X-ARAPUCA ABSOLUTE PHOTON DETECTION EFFICIENCY (DUNE FD-VD)

SENSE General Meeting
April 1st, 2025

Sergio Manthey Corchado - CIEMAT

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X-ARAPUCA: R&D

- **The X-ARAPUCA** R&D is a collective effort within the DUNE community.
- Many groups contributing internationally to **increase the Photon Collection Efficiency** @sites in CIEMAT (Madrid), CSU (Colorado), IFIC (Valencia), INFN Milano Bicocca, INFN Naples, and more!
- Most important **XA component-manufacturers** (with no particular order):
  - **SiPMs** → FBK (Italia) / Hamamatsu (日本)
  - Dichroic and pTP-coated **Substrates** → OPTO (Brazil) / ZAOT (Italia) / PhotonExport (España)
  - **WLS-bar** → ELJEN (USA) / Glass2Power (Italia)
  - Reflective Foil → VIKUITI 3M (USA)

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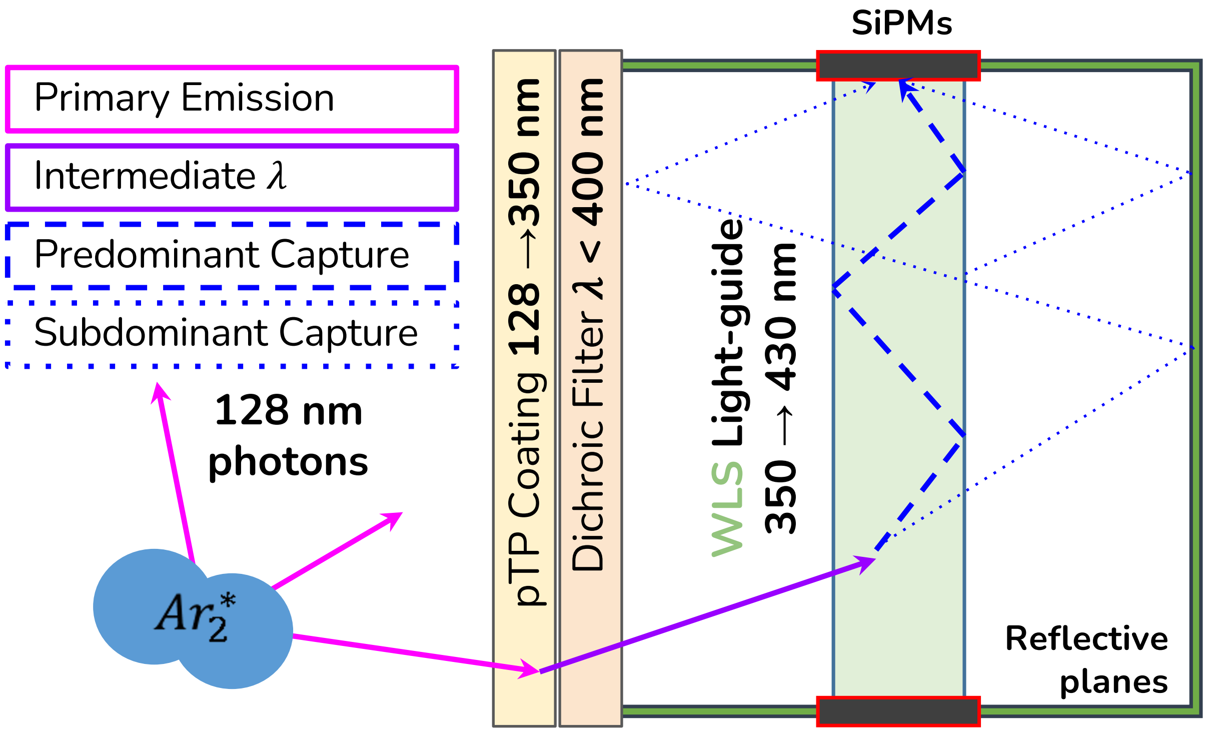
X-ARAPUCA: Concept

- **LAr** emits **scintillation** light in the VUV range **@128 nm**.
- VUV Photons are **shifted** to higher wavelengths with pTP & **trapped** by **dichroic filter** (400 nm cut-off) and **surface-reflection**.
- **WLS-bar further shifts & guides** light by internal reflection to surrounding **SiPMs** for **read-out**.
- **Large surface coverage** is achieved in a **cost-effective** manner.



[A.A. Machado et al 2018 JINST 13 C04026]

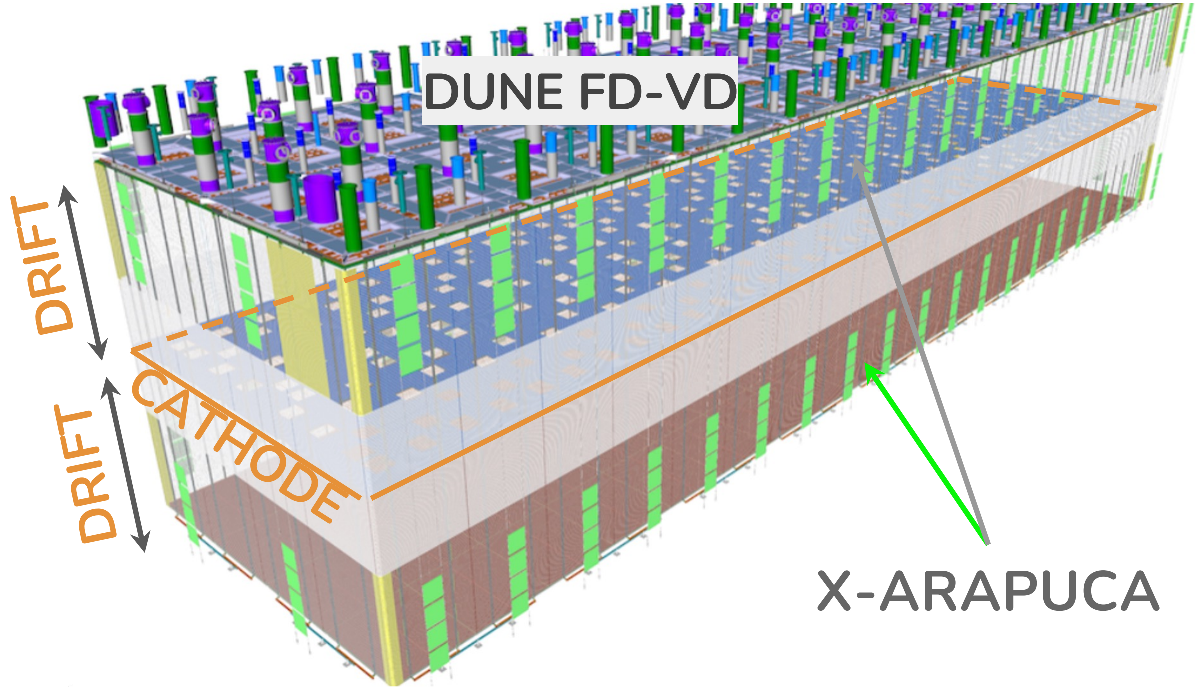
DUNE VD: Introduction

- DUNE: Long-baseline (**1300 km**) neutrino oscillation experiment.
- **Neutrino ν_μ 1.2 MW** beam power → upgradeable to > 2 MW.
- Far Detectors: **4 LAr-TPC** (~ 70 kT).

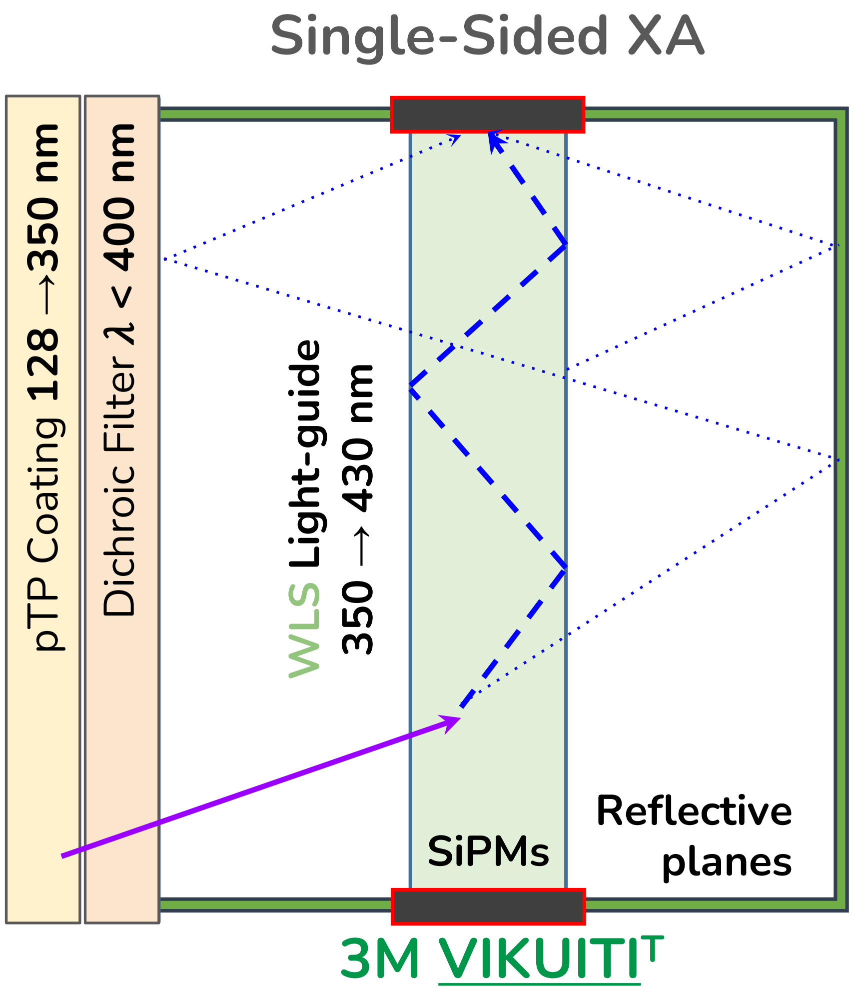
- Measurement of ν_μ/ν_e dis-/appearance:
  - Neutrino **mass ordering**.
  - **CP violation**.
  - Precision on **mixing parameters**.
  - BSM searches.

- Neutrinos from supernova bursts, sun and other low energy sources.

- **Photon Detection System (PDS)** measures LAr scintillation light.
- Composed of **672 X-ARAPUCA** tiles:
  - 320 **Cathode** mounted **double-sided.**
  - 352 **Membrane** mounted **single-sided.**



X-ARAPUCA: Single vs. Double-Sided



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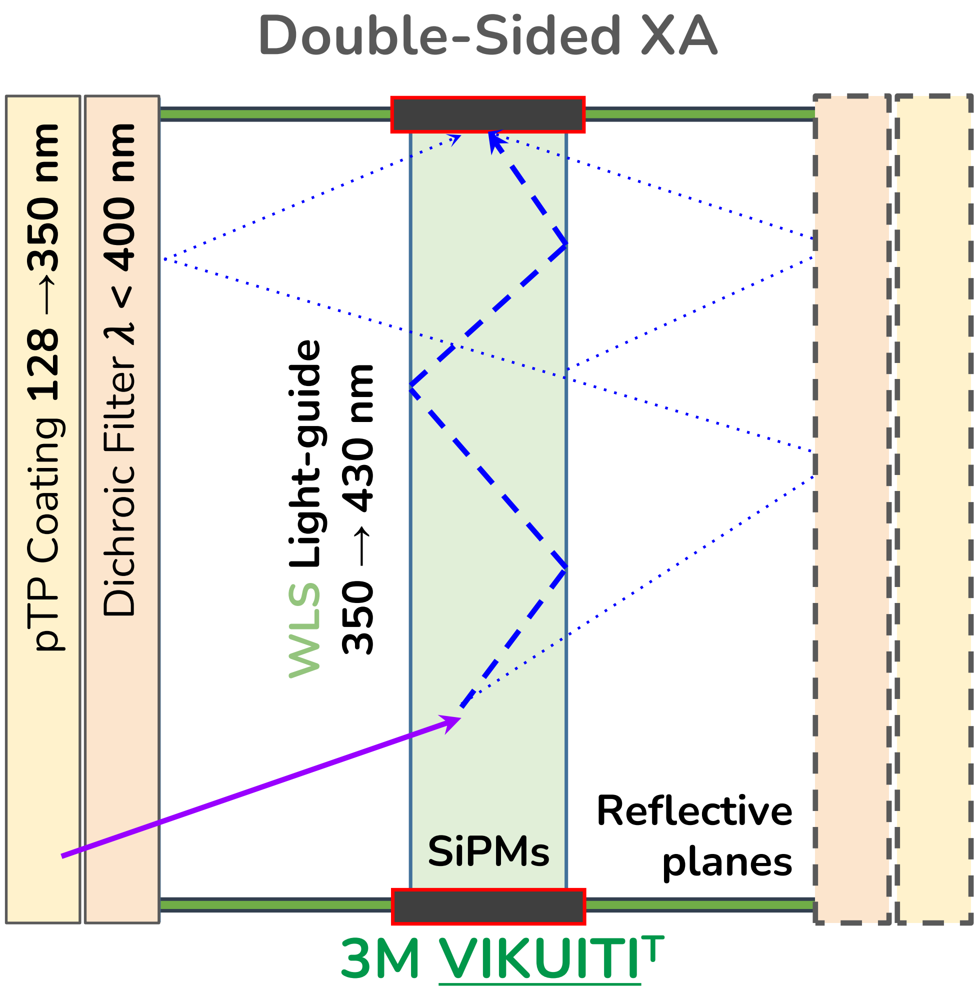
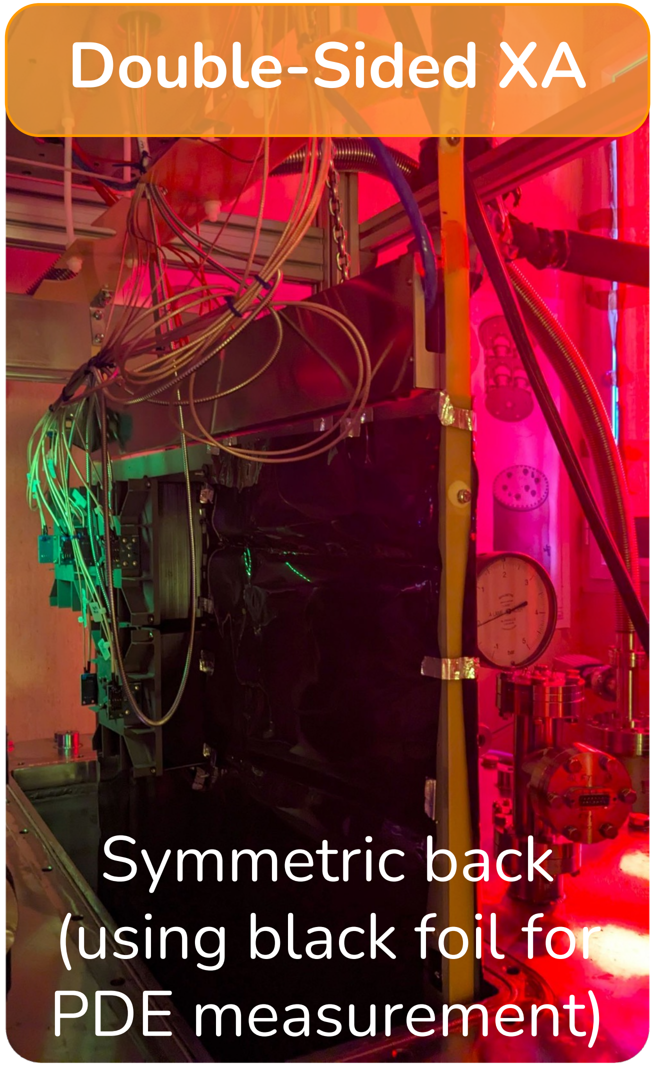
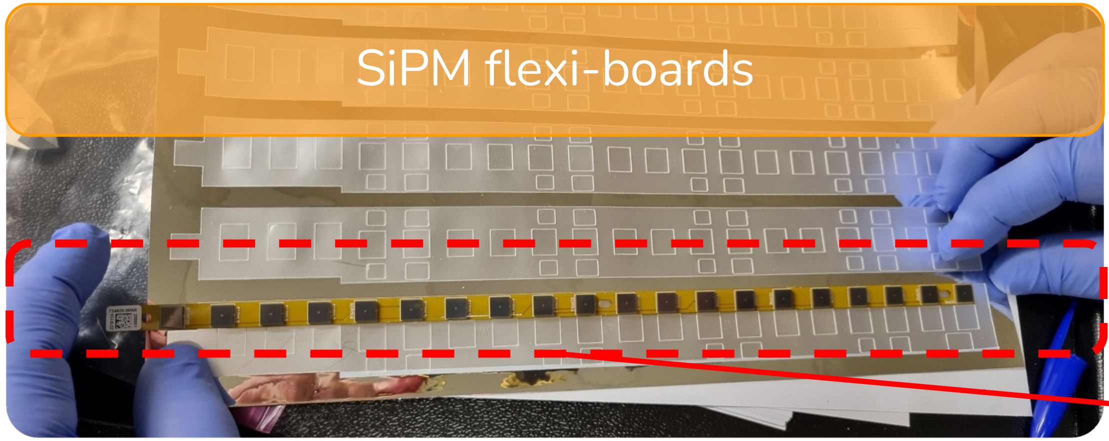


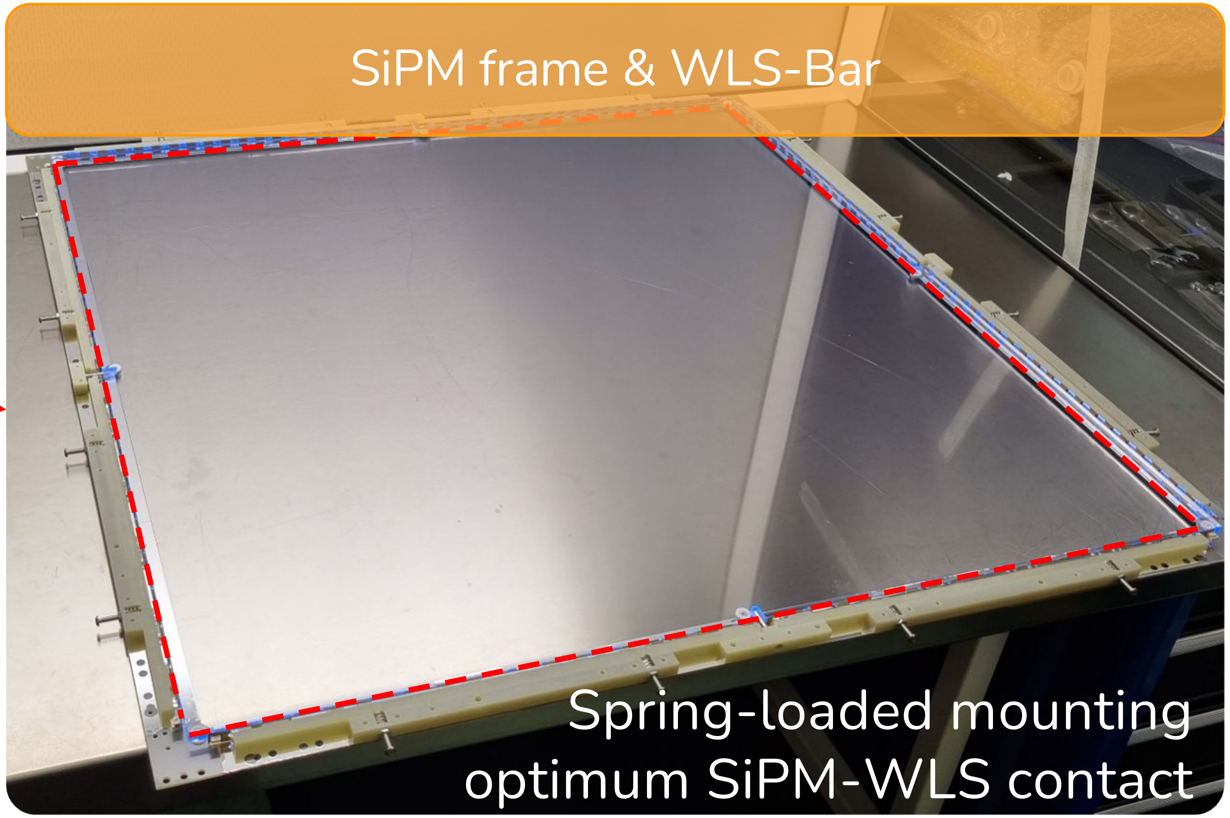


Gobierno de España – Ministerio de Ciencia e Innovación; Ciemat – Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas; cfp CIEMAT física de partículas

X-ARAPUCA: Vertical Drift Components

- **Design for VD**: XA tiles (~ 60 x 60 cm²) double-/single-sided for cathode/membrane.
- Mounted **160** sensors (flex circuits with 20 SiPMs passively ganged in groups of 5).





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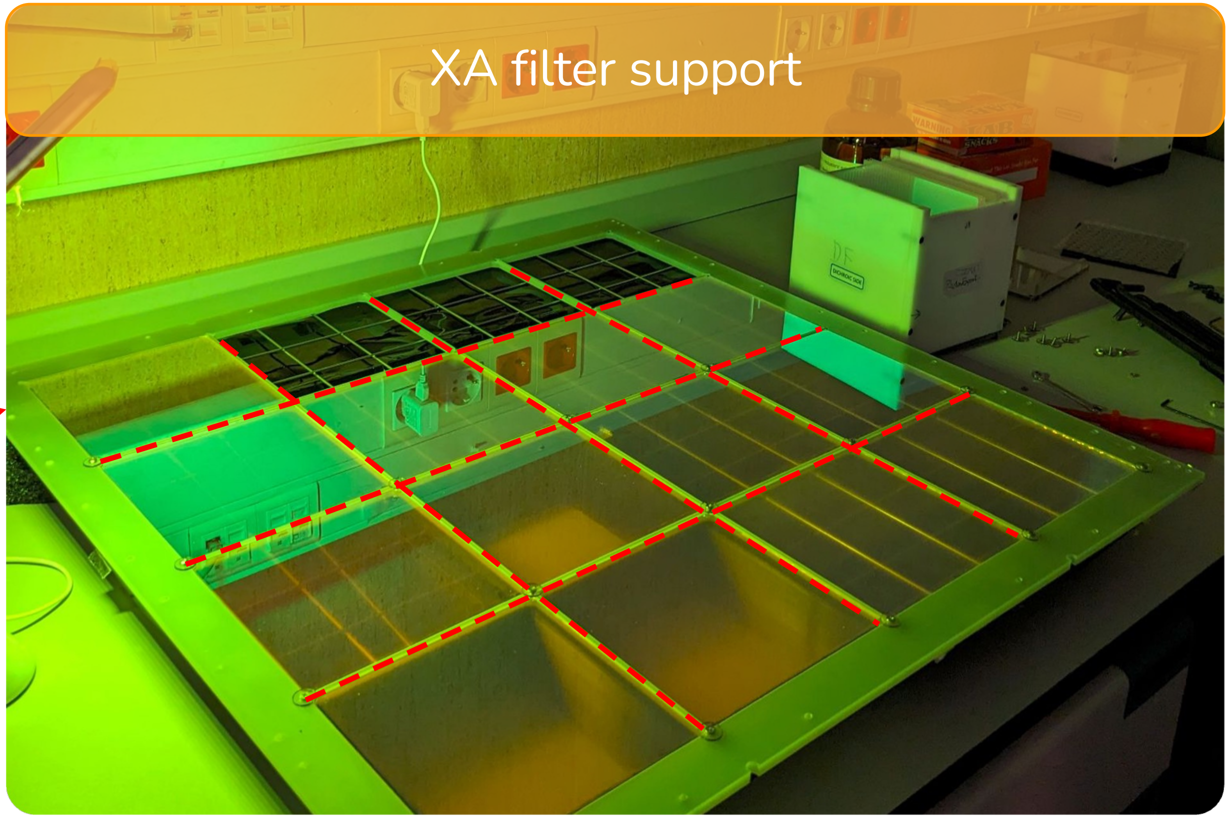

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X-ARAPUCA: Vertical Drift Tested Configurations

All tested XAs mount **FBK-TT SiPM**.

With and without dichroic filter:

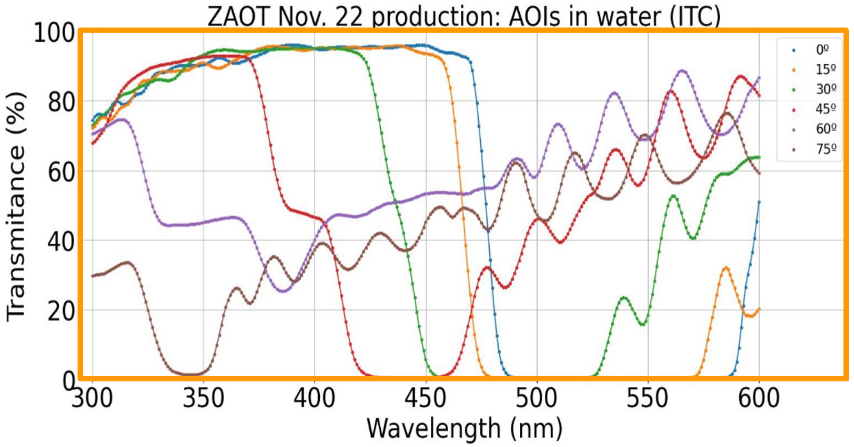
→ Test **non-ideal DF transmittance worsening PDE for VD-XA**.

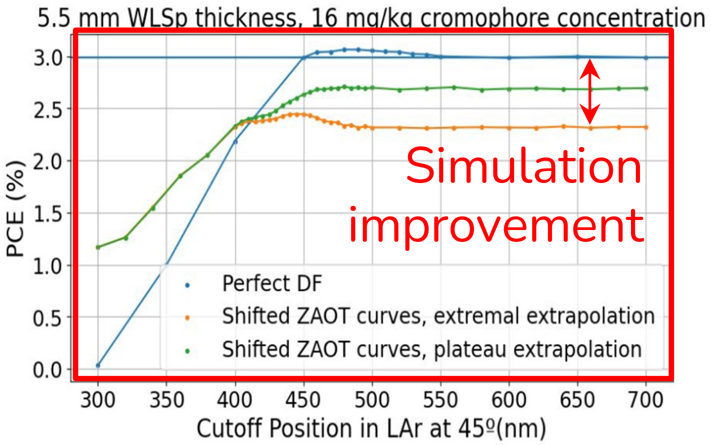
Optimize WLS-Bar **width** and **chromophore concentration** to reduce absorption.

→ Tested bars:

a. **3.8 mm & 80 mg/kg**
b. **5.5 mm & 24 mg/kg**

XA	WLS	Dichroic	pTP	Sided
1. Dichroic Single-Sided	a	Yes	ZAOT	Single
2. Dichroic Double-Sided	a	Yes	ZAOT	Double
3. Non-Dichroic Single-Sided	a	No	P.E.	Single
4. Non-Dichroic Double-Sided	a	No	ZAOT	Double
5. Non-Dichroic Single-Sided	b	No	P.E.	Single





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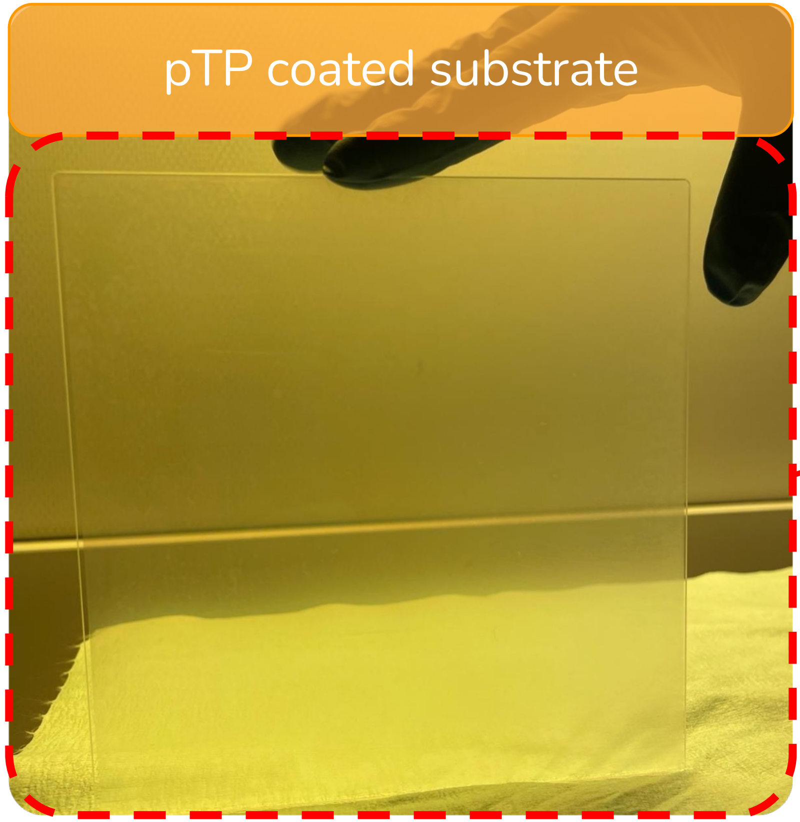

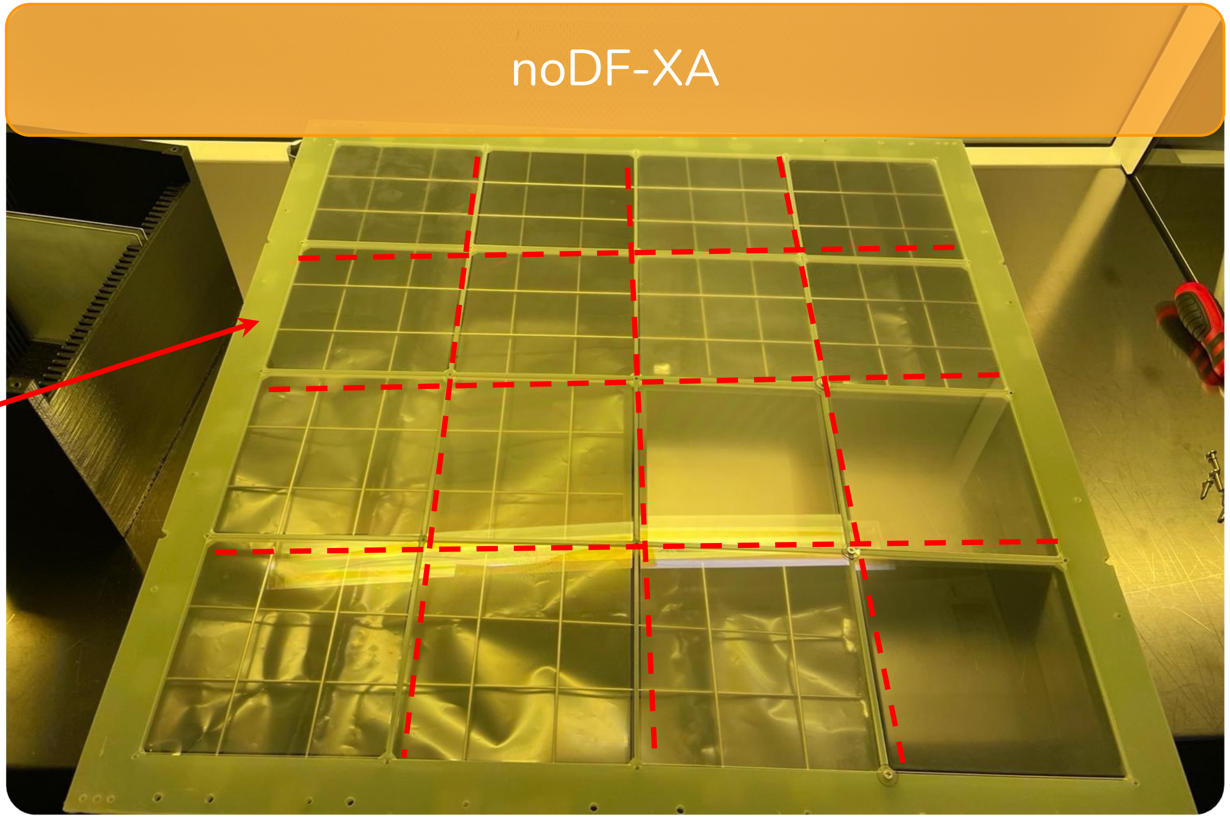

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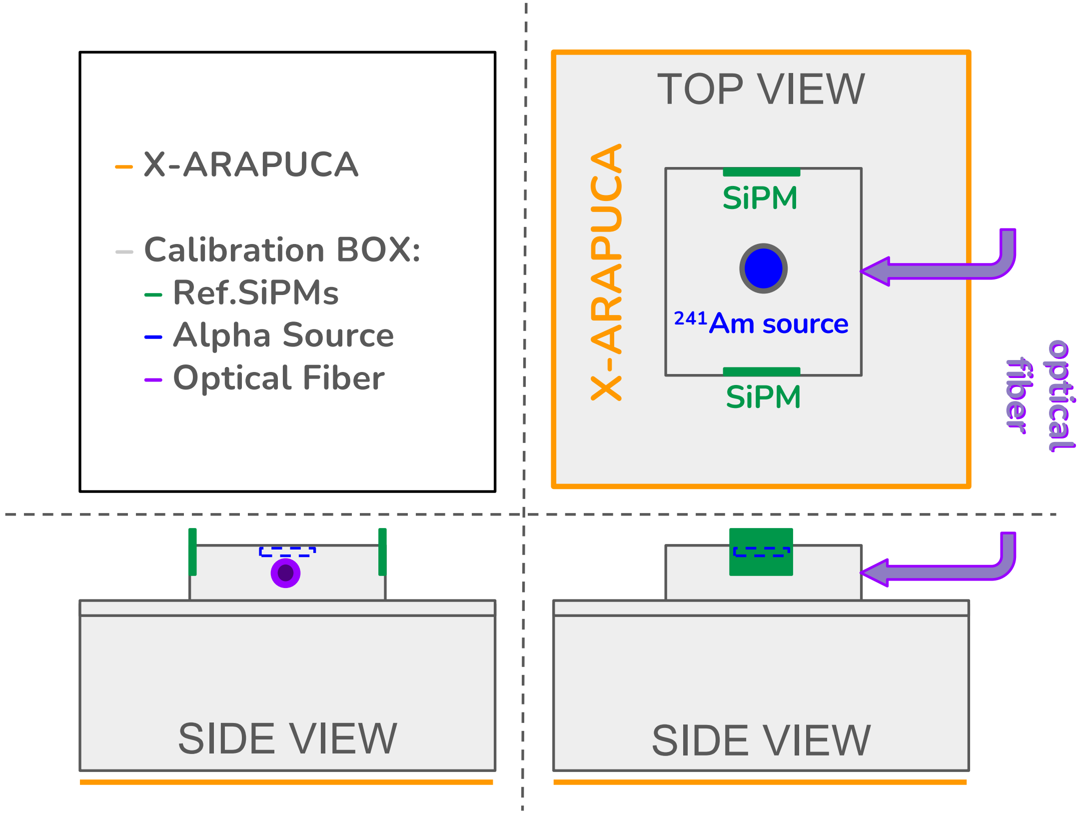
Photon Detection Efficiency Measurement

Direct PDE computation method.

$$\epsilon(XA) = \frac{\#PE_{XA}}{\#PE_{Ref.SiPM}} \cdot \epsilon(\text{Ref.SiPM}) \cdot f_{corr}$$

- $\#PE_{XA}$: PEs detected by the XA.
- $\#PE_{refSiPM}$: PEs detected by the reference SiPMs.
- **ε(ref SiPM)**: PDE for ref. SiPMs (from ref. [NIMA.2024.169347]).
- **Correction** factors ($f_{corr} = f_{geo} * f^{XA}_{XT} / f^{SiPM}_{XT}$):
  - f_{geo}: **Geometrical** → solid angle correction wrt. α source.
  - f_{XT}: **Cross-talk** → measurements on FBK/HPK SiPMs.



- **Mounted SiPMs: FBK-TT.**
- Characterised by **PDS Consortium.** [arXiv.2405.12014].
  - Cross-talk: (**16.1 ± 0.3**)%

- **Ref. SiPMs: HPK VUV4** S13370 – 6075CN.
- Characterised **@CIEMAT** for CT [NIMA.2024.169347].
  - Cross-talk: (**19.7 ± 0.3**)%
  - SiPM PDE @ VUV 128 nm: (**12.7 ± 1.1**)%

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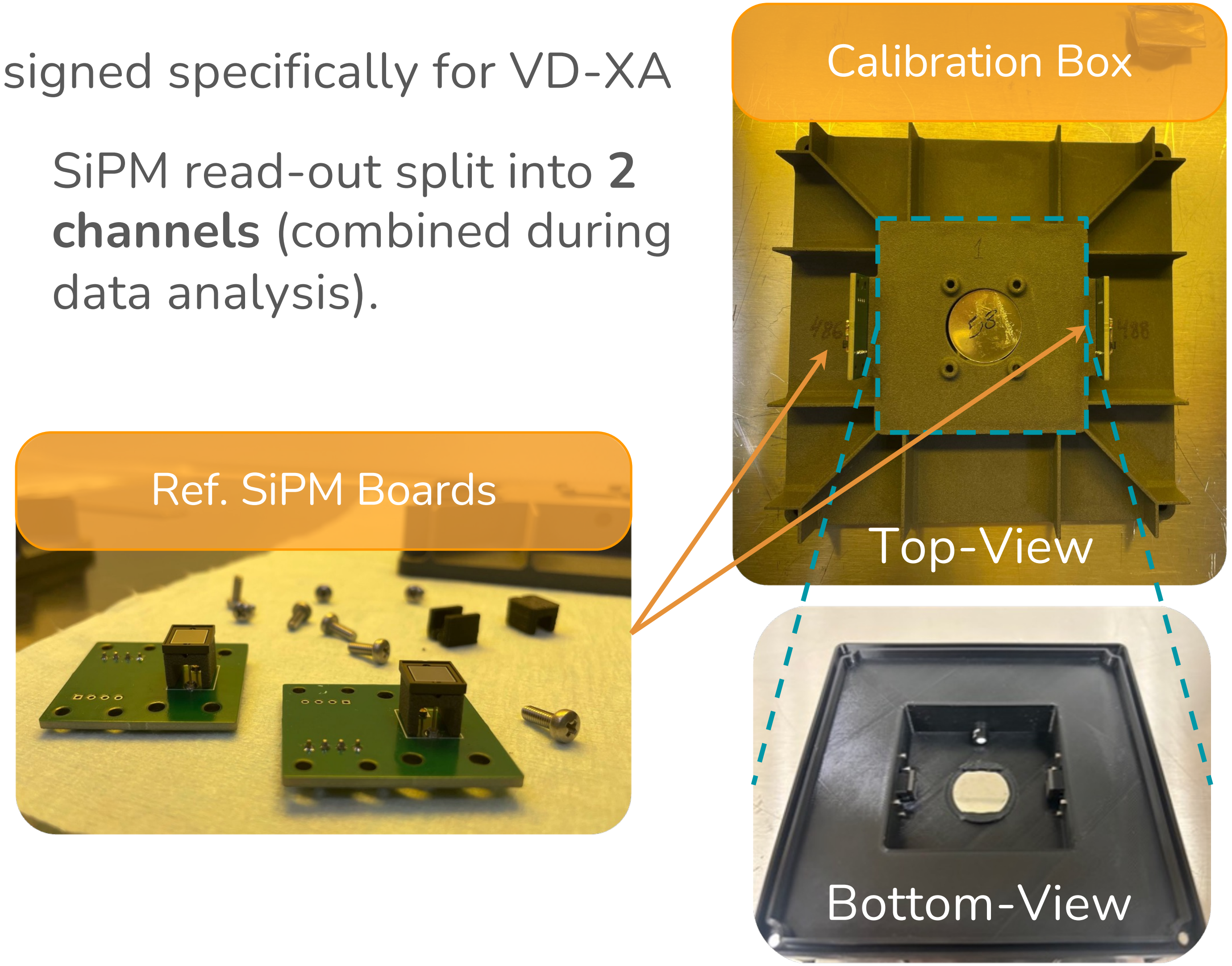
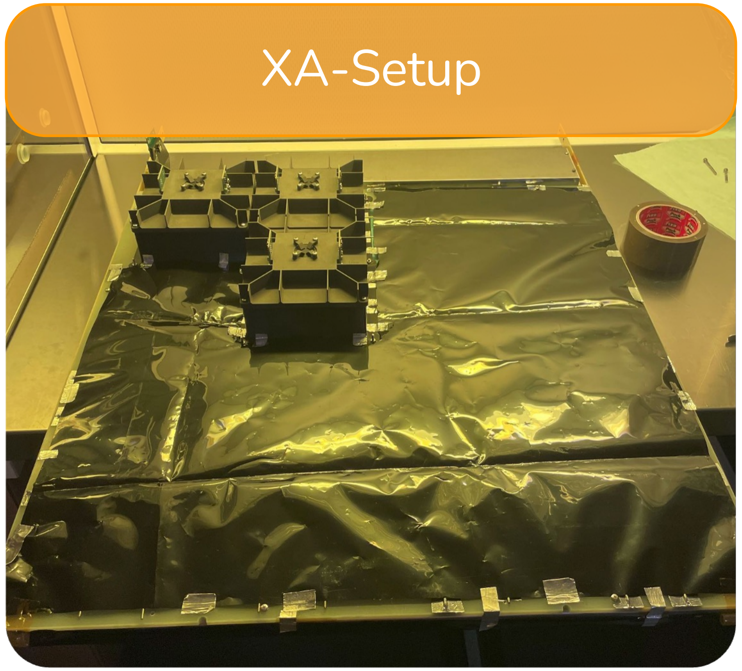
Calibration Box

Designed specifically for VD-XA

- SiPM read-out split into **2 channels** (combined during data analysis).



Once mounted on the XA the **surface is covered** if isolate from external sources and reflexions.



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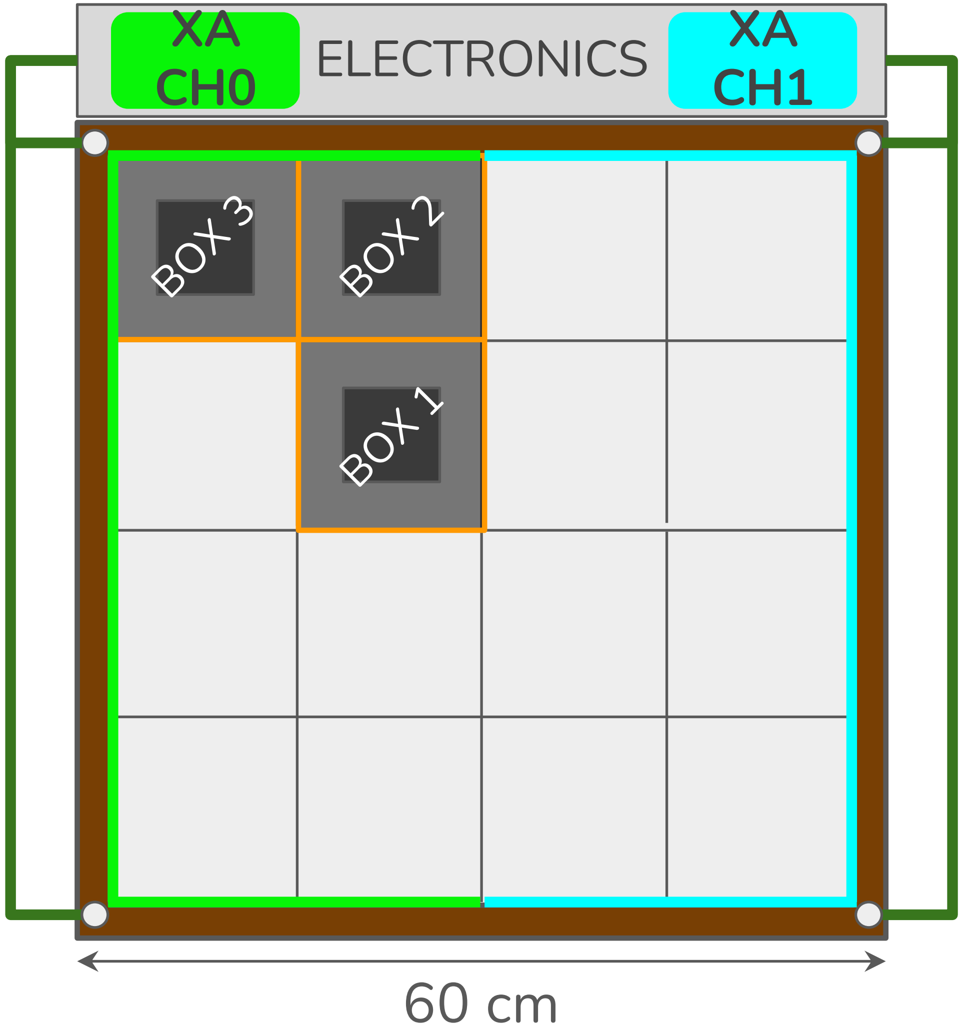
Calibration Layout

Absolute **PDE measurement**:

- XA read-out split into **2 channels** (combined during data analysis).
- **Calibration boxes** positioned in the **3 uniquely distinct** XA positions.
- Each box mounts **1 alpha source** & **2 ref. SiPM** with known PDE.
- **Average XA PDE** computed from weighted average of 3 calib. boxes.



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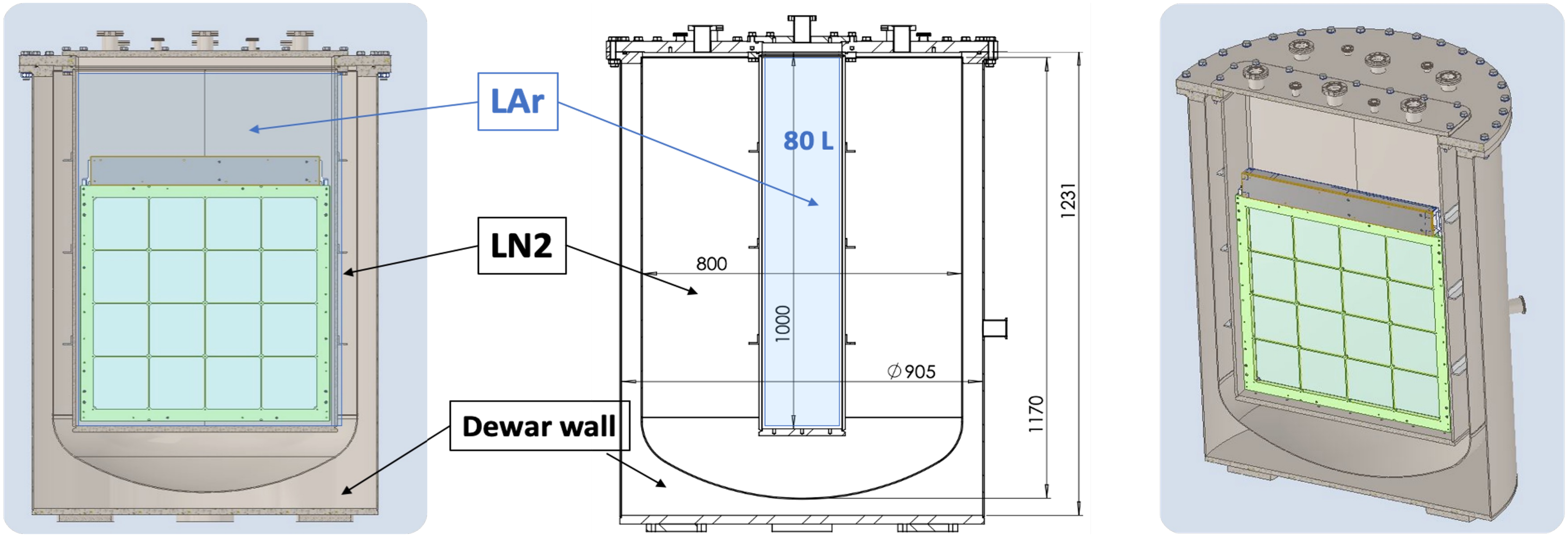
Cryogenic Setup @CIEMAT

- Cryogenic vessel allows to liquify GAr and to **detect scintillation light** with the XA in the same conditions as in the DUNE FDs.



*GAr (99.9999% purity) is liquified with LN_2 at 2.7 bar

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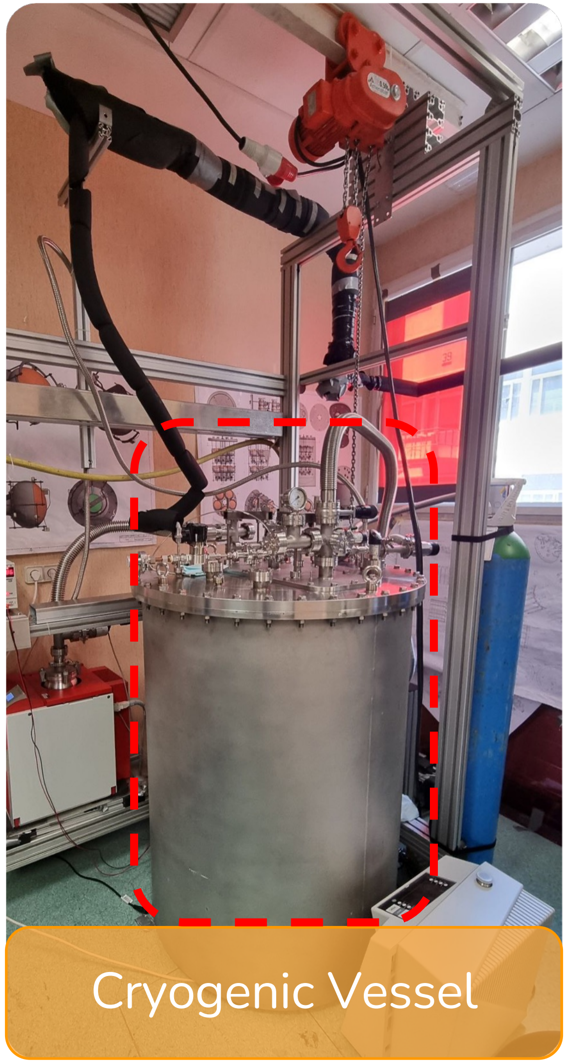
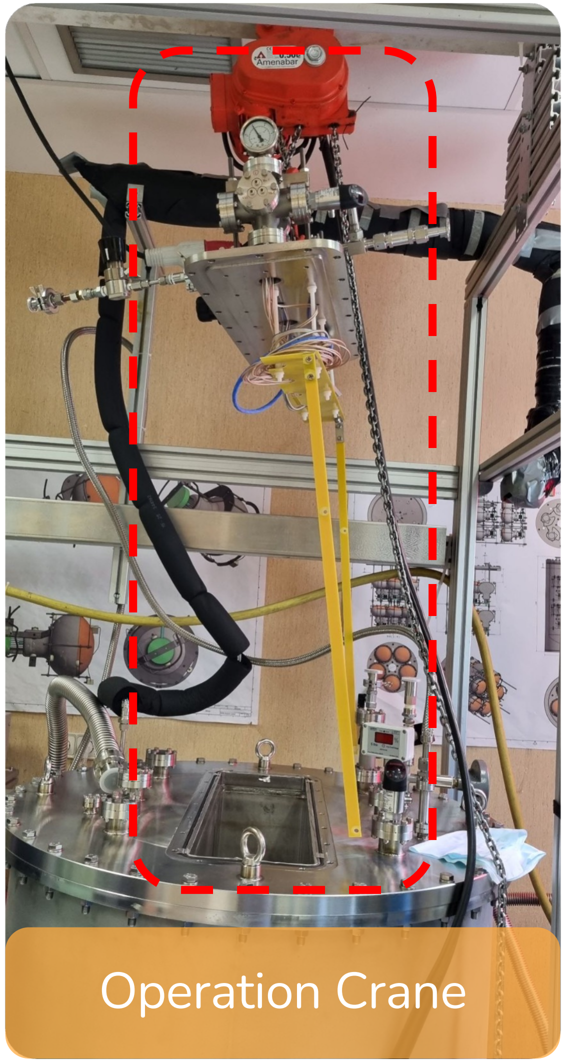
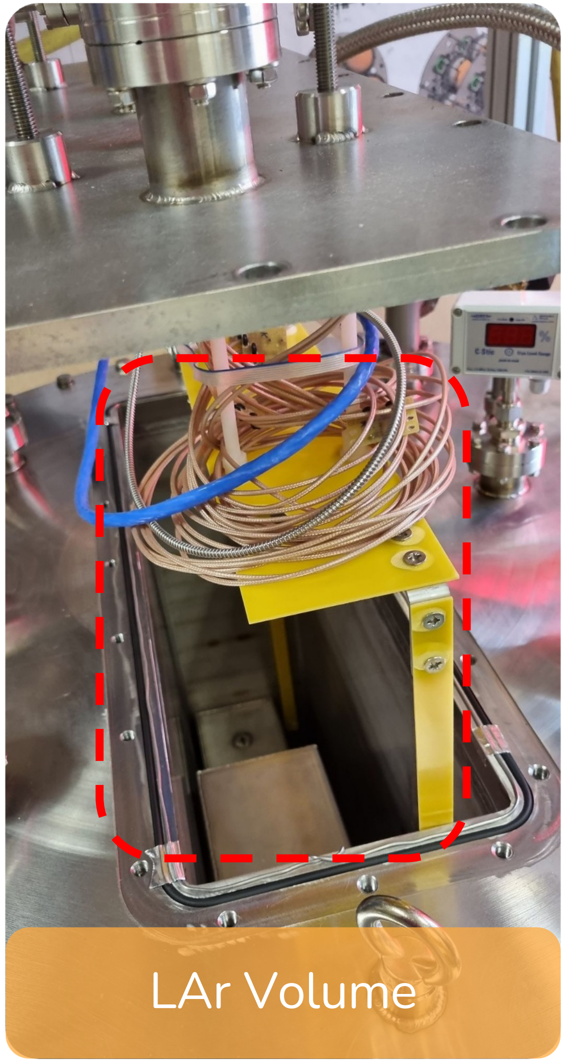


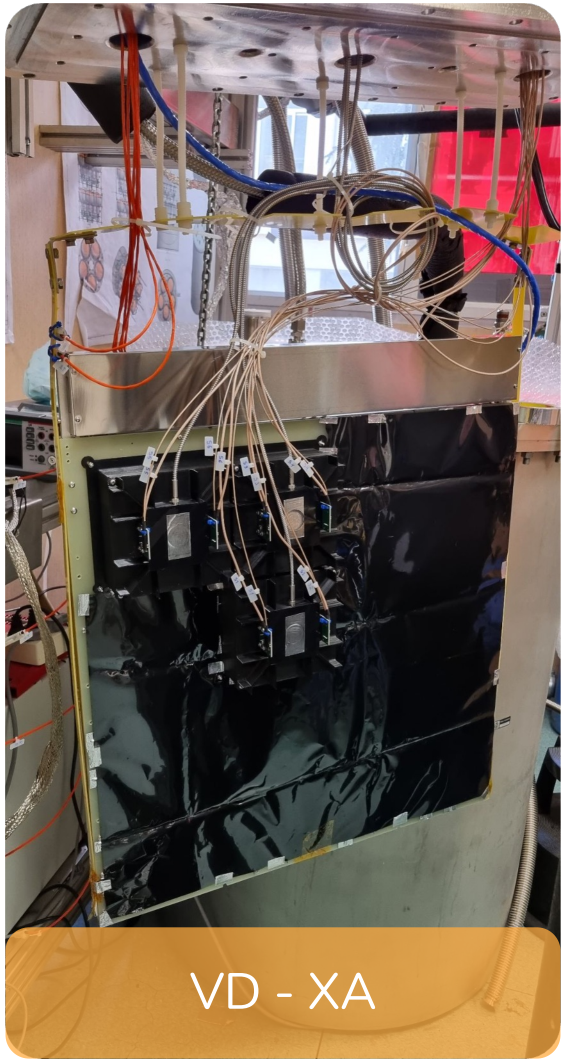
Cryogenic Vessel



Operation Crane



LAr Volume



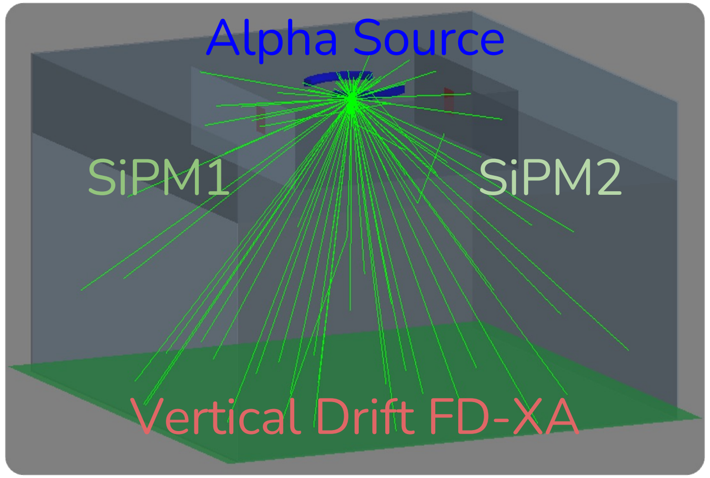
VD - XA

Calibration System Simulation

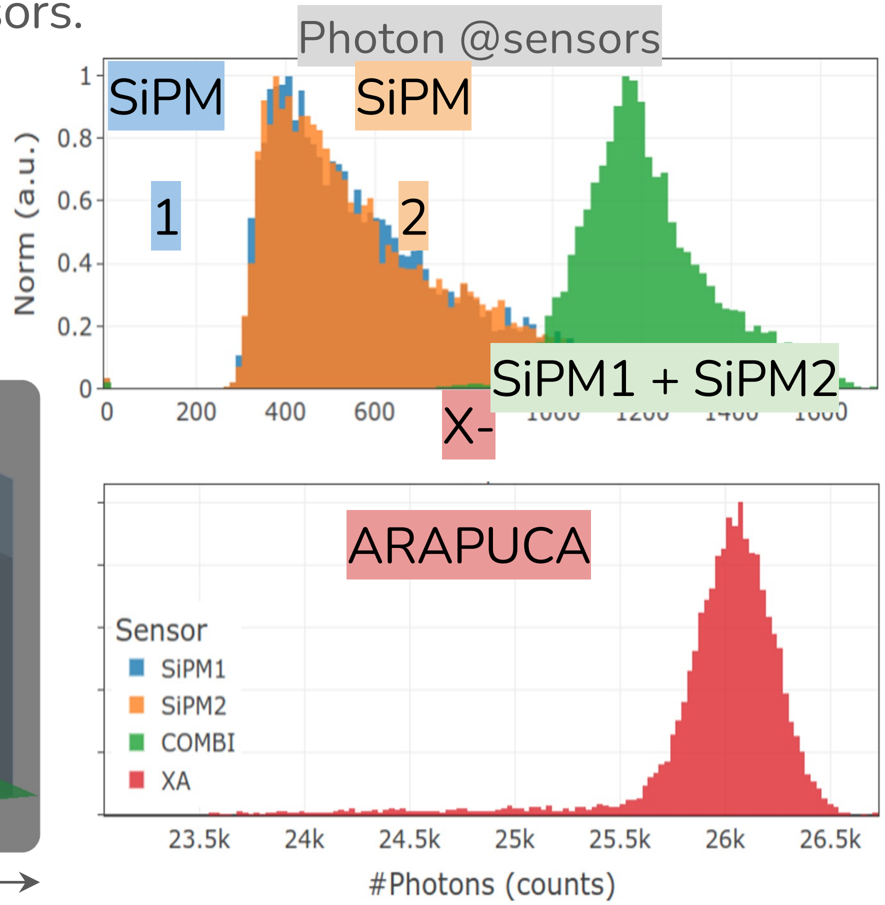
- Relative solid angle by **standalone GEANT4 simulation.**
- Accounts for the **differences in sizes/positioning** of ref. sensors.

$$f_{\text{geom}} = \frac{\Omega(\text{Ref.})}{\Omega(\text{XA})} = 0.047 \pm 0.001$$

Sensor	MEAN Ph.
XA-VD (21170 mm²)	25920
SiPM (12 mm²)	1206



14.55 x 14.55 cm²



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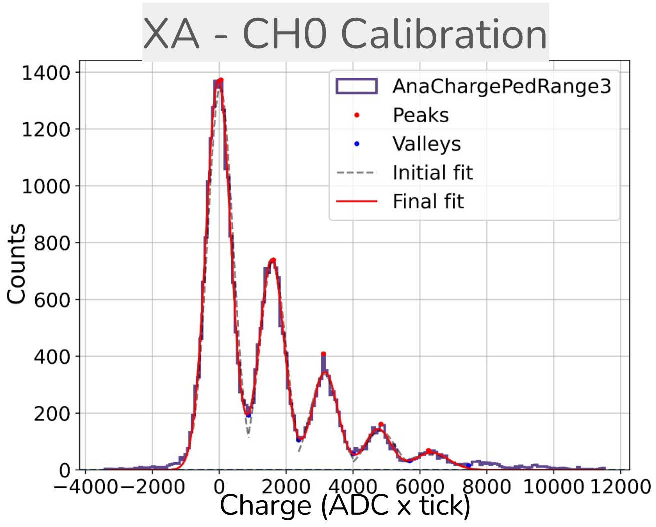
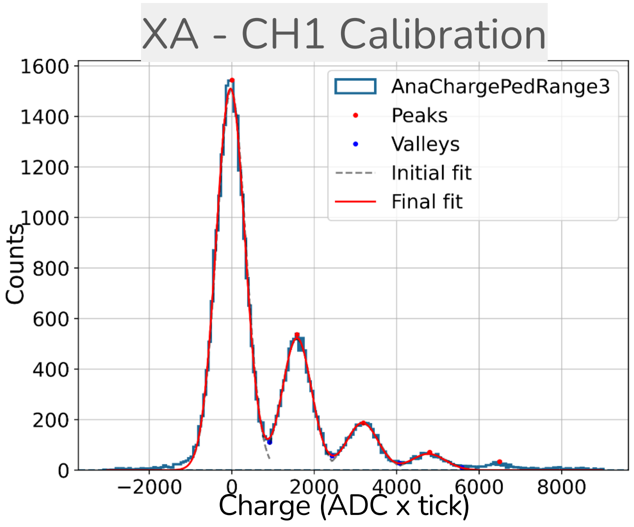
Data Taking: XA Characterization

- For each XA configuration & data-taking campaign.
- Calibration follows standard procedure: **compute baseline** from pretrigger, **subtract** to waveform, **integrate** pulse.

$$f(x) = \sum_{i=0}^{n} A_i \, e^{\frac{1}{2}\left(\frac{x-\mu_i}{\sigma}\right)^2}$$





$$S/N = \frac{\mu_1 - \mu_0}{\sigma}$$

	XA - CH0		XA - CH1	
OV	Gain (e^-)	S/N	Gain (e^-)	S/N
4.5	**(4.51 ± 0.02) · 10^5**	**4.3 ± 0.1**	**(4.54 ± 0.03) · 10^5**	**4.6 ± 0.2**
5.5	(5.45 ± 0.02) · 10^5	5.21 ± 0.09	(5.50 ± 0.02) · 10^5	5.5 ± 0.2
7.0	(6.88 ± 0.05) · 10^5	6.5 ± 0.3	(6.93 ± 0.02) · 10^5	6.8 ± 0.7

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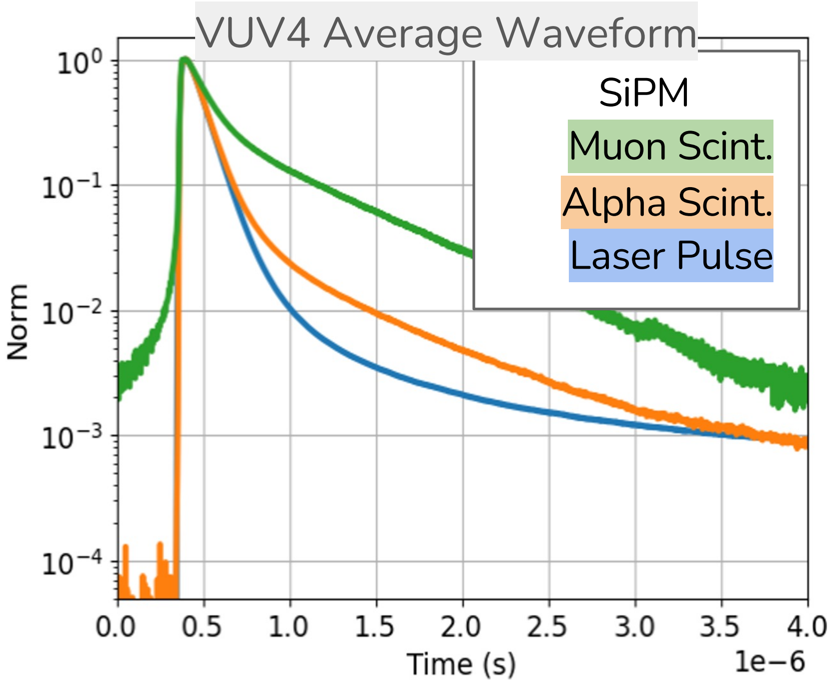
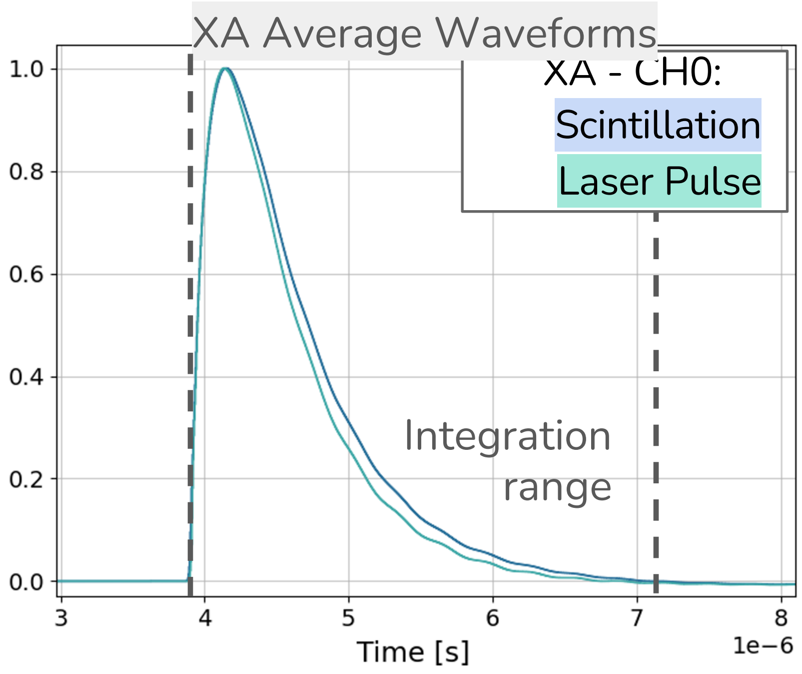
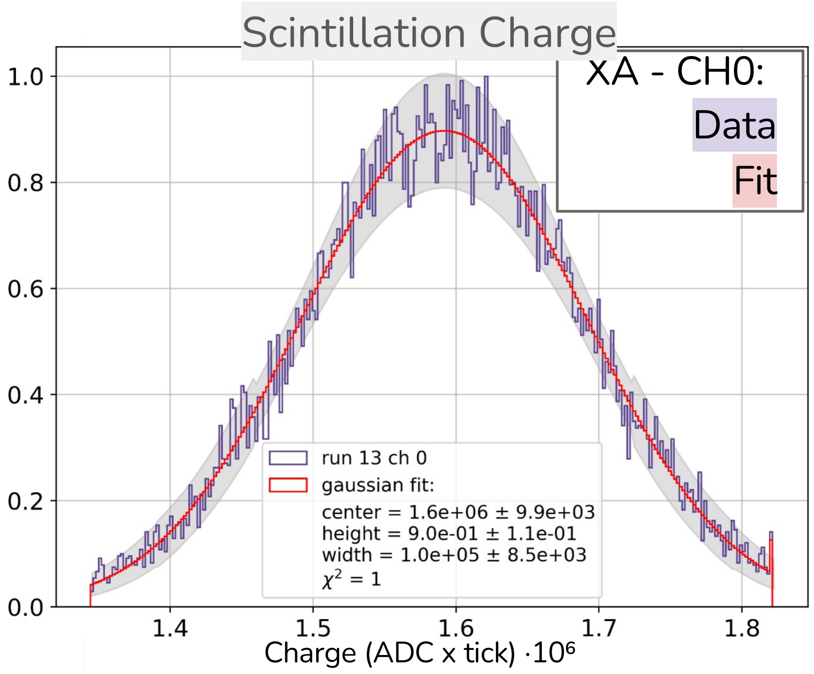
Data Taking: Scintillation

- Scintillation signals are **triggered** using **coincidence** in both **SiPM** channels..
- Comparing wrt. laser pulse average waveform, scintillation clearly observed.
- Fitted distribution provides PE values (for ref. SiPM **fitted in addition).**







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PDE Uncertainty

Error computation takes into account **uncertainties** associated to the following variables. Additional systematic uncertainties are being investigated.

- **Dominant**
  - **SiPM PDE (8.7%)**: From ref. constrained @CIEMAT [arXiv.2405.12014].
- Subdominant
  - XA #PE (~1%): From repeated gain measurement + gaussian fit of collected charge.
  - SiPM #PE (~2%): Gain + Gaussian fit of combined #PE collected per SiPM pair.
  - Geometric Factor (1.43%): From sim. + sensor deviation measurement.
  - XA XTALK (< 1%): From CIEMAT measurements.
  - SiPM XTALK (< 2%): From CIEMAT measurements.

PDE Results

- **PDE** values are computed from **weighted average** of 3 calibration boxes:
  - OV 4.5 V corresponding to 45 SiPM eff.

	Dichroic Filter	
	Single-Sided	**Double-Sided**
OV	1. DF-XA	2. DF-XA-DS
4.5	**(3.7 ± 0.3) %**	**(4.0 ± 0.4) %**

- Conclusions:
  - **Compatible performance** of **single vs. double-sided** **XA** configs.

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PDE Results

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	Dichroic Filter		Non-Dichroic Filter	
	Single-Sided	Double-Sided	Single-Sided	Double-Sided
OV	1. DF-XA	2. DF-XA-DS	3. noDF-XA	4. noDF-XA-DS
4.5	**(3.7 ± 0.3) %**	**(4.0 ± 0.4) %**	**(4.5 ± 0.4) %**	**(4.5 ± 0.4) %**

- Conclusions:
  - **Compatible performance** of **single vs. double-sided XA** configs.
  - **Improvement 18% (single-sided)** & **11% (double-sided)** when **removing dichroic filters** due to non-ideal entrance transmittance and shifting cut-off for different angles.

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	Dichroic Filter		Non-Dichroic Filter		
	Single-Sided	**Double-Sided**	**Single-Sided**	**Double-Sided**	**Single-Sided**
OV	1. DF-XA	2. DF-XA-DS	3. noDF-XA	4. noDF-XA-DS	5. noDF-XA_24mg
4.5	**(3.7 ± 0.3) %**	**(4.0 ± 0.4) %**	**(4.5 ± 0.4) %**	**(4.5 ± 0.4) %**	**(4.3 ± 0.4) %**

- Conclusions:
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  - **Improvement 18% (single-sided)** & **11% (double-sided)** when **removing dichroic filters** due to non-ideal entrance transmittance and shifting cut-off for different angles.
  - Compatible performance of both tested **WLS-bar** configurations.

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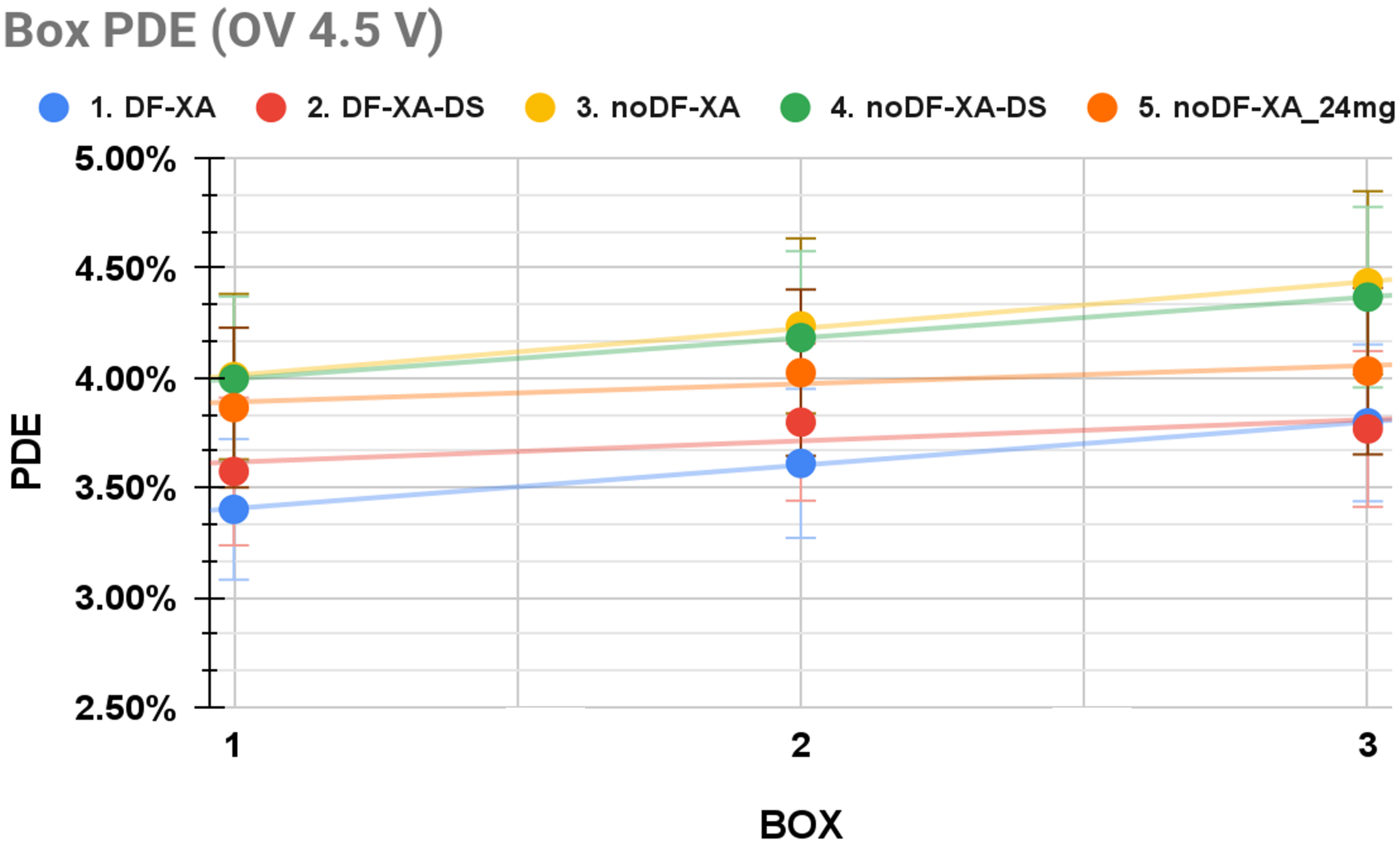
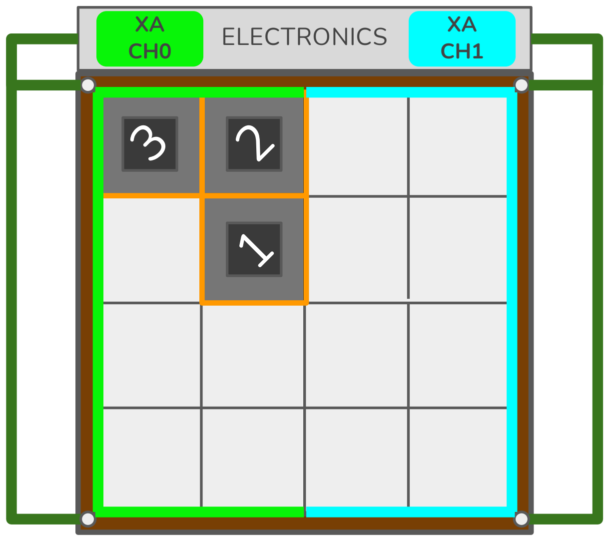
PDE Results

- PDE **homogeneity** across different positions always **within ~3%**. The **flattest distribution** corresponds to **XA 5.** mounting WLS-bar **model b** (chrom. 24 mg / kg & width 5 mm).



Calibration Box Arrangement



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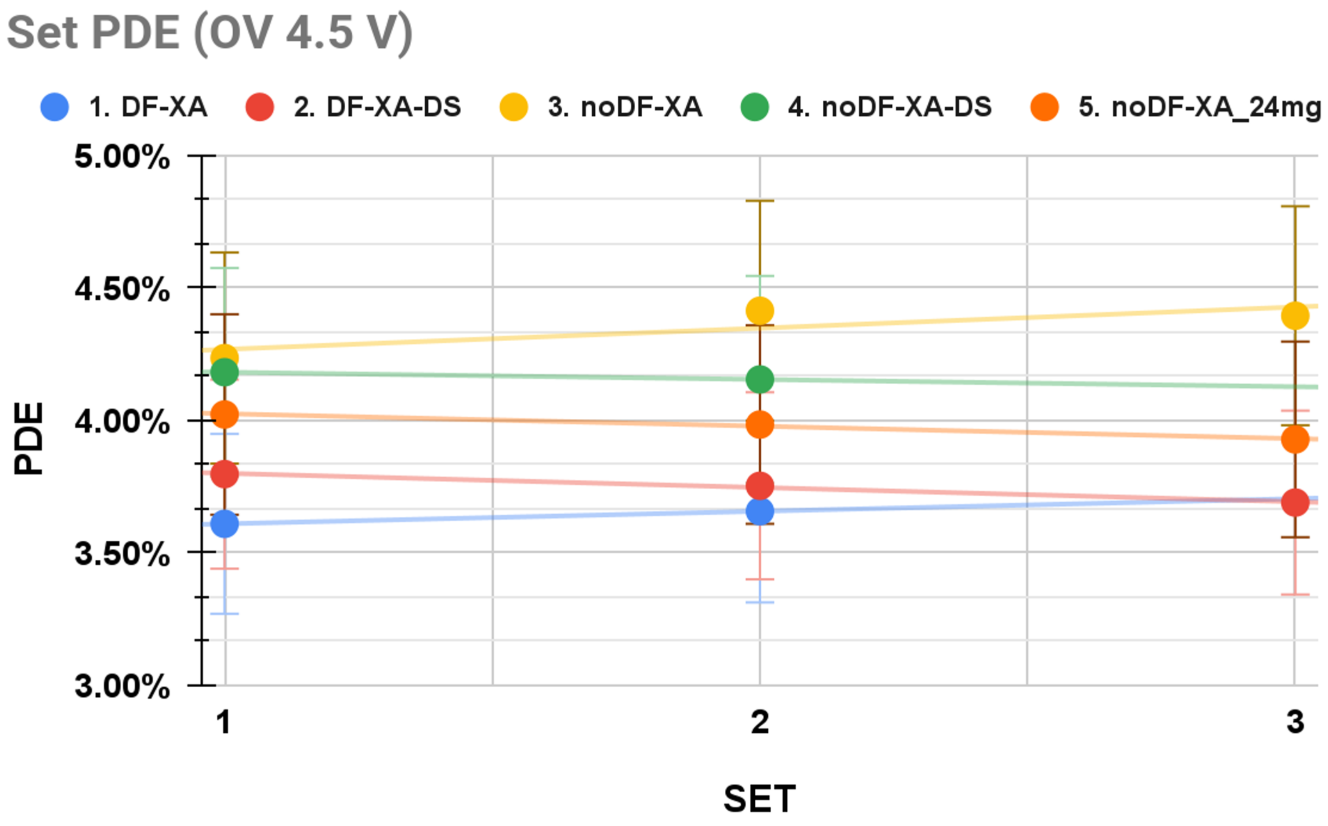
PDE Stability

- **PDE** measurement is **independent of the setup's LAr purity** (affects equally ref. SiPM and XA).
- To test this, taken up to **3 repeated sets** of data with **> 6 h spread** & up to **0.3 μs decrease in τ_{slow}** (as a measure of purity). **Standard deviation** across all measured values **2.23%**.



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Conclusions

- Ongoing international effort to **increase the Photon Detection Efficiency** of the X-ARAPUCA.
- **CIEMAT's cryogenic setup** is able to liquify Ar to measure the absolute PDE of big-size photon-detectors with VUV and visible light.
- For DUNE Far Detector (Vertical Drift):
    - Measured absolute **VD-XA PDE 4.5 ± 0.4 % @OV 4.5 V**. With compatible results between single- and double-sided measurements.
    - Confirmed **improvement in PDE (18 % & 11 %) without dichroic filters** for tested samples and configurations.
    - Further measurements needed to understand the PDE's dependency to WLS-bar **width & chromophore** concentration.

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