Cryogenic Readout Electronics Systems for Liquid Argon TPCs in Neutrino Experiments

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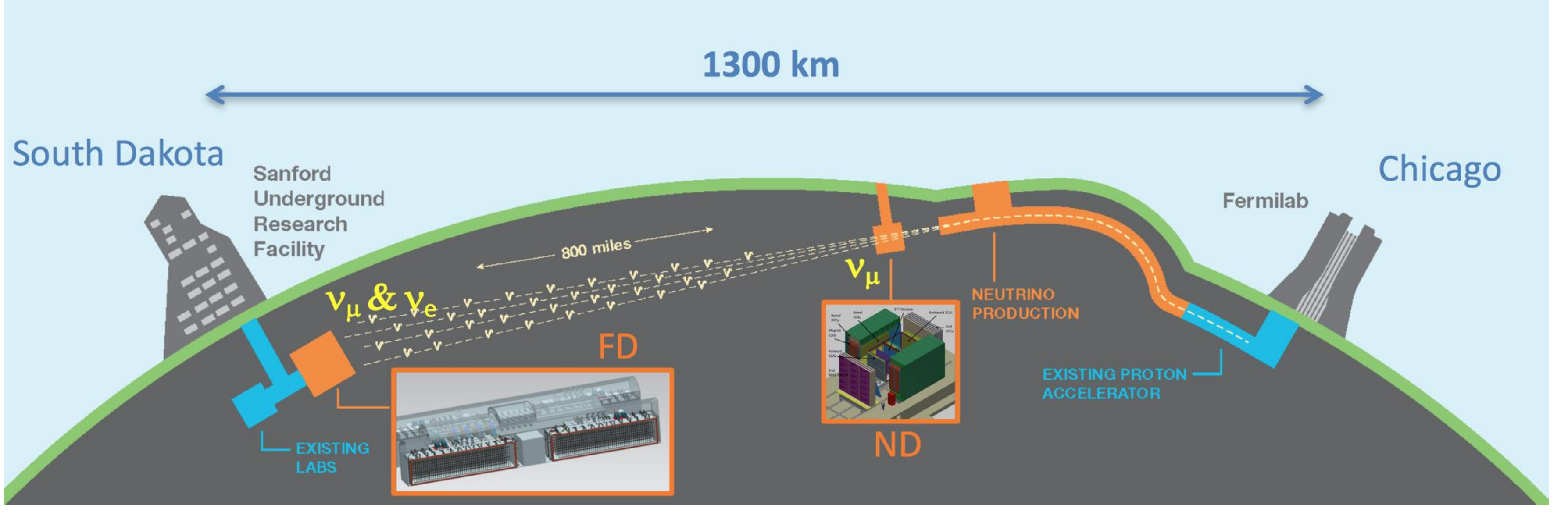
  - ProtoDUNE-SP
  - DUNE Far Detector

  } **Long Baseline Neutrino Experiments**
- Summary

Long Baseline Neutrino Program: LBNF/DUNE



An international flagship experiment to unlock the mysteries of neutrinos

Three major discovery areas

Origin of Matter

DUNE scientists will look at the differences in behavior between neutrinos and antineutrinos, aiming to find out whether neutrinos are the reason the universe is made of matter.

Unification of forces

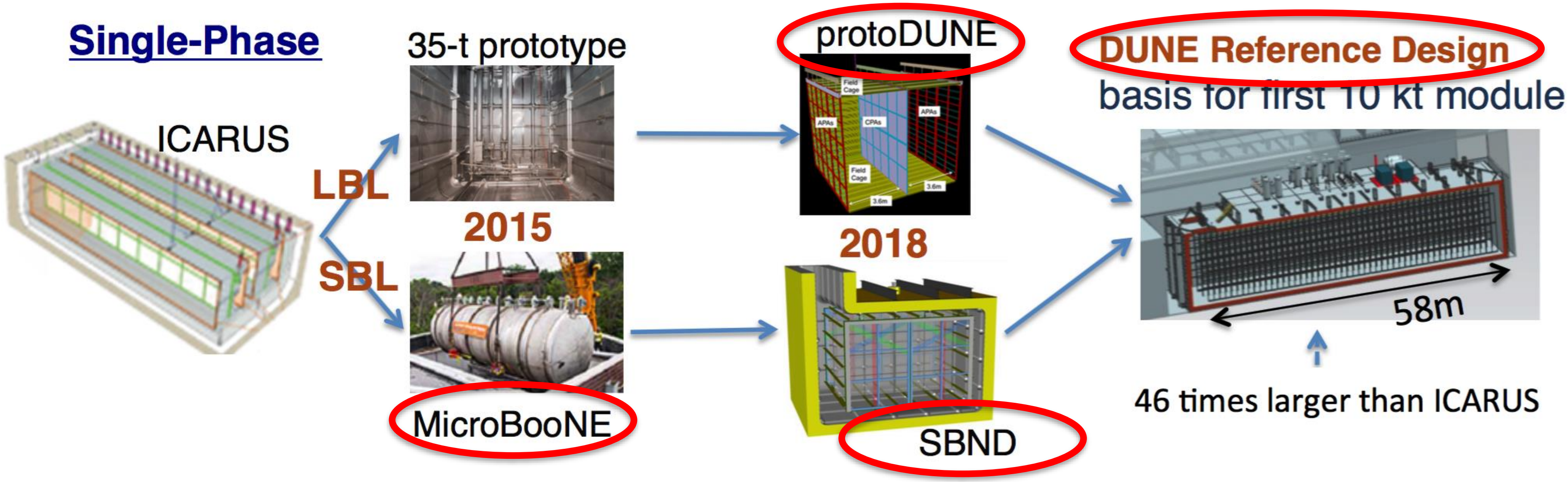
DUNE's search for the signal of proton decay—a signal so rare it has never been seen—will move scientists closer to realizing Einstein's dream of a unified theory of matter and energy.

Black hole formation

DUNE will look for the gigantic streams of neutrinos emitted by exploding stars to watch the formation of neutron stars and black holes in real time, and learn more about these mysterious objects in space.

Development of LArTPC for Neutrino Experiments

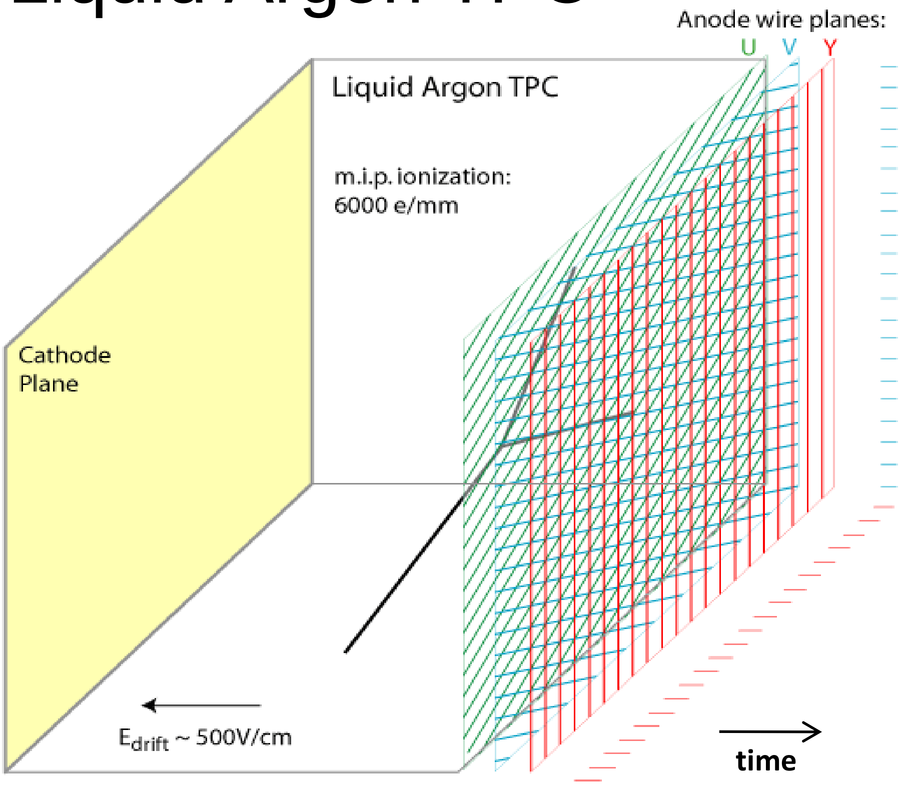
- **BNL is leading TPC readout electronics *SYSTEM* design**
  - Including MicroBooNE and SBND as part of the Short Baseline Neutrino Program



Note: Dual-Phase LArTPC is not included in this talk

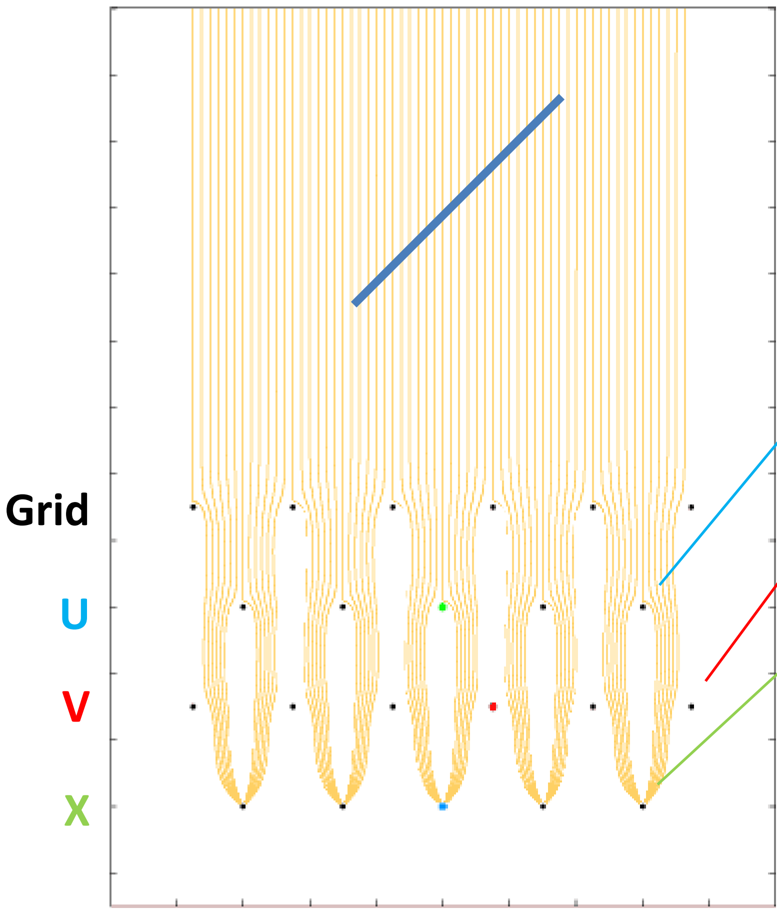
Liquid Argon TPC

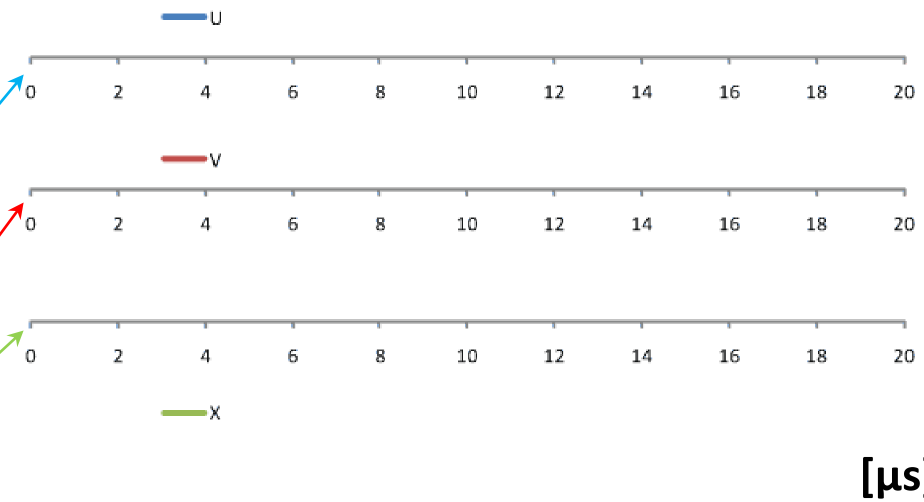
Charged particles passing through detector ionize the argon atoms, and the ionization electrons drift in the electric field to the anode wall on a timescale of milliseconds. The anode consists of layers of active wires forming a grid.



- 3 Wire Plane readout with Excellent Space and Energy resolution
- 3D-imaging: full event topology reconstruction
- Higher sensitivity to neutrino physics and for some of the proton decay channels (e.g. p → K**ν**)

Signal Formation:
Induced Signals from a Track Segment

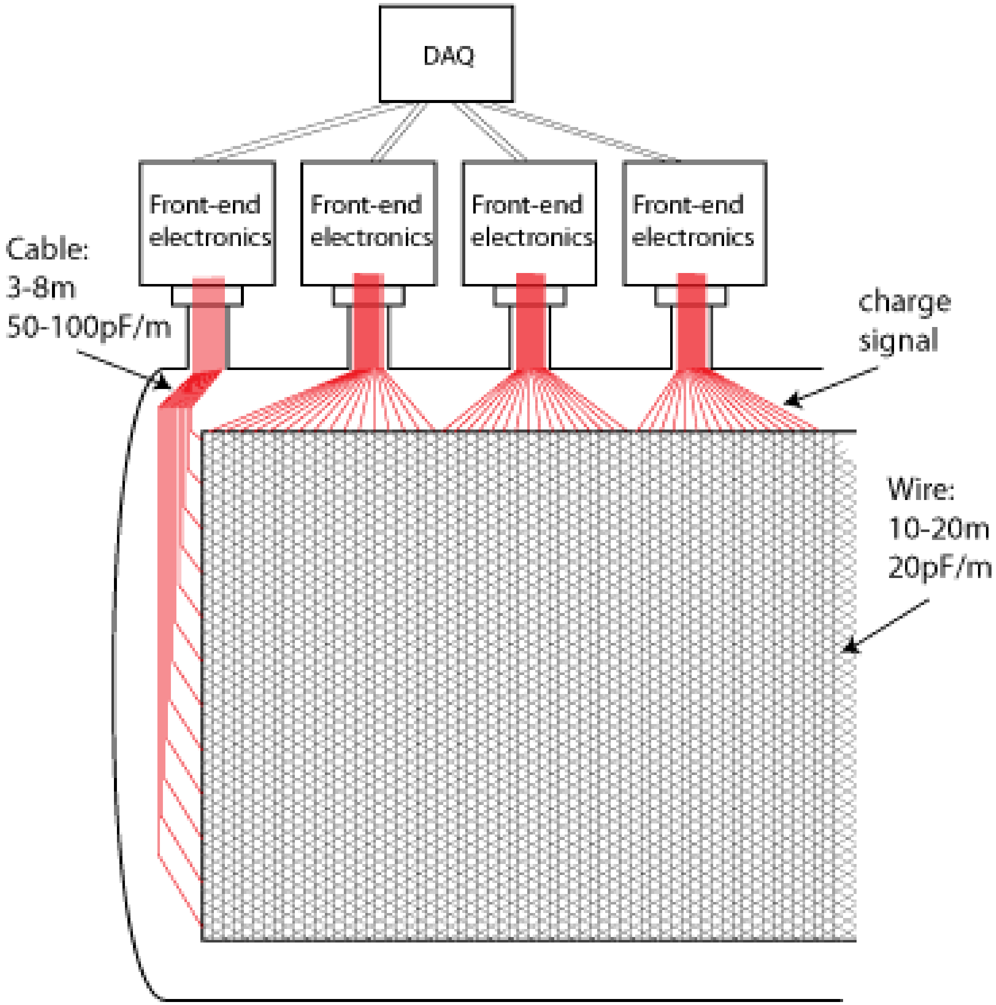




Charge signal is very small due to there is no electron amplification inside Lar.

DUNE style wire arrangement: 3 instrumented wire planes + 1 grid plane
Raw current waveforms convolved with a 0.5μs gaussian to mimic diffusion

"Warm" Electronics



- A typical readout configuration with warm electronics: long cables connect the sense wires to the FEE, resulting in high capacitance and large electronics noise.
- To reduce the cable length, one has to implement cold feedthroughs below the liquid level, which increases the cryostat complexity.

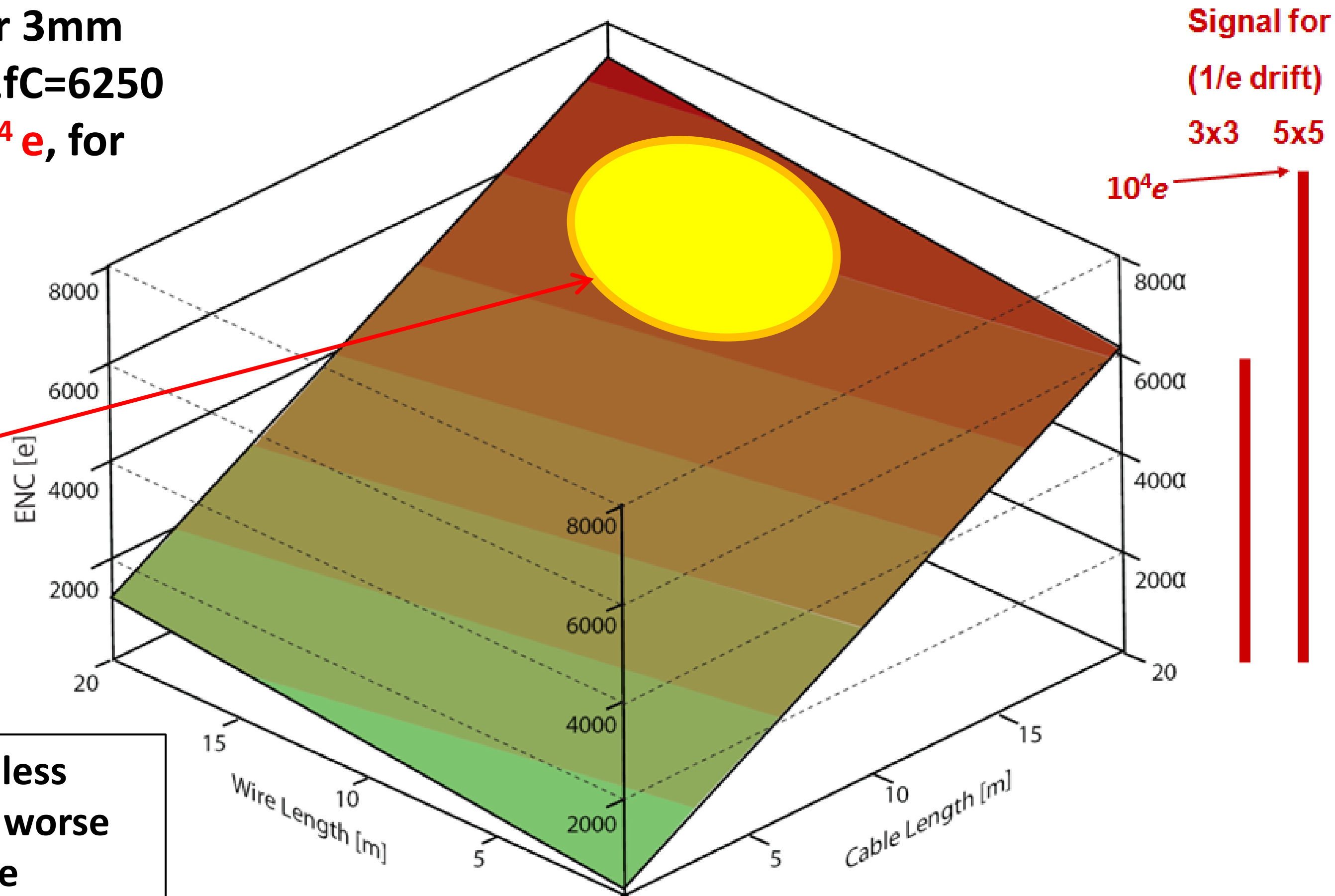
"Warm" Electronics

Noise (ENC) *vs* TPC Sense Wire and Signal Cable Length

MIP Signal for 3x3 and 5x5 mm Sense Wire Spacing

The expected signal for 3mm wire spacing is then ≈1fC=6250 e, … and for 5mm, ≈10^4 e, for the "collection signal"

10kton DUNE LArTPC with warm electronics (300K) ENC ~$6x10^3$ e rms



DUNE: Total ENC shall be less than 1/9 of the expected worse case instantaneous charge arriving at the APA from a MIP.

Cryogenic Electronics is the Optimal Solution for Large LArTPCs

Cold electronics for "Giant" Liquid Argon Time Projection Chambers

1st International Workshop towards the Giant Liquid Argon Charge Imaging Experiment (GLA2010)

Veljko Radeka[1*], Hucheng Chen[1], Grzegorz Deptuch[2], Gianluigi De Geronimo[1], Francesco Lanni[1], Shaorui Li[1], Neena Nambiar[1], Sergio Rescia[1], Craig Thorn[1], Ray Yarema[2] , Bo Yu[1]

[1] Brookhaven National Laboratory, Upton, NY 11973-5000, USA

[2] Fermi National Laboratory,

[*]Correspondence, e-mail: radeka@bnl.gov

Abstract. The choice between cold and warm electronics (inside or outside the cryostat) in very large LAr TPCs (>5-10 ktons) is not an electronics issue, but it is rather a major cryostat design issue. This is because the location of the signal processing electronics has a direct and far reaching effect on the cryostat design, an indirect effect on the TPC electrode design (sense wire spacing, wire length and drift distance), and a significant effect on the TPC performance. All these factors weigh so overwhelmingly in favor of the cold electronics that it remains an optimal solution for very large TPCs. In this paper signal and noise considerations are summarized, the concept of the readout chain is described, and the guidelines for design of CMOS circuits for operation in liquid argon (at ~89 K) are discussed.

Veljko Radeka

- https://www.bnl.gov/newsroom/news.php?a=220971

Veljko Radeka joined Brookhaven Lab's Instrumentation Division in 1962 where he has held numerous roles, including Division Head. For more than four decades he led and positioned the division as a world class organization. His unique contributions to the field of instrumentation are internationally recognized and encompass a broad range of scientific applications. Veljko is still a very active member of the scientific community, and his work has inspired colleagues and other researchers around the world.

Brookhaven's Veljko Radeka Recognized by International Committee for Future Accelerators

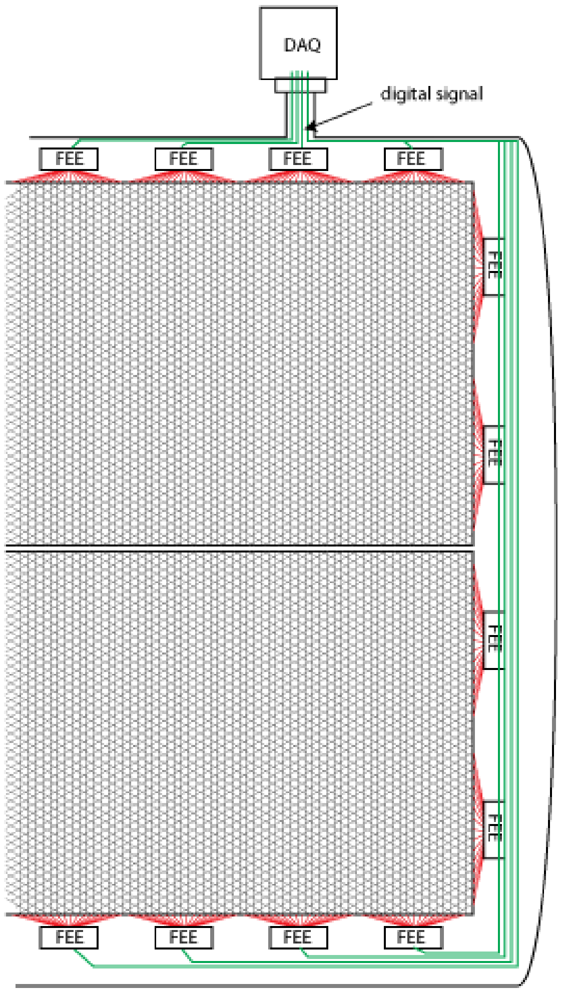
Radeka becomes one of the first recipients of the ICFA Instrumentation Award in its inaugural year

December 7, 2022

“I always felt that the purpose of instrumentation is to make Brookhaven Laboratory competitive,” said Radeka. “We want to **provide these scientists with the best tools** so that they can perform important work that is the basis of all nuclear and particle physics.”

Advantages of Cryogenic ("Cold") Electronics

- Having front-end electronics in the cryostat, close to the wire electrodes yields the best SNR. Noise is independent of the fiducial volume.
- Highly multiplexed circuits with fewer digital output lines not only greatly reduce the number of cryostat penetrations, but also give the designers of both the TPC and the cryostat the freedom to choose the optimum configurations

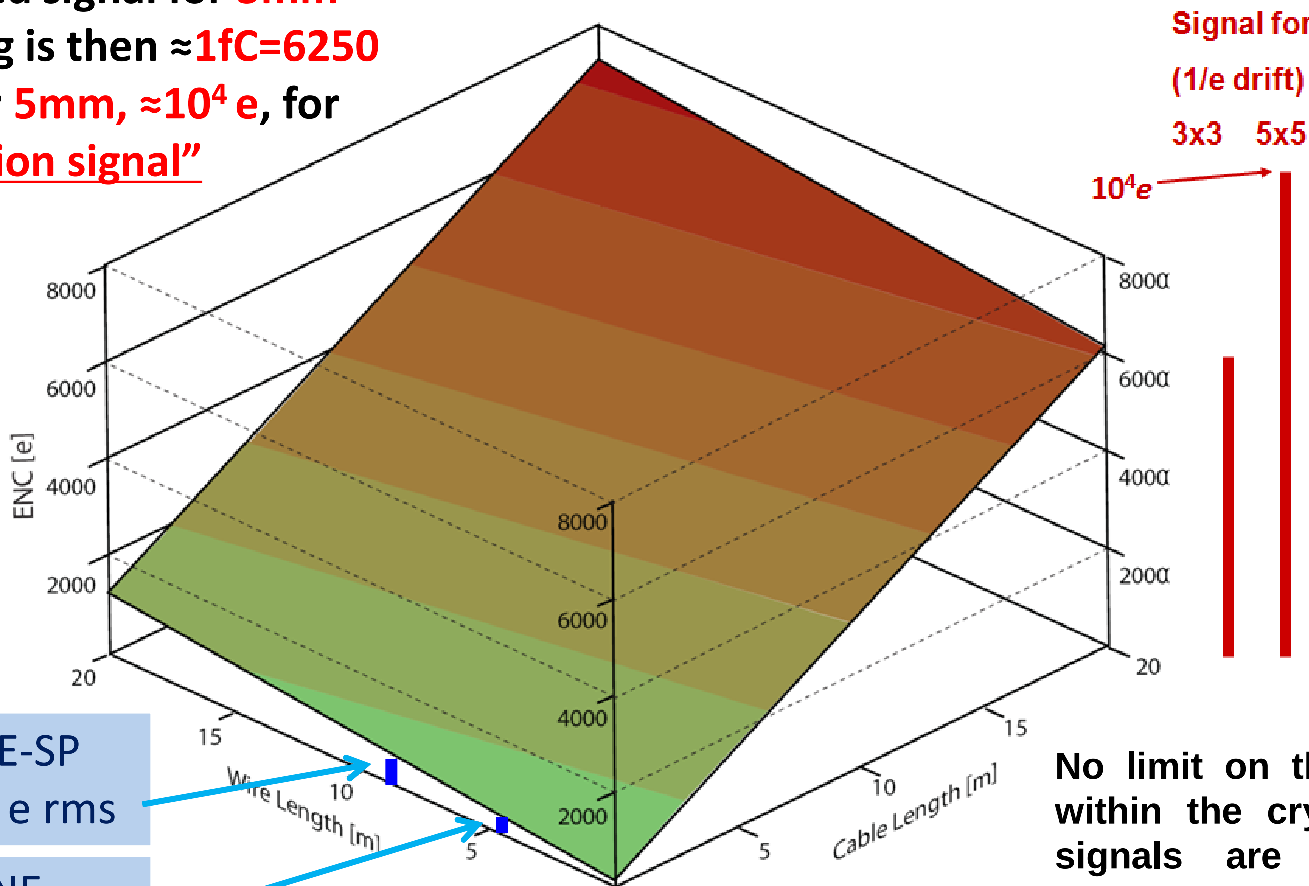


"Cold" Electronics as an Optimal Solution

Noise (ENC) *vs* TPC Sense Wire and Signal Cable Length

MIP Signal for 3x3 and 5x5 mm Sense Wire Spacing

The expected signal for 3mm wire spacing is then ≈1fC=6250 e, … and for 5mm, ≈10^4 e, for the "collection signal"

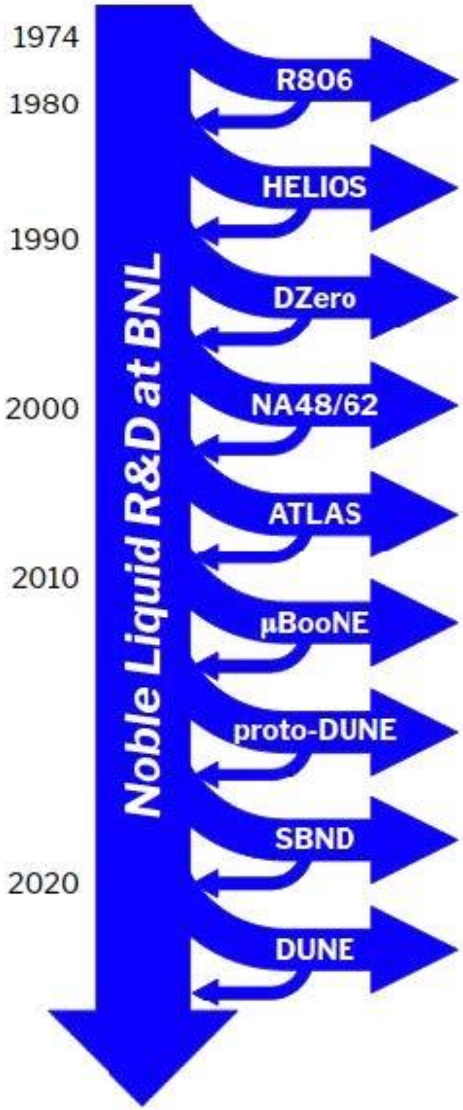


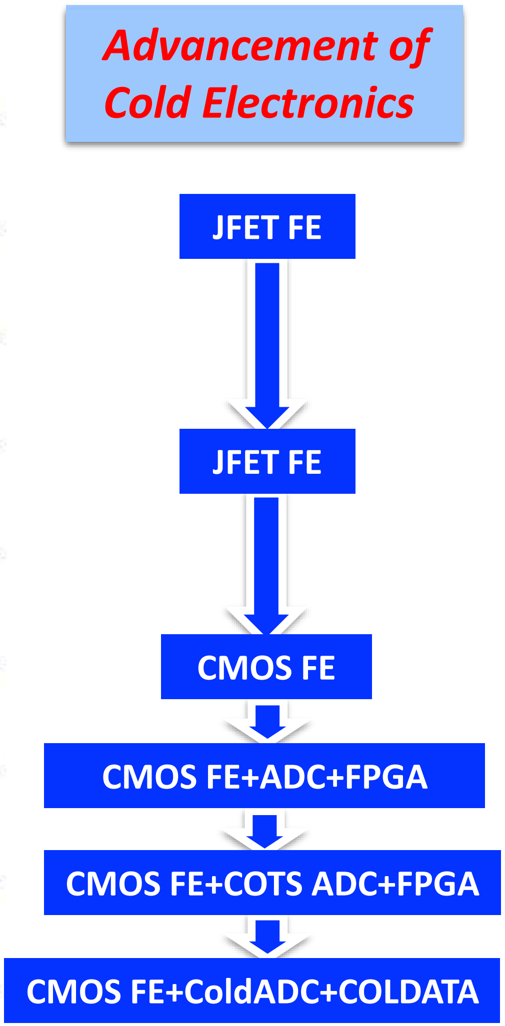
ProtoDUNE-SP
ENC ~600 e rms

MicroBooNE
ENC ~400 e rms

No limit on the cable length within the cryostat after the signals are amplified and digitized at the sense wires.

A Brief but Long History of CE Development





- BNL pioneered LAr based detector technology in 1974 [1]
- Physics/Engineering expertise which has made essential contributions to various programs, e.g. ATLAS, MicroBooNE
- Unique experience in cryogenic electronics and micro-electronics
- The R&D effort makes the experiments possible; the experiments, in turn, feed information back into the R&D process
- Cryogenic/Cold electronics development is making continuous advancement, from JFET to CMOS, from analog front-end to mixed signal ADC and FPGA
- ***A strong cold electronics team is built up as a core BNL competence, in close collaboration with other institutes, to realize various LAr TPC experiments***
- *[1] W. Willis, V. Radeka, Nucl. Instr. Methods, 120 (1974) 221*

Performance as ASIC is submerged in LN_2

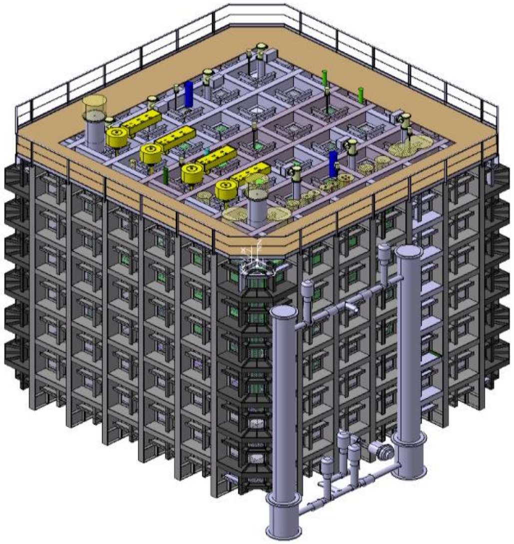
ProtoDUNEs

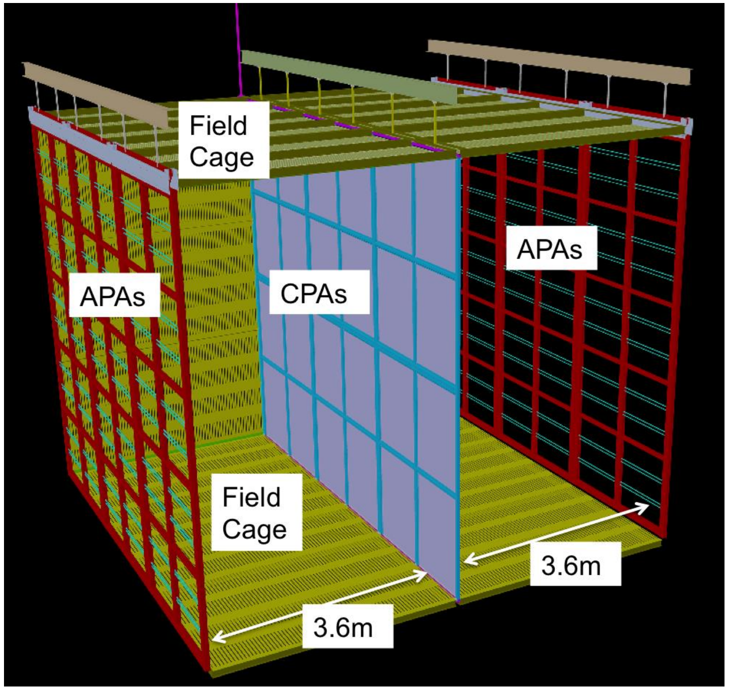
- ProtoDUNEs provide critical validation of technology, detector performance, and long-term stability

- BNL focused on ProtoDUNE-SP Cold Electronics R&D (both electrical and mechanical), production, installation and commissioning

ProtoDUNE-SP Phase I

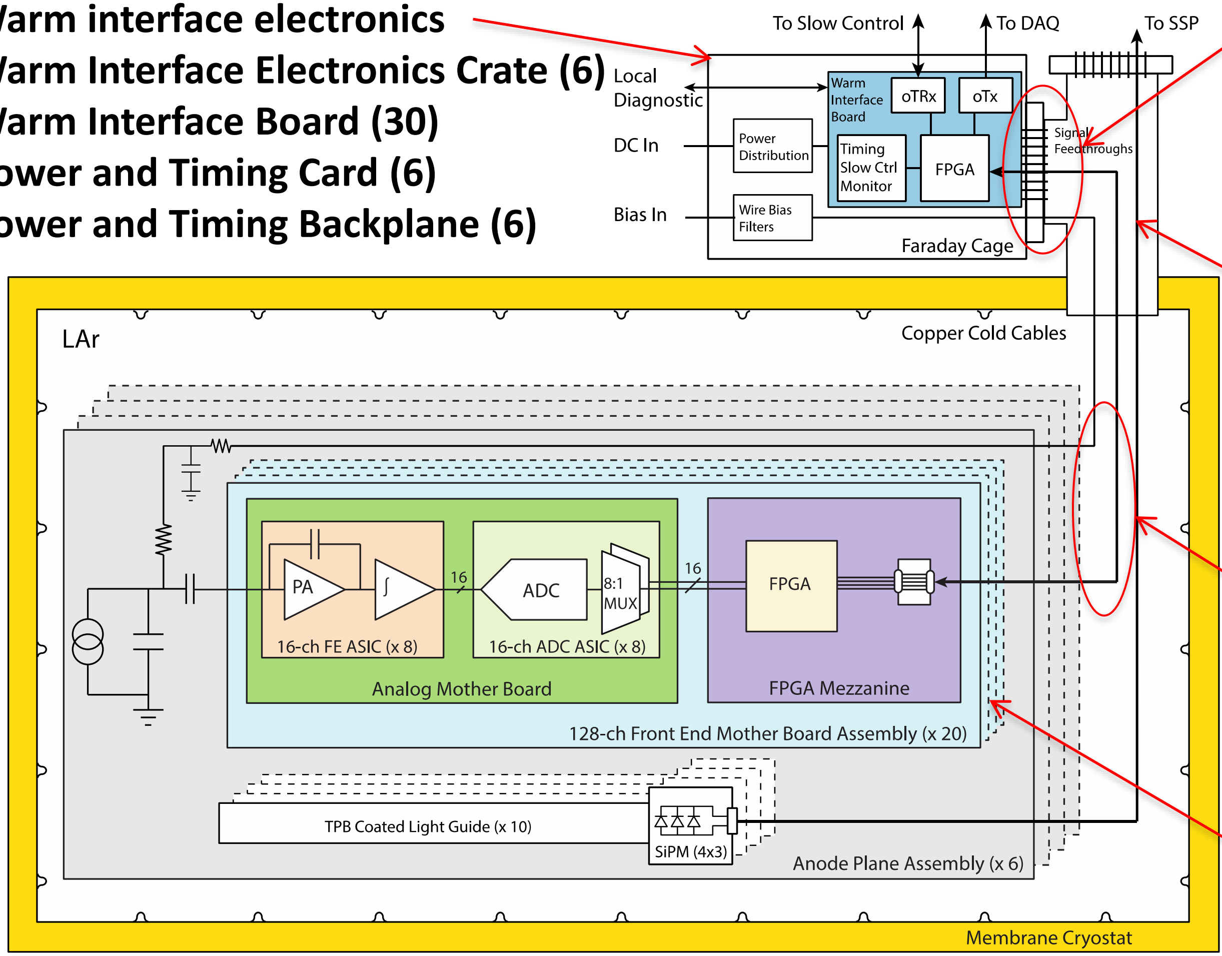
- NP04 experiment at CERN
  - 400-ton fiducial LArTPC
  - Sit in H4 beam line
- Single-phase TPC prototype
  - Use full scale components of DUNE far detector module
  - 6 full-size APAs plus 3 CPAs
    - 2 x 3.6m drift regions
  - Total 15,360 TPC channels
  - RUN I has been completed in 2020
  - RUN II is planned ~2022
- A key test of:
  - Components
  - Construction methods
  - Installation procedures
  - Commissioning
  - Detector response to particles
  - Confirm modeling and simulation





ProtoDUNE-SP Phase I Cold Electronics System

Warm interface electronics
Warm Interface Electronics Crate (6)
Warm Interface Board (30)
Power and Timing Card (6)
Power and Timing Backplane (6)



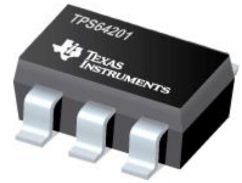
CE flange
Flange assembly with cable strain relief and flange PCB for cable/WIB connection (6)

Signal feed-through
Tee pipe with 14" Conflat flanges and crossing tube cable (CTC) support (6)

Cold cable
LV and data cable (120+120) to FEMB and APA wire-bias SHV cable (48)

Front End Motherboard (FEMB) 128 channels of digitized wire readout enclosed in CE Box (120)

Cold Electronics R&D

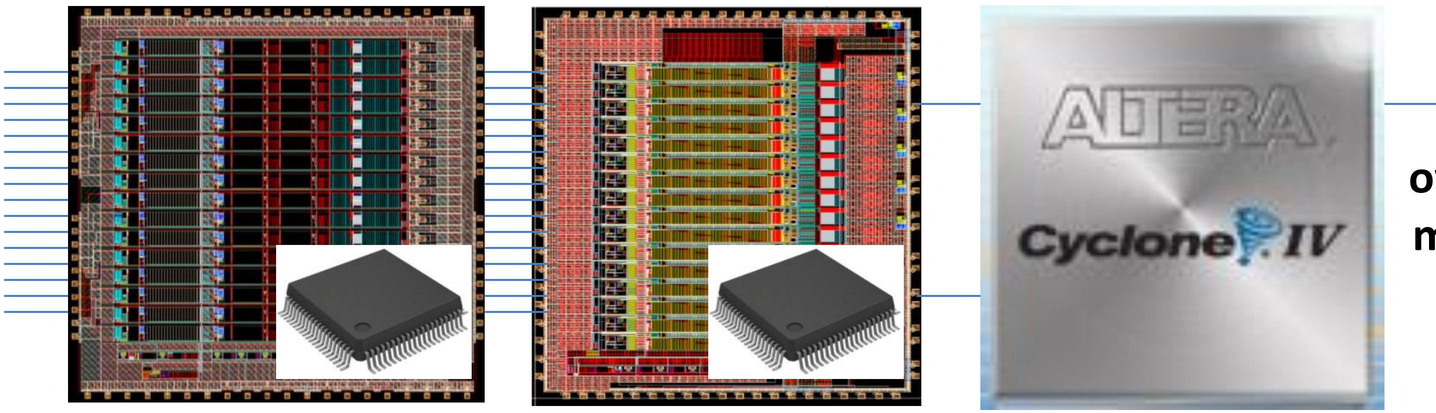


voltage regulation (COTS)
(< 100mV dropout)

Front end ASIC
~ 5mW/ch.

ADC ASIC
~ 5mW/ch.

FPGA (COTS)
~ 8mW/ch.

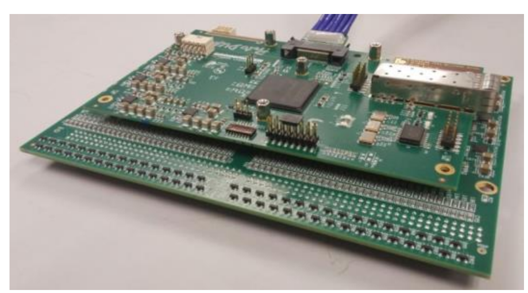


overall 128:4
multiplexing

1 x

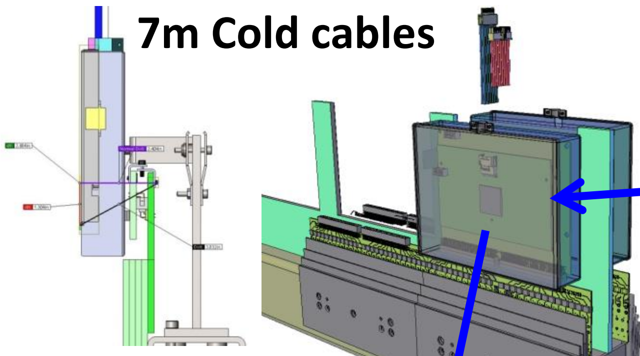
8 x

R&D produced key components to form a complete cold front-end readout chain for LAr TPC experiments

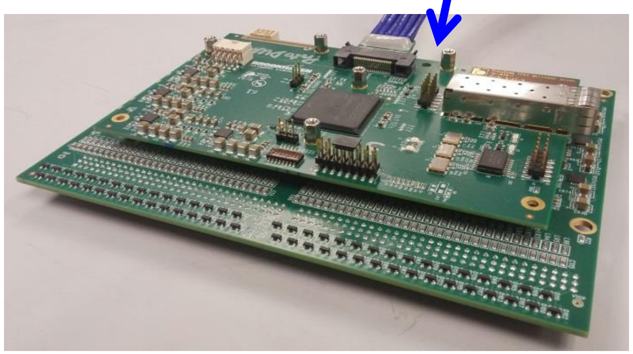


One WIEC for One APA Readout

7m Cold cables

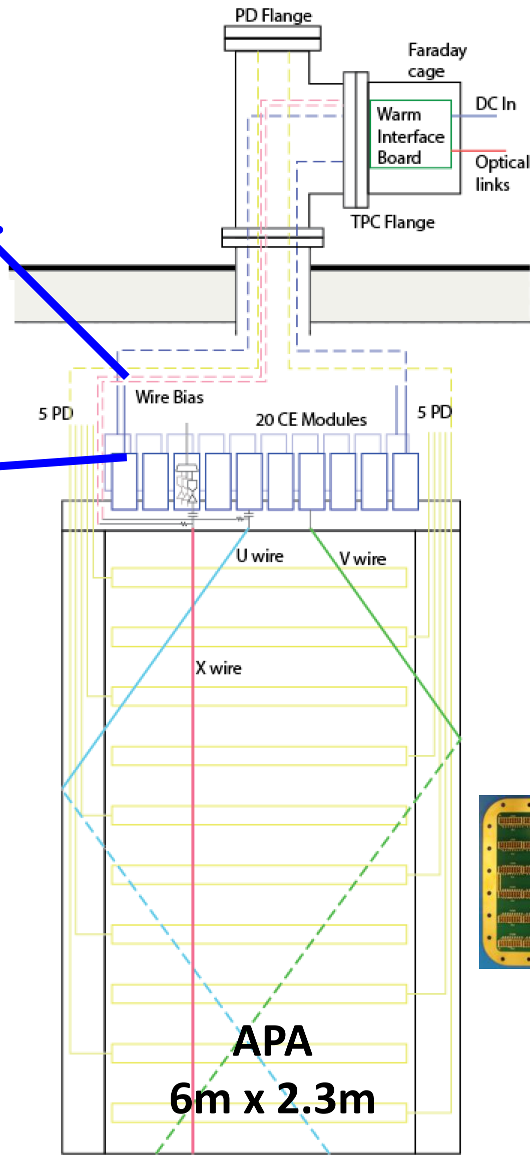


20 CE boxes on APA

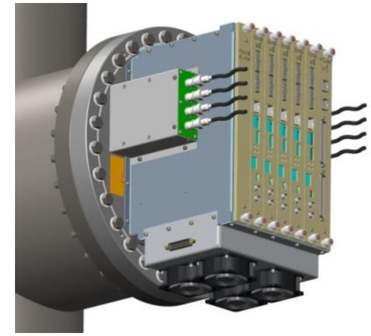


FEMB (inside CE box)

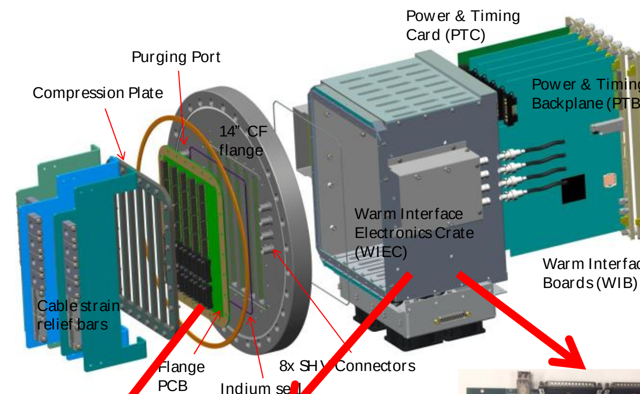
Cold Side

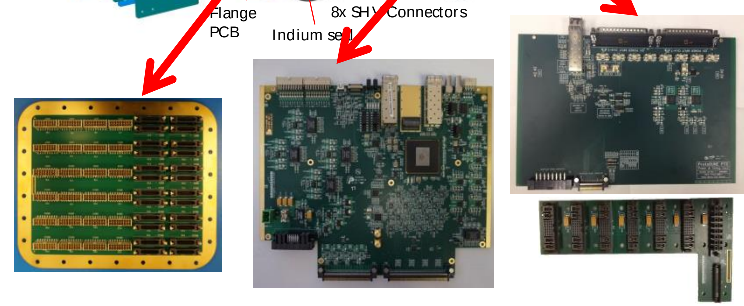


APA
6m x 2.3m



Signal Feed-through Assembly

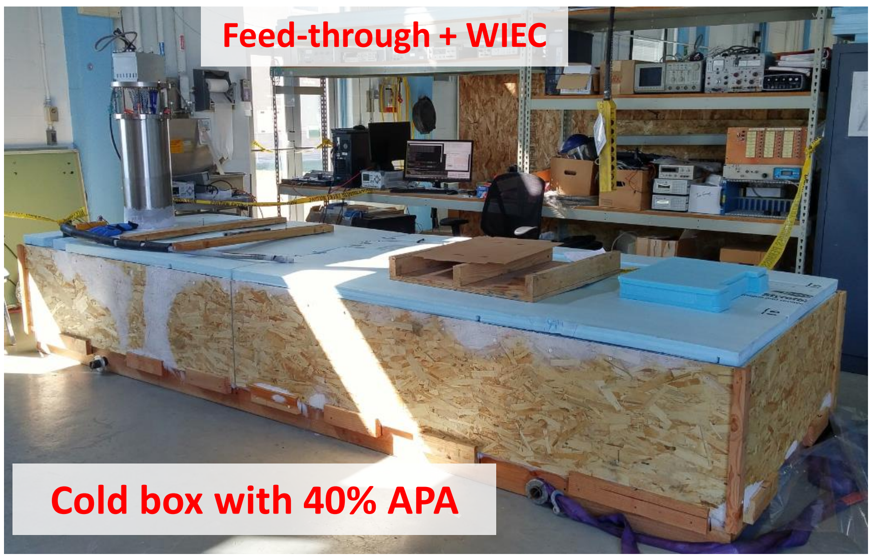




Flange Board, WIB, PTC, PTB

Warm Side

Integration Test Stands at BNL and CERN

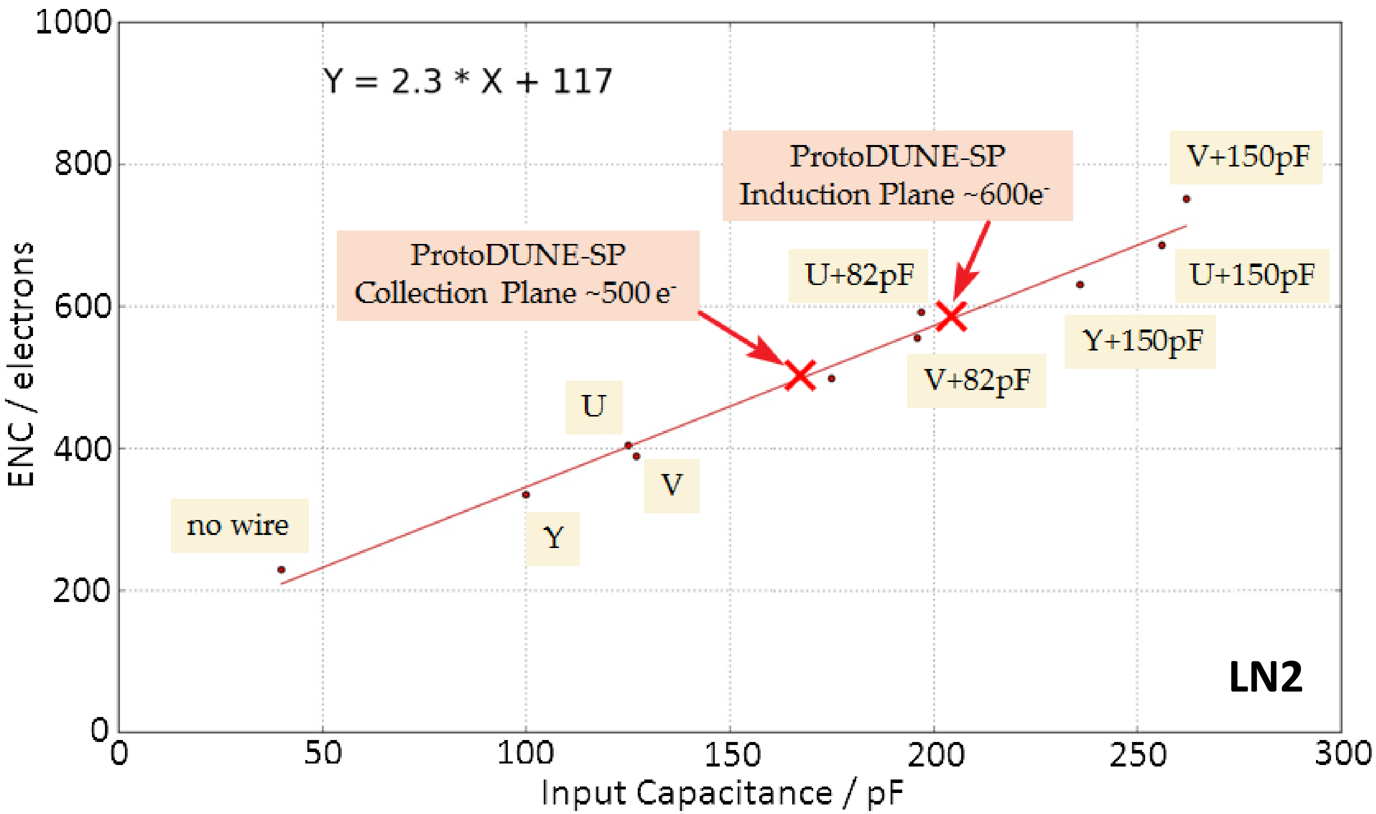


40% APA: 2.8m x 1.0m, 1024 wires

- Warm test
- Cooling down
- Cold test (~150 K)
- Warming up
- Warm test

DUNE APA: 6m x 2.3m, 2560 wires

ENC Projection Based on 40% APA



- **40% APA**
  - **U/V wire: 4.0 m**
  - **Y wire: 2.8m**

Note: 82pF and 150pF mica capacitors are added on some wires

- ProtoDUNE APA
  - U/V wire: 7.39m
  - Y wire: 6.0m

- **DUNE Far Detector**
  - Same APA as ProtoDUNE-SP
  - Threshold: 1,000 e^-
  - Goal: as low as possible

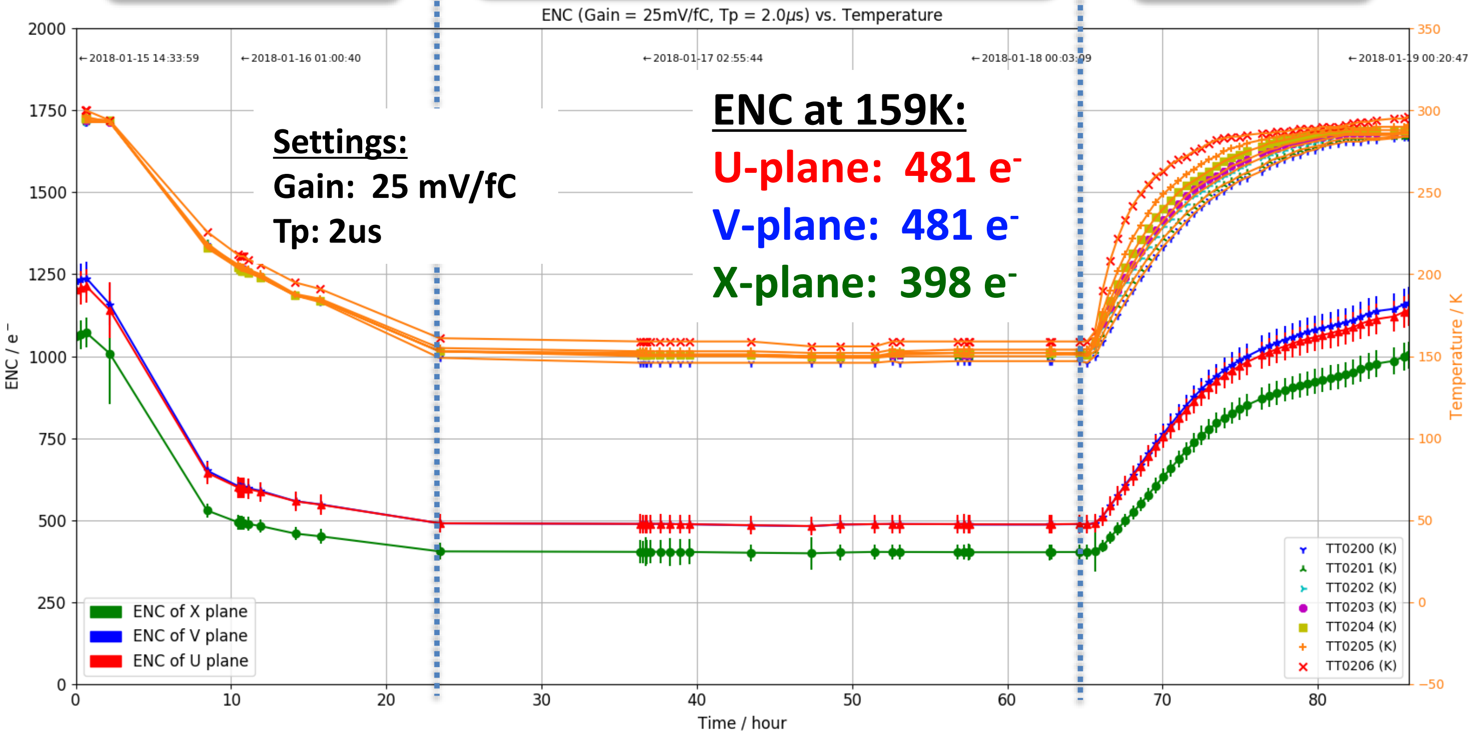
CERN Cold Box Integration Test

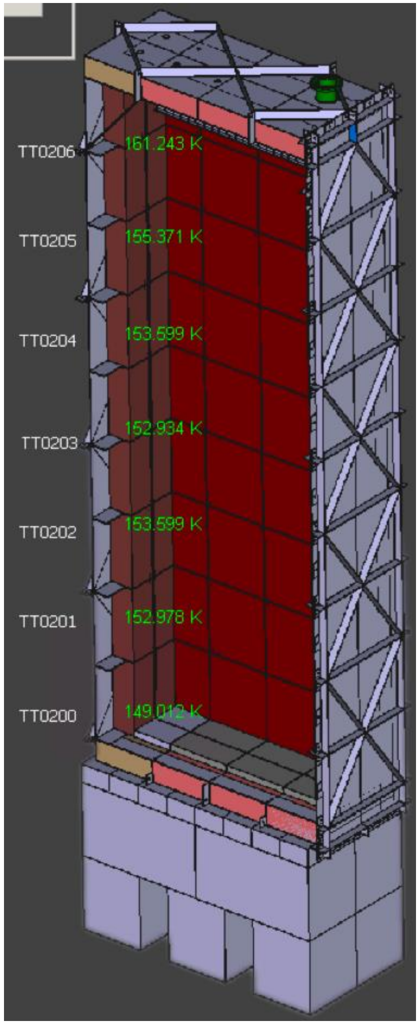
APA2 (2018-01) Cold nitrogen gas with lowest temperature reached ~ 159K

Cooling down | **Cryogenic temperature** | **Warming up**

Settings:
Gain: 25 mV/fC
Tp: 2us

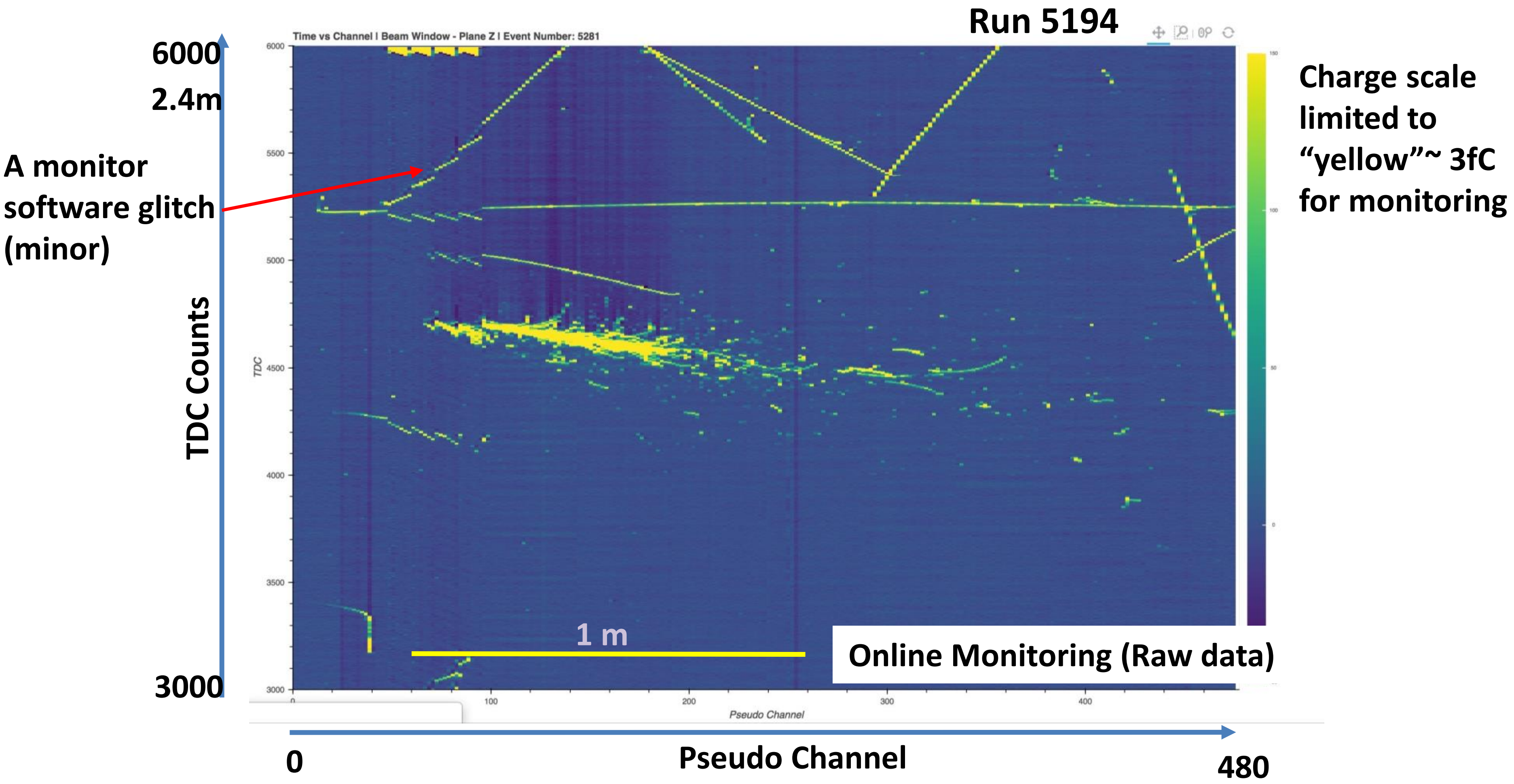
ENC at 159K:
U-plane: 481 e⁻
V-plane: 481 e⁻
X-plane: 398 e⁻





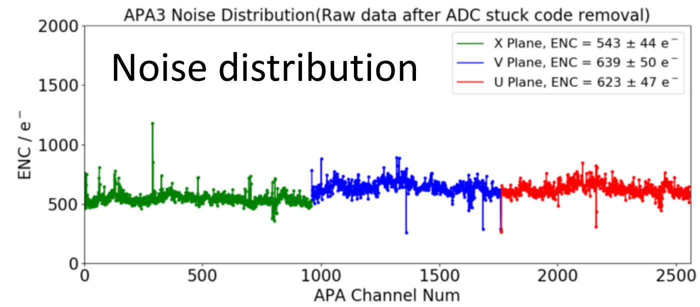
1. Uniform gain (77 e-/bin) is applied for calculating noise of all channels
2. HV Bias voltages were off
3. Data are read out chip by chip over local diagnostic GbE port.

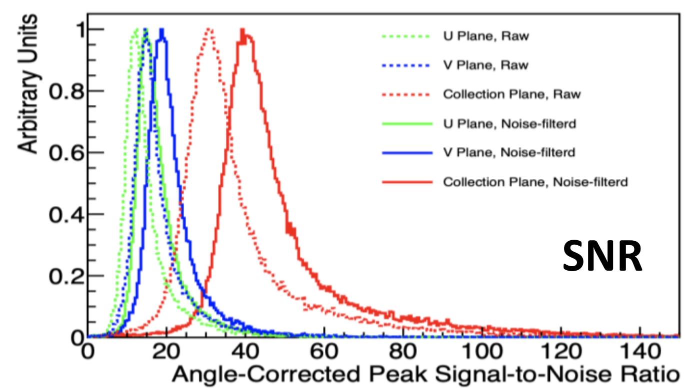
Shower Event under 7GeV Beam

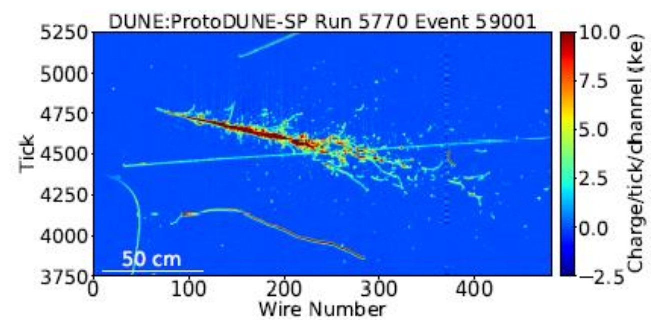


Excellent Performance of the ProtoDUNE-SP

- **High yield**
  - **99.74% (15320 of 15360) of TPC channels are active**
    - **Only 4 inactive cold electronics channels when commissioning started**
    - **2 more inactive cold electronics after >1 year running**
- **Low noise**
  - **92.83% TPC channels are good with excellent noise performance**
    - **Raw data: Collection ENC ~560 e^-, Induction ENC ~670 e^-**
- **Good stability**
    - **No measurable degradation is observed over a year**
- **CE is demonstrated as the promising technology towards DUNE LArTPC**
  - **Final design will be verified in ProtoDUNE-SP RUN-II in 2022**

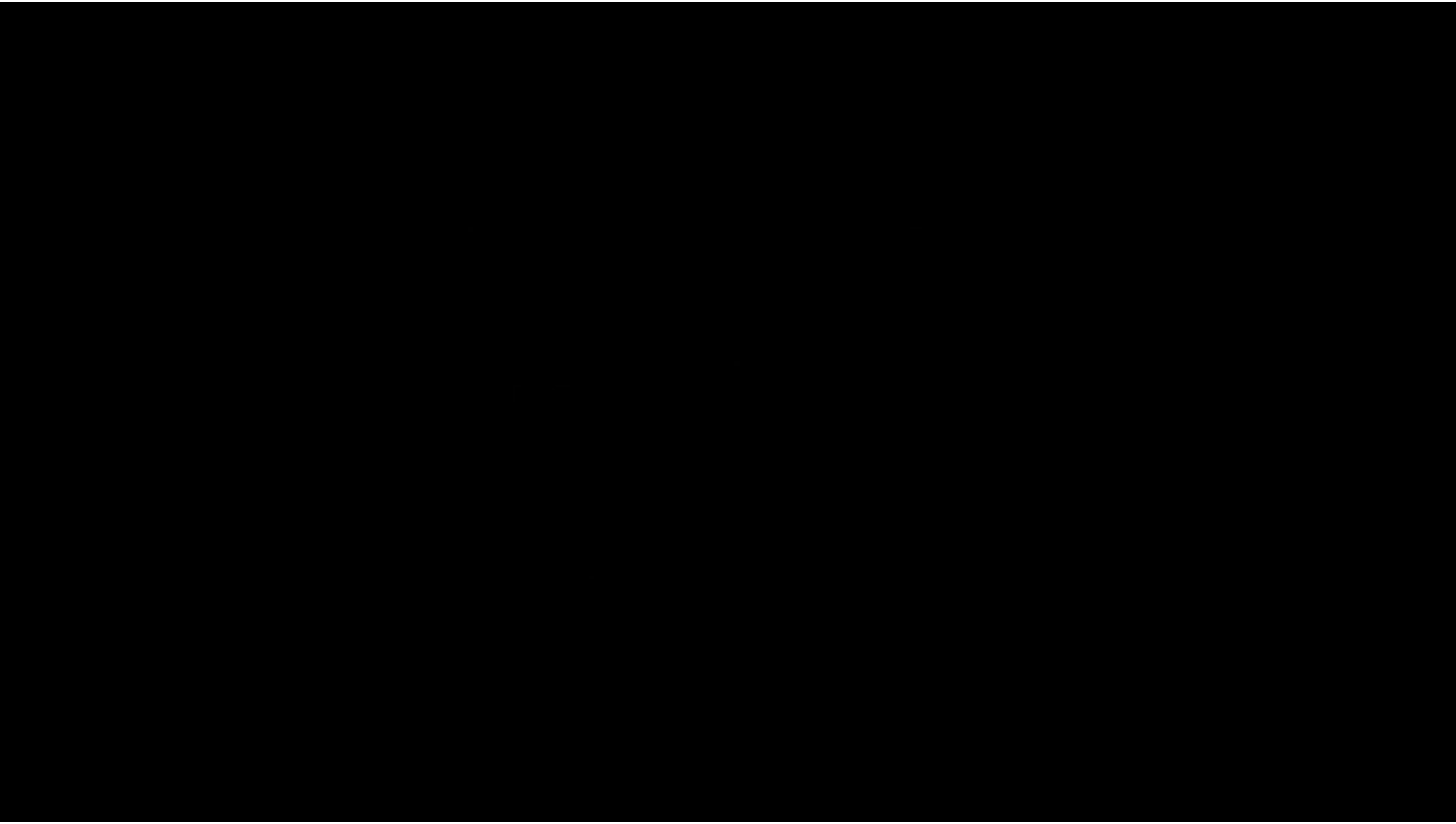




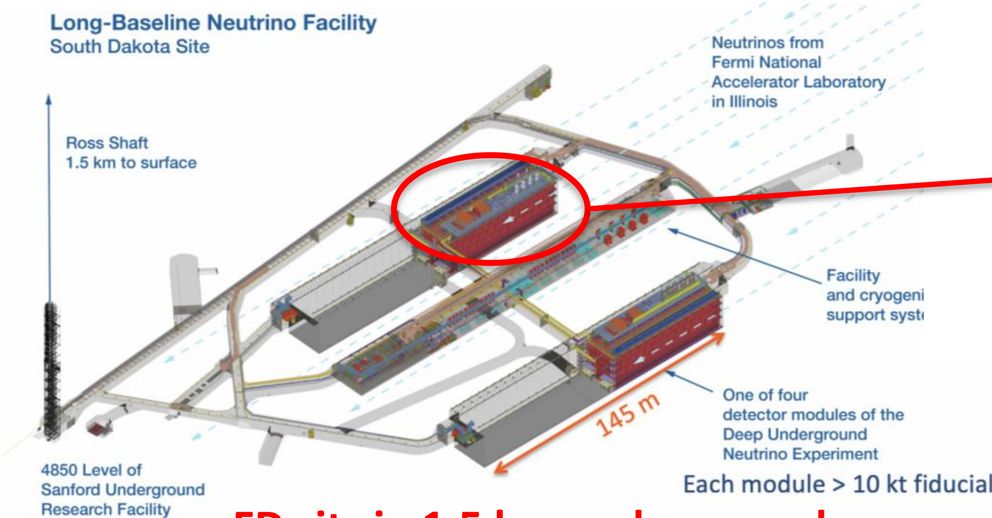


A 6 GeV/c electron candidate

NP04 (ProtoDUNE-SP) CERN Beam Test

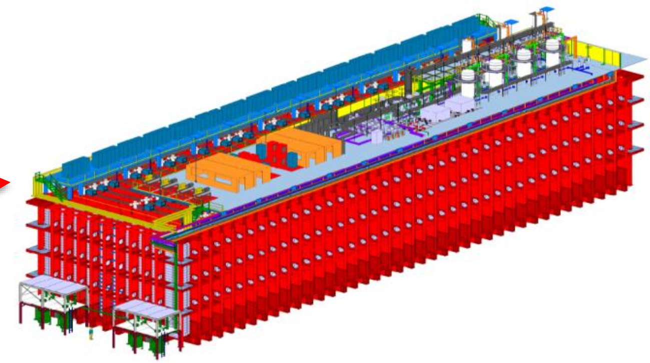


Single-Phase LArTPC for the First DUNE Far Detector Module



Each module > 10 kt fiducial

FD sits in 1.5 km underground

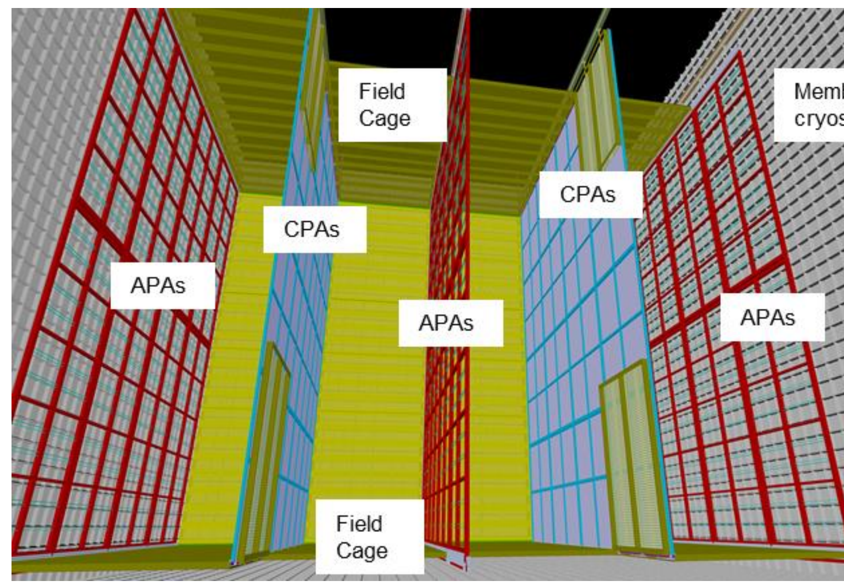


Outer:
65.8 m (L)
18.9 m (W)
17.8 m (H)

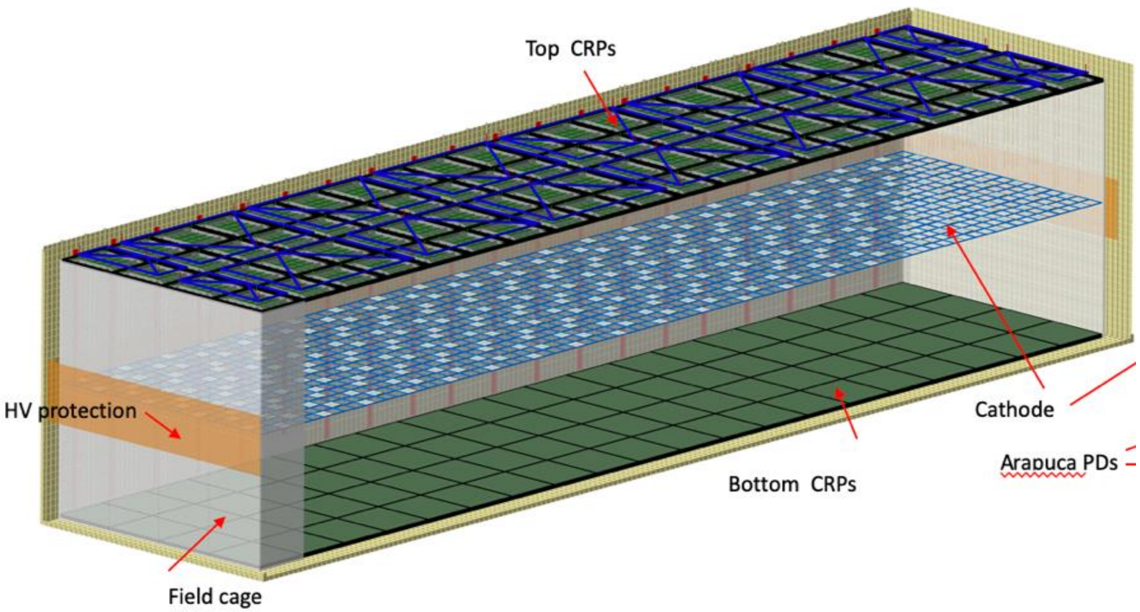
Inner active volume: 14.0 m (W) × 12.0 m (H) × 58.2 m (L)

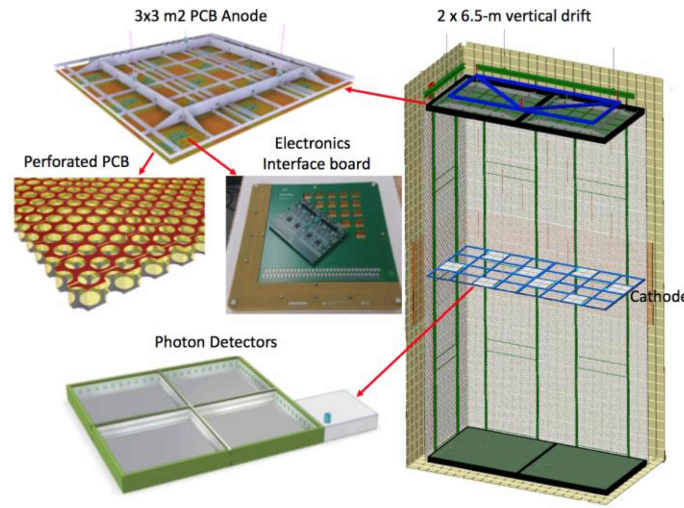
DUNE 10 kt Far Detector LArTPC CE

- 150 APA units
- *[384,000 channels]*
- 24,000 FE ASICs/24,000 ADC ASICs
- 6,000 COLDATA ASICs
- 3,000 Front End Mother Board assemblies
- **Aim for 30 years operation without replacement and maintenance**



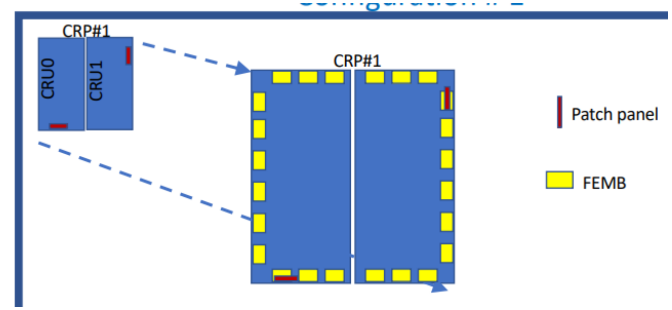
Vertical-Drift (VD) LArTPC for the 2nd Far detector





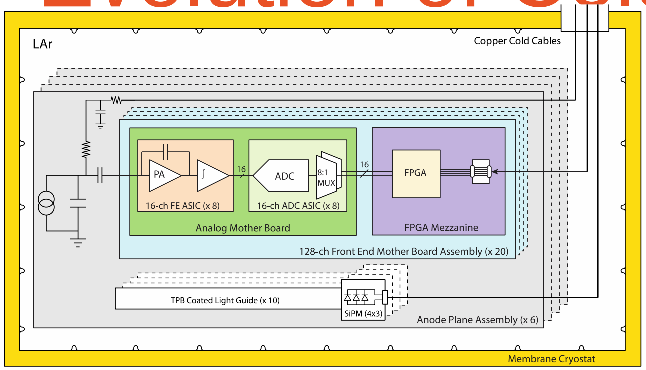
Builds on experience gained with Dual Phase detector and long e-lifetime achieved in ProtoDUNE

PCB-based charge readout

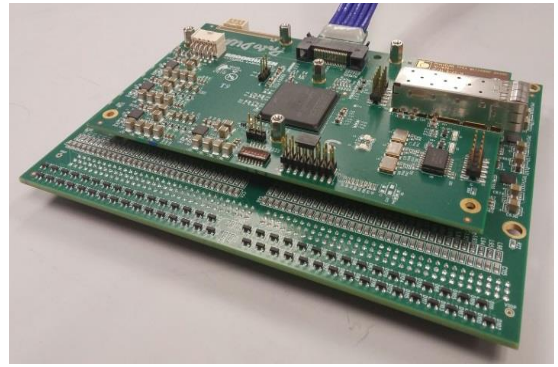


- Bottom Cold Electronics
  - CE requirements are similar between HD and VD
    - Share the same or minor-modified FEMB design
  - 80 CRPs to be readout
    - 24 FEMB per CRP (charge-readout unit)
- **ProtoDUNE-VD has been planed**
  - **2 CRP will be readout by CE (48 FEMBs in need)**

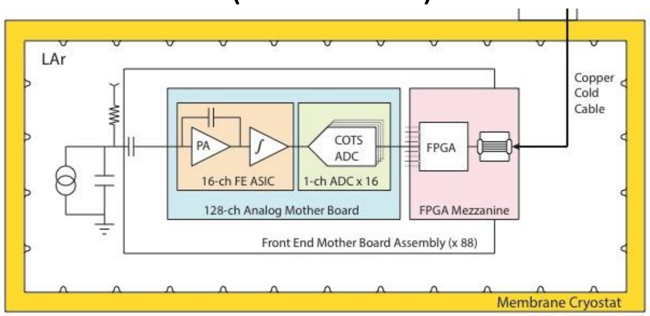
Evolution of Cold Electronics towards DUNE



ProtoDUNE (Cold FPGA)

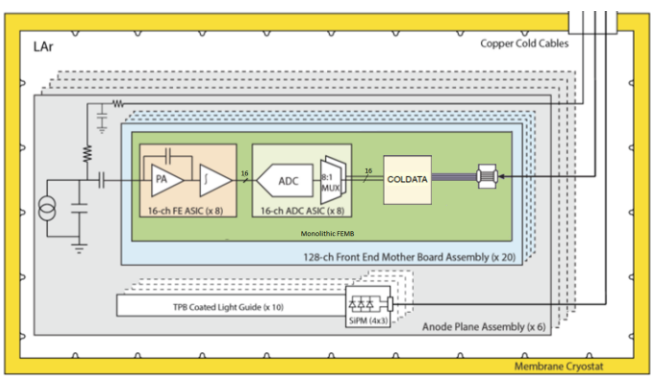


ProtoDUNE-SP FEMB with Cold FPGA successfully verified the feasibility of digitized readout at 7-89 K

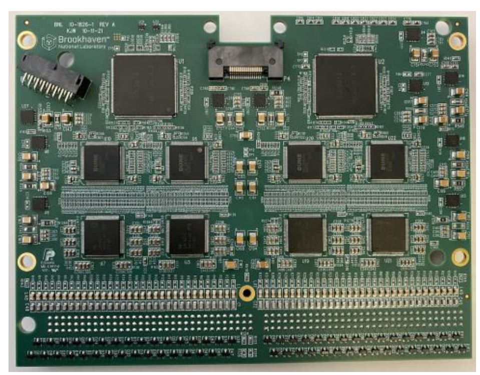


SBND (Cold FPGA + COTS ADC)

SBND FEMB with Cold FPGA and COTS ADC proves high-resolution readout can be achieved at 77-89 K



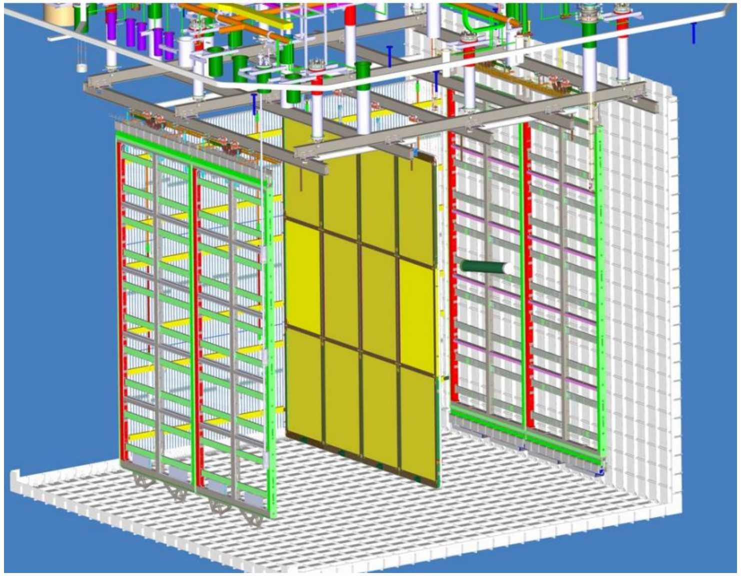
DUNE (3 Cryogenic ASICs)



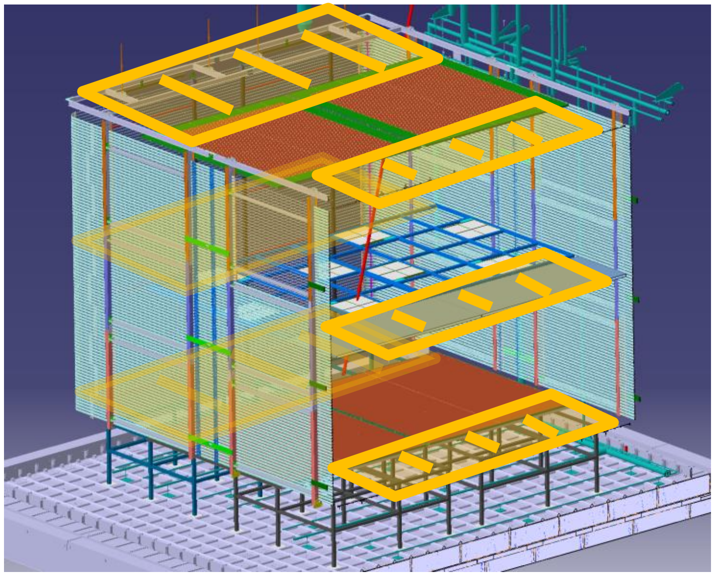
FEMB with **three** cryogenic-qualified ASICs (LArASIC, ColdADC, COLDATA) well addresses the long lifetime (30 years) and reliability requirements of DUNE far detector.

ProtoDUNE RUN-II (HD & VD)

- ProtoDUNE Horizontal Design (HD) and Vertical Design (VD)
  - Provide critical validation of technology, detector performance, and long-term stability
  - ProtoDUNE HD: 4x APA, 10,240 detector electrodes readout by cold electronics submerged in LAr
  - ProtoDUNE VD: 2x Bottom CRP, 6,144 detector electrodes readout by cold electronics submerged in LAr
- BNL focused on Cold Electronics R&D (both electrical and mechanical), production, installation and commissioning
  - ProtoDUNE HD: We delivered a full set of high-quality cold electronics to CERN. Detector installation and APA integration cold test are ongoing
  - ProtoDUNE VD: A CRP2b integration test at BNL will be performed in this month. CE production is planed.

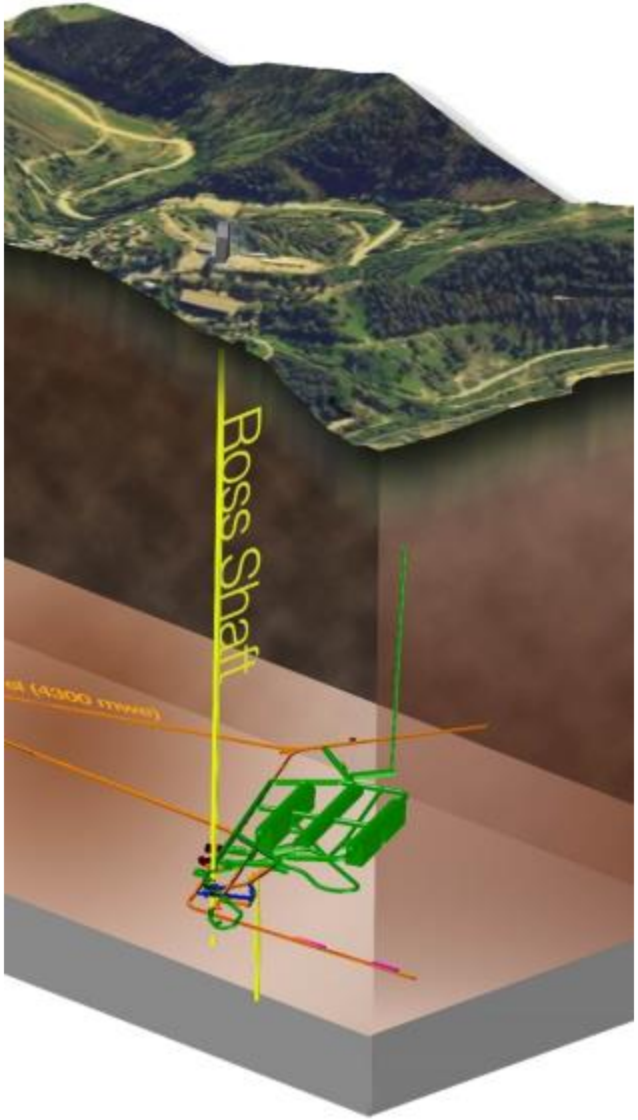


ProtoDUNE HD



ProtoDUNE VD

Cavern excavation for DUNE far detector modules



Summary

- Readout electronics developed for low temperatures (77 K – 300 K) is **an enabling technology** for noble liquid detectors for neutrino experiments
- Excellent performance of ProtoDUNE-SP
  - The integral design concept were sufficiently verified
  - High yield, low noise, good stability
  - A promising step towards DUNE-SP LArTPC
- **CE with 3 ASIC solution meets the DUNE performance needs**
  - Three cryogenic-qualified ASICs (LArASIC, ColdADC, COLDATA) for long lifetime (> 30 years) at 89K
  - ProtoDUNE-SP RUN-II in 2022 will be instrumented with final 3-ASIC FEMB
- **It is your excellent opportunity for groundbreaking discoveries**
  - DUNE experiment is expected to start in 2026, and last for 20-30 years
  - Provide the best detector to help you change our understanding of the universe
    - Origin of Matter, Unification of Forces, Black Hole Formation