Physics & Progress: DUNE's Path Forward

Meghna Bhattacharya, Fermilab
for the DUNE Collaboration

NuFact 2024, Argonne National Lab

September, 20th

Fermilab U.S. DEPARTMENT OF ENERGY | Office of Science DUNE

DUNE @ NuFact:

Jessie Micallef Machine Learning Reconstruction for DUNE's Near Detector Prototype

Wei Shi Tagging Neutron Capture on Argon for Energy Calibration and MeV Physics

Sindhujha Kumaran The Near Detector Liquid Argon (ND-LAr) 2x2 prototype of DUNE

Jose Soto ProtoDUNE Photon Detection System

Praveen Kumar Energy reconstruction and calibration techniques of the DUNE LArTPC

Ciaran Hasnip DUNE-PRISM

Alejandro Yankelevich The ICEBERG Test Stand for DUNE Cold Electronics Development

Andrew Cudd The DUNE 2x2 Demonstrator physics prospects and plans with neutrino data

Stephen Dolan Modeling neutrino-nucleus interaction uncertainties for DUNE long-baseline sensitivity studies

Liban Warsame DUNE long-baseline oscillation physics sensitivity

Wei Shi Photon Detection System for DUNE Phase II FD: Physics Prospects and Prototyping Status

Diana Leon Silverio R&D of Power Over Fiber in harsh environments and its novel application for the DUNE FD-VD Photon Detection System

Credit: Elena Gramellini & google earth

Physics motivation

Progress

Path forward

Three flavor neutrino oscillations:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \text{PMNS} \\ \text{matrix} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor (Interaction) — Mass (Propagation)

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

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

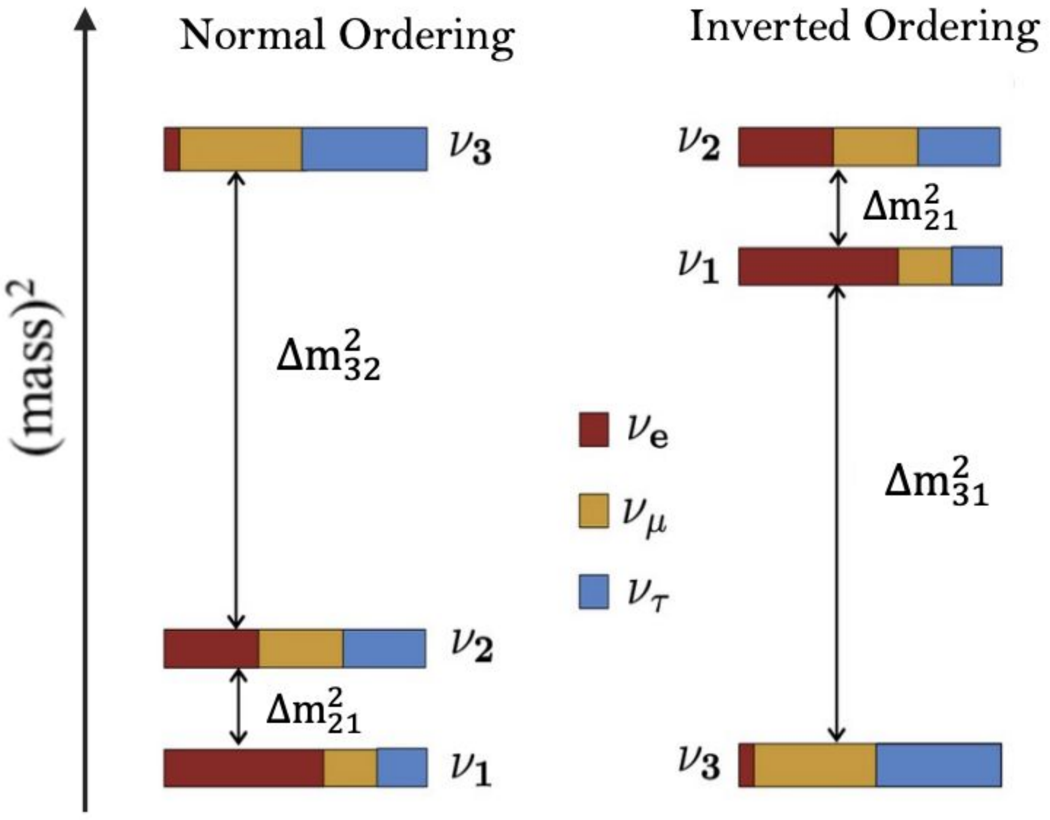
$$P(\nu_\alpha \to \nu_\beta) \sim \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right),$$

L : traveled distance
E : energy
$\Delta m^2_{ij} = m^2_i - m^2_j$

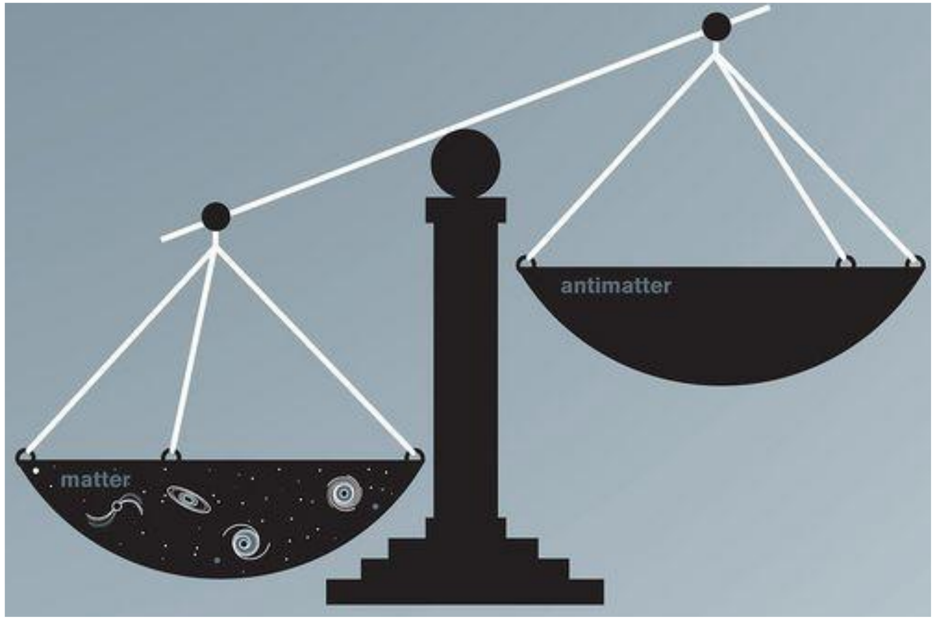
- Mass splitting (**Δm_{ij}^2**) → frequency of oscillation
- Mixing angles (**θ_{12}, θ_{13}, θ_{23}**) → magnitude of oscillation
- **δ_{CP}** → A measure of CP violation in neutrinos

Goals for next-generation experiments:

Determine the neutrino mass ordering



More matter in the universe - why?



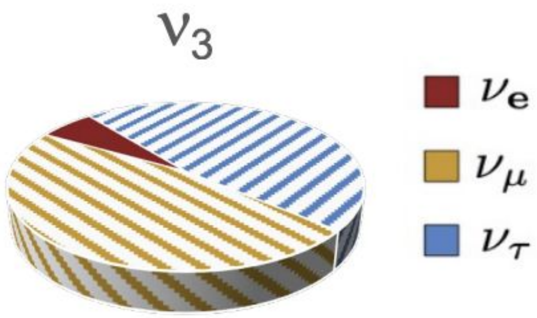
Measure δ_{CP} and determine if CP is violated

Goals for next-generation experiments:

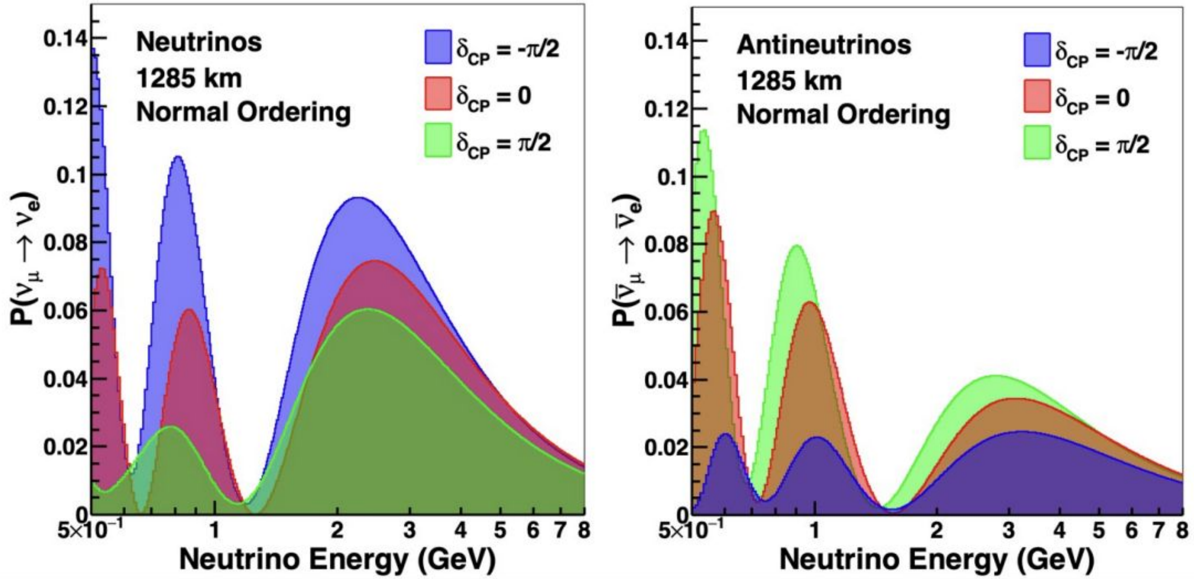
Determine the octant of θ_{23}

Current Measured Value : $\theta_{23} \sim 45°$

Precision : $\sin^2\theta_{23} \sim 5\%$



Is the 3-flavor model complete?



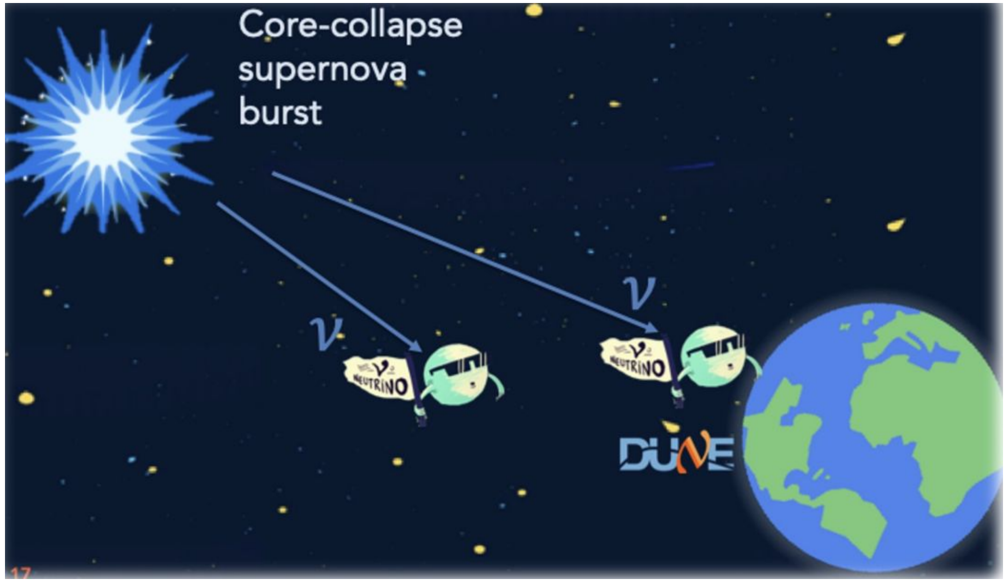
Measure neutrino and antineutrino oscillation as a function of L/E

Does the 3-flavor model describe the data?

Yes → **measure mixing angles, mass splittings, and CP phase**

No → **characterize new physics**

Broader Physics Scopes:

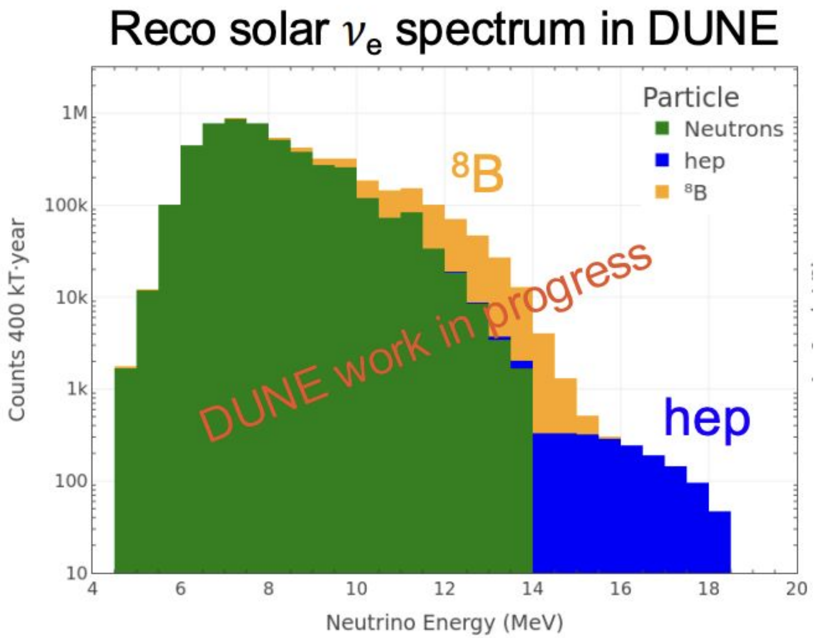


Large, sensitive underground detectors are excellent to:

- Observe supernova burst neutrinos
- Measure solar and atmospheric neutrinos
- Search for new physics (nucleon decays, cosmogenic dark matter)

Intense beams with capable near detectors are excellent to:

- Search for new physics produced in the beamline



Fermilab DUNE

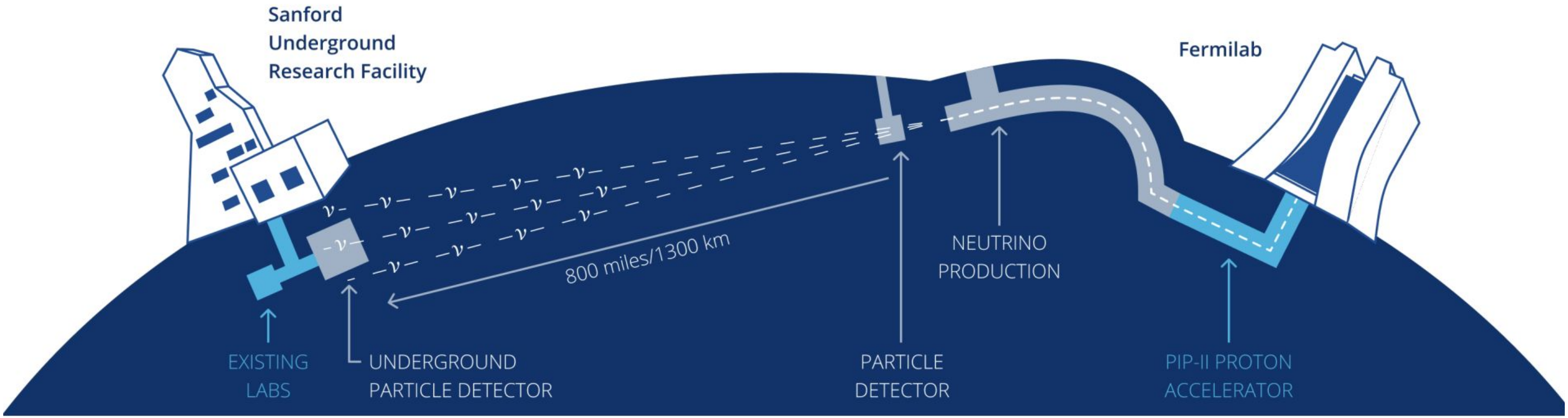
Credit: Elena Gramellini & google earth

Deep Underground Neutrino Experiment (DUNE)

Next-generation international neutrino experiment hosted in the US

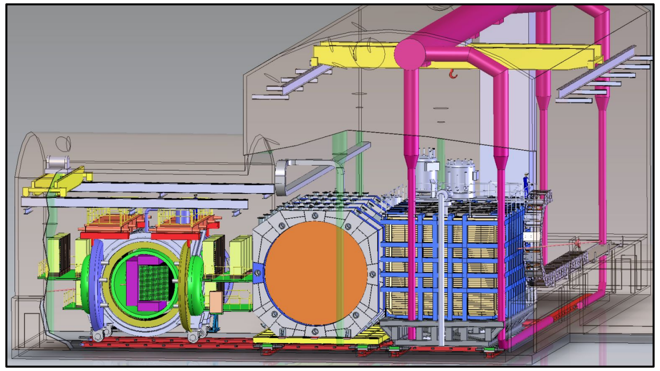
DUNE:

Wideband (anti)neutrino beamline with >2MW intensity

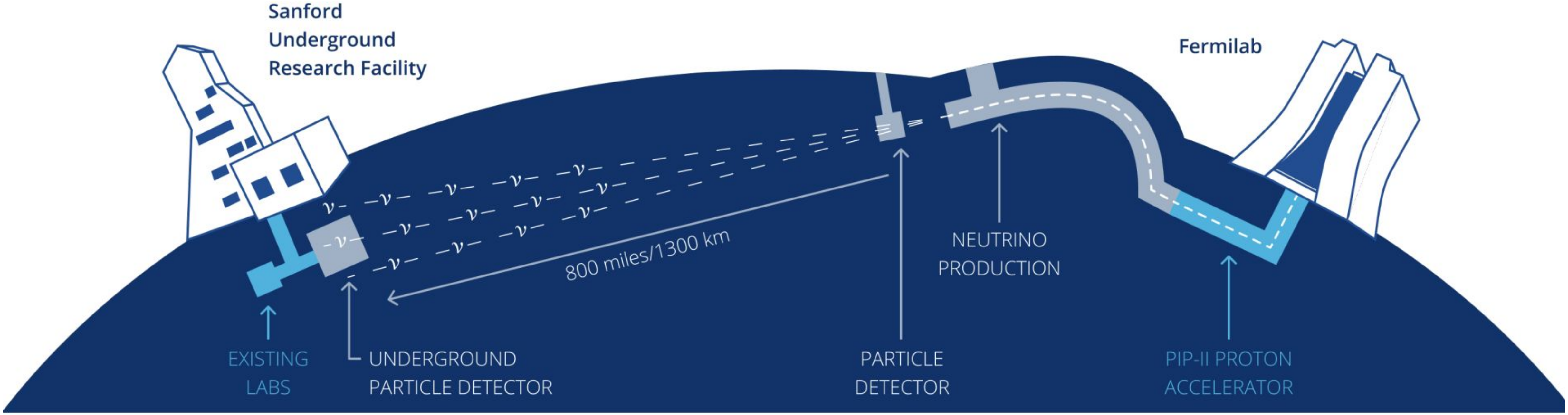


DUNE:

Movable LArTPC Near Detector, muon spectrometer and separate on-axis detector

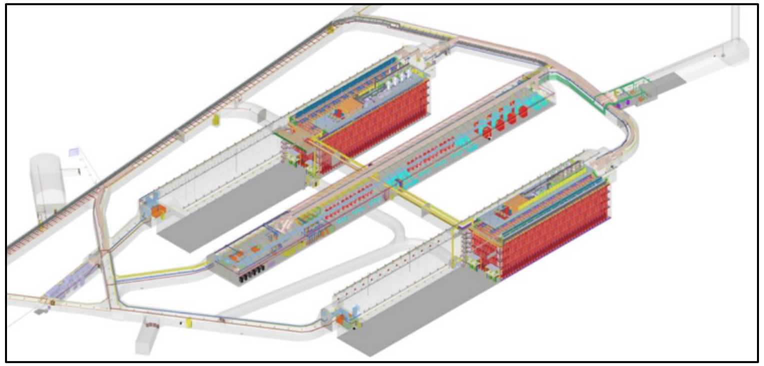


Wideband (anti)neutrino beamline with >2MW intensity

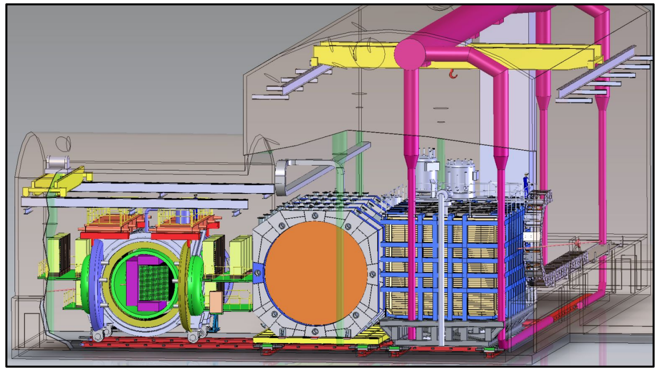


DUNE:

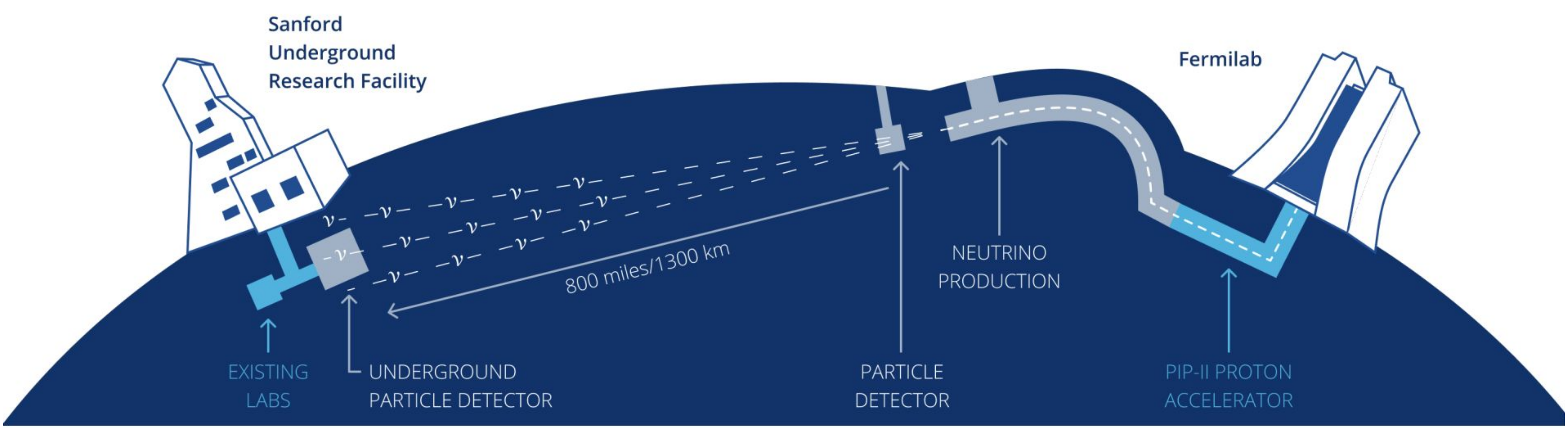
Underground, modular LArTPC Far Detector, ≥40 kt fiducial mass



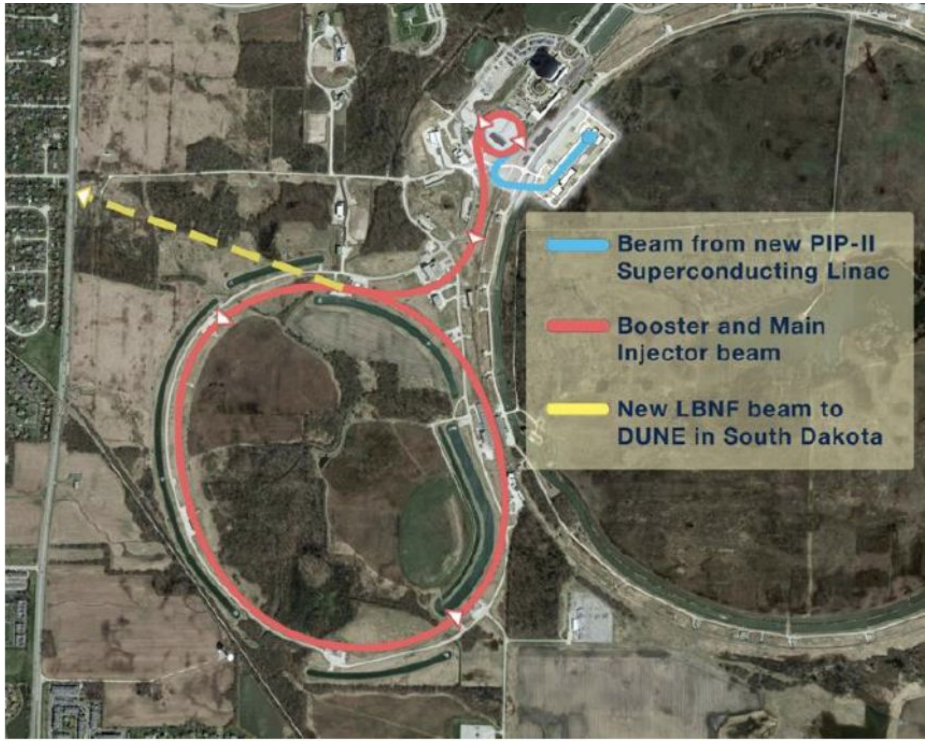
Movable LArTPC Near Detector, muon spectrometer and separate on-axis detector

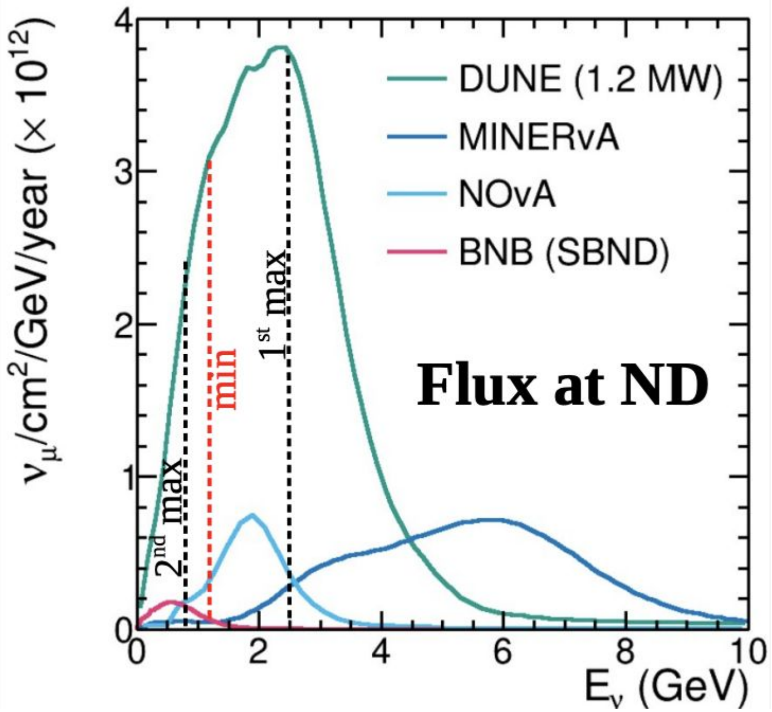


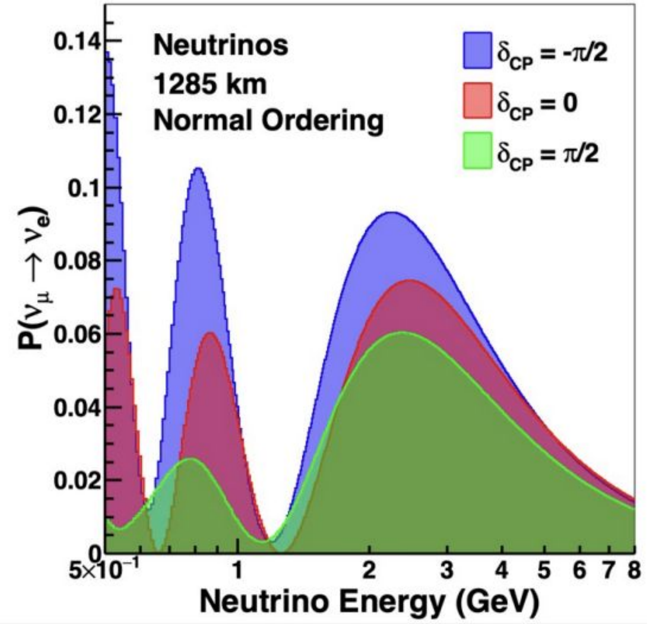
Wideband (anti)neutrino beamline with >2MW intensity



LBNF beamline: world-leading intensity



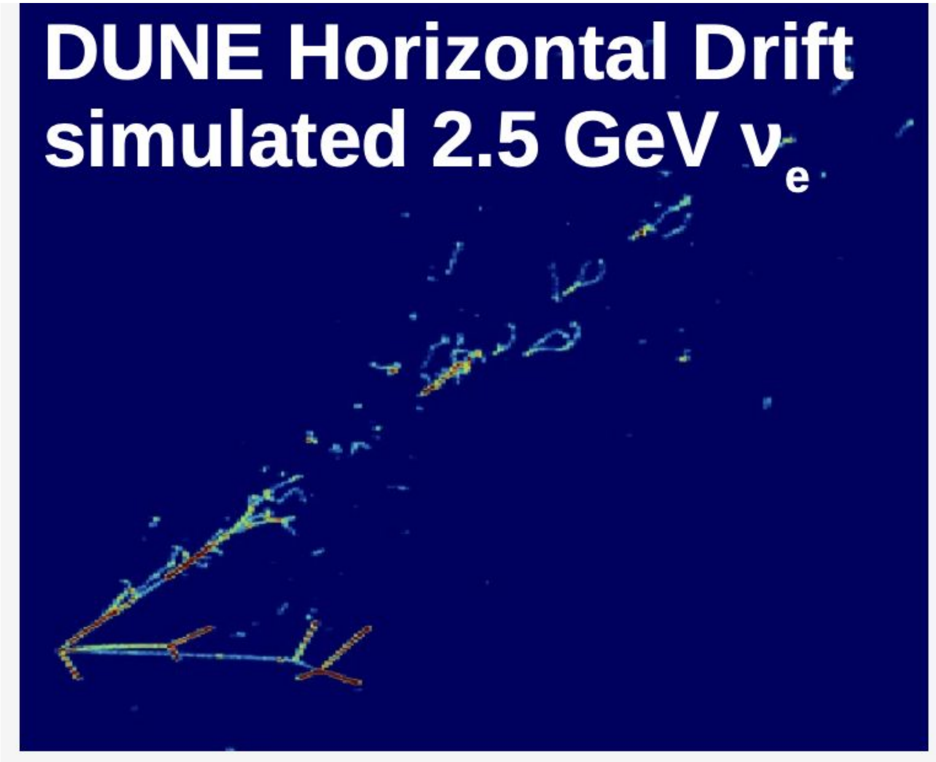


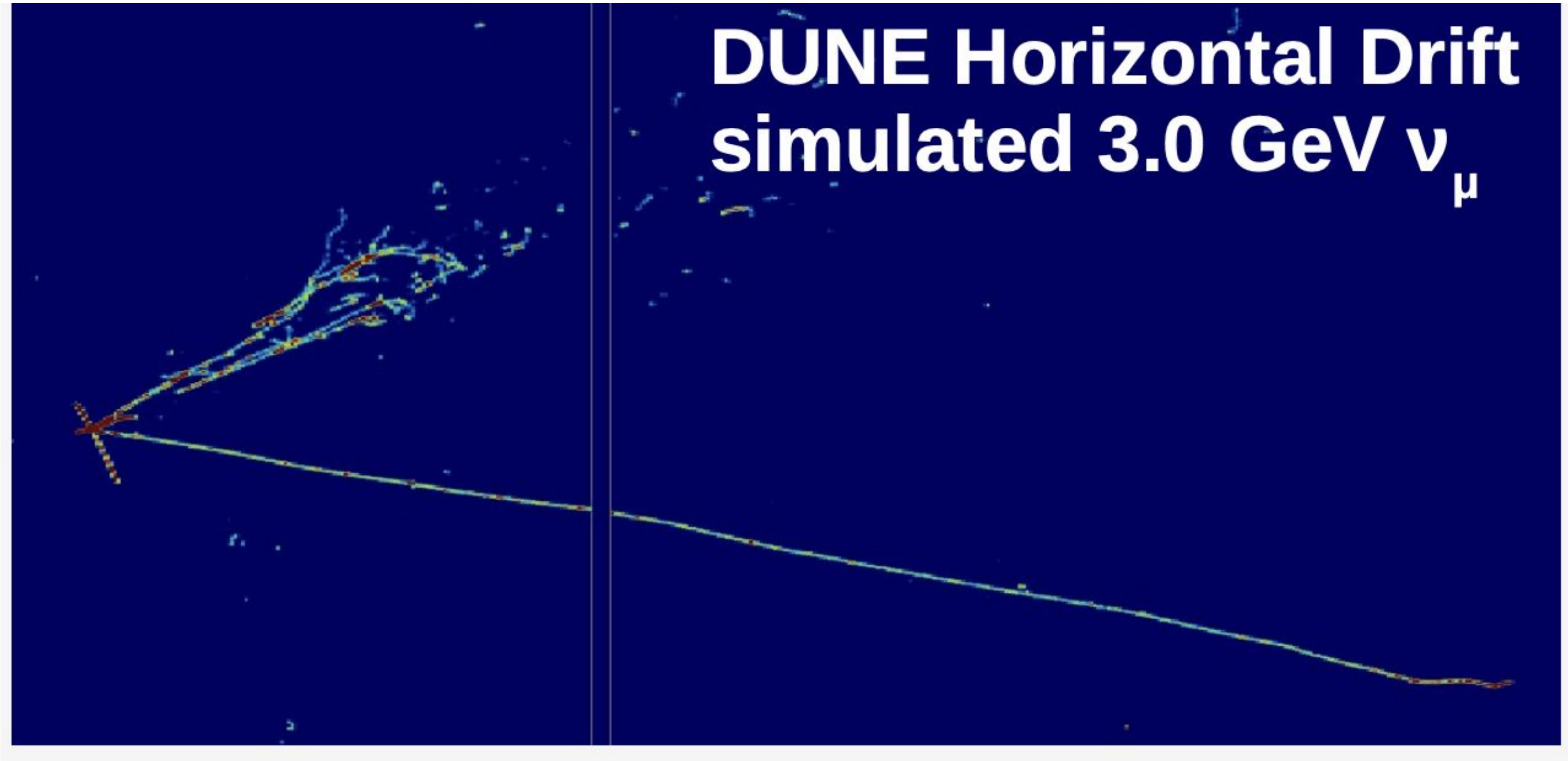


Eur.Phys.J.C 80 (2020) 10, 978

- Very high flux between oscillation minimum and maximum, with coverage of second maximum
- Proton Improvement Plan-II (PIP-II) is ongoing - 1.2 MW
- ACE-MIRT upgrade enables >2MW beam by ~doubling frequency of spills

LArTPCs:

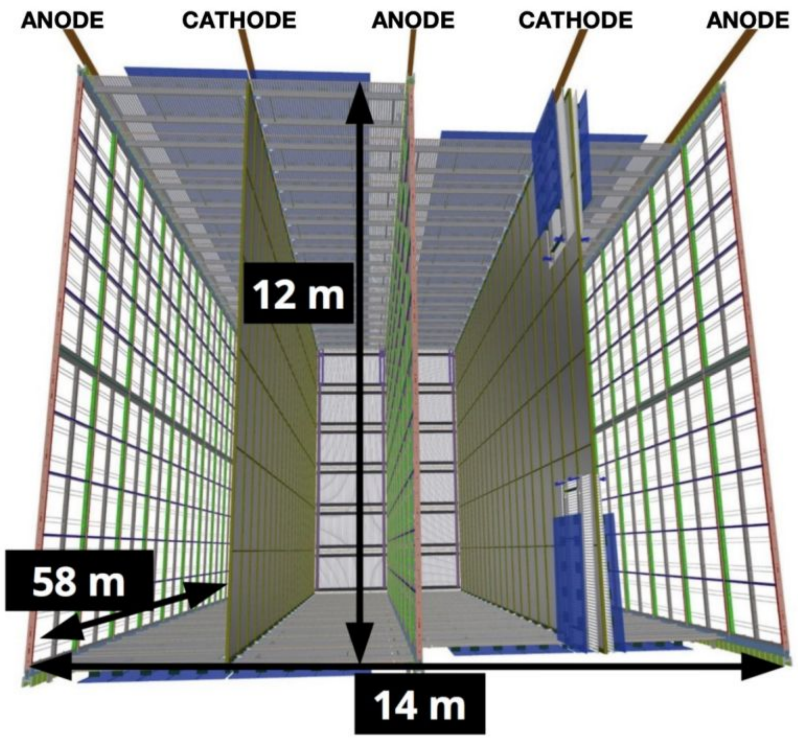




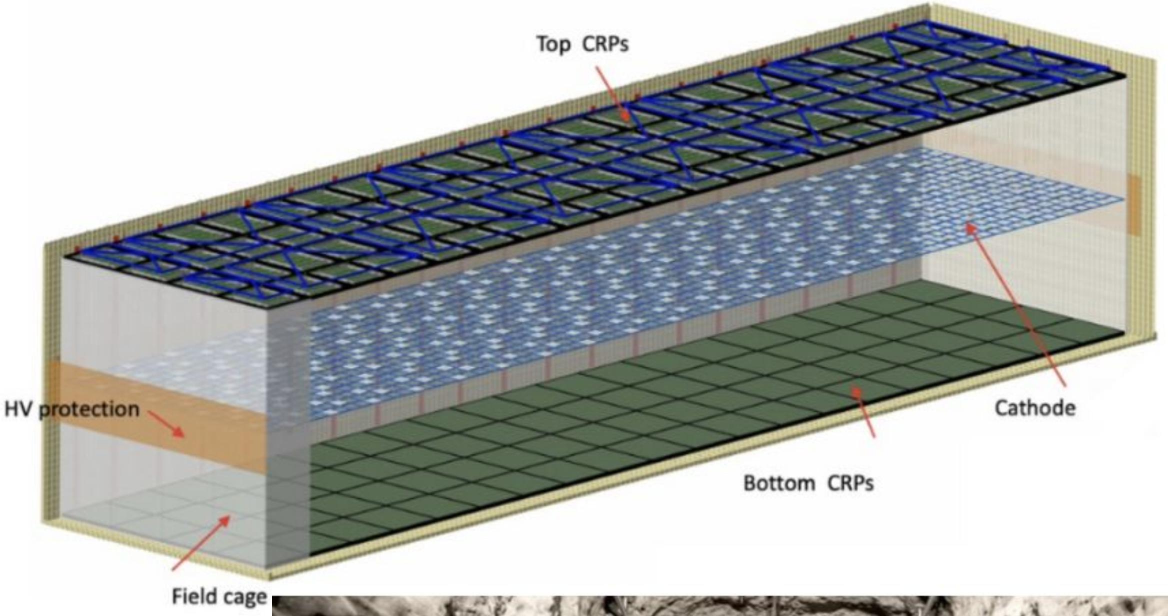
- Excellent imaging for neutrino flavor ID and energy reconstruction with high resolution
- Low thresholds for charged particles enable precise reconstruction of lepton and hadronic energy over a broad energy range

Far Detector:

JINST 15 T08010 (2020)



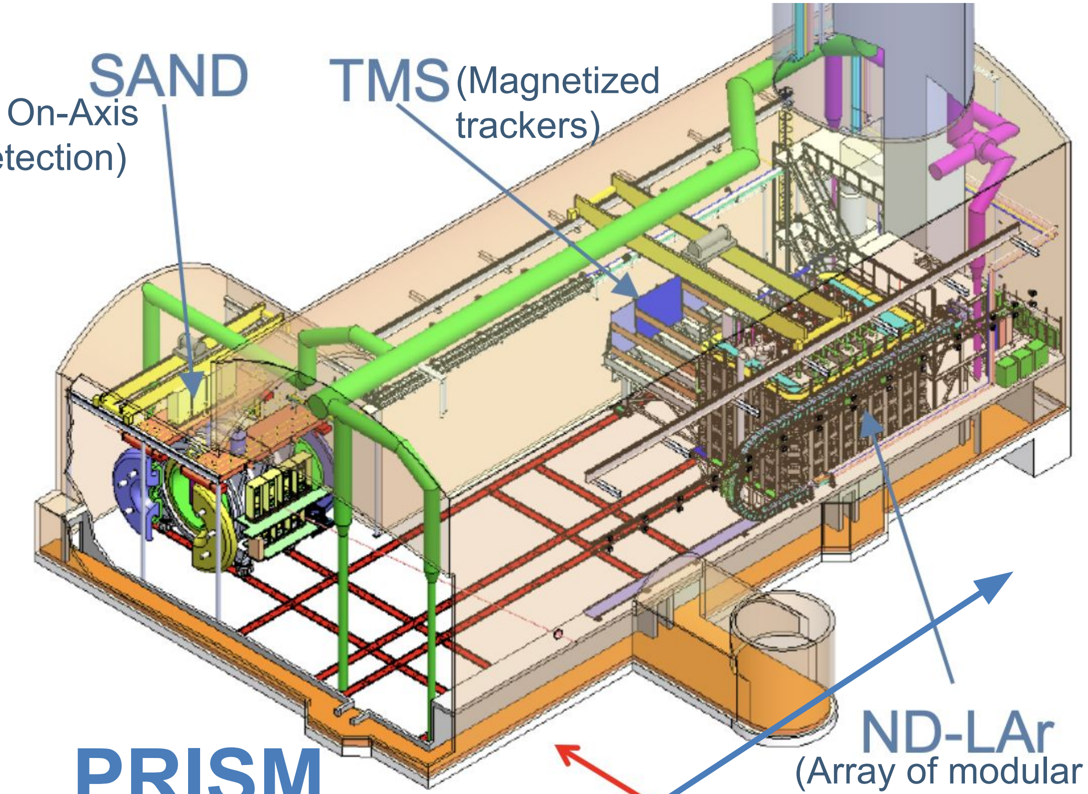
arxiv.org/abs/2312.03130(2023)



- Horizontal drift using wire readout planes, four drift regions (3.5m)
- Vertical drift (VD, right) using two 6.25m drift regions and central cathode
    - Simpler to install → first DUNE FD module will use vertical drift
    - VD is baseline design for modules 3 and 4

Near Detector:

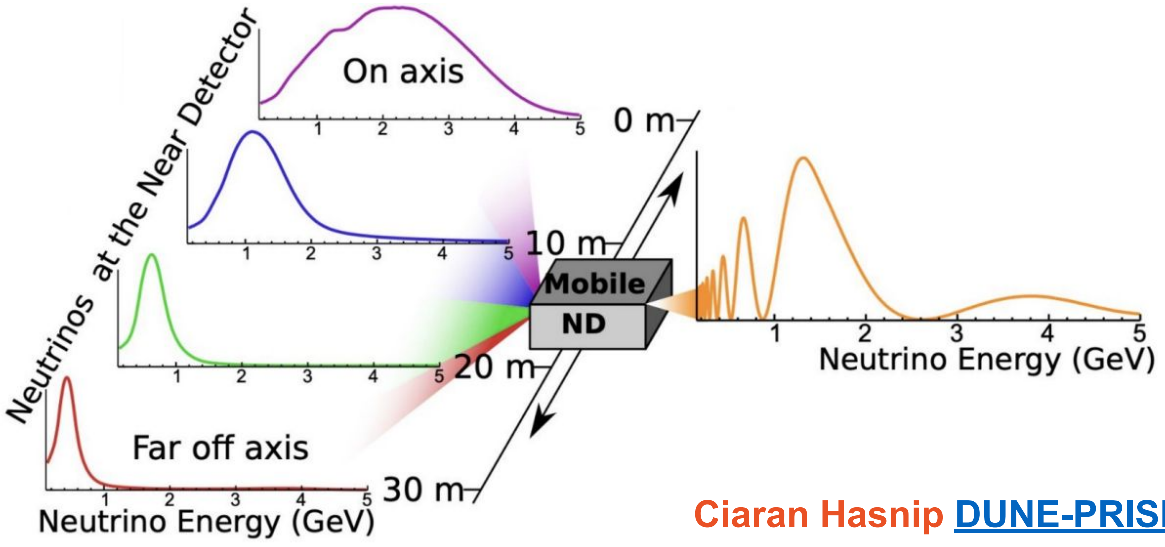
- A suite of near detectors designed to robustly constrain systematics and achieve required sensitivities
- Enables prediction of Far Detector reconstructed spectra
- Off-axis data in different neutrino fluxes constrains energy dependence of neutrino cross sections



PRISM

System for moving the LArTPC and tracker up to 30m transverse to the beam

ND hall: 574 m downstream from target



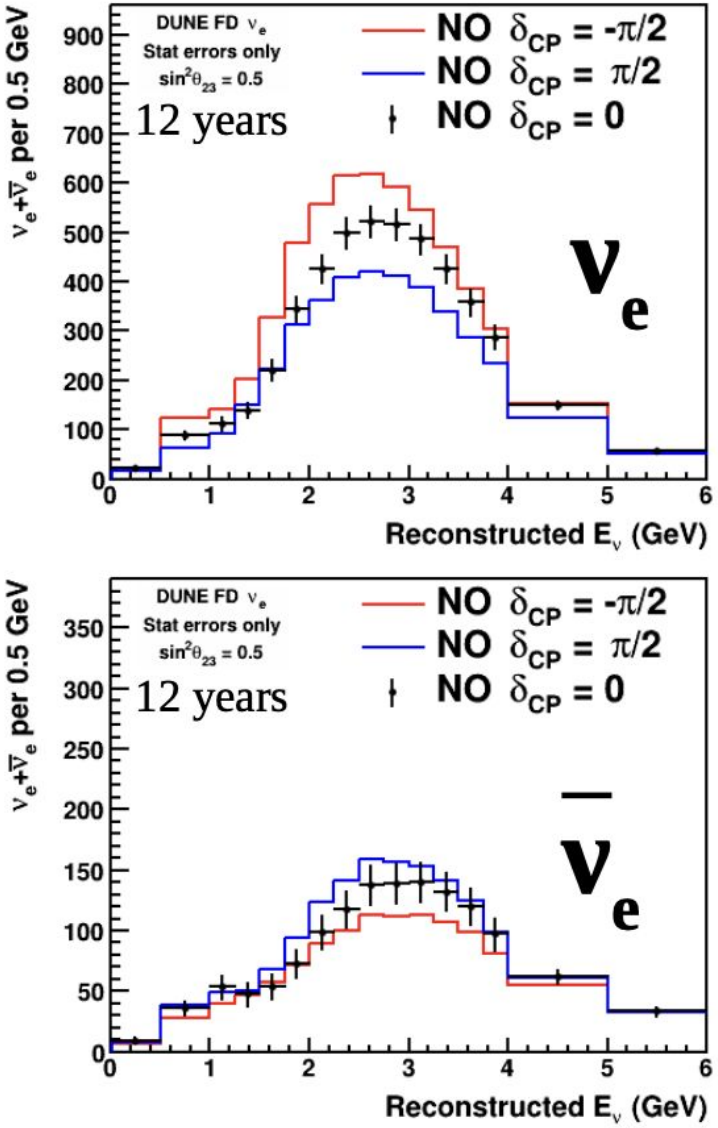
Ciaran Hasnip DUNE-PRISM

~60 interactions / 1.2 MW spill

Fermilab DUNE

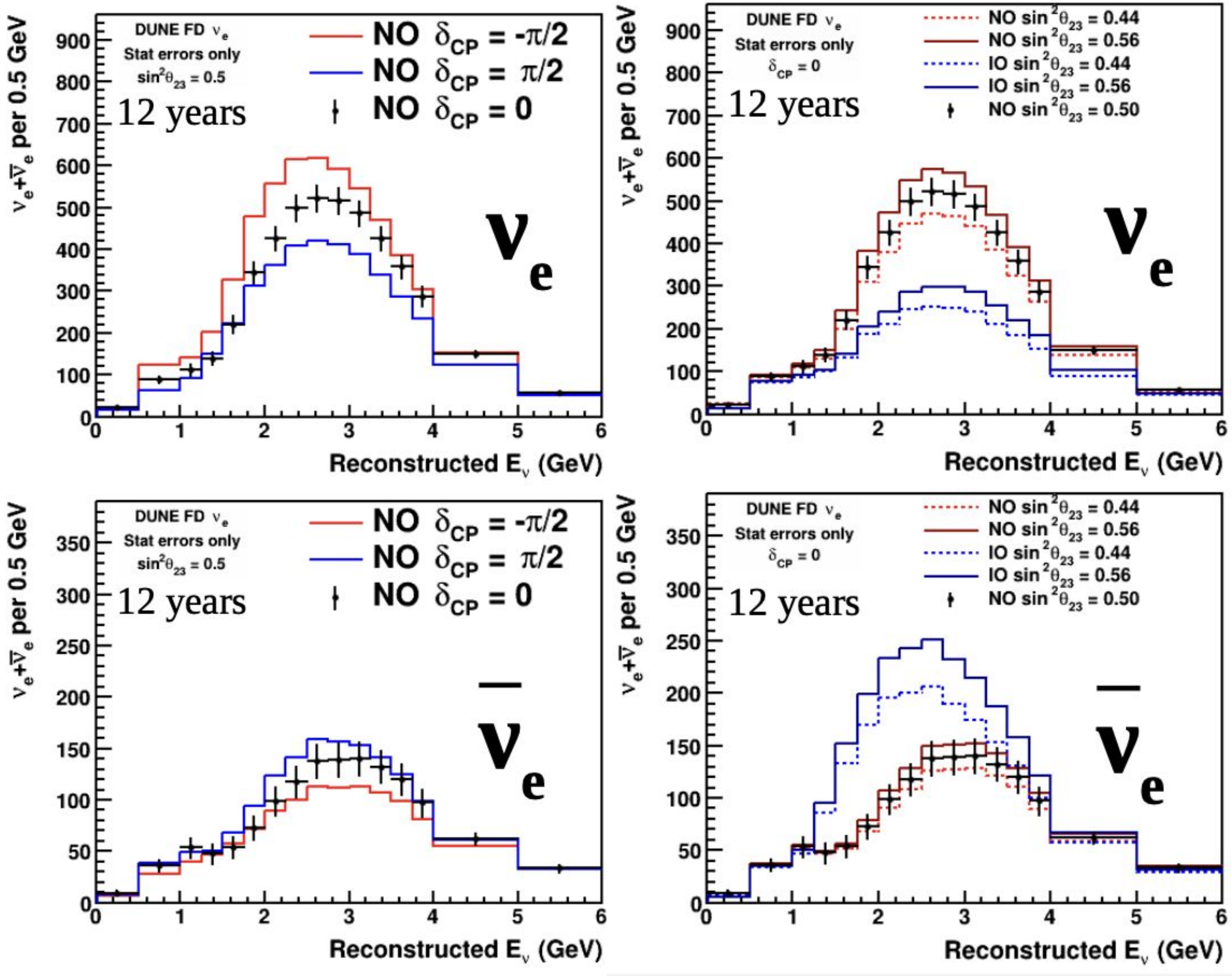
Neutrino energy spectra at the Far Detector

- **Sensitivity to δ_{CP}**
  - If δ_{CP} ~ -π/2, enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance



Neutrino energy spectra at the Far Detector

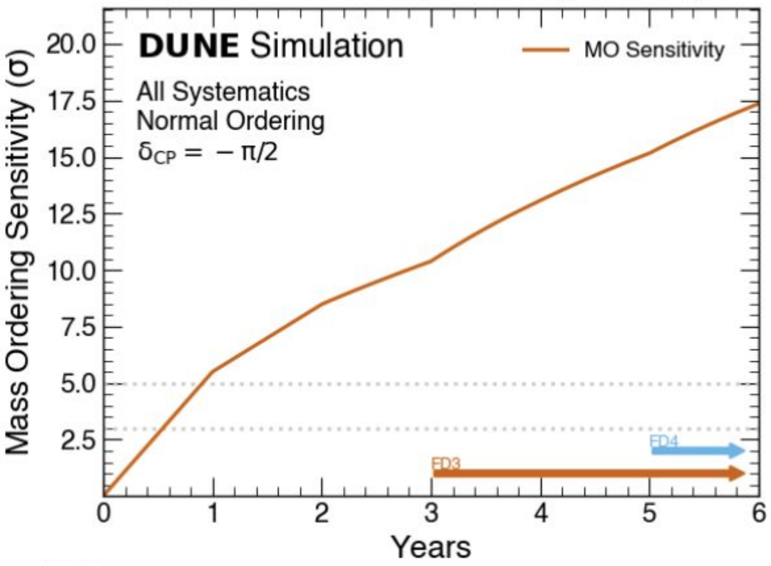
- **Sensitivity to δ_{CP}**
  - If δ_{CP} ~ -π/2, enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance
- **Sensitivity to mass ordering (MO)**
  - If MO is normal, a much larger enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance
- MO, δ_{CP}, and θ_{23} all affect spectra with different shape → additional handle on resolving degeneracies

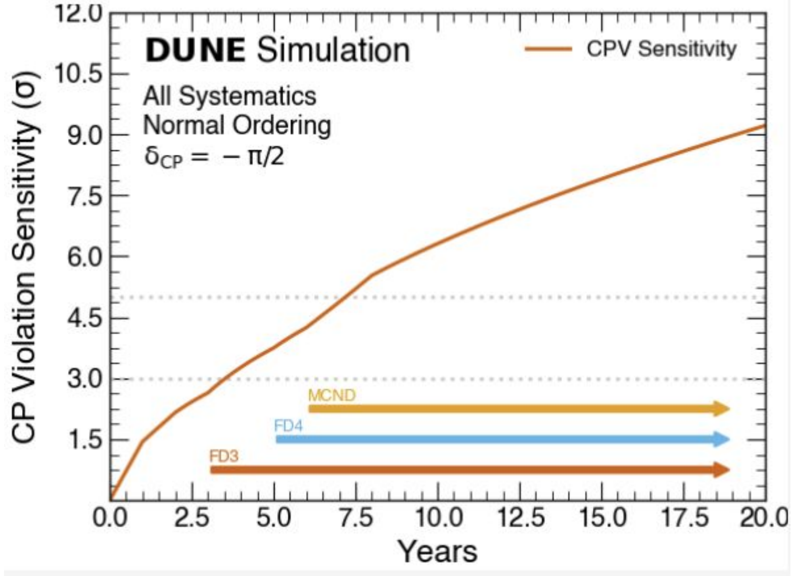


DUNE Sensitivity:

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

- δ_{CP} = -π/2
  - >5σ mass ordering sensitivity in 1 year
  - >3σ CPV sensitivity in 3.5 years



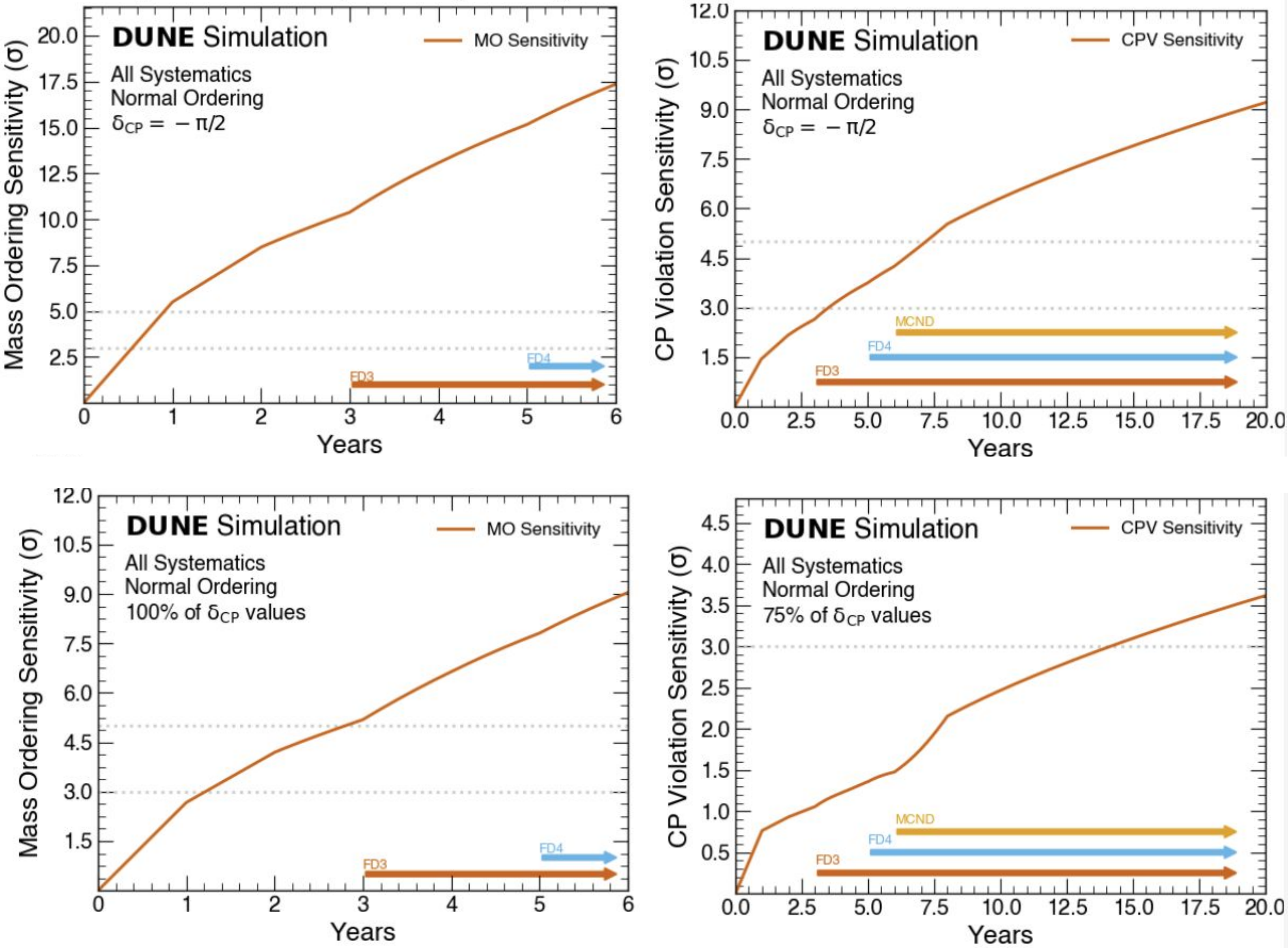


Fermilab DUNE

DUNE Sensitivity:

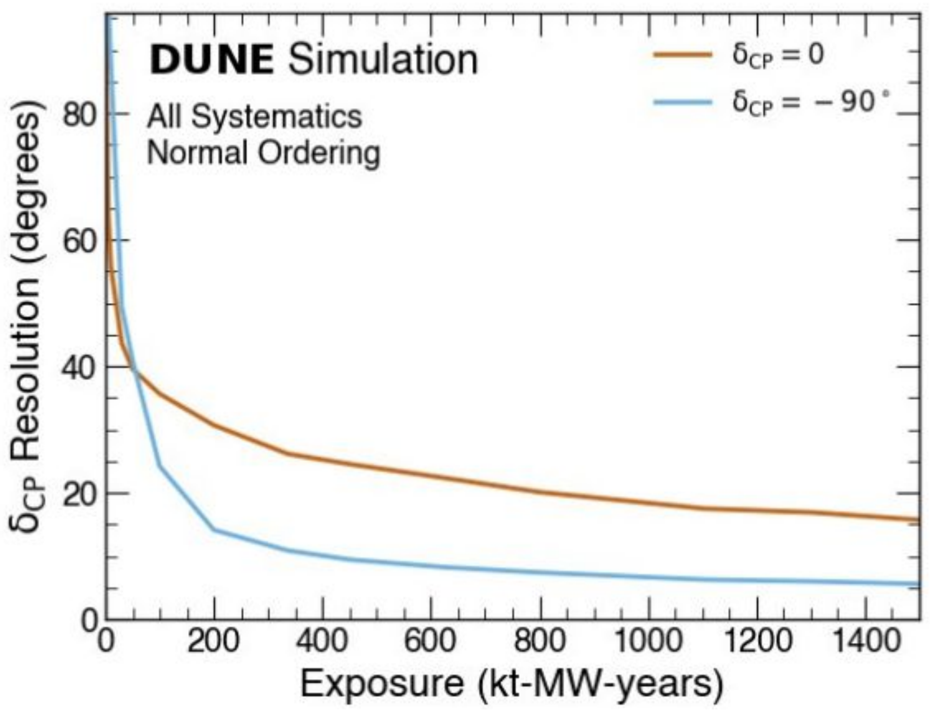
Eur. Phys. J. C 80, 978 (2020)

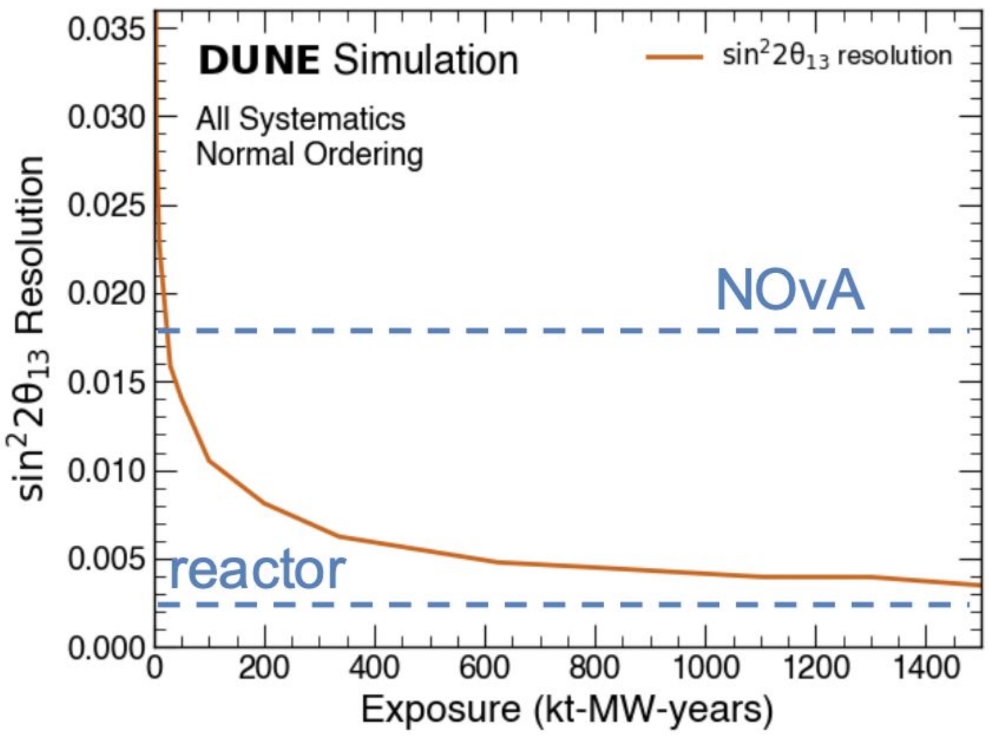
- δ_{CP} = -π/2
  - >5σ mass ordering sensitivity in 1 year
  - >3σ CPV sensitivity in 3.5 years
- All possible δ_{CP} values
  - >5σ mass ordering sensitivity in 3 years
- long term
  - DUNE can establish CPV over 75% of δ_{CP} values at >3σ



DUNE: precise measurements

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

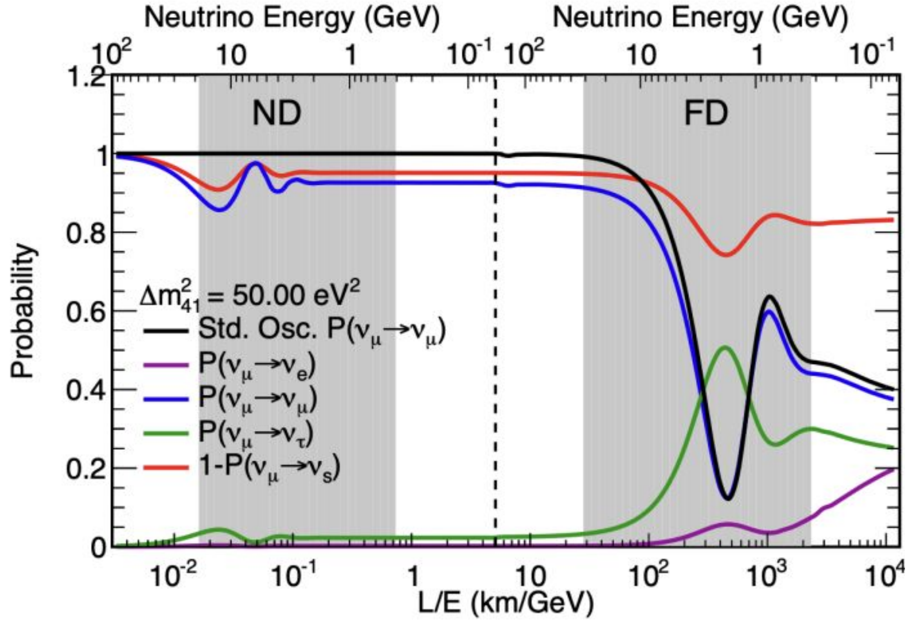


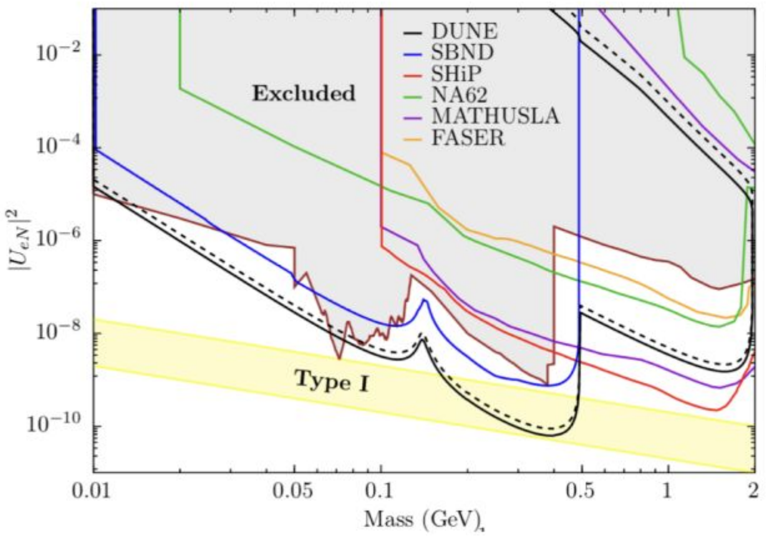


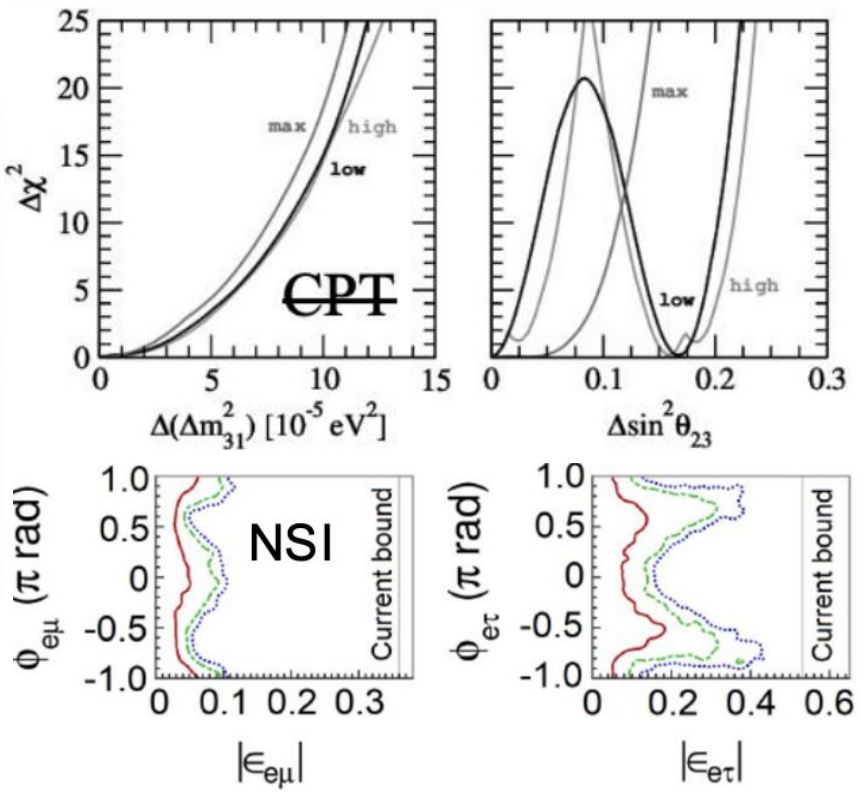
- Ultimate precision 6-16° in δ_{CP}
- World-leading precision (for long-baseline experiment) in θ_{13} and Δm^2 → comparisons with reactor measurements are sensitive to new physics

Beyond three flavors

[Eur. Phys. J. C 81, 322 (2021)]

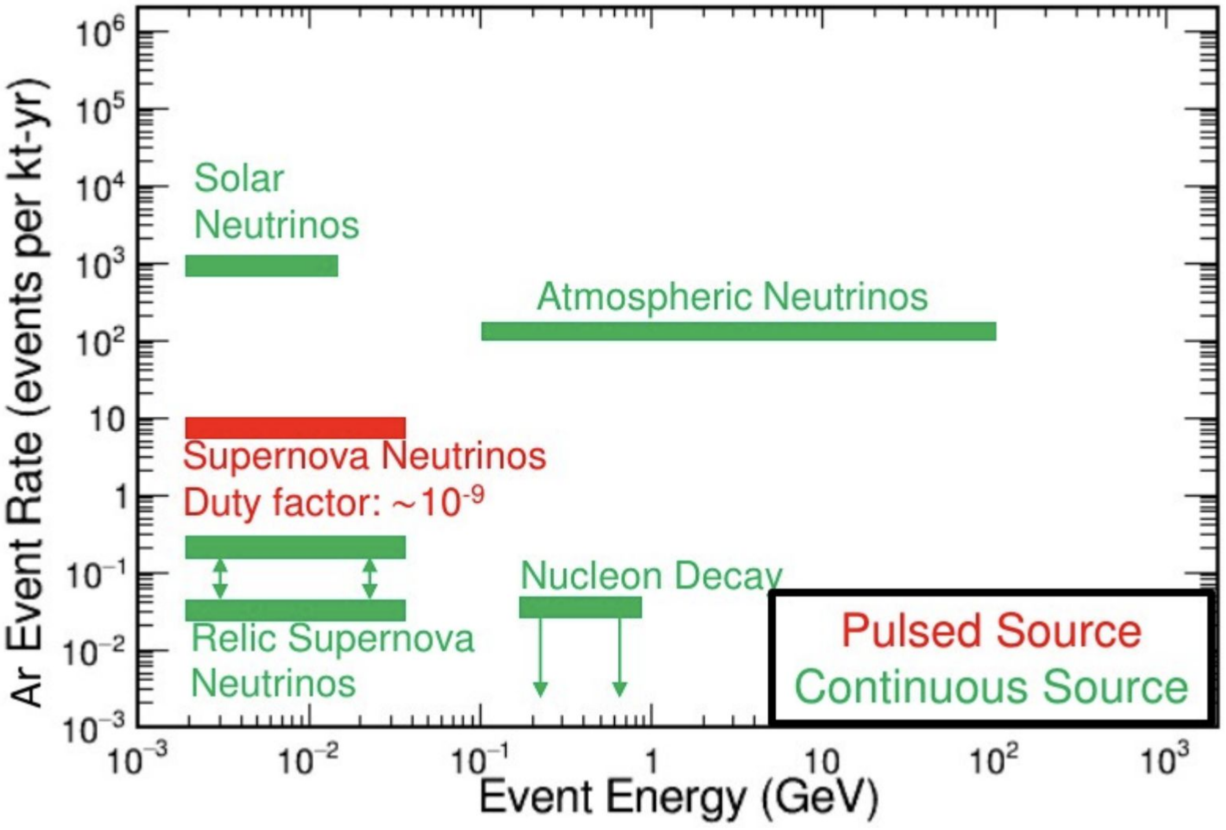






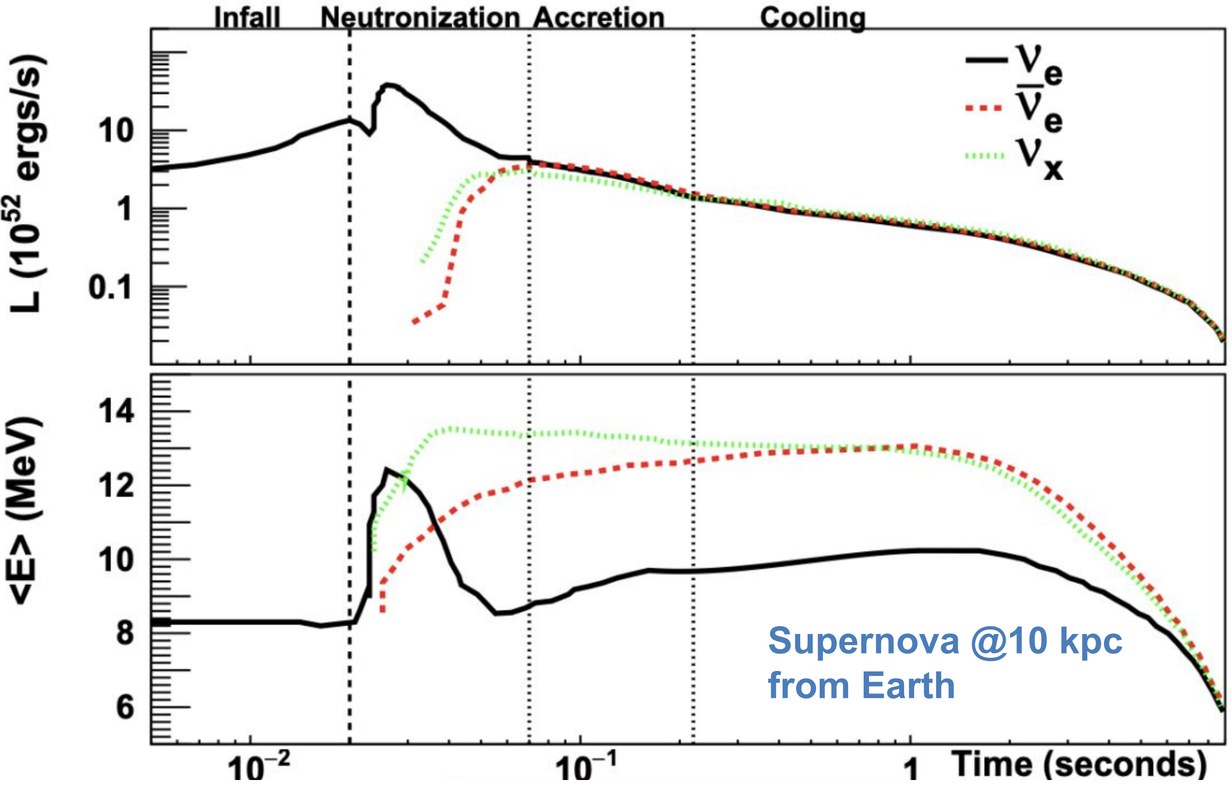
- Broad range of L/E at ND and FD → search for non-SM oscillations
- High statistics neutrino and antineutrino measurements → search for CPT violation
- Very large matter effect → unique sensitivity to some non-standard neutrino interactions (NSI)

DUNE FD: Neutrinos from beyond



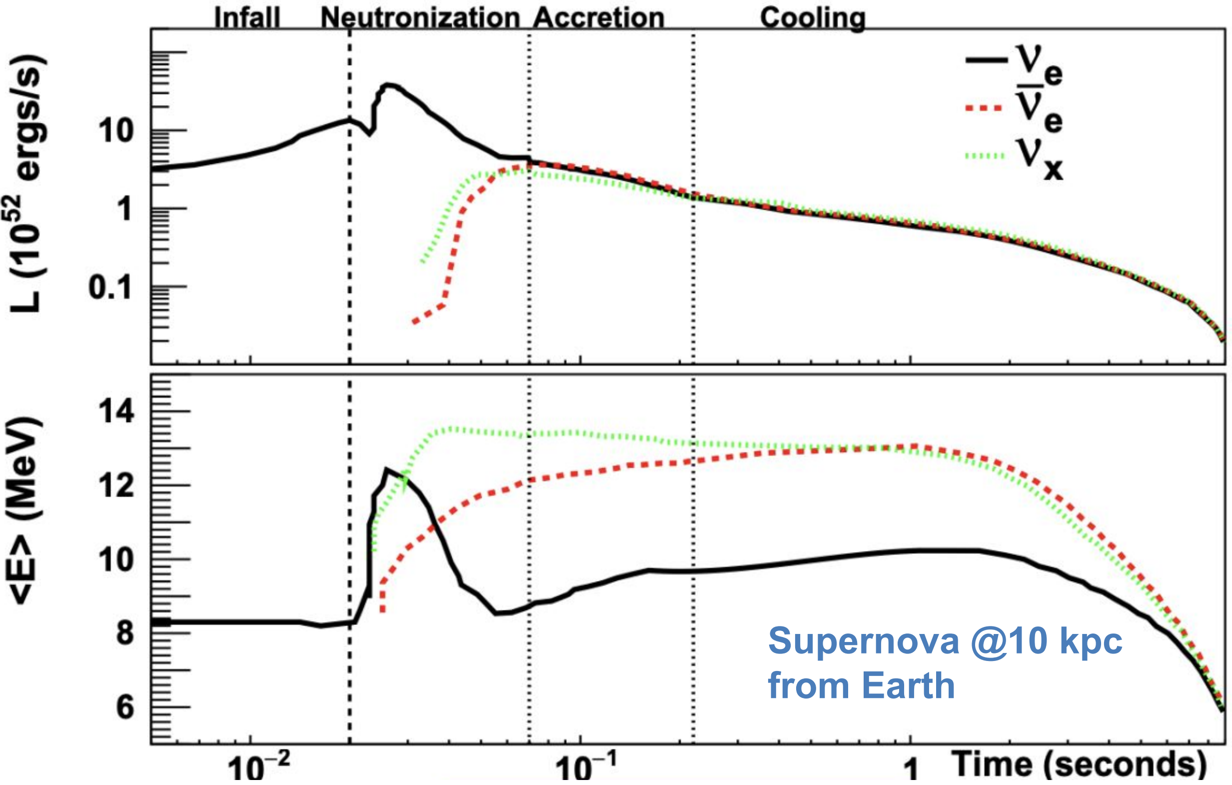
- Atmospheric, solar, and supernova neutrinos
- Unique sensitivity to MeV electron neutrinos:
  - $\nu_e + Ar \rightarrow e^- + 40K^*$ ($E_\nu > 1.5$ MeV)
  - $\bar{\nu}_e + Ar \rightarrow e^+ + 40Cl^*$ ($E_\nu > 7.5$ MeV)
  - $\nu_x + e^- \rightarrow \nu_x + e^-$
- Highly complementary to Hyper-K, JUNO that predominantly see $\bar{\nu}_e$ via IBD

DUNE FD: Neutrinos core-collapse supernovae

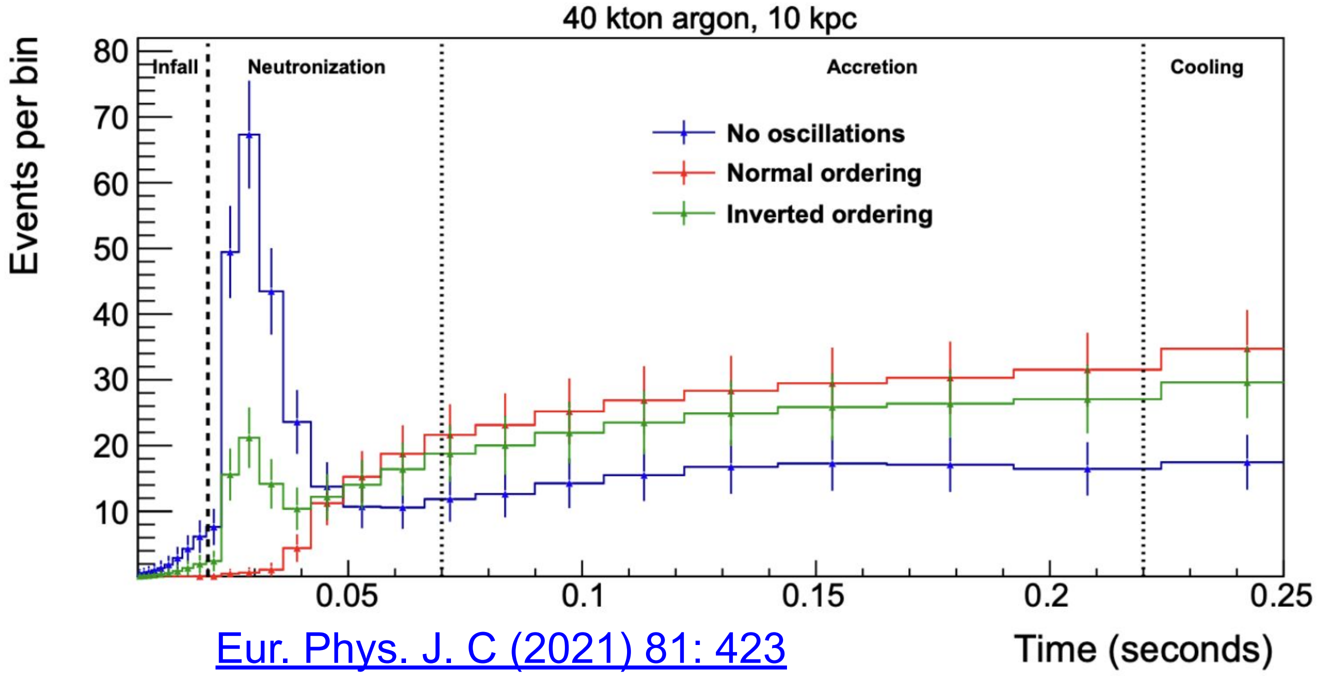


- DUNE will observe ~thousands of neutrino interactions from a galactic supernova burst
- Time and energy spectra are sensitive to core collapse mechanism and stellar evolution

DUNE FD: Neutrinos core-collapse supernovae



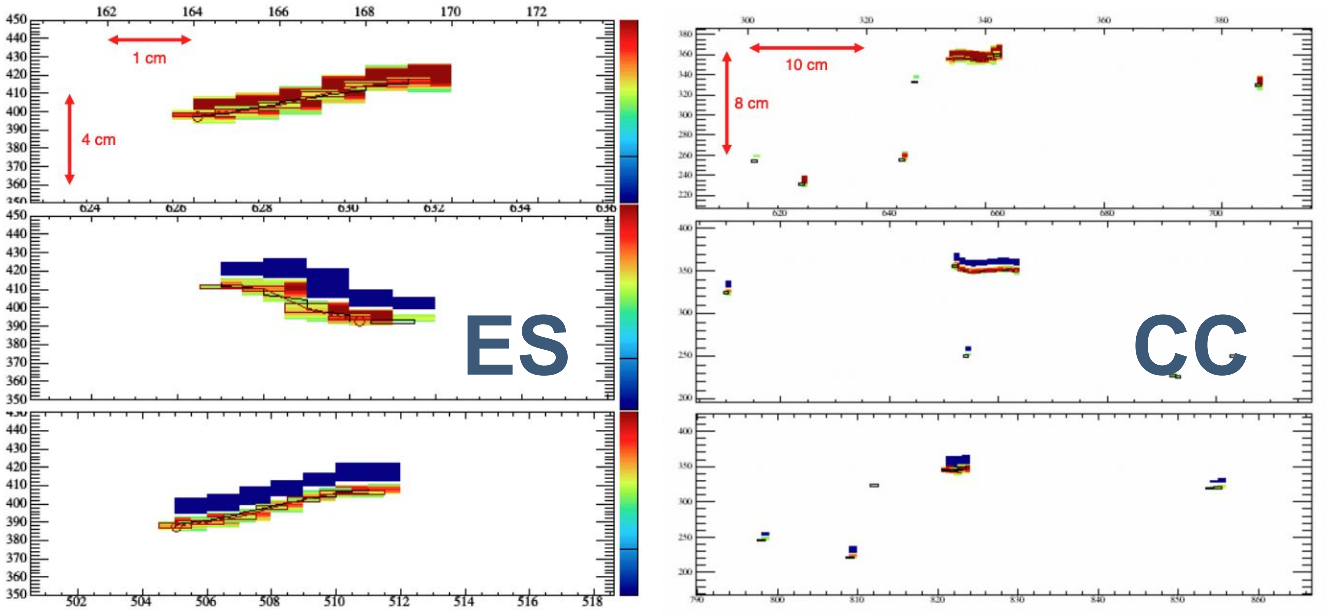
- DUNE will observe ~thousands of neutrino interactions from a galactic supernova burst
- Time and energy spectra are sensitive to core collapse mechanism and stellar evolution



[Eur. Phys. J. C (2021) 81: 423]

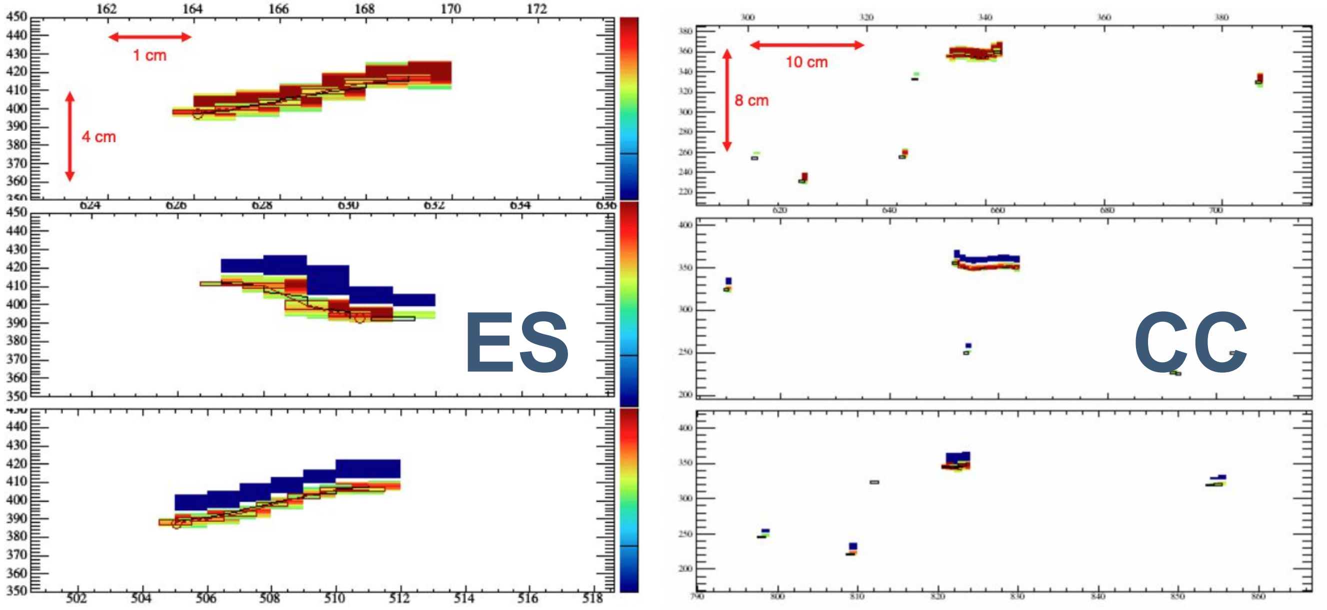
- Neutronization burst measurements → mass ordering measurement

DUNE FD: Neutrinos core-collapse supernovae

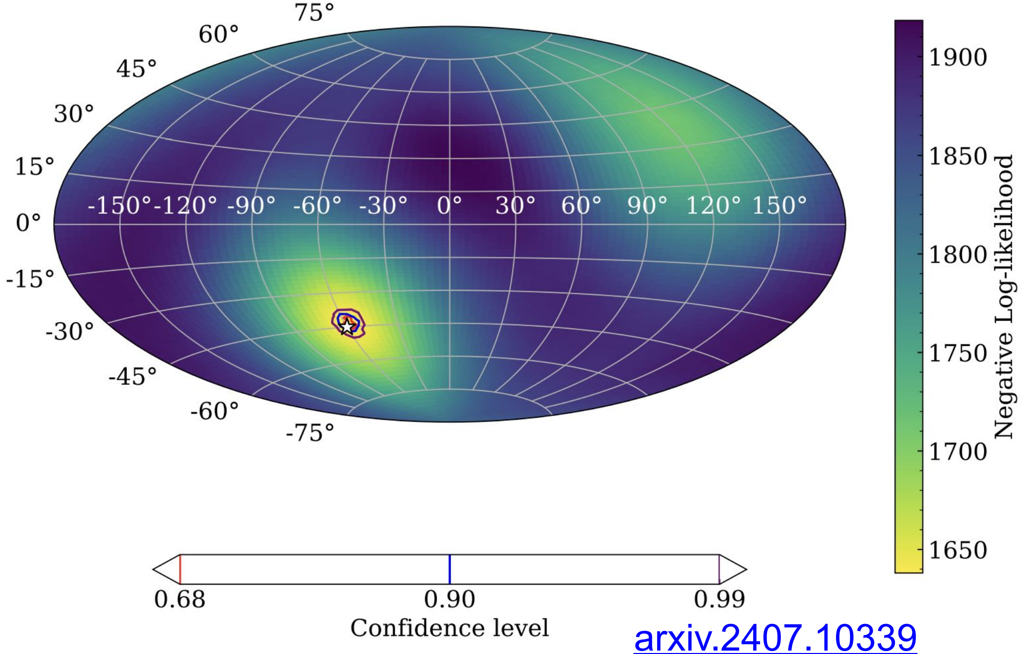


- **CC: ν_e + Ar → e$^-$ + 40K*** (~ 3k events @10 kpc)
- **ES: ν_e + e$^-$ → ν_e + e$^-$** (~ 0.3k events @10 kpc)

DUNE FD: Neutrinos core-collapse supernovae



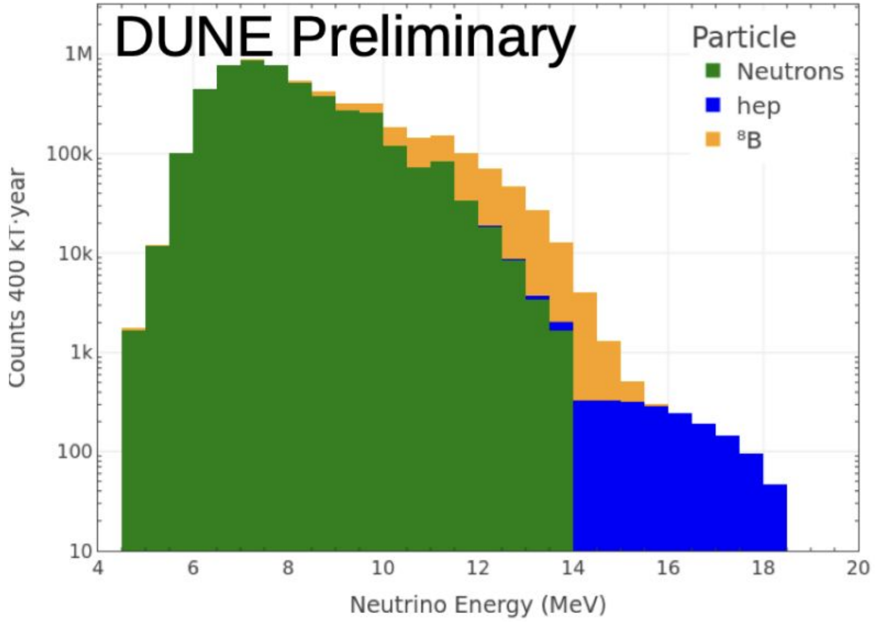
- **CC: ν_e + Ar → e$^-$ + 40K*** (~ 3k events @10 kpc)
- **ES: ν_e + e$^-$ → ν_e + e$^-$** (~ 0.3k events @10 kpc)

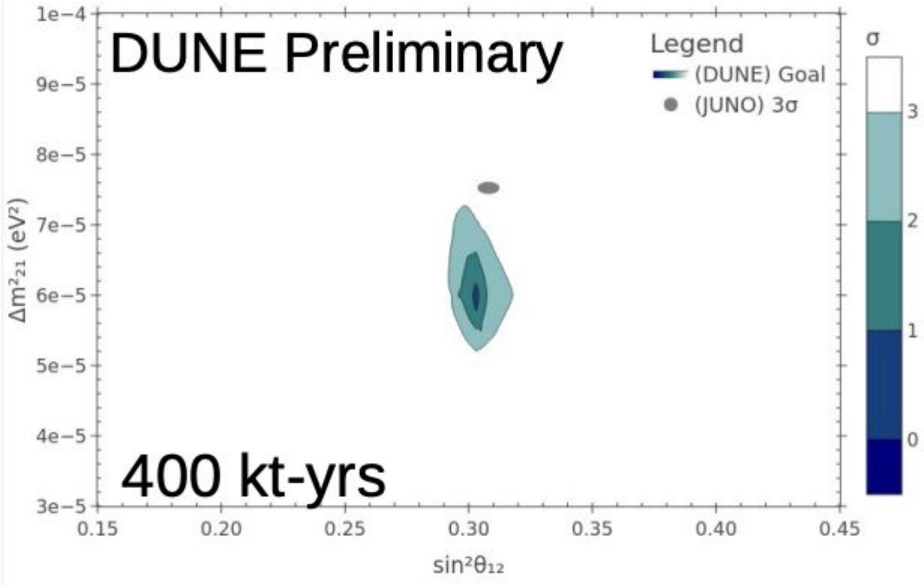


[arxiv.2407.10339](https://arxiv.org/abs/2407.10339)

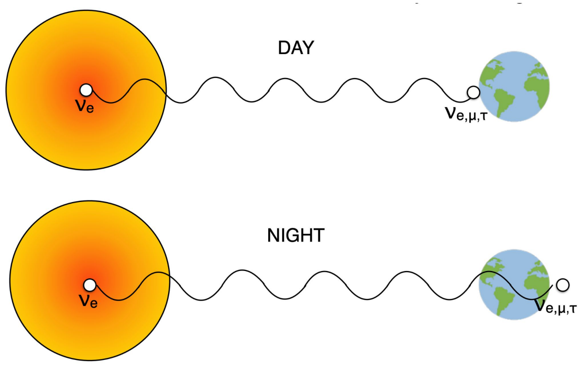
Channel tagging ν+e → ν+e enables ~5° pointing resolution (40 kt, 10 kpc)

DUNE FD: Neutrinos from the sun





- Excellent sensitivity to ^{8}B solar neutrinos above ~10 MeV
- Discovery sensitivity to the hep solar flux
  - ^{3}He + p → ^{4}He + e$^+$ + ν_e (hep)
- Improvement upon existing solar oscillation measurements
  - Day-night asymmetry induced by matter effects → comparison with JUNO



DUNE Phase I:

- DUNE Phase I
  - Full near + far site facility and infrastructure
  - Two 17 kt LArTPC modules
  - Upgradeable 1.2 MW neutrino beamline
  - Movable LArTPC near detector with muon catcher

2026 — Detector installation

2029 — Physics w/ Far Detector
Natural neutrino sources

2031 — Beam + Near Detector

Recommendation 1: As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science.

b. The first phase of DUNE and PIP-II to open an era of precision neutrino measurements that include the determination of the mass ordering among neutrinos. Knowledge of this fundamental property is a crucial input to cosmology and nuclear science (elucidate the mysteries of neutrinos, section 3.1)

DUNE Phase II:

- Two additional FD modules (≥40 kt fiducial in total)
- Beamline upgrade to >2 MW (ACE-MIRT)
- More capable Near Detector (ND-GAr)
- P5 report endorses FD3, ACE-MIRT, and MCND in the next decade, and R&D toward FD4

Recommendation 2: Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

A re-envisioned second phase of DUNE with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT— a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind (section 3.1).

Conduct R&D efforts to define and enable new projects in the next decade, including detectors for an e+e– Higgs factory and 10 TeV pCM collider, Spec-S5, DUNE FD4, Mu2e-II, Advanced Muon Facility, and line intensity mapping

DUNE: Construction Schedule

2024	2025	2025-26	2026-27	2028	2029	2031
Far site excavation	Building & Site Infrastructure work until mid-2025	Cryostat warm structure on its way to US from CERN to be installed	Far detector installation	Purge and fill with argon	Physics w/ Far Detector Natural neutrino sources	Beam + Near Detector

DUNE: Construction Schedule

- **2024** — Far site excavation
- **2025** — Building & Site Infrastructure work until mid-2025
- **2025-26** — Cryostat warm structure on its way to US from CERN to be installed
- **2026-27** — Far detector installation
- **2028** — Purge and fill with argon
- **2029** — Physics w/ Far Detector Natural neutrino sources
- **2031** — Beam + Near Detector

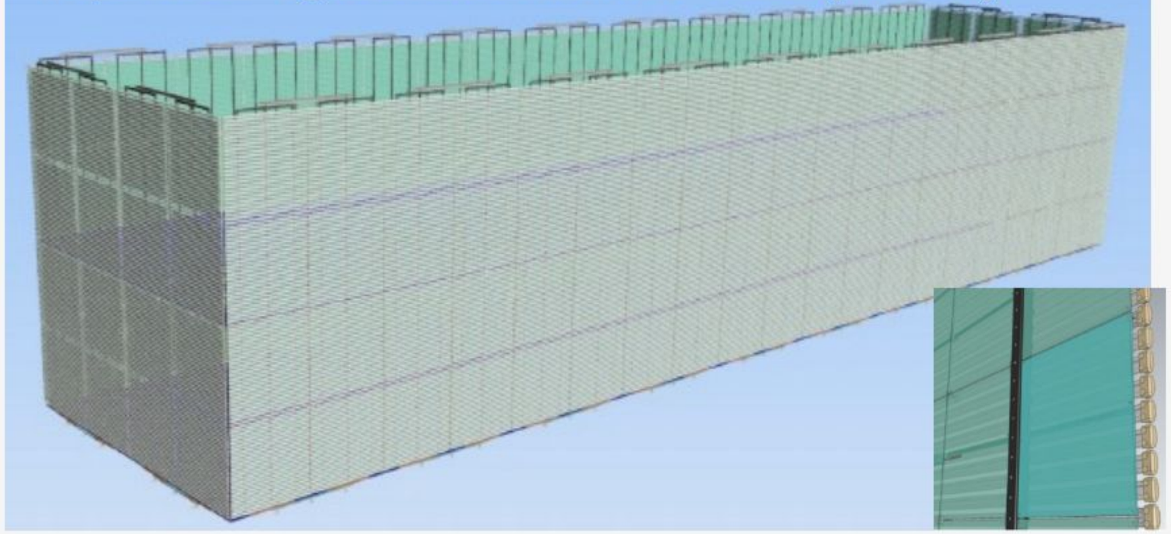
DUNE Phase II Detector R&D:

Diana Leon Silverio [R&D of Power Over Fiber in harsh environments and its novel application for the DUNE FD-VD Photon Detection System]

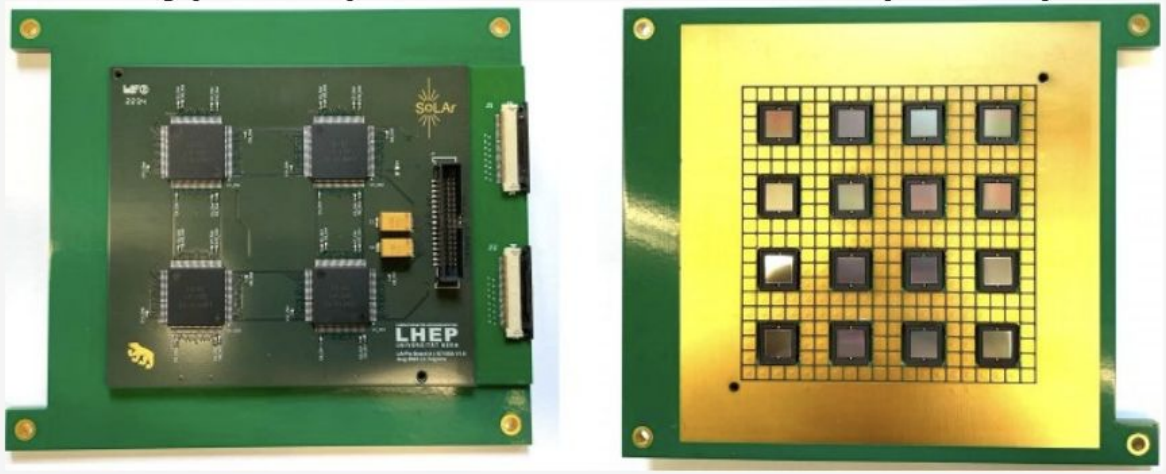
- Vertical Drift module is the baseline design for Phase II FD modules
- Pursuing low-hanging improvements to light collection for FD3, including Aluminum Profiles with Embedded X-ARAPUCA (APEX)
- Phased construction program allows the development of the technology to expand the DUNE physics scope (solar, supernova neutrinos, $0\nu\beta\beta$, dark matter…)
- FD4: "Module of Opportunity"
    - more ambitious designs are being considered, including pixel readout, integrated charge-light readout, low background modules, and nonLAr technologies

Wei Shi [Photon Detection System for DUNE Phase II FD: Physics Prospects and Prototyping Status]

Improved light collection for FD3 (APEX)

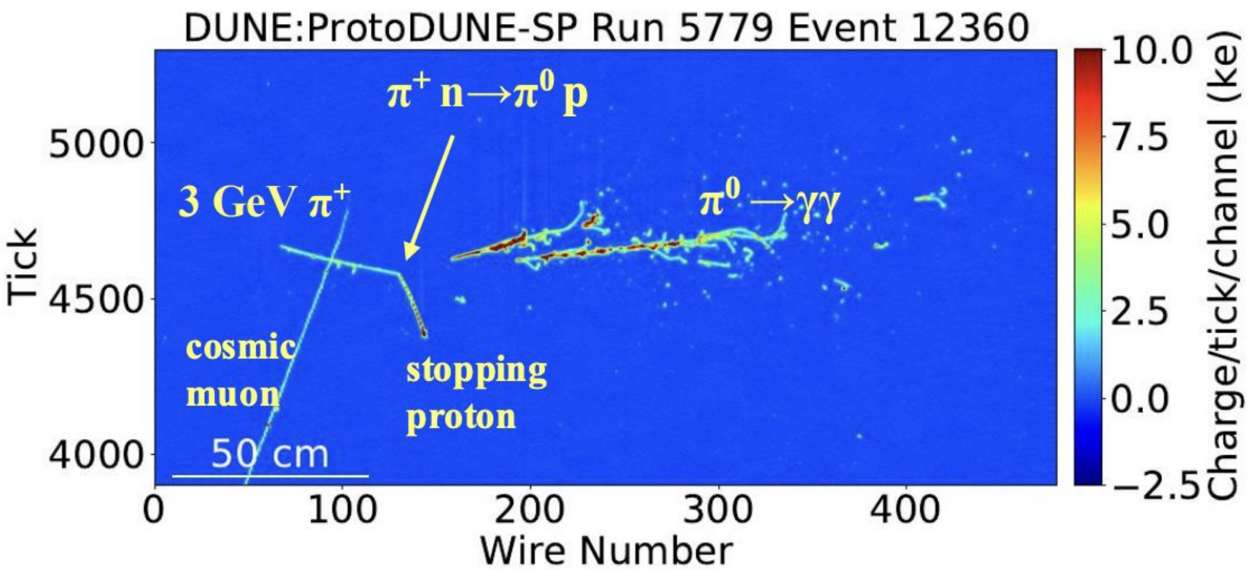


Prototype for possible FD4 readout (SoLAr)

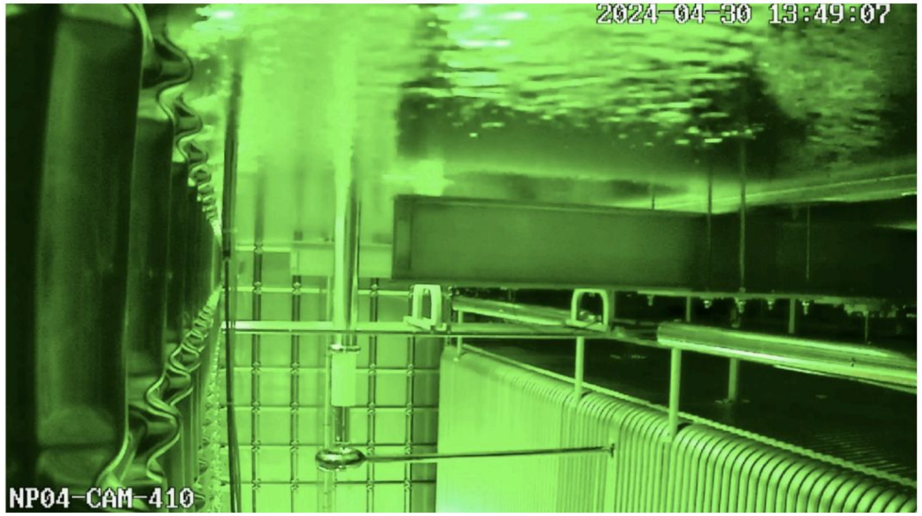


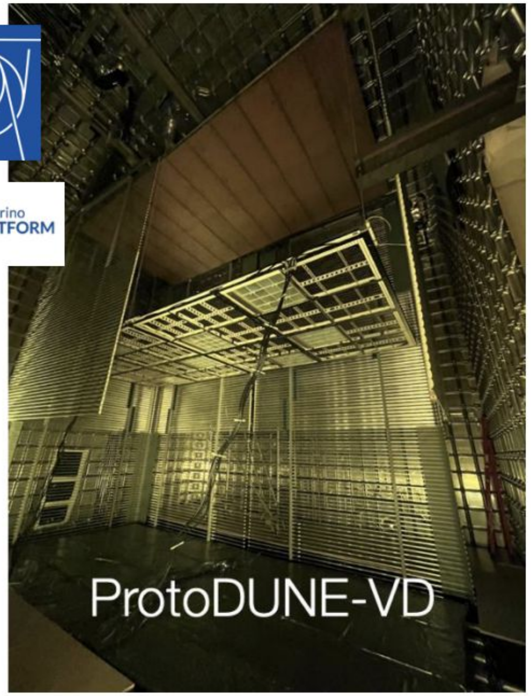
ProtoDUNE:

- Successful prototype of horizontal drift at CERN Neutrino Platform in 2018 (0.77-kt LAr)
- ProtoDUNE-HD: completed filling 30th April, currently taking data
- ProtoDUNE-VD: LAr will be transferred in October for running starting in early 2025



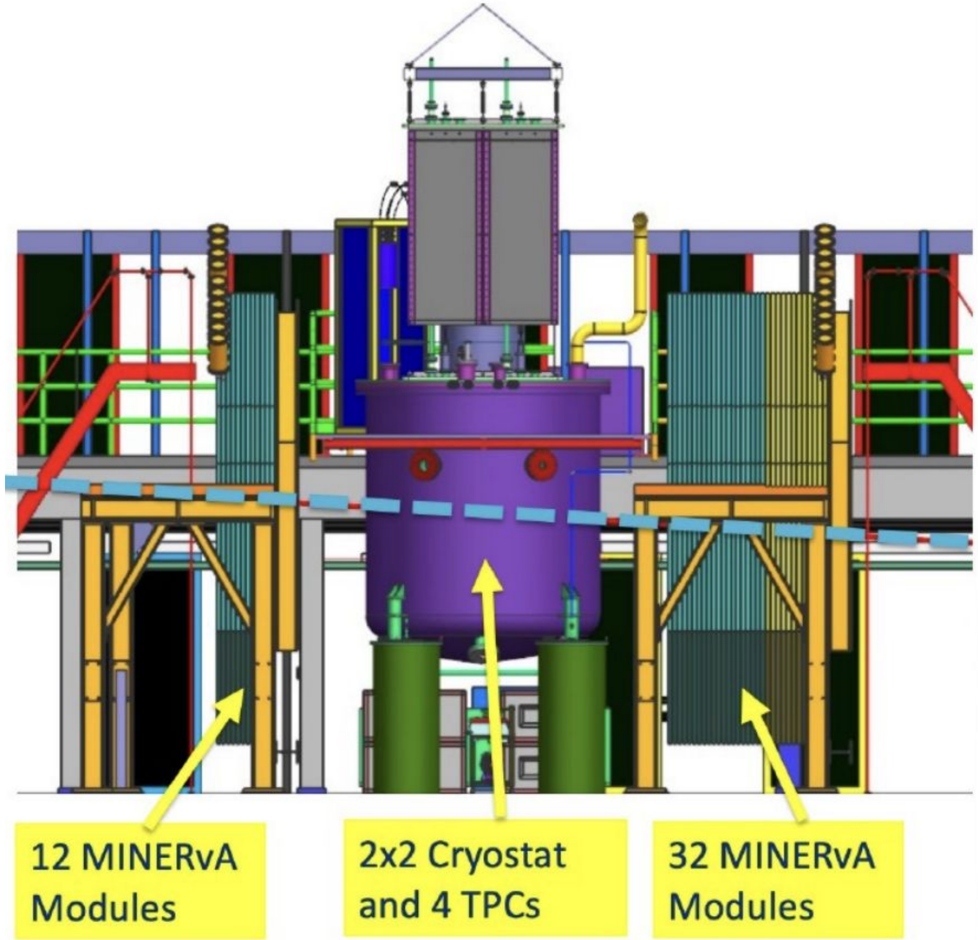
First week of beam : 19th-26th June, > 3M events





ND-LAr 2x2 prototype:

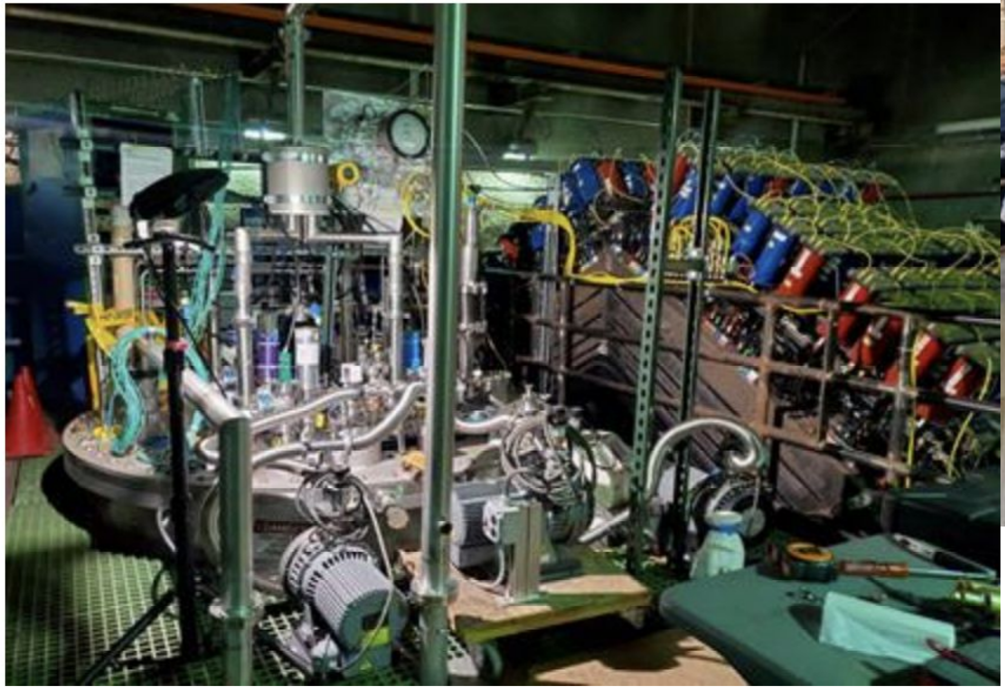
- “2x2” is a four LArTPC modules (at ~ 60% scale) integration test in the Fermilab NuMI beam
- Modules built and operated in LAr in Bern with a total of ~330k pixel channels
- Re-purposed MINERvA scintillator and calorimeter planes mimic the role of TMS in the DUNE ND
- Goals: Demonstrate reconstruction with natively 3D readout in a neutrino beam with similar event rate to DUNE

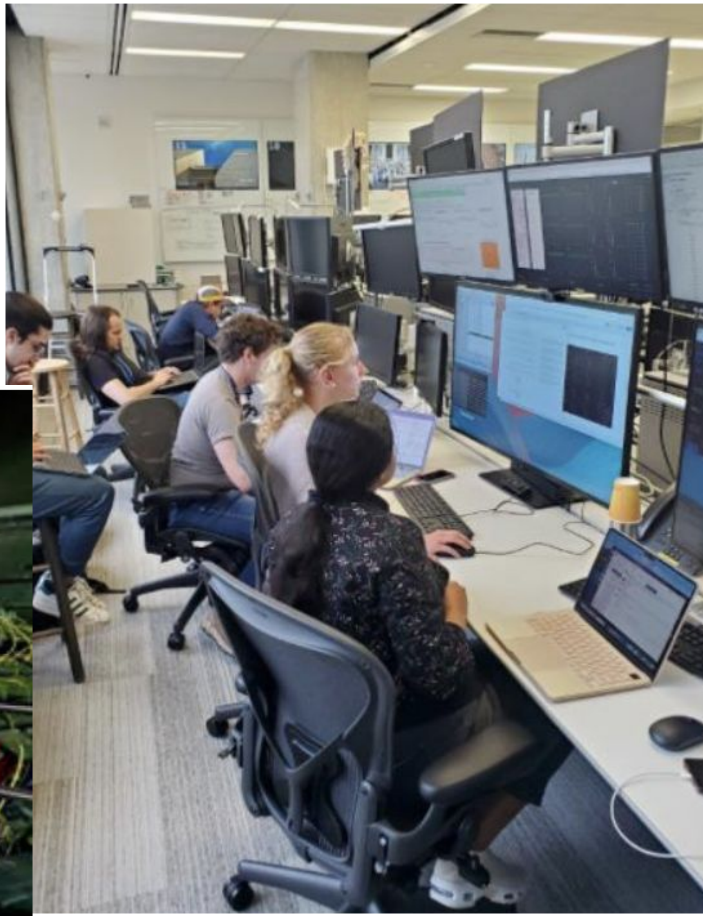


Jessie Micallef [Machine Learning Reconstruction for DUNE’s Near Detector Prototype]

ND-LAr 2x2 prototype:

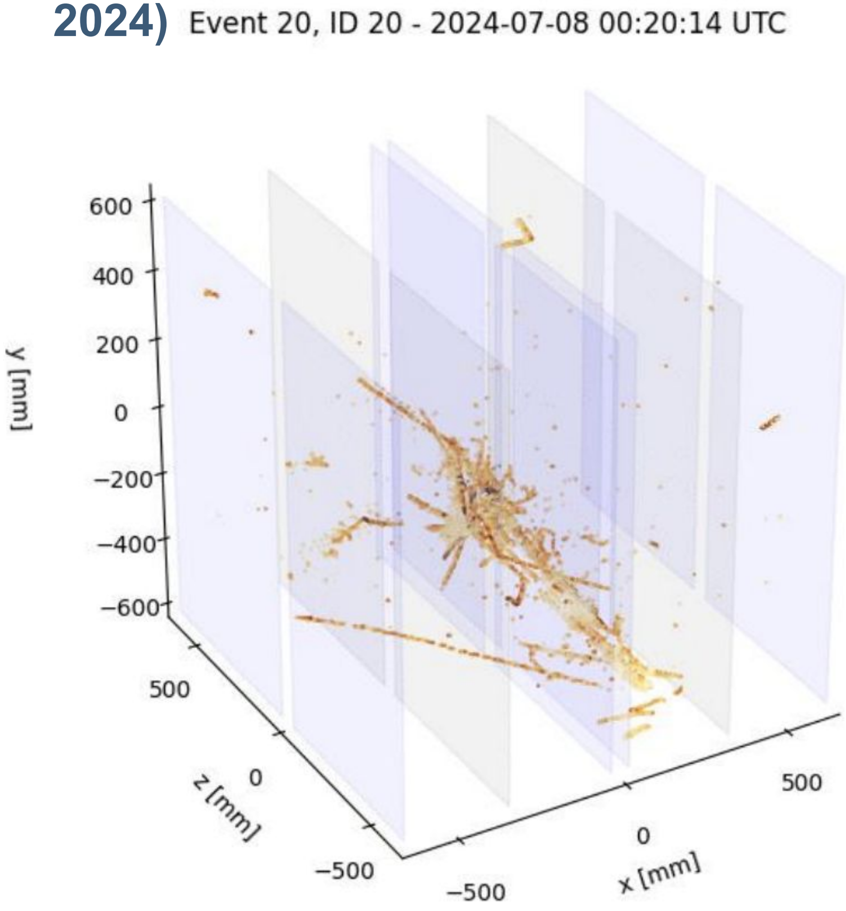
- Operating since July 8
- Monitored with 24- hour shifts since early June
- 10,000 events/day!





Andrew Cudd The DUNE 2x2 Demonstrator physics prospects and plans with neutrino data

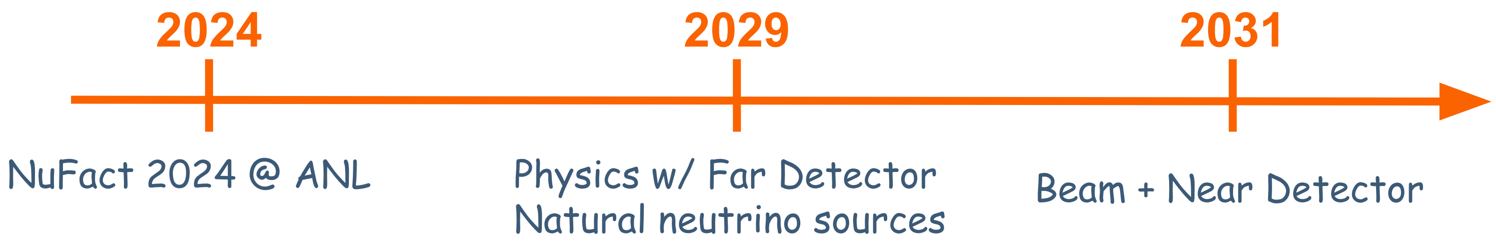
First DUNE Near Detector 2x2 Demonstrator neutrino events (July 2024)



Sindhujha Kumaran The Near Detector Liquid Argon (ND-LAr) 2x2 prototype of DUNE

Summary :

- DUNE will deliver groundbreaking results
    - Unambiguous determination of the neutrino mass ordering
    - Test of leptonic CP violation
- Sensitivity to supernovae neutrinos, potential to discover hep solar flux
- Rich and broad BSM program including search for oscillations beyond 3 flavors with large L/E range and large matter effect
- DUNE construction: excavation complete and components under construction
- DUNE science begins in this decade!



Thank you!

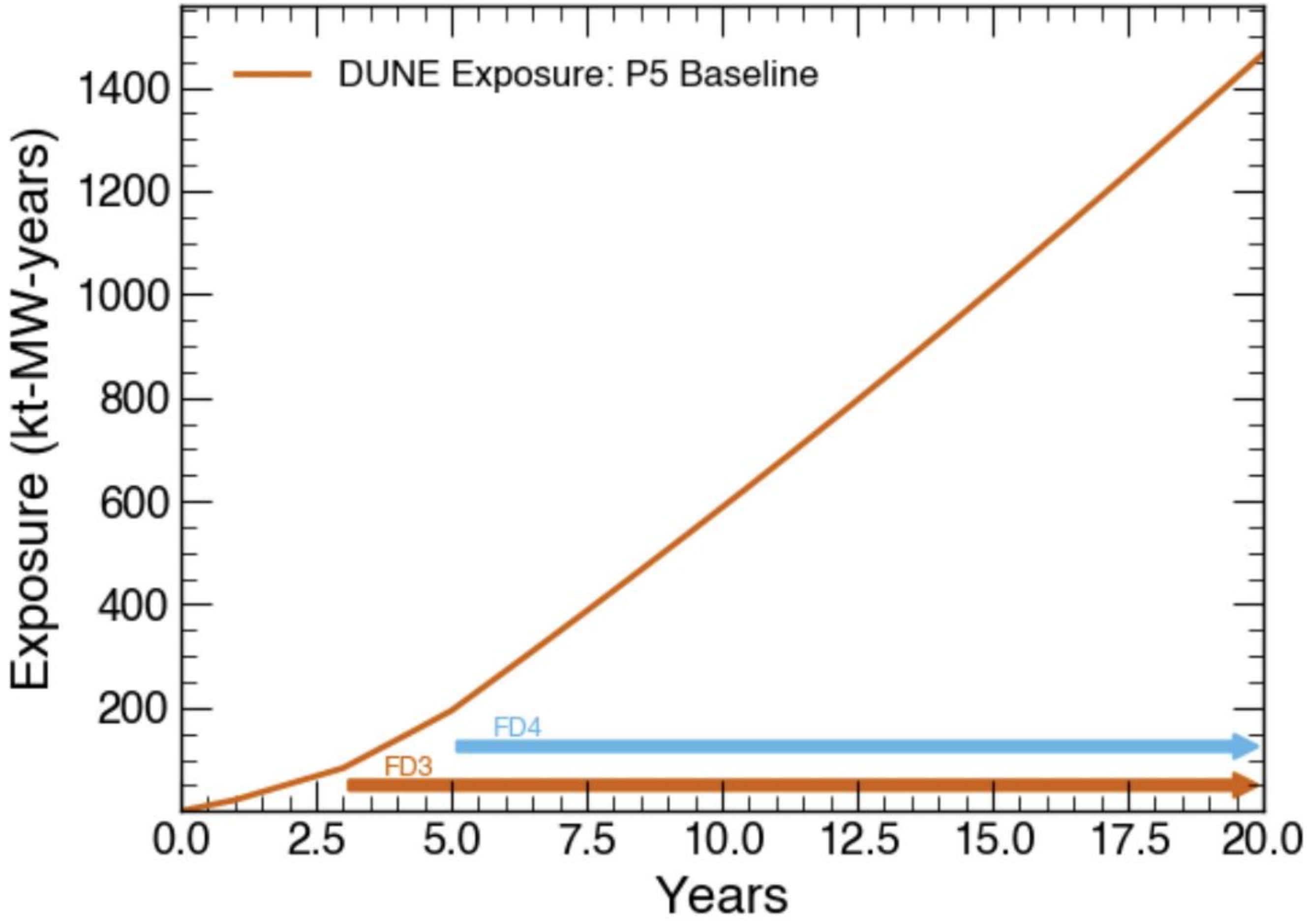
>1400 collaborators

207 institutions at Africa, Asia, Europe, North and South America as of July 2024

Back-up

DUNE Physics Sensitivity

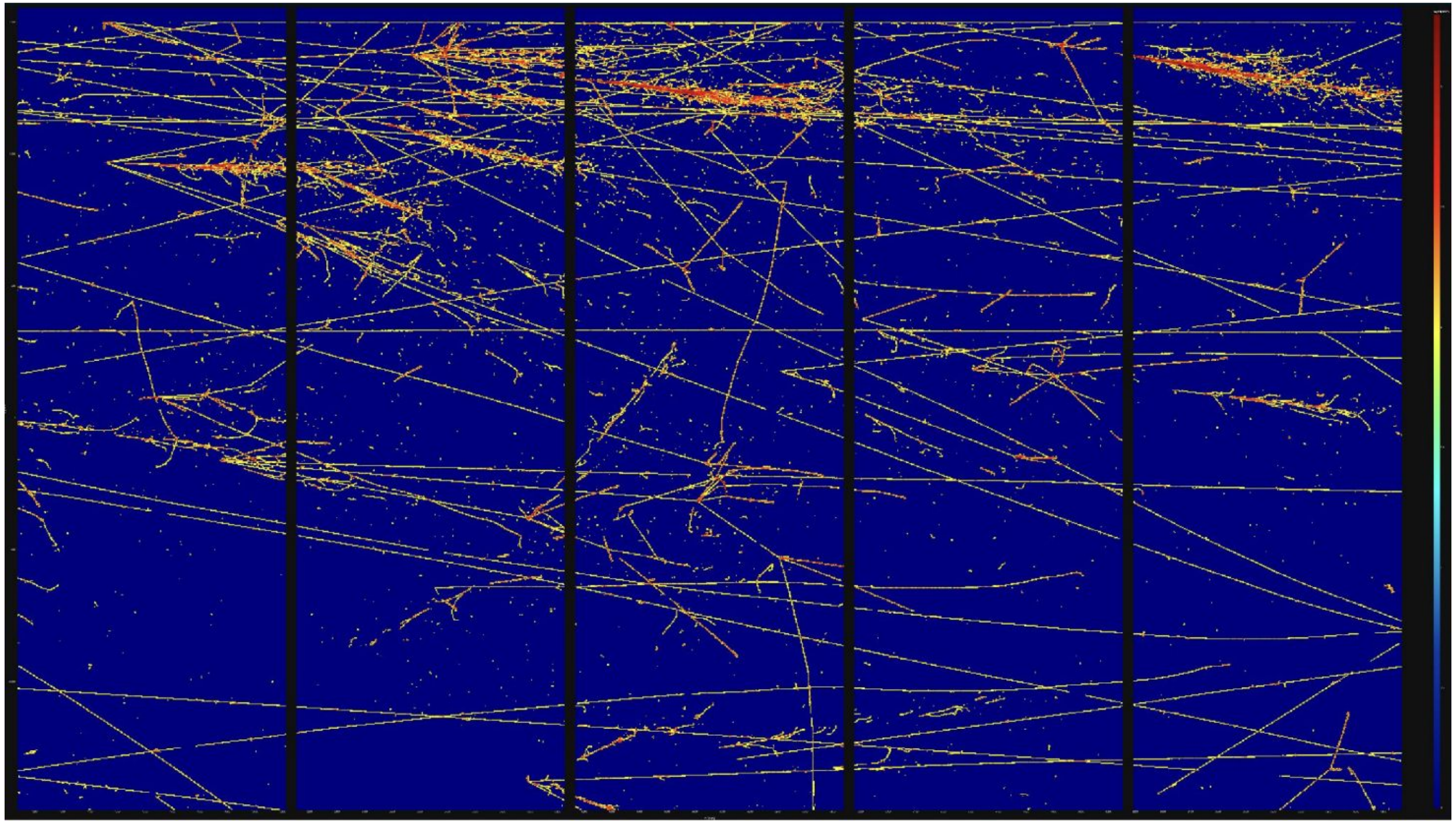
- Beam exposure scenario is based on the P5 baseline



Unique challenge for ND: pile-up

- LArTPC charge readout very slow compared to beam microstructure
  - ~300us maximum drift, ~10us beam spill
- Leverage scintillation light readout for timing information: must match charge to light → enabled through optical segmentation

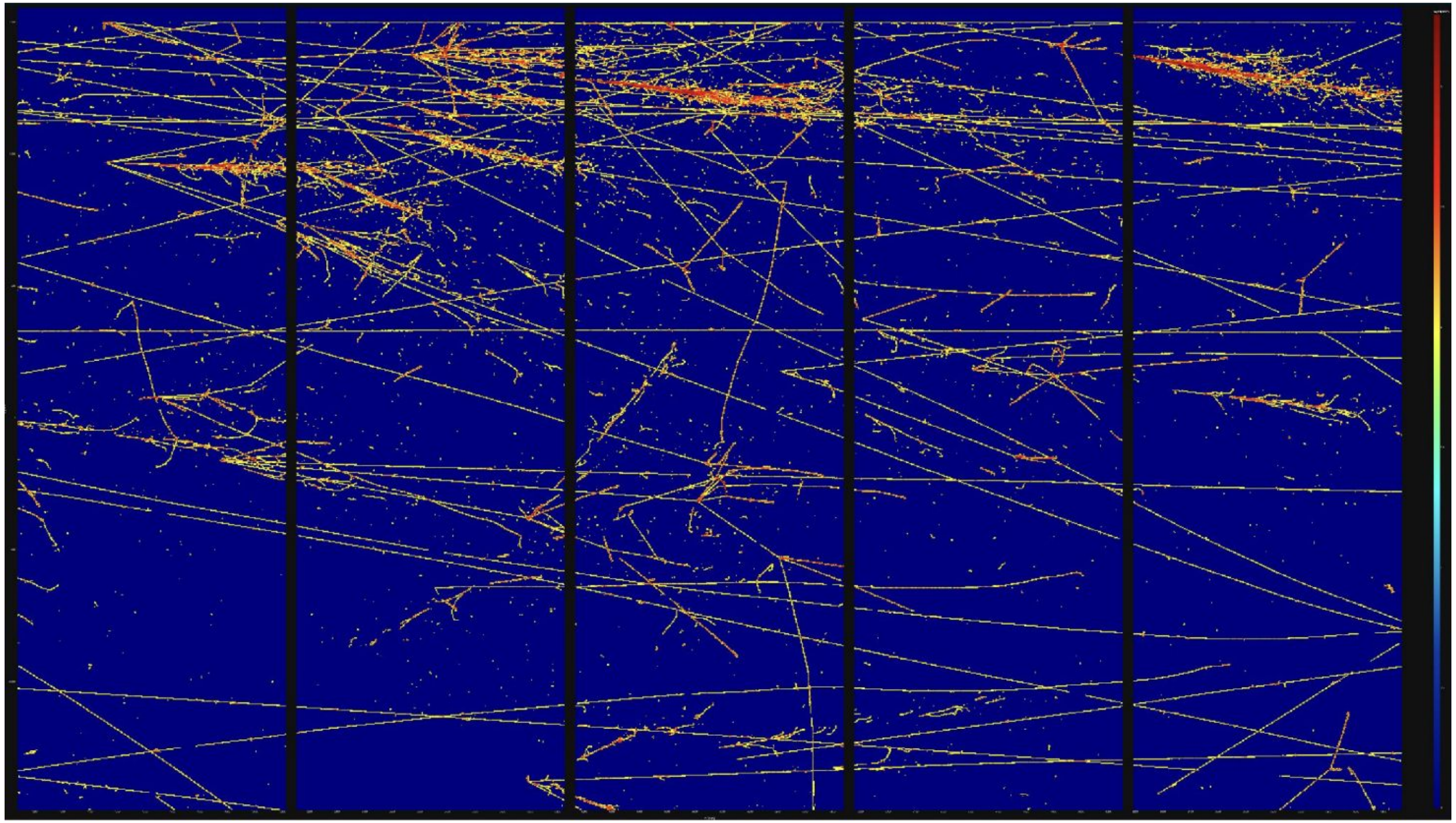
One beam spill at ND-LAr



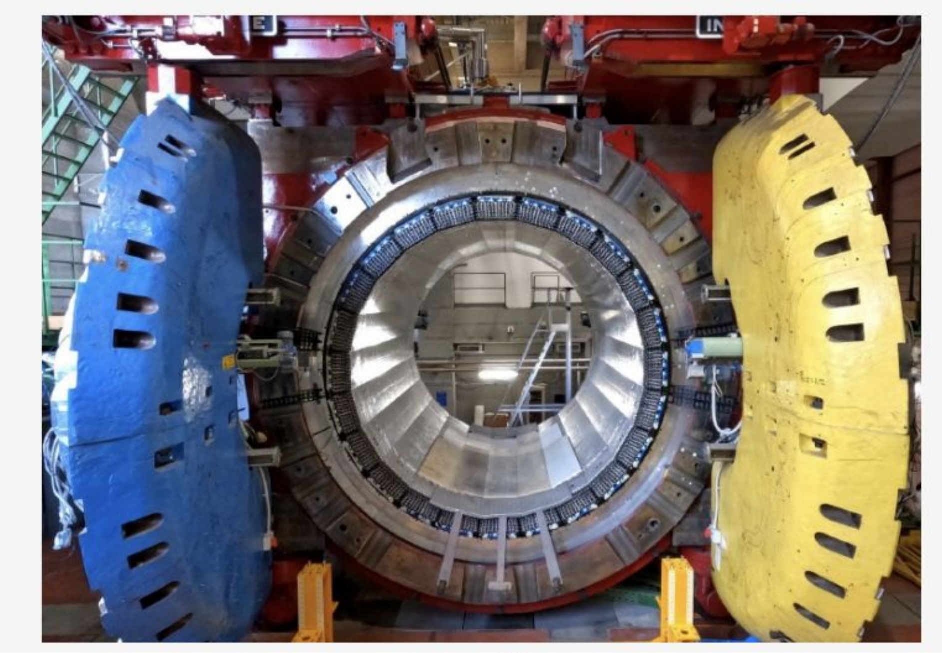
Unique challenge for ND: pile-up

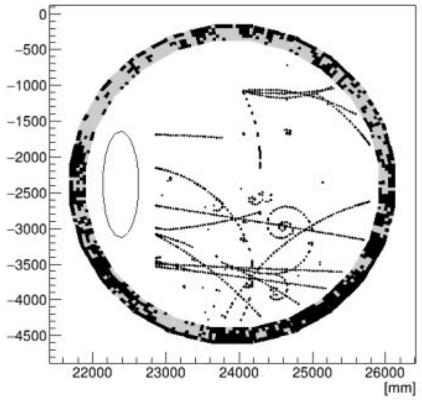
- Pixel readout: Natively 3D information in raw data, for resolving activity that would overlap in 2D projections
- Optical modularity: For charge-light matching, to allow association of detached energy (e.g. from neutrons)

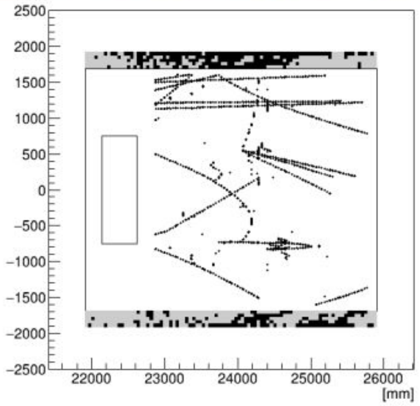
One beam spill at ND-LAr



SAND:

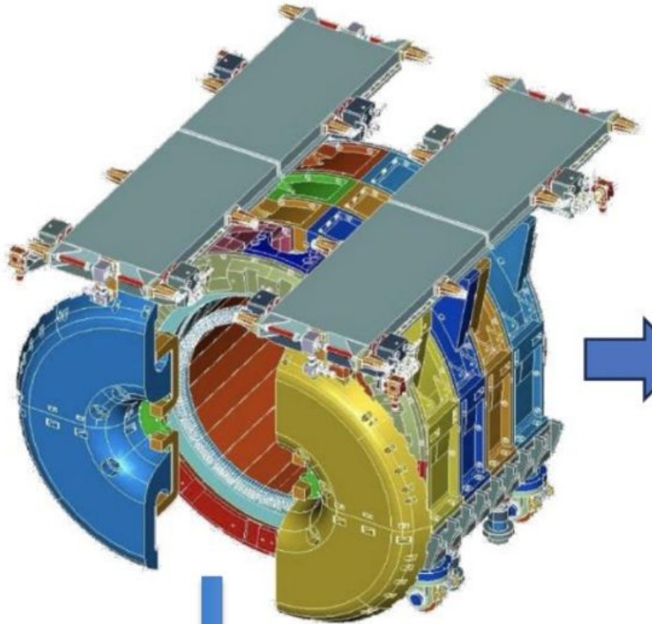


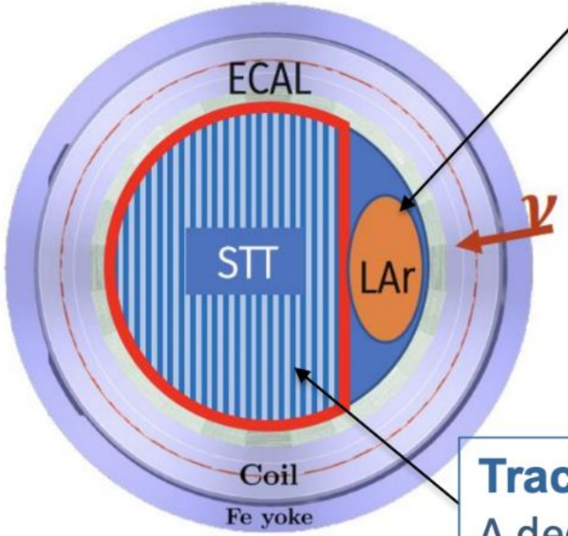




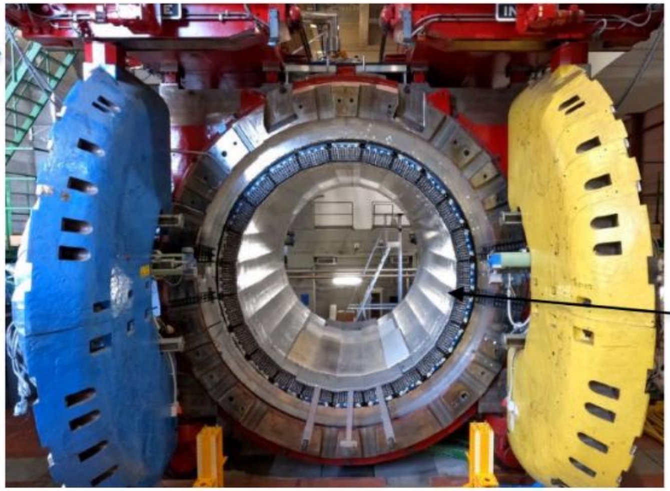
- Fixed component of ND repurposes existing solenoid magnet and ECAL from KLOE
- Plan is to build a collider-like detector in a neutrino beam: low-density tracker surrounded by calorimetry in magnetic field
- Fine-grained, particle-by-particle reconstruction with very low rescattering, excellent for highly exclusive neutrino-nucleus measurements
- Being taken apart at Frascati for the move to the US

SAND in detail





KLOE @ LNF



GRAIN (GRanular Argon for Interactions of Nu's) is an active target:

- ~ 1 ton FV LAr in a magnetized volume
- to study ν–Ar interactions with downstream tracker/calorimeter
- instrumented with sensors (SiPM arrays) for
  - collecting UV scintillation light by argon
  - performing imaging of the event (vertex location, event topology reco, time information)

Tracker

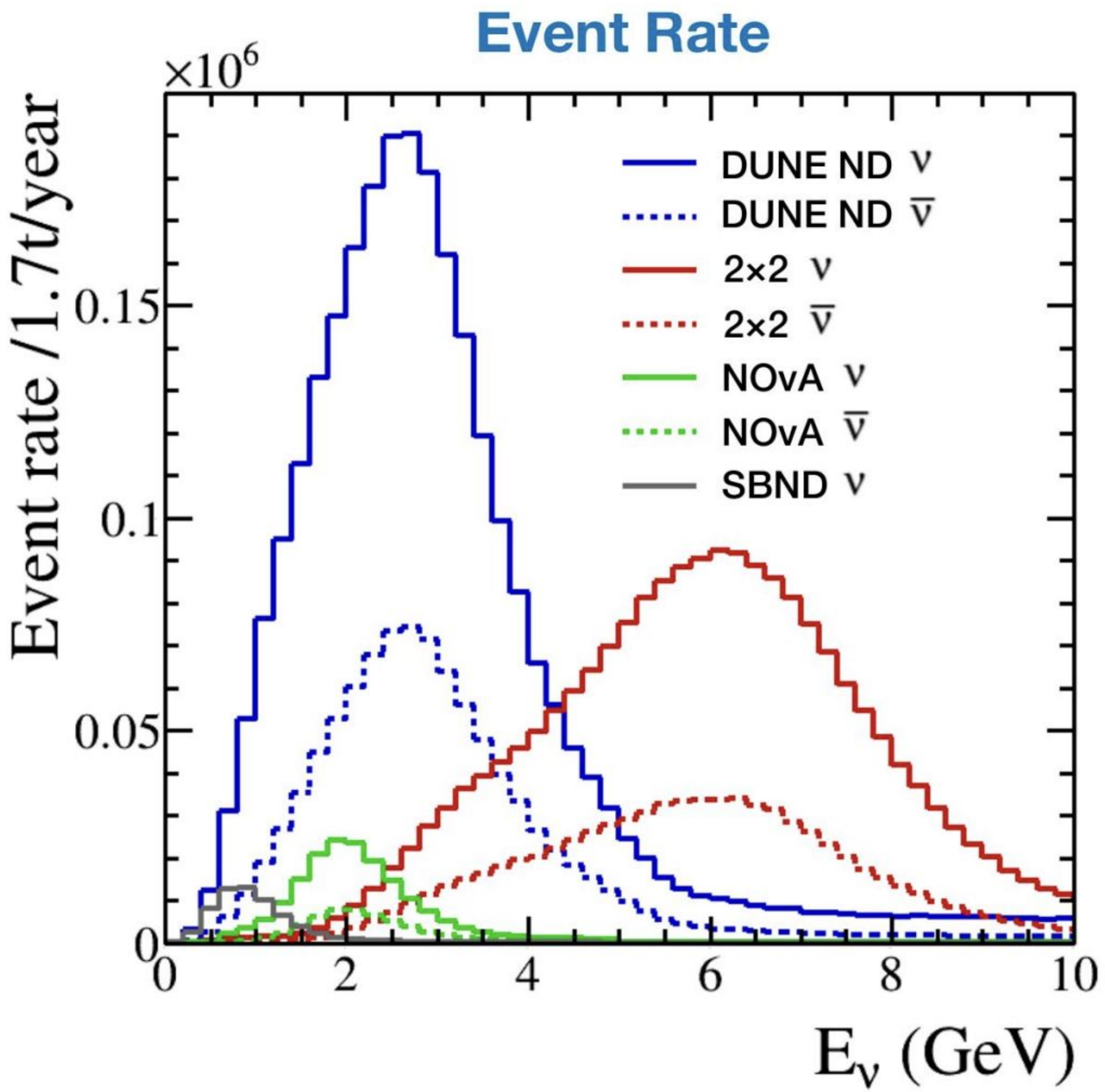
A dedicated **tracker system inside the magnet** for:

- separation of neutrino and anti-neutrino fluxes (charge ID)
- event-by-event detailed reconstruction
- neutron identification (jointly with ECAL)
- subtraction analysis to isolate free proton interactions.

ECAL

Exellent t and E resolution Electromagnetic Calorimeter, presently in the dismounting phase at LNF for refurbishing, tests with cosmic rays and delivery to FNAL

Event Rates ND:

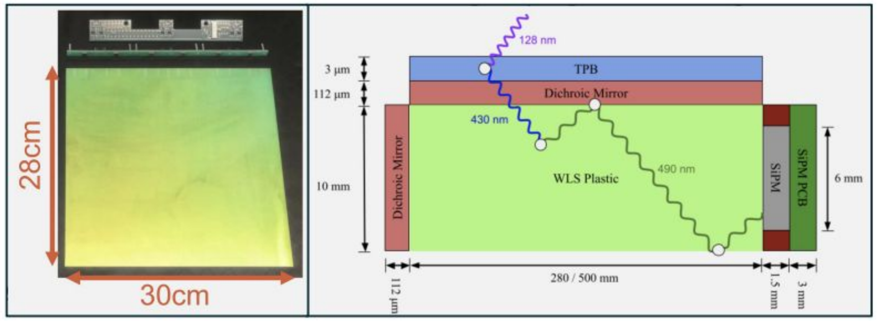


Light Readout System:

Two complementary designs for light traps – Increase coverage with fixed channel count

	ArcLight	LCM
Efficiency	~0.2%	~0.6%
Spatial resolution	~5cm	~10cm
Notes	– Large sense area – High dynamic range	– Scalable design – Mechanically robust

ArcLight module [prototype dimensions]

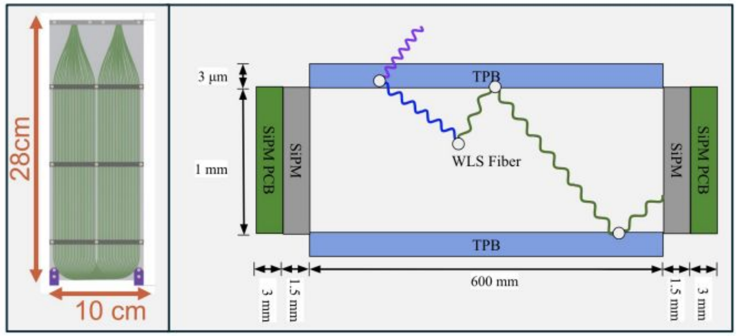


<10ns single hit timing resolution

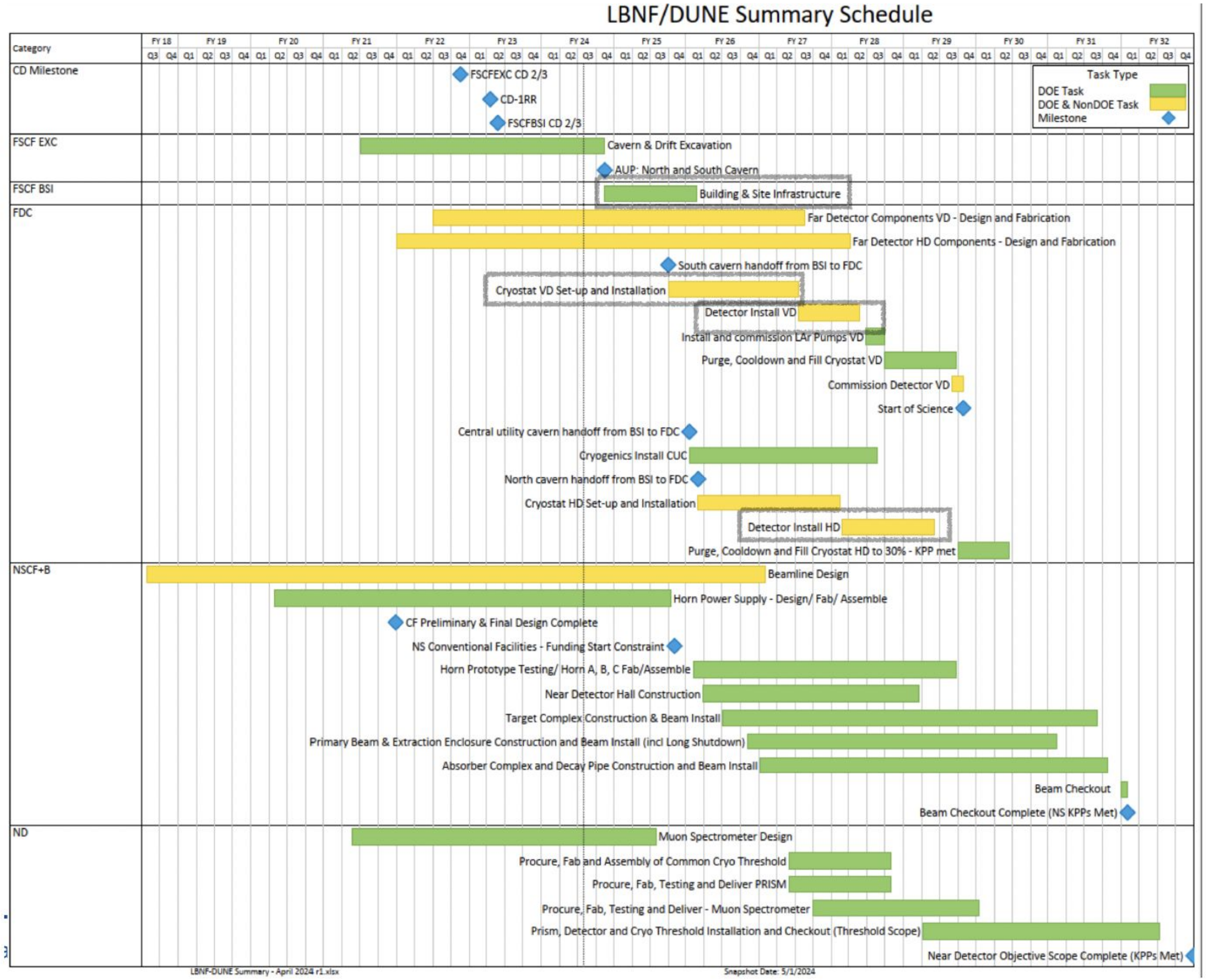
Common SiPM readout system

Common control and DAQ software

LCM [prototype dimensions]

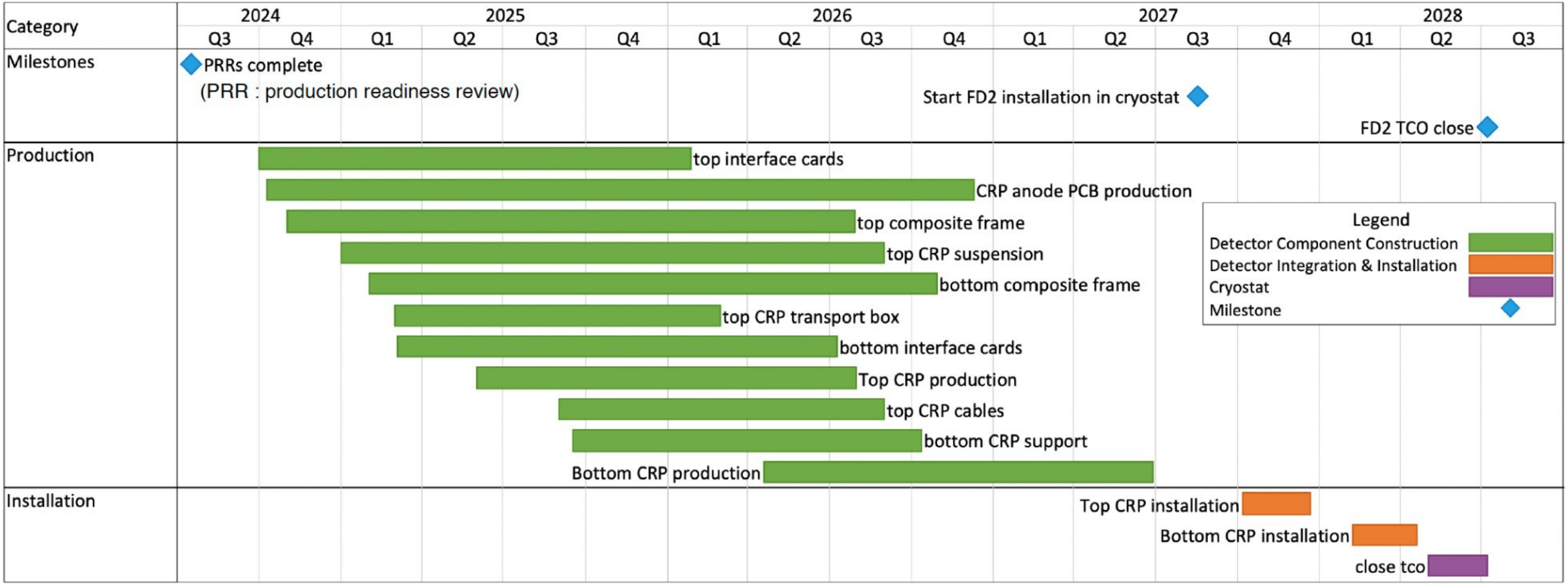


FD Site Plan


LBNF/DUNE Summary Schedule
Category
FY 18
FY 19
FY 20
FY 21
FY 22
FY 23
FY 24
FY 25
FY 26
FY 27
FY 28
FY 29
FY 30
FY 31
FY 32
CD Milestone
FSCFEXC CD 2/3
CD-1RR
FSCFBSI CD 2/3
Task Type
DOE Task
DOE & NonDOE Task
Milestone
FSCF EXC
Cavern & Drift Excavation
AUP: North and South Cavern
FSCF BSI
Building & Site Infrastructure
FDC
Far Detector Components VD - Design and Fabrication
Far Detector HD Components - Design and Fabrication
South cavern handoff from BSI to FDC
Cryostat VD Set-up and Installation
Detector Install VD
Install and commission LAr Pumps VD
Purge, Cooldown and Fill Cryostat VD
Commission Detector VD
Start of Science
Central utility cavern handoff from BSI to FDC
Cryogenics Install CUC
North cavern handoff from BSI to FDC
Cryostat HD Set-up and Installation
Detector Install HD
Purge, Cooldown and Fill Cryostat HD to 30% - KPP met
NSCF+B
Beamline Design
Horn Power Supply - Design/ Fab/ Assemble
CF Preliminary & Final Design Complete
NS Conventional Facilities - Funding Start Constraint
Horn Prototype Testing/ Horn A, B, C Fab/Assemble
Near Detector Hall Construction
Target Complex Construction & Beam Install
Primary Beam & Extraction Enclosure Construction and Beam Install (incl Long Shutdown)
Absorber Complex and Decay Pipe Construction and Beam Install
Beam Checkout
Beam Checkout Complete (NS KPPs Met)
ND
Muon Spectrometer Design
Procure, Fab and Assembly of Common Cryo Threshold
Procure, Fab, Testing and Deliver PRISM
Procure, Fab, Testing and Deliver - Muon Spectrometer
Prism, Detector and Cryo Threshold Installation and Checkout (Threshold Scope)
Near Detector Objective Scope Complete (KPPs Met)
LBNF-DUNE Summary - April 2024 r1.xlsx
Snapshot Date: 5/1/2024

VD Production Plan

arXiv:2312.03130



Performance - Summary

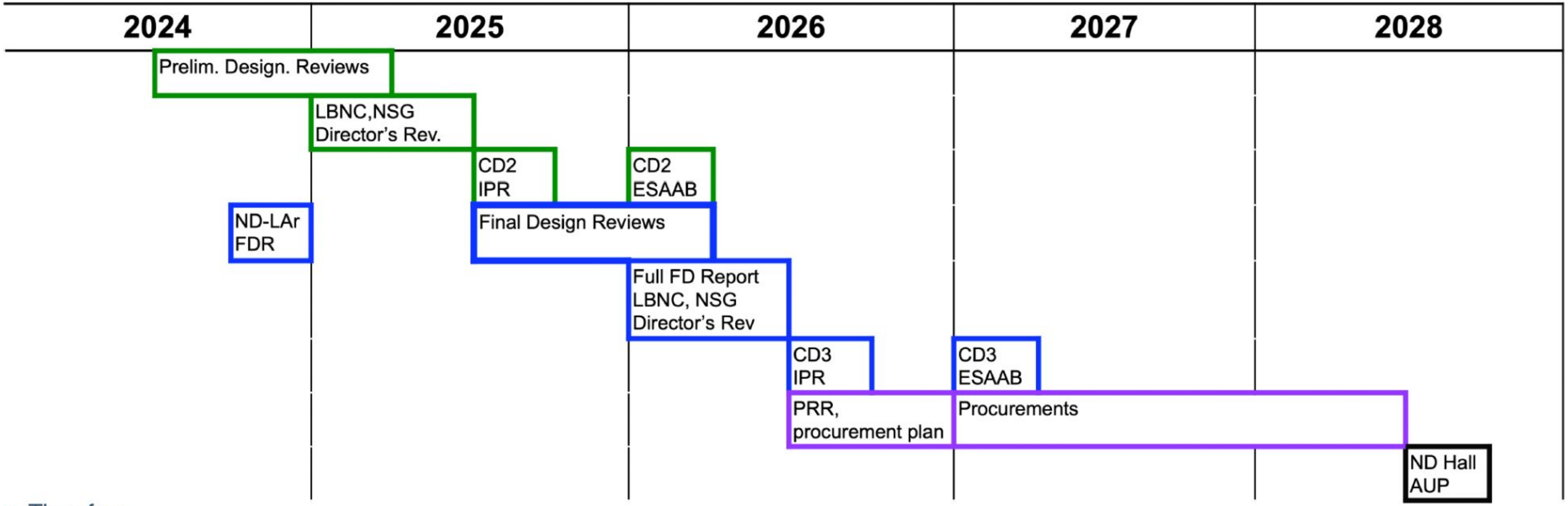
- ProtoDUNE-SP meets or surpasses the specifications set for the DUNE far detector
  - Effectiveness of the single-phase DUNE far detector design
  - Execution of the fabrication, assembly, installation, commissioning, and operations phases

Detector parameter	*ProtoDUNE-SP performance*	*DUNE specification*
Average drift electric field	500 V/cm	250 V/cm (min) 500 V/cm (nominal)
LAr e-lifetime	> 20 ms	> 3 ms
TPC+CE Noise Signal-to-noise ⟨SNR⟩	 (C) 550 e, (I) 650 e ENC (raw) (C) 48.7, (I) 21.2 (w/CNR)	 < 1000 e ENC
CE dead channels	0.2% 😁	< 1%
PDS light yield	1.9 photons/MeV (@ 3.3 m distance)	> 0.5 photons/MeV (@ cathode distance — 3.6 m)
PDS time resolution	14 ns	< 100 ns

JINST 15 (2020) 12, P1200

Fermilab DUNE

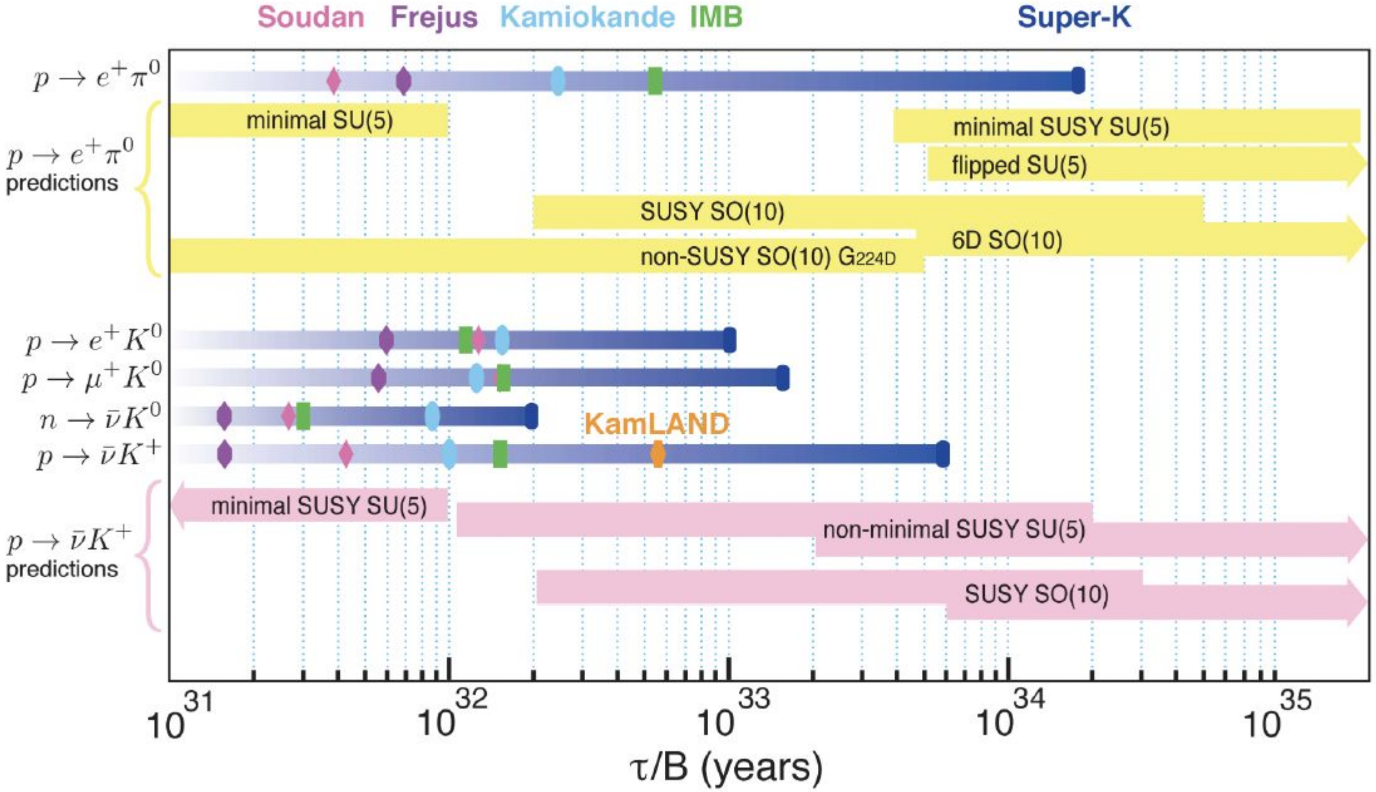
ND Plan



- Thus far:
  - Conceptual Design Report published in Sep 2021, Conceptual Design Review in July 2020
- Next step is to achieve Preliminary Design
  - Includes: preliminary Technical Design Report (PDR) and Preliminary Design Reviews of all subsystems by the LBNF/DUNE Review OFfice
- Goal: ready for installation when the Near Detector Hall is ready (second half of 2028)

DUNE Physics Sensitivity - Proton Decay

- With 30% detection efficiency for $p \rightarrow K^+\bar{\nu}$, DUNE Phase-II expected limit is 1.3×10^{34} years
  - Super-K : 5.9×10^{33} years
  - Hyper-K expected limit : 3×10^{34} years



DUNE Physics Sensitivity -δ_{CP}:

- Expected number of events

	Expected Events (3.5 years staged per mode)	
	ν mode	$\bar{\nu}$ mode
ν_e signal NO (IO)	1092 (497)	76 (36)
$\bar{\nu}_e$ signal NO (IO)	18 (31)	224 (470)
Total signal NO (IO)	1110 (528)	300 (506)
Beam $\nu_e + \bar{\nu}_e$ CC background	190	117
NC background	81	38
$\nu_\tau + \bar{\nu}_\tau$ CC background	32	20
$\nu_\mu + \bar{\nu}_\mu$ CC background	14	5
Total background	317	180

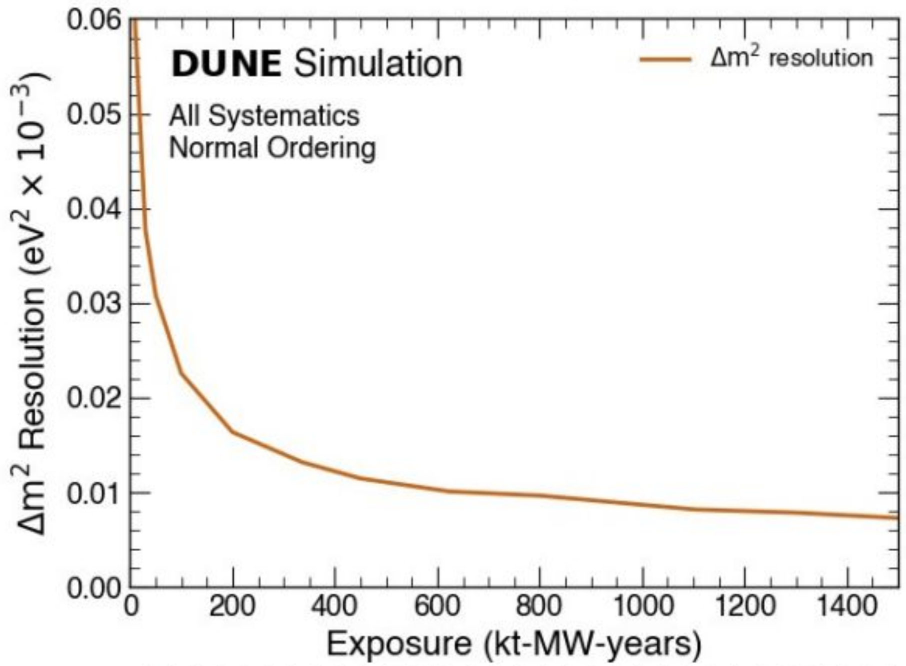
	Expected Events (3.5 years staged)
ν mode	
ν_μ Signal	6200
$\bar{\nu}_\mu$ CC background	389
NC background	200
$\nu_\tau + \bar{\nu}_\tau$ CC background	46
$\nu_e + \bar{\nu}_e$ CC background	8
$\bar{\nu}$ mode	
$\bar{\nu}_\mu$ signal	2303
ν_μ CC background	1129
NC background	101
$\nu_\tau + \bar{\nu}_\tau$ CC background	27
$\nu_e + \bar{\nu}_e$ CC background	2

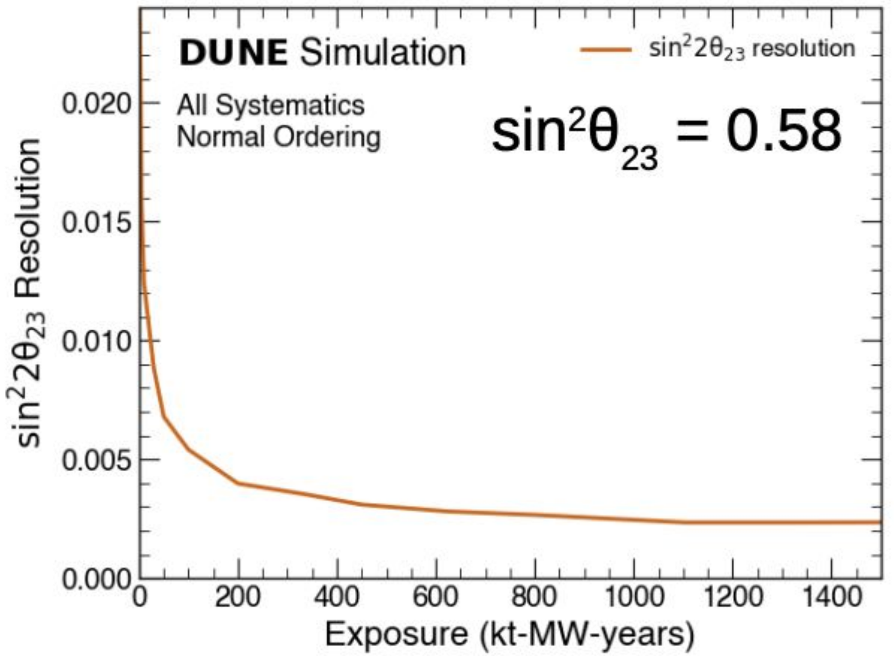
Resolution to disappearance parameters:

- Δm^2 is measured by location of dip in disappearance spectrum → high rate and on-axis location gives improved sensitivity relative to current LBL experiments

- Comparison with similar JUNO measurement is sensitive to new physics

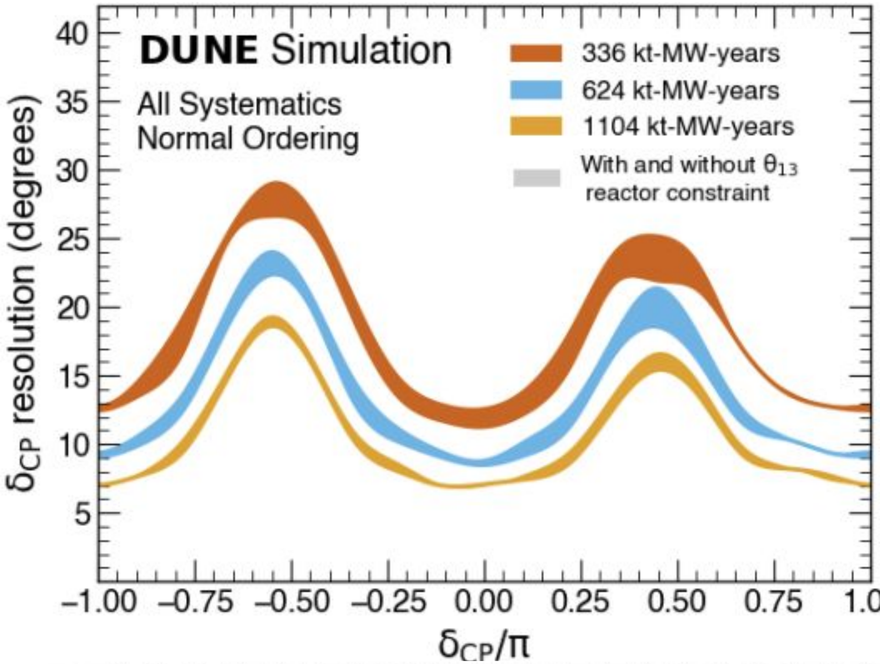
- Resolution to θ_{23} is complicated; strongly dependent on true parameter values, and correlated with other parameters

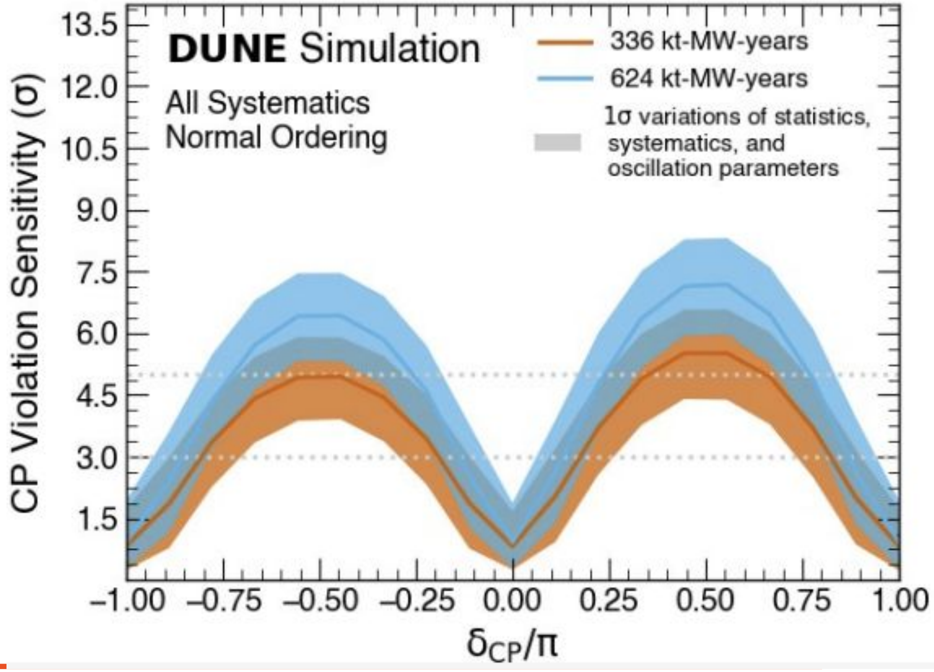




CP violation and δ_{CP} resolution:

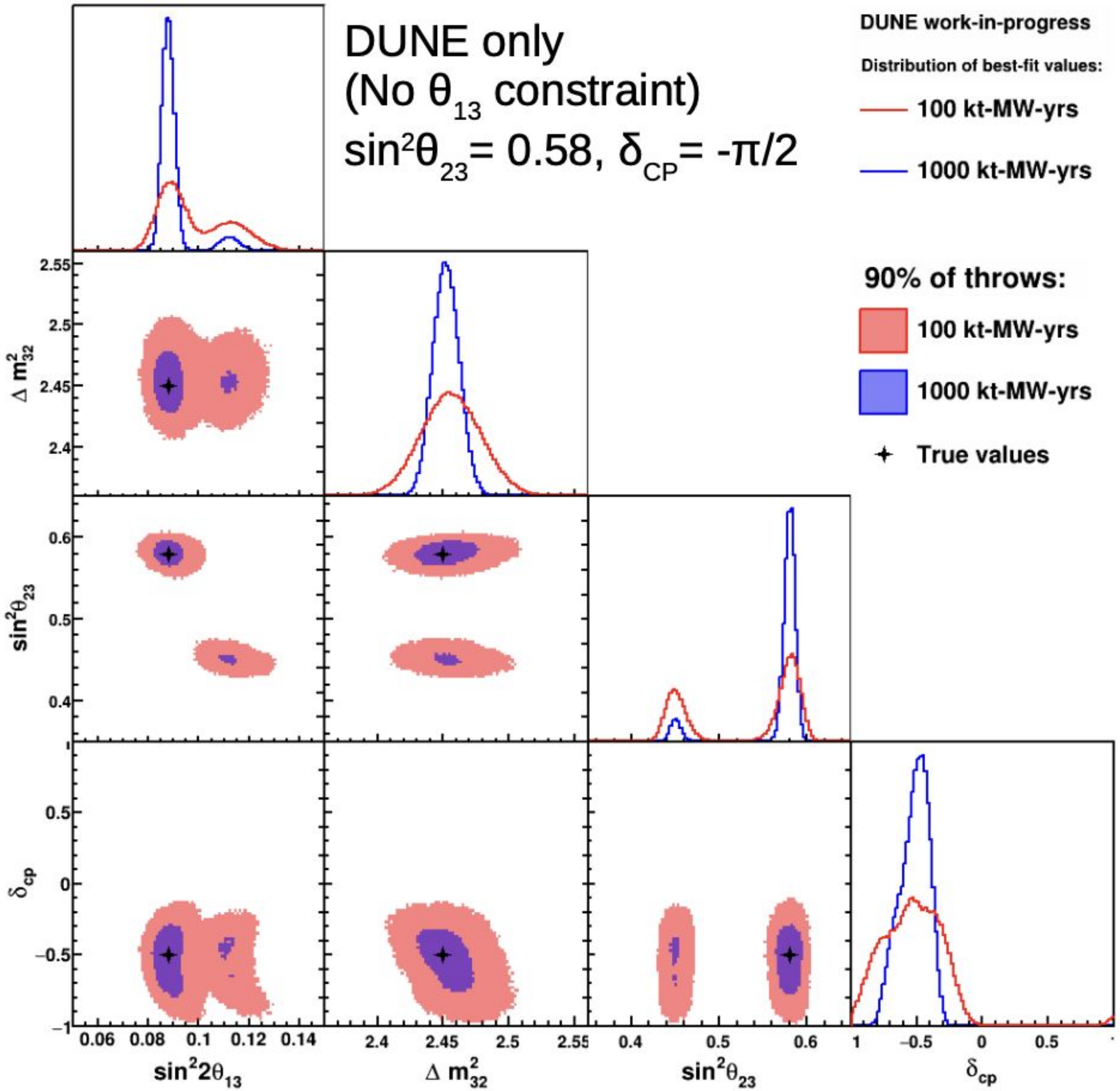
- δ_{CP} resolution is best at 0 and π because appearance at maximum is proportional to $\sin(\delta_{CP})$
- DUNE (and most experiments) typically quote median sensitivities, but statistical fluctuations and systematic uncertainties give a range of possible values shown by the bands





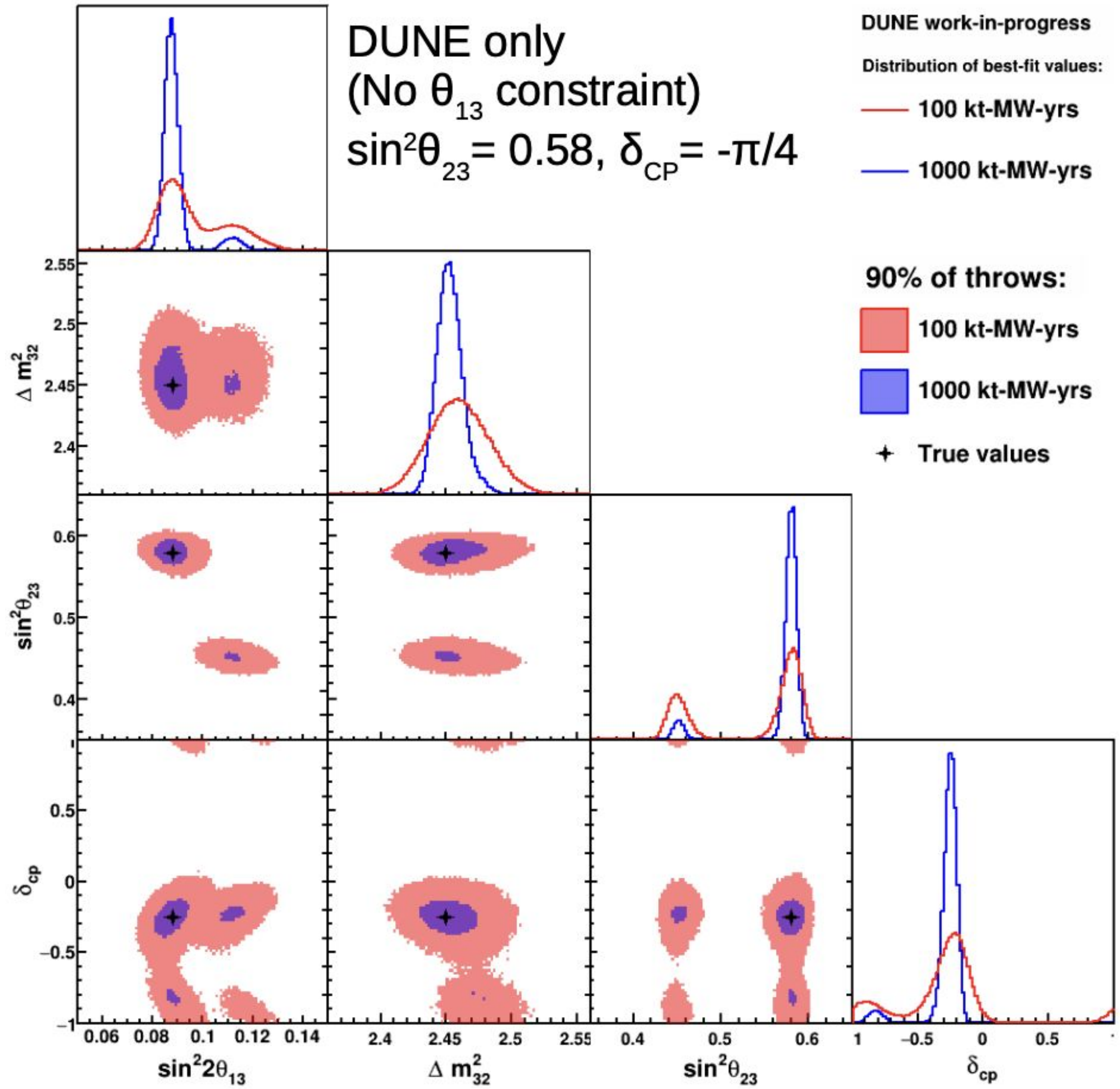
Resolving parameter degeneracies with spectral information:

- DUNE resolutions projected into different 2D spaces, for two different exposures
- Degeneracy between θ_{13} and θ_{23} in DUNE data is resolved by reactor θ_{13} data, which resolves θ_{23} octant
- For maximal δ_{CP}, CP conserving values are strongly excluded but resolution is relatively poor

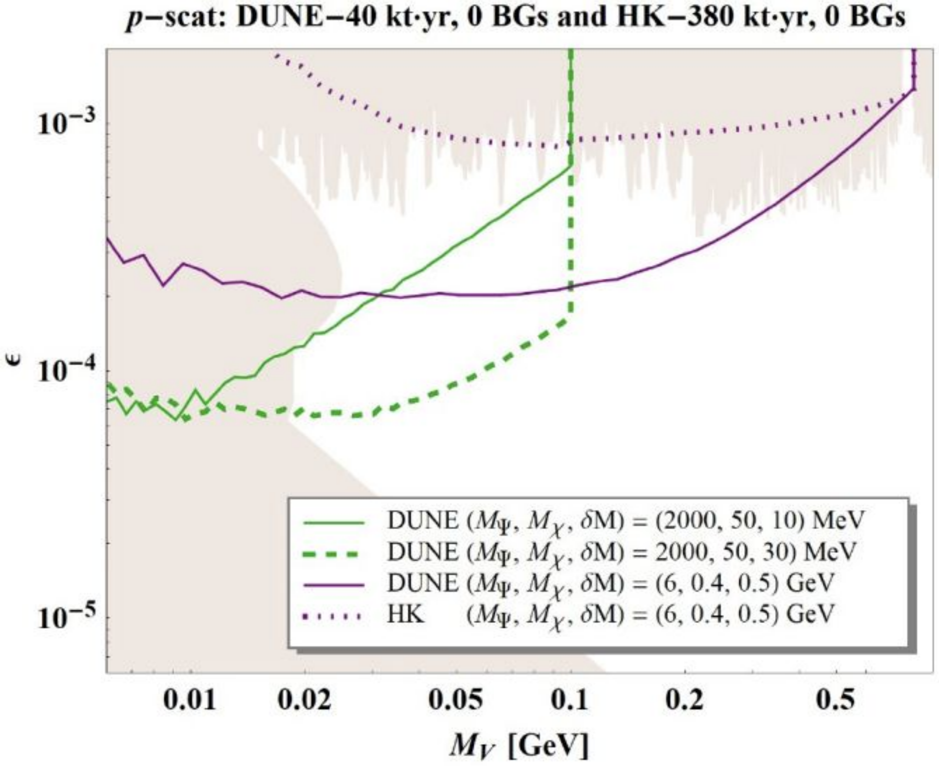


Resolving parameter degeneracies with spectral information:

- For non-maximal values of δCP, an additional degeneracy arises because $P(\nu_\mu \rightarrow \nu_e) \sim \sin\delta_{CP}$ at maximum
- DUNE can largely resolve this using its spectral information
- Combining experiments is challenging → we all need to publish this full 4D space!

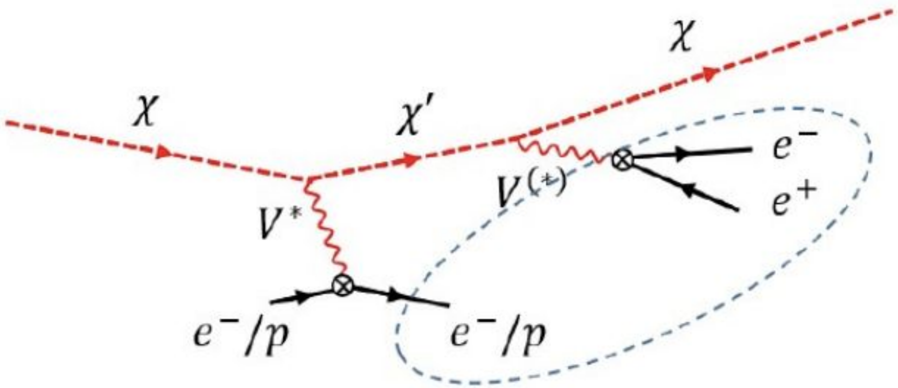


BSM searches with the Far Detector :



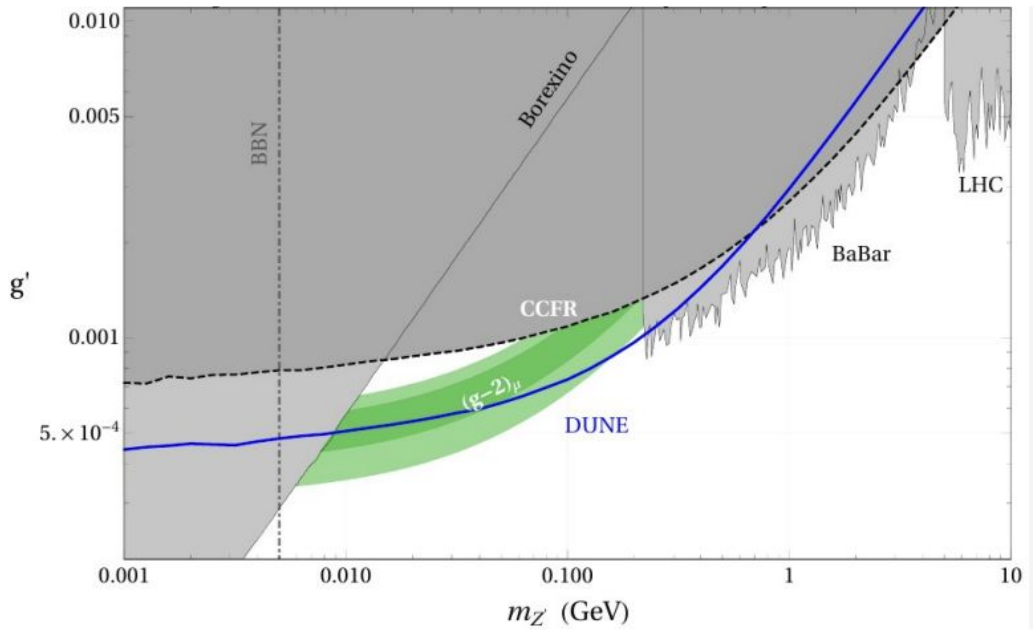
- DUNE Far Detector is sensitive to rare processes (nucleon decay, n-n oscillation, etc.) and new physics of cosmogenic origin

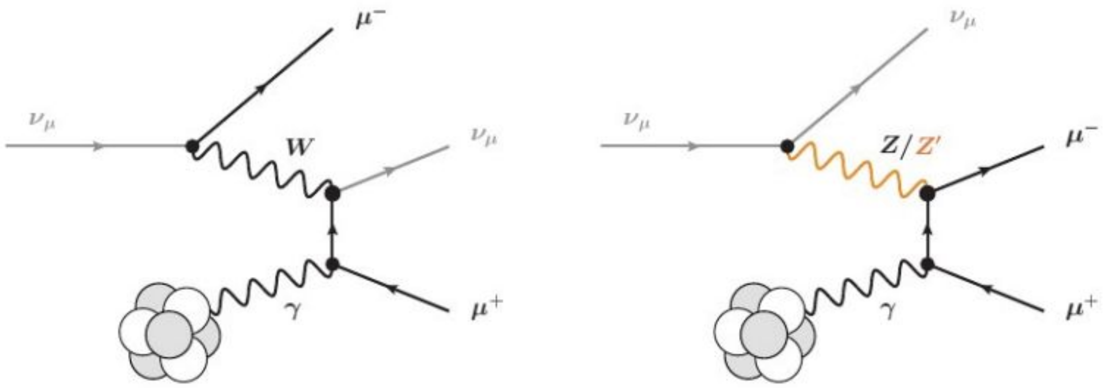
- Key strengths of DUNE:
    - Ability to detect low-energy particles (for iBDM, signal is a soft e/p and spatially proximate e+/epair)
    - Ability to reconstruct direction including hadrons (i.e. for BDM produced in Sun or Galactic Center)



BSM searches with the Near Detector :

- DUNE Near Detector is sensitive to rare processes in the beamline (HNL, LDM) and to BSM contributions to neutrino interactions (ν tridents)
- Key strengths of DUNE:
  - 120 GeV proton beam and very high intensity
  - LAr ND with 50-70t fiducial mass
  - Low density ND (SAND) → increased S/B for decays in ND volume



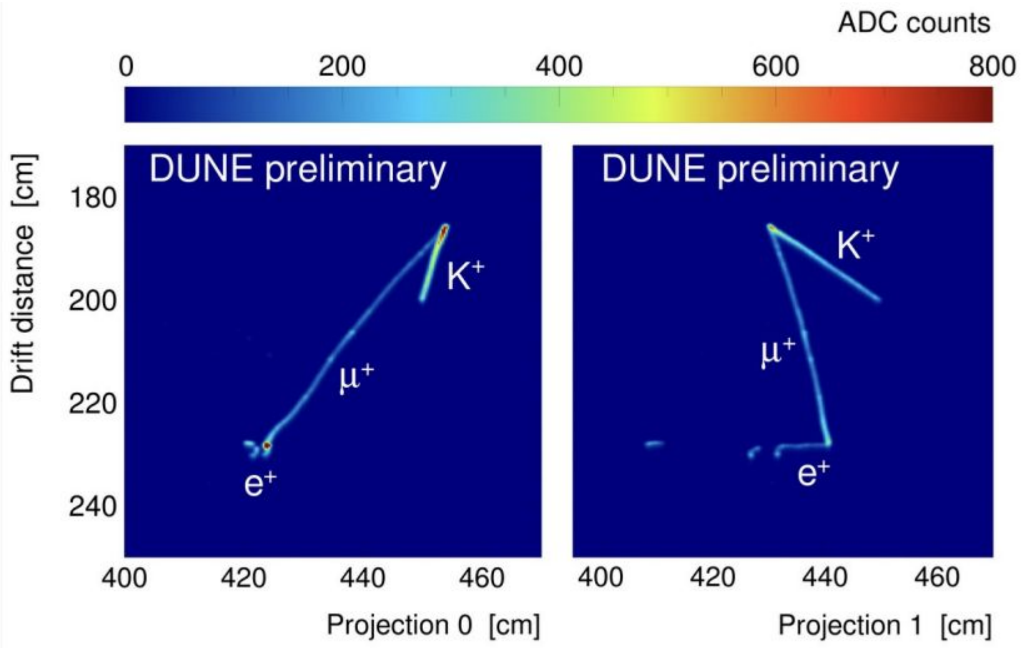


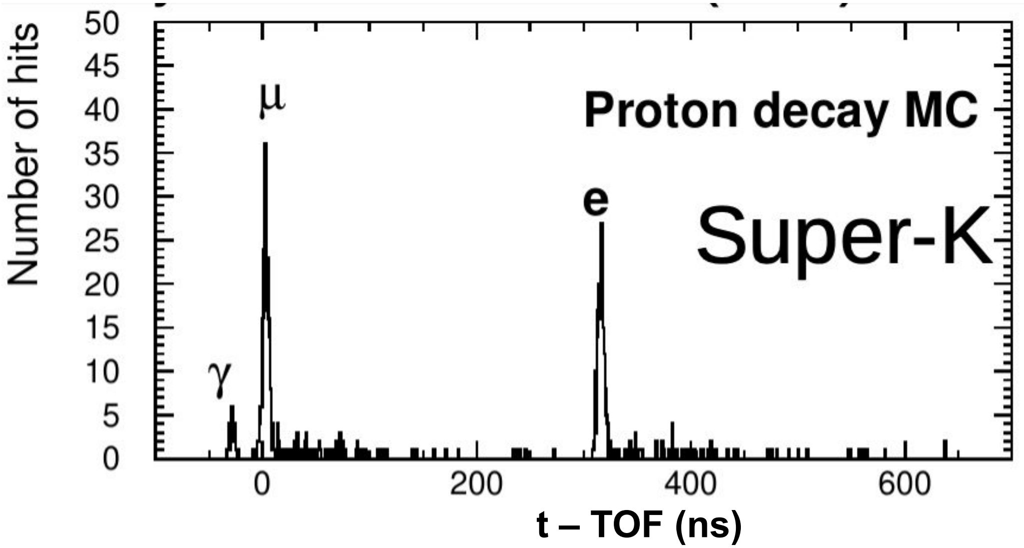
Nucleon decay $p \rightarrow K^{+}\nu$:

- Hyper-K can identify $p \rightarrow K^{+}\nu$ by timing, and identification of monoenergetic muon from kaon decay, with sensitivity to $\tau = 3\times10^{34}$ yrs

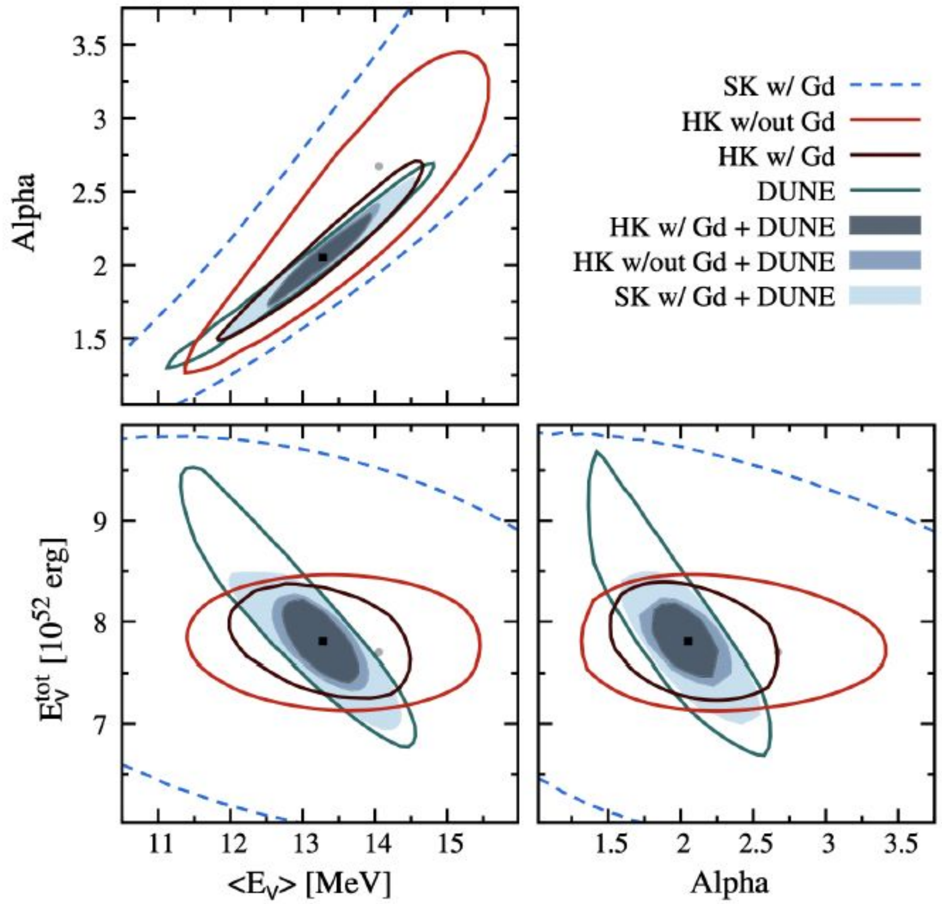
- DUNE can image all three particles, Phase II sensitivity beyond current Super-K limit

- If a signal is observed in Hyper-K it will be valuable to confirm the detection with a very different detector, different backgrounds, etc.





Supernova spectral measurements with DUNE + HK data:



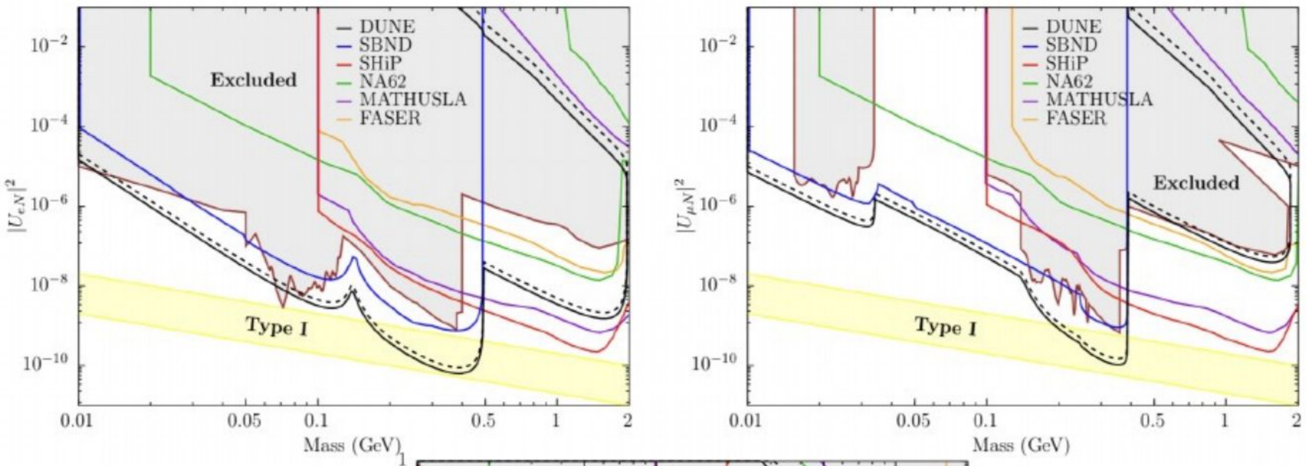
- Supernova spectrum can be parameterized by average neutrino energy and α
- DUNE and HK measure different fluxes → complementary ability to constrain spectral parameters
- DUNE Phase II (40 kt) shown in figure

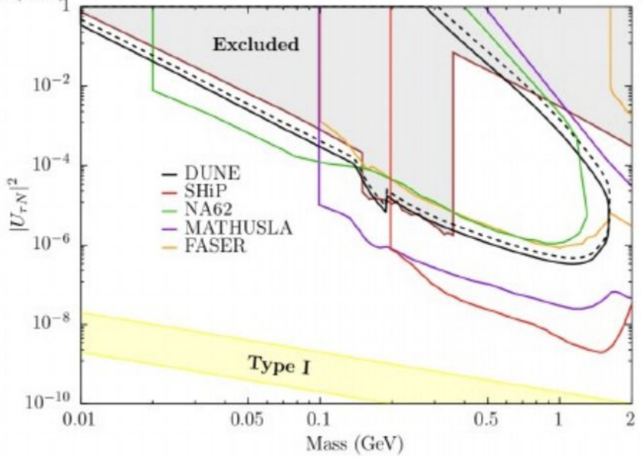
Supernova neutrino burst flux parameterization with α and $< E_\nu >$

$$\frac{dN_\nu}{dE_\nu}(E_\nu) = A\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^\alpha \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu\rangle}\right],$$

$$A = \frac{(\alpha+1)^{\alpha+1}}{\langle E_\nu\rangle\Gamma(\alpha+1)}$$

Sensitivity to Heavy Neutral Leptons produced in beam, decay in ND:

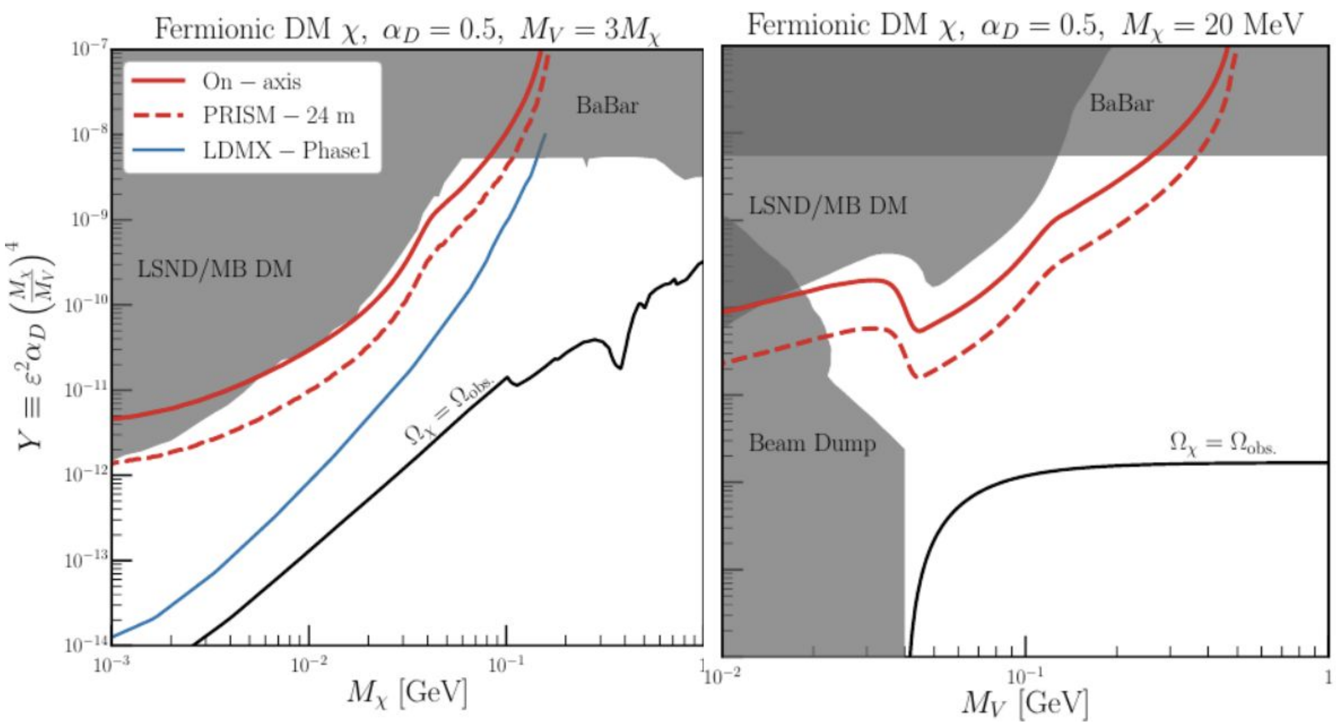




J. High Energ. Phys. 2020, 111 (2020)

- $N \rightarrow \nu ee, \nu e\mu, \nu\mu\mu, \nu\pi^0, e\pi, \mu\pi$
- Assumes 22 MW-yrs and zero backgrounds
- Reaching zero background not demonstrated, may be possible with ND-GAr

Light dark matter in beamline via χ-e:



- χe→χe scattering in ND-LAr, from boosted DM produced in the beamline
- Backgrounds from νe→νe have different spectrum
- DM and ν have different dispersion, and looking at offaxis ND-LAr data improves the statistical separation
- Sensitivity at low mass is potentially world-leading

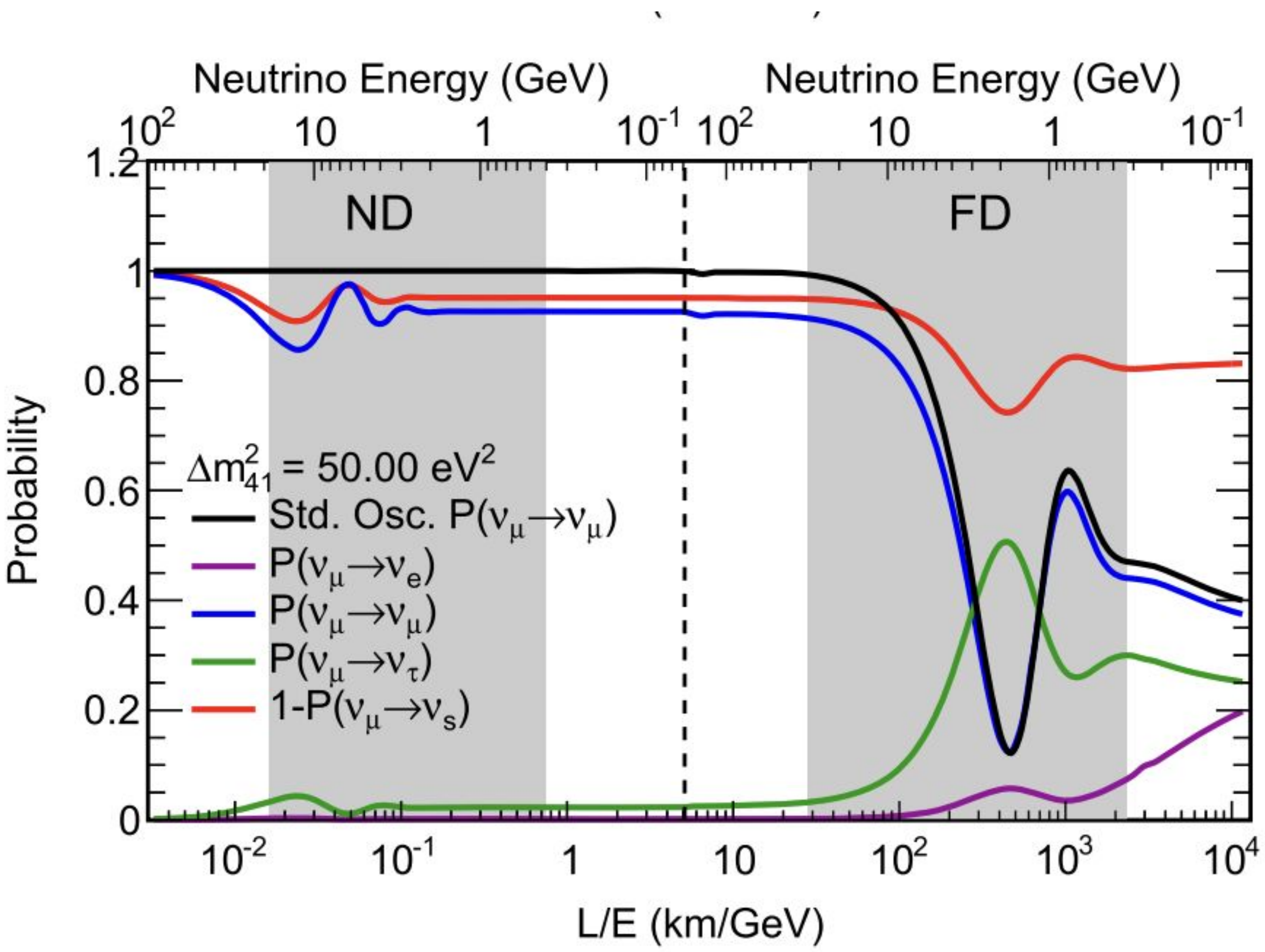


Fig. 1 Regions of L/E probed by the DUNE detector compared to 3-flavor and $3+1$-flavor neutrino disappearance and appearance probabilities. The gray-shaded areas show the range of true neutrino energies probed by the ND and FD. The top axis shows true neutrino energy, increasing from right to left. The top plot shows the probabilities assuming mixing with one sterile neutrino with $\Delta m^2_{41} = 0.05\,\text{eV}^2$, corresponding to the slow oscillations regime. The middle plot assumes mixing with one sterile neutrino with $\Delta m^2_{41} = 0.5\,\text{eV}^2$, corresponding to the intermediate oscillations regime. The bottom plot includes mixing with one sterile neutrino with $\Delta m^2_{41} = 50\,\text{eV}^2$, corresponding to the rapid oscillations regime. As an example, the slow sterile oscillations cause visible distortions in the three-flavor ν_μ survival probability (blue curve) for neutrino energies ~ 10 GeV, well above the three-flavor oscillation minimum

Atmospheric neutrinos: angle reconstruction including hadrons:

- Atmospheric neutrinos will be DUNE's first data; aim to combine with long-baseline
- Including reconstructed hadrons substantially improves angle resolution, especially at lower neutrino energies
- Potential to extend to low energies has been studied phenomenologically, see Phys. Rev. Lett. 123, 081801 (2019)
- DUNE analysis in progress