Vertical Drift Photon Detection System

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IRN Neutrino meeting

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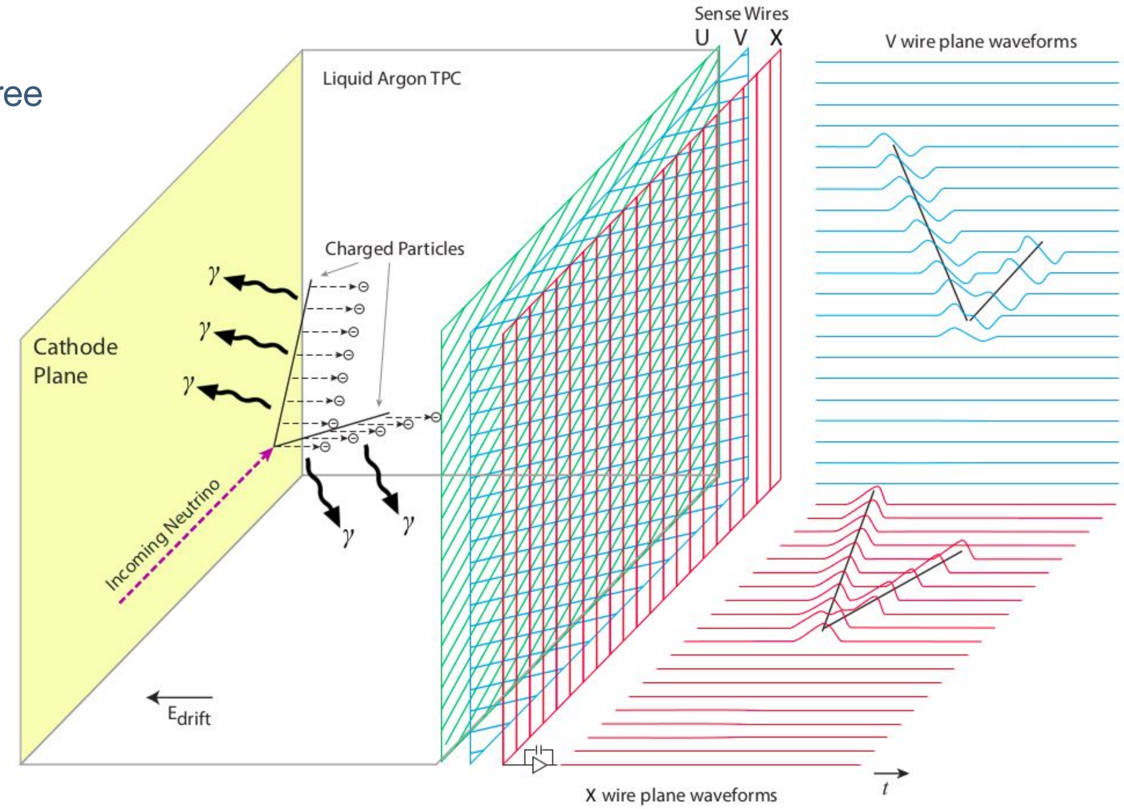
Motivation

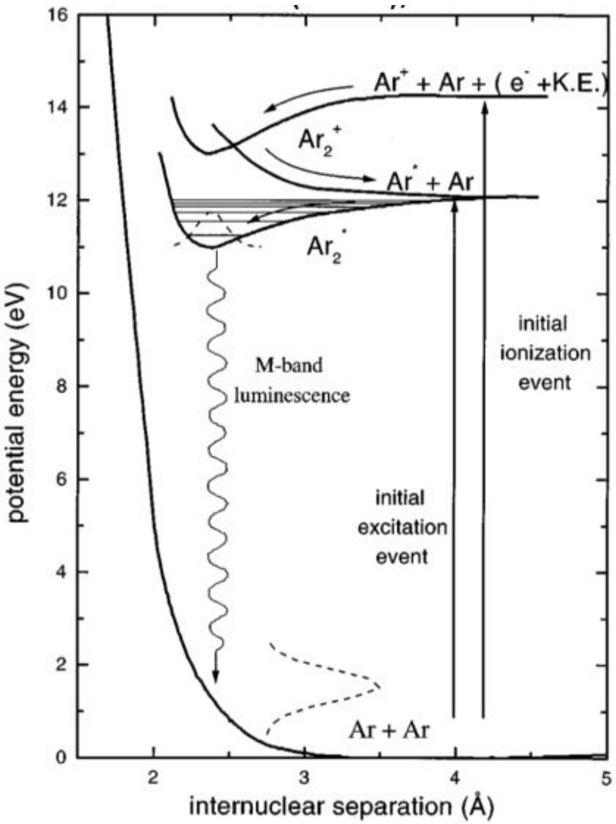
- The LArTPC is characterized by the free drifted electrons and light emission

- The detection of scintillation light can provide the absolute time (T0) of events and internal triggering for non beam events

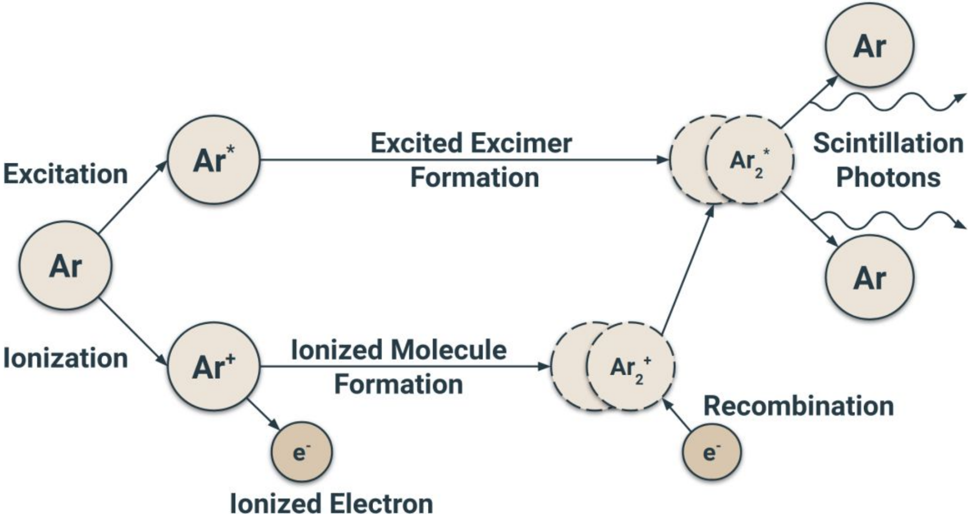
- Besides, light signals can improve position, time and energy resolution. Improve particle identification (PID) and improve background rejection by the proper fidualization of the detector.



LAr light production



ion



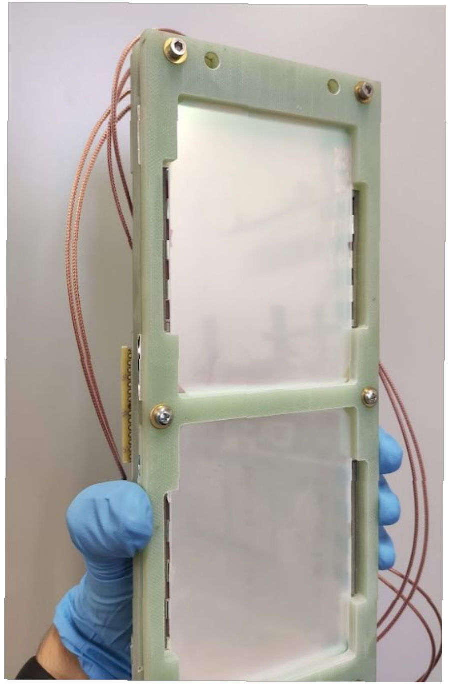
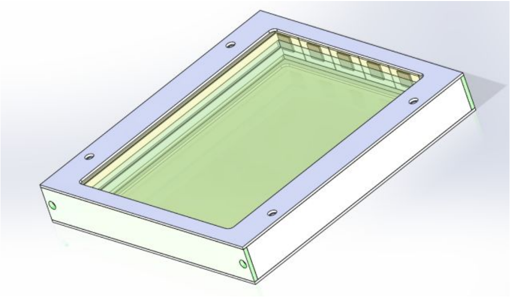
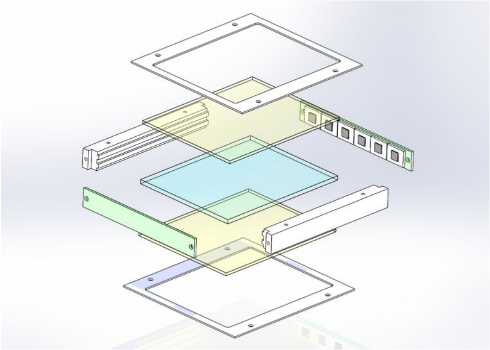
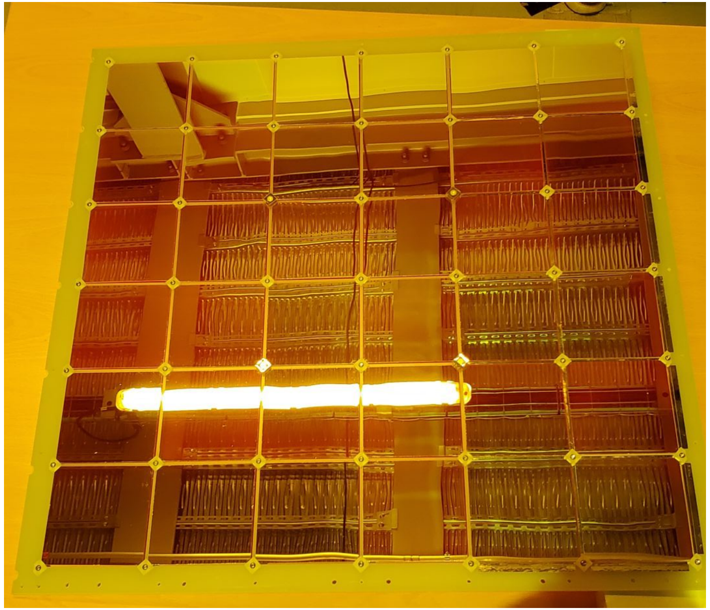
$$I(t) = A_S \exp\left(-\frac{t}{\tau_S}\right) + A_T \exp\left(-\frac{t}{\tau_T}\right)$$

$$\tau_S = 6 \text{ ns}$$

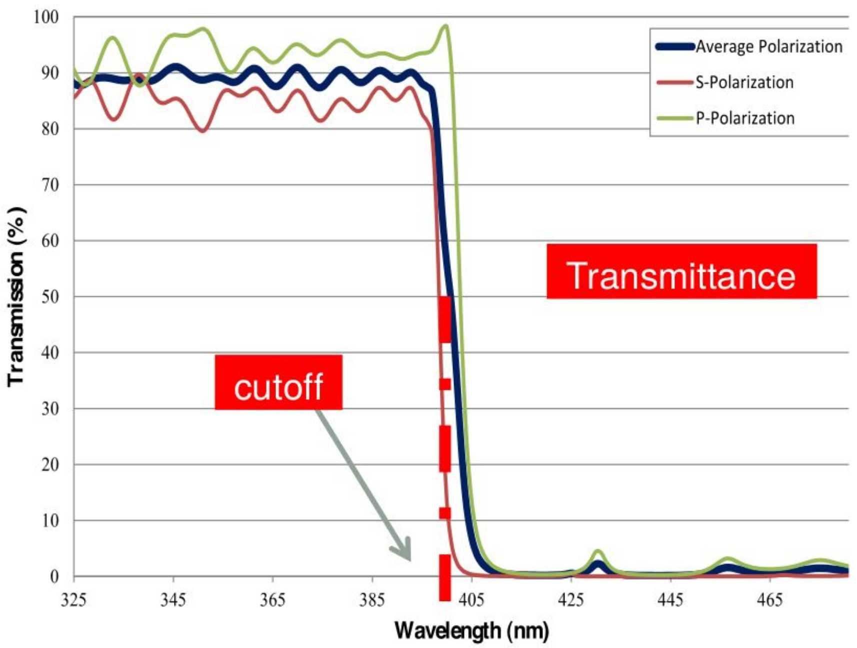
$$\tau_T = 1600 \text{ ns}$$

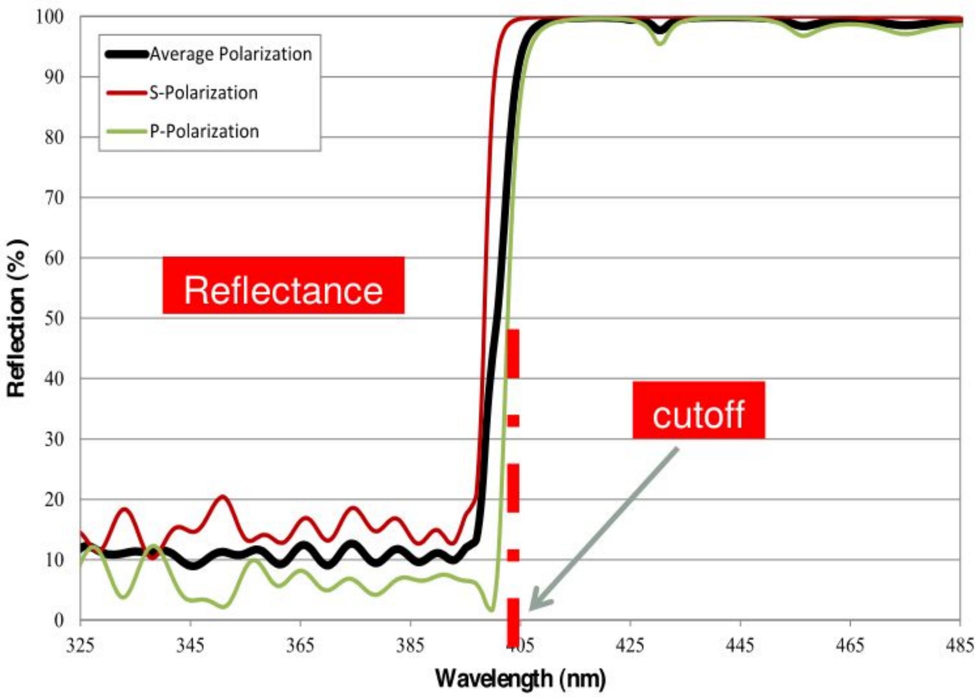
Photon detection system (PDS)

- Detecting 127 nm light is challenging. Besides, HD and VD requires that the photon detectors must have no more than 3 cm in thickness
- The PDS is based on the X-Arapuca device

X-Arapuca - Working principle





The device makes use of a dichroic filter in combination with two wavelength shifters (WLS)

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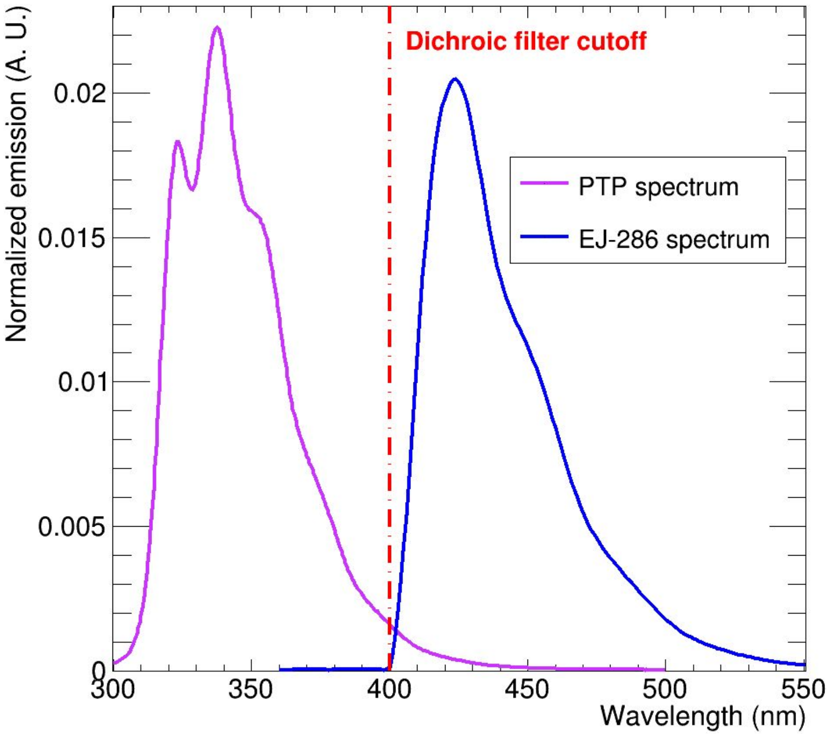
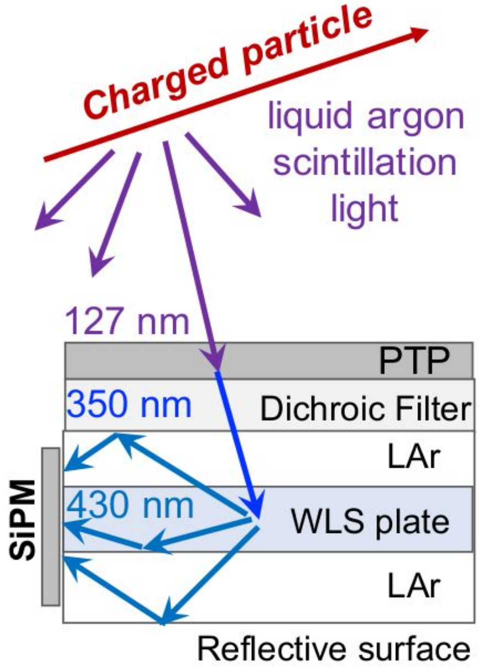


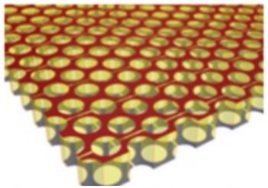
PTP → p-Terphenyl
SiPM → Silicon photomultiplier

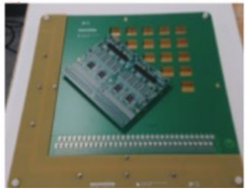


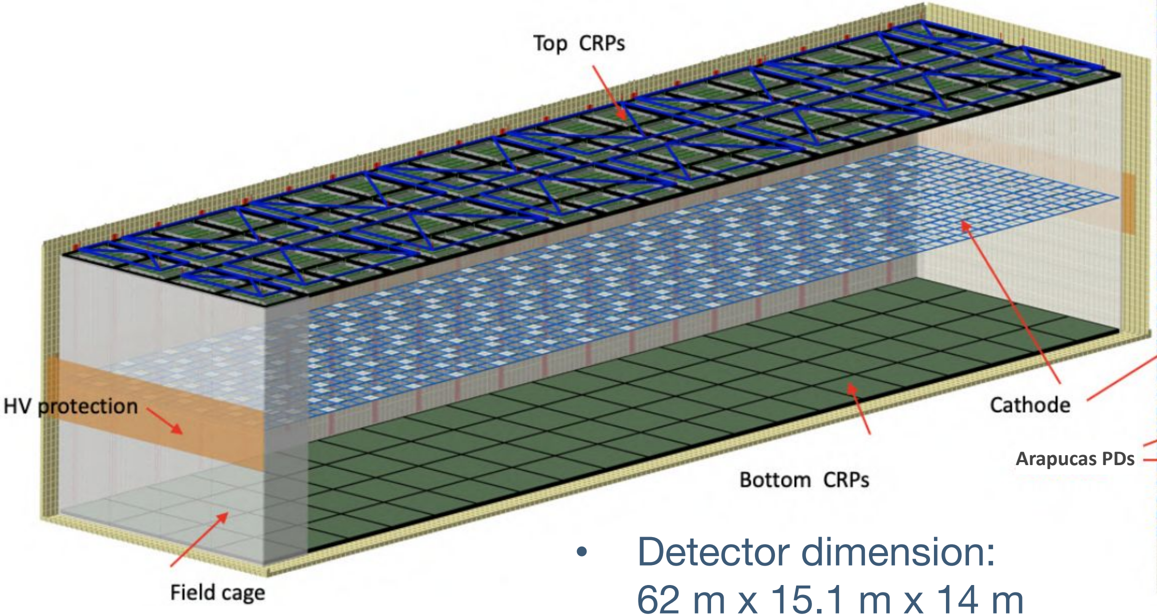
The device makes use of a dichroic filter in combination with two wavelength shifters (WLS)

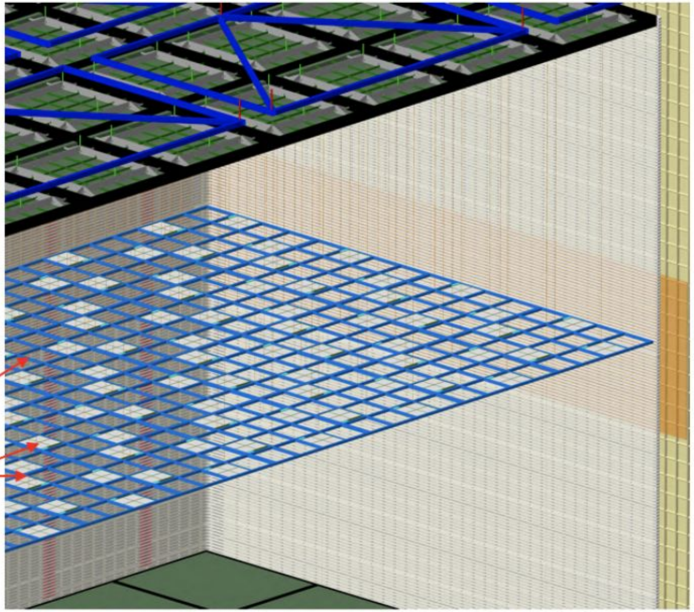
Vertical Drift (VD) module

- Charge-readout planes (CRP) (anode) on top and bottom.
- Cathode in the center at -300 kV
- 6,5 m drift distance
- Fiducial mass ~14.7 kt





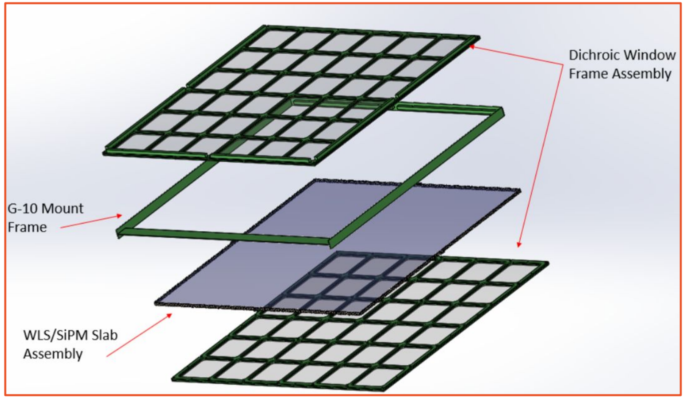


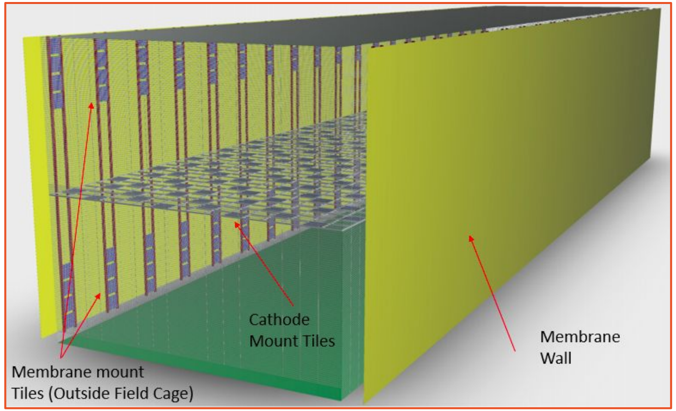


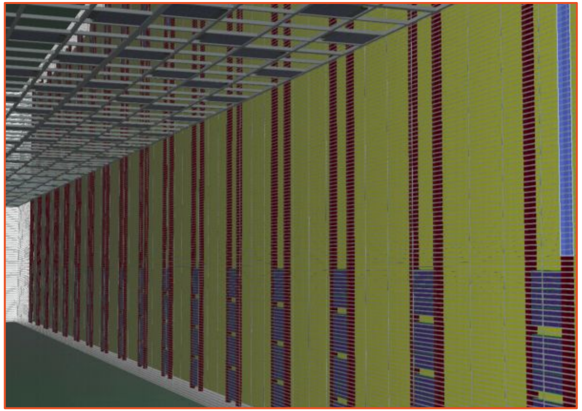
- Detector dimension:
  62 m x 15.1 m x 14 m

Photon detection system (PDS)

- Total area of 65 x 65 cm^2
- A total of 2 x 80 Silicon Photomultipliers (SiPMs) per module
- 2x36 dichroic filters coated with pTP
- These devices are installed on the Cathode at -300 kV
  - Power supply and signal must be transmitted over non-conducting materials

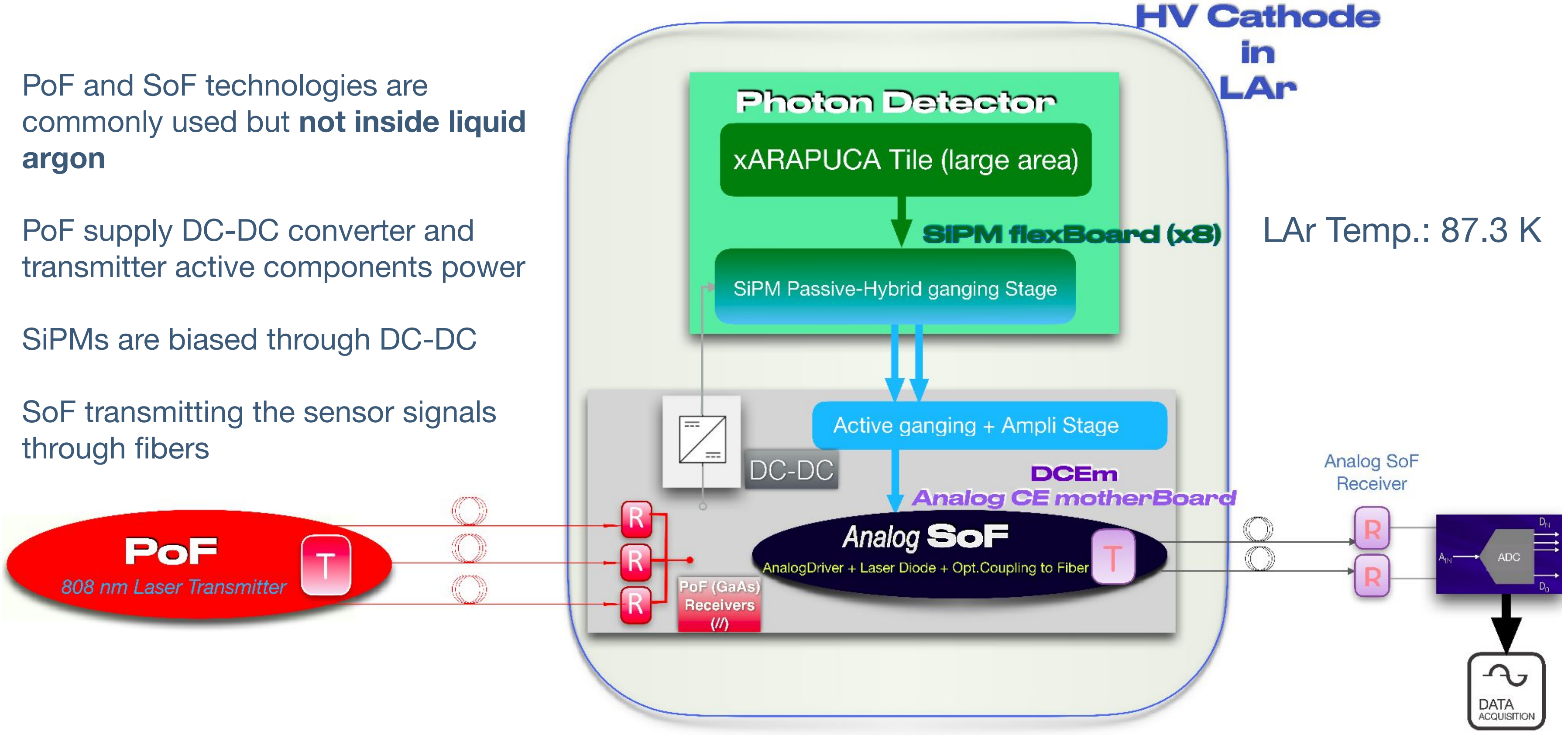






PDS: Power and Signal over Fiber

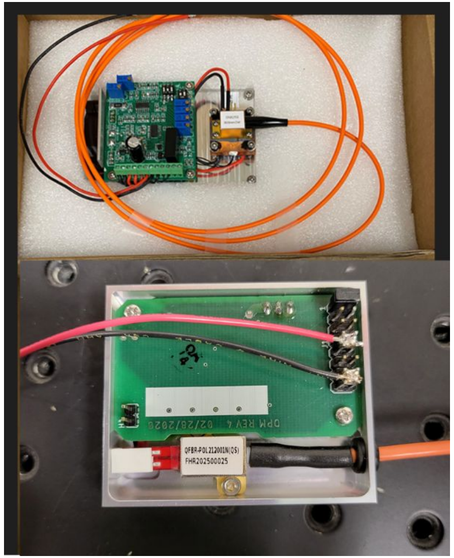
- PoF and SoF technologies are commonly used but **not inside liquid argon**
- PoF supply DC-DC converter and transmitter active components power
- SiPMs are biased through DC-DC
- SoF transmitting the sensor signals through fibers



Power over fiber

Low voltage (5 V) and high current PoF for DC-DC converter, OpAmps and other active analog electronics components.

Three receivers in parallel with efficiency >65%



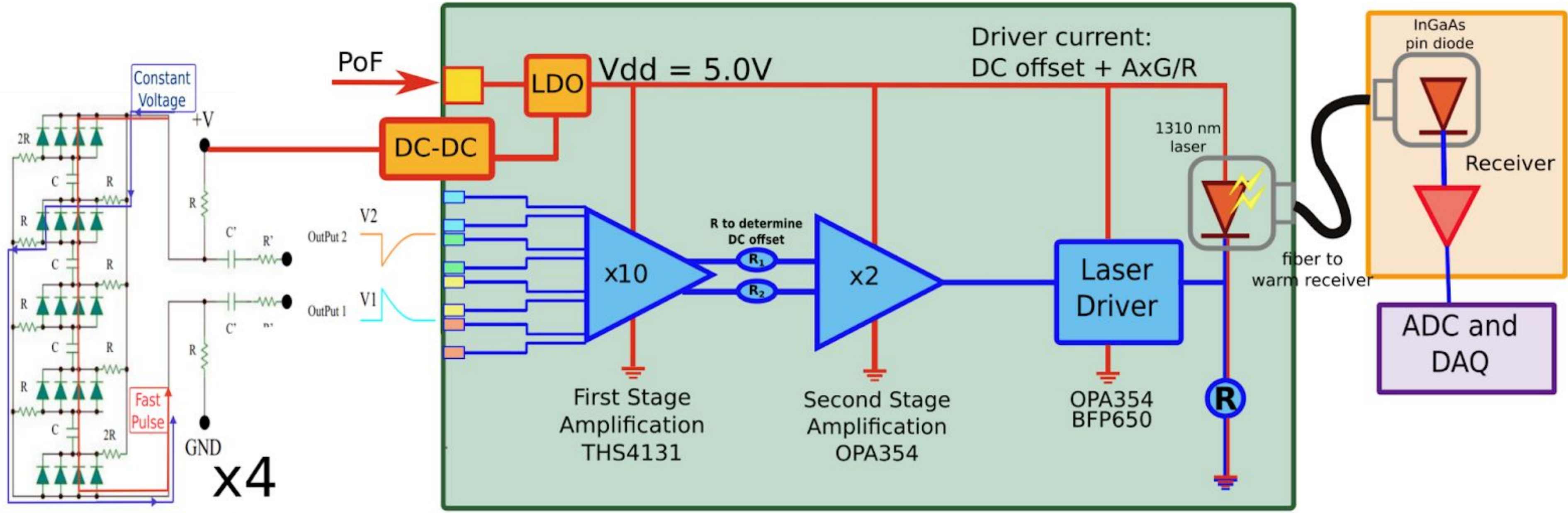
Multimode fiber with FC connector

PoF transmitter
808 nm 3 W laser

PoF Receiver
Gallium arsenide (GaAs)
Photovoltaic Power Converter (PPC) on heatsink

Signal over fiber

- DCem board (2 channels/board)
  - Fabry Perot 1310 nm lasers FC connector
  - Voltage gain ~x40
  - Laser optical power output ≲ 2 mW
- Integrated Photovoltaic Power Converter (PPC)
- Integrated DC-DC converter
- NTC resistor to enable warm and cold operation
- Low-Drop Out Voltage Regulator (LDO)



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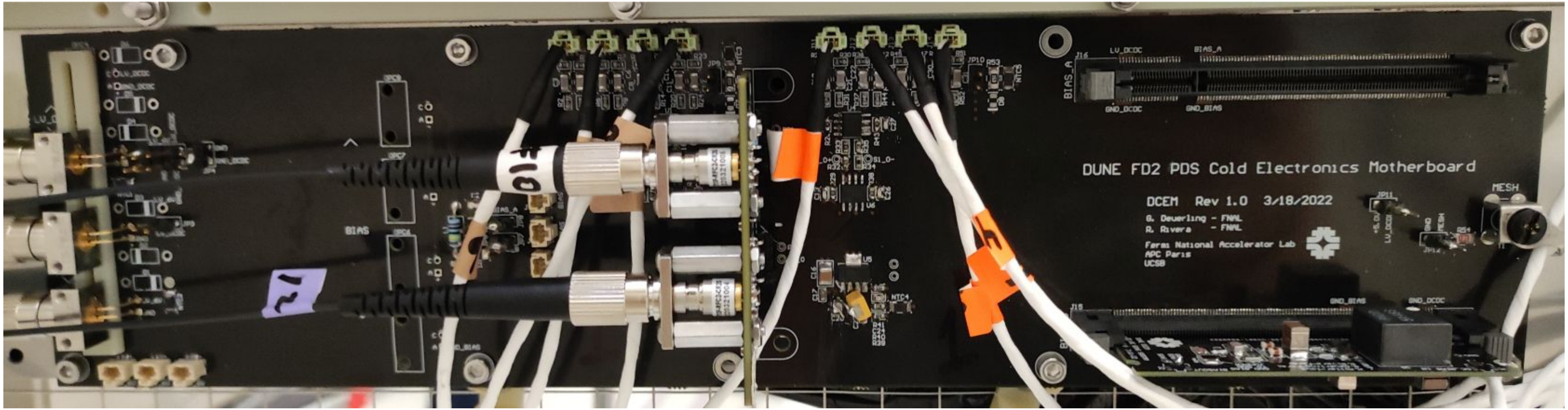


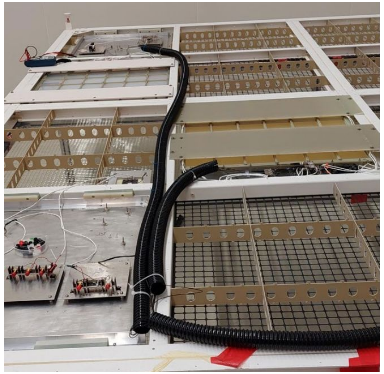
PoF and SoF operation

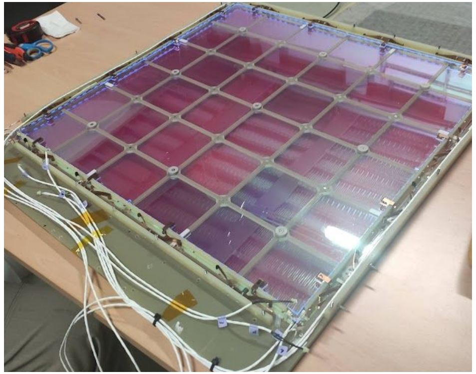
CERN Neutrino Platform **coldbox**:

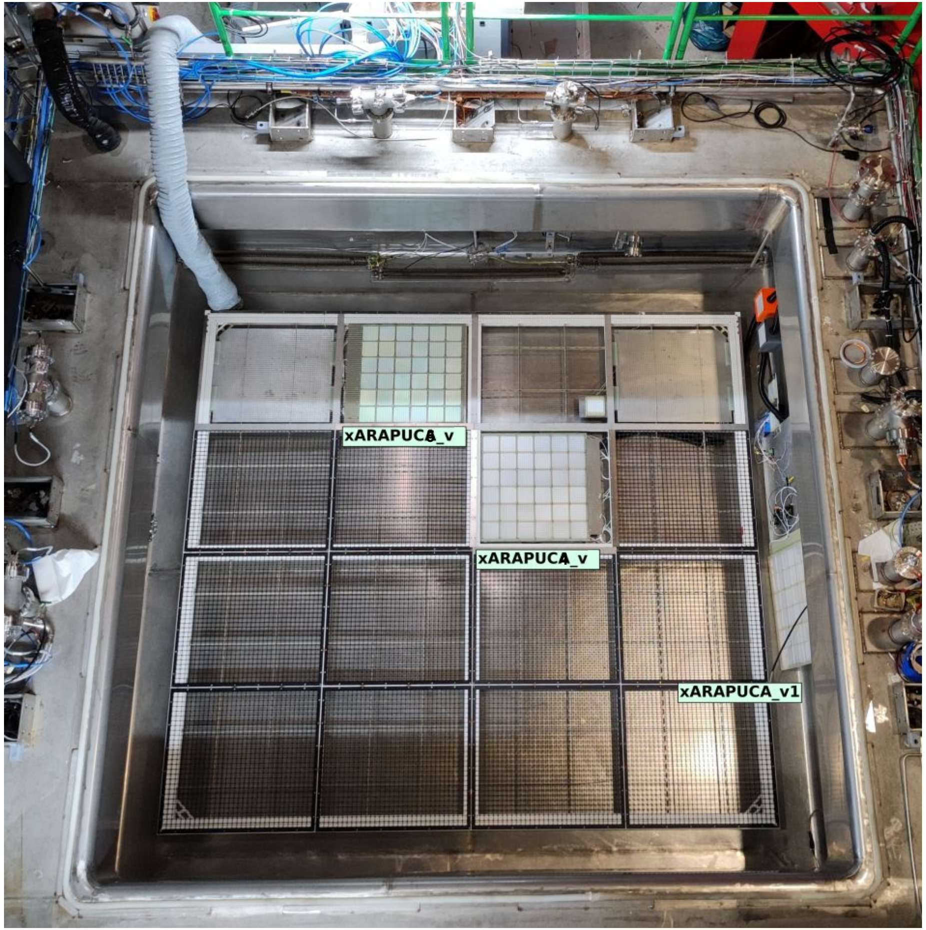
$3\times3\times1$ m^3 cryostat for LAr tests

Cathode placed on feet, anode is mounted on the coldbox cover (23 cm drift distance)

Target: operation of PD system in LAr
PD with signal and power transmission through fiber, operating on an HV surface







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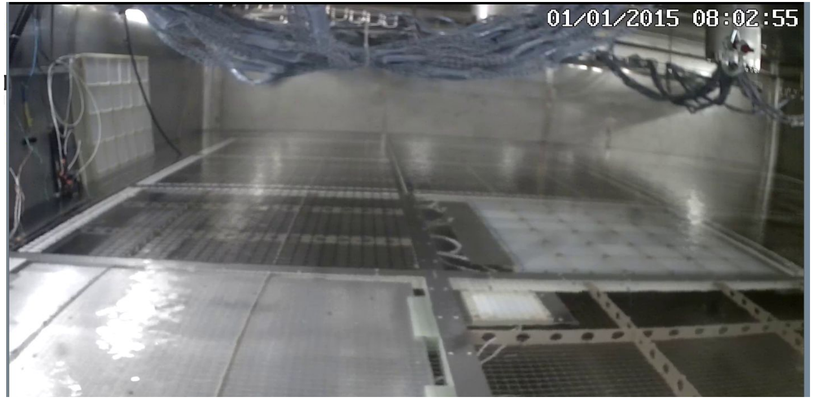
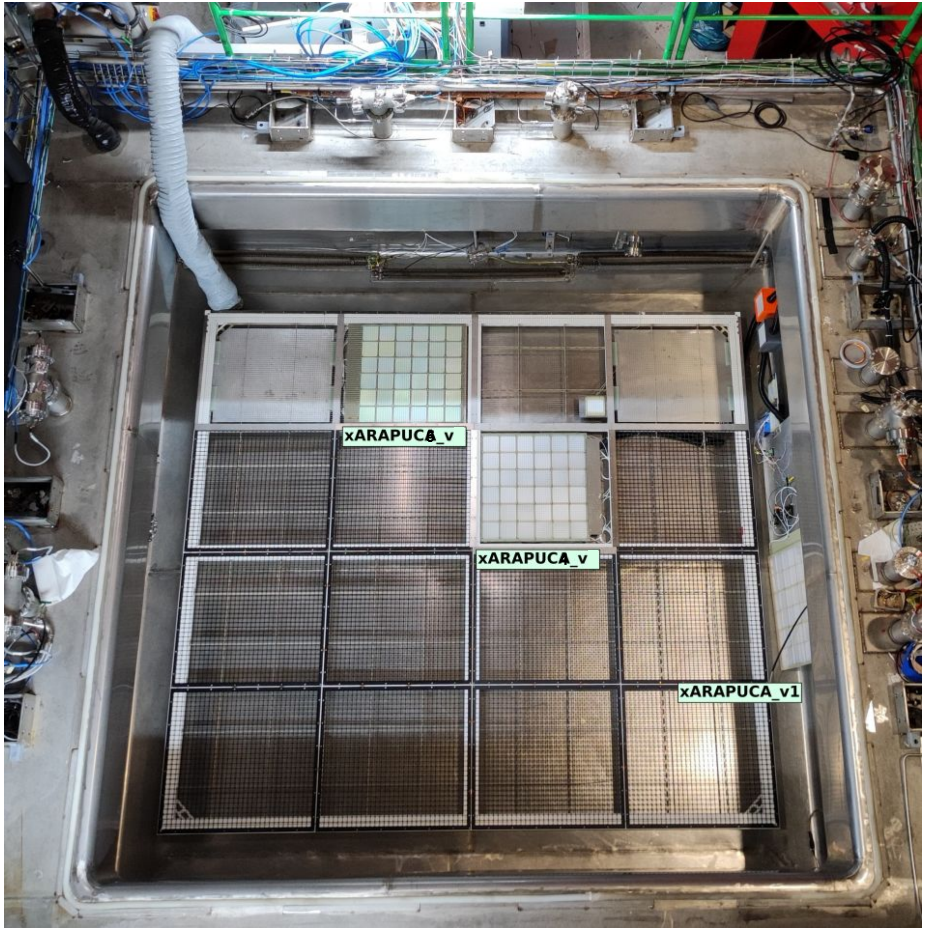
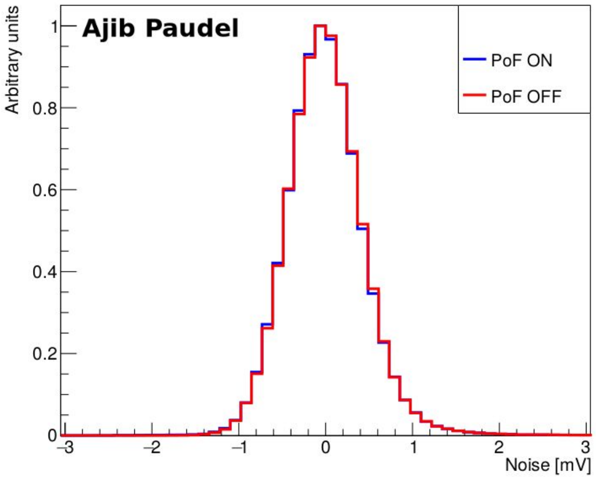
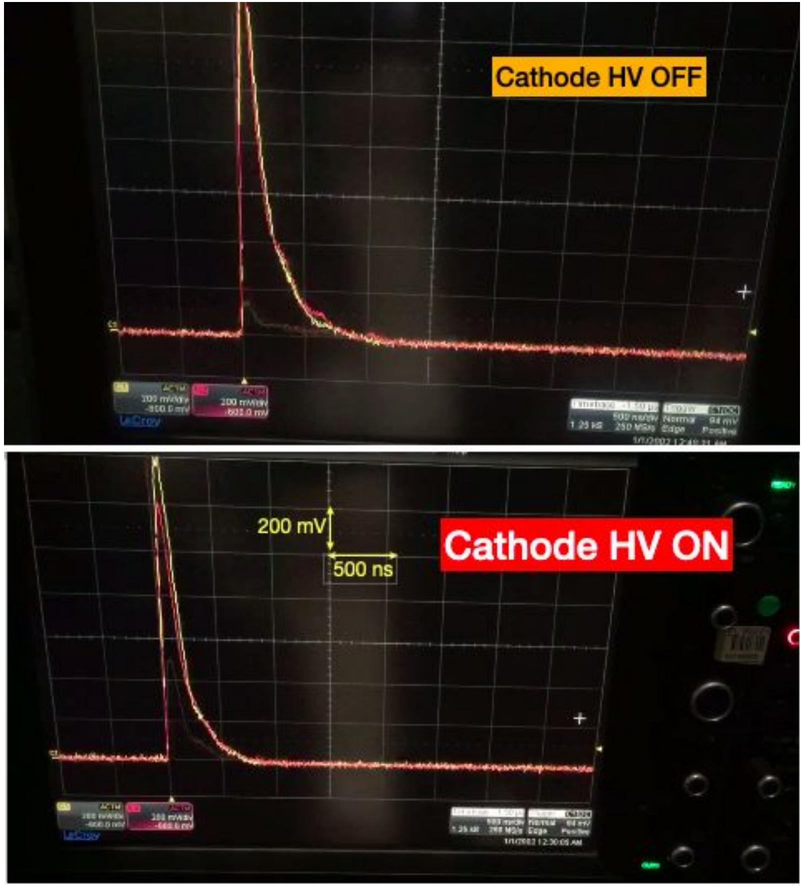




PoF and SoF operation

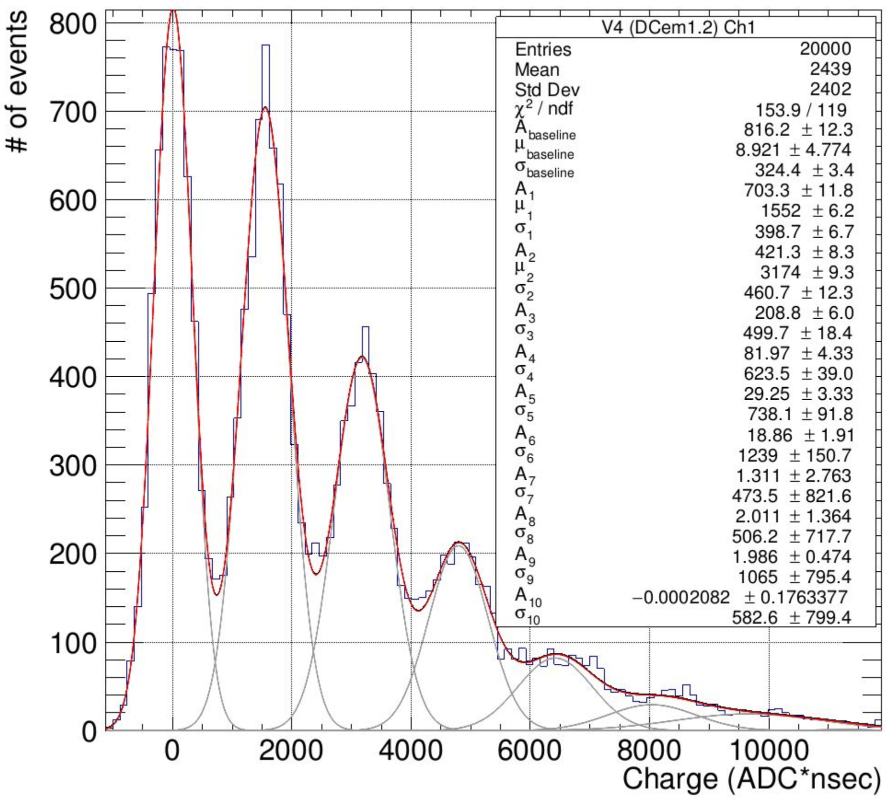
- Photon Detection System principle successfully demonstrated
  - Power and readout done through fiber only at liquid argon
  - Operation stable with High Voltage on and off
  - No interference in the TPC performance





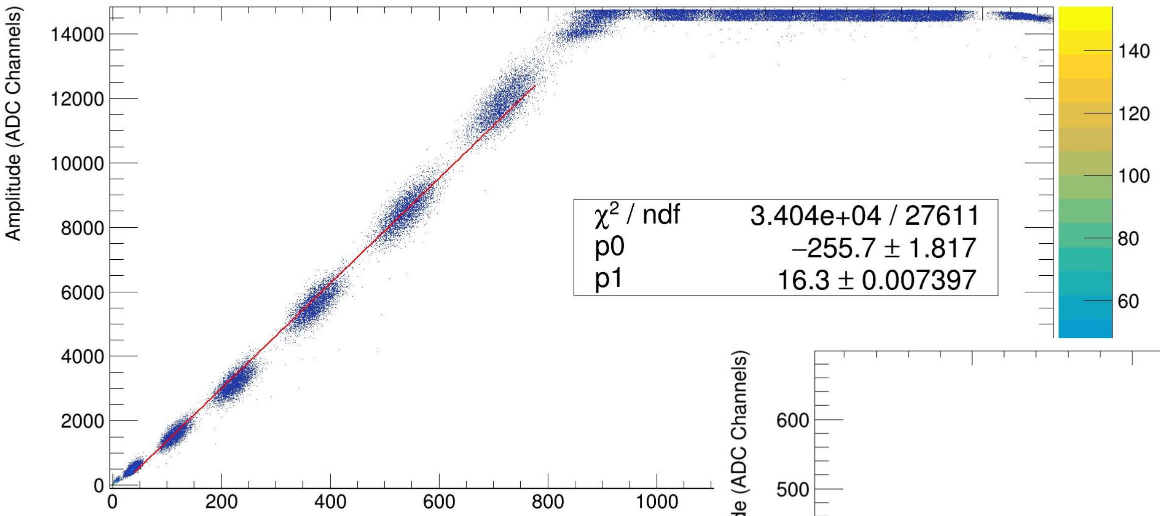
SoF operation

- LED flashes also made possible for single photo-electron calibration

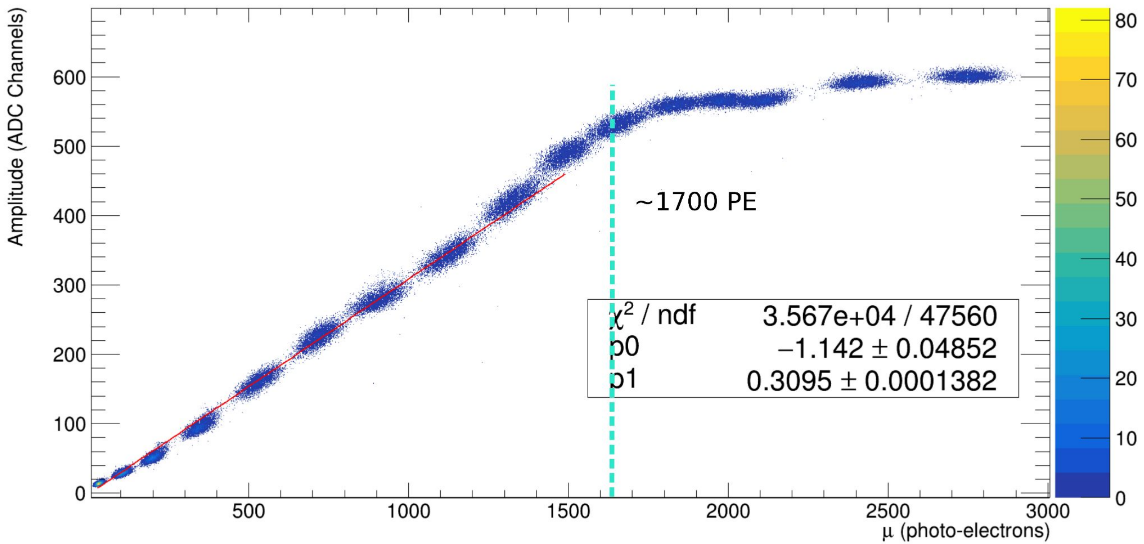


- X-Arapuca detector in the LArTPC cathode
- 80 SiPMs hybrid ganged
- Signal-to-noise ratio ~ 4.9
- Amplitude of 1 p.e. ~ 18 ADCs

SoF operation

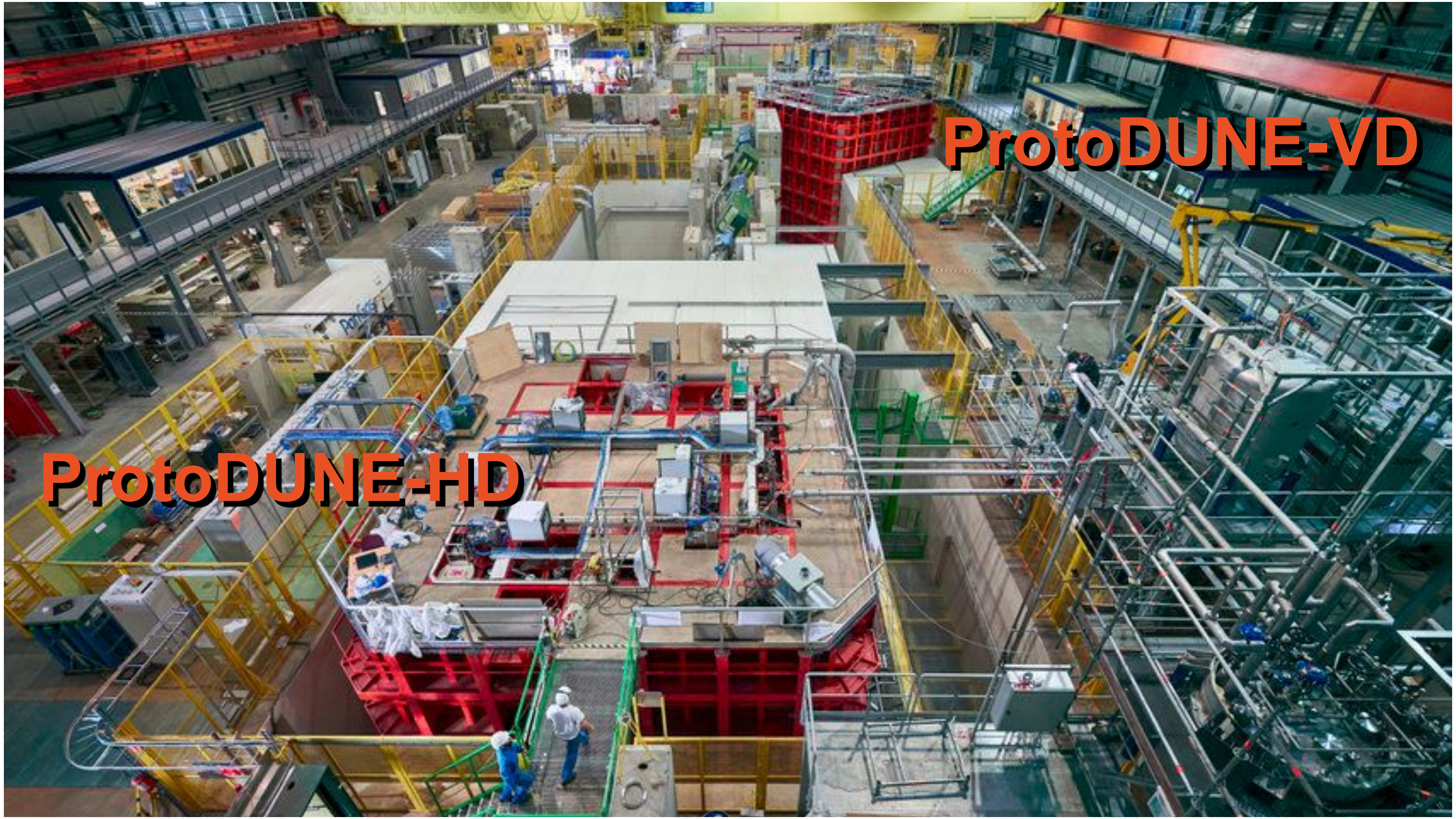


- Setup limitations: LED light non-linearities and commercial receiver saturation
- A light attenuator was added on the warm side to explore the full dynamic range of the cold electronics.



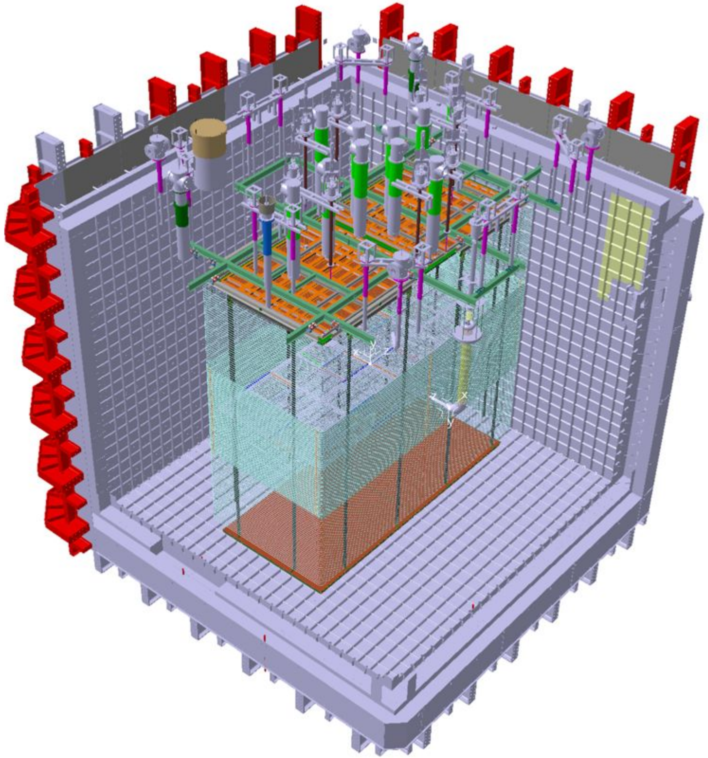
- On-going simulation-based studies to determine a physics-driven requirement for the dynamic range.

DUNE Prototypes



ProtoDUNE-VD (Module-0)

- Assembling on end of 2022.
- Operation on 2023



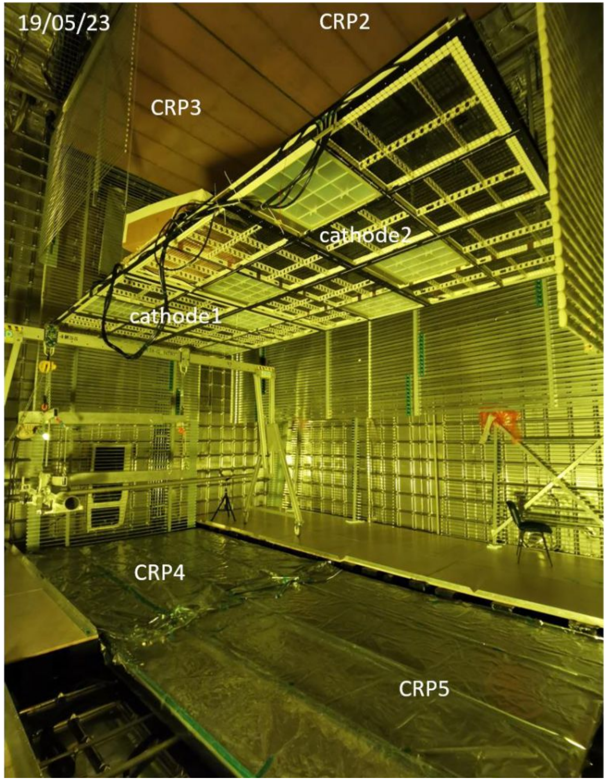


Photo from Dominique Duchesneau @ Collab. meeting

Conclusions

- Power and Signal over Fiber successfully tested in December 2021 in a 23 cm drift distance LArTPC.
  - Stable performance when cathode operated at 10 kV (~430 V/cm)
  - Dedicated measurements have shown a linear response of the device
  - No interference on the functioning of the TPC

- Reliable system, operated through 10 different runs.

- Research and Development still in progress, with tasks such as:
  - Improve and verify circuit stability for the ~30 years long experiment
  - Prove dynamic range to cover the desirable ~2000 photo-electrons

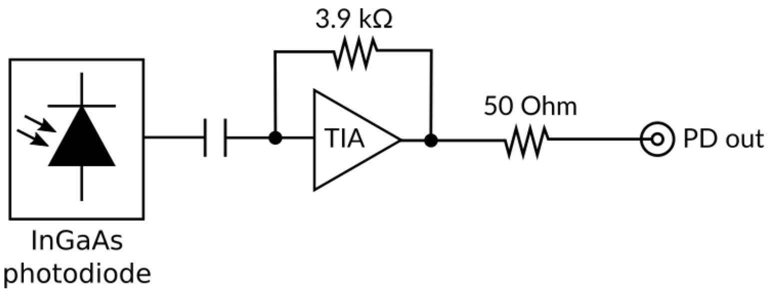
- System will be tested in the first DUNE VD Prototype (Module-0) during 2023

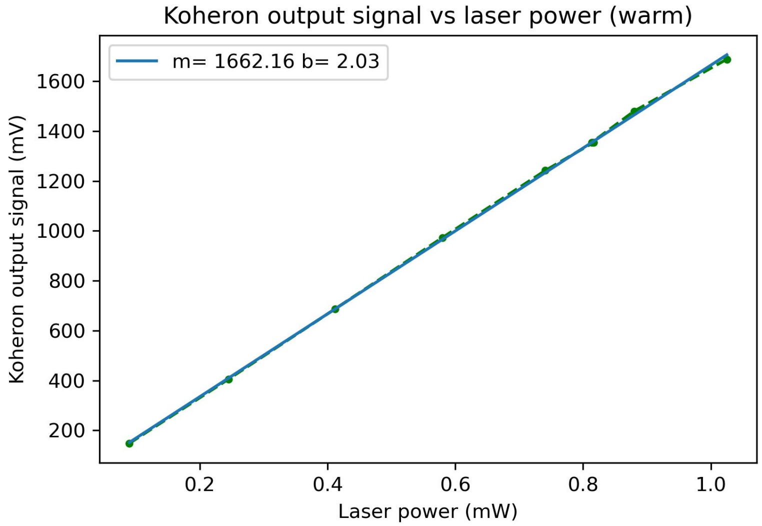
Thanks!

Signal over fiber

Koheron PD100 low noise photodiode

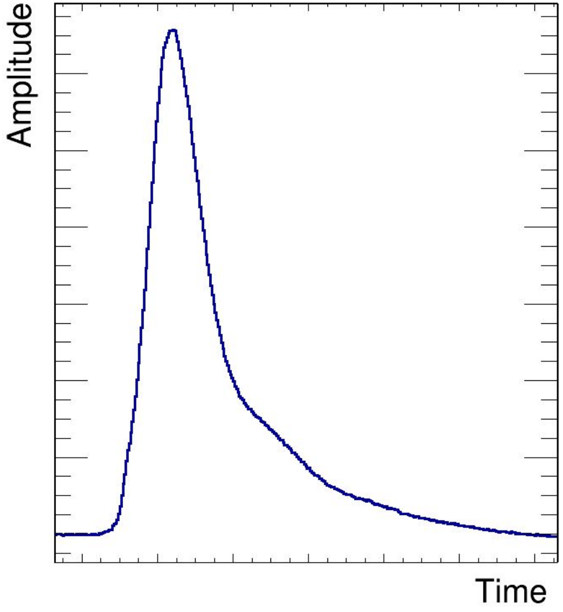
- single channel commercial solution - found early 2021
- Indium gallium arsenide (InGaAs) photodiode
- DC-coupled
- 0.9 A/W - 3.9 kV/A amplification
- 600 μW maximum input at 100 MHz
- ± 6V bias, ~40mA

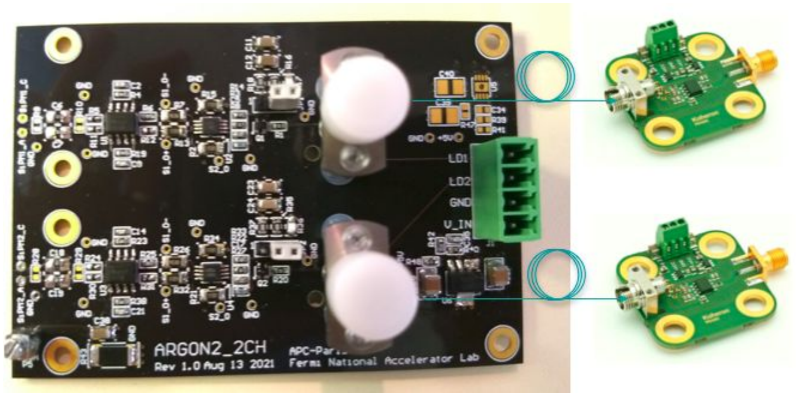




Signal over fiber

- **Board requirements**
  Efficiently transmit **single photo-electron** signals (also the signals from LAr scintillation, but this is mostly limited by the dynamic range)



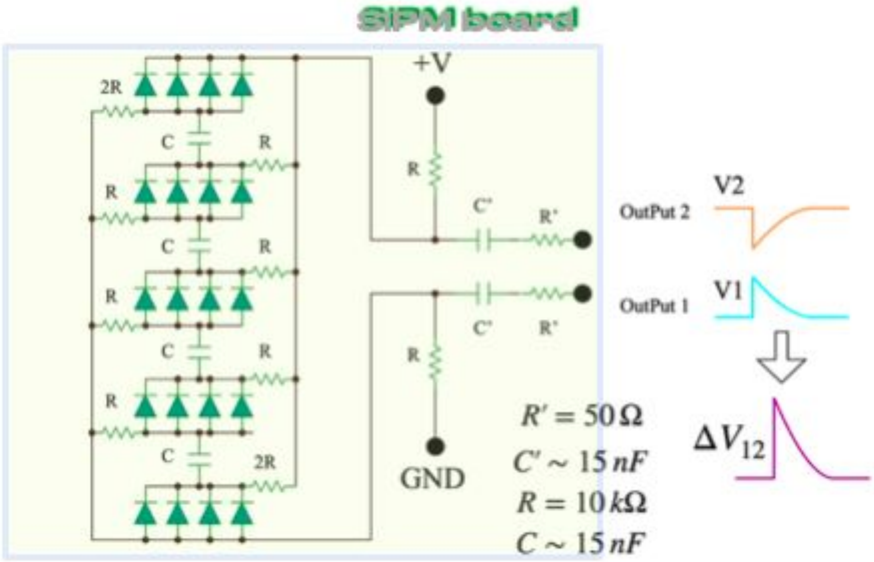


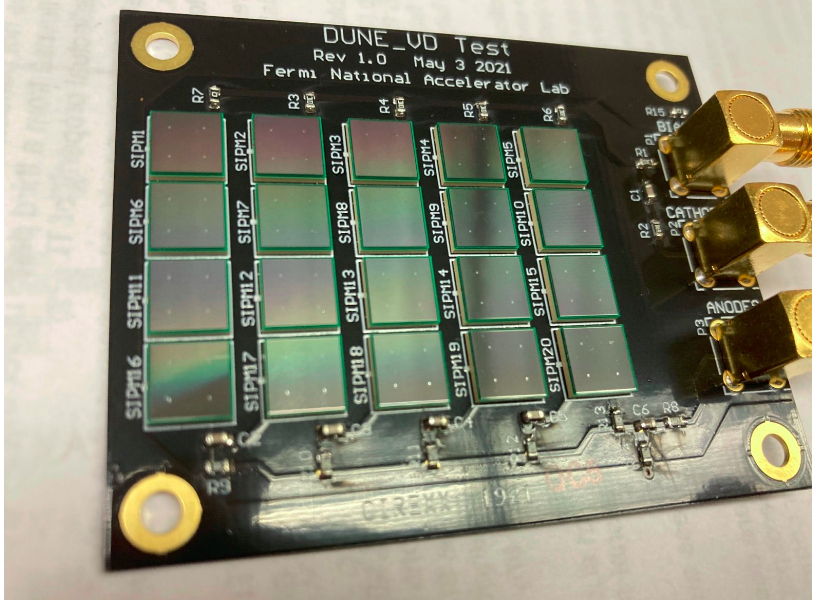
First prototype

Amplitude ~ 50 - 100 μV
Rise time ~ 20 to 80 ns
Discharge time constant ~ 100 to 300 ns

Bandwidth ~ 30 MHz
Signal-to-noise ratio > 4
Dynamic range* ~ 1000 photo-electrons

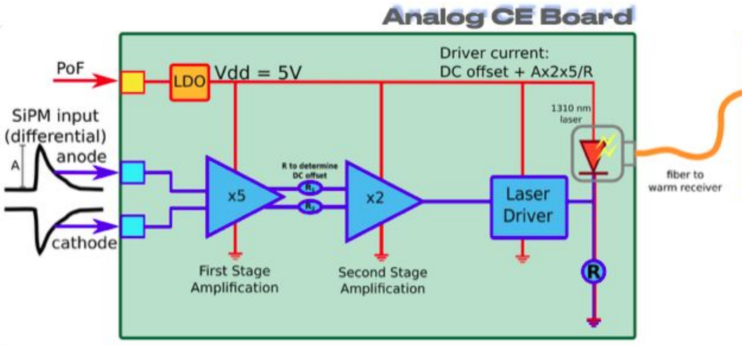
Backup slides

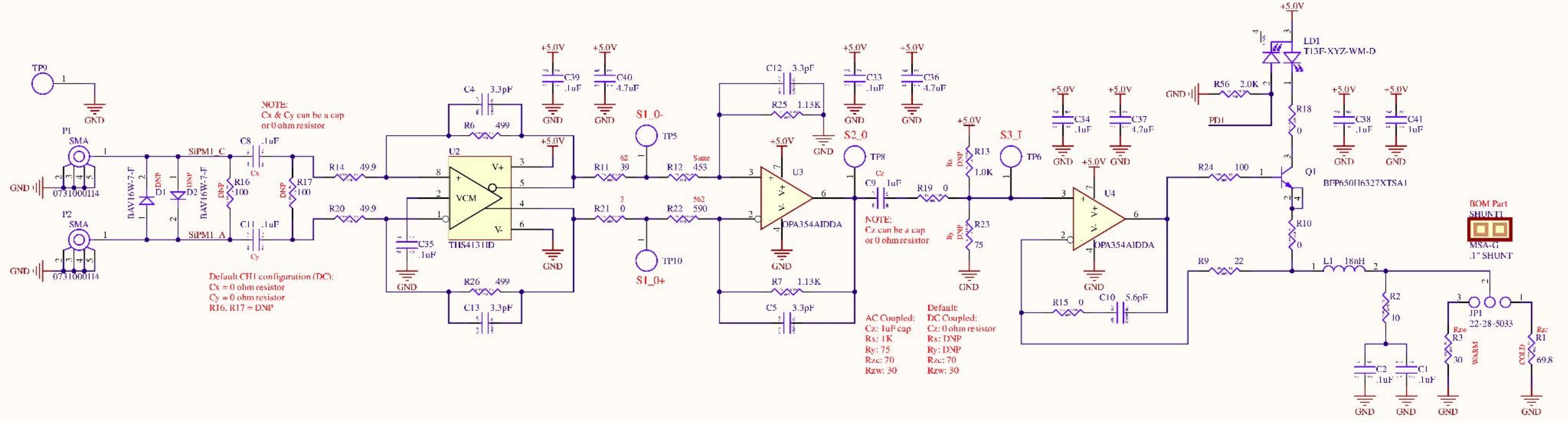




Backup slides

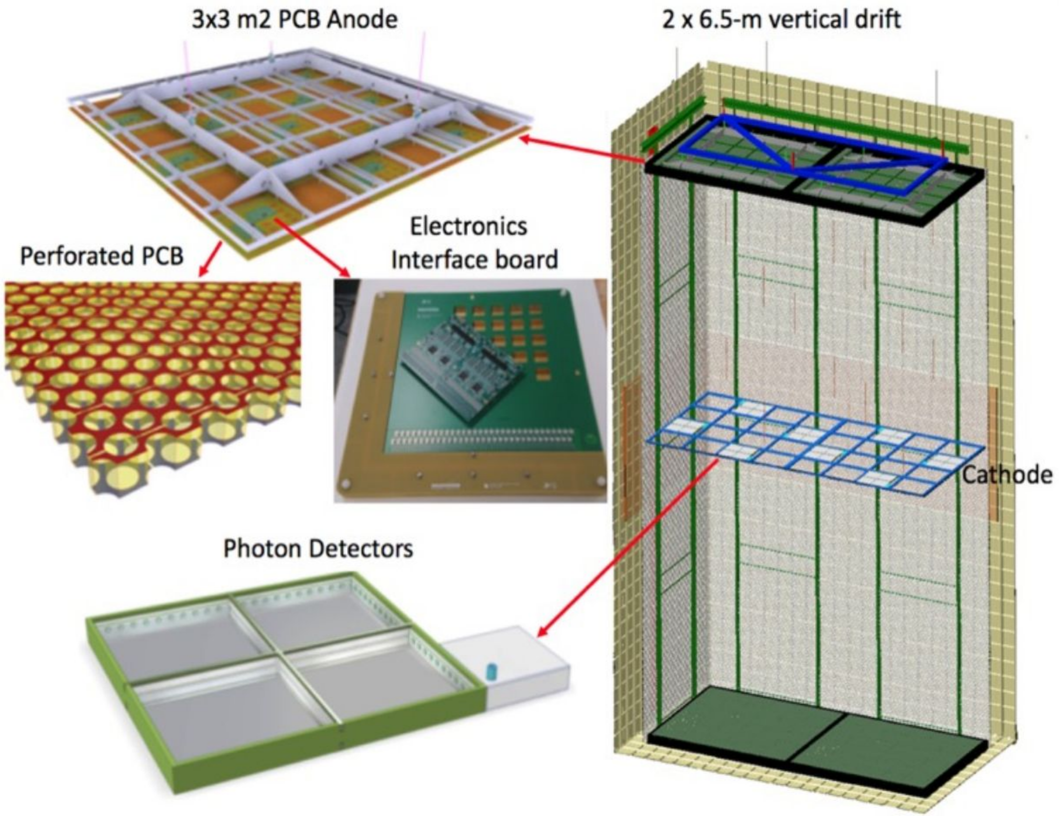
- ARGON2x2 (2 channels/board)
  - V = 5.1V, I < 35 mA (< 100 mW/ch)
  - FP 1310 nm lasers FC connector
  - Voltage gain ~20
  - Optical power ≲ 0.1 mW at receiver





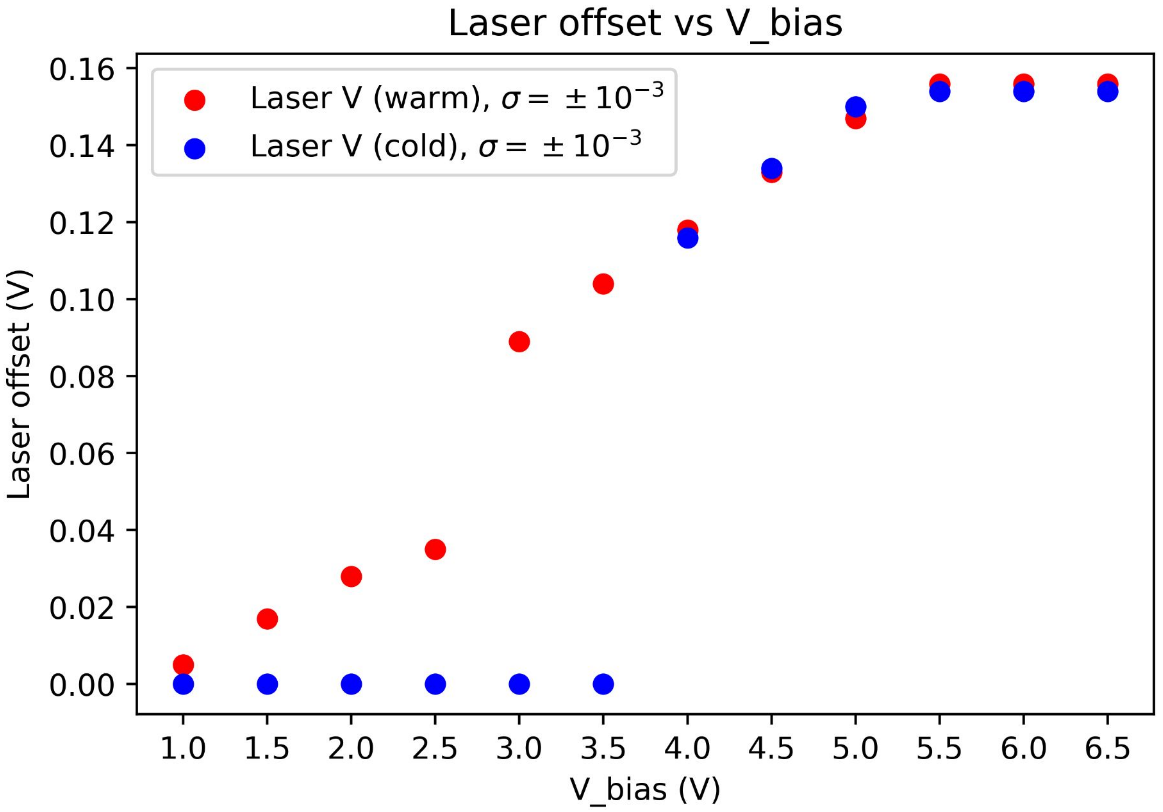
Vertical drift: but why?

- Tests with DUNE's prototypes (ProtoDUNE) shows **outstanding LAr purity**
  - **Drift distance** of 6 - 7 m allowed.
- **Vertical drift layout is simpler** to construct
  - More efficient use of LAr volume
  - Reduce schedule and financial risks
  - Lightweight CRP, no broken wires, easier installation, etc.
- Photon Detection System (PDS) installed on the TPC walls AND cathode allows **higher coverage, light uniformity, energy & position resolution and detection threshold.**



Backup slides

Laser offset in warm and cold



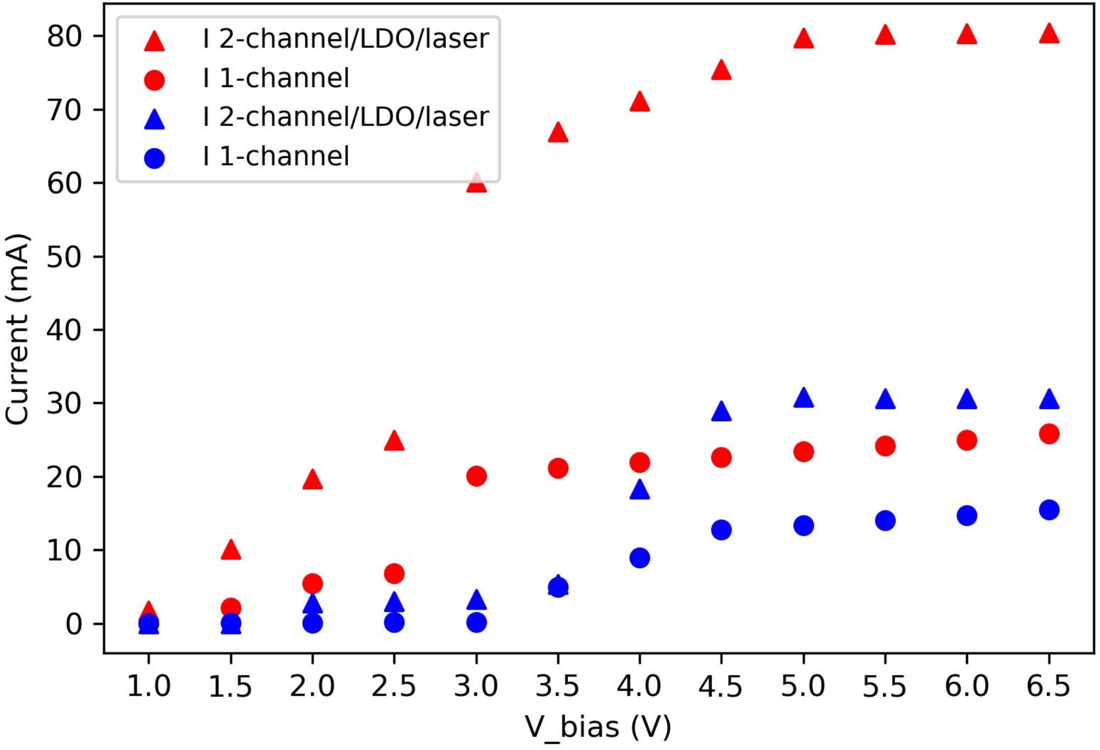
- Reminder: DC offset for laser to be in linear regime
- For V_bias > 4V, the laser DC offset values are the same

→ circuit DC behaviour is the same

- LDO keeps Vdd constant after 5.2V
- Points below 3V and 4V: bias not enough for amplifiers to work (OPA354 min bias specs is 2.5V).

Laser's nominal offset (156 mV) → 3.12 mA (cold), 14.2 mA (warm)

Backup



Full circuit in cold (2 channels - 2 lasers -LDO) ~35 mA

- Measurement for two boards, one with 2 channels + LDO + 1 laser, the other with just 1 channel

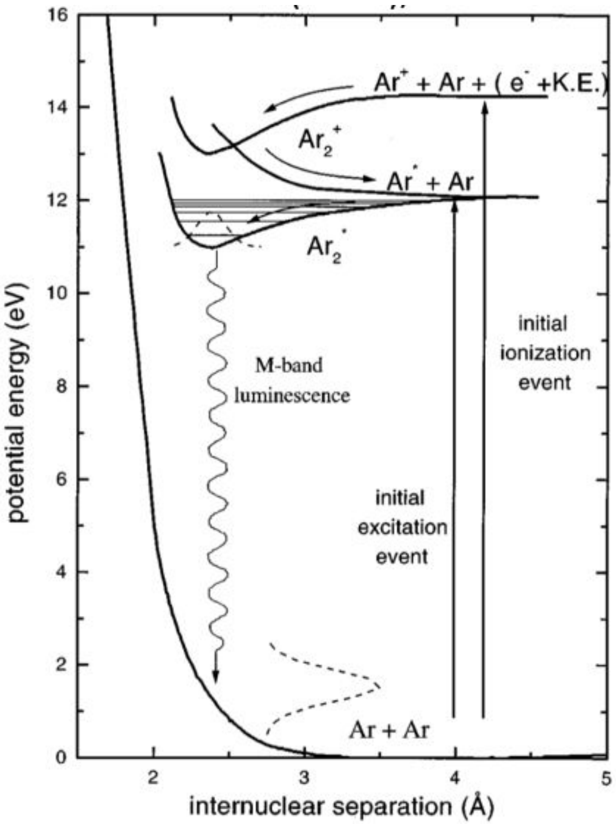
-The consumption in cold is lower than in warm:

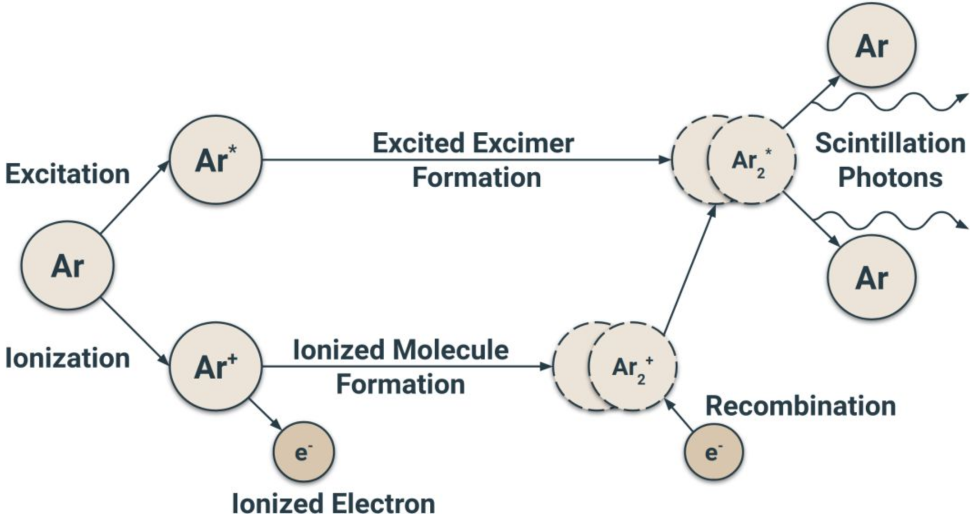
    - the circuit itself (40% less)
    - laser current ~15mA vs ~3mA

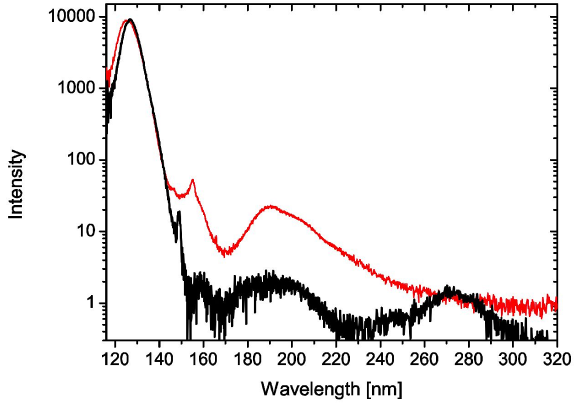
- Difference between the working start point for the Op. Amp. in both boards

-LDO works well in cold, regulating the voltage at a similar value (to 5.23 V measured in warm; PoF is at 5.6V)

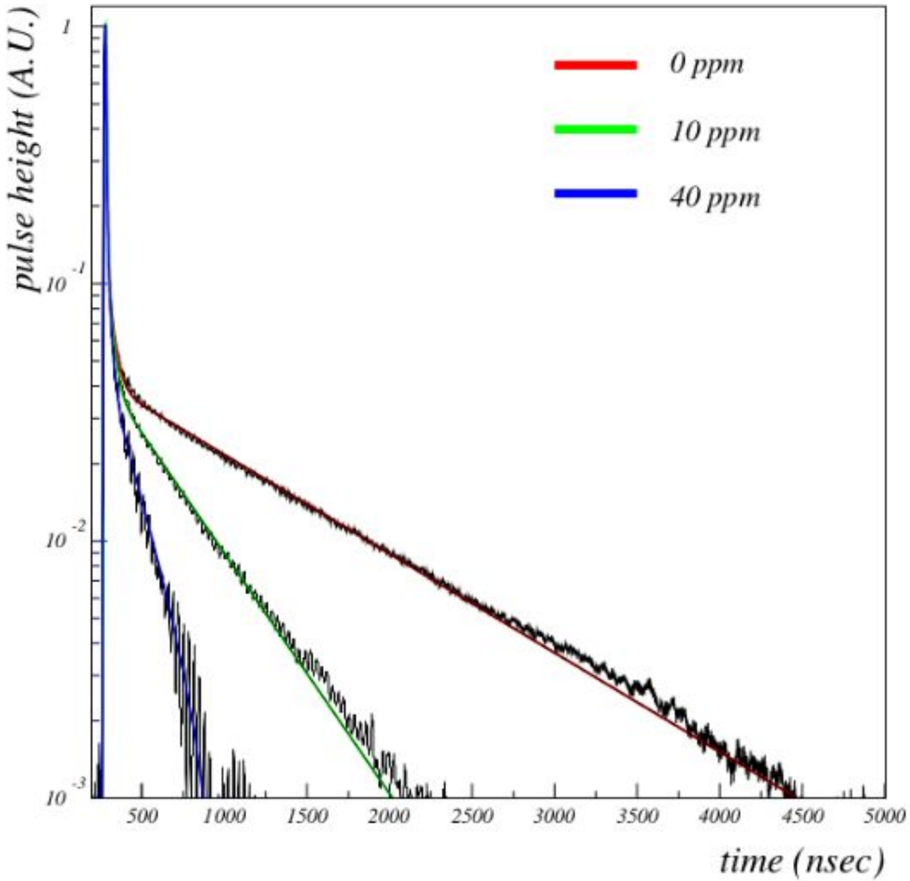
Backup slides

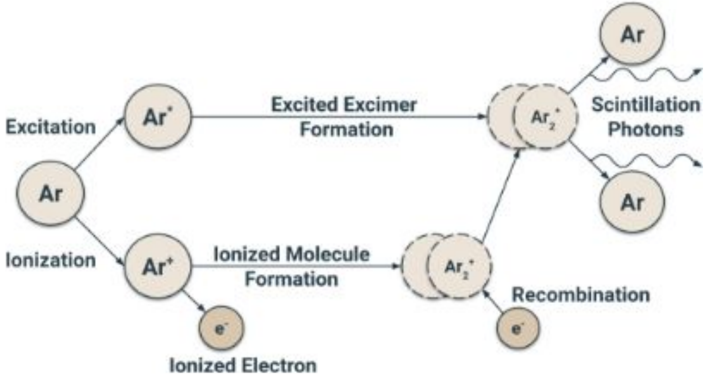






Backup slides





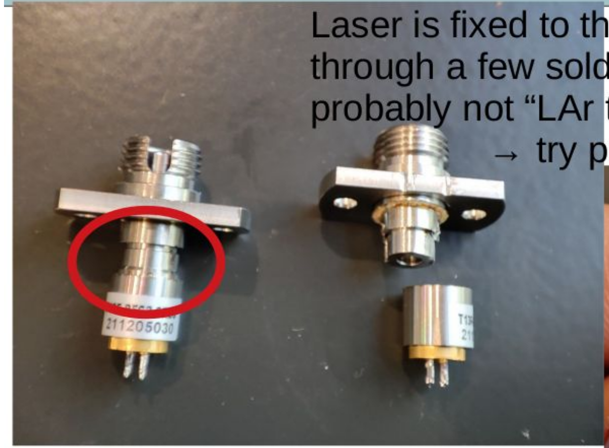
$$I(t) = A_S \exp\left(-\frac{t}{\tau_S}\right) + A_T \exp\left(-\frac{t}{\tau_T}\right)$$

$$\tau_S = 6 \text{ ns}$$

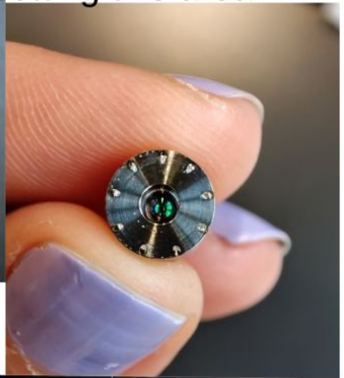
$$\tau_T = 1600 \text{ ns}$$

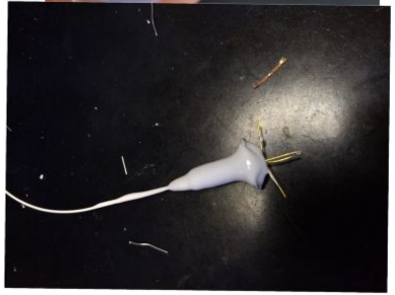
Backup slides

Lasermate FC connector



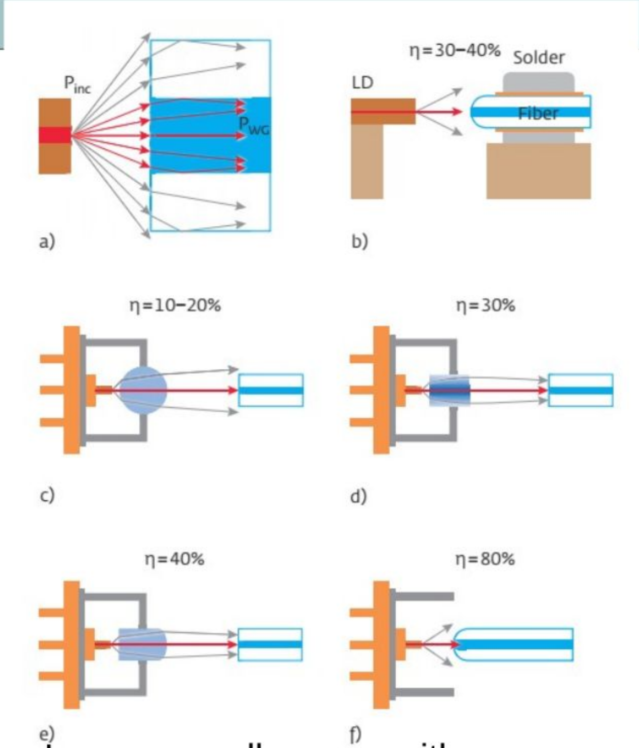
Laser is fixed to the FC connector through a few solder points: probably not “LAr tight”
→ try potting this area?





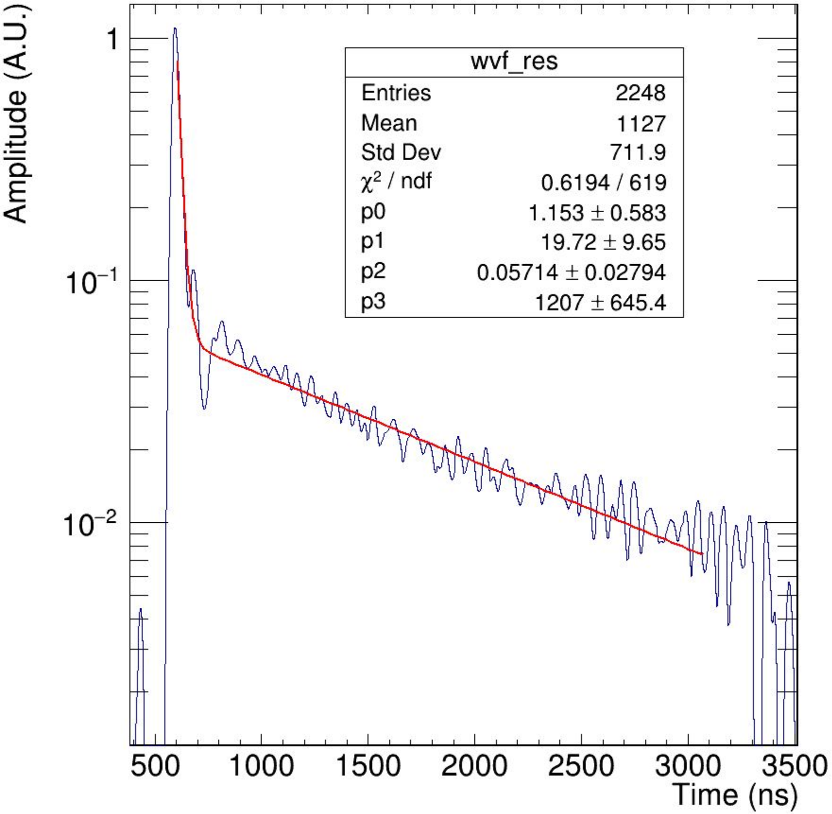
* There seems to be a lens inside → usually the laser beam has a focus point ~few mm from lens

* By fully potting a pigtailed laser we did not see the power output drop
* potting is not trivial

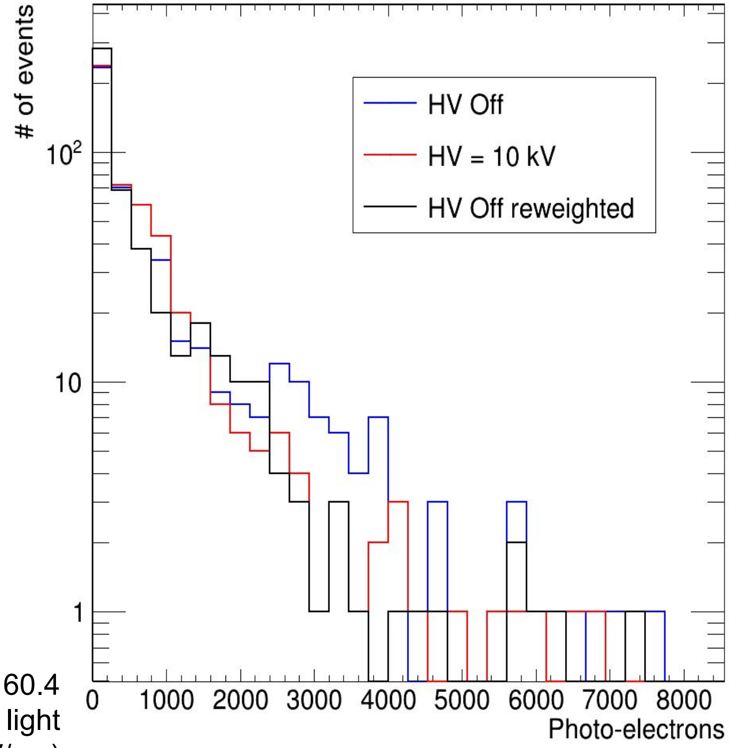


Lasers usually come with some kind of lens → not clear how LAr affects the focus

Backup slides



Scaling factor = 60.4
; would mean 60% of light
with 10 kV (430 V/cm)



Backup slides

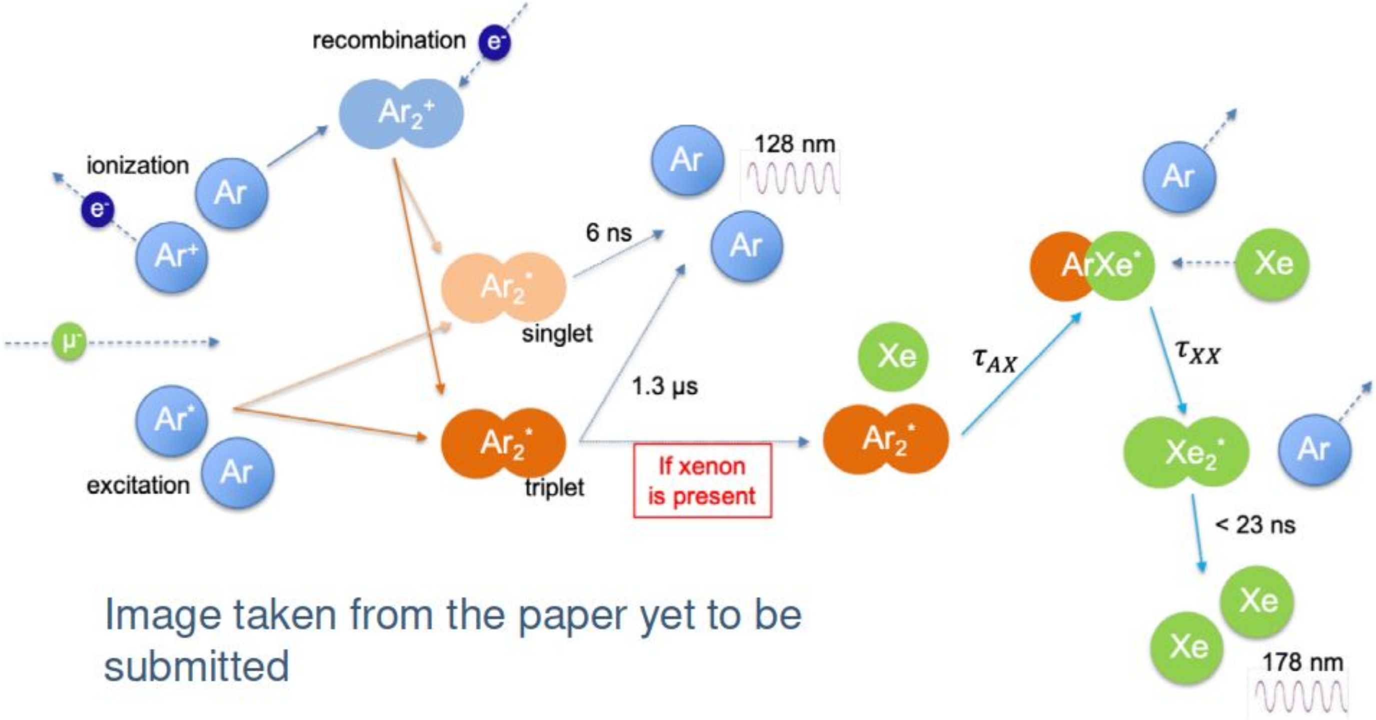
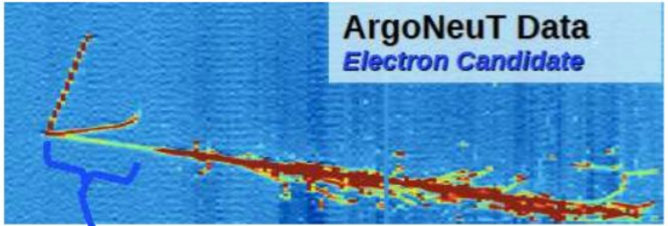
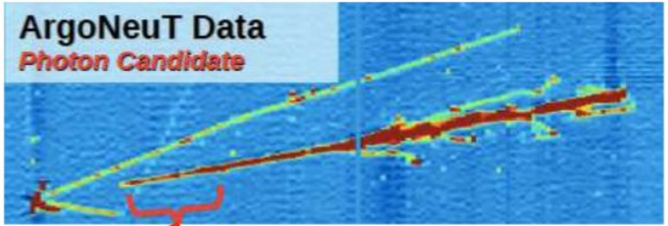
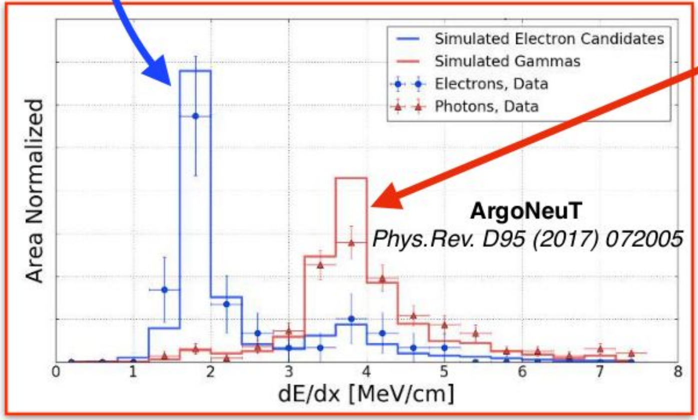


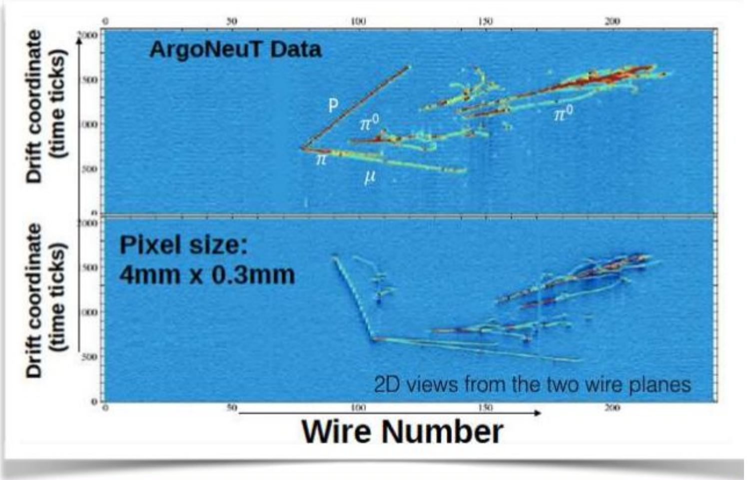
Image taken from the paper yet to be submitted







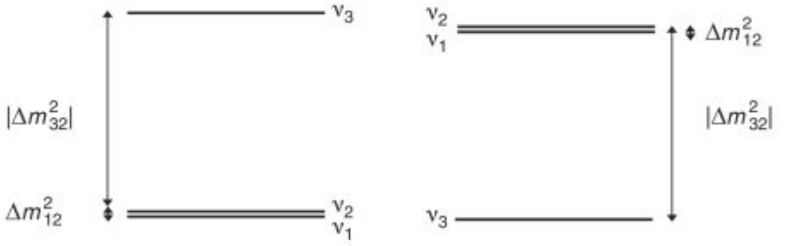
Analyzing topology and dE/dx

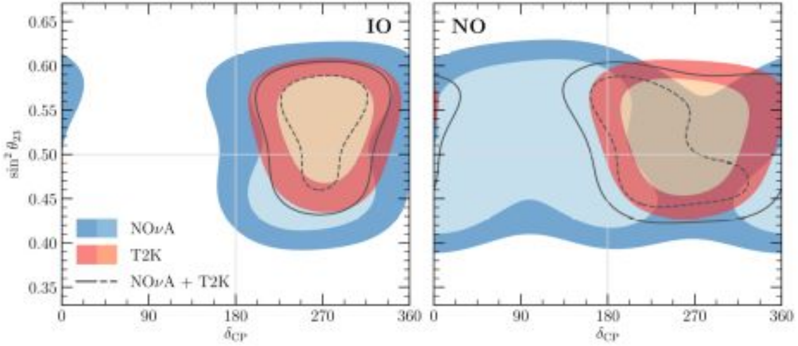


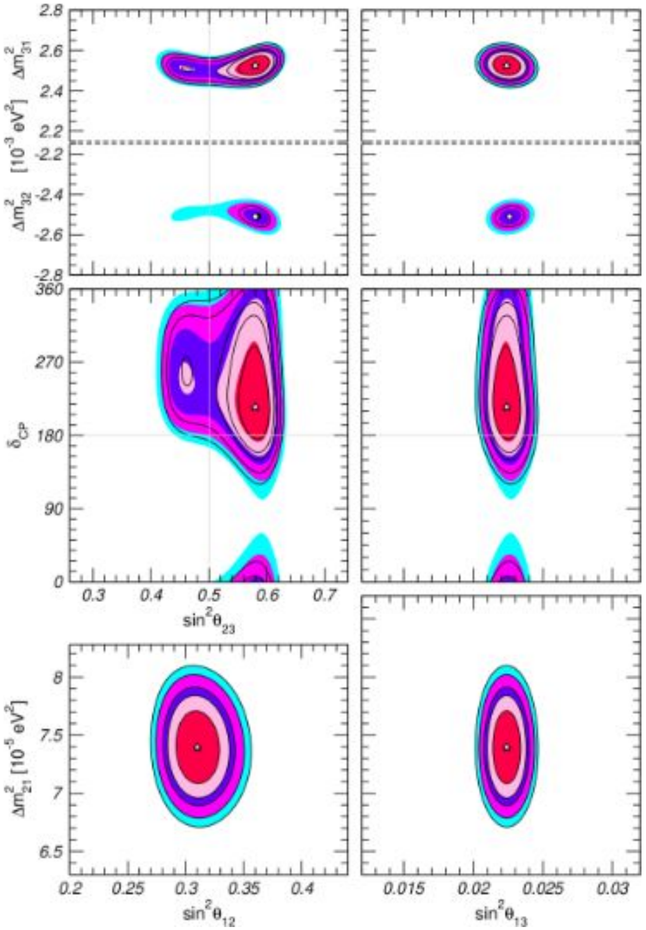
LAr TPC offers incredible fine tracking and calorimetry, along with electron/photon separation

BACKUPS

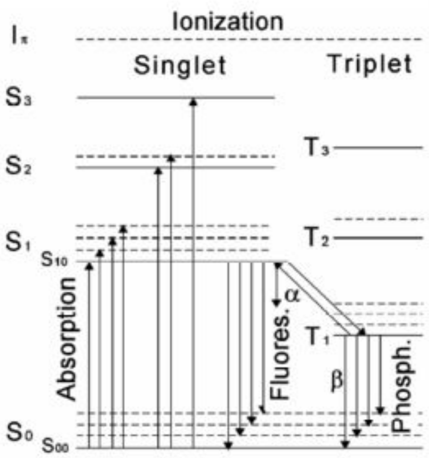
Oscillation parameter		central value	99% CL range
solar mass splitting	Δm^2_{12}	$= (7.58 \pm 0.21)\, 10^{-5}\, \mathrm{eV}^2$	$(7.1 \div 8.1)\, 10^{-5}\, \mathrm{eV}^2$
atmospheric mass splitting	$\lvert\Delta m^2_{23}\rvert$	$= (2.40 \pm 0.15)\, 10^{-3}\, \mathrm{eV}^2$	$(2.1 \div 2.8)\, 10^{-3}\, \mathrm{eV}^2$
solar mixing angle	$\tan^2\theta_{12}$	$= 0.484 \pm 0.048$	$31° < \theta_{12} < 39°$
atmospheric mixing angle	$\sin^2 2\theta_{23}$	$= 1.02 \pm 0.04$	$37° < \theta_{23} < 53°$
'CHOOZ' mixing angle	$\sin^2 2\theta_{13}$	$= 0.07 \pm 0.04$	$0° < \theta_{13} < 13°$

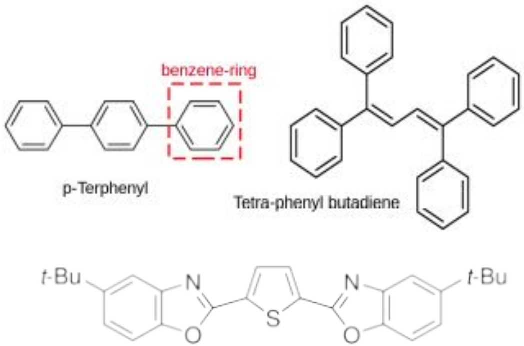


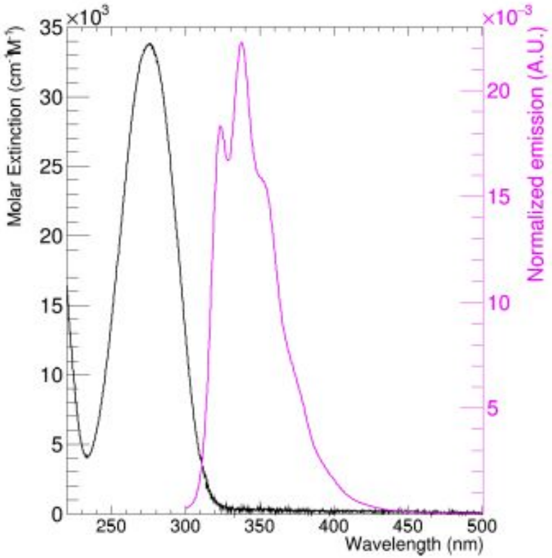


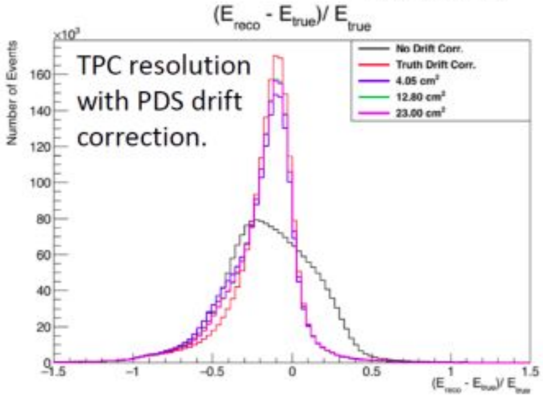


BACKUPS


Ionization
Singlet
Triplet
S3
S2
S1
S10
S0
S00
T3
T2
T1
Absorption
Fluores.
Phosph.
α
β


benzene-ring
p-Terphenyl
Tetra-phenyl butadiene
t-Bu
N
S
O


Molar Extinction (cm⁻¹M⁻¹)
Normalized emission (A.U.)
Wavelength (nm)

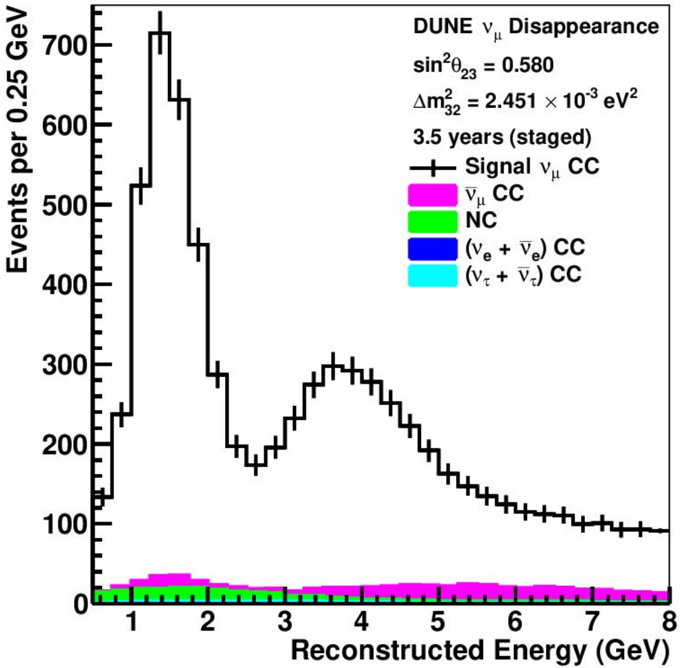

(E_reco - E_true)/ E_true
TPC resolution
with PDS drift
correction.
Number of Events
No Drift Corr.
Truth Drift Corr.
4.05 cm²
12.80 cm²
23.00 cm²

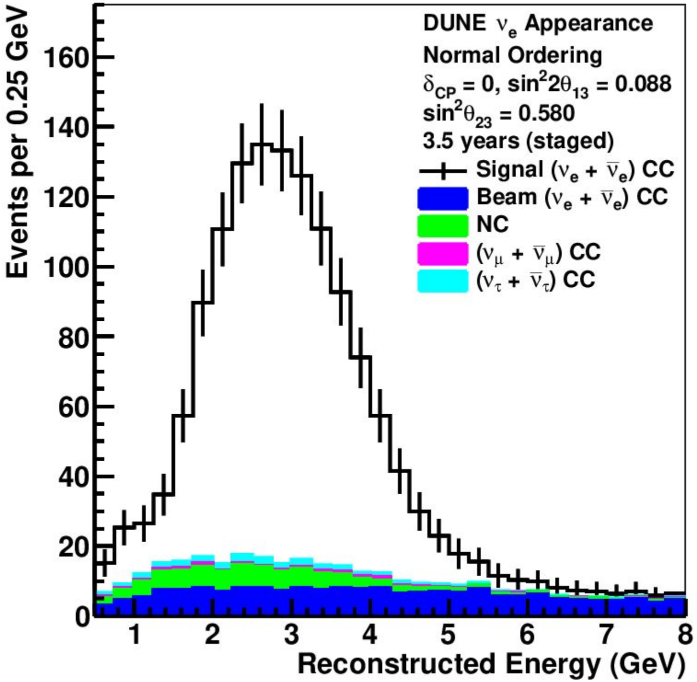
Why liquid argon ?

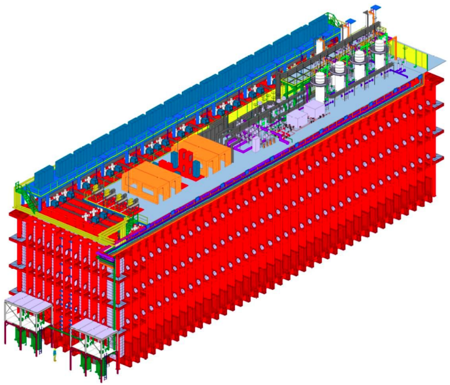
- **Noble gas:** electropositive and dielectric (low electron absorbance and high voltage allowed)
- **High density**
- **High radiation length** (allows good discrimination between electrons and photons and make it easier to retrieve neutrino vertex)
- **Abundant in nature**

	Water	He	Ne	Ar	Kr	Xe
Boiling point [K] @ 1 atm	373	4.2	27.1	87.3	120	165
Density [g/cm^3]	1	0.125	1.2	1.4	2.4	3.0
Radiation length [cm]	36.1	755.2	24	14	4.9	2.8
Scintillation [γ/keV]	-	19	30	40	25	42
Scintillation λ [nm]	-	80	78	128	150	175
dE/dx [MeV/cm]	1.9	0.24	1.4	2.1	3.0	3.8
Abundance (Earth atm) [ppm]	25×10^3	5.2	18.2	9300	1.1	0.09
Electron mobility [cm^2/V·s]	-	< 0.3	< 0.01	~500	~1800	~2200

DUNE: ν oscillation

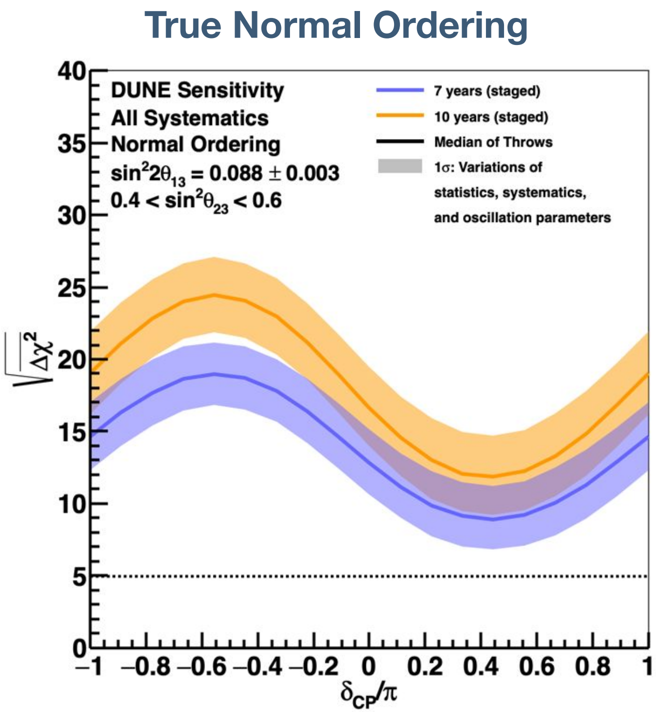


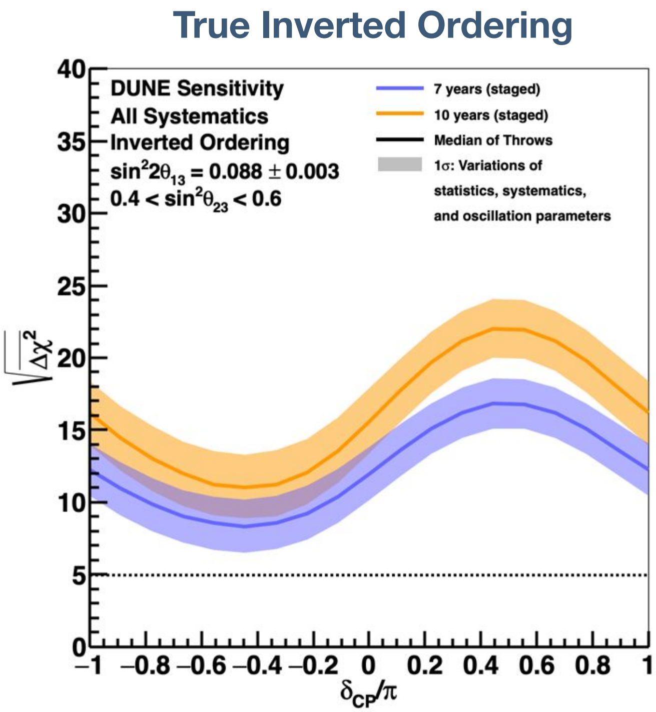


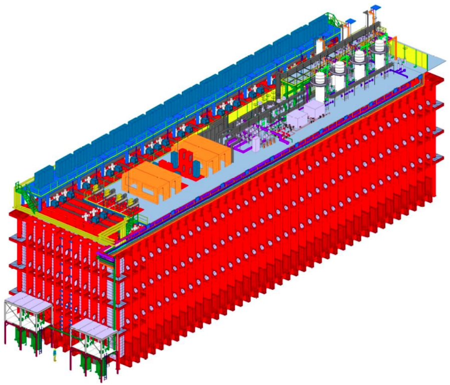


- Around ν_e 1,000 events over 7 years (staged)
- Around ν_μ 10,000 events over 7 years (staged)

DUNE: ν oscillation

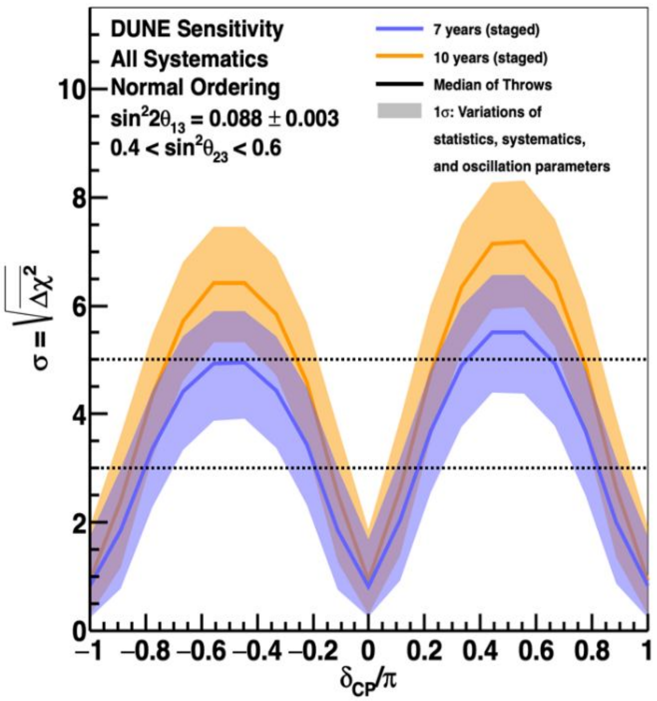


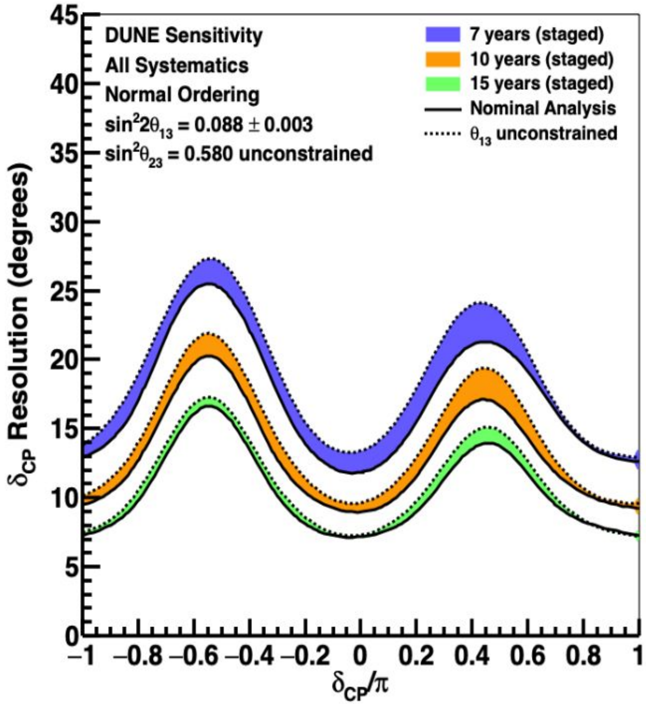


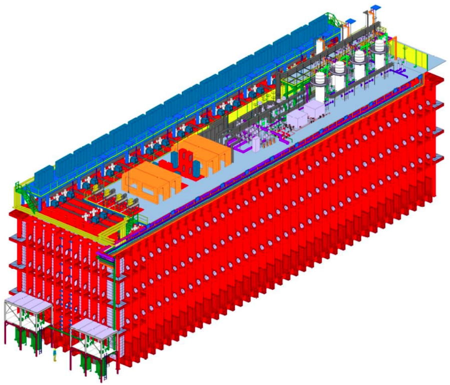


Definitive determination of neutrino mass ordering for all possible parameters

DUNE: ν oscillation



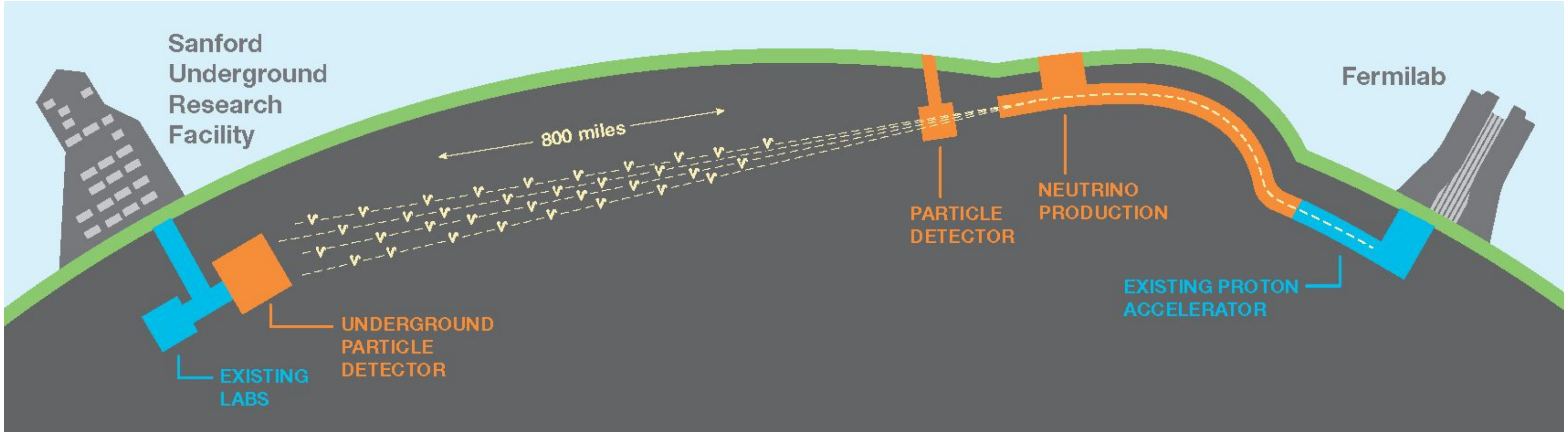




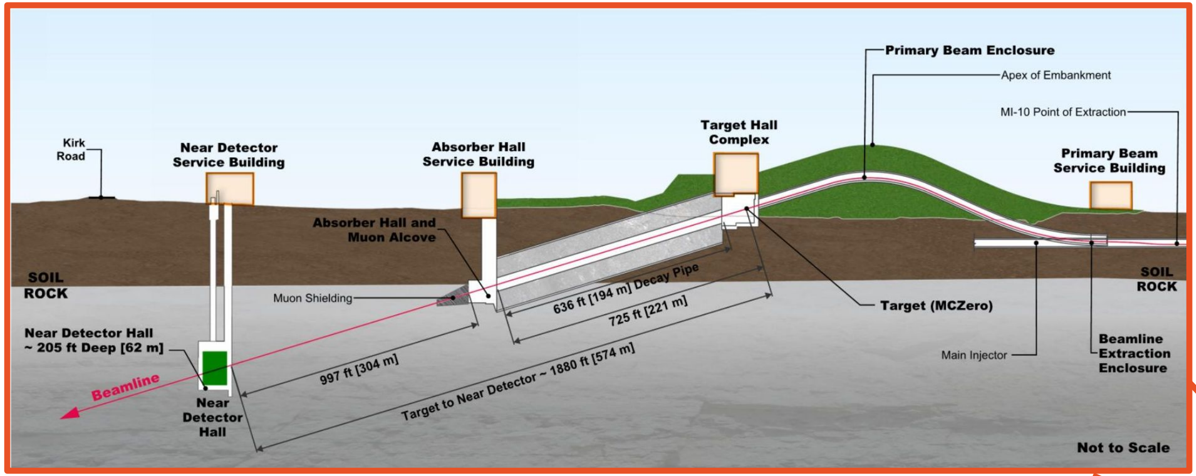
Significant CP violation discovery potential over wide range of true δ_{CP} values in 7-10 years (staged)

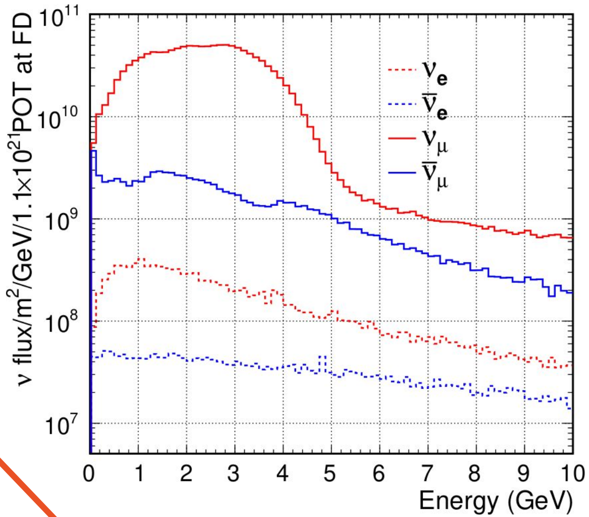
Deep Underground Neutrino Experiment (DUNE)

- Massive neutrino detector
- Four **Far Detector (FD) modules** of 17 kt each using Liquid Argon Time Projection Chambers (**LArTPC**)
- Neutrino **beam physics**, **supernova neutrinos**, **proton decay** and **solar and atmospheric neutrinos**
- The experiment search to answer open question in the field of particle physics, astronomy and cosmology (**CP violation phase** in the leptonic sector, octant of $\boldsymbol{\theta_{23}}$, **mass hierarchy**, etc.)
- Baseline of **1300** km and neutrinos energy from **0.1 to 10 GeV**

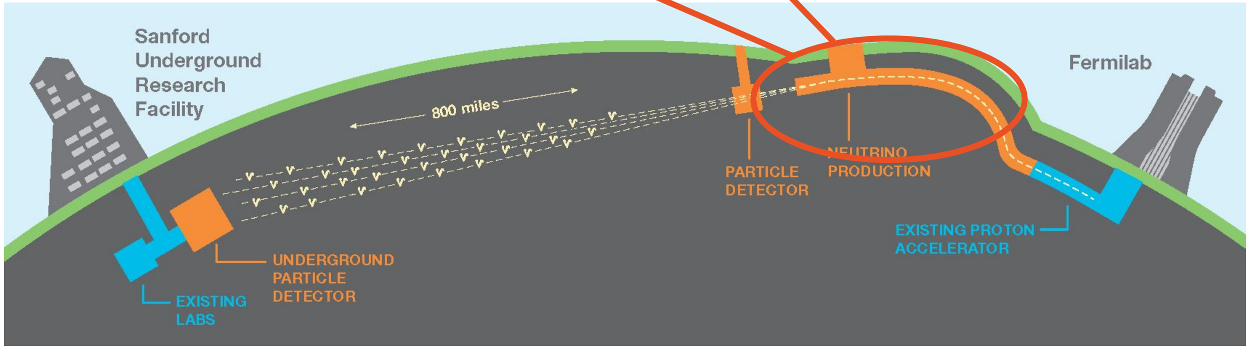


DUNE: LBNF Beam

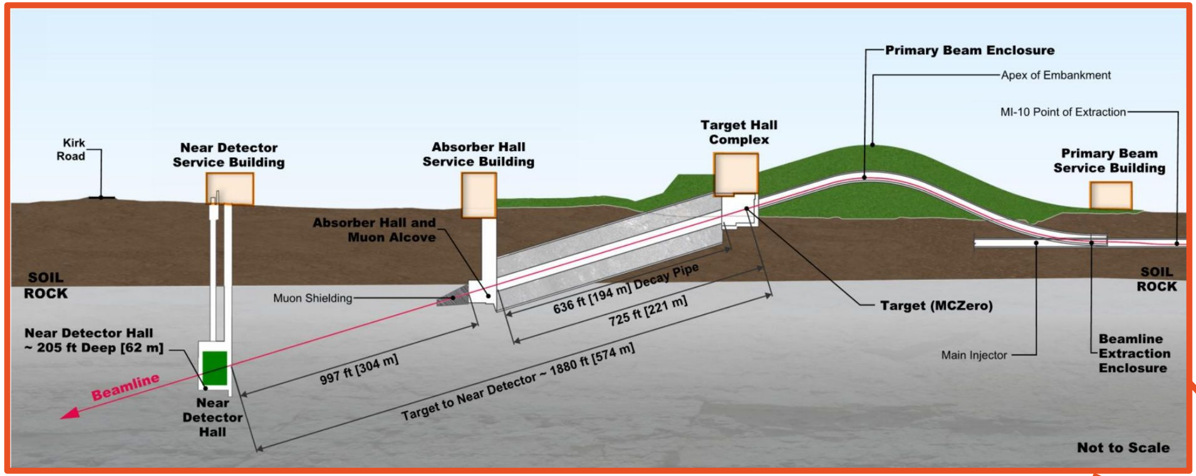


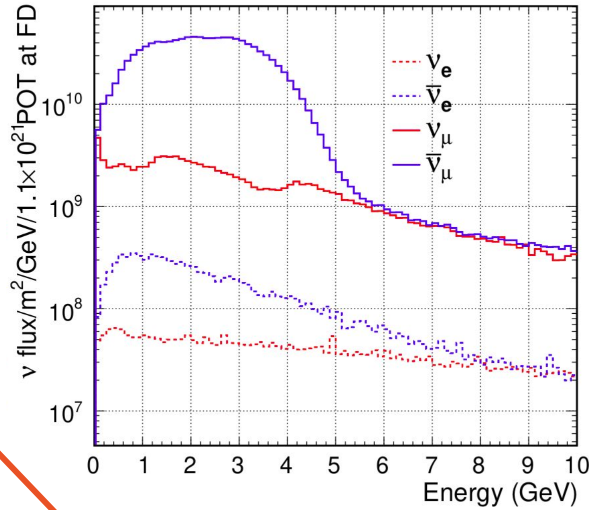


- 1.2 MW proton beam (upgradable to 2.4 MW)
- 10^{21} POT/year



DUNE: LBNF Beam





- **1.2 MW proton beam (upgradable to 2.4 MW)**
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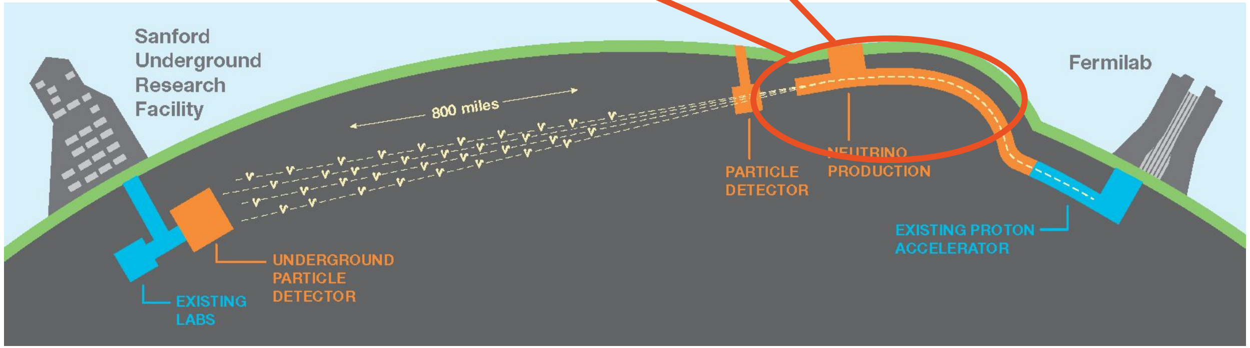
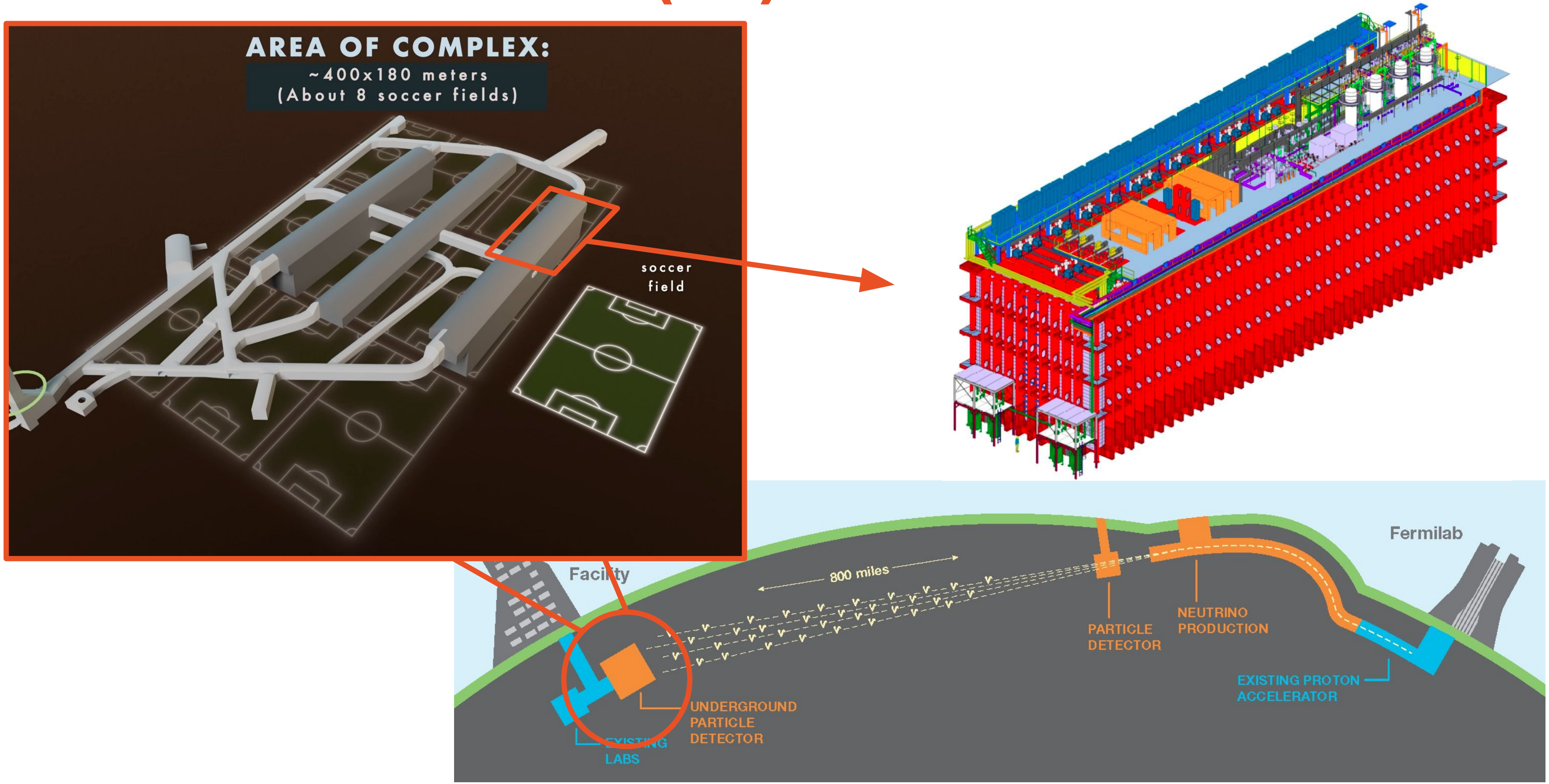
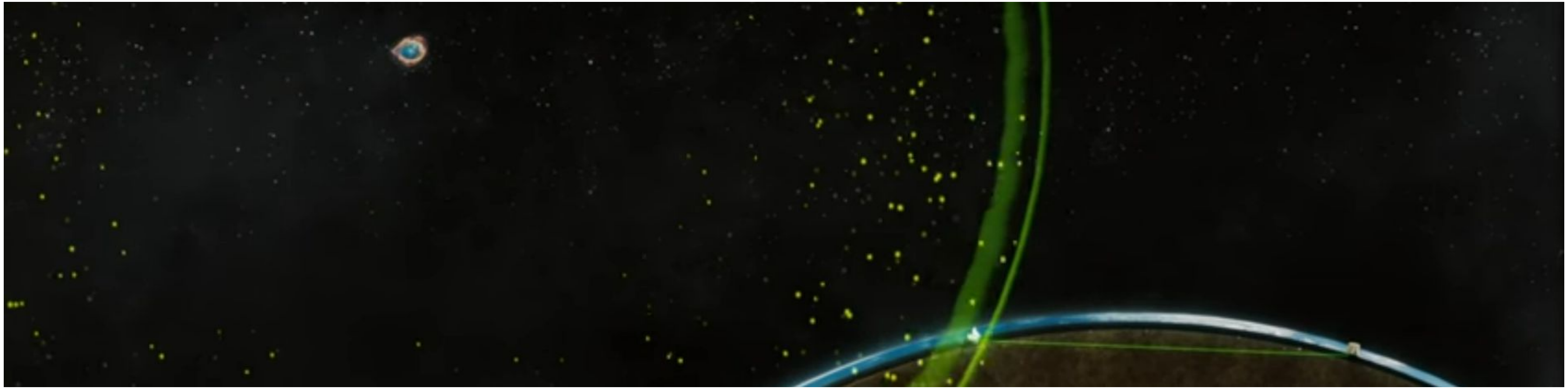


DUNE: Far Detector (FD)

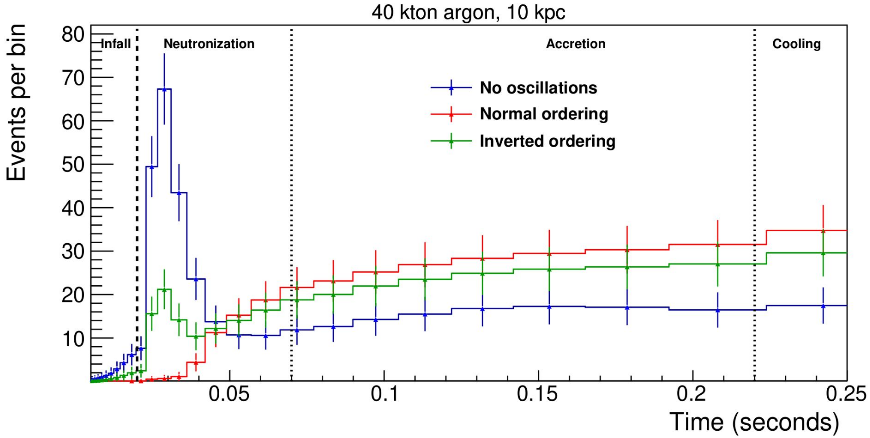


Supernova Neutrino Burst (SNB)



Energy ranging from 5 to 30 MeV (99% of the SN energy)

A few hundred to a few thousand events are expected in 10 seconds



Supernova Neutrino Burst (SNB)

Energy ranging from 5 to 30 MeV (99% of the SN energy)

A few hundred to a few thousand events are expected in 10 seconds

Proton decay search