The DUNE Photon Detection System (Phase I)

Gabriel Botogoske
On behalf of the DUNE collaboration

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UNIVERSITÀ DEGLI STUDI DI PADOVA
INFN NAPOLI
DUNE

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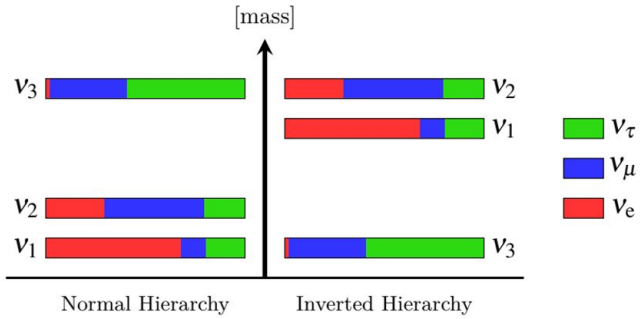
Mysteries of neutrinos

Even if neutrinos are fundamental particles which have been detected 70 years ago there **are still several open questions related to their properties**:

- Are neutrinos their own antiparticle ?
- What are the masses of neutrino?

- How are the mass ordered ? (mass hierarchy)
- Do neutrino and anti-neutrino oscillate in a different way? (CP violation)

- **Are there other neutrino types or interactions ?**



Neutrino Oscillation

$$\begin{bmatrix} 0.799 \ldots 0.844 & 0.516 \ldots 0.582 & 0.141 \ldots 0.156 \\ 0.242 \ldots 0.494 & 0.467 \ldots 0.678 & 0.639 \ldots 0.774 \\ 0.284 \ldots 0.521 & 0.490 \ldots 0.695 & 0.615 \ldots 0.754 \end{bmatrix}$$

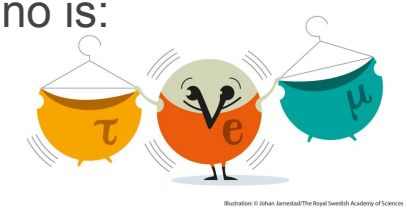
The flavor eigenstate of a neutrino is a linear combination of three mass eigenstates:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{Reactor \& LBL}} \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

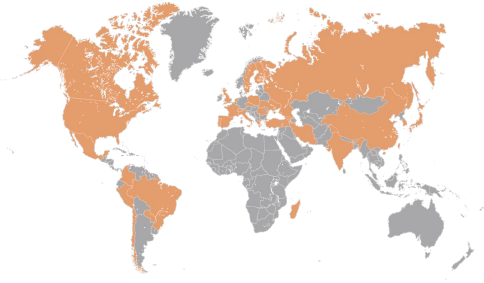
The probability of transition from a muon neutrino to an electron neutrino is:

$$P(\nu_\mu \rightarrow \nu_e) \sim \sin^2(2\,\theta_{13})\sin^2(\theta_{23})\sin^2(\Delta m_{12}^2 L/4E)$$

Where we neglect CP violation terms and matter effects.



Deep Underground Neutrino Experiment (DUNE)



Next generation international neutrino oscillation experiment

LBNF neutrino beam

Fermilab accelerators produce a 1 MW proton beam. The beam hits a target of graphite producing as a final result muonic neutrinos with an energy ranging from 0.5 to 5 GeV.

Power: 1.2 MW up to 2.1 MW

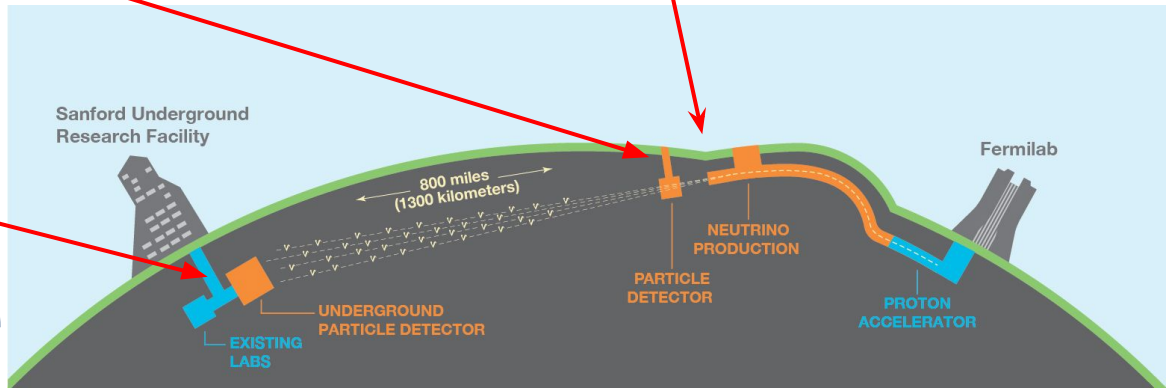
Near Detector

Two TPCs + magnetized beam monitor located at Fermilab, with the goal to characterize the neutrino beam

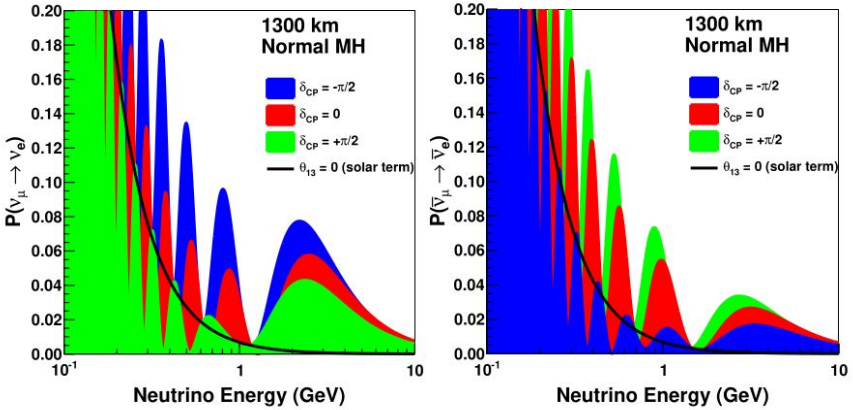
- ND-LAr
- TMS (Phase I)
- SAND

Far Detector

Phase I - FD1 and FD2
Phase II - FD3 and FD4

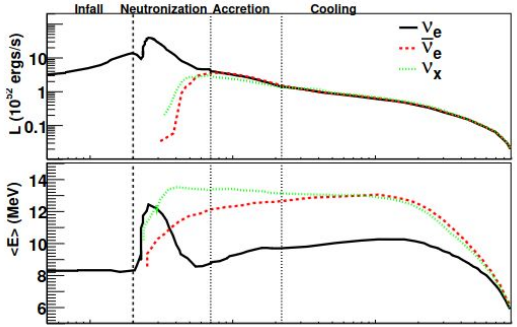


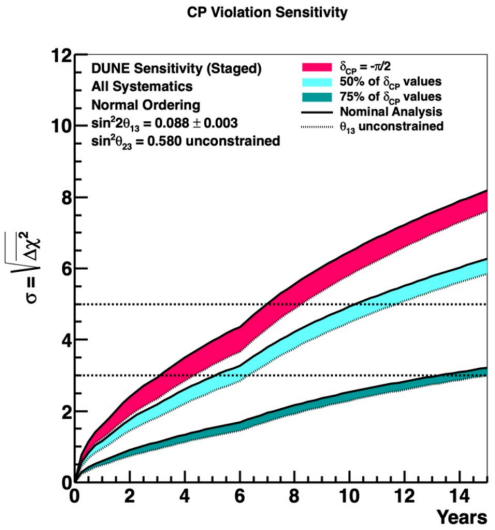
DUNE goals



- **Neutrino oscillation parameters:**
  - – Mass ordering
  - – CP violation
  - – Better precision on parameters
- **No beam data**
  - -Proton decay
  - -Solar neutrinos
  - -Supernova neutrinos
  - -BSM
  - -and more

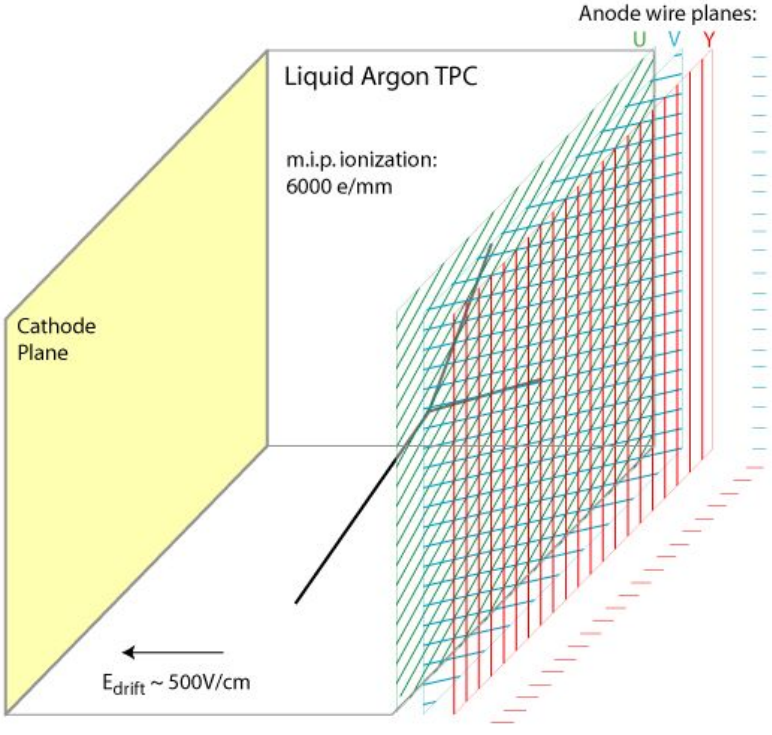
PDS very important to trigger



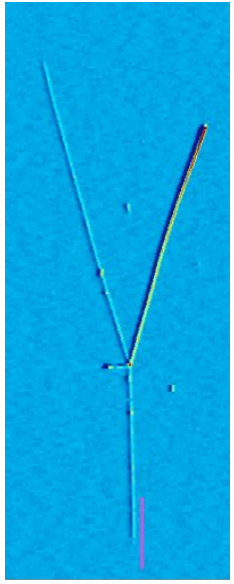


LArTPC (Liquid Argon Time projection Chamber)

Charged particle in LAr produces free **ionization electrons** and **scintillation light** (128 nm)

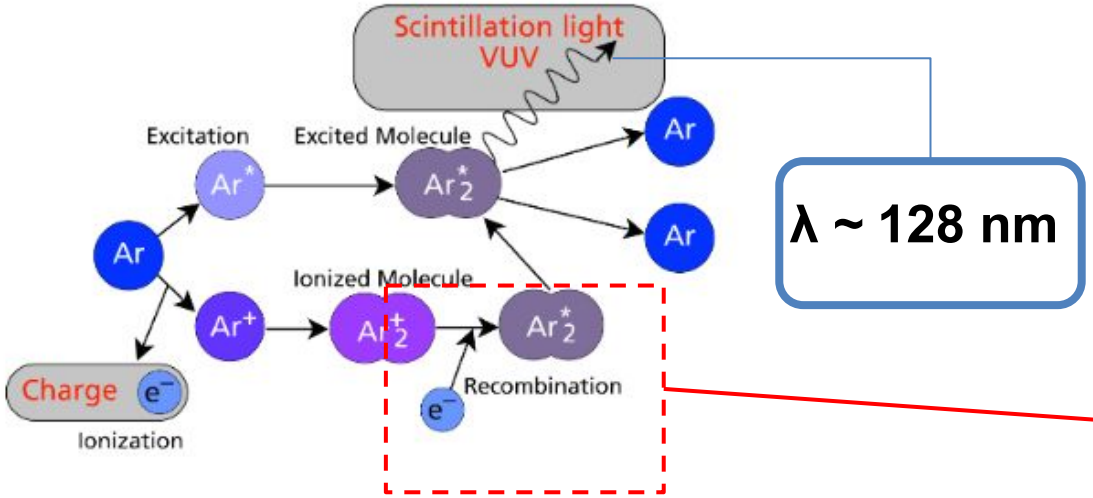


LArTPC DATA

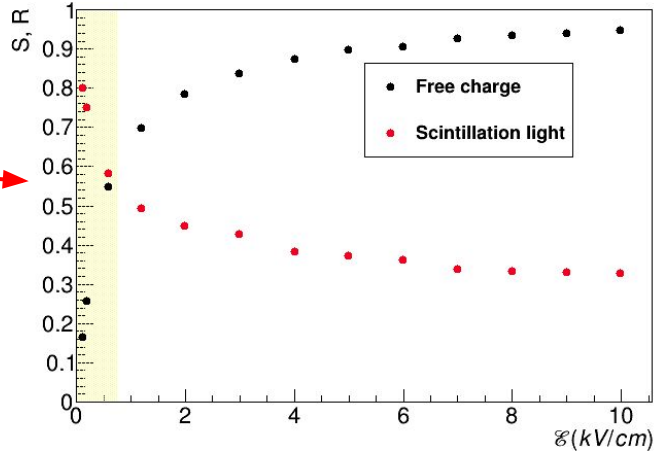


Scintillation

- Production of photons in argon: 40000 photons/MeV
  @ 0 kV/cm



λ ~ 128 nm



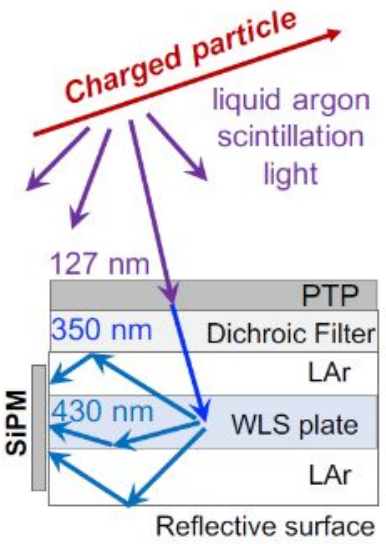
Slow component: 1.5 ~ 1.6 us
Fast component: 6 ~ 10 ns

Due to quenching,
it is possible to do particle discrimination:
Electron vs Nuclear recoil

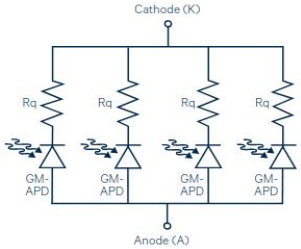
X-ARAPUCA

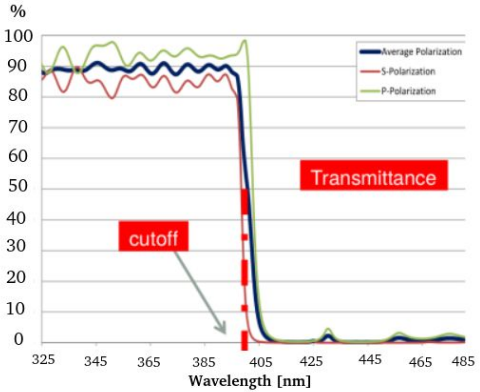
ARAPUCAs are light-collecting devices;

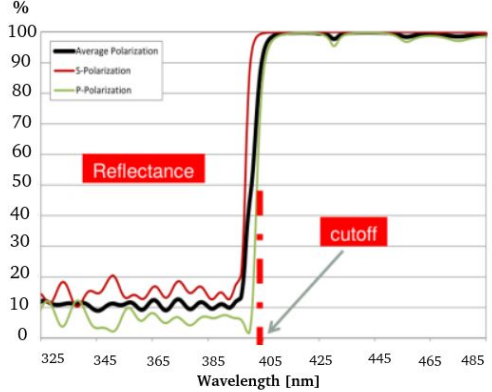
They are composed of:

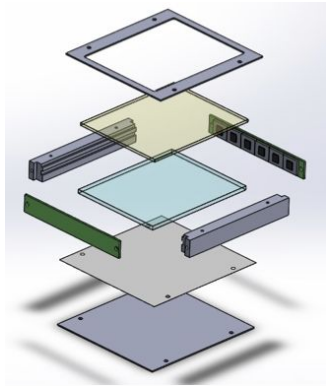


- Mechanical structure
- p-Terphenyl (pTP) layer
- Dichroic filter
- Light guide bar
- Reflective foil (Vikuiti)
- Silicon Photomultiplier (SiPMs)









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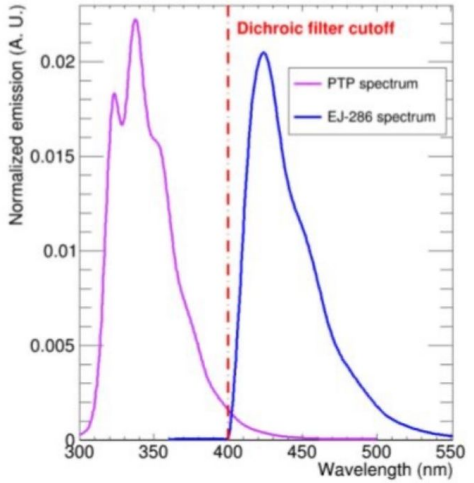
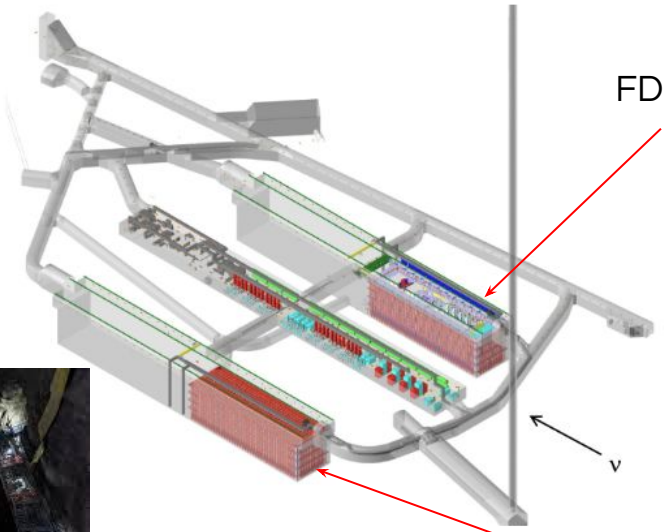
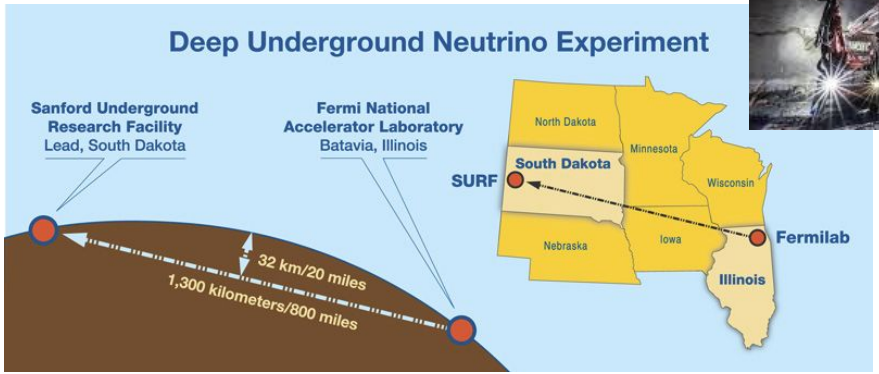


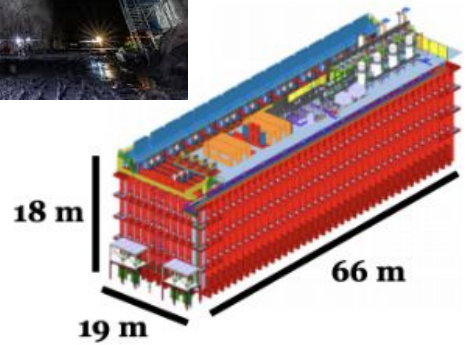
https://www.sciencedirect.com/science/article/abs/pii/S0168900220310457

DUNE Far Detectors

- **4 LArTPCs** of **17 kton** and **1.5 km** underground
- Phase I :
  - **FD1 - Horizontal Drift LArTPC**
  - **FD2 - Vertical Drift LArTPC**
- Phase II :
  - **FD3 and FD4:**
    - **Vertical drift**







FD1-HD

- 4 Drift Volume (3.6 m x 58 m x 12 m)
- 3 Anodes and 2 cathodes

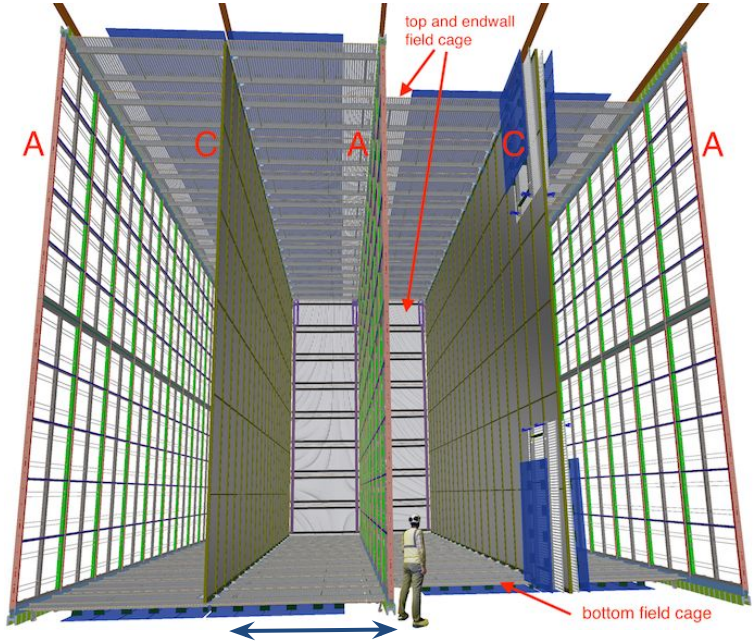
  - Cathode → 2 CPA array → each 150 (6x25) **C**athode **P**lane **A**ssembly (**CPA**) at: -180kV

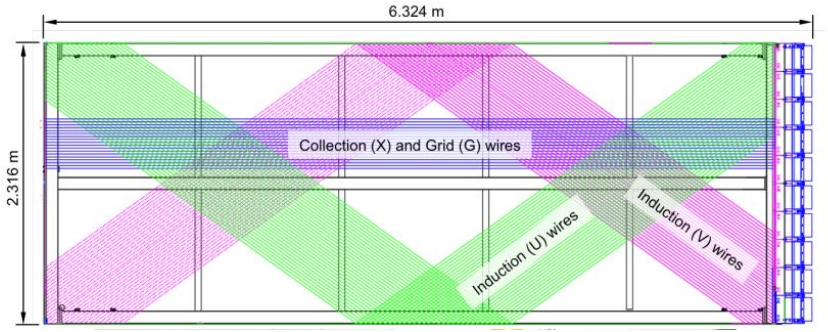
  - 3 Anode Plane → each 50 (2x25) **A**node **P**lane **A**ssembly (**APA**) at ground potential

    4 wire planes: 1 Collection (X),
    2 Induction (U,V) and 1 Grid (G)

- Fiducial volume: 10 kton
- Field Cage to uniform Electric Field

Electric field: 500 V/cm
25000 photons/MeV
and
27000 electrons/MeV



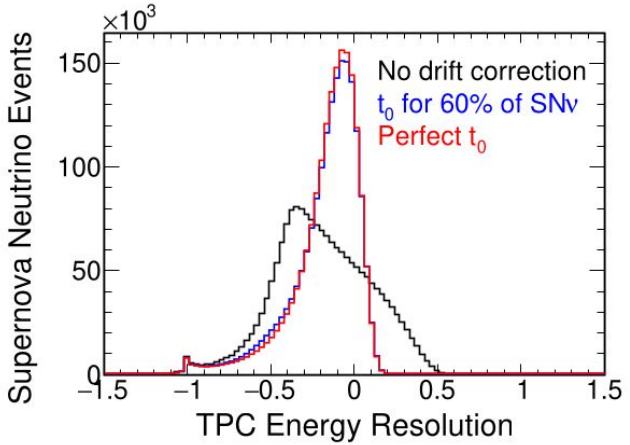


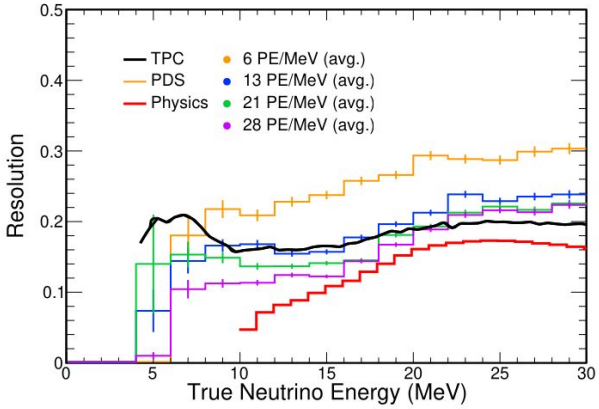
PDS

- What is the goal of PDS?

→ Increase energy resolution
→ Trigger for non beam events
→ Better time precision
→ Measurement of t_0
→ Cross check with charge measurements
→Charge correction

- electron drift speed: ~ 1.6 mm/μs
- photon speed: ~ 2x10^5 mm/μs



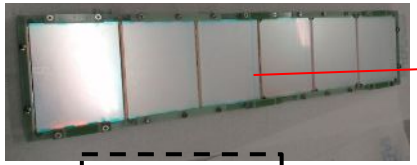


PDS-HD

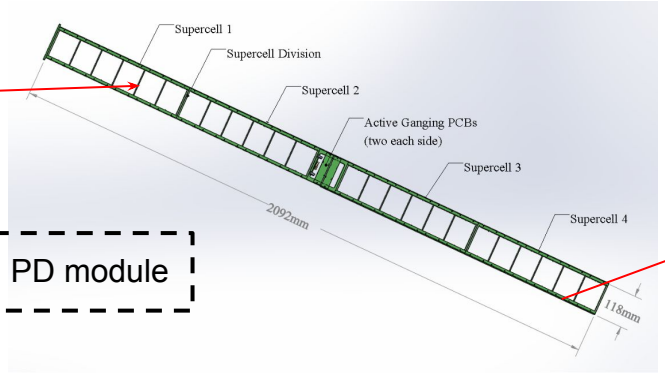
- 10 PD modules for APA → 1500 in total
- 1 PD module → 4 super cell X-ARAPUCA (49 cm x 10 cm)
- Inside the APA: not decrease the active volume

500 dual-face (middle anode)
1000 single-face (edge anodes)

PDE ~ 2%



Supercell



PD module

APA

SUPER CELL:
– EJ-286 WLS Light Bar (487 mm × 93 mm × 3.5 mm)
→ 48 SiPMS per SUPERCELL → 192 per PD module

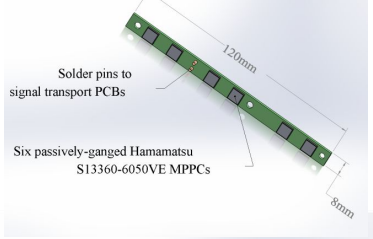
- 6 dichroic windows with a pTP layer

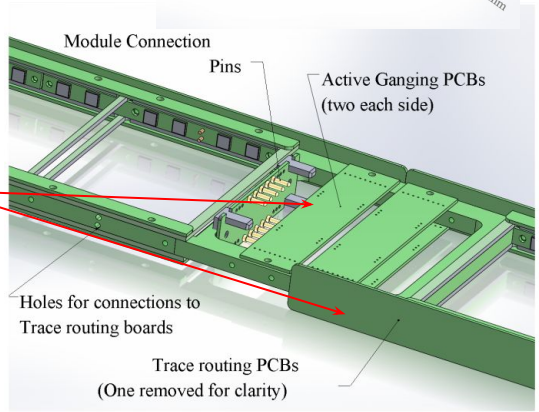
488 x 100 x 8 mm^3

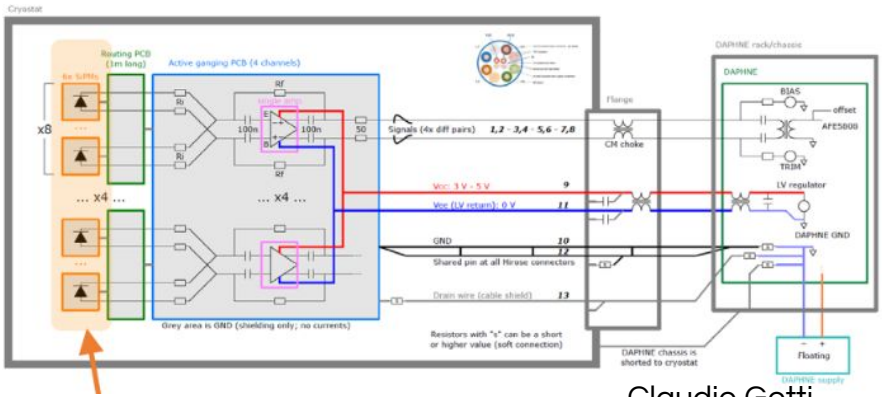
Channels and electronics

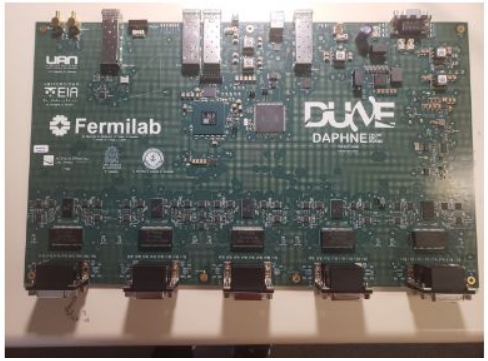
1 channel = 1 SuperCell (48 SiPMs)
→Bias and signal → same line

- Passive ganging: 6 SiPM from mounting board
- Active ganging: 8 SiPM mounting board
  Cold amplifier → Differential Signal
- Warm electronics: **DAPHNE** (**D**etector electronics from **A**cquiring **PH**otons from **NE**utrinos): Amplification, digitalization, sending to DAQ, and more
  based on **mu2e** cosmic ray veto





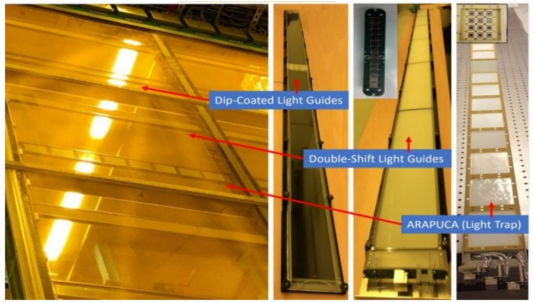


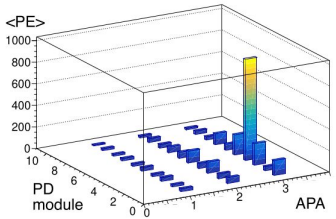


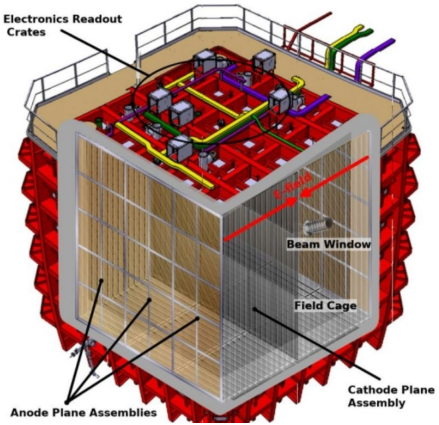
Proto-DUNE @CERN

Proto-DUNE SP

→0.42 kton fiducial LAr
→ 6 APAs



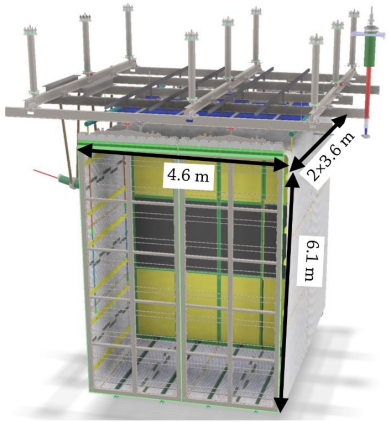




Successful

Proto-DUNE HD

→0.28 kton fiducial LAr
→ 4 APAs
→Moved to X-ARAPUCA



– 2 different WLS and SiPMs(Hamamatsu and FBK)

Data being collected at 2024

FD2-VD

- First module to be delivered
- It has evolved from old concept for FD2 Dual Phase LarTPC
- Two drifts volumes (each with **6.5 m** x 13.5 m x 60 m)

A lot of challenges due to the HV and dual phase characteristics

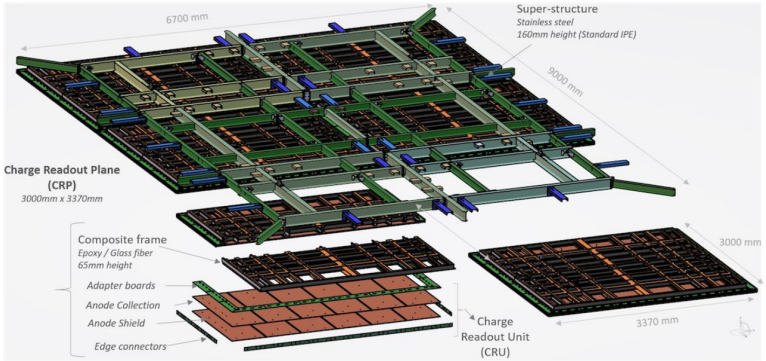
HD VS VD

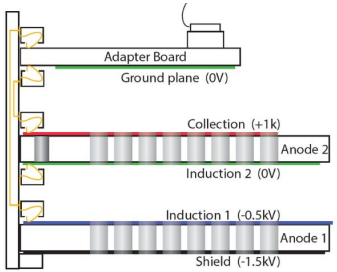
- cheaper and simpler than HD
- Better light coverage

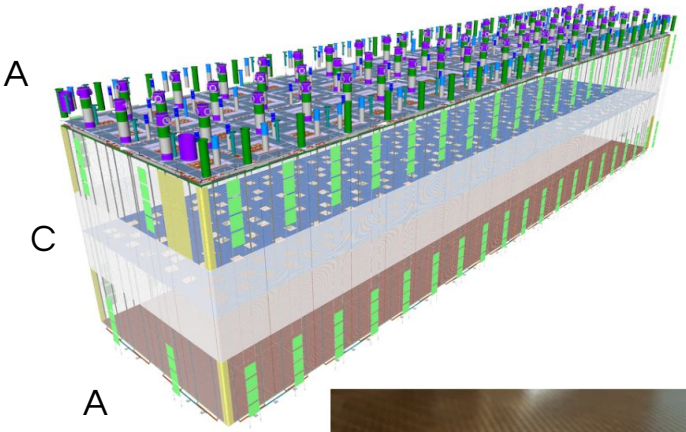
2 Anode Planes → 1 Anode Plane have 80 **C**harge **R**eadout **P**lanes **(CRP)**

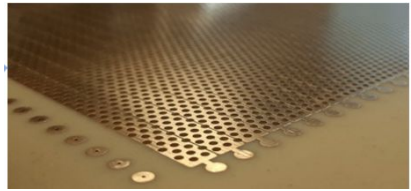
– CRP (3 m x 3.4 m) → Each CRP have 2 CRU (Charge Readout Unit)

–3 readout charge channel made of 2 perforated PCBs per CRU



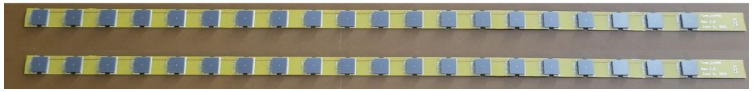


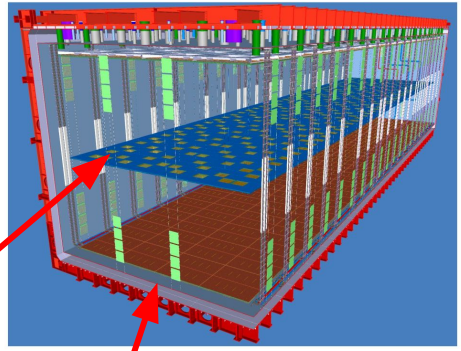




Cathode → -294 kV
Electric field = ~ 450 V/cm

PDS-VD



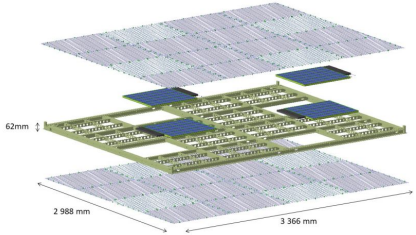


MEGACELL X-ARAPUCA

- Dimension 65 cm x 65 cm
- One WLS slab (Glass to Power)
- 160 SiPMs (40 at each side)
- SiPM → 6 mm x 6 mm
- 16 dichroic filter per side
- 2 channels → 80 SiPMs/channel

Double face module

Single face module

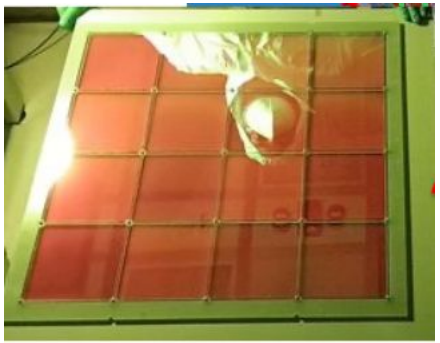


Cathode :

→ 80 cathode modules (same size of CRP)

→ Each cathode model has 4 X-Arapuca Megacell double-faced

→ total: 320 double faced Megacell



Walls :

→ Behind the field cage (70% transparent) on the four membrane walls

→320 at long walls (20 columns) + 32 short walls (4 columns)

= 352 single faced X-ARAPUCAs

Membrane Modules

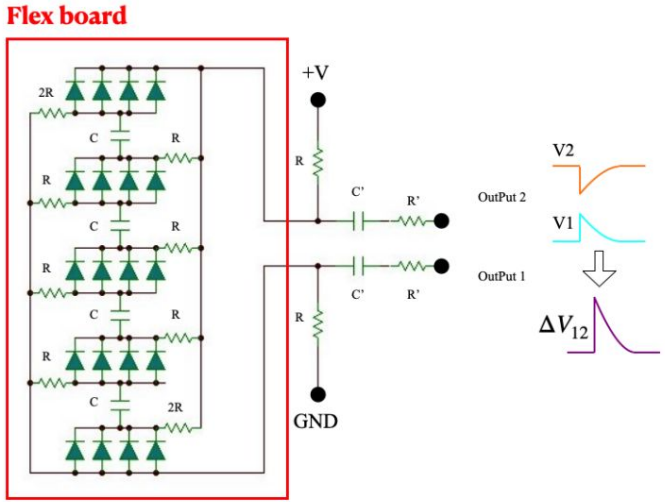
→ For all the modules (cathode and membrane):

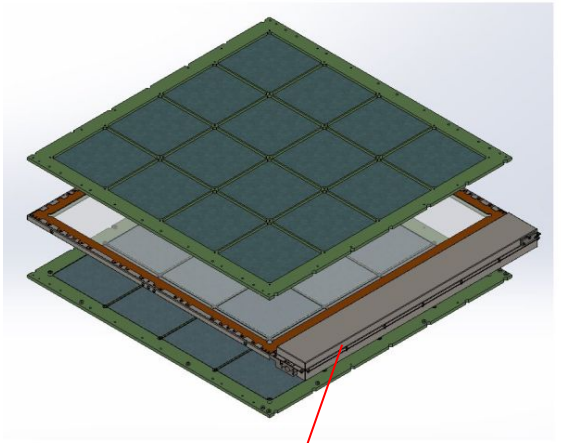
→20 SiPMs passively ganged (one flex PCB)

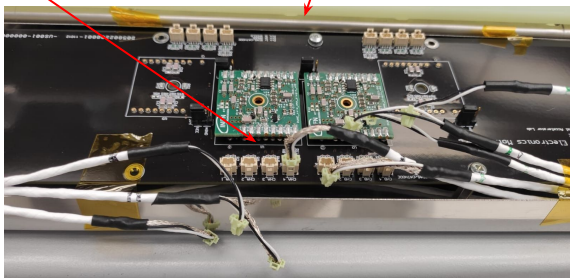
→ 4 flex PCBs are actived ganged: 80 SiPM→ 1 channel

→ Cold transimpedance amplifier

→ Fully differential amplifier





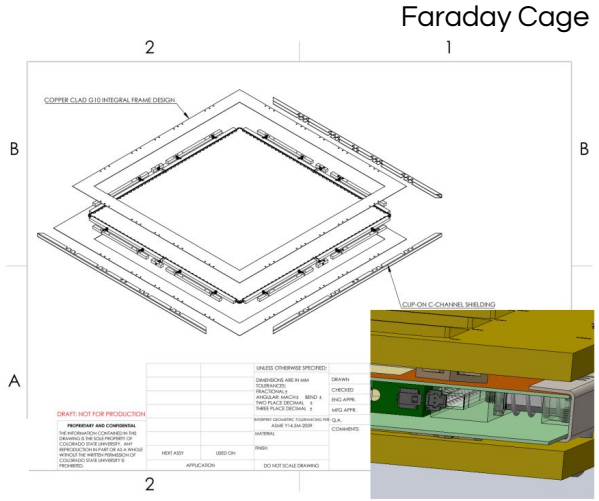


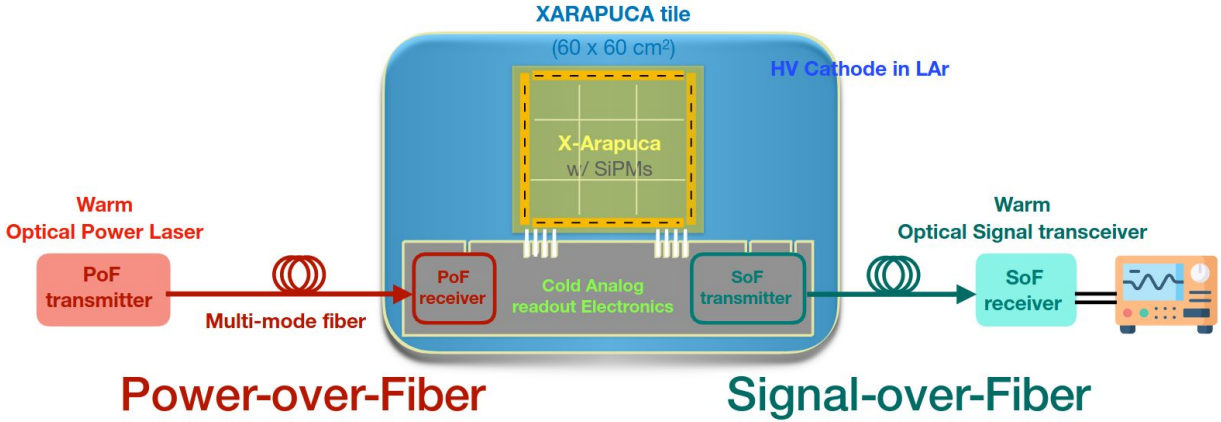
Cathode modules

- Cathode is almost at -294 kV → Avoid electric path

- Power-over-Fiber (PoF)
- Signal-over-Fiber (SoF)

- Noise Immunity
- Voltage Isolation
- Spark free

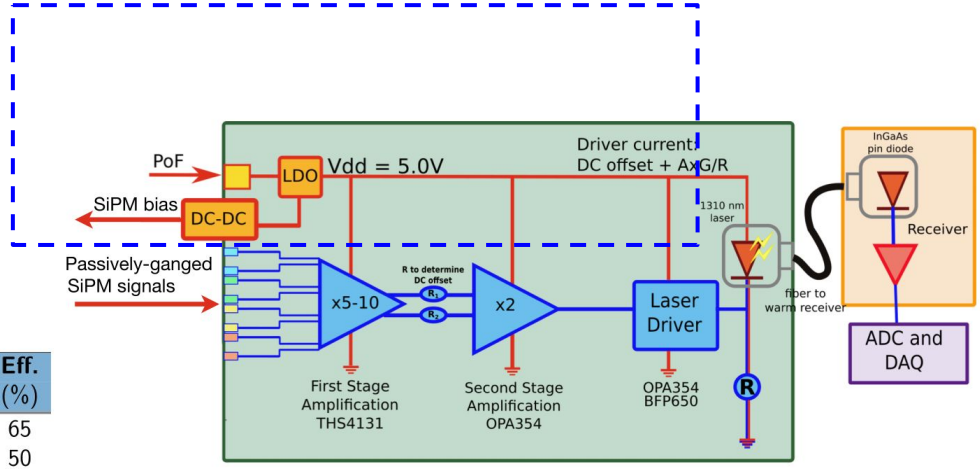




Power-over-Fiber

Laser (808 nm, 2 W)→ Optical fiber → Gallium Arsenide (GaAs) Photovoltaic Power Converters (PPC)

- Bias the cold electronics:
  PoF → PPC ~ 7 V (3 in parallel for more current output)
  → Low Dropout Regulator (LDR) → ~ 5 V
- Bias the SiPMs:
  → DC-DC Step-Up converter
  → up to 50 V



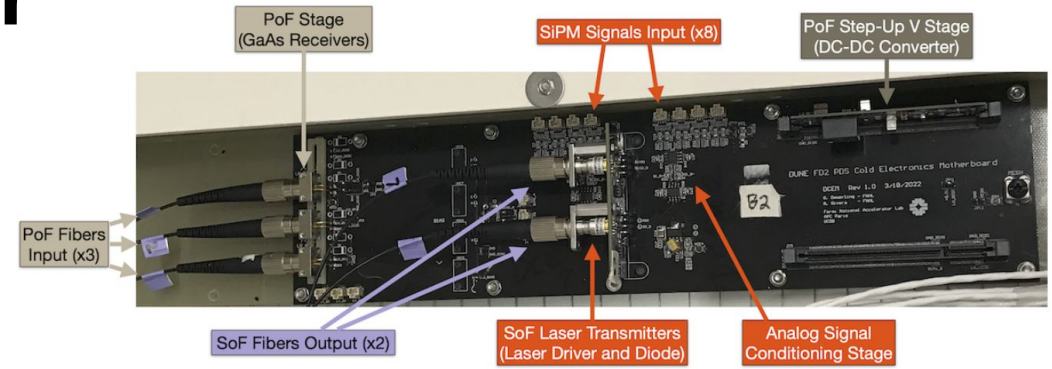
Del. Power (W)*	Type	Wavelength (nm)	Current (mA)	Voltage (V)**	Usable Power (W)	Eff. (%)
0.6	GaAs warm	808	70	5.5	0.40	65
0.4	GaAs cold	808	30	6.5	0.20	50

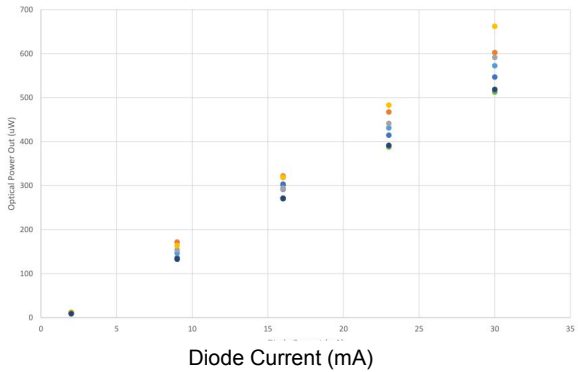
Signal-over-Fiber

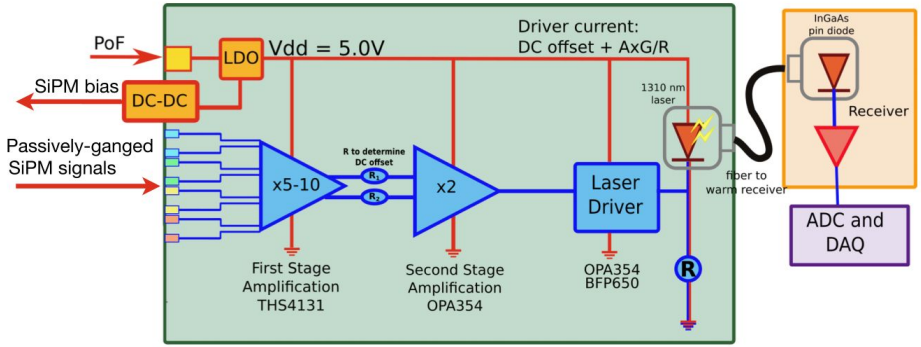
- Fabry-Pérot diode laser current
  →1310 nm (infrared)
- Optical Fiber → InGaAs PhotoDiodes

Electronics:

- First stage amplifier: active ganging (20x4 = 80 SiPMs)
- Second stage amplifier: Differential do single ended
- Laser Driver: Voltage to current







Proto-DUNE @CERN

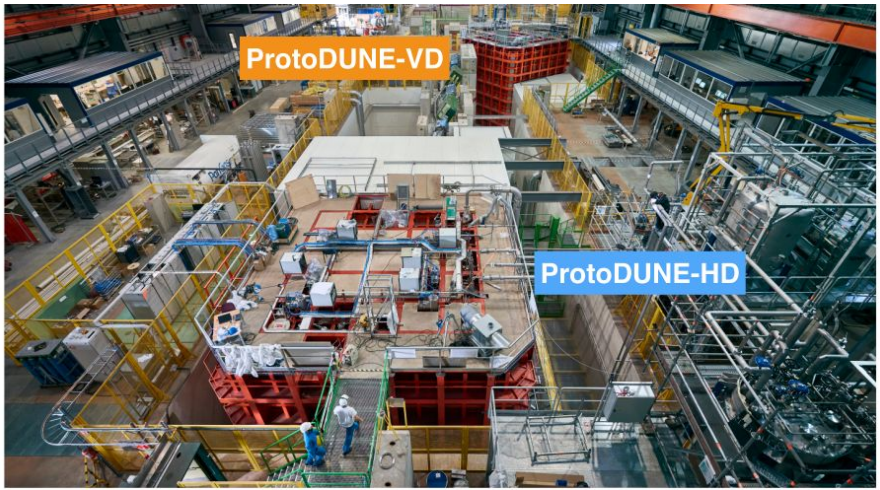
Proto-DUNE DP
→ Double phase
→ Based on PMTs
→ Problems with HV
→Validated some aspects of the actual FD2

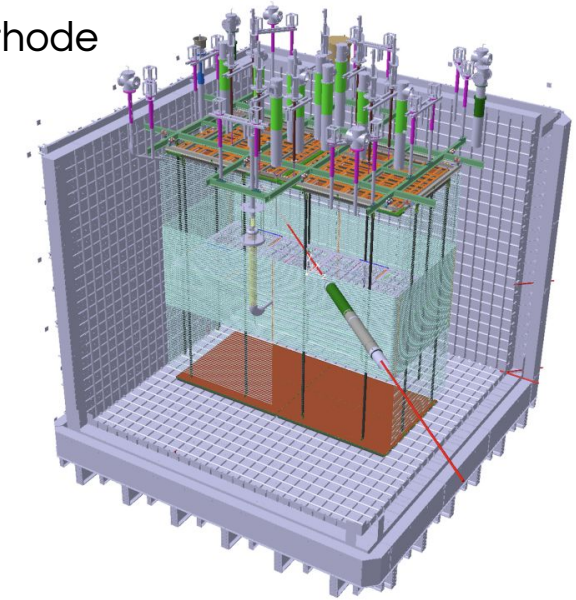
→ **Proto-DUNE VD**

→ 4 CRPs (2 on each anode) → 8 Cathode X-Arapucas
+8 Membrane X-ARAPUCA

Goals:

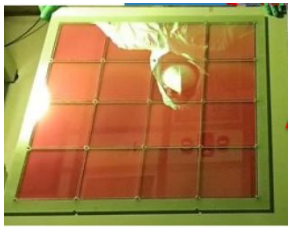
- Test of X-ARAPUCA on HV cathode
- 70% field cage
- more …





HD VS VD : PDS

Caracteristics	HD	VD
ARAPUCA geometry	SUPERCELL (49 cm x 10 cm)	MEGACELL (65 cm x 65 cm)
Average Light yield	~ 30 PE/MeV	39 PE/MeV
Light Coverage	~ 13% of the anode	15% (cathode) + 7.4% (walls)
SiPMs numbers	48 - 1 channel	160 - 2 channels
SiPMs coverage	3.8%	1.6%
Efficiency	2 ~ 3 %	~ 3%

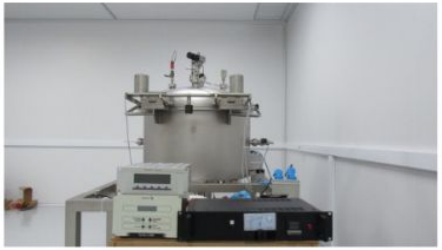


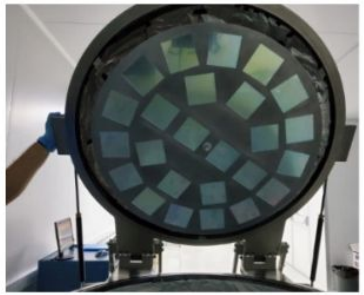
More on next talk from Sergio

X-ARAPUCAs coating

→ **SUPERCELL and MEGACELL**

UNICAMP
(Brazil/Campinas)
+
University Federico II
(Italy/Naples)





Conclusion

- X-ARAPUCAs devices to detect the light
- HD will use the supercell geometry while VD will use the megacell geometry with two different approaches: membrane and cathode modules
- ProtoDUNE SP showed good results with the ARAPUCAs, and the horizontal drift LArTPC design
- ProtoDUNE HD going to test the SUPERCELL at the HD geometry
- SoF and PoF already tested on cryogenic environment
- ProtoDUNE VD will start operation probably at the start of 2025 to validate more aspects of the PDS

BACK-UP

Xenon doping

It converts the slow component 127nm photons to 178 nm
Goals:

- Improve light detection:
  Rayleigh Scattering: 127nm: 1m
  178nm: 4m
- Mitigate Nitrogen Contamination
  → Nitrogen quenches Triplet states
  → Competition between Xenon and Nitrogen