Detection efficiency measurement and operational tests of the X-Arapuca for the first module of DUNE Far Detector

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September 2022

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DUNE

Overview

- **DUNE: Long-Baseline Neutrino Oscillation Experiment**
- **First Module of DUNE Far Detector**
- **Photon-Detection System: X-Arapuca**
- **Measurement of Absolute X-Arapuca Efficiency**
- **Massive tests of X-Arapucas for ProtoDUNE-II**

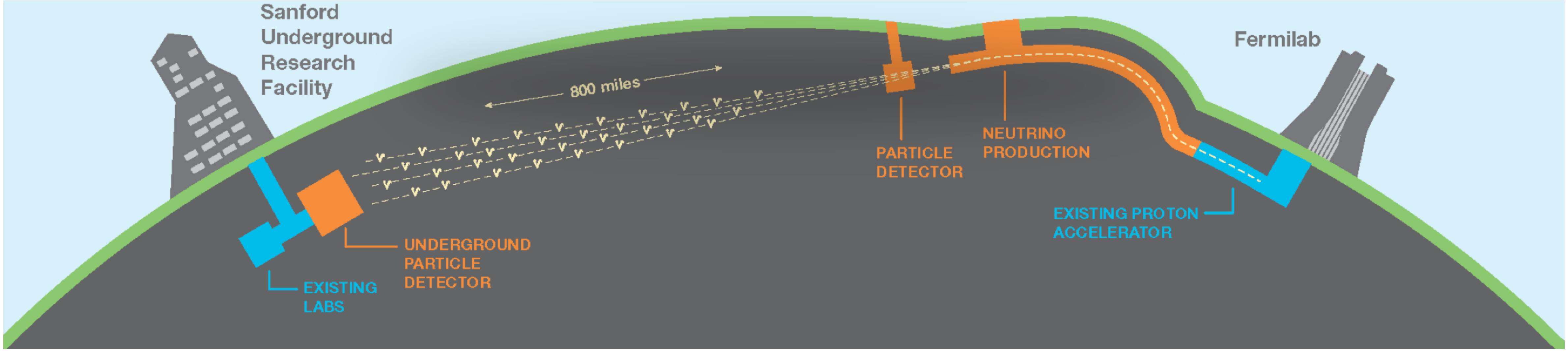
DUNE: Long-Baseline Neutrino Experiment

Far Detector
LAr-TPC
Measurement of
Oscillated neutrino beam

Neutrino Travel through the Earth 1300 km

Near Detector
Monitoring unoscillated neutrino energy spectra & composition

Muon neutrino beam
LBNF Neutrino Beam
1.2 MW beam power
→ Upgradeable to 2.4 MW

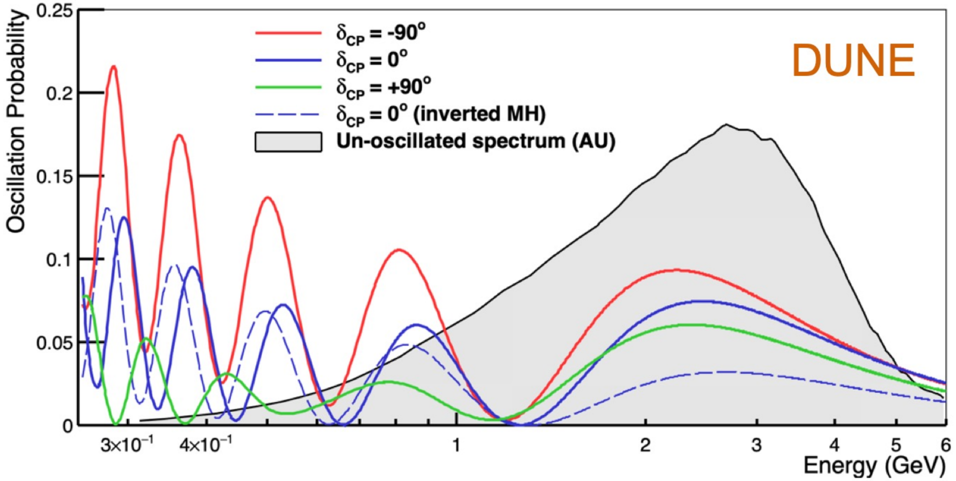


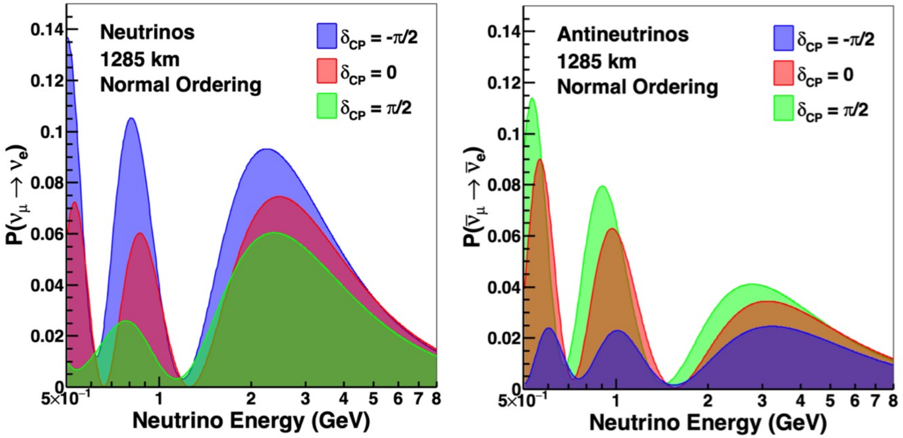
DUNE

Measurement of ν_e appearance and ν_μ disappearance with a wide range energy ν_μ beam at 1300 km would allow:

- Definitive measurement of neutrino Mass ordering
- Discovery potential for CP violation for wide range of δ_{CP}
- Precise measurement of neutrino mixing parameters

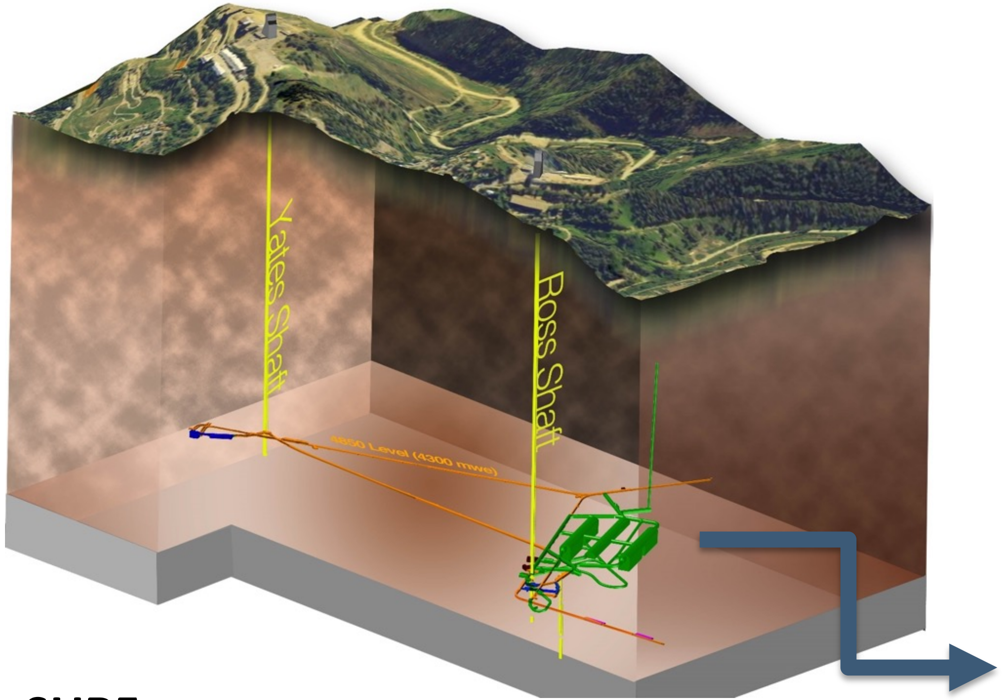
Supernova burst neutrinos and other low energy physics



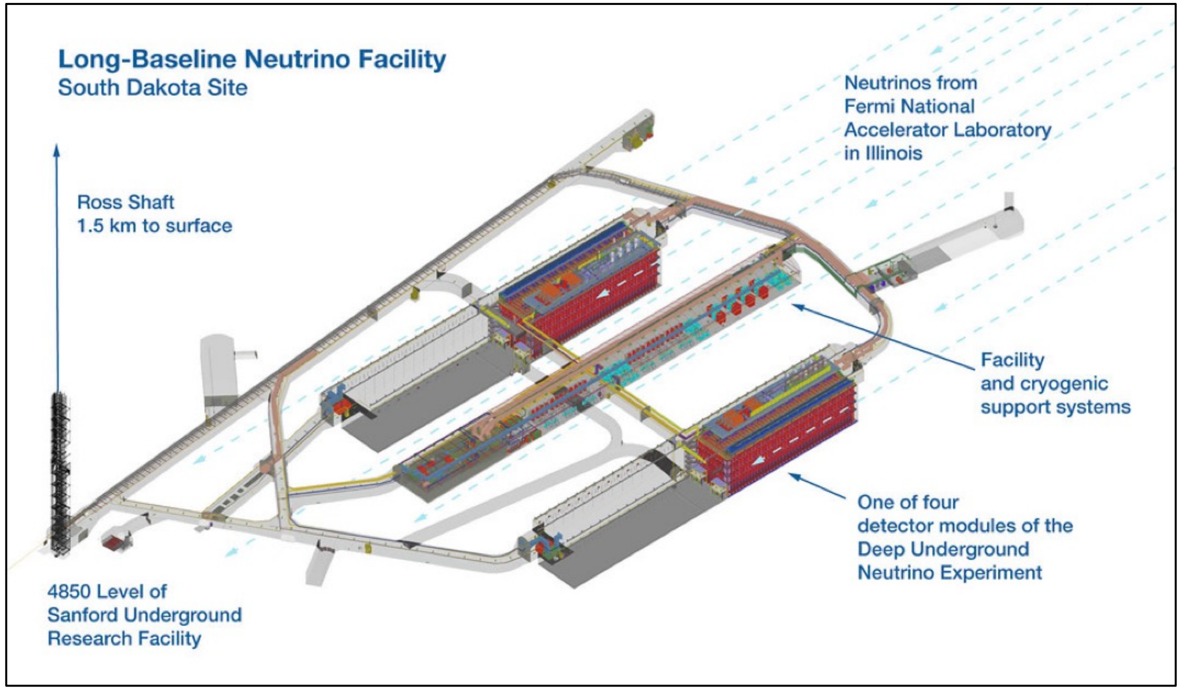


DUNE Far Detector

Four modules of 10-kt fiducial LAr TPC with integrated photon detection at 4850L of SURF (4300 mwe).



SURF
Sanford Underground Research Facility



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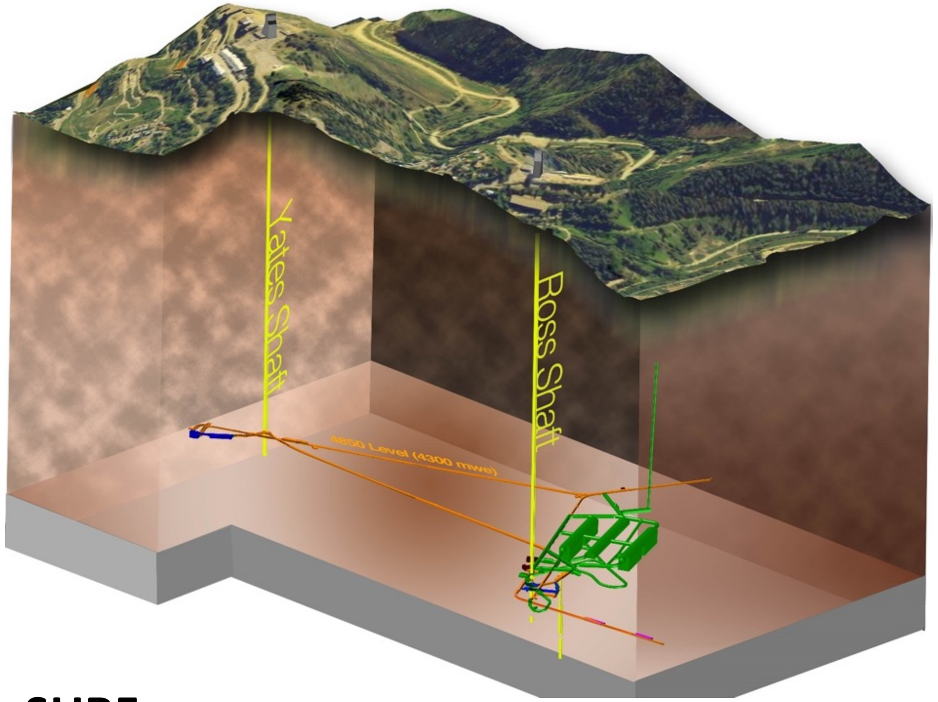

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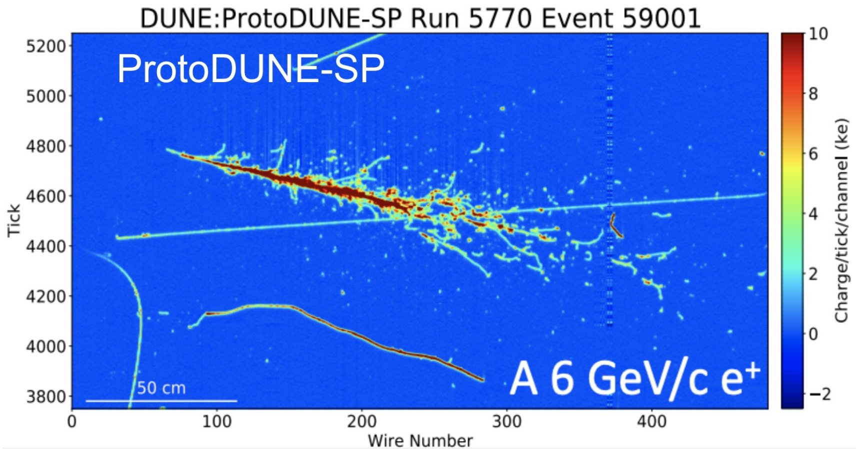
Four modules of 10-kt fiducial LAr TPC with integrated photon detection at 4850L of SURF (4300 mwe).

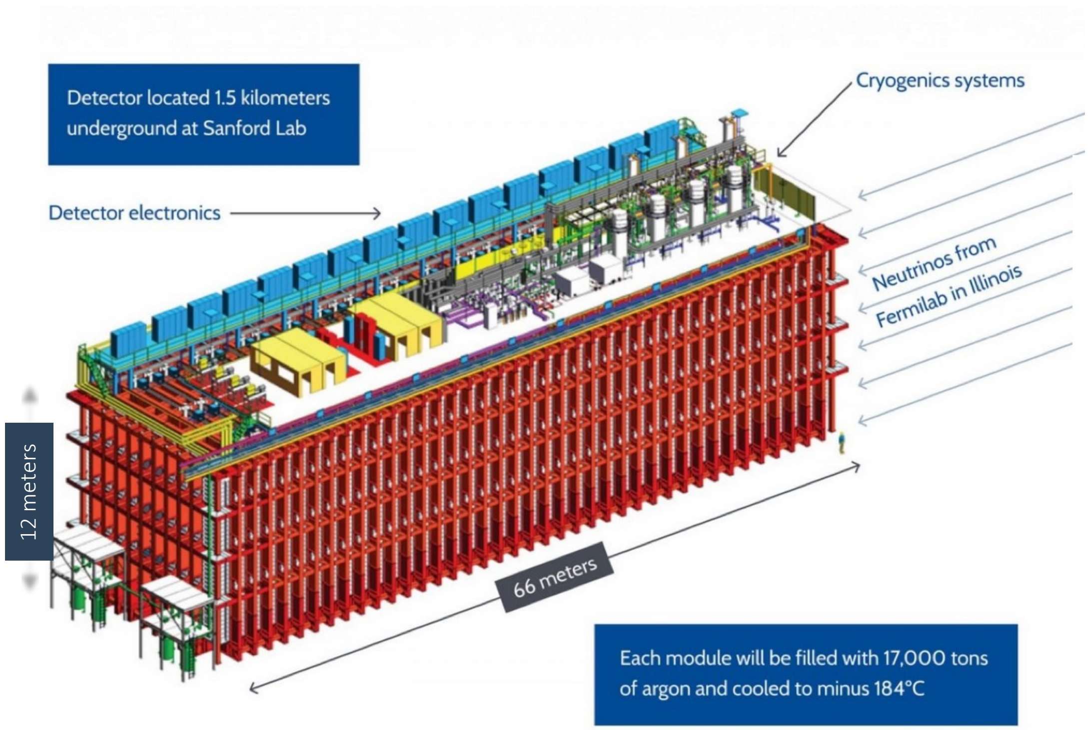
High resolution 3-D track reconstruction

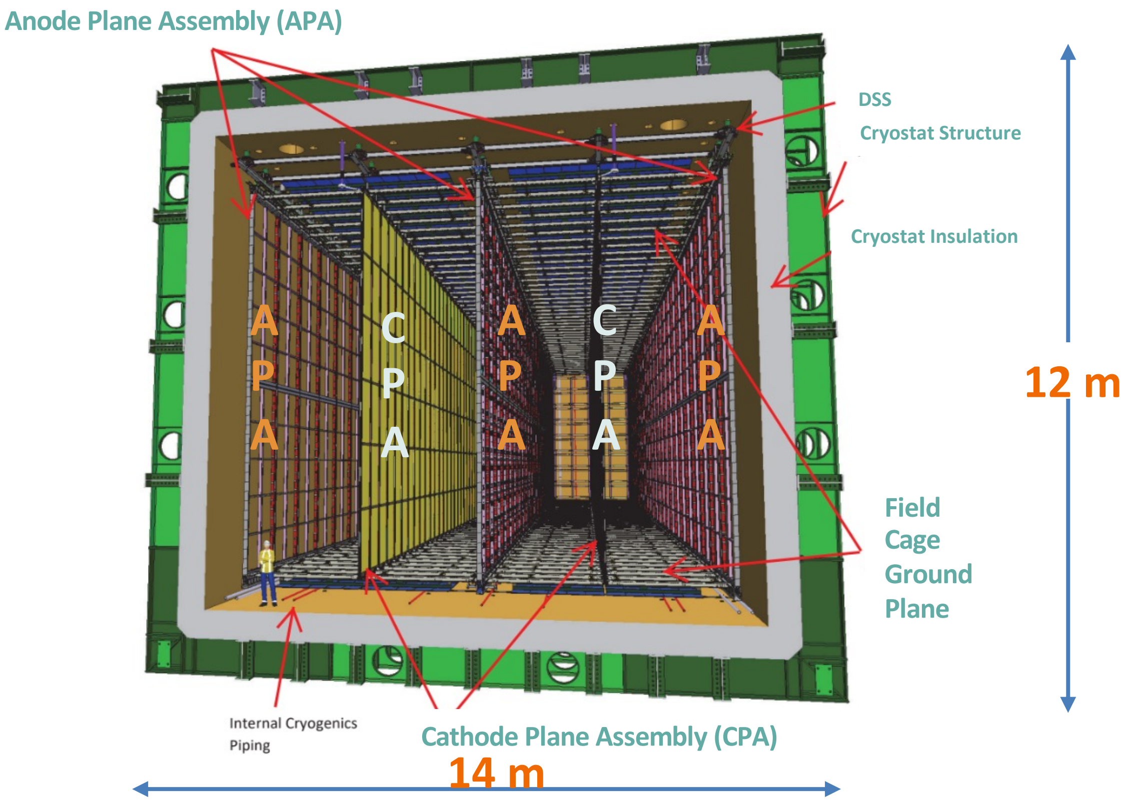


1st Module DUNE Far Detector

Divided in 4 drift volumes

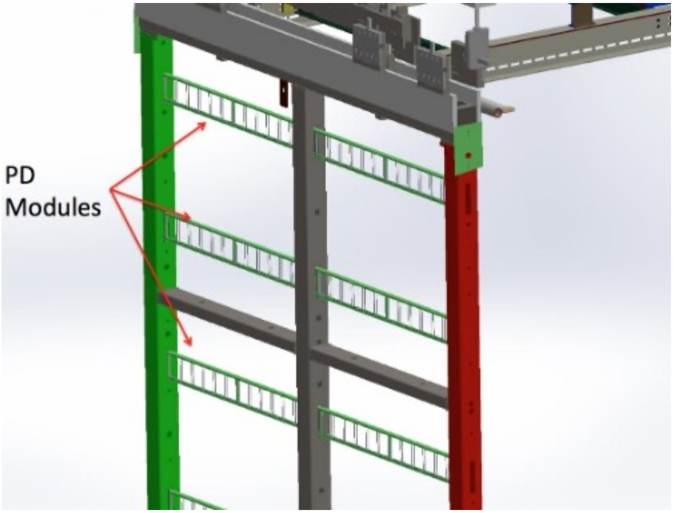
150 individual anode planes assemblies (APA) (2.3m x 6 m) 384,000 readout wires

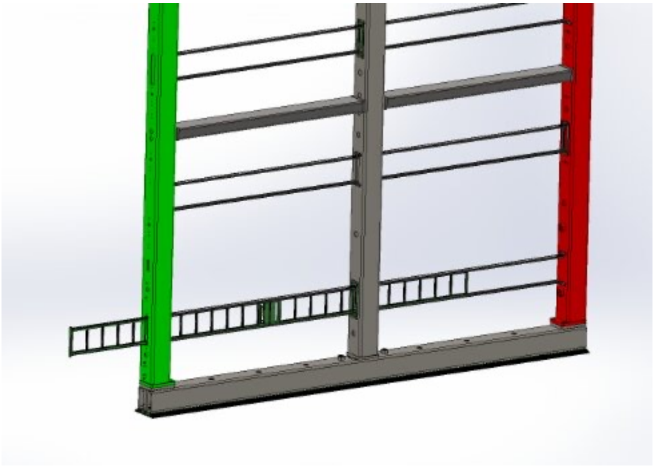


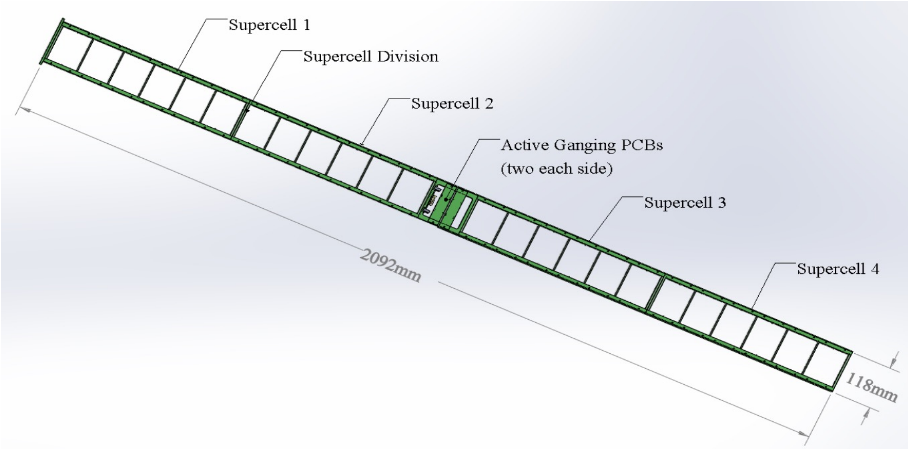


Photon-Detection System

- The Photon-Detection System (PDS) can enhance the detector capabilities for all DUNE physics goals and open new areas of investigation
- The PDS contributes to a more robust detector operation
- DUNE PDS: Efficient detection of VUV scintillation light (24ph/keV) using light collector modules in the inactive space of the APA's

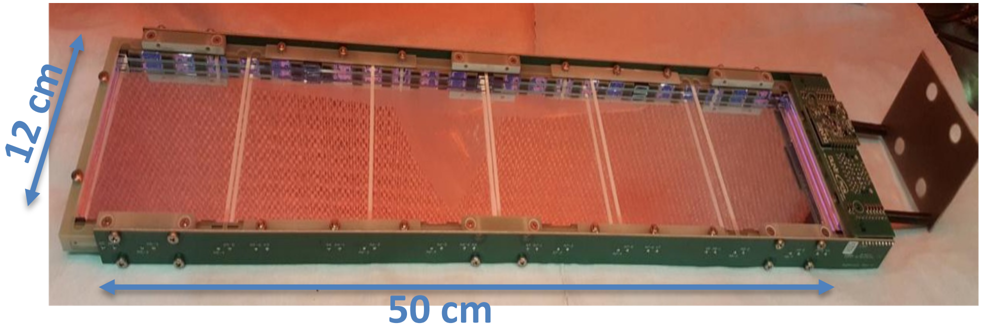


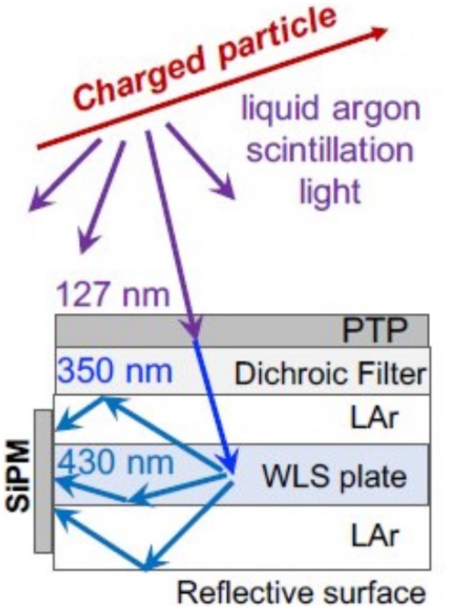


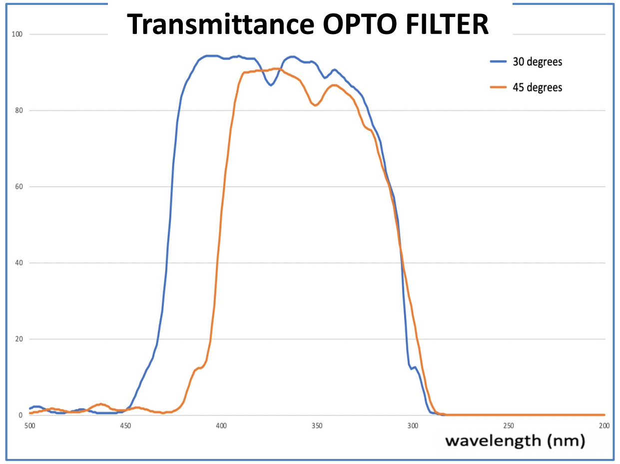


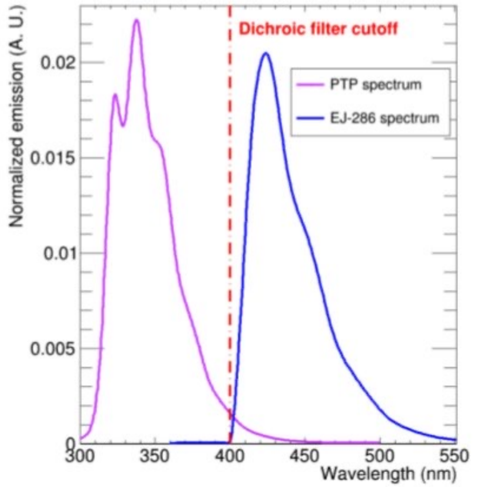
Photon-Detection System: X-Arapuca

- **X-Arapuca light collector:** Captures WLS photons in a reflective internal surfaces box where a WLS plate drives the photons to SiPM's









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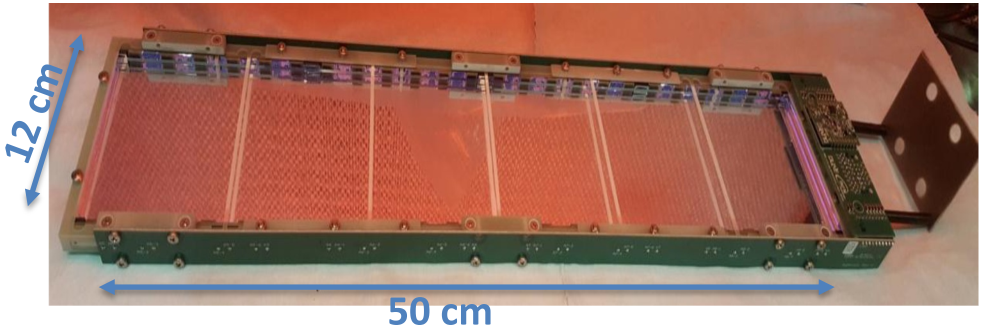
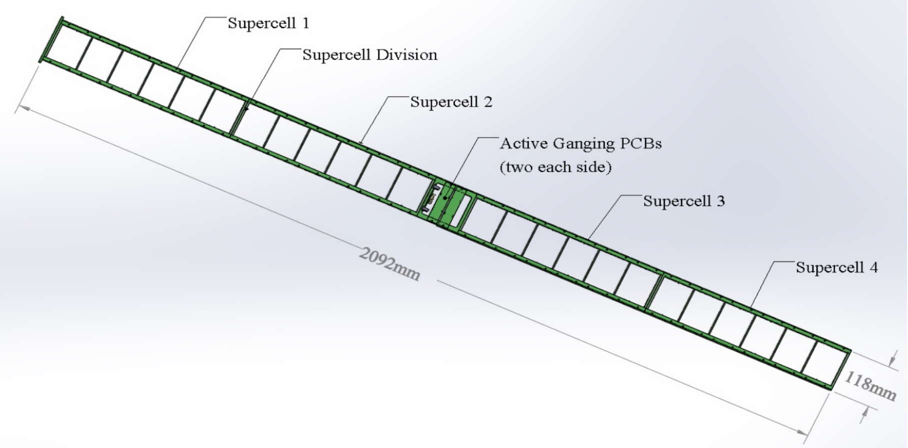


- **X-Arapuca Elements**. A Supercell contains:
  - **6 Dichroic filters 400 nm cutoff (OPTO)**
  - **1 WLS plate with an emission wavelength higher than the filter transmission threshold (2 suppliers Eljen and Glass-to-Power)**
  - **48 electrically ganged SiPMs 6x6 mm^2 (75μm HQR HPK and TT FBK)**
  - **1 readout channel**



Requirements:
for tagging 99% nucleon decay events → Eff ≳ 1.3%
for calorimetric low-energy events (SNB) → Eff ≳ 2.6 %

ProtoDUNE Phase II

Single-Phase (NP04)
300 t fiducial mass

ProtoDUNE program at CERN

- The final design of the 1st FD module (SP 3.5 m drift) will be validated in ProtoDUNE phase II (2022-2023) (NP04)

X-Arapuca will be tested for the first time

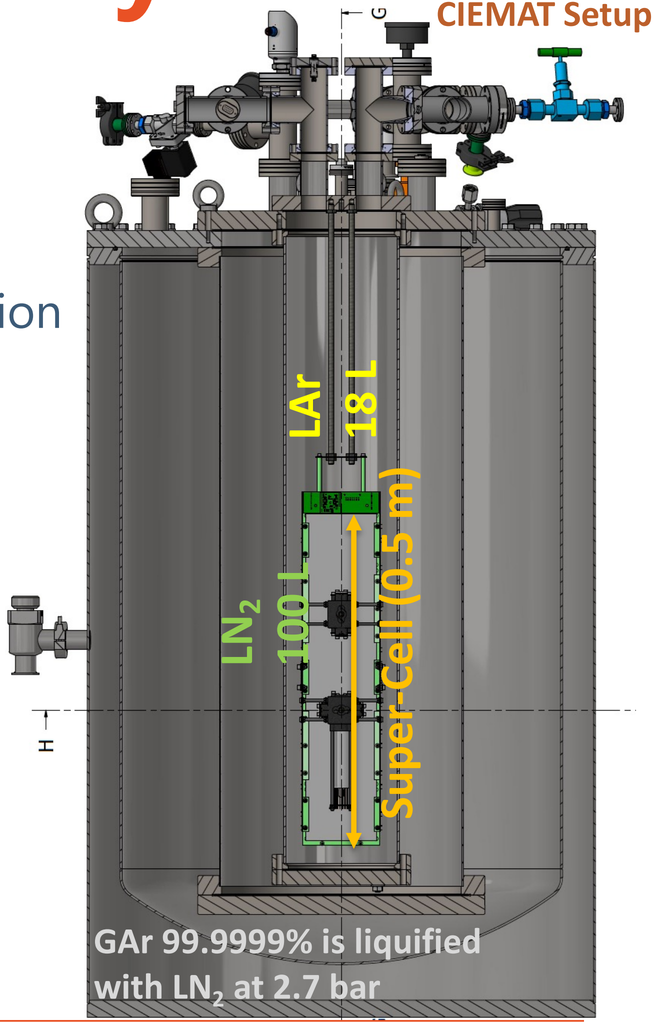
Measurement of X-Arapuca Efficiency

Setups:

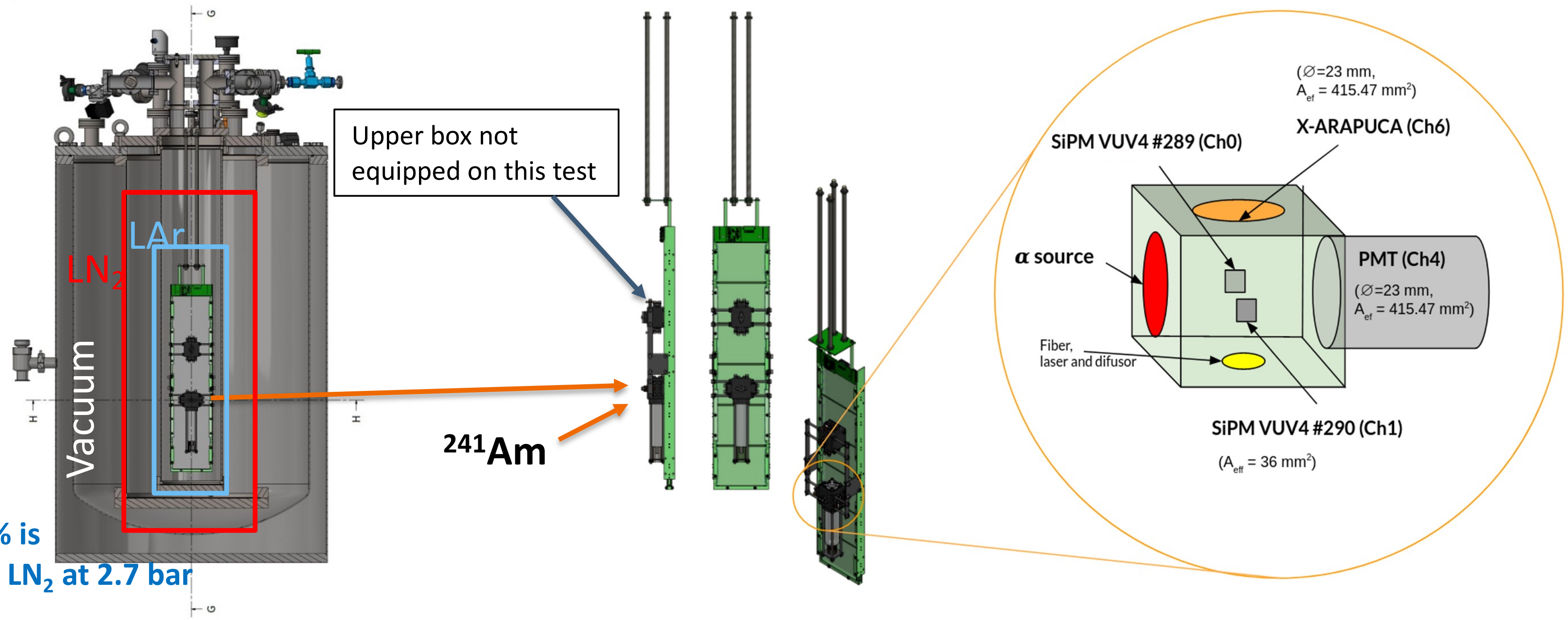
- X-Arapuca (XA) is submerged in LAr
- Low-activity electrodeposited ^{241}Am alpha source is used to produced scintillation light
- Two different setups:
  - CIEMAT (illumination of a fraction of XA surface)
  - Milano-Bicocca (MiB) (illumination of the whole XA 5cm away)

➢ Two Methods for determining the light arriving to the XA surface:
  - Comparison with another calibrated photo-sensor (Method A)
  - Estimation from source energy + LAr propagation properties + simulation (Method B)

CIEMAT Setup



CIEMAT Setup



GAr 99.9999% is liquified with LN_2 at 2.7 bar

- 2 VUV sensitive **SiPMs** are symmetrically placed with respect to the X-Arapuca and the α source
- **The efficiency is measured from the Reference SiPMs with known efficiency**
- 1” **PMT** (VUV sensitive) is used to get the τ_{slow} and Scintillation light monitoring

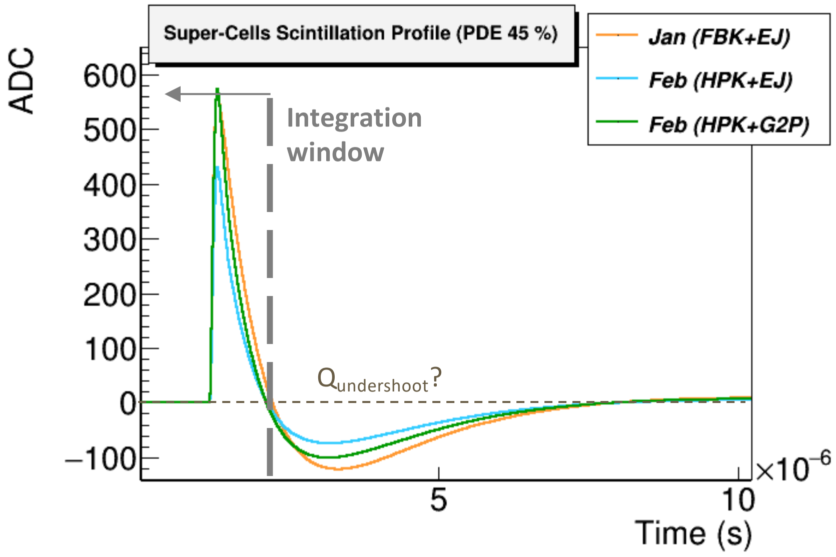
Reference SiPM: Hamamatsu VUV4 SiPMs S13370 – 6075CN

X-Arapuca efficiency measurement Method A

$$\epsilon_1(Arapuca) = \frac{\#PE_{mm^2}(Arapuca)}{\#PE_{mm^2}(Ref.SiPM)} \cdot \epsilon\,(Ref.SiPM) \cdot f_{corr}$$

f_{corr} includes:

- X-talk correction ~0.86 – 0.97 (±0.10)
- Fraction of integrated light
- Different solid angle (size/positioning)



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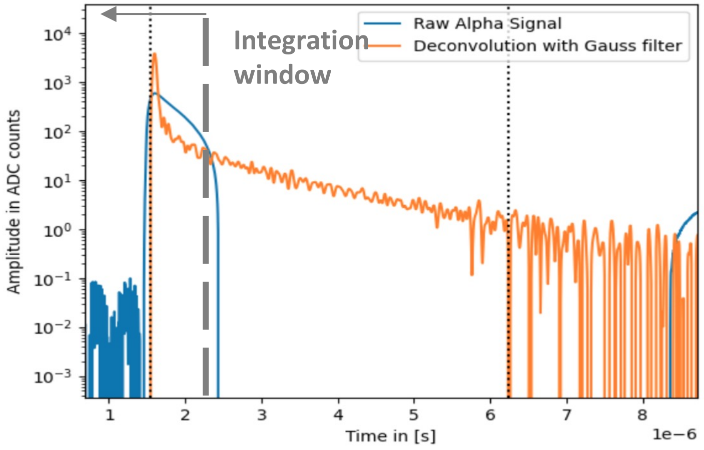
f_{corr} includes:

- X-talk correction ~0.86 – 0.97 (±0.10)
- Fraction of integrated light 1.08 ± 0.02
- Different solid angle (size/positioning)

HPK+G2P Deconvoluted Average Waveform



X-Arapuca efficiency measurement Method A

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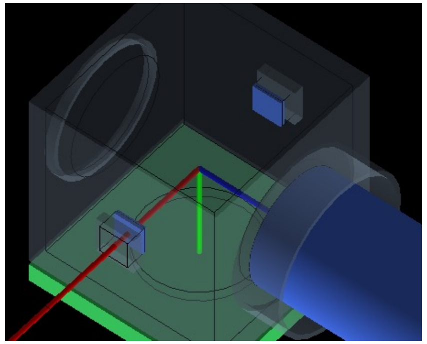
f_{corr} includes:

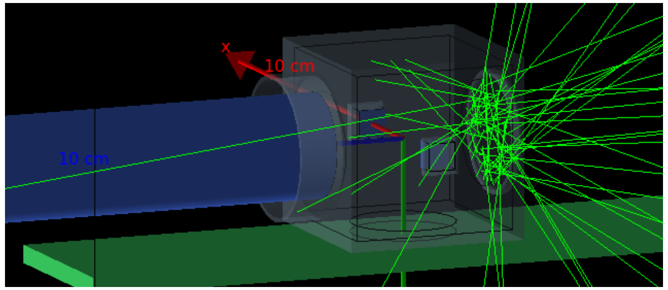
- X-talk correction ~0.86 – 0.97 (±0.10)
- Fraction of integrated light 1.08 ± 0.02
- Different solid angle (size/positioning) 1.35 ± 0.08

	X-Arapuca	SiPM
Solid angle (Ω)	0.29 ± 0.02	0.034 ± 0.003
Effective area (mm^2)	415.47	36.00
$\Omega\ per\ mm^2\ (10^4)$	6.9 ± 0.5	9.4 ± 0.8

X-Arapuca efficiency measurement Method B



Ω Determined with a dedicated simulation



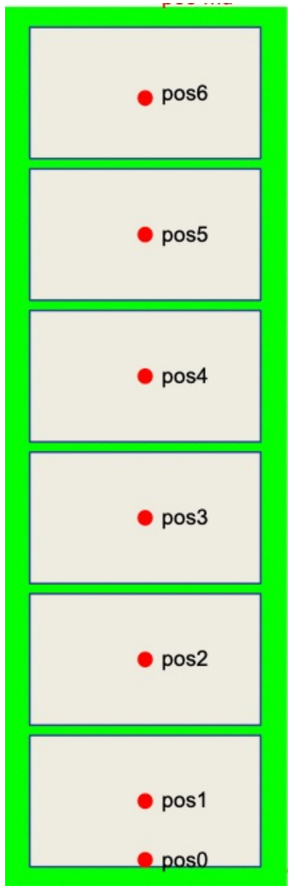
$$\epsilon_2(Arapuca) = \frac{\#PE(Arapuca)}{\#PE\ (Produced) \cdot \Omega} \cdot f'_{corr}$$

$$\#PE\ (Produced) = LY_{LAr} \cdot E_\alpha = 35000\ ph/MeV\ \cdot 5.48\ MeV$$

f'_{corr} includes:

- **X-talk correction**
- **Fraction of integrated light**
- **LAr purity correction** **~ 0.94 – 0.79** (depending on the campaign)

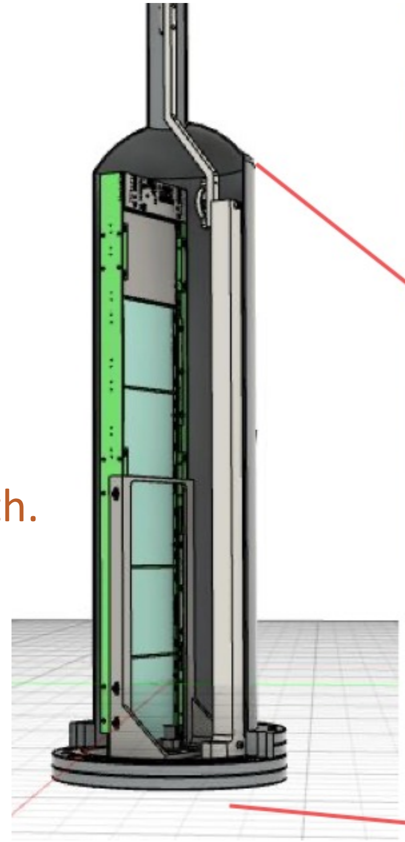
Milano-Bicocca Setup



α source – XA distance (55 ± 1) mm

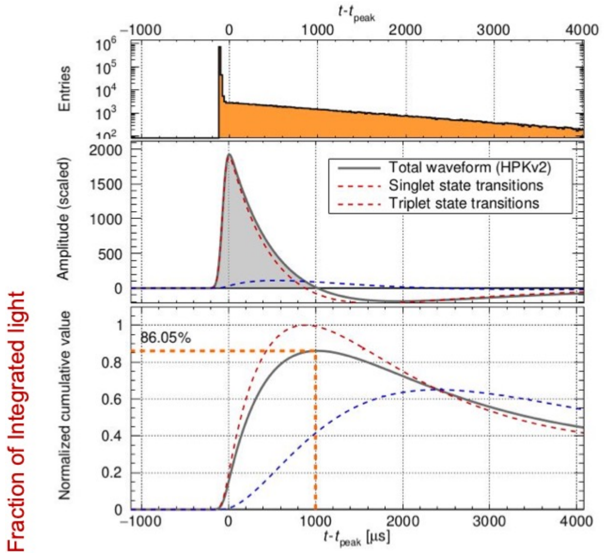
Z-scanning of the XA with the ^{241}Am source at 6 positions: centre of each dichroic filter and the lowest possible (~2 cm above the flange)

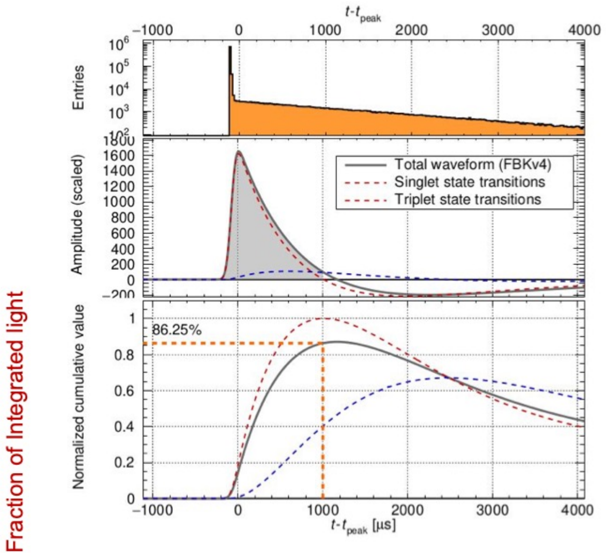
The XA installed in the test chamber.
The camber is pumped down to 10^{-4} mbar, then filled with GAr 6.0 grade that is continuously liquified by an external LAr bath.



X-Arapuca efficiency measurement Method B

Fraction of integrated light: Synthetic wfms
SPE ⊛ Scint. LAr Profile





$$\epsilon_2(Arapuca) = \frac{\#PE(Arapuca)}{\#PE\ (Produced)\cdot\Omega}\cdot f'_{corr}$$

$$\#PE\ (Produced) = LY_{LAr}\cdot E_\alpha = 35000\ ph/MeV\ \cdot 5.48\ MeV$$

f'_{corr} includes:

- ➔ **X-talk correction**
- ➔ **Fraction of integrated light 0.86**
- ➔ **LAr purity correction (negligible-5%)**

Results (preliminary)

X-Arapuca configurations

48 **FBK-TT** SiPMs + **Eljen** WLS plate

48 **FBK-TT** SiPMs + **Glass-to-Power** WLS plate

48 **HPK 75HQR** SiPMs + **Eljen** WLS plate

48 **HPK 75HQR** SiPMs + **Glass-to-Power** WLS plate

X-Arapuca Efficiency

LAB	($PDE_{XA\text{-}SiPM}$ = 45%)	FBK + EJ	FBK + G2P	HPK + EJ	HPK + G2P
CIEMAT	ϵ_A (%)	1.95 ± 0.22		2.19 ± 0.20	2.98 ± 0.27
	ϵ_B (%)	1.48 ± 0.33		1.72 ± 0.19	2.29 ± 0.25
MiB	ϵ_B (%)	1.44 ± 0.06	1.74 ± 0.06		2.13 ± 0.06

The three measurements lead to compatible results within errors

- Slightly higher efficiency using HPK SiPMs
- G2P plates increase the efficiency > 20%

Massive tests

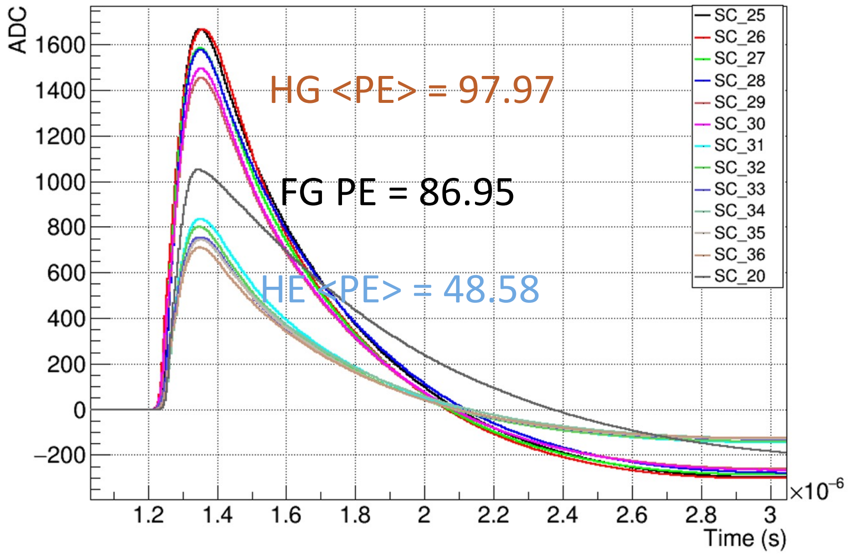
The X-Arapucas to be installed in ProtoDUNE-II have been tested prior to their assembly and installation at CERN

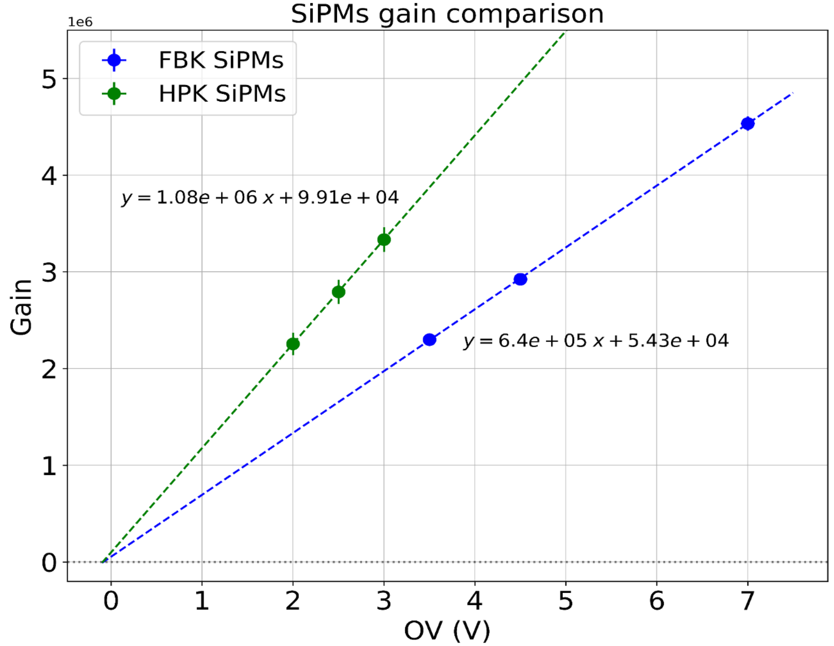
@ CIEMAT
- A vessel with 300 l of Liquid N_2 accommodating up to 14 XA's (w/o dichroic filters)
- Light from 405nm Laser
- CIEMAT has tested 74 XA out of 160

Goals:
- Test their correct operation in CT
- Characterization in terms of: Gain, SNR and Dark counts

Massive tests: some results

- 3 configurations tested: HPK+G2P (HG), FBK+G2P (FG) and HPK+Eljen (HE)





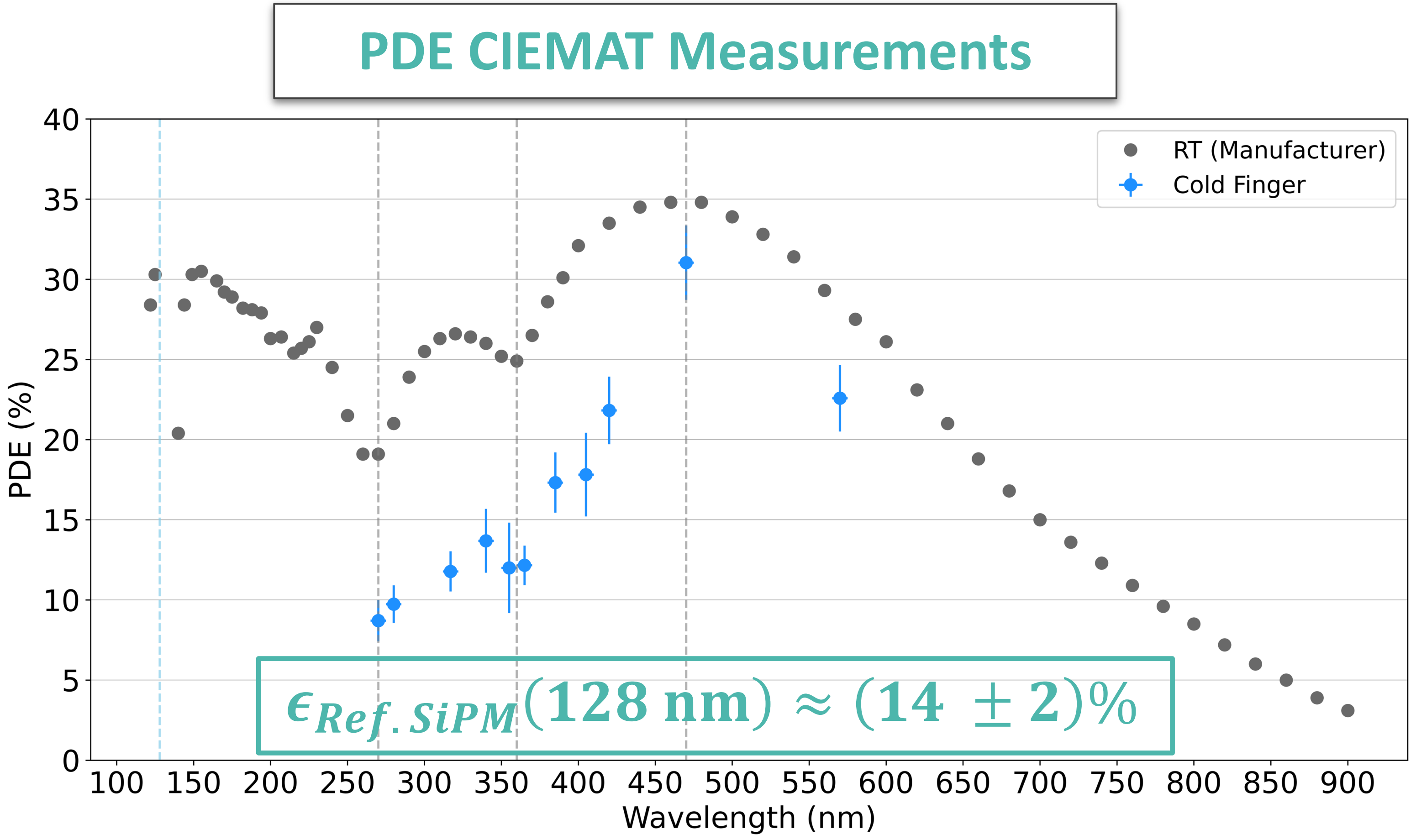
- SNR ~6.5 for PDE 45%
- Dark count is below requirement (<1.7 kHz) except for Eljen WLS plates

Conclusions

- DUNE physics will be enhanced with an efficient photon-detection system.
- ProtoDUNE phase II will test the current design of X-Arapucas in 2022/2023. All the modules have been tested and are currently being installed at CERN.
- The absolute efficiency of the X-Arapucas to be installed in ProtoDUNE-II has been measured by CIEMAT and MiB groups using two different setups and methodologies.
- The results shown an efficiency between 1.5 and 3% depending on the SiPM model, WLS plate manufacturer and XA SiPM's bias voltage.
- The 1st FD Module installation will start in 2024.
  - Some improvements on the design can be done (like better SiPM - WLS plate contact, lower transmittance of the dichroic filter above threshold).

BACKUP

Measurement of Reference SiPM at CT



- Measurements at CIEMAT estimate a decrease of ~50% for PDE at CT
- **S13370 PDE measurement at 128 nm and CT recently published** (arxiv-2202.02977)**:**

$$\epsilon_{Ref.\,SiPM}(128\text{ nm}) = 14.7^{+1.1}_{-2.4}\ \%$$

- **From Simultation method:**

$$\epsilon_{Ref.\,SiPM}(Sim) = (10.95 \pm 1.50)\ \%$$

Corrections: Purity factor (f_{purity})

The achieved purity changes along the different data taking periods:

FBK+EJ: $f^{jan}_{purity} \equiv \frac{Q_{exp}}{Q_{pure}} = \mathrm{A_{slow}} \cdot \frac{\tau_{exp}}{\tau_{pure}} + A_{fast}$

HPK+EJ/G2P: $f^{feb}_{purity} \equiv f^{jan}_{purity} \cdot \left.\frac{Q_{feb}}{Q_{jan}}\right|_{Ref.SiPM}$

τ_{pure}	$\mathrm{A_{slow}}$	A_{fast}
1.5 μs	0.21 ± 0.01	0.79 ± 0.02

	τ_{exp} (μs)	f_{purity}
FBK+EJ	1.09	**0.94 ± 0.05**
HPK+EJ	0.92	**0.78 ± 0.05**
HPK+G2P	0.99	**0.79 ± 0.05**

Efficiency computation: Baseline method

Baseline method (ϵ_1)

$$\epsilon_1(Arapuca) = \left[\frac{PE_{area}\,(Arapuca)}{PE_{area}(Ref.SiPM)}\right]_{exp} \cdot \left[\frac{f_{X-talk}\,(Arapuca)}{f_{X-talk}\,(Ref.SiPM)}\right] \cdot f_{geom} \cdot f_{int} \cdot \epsilon(Ref.SiPM)$$

X-Arapuca Absolute Efficiency (%)			
PDE	FBK + EJ	HPK + EJ	HPK + G2P
40%	1.70 ± 0.21	1.90 ± 0.18	2.63 ± 0.24
45%	**1.95 ± 0.22**	**2.19 ± 0.20**	**2.96 ± 0.27**
50%	2.29 ± 0.24	2.32 ± 0.21	3.10 ± 0.27