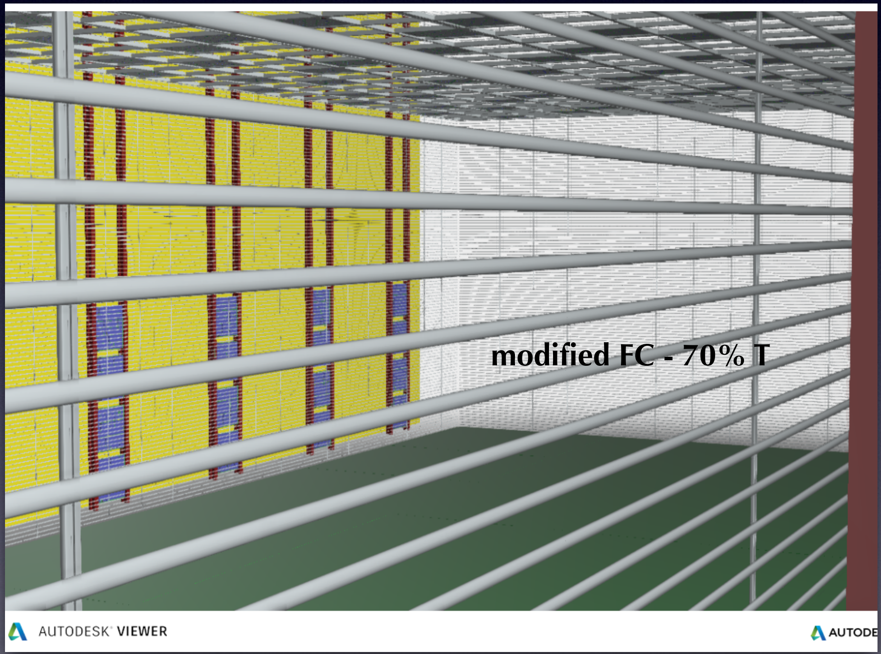
The new Photon Detection System for DUNE FD#2 Vertical Drift Module



View of the Lower Volume from behind the FC, with the Cathode plane at the top.

A new Photon Detector for the new DUNE FD2 VD Module

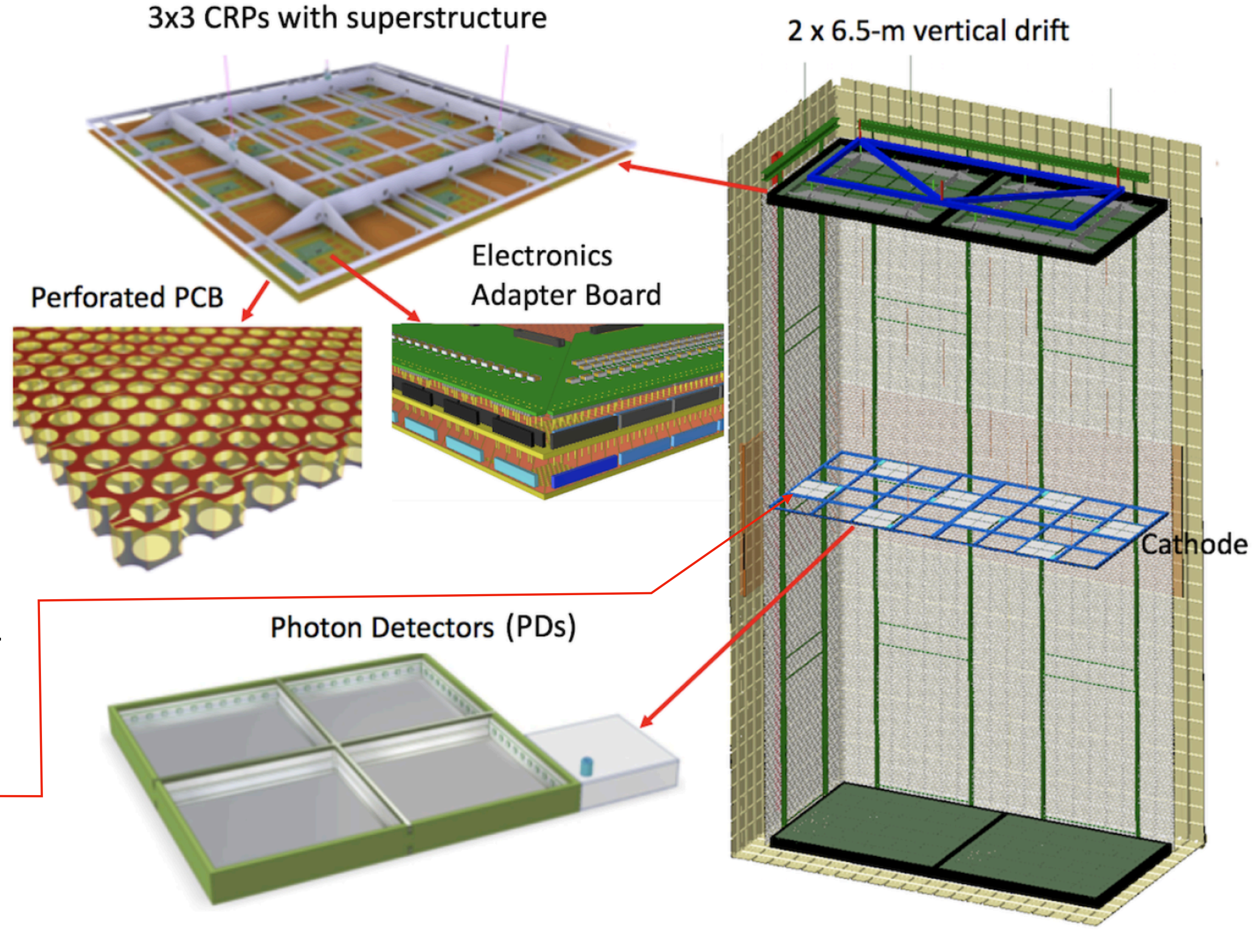
- Energy deposition in liquid argon yields two signals:
  - ***free charge*** from ionization
  - fast ***scintillation light***.

- **TWO DETECTORS in one LAr Volume**: LAr-TPC and LAr-PDS complementary for improved Detection Efficiency, enhanced Energy Resolution and max LiveTime

- PDS particularly important for detection & reconstruction of low energy underground events and background rejection

- Technology choice: **xARAPUCA** large area "*tile*" shaped modules

- PDS Optical coverage: **on the Cathode** (double-sided) and behind FC walls (single-sided) to provides high & *relatively* uniform Light Yield



In the FD#2-VD module the LAr target is segmented in two LArTPC active volumes, either side of central cathode.

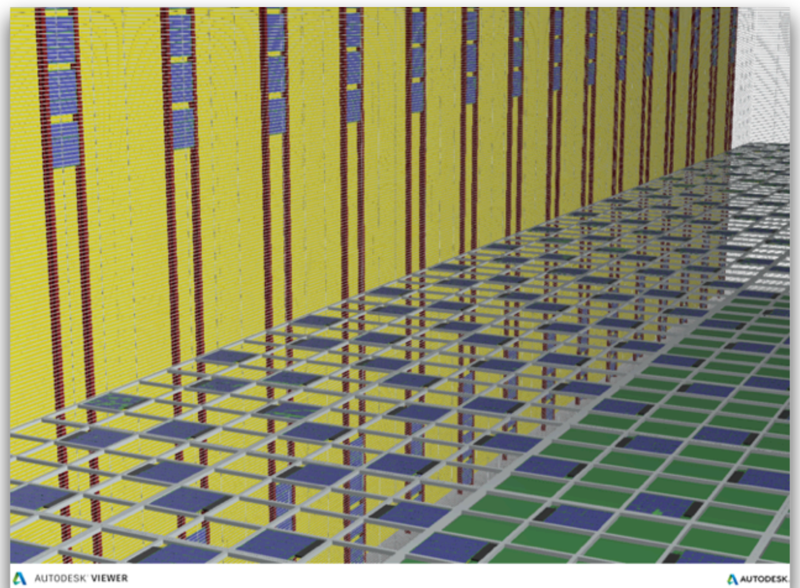
- *dimensions of the the LAr active volumes are bigger wrt FD#1-HD, with longer light source-detector distances*

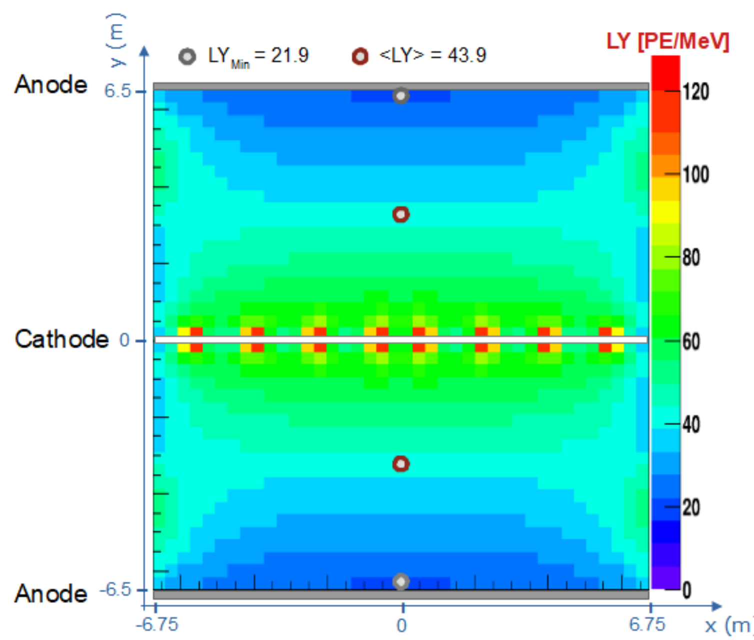
but

- *new/different opportunities are offered for a more even photo-sensitive area coverage around these volumes.*

In the FD#2-VD PDS Reference Design (CDR) the active **Optical Coverage** is distributed onto the 3 larger sides of the LAr Volume and Xe doping is adopted to minimize Rayleigh scatter for light at far distance.

LY is relatively uniform and high on average: ~44 PE/MeV and a min LY ~ 22 PE/MeV in small dimmer regions near the anode planes





GEANT MC simulations

PDS enabled to perform high resolution calorimetry and position reconstruction (and therefore also trigger with max efficiency) for neutrino events down to low threshold.

Operating PD on HV surface (Cathode) requires

electrically floating *Photo-sensors* and *r/o Electronics*

⇒ Power (IN) and Signal (OUT) transmitted via non-conductive cables (i.e. optical Fibers)

Existing PoF and SoF *(optolinks)* **technologies are employed for voltage isolation between source/receiver and embedded electronics in high voltage or high noise environments.**

however:

none of the commercially available technologies are rated to operate in Cold (at LAr Temperature)

⇒ A highly specialized *Technological Development Phase* has been launched (mid Mar '21)

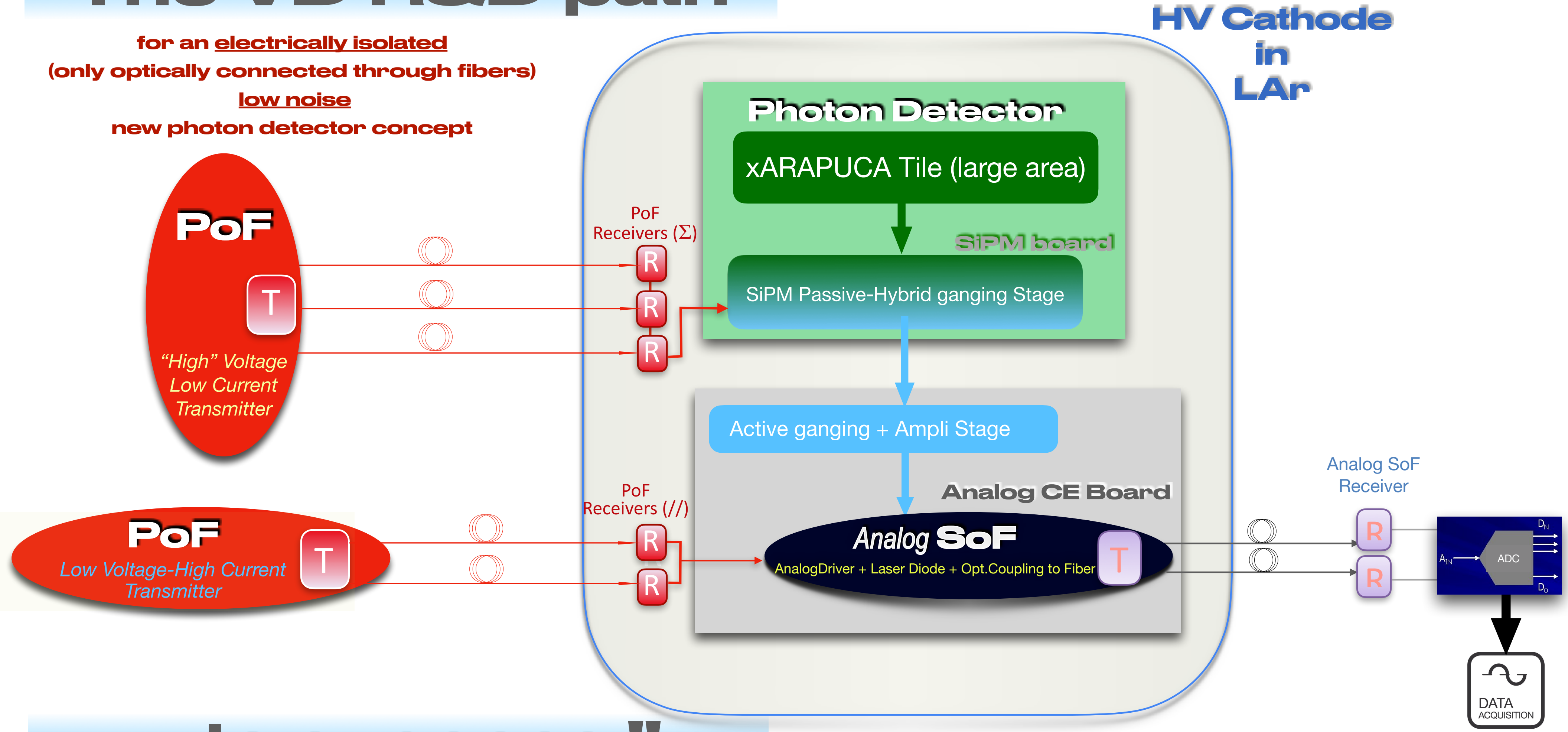
to customize and expand PoF and SoF technologies for Cold applications

the challenge:

the timeline of the Project required PoF and SoF development to be completed in ~6 months.
(with demonstration and validation of the new technology by fall '21)

The VD R&D path

for an electrically isolated
(only optically connected through fibers)
low noise
new photon detector concept



… to success !!

Physics Performance (from Simulation Studies)

Public Note in preparation/completed

Main Results on expected Physics Performance shown here below

Vertical Drift standalone Monte Carlo light simulation studies

F. Marinho *[1], L. Paulucci[2], F. Cavanna[3], A. Paudel[3], D. Totani[4], J. Yang[4], S. Brickner[4], L. Zhang[4], and X. Luo[4]

[1] *Universidade Federal de São Carlos, Araras, SP, 13604-900, Brazil*
[2] *Universidade Federal do ABC, Santo André, SP, 09210-170, Brazil*
[3] *Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[4] *University of California Santa Barbara, California, 93106, USA*

May 2, 2022

Contents

A Report on FD2 VD Photon Detector System: Concept, Development, Tests and First Validation

DUNE PD Consortium - FD2-VD Team

Contents

Detector Design and Development

Public Note completed

Main Results on R&D shown in following talks (FLC, D. Christian, S. Sacerdoti)

Reference design for the VD PD System

PD Active Optical Coverage distributed onto 3 sides of the LAr Volume

(Cathode side - OC=14% and 2 Long Membrane Cryostat sides - OC=8%, behind FC w/ modified Transparency - 70% T)

+

PD Passive Optical Coverage (reflector) on the Anode side

+

Xe doping (to minimize Rayleigh scatter for light at far distance)

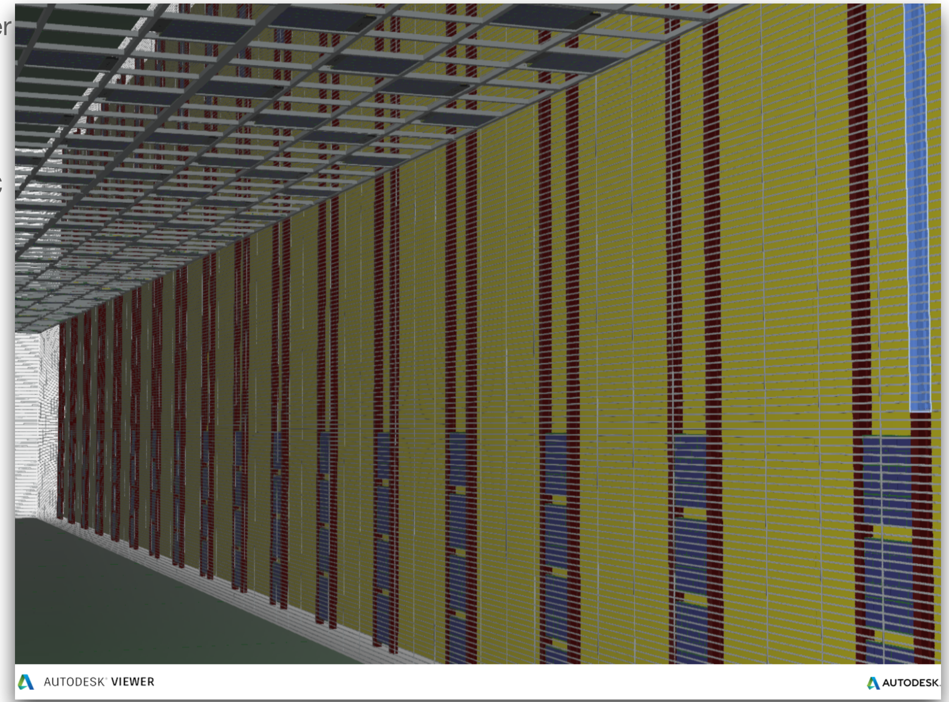
The Reference design endorses the ***~4π coverage concept (originally suggested in the VD proposal)****:*

⇒ good uniformity of response, very low detection&trigger threshold, energy resolution, position resolution and time resolution capabilities

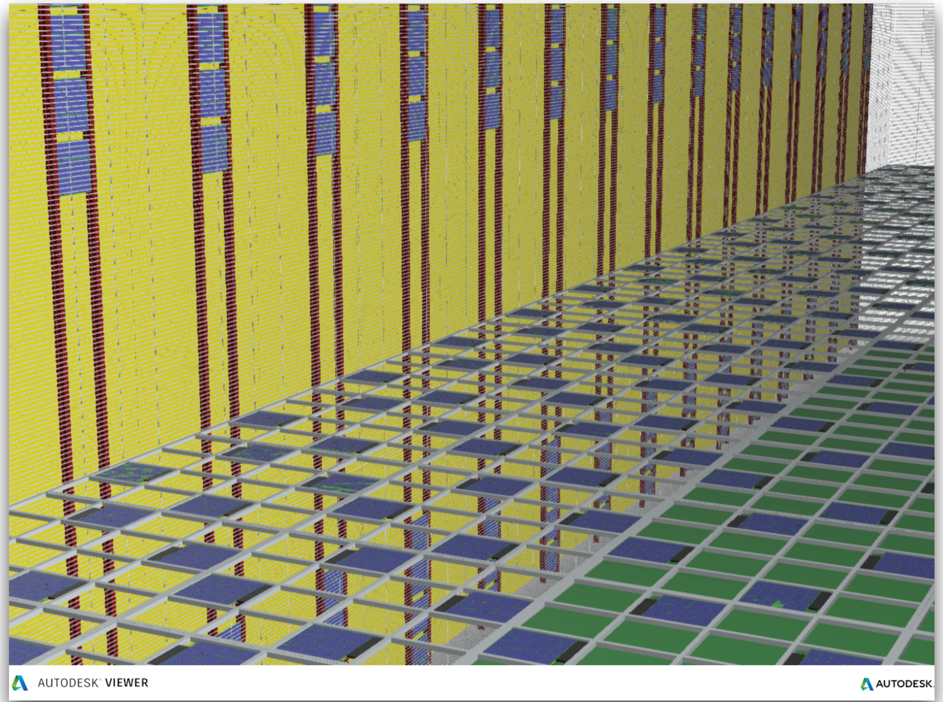
- ***Potential high impact on LowEn UG Physics*** *(PD standalone trigger and reconstruction)*
- *Further enhancement of response when combined with TPC*
- *Highest Live Time (PD active also when LArTPC may be OFF for purity drop/maintenance, HV issues/ maintenance,..) very relevant for UG Physics*

the Reference PD design layout

View from inside the Lower Volume with PD instrumented Cathode (above) and PD instrumented Membrane behind the FC

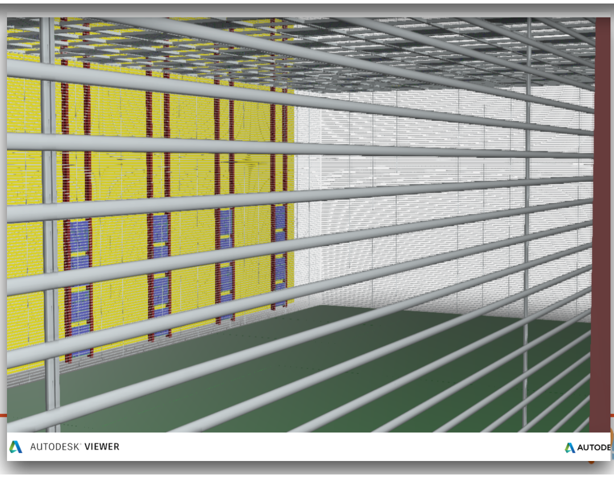


View from inside the Upper Volume with PD instrumented Cathode (below) and PD instrumented Membrane behind the FC



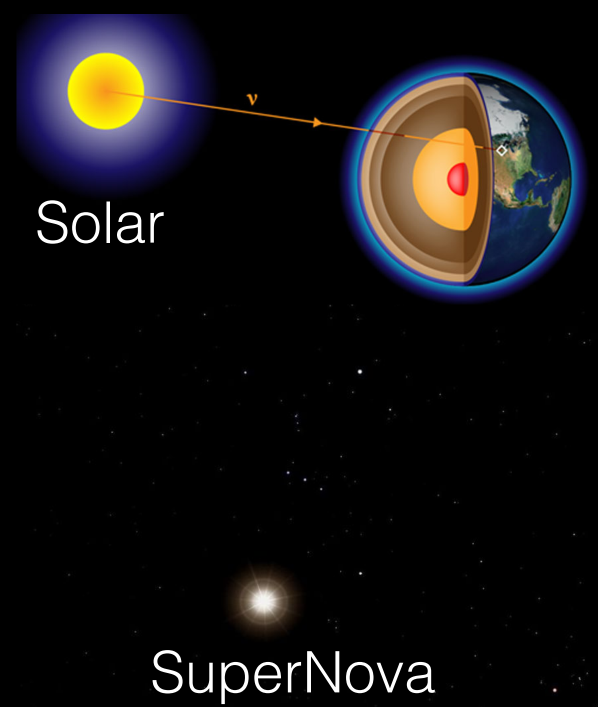
modified FC - 70% T

View of the Lower Volume from behind the FC, as seen by the Membrane PD modules



LEPLAr WS - fall 2020

Enlarging the DUNE Physics Scope



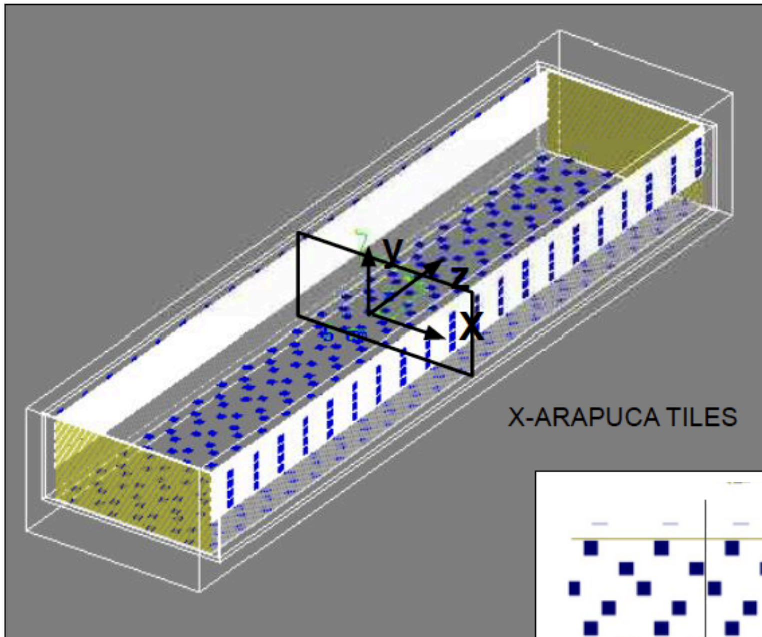
- CoreCollapse SN is the most spectacular phenomenon in Nature and is imprinted in neutrino signal
- Low energy UG neutrinos opened discovery space in particle and astro-particle physics
  - *It is critical to DUNE Science Program to succeed at measuring low energies rare UG neutrinos*
  - *It is is critical to lower Trigger E-threshold to extend range of SN detection (toward and beyond Galaxy edge).*
  - *It is critical to guarantee good Time resolution and improve Energy resolution for SN-signatures in time & energy spectra*

VD PDS Goals

Detector Goals	Value	Physics Goals
Trigger efficiency for interactions with energy deposit $E_{dep} \geq 5$ MeV in detector fiducial volume	$> 98\%$	- SN burst trigger up to the Large Magellanic Cloud (50 kpc) yielding 10 interactions in 10 kt LAr - Solar Neutrino trigger (from ^8B emission spectrum)
Spatial resolution for interactions with energy deposit $E_{dep} \geq 10$ MeV	< 1 m	- Background rejection for SN, solar, nucleon decay from external and detector material Radioactivity
Energy resolution for interactions with energy deposit $E_{dep} \geq 5$ MeV	$< 10\%$	- Identification of SN-ν energy spectrum features from different SN dynamical models - Identification of Solar-ν (^8B) energy spectrum
Time resolution	< 100 ns	- Identification of SN-ν time features due to standing accretion shock instabilities - Identification of SN-ν "trapping notch" (SN dip in luminosity)

Stand-alone full G4 Simulation

Reference Design

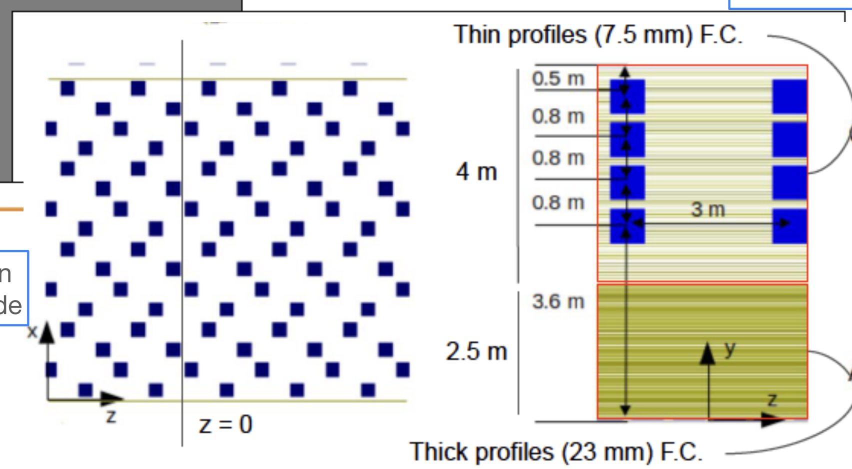


Simulation Parameters:

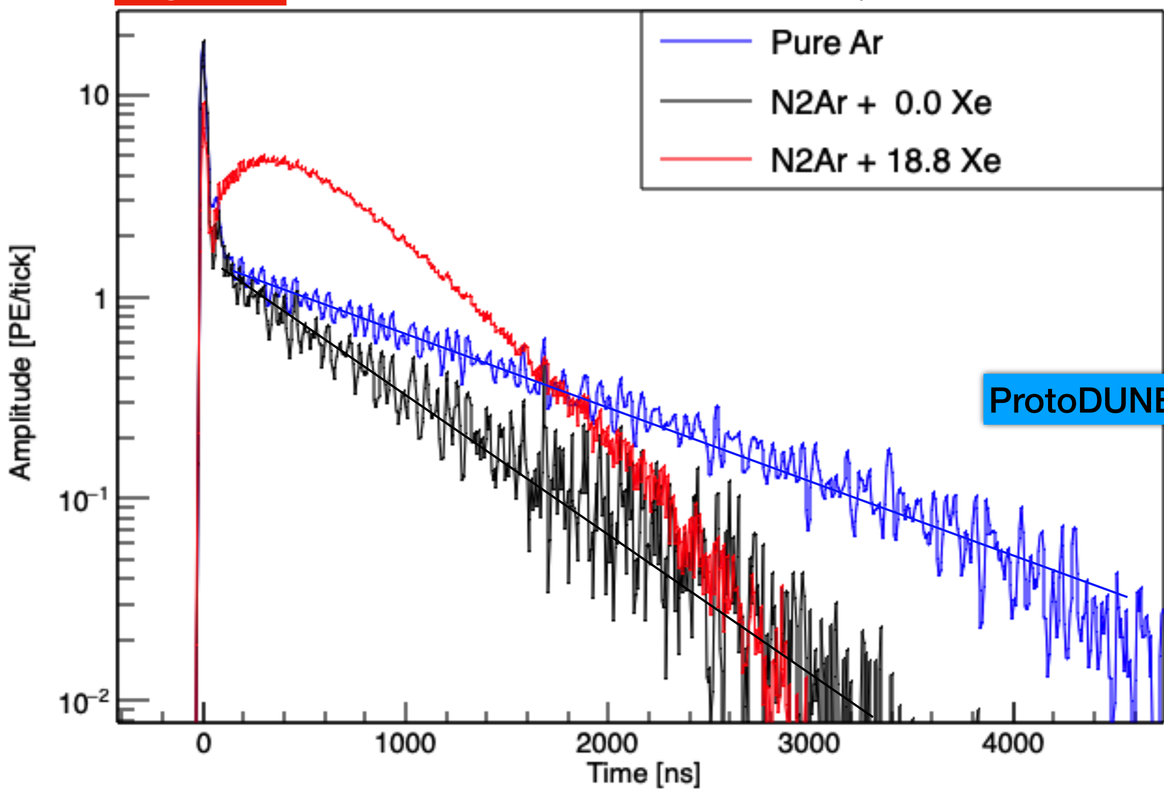
- Field cage volume (6.75 x 6.5 x 60) m³.
- 1 million photons for Xe and Ar wavelengths are simulated per point (to obtain an error of 1%) and the combined LY map is weighted according to Xe-doping studies.
- 2D maps of 400 bins (20x20) are simulated for z values between 0 - 3 m in 25 cm steps.
- The bins have a size of 33.75 x 32.5 cm² and the value corresponds to its mid-point.

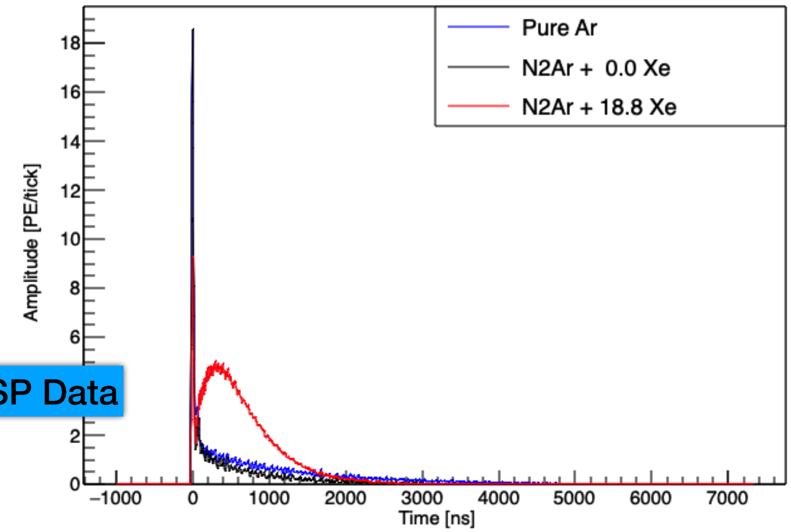
4x20 (x2) behind FC

320 on Cathode

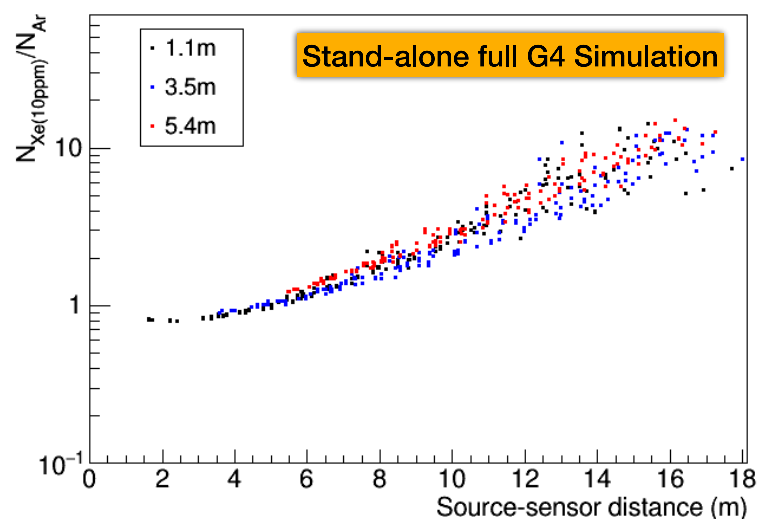


Log Scale ← same plot → Lin Scale



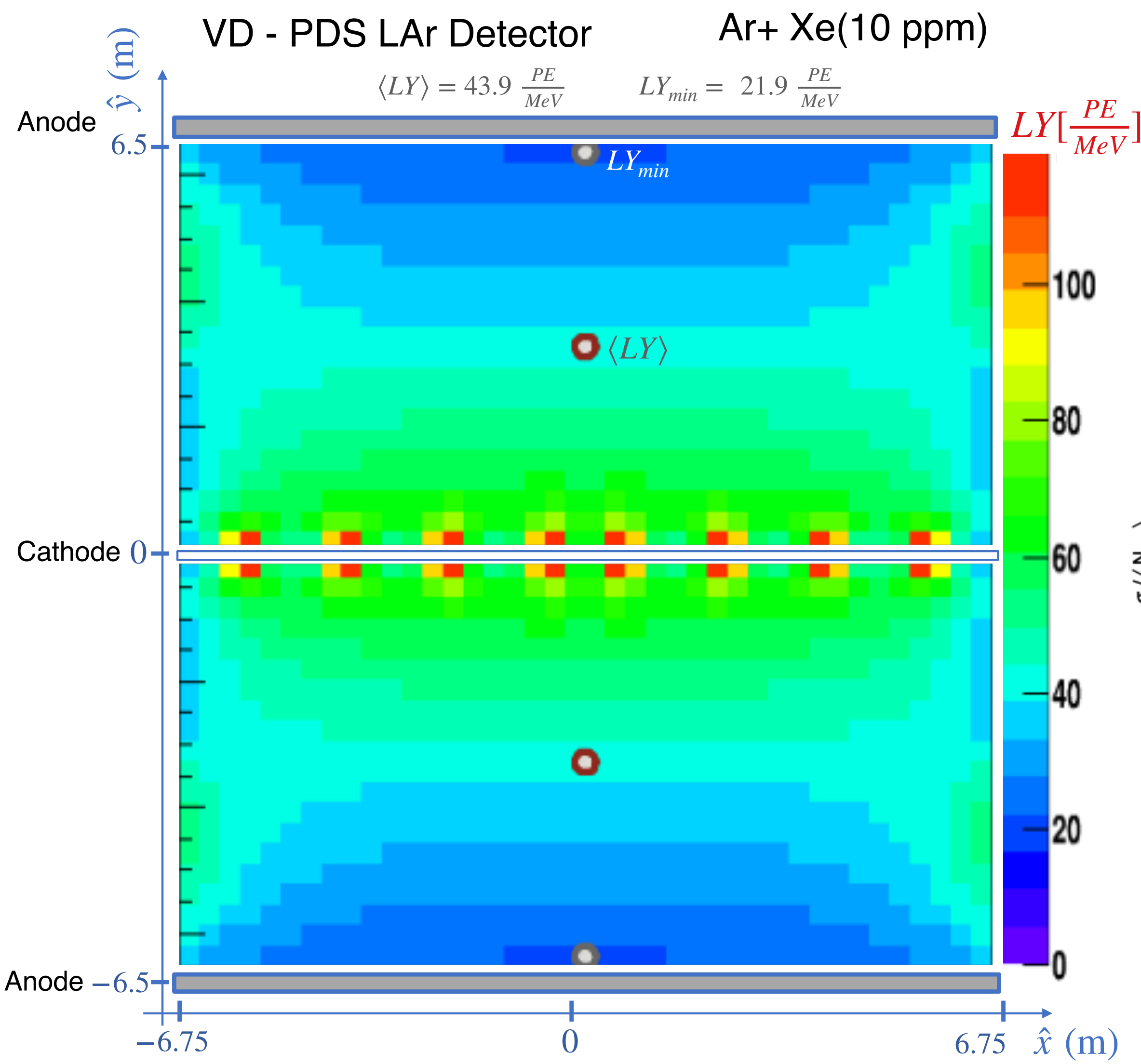


ProtoDUNE-SP Data



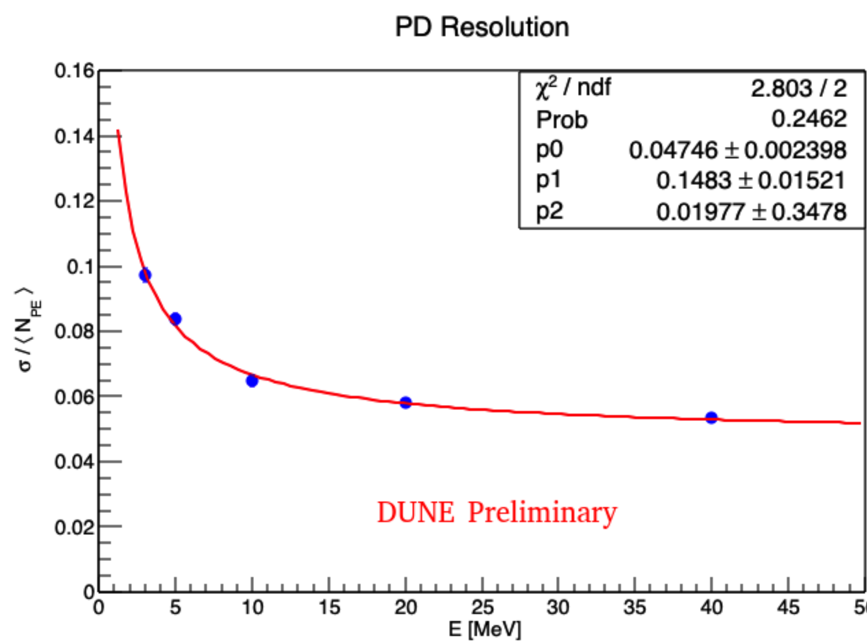
Liquid Ar + Xe mixture response

Light Yield Map in the Detector Transverse plane



Calorimetric Energy reconstruction from detected photon counting

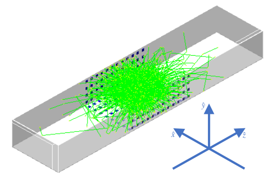
Energy Resolution
from statistical fluctuation (p1) on the number of detected PEs and from uncertainty on energy calibration (p0)

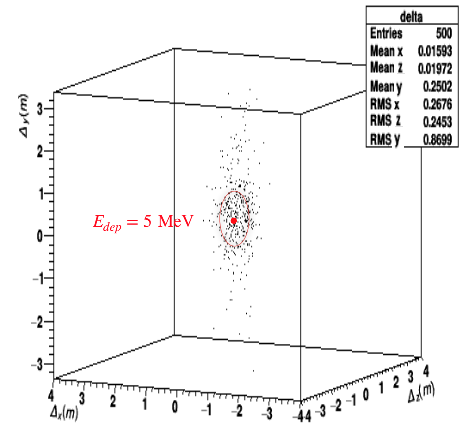


E = deposited visible energy
in Low-En point like neutrino interaction event
in $\langle LY \rangle$ positions

Position reconstruction and Spatial Resolution

position reconstruction from the barycenter of the detected light pattern of the event

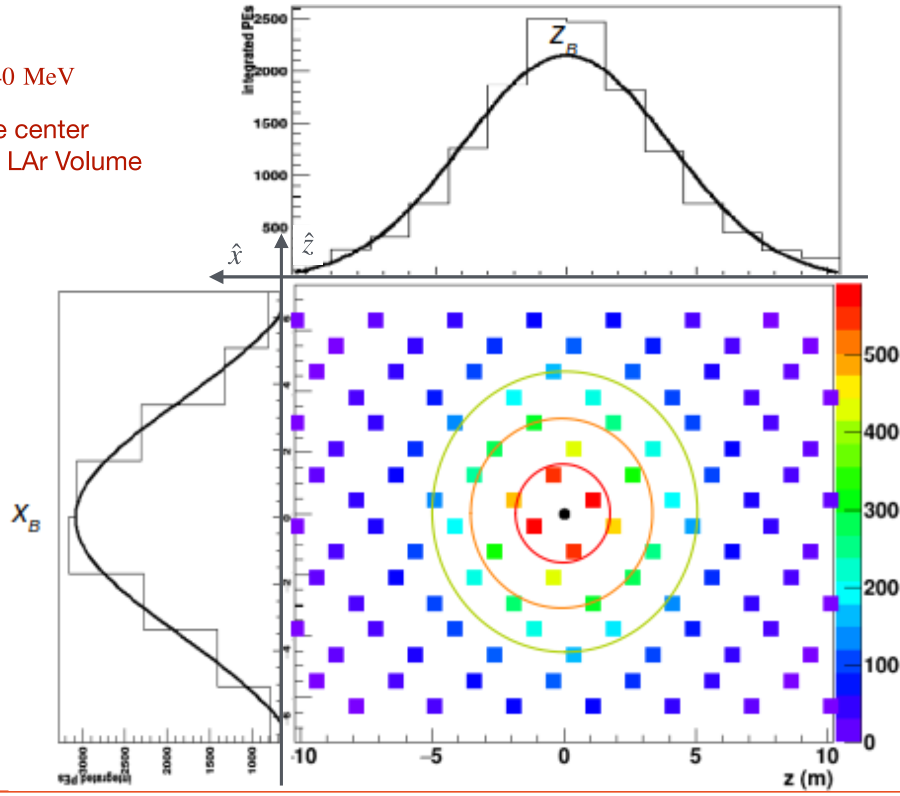


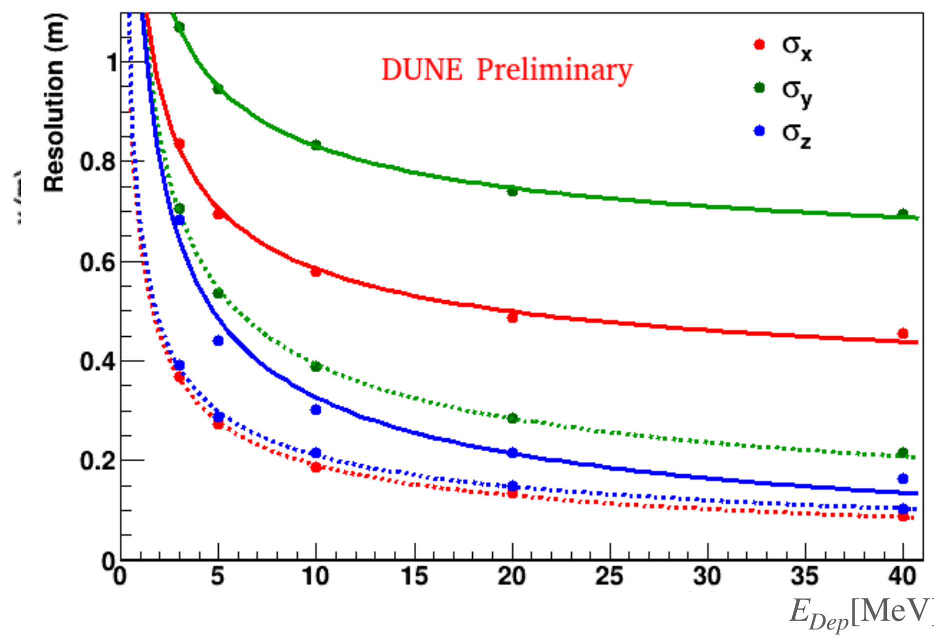


Space resolution = rms of the distributions of the difference between reconstructed and true position coordinates.

$E_{dep} = 40$ MeV

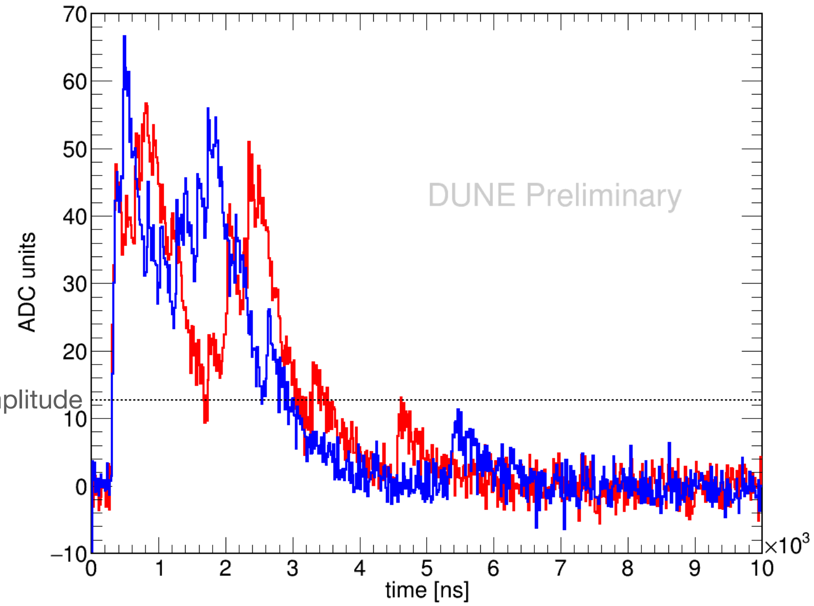
at the center of (upper) LAr Volume

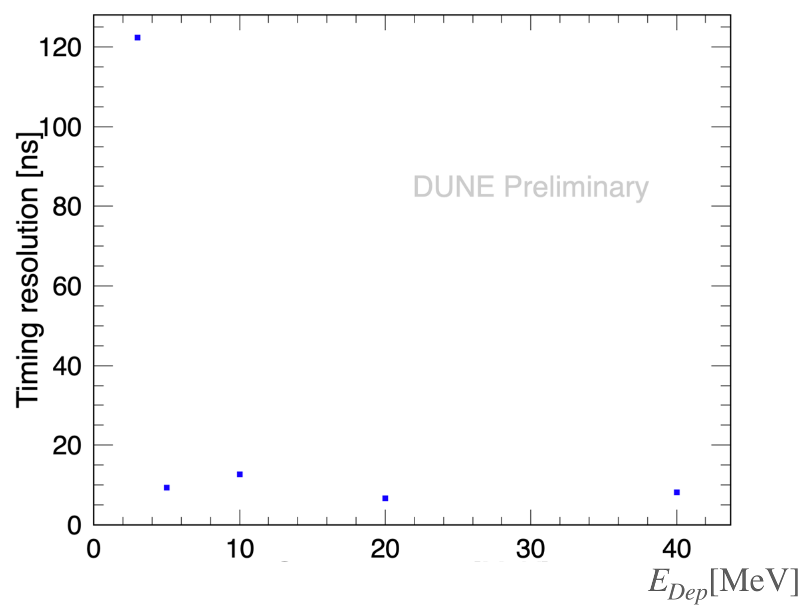




Time Resolution

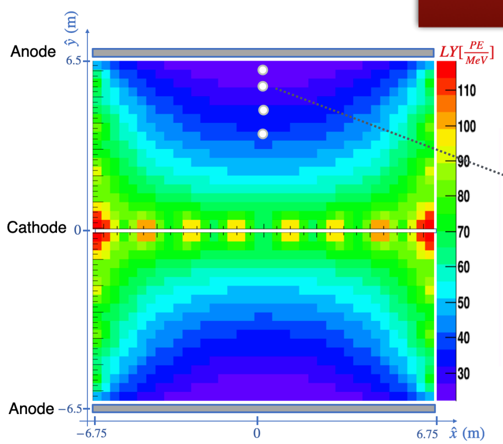
Determined from first photon arrival time by pair of adjacent photon detectors (identical light propagation time from source to detector)
The width of the distribution of the difference in the time measured gives a quantitative measurement of the timing resolution.

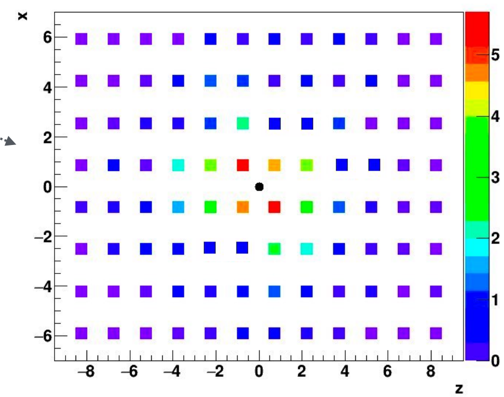




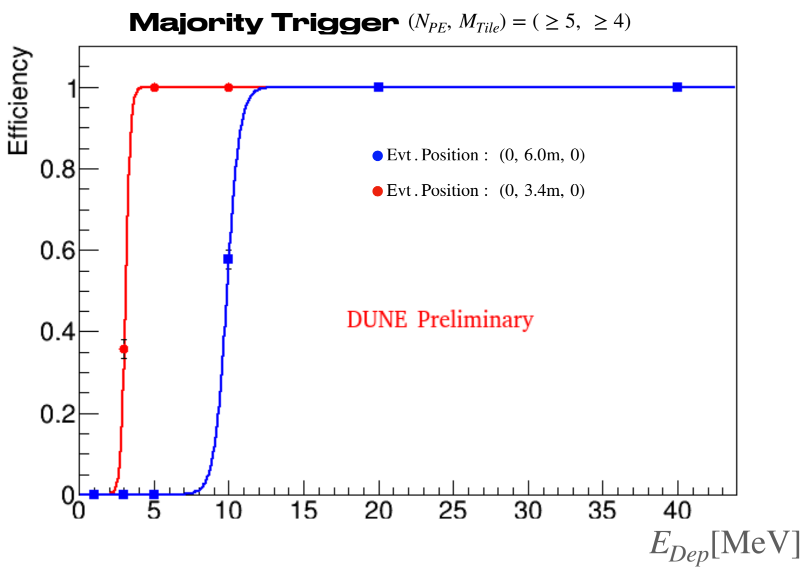
$\sigma_t \leq 15$ ns for $E_{dep} \geq 10$ MeV

(N_{PE}, M_{Tile})–Majority Trigger condition

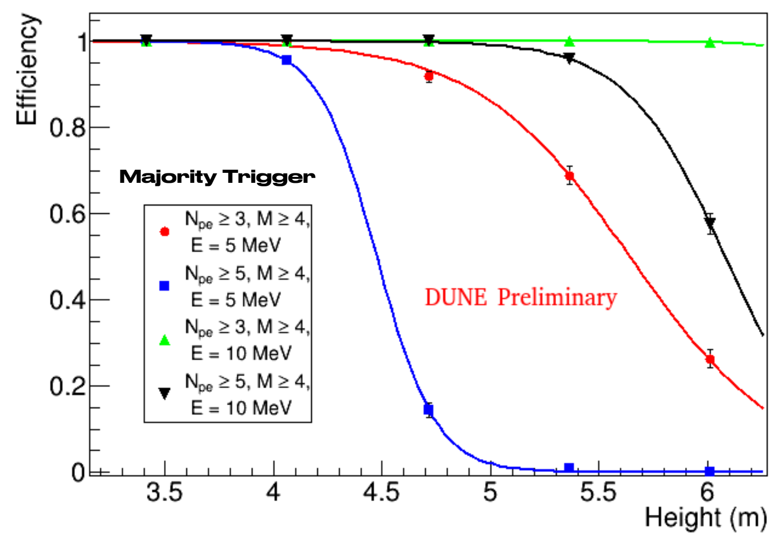




Trigger Efficiency $\geq 99\,\%$ for interactions with $E_{dep} \geq 5$ MeV expected in 100 % of a 10 kT Fiducial Volume



Relaxing (N,M)-Majority requirements enhance trigger efficiency, but also increase rate of false-positive triggers



in flow

- LArPDS Simulation from stand-alone G4 into standard LArSoft G4 + Neutrino event Generators [completed]
- MC Tuning of Scintillation Light emission processes and parameters for Ar+Xe mixture based on protoDUNE-SP and DP Xe doping tests [second round of tuning completed, but still lot to understand]
  - propagation in LAr volume (attenuation from Rayleigh and Absorption) and reflection at boundaries
- MC production (high stats, 100 k-evt) in progress for SN Neutrino events in the *tens of MeV* range (Marley Generator)
  - LArPDS-based energy resolution for SN Neutrino events - and comparison to LArTPC [preliminary results]
  - LArPDS-based SNB trigger efficiency as a function of neutrino energy and SN distance

- Detector Layout optimization
  - PD Modules on the Cathode: layout modification for HV discharge effects mitigation
  - PD Modules on Membrane Walls: layout modification for LY Uniformity improvement

Summary

DUNE Physics reach - specifically in the UG Low-Energy domain - can be further expanded if a robust LAr Photon Detector System is embedded into the LArTPC layout.

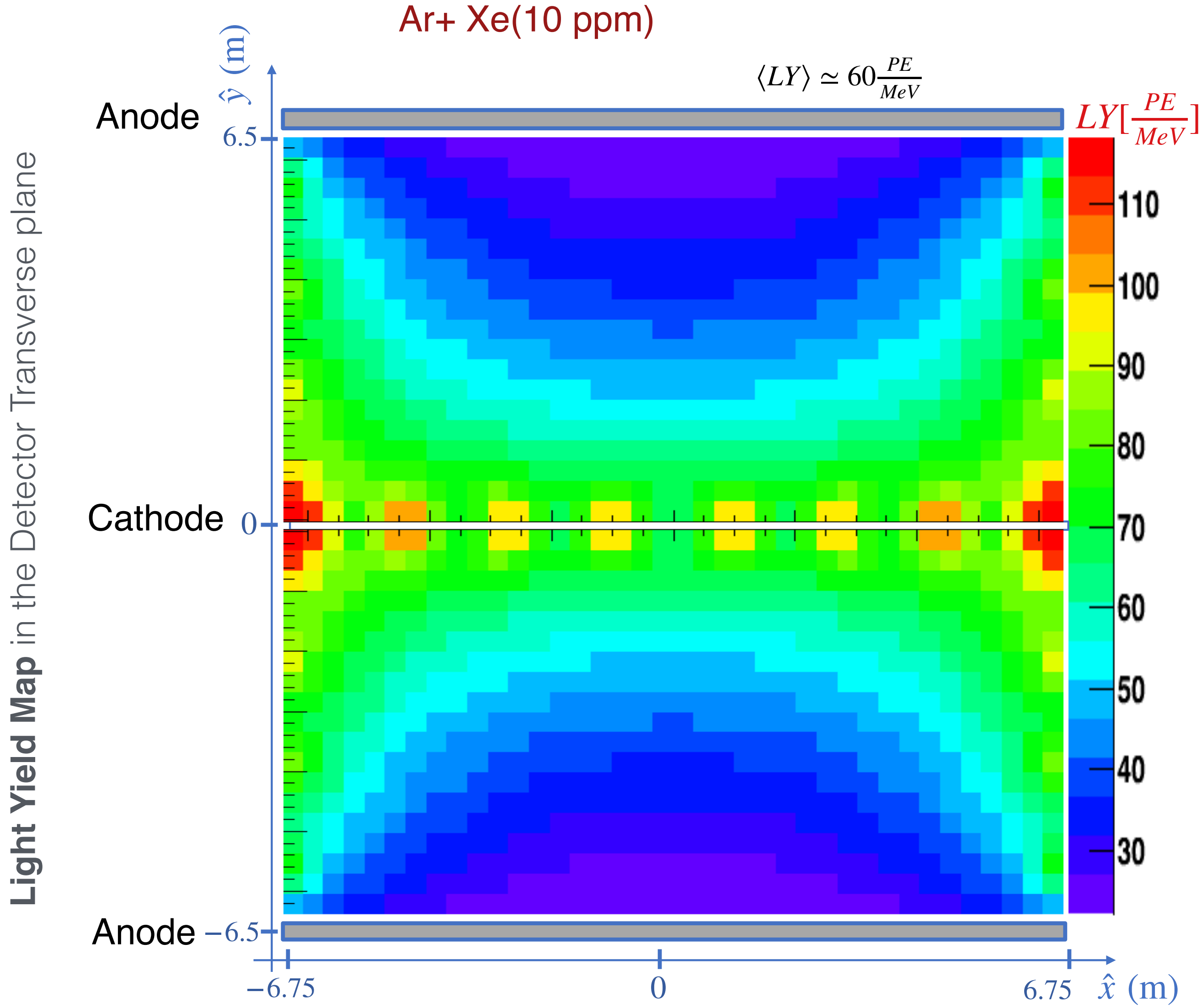
The LArPDS designed for FD2-VD module can provide high trigger efficiency ($\rightarrow 1$) for events with $E_{dep} \geq 5MeV$, improved energy resolution, good time resolution and additional position resolution useful for background rejection.

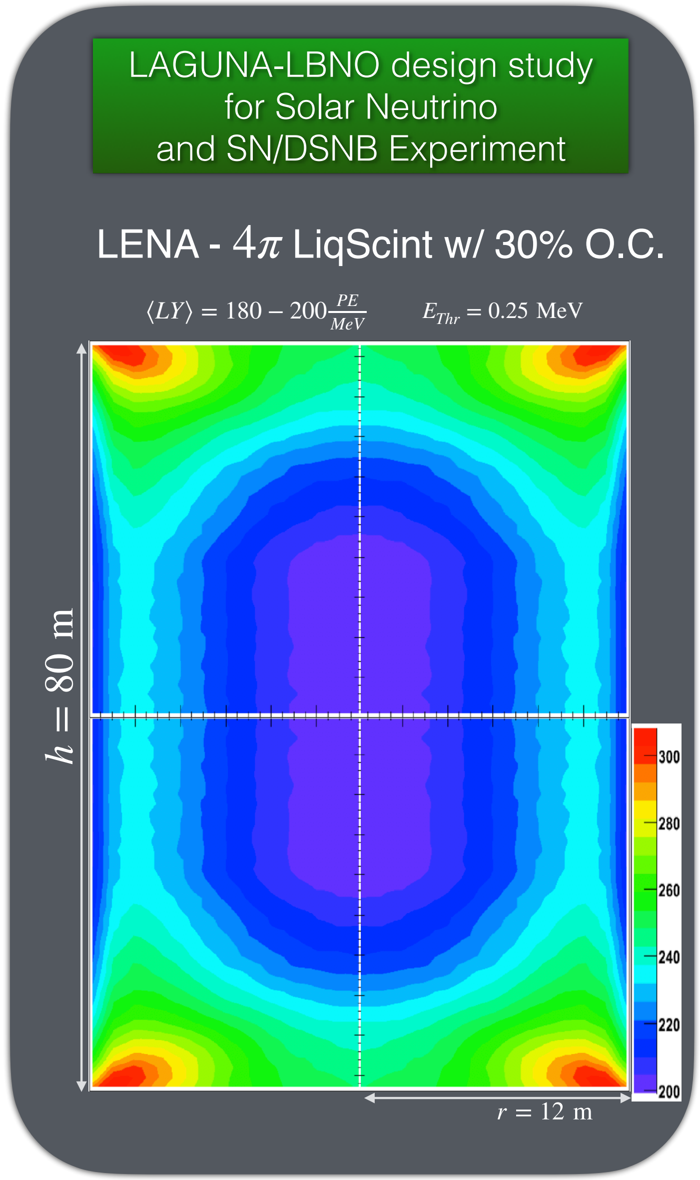
The FD2-VD LArPDS has great potential for Physics but it is also a technological challenge, requiring the detector to be operated on HV surfaces (Cathode)

Detector Component/Feature	Parameter	Demonstration
Scintillation medium composition	Ar+Xe(10 ppm) (Ar Slow-component full transfer to Xe)	*protoDUNE-SP and -DP*
X-ARAPUCA Technology Choice SiPM + Electronics read-out X-ARAPUCA efficiency PoF - Power Transmission SoF - Signal Transmission	 S/N ≥ 5 ϵ_D=3% Conversion Effic. 22% $\rightarrow$ 70% Usable Pwr: 4 W/PoF-Unit stability, noise at $V_{out} \sim 50$V	 *protoDUNE + prototype Tests* *+ ColdBox Tests 2021-23* *+ Module0 Tests 2023*
PDS Light Yield	$\langle$LY$\rangle \simeq 45$ LY$_{min} \simeq 25$	*from MC study* *from MC study*
Spatial resolution Energy resolution Time resolution	$\sigma_r \leq 0.7$ m $(E_{dep} \geq 5$ MeV) $\sigma_E/E \leq 10\%$ $(E_{dep} \geq 5$ MeV) ≤ 20 ns	*from MC study* *from MC study* MC study + (protoDUNE-SP)

BackUp

The VD $\sim 4\pi$-PD w/ $\sim 14\,\%$ Optical Coverage





Boundary conditions for FD2-VD PD

⇒ **Power budget and limitation for power dissipation in LAr**

⇒ **Cost envelop for VD PD**

[with baseline plan of substantial part of the “cathode” mounting scheme in DUNE-US Project]

⇒ **Creation of a new PD community from US, EU and International, within the existing DUNE PD Consortium**