DEEP UNDERGROUND
NEUTRINO EXPERIMENT

Next generation experiments (INFN)

- JUNO
  - anti-nu-e disappearance at reactors, 53 km baseline.
- KM3NeT
  - atmospheric nu (ORCA)
  - high-energy cosmic nu (ARCA)
- DUNE
  - nu-mu → nu-e appearance, accelerator-based, 1300 km baseline (LBNF)
  - atmospheric nu
- Hyper-K
  - nu-mu → nu-e appearance, accelerator-based, 295 km baseline (T2K)
  - atmospheric nu

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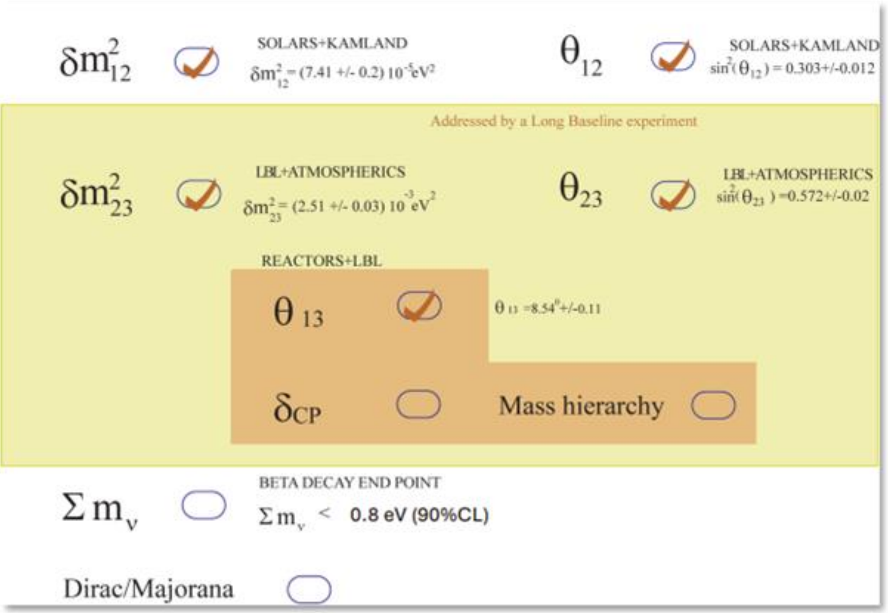
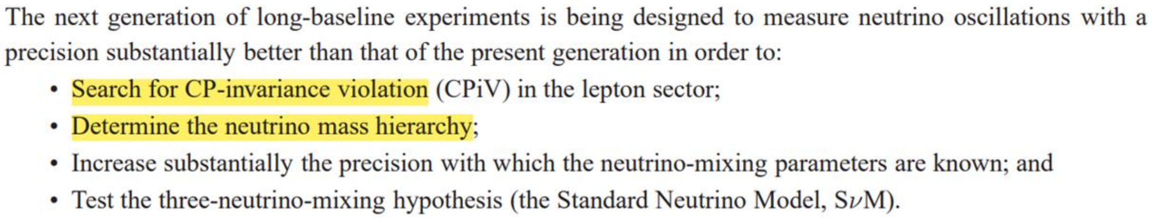
- ICARUS
  - nu-mu → nu-e appearance (sterile nu search), accelerator-based, short baseline





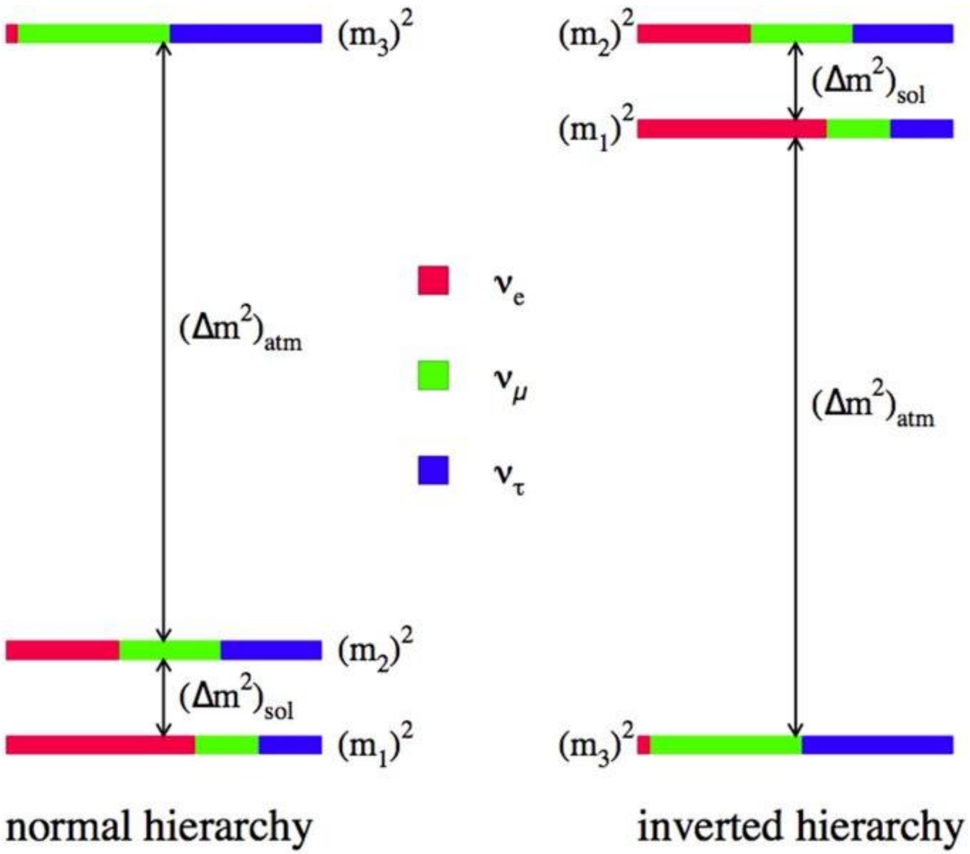
The next generation of long-baseline experiments is being designed to measure neutrino oscillations with a precision substantially better than that of the present generation in order to:

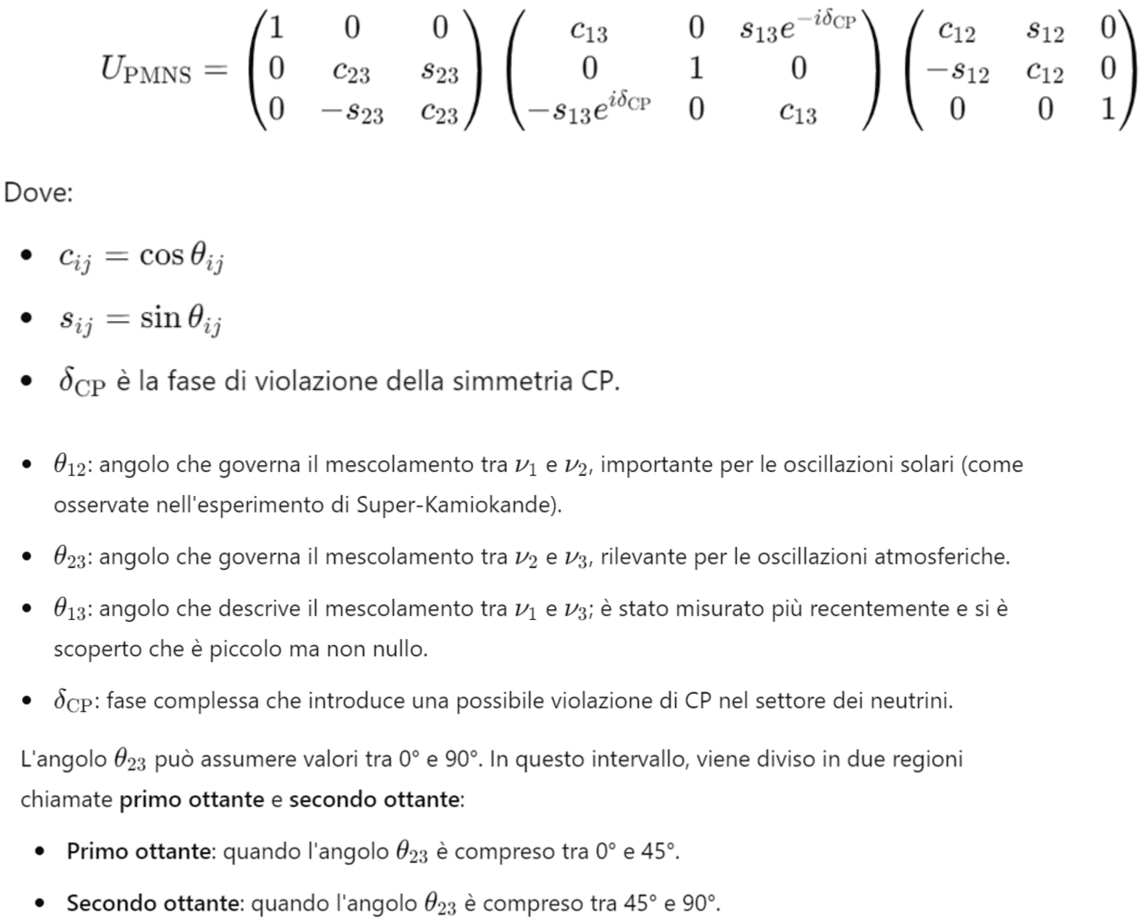
- Search for CP-invariance violation (CPiV) in the lepton sector;
- Determine the neutrino mass hierarchy;
- Increase substantially the precision with which the neutrino-mixing parameters are known; and
- Test the three-neutrino-mixing hypothesis (the Standard Neutrino Model, SνM).

Neutrino oscillation

U = matrice di Pontecorvo-Maki-Nakagawa-Sakata

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$





$$U_{\mathrm{PMNS}} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

Dove:

- $c_{ij} = \cos\theta_{ij}$
- $s_{ij} = \sin\theta_{ij}$
- δ_{CP} è la fase di violazione della simmetria CP.

- θ_{12}: angolo che governa il mescolamento tra ν_1 e ν_2, importante per le oscillazioni solari (come osservate nell'esperimento di Super-Kamiokande).
- θ_{23}: angolo che governa il mescolamento tra ν_2 e ν_3, rilevante per le oscillazioni atmosferiche.
- θ_{13}: angolo che descrive il mescolamento tra ν_1 e ν_3; è stato misurato più recentemente e si è scoperto che è piccolo ma non nullo.
- δ_{CP}: fase complessa che introduce una possibile violazione di CP nel settore dei neutrini.

L'angolo θ_{23} può assumere valori tra 0° e 90°. In questo intervallo, viene diviso in due regioni chiamate **primo ottante** e **secondo ottante**:

- **Primo ottante**: quando l'angolo θ_{23} è compreso tra 0° e 45°.
- **Secondo ottante**: quando l'angolo θ_{23} è compreso tra 45° e 90°.

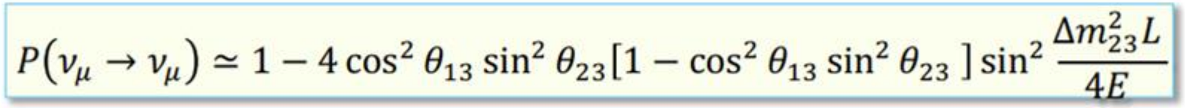
Long baseline experiments

Long baseline experiments produce intense ν_μ ($\bar{\nu}_\mu$) beams and detect them at the maximum of atmospheric oscillations.

Leading process are $\nu_\mu \to \nu_\tau$ oscillations, and so ν_μ disappearance, allowing to measure the atmospheric parameters θ_{23} and Δm^2_{23}

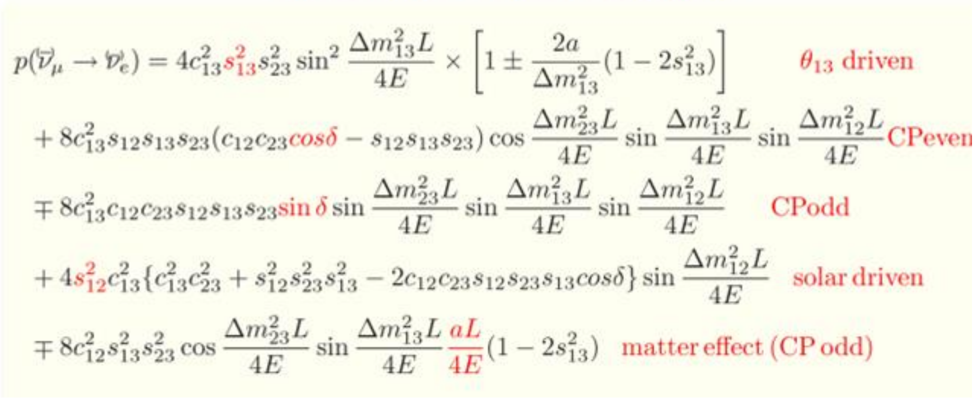
Subleading process are $\nu_\mu \to \nu_e$ oscillations, sensitive to θ_{13} and δ_{CP}

Disappearance formula



$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}[1 - \cos^2\theta_{13}\sin^2\theta_{23}]\sin^2\frac{\Delta m^2_{23}L}{4E}$$

Subleading ν_e appearance formula



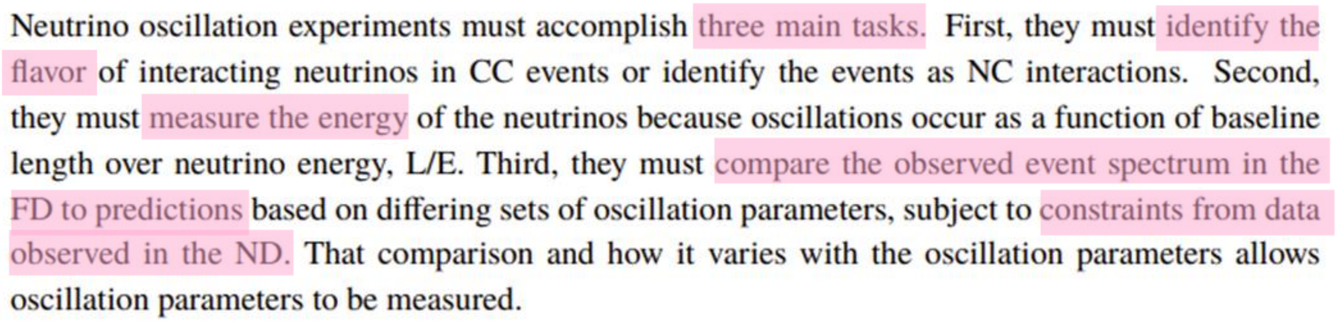
$$p(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) = 4c^2_{13}s^2_{13}s^2_{23}\sin^2\frac{\Delta m^2_{13}L}{4E} \times \left[1 \pm \frac{2a}{\Delta m^2_{13}}(1 - 2s^2_{13})\right] \qquad \theta_{13}\text{ driven}$$

$$+ 8c^2_{13}s_{12}s_{13}s_{23}(c_{12}c_{23}cos\delta - s_{12}s_{13}s_{23})\cos\frac{\Delta m^2_{23}L}{4E}\sin\frac{\Delta m^2_{13}L}{4E}\sin\frac{\Delta m^2_{12}L}{4E} \text{CPeven}$$

$$\mp 8c^2_{13}c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\frac{\Delta m^2_{23}L}{4E}\sin\frac{\Delta m^2_{13}L}{4E}\sin\frac{\Delta m^2_{12}L}{4E} \qquad \text{CPodd}$$

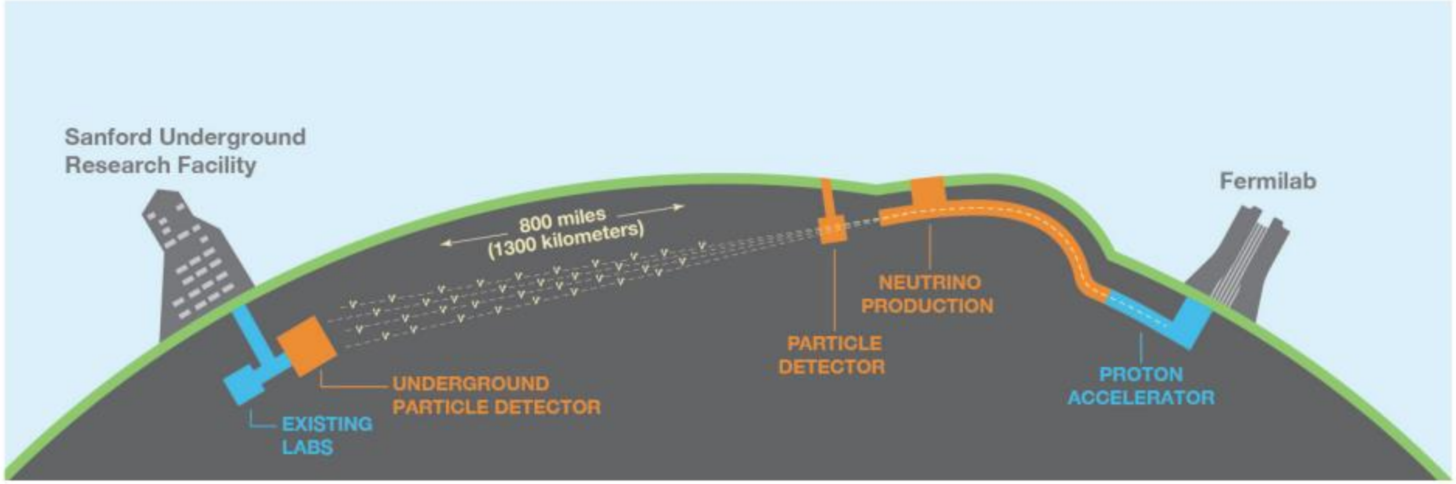
$$+ 4s^2_{12}c^2_{13}\{c^2_{13}c^2_{23} + s^2_{12}s^2_{23}s^2_{13} - 2c_{12}c_{23}s_{12}s_{23}s_{13}cos\delta\}\sin\frac{\Delta m^2_{12}L}{4E} \qquad \text{solar driven}$$

$$\mp 8c^2_{12}s^2_{13}s^2_{23}\cos\frac{\Delta m^2_{23}L}{4E}\sin\frac{\Delta m^2_{13}L}{4E}\frac{aL}{4E}(1 - 2s^2_{13}) \qquad \text{matter effect (CP odd)}$$



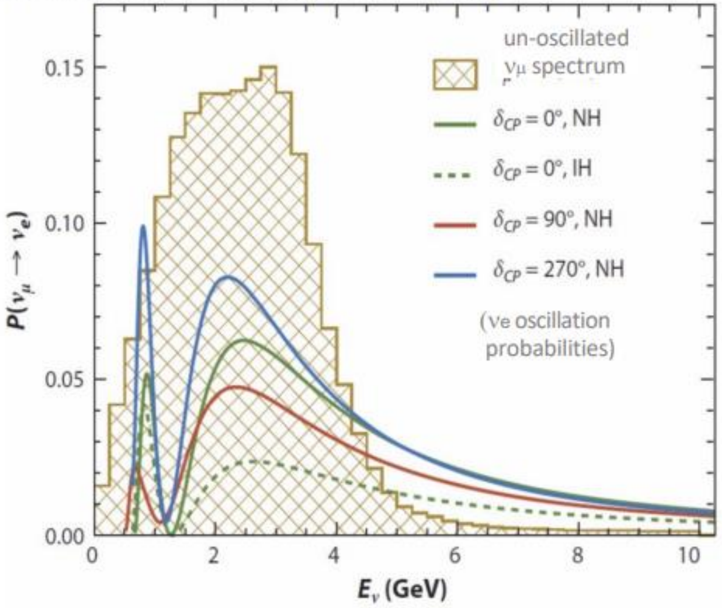
Neutrino oscillation experiments must accomplish three main tasks. First, they must identify the
1 flavor of interacting neutrinos in CC events or identify the events as NC interactions. Second,
2 they must measure the energy of the neutrinos because oscillations occur as a function of baseline
3 length over neutrino energy, L/E. Third, they must compare the observed event spectrum in the
FD to predictions based on differing sets of oscillation parameters, subject to constraints from data
observed in the ND. That comparison and how it varies with the oscillation parameters allows
oscillation parameters to be measured.

DEEP UNDERGROUND NEUTRINO EXPERIMENT



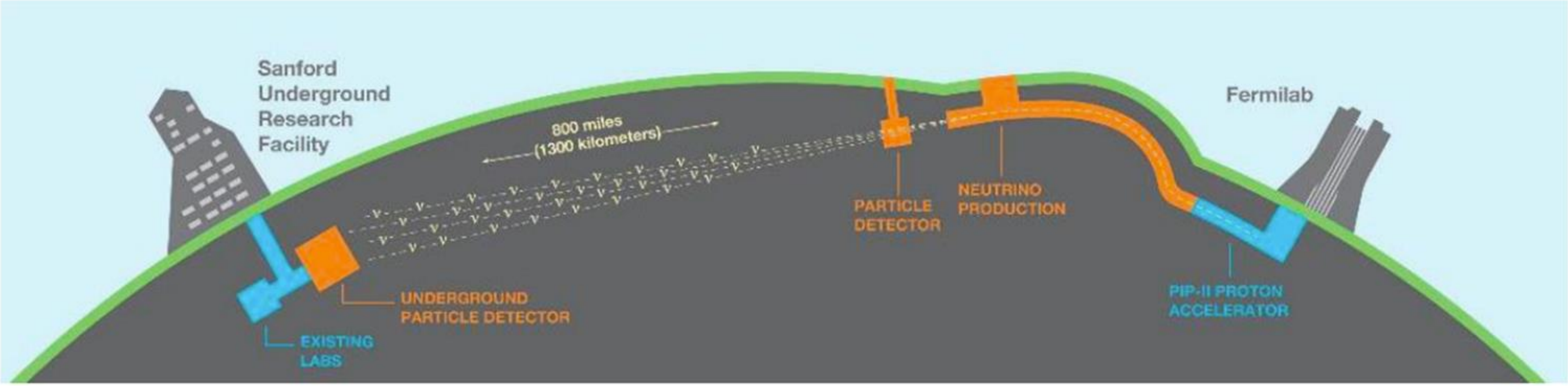
- 1450 collaborators
- 215 Institutes (11 INFN)
- 35 Countries

- On-axis, with a baseline of 1300 km
- Sensitive to first and second oscillation maxima
- Part of the spectrum above the tau creation threshold (~3.5 GeV)



- *High precision measurements of neutrino mixing in a single experiment.*
- Determination of the neutrino mass ordering in the first few years.
- Observation and measurement of CP Violation in the neutrino sector.
- Test of the 3-neutrino paradigm (PMNS unitarity).
- Observatory for astrophysical neutrino sources (solar, atmospheric, supernova).
- Search for BSM physics.

The Deep Underground Neutrino Experiment (DUNE)



- The most powerful neutrino beam **in the world** (1.2MW upgradable to 2.4 MW) will be sent from **Fermilab** (Chicago) to **SURF** (South Dakota) along 1300 km distance to be detected by four liquid argon **far detector** modules (70 kton LAr) at 1.5 km deep underground and a **near detector** complex at 560 m from the neutrino source
  - **wide-band neutrino energy spectrum** enables detailed fitting of the oscillation parameters
  - **Long-baseline** allows to unambiguous measurement of the neutrino mass ordering
  - **LAr TPC technology** allows for precise reconstruction of the neutrino interactions
  - The **Near Detector complex** allows for a careful control of systematics
  - The **underground location** of the Far Detector modules enables a wide astroparticle measurement program

LAr TPC: working principle

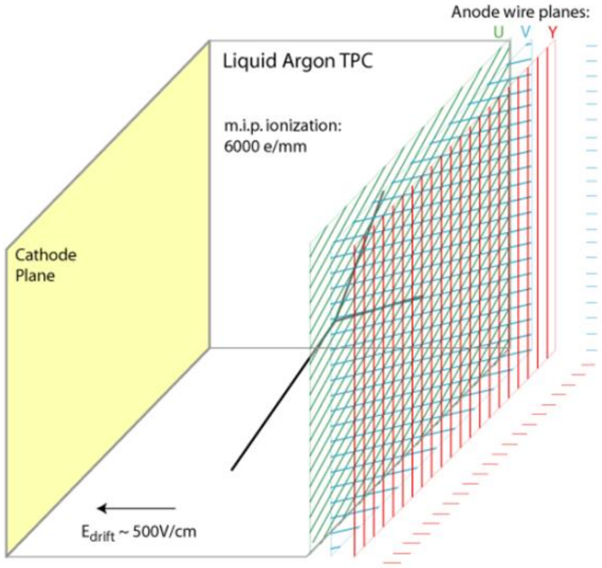
Detection principle first conceived by C. Rubbia (1977)

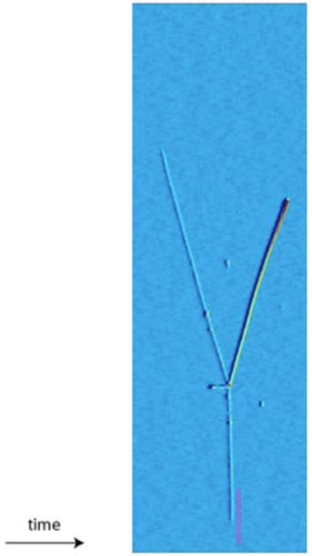
Charged particle from neutrino interaction in LAr produces free **ionization electrons** and **scintillation light** (128 nm)

Light is quickly detected by photon detection system

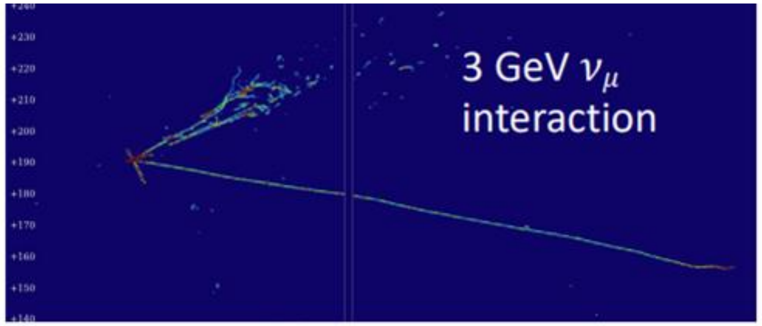
Electrons slowly drift to anode instrumented with readout wires/strip

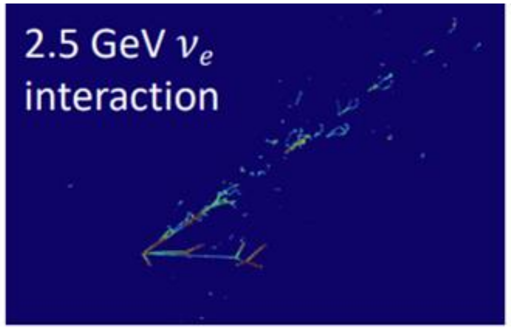
Each wire/strip plane provide a 2D (s, t) view of the ionization event. Multiple 2D views results in a 3D image of the event





Simulated neutrino events





Far detector: two different readout technologies

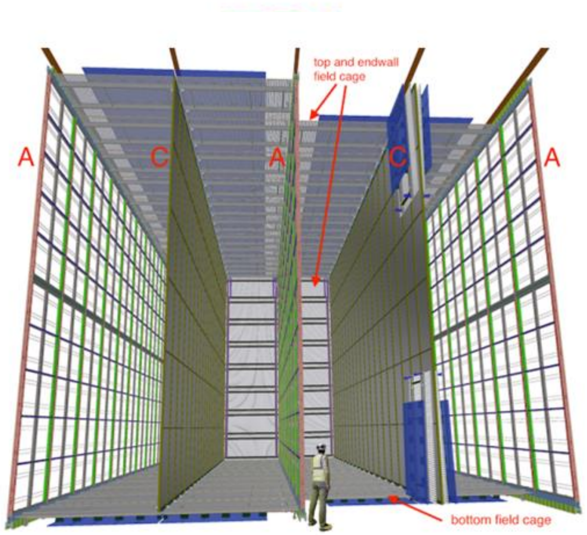
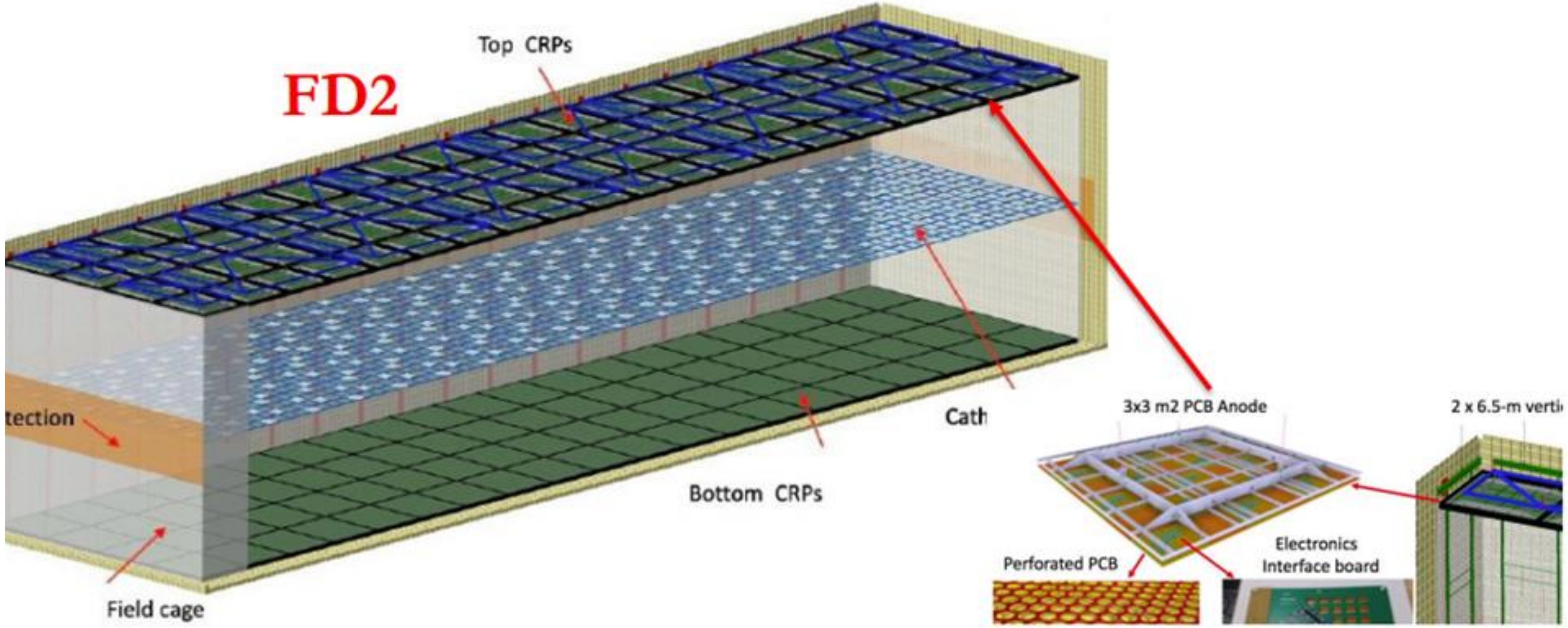


Figure 1.7. A 10 kt DUNE FD SP module, showing the alternating 58.2 m long (into the page), 12.0 m high anode (A) and cathode (C) planes, as well as the field cage (FC) that surrounds the drift regions between the anode and cathode planes. On the right-hand cathode plane, the foremost portion of the FC is shown in its undeployed (folded) state.



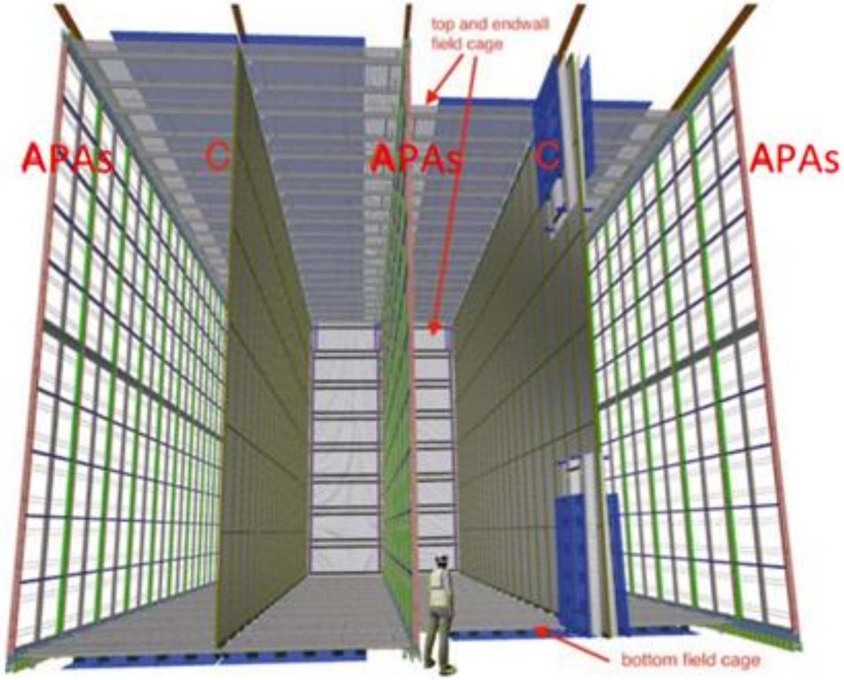
Charge Readout Planes (CRP)

- **FD1 module** will use Horizontal Drift technology: four **3.5 m drift** regions (3.5 m x 12 m x 58 m), charge readout with **348,000** wires in **150** Anode Planes Assembly (APA). Similar to ICARUS, MicrobooNE, SBND. Photon detection: X-Arapuca module (SiPM based light trap), about 300,000 SiPM
- **FD2 module** will use Vertical Drift technology (two volumes 13.5 m x **6.5 m drift** x 60 m), charge readout with strips (**perforated PCB**). Photon detection on the field cage walls and on the cathode@300 kV; decoupling from HV achieved with optical fibers for power and signal transmission. Larger active volume, cheaper than FD1 and similar performances

Far Detectors

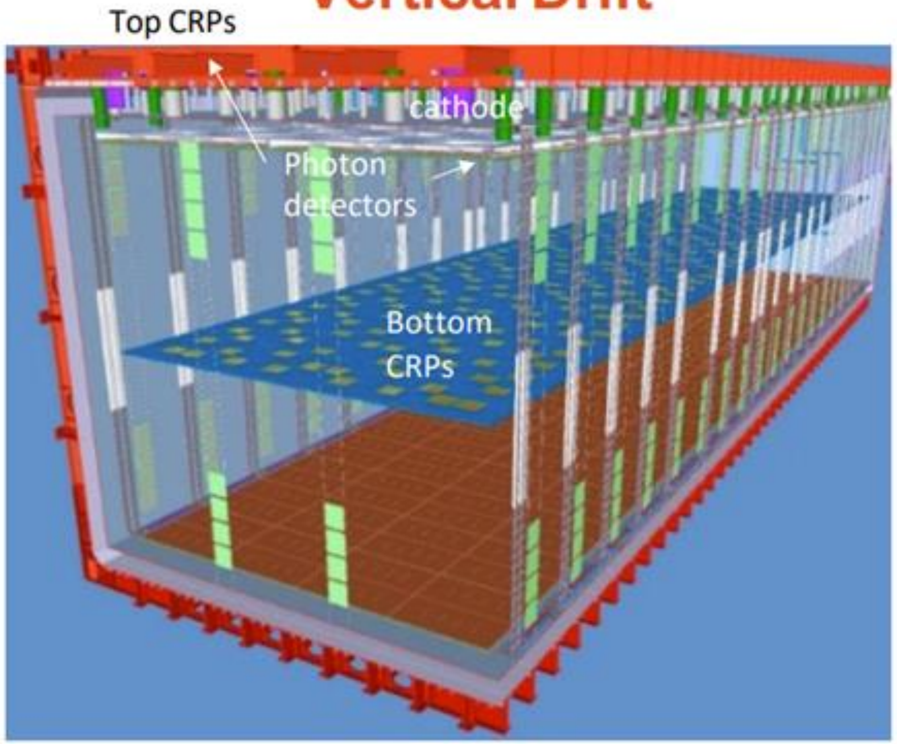
2 (max 4) LAr TPCs, 17 kt Argon total (10 kt fiducial) each one:

Horizontal Drift



- APA : based on a wire chamber technology
- Drift length ~ 350 cm -> ~ 180 KV on cathode
- ~ 9800 m^3 = ~ 13'661 tons of active LAr

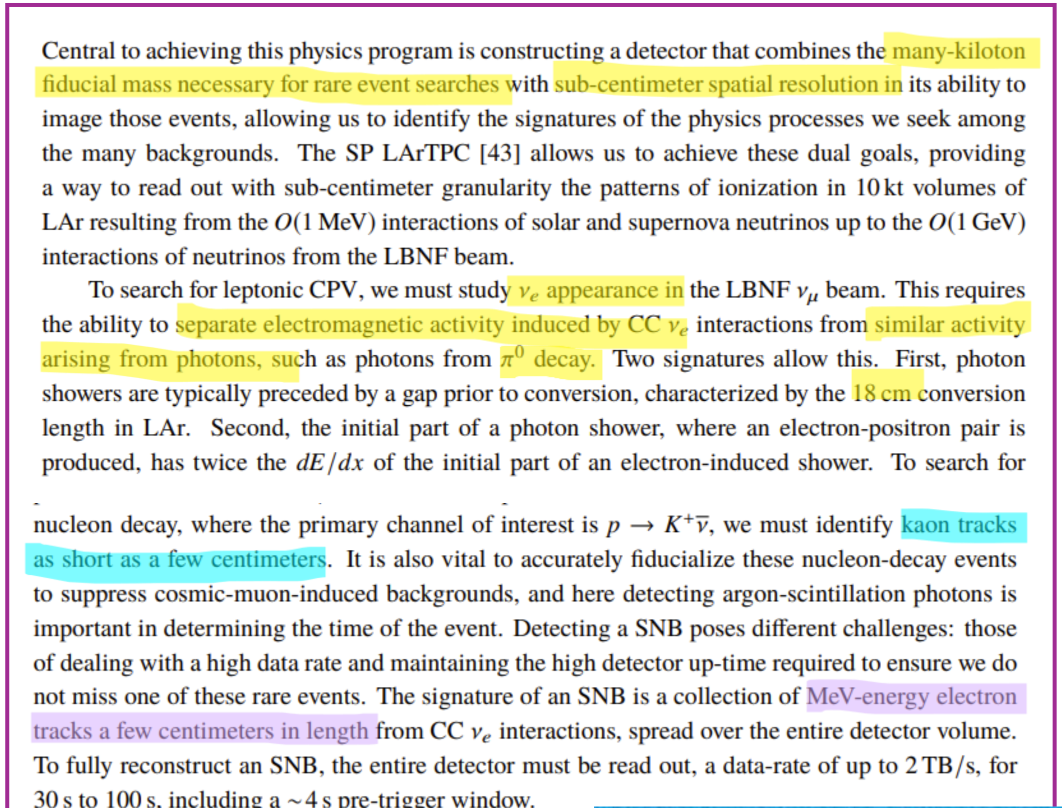
Vertical Drift



- CRP: based on perforated PCB technology
- Drift length ~ 640 cm → 300 kV on cathode
- Photon detectors on the cathode at 300 kV
- ~ 10180 m^3 = 14190 tons of active LAr

FD1→Single phase technology

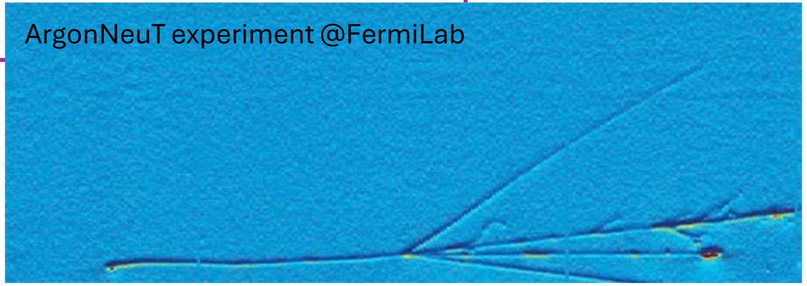
Why LAr ?



Central to achieving this physics program is constructing a detector that combines the many-kiloton fiducial mass necessary for rare event searches with sub-centimeter spatial resolution in its ability to image those events, allowing us to identify the signatures of the physics processes we seek among the many backgrounds. The SP LArTPC [43] allows us to achieve these dual goals, providing a way to read out with sub-centimeter granularity the patterns of ionization in 10 kt volumes of LAr resulting from the $O(1\text{ MeV})$ interactions of solar and supernova neutrinos up to the $O(1\text{ GeV})$ interactions of neutrinos from the LBNF beam.

To search for leptonic CPV, we must study ν_e appearance in the LBNF ν_μ beam. This requires the ability to separate electromagnetic activity induced by CC ν_e interactions from similar activity arising from photons, such as photons from π^0 decay. Two signatures allow this. First, photon showers are typically preceded by a gap prior to conversion, characterized by the 18 cm conversion length in LAr. Second, the initial part of a photon shower, where an electron-positron pair is produced, has twice the dE/dx of the initial part of an electron-induced shower. To search for

nucleon decay, where the primary channel of interest is $p \to K^+\overline{\nu}$, we must identify kaon tracks as short as a few centimeters. It is also vital to accurately fiducialize these nucleon-decay events to suppress cosmic-muon-induced backgrounds, and here detecting argon-scintillation photons is important in determining the time of the event. Detecting a SNB poses different challenges: those of dealing with a high data rate and maintaining the high detector up-time required to ensure we do not miss one of these rare events. The signature of an SNB is a collection of MeV-energy electron tracks a few centimeters in length from CC ν_e interactions, spread over the entire detector volume. To fully reconstruct an SNB, the entire detector must be read out, a data-rate of up to 2 TB/s, for 30 s to 100 s, including a ~4 s pre-trigger window.



ArgonNeuT experiment @FermiLab

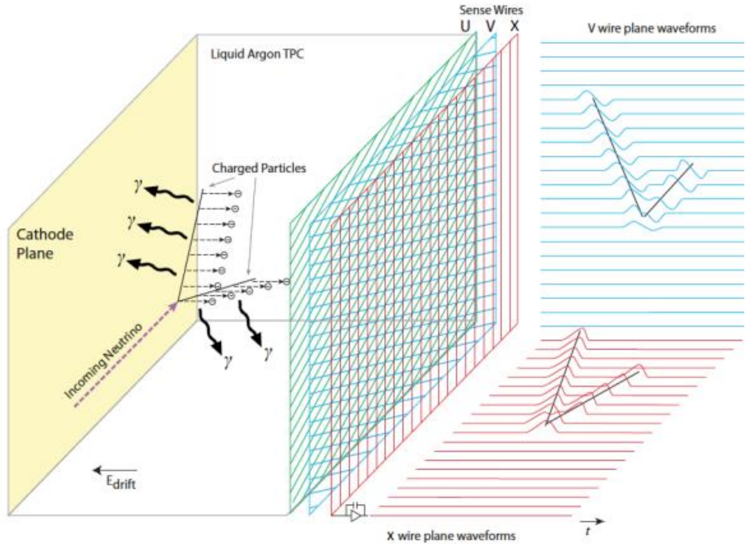
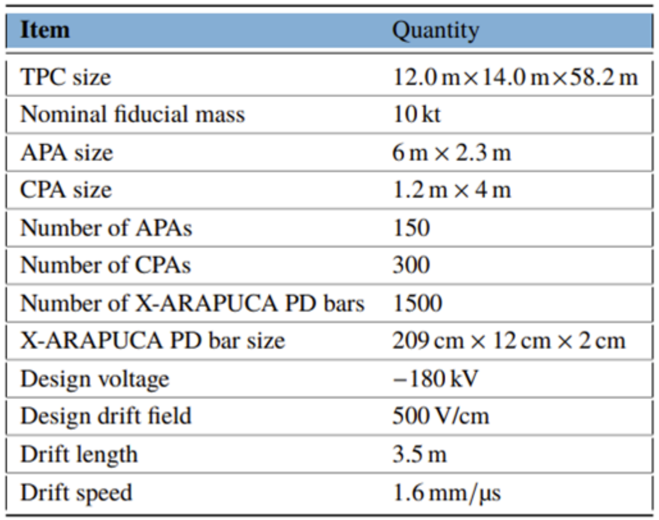


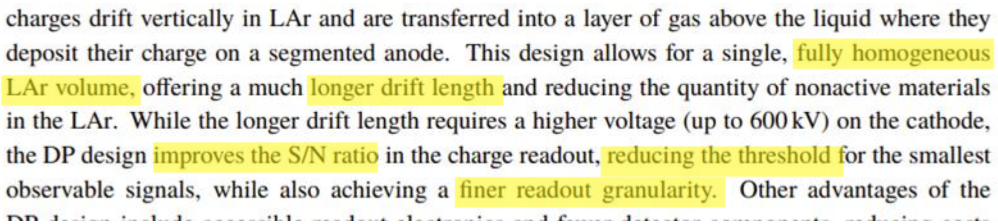
Figure 1.5. The general operating principle of the SP LArTPC. Negatively charged ionization electrons from the neutrino interaction drift horizontally opposite to the E field in the LAr and are collected on the anode, which is made up of the U, V and X sense wires. The right-hand side represents the time projections in two dimensions as the event occurs. Light (γ) detectors (not shown) will provide the t_0 of the interaction.

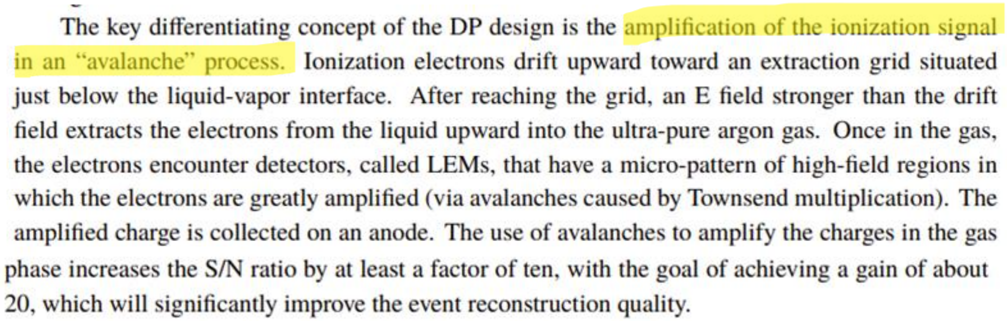
Table 3.1. Key parameters for a 10 kt FD SP module.



Item	Quantity
TPC size	12.0 m × 14.0 m × 58.2 m
Nominal fiducial mass	10 kt
APA size	6 m × 2.3 m
CPA size	1.2 m × 4 m
Number of APAs	150
Number of CPAs	300
Number of X-ARAPUCA PD bars	1500
X-ARAPUCA PD bar size	209 cm × 12 cm × 2 cm
Design voltage	−180 kV
Design drift field	500 V/cm
Drift length	3.5 m
Drift speed	1.6 mm/μs

FD2 → Dual-phase technology


charges drift vertically in LAr and are transferred into a layer of gas above the liquid where they deposit their charge on a segmented anode. This design allows for a single, fully homogeneous LAr volume, offering a much longer drift length and reducing the quantity of nonactive materials in the LAr. While the longer drift length requires a higher voltage (up to 600 kV) on the cathode, the DP design improves the S/N ratio in the charge readout, reducing the threshold for the smallest observable signals, while also achieving a finer readout granularity. Other advantages of the


The key differentiating concept of the DP design is the amplification of the ionization signal in an "avalanche" process. Ionization electrons drift upward toward an extraction grid situated just below the liquid-vapor interface. After reaching the grid, an E field stronger than the drift field extracts the electrons from the liquid upward into the ultra-pure argon gas. Once in the gas, the electrons encounter detectors, called LEMs, that have a micro-pattern of high-field regions in which the electrons are greatly amplified (via avalanches caused by Townsend multiplication). The amplified charge is collected on an anode. The use of avalanches to amplify the charges in the gas phase increases the S/N ratio by at least a factor of ten, with the goal of achieving a gain of about 20, which will significantly improve the event reconstruction quality.

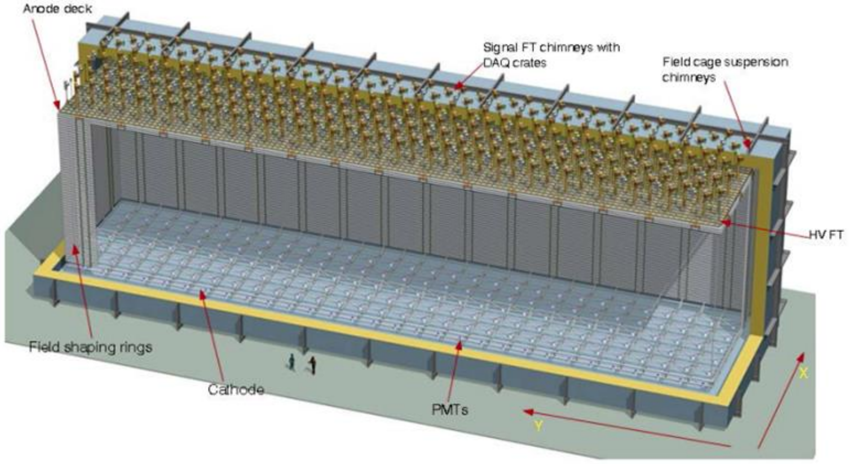


Figure 4.2. A DP module with cathode, PMTs, FC, and anode plane with SFT chimneys.

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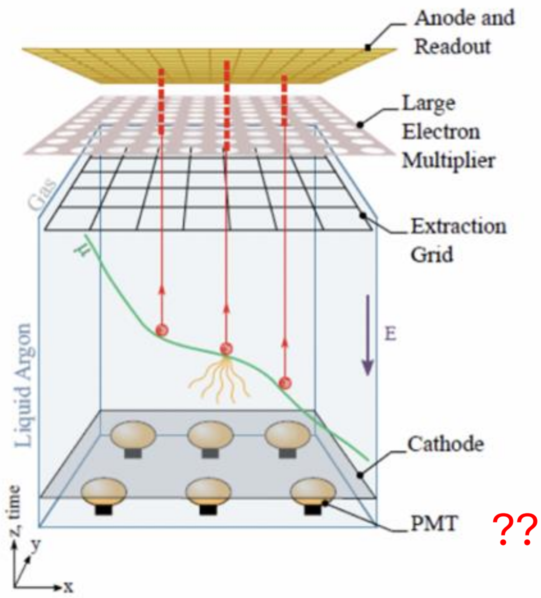

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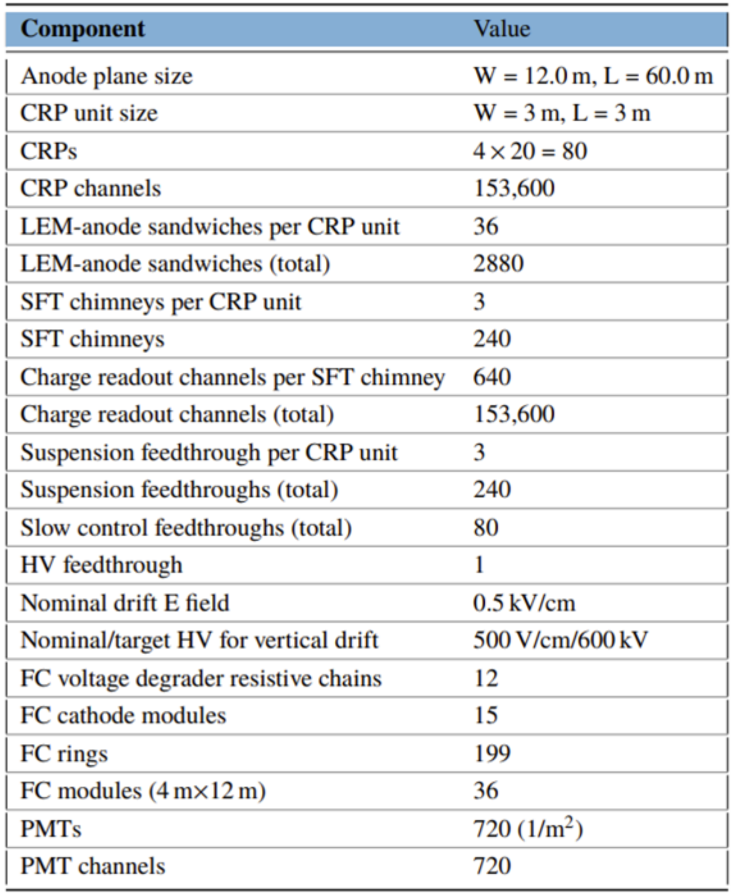
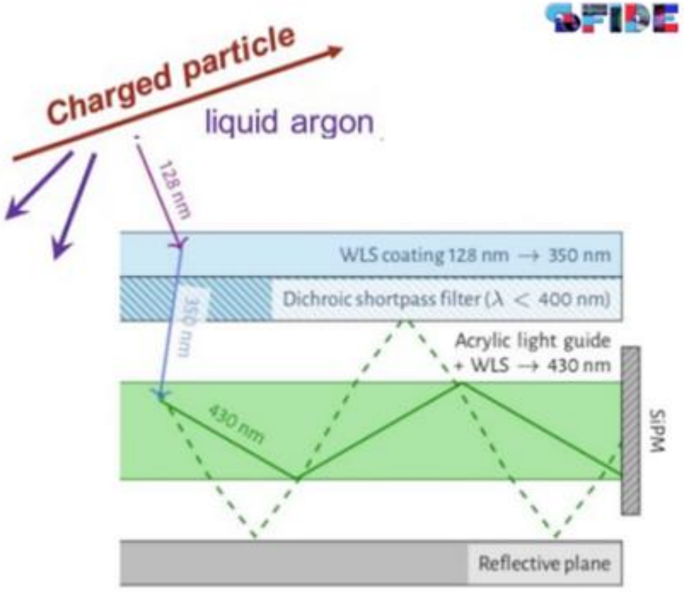
Figure 4.1. Principle of the DP readout.



Component	Value
Anode plane size	W = 12.0 m, L = 60.0 m
CRP unit size	W = 3 m, L = 3 m
CRPs	$4 \times 20 = 80$
CRP channels	153,600
LEM-anode sandwiches per CRP unit	36
LEM-anode sandwiches (total)	2880
SFT chimneys per CRP unit	3
SFT chimneys	240
Charge readout channels per SFT chimney	640
Charge readout channels (total)	153,600
Suspension feedthrough per CRP unit	3
Suspension feedthroughs (total)	240
Slow control feedthroughs (total)	80
HV feedthrough	1
Nominal drift E field	0.5 kV/cm
Nominal/target HV for vertical drift	500 V/cm/600 kV
FC voltage degrader resistive chains	12
FC cathode modules	15
FC rings	199
FC modules (4 m×12 m)	36
PMTs	720 (1/m^2)
PMT channels	720

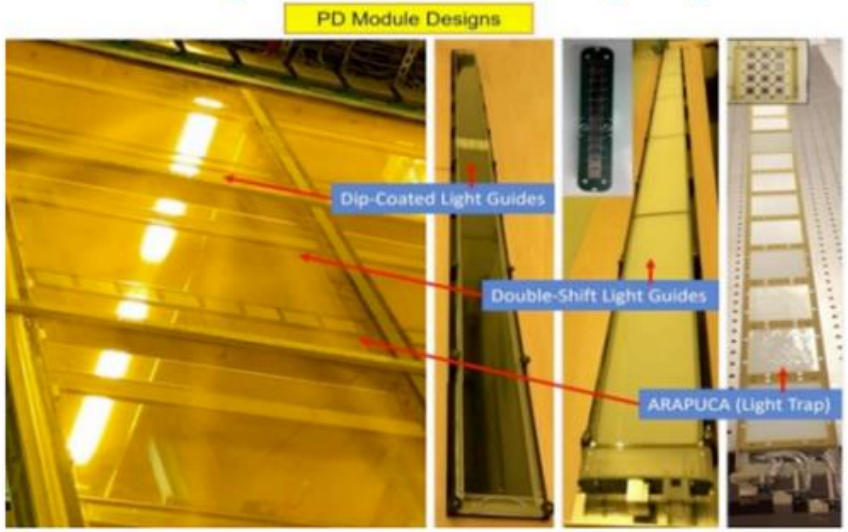
The Photon Detection System of DUNE (X-ARAPUCA)



The t_0 for the LAr TPCs is provided by scintillation light.
The wavelength of scintillation light in LAr doesn't match the sensitivity range of photodetectors.

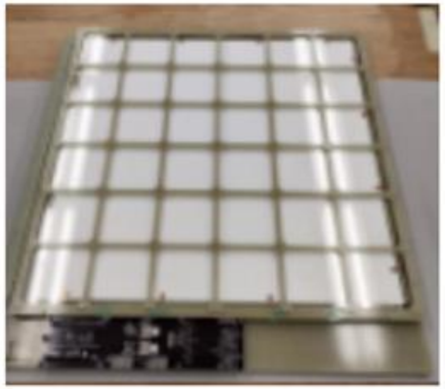
???? The 'X-ARAPUCA' technique, developed by INFN, is available in two types for the first (FD1-HD) and the second module (FD2-VD).

INFN plays a leading role in the Consortium, which has been further strengthened with the signing of the MoU for Vertical Drift



Horizontal Drift: 1500 rectangular 'modules' (2m x 20 cm^2),each with four channels, containing 48 SiPM (288000 SiPM in total)

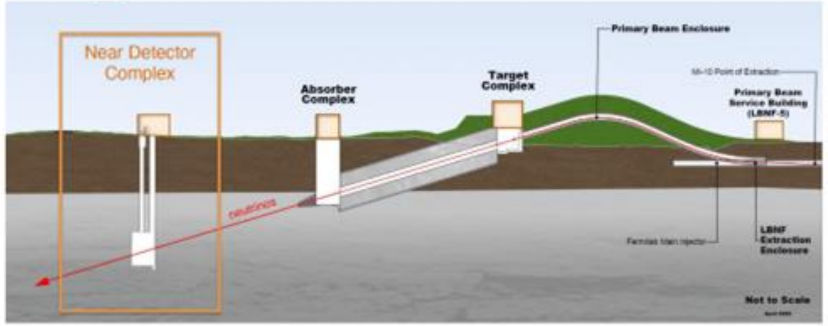
???? Vertical Drift: 672 square tiles (60 x 60 cm2), each with two channels containing 80 SiPMs (107000 SiPM in total)

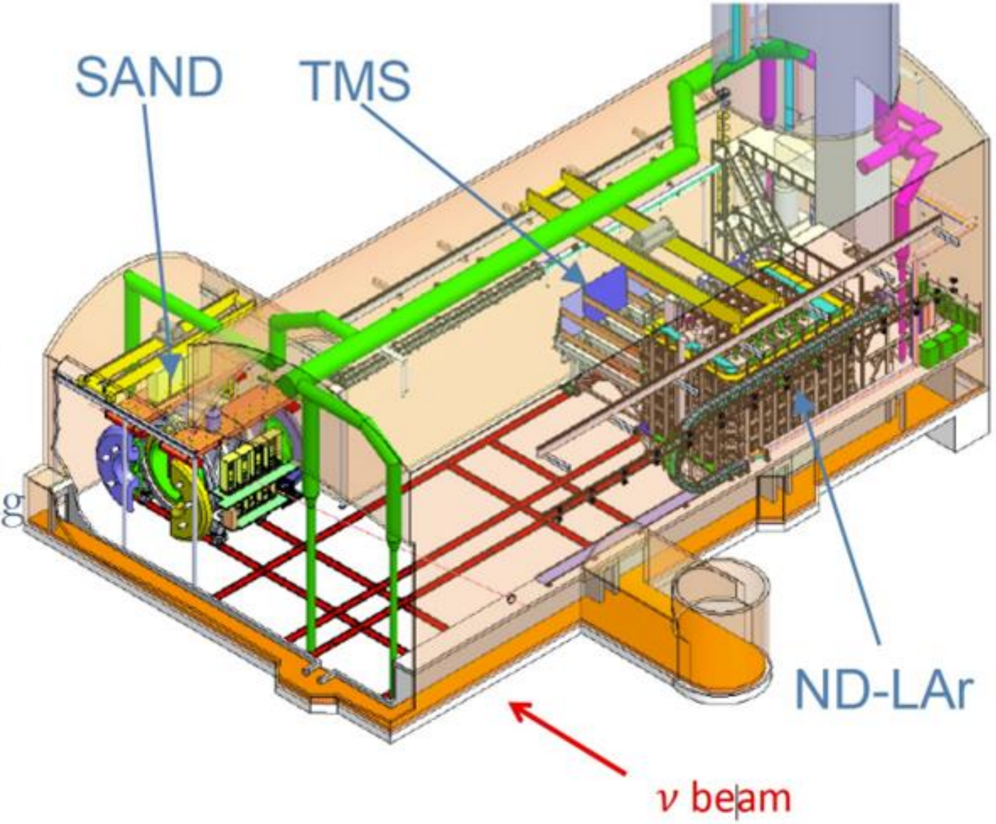


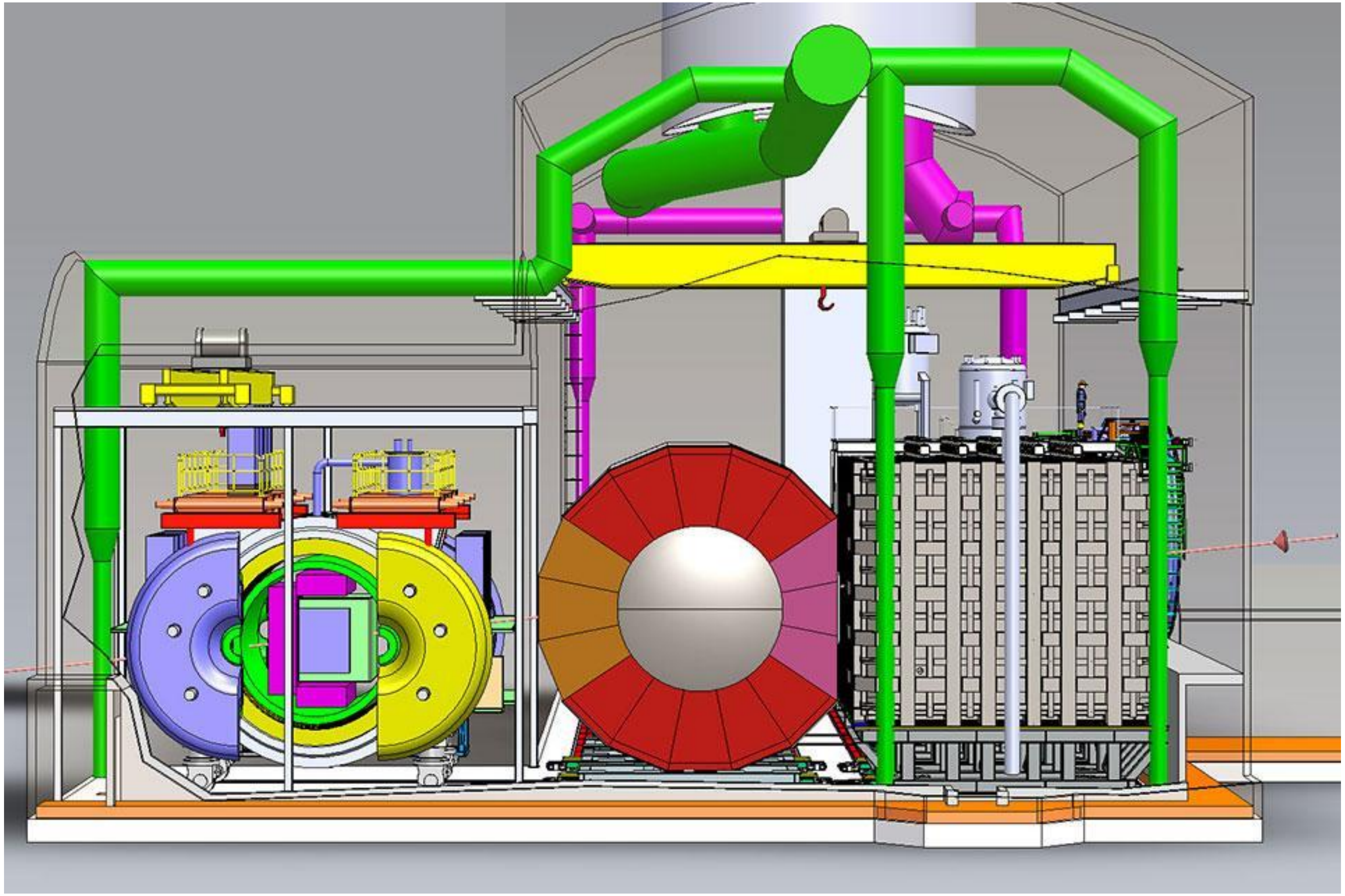
Half of SiPMs by FBK and half by Hamamatsu.

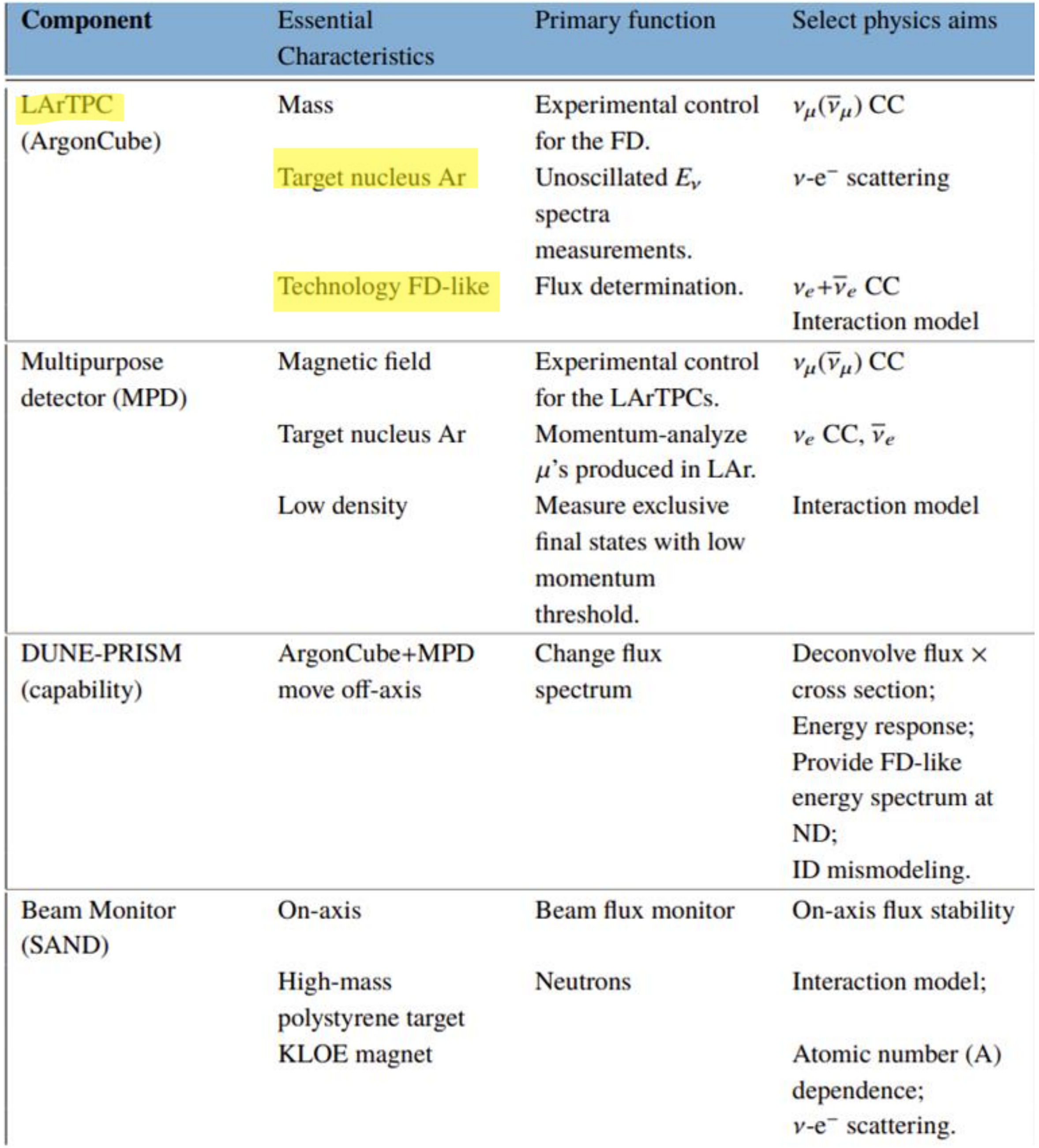
Near Detector Complex

- Main purpose is
  - **to measure the rate and spectrum of ν's before oscillations**
  - **Constraint systematic uncertainties (flux, cross-sections, detector response) for oscillation measurement**
- ND is a (movable) LArTPC (ND-LAr) + muon spectrometer (TMS) and a fixed magnetized tracker+calorimeter (SAND)
- Off-axis data constrains energy dependence of neutrino cross sections
- Same target and same technology to predict reconstructed Eν in Far Detector
- On-axis magnetized detector (SAND) for beam monitoring and neutrino energy measurement: repurposes solenoid magnet and ECAL from KLOE,
- SAND allows fine-grained, particle-by-particle reconstruction with very low rescattering, excellent for highly exclusive neutrino-nucleus measurements









Component	Essential Characteristics	Primary function	Select physics aims
LArTPC (ArgonCube)	Mass	Experimental control for the FD.	$\nu_\mu(\overline{\nu}_\mu)$ CC
	Target nucleus Ar	Unoscillated E_ν spectra measurements.	ν-e$^-$ scattering
	Technology FD-like	Flux determination.	$\nu_e+\overline{\nu}_e$ CC Interaction model
Multipurpose detector (MPD)	Magnetic field	Experimental control for the LArTPCs.	$\nu_\mu(\overline{\nu}_\mu)$ CC
	Target nucleus Ar	Momentum-analyze μ's produced in LAr.	ν_e CC, $\overline{\nu}_e$
	Low density	Measure exclusive final states with low momentum threshold.	Interaction model
DUNE-PRISM (capability)	ArgonCube+MPD move off-axis	Change flux spectrum	Deconvolve flux × cross section; Energy response; Provide FD-like energy spectrum at ND; ID mismodeling.
Beam Monitor (SAND)	On-axis	Beam flux monitor	On-axis flux stability
	High-mass polystyrene target	Neutrons	Interaction model;
	KLOE magnet		Atomic number (A) dependence; ν-e$^-$ scattering.

The core part of the DUNE ND is a LArTPC called ArgonCube. ArgonCube consists of an array of 35 modular TPCs sharing a cryostat. Figure 5.1 is a drawing of a prototype of the modular TPCs. This detector has the same target nucleus as the FD and shares some aspects of form and functionality with it, where the differences are necessitated by the expected intensity of the beam at the ND. This similarity in target nucleus and technology reduces sensitivity to nuclear effects and detector-driven systematic errors in the extraction of the oscillation signal at the FD. The LArTPC is large enough to provide high statistics ($10^8\,\nu_\mu$-CC events/year) and its volume is sufficient to provide good hadron containment. The tracking and energy resolution, combined with the mass of the LArTPC, will allow the flux in the beam to be measured using several techniques, including the well understood but rare process of ν_μ-e$^-$ scattering.

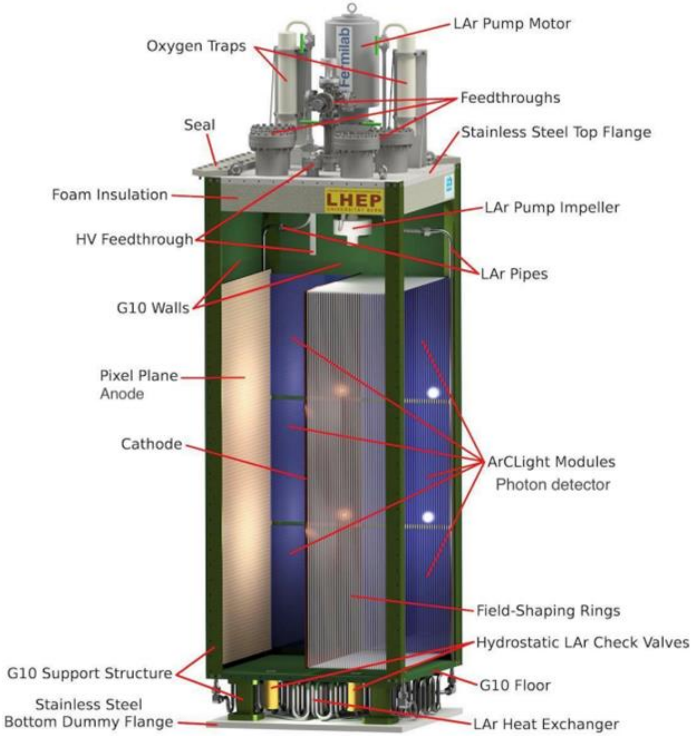
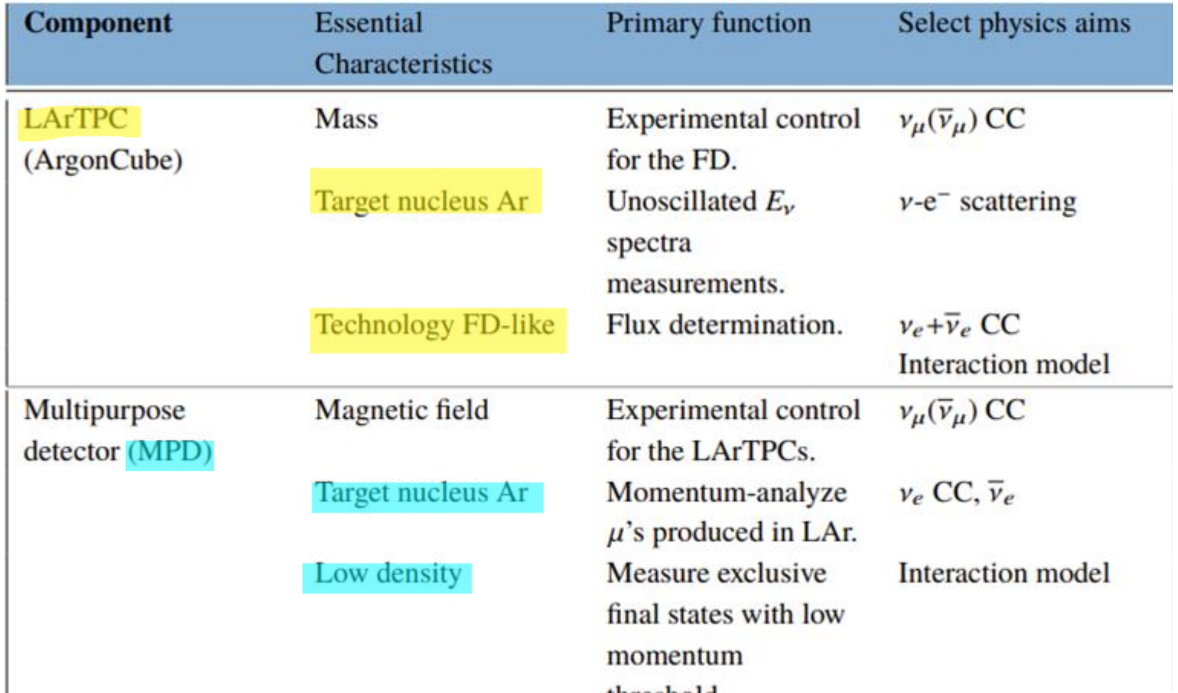
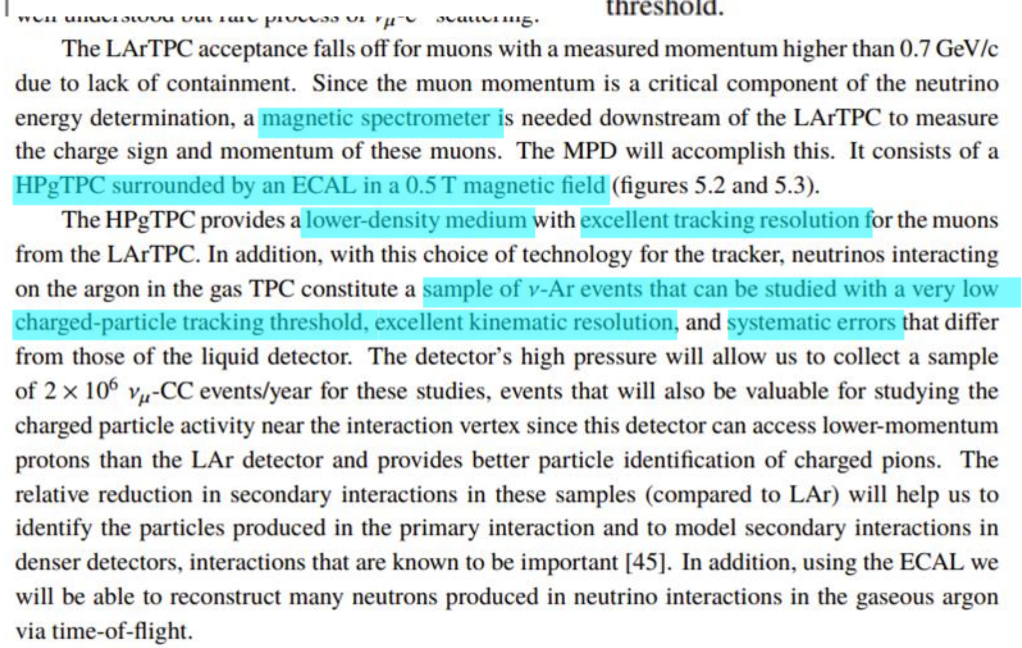


Figure 5.1. Cutaway drawing of a 0.67 m × 0.67 m × 1.81 m ArgonCube prototype module. For illustrative purposes, the drawing shows traditional field-shaping rings instead of a resistive field shell. The G10 walls will completely seal the module, isolating it from the neighboring modules and the outer LAr bath. The modules in this prototype system will not have individual pumps and filters.



Component	Essential Characteristics	Primary function	Select physics aims
LArTPC (ArgonCube)	Mass	Experimental control for the FD.	$\nu_\mu(\overline{\nu}_\mu)$ CC
	Target nucleus Ar	Unoscillated E_ν spectra measurements.	ν-e$^-$ scattering
	Technology FD-like	Flux determination.	ν_e+$\overline{\nu}_e$ CC Interaction model
Multipurpose detector (MPD)	Magnetic field	Experimental control for the LArTPCs.	$\nu_\mu(\overline{\nu}_\mu)$ CC
	Target nucleus Ar	Momentum-analyze μ's produced in LAr.	ν_e CC, $\overline{\nu}_e$
	Low density	Measure exclusive final states with low momentum threshold.	Interaction model



well understood but rare process of ν_μ-e$^-$ scattering.

The LArTPC acceptance falls off for muons with a measured momentum higher than 0.7 GeV/c due to lack of containment. Since the muon momentum is a critical component of the neutrino energy determination, a magnetic spectrometer is needed downstream of the LArTPC to measure the charge sign and momentum of these muons. The MPD will accomplish this. It consists of a HPgTPC surrounded by an ECAL in a 0.5 T magnetic field (figures 5.2 and 5.3).

The HPgTPC provides a lower-density medium with excellent tracking resolution for the muons from the LArTPC. In addition, with this choice of technology for the tracker, neutrinos interacting on the argon in the gas TPC constitute a sample of ν-Ar events that can be studied with a very low charged-particle tracking threshold, excellent kinematic resolution, and systematic errors that differ from those of the liquid detector. The detector's high pressure will allow us to collect a sample of 2×10^6 ν_μ-CC events/year for these studies, events that will also be valuable for studying the charged particle activity near the interaction vertex since this detector can access lower-momentum protons than the LAr detector and provides better particle identification of charged pions. The relative reduction in secondary interactions in these samples (compared to LAr) will help us to identify the particles produced in the primary interaction and to model secondary interactions in denser detectors, interactions that are known to be important [45]. In addition, using the ECAL we will be able to reconstruct many neutrons produced in neutrino interactions in the gaseous argon via time-of-flight.

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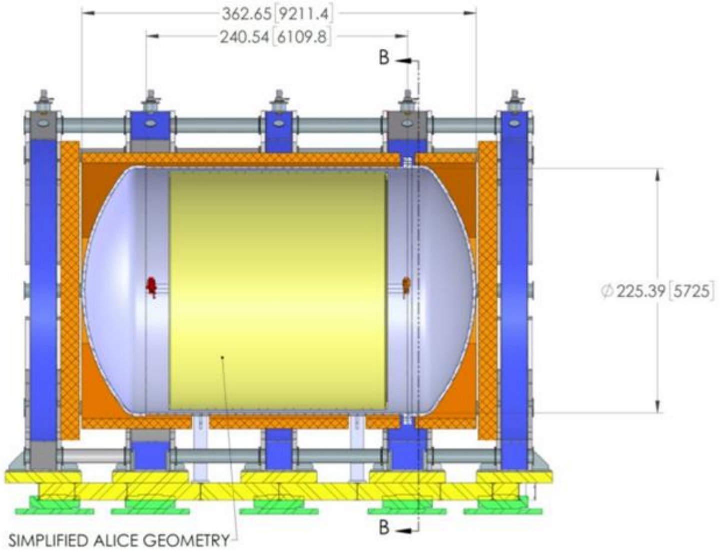


Figure 5.2. The conceptual design of the MPD system for the ND. The TPC is shown in yellow inside the pressure vessel. Outside the pressure vessel, the ECAL is shown in orange, and outside that are the magnet coils and cryostats. The drawing illustrates the five-coil superconducting design.

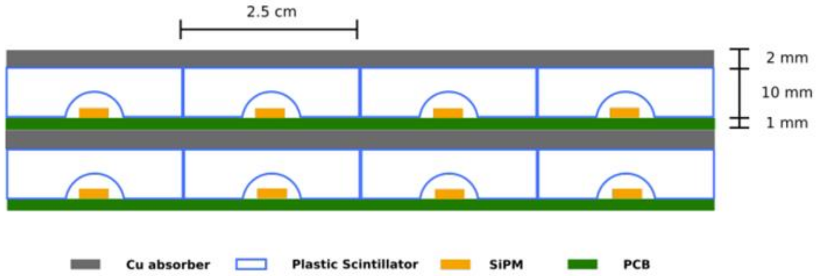
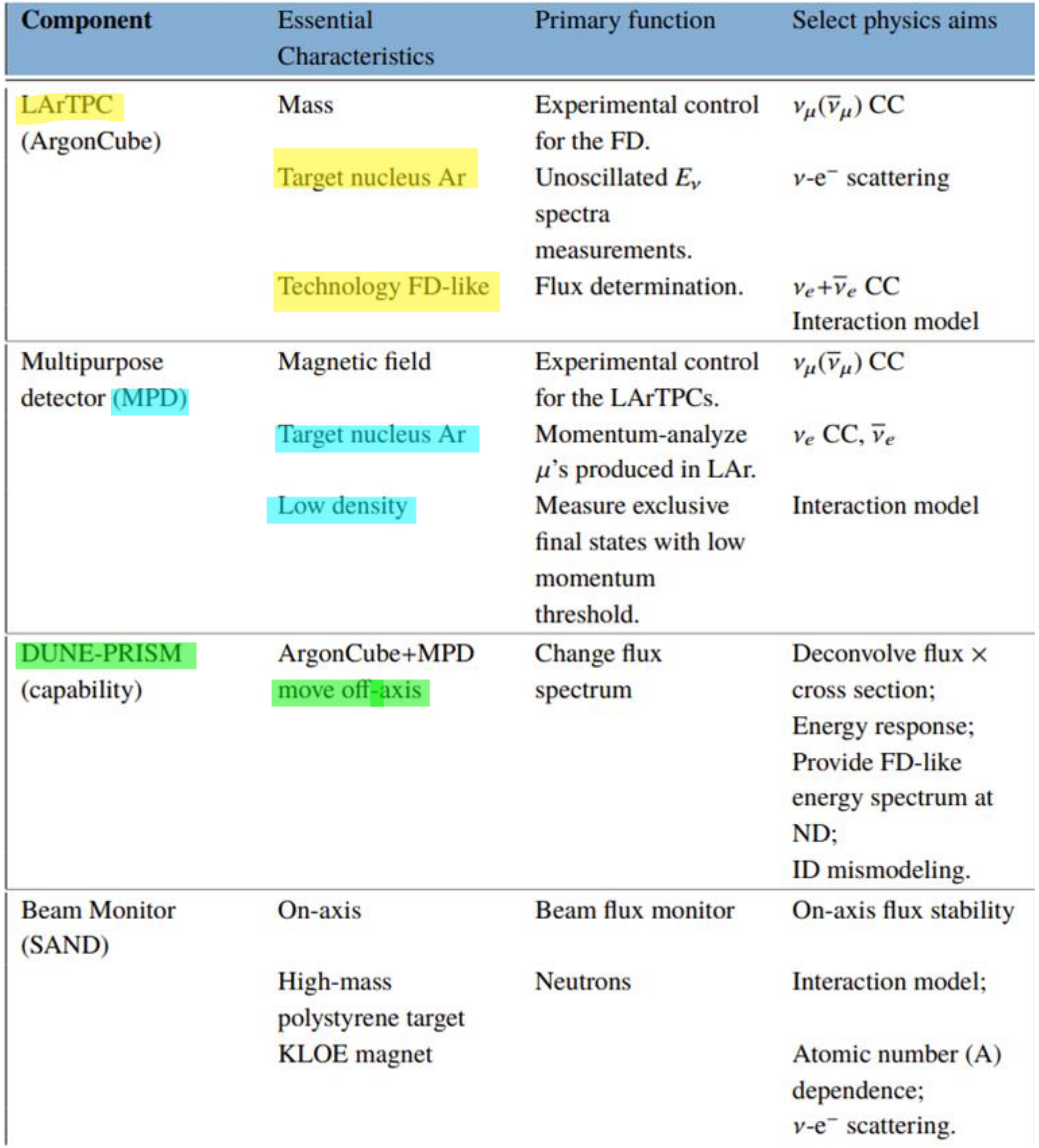
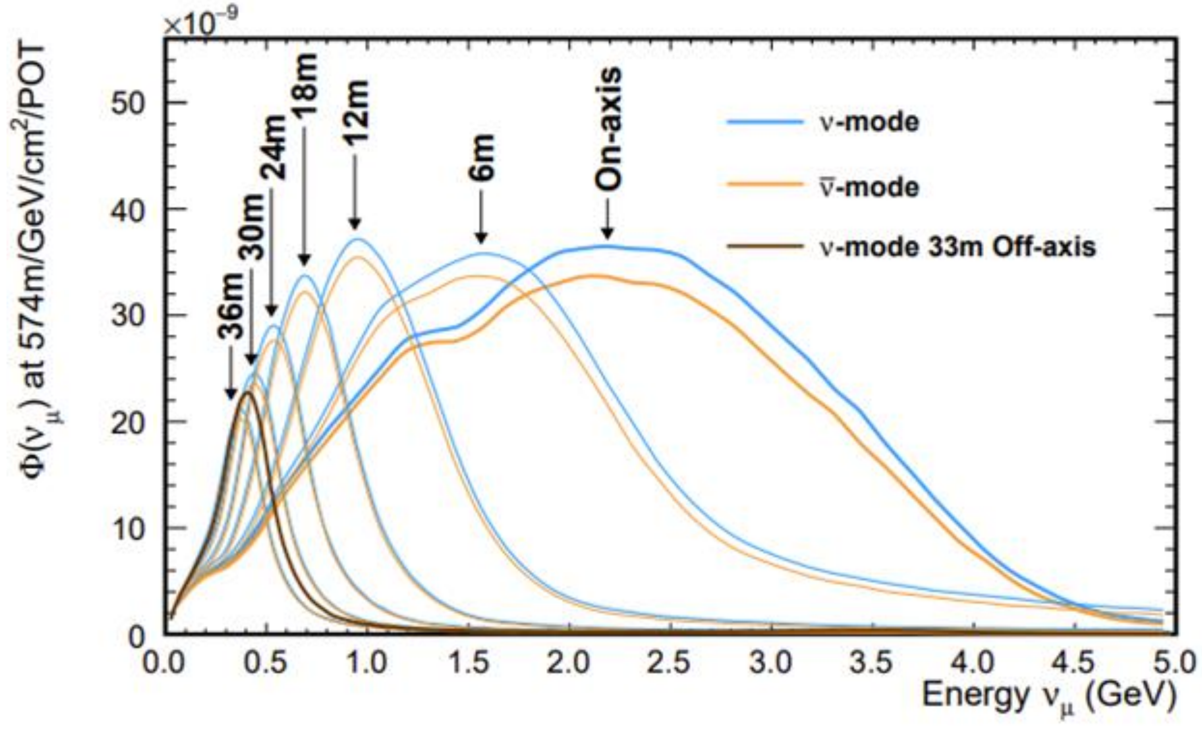
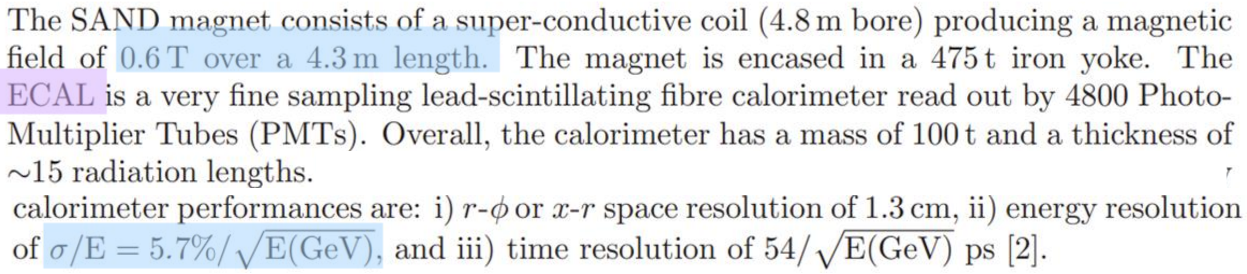


Figure 5.3. Conceptual layout of the calorimeter showing the absorber structure, scintillator tiles, SiPMs, and PCB. The scintillating layers consist of a mix of tiles and cross-strips with embedded wavelength shifting fibers to achieve a comparable effective granularity.



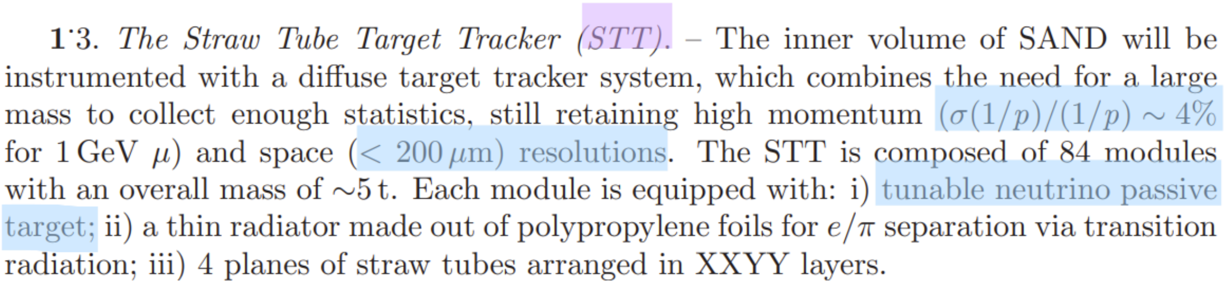
Component	Essential Characteristics	Primary function	Select physics aims
LArTPC (ArgonCube)	Mass	Experimental control for the FD.	$\nu_\mu(\bar{\nu}_\mu)$ CC
	Target nucleus Ar	Unoscillated E_ν spectra measurements.	ν-e$^-$ scattering
	Technology FD-like	Flux determination.	$\nu_e+\bar{\nu}_e$ CC Interaction model
Multipurpose detector (MPD)	Magnetic field	Experimental control for the LArTPCs.	$\nu_\mu(\bar{\nu}_\mu)$ CC
	Target nucleus Ar	Momentum-analyze μ's produced in LAr.	ν_e CC, $\bar{\nu}_e$
	Low density	Measure exclusive final states with low momentum threshold.	Interaction model
DUNE-PRISM (capability)	ArgonCube+MPD move off-axis	Change flux spectrum	Deconvolve flux × cross section; Energy response; Provide FD-like energy spectrum at ND; ID mismodeling.
Beam Monitor (SAND)	On-axis	Beam flux monitor	On-axis flux stability
	High-mass polystyrene target KLOE magnet	Neutrons	Interaction model; Atomic number (A) dependence; ν-e$^-$ scattering.



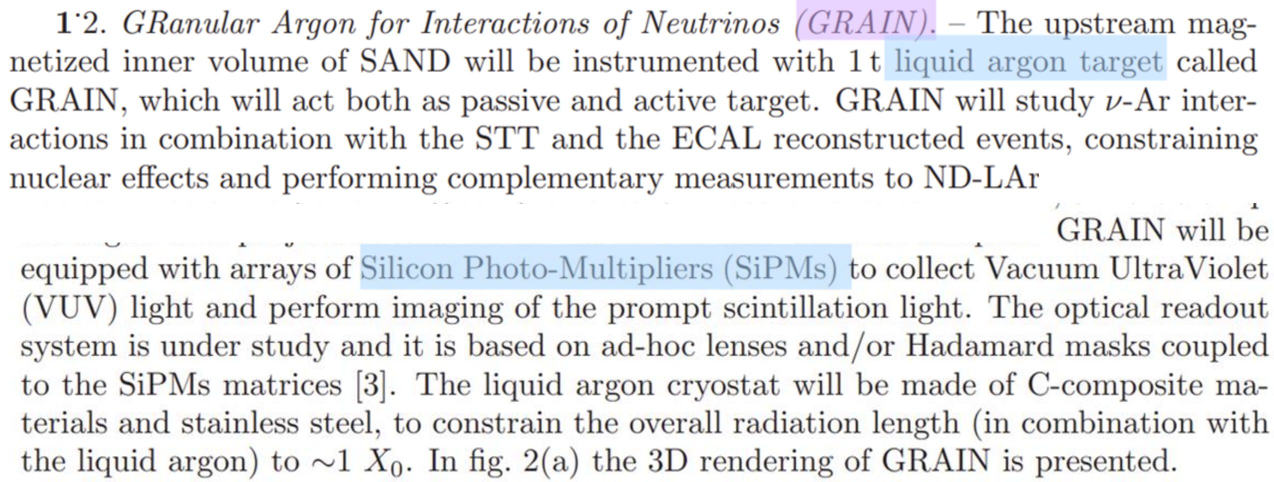


The SAND magnet consists of a super-conductive coil (4.8 m bore) producing a magnetic field of 0.6 T over a 4.3 m length. The magnet is encased in a 475 t iron yoke. The ECAL is a very fine sampling lead-scintillating fibre calorimeter read out by 4800 Photo-Multiplier Tubes (PMTs). Overall, the calorimeter has a mass of 100 t and a thickness of ∼15 radiation lengths.

calorimeter performances are: i) r-ϕ or x-r space resolution of 1.3 cm, ii) energy resolution of $\sigma/\mathrm{E} = 5.7\%/\sqrt{\mathrm{E(GeV)}}$, and iii) time resolution of $54/\sqrt{\mathrm{E(GeV)}}$ ps [2].



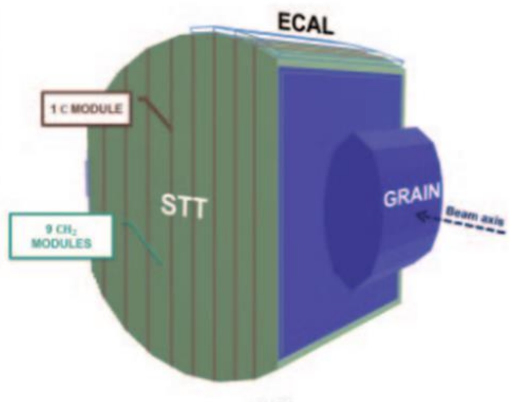
1·3. *The Straw Tube Target Tracker (STT).* – The inner volume of SAND will be instrumented with a diffuse target tracker system, which combines the need for a large mass to collect enough statistics, still retaining high momentum $(\sigma(1/p)/(1/p) \sim 4\%$ for 1 GeV μ) and space $(< 200\,\mu\mathrm{m})$ resolutions. The STT is composed of 84 modules with an overall mass of ∼5 t. Each module is equipped with: i) tunable neutrino passive target; ii) a thin radiator made out of polypropylene foils for e/π separation via transition radiation; iii) 4 planes of straw tubes arranged in XXYY layers.



1·2. *GRanular Argon for Interactions of Neutrinos (GRAIN).* – The upstream magnetized inner volume of SAND will be instrumented with 1 t liquid argon target called GRAIN, which will act both as passive and active target. GRAIN will study ν-Ar interactions in combination with the STT and the ECAL reconstructed events, constraining nuclear effects and performing complementary measurements to ND-LAr

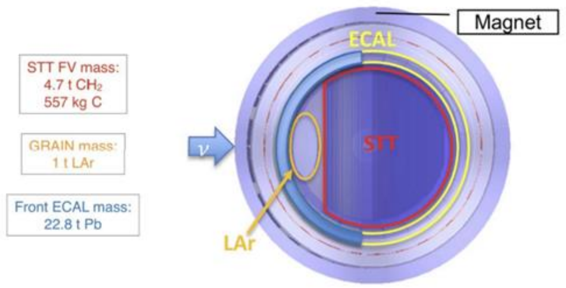
GRAIN will be equipped with arrays of Silicon Photo-Multipliers (SiPMs) to collect Vacuum UltraViolet (VUV) light and perform imaging of the prompt scintillation light. The optical readout system is under study and it is based on ad-hoc lenses and/or Hadamard masks coupled to the SiPMs matrices [3]. The liquid argon cryostat will be made of C-composite materials and stainless steel, to constrain the overall radiation length (in combination with the liquid argon) to ∼1 X_0. In fig. 2(a) the 3D rendering of GRAIN is presented.

(esiste un progetto alternativo per il tracciatore...)



(b)

SAND: on-axis magnetized neutrino detector, multipurpose detector with a high-performant ECAL, light-targeted tracker, a thin LAR "lens", all of them in a magnetic field, mostly recovered by **KLOE** (LNF), in-kind contribution to DUNE from INFN, with new TRACKER and the thin LAr "lens



2·1. *ν/ν̄ beam monitoring.*

2·2. *Flux measurements.*

2·3. *Constraining nuclear effects.*

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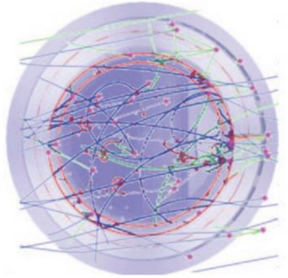
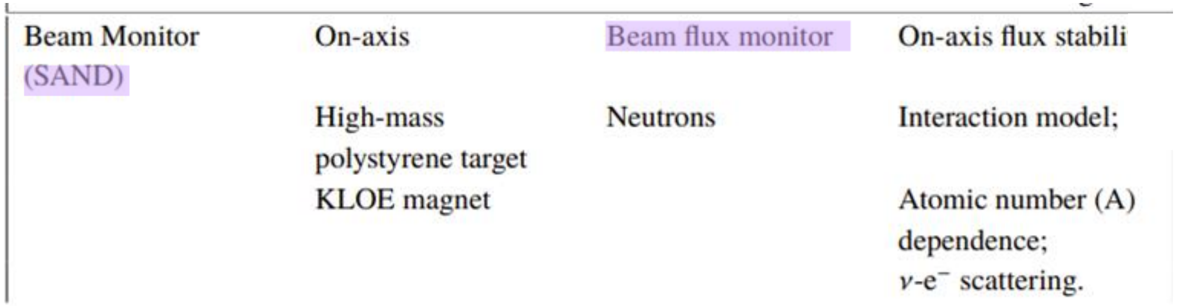


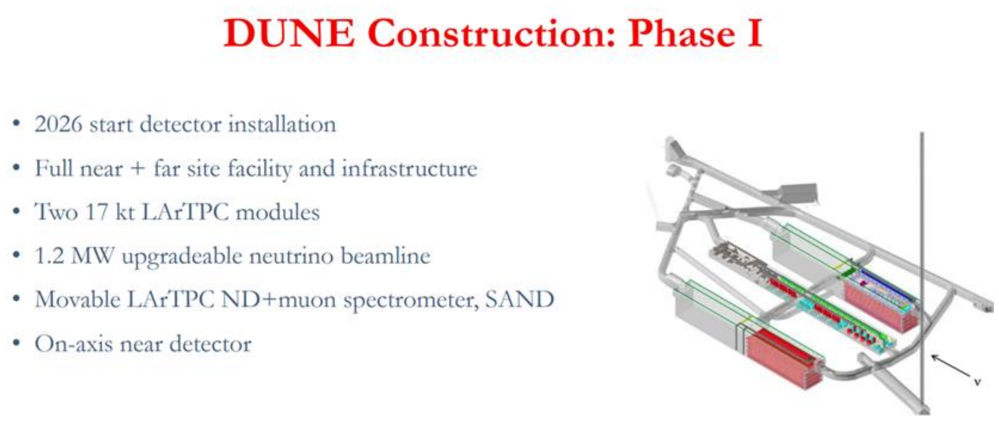


Beam Monitor (SAND)	On-axis	Beam flux monitor	On-axis flux stabili
	High-mass polystyrene target	Neutrons	Interaction model;
	KLOE magnet		Atomic number (A) dependence; ν-e$^-$ scattering.

Current status and future plans in a nutshell

- LBNF is being delivered in its entirety.
- DUNE Phase I:
  - FD (approved): 2 x 17 kt (total) LAr TPCs: one Horizontal Drift (ready in 2029), one Vertical Drift (ready in 2030).
  - ND (baseline TBC and approved by 2025): NDLAr with TMS; DUNE-PRISM; SAND on-axis.
- PIP II: ongoing construction, first beam in 2031, reaching 1.2 MW by end 2032.

- Phase 2, as submitted to P5 (report due in early December):
  - DUNE ND plan: More Capable Near Detector (HPGAr TPC, magnet, calorimeter).
  - DUNE FD plan: FD3, FD4.
  - Fermilab plan: ACE: MIRT, Booster Replacement. Can provide up to 2.1 MW at DUNE start.

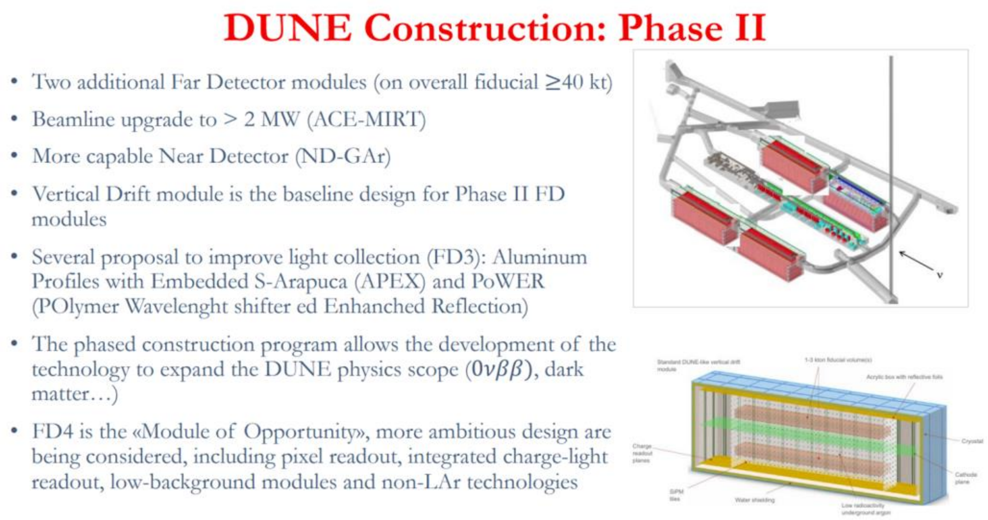


DUNE Construction: Phase I

- 2026 start detector installation
- Full near + far site facility and infrastructure
- Two 17 kt LArTPC modules
- 1.2 MW upgradeable neutrino beamline
- Movable LArTPC ND+muon spectrometer, SAND
- On-axis near detector

Building DUNE: construction schedule

- **Far site excavation is complete**
- Next: Building and Site infrastructure work until mid-2025
- Cryostat warm structure has been shipped from CERN to US, to be installed in 2025-26
- Detector installation in 2026-27
- Purge and fill with liquid argon in 2028
- Physics in early 2029
- **Beam physics with Near Detector 2031**

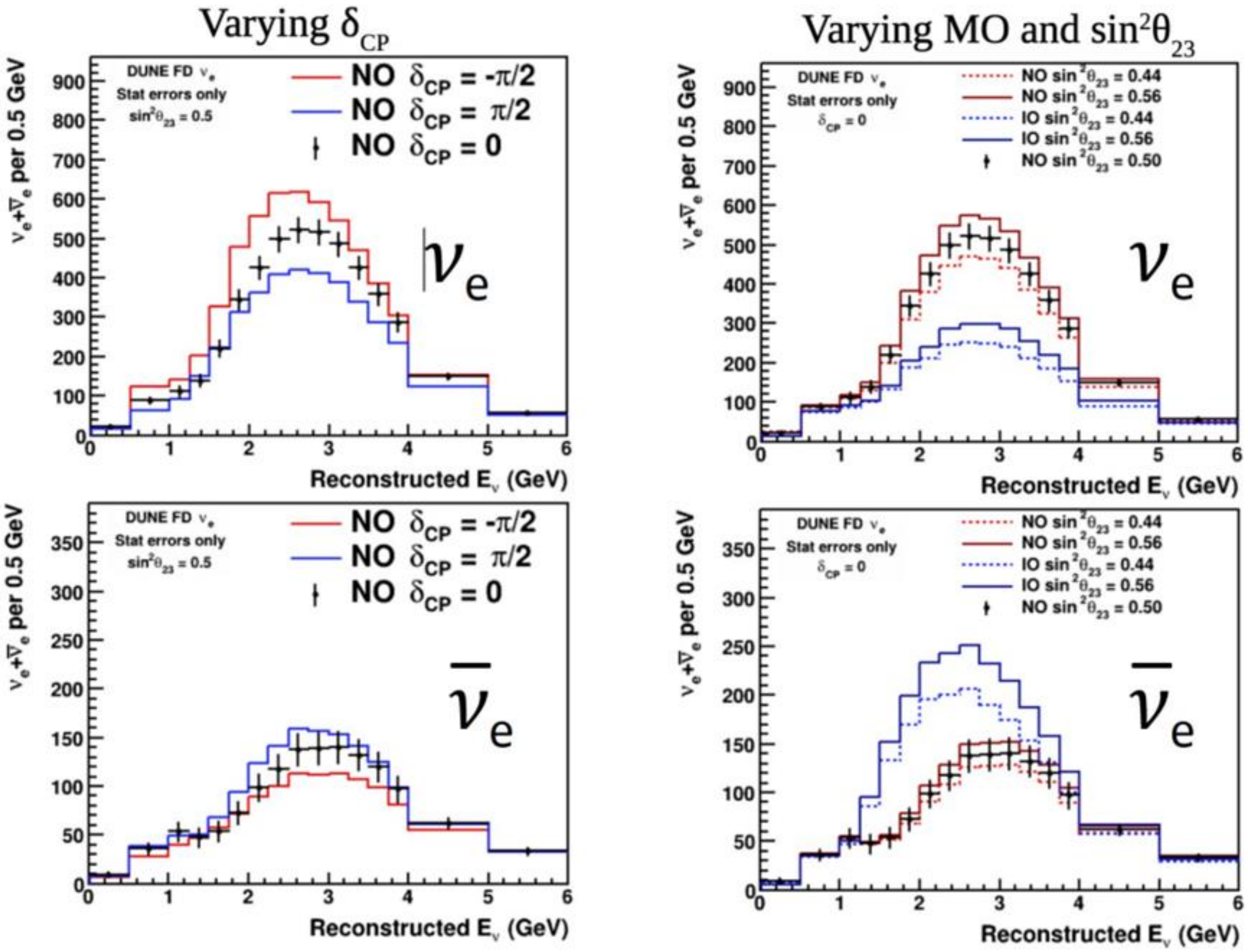


DUNE Construction: Phase II

- Two additional Far Detector modules (on overall fiducial ≥40 kt)
- Beamline upgrade to > 2 MW (ACE-MIRT)
- More capable Near Detector (ND-GAr)
- Vertical Drift module is the baseline design for Phase II FD modules
- Several proposal to improve light collection (FD3): Aluminum Profiles with Embedded S-Arapuca (APEX) and PoWER (POlymer Wavelenght shifter ed Enhanched Reflection)
- The phased construction program allows the development of the technology to expand the DUNE physics scope ($0\nu\beta\beta$), dark matter…)
- FD4 is the «Module of Opportunity», more ambitious design are being considered, including pixel readout, integrated charge-light readout, low-background modules and non-LAr technologies

Neutrino energy spectra at Far Detector

- **Sensitivity to $\boldsymbol{\delta_{CP}}$**
  - If $\boldsymbol{\delta_{CP}} \sim -\pi/2$ is DUNE will measure an enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance
- **Sensitivity to mass ordering (MO)**
  - If MO is normal, DUNE will measure a **much larger** enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance, with respect to inverted order
- **MO, $\boldsymbol{\delta_{CP}}$ and $\boldsymbol{\theta_{23}}$** all affect spectra with different shape, additional handle on resolving degeneracies



Mass order and CPV DUNE Sensitivity

- **For best-case oscillation scenario DUNE will reach**
  - $>5\sigma$ Mass Ordering sensitivity in 1 year
  - $>3\sigma$ CPV sensitivity in 3.5 years
- **For worst-case oscillation scenario**
  - $>5\sigma$ Mass Ordering sensitivity in 3 year (no matter the value of δ_{CP} or any other parameter)
- **In long term** DUNE can establish CP violation at $> 3\sigma$ for 75% possible values of δ_{CP}

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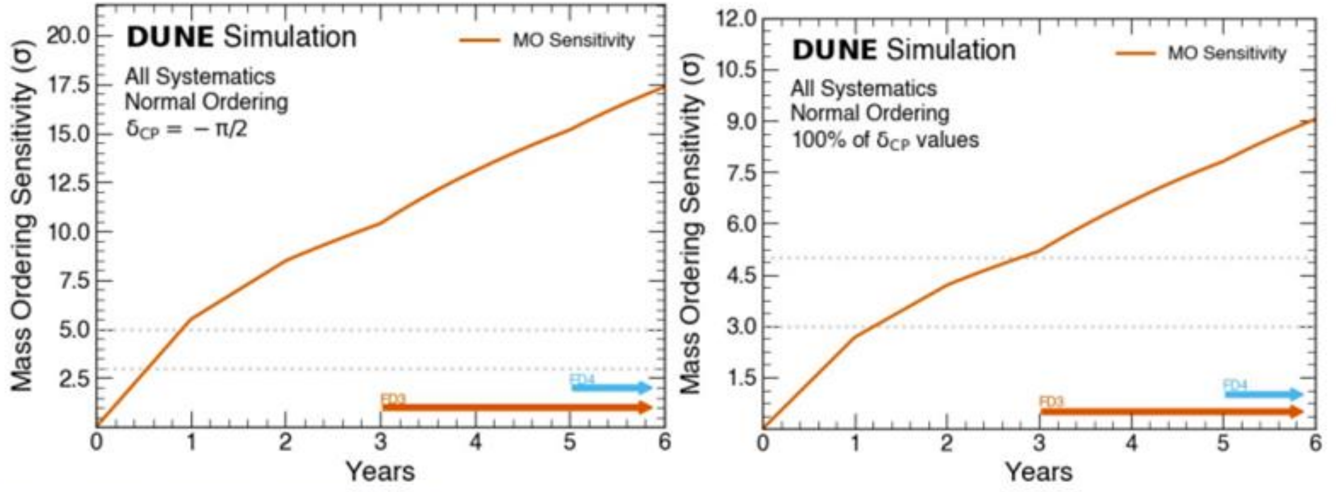
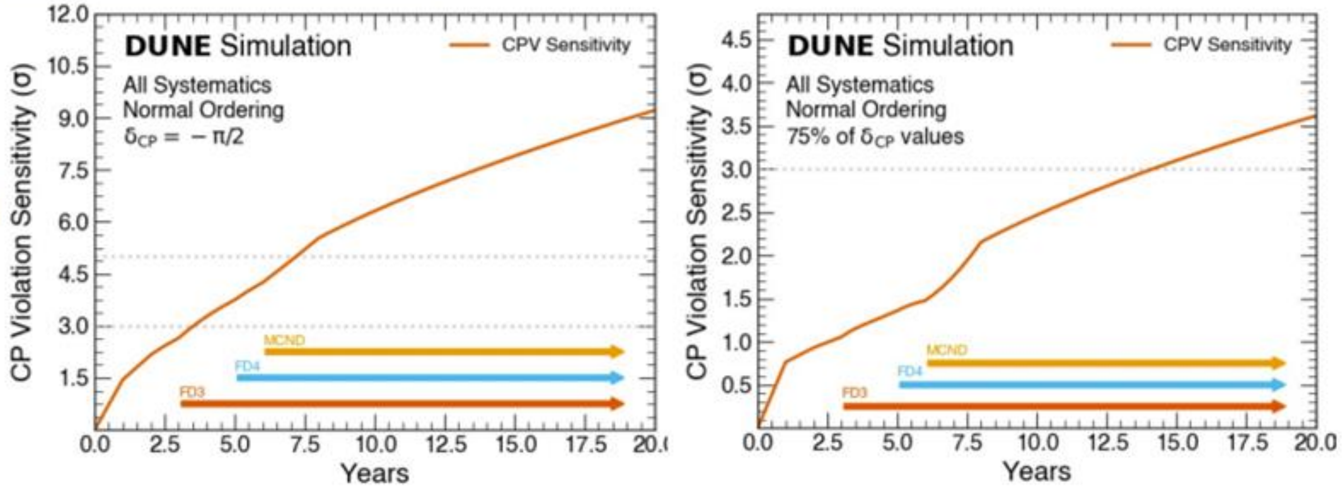
Eur. Phys. J. C 80, 978 (2020)

Neutrino mass ordering



CP violation sensitivity



DUNE precision measurements

- Ultimate precision 6°-16° in δ_{CP}
- World-leading precision (for long baseline experiments) in θ_{13}

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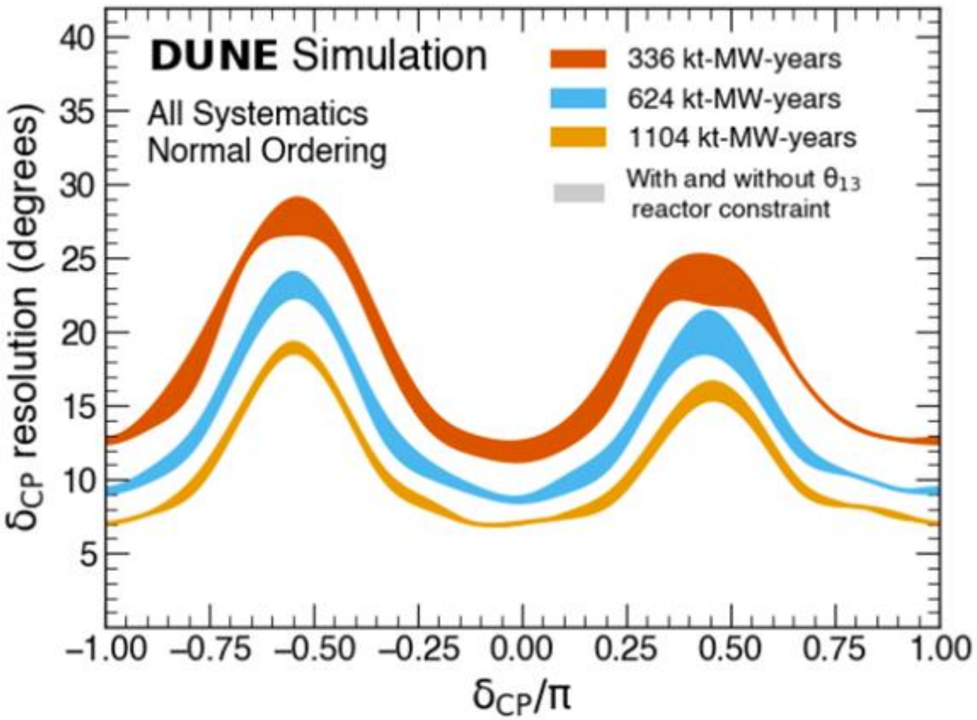
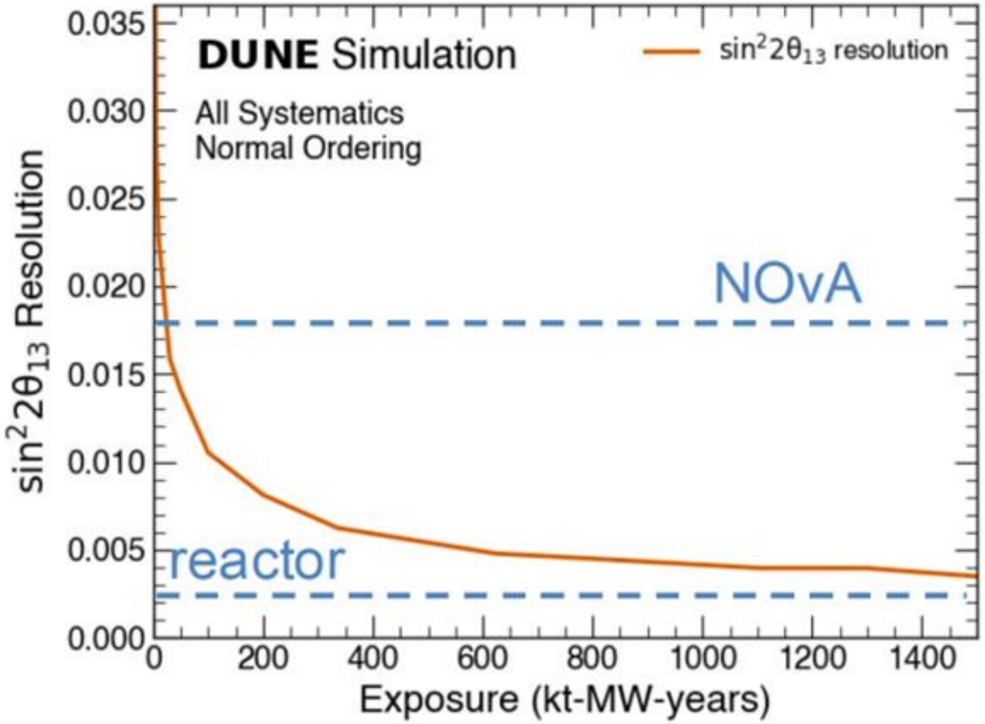




Astrophysical neutrinos in DUNE

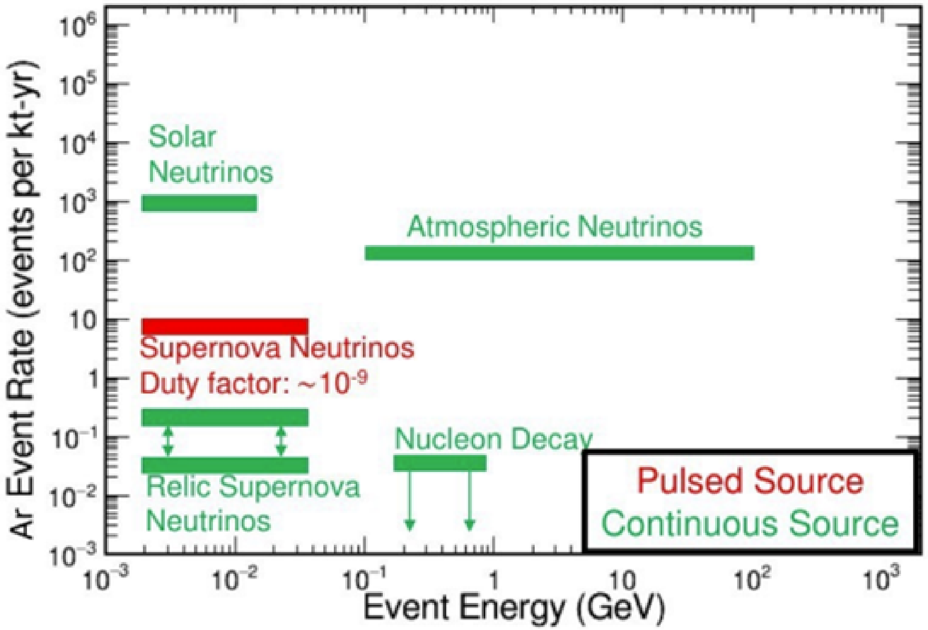
- **Neutrinos from atmospheric, solar and core collapse supernovae**
  - Argon target gives unique sensitivity to MeV-scale electron neutrinos
    - **Charged Current (CC) interaction on Ar**

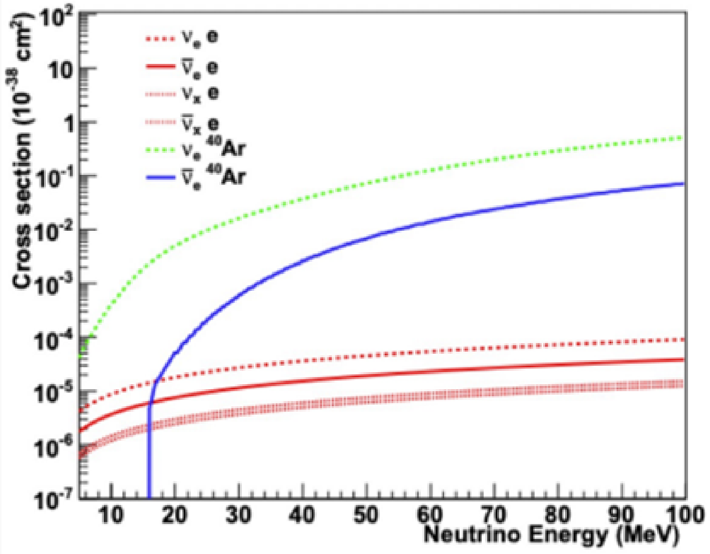
      $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ (E_ν>1.5 MeV)

      $\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$ (E_ν>7.5 MeV)
    - **ES on electrons**

      $\nu_x + e^- \rightarrow \nu_x + e^-$ (pointing)
    - **Neutral Current (NC) interaction on Ar**

      $\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$





Supernova burst neutrinos

- **DUNE will observe thousand of neutrino interactions from a galactic supernova burst**
- **Time and energy spectra are sensitive to core collapse mechanism and stellar evolution**
  - Neutronization through electron capture (depending from oscillation and MO)
  - Matter falling into core during accretion
  - Emission cools as neutrinos diffuse
- **Pointing capabilities: ES channel. about 5° resolution**

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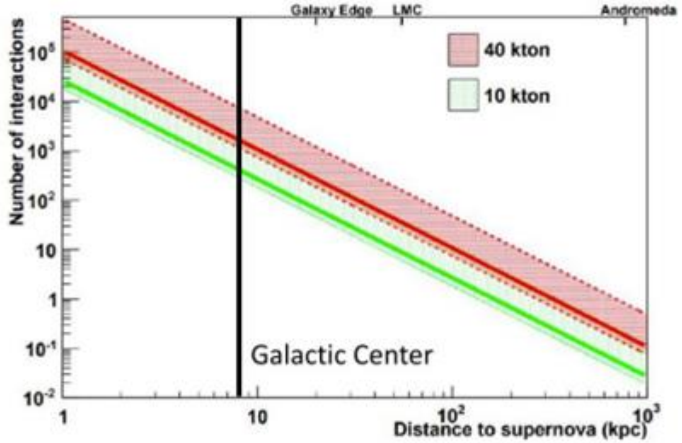

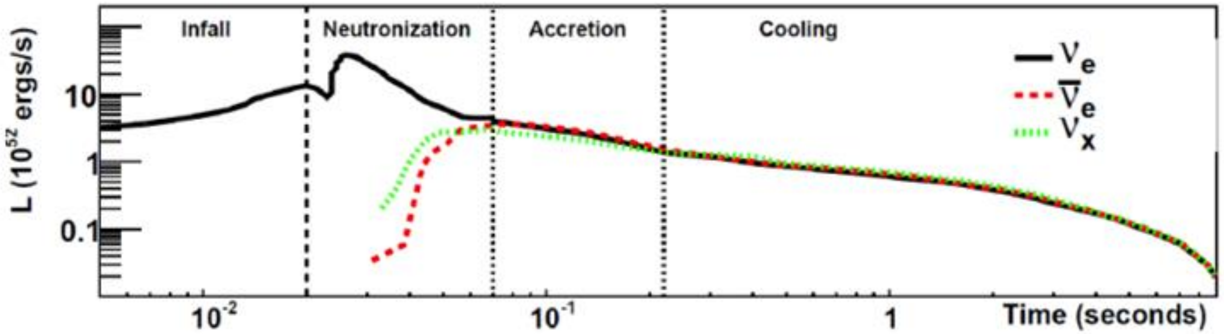

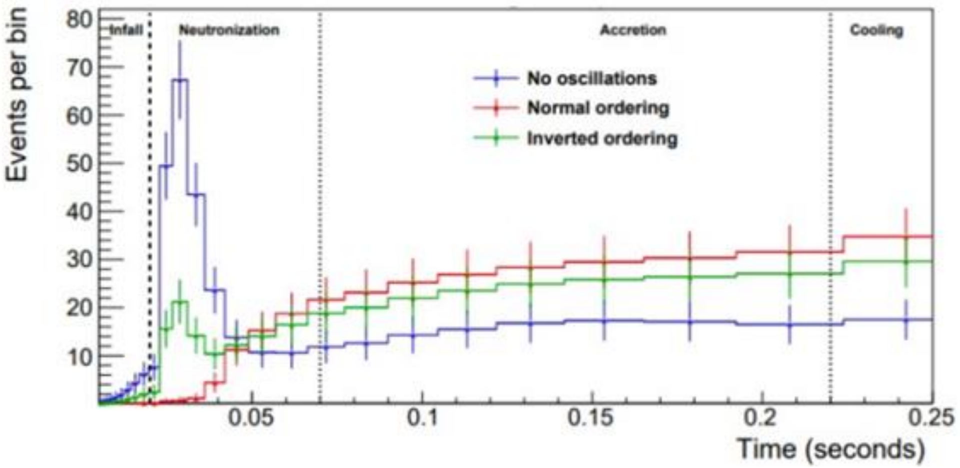

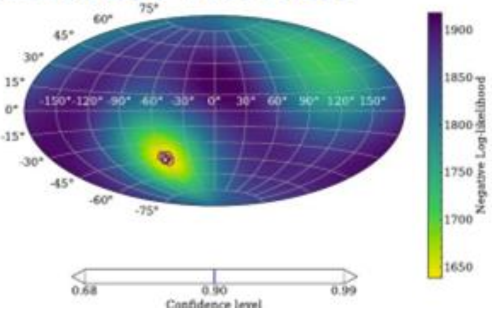

About the complementarity of Hyper-K and DUNE

Discussed the first time by the ICFA Neutrino Panel: arXiv:1501.03918

To make the most of complementarity, it would be necessary to form and support a joint working group. After the very positive experience of the T2K-NOvA combined analysis.

- Same L/E but the baselines, L, and energies, E, differ by almost a factor of 5.
- Hyper-K is off-axis, with a narrow neutrino spectrum optimized to the first oscillation maximum
- DUNE is on-axis with a wide spectrum that can cover the second oscillation maximum and with a tail above the tau production threshold
- The differing degree to which the matter effect modifies the oscillation probabilities at Hyper-K and DUNE may be exploited to break parameter degeneracies
- To fully understand the mechanisms of supernova explosion requires accurate measurements of the ν_e and $\bar{\nu}_e$ fluxes, along with some neutral current data (which is sensitive to the flux of $\nu_{\mu,\tau}$). These measurements can not be made with Hyper-K or DUNE alone (and also JUNO contribution is important).

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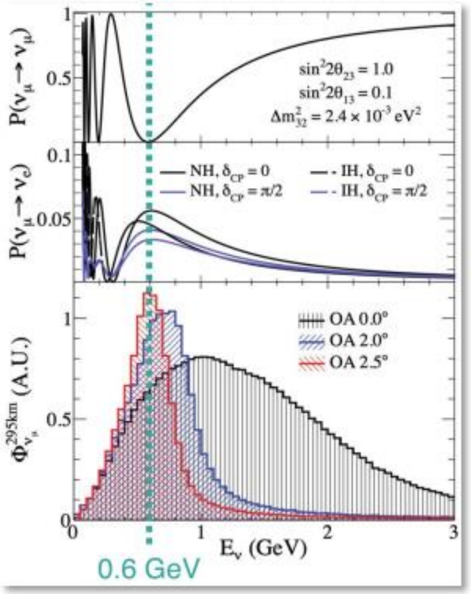
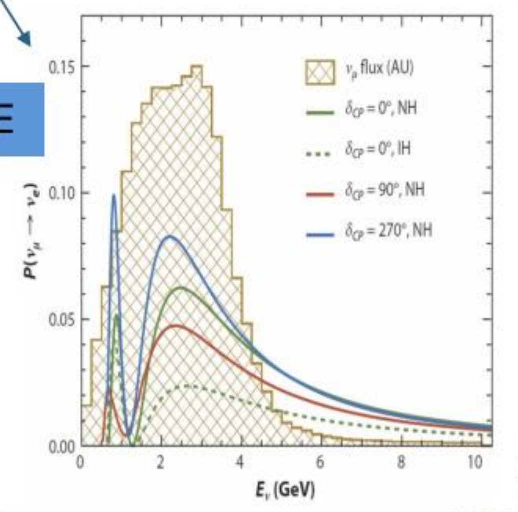
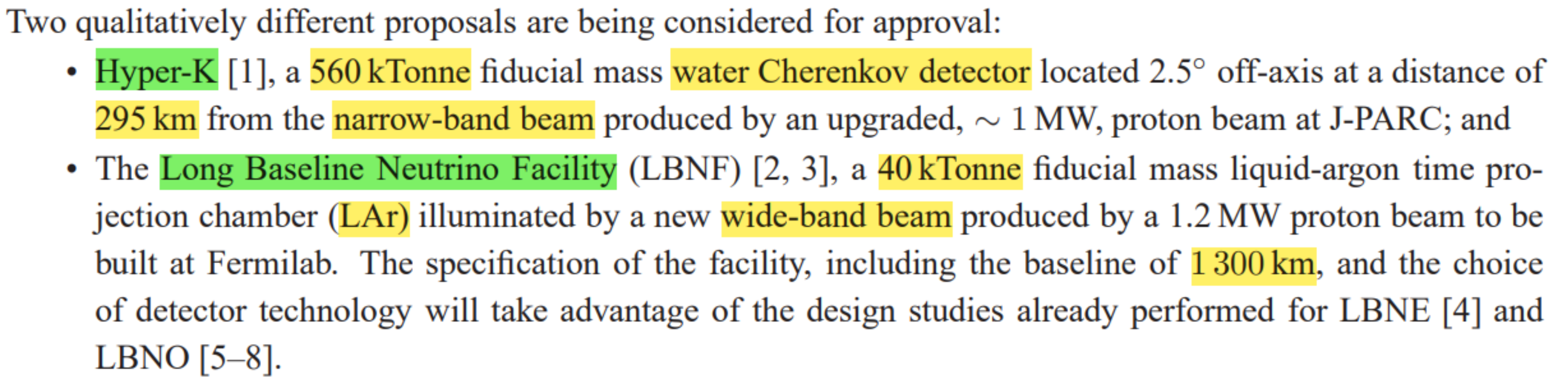
HK



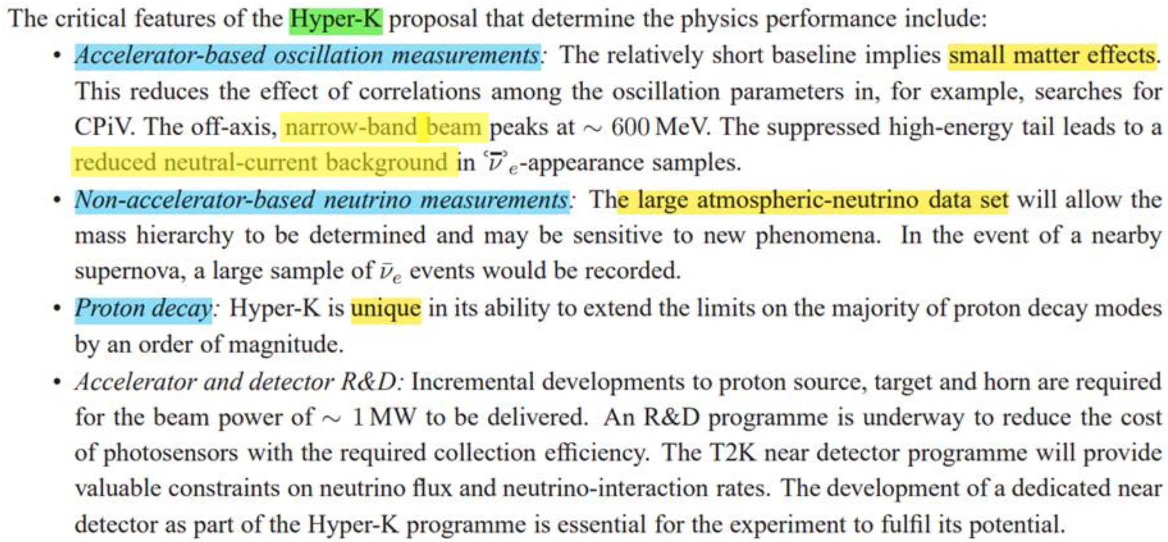
DUNE





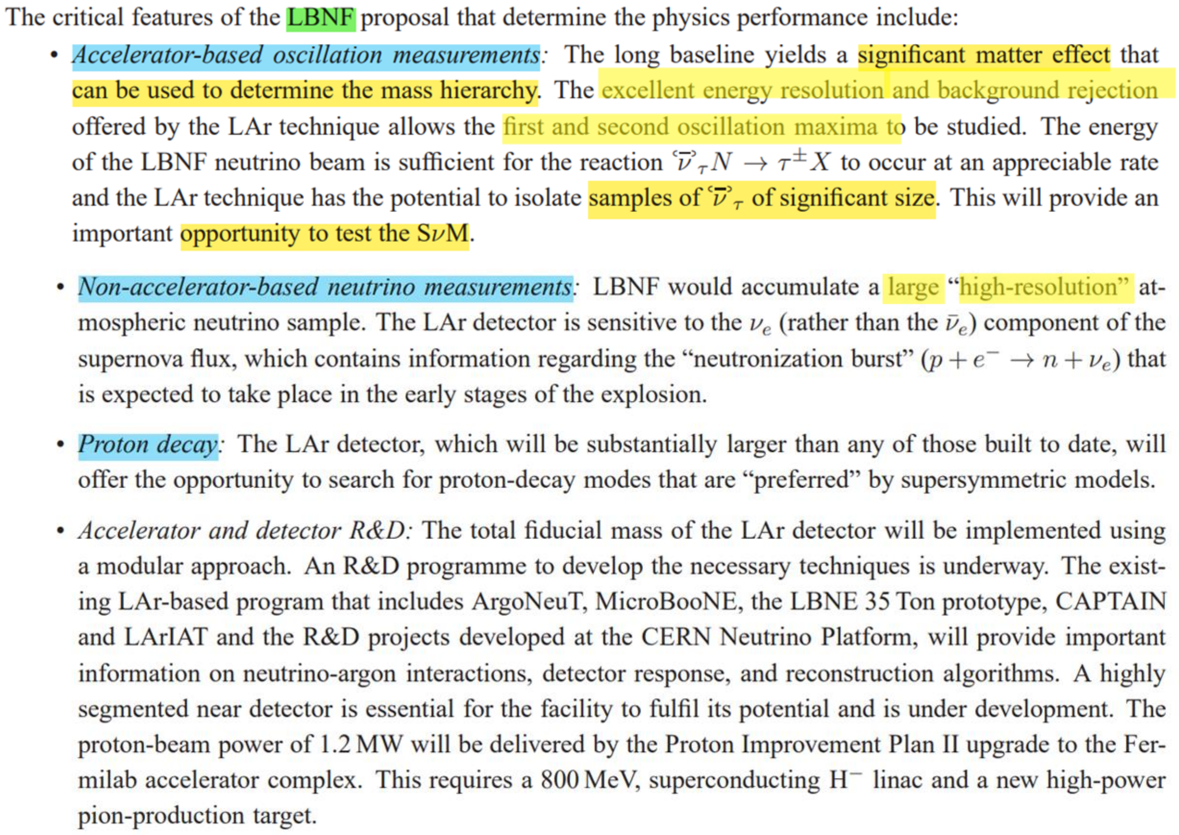
Two qualitatively different proposals are being considered for approval:

- Hyper-K [1], a 560 kTonne fiducial mass water Cherenkov detector located 2.5° off-axis at a distance of 295 km from the narrow-band beam produced by an upgraded, ∼ 1 MW, proton beam at J-PARC; and
- The Long Baseline Neutrino Facility (LBNF) [2, 3], a 40 kTonne fiducial mass liquid-argon time projection chamber (LAr) illuminated by a new wide-band beam produced by a 1.2 MW proton beam to be built at Fermilab. The specification of the facility, including the baseline of 1 300 km, and the choice of detector technology will take advantage of the design studies already performed for LBNE [4] and LBNO [5–8].



The critical features of the Hyper-K proposal that determine the physics performance include:

- *Accelerator-based oscillation measurements:* The relatively short baseline implies small matter effects. This reduces the effect of correlations among the oscillation parameters in, for example, searches for CPiV. The off-axis, narrow-band beam peaks at ∼ 600 MeV. The suppressed high-energy tail leads to a reduced neutral-current background in $\overset{(-)}{\nu}_e$-appearance samples.
- *Non-accelerator-based neutrino measurements:* The large atmospheric-neutrino data set will allow the mass hierarchy to be determined and may be sensitive to new phenomena. In the event of a nearby supernova, a large sample of $\bar{\nu}_e$ events would be recorded.
- *Proton decay:* Hyper-K is unique in its ability to extend the limits on the majority of proton decay modes by an order of magnitude.
- *Accelerator and detector R&D:* Incremental developments to proton source, target and horn are required for the beam power of ∼ 1 MW to be delivered. An R&D programme is underway to reduce the cost of photosensors with the required collection efficiency. The T2K near detector programme will provide valuable constraints on neutrino flux and neutrino-interaction rates. The development of a dedicated near detector as part of the Hyper-K programme is essential for the experiment to fulfil its potential.

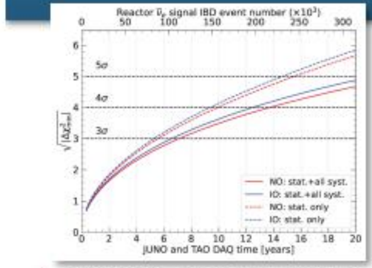


The critical features of the LBNF proposal that determine the physics performance include:

- *Accelerator-based oscillation measurements:* The long baseline yields a significant matter effect that can be used to determine the mass hierarchy. The excellent energy resolution and background rejection offered by the LAr technique allows the first and second oscillation maxima to be studied. The energy of the LBNF neutrino beam is sufficient for the reaction $\overset{(-)}{\nu}_\tau N \to \tau^\pm X$ to occur at an appreciable rate and the LAr technique has the potential to isolate samples of $\overset{(-)}{\nu}_\tau$ of significant size. This will provide an important opportunity to test the SνM.
- *Non-accelerator-based neutrino measurements:* LBNF would accumulate a large "high-resolution" atmospheric neutrino sample. The LAr detector is sensitive to the ν_e (rather than the $\bar{\nu}_e$) component of the supernova flux, which contains information regarding the "neutronization burst" ($p + e^- \to n + \nu_e$) that is expected to take place in the early stages of the explosion.
- *Proton decay:* The LAr detector, which will be substantially larger than any of those built to date, will offer the opportunity to search for proton-decay modes that are "preferred" by supersymmetric models.
- *Accelerator and detector R&D:* The total fiducial mass of the LAr detector will be implemented using a modular approach. An R&D programme to develop the necessary techniques is underway. The existing LAr-based program that includes ArgoNeuT, MicroBooNE, the LBNE 35 Ton prototype, CAPTAIN and LArIAT and the R&D projects developed at the CERN Neutrino Platform, will provide important information on neutrino-argon interactions, detector response, and reconstruction algorithms. A highly segmented near detector is essential for the facility to fulfil its potential and is under development. The proton-beam power of 1.2 MW will be delivered by the Proton Improvement Plan II upgrade to the Fermilab accelerator complex. This requires a 800 MeV, superconducting H$^-$ linac and a new high-power pion-production target.

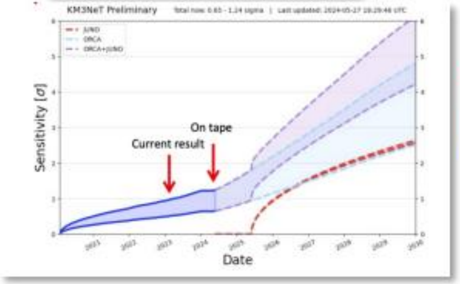
... The race for neutrino mass ordering (aka hierarchy)

NMO can only be +/-1, so sensitivity means wrong ordering rejection



JUNO

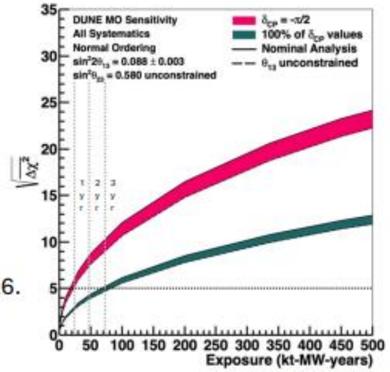
arXiv:2405.18008



ORCA/KM3NeT

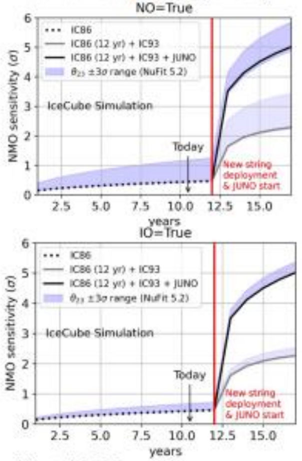
Most recent update of Eur.Phys.J.C 82 (2022) 1, 26.

DUNE Phase 1: 1yr=24 kt-MW



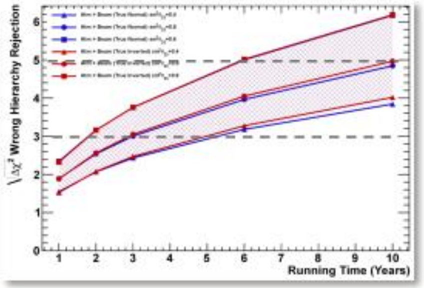
Vertical Drift TDR: arXiv:2312.03130

IceCube (+Upgrade)



Neutel 2023: https://doi.org/10.5281/zenodo.10567782

Computed for θ_{23}=40°



HK (mostly from atmospherics)

HK TDR arXiv:1805.04163

Nominal Starting Dates

2025: JUNO and IceCube Upgrade

2027: Hyper-K

2028: Full ORCA

2031: DUNE Phase I

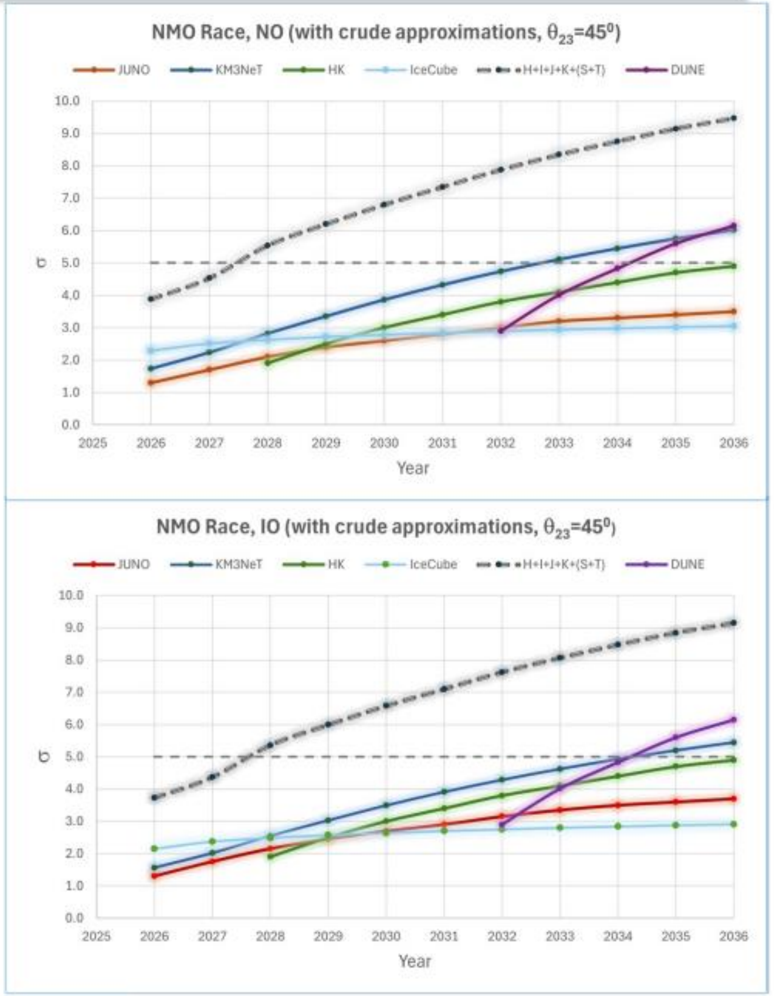
(T2K joint SK @ full statistics :$\Delta\chi^2$=8)

Depend on:

- Assumptions on θ_{23} (atmospherics have terms ∝ $\sin^4\theta_{23}$)
- Assumptions on δ_{CP} (DUNE)
- True Ordering
- Degree of optimism in the calculation of systematic errors
- Performance of the detector (JUNO)
- Fiducial mass (ORCA)

No way to display these curves in a single plot keeping the same assumptions

... anyway



H+I+J+K+(S+T): combination of HK, IceCube, JUNO, KM3NeT and joint analysis of SK and T2K at full statistics