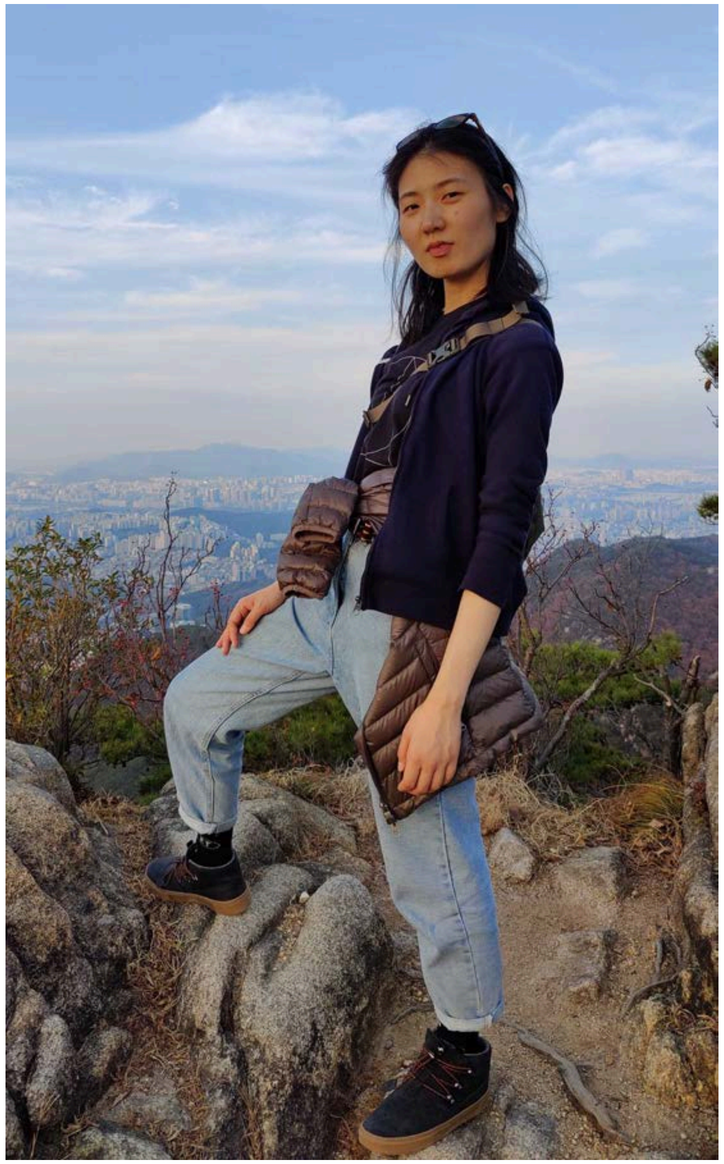
DUNE: Instrumentation, Development and Sensitivity



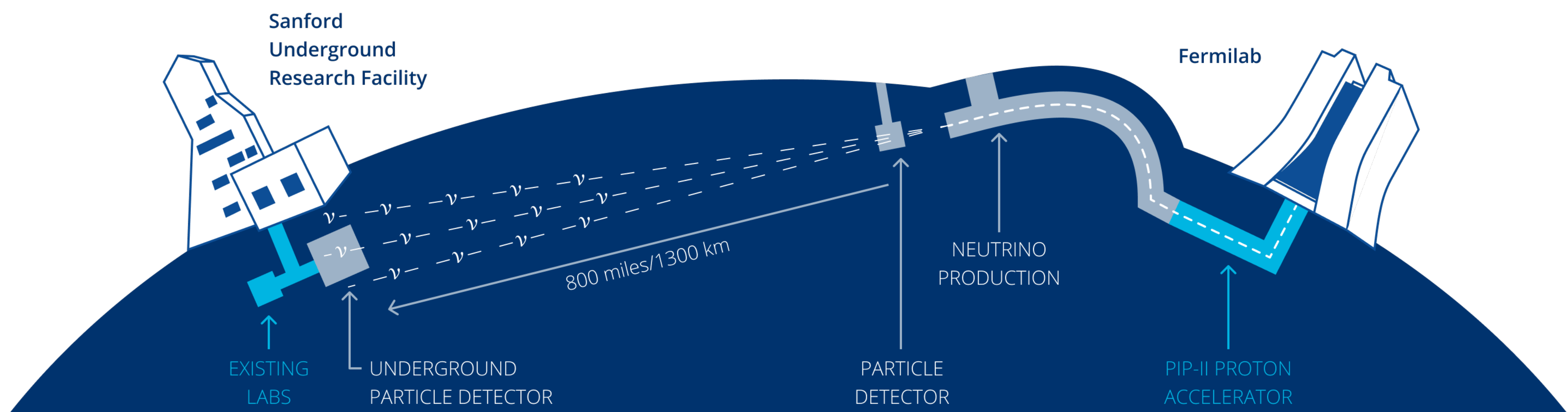
Yifan Chen
SLAC, Stanford University

University of Tokyo
28th March 2024

Future Neutrino Experiments

Mega Pool and 

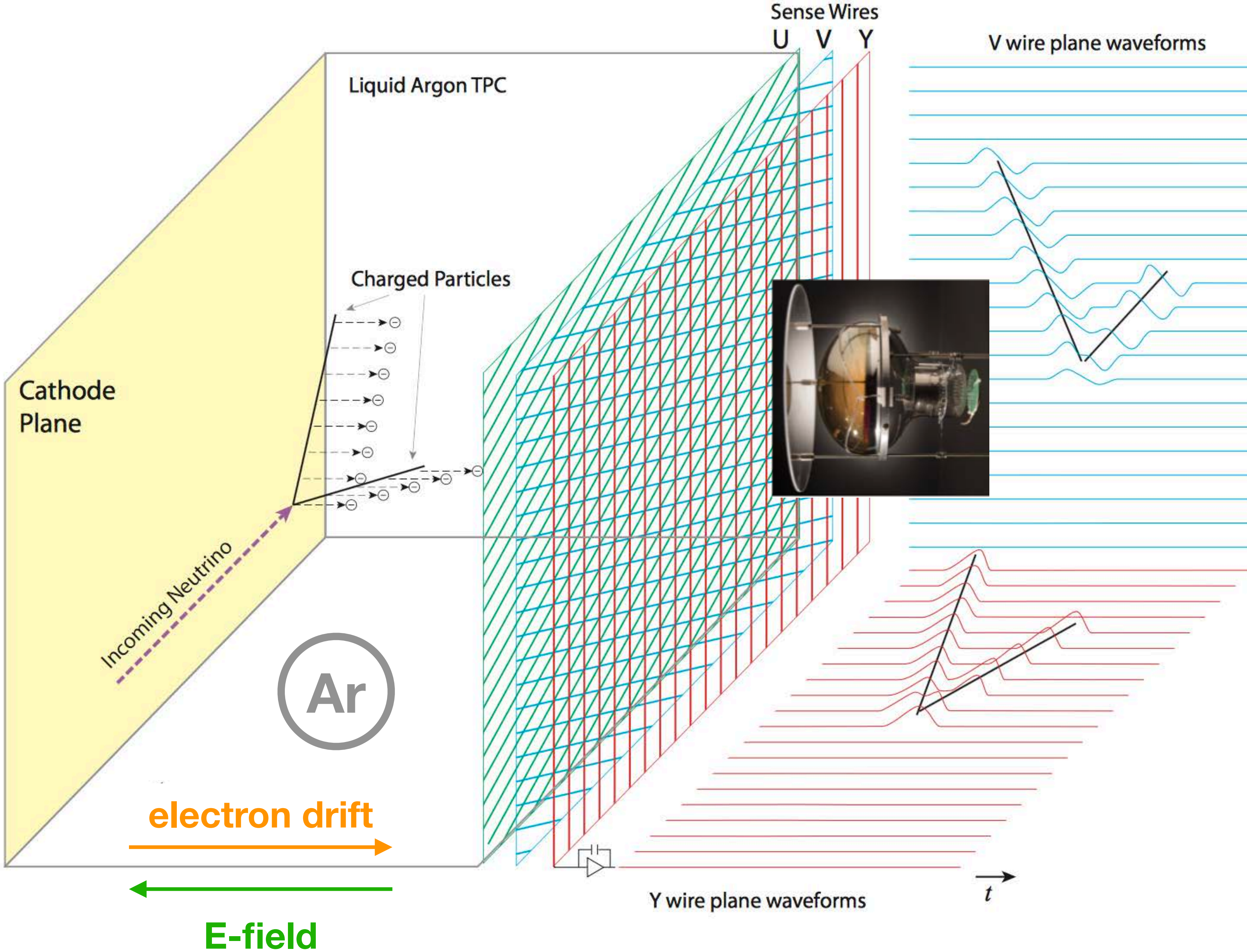
A massive international collaboration (~1500 collaborators)
A next-generation flagship neutrino experiment
An accelerator-based neutrino oscillation experiment, and more



Liquid Argon Time Projection Chamber (LArTPC)

Primary detector technology for DUNE
Record neutrino interaction products

- **Charge:**
  - Charged particles ionize LAr
  - Ionization electrons drift to the anode plane along the electric field
  - 3D tracking and calorimetry
- **Light:**
  - 128 nm UV photons produced by de-excitation of LAr excimer
  - LAr is transparent to its own scintillation
  - Scintillation light can help identify the interaction time
  - Light detection system O(μs) vs. Charge readout O(ms)



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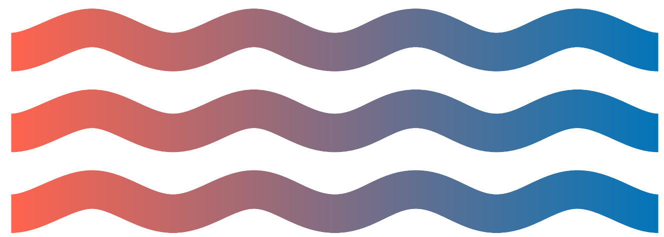
Neutrino Oscillation

Oscillation probability $P_{\nu_\alpha \to \nu_\beta}(L, E)$

ν_μ  ν_e

Neutrino Mixing

Neutrino flavour eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino mass eigenstates

Neutrino Mass Splitting

$$P_{\nu_\alpha \to \nu_\beta, \alpha \neq \beta} = \sin^2(2\theta) \sin^2(1.27 \frac{\Delta m^2 L}{E})$$

2015 Nobel Prize

Super-Kamiokande
SNO

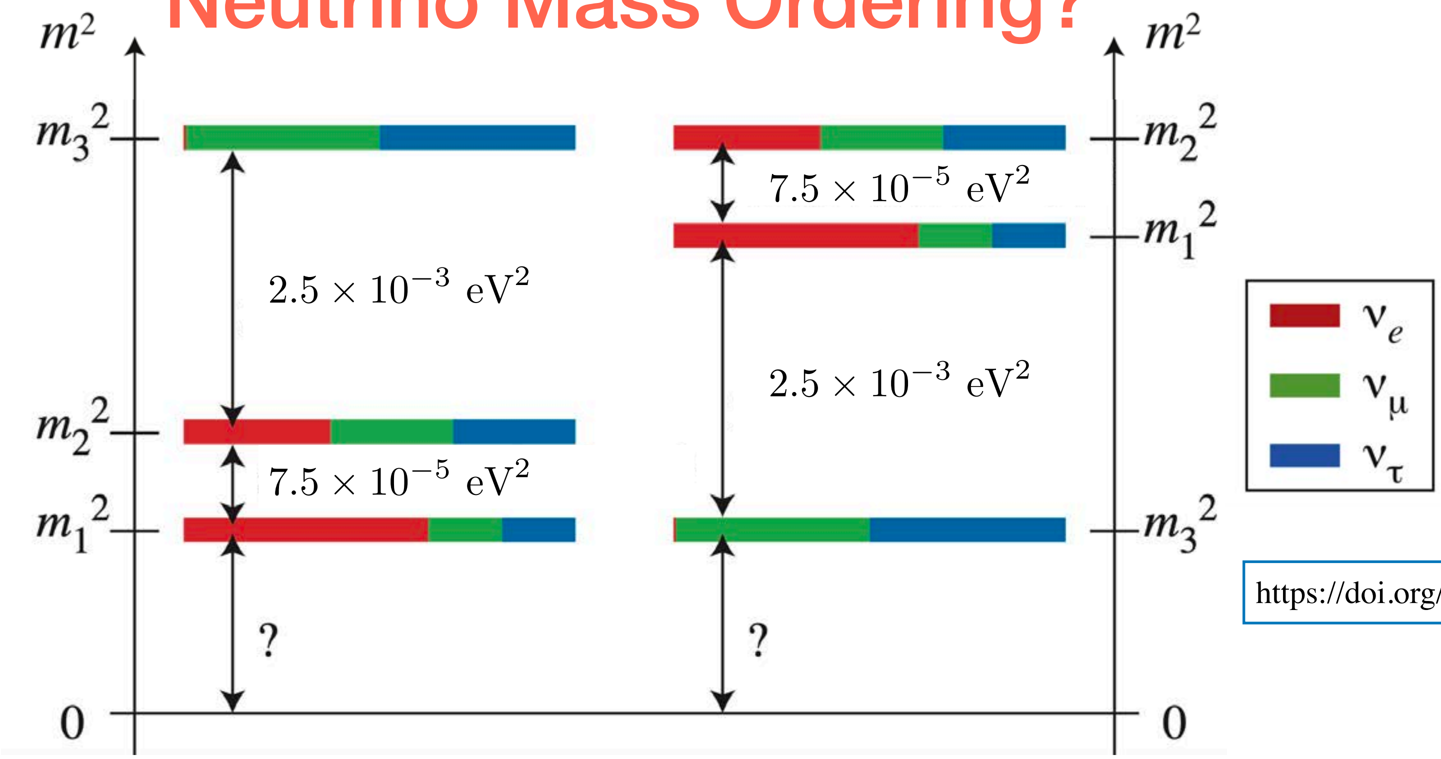
- **Non-zero neutrino mass**
- **Nature of neutrino mixing**

Open Questions for Neutrinos

- Neutrino Mass ordering
- Charge-parity (CP) violation in the lepton sector
- Are there more than three neutrinos?
- Unitarity of PMNS matrix
- What are the neutrino masses?
- Are neutrinos Dirac or Majorana? $\nu = \bar{\nu}?$
- …

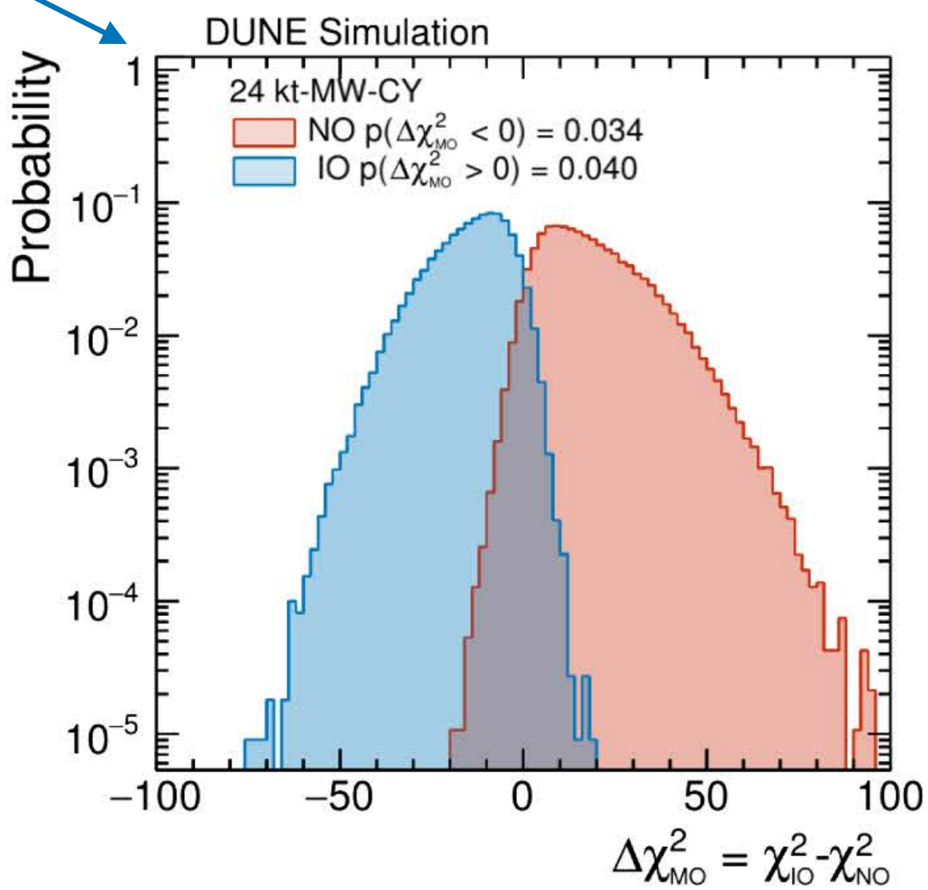
DUNE Neutrino Oscillation Physics Sensitivity 1

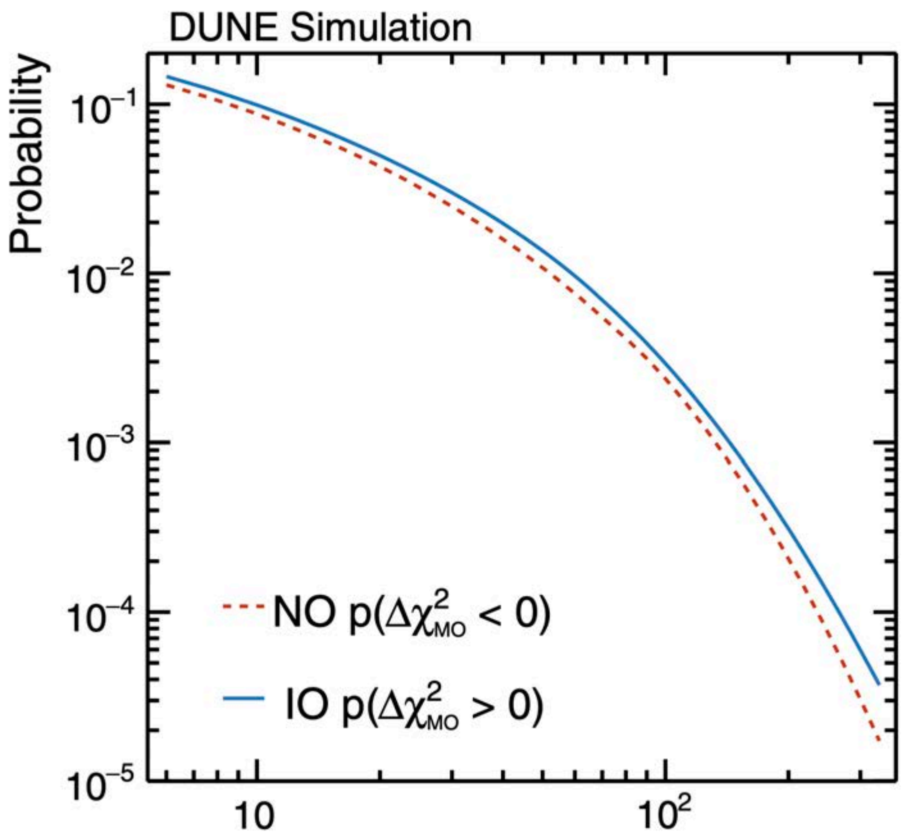
Neutrino Mass Ordering?



https://doi.org/10.1016/j.ppnp.2017.01.003

One year of data





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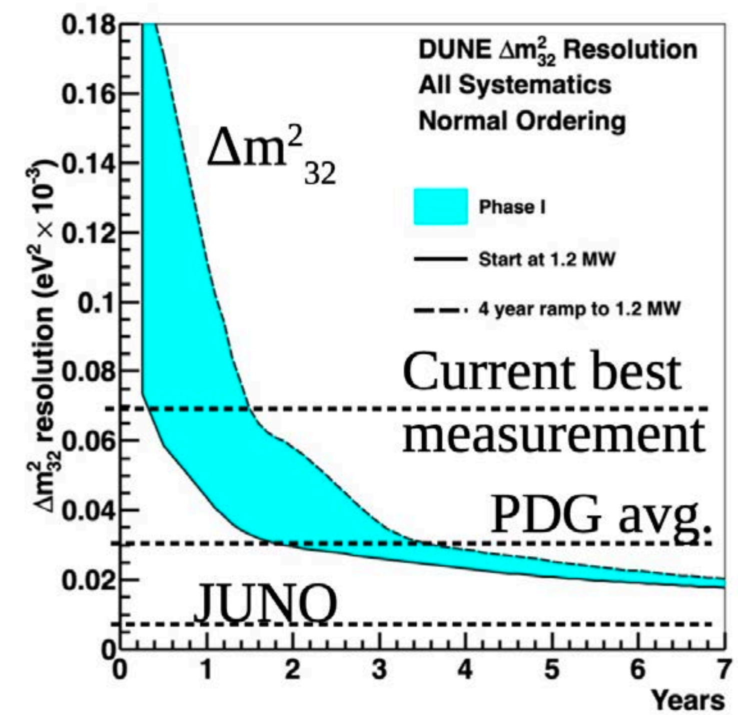
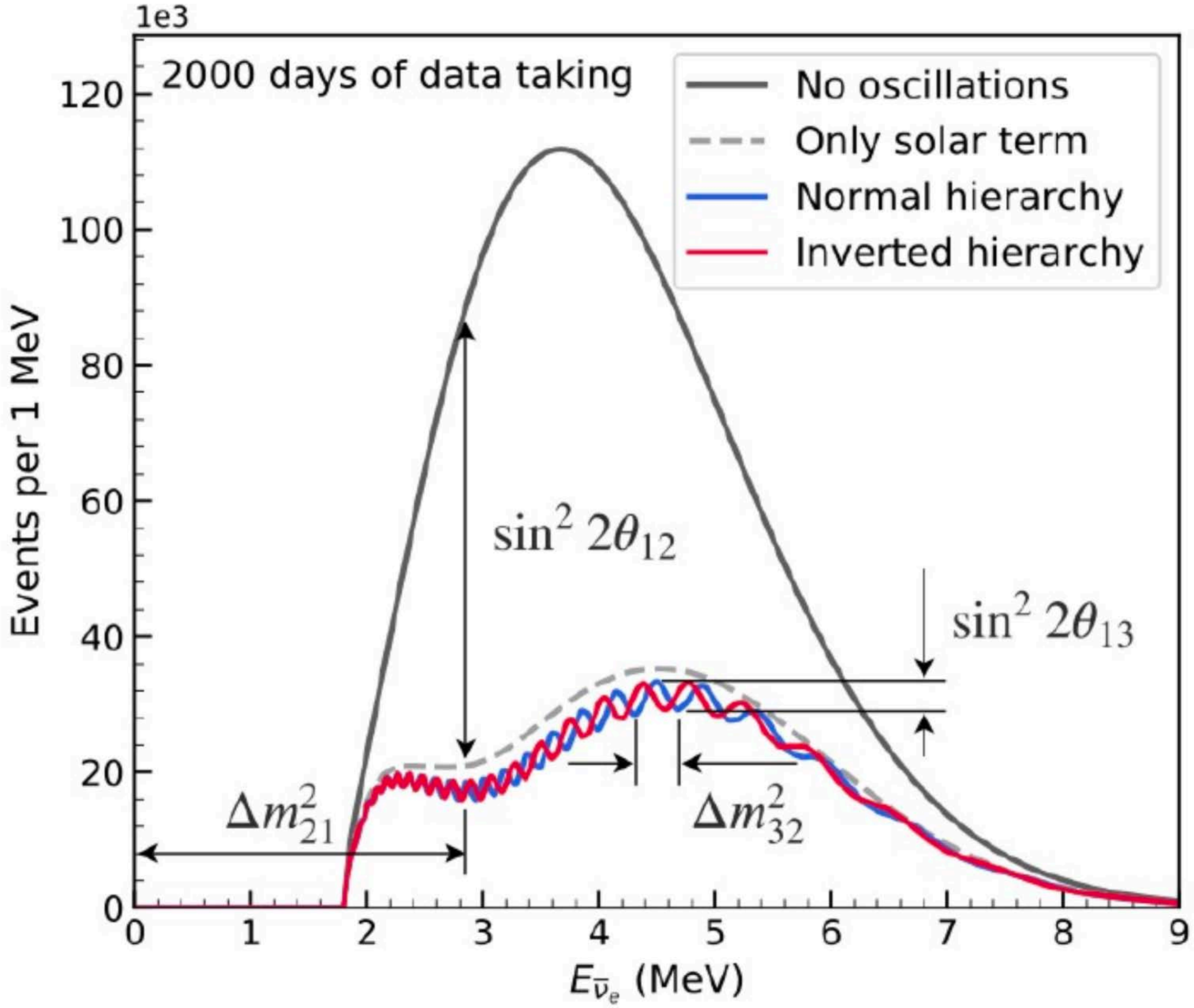
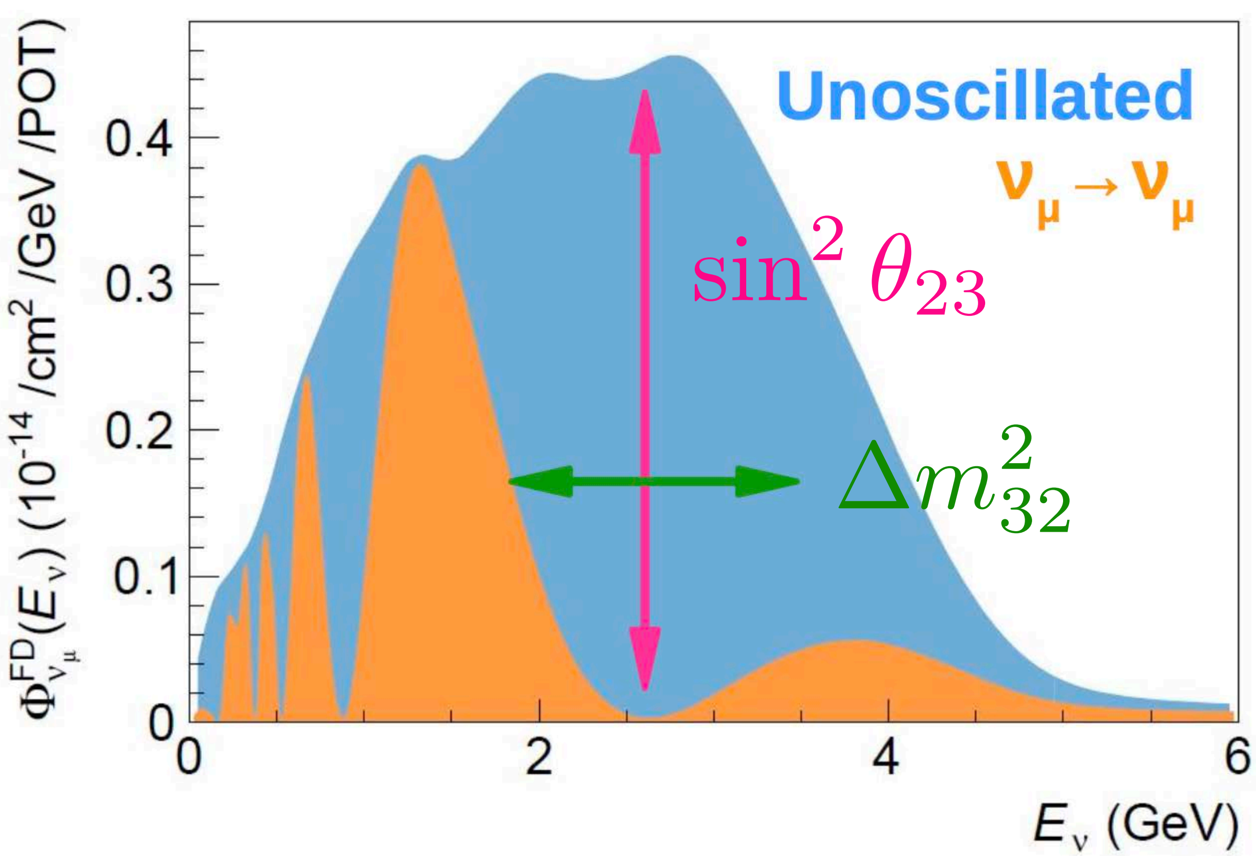
Synergy with JUNO

- JUNO measures frequency with precision of ~0.2%
- DUNE can achieve ~1% precision
- DUNE is not sensitive to other oscillation parameter values
- Sensitive to new physics by comparing few MeV $\overline{\nu}_e$ and few GeV ν_μ







DUNE Neutrino Oscillation Physics Sensitivity 2

Matter-Antimatter Asymmetry: CP Violation?

$$\delta \neq 0, \pi?$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)?$$

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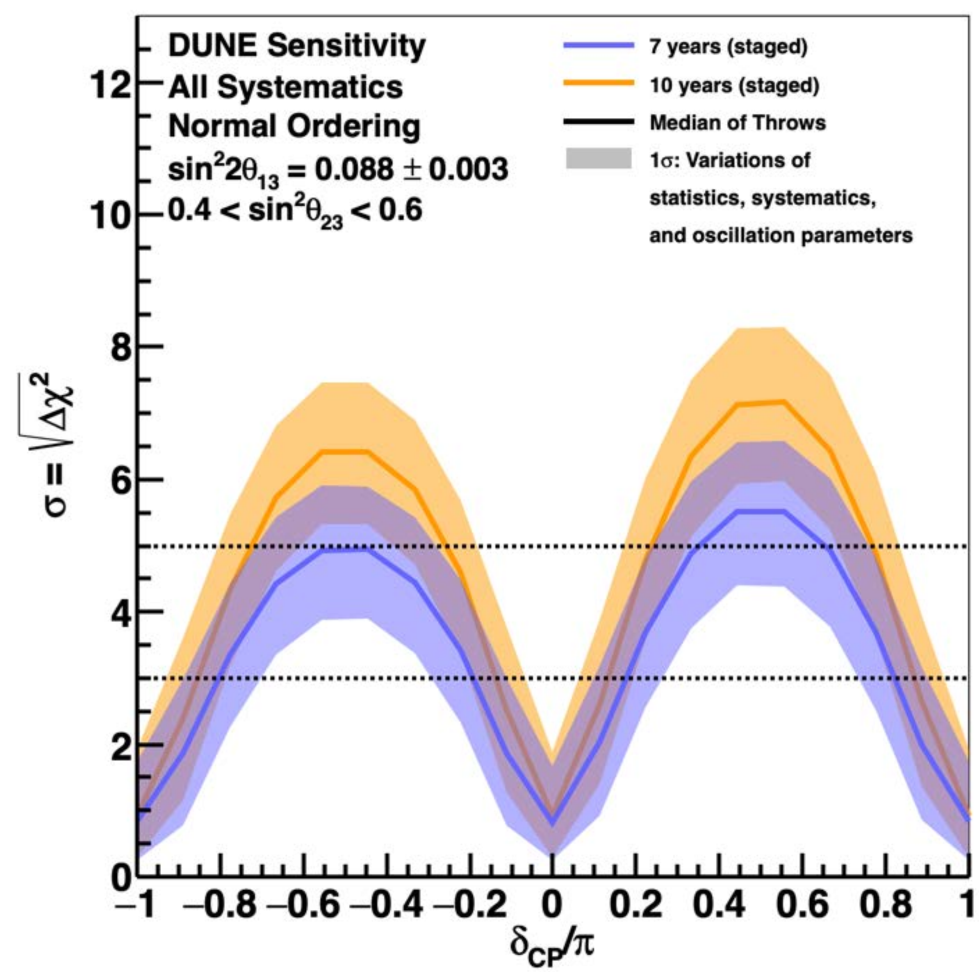
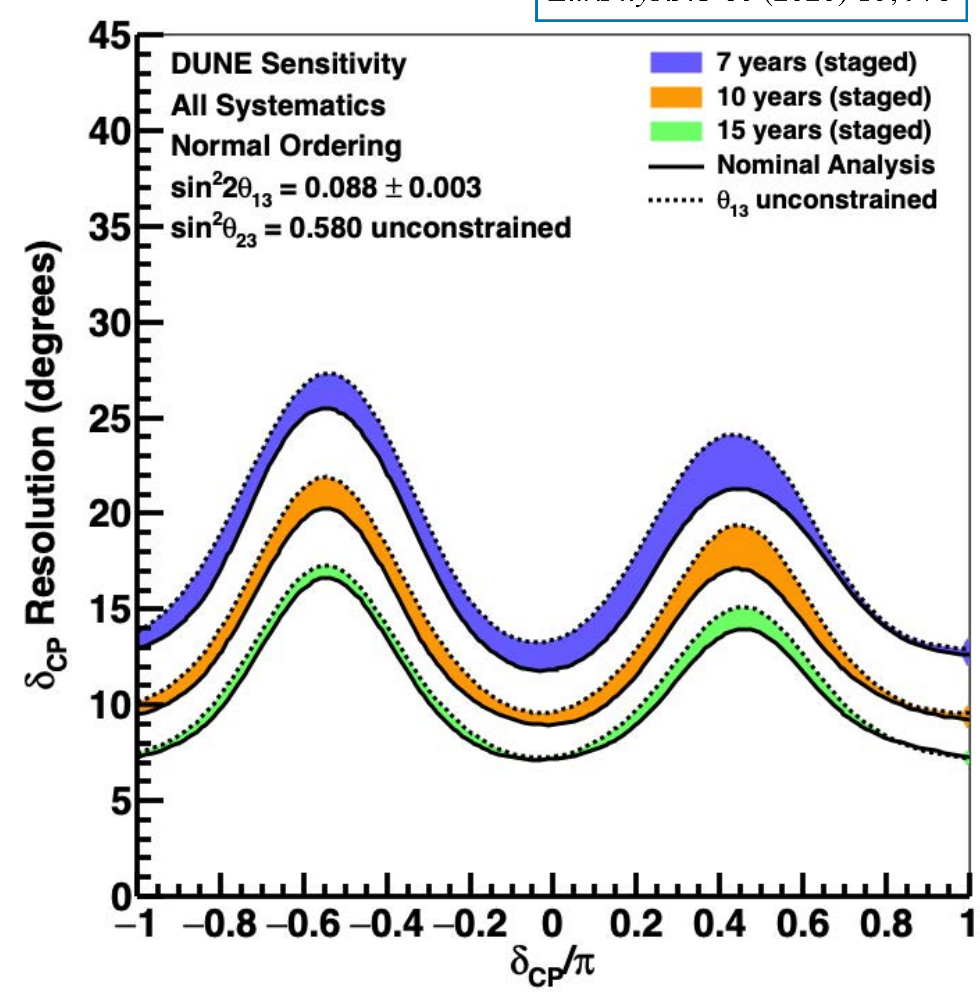
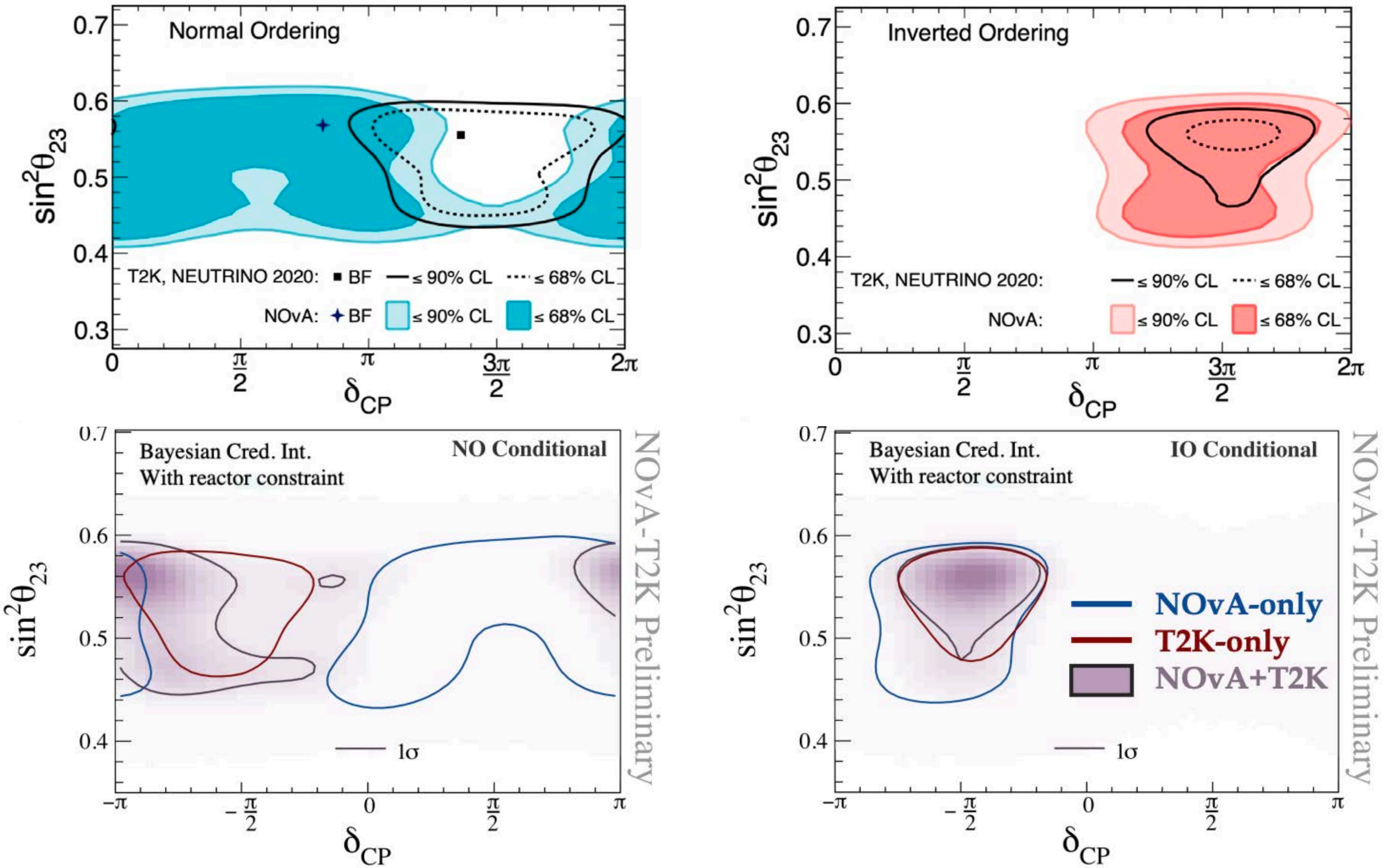




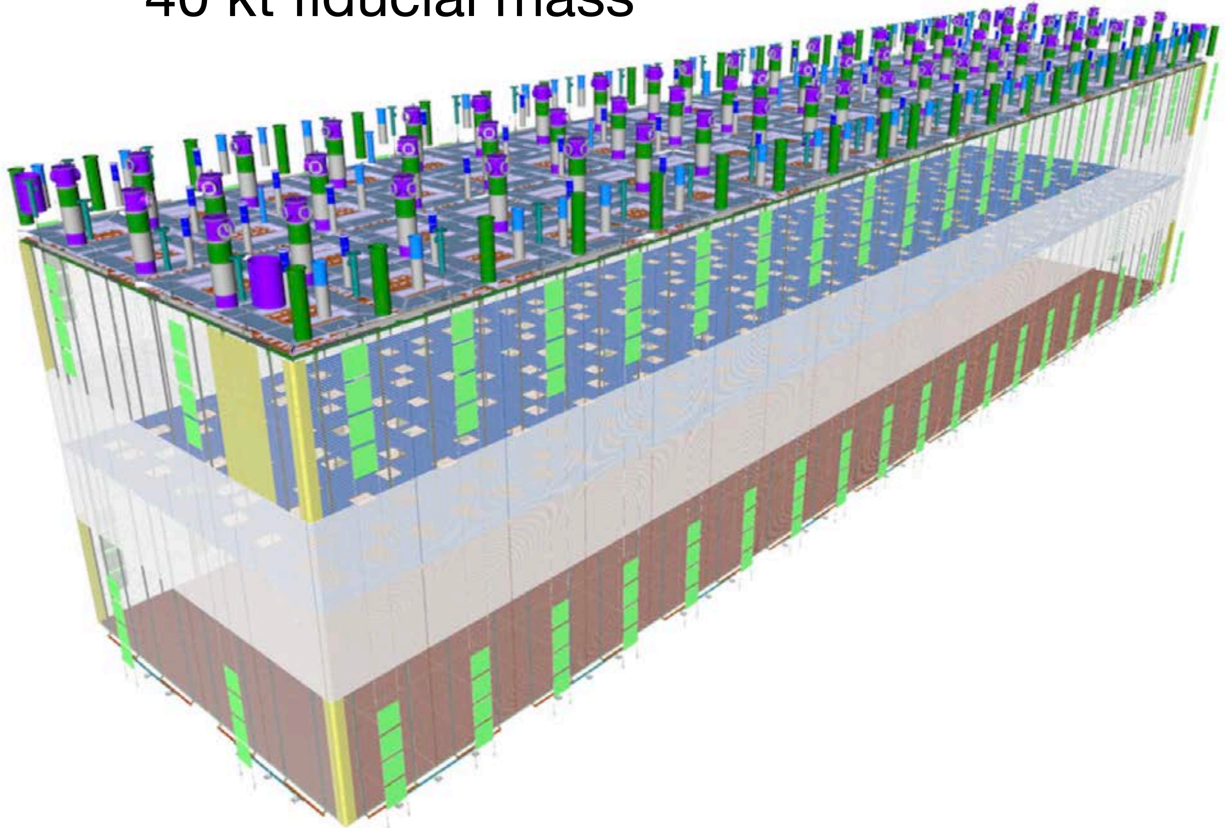
Current Generation Experiments: T2K, NOvA

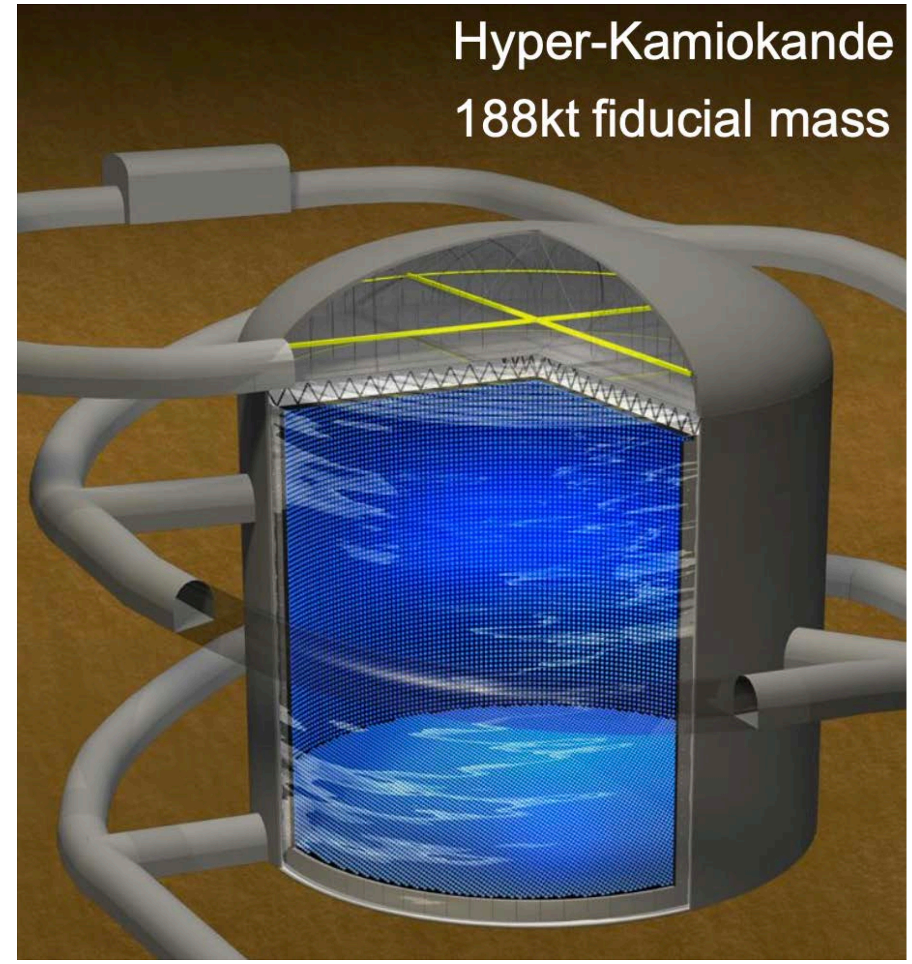
- Weak preference for normal ordering
- Oscillation results are statical limited
- Collaboration initiated T2K-NOvA joint fit
- Mass ordering and CP violation remain unsolved



Next Generation Experiments: Hyper-K, DUNE

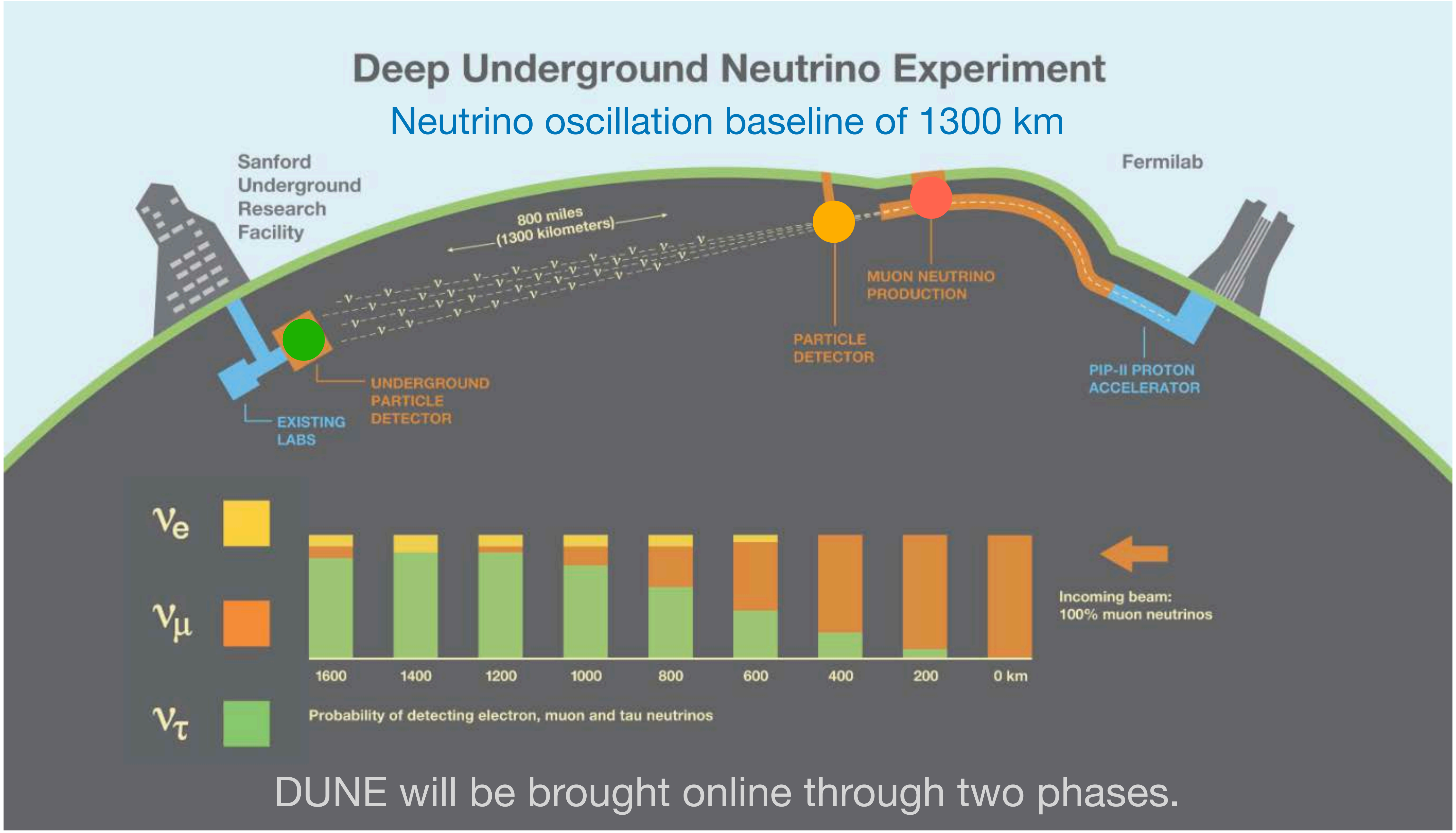
DUNE
40 kt fiducial mass





- DUNE (1300 km) has a longer oscillation baseline than Hyper-K (295 km), seeing larger matter effect
- DUNE is on-axis and has a broad neutrino beam spectrum;
  Hyper-K is located off-axis and has a narrower neutrino spectrum
- DUNE uses **LAr**TPC (40 kt);
  Hyper-K uses **water** Cherenkov detector (188 kt)
- Both have highly capable near detectors to constrain systematic uncertainties

Design of the DUNE Experiment



- High intensity neutrino beam
- Near detector complex at Fermilab
- Large, deep underground far detectors at SURF

The Oscillation Baseline and Flux for DUNE

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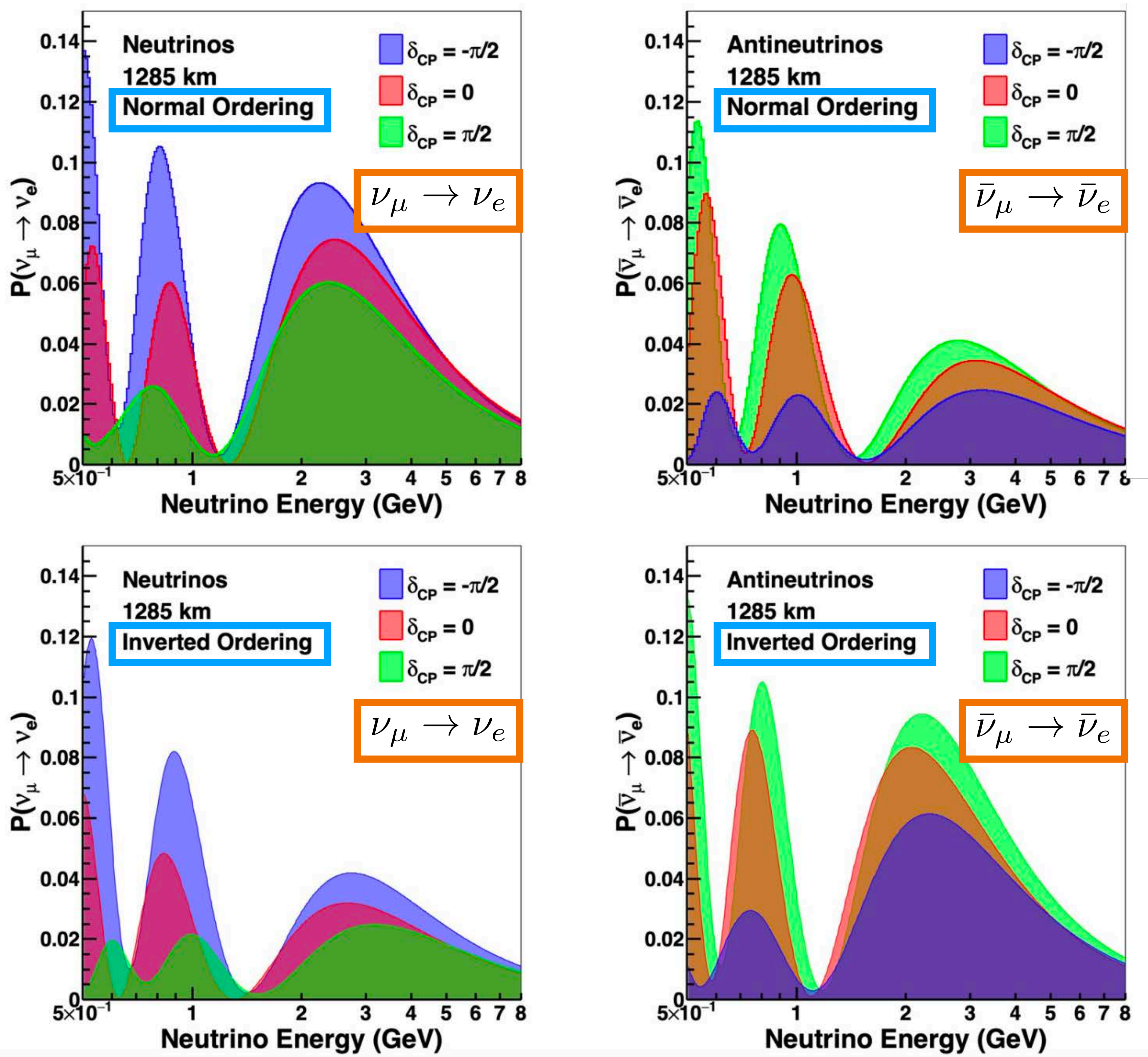
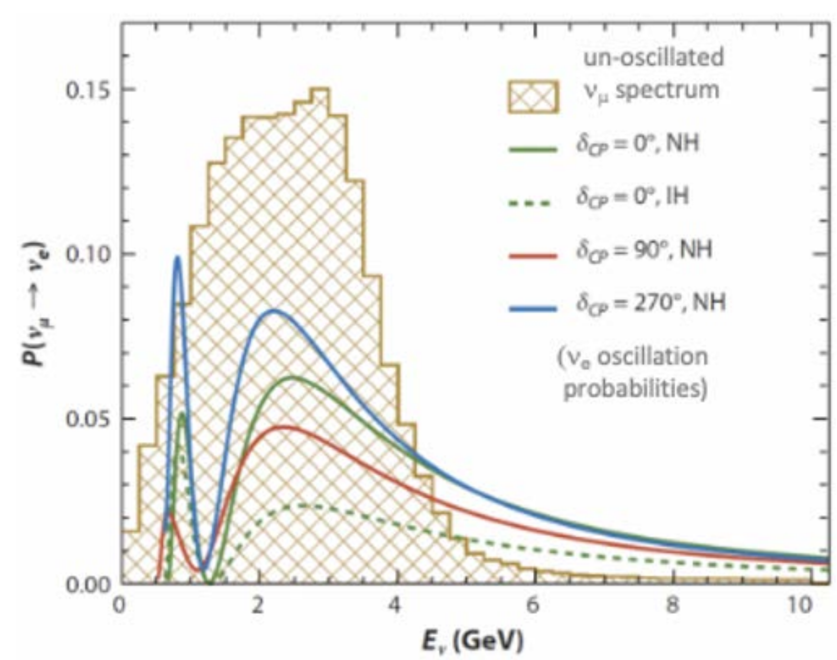


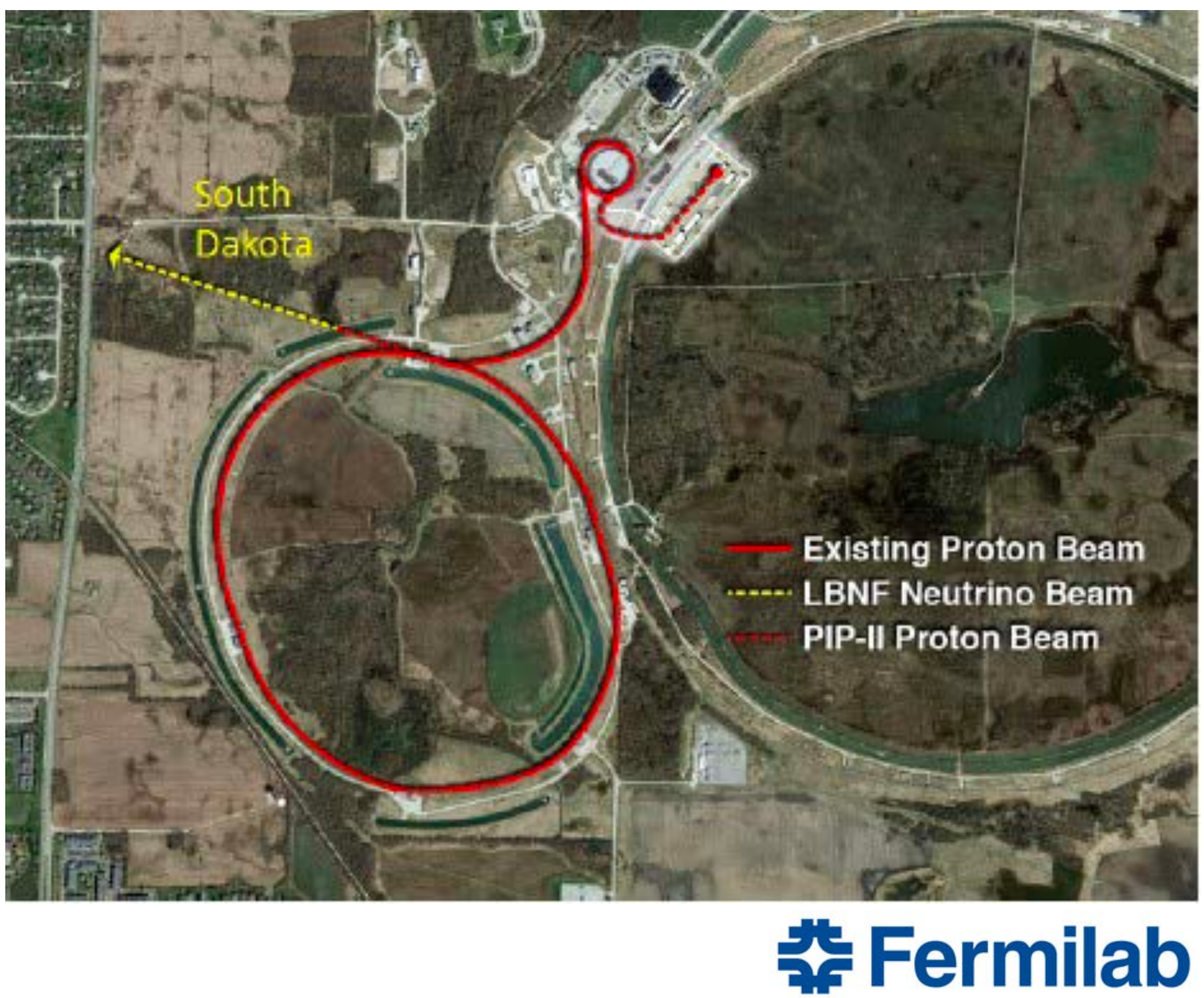


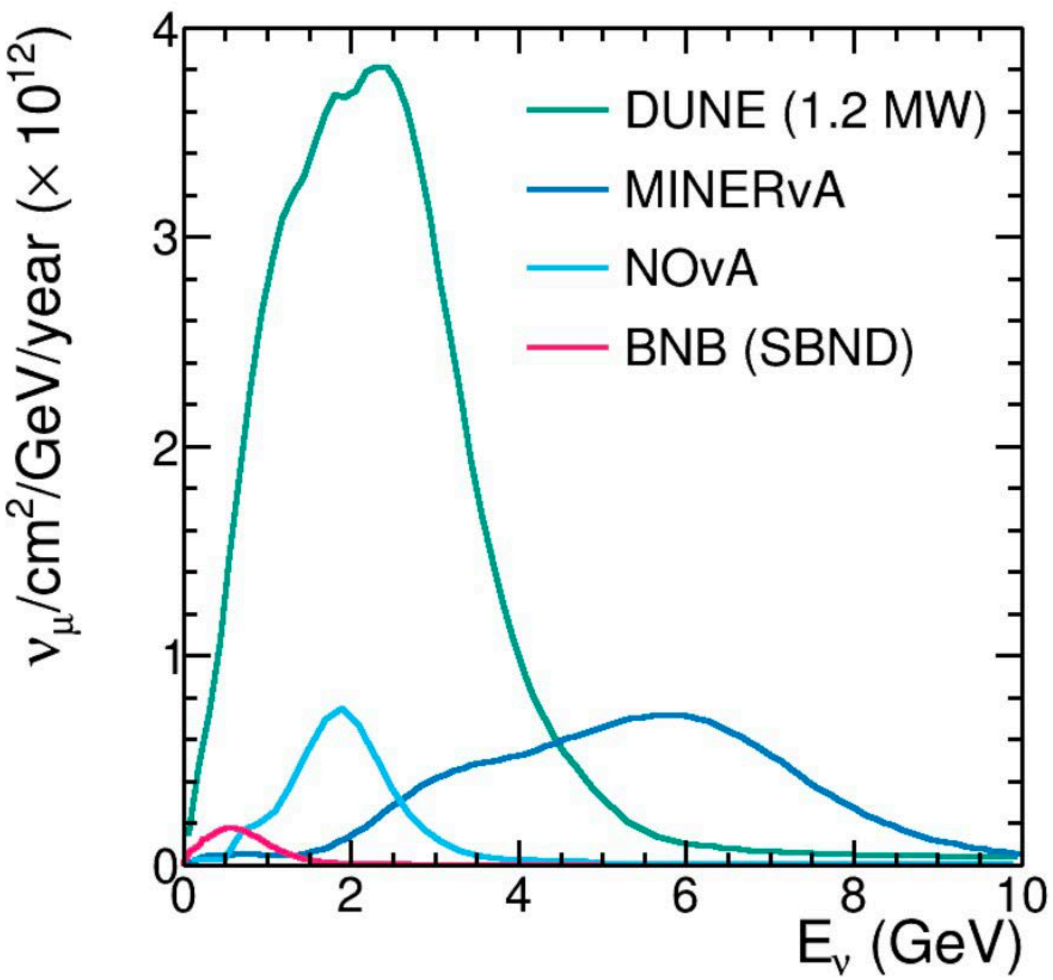
- Broad spectrum to probe the shape of the oscillation probability
- Complimentary to other experiments with narrow beam spectra

High Intensity Beam and the Broadband DUNE Flux

1.2 MW proton beam (Phase I)

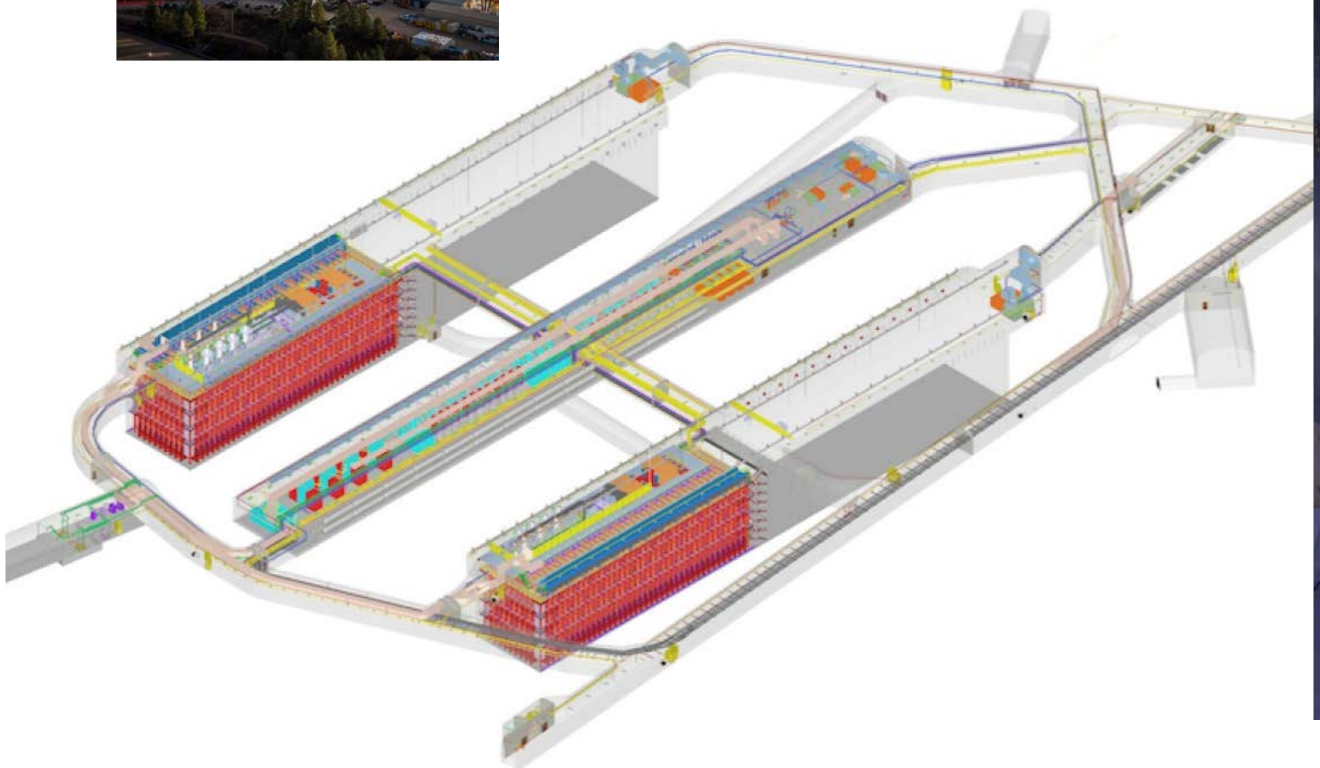
> 2 MW proton beam (Phase II)





DUNE Far Detector

SURF



- Four far detector modules
- Excavation fully completed
- Primary detector technology: LArTPCs, 4 x 17 kt (>10 kt fiducial mass)
- Phase I: one LArTPC with horizontal drift, one LArTPC with vertical drift
- Phase II: 3rd + 4th modules
- Module opportunity workshop: BNL 2019, Valencia 2022

What will DUNE See for Oscillation?

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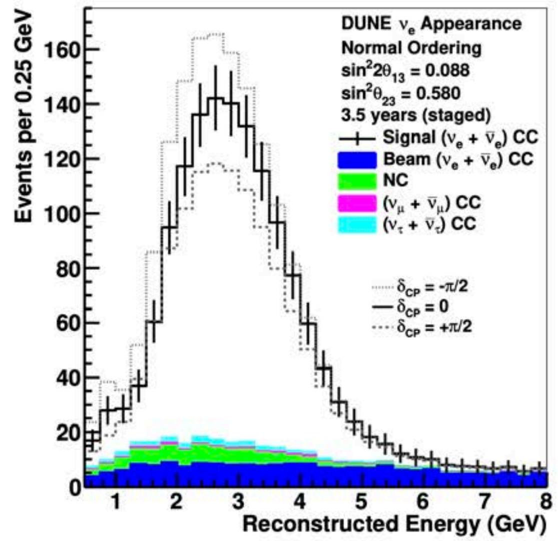
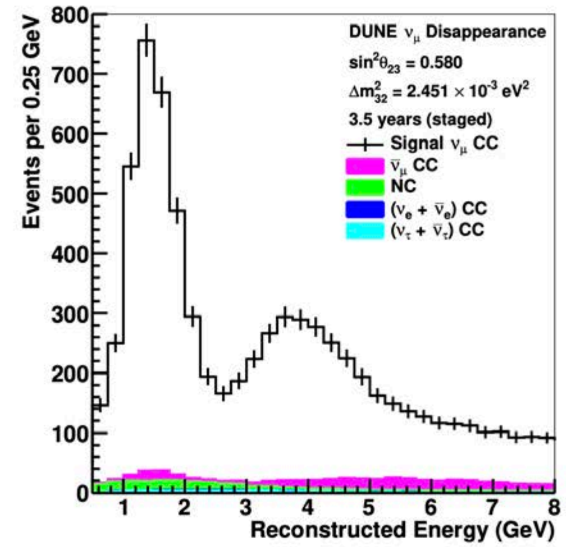
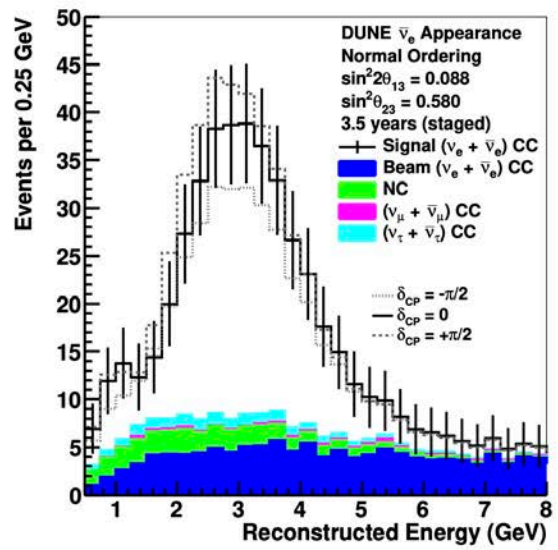
$\nu_\mu \to \nu_e$

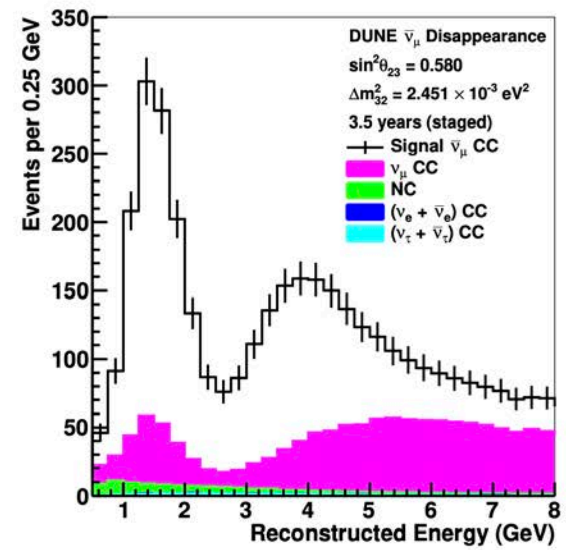




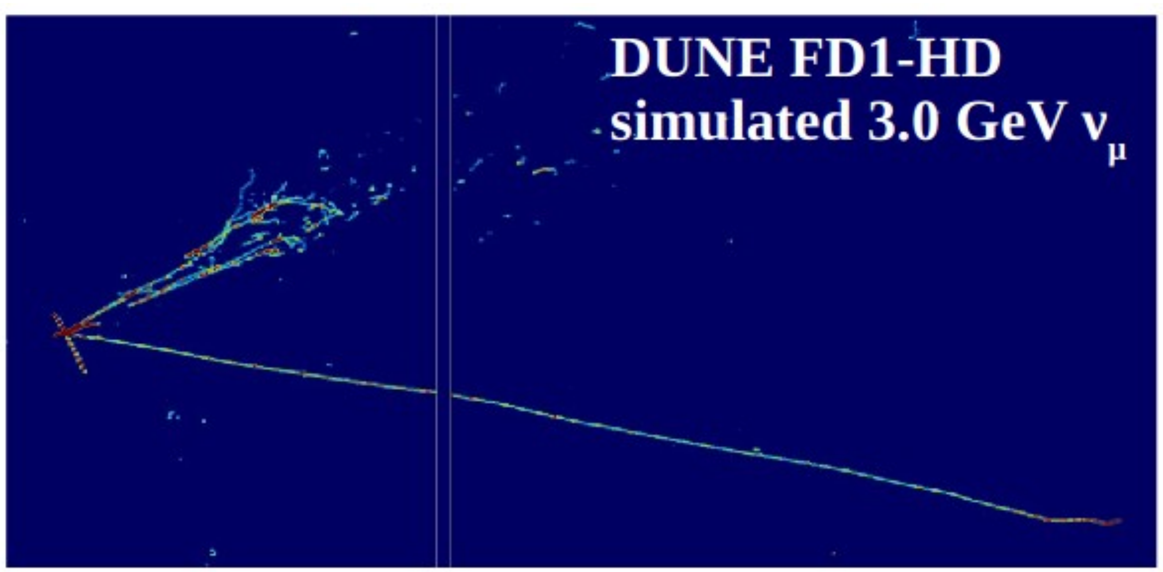
$\nu_\mu \to \nu_\mu$

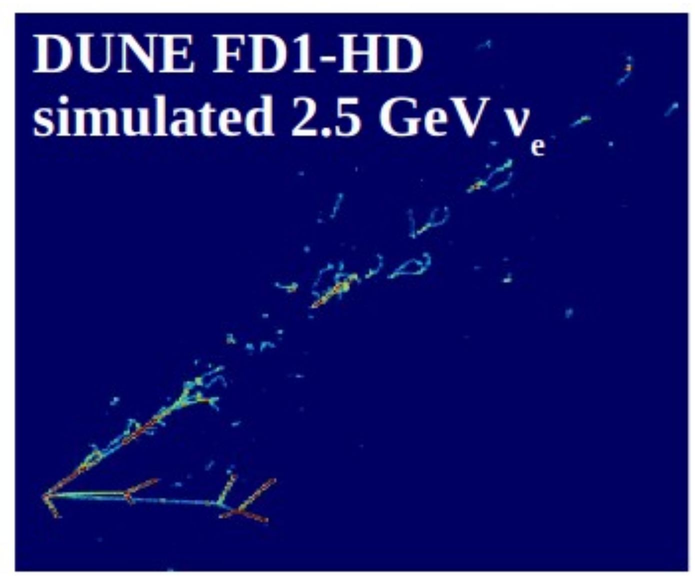
$\bar{\nu}_\mu \to \bar{\nu}_e$



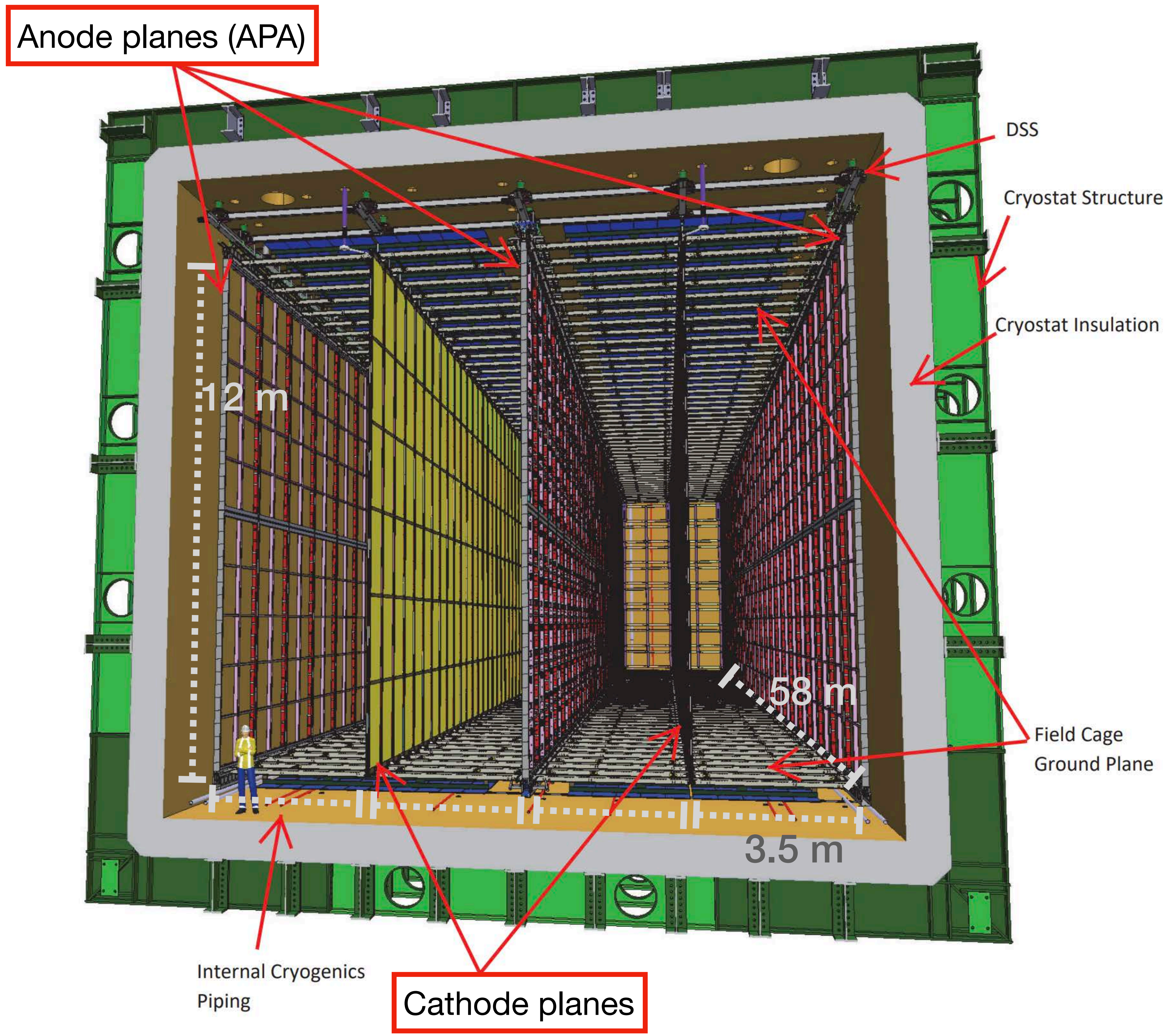


$\bar{\nu}_\mu \to \bar{\nu}_\mu$

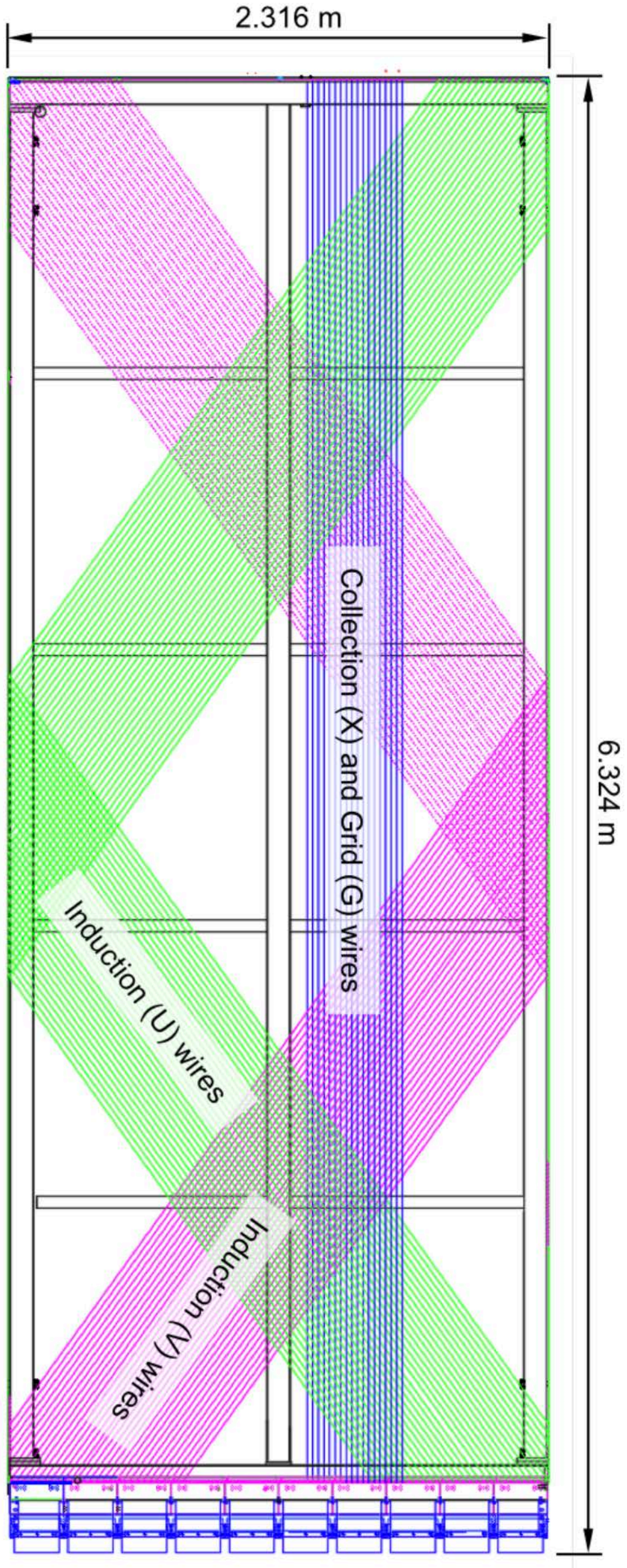




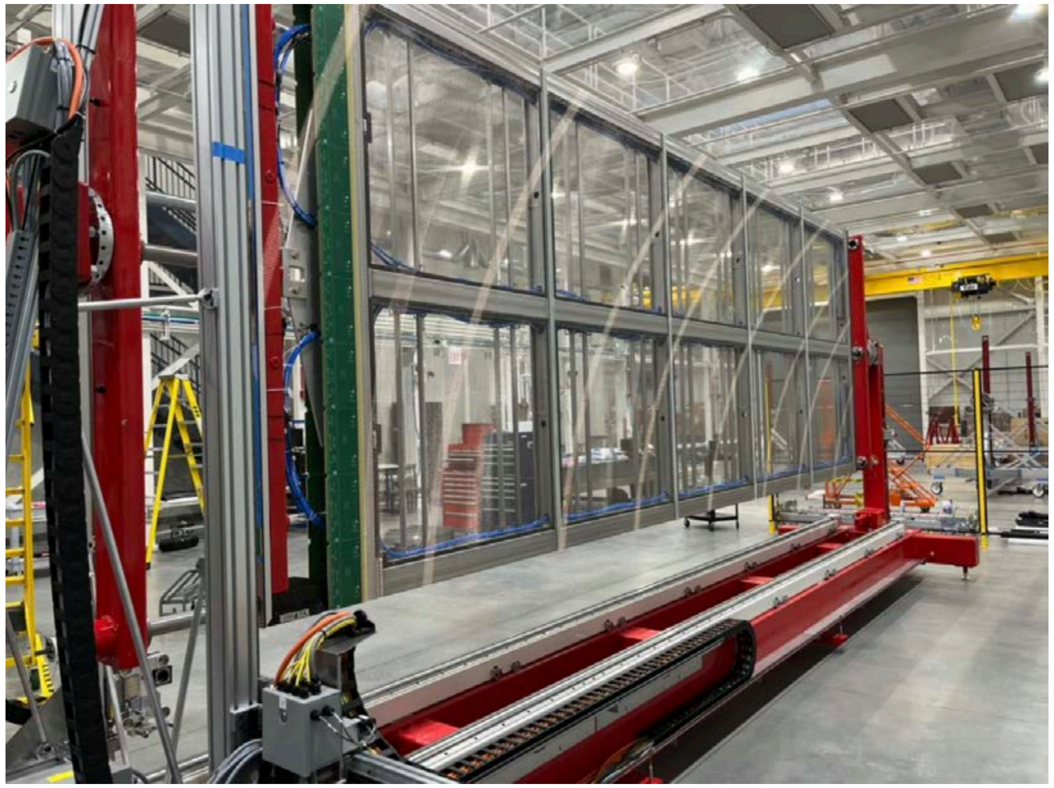
Far Detector 1: LArTPC with Horizontal Drift (HD)

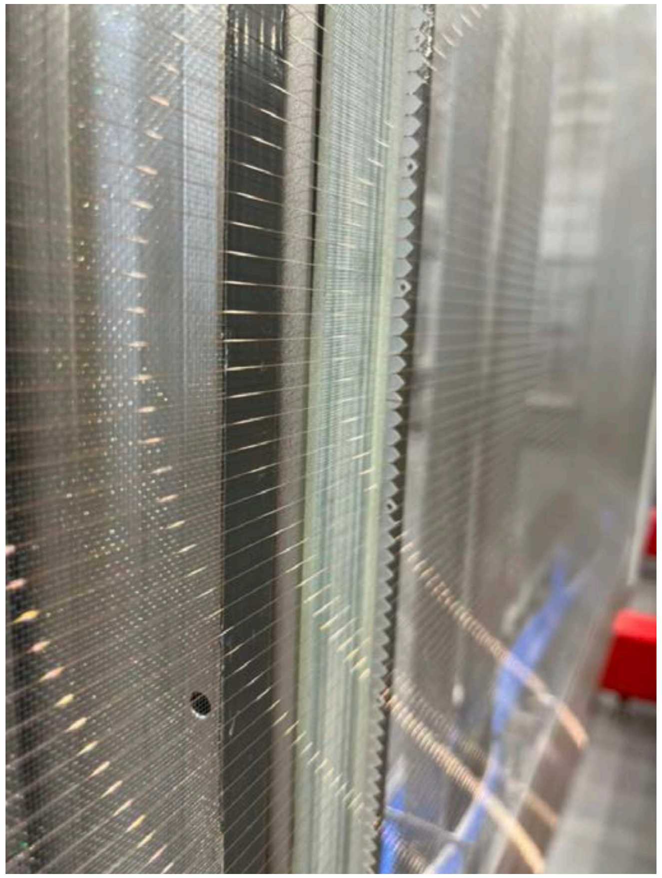


Far Detector 1: Wire Readout Plane

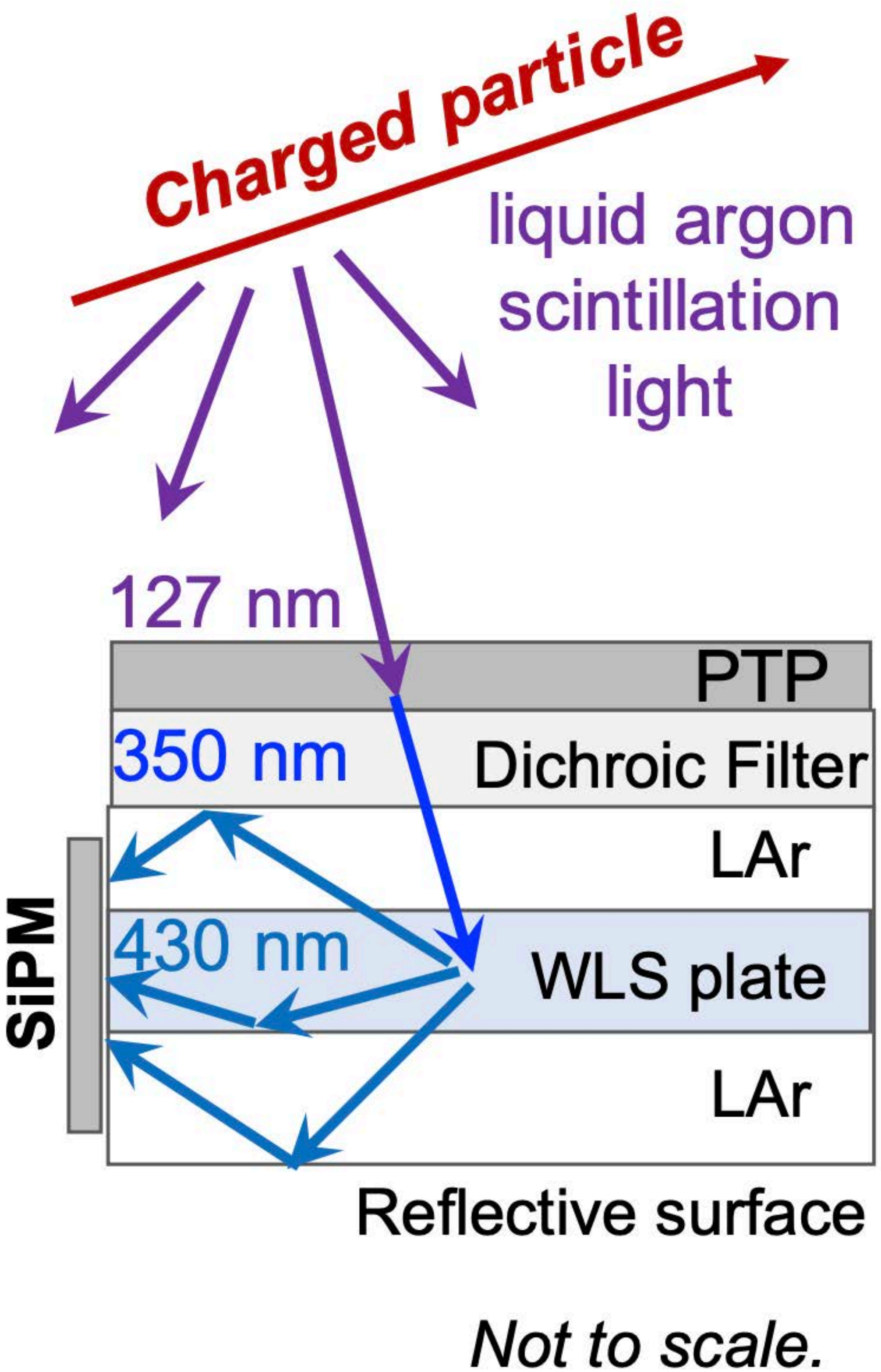


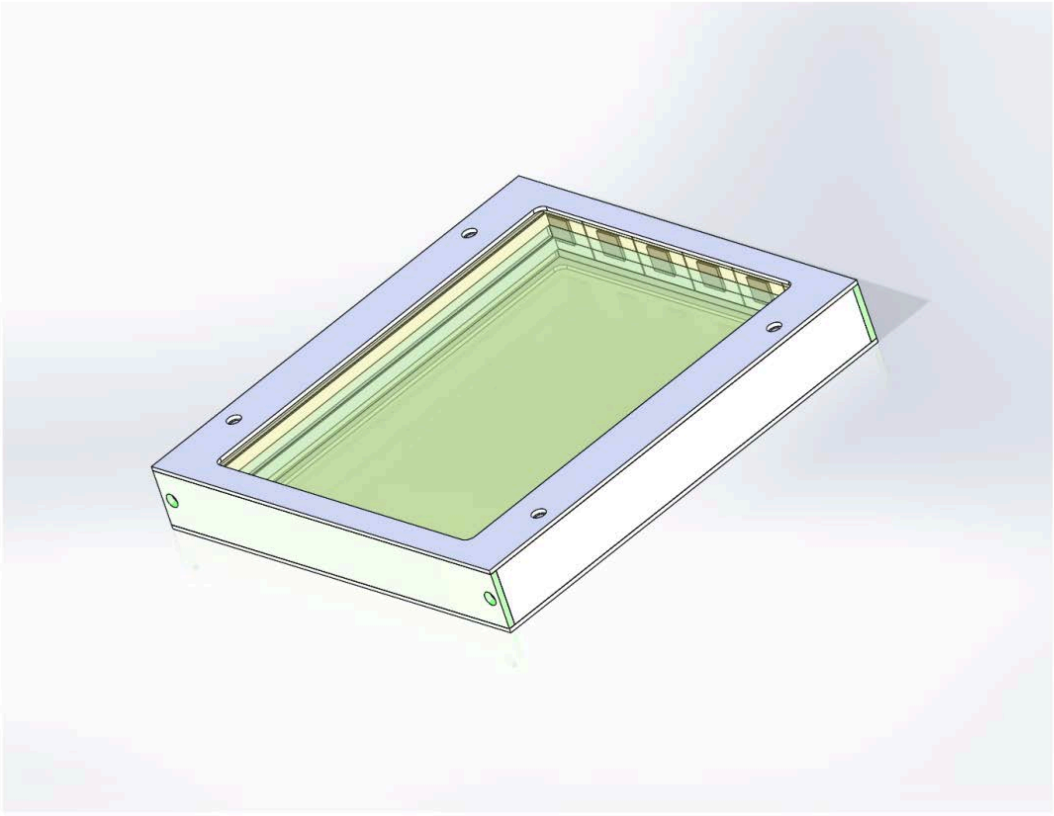
Modularized anode plane (APA)
> 3000 wires per anode module
Two APA factories: UChicago (US), Daresbury (UK)

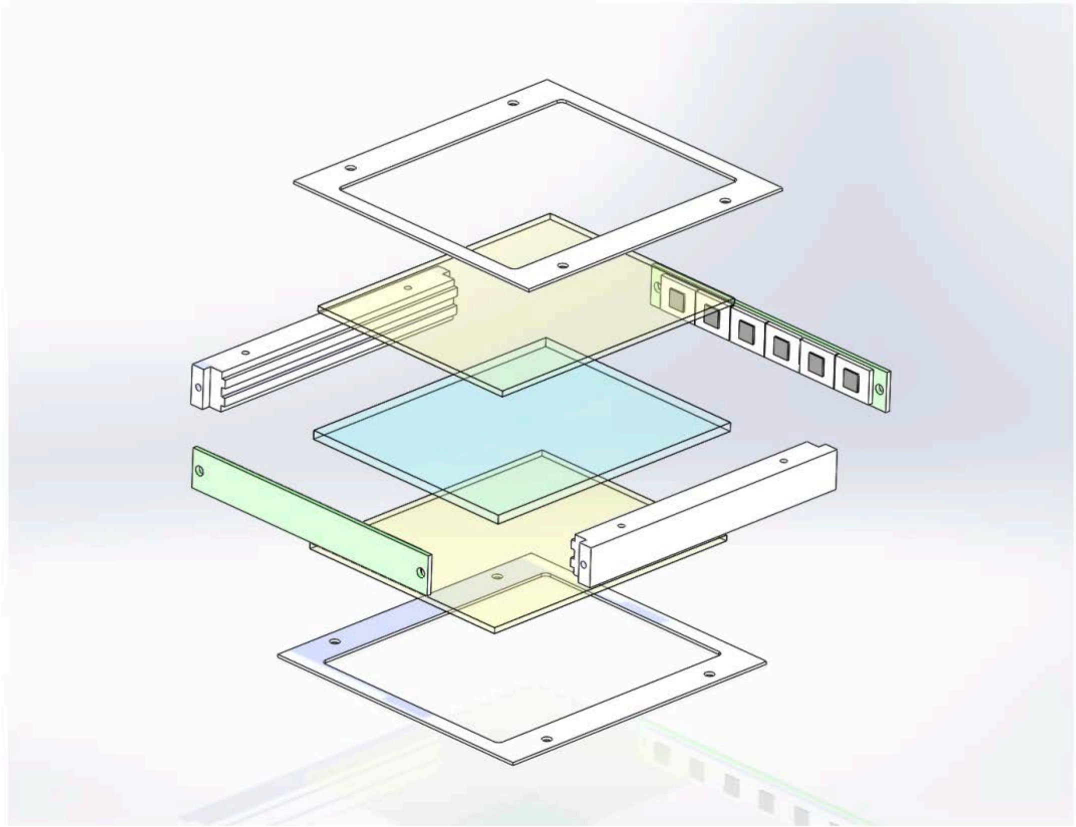




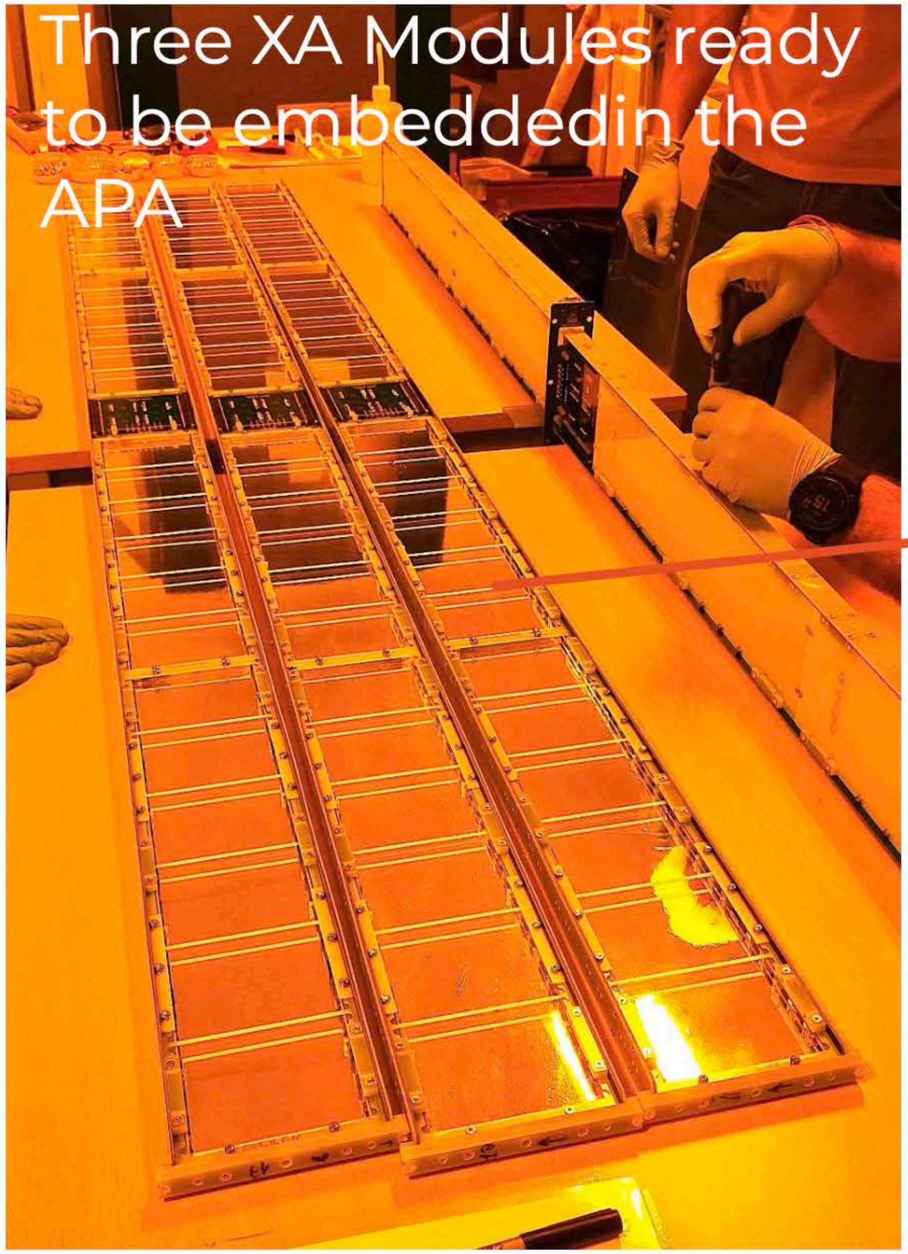
Far Detector 1 and 2: Light Detector X-Arapuca

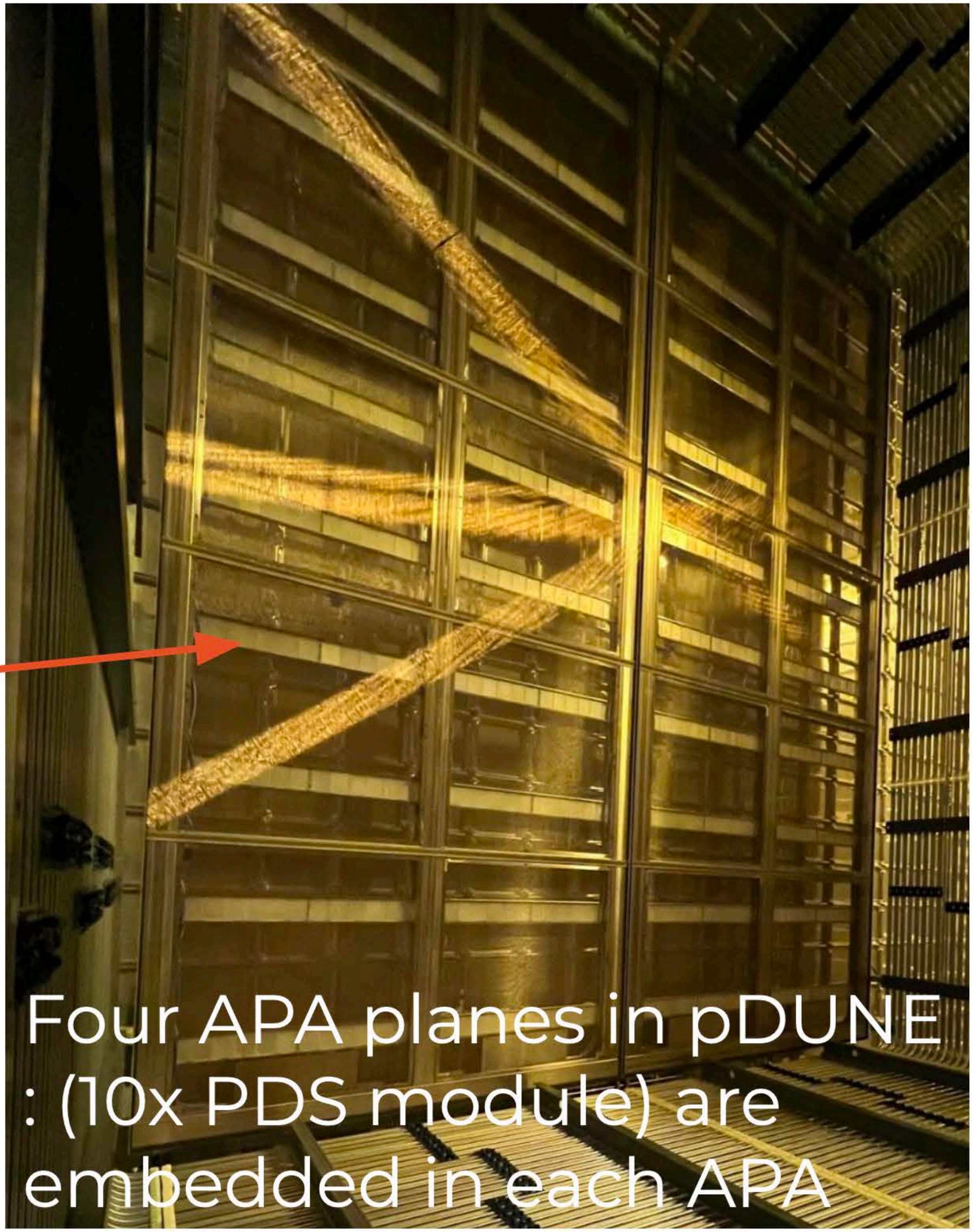




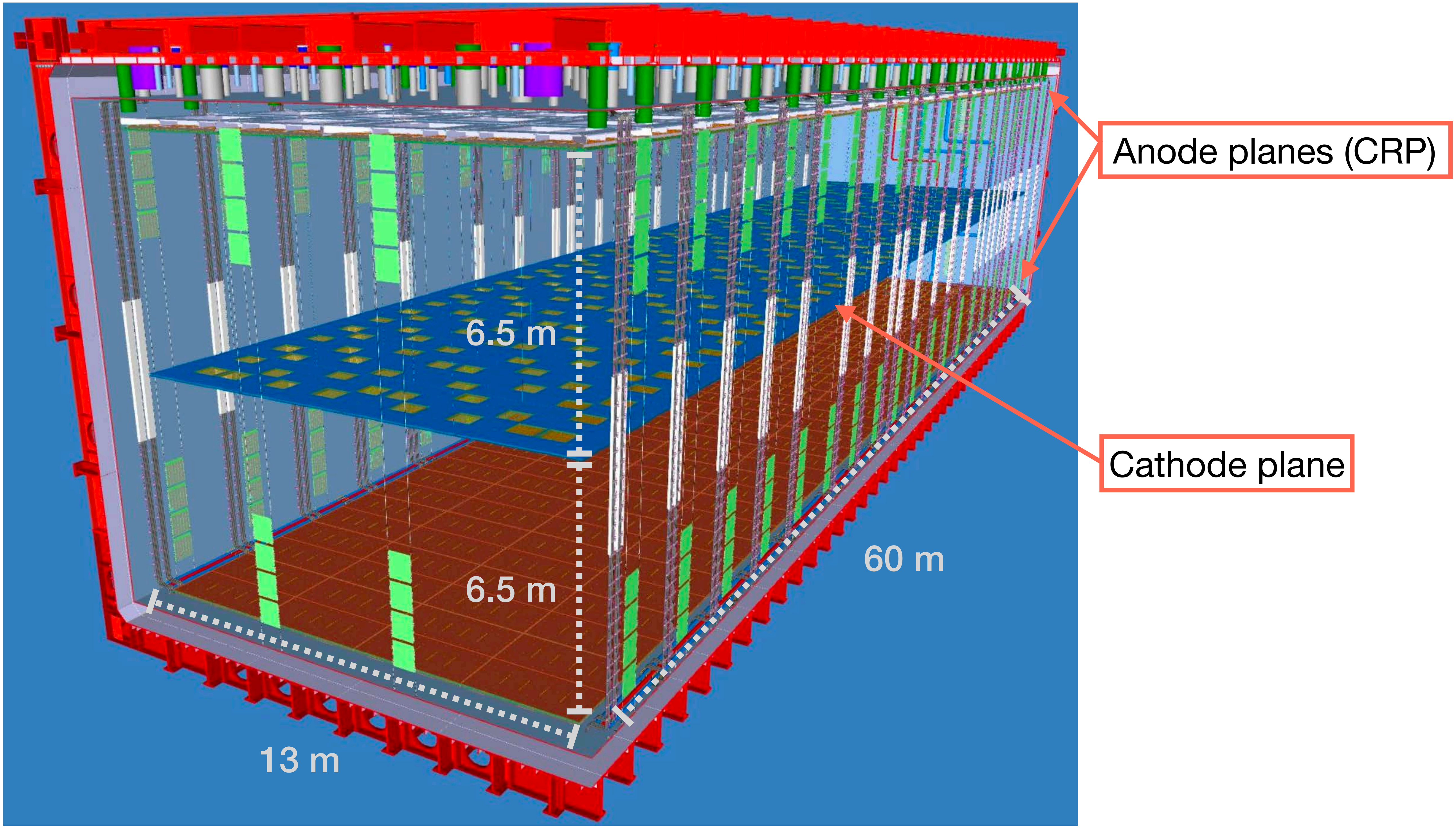


Far Detector 1: Light Detector

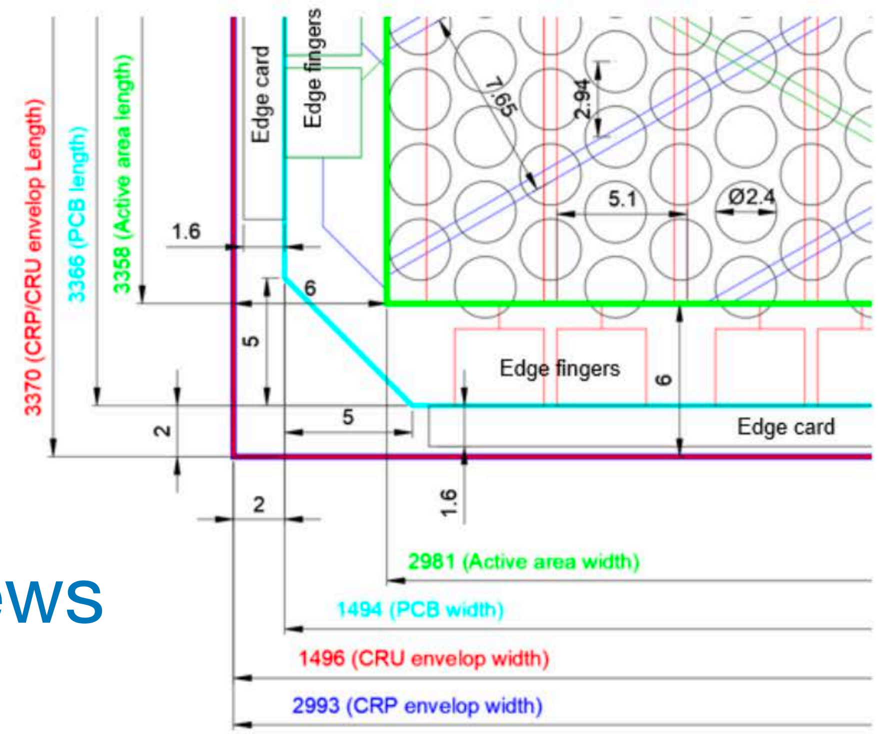




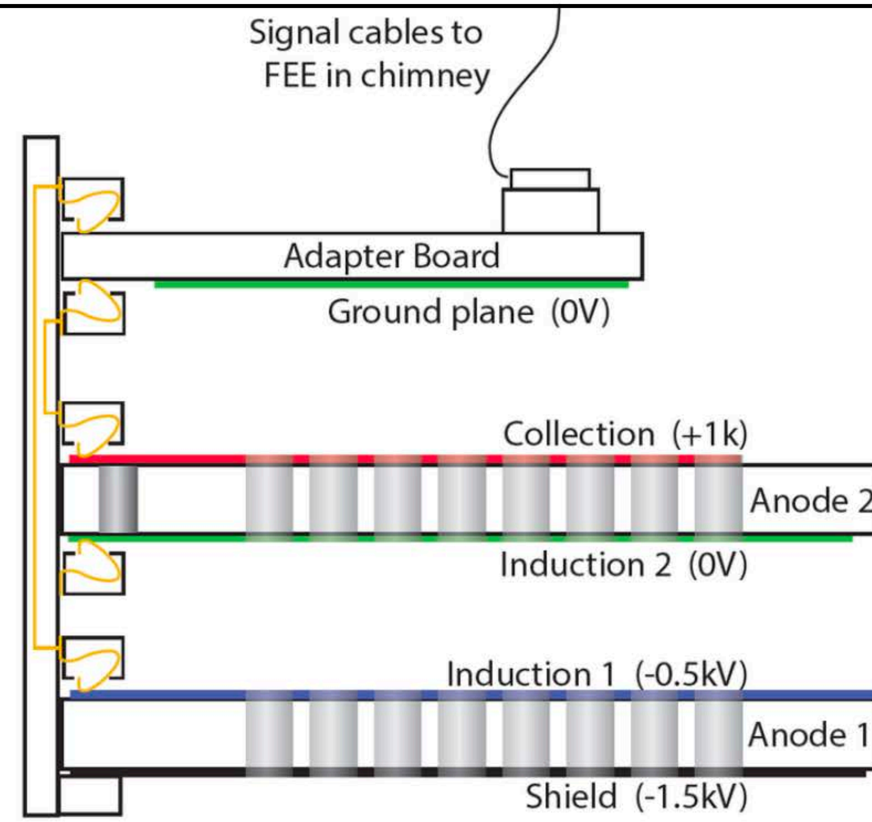
Far Detector 2: LArTPC with Vertical Drift (VD)

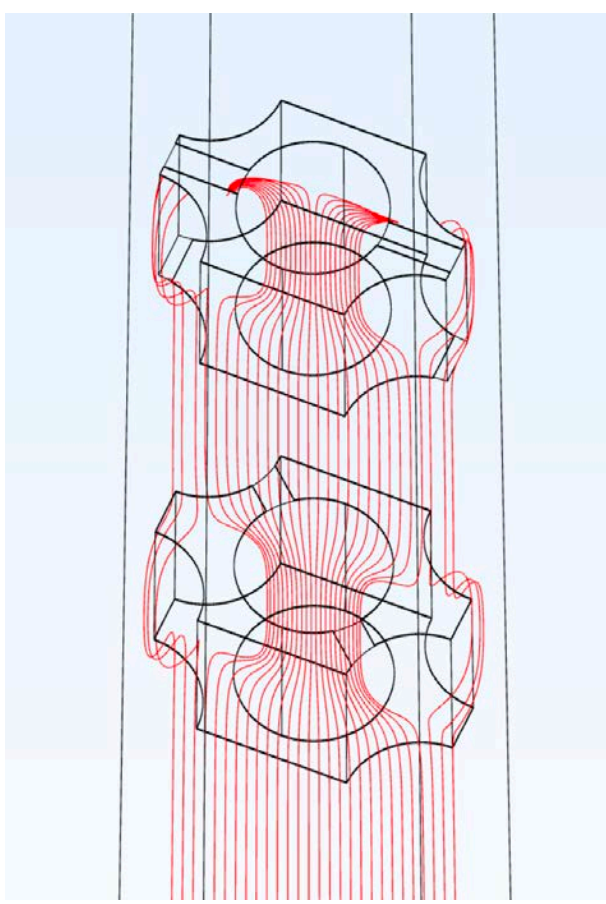


Far Detector 2: Charge Readout Planes (CRP)



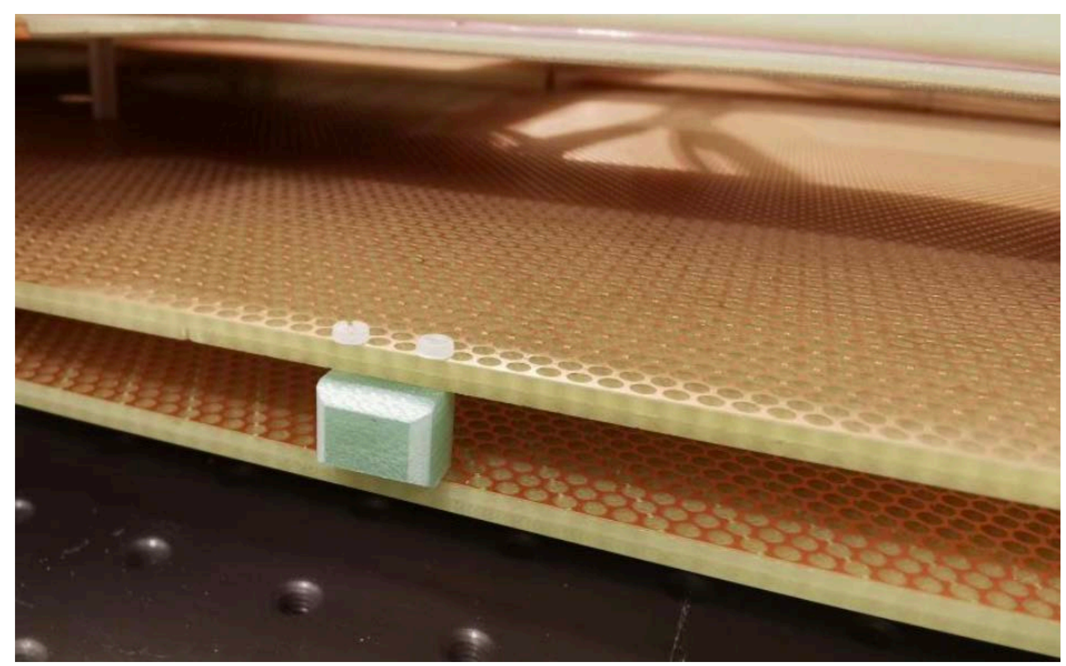
3 views



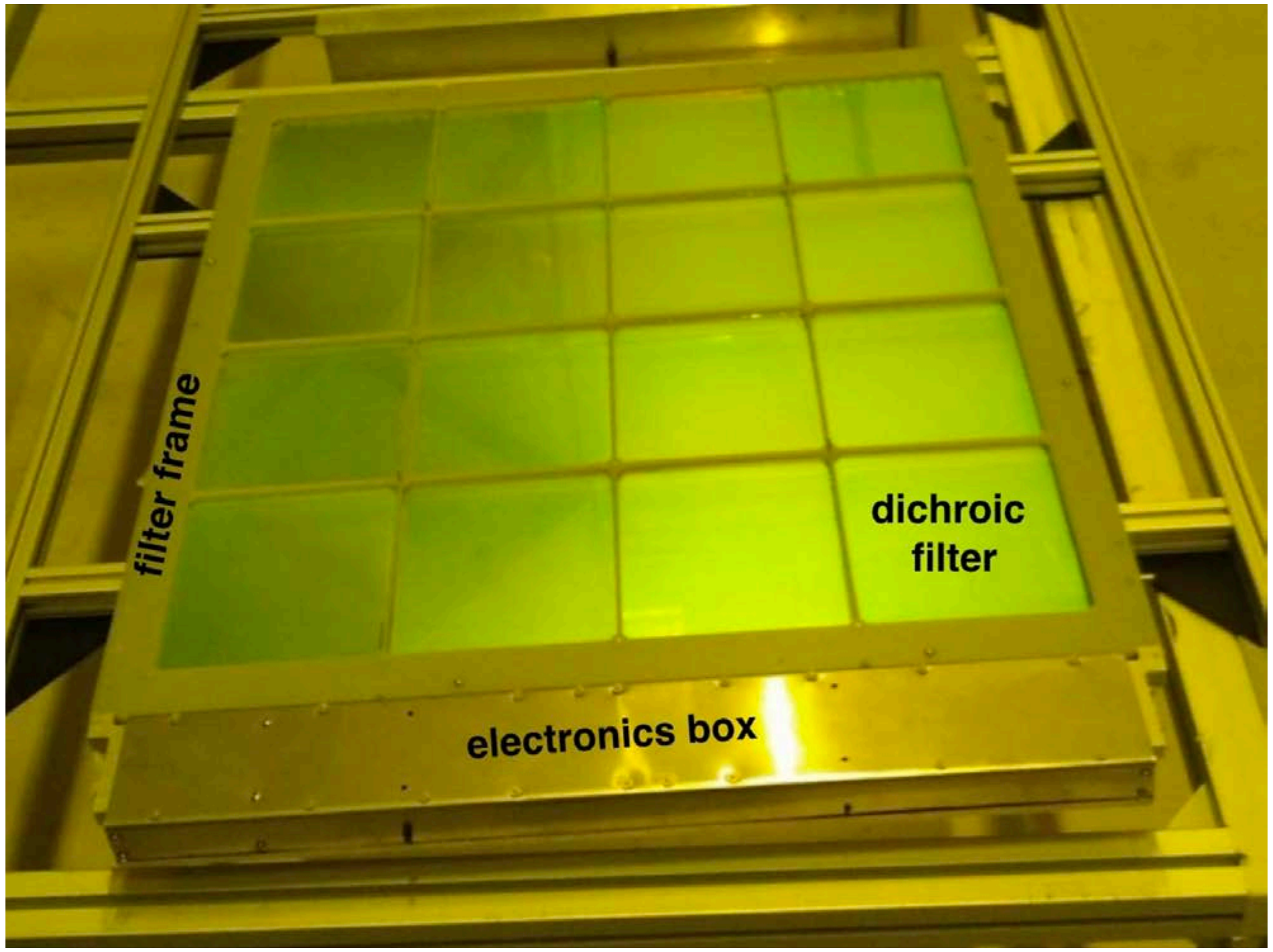


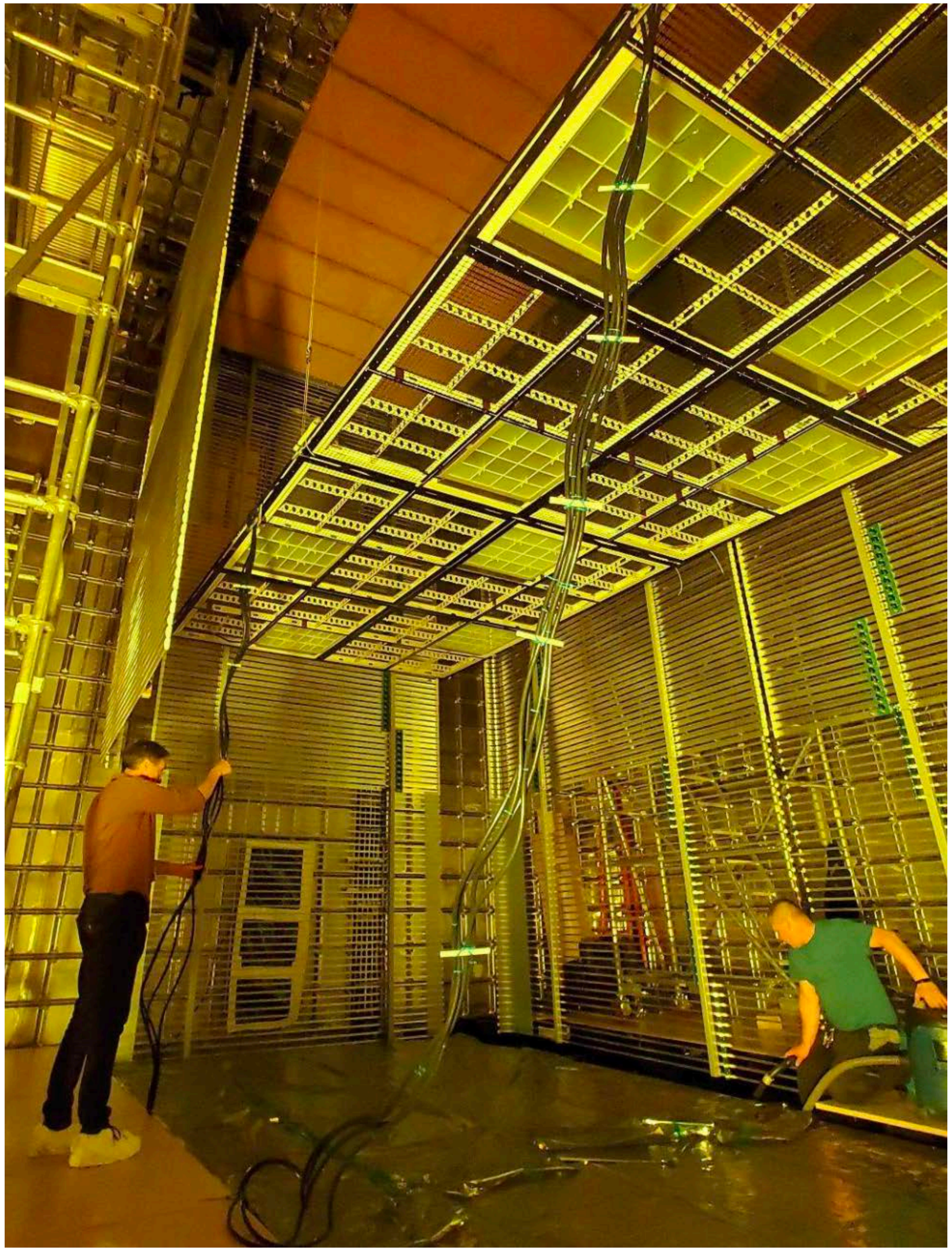
A CRP module of 3 m x 3.3 m

Two CRP factories: Grenoble (FR), Yale (US)

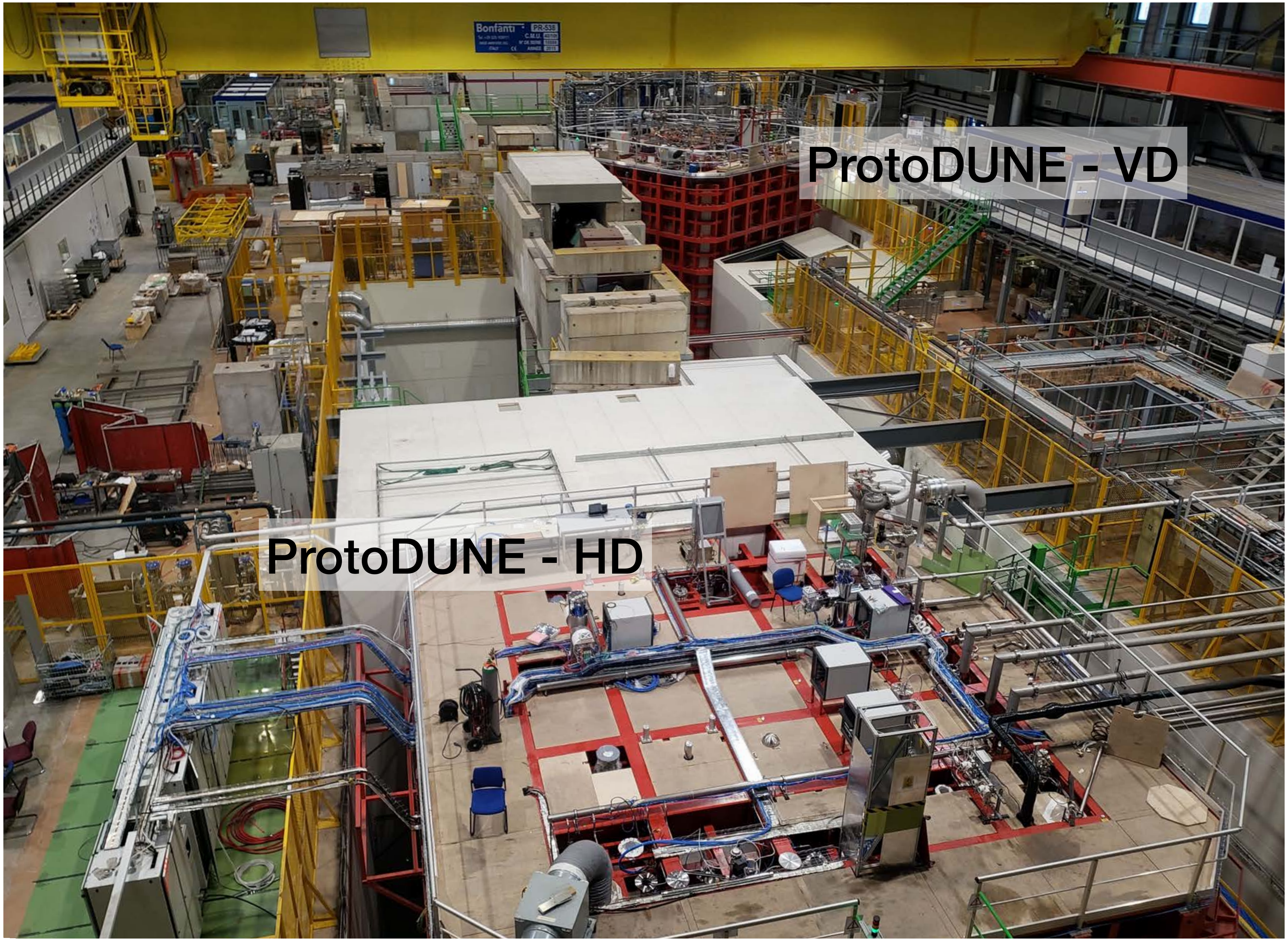


Far Detector2: Light Readout





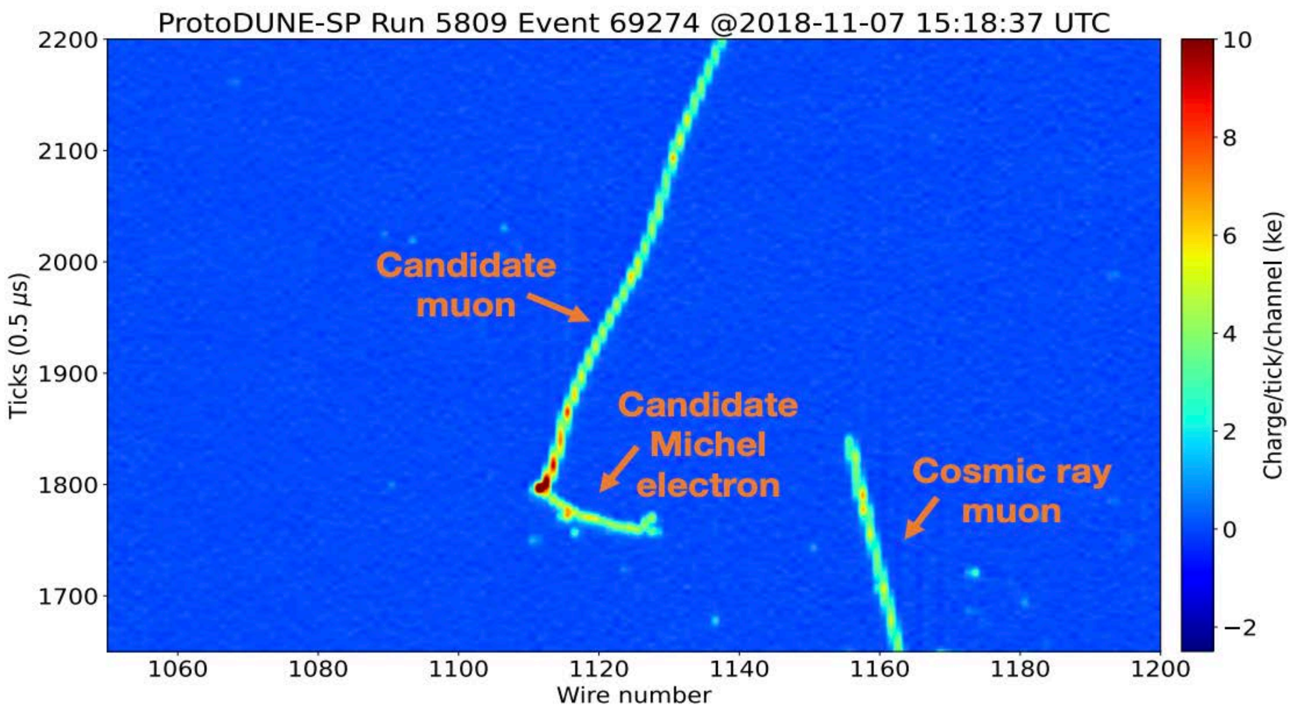
ProtoDUNE



Charged particle beam

ProtoDUNE

Detector characterization
Reconstruction development



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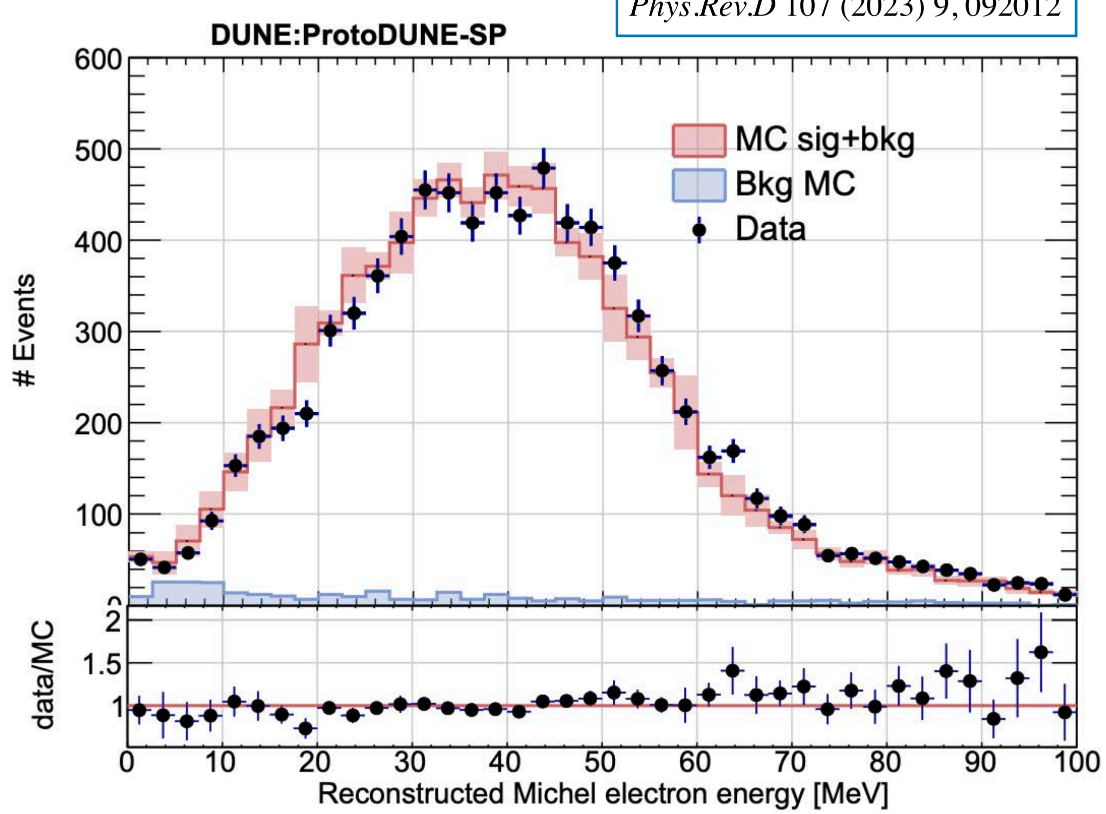
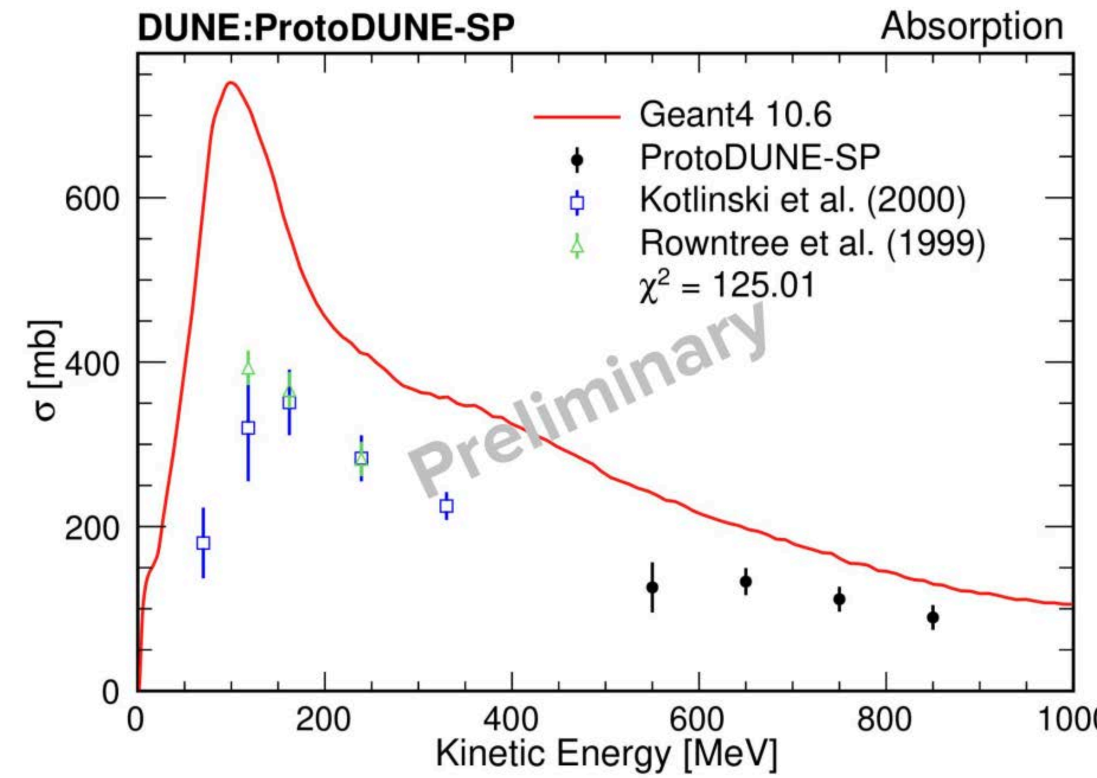
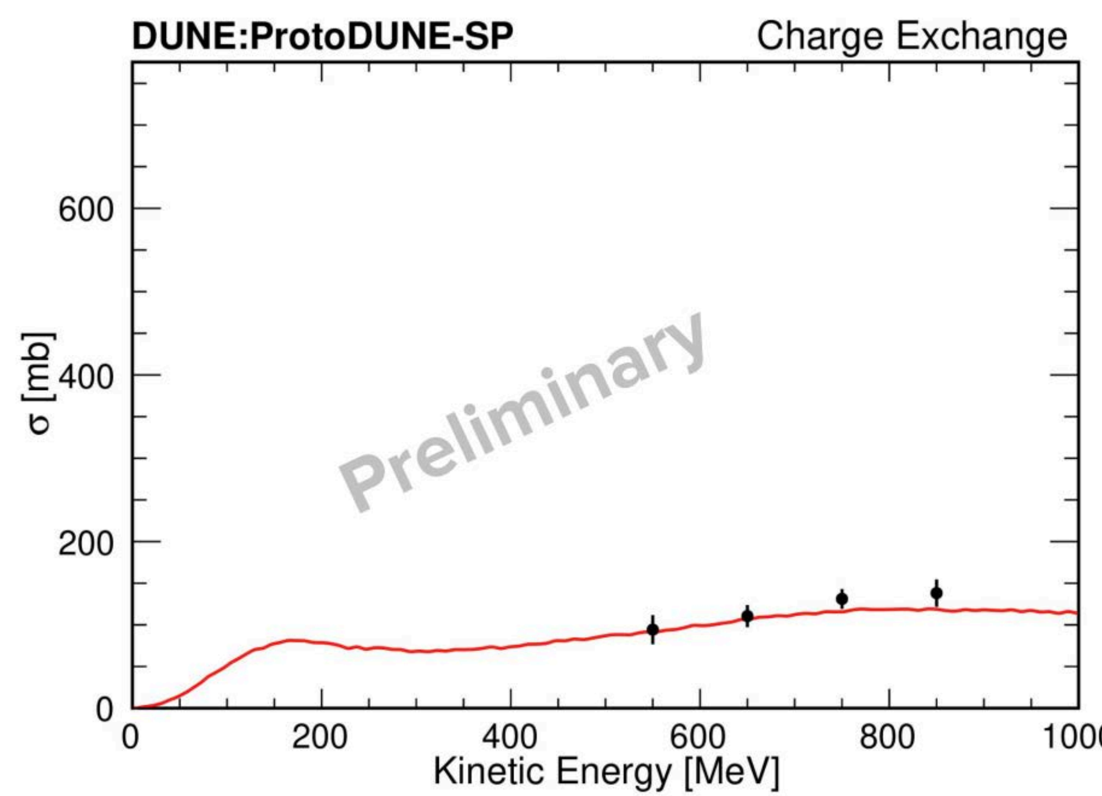


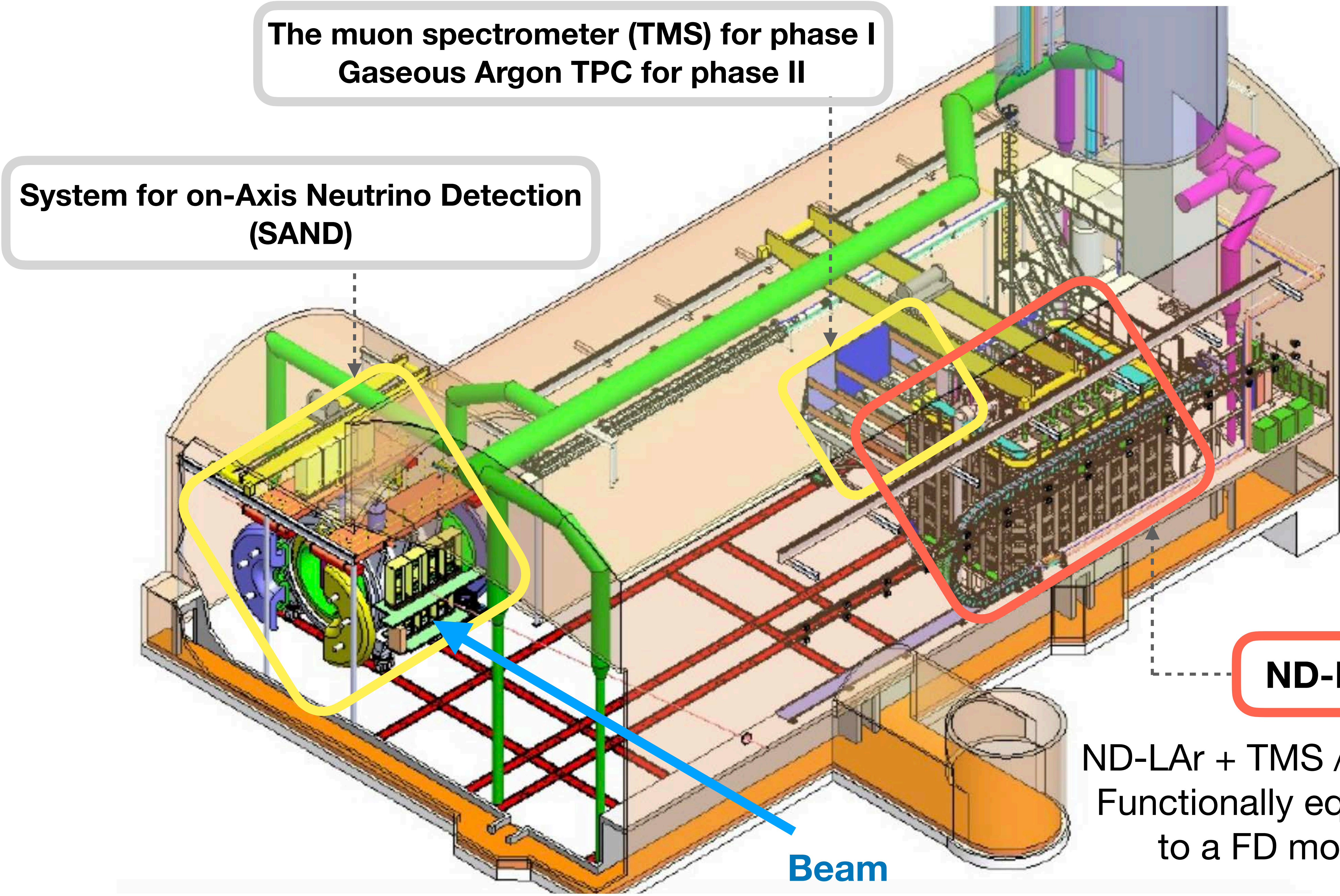
Hadron cross-section





Near Detector Complex (ND)

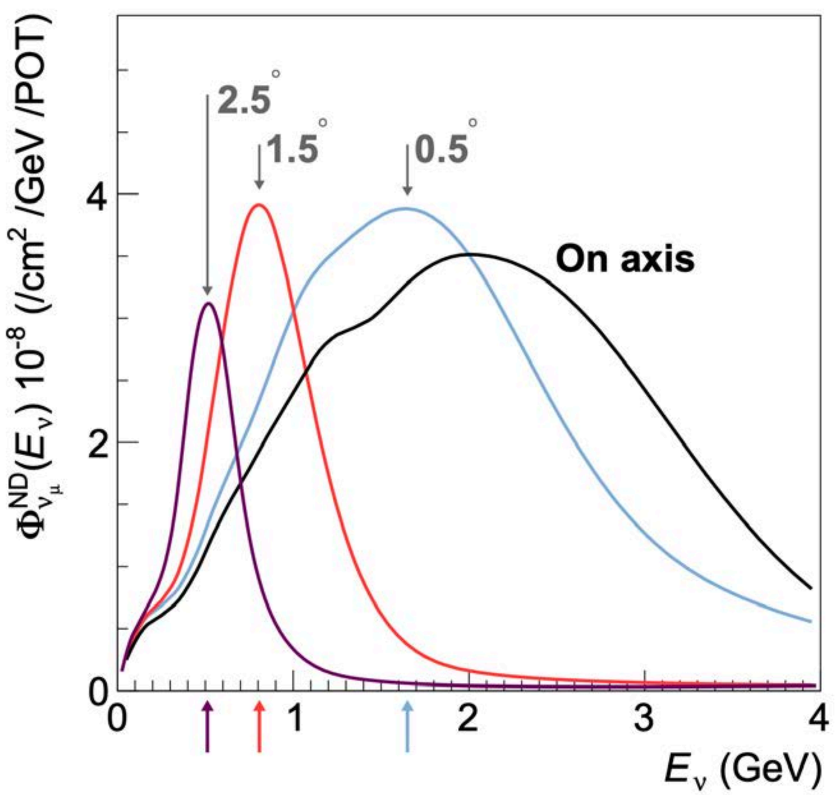
ND phase II workshop: London 2023



ND-LAr + TMS / ND-GAr
Functionally equivalent
to a FD module

DUNE PRSIM

Linear combination of ND fluxes to match with FD oscillated spectra



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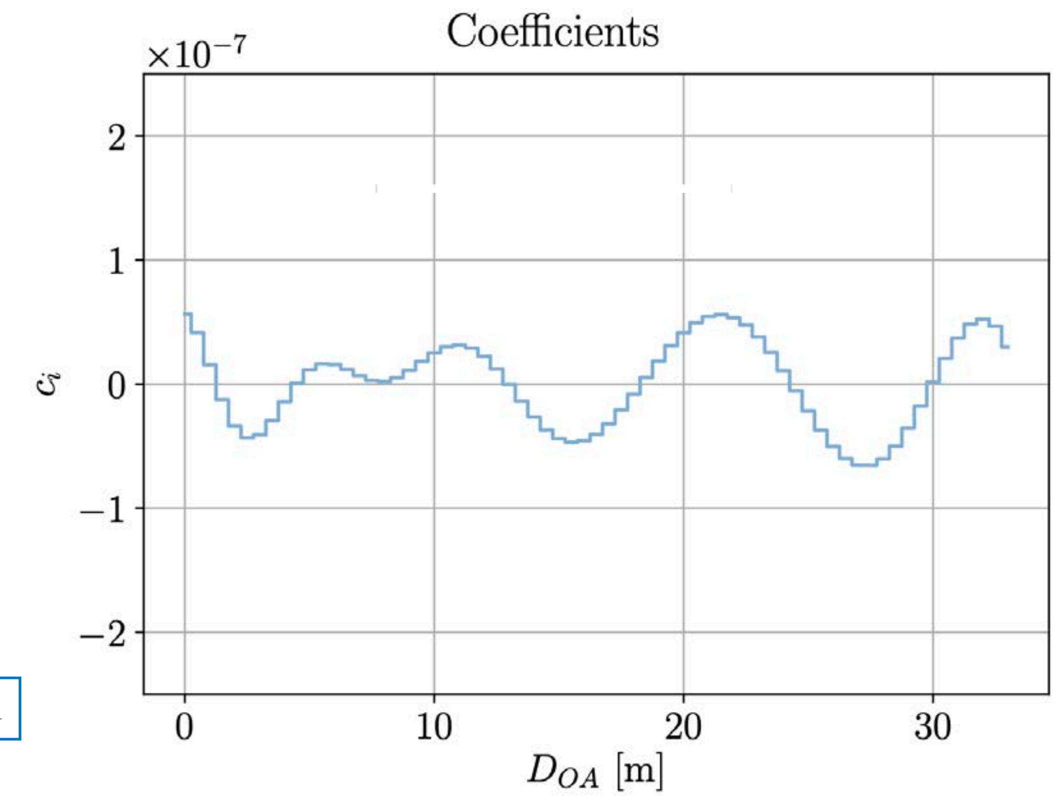
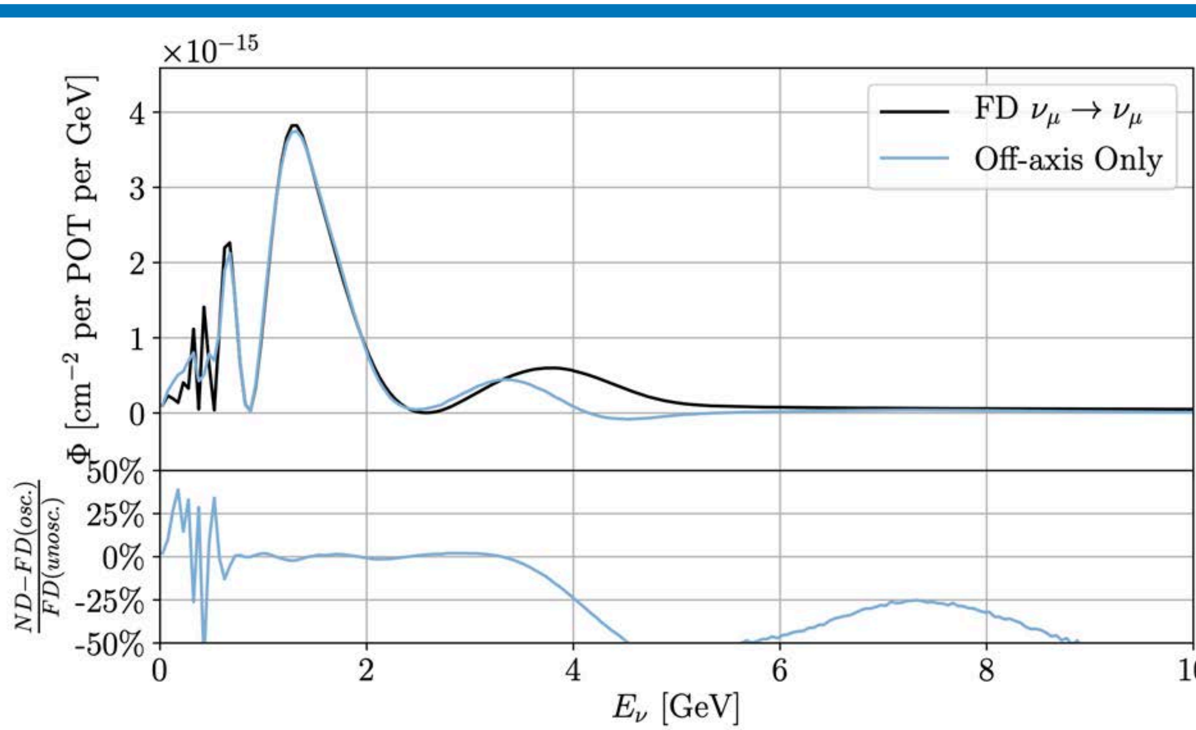
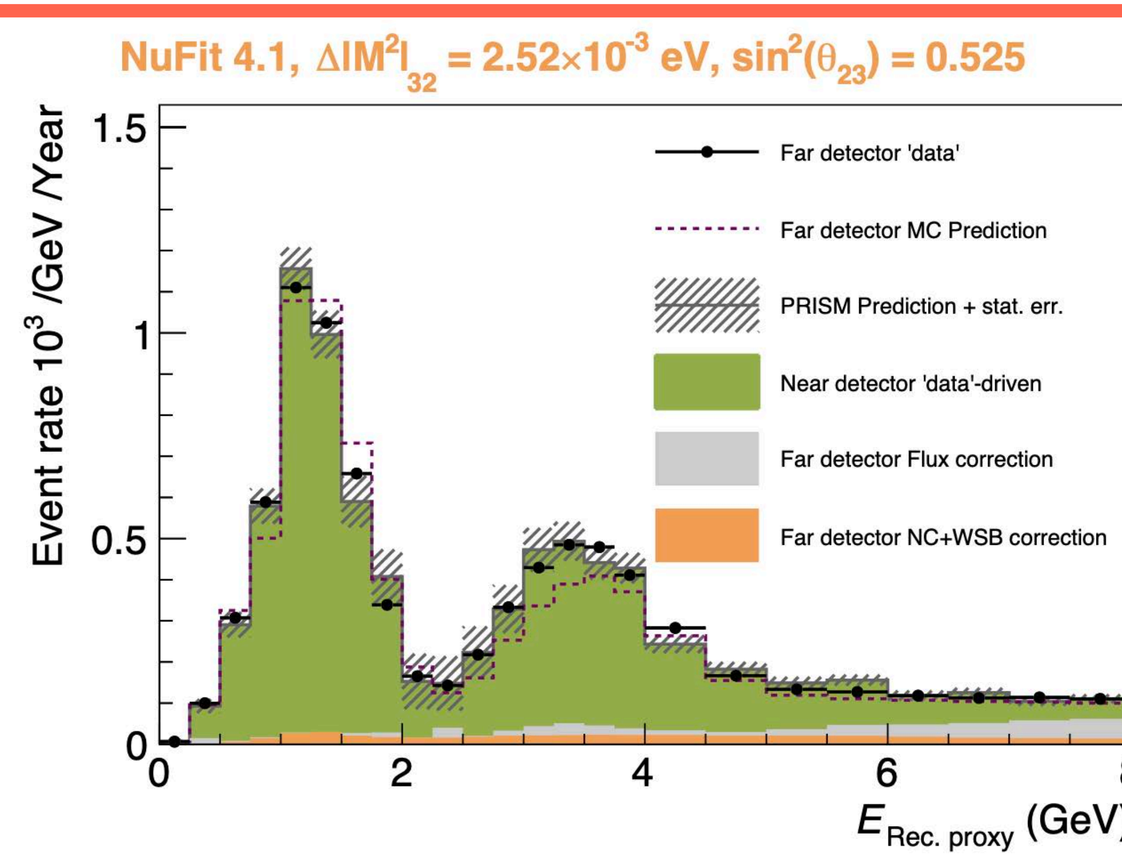




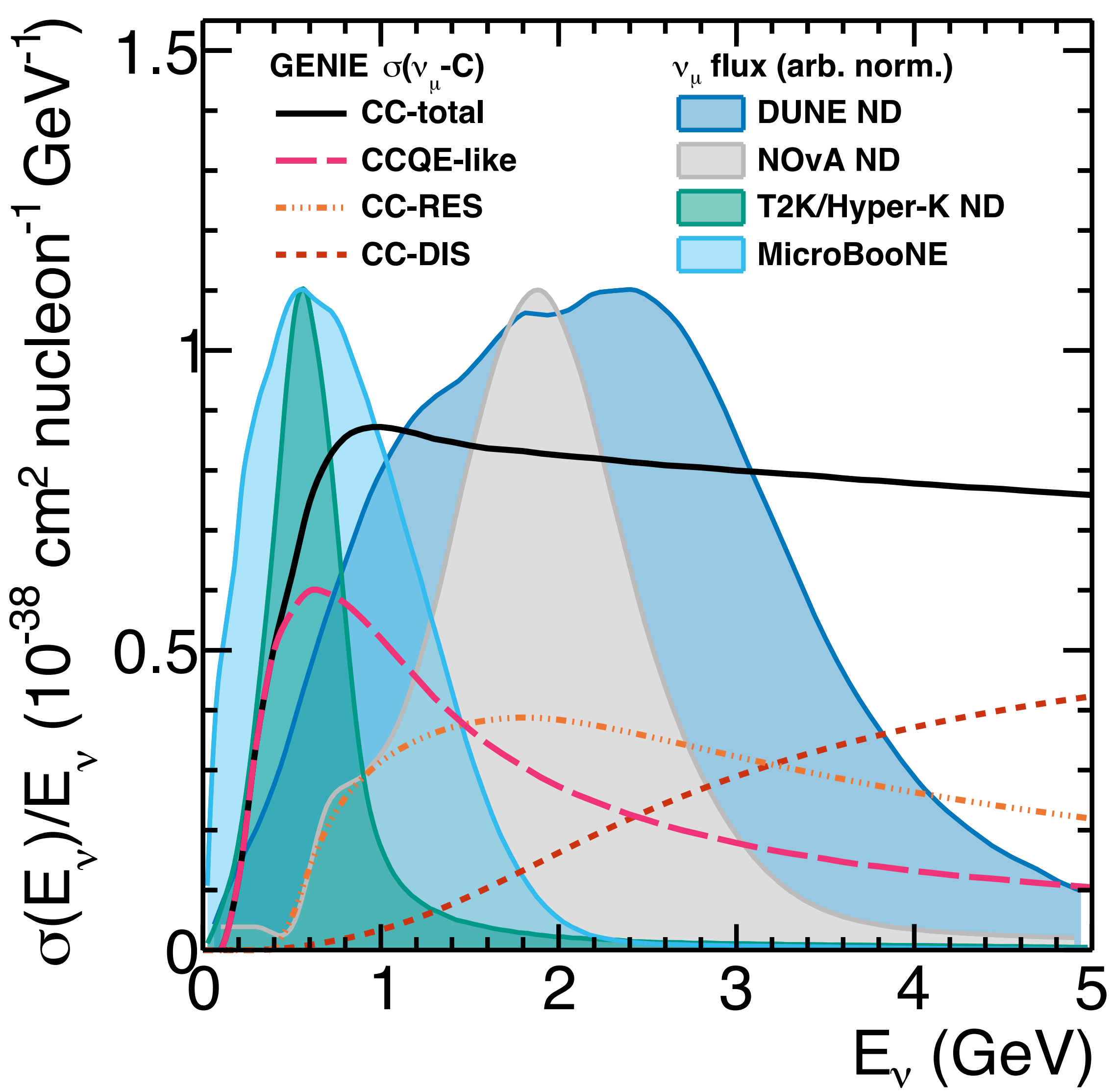


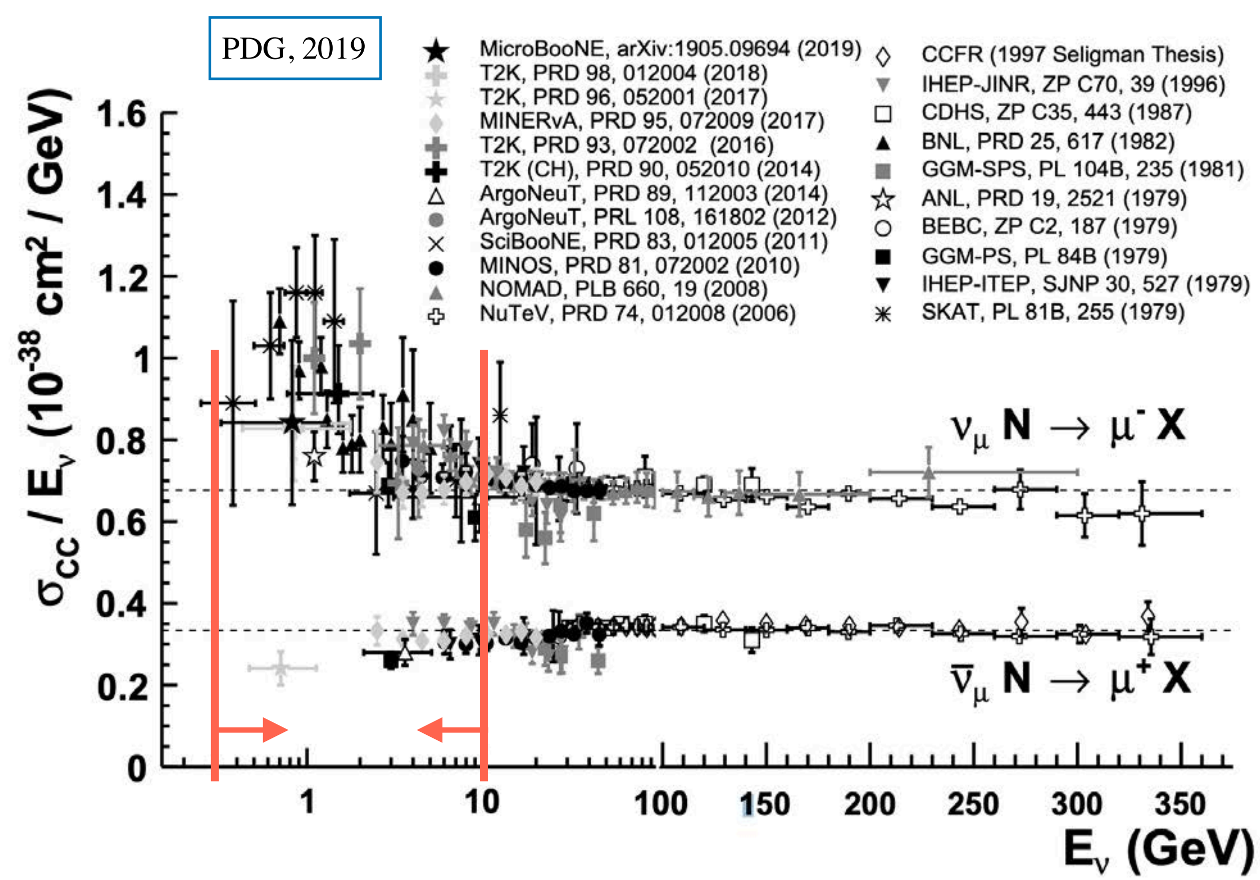
Neutrino Interactions at Few-GeV Range

What we can measure:

$$R(x) = \sum_{i}^{\text{process}} \sum_{j}^{\text{target}} \int_{E_{\min}}^{E_{\max}} \Phi(E_\nu) \times \sigma_i(E_\nu, x) \times \epsilon(x) \times N_j \times P(E_\nu, \nu_\alpha \rightarrow \nu_\beta)$$

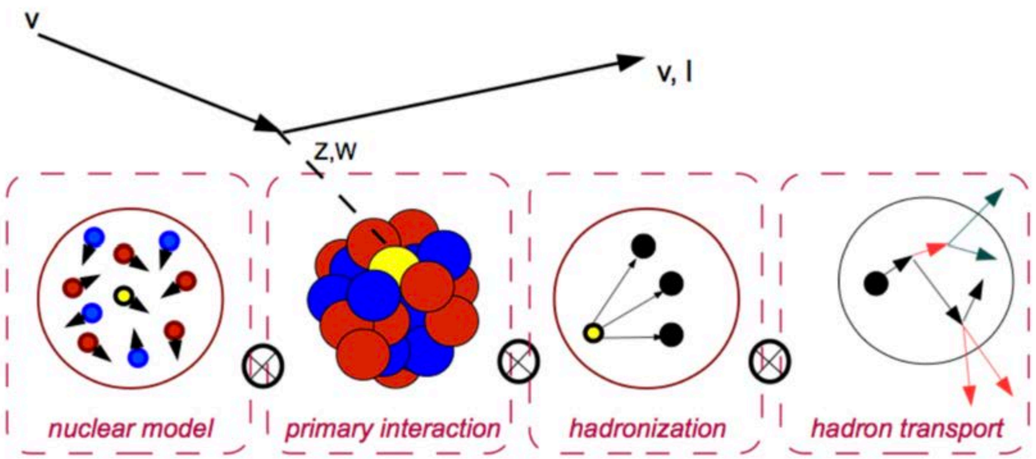
A mix of neutrino interaction modes in the relevant neutrino energy range for DUNE and other oscillation experiments

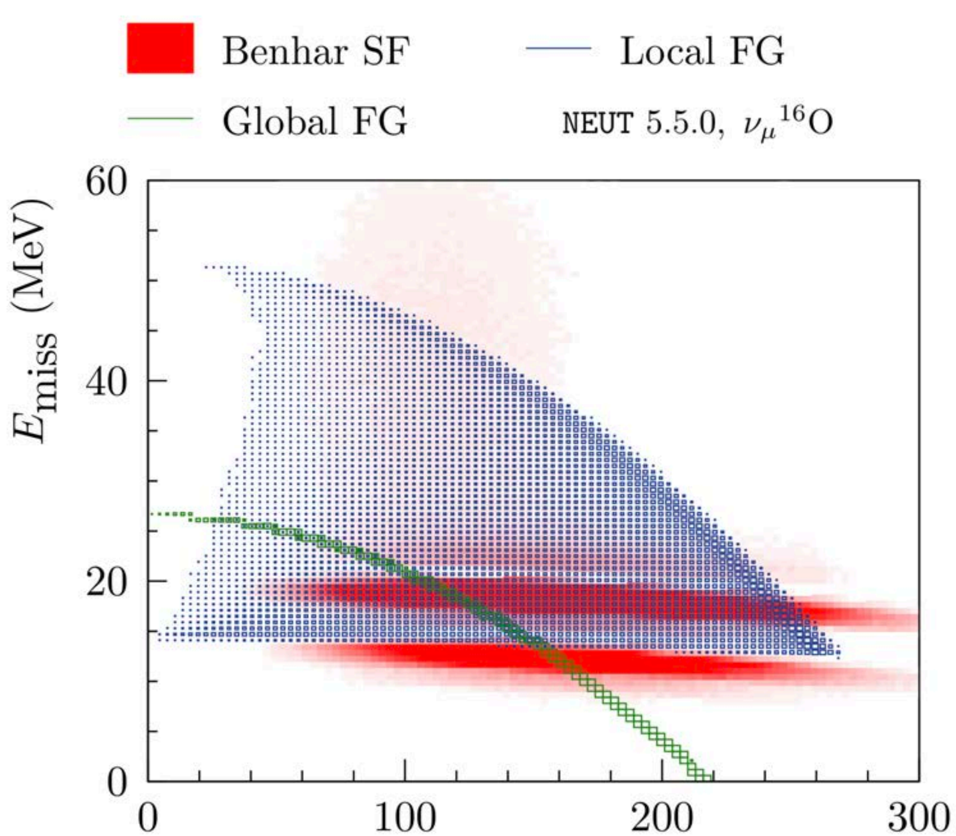




The Importance of the DUNE near detector

- DUNE's oscillation analysis will likely to be systematics limited
- Near detector is critical to reduce flux and neutrino interaction uncertainties





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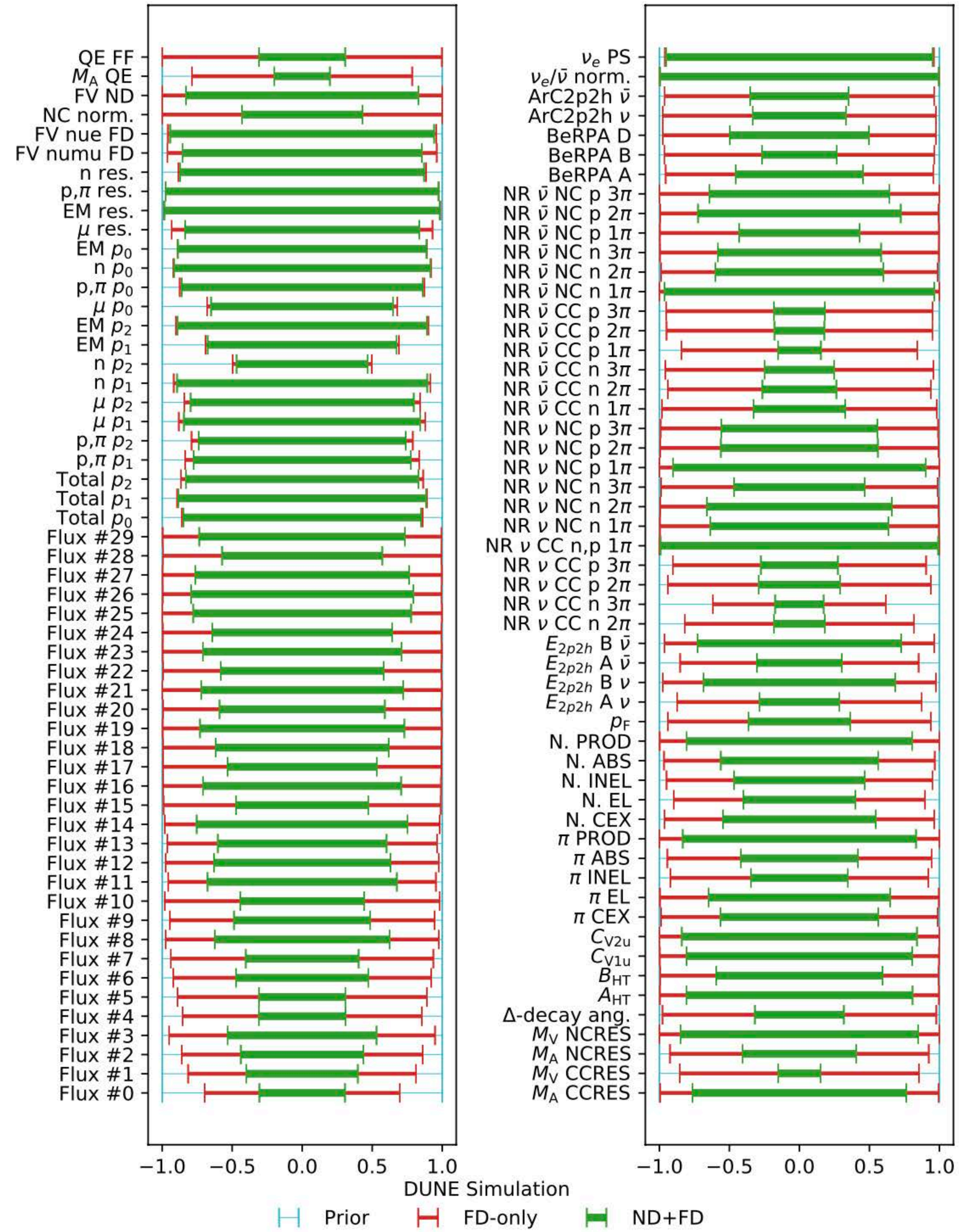


The Challenge for DUNE ND-LAr

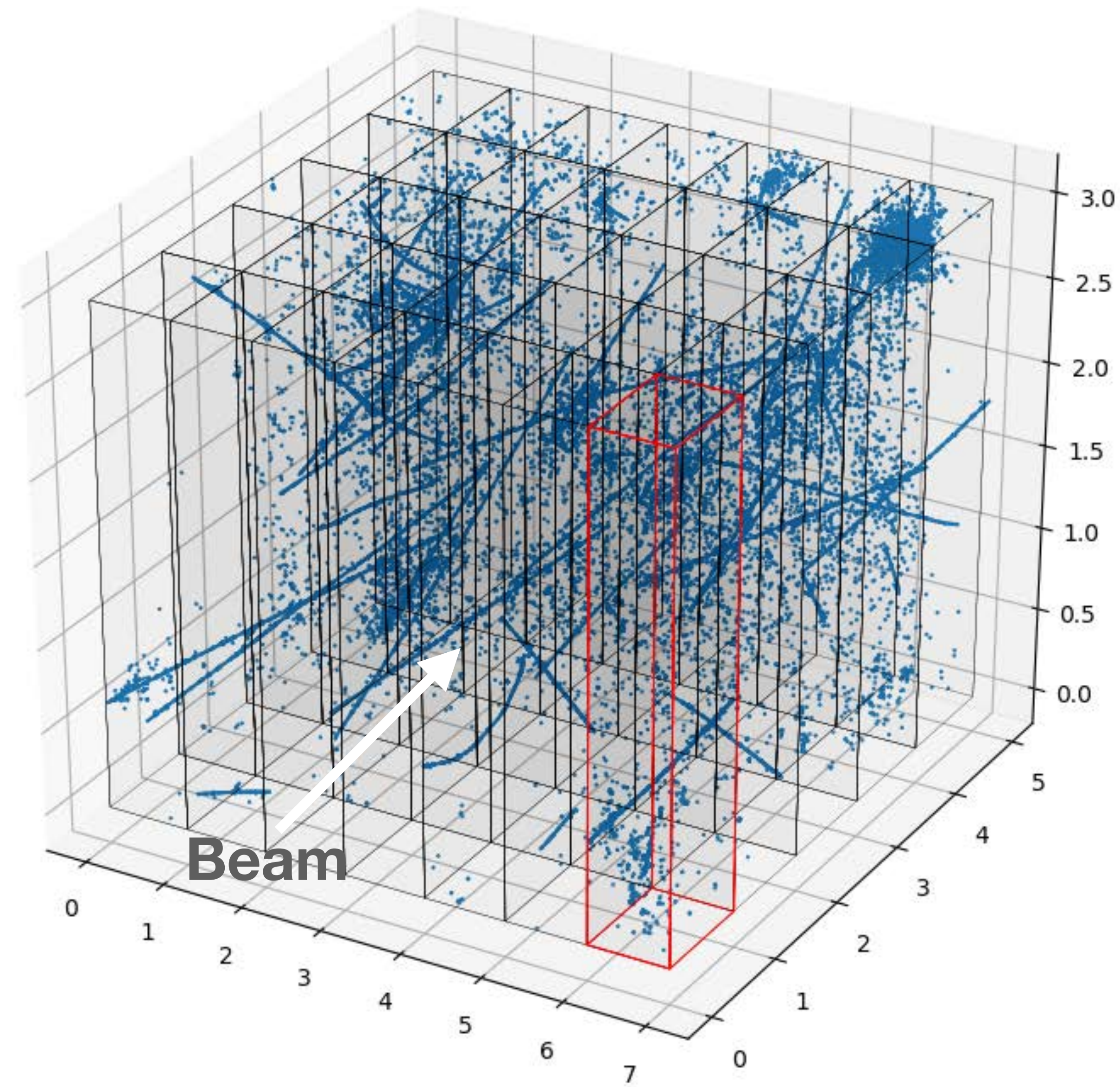
- ND-LAr is designed to contain hadrons and electrons from the beam neutrino interaction
- Active volume of ~ 5 m (L) × 7 m (W) × 3 m (H)

Main challenge: neutrino pile-up

- ~50 neutrino interactions per beam spill
- Existing LArTPCs deal with 0-1 neutrino per beam spill
- Beam spill O(μs) and LArTPC charge O(ms)

Solution: Modularized LArTPC

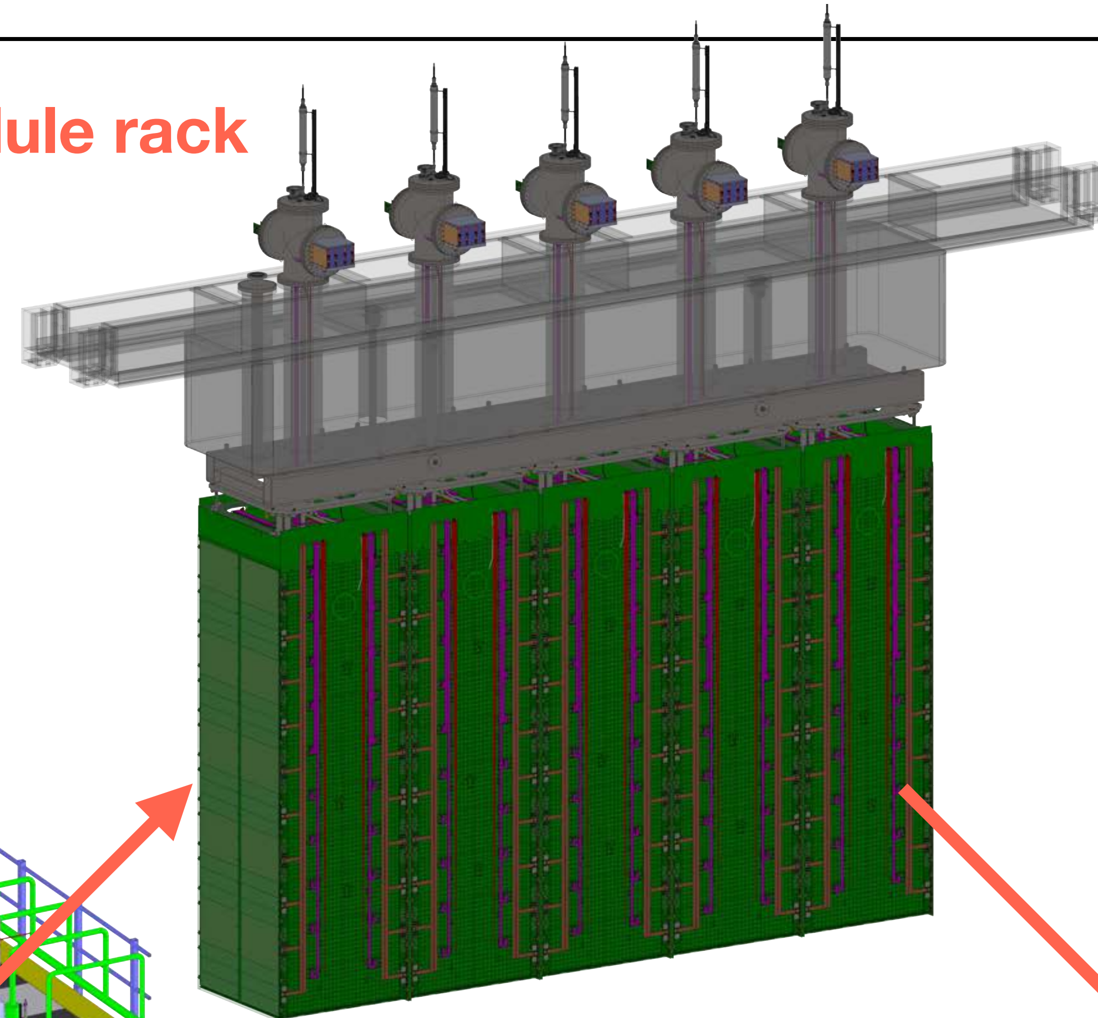
- LArTPC light readout O(ns)
- Localized scintillation light
- Light—Charge matching to tackle pile-up



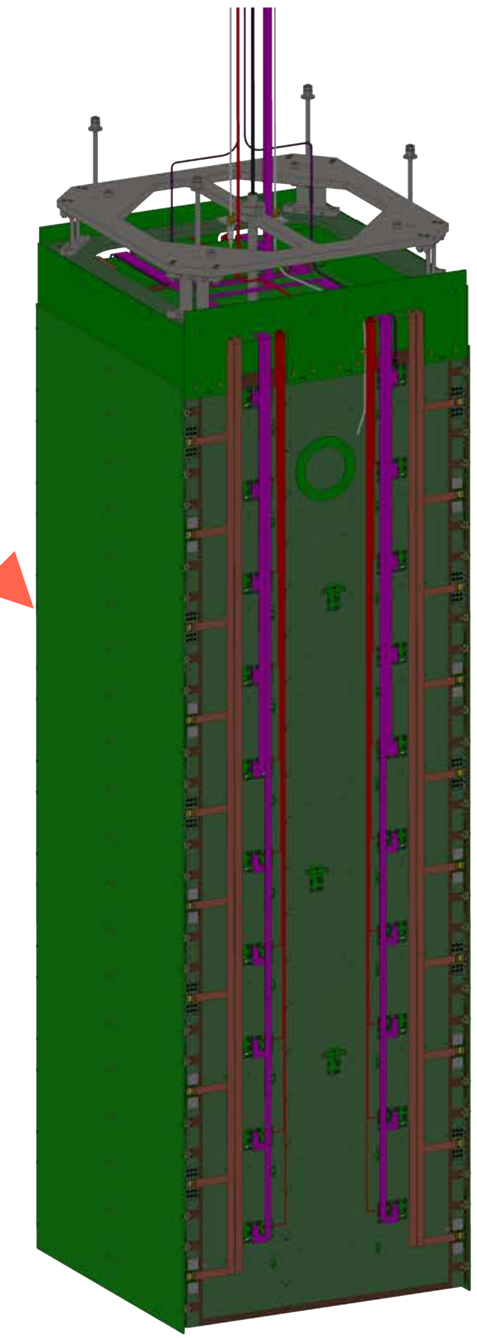
Simulated neutrino interactions of one beam spill (1.2MW) in ND-LAr

ND-LAr: Modularized LArTPCs

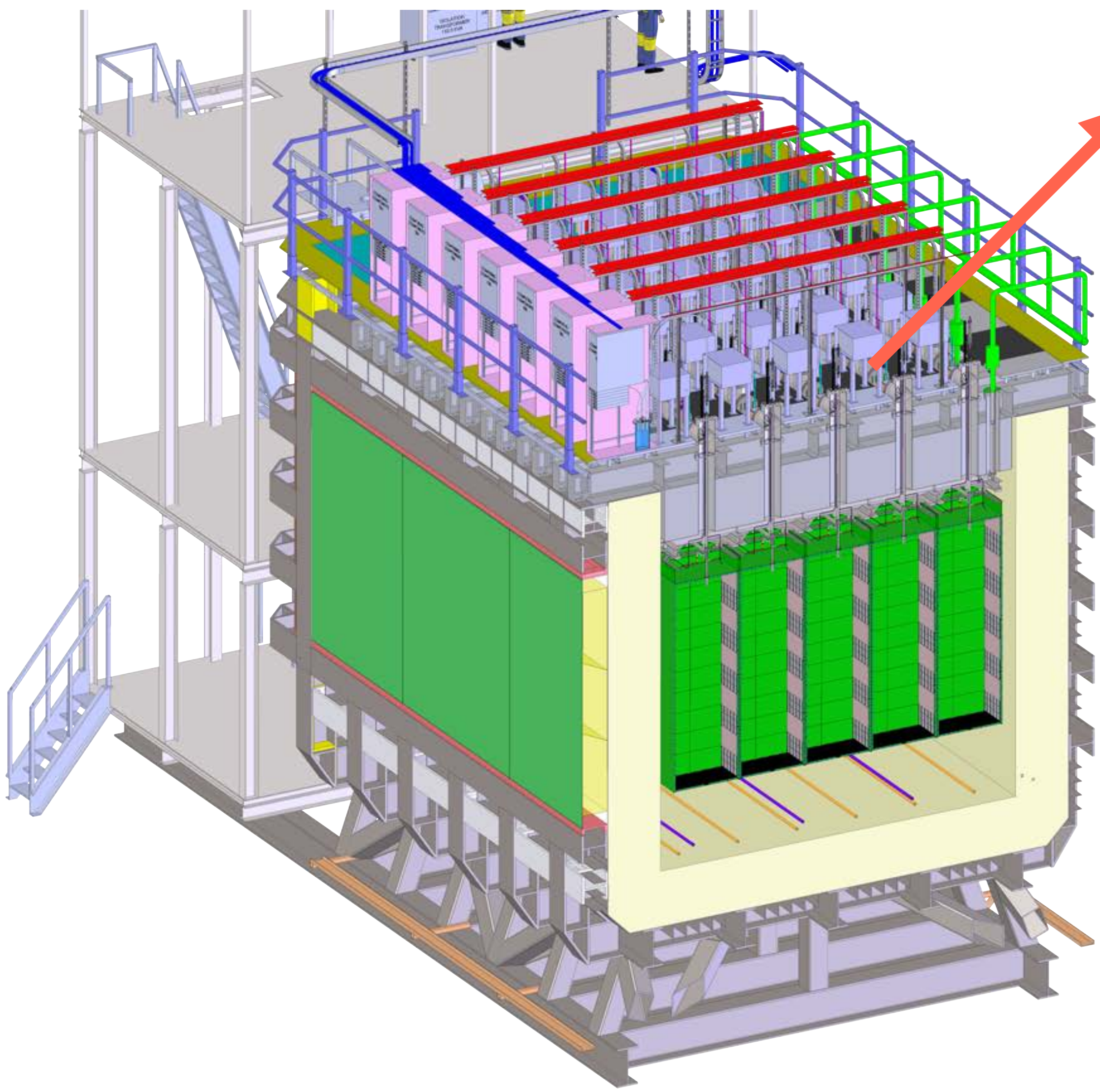
A 5-module rack



A single module

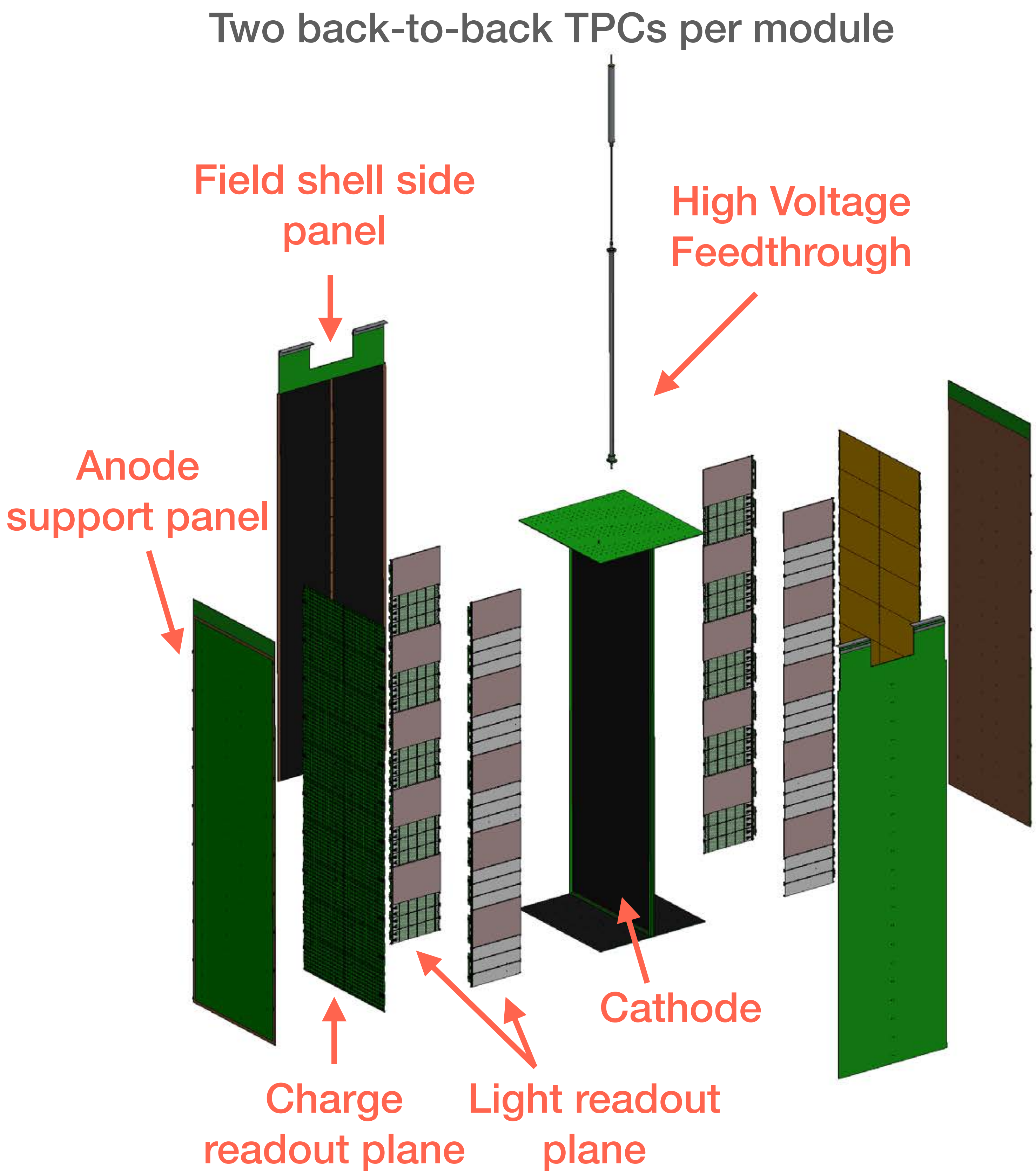


ND-LAr



- ND-LAr contains 5×7 modules
- Modules are assembled into rows of 5 along the beam direction when on-axis
- Each module has a size of 1×1×3 m^3

ND-LAr Module Design



Short drift length (50 cm)

- Significantly reduced cathode voltage and associated risks
- Simplifies electric field shaping
- Diffusion becomes subdominant

Pixelated charge readout

- True 3D position + charge mitigates ambiguities for reconstructing multi-neutrino events
- Low channel capacitance reduces noise
- PCB-based construction; mechanically robust; scalable

High-performance light readout

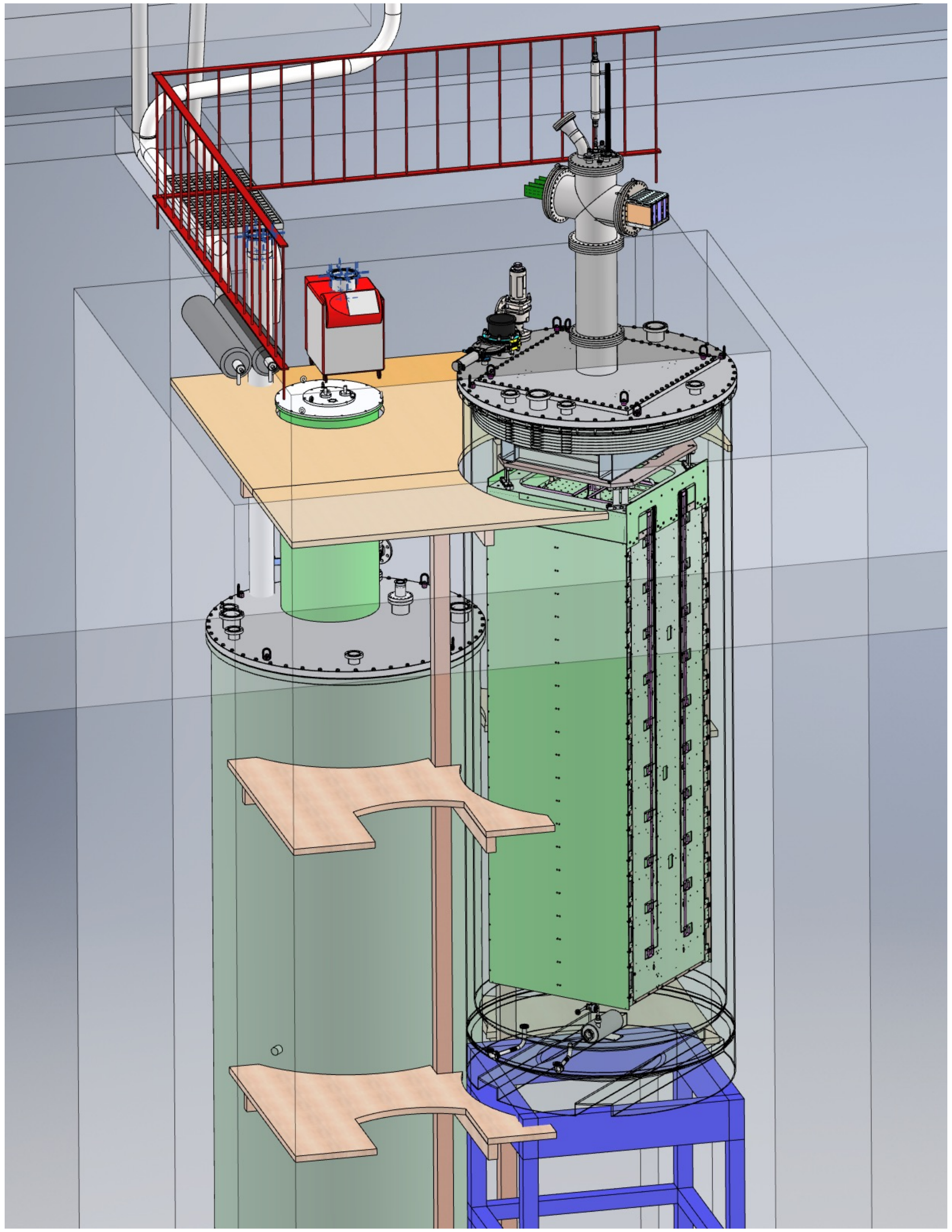
- 30% surface coverage
- O(5cm) spatial resolution

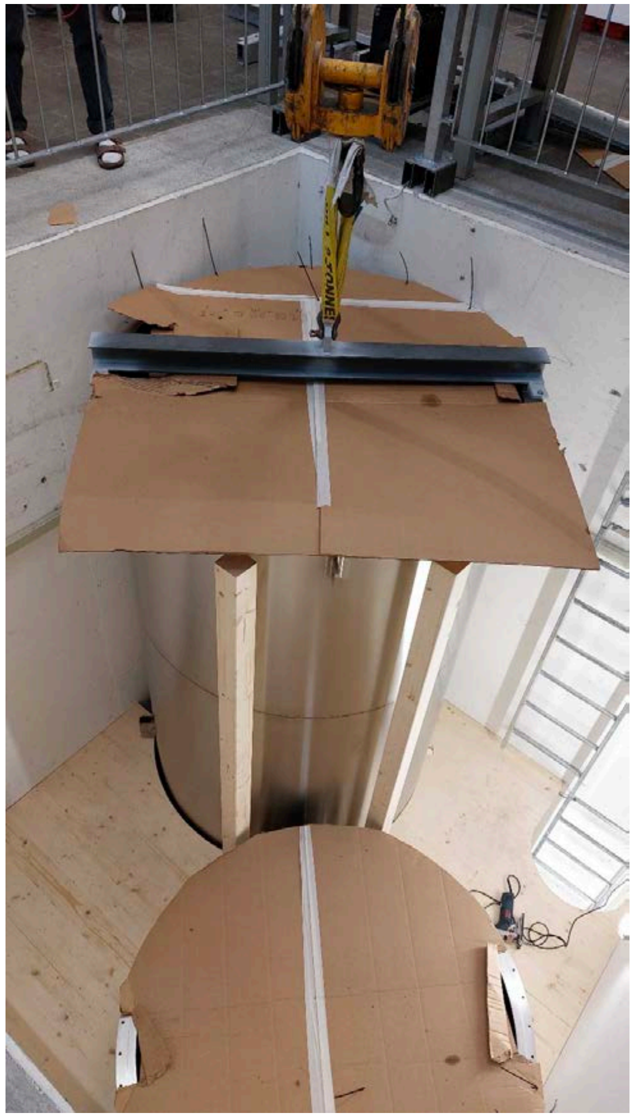
Modularized TPC

- Scintillation light tight
- Isolate potential failures

ND-LAr Full Scale Demonstrator

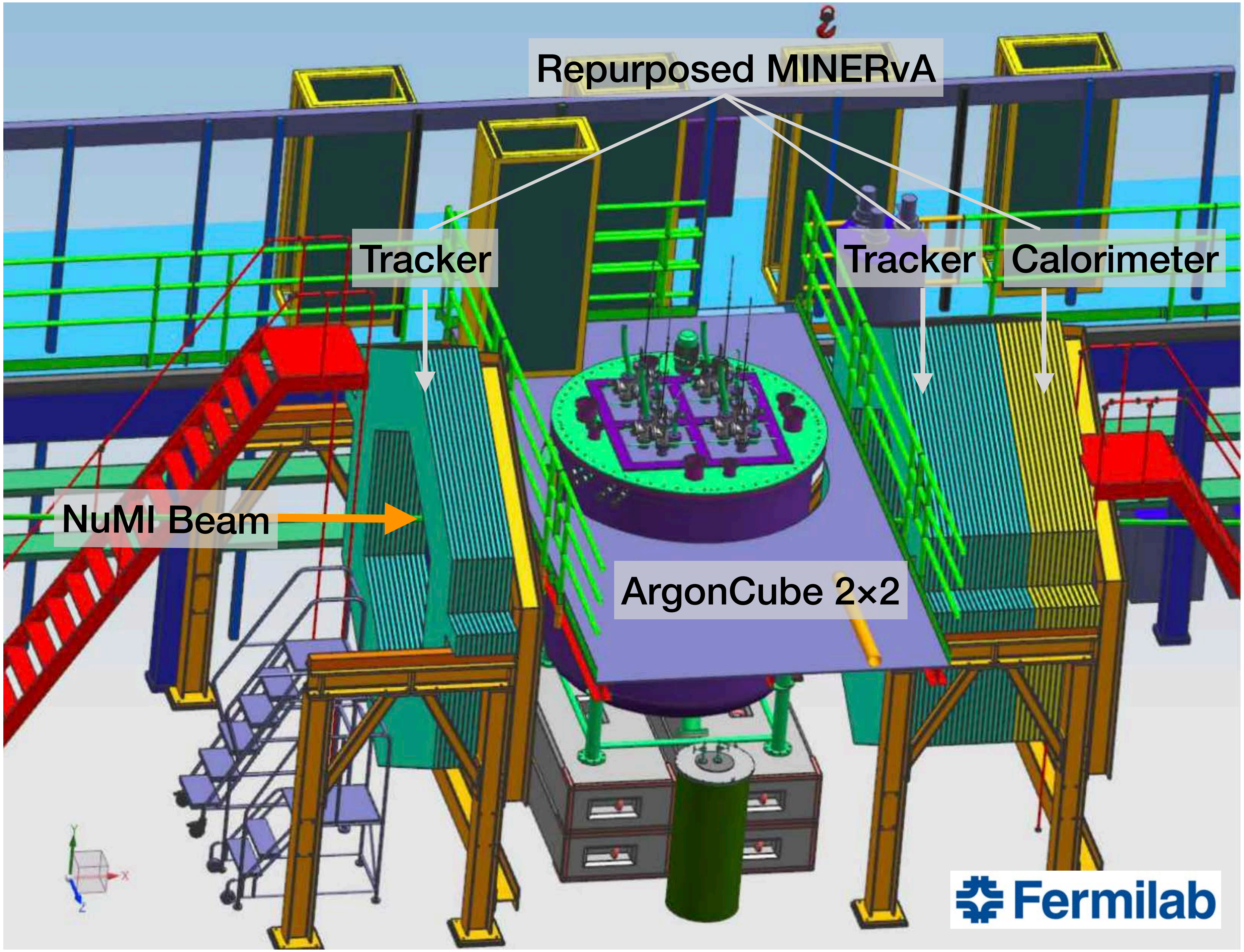
Scheduled to be tested in Bern in 2024
Cryo run in May; First full system operation in August
Current phase: system design and the production of the detector components



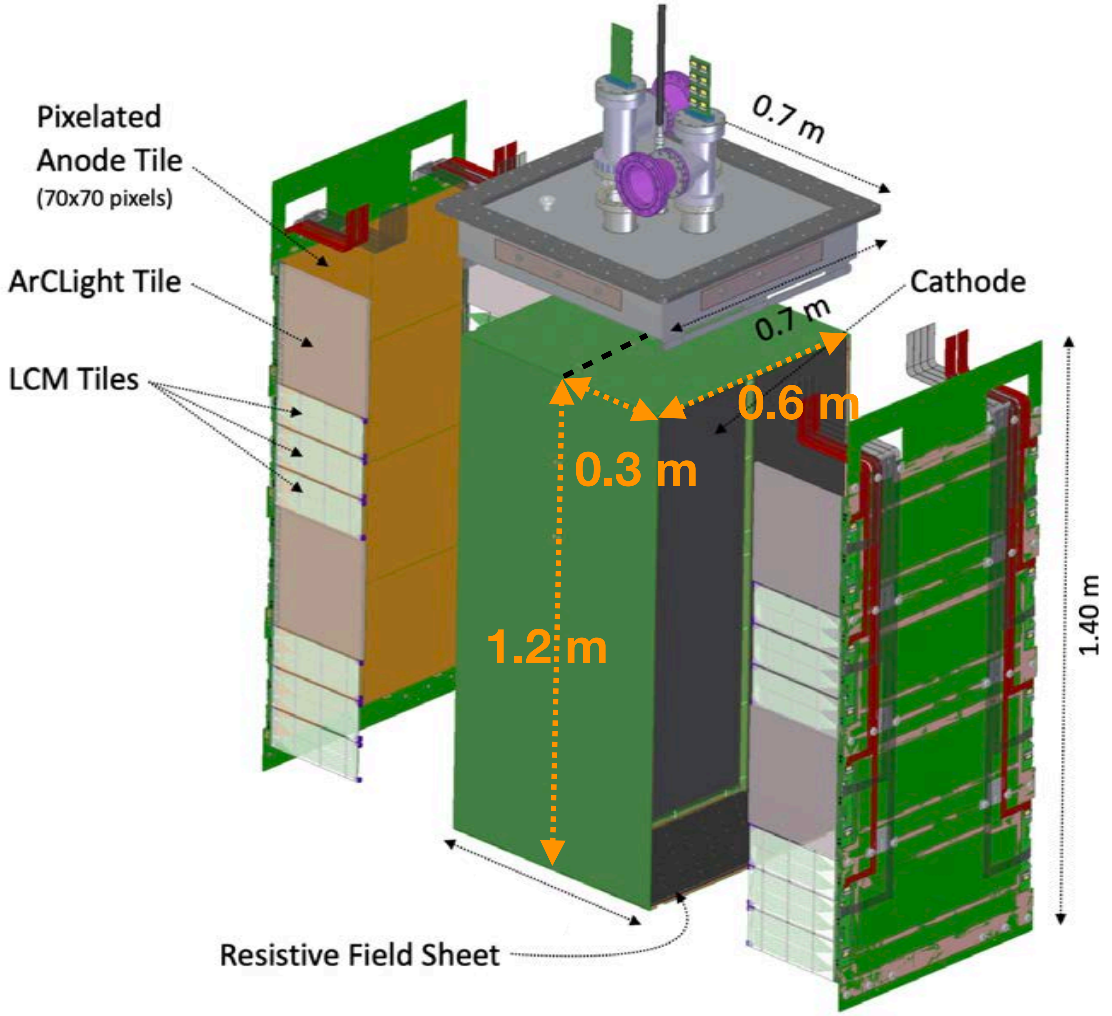


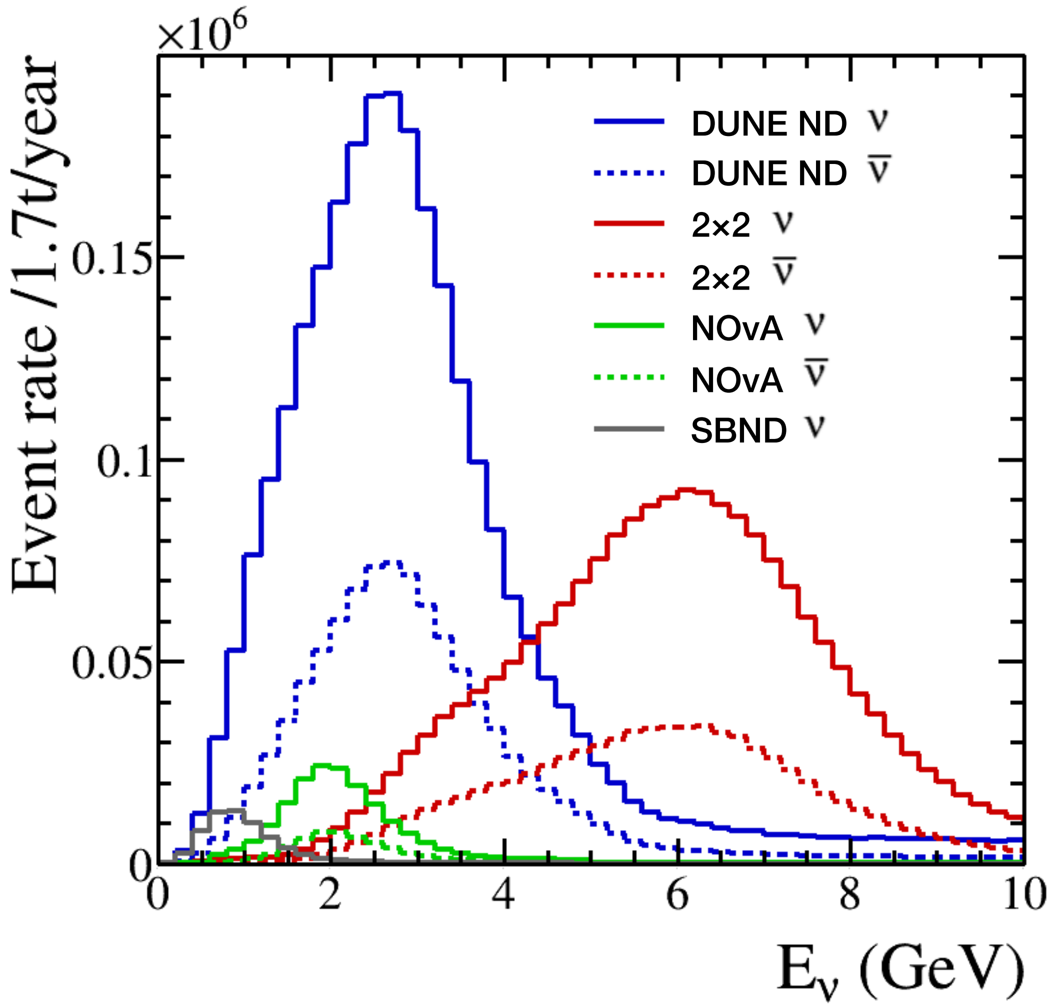
ND-LAr Prototype (2x2) in the NuMI Beam

Data taking with the full system will start in spring 2024.



A unique test bench and a realistic R&D Environment





Demonstration of a modularized LArTPC

- Exercise module integration
- Trigger, DAQ, cryogenic systems

Intense ν and $\bar{\nu}$ beam data (DUNE ND-like environment)

- Develop an end-to-end analysis infrastructure

Neutrino cross-section measurements

- Improve neutrino interaction models for future accelerator neutrino experiments

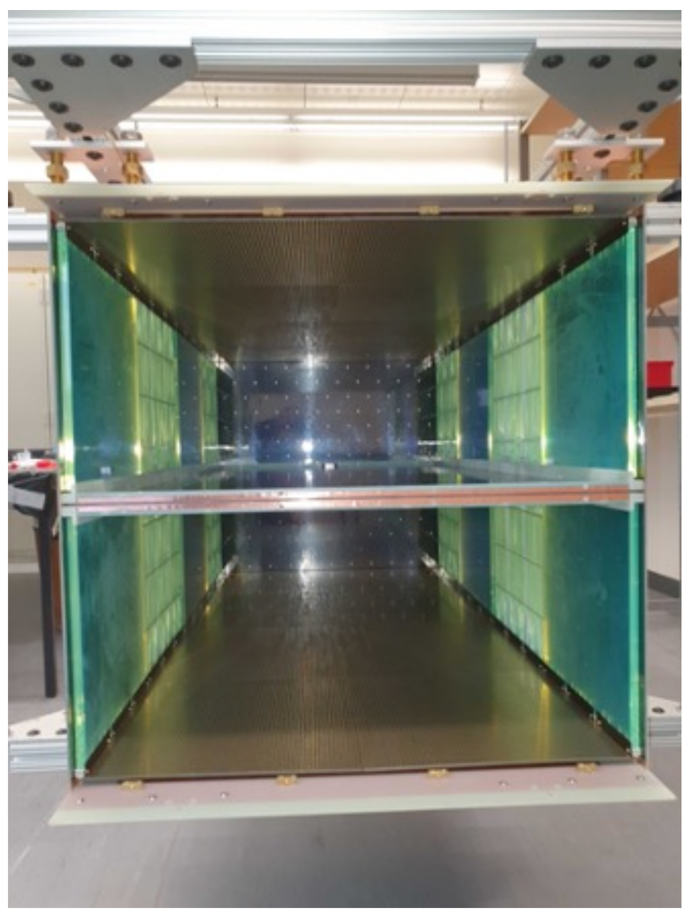
Single 2×2 Modules

Module tests in Bern (proof of module integrity)

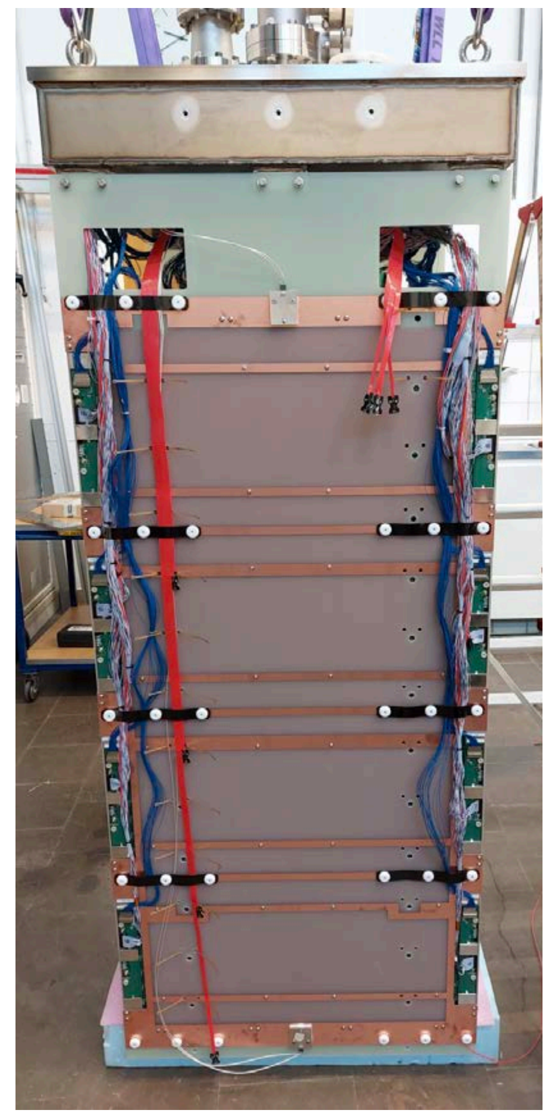
Module 0 **Module 1** **Module 2** **Module 3**

Detector components assembled as modules in Bern
Tested and operated for cosmic data taking

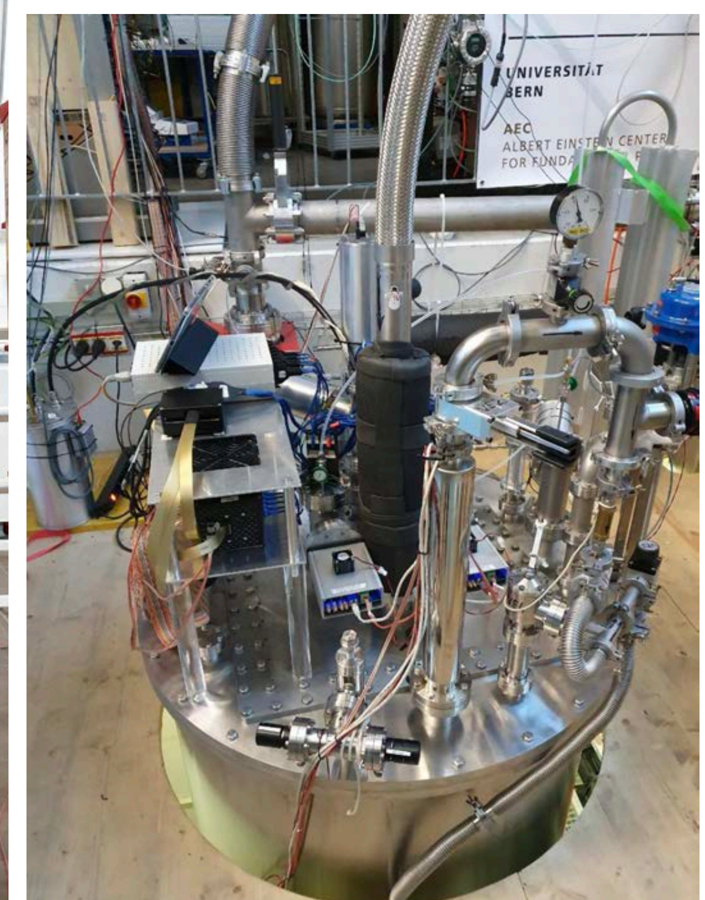
Single 2×2 module cryostat



View of the TPCs from the bottom

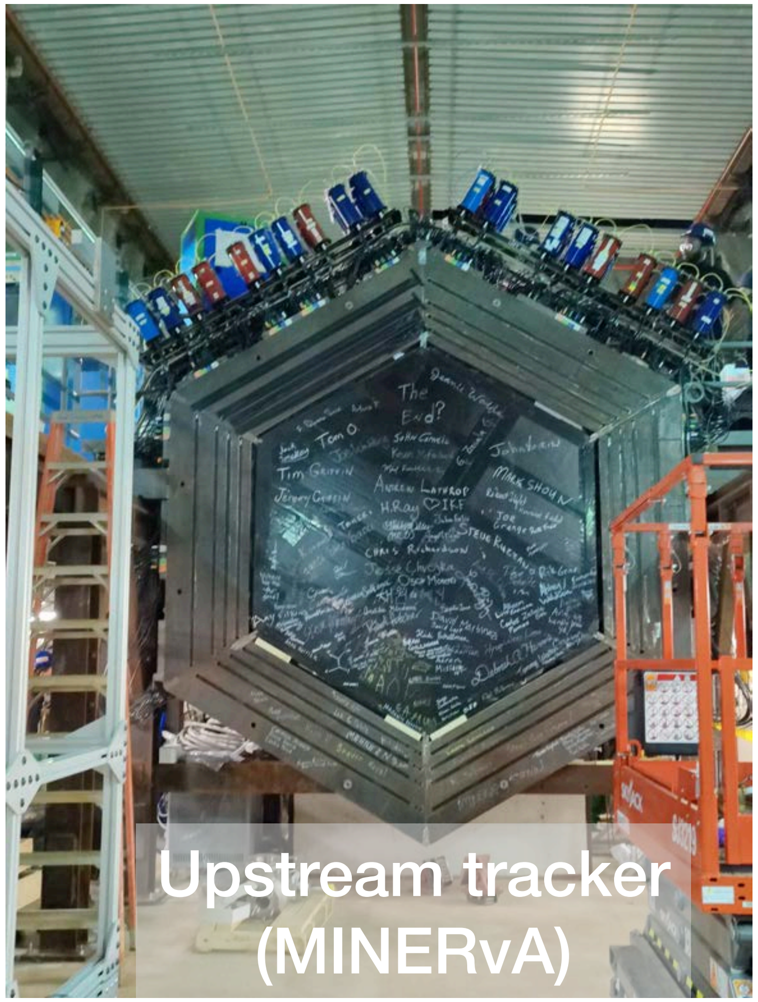


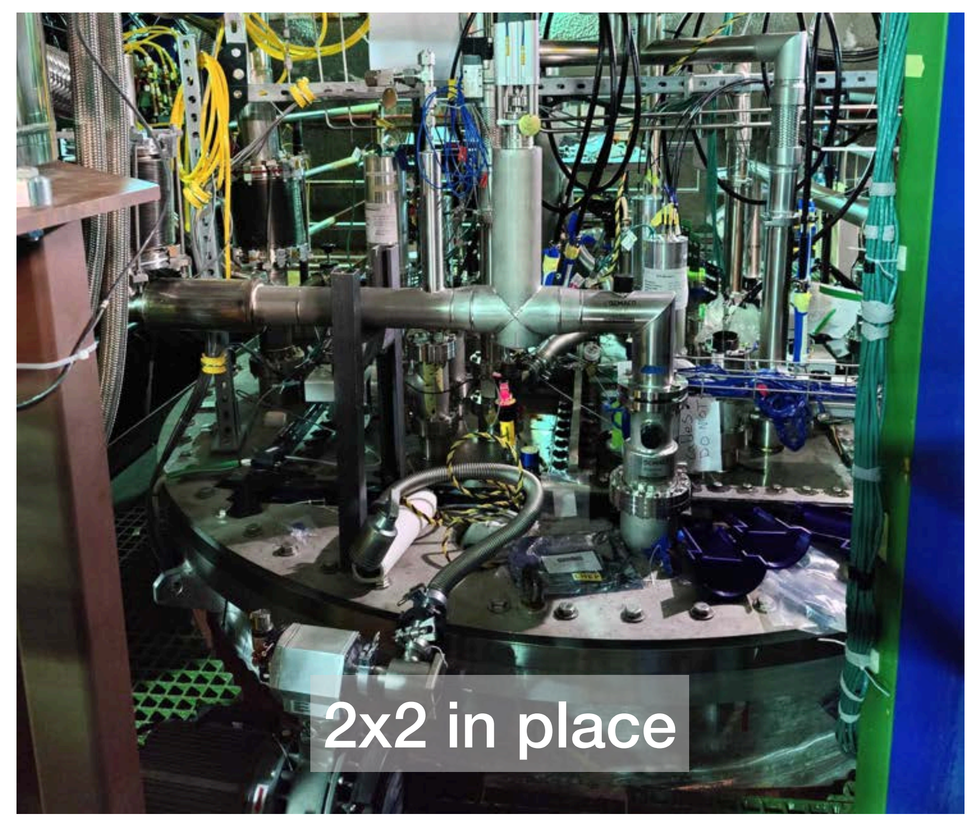
Assembled module



Module in operation

2x2 in the MINOS Hall at Fermilab





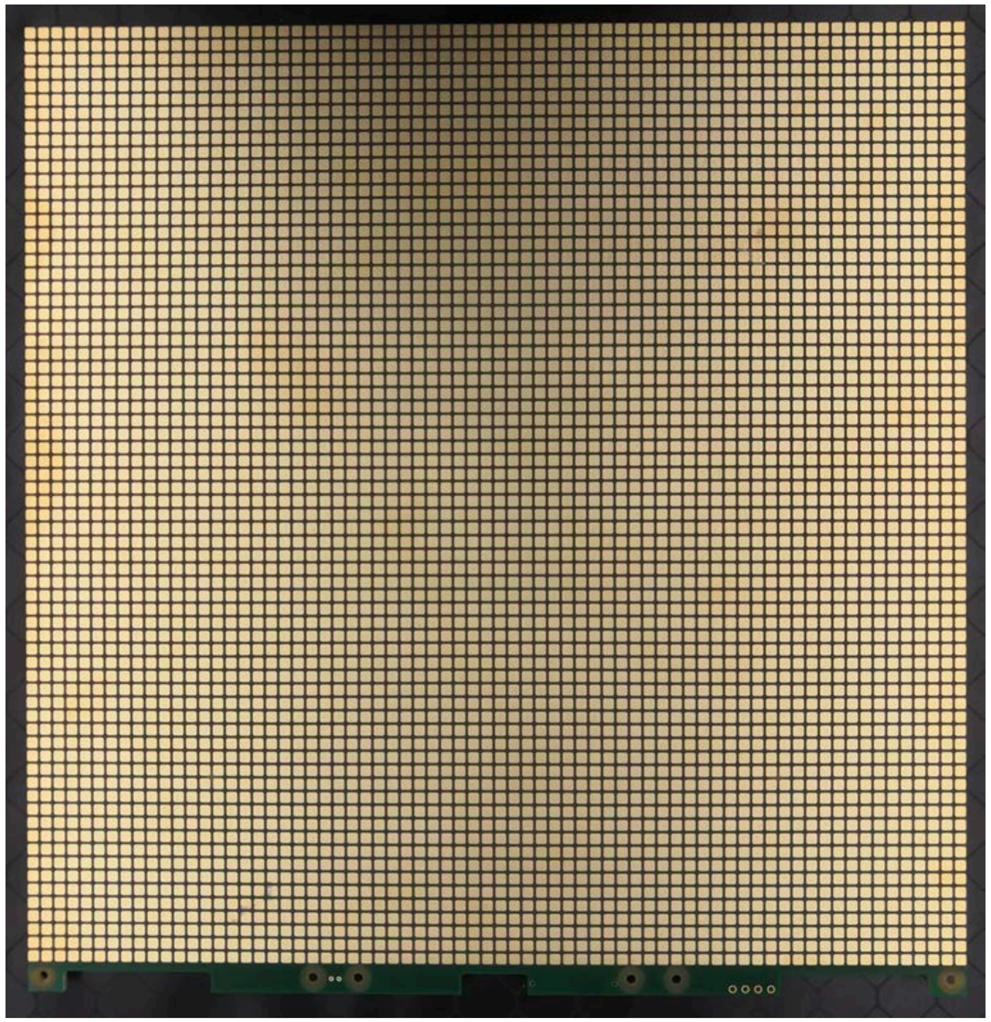
ND-LAr Pixelated Charge Readout: LArPix

LArPix-v1

JINST **13** (2018) P10007

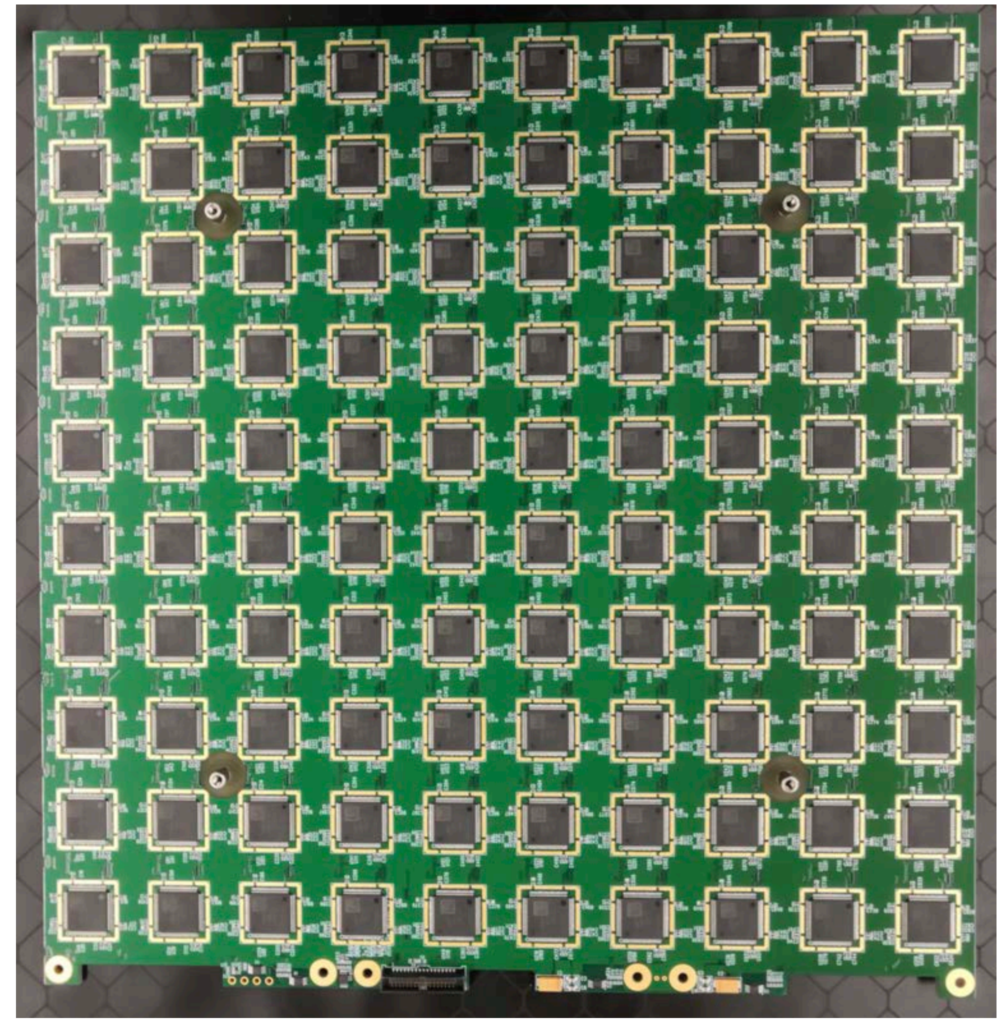
LArPix v2 Tile

Front



- 32 × 32 cm^2 LArPix tile
- 8 LArPix tiles per TPC
- 4900 square pixels per tile
- 4.4 mm pixel pitch
- ~300k channels in 2×2
- Each pixel can be independently self-triggered

Back



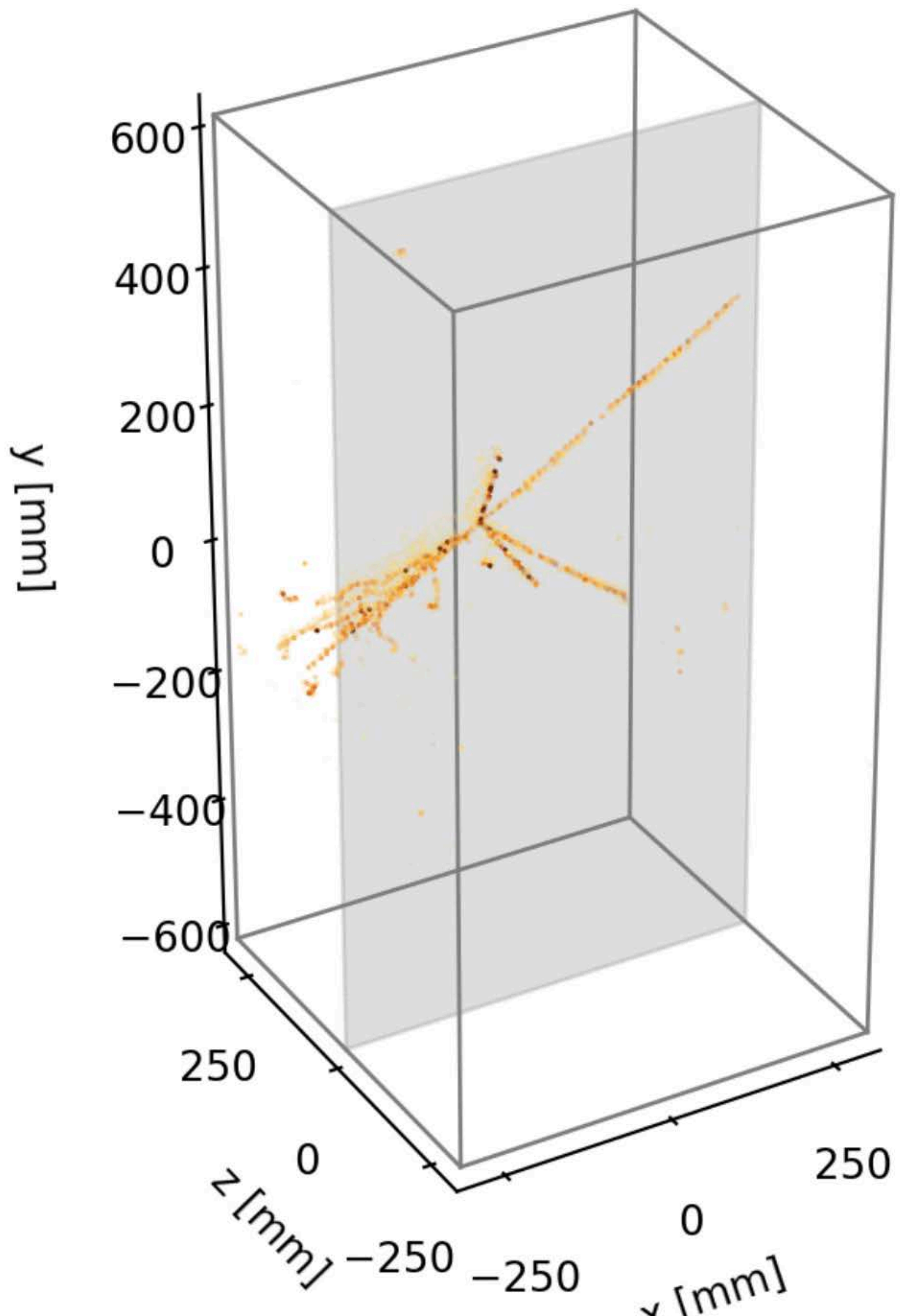
- 10×10 grid of ASICs
- Continuous readout
- Hydra-I/O: dynamic routing, robust to chip failure
- Robust to repeated cryogenic cycling
- Flexible tile config for scaling
- Commercial mass production

LArPix to Ease Pile-up in ND-LAr

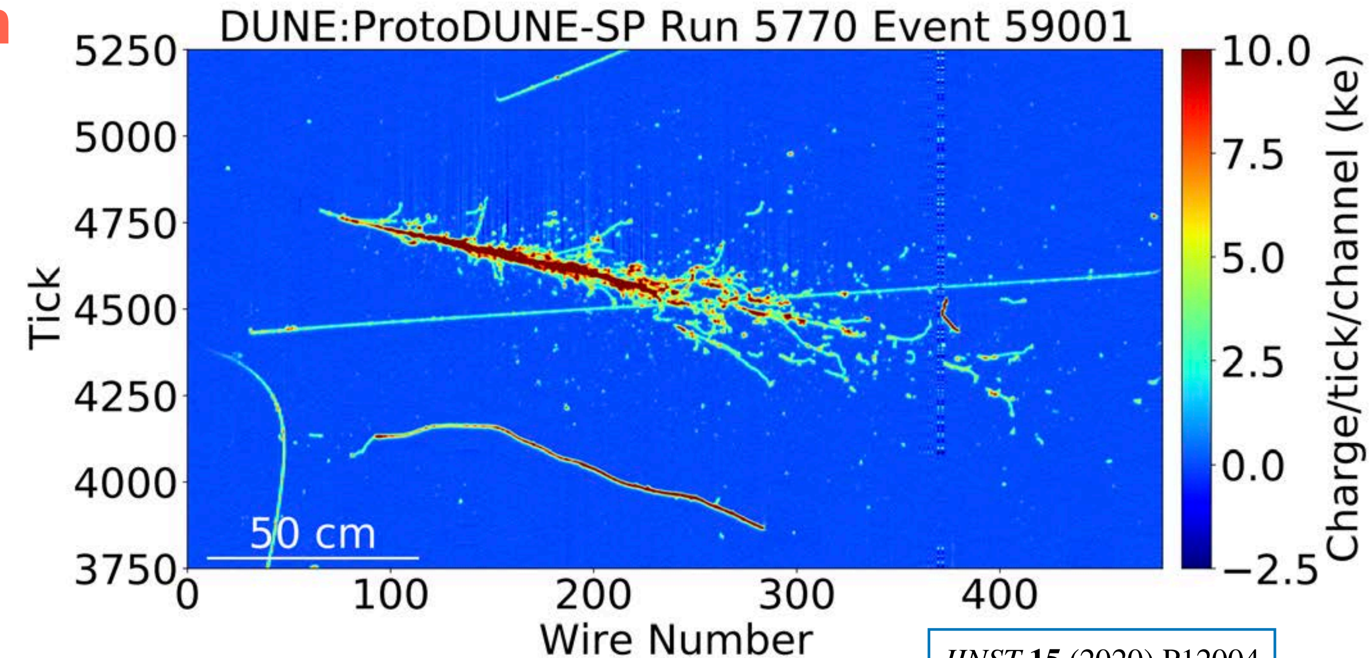
LArPix Charge Readout

Raw data from Module 1 cosmic run

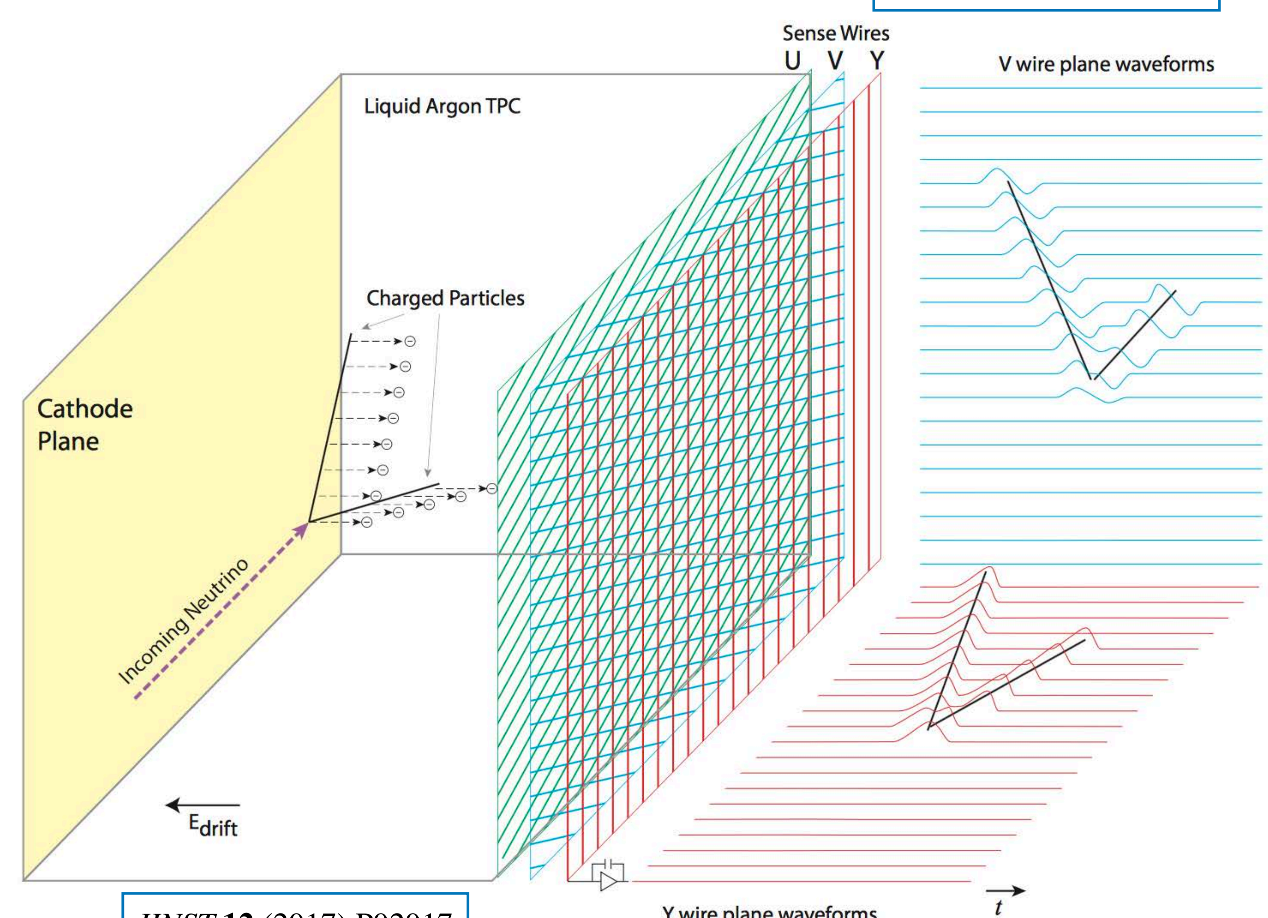
True projected 3D position



Conventional wire readout



JINST **15** (2020) P12004



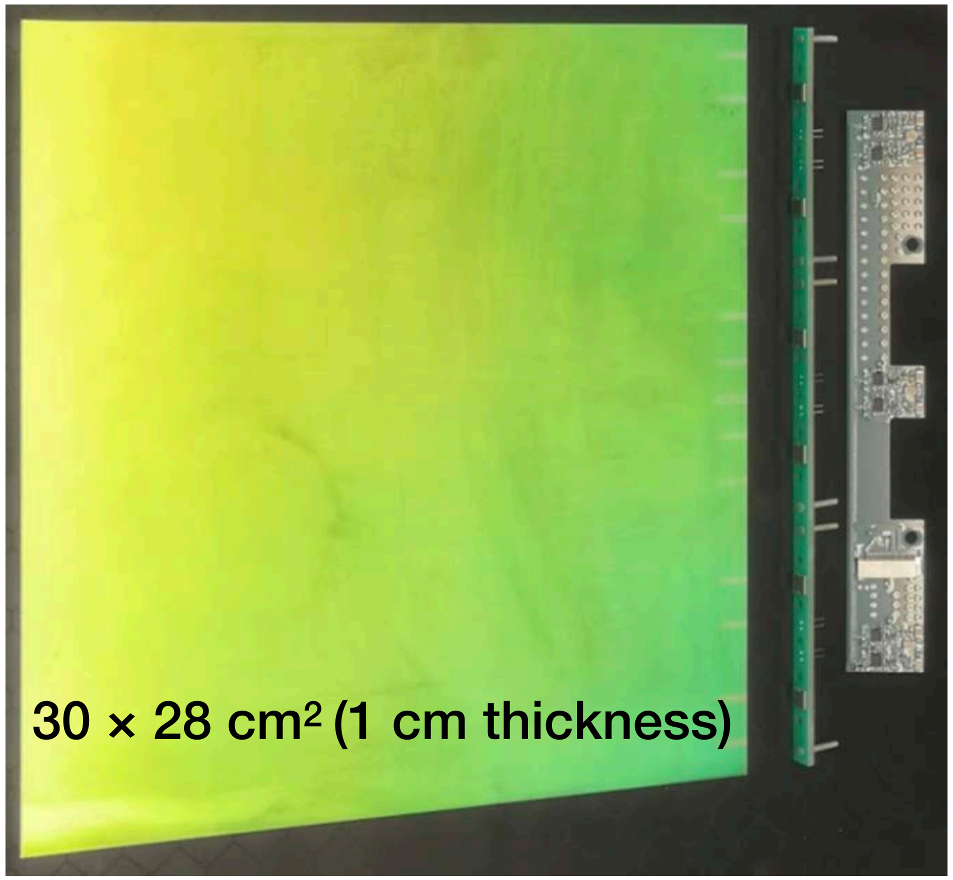
JINST **12** (2017) P02017

ND-LAr Light Detector: ArCLight and LCM

ArCLight

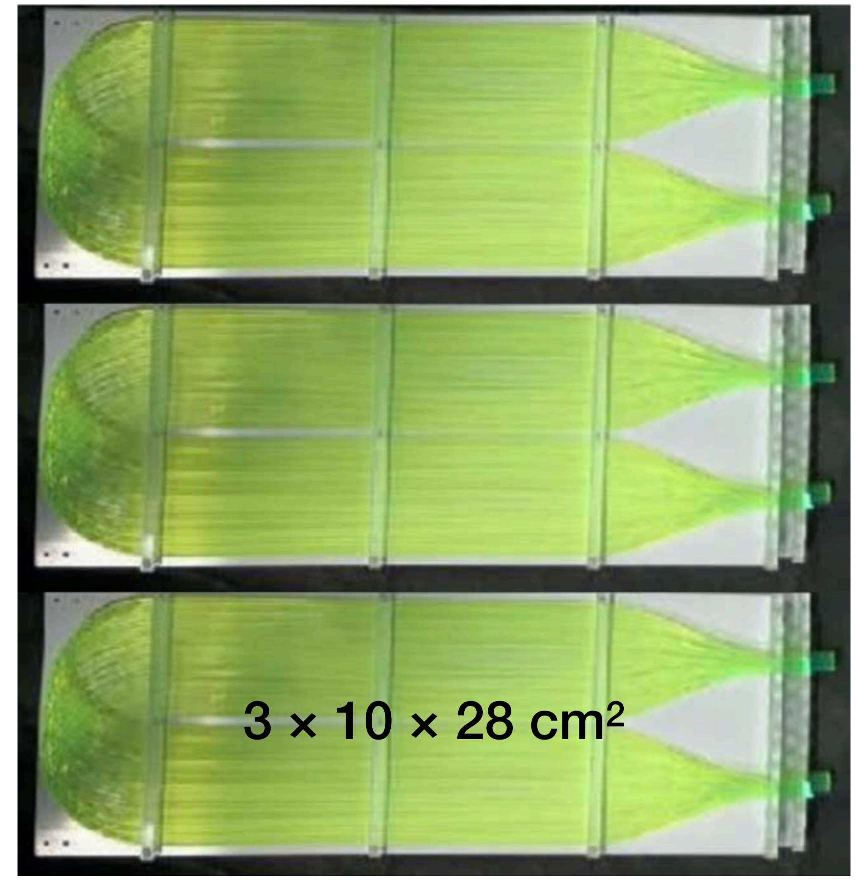
Instruments **2018**, 2(1), 3

Good at position sensitivity



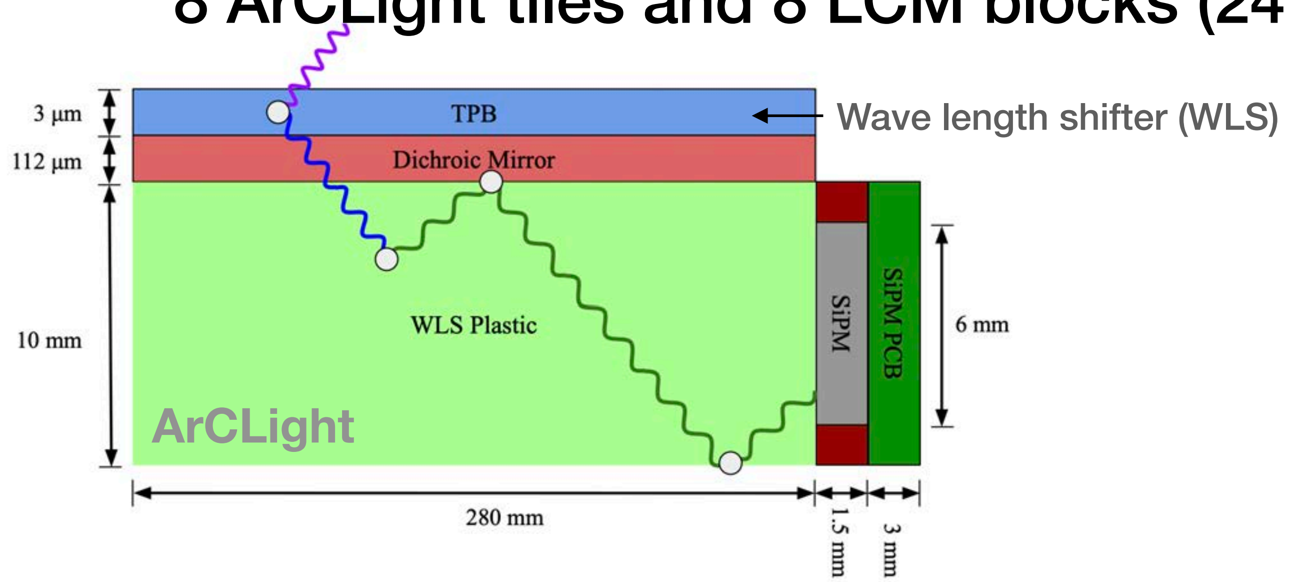
LCM

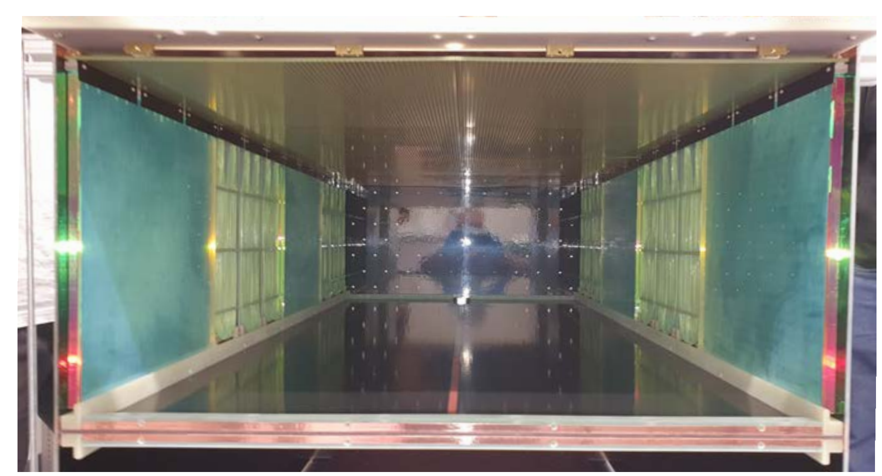
Good at detection efficiency



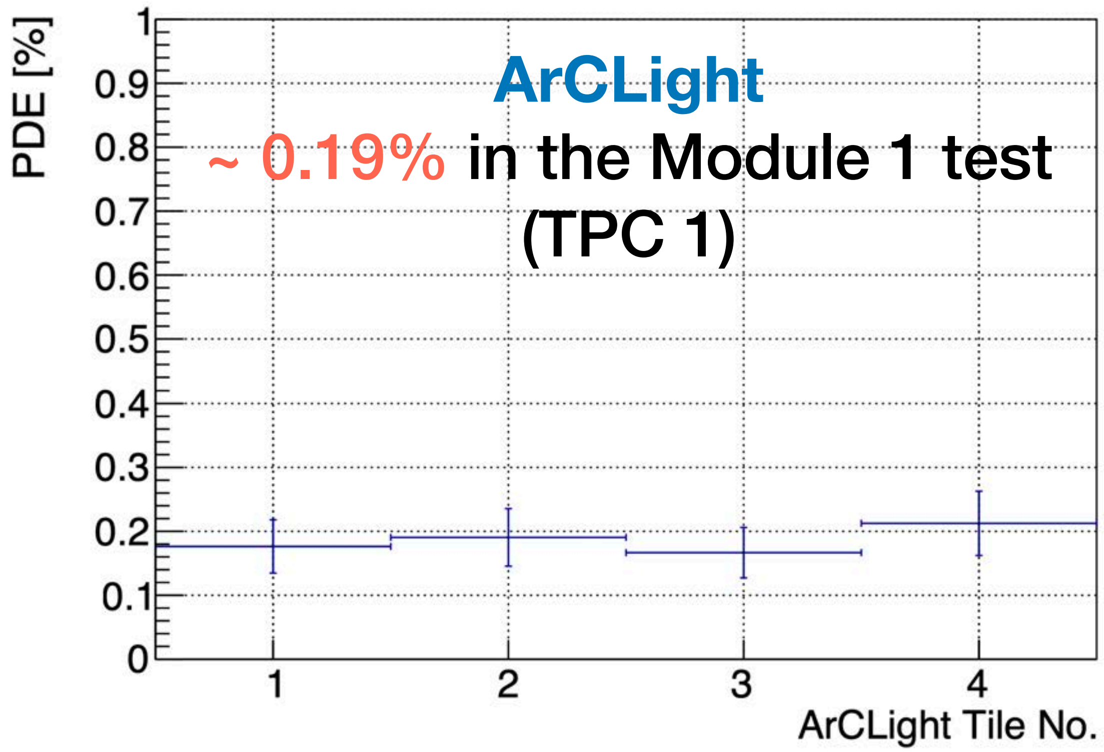
6 SiPM per light detector block; ~400 SiPM channels for 2×2

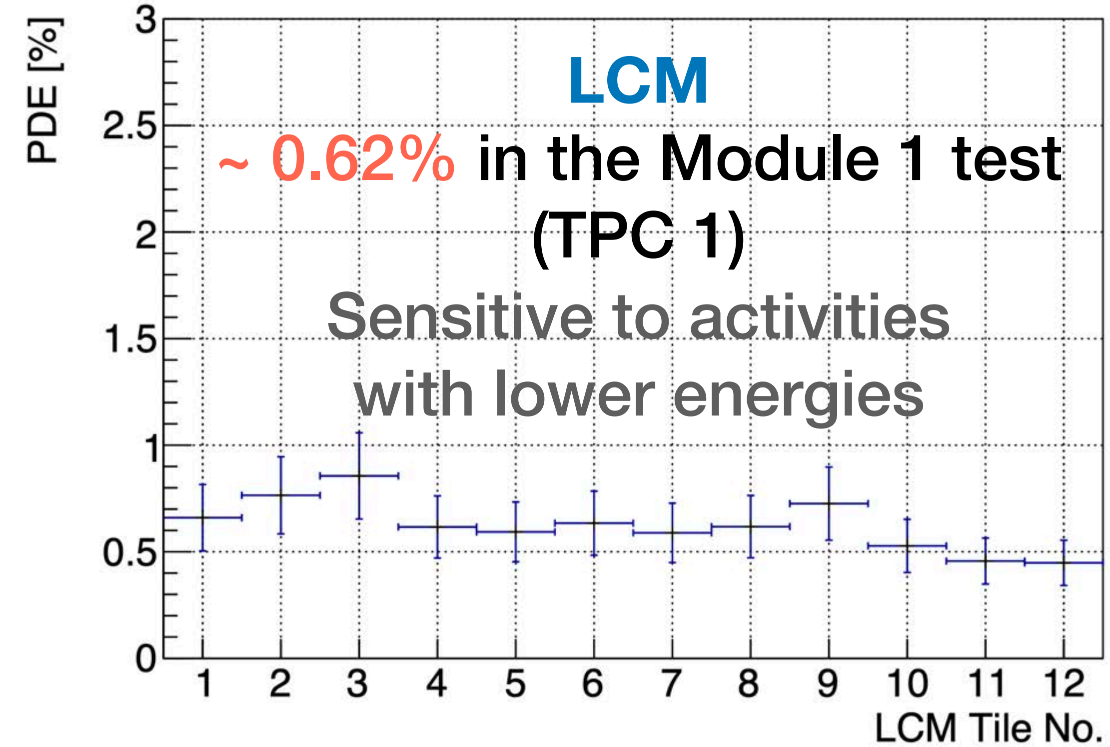
8 ArCLight tiles and 8 LCM blocks (24 LCM tiles) per 2×2 Module

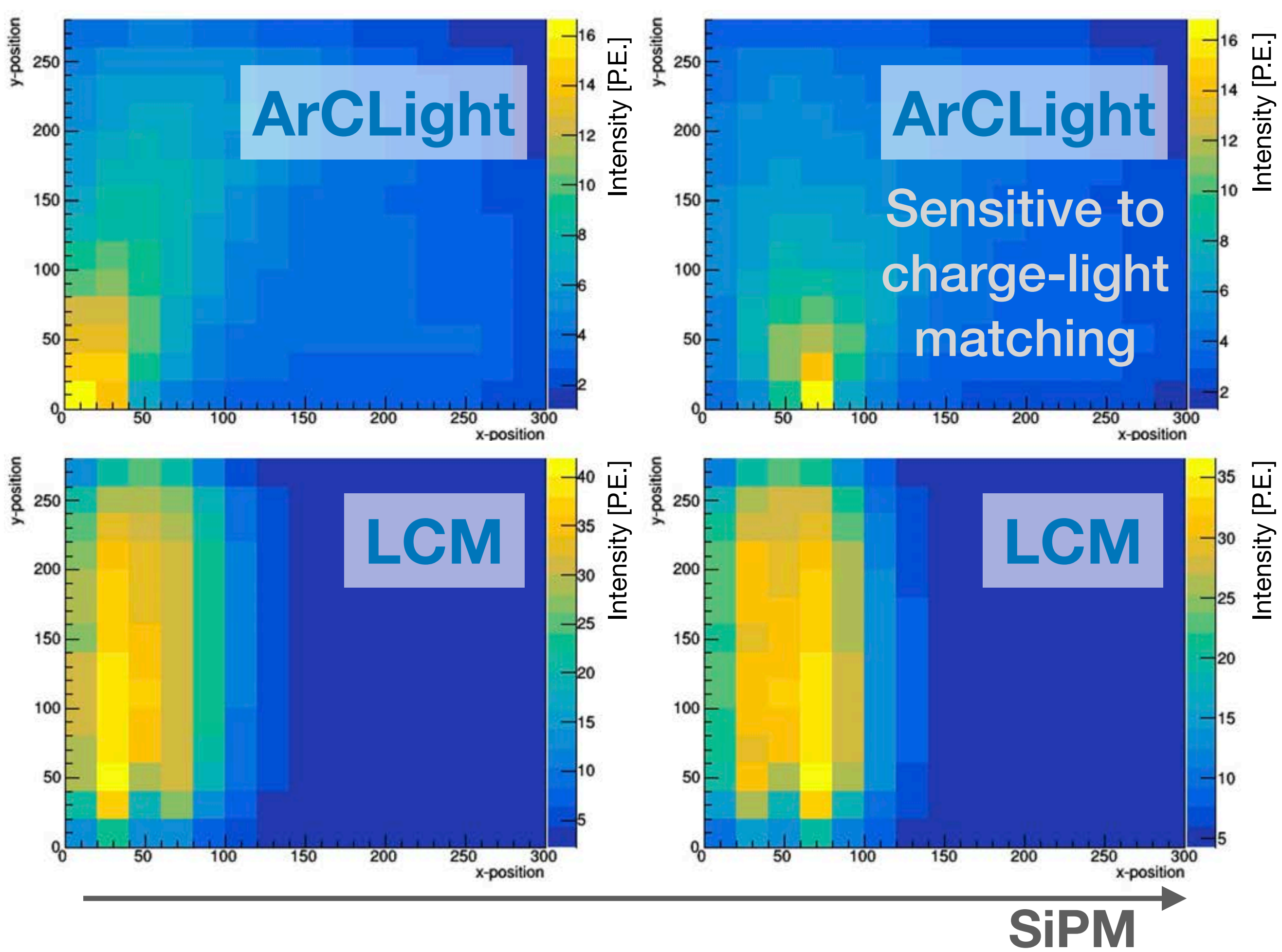


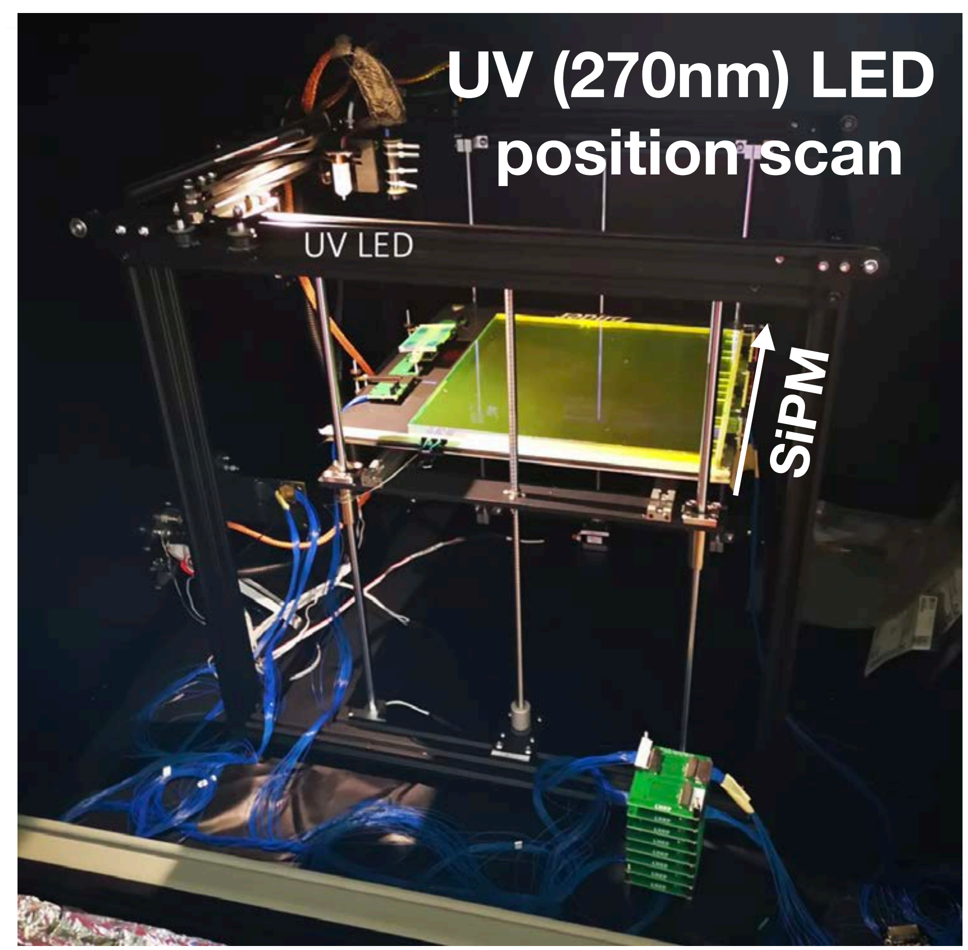


Photon Detection Efficiency and Position Sensitivity



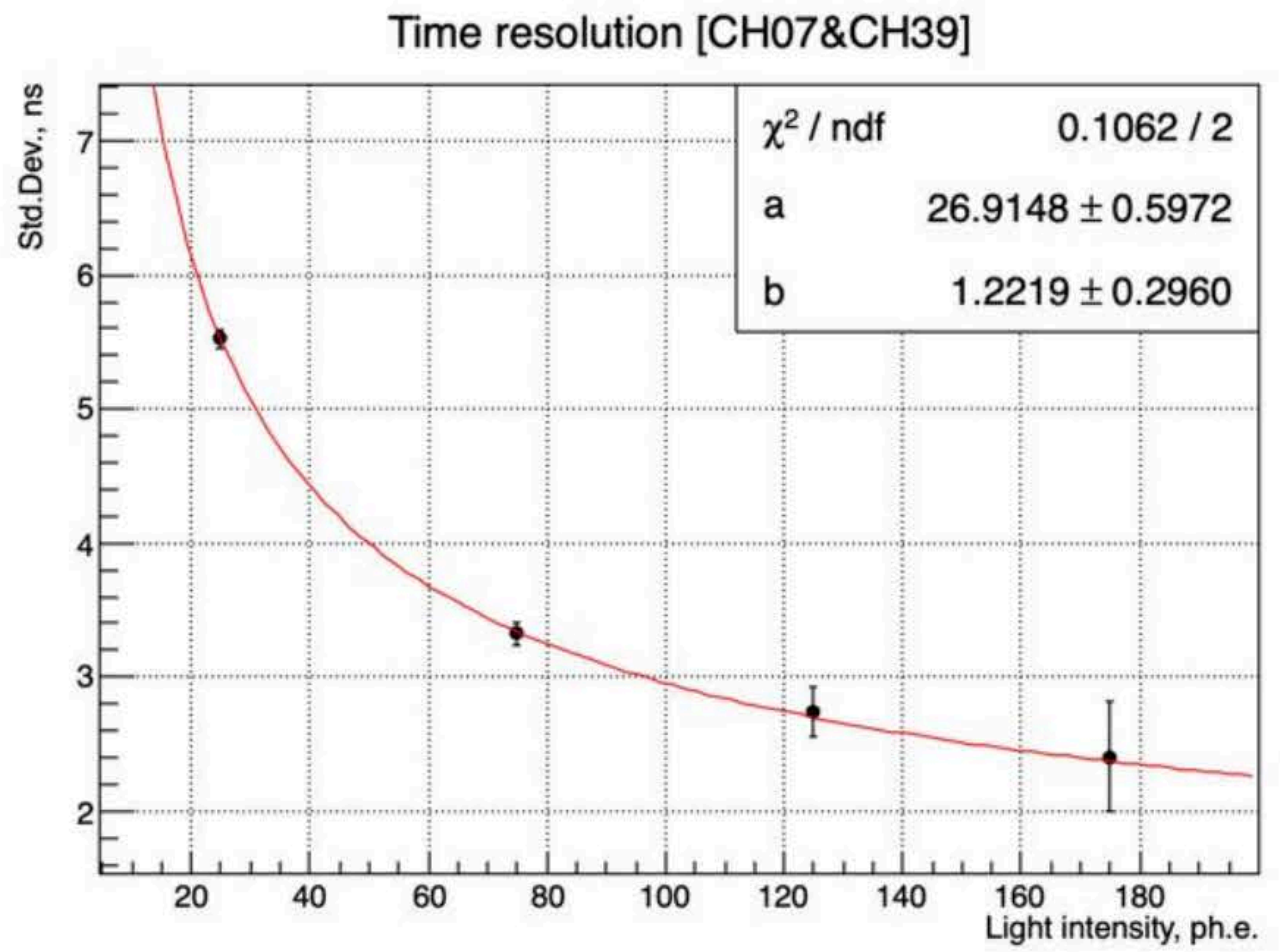






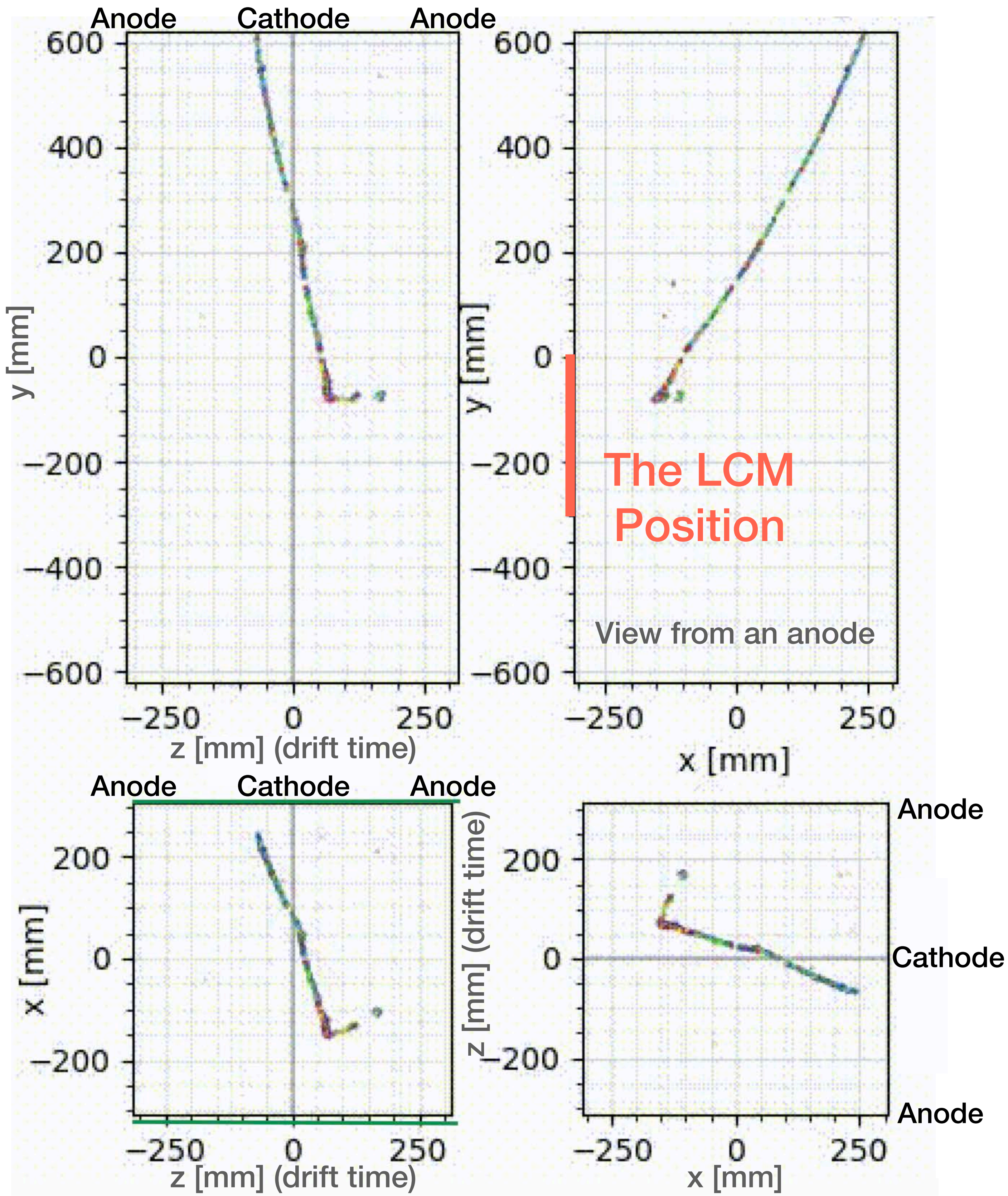
Timing Resolution from Module Tests

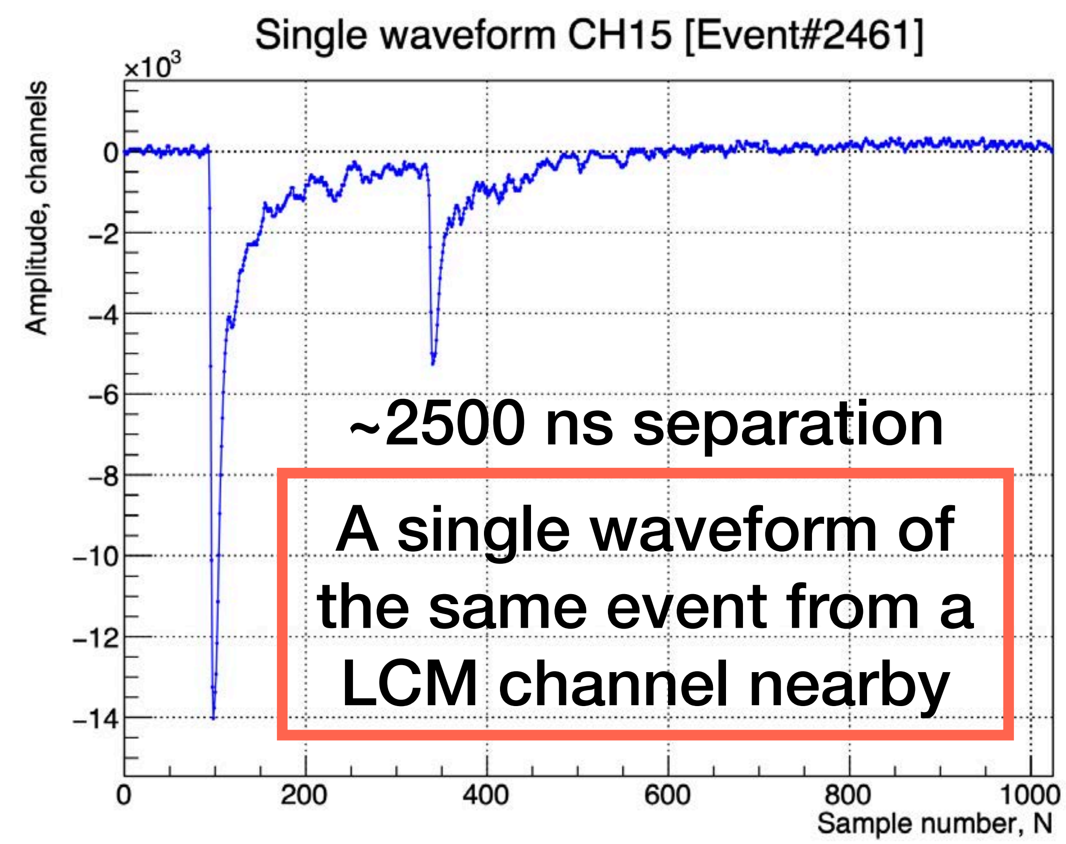
Standard deviation of the light waveform rising time of the same events from different channels



Michel Electrons in 2×2 Modules

An example of Michel electron in Module 0 test





- Michel electron energy O(10 MeV)
- Able to distinguish two light signals ~250 ns apart in Module 0 data and double-pulse LED signals with 100 ns separation
- Modules are scintillation light tight; prevent optical pile-up
- Potential to identify disconnected charge deposit (e.g. neutron recoil)

Continuously Resistive Field Shell

Reference design applied in 2×2 modules

Resistive foil laminated on to copper-clad FR4 using epoxy

Top, bottom and side panels use Dupont carbon-doped polyimide Kapton sheets (DR8)

Cathodes use Kapton XC O(1 MΩ/sq.)

Advantage:

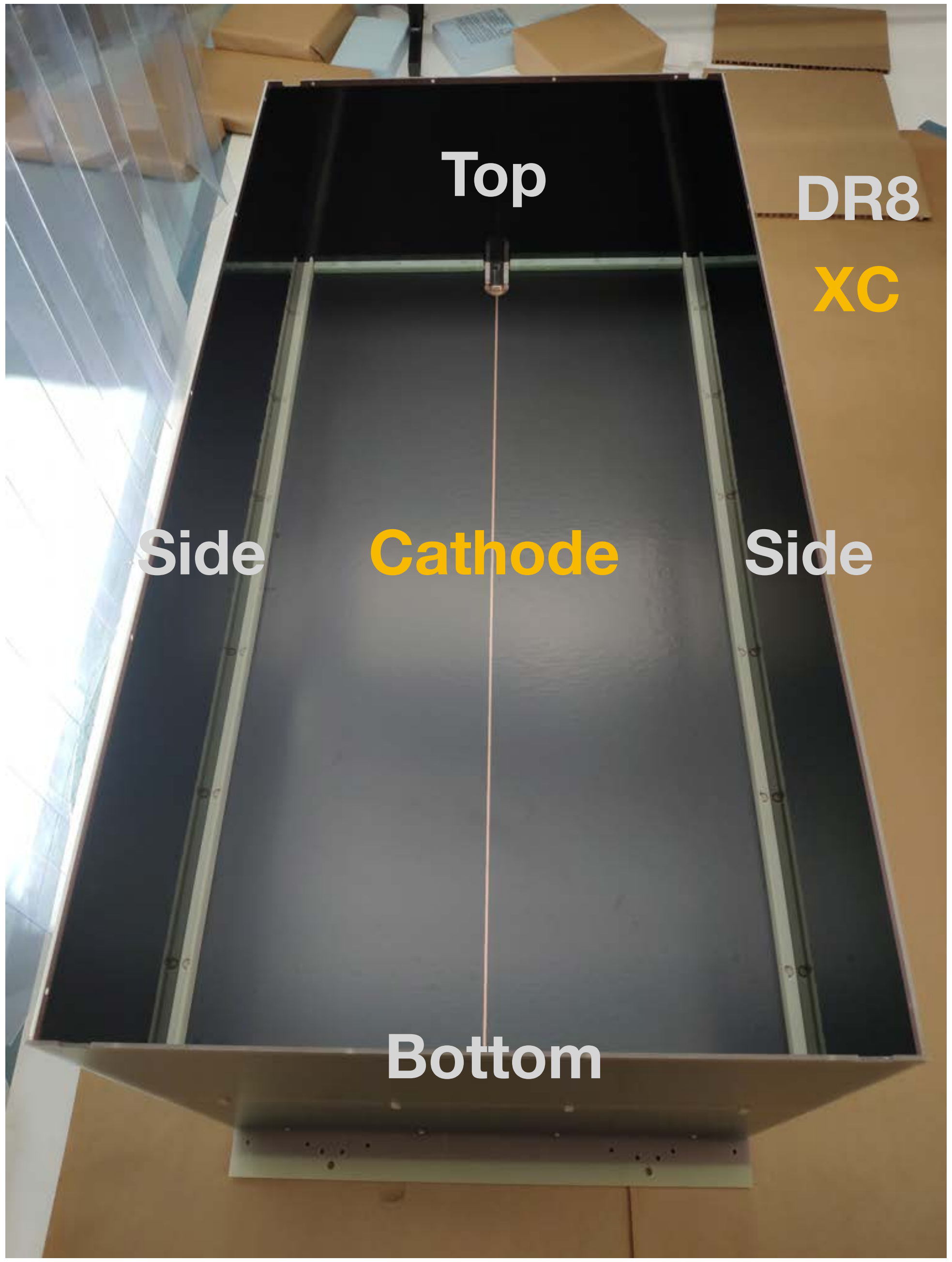
- Minimal footprint in a modular design
- Avoid serial structure, no single point of failure
- Uniform heat dissipation
- No discrete field shaping steps

Material specification:

- Macroscopically uniform sheet resistance
- Cryo-compatibility (conducts and mechanically robust in LAr)
- O(1 GΩ/sq.) sheet resistance at the nominal electric field (0.5 kV/cm)

Successful tests of Module 0 and 1:

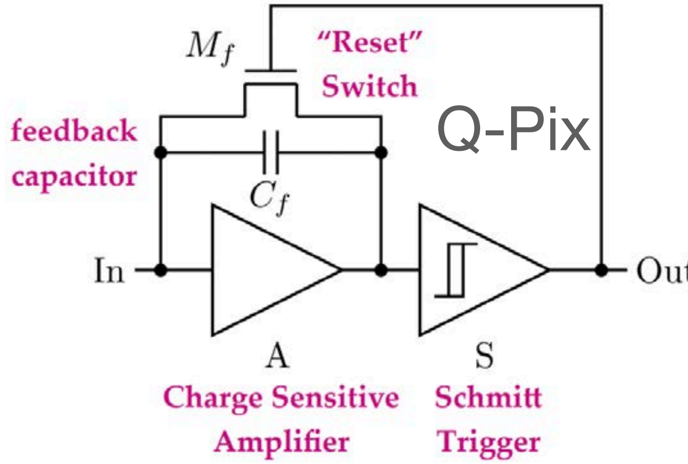
- Can be operated stably at 30 kV (1 kV/cm, twice of the nominal electric field)
- Achieved measurable required electric field uniformity; Observed maximum spatial displacement ~1 cm (near the cathode)



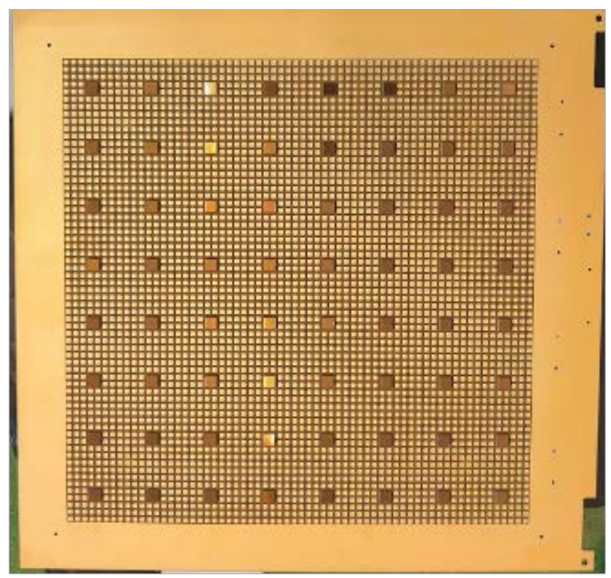
Future Possibilities for DUNE

ARIADNE

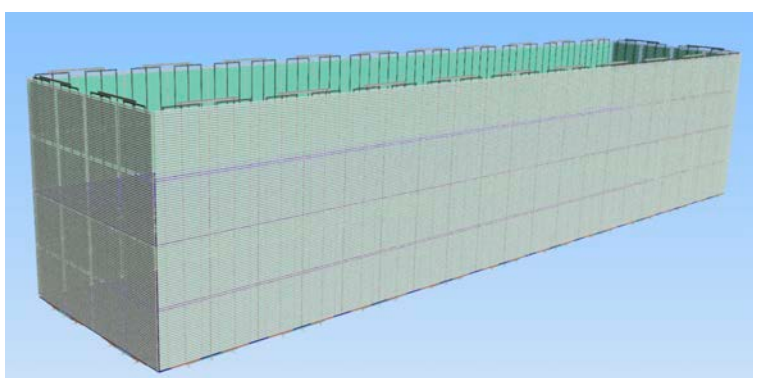
Q-Pix



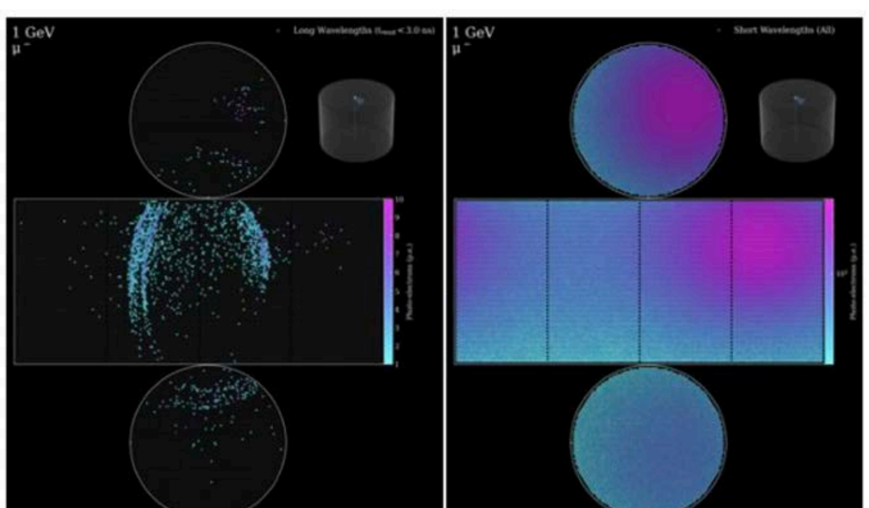
SoLAr



APEX

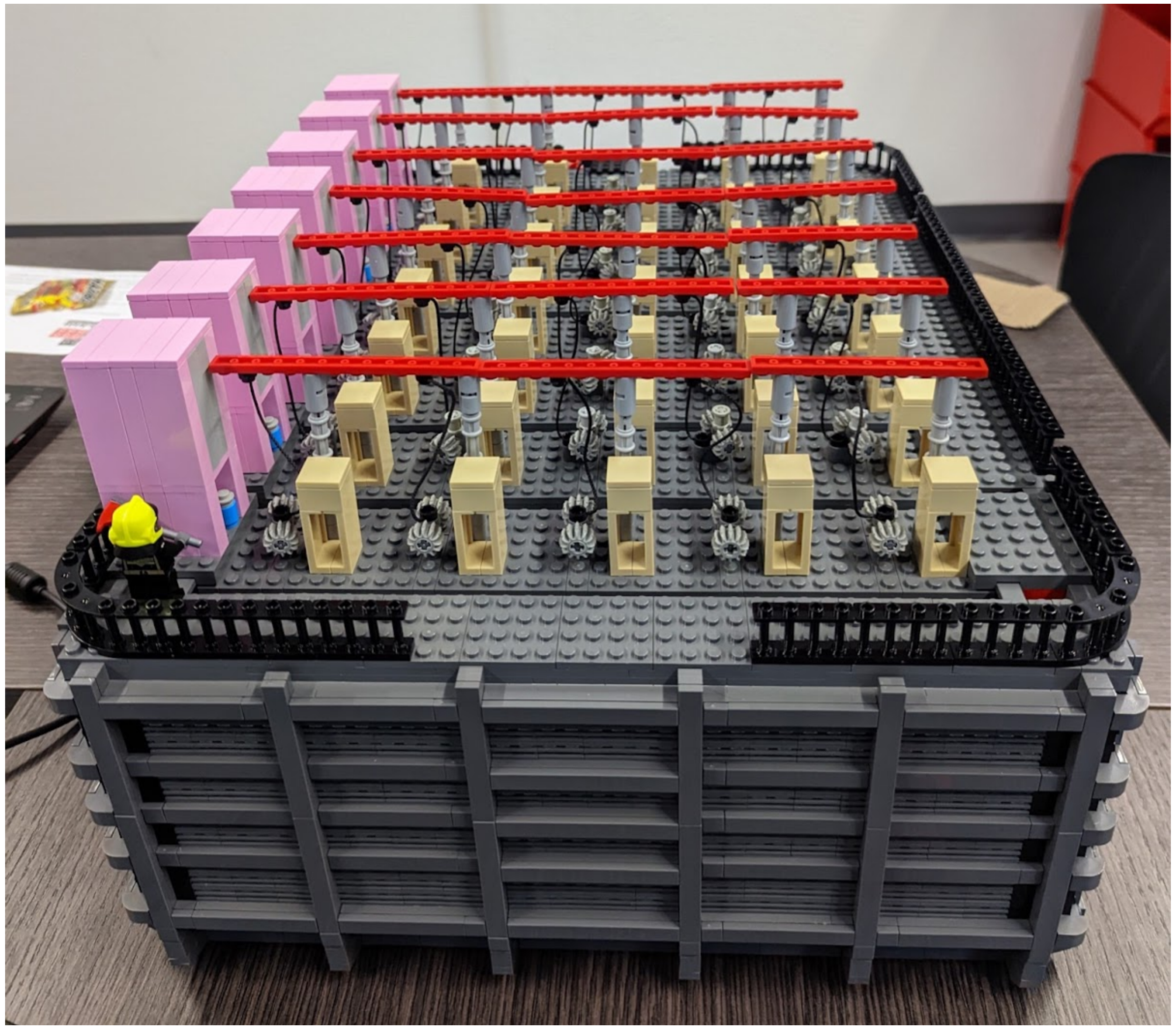


WbLS (Theia)



Technology	Option for FD3	Option for FD4	Option for ND	LArTPC Integration
SoLAr (Integrated charge-light pixel readout)	(✓)	✓		LArPix, Q-Pix, APEX
ARIADNE (Dual-phase with optical readout of ionization signal)		✓		APEX
LArPix (Pixel Readout; charge)	(✓)	✓	✓	APEX, SoLAr
Q-Pix (Pixel Readout; charge)	(✓)	✓	✓	APEX, SoLAr
APEX (ARAPUCA-based light readout on field cage with SiPMs)	✓	✓		CRP, Q-Pix, SoLAr, LArPix
WbLS (Water-based liquid scintillator)		✓	✓	None (complementary to LAr)

DUNE: Ready to Go



- DUNE is in a phase of refining detector designs, testing prototypes and construction
- The beam tests with DUNE prototypes will help us understanding the detectors and the neutrino interactions
- A concrete path has been laid out for the next generation neutrino physics discoveries