Physics Requirements for the Single Phase Photon Detection System

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60% Single Phase Photon Detector Design Review

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Introduction

- In this talk, we will walk through:
  - How scintillation in liquid argon works.
  - The role of the photon detectors in DUNE physics.
  - How those physics roles define requirements.

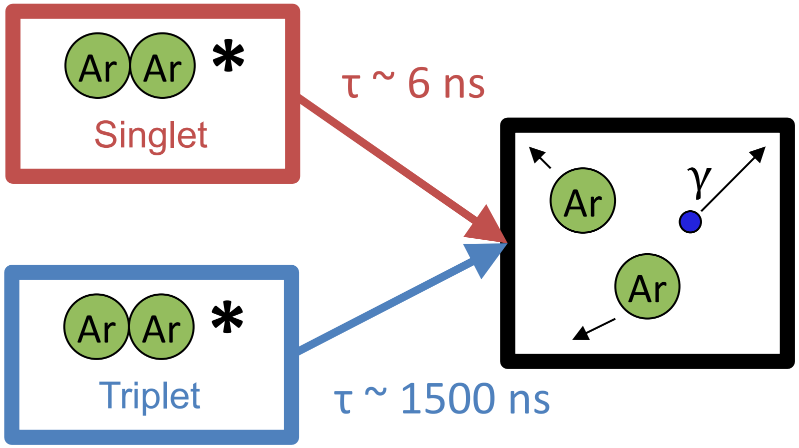
- Some key things to remember as we go through the talk:
  - The PDS is designed to work in concert with the TPC.
  - More than half of the deposited energy goes into light
  - Photons are recorded within μs instead of ms
  - The scintillation time structure and a short scattering length can make using the light challenging.

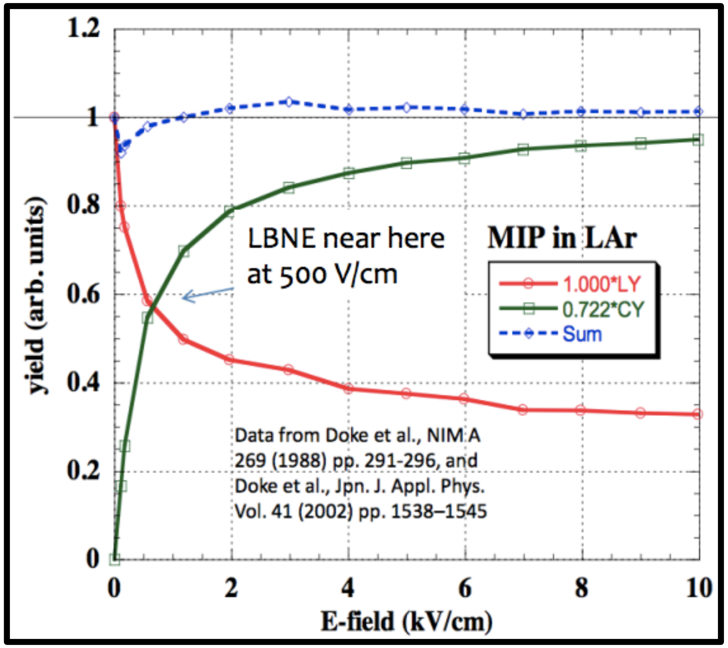
Physics with Photon Detectors

- **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…

Argon Scintillation

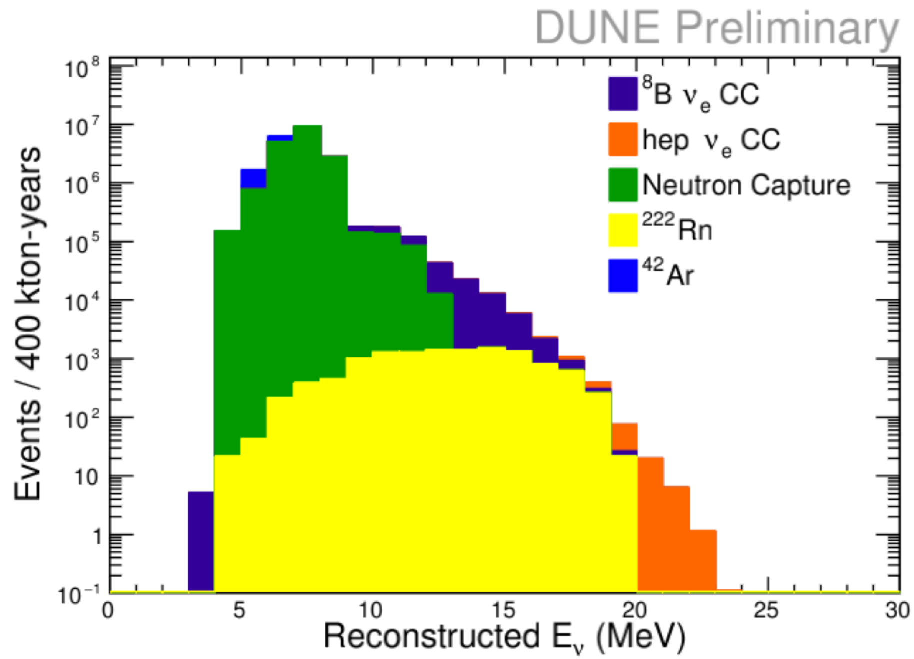
- Light is produced wehn an Ar-Ar* excimer decays.
  - ~25% is in the Singlet state which decays in ~6 ns.
  - Remainder is in the Triplet state with decays in ~1500 ns.
- Argon is a strong scintillator: **24k γ/MeV** at nominal DUNE field.
  - ~60% of the energy goes into photons.
- The amount of charge and light produced by a particle is anti-correlated.
  - Some excimers produced via ionization and recombination.



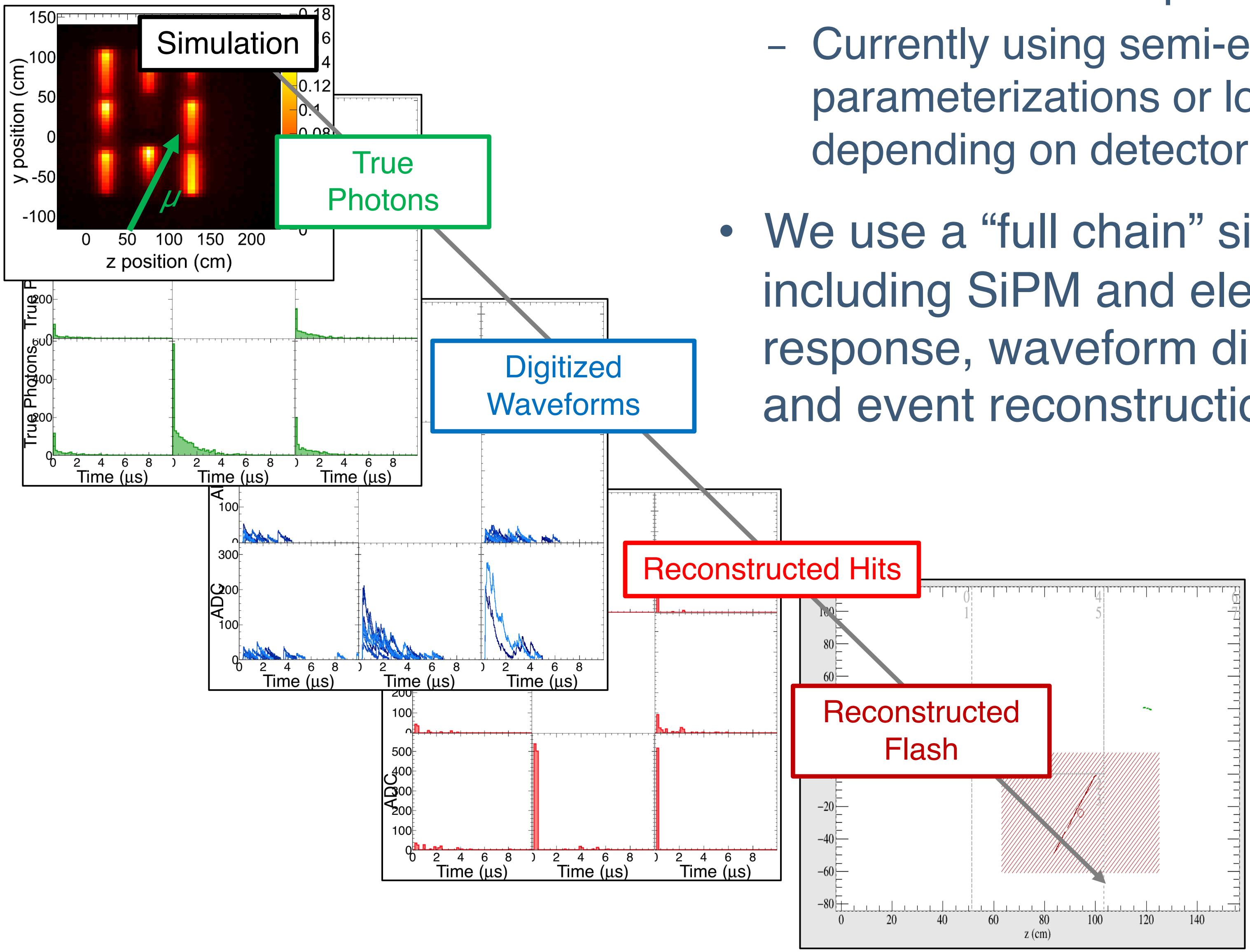


How We Simulate Light

- Scintillation light produced when particles deposit energy in LAr in Geant4.
- In addition to signals (supernova ν, solar ν, NDK, etc.) we have a radiological model with growing sophistication.
  - Includes both bulk contaminants (^{39}Ar, ^{42}Ar) and those expected to plate onto PDS surfaces (α emitters).

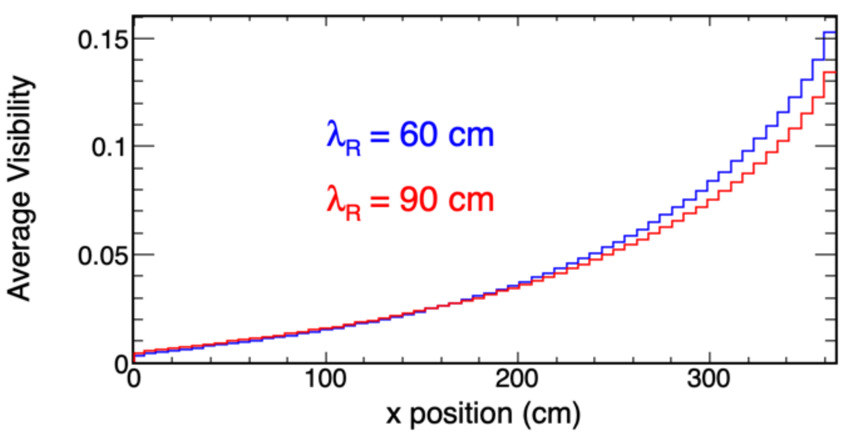


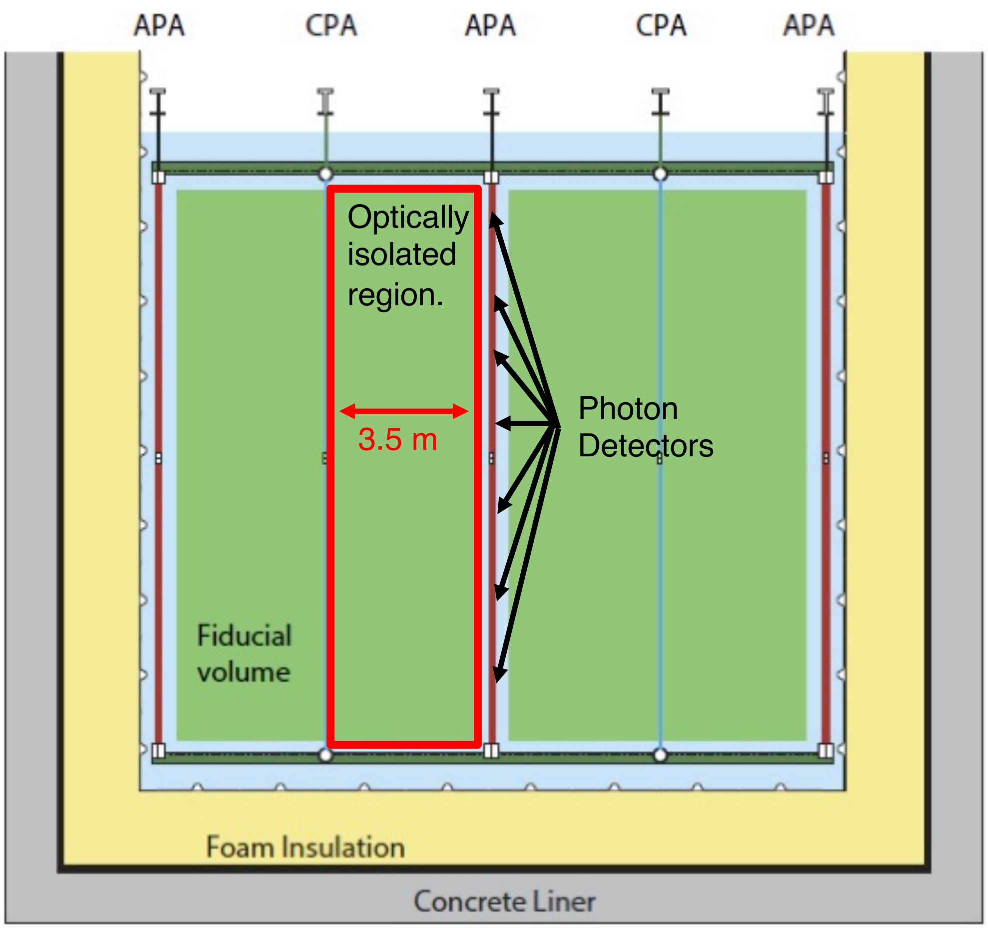
- We use "fast simulation" techniques trained on Geant4 photon tracking.
  - Currently using semi-empirical parameterizations or look-up libraries, depending on detector geometry.
- We use a "full chain" simulation including SiPM and electronics response, waveform digitization, hit and event reconstruction.



Optical Properties and Uniformity

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





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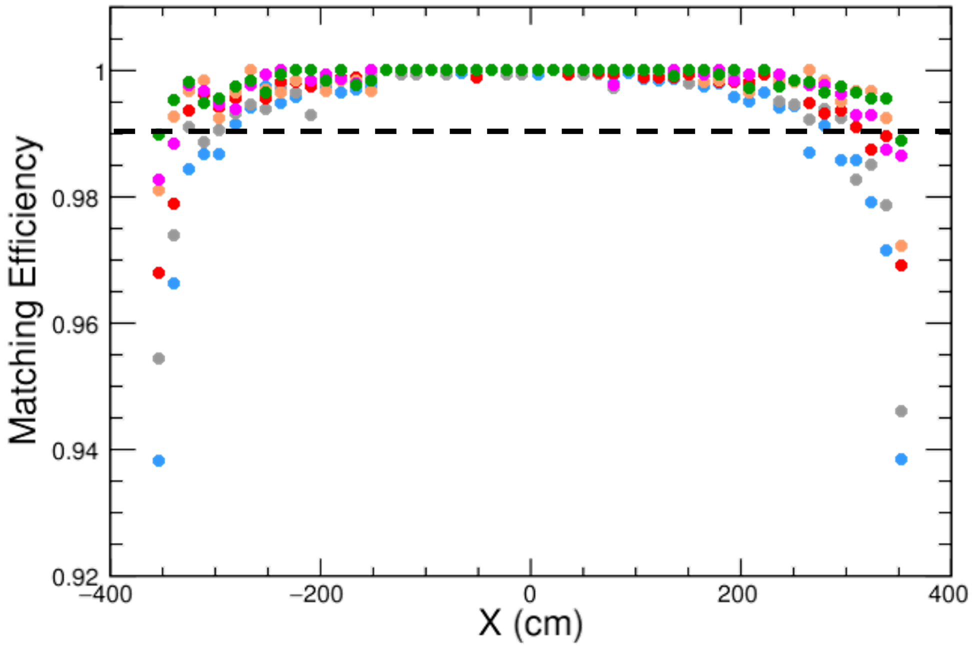
Sets **minimum light yield** in any region of the detector.

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 **collection efficiency of 1.3%**, well below the current designs with ~3% efficiency.



Collection Efficiency	Mis-ID Rate at CPA (%)
0.2%	6.2 ± 0.4
0.3%	5.0 ± 0.4
0.4%	3.2 ± 0.4
0.7%	2.3 ± 0.4
0.9%	1.6 ± 0.2
1.3%	**1.1 ± 0.2**

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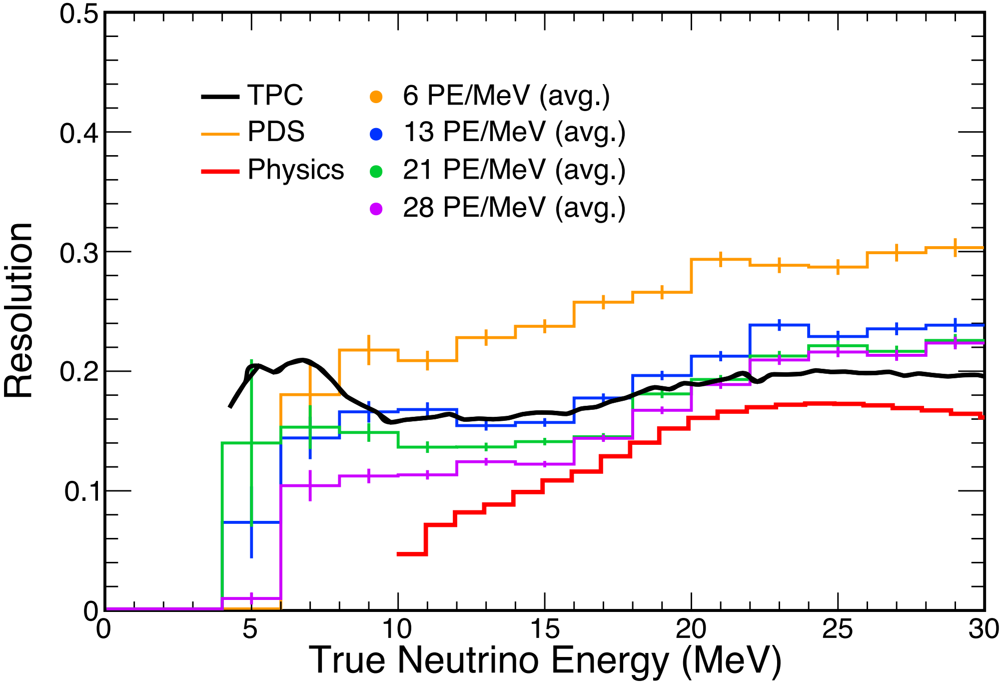
Sets required **average light yield** throughout the detector volume.

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, or 2.5% collection efficiency.**
- Important caveat: only applies to the 60-70% of events which are bright enough to reconstruct.



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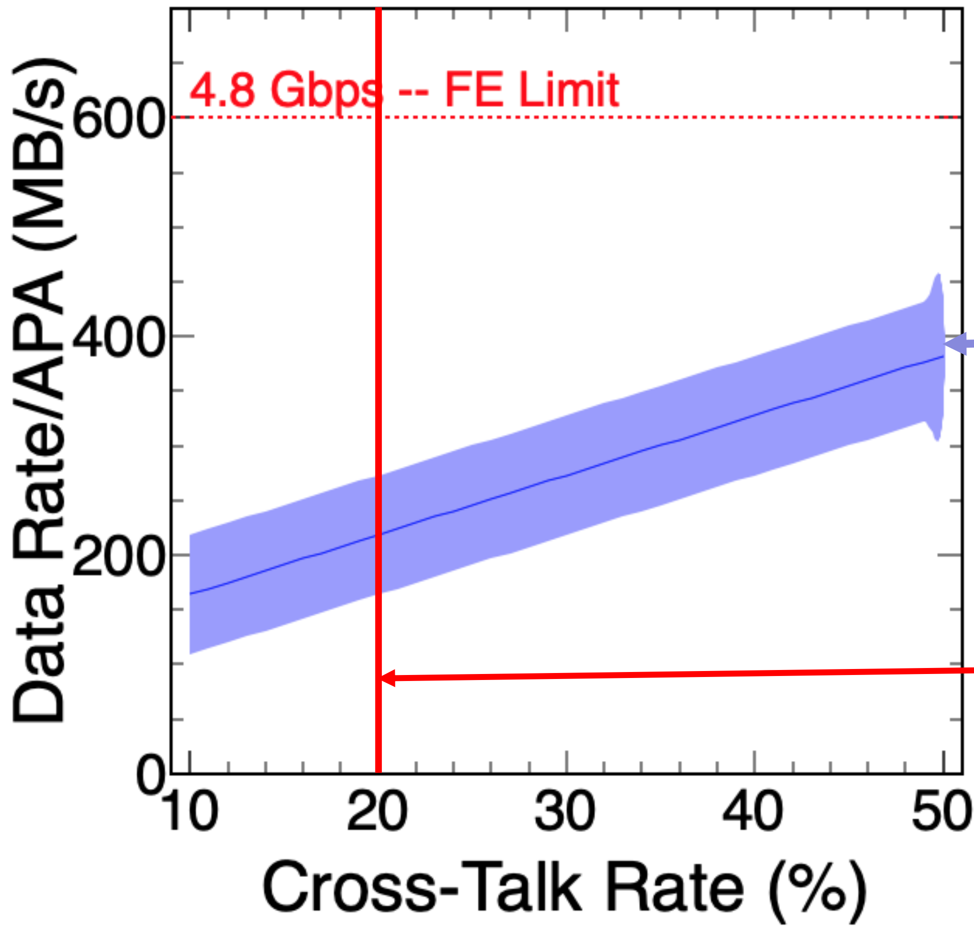
Also sets requirements on **data rate, noise rate,** and **cross-talk rate.**

Setting Electronics Requirements

- Important background on PDS operation:
  - Each channel must perform independent “zero suppression” or “self-triggering.”
  - Can tolerate sending mostly background out from the FE since the DAQ will perform buffering and high-level triggering.
- Studies of supernova neutrinos show that we can operate with a 1.5 PE threshold.
  - Channels with *only* single PE signals are likely to be background.
  - 1 PE signals which follow a 2+ PE signal will still be recorded.
- **Requirement:** The minimum data rate from the electronics must be sufficient to support the maximum allowed rate of 2 PE “noise” signals.



2 PE rate has two components:

- **2.4 kHz** from 2+ PE radiologicals
- **12.2 kHz × (cross-talk rate)** from 1 PE signals

Rate → data rate assuming 14-bit, 5 μs waveform readout.

Current expected FE and sensor performance meet these requirements with safe margins.

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Beam ν	Nucleon Decay	Supernova ν
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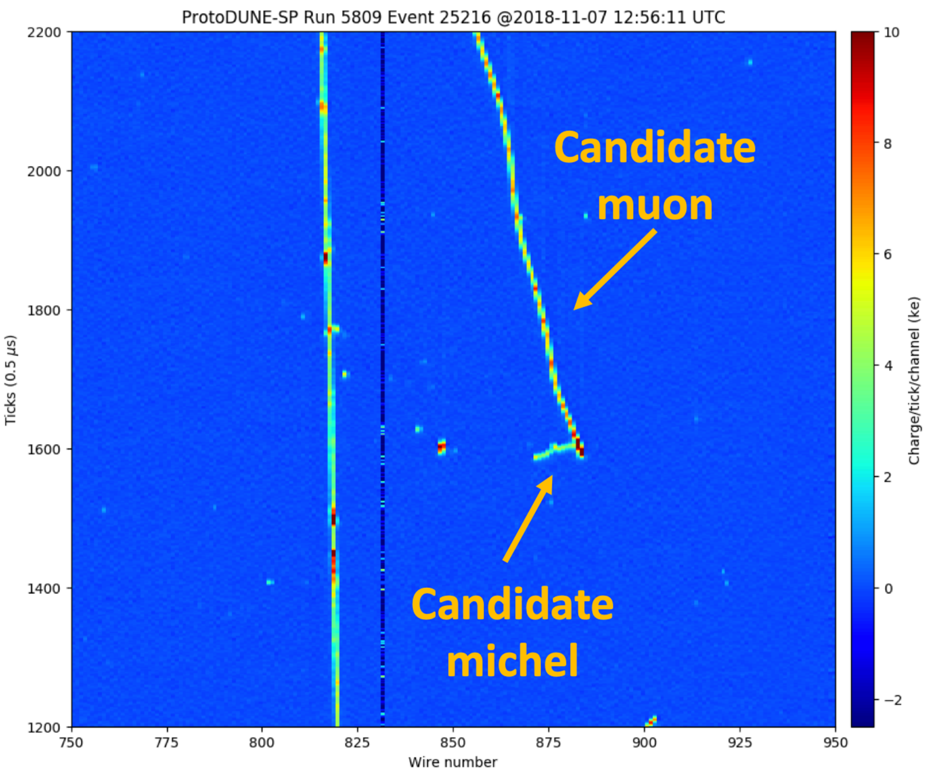
Sets a requirement on **dynamic range** of the sensors and electronics.

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.

Michel Electron Tagging

- **Physics Goal**: The PDS should be able to identify Michel electrons from muon and pion decays.
  - They help with background rejection
  - Can be challenging to reconstruct
- PDS needs to identify Michel on top of the triplet light.
- Plan on waveform readout to allow algorithms to try to identify them.
  - Since algorithms don't exist yet, no further quantitative requirements.



Room to Improve

- Later, you'll be presented some options to increase the light yield uniformity with reflector foils and Xenon doping. Here's some physics they could improve:
- **Supernova and solar triggering**
  - TDR design is highly efficient throughout the Milky Way, but becomes challenging in the Large Magellanic Cloud, where we could have as few as 6 neutrinos per 10 kTon module.
  - If light yield is more uniform, we can trigger even if all 6 neutrinos are distant from the photon detectors.
  - With reflector foils, online X-position determination could be used to further reduce backgrounds.
- **Beam and Supernova calorimetry**
  - Greater uniformity will reduce systematic impact from LAr optical properties.
  - Would allow PD calorimetry to apply to a larger fraction of supernova events.
- **Michel Electron tagging**
  - Xe doping significantly reduces the late light component, so Michel electrons will be easier to identify.

TDR Requirements

- **SP-FD-3**: Average (minimum) light yield > 20 (0.5) PE/MeV
  - Rationale: Supernova calorimetry and NDK fiducialization
  - Detector specification: collection efficiency > 2.5%, and the X-ARAPUCA efficiency has been measured to be ~3%.
- **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-13**: Data transfer < 8 Gbps to DAQ
  - This requirement has changed substantially since the TDR as part of the further development of our DAQ interface.
  - Now, best thought of as needing to "match" DAQ expectation of 4.8 Gbps or 9.6 Gbps and having sufficient bandwidth for physics.
  - Minimum requirement from physics is 1-3 Gbps, depending on radiological and cross-talk rates.
  - Current DAPHNE design supports 4.8 Gbps.
- **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
  - Being considered as part of a set of sensor and electronics properties which need to be optimized together.

TDR Requirements

- **SP-PDS-15**: Dark noise rate < 1 kHz
  - Rationale from physics: at this rate, the likelihood of having a dark noise hit in a physics waveform is only ~0.5%.
  - Rationale from electronics: ensure that dark noise rate is not the dominant source of single-PE noise **but…**
  - With a 2 PE threshold, cross-talk is more relevant than dark rate.
  - Being considered as part of a set of sensor and electronics properties which need to be optimized together.
- **SP-PDS-16**: Dynamic range < 20%
  - This requirement was also updated substantially since the TDR.
  - 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.
  - Being considered as part of a set of sensor and electronics properties which need to be optimized together.

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
  - Dynamic range
  - Noise rate
  - Data rate
- There is still some room for improvement, particularly with supernova and solar neutrino triggering, which will be enabled by enhancements in light yield uniformity.