

Neutrino Physics

Carmen Palomares for the CIEMAT neutrino group

Scientific Advisory Committee
12 March 2026



Scientific Goals

Neutrino Oscillations:

- Testing of 3-flavour unitary mixing model: Precise measurement of its parameters, including the CP-violation phase
- Neutrino mass ordering

$$\mathbf{U}_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

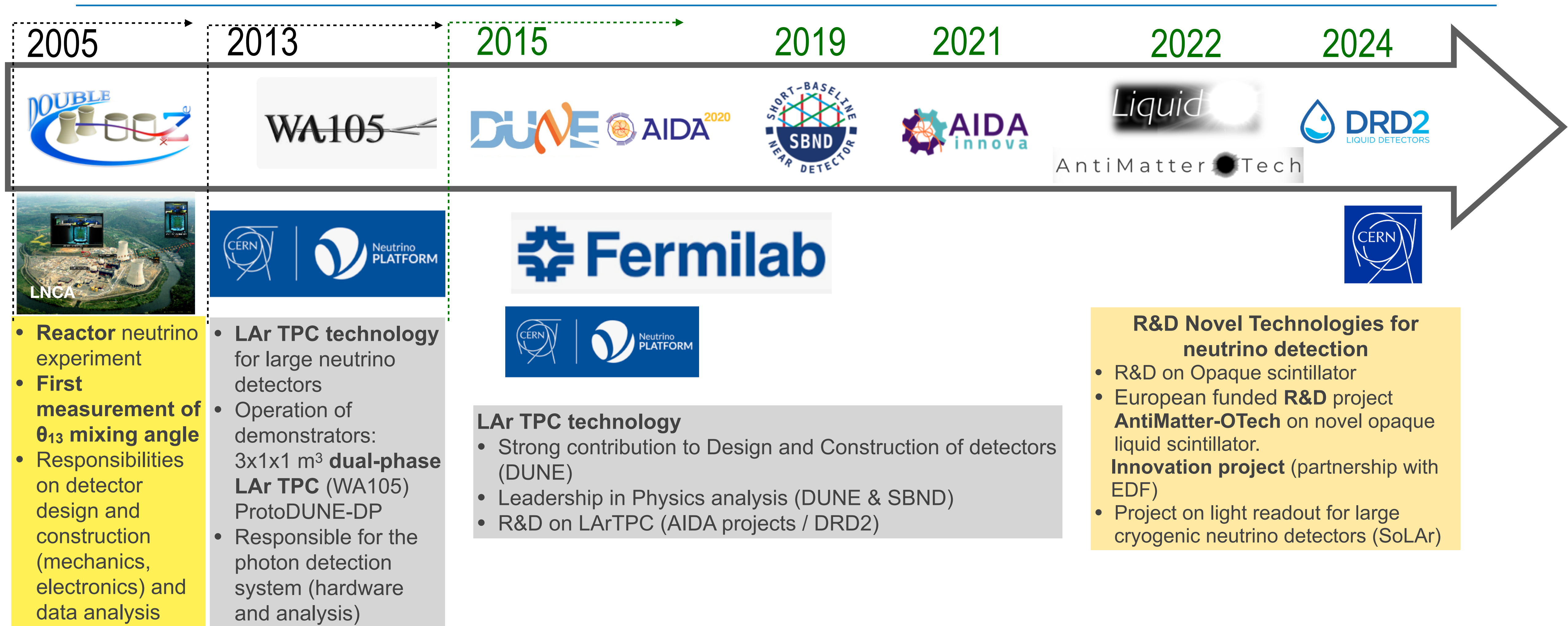
Astrophysical neutrinos:

Neutrinos can help to understand astrophysical processes such as a core collapse Supernova or Sun nuclear reactions

Development of neutrino detection:

- Contribution to the Design and Construction of new, more performant detectors
- R&D on new technologies that drive cutting edge detection techniques

Neutrino Projects



CIEMAT Neutrino Group



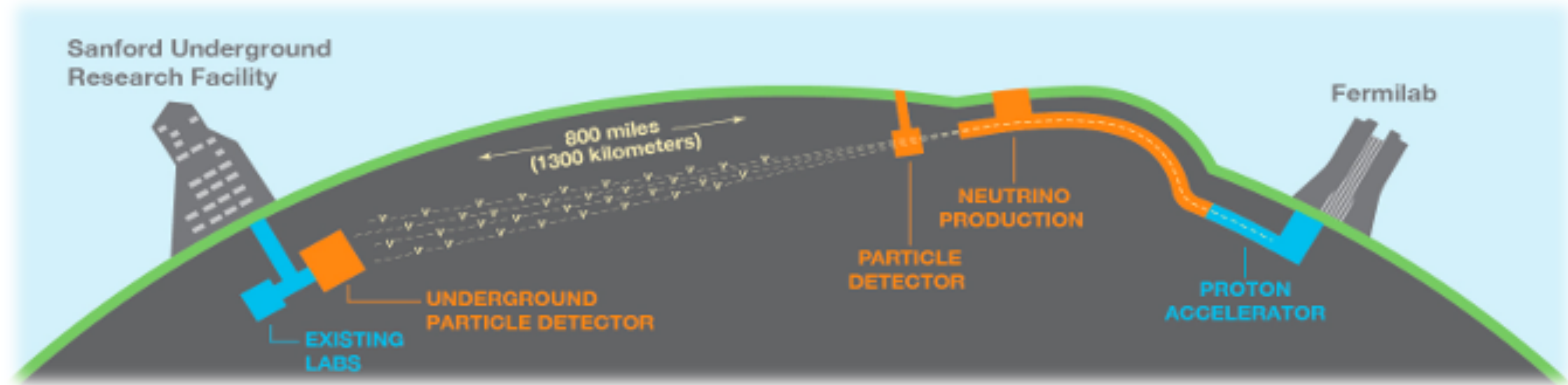
Mid 2023 - Mid 2025

- **Research scientists:** 5
- **PhD students:** 5 (2 ended in 2025) (+1 starting in March)
- **Research assistant:** 1
- **Engineers:** 3 (1 ended in 2025) (+1 starting in March)
- **Technicians:** 2 (1 ended in 2024) (+1 starting in April)

TOTAL = 16 (4 left the group and 3 starting soon)

- Cohesive core team working together for more than 20 years.
- **Strong technical expertise** (mechanics, electronics, photo-detection, cryogenics, vacuum...).
- **Leading physics analyses** and MC simulations.
- Temporary: 6 TFMs, 2 internships, 1 sabbatical prof. (UC Davis), 6 international internships.
- Continuously funded in competitive calls by the Spanish National Program since 2005 and MICINN, EU H2020, Horizon Europe, EIC, CAM and private calls.

DUNE: Long-baseline neutrino experiment

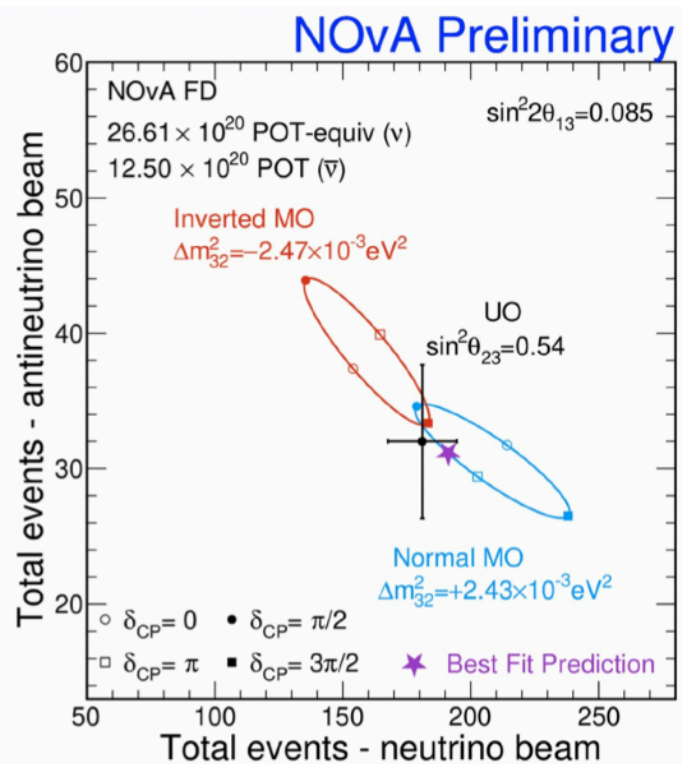


- **LBNF ν_μ and $\bar{\nu}_\mu$ beam** operating at 1.2 MW → Upgradeable to 2.4 MW. Wide-band high purity ν_μ -beam with peak flux at 2.5 GeV.
- **Near Detector Complex** at 540m from neutrino source: pixelated-LArTPC, TMS/magnetised GAr TPC & magnetised beam monitor. Movable ND. Critical for systematic error control.
- **LArTPC Far Detector**: 70 kton (4 x 10 kt fiducial) at 1480 m depth (4300 mwe) at SURF measuring neutrino spectra at 1300 km

DUNE

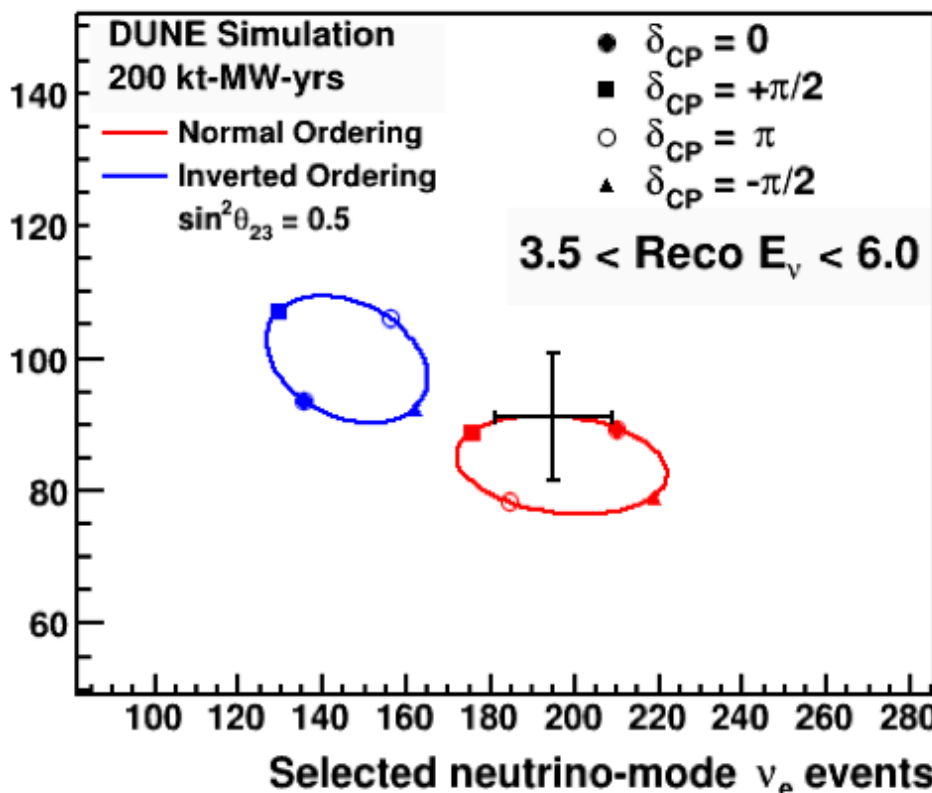
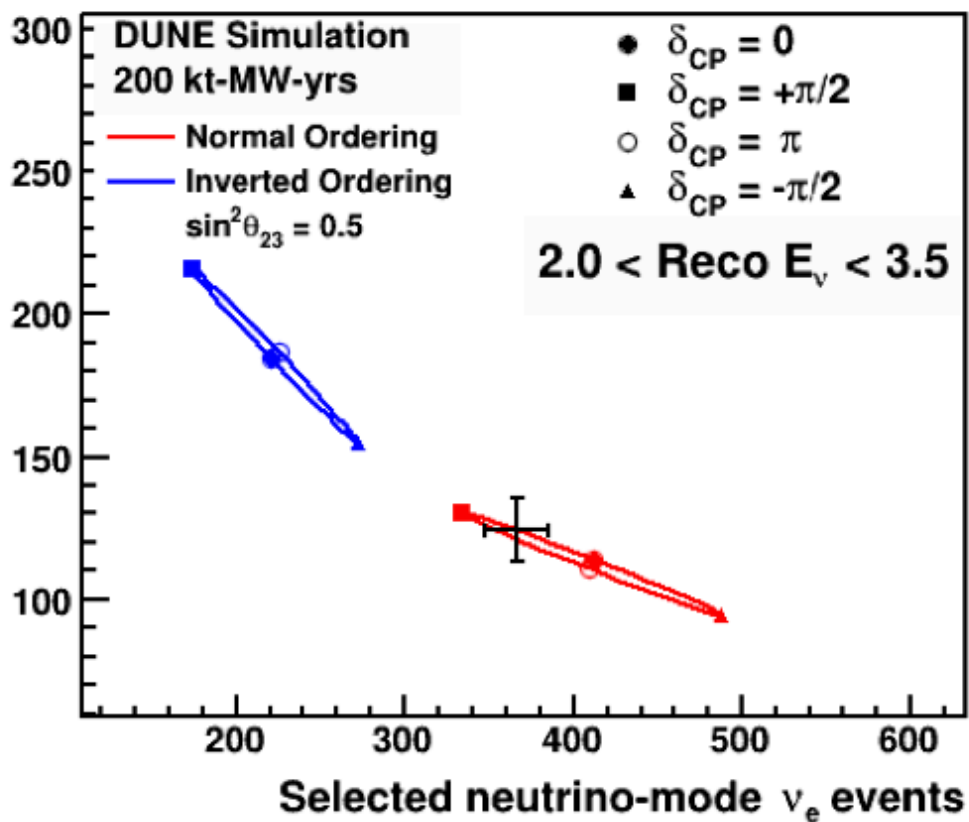
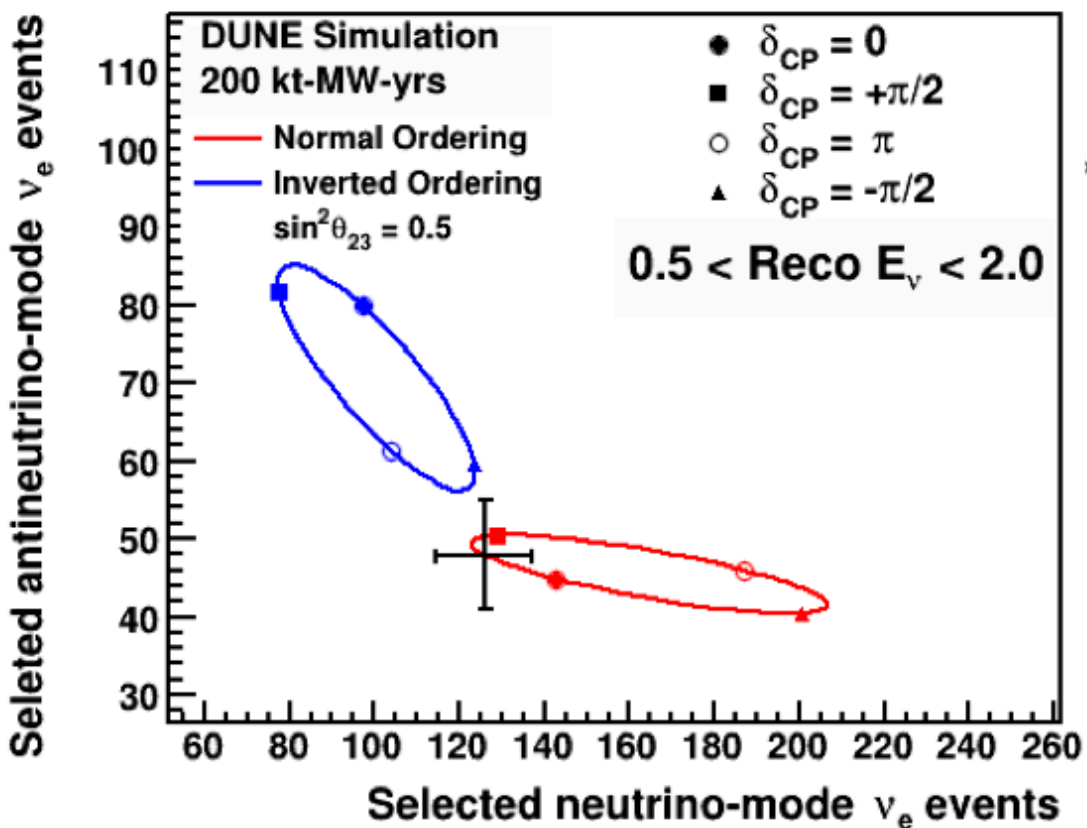
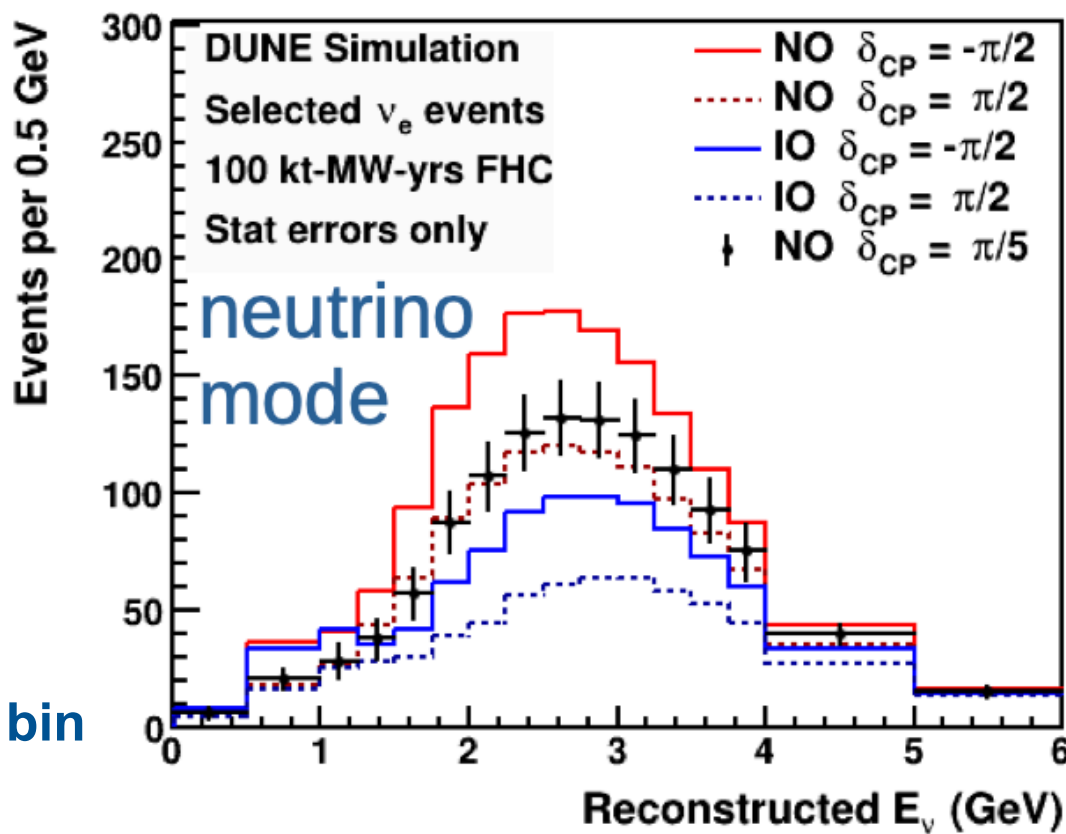
Measurement of ν_e appearance and ν_μ disappearance with a wide range energy ν_μ beam at 1300 km would allow:

- Measurement of **neutrino Mass ordering at 5σ** in 1-3 years of data taking
- Discovery potential for **CP violation for wide range of δ_{CP}**
- Precise measurement of **neutrino mixing parameters**



From **NovA**
to **DUNE**

- Parameters are not degenerate in DUNE
- They can be measured at each L/E bin
- If 3-flavour PMNS correct same values in every bin
- New physics can distort this result



>1500 collaborators from
~250 institutions in > 35 countries + CERN.
5 institutions, ~ 50 collaborators.



No Beam Physics

- Supernova Neutrino Burst: ν_e sample providing unique information of the neutronization phase.
 - Solar neutrino: sensitive to hep reaction
 - BSM physics
- CIEMAT is leading sensitive studies for Supernova and Solar neutrinos (low-energy Physics coordination)

CIEMAT leading role as physics coordinator

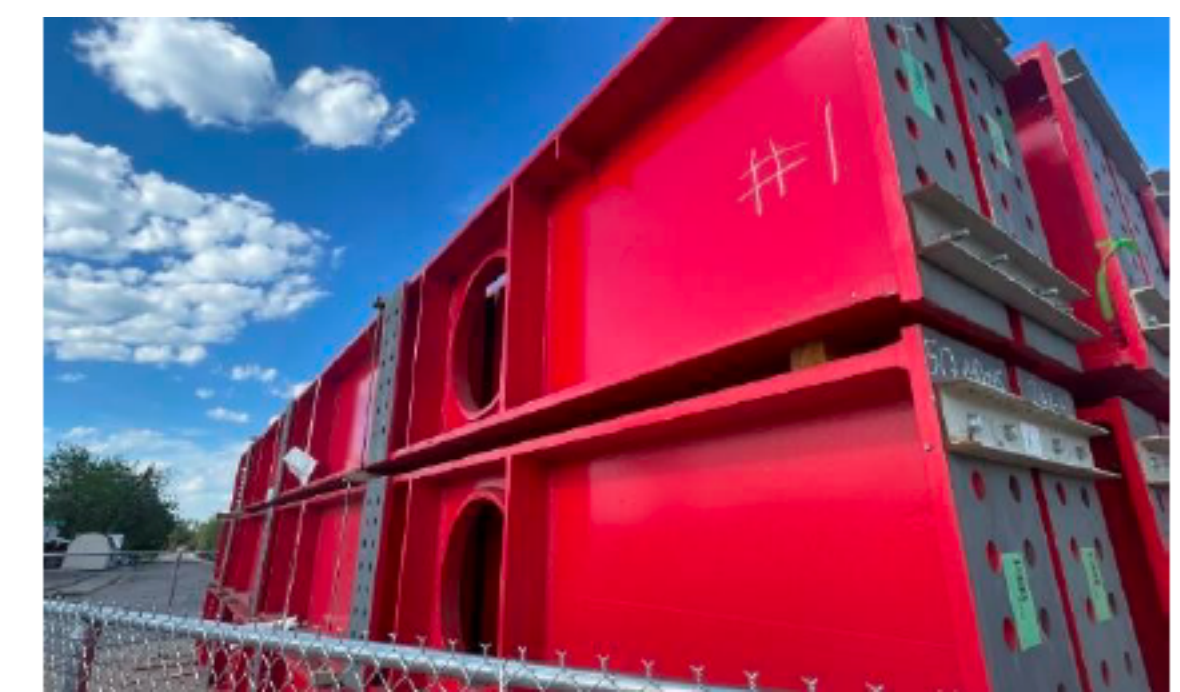
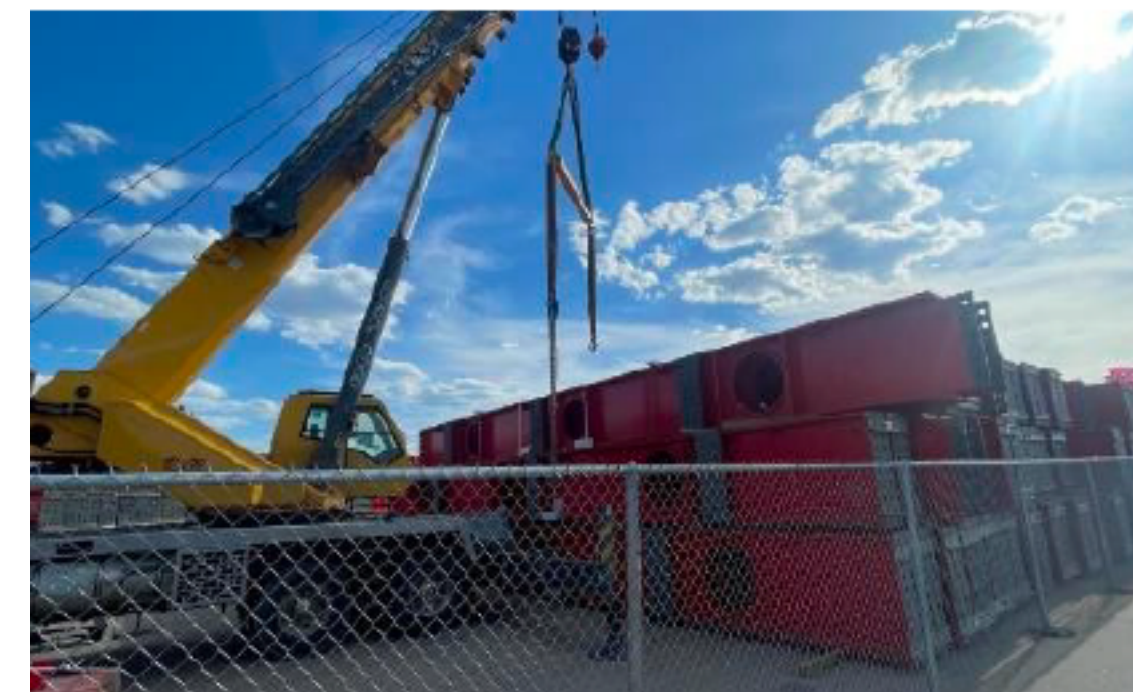
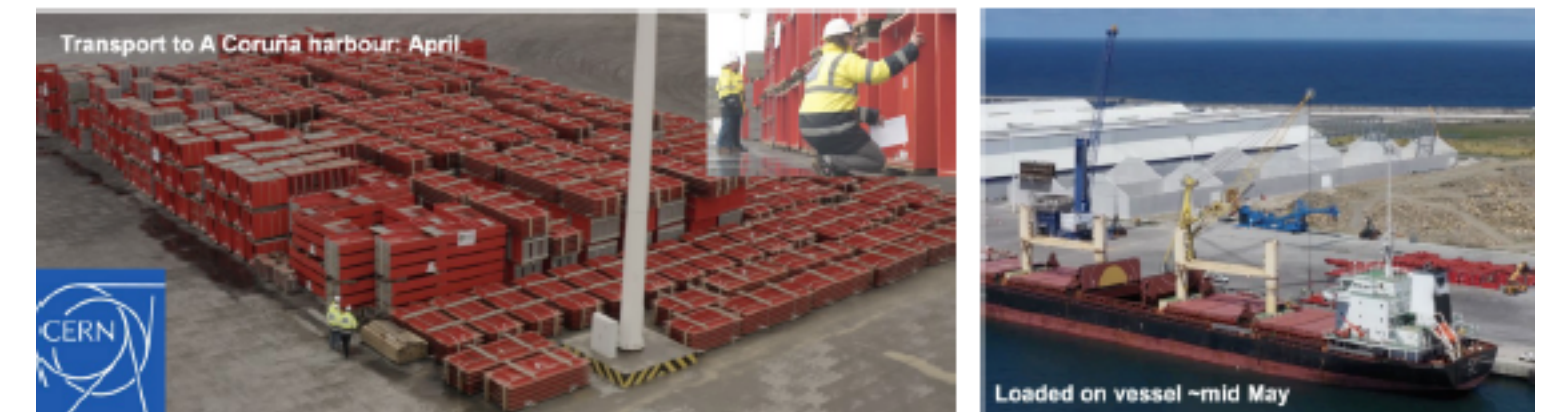
DUNE Status and time

- Far site excavation complete ✓
- Building & Site Infrastructure ongoing
- Cryostat installation by 2026
- Far detector 1 installation by mid 2027
- Far detector 2 installation by 2028
- Physics by 2030

Solar, atmospheric and astrophysical neutrinos

- Beam physics with near detector by 2032

Full physics scope



DUNE Status and time

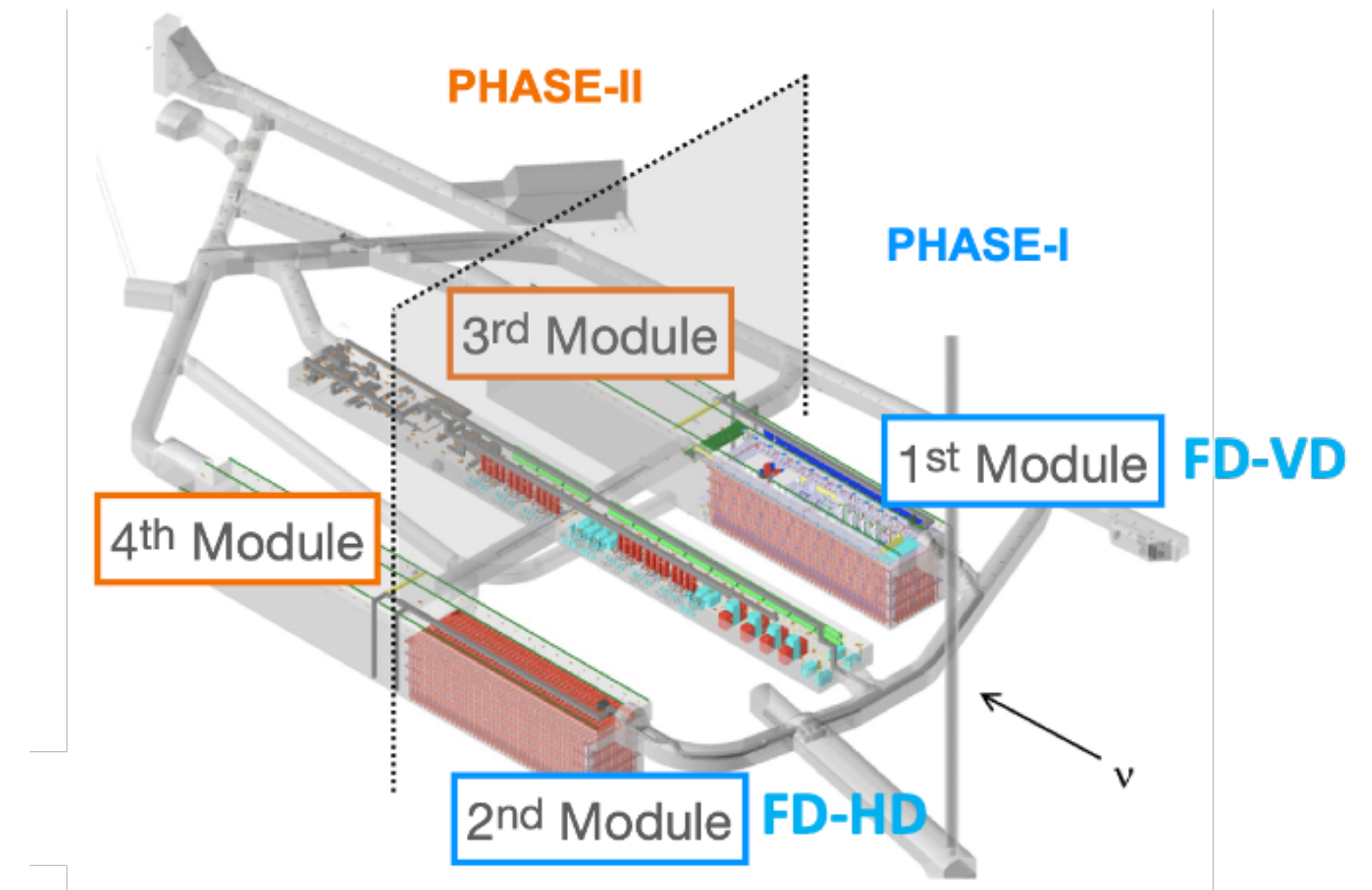
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Solar, atmospheric and astrophysical neutrinos

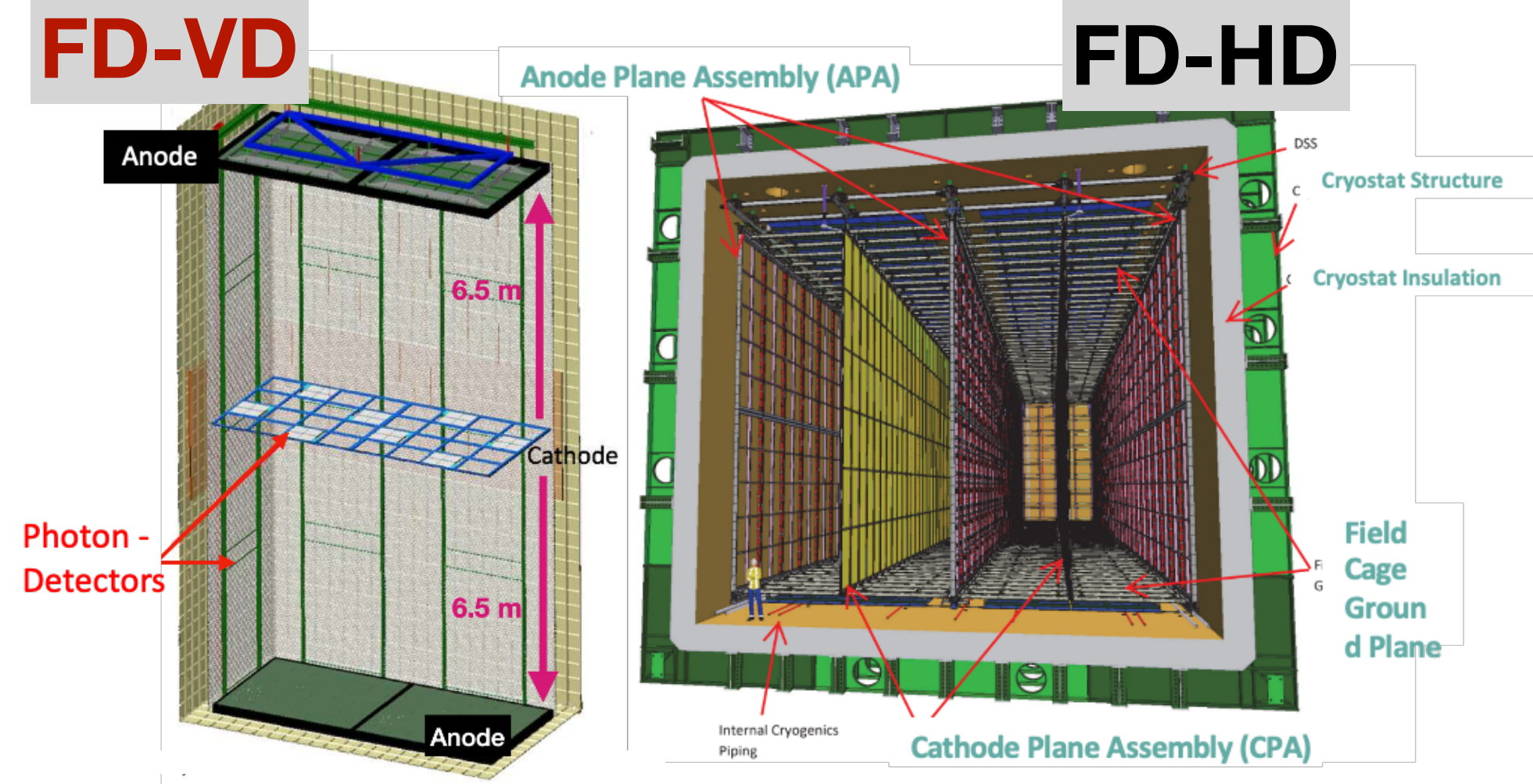
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Full physics scope

Two-phase approach
Improvements in technology
implemented in Phase-II

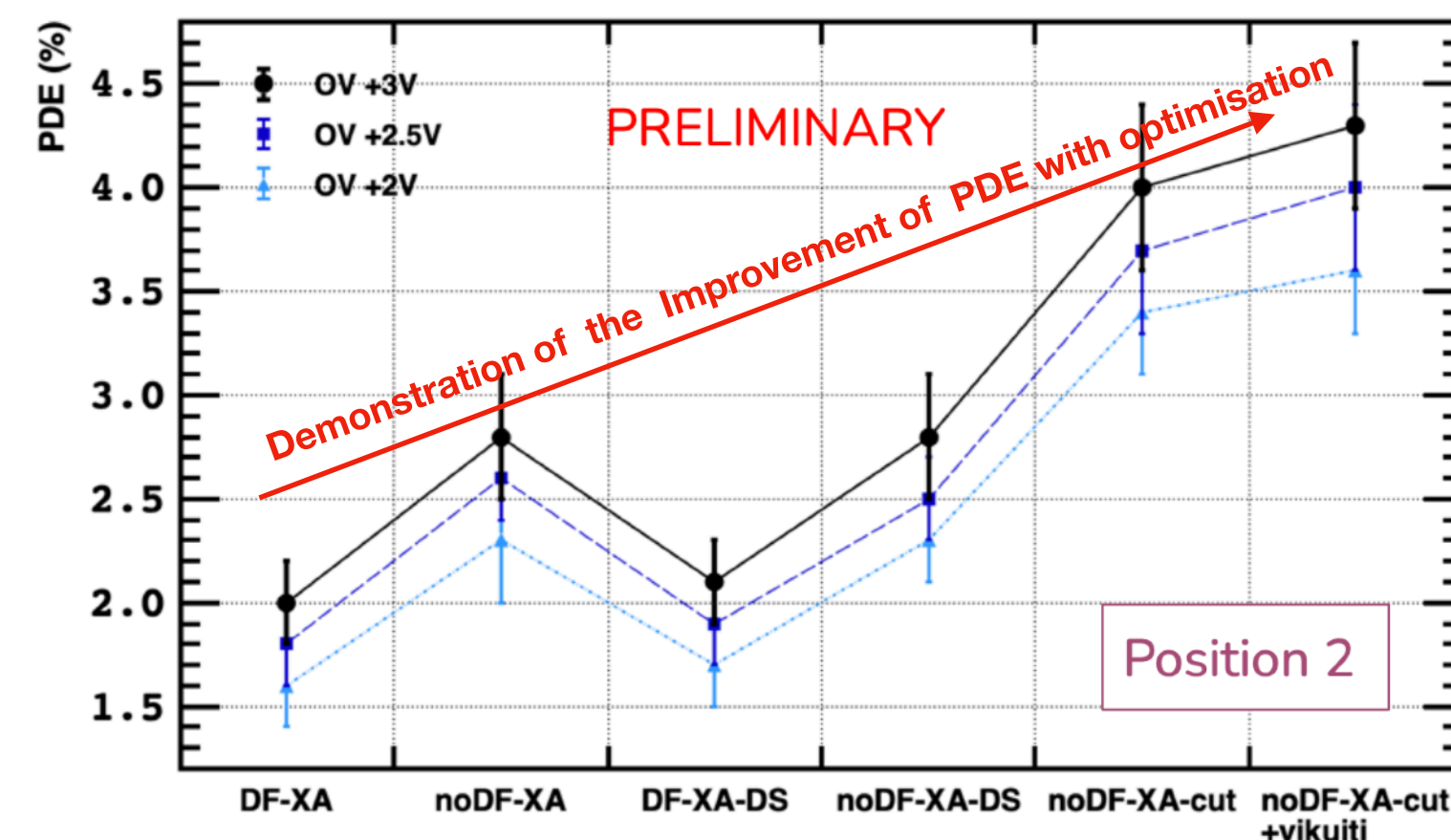
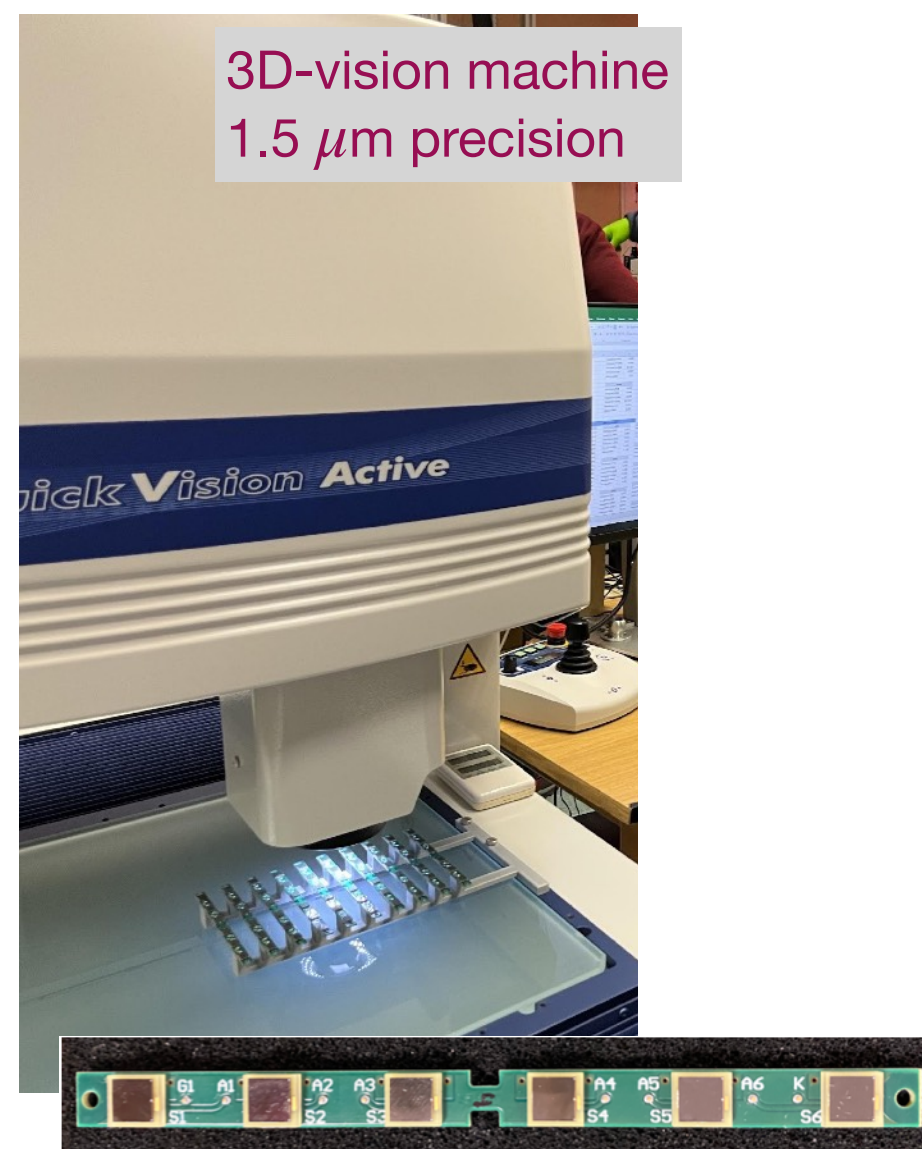


DUNE Far Detector

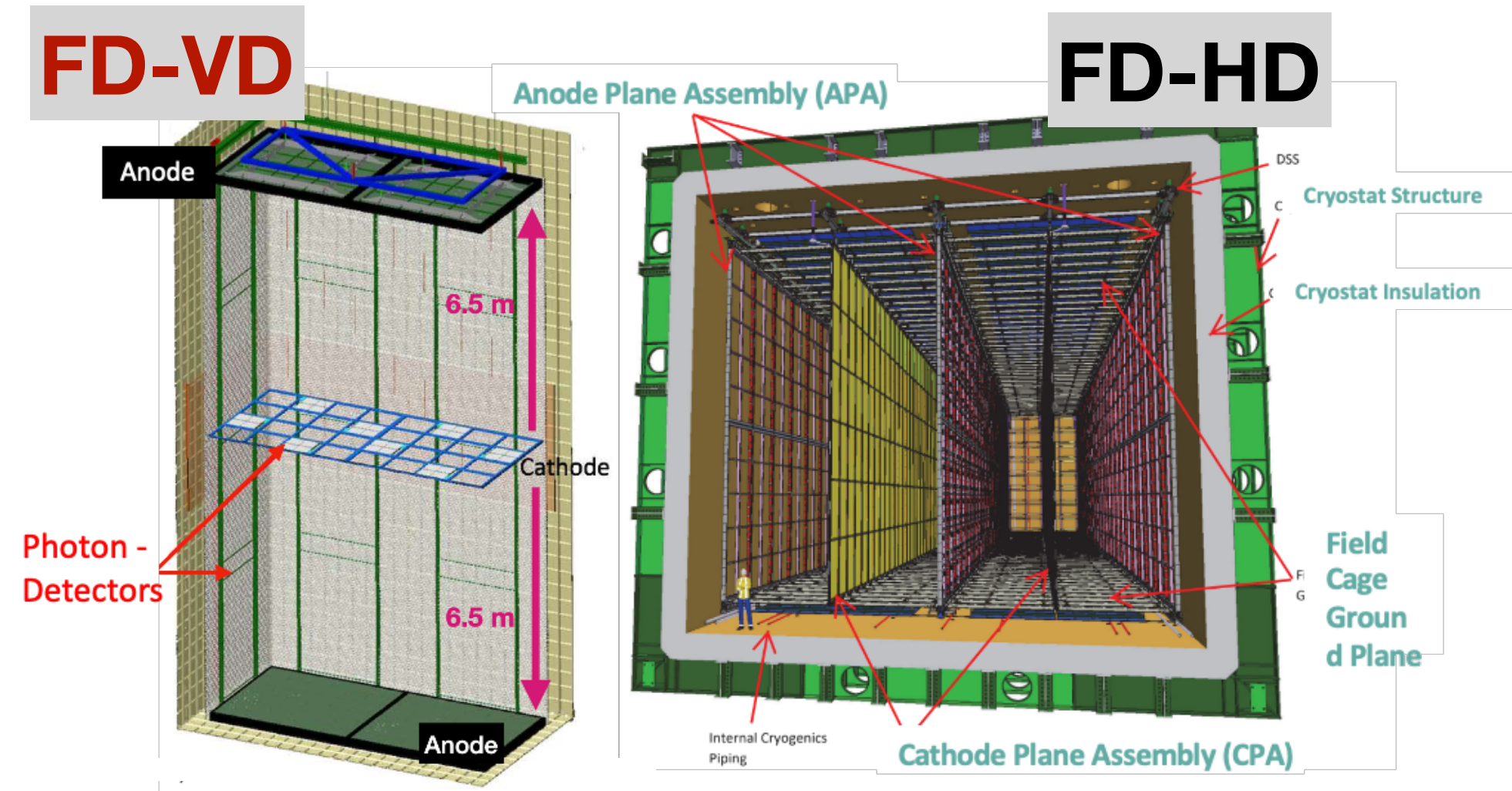


CIEMAT main responsibilities in Photon-Detection System for both modules

- Characterisation and optimisation of the X-Arapucas modules @CIEMAT for FD-HD / VD [Measurement of the absolute efficiency of the X-ARAPUCA photon detector for the DUNE Far Detector 1 published in Eur. Phys. J C 84 \(2024\) 1004](#)
- Purchased by DUNE Spain and responsible of Q&C of 200,000 SiPMs
- (FD-VD) PDS Calibration System (inner part)
- (FD-VD) Design and fabrication of X-Arapuca support structure
- (FD-VD) CIEMAT is the EU assembly and cryogenic testing centre
- Warm readout electronics



DUNE Far Detector



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DUNE Computing Consortium

Spain has pledged resources since 2021.

One of only 5 non-US countries providing sustained support (with CA, FR, NL, UK).

CIEMAT Chair the Computing Contributions Board (CCB) since 2024

Cryogenic characterization of Hamamatsu HWB MPPCs for the DUNE photon detection system. JINST 19 01 (2024)

T01007

Cryogenic characterization of FBK NUV-HD-Cryo 3T SiPM sensors for the DUNE photon detection system. JINST 21

02 (2026) P02047

Measurement of the photon detection efficiency of Hamamatsu VUV4 SiPMS at cryogenic temperature. Nucl. Inst. Meth. A 1064 (2024) 169347

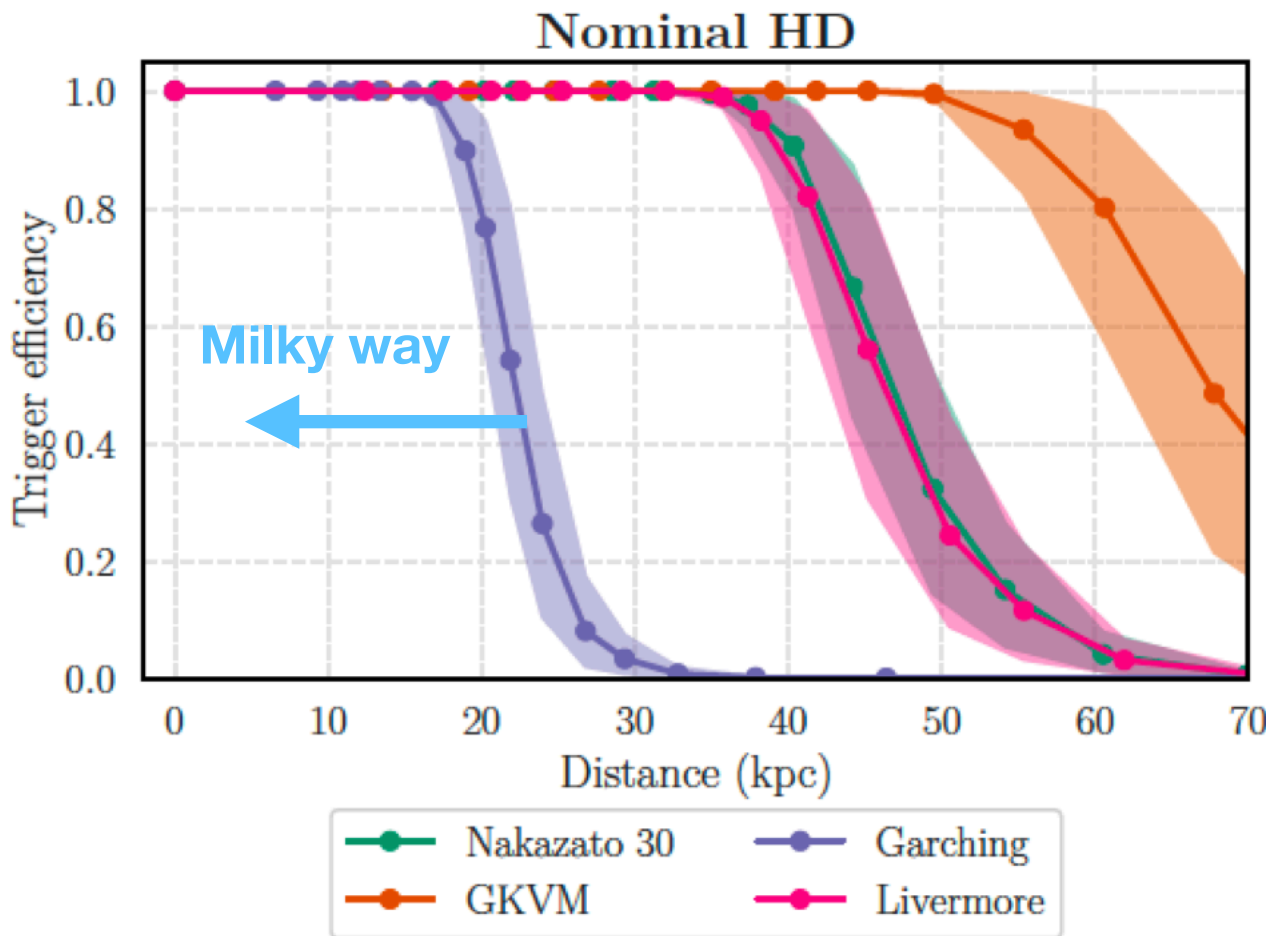
DUNE Physics

Highlight

CIEMAT activity focused on the detection of low-energy neutrinos from astrophysical sources

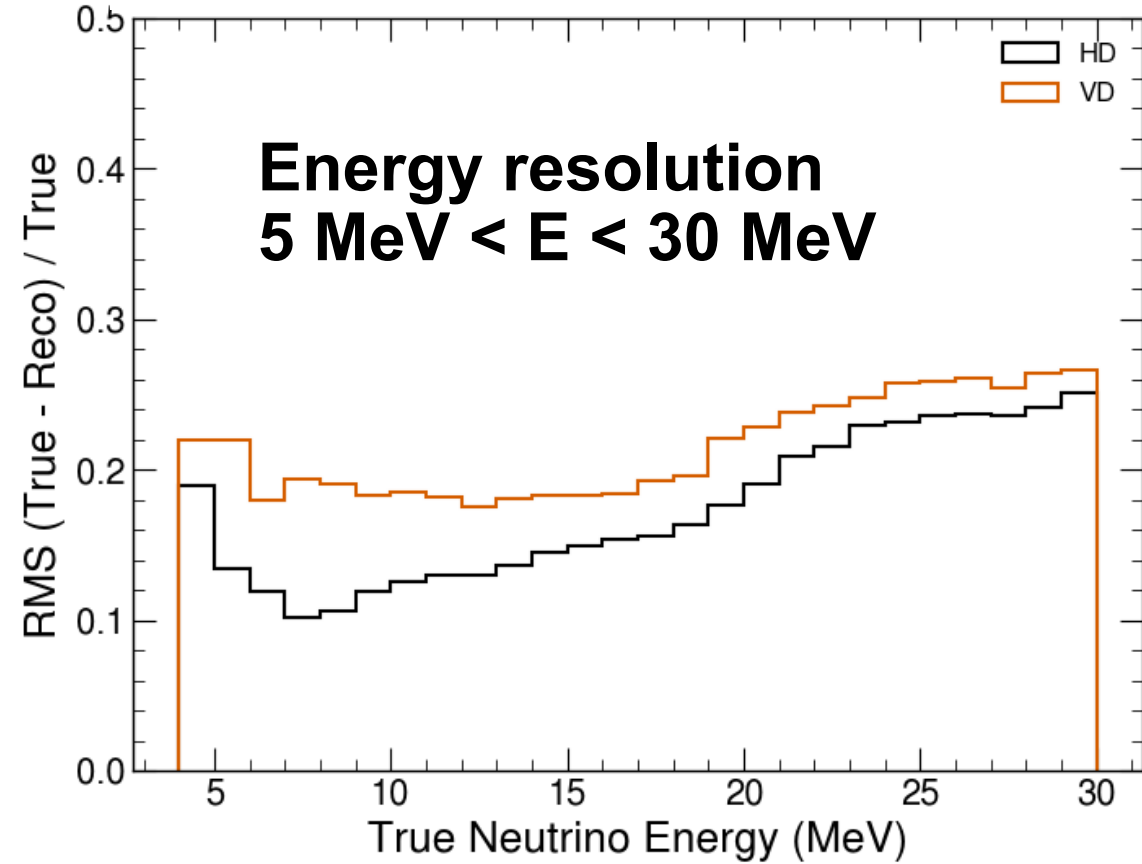
Core collapse **supernova neutrinos**

Triggering efficiency of the PDS to detect Supernova neutrinos



P. Barham PhD Thesis 2025

Developing **reconstruction tools** of low energy neutrinos

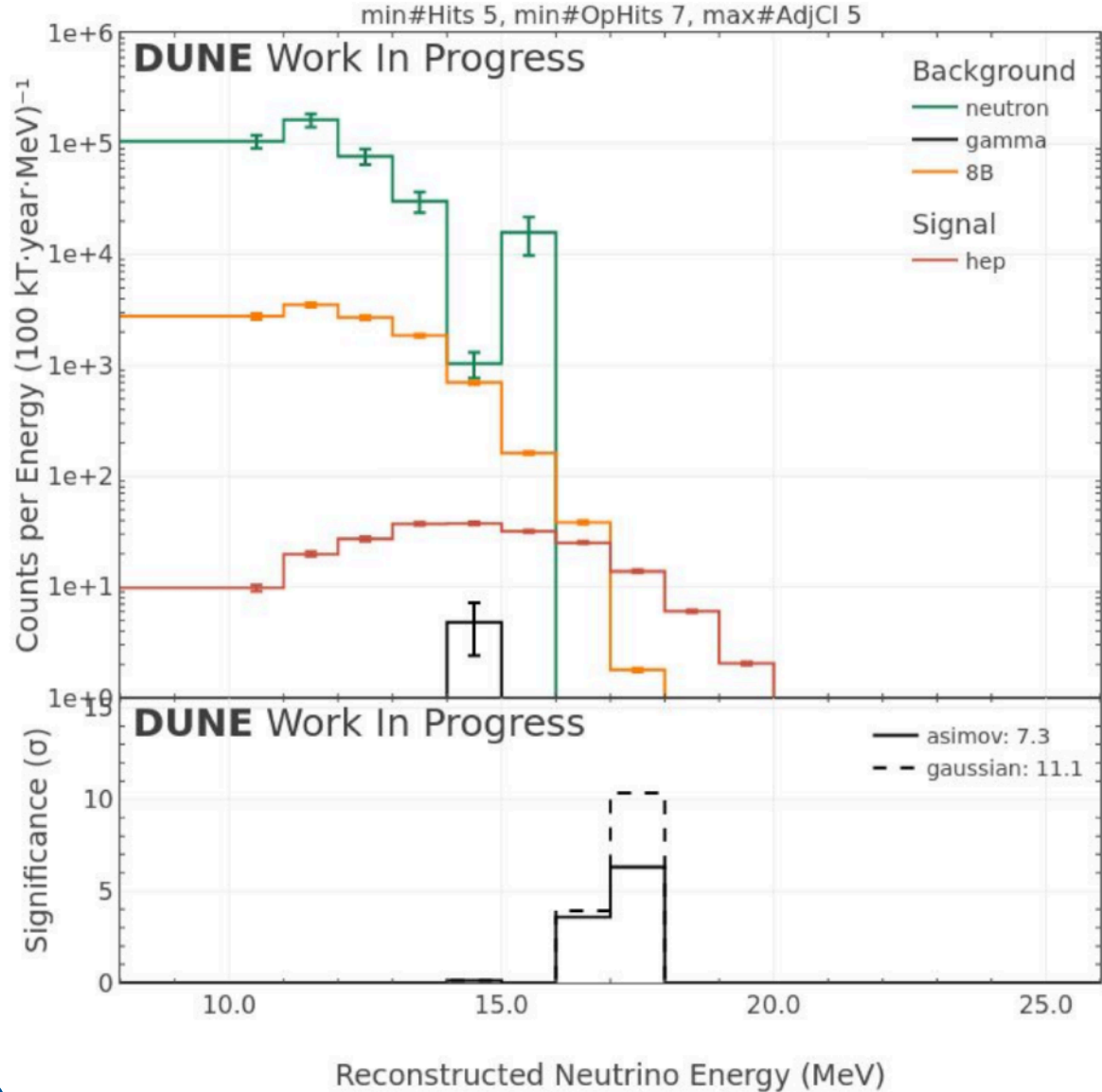
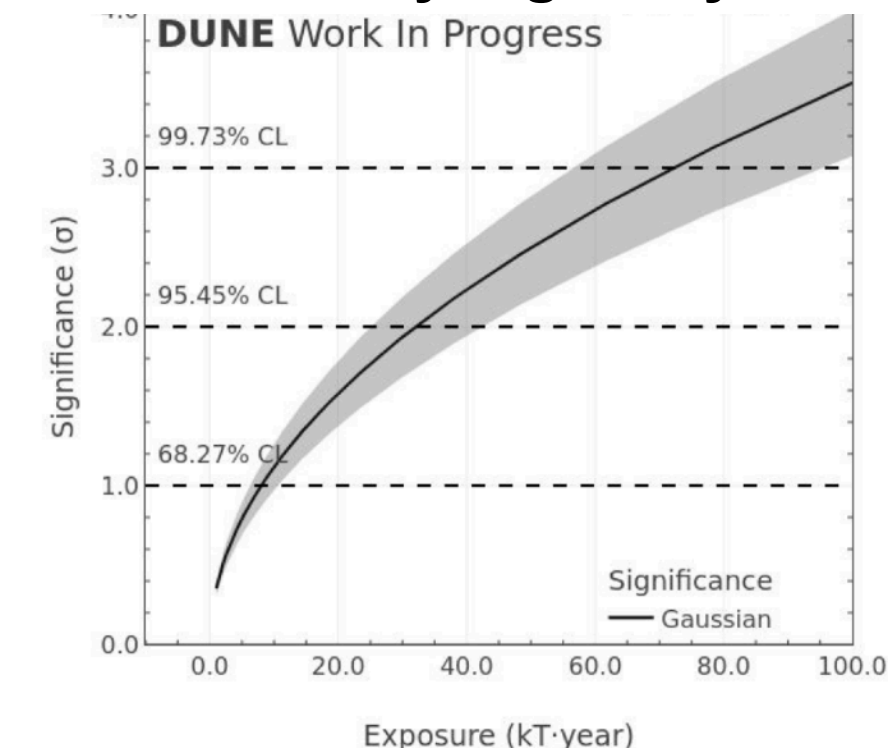


CIEMAT primary authors of publication under Collaboration review

Solar neutrinos

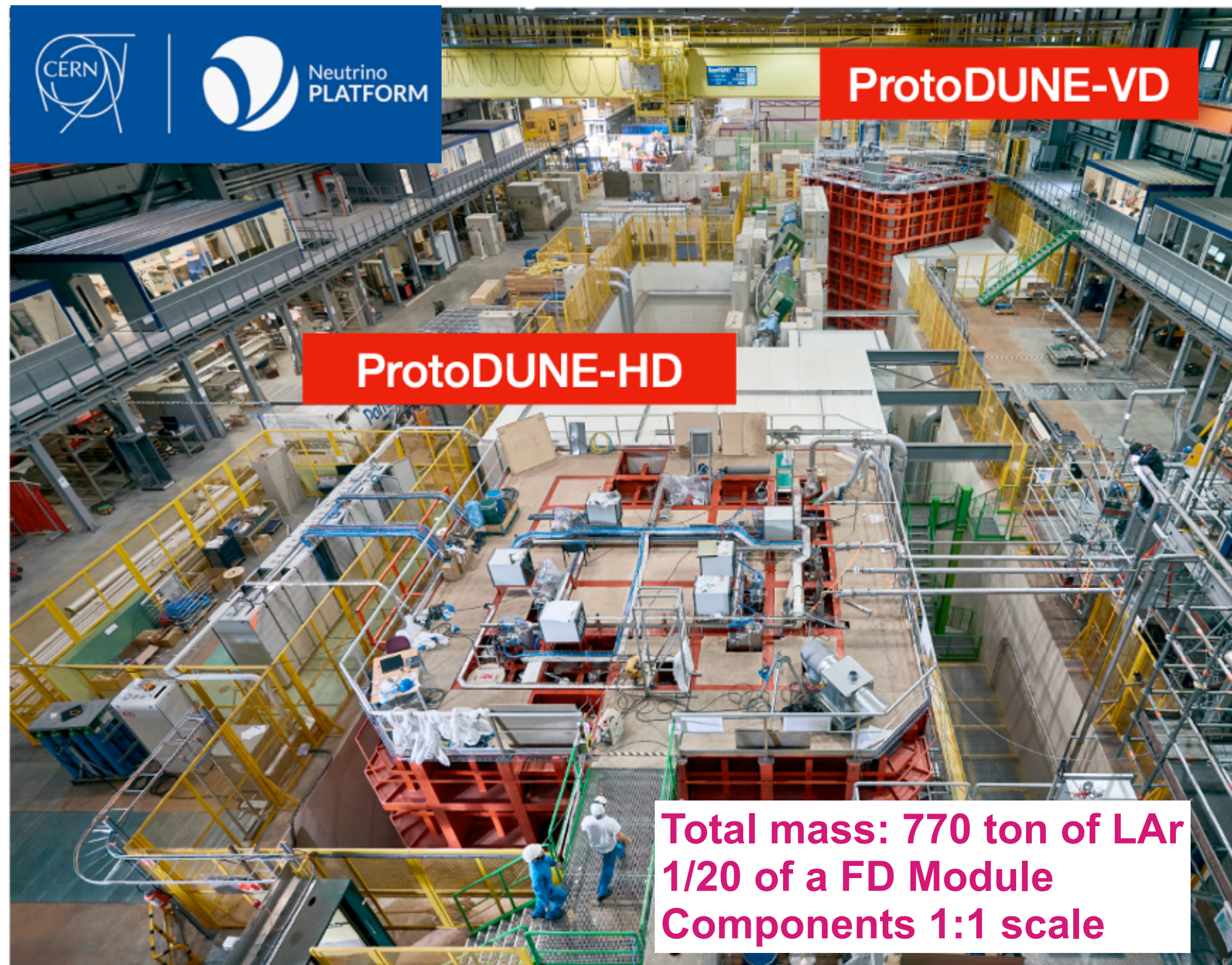
Evaluation of **DUNE's sensitivity** for the detection of hep solar neutrinos and probing solar neutrino oscillation

From solar day-night asymmetry



S. Manthey PhD Thesis (foreseen by 2026)

ProtoDUNE



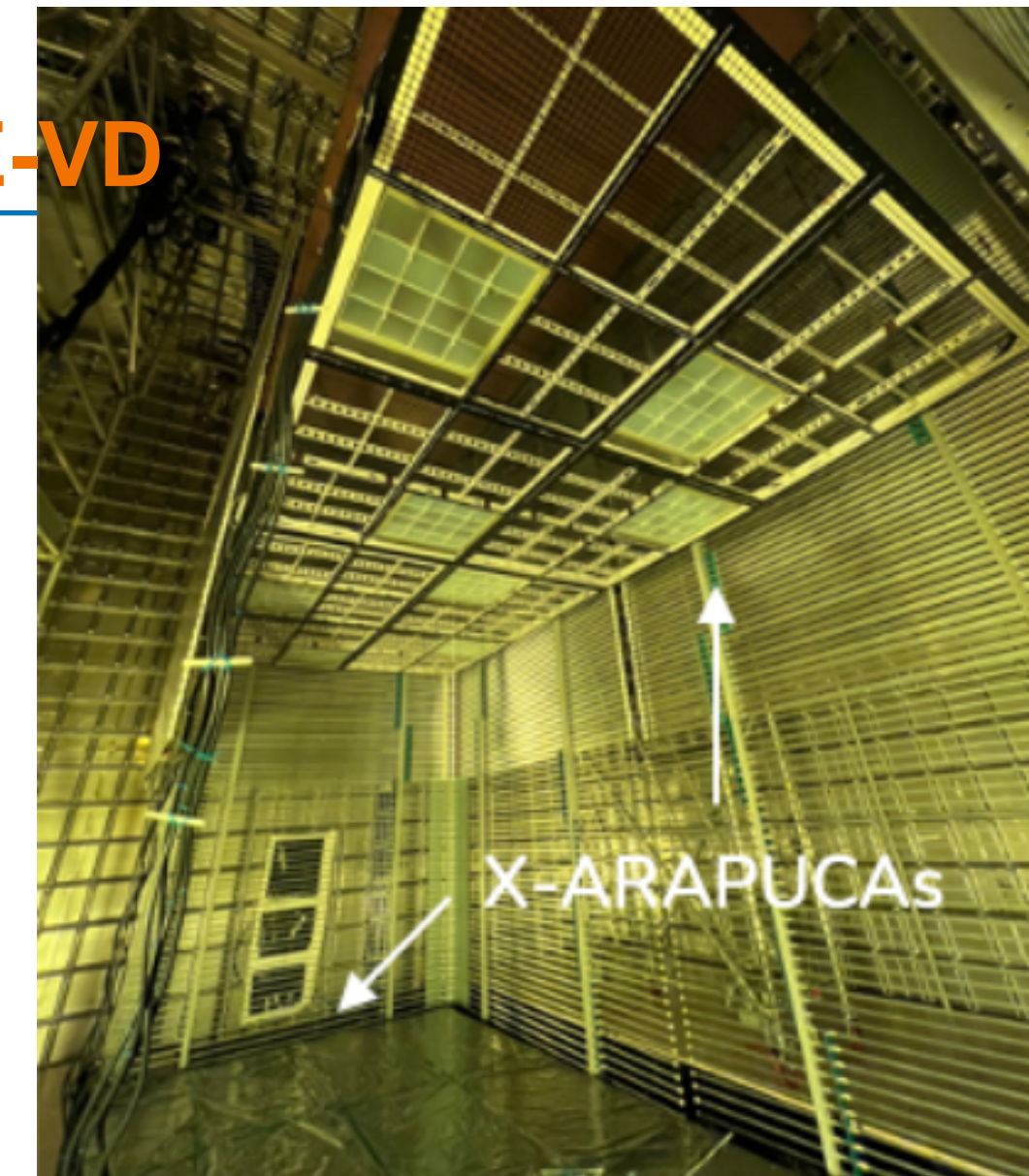
ProtoDUNE-VD

Beam data summer 2025

- Test the VD concept for the first time at large scale

CIEMAT contribution:

- Installation and commissioning of light calibration system
- Installation of reference sensors (PMT) for Xe doping studies
- X-Arapucas support structure



ProtoDUNE-HD

Beam data in summer 2024

- Test of upgraded components in their final design
- Demonstration of the correct performance of 40 X-Arapuca modules ✓

CIEMAT contribution:

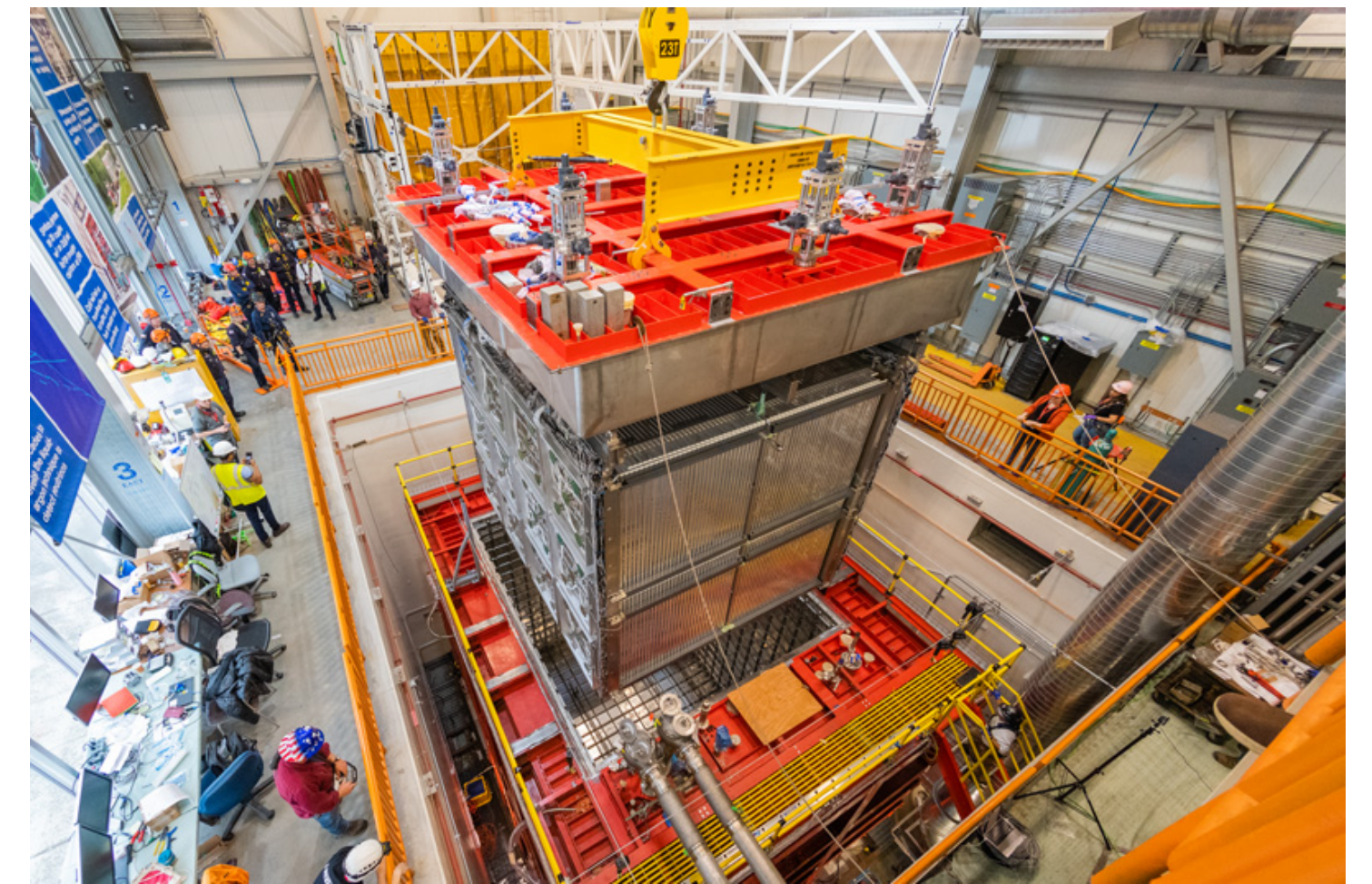
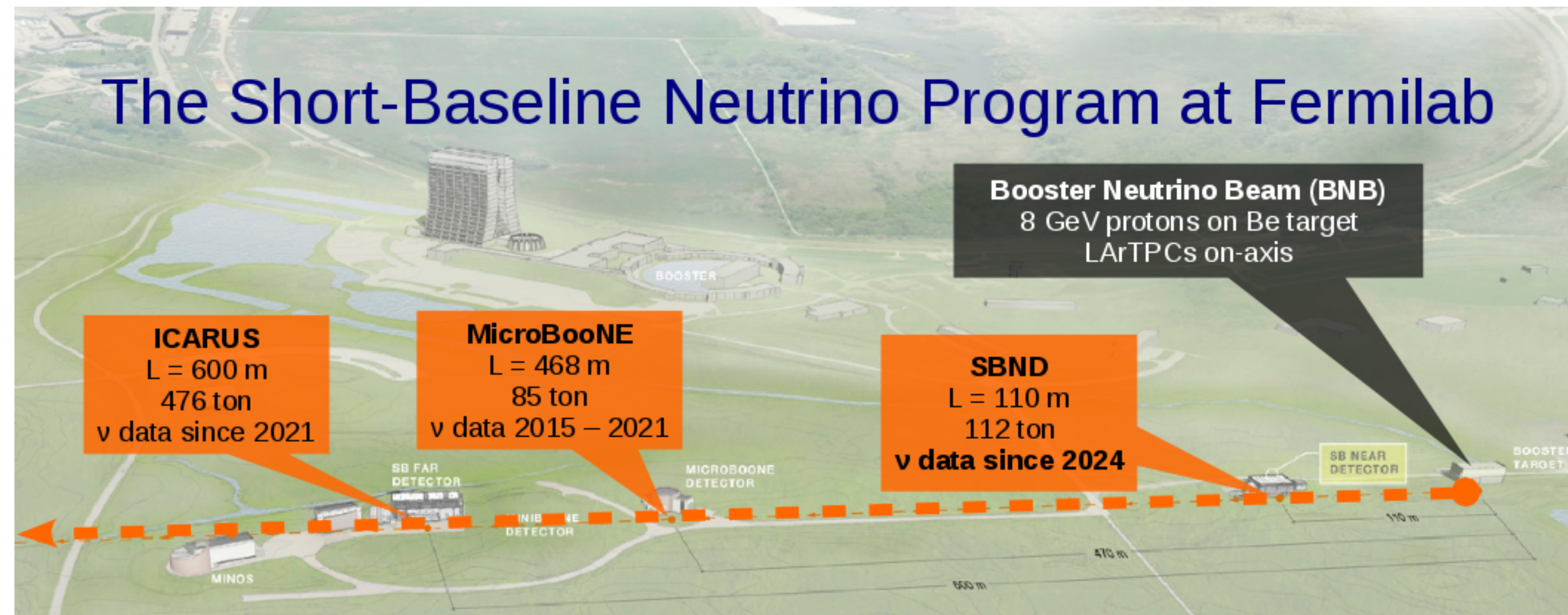
- Measurement of XA PDE
- Testing new ML reconstruction tools (SPINE) with Michel-e-

L. Pérez-Molina PhD (foreseen for 2026)



Highlight

SBND (Short Baseline Near Detector)



Physics program:

- Address the sterile-neutrino oscillation anomalies (LSND and MiniBooNE).
- High-precision measurements of cross-sections of ν_μ and ν_e on Ar.
- Search for Beyond Standard Model physics.
- Advance the LArTPC detector technology towards DUNE.

Physics beam data taking since December 2024 → **Largest neutrino-argon interaction dataset available in the world.**

Approved to run until Fermilab accelerator long-shutdown (end of 2027/early 2028)
[[Input to the European Strategy for Particle Physics 2026 Update](#), arXiv:2504.00245]
(CIEMAT primary authors)

Highlight



SBND (Short Baseline Near Detector)

CIEMAT Contribution:

Leaders of scintillation light simulation, reconstruction, calibration and analysis **with X-ARAPUCAs** → transference to DUNE.

Scintillation Light in SBND: Simulation, Reconstruction, and Expected Performance of the Photon Detection System published in Eur. Phys. J. C 84, 1046 (2024)

→ Pioneering machine-learning reconstruction techniques for Ar scintillation light

→ Readout system of X-ARAPUCAs. Commissioning and calibration

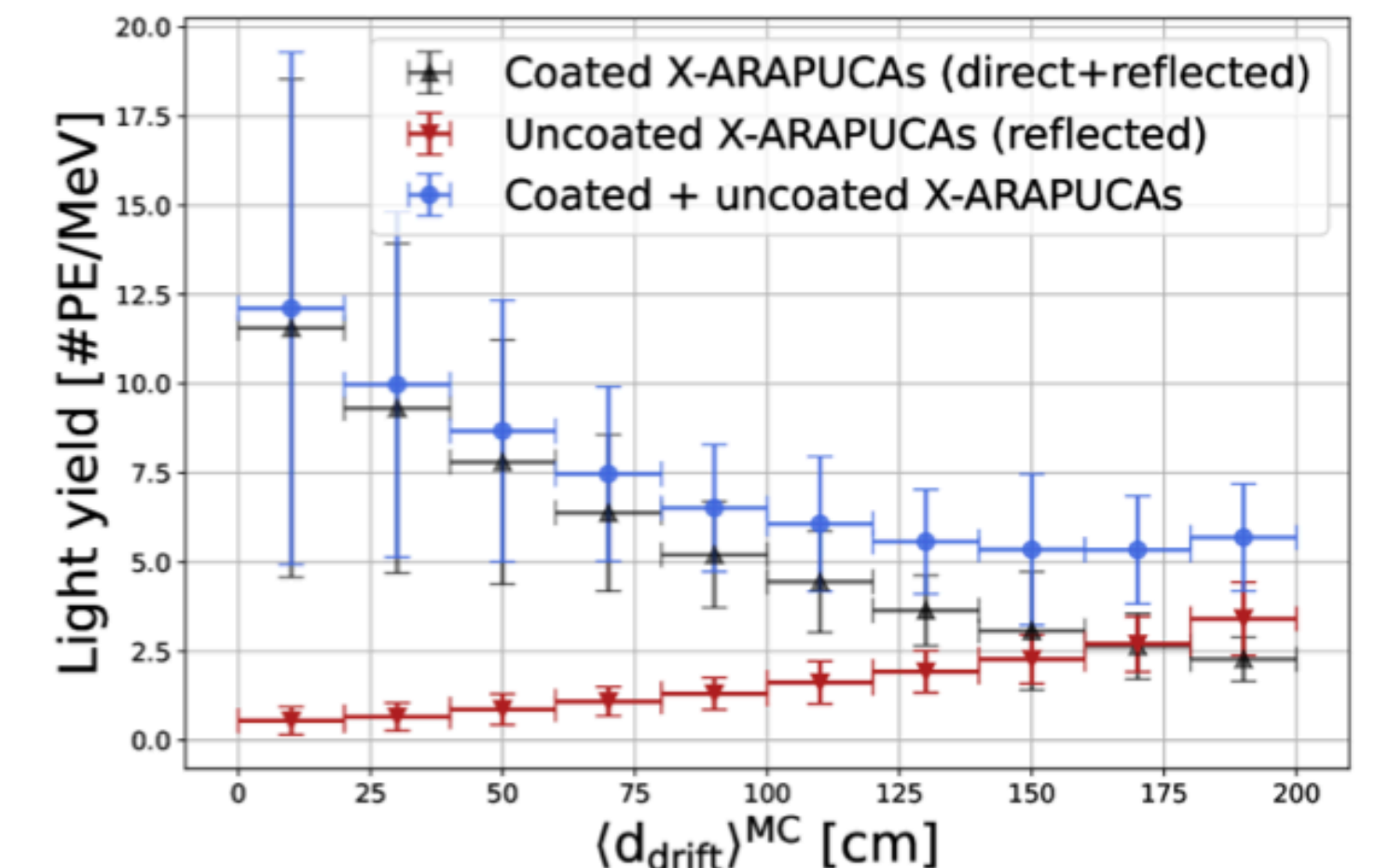
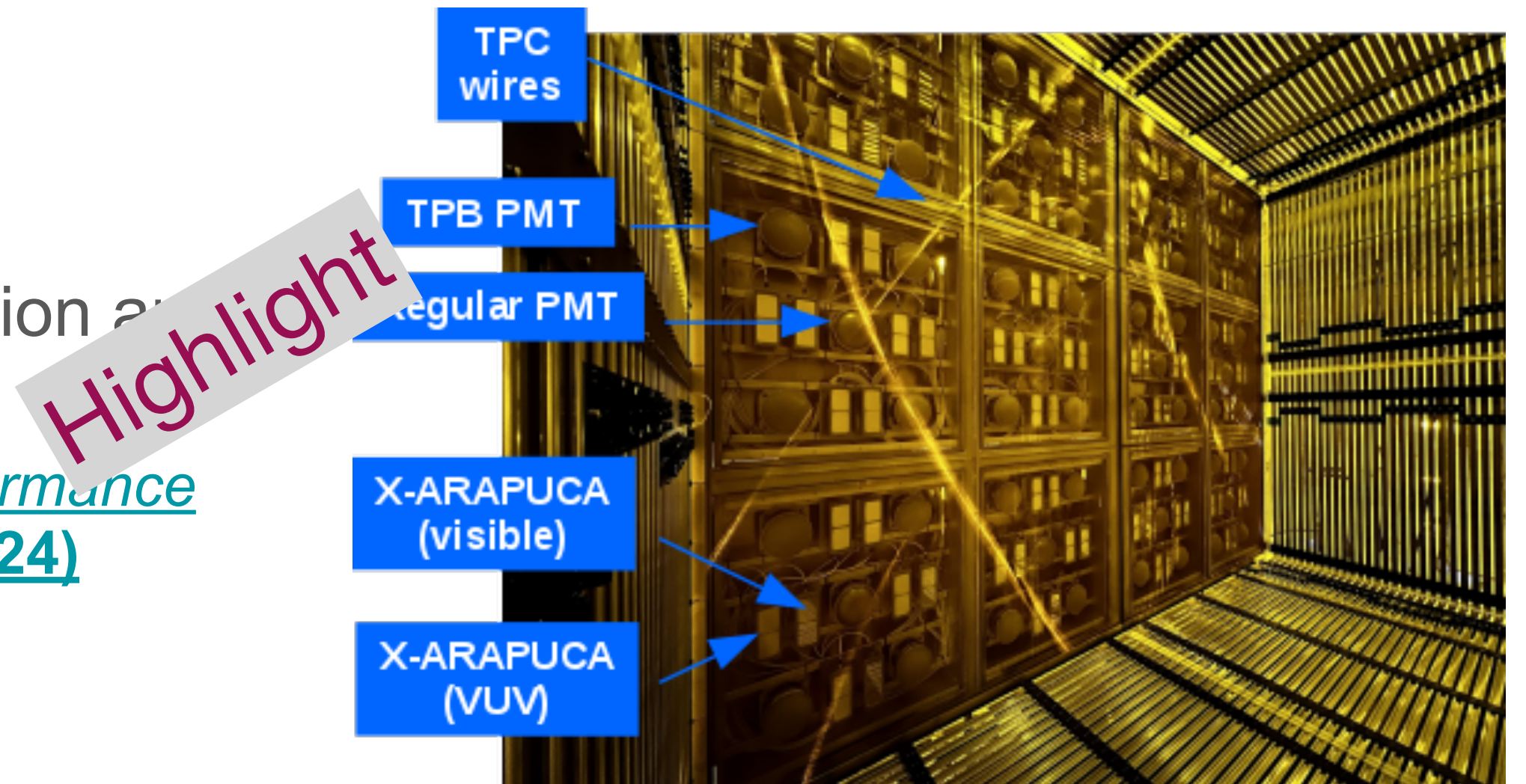
BSM Physics:

Leaders of BSM physics program of SBND

CIEMAT primary authors of upcoming publications:

- BSM event generator for SBND and ICARUS (publication under collaboration review)
- SBND BSM sensitivity study (publication in preparation)

R. Álvarez-Garrote PhD Thesis on search for Heavy Neutral Leptons (2025)

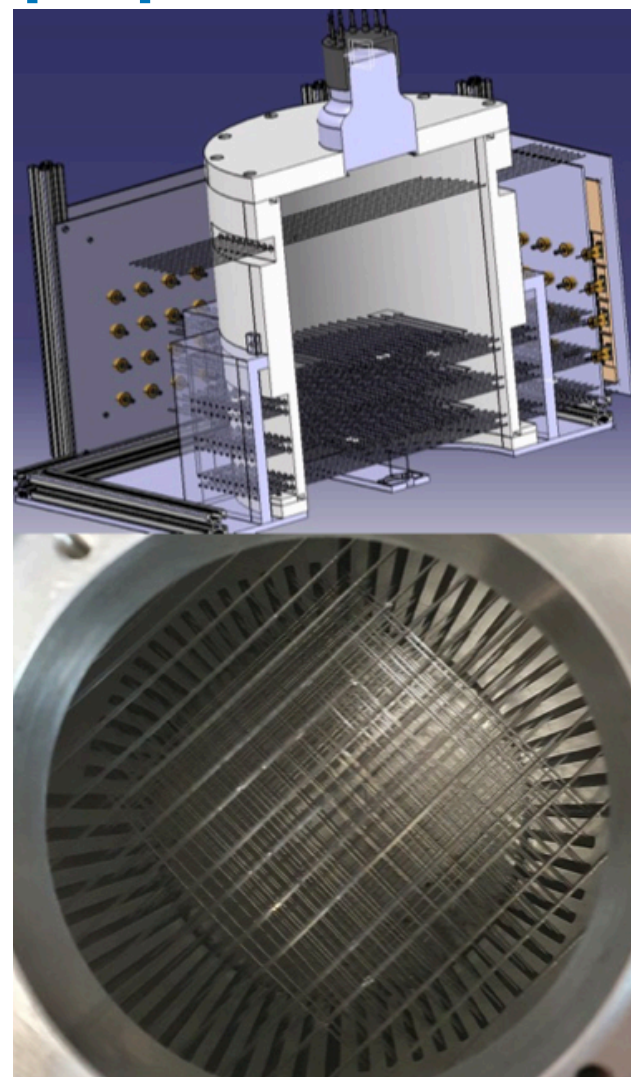


LiquidO

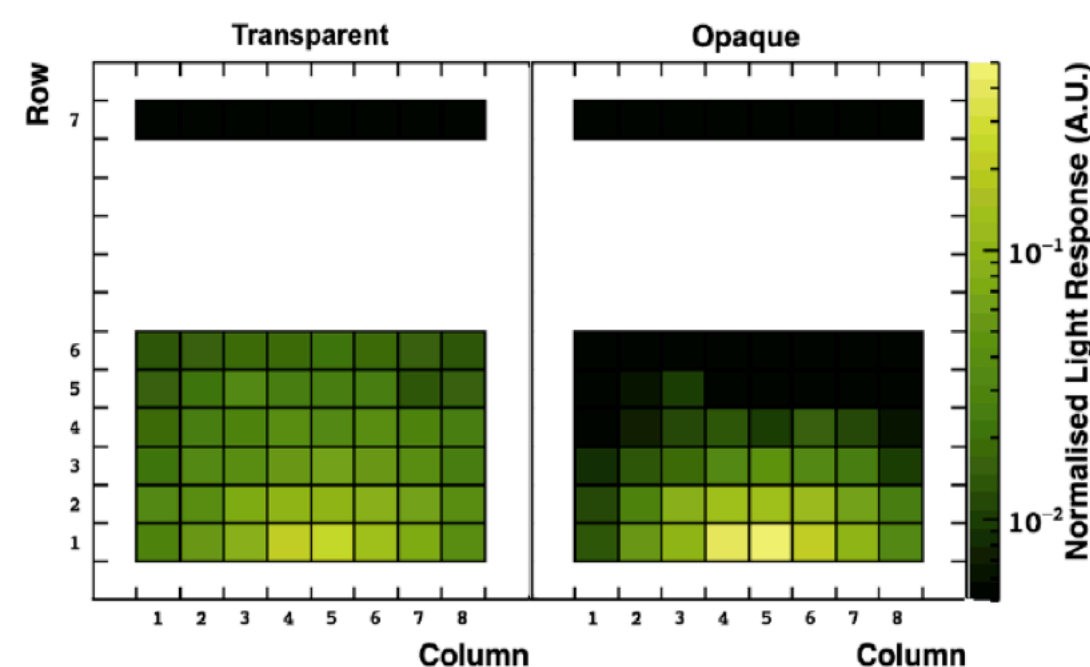
R&D Project on Opaque Scintillator Detectors for Neutrino research and Rare events experiments

Topological information preserved by confining light near its creation point. Light collected by WLS fibres and SiPMs

10 L prototype operated with LAB+PPO and opaque formulation



Demonstration that ~90% of 1 MeV e^- light is confined within a few cm,s radius



Highlight

AntiMatter-OTech

HORIZON-EIC-2021-PATHFINDEROPEN-01 (2023 – 2029)

10 ton-scale LiquidO detector

Innovation project: Development of a new instrumentation to use anti-neutrinos as a direct probe of the functioning of industrial nuclear reactor

- IJCLAB, Subatech / CNRS (France)
- J-G Universität Mainz (Germany)
- CIEMAT (Spain)
- Sussex University, RAL (UK)
- IST, LIP (Portugal)
- EDF (France)

Main CIEMAT contribution:

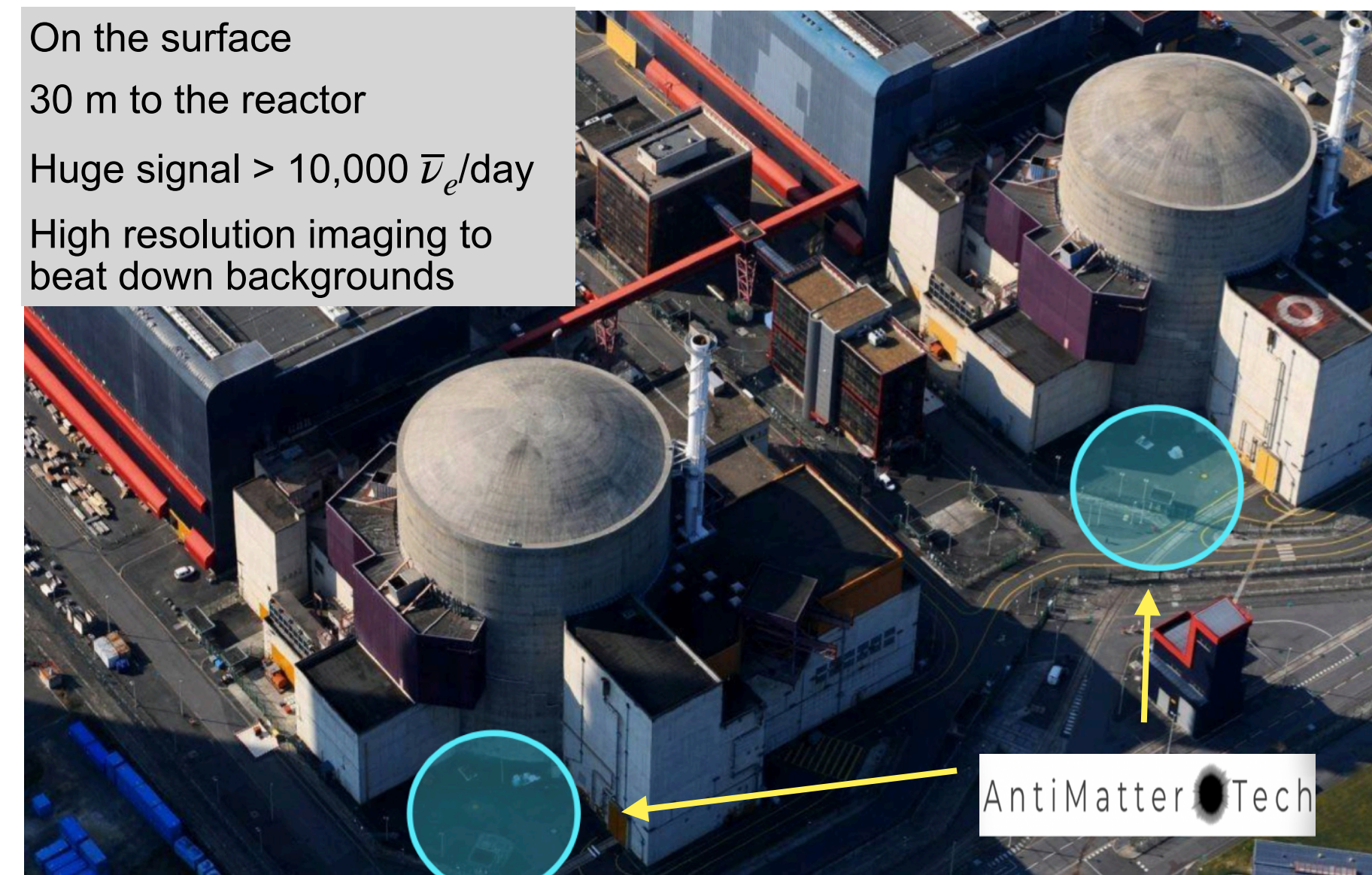
- External shielding
- Physics coordination (design-guiding studies)
- Software development



Co-funded by
the European Union



On the surface
30 m to the reactor
Huge signal $> 10,000 \bar{\nu}_e/\text{day}$
High resolution imaging to beat down backgrounds

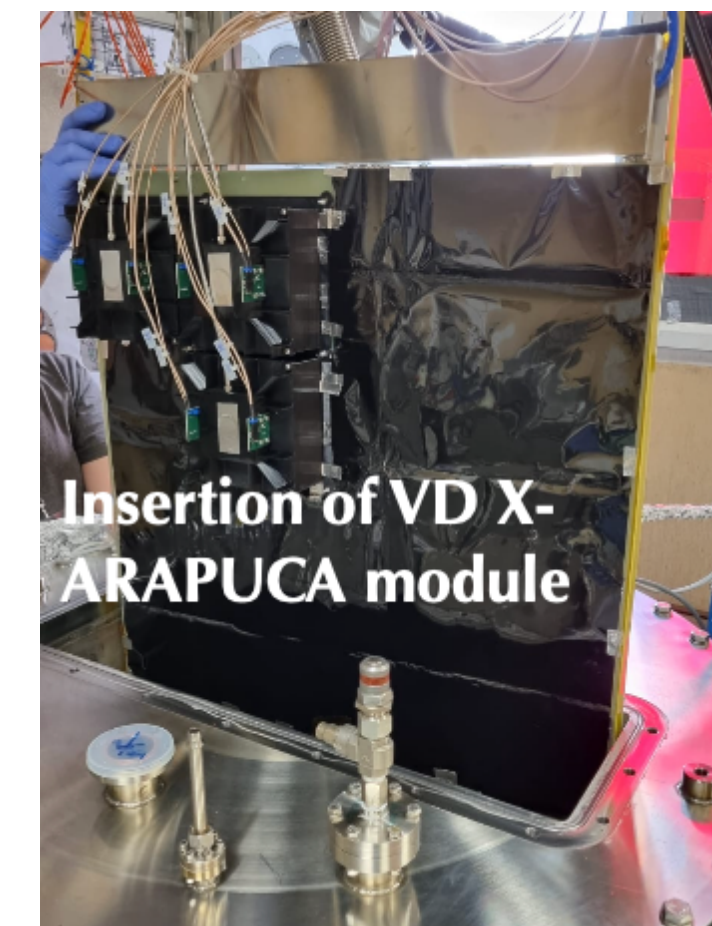
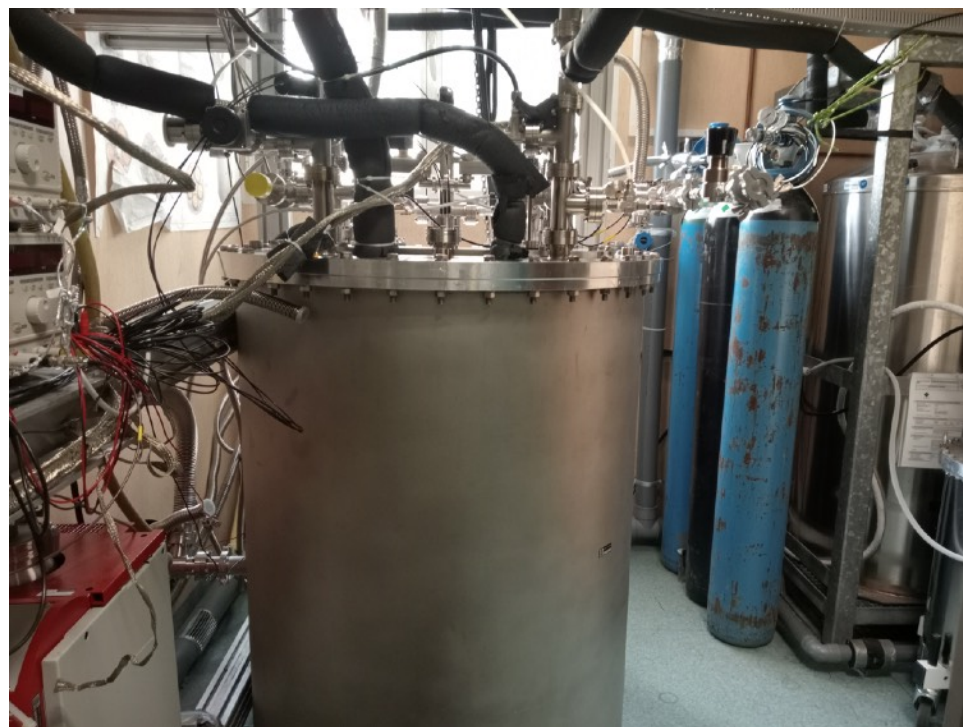


AntiMatter-OTech

R&D on new technologies for LAr TPC

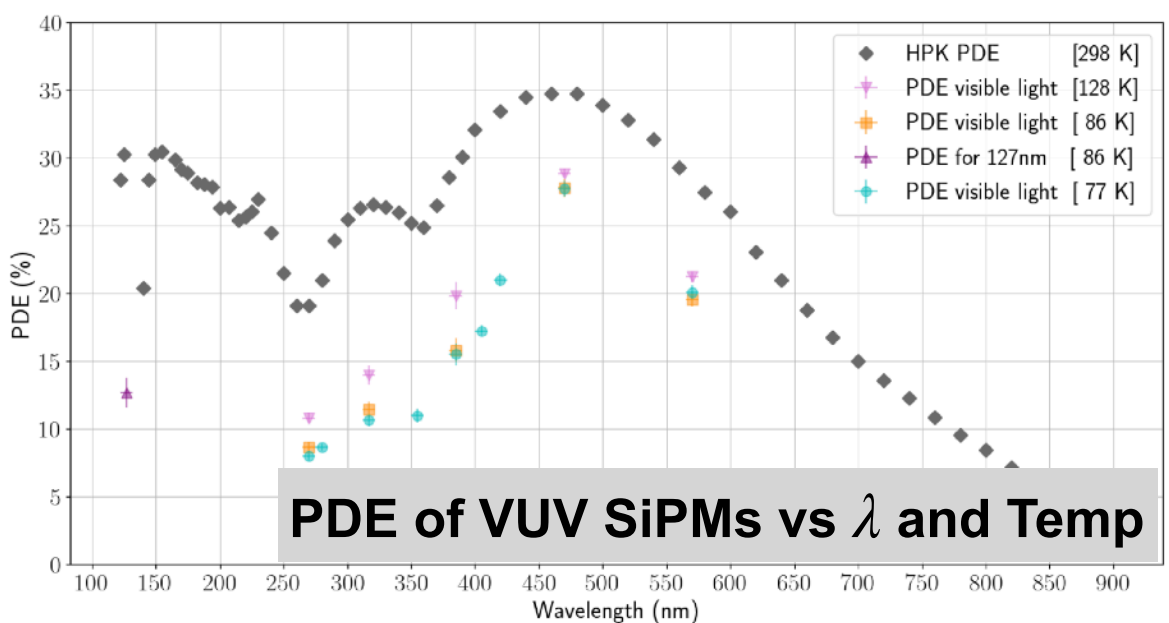


Cryogenic lab for photosensor characterisation in liquefied noble gases



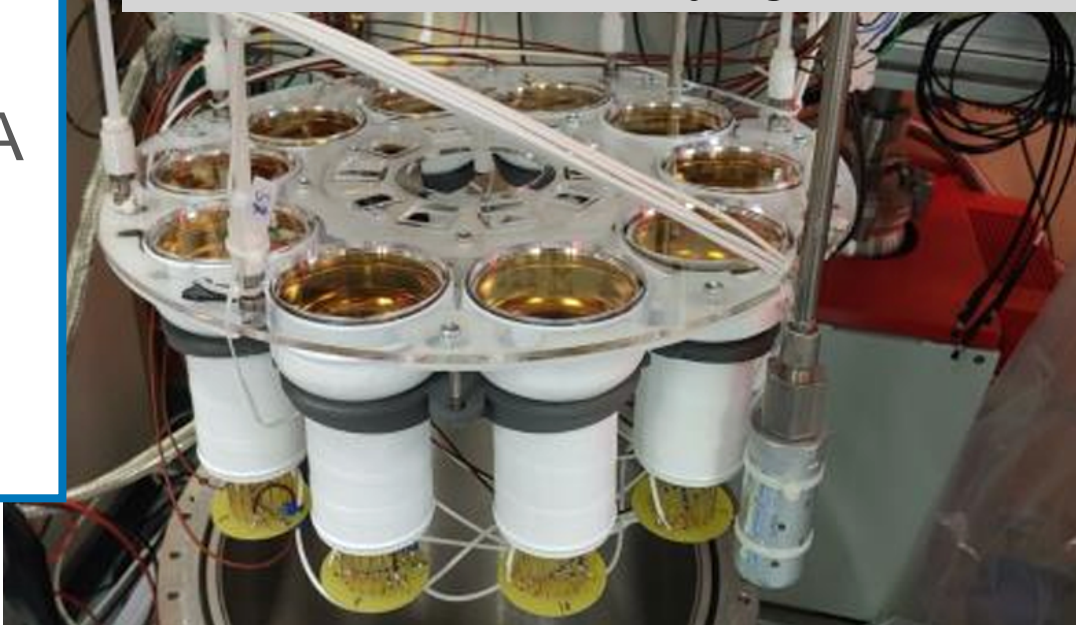
R&D on VUV photosensors

- **VUV SiPMs** used as **reference sensors** in X-ARAPUCA PDE measurement
- Aiming for installation on next generation LAr detectors
- Agreement with Hamamatsu Photonics (HPK) to characterize **VUV-sensitive PMTs**.

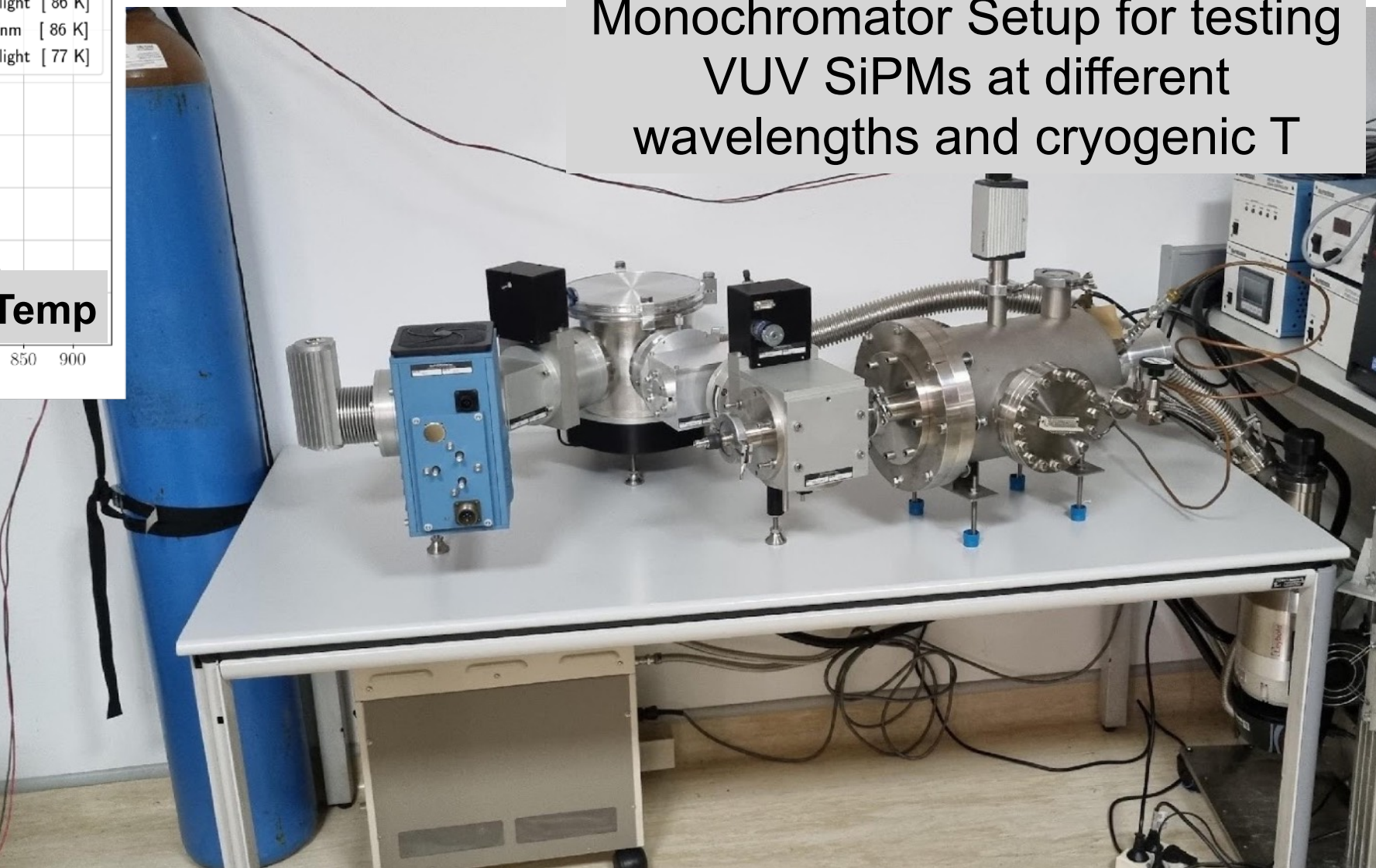


[Measurement of the PDE of Hamamatsu VUV4 SiPMs at cryogenic temperature published in JINST 19 \(2024\) C03027](#)

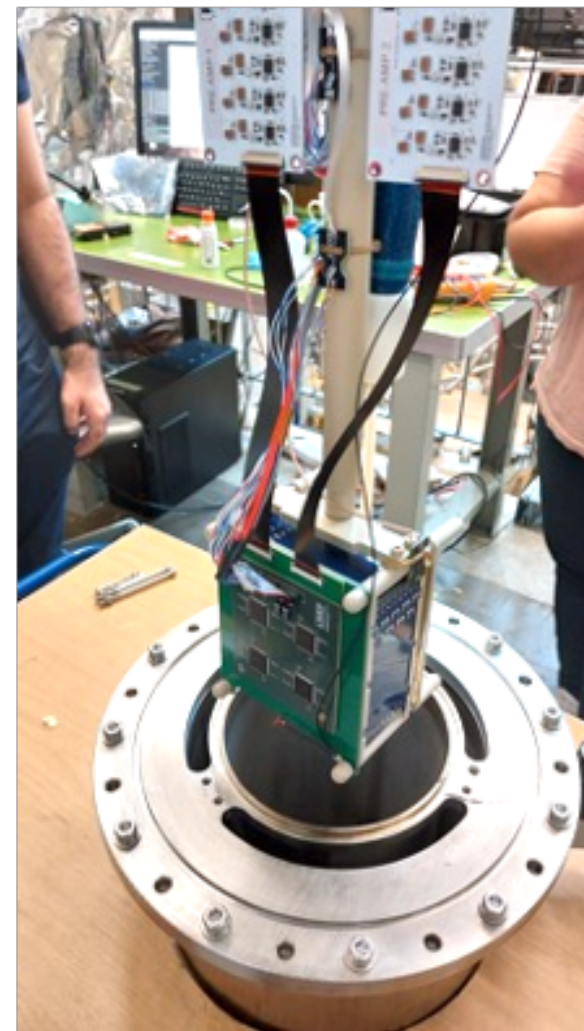
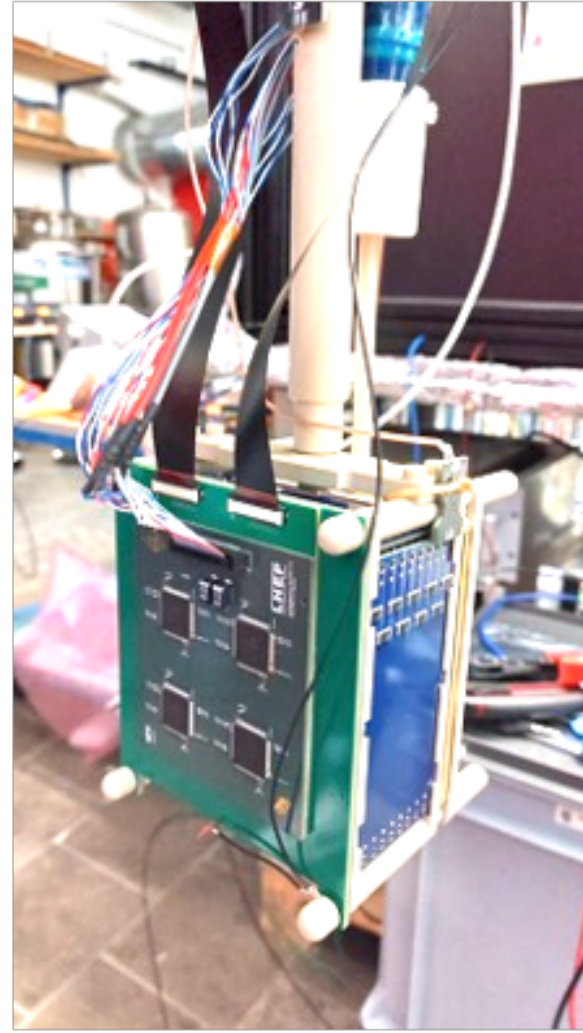
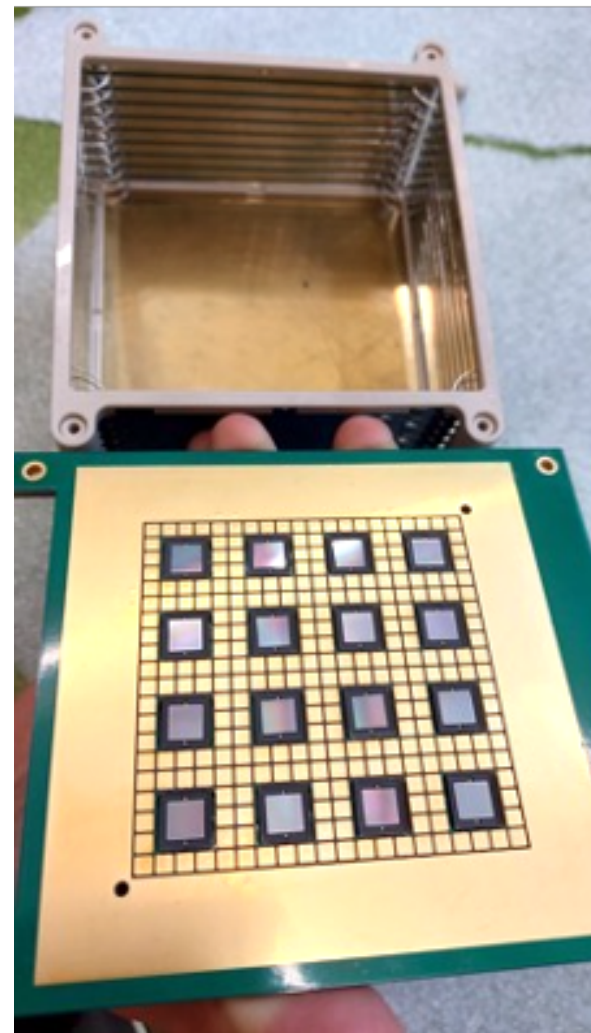
Setup for testing VUV PMT from HPK in cryogenics



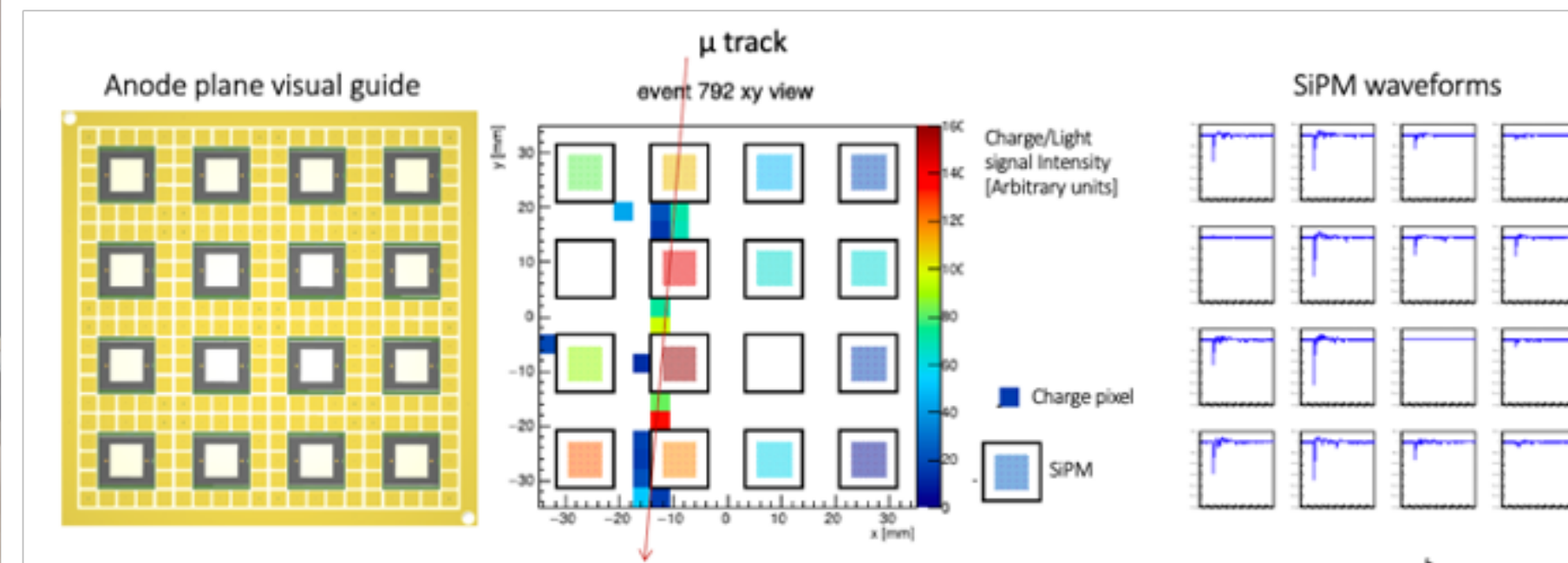
Monochromator Setup for testing VUV SiPMs at different wavelengths and cryogenic T



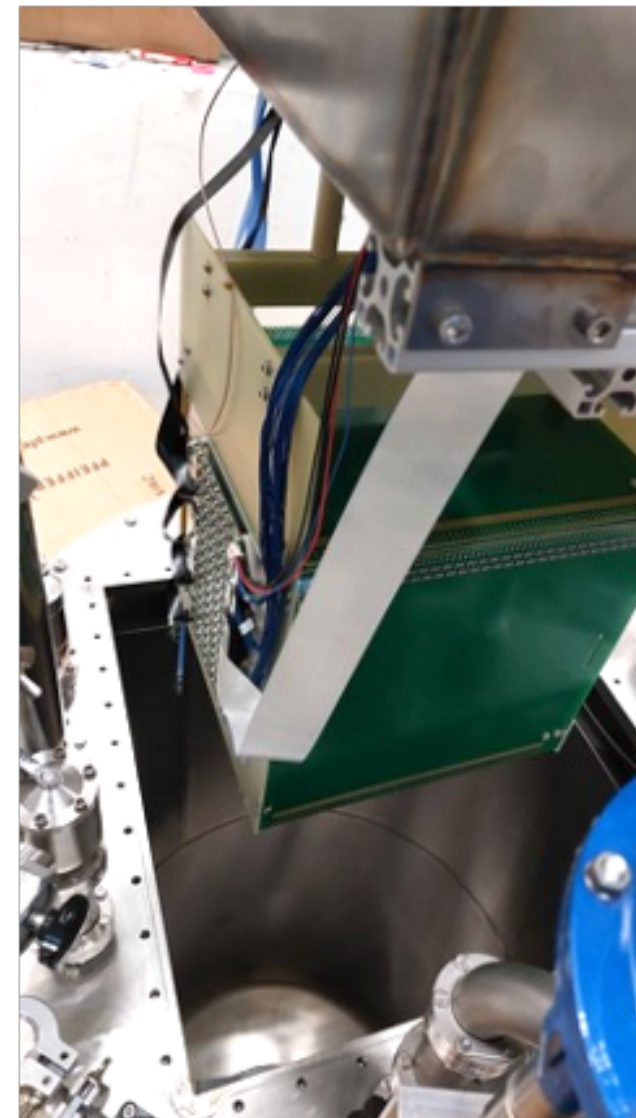
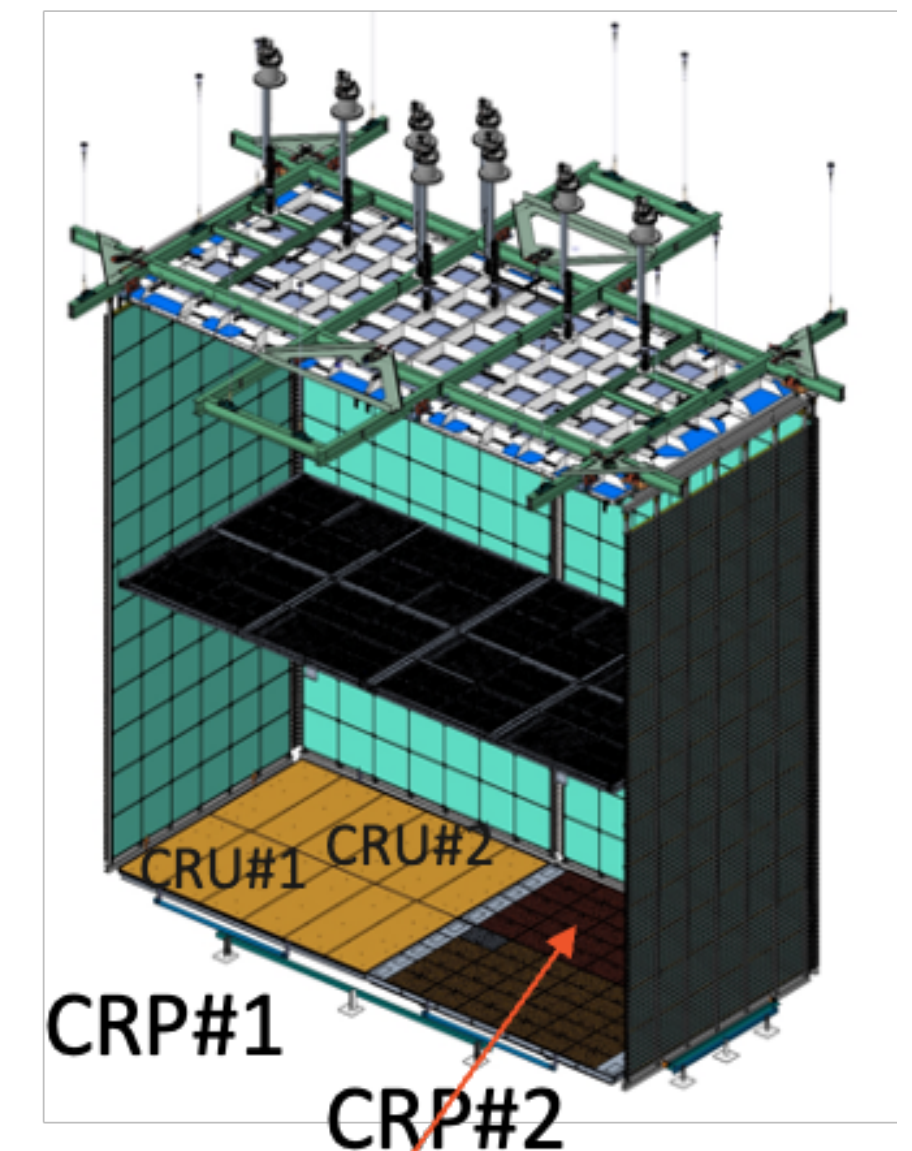
SoLAr - Pixelated readout with VUV SiPMs



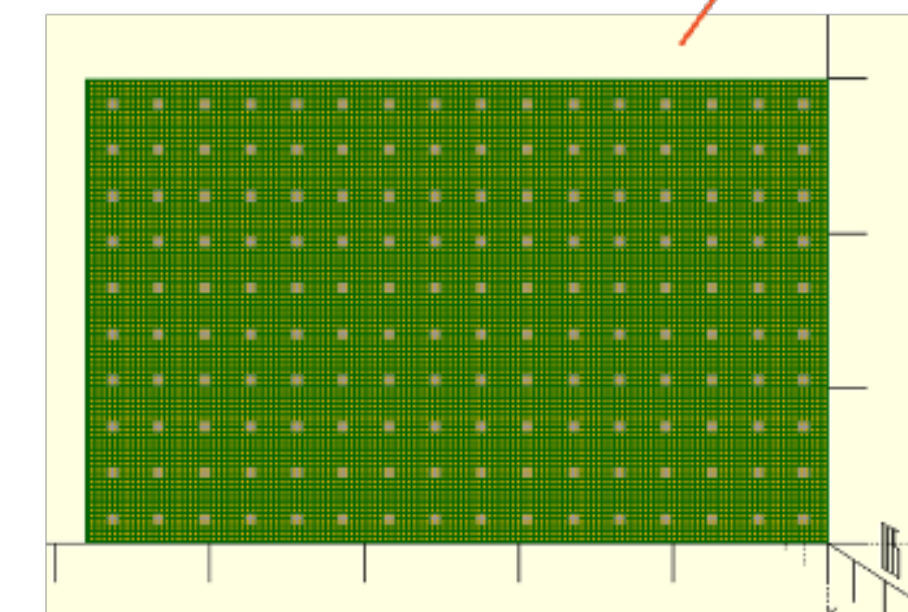
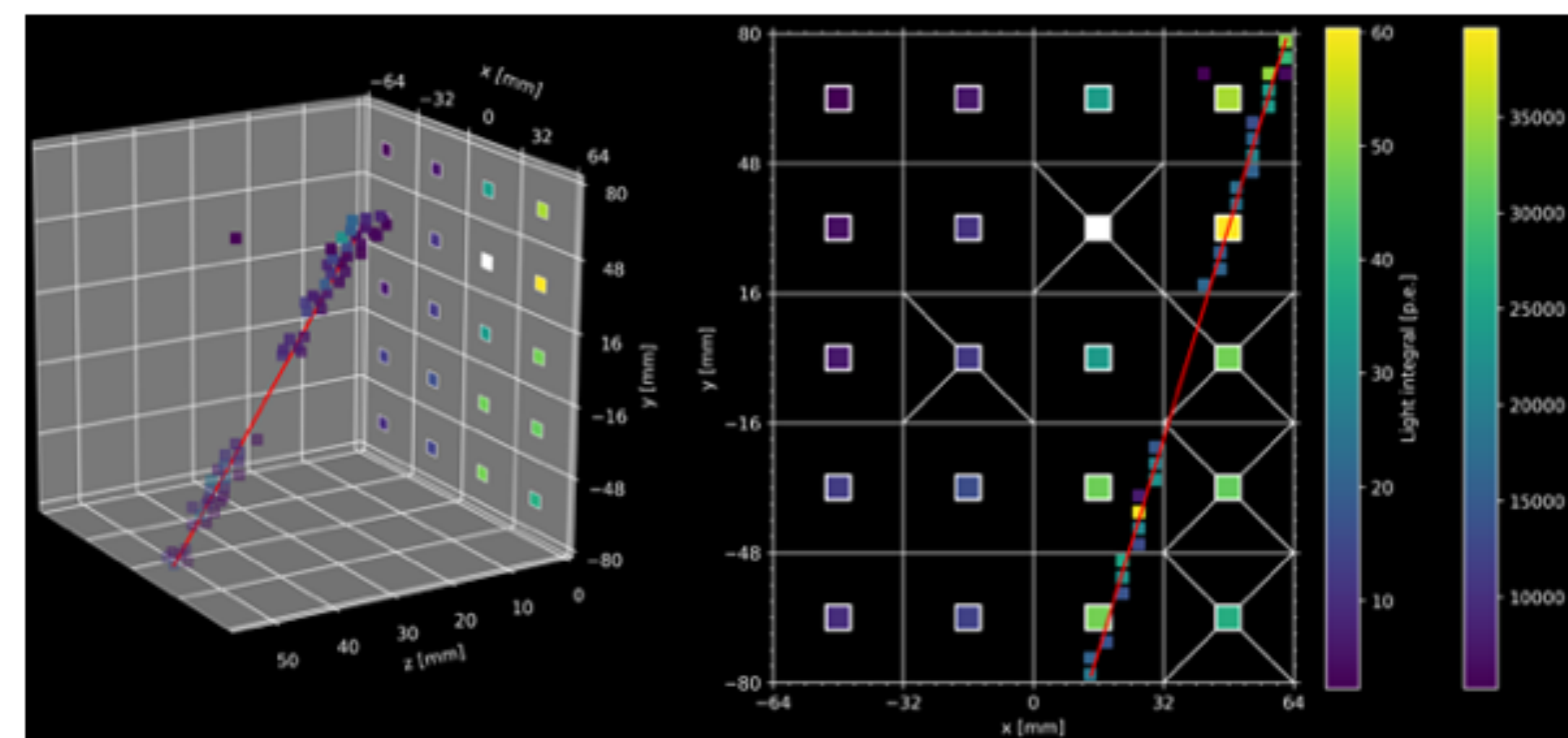
First demonstration of a combined light and charge pixel readout on the anode plane of a LArTPC [JINST 19 \(2024\) 11, P11010](#)



ProtoDUNE-III



Cosmic Ray Measurements Using Charge and Light Readout in a Pixelated Liquid Argon Time Projection Chamber [arXiv:2512.10830](#)



SoLAr tile 30 cm x 48 cm (160 LArPix, 160 SiPMs)

Short and mid-term activities

ProtoDUNE-VD data analysis (2026 - 2028)

- PDS system performance analysis
- Performance validation with Xe doping
- Validation of the calibration system
- Physics analysis



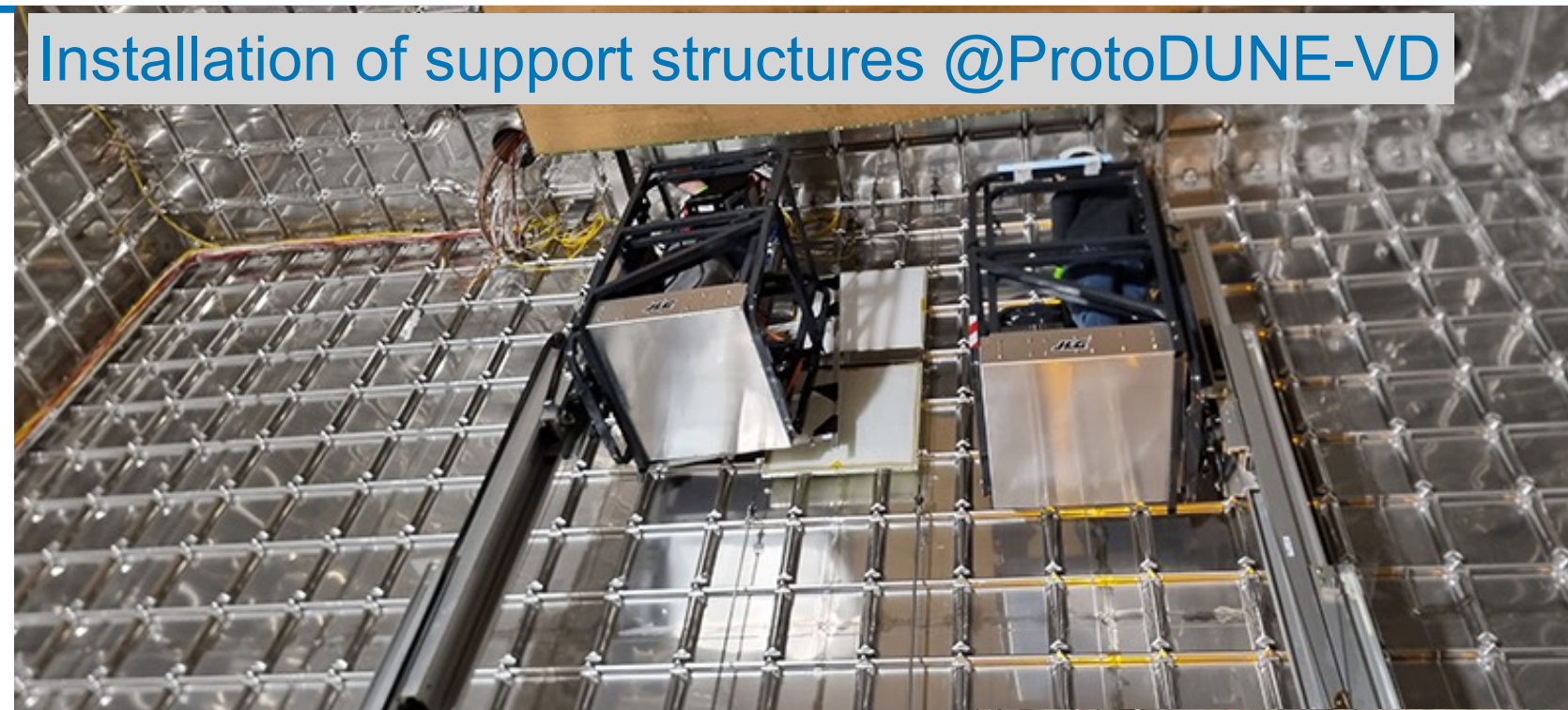
Physics (2026 -)

Preparation for first data analysis with FD on Supernova & solar neutrino analyses

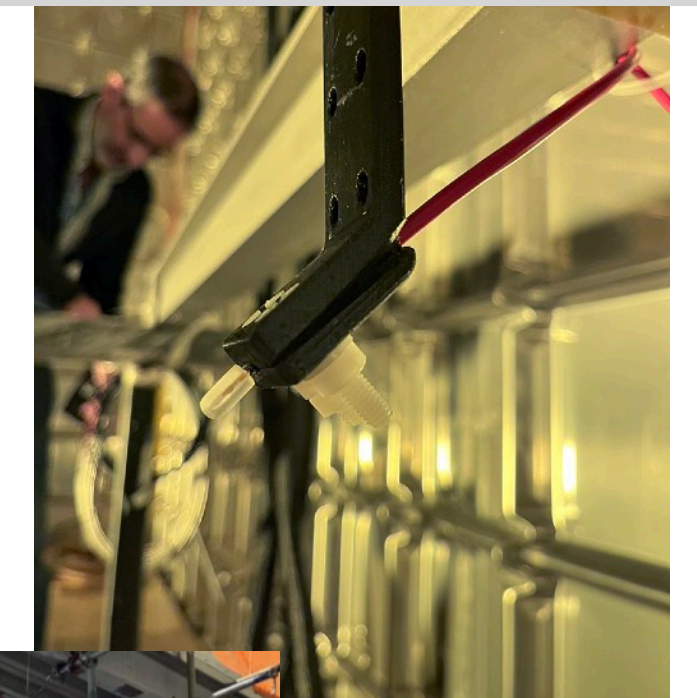
DUNE FD Phase I construction (2026 - 2029)

- Assembly and cryogenic characterisation of 352 PDS modules @CIEMAT
- Construction of X-Arapucas support structure
- Procurement of internal elements for the calibration system
- Installation of support structure and calibration fibres in the detector at SURF

Installation of support structures @ProtoDUNE-VD



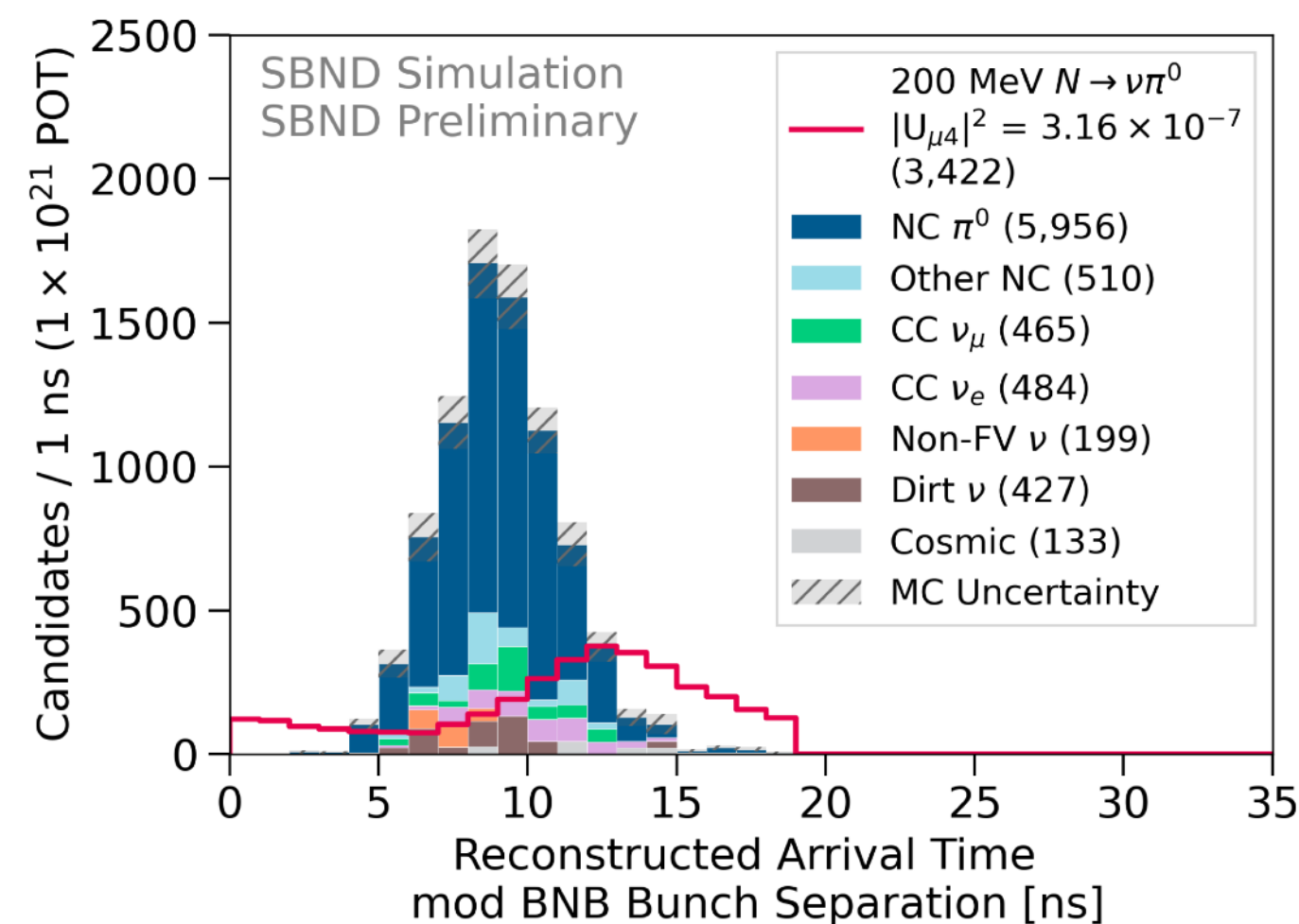
Optical fibre and diffuser for calibration system



Short and mid-term activities

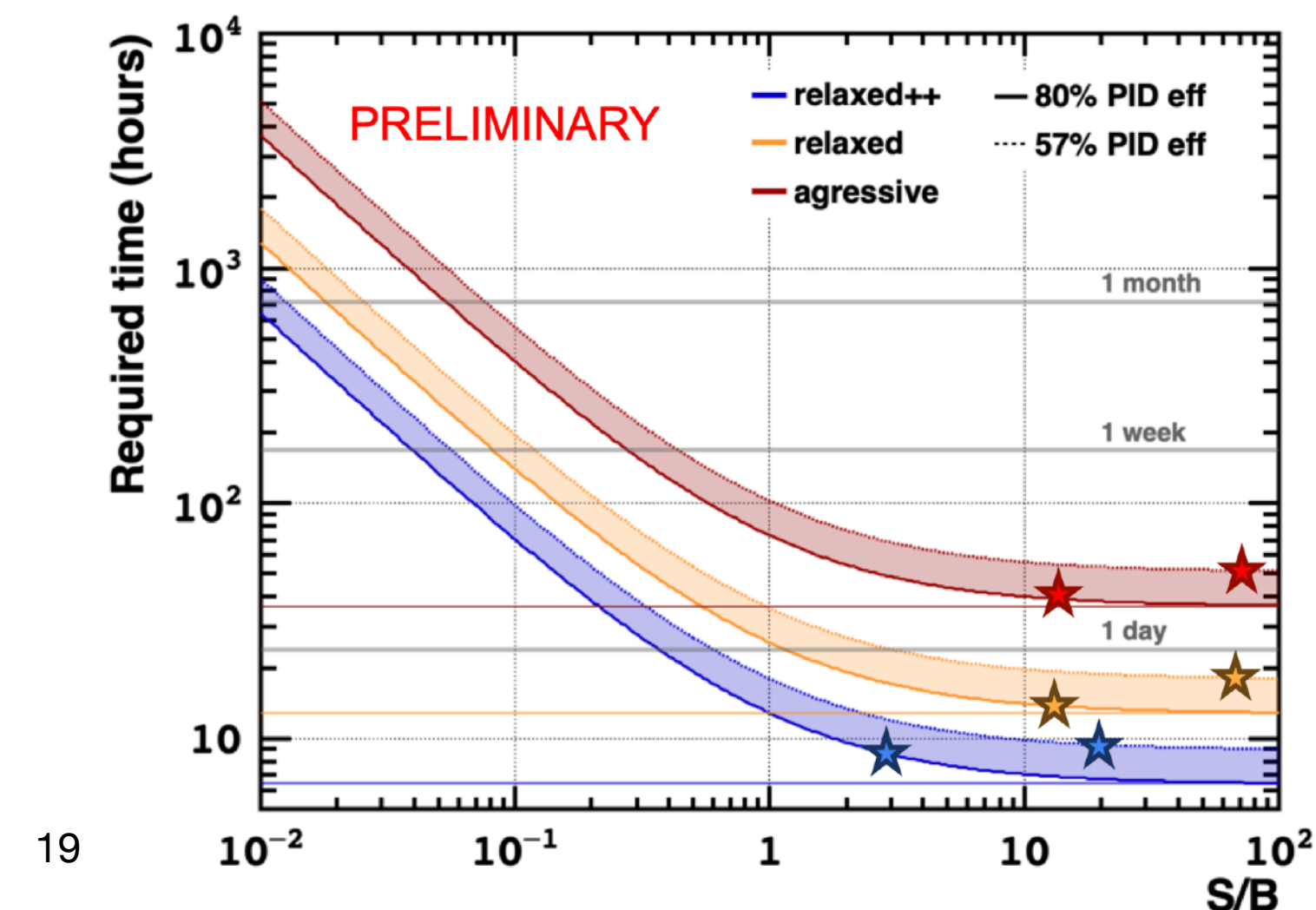
SBND

- Operation until late 2027/early 2028. Physics exploitation will continue beyond that.
- Coordination of BSM physics → First search for heavy neutral leptons with SBND data
- Operation of X-Arapuca readout. Calibration and performance analysis of X-Arapuca over years → Longest test for DUNE
- Scintillation light reconstruction with deep neural networks



LiquidO - AntiMatter-OTech (2026 - 2029)

- Contribution to the operation and data analysis of a 2m-prototype (190 L)
- Design and purchase of the external shielding
- Physics coordination: Supervision of the link Physics-Detector design, Development of strategies to monitor the reactor functioning
- Software development: Detector simulation, ML algorithms for signal identification
- Operation and data analysis of a 10 ton detector

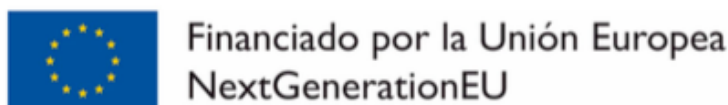


5% variation in neutrino flux with a 3σ significance

Major responsibilities

Inés Gil - Botella	DUNE Physics coordinator since 2021
Inés Gil - Botella	Member of the DUNE management Board since 2021
Inés Gil - Botella	Member of the DUNE Executive Board since 2018.
Inés Gil - Botella	Convenor of the DUNE photosensors WG. 2020 - 2025
Clara Cuesta	DUNE Low Energy Physics Convener since Dec. 2020
José Crespo Anadón	SBND Beyond Standard Model Physics Convener since June 202
José Crespo Anadón	MicroBooNE Institutional Board member since May 2020
José Crespo Anadón	SBND Community Agreement Committee. April 2022 - Oct. 2024
Inés Gil-Botella	SBND Publication Committee since 2024
Carmen Palomares	DUNE Authorship and publication board since Jan. 2024
Carmen Palomares	Convenor of the DUNE photon collector WG. June 2021 - Dec. 2024
Carmen Palomares	AntiMatter-OTech Physics coordinator, Jan. 2024 - Oct. 2025
Carmen Palomares	Member of the AntiMatter-OTech Executive Board since May 2025
Carmen Palomares	Member of the AntiMatter-OTech Steering Committee since Dec 2022
Diana Navas	Member of the AntiMatter-OTech Executive Board since May 2025
Diana Navas	AntiMatter-OTech Physics coordinator since Mar. 2024
José Crespo Anadón	DRD2 Liquid Detectors: Task Leader of Large-Area Readouts since April 2023
Clara Cuesta	DRD2 Liquid Detectors: working group leader of Common Infrastructures & Facilities since July 2024
Clara Cuesta	Member of the DRD2 Collaboration Board since February 2024
Gonzalo Merino	Chair of the Computing Contributions Board (CCB) since 2024

Funding resources (2023 - 2025)



2024 - 2027	PID2023-147949NB-C51 CIEMAT contribution to advance DUNE experiment (455 k€)
2024 - 2026	CNS2023-144183 Neutrinos de Baja Energía en DUNE (200 k€)
2023 - 2025	CNS2022-136022 Reconstrucción temporal de precisión del centelleo para nueva física en SBND (200 k€)
2022 - 2027	HORIZON-EIC-2021 Pathfinder AntiMatter-OTech: Novel Opaque Scintillator Technology for Nuclear Industry (800 k€)
2022 - 2026	HORIZON-MSCA-2021-SE SENSE: Search for new physics and technological advancements from neutrino experiments (travels)
2021 - 2025	H2020-INFRAINNOV-2020 AIDAinnova: Advancement and Innovation for Detectors at Accelerators
2019 - 2024	2020-MSCA-RISE-2018 INTENSE: Particle physics experiments at the high intensity frontier (travels)
2021 - 2025	NextGenerationEU: Spain contribution to the DUNE FD1 & FD2 (3 M€ core + 1 technician, 1 engineer + 1 PhD student)
2024 - 2025	Ayudante de Investigación PEJ-CAM (2 year graduate degree)
2023 - 2024	Beca Leonardo a Investigadores en Física “Detección de neutrinos de supernova en DUNE” (40 k€)

Spain and the US signed an MoU for the contribution to the first DUNE Far Detectors

 ciencia.gob.es/Noticias/2024/Noviembre/espana-eeuu-proyecto-dune.html

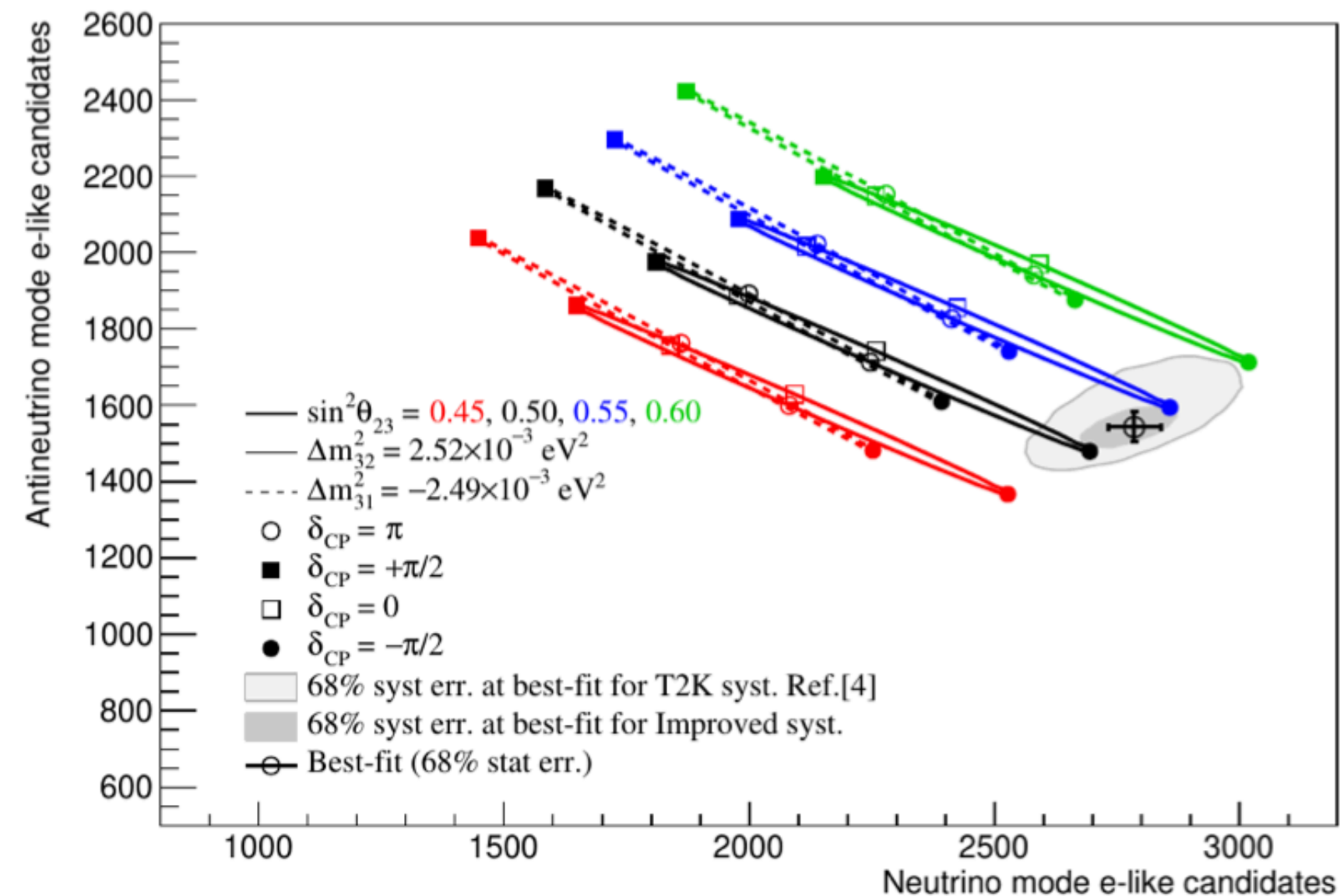
05-11-2024



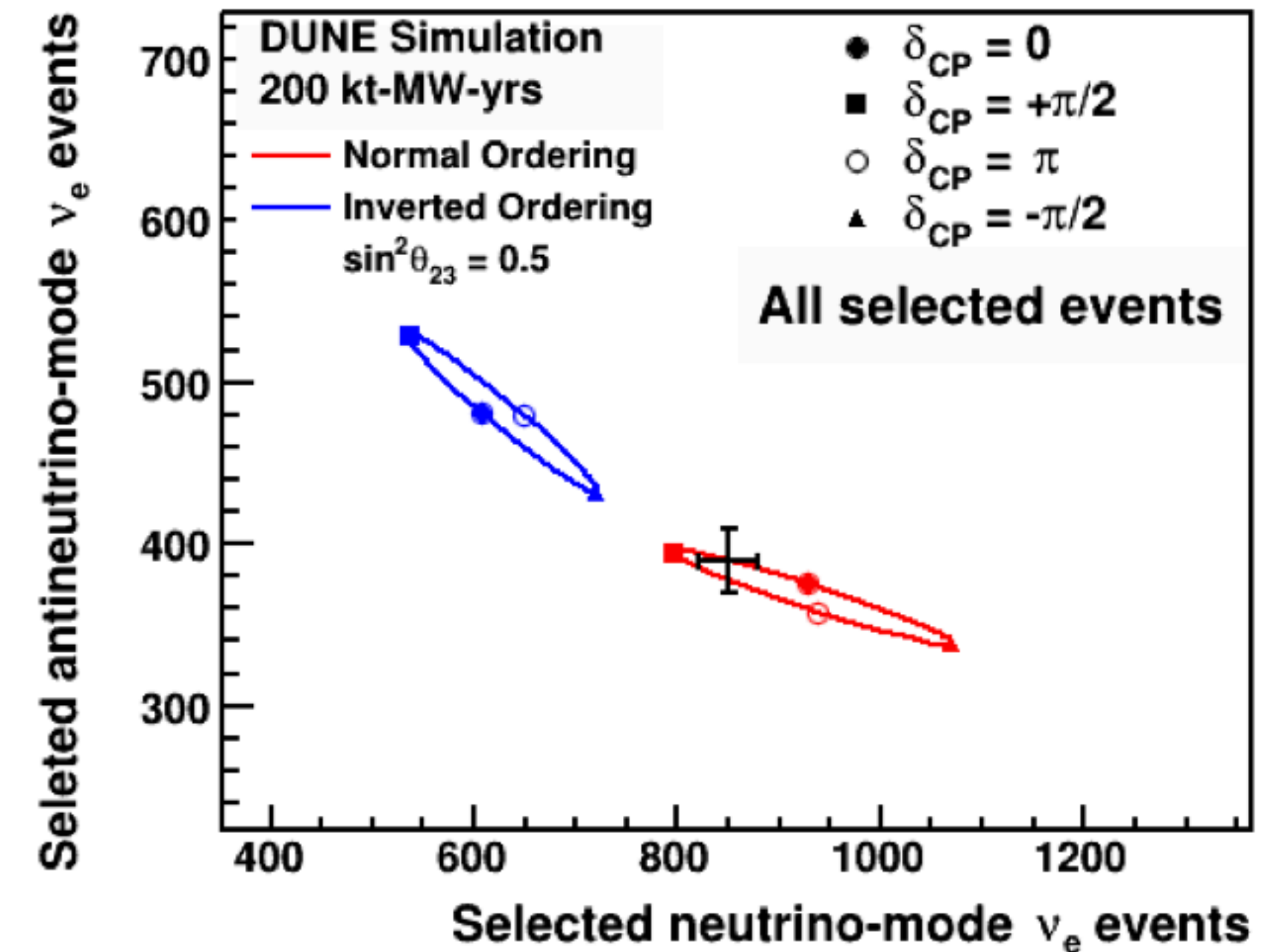
BACKUP

Hyper-K vs DUNE

Hyper-K



DUNE

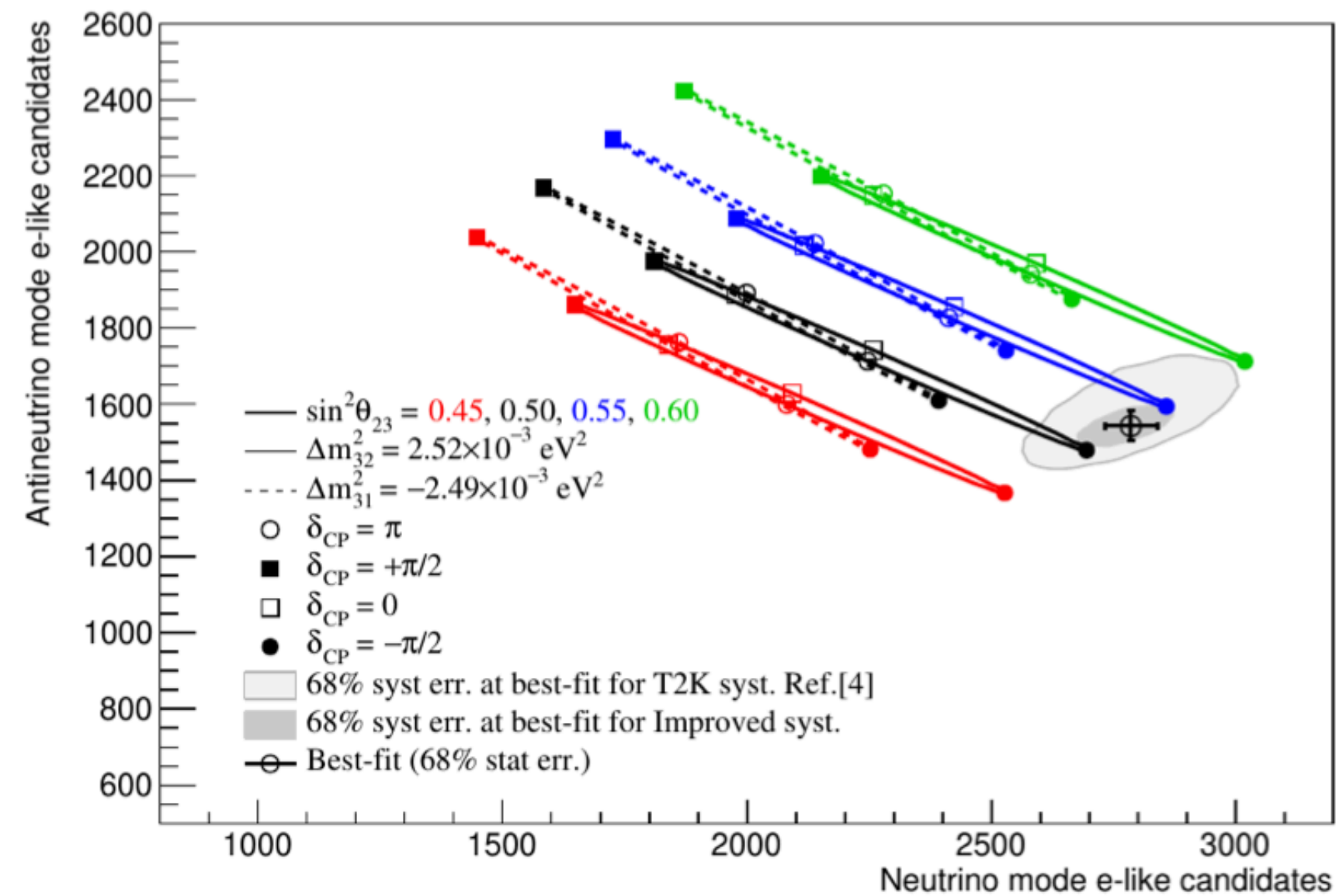


- Very good at distinguishing CP conserving vs. CP violating values **provided MO is known**
- Degeneracy between MO and δ_{CP} , and between different values of δ_{CP} with same $\sin(\delta_{CP})$

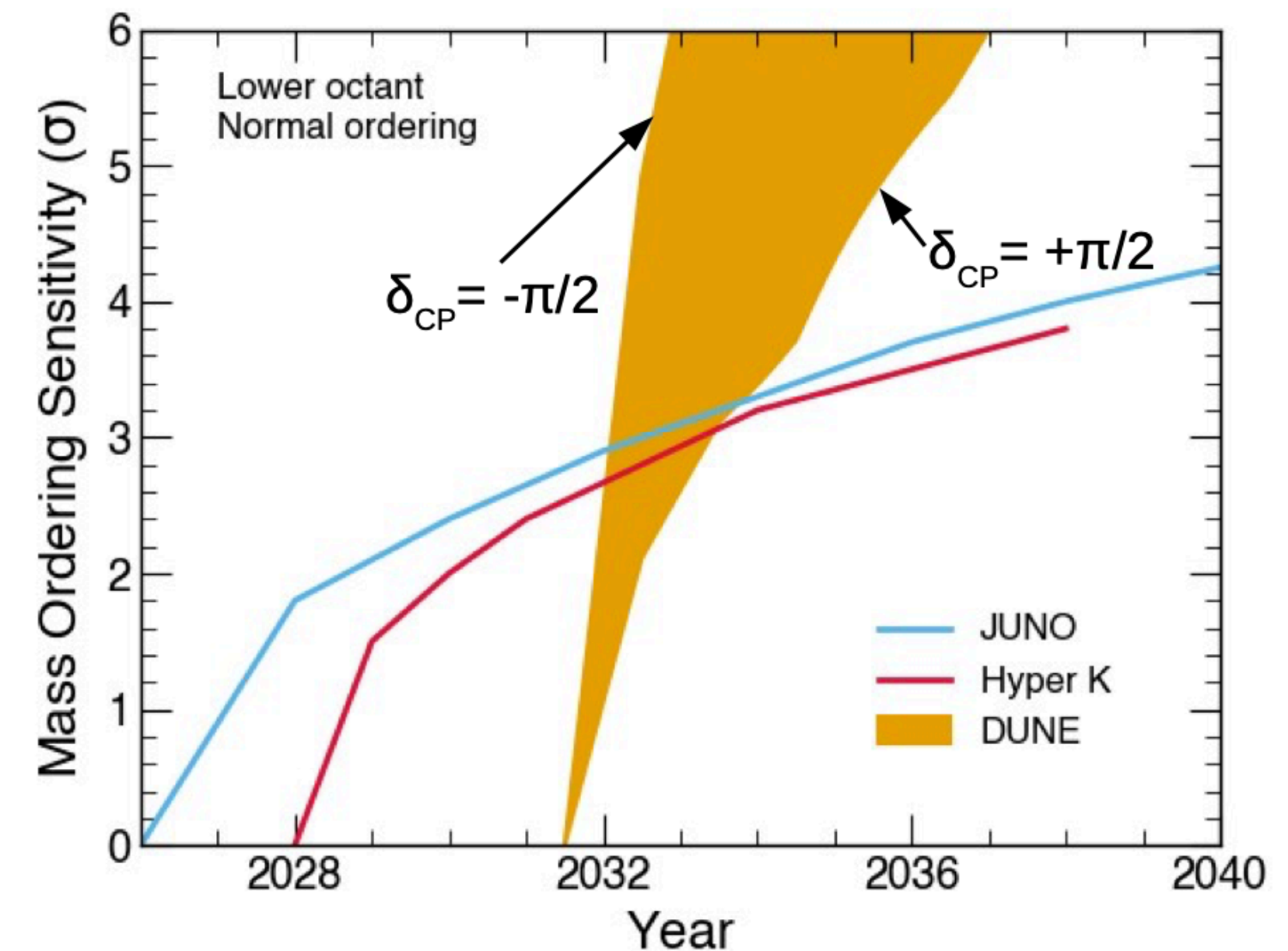
- No overlap, parameters are not degenerate
- Only experiment that measures the MO by separately measuring $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations
- MO sensitivity depends the δ_{CP} . MO measured at 5σ in 1 - 3 years

Hyper-K vs DUNE

Hyper-K



DUNE

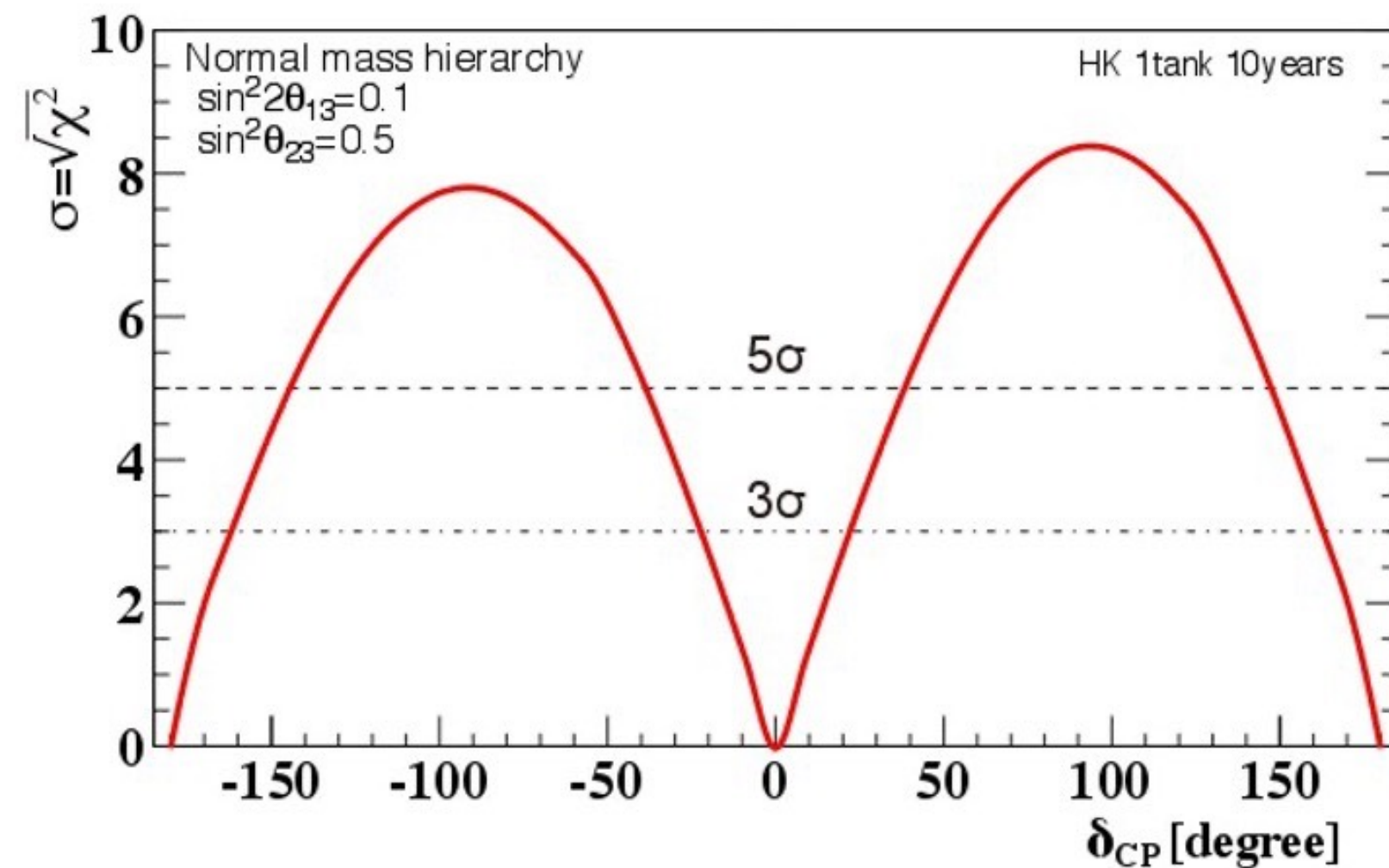


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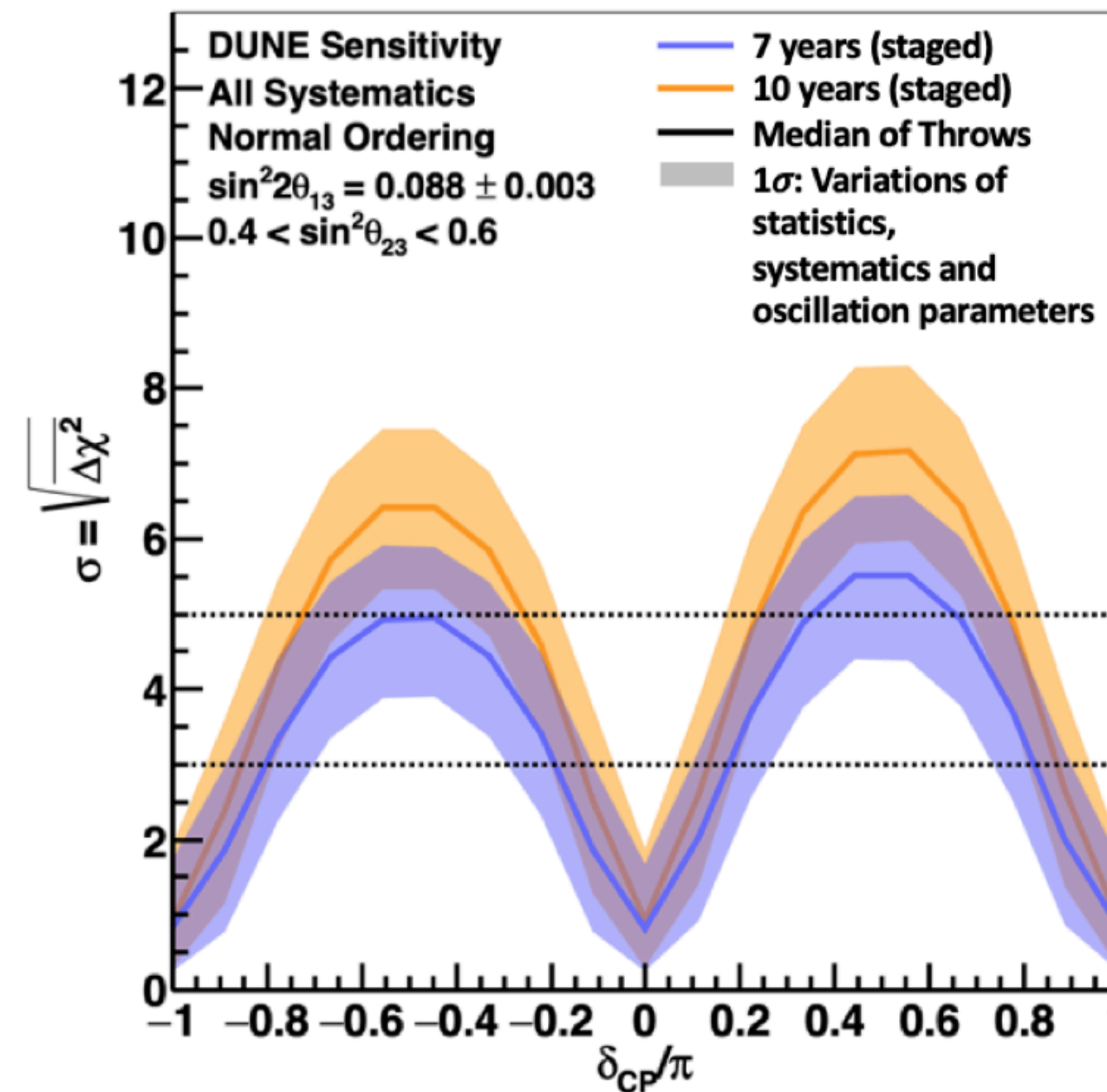
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Hyper-K vs DUNE

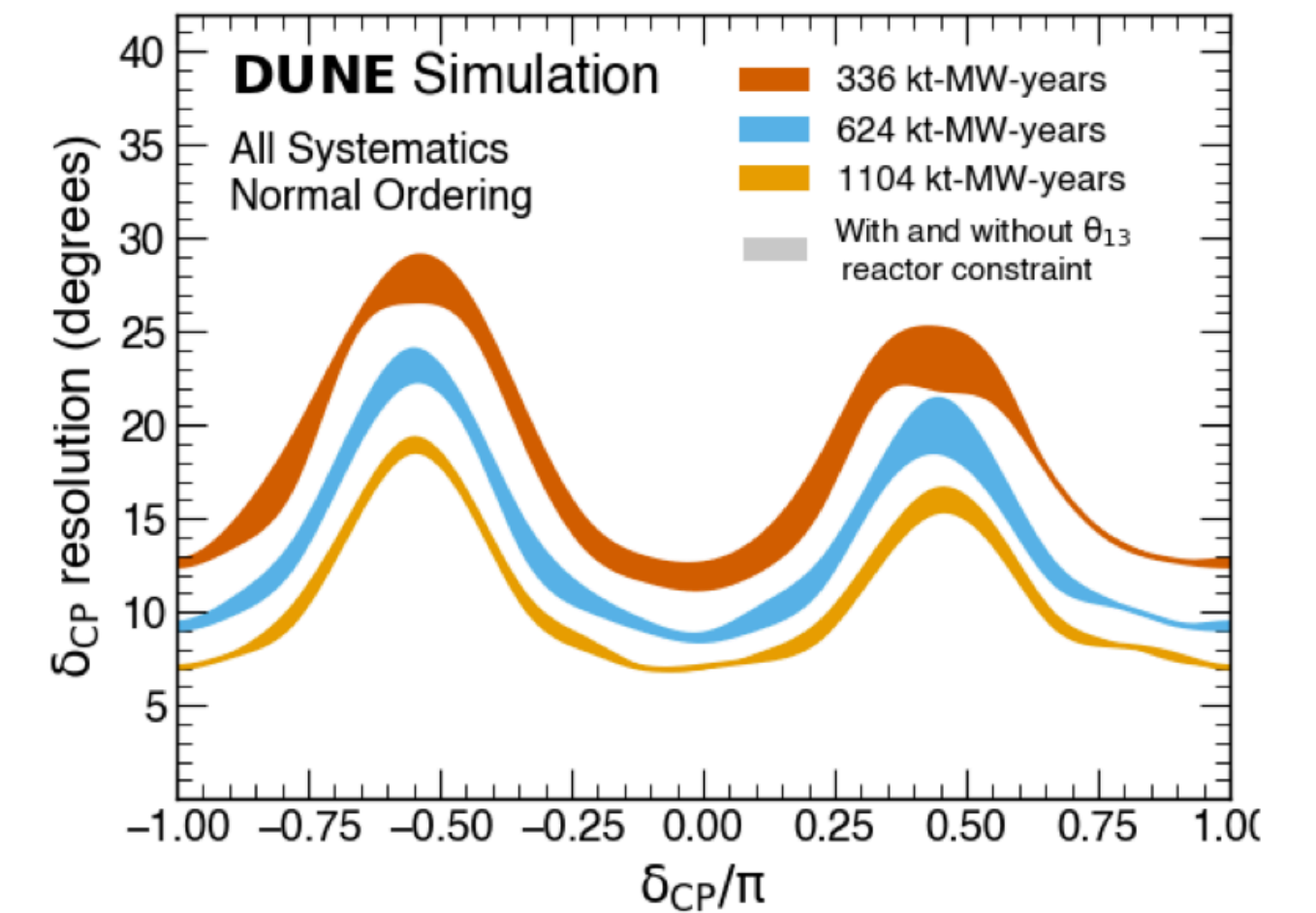
Hyper-K



True Normal Ordering

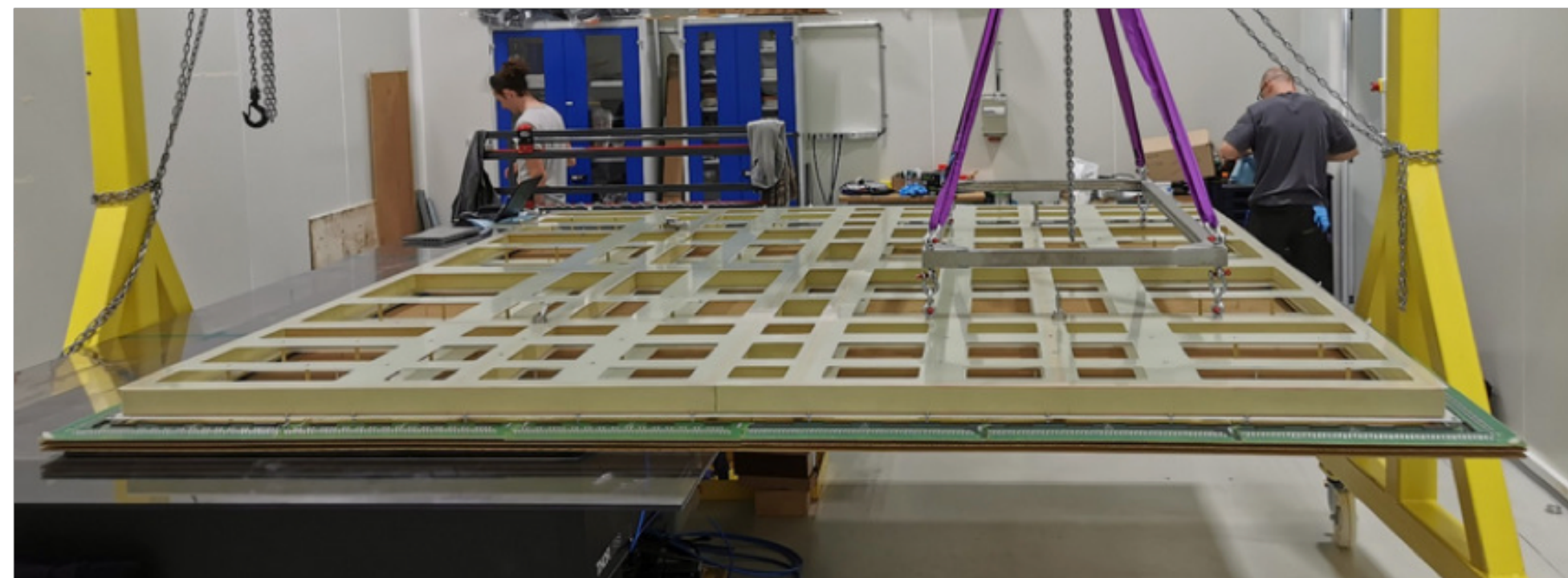


DUNE

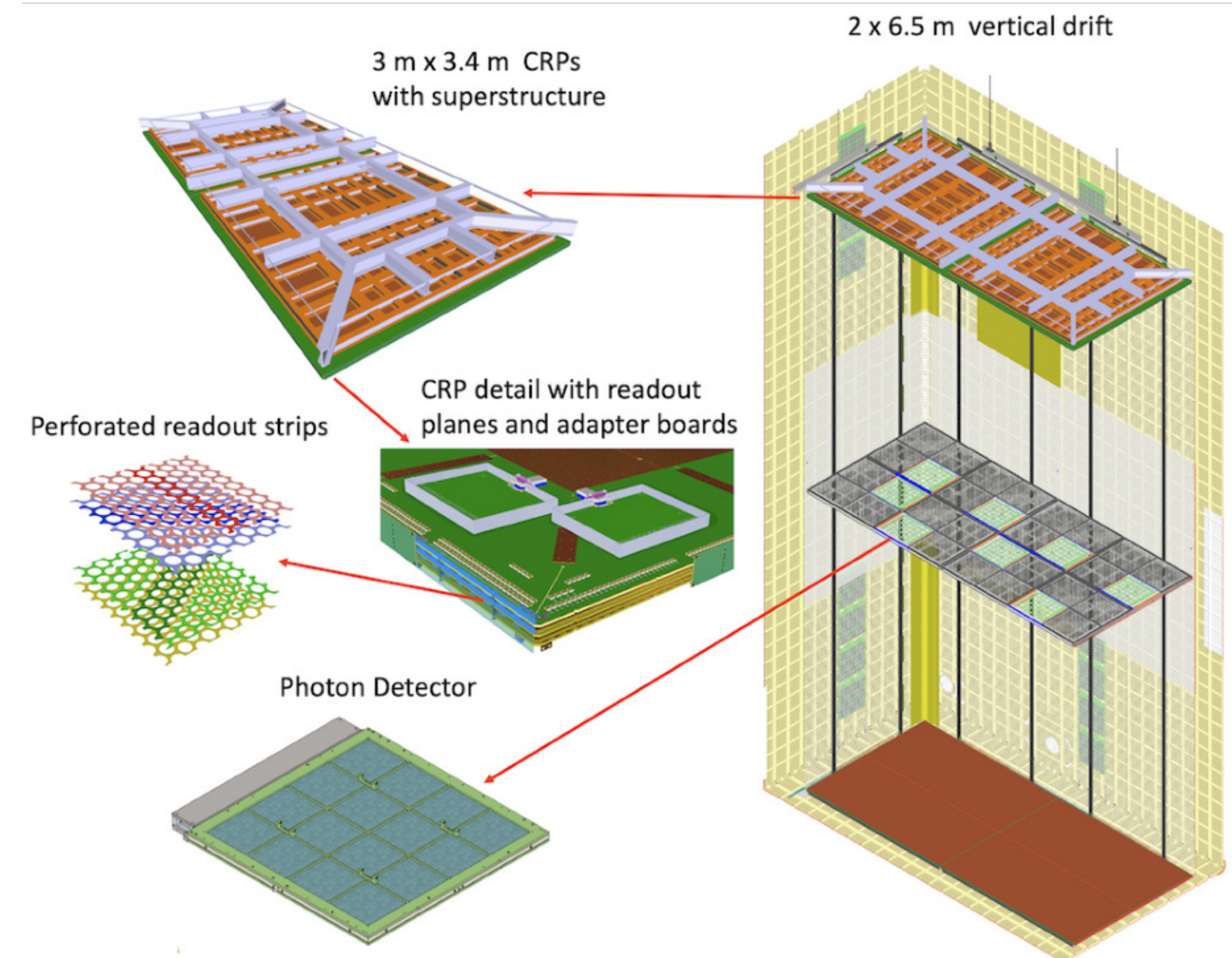
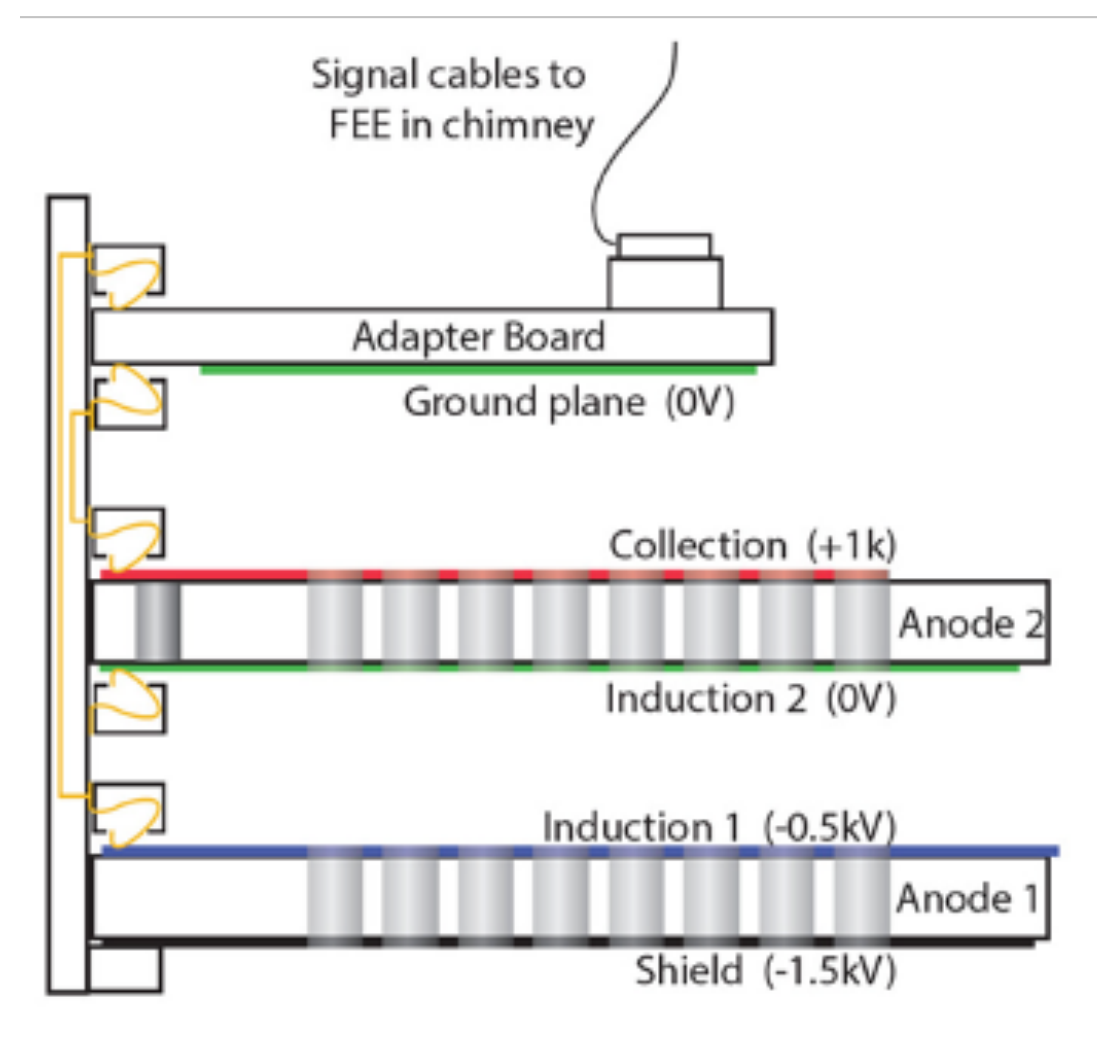


DUNE has the best ultimate δ_{CP} resolution, especially if CP is violated

DUNE Far Detector VD

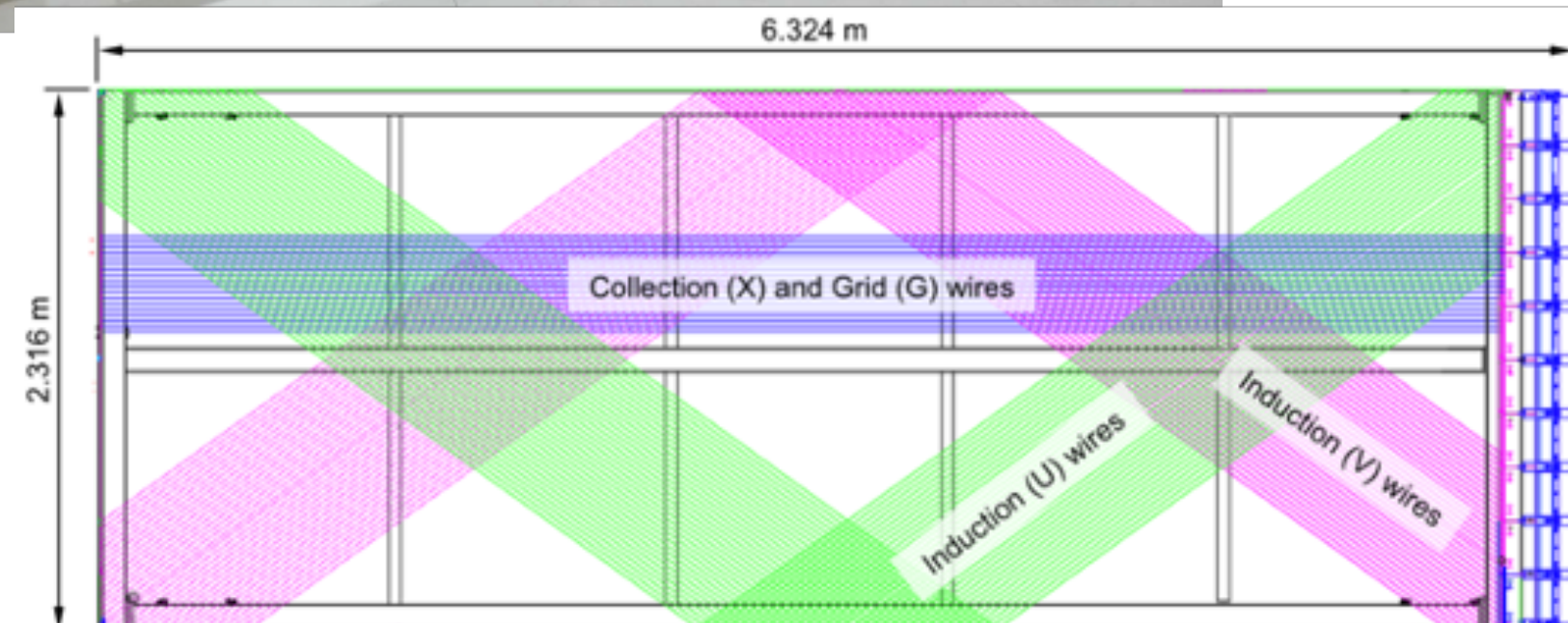
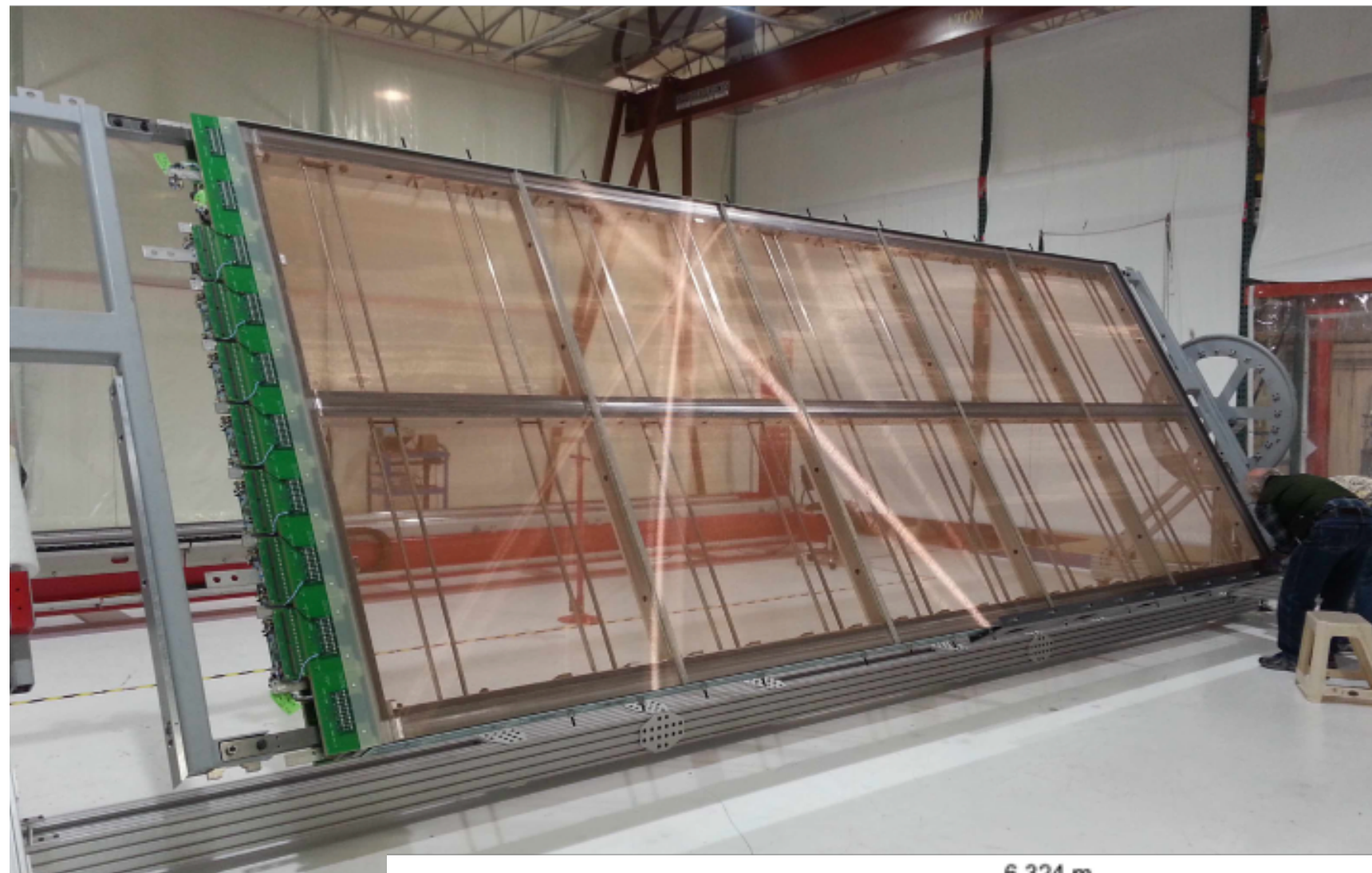


Divided in 2 drift volumes (6 m)
160 PCB-based Charged Readout Planes (CRP) (3 m x 3.4 m)



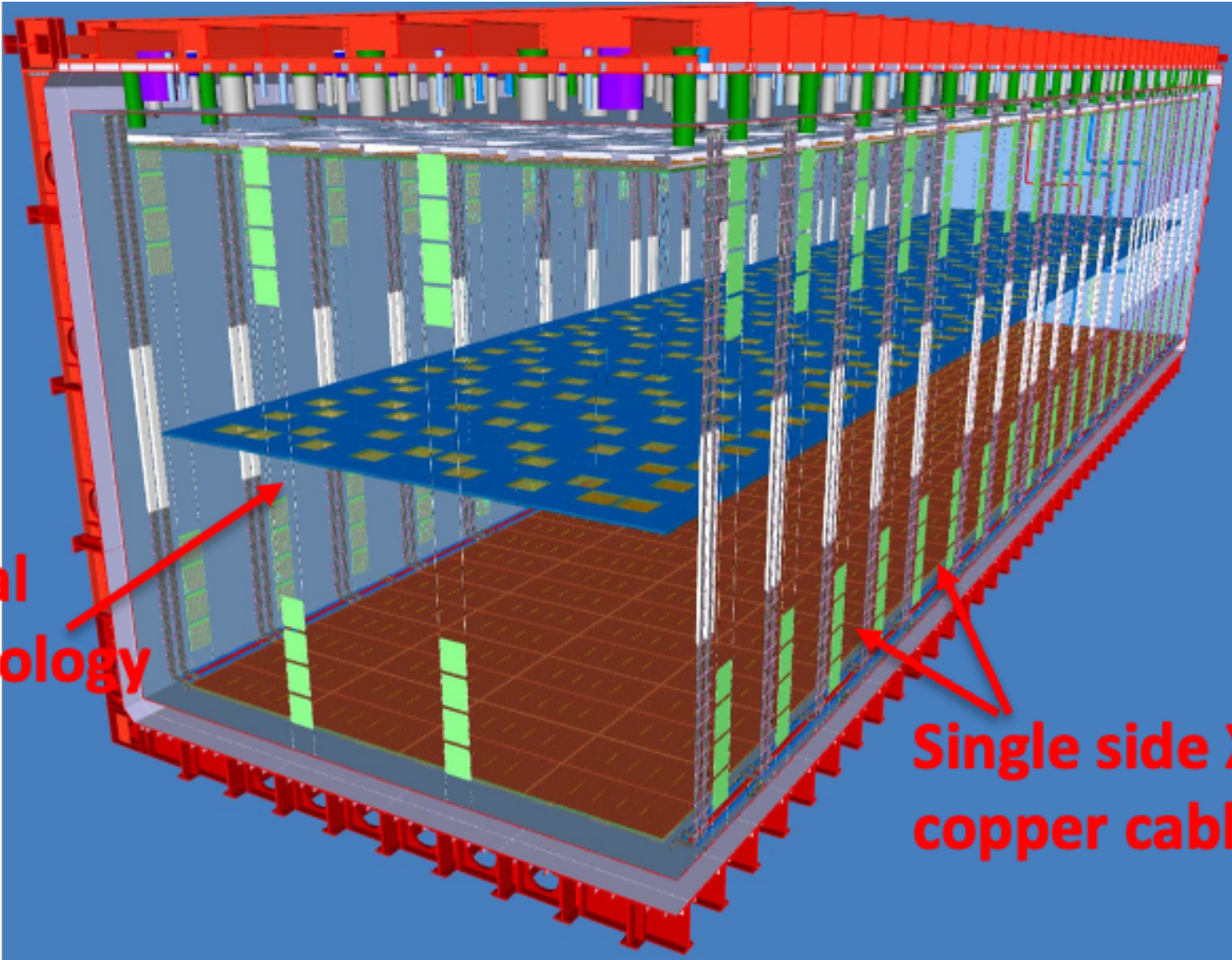
DUNE Far Detector HD

Divided in 4 drift volumes (3.6 m)
150 individual Anode Planes Assemblies (APA) (2.3 m x 6 m)



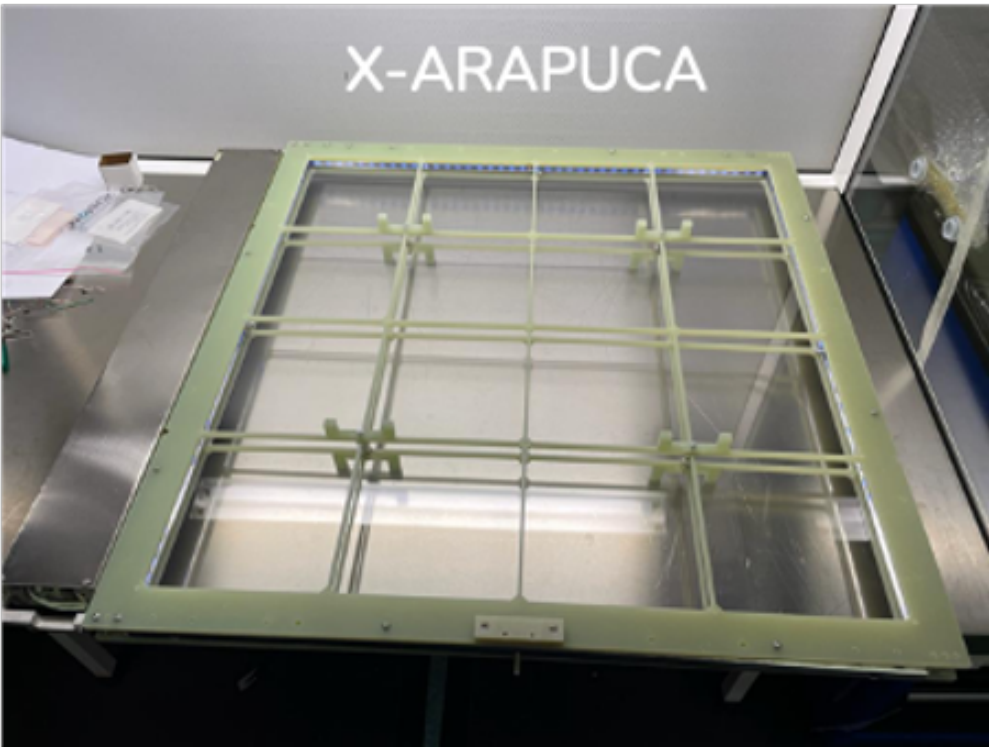
DUNE Photon-Detection System

FD-VD



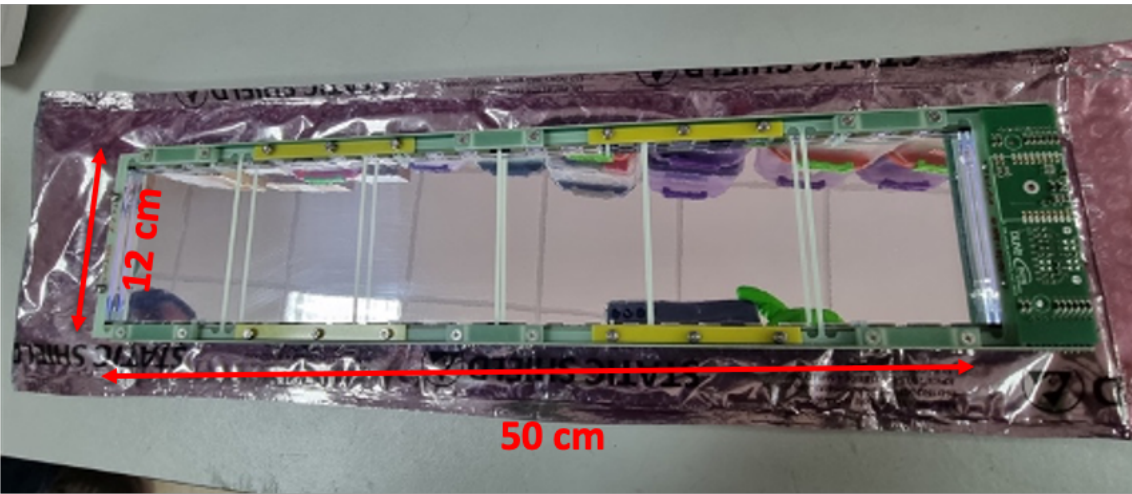
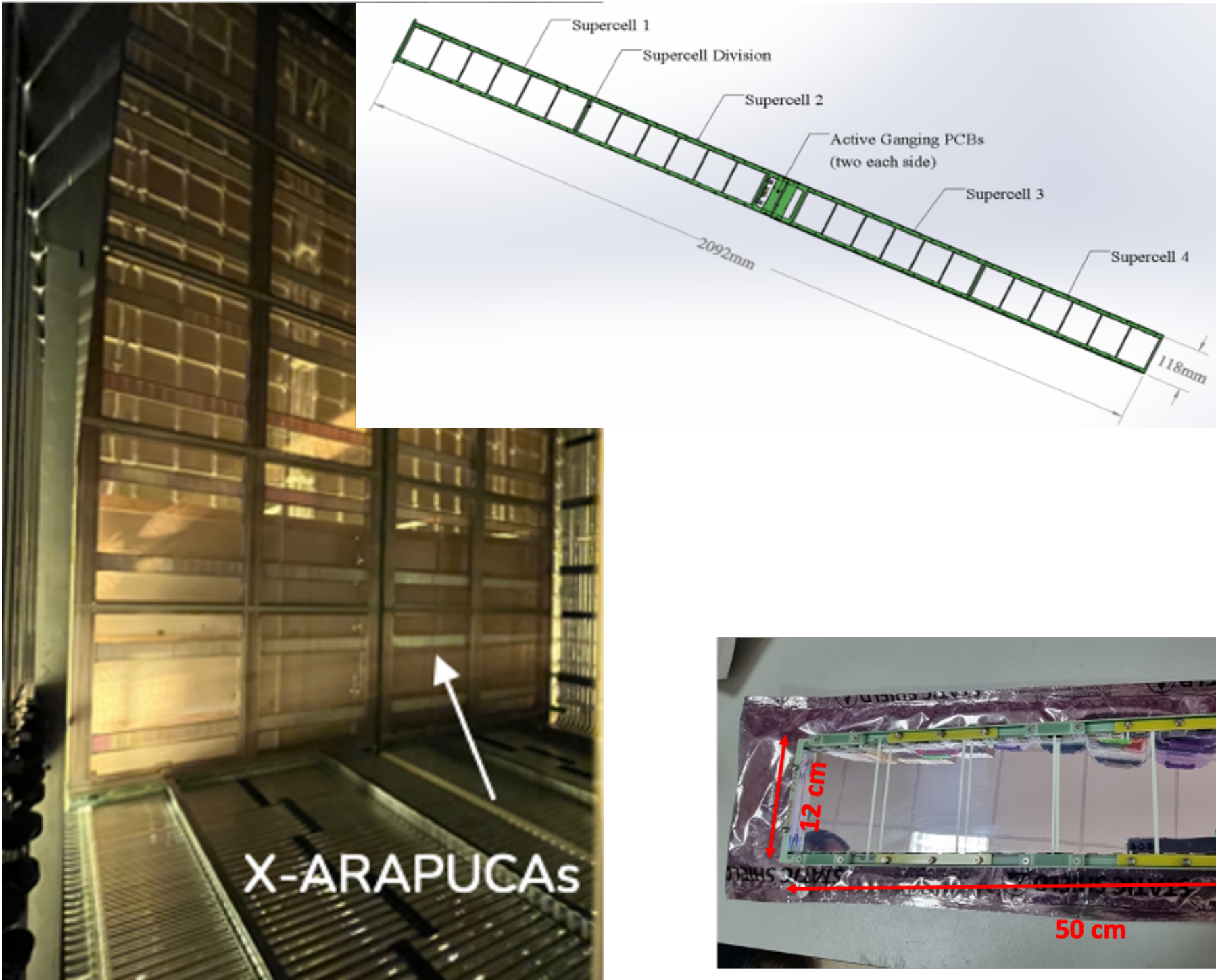
Double-side XA
power and signal
over fiber technology

Single side XA
copper cables

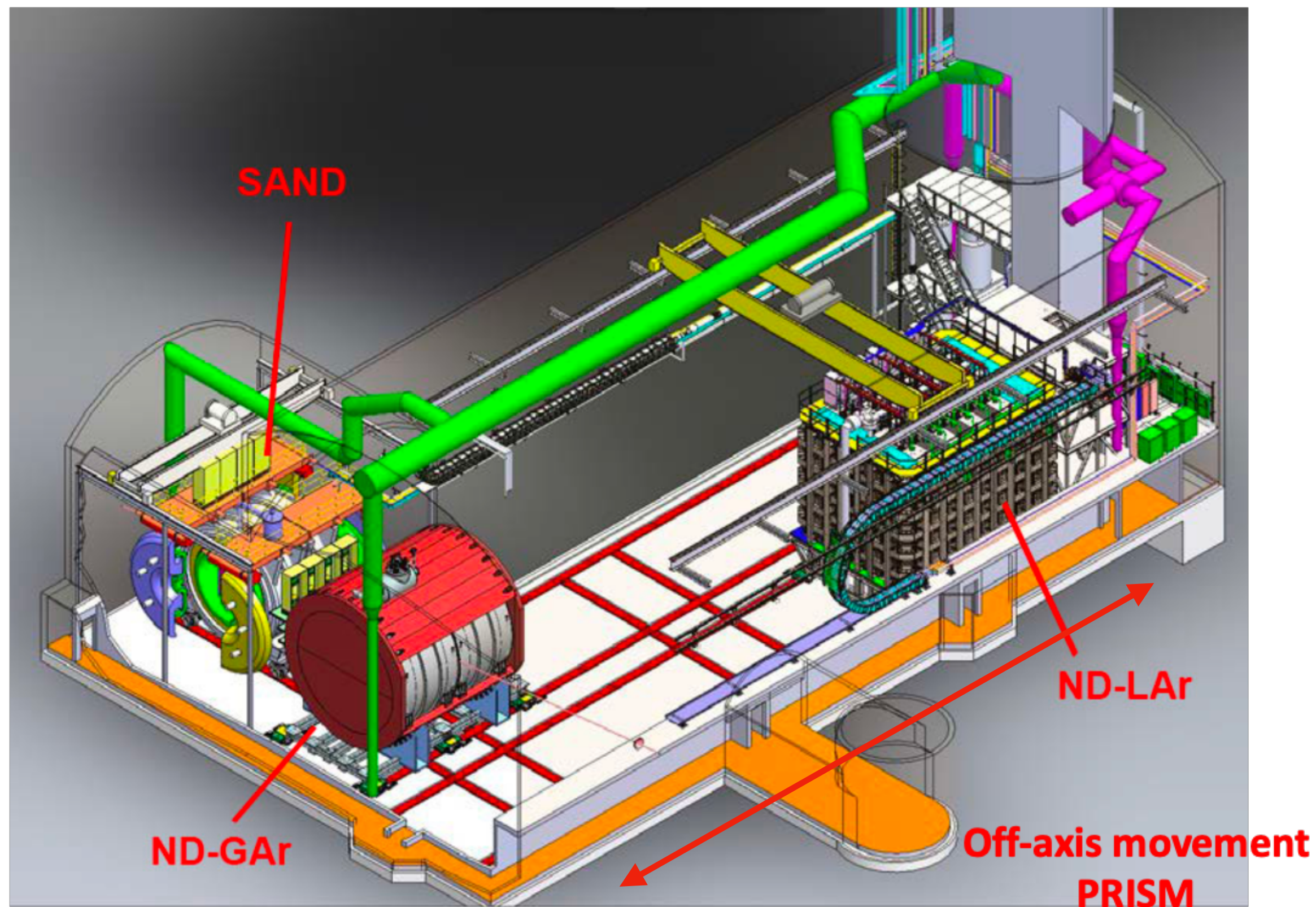


FD-HD

ProtoDUNE-HD



DUNE Near Detector



NDLAr: 150 ton LAr TPC → Flux determination

NDGAr: Magnetized High-pressure GAr TPC
→ high-precision measurements of neutrino interaction

PRISM: change flux spectrum. Provide FD-like energy spectrum at ND

SAND: on-axis beam monitor. Superconducting magnet + calorimeter + Inner tracker

New laboratory

Building **beneficial occupancy** in Nov. 2025

- **Cryogenic** capability (liquid nitrogen and liquid argon): 3 dewars (300 L, 600 L, 2000 L) and 3 turbomolecular pumps.
- **Crane** rated for 2 ton load.
- **4 electronics racks** (22U).
- **UPS** (5 kW continuous, 5kWh capacity) and clean ground.
- **3D vision machine**: QUICK VISION Active 404.
Precision: $\pm 1.5 \mu\text{m}$.
DUNE SiPM measurements on-going.



Next task:

- Assembly of 352 X-Arapucas and cryogenic characterisation prior to shipment to SURF

