Photon Detector Requirements, Simulation, and Reconstruction

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ProtoDUNE Photon Detector Review
University of Chicago

August 2nd, 2016

Introduction

- Why we need photon detectors in DUNE.
  - And why we need them in protoDUNE.
- How we simulate and reconstruction photon detector signals.
- Detector performance estimates.
  - Proton decay
  - Supernova neutrinos

Addressing point 1 of the charge.

Role of Photon Detectors in DUNE

- A time projection chamber relies on having a time to locate an event in space.
  - Light is detected ~instantly relative to the drift time of charge in the TPC.
  - This is needed to correct the calorimetric energy measurement for attenuation and in order to properly fiducialize events.

- We need t_0 to enable the non-beam parts of the DUNE physics programs.
  - Nucleon decay
  - Supernova neutrinos

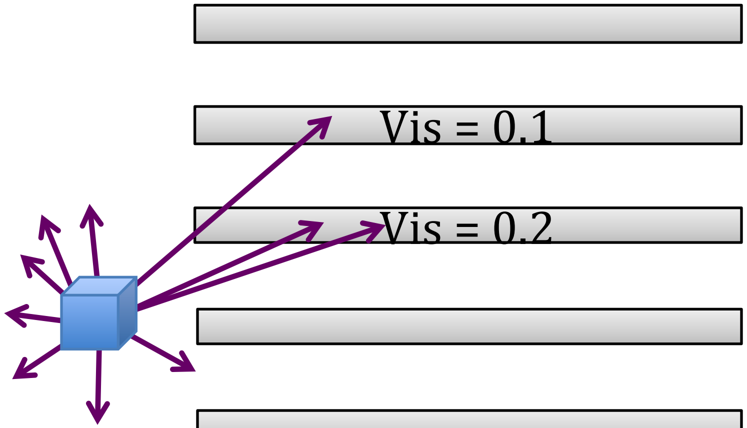
- Photon detectors in protoDUNE:
  - We need to evaluate light yield and other performance metrics in practice.
  - May also enable better identification and rejection of cosmic rays overlaid on the beam events.

Official Photon Detector Requirements

- Event time shall be measured with high efficiency to allow the measurement of the drift coordinate with sufficient precision for events with visible energy above 200 MeV.
- Event time for events with visible energy <200 MeV shall be measured with high efficiency and sufficient precision to correct for drift time and improve energy resolution.
- Absolute event time shall be measured with sufficient accuracy to allow global analysis of supernova neutrino wave front.
- We have estimated the that 0.1 PE/MeV at the CPA is required to meet these goals.

Simulating Optical Transport

- Adopt a strategy developed by μBooNE: **Photon Library**
- Lookup table giving "visibility" of each position in the detector for each optical detector
  - For each "voxel" in the detector, generate isotropic photons
  - Visibility: fraction that end up on each optical detector.



LAr Optical Properties	
Absorption Length	20 m
Rayleigh Scattering	60 cm

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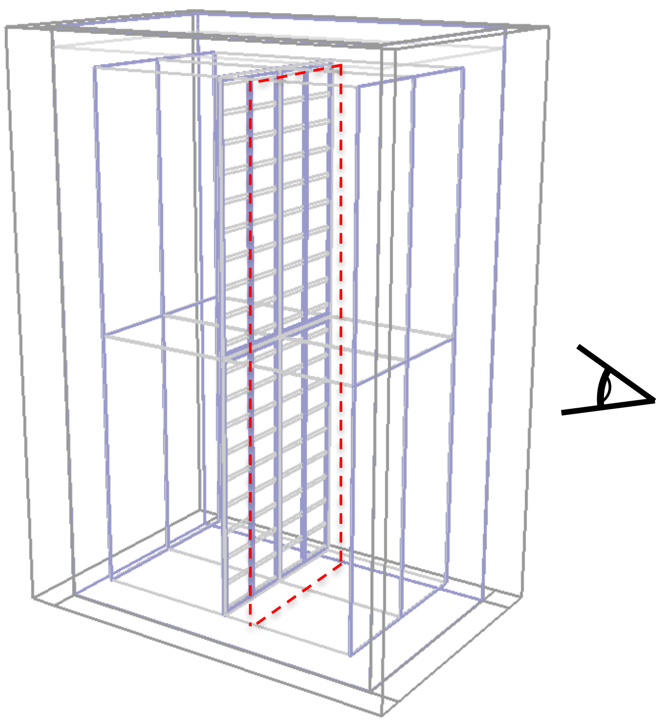
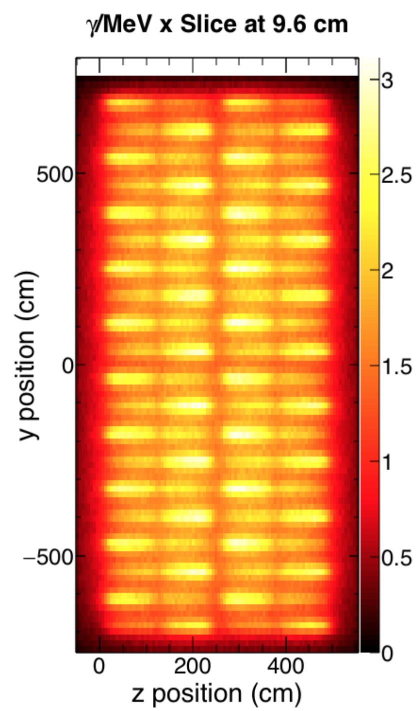
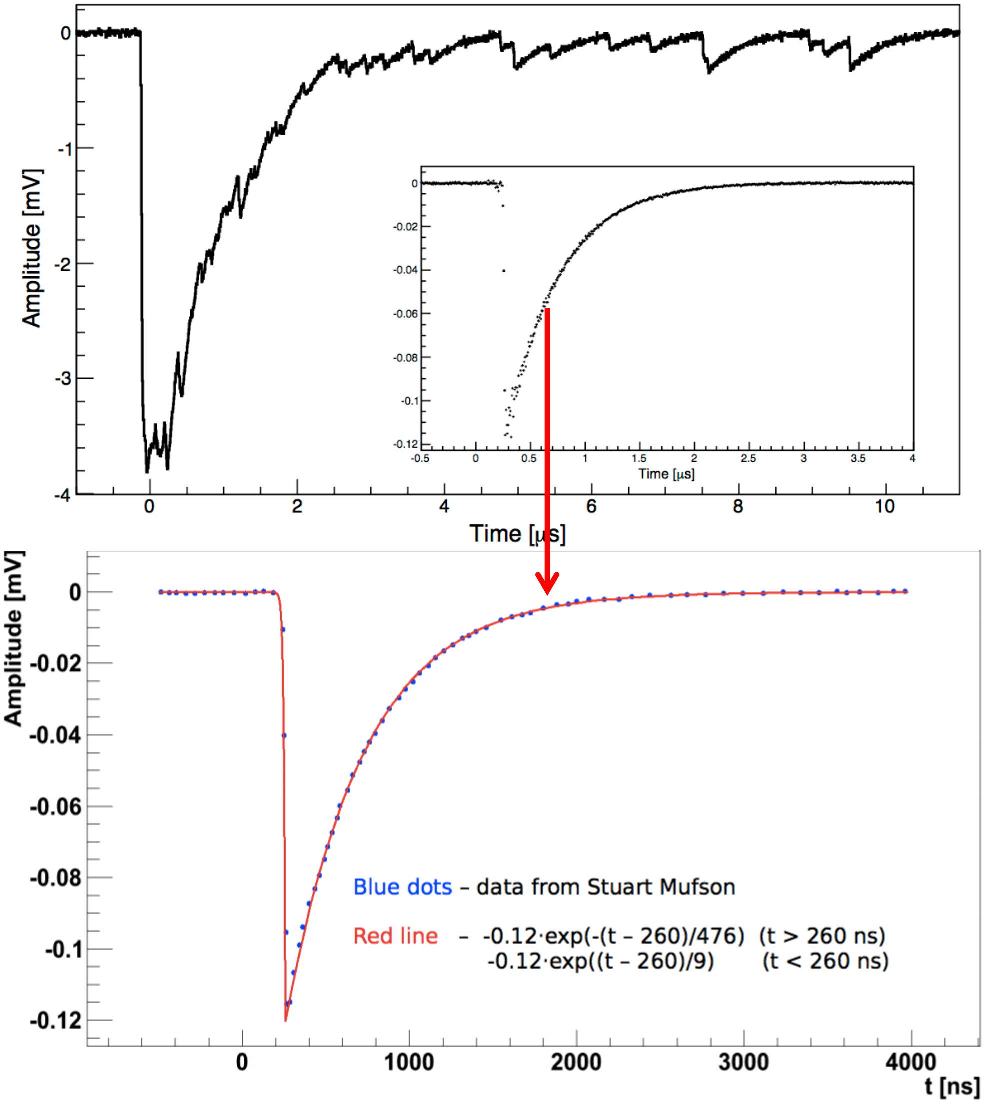


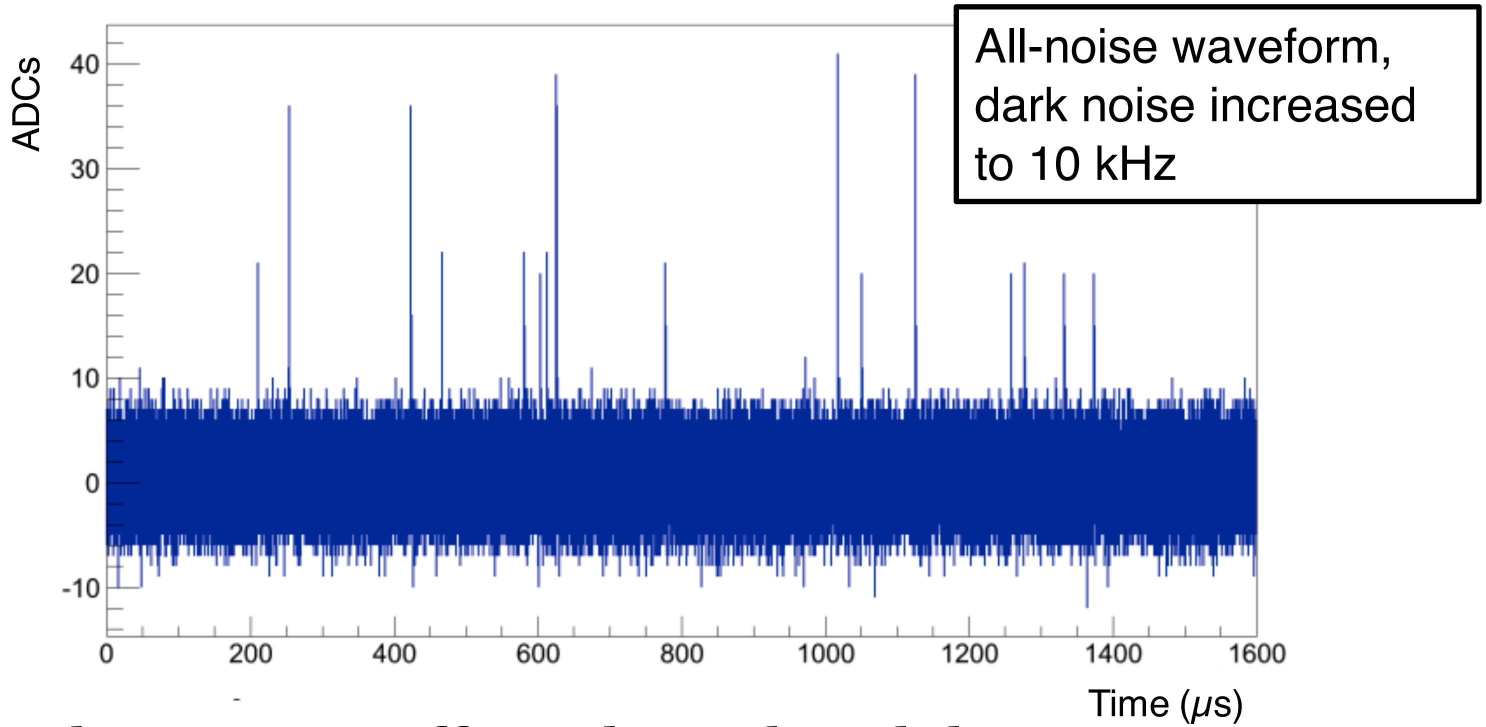


Simulating Electronics Response

- Once photons arrive at optical detectors, introduce:
  - Mapping to multiple electronics channels
  - Scintillation time distribution: early (6 ns) and late (1.6 μs)
- Simulate signals by adding together single-PE waveforms.
  - Based on measurements made at IU (arXiv:1408.1763)
- Simulating response with 3 ganged SiPMs in the works by a student at KSU.
  - Also based on IU measurements.

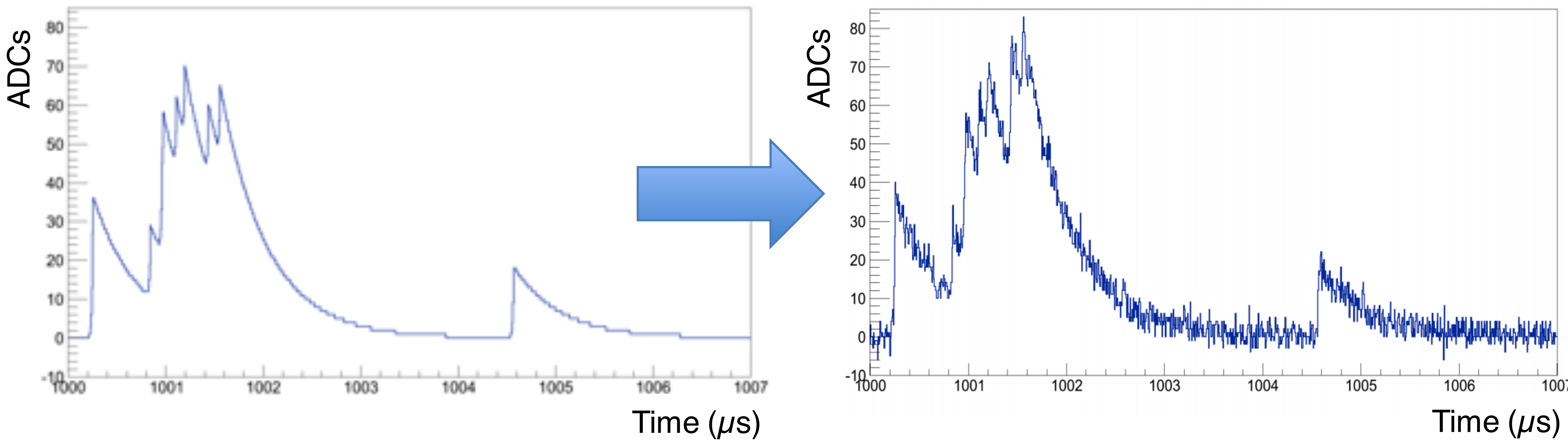


Simulating Electronics Response



- Other electronics effects based on lab measurements at IU and Hawaii
  - Line noise (σ=2.6 ADCs)
  - Dark noise (10 Hz/SiPM)
  - Cross talk (16%)

Simulating Electronics Response



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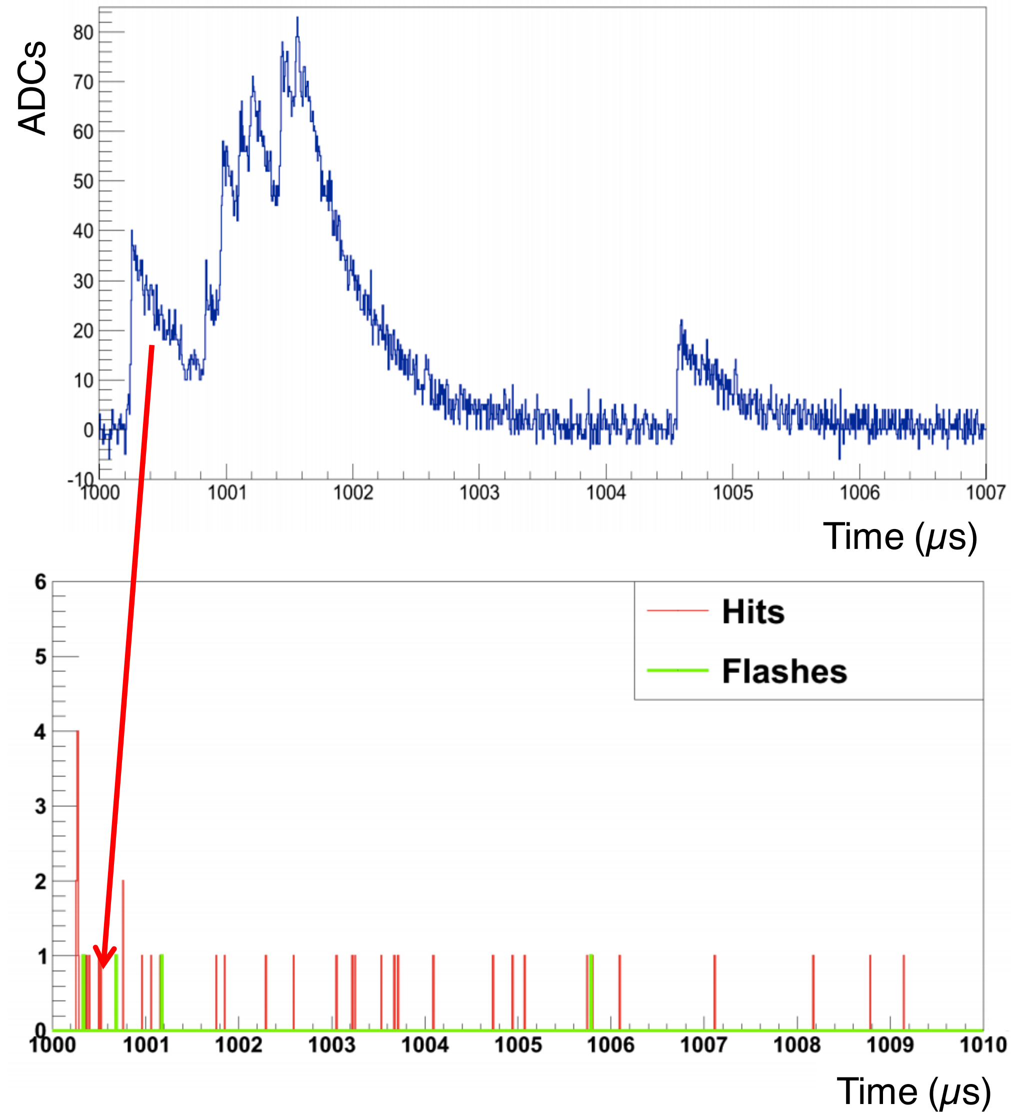
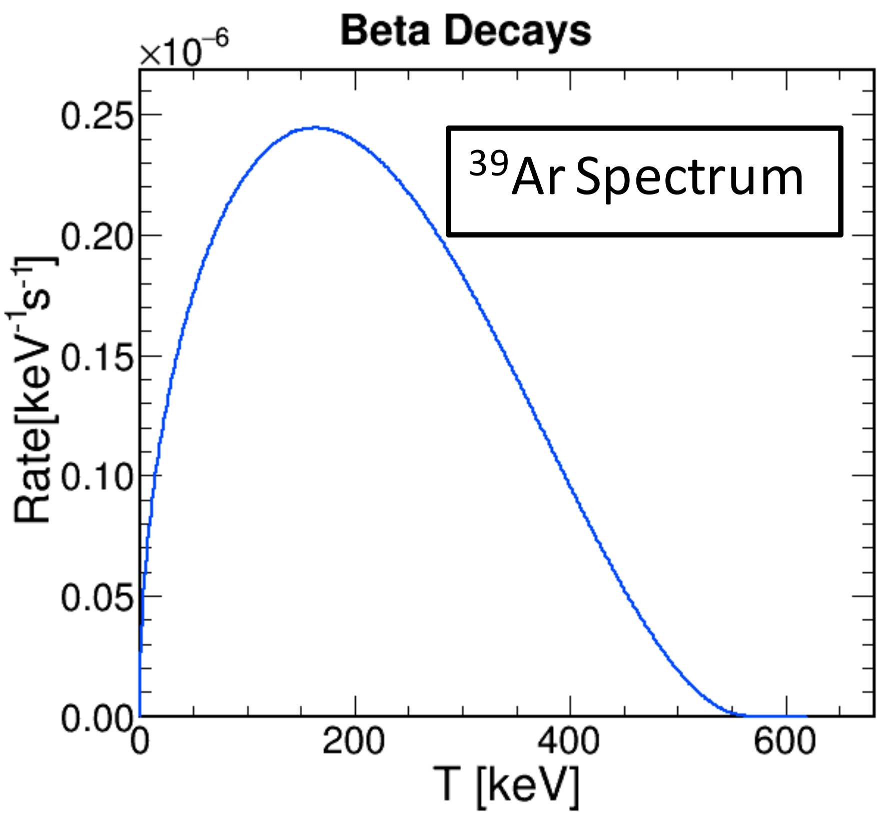
Reconstructing Optical Signals

- Reconstruct "Optical Hits"
  - Identify pulses of light in a single channel
- Reconstruct a "Flash"
  - Collect hits which are close in time across multiple channels
- A flash should correspond to a single light source within the detector
  - A time, an amount of light, an approximate position

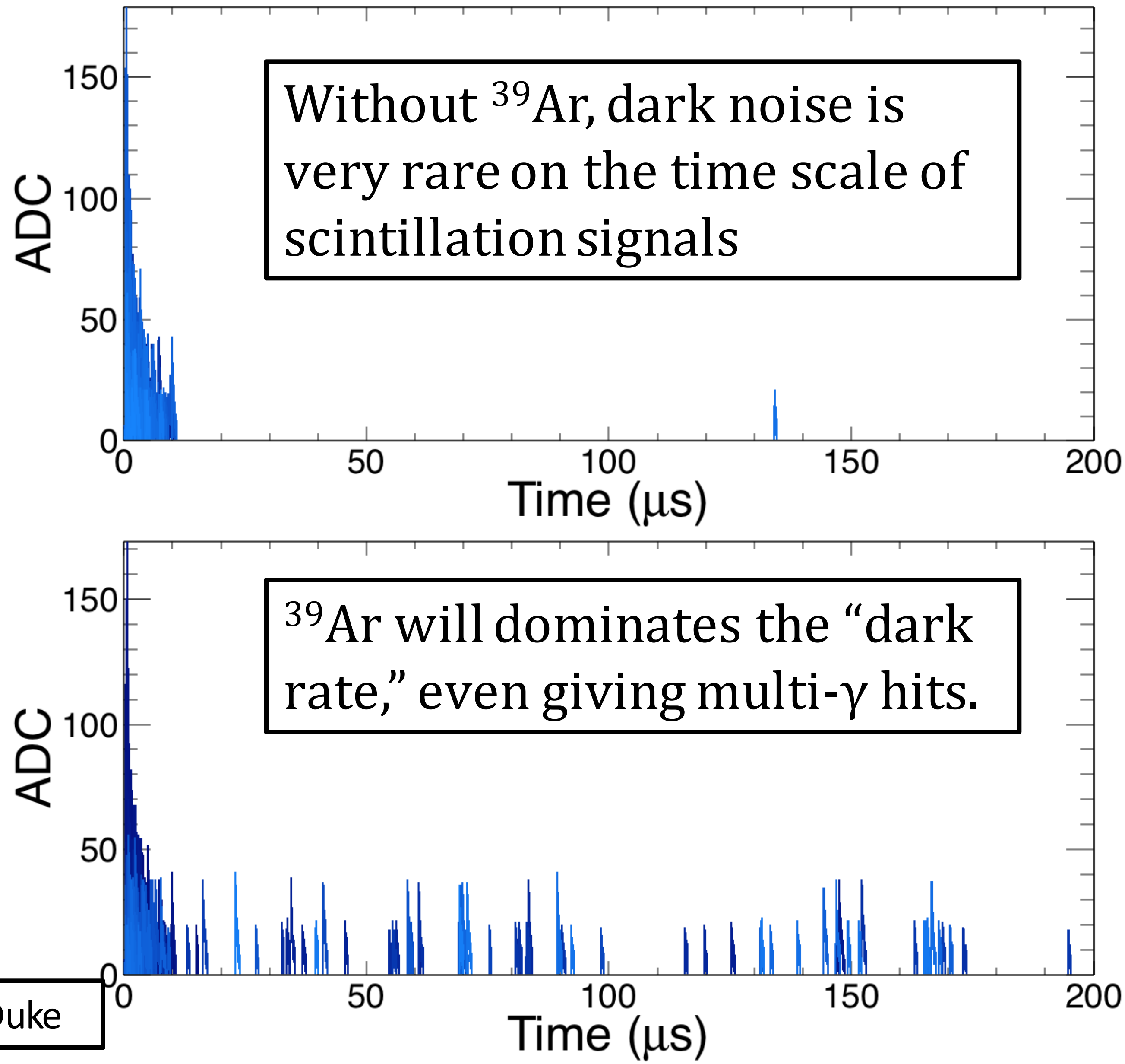


Photons from ^{39}Ar

- ^{39}Ar β decays, ~500 keV endpoint
  - 12,000 photons
- Energy is low, but visible if close to the PDs
  - 3.5 γ's if decay is close to the PDs
    - geo ε = 10%, det. ε = 0.3%
- A potentially significant background rate
  - 1.01 Bq/kg
- Simulate in both active and passive LAr.



Radiological Backgrounds



Gleb Sinev, Duke

Performance Estimates

- The obvious question: what collection efficiency is needed to meet the DUNE physics goals?
  - Reconstruct nucleon decays and exclude nucleon decay backgrounds throughout the detector volume, especially entering cosmogenics.
  - Have good efficiency for identifying t_0 for supernova neutrino events.

- Difficult to do the "inverse" problem with simulation.
  - Instead we will posit a "reasonable" performance for the photon detectors, and then show how that performs with:
    - Nucleon Decays
    - Supernovas
    - ^{39}Ar Backgrounds

- We will show you the current state of the art – reconstruction efficiency for nucleon decay and SN-like events and expected ^{39}Ar backgrounds at a range of thresholds.
  - We are working with much more realistic performance estimates – we expect to do better with time.

How much light do we need?

40,000 × 0.62 = 24,600 γ produced/MeV deposited

- Assumes nominal drift field
- Right now same yield per energy deposited is assumed

24,600 × 4.7%* = 1,200 γ/MeV reaching detectors

* Average geometrical acceptance

- Includes 30% shadowing from wire mesh.
- Scattering length ~60 cm

1,200 × **60%† × 0.5%‡** = 3.8 PE/MeV digitized

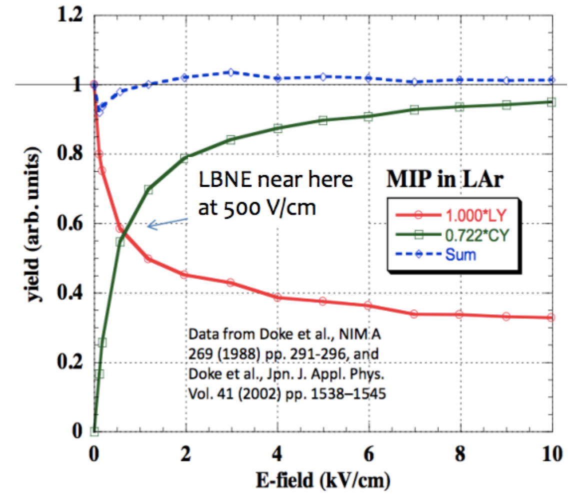
† Average with 2 m attenuation length

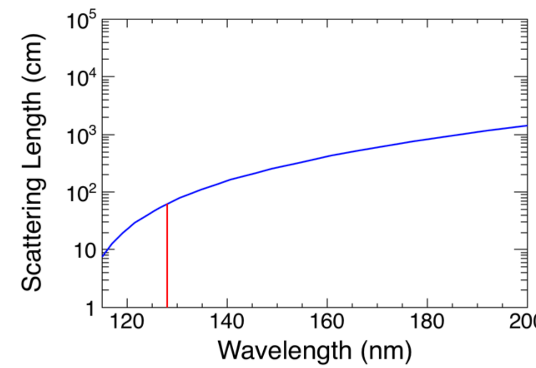
‡ Target efficiency at SiPM

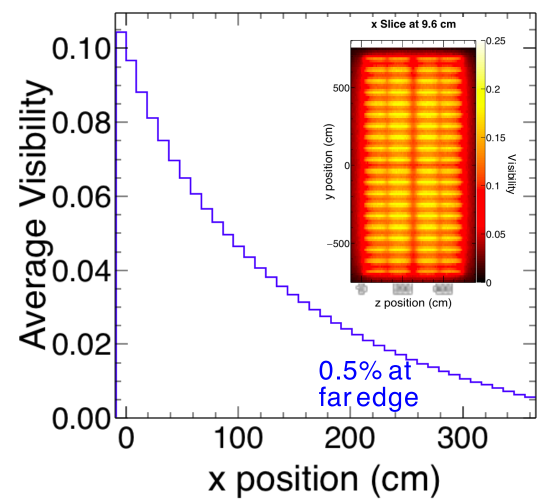
- About 10× lower at the CPA.

Not all late light will be usable, so in practice we expect **more than 1 PE/MeV and less than 4 PE/MeV.**

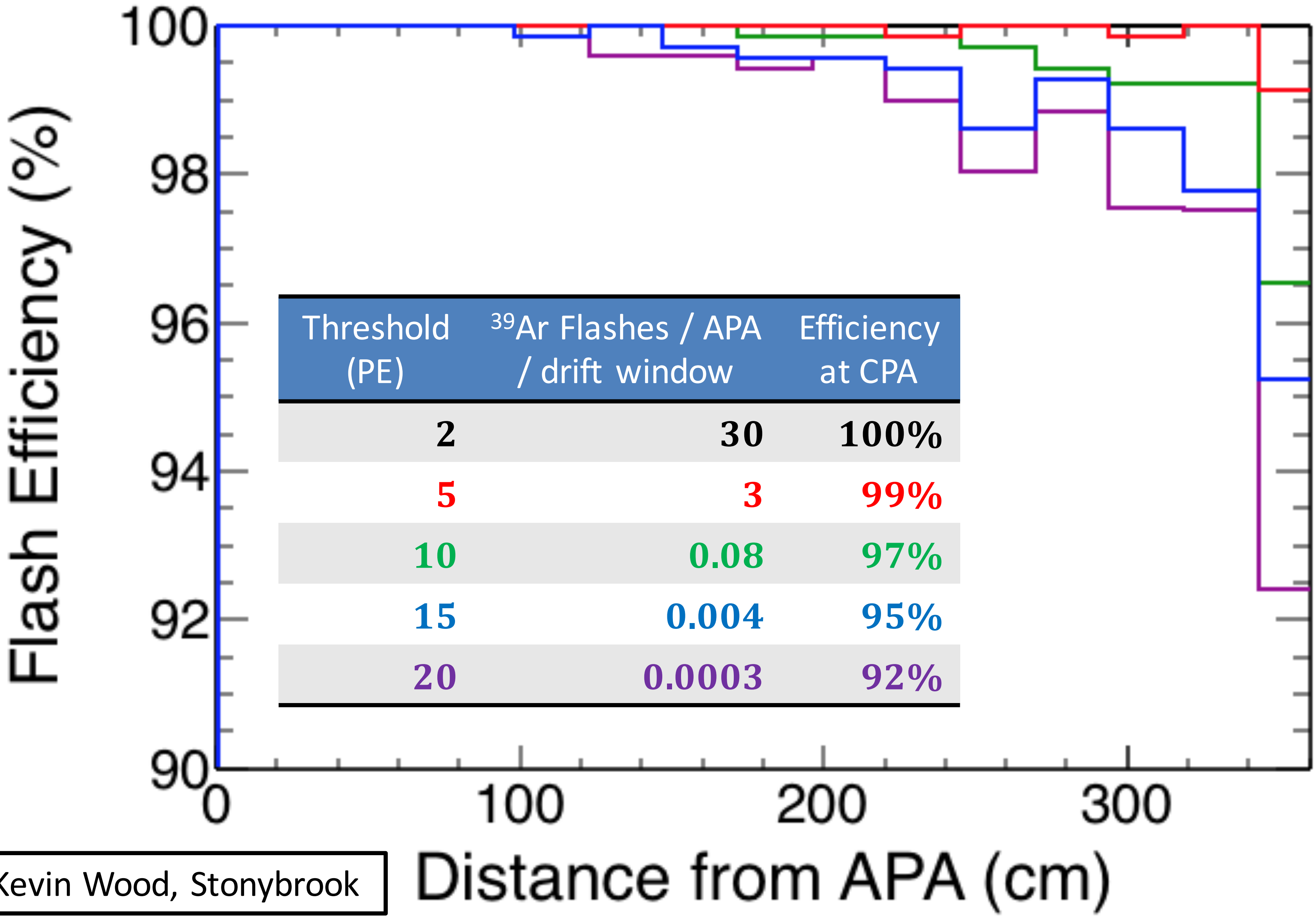
- 0.1 to 0.4 PE/MeV at the CPA







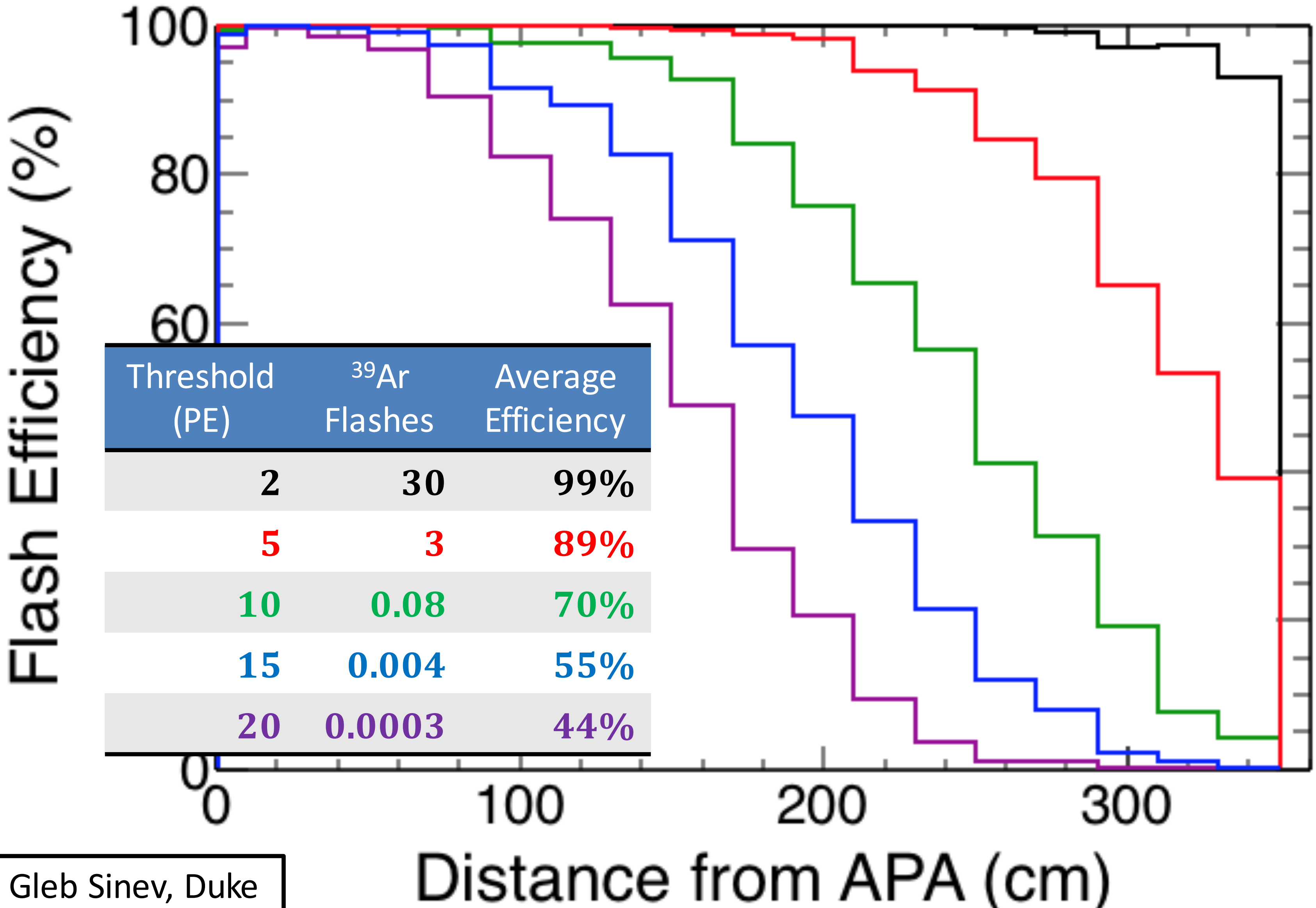
Nucleon Decay



Threshold (PE)	^{39}Ar Flashes / APA / drift window	Efficiency at CPA
2	30	100%
5	3	99%
10	0.08	97%
15	0.004	95%
20	0.0003	92%

Kevin Wood, Stonybrook

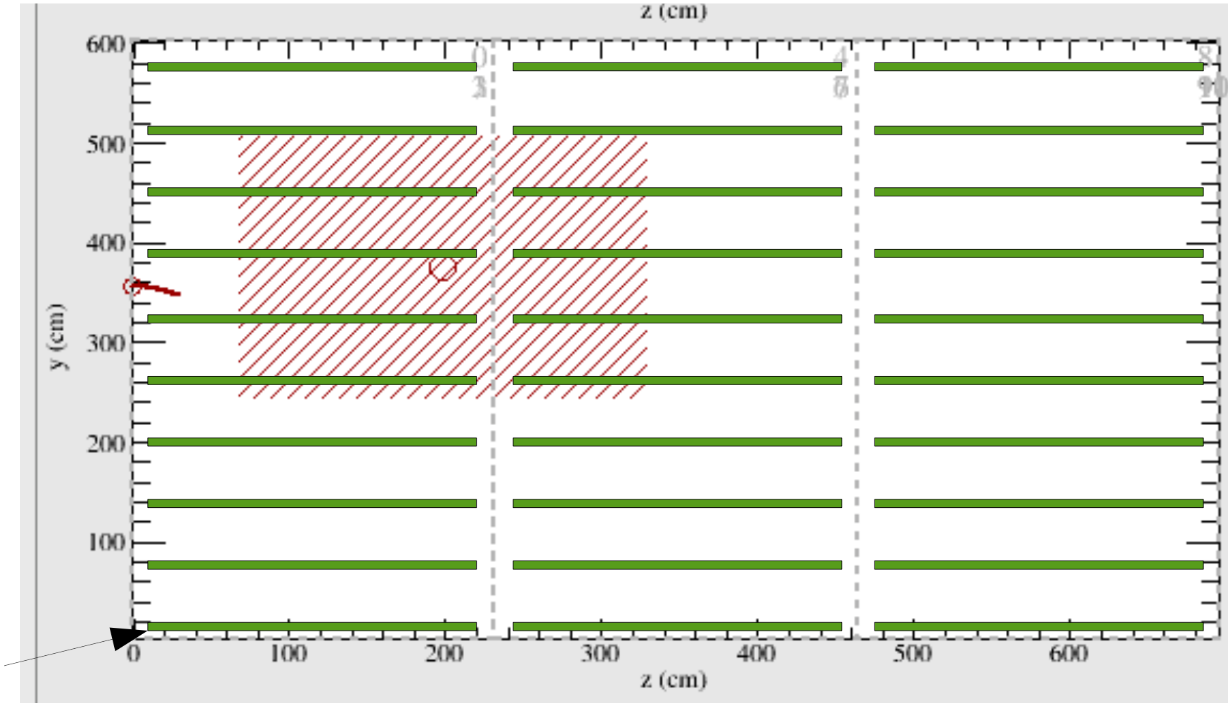
8 MeV Electrons (Supernova-like)



Threshold (PE)	^{39}Ar Flashes	Average Efficiency
2	**30**	**99%**
5	**3**	**89%**
10	**0.08**	**70%**
15	**0.004**	**55%**
20	**0.0003**	**44%**

Gleb Sinev, Duke

Photon Simulation in ProtoDUNE



- Also still a work in progress, but we are getting ready now.
- An early observation:
  - The coarseness of the PD "binning" in the beam direction skews the reconstructed position away from where we know the particles enter.
  - We are considering how to handle this now.

Bruce Howard, IU

Conclusions

- With our estimates of eventual detector performance, we enable the non-beam physics program at DUNE.
  - Excellent performance for nucleon decay.
  - Some efficiency even at the lowest supernova energies.

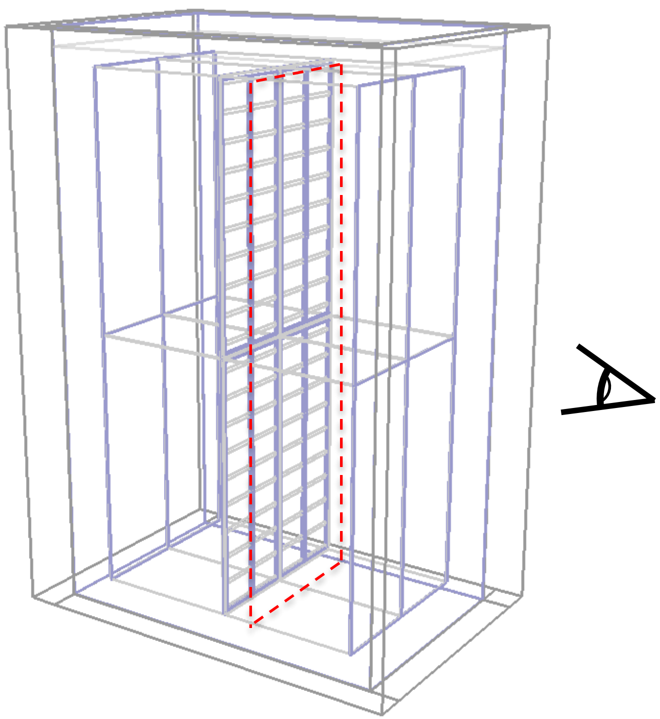
- However, we must **confirm** this before before we undertake the far detector.
  - We need better estimates of the real light yield in situ in **protoDUNE**.
  - We will continue to push on photon detector analysis tools like selections to mitigate ^{39}Ar…
  - and test the performance of those algorithms in **protoDUNE**.

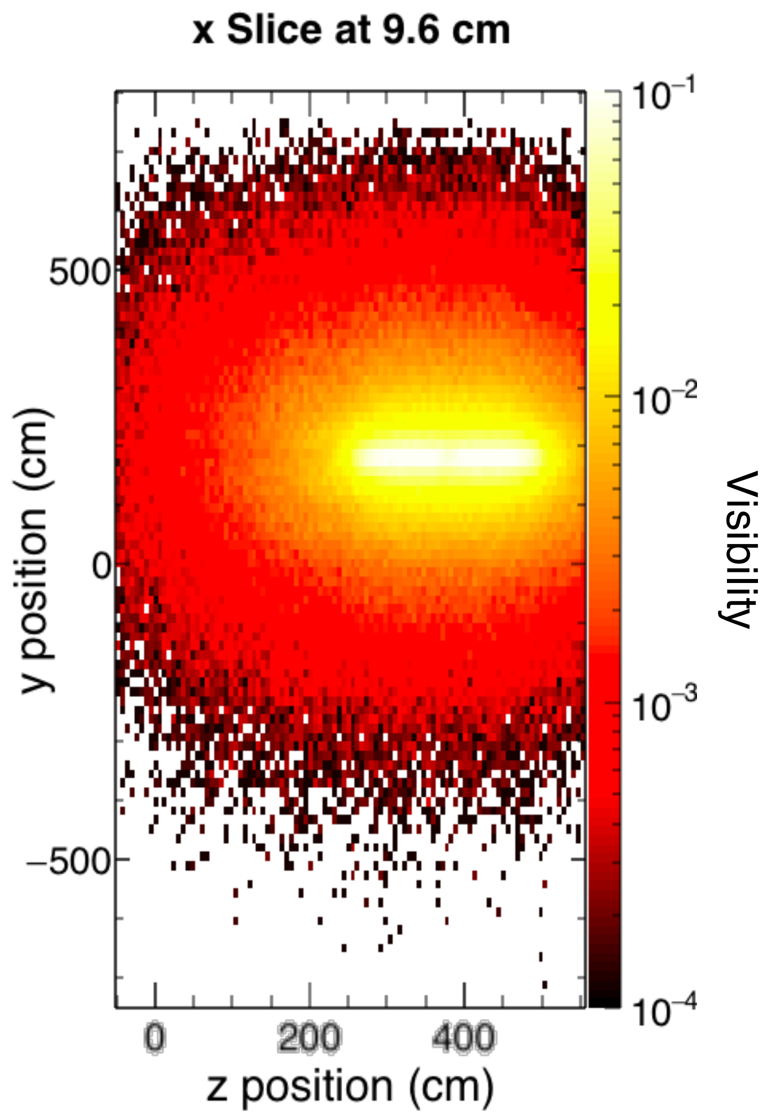
- We are also looking into what physics possibilities are opened up with a much more capable system, but that is beyond the scope of this review.

Backups

Simulating Optical Transport

- At right, a 2D slice from the Photon Library for a single photon detector.





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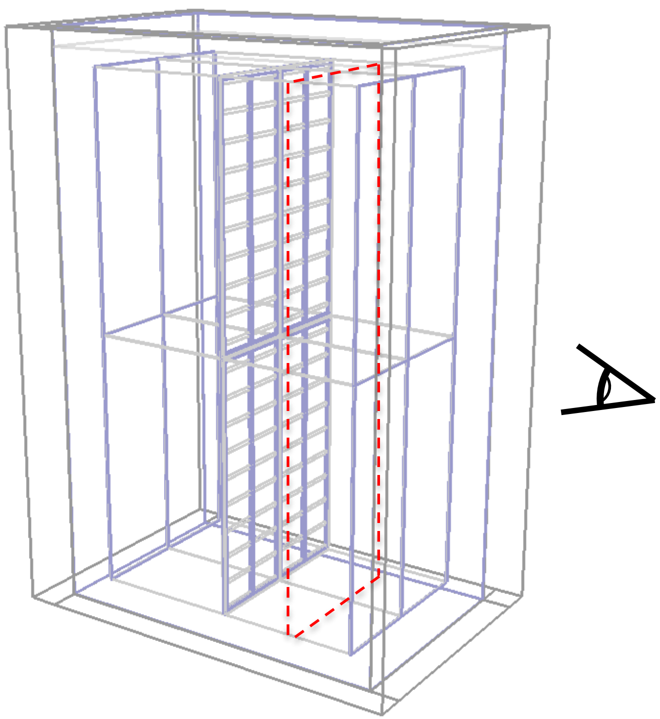

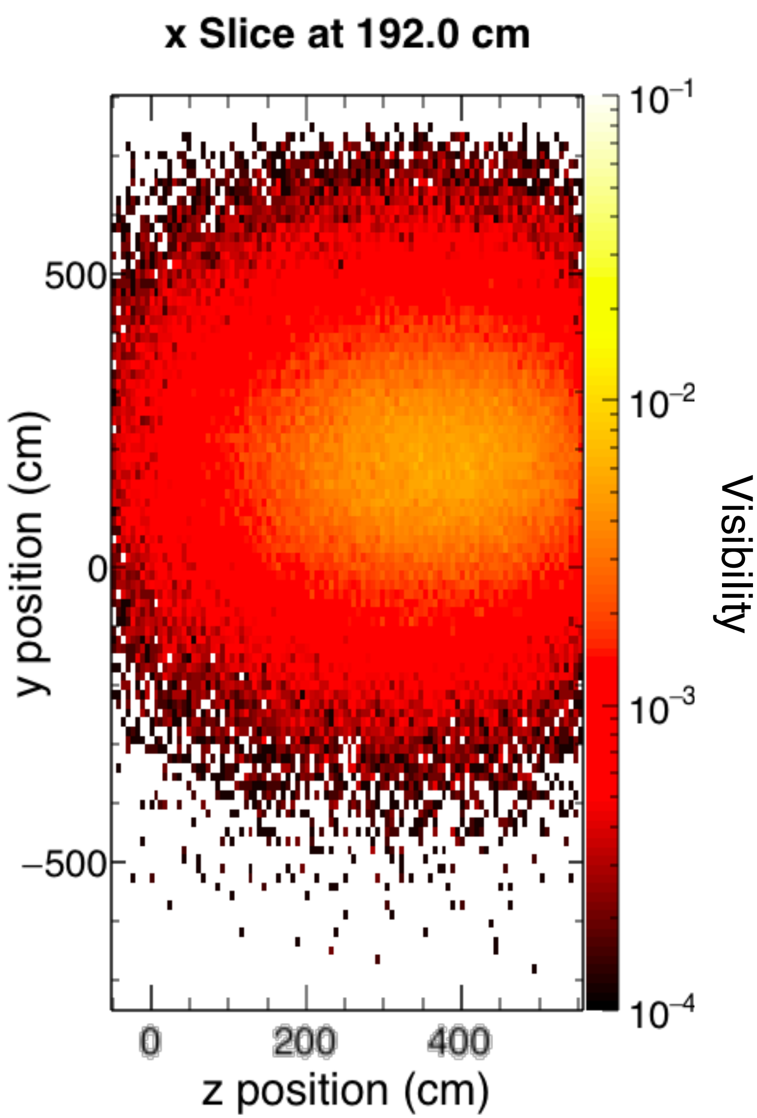

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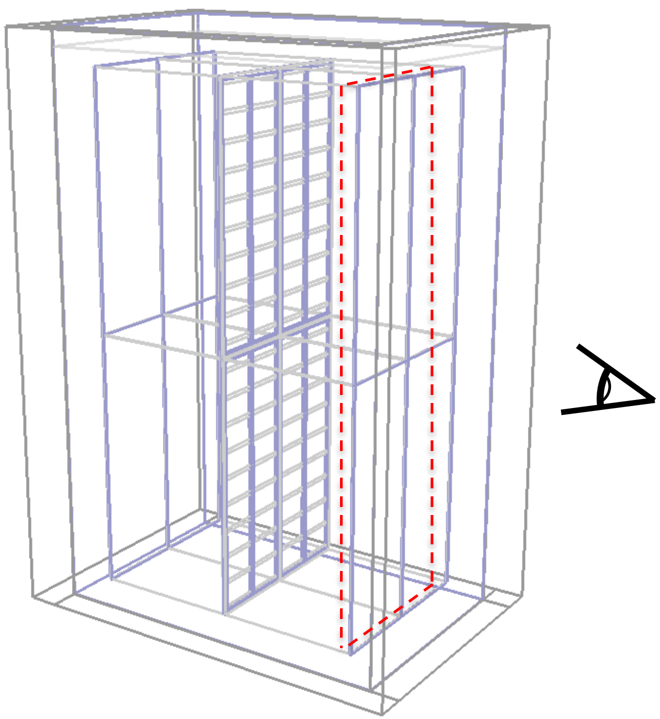
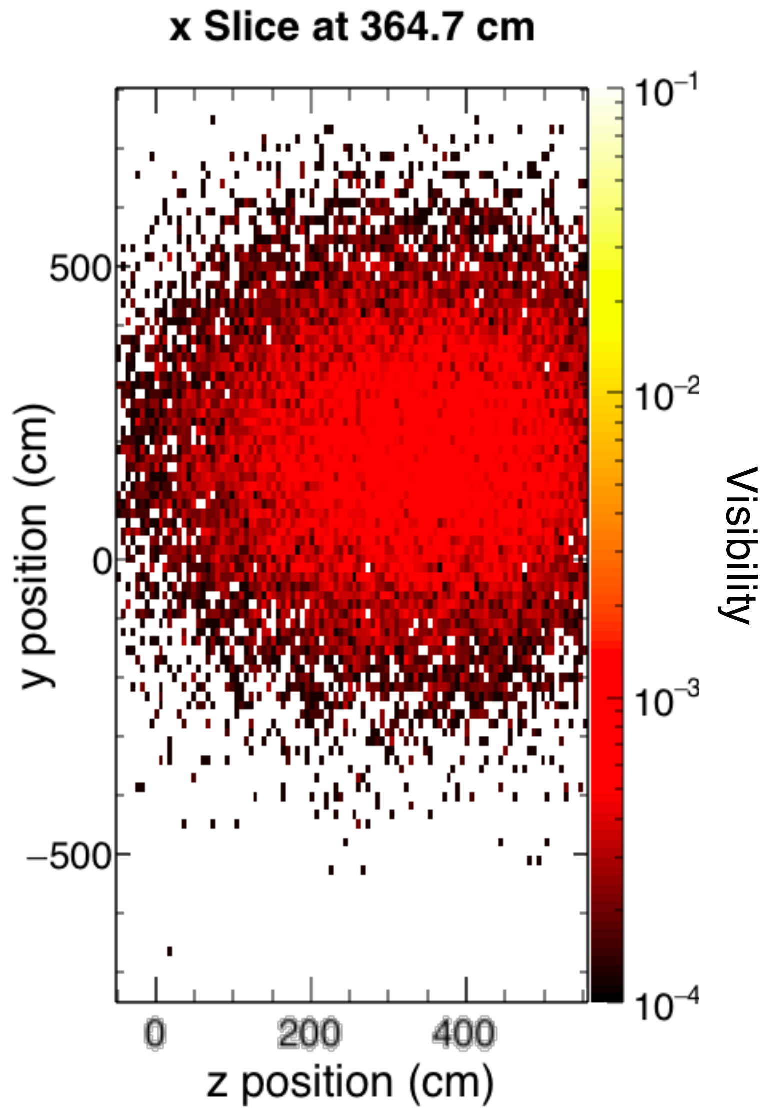
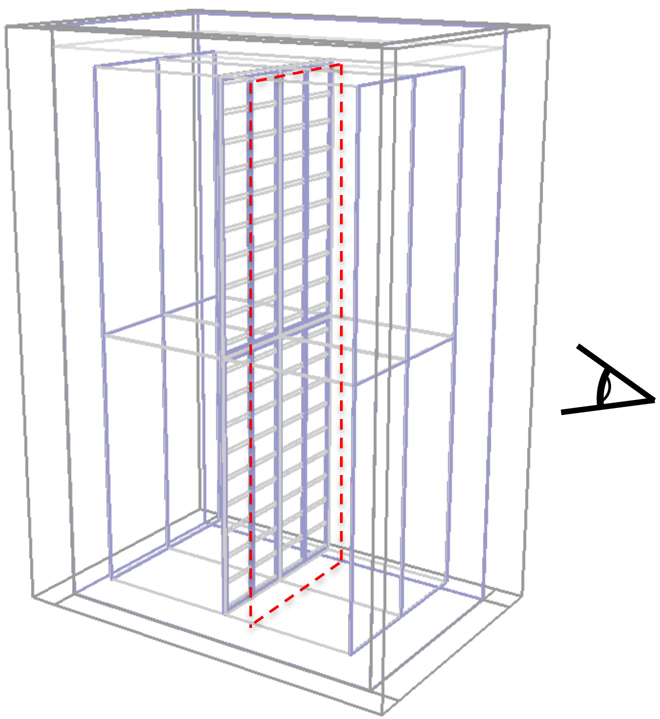
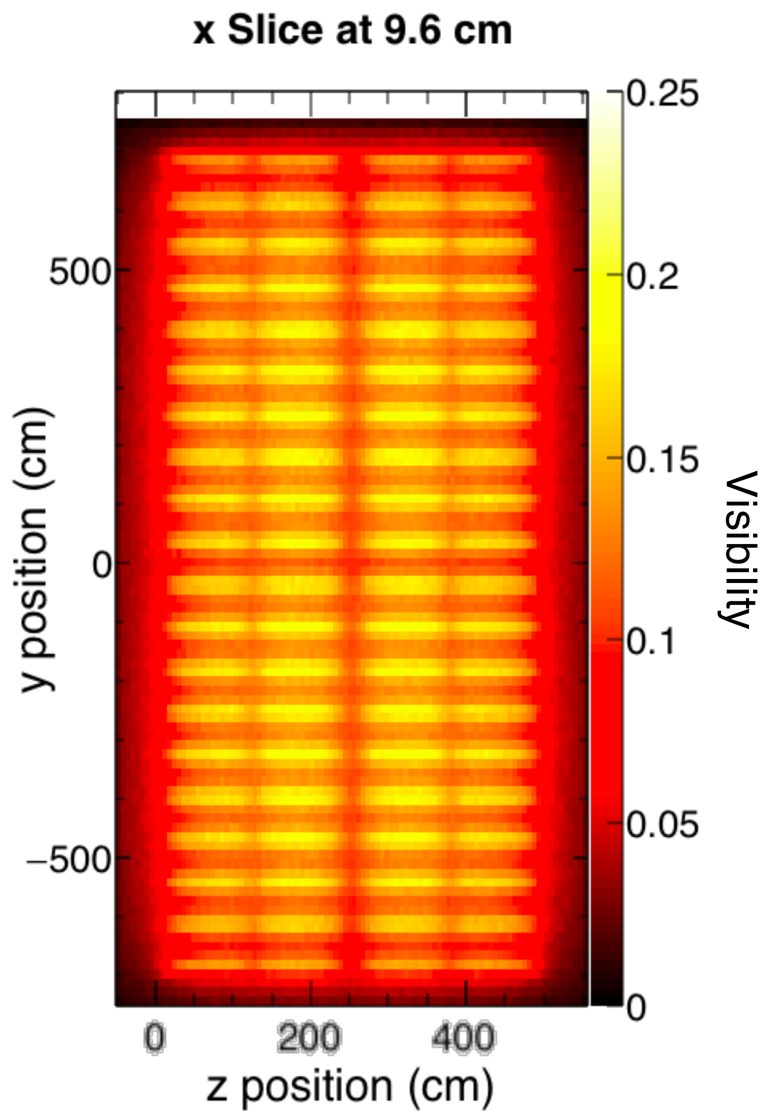




Simulating Optical Transport

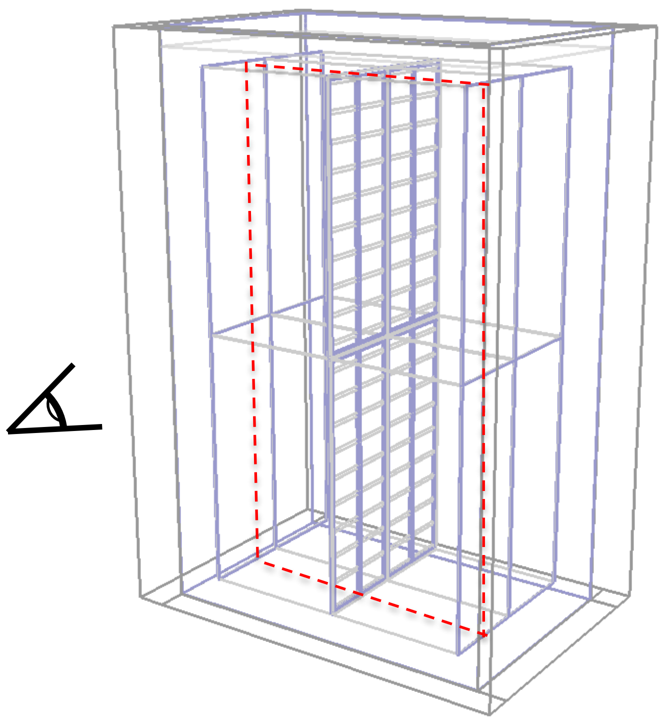
- Sum over all photon detectors.
  - Now can see the structure of the PD arrangement.

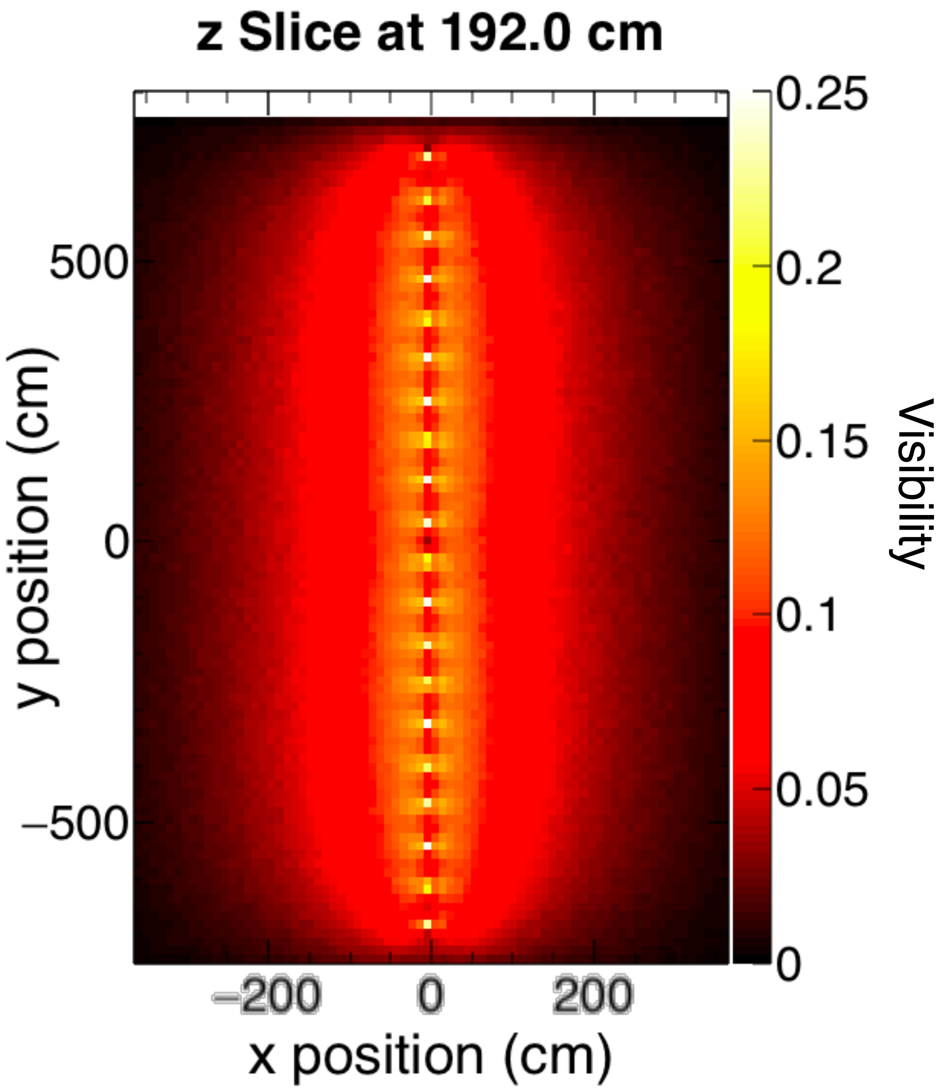




Simulating Optical Transport

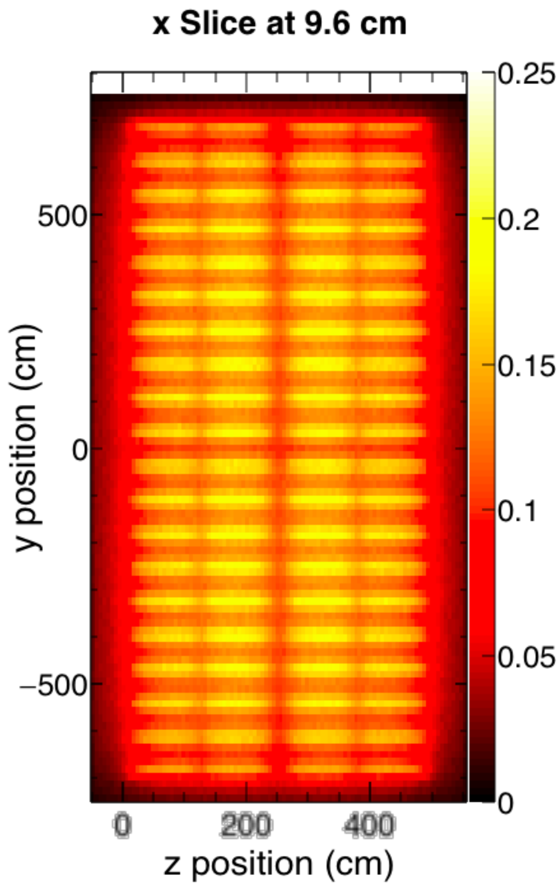
- Rotate our view 90° and we can visually see the fall-off in collection efficiency.

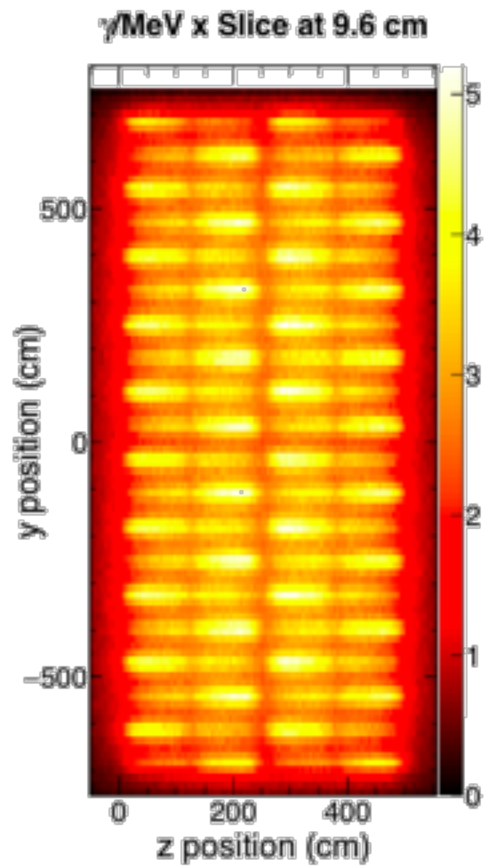




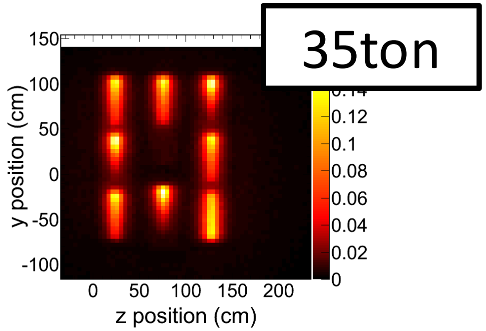
Simulating Optical Transport

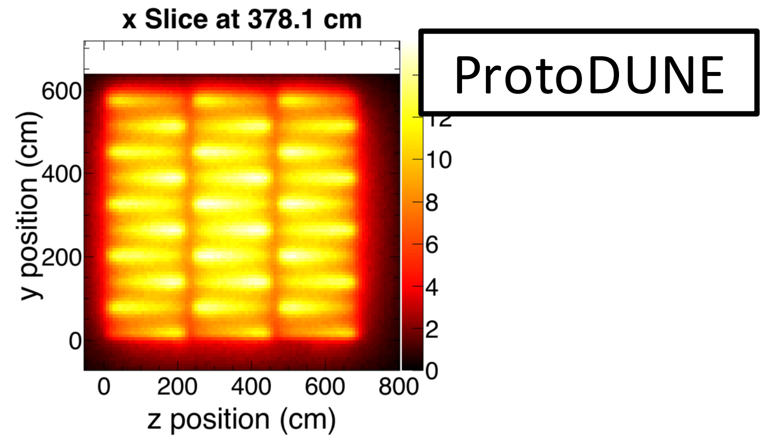
- Libraries can also include the attenuation within the light guides.
- Attenuation parameterization based on measurements in the lab

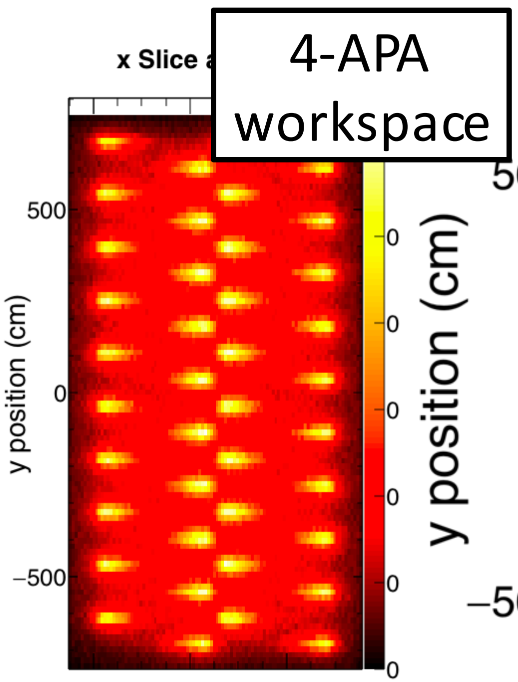


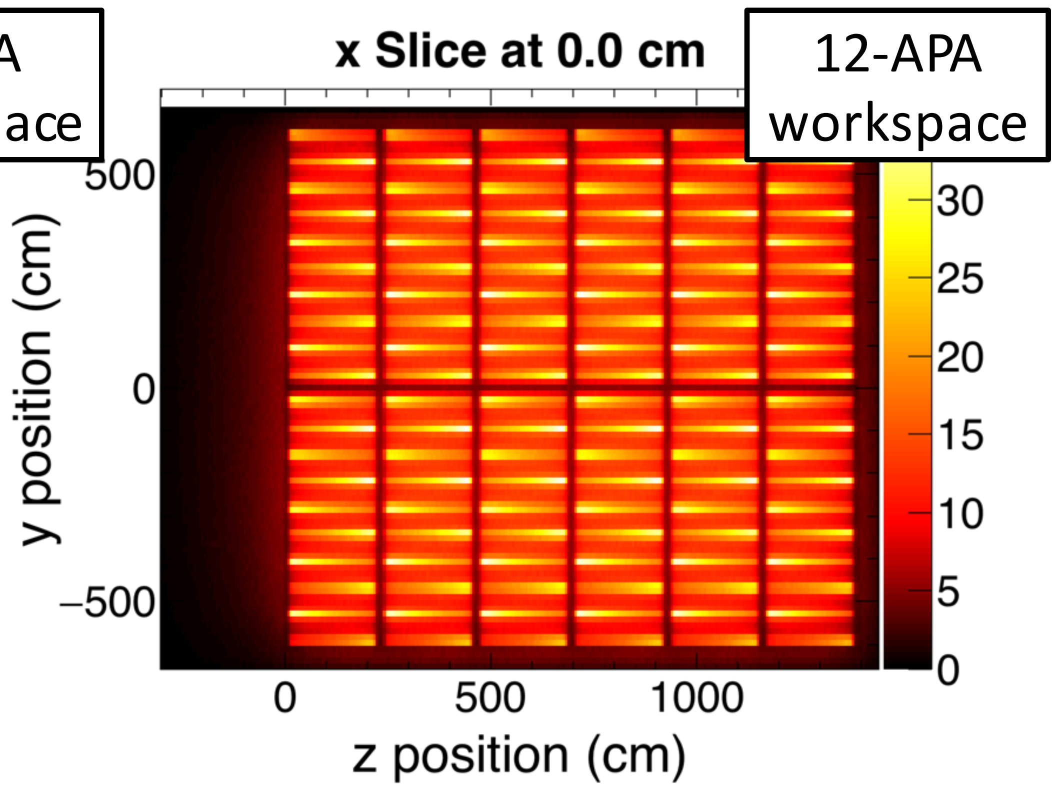


Supported Geometries









Wire and Mesh Shadowing

- There is also a shadowing effect from the wire planes and mesh
  - Measured in the lab at Duke
  - $1/\sin(\theta)$ angular dependence
  - Scaled by gauge/pitch
  - Screen: 80 μm/0.9 cm
  - Wire planes: 150 μm/5 mm
- Approximate as 30% shadowing
  - Not yet fully implemented in our simulation
  - 27% straight ahead, more at steep angles