# Physics Requirements for Far Detector 1 – Horizontal Drift Photon Detection System

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Final Design Review for the DUNE FD1 Photon Detection System

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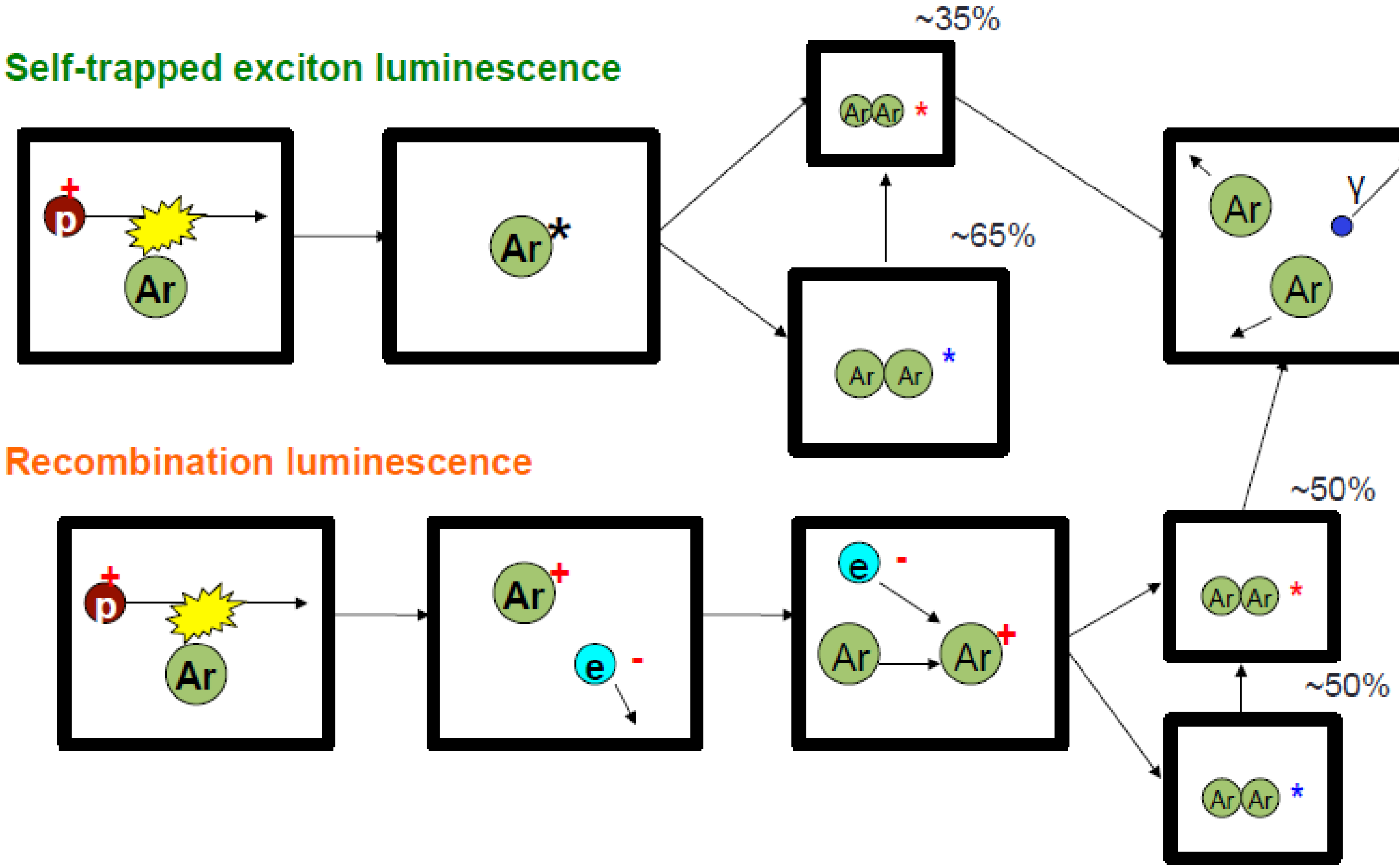
# Outline

- Scintillation light in liquid argon
  - Generation
  - Simulation and Reconstruction
- The role of the photon detectors in DUNE physics
- How those physics roles define the PDS requirements
  - How requirements are met by the proposed PDS
- Conclusions

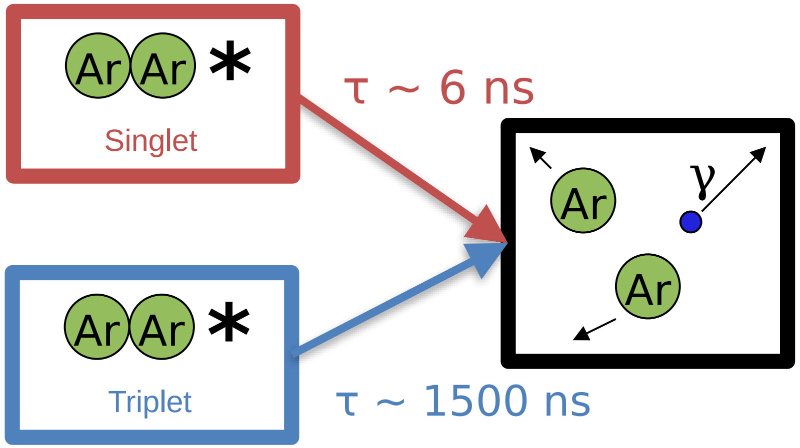
# Argon scintillation

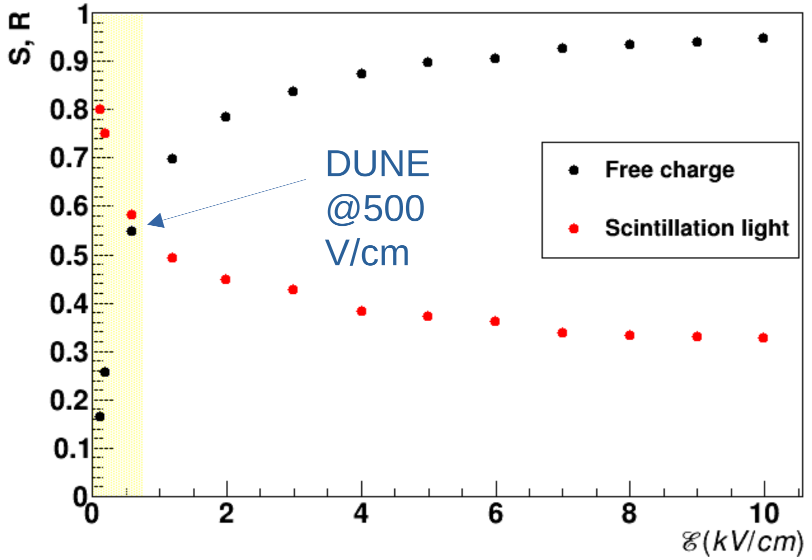
- The amount of charge and light produced by a particle is anti-correlated



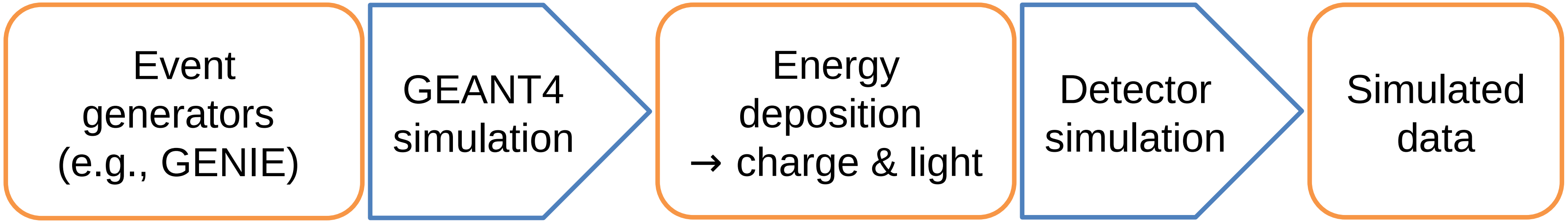
# Argon scintillation

- Light is produced when an Ar-Ar* excimer decays
  - ~25% is in the Singlet state which decays in ~6 ns
  - Remainder is in the Triplet state which decays in ~1500 ns
- Argon is a **strong scintillator: ~24 γ/keV** at nominal DUNE field
  - ~60% of the energy goes into photons





# Scintillation light simulation in the DUNE FD


Event generators (e.g., GENIE)

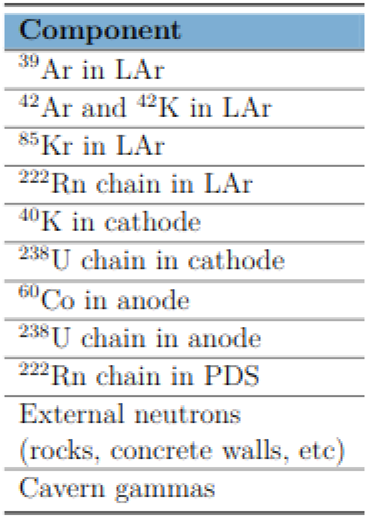
GEANT4 simulation

Energy deposition → charge & light

Detector simulation

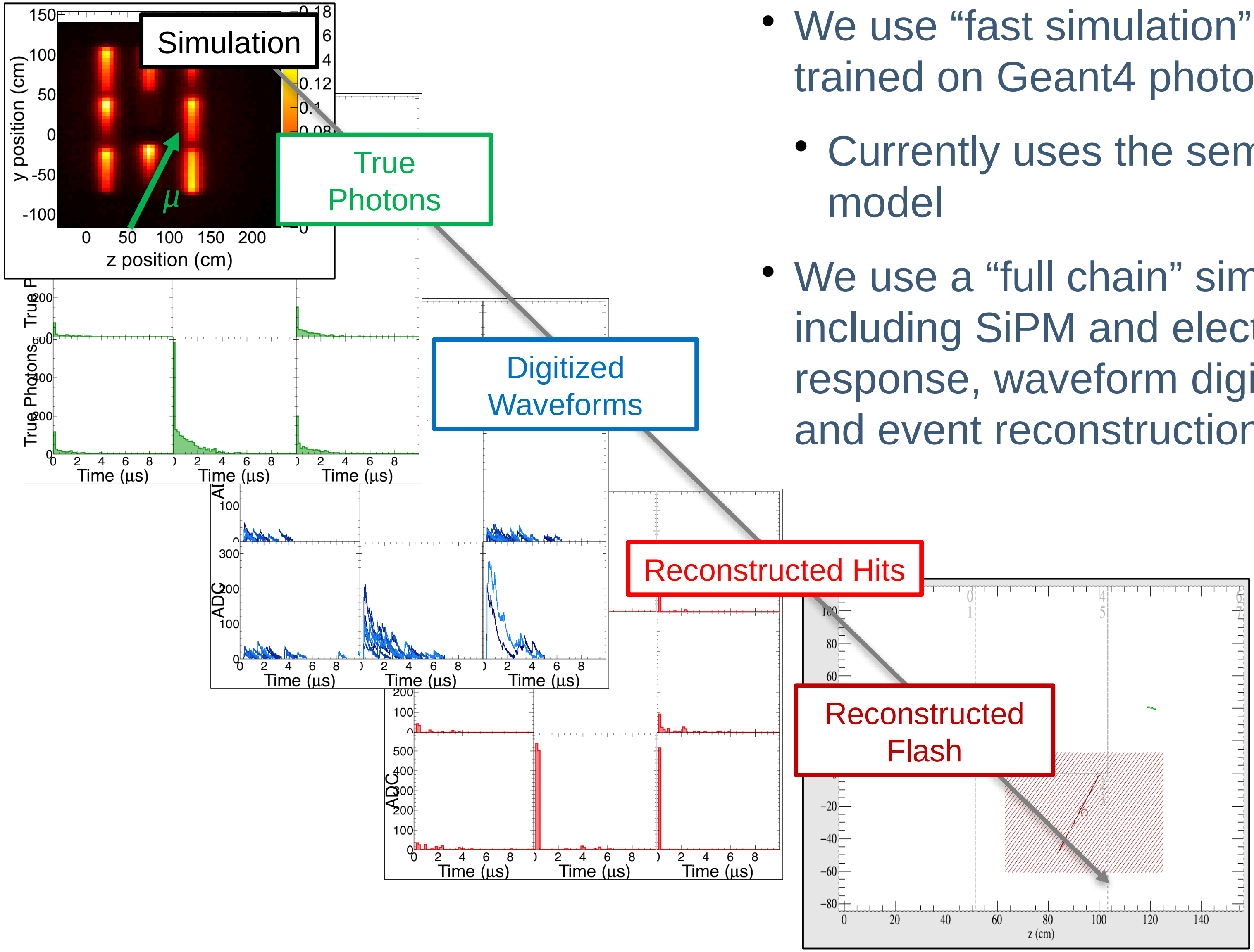
Simulated data

- Simulation implemented within common LArSoft framework
- GEANT4 tracks primary particles and their daughters through the detector geometry → energy depositions → number of ionization electrons and scintillation photons
- In addition to signals (supernova ν, solar ν, NDK, ...) we have a radiological model with growing sophistication
  - Includes bulk contaminants, those expected to come from other materials, and external source



| Component |
|---|
| $^{39}$Ar in LAr |
| $^{42}$Ar and $^{42}$K in LAr |
| $^{85}$Kr in LAr |
| $^{222}$Rn chain in LAr |
| $^{40}$K in cathode |
| $^{238}$U chain in cathode |
| $^{60}$Co in anode |
| $^{238}$U chain in anode |
| $^{222}$Rn chain in PDS |
| External neutrons (rocks, concrete walls, etc) |
| Cavern gammas |

# Scintillation light simulation in the DUNE FD



Simulation

True Photons

Digitized Waveforms

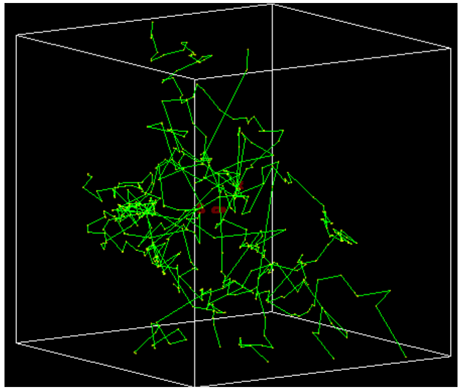
Reconstructed Hits

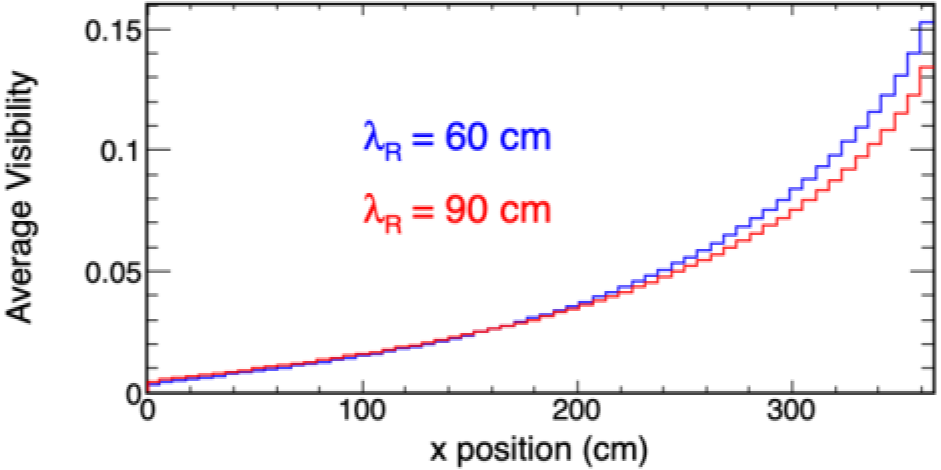
Reconstructed Flash

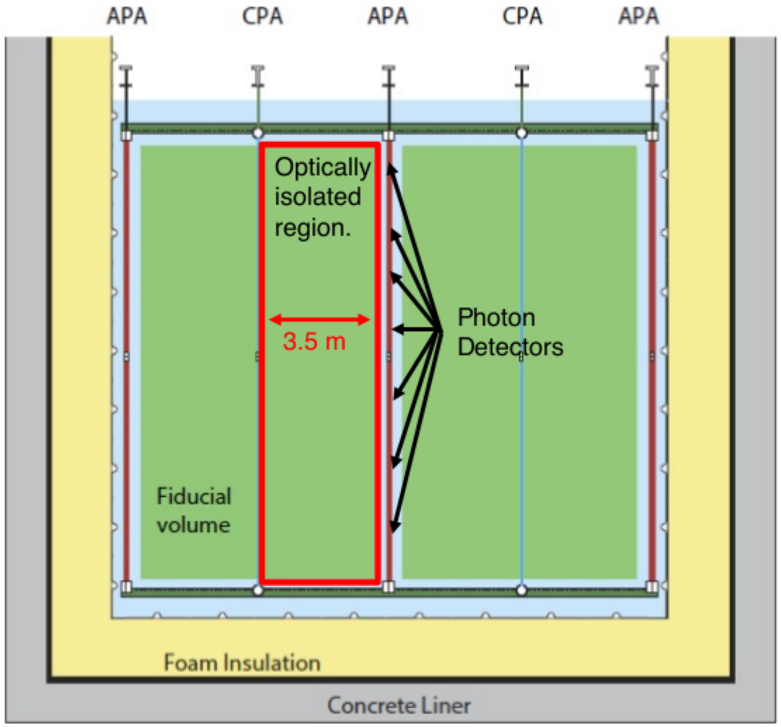
- We use “fast simulation” techniques trained on Geant4 photon tracking
  - Currently uses the semi-analytical model
- We use a “full chain” simulation including SiPM and electronics response, waveform digitization, hit and event reconstruction

# Impact of optical properties

- Rayleigh scattering length in LAr is short relative to 3.5 m drift distance
- TDR Studies assumed $\lambda_R$ = **60 cm** at 128 nm
- Recent measurements suggest $\lambda_R$ = **90-100 cm**
- Studies were likely too pessimistic, not yet carefully quantified







# Physics with the Photon Detector System

- **Determination of T0 in all non-beam physics.**
  - T0 → absolute distance from the readout plane
  - Useful for:
    - Fiducial volume selection (e.g. exclude nucleon decay backgrounds)
    - Correcting for attenuation in TPC signals
- **Triggering**
  - An alternative “trigger primitive” for identifying supernova bursts.
  - Combine with the TPC for a sophisticated solar neutrino trigger.
- **Calorimetry**
  - A complimentary energy measurement, even at a few MeV.
- **And possibly more:**
  - Michel tagging, pulse shape discrimination for PID…

# From Physics to Requirements

- In order to set requirements, we look at the different potential applications in different physics samples and determine which sets the tightest constraints on different PDS properties.

| **Beam ν** | **Nucleon Decay** | **Supernova ν** |
|---|---|---|
| Calorimetry | T0 Determination | T0 Determination |
| Michel Electron Tagging | | Burst Triggering |
| | | **Calorimetry** |

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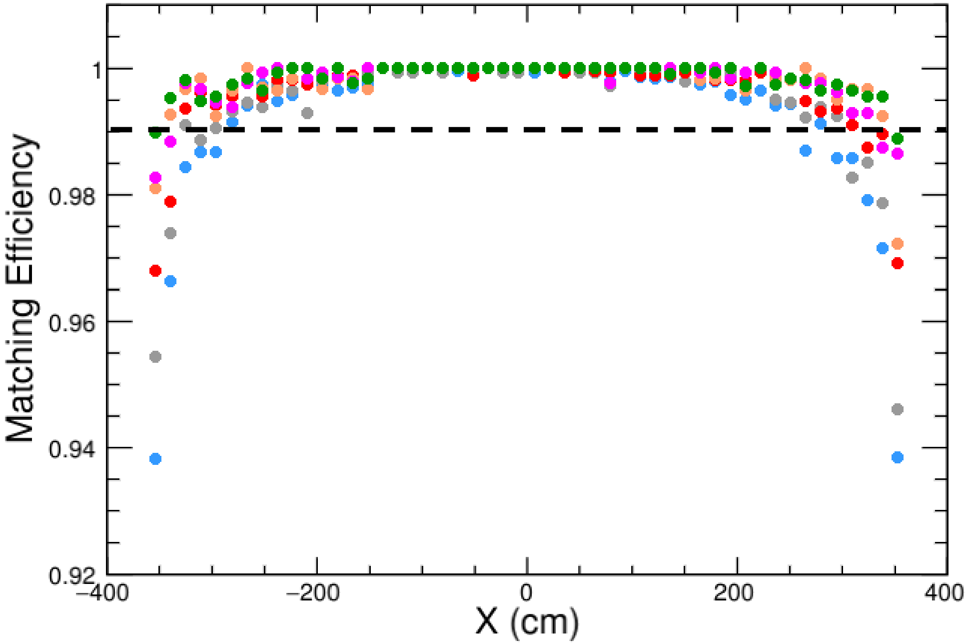
Sets **minimum light yield** in any region of the detector.

# T0 for Nucleon Decay Events

- **Requirement**: Must be able to determine T0 (e.g. tag with light) with >99% efficiency for all points throughout the detector volume.
  - The big worry with nucleon decay is background, and the photon detectors allow fiducialization to exclude entering backgrounds.
- Sets a **minimum light yield of 0.5 PE/MeV**.



| CPA Light Yield (PE/MeV) | Mis-ID Rate at CPA (%) |
|---|---|
| 0.09 | 6.2 ± 0.4 |
| 0.28 | 2.3 ± 0.4 |
| 0.33 | 1.6 ± 0.2 |
| **0.50** | **1.1 ± 0.2** |

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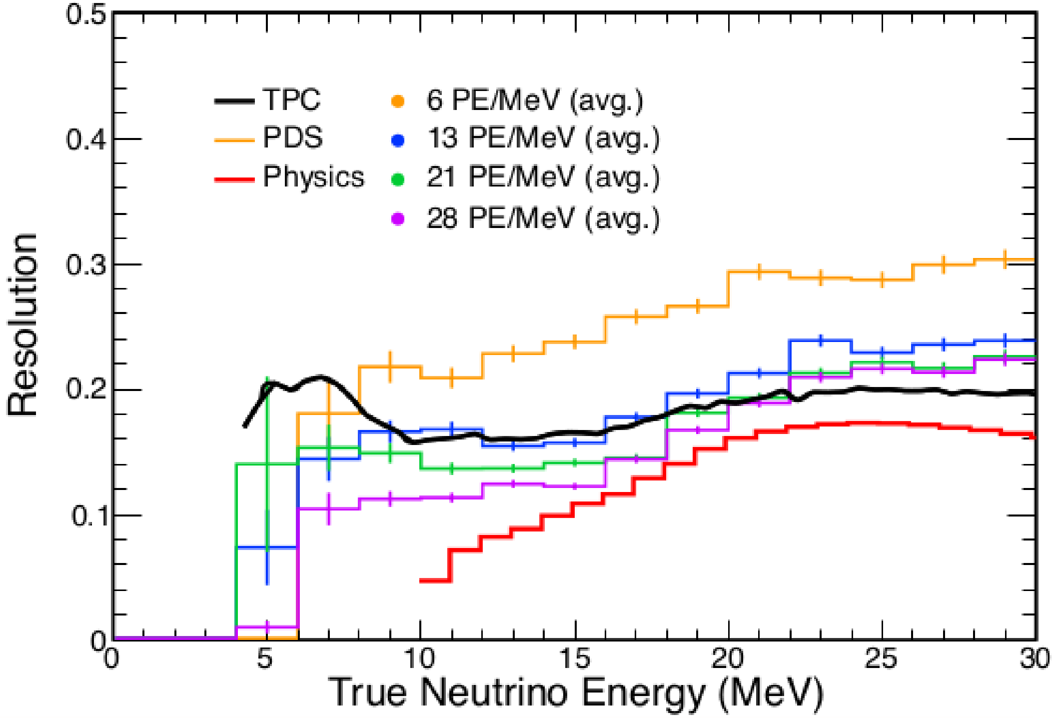
Sets required **average light yield** throughout the detector volume.

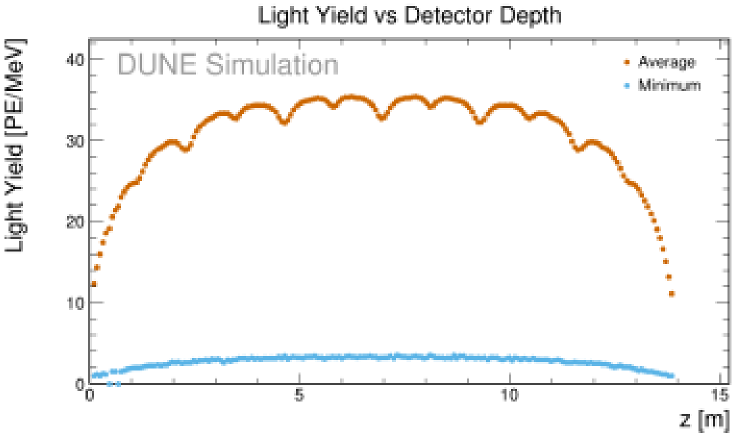
# Supernova Calorimetry

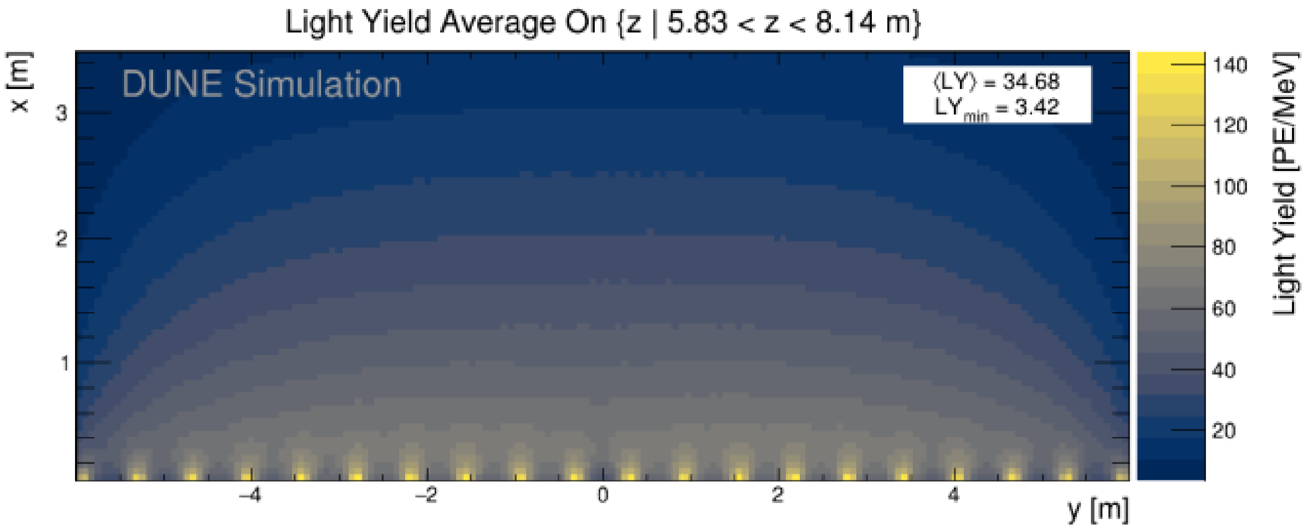
- **Requirement**: Comparable energy resolution to that of the TPC for supernova neutrinos below 20 MeV.
  - Allows us to take full advantage of the anti-correlation between light and charge when reconstructing the SN spectrum.
  - Also mitigates risk by allowing some measurement when TPC is not operating or purity is poor when a Supernova burst occurs.
- Developed a proto-analysis to:
  - Reject radiological bkgd.
  - Correct for attenuation vs. and the relationship between photos and true energy.
- **Sets a minimum average light yield of 20 PE/MeV.**
- Important caveat: only applies to the 60-70% of events which are bright enough to reconstruct.



# HD PDS and LY Requirements

- The HD PDS is a capable system that is built to comply with all physics requirements
- Parameters of the simulation
  - Rayleigh scattering ~1m
  - Absorption length = 20m (3 ppm of $N_2$)
  - X-Arapuca efficiency = 3%





# HD PDS and LY Requirements

- The HD PDS is a capable system that is built to comply with all requirements

| X-Arapuca efficiency | Average LY (central) | Average LY (all volume) | Minimum LY |
|---|---|---|---|
| 3.0% | 34.7 | 30.7 | 0.9 |
| 2.5% | 28.9 | 25.6 | 0.8 |
| 2.0% | 23.1 | 20.4 | 0.6 |
| 1.0% | 11.6 | 10.2 | 0.3 |
| 0.5% | 5.8 | 5.1 | 0.1 |

# From Physics to Requirements

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| | | **Calorimetry** |

Also sets specifications on **data rate, noise rate,** and **cross-talk rate.**

# From Physics to Requirements

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| | | **Calorimetry** |

Sets a requirement on **dynamic range** of the sensors and electronics.

# Beam Neutrino Calorimetry

- **Requirement:** Have sufficient dynamic range so that most channels in most beam neutrino events are not saturated, while also preserving single photon sensitivity for low-E physics.
    - Some channels saturating is tolerable, since there are two possible mitigation schemes: waveform shape and looking at neighboring channels.
    - Without those algorithms in hand, however, setting this requirement will need to be based on “reasonable limits.”
- Since the TDR, some further studies were performed, and the minimum requirement was set at **1-2000 photons**.
    - Only a few percent of beam neutrino events are likely to have saturating channels.
    - A 14-bit ADC operating at a gain with 8 ADC/PE, meets these requirements.

# TDR Requirements

- **SP-FD-3**: Average (minimum) light yield > 20 (0.5) PE/MeV
  - Rationale: Supernova calorimetry and NDK fiducialization
  - Detector specification: collection efficiency > 2.0%, and the X-ARAPUCA efficiency has been measured to be >~2%.

- **SP-FD-4**: Time resolution < 1 µs (goal < 100 ns)
  - (Didn't discuss much, so we meet this requirement trivially.)
  - Rationale: 1 µs will allow mm-scale resolution in the drift direction, needed for nucleon decay fiducialization. Better time resolution will help with Michel electron tagging.
  - Detector specification: sufficient fast sampling (62.5 MHz is plenty). Also constrains the impedances and shaping in cold electronics.

# TDR Requirements

- **SP-PDS-14**: Signal-to-noise > 4
  - Rationale from physics: need to see single PEs
  - Rationale from electronics: need to keep data rate within limits
  - S/N>5 was obtained from dedicated tests

- **SP-PDS-16**: Dynamic range < 20%
  - Requirement set at a range of 1-2000 photons
  - Rationale: ensure that we can correct for any saturation which occurs to allow for accurate calorimetry of beam neutrinos while still recording single PEs.

# Conclusions

- We have developed a suite of requirements to ensure **the single-phase photon detection system does its part in meeting the high-level physics goals of DUNE**
- The current design of light collectors, sensors, and electronics meets the requirements in:
  - Minimum light yield
  - Average light yield
  - Time resolution
  - Dynamic range
  - Signal to Noise
  - Data rate
- There is still some room for improvement, particularly with supernova and solar neutrino triggering