# Photon Detection System

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*UNICAMP (Brazil)*

*Final Design Review PDS-FD2*

*CERN – April 18th 2023*

Conselho Nacional de Desenvolvimento Científico e Tecnológico

SÃO PAULO RESEARCH FOUNDATION

UNICAMP

# Charge

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

## DUNE Final Design Review Charge

### FD2 Photon Detection System

**18-19 April 2023**

The committee is requested to review the final design of the DUNE FD2 Photon Detection System (PDS). The review scope includes all mechanical and electrical aspects of the PDS design, including the membrane and cathode systems. A summary of the documents released for this review can be found in edms-2824342. For reference, the final committee report from the PDS Preliminary Design Review can be accessed at edms-2681915.

The committee should assess whether the design is expected to meet the technical specifications, and whether the design maturity and documentation, including production planning, are appropriately advanced for this stage of the project (90% complete). For reference, the LBNF/DUNE Review Plan (edms-2173197) and DUNE Far Detector FDR deliverables (edms-2413117) are available in edms.

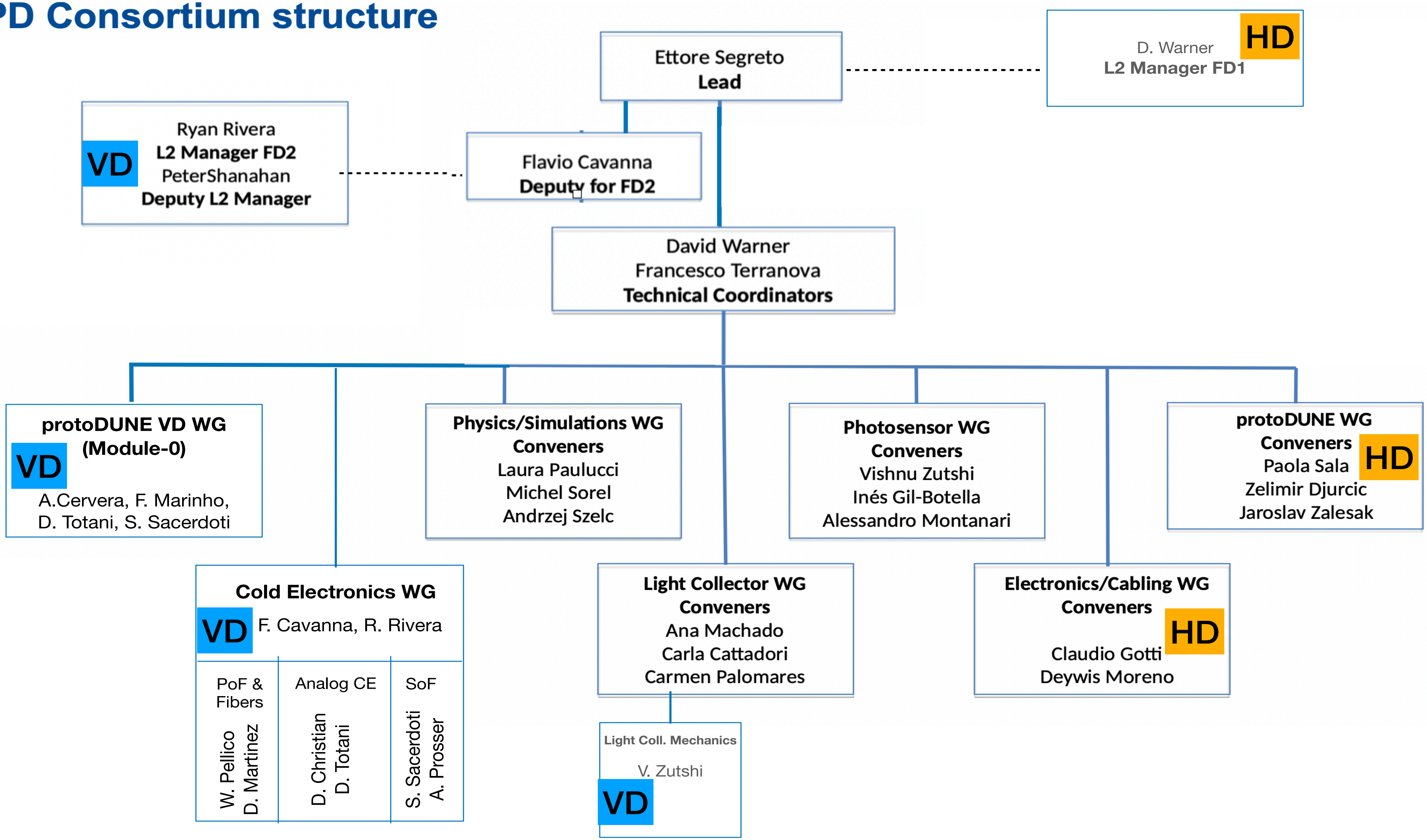
The committee should consider:

1. How design choices satisfy the requirements:
   - Have the chosen design elements been sufficiently well tested including in LAr at cathode HV? Including power over fiber, signal over fiber, DC-DC converters, …
   - Have the components in the cold been sufficiently well validated for 30-year lifetime or if not completely, is there a path to validate?
   - Have the technical risks been identified with appropriate mitigation in place?
2. Whether lessons learned from cold box tests, ProtoDUNE-SP and other prototypes have been appropriately incorporated in the current design and if the design has been validated through the integration, testing, and installation in the cold box and ProtoDUNE-VD.
3. The completeness of the documentation of mechanical specifications, including 3D model and the 2D drawings for standard and custom components as well as the Compliance Office safety evaluation.
4. The completeness of the documentation of electrical specifications, including system schematics, drawings, connections, safety analysis and grounding details.
5. Whether transportation and installation plans are mature enough to provide assurance that the PDS components, as currently designed, can be safely transported and installed within the detector.
6. If draft documentation detailing plans for procurement, manufacturing, quality control and part identifiers exists at a sufficient level of maturity for this stage of the design.
7. If project planning materials including interface documents, risk assessment and schedules exist at a sufficient level of development for this stage of the design.
8. Whether recommendations from previous reviews have been appropriately addressed.
9. Is the present level of effort appropriate for reaching the PRR and are plans in place to fully staff for production? Based on the MoU Annex and Interface Documents, is the scope of the subsystem complete and the contribution from each funding agency sufficiently well defined?

**Review Findings:**

The committee should present its findings, comments and recommendations in a preliminary report April 19, 2023 and a final report by April 28, 2023.

# PD Consortium structure



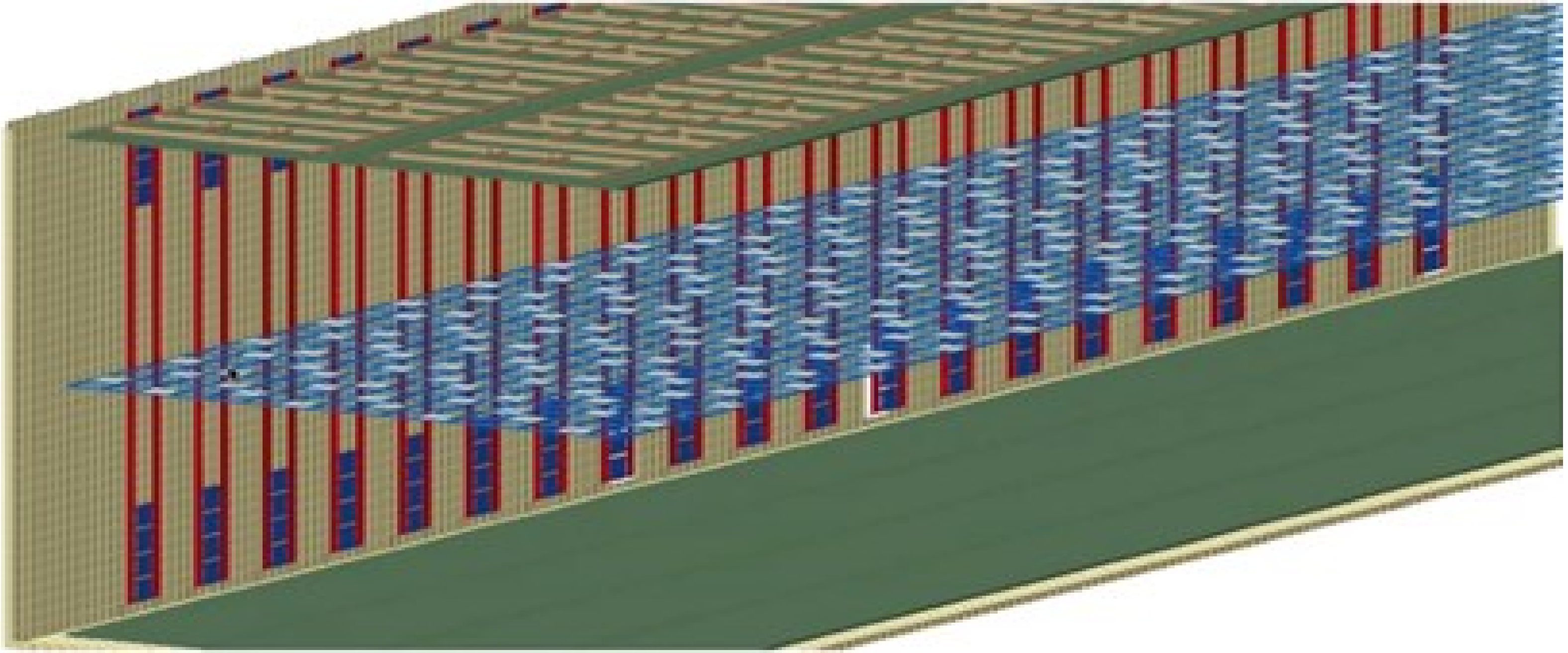
# PDS-FD2-Contributing Institutions

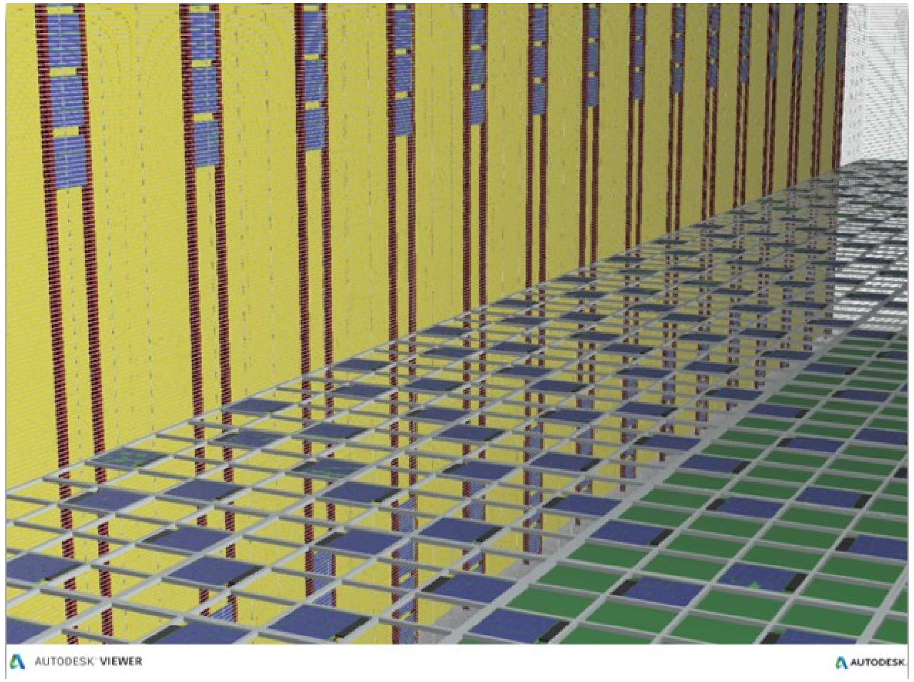
| Institution | Country |
|---|---|
| FNAL | *USA* |
| BNL | *USA* |
| ANL | *USA* |
| CSU | *USA* |
| UCSB | *USA* |
| NIU | *USA* |
| U. Iowa | *USA* |
| SDMST | *USA* |
| U. Illinois UC | *USA* |
| Stony Brook | *USA* |
| U. Michigan | *USA* |
| Indiana U. | *USA* |
| Unicamp | *Brazil* |
| UFABC | *Brazil* |

| Institution | Country |
|---|---|
| ITA | *Brazil* |
| APC-Paris | *France* |
| INFN-MiB | *Italy* |
| INFN-Mi | *Italy* |
| INFN-Bo | *Italy* |
| INFN-Fe | *Italy* |
| INFN-Na | *Italy* |
| INFN-Pv | *Italy* |
| CIEMAT | *Spain* |
| IFIC | *Spain* |
| U. Granada | Spain |
| CAU | *Korea* |
| U. Antioquia | *Colombia* |
| U. EIA | *Colombia* |

| Institution | Country |
|---|---|
| U. Atlantico | *Colombia* |
| U. A. Nariño | *Colombia* |
| CONIDA | *Perú* |
| UNI | *Perú* |
| UNA | *Paraguay* |
| FZU-Prague | *Czech Rep.* |

# FD2 – PDS Baseline design






- 320 cathode mounted double sided X-ARAPUCAs (detect light from both sides)
- 320 + 32 membrane mounted single sided X-ARAPUCAs (detect light just from one side)
- 70% transparent field cage to increase photon collection on the cathode
- Xenon doping of LAr (10 ppm) to improve uniformity of light collection

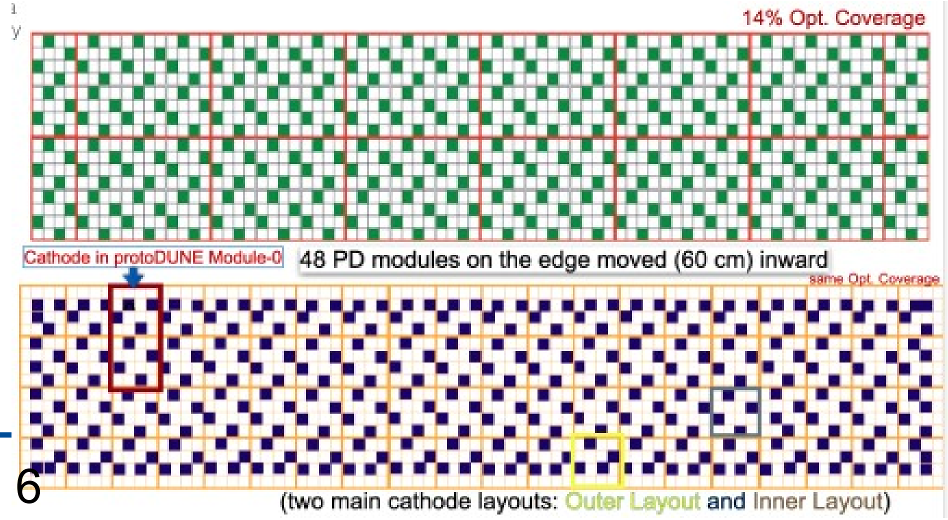
# FD2 – PDS Baseline design

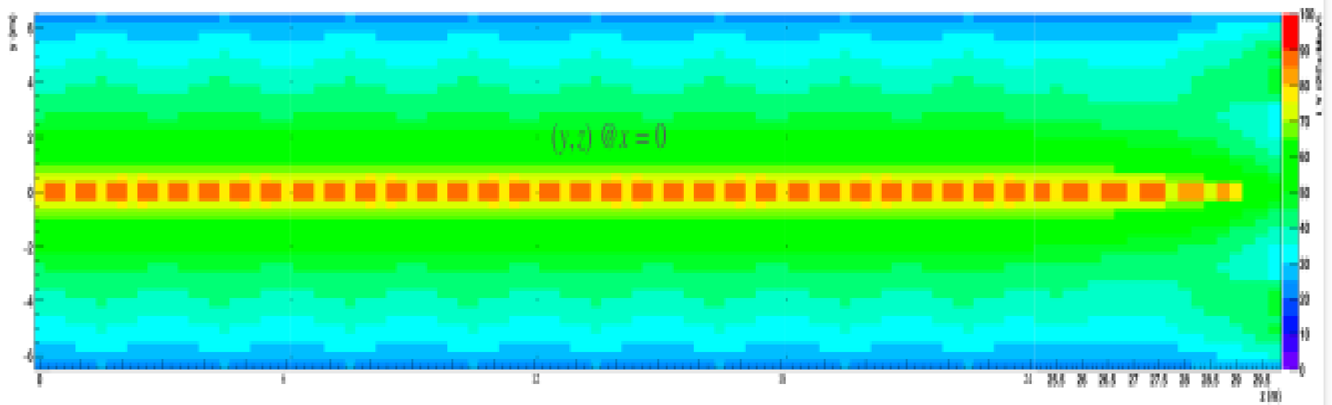
- **Baseline design follows a ~ 4π scheme**, which favors ***uniformity*** in light collection and ***enhances the light yield***

- Design validated and optimized through an ***impressive progression of tests at the CERN Cold Bo***x (F. Cavanna Talk)

- *Fallback solution with all the modules on the membrane moved as Risk Mitigation*

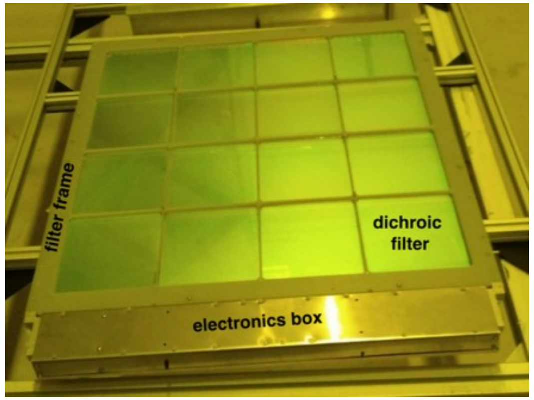
- HV discharge risk mitigated through *the shielding of X-ARAPUCA* modules and the proper *positioning of the modules on the cathode* (two independent studies at BNL and Fermilab). See F. Cavanna Talk



# PDS-FD2 components

***X-ARAPUCA***




***Cold Electronics***

***Cold cables/fibers***

***Feedtrhough***

***Warm cables/fibers***

***DAPHNE***

***Class 4 laser PoF***


Credits: A. Cervera

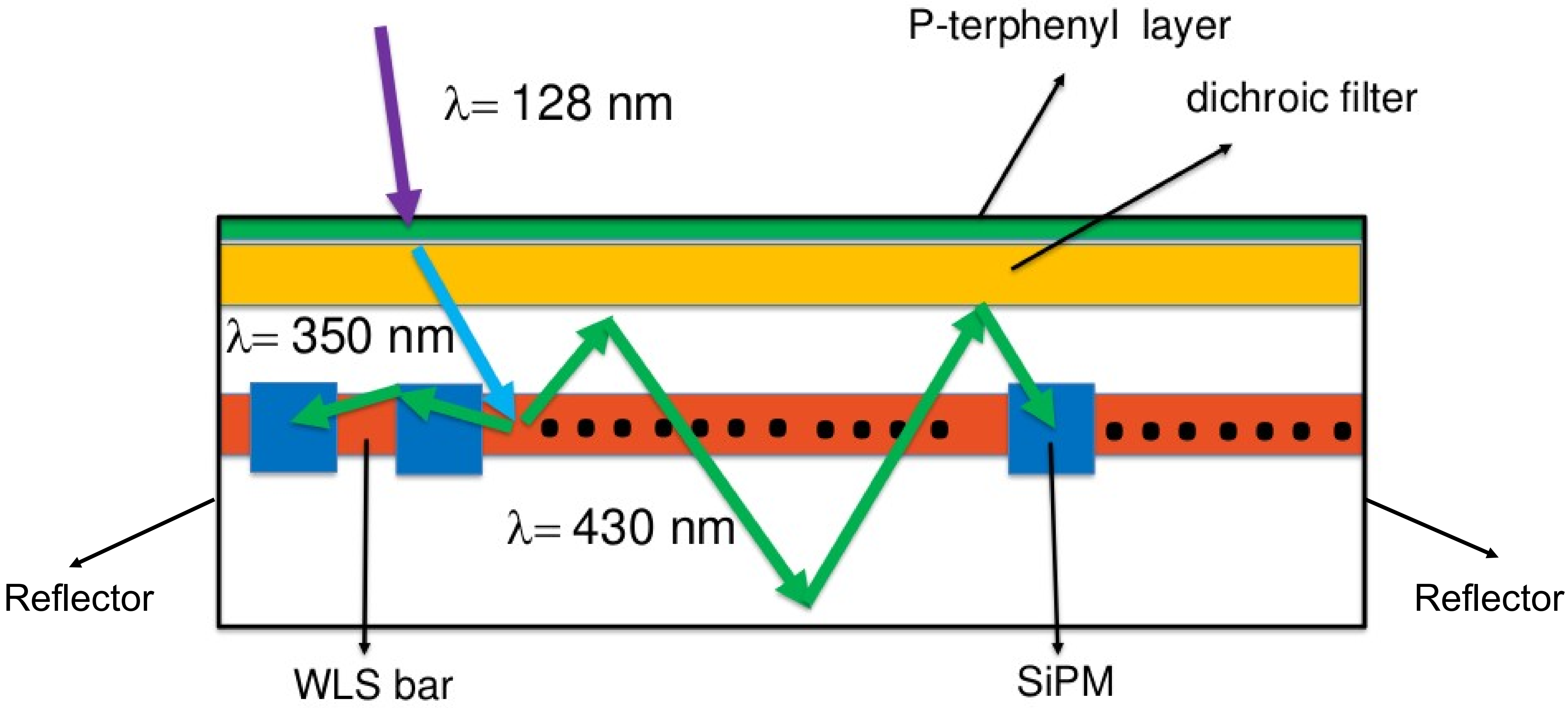
## Light Collection - Uniformity

- Light collection will be ***much more uniform*** in FD2 than in FD1. *This will be possible thanks to few, important factors:*
  - **The design of the Time Projection** with a single, non segmented active volume
  - **The X-ARAṔUCA technology**, *flexible enough to allow to install photosensitive modules on the cathode and on the membrane walls with an high coverage*
  - **Power over fiber and Signal over Power technologies** which allow to bias and read-out electronic modules operating inside the cathode plane ar 300 kVolt

- ***Uniformity in light collection*** will *improve the quality of the analysis of light signals in FD2*, since it will not be necessary to use big corrections to do calorimetry, particle identification and implement reliable trigger algorithms.

- This is true **for all the physics drivers of the experiment** and is *independent of the absolute value of the Light Yield*

# X-ARAPUCA efficiency – why being optimistic



# X-ARAPUCA efficiency – why being optimistic

- The LY studies which will be presented in this review are based on the assumption that ***the absolute detection efficiency of FD2-X-ARAPUCAs (Megacells) is comparable to that of FD1 ones (Supercells). Around 3%***

- The ratio of active SiPM surface to acceptance window is *unfavorable for Megacells (FD2) wrt Supercells* (FD1). **0.045 cm$^{-2}$ (FD2) against 0.1 cm$^{-2}$ (FD1)**

- **X-ARPAUCA implements two trapping mechanisms:**

  1) ***Standard ARAPUCA mechanism***: double shift of the light, dichroic filter and highly reflective internal surfaces
  2) ***Trapping inside the WLS*** plate through total internal reflection of the photons and reflections on the sides

- *Mechanism 1) depnds on the ratio of SiPM active surface to acceptance window*, while **mechanism 2) depends on the density of SiPM on the perimeter of the WLS** plate and in this case **Megacells (FD2) are superior to Supercells (FD1)**. **$Q_{FD2}$ = 0.67 cm$^{-1}$ (FD2) against $Q_{FD1}$ 0.4 cm$^{-1}$ (FD1)**

# X-ARAPUCA efficiency – why being optimistic

- In the case of mechanism 2) the *Q need to be scaled by a factor taking into account the attenuation of the light inside the WLS plate*: **exp (-L/λ)**. Where *L is the average distance between photon production/reflection and the sides of the WLS*. L=60 cm for FD2 and L=17 cm for FD1 (L=4XArea/Perimeter)

- **λ is the attenuation** length which *includes re-emission, absorption, scattering and losses at each total internal reflection*

- About 50%-60% of the photons are initially trapped through mechanism 2)

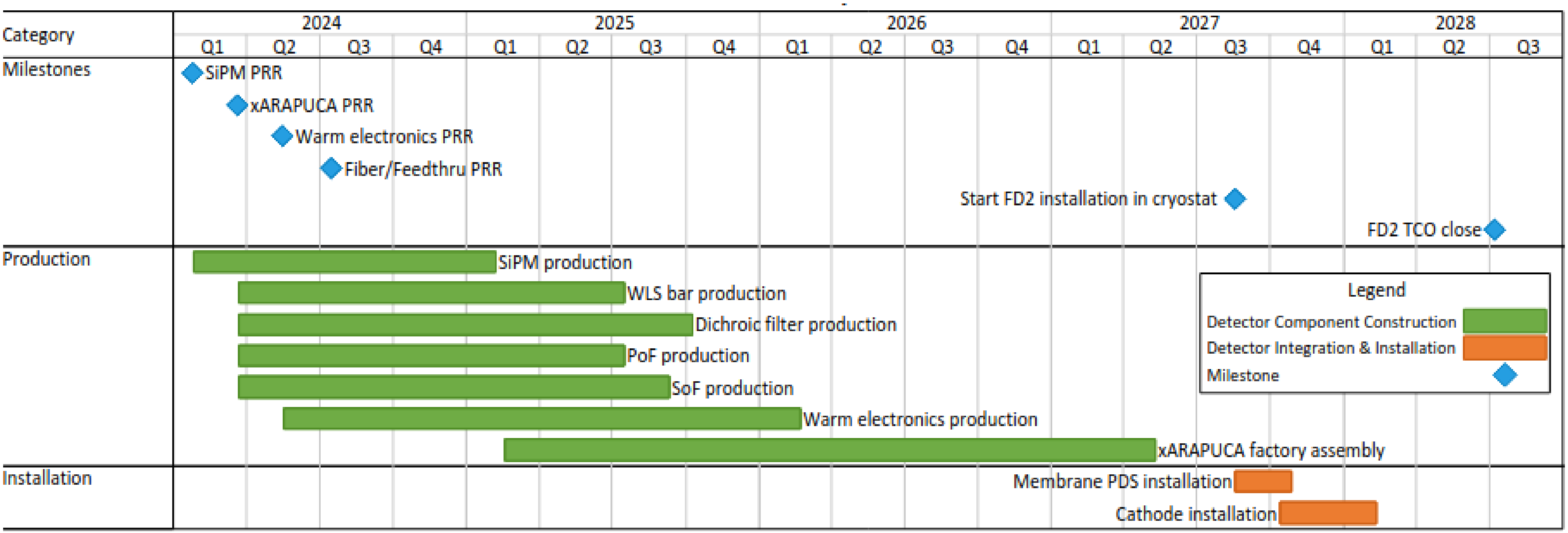
- *The optical contact between the WLS and SiPM has been improved in FD2* (D. Warner talk)

- **Dichroic filters** have been **slightly improved** to benefit mechanism 1) (C. Cattadori talk)

- *We are optimistic that the absolute photon detection efficiency of Megacells (FD2) will not be too different from (FD1)*

- *Measurements of absolute PDE are on the way of being performed (Napoli, CERN and Madrid)*

# Schedule and Milestones




R. Rivera talk

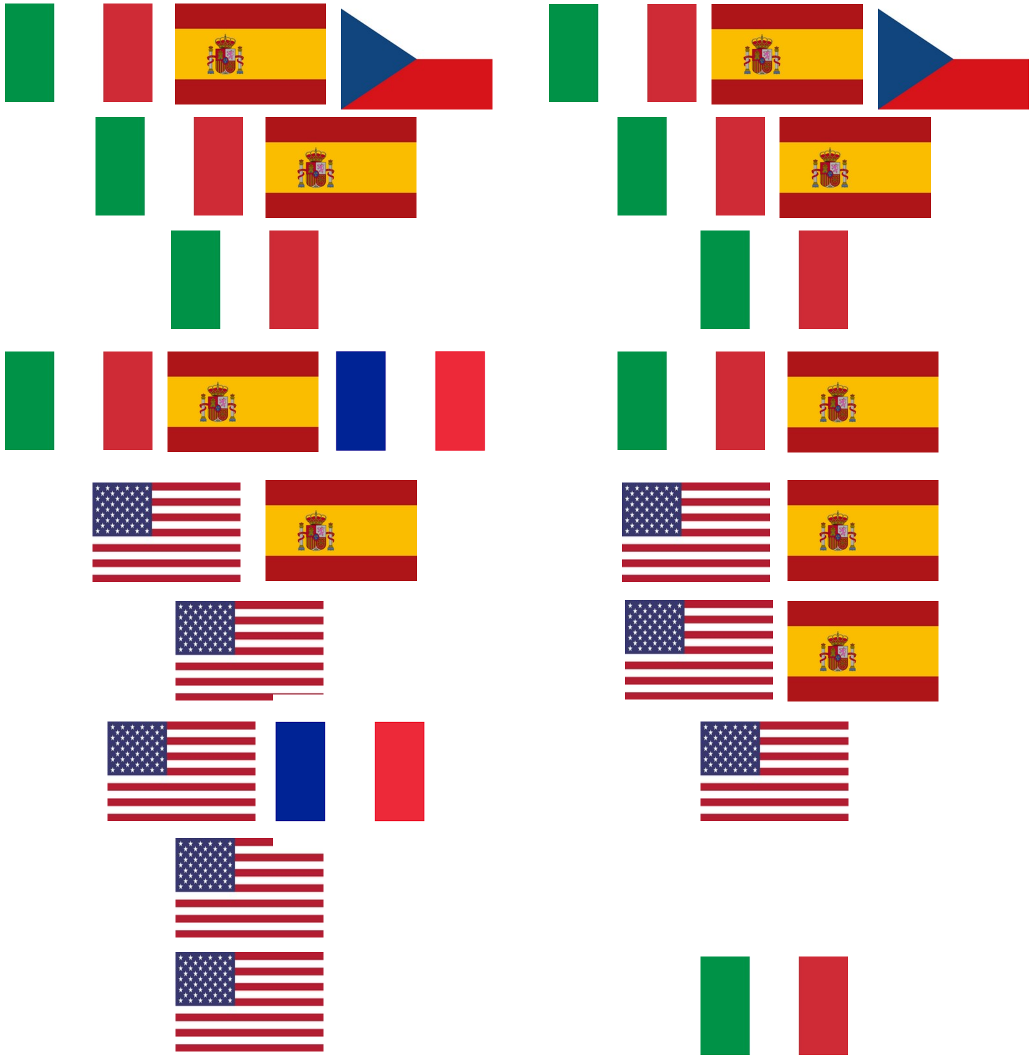
# Core Costs Summary

| FY24-28 FD2 PDS Production Line Items | Core Estimates (k$) | DOE | Non-DOE | DOE (k$) | Non-DOE (k$) |
|---|---|---|---|---|---|
| SiPMs | 1641 | | X | | 1641 |
| SiPM flex circuits | 330 | X | | 330 | |
| WLS bars | 293 | | X | | 293 |
| Dichroic filters | 1043 | | X | | 1043 |
| PoF of receivers | 369 | X | | 369 | |
| PoF transmitter box and components | 300 | X | | 300 | |
| Cold electronics motherboard and components | 355 | X | | 355 | |
| SoF of transmitter daughtercard and components | 115 | | X | | 115 |
| Bias daughtercard and components | 53 | X | | 53 | |
| Copper transmitter daughtercard and components | 63 | X | | 63 | |
| short-run cables | 229 | X | | 229 | |
| X-ARAPUCA frame components | 1778 | X | | 1778 | |
| | | | | | |
| Warm electronics digitizer cards | 216 | | X | | 216 |
| Warm optical-to-electrical converters | 119 | X | | 119 | |
| PoF warm and cold fibers | 244 | X | | 244 | |
| SoF warm and cold fibers | 244 | X | | 244 | |
| Membrane long-run warm and cold cables | 31 | X | | 31 | |
| Fibers for Response & Monitoring warm paths | 208 | X | | 208 | |
| Fibers for Response & Monitoring cold paths | 208 | | X | | 208 |
| Flanges | 161 | X | | 161 | |
| Membrane-module feedthroughs | 14 | X | | 14 | |
| Cathode-module feedthroughs | 60 | X | | 60 | |
| Response Monitoring feedthroughs | 86 | X | | 86 | |
| Membrane-module Support System | 130 | | X | | 130 |
| | | | | | |
| SiPMs population on flex circuits | 278 | | X | | 278 |
| **Total:** | **8569** | | | **4644** | **3925** |

# Responsibility matrix – PDS-FD2

- SiPMs
- Dichroic Filters
- Light guides
- Warm Electronics
- Monitoring System
- X-ARAPUCA mechanics
- Cold Electronics
- Power over Fiber
- Fibers/Cables/Flanges

***Cathode*** ***Membrane***



## Conclusions

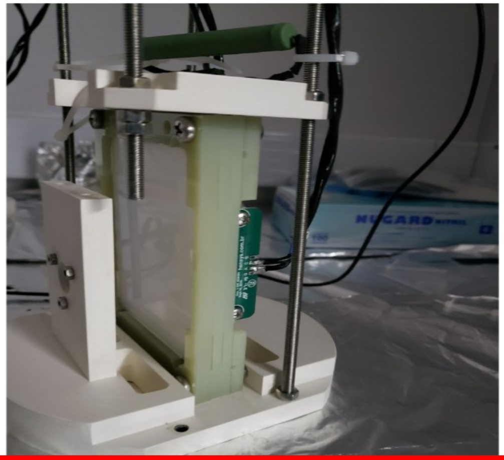
- The geometry of the TPC of FD2 allows for a 4π design of the PDS, which ensures an high degree of uniformity in terms of Light Collection
- The optimized geometry of the PDS module will guarantee and overall higher LY wrt FD1
- The enlarged Conosrtium structure allowed to face the technological challenges of bribging PoF and SoF to maturity
- The entire  PDS Consortium made an impressive work in the last two years, which materilaized in the progression of Cold Box tests at CERN and in the validation of th ebaseline design
- We took great advantage of the pre-existing structure of the Consortium and of the developments made for FD1
- Resources for building the PDS are in place



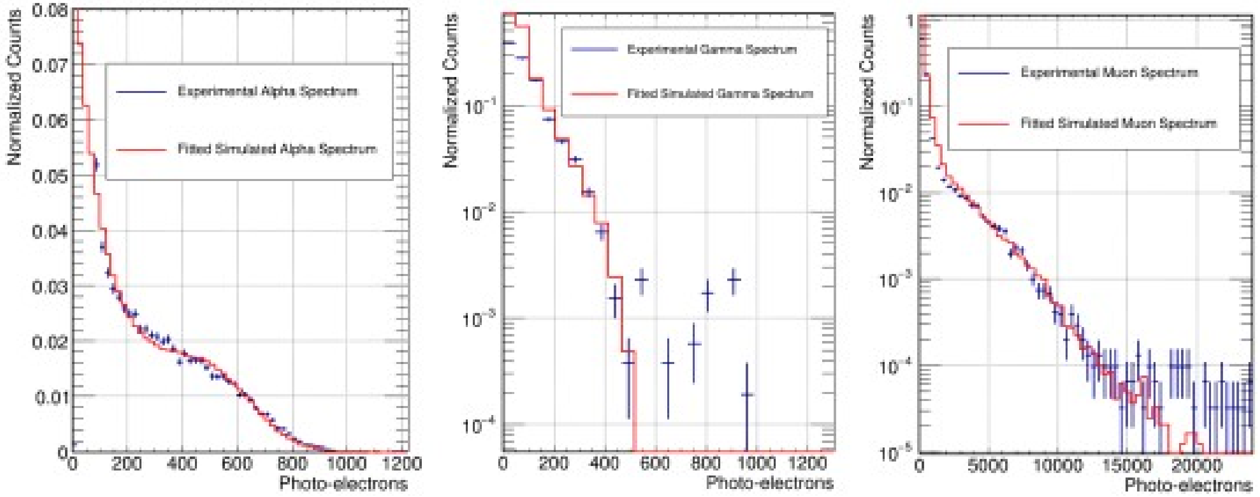
LBNF/DUNE

# *Back-up Slides*

# X-ARAPUCA-FD1 validation – small scale prototypes



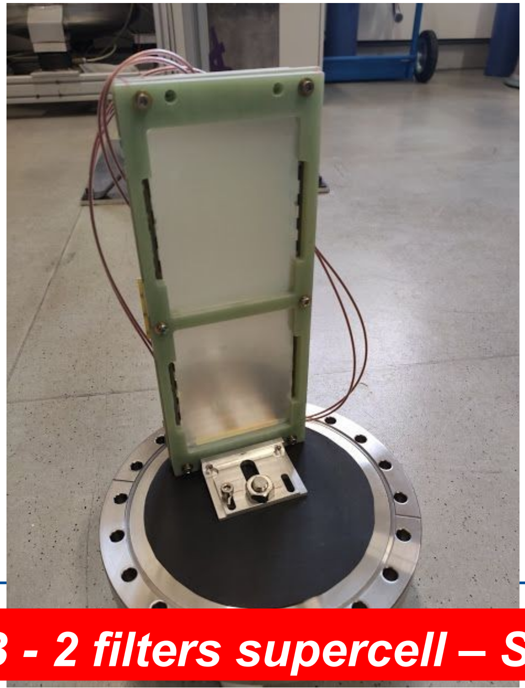
**_UNICAMP - 1 filter supercell_**



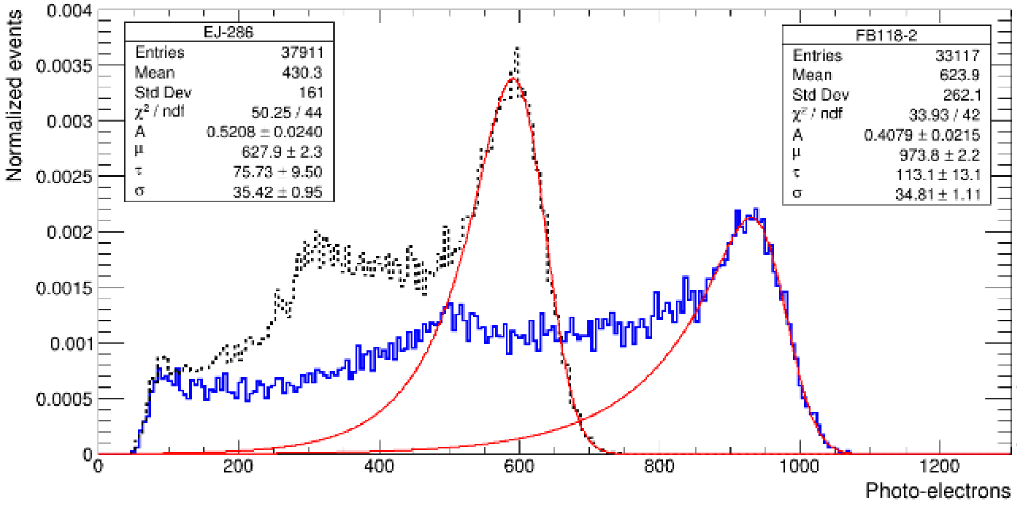

**_Efficiency estimated with α, μ_**

- 8 Hamamatu MPPC (non-downselcted)
- 1 ELJEN WLS plate
- 1 OPTO filter

ε = 2.3 ± 0.4 % @ 50% PDE



**_MiB - 2 filters supercell – SBND model_**




**_Efficiency estimated with α particles_**

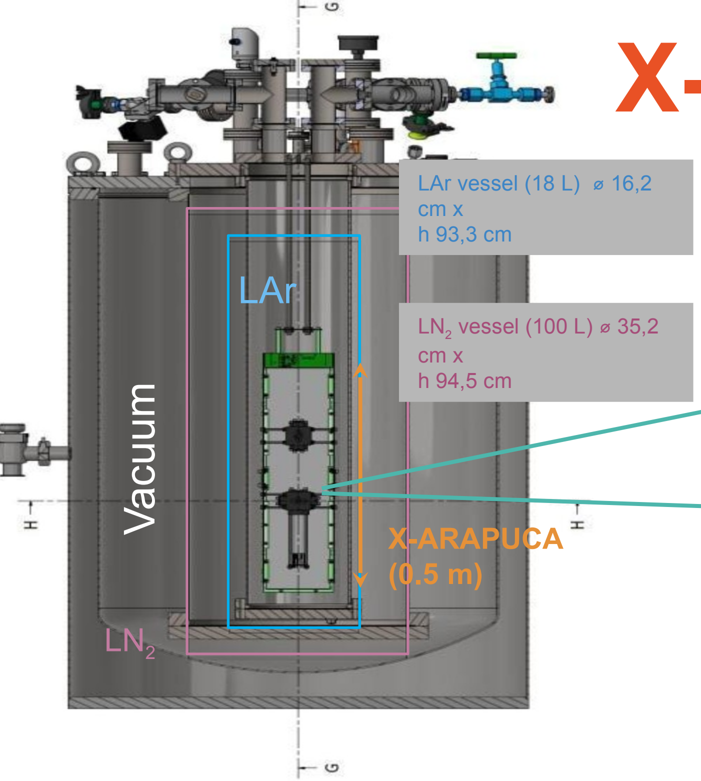
- *16 Hamamatsu MPPC (non-downselcted)*
- *1 G2P (ELJEN) WLS plate*
- *2 OPTO filters*

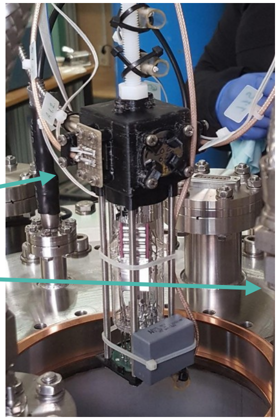
$\varepsilon_{ELJ}$ = 1.9 ± 0.1 % (@ 50% PDE – ELJ)

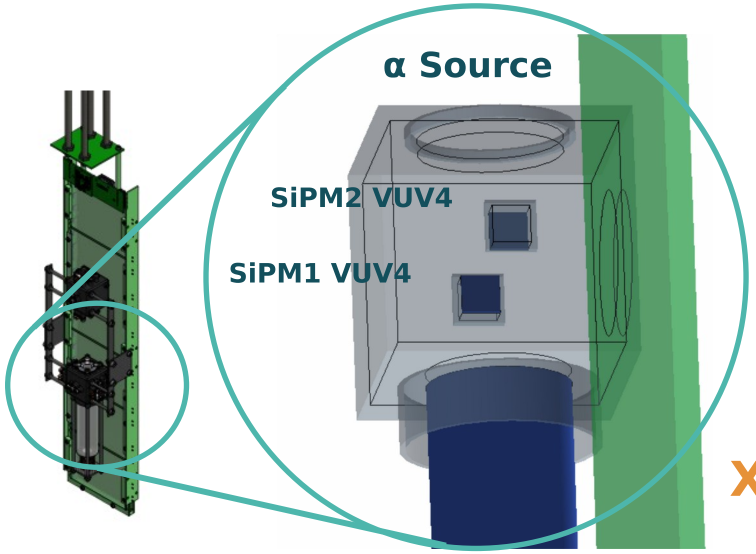
$\varepsilon_{G2P}$= 2.9 ± 0.1 % (@ 50% PDE - G2P)

# X-ARAPUCA-FD1 validation

CIEMAT






X-ARAPUCA

**2 VUV** sensitive **SiPMs** are symmetrically placed with respect to the **X-ARAPUCA** and alpha source ($^{241}$Am)

$$\epsilon_{XA}\,(\%) = \frac{PE_{mm^2}\,(XA)}{PE_{mm^2}\,(Ref.\ SiPM)} \cdot f_{corr} \cdot \epsilon(Ref.\,SiPMs)$$

$$\epsilon_{XA}\,(\%) \;=\; 100 \cdot \frac{PE(XA)}{\gamma_{\text{expected}}} \cdot f'_{corr}$$

**ϵ(Ref. SiPMs) = 11.3%**

## $\varepsilon_{XA}$(%) - DIRECT MEASUREMENT (VUV4 Comparison)

| | FBK+EJ | HPK +EJ | HPK +G2P |
|---|---|---|---|
| **PDE 40%** | 1.41 ± 0.11 | 1.56 ± 0.12 | **2.12 ± 0.16** |
| **PDE 45%** | 1.63 ± 0.12 | 1.78 ± 0.14 | **2.38 ± 0.18** |
| **PDE 50%** | 2.01 ± 0.15 | 1.93 ± 0.15 | **2.58 ± 0.20** |

## $\varepsilon_{XA}$(%) - CROSSCHECK (From known LY and MonteCarlo)

| FBK+EJ | HPK +EJ | HPK +G2P |
|---|---|---|
| 1.34 ± 0.10 | 1.51 ± 0.12 | **2.02 ± 0.17** |
| 1.56 ± 0.12 | 1.72 ± 0.14 | **2.28 ± 0.19** |
| 1.93 ± 0.15 | 1.87 ± 0.15 | **2.51 ± 0.21** |



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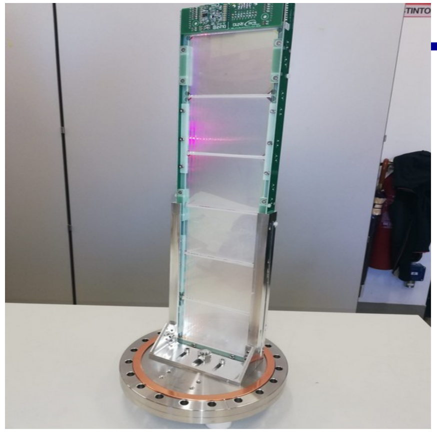
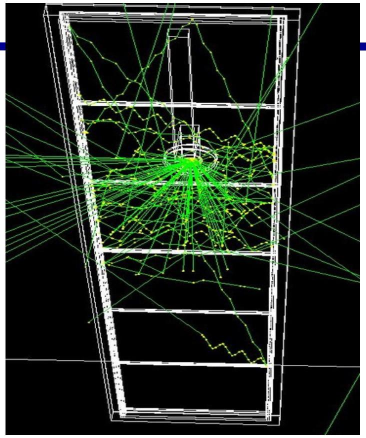
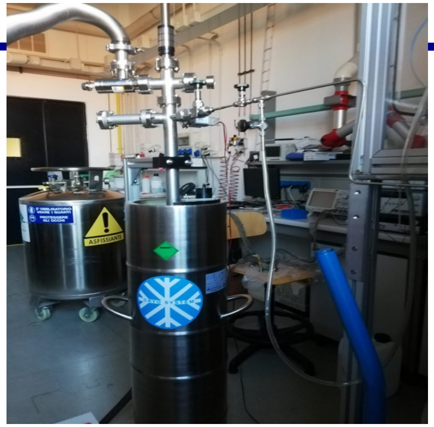
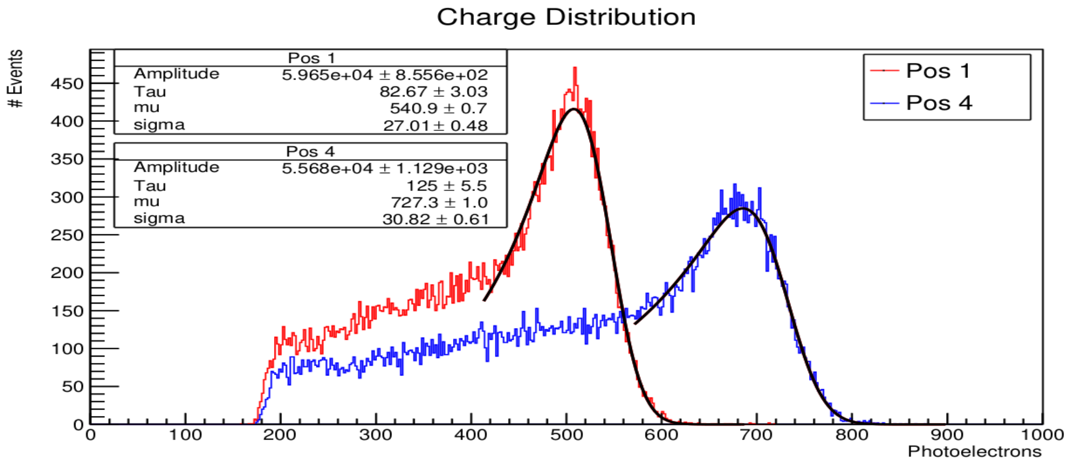
# X-ARAPUCA validation – supercell





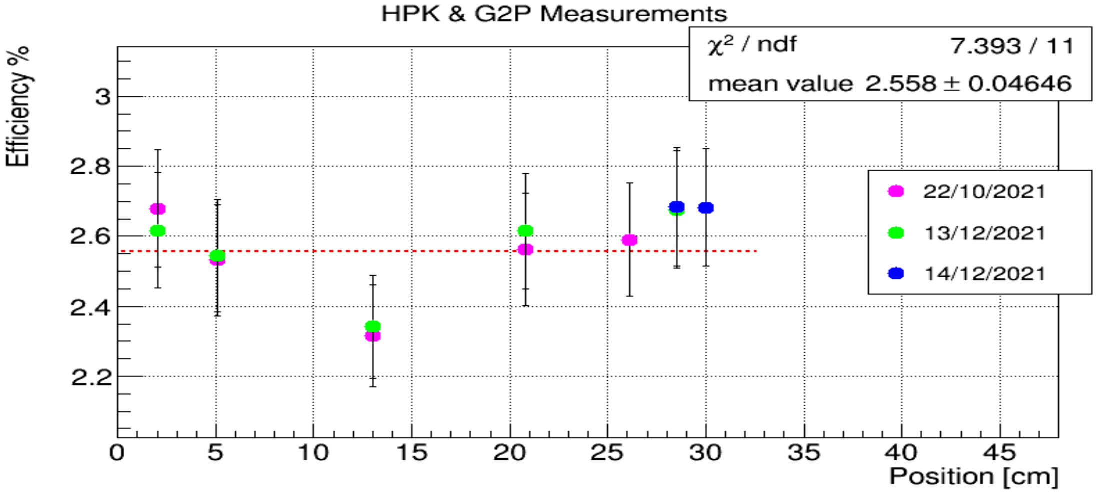





Method: z-scanning of the whole cell (~2 Sr) with an $^{241}$Am exposed $\alpha$ source

(JINST 16 (2021)09027).

$$\epsilon = \frac{4\pi \cdot \alpha\ \mathrm{peak(ADC)}}{\mathrm{s.ph.e.(ADC)} \cdot f_{int} \cdot \mathrm{LY_{LAr}} \cdot \mathrm{En}_{\alpha} \cdot \mathrm{q}_{\alpha} \cdot \Omega}$$




No correction for LAr purity applied. Expected: +2% to +5%

| | SiPM PDE | XA PDE MiB Xtalk corr. | XA PDE CIEMAT Xtalk corr. |
|---|---|---|---|
| HPK & G2P | 50% | **2.2** (0.15) | **2.51** (0.21) |
| FBK & G2P | 50% | **2.0** (0.14) | |
| FBK & Eljen | 50% | **1.7** (0.14) | **1.56** (0.12) |

- The efficiency can be slightly improved ***with the optimization of AOI of the filters***

# Stability of pTP films

- pTP film is coated on the glass side of the dichroic filter. **The film is robust and mechanically stable at LAr temperature**. *Cooling down needs to be relatively slow (few mm/min during our tests)*
- **No evidence of cracking or of detachment** in tens of tests performed at *UNIMCAP, MiB, CIEMAT, CSU and in the ARAPUCAs extracted from protoDUNE (Run 1)*
- The eventual solubility of pTP in LAr will be studied at the *PULArC* facility at UNICAMP;
- PULArC is a complete test stand for the purification of LAr. It consists of a 90 liters, vacuum tight cryostat, a Barber Nichols submerged pump, two purity monitors, scintillation light detectors. Possibility of using different filtering media;
- pTP coated filters will be immersed in liquid argon for few days and then the liquid will be filtered through a sintered disk to remove flakes and through a molecular sieve to capture dissolved pTP. Molecular sieve will be analyzed to check for the presence of captured pTP. Same procedure as https://arxiv.org/pdf/1804.00011.pdf (J. Asaadi et al.)