Photon Detector Reconstruction (and Simulation) at DUNE

Alex Himmel

Fermilab

Workshop on Calibration and Reconstruction for LArTPC Detectors
Fermi National Accelerator Laboratory
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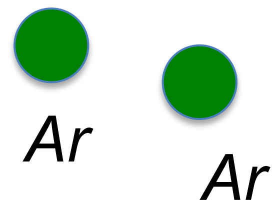
Introduction

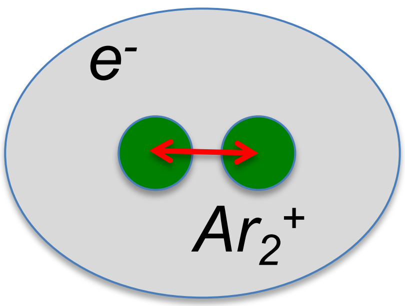
- A bit of an unusual talk: the photon detector (PDS) reconstruction (and simulation, and analysis) in DUNE is still in fairly early days.
- We have built enormously on work done for other LArSoft experiments, but…
- There are many issues with photons in DUNE that are quite different from other LAr experiments.
  - We have made some adaptions to handle these.
  - Many more are needed, some quite fundamental.
- In this talk:
  - Basics of scintillation in Argon
  - Overview of the DUNE photon detection system
  - Photon simulation, reconstruction, and analysis
    - And where we need to improve – accepting volunteers!

Mechanisms of Scintillation in Argon

- **Ground state** of 2 argon atoms is unbound

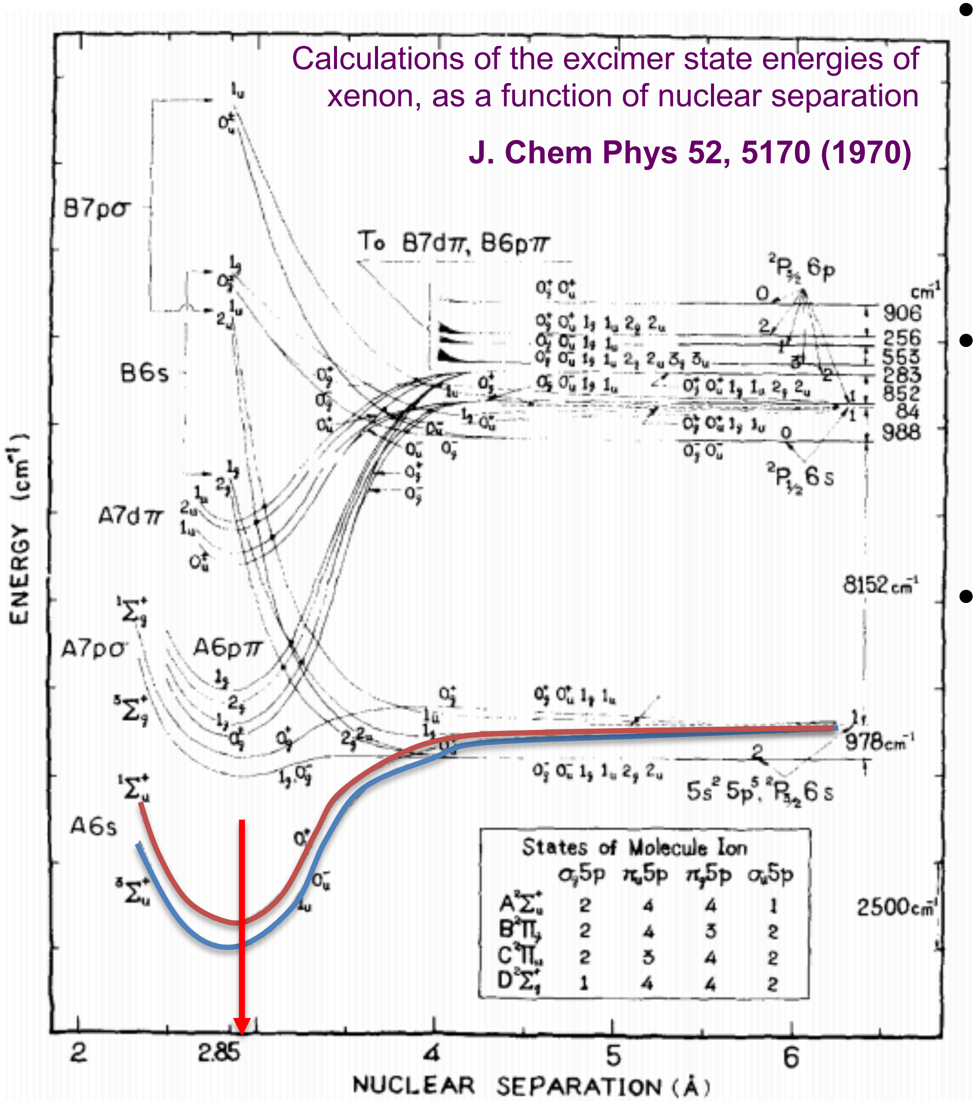


- **Excimer states** are Rydberg states : Ar^{2+} core with a bound electron

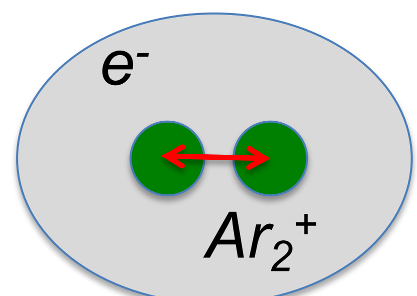


Credit: Ben Jones

Mechanisms of Scintillation in Argon



- There are two low lying excited states:
  - A singlet state 1Σu+
  - A triplet state 3Σu+
- Refers to symmetric/anti-symmetric spins between the excited electron and the Ar-Ar dimer.
- Both states emit 128 nm light
  - Means we will need a wavelength shifter to see it



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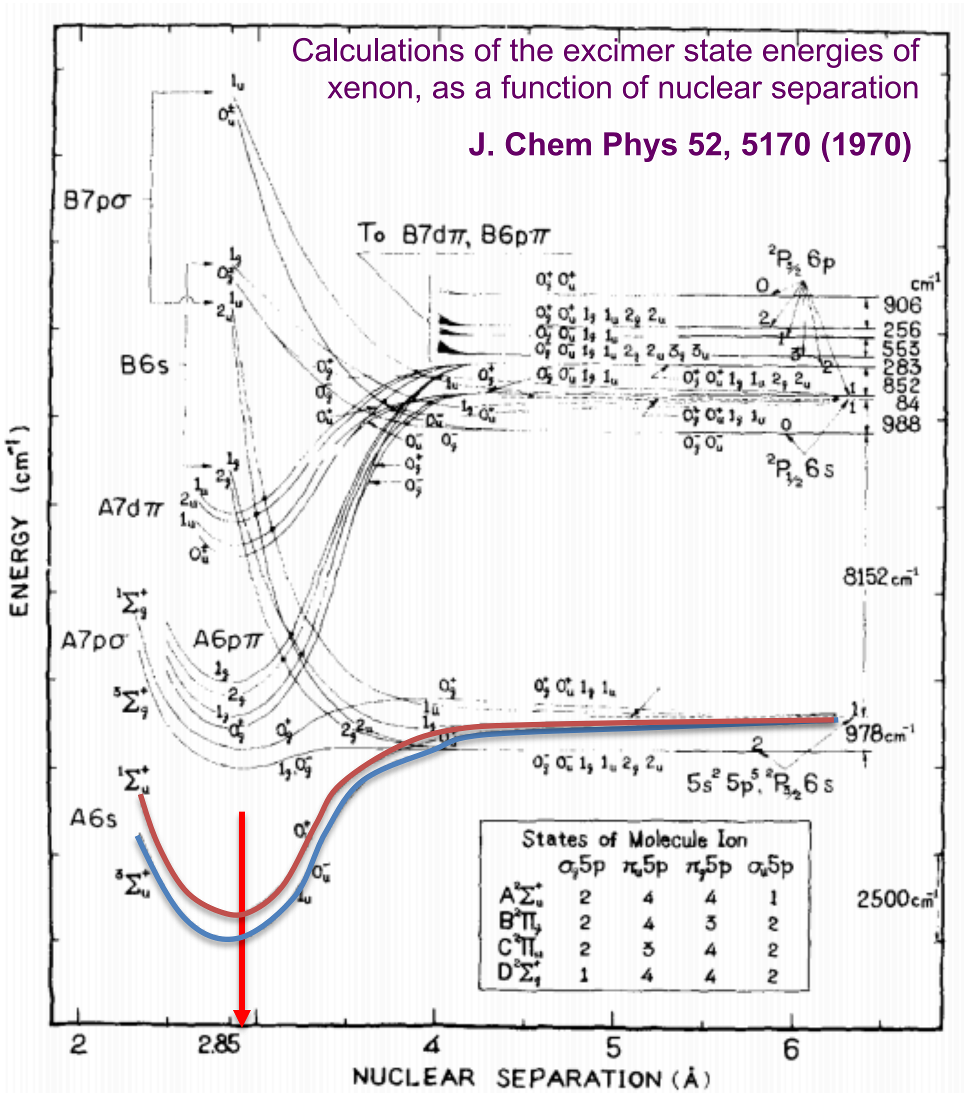
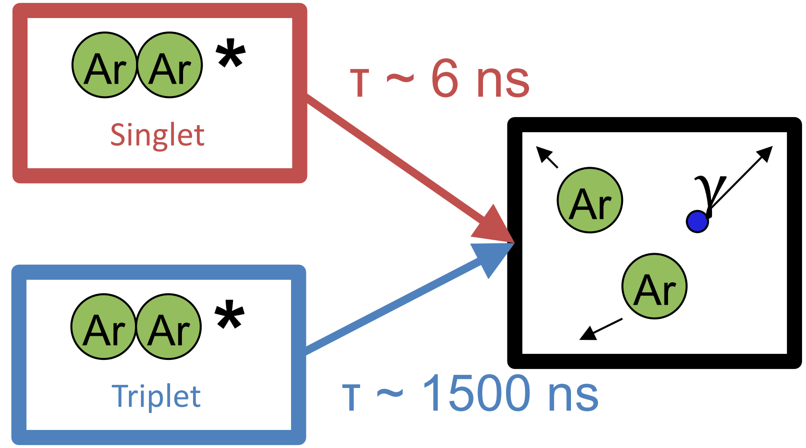


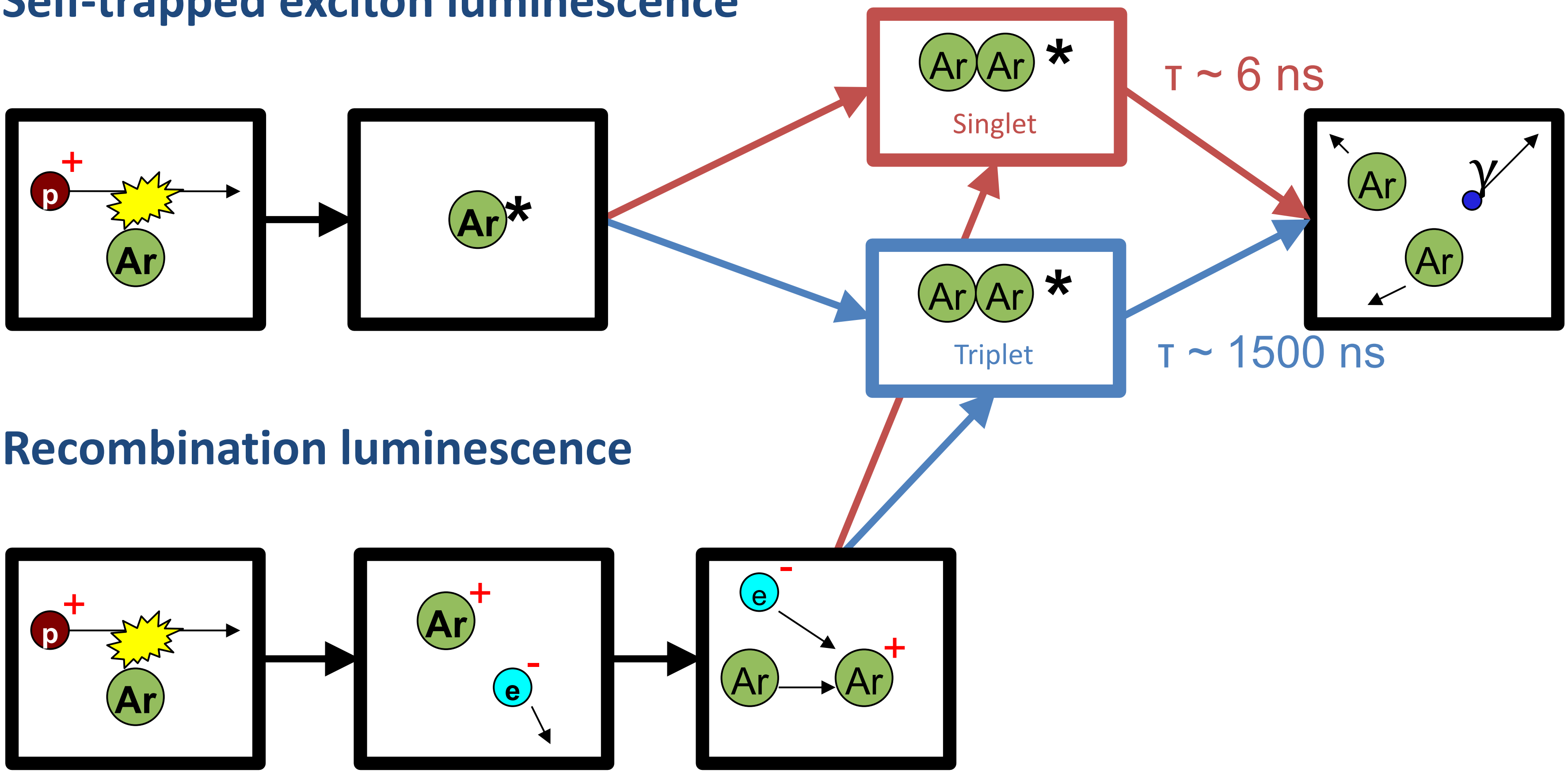


- The difference is in the time-constant of the scintillation.

Mechanisms of Scintillation in Argon

Self-trapped exciton luminescence

Recombination luminescence



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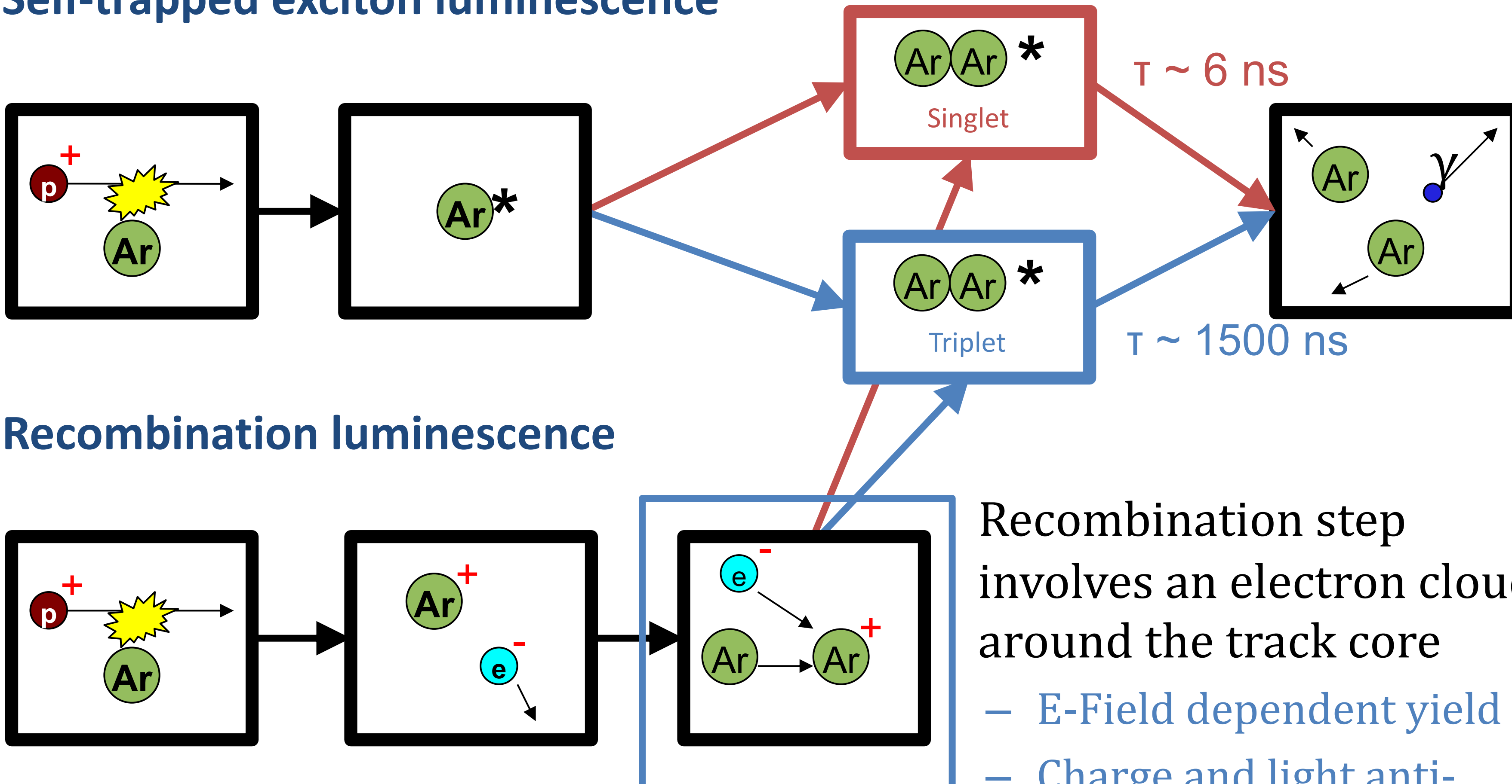
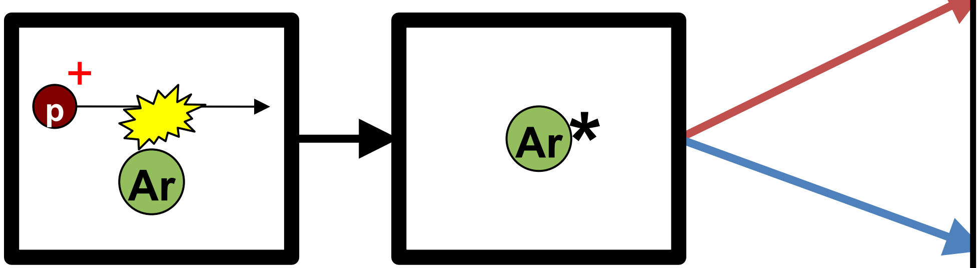


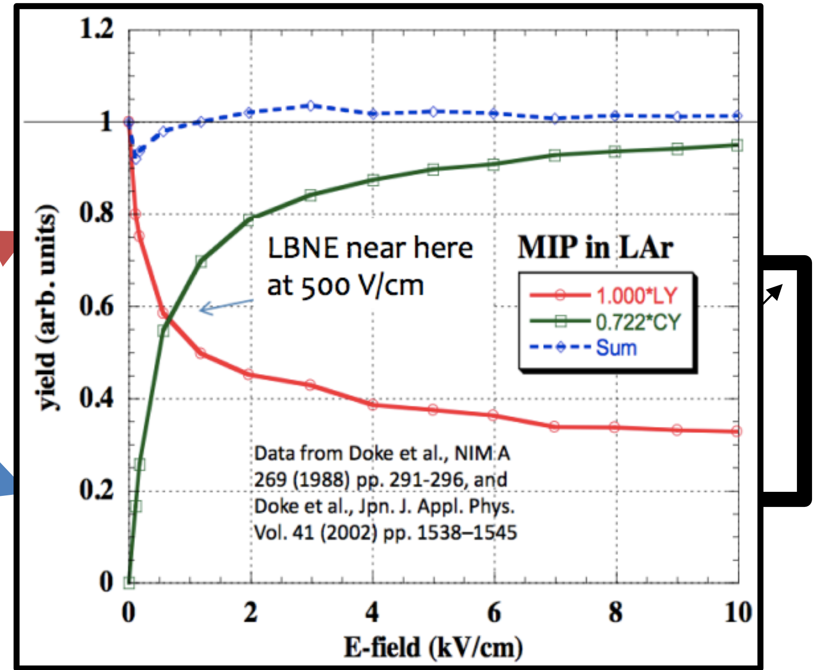
Recombination step involves an electron cloud around the track core

- E-Field dependent yield
- Charge and light anti-correlation
- dE/dx dependent yield

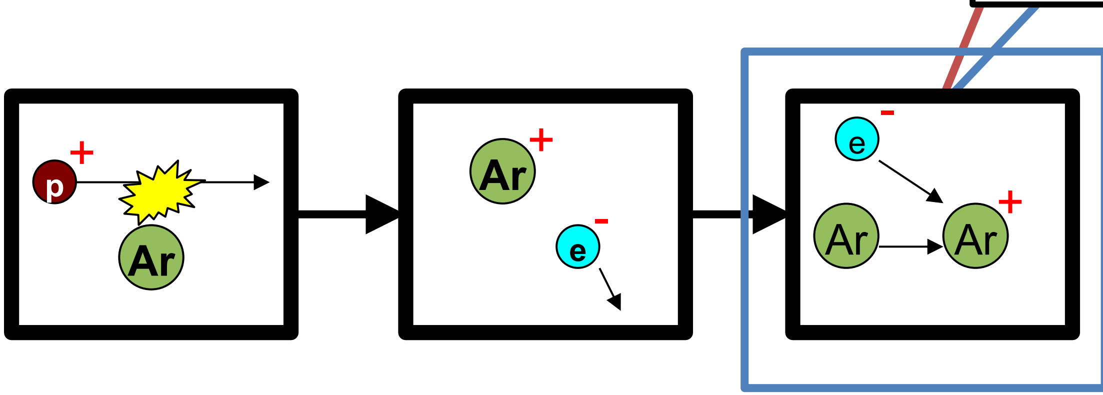
Mechanisms of Scintillation in Argon

Self-trapped exciton luminescence





Recombination luminescence



Recombination step involves an electron cloud around the track core

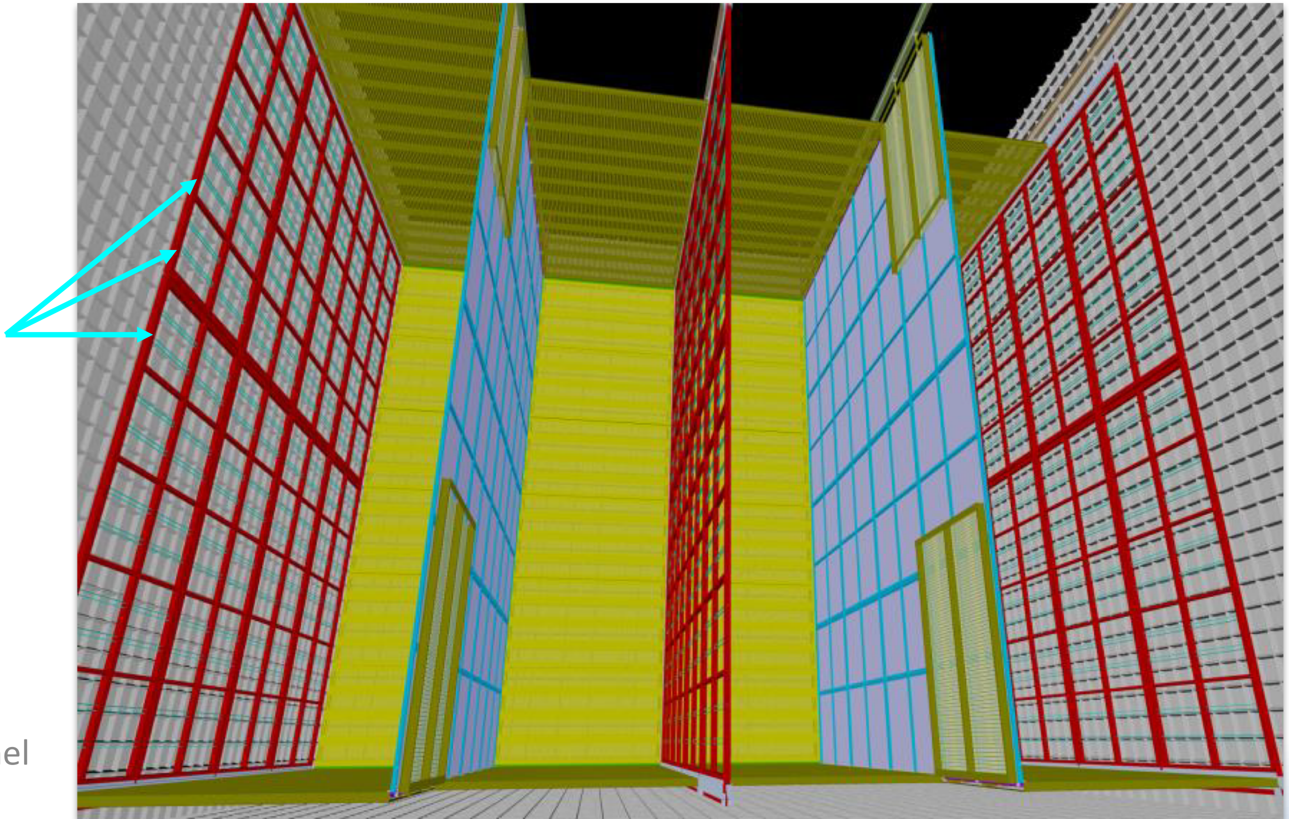
- E-Field dependent yield
- Charge and light anti-correlation
- dE/dx dependent yield

What is Scintillation Light For?

- There are a variety of applications touching on all aspects of the DUNE physics program:
- T0 determination for non-beam events:
  - Fiducialize events along the drift direction
  - Correct for charge attenuation
  - Nucleon decays, supernova neutrinos, solar neutrinos
- Triggering
  - Primarily important for supernova bursts.
- Calorimetry
  - Provide an additional handle on energy for all types of events
- Michel tagging
  - Not studied much in DUNE (yet), but seeing promise in other LAr experiments.

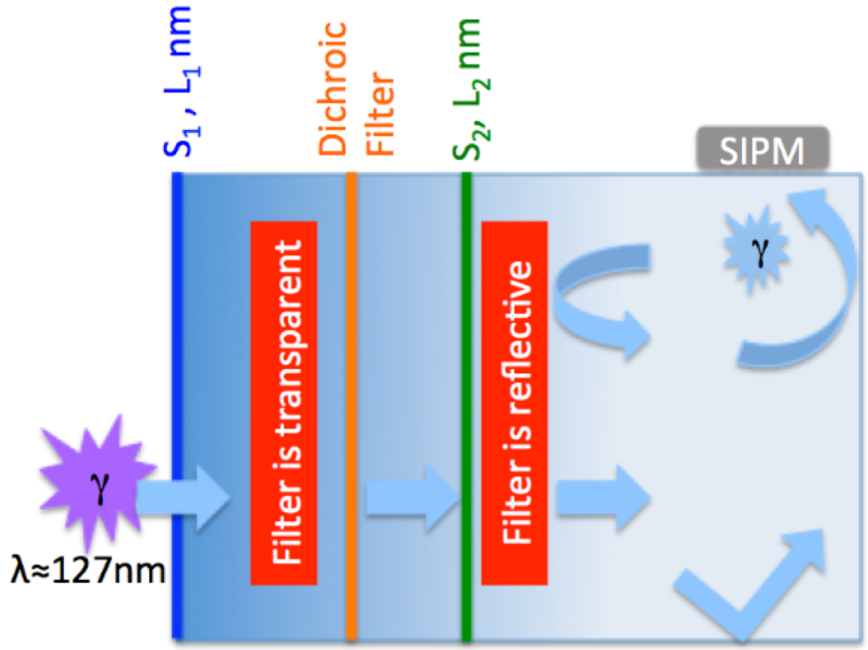
The (Planned) Photon Detection System at DUNE

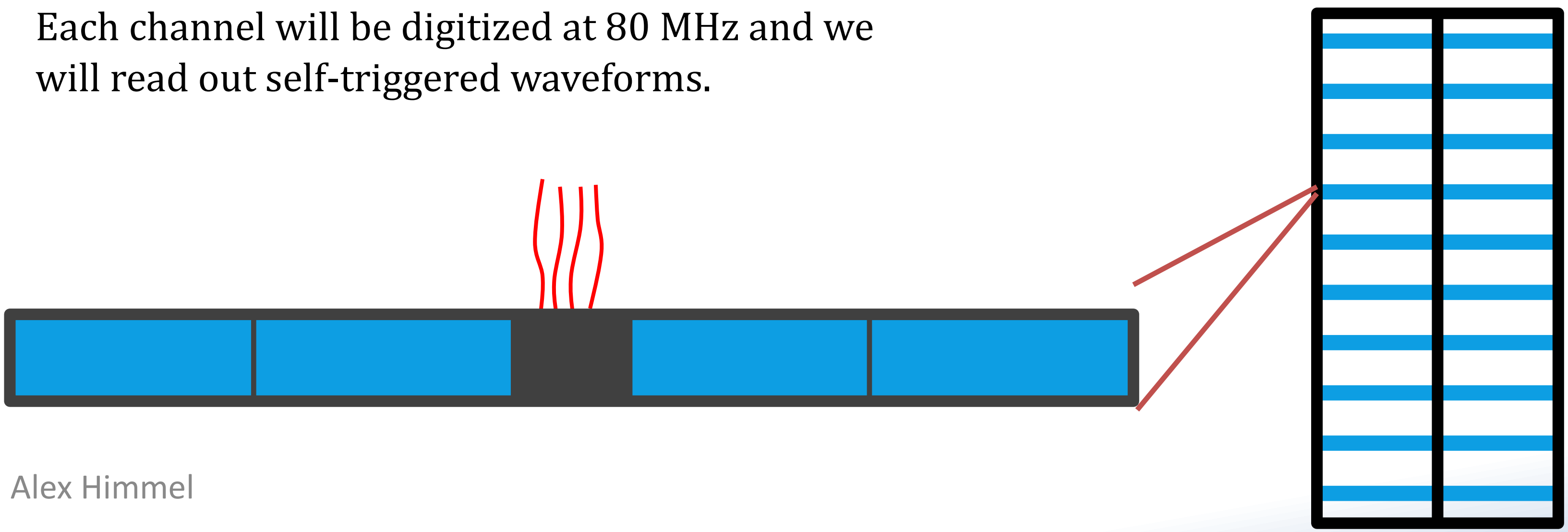
- The DUNE PDS strategy starts from constraints:
- The detectors must sit *inside* the APA.
  - It is in the only field-free region available in the central drift regions.
- Many specific designs under consideration, but a common elements:
  - Silicon photosensors (which are small)
  - coupled to a bar-shaped light collector to increase effective area
  - which also shift 128 nm (VUV) light to the visible



The (Planned) Photon Detection System at DUNE

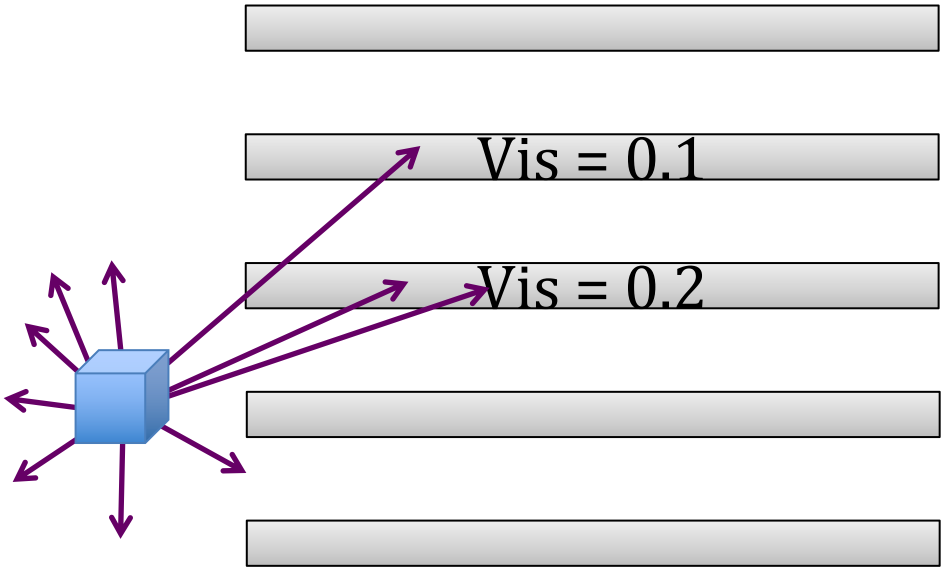
- ARAPUCA Light Traps
  - Use a Dichroic filter
    - Sharp wavelength cut-off between transparent and reflective.
  - First shift: VUV to DF transparent
  - Second shift: DF transparent to DF reflective
  - Exact details still under R&D
- 4 ARAPUCA "supercells" will be arranged into a 2 m-long "bar."
  - Each supercell will have multiple SiPMs actively ganged in the cold into 1 channel.
- 10 bars will be inserted into slots in the APA frame.
- Each channel will be digitized at 80 MHz and we will read out self-triggered waveforms.





Simulating Optical Transport

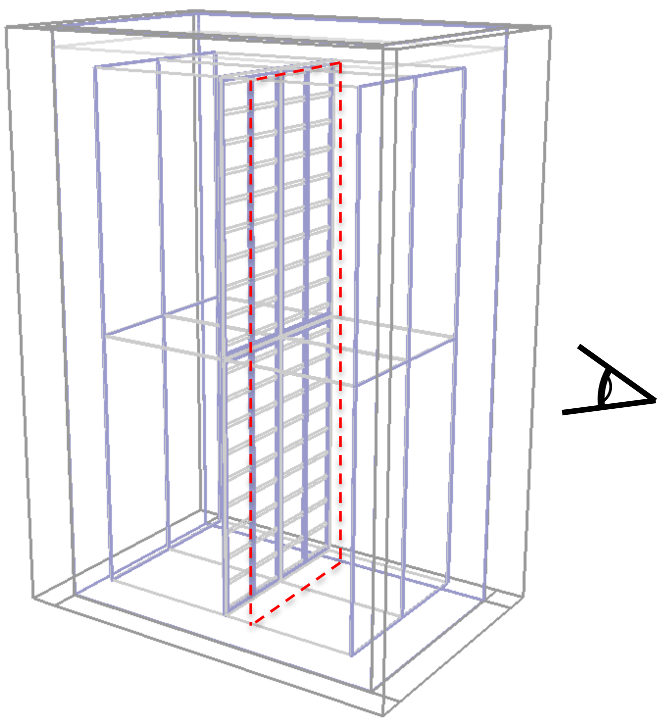
- Adopt the common LArSoft strategy: **Photon Library**
- Lookup table giving "visibility" of each position in the detector for each optical detector
  - For each "voxel" in the detector, generate isotropic photons
  - Visibility: fraction that end up on each optical detector.

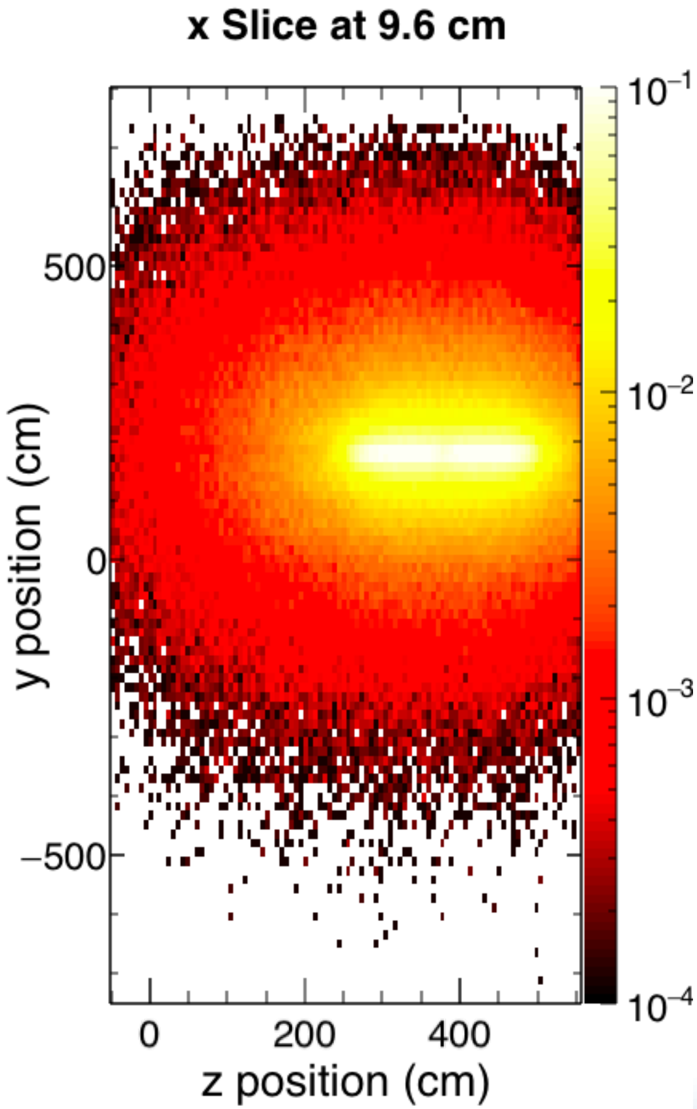


LAr Optical Properties	
Absorption Length	20.0 m
Rayleigh Scattering	~60 cm

Simulating Optical Transport

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





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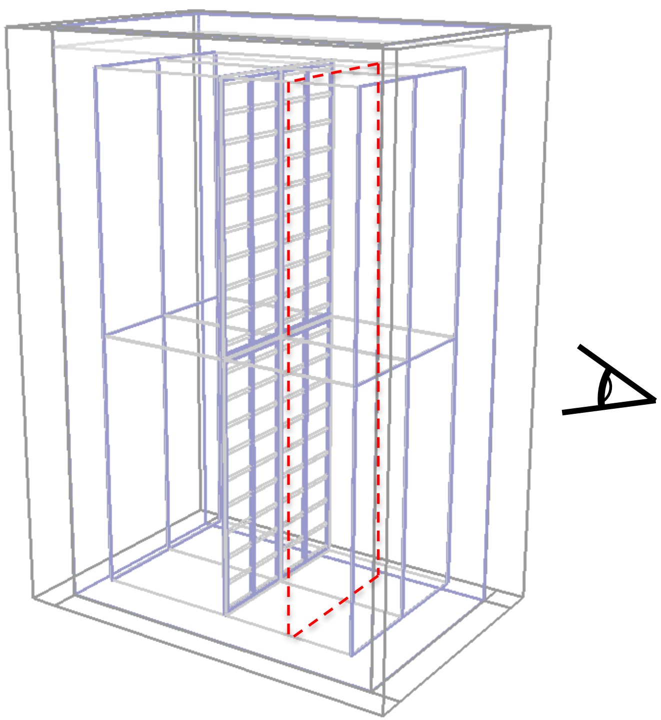

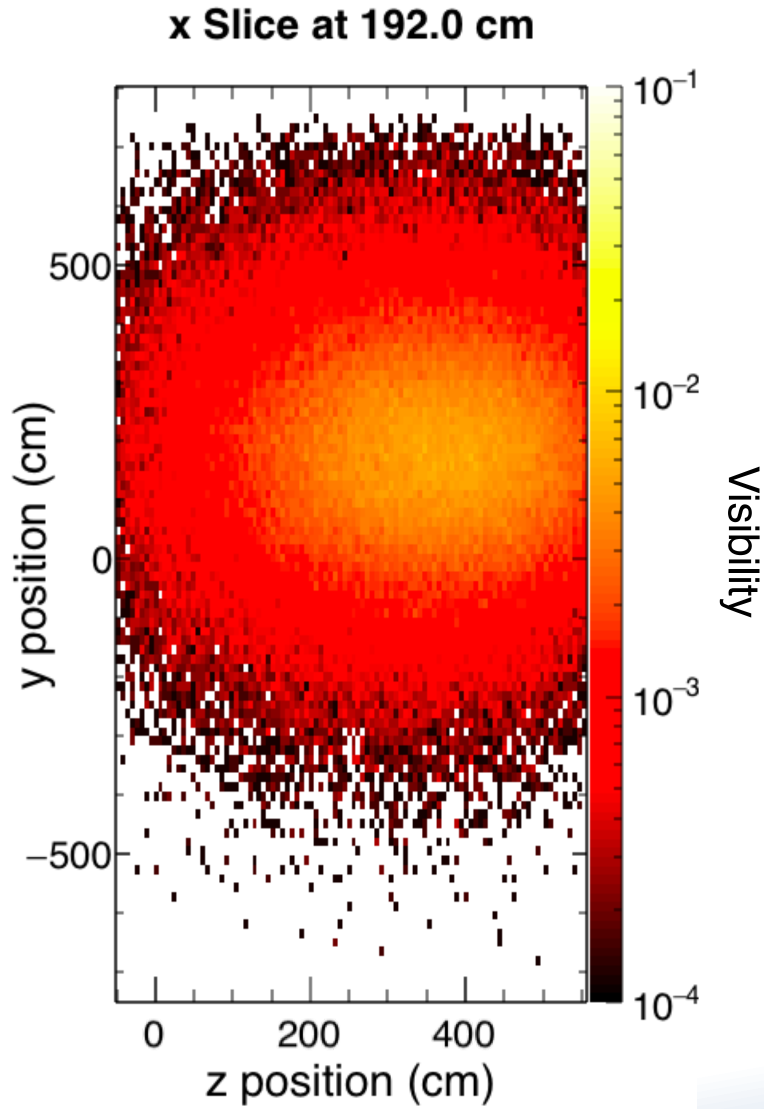

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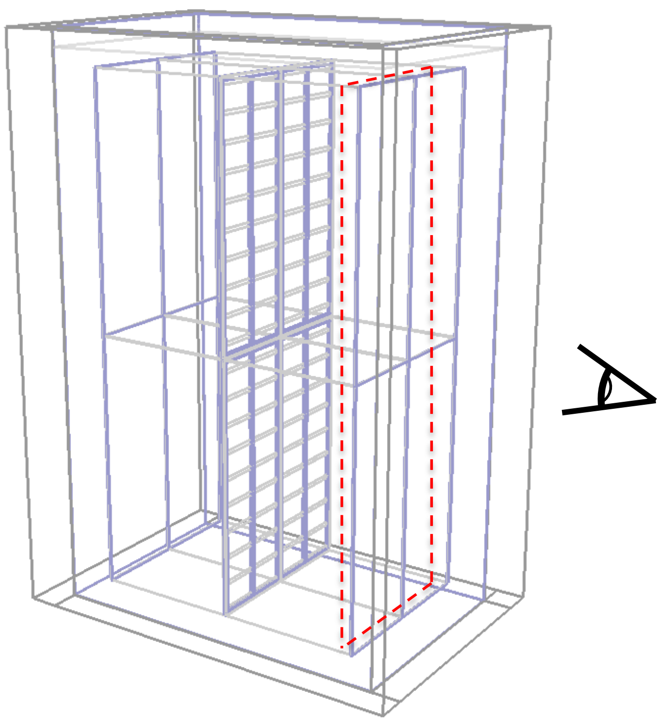
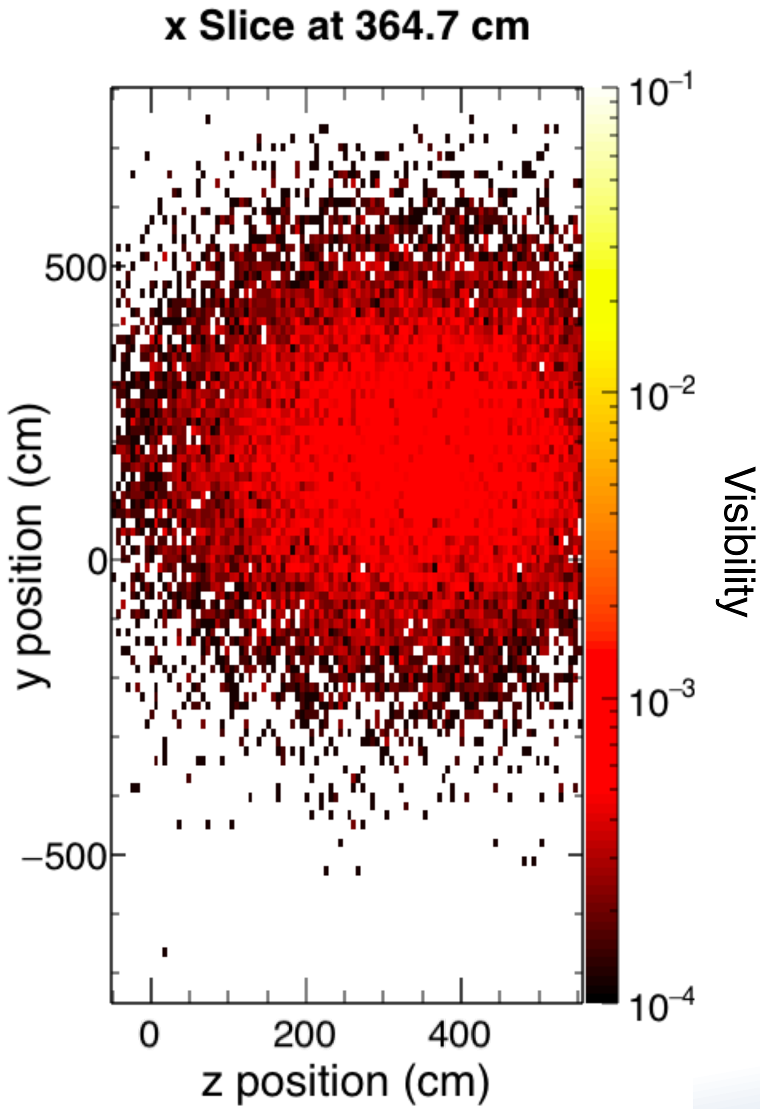
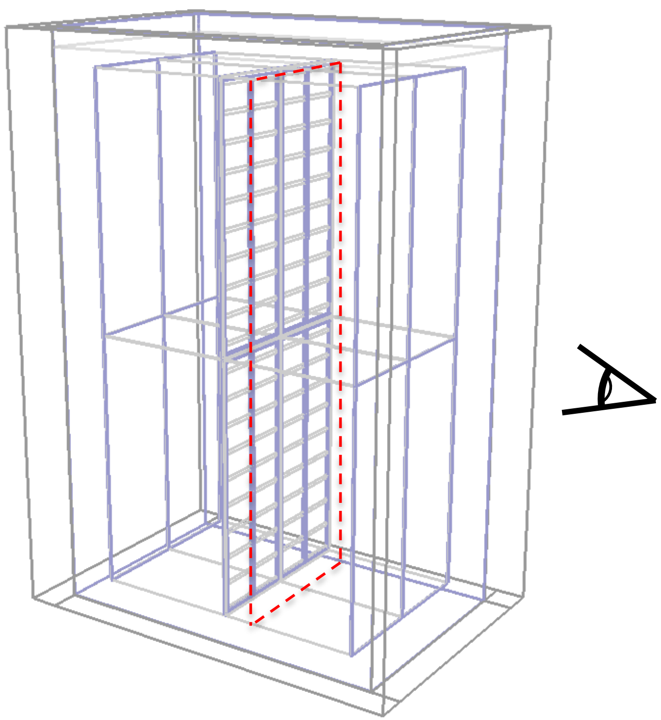
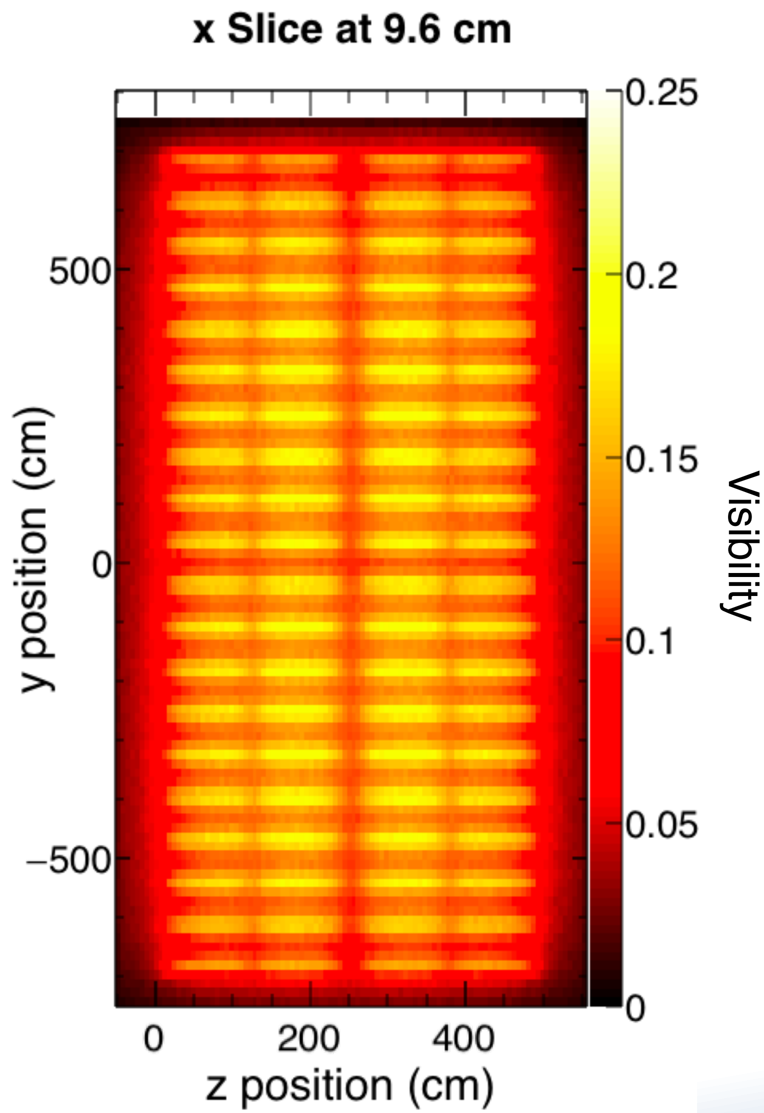




Simulating Optical Transport

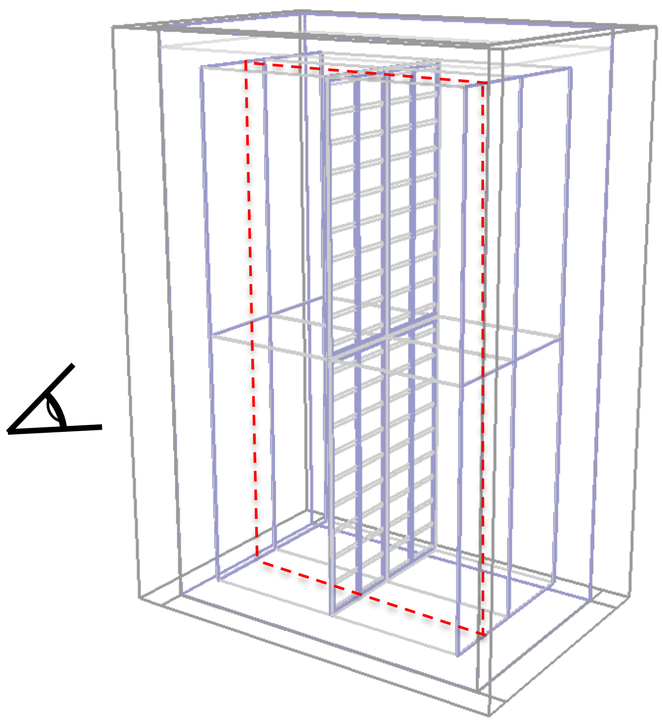
- Sum over all photon detectors.
  - Now can see the structure of the PD arrangement.

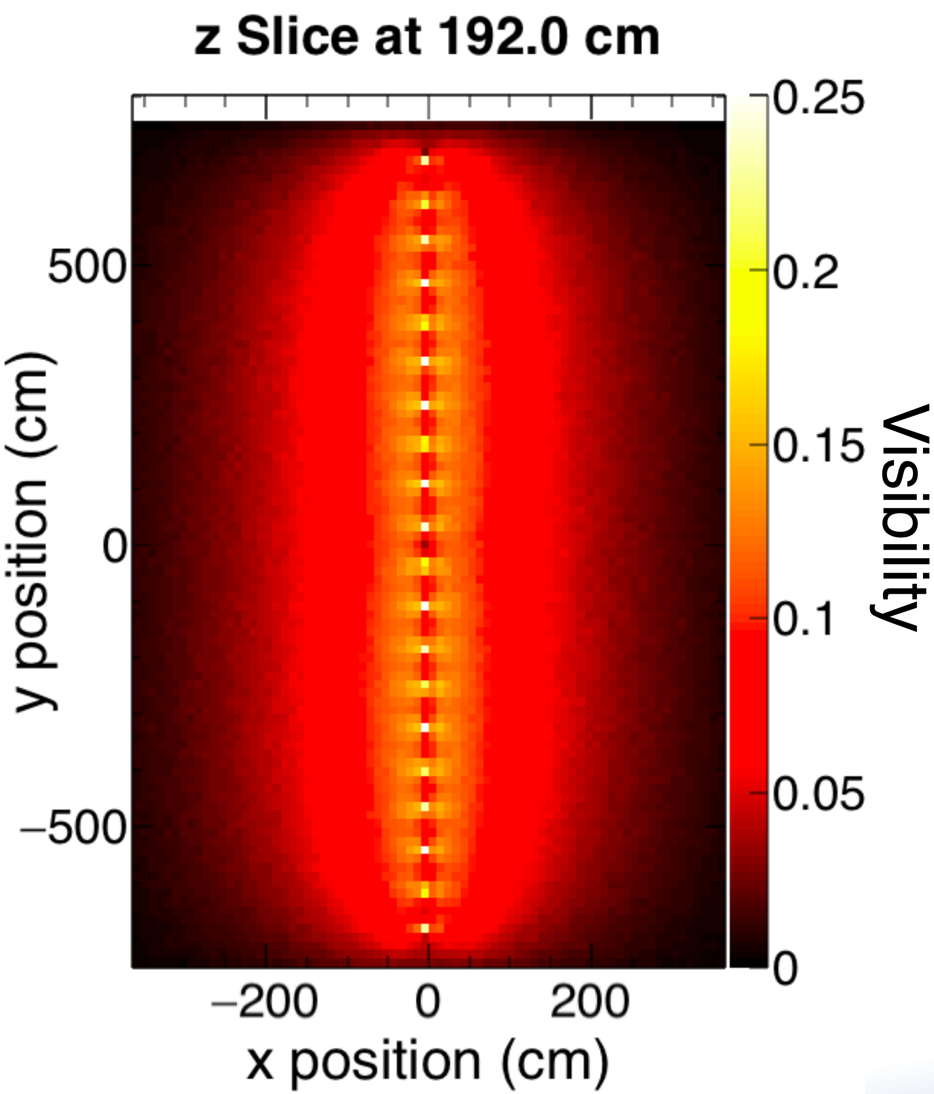




Simulating Optical Transport

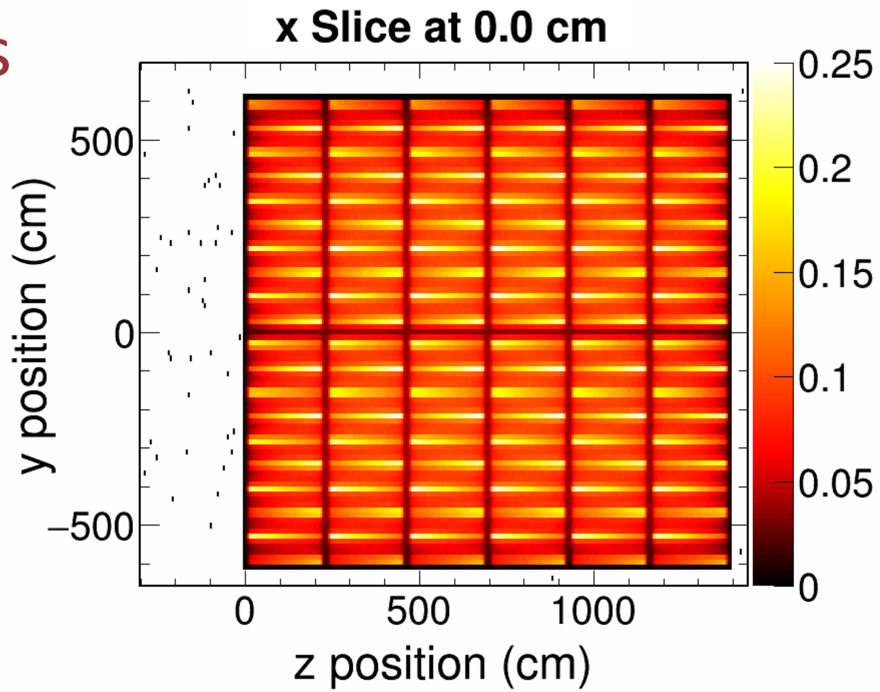
- Rotate our view 90° and we can visually see the fall-off in collection efficiency.

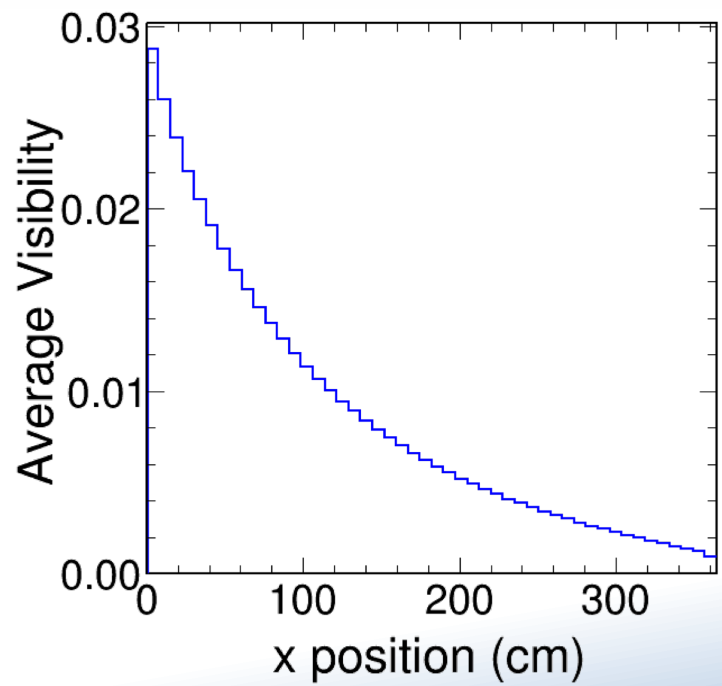




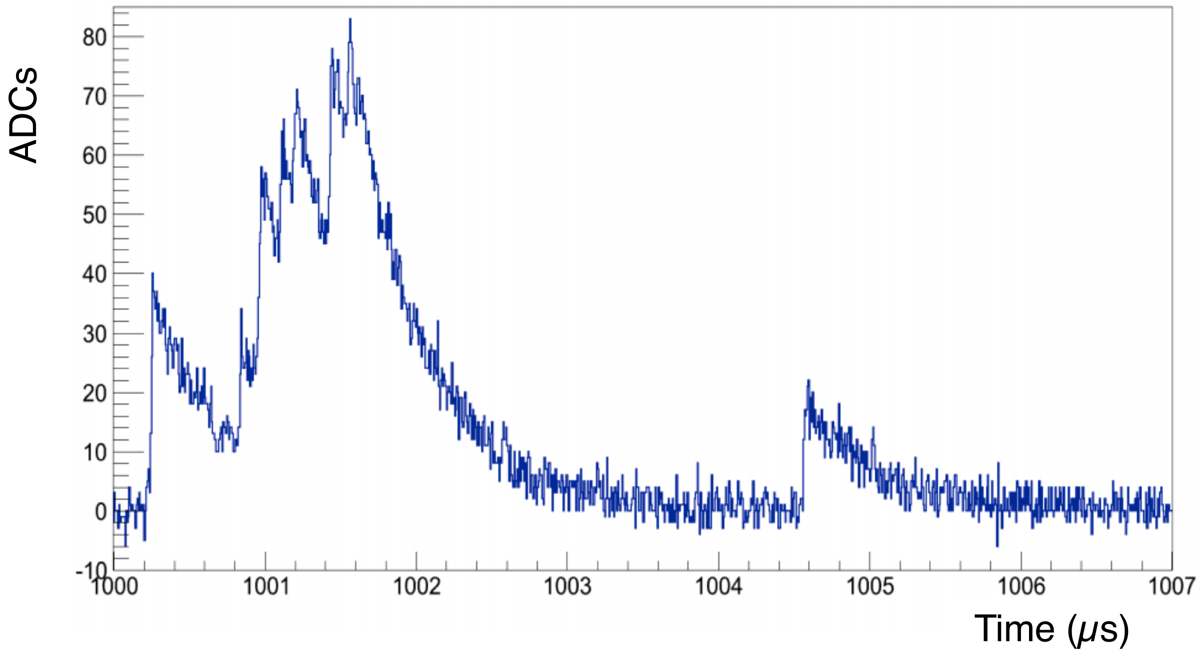
Problems with Photon Libraries

- Cannot simulate the full detector
  - We use a 12-APA test geometry for all our studies.
  - Large enough to contain all the light from an interaction near the middle.
  - Small enough that we can make a photon library for it.
- Voxels are large relative to the size of the photon detectors, particularly in Y.
- Cannot introduce additional granularity since we are at the limit of library size.
- Cannot simulate directional Cherenkov light.
- Visibility is very low far from the PDs.
  - ×20 less light 3.6 m away
  - Hard to calculate visibilities in those regions.
- We have been exploring alternatives for a long time, but it's a hard problem.



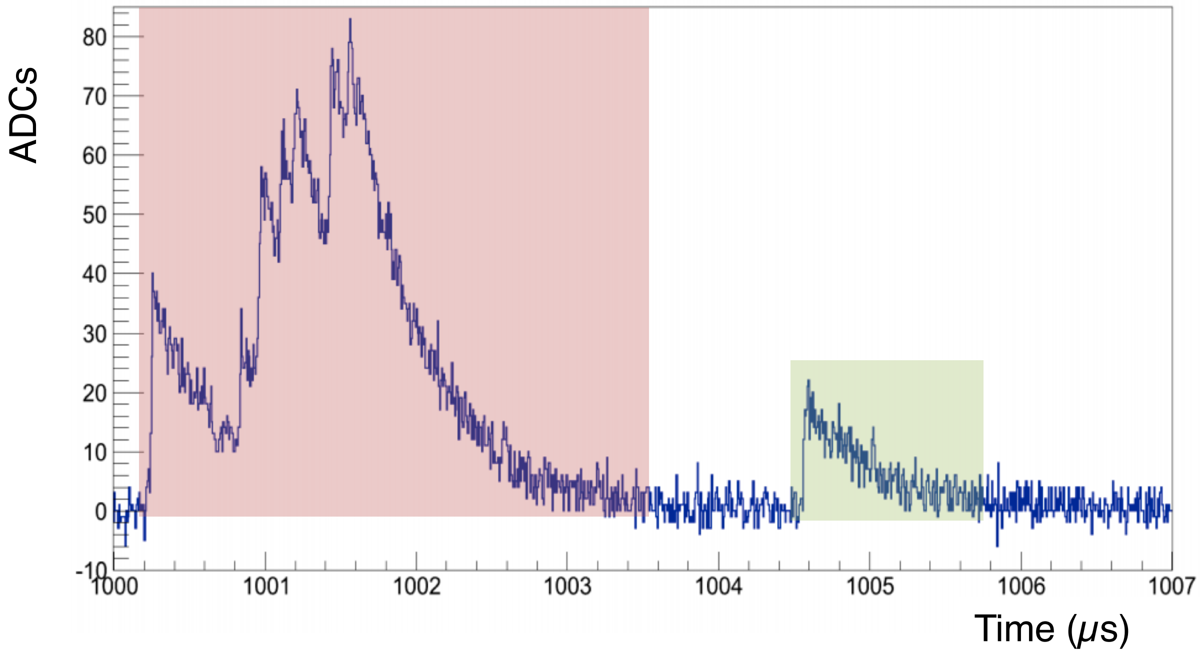


Sensor and Electronics Simulation



- Build up waveforms with simulations of the sensors and electronics.
- Photosensors
  - Add single PE waveforms based on lab measurements for each arriving photon and random dark noise.
  - Add a second one some fraction of the time to account for cross-talk.
  - Electronics teams have a more sophisticated simulation of the ganged SiPMs – not incorporated yet.
- Electronics
  - Digitize at 80 MHz
  - Apply a leading edge discriminator to simulate self-triggering.
  - Add random uncorrelated noise to each sample.

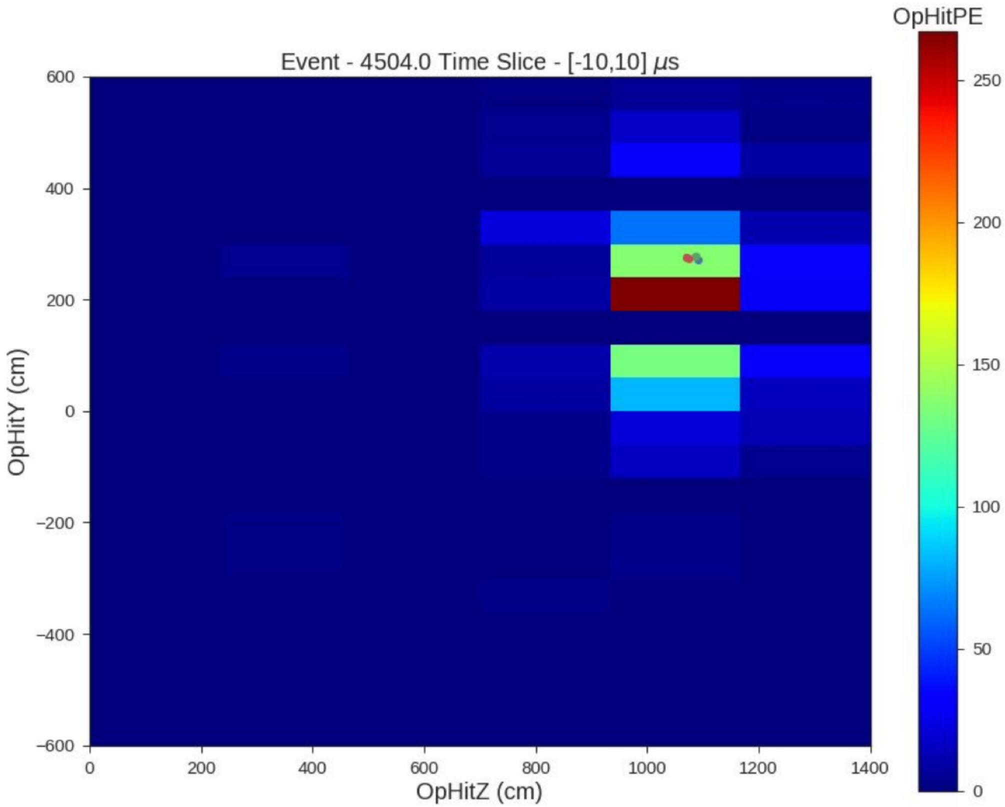
Reconstruction: Hit Finding



- Hit finding identifies signals on individual channels by looking for contiguous sets of samples above a threshold.
  - Pedestal is determined waveform-by-waveform by looking at the first and last samples.
  - Often means what are visually separate "peaks" get merged together.
- The time is assigned to the *first* peak, not the highest.
  - We want to associate the event time with the time of the early light, even if we actually see a larger peak in the late light.
- Because of the many overlapping peaks staggered in time, we use integral (rather than height) to convert back to Photoelectrons (PE).

Reconstruction: Flash Finding

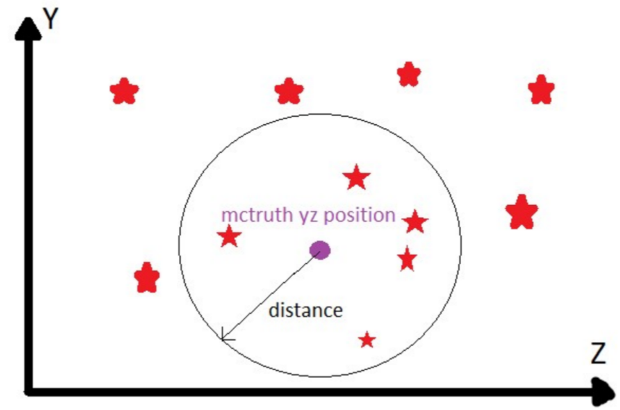
- A "Flash" is intended to correspond to the light produced by a single event in the detector.
- We construct the flash by looking for hits which are coincident in time.
  - Obviously a bad choice for a detector with optically separated regions!
  - Algorithm was originally written for much smaller detectors like μBooNE.
- For now, we approximate spatial coincidences by using the small detector geometry.
  - Still, we have 10-20% radiological contamination in the flashes from supernova ν's.
- Low-hanging fruit for someone interested in writing a new reco. algorithm. 😉

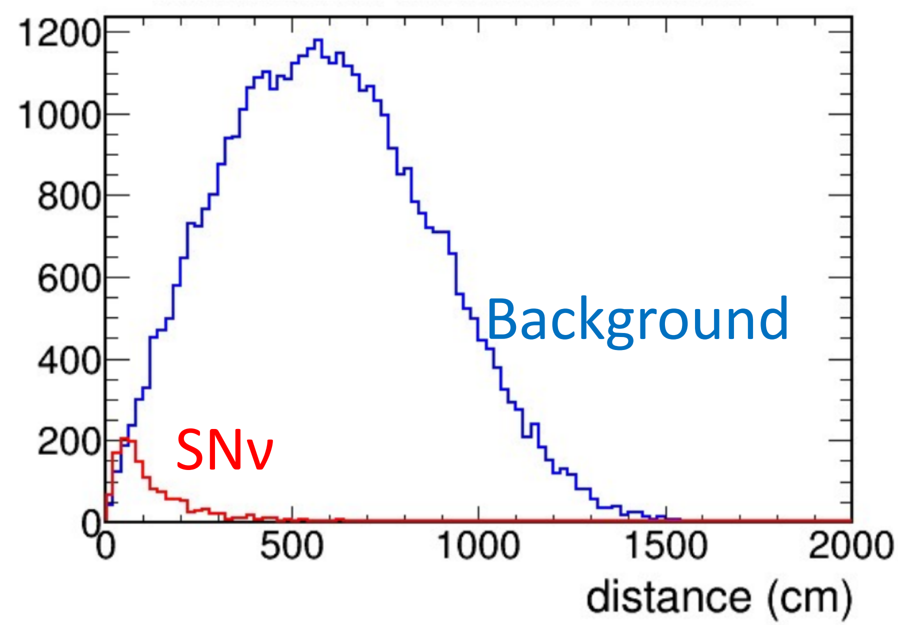


Credit: Lucas Mendes

Reconstruction: Flash Matching

- During any readout window with a TPC signal there will generally be *many* flashes, even in the test geometry.
- So, we must use criteria to "match" the flash to the TPC event.
- Three steps:
  - Require that the flash be within 1 drift time before the TPC time.
  - Require the charge-weighted flash center to be within 2.4 m of the TPC event in the Y-Z plane.
  - Take the largest flash that remains as the match.

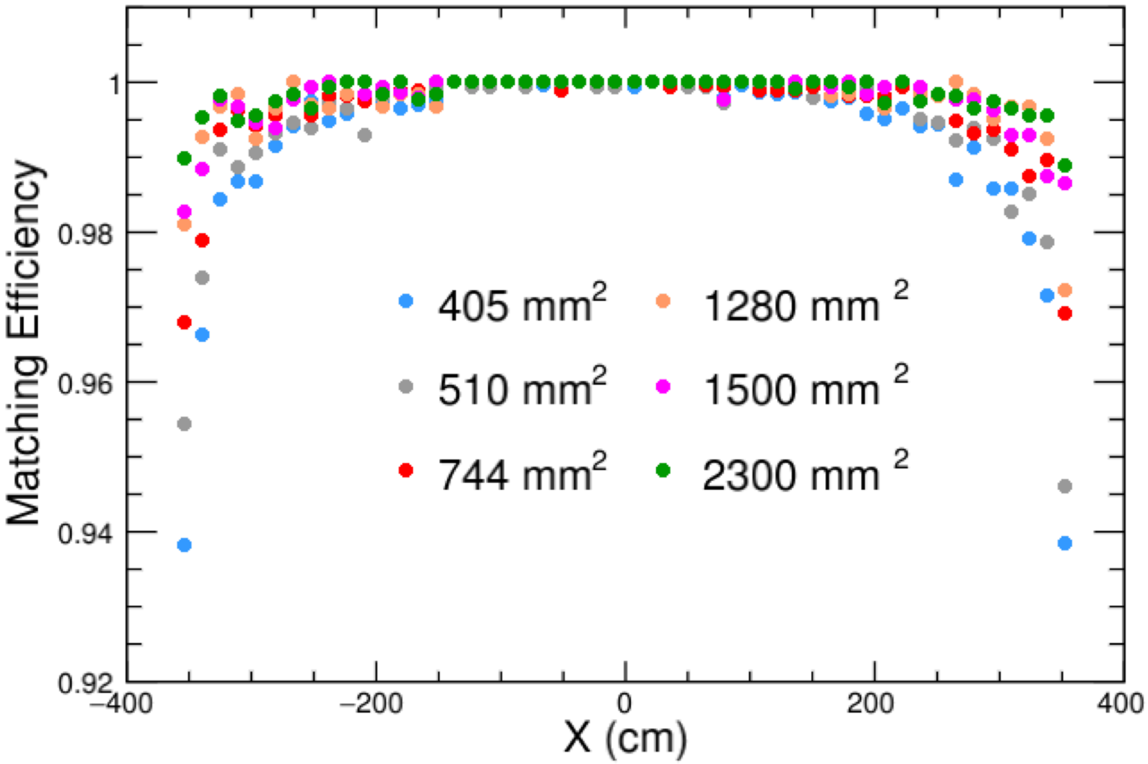




Credit: Logan Rice

Flash Finding for Nucleon Decays

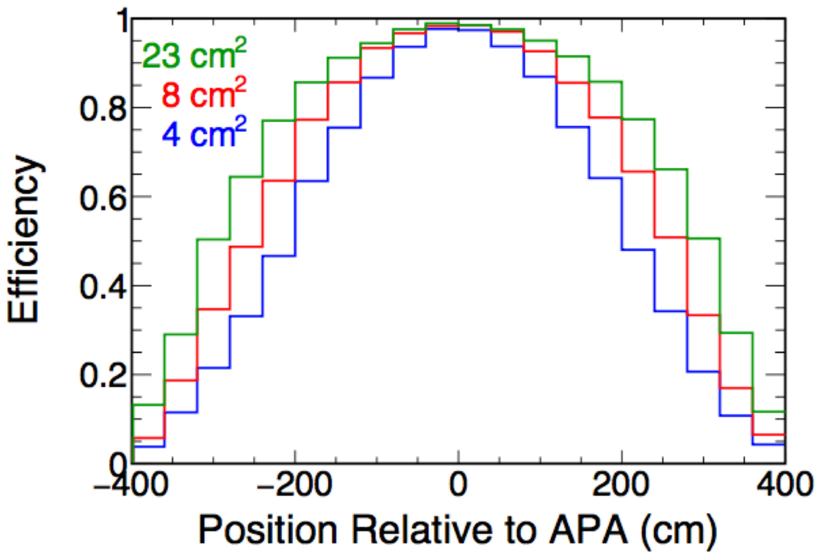
- Efficiency for associating the right flash with nucleon decay events for a range of detector "effective areas" (efficiency × active area).
  - 4 cm^2 = ProtoDUNE light guide
  - 23 cm^2 = ARAPUCA prototype
- Our requirement here is 99%, which the ARAPUCAs appear to meet.

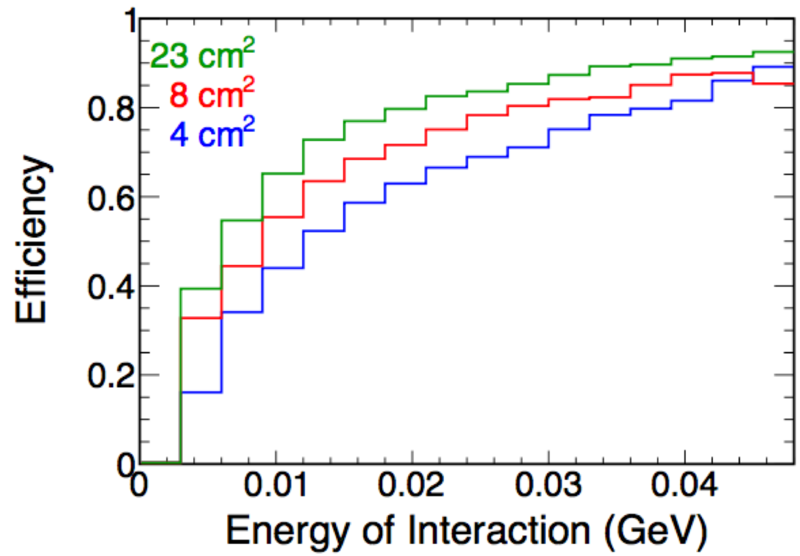


Effective Area (cm^2)	Mis-ID Rate at CPA (%)
4.05	6.2 ± 0.4
5.10	5.0 ± 0.4
7.44	3.2 ± 0.4
12.8	2.3 ± 0.4
15.0	1.6 ± 0.2
23.0	1.1 ± 0.2

Credit: Dan Pershey

Flash Finding Efficiency for SN Burst Neutrinos





- Efficiency for associating the right flash with SNν events for a range of detector “effective areas” (efficiency × active area).
  - 4 cm^2 = ProtoDUNE light guide
  - 23 cm^2 = ARAPUCA prototype
- Performance far from the PDs improves very slowly: flashes are diffuse and not much light is seen.
  - We are exploring options to improve uniformity like reflector foils and doping with Xe.

Credit: Logan Rice

Conclusions

- Primary role of the DUNE photon simulation today is to inform detector design decisions.
  - For this use, we can tolerate some significant approximations, particularly if they lean in a pessimistic direction.
- Numerous simulation improvements are going to be needed in order to match what we expect to see in the real far detector.
- Significant scope for improvement in reconstruction algorithms, too, and those can be used now on ProtoDUNE data.
- If you have ideas and want to contribute, you are more than welcome.