The Photon Detection System of the DUNE experiment

RENATA parallel session

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Hamza Amar Es-sghir

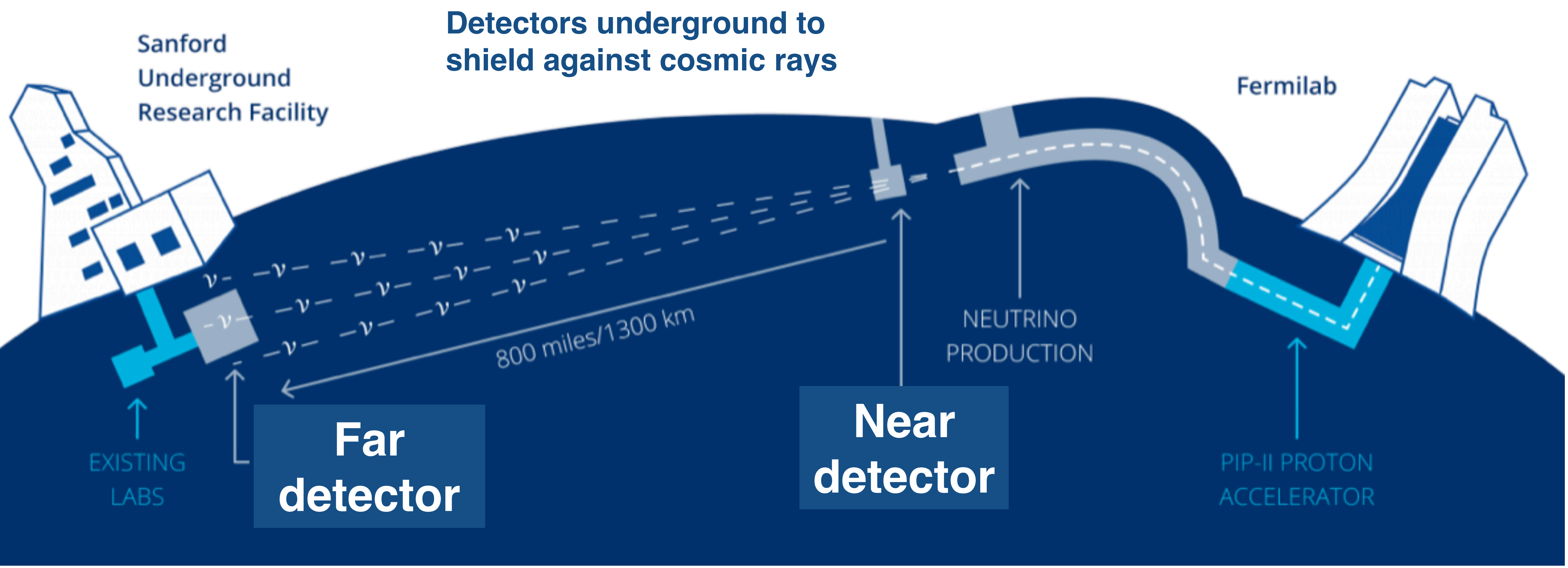
DEEP UNDERGROUND NEUTRINO EXPERIMENT

IFIC INSTITUT DE FISICA CORPUSCULAR

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

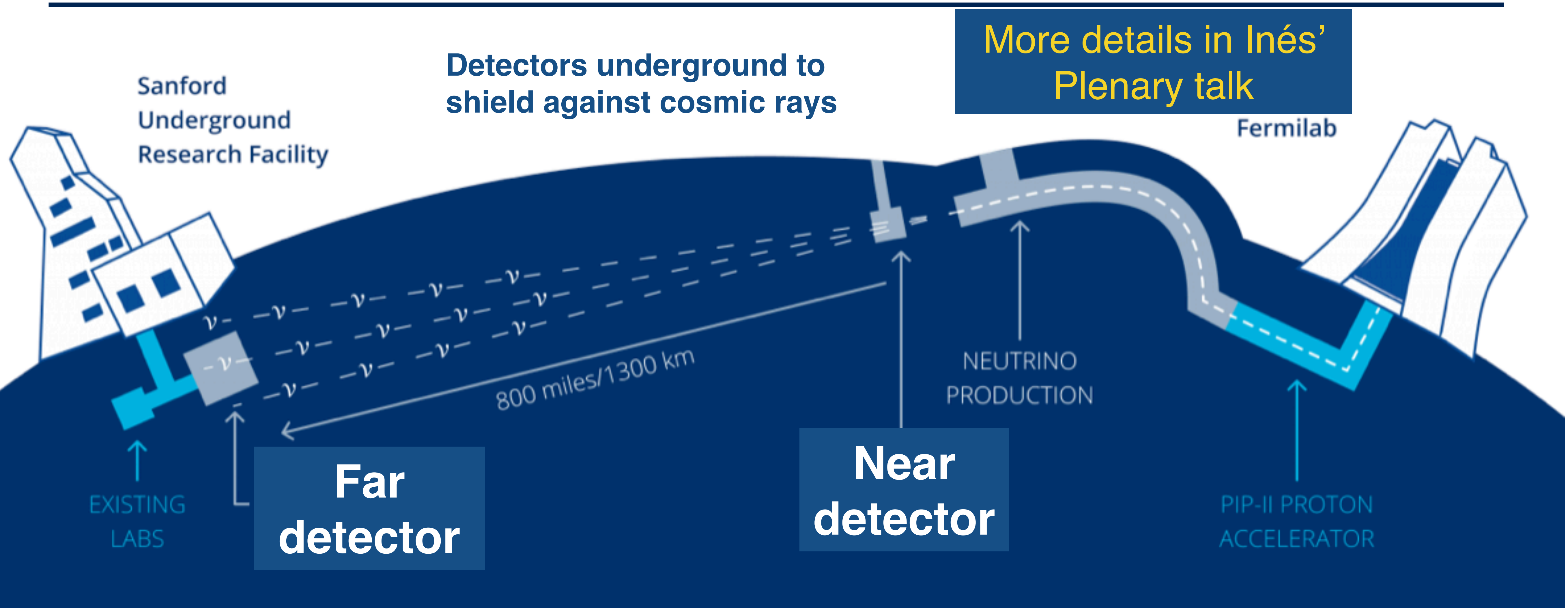
VNIVERSITAT DE VALÈNCIA

The DUNE experiment: *What is DUNE?*



- Deep Underground accelerator Neutrino Experiment for a broad physics program.
- Future long-baseline neutrino oscillation experiment.
- DUNE mainly consists of:
  - The world's most intense neutrino beam.
  - The Near and Far detectors.

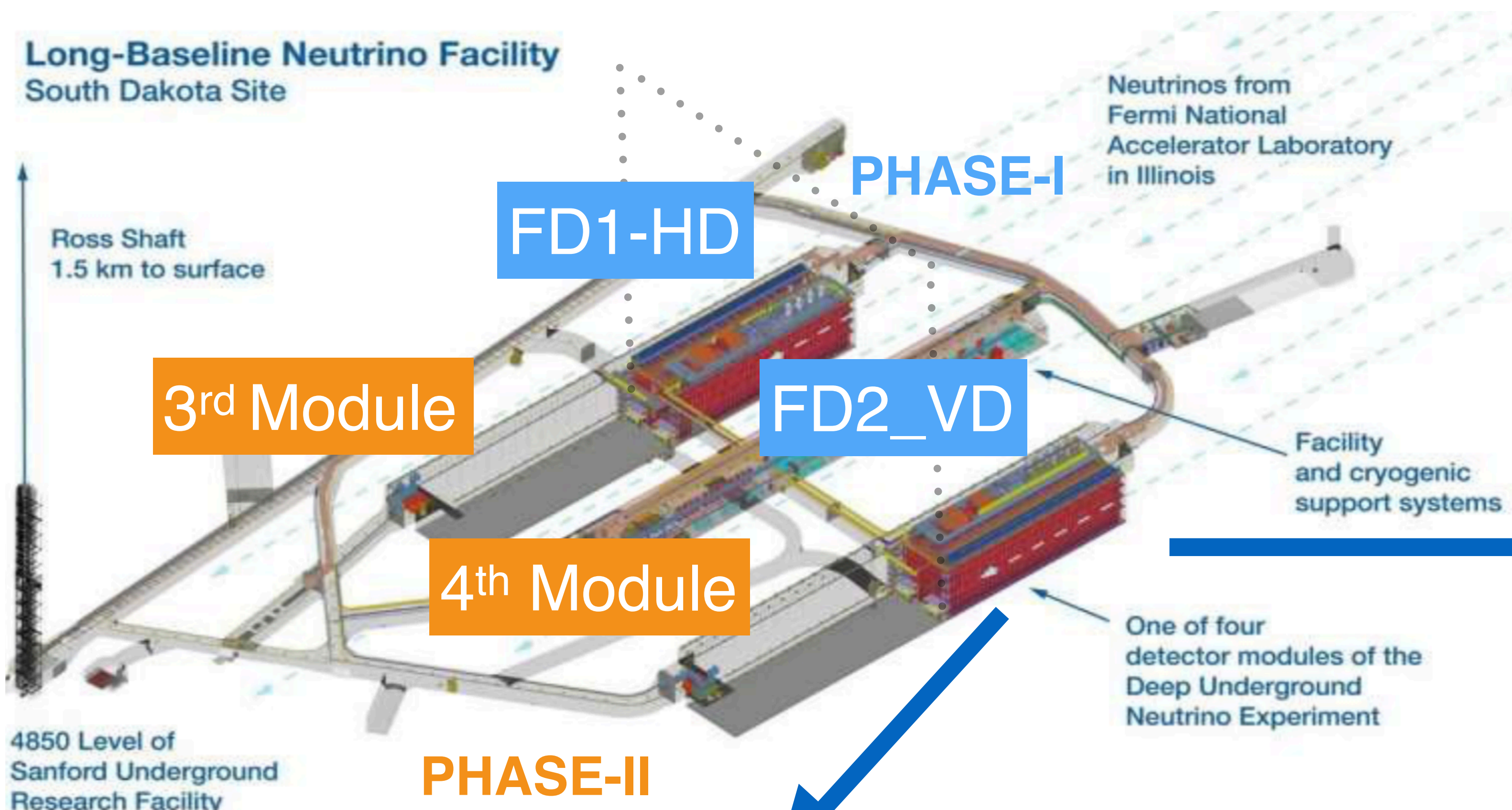
The DUNE experiment: *Science goals*

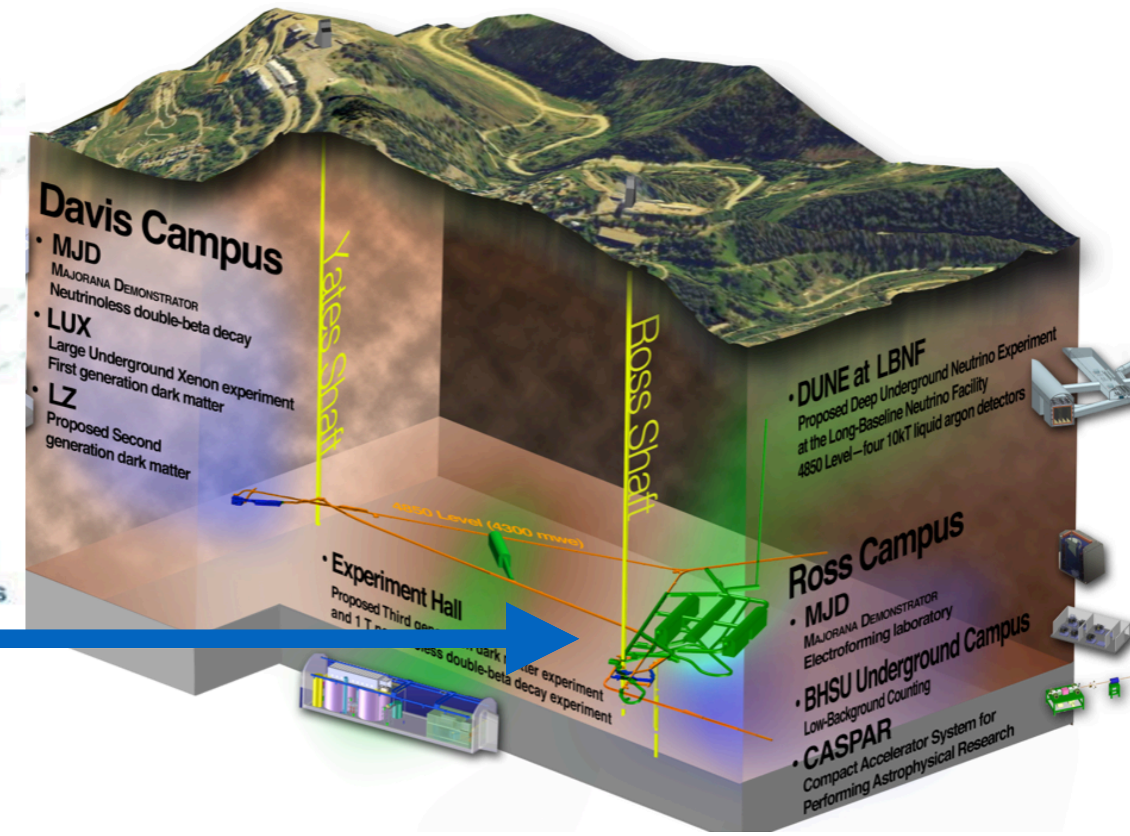


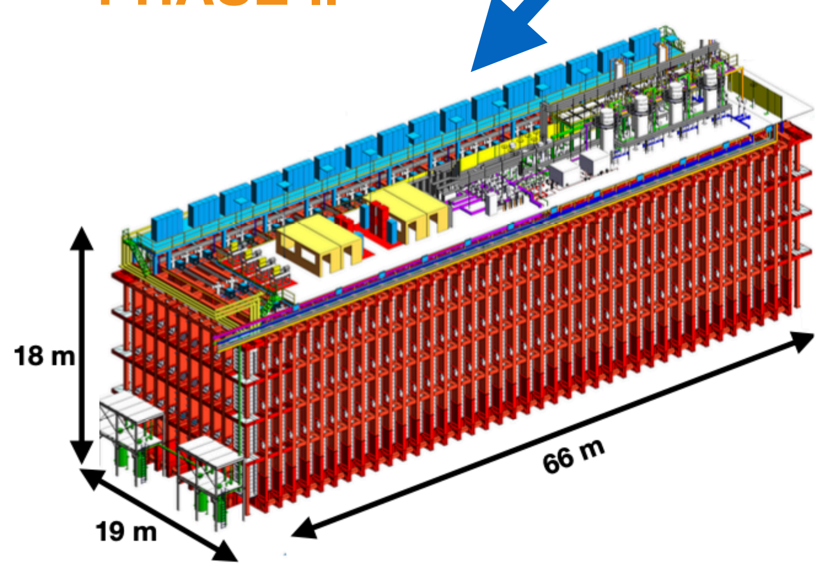
- Determine mass hierarchy with 5σ, discovery sensitivity to CPV (wide range of δ_{CP}) and precision test of the 3-neutrino oscillation parameter paradigm in a single experiment.
- Sensitivity to neutrinos from core-collapse supernova and solar neutrinos (see Sergio's talk).
- BSM physics searches: nucleon decay, non-standard interactions, Dark Matter, …

The DUNE experiment: *The Far Detector*

4 modules of 17 kton mass each (10 kton fiducial volume).
Based on the Liquid Argon Time projection Chamber (LArTPC) technology. → Precision imaging.







Detector organization in stages:

- DUNE Phase-I (FD1 & FD2).
- DUNE Phase-II (Modules 3 & 4).

Implementation of improvements in the LArTPC technology.

DUNE Far Detector LArTPC: *The working principle*

When an interaction in a LArTPC occurs, two signals proportional to the energy deposit are generated.

Ionization electrons
~ 27000 e-/MeV

500 V/m E field

Drifted and collected in charge readout planes (CRP)

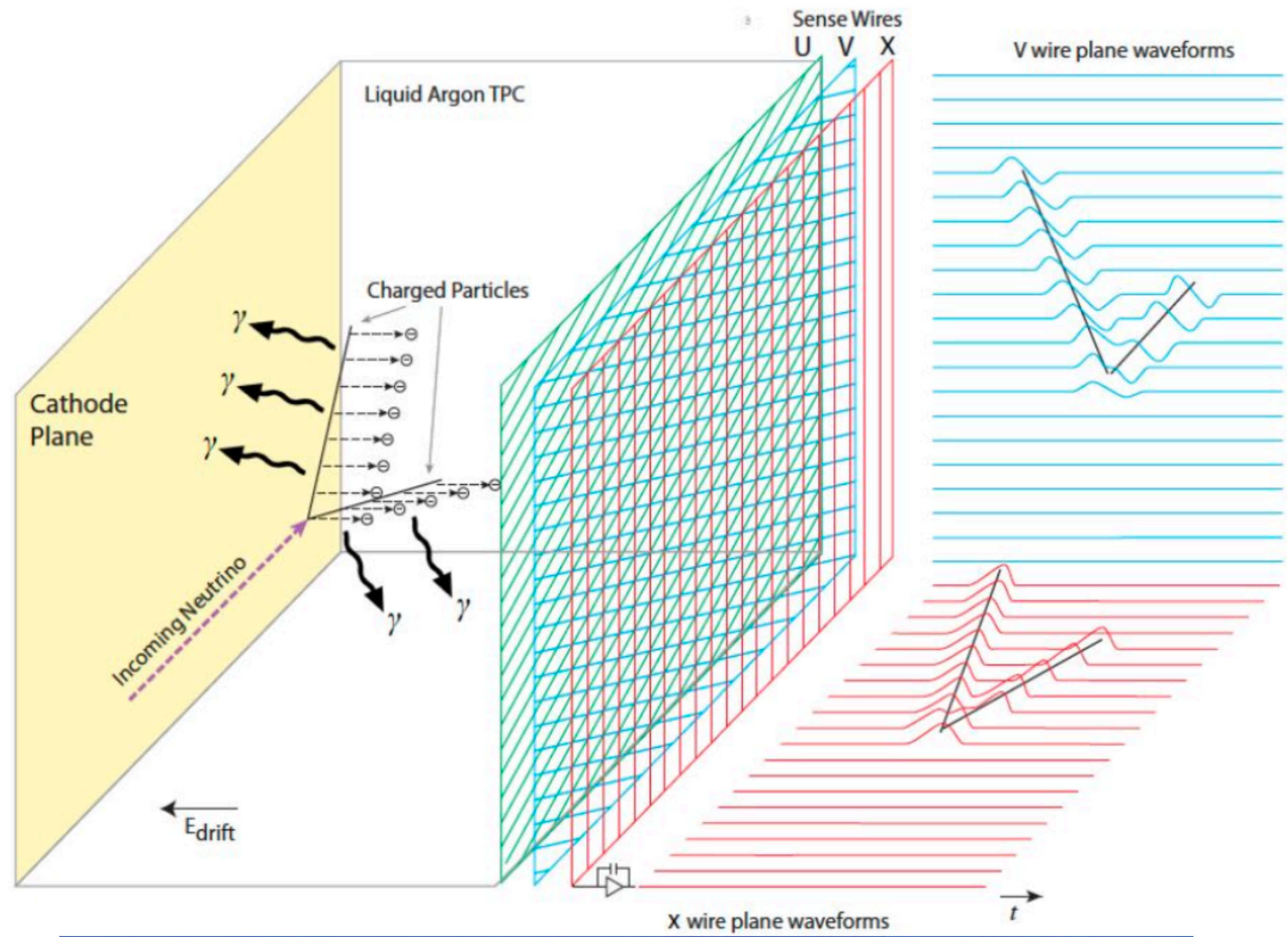
3D precision tracking & calorimetry (dE/dX) of charge particles.

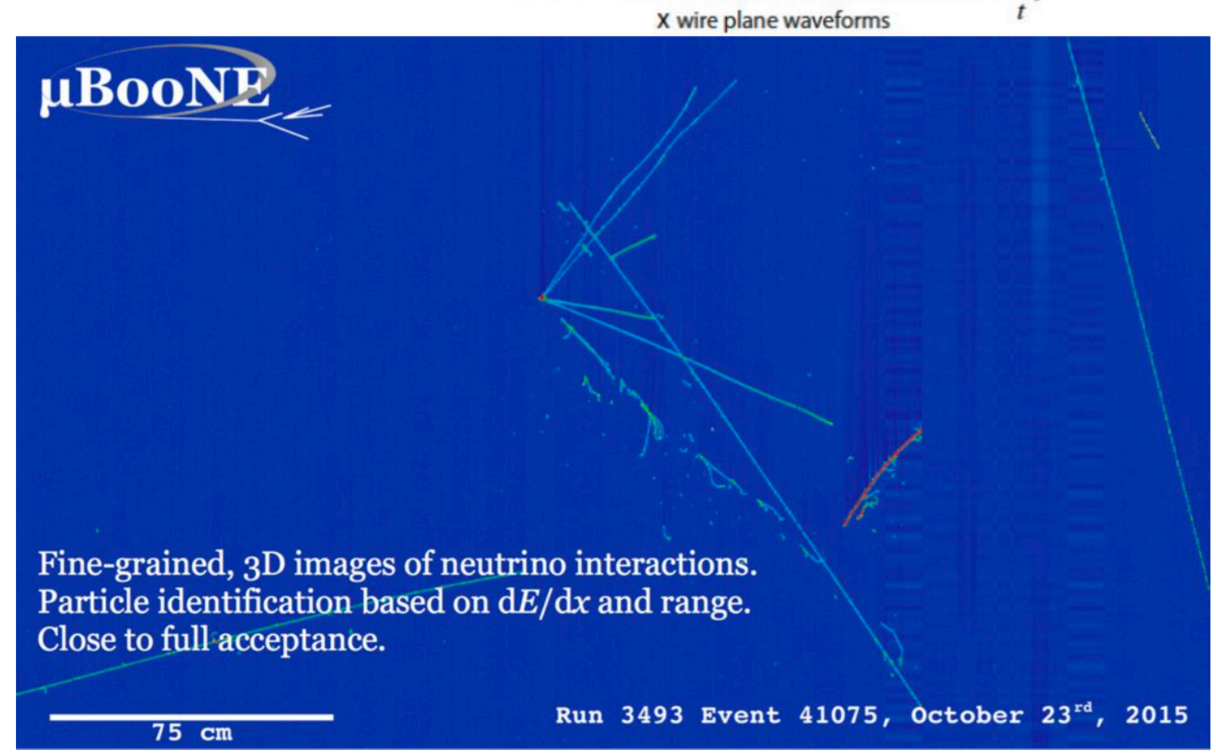
Scintillation photons
~ 24000 ph/MeV

Detected via the photon detection system (PDS)

Initial time of interaction (t_0) & complementary calorimetry.

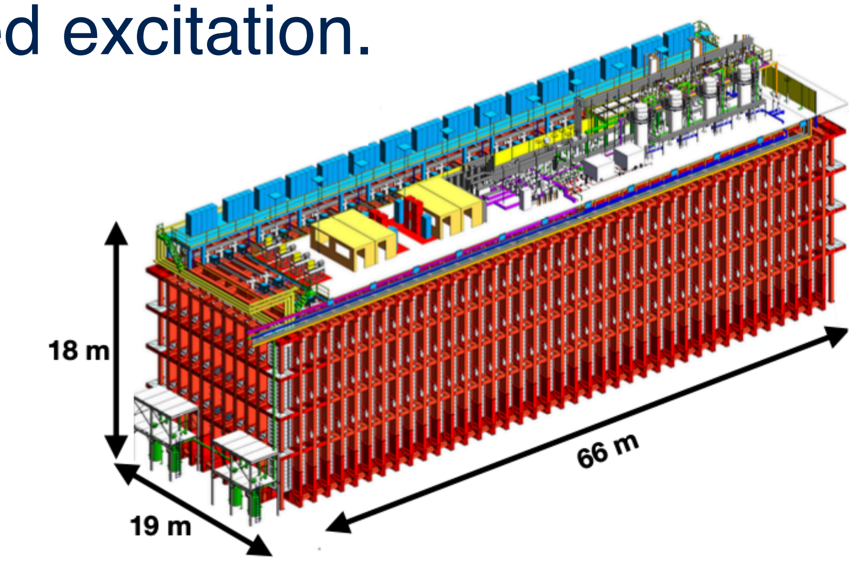
P. Sánchez-Lucas, LIDINE 2023





DUNE Far Detector: *Importance of LAr VUV light*

- LAr VUV (vacuum ultraviolet) scintillation light (**λ = 128 nm**).
- Luminescence mechanisms: recombination & self-trapped excitation.
- The PDS has a relevant role in DUNE physics:



Triggering

- Trigger of the data acquisition (DAQ) systems.

Event t_0 measurement offline

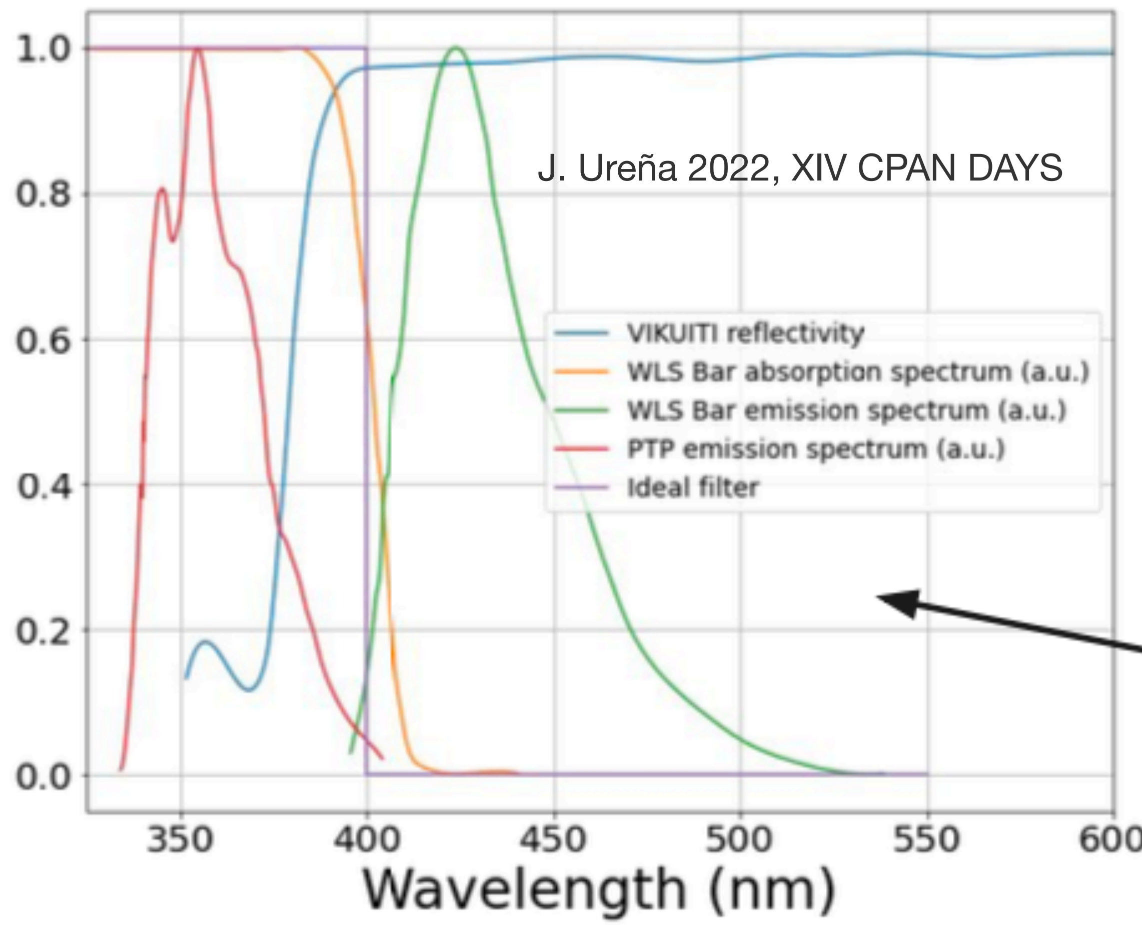
- Essential for event 3D localization for all non-beam events
- Essential for event fidualization. ⇒ Background rejection.

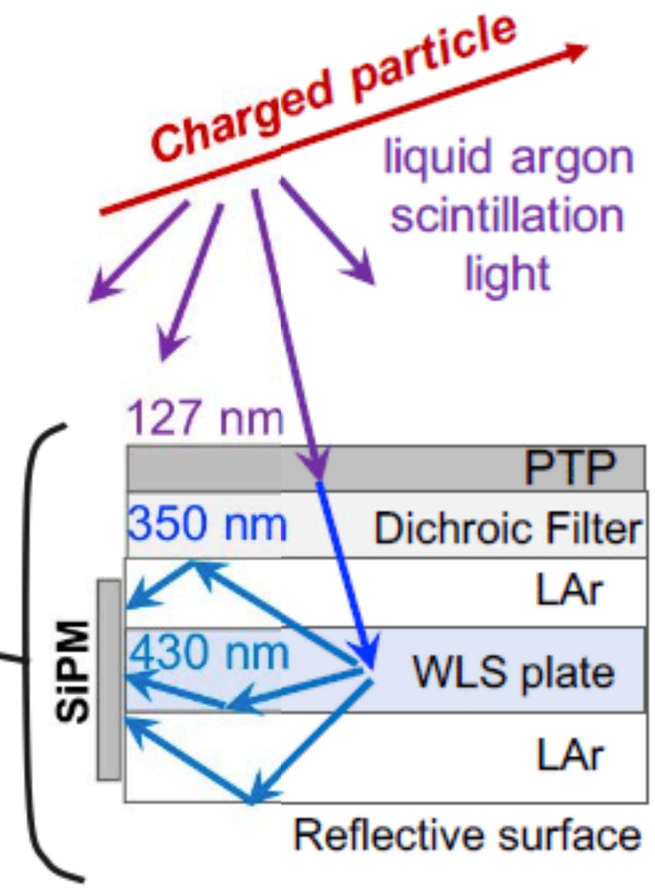
Calorimetry

- Crosscheck for the charge signal.
- Improved energy resolution (charge + light), especially for low energy (~ MeV).

- Large volume to cover it with SiPMs. A new photon collector concept is needed.

DUNE Far Detector: *The X-ARAPUCA concept*





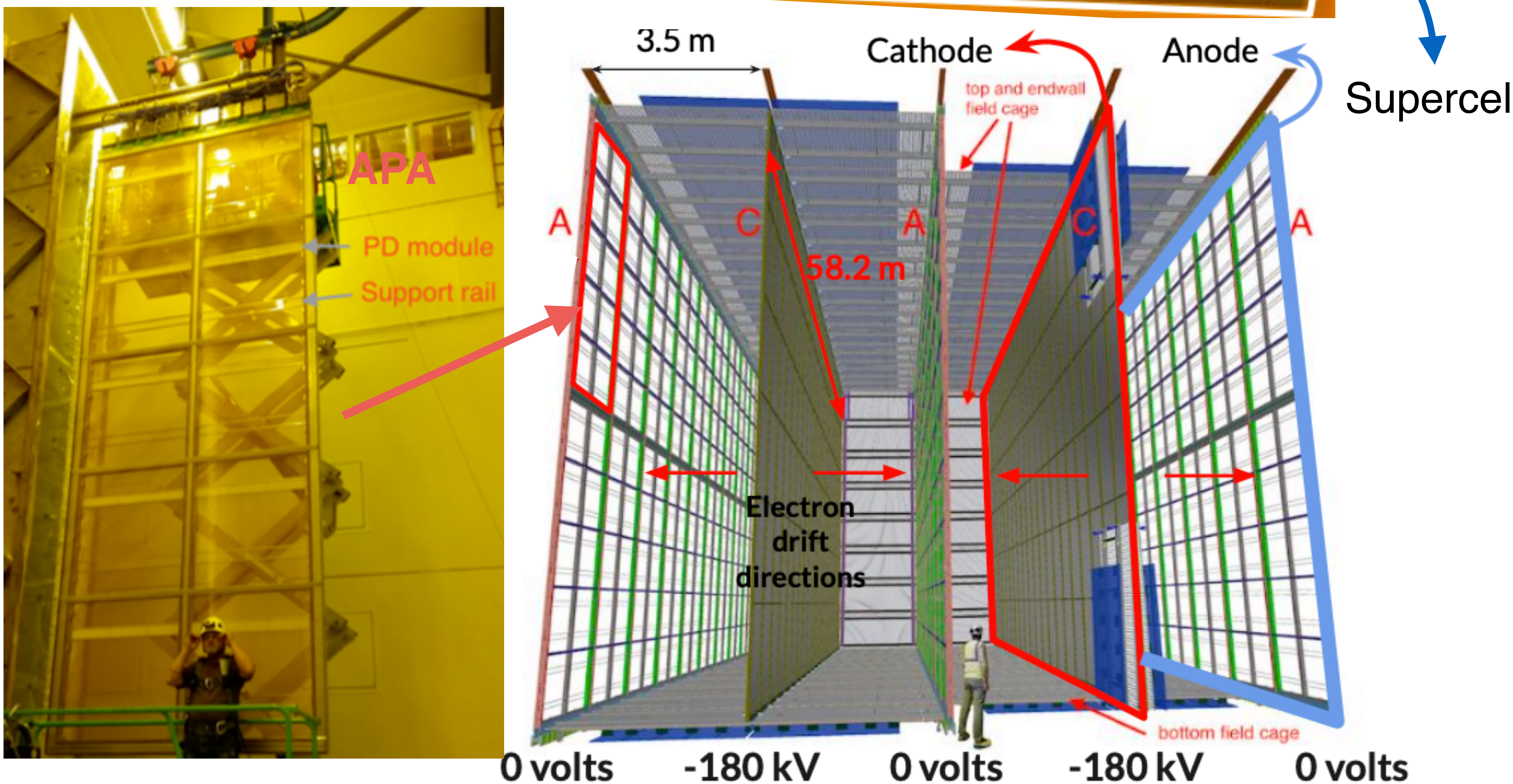
H.V. Souza *et al* 2021 *JINST* **16** P11002

Trapping mechanism for VUV light detection (128 nm):

- Dichroic Filter (DF) designed to be a shortpass filter tuned at 400 nm.
- pTP wavelength shifter (WLS) on top of DF. Conversion into mainly 350 nm light.
- WLS plate within X-A absorbs pTP-shifted light. Reemission to mainly 430 nm.
- DFs and inner components are reflective to 400-500 nm light.
- Trapped photons eventually reach a SiPM after several reflections.

Far Detector 1-HD: *Photon Detection System*

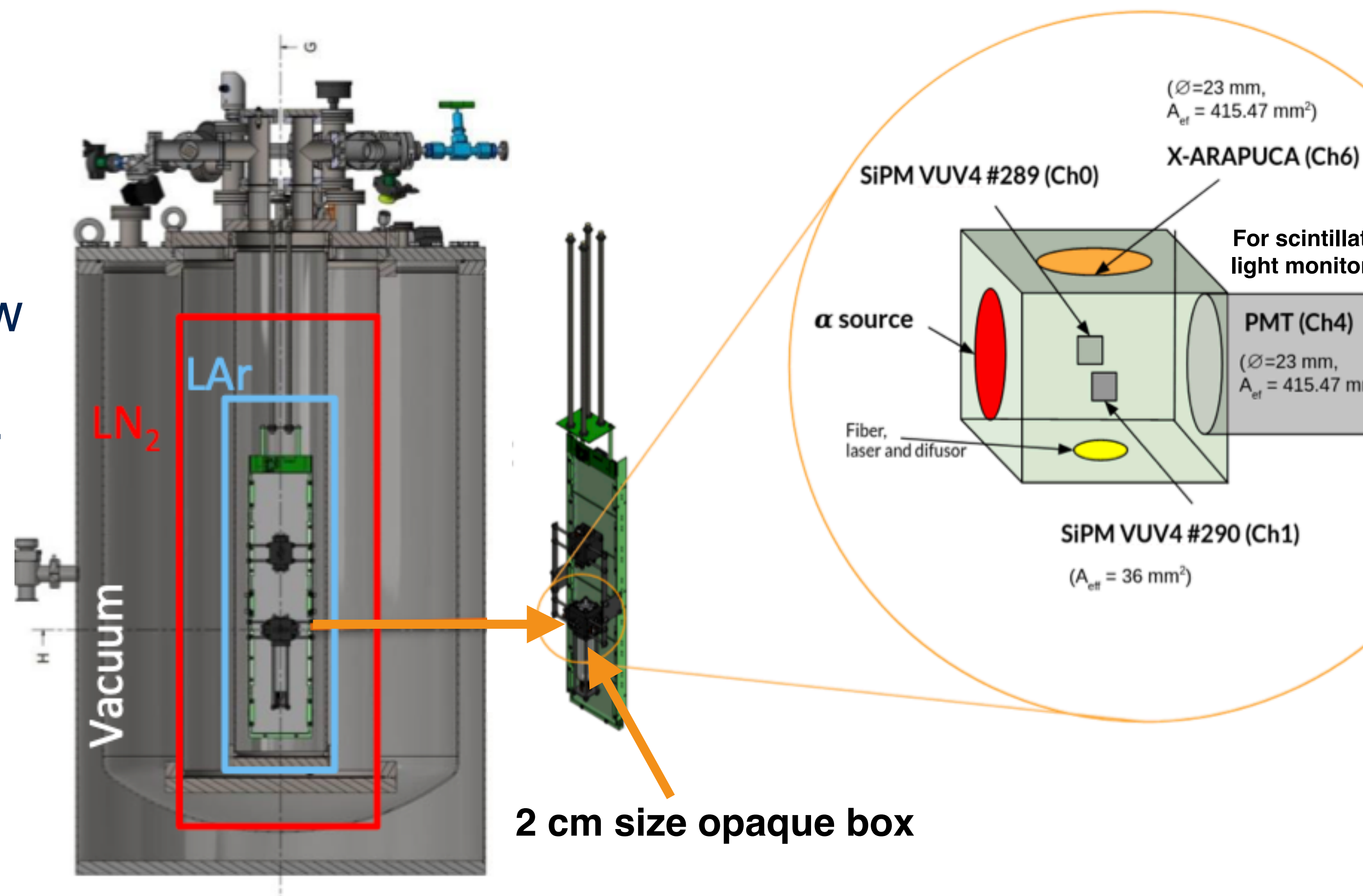
- Photon detectors (PDs) integrated in anode planes (APA).
- X-ARAPUCA with rectangular arrangement (4 supercells).



Far Detector 1-HD: *Performance*

- The X-ARAPUCA Photon Collection Efficiency (PCE) is carried out (measurements performed at CIEMAT) by irradiating a central spot of the devices (Ø = 23 mm) with a low activity ^{241}Am alpha source located in a black box together with two calibrated SiPMs.
- PCE of the X-ARAPUCA is calculated from the ratio of the light detected at the α peak to the light detected by the calibrated SiPM.
- PCE ~ 2 - 3%, with an uncertainty on the measured values of about 10%.

C. Palomares and on behalf of DUNE collaboration 2023 *JINST* **18** C02064
L. Pérez-Molina 2022, XIII CPAN DAYS



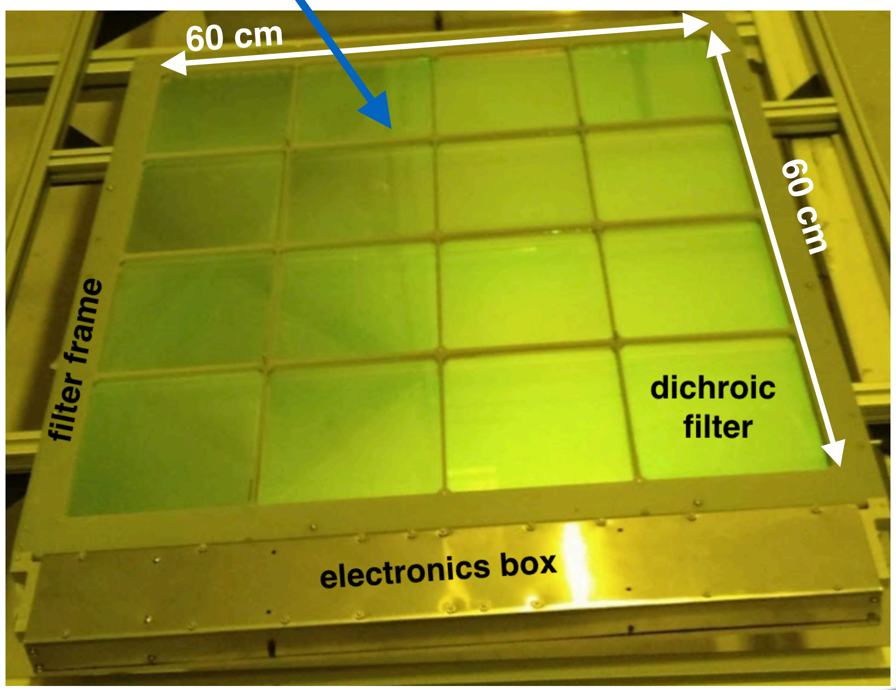
Geometrical factor

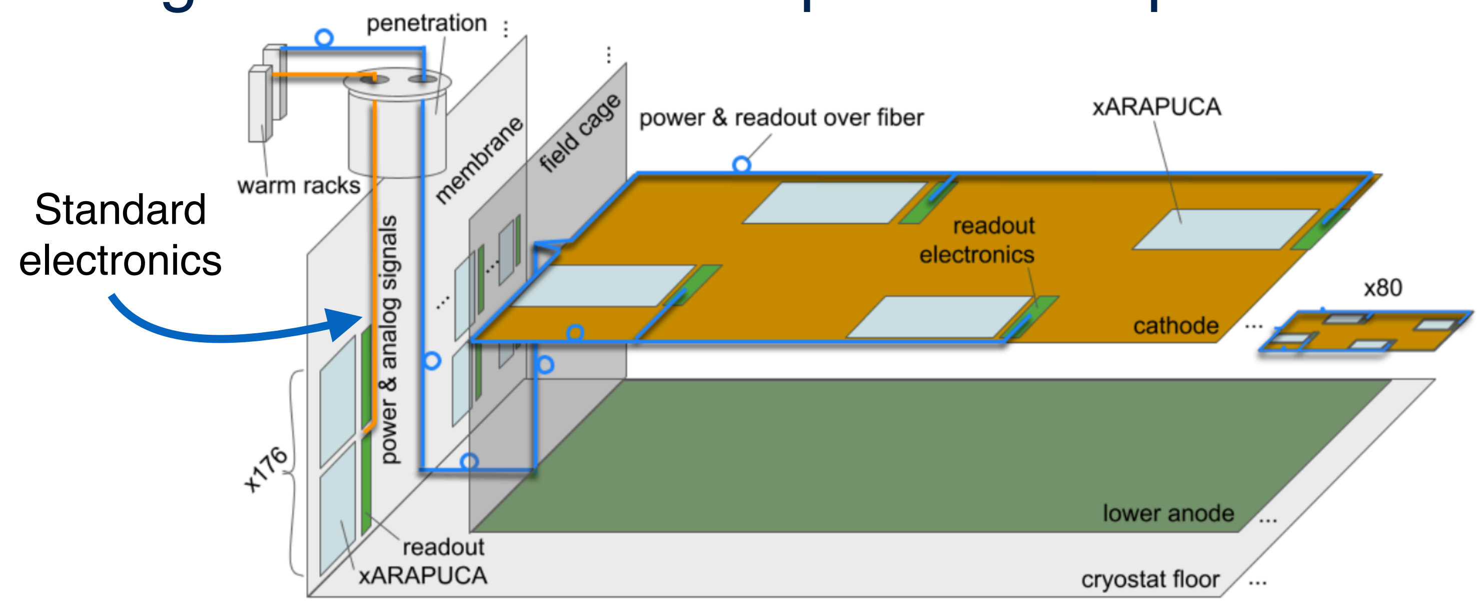
$$\epsilon_1(Arapuca) = \left[\frac{PE_{area}\,(Arapuca)}{PE_{area}(Ref.SiPM)}\right]_{exp} \cdot \left[\frac{f_{X-talk}\,(Ref.SiPM)}{f_{X-talk}\,(Arapuca)}\right] \cdot f_{geom} \cdot \epsilon(Ref.SiPM)$$

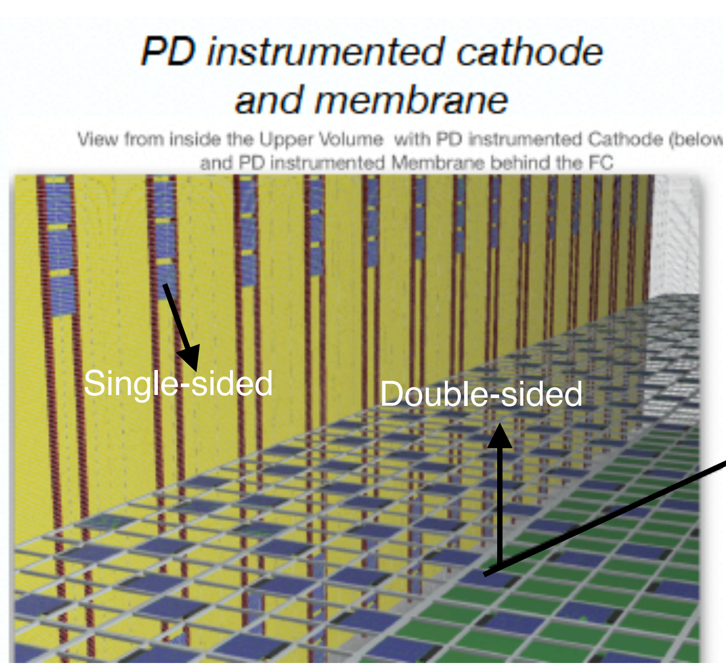
PE stands for photo-electrons

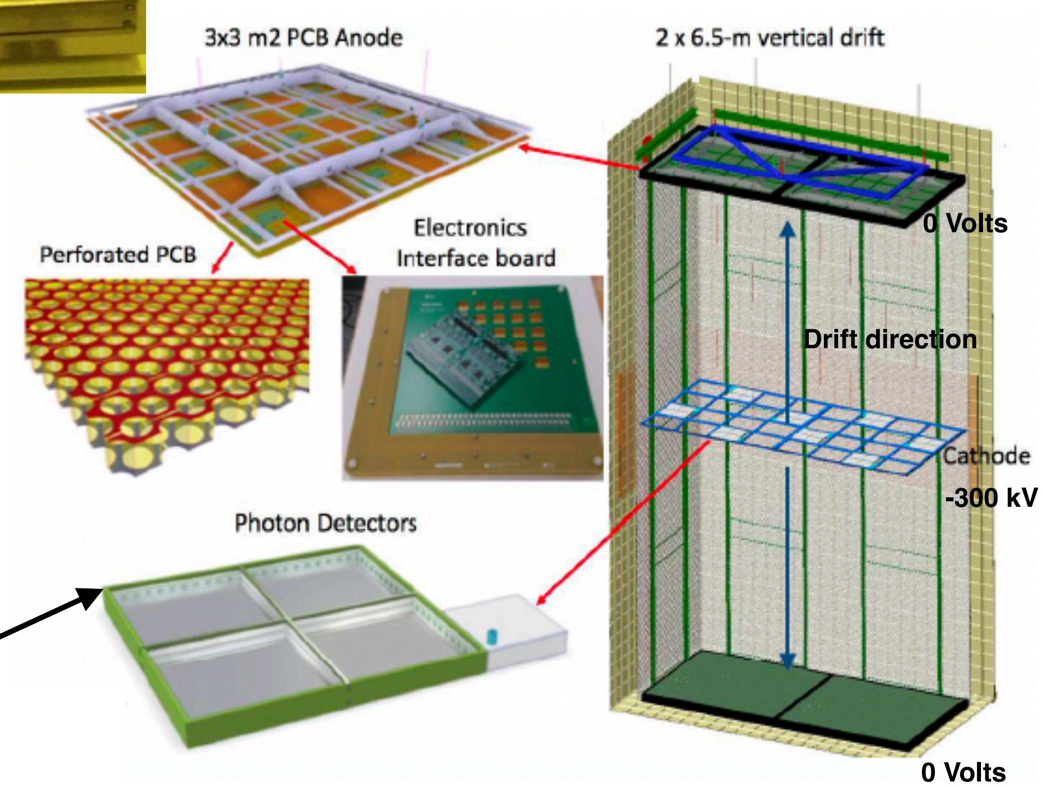
Far Detector 2-VD: *Photon Detection System*

- Photon detectors (PDs) integrated in cathode frame and on membrane walls.
- X-ARAPUCA with square arrangement. All this to improve the optical coverage.









- Cathode modules require new solutions for operation on high voltage (- 300 kV) surface, using non-conductive (fiber) solutions for power and signal extraction.

Far Detector 2-VD: *Performance*

The light yield (*LY*, detected photons per unit deposited energy) is the most important PDS property.

Requirements

Average *LY*
> 20 PE/MeV

Minimum *LY*
> 0.5PE/MeV

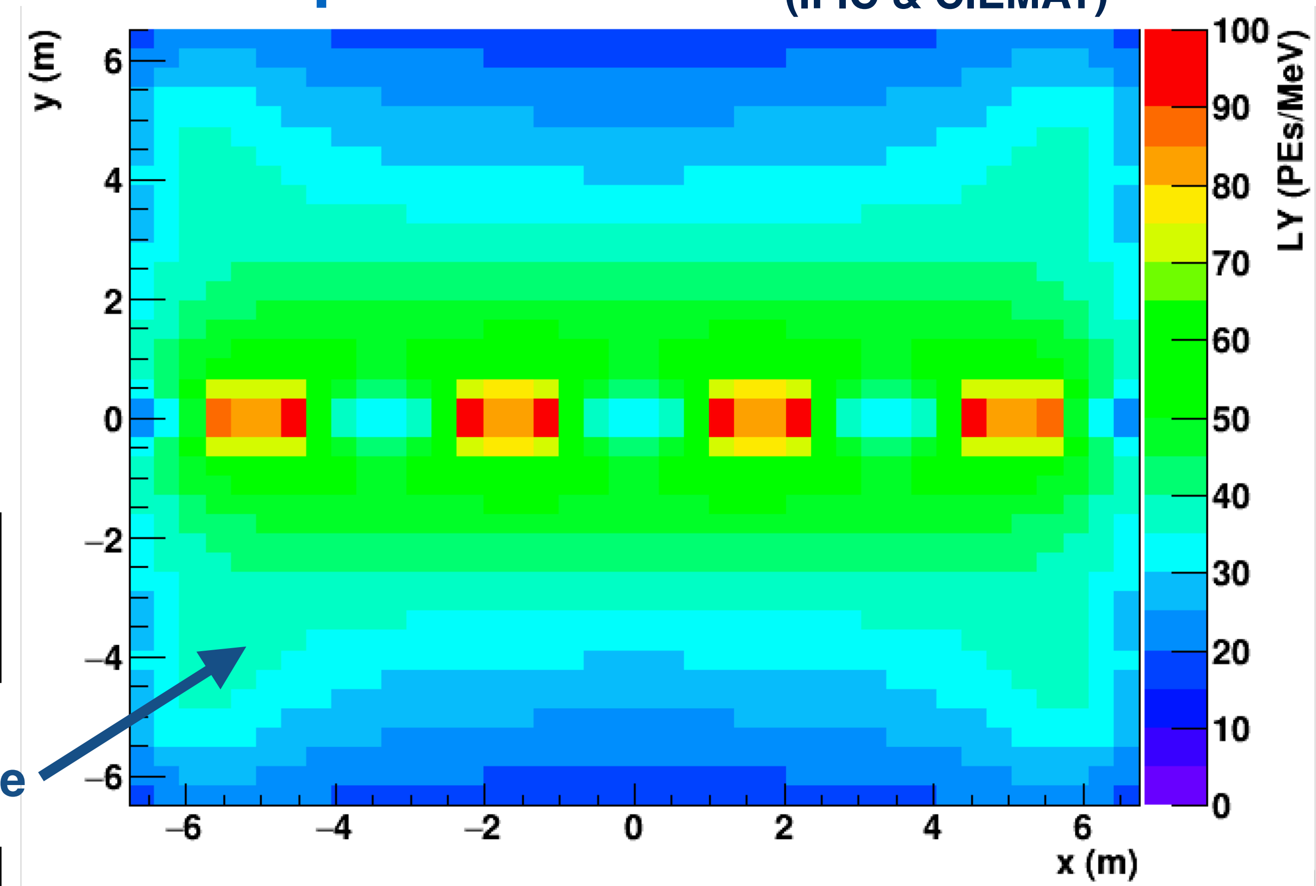
Performance

$\langle LY \rangle \simeq 39$ PE/MeV

$LY_{min} \simeq 16$ PE/MeV

Gives PDS energy resolution comparable to that of the TPC for 5-7 MeV supernova (SN) ν's, and allows tagging of > 99% of nucleon decay backgrounds with light at all points in detector.

LY map for FD2-VD (IFIC & CIEMAT)



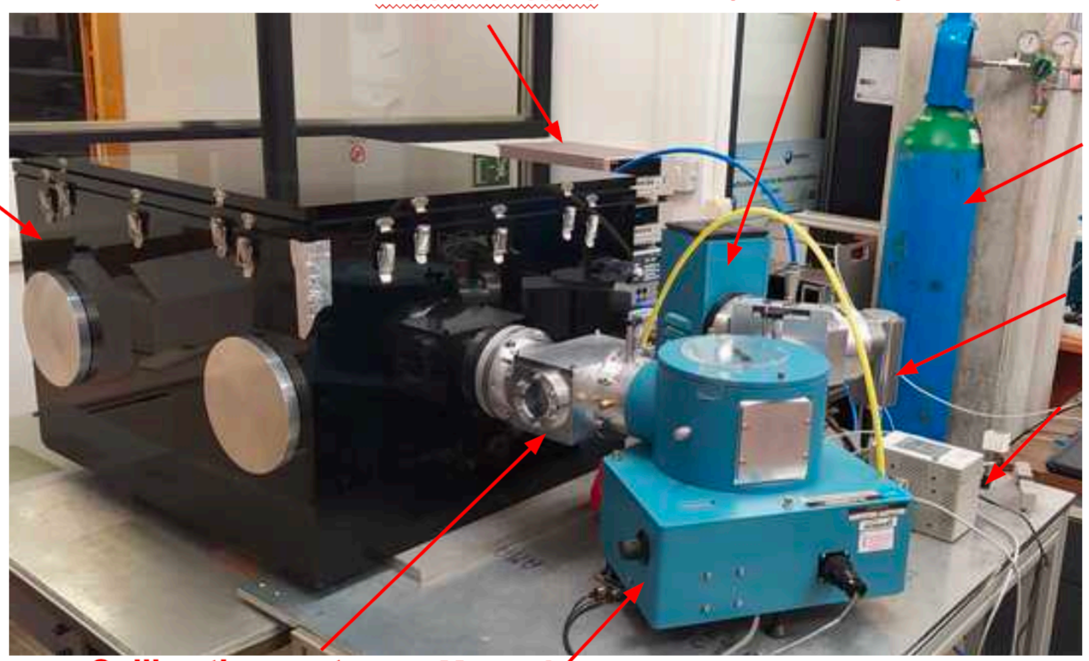
- Complex simulations involving light propagation, with absorption and Rayleigh scattering and reflections in detector components.
- Much better than the FD1-HD PDS values, particularly with regard to the spatial uniformity of the detector response.

Far Detector 2-VD: *Towards a PDS optimization at IFIC*

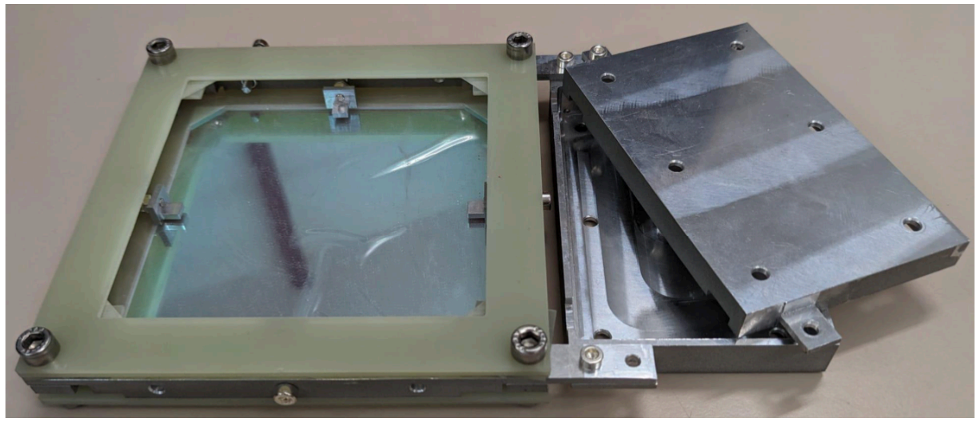
Optical measurements in the vacuum ultraviolet are critical for a better understanding and optimization of the photon detection system.

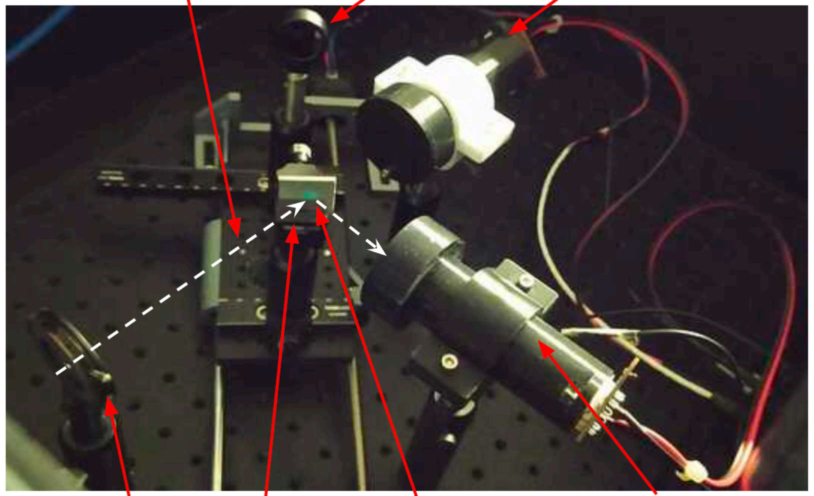
At IFIC our aims are:

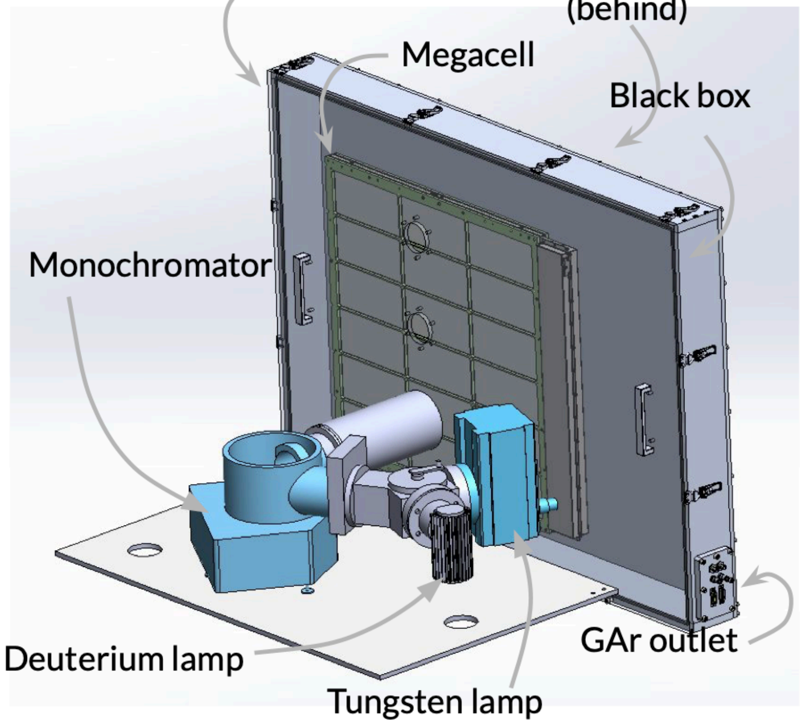
- **Photon collector design and optimization.**
  - Characterization of individual components (SiPM, WLS, DF, pTP…) with a mini-ARAPUCA.
  - Feedback from/to simulations to predict Photon Collection Efficiency (PCE).
  - PCE measurements with monochromator, which displays monochromatic VUV light,
- **Total light yield in *Far Detectors:*** specular and diffuse reflectance of all FD materials.



Mini-ARAPUCA

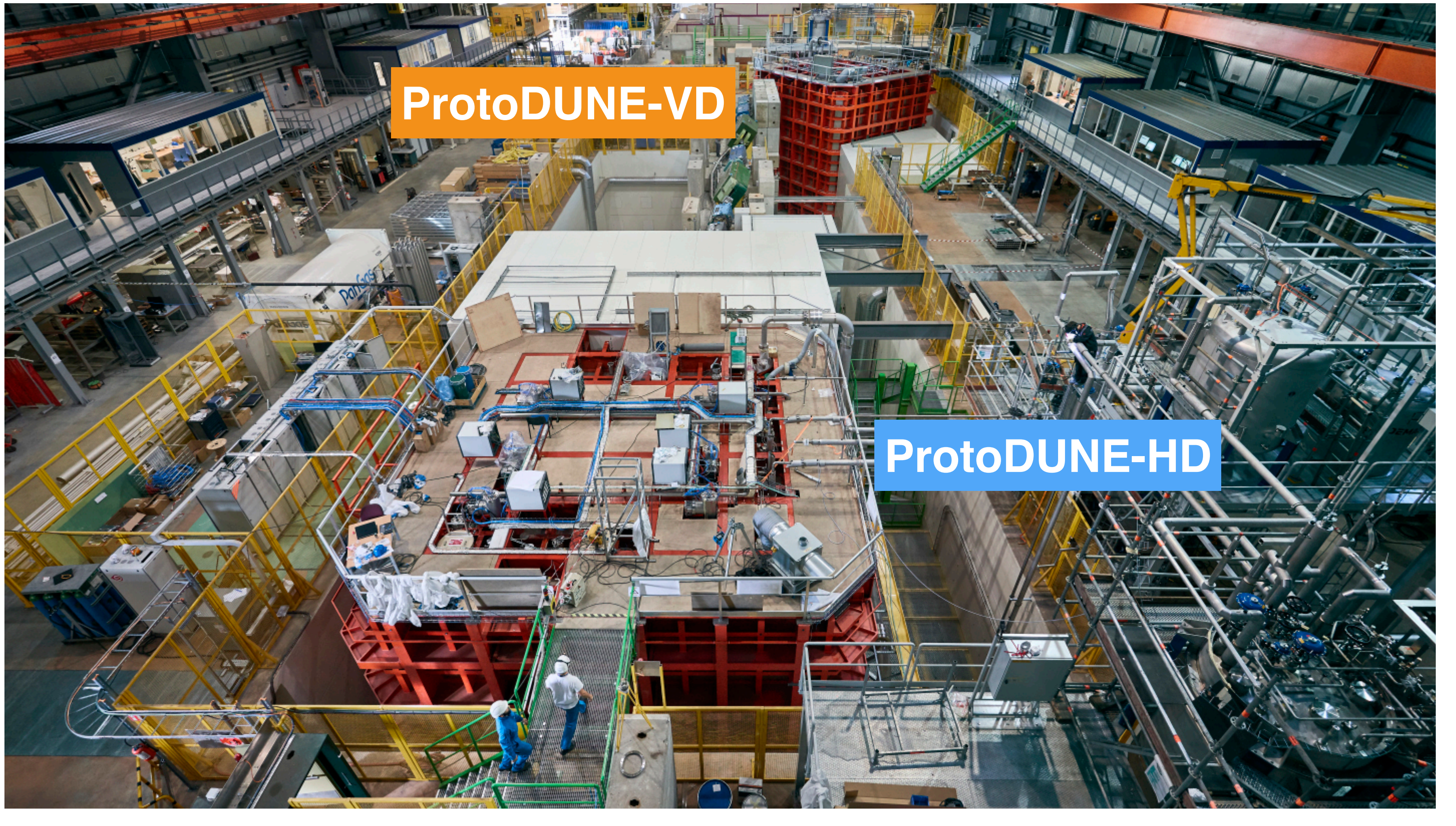




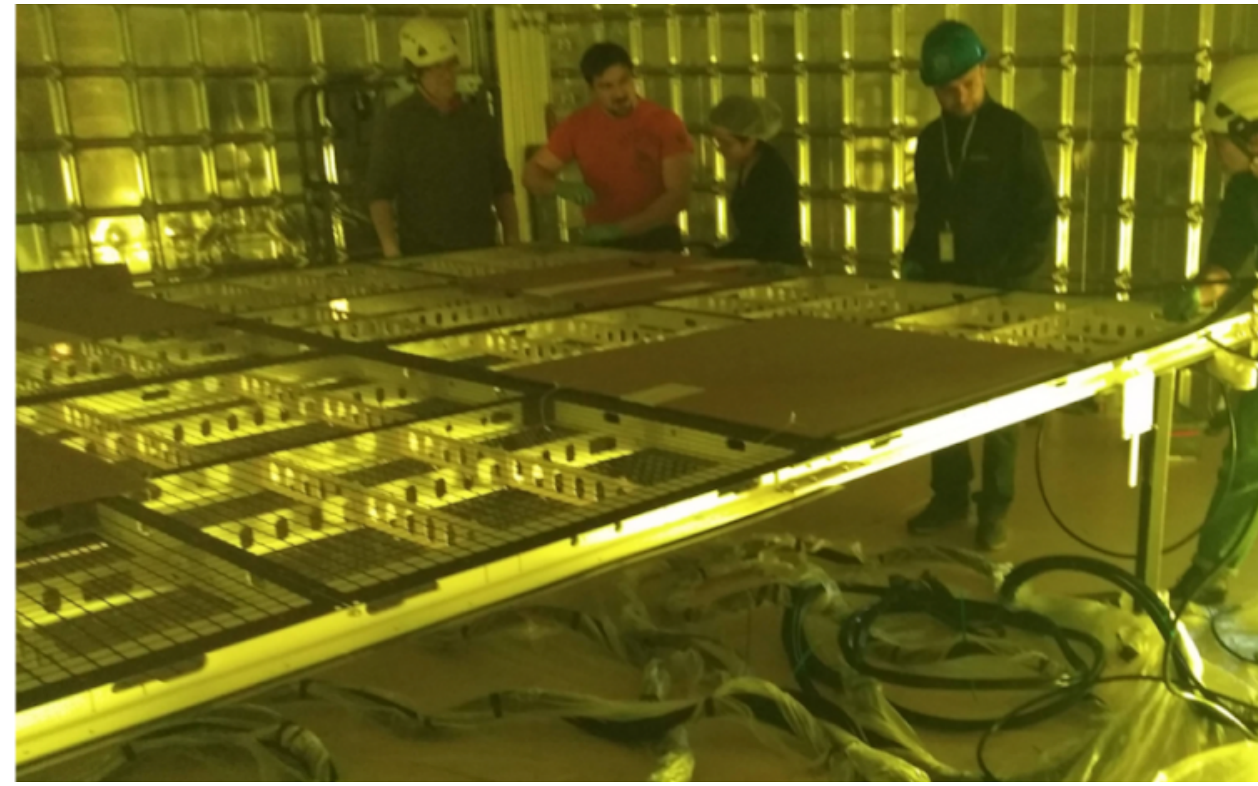


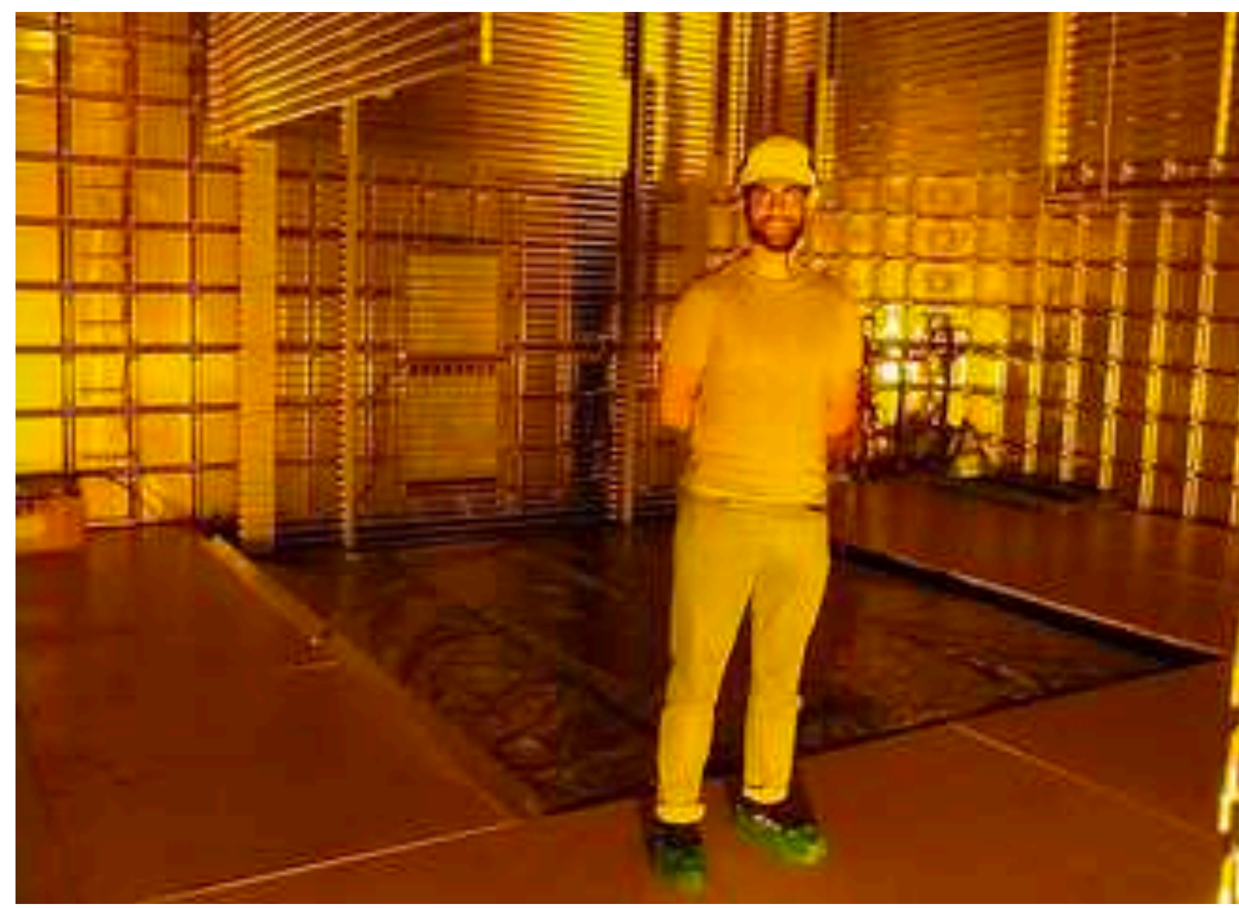
ProtoDUNE: *validation of the technology at CERN*

- Validation and technology choices based on tests in prototypes.
  - X-ARAPUCA concept proved to be suitable. PDE ≈ 2-3 %.
- New prototypes to replicate FD1-HD and FD2-VD designs.
- Upcoming run in January 2024 to test:
  - 40 PDs in ProtoDUNE-HD.
  - 16 PDs in ProtoDUNE-VD. (PDS is coordinated by A. Cervera, PI at IFIC).



ProtoDUNE: *validation of the technology at CERN*



The DUNE experiment: *summary*

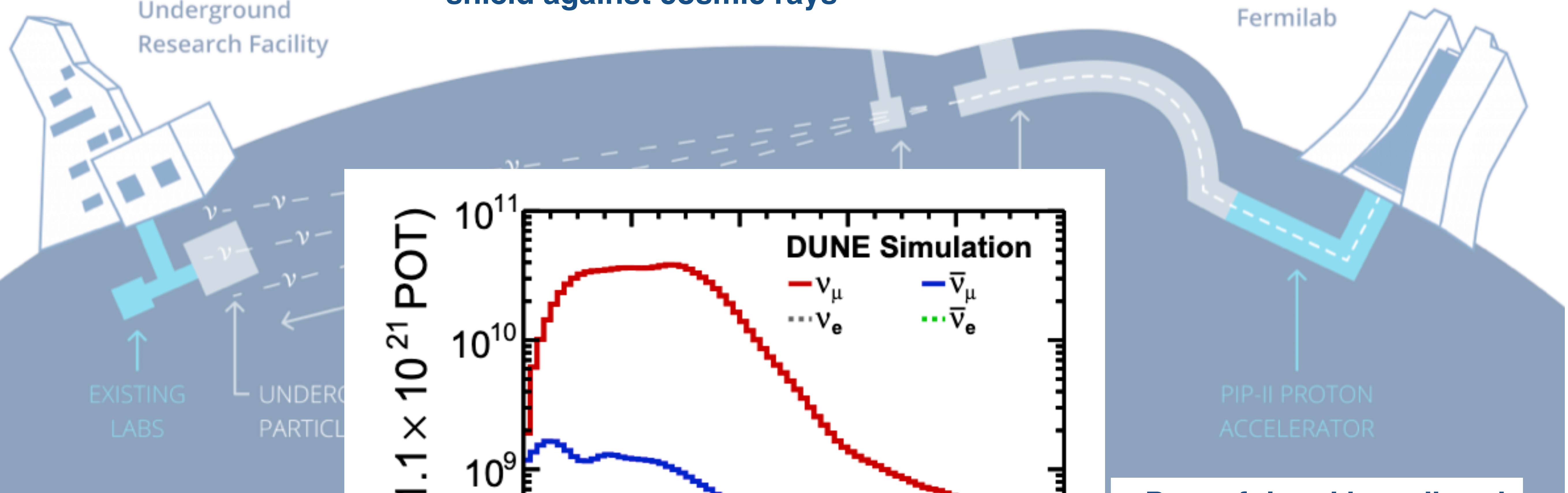
- The Photon Detector System (PDS) is a critical component of DUNE's far detector modules at SURF.
- PDS triggering, event t_0 measurement and precision calorimetry capabilities are all essential ingredients to meet DUNE's scientific program in long-baseline physics, neutrino astrophysics and BSM searches.
- For the past several years, DUNE-Spain groups have been contributing to the design, R&D and construction of the PDS systems for the FD1 and FD2 modules at SURF, and for their large-scale demonstrators at CERN.
- DUNE's far detector now under construction, with installation and operations starting in 2026 and 2029, respectively.

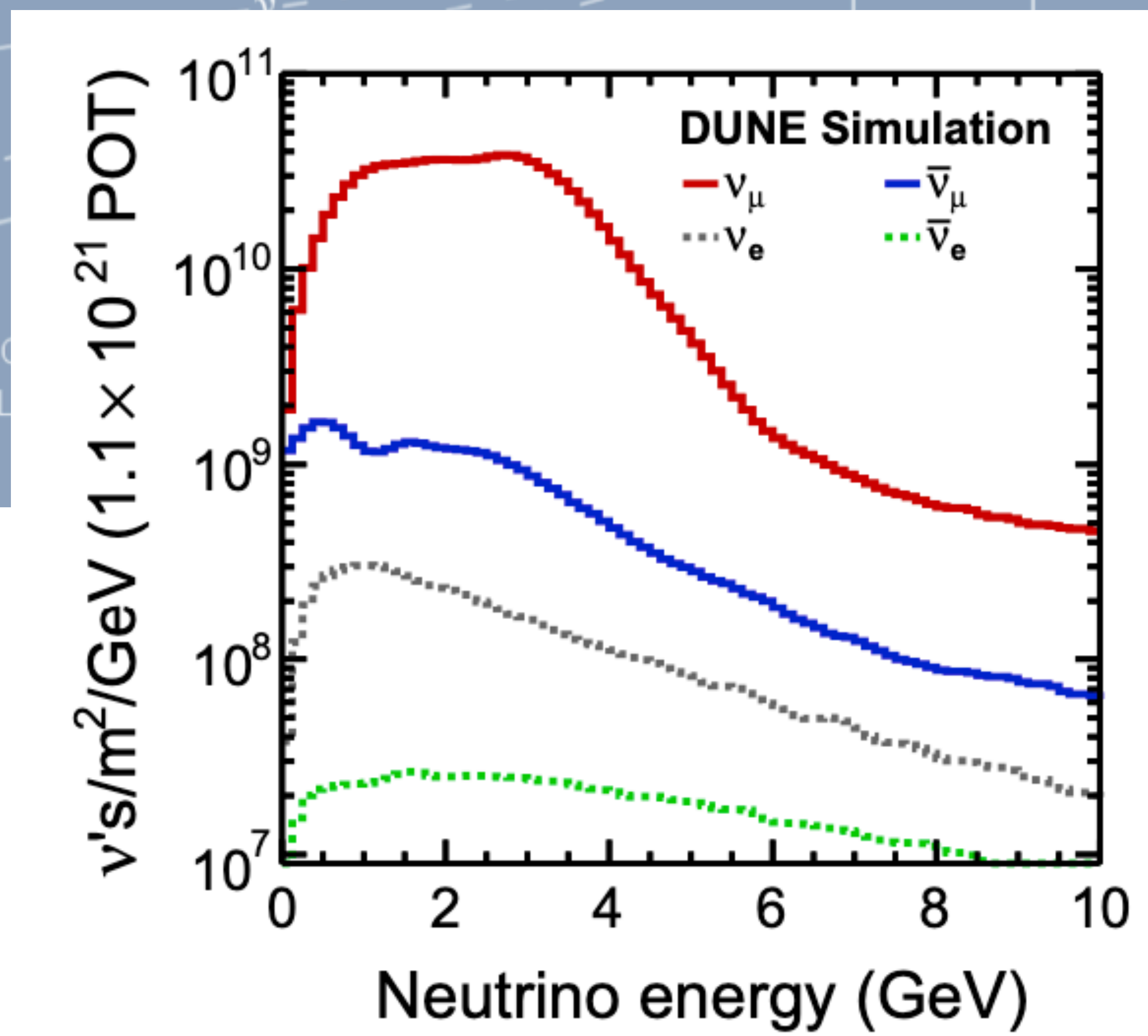
Stay tuned!!!

Backup

The DUNE experiment: *The LBNF neutrino beam*

Detectors underground to shield against cosmic rays

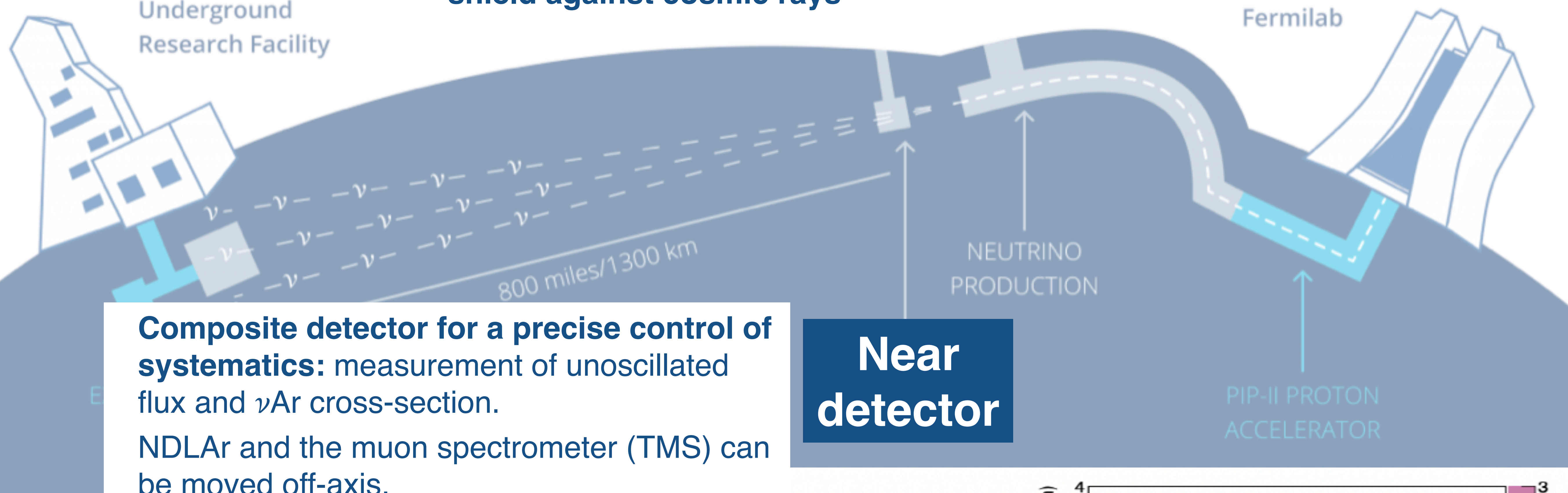




Powerful and broadband muon neutrino beam (foreseen proton beam power is 1.2 MW [upgradable up to 2.4 MW in a second phase]).

The DUNE experiment: *The Near Detector*

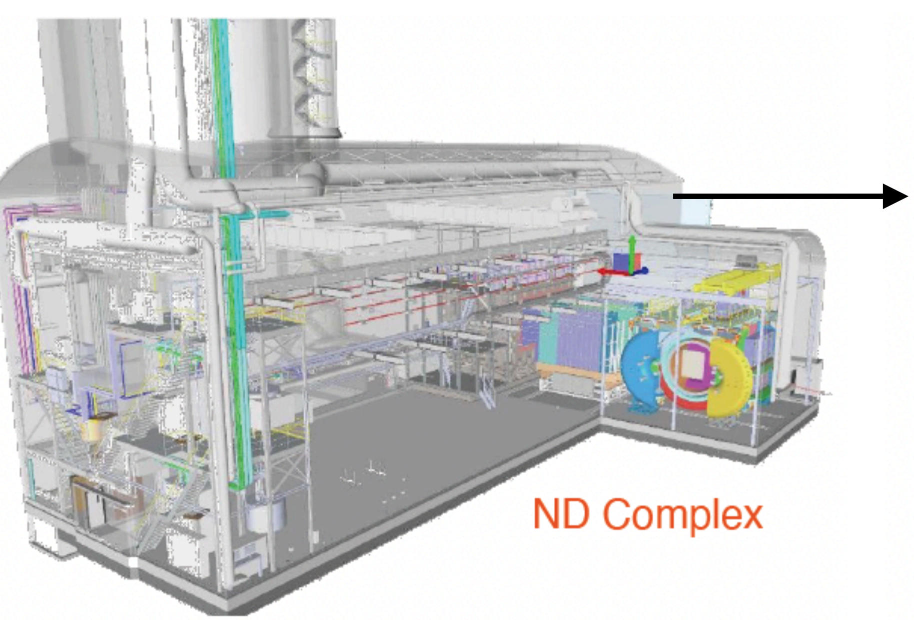
Detectors underground to shield against cosmic rays

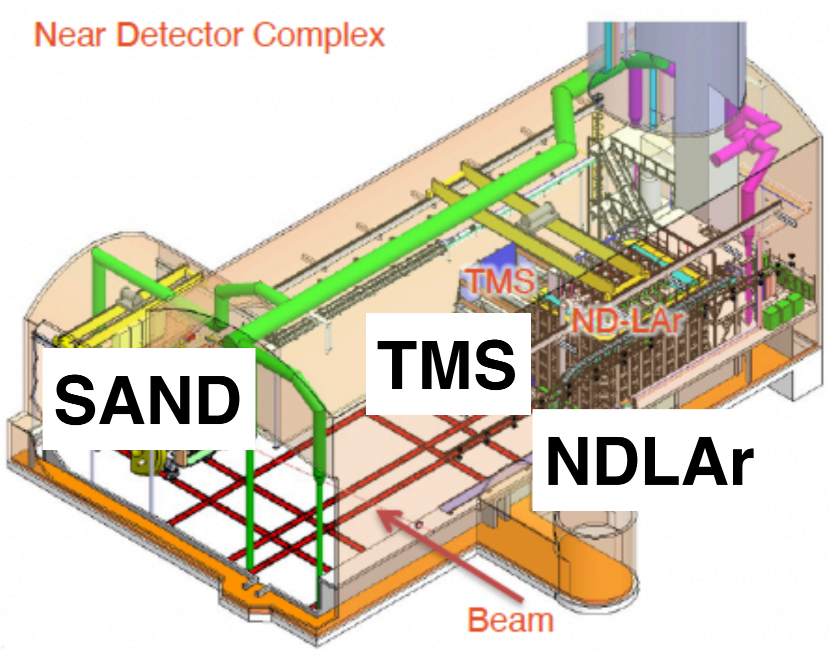


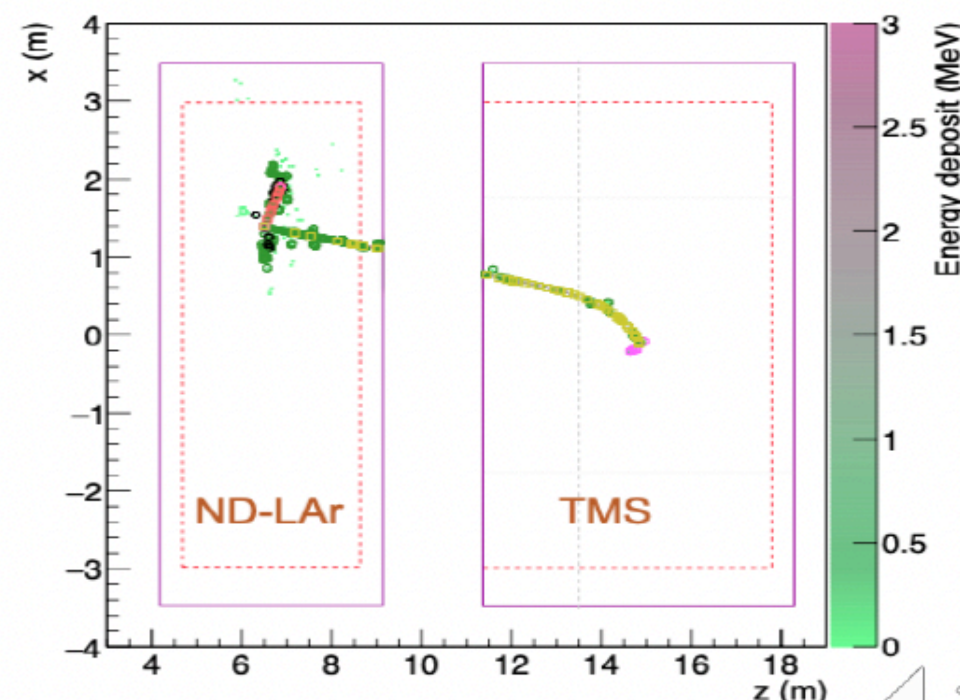
Composite detector for a precise control of systematics: measurement of unoscillated flux and νAr cross-section.

NDLAr and the muon spectrometer (TMS) can be moved off-axis.

Near detector





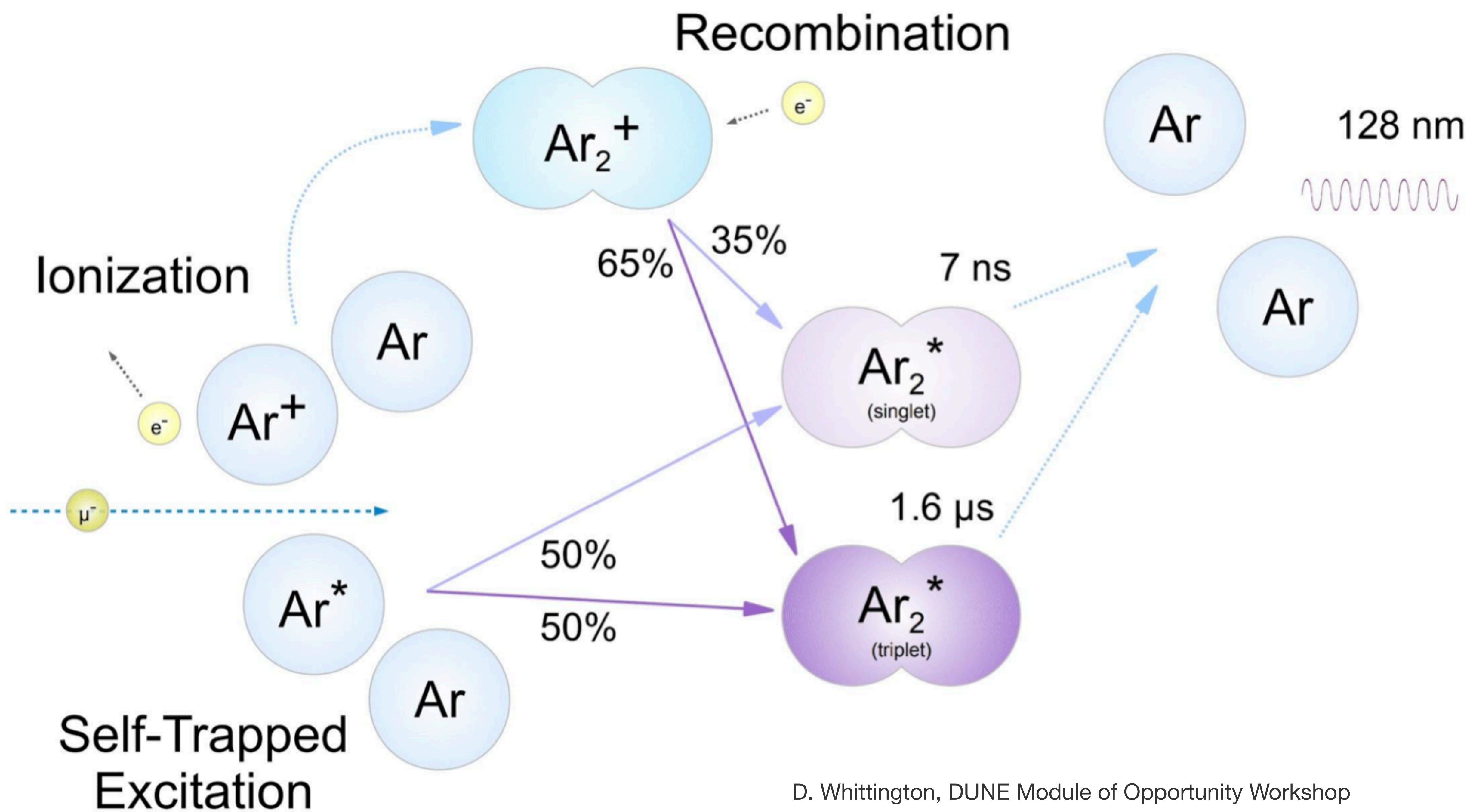


From M. Muether, *NEUTRINO2022*

TMS upgraded to NDGAr in a second phase (*IFIC is involved in the design and physics analysis*).

DUNE Far Detector: *LAr VUV light production*

- LAr VUV (vacuum ultraviolet) scintillation light (**λ = 128 nm**).
- Luminescence mechanisms: recombination & self-trapped excitation.

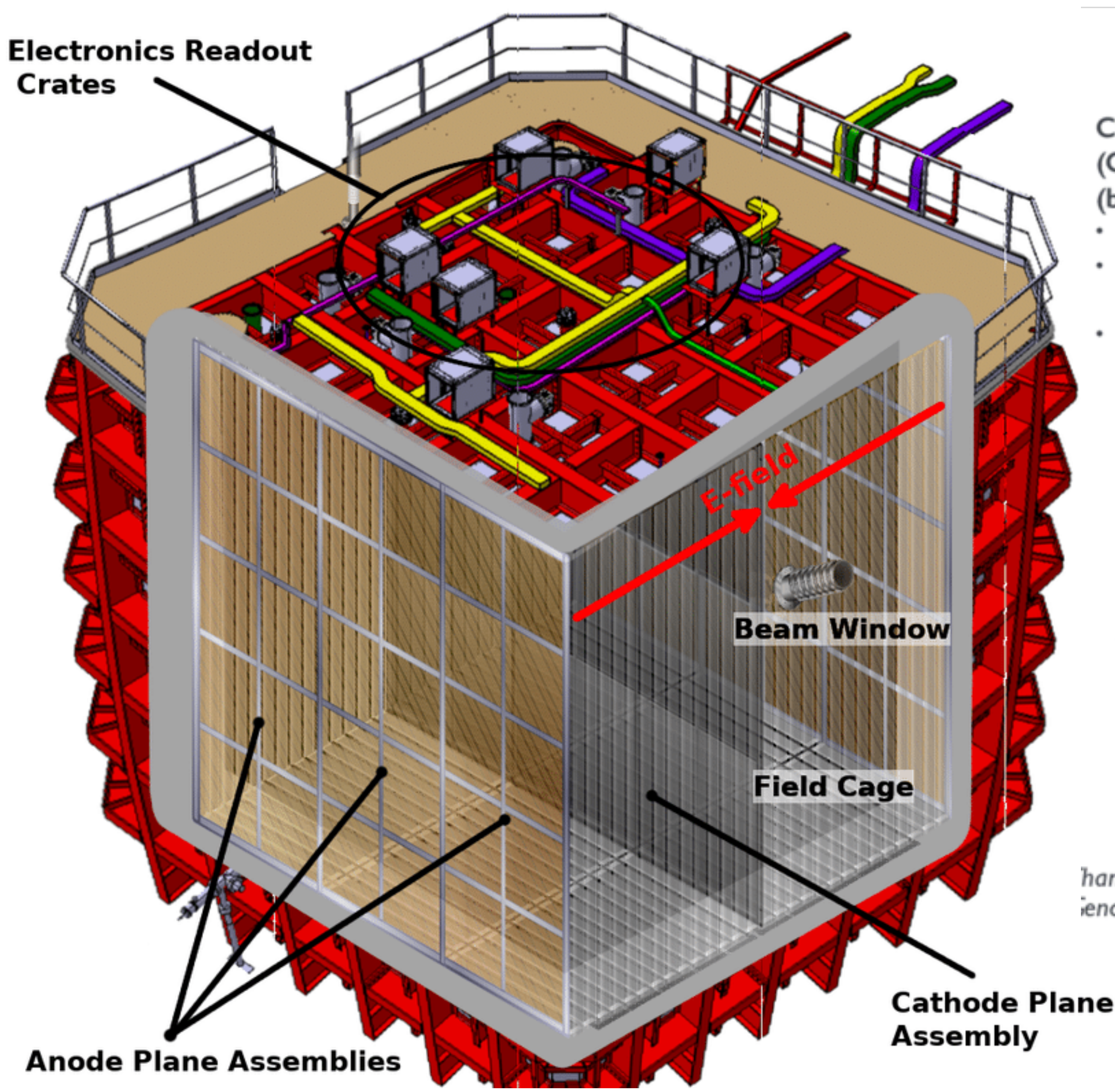


D. Whittington, DUNE Module of Opportunity Workshop

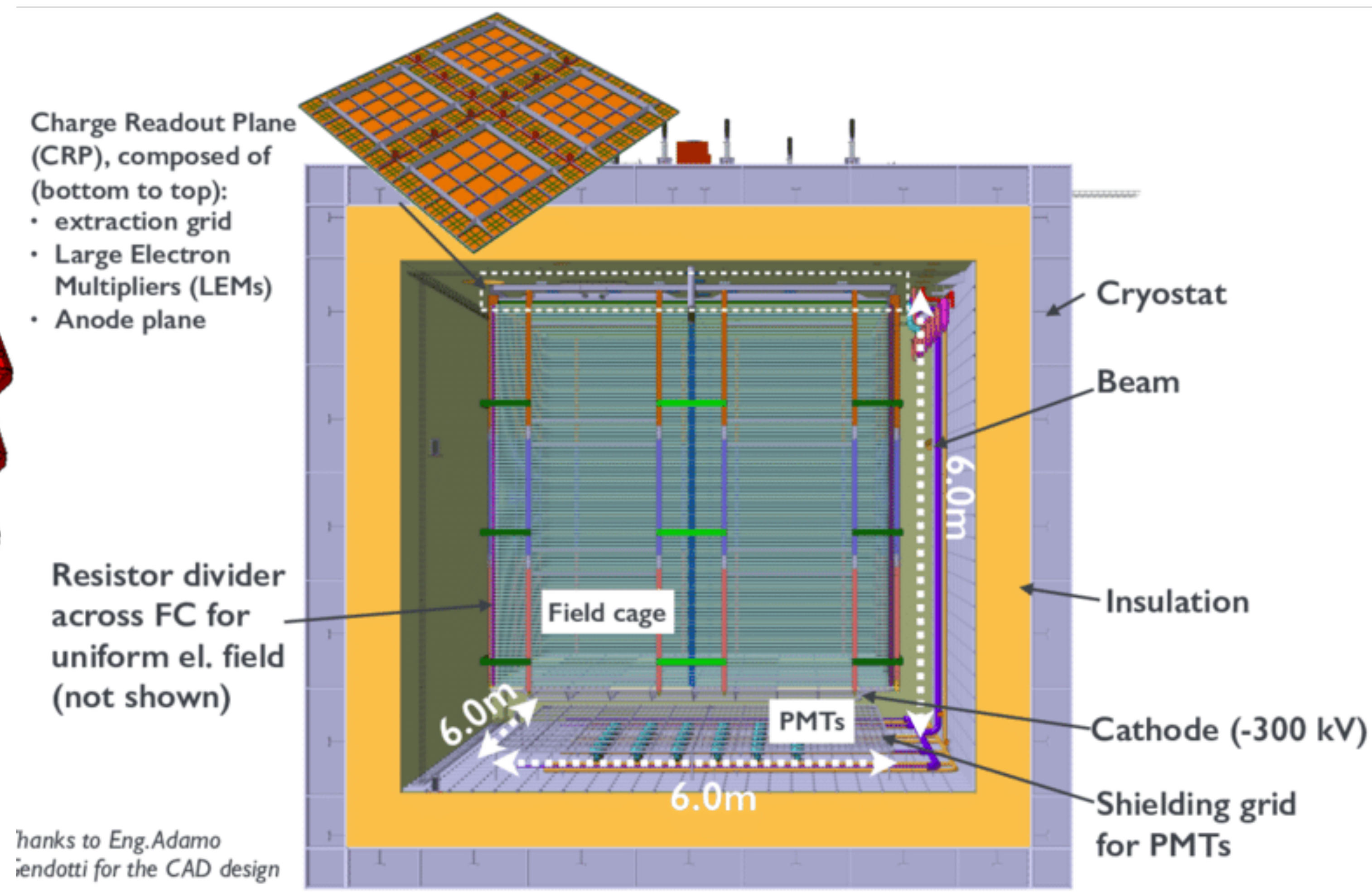
ProtoDUNE: *validation of the technology at CERN*

- Validation and technology choices based on tests in prototypes.
  - X-ARAPUCA concept proved to be suitable. PDE ≈ 2-3 %.
- The first run (2018-2020) served to opt for single phase technology (LAr only).

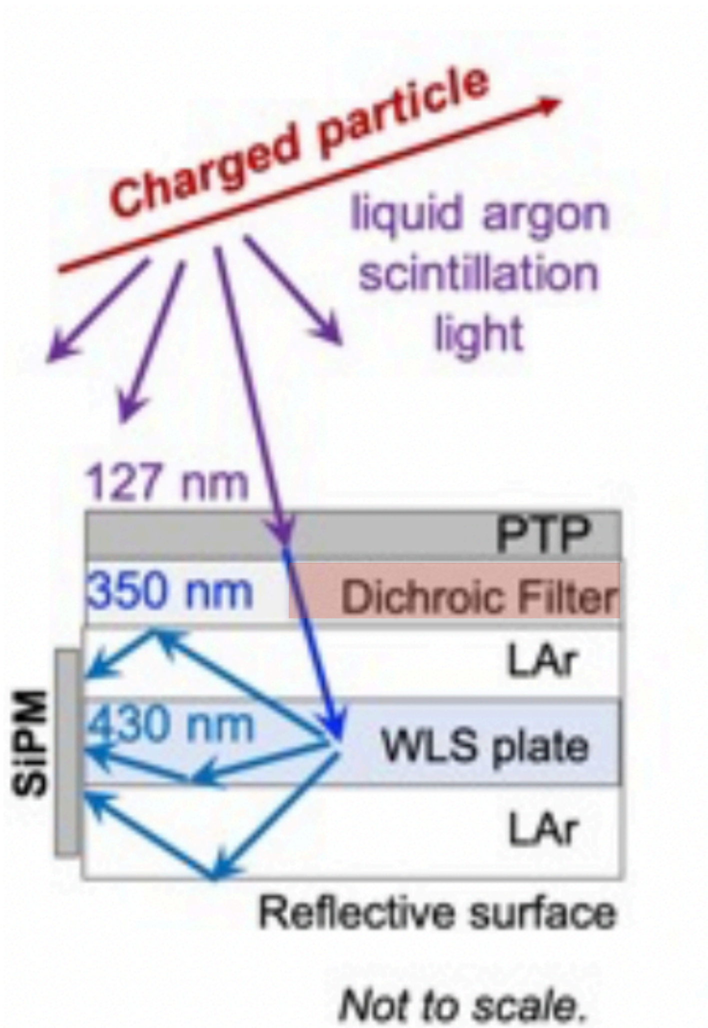
ProtoDUNE-SP



ProtoDUNE-DP



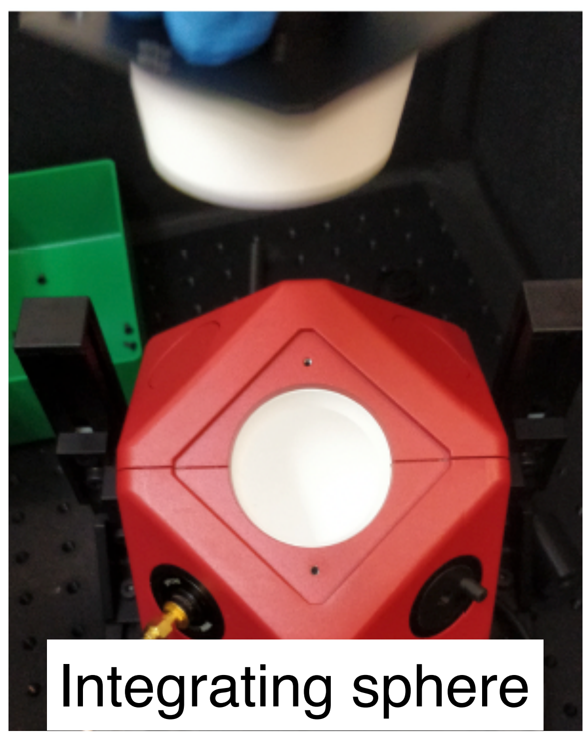
The DUNE experiment: *Towards FD2*



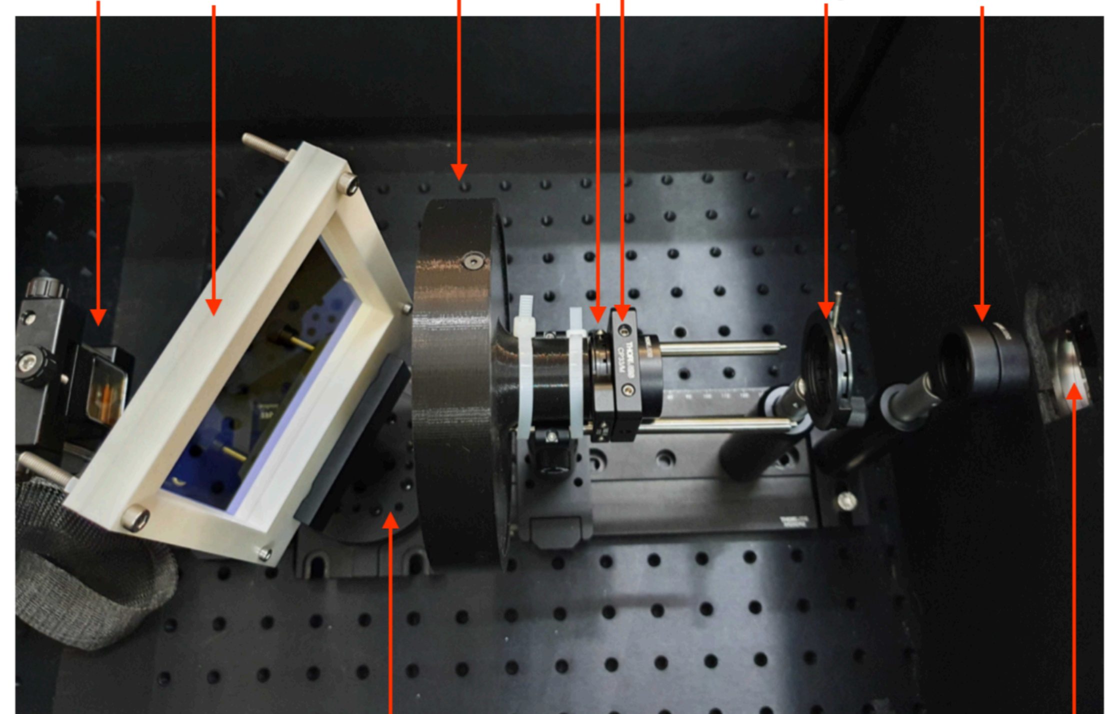
R&D

- IFIC involved in the characterisation and optimisation of the X-ARAPUCA components towards an optimised design for FD2. R&D in dichroic filters in collaboration with the Spanish company PhotonExport.

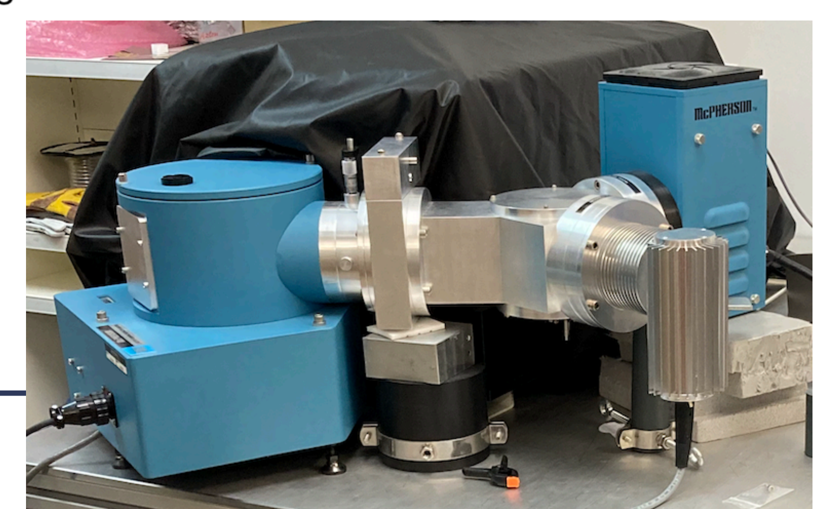
New optics and cryogenic laboratory settled at IFIC



Integrating sphere

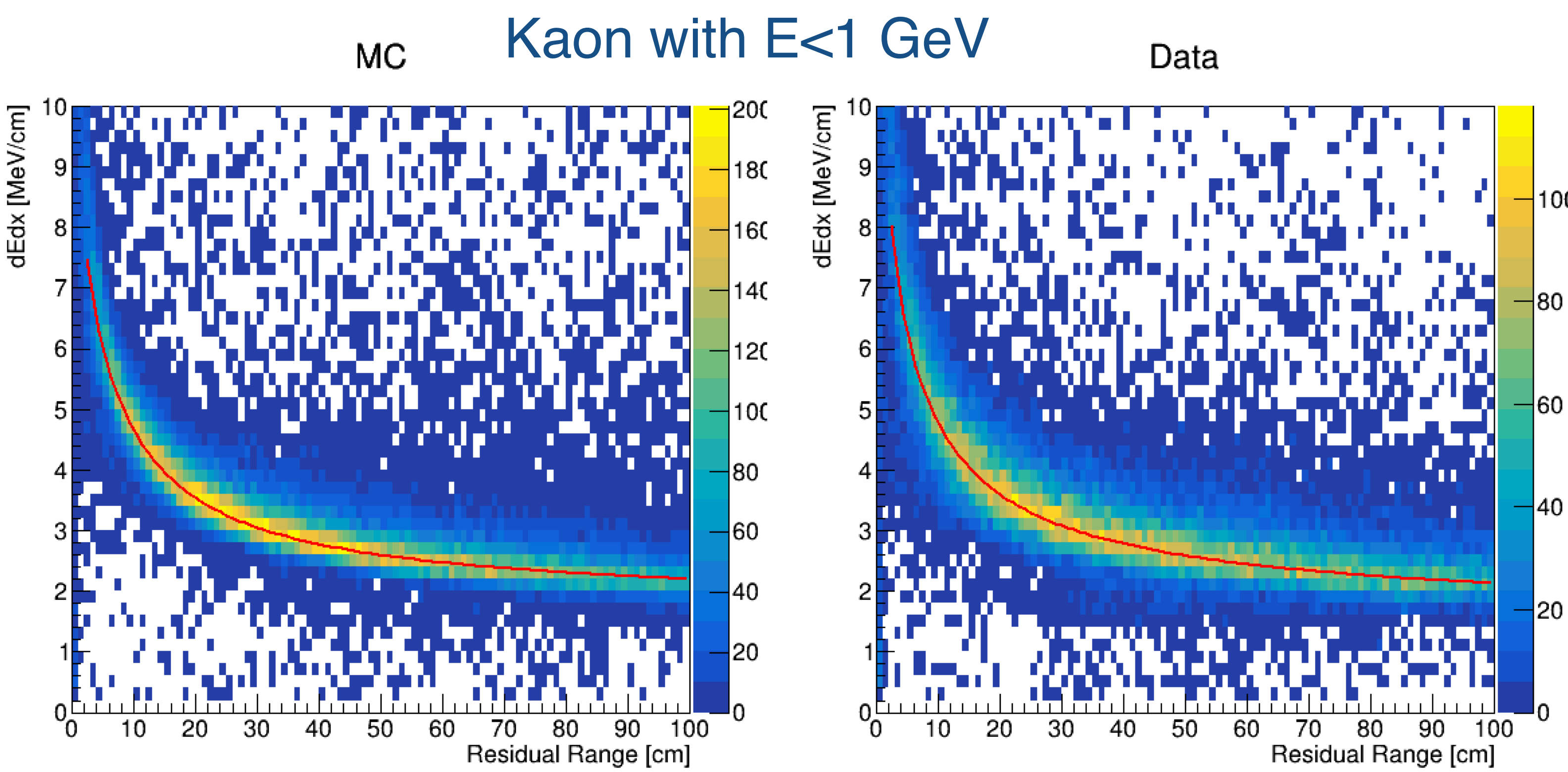


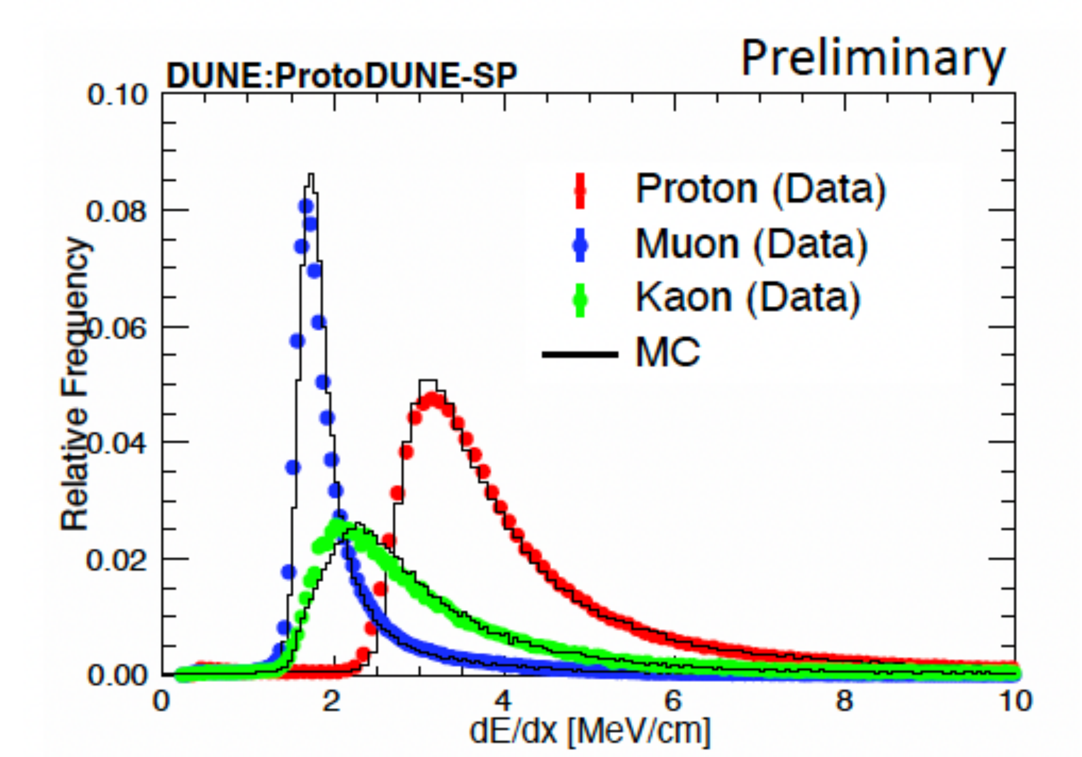
- Optimisation of the layout of the light collectors to maximise the light yield in FD2 through simulations.
- Optimisation of the photon-detector system through simulations towards low energy searches such as proton decay (co-convener of "PDS physics and simulations" M. Sorel.).



The DUNE experiment: *Analysis of ProtoDUNE data*

Searches for ***proton decay*** $\boldsymbol{p \rightarrow K^{+} + \bar{\nu}}$ rely on the ability to distinguish a single K+ originating inside the fiducial volume of the detector





M. Peris, PhD student of A. Cervera