LArTPC Signal Processing

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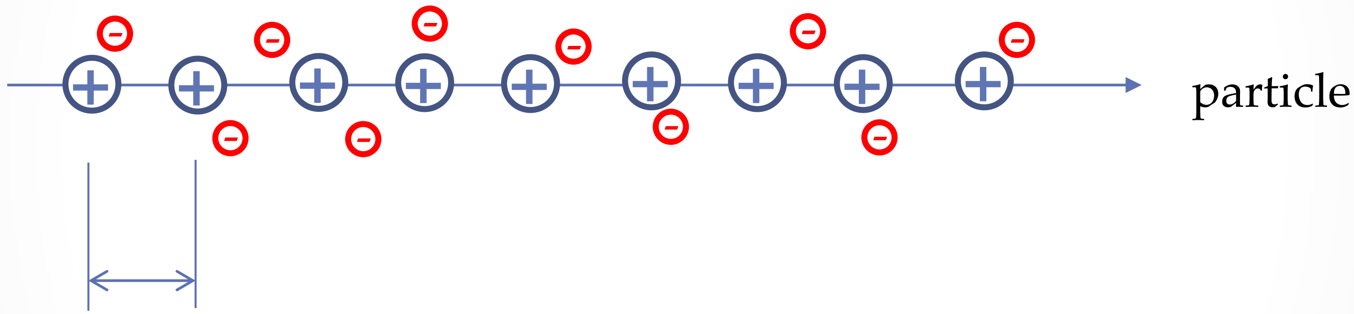
LArTPC R&D Workshop 2014

Outline

- Liquid state signal generation
  - Ionization
  - Thermalization
  - Recombination
  - Electron attachment & diffusion
- Signal generation in wire planes
  - Field response
  - Electronics response
- Convolution and deconvolution
- Closing comments

Ionization Nano-Physics in LAr

$r_{ion\text{-}electron}$ ~ 0.5 nm with $E_{electron}$ ~ 5 eV

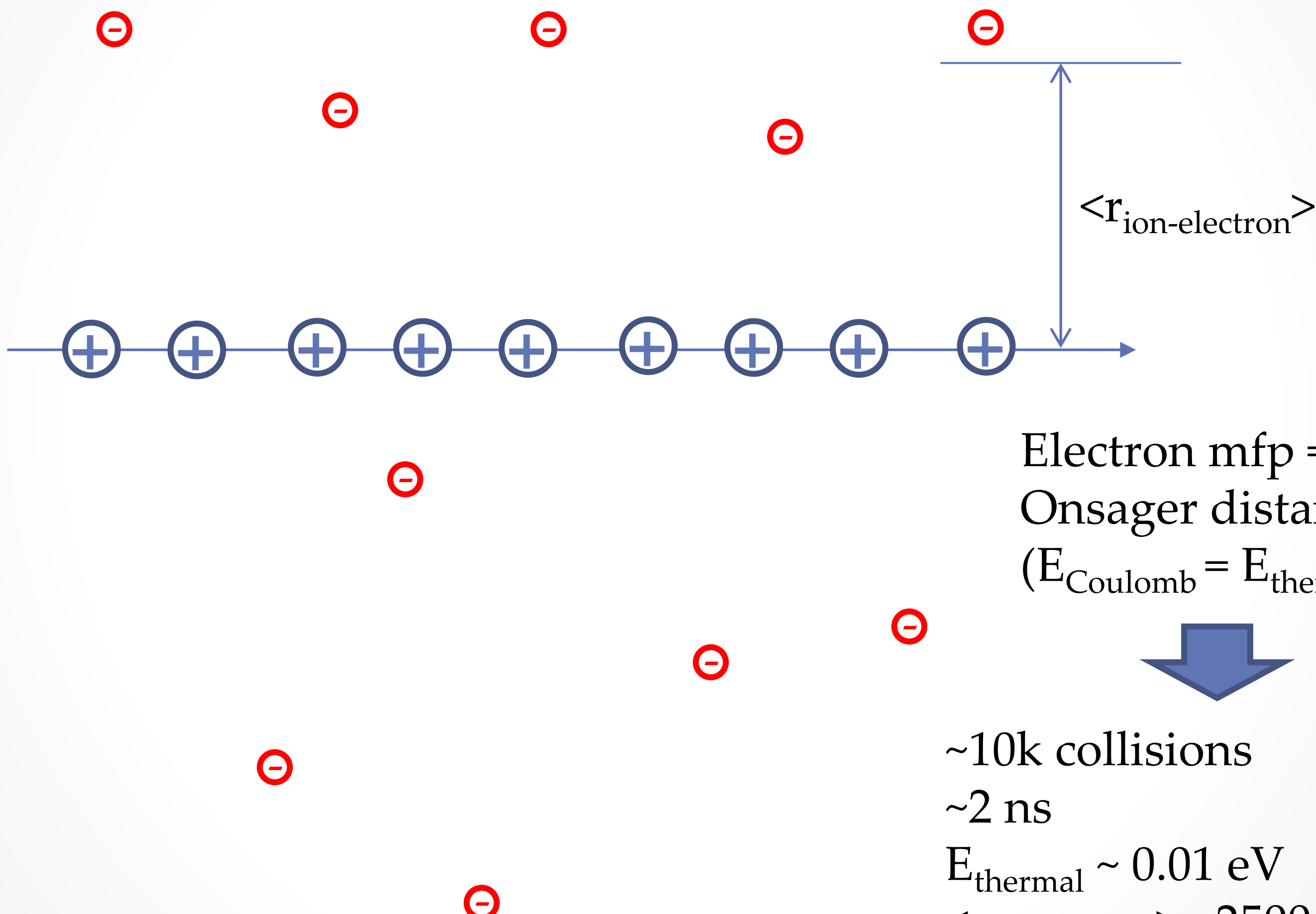


r_{ion} = 23.6 eV / (dE/dx)

MIP dE/dx = 2.1 MeV/cm → r_{ion} ~ 100 nm
HIP dE/dx ~ 25 MeV/cm → r_{ion} ~ 10 nm

Ref: LAr atomic spacing ~ 0.4 nm (= 4 Å)

After Thermalization

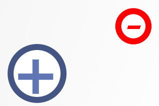


Electron mfp = 20 nm
Onsager distance 120 nm
($E_{\text{Coulomb}} = E_{\text{thermal}}$)

~10k collisions
~2 ns
E_{thermal} ~ 0.01 eV
$\langle r_{\text{ion-electron}} \rangle$ ~2500 nm (2.5 μm)

Jaskolski, Wojcik J. Phys. Chem. A 115 (2011) 4317
Sowada, Phys. Rev. B 25 (1982) 3434

Recombination Theories



Geminate

Small $r_{\text{ion-electron}}$

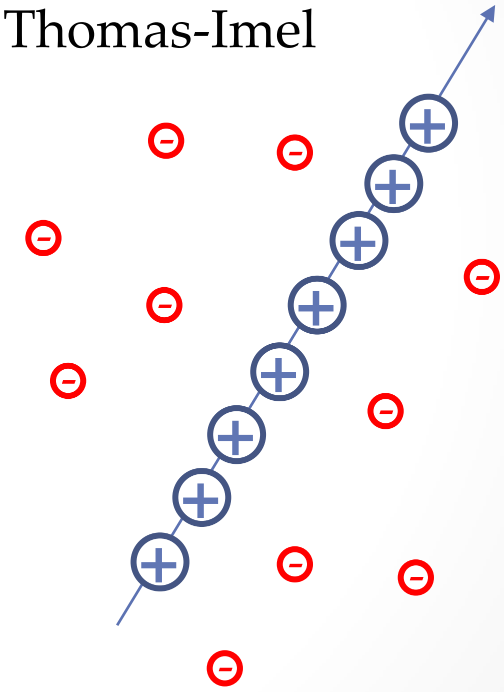
~0.1% in LAr

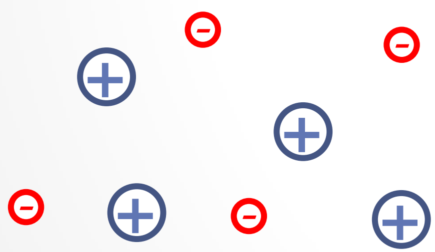
Onsager

Columnar

Large $r_{\text{ion-electron}}$

Jaffe, Thomas-Imel





Bulk

Debye-Smoluchowski

Jaffe, Ann. Phys. 42 (1913) 303

2. Zur Theorie der Ionisation in Kolonnen;
von George Jaffé.

Leipzig, im Mai 1913.

(Eingegangen 30. Mai 1913.)

$$(32') \quad Y_3(X) = \frac{1}{1 + \frac{\alpha N_0}{8\pi D}\sqrt{\frac{\pi}{z'}}\, S(z')}, \qquad z' = \frac{b^2 u^2 X^2 \sin^2\varphi}{2 D^2}.$$

Birks model (1951)

$Y_3(X)$ = recombination factor $\mathcal{R}$
→ fraction of electrons that escape vs E field strength X

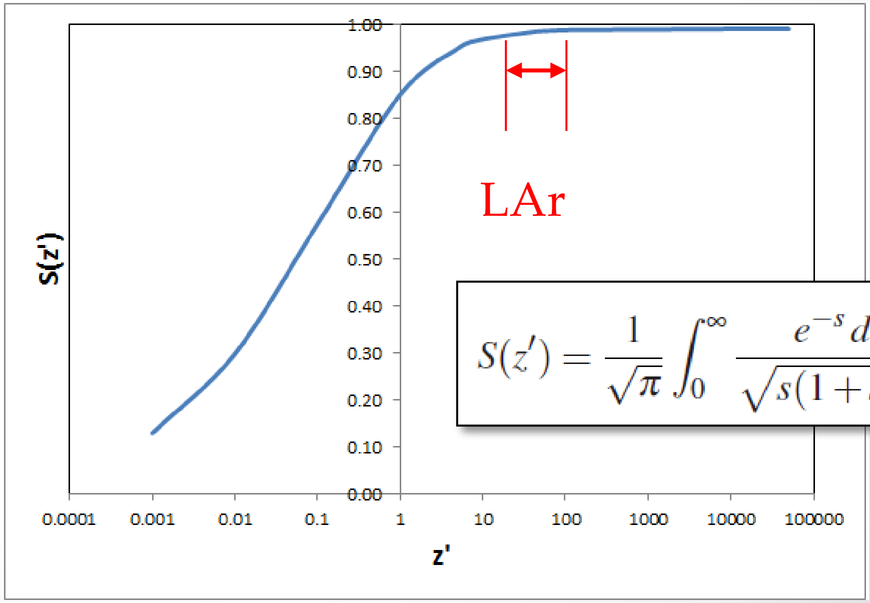
Assumptions

Recombination ~ charge density

No Coulomb interactions

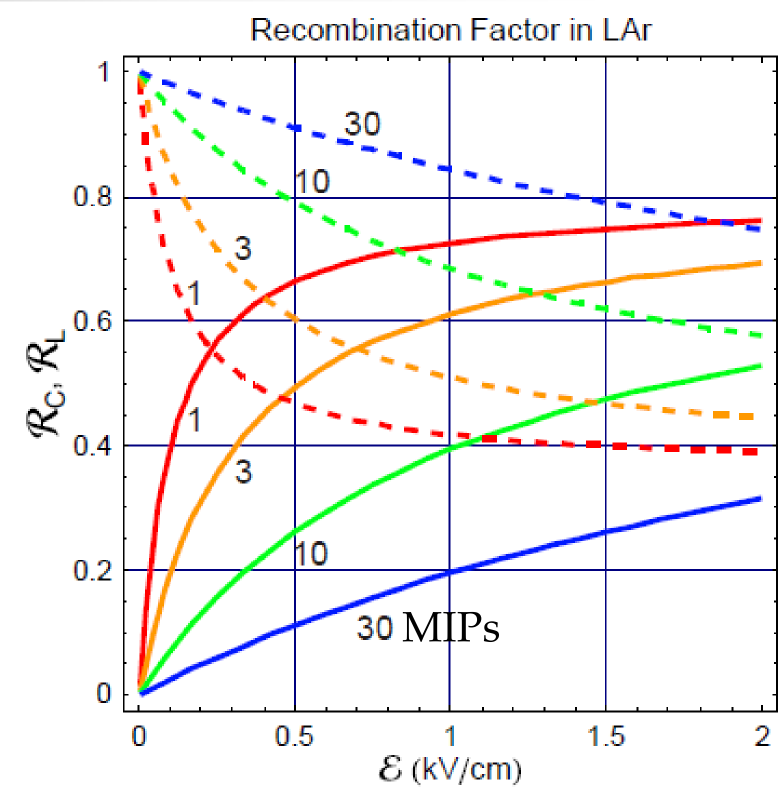
Ion mobility = electron mobility

Electrons & ions have the same Gaussian distribution



$$S(z') = \frac{1}{\sqrt{\pi}} \int_0^\infty \frac{e^{-s}\, ds}{\sqrt{s(1+s/z')}}$$

Recombination in Practice



$$R_C = \frac{Q}{Q_\infty} = \frac{A}{1 + \frac{k}{\mathcal{E}} \times \frac{dE}{dx}}$$

Charge recombination factor

$$R_L = \frac{L}{L_0} = 1 - \alpha R_C$$

Light recombination factor

$\mathcal{E}$ is electric field in kV / cm

<u>ICARUS</u>

$A = 0.800 + 0.003$

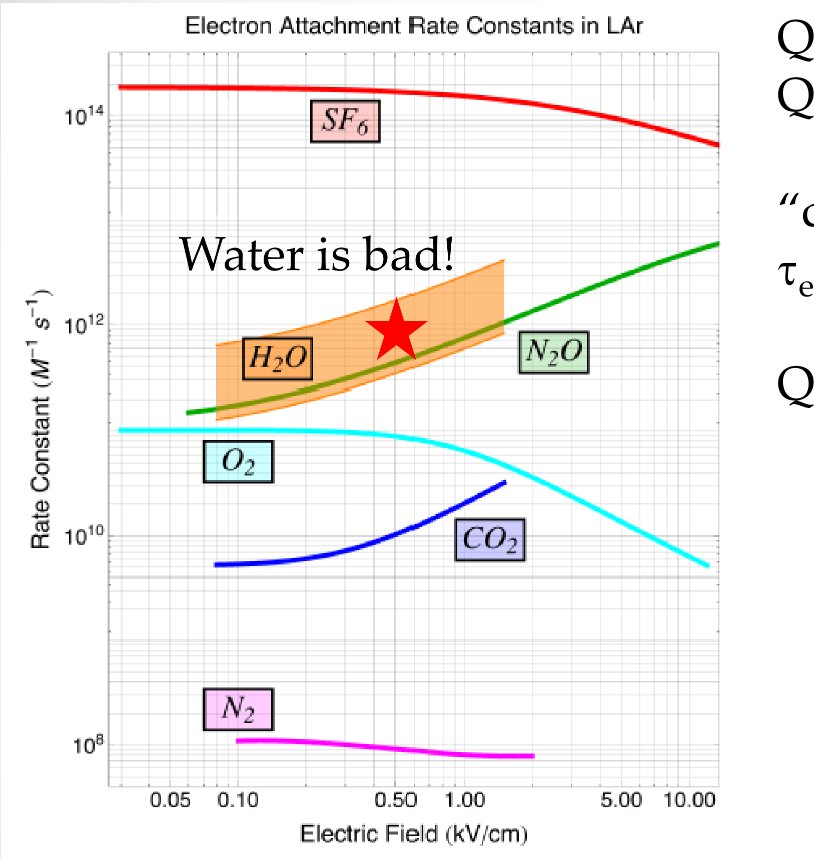
$k = 0.0486 + 0.0006$ kV/cm (g/cm^2/MeV)

Amoruso, et al NIM A 523 (2004) 275

Less charge = more scintillation light

Craig Thorn, "Properties of LAr v9a", MicroBooNE doc #412, LBNE doc #4482

Electron Attachment & Diffusion



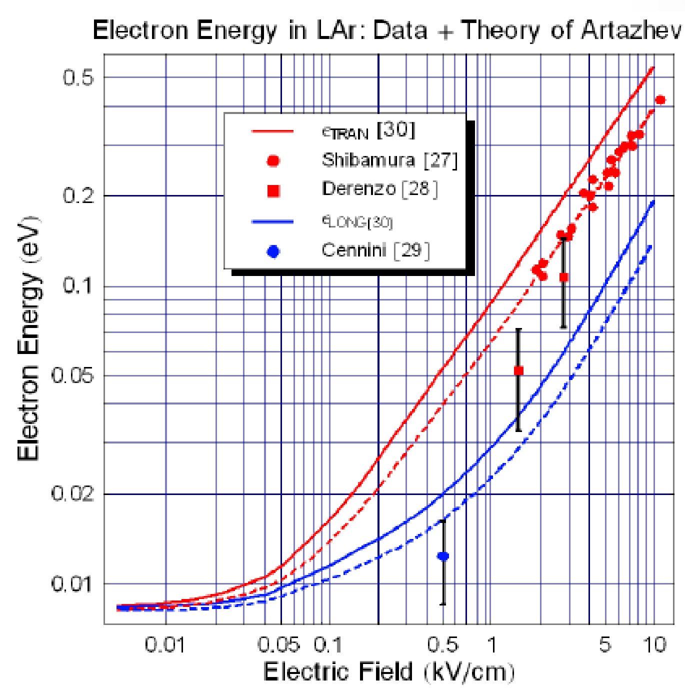
Q_o = electron charge after recombination

Q = charge arriving at the wire planes

"drift electron lifetime"

$\tau_{electron} = 1/$ (Rate Constant x concentration)

$Q = Q_o \exp(-t_{drift} / \tau_{electron})$

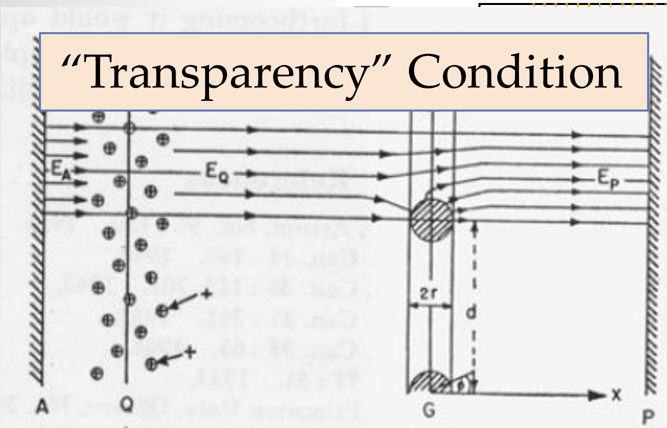


Longitudinal / Transverse diffusion rms

$$\sigma_{T(L)} = \sqrt{\frac{2\,\varepsilon_{T(L)}\,\Delta z}{E}}$$

Craig Thorn, "Properties of LAr v9a", MicroBooNE doc #412, LBNE doc #4482

Electron Transport in Wire Planes

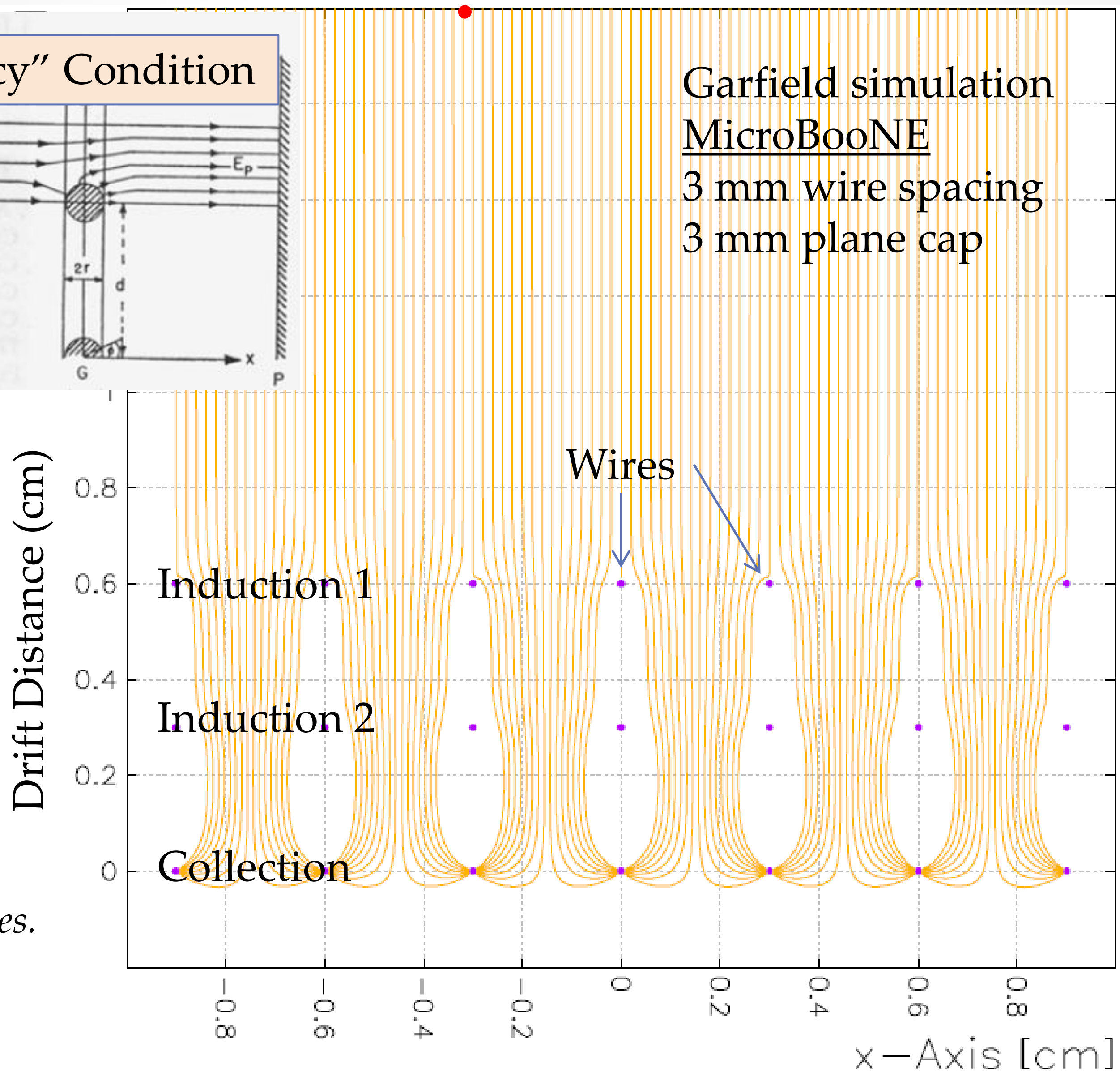


$\rho = 2\pi r / d$

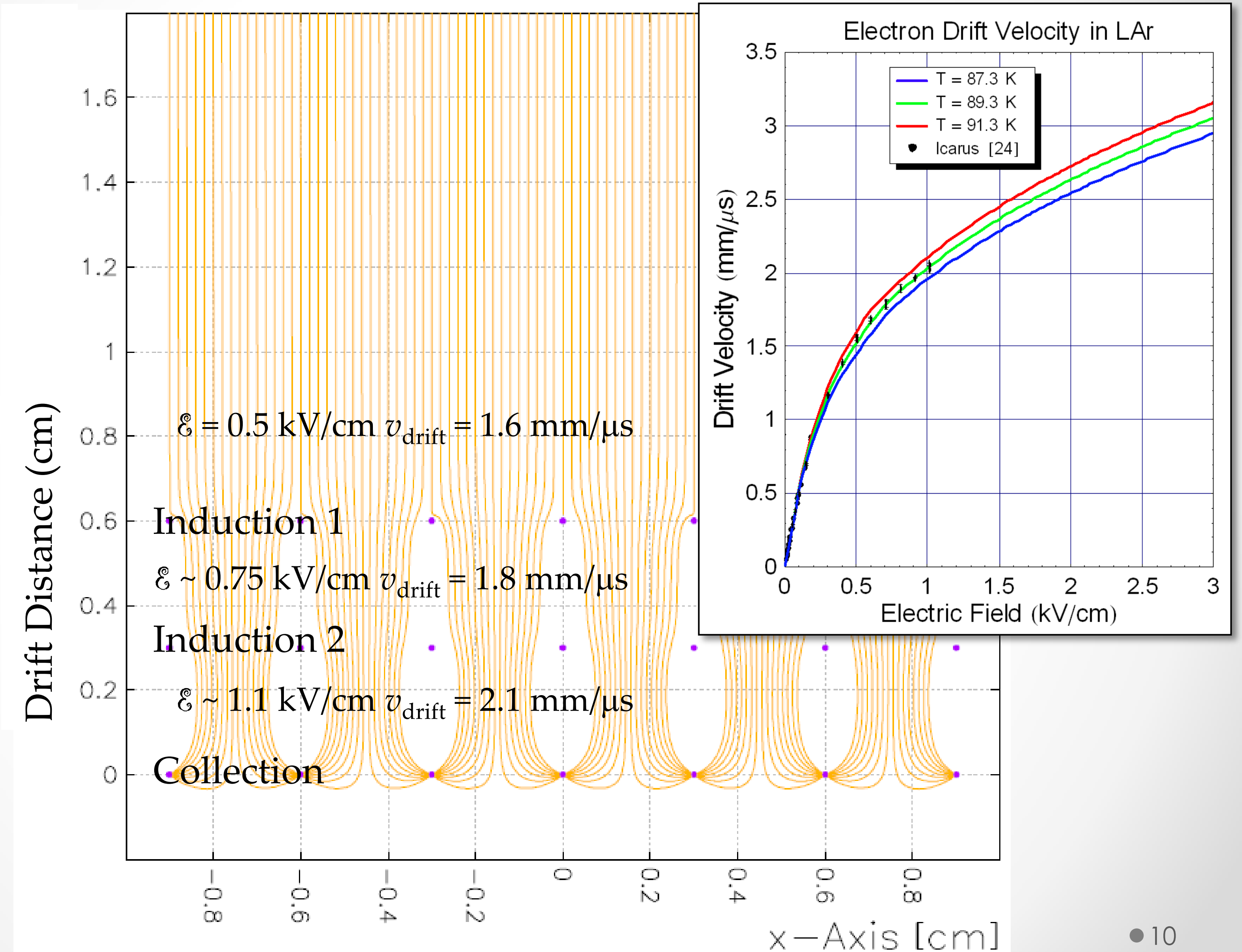
$$\frac{E_P}{E_Q} = \frac{1+\rho}{1-\rho}$$

1.37 for uB

Buneman, Can. J. Res. A27 (1945) 191

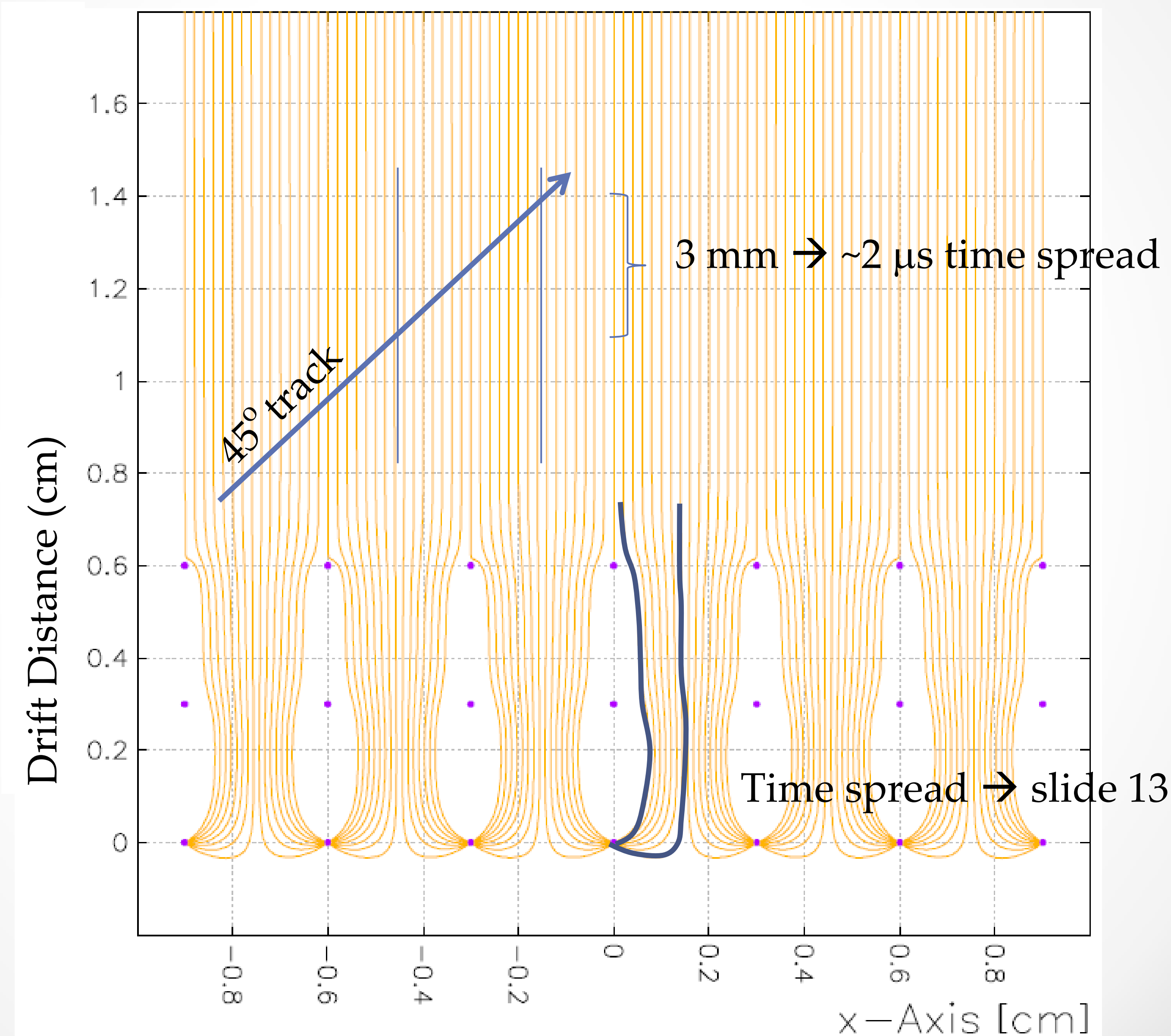


Electron Transport in Wire Planes

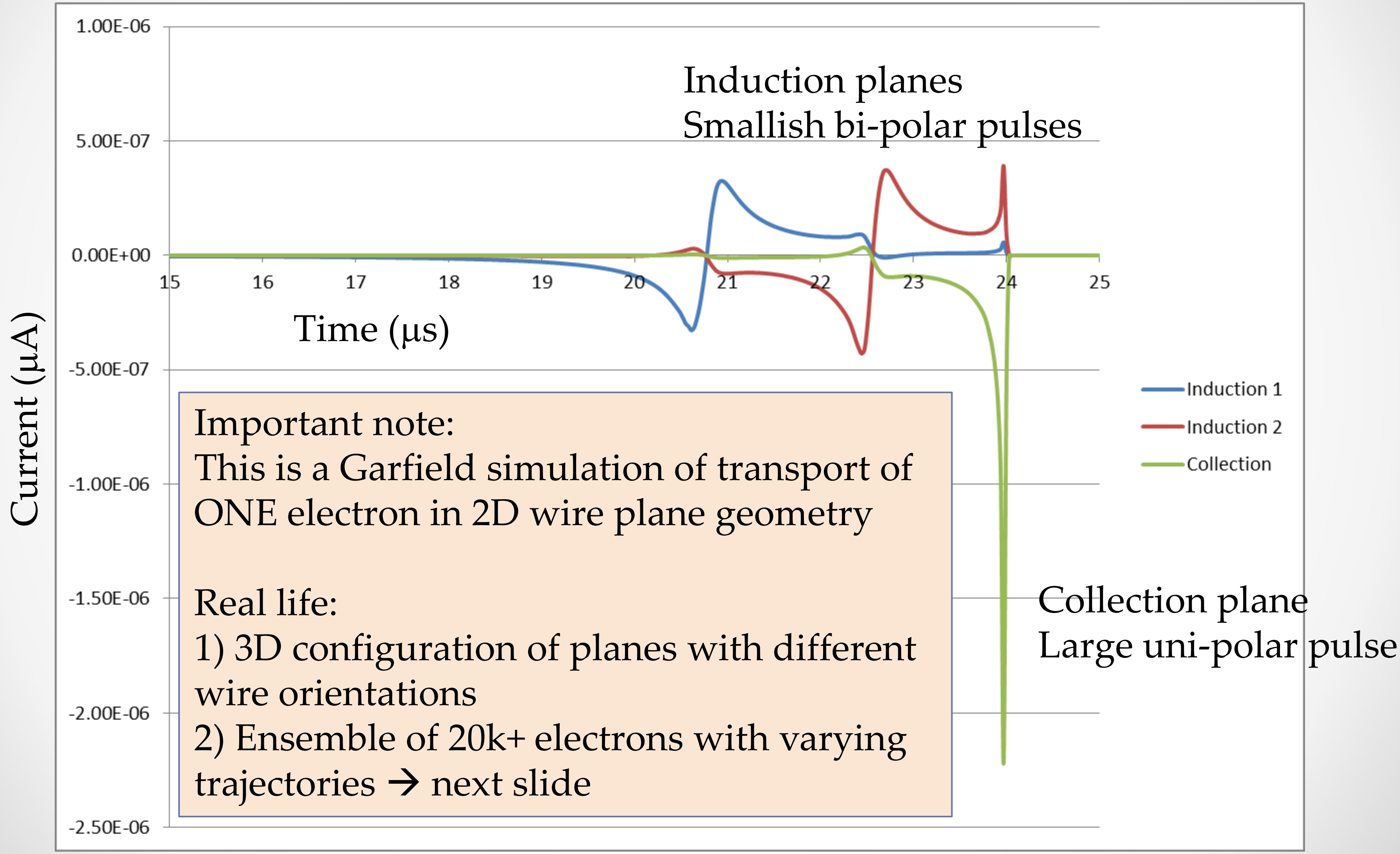


Set E field ratio ~ 1.5

Electron Transport in Wire Planes

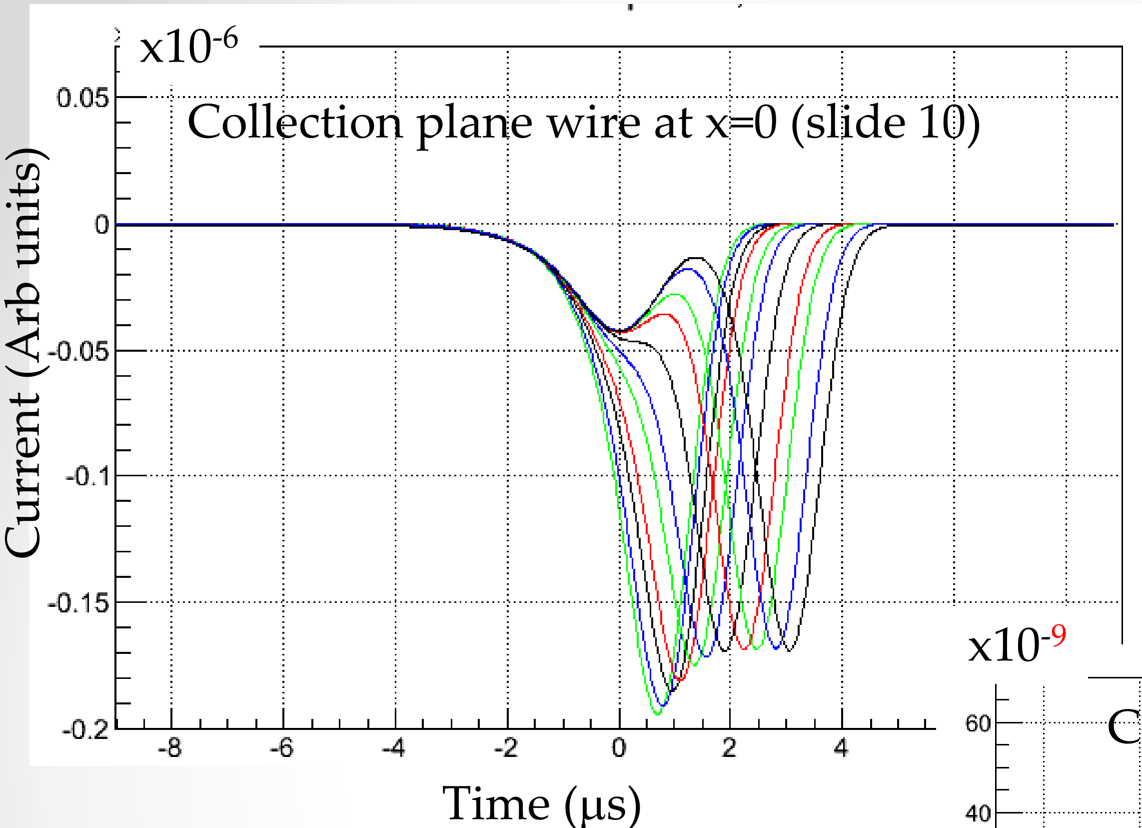


Field Response



Important note:
This is a Garfield simulation of transport of ONE electron in 2D wire plane geometry

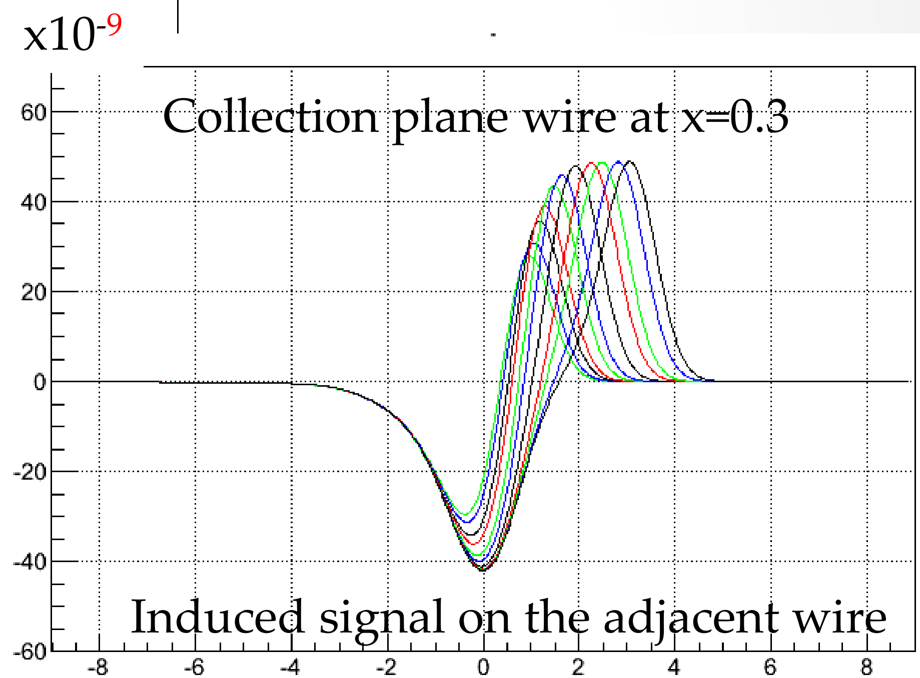
Real life:
1) 3D configuration of planes with different wire orientations
2) Ensemble of 20k+ electrons with varying trajectories → next slide



Convolute field response with 0.5 μs electronics shaping time

Different curves are for electrons starting at $0 < x < 1.5$ mm

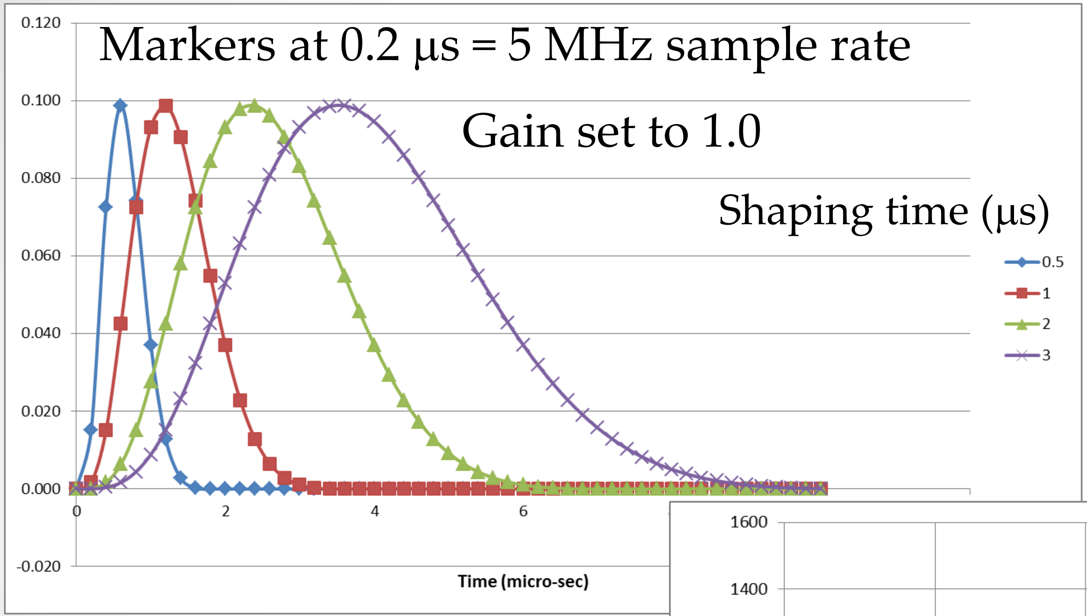
~2 μs

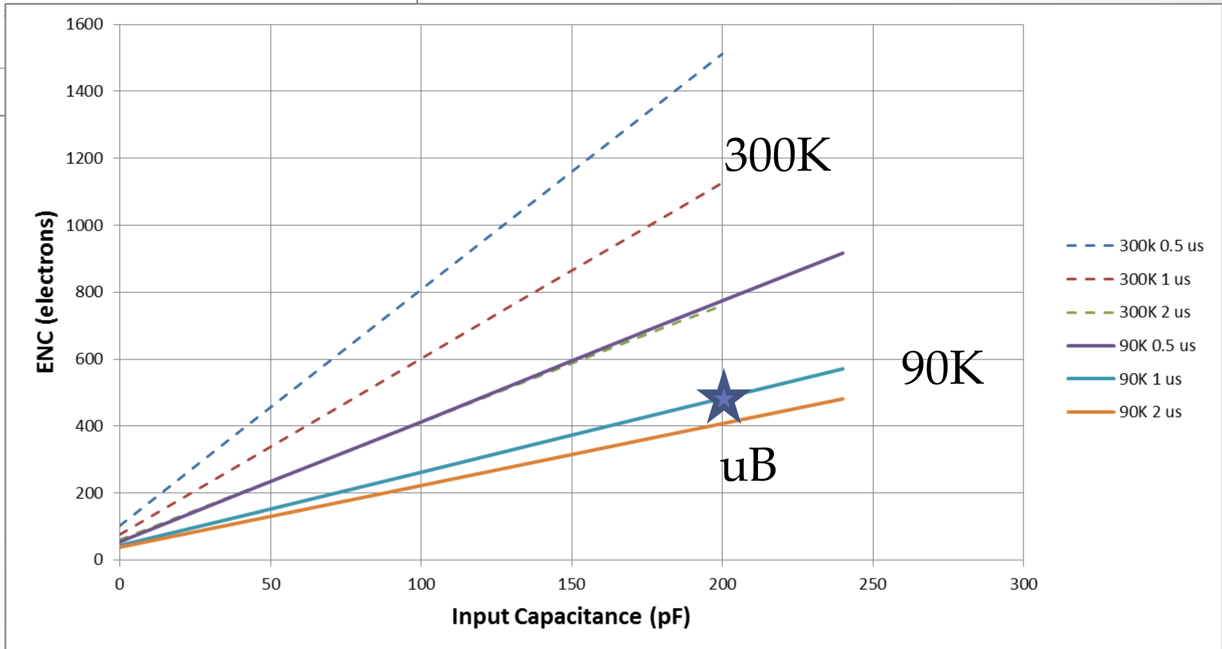


Leon Rochester (SLAC) for MicroBooNE

Electronics Response

Using BNL – Nevis electronics chain





$ENC = A + B\,C_{in}$

Rough approximation

$A_{300K} = 2 \times A_{90K}$

$B_{300K} = 2 \times B_{90K}$

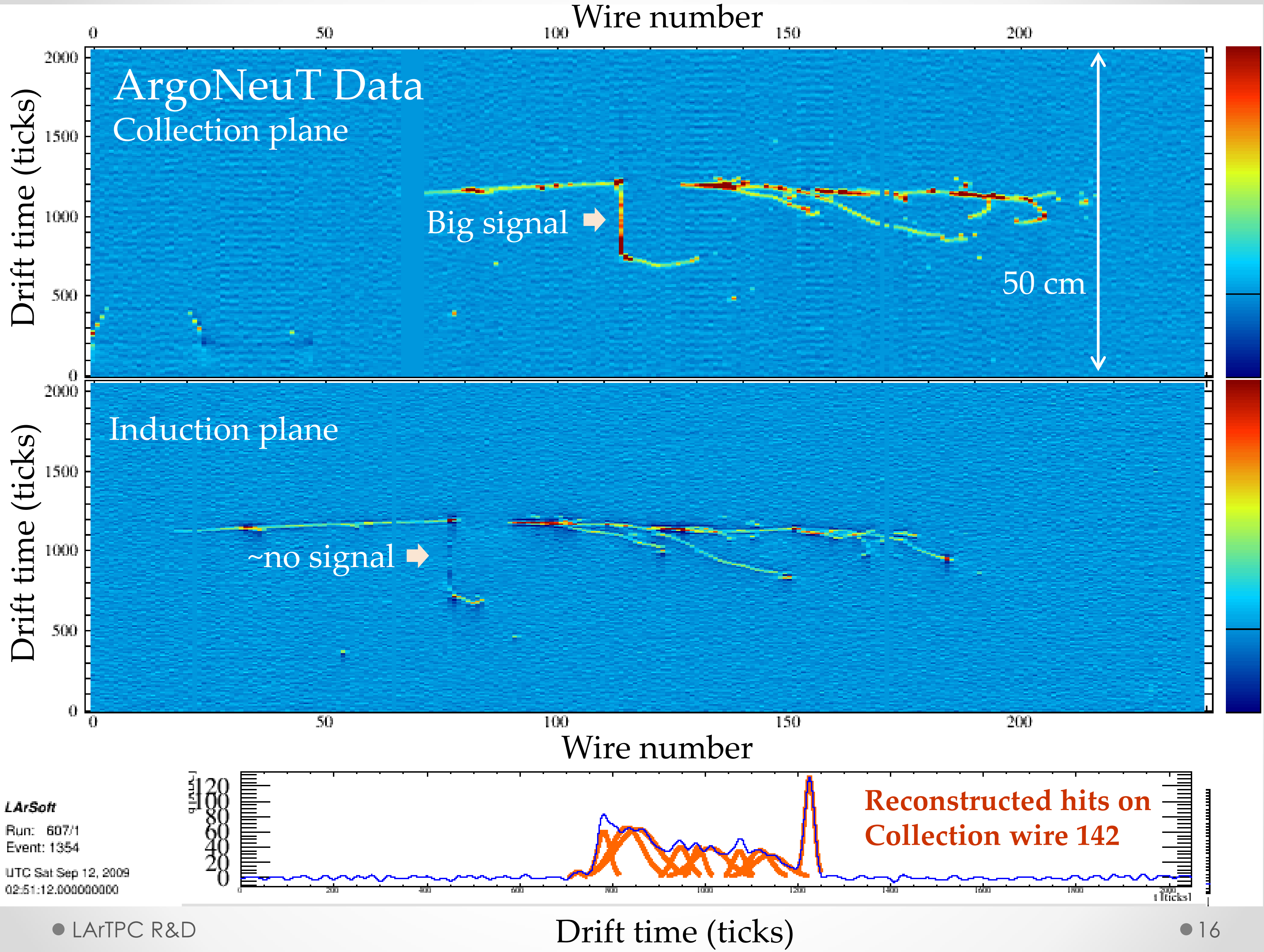
Signal Processing Chain

Time spread, comments

Thermalization	2 ns
Recombination	~10 ns, charge loss
Diffusion	~1 μs, Gaussian
Field Response	~2 μs, complex, ∠ dependent
Electronics Response	~0.5 - 3 μs, ~Gaussian
Sampling, DAQ	

Issues: sampling rate, position resolution, two-track resolution, S/N

- Deconvolution?
- Hit finding/fitting
- 2D,3D reconstruction
- Calculate dE & dx
- PID & energy


Wire number
ArgoNeuT Data
Collection plane
Big signal
50 cm
Drift time (ticks)
Induction plane
~no signal
Wire number
LArSoft
Run: 607/1
Event: 1354
UTC Sat Sep 12, 2009
02:51:12.000000000
Reconstructed hits on
Collection wire 142
Drift time (ticks)

Convolution and Deconvolution

Convolution

Signal = Ionization ⊗ diffusion ⊗ field ⊗ electronics

$\mathcal{F}$ = Fourier Transform

$$\text{Signal} = \mathcal{F}^{-1}\{\,(\mathcal{F}(\text{ionization}) * \mathcal{F}(\text{diffusion}) * \underbrace{\mathcal{F}(\text{field}) * \mathcal{F}(\text{electronics})\,}_{\text{Convolution kernel } \mathcal{K}}\}$$

De-convolution & Filter

Ionization ⊗ diffusion = $\mathcal{F}^{-1}\{\,\text{Filter} * \mathcal{F}(\text{Signal}) / \mathcal{K}\}$

Filter protects when $\mathcal{K} \rightarrow 0$ or to remove coherent noise

Generalization

Signal for single hit
e.g. induction plane

Response
Function

Desired Output
Shape, e.g. Gaussian

Determine R

$$\mathcal{F}(\mathcal{R}) = \mathcal{F}(G_1) \,/\, \mathcal{F}(ADC_1)$$

De-convolute hits in
the ADC channel to
a Gaussian form

$$G_n = \mathcal{F}^{-1} \{ \text{Filter} * \mathcal{F}(ADC) \,/\, \mathcal{F}(\mathcal{R}) \}$$

Cons
Developing convolution kernels and filters takes special effort
Computational cost

Closing Comments

- In-liquid signal formation well understood
    - Charge loss due to recombination and electron attachment are not…
- Complex field response in the wire planes
    - Motivates setting electronics shaping time >~ field response time spread
- BNL ASIC designed for LArTPCs
    - Programmable gain and shaping time
    - Peak amplitude independent of the shaping time
    - Charge injection calibration
- Deconvolute signals?
    - Bipolar induction plane signals → unipolar collection plane signals
        - Common hit finding and hit reconstruction code
    - Convert to a "standard" shape, e.g. Gaussian
    - No obvious benefit for collection plane signals for long shaping times
    - Remove coherent noise using a notch filter
    - Computational and human cost of developing kernels & filters