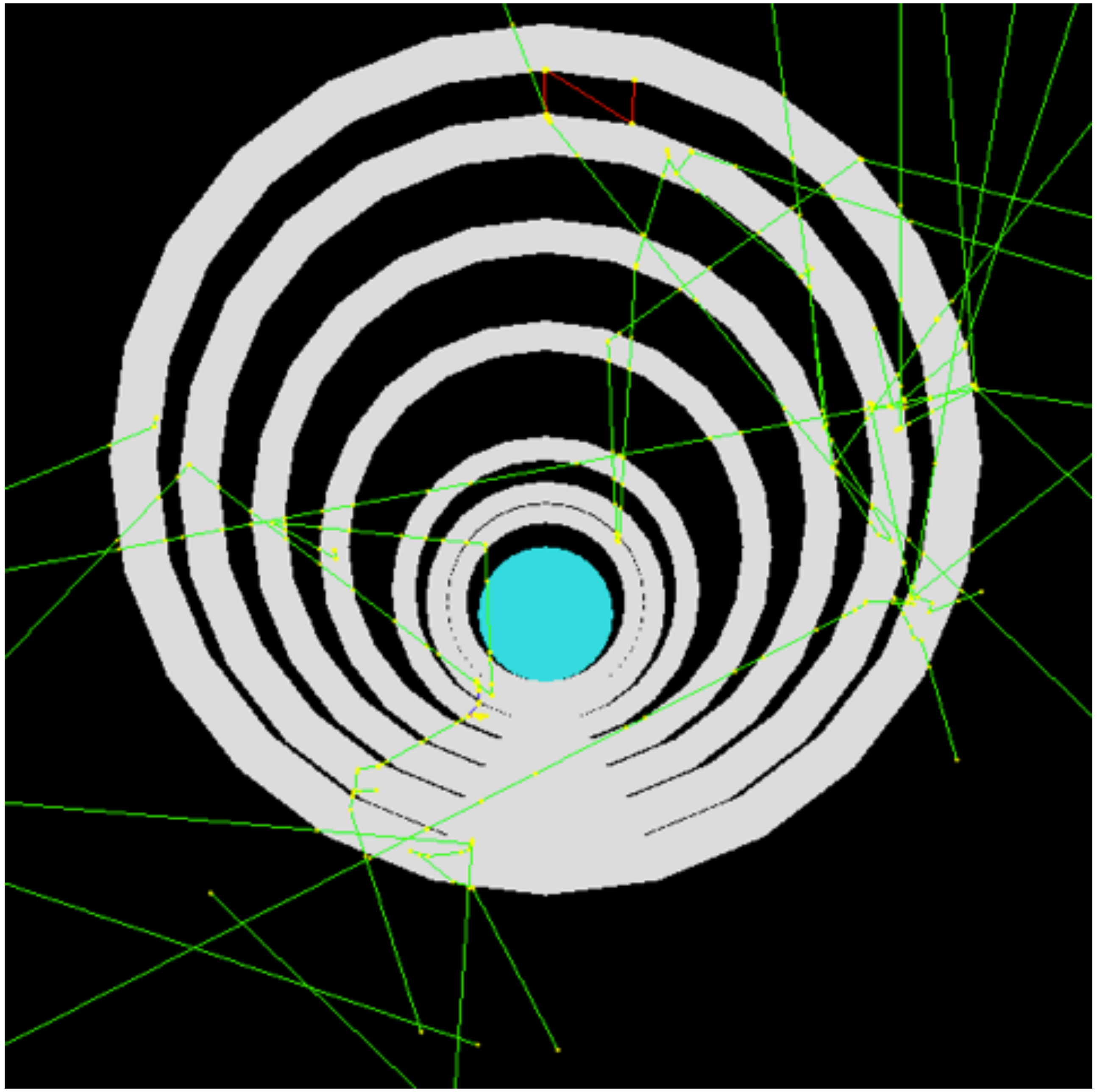
- reproduces work by SNO collaboration
- simple model of space charge effect
- simple diffusion model
- simple electron avalanche model
- induced current and electronics simulation

analysis

- save truth and reconstructed info to tree
- save simulated traces

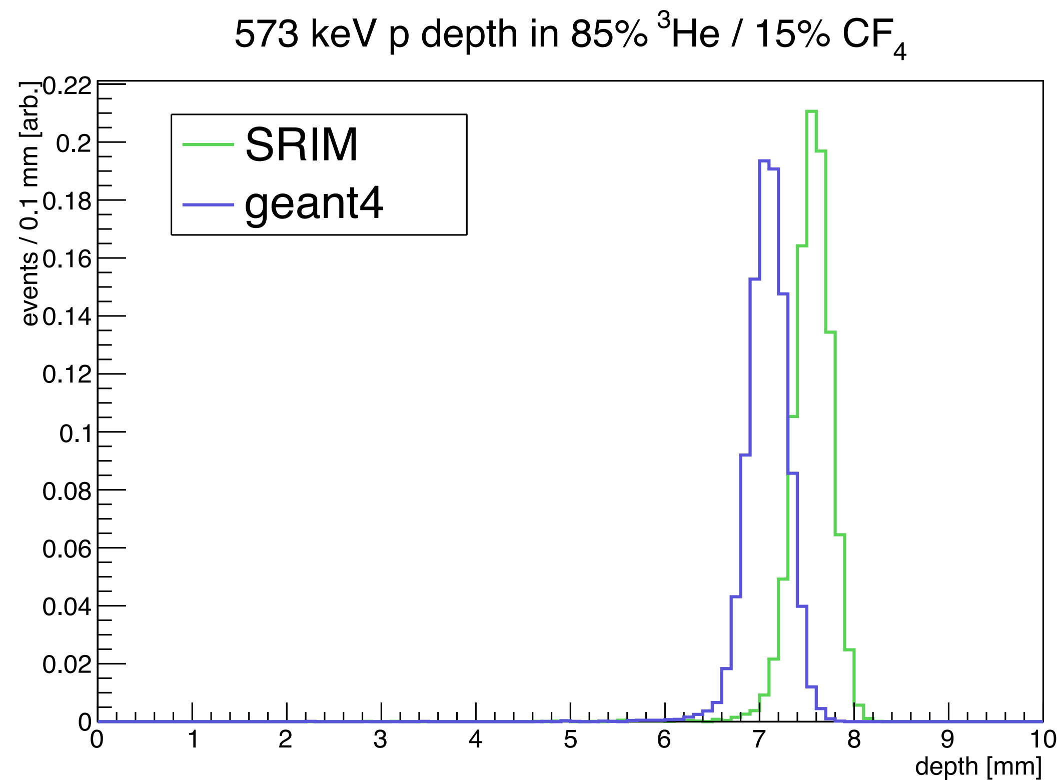
physics simulation

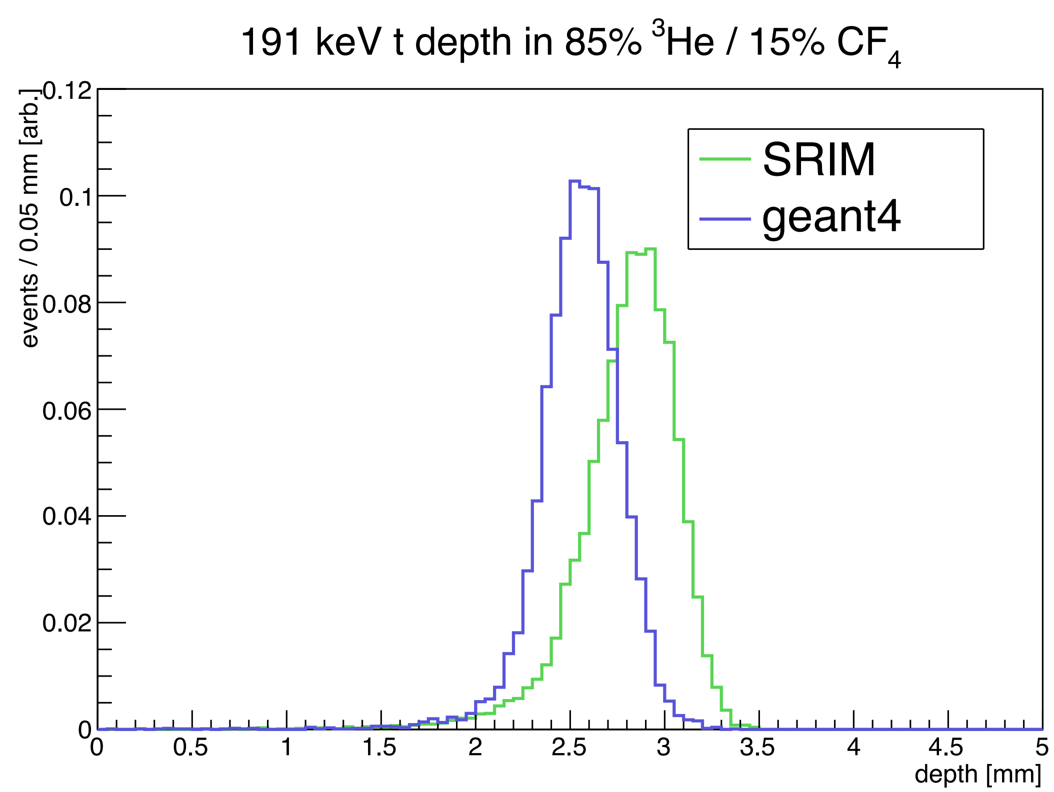
- Use geant4 to handle physics simulation up to proton-triton propagation
- Include realistic geometry, variable shielding layers, material properties
- SNO did not use geant4: using it massively simplifies the task of writing the simulation!



physics simulation: hacking geant4 for ions

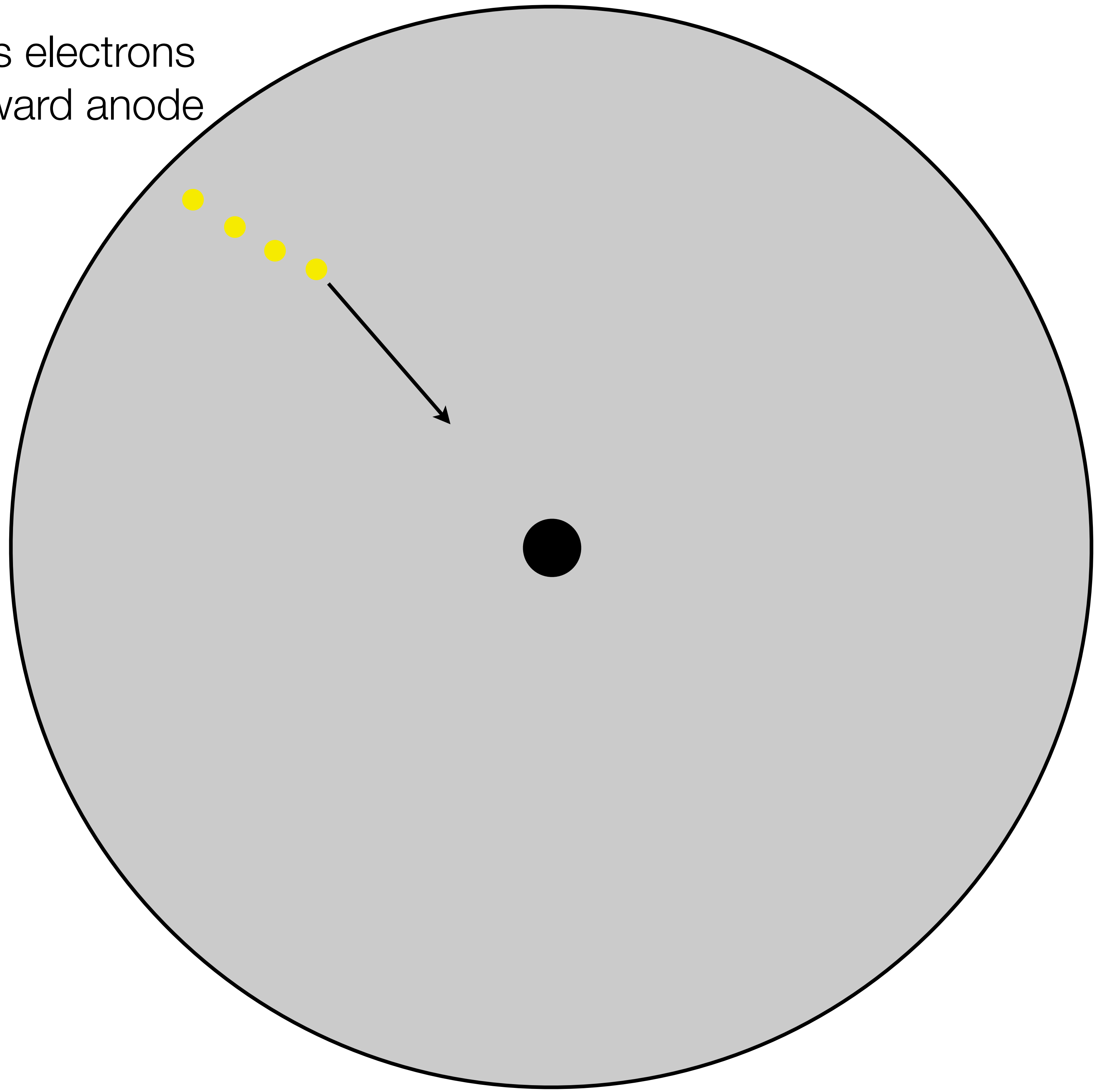
- geant4 does not model ion propagation well in reference physics models
- solve problem with custom physics model for screened Coulomb scattering (arXiv:physics/0406066)
- model benchmarks show excellent agreement with SRIM
- our work shows fair ~5-10% agreement with SRIM





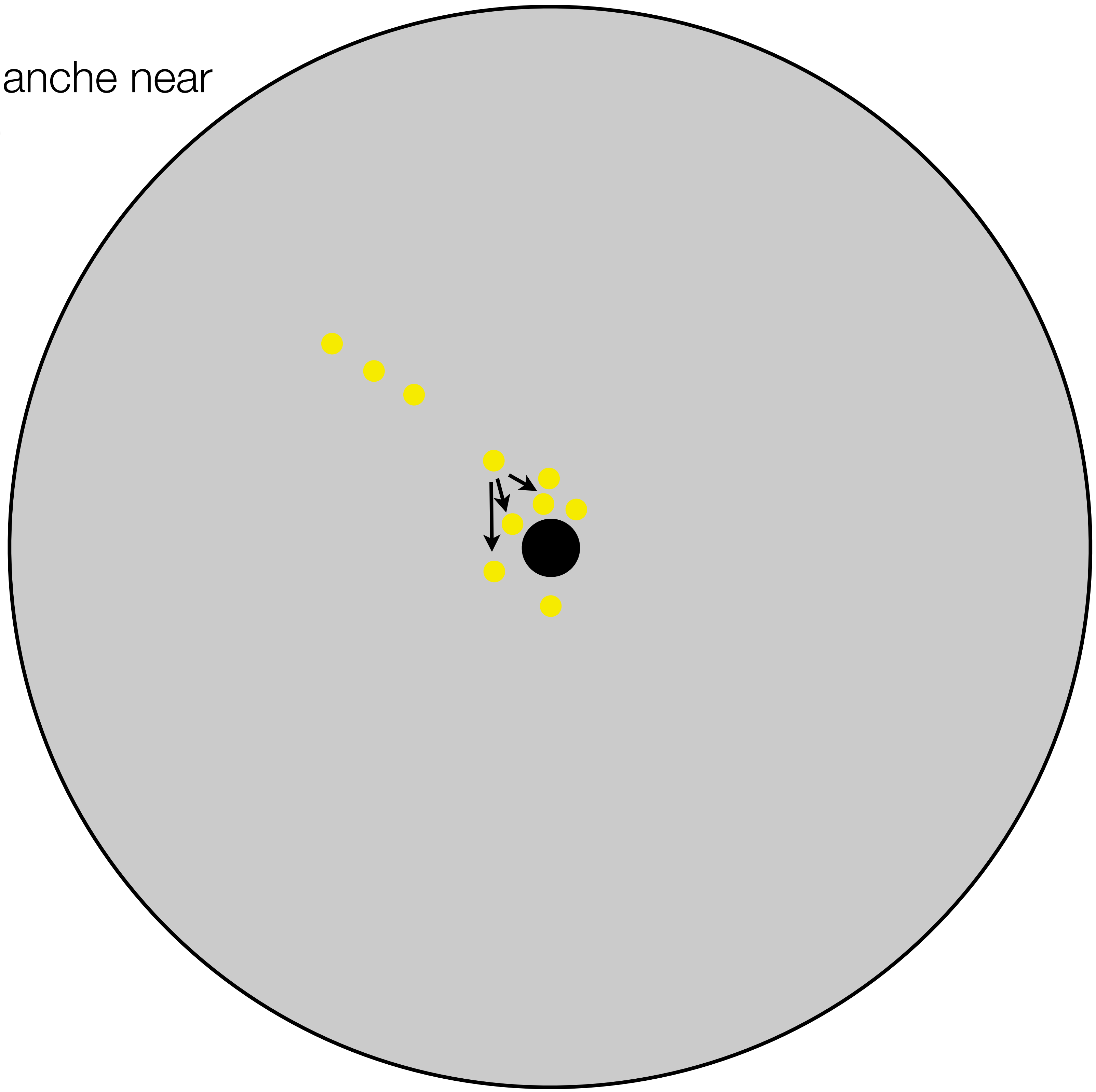
charge propagation overview

p-t track produces electrons
that propagate toward anode



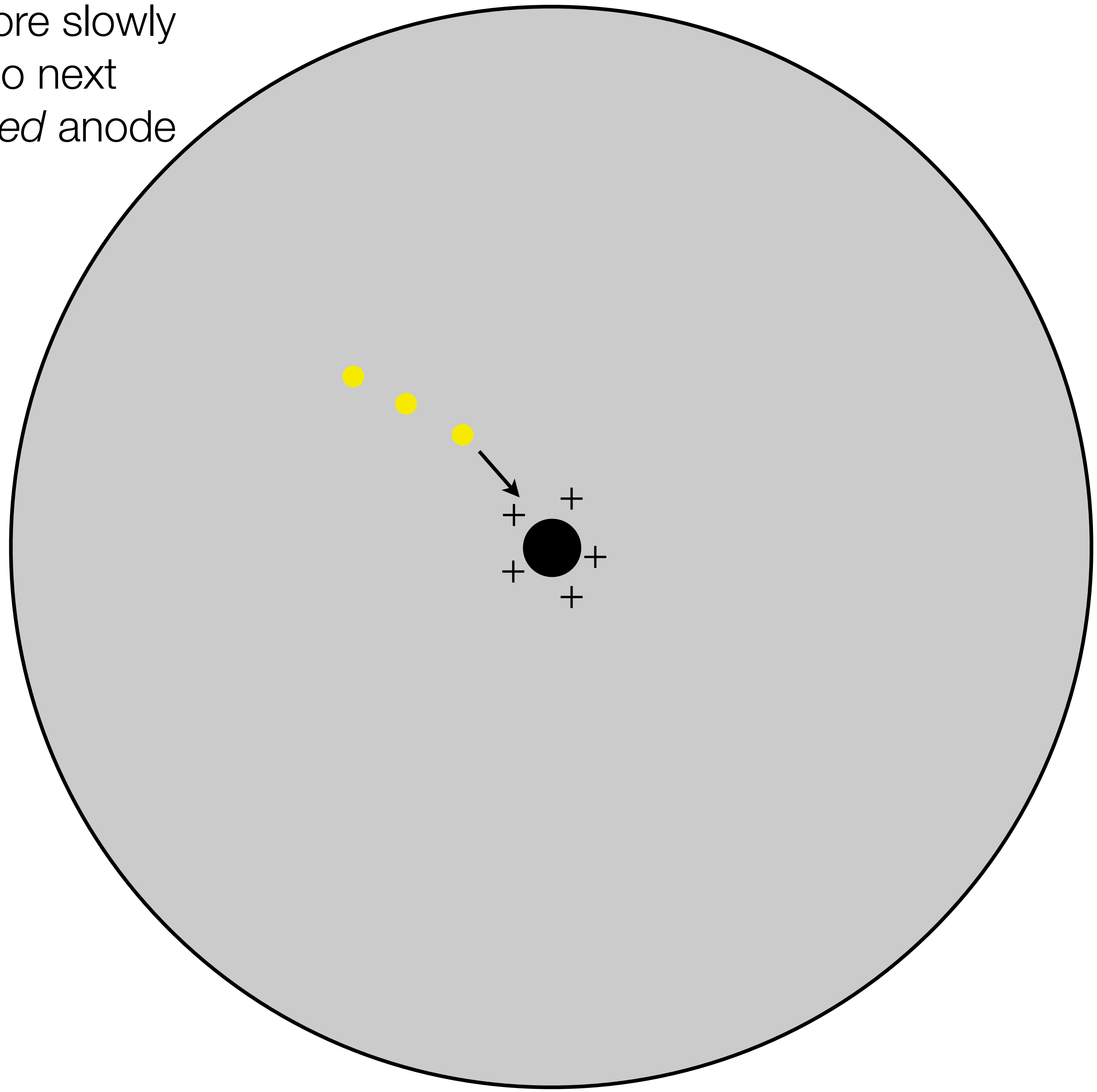
charge propagation overview

multiplication avalanche near anode



charge propagation overview

ions move much more slowly than electrons, so next charges see *screened* anode



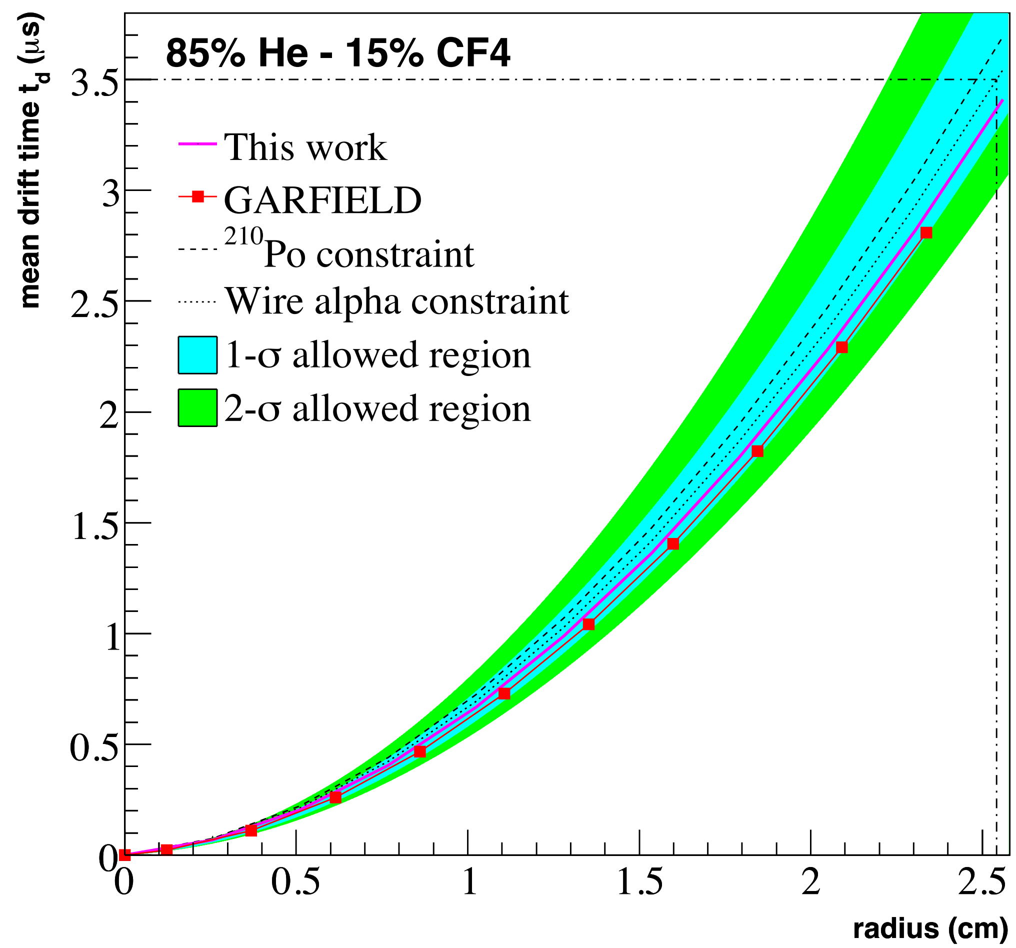
detector simulation: charge propagation

- simulation rewritten from SNO work (arXiv:1104.2573)
- simple functional form model for drift time and diffusion
- exponential model for single-electron gain:

$$P(G_i) = \frac{1}{220} e^{-G_i/220}$$

- gain well-modeled by standard Diethorn formula

$$\ln\bar{G} = C\frac{\lambda \ln 2}{2\pi\epsilon_0 \Delta V}\ \ln\left[\frac{\lambda}{2\pi\epsilon_0 a\, E_{min}}\right]$$



detector simulation: space charge

- simulation rewritten from SNO work (arXiv:1104.2573)

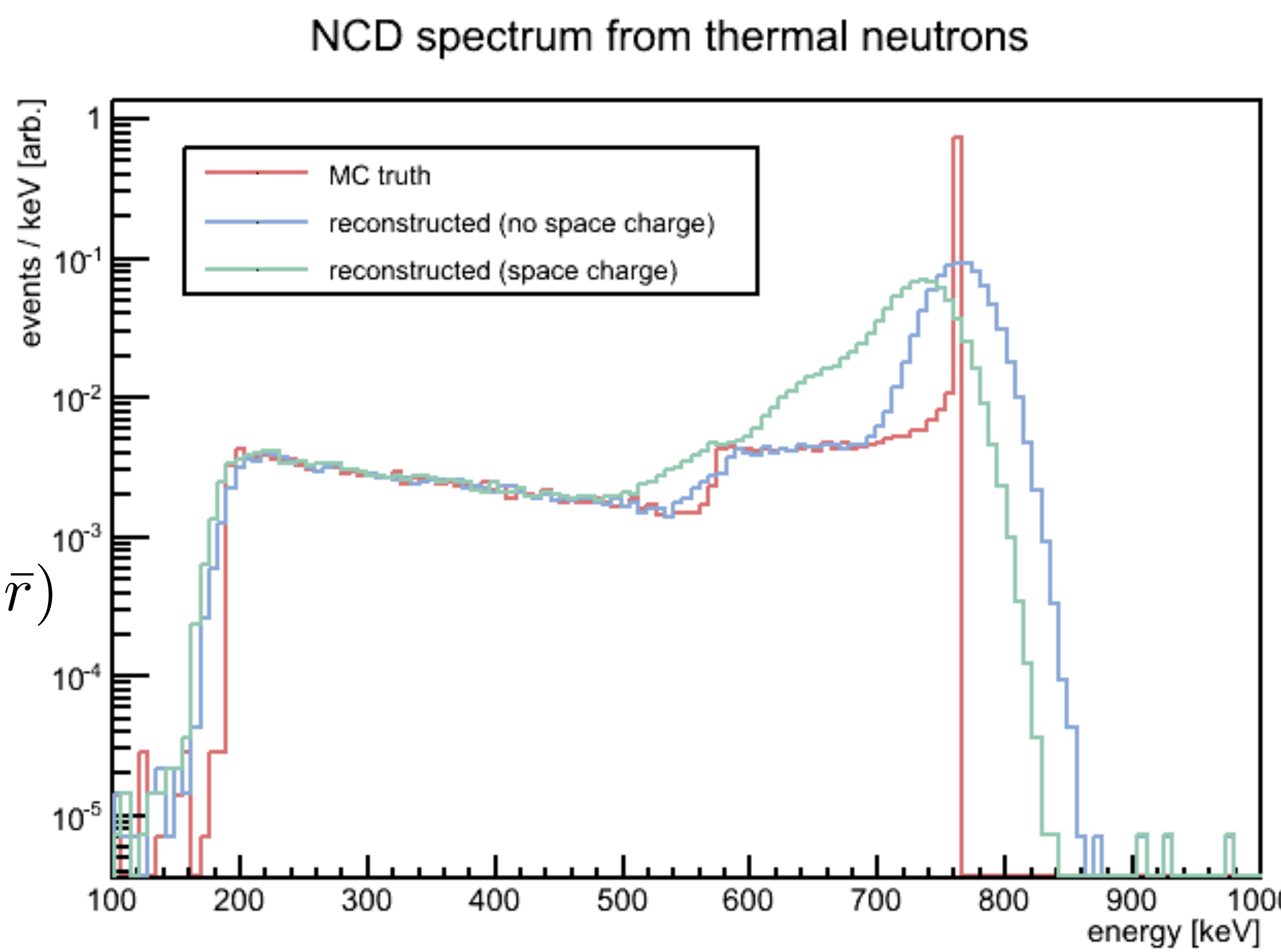
- idea: gain for *i*th electron obtained from Diethorn correcting for induced charge due to ions from electrons < *i*

$$\delta G \propto \overline{G}\ln\overline{G}\frac{\ln(b/a)}{2\pi\epsilon_0 V}\left(1+\frac{1}{\ln(r_{\mathrm{av}}/a)}\right)\delta\lambda(\bar{r})$$

$$\delta\lambda(r) = \frac{q}{\mathcal{W}_s}\frac{\ln(b/\bar{r})}{\ln(b/a)}$$

shower width parameter

mean avalanche radius
~ 50 microns



current simulation systematics

- Induced charge on anode due to single ion:

$$\delta Q = q \frac{\ln(b/r)}{\ln(b/a)}$$

- Differentiate w.r.t time and use ion e.o.m to obtain induced current on anode:

$$\frac{dr}{dt} = \mu E(r) \qquad i(t) = \frac{-q}{2\ln(b/a)} \frac{1}{t - t_0 + \tau}$$

- Experimentally measured output is convolution of:

$$\mathcal{O}(t) = Q(t) * i(t) * h(t)$$

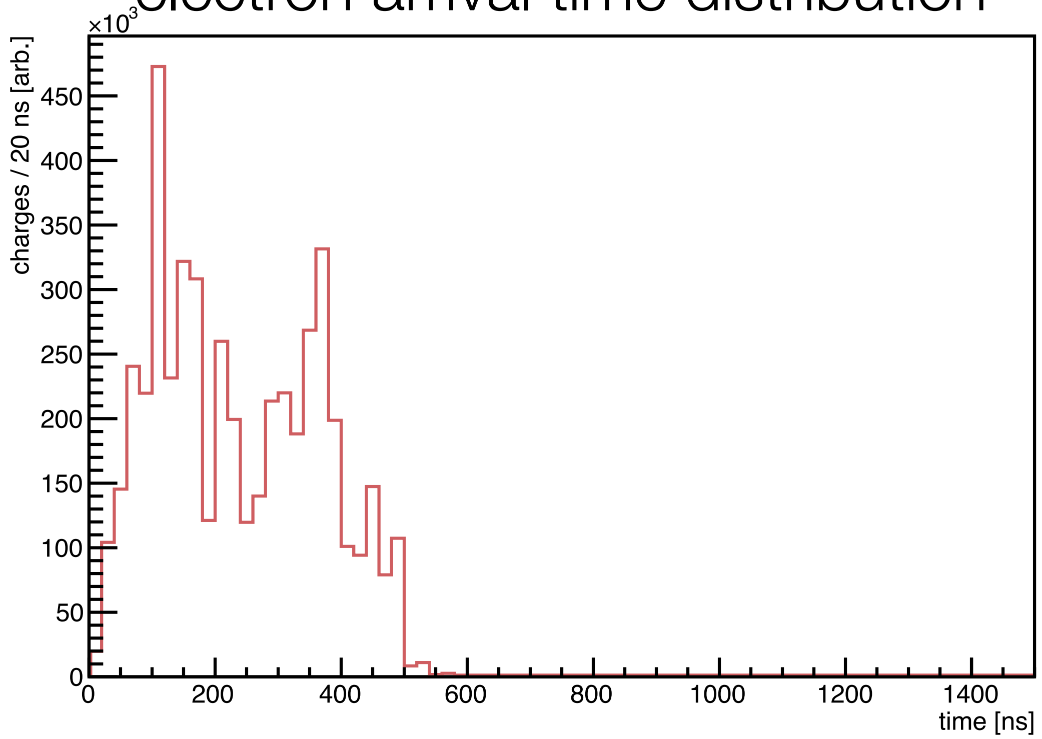
output voltage
electron arrival time distribution
current due to single ion
preamp transfer function

- Use steepest slope events to estimate this part of the transfer function:

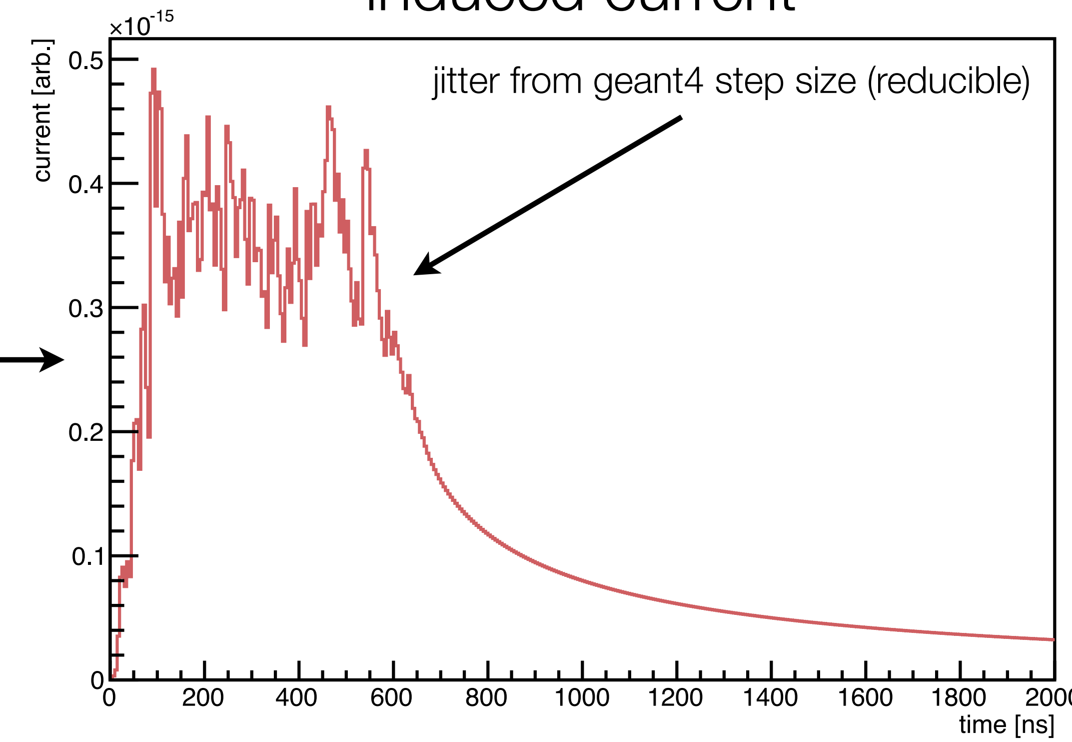
$$\begin{aligned} i(t) * h(t) * d(t) &\simeq i(t) * h(t) * \delta(t) \\ &= i(t) * h(t) \end{aligned}$$

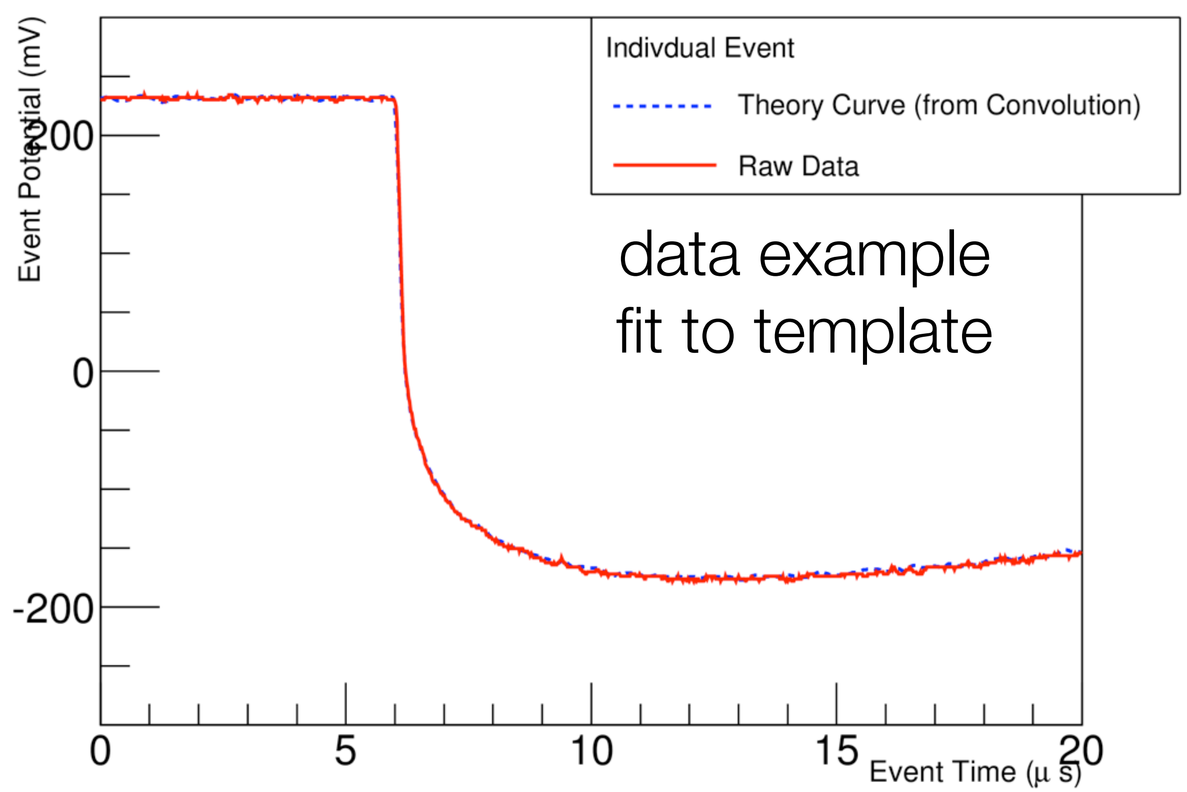
electronics simulation

electron arrival time distribution



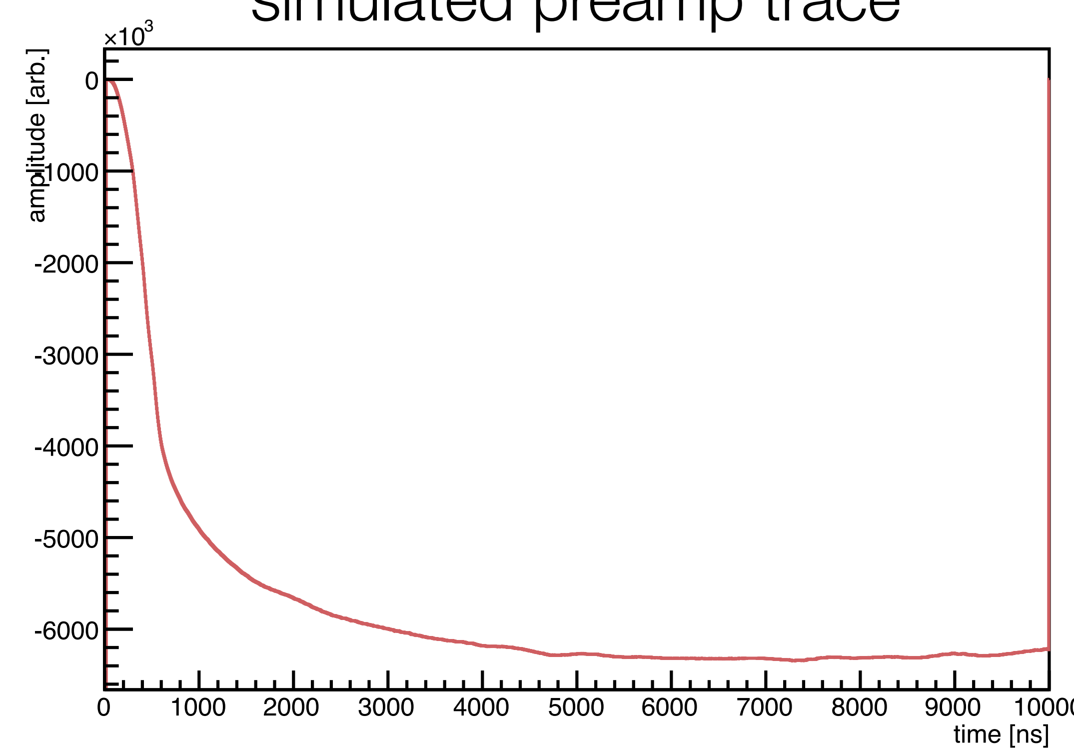
induced current



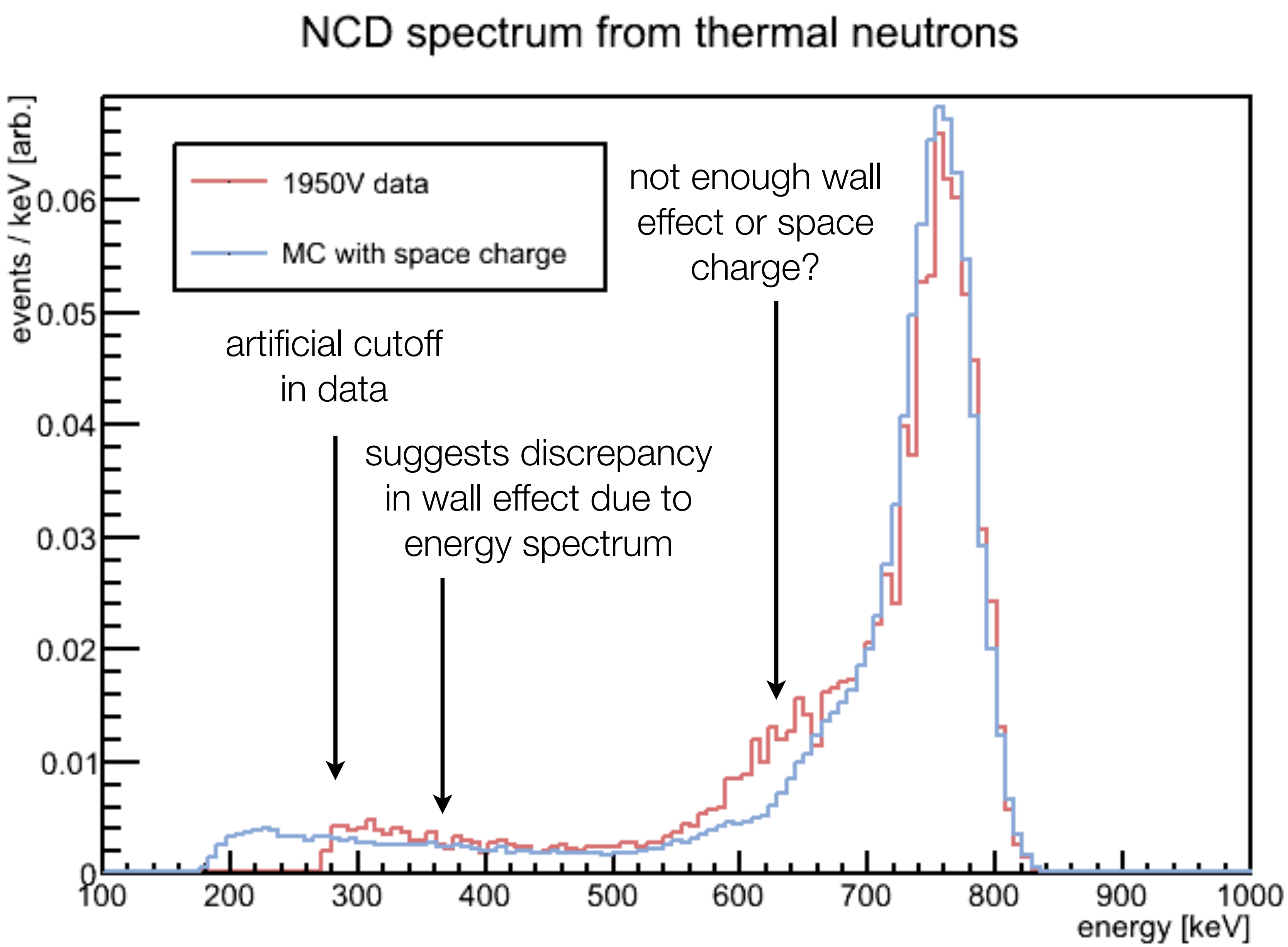


data example
fit to template

simulated preamp trace



validation: energy spectrum

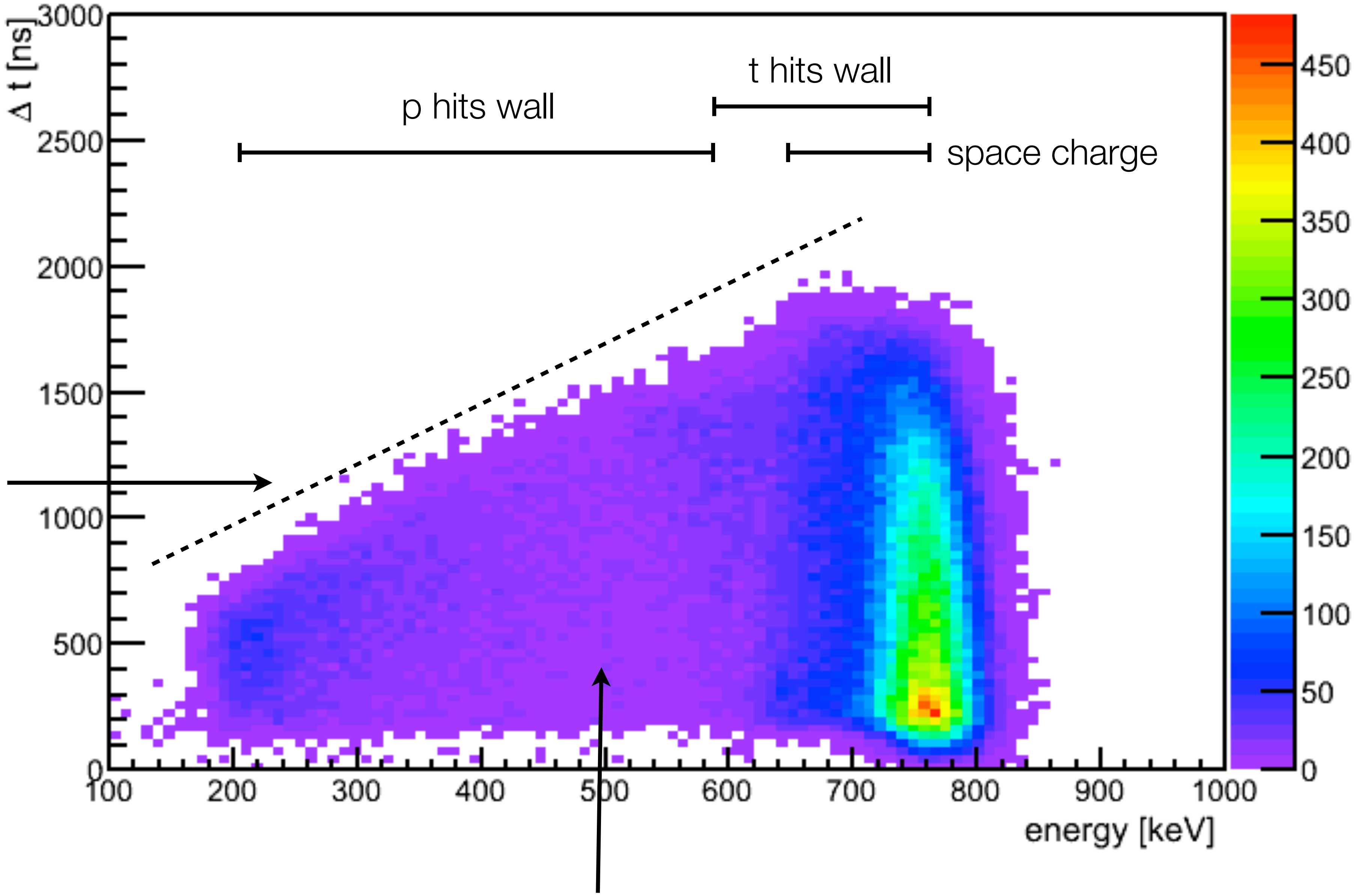


good general agreement remaining systematics likely due to poor modeling of atmospheric neutron flux

energy vs. duration of e arrival times

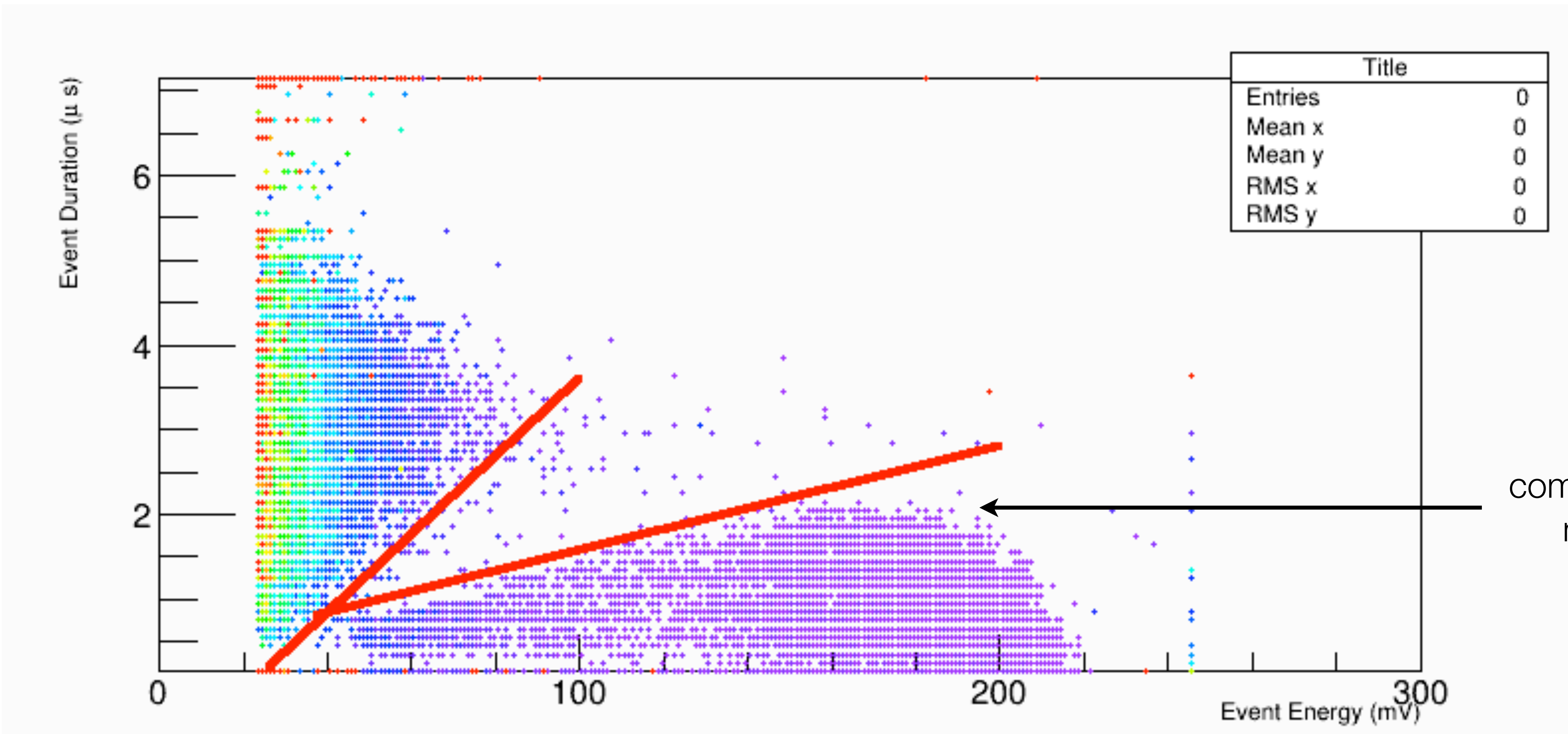
still sorting out timing bug in Geant4 kernel:
very small effect on these results

ER/NR cut is
~100% efficient



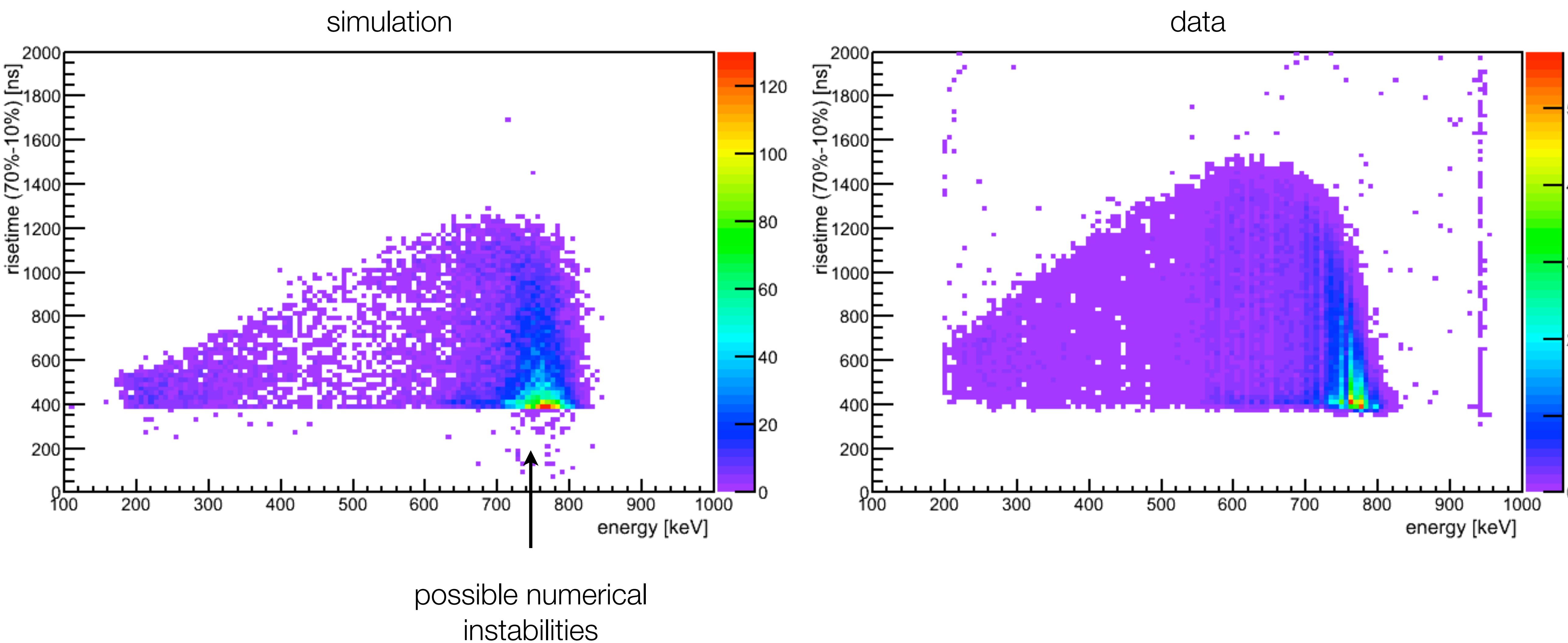
deficit due to p
Bragg peak

data comparison



comparable 2 us maximum

70%-10% risetime after pulse simulation



good qualitative agreement with data...

need to validate against data more quantitatively

conclusion

- Complete end-to-end simulation of NCDs implemented
- Integral part of analysis for generating transfer functions used in deconvolution
- Qualitative validation excellent
- More quantitative validation ongoing
- Built on the shoulders of SNO work, but encapsulation with geant4 allows simulation to be single compact application