Liquid Argon Detector Technologies

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Nufact25, Liverpool, September 5th 2025

Outline

Single Phase LAr Neutrino TPCs and R&D

- **Wire Technology**
  (ICARUS T600, MicroBooNE, SBND, Proto/DUNE HD/VD)
- **Perforated PCB anode**
  (Vertical Drift)
- **Pixelated Charge**
  (DUNE ND/LArPix/QPiX/SoLAr)

Dual Phase LAr TPCs and R&D

Neutrinos

- **S2 Optical readout**
  (ARIADNE)

Dark Matter

- **S1 and S2 Light Readout**
  (Darkside-20k)

Knowledge exchange & S1 Light collection optimization efforts (ie APEX, PoWER)

Note: Material presented is the work of many people/collaborations, public links provided where possible

Why Liquid Argon?

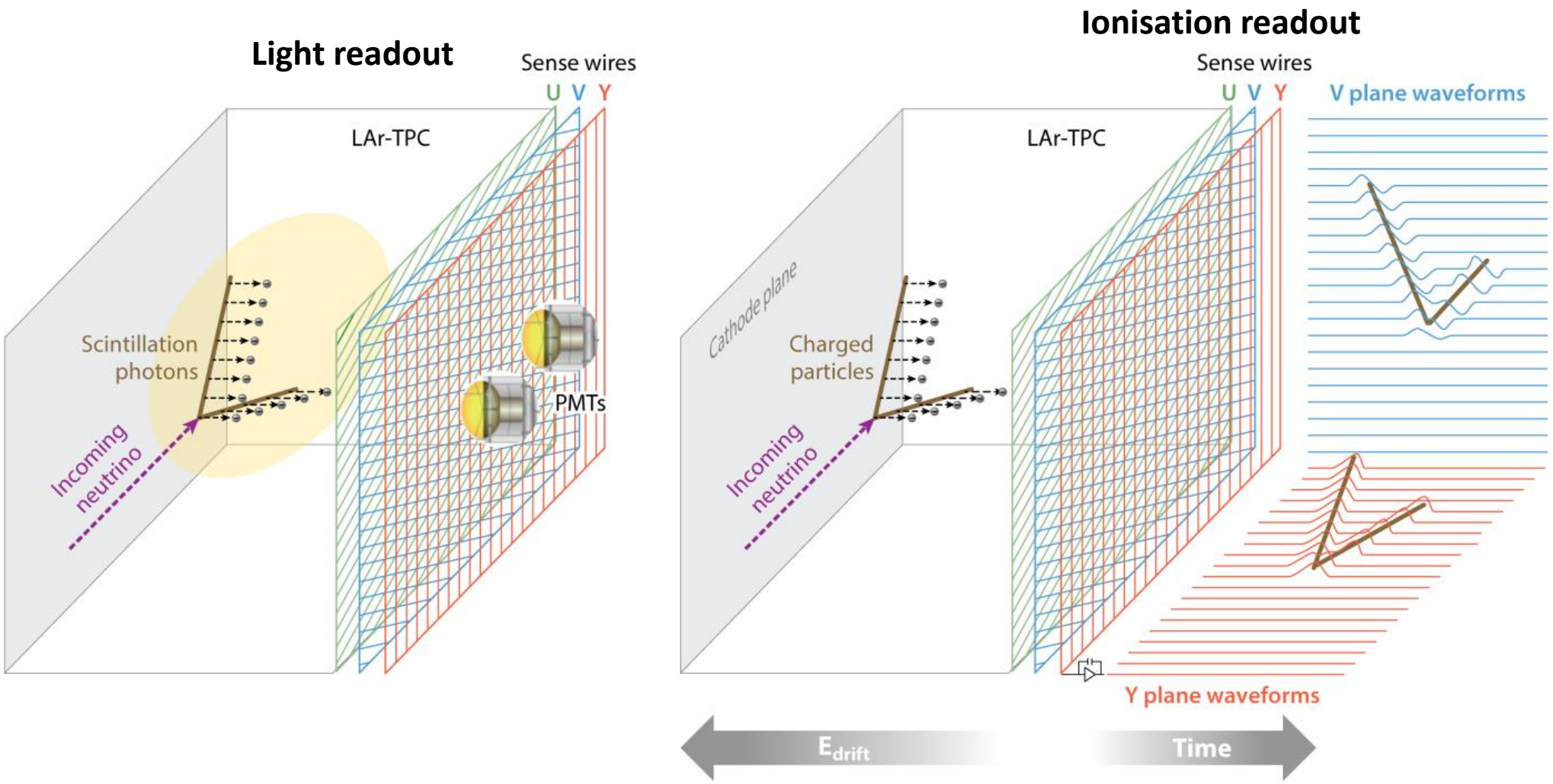
- ✓ **Dense**: 40% denser than water
- ✓ **Easy ionization**: 55 000 e^-/cm for MIPs
- ✓ **High electron lifetime** if purified → long drifts
- ✓ **High scintillation light yield**: 40k γ/MeV
- ✓ **Pulse shape discrimination ability:** (S1:fast 6ns/slow 1.6 μs)
- ✓ **Abundant:** ~1% of the atmosphere (needs ^{39}Ar depletion for DM)
- ✓ **Cheap**: $2/L ($3000/L for Xe, $500/L for Ne)

Major R&D challenges toward kton scale LAr TPCs

kton scale LAr TPCs

- Ultra-high purity liquid argon in non evacuated vessels
- Very long e^- drift length requires very high voltage Systems 100kV - 600 kV
- Scalable light readout methods – high granularity tracking & good energy threshold
- Cryostats & cryogenics
- multichannel DAQ system & Cold electronics
- Scalable charge readout methods – high granularity tracking & good energy threshold

LAr Single Phase Wire Technologies



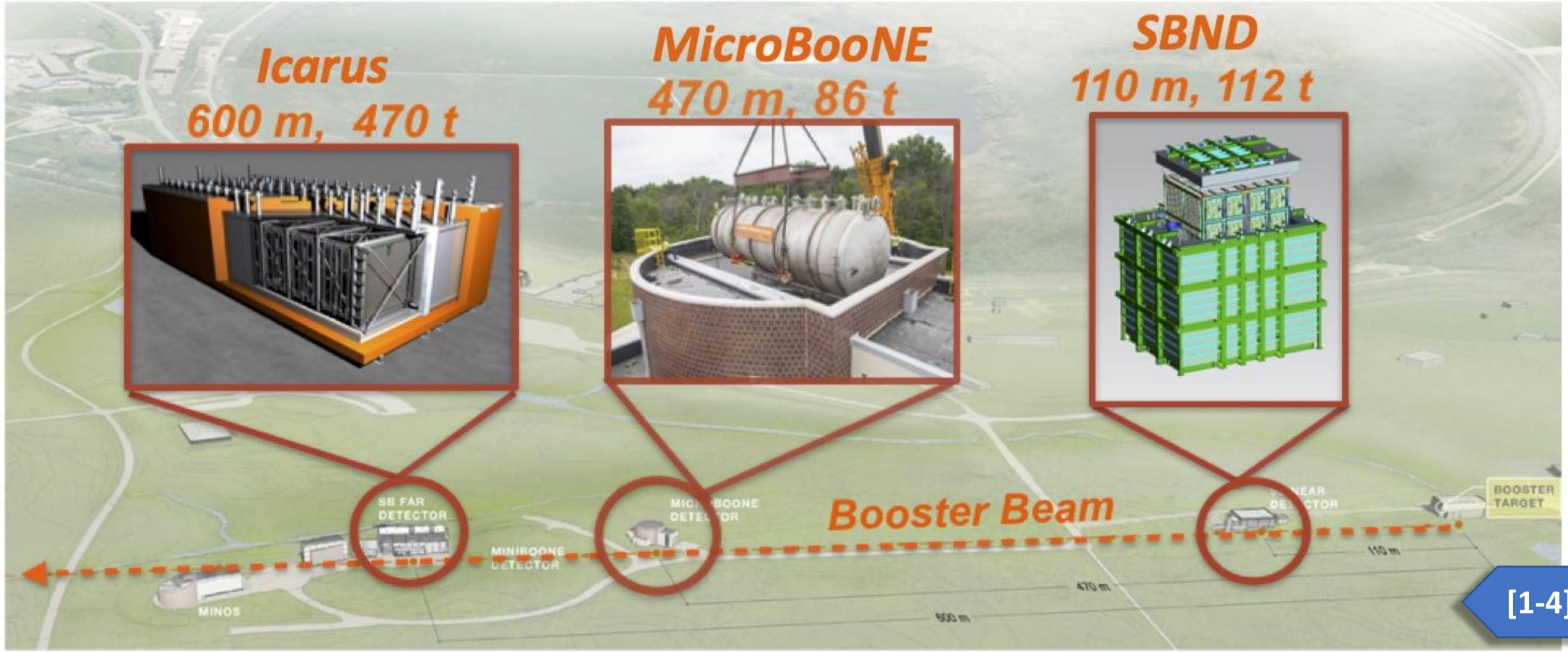
3D image reconstruction by combining coordinates on different wire planes at the same drift time

No electron gain from the wires

Machado PAN, et al. 2019.
Annu. Rev. Nucl. Part. Sci. 69:363–87

LAr Single Phase Experiments in the SBN Program

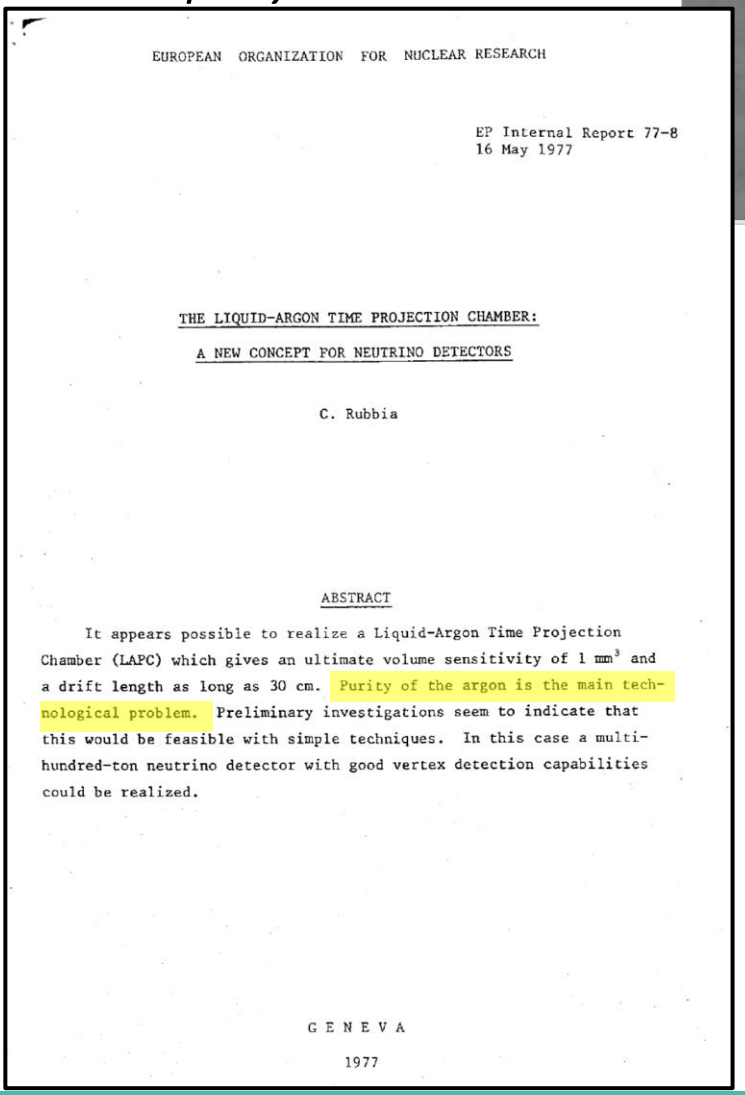
- Program aims at solving the “sterile neutrino puzzle” by exploiting the well characterized FNAL Booster ν beamline



[1-4]

ICARUS T600

1977 - the LArTPC
Concept by C. Rubbia



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

EP Internal Report 77-8
16 May 1977

THE LIQUID-ARGON TIME PROJECTION CHAMBER:
A NEW CONCEPT FOR NEUTRINO DETECTORS

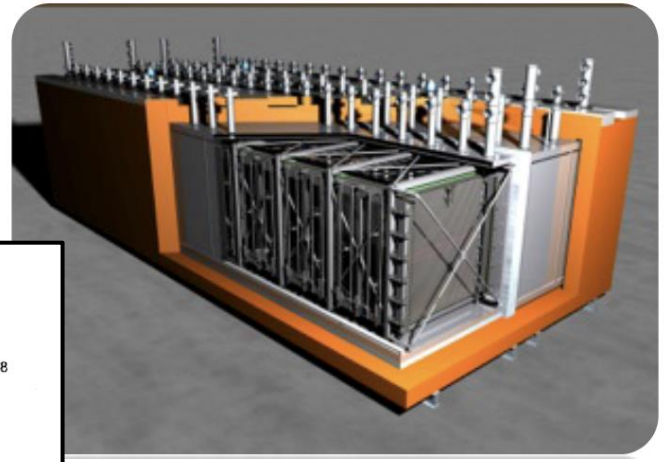
C. Rubbia

ABSTRACT

It appears possible to realize a Liquid-Argon Time Projection Chamber (LAPC) which gives an ultimate volume sensitivity of 1 mm^3 and a drift length as long as 30 cm. Purity of the argon is the main technological problem. Preliminary investigations seem to indicate that this would be feasible with simple techniques. In this case a multi-hundred-ton neutrino detector with good vertex detection capabilities could be realized.

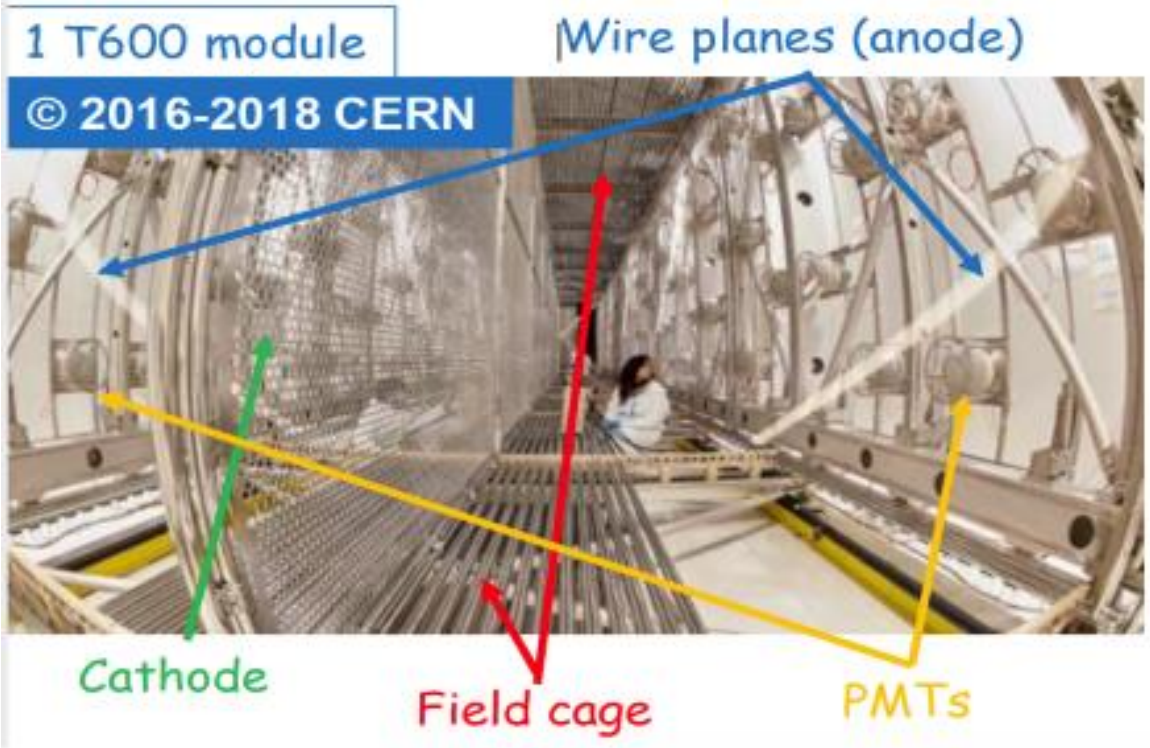
G E N E V A

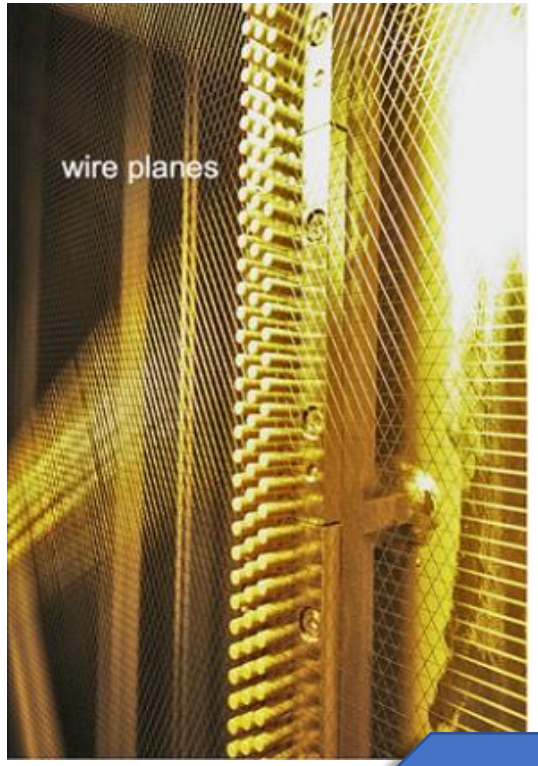
1977



- **ICARUS _ Running**
  - 760 t of LAr (476 t active), 600 m from target.
  - 4 TPCs with 1.5 m drift.
  - 360 8” PMTs coated with TPB.
  - Almost full CRT coverage.

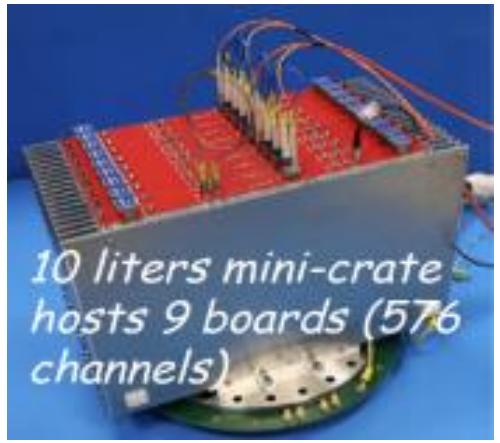
First physics result, Phys. Rev. Lett. 134, 151801 (2025)



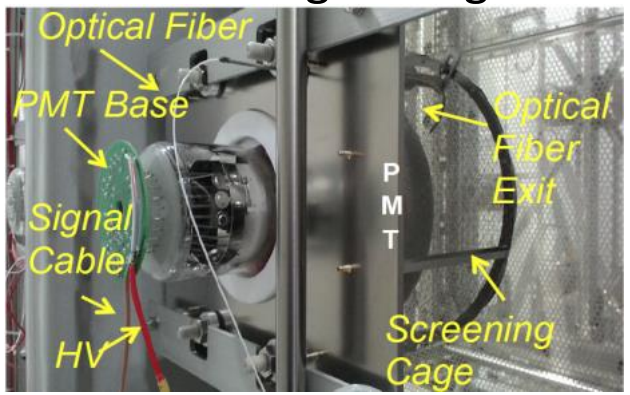


[1-4,19]

ICARUS T600



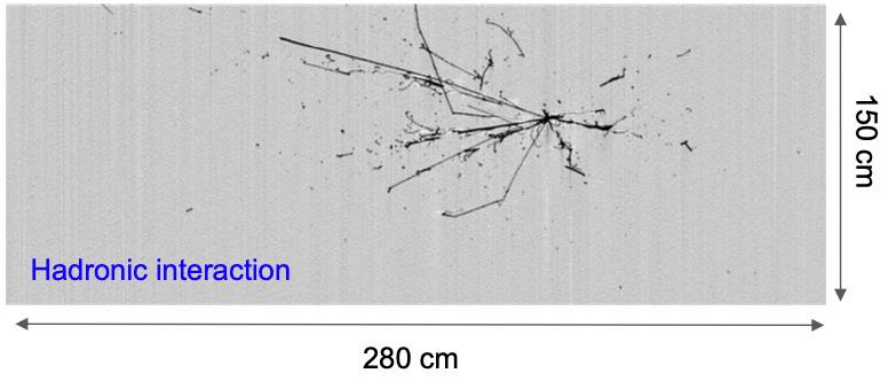
- "warm" low-noise front-end amplifier
- Compact layout: both analog+digital electronics hosted on a single flange

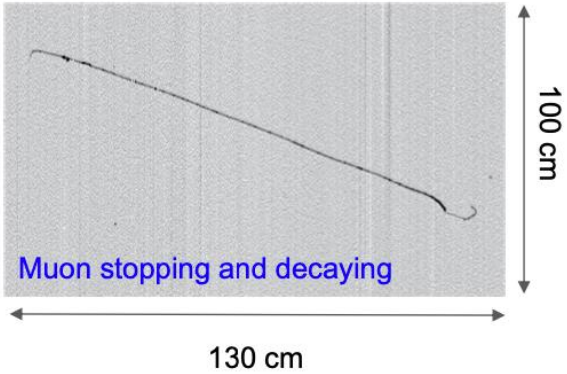


ICARUS PMTs behind the wire planes (90 per TPC)

Provide $\mathbf{t_0}$ of any ionizing event in the TPC

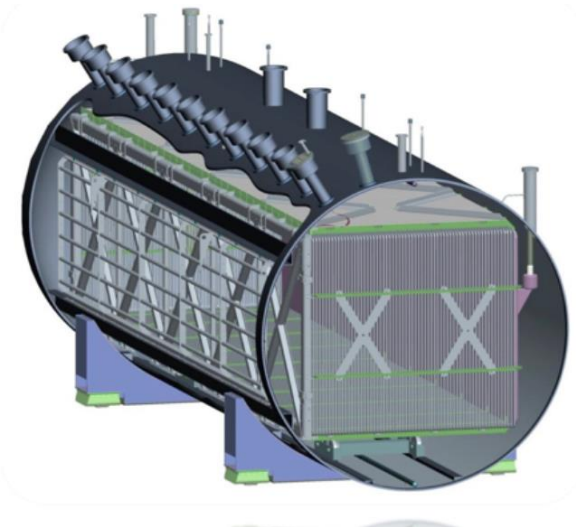
Sample Icarus event displays





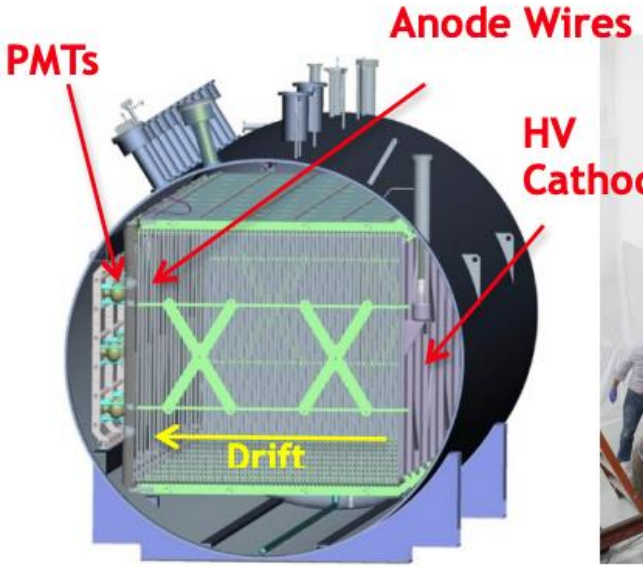
[1-4]

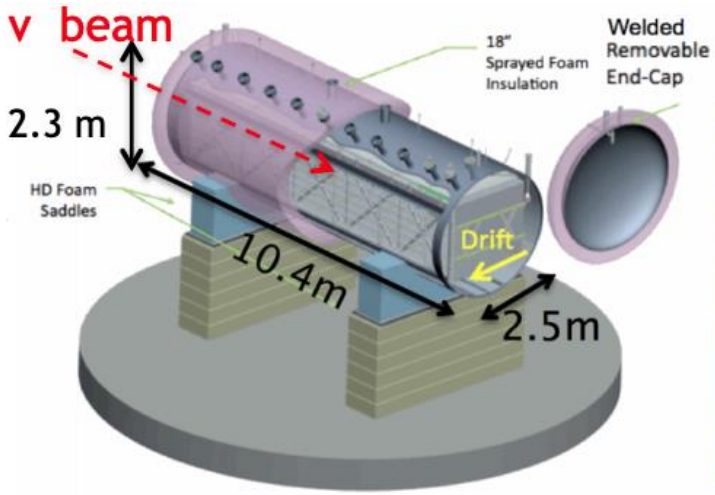
MicroBooNE



- **MicroBooNE _ physics run completed**
  - 170 t of LAr (87 t active), 470 m from target.
  - 1 TPC with 2.5 m drift.
  - 32 8” PMTs on acrylic support coated with TPB.
  - Top and side CRT.
  - UV calibration LASER

(See slides also from Magnus Handley and Afroditi Papadopoulou @Nufact 25)





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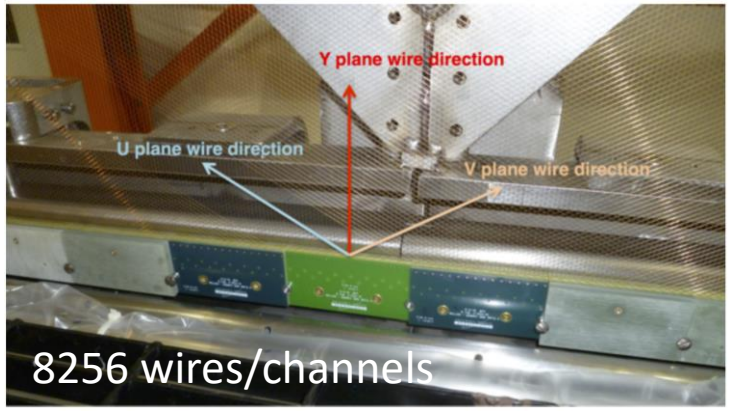
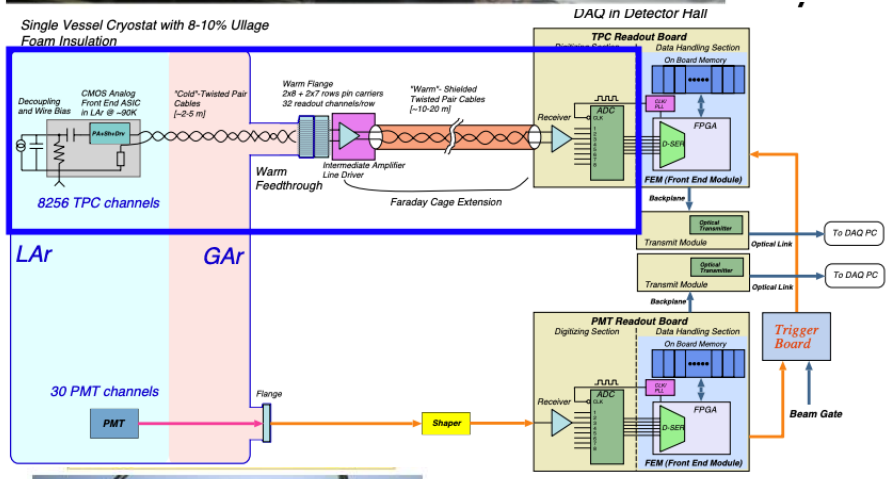
MicroBooNE

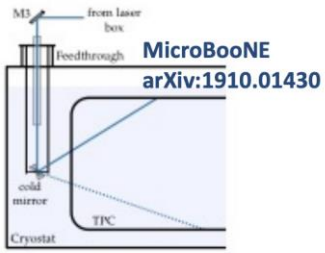


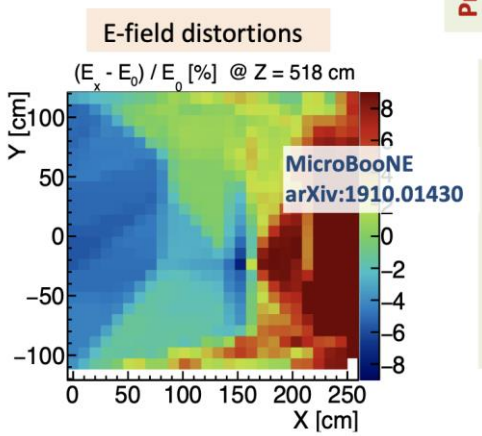


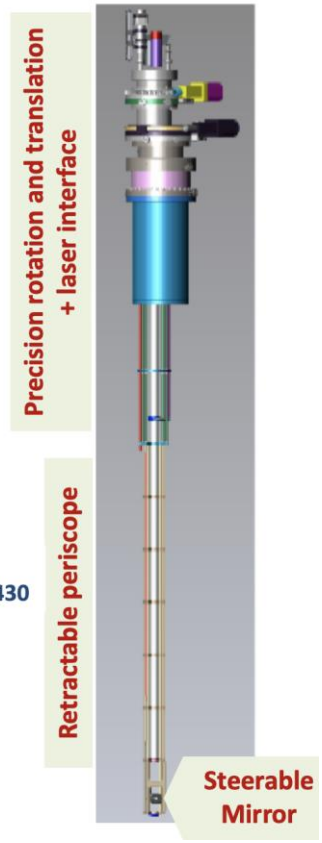
ASIC Configuration Board

MicroBooNE is the first experiment instrumented with cold CMOS ASICs

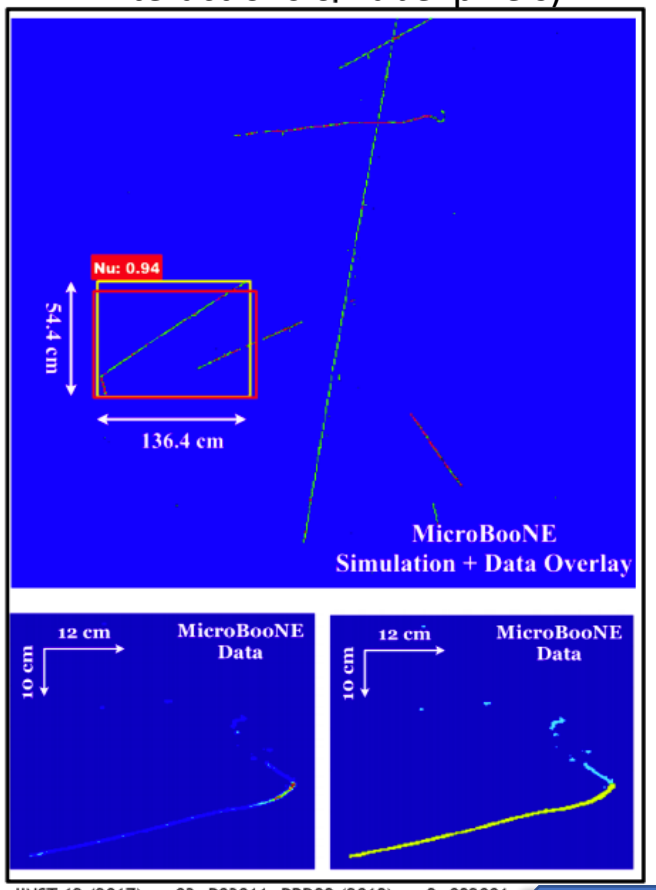
Calibration LASER
(multiphoton ionization)







Deep Learning
Convolutional Neural Nets
(Leverage advances in computer vision and AI techniques to identify neutrino interactions or label pixels)



JINST 12 (2017) no.03, P03011, PRD99 (2019) no.9, 092001

[1-5]

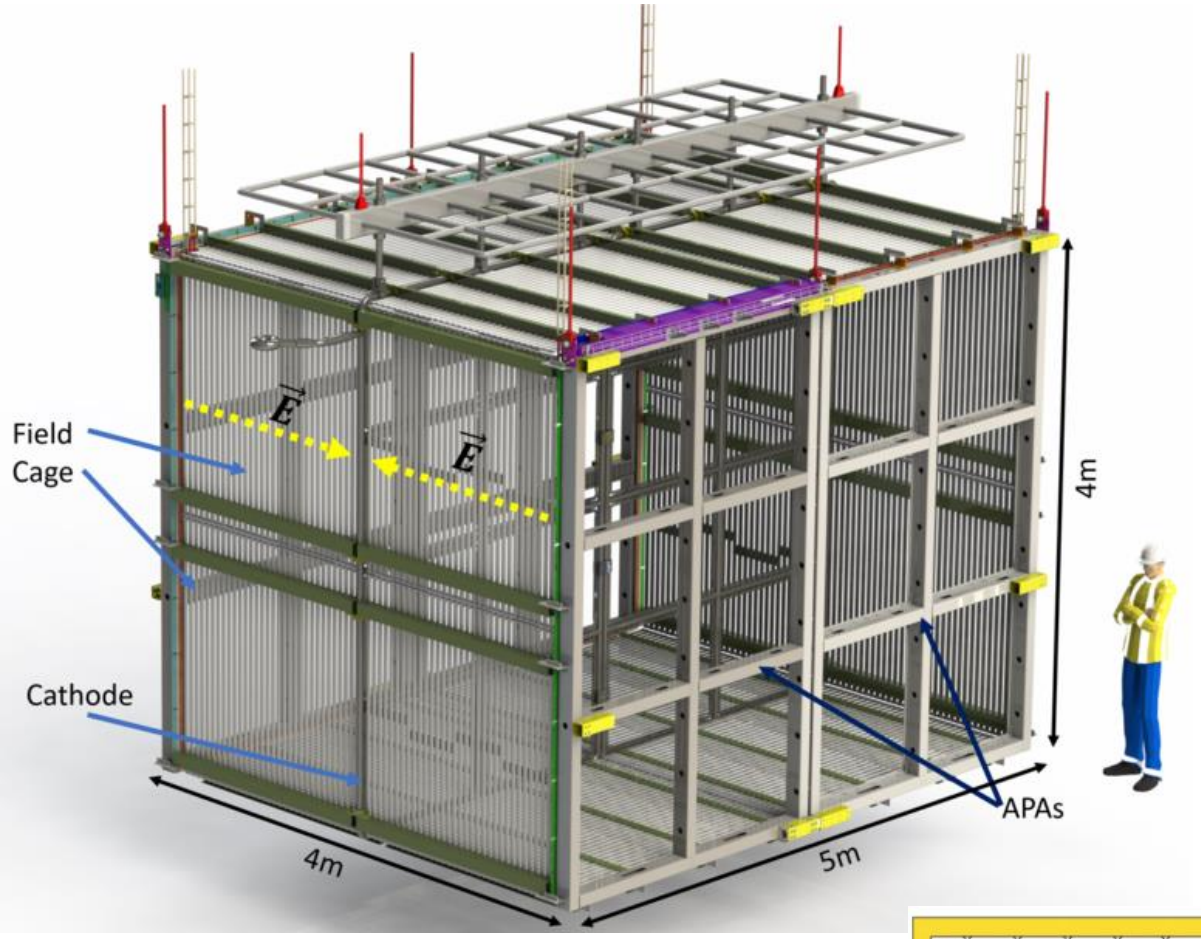
SBND

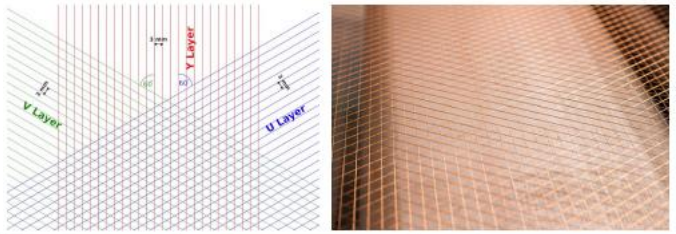
- **SBND _** Running (first physics run completed)
  - 260 t of LAr (112 t active), 110 m from target.

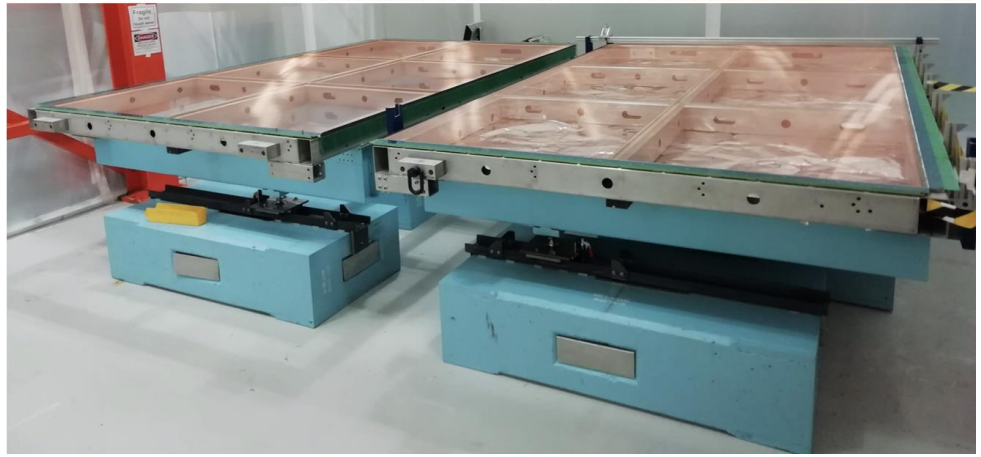
    2 TPCs with 2 m drift

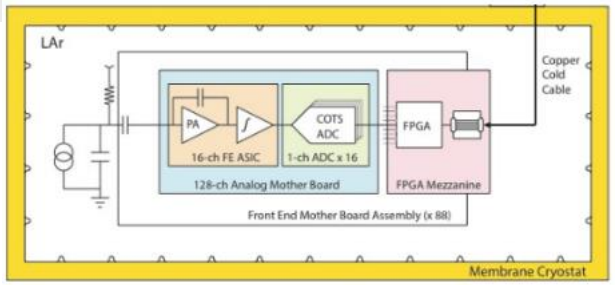
    120 8” PMTs (96 coated with TPB), 192 X-ARAPUCA modules, TPB coated reflector foils on the cathode.

    4π CRT (cosmic ray tagger) coverage









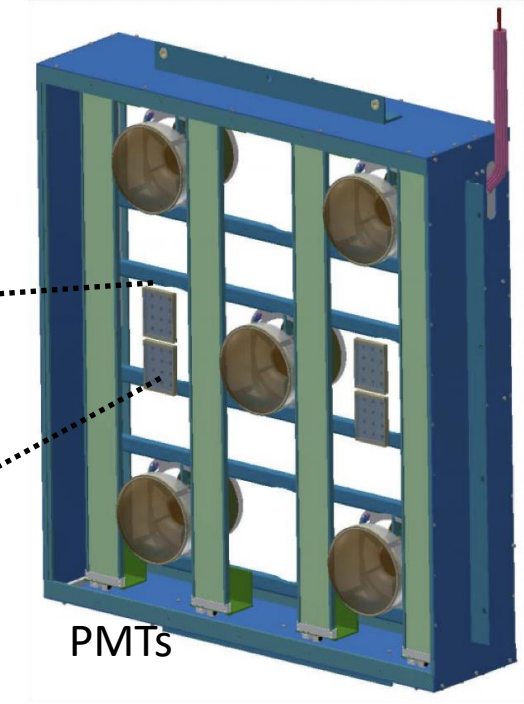
Improved Cold electronics similar to ProtoDUNE SP (FPGA also in cold)

11,264 wires/channels

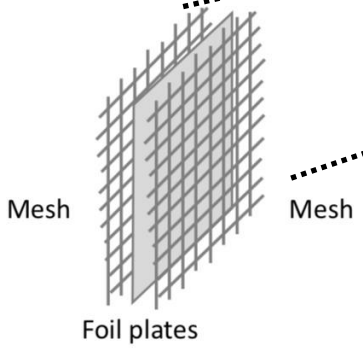
[1-5,20]

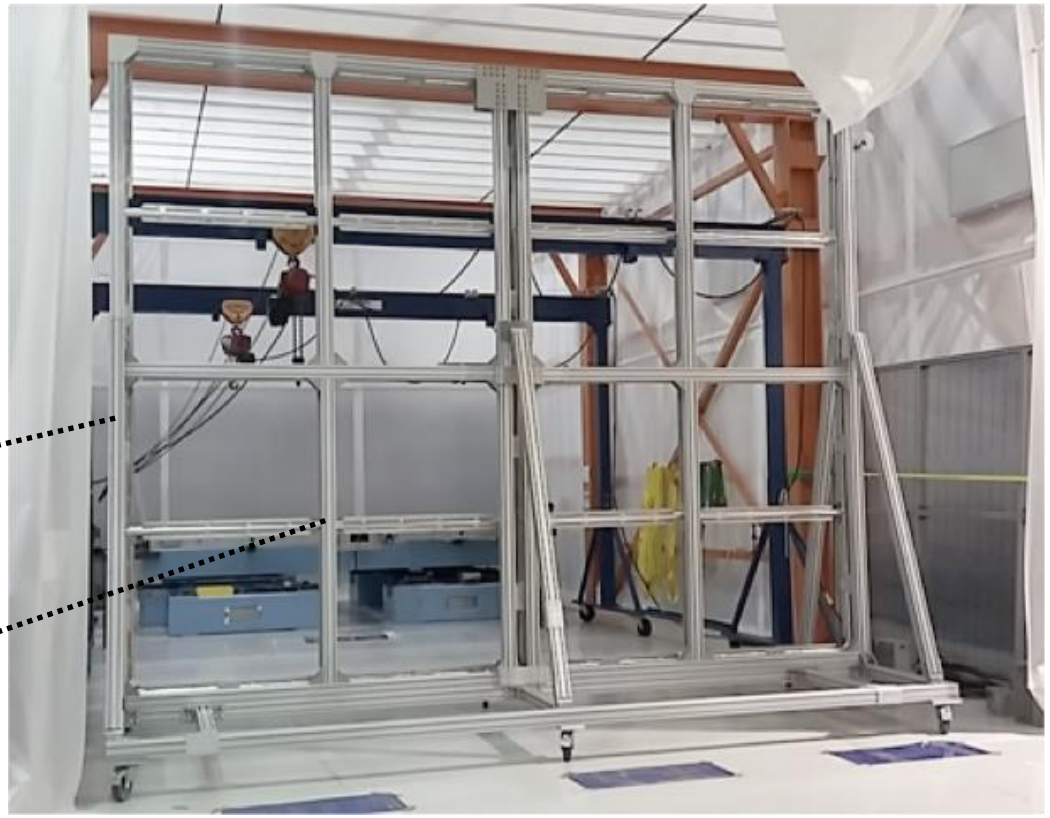
SBND –Photon Detection system

Modular photon detection system mounted behind APAs



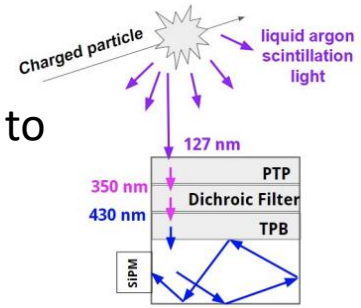
ARAPUCA





Wavelength-shifting reflector foils (TPB coated) mounted at the cathode to Improve the uniformity of collected light

X-ARAPURCA R&D
(A device for “trapping” photons to increase the active area of SiPM)



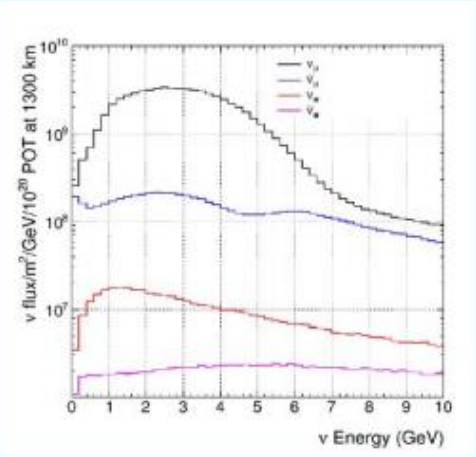
[1-5,20]

DUNE

Deep Underground Neutrino Experiment (DUNE)

1100+ collaborators from 178+ institutions in 32+ countries

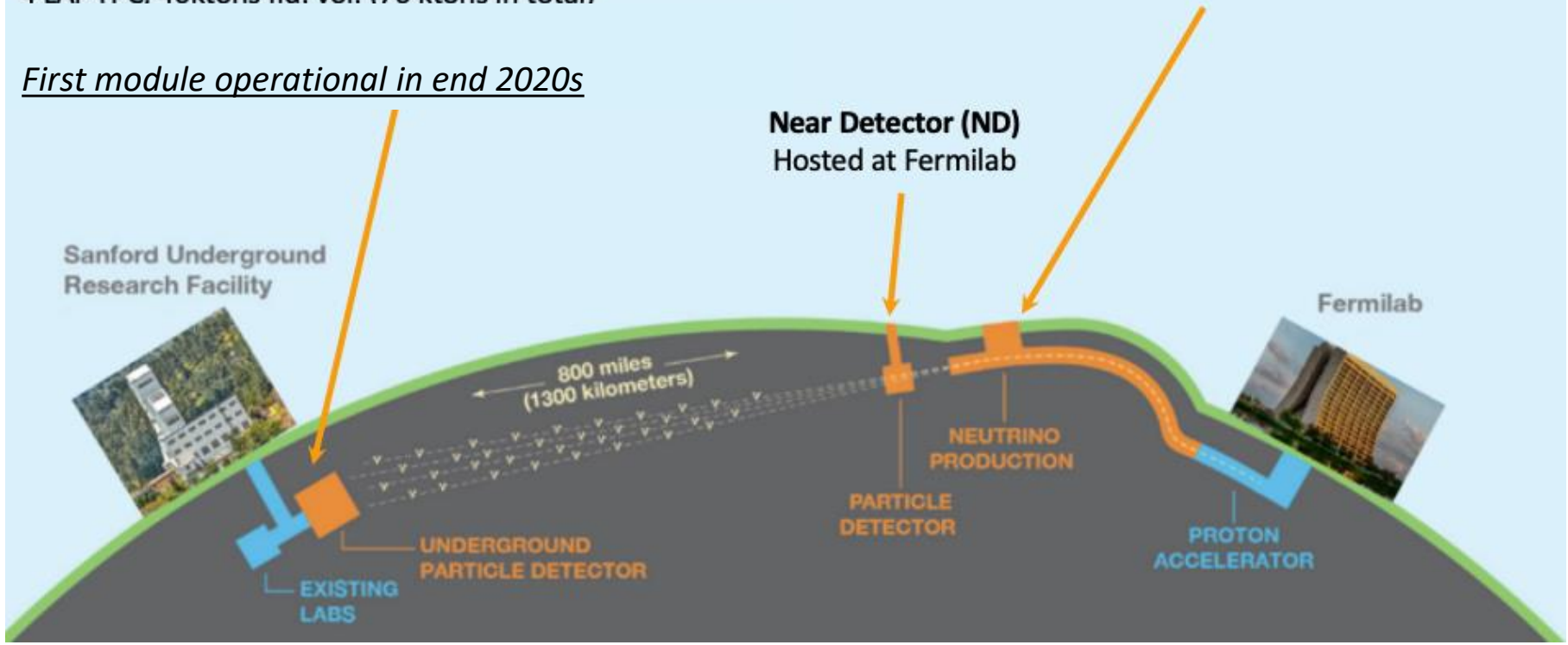
$\nu_\mu / \bar{\nu}_\mu$ Beam
1300 km baseline, from Fermilab to SURF
1.2 MW power (2026), up to 2.4 MW (II phase, 2032)



Far Detector (FD)
Hosted at SURF, South Dakota
New hall, 1.5 km depth
4 LAr-TPC. 40ktons fid. vol. (70 ktons in total)

First module operational in end 2020s

Near Detector (ND)
Hosted at Fermilab

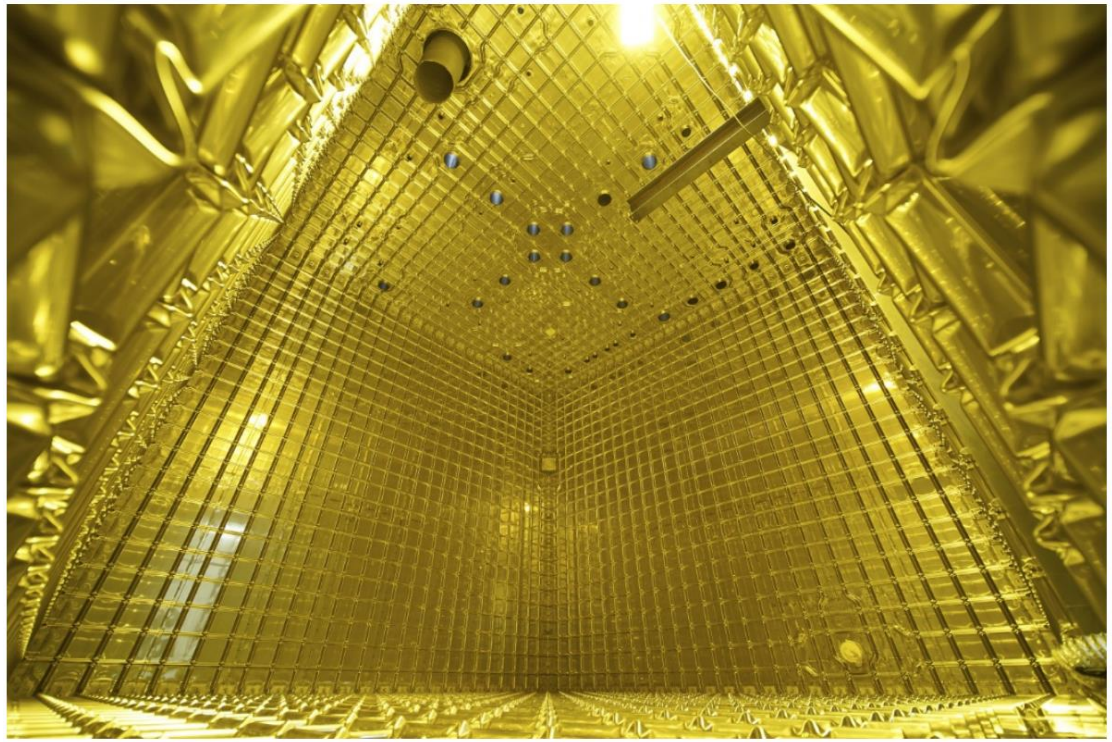


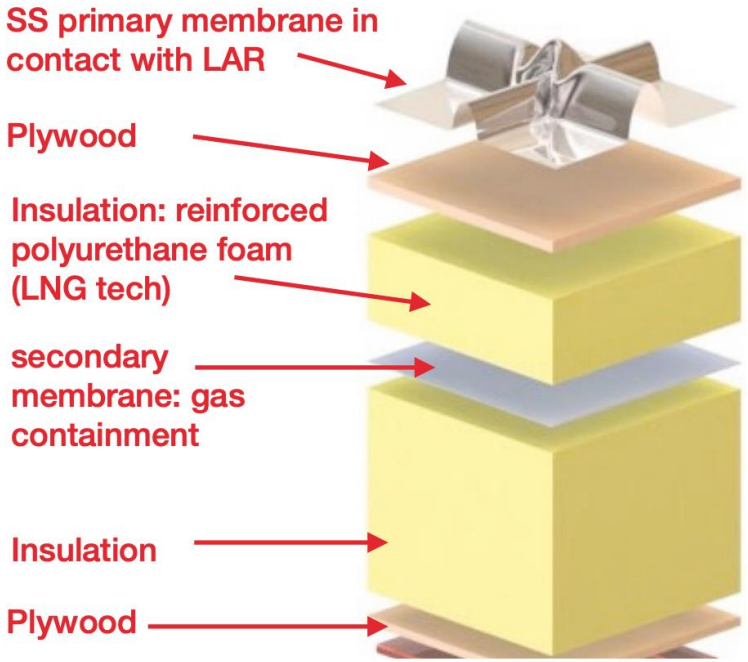
(See also slides from Pierre Granger @Nufact25)

[6-8,21]

Membrane Cryostat Technology

- Membrane cryostat technology developed for LNG transport ships → re-engineered for LAr-TPC detectors
- Used by protoDUNEs, DUNE, SBND and Darkside-20k



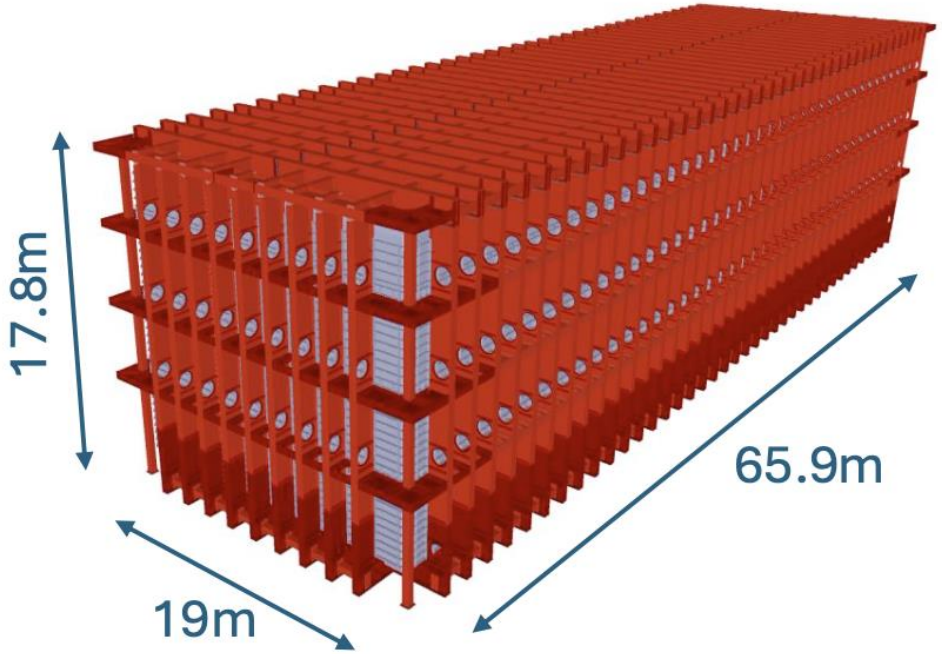


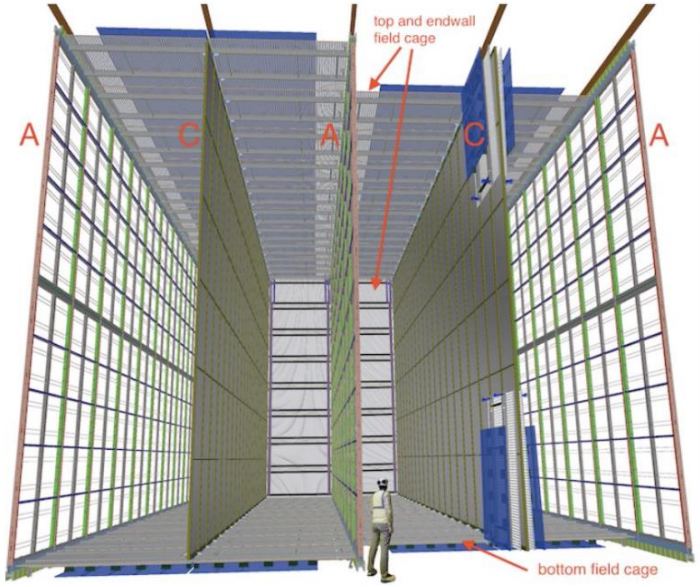
[6-8]

DUNE Far Detectors: two realizations: HD, VD

First 2 modules, each one holds 17 kt Argon total :

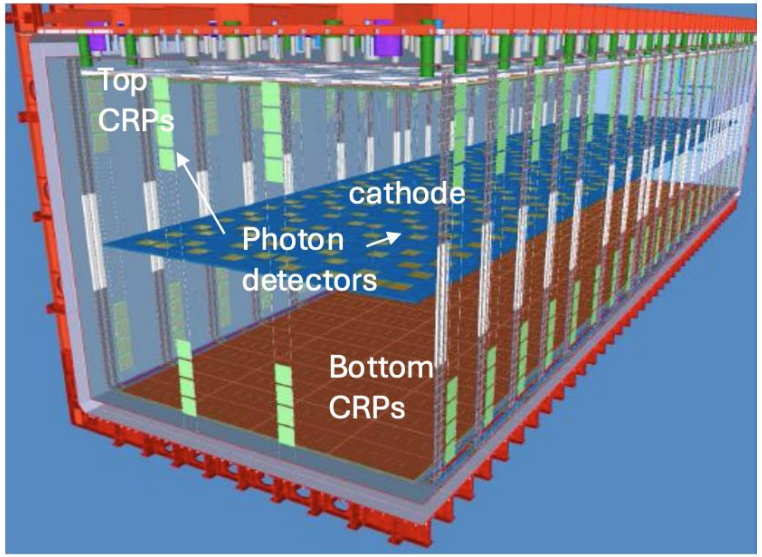
- Horizontal (charge) Drift
- Vertical (charge) Drift





HD

Anode Plane Assemblies :
Wire chamber technology
Drift length 350 cm -> ~ 180 KV
9800 m3 = 13.2 ktons active LAr



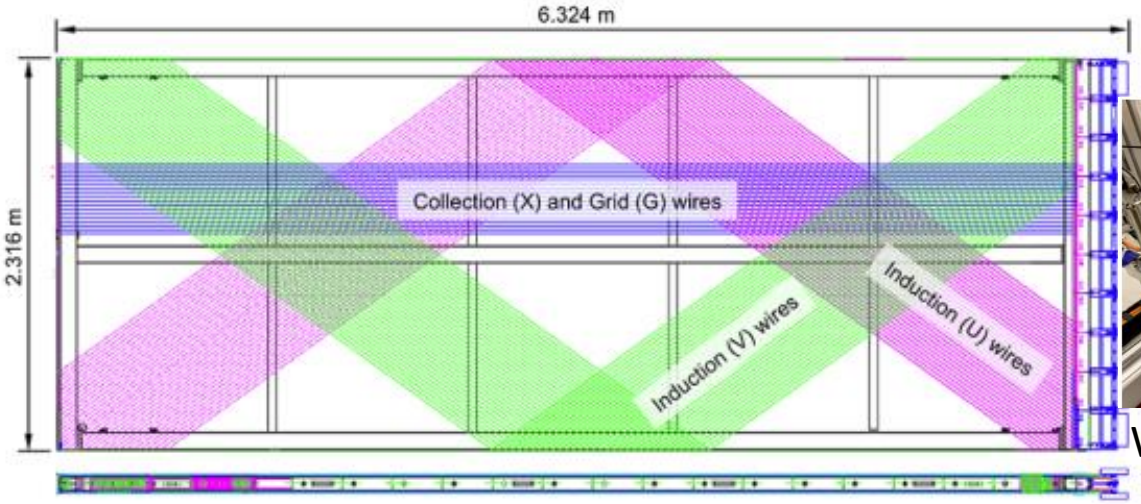
VD

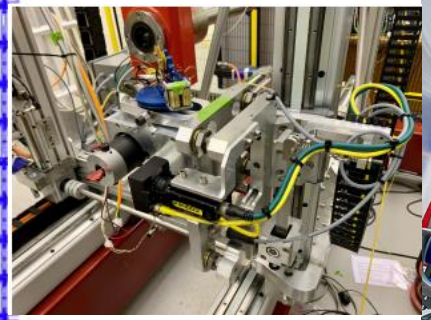
Charge Readout Planes :
perforated PCB technology
Drift length ~ 640 cm -> ~ 300 KV
10180 m3 = 14.2 ktons active LAr
Photon detectors on the cathode at 300 KV

[6-8, 22]

DUNE APA Factories

Aiming to produce 150 APAs in total

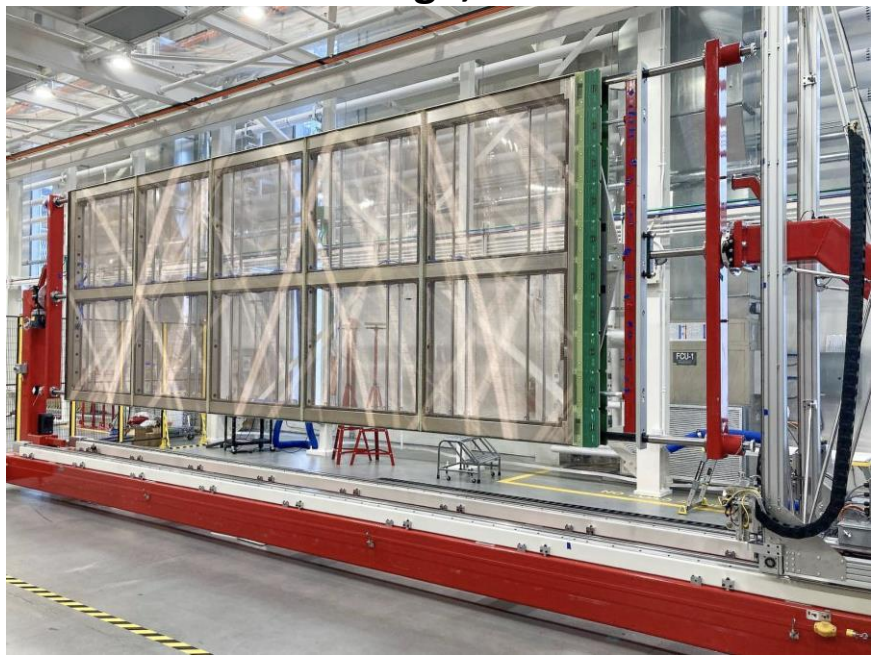


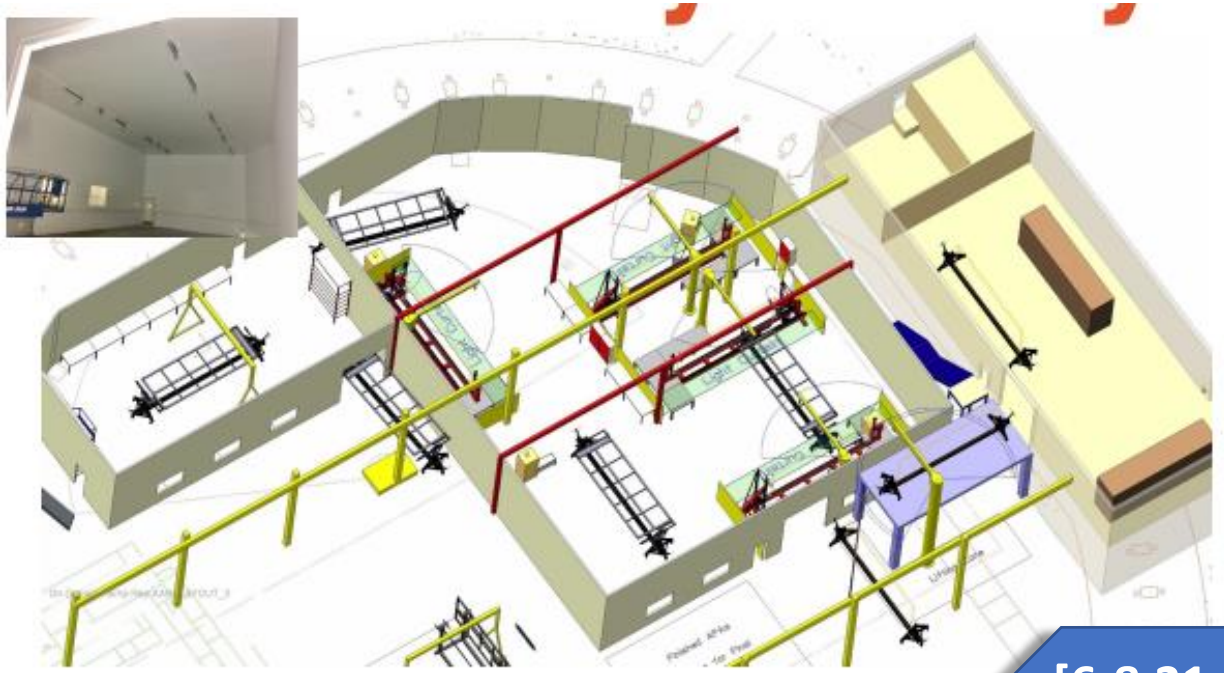


Wiring head

Daresbury, UK

Chicago, USA

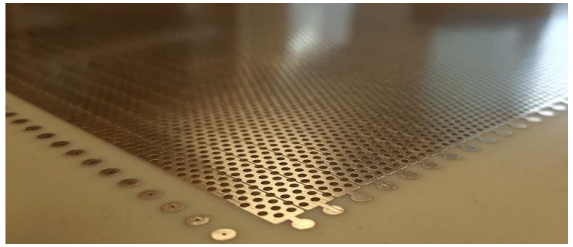


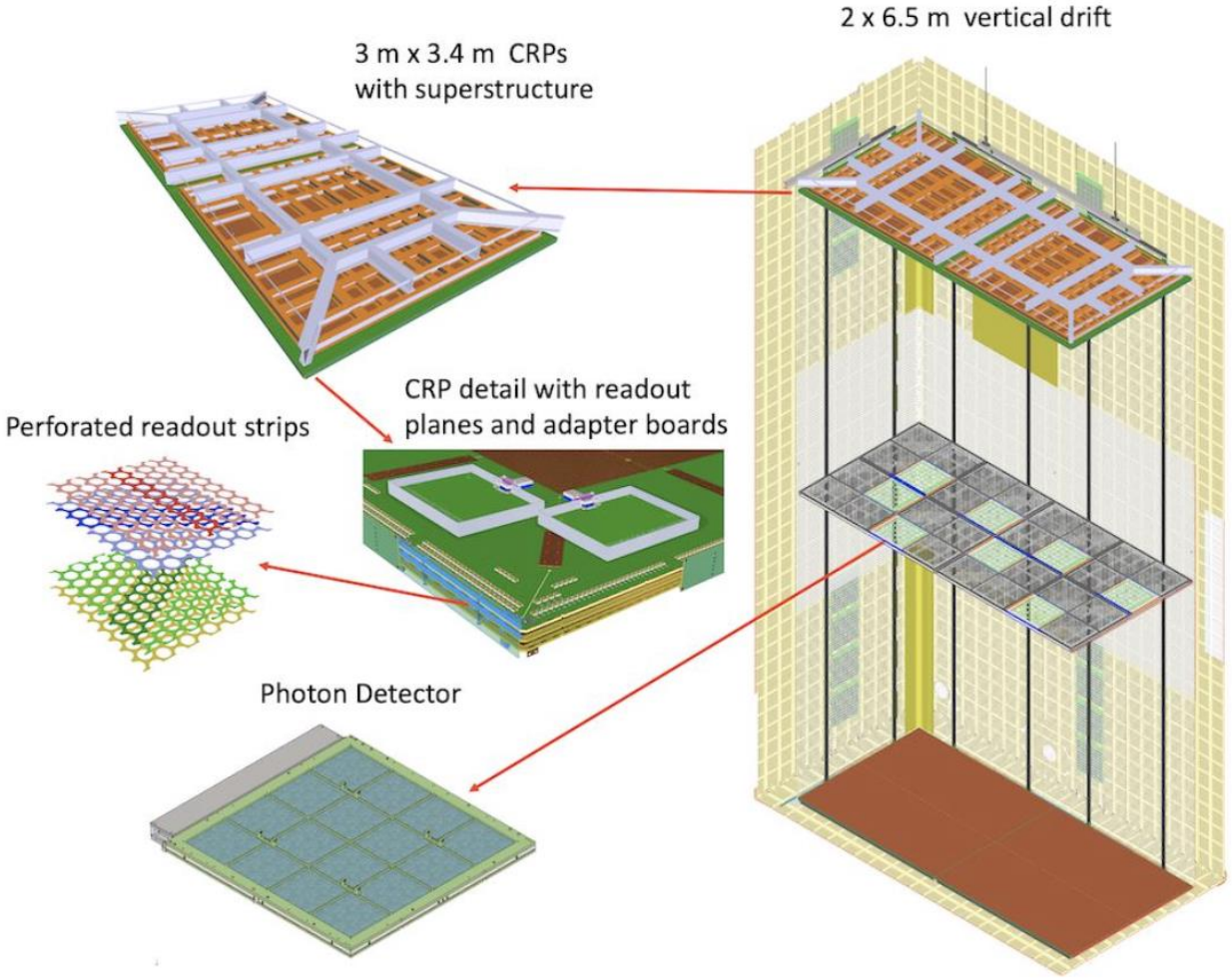


[6-8,21,22]

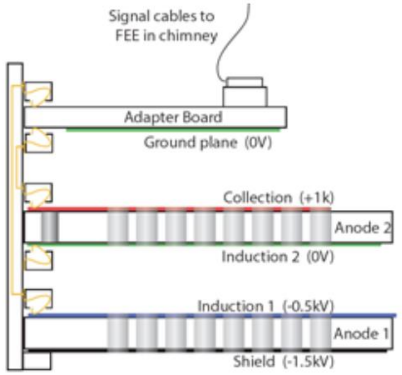
Vertical Drift Single Phase LAr TPC with PCBs

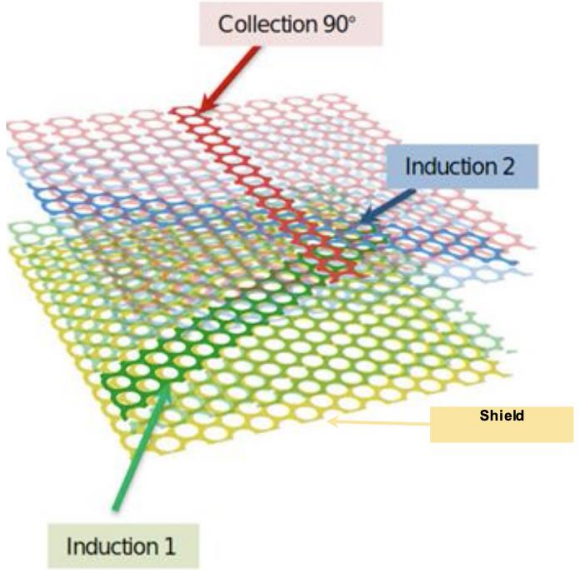
Evolution from ProtoDUNE DP





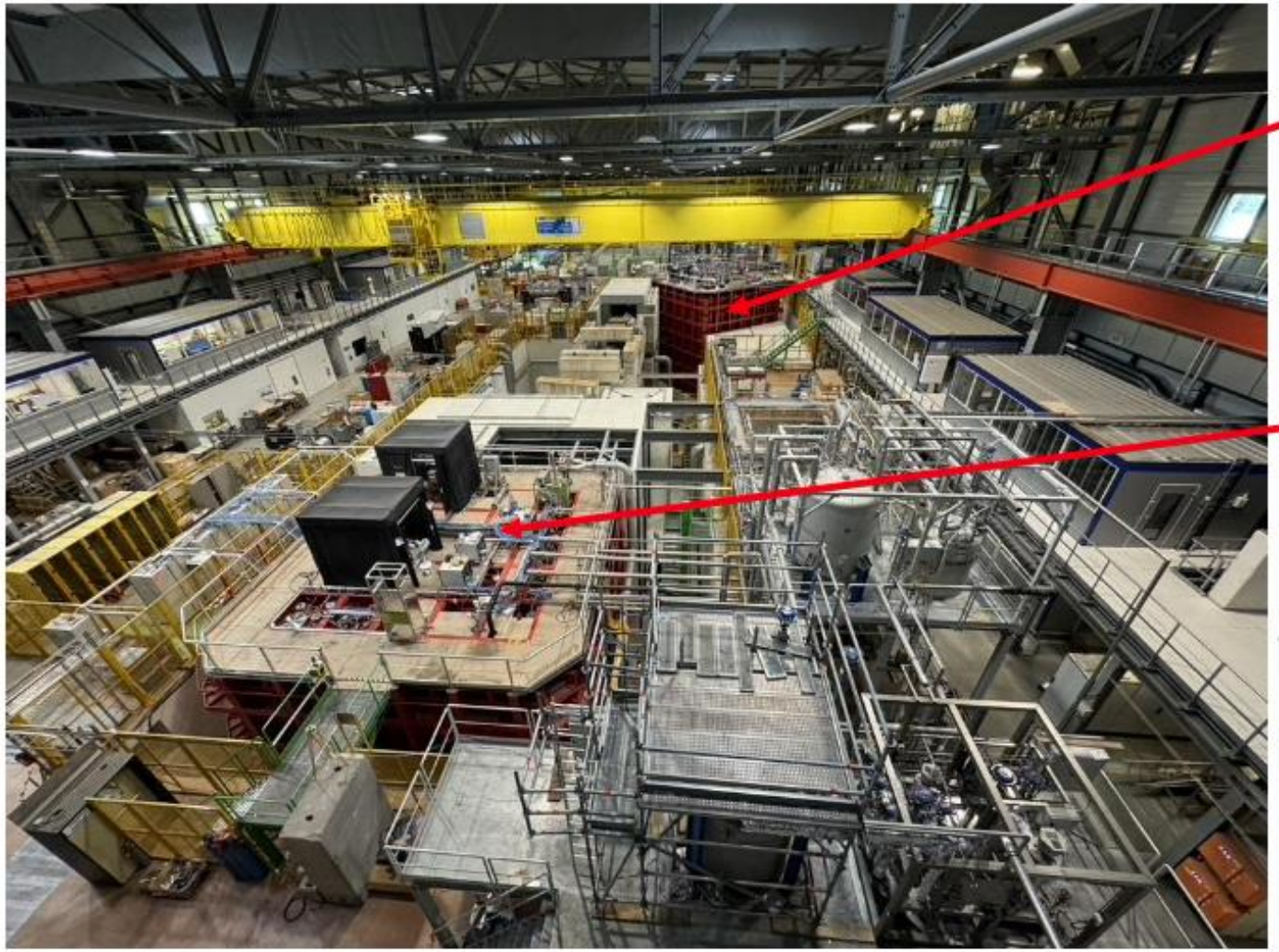
- Three view anode layout with perforated PCBs
  - +30°, -30°, 90° strip orientation with 5.1mm collection, 7.65mm induction strip pitches
  - 3072 readout channels for each CRP



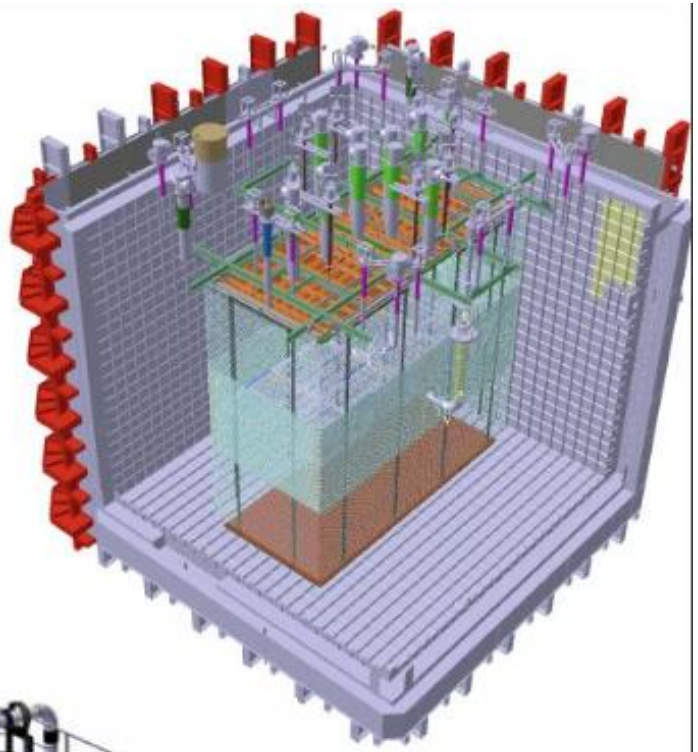


[9, 22]

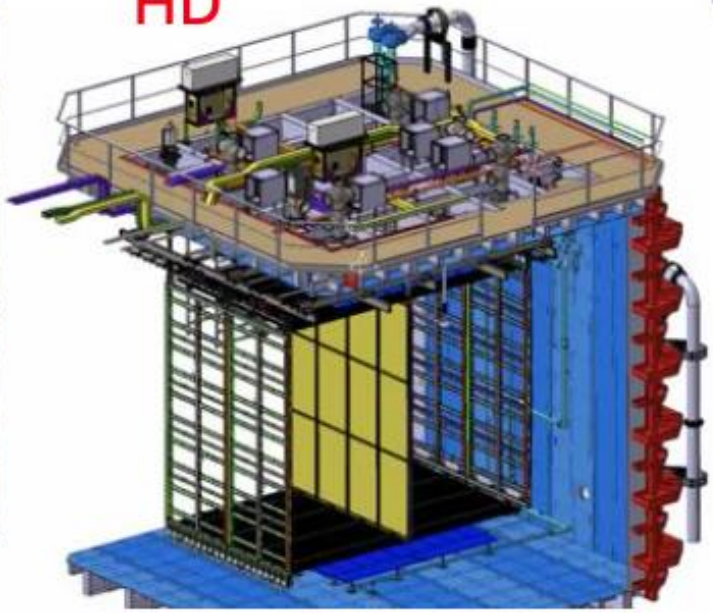
ProtoDUNEs at the CERN NP



NP02
VD

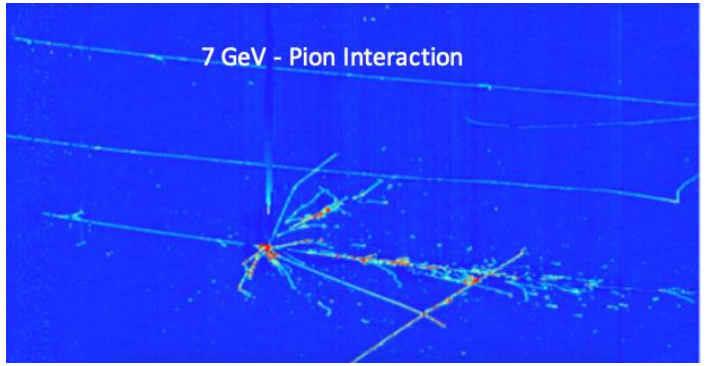


NP04
HD

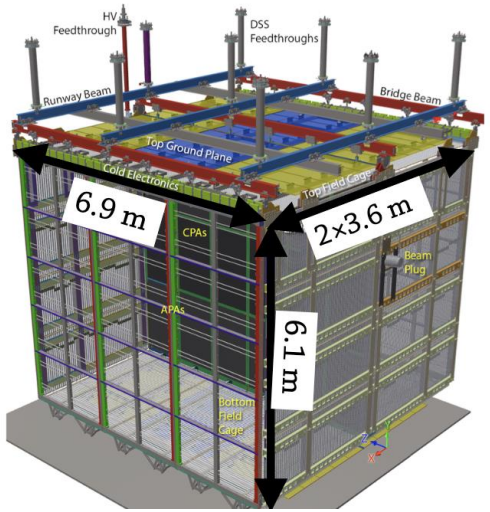


[6-8, 22]

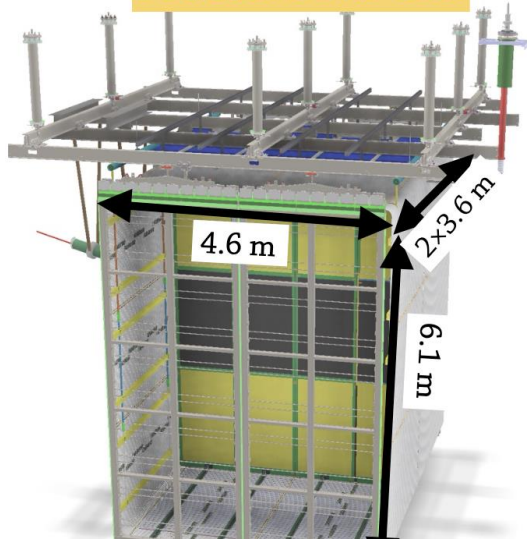
ProtoDUNE SP/HD (Wires)



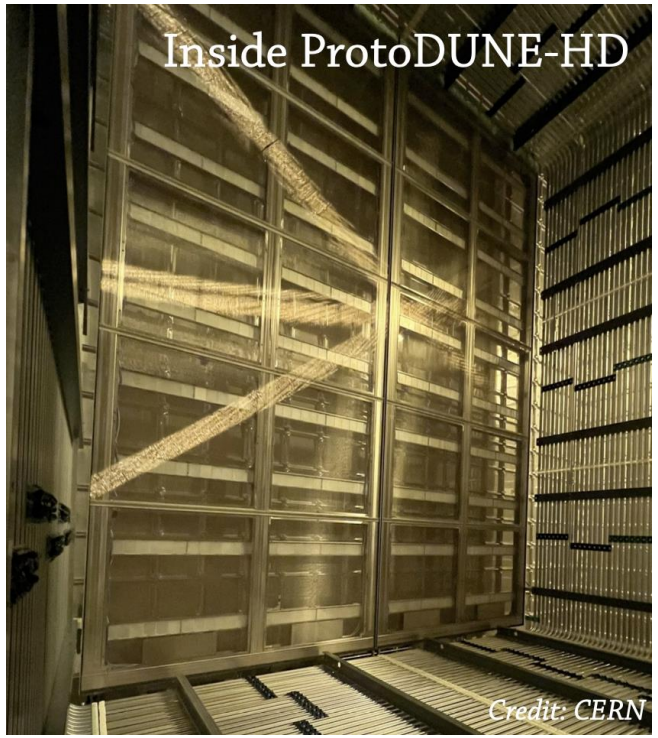
ProtoDUNE-SP



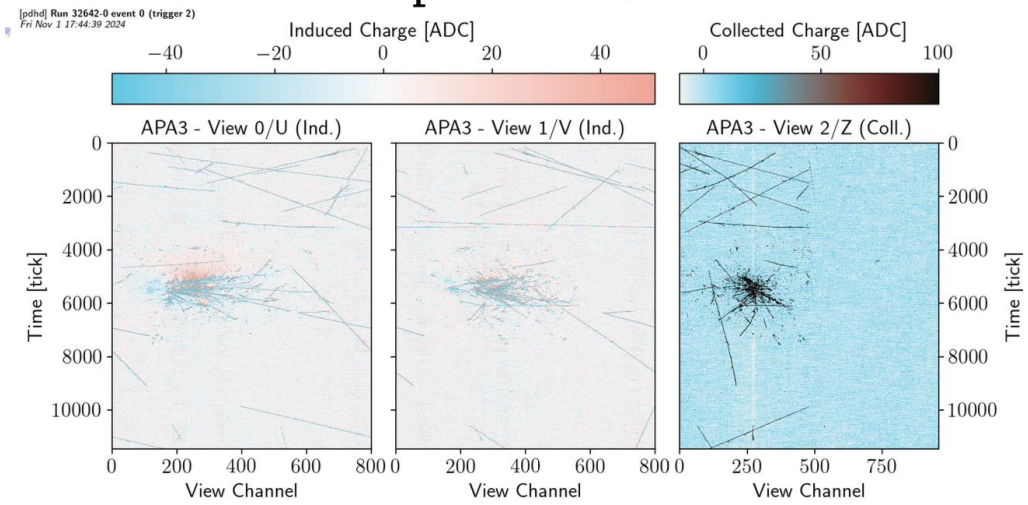
ProtoDUNE-HD



APA insertion ↓



Example of cosmic data:



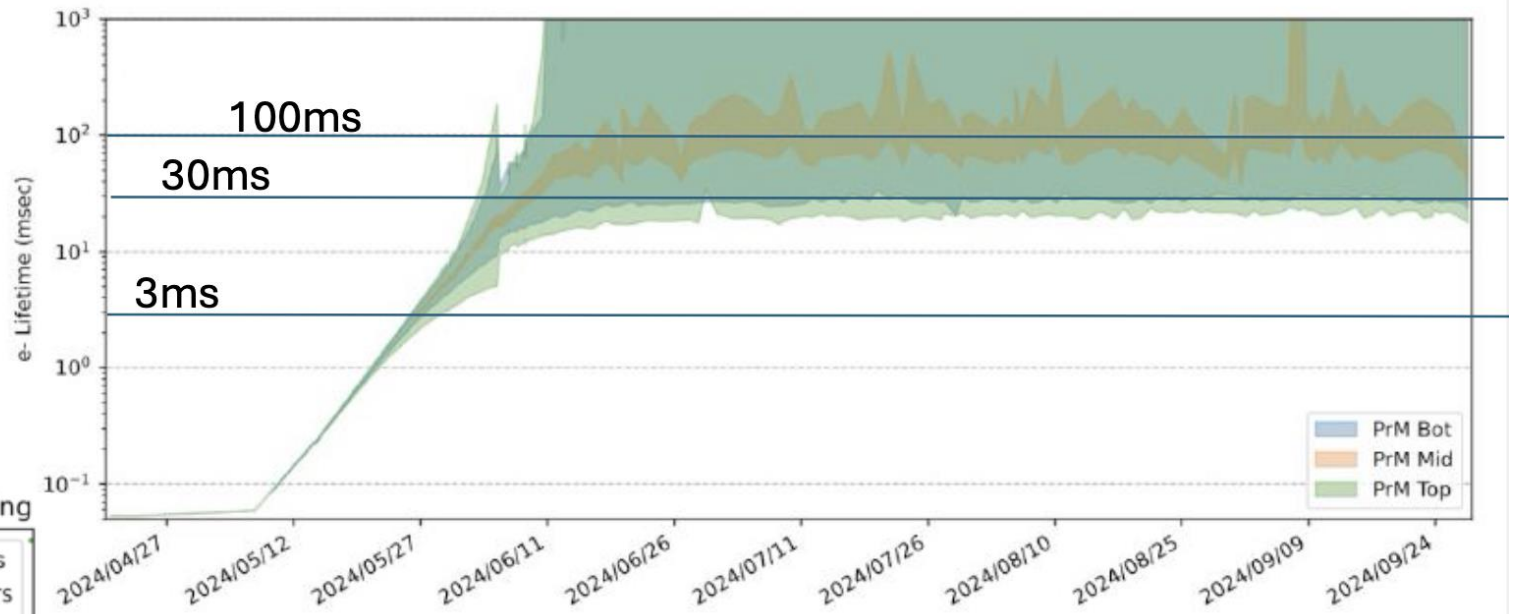
[6-8,21,22]

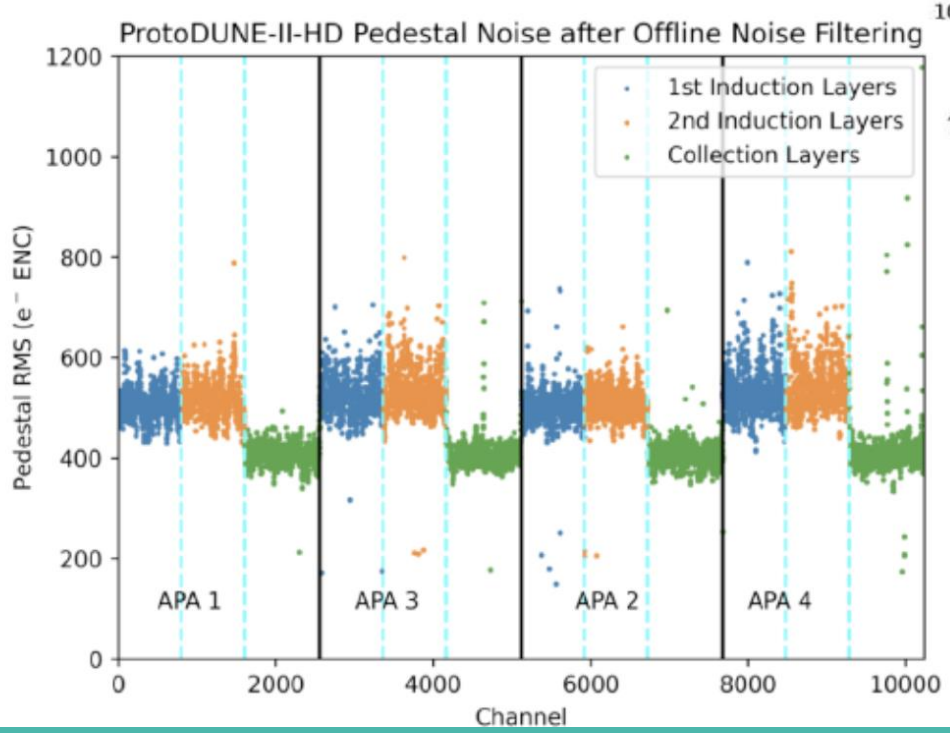
Argon purification

NP04 run in 2024

Purity levels of LAr x10 higher than required

No purity loss in 6 months

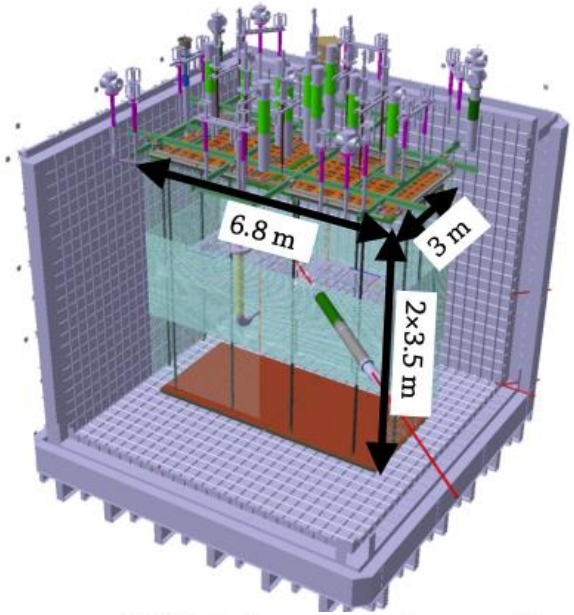




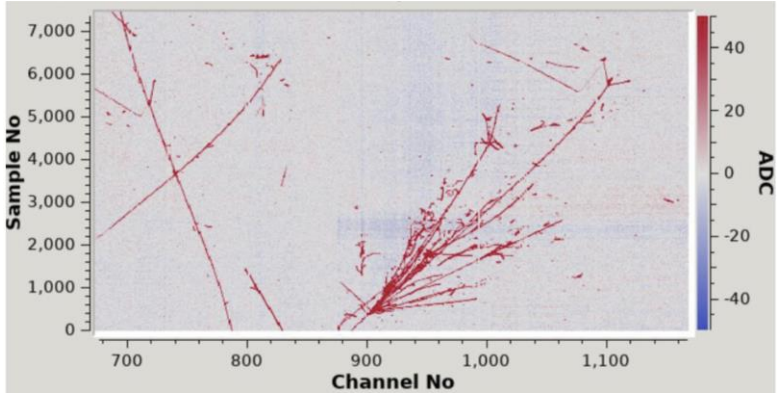
Excellent overall noise performance (comparable or better than ProtoDUNE I)

[6-8, 22]

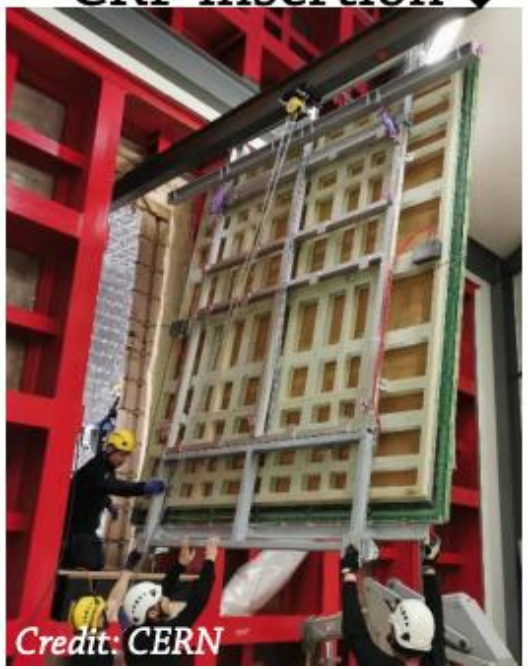
ProtoDUNE VD



Cosmics sample event

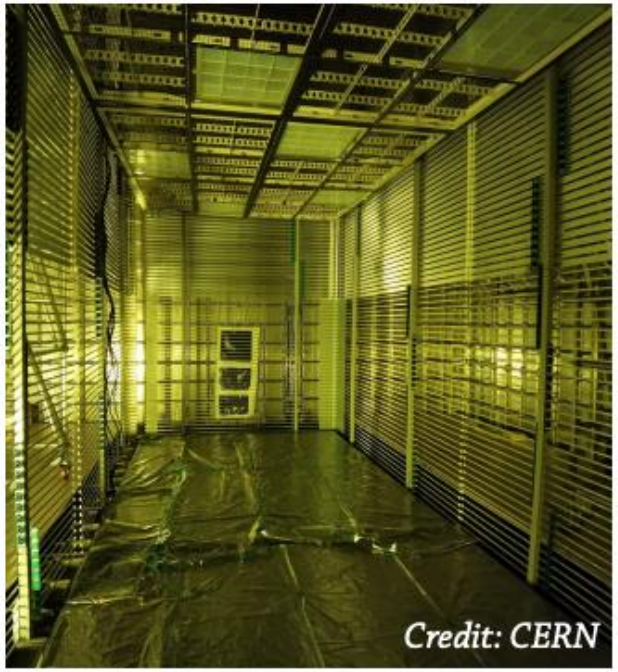


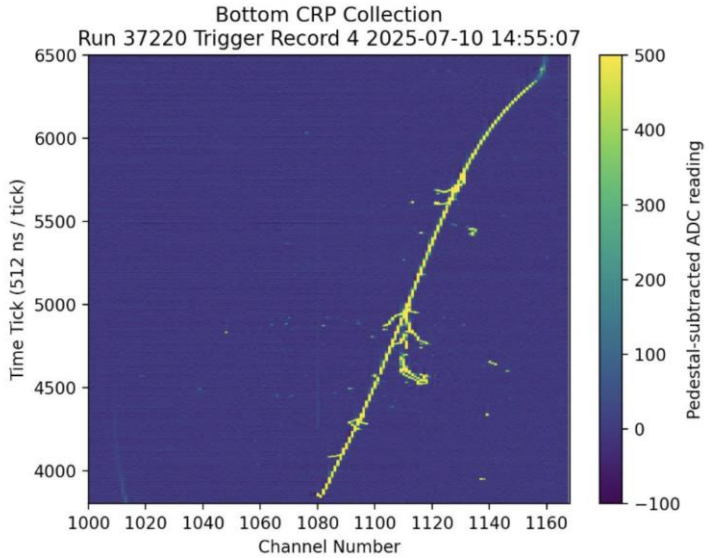
CRP insertion ↓



Top volume

Bottom volume



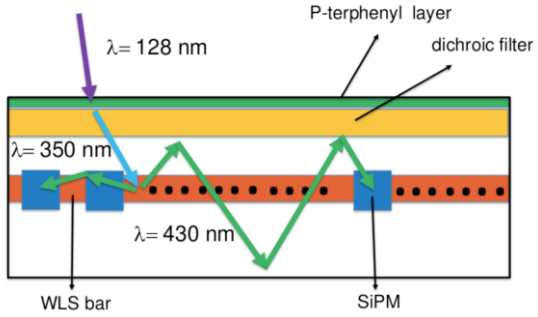


[6-8,21,22]

DUNE Photon Detection System: X-ARAPUCA

(See also talk by Carmen Palomares @Nufact25)

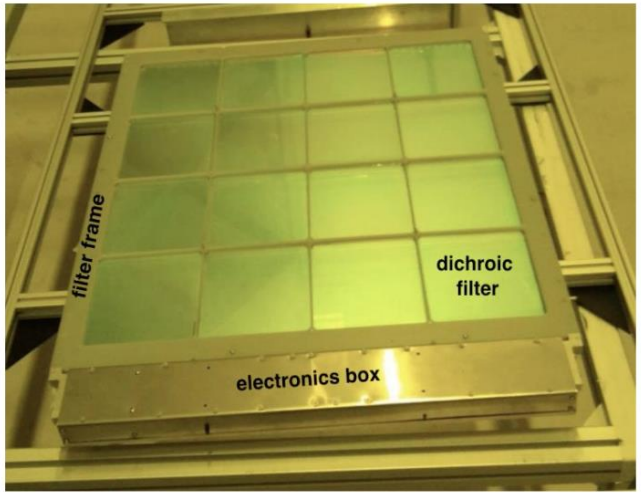
Photon trapping through:
Total internal reflection in the WLS
Trapping through dichroic filter



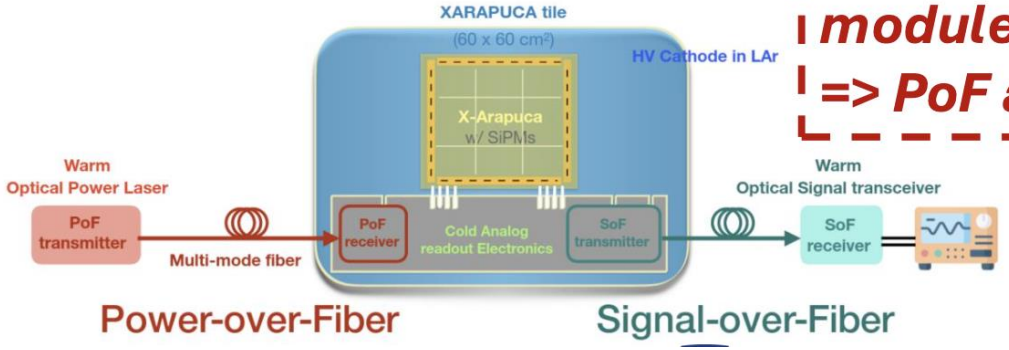
- ✓ Bar shaped modules
- ✓ 200 x 10 cm^2
- ✓ 4 independent read-out channels
- ✓ 4 x 48 SiPMs ganged together

- ✓ Square modules
- ✓ 60 x 60 cm^2
- ✓ 2 independent read-out channels
- ✓ 2 x 80 SiPMs ganged together

Efficiencies between 2% - 4%



Half of the modules at 300 kV => PoF and SoF

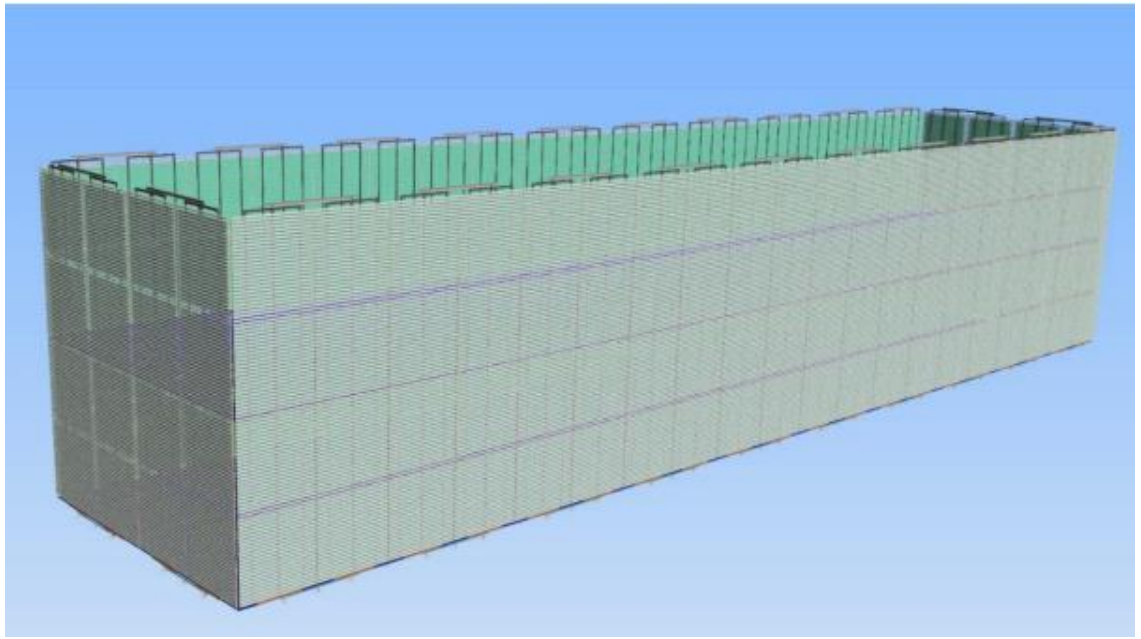


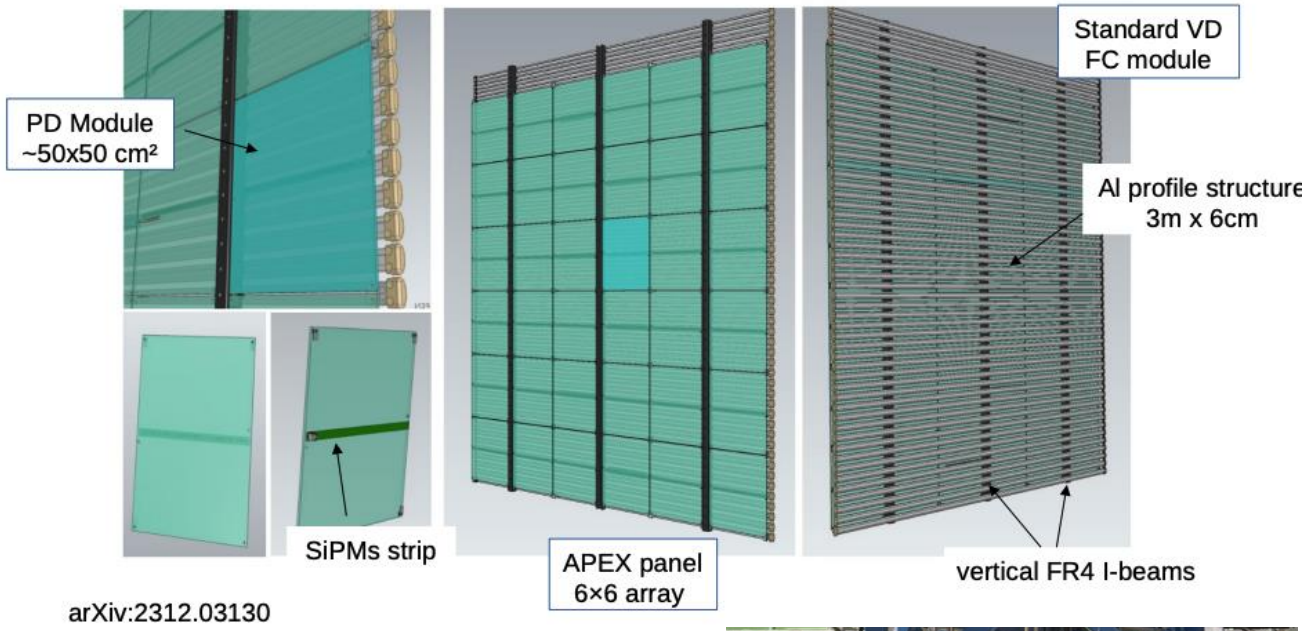
[6-8, 22]

Optimising further S1 photon detection efficiency – APEX

R&D for phase II of DUNE

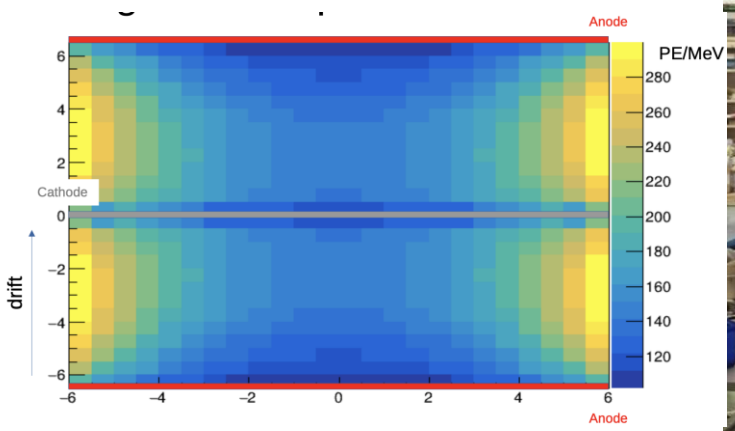
APEX: Aluminum profiles with embedded X-ARAPUCA





arXiv:2312.03130

- Optical coverage >55% with light trap technology
  - Enhanced light yield (LY) and uniformity of PDS response
- Integrated VD TPC Field Cage + Photon Detector System
- P(S)oF technology for power and signal in/out of the field cage
  - Non-conductive optical fibers, readout electronics on HV surface



[23]

Optimising further S1 photon detection efficiency -PoWER

R&D for phase II of DUNE

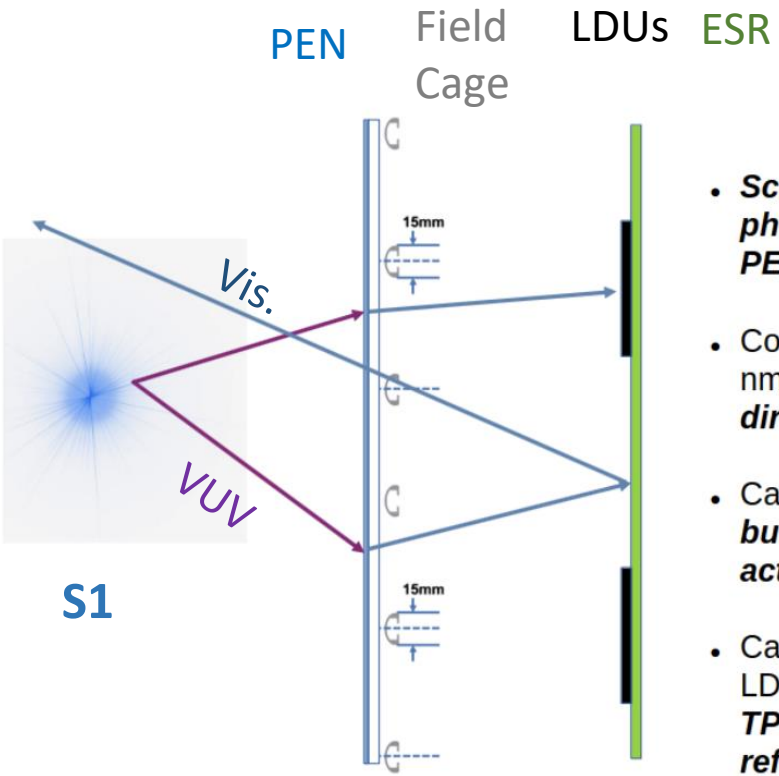
Full coverage of the field cage with PEN WLS

Large arrays of SiPMs mounted on the membrane - Light Detection Units (LDUs).

VUV-sensitive SiPM as an active veto;

ESR reflector (reflectivity 98% in the visible) installed on the membrane;

Cathode (partially) covered with PEN and eventually reflector

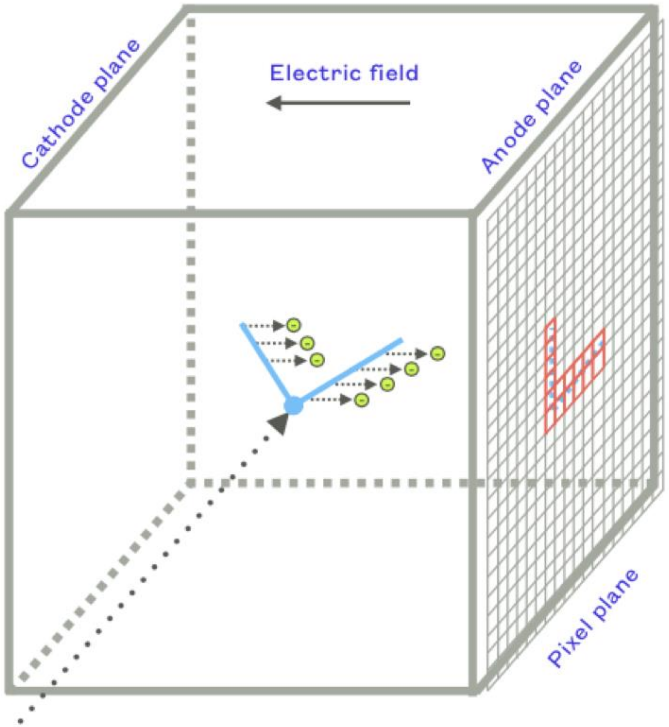


- ***Scintillation VUV photons converted by PEN***
- Converted photons (420 nm) can be detected ***directly on the LDU***
- Can hit the reflector and ***bunched back in the active volume***
- Can be detected by an LDU ***on the other side of TPC, or after several reflections***

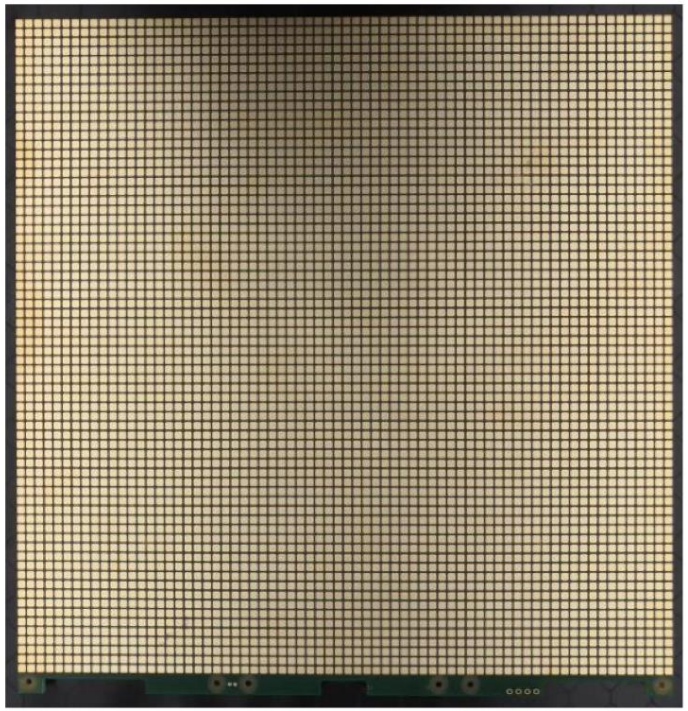
See slides from André Steklain @Nufact 25

LArTPC single phase Pixel Technologies

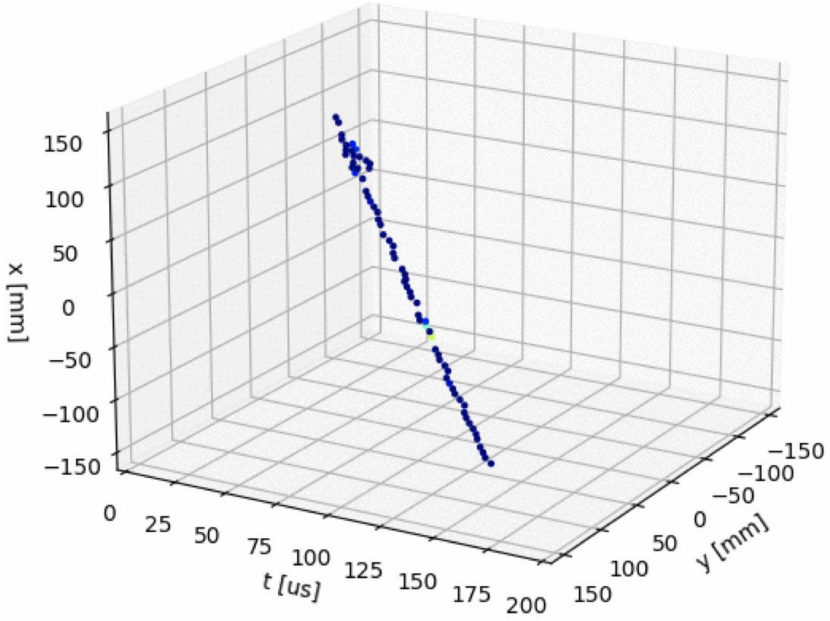
3D Pixel TPC



6.4k-channel LArPix prototype pixel anode tile



Raw 3D Cosmic Ray images in LArPix prototype LArTPC



Motivation: The anode is made of a grid of pixels, which can directly detect the ionization charge at a specific (X, Y) position without needing projections.

[10,11,25]

LArPiX

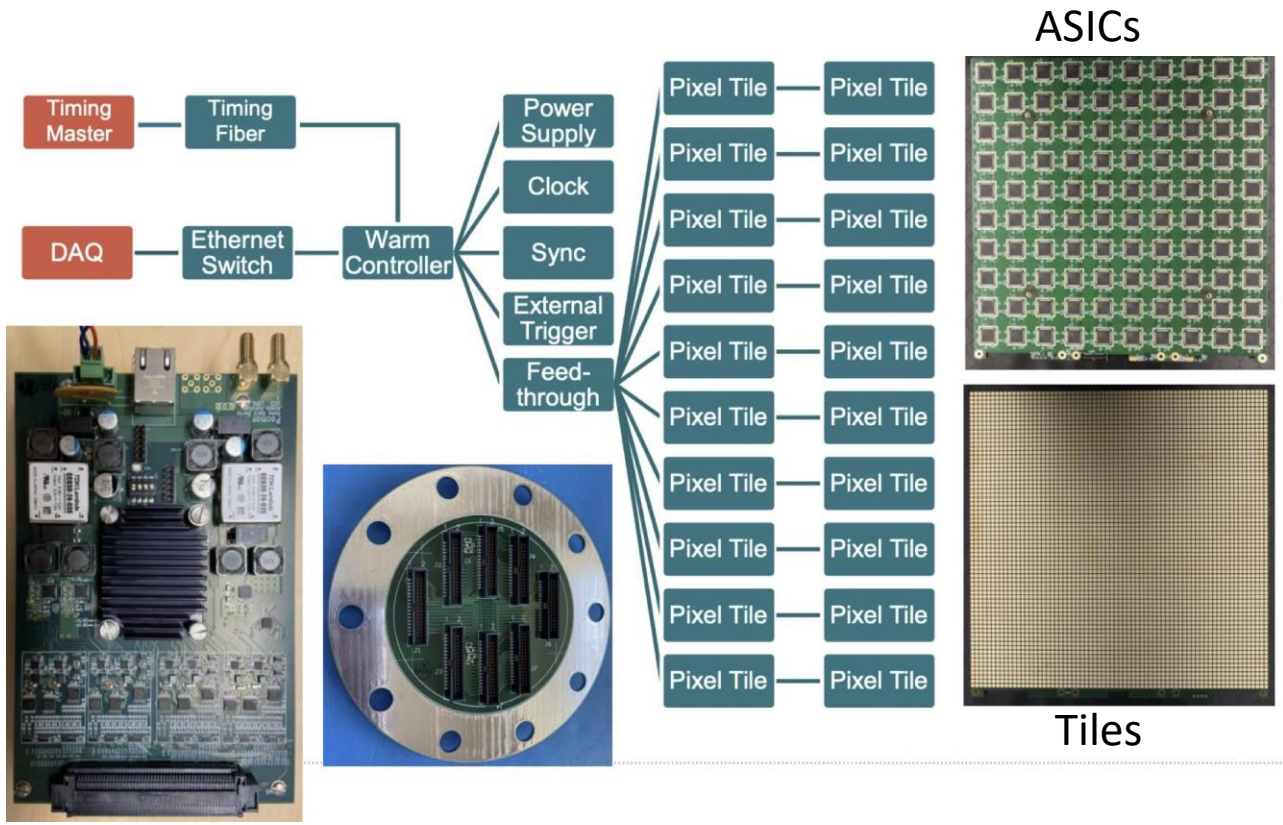
- Multi-channel charge processing ASICS: **LArPix** new generation, speed up, more channels, lower power.
- **Continuous readout**, ~100% uptime

[10,11,25]

LArPix: Design Concept

Each pixel operates as an independent detector

- LAr data is inherently sparse
- Self-triggering and digitization for each pixel [O(100) keV threshold]
- Only digitize and readout pixels with signals



Pixelated anode based on LArPix V2 ASIC (LBNL) Pixel tile: 30x30 cm, 100 ASICs, 4900 pixels

Pixel rate 0.4 Hz/pixel, Tile rate 2 kHz
Data rate - 32 kB/s per tile or ~1 MB/s/m^3

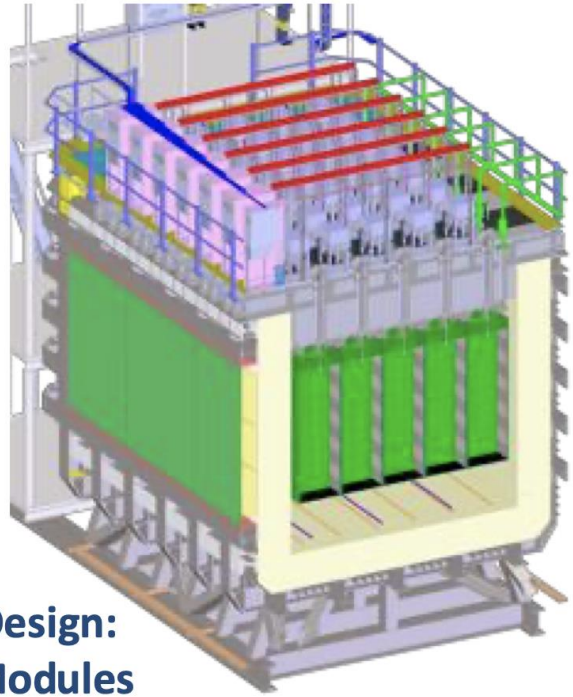
P = 64 uW/ch, Total power 0.3 W/tile or 3W/m^2

LArPix and DUNE ND-LAr

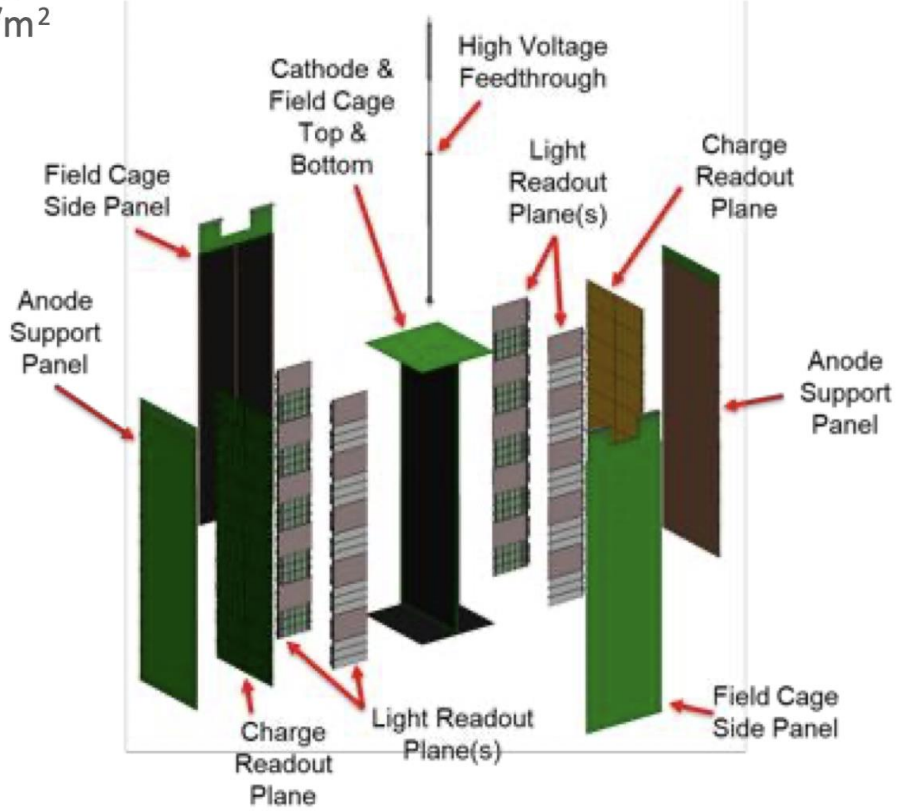
[10,11,25]

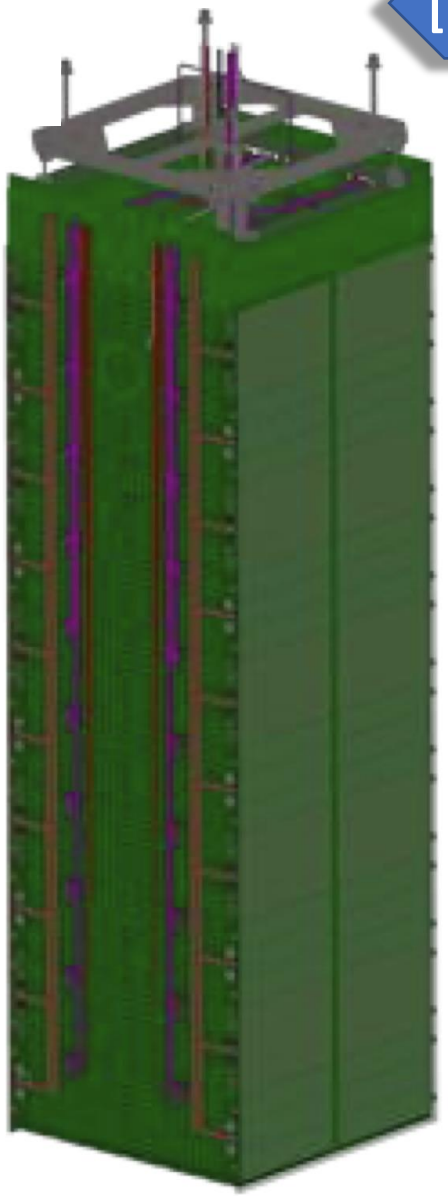
ND-LAr Full-Scale Demonstrator (FSD)

- Completed second-generation (LArPix-v2d) system design
- Built and operated one full-size ND-LAr TPC Module (1m x 1m x 3m active) @ Univ. of Bern
- 6 m^2 of LArPix anode (409,600 pixels at 3.7 mm pitch)
- Exercised large-scale production and testing program
- Achieved system production cost goal of ~$10k/$m^2$



ND-LAr Design:
35 TPC Modules



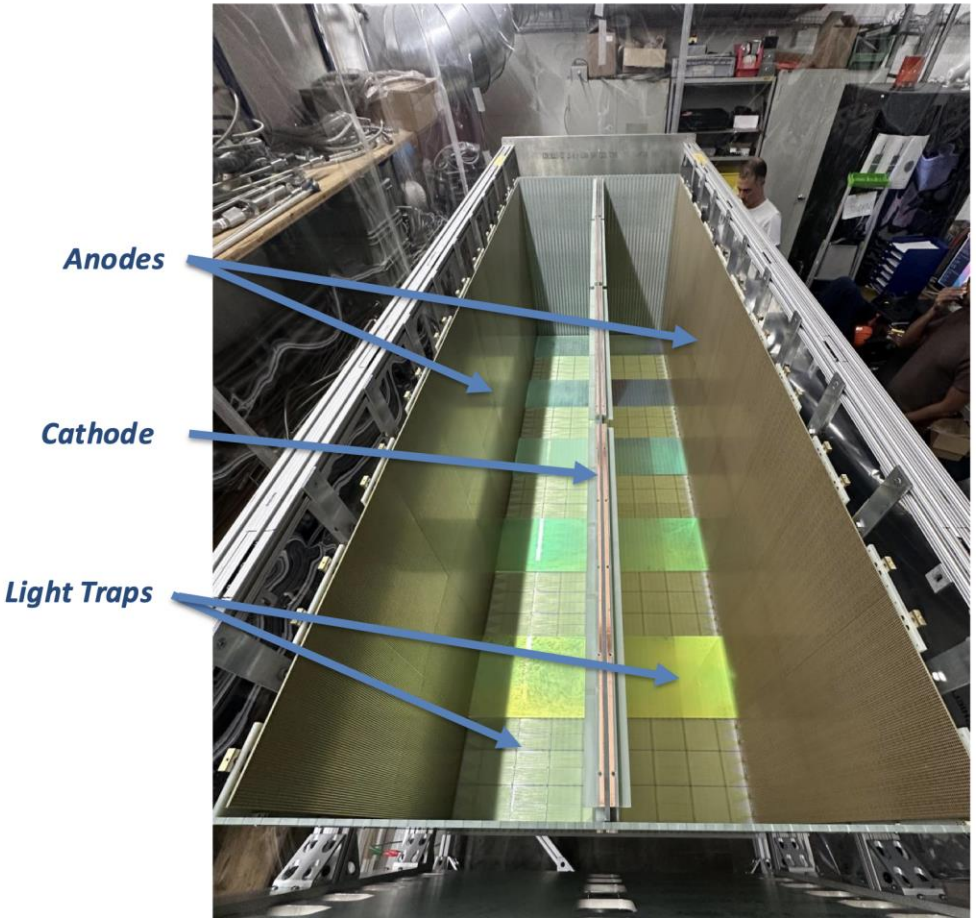


One Full-scale ND-LAr Module

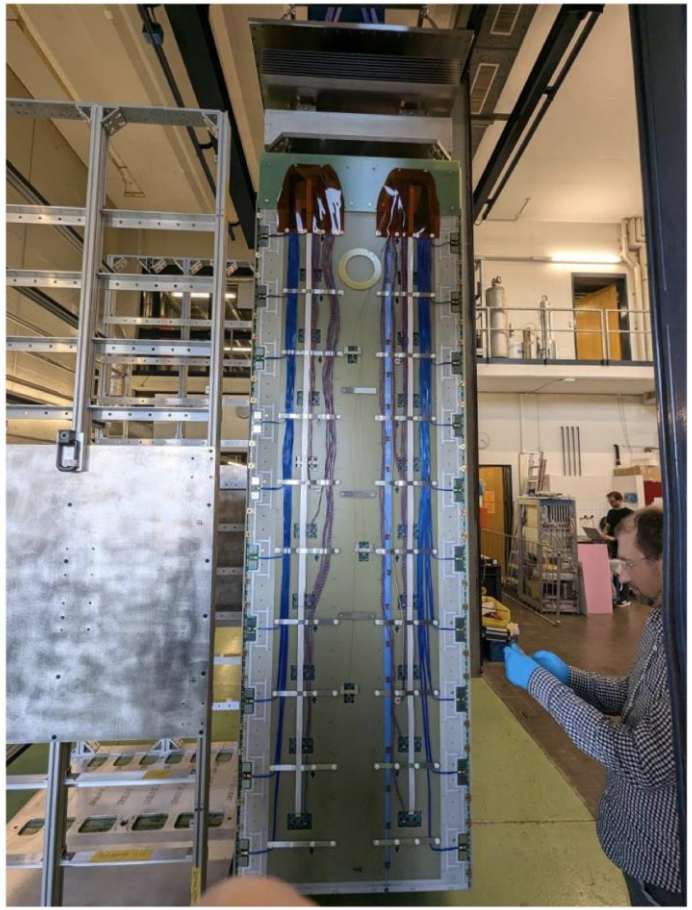
LArPix and DUNE ND-LAr

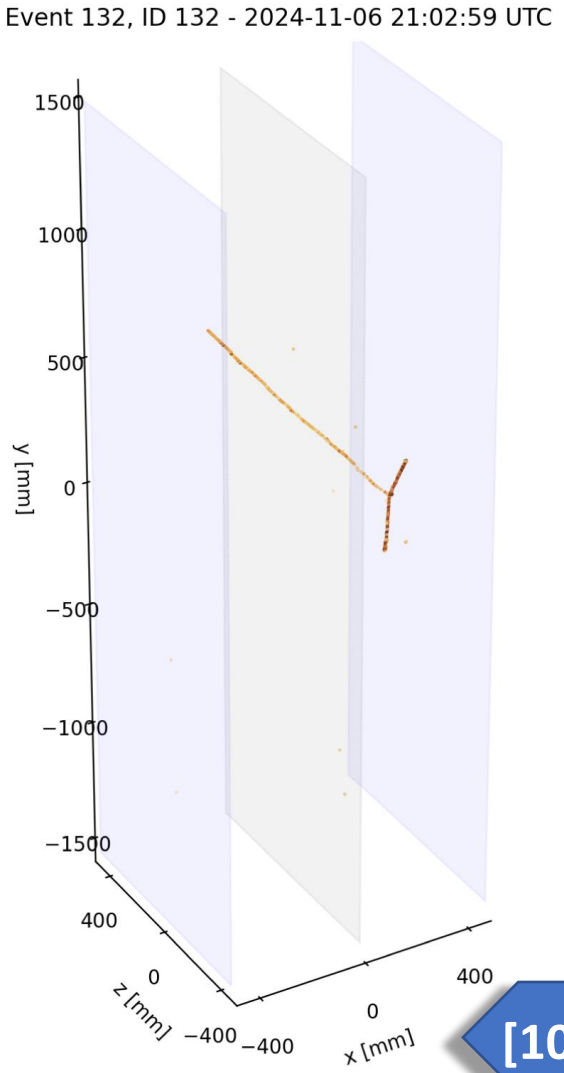
FSD Operation @ Univ. of Bern, 21 Oct – 15 Nov, 2024

FSD Anode Assembly



Fully-assembled FSD LArTPC





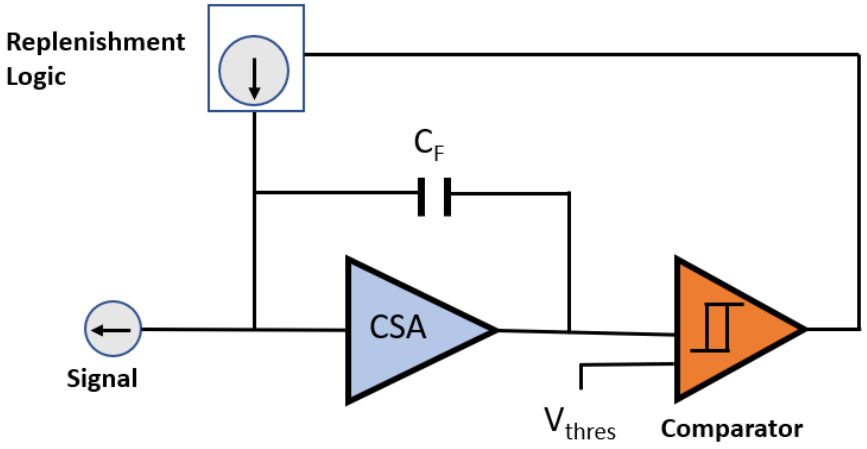
[10,11,25]

QPIX

- D. Nygren's **Qpix** ASIC (time-to-charge approach)

[25, 26]

Charge integrate/replenishment circuit



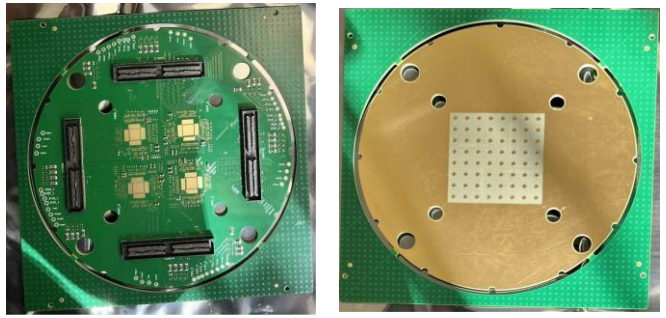
Q-Pix summary:

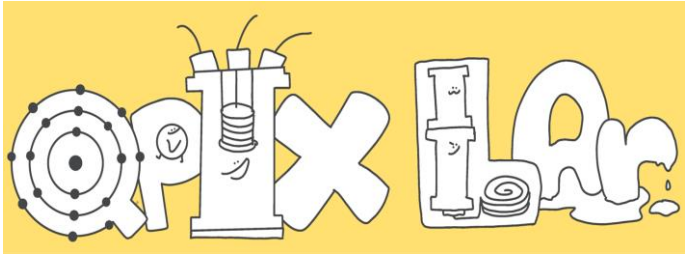
- Measures the time to integrate a pre-defined integrated charge (ΔQ).
- Average detector current is encoded in the reset rate
- Self-triggered, per pixel

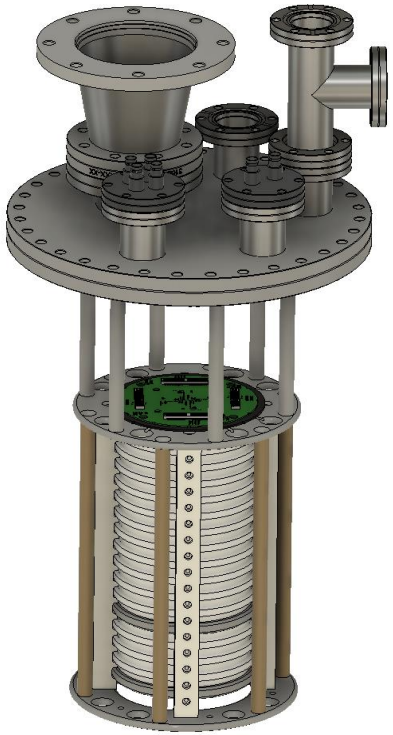
$$\Delta Q = \int I(t)dt = I_{avg} \cdot \Delta t$$

$$I_{avg} \propto 1/\Delta t$$

replenishment time difference (RTD)







64-channel Q-Pix prototype (QPixLAr)

Multimodal pixel readout – SoLAr

A pixel plane which is sensitive to (UV-VIS) photons (L) and ionizationcharge (Q) simultaneously

Multiple ways to achieve this concept

SoLAr: Integration of conventional light detectors (e.g. VUV SiPM's) into the pixel plane

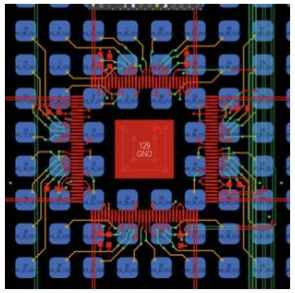
Tile dimension: $32 \times 32\ \mathrm{cm}^2$
(active area $25.6 \times 25.6\ \mathrm{cm}^2$)

Divided into 8×8 regions ($64 - 4$ pixel, 1 SiPM)

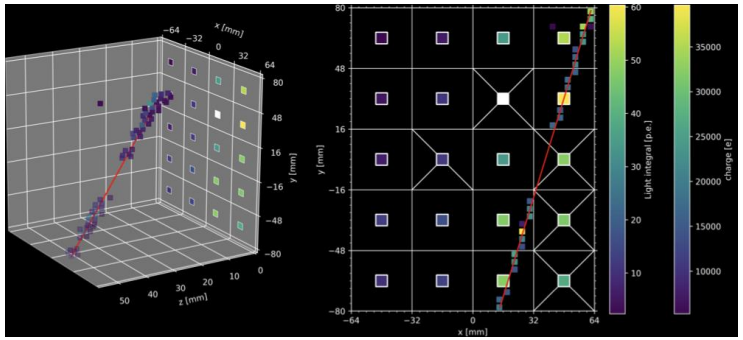
20 LArPix (room for 64)

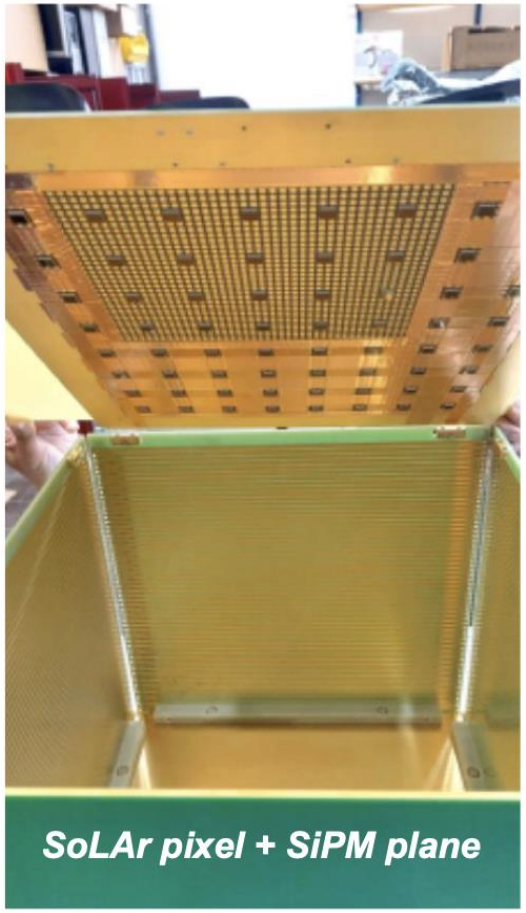
64 Hamamatsu VUV MPPC with independent readout (cold preamplifier + warm electronics)

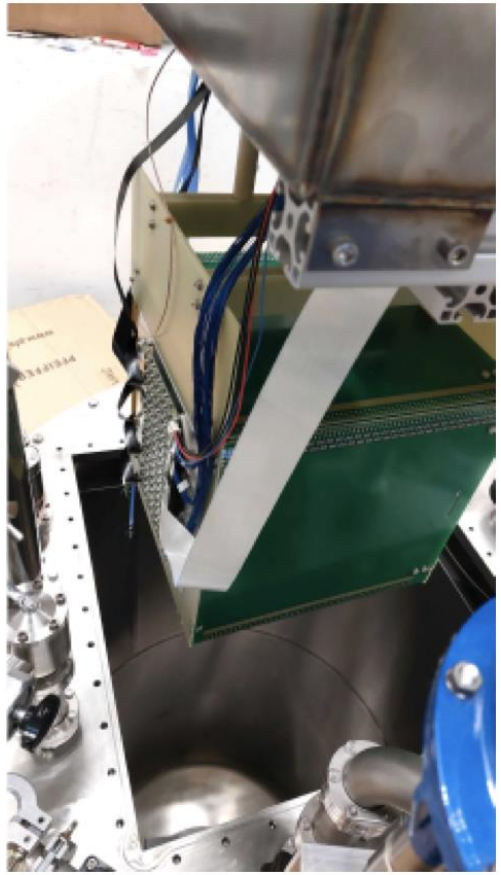
SoLAr tile V2



Single multilayer PCB



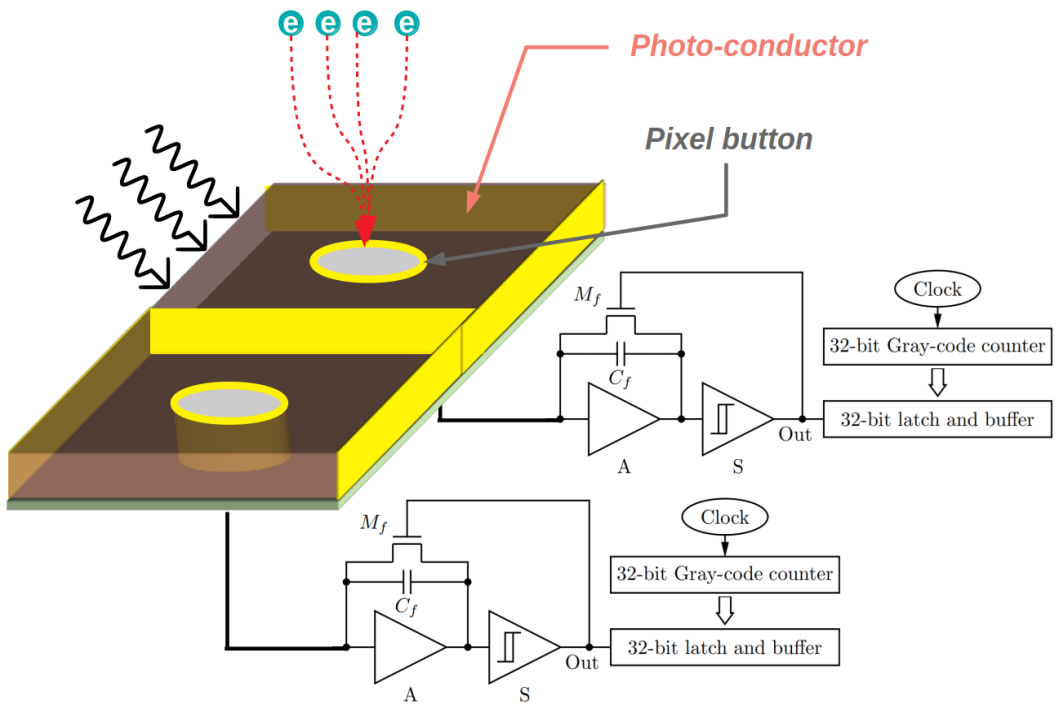




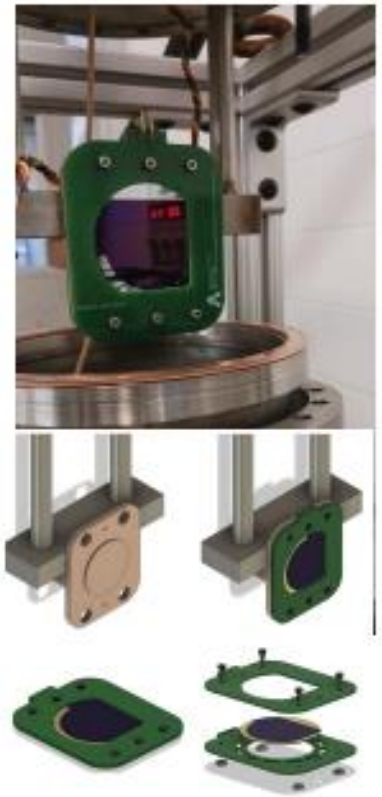
[25]

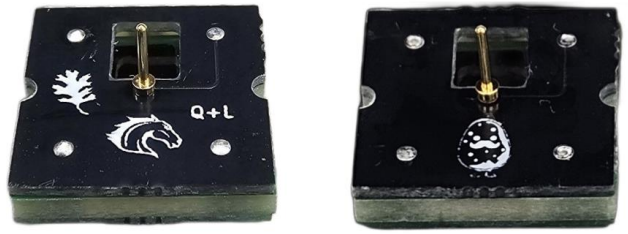
Multimodal pixel readout –aSe photoconductor

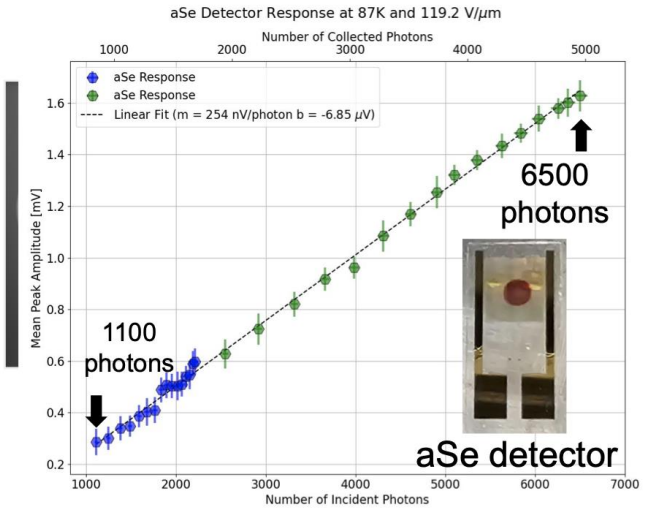
(Elena Gramellini *et al*)



- Amorphous selenium (aSe)
- Direct sensitivity to VUV light with low detection threshold
- large area coverage & avalanche gain possible Demonstrated at both room and LAr temperature





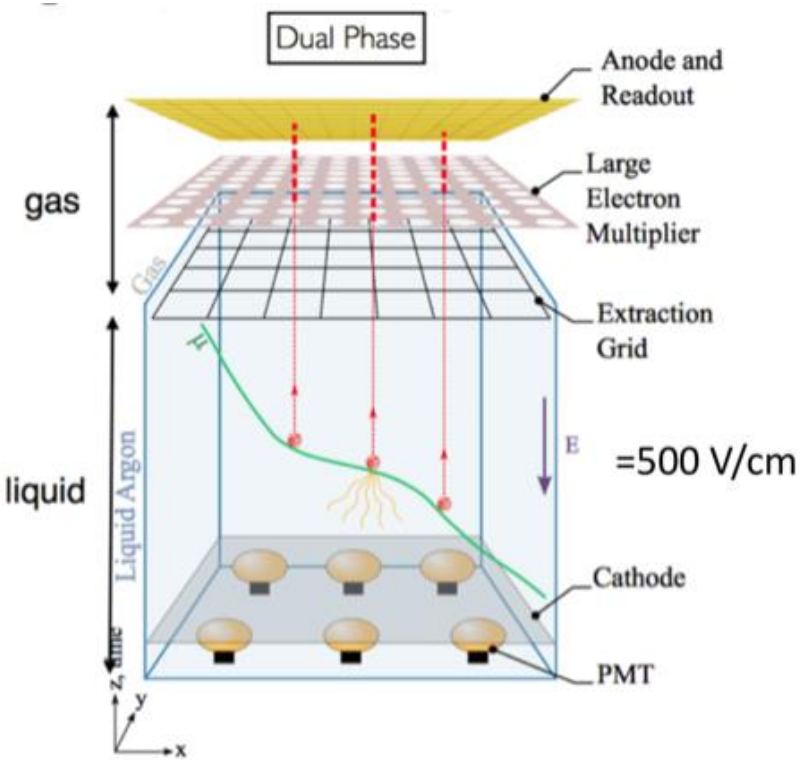


[25]

Dual Phase LAr Detector Operation Principles

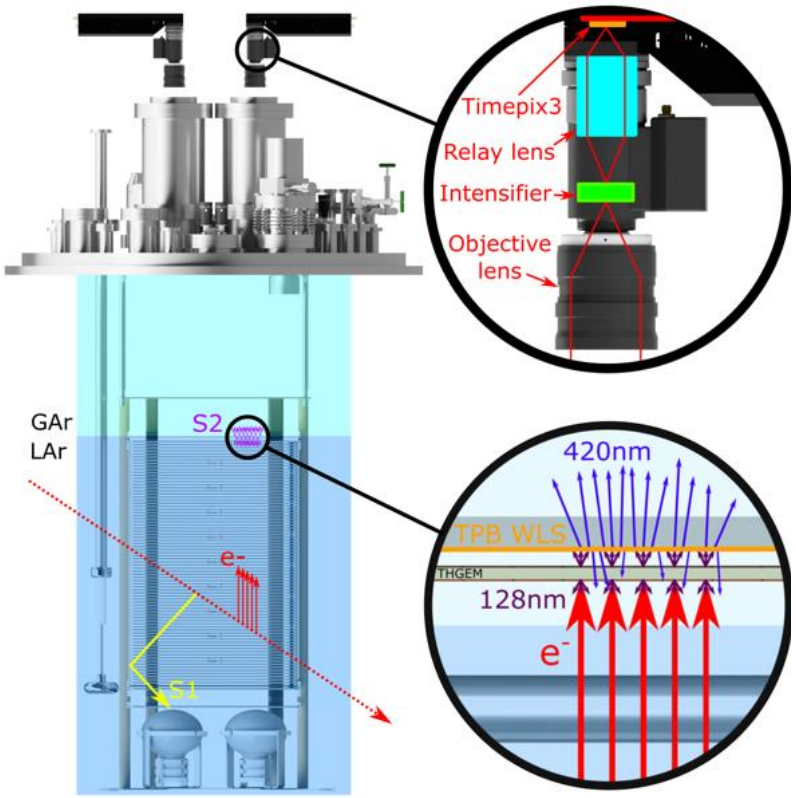
ProtoDUNE DP

Charge amplification and readout



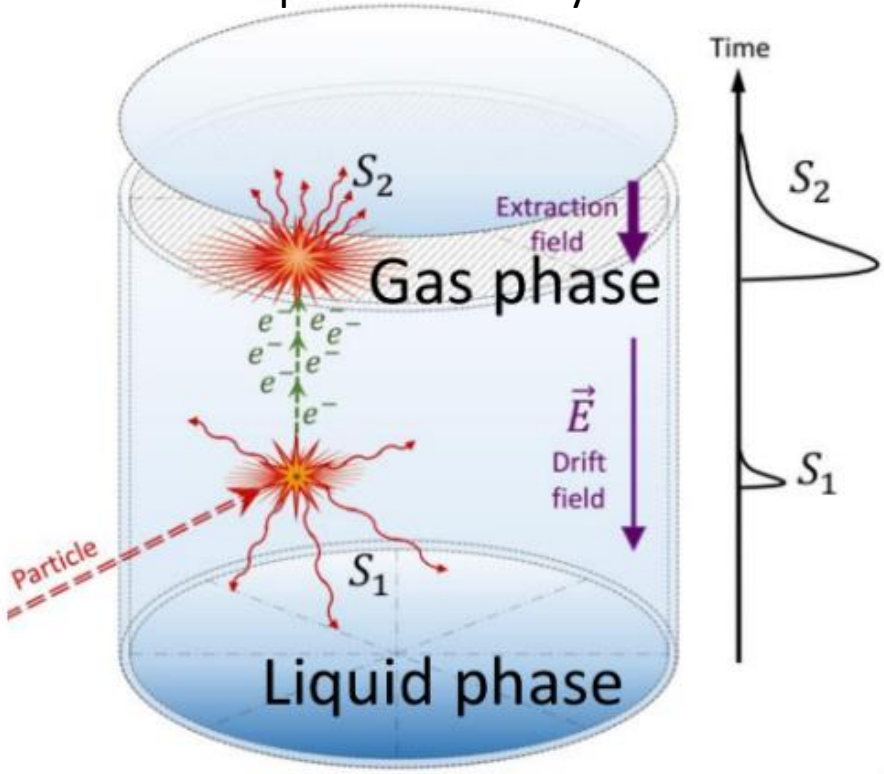
ARIADNE

Charge amplification and light readout with fast cameras



Darkside

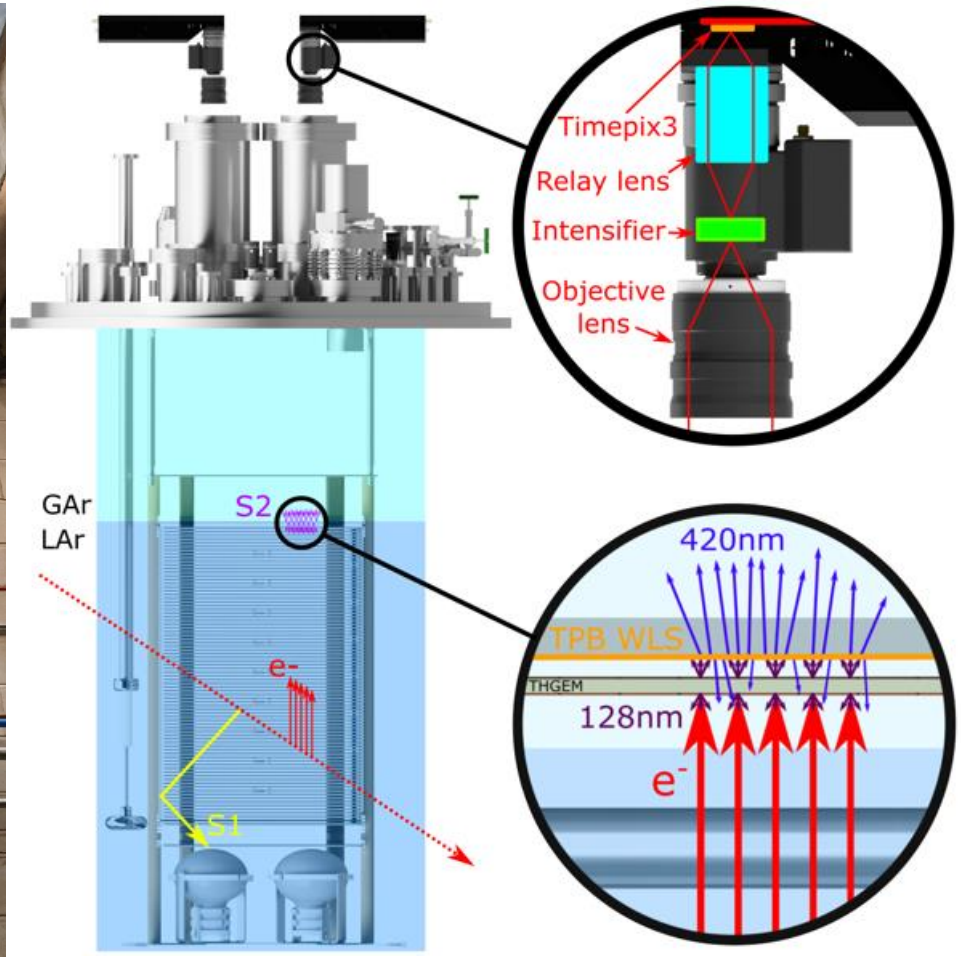
Electroluminescence light (no e⁻ avalanche) readout with radiopure SiPM array



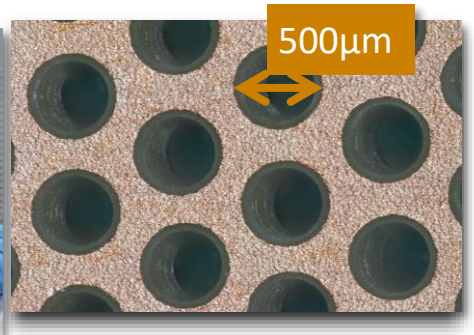
ARIADNE (1ton): Optical LArTPC with TPX3Cam

[13-15]

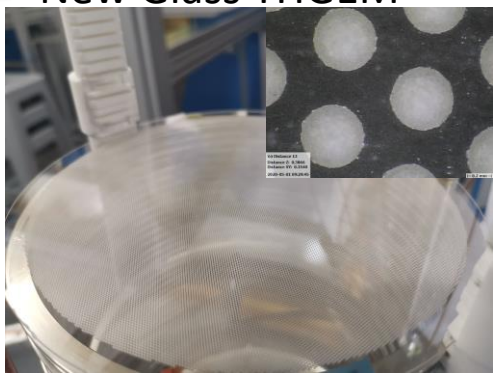
1-ton Detector at Liverpool



Instead of reading out the charge from the THGEM, fast TPX3 Cameras photograph the S2 light generated in the THGEM holes



New Glass THGEM



New Manufacturing glass THGEM technique (patent pending) allows use of large scale radiopure glass opening application also to Dark Matter

ARIADNE: Optical LArTPC with TPX3Cam

Full 3D Readout
Silicon pixel readout chip developed by the Medipix collaboration. **Very well established** technology at CERN.

Simultaneous 10 bit Time over Threshold (ToT) and 18 bit Time Of Arrival (TOA).

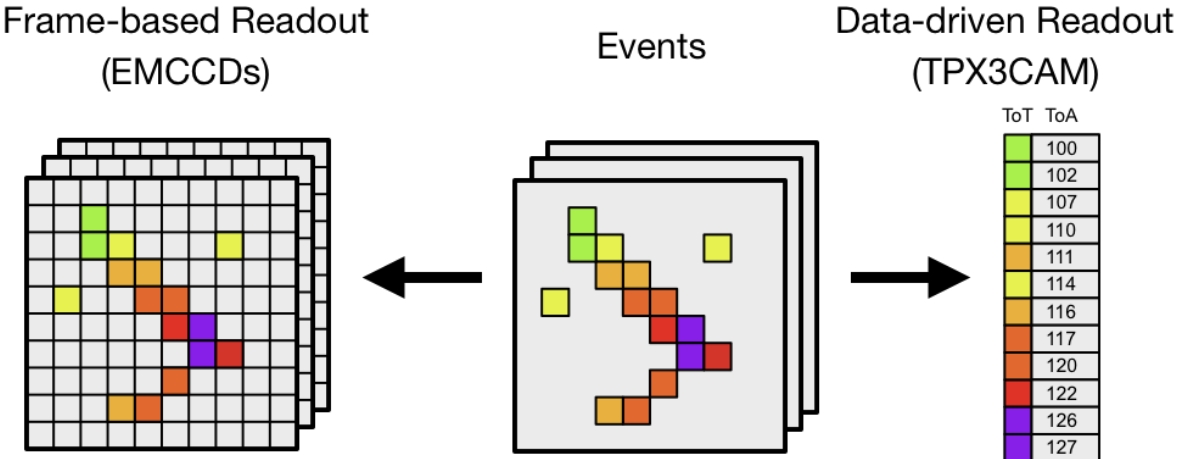
ToT allows accurate calorimetry measurements.

TOA accurate timing and 3D reconstruction.

"Data driven readout": pixels read out asynchronously, allows very efficient sparse readout.

Possible to have continuous trigger-free readout.

Sensor resolution	256x256 pixels
Pixel size	55μm x 55μm
Max readout rate	40Mhits•cm^{-2} •sec^{-1}
Time resolution	1.6 ns

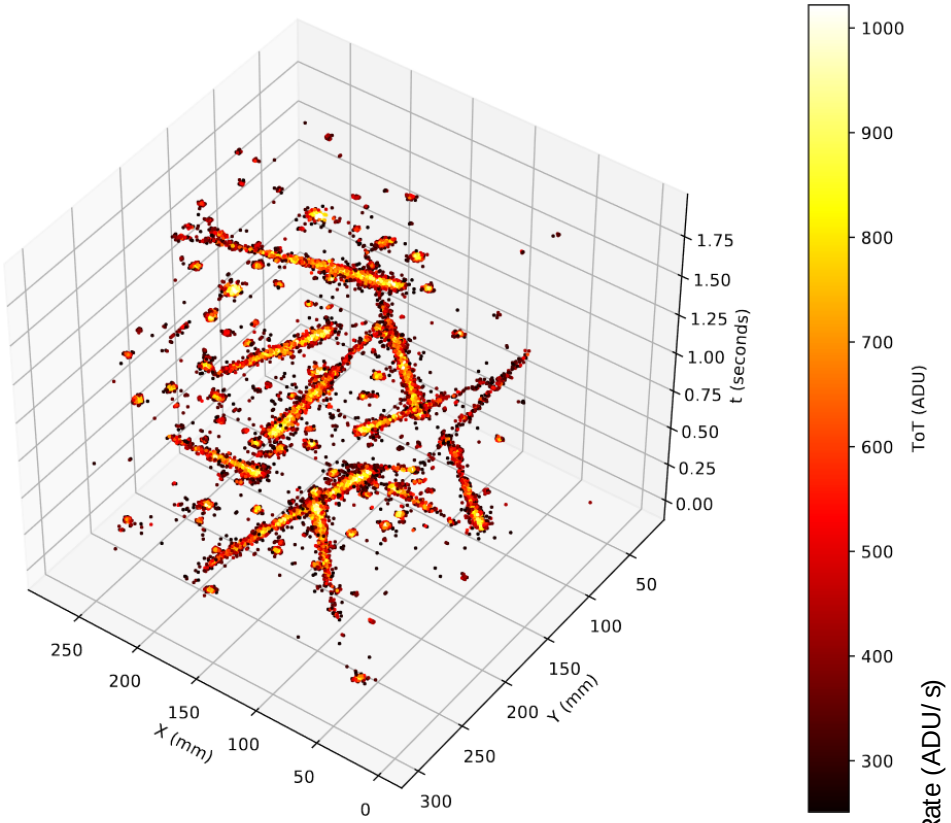


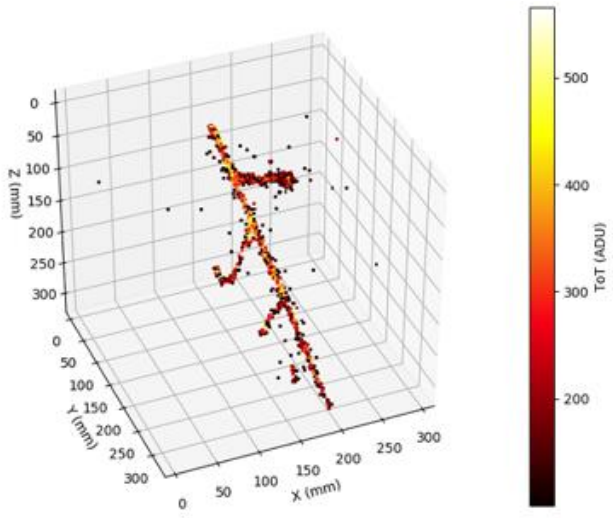
- All pixels read out
- No timing data within event

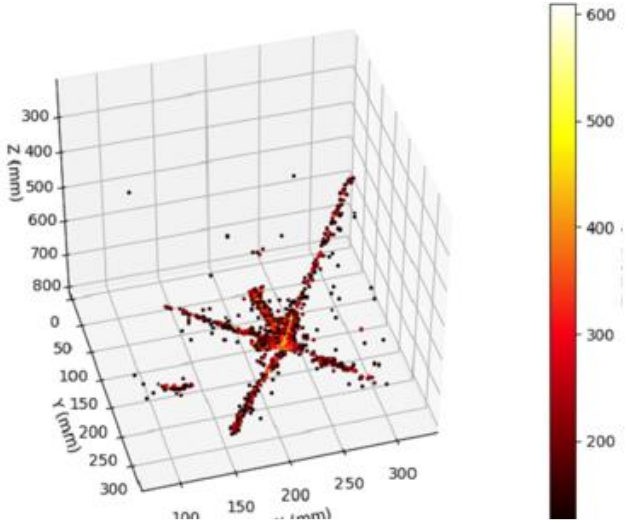
- Only active pixels read out
- Per pixel timing information

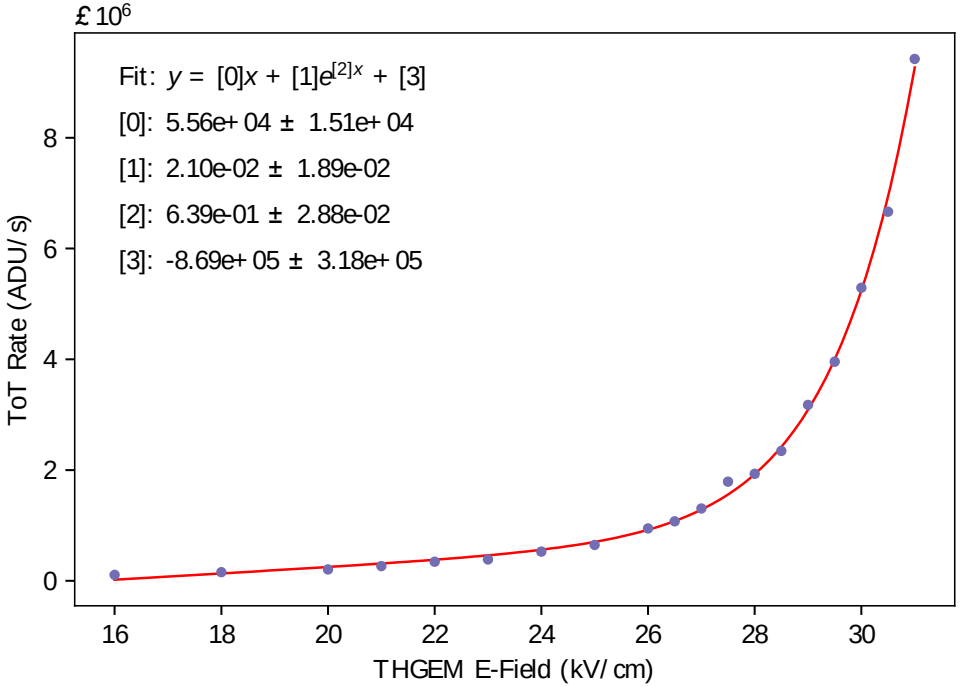
[13-15]

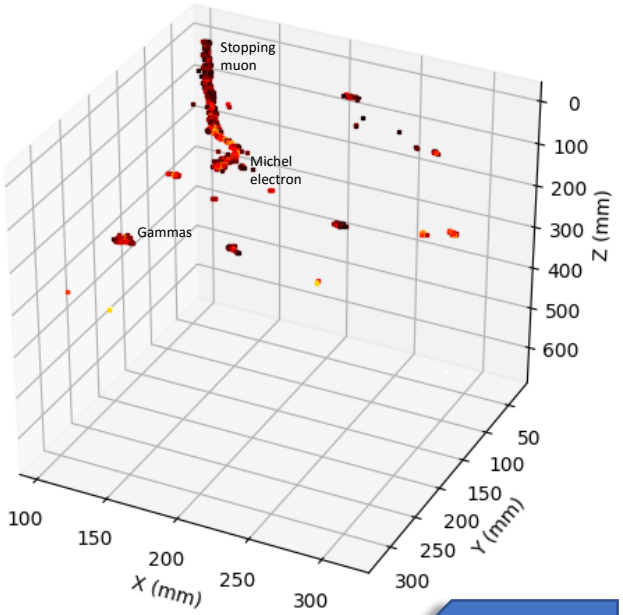
ARIADNE: LAr Cosmics









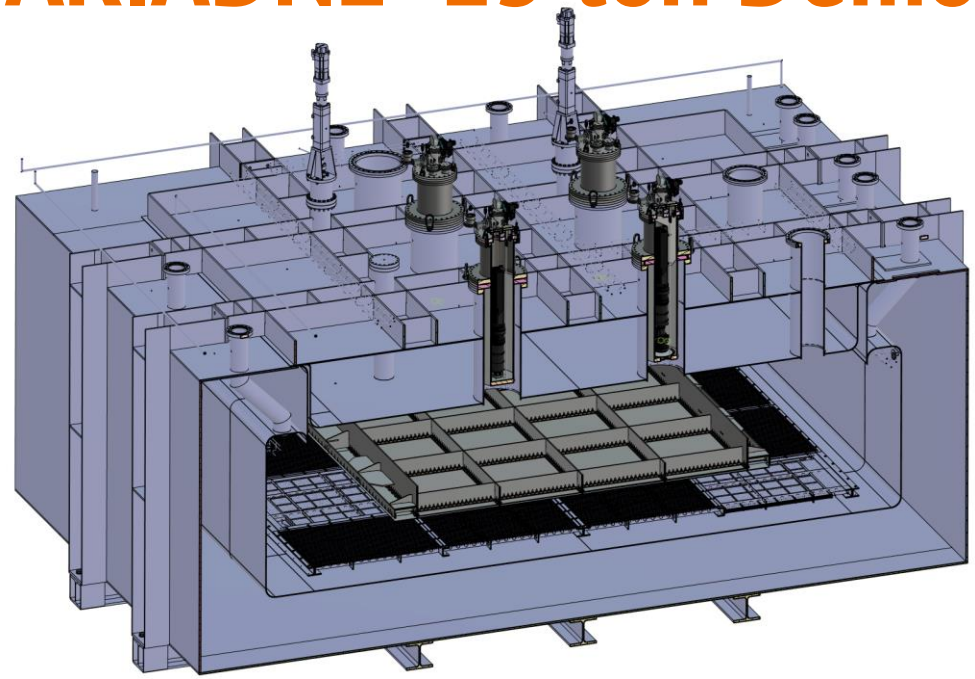


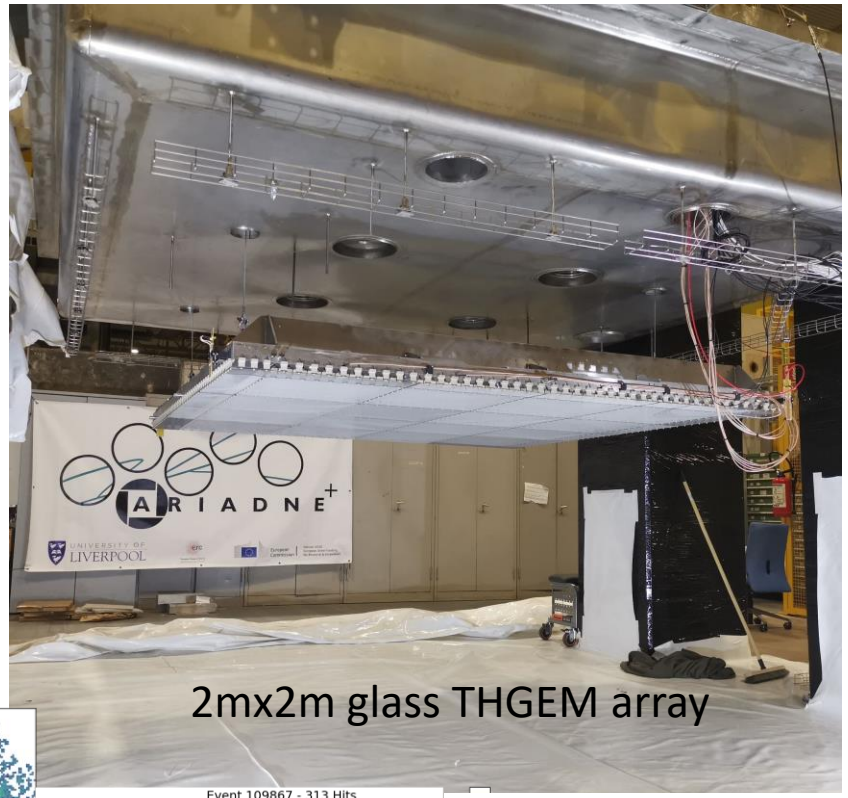
- 1.75 sec streaming (ie equivalent to 3k e^- drift)
- ~1mm/pixel
- Raw 3D only ToT cut
- Camera can cover 1mx1m at 4mm/pix

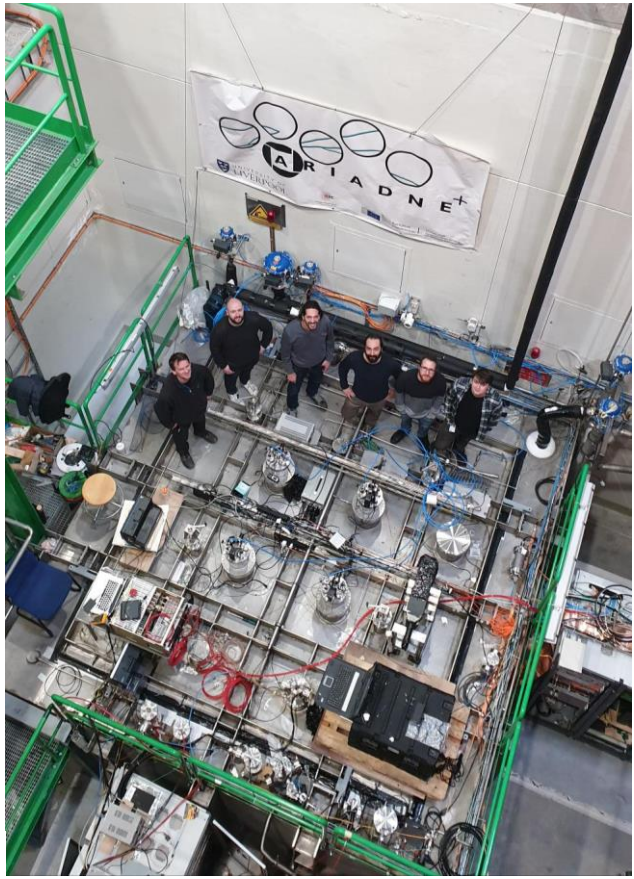
TPXCam sensitive to electroluminescence regime (no e^- gain)

[13-15]

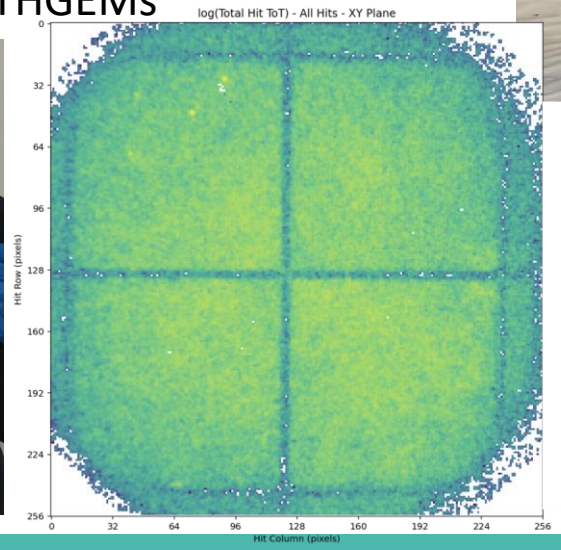
ARIADNE+ 15 ton Demonstration @CERN

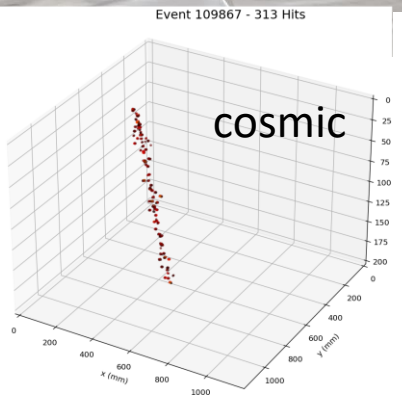


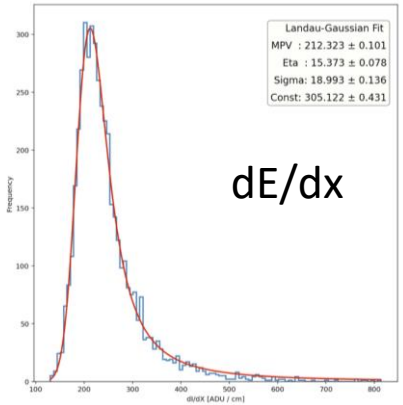




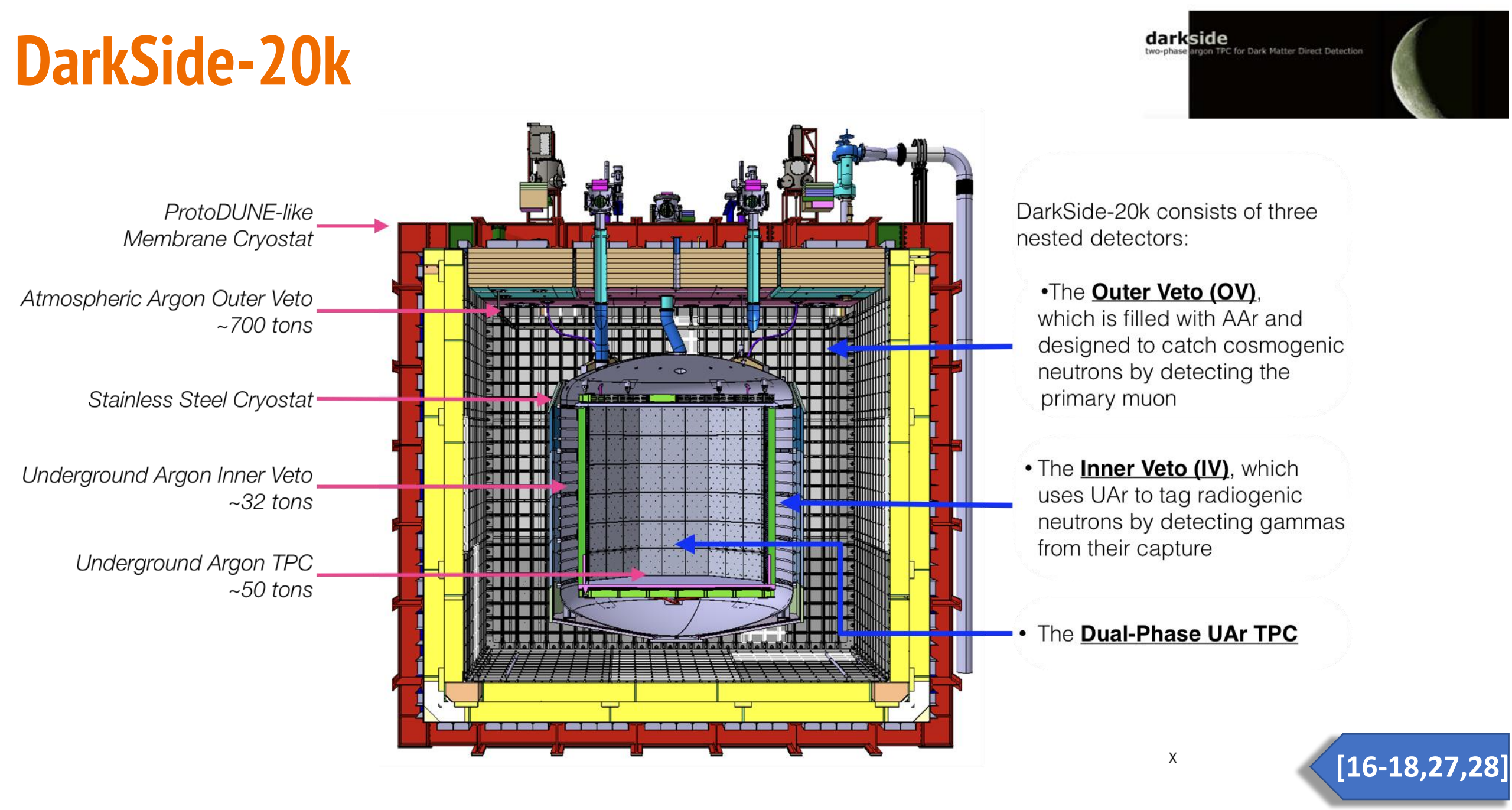
Sixteen 50cm x 50cm glass THGEMs



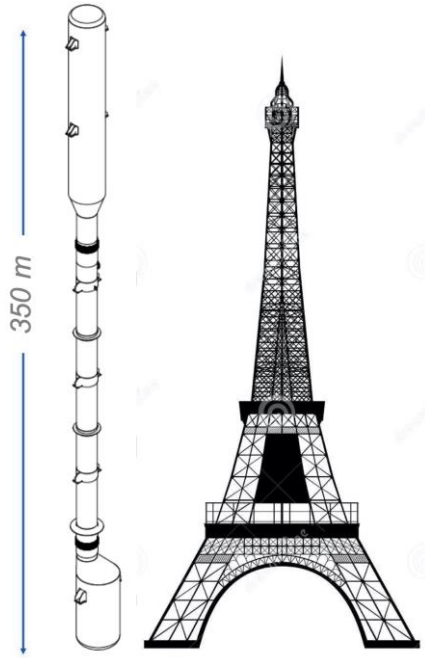




DarkSide-20k



DarkSide-20k ^{39}Ar depletion & Large Area SiPM Readout



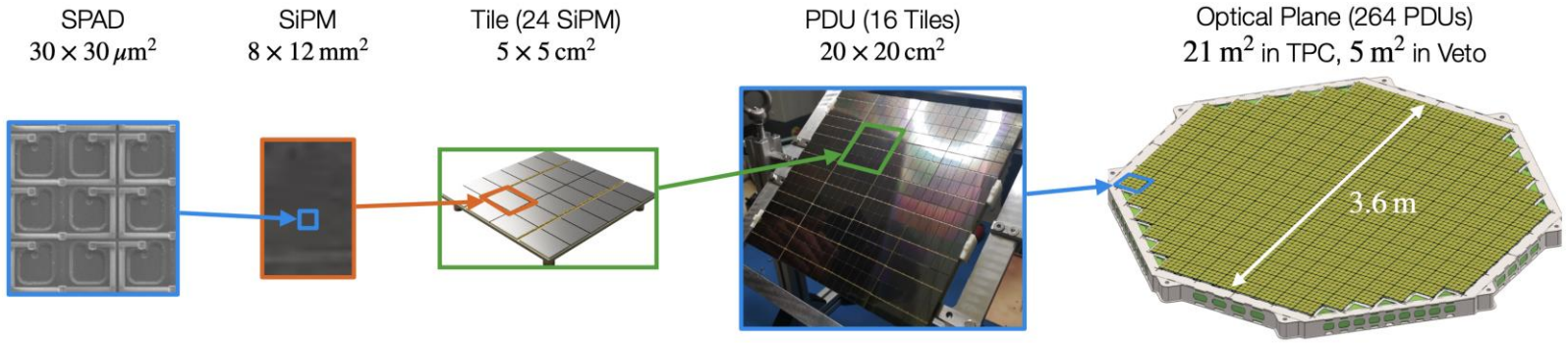
ARIA -distillation column

ARIA project (Darkside Collab.), production of depleted argon, below the UAr levels

Silicon is intrinsically radiopure

- Developed with Fondazione Bruno Kessler (FBK)
  - Photon detection efficiency: $> 40\,\%$ at 77K
  - Dark count rate: $< 0.01\ \mathrm{Hz/mm^2}$ at 77K (7 VoV)
  - SNR: > 8 (TPC PDU)

PDU packaging and assembly at Nuova Officina Assergi (NOA) at LNGS



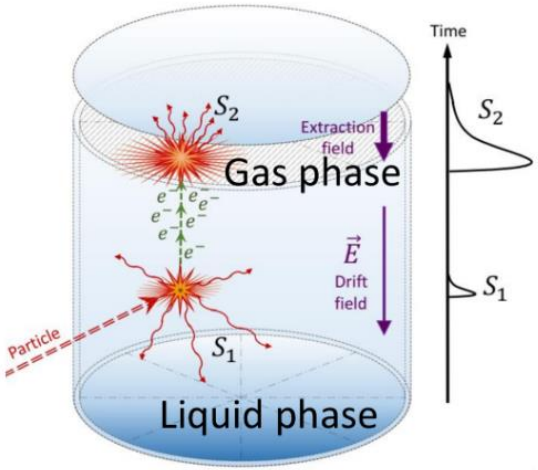
DarkSide Collaboration: "Cryogenic Characterization of FBK RGB-HD SiPMs", JINST 12 P09030 (2017)

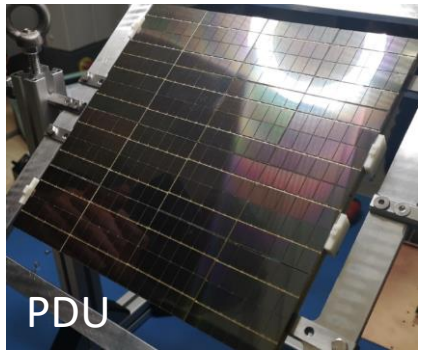
IEEE Trans.Electron.Dev. 64 2, 521-526
IEEE Trans.Nucl.Sci. 65 (2017) 1, 591-596
IEEE Trans.Nuc.Sci. 65, no. 4, pp. 1005-1011, April 2018

Sensors (Basel). 2019;19(2):308.
F.Acerbi et al.,IEEE Trans. Electron Dev. 64, 2, (2017), 521-526

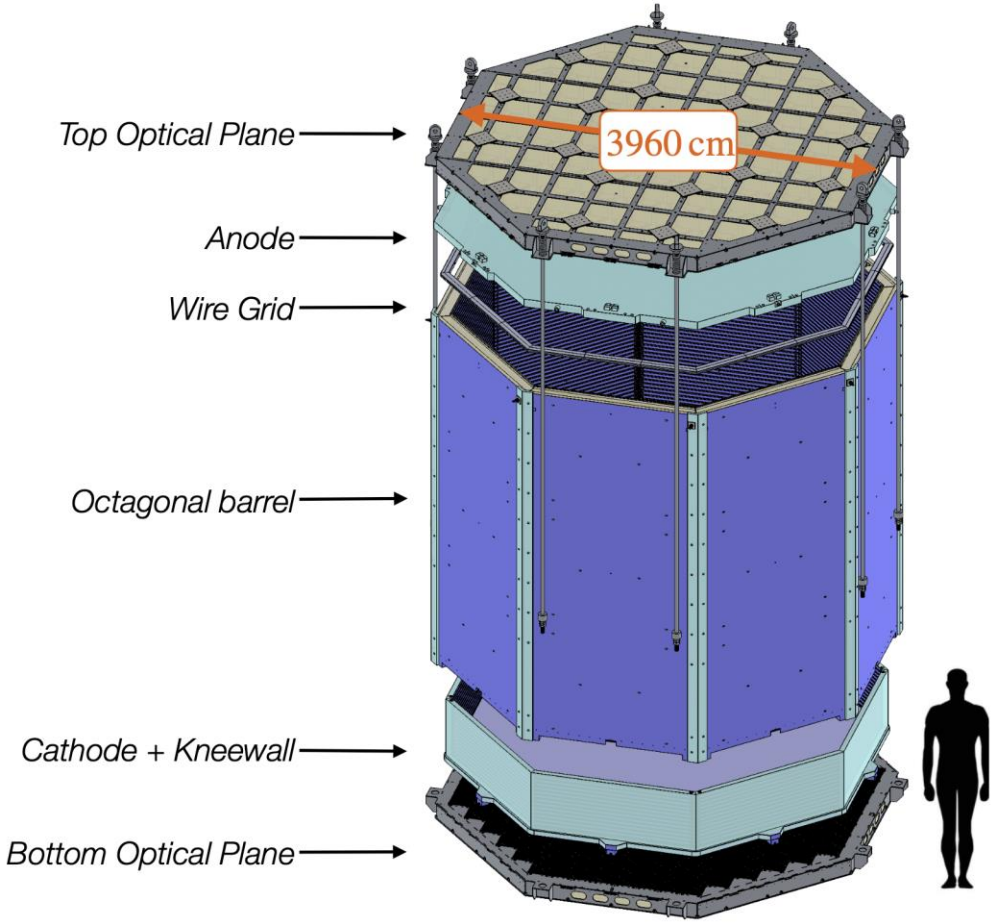
[16-18,27,28]

DarkSide-20k inner detector





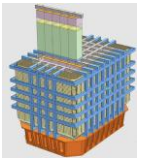
- Octagonal vessel made from ultra-pure PMMA
  - Operated as a dual-phase time projection chamber (TPC)
- Two stainless steel optical planes with 528 light readout channels each (total of $20\,\mathrm{m}^2$ of light sensors)
  - Light wavelength-shifted via TPB from $128\,\mathrm{nm}$ to $420\,\mathrm{nm}$
  - Visible light reflected by foils of Enhanced Specular Reflector (ESR)
- Drift field of $200\,\mathrm{V/cm}$ ($V_{\mathrm{Cathode}} = 75\,\mathrm{kV}$)



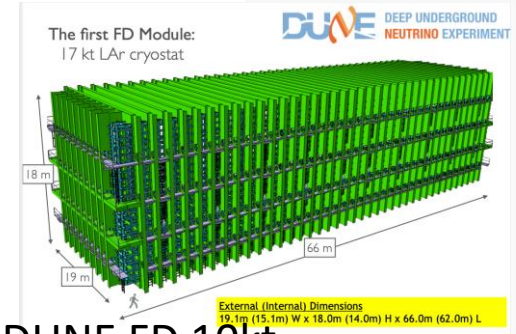
Outer detector PDUs similar with the inner. Production in UK close to completion.

[16-18,27,28]

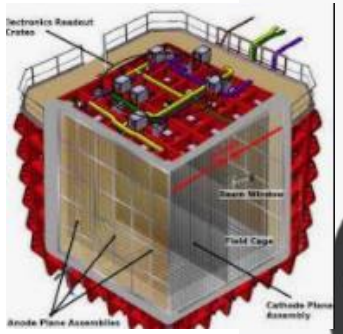
A very Exciting Era for LAr Detectors



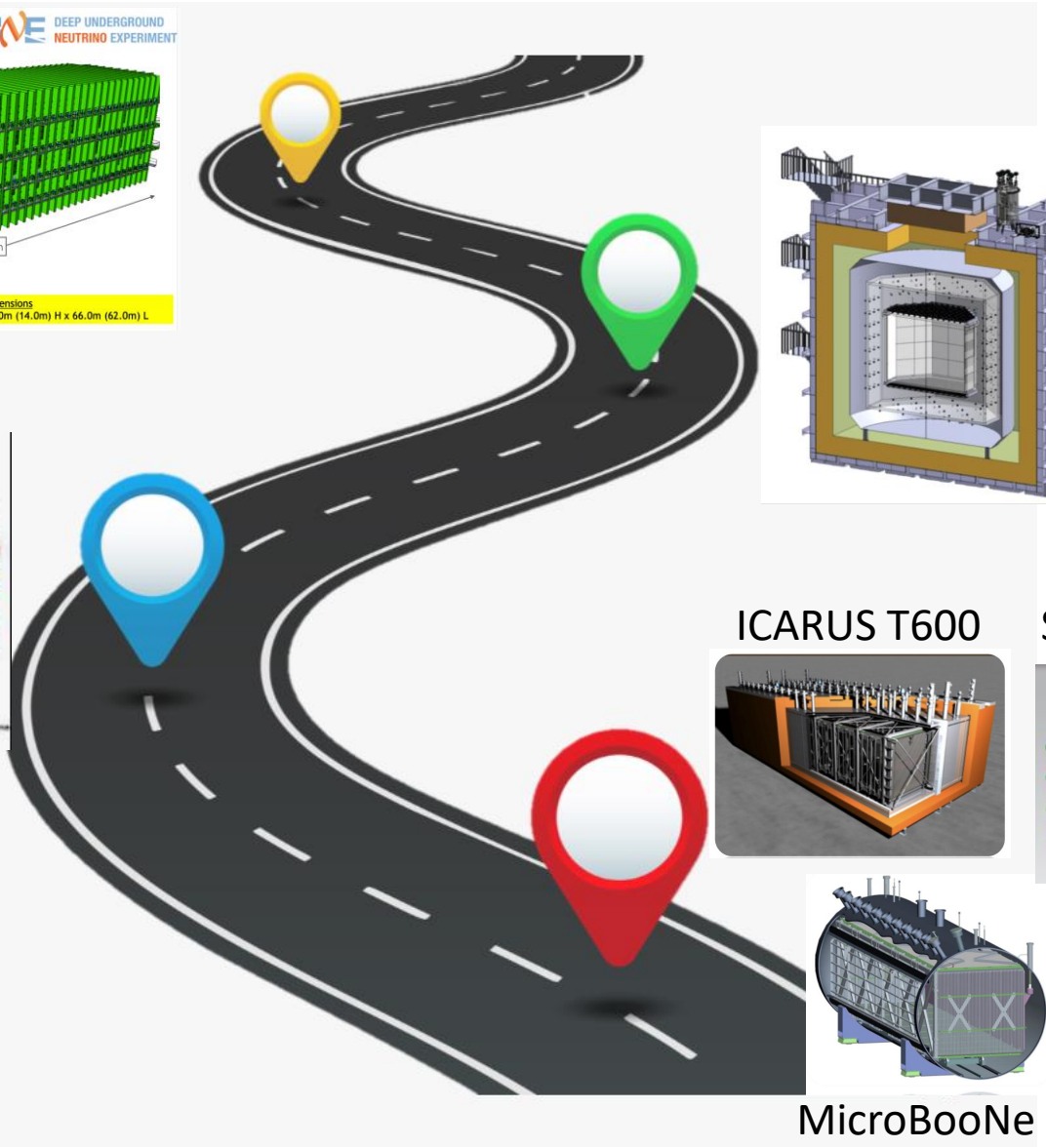
DUNE- ND LAr

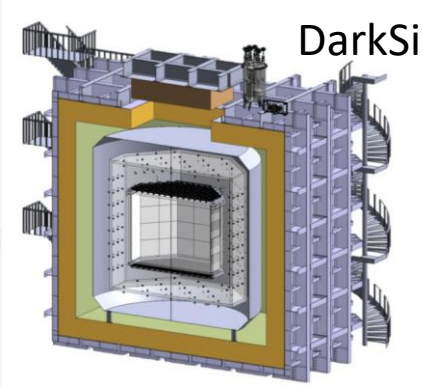


DUNE FD 10kt



ProtoDUNEs
750t @CERN



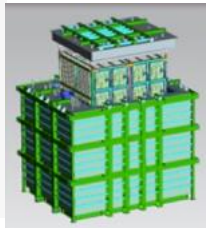


DarkSide-20k

Thank You!

ICARUS T600

SBND -112t



MicroBooNe

1-ton prototypes
ARIADNE

Citations

1. https://indico.cern.ch/event/768000/contributions/3275101/attachments/1817037/2970272/NeutrinoTelescopes2019Varanini.pdf
2. https://agenda.infn.it/event/24250/contributions/127449/attachments/79423/103217/Fava_SBN_Neutel_2021.pdf
3. JINST 13 (2018) P12007
4. https://indico.cern.ch/event/835190/contributions/3576893/attachments/1941976/3220400/Toups_NNN_2019.pdf
5. https://indico.fnal.gov/event/14063/contributions/23475/attachments/15115/19246/SBNDUNE.20170515.pdf
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7. https://indico.cern.ch/event/881818/attachments/1972807/3299895/CERN-Colloquium-Jan-20-60MB.pdf
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9. https://edms.cern.ch/ui/#!master/navigator/document?P:100722921:100738064:subDocs
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12. https://indico.in2p3.fr/event/19194/contributions/73346/attachments/54154/70767/ProtoDUNE-DP-duchesneau-250619.pdf
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16. https://indico.fnal.gov/event/19947/contributions/54727/attachments/34154/41785/DarrenPrice_DMUK_DarkSide20k.pdf
17. https://iopscience.iop.org/article/10.1088/1748-0221/15/03/C03038/pdf
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22. https://indico.cern.ch/event/1492360/attachments/3006084/5298729/CT-CERNcolloquium25.pdf
23. https://indico.cern.ch/event/1390649/contributions/6061504/attachments/2916604/5118565/DUNE_APEX_PHASEII_LIDINE2024_v0.pdf
24. https://indico.fnal.gov/event/67540/timetable/#20250312
25. https://indico.cern.ch/event/1485254/timetable/#20250211.detailed
26. Qpix: https://indico.phy.ornl.gov/event/510/contributions/2165/
27. https://indico.global/event/652/contributions/16971/attachments/57443/110377/CaminataUCLA.pdf
28. https://indico.global/event/652/contributions/16907/