Simulation Studies and Requirements

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DUNE-SP Photon Detection System
Conceptual Design Review
November 12th, 2018

Introduction

- Current requirements and where they come from
- Overview of the simulation and reconstruction
  - Geant4-based simulation of detector designs for extrapolating from measured prototypes to baseline design.
  - LArSoft-based simulation for connecting system performance to physics goals.
- New physics requirements which will inform new detector requirements for the TDR
  - Start from DUNE physics goals…
    - Beam ν, supernova ν, and nucleon decay.
  - Flow down to detector requirements
    - In progress: status of studies so far
- Performance requirements which need to be confirmed with R&D in the near future.

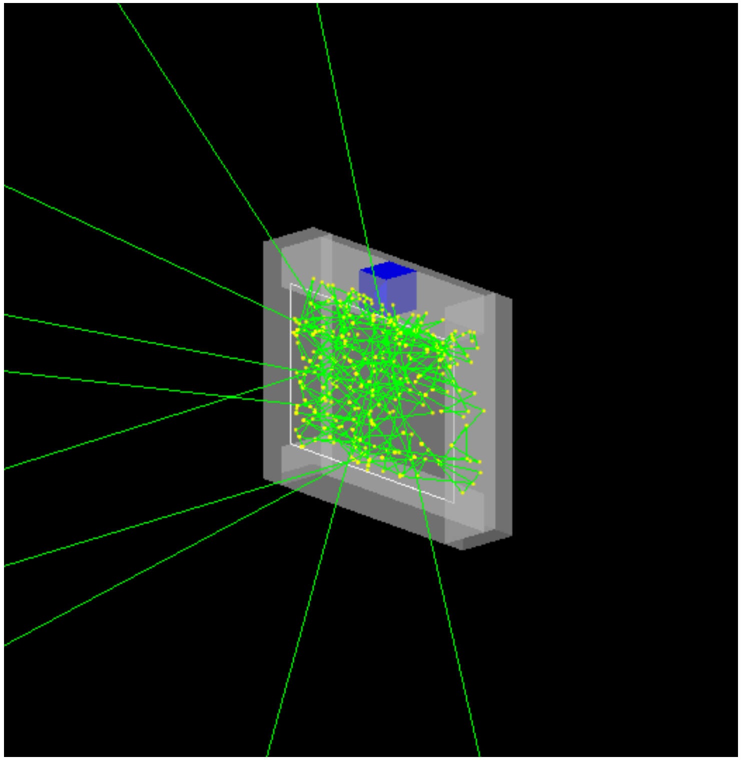
Current Scientific Requirements

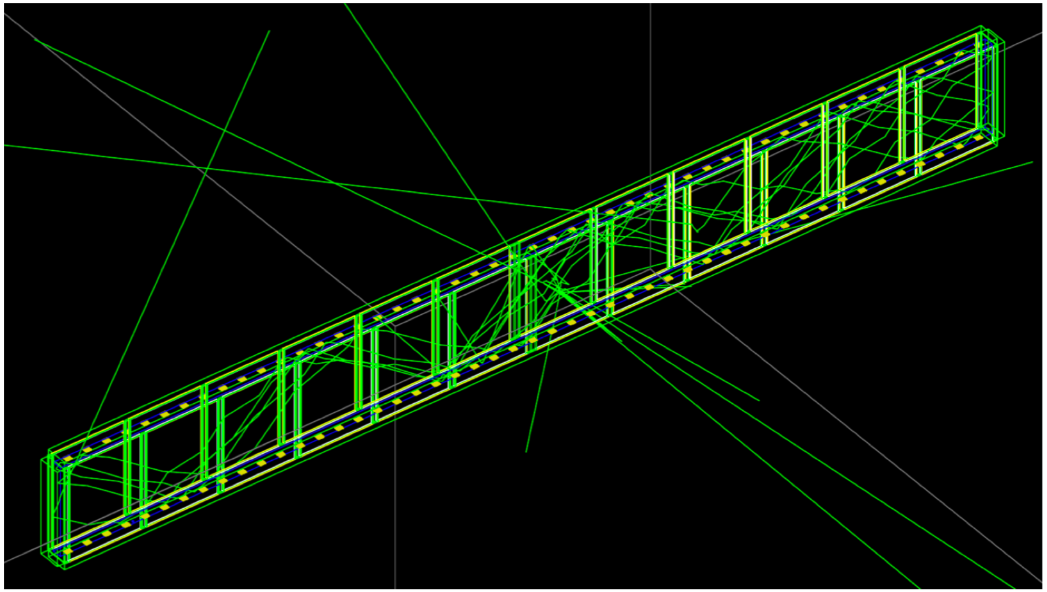
	Requirement	Goal
Light Yield	> 0.5 PE/MeV	> 5 PE/MeV
Time Resolution	< 1 μs	< 100 ns

- The light yield *requirement* is based on nucleon decay events.
  - **Physics requirement:** high efficiency (>99%) for tagging nucleon decay events with T0 to eliminate backgrounds from outside the detector.
  - Based on MC truth studies done before the ProtoDUNE review.
- The light yield *goal* is based on supernova events.
  - A high-level approximation of the amount of light needed for calorimetry with the PDS comparable to the TPC.
  - This will be replaced with a full suite of physics requirements. Will discuss at length later.
- Timing resolution:
  - 1 μs is required for mm precision in X, comparable to the TPC in Y and Z.
  - 100 ns goal would allow observing finer details in the time structure (pulse-shape discrimination or Michel-e tagging).

Stand-Alone Detector Simulations

- 2 different simulations were developed.
  - Simulation for optimizing ARAPUCA designs developed in Brazil
  - Simulation tool for examining a variety of light guides developed at Syracuse

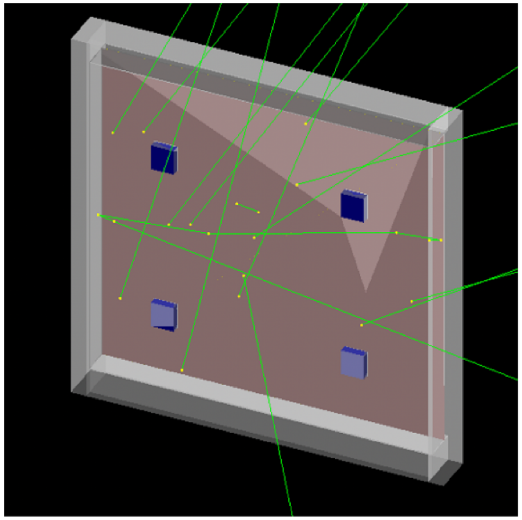




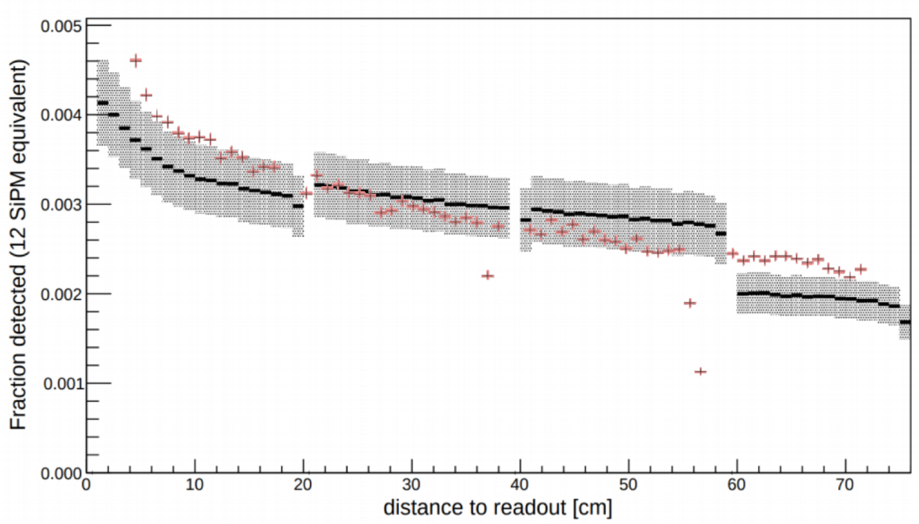
Verification with R&D Data

ARAPUCA

- Efficiency at LNLS:
  - Simulation: (1.5±0.3)%
  - Measured: (1.10±0.15)%
- Efficiency at TallBo
  - Simulation: (0.6±0.2)%
  - Measured: (0.77±0.05)%
    - Cross-talk and after-pulsing not corrected for.



General Light Guide



- Reproduced attenuation behavior of double-shift light guide.
  - Variation in plate quality means some freedom in absolute scaling.
- ARAPUCA efficiency at TallBo
  - Simulation: 1.1%
  - Measured: 0.77%
- Correct simulation for difference in observed efficiency and cross-talk in measurement.

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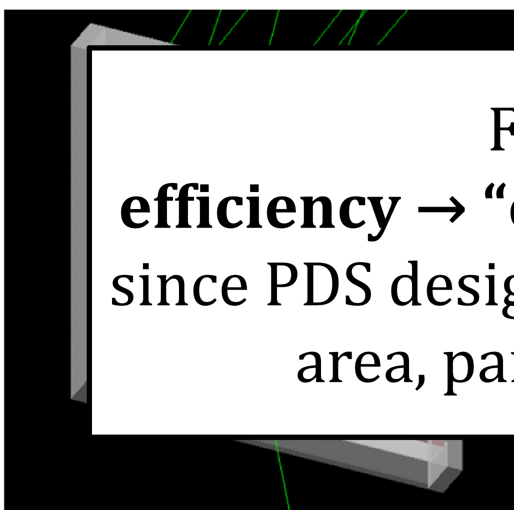
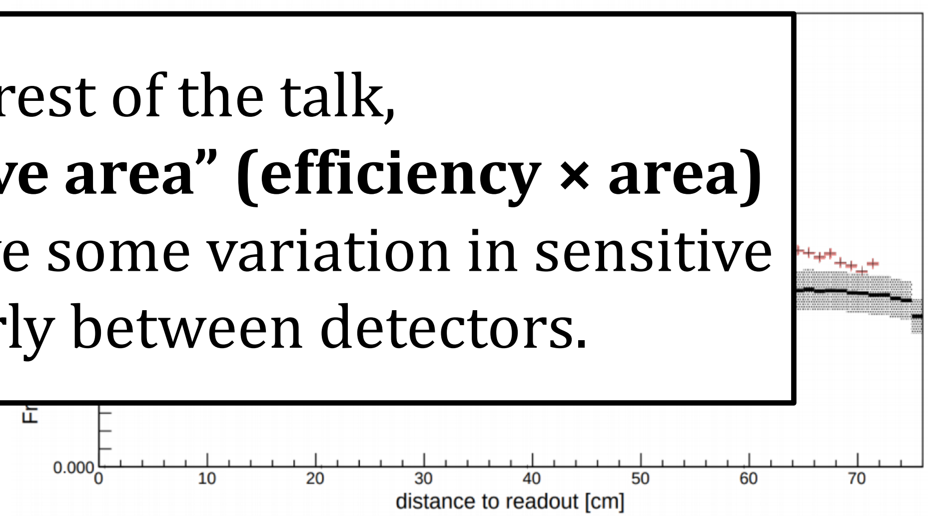
  - Measured: 0.77%
- Simulation 30% high – keep this correction in later simulations.

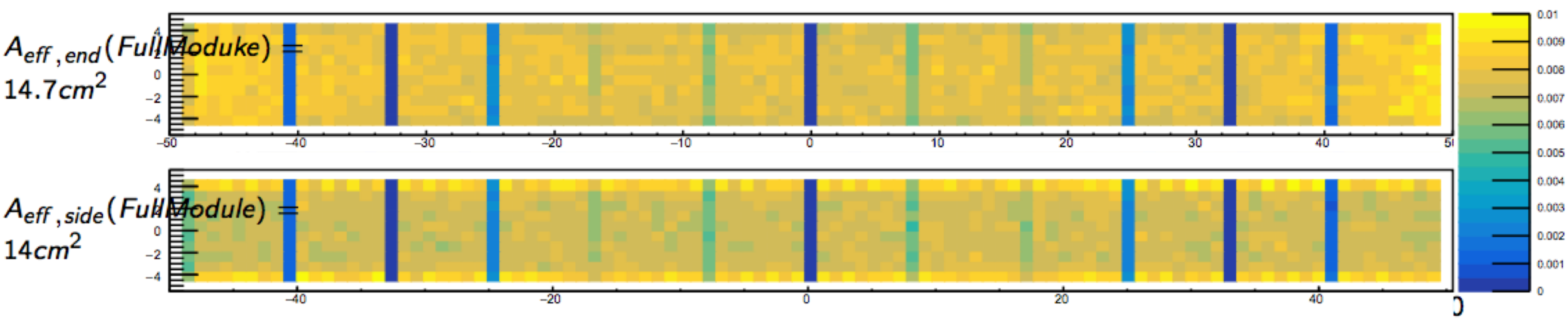




For the rest of the talk,
efficiency → "effective area" (efficiency × area)
since PDS designs have some variation in sensitive area, particularly between detectors.

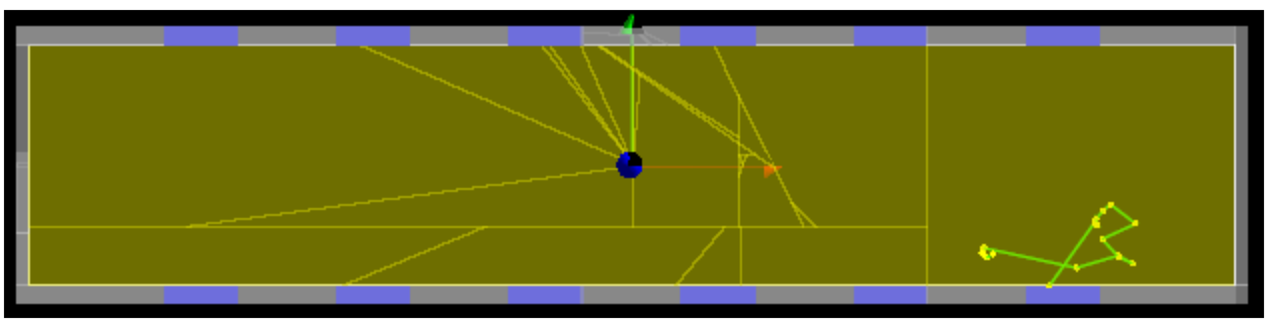
Extrapolation to Far Detector Designs

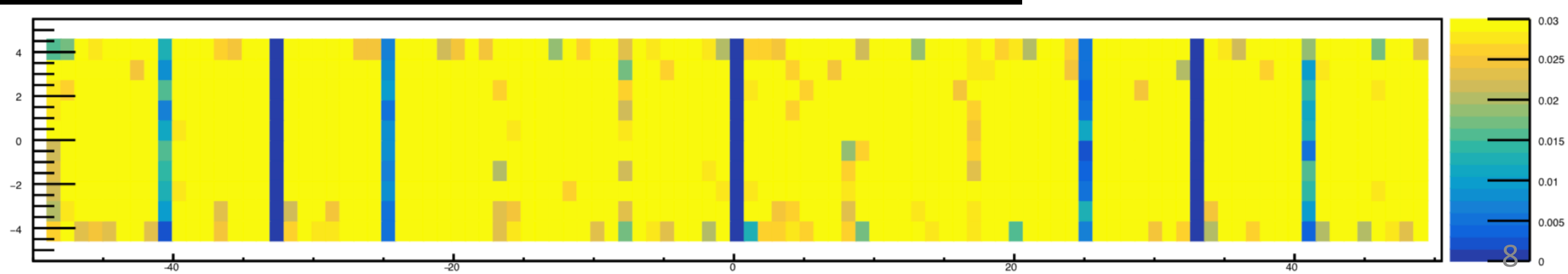
- Straightforward modifications of the ProtoDUNE double-shift light guide design.
  - Shorter, wider sections.
  - Comparison of side vs. end-mounted SiPMs.
- Effective area: ~14 cm^2
  - ProtoDUNE PDs have an A_{eff} of ~5 cm^2
- Not a baseline design, but including as a reference point for detector performance we are very confident can be achieved.



Extrapolation to Far Detector Designs

- Previous ARAPUCA designs have been single-sided.
- Double-sided ARAPUCA efficiency has been estimated in both simulations.
  - ARAPUCA Simulation: 47 cm^2
    - 12 SiPMs/cell
  - Light Guide Simulation: 23 cm^2
    - 8 SiPMs/cell





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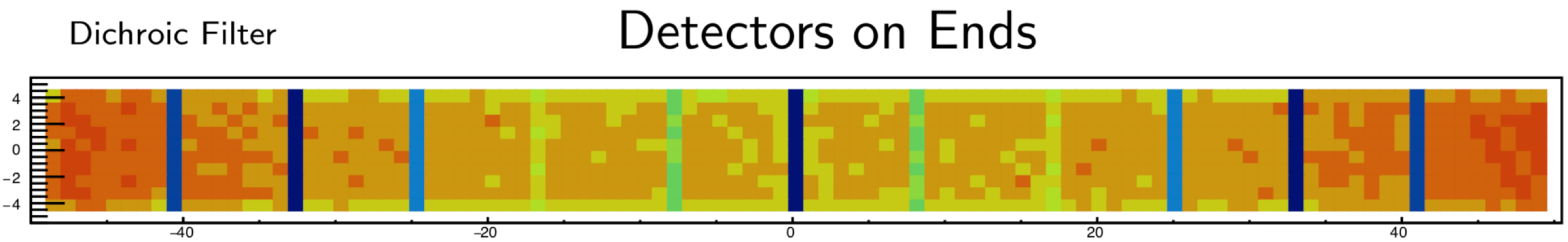
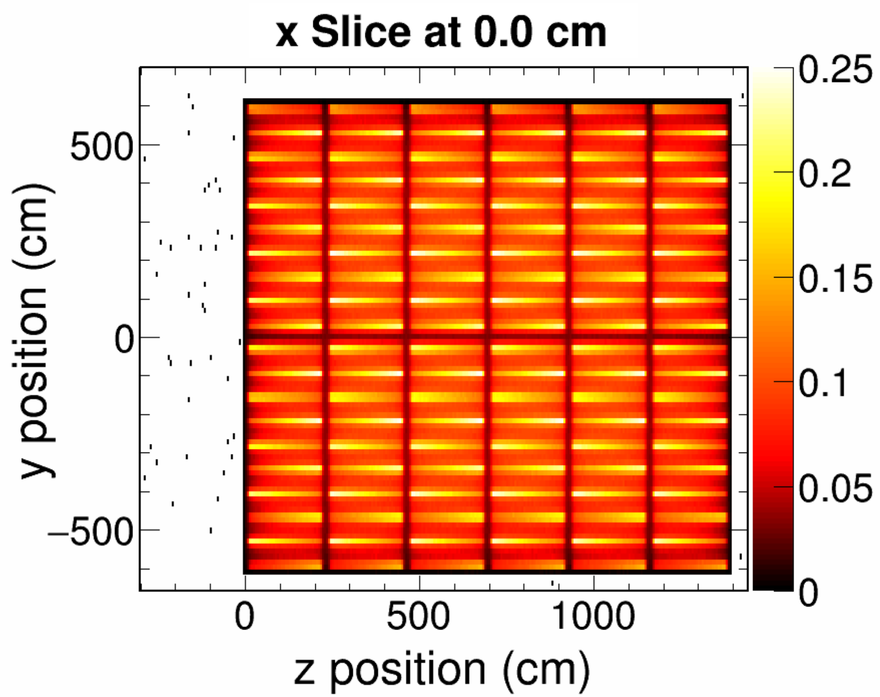
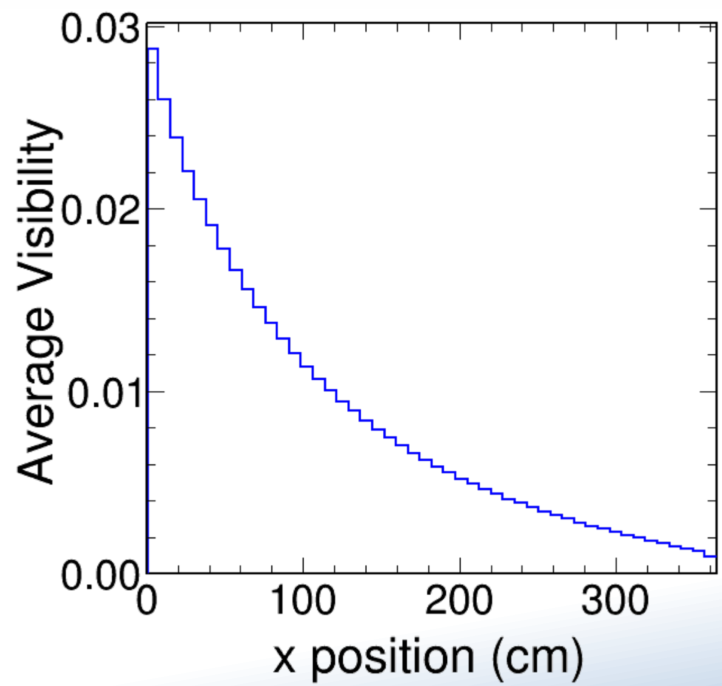


- X-ARAPUCA, the baseline design, uses ideas from both the ARAPUCA and light guide designs.
- The Light Guide simulation predicts an A_{eff} of 48 cm^2.
- Also shows equivalent performance with 48 SiPMs on 4 ends as with 192 SiPMs along the sides.

Overview of System Simulation

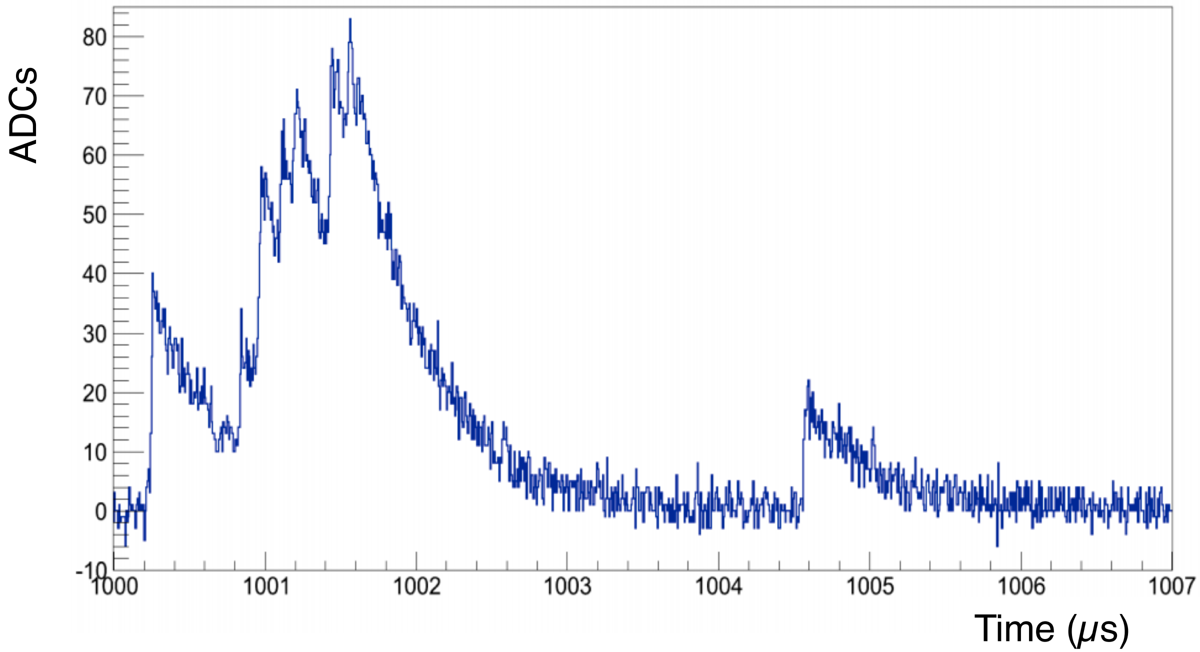
- We generate 24,600 128 nm γ's per MeV.
  - 41 kγ × 0.6 (yield @ 500 V/cm)[1]
  - Includes ArgoNeuT recombination effects
- Light is transported to photon detectors via a Photon Library. Uses:
  - Rayleigh scattering length ~60 cm for VUV
    - This is a moving target in the literature, so using a conservative choice.
  - Long absorption length (20 m)
    - Equiv: low N_2 contamination
  - 25% reflectivity from Al, steel
- Working in a small geometry 6 APAs long.
  - Large enough to contain flashes produced in the middle sections.
  - Small enough that a library can be generated for it.
- Scintillation time constants:
  - 30% fast (6 ns)
  - 70% slow (1.6 μs)





[1] Doke et al. Jpn. J. Appl. Phys. 41, 1538 (2002)

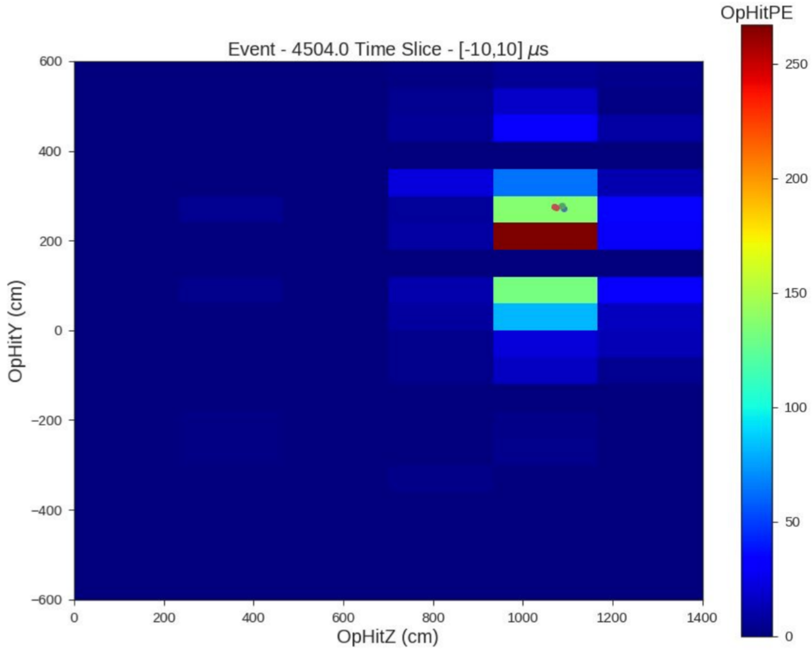
Overview of System Simulation

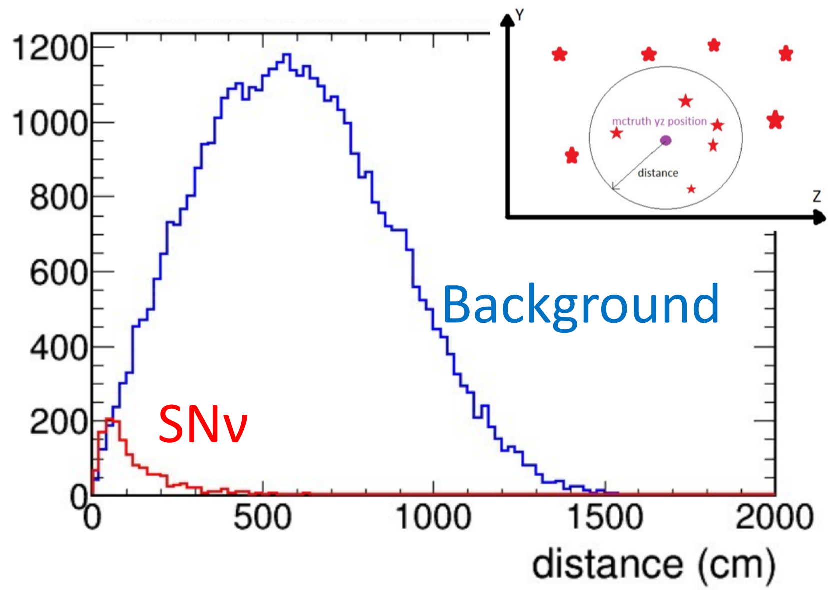


- Build up waveforms with simulations of the sensors and electronics.
- SiPM
  - Single PE shape from 3 Sensl SiPMS passively ganged
  - Add Dark current: assumed 10 Hz/channel until now
  - 20% cross-talk probability, No afterpulsing
- Electronics
  - SSP leading-edge discriminator, 0.5 PE threshold
  - Random noise on each sample, assume signal-to-noise of 7 until now

Photon Detector Reconstruction

- Hit finding:
  - Identify peaks on each channel separately
  - Overlapping peaks are merged together
- Flash finding:
  - Look for coincidences in time across channels.
  - Currently does not require hits close in space, but the small geometry approximates this effect.
- Flash matching:
  - In any given event, there will be numerous flashes from radiological backgrounds.
  - The “match” is the largest flash within 2.4 m of the vertex in the Y-Z plane.





Simulation Assumptions and Caveats

- Studies up until now had some assumptions which we think are overly optimistic for the current baseline:
  - Signal/noise: 7
  - Dark rate/channel: 10 Hz
  - Digitization at 128 MHz
- Library:
  - Voxels are 5 cm × 10 cm × 6 cm: Large on the scale of the PDs in Y, so simulation is off when very close to the APA.
    - Only real solution is to move away from photon libraries.
    - We've been working on that for more than a year, but it is challenging to do.
  - Timing simulation not accurate to better than 10 ns since photon transport time not considered.
    - This is an upgrade under active development, may be available between now and the TDR.

Plans for Updated Simulation

- New simulation is being produced now which better reflects the baseline design and likely variations covering pessimistic and optimistic assumptions.
  - Baseline digitization frequency: **80 MHz**
  - Light yield: **15 cm^2 – 60 cm^2**
    - 15 cm^2 is simple improvements to double-shift light guide from protoDUNE
    - 60 cm^2 is past best estimate of X-ARAPUCA
  - Dark rate: **10 Hz – 1 kHz**
  - Signal to Noise: **3 – 7**
    - These cover previous optimistic assumptions to worse than current expecations
  - Reflector foils: **optimistic** and **pessimistic**
    - Exact performance of these devices not known yet, so trying to cover likely range.
- Prioritizing supernova samples since that is where we need new simulation to reach conclusions on new requirements.

Developing New Requirements for the TDR

- We are in the process of updating the **detector requirements** for the TDR, based on an more complete set of **physics requirements**.
  - Detector requirement: a capability the detector component needs to have (light yield, noise, etc.)
  - Physics requirement: a capability we need to reach DUNE physics goals (trigger efficiency, resolution, etc.)

- We will look now at the new set of **physics requirements**.
- We are in the process of flowing down the **physics requirement** to **detector requirements**.

<table>
<tr><th>Beam ν</th><th>Nucleon Decay</th><th>Supernova ν</th></tr>
<tr><td>Calorimetry</td><td>T0 Determination</td><td>T0 Determination</td></tr>
<tr><td colspan="2">Michel Electron Tagging</td><td>Burst Triggering</td></tr>
<tr><td></td><td></td><td>Calorimetry</td></tr>
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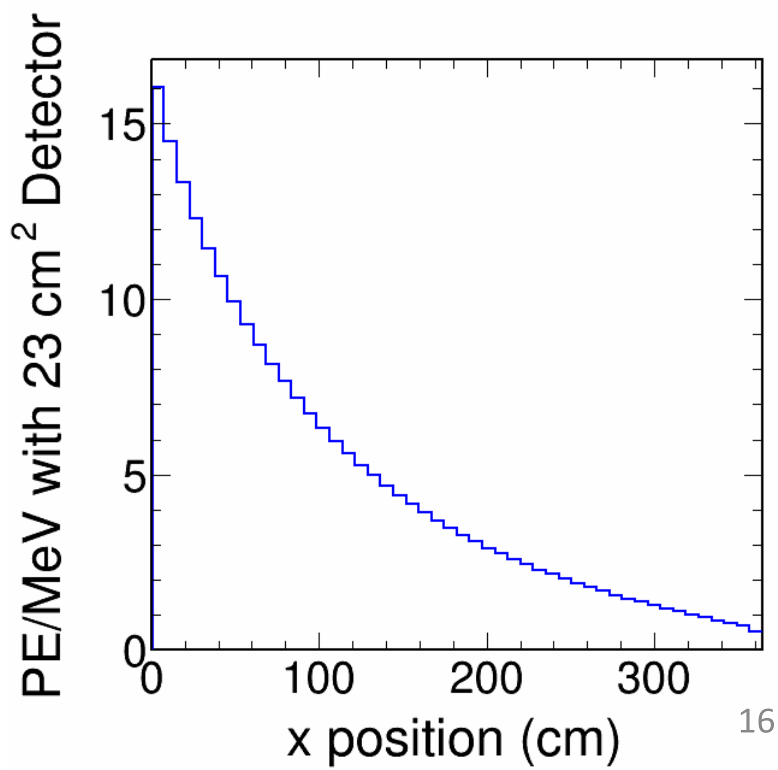
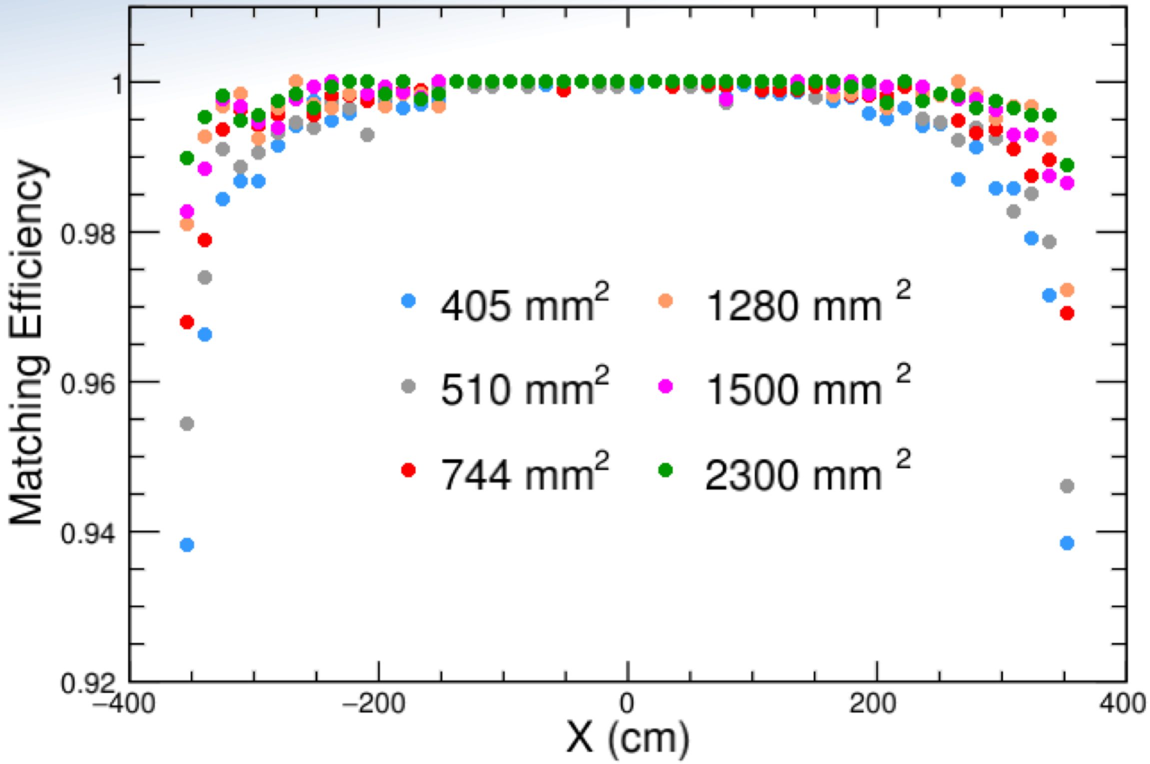
T0 for Nucleon Decay Events

- **Physics Requirement:** The PDS must be able to determine T0 with better than 1 μs resolution for events with visible energy > 200 MeV throughout the active volume.
  - This is the region for nucleon decay and atmospheric neutrinos.
  - The time measurement is needed for event localization for optimal energy resolution and rejection of entering backgrounds.
  - The resolution is required for comparable spatial resolution to the TPC along the drift direction.
- This creates **detector requirement for light yield**, but would also benefit from increased uniformity.
- Existing requirement: 0.5 PE/MeV throughout the detector volume.
  - Requirement came from MC-truth studies.
  - This corresponds to a detector with 23 cm^2 effective area.



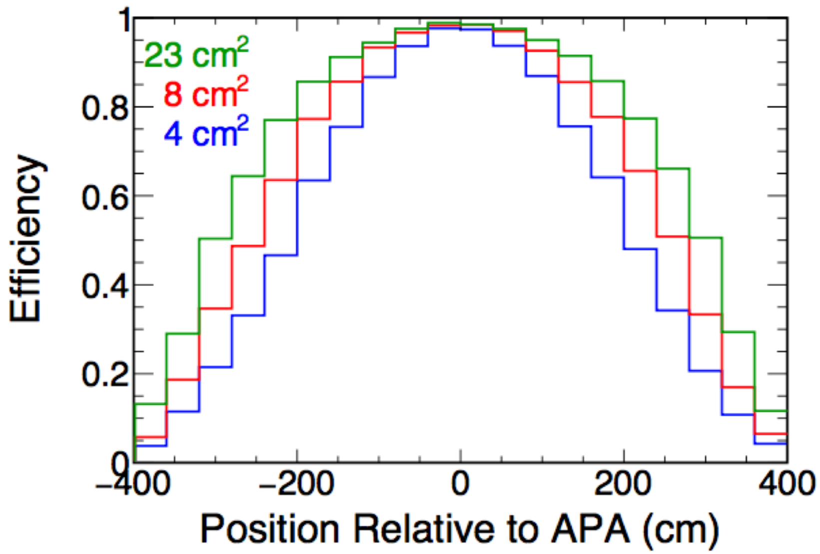


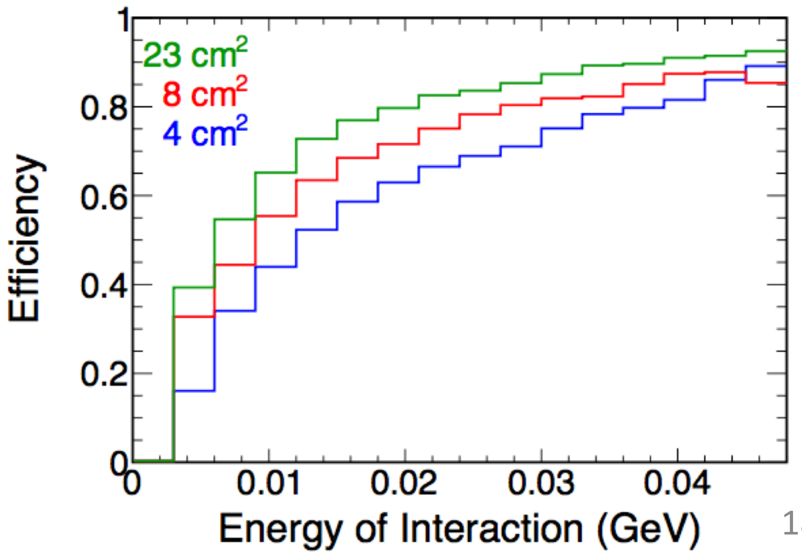
Effective Area (cm^2)	Mis-ID Rate at CPA (%)
4.05	6.2 ± 0.4
5.10	5.0 ± 0.4
7.44	3.2 ± 0.4
12.8	2.3 ± 0.4
15.0	1.6 ± 0.2
23.0	1.1 ± 0.2

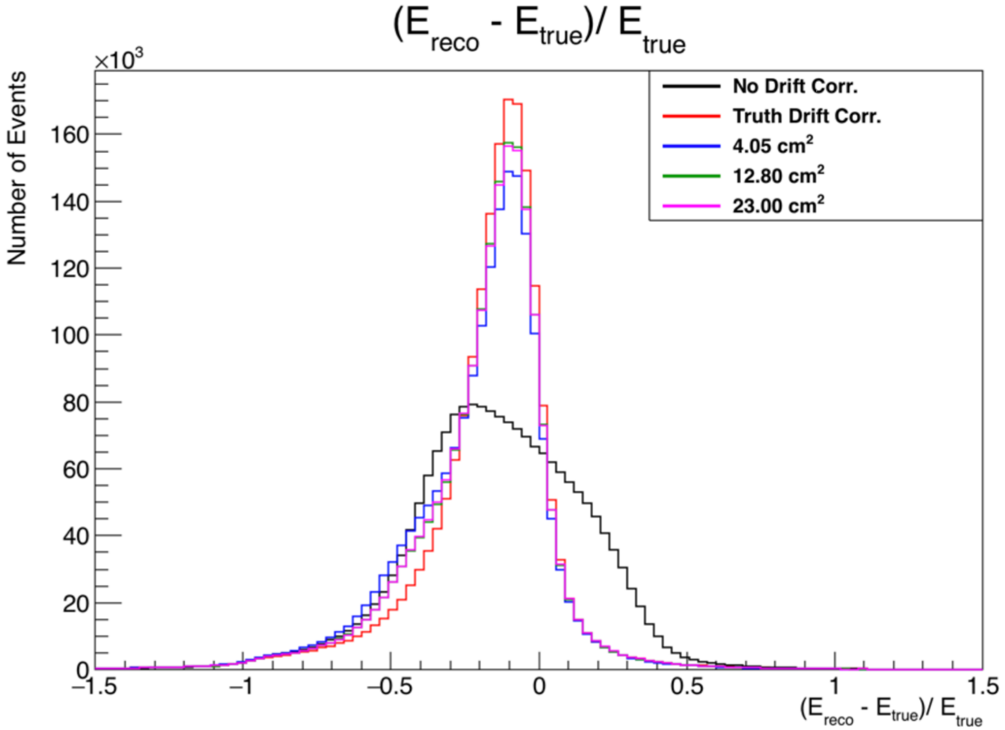
- This is an updated study with full simulation and reconstruction of nucleon decay events.
  - The requirement is really on background, not signal, but…
  - It's more efficient to simulate signal which should be representative of problematic backgrounds.
- Confirms the detector requirement of 23 cm^2 effective area detectors or 0.5 PE/MeV throughout the volume.

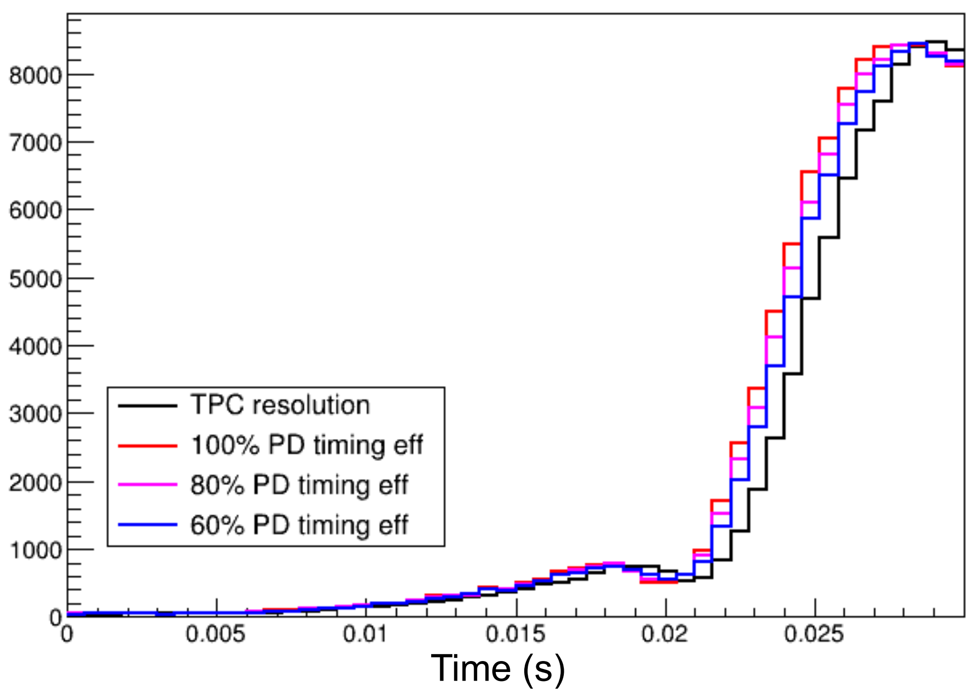
T0 from Light-TPC Matching for Supernova Neutrinos

- **Physics Requirement**: The PDS must be able to provide T0 determination with better than 1 μs resolution for at least 60% of neutrinos in a typical supernova energy spectrum.
  - Matters primarily for a nearby supernova where statistics are high.
  - T0's improve TPC energy resolution by allowing for drift attenuation correction.
  - The faster timing resolution also allows short time features (ms) to be resolved more easily.
- What does 60% efficiency mean in terms of detector performance?
  - Corresponds to an effective area of 4.05 cm^2 – ProtoDUNE-type light guides.
  - Or, >0.5 PE/MeV for at least 60% of the detector volume.





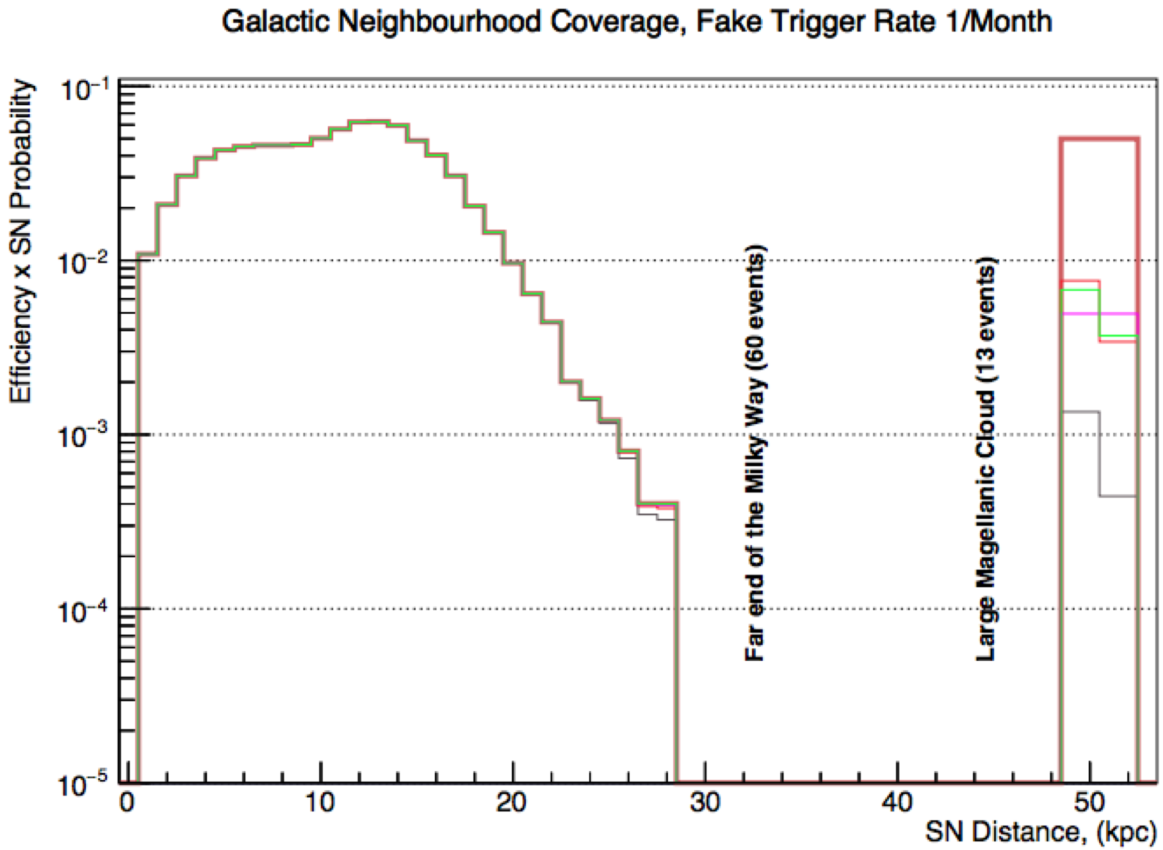




- Some photon detectors make a big improvement.
  - Compare color to black.
- However, once a majority are drift corrected, little additional benefit.
  - Compare other colors to red (100% efficiency).
- Using the "notch" before neutronization as a sample ms-scale feature.
- Again, a visible improvement going from none to some.
  - Green to other colors.
- However, little improvement past 60% efficiency

Supernova Burst Triggering

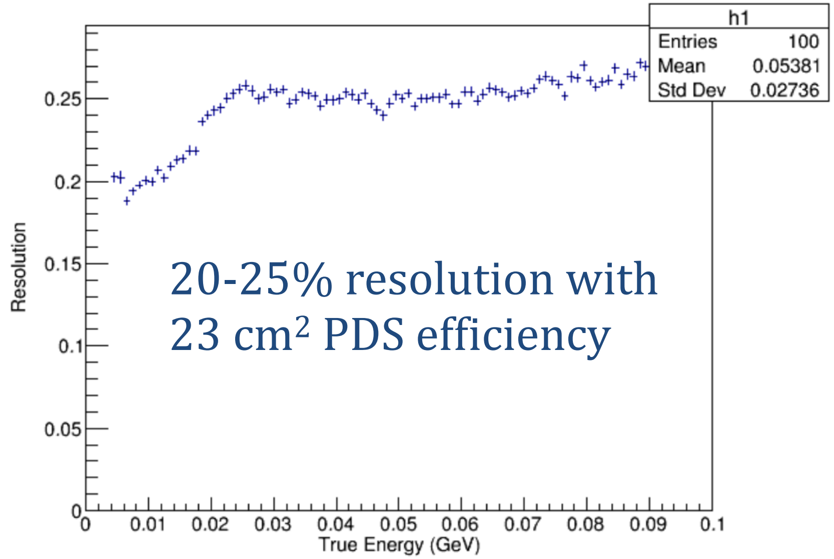
- **Physics Requirement:** The PDS must be able to trigger on supernova bursts in our galaxy and the Large Magellanic Cloud with efficiency similar to the TPC, with a false positive rate of less than one per month.
  - For distant SNBs, the challenge is triggering on them. Most physics will be limited by statistics rather than resolution.
  - We want redundant triggers to reduce the risk of missing so rare an event.
  - 1/month fake rate limit is imposed by DAQ and data handling concerns.
- Creates **detectors requirements for light yield** and benefits from improved uniformity.



- Thick red line is perfect efficiency
- 4 detector performances shown here:
  - 4 cm^2, 7 cm^2, 15 cm^2, 23 cm^2
- ~100% efficiency throughout the galaxy.
- Now, neither the TPC nor the PDS is 100% efficiency for the LMC.
  - PDS is ~10% and TPC (not shown) is ~50%
  - Expecting improvements from higher efficiency and reflector foils.

PDS Calorimetry for Supernova Neutrinos

- Physics requirement: The PDS should be able to provide a calorimetric energy measurement for low energy events, like supernova neutrinos, complementary to the TPC energy measurement.
  - Improved energy resolution, up to the fundamental limits imposed by invisible particles in the interaction, will enable us to extract the maximum physics from a supernova burst.
  - With energy resolution comparable to the TPC, full advantage can be taken of the anti-correlation between the emission of light and charge signals imposed by the conservation of energy.
- Creates **detector requirements for light yield** and benefits from improved uniformity, calibration, and knowledge of LAr properties.



PDS Calorimetry for Beam Neutrinos

- **Physics Requirement:** The PDS should be able to provide a calorimetric energy measurement for high energy events, like neutrinos from the LBNF beam, complementary to the TPC energy measurement.
  - Neutrino energy is an observable critical to the success of the oscillation physics program.
  - A second independent measurement can provide a cross-check which reduces systematic uncertainties or directly improves resolution for some types of events.
- Creates **a detector requirement for dynamic range**, and benefits from improved uniformity, improved knowledge of LAr properties.

Goal: Michel Electron Tagging

- **Physics Goal**: The PDS should be able to identify Michel electrons from muon and pion decays.
  - The identification of Michel electrons can improve background rejection for both beam neutrinos and nucleon decay searches.
  - Some Michel electrons are difficult to identify with the TPC since they appear simultaneous within the TPC's time resolution and colinear with their parent.
- Not a *requirement* since we have no studies in hand so far.
  - Was not considered a realistic option until recently when more capable detectors looked like a real possibility.
- Would create a detector requirement for light yield, and require that the electronics record the detailed time-structure of the light.
  - Simplest solution is waveform readout, though online deconvolution of the SiPM response could work as well.
  - Doping with Xe to reduce the late light would also be a benefit.

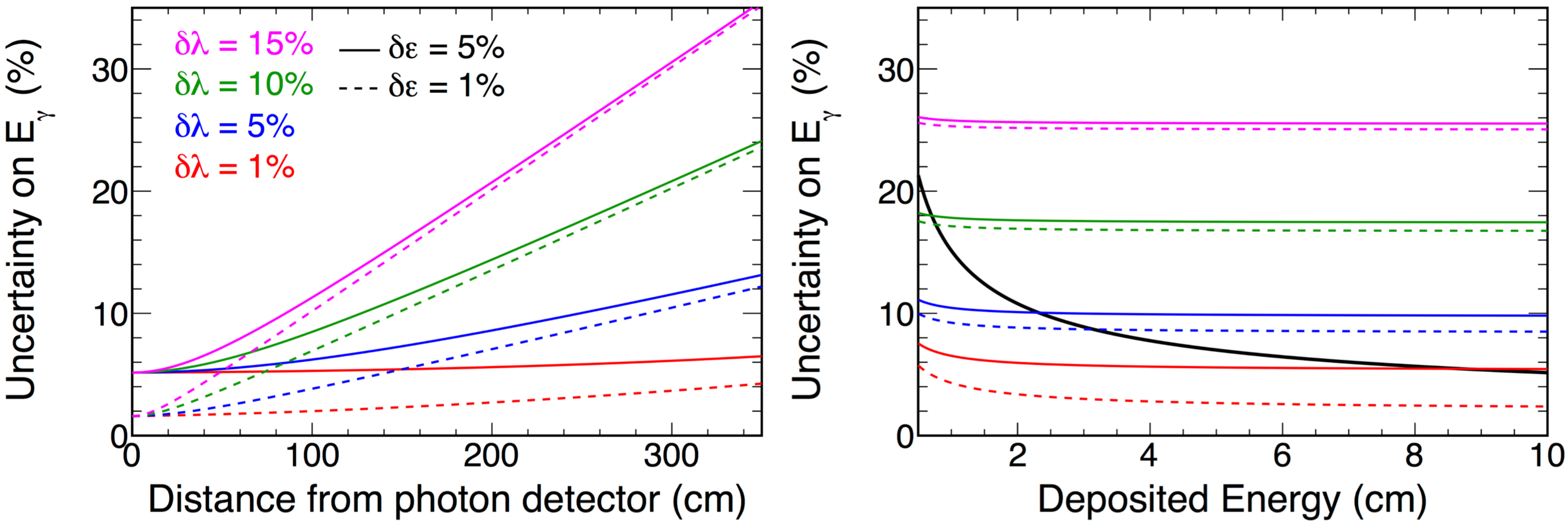
Detector Requirements to Verify with R&D

- Determine absolute detector efficiency
  - Or relative efficiency to a design with a known absolute efficiency.
- Demonstrate the detectors can be calibrated
  - Gain by identifying single PE's, stability using flashing system
- Signal-to-noise in the baseline electronics
- Time resolution with baseline sensors and ganging
- Dark current in the ganged SiPM array
- Data rates within limits from the electronics
  - By necessity this will need to be an extrapolation since it is difficult to replicate the conditions of an underground detector on the surface.

Conclusions

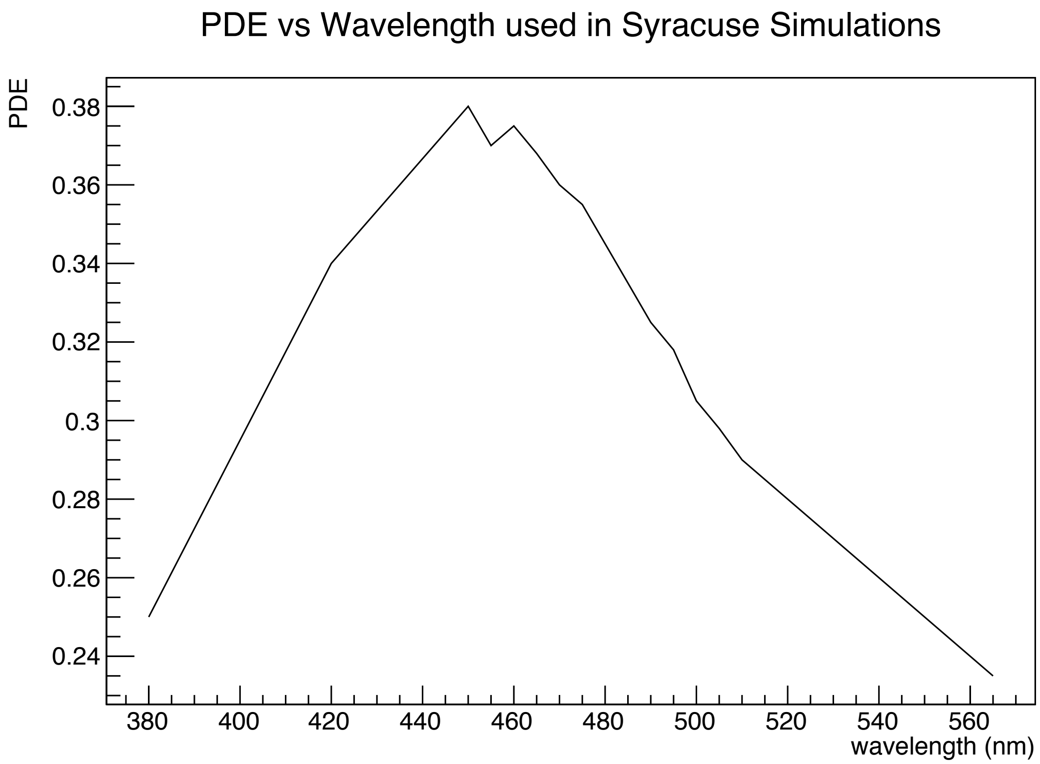
- The current baseline design with X-ARAPUCAs and Mu2e-style electronics meets the requirements for nucleon decay and beam neutrinos.
  - >99% T0 efficiency for NDK events
  - Sufficient dynamic range for >99% of beam ν's
- New supernova physics requirements have been defined
  - Covering triggering, T0 determination, and calorimetry
  - New simulation is being produced now to flow these physics requirements down to precise detector requirements.
- We will also explore the potential benefits of and paths to improved uniformity.
  - Full simulation studies with reflector foils.
  - Some initial looks at uniformity with Xe doping.

Backups



- **Why only dynamic range?**
- Energy resolution will be more limited by knowledge of attenuation in LAr than photon counting statistics.
- The only design consideration now: don't make things worse by having the electronics saturate with high-energy events.
- For DUNE we will need improved knowledge of LAr optical properties.
  - This effort being undertaken by a number of groups in the US and Europe.

Photosensor Properties in Stand-alone Simulations



- PDE used is based on the Sensl SiPMs, but is relatively similar to that expected from other manufacturers.