DUNE
The Deep Underground Neutrino Experiment

INSTITUTE OF PARTICLE PHYSICS

INSTITUT DE PHYSIQUE DES PARTICULES

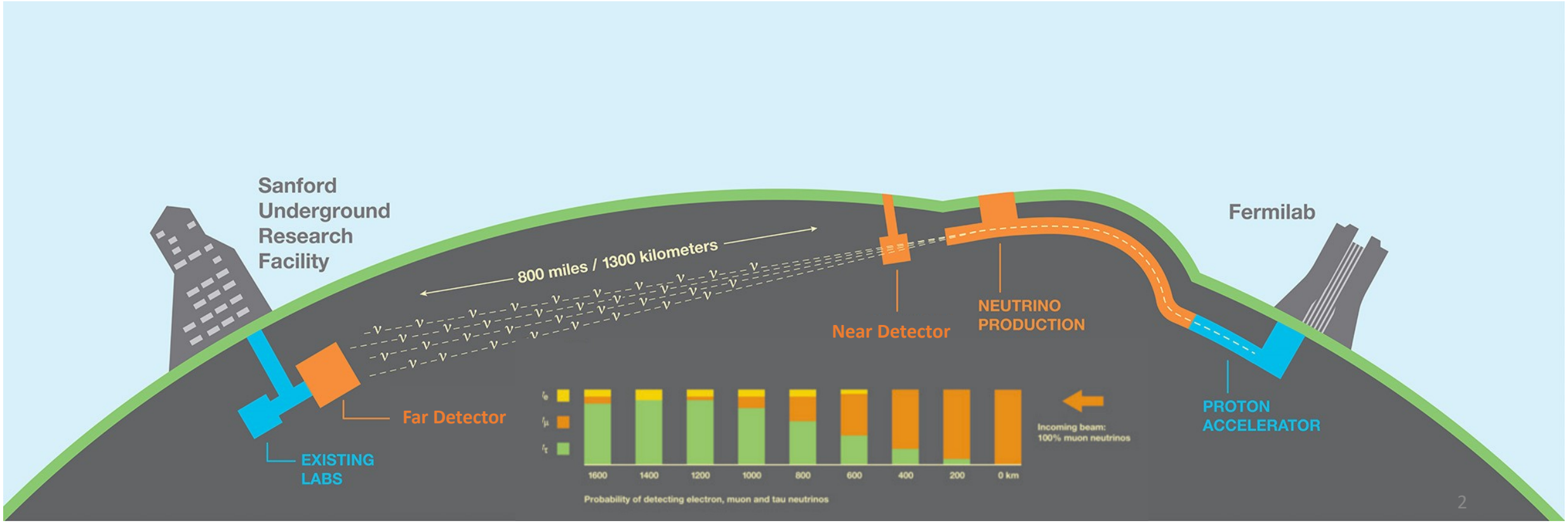
Nikolina Ilic on behalf of DUNE

Institute of Particle Physics & University of Toronto

EPS 2023, Hamburg

LBNF DUNE Facility

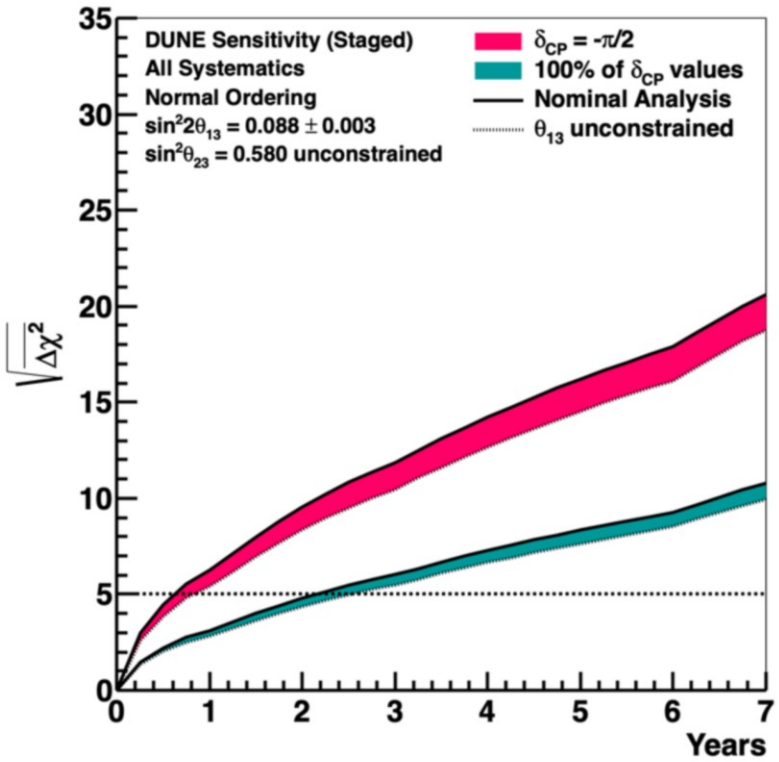
- 1-6 GeV muon neutrinos/antineutrinos from high-power proton beam (1.2 MW – upgradable to 2.4 MW)
- Near detector measures fluxes & constrains systematics (100s of millions of neutrino interactions)
- Far Detector is a Liquid Argon Time Projection Chambers (LAr TPC) – fine granularity (1.5 km underground)



DUNE Collaboration is 1,402 collaborators from 206 institutions in 37 countries including CERN

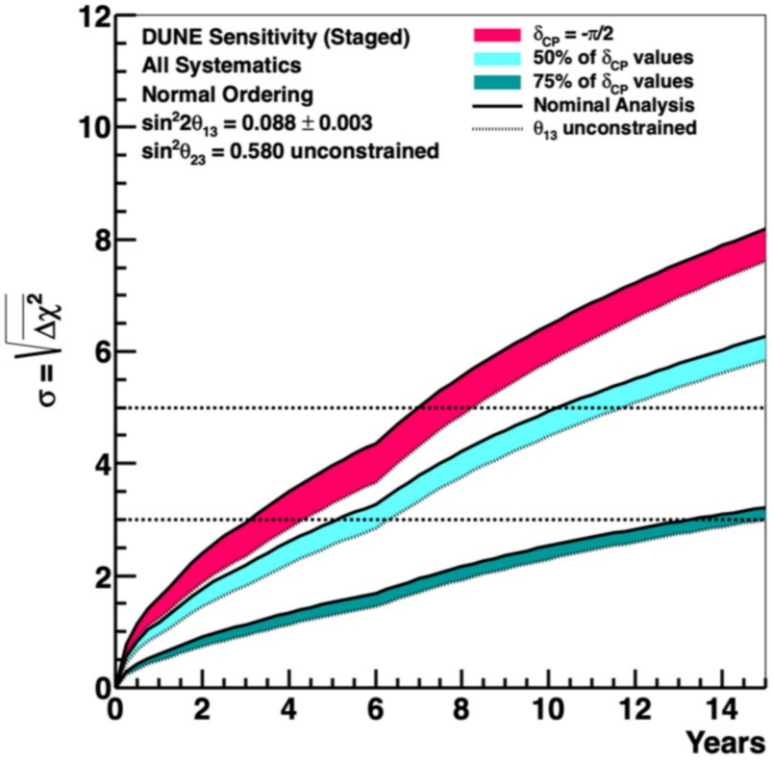
Motivation: Mass Ordering and CP violation

Mass Ordering Sensitivity



- 5σ sensitivity after ~2 years of running

CP violation Sensitivity



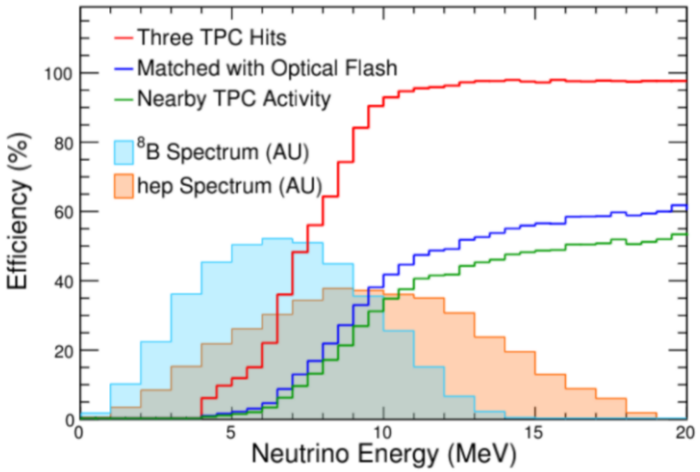
- 5 σ sensitivity after 10 years of running for 50% of δ_{CP} values

+ High precision measurement of $\Delta m^2_{32}, \delta_{CP}, \sin^2\theta_{23}, \sin^2 2\theta_{13}$

DUNE: A general purpose detector

Atmospheric & Solar neutrinos ($^8B/hep$)

- additional probe to neutrino properties and BSM
- DUNE can identify first hep neutrinos
- verify the standard solar model, measure sun's core temperature, characterize neutrino floor, resolve tension between global solar neutrino measurements & KamLAND, characterize MSW affect, measure matter profile of the earth



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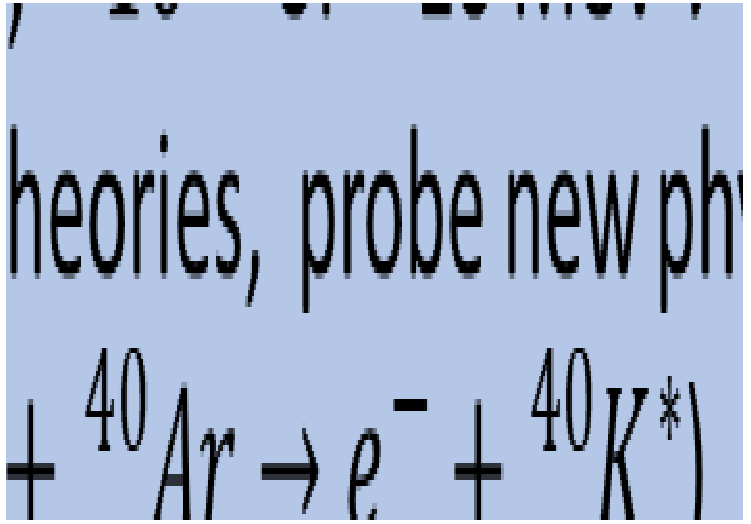
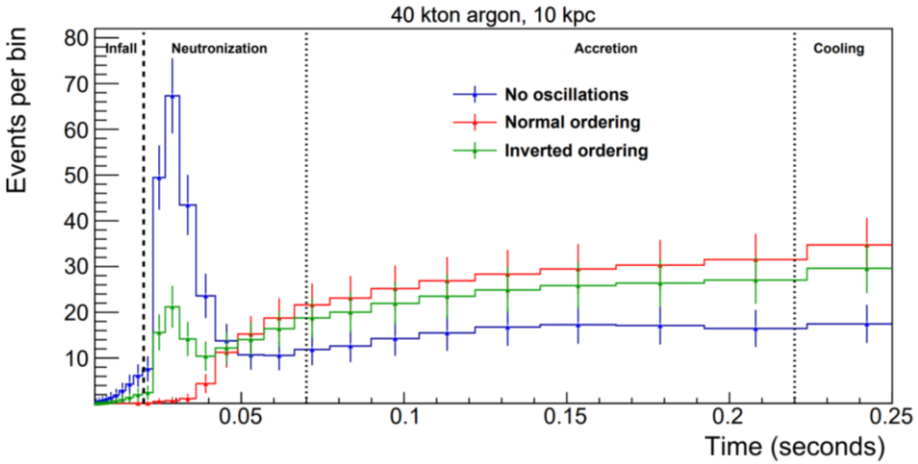
Supernova neutrinos: Core collapses expected to occur few times per century (at 10-15 kpc), ~ 10^{58} of ~ 10 MeV ν emitted for few seconds.
- Test astrophysical theories, probe new physics
- DUNE sees ν - ($\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$)





DUNE: A general purpose detector

Tau neutrino appearance

Atmospheric & Solar neutrinos ($^8B/hep$)

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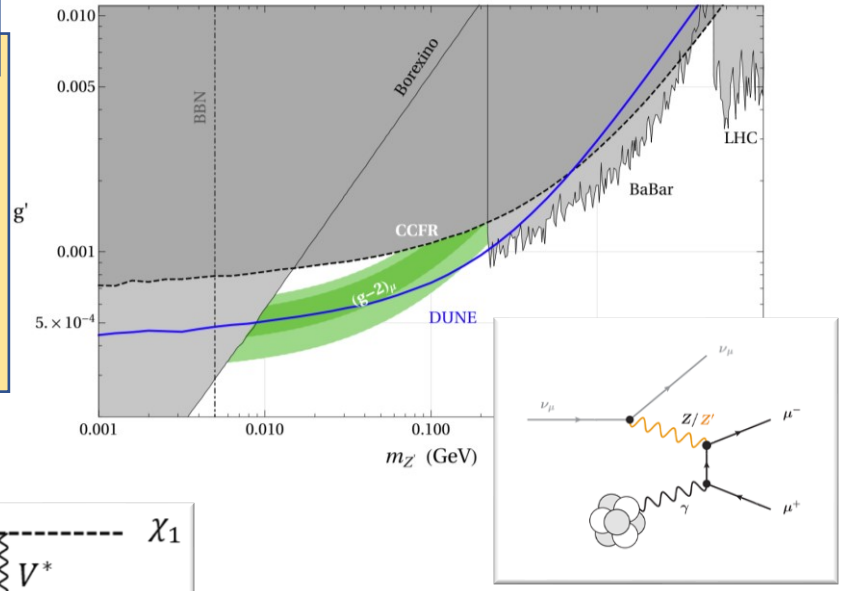

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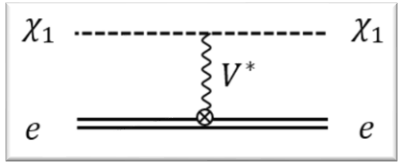
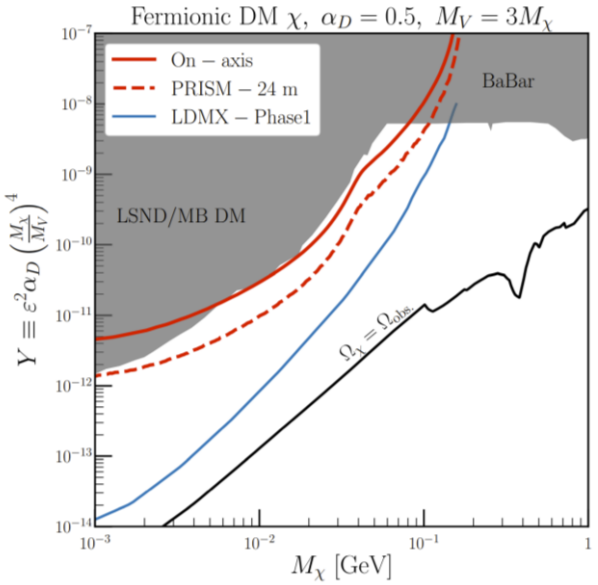
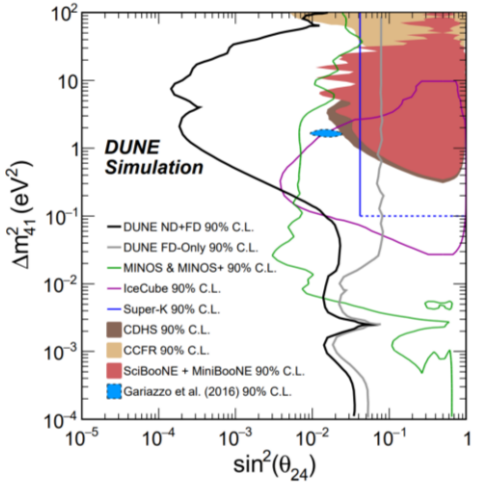


Beyond standard Model

- Light Sterile ν (could explain short baseline/gallium anomalies, hints of CKM non-unitarity and LFV)
- Neutrino tridents (Z' in gauged $L_\mu - L_\tau$ can explain g-2/B-anomalies)
- Non-standard interactions (could explain B-anomalies)
- Dark Matter, Heavy Leptons, Non-PMNS unitarity, Lorentz violation…

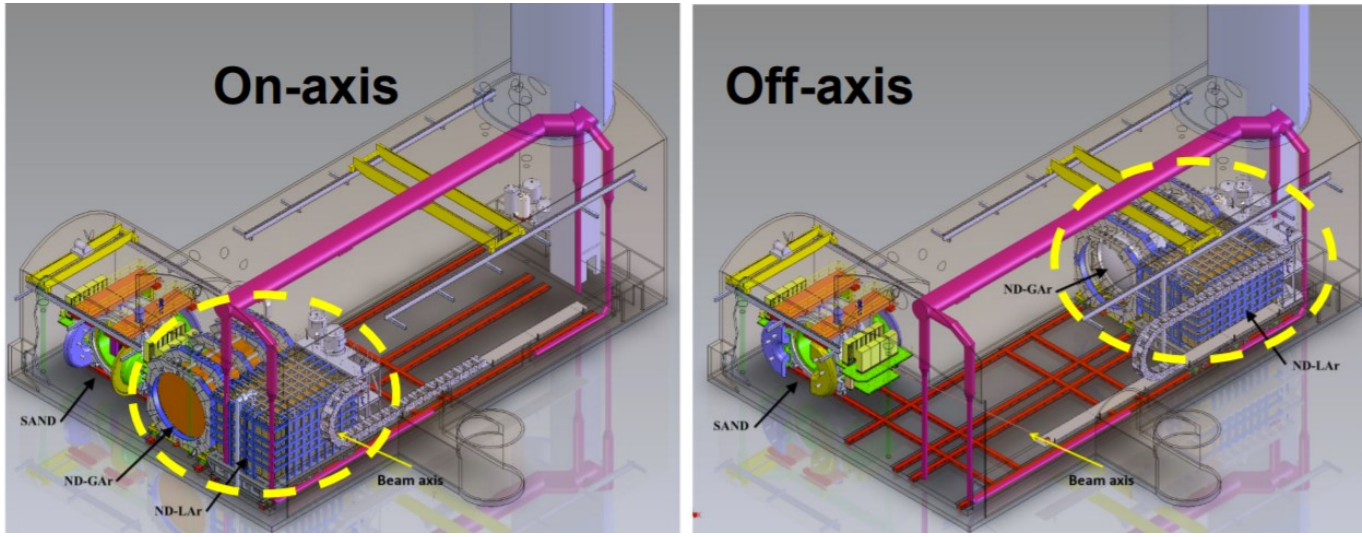




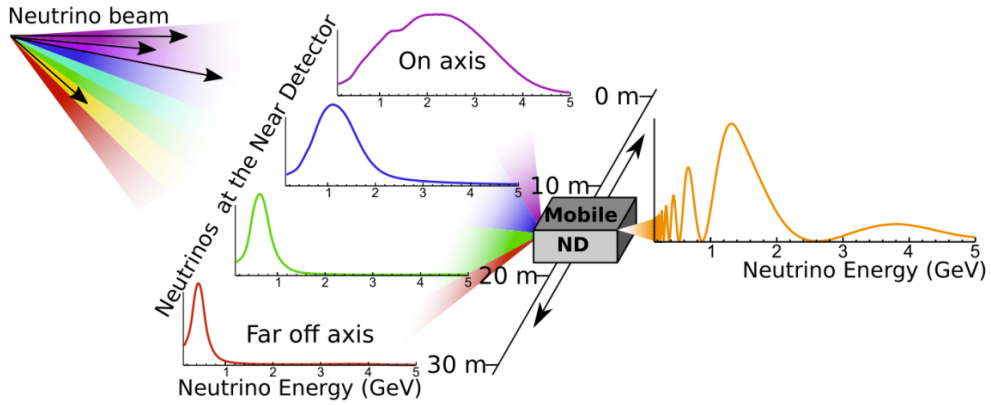
Proto Decay, Baryon Number Violation

DUNE Near Detector

- **ND-LAr:** liquid argon TPC with muon spectrometer (TMS) 50t fiducial mass, modular detector with pixel readout to reduce pileup
  - Similar to FD to characterize beam flux and neutrino interactions
- **ND-GAr**: Gaseous argon detector
  - surrounded by ECAL and muon system in magnetic field
  - good tracking resolution, can study low-p_T ν Ar interactions
- **SAND**: System for on-Axis Neutrino Detection
  - Inner tracker & ECAL in magnetic field to measure neutrino cross sections & monitor beam
- **PRISM** for ND-LAr/GAr: Precision Reaction-Independent Spectrum
  - Can measure flux at different off-axis angles,

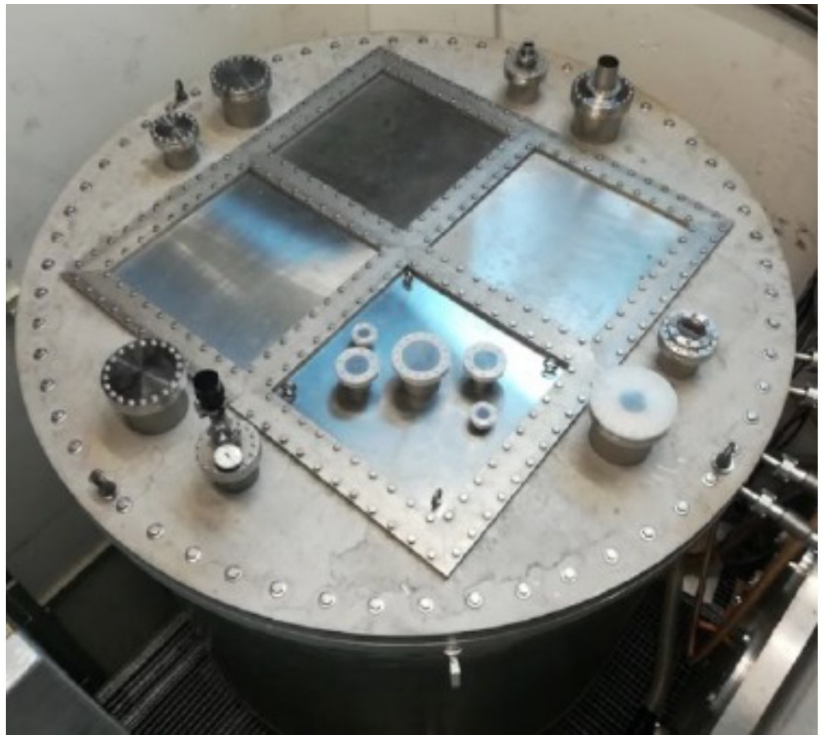


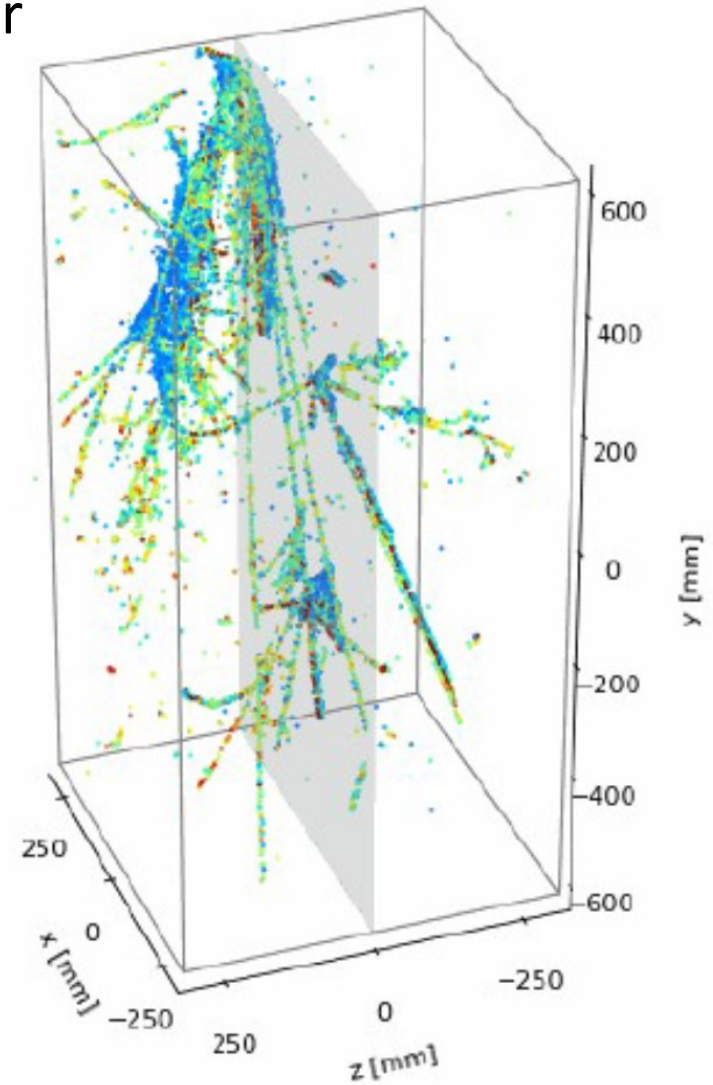
DUNE PRISM



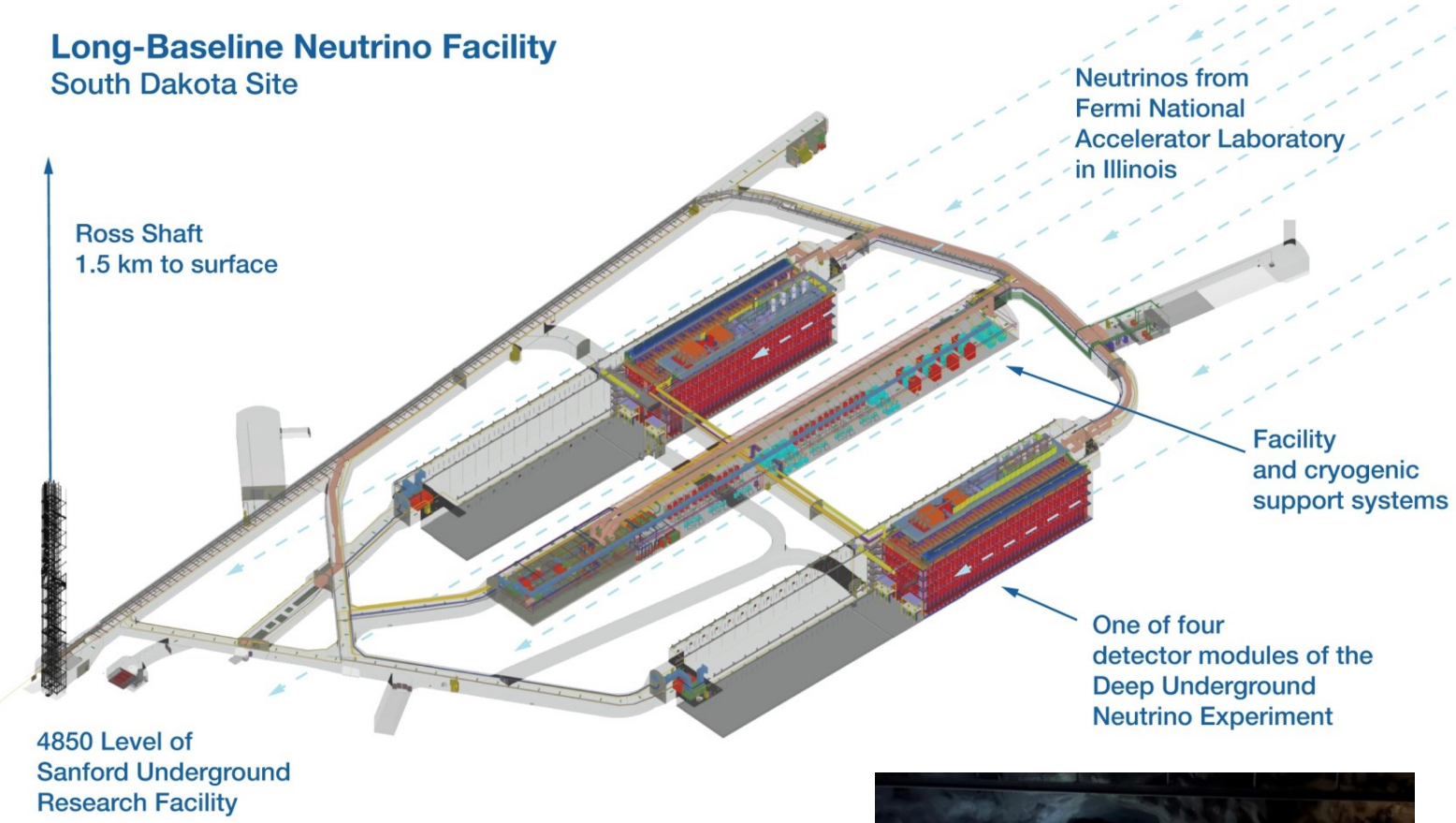
DUNE Near Detector Prototype

- ND-LAr 2x2 prototype modules constructed at Bern
- Being shipped Fermilab in the fall for run with NuMi next year
- re-purposed MINERvA scintillator and calorimeter planes are installed as a muon telescope and calorimeter





DUNE Far Detector



Excavation 75% completed!

- 4 Far Detector modules in cryostats (15.1m wide x 14 m high by 62 m long) of about 17 kt mass

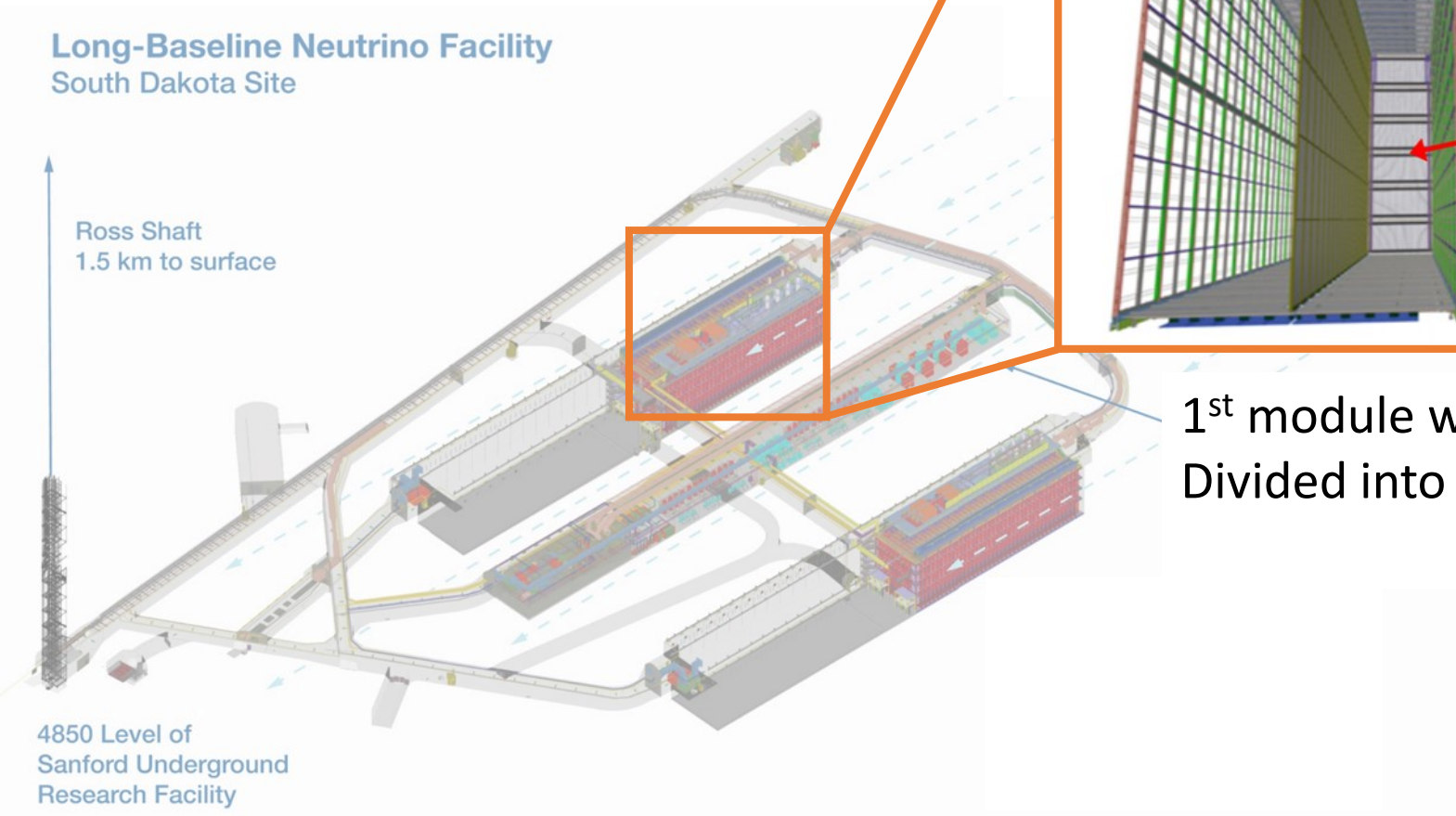
Phase I

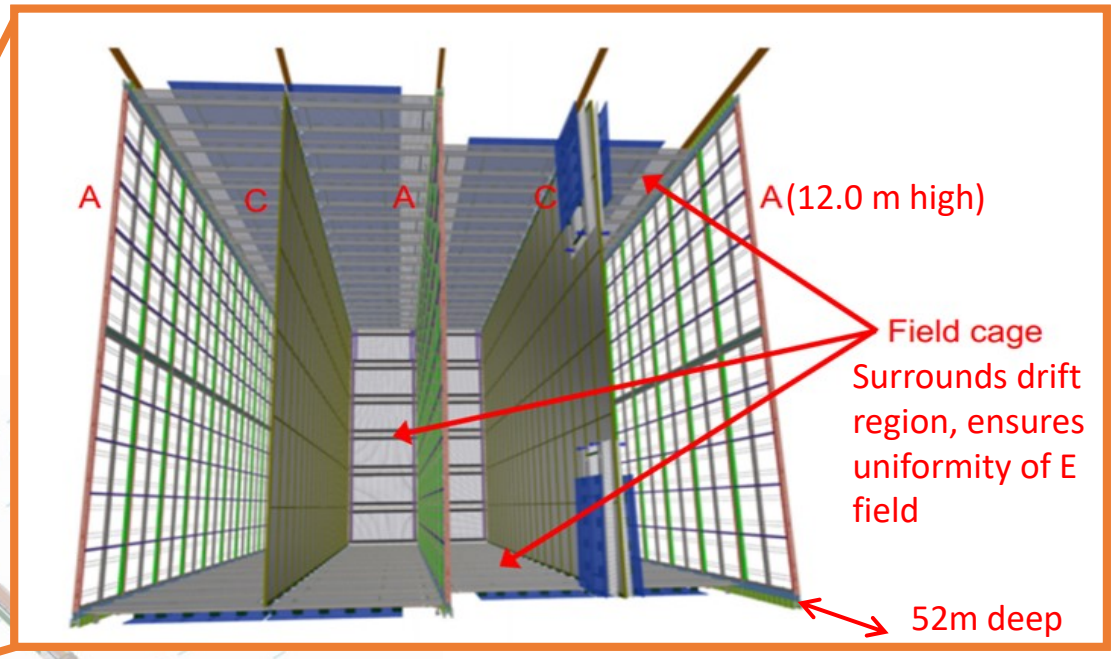
- 1st module - Single Phase (SP), horizontal drift, LAr Time Projection Chamber (LArTPC), data taking 2028
- 2nd module - SP vertical drift LAr TPC
- ND: NDLAr+TMS+SAND
- 1.2 MW beam power

Phase II

- 3rd / 4th module - to be defined
- ND-GAR
- up to 2.4 MW beam power

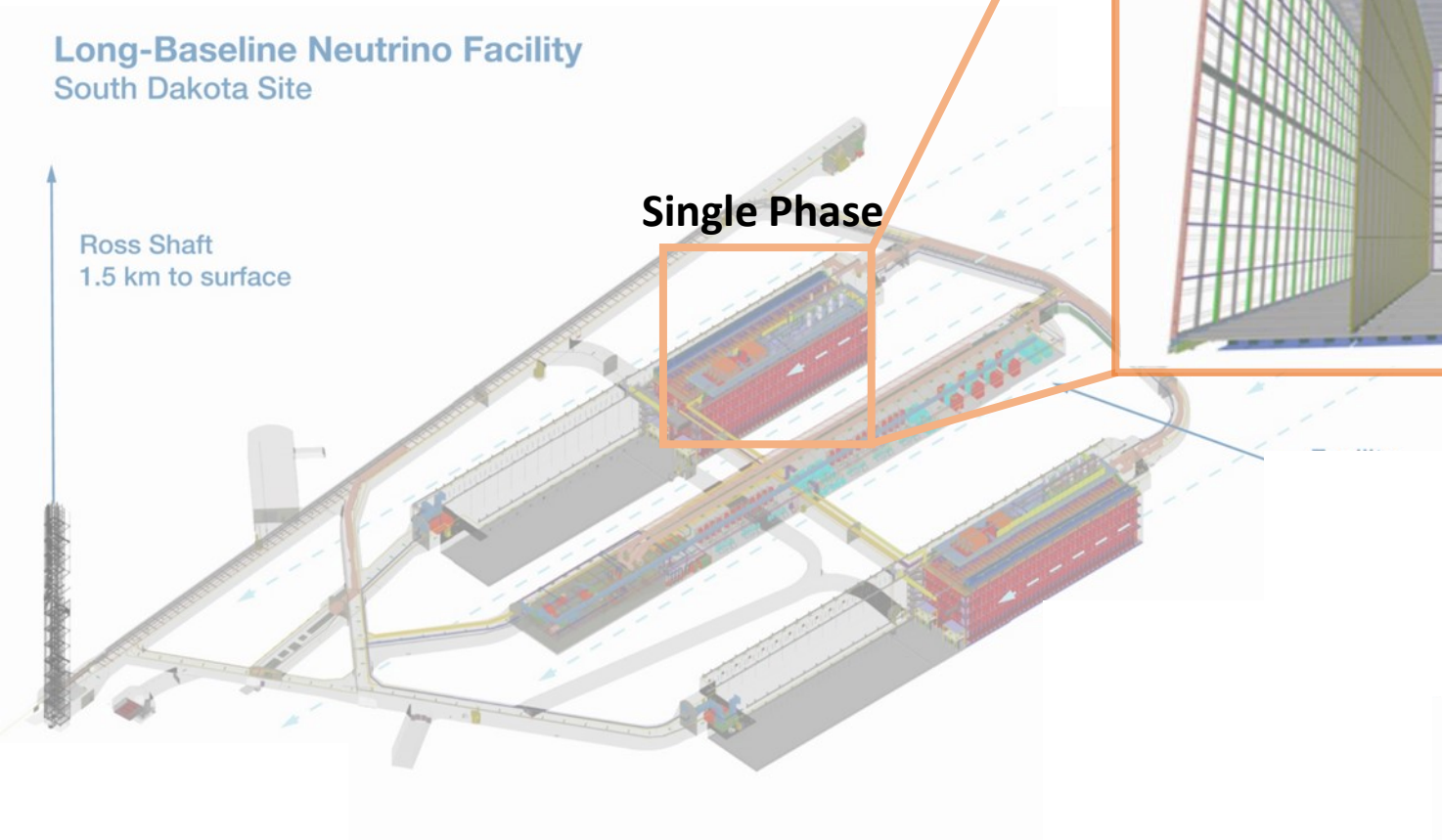
DUNE 1st Module

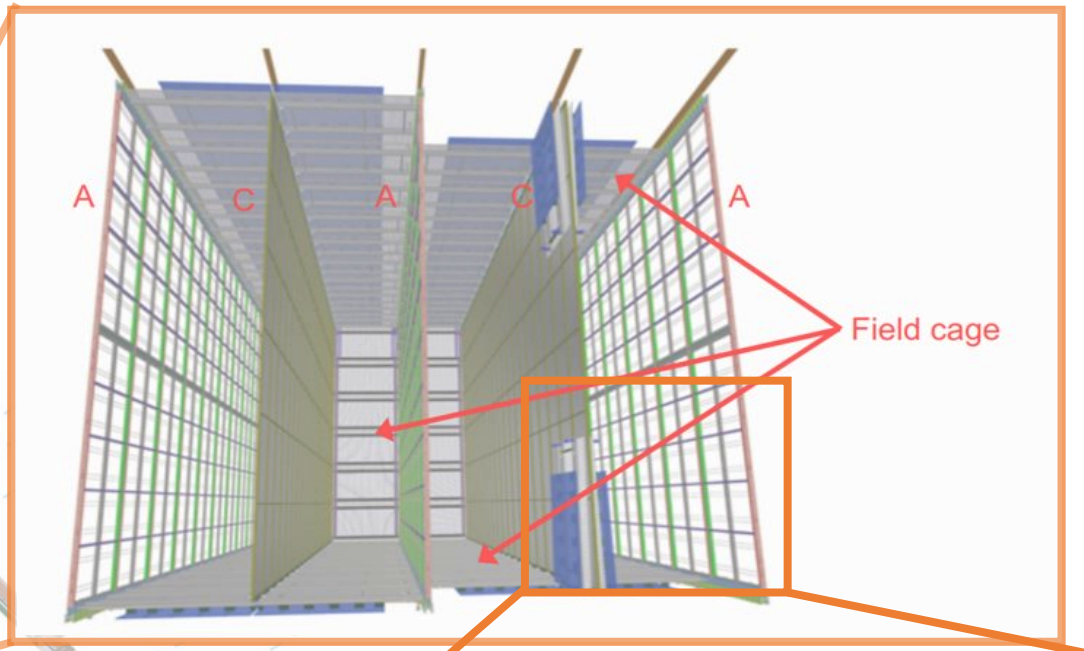


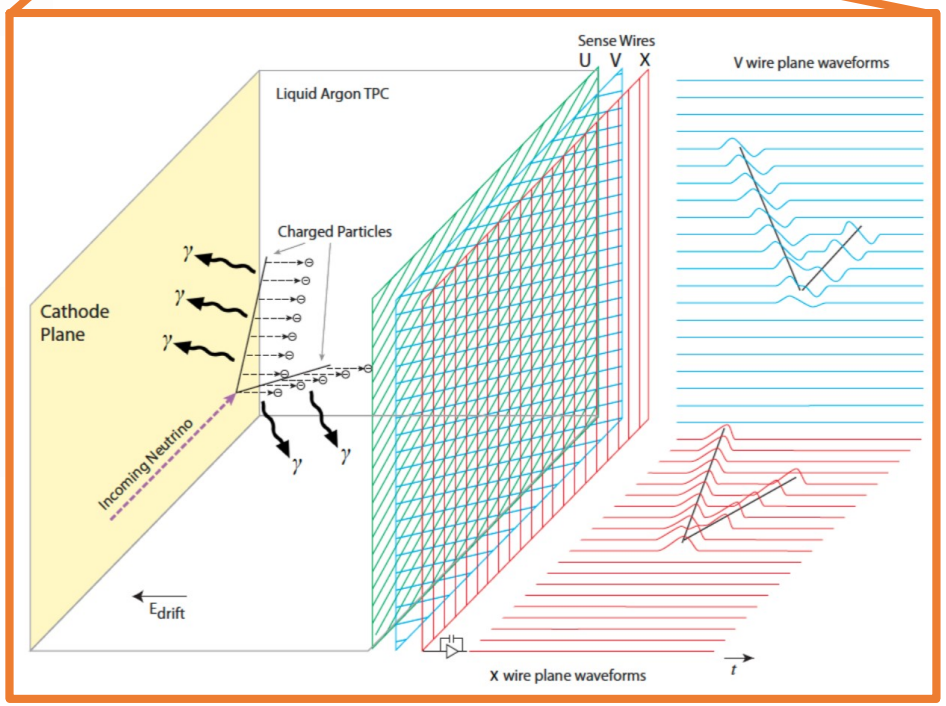


1st module will be Single Phase (SP), LAr TPC.
Divided into 4 sections

DUNE 1st Module



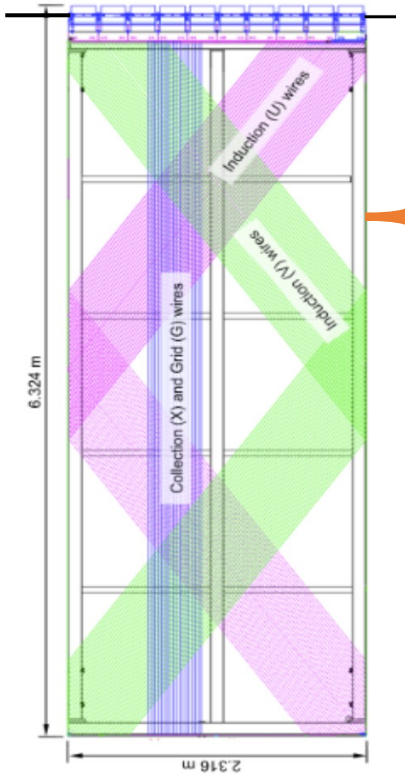


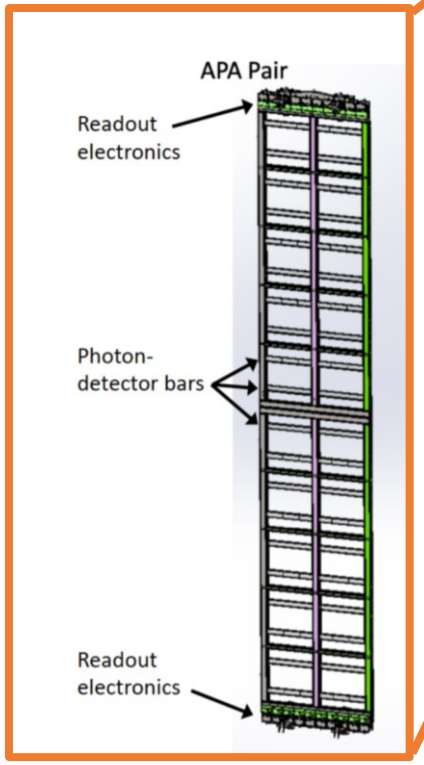


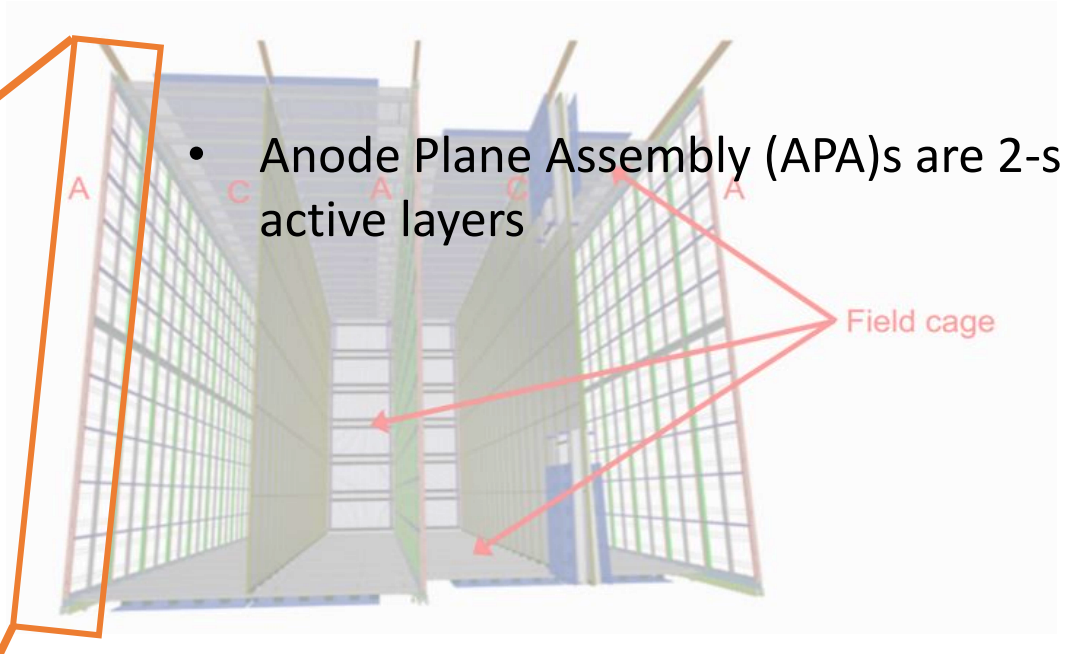
- 3D image of neutrino interactions with mm resolution
  - 3.5m drift region, E field of 500 V/cm, Cathode HV 180 kV

- LAr is good scintillator ⇒ provide t_0 (non-beam trigger)

DUNE 1st Module

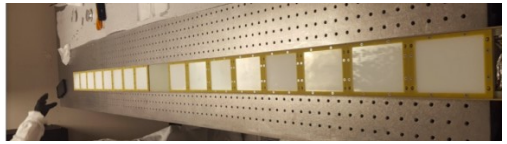


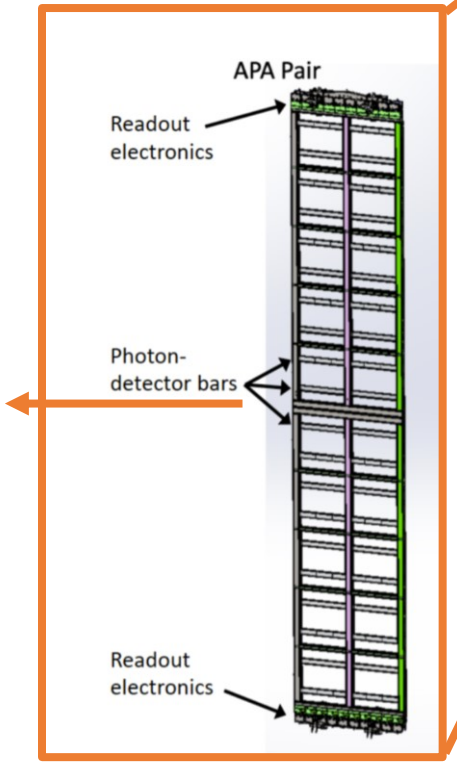


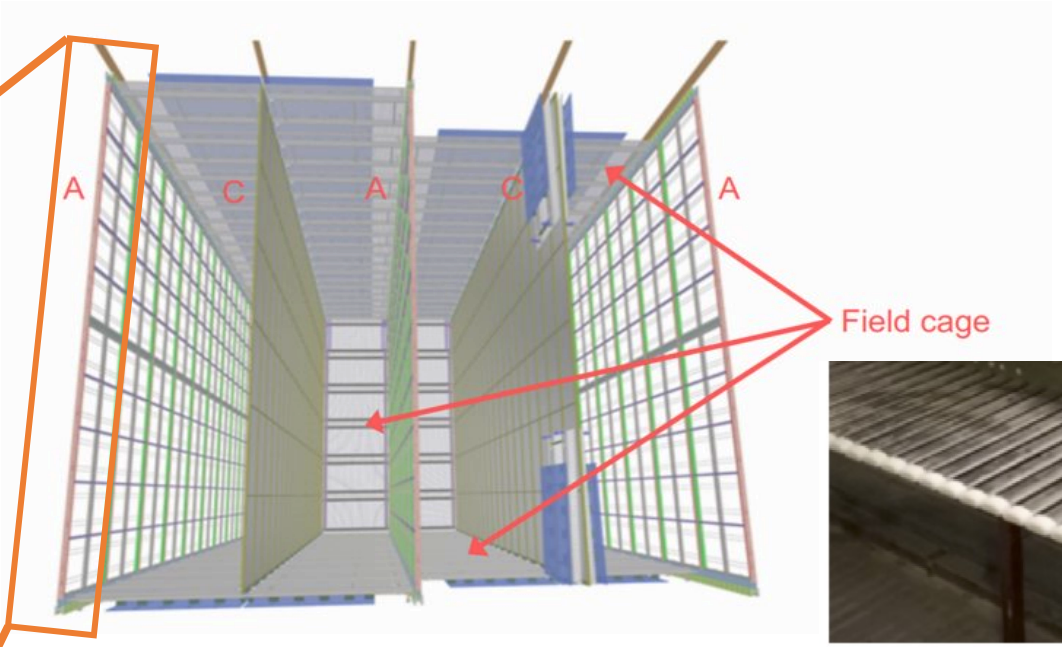


- Anode Plane Assembly (APA)s are 2-sided, with 3 active layers

DUNE 1st Module



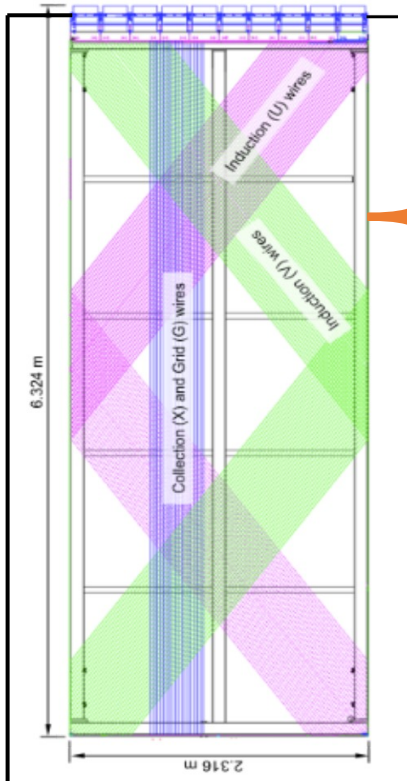


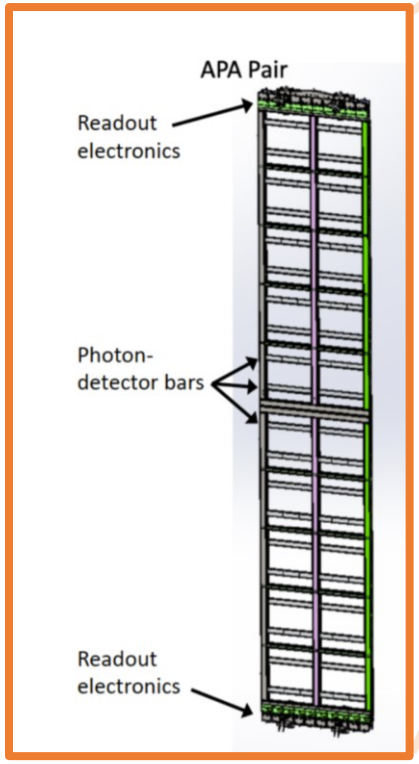


aluminum with white polyethylene caps on the ends to prevent discharges

- Photon detection provides time of interaction, and can serve to identify backgrounds, non-beam physics trigger (Supernova, proton decay, etc.)
- Photons collected by X-ARAPUCAs
  - layers of dichroic filter and wavelength-shifter
- Signals sent to feedthroughs in roof of cryostat, merged with APA data at DAQ

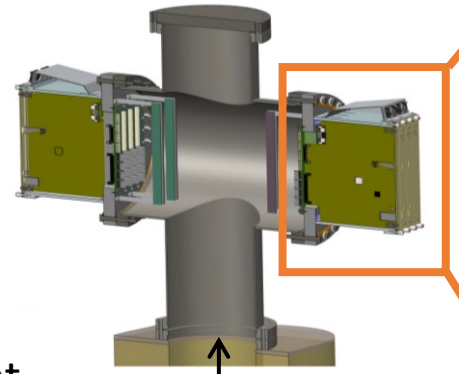
DUNE 1st Module

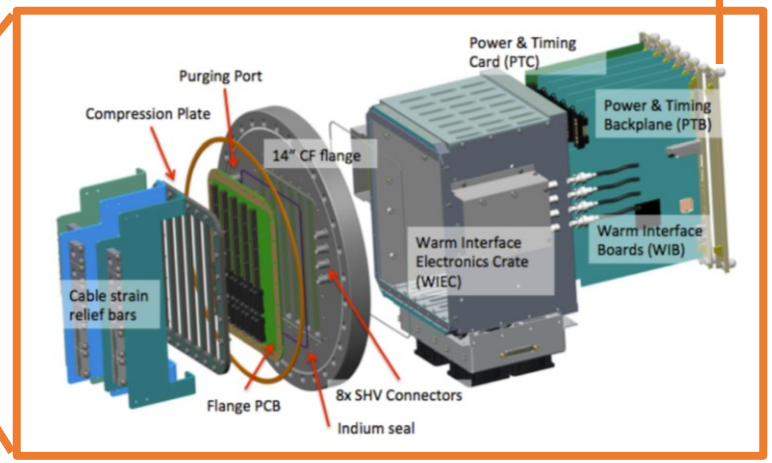




- Anode Plane Assembly (APA)s are 2-sided, with 3 active layers
- Front-end motherboards (FEMBs) in the cryostat (87K) to reduce thermal noise shape, amplify, digitize signal
- Outside cryostat, signals go warm interface boards (WIBs) that put the signals onto 10 GB optical fibers, that are connected to upstream DAQ

DAQ





Front-end motherboard

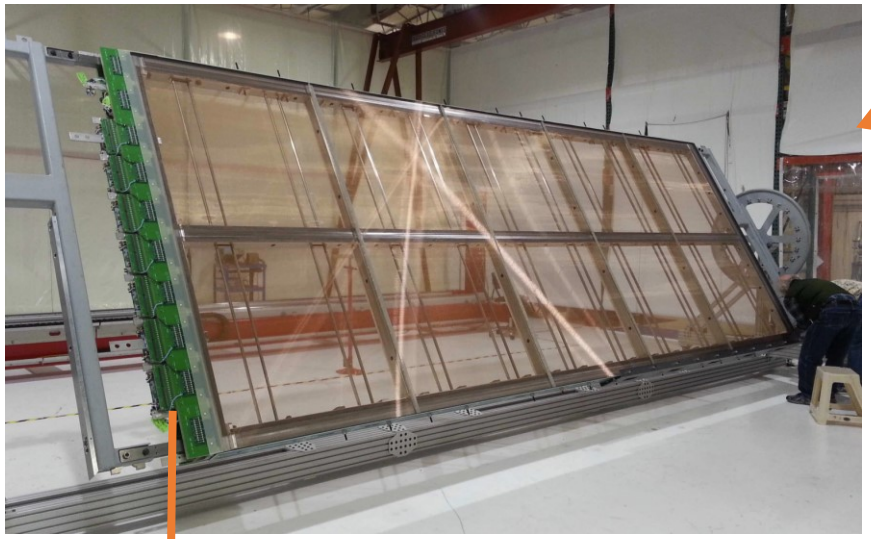
40 u wires
40 v wires
48 x wires (collection)

FE ASIC	x8	ADC ASIC	x8	COLDATA ASIC	x2
Shaping & amplification		Analogue to digital		Merge data streams Control & comms	

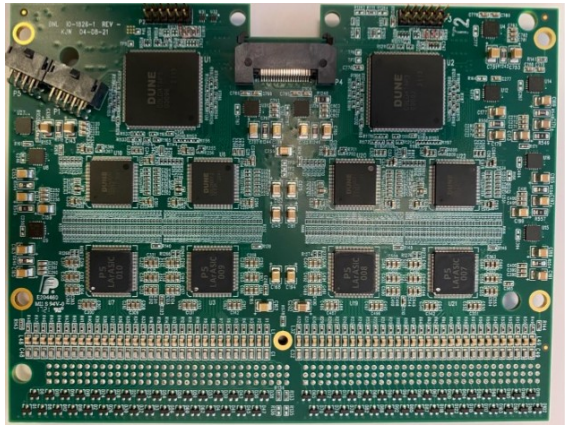
Outside Cryostat

x 20 per APA

Prototyping



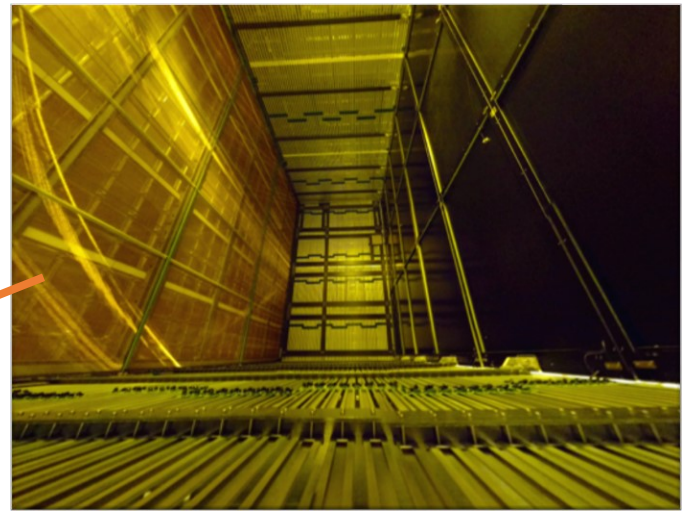
APA



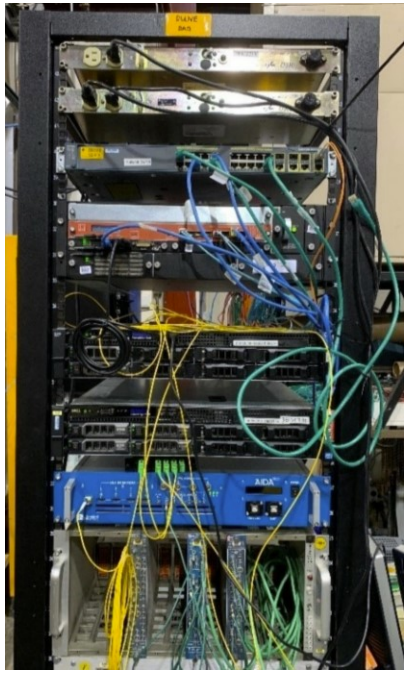
FEMB

Outside Cryostat

WIB

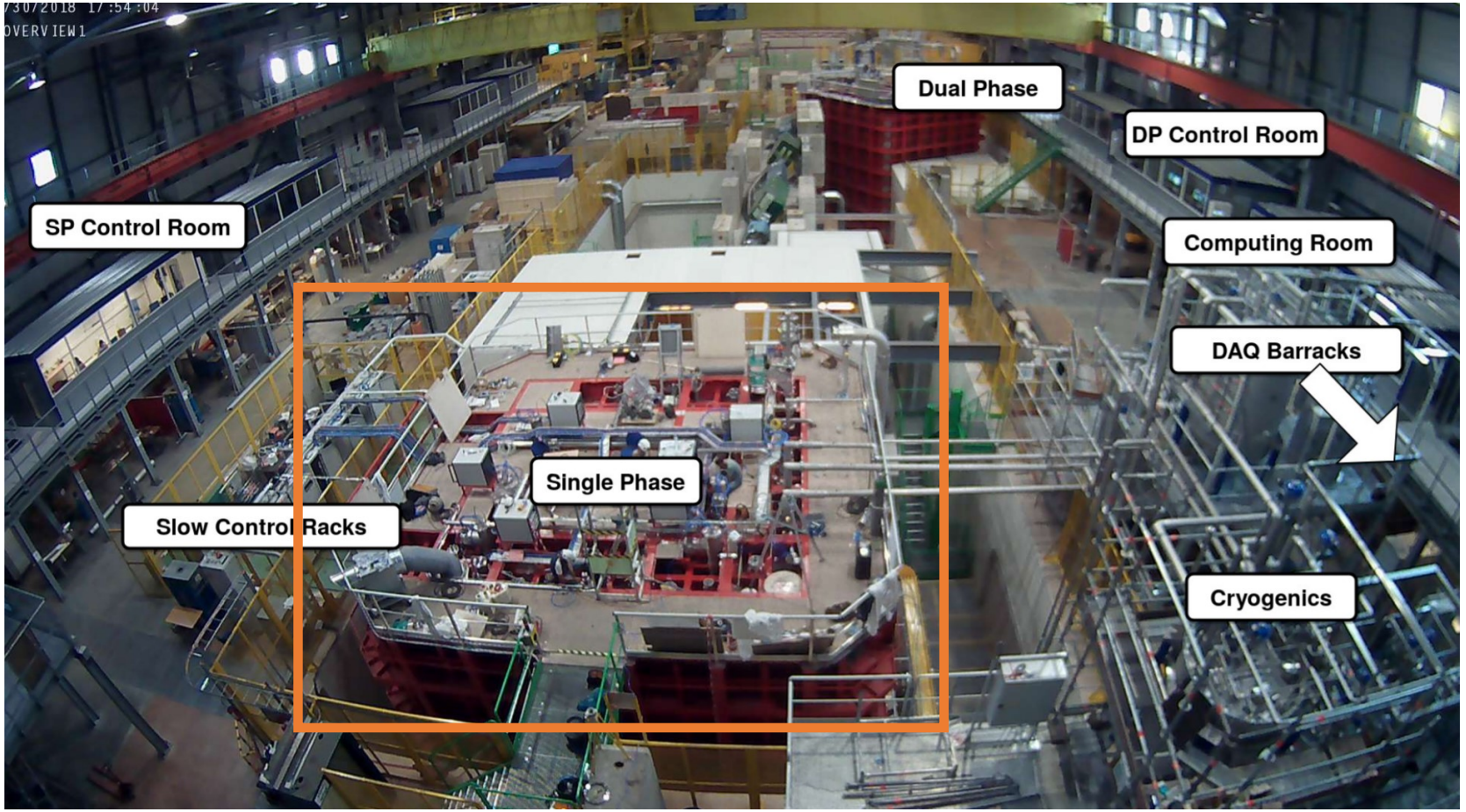


ProtoDUNE SP Drift Region

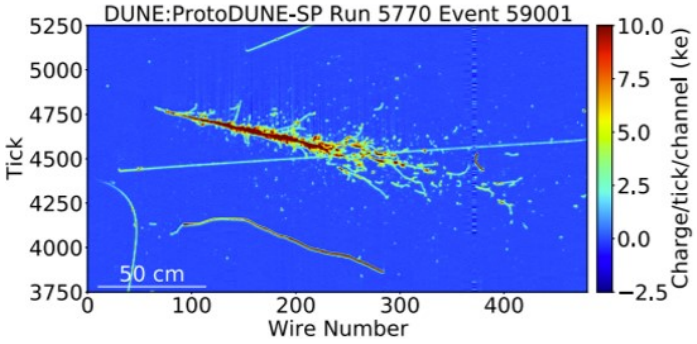


DAQ

ProtoDUNE



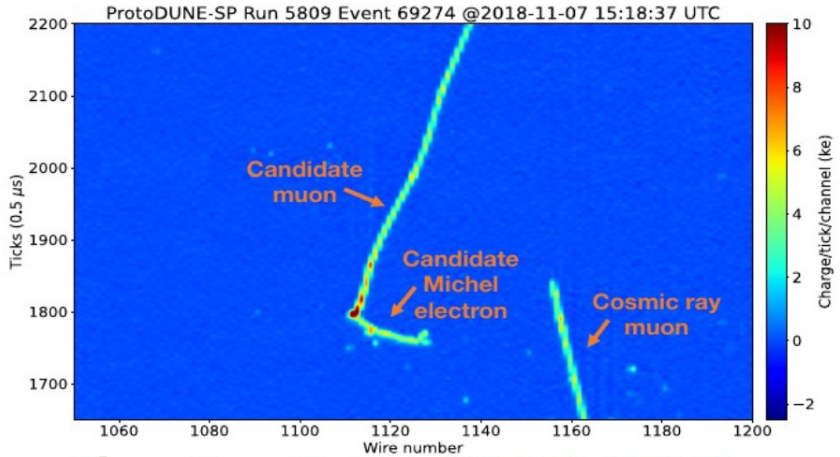
- At CERN neutrino platform, have built 2 prototypes, protoDUNE (15K sense wires)
- Collected hadron data 2018-2020, excellent performance!
  - 99.7% of electronics responsive, 99% HV uptime, high purity
- Will run again next year with vertical drift design!



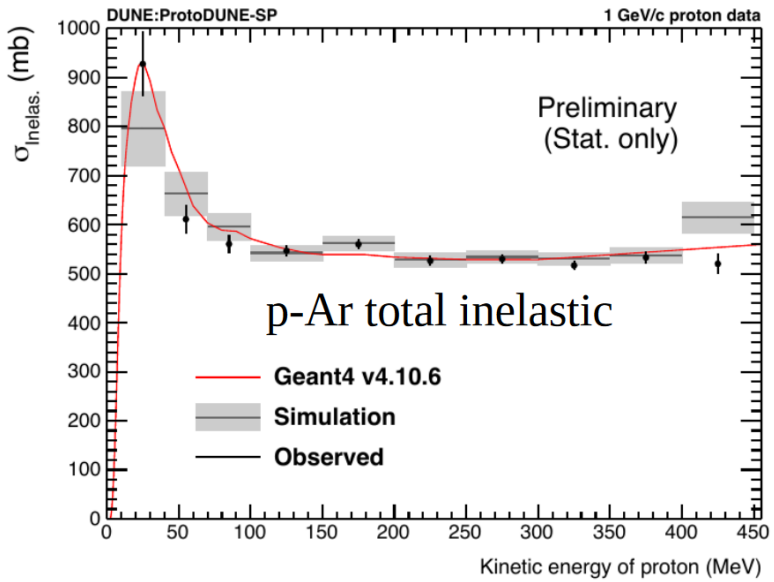
6 GeV electron

JINST 15 (2020) 12, P12004
JINST 17 (2022) 01, P01005

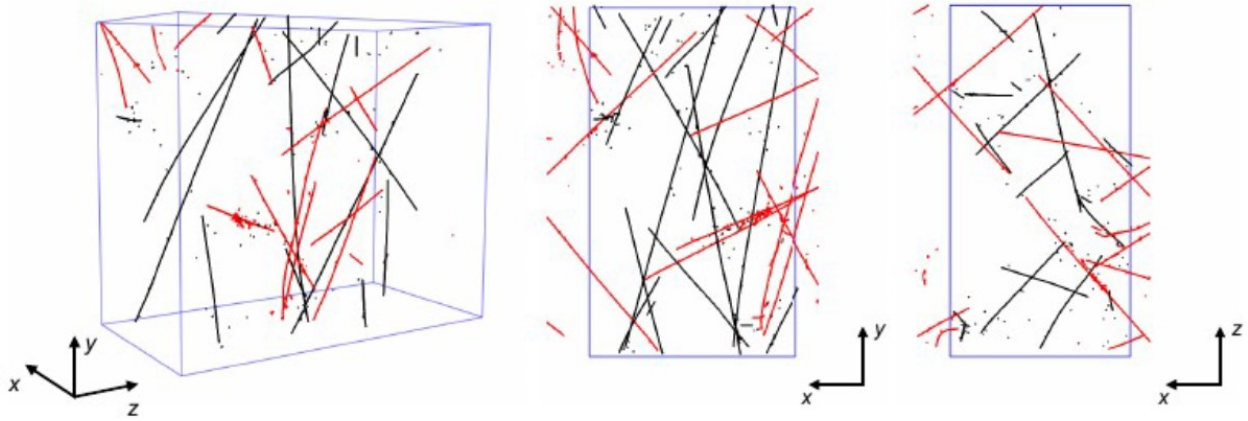
ProtoDUNE Physics



Phys. Rev. D 107, 092012 (2023)



Eur. Phys. J. C 83, 618 (2023)



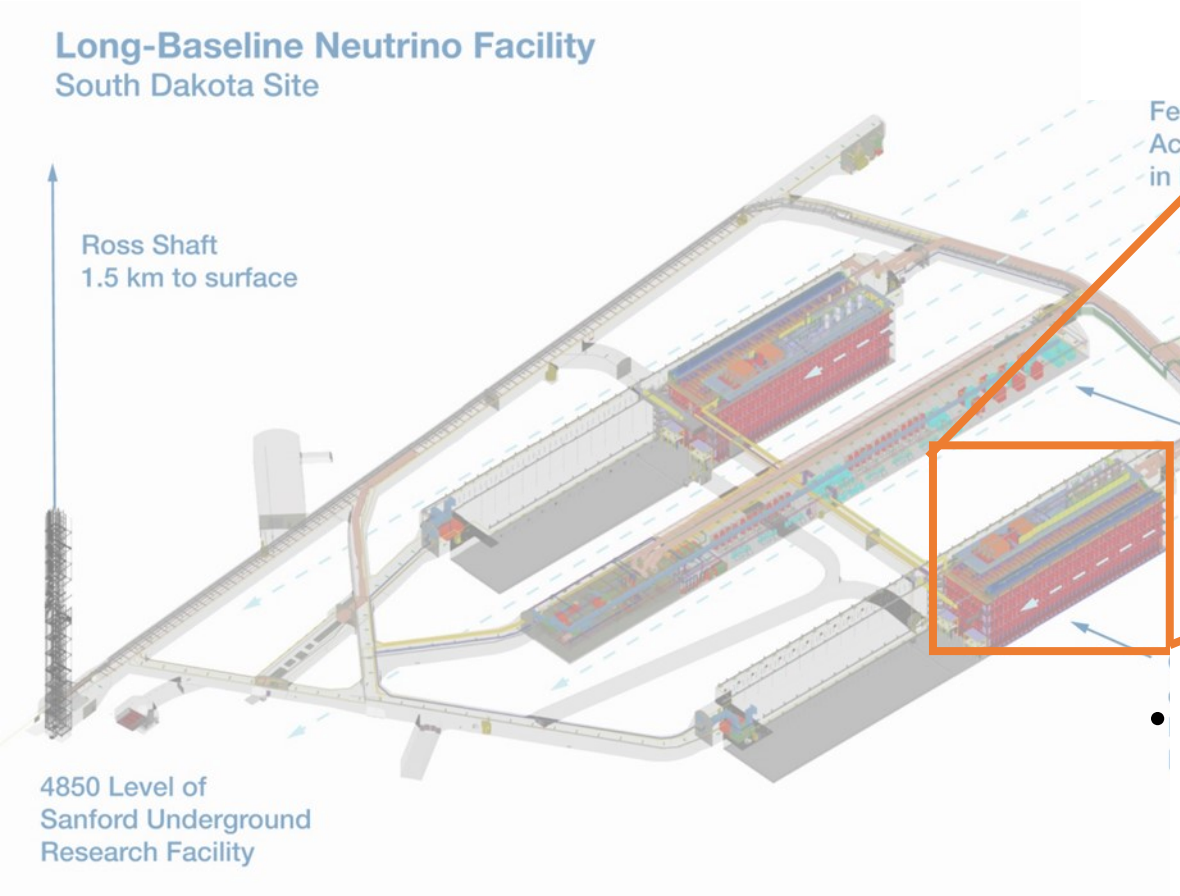
Two new papers on:

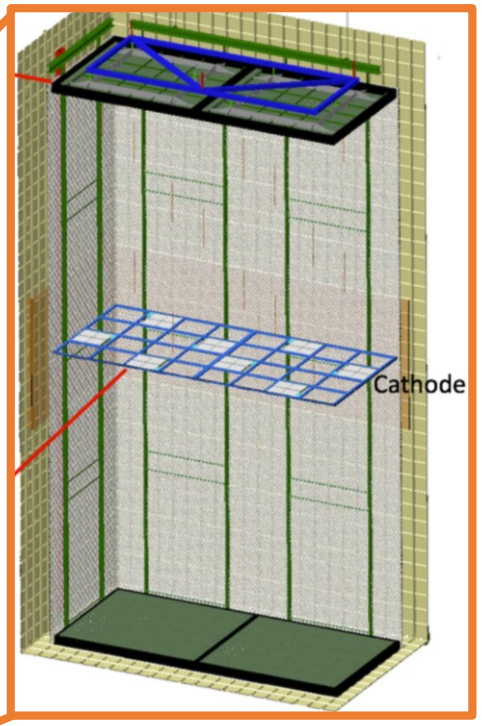
- Identifying and reconstructing Michel electrons from stopping muons
- Pandora reconstruction performance for cosmic rays and beam particles

One coming next year:

- Measurements of pion/proton/neutron/kaon-Argon inelastic scattering, absorption, and charge exchange

DUNE 2nd Module





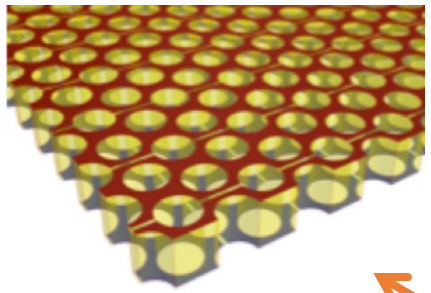
- The large measured value of electron lifetime (> few ms) in big LArTPCs allows for vertical drift without signal amplification

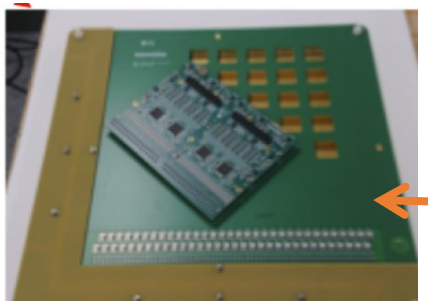
- Ionized charges drift vertically, read out on horizontal PCB anode and cathode planes (two 6.5 m drift volumes). E field 450 V/cm
- This design simplifies construction/installation and reduces cost

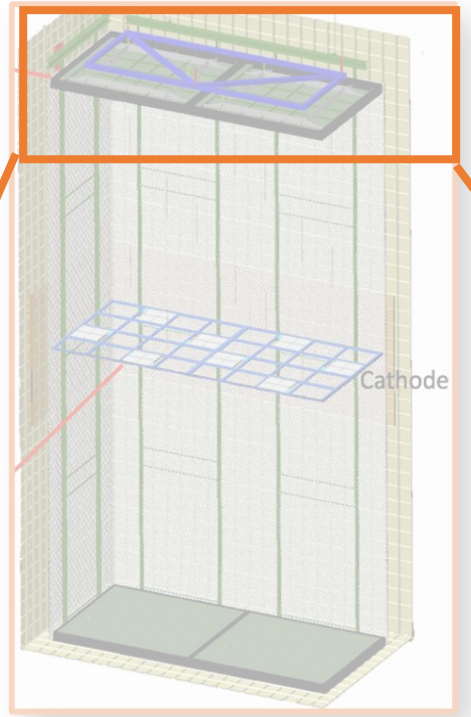
DUNE 2nd Module

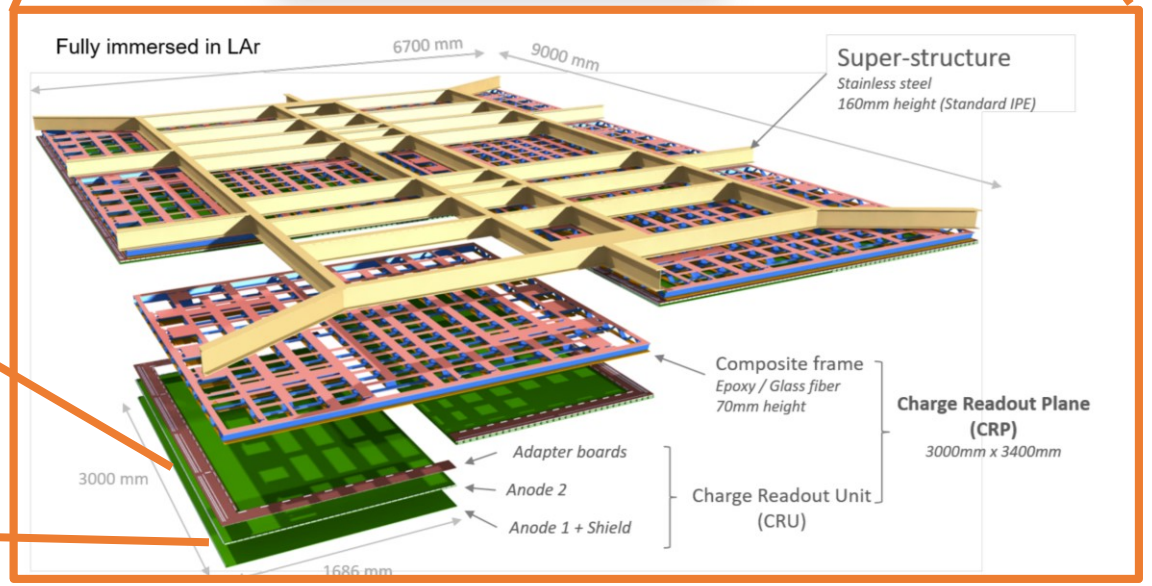
- Charge Readout Plane (CRP) consists of anodes made from two double-sided perforated PCBs (3.2 mm thick), and steel frame. Perforated PCBs have holes so electrons can go to collection strips. Emersed in LAr
- Top CRPs suspended from cryostat roof using superstructure, bottom CRPs supported by posts

- Anode 1 (facing drift volume) has a copper guard plane to absorb unexpected discharges. Anode 2 has induction plane strips facing the drift volume, and collection plane strips on the reverse side
- 3 of electrode strips segmented at 5 mm pitch and set at different angles to give different projections



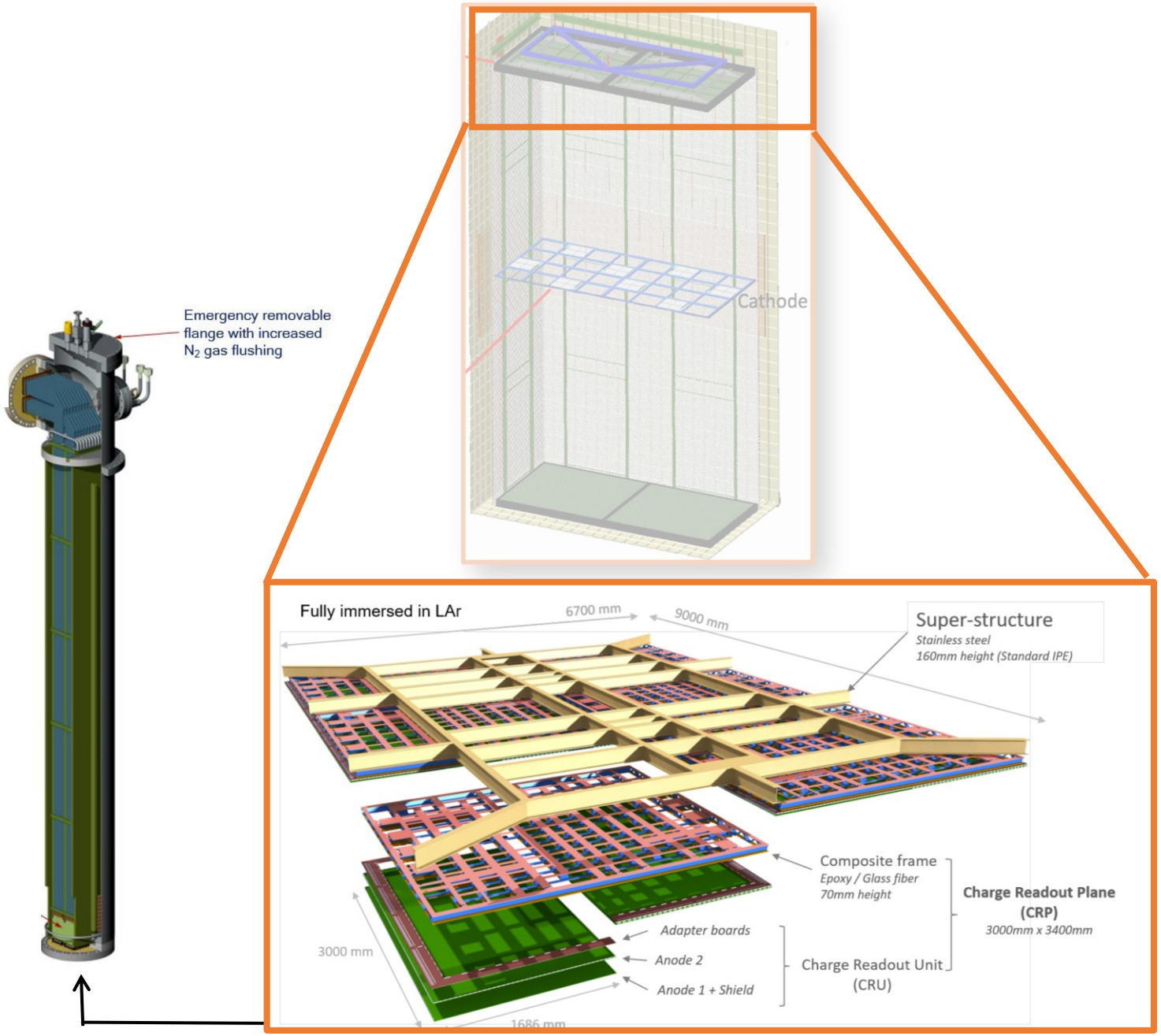






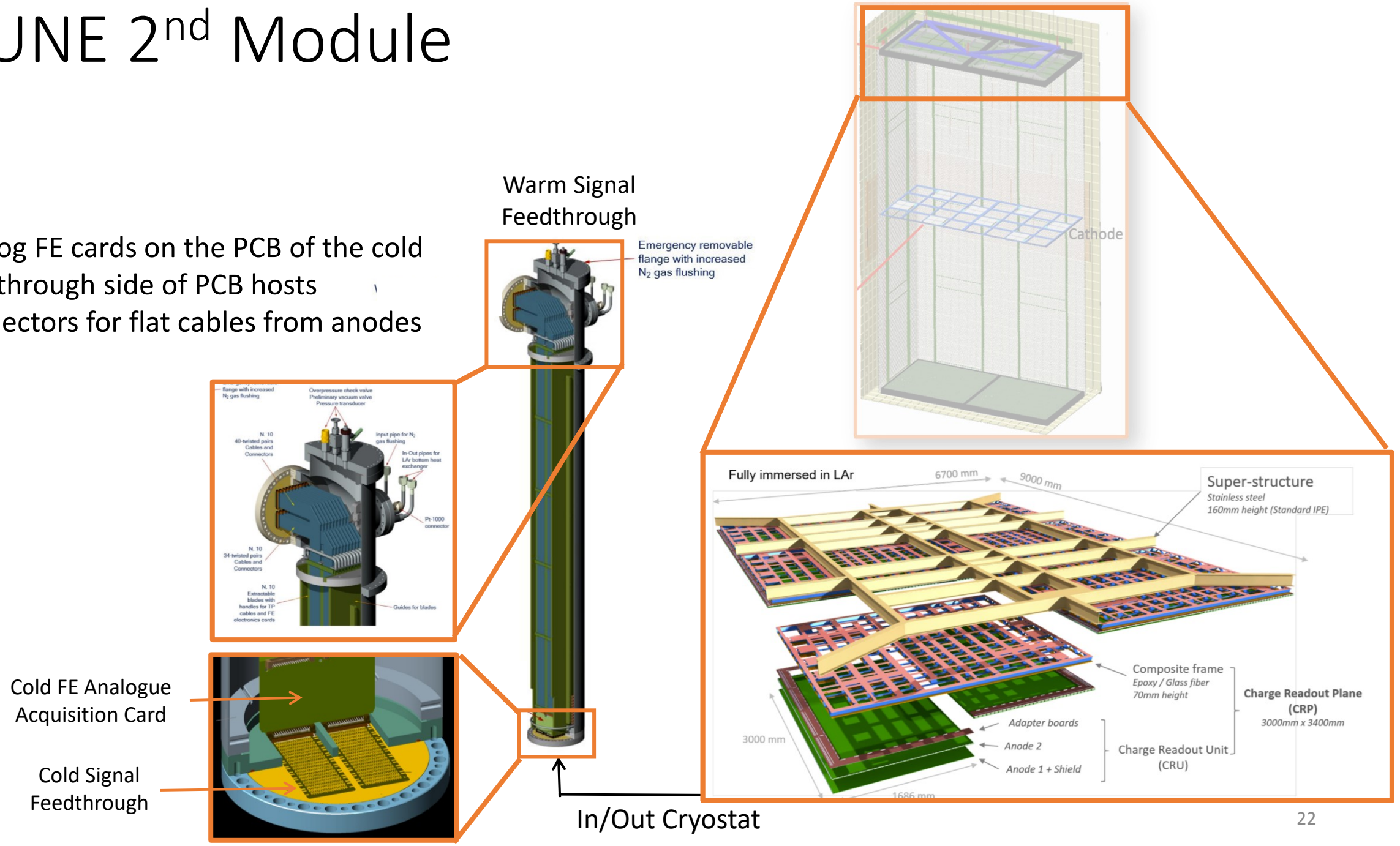
DUNE 2nd Module

- Signals from bottom CRP readout like the APAs in horizontal drift detectors
- Signals from top CRP collected by Signal Feedthrough Chimneys (SFC), which are pipes that penetrate the cryostat. SFCs are filled with nitrogen gas and sealed by ultra-high vacuum flanges

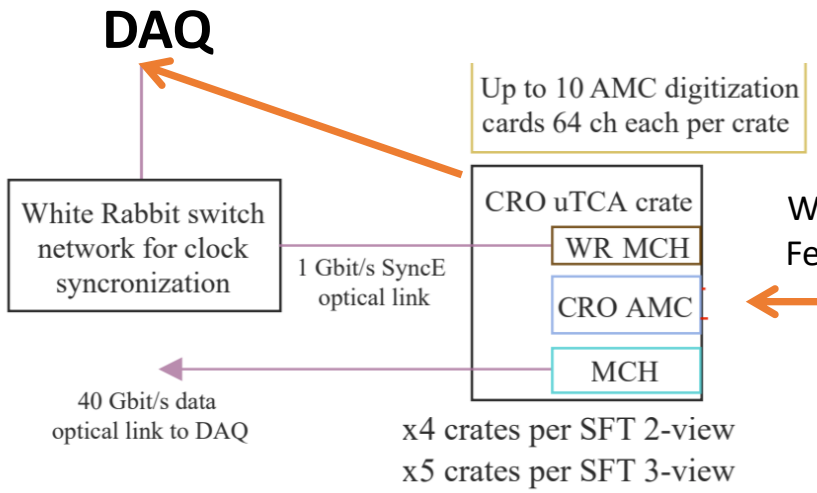


DUNE 2nd Module

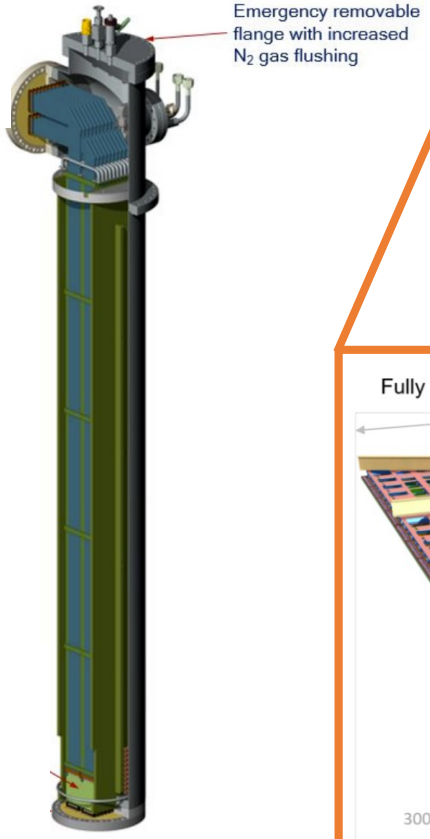
- Analog FE cards on the PCB of the cold feedthrough side of PCB hosts connectors for flat cables from anodes

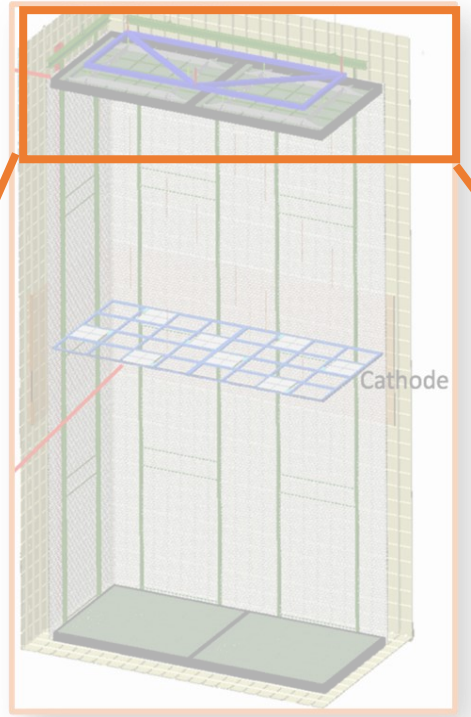


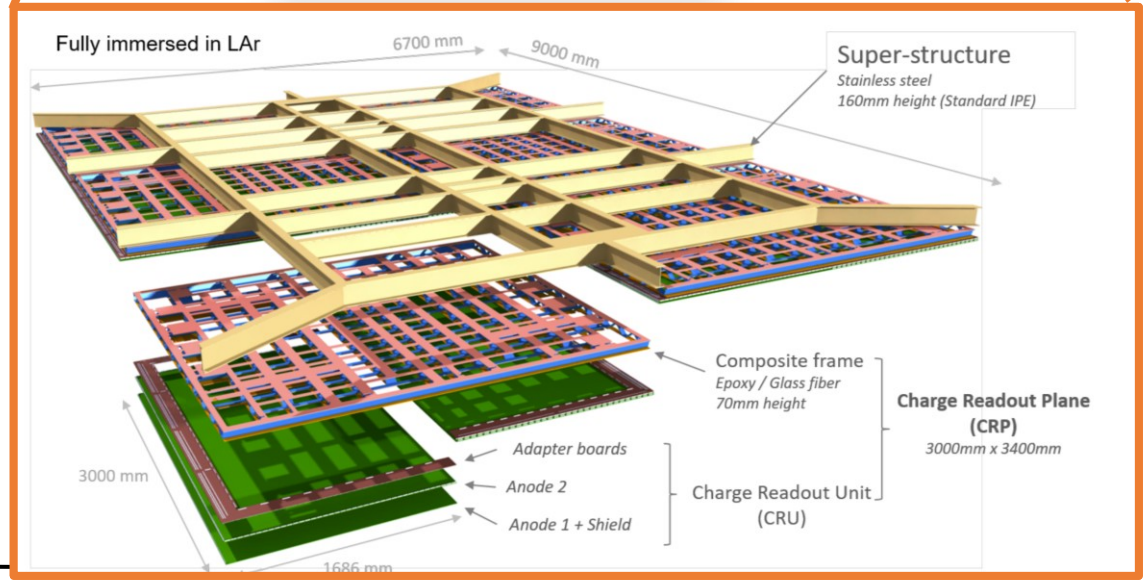
DUNE 2nd Module



Warm Signal Feedthrough







In/Out Cryostat

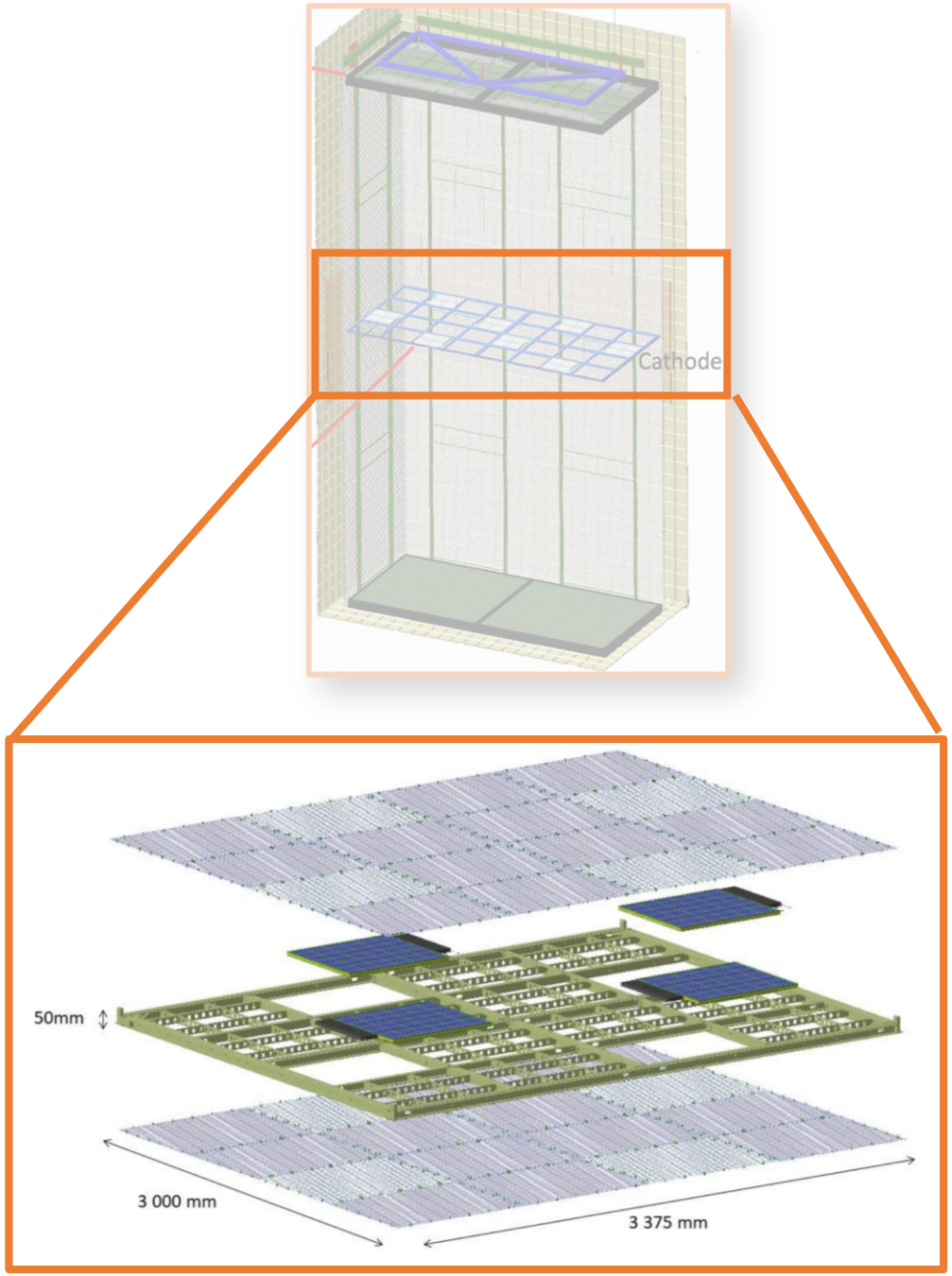
- Each SFT chimney sends data to Micro Telecommunications Computing Architecture (µTCA) crate, containing AMC cards.
- AMC cards read and digitizes signal and sends to DAQ via optical fiber. AMCs have ADC chips and FPGA (Alterra6 Cyclone V)

DUNE 2nd Module

- Cathode modules mounted on fiber reinforced plastic (FRP) frames. Hangs from top support structure and held at −294 kV (a challenge!)

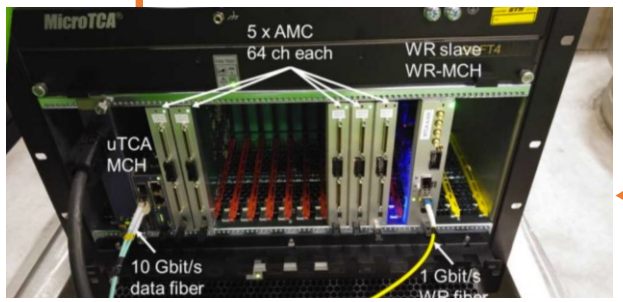
- Although CRP is perforated, opaque to light and therefore PDs can't be installed at anode. Thus each cathode module holds 4 double-sided X-ARAPUCA PD modules, exposed to top and bottom drift volumes. Frame has openings for PDs (blue)
  - Wavelength-shifted photons converted to electrical signals by 160 SiPMs that sit around perimeter of module

- Challenge: converting electrical signals to optical signals in LAr- R & D on the way to identify cold transceiver solutions operating at LAr temperature

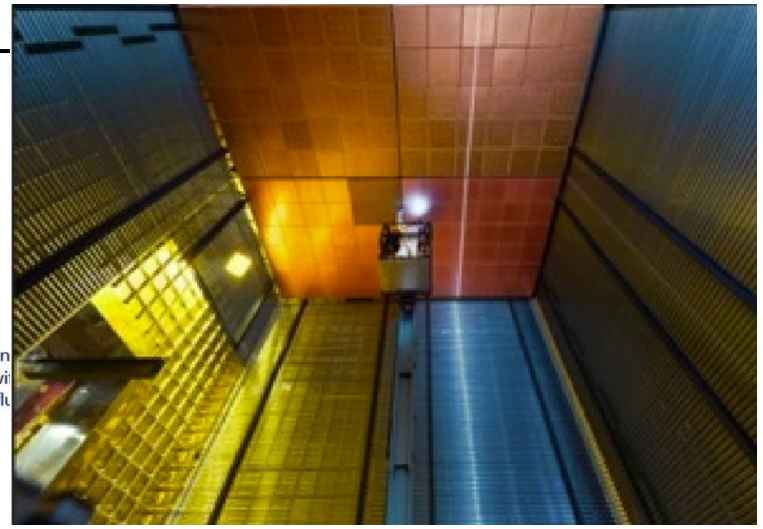


Prototypes

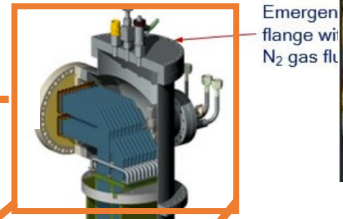
DAQ



μTCA with AMCs

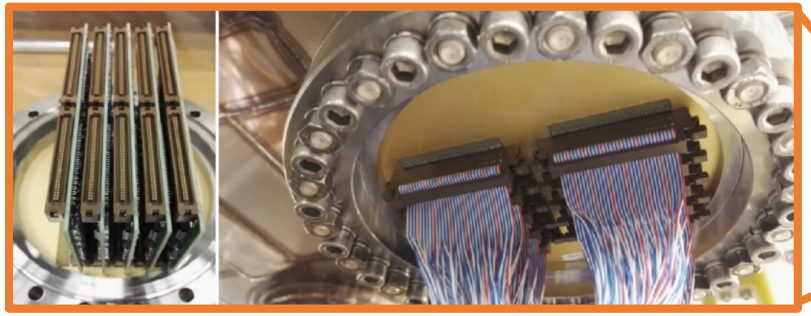


ProtoDUNE vertical drift run in 2024



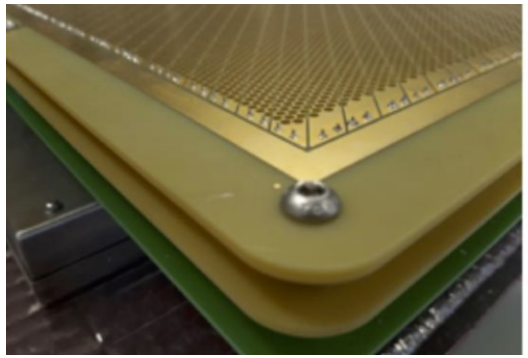
Vertical Drift Chamber
(from ProtoDUNE)

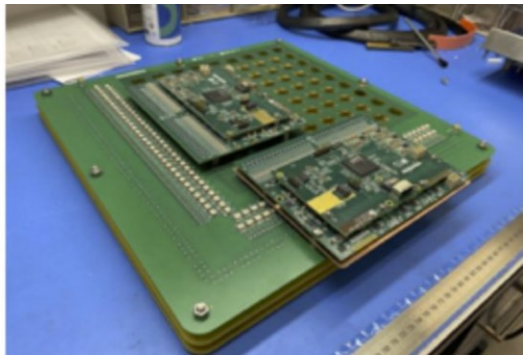
Warm Signal Feedthrough



Cold FE Analogue Acquisition Card

ANODE & Cold FEMBs
(from test stand)





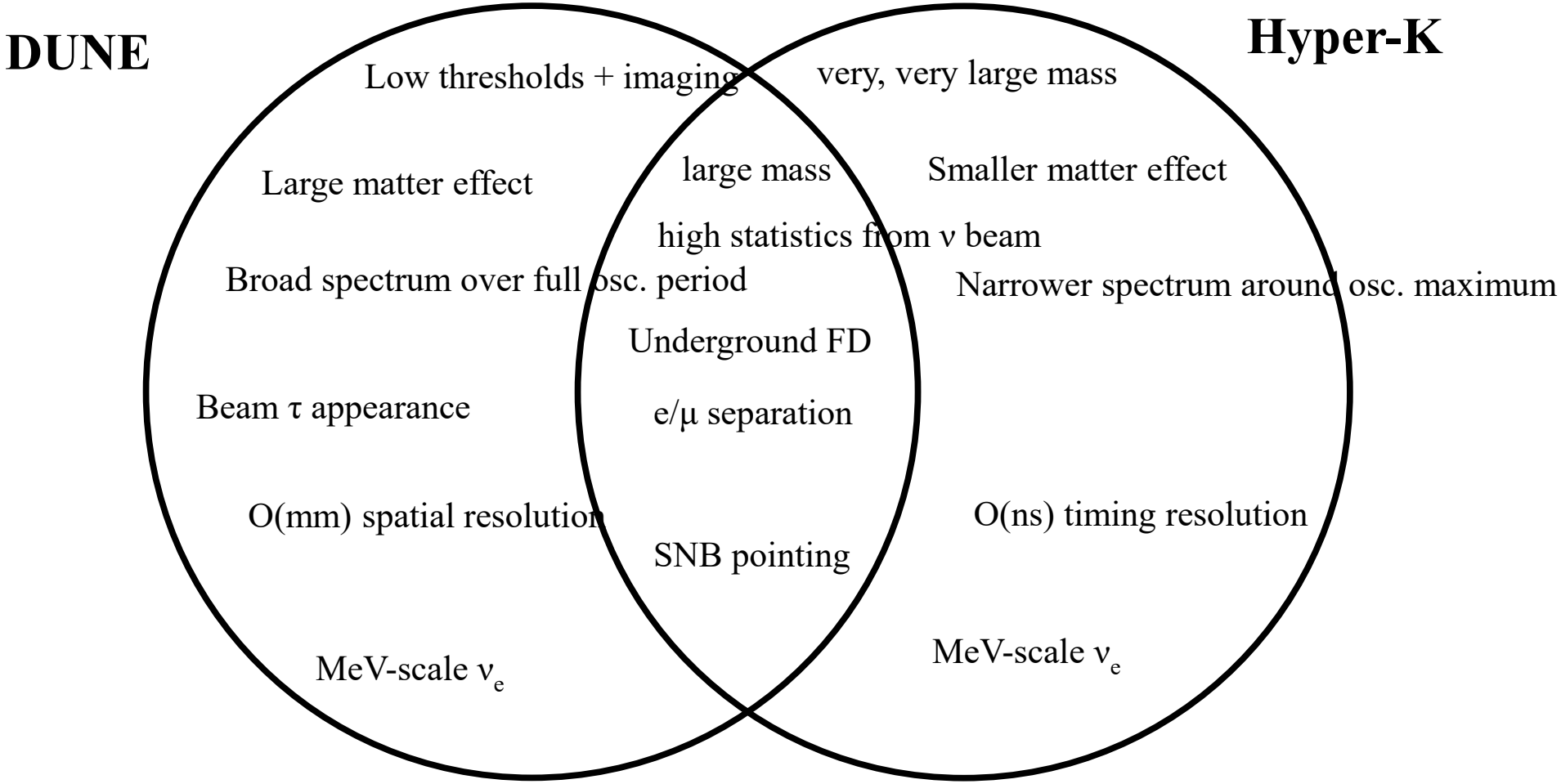
Summary & Outlook

- DUNE will have a large physics program: unprecedented sensitivity to neutrino mass hierarchy, CP violation; a rich atmospheric, solar, and supernova neutrino program; sensitivity to many BSM signals
- ProtoDUNE ran smoothly and performed well, next year will run again to test vertical drift technology
- Excavation 75% complete, detector construction underway
  - 10 APAs assembled at Daresbury factory (150+2 total APAs)
- MOUs signed and being finalized
- TDRs completed: JINST 15 (2020) 08, T08008, T08009, T08010, arXiv:2002.03005 (2020)), ***CD1-RR Review passed***
- In November, Anode Plane Assembly (APA) test lift was successfully completed at SURF demonstrating that largest detector components can be successfully moved
- Far detector expected to take physics data in late 2020s (first module 2028)
- Neutrino beam expected on similar time scale

APAs being tested at Daresbury Laboratory, UK; one 2.3m x 6.3m APA is shown

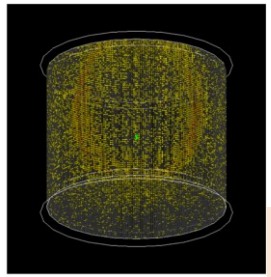
BACKUP

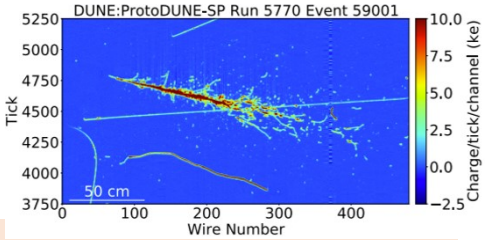
Complementarity



DUNE & Hyper-K

- Effect on matter on neutrino oscillations complicates some measurements
- Matter does not have same effect on neutrino and anti-neutrino oscillations – complicates CPV measurement
- Possible strategies:





Small oscillations length (~300 km) = insignificant matter effects
Off axis beam gives high flux at oscillation maximum, narrow energy range

Hyper-Kamiokande

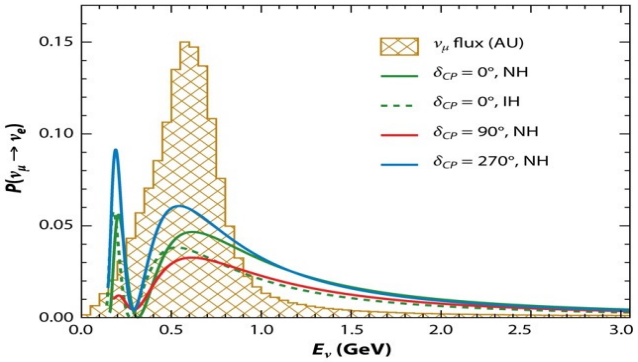
Large oscillations length (~1000 km) = significant matter effects
On axis beam gives wide range of neutrino energy – differentiate CPV effects from matter effects through energy dependence

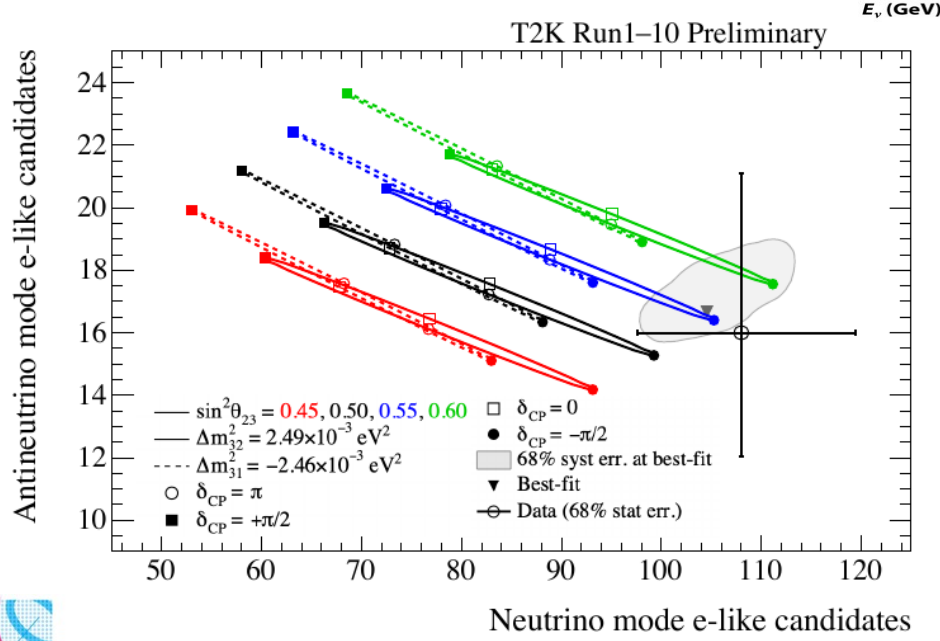
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

DUNE & Hyper-K

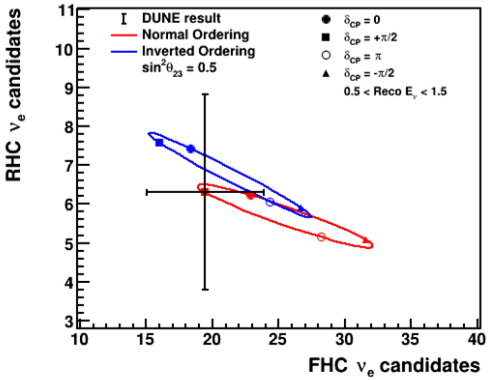
- Count ν_e events in neutrino mode (x axis), and count ν_e in antineutrino mode (y axis)
- Ellipses represent effect of $\delta_{CP,}$ Matter effect splits the NH and IH ellipses about y=x, $\sin^2\theta_{23}$ moves ellipses along y=x

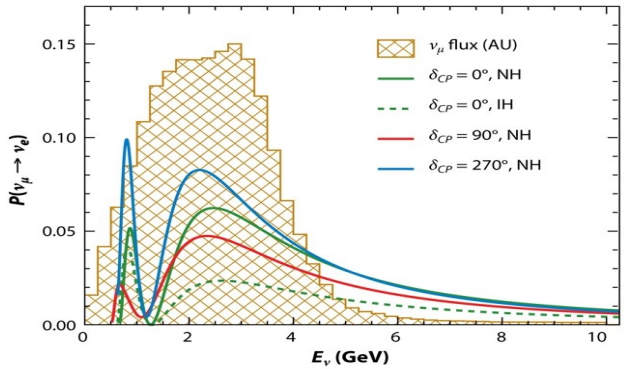
Getting as many neutrinos at one energy at possible to maximize event rate

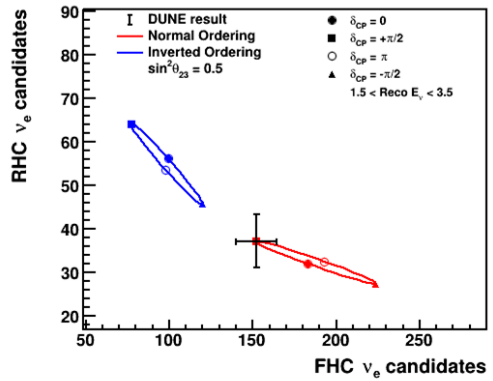


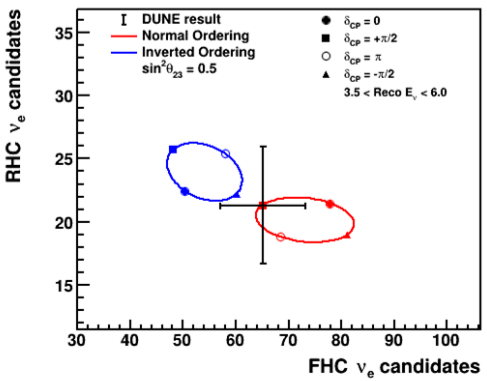


Detector optimized for higher energies









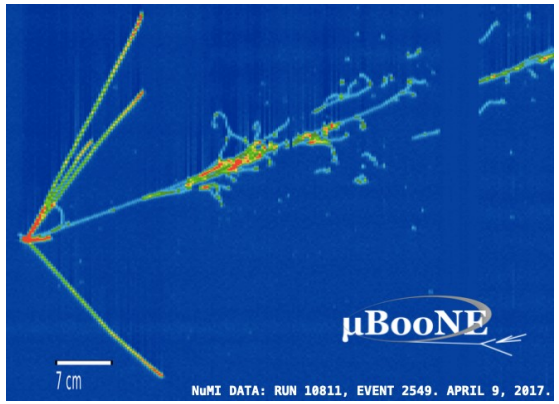
Hyper-Kamiokande

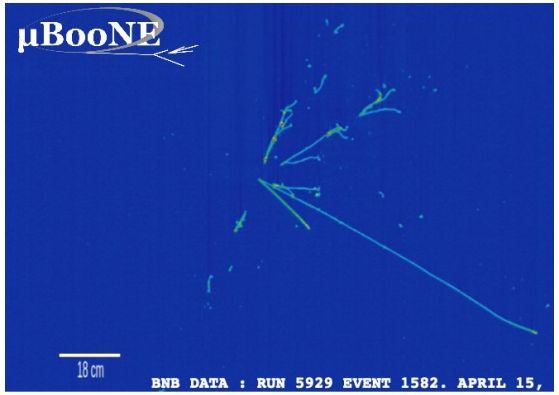
DEEP UNDERGROUND NEUTRINO EXPERIMENT

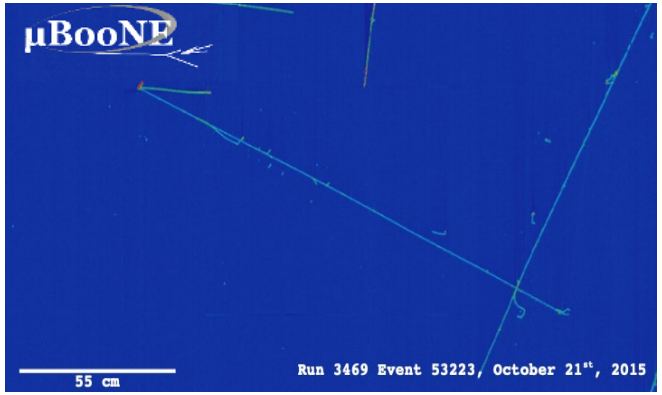
Use of Lar allows DUNE to see hadronic interactions

- Can measure both the hadronic and leptonic parts of the ν event with very high precision, improved event classification and energy determination

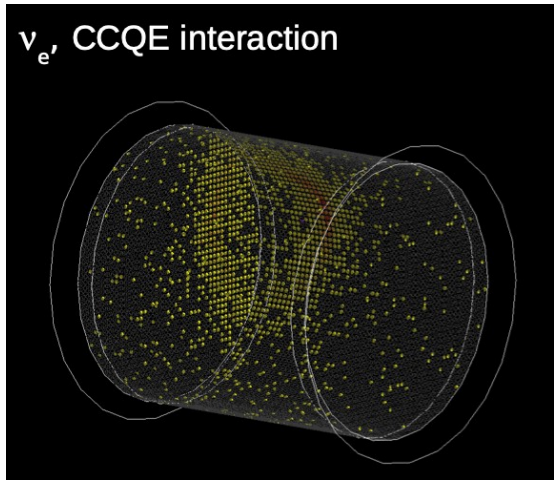
LAr → TPC

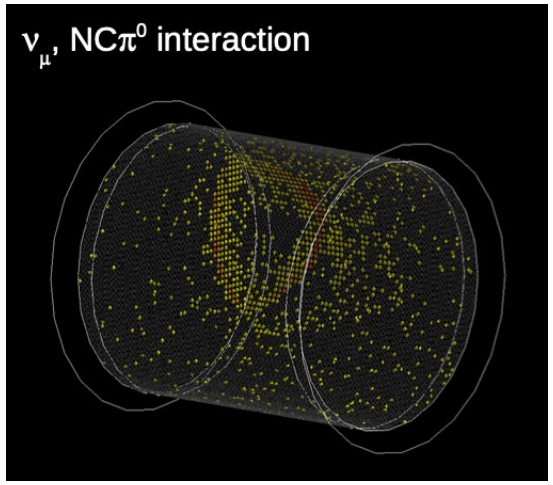


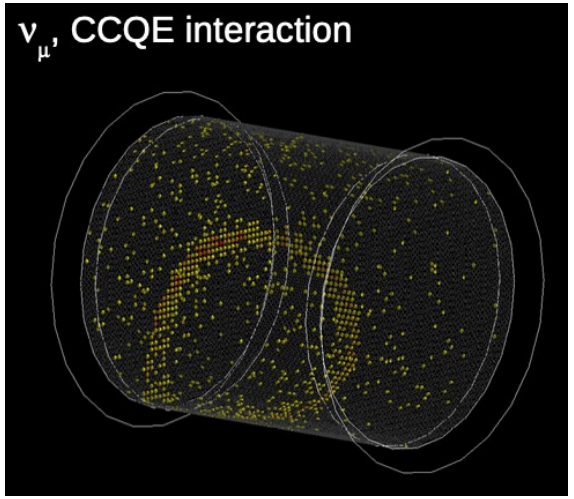




Water → Cerenkov

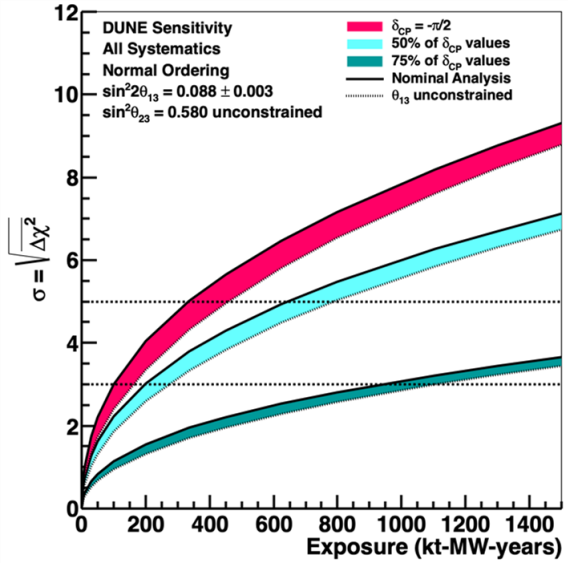


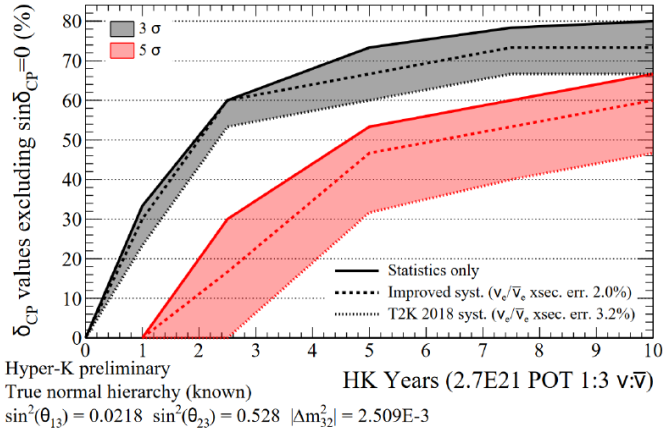




When will CP violation be established?

Slide from S. Zeller





- DUNE can establish CP violation at 3σ in 4 years (if δ_{CP} = 90°), or 6 years (δ_{CP} = 45°), or 14 years (if δ_{CP} = 22°), or establish that CP is **not** violated (if δ_{CP} = 0°)
- DUNE can establish CP violation at 5σ in 7 years (if δ_{CP} = 90°), or 10 years (δ_{CP} = 45°), or ~16 years (if δ_{CP} = 30°)
- With current T2K systematics, and assuming that J-PARC turns on at full power, Hyper-K can establish CP violation at 3σ in 1 year (if δ_{CP} = 90°), or 2 years (δ_{CP} = 45°), becoming systematically limited around δ_{CP} = 30°
- With “improved” systematics, 3σ reach goes out to ~24°
- For 5σ, depending on systematics Hyper-K can establish CP violation for δ_{CP} = 45° between 6-13 years, and becomes limited between 35-45°
- Hyper-K reach assumes that the mass ordering is determined externally

DUNE ν_e and $\bar{\nu}_e$ spectra can distinguish MO in Phase I

Slide from S. Zeller

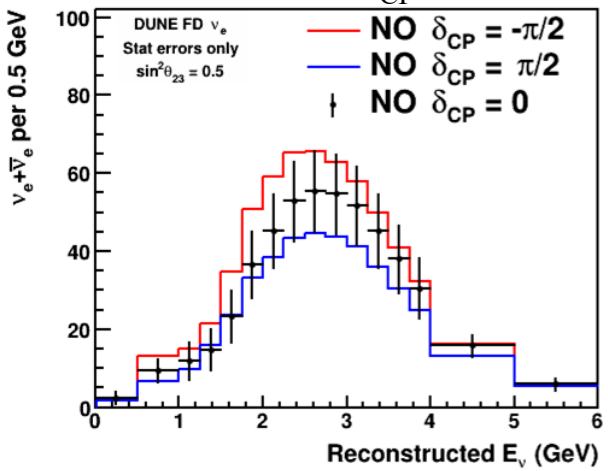
Data points show NO, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

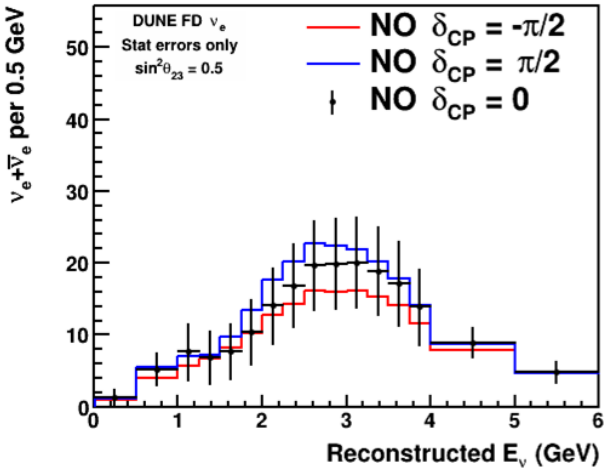
Neutrino mode

Phase I

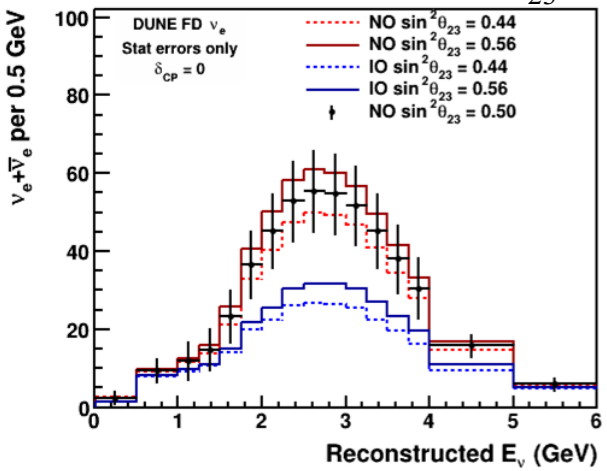
Antineutrino mode

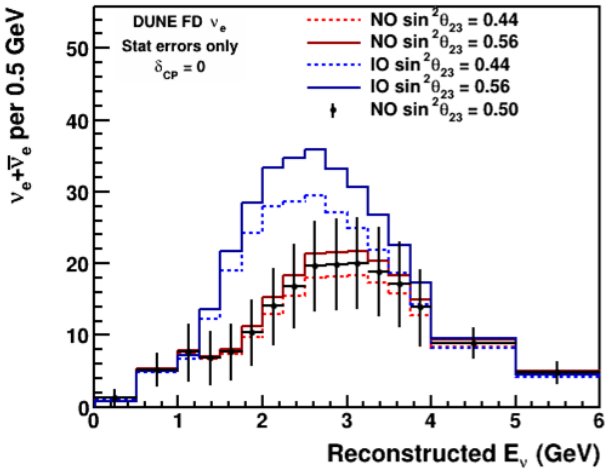
Varying δ_{CP}





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





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

Slide from S. Zeller

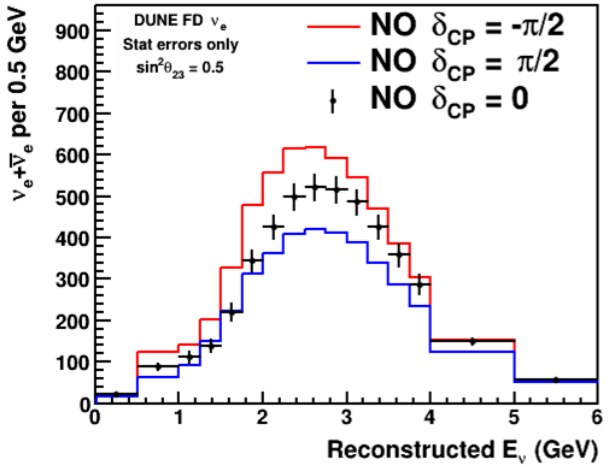
Data points show NO, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

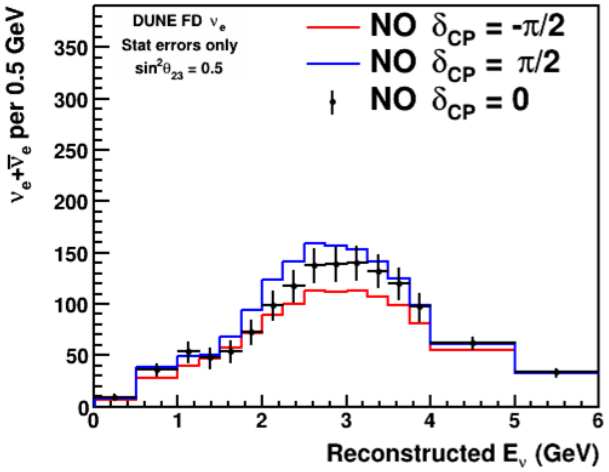
Neutrino mode

Phase II

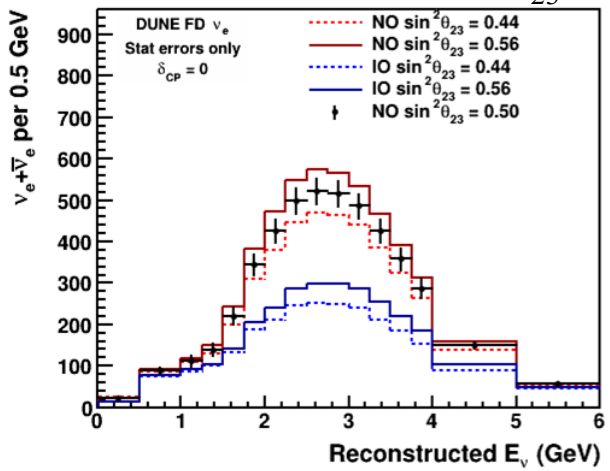
Antineutrino mode

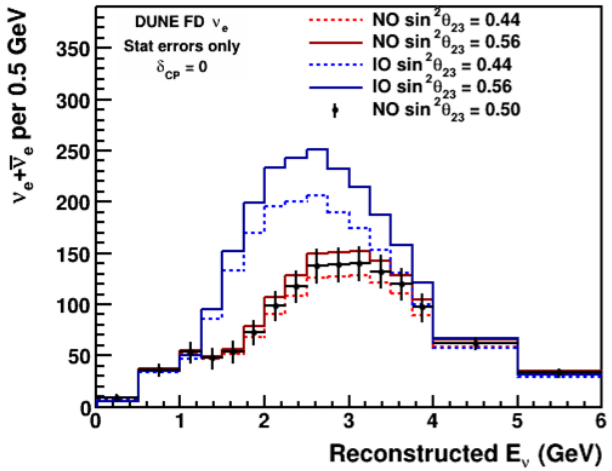
Varying δ_{CP}





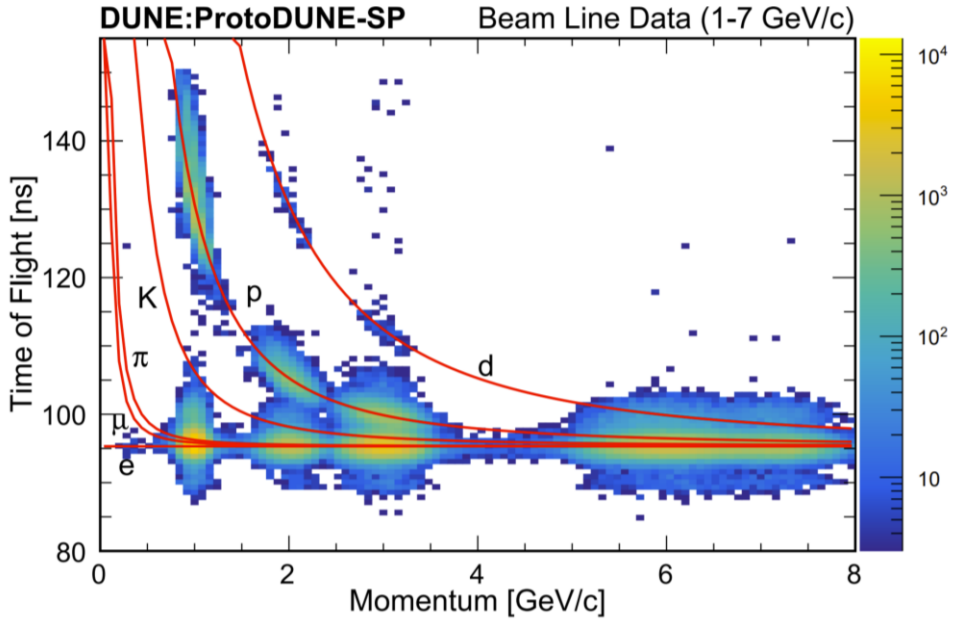
Varying MO and $\sin^2\theta_{23}$

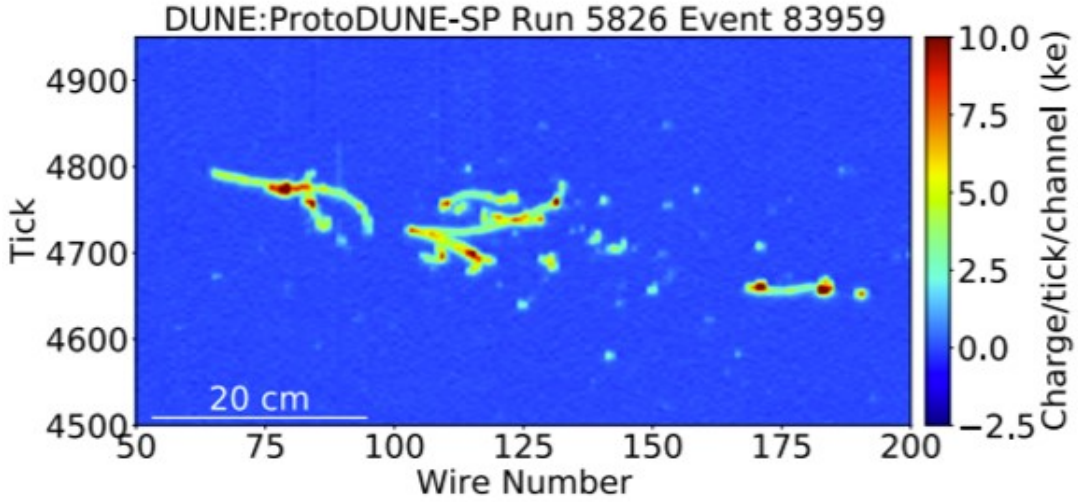




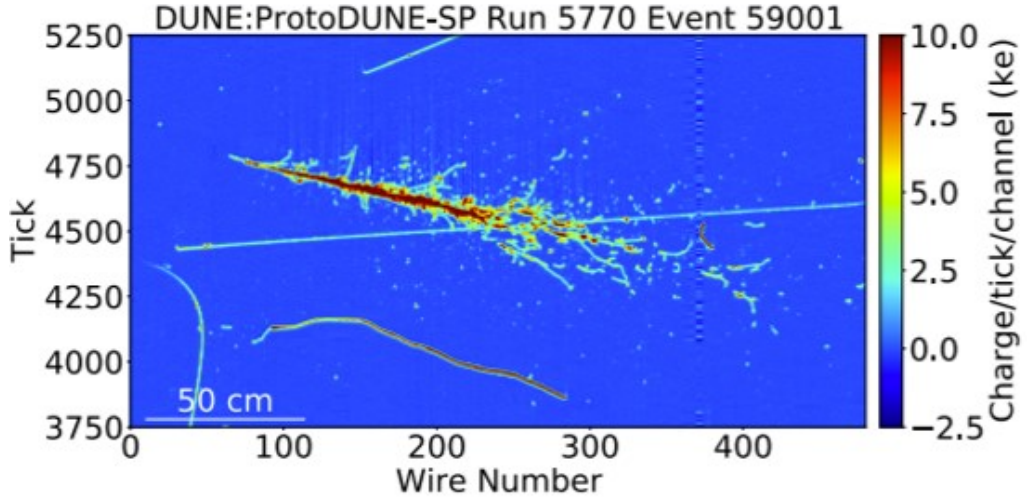
ProtoDUNE SP Performance

- Excellent performance!
- Low noise: Noise charge of ~ 550 (650) e^- on collection (induction) wires -> HALF of the maximum allowed noise
- 99.7% of the 15360 TPC electronics responsive, 99% HV uptime, high purity





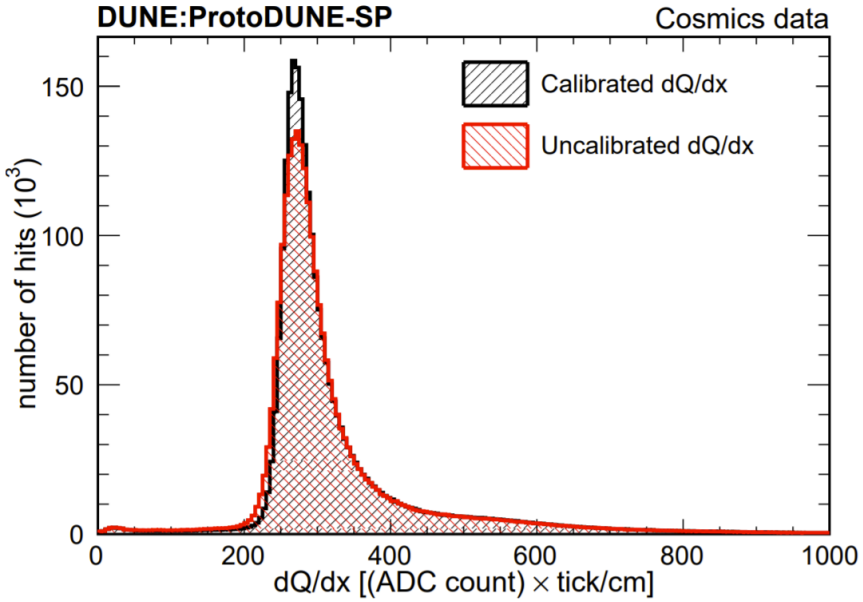
0.5 GeV electron

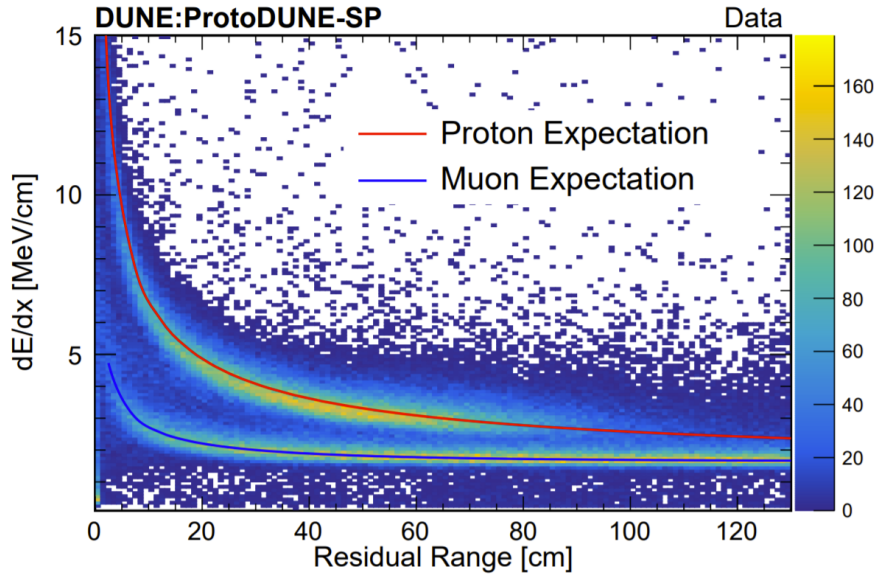


6 GeV electron

ProtoDUNE SP Performance

- Charge deposited along track converted energy loss (dE/dx) using stopping cosmic ray muons
- Calibration constants derived and applied to beam particles (muons, pions, protons, positrons)
- Charge deposition per unit length (dQ/dx) affected by space-charge effect, recombination effect, electron attenuation, diffusion, electronics gain variation
- Detector response calibration is based on cosmic muons – shows good results for test beam protons and muons
- High quality of ProtoDUNE-SP demonstrated by excellent proton-muon separation



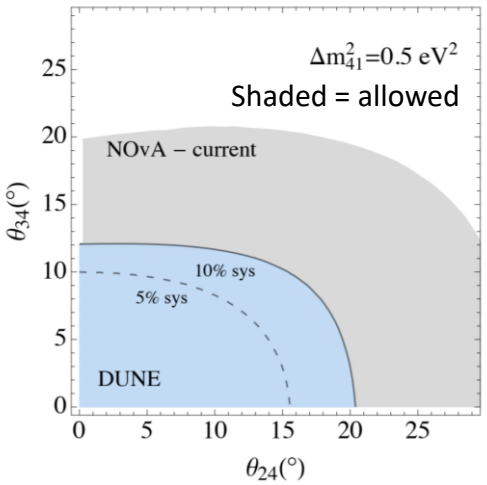


Sensitivity to Sterile Neutrinos

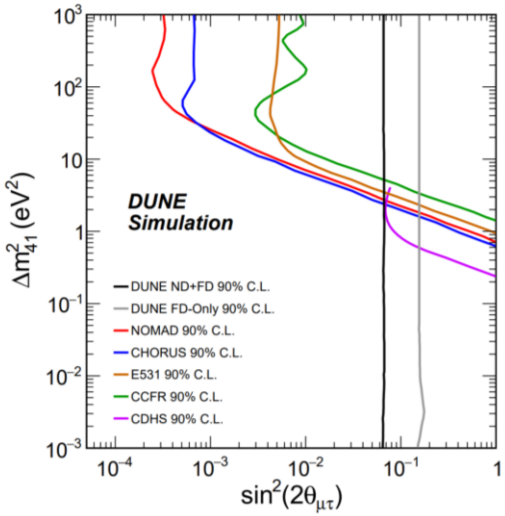
Case 1 ($\Delta m^2_{14} \sim 0.1 - 1\ eV^2$): slow light-sterile neutrino oscillations, underdeveloped in ND, averaged out in FD

$\Delta m^2_{14} > 0.1\ eV^2$ (LSND)
$> 0.5\ eV^2$ (reactor)
Arxiv:1901.08330v1

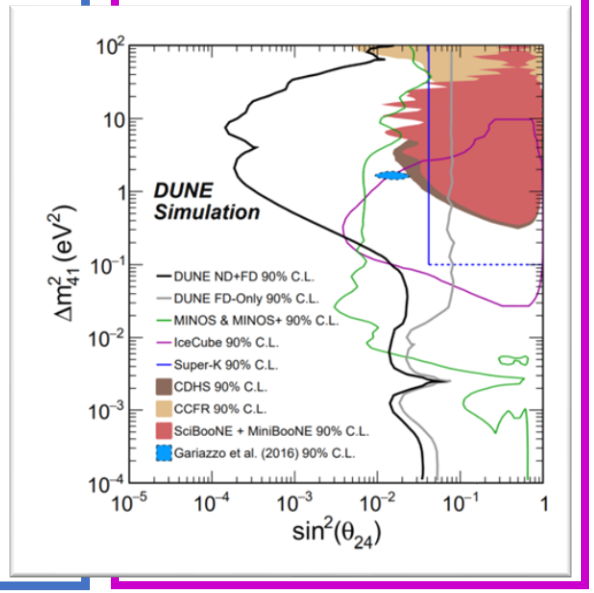
arXiv:1707.05348v1



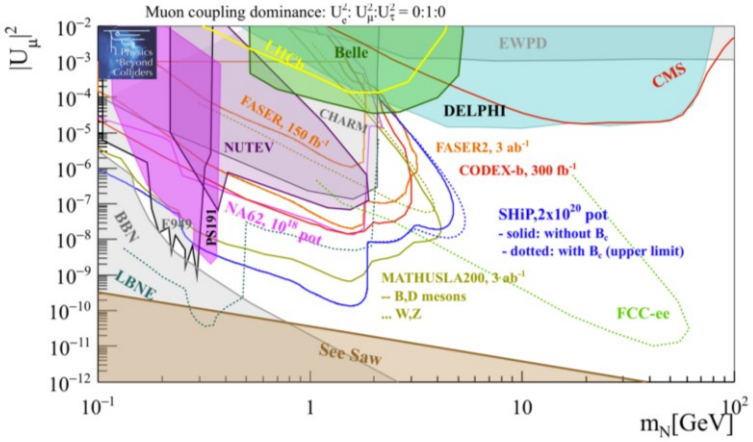
3+1



Case 2 ($\Delta m_{14} > 1\ eV^2$) : light-sterile oscillation frequency matches ND distance.
Preferred by LSND & MiniBoone anomalies & DANSS & NEOS : arXiV: 1803.10661v1 (2018)



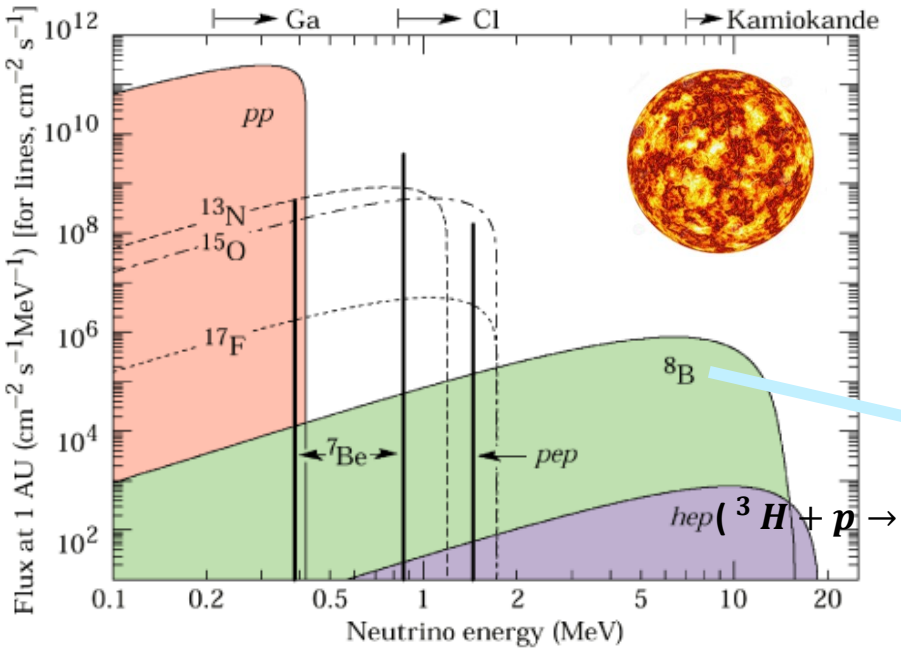
Case 3 ($\Delta m^2_{14} > 100\ eV^2$) : fast sterile neutrino oscillations, averaged out in ND and FD (same as PMNS non-unitarity from heavy neutrinos)



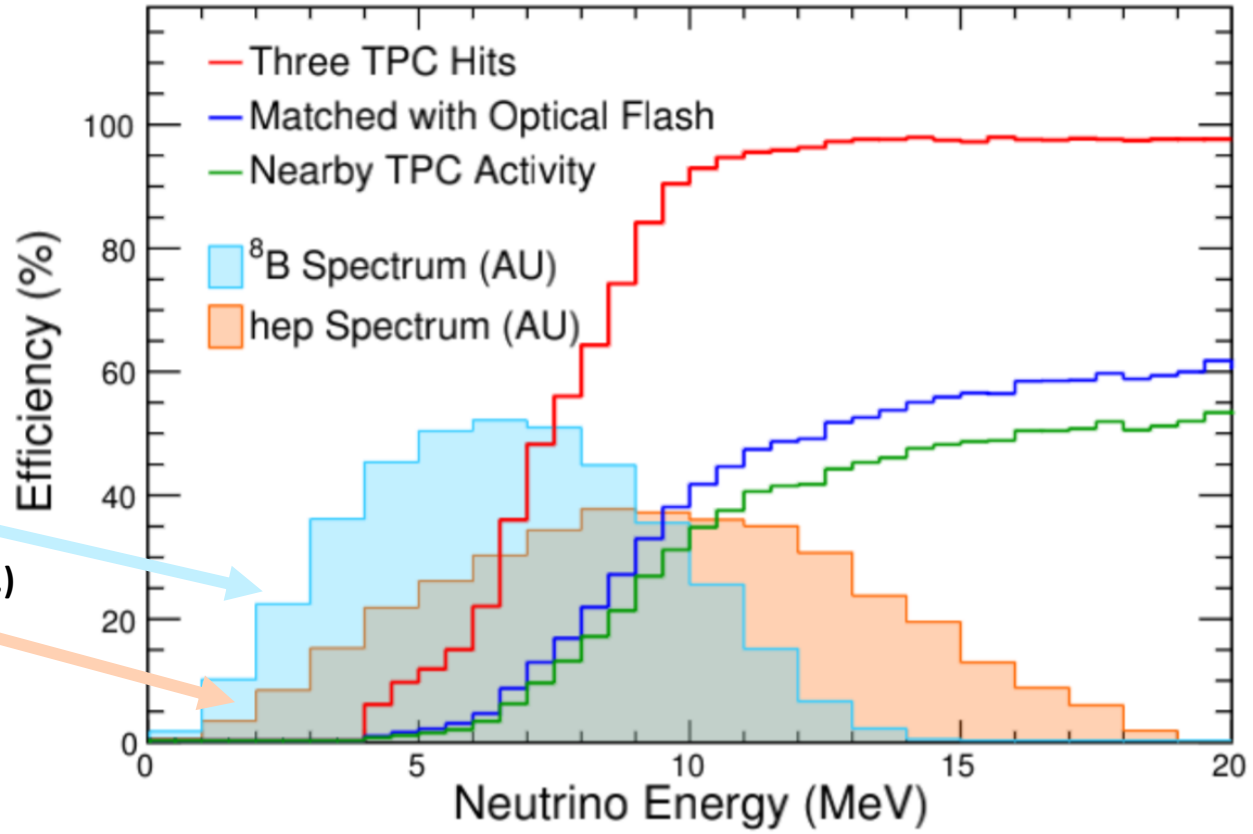
10^{-3}eV 10^{-2}eV 10^{-1}eV eV KeV MeV GeV 100 GeV

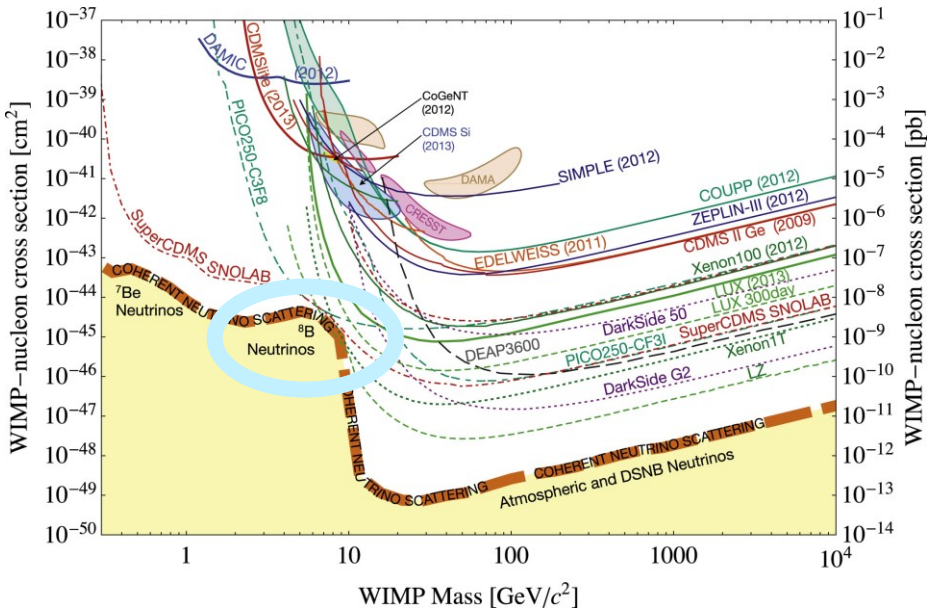
Extra Neutrino mass

Solar Neutrinos



$hep\left(^{3}H + p \rightarrow {}^{4}H + e^{+} + \nu_e\right)$

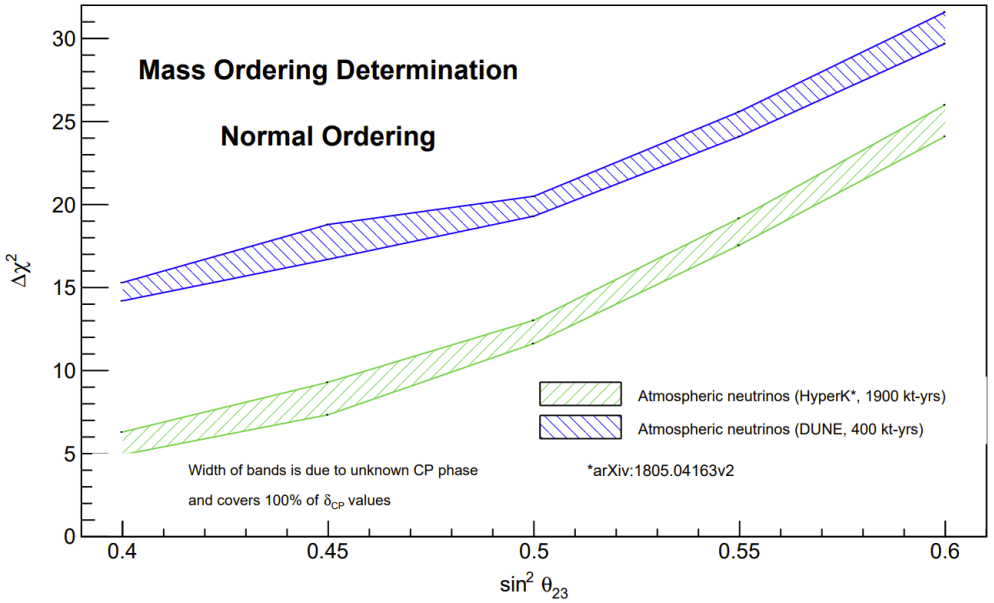




- DUNE can measure solar neutrinos to help verify the standard solar model, measure sun's core temperature, characterize neutrino floor, resolve tension between global solar neutrino measurements & KamLAND (arXiv:1808.08232), characterize MSW affect

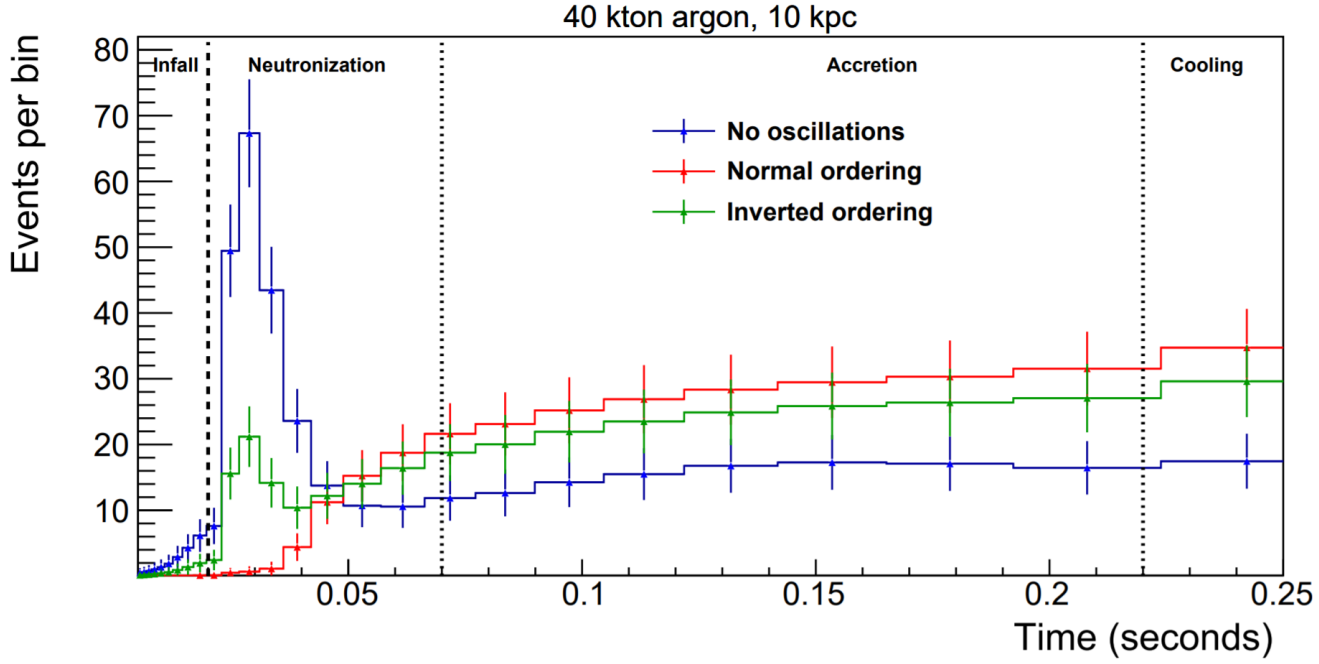
Atmospheric & SuperNova Neutrinos

- Can use atmospheric neutrinos to extract neutrino properties



- Core collapses expected to occur few times per century (at 10-15 kpc): test astrophysical theories, probe new physics
- When massive star collapses to neutron star/black hole, ~ 10^{58} of ~ 10 MeV ν emitted for a few seconds.
- DUNE sensitive to ν_e supernova neutrinos- this is unique among supernova neutrino detectors for the next decades. Tracks can indicate direction of supernova

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



Tau Neutrino

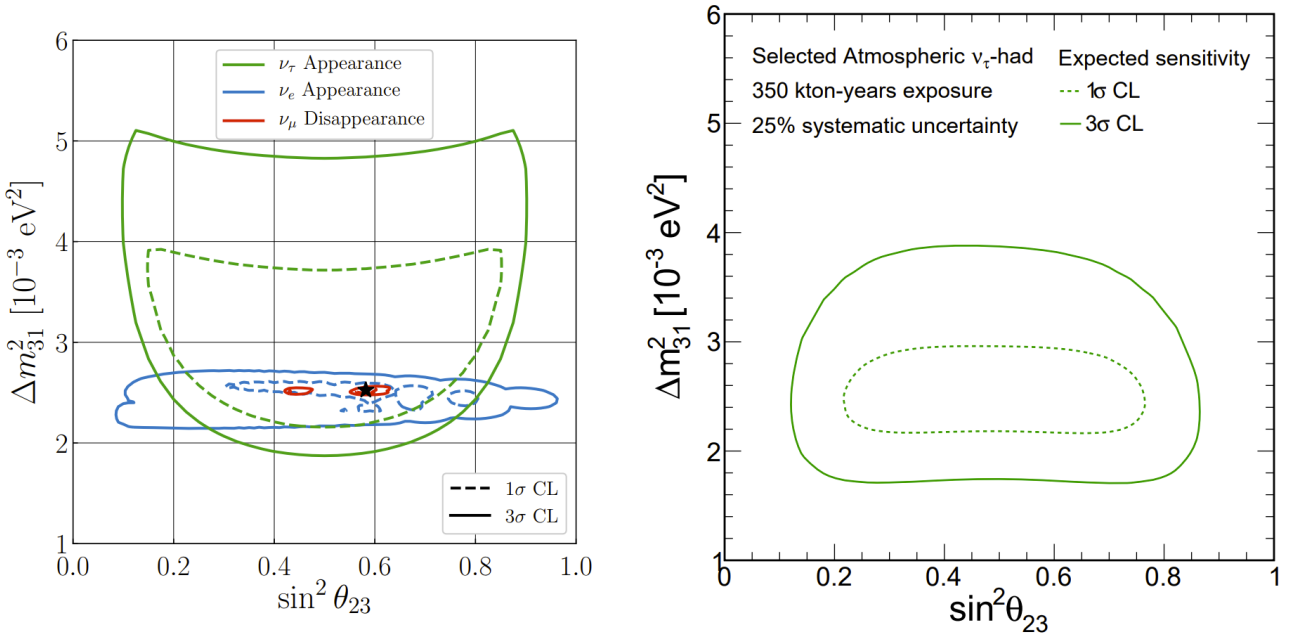


Figure 8.26: The 1σ (dashed) and 3σ (solid) expected sensitivity for measuring Δm^2_{31} and $\sin^2\theta_{23}$ using a variety of samples. Left: The expected sensitivity for seven years of beam data collection, assuming 3.5 years each in neutrino and antineutrino modes, measured independently using ν_e appearance (blue), ν_μ disappearance (red), and ν_τ appearance (green). Adapted from Ref. [498]. Right: The expected sensitivity for the ν_τ appearance channel using 350 kton-years of atmospheric exposure.

Proton Decay

- The 90% CL limit of a bound neutron lifetime is 6.45 × 1032 years for a 400 kt · year exposure. The corresponding limit for the oscillation time of free neutrons is calculated to be 5.53 × 108 s. This is approximately an improvement by a factor of two from the current best limit, which comes from Super–Kamiokande

- With a 30% signal efficiency and an expected background of one event per Mt · year , a 90% CL lower limit on the proton lifetime in the p → K+ν channel of 1.3 × 10^34 years can be set, assuming no signal is observed over ten years of running with a total of 40 kt of fiducial mass. This calculation assumes constant signal efficiency and background rejection over time and for each of the FD modules.

(from TDR)

Dark Matter

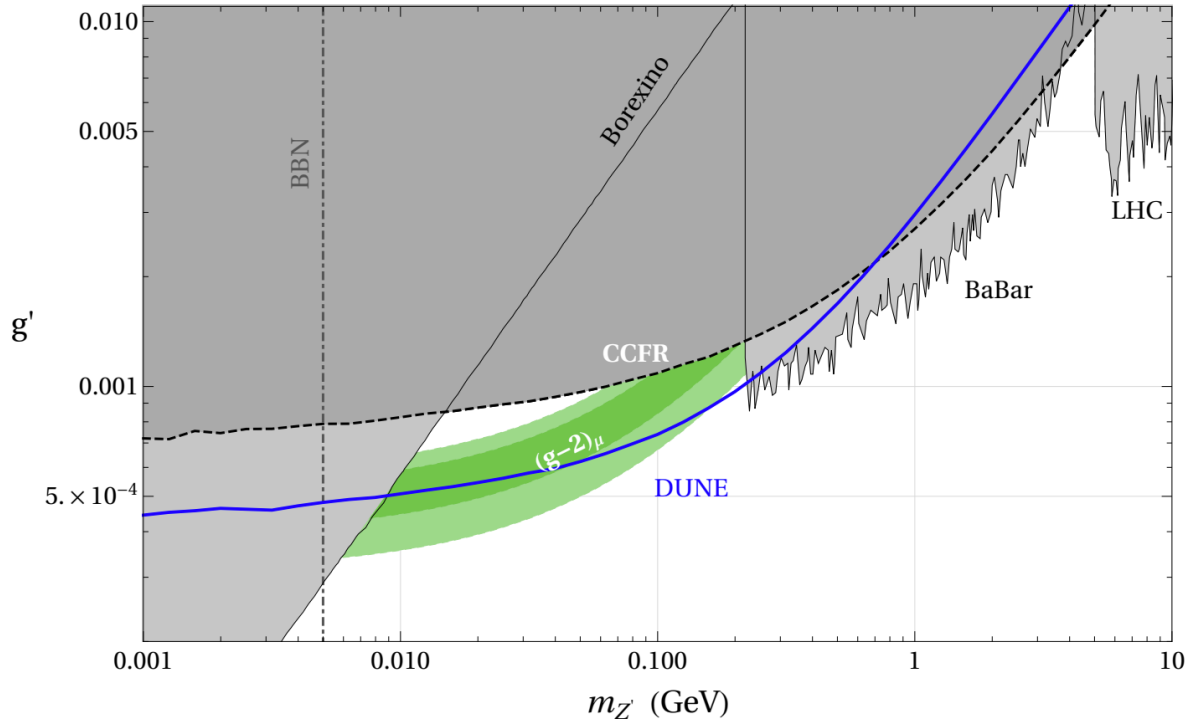
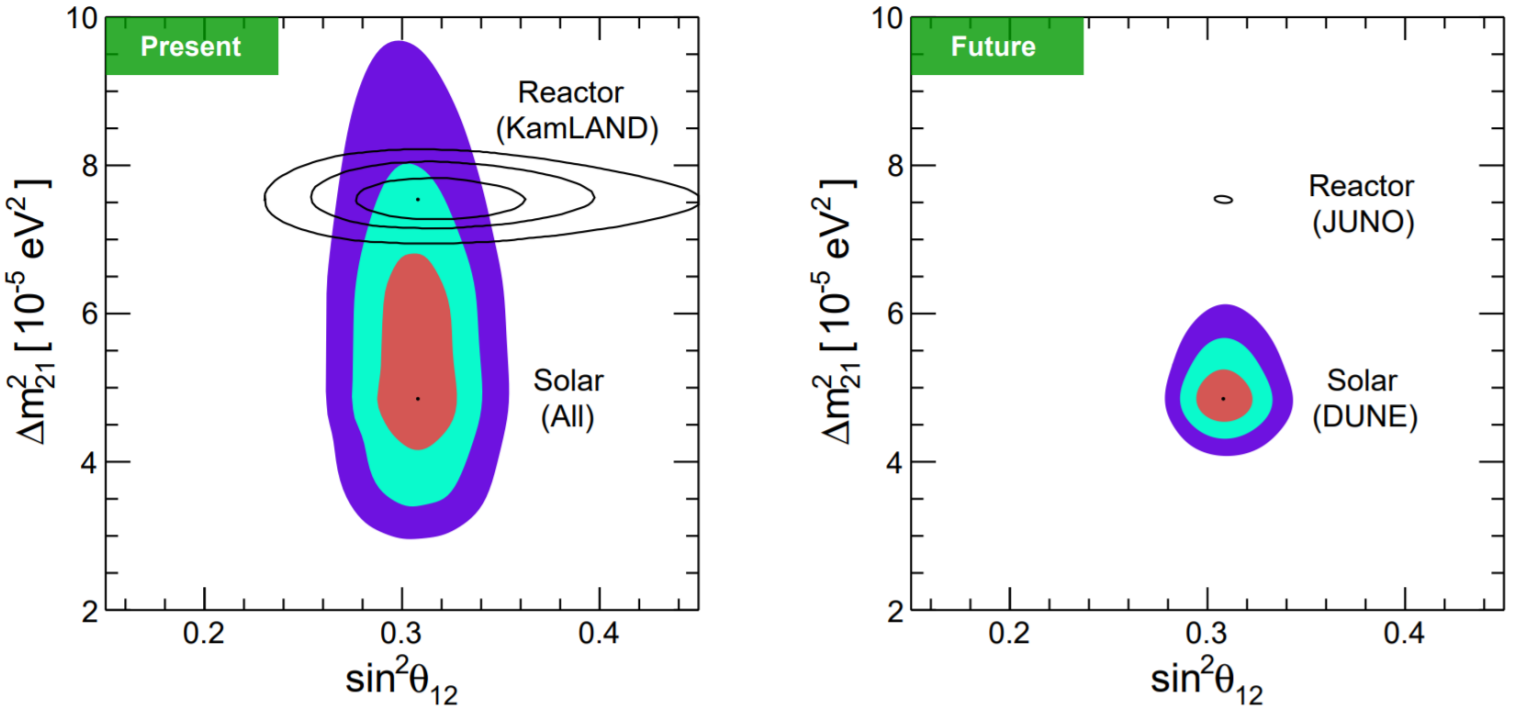


Figure 8.15: Existing constraints and projected DUNE sensitivity in the $L_\mu - L_\tau$ parameter space. Shown in green is the region where the $(g-2)_\mu$ anomaly can be explained at the 2σ level. The parameter regions already excluded by existing constraints are shaded in gray and correspond to a CMS search for $pp \to \mu^+\mu^- Z' \to \mu^+\mu^-\mu^+\mu^-$ [444] ("LHC"), a BaBar search for $e^+e^- \to \mu^+\mu^- Z' \to \mu^+\mu^-\mu^+\mu^-$ [445] ("BaBar"), precision measurements of $Z \to \ell^+\ell^-$ and $Z \to \nu\bar{\nu}$ couplings [446, 441] ("LEP"), a previous measurement of the trident cross section [434, 436] ("CCFR"), a measurement of the scattering rate of solar neutrinos on electrons [447, 448, 449] ("Borexino"), and bounds from big bang nucleosynthesis [450, 451] ("BBN"). The DUNE sensitivity shown by the solid blue line assumes a measurement of the trident cross section with 40% precision.

DUNE as the Next-Generation Solar Neutrino Experiment

- https://arxiv.org/pdf/1808.08232.pdf



ProtoDUNE calibration

$$\left(\frac{dE}{dx}\right)_{\text{calibrated}} = \left(\exp\left(\frac{(\frac{dQ}{dx})_{\text{calibrated}}}{C_{\text{cal}}}\frac{\beta' W_{\text{ion}}}{\rho \mathscr{E}}\right) - \alpha\right)\left(\frac{\rho \mathscr{E}}{\beta'}\right)$$

C_{cal} = Calibration constant used to convert ADC values to number of electrons,
W_{ion} = 23.6×10^{-6} MeV/electron (the work function of argon),
$\mathscr{E}$ = E field based on the measured space charge map,
ρ = 1.38 g/cm^3 (liquid argon density at a pressure of 124.106 kPa),
α = 0.93, and
β' = 0.212 (kV/cm)(g/cm^2)/MeV.

The calibration constant C_{cal} is normalized so that the unit ("ADC×tick") corresponds to 200 electrons. In the case where the detector response is perfectly modeled (e.g. in the simulation), the calibration constant C_{cal} should be exactly 1/200 = 5×10^{-3} ADC×tick/e. The calibration constants derived for the collection plane by fitting the stopping muon samples to the predicted dE/dx curve are shown in table 5. The uncertainties are statistical only. The difference between data and MC calibration constants is caused by the uncertainties on the gain measurement and the simulation of detector response.

From DUNE Physics TDR

Parameter	Central Value	Relative Uncertainty
θ_{12}	0.5903	2.3%
θ_{23} (NO)	0.866	4.1%
θ_{23} (IO)	0.869	4.0%
θ_{13} (NO)	0.150	1.5%
θ_{13} (IO)	0.151	1.5%
Δm^2_{21}	7.39×10^{-5} eV^2	2.8%
Δm^2_{32} (NO)	2.451×10^{-3} eV^2	1.3%
Δm^2_{32} (IO)	-2.512×10^{-3} eV^2	1.3%

Table 5.1: Central value and relative uncertainty of neutrino oscillation parameters from a global fit [2, 3] to neutrino oscillation data. Because the probability distributions are somewhat non-Gaussian (particularly for θ_{23}), the relative uncertainty is computed using 1/6 of the 3σ allowed range from the fit, rather than the 1σ range. For θ_{23}, θ_{13}, and Δm^2_{31}, the best-fit values and uncertainties depend on whether normal mass ordering (NO) or inverted mass ordering (IO) is assumed.

x_P	Description of P	P_{CV}	$\delta P/P$
	Quasielastic		
$x^{CCQE}_{M_A}$	Axial mass for CCQE		$^{+0.25}_{-0.15}$ GeV
x^{CCQE}_{VecFF}	Choice of CCQE vector form factors (BBA05 $\leftrightarrow$ Dipole)		N/A
x^{CCQE}_{kF}	Fermi surface momentum for Pauli blocking		$\pm$30%
	Low W		
$x^{CCRES}_{M_A}$	Axial mass for CC resonance	0.94	$\pm$0.05 GeV
$x^{CCRES}_{M_V}$	Vector mass for CC resonance		$\pm$10%
$x^{\Delta Decay}_{\eta\ BR}$	Branching ratio for $\Delta \to \eta$ decay		$\pm$50%
$x^{\Delta Decay}_{\gamma\ BR}$	Branching ratio for $\Delta \to \gamma$ decay		$\pm$50%
$x_{\theta^{\Delta Decay}_{\pi}}$	θ_π distribution in decaying Δ rest frame (isotropic $\to$ RS)		N/A
	High W		
$x^{DIS}_{A^{BY}_{HT}}$	A_{HT} higher-twist param in BY model scaling variable ξ_w		$\pm$25%
$x^{DIS}_{B^{BY}_{HT}}$	B_{HT} higher-twist param in BY model scaling variable ξ_w		$\pm$25%
$x^{DIS}_{C^{BY}_{V1u}}$	C_{V1u} valence GRV98 PDF correction param in BY model		$\pm$30%
$x^{DIS}_{C^{BY}_{V2u}}$	C_{V2u} valence GRV98 PDF correction param in BY model		$\pm$40%
	Other neutral current		
$x^{NCEL}_{M_A}$	Axial mass for NC elastic		$\pm$25%
x^{NCEL}_{η}	Strange axial form factor η for NC elastic		$\pm$30%
$x^{NCRES}_{M_A}$	Axial mass for NC resonance		$\pm$10%
$x^{NCRES}_{M_V}$	Vector mass for NC resonance		$\pm$5%
	Misc.		
x_{FZ}	Vary effective formation zone length		$\pm$50%

Table 5.4: Neutrino interaction cross-section systematic parameters considered in GENIE. GENIE default central values and uncertainties are used for all parameters except $x^{CCRES}_{M_A}$. Missing GENIE parameters were omitted where uncertainties developed for this analysis significantly overlap with the supplied GENIE freedom, the response calculation was too slow, or the variations were deemed unphysical.

Uncertainties

Prefit uncertainties on flux and cross section parameters are at the level of ~10%. These uncertainties become constrained in the fit, especially by the ND.

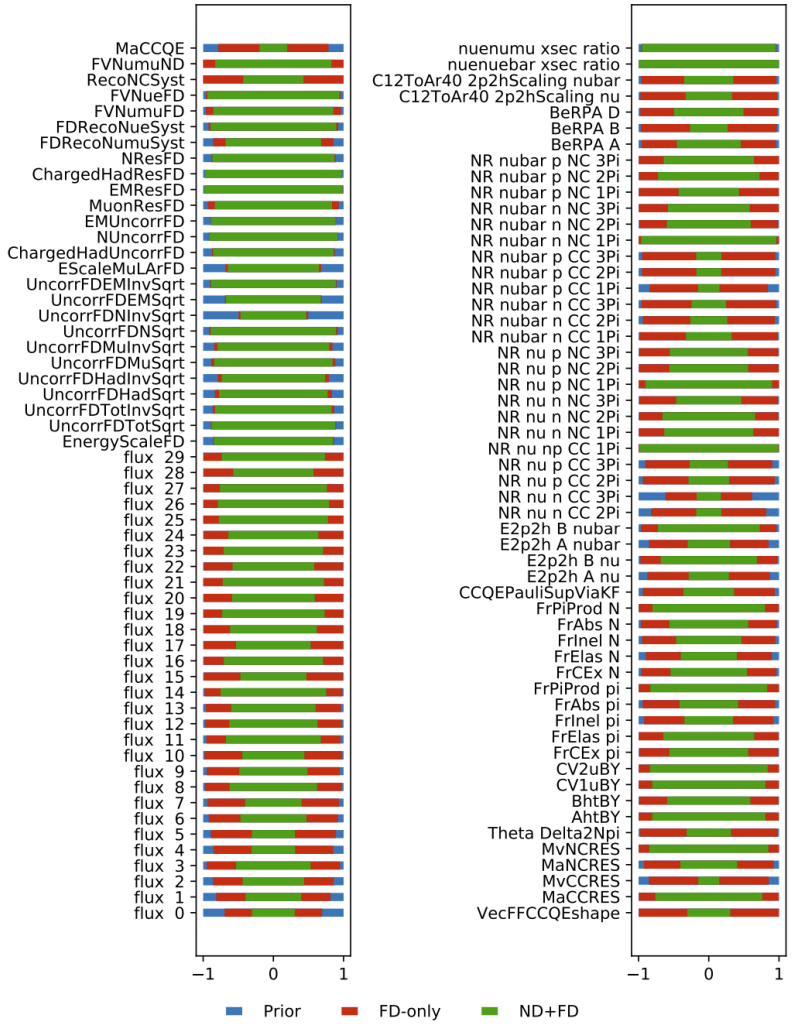


Figure 5.34: The ratio of post-fit to pre-fit uncertainties for various systematic parameters for a 15-year staged exposure. The red band shows the constraint from the FD only in 15 years, while the green shows the ND+FD constraints. Systematic parameter names are defined in Table 5.12.

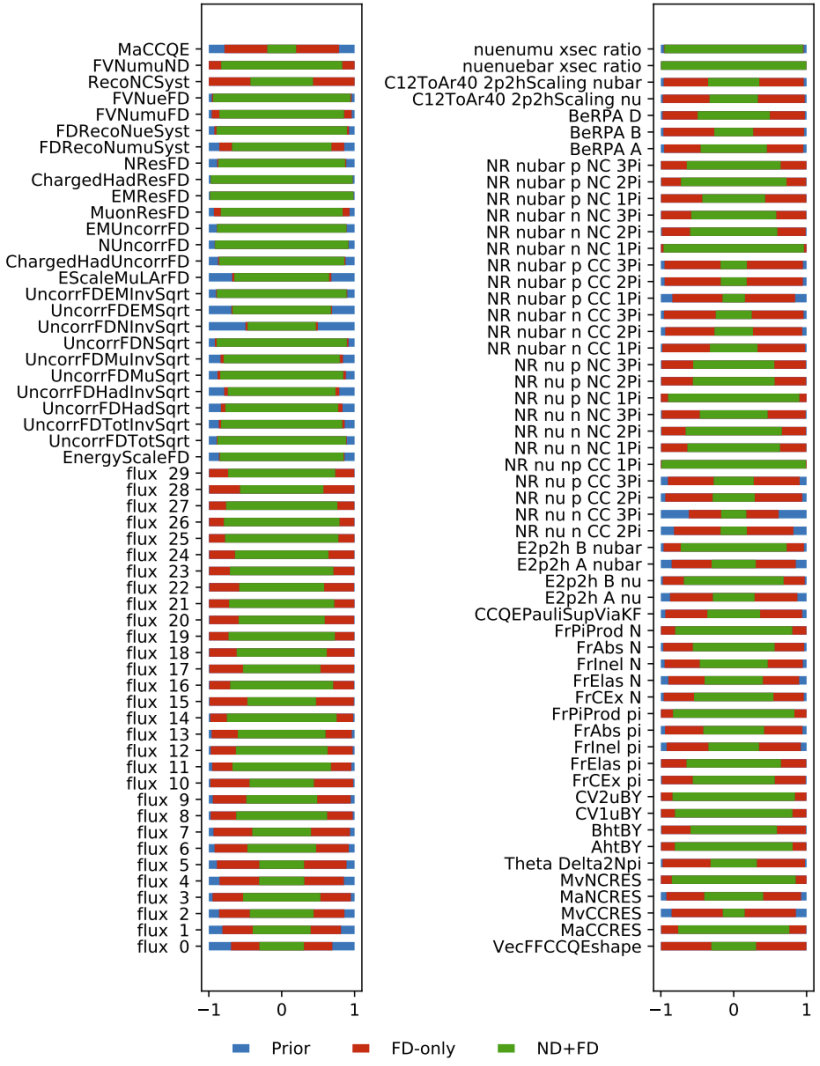


Figure 5.34: The ratio of post-fit to pre-fit uncertainties for various systematic parameters for a 15-year staged exposure. The red band shows the constraint from the FD only in 15 years, while the green shows the ND+FD constraints. Systematic parameter names are defined in Table 5.12.

SuperNova Neutrinos

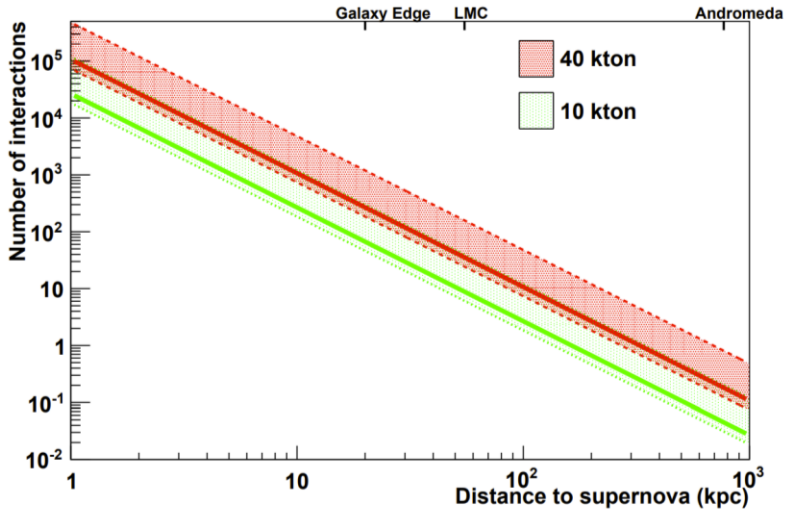


Figure 7.7: Estimated numbers of supernova neutrino interactions in DUNE as a function of distance to the supernova, for different detector masses (ν_e events dominate). The red dashed lines represent expected events for a 40-kton detector and the green dotted lines represent expected events for a 10-kton detector. The lines limit a fairly wide range of possibilities for "Garching-parameterized" supernova flux spectra (Equation 7.1) with luminosity 0.5×10^{52} ergs over ten seconds. The optimistic upper line of a pair gives the number of events for average ν_e energy of $\langle E_{\nu_e} \rangle = 12$ MeV, and "pinching" parameter $\alpha = 2$; the pessimistic lower line of a pair gives the number of events for $\langle E_{\nu_e} \rangle = 8$ MeV and $\alpha = 6$. (Note that the luminosity, average energy and pinching parameters will vary over the time frame of the burst, and these estimates assume a constant spectrum in time. Oscillations will also affect the spectra and event rates.) The solid lines represent the integrated number of events for the specific time-dependent neutrino flux model in [249] (see Figures 7.1 and 7.2; this model has relatively cool spectra and low event rates). Core collapses are expected to occur a few times per century, at a most-likely distance of around 10 to 15 kpc.

BSM Simulation Assumptions

Energy (GeV)	Beam Power (MW)	Uptime Fraction	POT/year
120	1.2	0.56	1.1×10^{21}

Table 8.2: ND properties used in the BSM physics analyses.

ND Properties	Values
Dimensions	7 m wide, 3 m high, and 5 m long
Dimensions of fiducial volume	6 m wide, 2 m high, and 4 m long
Total mass	147 ton
Fiducial mass	67.2 ton
Distance from target	574 m

Table 8.3: FD properties used in the BSM physics analyses.

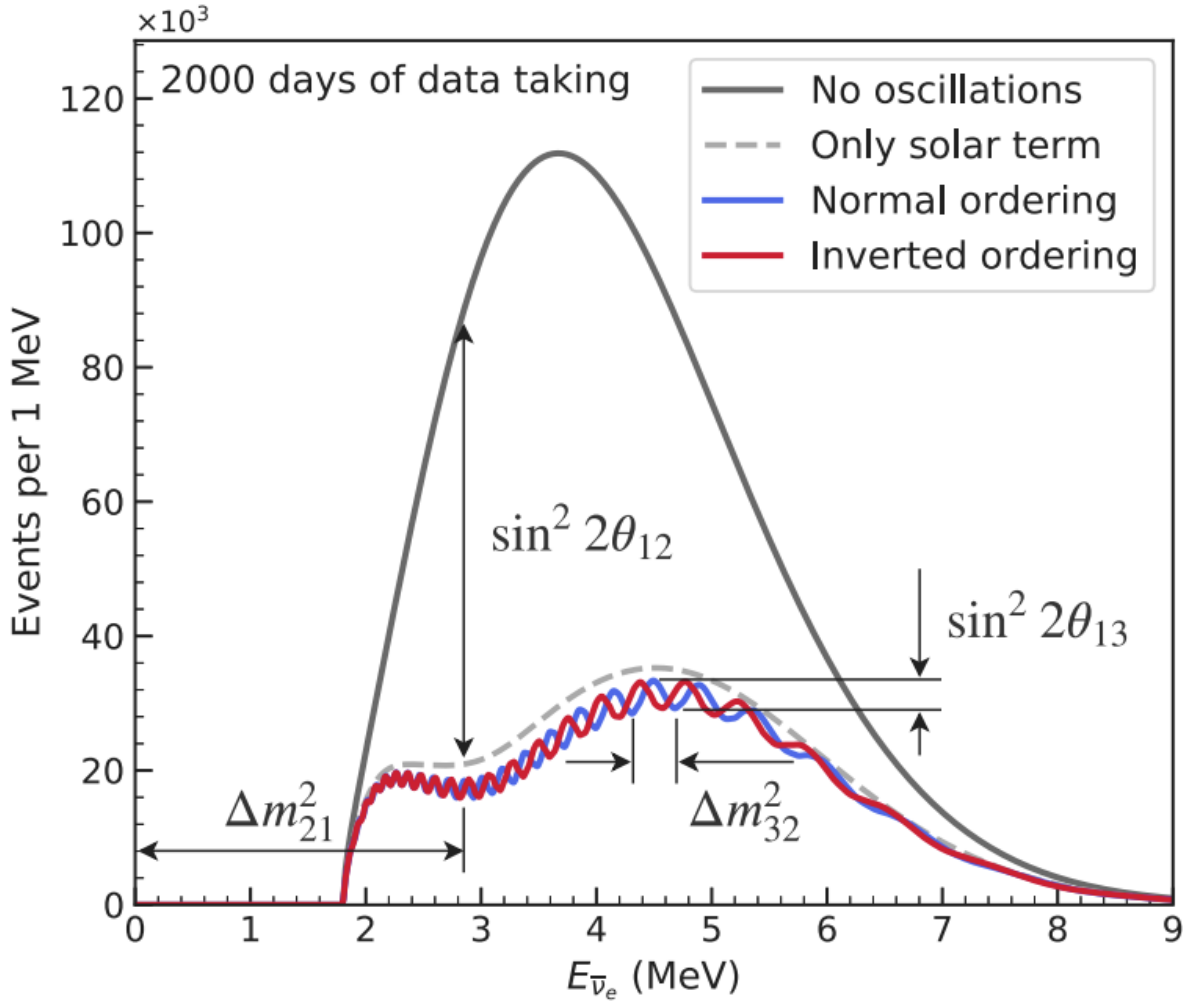
Particle Type	Threshold	Energy Resolution	Angular Resolution
$\mu^{\pm}$	30 MeV	Contained track: track length	1°
$e^{\pm}$	30 MeV	2%	1°
$\pi^{\pm}$	100 MeV	30%	5°

LBNF/DUNE Cost Phase I

Subprojects	Subproject Title	Actuals thru Mar-22	Budget-at-completion (BAC)	Estimate-to-completion (ETC)
FSCFBSI	FSCF Building & Site Infrastructure (BSI)	$ M	$146 M	$145 M
FSCFEXC	Far Site Conventional Facilities Excavation	$360 M	$571 M	$213 M
FDC	Far Detectors + FS Cryogenic Infrastructure	$173 M	$802 M	$632 M
NSCFB	Near Site Conventional Facilities + Beamline	$119 M	$814 M	$693 M
ND	Near Detector	$23 M	$147 M	$124 M
Total		**$674 M**	**$2,480 M**	**$1,808 M**
			(Actual costs to date, except FSCFEXC)	**$315 M**
			(Estimate to Complete (ETC), excpet FSCFEXC)	**$1,594 M**
			(Budget at Completion FSCFEXC)	**$571 M**
			Contingency	**$648 M**
			Total (Actuals + ETC+Contingency)	**$3,130 M**

Total Project Cost = Actuals + Estimate to Complete + Contingency

JUNO



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