Deep Underground Neutrino Experiment: DUNE

Andrea Falcone

University of Milano Bicocca and INFN Milano Bicocca

for the DUNE Collaboration

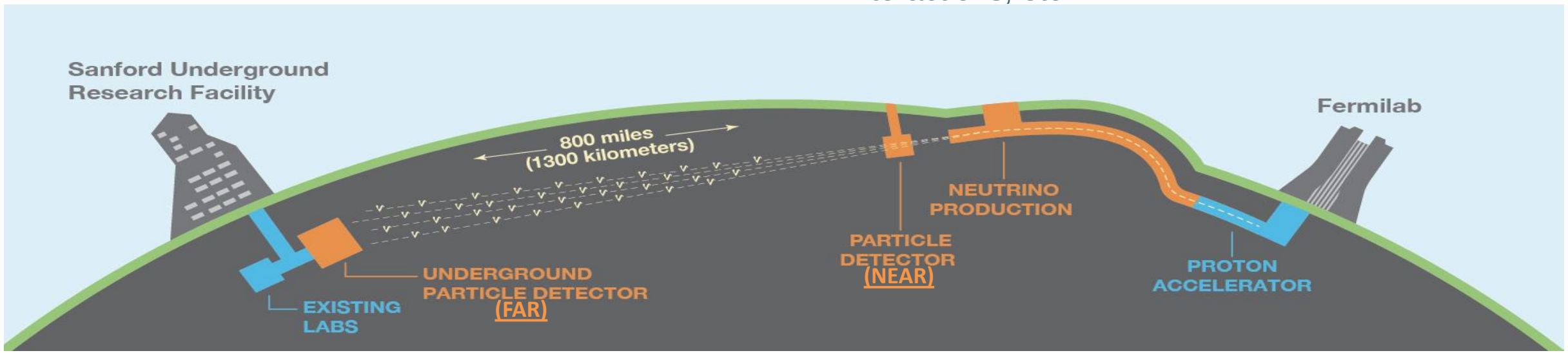
Vienna Conference on Instrumentation

21-25 Feb 2022

Deep Underground Neutrino Experiment

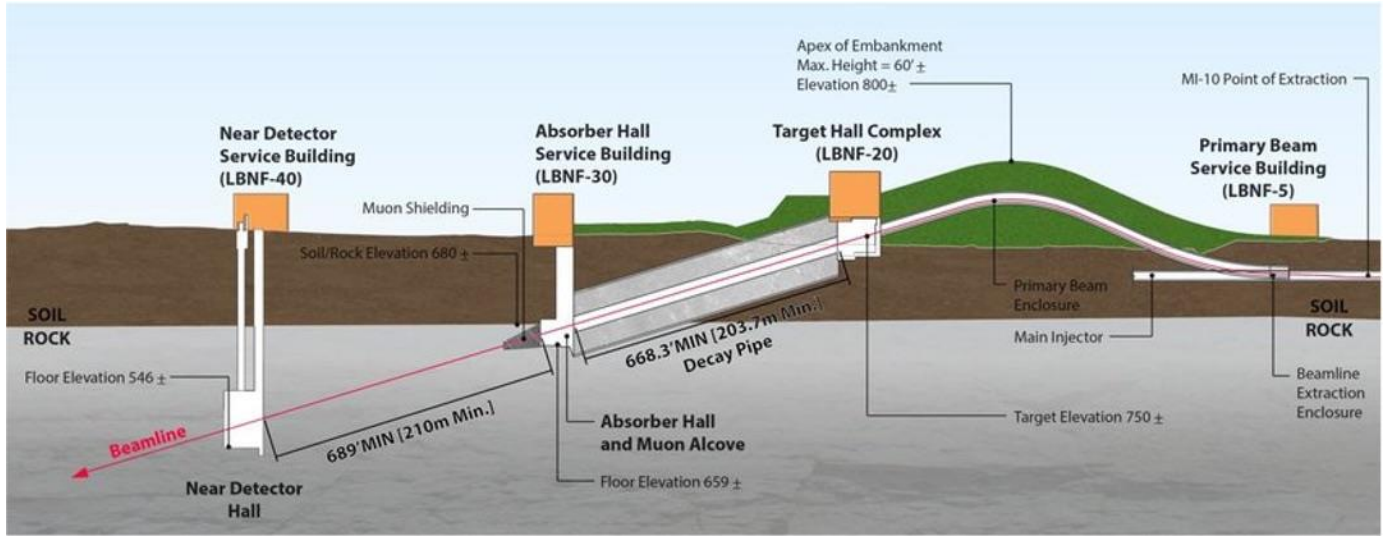
- Long-baseline (LB - 1300 km) experiment:
  - ✓ Neutrino and antineutrino beams
- ~ 70 kton volume far detector, 1.5 km underground, divided in 4 modules
- Multi-technology Near Detector, focused on beam characterization and physics
- > 20 years foreseen life span

- Primary physics goals:
  - ✓ 3-neutrino oscillations parameters: $\nu_\mu/\overline{\nu_\mu}$ disappearance, $\nu_e/\overline{\nu_e}$ appearance
  - ✓ δ_{CP} ; mass hierarchy
- SuperNova burst neutrinos
- Beyond-Standard-Model physics: baryon number violation, sterile neutrinos, non-standard interactions, etc.

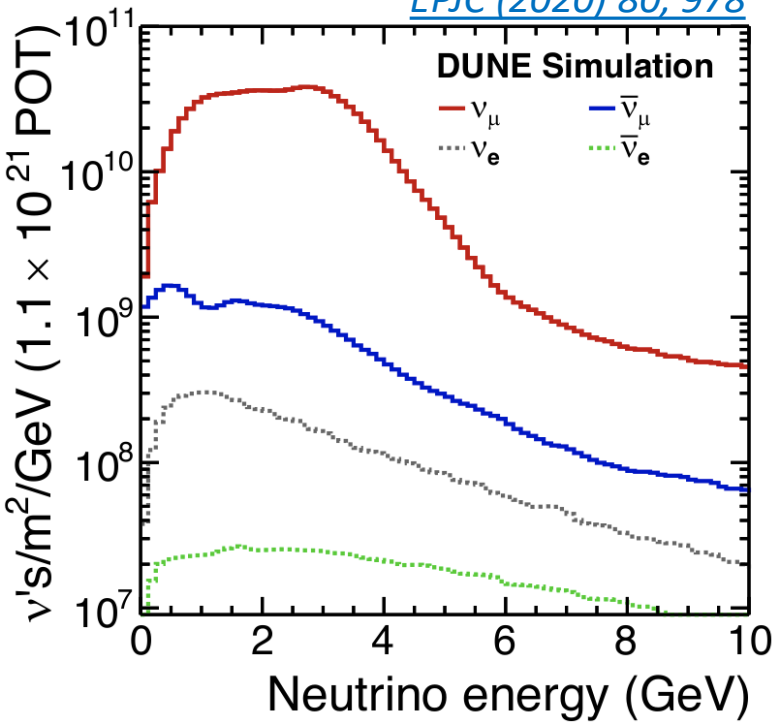


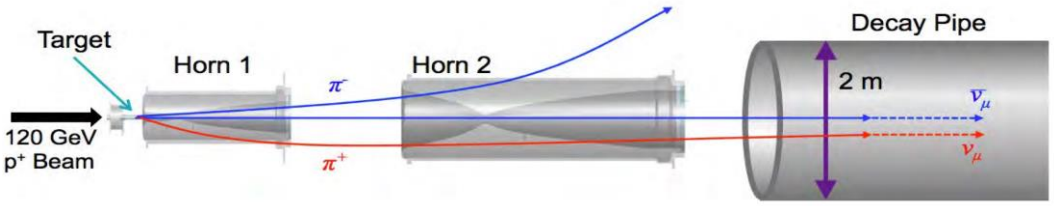
Long Baseline Neutrino infrastructure

- Beam line design under way
  - ✓ 60-120 GeV proton beam
  - ✓ 5.8 degree vertical bend, to reach SURF
  - ✓ 1.2 MW by late 2020's, upgradable to 2.4 MW
  - ✓ Assumed minimum uptime of 55%
- (1.1-1.9) x 10^{21} POT/y @ 1.2 MW - 10 μs pulse duration



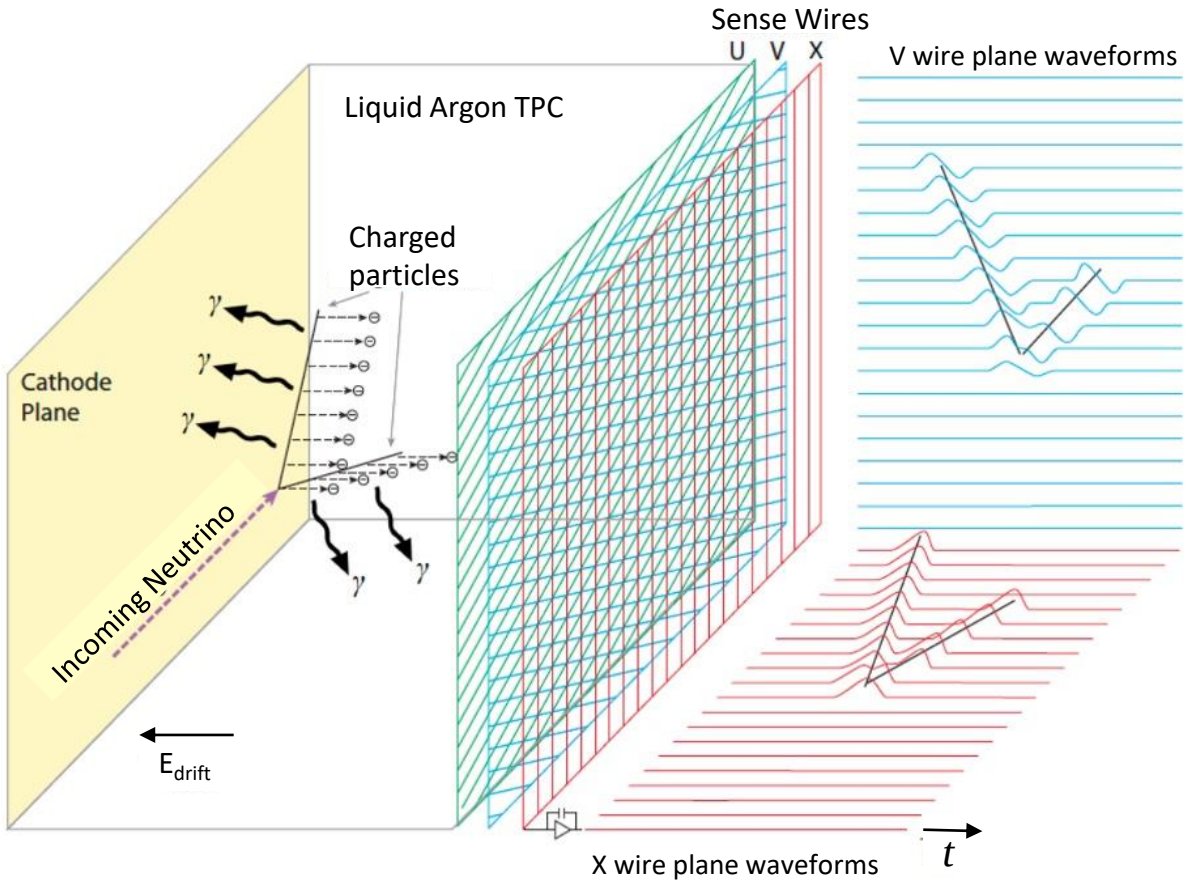
EPJC (2020) 80, 978



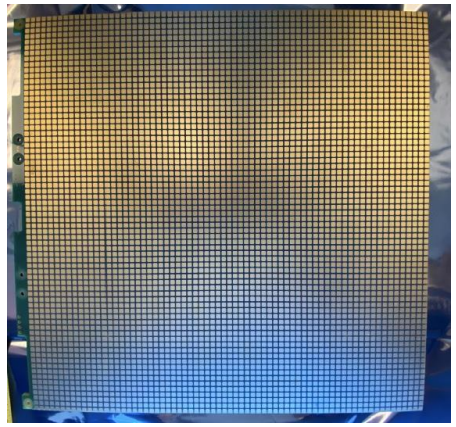


LAr TPC

- Charge/light production and collection with wire read-out (HD technology)

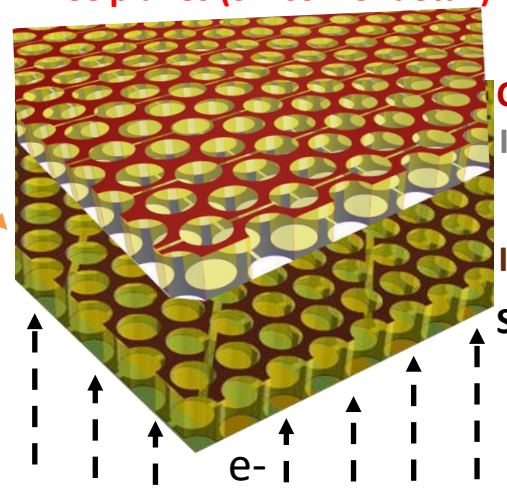


- Other read-out solutions:
  - ✓ Pixels (ND LAr-TPC)
  - ✓ Perforated PCBs (Vertical Drift)



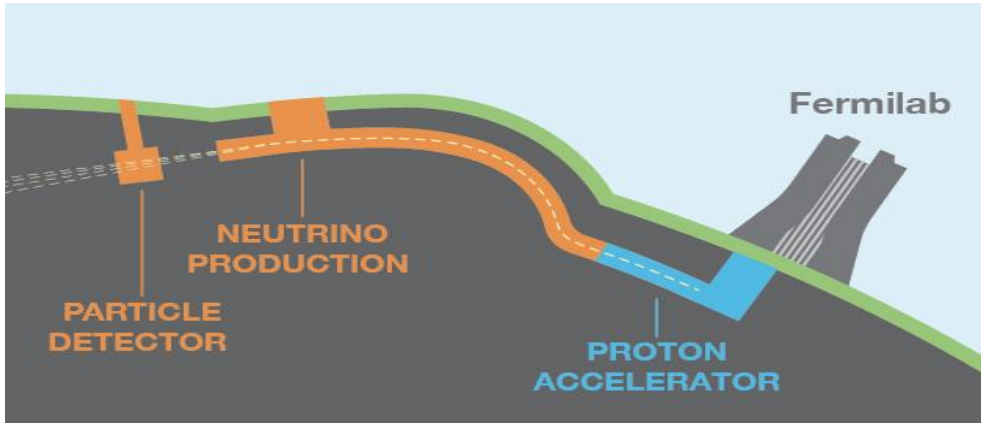
LArPix anode
32 x 32 cm
4.9k pixels

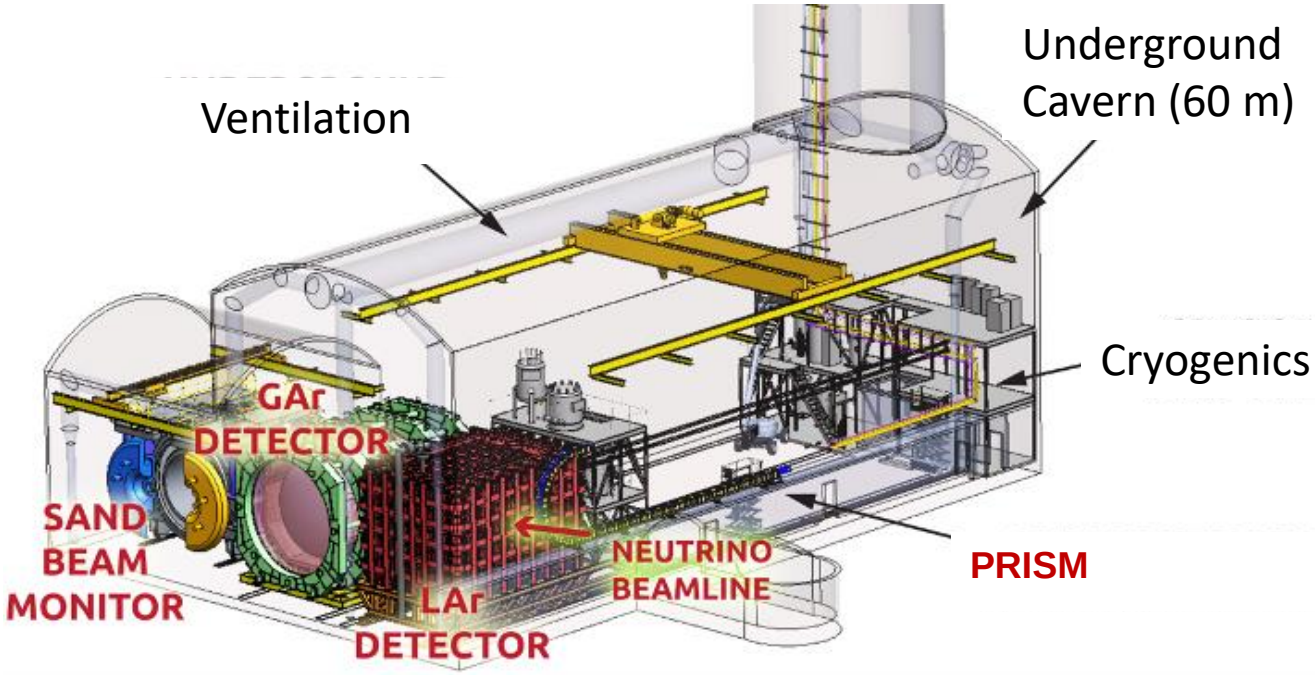
Three planes (3D corner detail)



Near Detector

- DUNE ND complex
  - ✓ Located 574 m from proton beam target
  - ✓ Precise characterization of neutrino beam
  - ✓ Limitation of cross-section uncertainties for LB neutrino oscillation measurements



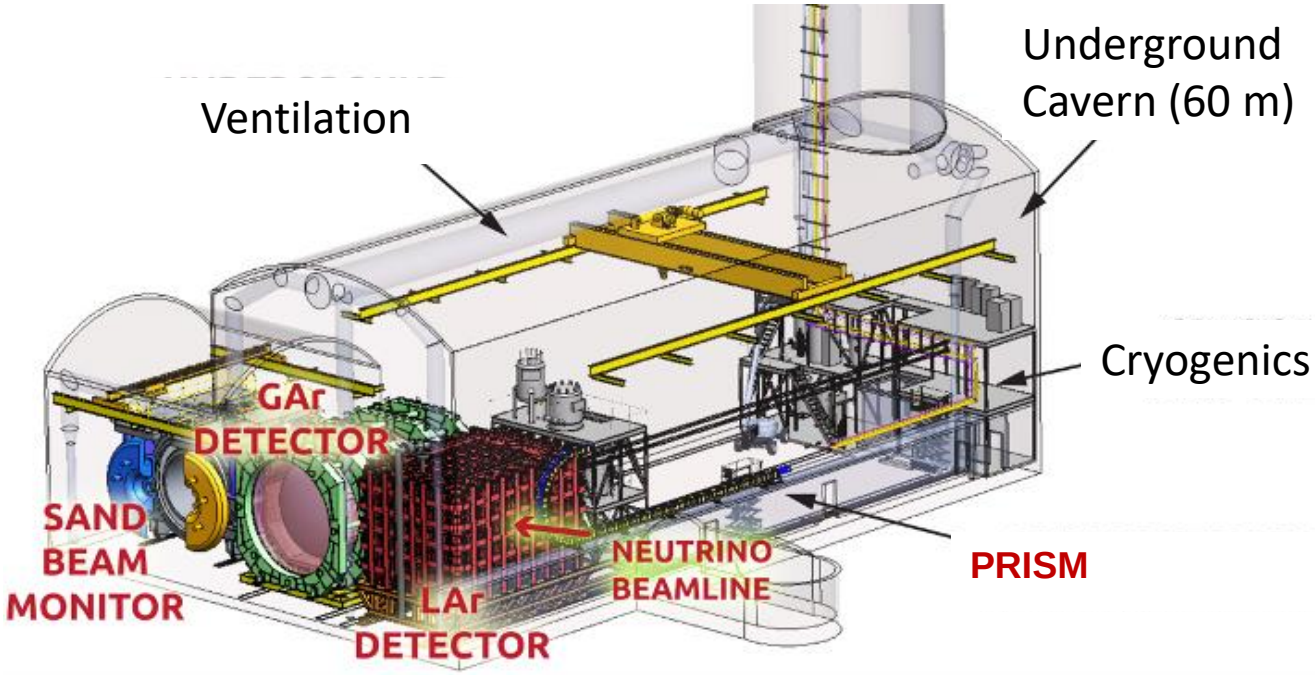


Near Detector

Multiple complementary systems:

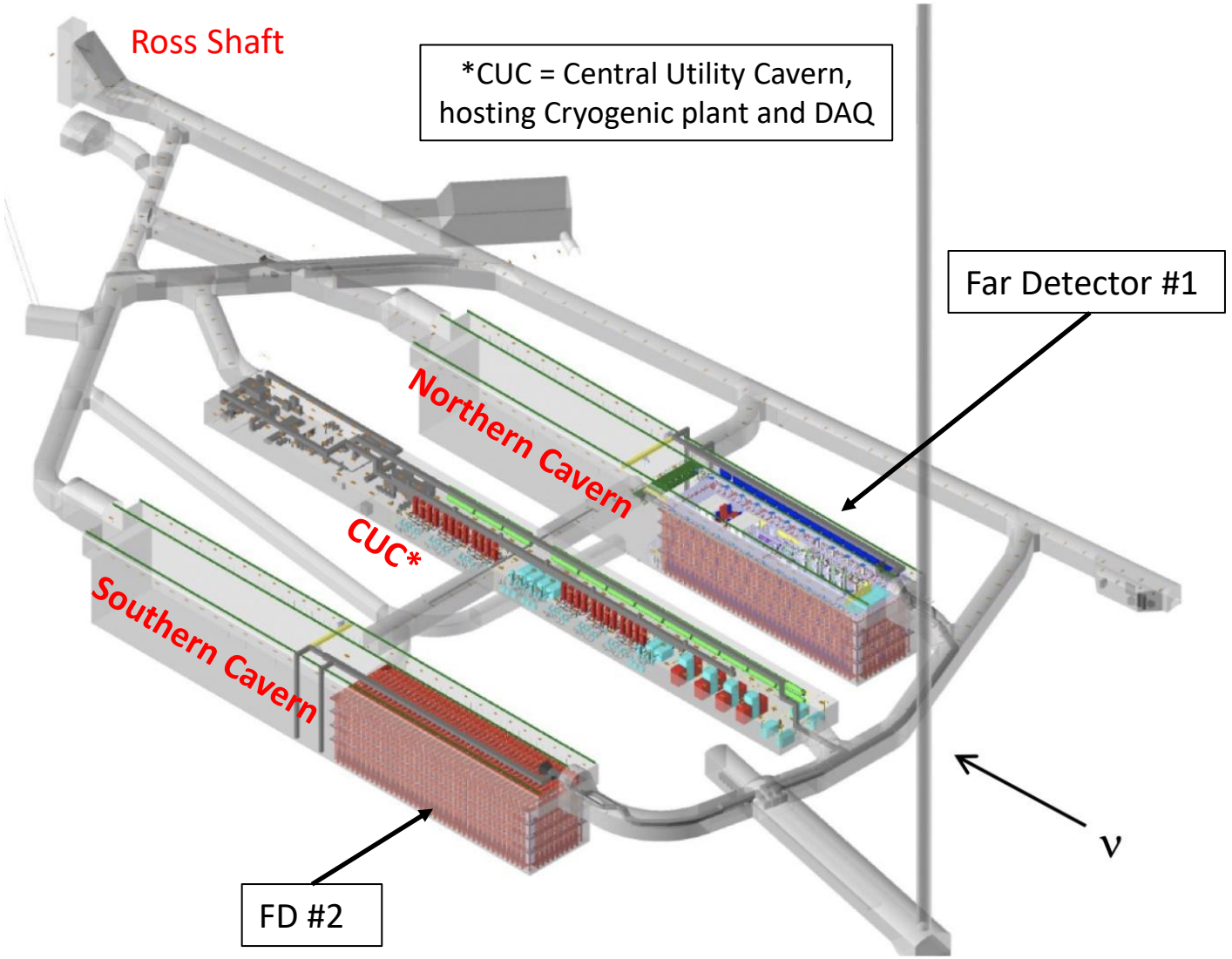
- **ND-LAr** primary target, 35 optically separated LArTPC, pixelated charge read-out Lar-TPC (300 ton)
  - ✓ Module 0 successfully tested at Univ. Bern
- **ND-GAr**: high-pressure GAr-TPC, surrounded by ECAL and 0.5 T magnet
  - ✓ intercepts muons escaping LAr-TPC
  - ✓ Muon spectrometer; nuclear interaction model constraints
  - ✓ Will come at a later stage. A Temporary Muon Spectrometer (TMS) will be installed at Day 1
- **SAND**: inner tracker surrounded by 100 ton ECAL and SC magnet (0.6 T) from KLOE
  - ✓ On-axis beam monitor (spectrum/stability)

PRISM: ND-LAr and TMS/ND-GAr can move up to 33 m Off-Axis for beam characterization and lower-energy ν detection

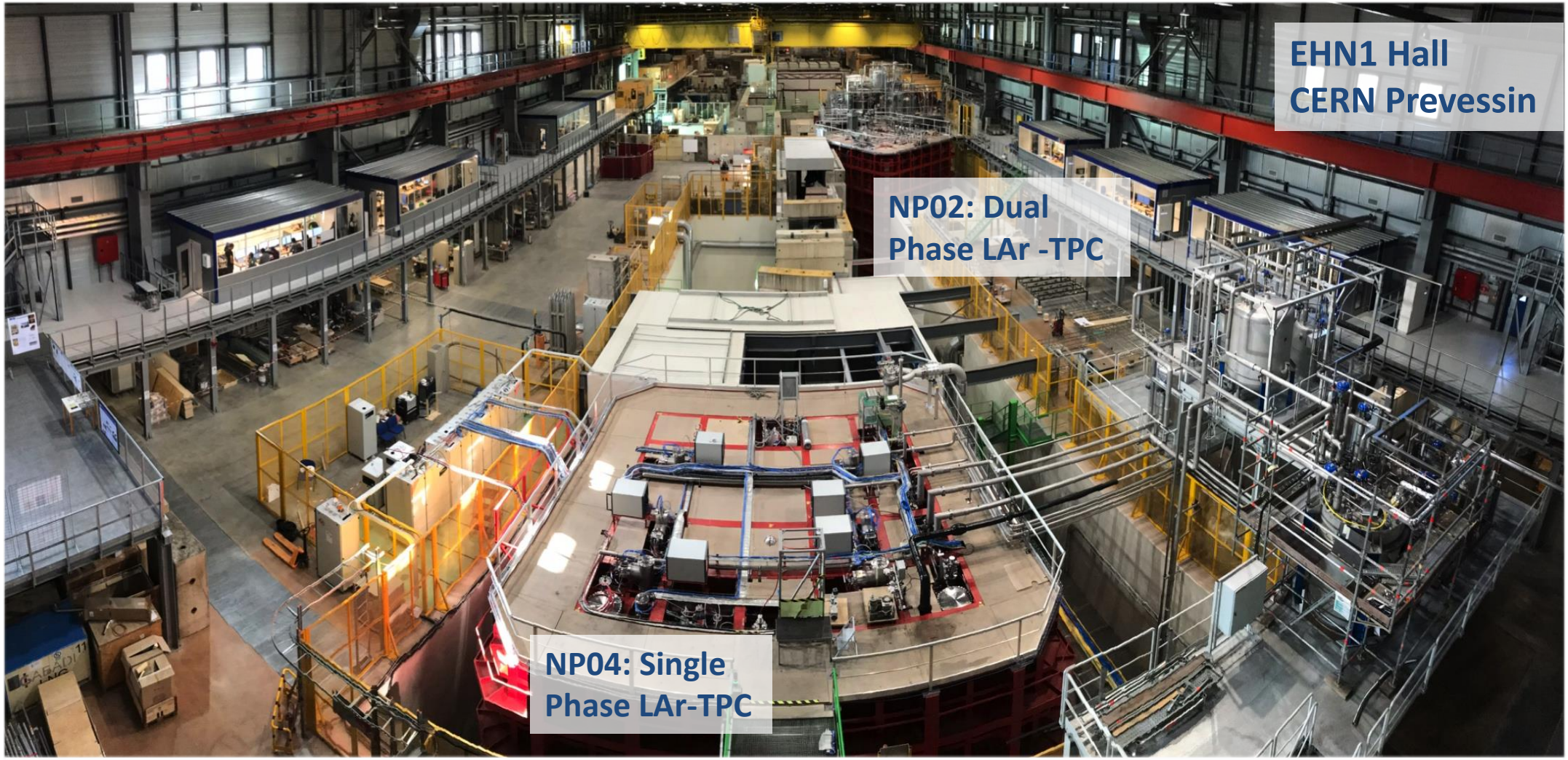


Far Detector

- 4 Detector modules, ~17 kton total volume each
  - ✓ Construction in stages
- FD 1 and 2 will be single-phase LAr-TPCs, with Horizontal Drift (HD) and Vertical Drift (VD), respectively
- FD 1 construction starts in mid 2020's
- Maximal cryostat external dimensions: ~ 66 x 19 x 18 m (LxWxH)

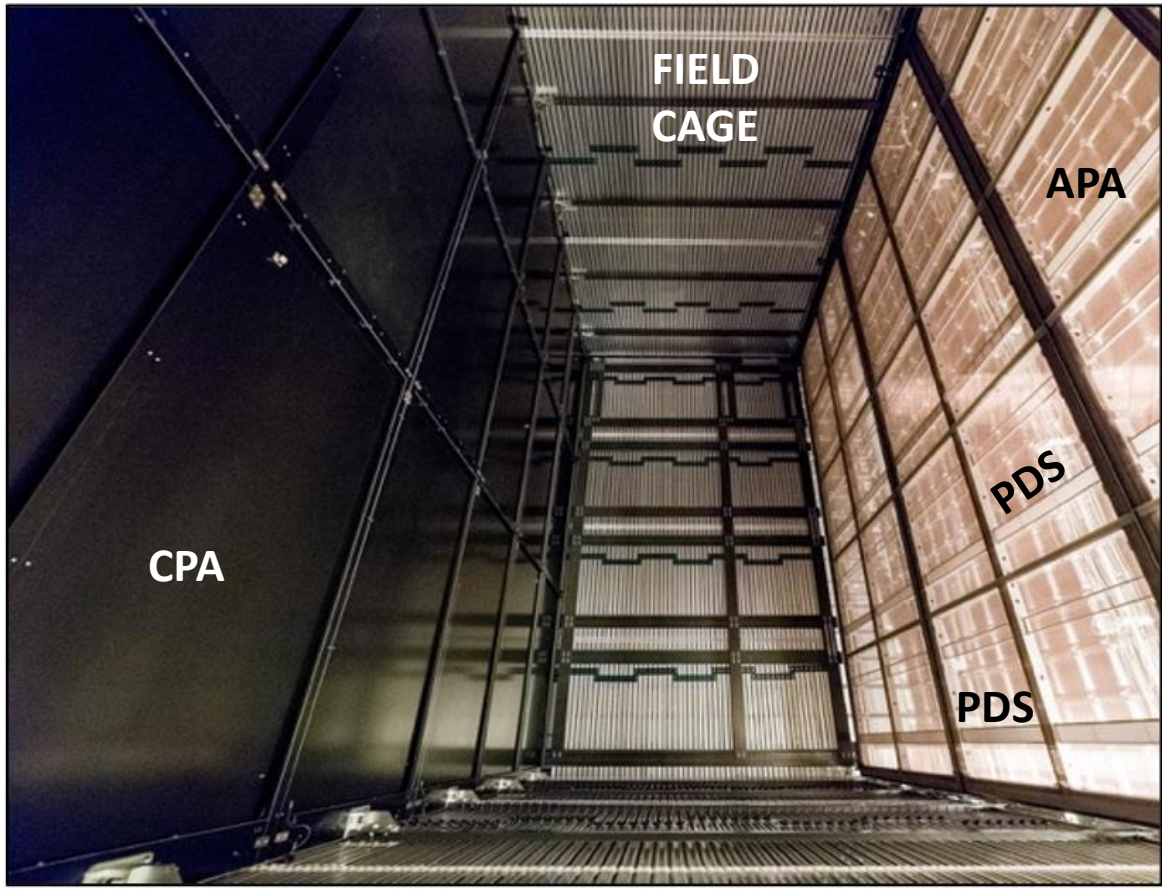


Proto DUNE


EHN1 Hall
CERN Prevessin
NP02: Dual
Phase LAr -TPC
NP04: Single
Phase LAr-TPC

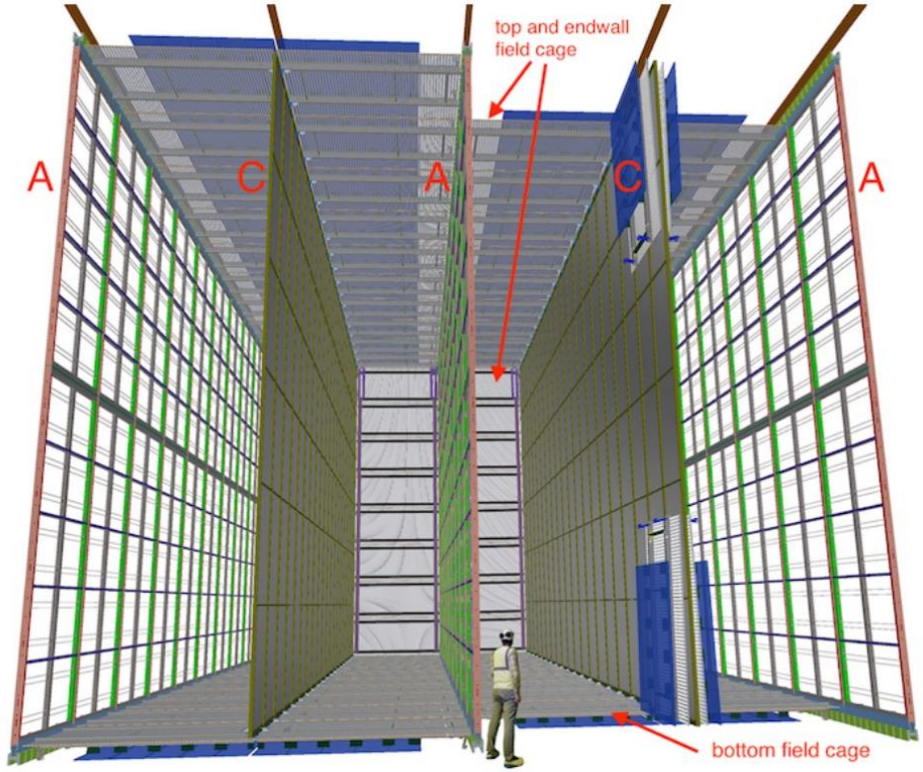
Proto DUNE

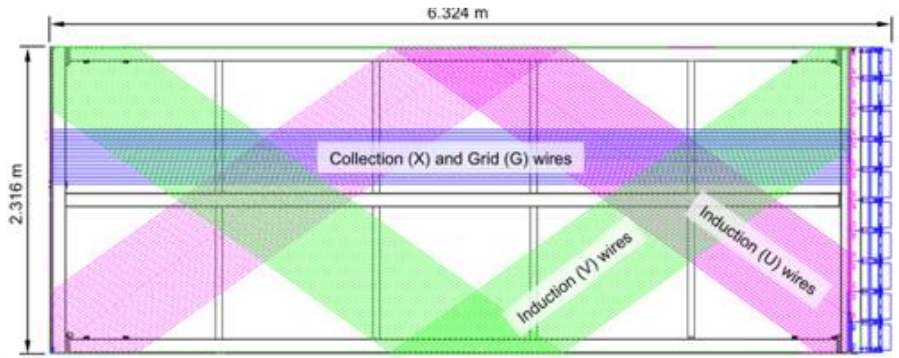
- Two ~1 kton prototypes (6 x 6 x 6 m inner dimensions)
- Validation of DUNE components design & installation, commissioning and performance study: full-scale prototypes
- **ProtoDUNE-Single Phase** operated 2018–2020
  - ✓ 4-month beam run in late 2018, then cosmics
  - ✓ Event reconstruction/identification training
  - ✓ R&D site: low-energy calibration (neutron gun), Xenon doping, Higher Voltage tests, …
  - ✓ Upcoming Phase-II on beam with updated design
- **ProtoDUNE-Dual Phase** operated 2019–2020
  - ✓ Very High Voltage / large drift studies
  - ✓ Evolved into Vertical Drift -> Phase II



ProtoDUNE SP drift volume (3.6 m)

Far Detector – Horizontal Drift

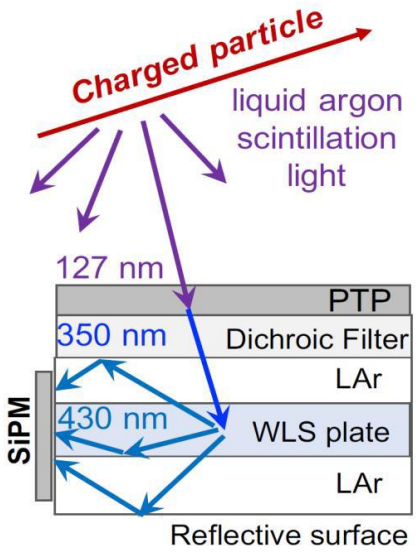


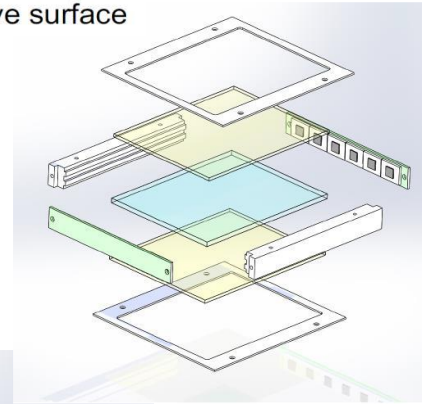


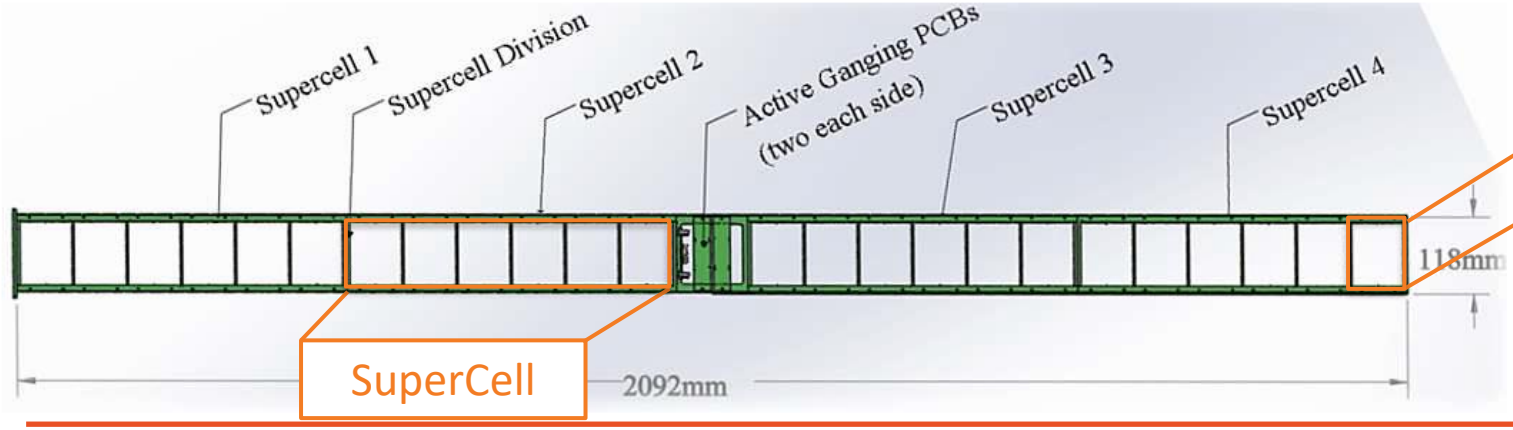
- Structure wholly suspended on roof
- Alternating Anode and Cathode Plane Assemblies (APA – CPA)
  - ✓ 4 drift volumes, 3.6 m drift
  - ✓ Electric field = 500 V/cm (HV = -180 kV)
  - ✓ High-resistivity CPA for fast discharge prevention
- Anode: 150 APAs, each with 4 wire planes (Grid, 2 x Induction, Collection)
  - ✓ Wrapped induction wires
  - ✓ 2560 wires/unit -- Inter-plane distance = 4.75 mm
- Photon Detectors: X-ARAPUCA light traps
  - ✓ 10 modules / APA
  - ✓ Timing
  - ✓ Cosmic / SN / BSM event triggering

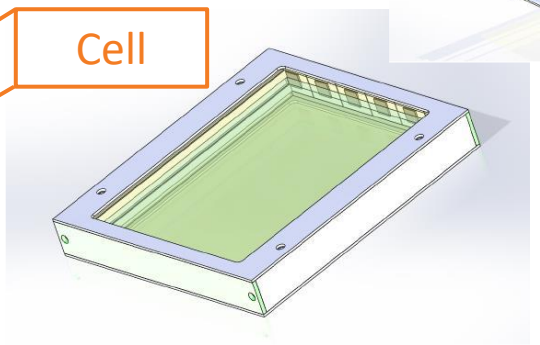
PDS - X-Arapuca

- The **X-ARAPUCA** design makes use of total internal reflection and highly reflective boxes to capture wavelength-shifted photons to improve detection efficiency.
- Keys to an effective PD system in DUNE:
  - ✓ Efficient conversion of VUV photons to captured photons.
  - ✓ High fraction of captured photons incident on photosensors.
  - ✓ Efficient photosensors for converting photons into electric signals.
- **Supercell**: 6 **cells** 488 × 100 × 8 mm^3.
- **Module**: 4 supercells 2092 × 118 × 23 mm^3 (bars configuration).



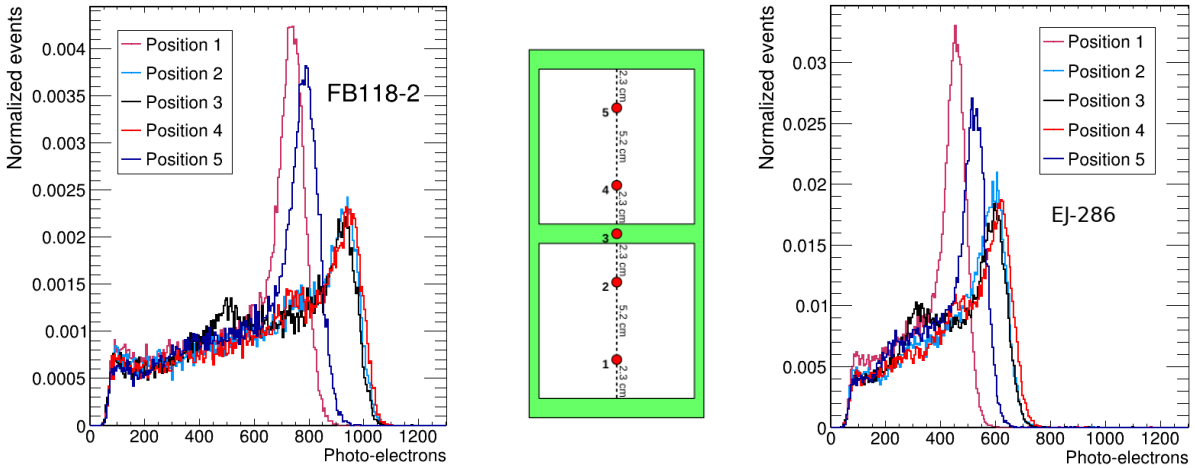


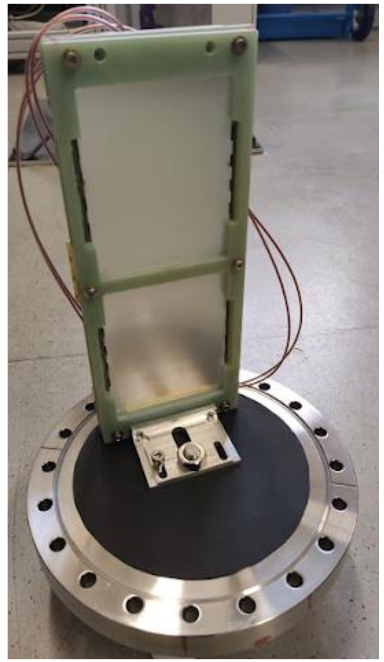




PDS - X-Arapuca

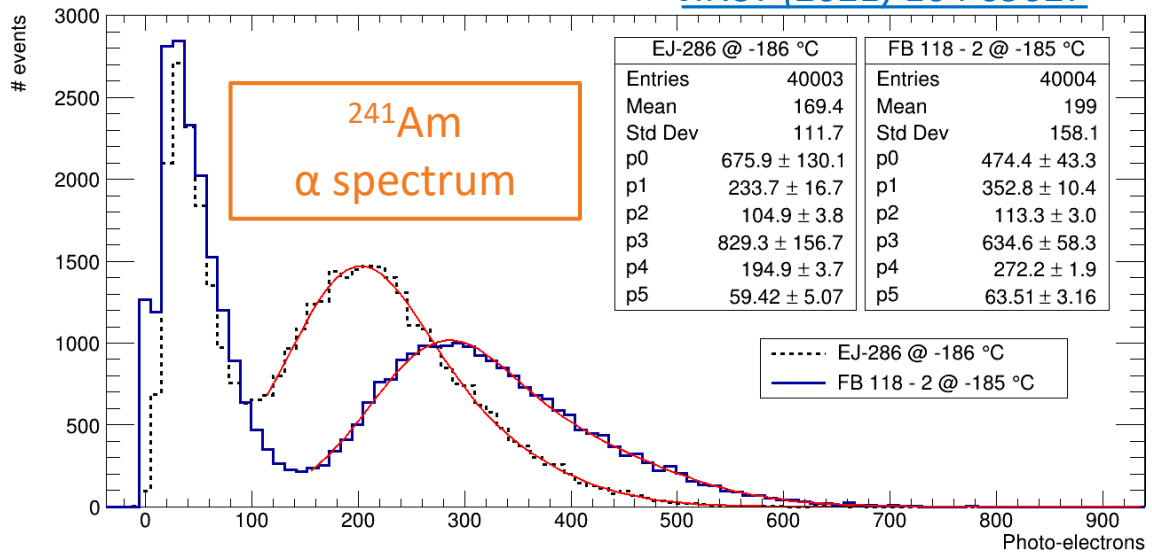
- Supercell test: 2-window supercell tested.
- Test on light collection uniformity and efficiency.





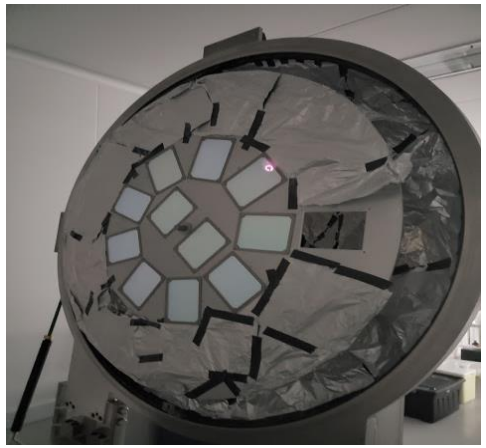
- Test on different WLS plates:
  - ✓ Commercial (Eljen 286) WLS plate, with measured PDE of 2.8%.
  - ✓ New WLS bars (FB118-2, Acrylic matrix, higher efficiency) developed at MiB with PDE measured in same test stand 3.8%.

JINST (2021) 16 P09027



PDS - X-Arapuca

- ❑ Module test
  - ✓ 2 supercells (half module)
  - ✓ Allow to test all the electrical boards for DUNE
- ❑ Coating and assembly infrastructure are being completed



PDS - SiPMs

- ❑ 48 SiPMs per Supercell
- ✓ 6 SiPMs per PMB passively ganged
- ✓ 8 PMB actively ganged

- ❑ 192 SiPMs per PD module
- ✓ 4 electronics readout channels
- ✓ 288,000 SiPMs in total

- ❑ Two photosensor vendors are being investigated: Hamamatsu (**HPK**) and **FBK**
- ✓ 6 types (splits) of 6x6 mm^2 SiPMs developed specifically for DUNE: 4 from HPK (S13360 – LQR/HQR – 50/75 µm pitch) and 2 from FBK (NUV HD LF single/triple trench)

PMB for passive ganging

Low level specs	Value
Max nominal operating V	[50 V at cold]
Dark count rate (DCR)	<100 mHz/mm^2
Correlated noise	<35%
Time resolution	<1 µs
Thermal cycles	>20
Recovery time	$\tau \sim$ a few µs
PDE at 87 K	>35% at nominal OV
High level specs	**Value**
Dynamic range	1-2000 p.e.
S/N>4	Per supercell (48 SiPMs)
Trigger	1.5 p.e.

SiPMs : selection procedure

- ❑ 25 SiPMs of each type fully characterized at single SiPM level:
  - ✓ IV curve measurements at room T at 77 K;
  - ✓ gain, S/N and DCR measured (77K) at OV to obtain 40%-45%-50% of PDE;
  - ✓ 20 thermal cycles with controlled cooling down and warming up;
  - ✓ all measurements repeated after the thermal stresses.
- ❑ 250 SiPMs per type per in the DUNE SiPM board and tested at single SiPM level (sample):
  - ✓ IV measurements for all SiPMs at room T and 77K;
  - ✓ 20 thermal cycles with controlled cooling down and warming up;
  - ✓ IV measurements repeated for all SiPMs and complete characterization for 5% sample per split.
- ❑ HPK HQR 75 µm and FBK Triple Trech down selected.
- ❑ 3000(+1000) SiPMs FBK and 3000(+1000) SiPMs Hamamatsu for the Run II of ProtoDUNE.
  - ✓ Dedicated test stand for automatized IV curve and DCR measurements.

HPK HQR 75 µm

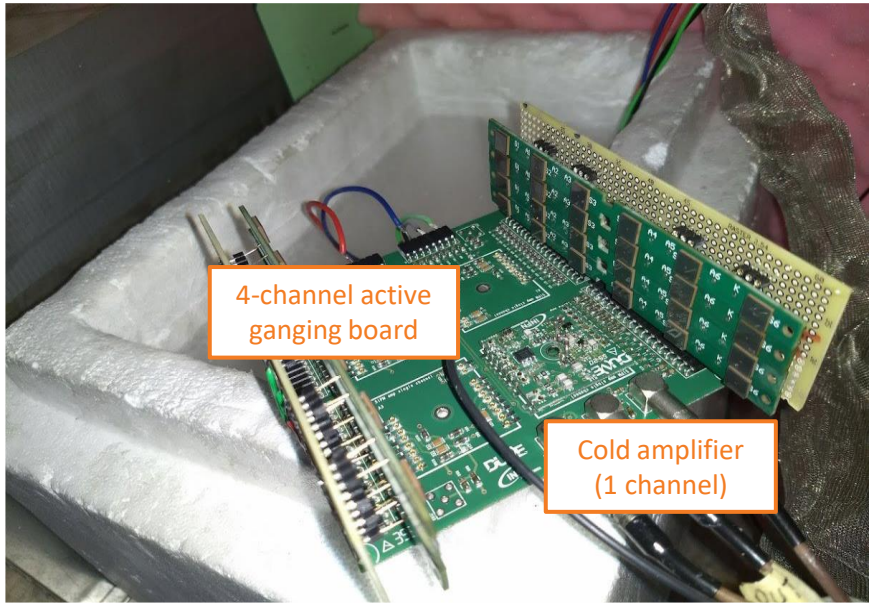
PDE	Gain (10^6)	DCR (mHz/mm^2)	Cross -talk	After pulse
40	3.73	57.54	6.62	0.86
45	4.59	64.97	8.97	1.10
50	5.44	66.32	10.96	1.30

FBK Triple Trench

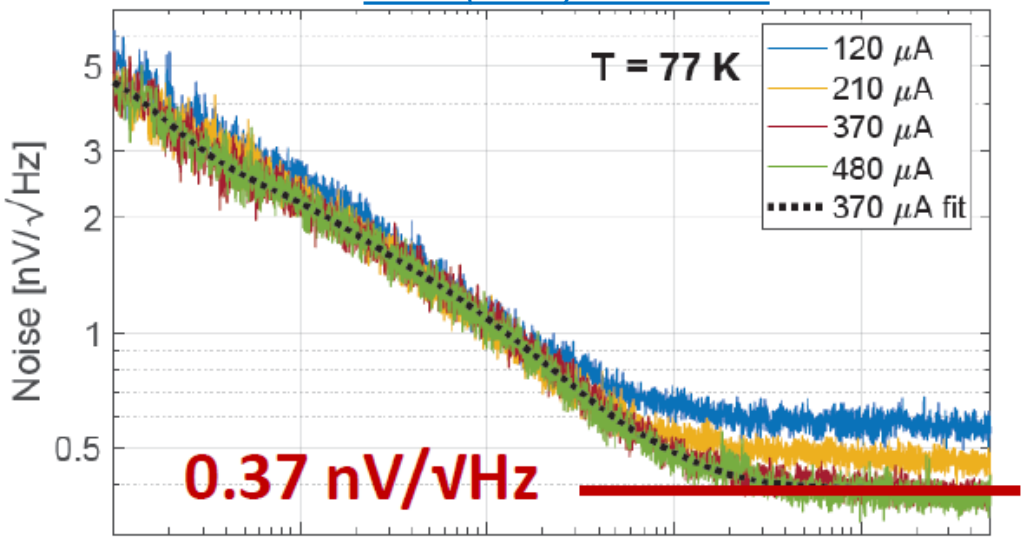
PDE	Gain (10^6)	DCR (mHz/mm^2)	Cross -talk	After pulse
40	4.73	80.79	13.76	2.85
45	6.01	86.33	15.67	3.25
50	8.21	93.35	40.50	4.05

PDS - Cold electronics

- Used to collect the signals of 48 SiPMs of a supercell into a single readout channel.
- Each channel reads out 48 6x6 mm2 SiPMs → 60 nF total input capacitance.
- 1 channel per SuperCell, 4 channels per module, 6000 channels in DUNE (1st module).
- Two-stage amplifier - SiGe bipolar transistor + fully differential op-amp.
- Low series noise is required → SiGe input transistor gives 0.37 nV/√Hz at cryo temperature.
- Low power consumption (2 mW/channel) to prevent boiling of LAr.

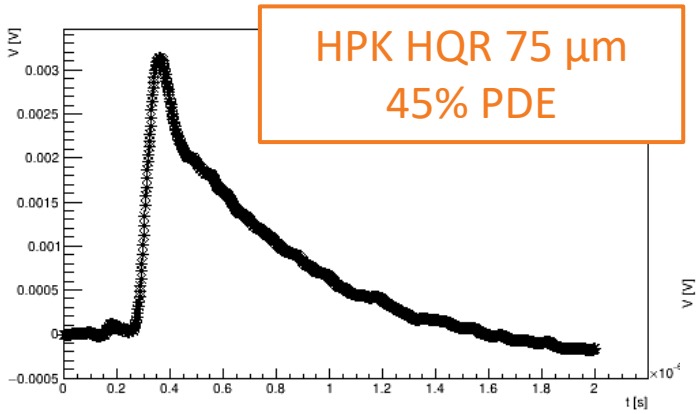


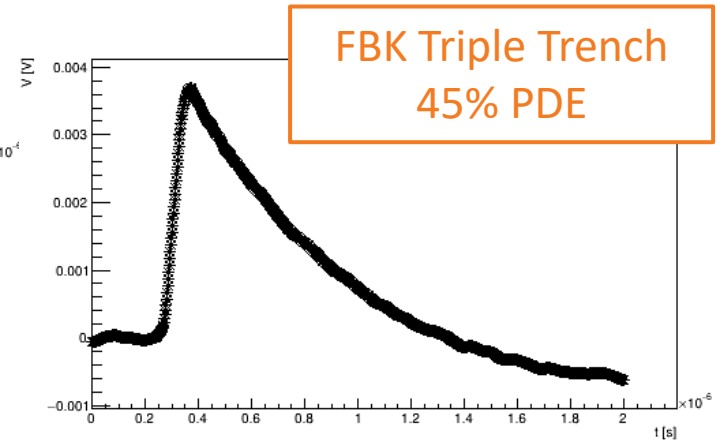
JINST (2020) 15 P01008

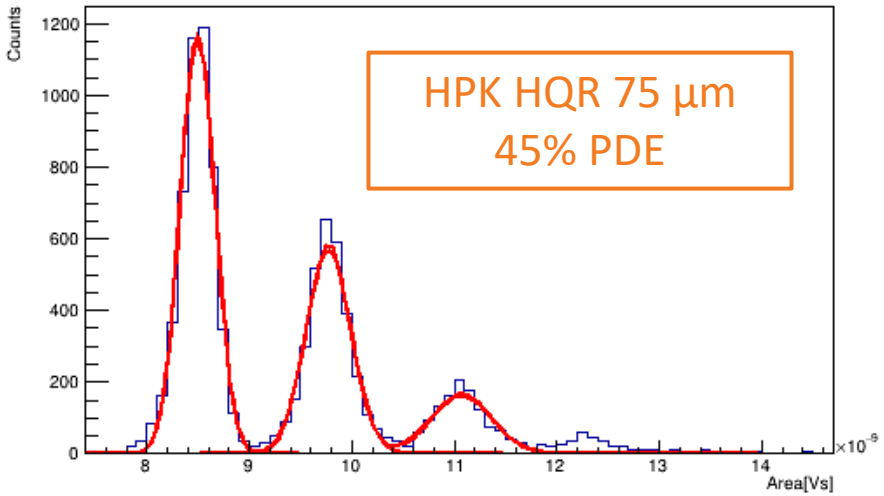


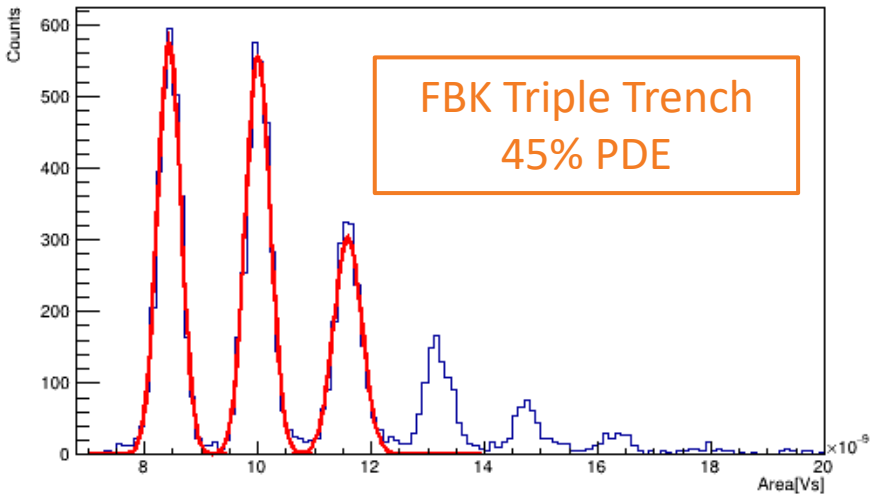
PDS- Cold electronics

- ❑ Tested with all candidate SiPMs for DUNE.
- ❑ Fast response: <100 ns rise time.
- ❑ Dynamic range 2000 p.e.
- ❑ Good S/N ≈ 5-10 depending on SiPM type and overvoltage → Allows clear separation of photoelectron peaks (with 48 SiPMs in parallel).
- ❑ At 45% PDE:
- ✓ HPK HQR 75 µm: 5.96 ;
- ✓ FBK Triple Trech: 7.16.
- ❑ Next → Integration of all the cold parts (SiPM+routing+cold amp+cable).



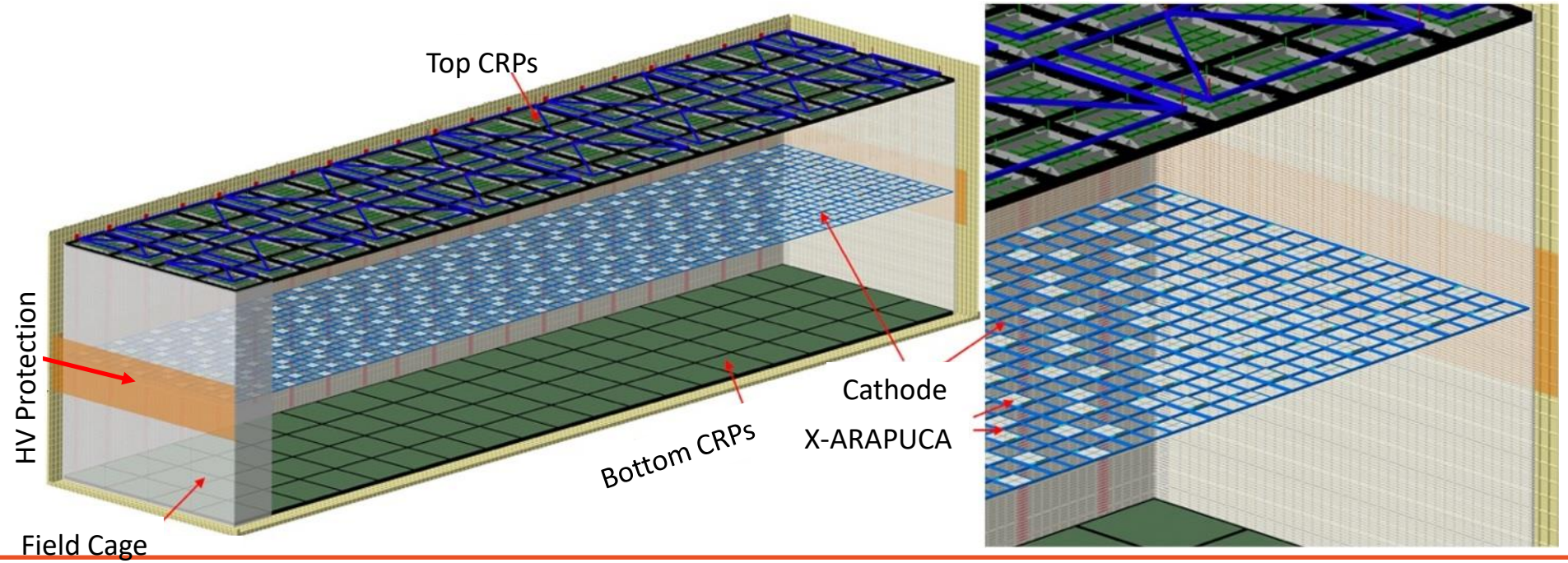




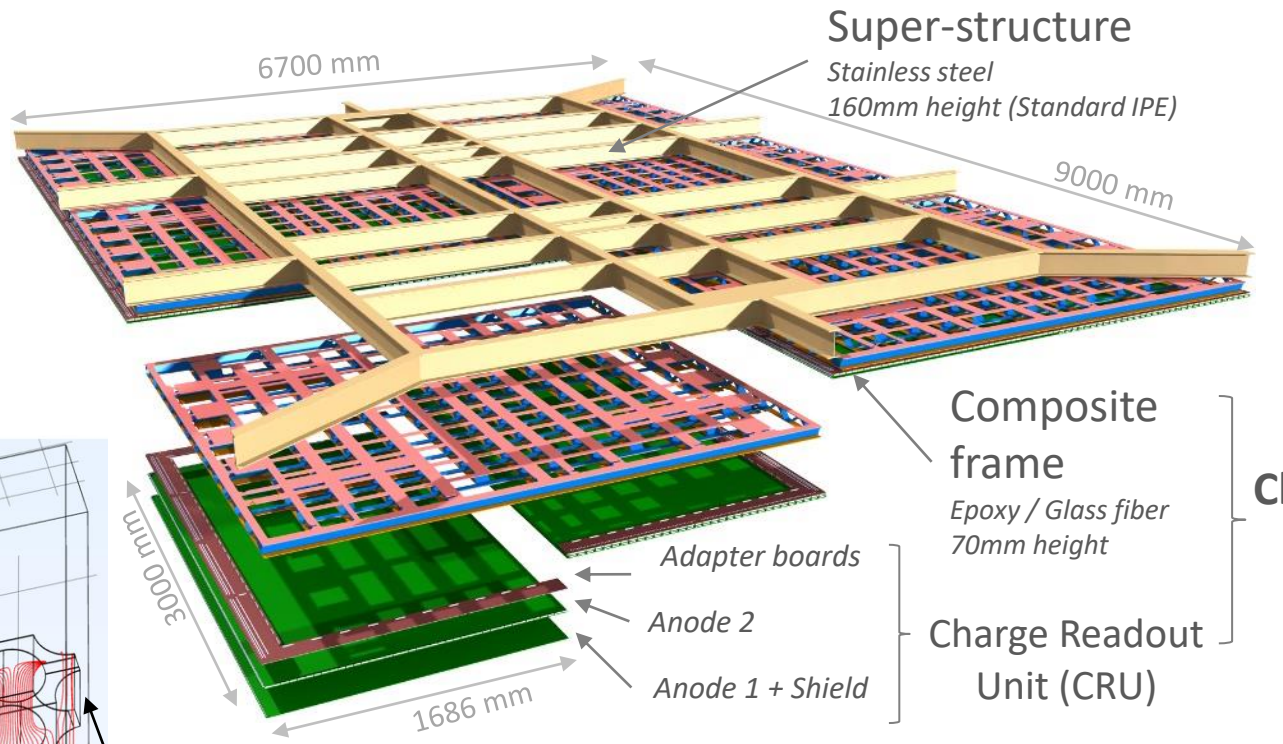


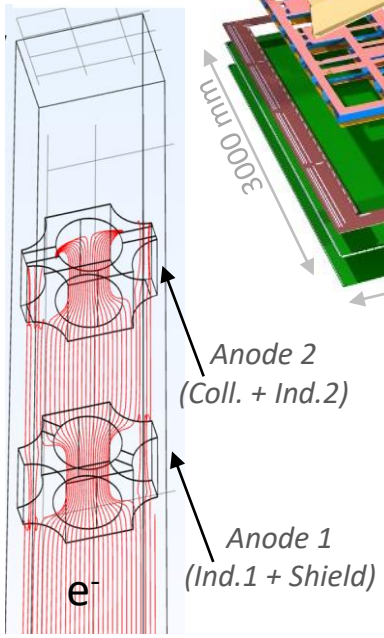
Far Detector – Vertical Drift

- Single-phase, read-out on cryostat top and bottom
- 2 x 6 m drift ⇔ 300 kV HV on (central) cathode
- Technological challenges on many detector aspects (HV, LAr Purity, Photon Detection,…)
- Strong R&D program at FNAL, CERN, …
- Dedicated set-up for small-scale tests: 50 liters LAr-TPC
- Large-scale tests of anode and cathode+PD modules in dedicated “cold-box”



Far Detector – Vertical Drift



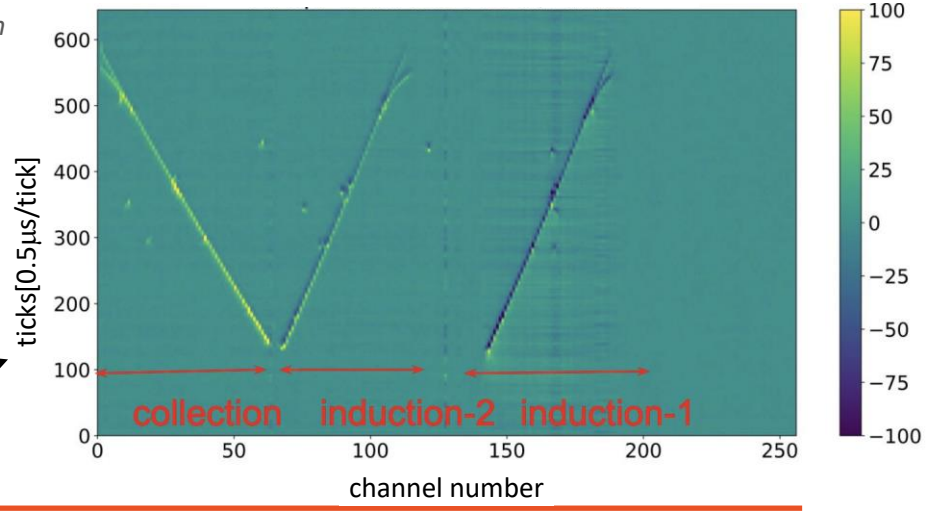


Anode

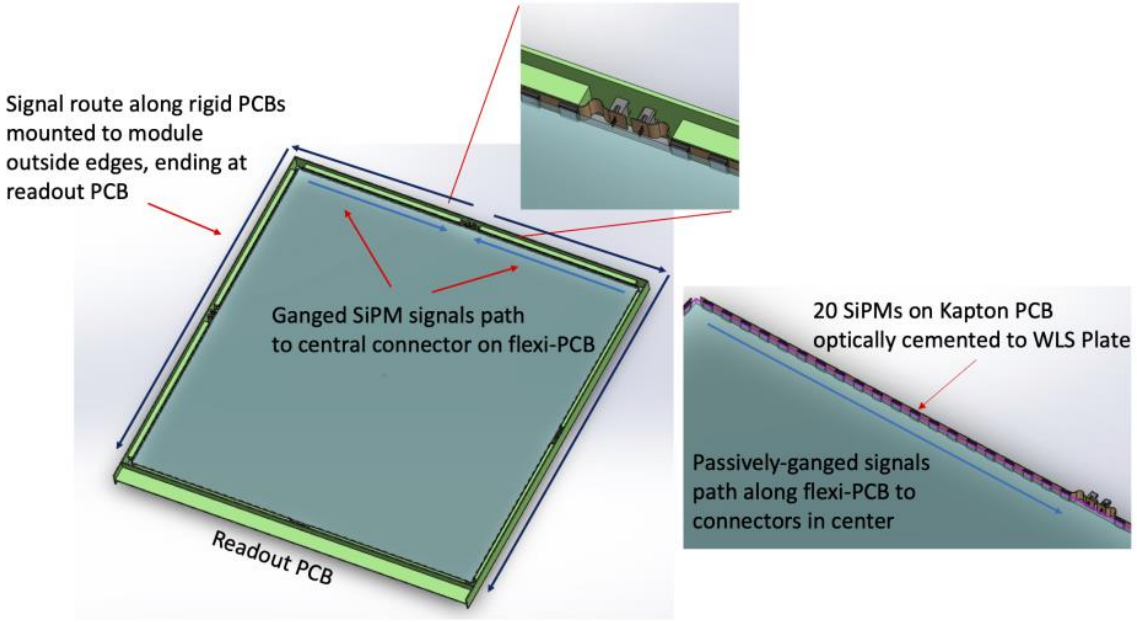
- ❑ Perforated PCB anode, fully immersed in LAr
- ❑ Reference: 3-view design plus shield (2 anodes)

50L test set-up

- 3-view anode: two 35 x 35 cm PCBs, overseeing a 50 cm drift volume.
- Very promising first data (cosmic μ's)



Far Detector – Vertical Drift



- 320 X-ARAPUCA 60 x 60 cm^2 on cathode, analog readout
- 320 X-ARAPUCA 60 x 60 cm^2 on cryostat membrane, ~3 m from cathode
  - Enhanced field cage transparency -> 70%

Photon Detection

- Based on X-ARAPUCA – "4π" reference design
- SiPM and electronics on Cathode: @ 300 kV
- Aggressive R&D program concerning Power-over-Fiber and Signal-over-Fiber technology
- Enhanced scintillation yield by doping with xenon, with high trigger efficiency down to 10 MeV.

Conclusions

- DUNE: next-gen neutrino experiment, will allow precision neutrino physics measurements:
  - ✓ Oscillation parameters, mass hierarchy, CP violation
  - ✓ SN burst neutrinos
  - ✓ Possibility to probe several BSM channels (sterile ν's, Dark Matter, proton decay)
- Beam Line & Near Detector Infrastructure designs under way
- Near Detector technology (multi-station) is defined
  - ✓ Design finalization in a few months
- Far detector technology defined for FD #1 (Horizontal Drift)
  - ✓ Design validation with "Module 0" in upcoming ProtoDUNE SP Run-II
- Vertical Drift LAr-TPC proposed for FD #2, aggressive R&D program

✓ Design validation in ProtoDUNE NP02 with HV test and "Module 0"

Thanks!