



CPAN NETWORK
ON INSTRUMENTATION
AND DETECTORS



TIDPAN 2026 (15-26 junio 2026)

ARGON DETECTORS

INÉS GIL BOTELLA (CIEMAT)



MINISTERIO
DE CIENCIA, INNOVACIÓN
Y UNIVERSIDADES



Cofinanciado por
la Unión Europea



AGENCIA
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40 **Ciemat**
aniversario

Outline

1) Why (liquid) argon detectors?

- Physics motivation
- Liquid vs gas
- Signals on argon detectors: scintillation and ionization

2) Basic principles of LArTPCs and technologies

- Single and dual phase TPCs
- Charge readout
- Cryogenic photon detection

3) From sensors to large-scale detectors

- Main challenges (large cryostats, high HV, excellent purity, stability, doping, underground...)

4) Applications to neutrino and dark matter experiments

5) New technological directions

Recommended readings

- W. M. Bonivento and F. Terranova, “The science and technology of liquid argon detectors”, Review of Modern Physics, Volume 96, Oct-Dec 2024
- J. Assadi, D. A. Dwyer and Brooke Russell, “Novel Liquid Argon Time-Projection Chamber Readouts”, Annu. Rev. Nucl. Part. Sci. 2024. 74:529–55
- DUNE Collab., “Volume IV. The DUNE far detector single-phase technology”, *JINST* **15** T08010 (2020)
- DUNE Collab., “The DUNE Far Detector Vertical Drift Technology. Technical Design Report”, *JINST* **19** T08004 (2024)

SECTION 1

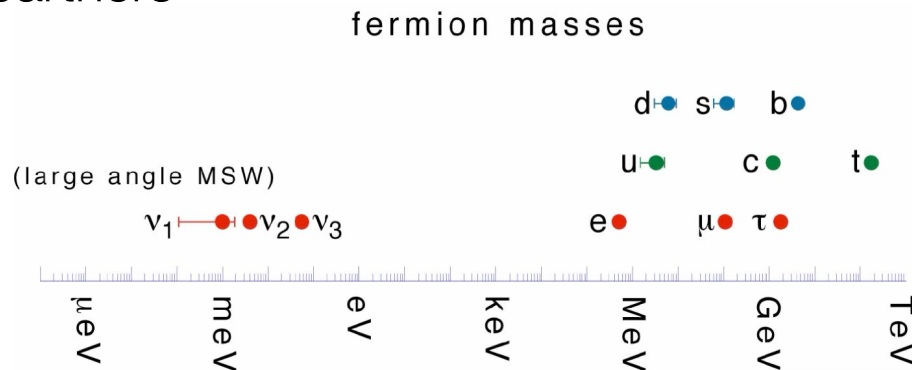
Why (liquid) argon detectors?

Physics first

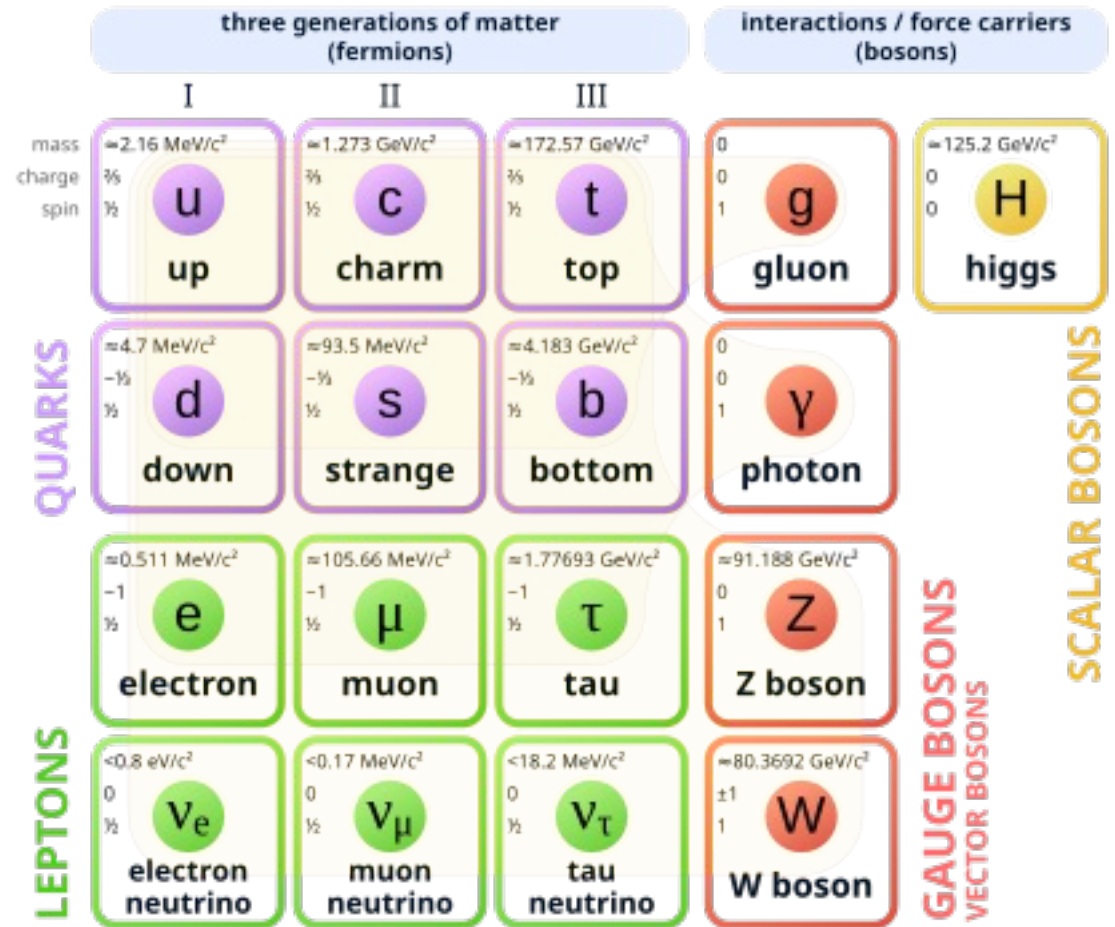
- Main physics motivation for argon detectors:
 - **NEUTRINO DETECTION** and **dark matter** searches
 - Also, particle calorimetry
- I will concentrate on **Ar detectors for neutrinos**
 - Some mention on technologies for dark matter searches **on Ar**
 - Dedicated talks on WIMPs, radiopurity ... already covered at the school

Main basic properties of neutrinos

- Neutrinos are (with photons) the most **abundant** elementary particles in the Universe
- Electrically **neutral**
- **Only weak interaction** with matter
- There are **three types** of neutrinos
- Much **lighter** than their charged leptonic partners

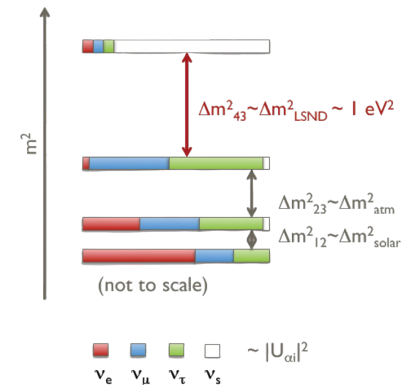
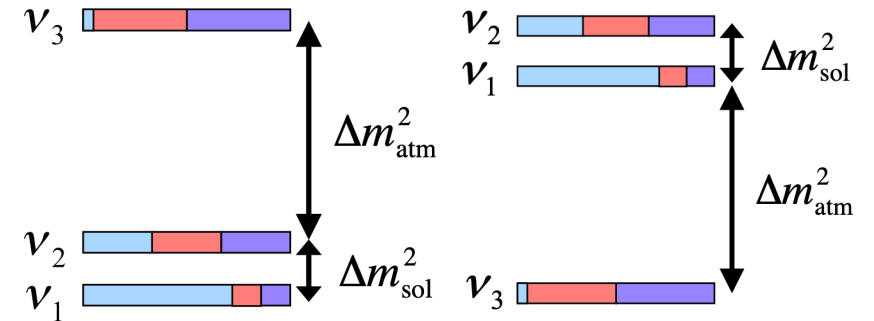


Standard Model of Elementary Particles



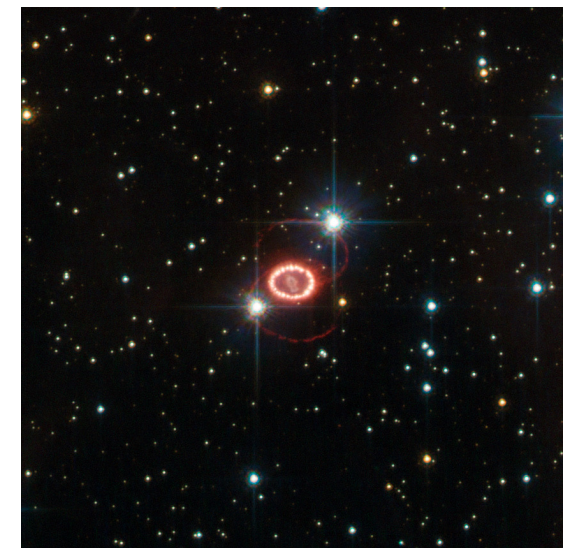
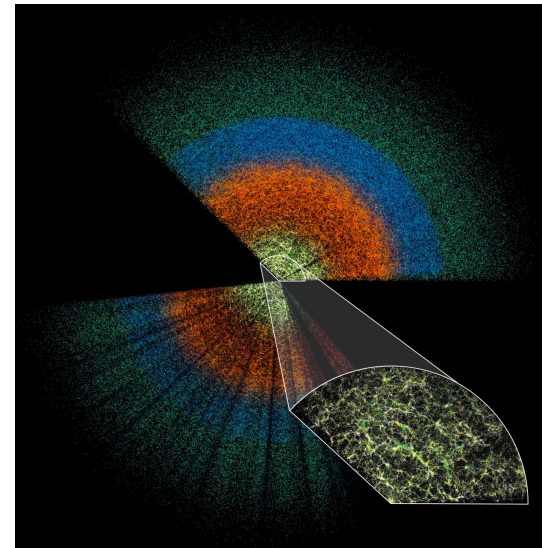
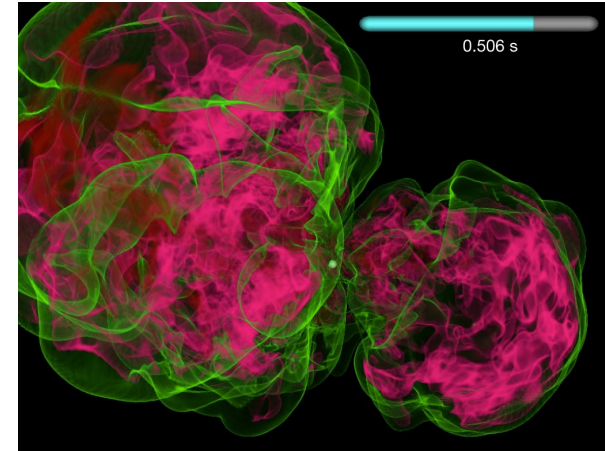
Open questions in neutrino physics

- What is the absolute **neutrino mass** scale?
- Are neutrinos their own antiparticle? **Dirac** or **Majorana**?
- Why are neutrinos much lighter than the other fermions?
- What is the neutrino **mass ordering**?
- Do neutrinos and antineutrinos oscillate differently? Do neutrinos **violate CP**?
- Are there any **sterile neutrino** states? If so, what are their masses?
- Is our **three-flavor** picture of oscillations complete?

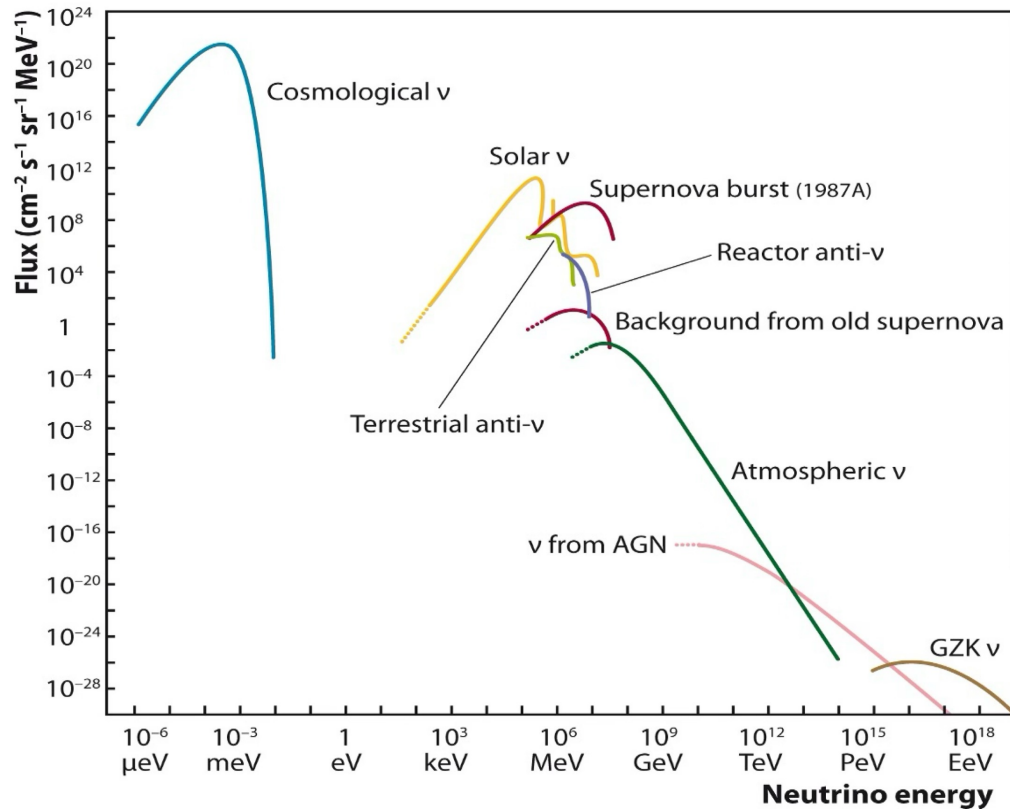


Connections with astrophysics and cosmology

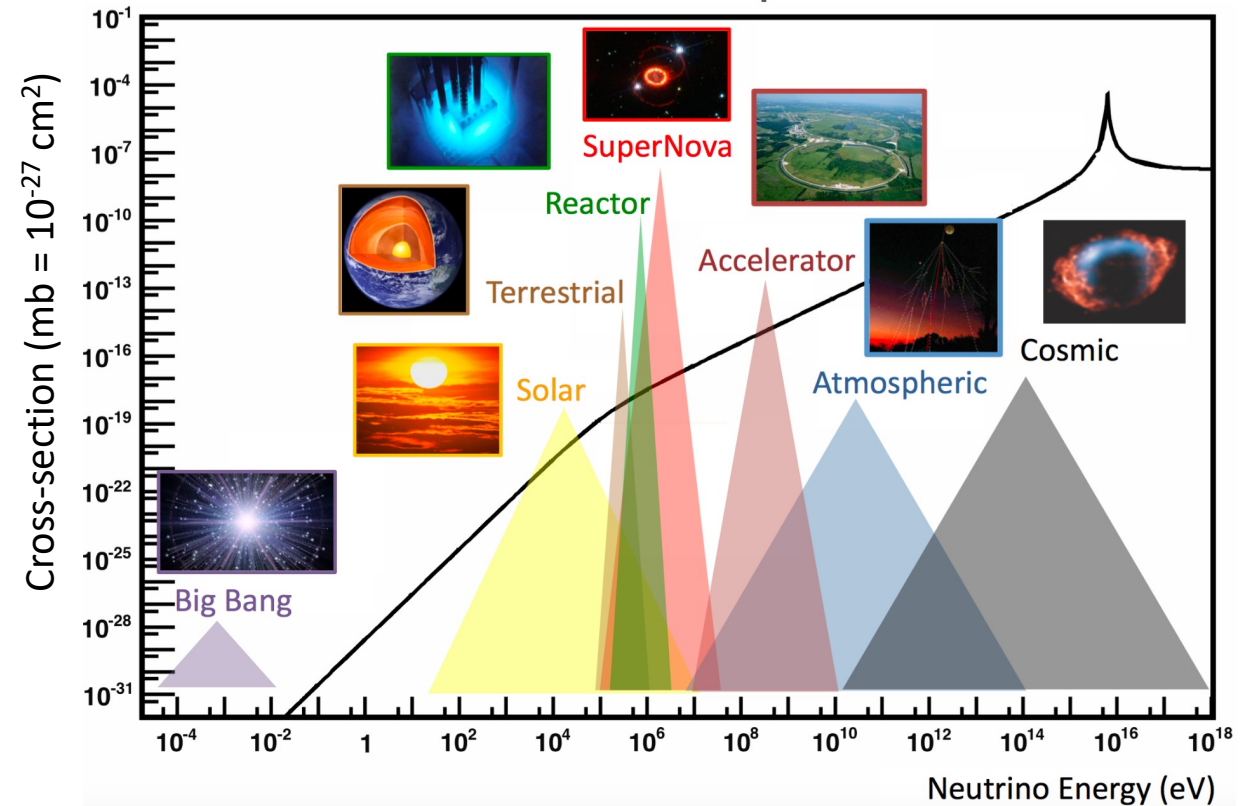
- Neutrinos as **probes of the Universe**:
 - High energy neutrino physics
 - New astrophysical sources
 - Core-collapse supernova and diffuse SN neutrino background
 - Relic neutrinos from early Universe
 - Matter-antimatter asymmetry relation
 - Sterile neutrinos as dark matter



Neutrino energies and cross-section



HUGE neutrino fluxes
>20 orders of magnitude in energy

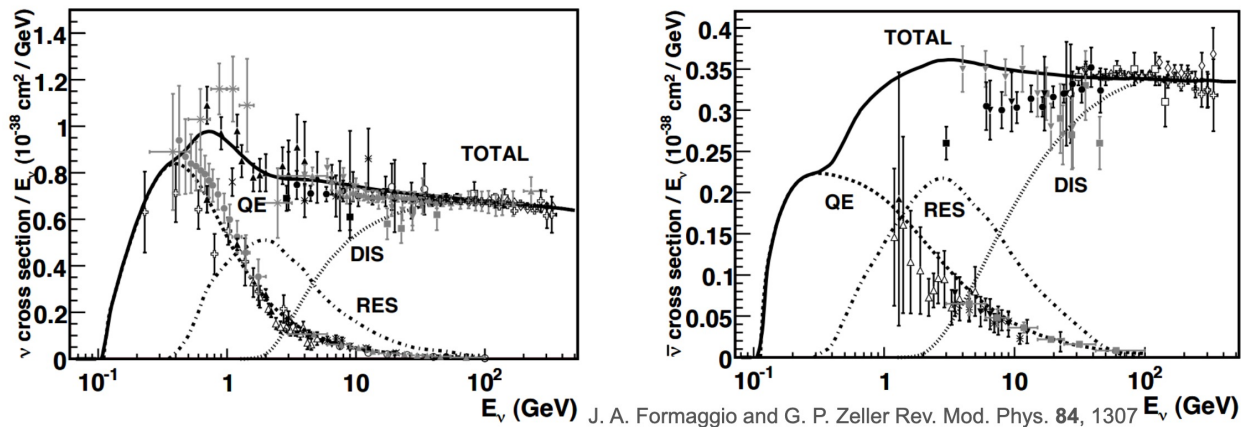
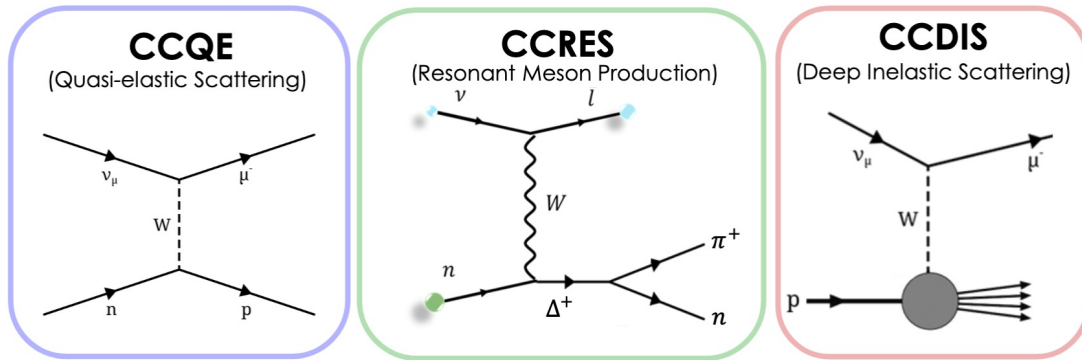


TINY neutrino cross-sections

For comparison: inelastic p-p cross section at 13 TeV **$\sim 75 \text{ mb}$**

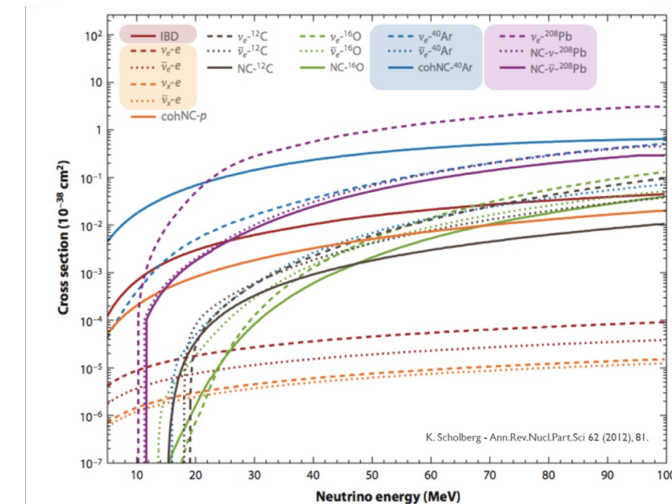
Neutrino interactions

GeV interactions



MeV interactions

- Elastic scattering on electrons:
 $\nu + e^- \rightarrow \nu + e^-$
- Inverse beta decay (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$
- CC on nuclei: $\nu_e + (N, Z) \rightarrow e^- + (N - 1, Z + 1)$
 $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N + 1, Z - 1)$
- NC on nuclei: $\nu + A \rightarrow \nu + A^*$
- CEvNS: $\nu + A \rightarrow \nu + A$ (nuclear recoil)



Why LAr detectors?

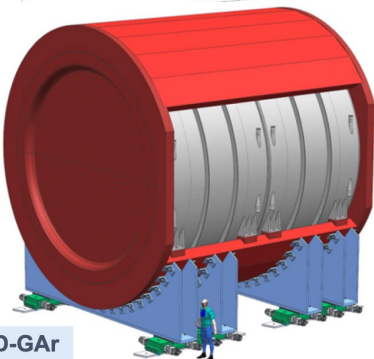
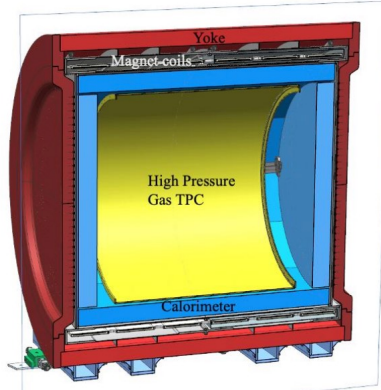
- **Detector requirements** to cover all these topics:
 - large mass detectors
 - excellent energy resolution
 - tracking capabilities
 - particle identification... over a wide energy range
- **Liquid Argon detectors:**
 - Large mass (LAr density = 1.4 g/ml at 83.7 K)
 - Excellent energy resolution $\sim 15\%/\sqrt{E} + 10\%$
 - Excellent 3D imaging
 - Fully sensitive medium (few mm resolution readout)
 - Good particle identification (electrons vs gammas)
 - Trigger and imaging from MeV to GeV

GAr vs LAr

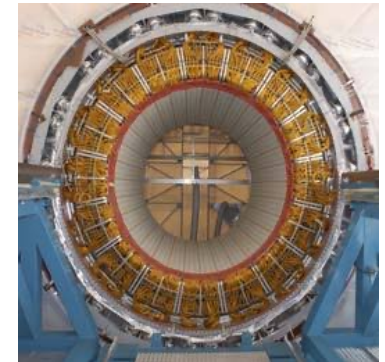
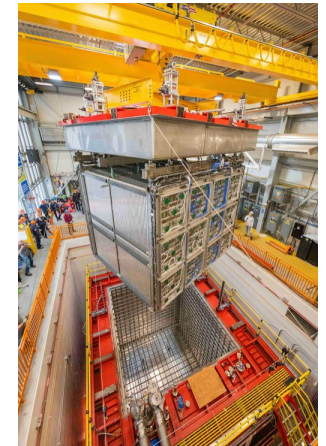
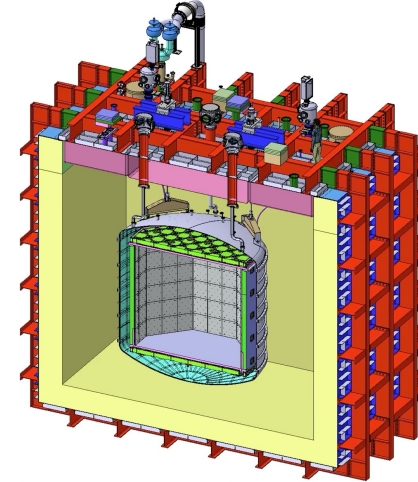
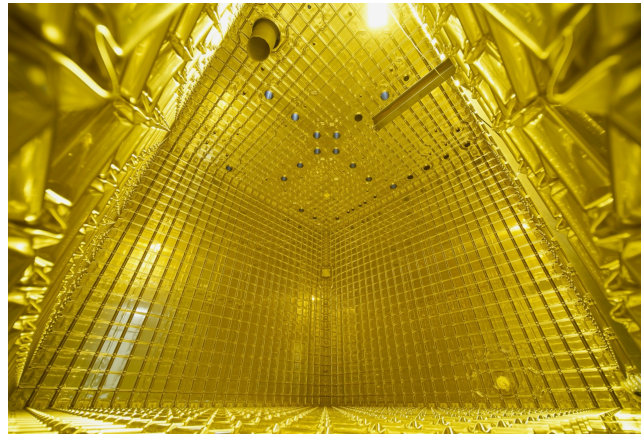
FEATURE	Gas Ar	Liquid Ar
Density & Target Mass	Very low density; requires large volumes to achieve a sizable target mass (or high pressure)	Extremely dense (~1.4 g/cm ³); allows for compact, massive detectors
Operating Conditions	Room temperature (or slightly controlled); uses high voltage and gas amplification	Cryogenic; must be maintained continuously at ~87 K (-186°C) in insulated cryostats
Signal yield	Lower ionization signal per unit of distance	Produces (~55,000) free electrons per cm for minimum ionizing particles
Spatial Resolution	Exceptional; allows for microscopic separation of overlapping tracks and decays	Excellent, but limited by the physical diffusion of electrons over long drift distances
Signal Amplification	Requires high electric fields at anode wires to achieve gas gain and read out signals	Relies on charge drift and collection; no internal gas amplification is used; cold and warm amplification
VUV scintillation light yield	127 nm scintillation photons (40-50 k γ /MeV at 1 atm); Singlet and triplet excimer de-excitation; Longer slow component ($\approx 3.2 \mu\text{s}$) due to lower non-radiative quenching	127 nm scintillation photons (40-50 k γ /MeV at 0 V/cm); Excimer de-excitation + electron-ion recombination; Shorter slow component ($\approx 1.6 \mu\text{s}$) due to higher dense-medium quenching

GAr and LAr detectors

High-pressure GAr TPC (proposed for DUNE ND)



LAr detectors (DUNE, DarkSide, DEAP, ICARUS, SBND, ATLAS calo)



Argon properties

- High density (40% more dense than water)
- Abundant (1% atmosphere)
- Energy to produce e-/ion pair ($W\text{-value} = 23.6 \text{ eV}$)
- Ionizes easily ($\sim 55,000 \text{ electrons/cm}$)
- Quasi-free electrons from ionization are drifted in LAr (87 K, 1 bar) by E field
- Electron drift velocity $\sim 2 \text{ mm/us}$ @1kV/cm (1.5 m/ms @0.5 kV/cm)
- Electron cloud diffusion is small ($\sqrt{2Dx / v_{\text{drift}}} \sim \text{mm}$ after several meters of drift)
- High scintillation light ($\sim 40,000 \text{ } \gamma/\text{MeV}$) @127 nm
- $W_{\text{ph}} = 19.6 \text{ eV}$

Xe vs Ar

Element	Xenon	Argon
Atomic Number Z	54	18
Atomic mass A	131.3	40.0
Boiling Point T_b [K]	165.0	87.3
Liquid Density @ T_b [g/cm ³]	2.94	1.40
Fraction in Earth's Atmosphere [ppm]	0.09	9340
Price	\$\$\$\$	\$
Scintillator	✓	✓
$W_{\text{ph}} (\alpha, \beta)$ [eV]	17.9 / 21.6	27.1 / 24.4
Scintillation Wavelength [nm]	178	128
Ionizer	✓	✓
W (E to generate e-ion pair) [eV]	15.6	23.6

- **Ar** is highly abundant and offers superior background discrimination
- **Xe**'s high atomic mass and lack of intrinsic radioactivity make it the premier choice for ultra-low-background, high-sensitivity targets

Signals in Ar: ionization & excitation

- **Ionization** process:

- $W_e = 23.6 \pm 0.3 \text{ eV}$
- $N_e \sim 42000 \text{ } e^-/\text{MeV}$

→ **CHARGE (precise imaging)**

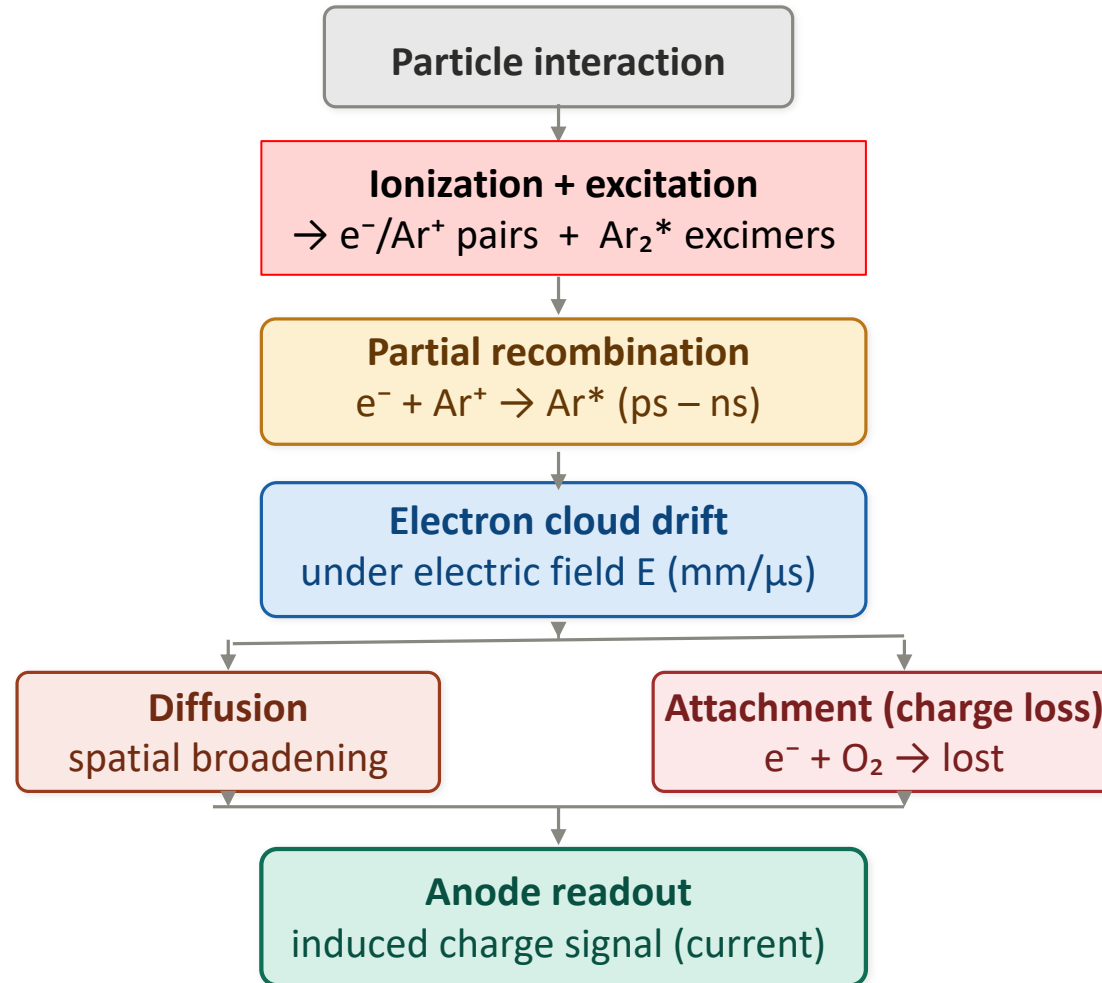
- **Excitation** process:

- $W_{ph} = 19.5 \text{ eV}$
- VUV light ($\lambda = 127 \text{ nm}$)
- Argon is transparent
- $N_\gamma \sim 40000 \text{ photons/MeV}$

→ **LIGHT (precise timing)**

- Cherenkov light (if relativistic)

Ionization charge in LAr



Electron-ion recombination process

- Argon is a dense medium
- Some electrons **recombine** with argon:



- It depends on the deposited energy density (dE/dx), electric field, particle type, track topology
 - For $E_{\text{drift}} = 500 \text{ V/cm}$ and a MIP, **recombination losses are about 20-30%**
 - Collected $N_e = 30000\text{-}35000 \text{ e}^-/\text{MeV}$ ($Q \sim 5 \text{ fC/MeV}$)
- Losses increase with ionization density and decrease with drift field strength

- For a minimum ionizing muon ($dE/dx \sim 2.1 \text{ MeV/cm}$) after recombination:
 $N_e \sim 60000\text{-}70000 \text{ e}^-/\text{cm}$ ($\sim 10 \text{ fC/cm}$)
- For a good S/N, ENC $\sim 500\text{-}1000 \text{ e}^-$
- The recombination is parametrized by a semiempirical law (similar to Birk's law, valid for E field 0.1-1 kV/cm)

$$Q = A \frac{Q_0}{1 + (k/\mathcal{E}) \langle dE/dx \rangle}$$

Q = charge collected at the anode

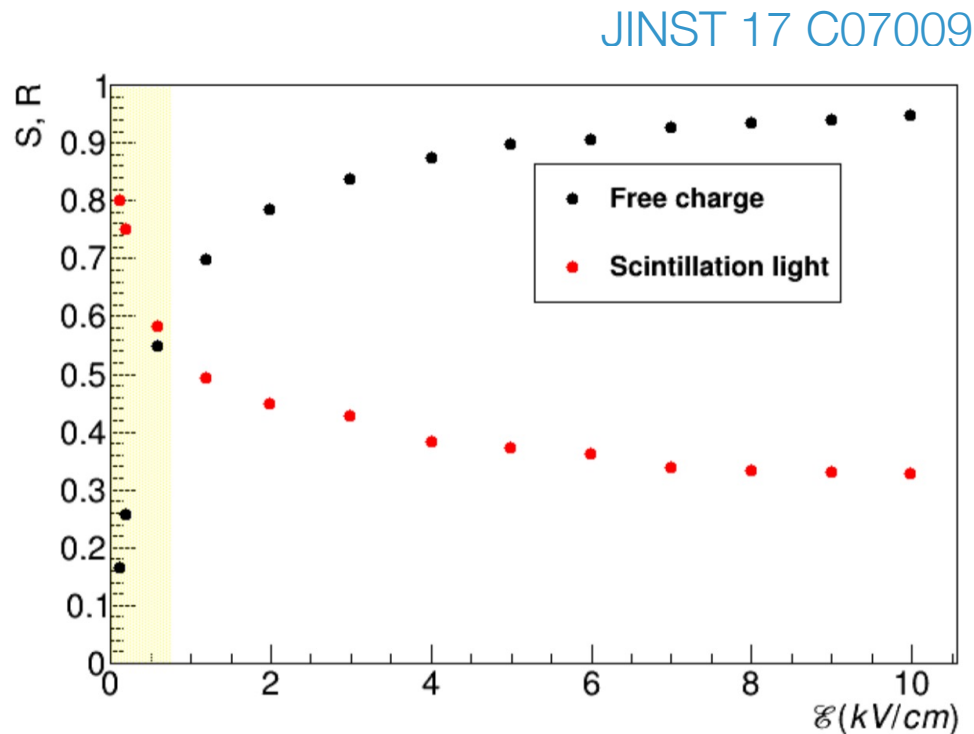
Q_0 = initial ionization charge

$\mathcal{E}$ = electric field

dE/dx = particle stopping power

Charge-light relation

- The recombination also leads to the formation of excimer states of Ar that decay via emission of VUV photons (**light and charge anti-correlation**)

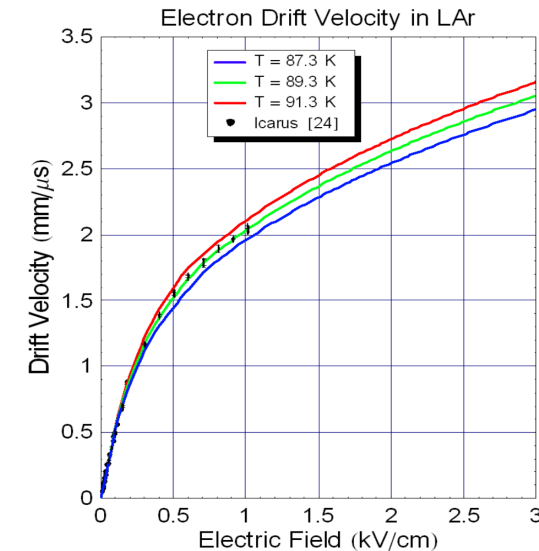


$$Q(dE/dx, \mathcal{E}) + L(dE/dx, \mathcal{E}) = N_i + N_{ex}$$

Charge and light calorimetric
information enhances energy
resolution

Ionization charge transport and attenuation

- Charge **transport**: electron drift
 - **Drift velocity** depends on electric field and temperature
 - At fixed T and P, drift velocity (v_d) is proportional to the E_{field} and electron mobility (μ)
 - For $E \sim 500$ V/cm $\rightarrow v_d = 1.6$ mm/ μ s $\rightarrow t_{\text{drift}} \sim 2.2$ ms (for a 3.5 m drift) – long drifts!
 - For comparison, velocity of positive ions ~ 5 -10 mm/s (6 orders of magnitude slower)



- Charge **attenuation**: impurity captures
 - Electrons can be captured by electronegative impurities (oxygen, water...)
 - The surviving charge is:

$$N(t) = N_0 e^{-t/\tau_e}$$

N_0 = initial electrons after recombination
 τ_e = electron lifetime

For $\tau \sim 3$ (10) ms, and $t_d \sim 2.2$ ms, **only ~50% (80%) of electrons survive**

Electron lifetime is a useful tool to estimate the purity of LAr

$$\tau \simeq \frac{300}{[\text{O}_2](\text{ppb})} \mu\text{s}$$

Charge diffusion

- Electron **diffusion** (spreading of the charge cloud; dN/N = charge distribution)
 - The size of the diffusion coefficient D determines the width of the distribution, and hence the localization of the electrons (spatial resolution)

$$\frac{dN}{N} = \frac{1}{\sqrt{4\pi Dt}} \exp\left(-\frac{x^2}{4Dt}\right)$$

$$\sigma_x = \sqrt{2Dt} \sim \mathbf{1.3\text{ mm}}$$

(at 500 V/cm and 1m drift)

- Transverse diffusion: $D_T \sim 13.2\text{ cm}^2/\text{s}$ $D_T = \frac{kT}{e} \mu$
- Longitudinal diffusion: $D_L \sim 6.6\text{ cm}^2/\text{s}$ $D_L \simeq \frac{kT}{e} \left(\mu + |\mathbf{E}| \left| \frac{\partial \mu}{\partial |\mathbf{E}|} \right| \right)$

Anode segmentation below 1 mm is unnecessary due to the intrinsic limitations from diffusion

Mobility in LAr decreases when E increases $\rightarrow D_L < D_T$

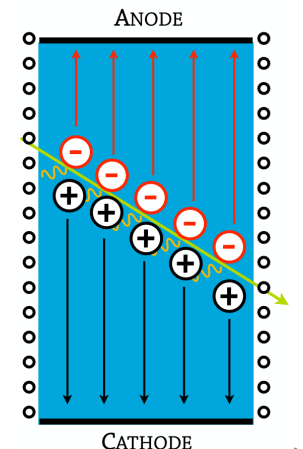
Ionization summary

Recombination	Birk's law	Charge reduction
Drift	$v_d = \mu E$	Determines time and detector size
Impurity capture	$N(t) = N_0 e^{-t/\tau_e}$	Charge reduction
Diffusion	$\sigma = \sqrt{2Dt}$	Charge cloud broadening

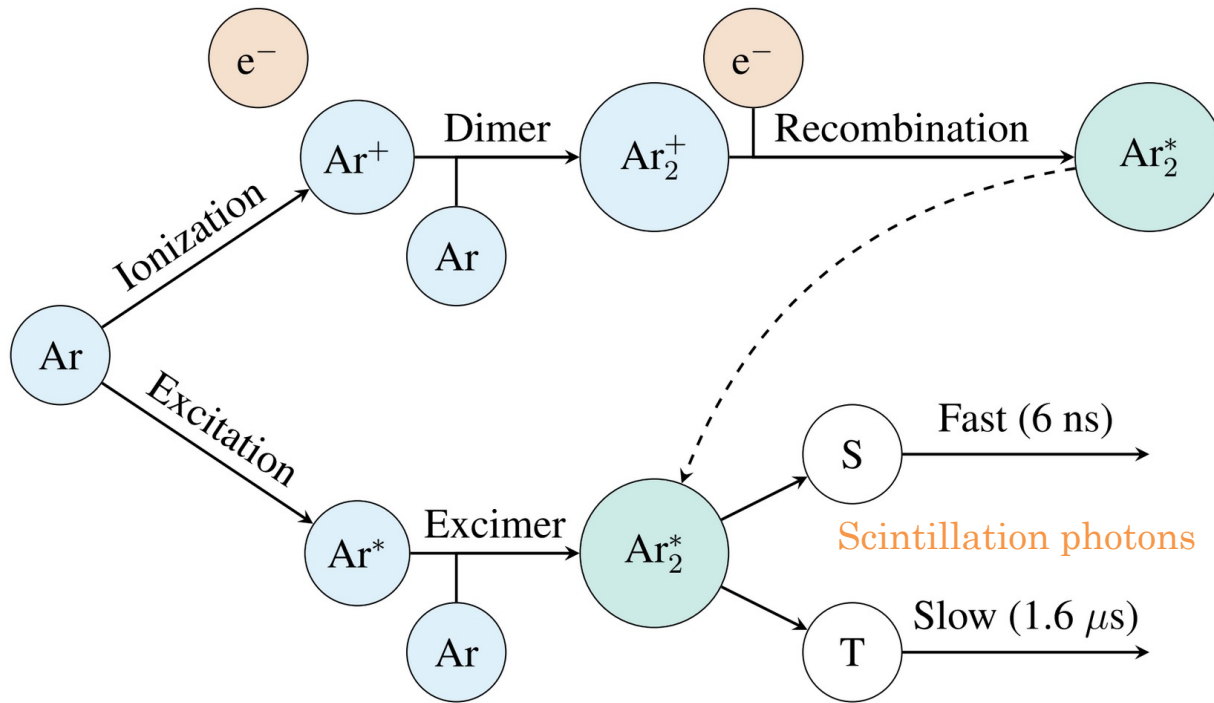
TABLE III. Drift and diffusion parameters of liquid argon at $|\mathbf{E}| = 500 \text{ V/cm}$ and $T = 87 \text{ K}$ (Li *et al.*, 2016).

Property	Value
Electron mobility μ	$320.2272 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$
Electron drift velocity v	$0.1601 \text{ cm}/\mu\text{s}$
Longitudinal diffusion coefficient D_L	$6.6270 \text{ cm}^2/\text{s}$
Transverse diffusion coefficient D_T	$13.2327 \text{ cm}^2/\text{s}$
Attachment rate constant (O_2) k_A	$3.3410 \times 10^{12} \text{ s}^{-1}$
Electron lifetime (for 0.1 ppb O_2)	$\tau = 2.9931 \text{ ms}$

Space-charge effects: positive argon ions drift toward the cathode. For a LArTPC operating on the surface, the continuous flux of cosmic muons produces a large accumulation of positive ions inside the drift volume. This distorts the electric field lines inside the TPC



Scintillation and photon transport



- Argon is an excellent scintillator
 - ~40,000 photons/MeV @127 nm; fast prompt signal ~6 ns (singlet), slow signal ~1.4 μs (triplet)
 - The relative abundance of both components strongly depends on the ionizing particle type (PID)
 - Transparent to its own light (absorption length = 20 m; Rayleigh scattering length = 1 m)
 - Possibility to be doped with Xe $\mathcal{O}(10$ ppm): improve light detection uniformity

Scintillation is affected by:

- **Electric field**

- It reduces the light yield (less recombination → less excited states → less scintillation light)

- **Impurities** (N_2 , O_2 , ...)

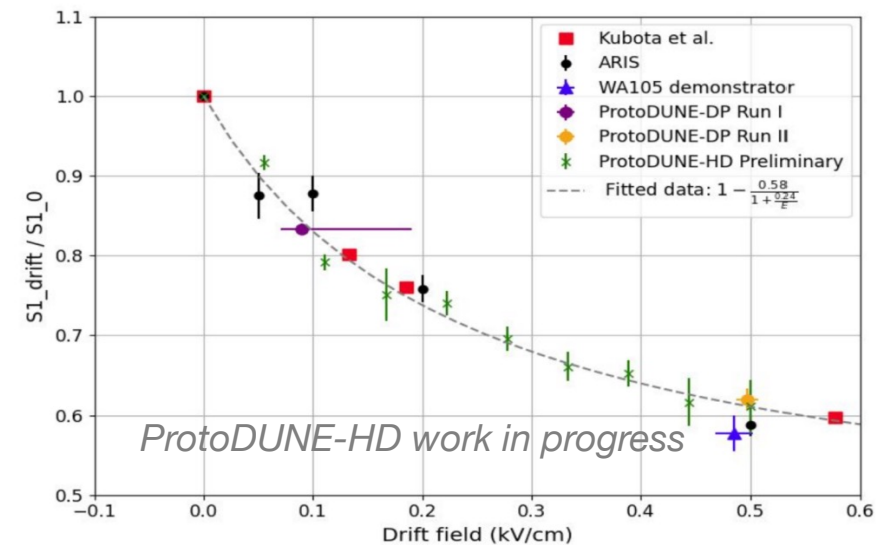
- **Quenching**: reduction of photons at the production due to a competing process $Ar_2^* + X \rightarrow 2 Ar + X^*$
 - This process reduces mainly the excimers in the triplet state
- **Absorption** of photons during propagation

$$N_\gamma(x) = N_0 e^{-x/\lambda_{abs}} \quad (\lambda_{abs} \sim 20 \text{ m for 3 ppm } N_2)$$

- **Scattering**

- Rayleigh scattering changes photon direction
- Typical $\lambda_{RS} = 1 \text{ m}$

Light yield vs electric field



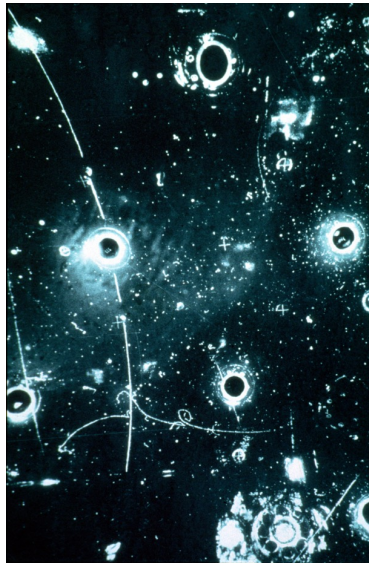
For $E = 0.5 \text{ kV/cm}$, light yield drops to ~ 25000 photons

SECTION 2

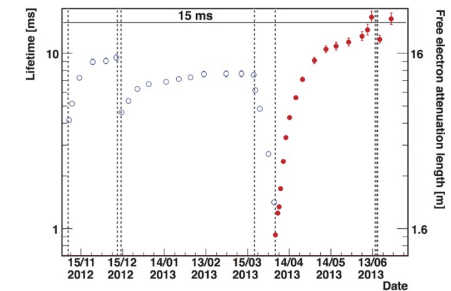
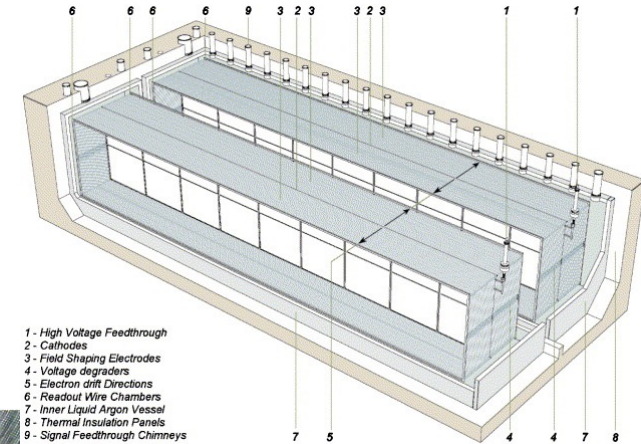
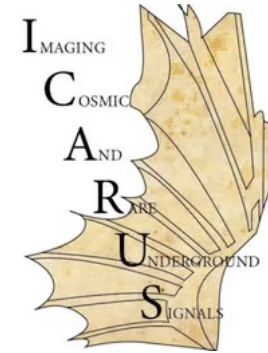
Basic principles of LArTPCs and technologies

The beginning...

- (1973) Discovery of leptonic neutral currents at CERN with the Gargamelle bubble chamber detector

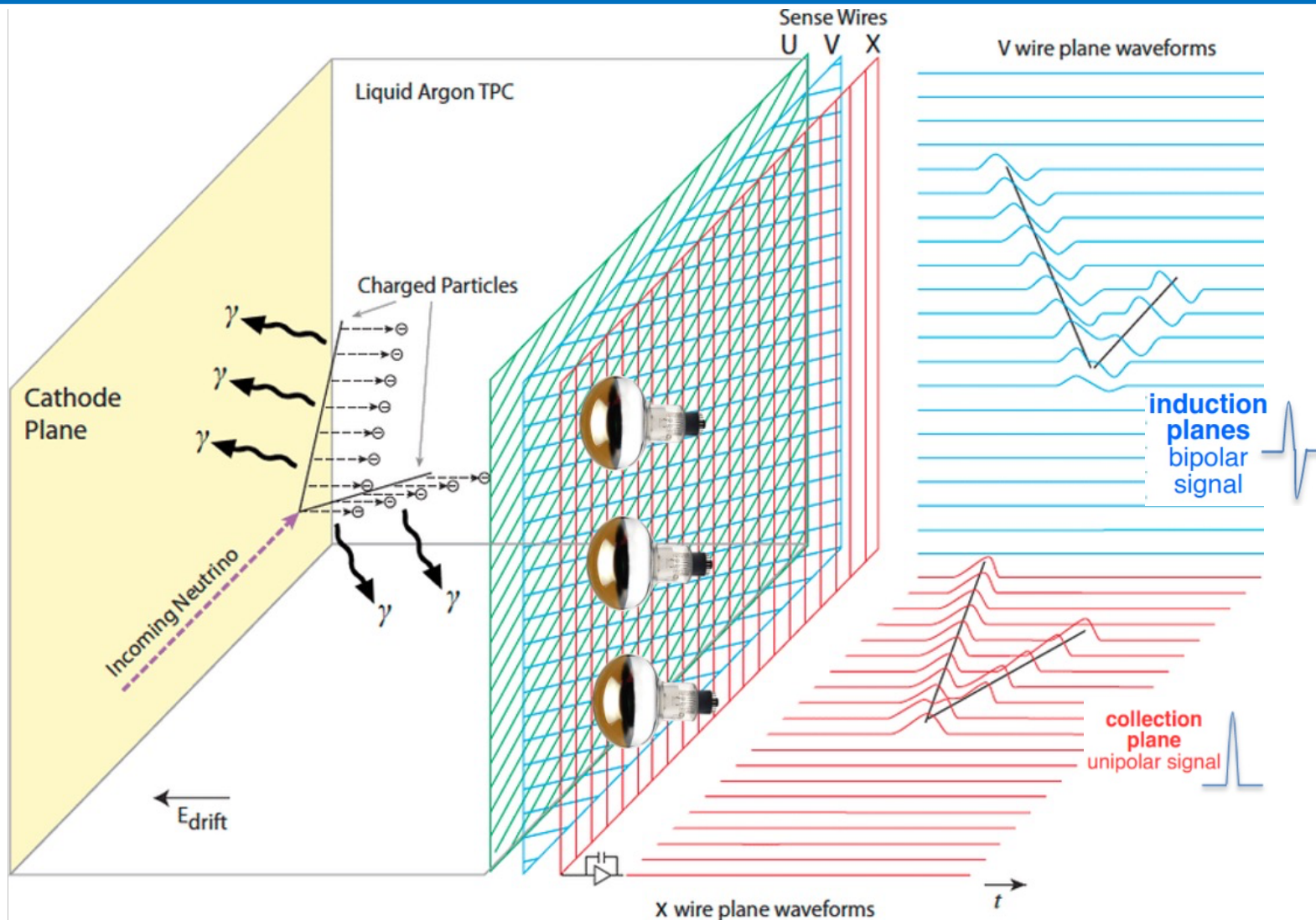


- (1977) Carlo Rubbia: LAr Time Projection Chambers for neutrino detection
 - Electronic bubble chambers with large mass, timing and full imaging

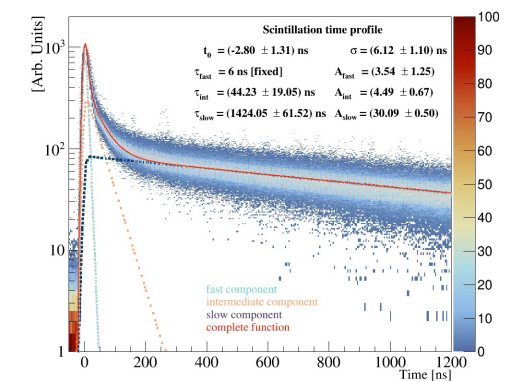


- Pioneer LArTPC at large scale (600 tons)
- Demonstration of basic performance and reference for the following LArTPCs

LArTPC detection principle



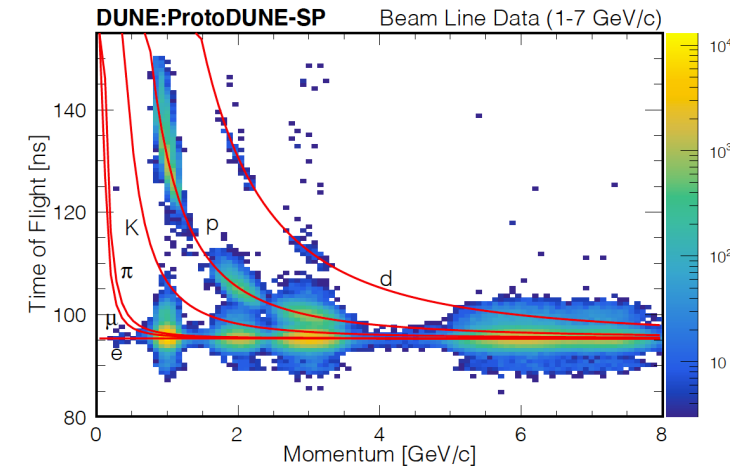
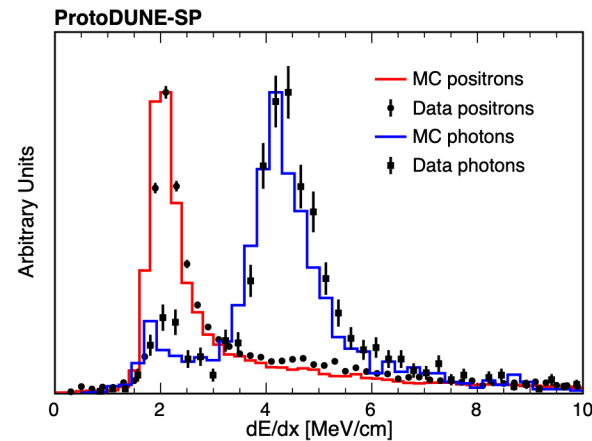
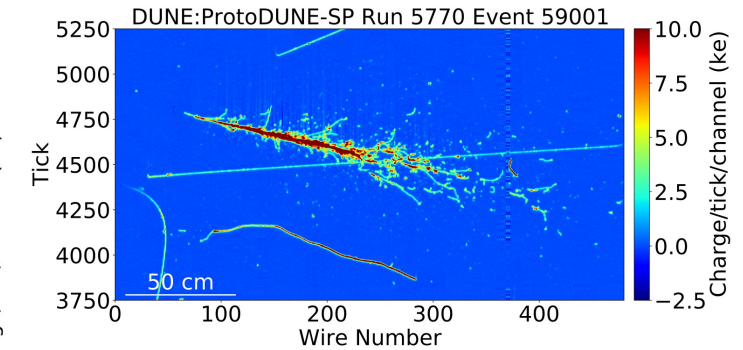
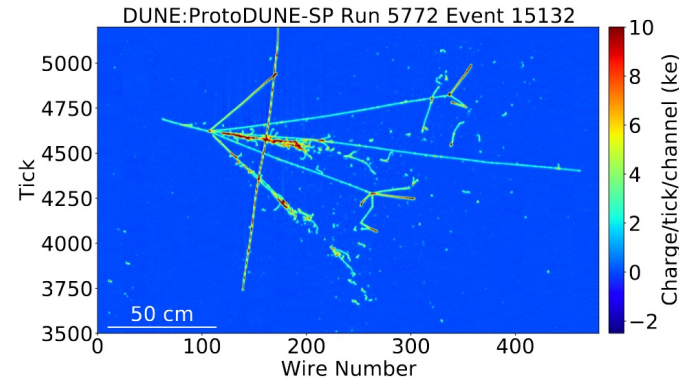
- A charged particle interacting in LAr creates:
 - **Ionization electrons** ($\sim 42k$ ion-electron pairs/MeV) drifted to the anode readout ($\sim ms$) thanks to an electric field and then collected and readout by wires/pixels
 - Fast **scintillation signals** ($\sim 40k$ γ /MeV) collected by photodetectors provides absolute timing



- **3D reconstruction** of interactions from charge and light readout

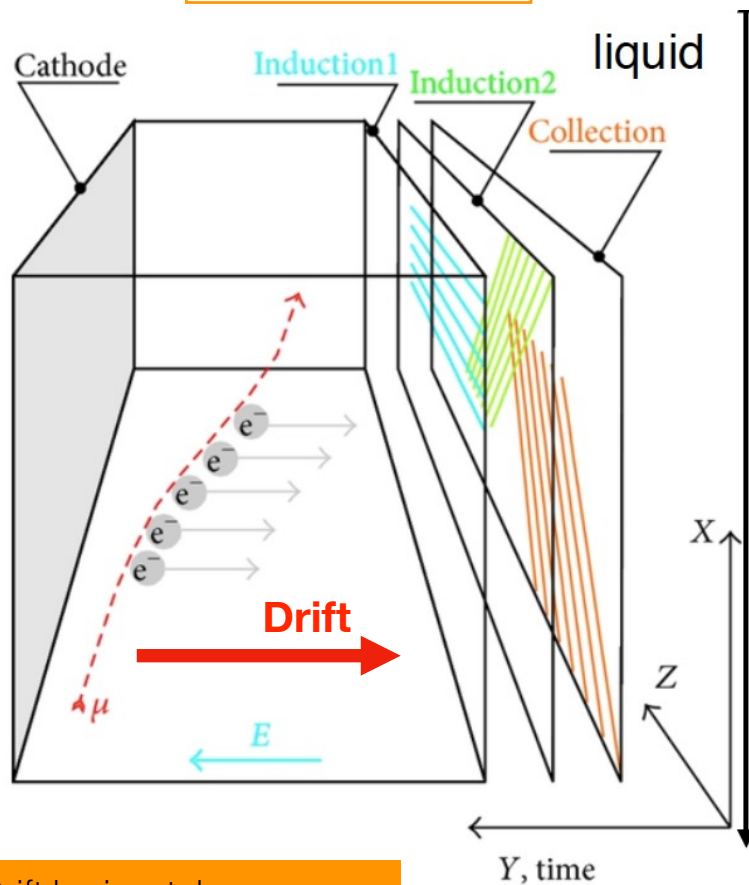
Liquid Argon technology

- LAr TPC is the **leading technology** for short/long-baseline accelerator neutrino oscillation experiments
- The LAr TPC technology provides:
 - excellent **3D imaging capabilities**
 - few mm scale over large volume detector
 - **excellent energy measurement capability**
 - totally active calorimeter
 - **particle ID** by dE/dx , range, event topology, ...
 - **scalability** to large detectors
 - high signal efficiency and background discrimination



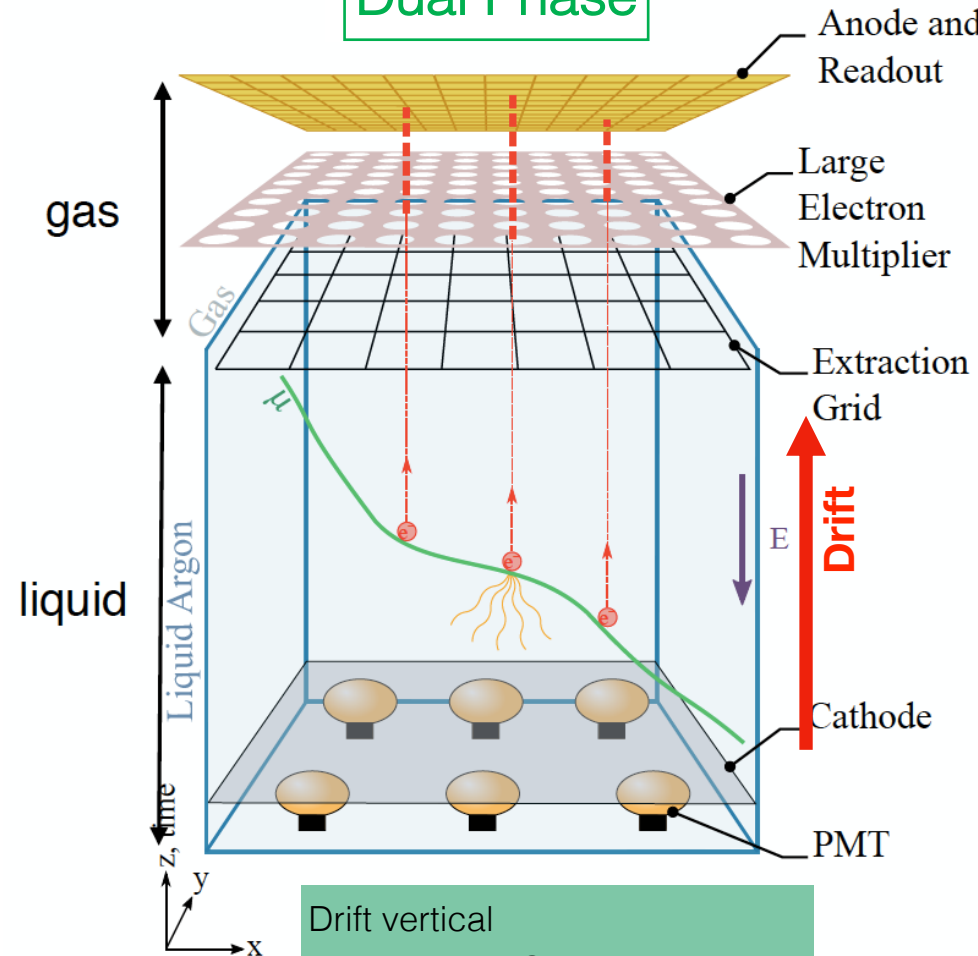
Single vs Dual phase LArTPCs

Single Phase

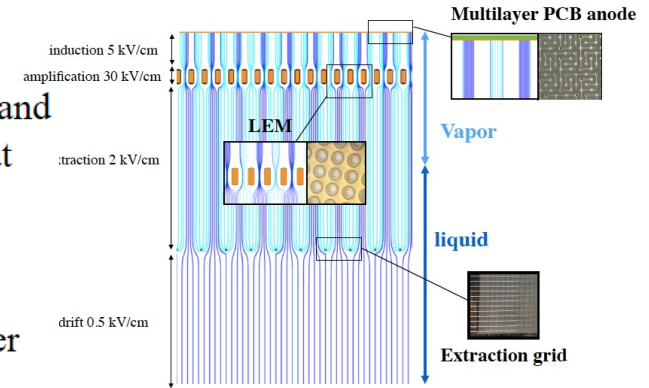


Drift horizontal
Readout by wire planes
No amplification of charge

Dual Phase



Drift vertical
Readout by PCB anodes
Amplification of charge in LEMs

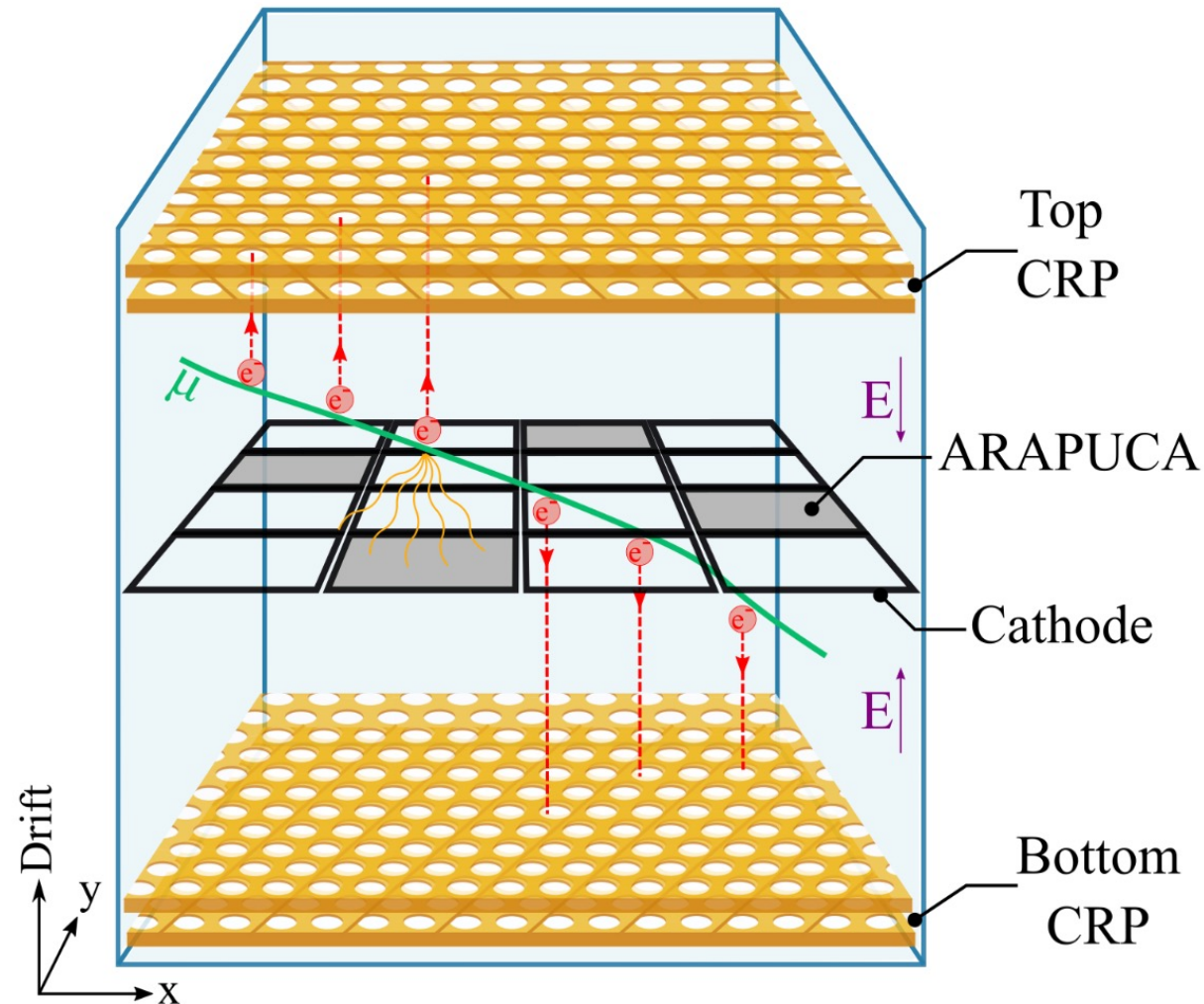


- **Charge from ionization:** tracking and calorimetry

Dual-phase: multiplication and detection in gas to increase gain and allow for long drift distances ($> 5\text{m}$) and low energy thresholds

- **Scintillation light:** primary scintillation S1 (trigger and to) & secondary scintillation S2 in gas

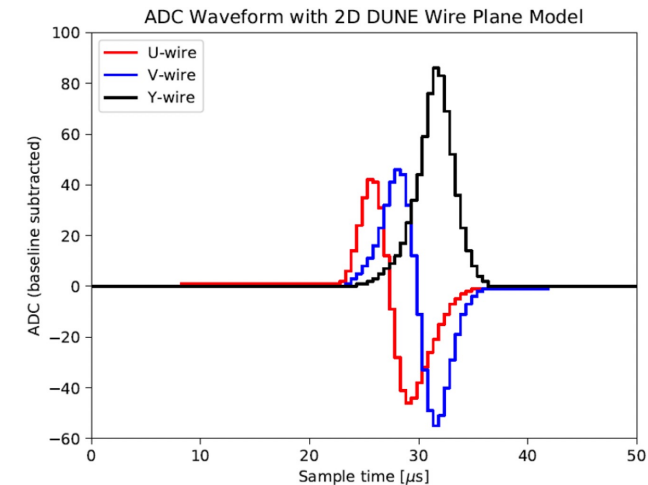
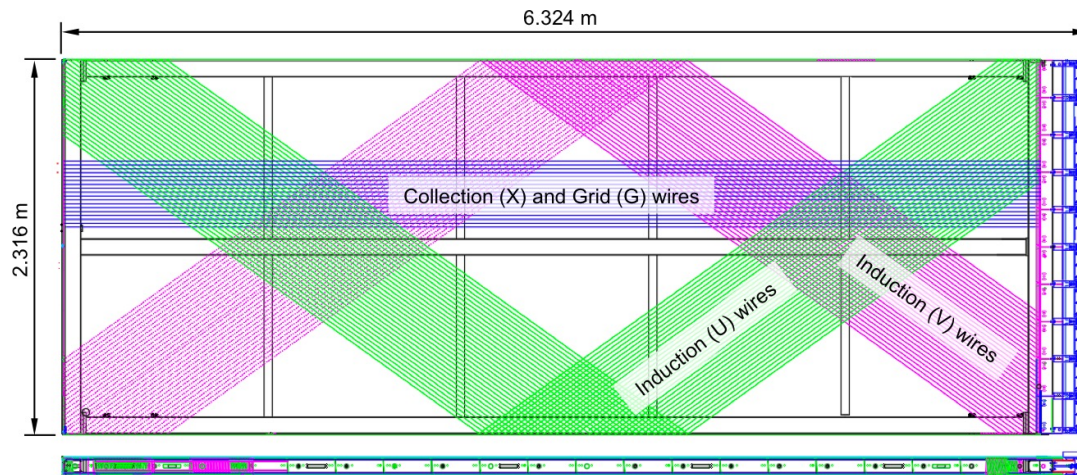
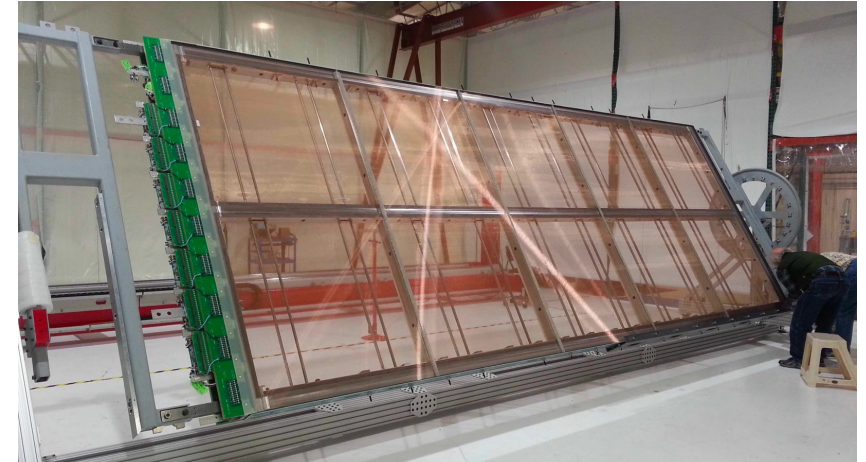
Single Phase Vertical Drift



- Simplification of dual-phase design keeping vertical drift
- No more gaseous layer nor signal amplification: single-phase type
- Detector split into two drift volumes: 'top' and 'bottom'
 - Cathode suspended in the center

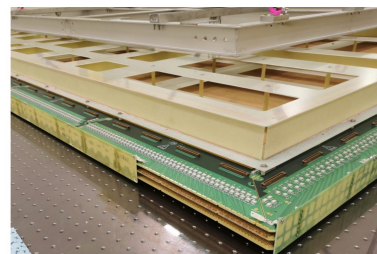
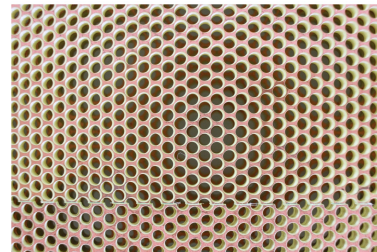
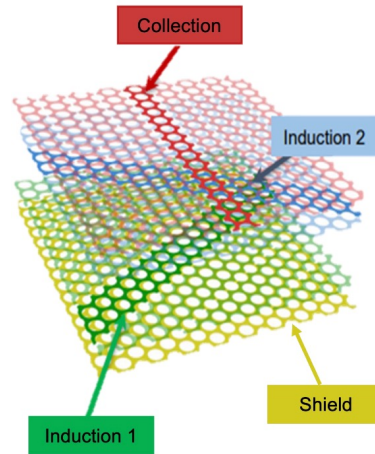
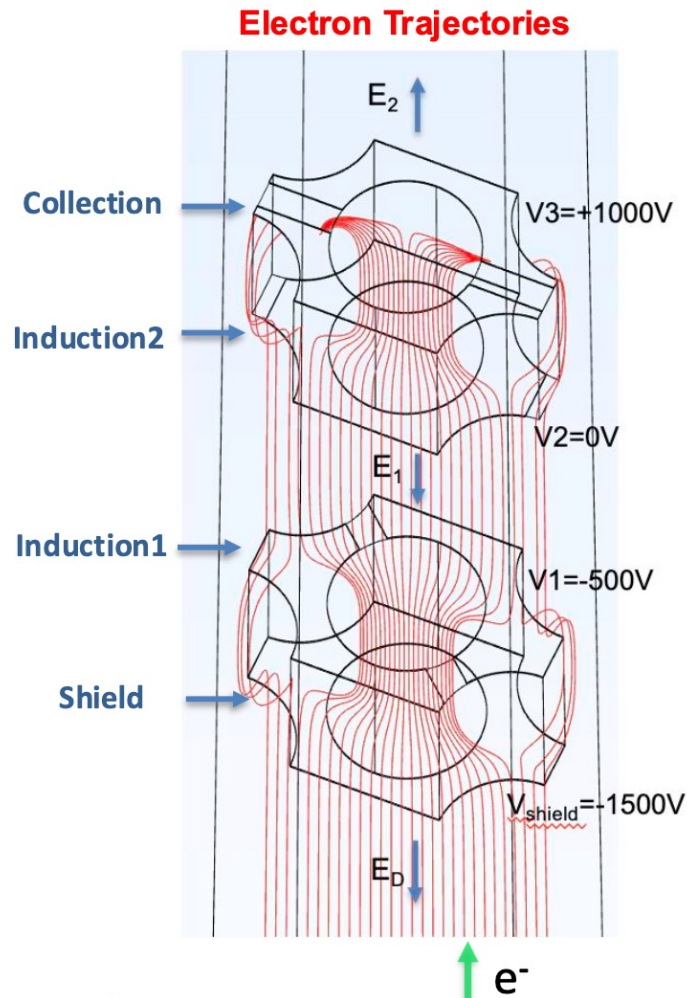
Charge readout (wires)

- Sequence of parallel wire planes at different voltages: electrons pass through induction planes and are absorbed by the collection plane
- Three planes oriented at angles to each other: a collection plane at 0° , X, and two induction planes at $\pm 35.7^\circ$ to the vertical, U and V.
- Having three planes allows multi-dimensional reconstruction of particle tracks even when the particle propagates parallel to one of the wire plane directions.



DUNE FD-HD

Charge readout (perforated strips)

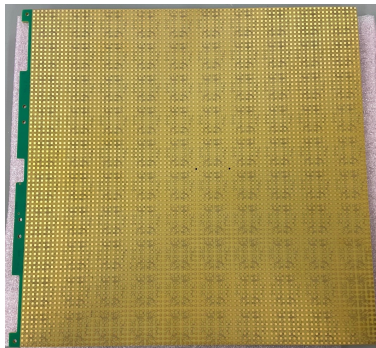
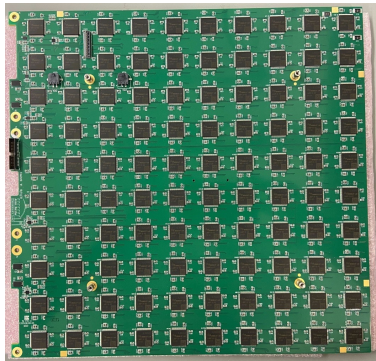


- New **perforated anode technology**
 - Stack of 2 perforated Printed Circuit Boards (PCB) (3.2 mm thick, 1cm gap)
 - Etched copper electrode strips on each PCB face - drilled with holes ($\varnothing=2.4\text{mm}$) arranged in a hexagonal layout
 - A sub-centimeter spatial resolution
 - Module called Charge-Readout Planes (CRP) $\sim 3 \times 3 \text{ m}^2$
- Shield + 3 different charge readout layers (-30° , $+30^\circ$, 90° wrt beam)

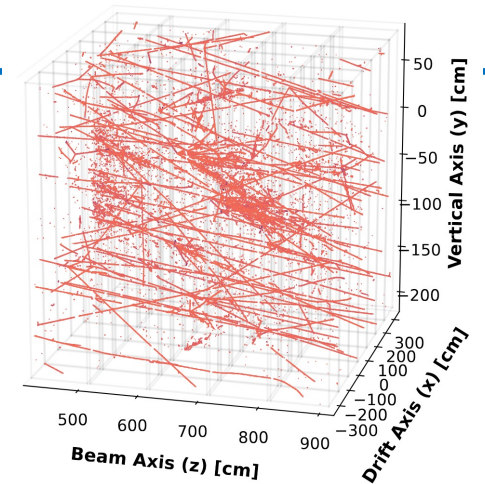
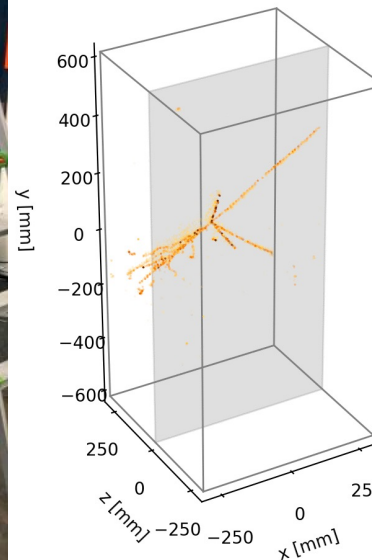
DUNE FD-VD

Charge readout (pixels)

- LArPix charge readout system
- LArPix ASIC: Low-power, cryo-compatible 64-channel custom detector system-on-a-chip for charge-sensitive signal amplification and self-triggered digitization



DUNE ND-LAr



Full spill event display simulation

Specification @ 77K	LArPix-v2b	LArPix-v3
CMOS technology	180 nm	130 nm
Noise	800 ENC	500 ENC
Power per channel	142 μ W	173 μ W*
ADC resolution	8 bits	10 bits
Dynamic range	300 ke-	400 ke-
Minimum resample time	1.1 μ s	1.4 μ s

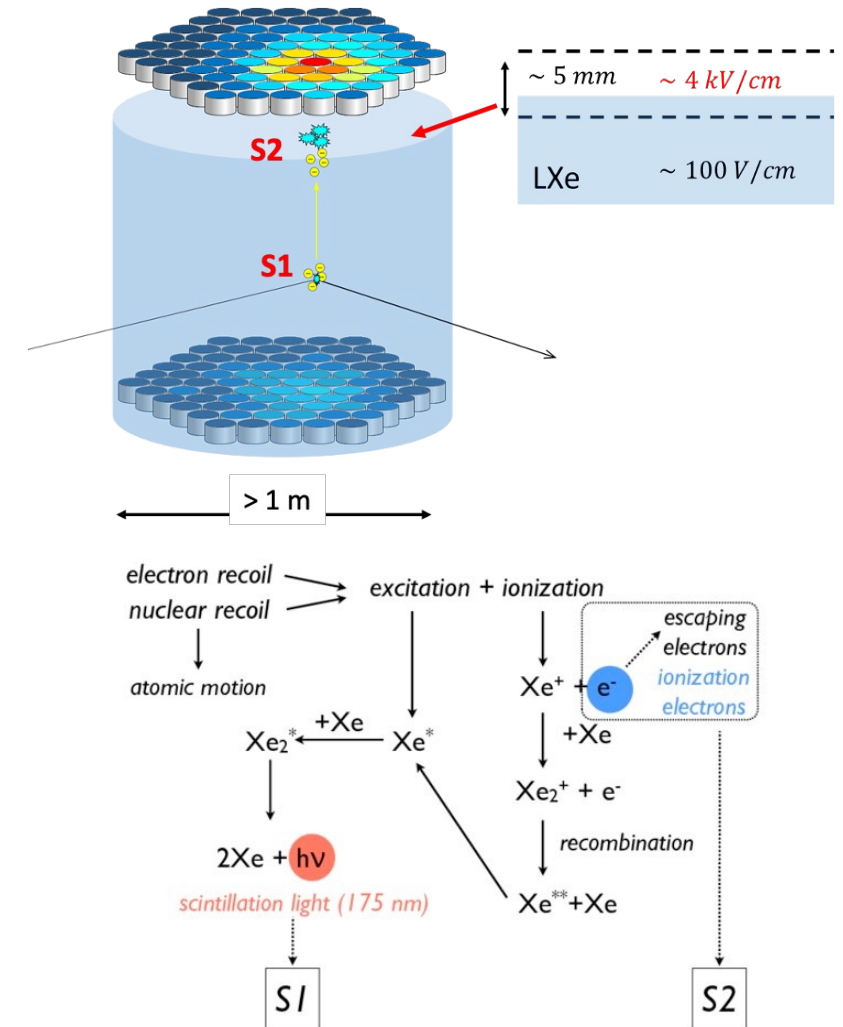
*Dominated by analog power, can be reduced with reduction in dynamic range

Photon detection requirements for ν detection

- Photodetectors are key systems in LArTPCs with the goals:
 - Provide the drift coordinate of the interaction (t_0) → needed for correct estimation of the energy with the TPC
 - Provide trigger for non-beam events (SNB, solar neutrinos, cosmics, BSM...)
 - But also, PDS could be used to provide calorimetric info and veto cosmics or external backgs
- Challenges:
 - Be sensitive to **127 nm** (VUV) scintillation photons
 - Work in **cryogenics** environment for **long time**
 - Cover **large detector areas** in **difficult regions** (limited space, HV...)
 - **Match light** with **charge**

Photon detection requirements for DM

- Dark matter detectors seek for any measurable effects in the target medium caused by the recoil events depositing their energy
- LAr/LXe DM detectors: only optical measurement!
- Measurement of the two signals is the basis for electron/nuclear recoils discrimination
 - The threshold is determined by S1 (usually 2 or 3 phe are required in coincidence)
 - S2 provides energy and position in (x,y) – typically ~ 300 ph/e
- In addition to previous challenges, PDS needs low background, low noise photosensors
 - In the case of LXe: sensors sensitive to 175 nm at 165 K



Cryogenic photosensors developments

Cryogenic photomultiplier tubes (active area from ~ 1 cm to 20" $\varnothing$)

- Many developments in the past by dark matter and neutrino experiments in collaboration with manufacturers
- Used in current LArTPC detectors (ICARUS, SBND) and DM LAr/LXe detectors (XENONnT, LZ, PANDAX-4T)

► Pros:

- * Large active area
- * High gain
- * Mature technology

► Cons:

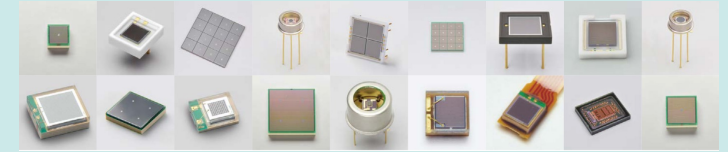
- * High bias voltage
- * Fragile
- * Sensitive to magnetic field
- * Difficult/expensive scaling-up



Cryogenic silicon photomultipliers ($\sim 1 \times 1$ mm² - 6x6 mm²)

► Pros:

- * Low bias voltage
- * Low dark noise rate
- * High gain and PDE
- * Excellent time resolution
- * Insensitive to magnetic field
- * Compactness
- * Radiopurity



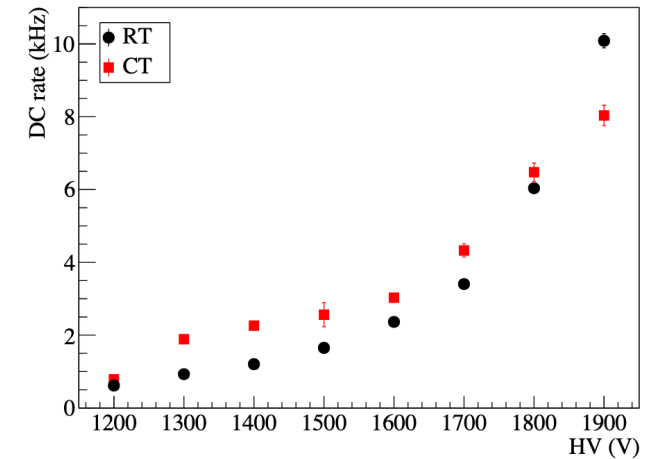
► Cons:

- * Small active area
- * Optical crosstalk and afterpulsing

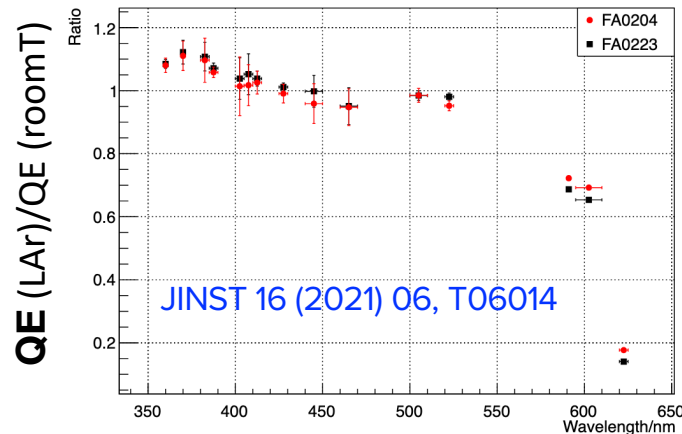
- Active R&D ongoing to improve performance at cryogenic T and VUV (PDE, correlated noise, fill factor, ...)

Temperature dependence (PMTs)

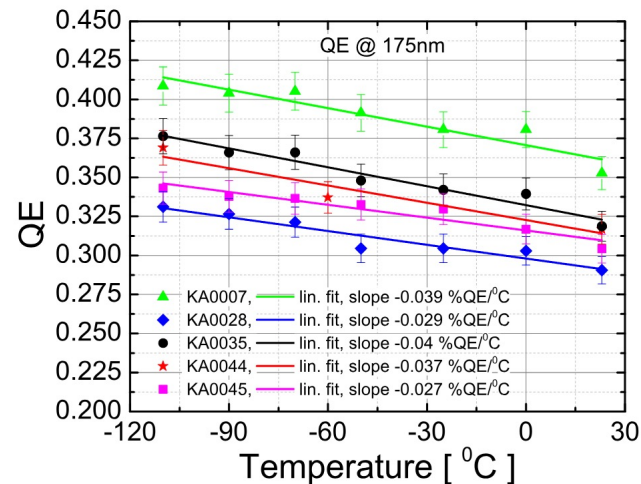
- Cryo PMTs (ex: 8" Hamamatsu R5912-20MOD)
 - (Non-thermal) **DCR increases** at cryogenic T
 - **Gain decreases** at cryogenic T
 - **QE** is ~18% and remains within 5% at cryogenic T at 420 nm



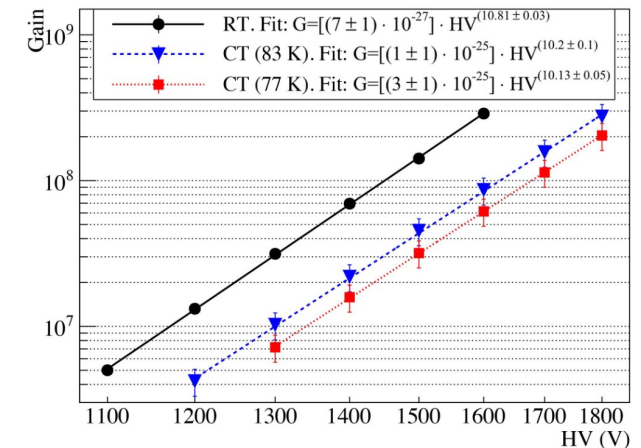
JINST 13 (2018) 10, T10006



JINST 16 (2021) 06, T06014

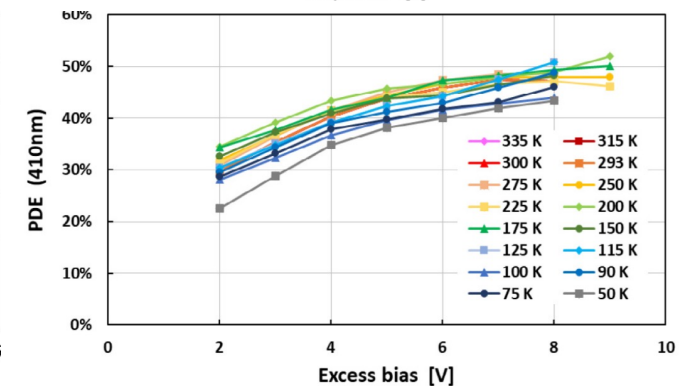
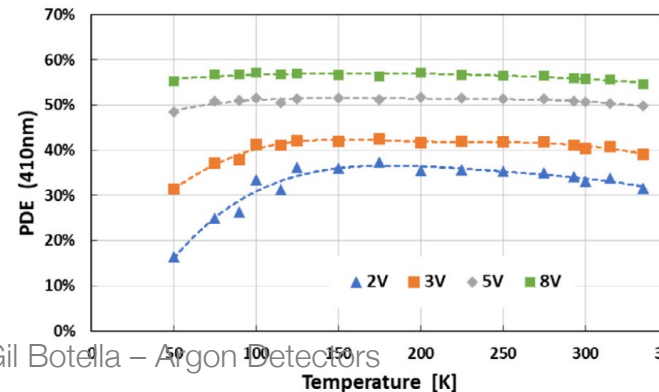
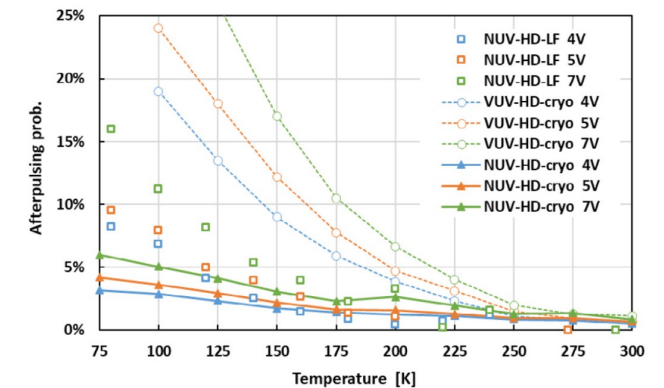
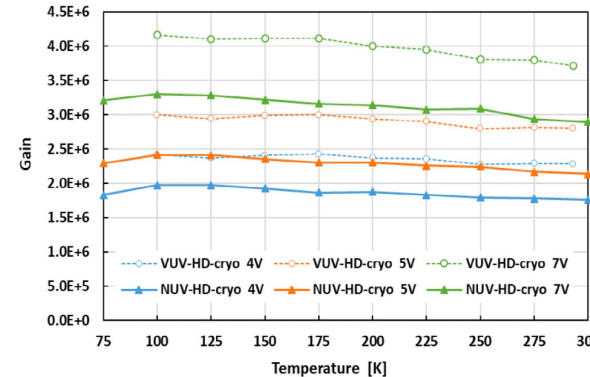
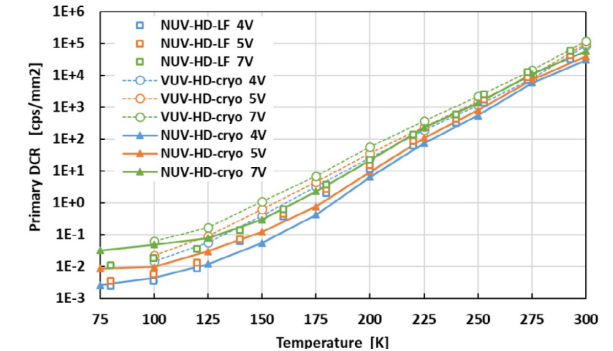
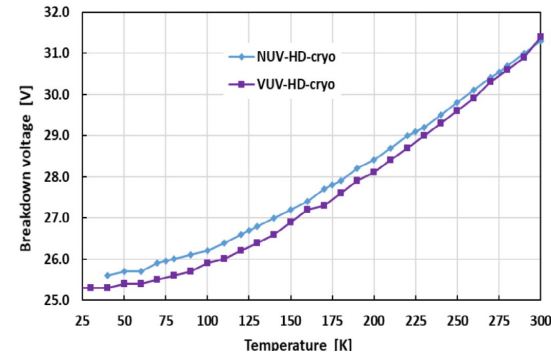


JINST 9 (2014) 11, P11021

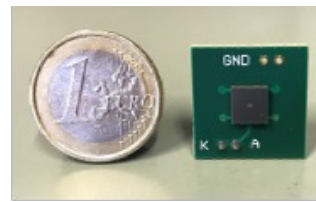


Temperature dependence (SiPMs)

- SiPMs (ex: NUV-HD-cryo & VUV-HD-cryo)
NIMA 1046 (2023) 167683
 - Vbr, DCR decrease at cryogenic T
 - Microcell **gain** and the prompt **crosstalk** probability have very little dependence with T
 - **Afterpulsing** increases at cryogenic T
 - **PDE** (in general) decreases at cryogenic T but it depends on the wavelength and OV



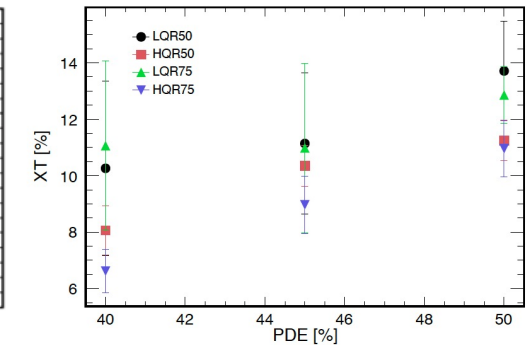
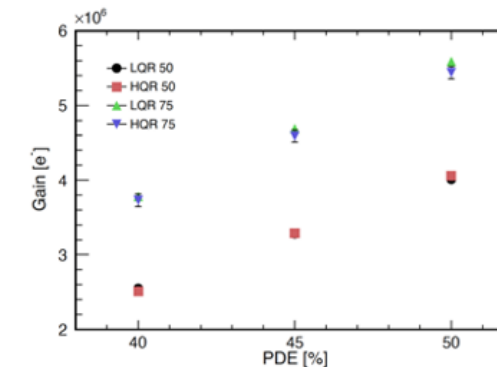
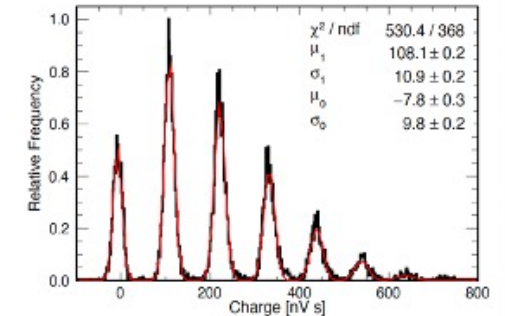
HPK cryo SiPMs



JINST 19 (2024) 01, T01007

- High-efficient low-noise cryogenic SiPM development in collaboration with HPK and FBK:
 - New cryogenic sensors fulfilling the DUNE requirements
 - 4 HPK types tested (6x6 mm²)
- **Characterization and cryo reliability tests** of standalone SiPMs and groups of 6 sensors per PCB (ganging mode):
 - At room T and after 20 thermal cycles in LN₂ (77 K)
 - IV-curves, gain, S/N, DCR, cross-talk, afterpulses
 - Individual and ganged tests
- 150,000 HPK SiPMs tested at CACTUS sites

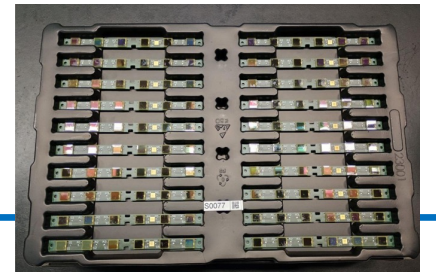
Model	Characteristics
HPK S13360-9932 50μ-LQR	Cell pitch 50μm, low quenching resistance (280 kΩ) at 77 K
HPK S13360-9933 50μ-HQR	Cell pitch 50μm, high quenching resistance (660 kΩ) at 77 K
HPK S13360-9934 75μ-LQR	Cell pitch 75μm, low quenching resistance (280 kΩ) at 77 K
HPK S13360-9935 75μ-HQR	Cell pitch 75μm, high quenching resistance (660 kΩ) at 77 K



HPK HRQ 75μm selected for DUNE

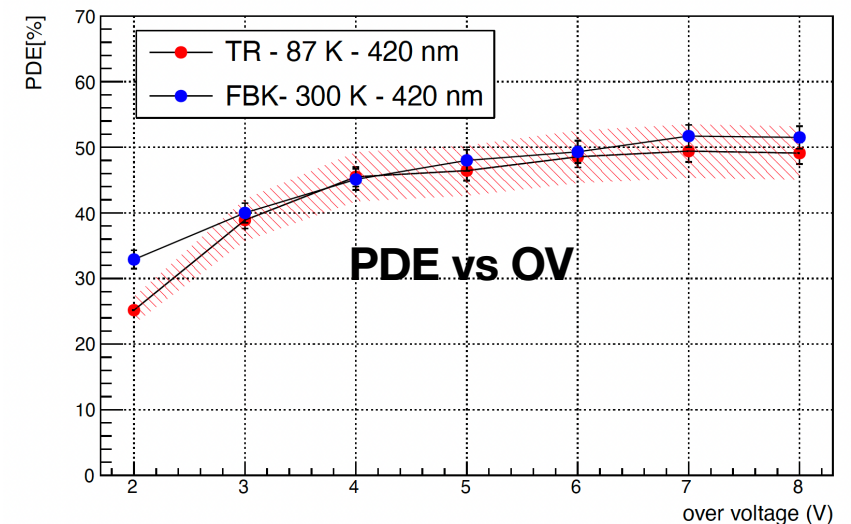
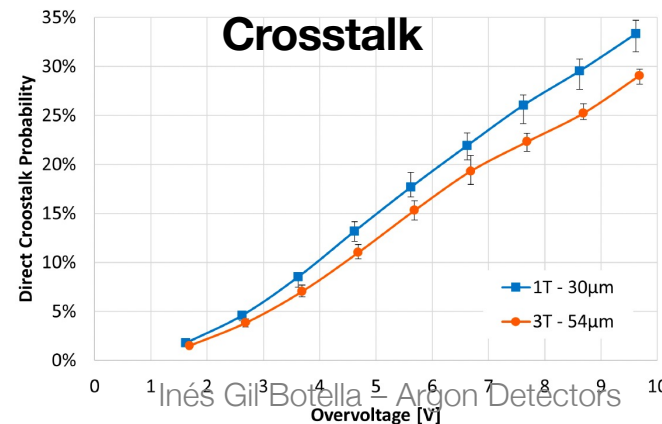
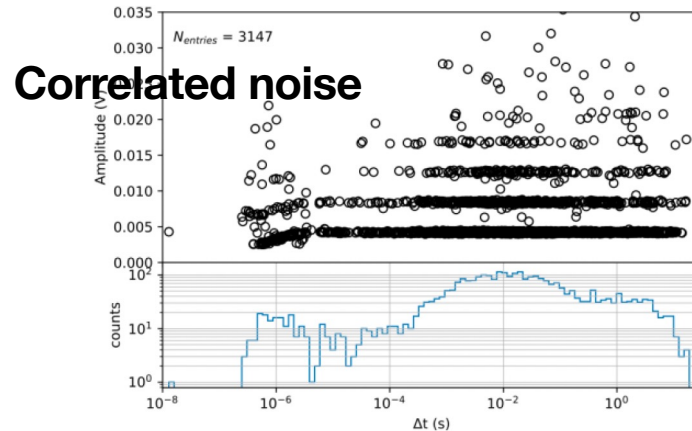
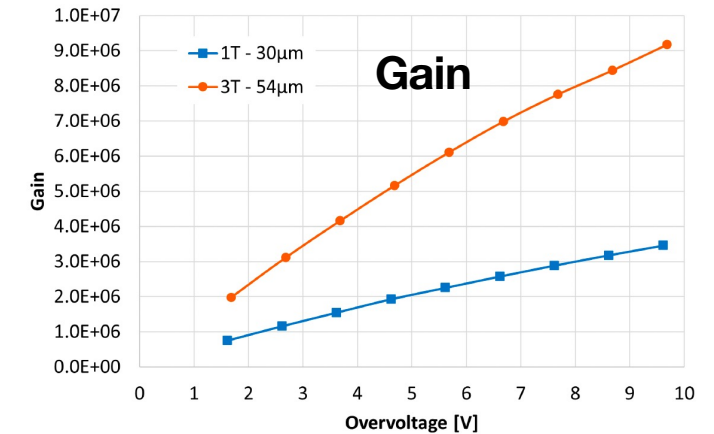
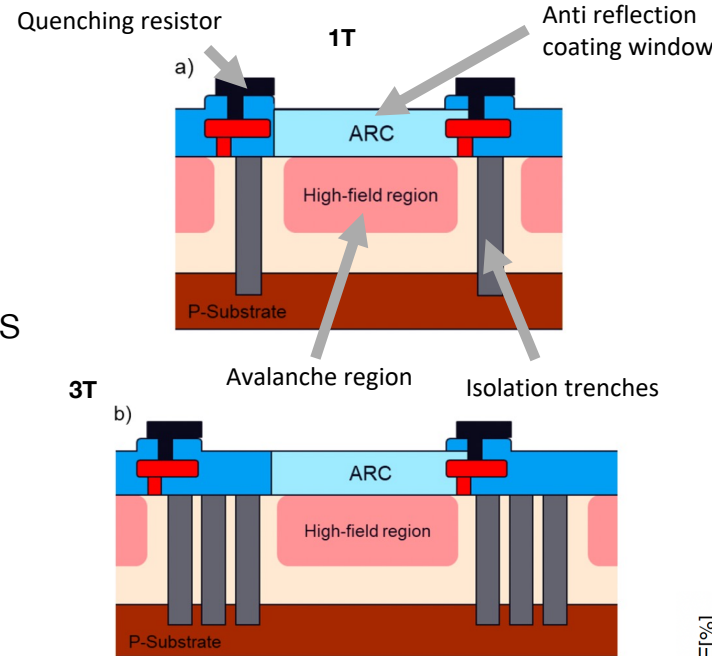
Parameter	Requirement	Test Result (Mean/Std Dev)
Gain	2 to 8·10 ⁶	5.7·10 ⁶ / 9.08·10 ⁴
Cross-talk probability	<35% at V _{op}	13.62% / 1.29%
After-pulsing probability	<5% at V _{op}	1.49% / 0.35%
Global DCR	< 100 mHz/mm ²	73.68 mHz/mm ² / 26.6 mHz/mm ²
Thermal cycles	>20	Negligible variation on V _{bd} R _q after 20 cycles

FBK NUV-HD Cryo Triple Trench



- Customization for DUNE experiment
- Based on the NUV-HD Cryo technology
- 54 μm cell pitch and $6 \times 6 \text{ mm}^2$ area
- 3 isolating trenches (3T) between cells to decrease crosstalk probability
- PDE = 50% at 420 nm at OV7
- 150,000 FBK SiPMs being tested at CACTUS sites

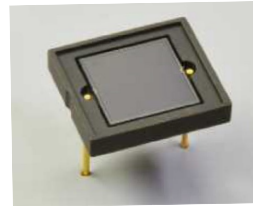
JINST 21 (2026) 02, P02047



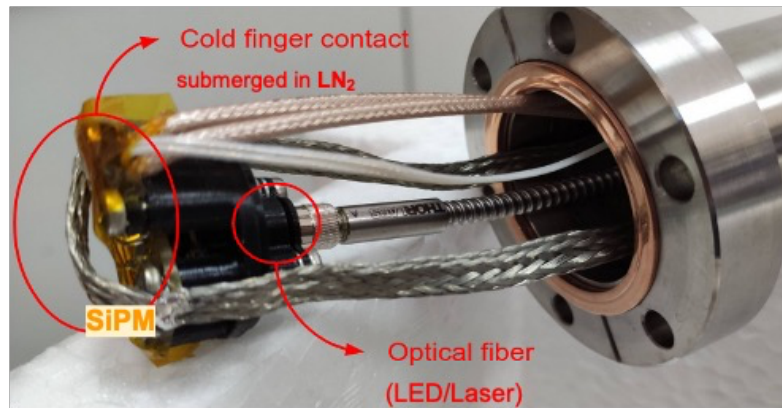
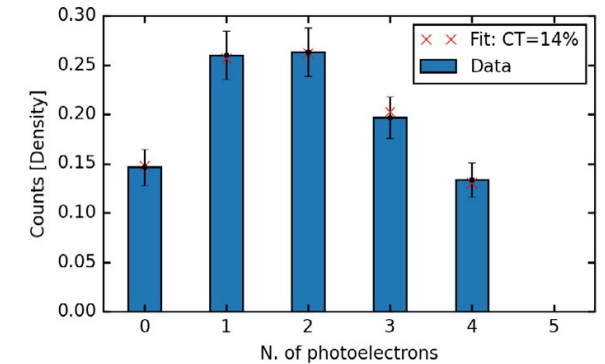
HPK VUV4 cryo SiPMs

NIMA 1064 (2024) 169347

- S13370–6075CN (6x6 mm²)
- Sensitive to 127 nm**
- PDE measurement vs wavelength at different temperatures at CIEMAT

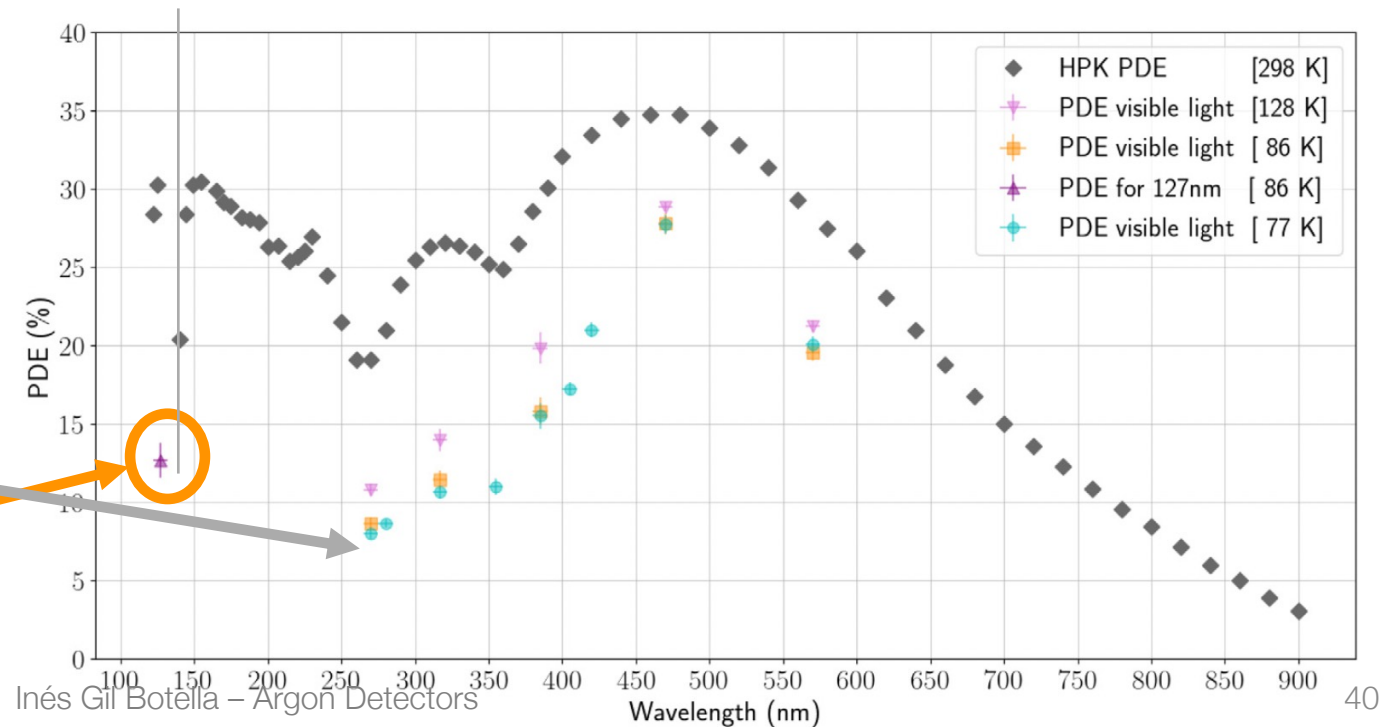


Parameter	Value
Effective photosensitive area	(6 × 6) mm ²
Size	(10 × 9) mm ²
Pixel pitch	75 μm
Terminal capacitance	1.28 nF
Fill factor	70%
Crosstalk probability	5%
Gain	5.8 · 10 ⁶
Dark counts (typ.)	0.11 MHz
Breakdown voltage	(55 ± 0.2) V
Breakdown voltage [86.15 K]	(42 ± 0.2) V]



$$PDE_{CT} = \frac{PE_{CT}}{PE_{RT}} PDE_{RT}$$

- Strong decrease of PDE wrt room T
- PDE at 127 nm at 86 K with ²⁴¹Am source
 - ~12% at OV4



SECTION 3

From sensors to large-scale detectors

Large (~kton) LAr TPC challenges

1. Large cryogenic vessels

- Very large LAr masses are needed

2. Liquid purification

- Needed to ensure long drift path of ionization electrons without attenuation

3. High voltage systems

- 0.5-1 kV/cm drift field → long drift distances

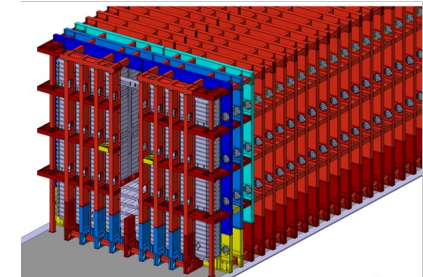
4. Electronics and DAQ

- Low noise electronics at cold

5. Scintillation light detection

- VUV sensitive, long-term performance

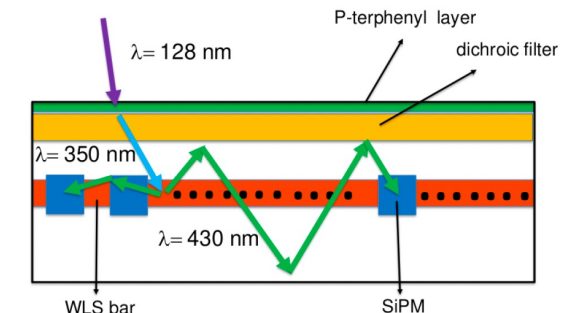
CERN led the R&D on large cryogenic vessels: new cryogenic and purification systems, new cold cryostats and passive insulators



Demonstrated electron lifetime up to >30ms at CERN

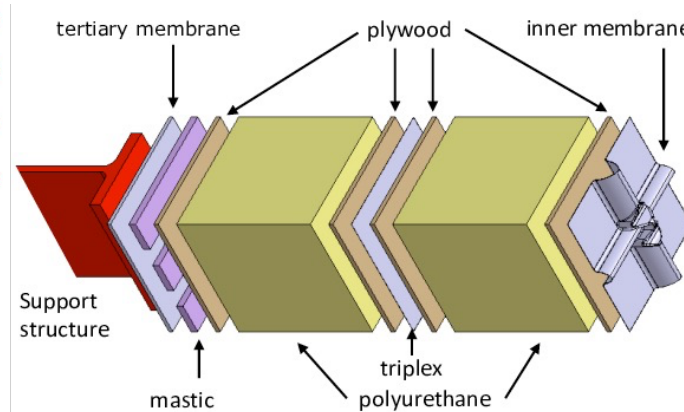
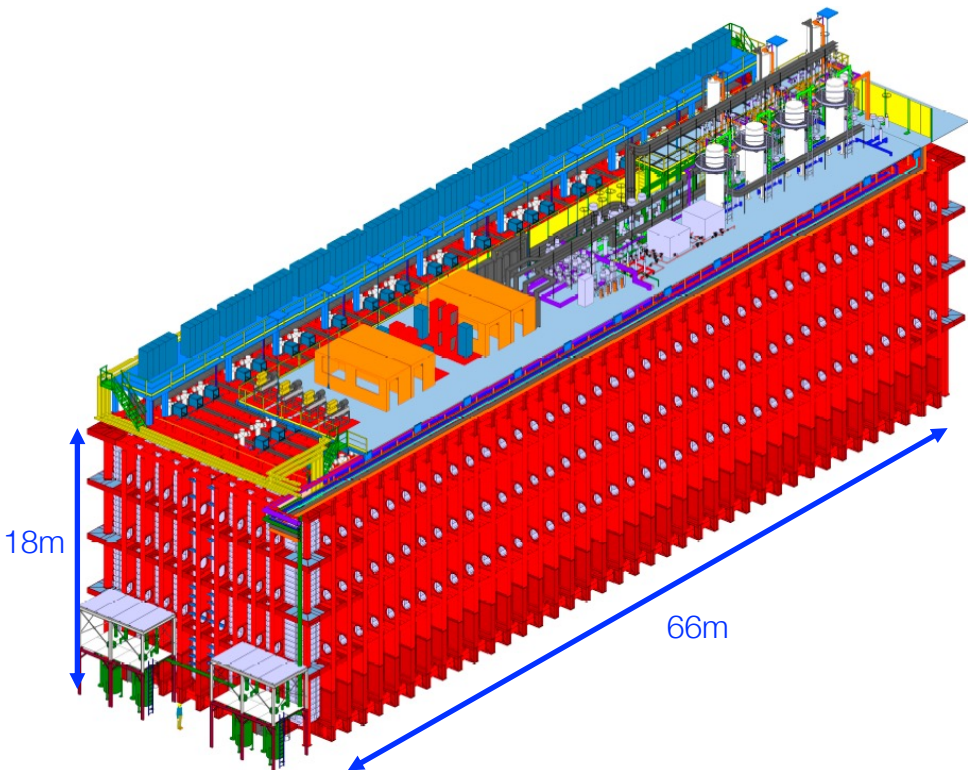
Demonstrated 6m drift distance at CERN (300 kV on the cathode)

Several proposals: wavelength-shifting techniques, photon collectors

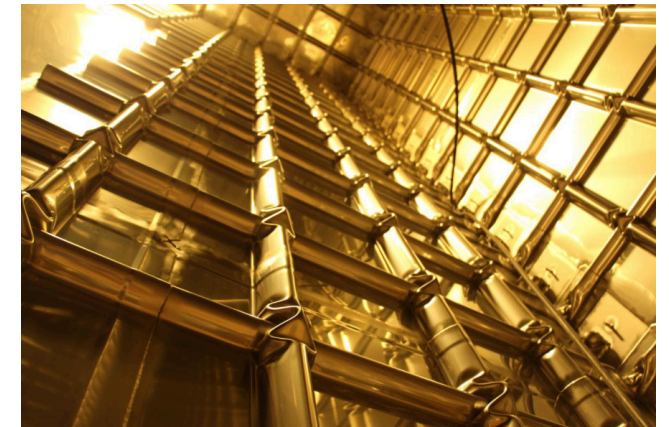


Large cryogenic vessels

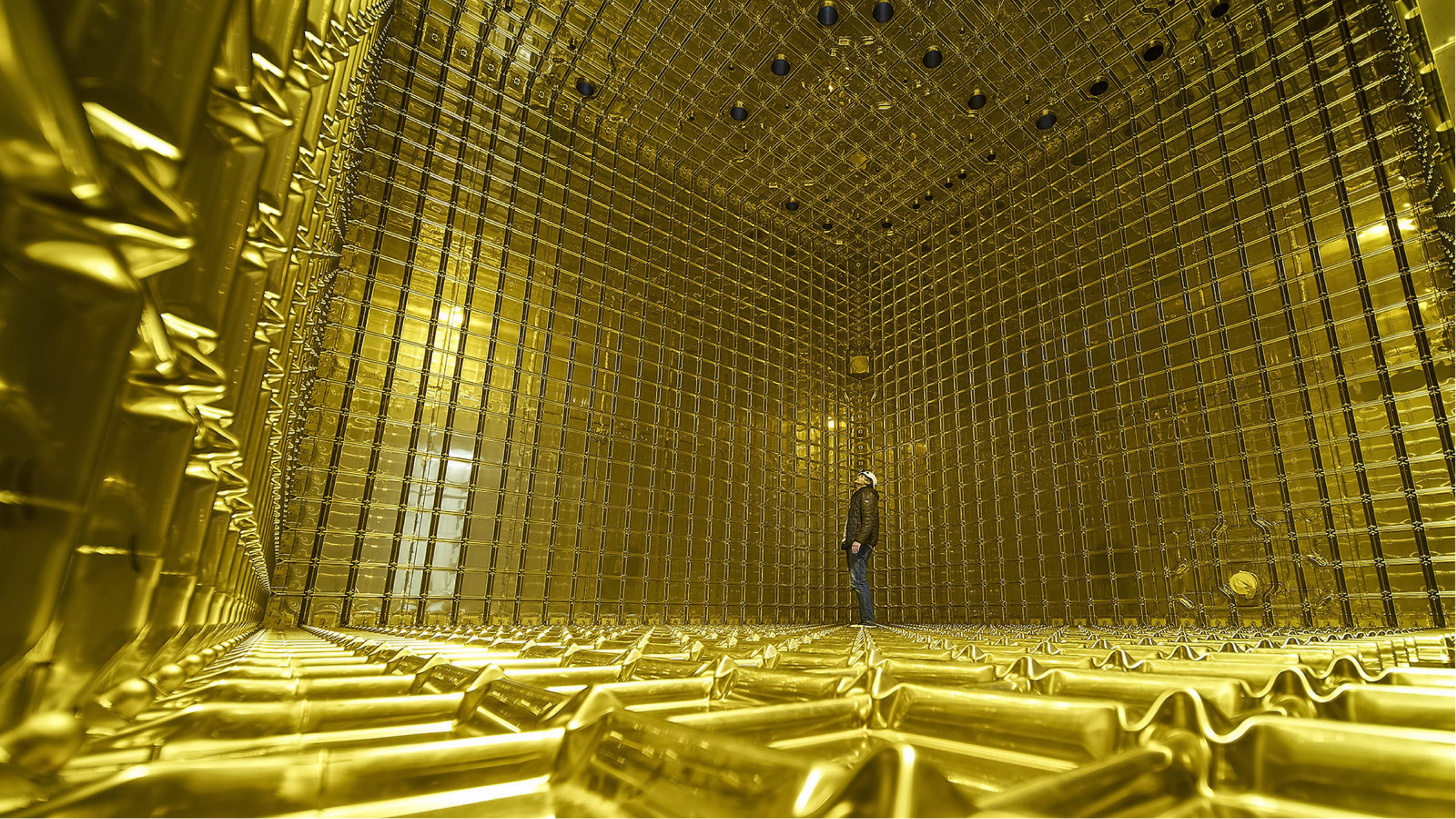
- CERN led the R&D on large cryogenic vessels: new cryogenic and purification systems, new cold cryostats and passive insulators
- Royalties' owner: GTT (France); Licensee: **Gabadi (Spain)** among several



Inner membrane (ProtoDUNE)

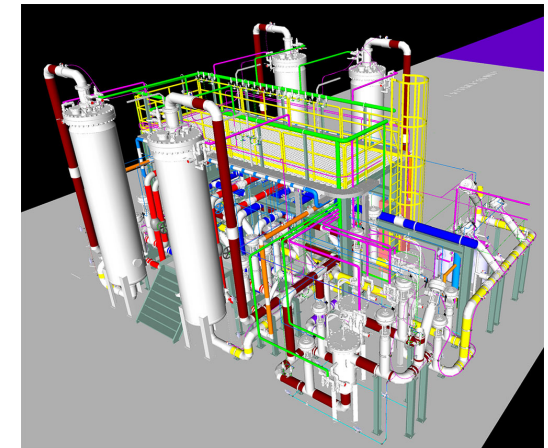
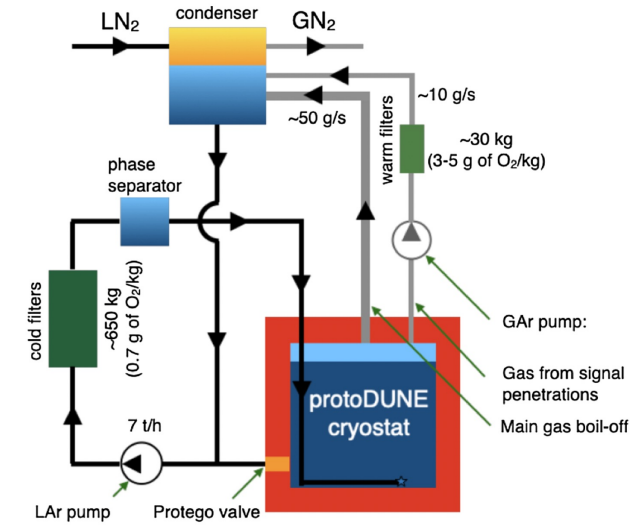
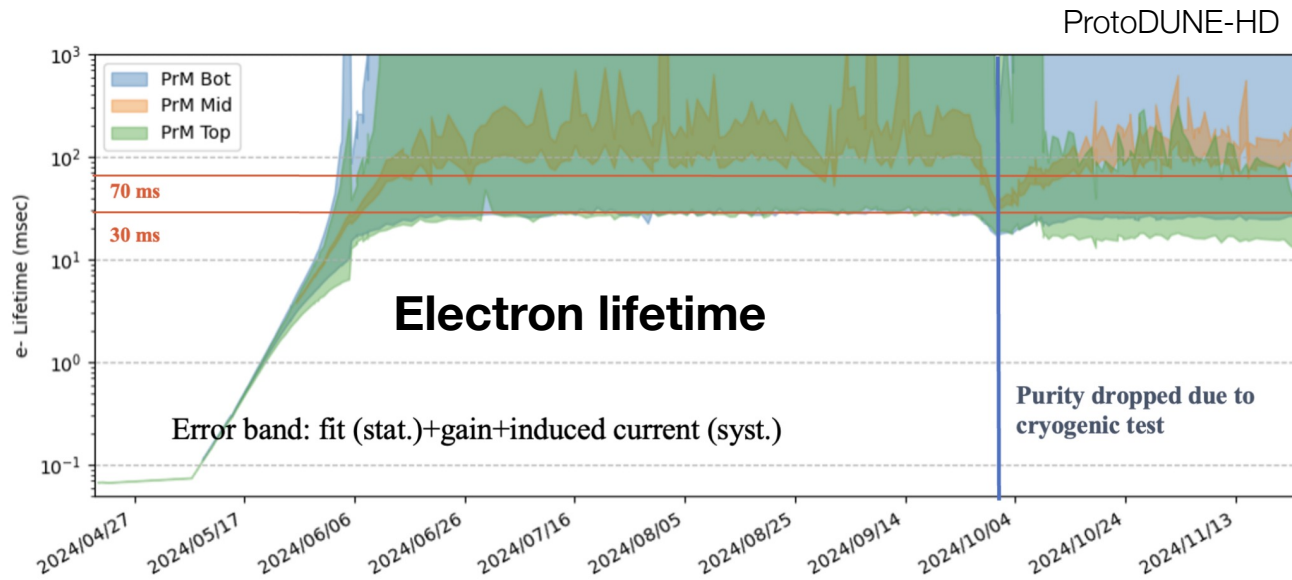


Corrugation allows the structure to expand and contract



Liquid purification

- Achieved electron lifetime **above 70 ms** at ProtoDUNE-HD!
- DUNE requirement was 3 ms (goal: 10 ms)

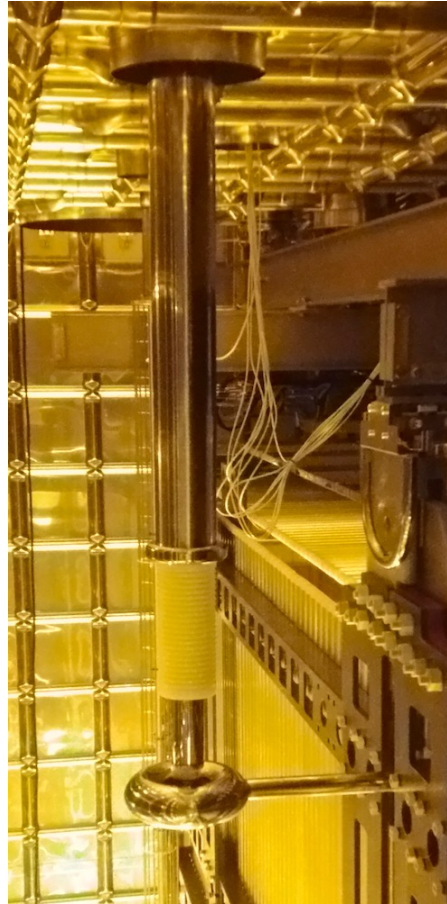


LAr purification system designed for a DUNE far detector cryostat

High voltage systems

- HV operation at -300 kV on the cathode
- Critical elements of the HV distribution: “extender” + coupling with HV feedthrough
- Long term stability runs demonstration in ProtoDUNE-VD and 6 m drift

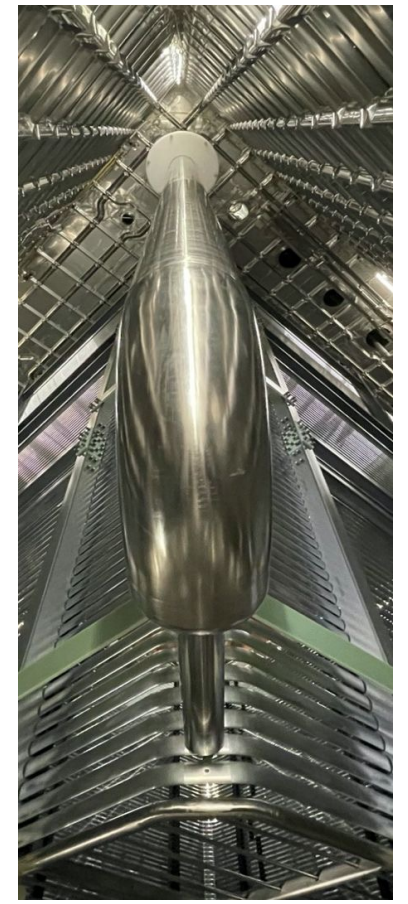
HVFT



HV power supply

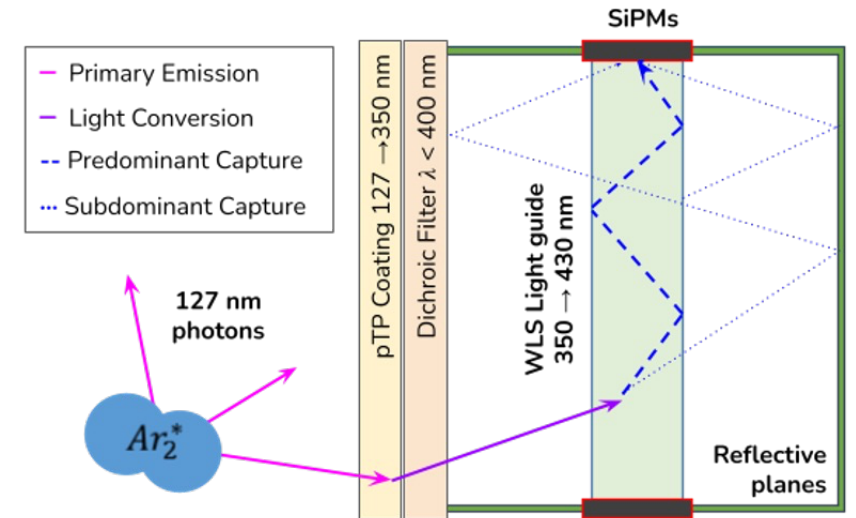
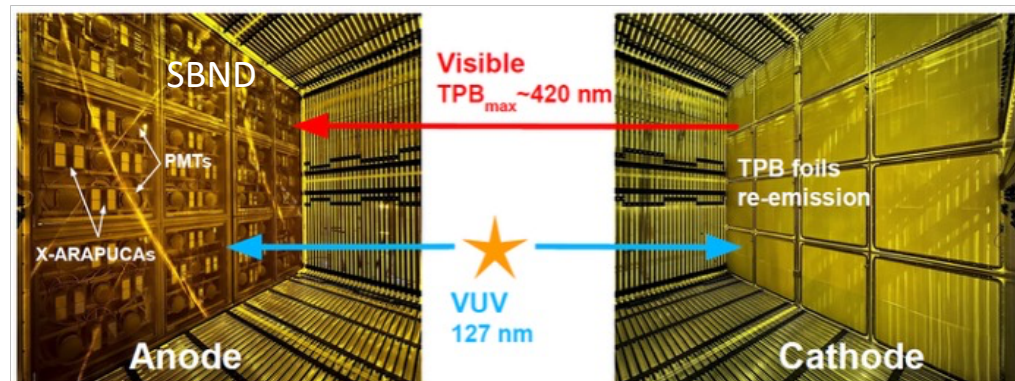


HVS extender

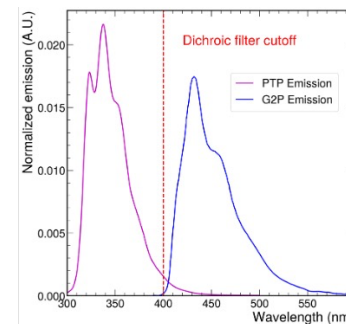


Photon Detection: Shifting VUV to visible light

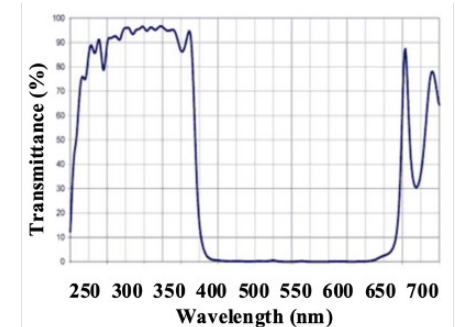
- **X-ARAPUCA concept** (VUV light trap)
 - Initially proposed by E. Segreto and A. Machado (Campinas)
 - Allows to shift VUV light to visible light covering large areas
 - First light conversion by the pTP → transmission through DF → second conversion by the WLS light guide towards SiPMs → DF blocks photons inside XA → photon detection by SiPM
 - XA Photon Detection Efficiency quite low ~2%
- **Reflective foils**
 - TPB-coated PTFE reflectors to shift 127 nm to visible light



pTP & WLS emission

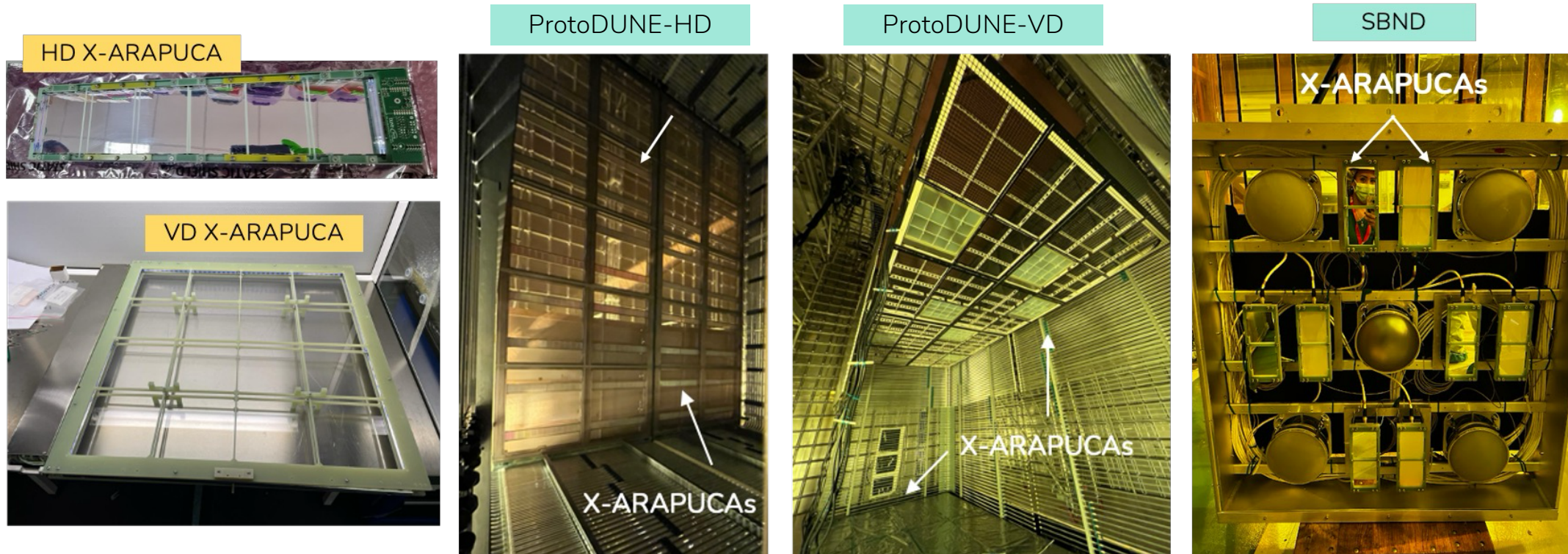


Ideal DF transmittance



X-ARAPUCAs in DUNE and SBND

- DUNE HD X-ARAPUCAs (10x50 cm²): 48 SiPMs/module - 6000 modules in DUNE FD (tested in ProtoDUNE-HD)
- DUNE VD X-ARAPUCAs (60x60 cm²): 160 SiPMs/module - 672 modules in DUNE FD (tested in ProtoDUNE-VD)
- SBND X-ARAPUCAs (10x24 cm²): 4-8 SiPMs/module - 192 modules (visible and VUV sensitive) – in use

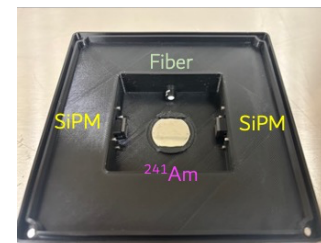


Photon Detection Efficiency measurement

- X-ARAPUCA optimization focused on increasing PDE:
 - better coupling WLS plate-SiPMs
 - more efficient WLS plate
 - optimized dichroic filter cutoff for LAr light
 - replacement of filter by pTP-coated glass substrates
 - improved reflective surfaces
- Dedicated cryogenic facilities developed to characterize the PDS performance
 - ^{241}Am alpha source + 2 VUV reference SiPMs in a calibration black box



Calibration box



Optimized XAs: PDE results

- XA-VD: PDE ~4-6%** (~22% PDE increase by removing the dichroic filters (noDF) due to the non-ideal DF transmittance)

VD-XA PDE Results (%)

XA-DS: double-sided XA
FBK NUV-HD-CryoSiPMs

Config	OV 3.5 V	OV 4.5 V	OV 7 V
1 DF-XA	3.2 ± 0.2	3.7 ± 0.3	4.7 ± 0.3
2 DF-XA-DS	3.5 ± 0.3	4.0 ± 0.4	5.0 ± 0.5
3 noDF-XA	3.9 ± 0.4	4.5 ± 0.4	5.8 ± 0.6
4 noDF-XA-DS	3.8 ± 0.4	4.5 ± 0.4	5.6 ± 0.6
5 noDF-XA_24mg	3.6 ± 0.4	4.3 ± 0.4	5.5 ± 0.6

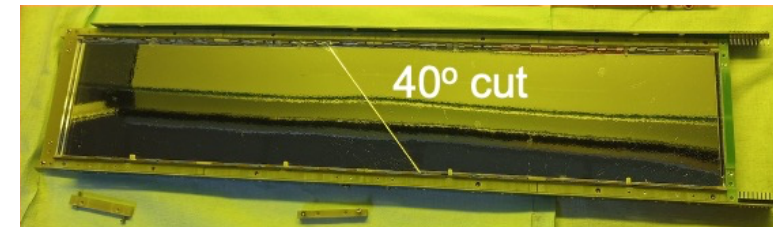
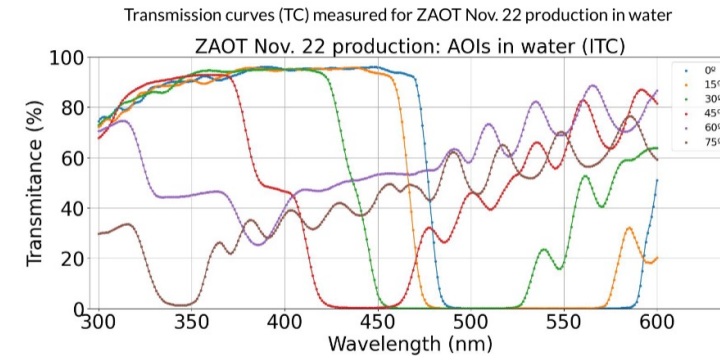
arXiv: 2511.12328



- XA-HD: PDE ~ 4%** (~80% PDE increase by removing DF and adding a cut on the WLS bar) HPK SiPMs

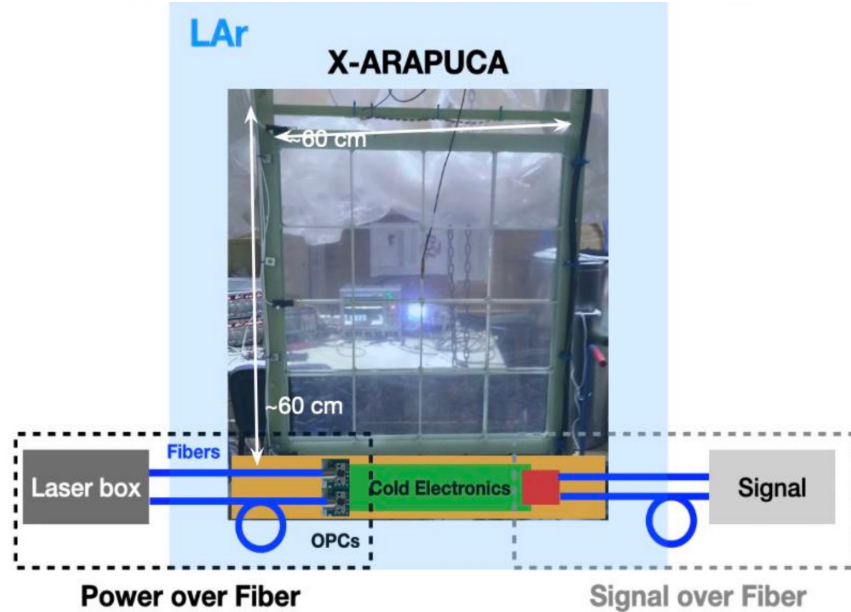
OV	Relative PDE noDF/DF	Relative PDE cut/no_cut
2 V	1.36 ± 0.02	1.33 ± 0.01
2.5 V	1.38 ± 0.02	1.32 ± 0.01
3 V	1.40 ± 0.02	1.31 ± 0.01

paper in preparation

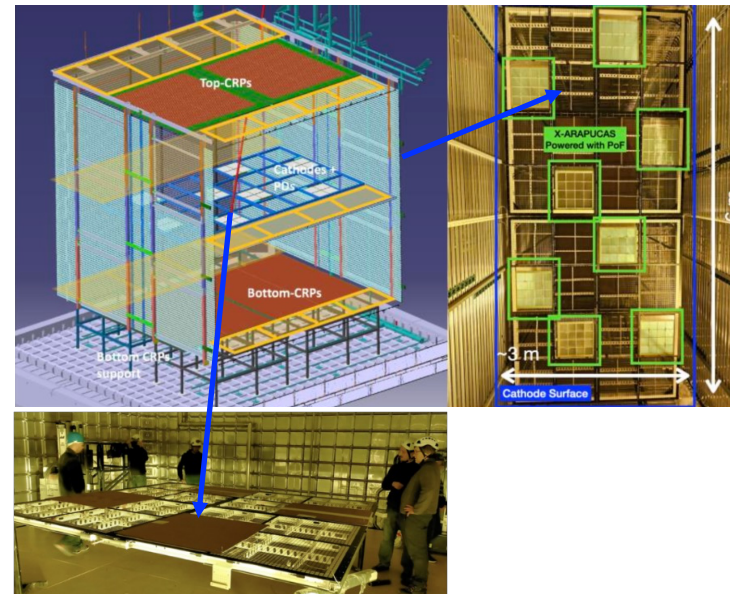


Photodetectors in HV environment

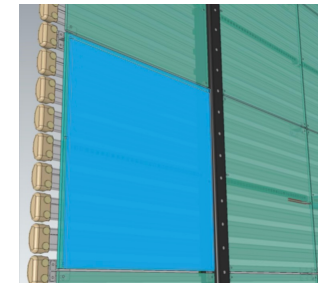
- Instrument field cage and cathode to increase photocoverage in TPCs using Power-over-Fiber (PoF) and Signal-over-Fiber (SoF) transmission technologies
 - It provides voltage isolation in both signal reception and transmission
 - PoF and SoF are a well-established technology, but extensive use in a cryogenic detector is a new application [JINST 19 \(2024\) P10019](#)



ProtoDUNE-VD



XAs on the field cage



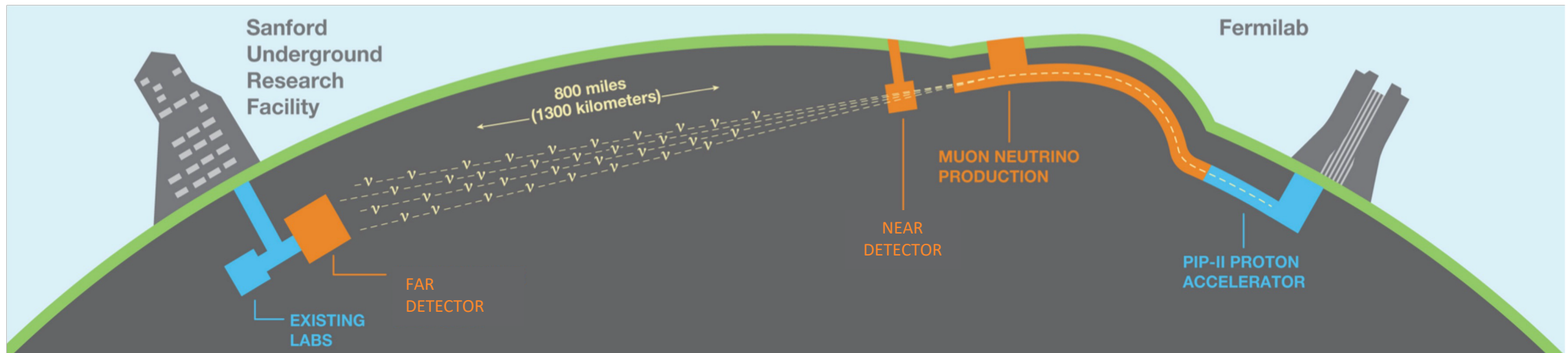
SECTION 4

Applications to neutrino and dark matter experiments

The Deep Underground Neutrino Experiment

DUNE TDR Volumes: JINST 15 (2020) 08, T08008, T08009, T08010, arXiv:2002.03005, JINST 19 (2024) 08, T08004

ND CDR Instruments 5 (2021) 4, 31

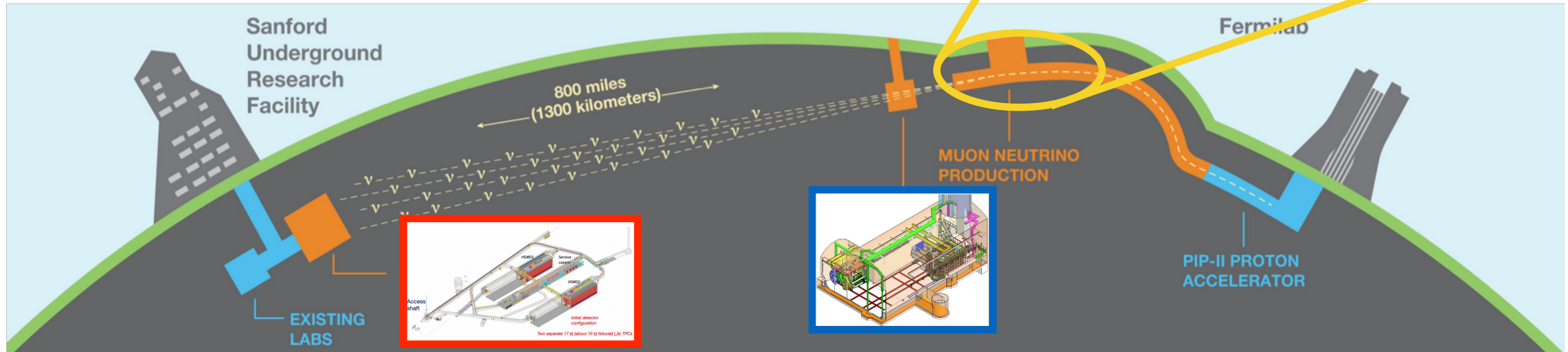


The **most powerful neutrino beam in the world** (>2 MW) will be sent from Fermilab (Chicago) to SURF (South Dakota) along 1300 km distance to be detected by **four liquid argon far detector modules** (70 kton LAr) at 1.5 km deep underground and a **near detector complex** at 560 m from the neutrino source

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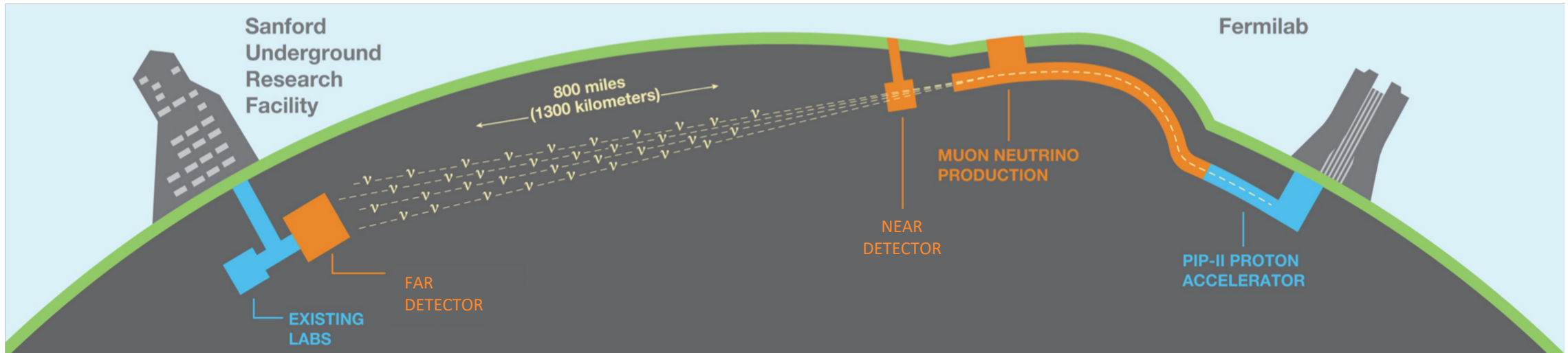


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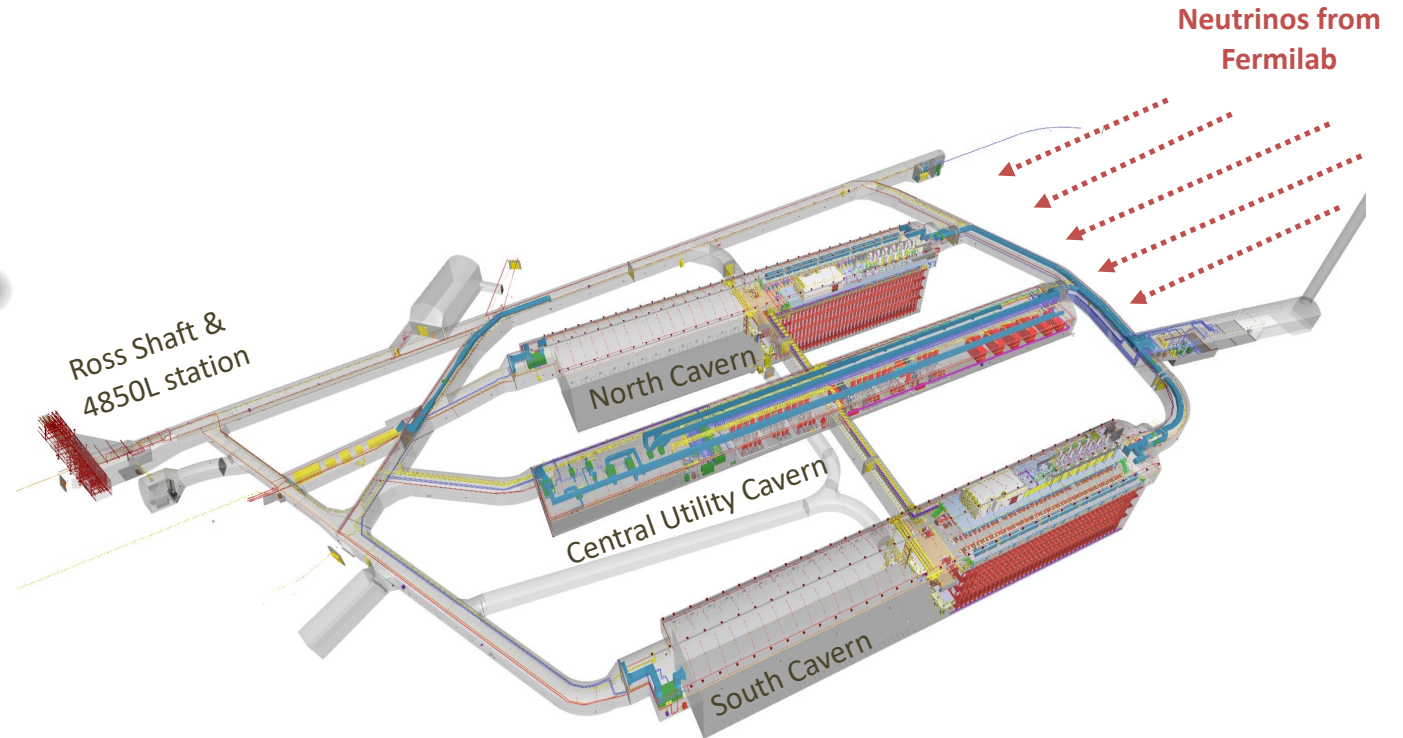
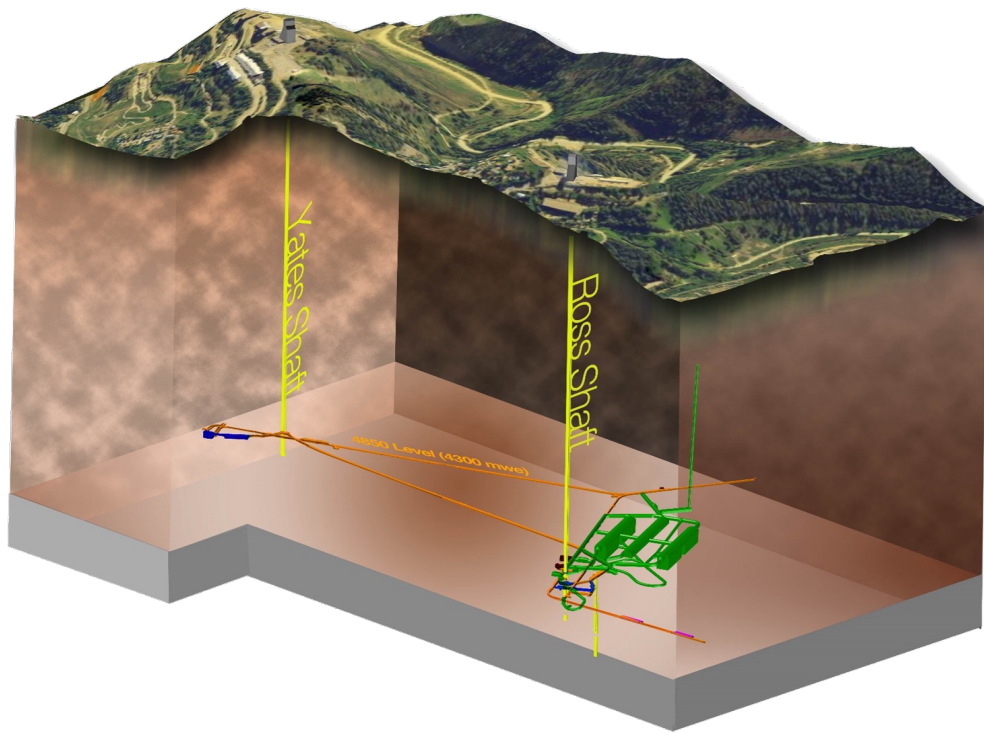
ND CDR Instruments 5 (2021) 4, 31



UNIQUE FEATURES

1. The **very long baseline** enables an unambiguous measurement of the **neutrino MO** (no degeneracy between CPV and matter effect)
2. The **wide-band neutrino energy spectrum** enables detailed fitting of the **oscillation parameters**
3. The **LArTPC technology** enables precise reconstruction of the **neutrino interactions**
4. The **ND complex with movable NDs** enables unprecedented control of **systematic uncertainties**
5. The FD **underground location** enables **astrophysical measurements**

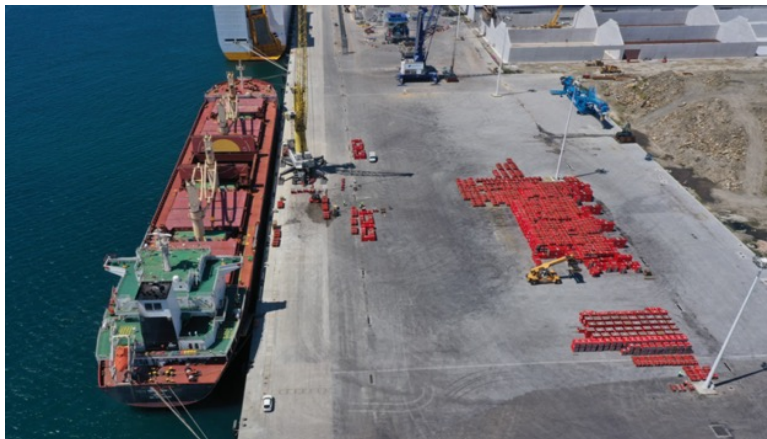
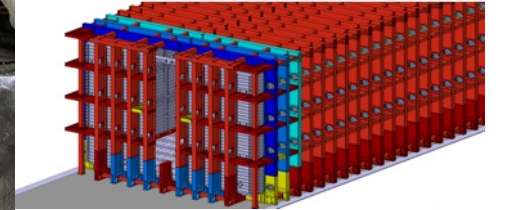
LBNF Far Site at SURF (South Dakota)



DUNE is under construction



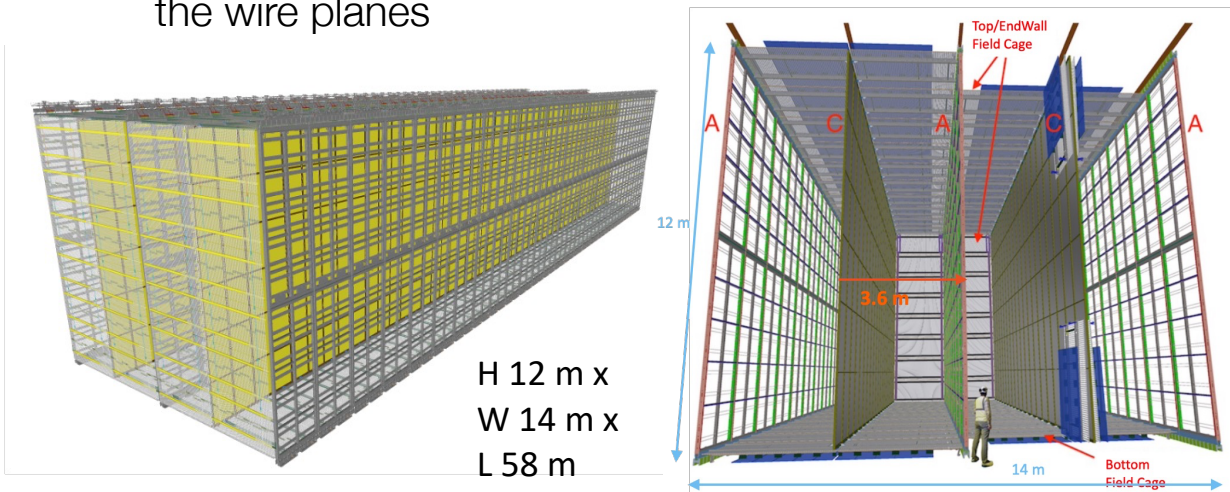
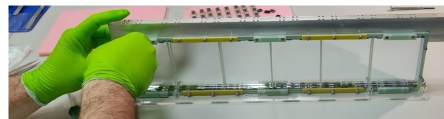
SURF caverns completed in 2024



DUNE Far Detectors

- **FD-HD: Horizontal Drift LArTPC**

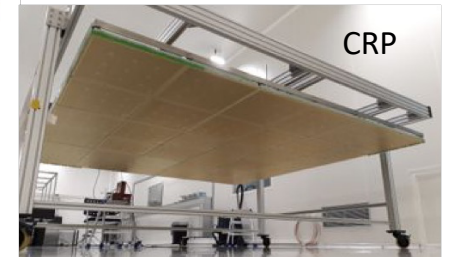
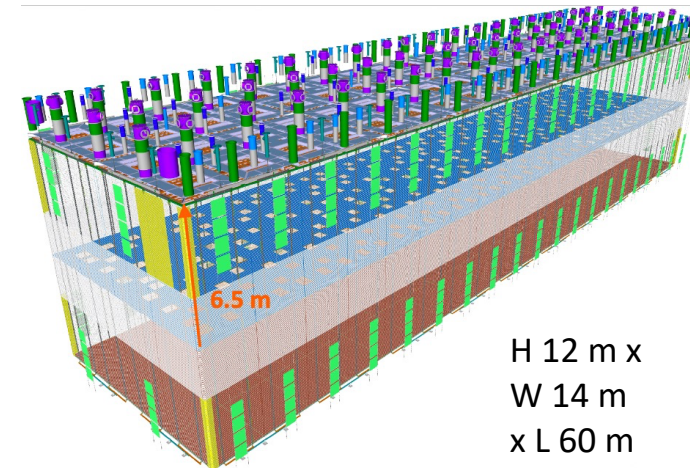
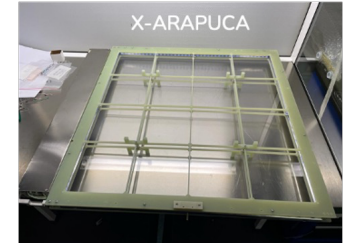
- Four 3.6 m drift regions
- Wire readout plane (APA) technology
- Photon detectors (X-ARAPUCAs) inserted behind the wire planes



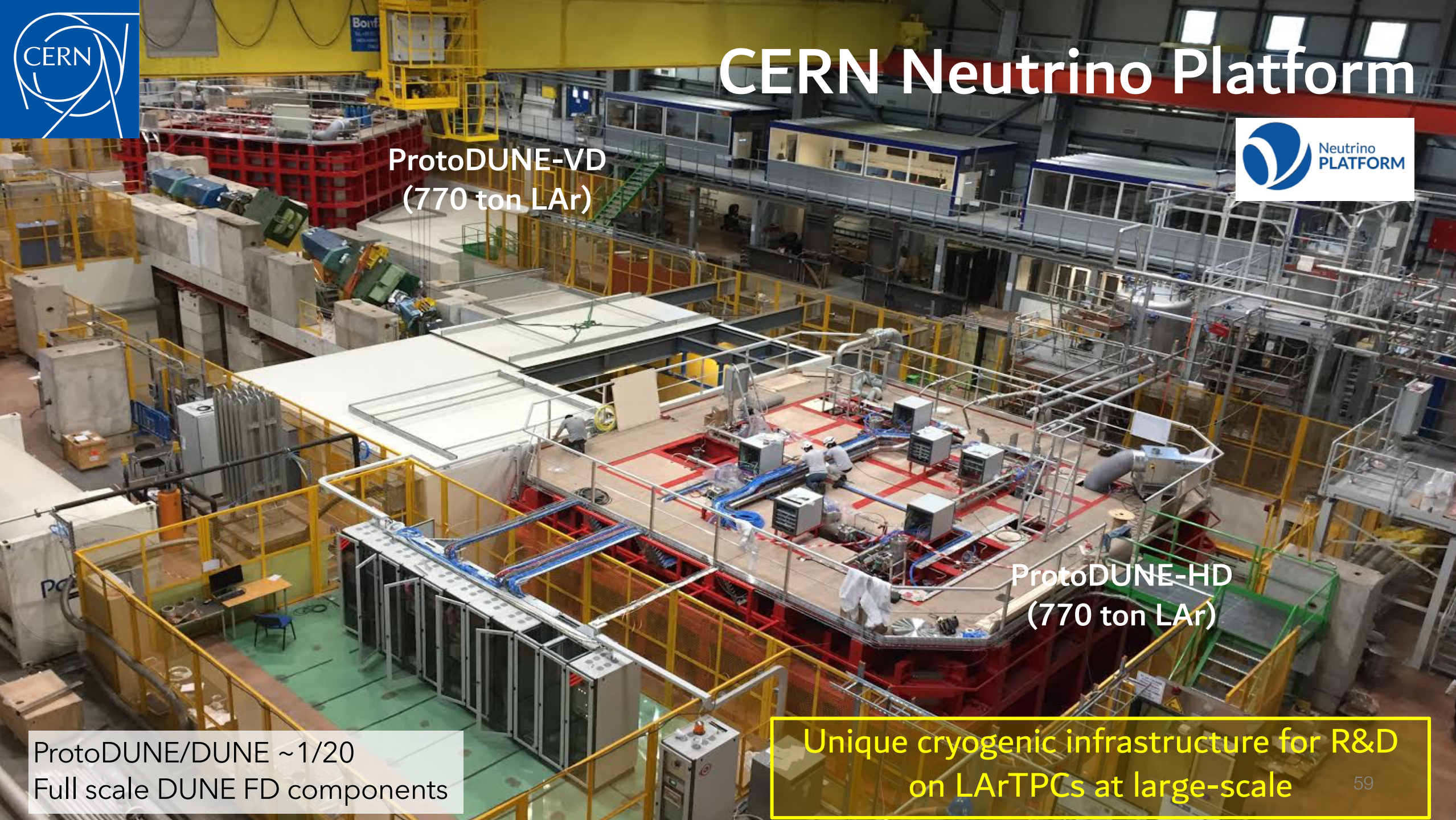
FD-HD: JINST 15 T08010 (2020)

- **FD-VD: Vertical Drift LArTPC**

- Two 6.5 m drift regions
- Charge readout plane (CRP) technology
- Photon detectors (X-ARAPUCAs) on cathode plane and membrane walls



FD-VD: JINST 19 (2024) 08, T08004



CERN Neutrino Platform



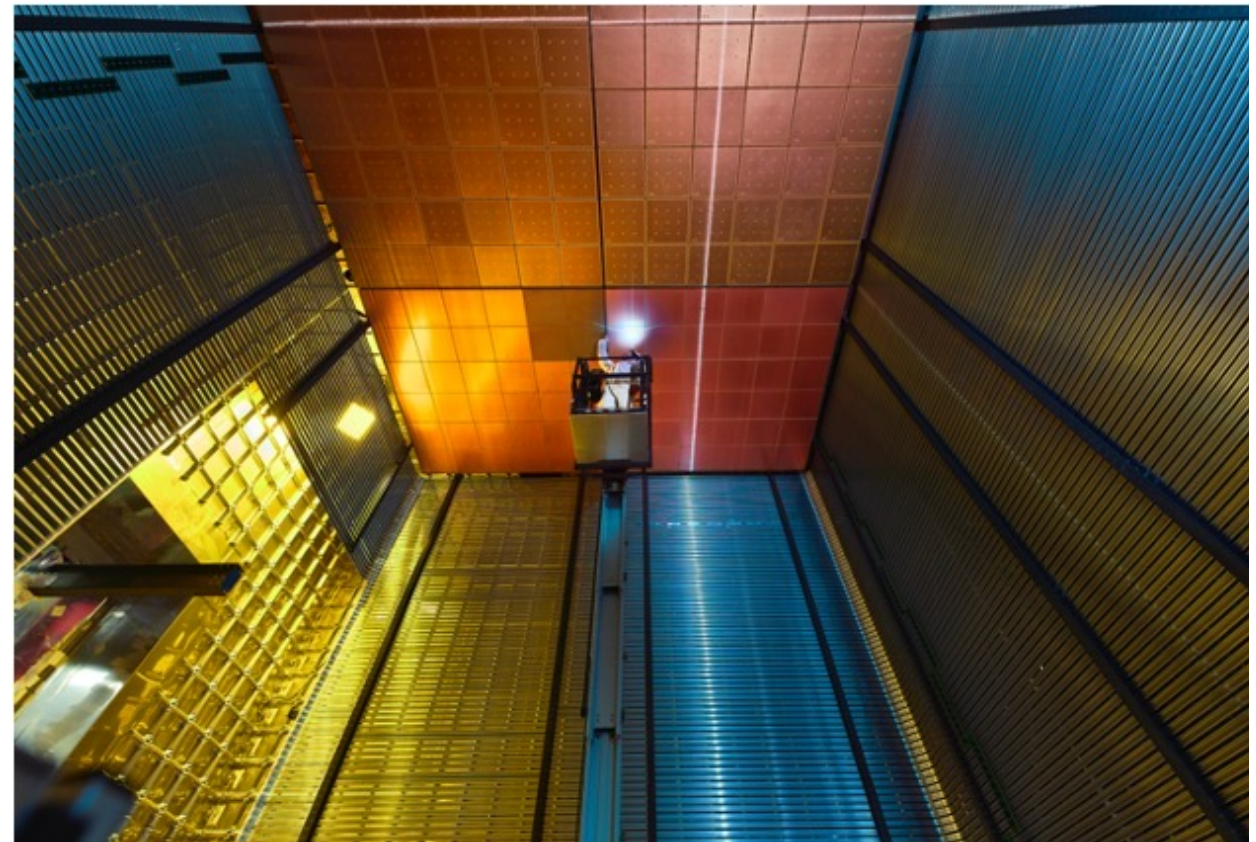
ProtoDUNE-VD
(770 ton LAr)

ProtoDUNE-HD
(770 ton LAr)

ProtoDUNE/DUNE ~1/20
Full scale DUNE FD components

Unique cryogenic infrastructure for R&D
on LArTPCs at large-scale

Inside ProtoDUNE



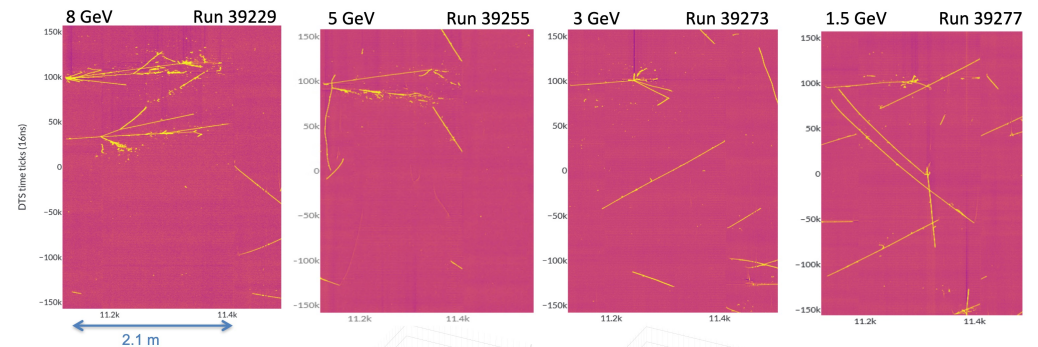
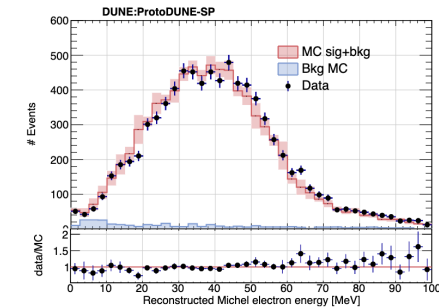
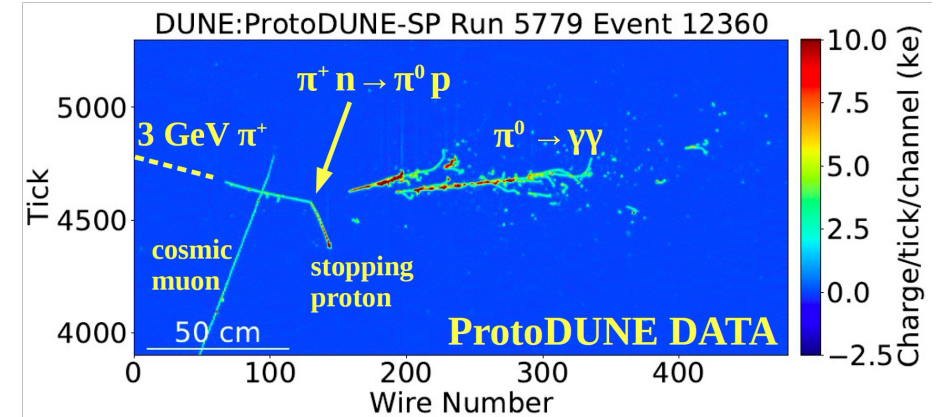
ProtoDUNE_s at CERN

FIRST PHASE PROTODUNE_s (2018-2020)

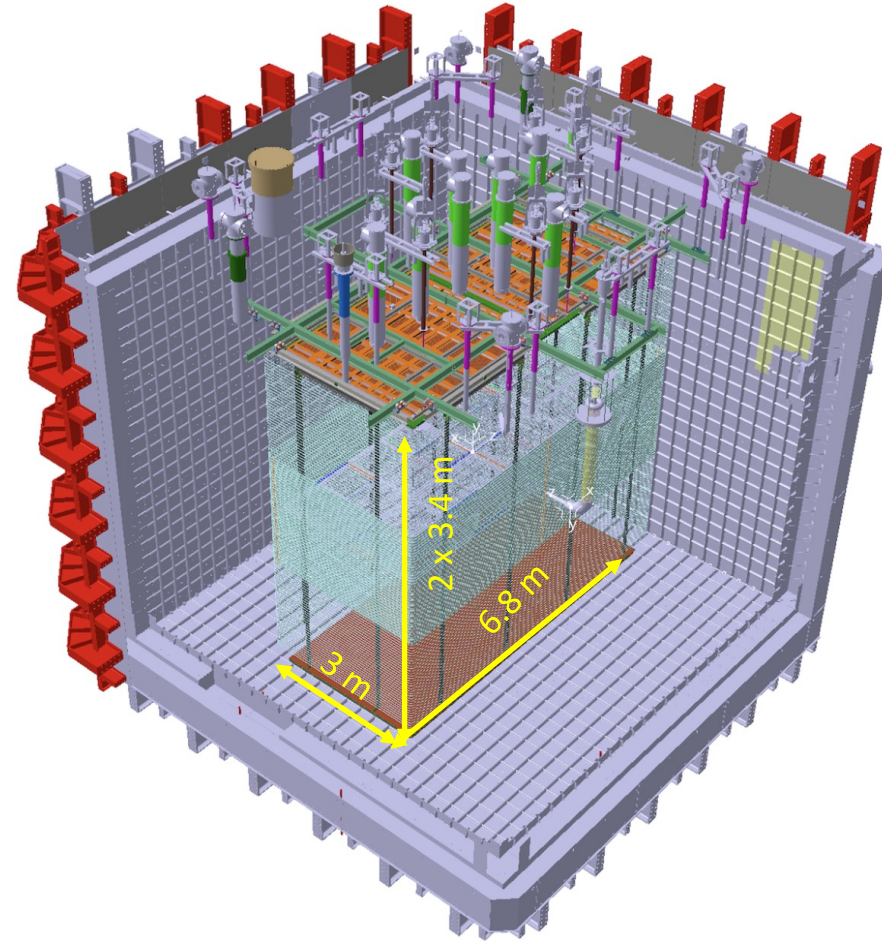
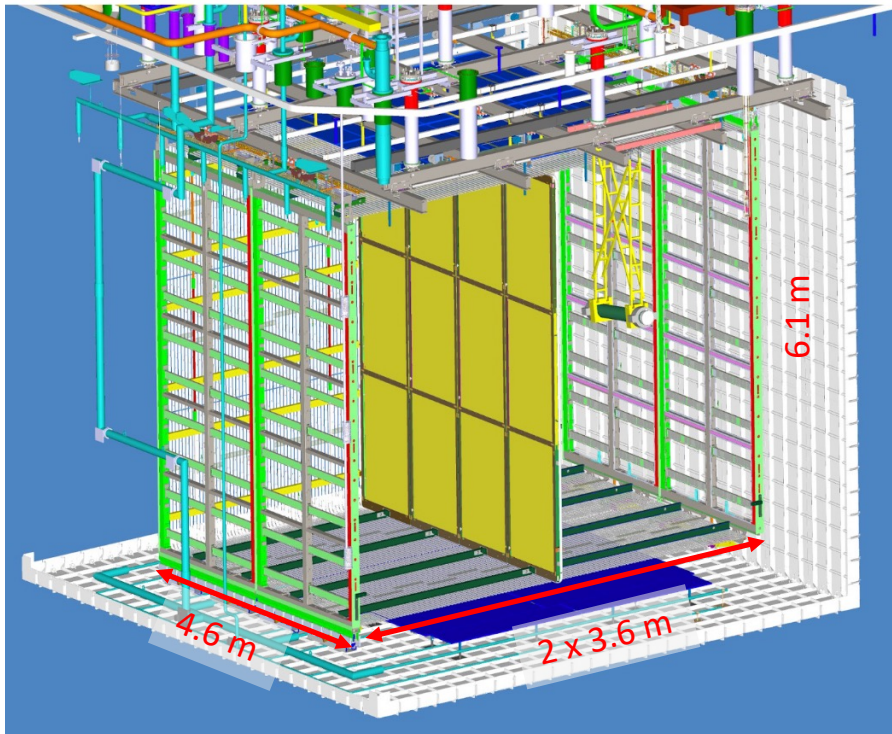
- Construction and operation of ProtoDUNE_s at CERN (2018-2020)
- Successful demonstration of the DUNE LAr TPC performance
- Dual-Phase evolved towards a single-phase vertical (VD) drift technology
- Physics analyses: Michel electrons, measurement of p/π/K – Ar cross sections (inclusive/exclusive), ...

SECOND PHASE PROTODUNE_s (2020-now)

- **ProtoDUNE-HD** (operation in 2024)
 - Final technical solutions for all FD-HD subdetectors
 - Data taking in 2024 with test-beam and cosmic muons
- **ProtoDUNE-VD** (operation in 2025)
 - Installation completed in Nov 2024
 - Charged-particle beam data taken in 2025 and continuing with cosmic runs



ProtoDUNE-HD / ProtoDUNE-VD





Horizontal Drift

- APA: three sets of wires winded around a SS frame
- Electronics in LAr including digitisation
- Drift of 3.5 m, CPA at -175 kV nominal voltage
- PDS embedded in the APA frames

ProtoDUNE-HD

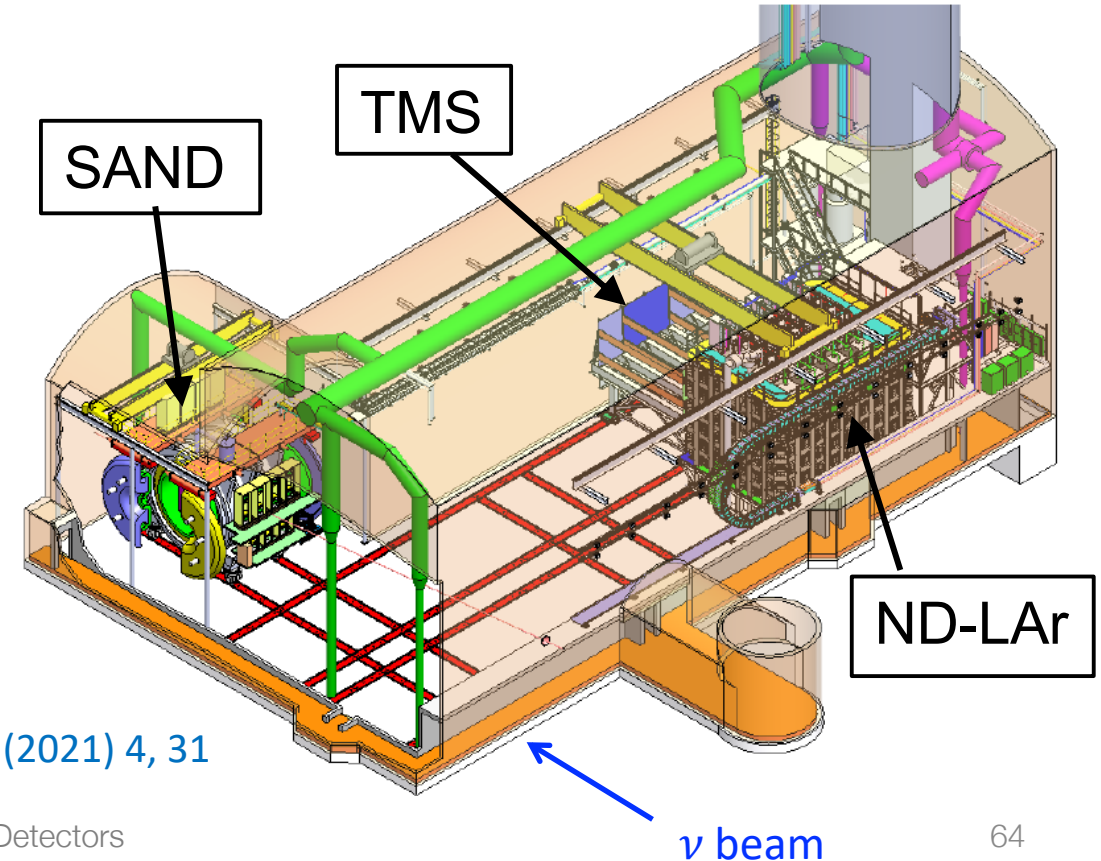
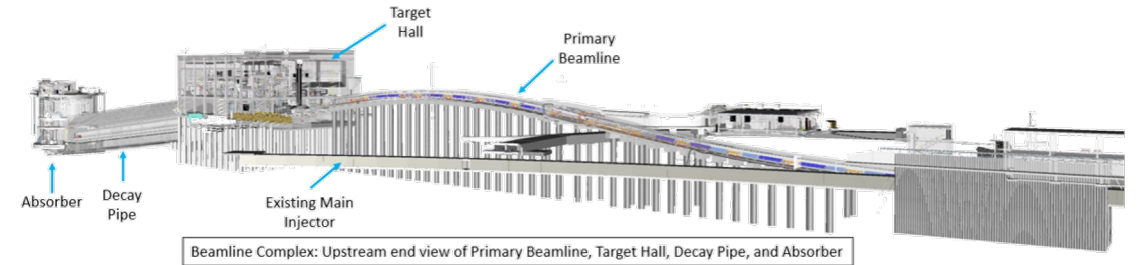
Vertical Drift

- CRP: perforated PCBs stuck with electrodes segmented
- Top CRPs readout with accessible electronics
- Bottom CRPs electronics in LAr including digitisation
- Cathode in the middle, 3.2 m drift, -300 kV nominal
- PDs on the cryostat walls and on the cathode

ProtoDUNE-VD

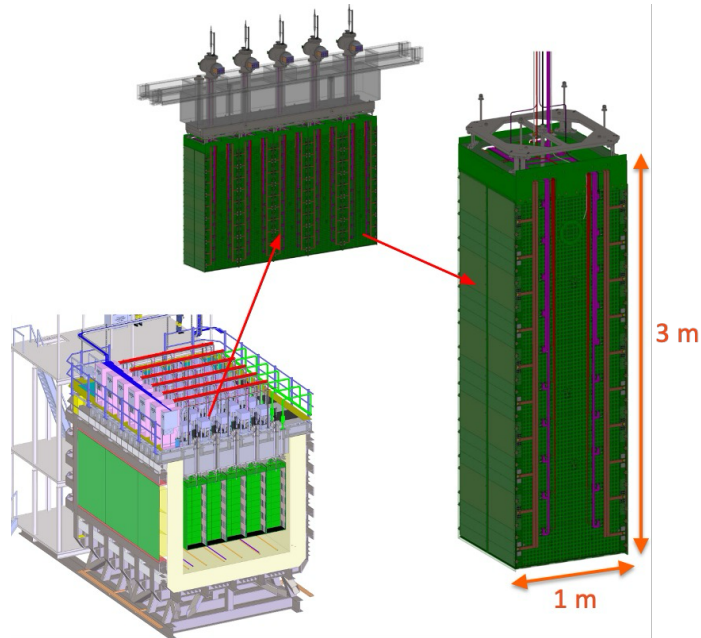
DUNE Near Detector Complex

- Main purpose: enable prediction of Far Detector reconstructed spectra
- **Movable detector system** (DUNE-PRISM): LArTPC (**ND-LAr**) with muon spectrometer (**TMS**)
 - Off-axis data in different neutrino fluxes constrains energy dependence of neutrino cross sections
 - Same target, same technology → inform predictions of reconstructed E_ν in Far Detector
- On-axis magnetized detector (**SAND**) for beam monitoring and neutrino measurements

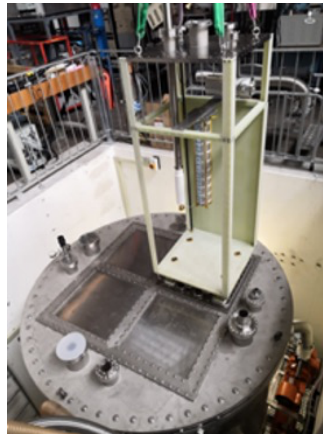


CDR: Instruments 5 (2021) 4, 31

ND-LAr pixelated detector



ND-LAr 2x2 demonstrator: Operation of a 330k pixel LArTPC in a GeV-energy antineutrino NuMI beam

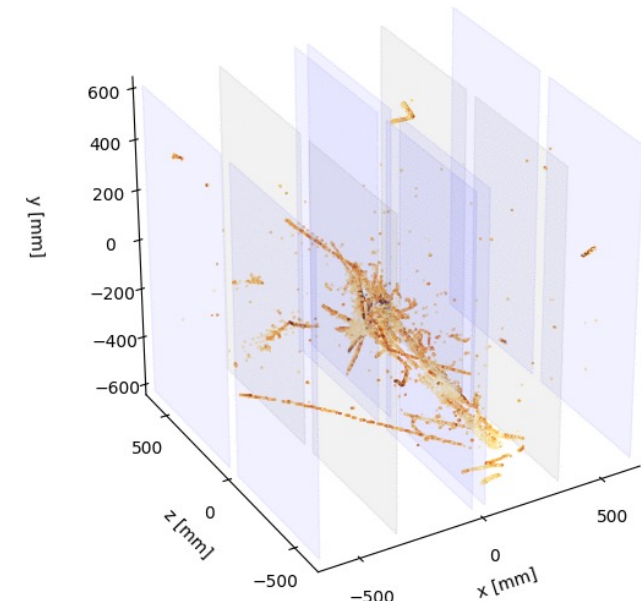


- Modules suspended from cryostat lid, immersed in LAr bath
- **ND-LAr TPC Module (150 ton)**
 - A fiberglass box, 1m x 1m, 3m tall
 - Divided vertically by a cathode (resistive film on fiberglass)
 - Two pixelated anodes (printed circuit boards) opposite cathode
 - Remaining walls provide field cage (resistive film on fiberglass)
 - Side field cage walls covered by scintillation light traps (two types)
 - Top/bottom walls perforated (allows LAr flows from top to bottom)



First DUNE Near Detector 2x2 Demonstrator neutrino events (July 2024)

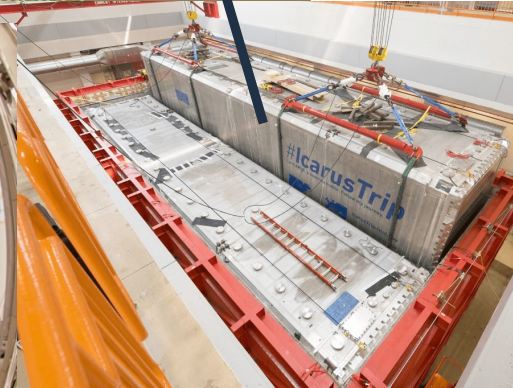
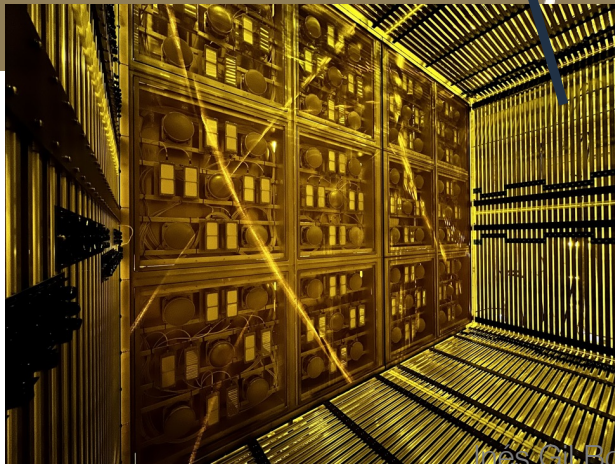
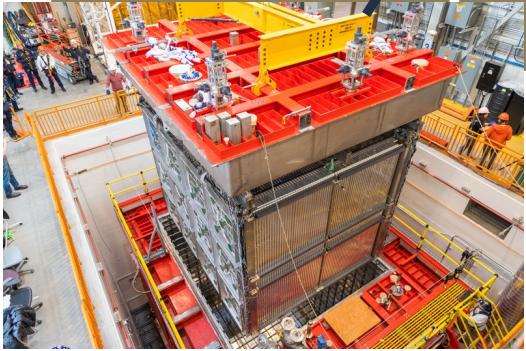
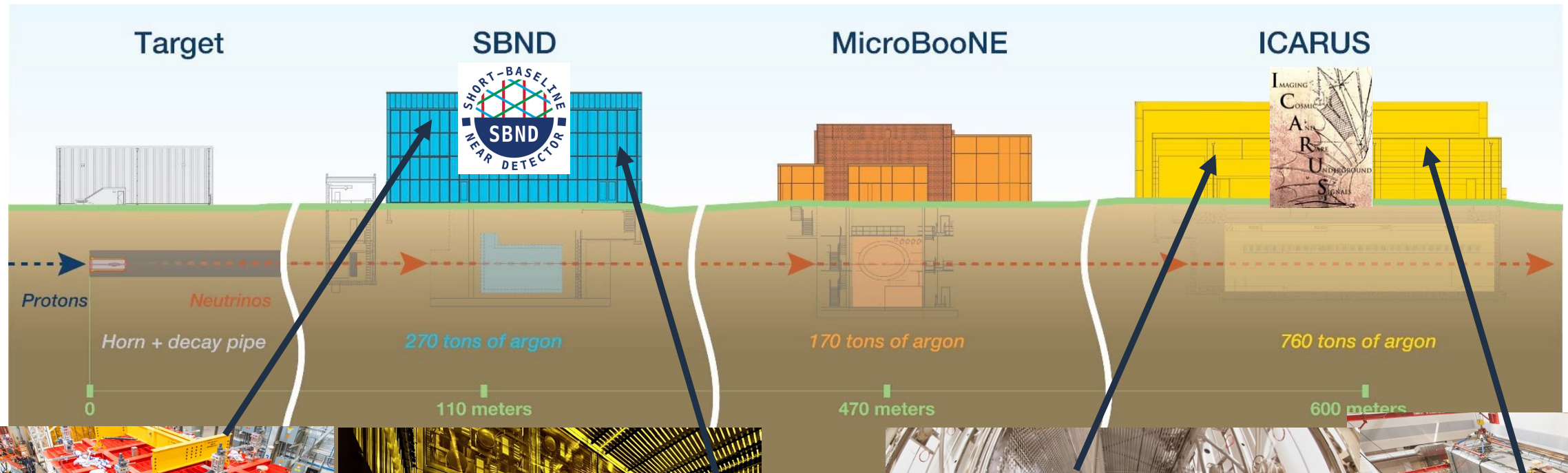
Event 20, ID 20 - 2024-07-08 00:20:14 UTC



Full-Scale Demonstrator ND-LAr module operated at Uni Bern (70M cosmic ray events)

Short-Baseline Neutrino Program at FNAL

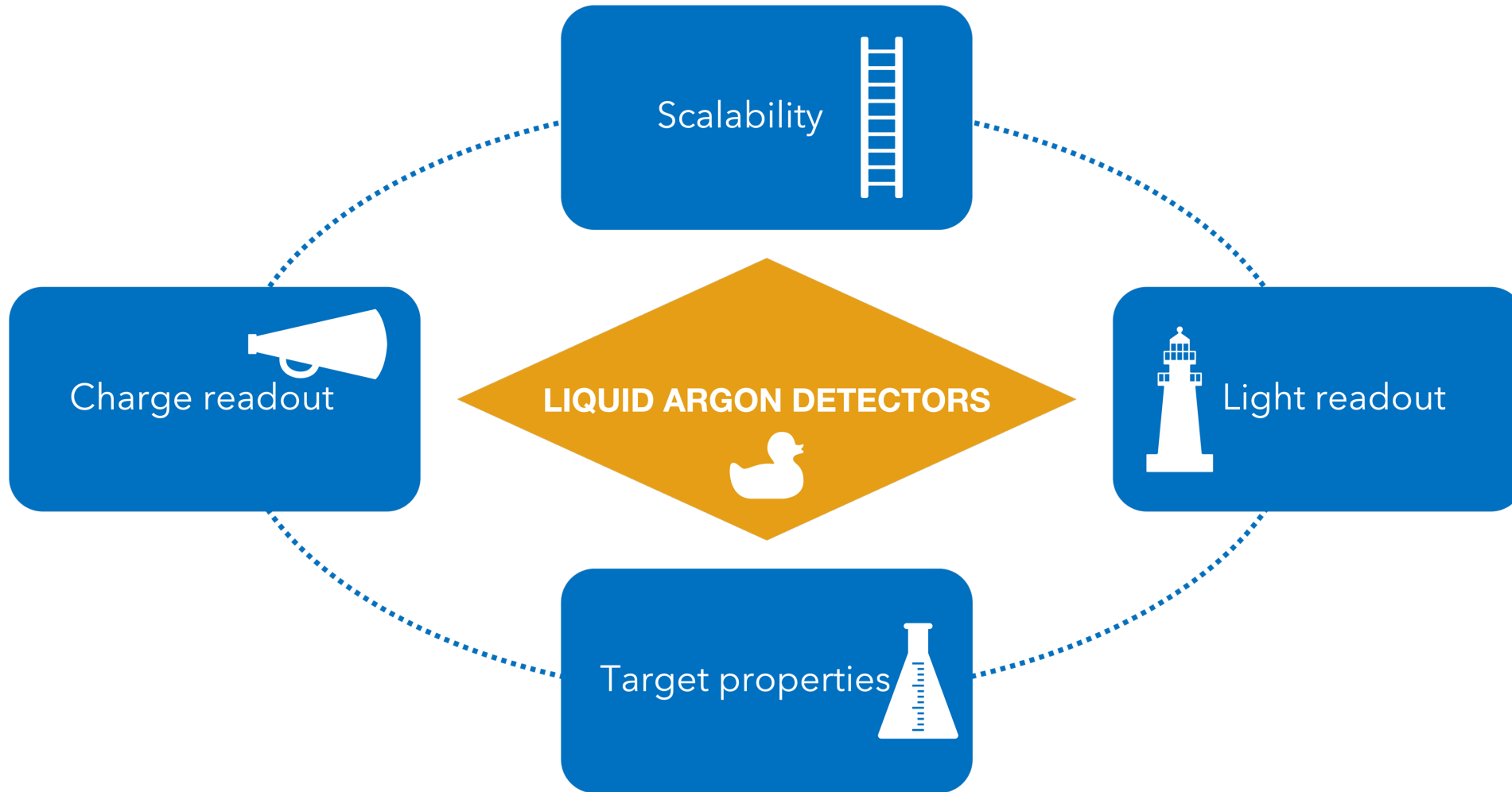
3 LArTPCs along the Booster Neutrino Beam line (ICARUS & SBND in operation)



SECTION 5

New technological directions

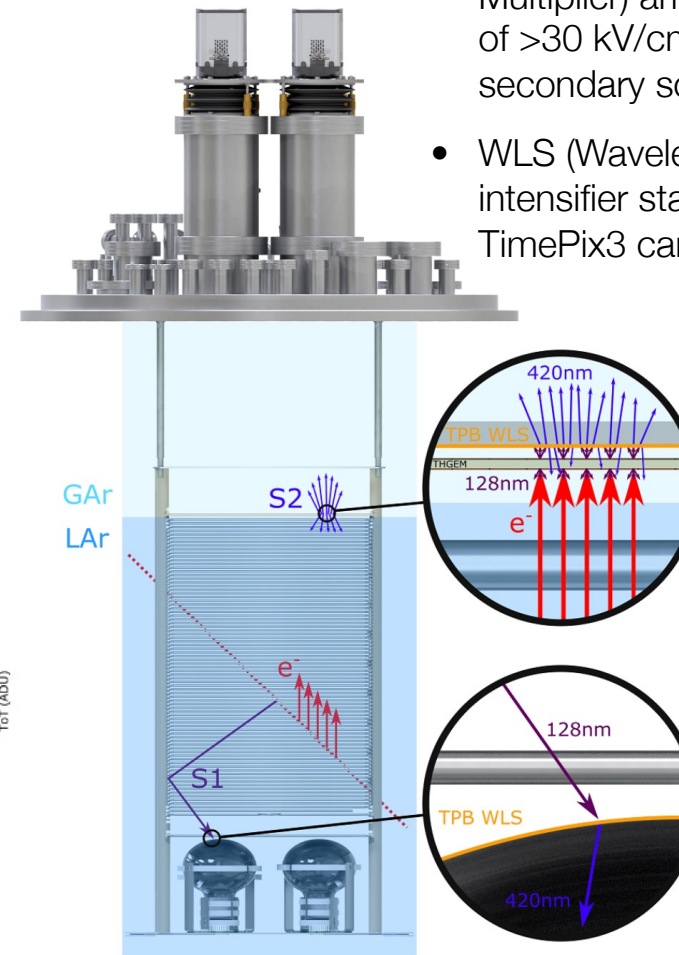
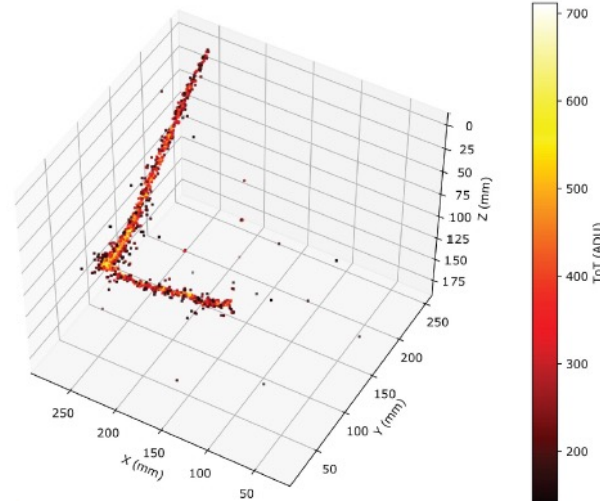
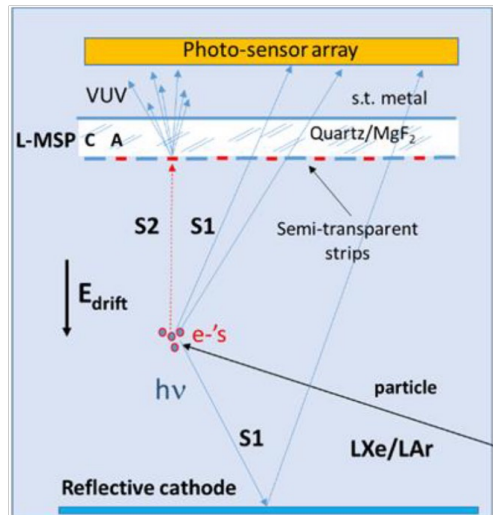
Main R&D topics on argon detectors





Charge readout

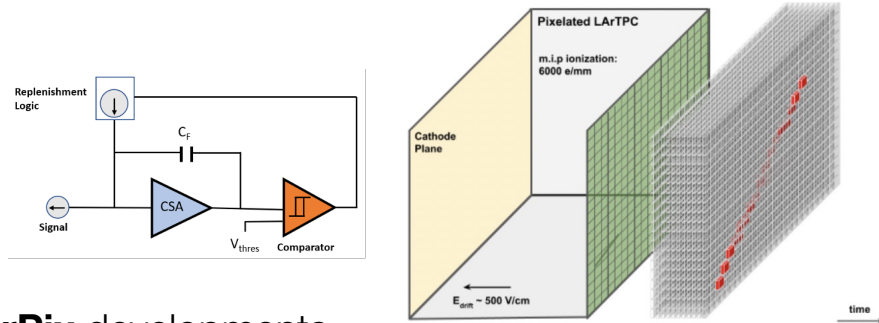
- R&D on technologies to amplify the charge signal in liquid noble time projection chambers (TPCs)
 - S2 light signal in dual-phase Ar and Xe optical TPCs
 - Charge amplification in LArTPCs and conversion to light
 - Novel microstructures for light production



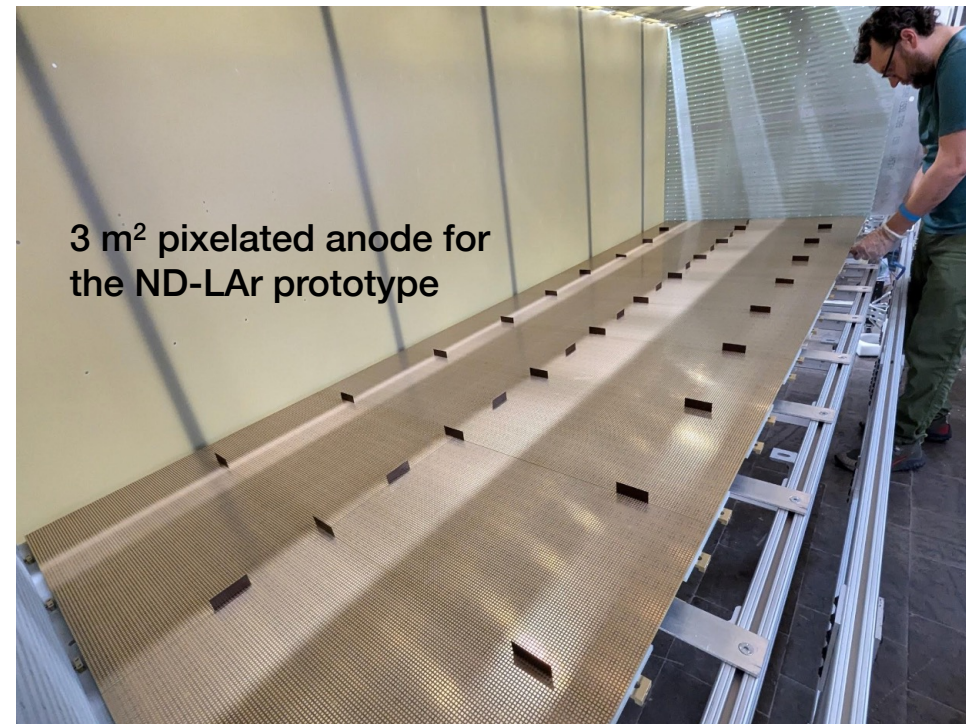
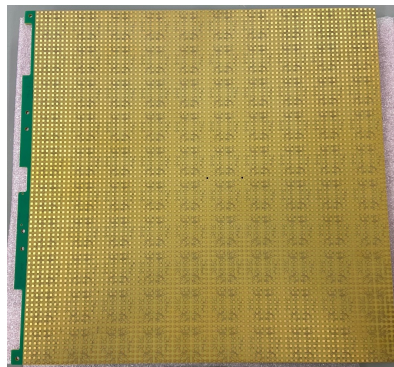
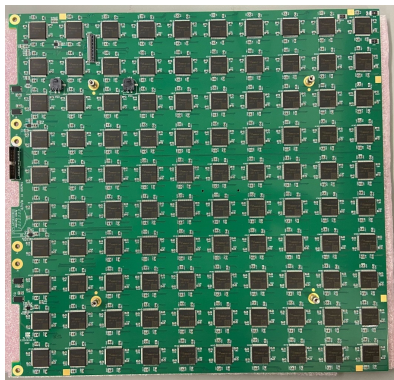
- A THGEM (THick-Gaseous Electron Multiplier) amplifies drift charge (capable of >30 kV/cm in LAr) generating secondary scintillation light (S2)
- WLS (Wavelength Shifting) for an intensifier stage before imaging with TimePix3 camera

R&D on pixel readouts

- 3D imaging, lower power, lower pixel thresholds
- **Q-Pix** developments

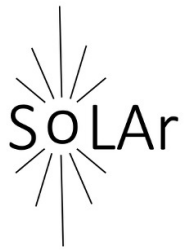


- **LArPix** developments
 - Low power, integrating amplifier with self-triggered digitization and readout
 - Constructed LArPix v1 ASIC: Cryogenic-compatible, Low-power: 62 $\mu\text{W}/\text{channel}$, Low-noise: 275 e^- ENC @ 87K; improved LArPix v3 under testing



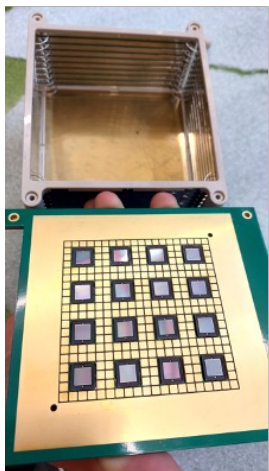
3 m² pixelated anode for the ND-LAr prototype

SoLAr project: pixels + light readout

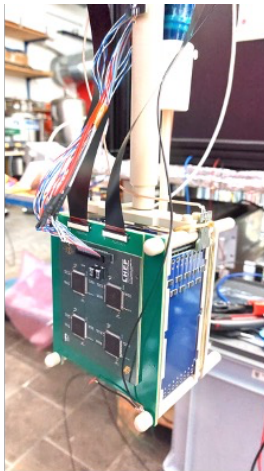


- **Pixelated charge readout** (enhanced event reconstruction) **with HPK VUV4 SiPMs integrated in the anode** (Q+L calorimetry and enhanced E resolution $\sim 7\%$) with background suppression (passive shielding, PSD, ...)
- Physics goal: enhance the detection of low-energy neutrino signals (in particular solar ν s)
- Prototype v1 (LAr TPC 12x11 cm² x 5 cm drift): cosmics test run at Bern in Oct 2022
 - First demonstration of combined light and charge readout on the same anode plane
- SoLAr_v1 prototype demonstrator published: [JINST 19 \(2024\) 11, P11010](#)

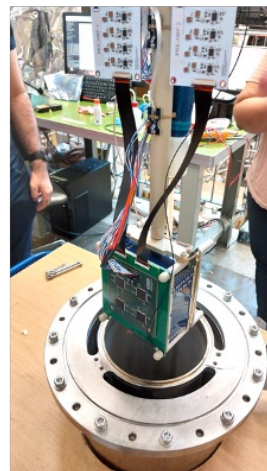
- Charge pixel pads: 3mm
- Pixel pitch: 3.5mm
- SiPM sensitive area: 6mm x 6mm
- SiPM pitch: 17.5mm
- Readout area: 70mm x 70mm



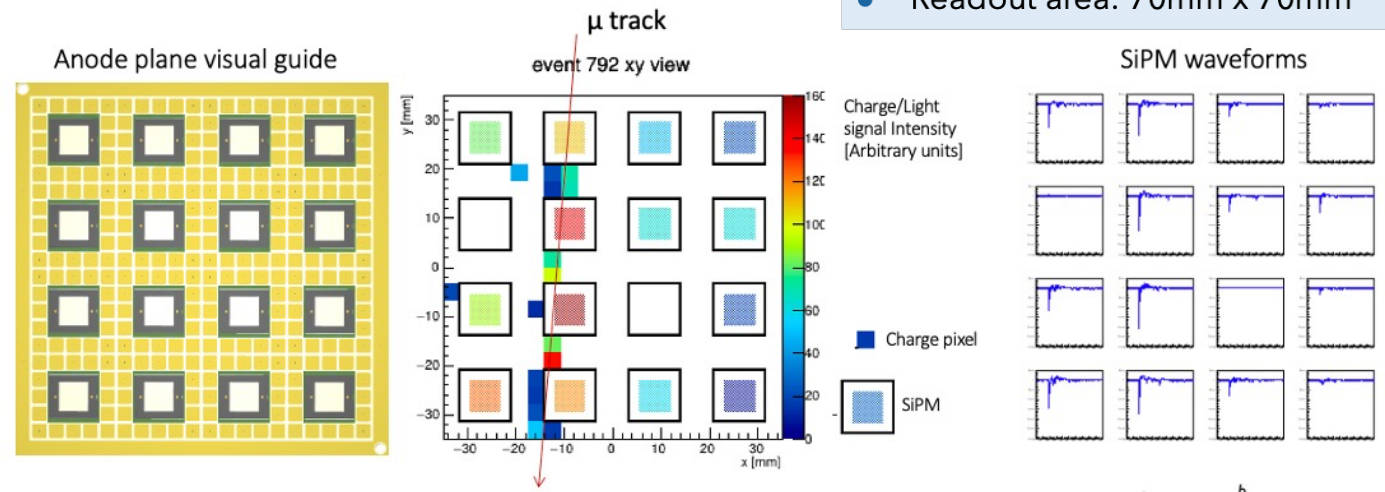
Inside the TPC



SoLAr-v1 TPC



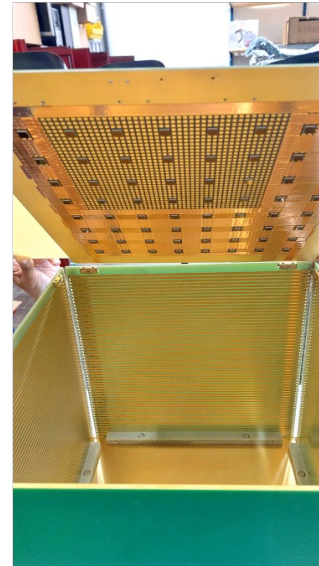
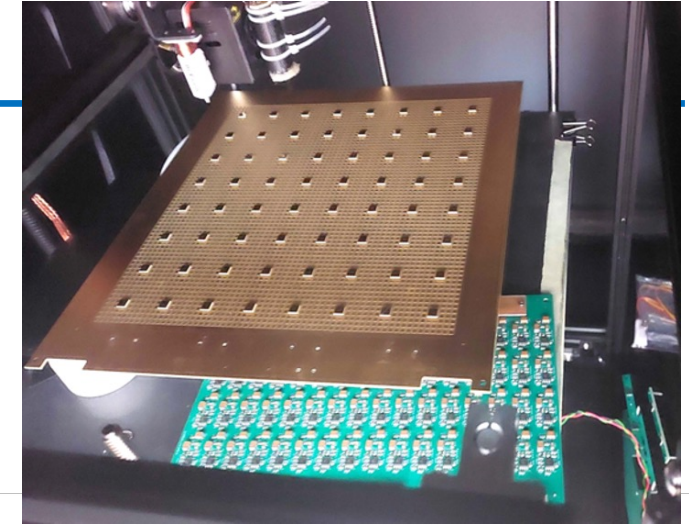
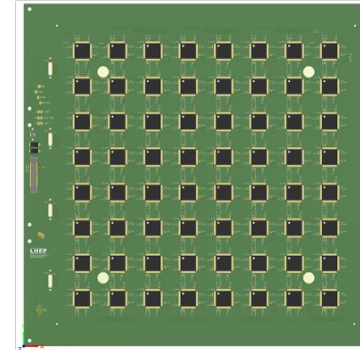
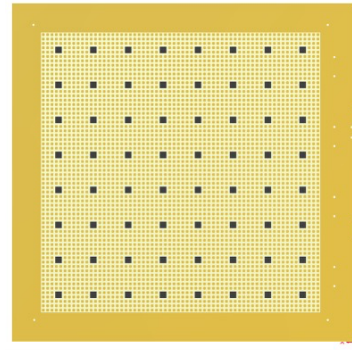
Insertion into cryostat



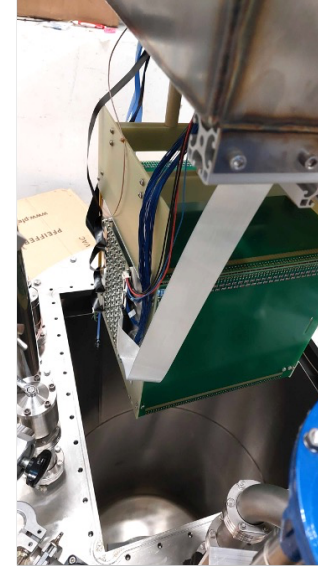
SoLAr prototype v2

JINST 21 (2026) 04, P04008

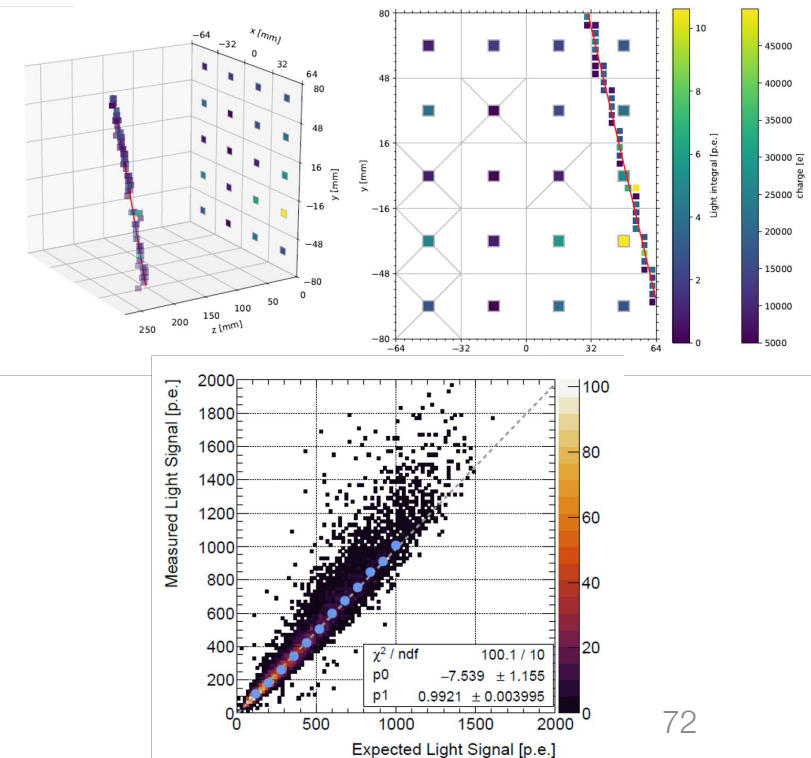
- New LArTPC prototype
 - 8-layer PCB, dimensions 31cm x 32 cm
 - Divided into 8x8 regions: 1 region = 60 pixels+1 SiPM; pixel pitch: 4mm
- 64 LArPix (60 routed channels)
- 64 Hamamatsu VUV SiPMs
 - SMD type, 6 mm x 6 mm
 - SiPM pitch: 32 mm
- Cosmics test run at Bern in July 2023 at nominal HV 15 kV and special Cobalt-60 source run
- Anode tile was populated with 64 VUV SiPMs and 20 LArPix v2b chips

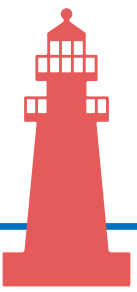


Inner view of the TPC



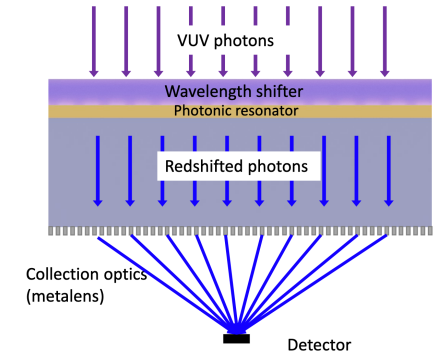
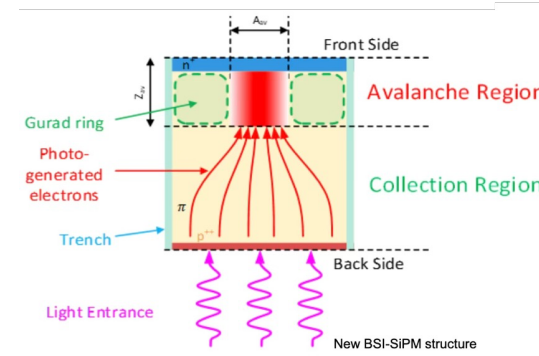
Insertion into cryostat



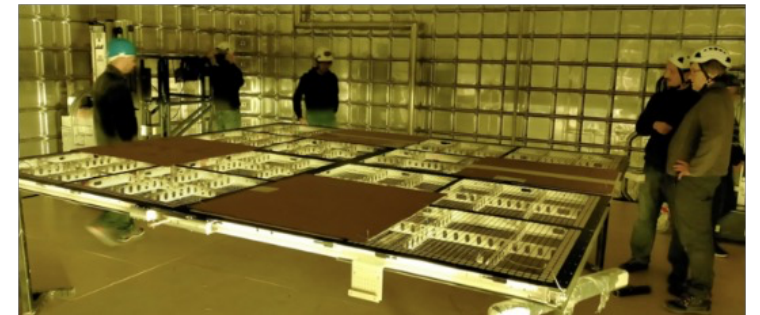
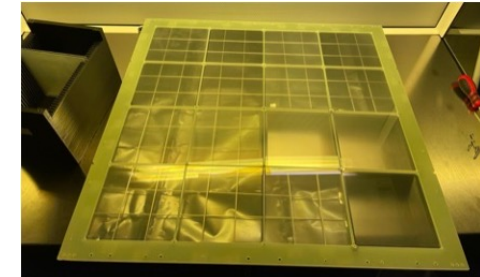
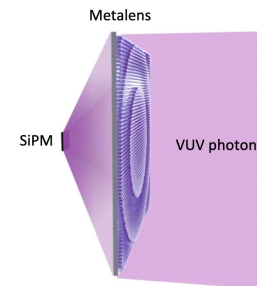


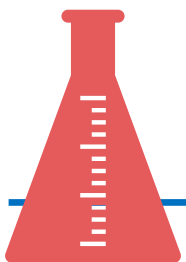
R&D on VUV light detection

- Goal: increase **photon detection efficiency** and **photon collection capabilities**
 - Large area WLS and reflectors: new materials, characterization facilities
 - Organic photosensors & digital cryogenic SiPMs (CMOS SPADs and plans for BSI SPADs)
 - Photodetectors in HV environment:
 - Instrument field cage and cathode to increase photocoverage in TPCs using Power-over-Fiber and Signal-over-Fiber
 - Development of dedicated cryogenic facilities for VUV sensor characterization and optimization
- But also **improving timing** capabilities (~ 100 ps) of VUV-sensitive cryogenic photon detectors
- R&D on cryogenic **back-side illuminated SiPMs**
 - R&D with FBK NUV-BSI SiPMs



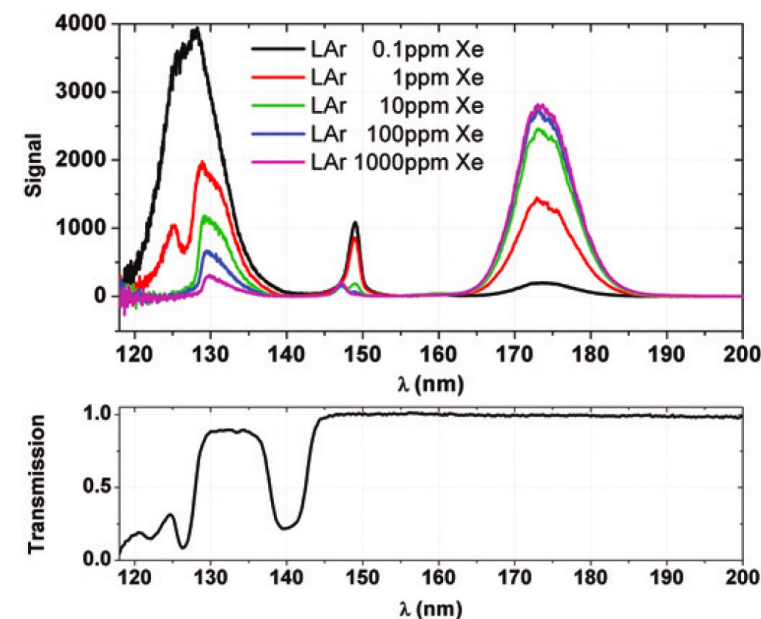
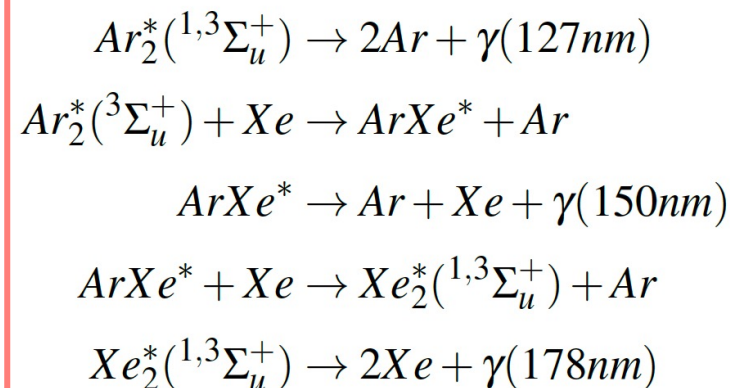
Light concentration with a VUV metalens





Target properties

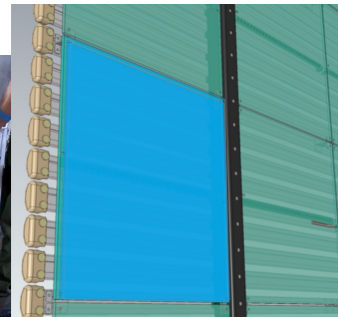
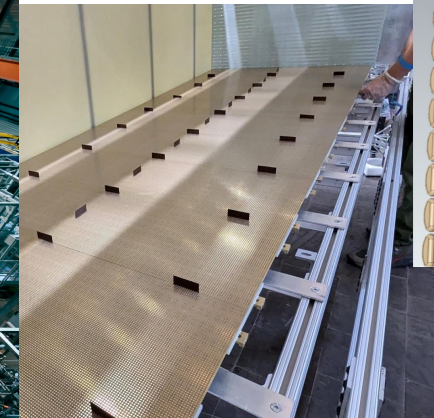
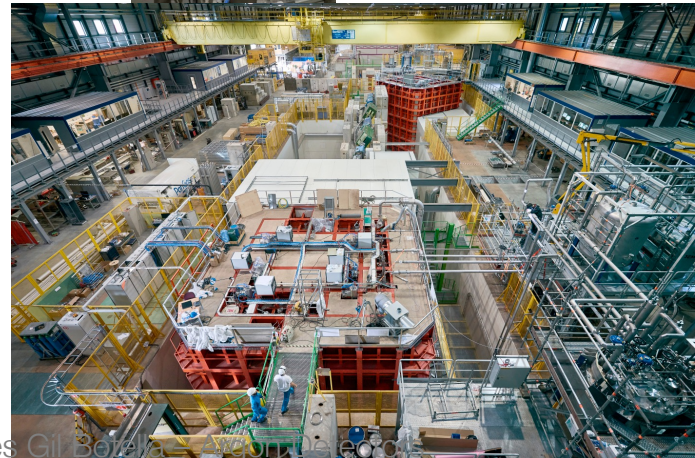
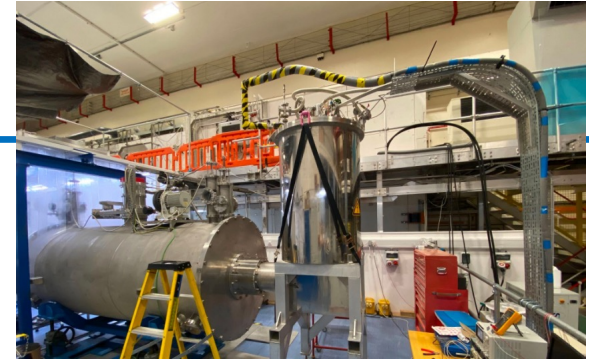
- **Isotope loading** of noble liquids
 - **Xenon doped-LAr**: shift 127 nm wavelength to 178 nm
 - Xe also affects photon propagation
 - It acts as an impurity, suppressing part of the spectrum at 127 nm (mainly fast component)
 - For 150 and 178 nm photons in LAr, $\lambda_{RS} \sim 3.5$ m and 8.3 m, respectively.
 - Advantages:
 - More uniform light distribution
 - Increase light yield and detection efficiency
 - Possible mitigation for N₂ contamination
 - Being tested at large-scale in ProtoDUNE at CERN





Scalability

- Radiopurity & background mitigation
 - Radioassay techniques
 - Novel materials for background suppression
 - Rn emanation facilities
- Target procurement, production & purification
 - Underground Ar: low radioactivity argon i.e. depleted in ^{39}Ar
 - URANIA extraction plant & ARIA & DART
 - LowRad: ^{85}Kr and ^{222}Rn cryogenic distillation & novel purification
- Large-area readouts
 - Large-scale testing facilities
 - Large-scale charge and light readout systems





SUMMARY

Summary

- Argon detectors are a cornerstone technology for current and next-generation neutrino and dark matter experiments.
- Significant R&D efforts have successfully tackled major engineering and physics challenges, enabling large-scale detector implementation (~kton LArTPCs).
- Exciting new technologies are being explored for liquid noble gas detectors, pushing performance beyond the current limits.
- Active R&D efforts include new cryogenic VUV photosensors, enhanced timing, novel charge readout, scalability, characterization infrastructures, among others.
- Argon detectors are well placed to drive major physics discoveries.

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