Cryogenic Readout Electronics Systems for Liquid Argon TPCs in Neutrino Experiments

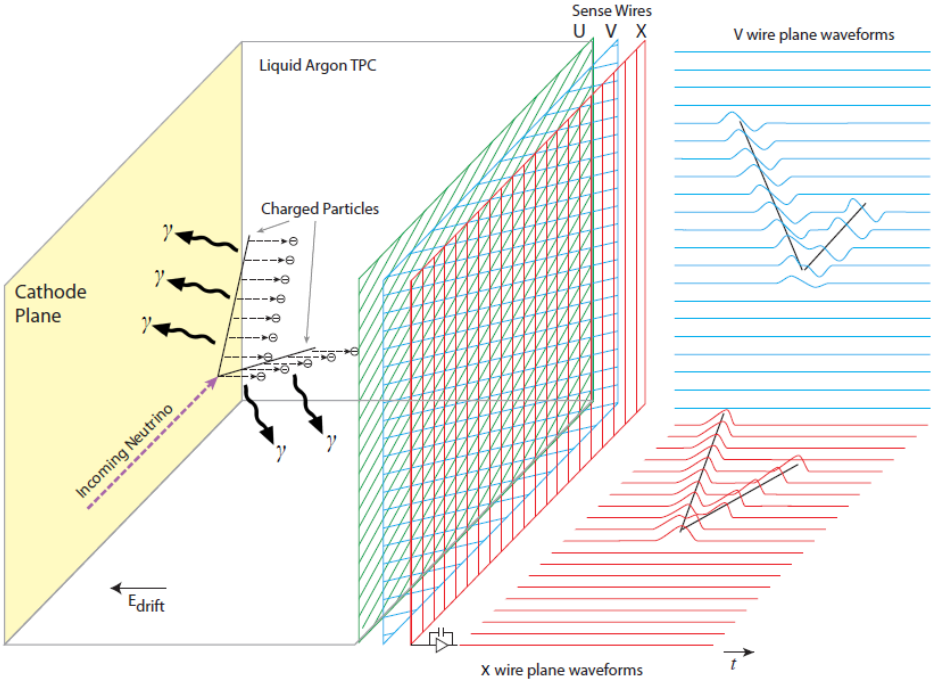
Shanshan Gao

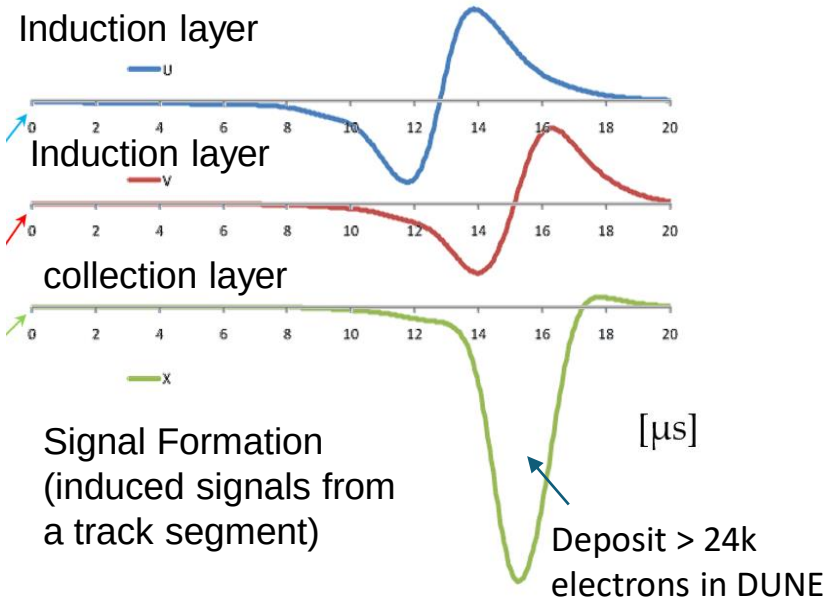
09/09/2022

@BrookhavenLab

LArTPC (Liquid Argon Time Projection Chamber)

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.

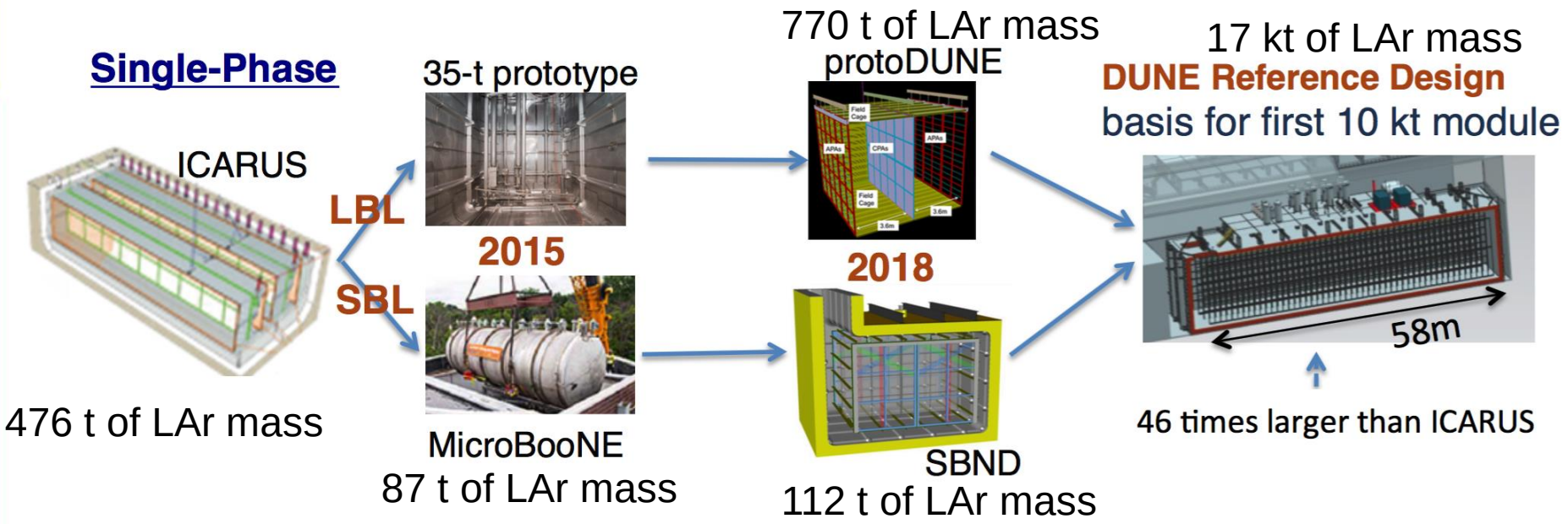




Time information: when ionization electrons arrive (drift distance)
Geometry information: which wires are fired (transverse position)
Charge information: how many ionization electrons (energy deposition)

Brookhaven National Laboratory DUNE

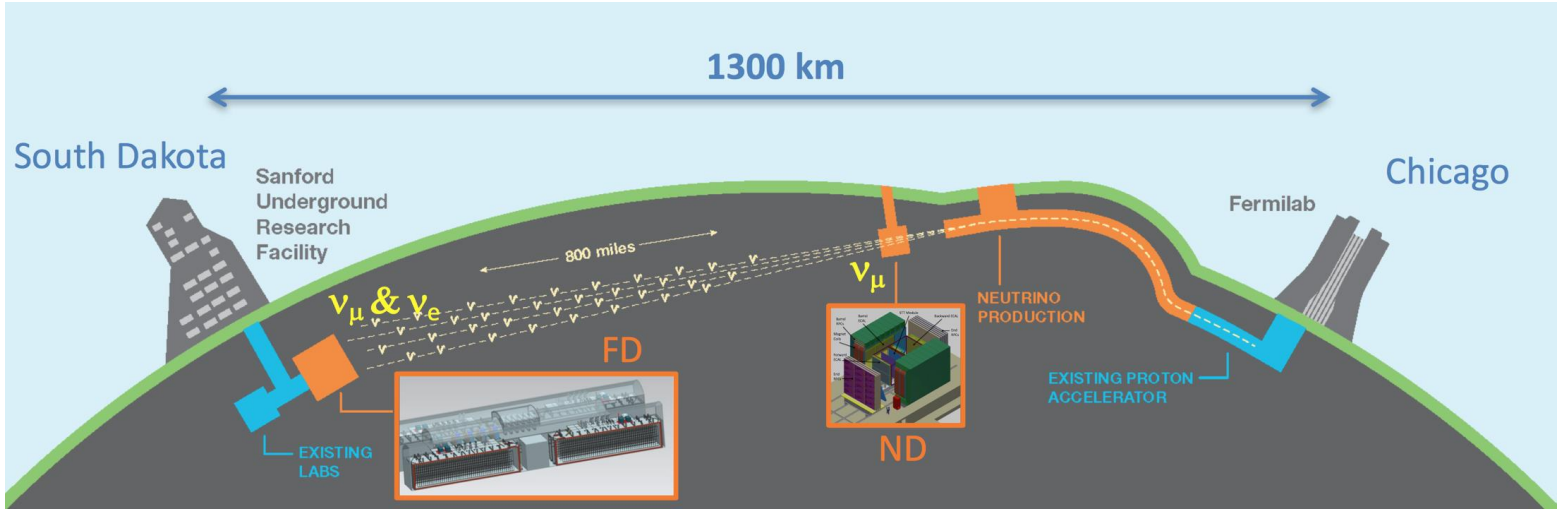
Development of LArTPC for Neutrino Experiments



- **Cold Electronics is the key technology for Large LArTPCs**
  - "The cold electronics that it remains an optimal solution for very large TPC"
    - Cited from **Veljko Radeka**, et al. Cold Electronics for "Giant" Liquid Argon Time Projection Chambers. 1st International Workshop towards the Giant Liquid Argon Charge Imaging Experiment (GLA2010)
  - **BNL is leading TPC readout electronics *SYSTEM* design**

Brookhaven National Laboratory DUNE

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.

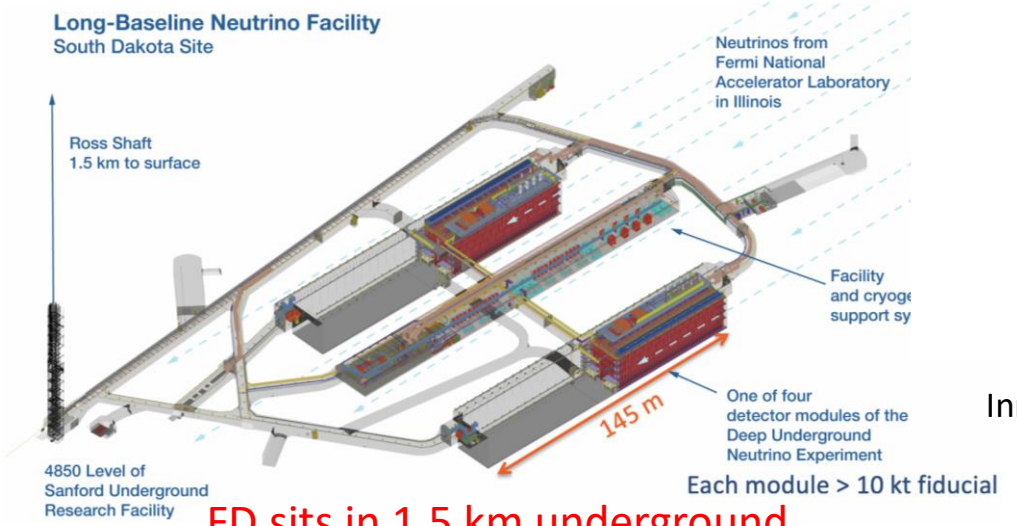
Black hole formation

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.

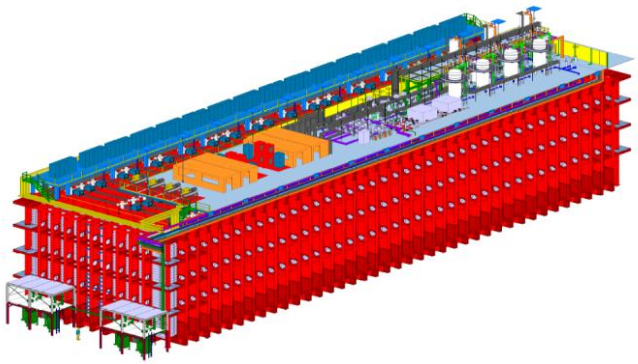
BNL proposed CE solution will be instrumented for two 10-kton far detector modules

Brookhaven National Laboratory DUNE

CE is chosen for DUNE FD1-HD and FD2-VD (BDE)

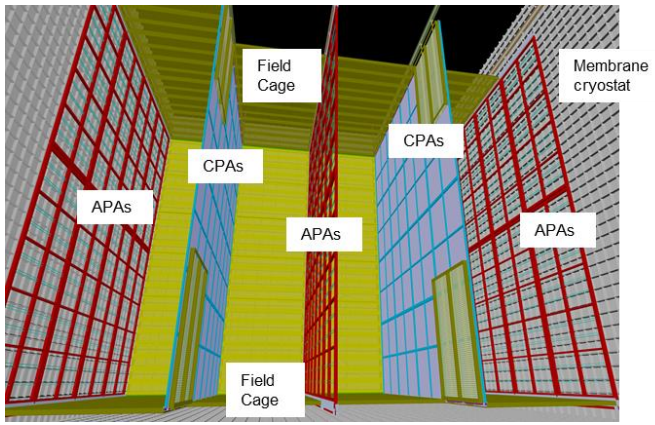


FD sits in 1.5 km underground

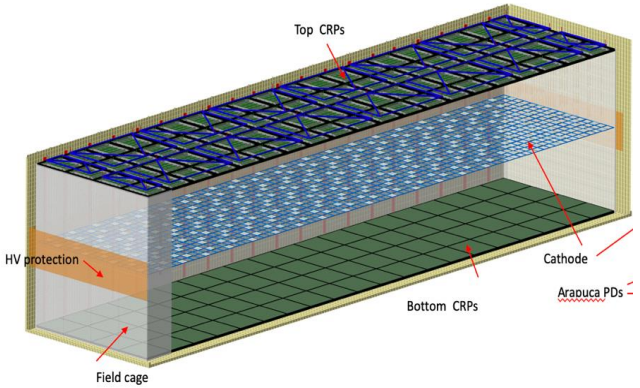


Outer:
65.8 m (L)
18.9 m (W)
17.8 m (H)

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



FD1: 150 APAs , **384,000** detector channels



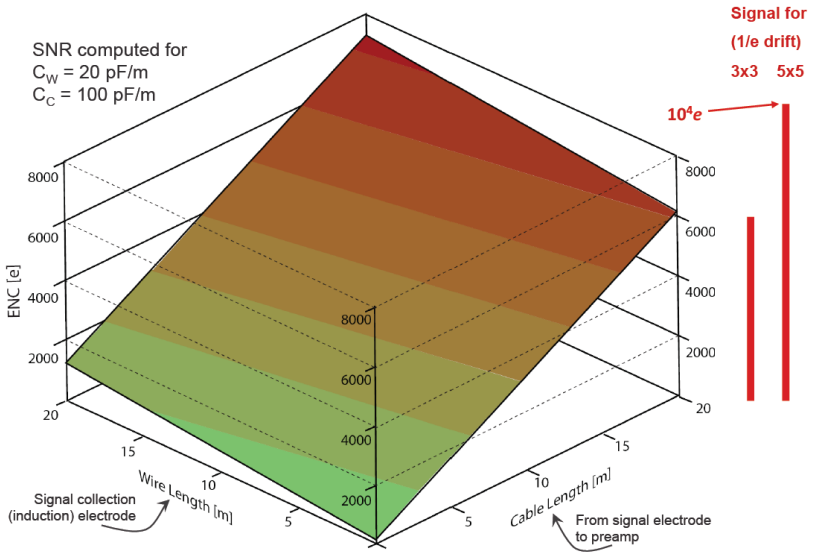
FD2: 80 Bottom Drift CRPs, **245,760** detector channels

A strong cold electronics team is built up as a core BNL competence, in close collaboration with other institutes, to realize various LArTPC experiments.

Brookhaven National Laboratory DUNE

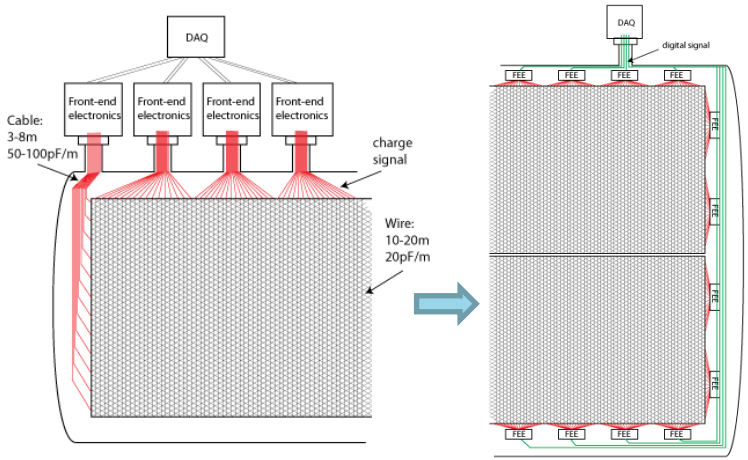
Advantages of CE in Large LAr TPC

Much lower noise



- Integrated front-end electronics close to detector electrodes yields the best SNR
- CMOS in LAr has less than half the noise as that at room temperature

Much less cryostat penetrations



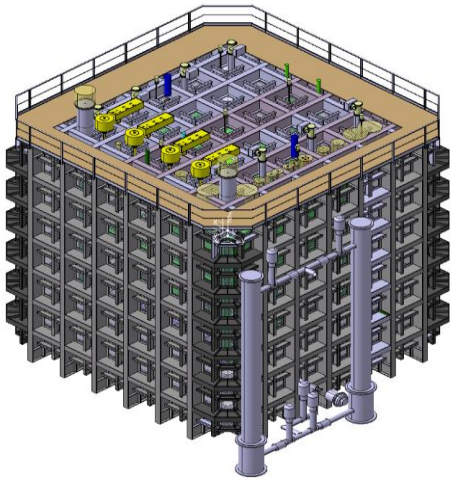
Warm Readout vs. Cold Readout

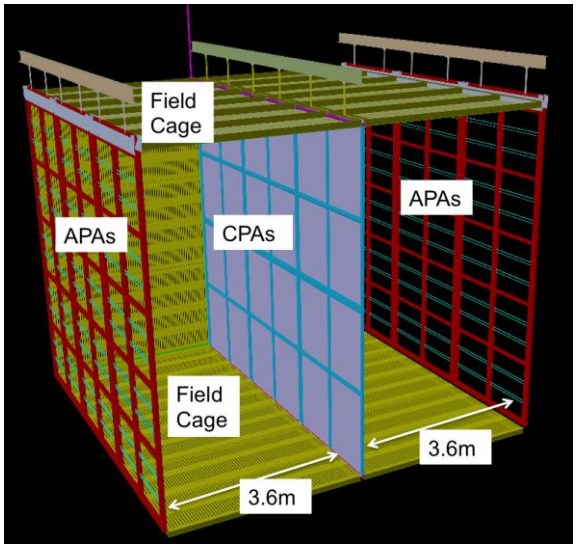
- Signal digitization and multiplexing to high-speed links inside the cryostat results in large reduction in cables and feed-through penetrations, and the freedom to choose the optimum configurations for both the TPC and the cryostat

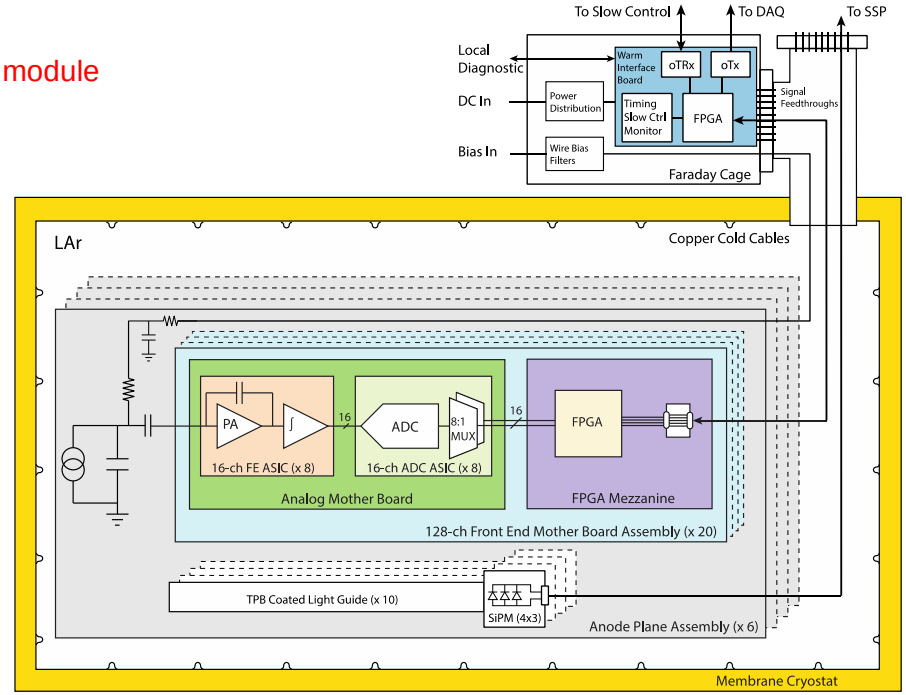
Brookhaven National Laboratory DUNE

ProtoDUNE-SP HD RUN-I

- NP04 experiment at CERN
  - 770-ton LAr mass (1/20 of DUNE 1st far detector)
  - Sit in H4 beam line
- Single-phase TPC prototype
  - 6 full-size APAs plus 3 CPAs (2 x 3.6m drift regions)
  - Total 15,360 TPC channels (1/25 of DUNE 1st LArTPC)
  - RUN-I has been completed in 2020
  - **RUN-II is planned in 2022/2023**
    - Use full scale components of DUNE far detector module





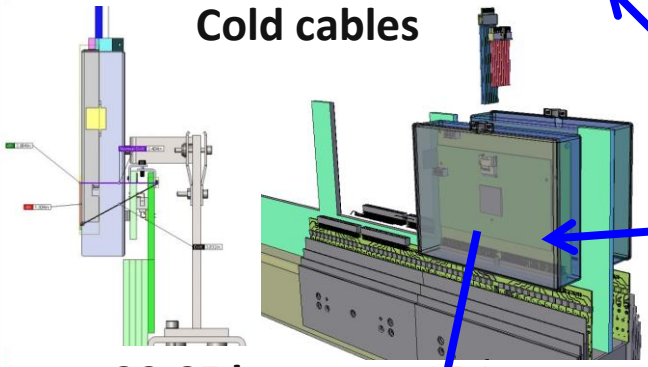


The cryogenic readout solution instrumented by BNL

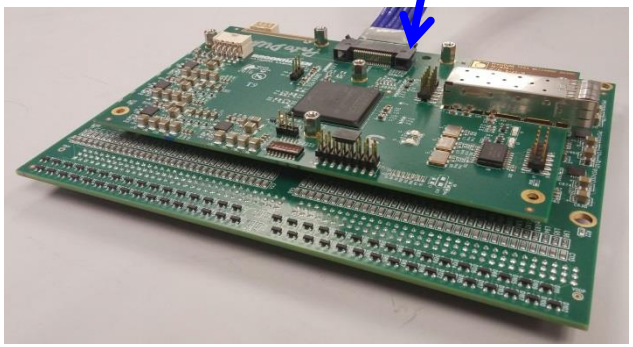
Brookhaven National Laboratory DUNE

Integral System Design Concept

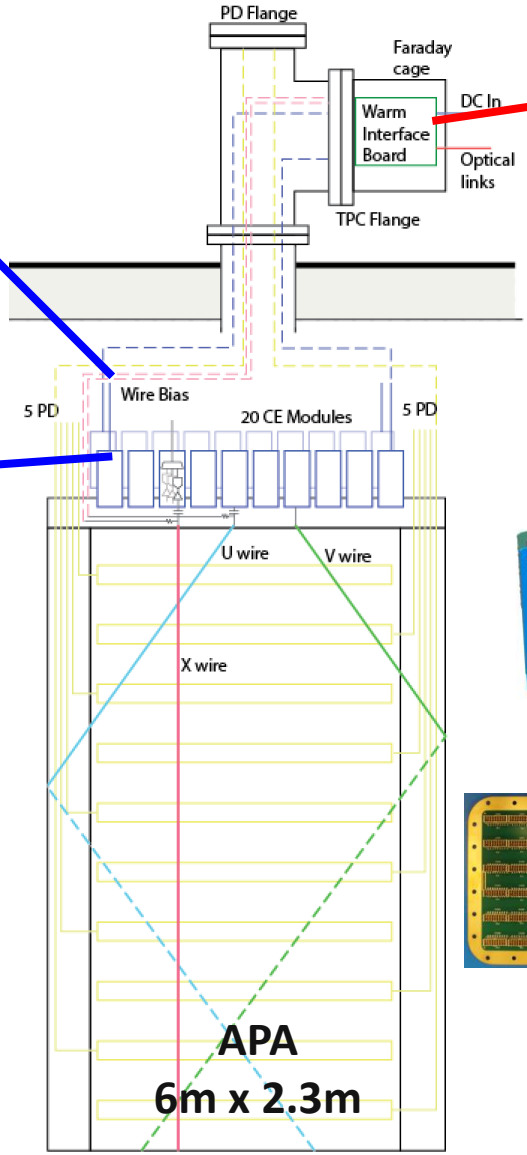
Cold cables

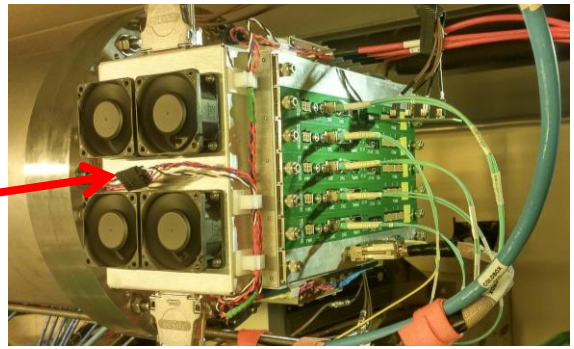


20 CE boxes on APA

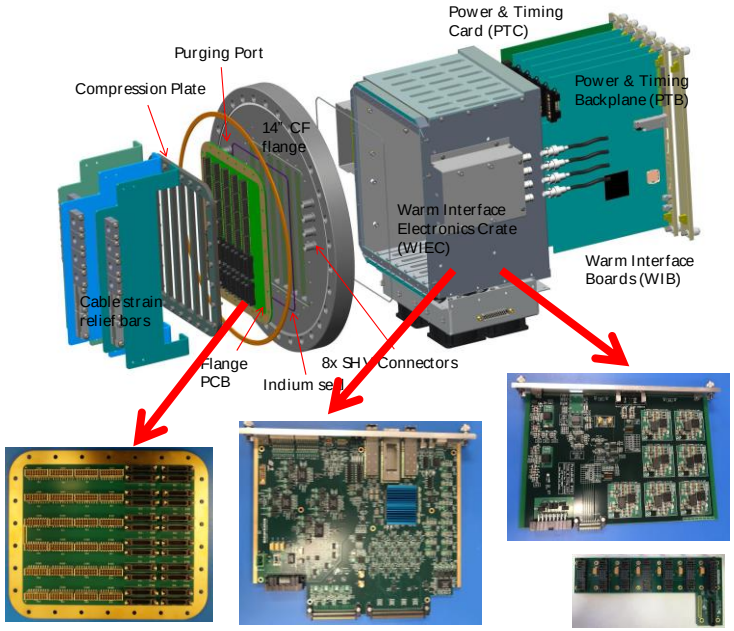


FEMB (inside CE box)





Signal Feed-through Assembly



Flange Board, WIB, PTC, PTB

Cold Side

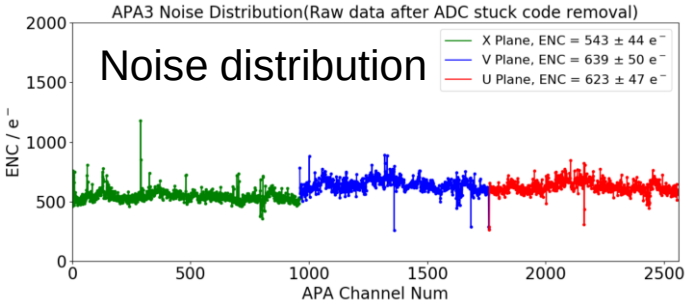
Warm Side

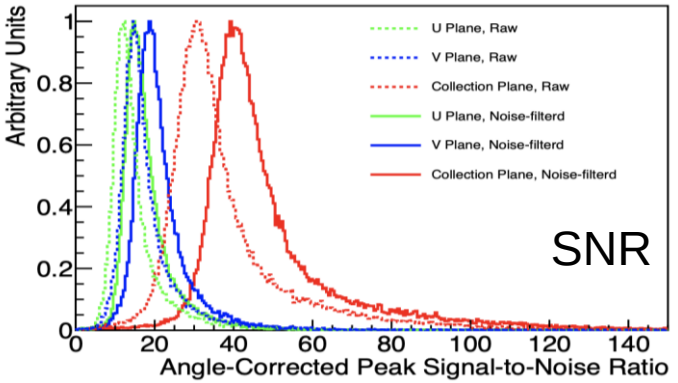
Brookhaven National Laboratory

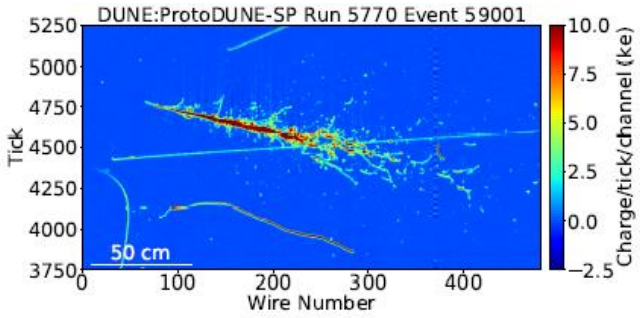
DUNE

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

Summary

Readout electronics developed for low temperatures (77 K – 300 K) is an enabling technology for noble liquid detectors for neutrino experiments.

- **BNL is leading TPC readout electronics SYSTEM design**

Excellent performance of ProtoDUNE-SP RUN-I

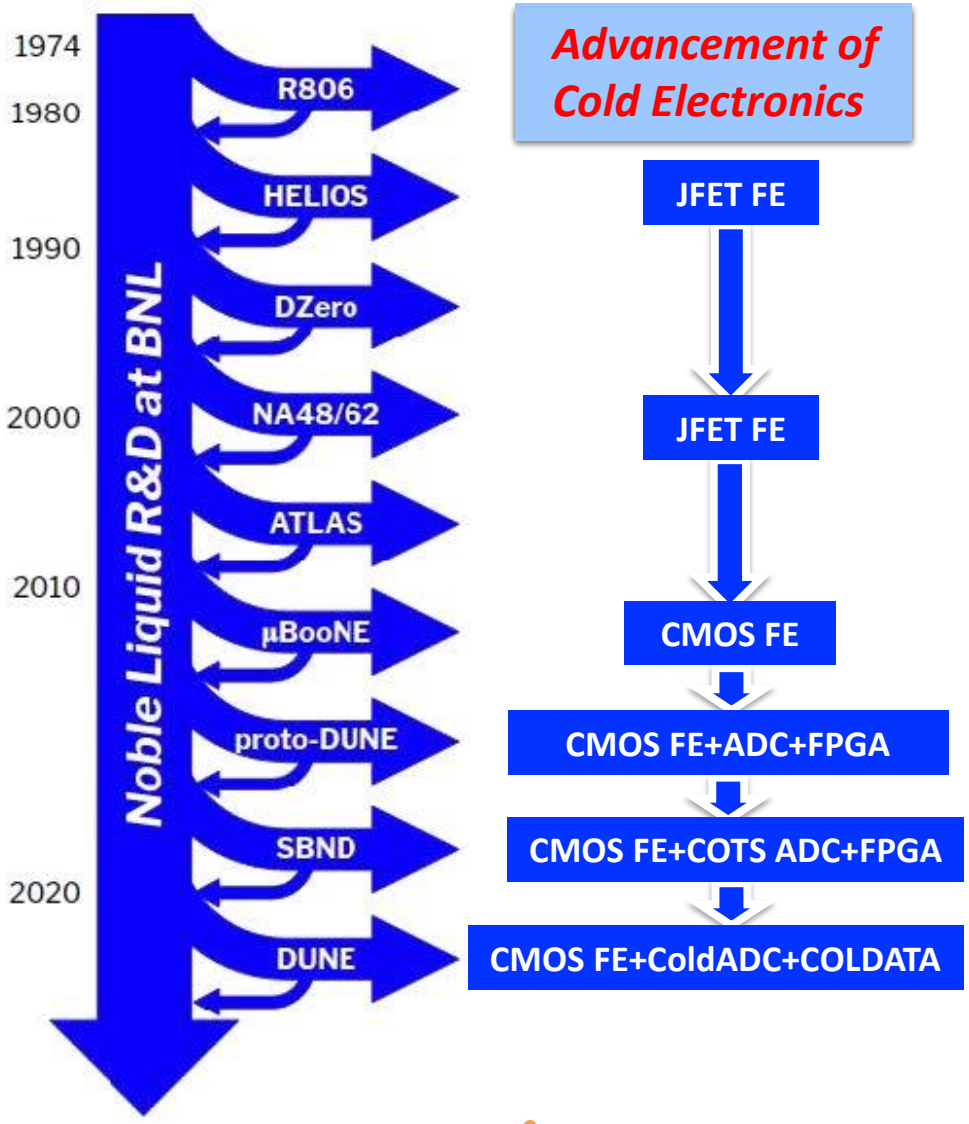
- The integral design concept were sufficiently verified
- High yield, low noise, good stability
- A promising step towards DUNE-SP LArTPC

CE is chosen for DUNE FD1-HD and FD2-VD (BDE)

- BNL makes significant contributions on Cold Electronics R&D (both electrical and mechanical), production, installation and commissioning

Thanks!

A Brief but Long History of CE Development

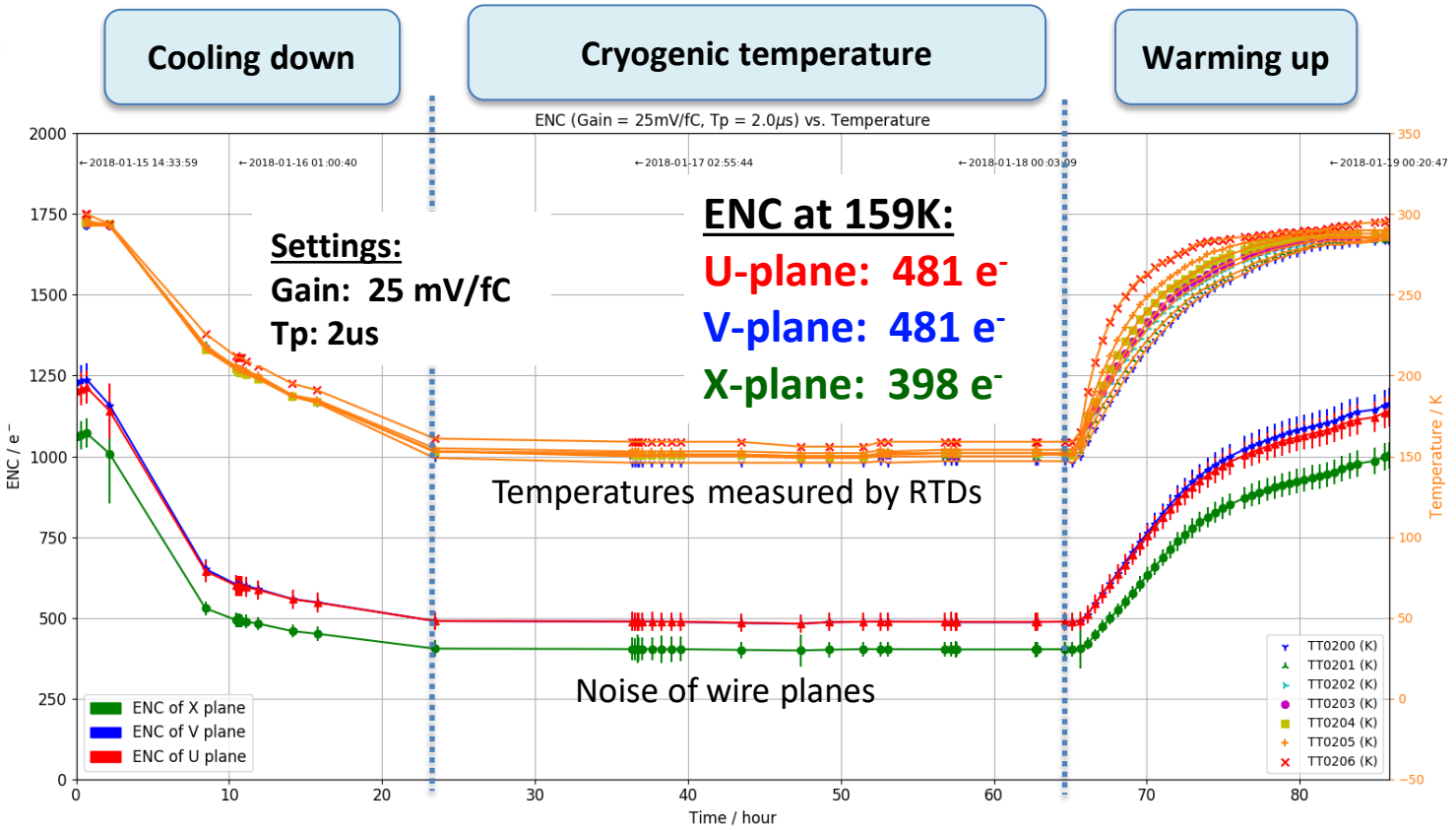


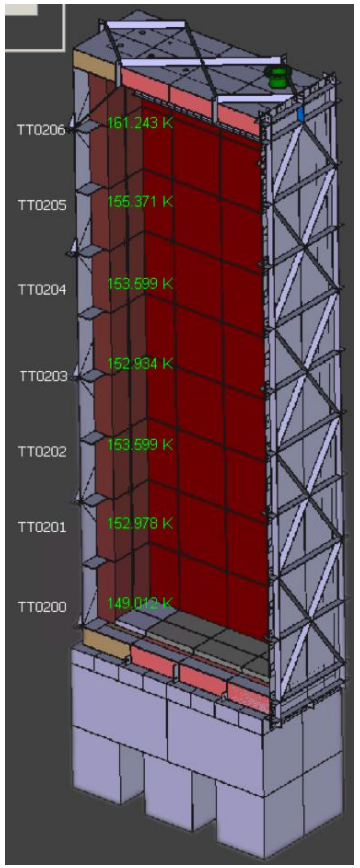
- BNL pioneered LAr based detector technology in 1974 [1]
- Physics/Engineering expertise which has made essential contributions to various programs, e.g. ATLAS, MicroBooNE
- Unique experience in cryogenic electronics and micro-electronics
- The R&D effort makes the experiments possible; the experiments, 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*

Brookhaven National Laboratory

CERN Cold Box Integration Test

Cold nitrogen gas with the lowest temperature reached ~ 159 K

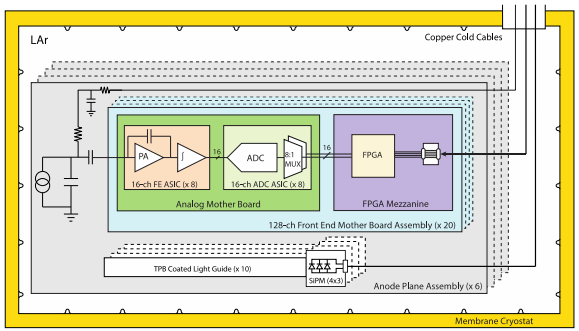




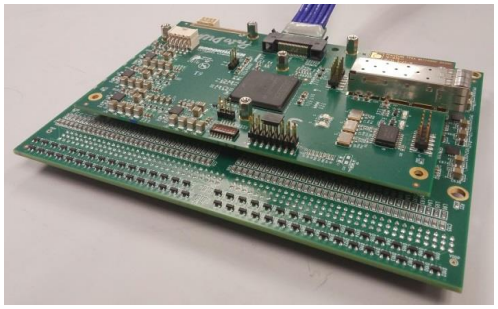
A necessary (but not sufficient!) condition to achieve a good performance, **the integral design concept** of APA + CE + Feed-through, plus Warm Interface Electronics with **local diagnostics** and strict isolation and **grounding rules** will have to be followed.

Brookhaven National Laboratory DUNE

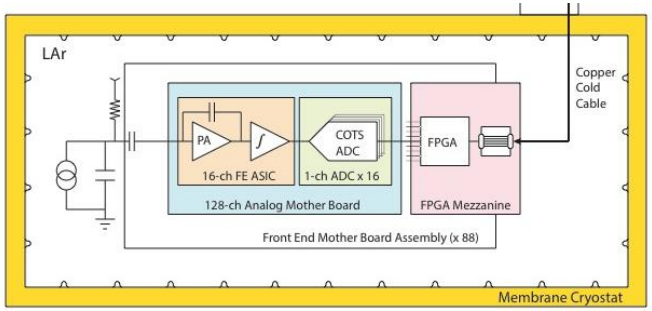
Evolution of Cold Electronics towards DUNE



ProtoDUNE (Cold FPGA)

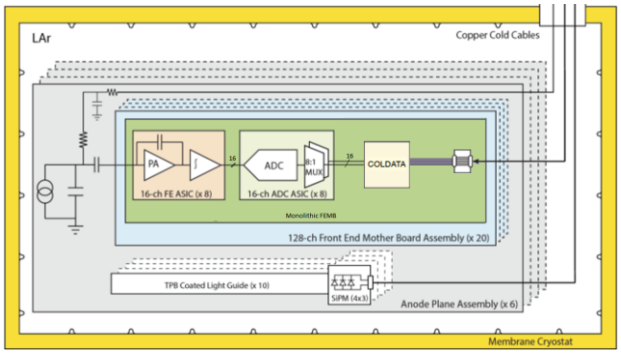


ProtoDUNE-SP FEMB with Cold FPGA successfully verified the feasibility of digitized readout at 77-89K

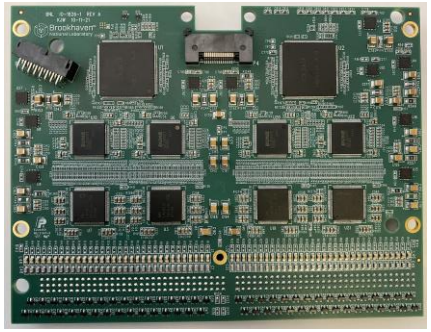


SBND (Cold FPGA + COTS ADC)

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



DUNE (3 Cryogenic ASICs)



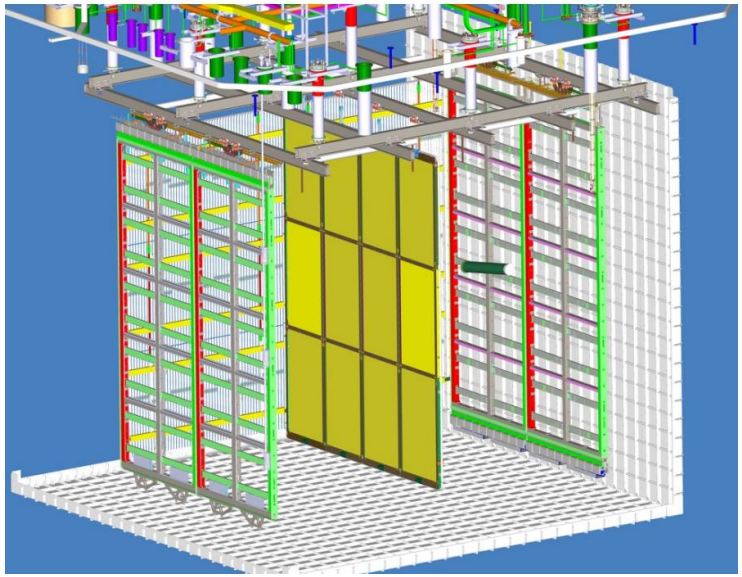
FEMB with **three** cryogenic-qualified ASICs (LArASIC, ColdADC, COLDATA) well addresses the long lifetime (30 years) and reliability requirements of DUNE far detector.

Brookhaven National Laboratory

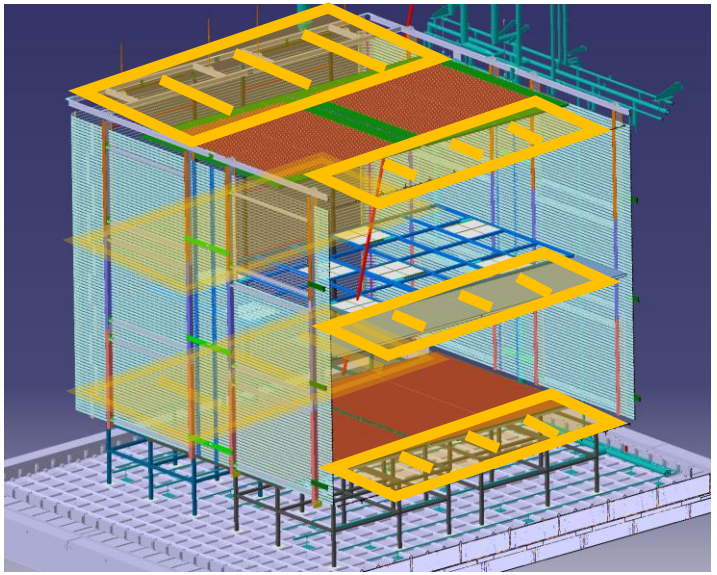
DUNE

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

Brookhaven National Laboratory DUNE