WORKSHOP: Multi-Aspect Young-ORiented Advanced Neutrino Academy (MAYORANA) - International Workshop

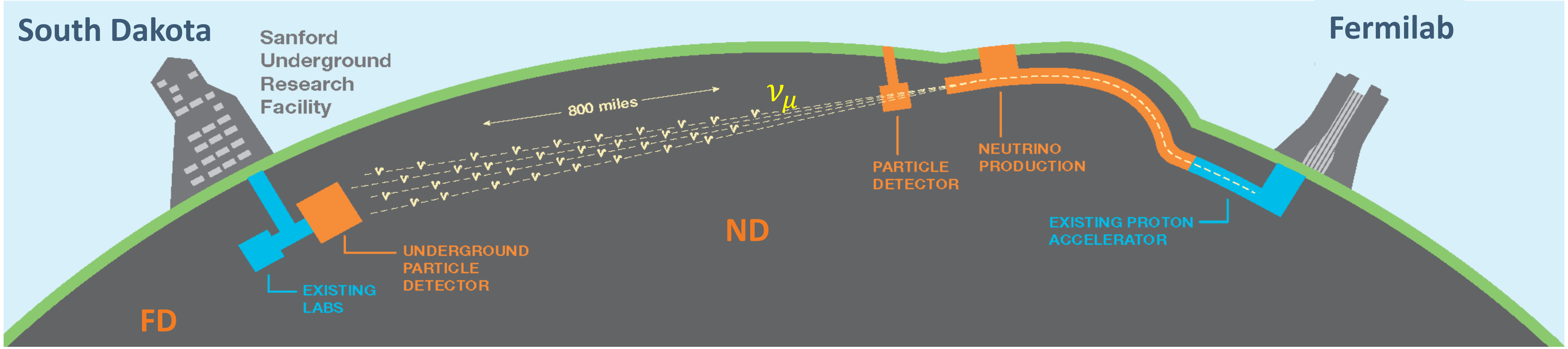
Science and Status of the DUNE Experiment

Laura Patrizii (INFN Bologna)
for the DUNE Collaboration

July 14, 2023

INFN DUNE

The Deep Underground Neutrino Experiment (DUNE)

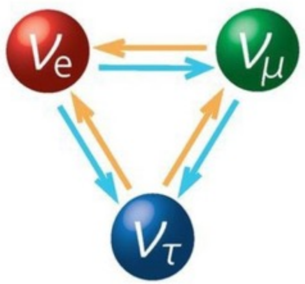


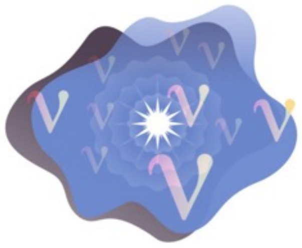
A new generation Long Baseline – 1300 km – neutrino oscillation experiment based on

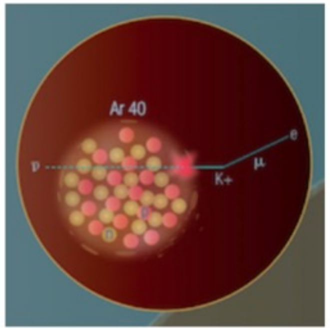
- a wide band high intensity (1.2 MW upgradable to 2.4 MW) $\nu/\bar{\nu}$ neutrino beam produced at Fermilab
- a large total mass (~70 kton) Far Detector at the Sanford Underground Neutrino Facility (SURF) 1.5 km underground exploiting the Liquid Argon Time Projection Chamber (LArTPC) technology
- a Near Detector complex (ND) at Fermilab providing control of systematic uncertainties

enabling a rich physics program

DUNE: Key Features and Physics Program







- Long- baseline wide-band neutrino beam
  - Measurement of CP violation phase and determination of the neutrino mass ordering in a single experiment using spectral information
- Underground location → access to astrophysical neutrinos
  - Supernova neutrino burst detection – sensitive to the ν_e component
  - Atmospheric neutrino – capability of ν_τ identification
  - Solar neutrinos – potential for detection of hep flux
- Massive detectors with excellent tracking and calorimetric information
  - Search for baryon number violating processes – $p \rightarrow \nu K^+$, $n\ \bar{n}$
- Long baseline + higher energy neutrino beam
  - ν_τ appearance, NSI searches
- Capable Near Detector Complex
  - Precise neutrino physics (cross sections, nuclear effects)
  - BSM searches

arXiv 1807.10334

Neutrino oscillations in the 3-neutrino framework

PMNS Matrix

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$

PDG 2022

ν_e appearance : mass ordering, δ_{CP} , octant of θ_{23}

$$P_{\nu_\mu\to\nu_e,(\bar\nu_\mu\to\bar\nu_e)} \approx 4\,\sin^2\theta_{13}\,\sin^2\theta_{23}\frac{\sin^2\Delta}{(1-A)^2} + \alpha^2\sin^2 2\theta_{12}\,\cos^2\theta_{23}\frac{\sin^2 A\Delta}{A^2} + 8\,\alpha\,J_{\rm CP}^{\rm max}\cos(\Delta\pm\delta_{\rm CP})\frac{\sin\Delta A}{A}\,\frac{\sin\Delta(1-A)}{1-A}$$

for $\bar\nu$
- «minus» sign
- V→ -V

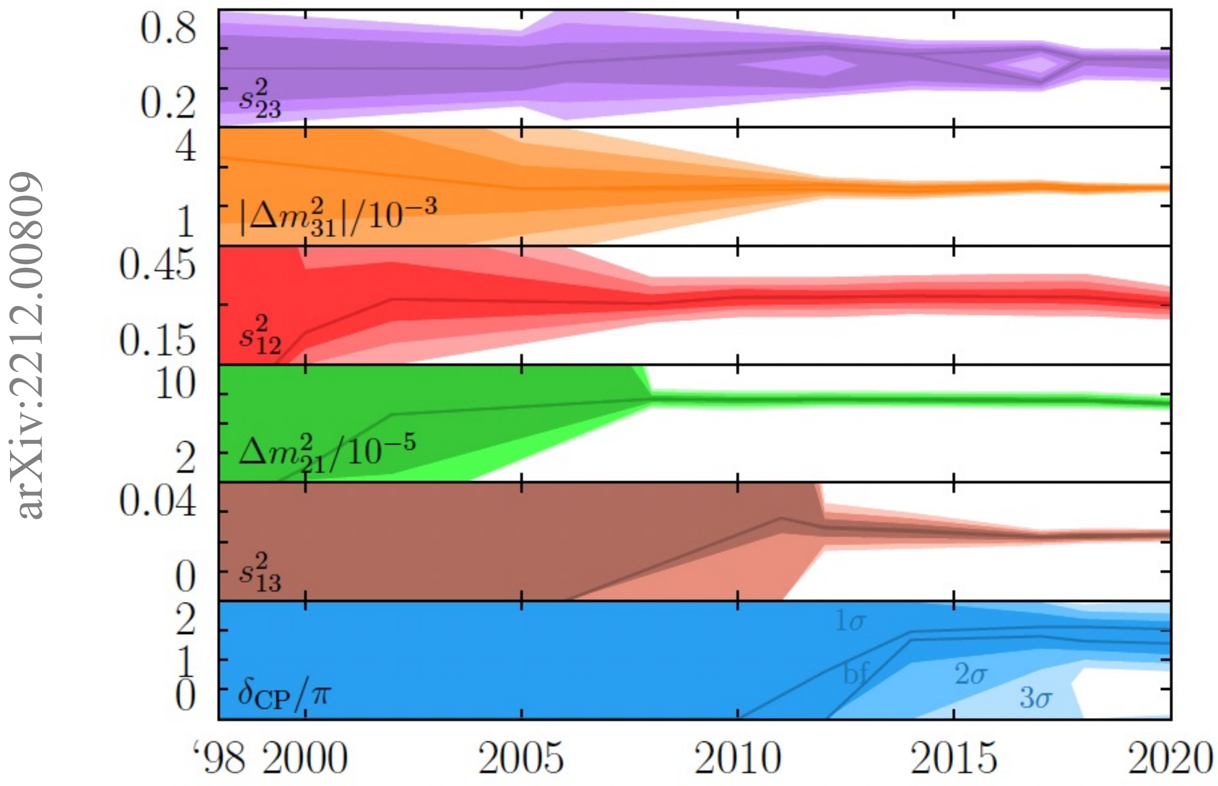
ν_μ disappearance: $|\Delta m^2_{32}|$, $\sin\vartheta^2_{23}$, constrain octant

$$J_{\rm CP}^{\rm max} = \cos\theta_{12}\sin\theta_{12}\cos\theta_{23}\sin\theta_{23}\cos^2\theta_{13}\sin\theta_{13}$$

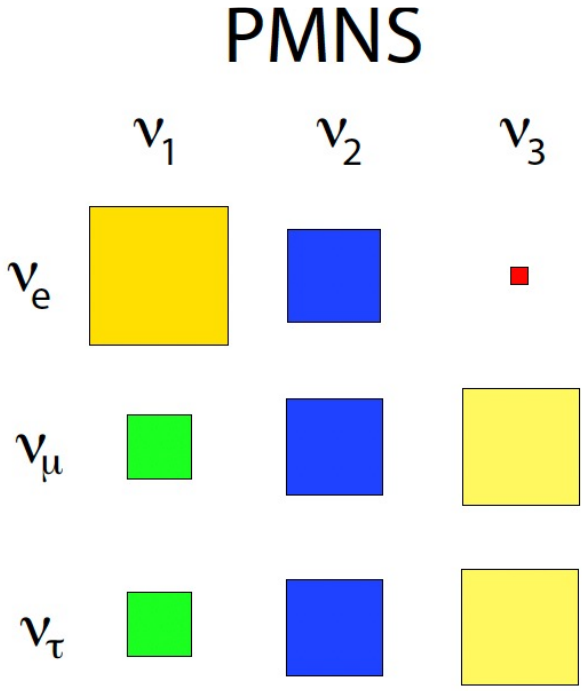
$$\Delta \equiv \frac{\Delta m^2_{31}L}{4E_\nu} \qquad A \equiv \frac{2E_\nu V}{\Delta m^2_{31}} \qquad \alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} \qquad V_C = \sqrt{2}G_F n_e\,.$$

α, Δ , A are sensitive to the sign of Δm^2_{31}

Impressive progress since 1998

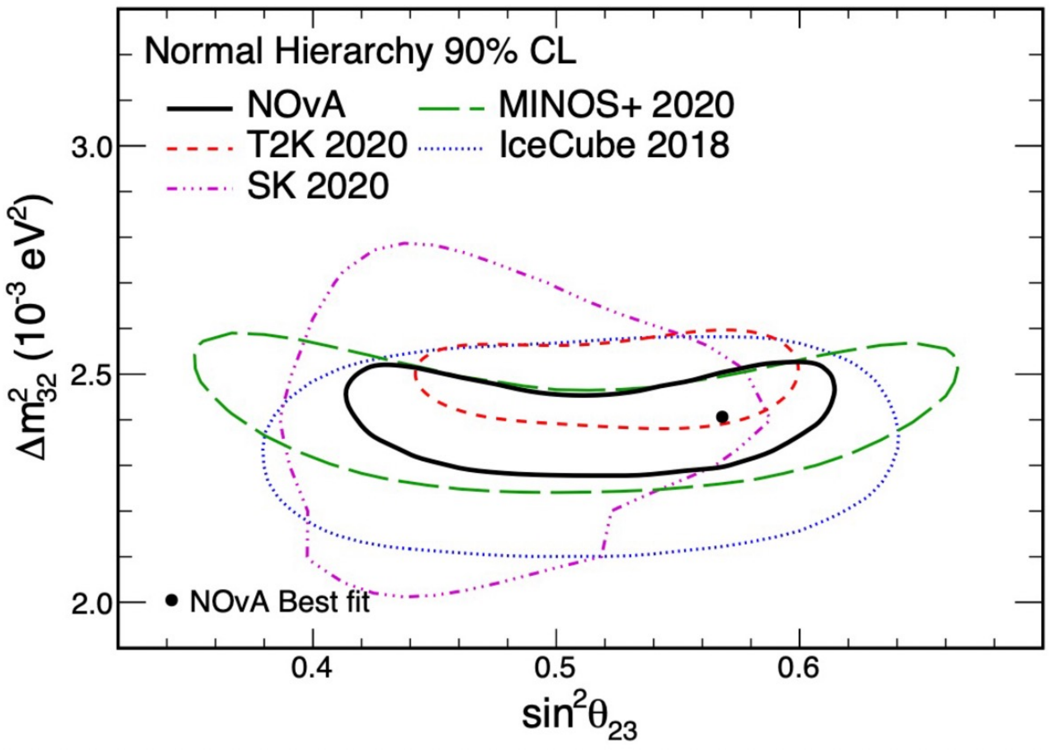


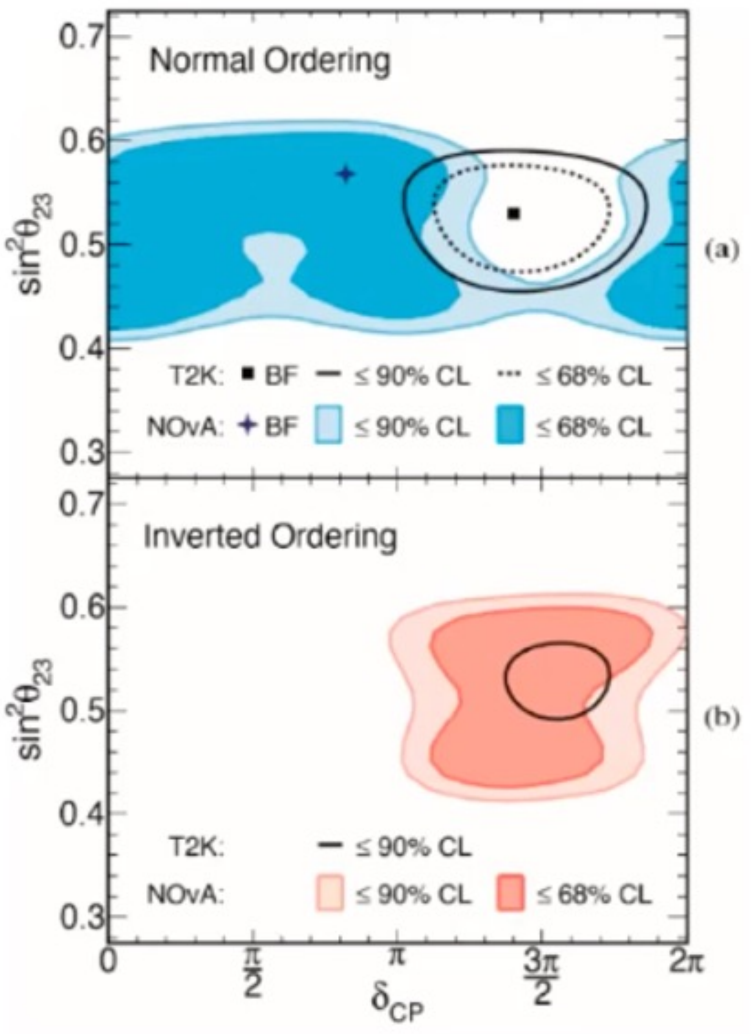
	θ_{23}	θ_{13}	θ_{12}	δ
Leptons	$\sim 45°$	8.5°	34°	?
Quarks	2.4°	0.20°	13°	69°



arXiv:1212.6374v2

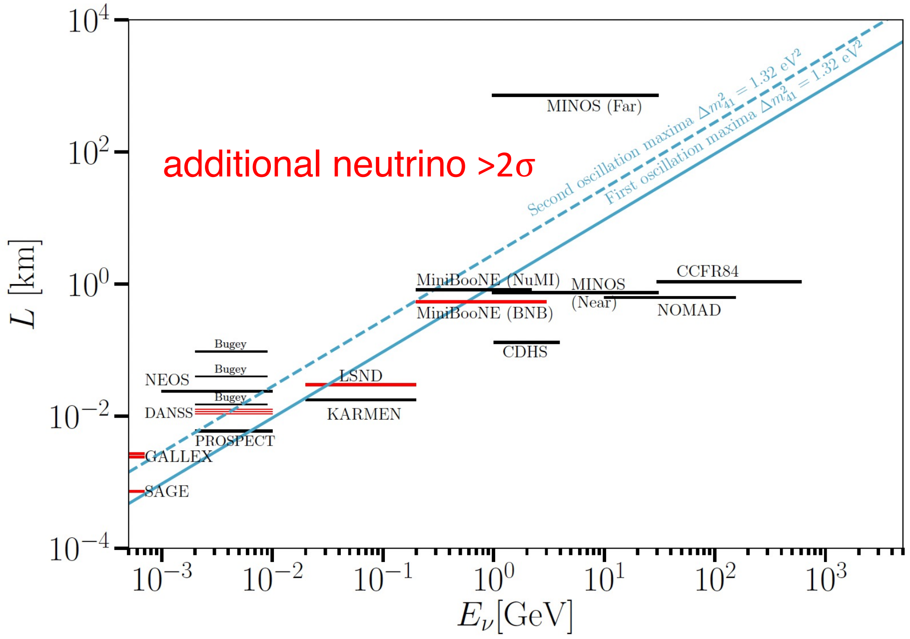
… not a complete clear picture yet



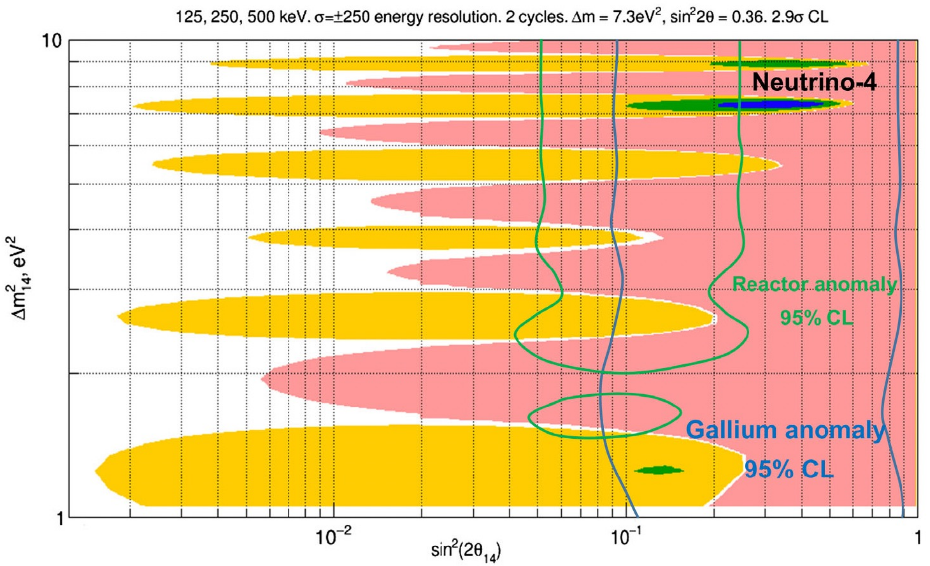


ref. A. Gugliemi 's talk on ICARUS

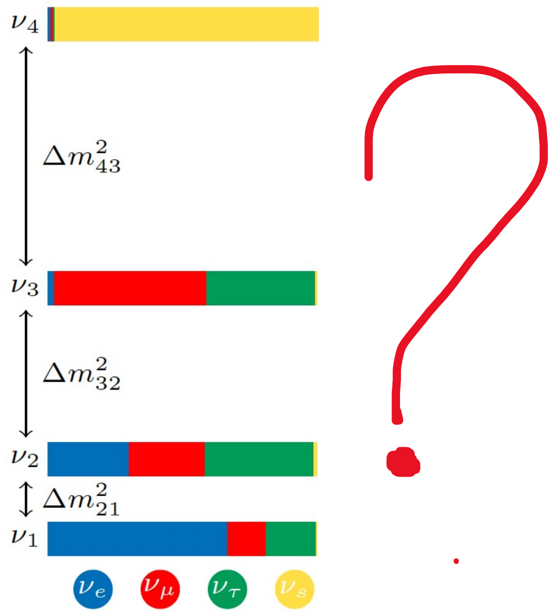
The «anomalies»



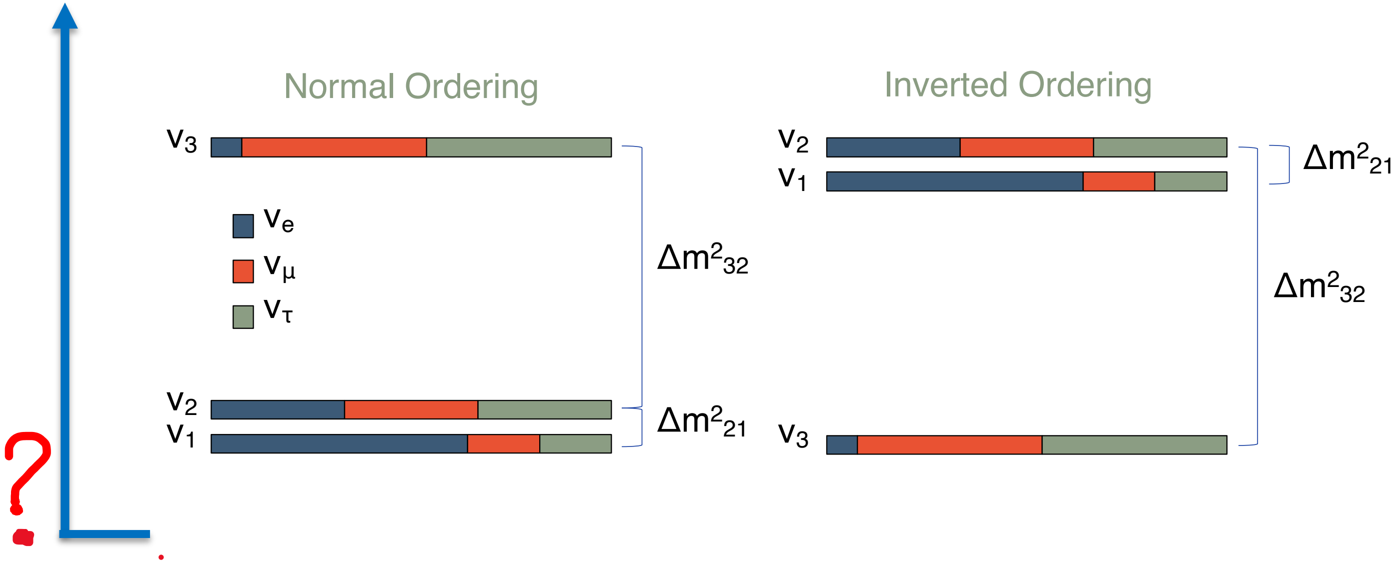
[arXiv:1906.00045



Phys.Rev.D 104, 032003 (2021)



Open Questions and Unknowns

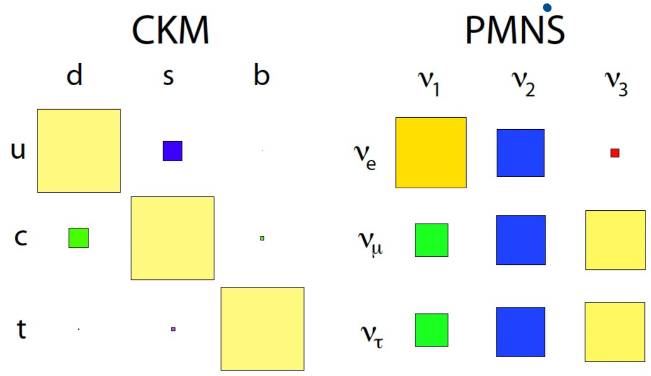


- What is the neutrino mass ordering? (Is Δm^2_{32} positive or negative?)
- Is there leptonic CP violation?
- Is θ_{23} mixing maximal?
- Is the PMNS matrix unitary?

- Can neutrinos explain the matter-antimatter asymmetry in the Universe?
- What is the neutrino absolute mass scale?
- Are neutrinos Majorana particles?

	θ_{23}	θ_{13}	θ_{12}	δ
Leptons	$\sim 45°$	8.5°	34°	?
Quarks	2.4°	0.20°	13°	69°

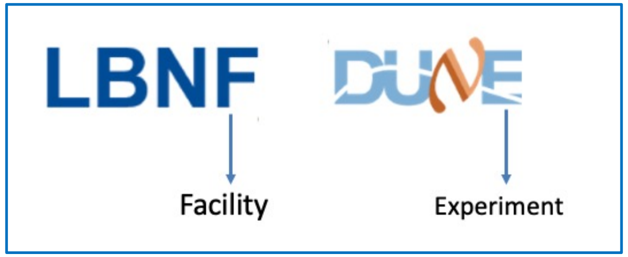
Is the θ_{23} mixing maximal?
$\theta_{23} = 45° \rightarrow |U_{\mu 3}| = |U_{\tau 3}|$

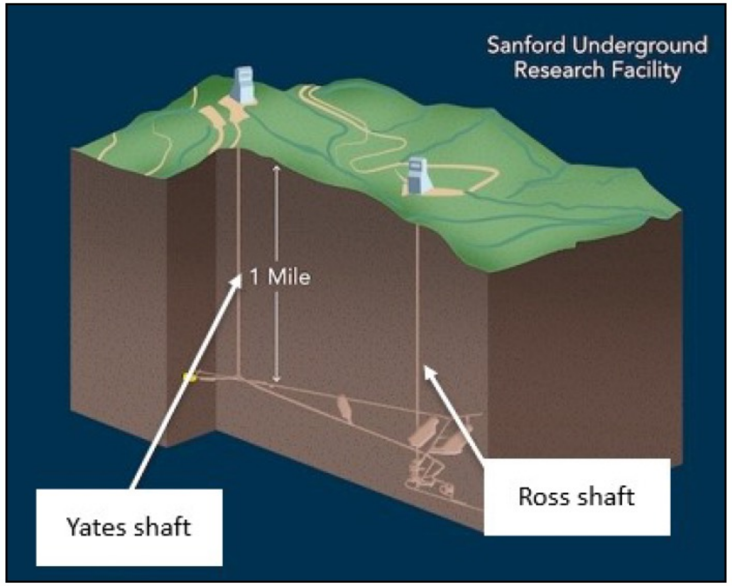


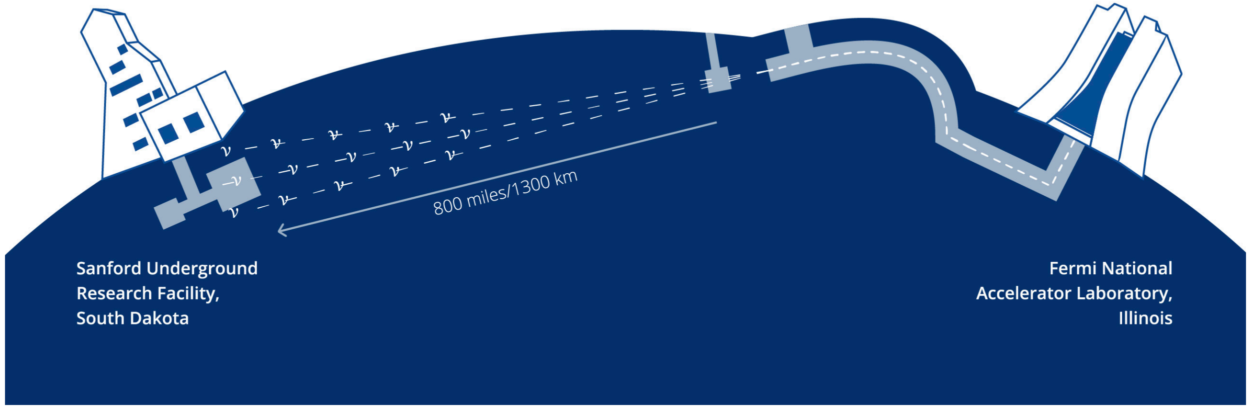
The Long Baseline Neutrino Facility (LBNF) and DUNE

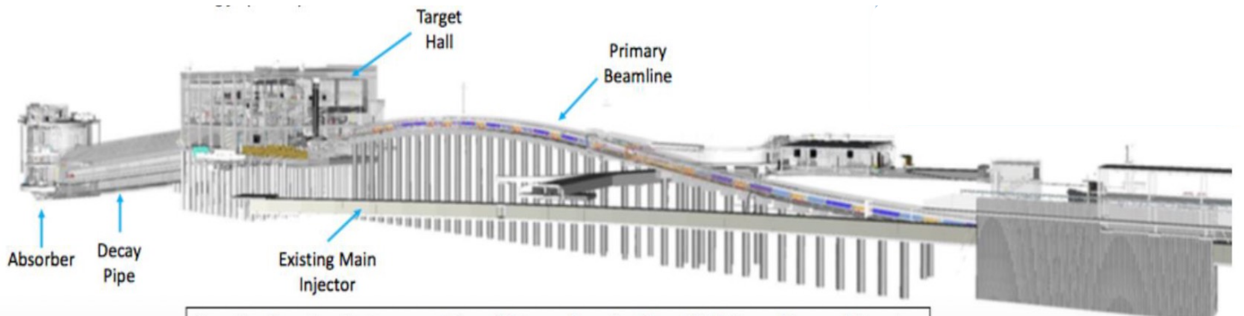
DUNE experiment is enabled by LBNF which provides

- a high intensity wide-band neutrino beam
- a deep underground lab in South Dakota and Near Detector infrastructures





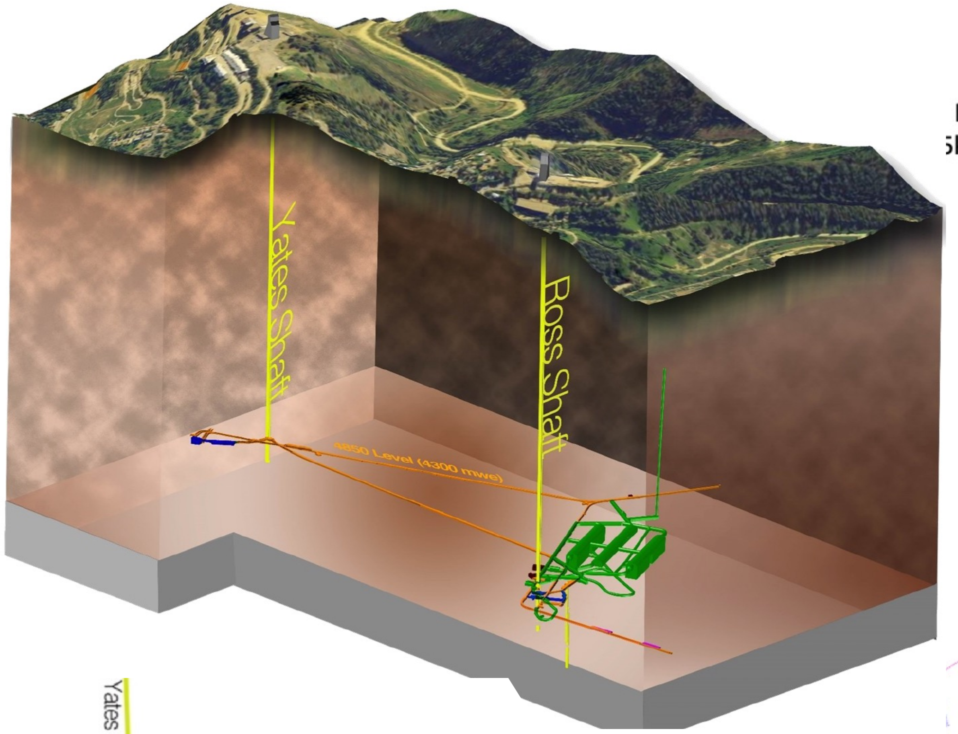


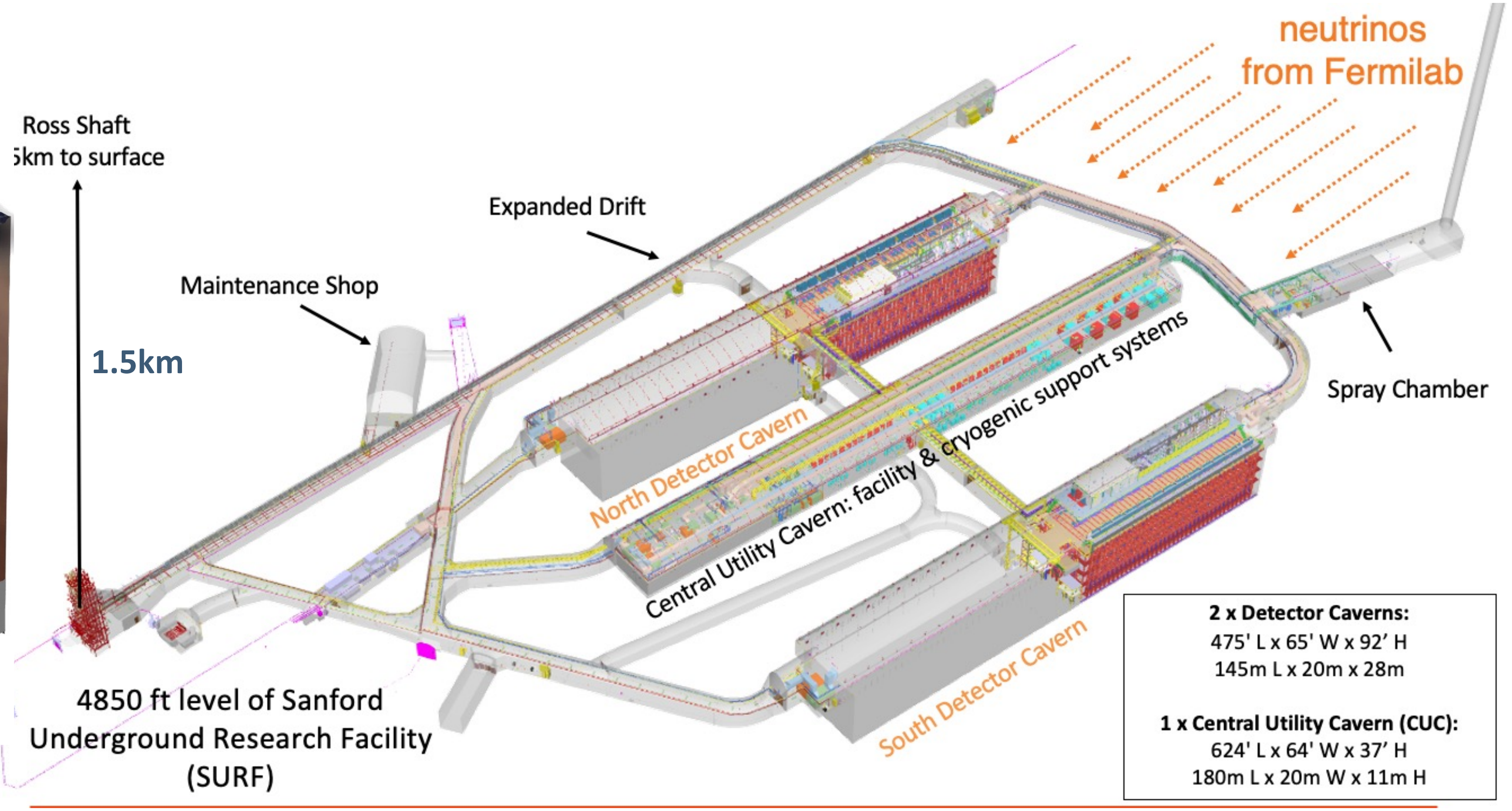


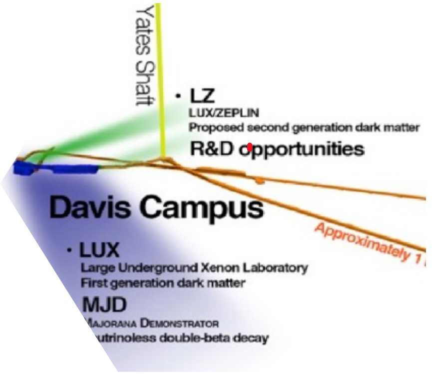
Beamline Complex: Upstream end view of Primary Beamline, Target Hall, Decay Pipe, and Absorber

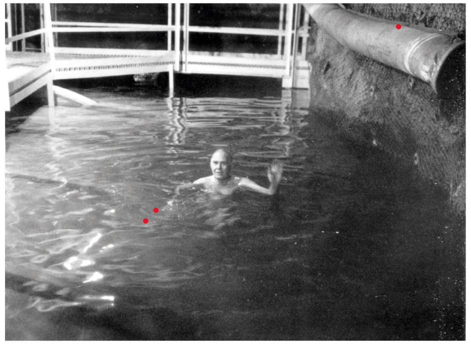
Sanford Underground Research Facilities

Previously known as the Homestake (gold) Mine in the Black Hills









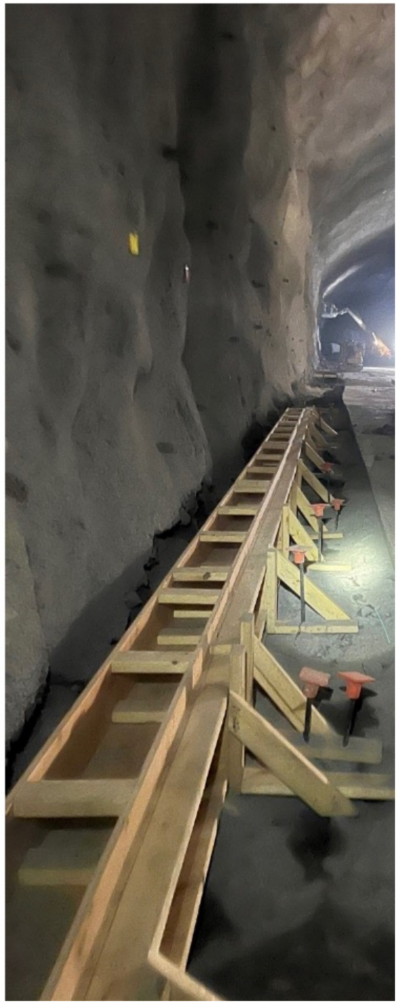
R.J Davis

Excavations at SURF 70% complete (July 2023)

North Cavern – adjusting ventilation

North Cavern –midpoint connection drift

Blow piping central utility cavern



Central utility cavern corner trench drain

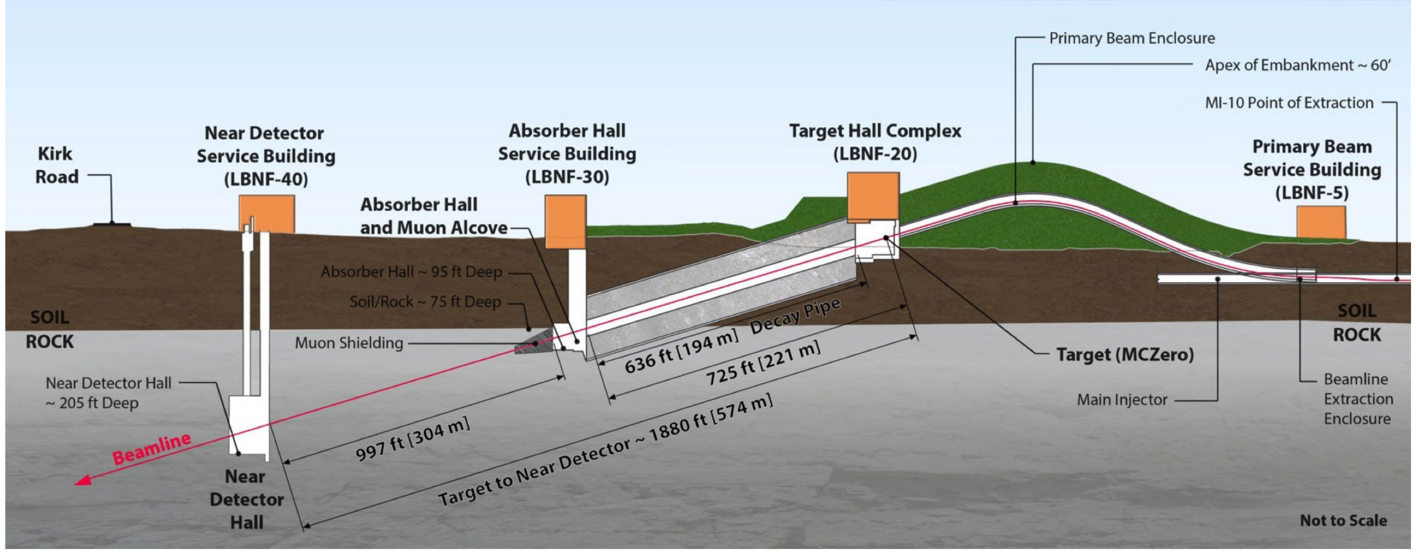
The LBNF beamline at FNAL

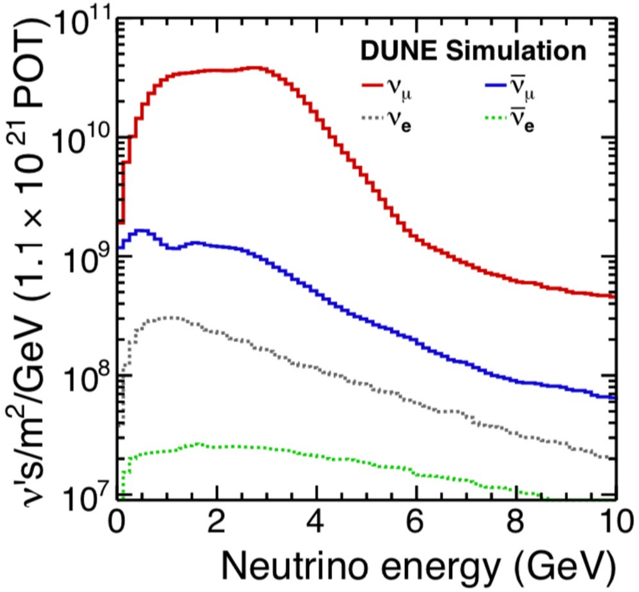
LBNF will use protons from the Main Injector

- **MI will start at 1.2 MW and be upgradeable to 2.4 MW**

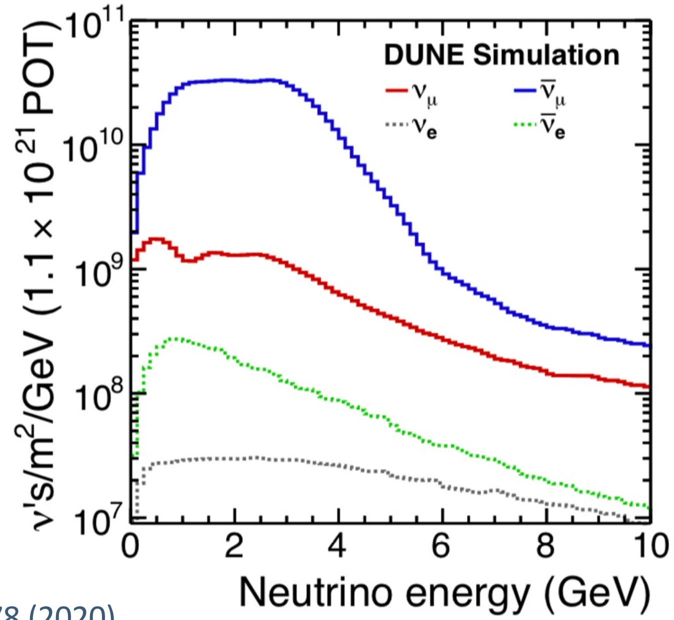
Proton Improvement Plan (PIP II): upgrade of LINAC to reach 1.2 MW

The LBNF beam





FHC
(ν-mode)



RHC
($\bar{\nu}$-mode)

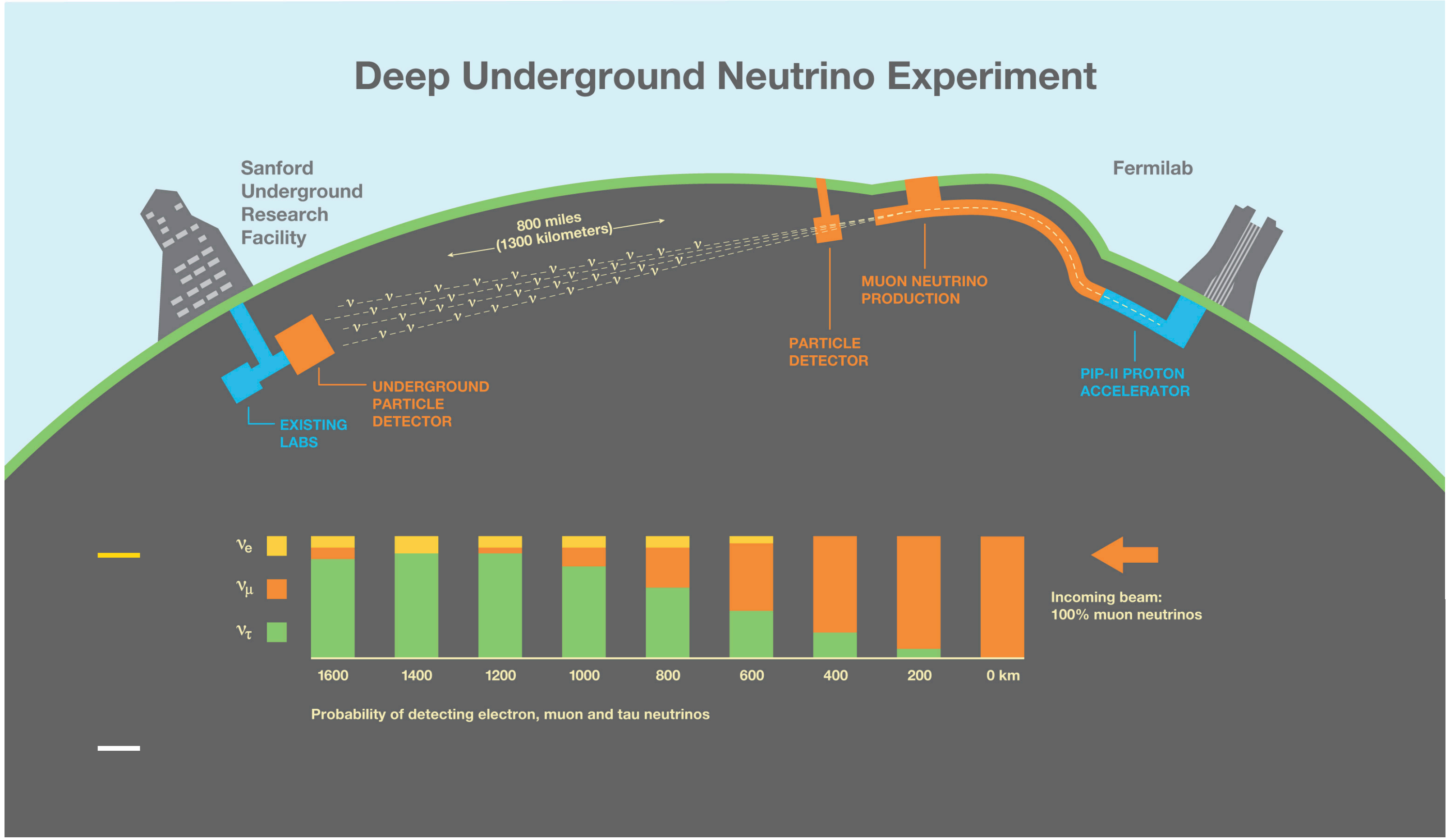
- Neutrino beamline at a slope of 5.8°
- High intensity primary proton beam (60-120 GeV) on a graphite target (1.1 – 1.9)x10^{21} pot/yr
- Horns/beam line designed to maximize CP violation sensitivity
- Pulse duration: 10 µs

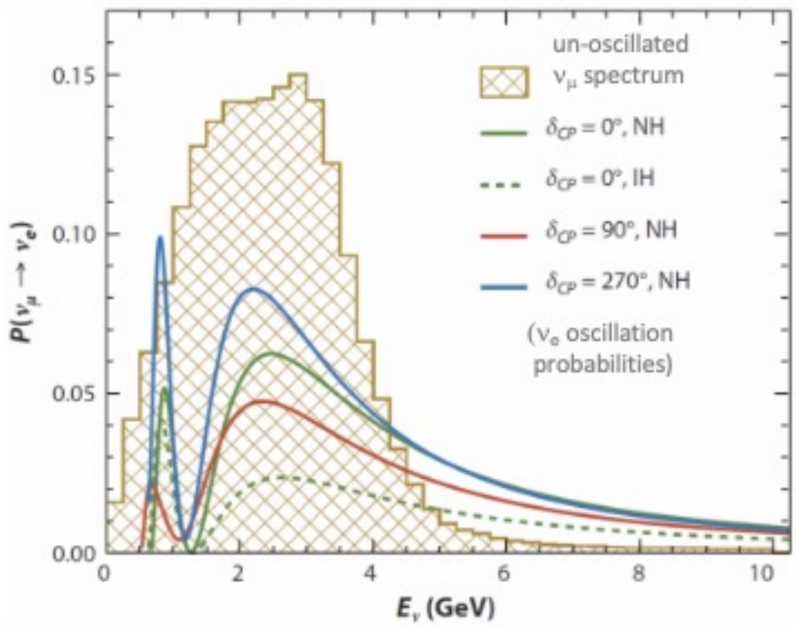
Expected neutrino fluxes :

- Forward Horn Current (FHC) neutrino-enhanced,
- Reverse Horn Current (RHC) antineutrino-enhanced,
- Wide band beam

Eur. Phys. J. C **80** 10, 978 (2020)

Neutrino Oscillations in DUNE



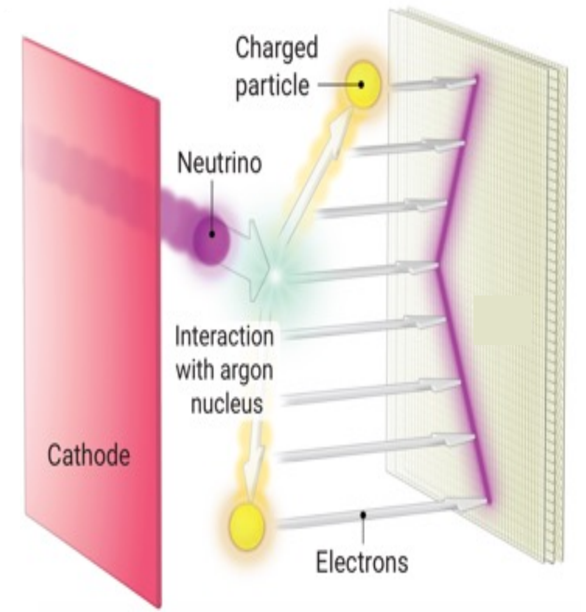


beam spectrum covers the full neutrino oscillation curve

not simply a counting experiment

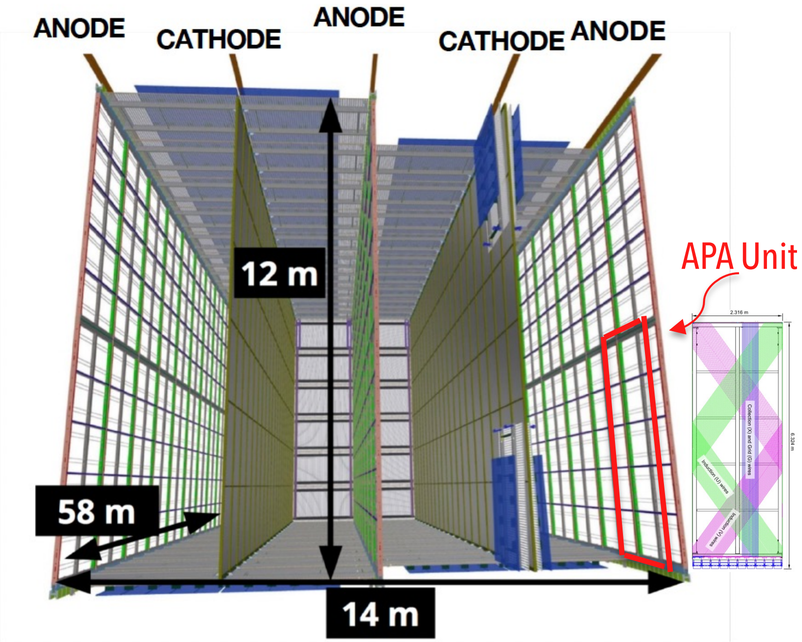
DUNE Far Detectors – 2 x 17 kt modules (Phase I)

LAr TPC



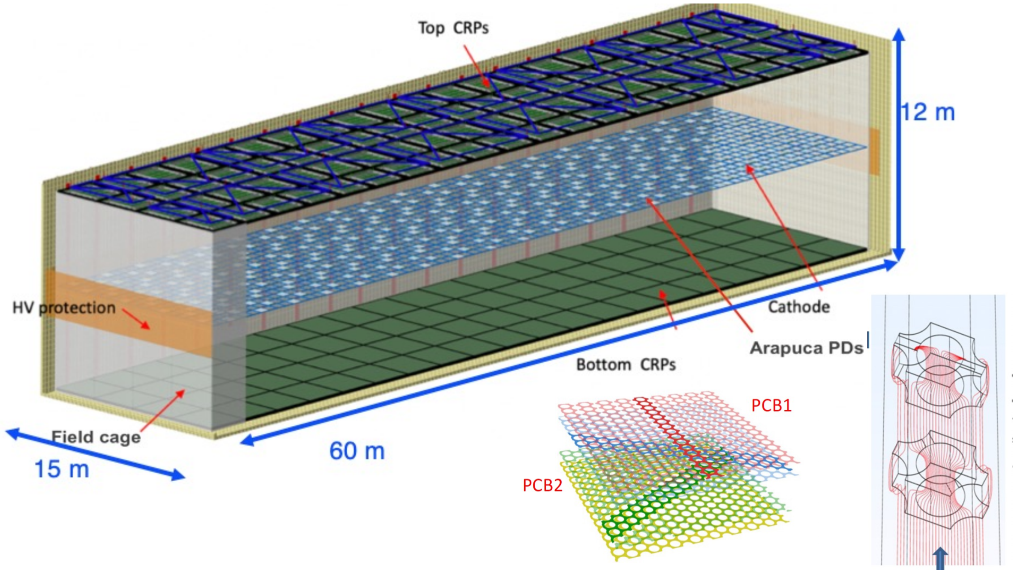
Liquid Argon TPC (C. Rubbia, 1977) is the technique with the best particle imaging capability at kton scale:

FD1-HD «Horizontal drift»



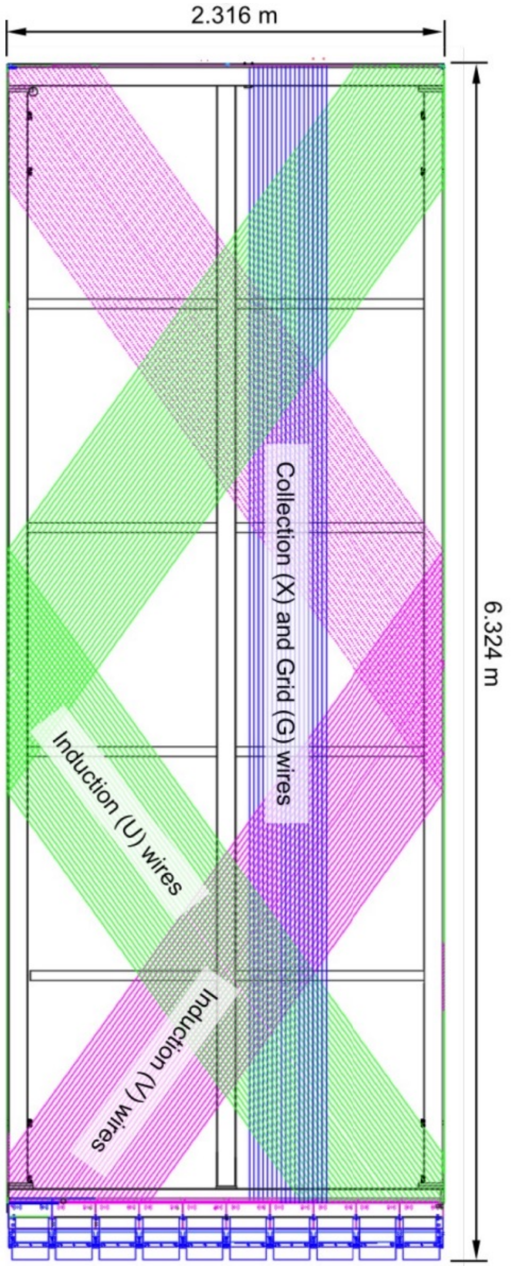
- 150 Anode Plane Assemblies (APAs)
- 384,000 readout wires
- Anode-Cathode 3.5 m drift;
- 500 V/cm field; cathode at -180 kV;
- 6000 photon detection system (PDS) ch.
- PDS X-Arapuca modules embedded in APA

FD2-VD «Vertical drift»

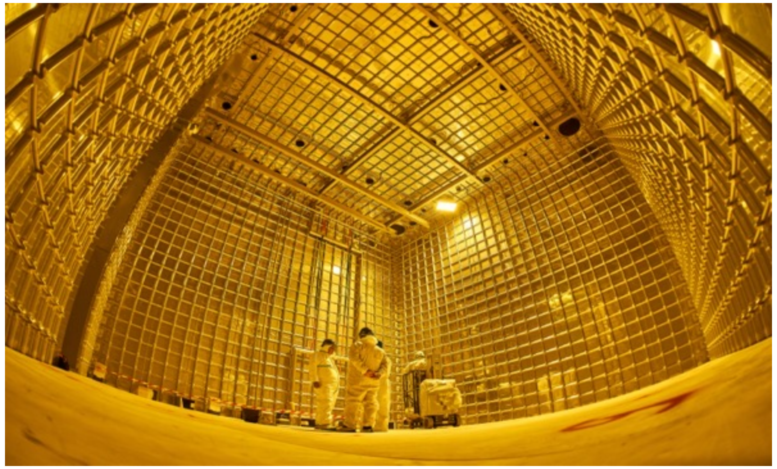


- Charge Readout Planes : perforated PCB's with segmented electrodes (strips)
- CRPs at the top and bottom
- Cathode (-300 kV) in the middle
- two 6.5 m drift chambers 450 V/cm field
- X-Arapuca modules integrated on cathode and on cryostat walls
- - decoupling from HV by optical fibres for signal and power transmission

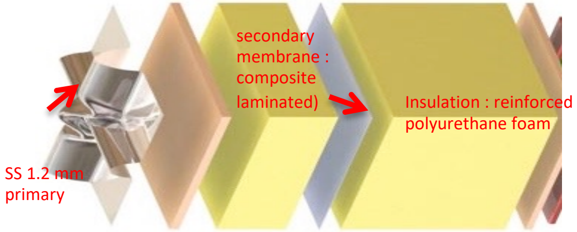
Construction of APAs



The Cryostats



4 vessels already constructed (protoDUNE, SBND,..)



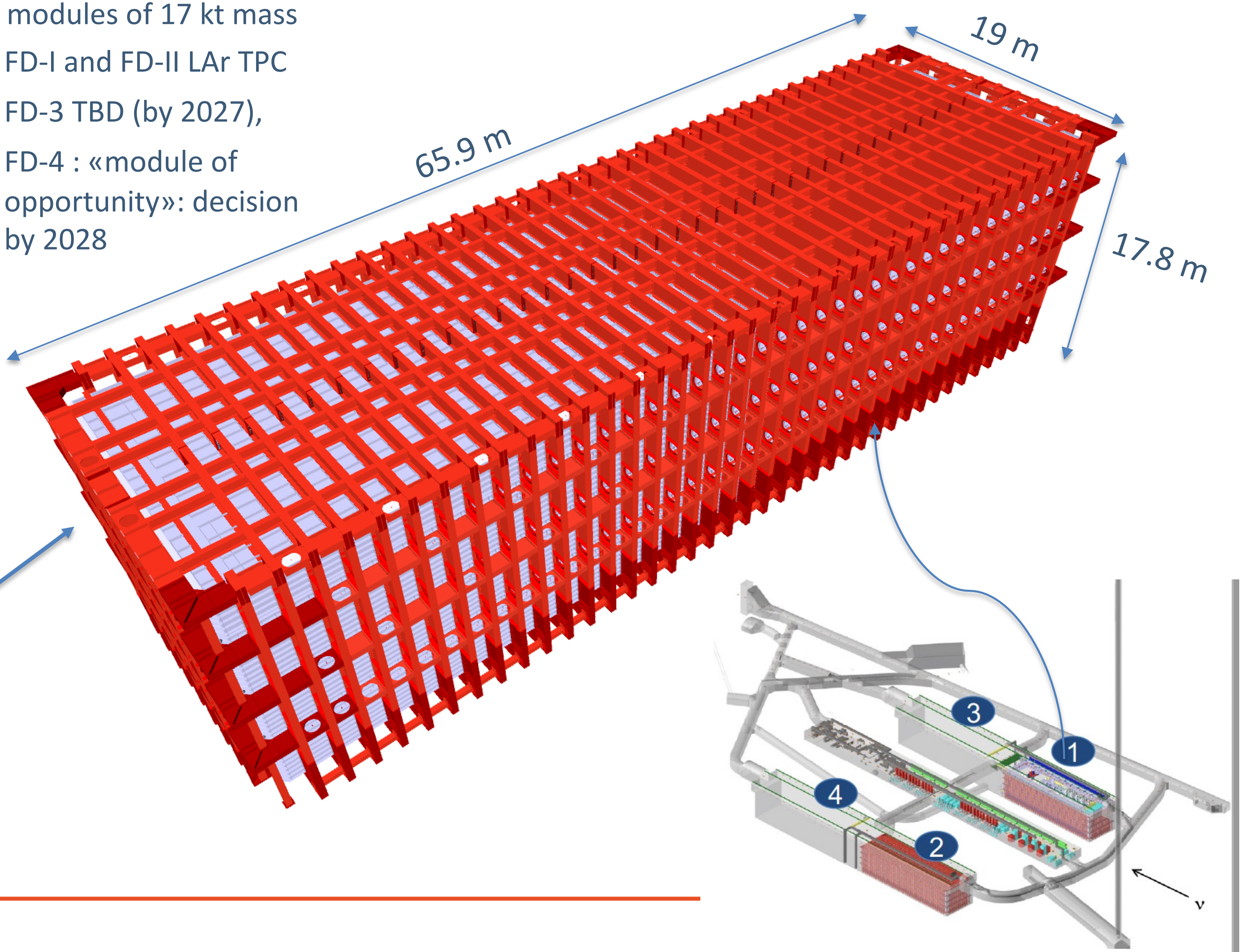
Membrane cryostat with passive insulation (CERN/GTT design)

internal volume : ~28’500 m^3

~17’500 tons of LAr

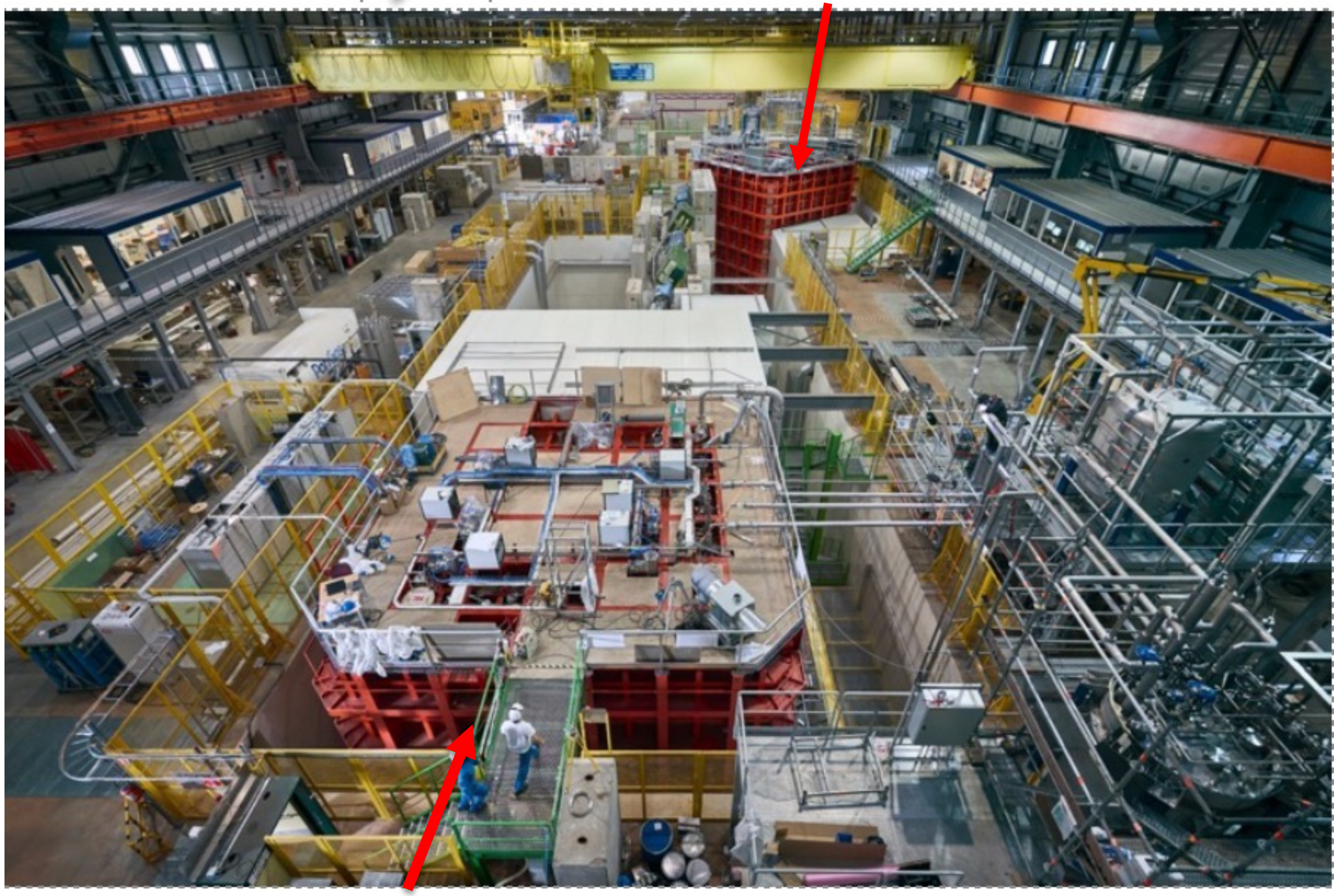
4 modules of 17 kt mass

- FD-I and FD-II LAr TPC
- FD-3 TBD (by 2027),
- FD-4 : «module of opportunity»: decision by 2028

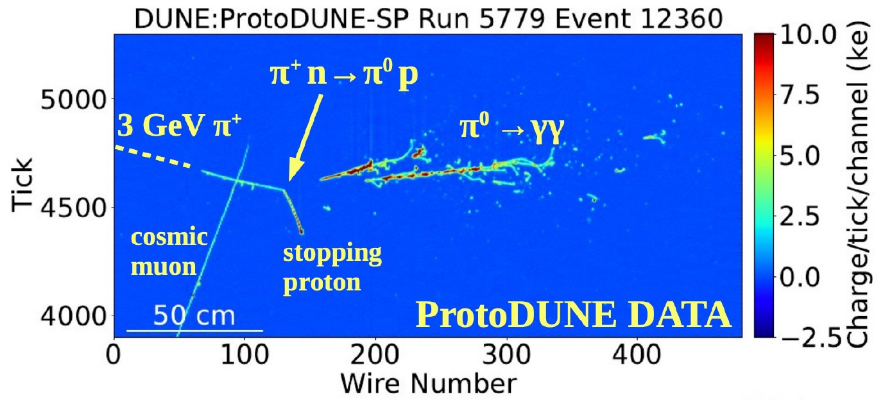


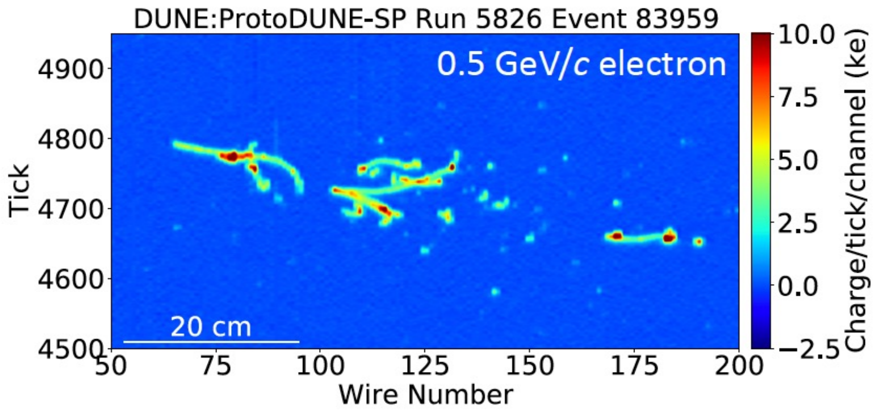
ProtoDUNE's @ the CERN Neutrino Platform

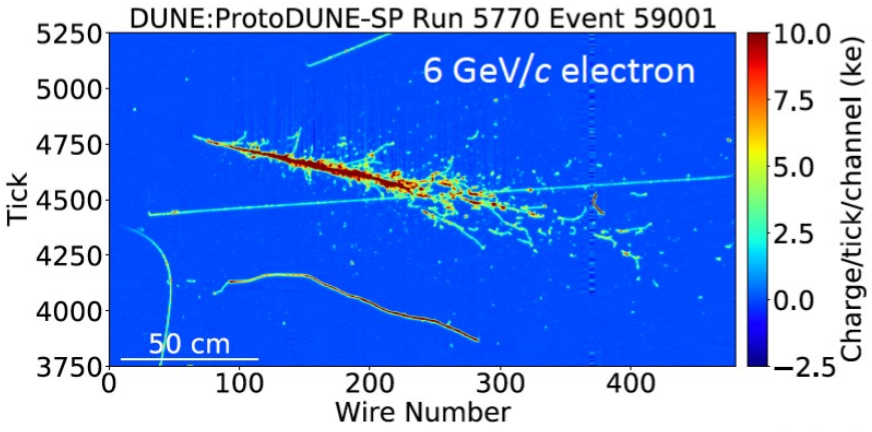
- Two 750 t prototypes ~8 x 8 x 8 m^3
- Design validation of all FD components at full scale
- ProtoDUNE Single-Phase Horizontal Drift:
  - Charged particle beam + cosmic rays runs (2018-2020)
  - Event reconstruction, full analysis
  - Excellent performance
  - SP-HP Module-0 :final validation of
    - Components production
    - Assembly procedures
    - Detector performance and stability
- ProtoDUNE Dual-Phase evolved to Single Phase Vertical Drift late 2020
  - SP-VD charged beams + CRs in 2024

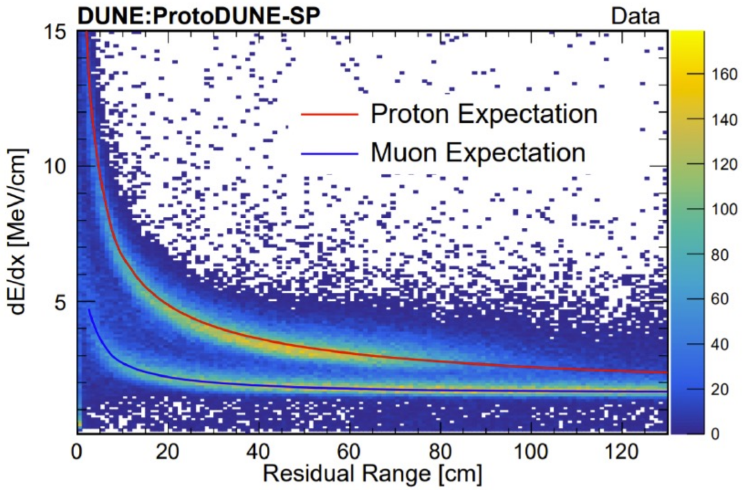


ProtoDUNE SP-HD Performance









Rich test-beam data with charged particles (charged pions, kaons, protons, muons and electrons) with different momenta

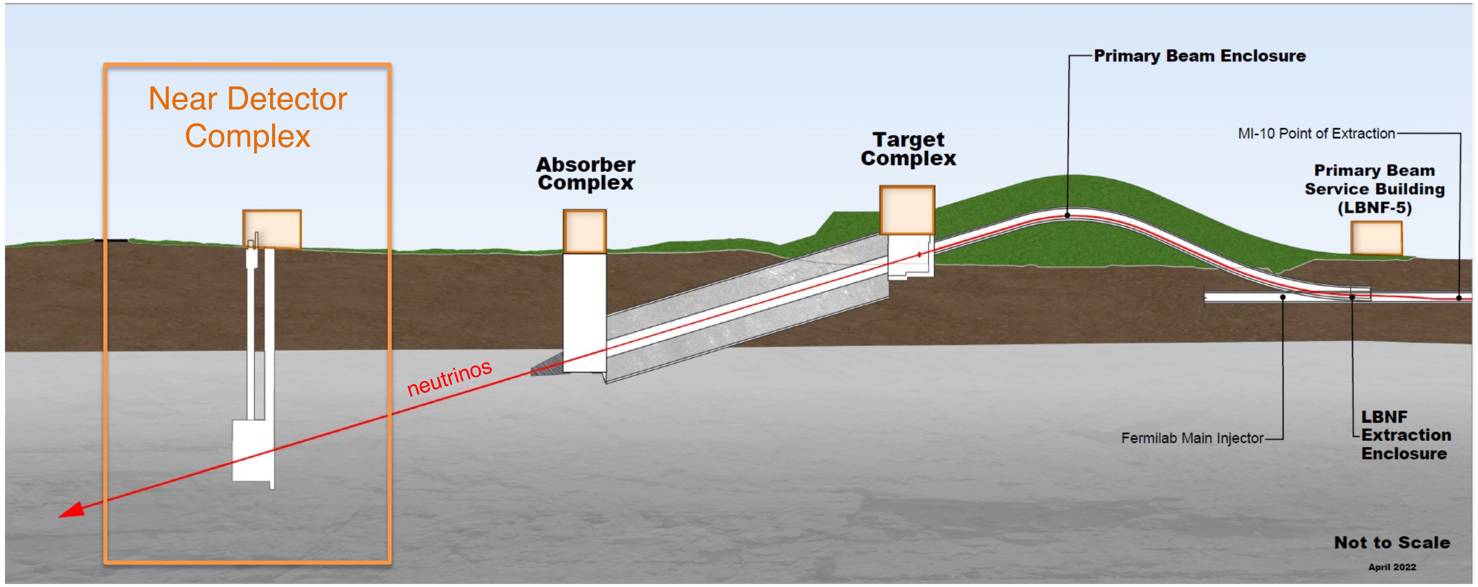
Excellent imaging capabilities for neutrino flavor ID and energy reconstruction.

Multiple papers on calibration, detector physics measurements and reconstruction

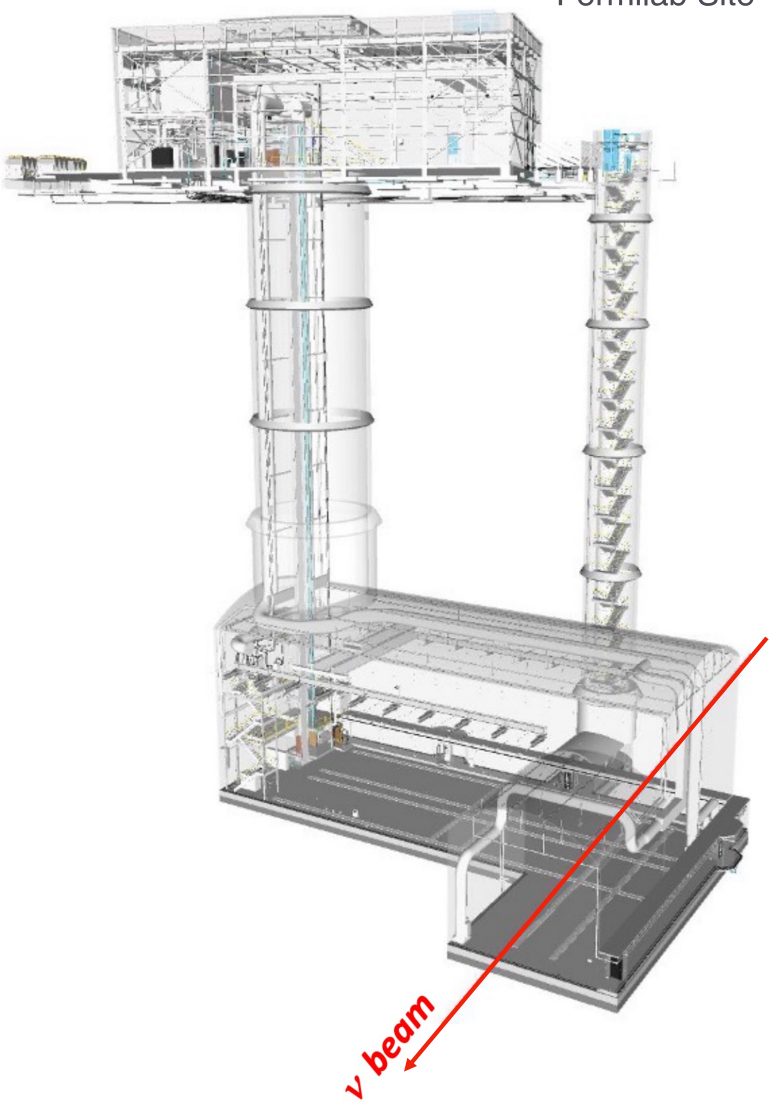
JINST, P12004 (2020)

Eur. Phys. J. C82, 903 (2022)

Near Detector Facility

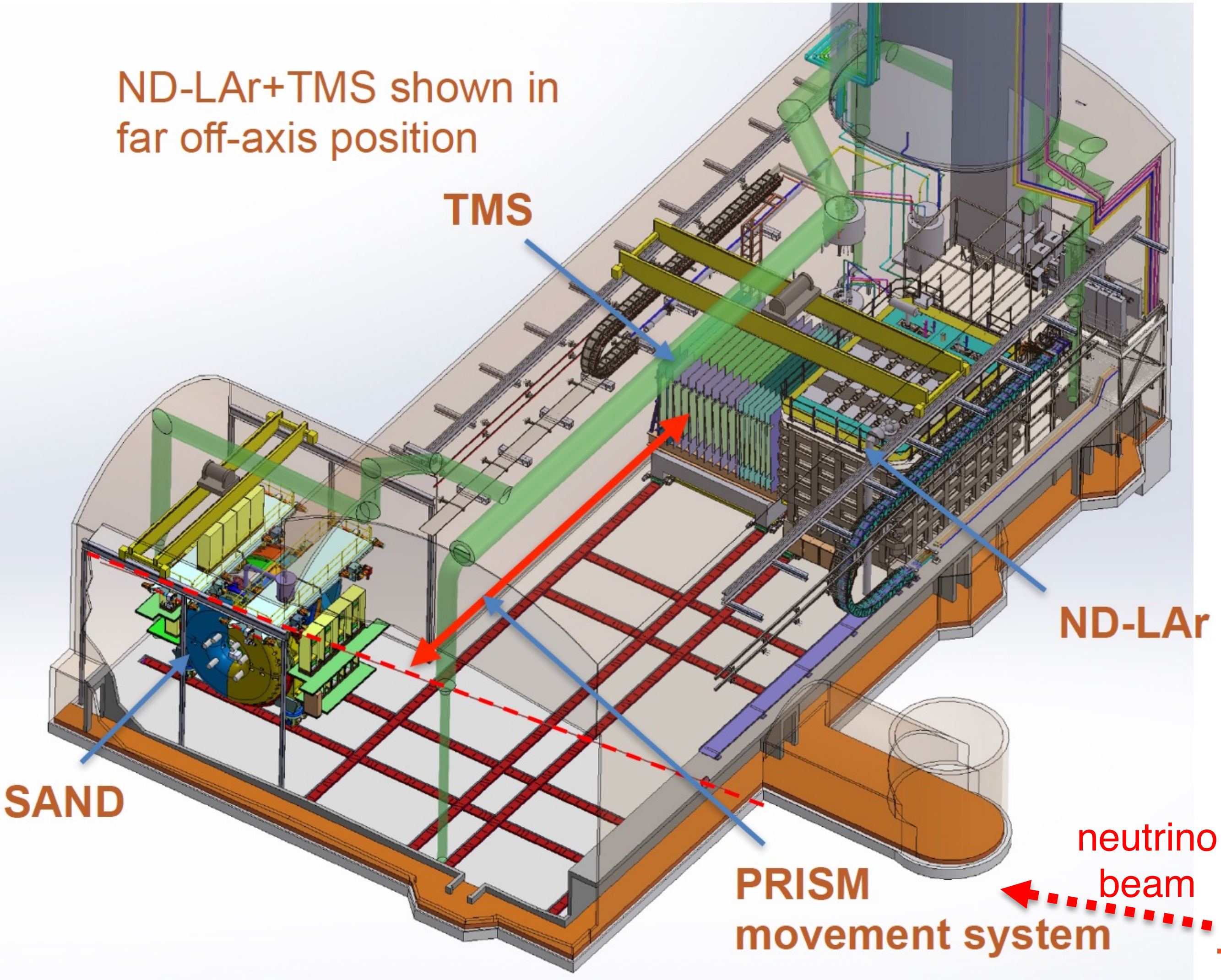


Fermilab Site



- Hall location : 574 m from LBNF target; 60 m underground
- Beneficial Occupancy: 2028

The Near Detector Complex (Phase I)



- Measure the neutrino beam rate and spectrum to predict un-oscillated event rates in the far detector
- Constrain systematic uncertainties (flux, cross sections, detector response) for oscillation measurements
- A facility for neutrino physics

- **ND-LAr:** 7 x 5 array of modular 1x1x3 m^3 LArTPCs with pixel readout
- **TMS:** Magnetized steel range stack for measuring muon momentum/sign from ν_μ CC interactions in ND-LAr
- **DUNE-PRISM: ND-LAr + TMS** move up to 28.5 m off-axis

SAND:

- On-axis magnetized neutrino detector with LAr target (GRAIN), tracking (STT), and calorimeter (ECAL)

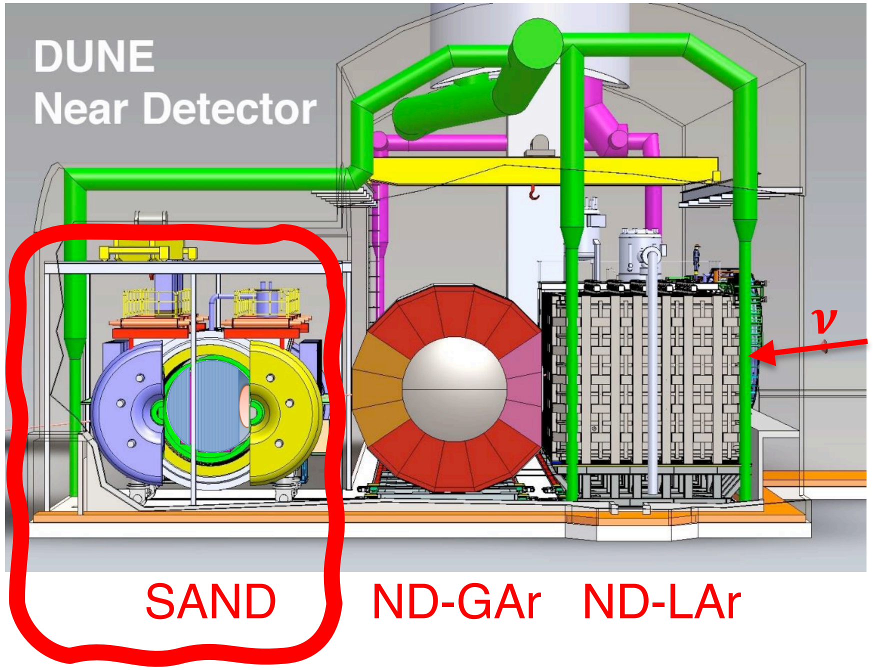
The System for on Axis Neutrino Detection

SAND: the only component of the ND that will be permanently located **on-axis**

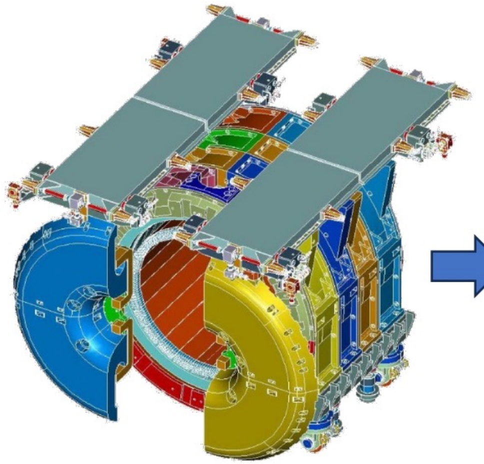
- **Superconducting magnet**
- **Electromagnetic Calorimeter (ECAL)**

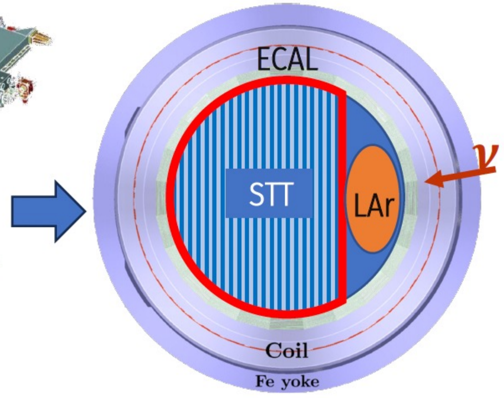
} from KLOE

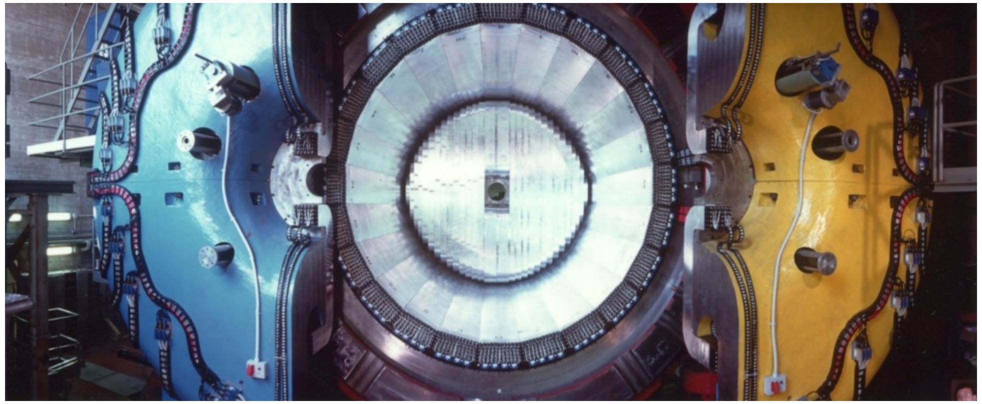
- **Straw-Tube-Tracker and CH_2, C target**
- **1-ton LAr Active target (GRAIN)**



- **On axis ν spectrum monitor** : detect changes in the beam on a weekly basis
- Perform independent in situ measurements of ν_μ , $\bar{\nu}_\mu$, ν_e , $\bar{\nu}_e$ **fluxes and energy spectra**
- **Constrain** systematics from **nuclear effects** by measuring ν and $\bar{\nu}$ cross sections on nuclei other than argon (carbon and hydrocarbons)
- Exploit **high statistics** to perform **physics program besides oscillations**



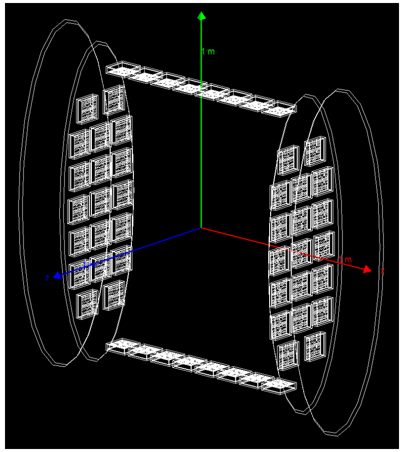


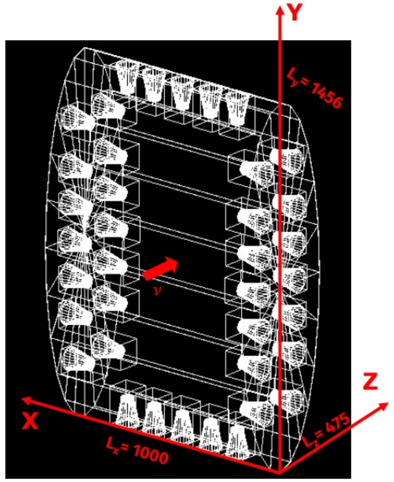


GRAIN in SAND

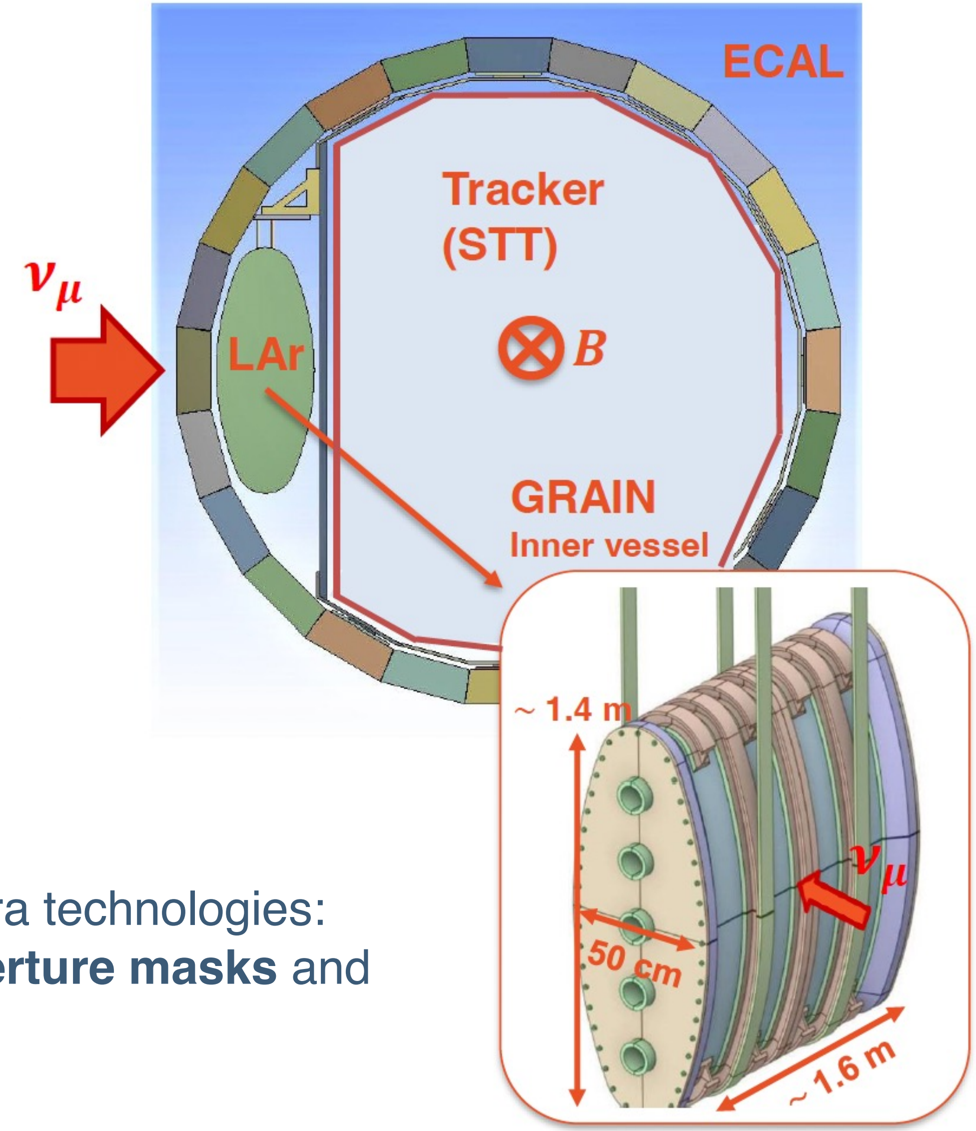
A LAr imaging detector

- 1 ton LAr ($\sim 1X_0$) inside the magnetic field.
- study ν-Ar interactions with downstream tracker/calorimeter
- LAr scintillation light collected with arrays of SiPMs for timing and calorimetry
- perform imaging of the event with scintillation light (**R&D in progress**)

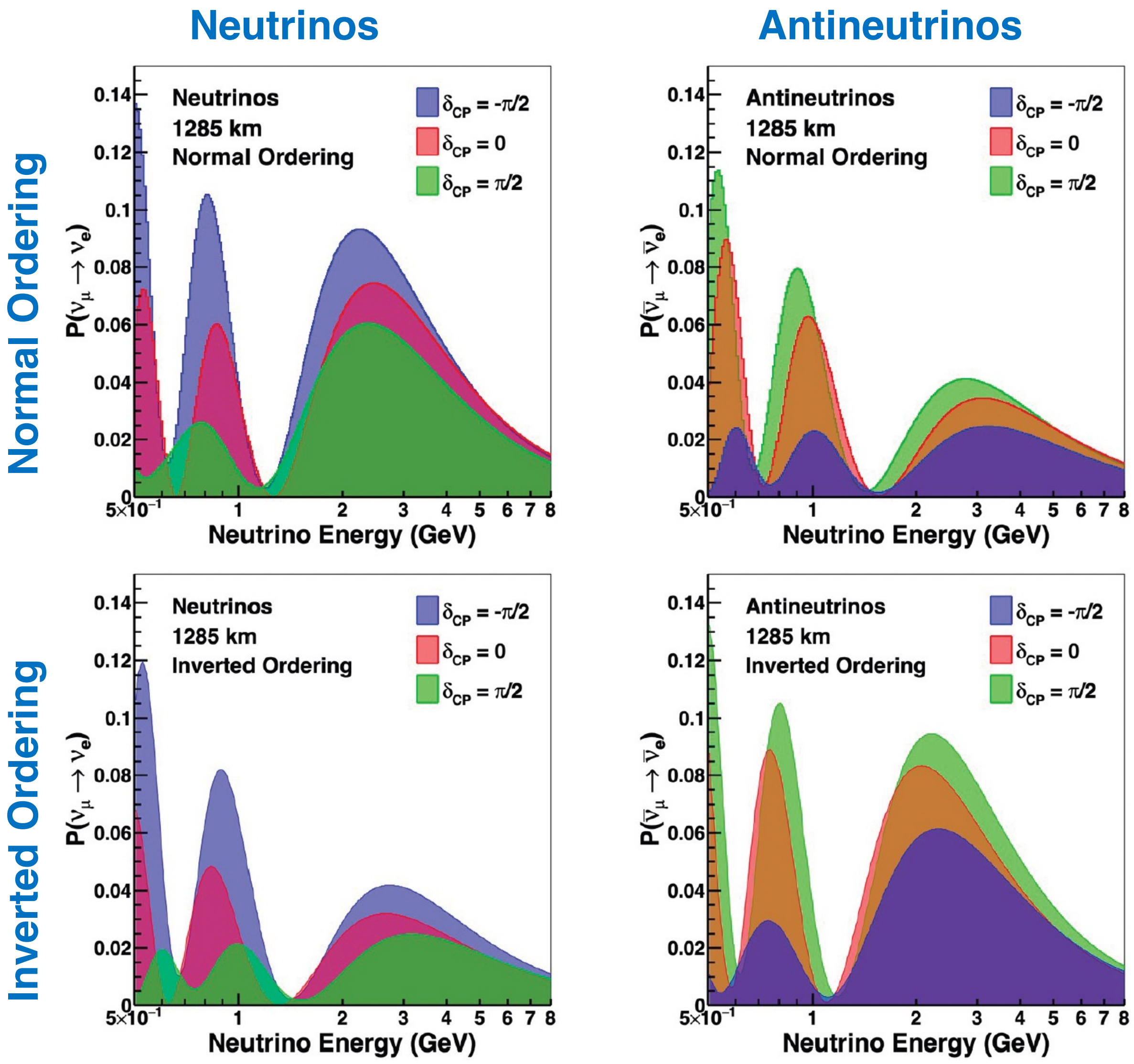




Two camera technologies: **coded aperture masks** and **lenses.**



ν_e , $\bar{\nu}_e$ oscillation shapes



$P(\nu_\mu \rightarrow \nu_e)$ vs $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

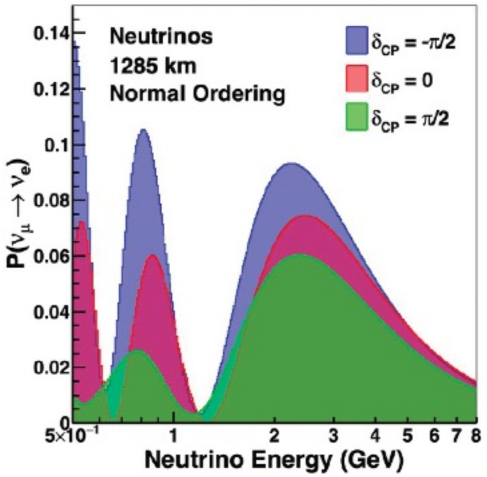
Mass ordering and CP violation induce different shapes in ν_e , $\bar{\nu}_e$ oscillation probabilities

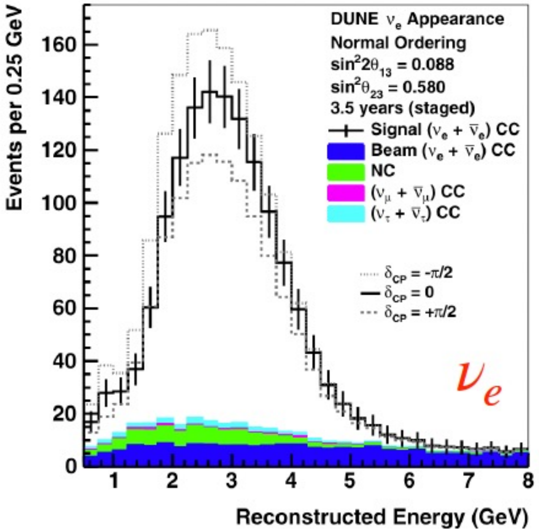
DUNE's unique capability: with a wide band beam measures these shapes over more than a full period, resolving degeneracies and measure

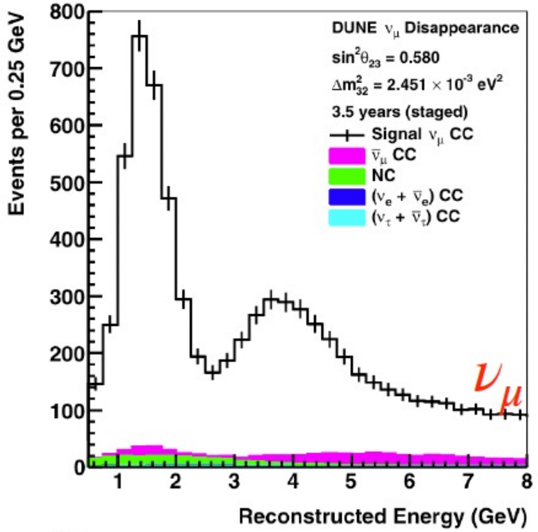
- **mass ordering**
- **CP violation**
- θ_{23} **octant**

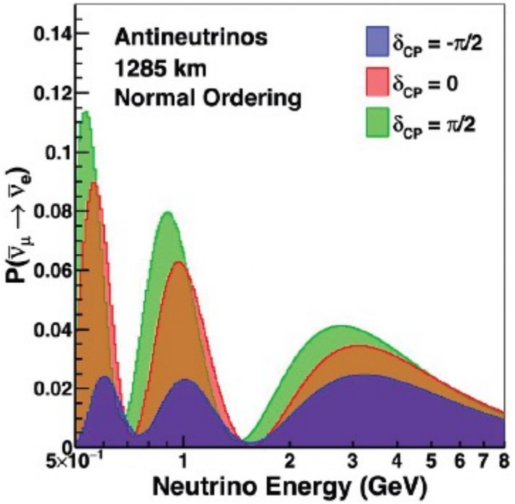
with a single experiment

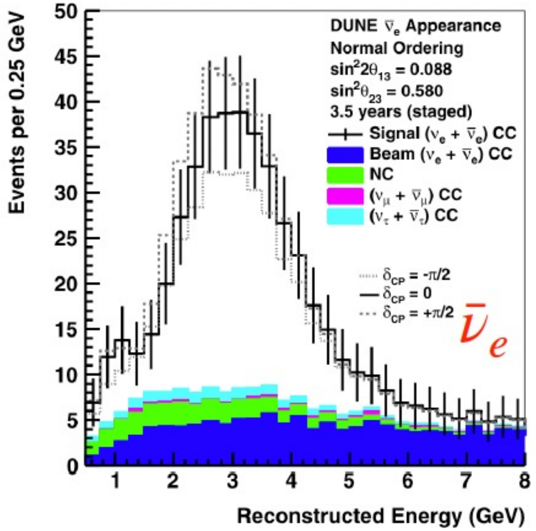
DUNE FD Data

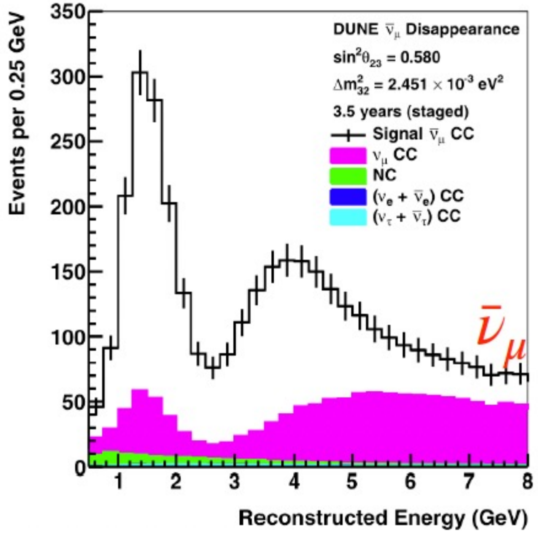












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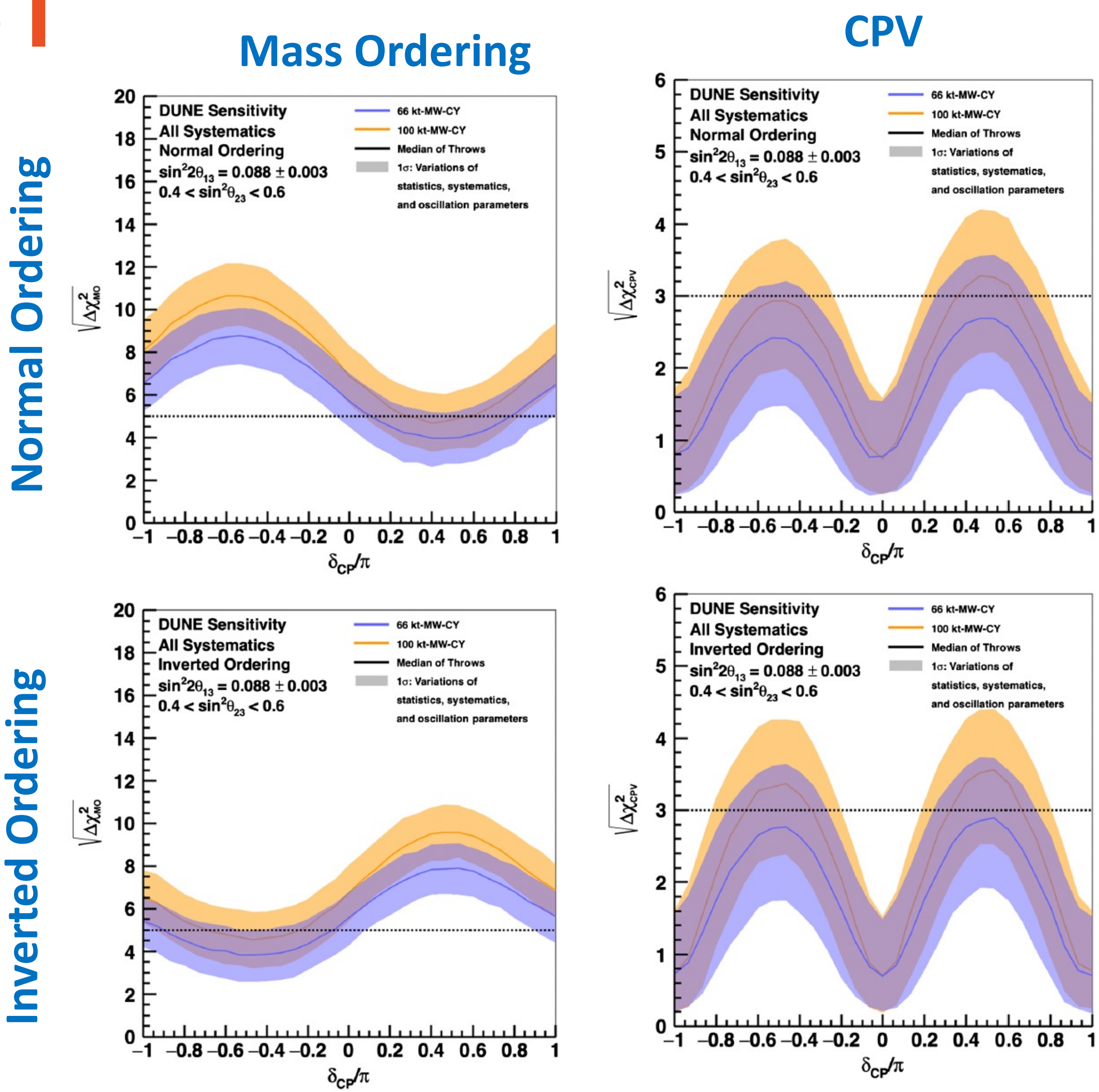
Convolution of oscillation probabilities with neutrino beam flux and cross sections and detector response

Oscillation sensitivities: simultaneous fit over four components of FD data (disappearance and appearance spectra) with ND constraints

DUNE sensitivities - Phase I

DUNE will unambigously resolve the neutrino mass ordering at 3σ (5σ) level with a 66 (100) kt-MW-yr exposure

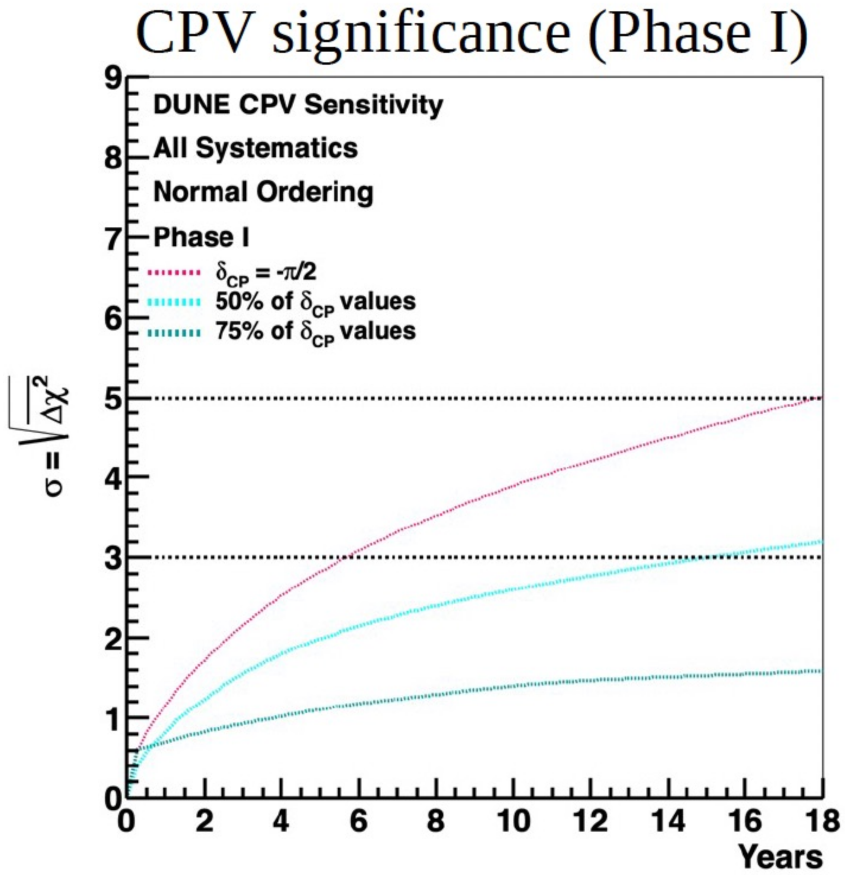
DUNE can measure CPV at 3σ level with a 100 kt-MW-yr exposure for the maximally CP-violating values $\delta_{CP} = \pm \pi/2$

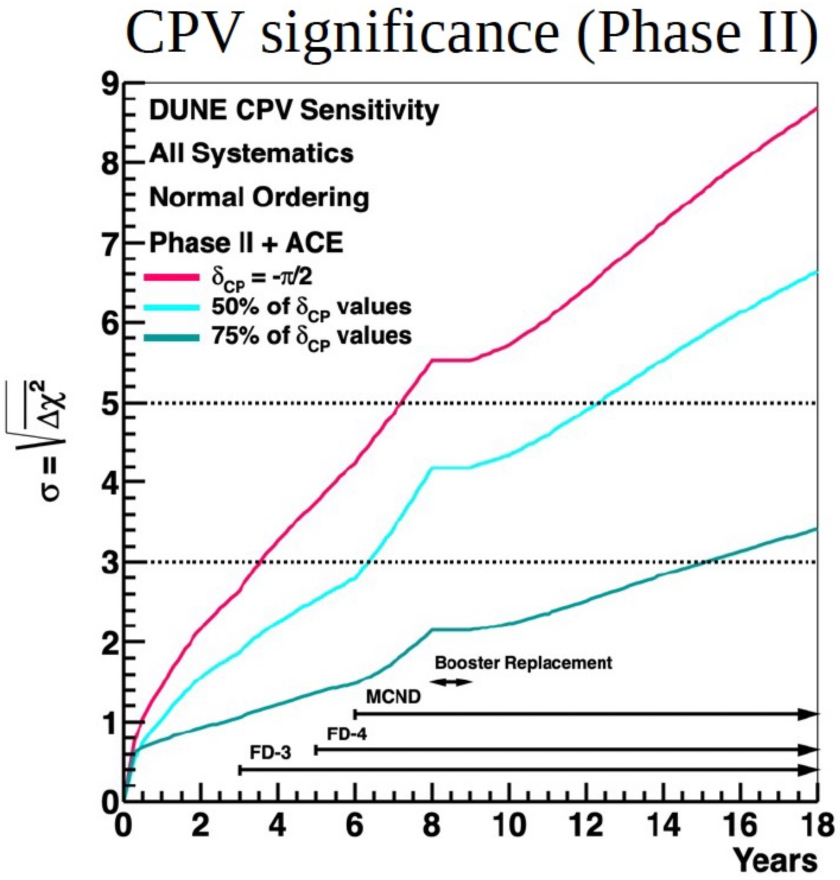


Phys. Rev D 105 (2022) 072006

DUNE sensitivities at higher exposures (Phase II)

Beam upgrade to > 2 MW, additional FD mass to 40 kt, near detector upgrade





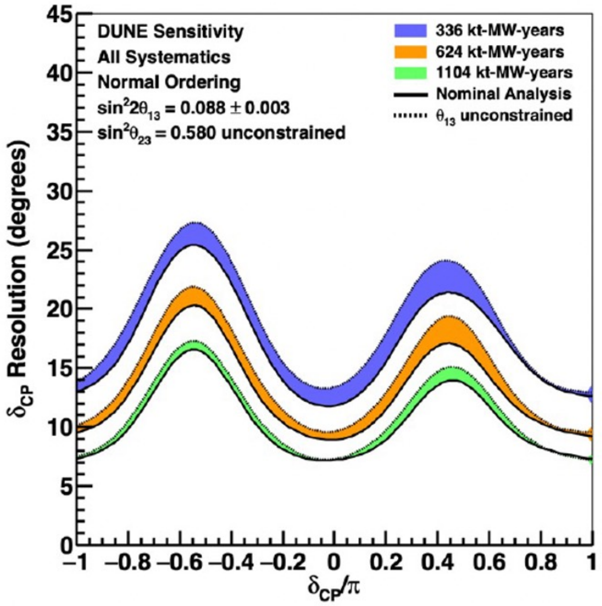
If $\delta_{CP} = \pm 90°$, CP violation at 3σ in Phase I

Phase II: If $\delta_{CP} = \pm 90°$ 3σ CPV in 3.5 years, 5σ in 7 years
For 50% of δ_{CP} values 5σ CPV in 12 years

DUNE resolution

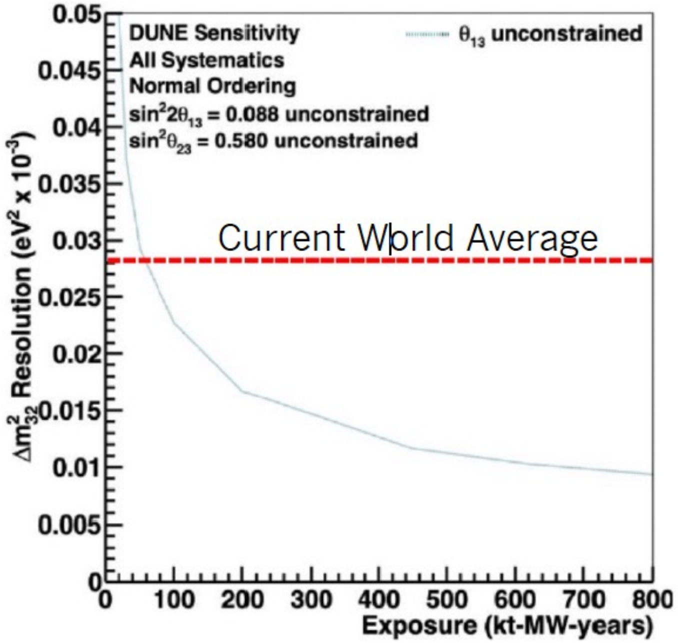
Δm^2_{32}, δ_{CP}, θ_{23} and θ_{13}

measured with high precision
with a single experiment

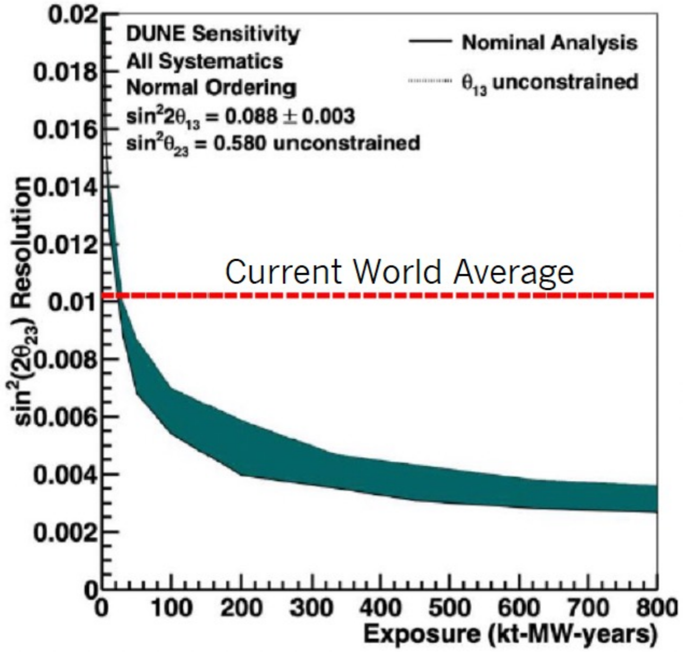


δ_{CP} resolution 6° ÷16°

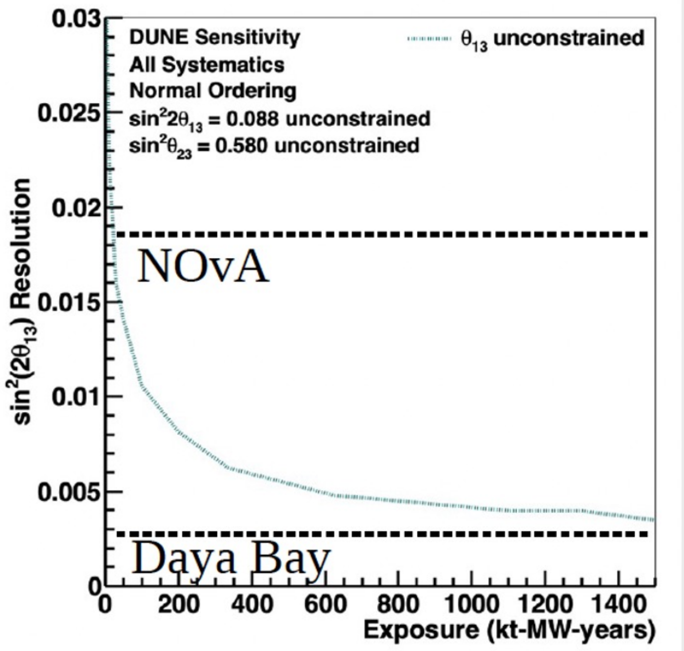
Δm^2_{32}



θ_{23}

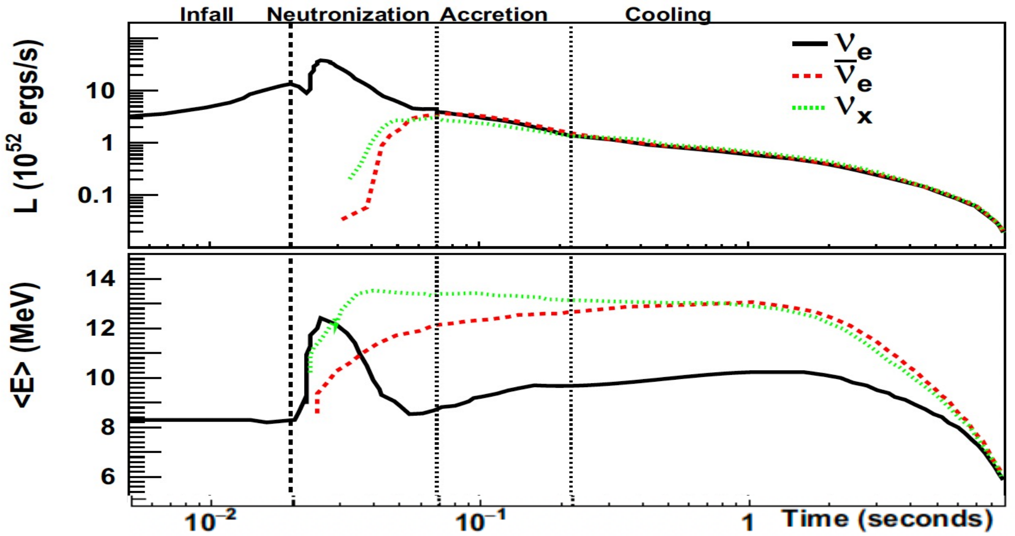


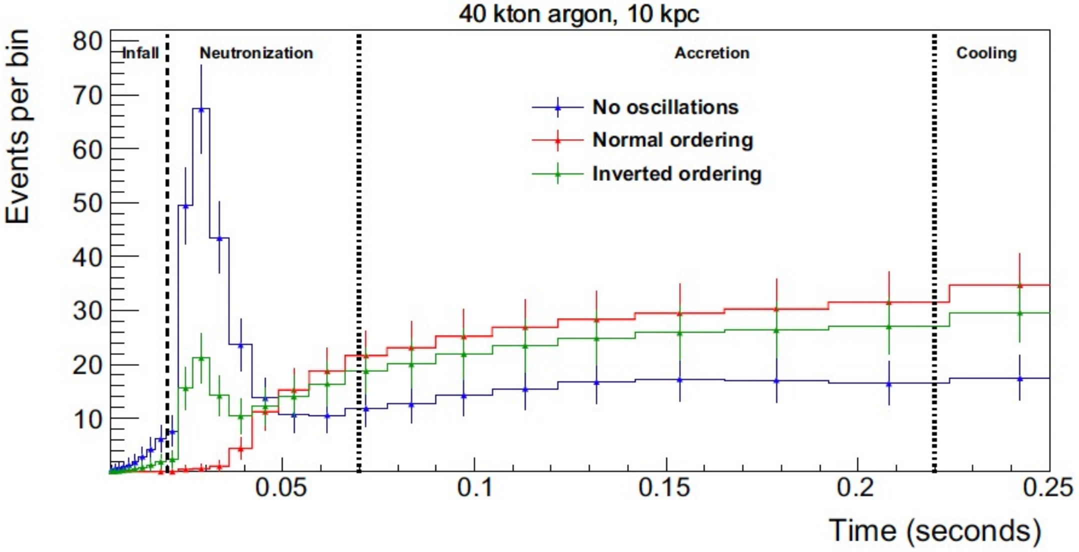
θ_{13}



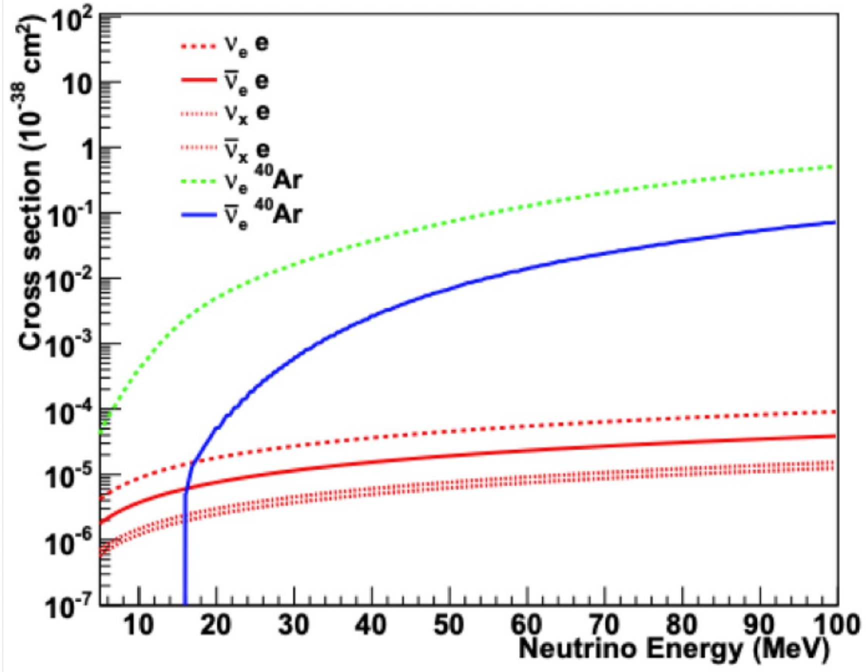
SN burst neutrinos

Eur. Phys. J. C (2021) 81





DUNE is sensitive to ν_e CC events by ν_e + ^{40}Ar → e$^-$ + ^{40} K* (exploiting the Ar target) and to ν ES on electrons (thanks to its huge mass)



Solar neutrinos

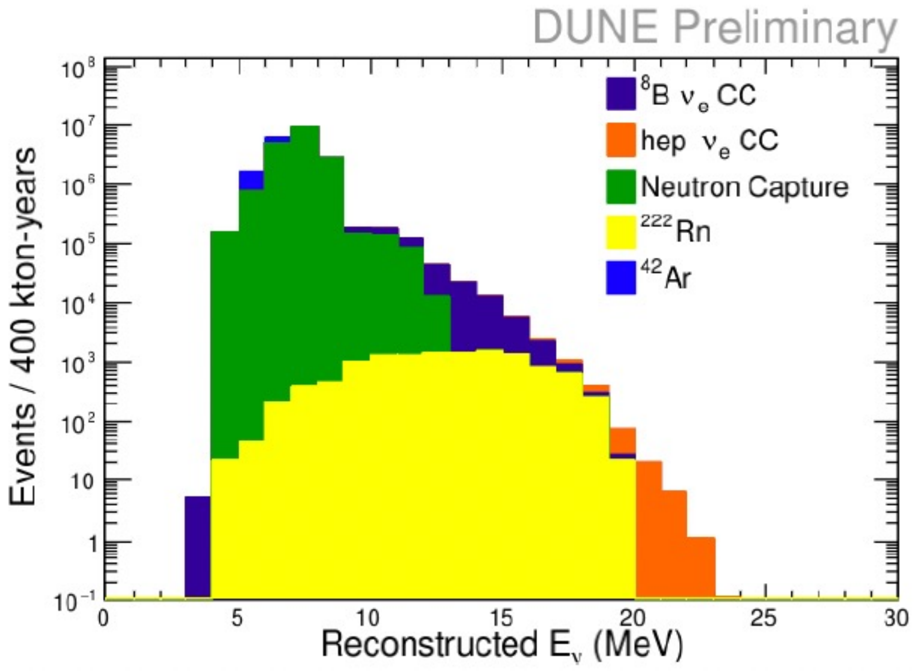
DUNE is sensitive to

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

$$\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^-,$$

This feature gives its best with solar neutrinos where we have an observable only sensitive to electron flavor and another observable sensitive to all flavors.

(*) F. Capozzi et al PRL 123 (2019) 13



DUNE has not been optimized for low energy (<10 MeV) physics in neither granularity nor radiopurity. Still the mass and background rejection capability may provide the first evidence of neutrinos from He-p fusion ("hep") even using the technology of the "Phase I" modules. And "Phase II"" may provide an enhanced opportunity.

BSM Physics

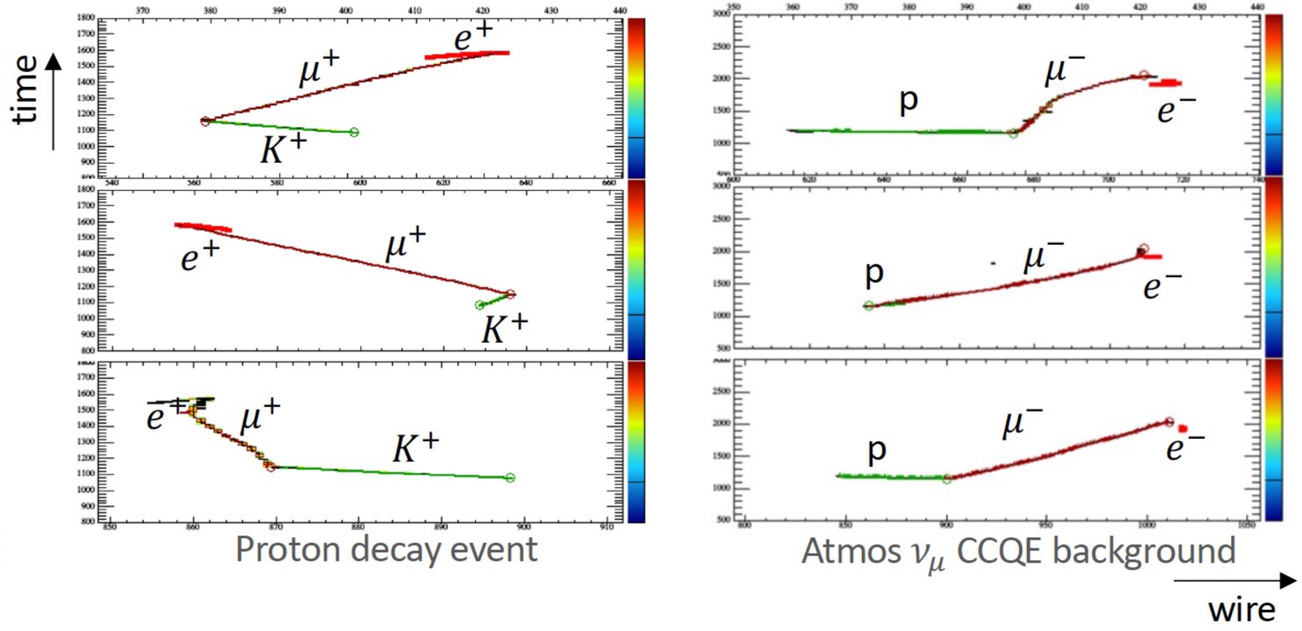
Baryon number violation, dark matter searches, sterile neutrinos, etc.

Example: proton decay

- Underground location
- Large fiducial mass
- Imaging capabilities

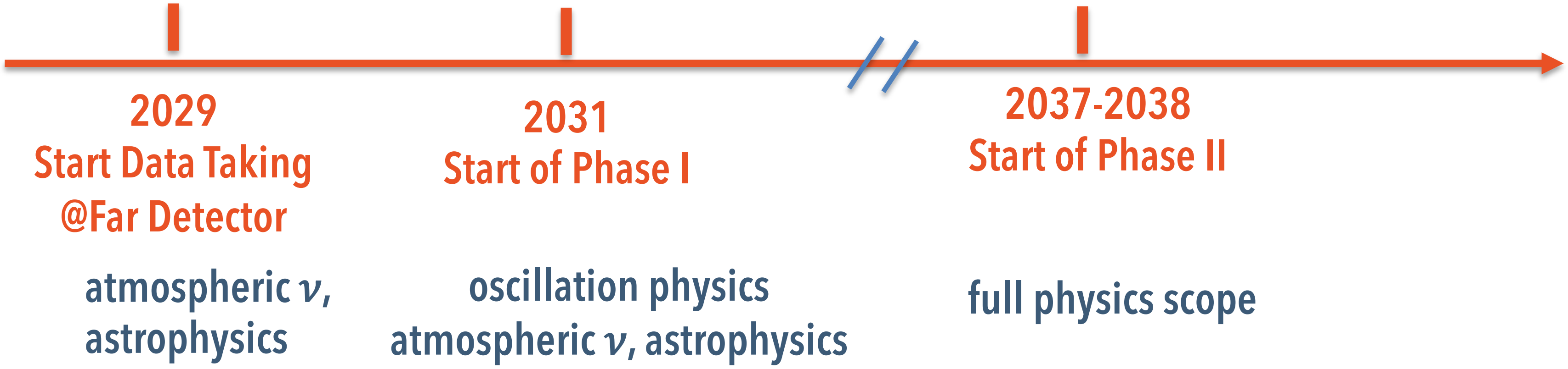
p → $K^+ \bar{\nu}$
(dominant SUSY GUT model)

- Identify kaon by dE/dx and decay products
- Main background: atmospheric neutrinos



Conclusions

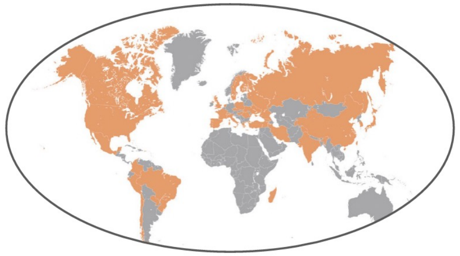
- LBNF/DUNE: the ultimate neutrino facility/observatory
- DUNE will enable very rich physics program in the next decades (LifeCycle 20 years):
  - Neutrino oscillations
  - Studies of MeV-scale neutrinos
  - Several BSM searches
- LBNF and DUNE making rapid progress on facility construction, detector design, and physics analysis



Thank You!

DUNE's attracting the world

- 1440 collaborators
- 37 countries
- 208 institutions including CERN



DUNE Collaboration Meeting, Fermilab, May 2023

Mary Bishai

Sergio Bertolucci

DUNE's spokespersons

DUNE's Phased Approach

Phase I

- Far detector : 2 modules , 17 kt LAr each
- Beam : 1.2 MW
- Near Detector Complex in its full configuration (SAND, ND-LAr, TMS)

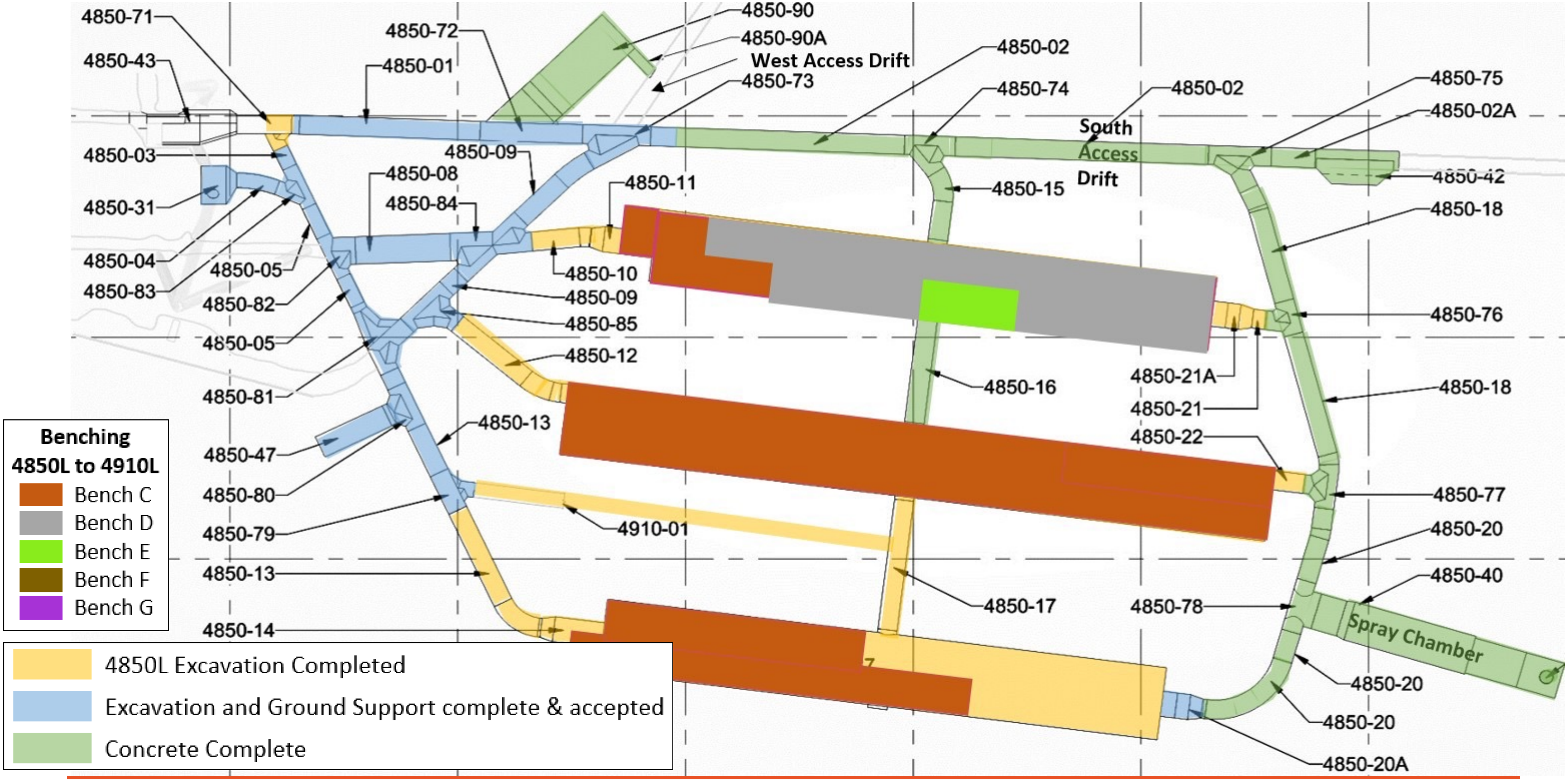
Determine mass ordering
Establish CP violation at 3σ if nearly maximal in 5 years running

Phase II

- FD mass: 17 kt x 4 modules
  - Modules 1, 2 & 3 LAr-TPCs
  - Module 4: "Module of Opportunity"
- Beam upgrade to > 2 MW
- More Capable Near Detector Complex (SAND, ND-LAr, ND-Gar)

Precision Long Baseline Physics
(e.g. resolution in δ_{CP} ~ 10° depending on true value)

Excavation Progress – Reached 68% on 30 June 2023



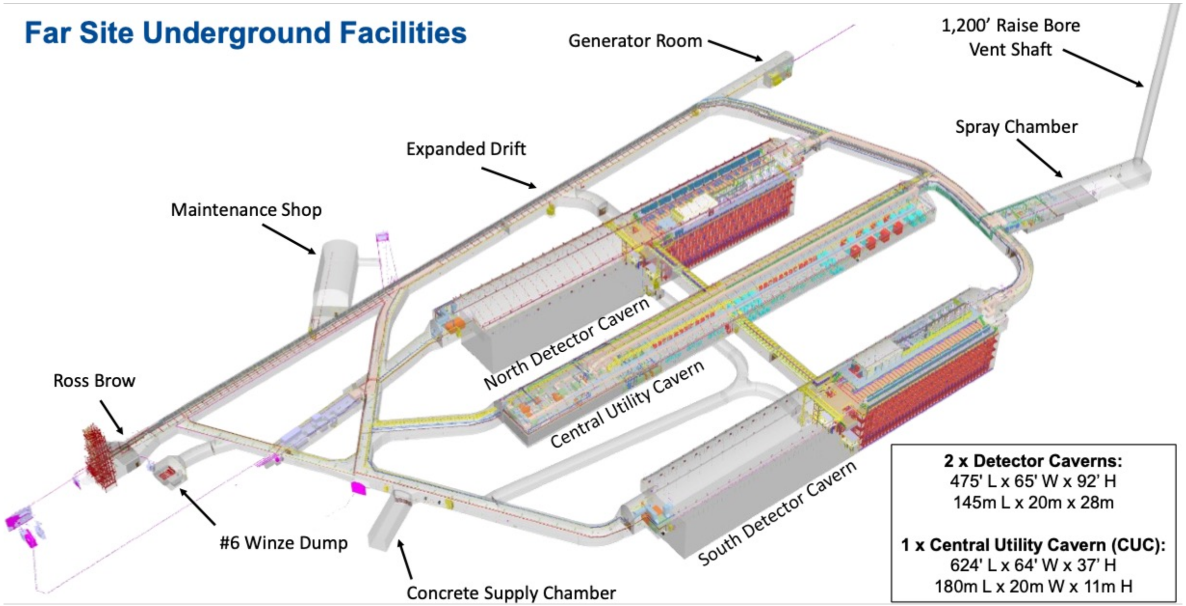
INFN DUNE

DUNE Far Detector: Phased Construction

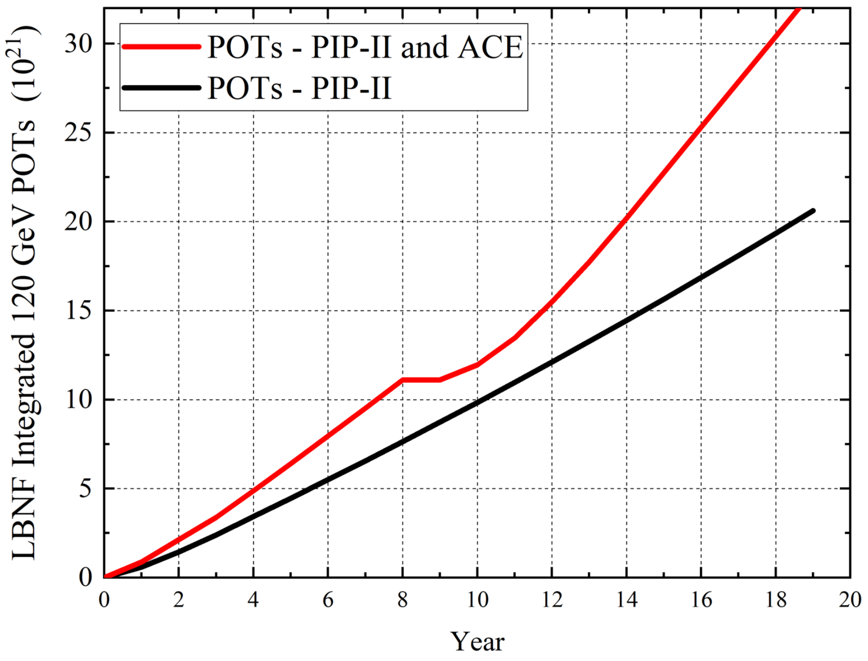
Four 17-kton modules

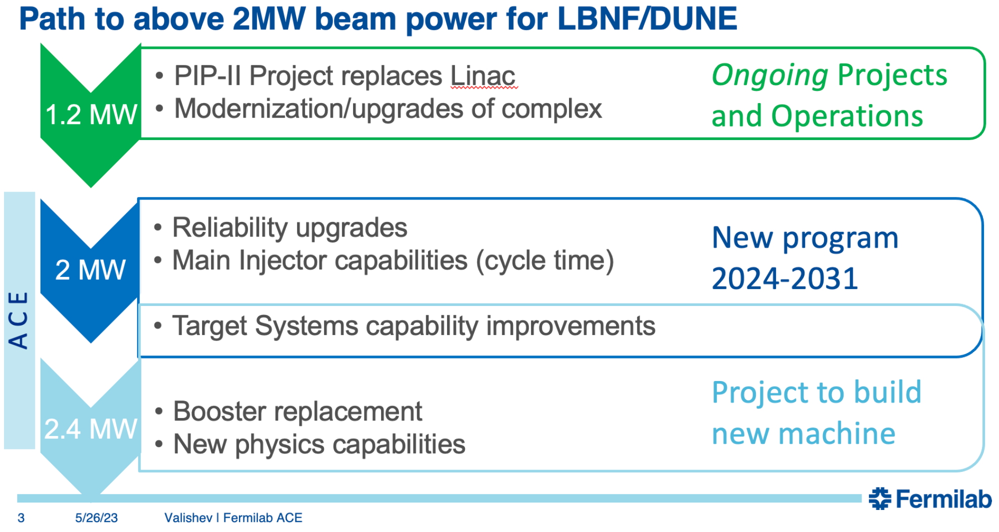
- Modules 1, 2 & 3 LAr-TPCs
- Module 4: "Module of Opportunity"

Expand physics scope
Several technologies being considered



- Optimized VD for FD#3,4: optimized r/o CE (digital) & SoF (large bandwidth) for higher ch count
- SLoMo : A SURF Low Background Module
- SoLAr : novel pixelated charge readout
- Xe-doped LArTPC : $0\nu\beta\beta$ decay concept
- Theia : A hybrid Cherenkov/scintillation detector module
- LiquidO : Opaque Liquid Scintillator





ACE: Accelerator Complex Evolution

- Main Injector Cycle time shortening
- Target System upgrade

- enable delivery of more POTs
- accelerate the achievement of DUNE science goals with respect to the present PIP-II plan

2024-2031 program

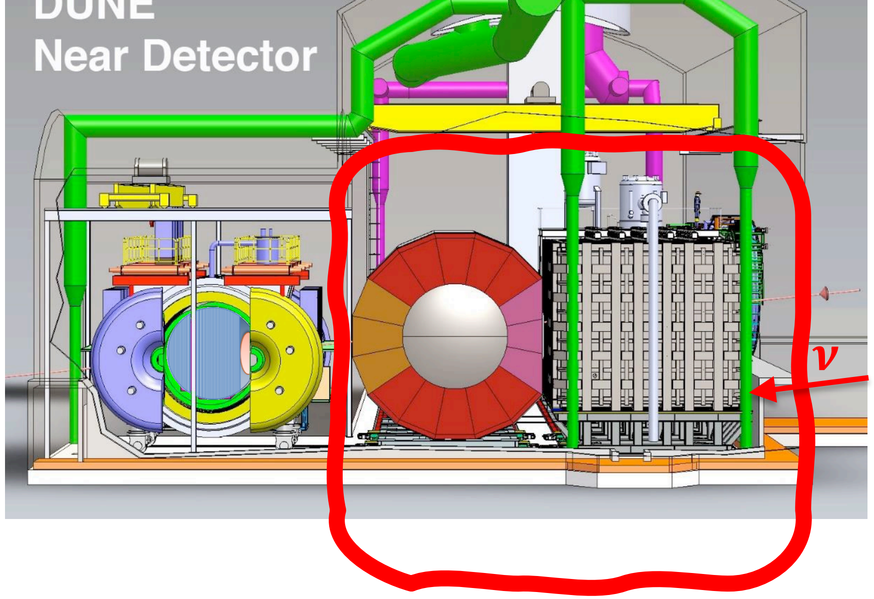
PIP-II & reduced MI cycle time:
1.2 sec → 0.9 sec → 0.7 sec
1.2 MW → 1.6 MW → 2.1 MW

Booster upgrades for 2.4 MW (beyond 2031)

PRISM Concept

PRISM (Precision Reaction-Independent Spectrum Measurement)

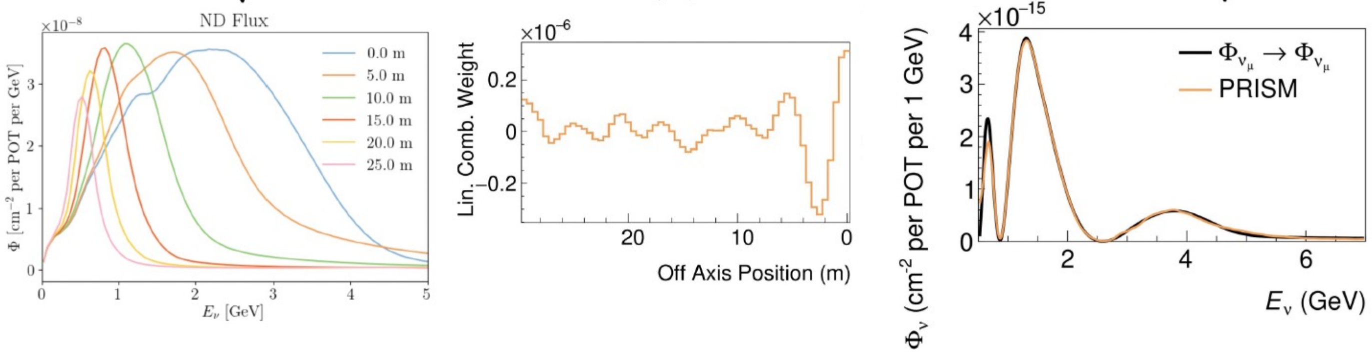
ND-LAr + TMS (ND-Gar) will move as far as 30 m transversally to the beam to collect data at different off-axis positions:

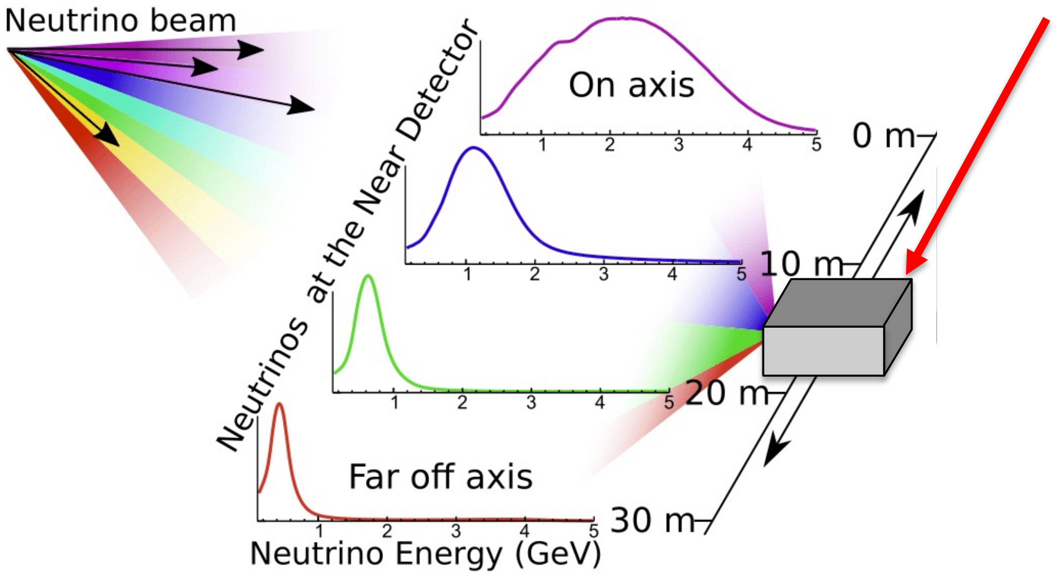


SAND ND-GAr ND-LAr

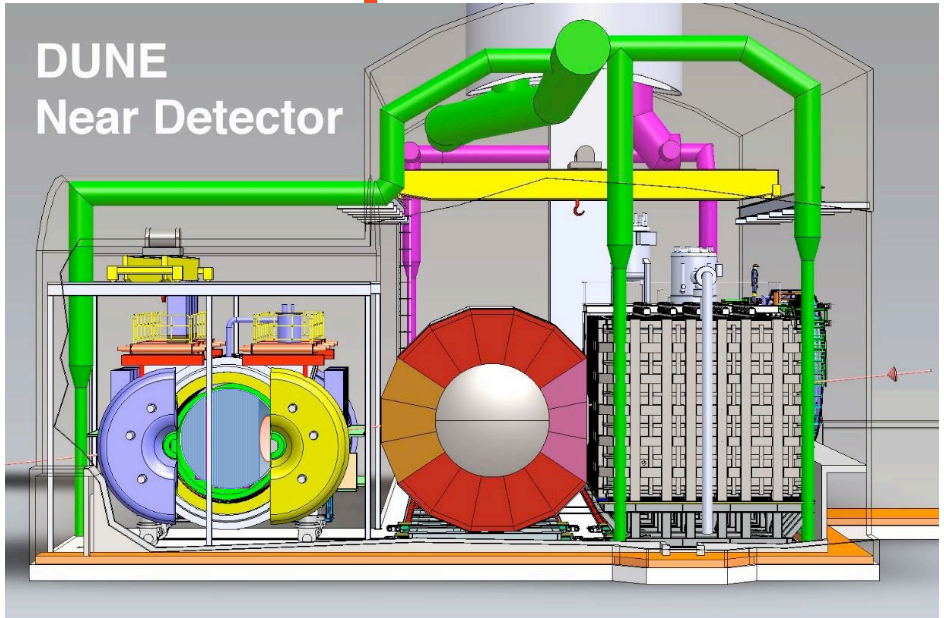
Build a linear combination of ND fluxes measured at different off-axis positions to predict oscillated neutrino event spectra at FD with reduced dependence on neutrino-argon interaction model

$$\Phi^{ND}(E_\nu, x) \cdot C(x) = \Phi^{FD}(E_\nu)$$

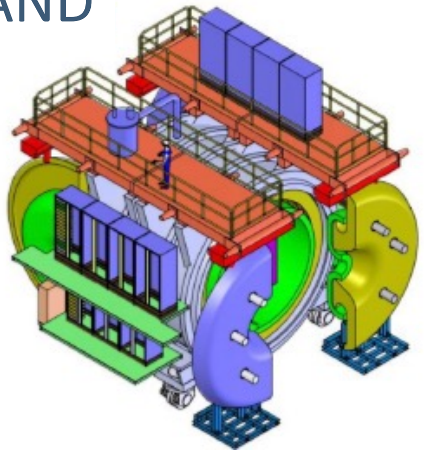




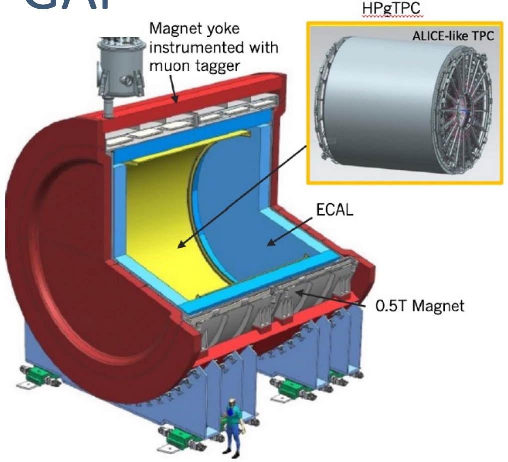
The Near Detector Complex – Phase II



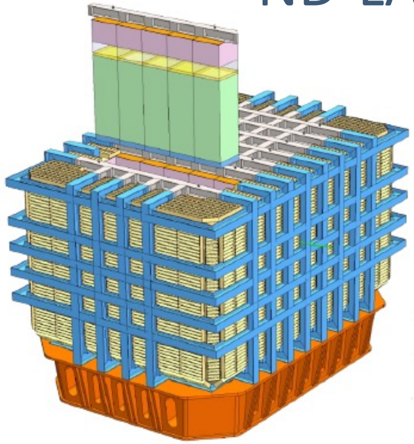
SAND



ND-GAr



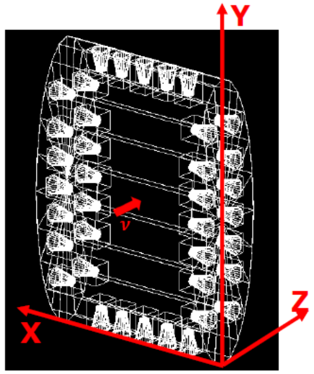
ND-LAr



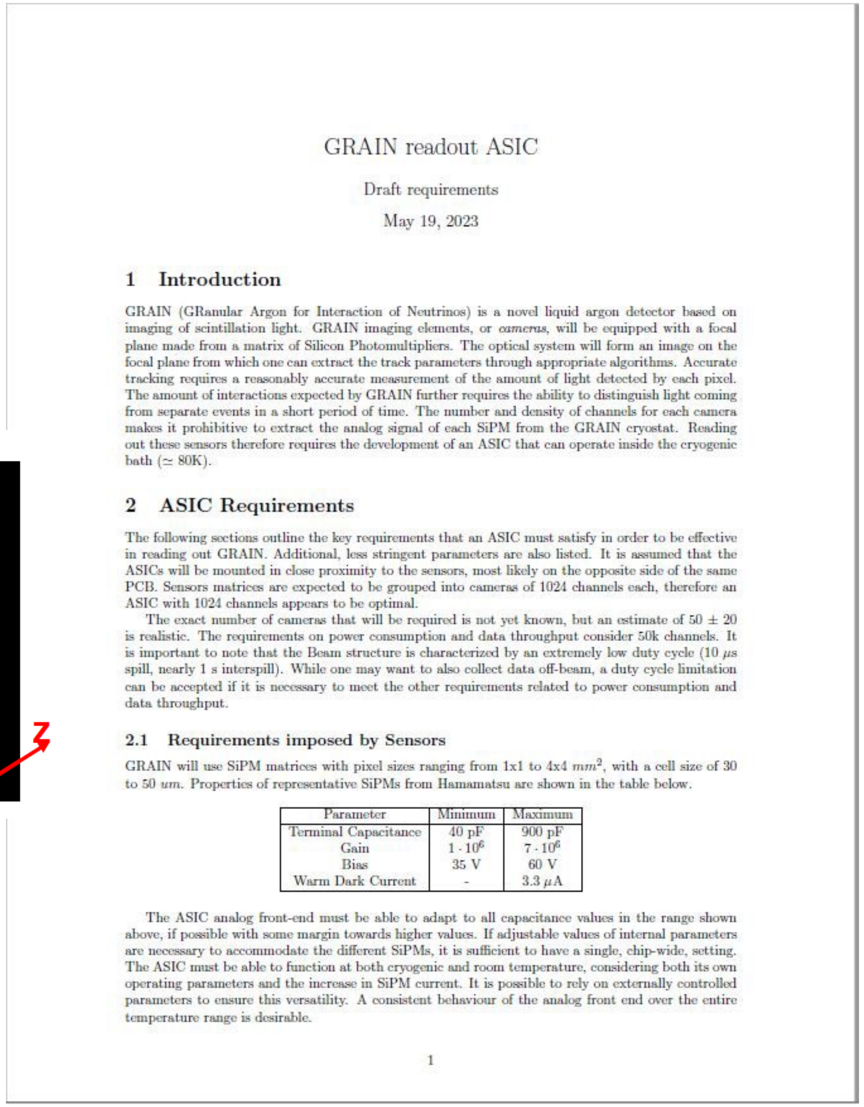
A new ASIC for GRAIN

- We plan to implement imaging of tracks in LAr by means of cameras based on a 32x32 matrix of SiPMs where all 1024 channels are readout individually
- Tens of cameras will cover the whole volume for a total of about 50k channels
- We need a cryogenic ASIC that fits our requirements

GDML:



- The INFN group from Torino agreed to produce a new ASIC with 1024 channels
- Much less output lines and simpler feedthrough



GRAIN readout ASIC

Draft requirements

May 19, 2023

1 Introduction

GRAIN (GRanular Argon for Interaction of Neutrinos) is a novel liquid argon detector based on imaging of scintillation light. GRAIN imaging elements, or *cameras*, will be equipped with a focal plane made from a matrix of Silicon Photomultipliers. The optical system will form an image on the focal plane from which one can extract the track parameters through appropriate algorithms. Accurate tracking requires a reasonably accurate measurement of the amount of light detected by each pixel. The amount of interactions expected by GRAIN further requires the ability to distinguish light coming from separate events in a short period of time. The number and density of channels for each camera makes it prohibitive to extract the analog signal of each SiPM from the GRAIN cryostat. Reading out these sensors therefore requires the development of an ASIC that can operate inside the cryogenic bath ($\simeq$ 80K).

2 ASIC Requirements

The following sections outline the key requirements that an ASIC must satisfy in order to be effective in reading out GRAIN. Additional, less stringent parameters are also listed. It is assumed that the ASICs will be mounted in close proximity to the sensors, most likely on the opposite side of the same PCB. Sensors matrices are expected to be grouped into cameras of 1024 channels each, therefore an ASIC with 1024 channels appears to be optimal.

The exact number of cameras that will be required is not yet known, but an estimate of 50 ± 20 is realistic. The requirements on power consumption and data throughput consider 50k channels. It is important to note that the Beam structure is characterized by an extremely low duty cycle (10 μs spill, nearly 1 s interspill). While one may want to also collect data off-beam, a duty cycle limitation can be accepted if it is necessary to meet the other requirements related to power consumption and data throughput.

2.1 Requirements imposed by Sensors

GRAIN will use SiPM matrices with pixel sizes ranging from 1x1 to 4x4 mm^2, with a cell size of 30 to 50 um. Properties of representative SiPMs from Hamamatsu are shown in the table below.

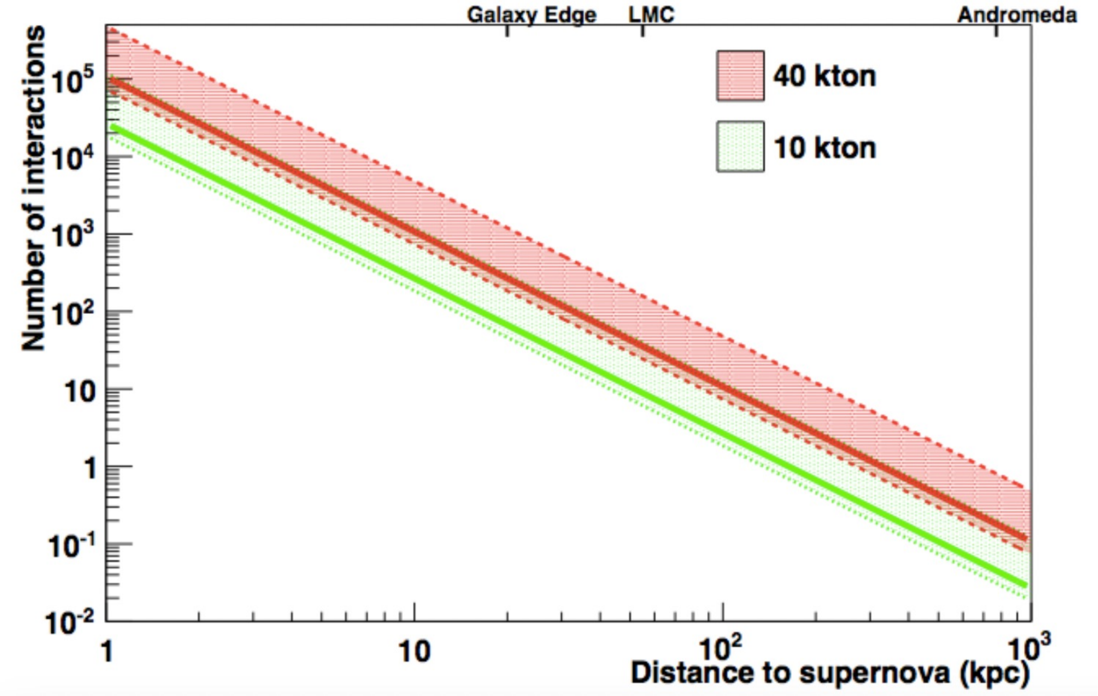
Parameter	Minimum	Maximum
Terminal Capacitance	40 pF	900 pF
Gain	$1 \cdot 10^6$	$7 \cdot 10^6$
Bias	35 V	60 V
Warm Dark Current	-	3.3 μA

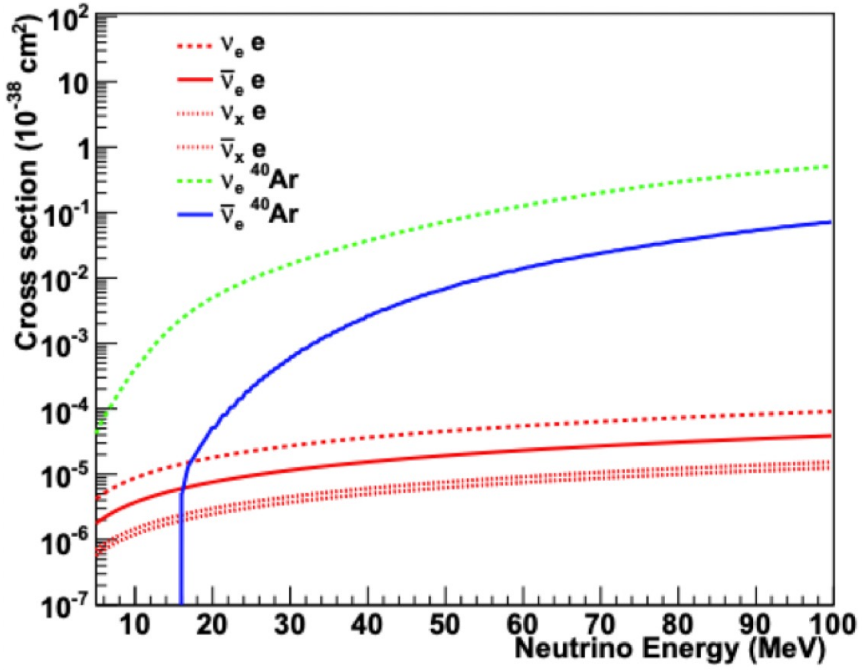
The ASIC analog front-end must be able to adapt to all capacitance values in the range shown above, if possible with some margin towards higher values. If adjustable values of internal parameters are necessary to accommodate the different SiPMs, it is sufficient to have a single, chip-wide, setting. The ASIC must be able to function at both cryogenic and room temperature, considering both its own operating parameters and the increase in SiPM current. It is possible to rely on externally controlled parameters to ensure this versatility. A consistent behaviour of the analog front end over the entire temperature range is desirable.

1

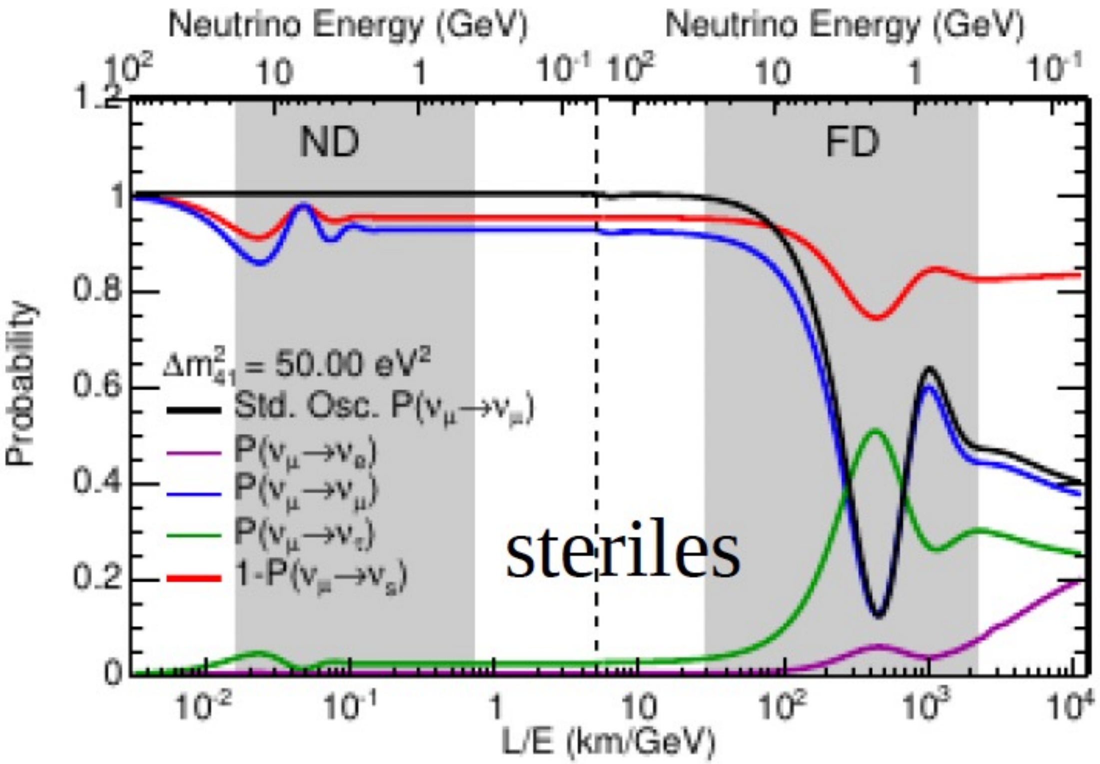
Signal energies and expected rates in LAr

Signal	Energy range	Expected Signal Rate per kton of LAr (yr^{-1} $kton^{-1}$)
Proton decay	~ GeV	< 0.06
Atmospheric neutrinos	0.1-100 GeV	~120
Supernova burst neutrinos	few-50 MeV	~100 @ 10 kpc **over ~30 secs**
Solar neutrinos	few-15 MeV	1300
Supernova relic neutrinos	20-50 MeV	< 0.06

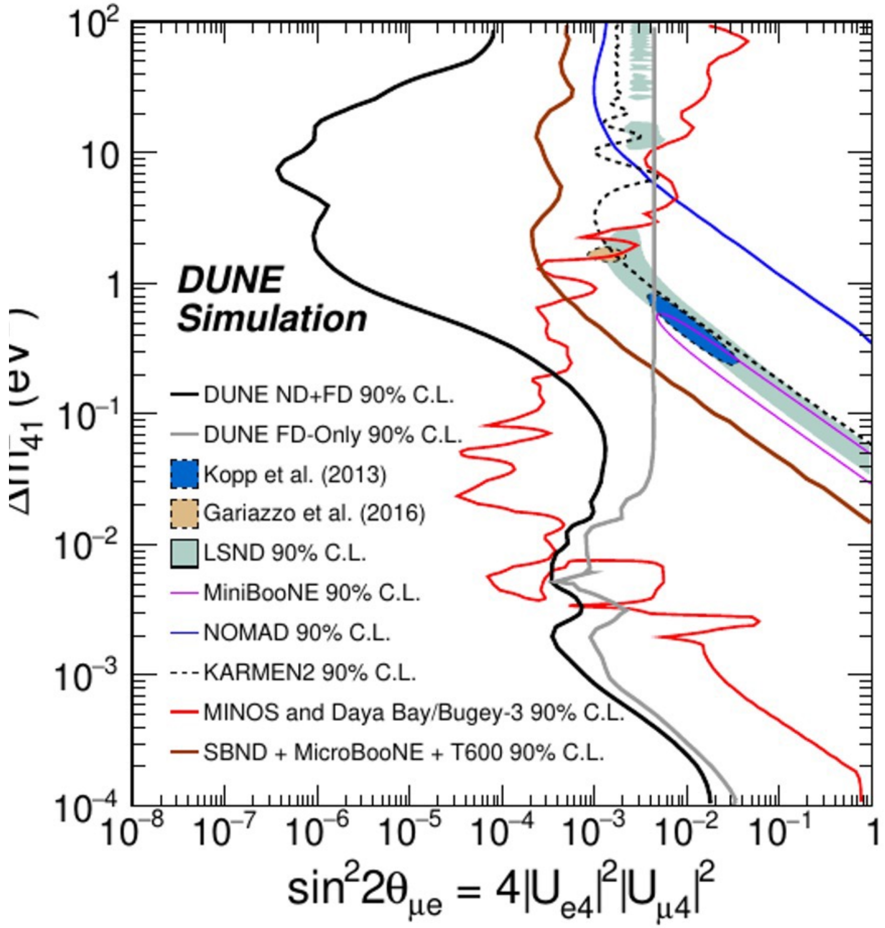

Galaxy Edge
LMC
Andromeda
40 kton
10 kton
Number of interactions
Distance to supernova (kpc)


ν_e e
$\bar{\nu}_e$ e
ν_x e
$\bar{\nu}_x$ e
ν_e ^{40}Ar
$\bar{\nu}_e$ ^{40}Ar
Cross section (10^{-38} cm^2)
Neutrino Energy (MeV)

Sterile Neutrinos



Sterile Neutrino Sensitivity
(ν_e CC appearance at ND)



DUNE ν_e , $\bar{\nu}_e$ spectra can distinguish Mass Ordering in Phase I

Data points show NO, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

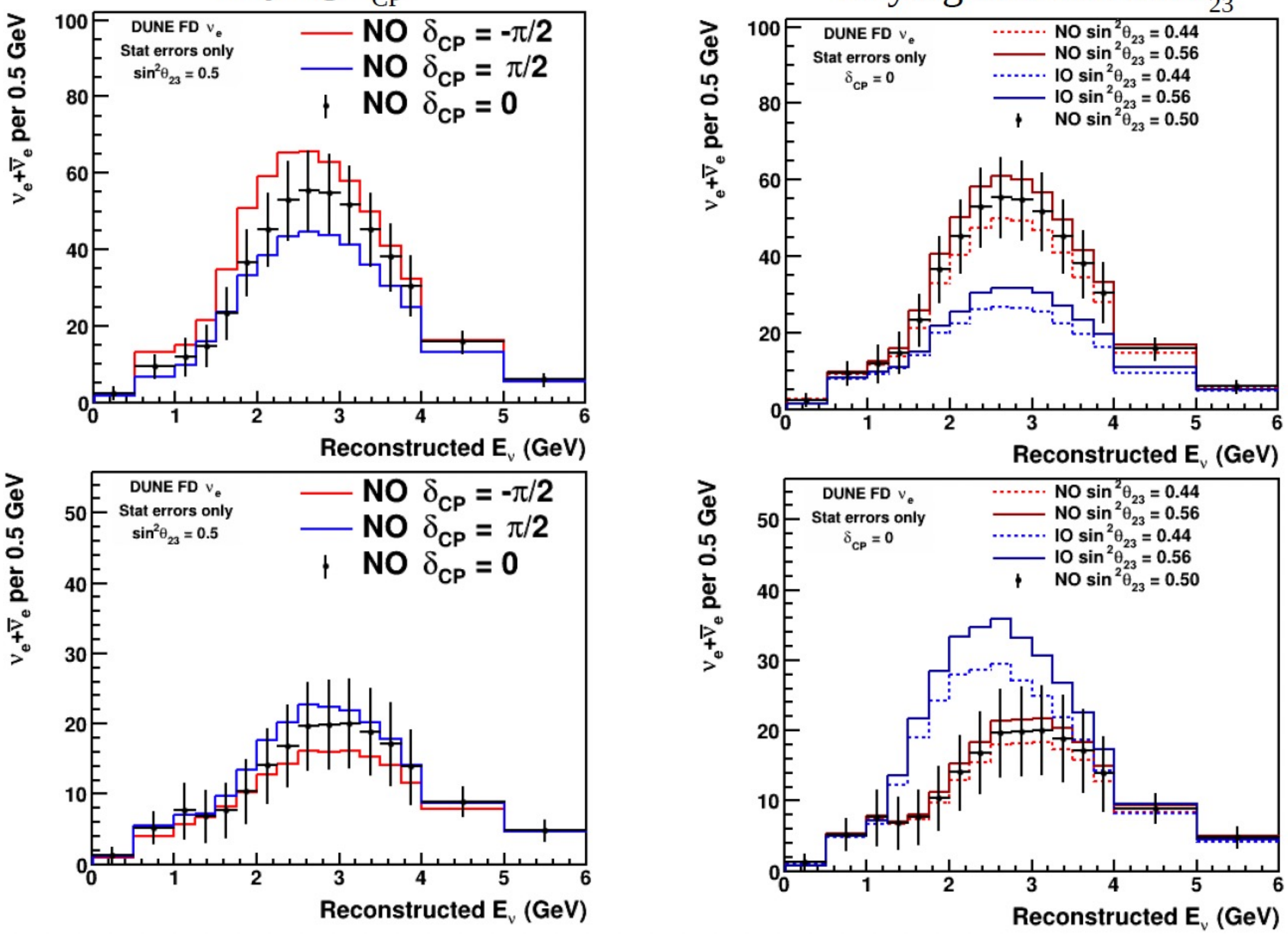
Neutrino mode

Phase I

Antineutrino mode

Varying δ_{CP}

Varying MO and $\sin^2\theta_{23}$



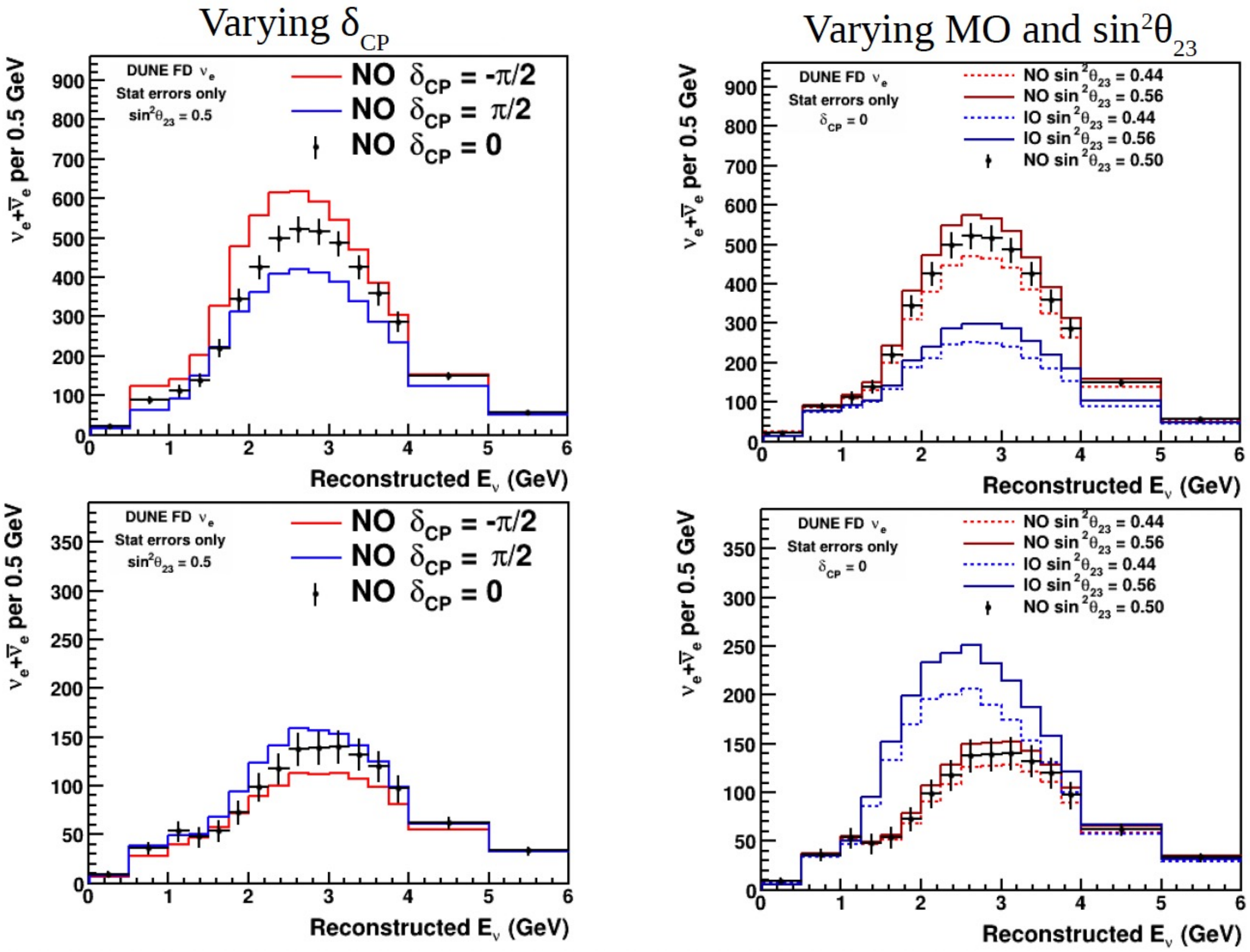
DUNE ν_e , $\bar{\nu}_e$ spectra can measure δ_{CP}, θ_{23} octant in Phase II

Data points show NO, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

Neutrino mode

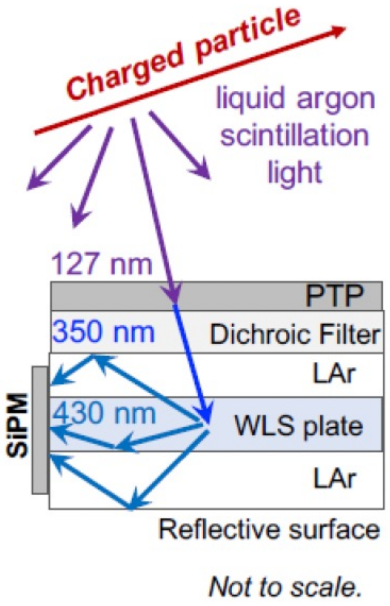
Phase II

Antineutrino mode



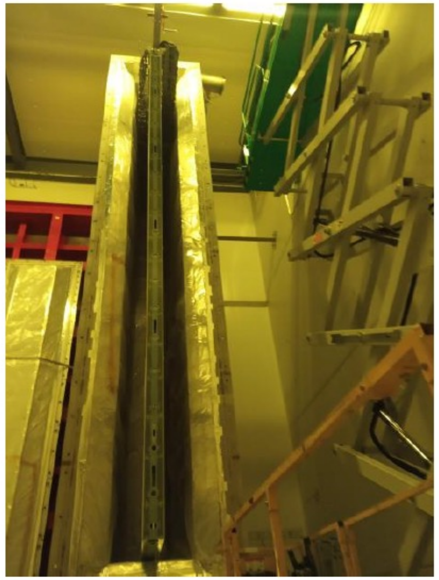
The DUNE Photon Detection System

In the course of the construction of ProtoDUNE-SP, a new technology has emerged for the observation of the VUV (128 nm) scintillation light of liquid argon

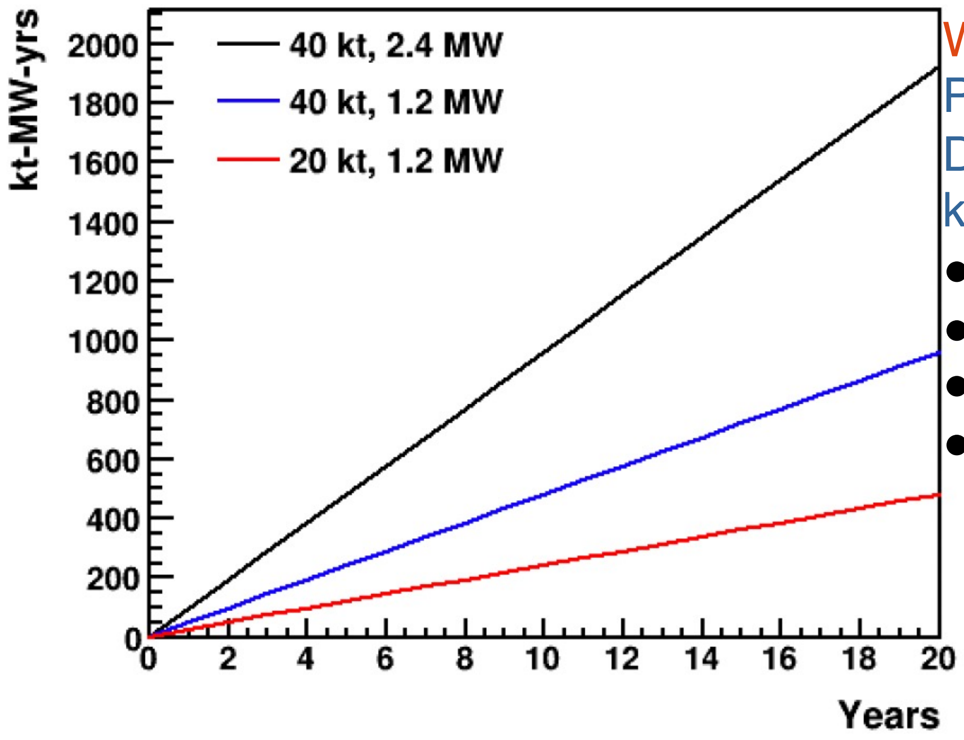


The X-ARAPUCA

A.A. Machado, E. Segreto, JINST 11 (2016) 02, C02004



Compactness, low number of active detectors (SiPM), high efficiency (2-3%). A major effort to bring this technology at production level: the system was installed in ProtoDUNE-HD in Sep 2022



Why 2.4 MW beam?

Precision physics of DUNE requires O(1000) kt-MW-yr beam exposure

- We want to achieve this in ~1 decade
- 46 years in Phase I
- 23 years with 40 kt but still 1.2 MW
- 11.5 years with 40 kt and 2.4 MW

PIP-II and LBNF accelerator milestones

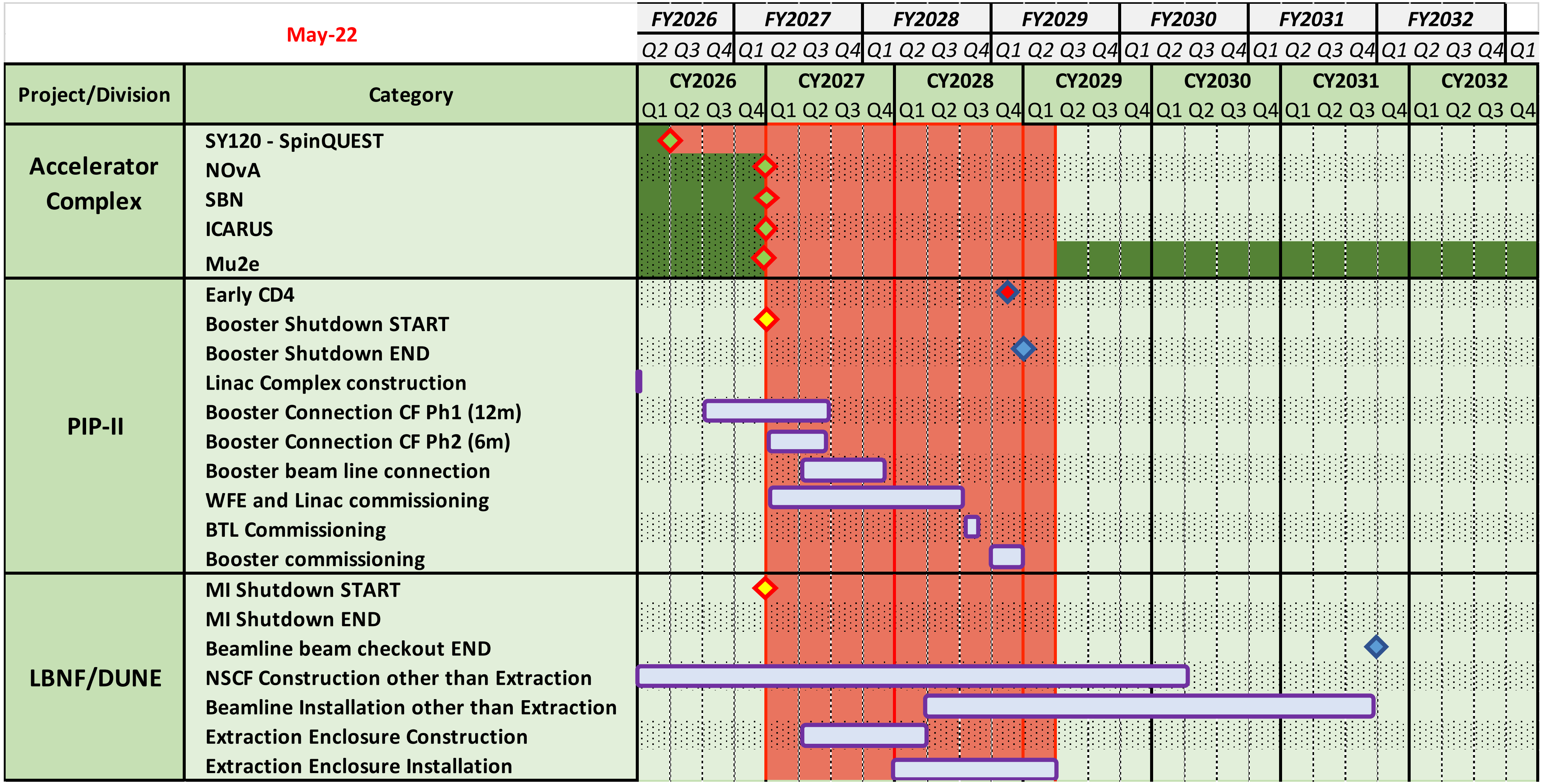


Table 4. APA design parameters.

Paramater	Value
Active Height	5.984 m
Active Width	2.300 m
Wire Pitch (U,V)	4.669 mm
Wire Pitch (X,G)	4.790 mm
Wire Position Tolerance	0.5 mm
Wire Plane Spacing	4.75 mm
Wire Angle (w.r.t. vertical) (U,V)	35.7°
Wire Angle (w.r.t. vertical) (X,G)	0°
Number Wires / APA	960 (X), 960 (G), 800 (U), 800 (V)
Number Electronic Channels / APA	2560
Wire Tension	5.0 N
Wire Material	Beryllium Copper
Wire Diameter	150 µm
Wire Resistivity	7.68 µΩ-cm @ 20° C
Wire Resistance/m	4.4 Ω/m @ 20° C
Frame Planarity	5 mm
Photon Detector Slots	10

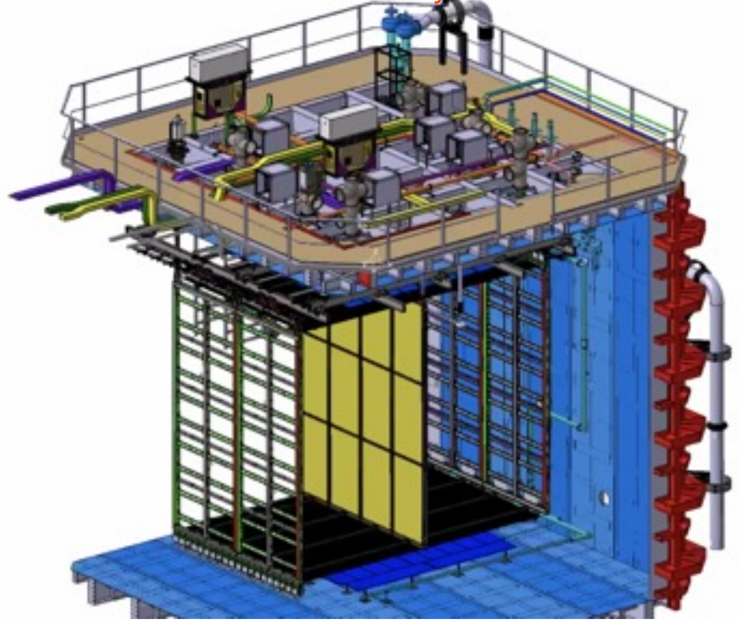
Table 5. Bias voltages for APA wire planes and mesh.

APA layer	Bias voltage
Grid (G)	−665 V
Induction (U)	−370 V
Induction (V)	0 V
Collection (X)	820 V
Mesh (M)	0 V

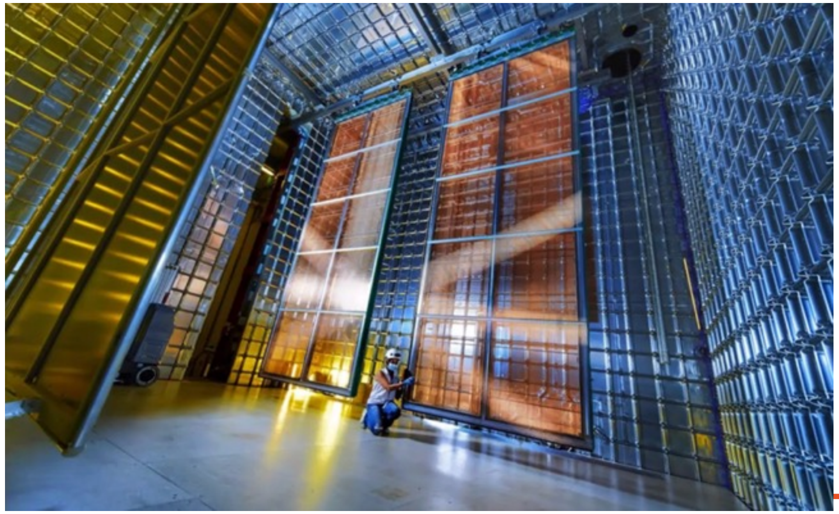
2022 JINST 17 P01

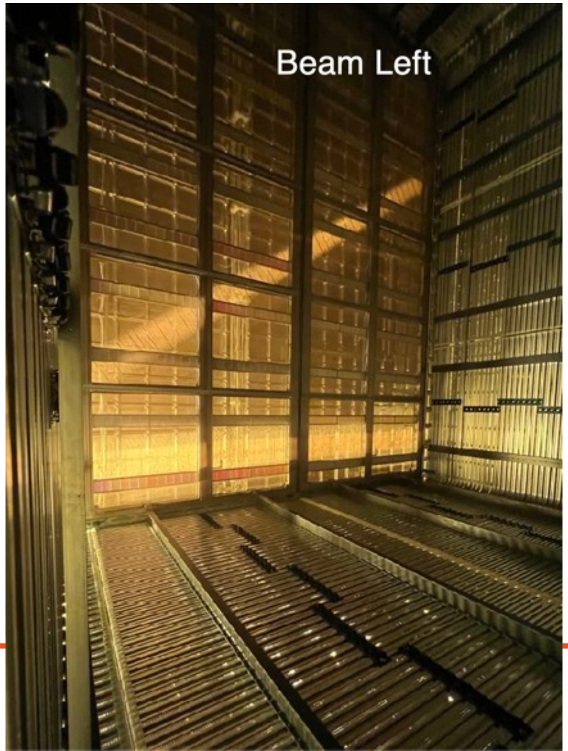
CREDIT: Marzio Nessi Slide I NSG FDC Overview May'23

FD1 prototyping activities : Module-0



- All components in pre-production mode, with final technology (incl. cold electronics)
- All 4 APAs tested in cryogenic conditions prior installation in the NP04 cold box
- APA1 and APA2 (beam right) installed and connected in cryostat mid of Oct. '22
- PDs and APAs successfully integrated in the DAQ
- Beam right drift closed on the 11th of November '22
- Beam plug successfully installed at the beginning of November '22
- APA3 and APA4 (beam left) installed and connected in cryostat mid Nov. '22
- Successful integration in the DAQ followed
- Beam left drift closed on the 22nd of November
- Plan to close the TCO (cryostat access window) in Summer '23
- Fill before end of the year '23 if Liquid Argon is finally available





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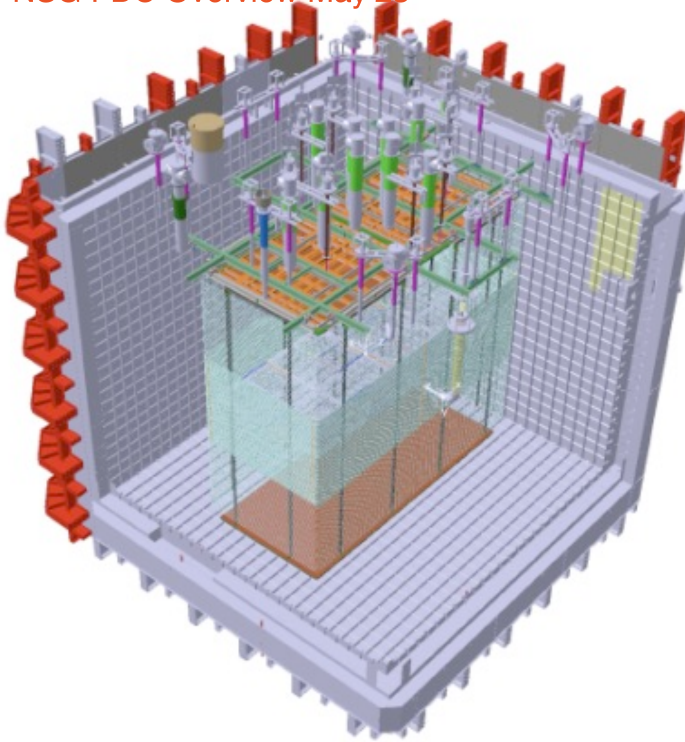
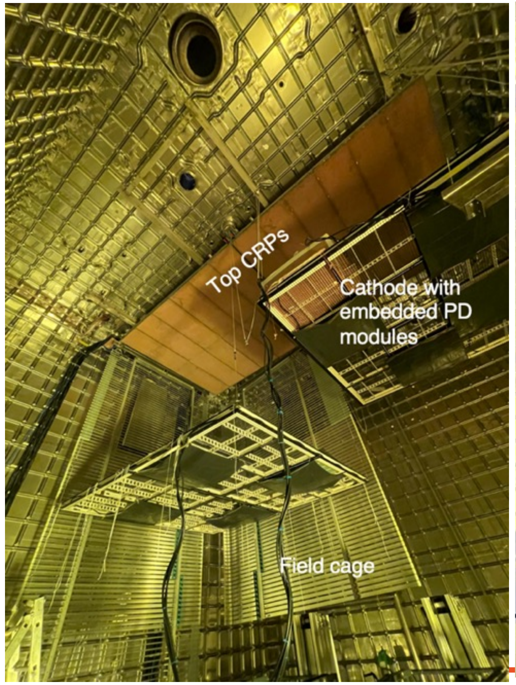
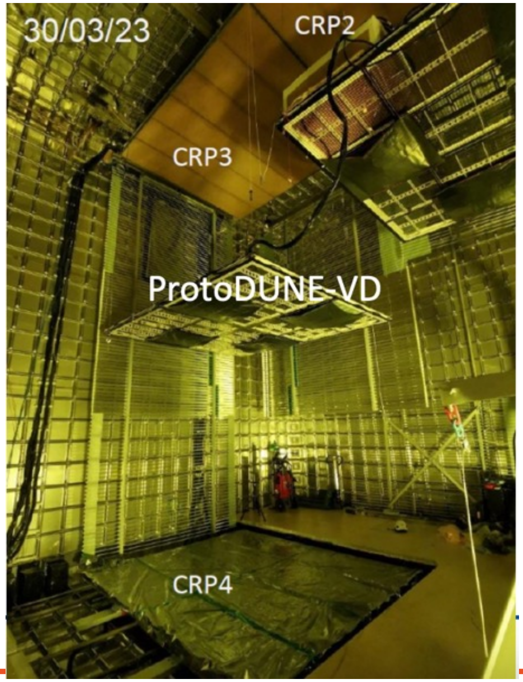
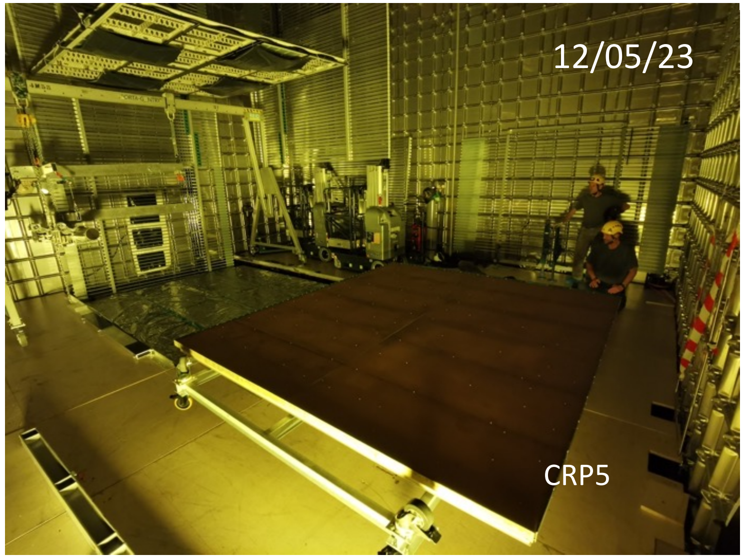
FD2 prototyping activities : Module-0

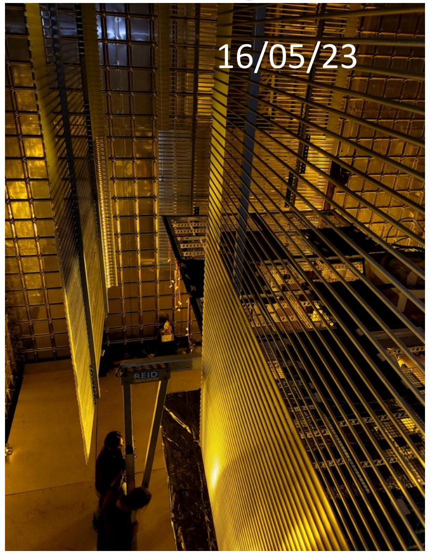


- All components in pre-series mode, with final technology (incl. electronics)
- All 4 CRPs tested in cryogenic conditions prior installation in the NP02 cold box
- All x-Arapuca tested in cryogenics conditions prior installation in the NP02 cold box
- PDs readout capability at HV on the cathode demonstrated '23
- Successful integration in the DAQ
- Installation in NP02 started in Jan '23 and will finish by end May '23
- Plan to close the TCO (cryostat access window) in Fall '23
- Fill before mid of the year '24, possibility to decide to swap filling of NP04 and NP02



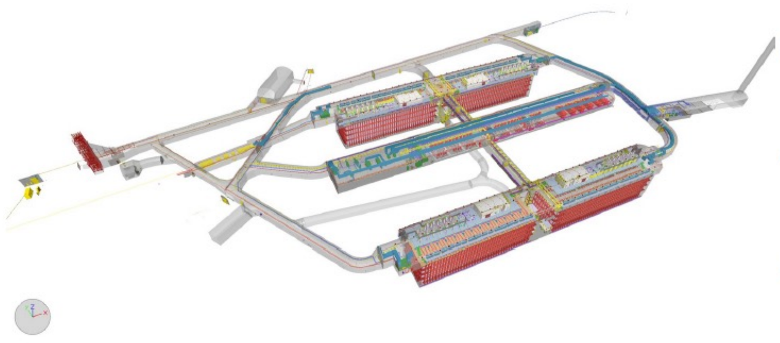


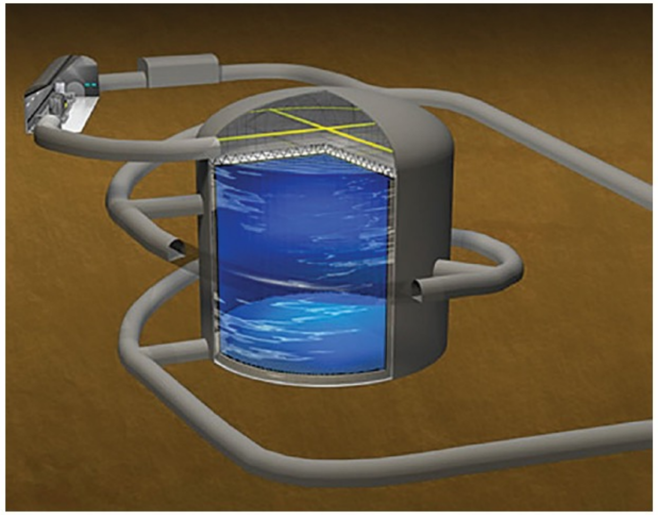




INFN DUNE

DUNE and Hyper-K: different strategies, different detectors





- DUNE:
  - Very long baseline → large matter effect → unambiguous mass ordering and CPV
  - Broadband neutrino beam → high statistics over full oscillation period
  - Reconstruct E_ν over broad range → imaging + calorimetry → LArTPC technology
  - Highly-capable near detector to constrain systematic uncertainties
- Hyper-K:
  - Shorter baseline → small matter effect
  - Off-axis location & narrowband beam → very, very high statistics at oscillation maximum, less feed-down
  - Lower energy and mostly CCQE → very large water Cherenkov detector
  - Highly-capable near detector to constrain systematic uncertainties

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