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U.S. DEPARTMENT OF ENERGY
Office of Science

Cryogenic Charge Readout Electronics for the ProtoDUNE-II Program and DUNE

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For the DUNE Collaboration

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Calaserena Resort, Sardinia, Italy
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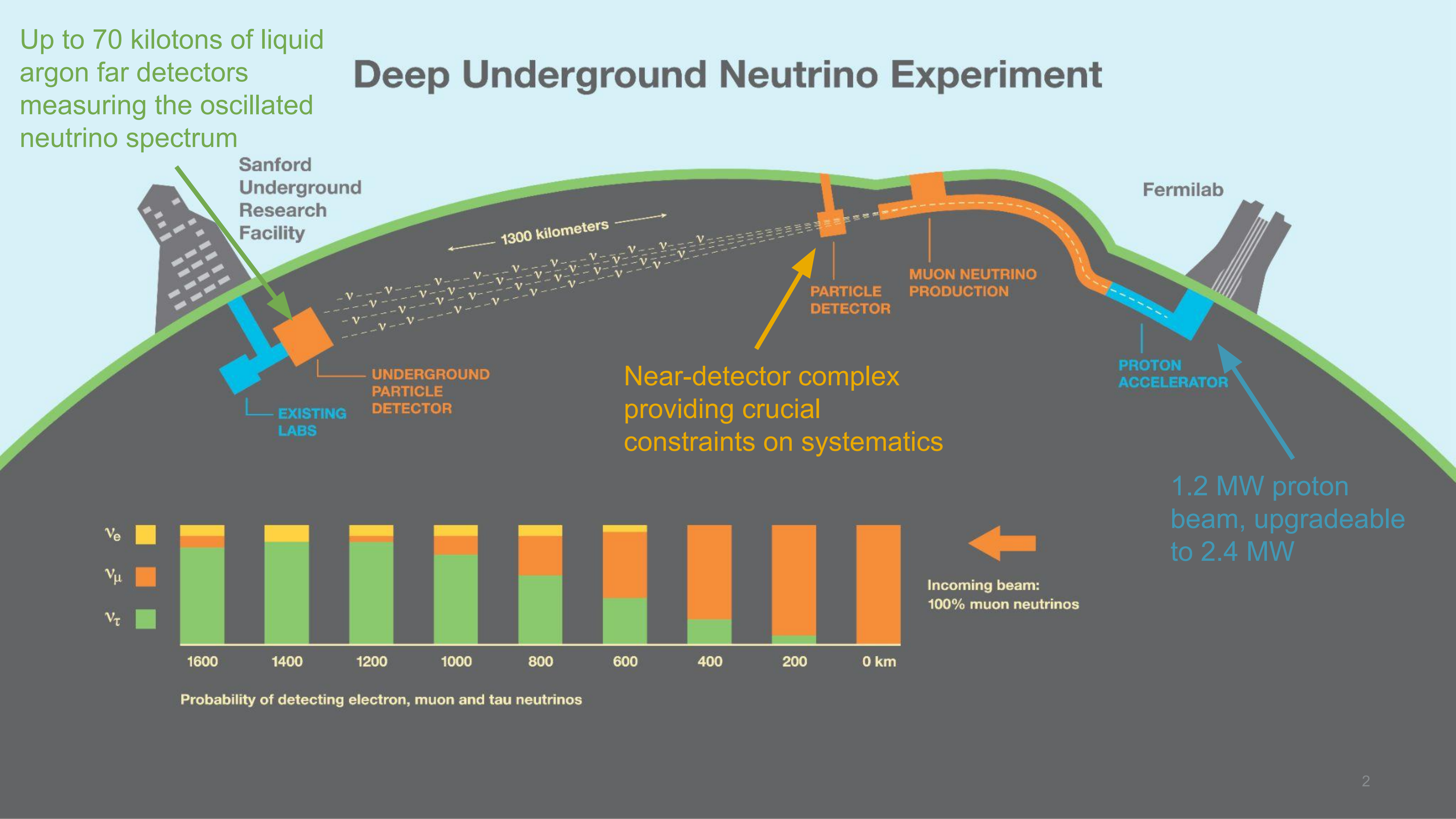
DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

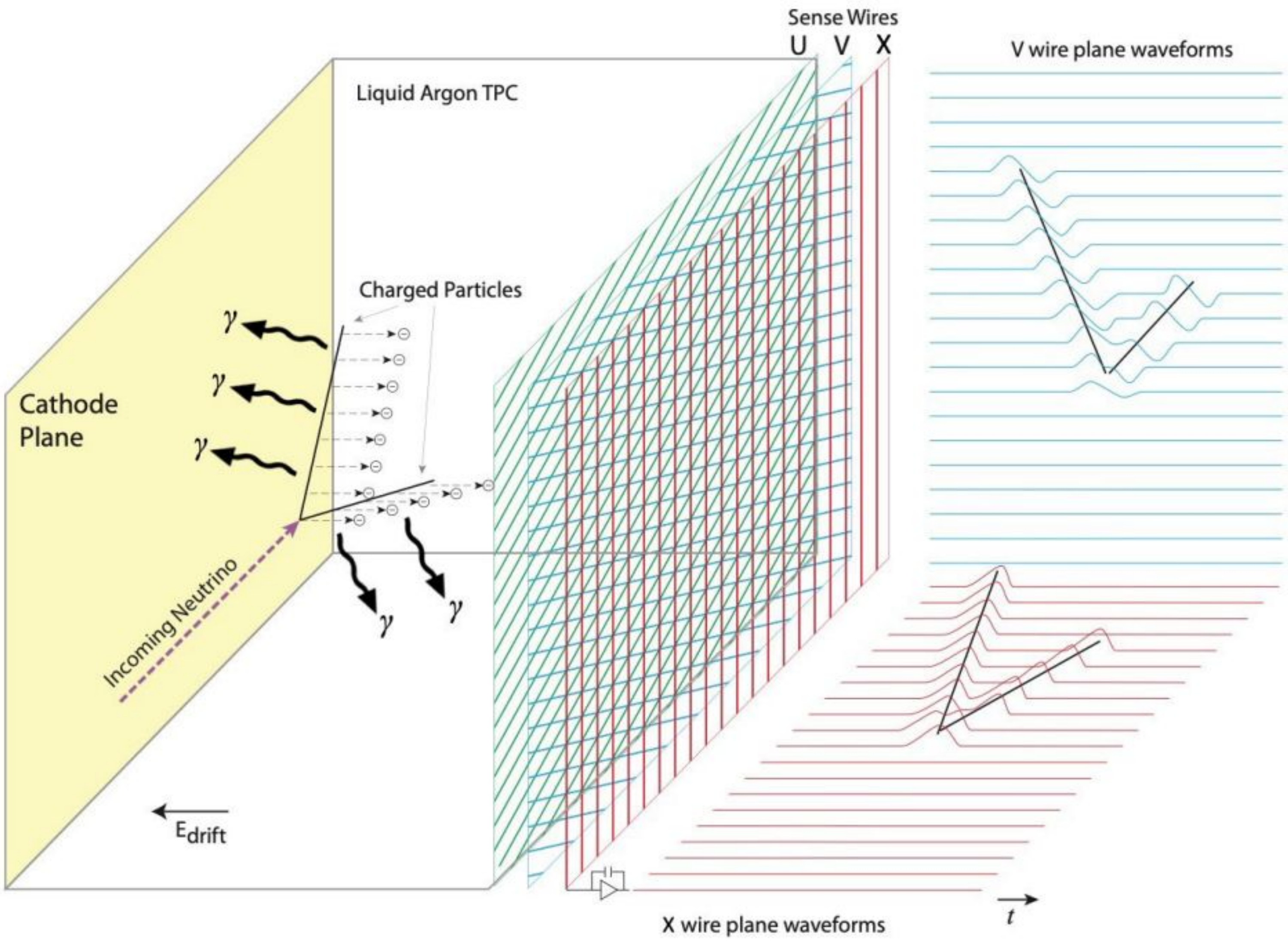


Up to 70 kilotons of liquid argon far detectors measuring the oscillated neutrino spectrum
Deep Underground Neutrino Experiment
Sanford Underground Research Facility
1300 kilometers
Fermilab
PARTICLE DETECTOR
MUON NEUTRINO PRODUCTION
UNDERGROUND PARTICLE DETECTOR
EXISTING LABS
Near-detector complex providing crucial constraints on systematics
PROTON ACCELERATOR
1.2 MW proton beam, upgradeable to 2.4 MW
νe
νμ
ντ
1600
1400
1200
1000
800
600
400
200
0 km
Incoming beam: 100% muon neutrinos
Probability of detecting electron, muon and tau neutrinos

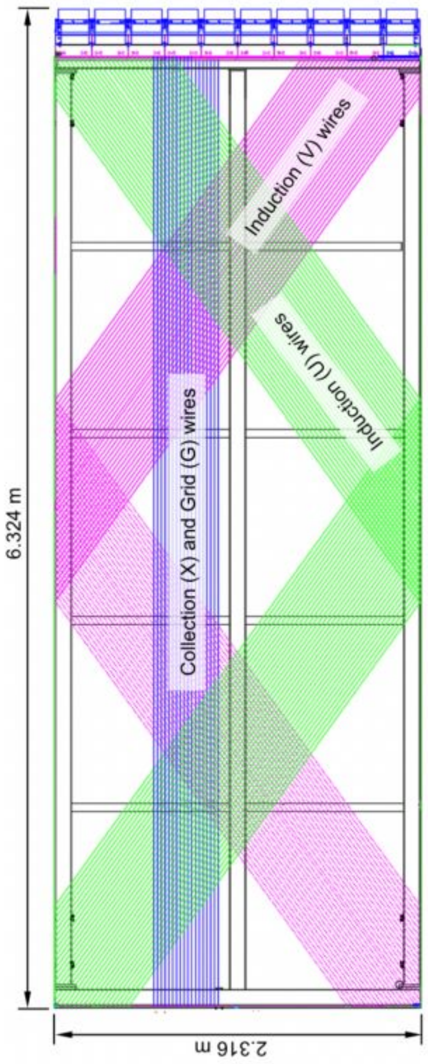
Liquid Argon Time Projection Chambers

LAr TPCs allow for high-resolution 3D event reconstruction

- Apply a strong electric field across a **drift volume**
  - ~500 V / m across a distance of 3-6 m
- Charged particles ionize electrons as they pass through
- **Scintillation light** from the initial interaction provides a t=0
  - ~24000 scintillation photons / MeV
- **Drift time** to sensing wires provides 1 dimension
  - Drift velocity of ~1.6 mm / us
- Sense wire signals provide the other 2 dimensions
  - ~5 mm wire spacing

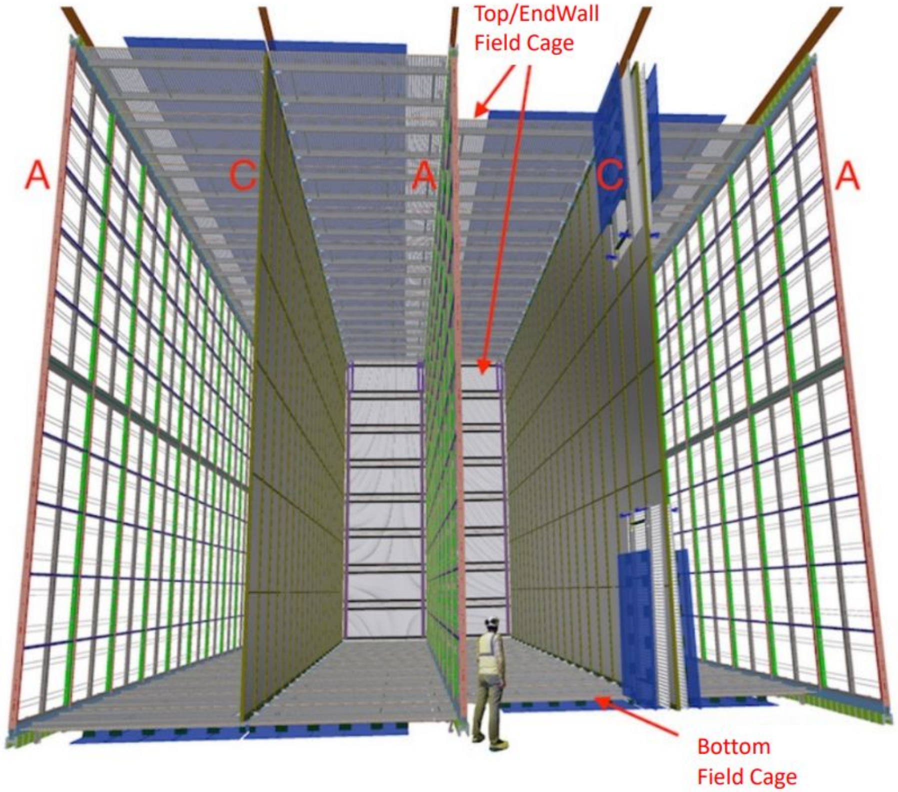


DUNE Far Detectors



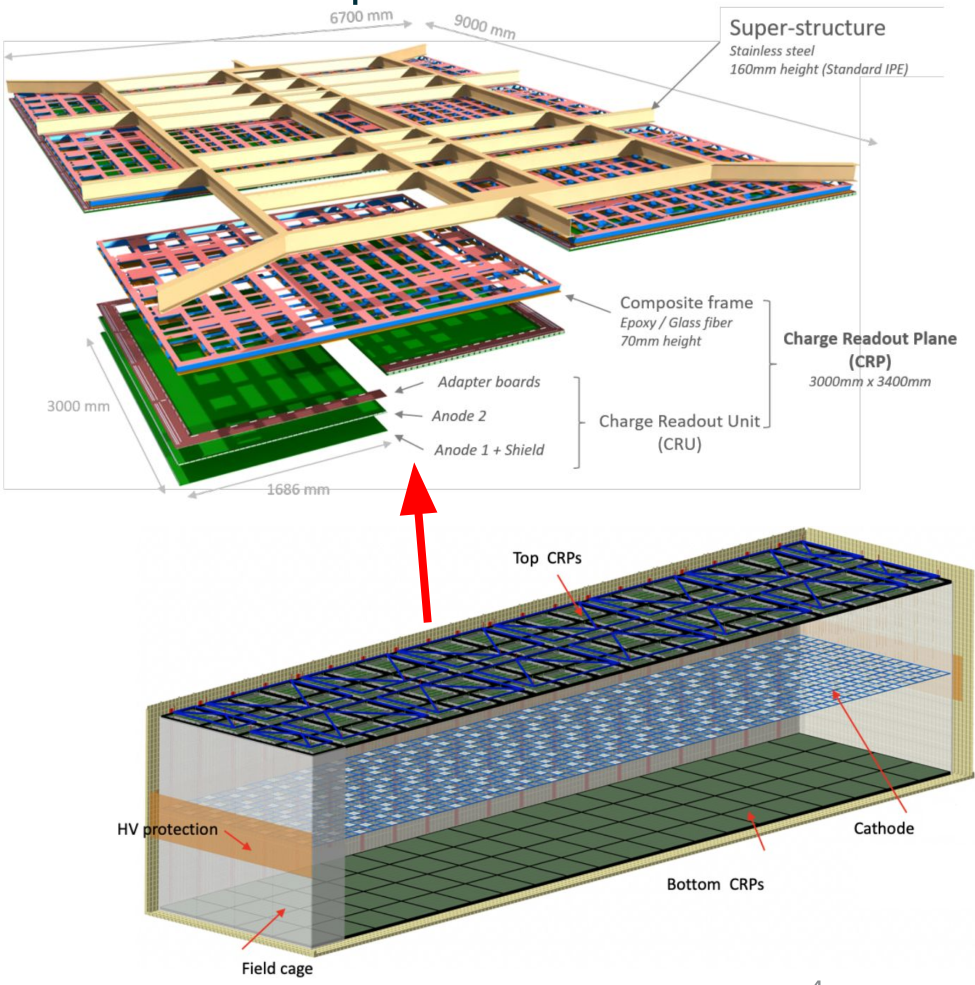
FD1 - Horizontal Drift:

- 150 wire-plane anode plane assemblies (APAs), arranged into 4 drift volumes
- 2560 channels per APA



FD2 - Vertical Drift:

- 160 charge-readout planes (CRPs), using PCB strips instead of wires for charge readout
- 3072 channels per CRP

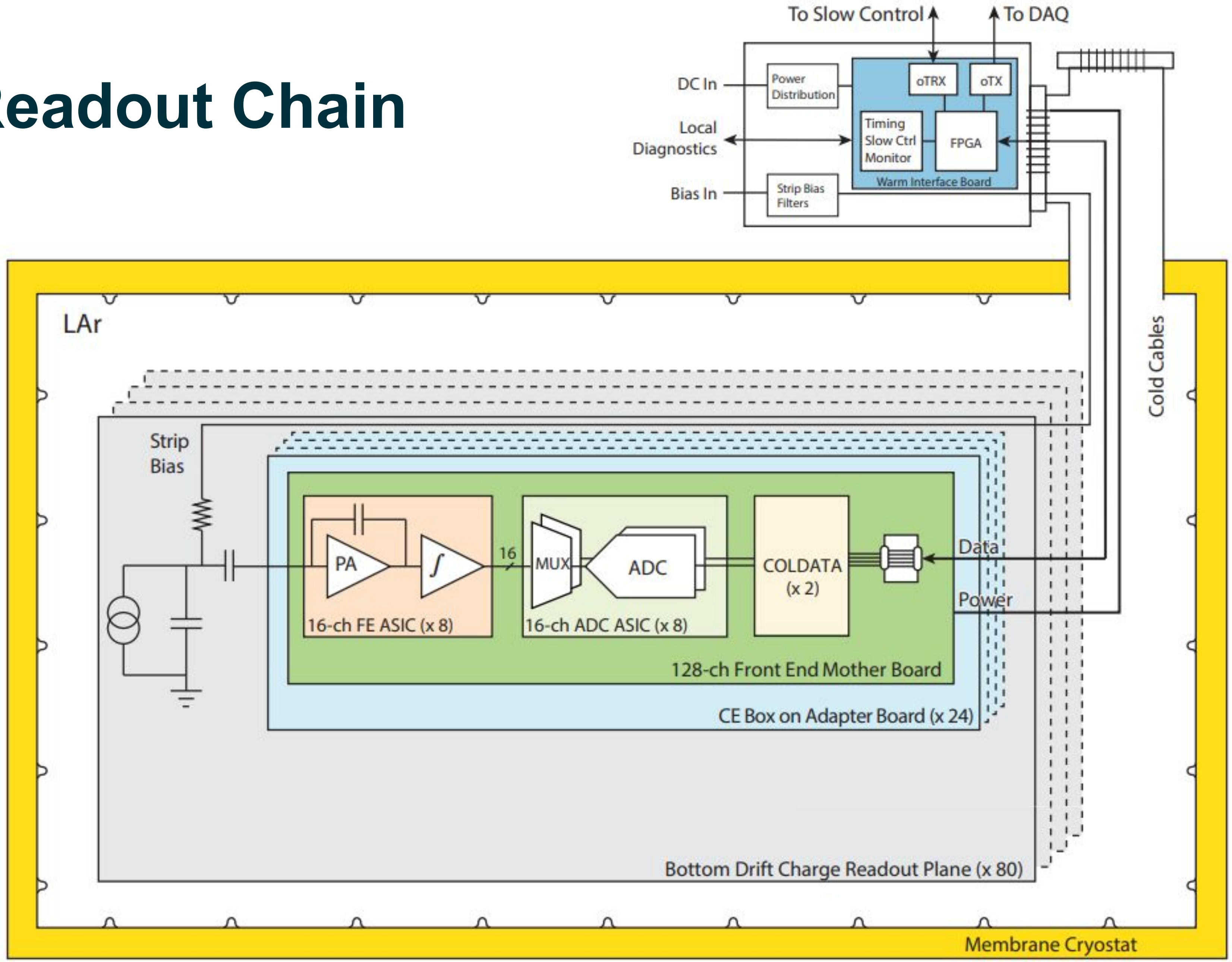


Cold TPC Readout Electronics for DUNE

- Both far detectors face a similar problem for detector readout: significant number of the charge-sensing components are deep in the LAr cryostat
  - Warm electronics on the cryostat roof could be more than 20 meters away from sensors at the bottom of the cryostat
- Solution: **charge amplification, digitization and readout electronics operating in liquid argon** (~87 K)
  - Used for all FD1 readout, and readout of the bottom detectors in FD2
- Challenges:
  - Noise levels with baseline RMS < 1000 electrons equivalent noise charge (ENC), and requirements on linearity and dynamic range
  - Low power consumption to not cause argon boiling (< 50 mW / channel)
  - Electronics in the cryostat will never be replaced => need ~20-30 year lifetime
  - Consistency in electronics quality in tens of thousands of chips

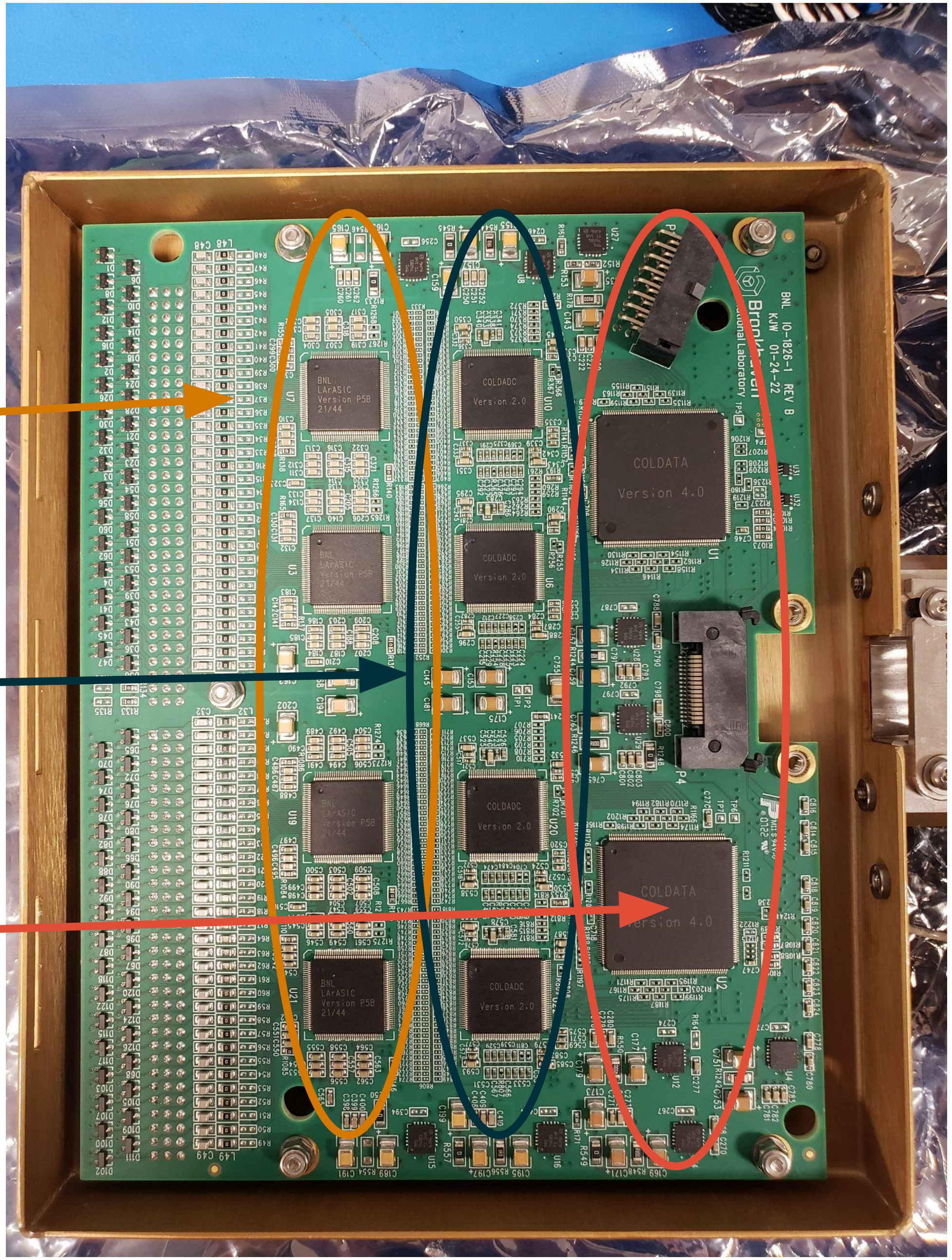
TPC Electronics Readout Chain

- Charge readout performed by 128-channel **front-end motherboards (FEMBs)** placed in close proximity to the sensing wires/strips
  - 3000 FEMBs for FD1
  - 1920 FEMBs for FD2
- Warm electronics provide power and digital control of the FEMBs, and provide the interface with the DAQ system
  - 4 FEMBs per warm interface board



Front-end Motherboards

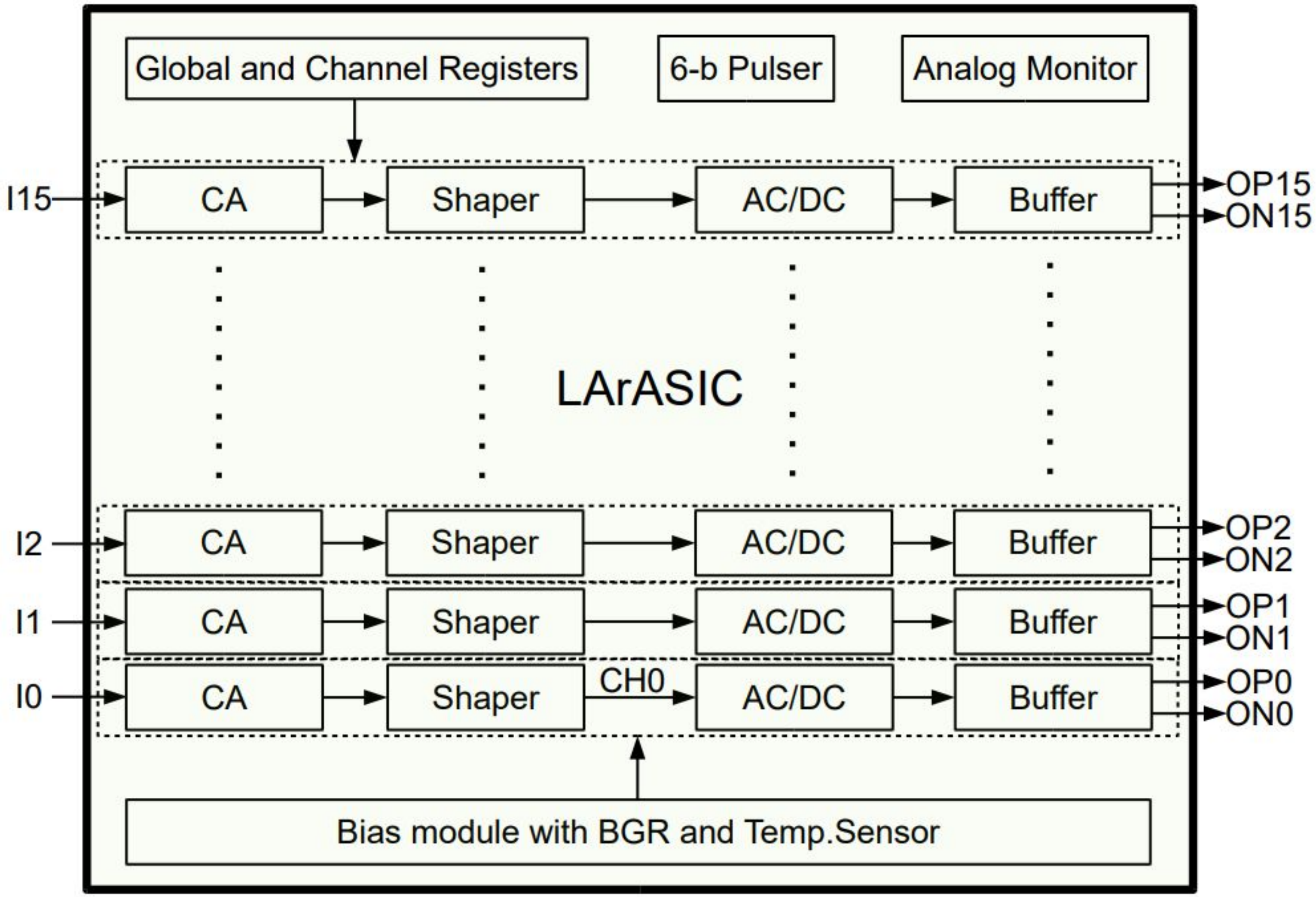
- Each FEMB consists of:
- **8 LArASIC** chips for analog charge amplification
  - Includes configurable shaper, different baseline and gain settings, and internal pulser for calibration
- **8 ColdADC** chips for digitization
  - Digitizing to 14-bit signals at ~2 MHz (< 1 mm spatial resolution in the TPC)
- **2 COLDATA** chips for control of and communication with LArASICs and ColdADCs
  - Receives commands from and sends serial data to the warm electronics
- Each ASIC and assembled FEMB undergoes QC testing before installation on detectors



Note: 4 LArASICs and 4 ColdADCs on other side of the board

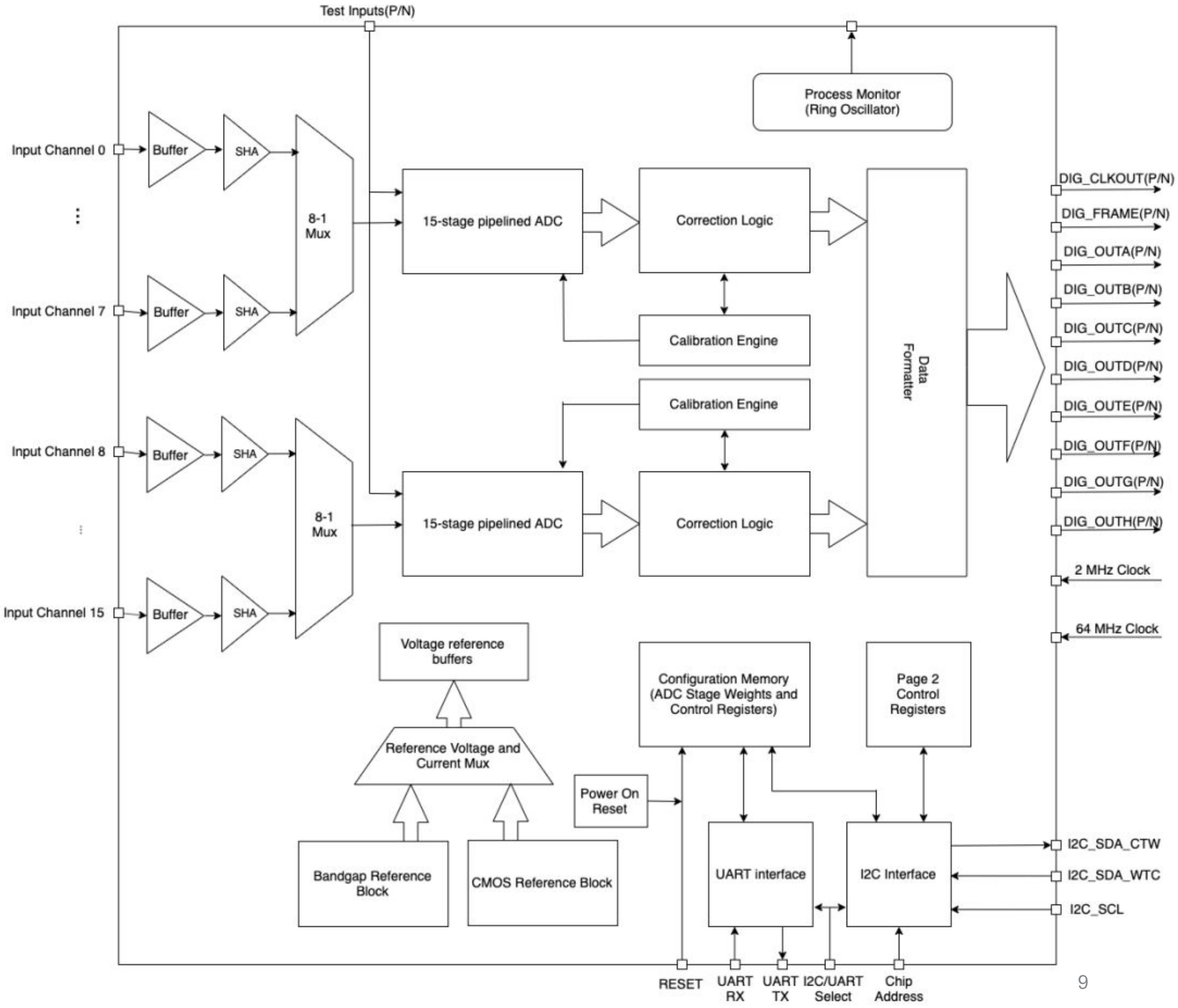
LArASIC Overview

- Built in 180 nm CMOS process
- 16 channels / chip, each with SE or differential output
- Two-stage charge amplifier and 5th order shaper
- Input charge range of 56-300 fC, depending on gain selection (60x to 320x)
- Channels configured through SPI interface
- Bias voltages generated internally with BJT bandgap reference



ColdADC Overview

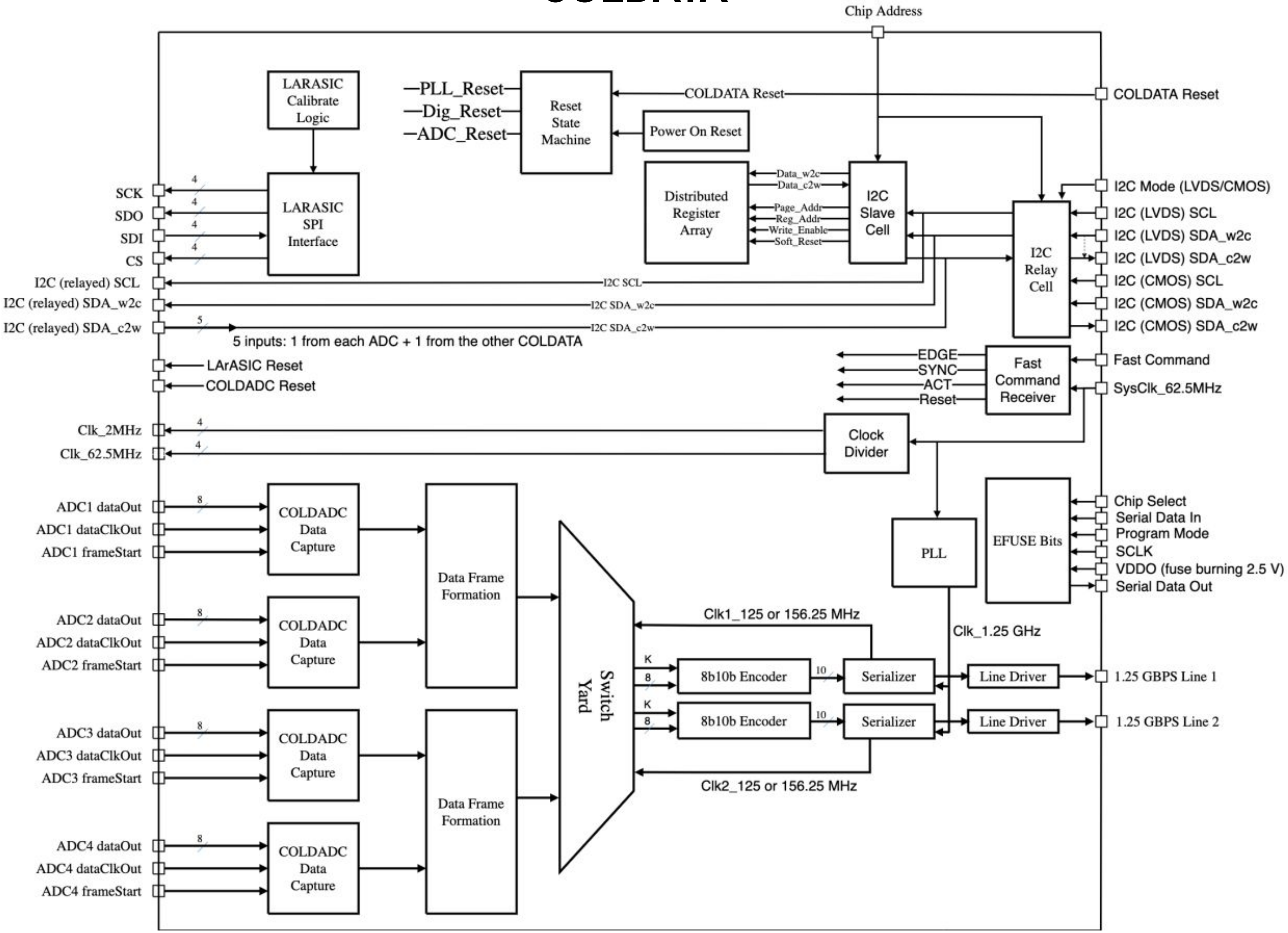
- Built in 65 nm CMOS process
- 16 input/output channels, with 2 groups of 8 SHAs with 8:1 mux of input channels to ADCs
- 15-stage pipelined ADC with self-calibration engine
- Configurable through UART or I2C-like interface
- Dominates power dissipation on FEMB: ~20 mW / channel in liquid argon



COLDATA Overview

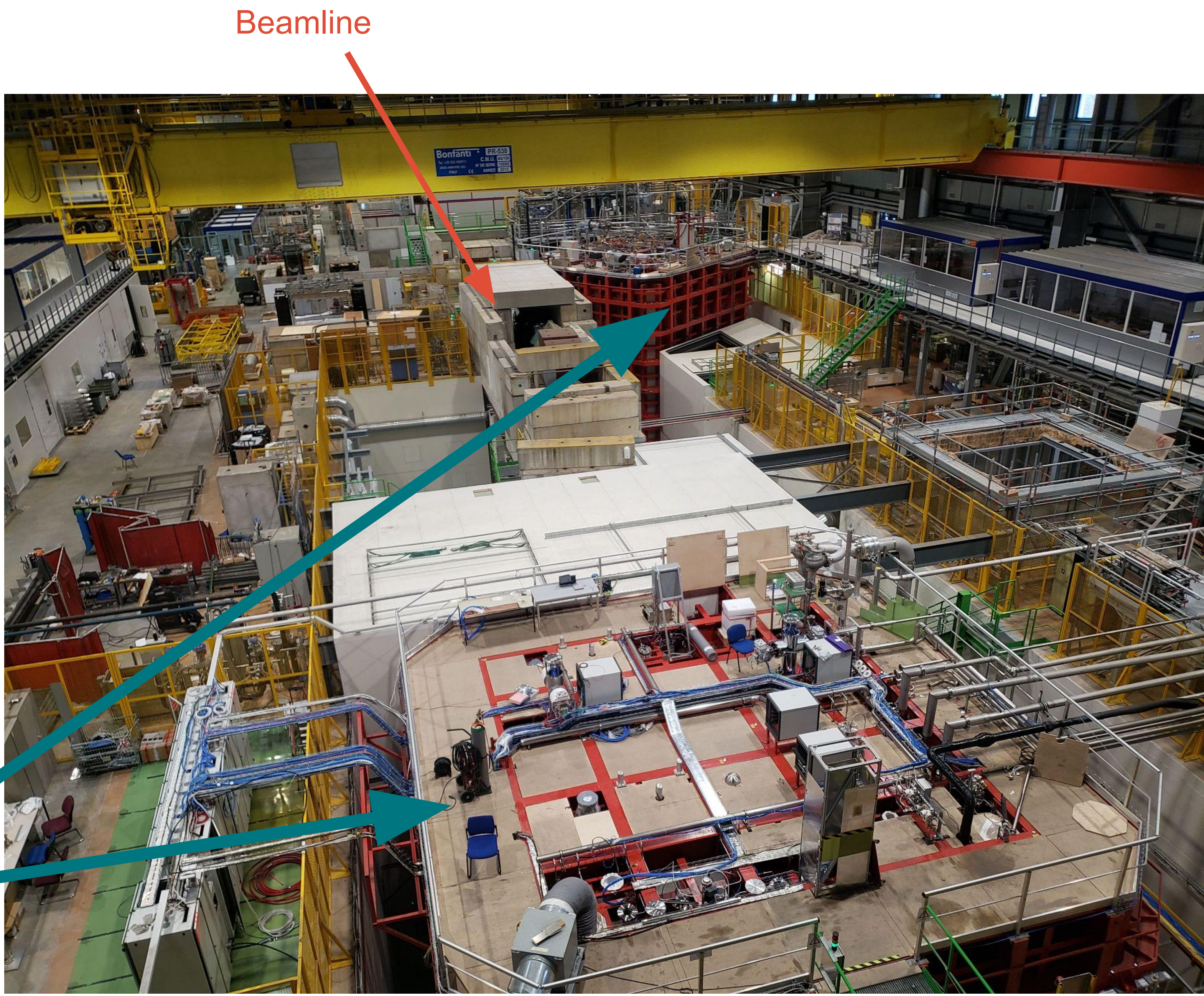
- Built in 65 nm CMOS process
- I2C-like communication via LVDS with warm interface electronics
- Controls and configures 4 ColdADCs and 4 LArASICs
- PLL generates 1.25 GHz clock for data serializers
- Configurable line driver for sending 8b10 encoded data to warm electronics

COLDATA



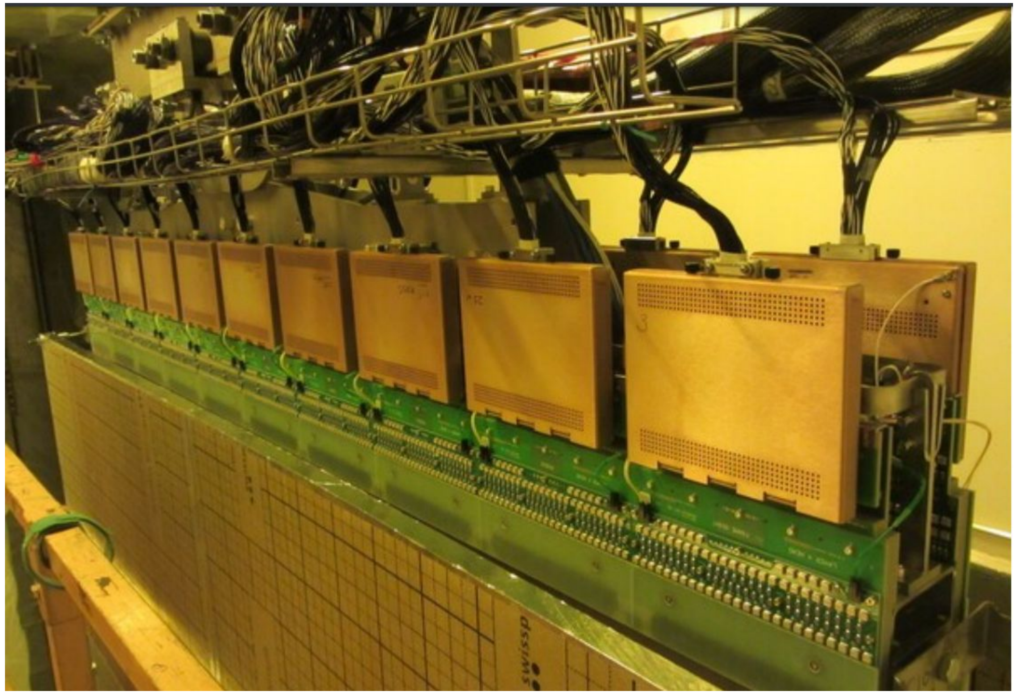
ProtoDUNE-II at CERN

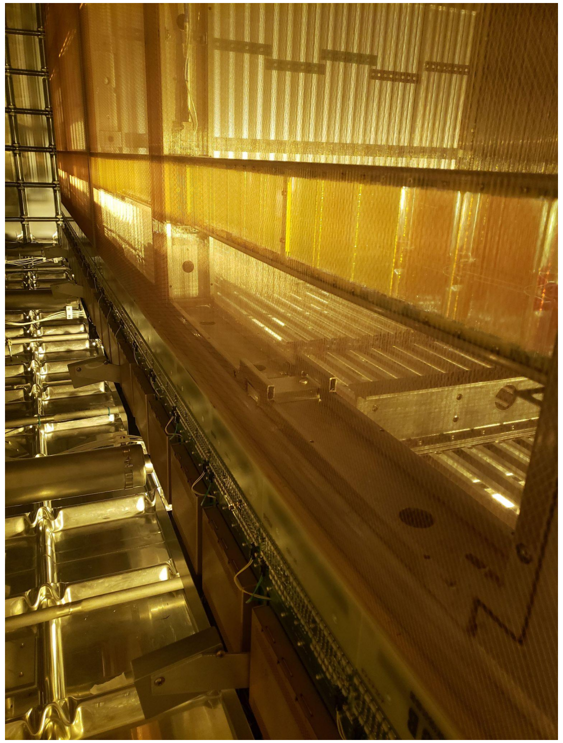
- **ProtoDUNE-II-HD** and **ProtoDUNE-II-VD** will serve as the final prototypes prior to beginning of far detector construction
  - Using final designs of detector components and electronics that will be in FD1 and FD2 respectively
- **800 ton LArTPCs** at CERN's neutrino platform



ProtoDUNE-II-HD

- Cryostat will contain 2 drift volumes, read out by 4 APAs
- Each APA tested with all readout electronics in a **nitrogen gas coldbox** (down to ~160 K)





TPC Electronics Performance for ProtoDUNE-II-HD

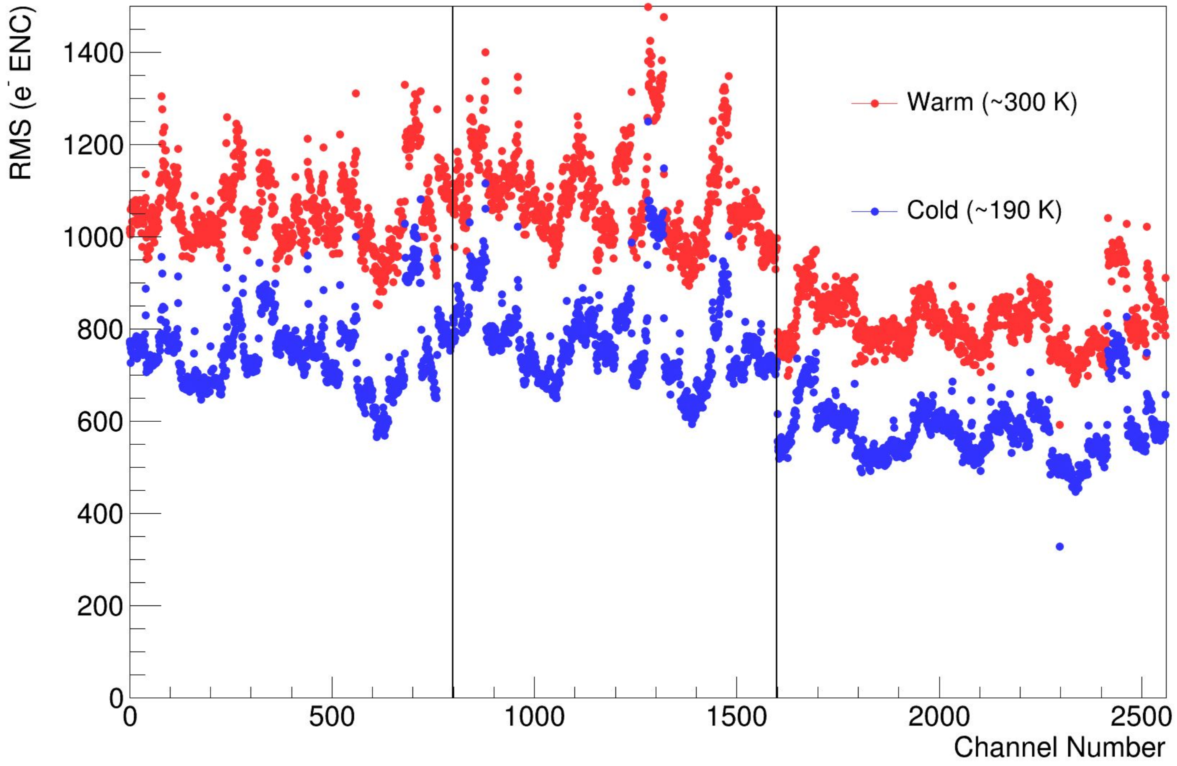
General noise performance of electronics at cold is well below the desired ~1000 e^- equivalent noise charge (ENC) for DUNE

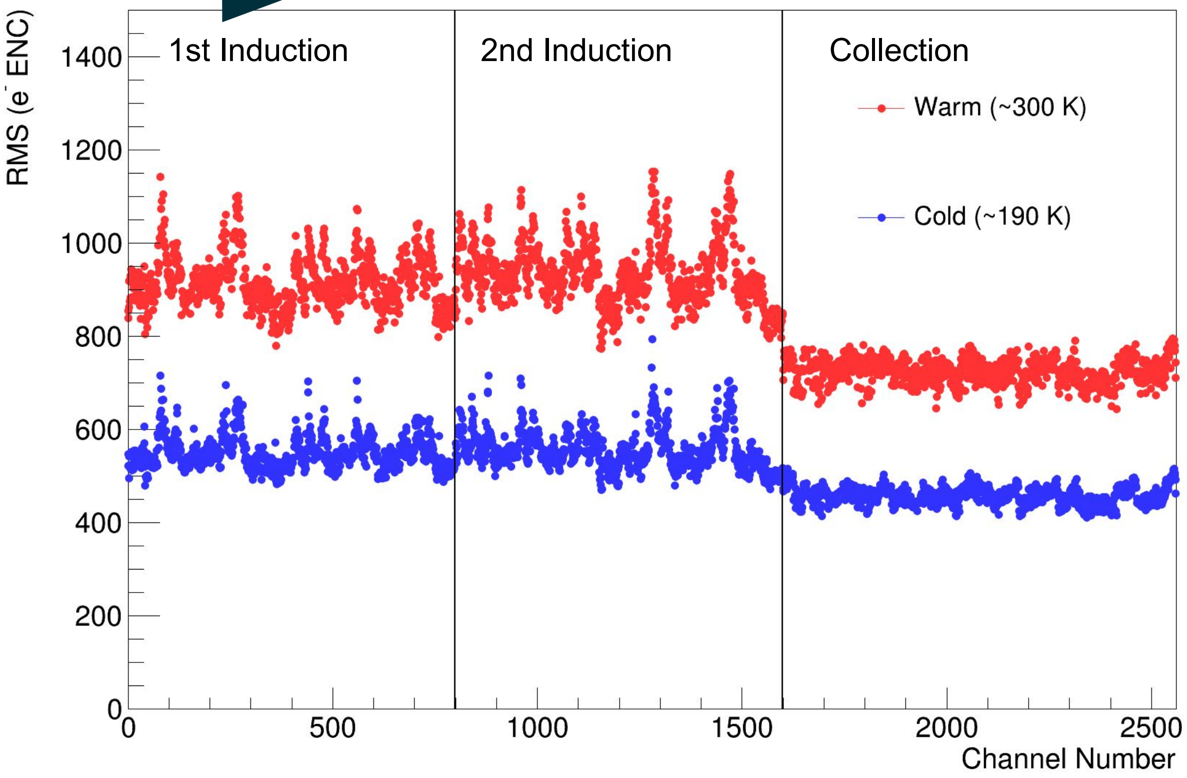
- Minimum-ionizing particle releases >10000 electrons onto each collection wire

APA1 Noise Performance without CNR

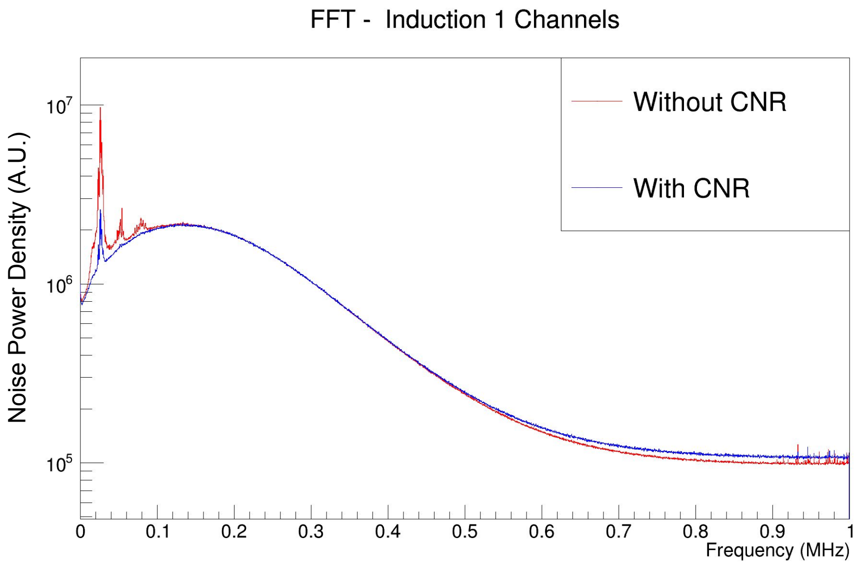
Coherent Noise Removal →

APA1 Noise Performance with CNR





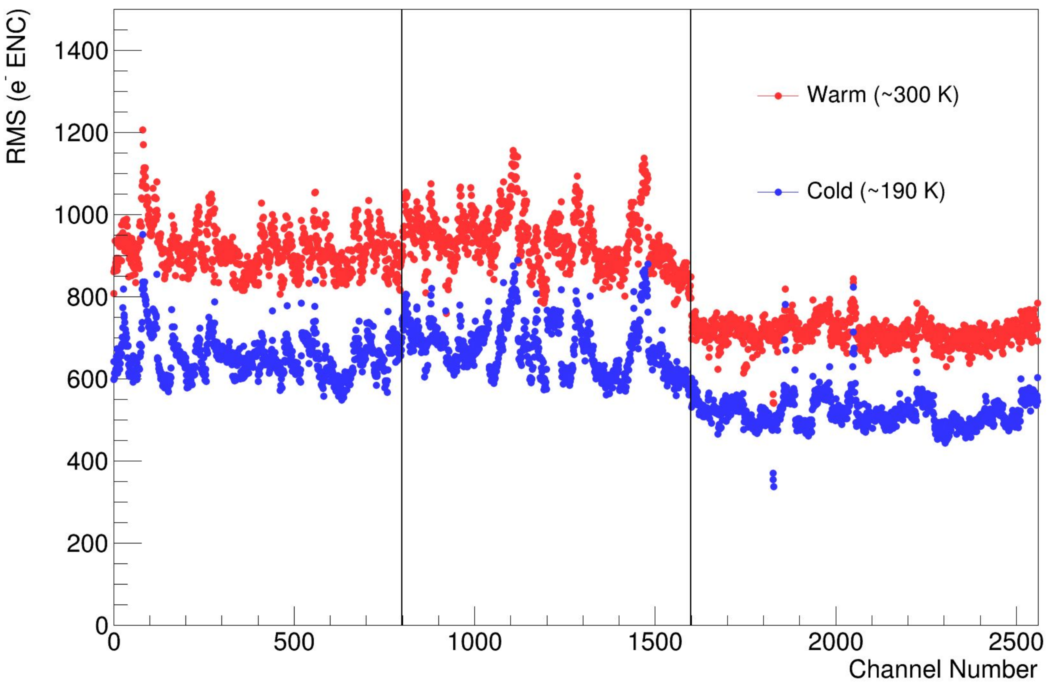
TPC Electronics Performance for ProtoDUNE-II-HD

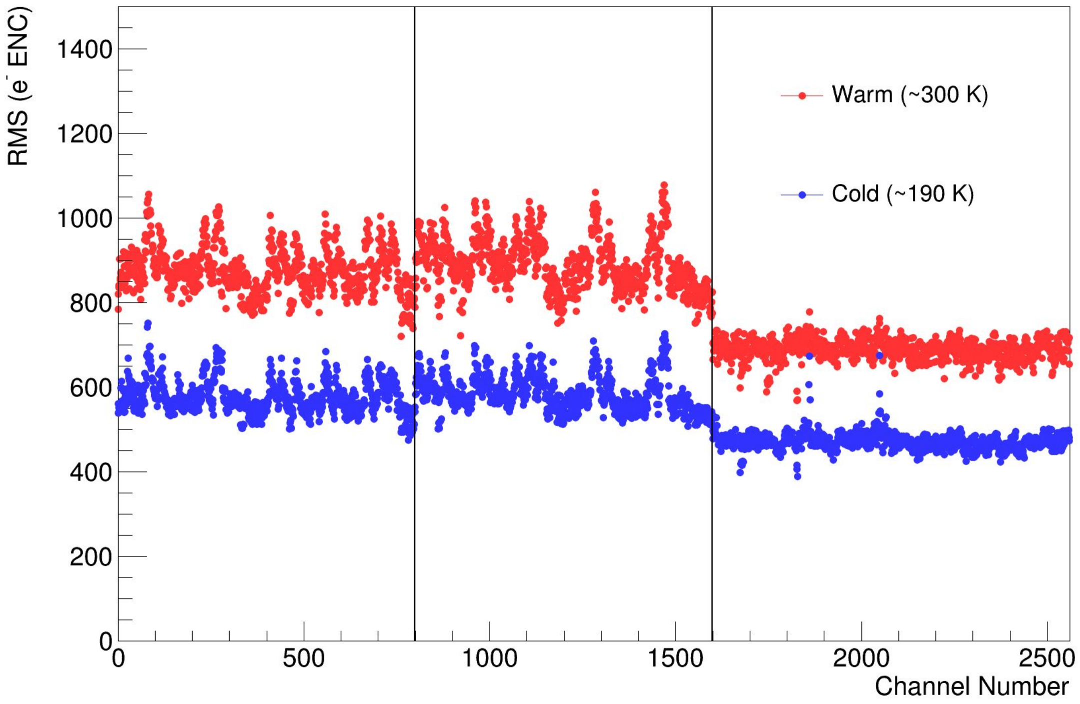


- Some APAs experience slightly stronger coherent noise pickup, but baseline noise levels after coherent noise removal are comparable

Coherent Noise Removal

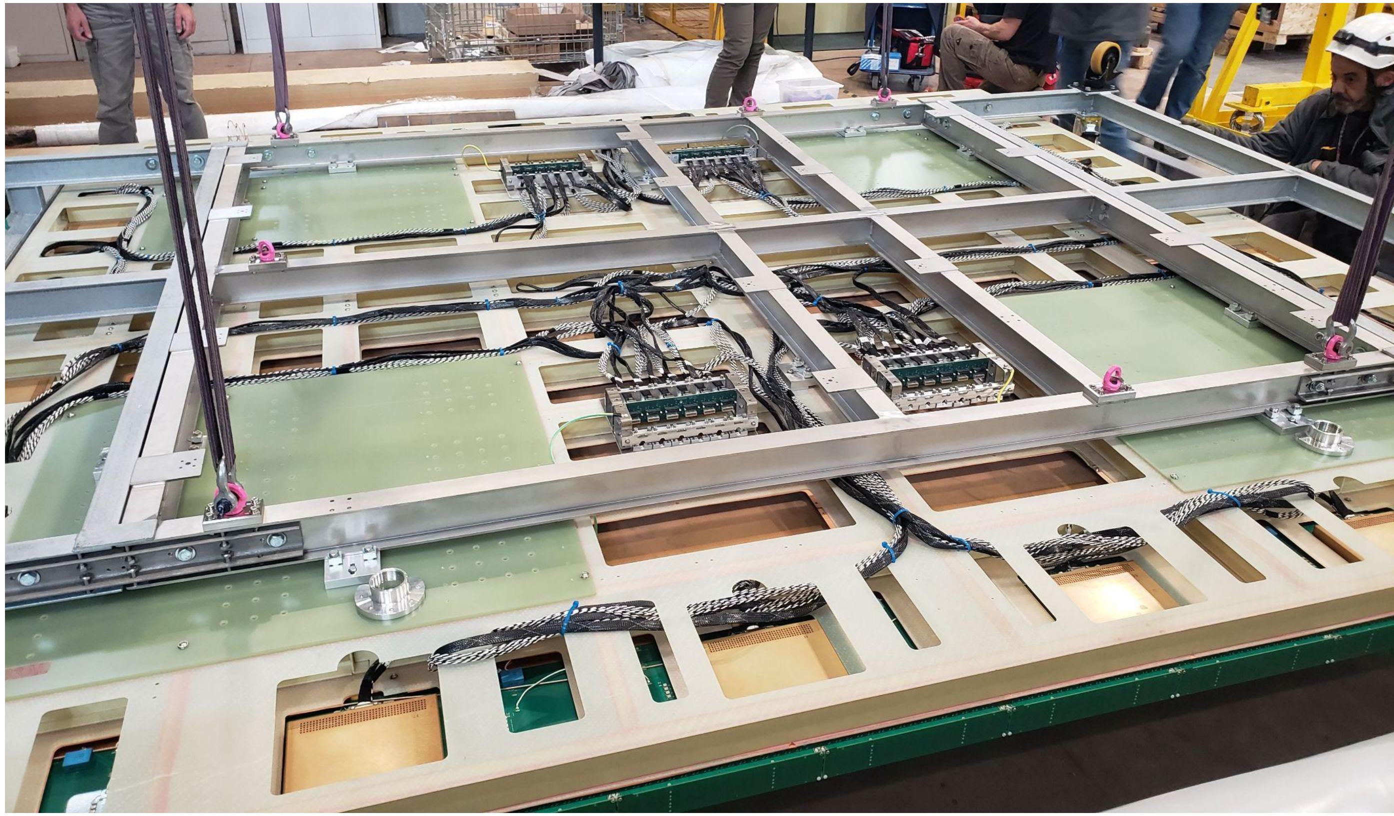
APA4 Noise Performance without CNR → APA4 Noise Performance with CNR



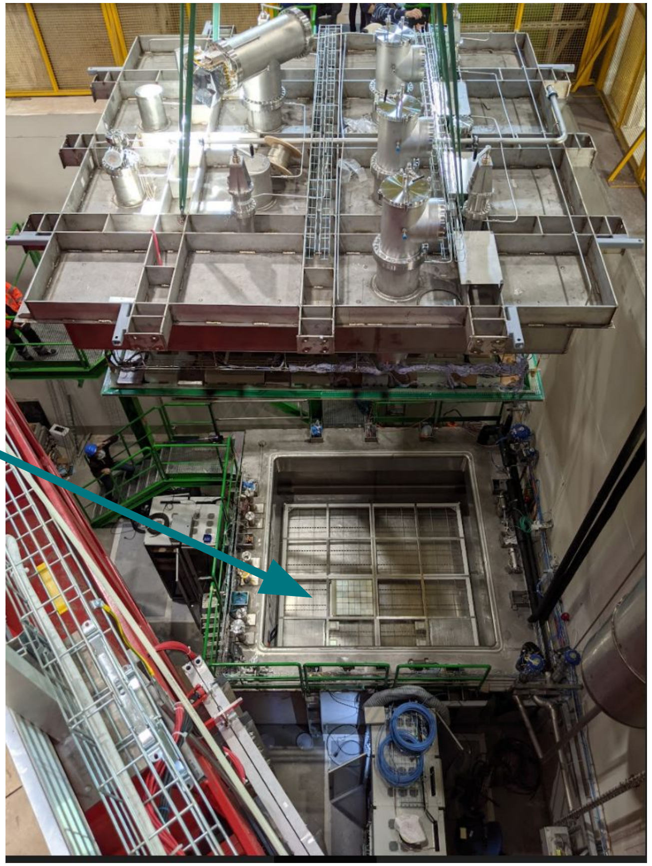


ProtoDUNE-II-VD

- Cryostat will contain 4 CRPS (3m x 3.4m each), with 2 for top-half readout and 2 for bottom-half readout



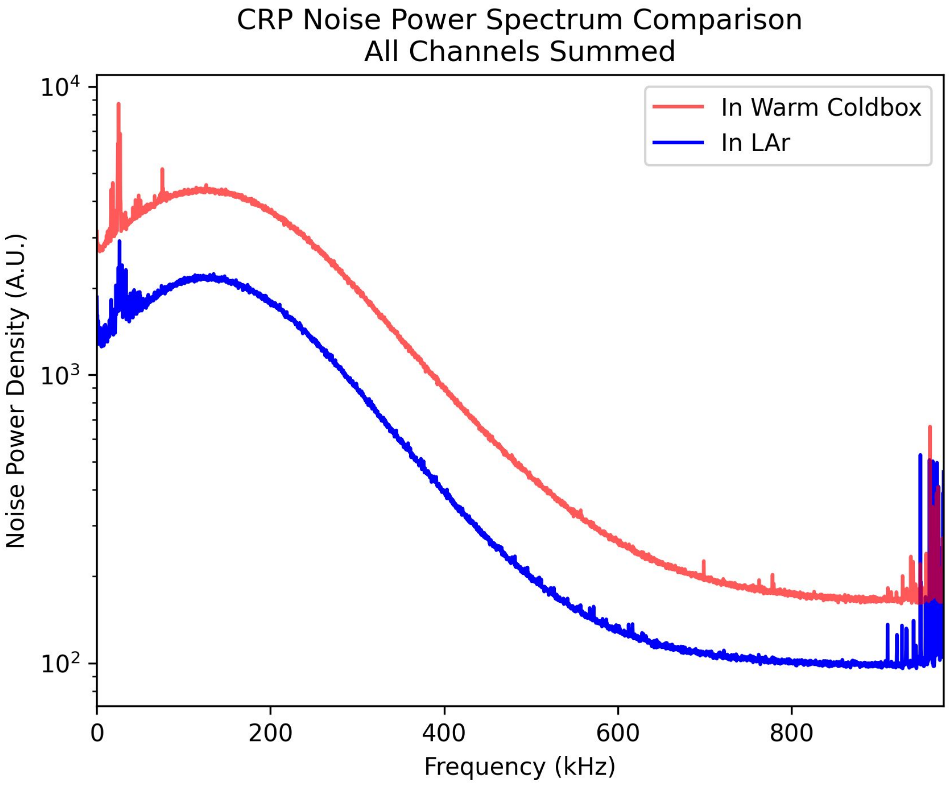
Vertical-drift detectors tested in a liquid argon coldbox, which is a fully functional mini-TPC with ~30 cm drift

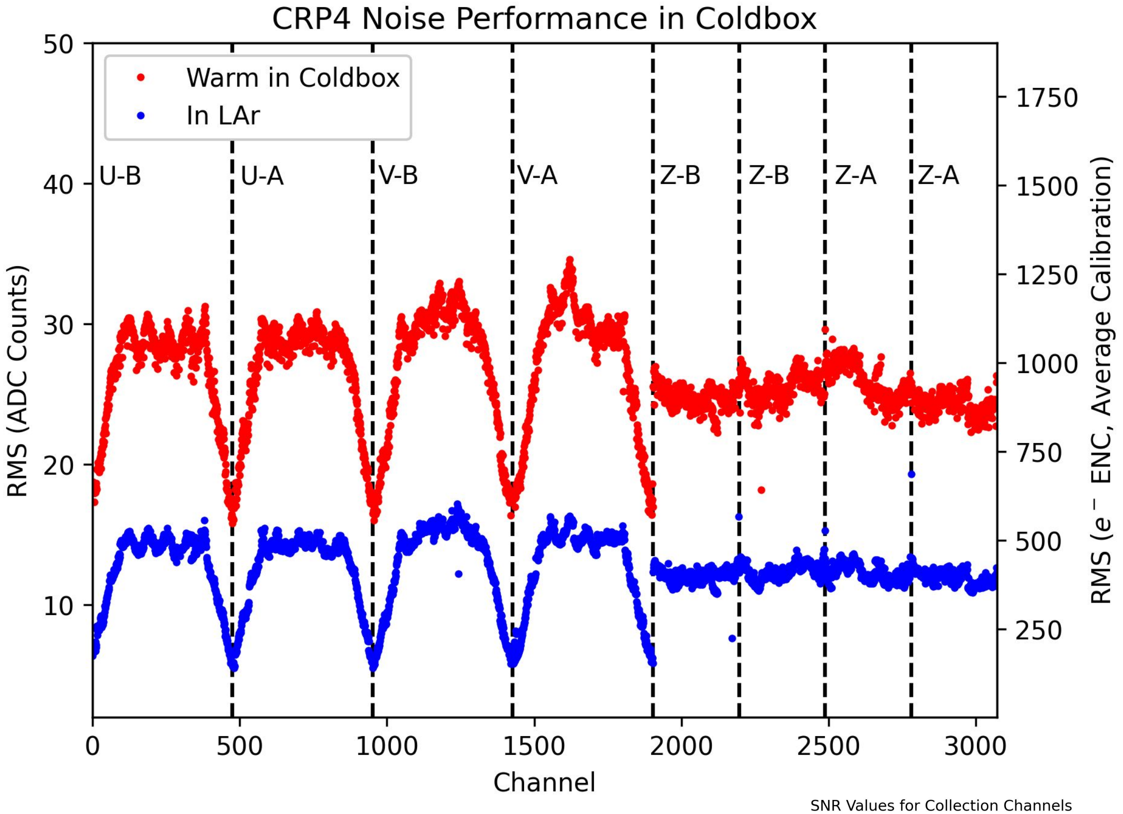


- 24 FEMBs sit under each bottom CRP
  - Identical FEMB design as the APAs, other than mechanical components
  - Total of ~29 meters of cable between each FEMB and the warm readout electronics

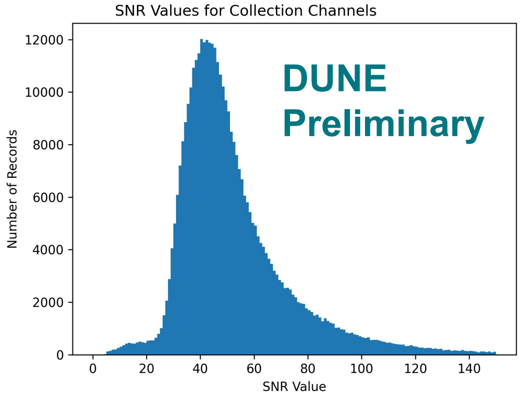
TPC Electronics Performance for ProtoDUNE-II-VD

- LAr coldbox tests of individual CRPs show excellent noise performance
- Minor contributions from coherent noise pickup around ~25 kHz



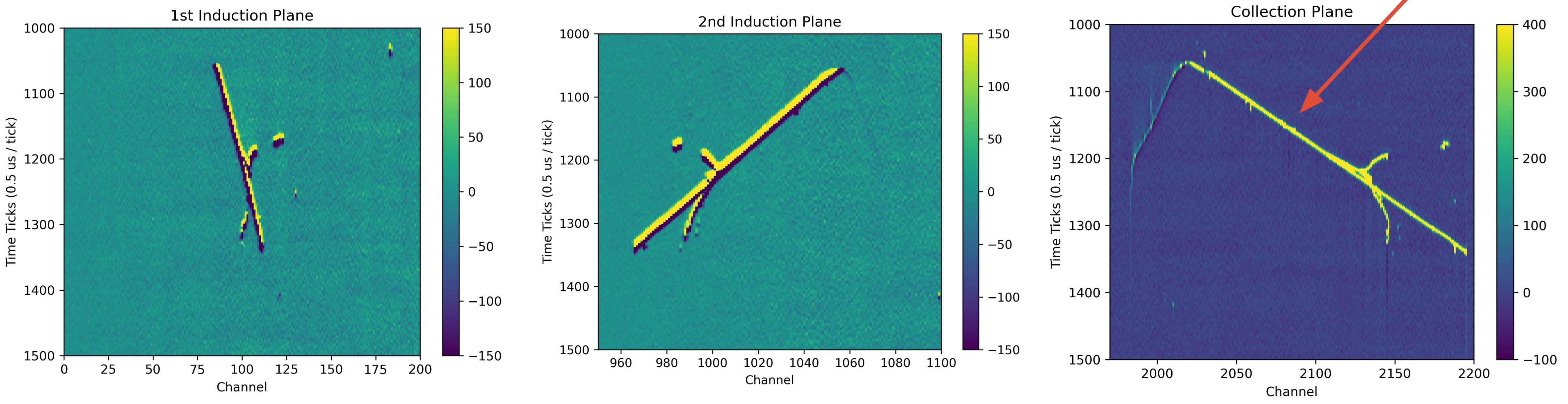


- Simple SNR estimate of the collection channels using throughgoing muons gives a MPV of ~45
  - No noise-filtering or lifetime and geometry corrections

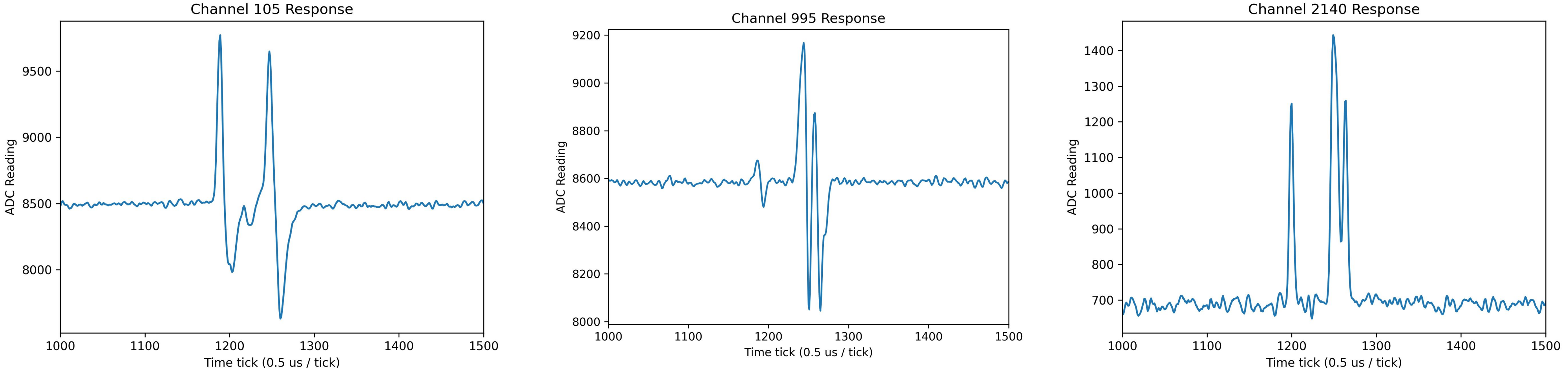


Tracks from CRP Coldbox Test

~90 cm track



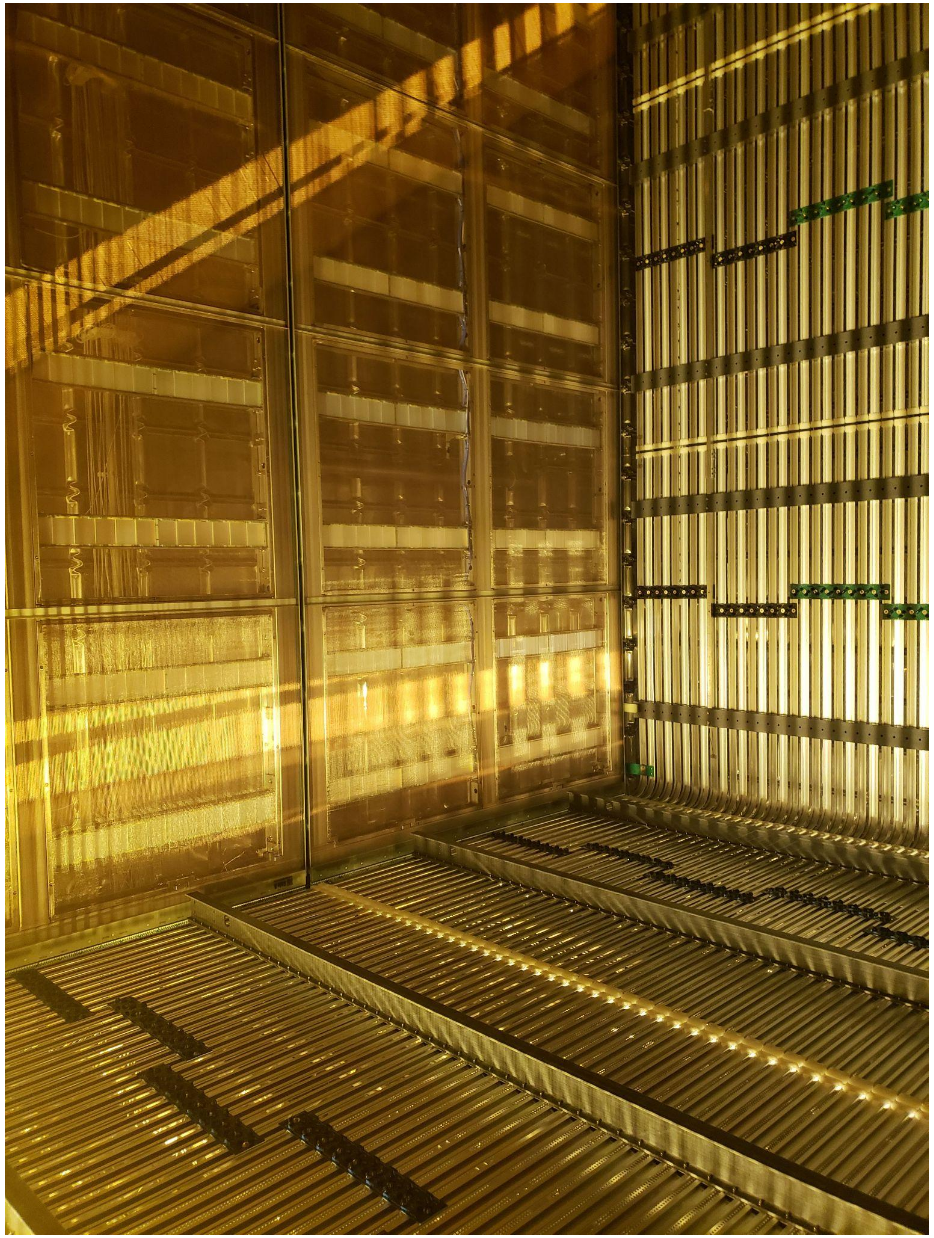
Raw data waveforms:



Inside one of the ProtoDUNE-II-VD drift volumes

Summary

- Assembly of both ProtoDUNE-II-HD and ProtoDUNE-II-VD have been completed, with the cryostats awaiting argon
- Design of the cryogenic charge readout electronics for the first 2 DUNE far detectors is now finalized
  - Performance has been vetted in coldbox tests of the CRP and APA modules
  - Additional validation will come from the upcoming ProtoDUNE-II program



Inside one of the ProtoDUNE-II-HD drift volumes