DUNE Phase II Detector R&D

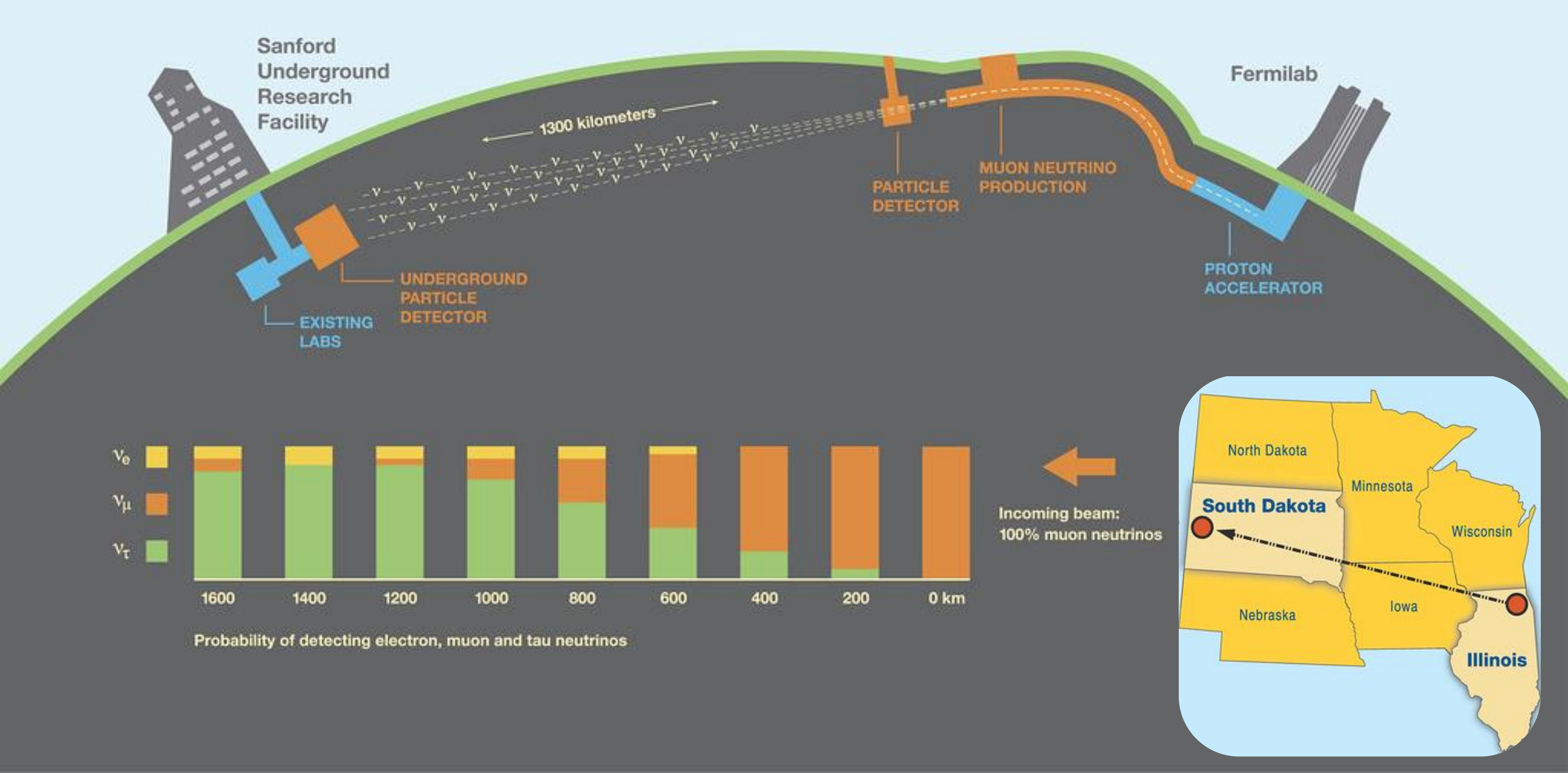
Brooke Russell on behalf of the DUNE collaboration

CPAD 2025 @ Penn

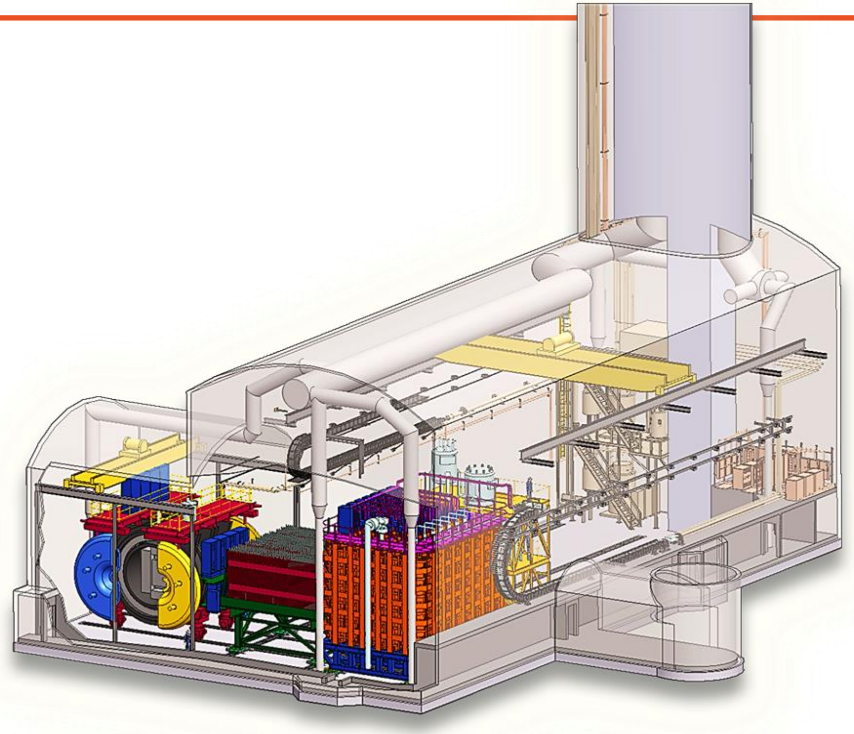
October 10, 2025

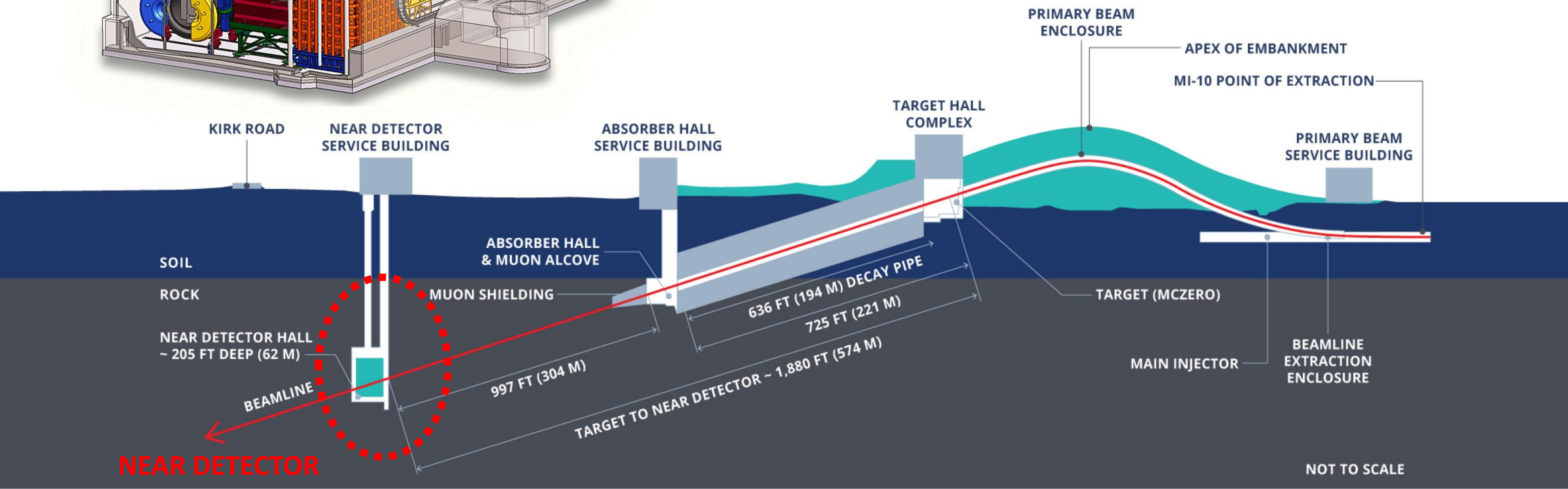
Massachusetts Institute of Technology

Deep Underground Neutrino Experiment

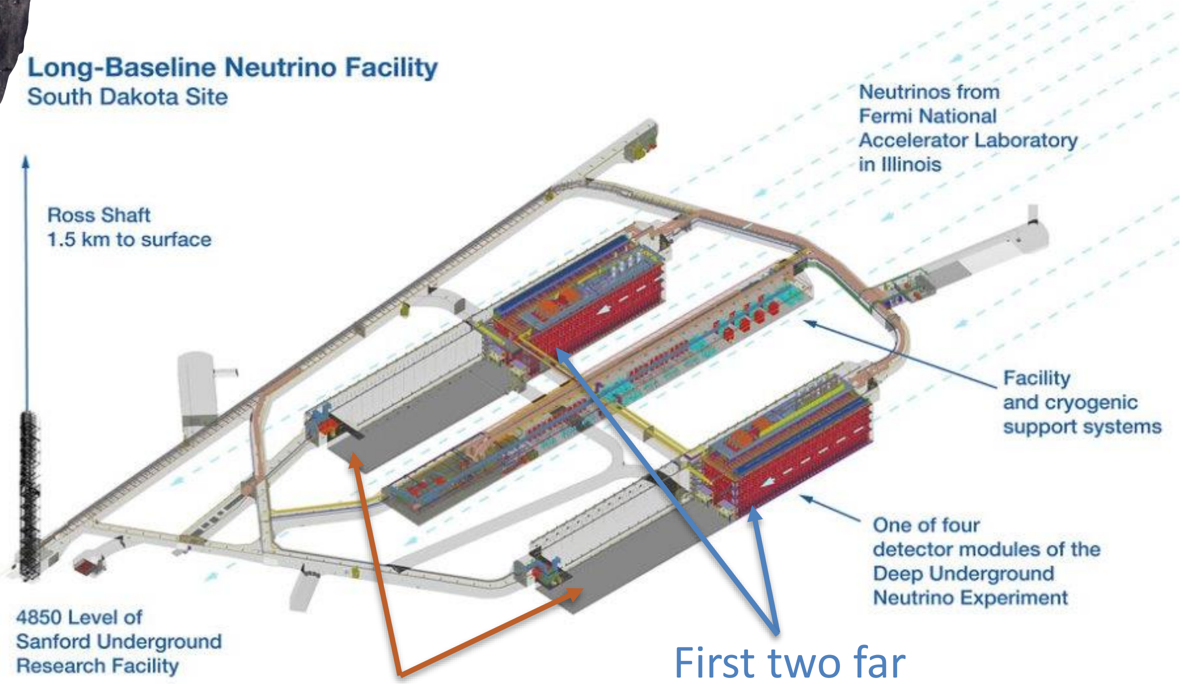


DUNE Near Detector sited in the world's most intense neutrino beam





Far Detector

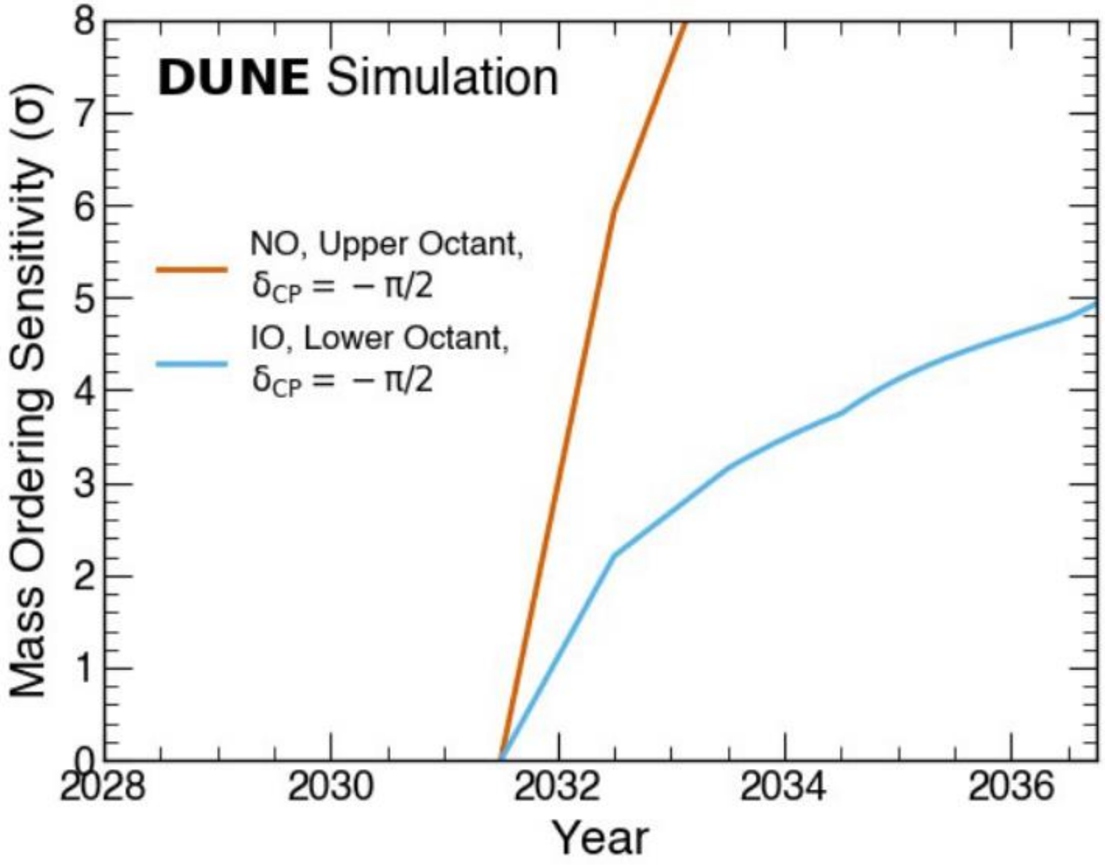


Second two far detectors in DUNE Phase II

First two far detectors in DUNE Phase I

Unambiguous neutrino mass ordering determination in Phase I

- Δm^2_{atm} precisely measured with both muon and electron neutrinos
  - DUNE is the only experiment that measures mass ordering with electron (anti)neutrino appearance oscillations
- Observe oscillations over many periods
- Spectral information is key to extracting mass ordering irrespective of true oscillation parameters



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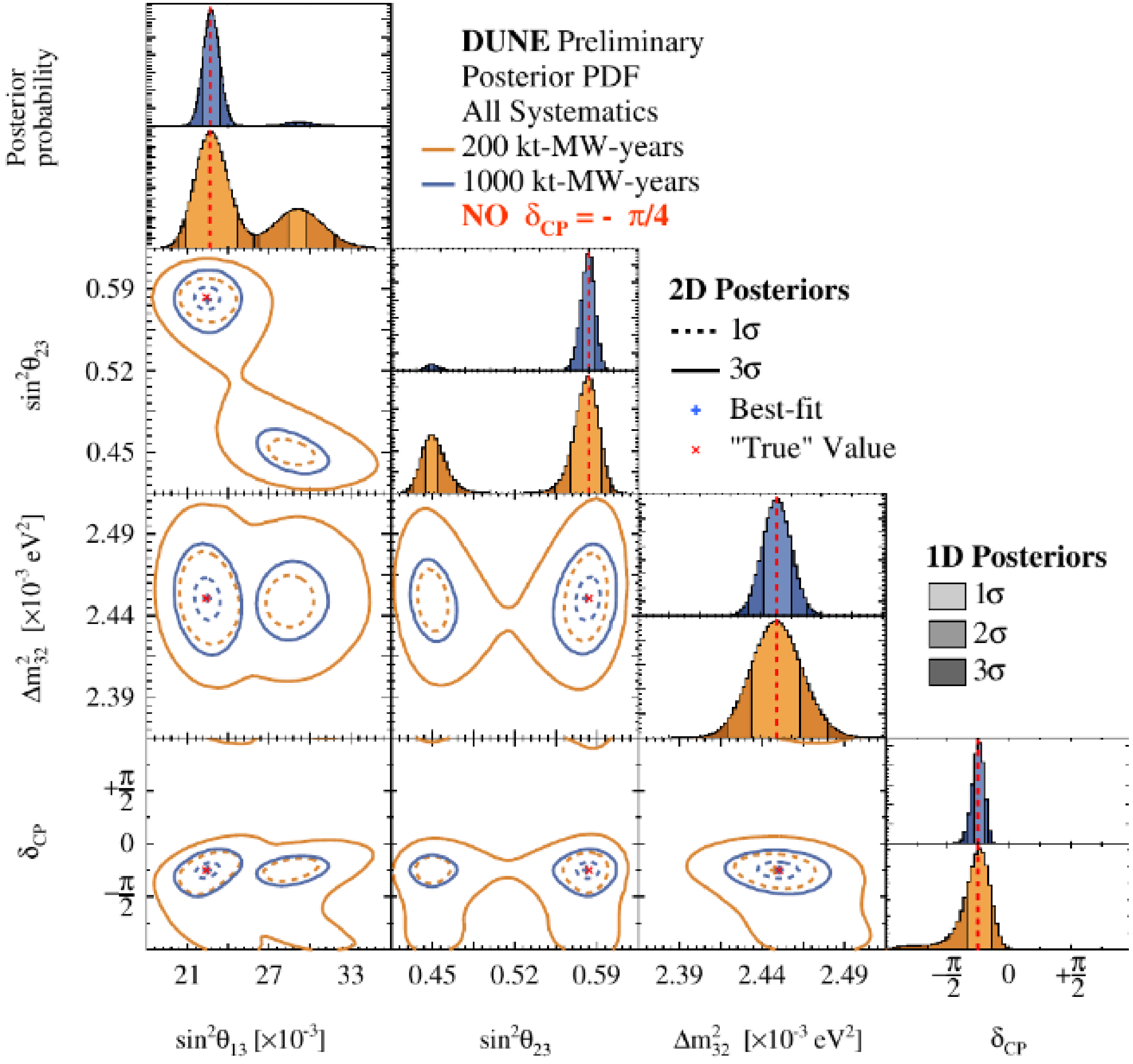
Phase II is integral to DUNE physics

- DUNE measures all neutrino mixing parameters in one experiment
- 4D posterior probability density in three-flavor parameter space, without any external inputs
- With a large exposure, DUNE can resolve parameter degeneracies



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HEPAP Subpanel on DOE Facilities

- ACE-MIRT, Far Detector 3 (FD3), and More Capable Near Detector (MCND) assessed as absolutely central
- FD3 evaluated as "ready to initiate construction" under technical readiness
- For FD4, ongoing R&D will clarify performance advancement in neutrino astro and BSM physics

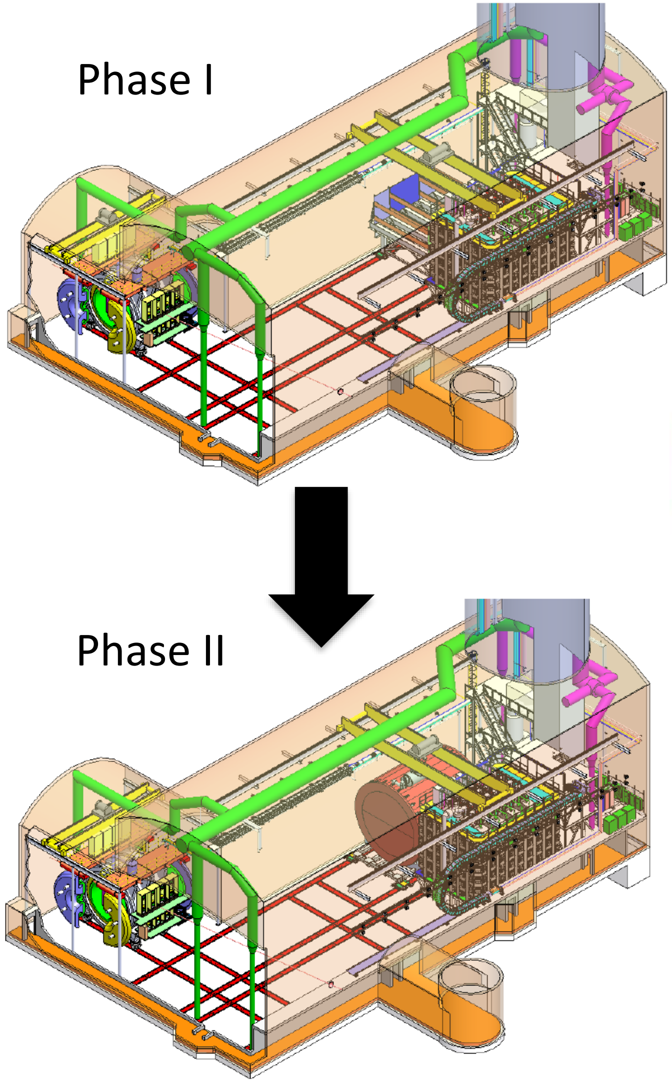
		Science Assessment				Technical Readiness		
		Absolutely central	Important	Lower priority	Don't know	Ready to initiate construction	Significant scientific/ engineering challenges remain	Mission and technical requirements not fully defined
		A	B	C	D	A	B	C
LBNF/DUNE Phase 1		●				●		
LBNF/DUNE Phase 2	ACE-MIRT	●				●		
	FD3	●				●		
	MCND	●					●	
FD4					●			●
CMB-S4		●				●		
Spec-S5		●				●		
G3 Dark Matter		●					●	
Off-Shore Higgs Factory		●				●		
AATF - kBELLA		●					●	
ACE-BR					●			●
10 TeV pCM Collider		●						●

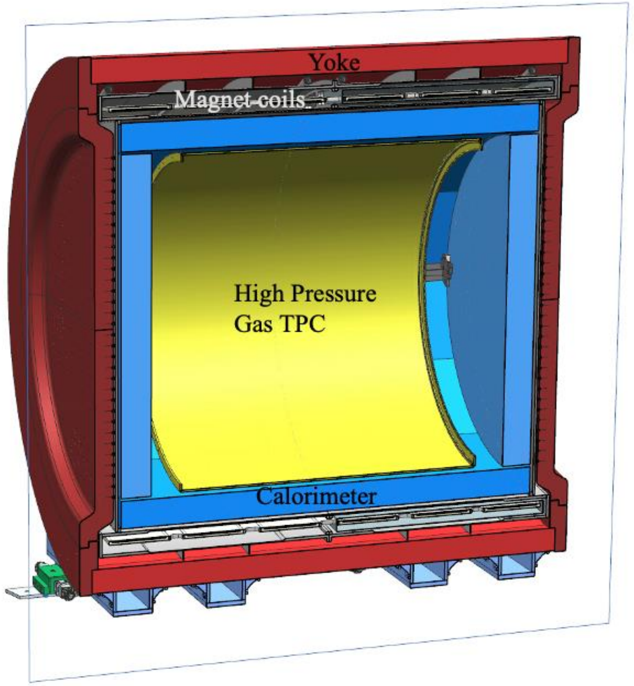
Parameter	Phase I	Phase II	Impact
FD mass	2 FD modules (20 kt fiducial)	4 FD modules (40 kt fiducial LAr equivalent)	FD statistics
Beam power	1.2 MW	Up to 2.3 MW	FD statistics
ND configuration	ND-LAr+TMS, SAND	ND-LAr, ND-GAr, SAND	Systematics

[N. Roe (LBNL) at May 2024 HEPAP subpanel]

More Capable Near Detector (MCND)

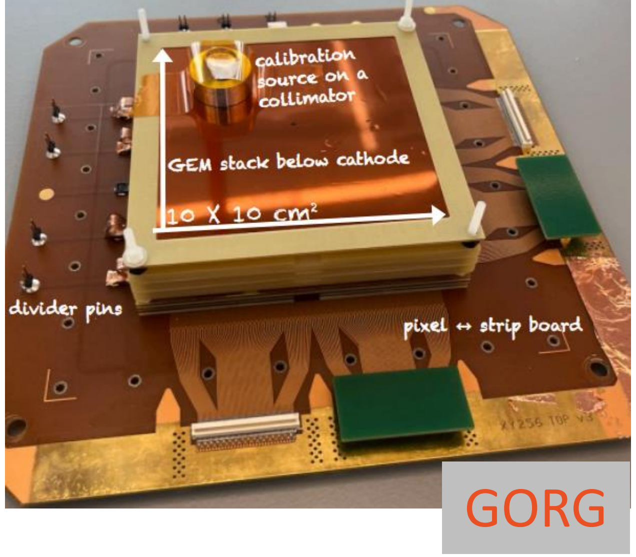
- Cylindrical volume of 5 m linear dimensions filled with gas at 10 bar (~1 ton of Ar)
- Baseline concept includes:
  - Pressurized gaseous argon TPC
  - Surrounding calorimeter
  - Magnet: solenoid with a partial return yoke
  - Muon-tagging system
- Light detection system maybe necessary to reduce pileup, and to provide the event t0 in events that do not reach the calorimeter
- Will move perpendicularly to beam with ND-LAr (DUNE-PRISM concept)

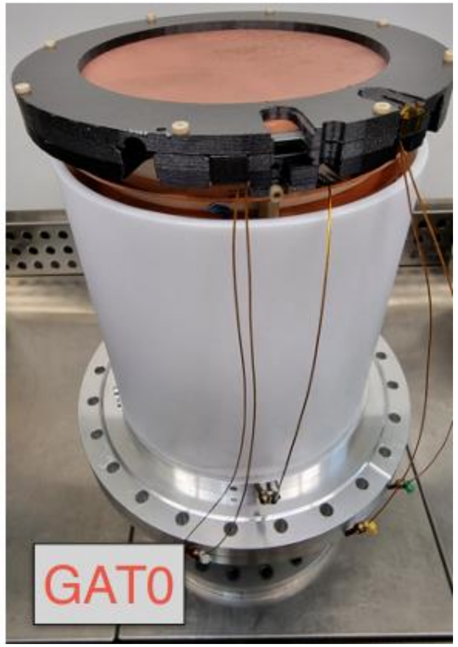




MCND R&D

- GORG (GEMs Over pressurized with Reference Gases) - testing GEMs in high pressure
  - First pressure scans completed
- TOAD (Test stand for Over pressurized Argon Detector) - full electronics Slice Testing of ALICE multi-wire chambers in the Fermilab Test Beam
  - Electronics paper submitted to journal
- Optical TPC Demonstrator GAT0 – investigating the optical gain of TGEMS at high pressure
  - Benchmarks at 1 and 1.5 bar in Ar/CF_4 mixtures





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Phase II Far Detector 3 LArTPC Optimized Readout

Aimed at upgrading nominal vertical drift design to broaden the physics program towards expanded sensitivity for MeV-scale physics

- Energy Deposits in LArTPC
  - Ionization electrons
    - Electrons
      - Improved 2D strip R/O (CRPs)
      - 3D pixel R/O (LArPix, Q-Pix, GAMPix)
    - Photons
      - 3D camera R/O (ARIADNE)
  - Primary scintillation light
    - Photons
      - Field cage X-ARAPUCAs (APEX)
      - PEN + reflectors + SiPMs (PoWER)
      - SiPMs on anode (LightPix, SoLAr)
      - Photo-conductors on anode (Q-Pix-LiLAr)

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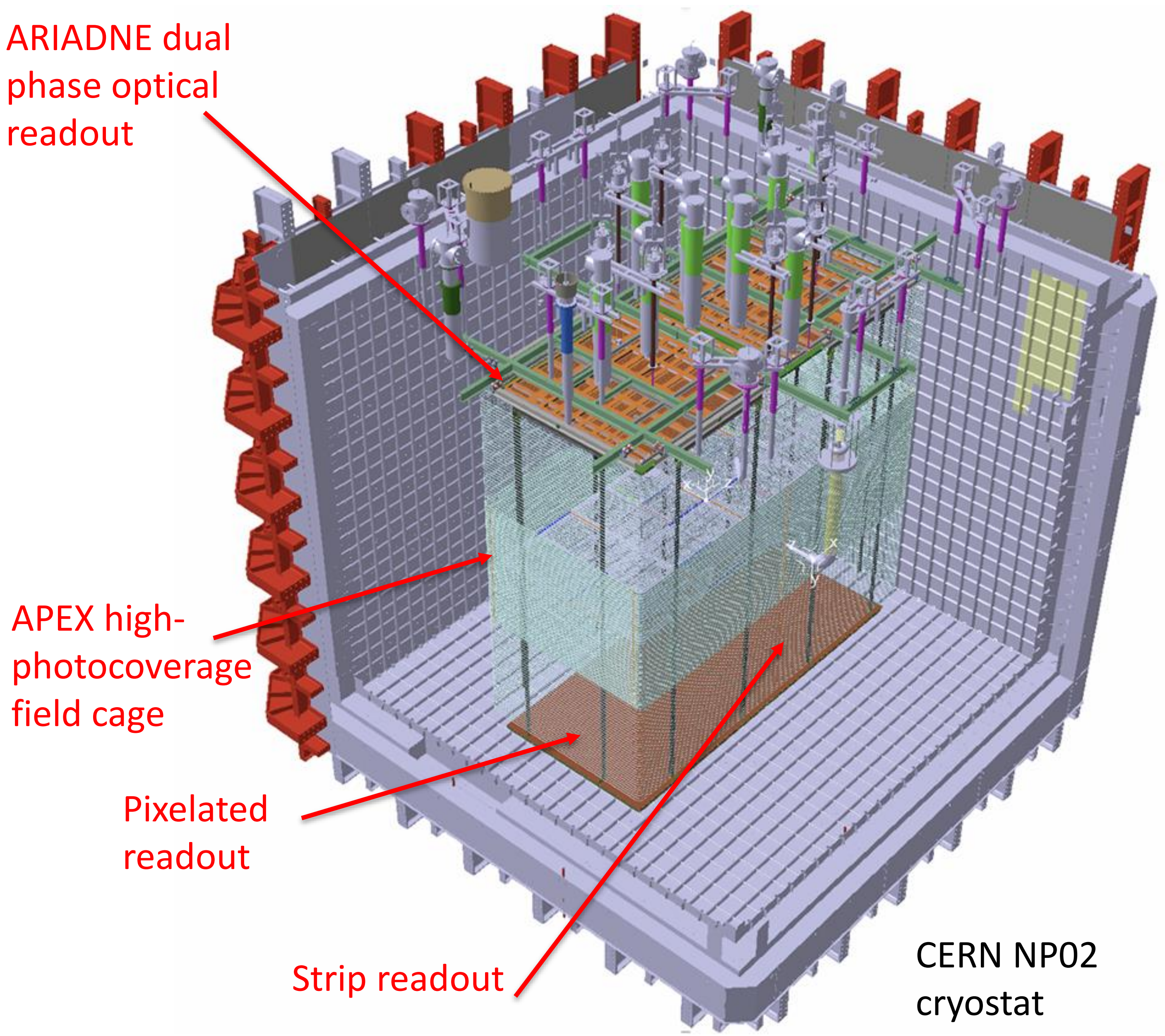
Proposed deployment in ProtoDUNE III

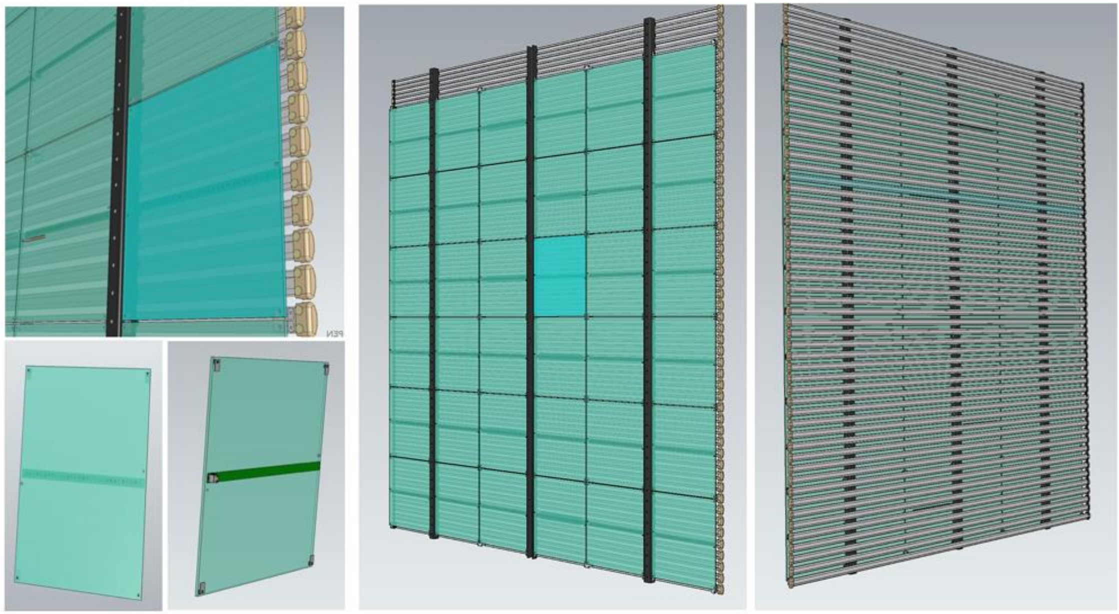
ProtoDUNE III

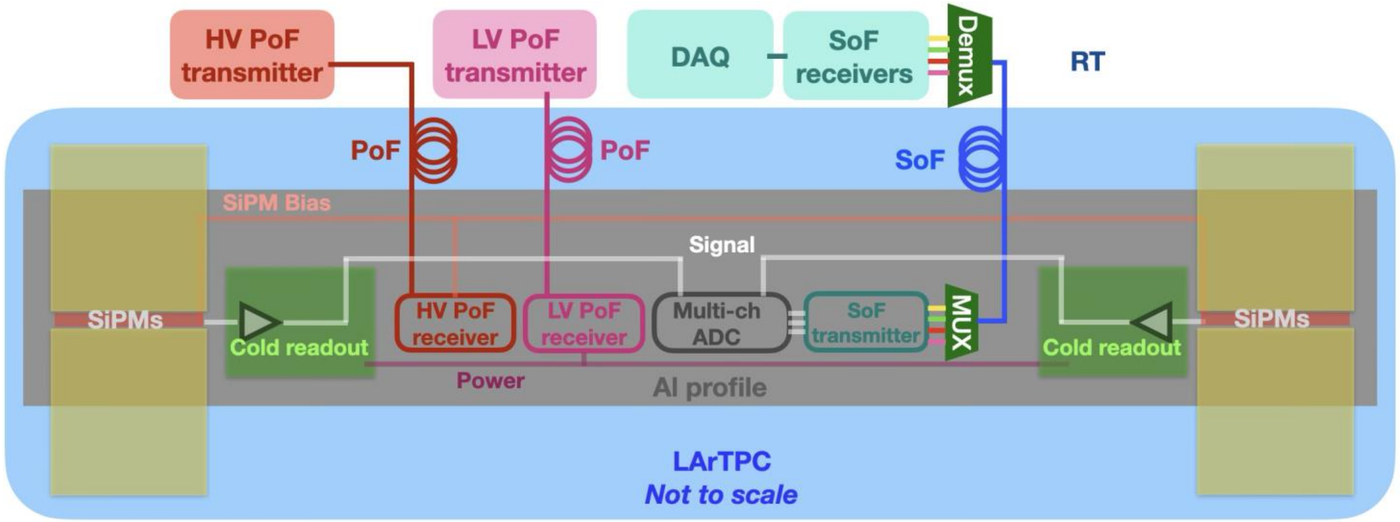
- Large scale engineering prototype for mass production, installation, and integration of Phase II components at full Far Detector dimensions
    - Integrated charge/light readout and associated electronics
    - Upgrades to HV distribution system
    - Possible upgrades to DAQ, calibration sources, and cryogenic instrumentation
- Longitudinal study of operational performance
- Proposed operation in 2028-2029 during CERN SPS accelerator Long Shutdown 3 (LS3)



APEX (Aluminum Profiles with Embedded X-Arapucas)

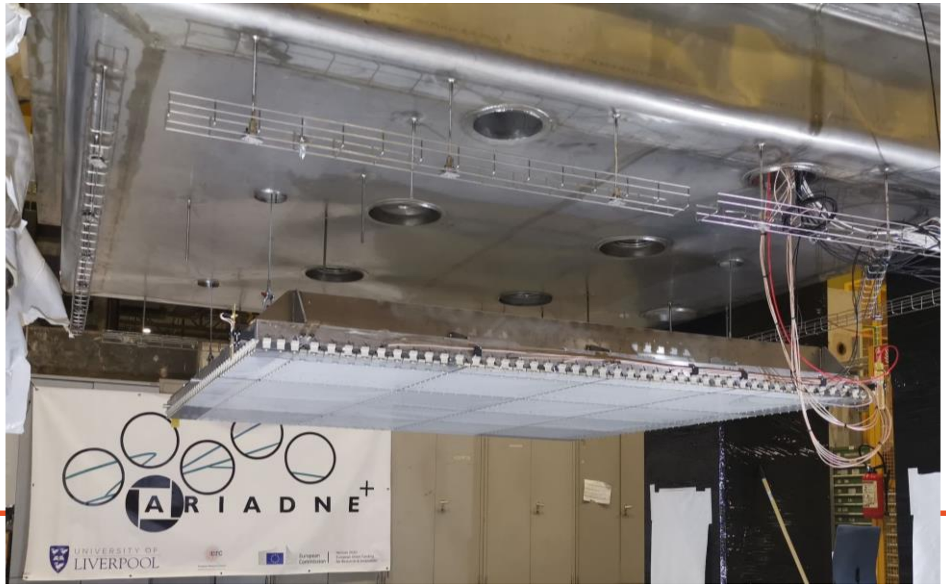
- A fully integrated photon detection system within the TPC field cage
  - Simplified ARAPUCA light trapping technology to increase photon system coverage
  - Expanded Power over Fiber (PoF) & Signal over Fiber (SoF) technologies, adopting digital optical readout
- CERN 2-ton APEX prototyping

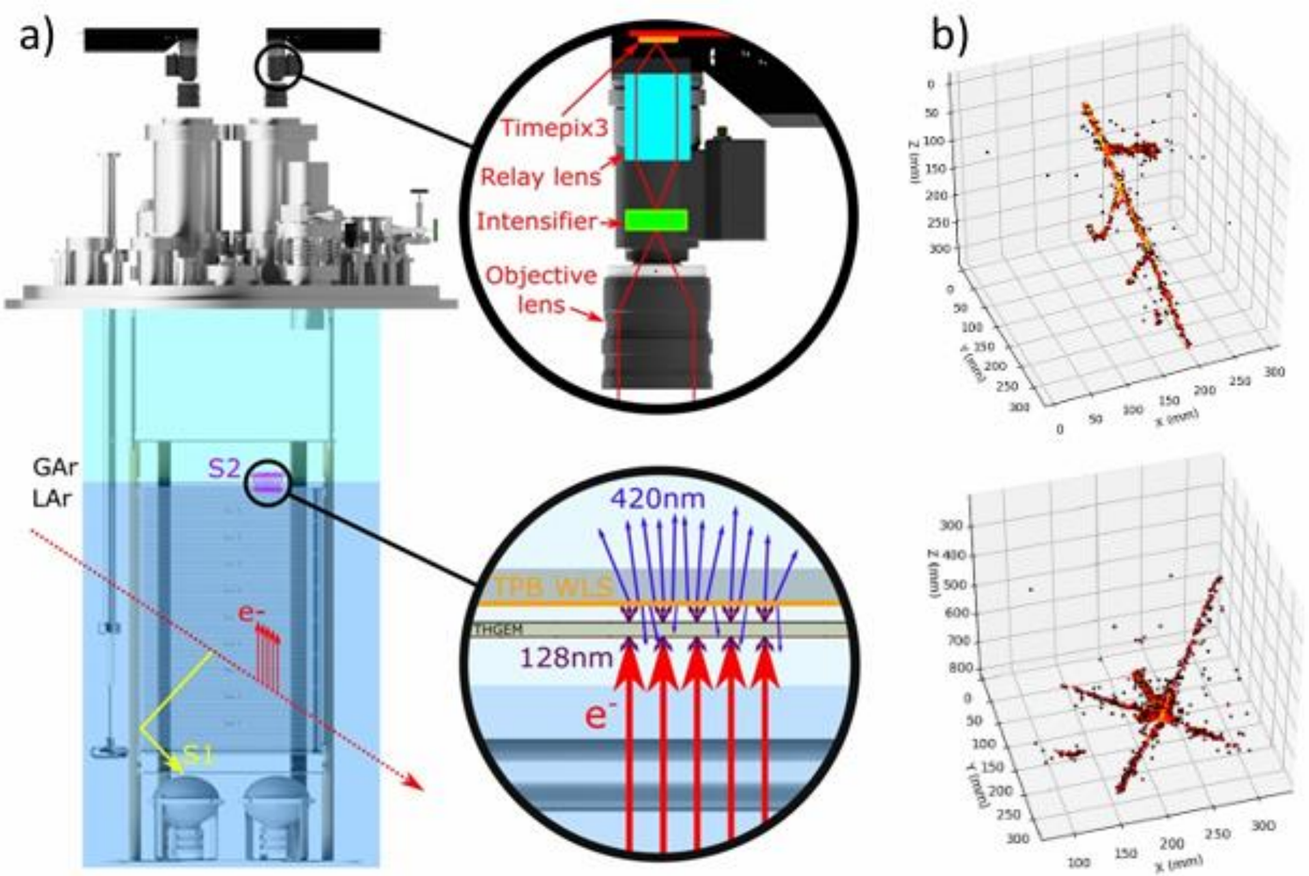




ARIADNE

- Dual-phase optical readout TPC detection principle
  - Secondary scintillation light produced by glass THGEM readout by TimePIX3 cameras
  - Threshold-based continuously streaming readout
    - 1.6 ns ToA resolution
    - 10-bit ToT calorimetry
- Successfully prototyped at the tonne scale
  - 2.3 m x 2.3 m ARIADNE+ LRP imaged cosmic rays in the CERN Cold Box

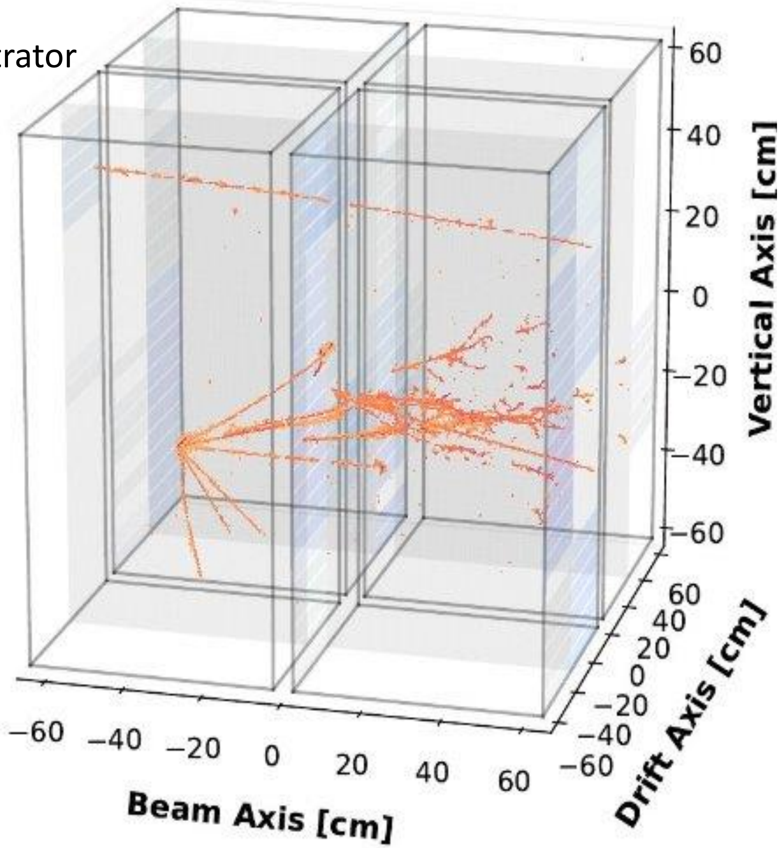


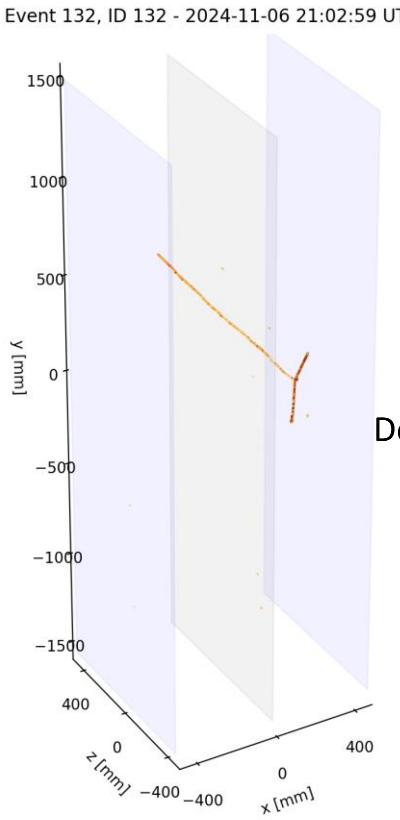


LArPix

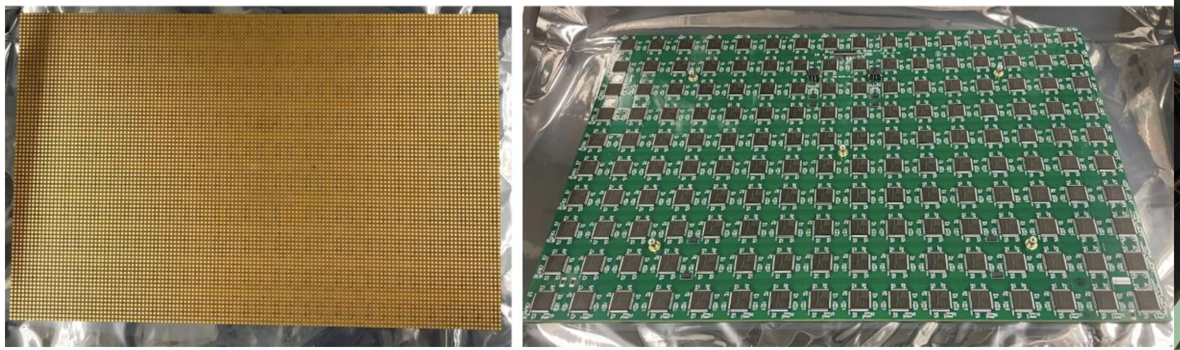
- Pixelated readout system architecture demonstrated in multiple ton-scale detectors at the O(10^5)-channel scale
- Design adaptation for far detector:
  - Multiplex anode tiles to reduce cable plant
  - Pixel data driven over 30 m of cable to warm-side electronics
  - Mechanical interfaces

2x2 Demonstrator





Full-Scale Demonstrator



30 cm x 48 cm LArPix anode tile with 10240 pixels at 3.72 mm pitch

Pixel CRP frame

Grenoble cryotest

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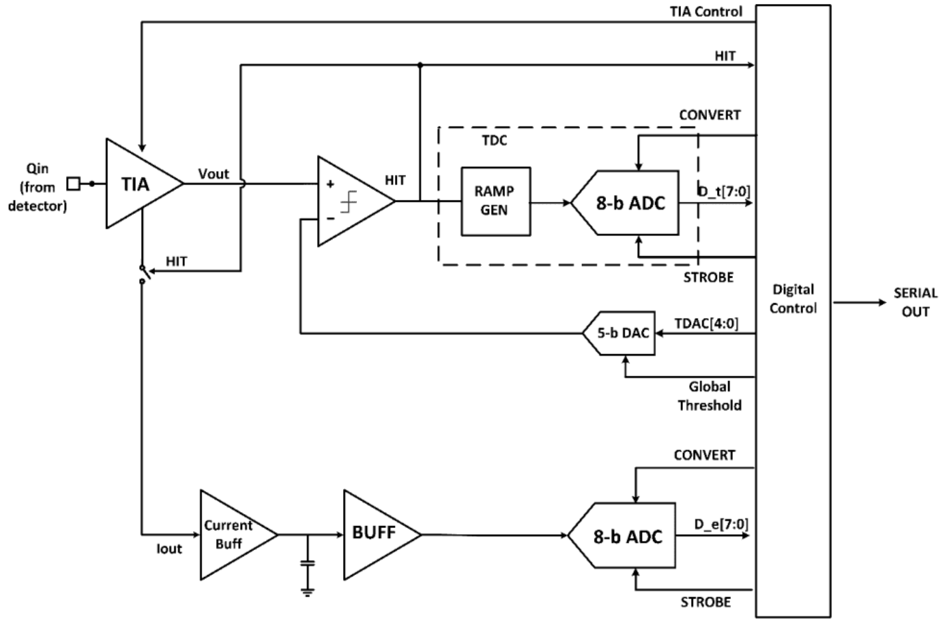
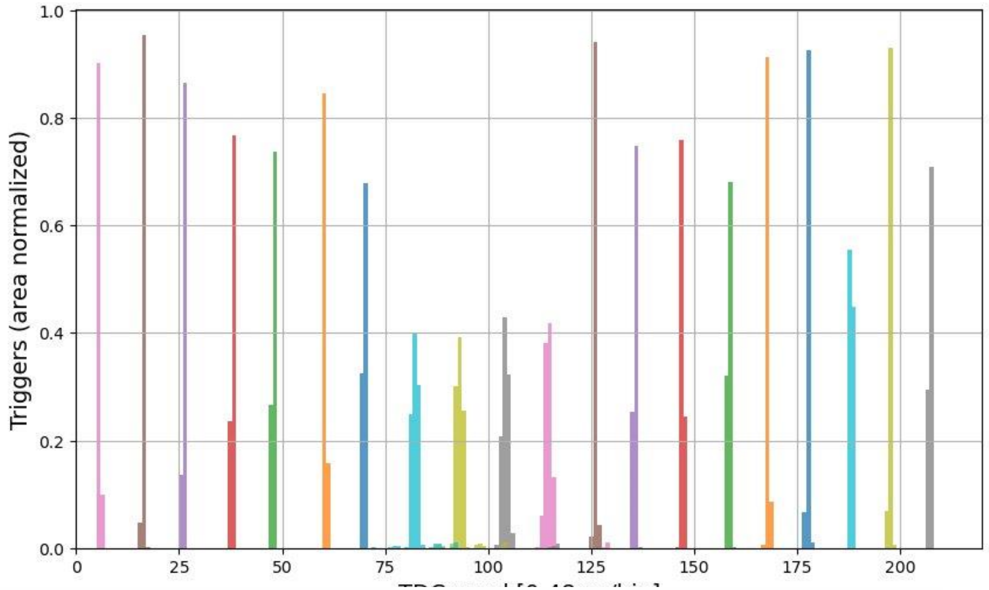
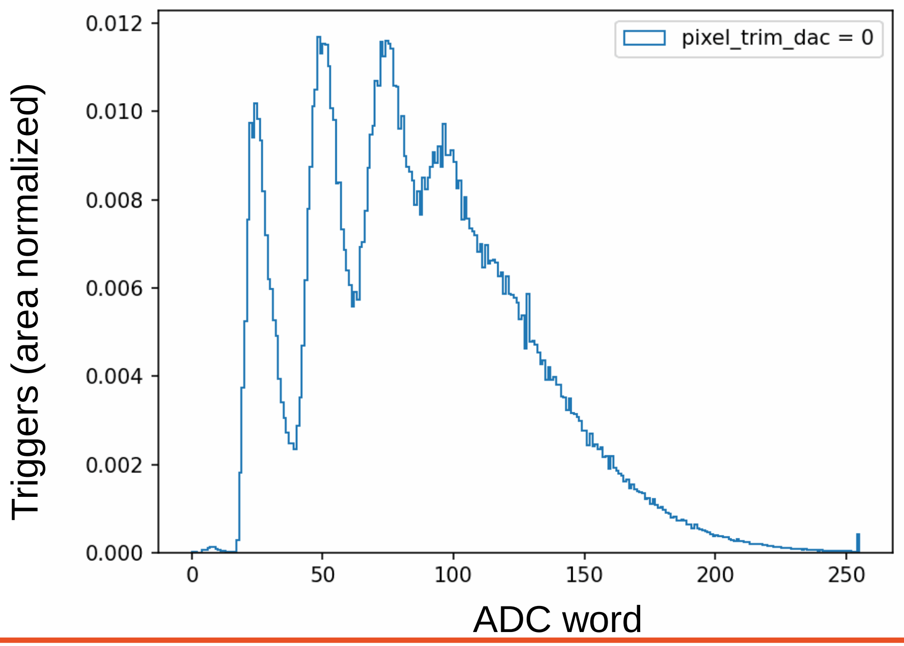
LightPix

- Cryo-compatible 'pixelated' SiPM readout with unique channel for each SiPM
  - 32 "super channels" with sub-ns timing + calorimetry per ASIC
  - Synergistic system architecture with LArPix pixelated charge readout
- Fully differential clock and digital I/O





TDC resolution and linearity < 1 ns



Demonstrated multi-PE discrimination and single-PE self-trigger efficiency

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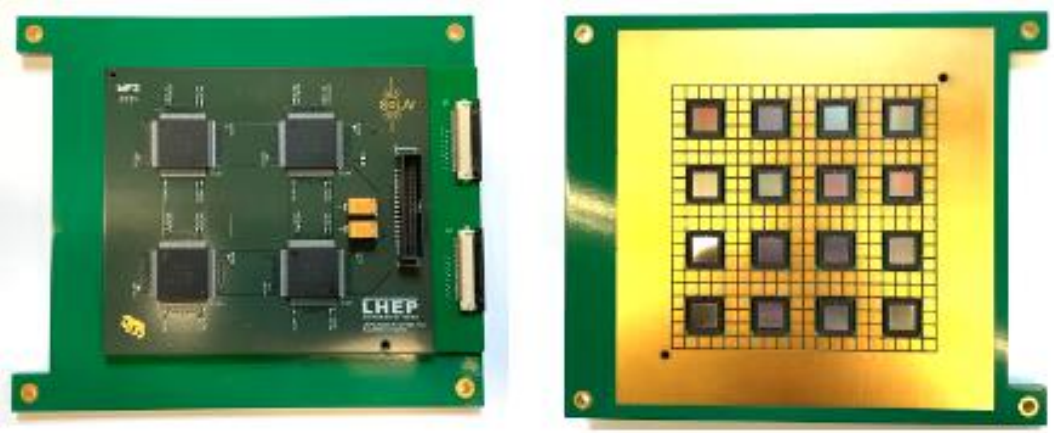
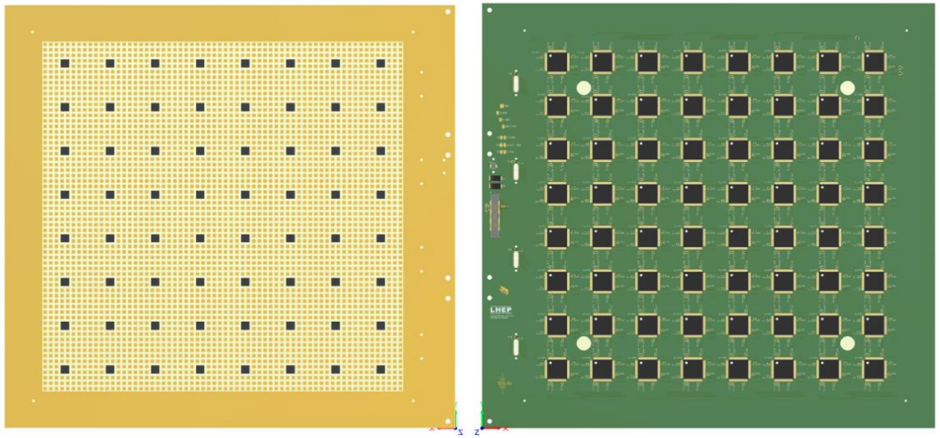
SoLAr

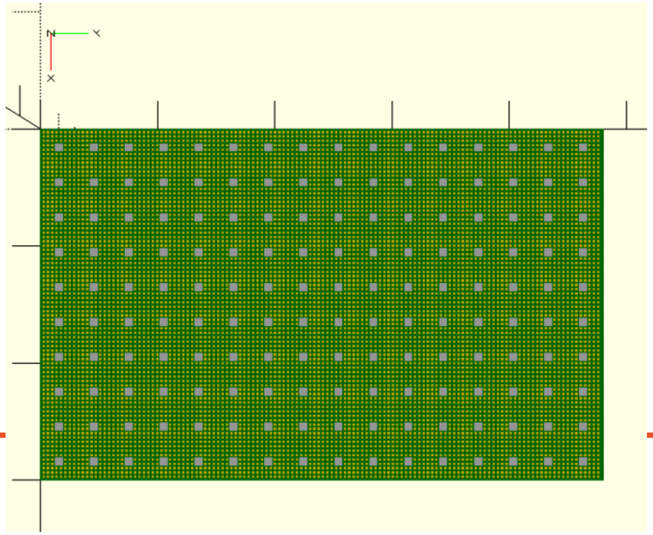
- Combined light+charge calorimetry from the same plane of view (anode) for increased detection of low energy (5-20 MeV) neutrino events
- Distributed array of VUV SiPMs incorporated into pixelated charge readout plane
  - LArPix pixel readout + LightPix SiPM readout
  - LArPix + cryogenic preamplification, warm-side digitization



v1 prototype

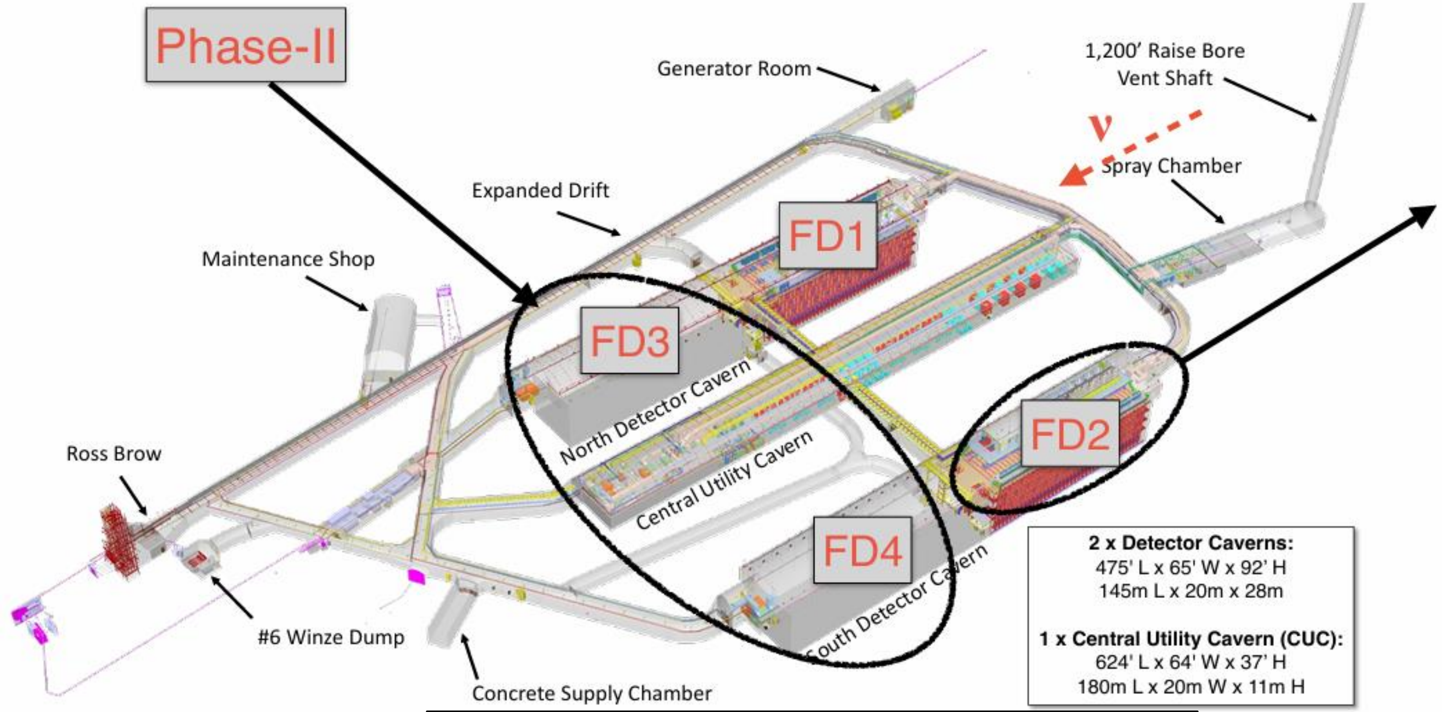


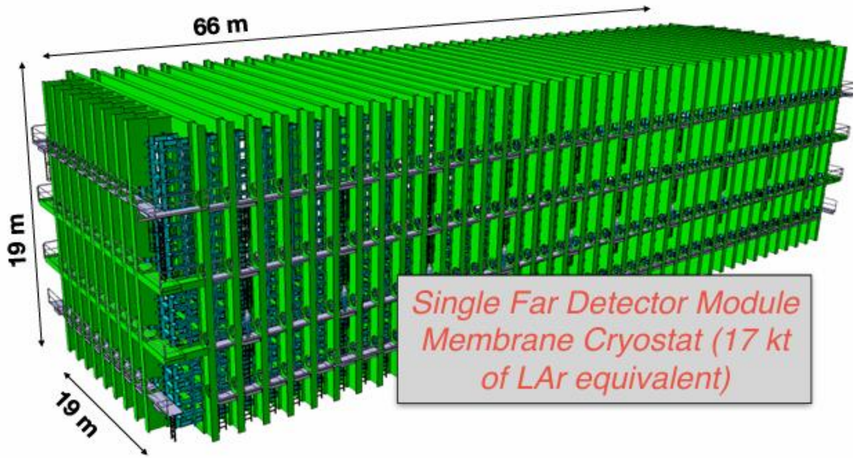
v2 prototype

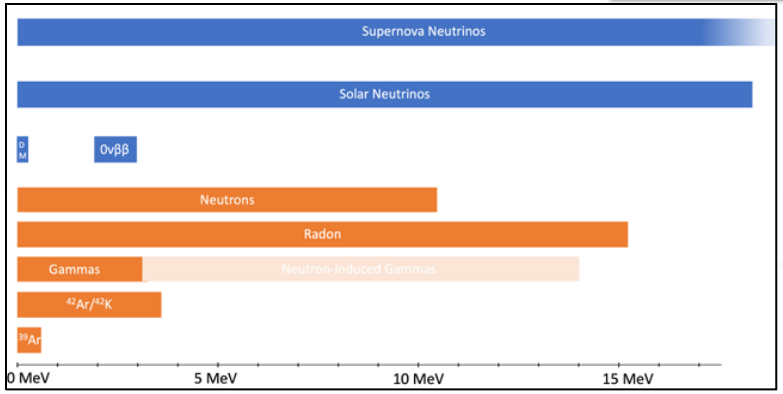


Proposed ProtoDUNE III charge+light integrated anode tile

Phase II Far Detector





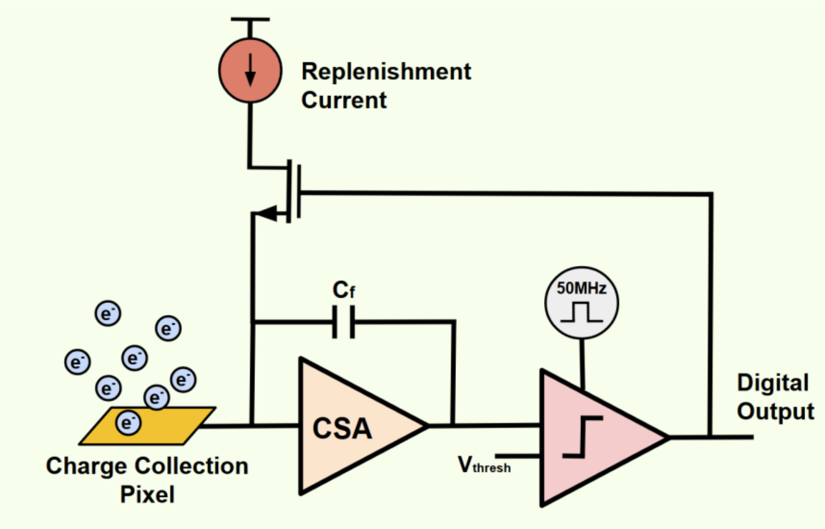


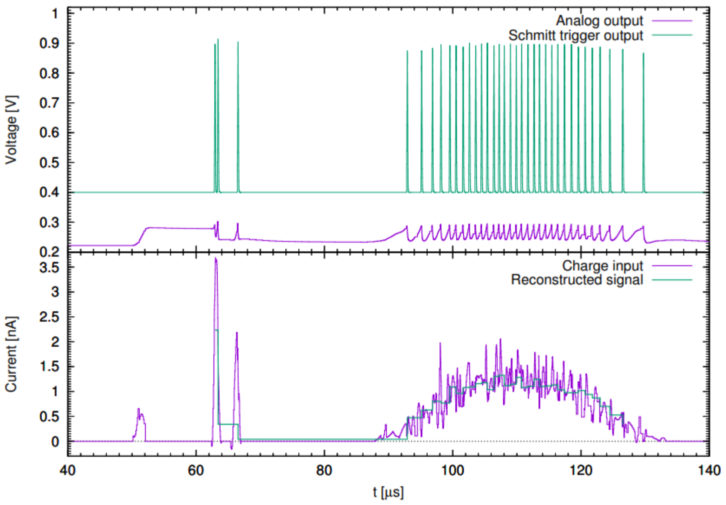
The first three DUNE FD modules will be Liquid Argon Time Projection Chambers (LArTPCs) with 17 kt total mass each

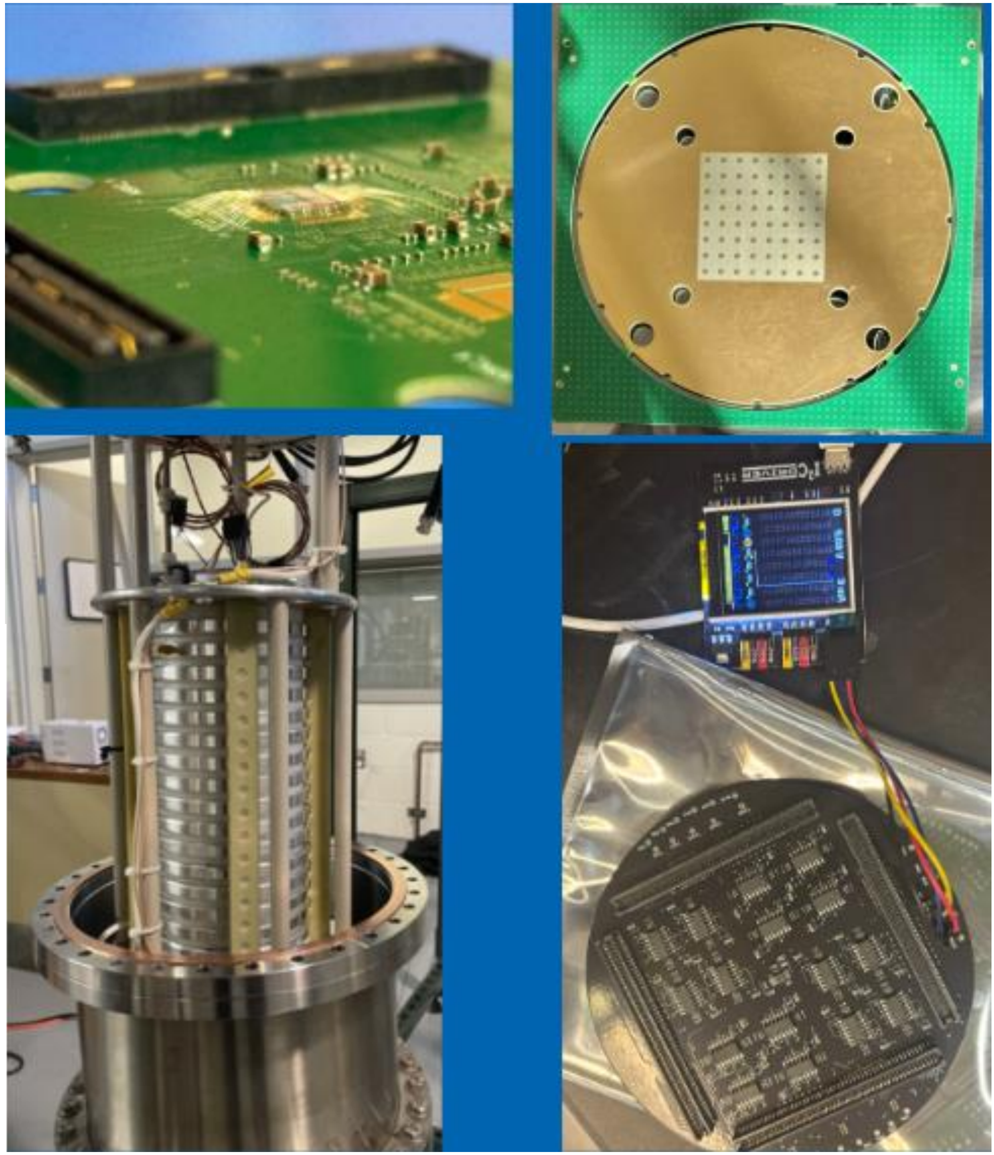
- **FD1**: Horizontal Drift (HD)
- **FD2**: Vertical Drift (VD)
- **FD3**: Improved VD-LArTPC
- **FD4:** Module of opportunity *(both LAr and non-Argon options being explored)*

QPix

- Time to fixed charge measured on pixel sensor
- 16-channel analog front-end chip characterized and deployed in a 64-channel TPC

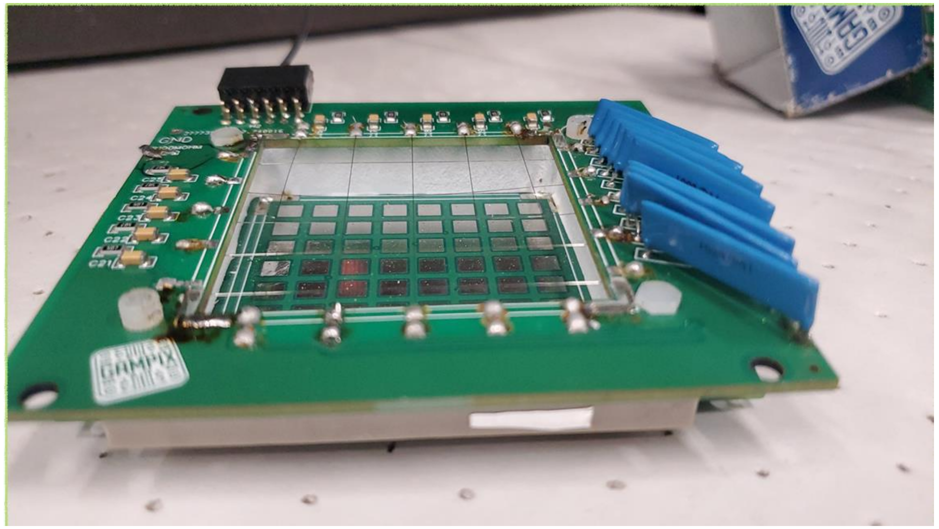


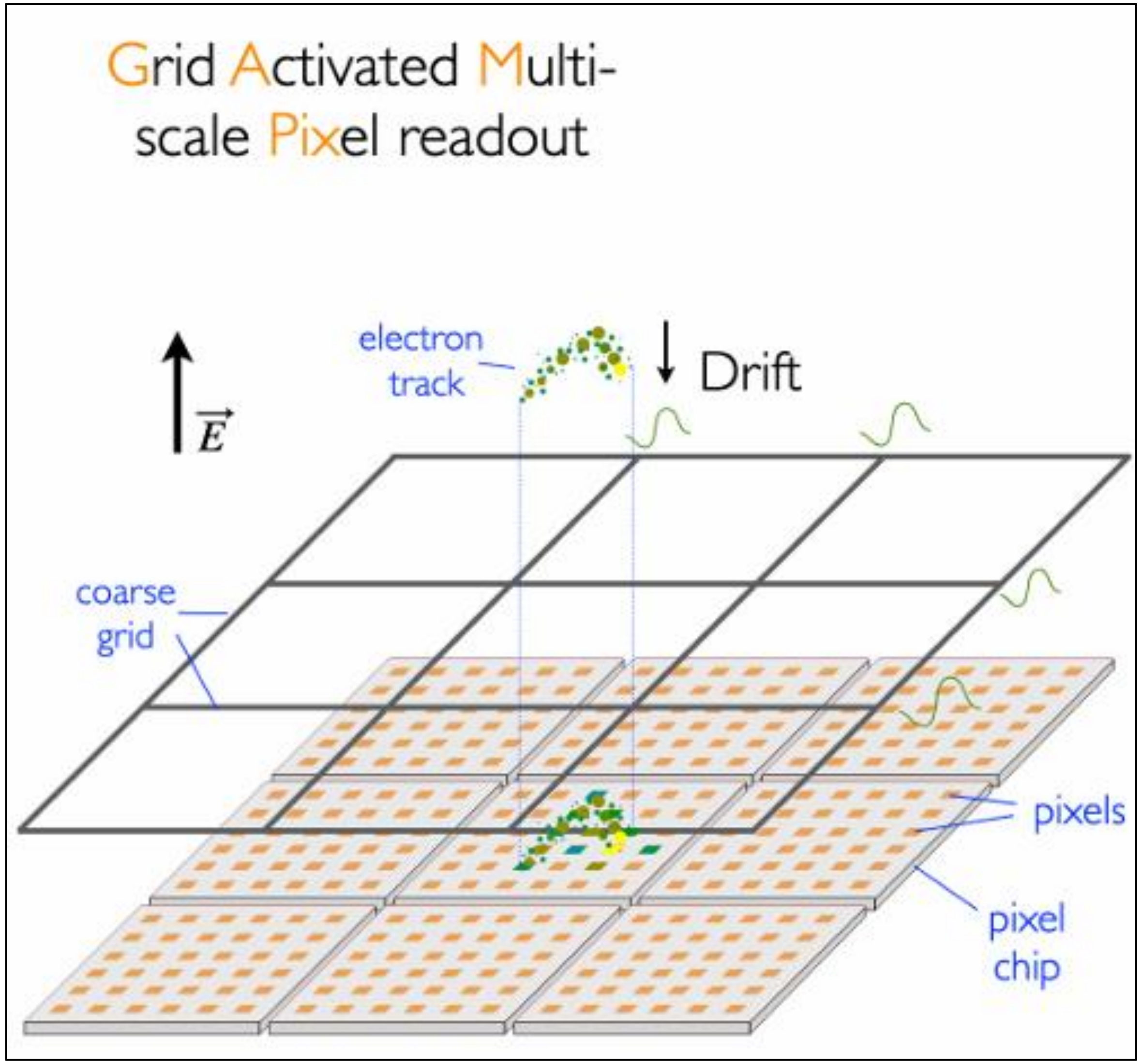




GamPix

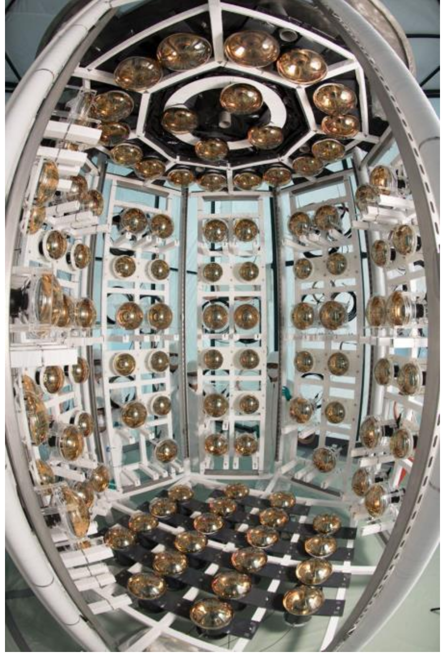
- Power up pixels in <1 µs when triggered by coarse grid
- 64-channel prototype in hand
  - 10-bit ADC
  - Full pixel ENC: ~40 e-
  - Power dissipation:
    - On: ~0.22 mW/pixel
    - Off: ~280 nW/pixel



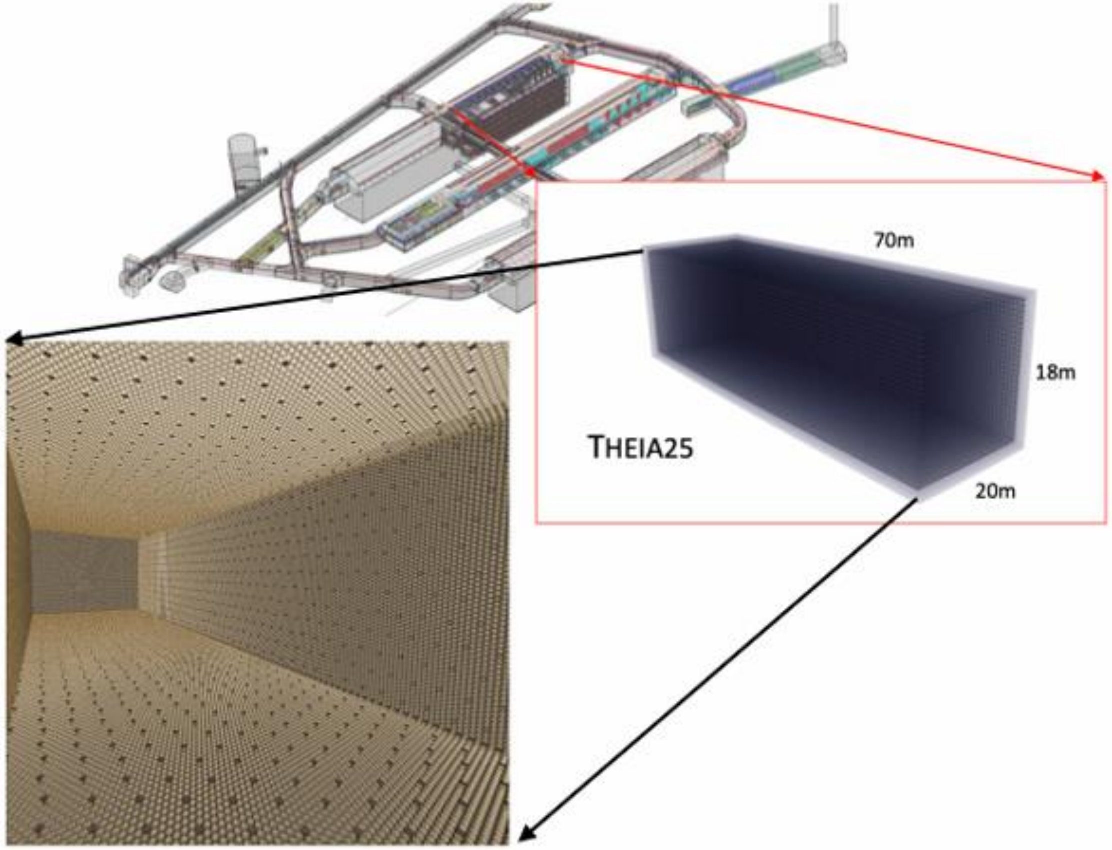


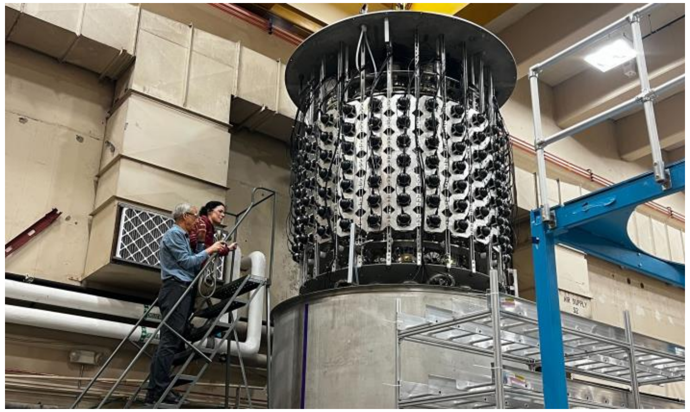
Theia

- WbLS with fast photon detectors and dichroic filters
  - Hybrid optical technology for Cherenkov-scintillation light separation
- Prototypes from existing large detectors (30-ton at BNL, EOS at Berkeley, ANNIE at FNAL, BUTTON at Boulby) demonstrate the conceptual feasibility
- Prototypes underway will demonstrate the full range of capabilities

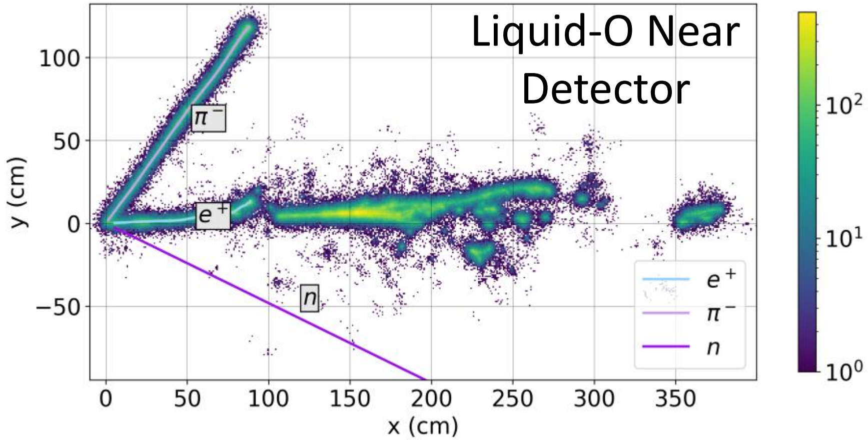


ANNIE at FNAL





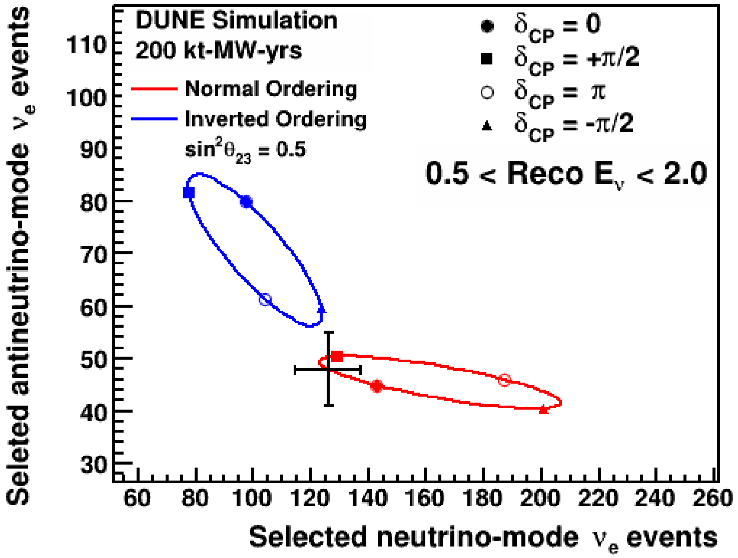
EOS at UC Berkeley

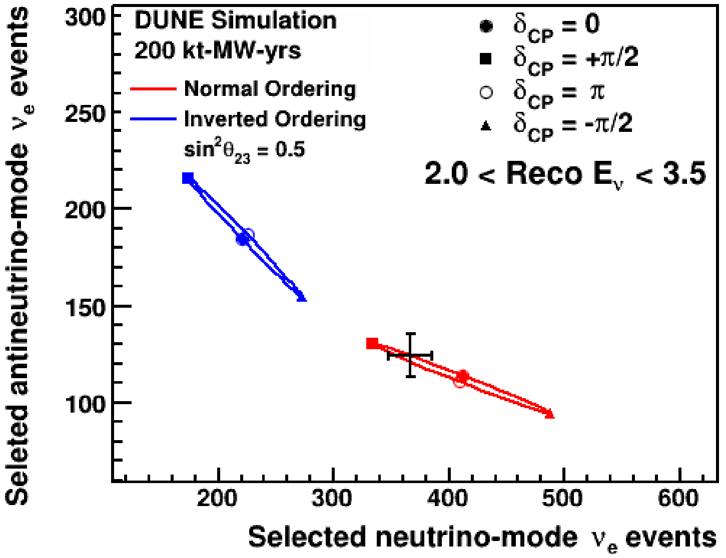


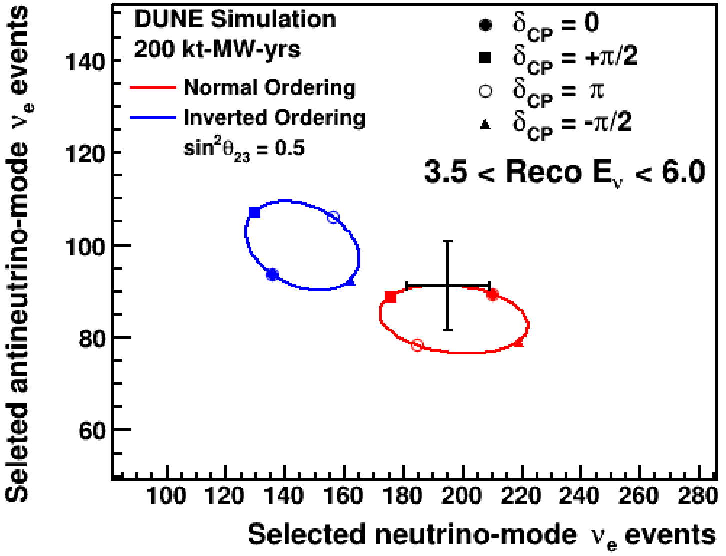
Summary

- Phase II is essential to realize DUNE's full physics potential
  - Strongly endorsed by 2023 US P5 and European Strategy for Particle Physics
  - DUNE Phase II near term plan: A. Abed Abud et al 2024 JINST 19 P12005
- Global R&D collaborations (CPAD RDCs & ECFA DRDs) have been critical to driving the maturation of DUNE Phase II R&D, with several active DUNE R&D discussed at this meeting
- DUNE timeline
  - Phase I is in construction
  - First data from far detector anticipated in 2029
  - Phase II technically-limited schedule, to follow immediately after Phase I

Sensitivity to new physics in neutrino oscillations







- DUNE's wideband spectrum is key to resolving all neutrino mixing parameters at once
  - Can measure oscillation parameters at each bin of L/E
  - Data should prefer the same point in every bin if the 3-flavor PMNS picture is correct
- DUNE is sensitive to small deviations in 3-flavor mixing particularly as a function of L/E

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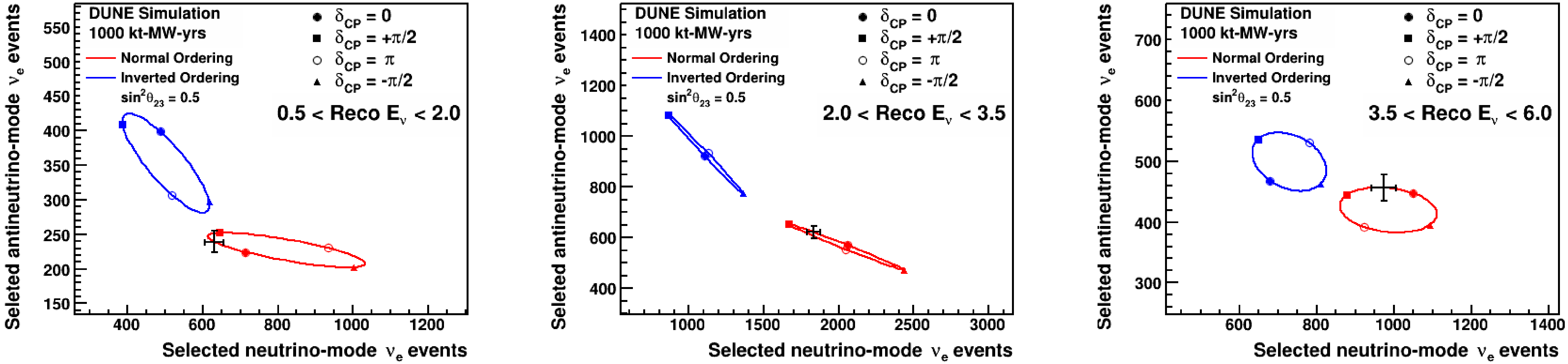

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