LArSoft
as
LArTPC Simulation Software

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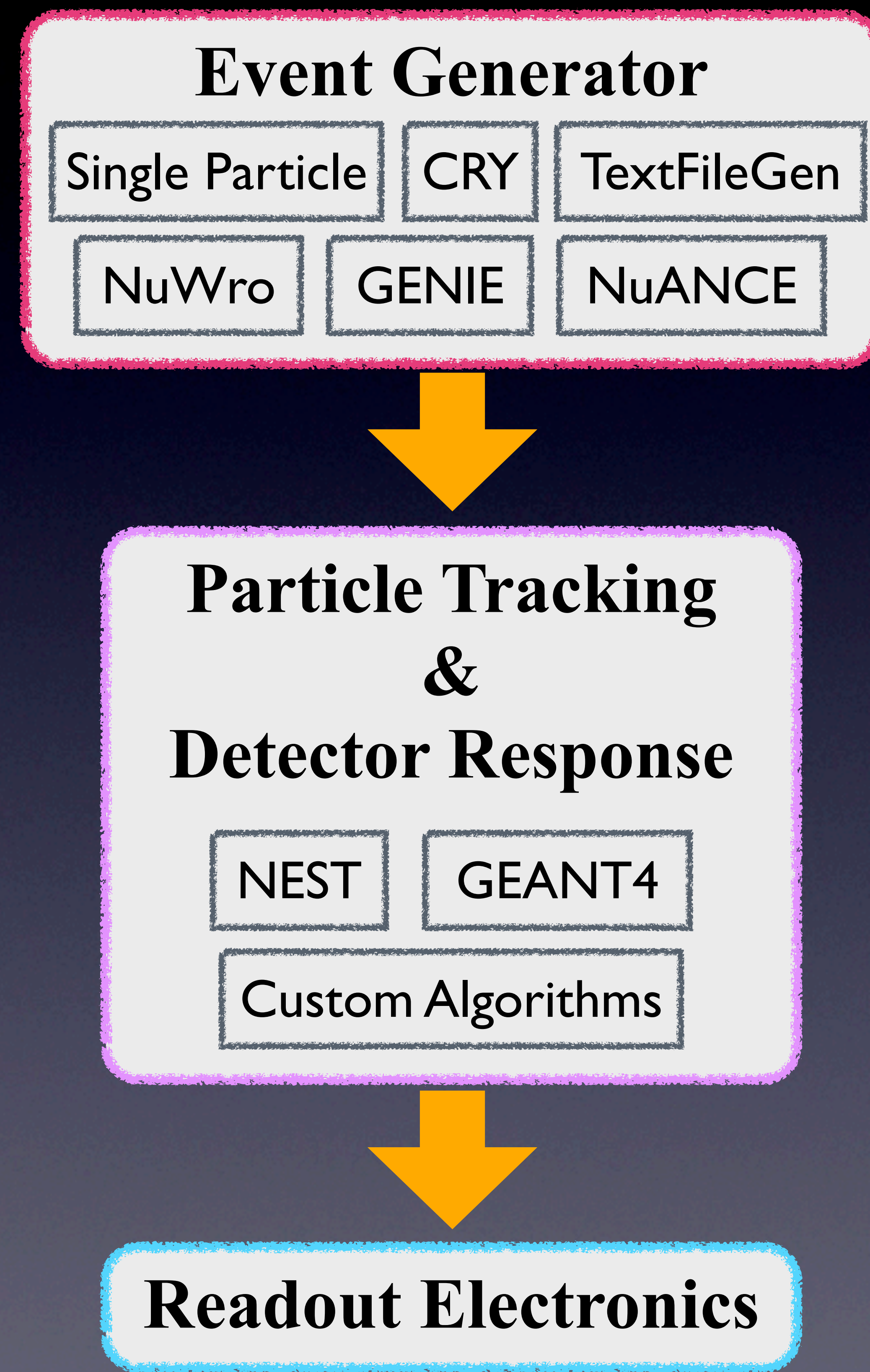
Monte Carlo Simulation For LArTPC

- **LArSoft**

Quote from LArSoft Wiki

The LArSoft software is designed to work for all planned and running liquid argon experiments at Fermilab. It is written in C++ and built on the ROOT data analysis software, and the art analysis framework supported by the Fermilab Scientific Computing Division for intensity frontier experiments.

- ... as a noble **simulation tool**
  - Interface to event generators
  - G4 wrapper for LArTPC geometry
  - Simulates LArTPC detector response
  - Provide infrastructure for the TPC and optical detector readout implementation

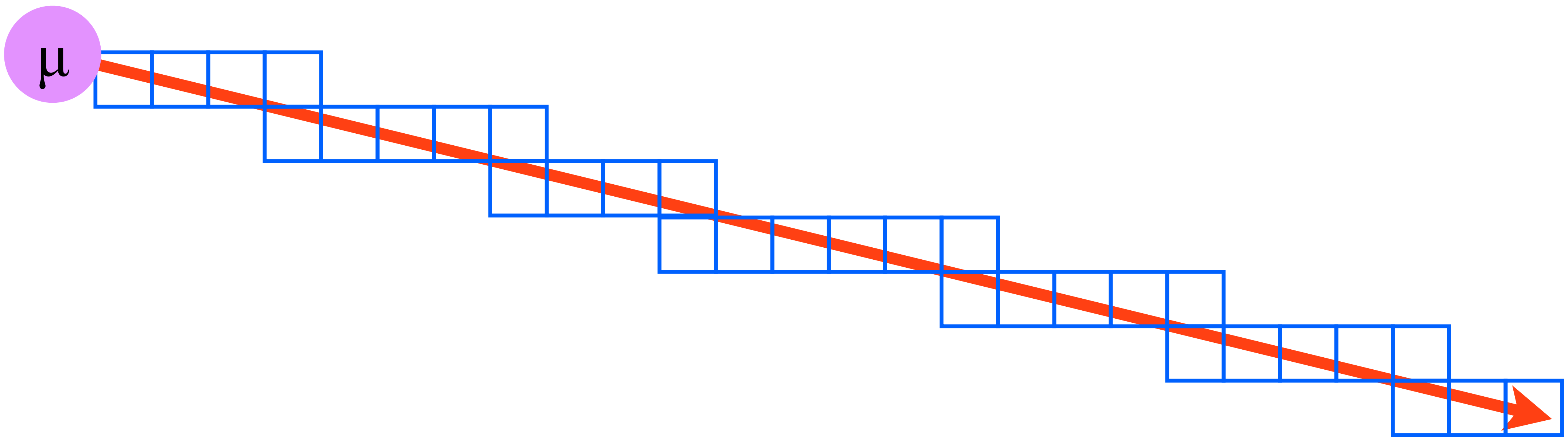


What To Talk in 15 Minutes?

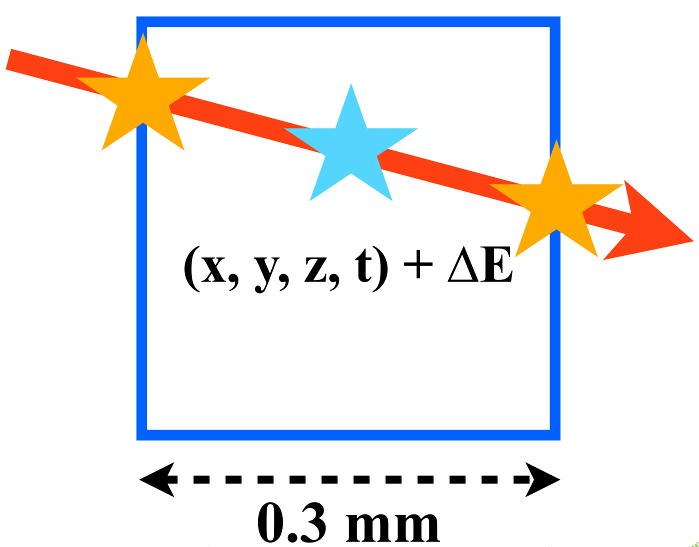
- Report from M. Kirby @ LArTPC 2013 ... here
- I'll cover...
  - Brief summary on detector response simulation
  - What's new? + To-Do's (from MicroBooNE and LBNE)

Detector Response Simulation

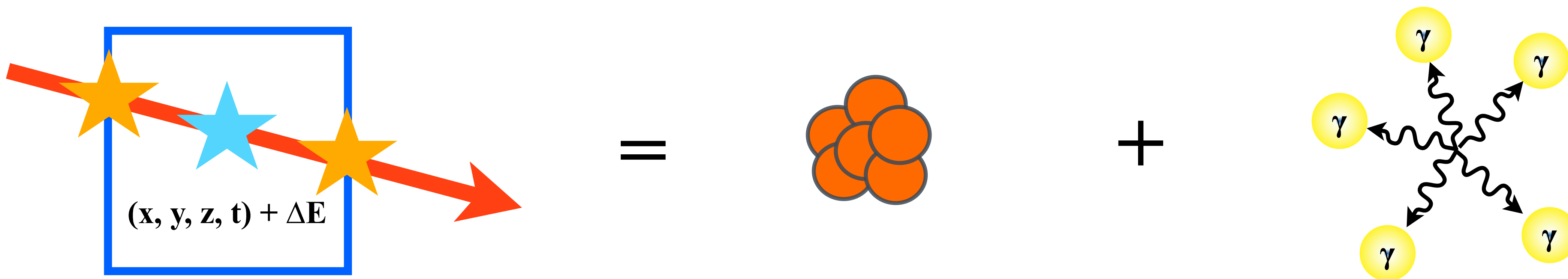
Particle Interaction



- Geant4 simulates particle tracks inside/outside detector
  - Geometry, physics parameters configurable @ run-time
- Sensitive volume is voxelized (default: 0.3 x 0.3 x 0.3 mm)
- Particles forced to step at voxel boundaries
- Energy deposition is measured at each voxel
  - ΔE = energy difference between entrance & exit
  - Deposition position @ middle of track-in-voxel



Energy Deposition Model



Energy Deposition **Ionization Electrons** **Scintillation Light**

$$
\begin{aligned}
N_e &= Y_{e^-} \times \Delta E \times \mathcal{E}_{recomb}(\vec{E}, \rho) \\
N_\gamma &= Y_\gamma \times \mathcal{E}_{saturation}(\vec{E}, dE/dx)
\end{aligned}
$$

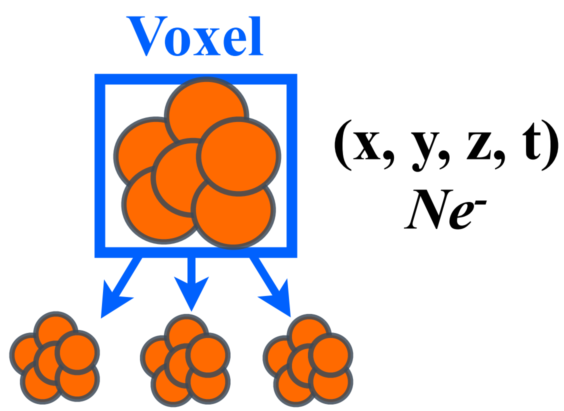
Based on 23.6 eV per ion pair → $Y_e \ldots 42370 \ \frac{\text{electrons}}{\text{MeV}}$

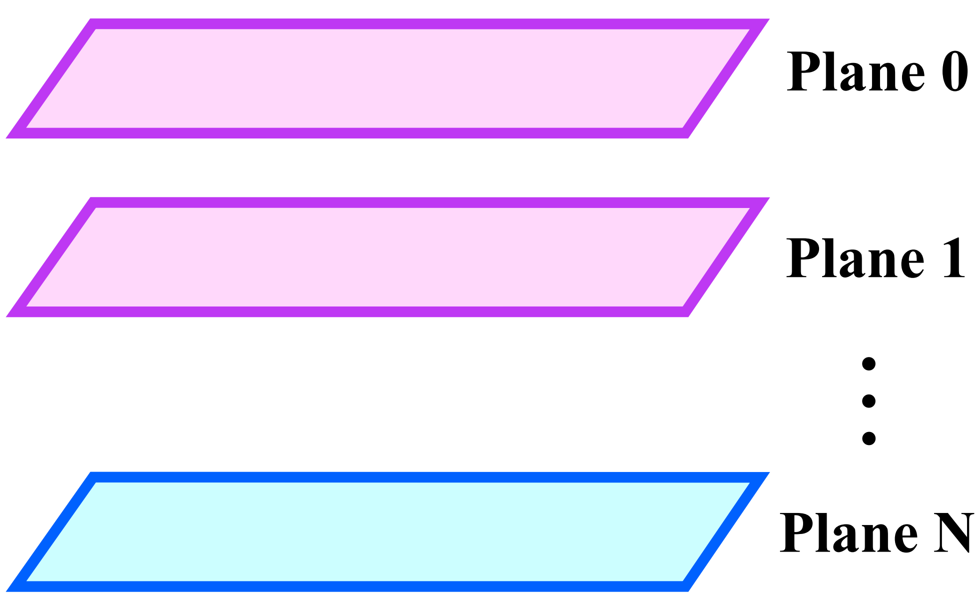
Total light yield @ 500 V/cm → $Y_\gamma \ldots 24000 \ \frac{\text{photons}}{\text{MeV}}$

- Saturation effect is G4's default Birk's quenching model
- Recombination effect: "Birk's" vs. "Modified Box Model"

Electron Drift

1. e^- in a voxel **sub-divided into a smaller bulk**
   - 600 e^- per cluster (configurable)





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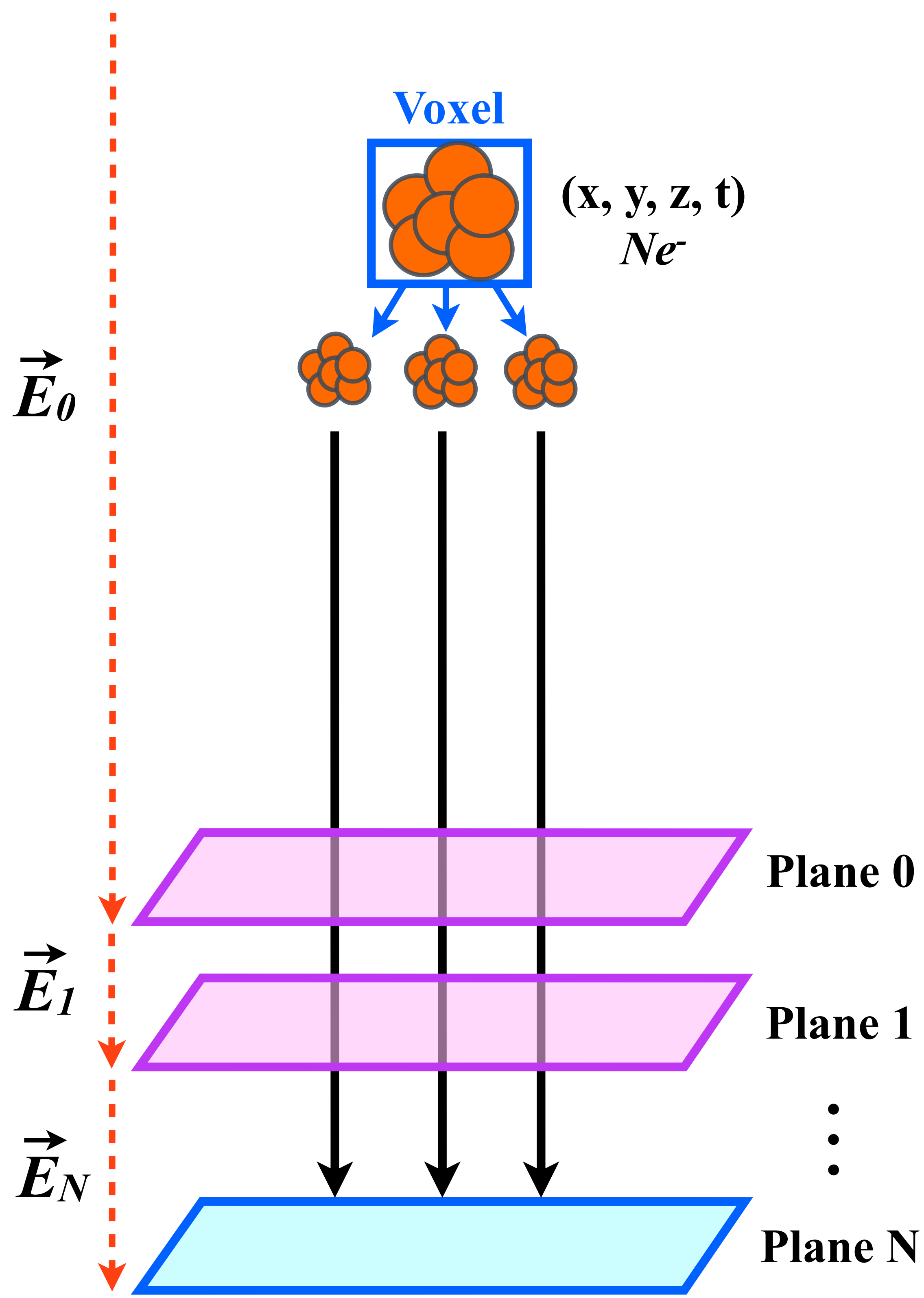
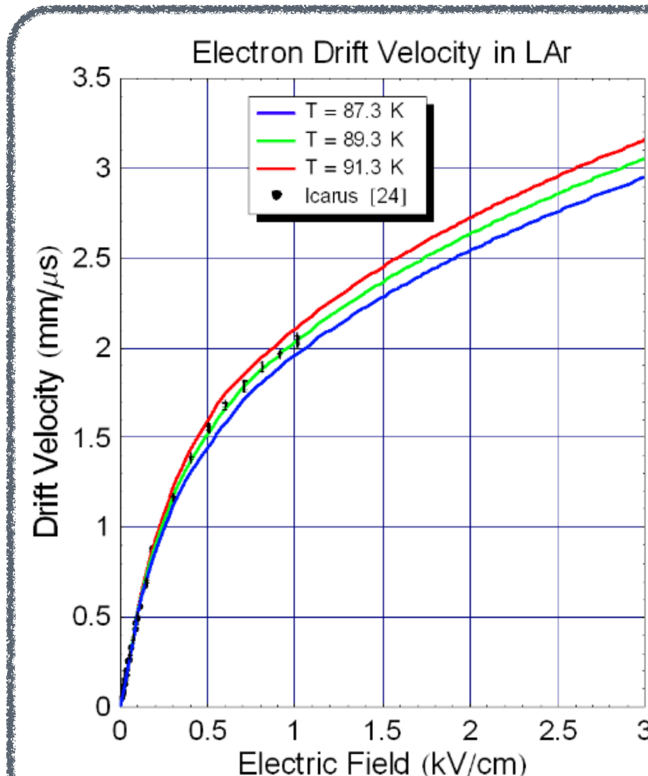


1. e^- in a voxel **sub-divided into a smaller bulk**
   - 600 e^- per cluster (configurable)
2. **Drift velocity per plane**

Drift velocity depends on **T** & $|E|$

$$v_d(T,|\boldsymbol{E}|) = (P_1(T - T_0) + 1)\left(P_3|\boldsymbol{E}|\ln\left(1 + \frac{P_4}{|\boldsymbol{E}|}\right) + P_5|\boldsymbol{E}|^{P_6}\right) + P_2(T - T_0).$$

W. Walkowiak NIM A449 p.288 (2000)

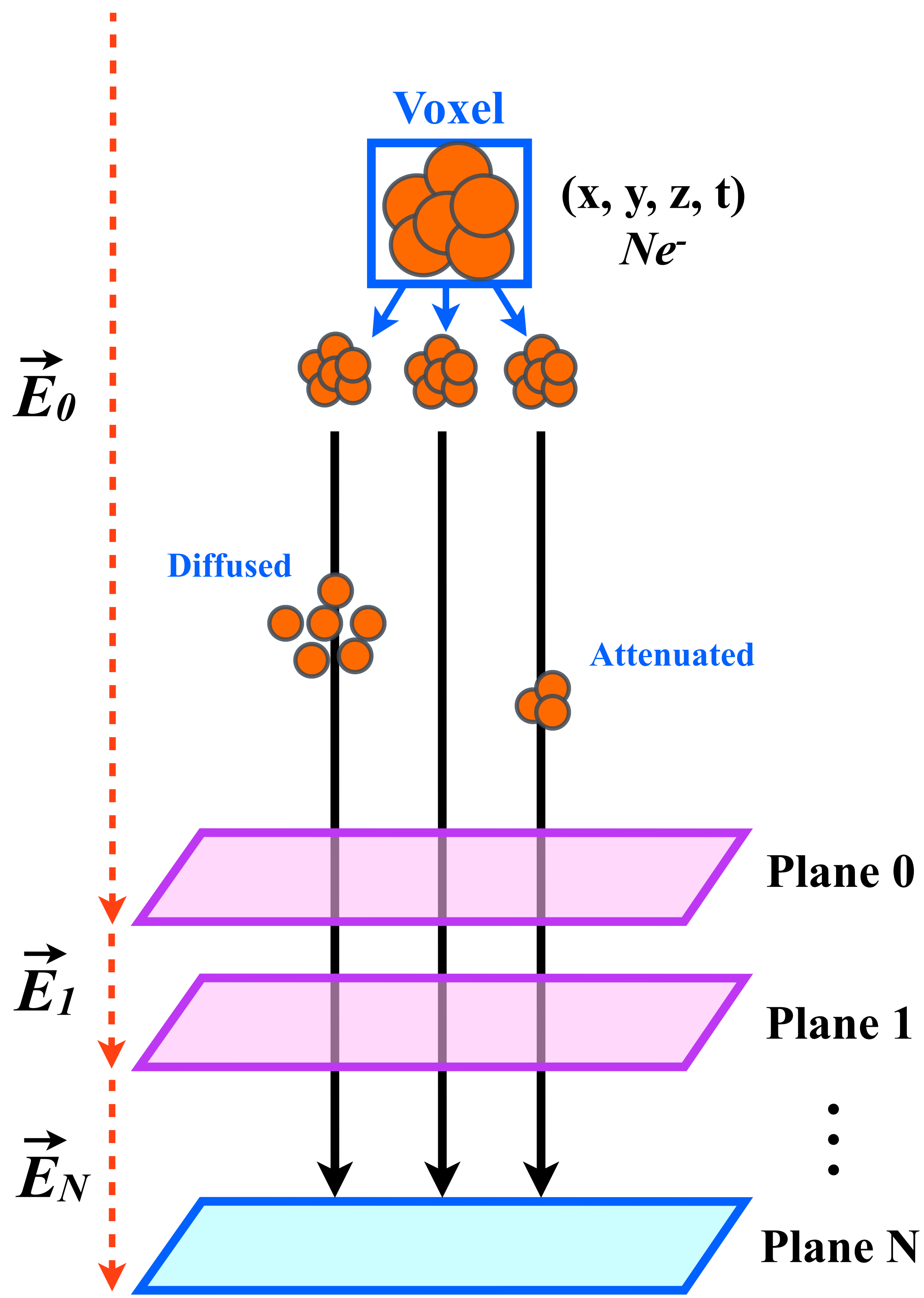


E field & Temperature Dependency

Parameter	Value
P_1	$-0.01481 \pm 0.00095\ \mathrm{K}^{-1}$
P_2	$-0.0075 \pm 0.0028\ \mathrm{K}^{-1}$
P_3	$0.141 \pm 0.023 \left(\frac{\mathrm{kV}}{\mathrm{cm}}\right)^{-1}$
P_4	$12.4 \pm 2.7 \left(\frac{\mathrm{kV}}{\mathrm{cm}}\right)$
P_5	$1.627 \pm 0.078 \left(\frac{\mathrm{kV}}{\mathrm{cm}}\right)^{-P_6}$
P_6	0.317 ± 0.021
T_0	90.371 (Fixed) K

Parameterization

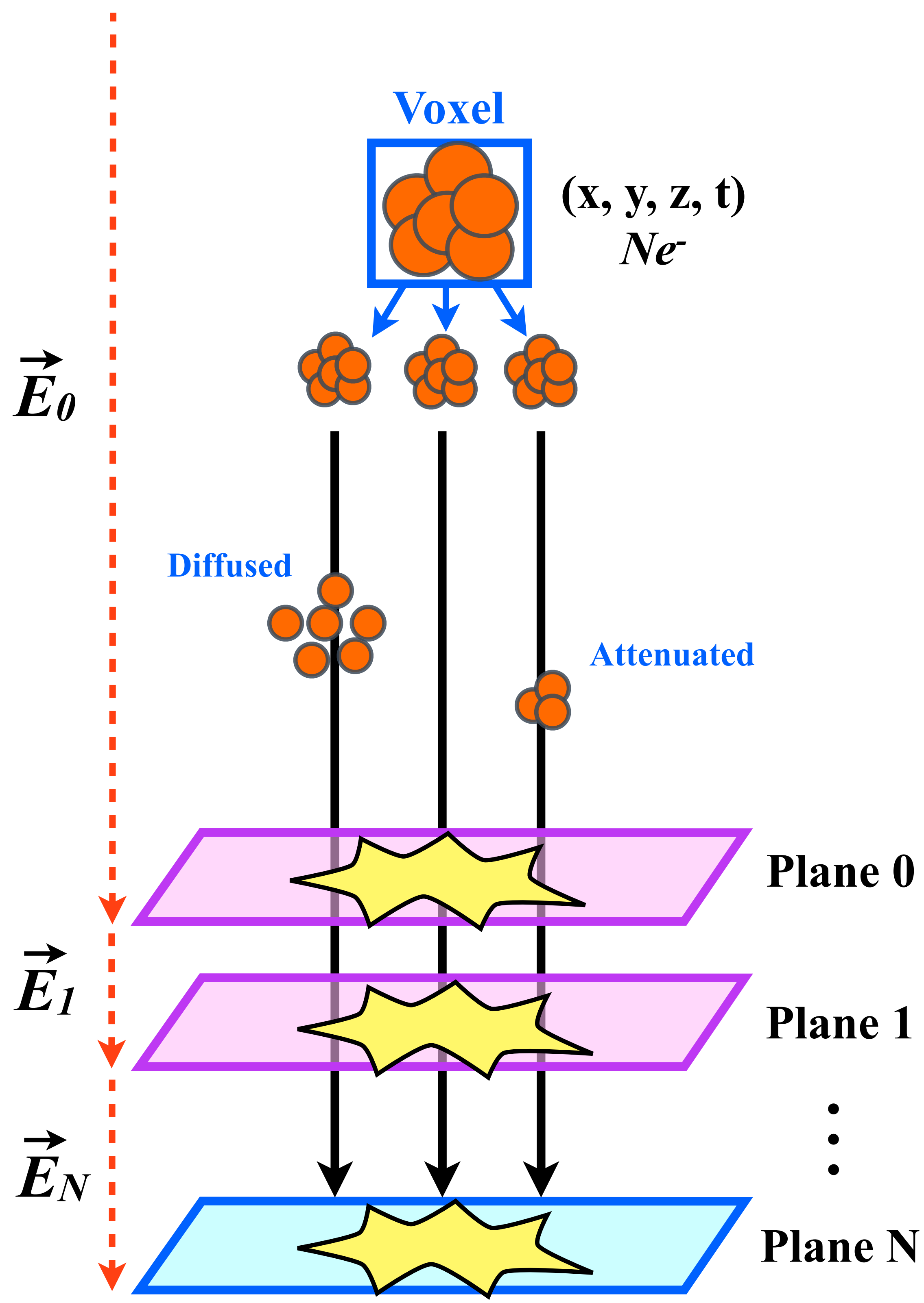
Electron Drift



1. e^- in a voxel **sub-divided into a smaller bulk**
   - 600 e^- per cluster (configurable)
2. **Drift velocity per plane**
3. **Electron attenuation** $\boxed{N_e' = N_e \exp\left(-t/\tau_e\right)}$
4. **Diffusion** ... modeled as gaussian smearing

$$\boxed{\begin{aligned} \sigma_x &= \sqrt{2 \cdot t_{\mathrm{drift},0} \cdot D_{\mathrm{long}}} \\ \sigma_{y,z} &= \sqrt{2 \cdot t_{\mathrm{drift},0} \cdot D_{\mathrm{trans}}} \end{aligned}}$$

Electron Drift



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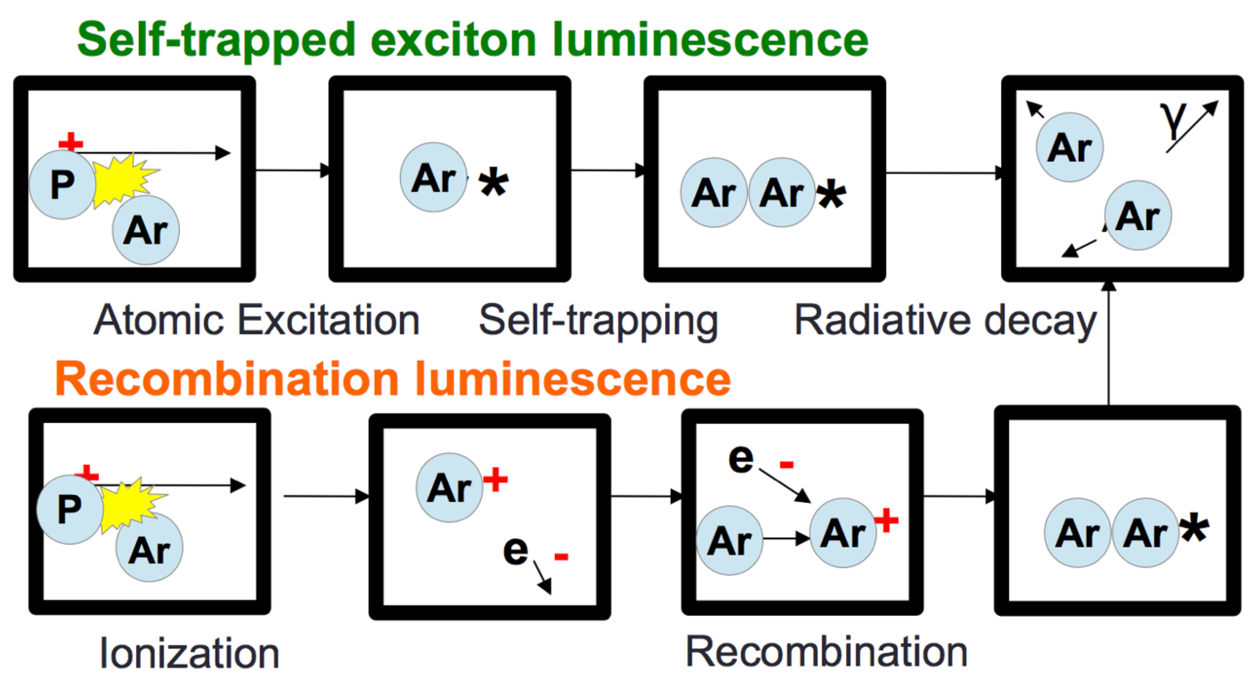
5. **Detection**
   - Drifted position ⇒ nearest wire
   - Drift time ⇒ digitized clock count
6. **Data product**
   - **Wire & digitized time**
   - MC info (original position, ΔE, particle track ID)

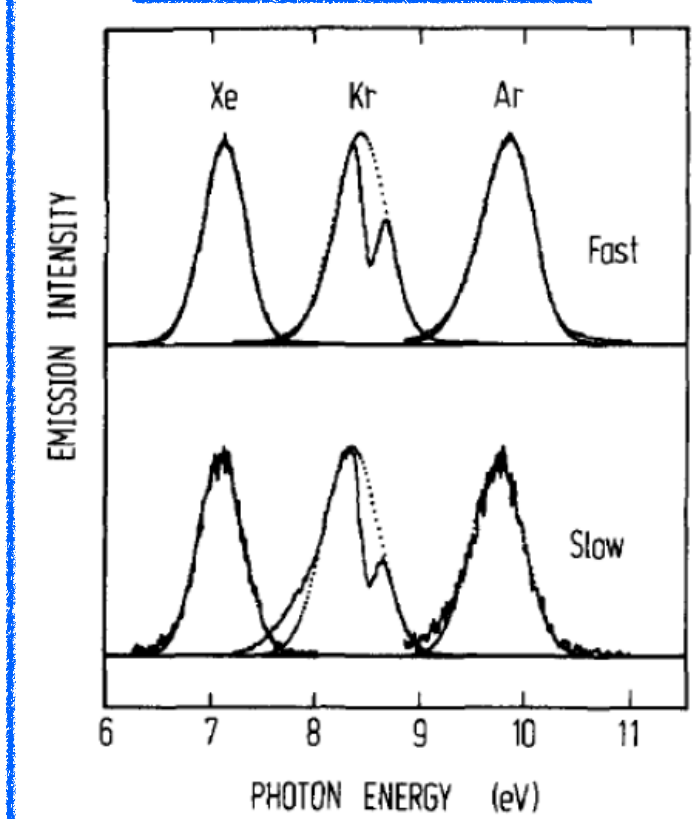
Simulation of Photons

Image Credit: B. Jones



- Optical physics in LAr
  - See **Ben Jones' talk for physics**!
  - **Fast** and **slow scintillation light**
  - **Cerenkov light**
  - Rayleigh scattering
  - Surface reflection and absorption
  - Bulk absorption
  - Wavelength Shifter (absorption & emission)

J Chem. Phys. v91 (1989) 1469
E Morikawa et al.

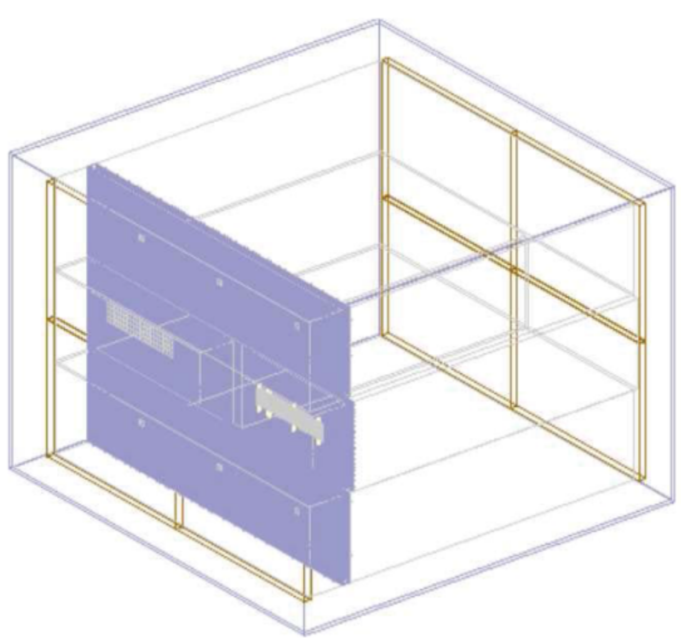


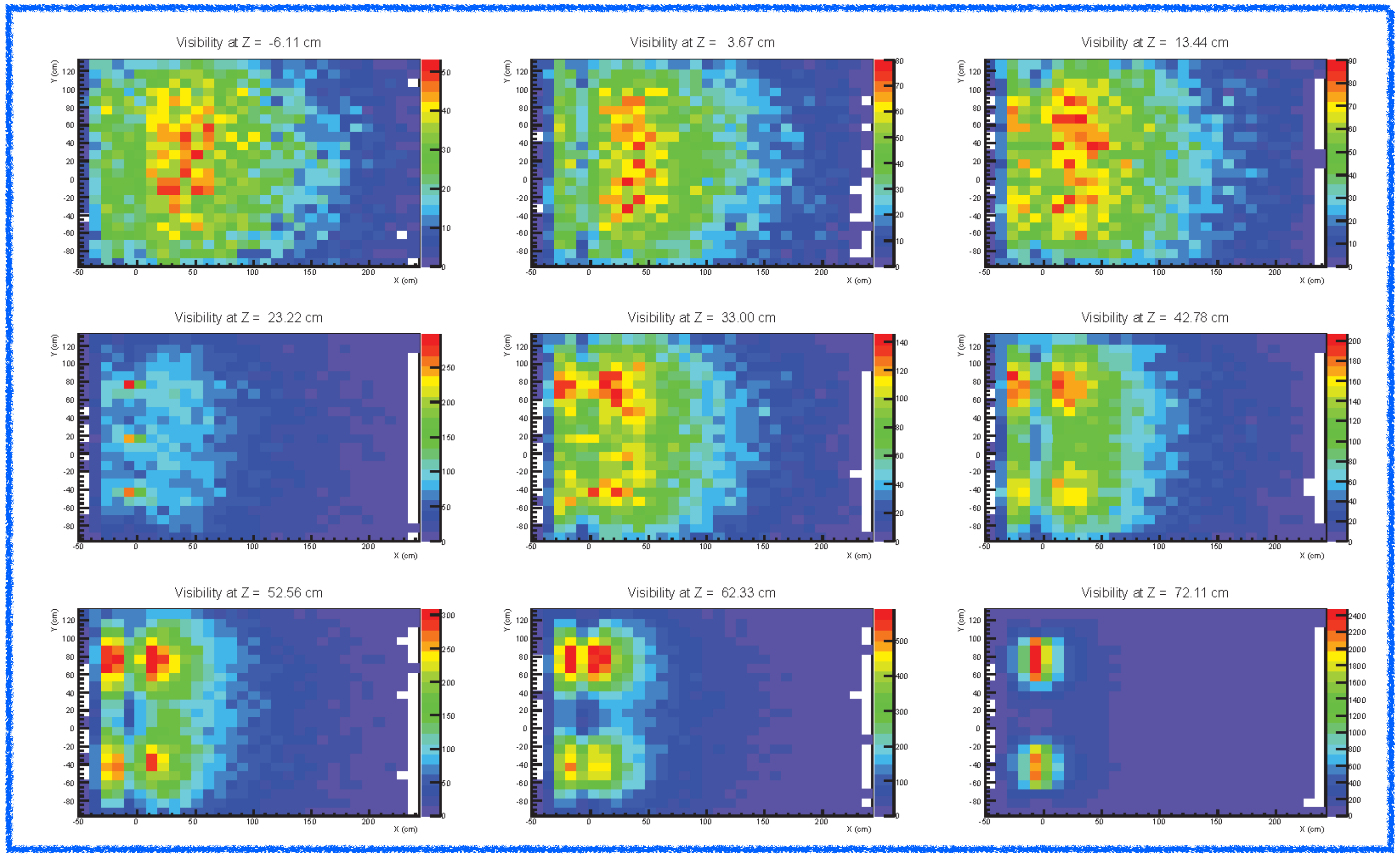
- **LArSoft has most** of this physics implemented
- ... **but lacks some**:
  - No simulation of WLS material
  - Purity dependency (light yield & quenching)
  - Electric field dependency (light yield, time constants)
    - larger scope effort: introduction of field non-uniformity

Photon Propagation

- Photon propagation technique
  - **Full simulation** ... **individual photon propagation** through the detector medium
  - **Fast simulation** ... uses “PhotonLibrary” and **avoids individual photon propagation**
    - A look up table of acceptance per optical detector per voxel
    - Only for isotropic source (not Cerenkov)
    - **Much less CPU time** than FullOptical, **but more memory usage**
      - But library needs to be pre-built (or rebuilt for a change in geometry)

LBNE 35t **geometry (below)** and **photon visibility map (right)** for “fast” simulation (from Y. Sun)



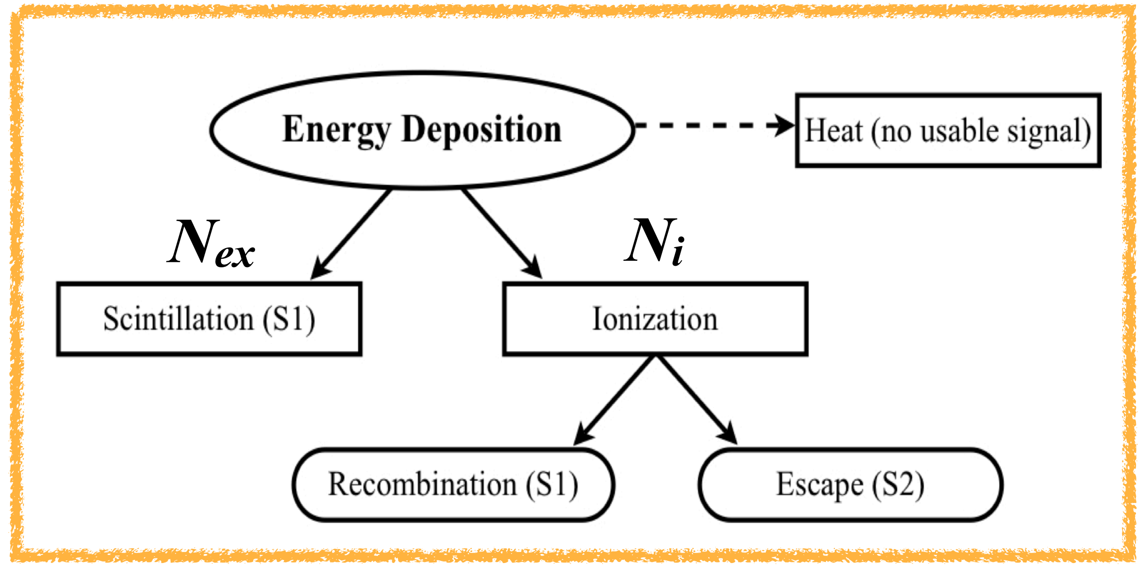


Advanced Energy Deposition Handle: NEST

- Noble Element Simulation Technique
  - http://nest.physics.ucdavis.edu/site/
  - Derive ionization & scintillation together
    - Reproduces light/ionization yield anti-corr.
    - Toward better reconstructed energy resolution
  - Dedicated scintillation processes handling
    - particle type, electric field, dE/dX dependency

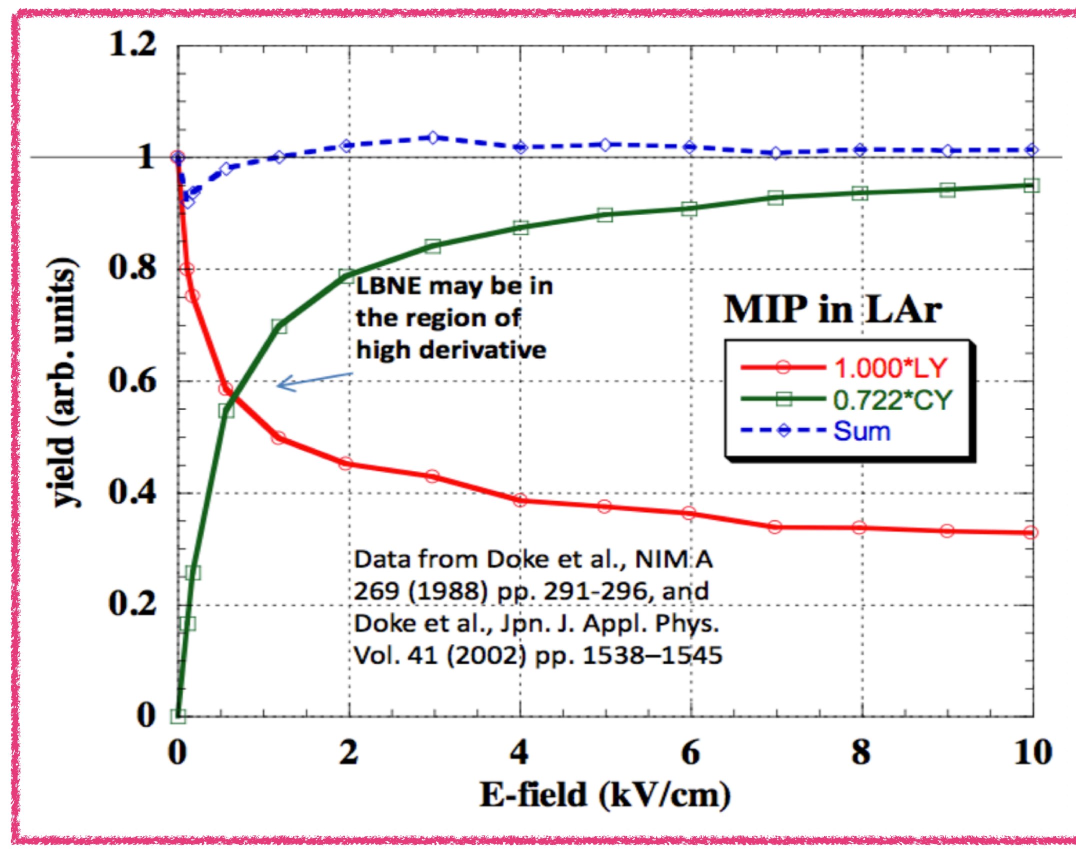
- LArSoft implementation
  - Algorithm available in LArSoft
    - Combined charge + light yield calculation
    - Awaiting for a comparison study
  - Future: use NEST as an external product
    - Currently just a copy of algorithm source code

M Szydagis *et al* 2011 *JINST* 6 P10002



$$\boxed{\begin{aligned} N_{ph} &= N_{ex} + rN_i \\ N_e &= N_i(1-r) \end{aligned}}$$

"r" is recombination probability



What's New?

~ From LBNE & MicroBooNE ~

What's New?

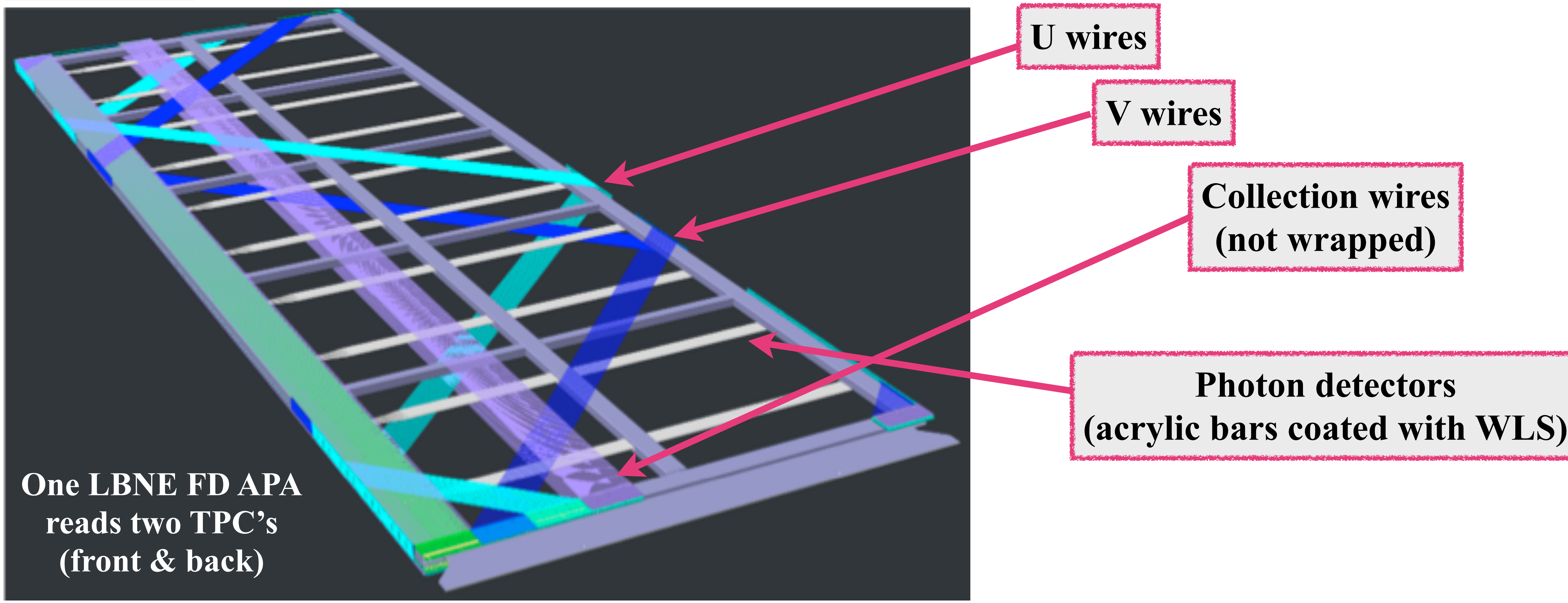
- **LBNE**
  - Geometry
    - New 35t geometry
    - Initial ICARUS & 34kt underground geometry (45 & 36 degree wires)
  - Photon propagation
    - PhotonLibrary for 35t
    - Studying 3 photon collection devices (all read out by SiPM)
  - Better handling of drift charge on the same channel from different TPCs

- **MicroBooNE**
  - Optical readout & trigger electronics simulation
    - FPGA logic for ADC ⇒ Discriminator logic ⇒ Trigger ⇒ DAQ readout
  - Full MC simulation chain working for large MC production
    - 4.8 ms TPC readout + 6.4 ms Optical readout + Trigger
  - Updated detector geometry

LBNE
Detector Geometry Implementation

LBNE’s Wrapped Induction-Plane Wires

B. Yu (BNL)



Wrapping needed to fit frames on trucks / down shaft, & readout wires on ends

- Smaller U and V angles would wrap fewer times
- 45° has ≃ 2 crossings of U and a collection wire on the same side (and 2 more on the other side)
- 36° wires cross the collection wires just once a side

LBNE Far Detector Geometries

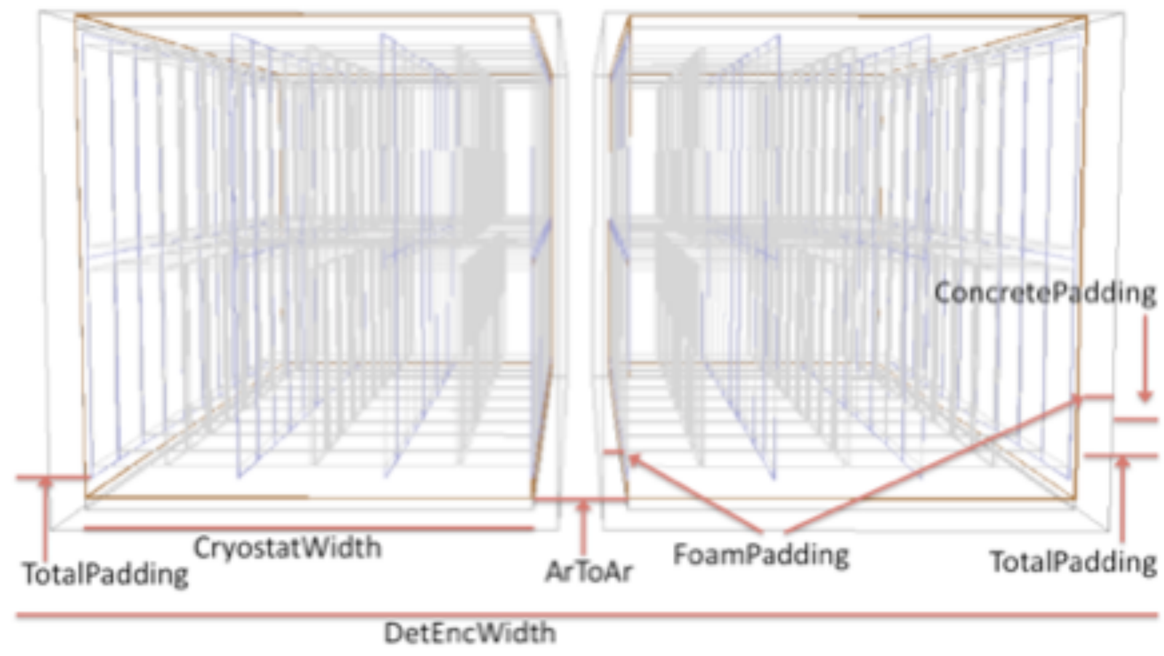
LBNE (as part of the facility LBNF) has special geometry needs:

- Experiment design is still underway... options:
  - 10 kt, 34 kt, or more? (P5 suggests ≧ 40 kt)
  - Surface or underground
    - affects choice of max. drift length to mitigate space charge effects
    - 2.5 m drift on surface, 3.5 m drift underground
  - Induction-plane wire angle
    - ± 45° was optimized for resolution on γ conversion distances in π^0 decay in three views
    - Wrapped induction wires cause ambiguities (more on this later)
  - Other detector technologies may be chosen. Two-phase, or other ideas brought by international collaborators

A **10 kt surface far detector** geometry with 240 TPC's

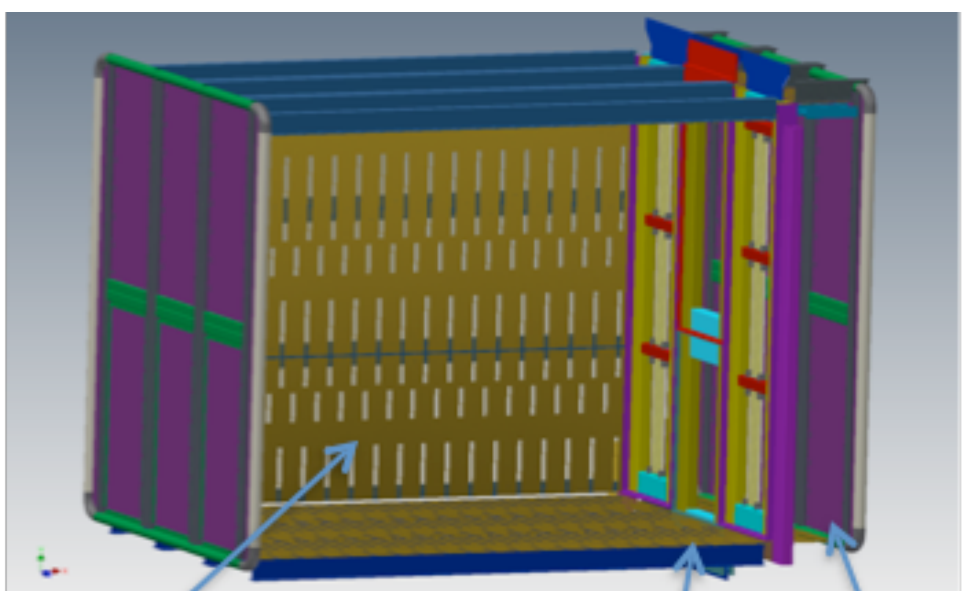
The size creates **computing challenges** (see Gianluca's talk)

T. Alion (S. Carolina)



LBNE’s 35 t Prototype Geometry

- Narrow APA’s
- 45° wires
- More wrapping turns than even in the far detector!
  - Harder reconstruction than even FD
- Three kinds of photon detectors
- Need detailed simulations of photon propagation
  - Necessary for fair comparisons of detector performance

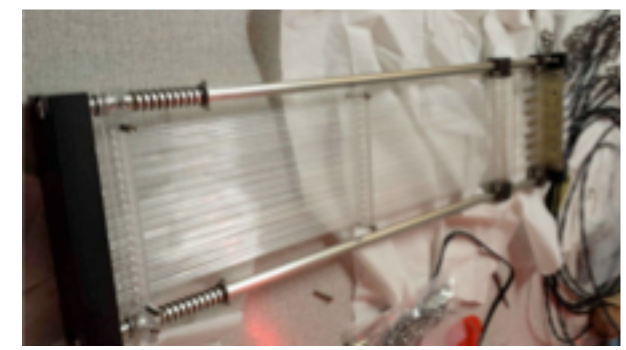


long drift volume (2.5m)

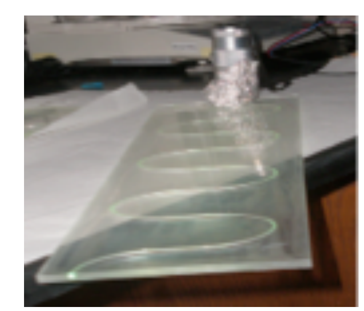
Anode plane assmblies

Short drift volume

Bars coated with WLS

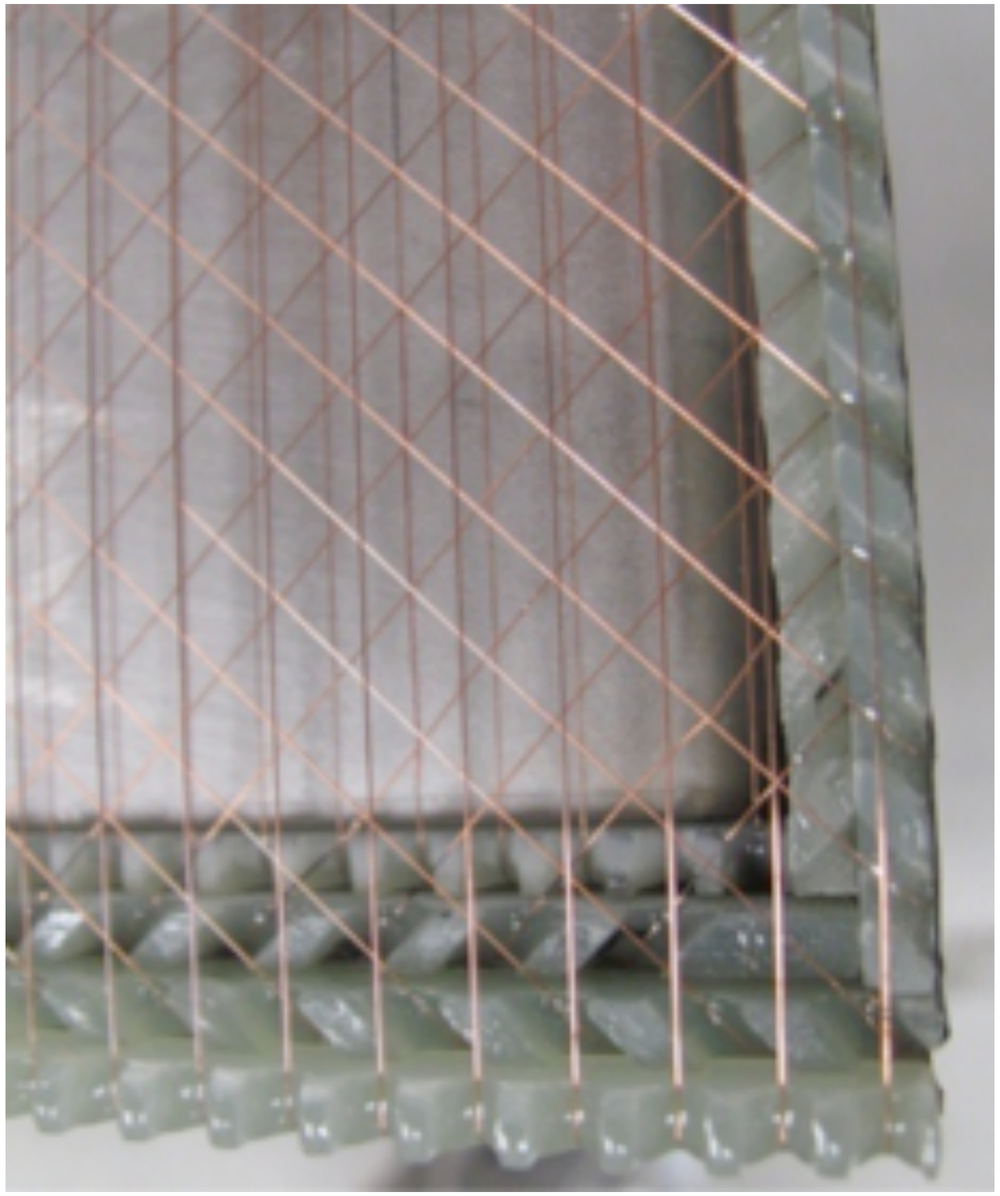


Fibers coated with WLS



Two-step WLS
(second WLS on embedded fiber)

Drift Modeling with Wrapped Wires



Potential map far away from the edges. How is this modified as wires wrap around? G10 combs may collect surface charge

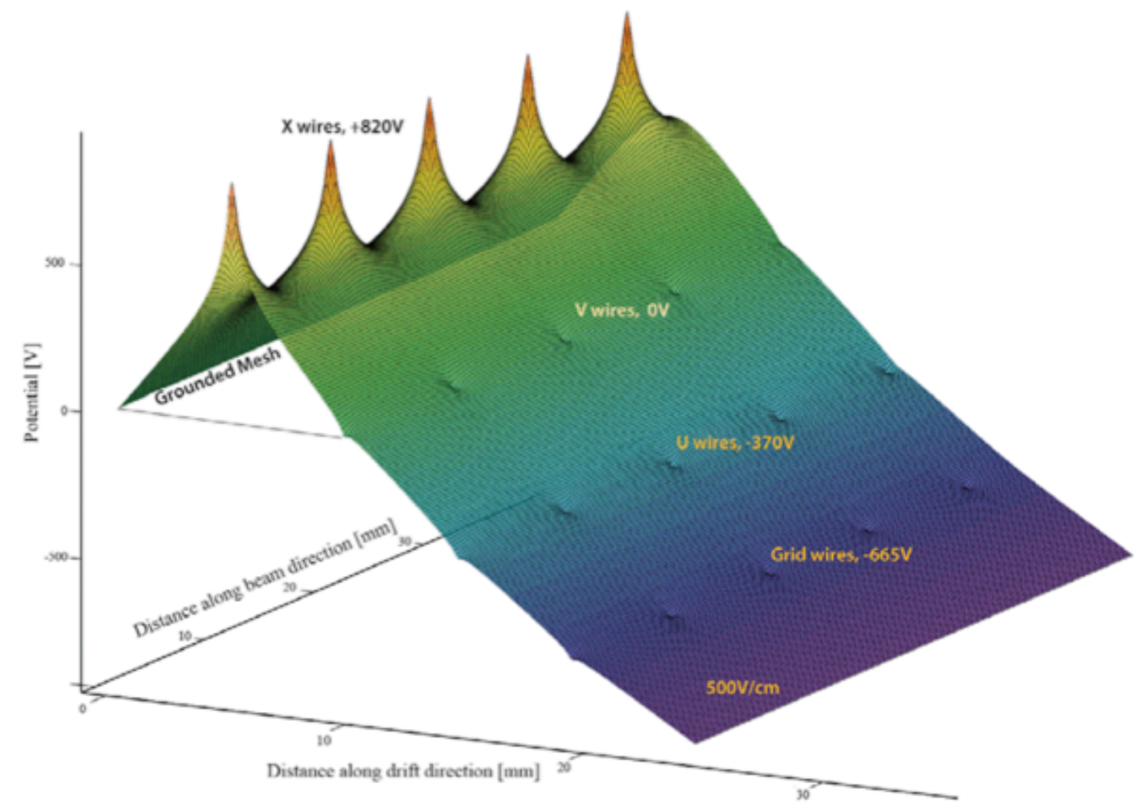


Figure 3–3: A surface plot of the electric potential distribution near the wire planes. The voltages on the wire planes are biased to provide complete electron transparency through the first three planes, and complete collection on the fourth plane.

Electric Field in the edges/corners is not known precisely

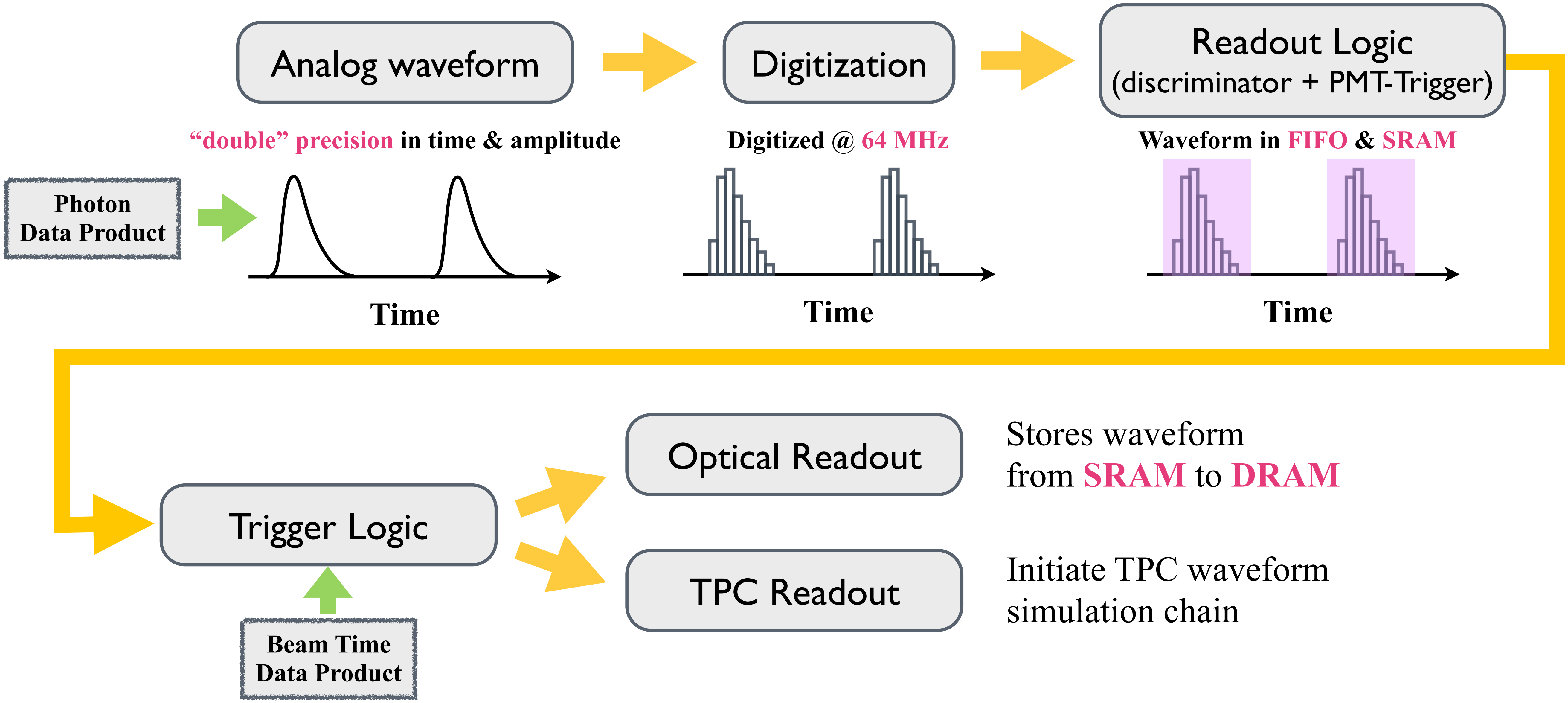
- Hits are lost?
- Hits are distorted?
- Charge is collected on induction plane wires?
- Maybe all of the above?

One of the main goals of the 35 ton prototype is to characterize the impact of wrapped wires on our ability to make measurements.

MicroBooNE
Readout Electronics
Simulation

Readout Electronics Simulation ... Optical

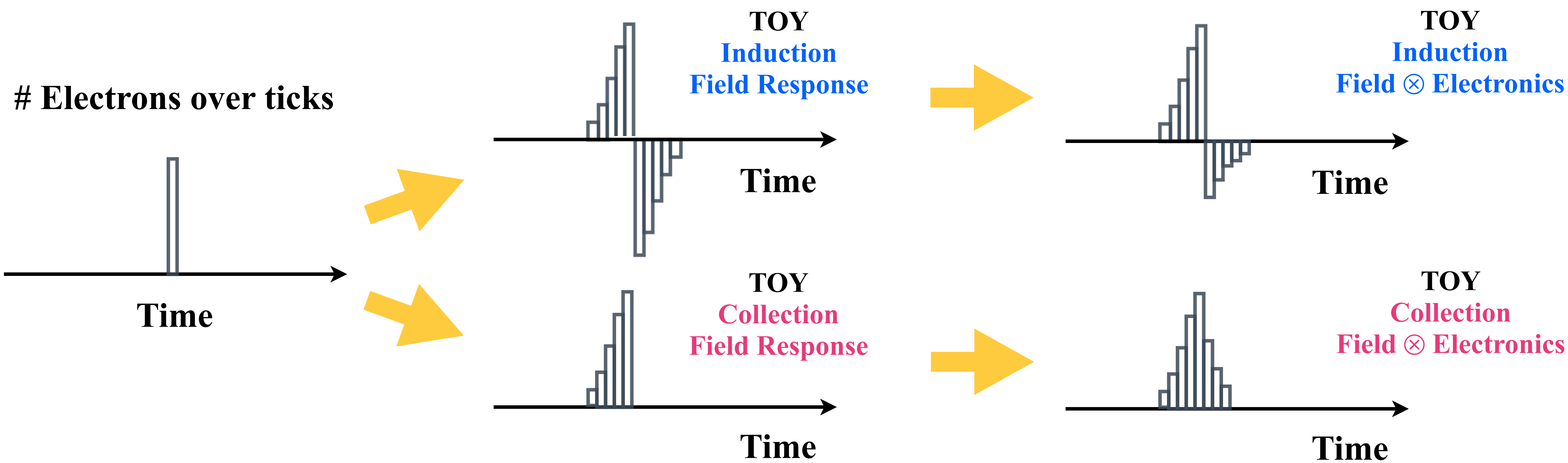
- Optical detector readout ... Discriminator & Trigger
  - Each optical detector receives a collection of photons
  - Simulate **analog waveform**, **digitizer**, **discriminator readout logic**
  - **Trigger** algorithm issues readout trigger for TPC and optical detector
    - “AND” condition among PMT-Trigger (from discriminator) and Beam



Readout Electronics Simulation ... TPC

- TPC ... improvements in Signal Shaping
  - Input: # of drifted electrons per wire, per digitization tick
  - **Signal shaping** ... 2 ingredients
    - **Field response** function
    - **Electronics response** function
    - Idea behind: same convolution kernel can be used for reconstruction
  - **Improving ingredients**
    - Incorporating noise & gain from testing the real electronics + cryostat
    - Detailed study on how impact parameter affects field response

Bruce will cover this
in his talk with very much detail



To-Do's?

~ From LBNE & MicroBooNE ~

High Priority To-Do's

- **LBNE**
  - Finalize optical detector geometry & simulation for 35t detector
    - To do for a large MC production
  - Figure out which one is better: 36 or 45 degree wire angle?
    - Decision by reco group
  - Optimize FD simulation resource usage
  - Figure out what to do with charge drift in between APA's (35 ton first)

- **MicroBooNE**
  - Introduction of field non-uniformity
    - Considering a possibility for drift electrons (no discussion for optical yet)
  - Comparison of NEST vs. existing algorithms
  - Optical simulation update
    - New PhotonLibrary for the updated geometry
    - Incorporate WLS in simulation (smearing of timing)
    - Incorporate photon ToF & Cerenkov light in "fast" simulation
  - With data from TPC electronics testing, revisit the MC signal shaping for TPC
  - Studying an impact of precise drift time/position for field response simulation

Summary

Summary

- **LArSoft** as a LArTPC simulation framework
  - Working framework being used by number of experiments
- Briefly described **current detector response simulation**
  - Voxelization and energy deposition
  - Production and transportation of drift electrons and scintillation light
    - NEST: a handle for better simulation model
  - Readout electronics simulation
    - The crucial part: signal shaping by Bruce B. (next talk)
- **News from MicroBooNE & LBNE**
  - They have done a lot! In particular...
    - geometry & optical simulation related items for LBNE
    - geometry & readout electronics simulation for MicroBooNE
  - ... and (found) a lot more to be done :)

Back Up Slides

Event Generator Interface

- Three kinds of interfaces
  - **Running a generator algorithm on the fly**
    - GENIE, CRY ...
  - Dedicated interface module to **read in (externally) generated events**
    - Such as generated events stored in a particular ROOT TTree format data
  - Interface to read in **generic HEPEvt format text file**
- Produce a data product: "MCTruth"
  - Part of "NuTools" (on which LArSoft depends)
  - MCTruth information is taken by LArG4 module
    - LArSoft native data producer module to run Geant4 simulation

Next: Produced particle tracking using Geant4

Energy Deposition Model

$$\mathcal{E}_{recomb}(\vec{E}, \rho)$$

Birk's Model

$$\frac{A}{1 + k/\mathcal{E} dE/dx}$$

$$A_{3t} = 0.800 \pm 0.003$$

$$k_{3t} = 0.0486 \pm 0.0006 \ \mathrm{kV/cm} \frac{\mathrm{g/cm^2}}{\mathrm{MeV}}$$

NIM A523:275-286,2004

Used by ICARUS

Modified Box Model

$$\frac{\ln(A + B/\mathcal{E} \ dE/dx)}{B/\mathcal{E} \ dE/dx}$$

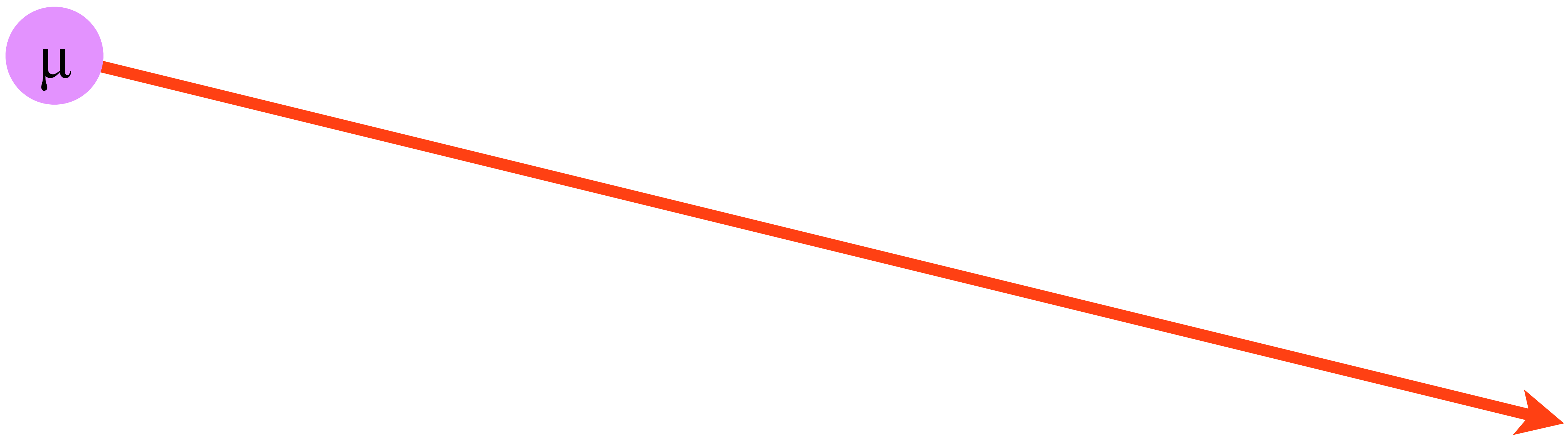
$$A = 0.930$$

$$B = 0.212 \ (g/MeV\,cm^2)(kV/cm)$$

JINST 8 (2013) P08005

Used by ArgoNeuT

Particle Interaction



- Run-time configuration of simulation parameters
  - Geant4 physics lists
    - “QGSP_BERT” by default (+ “Optical” for MicroBooNE)
  - Detector / material properties
    - Electric field, temperature, electron life-time
    - Some derived parameters
      - ✓ Density = $-0.00615 \times T + 1.928$ [g/cm^3]

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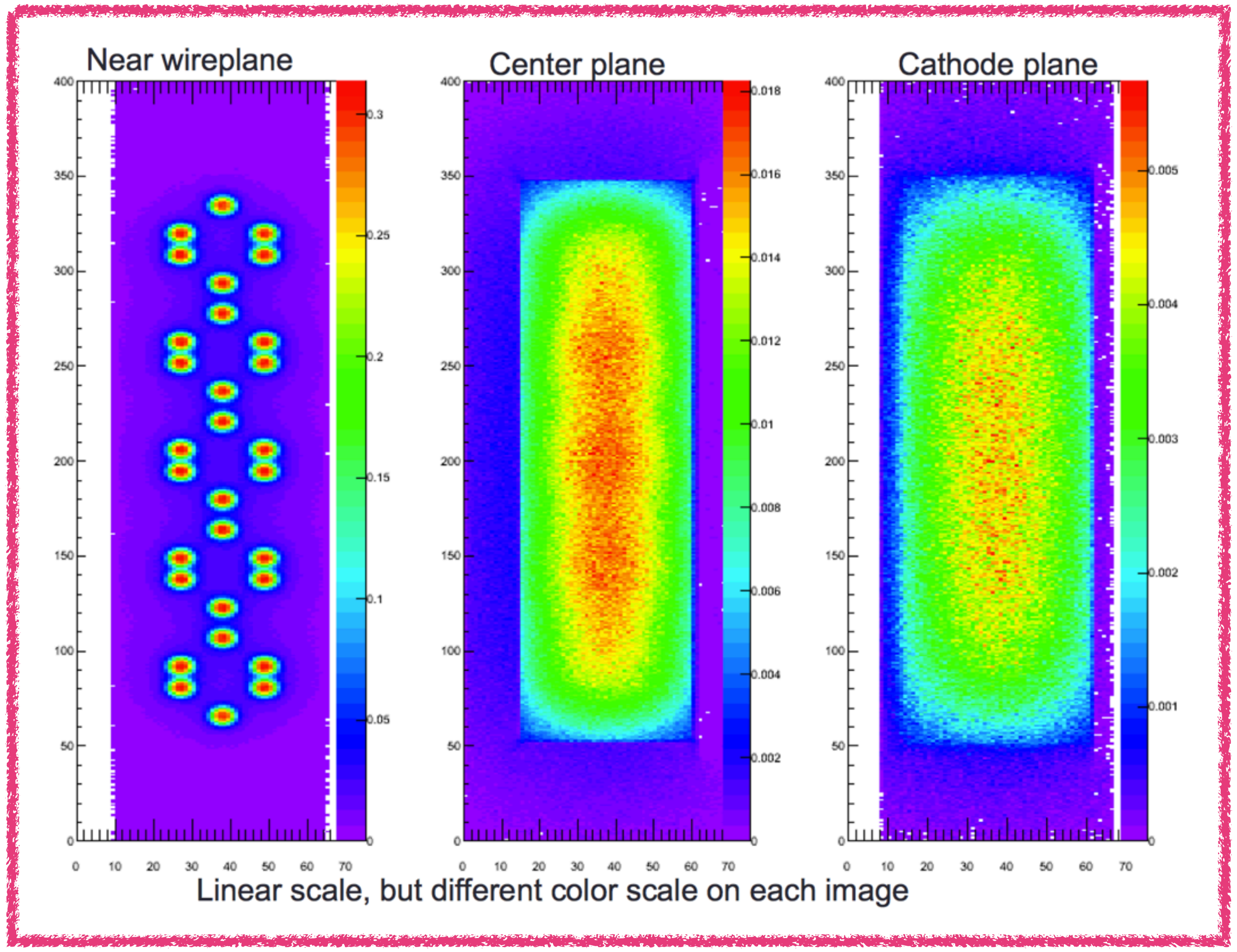
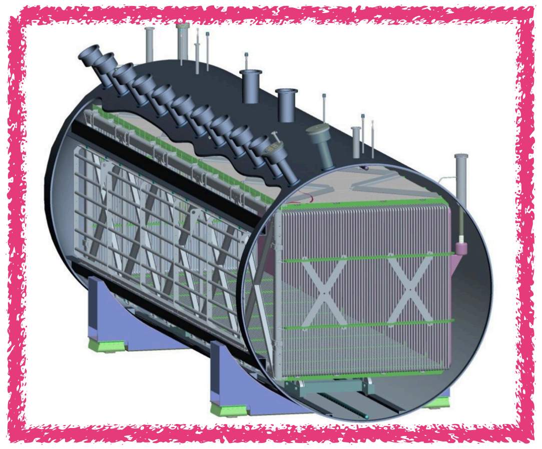


PhotonLibrary
Acceptance map produced for MicroBooNE geometry



Slide: courtesy of Ben Jones