DUNE Photon Detection System

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For the Photon Detection Group – and others

Colorado State University

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Outline

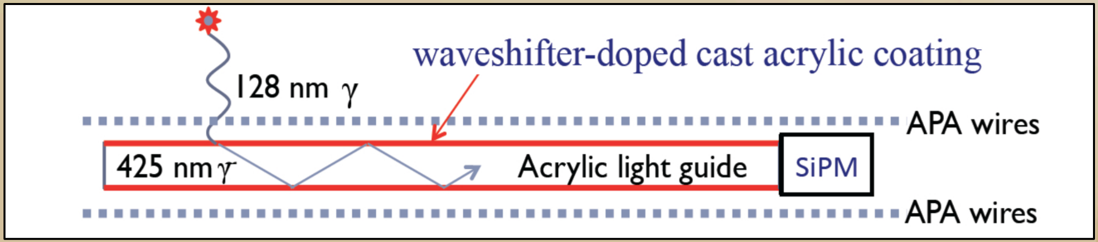
- Motivation and requirements
- Reference Design
- Alternative Prototypes and Ideas
- Future Planning – opportunities for synergy with SBND (and others)

Motivation

While the TPC will provide excellent spatial resolution it is not able to provide the location of an interaction within the drift region

Liquid argon scintillates with a high light output of about 40,000 γ/MeV of deposited energy – in the absence of an external electric field (about 24,000 γ/MeV in the DUNE TPC E-field)

- 1/4 of the light is emitted with lifetime 6 ns, remainder comes later with a time constant of 1.6 μs.
- Scintillation light has wavelength tightly centered around 128 nm in the vacuum ultra-violet (VUV) part of the spectrum
- Rayleigh scattering length of (66 ± 3) cm* and >200 cm absorption length



* Ishida N. *et al*, “Attenuation length measurements of scintillation light in liquid rare gases and their mixtures using an improved reflection suppresser,” Nucl. Inst. and Meth. in Phys. Res. Sec. A., vol. 384, pp. 380–386, 1997.

Performance Requirements

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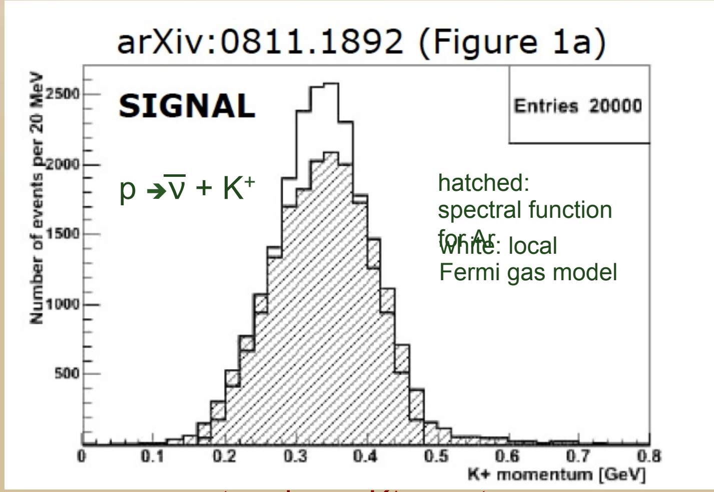
- Timing accuracy of better than a microsecond
  - gives event z-location accuracy of a few mm
  - sufficient for fiducial cuts and dE/dx corrections
- Ability to trigger on non-beam events
- No injection of unnecessary noise into TPC electronics
- No reduction in LAr purity due to materials used in PD system

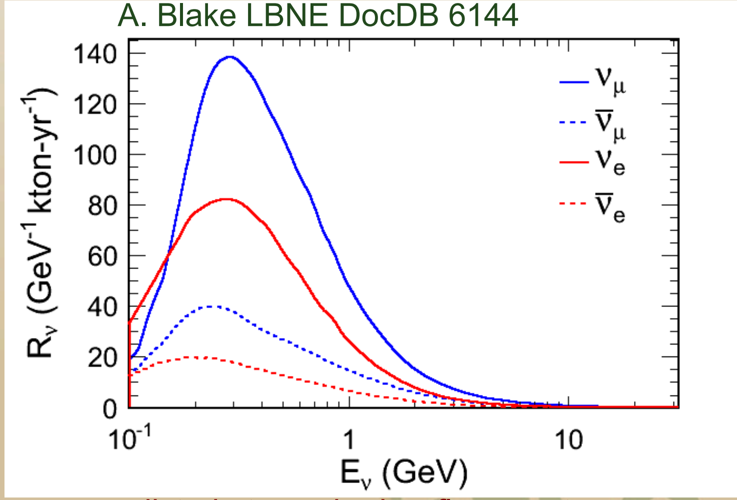
events with $E_{dep} \gtrsim 200$ MeV

PDK detection:

- Reference design (88% efficiency averaged over full volume – 99% efficiency for closest ½ of volume)
- Alternate design (99% efficiency everywhere)



proton decay K^+ spectrum



predicted atmospheric ν flux spectrum

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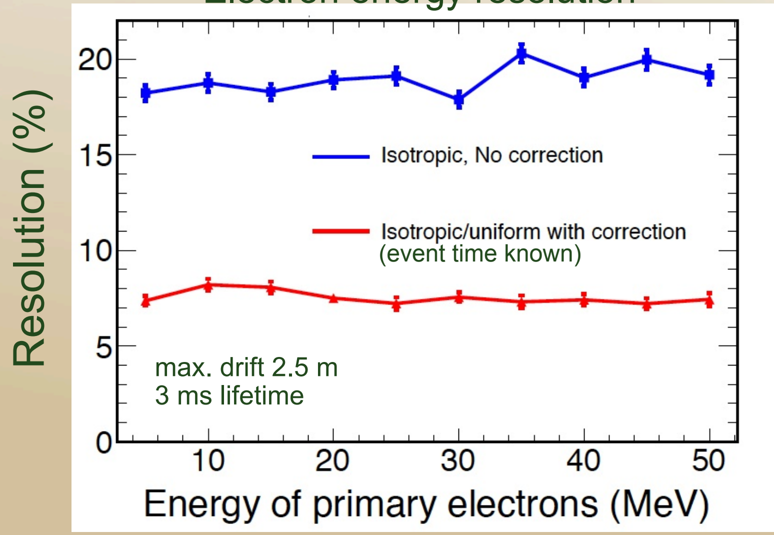
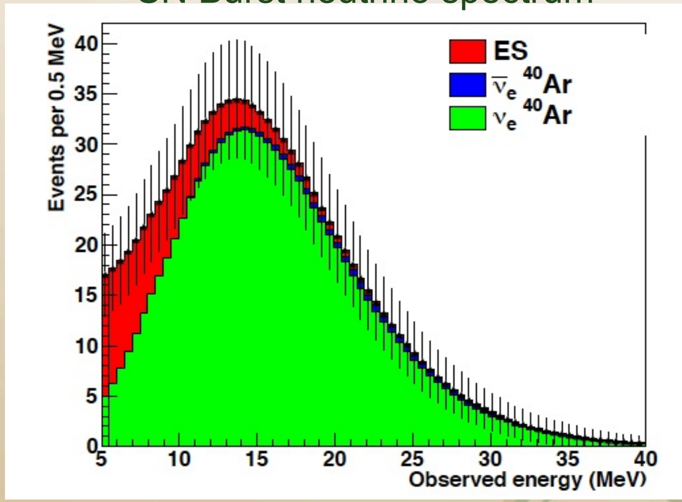
Performance Goal

In addition to the aforementioned requirements the photon detector can improve SN neutrino energy and timing resolution if the detection threshold is pushed down…

Electron energy resolution



SN Burst neutrino spectrum



Improving upon the PD reference design will allow t_0 determination of an increased number of SN burst neutrinos which will improve the energy and time resolution.

- reference design (5 MeV detection may reach 20% efficiency)
- alternate design (5 MeV detection may reach 74% efficiency)

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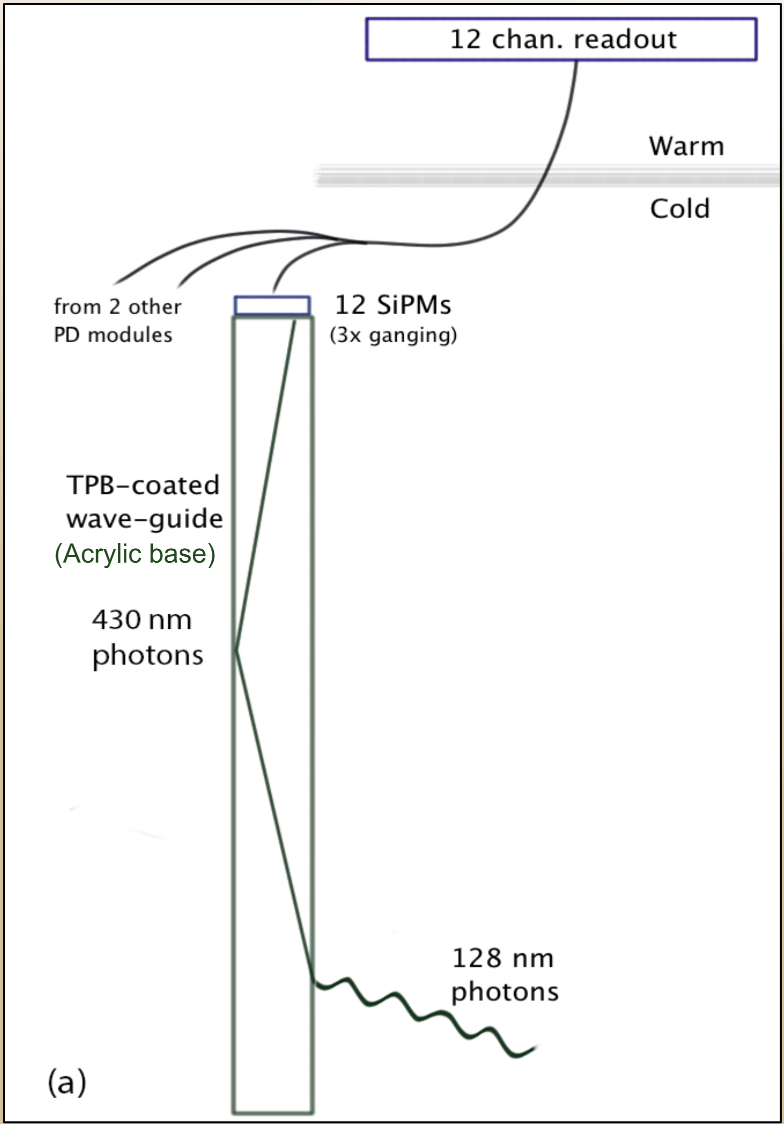
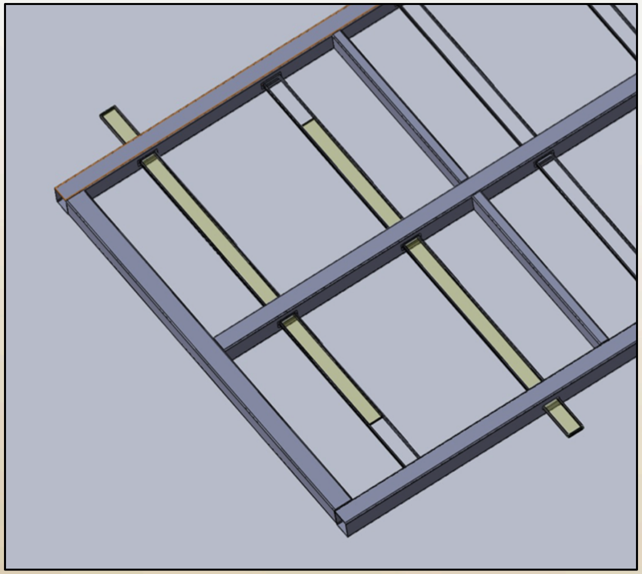
Reference Design





Reference Design

- 10 PDs (2 m × 6 mm × 83 mm) per APA frame
- 12 SiPMs per PD
- 3 SiPMs per readout channel

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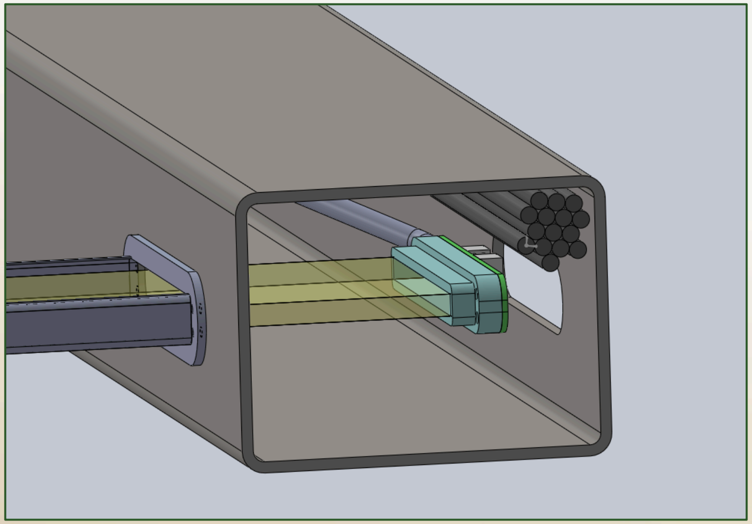
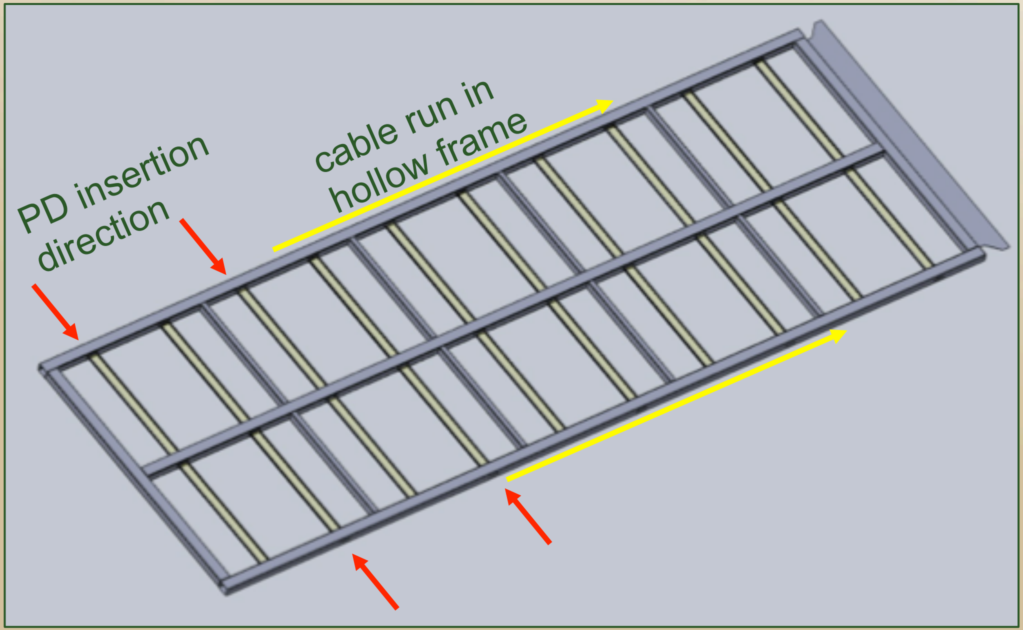
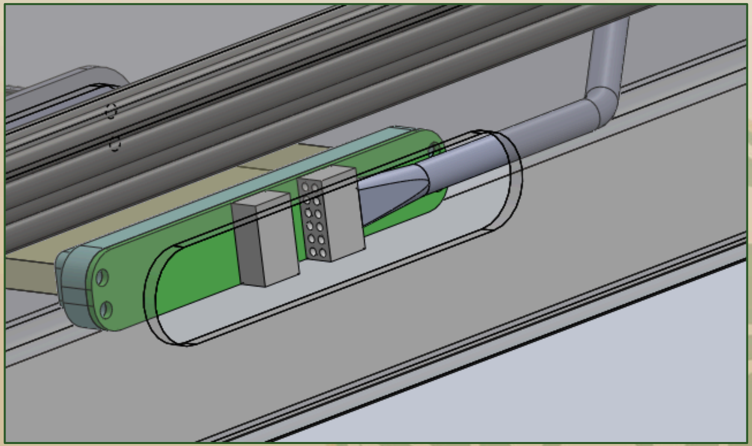
Reference Design

- PDs inserted into frame post-wire wrapping
- Alternate frame sides to balance frame penetrations and for cable management
- Late insertion allows greater control over PD handling and prevents accelerated production schedule







Reference Design

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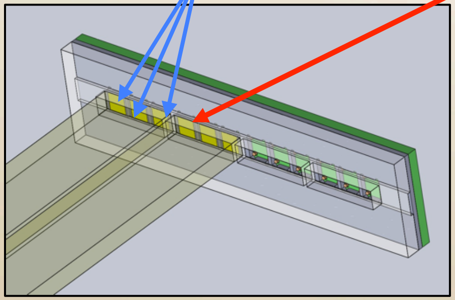
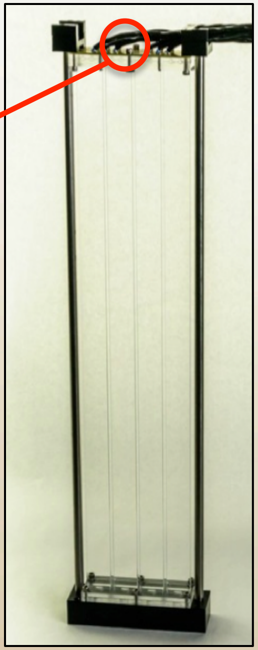
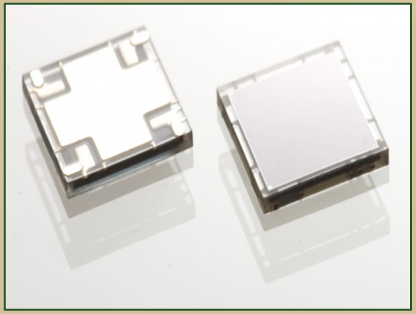
All designs use SiPMs (SensL C-series)



readout end of paddle



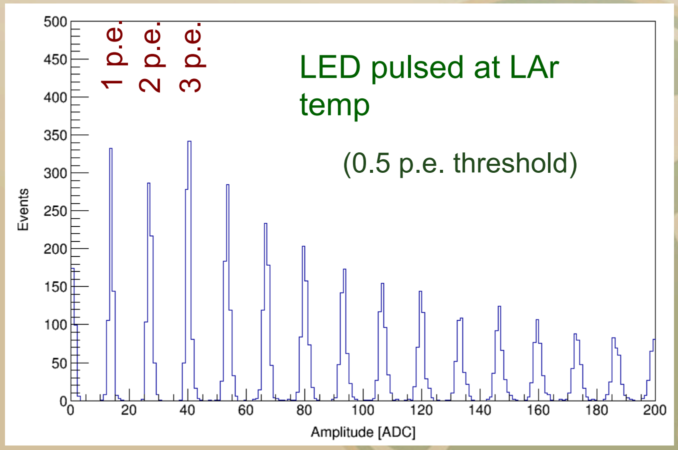
Prototype shown is 20" version mounted in frame for 35t phase 2 test.



SensL MicroFC-60035-SMT SiPM

- 6 mm x 6 mm active sensor (~19000 microcells)
- 24.5 V breakdown voltage (V_{br})
- peak wavelength 420 nm
- Det. Eff. 41% @ V_{br} + 2.5 V
- Gain 3E6 @ V_{br} + 2.5 V

(data at room temp)



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Readout Electronics

- The Silicon Photo-multiplier Signal Processor (SSP) prototype module:
  - High-speed waveform digitizer
  - Current sensitive, differential input amplifiers → Good noise performance over long cables
  - Each channel has a ***14-bit, 150 MSPS ADC***
  - ***Timing*** obtained using signal processing techniques on leading edge of SiPM signal
  - 12 channels per module
  - Uses Artix FPGA for sig. proc.
  - Has NOvA Timing Interface
  - Uses 120VAC; On-board LV power
  - Has internal prog. SiPM bias (30V)
  - Trigger: self or external
  - ***Has Trigger Out signal***
  - Deep data buffering – 13 μSec
  - No dead-time (up to 30 KHz/ch)
  - Programmable DAQ interface
  - USB & GbE communications
  - Internal charge injection
  - Internal bias monitoring

⇨ ***1U rack-mounted unit***

⇨ ***Completely self-contained: Plug & Play***

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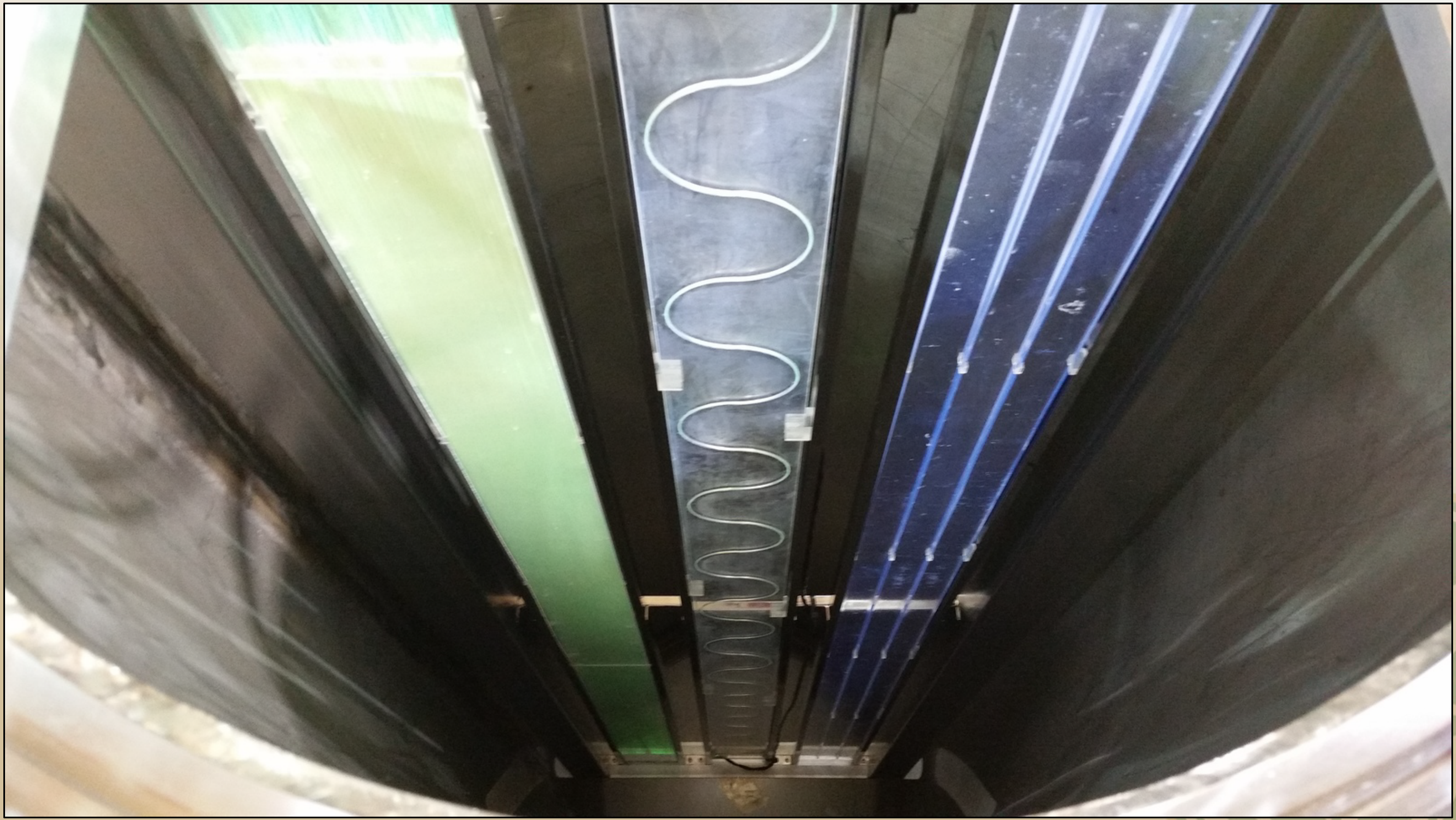
Detector Components

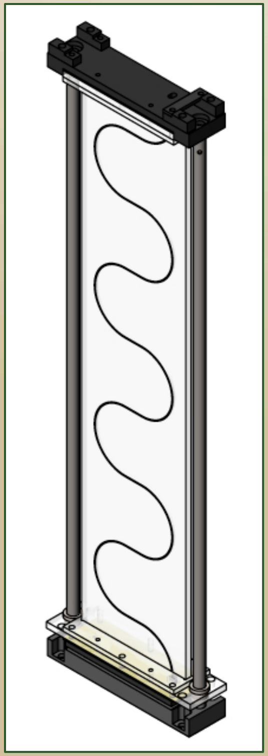
Components required to build (reference design) photon detector for 10 kt.

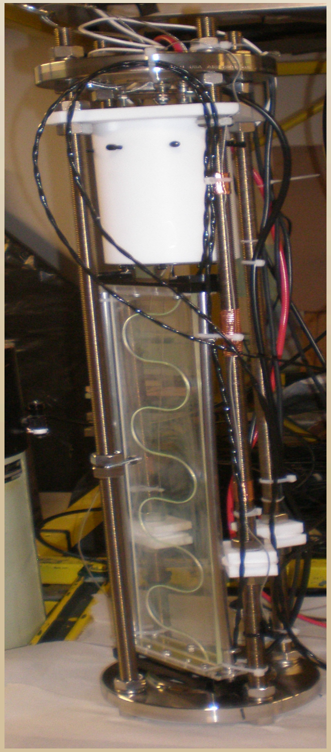
Component	Description	Number (for 10 kt)
TPC-coated acrylic bar	Light guide (2 m × 6 mm × 83 mm)	1,500
SensL MicroFC-60035-SMT	Silicon photo-multiplier	18,000
SiPM mount PCBs	Boards SiPMs mount to in PD frame	1,500
Short cables w/connector	Readout cables from PD to outside APA	6,000
Long cables w/connectors	Cables from APA to feedthrough and feedthrough to SSP rack (34 m total)	6,000
SSPs	SiPM Signal Processing modules (16 chan)	375

Alternate Designs



Alternative – Acrylic Panel w/ Embedded WLS Fiber (LSU)





WLS-doped clad Y11 fiber(s) embedded in TPB-coated plate.

- 2 SiPMs used in module (one at each end of fiber
- Additional fibers can be stacked in groove to increase acceptance

Potential for significant coverage

- low readout channel count leads to large scale-up
- Doped fibers could be optimized to match TPB emission and SiPM QE.

Alternate Designs

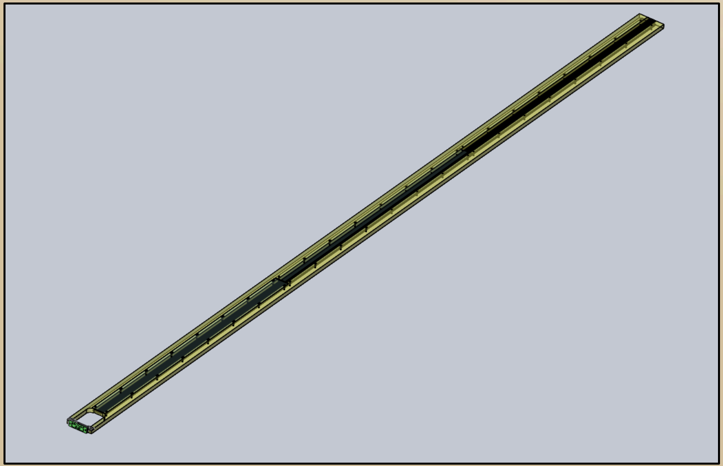
Radiator + Fiber Bundle (CSU)

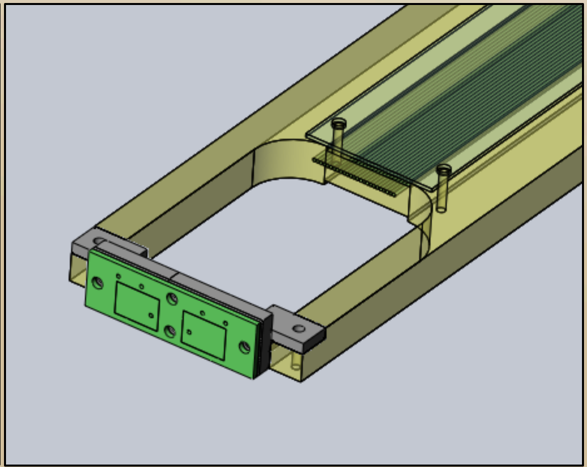
TPB-coated thin plastic radiator in front of Y11 (blue ➔ green)

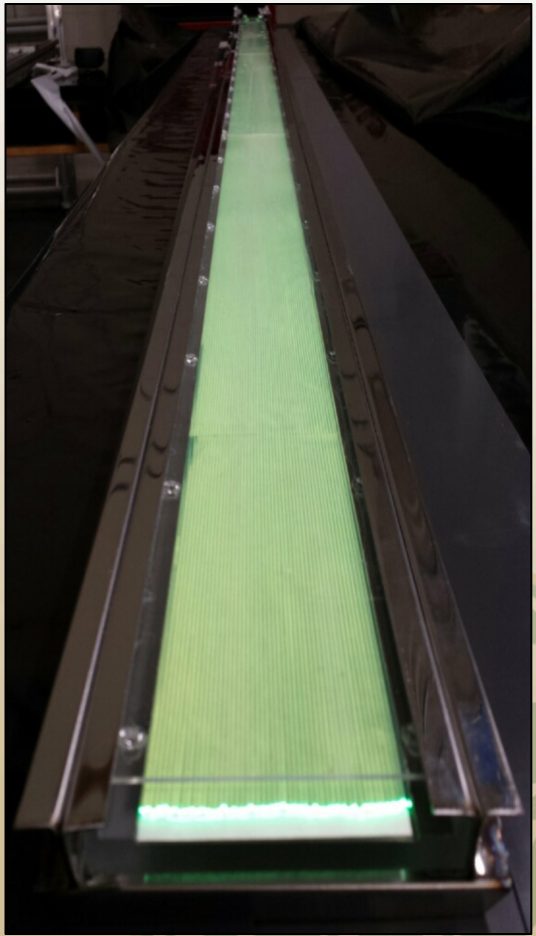
- Motivation: mitigate short attenuation length of TPB-coated acrylic
- 100% of fiber mapped to SiPM
- Double-sided with opaque reflector between two sides

Cost comparable to reference bar design

- Only 6 SiPMs required to readout out full PD module (both sides)
- Fibers are commercially available







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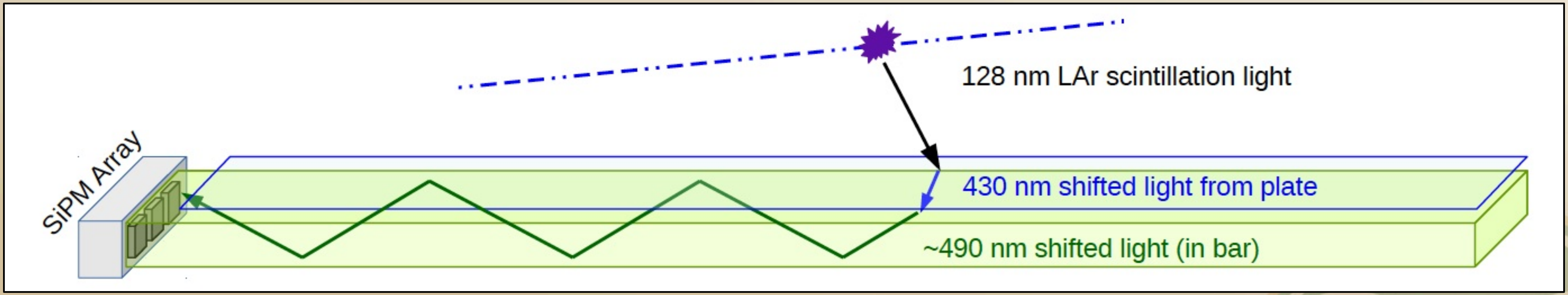
Alternate Designs

Radiator + WLS Bar (IU)

Alternate design that meets DUNE PD requirements – WLS polystyrene bar utilizing a thin TPB-treated radiator (developed by Indiana University)

Design separates the UVU → UV conversion from light-guide transmission to SiPM processes.



Design is not significant mechanical change from reference design but results in significant performance gain.

Best performing alternate design currently under consideration – although MIT's "Wunderbars" look extremely promising.

Improving Attenuation Length and Brightness (MIT ideas)

“Wunderbars”

Concept:
Improve the coating, which consists of an acrylic matrix embedded with TPB
Experimentally, identify a solvent mixture that produces a smoother coating and also has a better TPB: acrylic ratio than 2014 design (2014 paper: http://arxiv.org/abs/1410.6256)

Result:
Tinkering w/ coating was a resounding success – x4 attenuation length, and we think x2 the brightness (needs study)

Plan:
Teach people how to make these light guides (step-by-step how-to in backups)
Work on a list of potential improvements (next slide)
Run these in as many venues as possible to maximize understanding.

Anode Coupled Readout (MIT)

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Concept: (http://arxiv.org/abs/1507.01997)

Replace the dedicated readout of optical system with a wire-based readout.
Use a capacitive plate to transfer signal from SiPMs to wires.

Result:

Single PE signals should be detectable (warm tests were too noisy to prove this)
Very nice multi-PE signals are clearly observed.
Interference between signal from light on wires and event on wires is negligible
Cosmic ray rate low so signal on wires from cosmic light will not clobber event charge
Dark rate appears to not be a problem when scaled for LAr temps.
^{39}Ar rate needs investigation.

→ 30 ns resolution on the t_0 is feasible. Very useful for non-beam events!

Saves money, eliminates cables and feedthroughs, simplifies system

MIT Plan:

Test the system in Lar using TallBo, ProtoDUNE@CERN and maybe LArIAT.

The WA105 photon system

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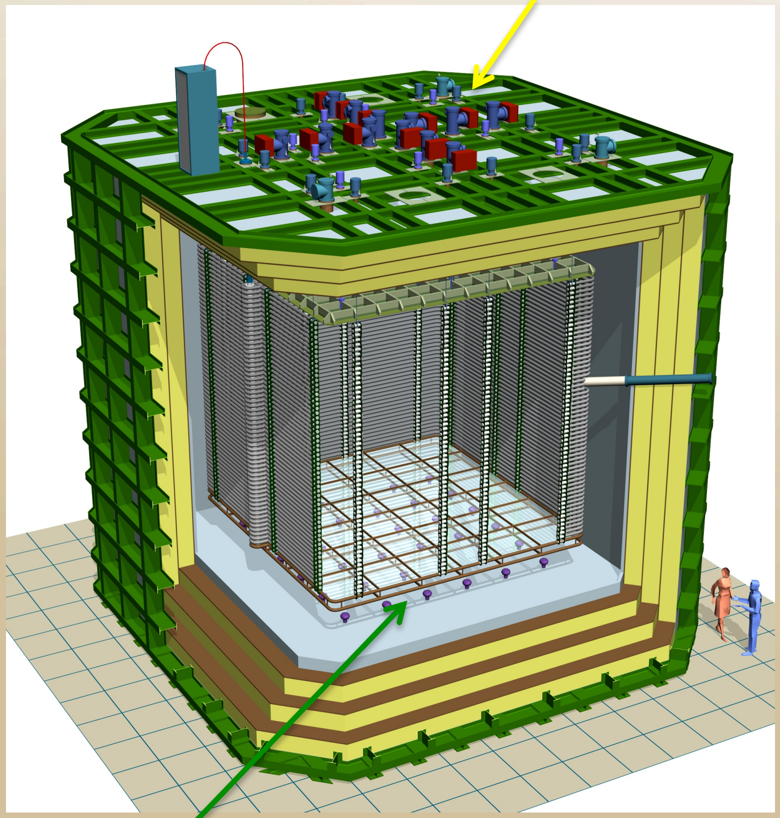

- **Basic configuration**:
  - 36 cryogenic photomultipliers
  - Wavelength-shifter: TPB coating on the PMT (or on external plates)
  - Voltage divider base + single HV-signal cable + splitter (external)
  - DAQ system (external)
- **Goals**:
  - Trigger for non-beam events
  - t0 for for both beam and non-beam events (cosmic background rejection)
  - Possibility to perform calorimetric measurements and particle identification

PMTs

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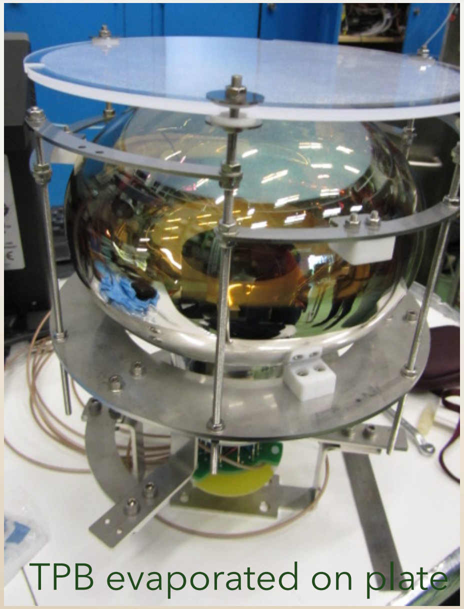
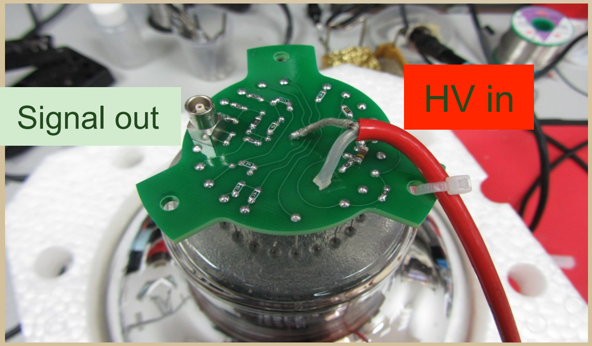
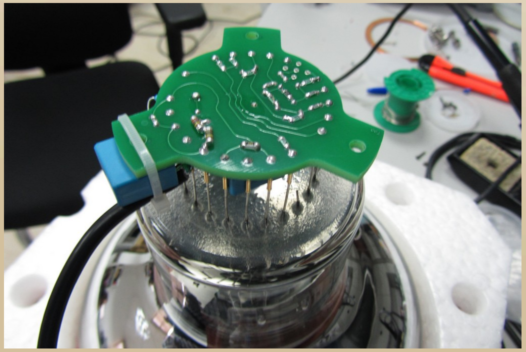
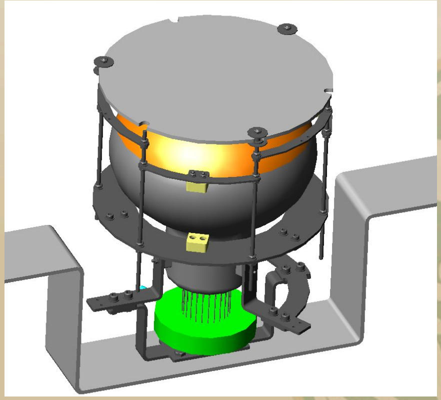
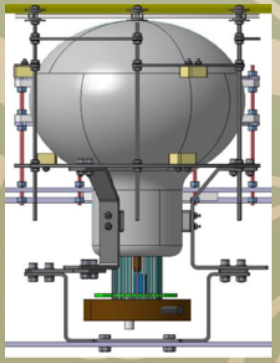
- Hamamatsu R5912-02mod 8” PMTs
- 2 possibilities are considered for the wavelength shifter
  - TPB on the PMT
  - TPB on external plates
- Mechanical structure designed accordingly
- 2 possibilities for power supply and cabling:
  - Negative HV
  - Positive HV











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Future Planning

- Expect to have a new reference design this fall.
- There is MUCH work to be done to optimize and qualify the components of the selected design
  - SiPM qualification and performance
    - What is the survival probability of the SiPMs and readout/mounting boards under thermal cycles
    - What is the survival probability of 18,000 SiPMs (1 10 kt module) over 20 years?
    - How does the SiPM performance (gain, dark rate, breakdown voltage,…) degrade over time – if at all
  - Light guides (possibly radiators)
    - How do the light guides and radiators behave under thermal cycles?
    - Does performance degrade over time in LAr?
    - What is the optimum doping level and application method
  - Readout electronics
    - Do we need (can we use) the late light?
    - What is the effect of ^{39}Ar on the detector response
    - How much would a simpler system degrade the PD physics potential?

Future Planning

- System Performance
  - ^{39}Ar and other radiologicals
  - What is an acceptable rate of SiPM failures (device gives no usable response)?
  - What is an acceptable degradation of SiPM performance (eg. gain loss or dark rate increase)?
  - What is an acceptable LN2 leak rate (2 ppm total LN2 after 20 years)?
- These performance questions must also be convolved with one another – eg. LN2 leak & SiPM failure rates.
- There are also many engineering and handling considerations that I haven't gone into my presentation
- In short there is not only room for discussion and contributions – these are critical!

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Back-up

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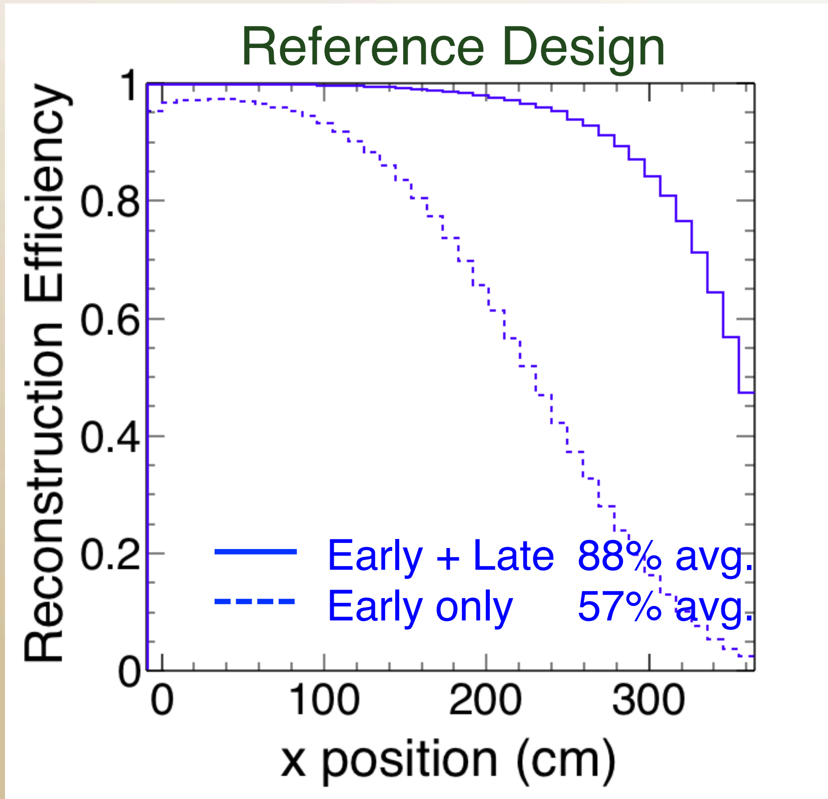
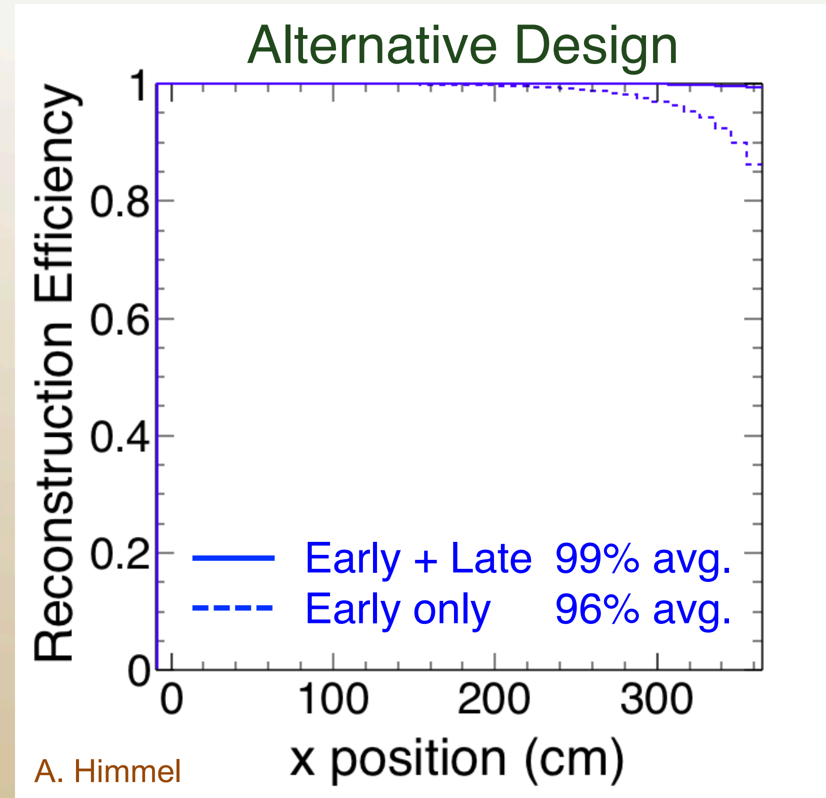
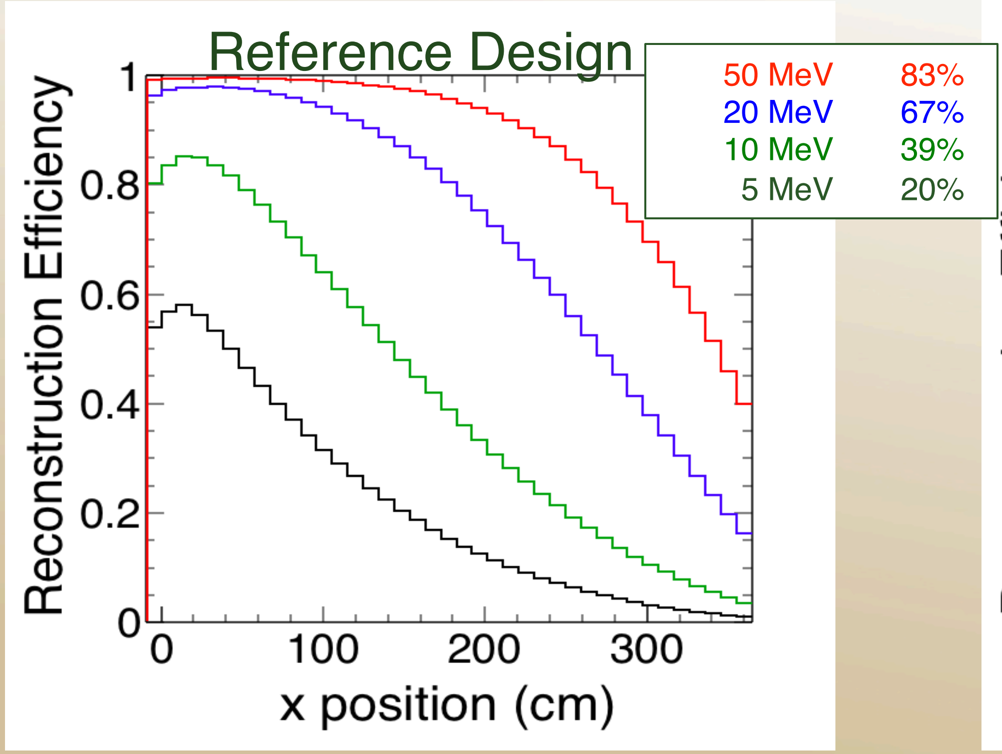
Proton Decay Reconstruction Efficiency

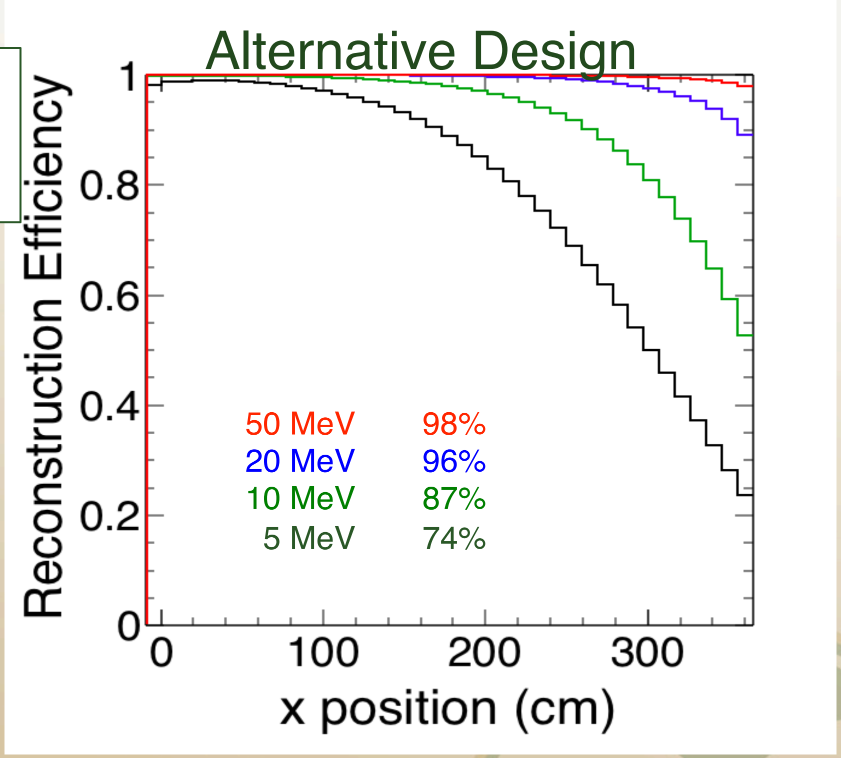




- Assuming 200 MeV visible energy (conservative estimate)
- Reference design only covers half the volume at 99% efficiency.
- Alternative design with late light covers everything at >99% efficiency.

Supernova Reconstruction Efficiency





- Using early and late light, requiring 2 coincident photons (optimistic!)
- Reference design still limited to a fraction of 5 MeV events.
- Alternative design is at about the design goal

Technology Selection

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- Principle metric physics performance
- The system must meet the requirements for proton decay and atmospheric physics
  - Improving the physics resolution for SN physics is important
- Technical considerations, given similar performance in terms of above criteria, are complexity of design and robustness
- Relative performance tests have been performed, and additional tests are planned
- 35t test data (timing, multi-month operation in LAr, and look for any noise injected into TPC data)
- Light yield vs cost will be a critical deciding factor
- Contributions and design considerations for international partners will be an important factor

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Schedule Overview

Photon Detector