The DUNE Experiment

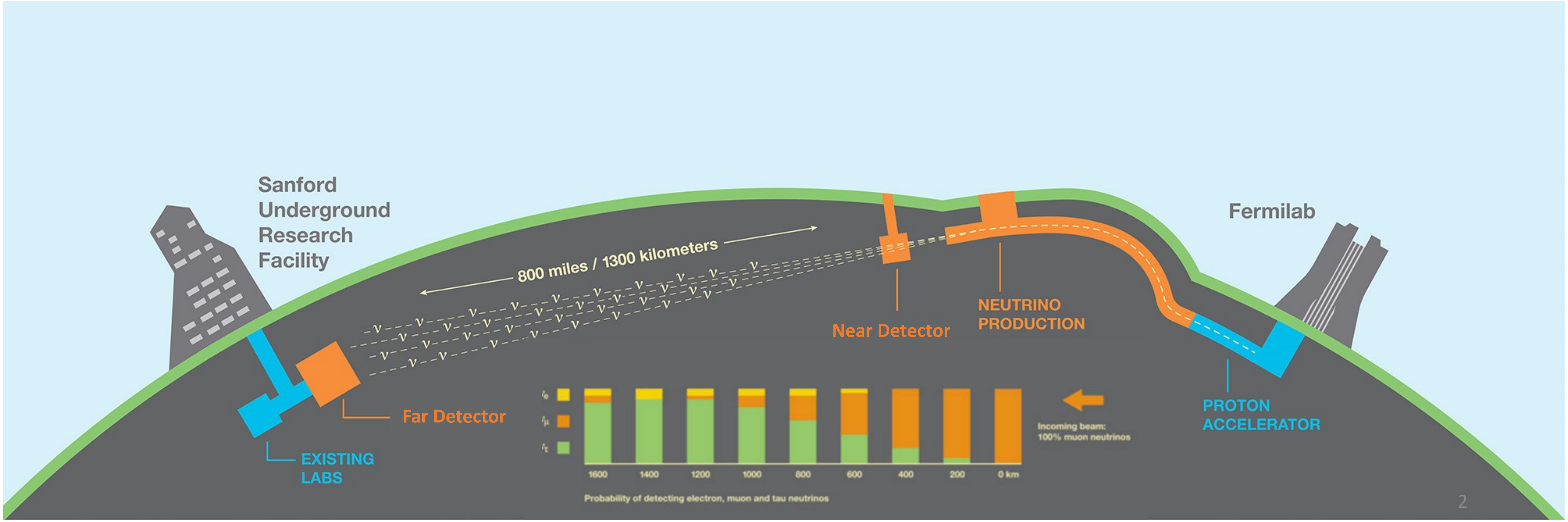
Nikolina Ilic on behalf of DUNE Canada

Institute of Particle Physics & University of Toronto

IPP 50th Anniversary Symposium

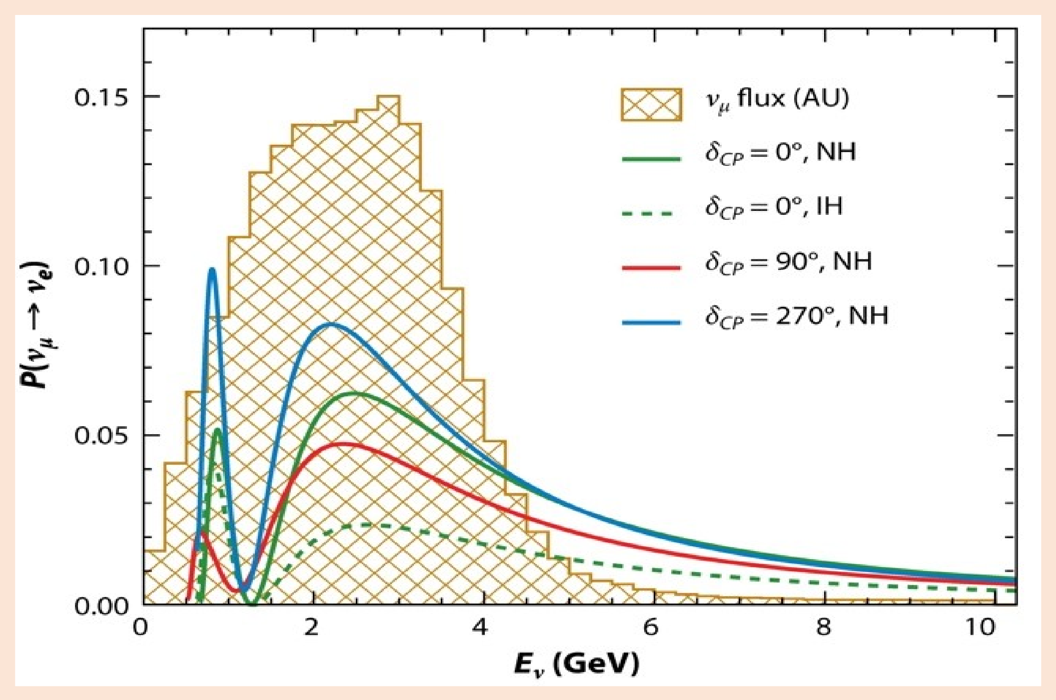
LBNF DUNE Facility

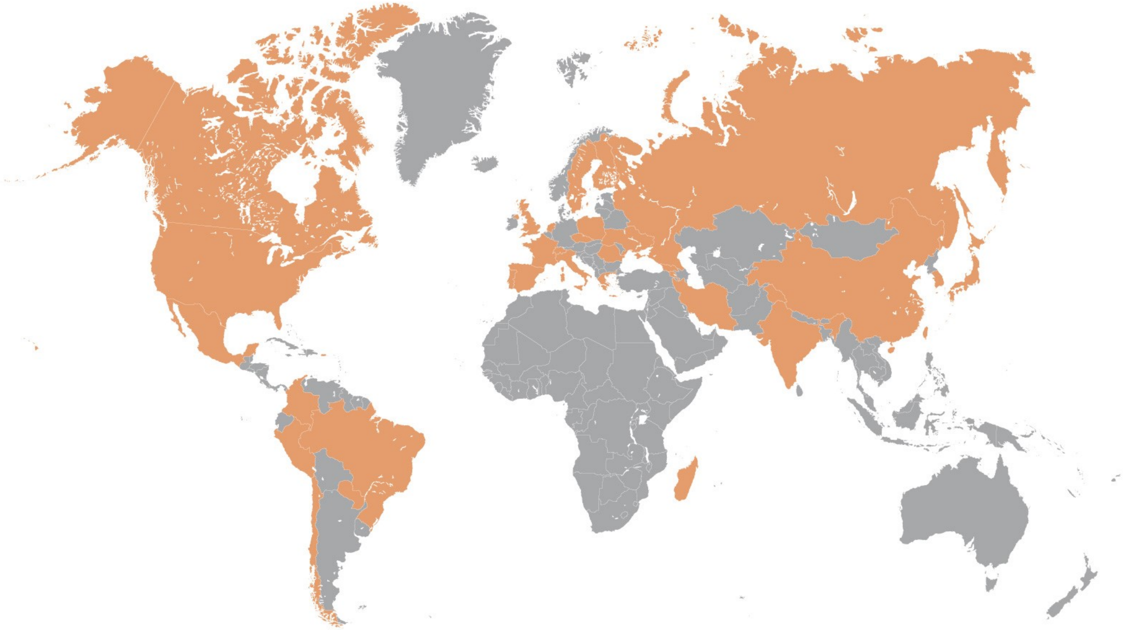
- 1-6 GeV muon neutrinos/antineutrinos from high-power proton beam (1.2 MW – upgradable to 2.4 MW)
- Near detector measures fluxes & constrains systematics (100s of millions of neutrino interactions)
- Far Detector is a Liquid Argon Time Projection Chambers (LAr TPC) – fine granularity



DUNE

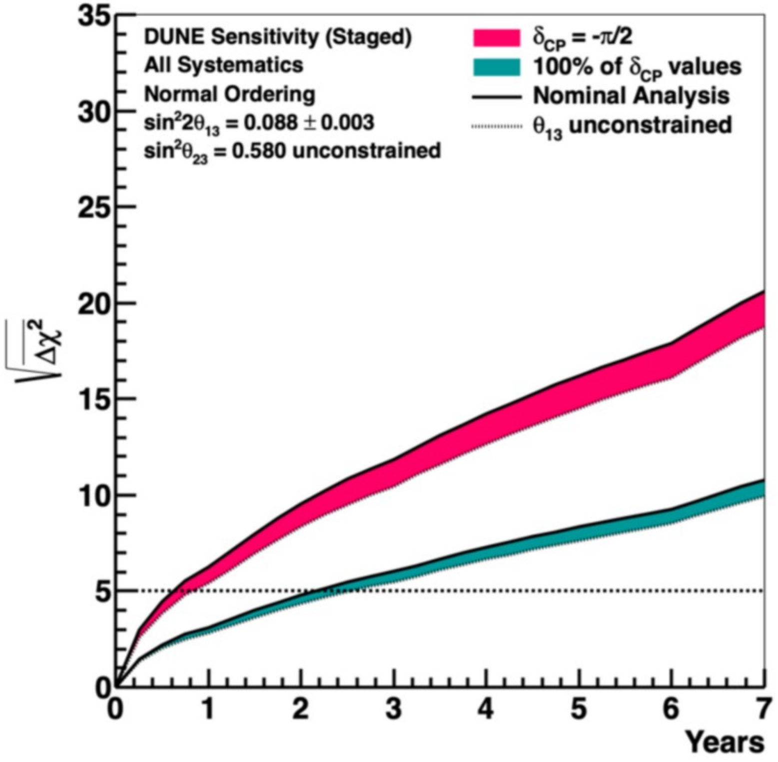
- On axis beam gives wide range of neutrino energies so we can “see” oscillations
- Motivates the use of LAr detectors that have very good energy reconstruction for a wide range of energies
- The DUNE Collaboration consists of >1000 collaborators from >180 institutions in >30 countries





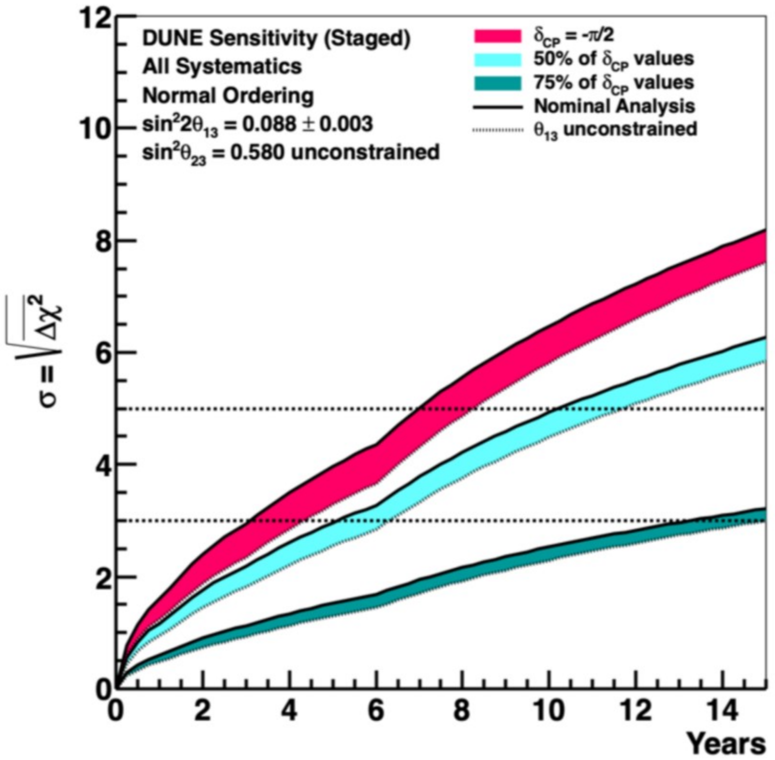
Motivation: Mass Ordering and CP violation

Mass Ordering Sensitivity



- 5σ sensitivty 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 $\Delta m^2_{32}, \delta_{CP}, \sin^2\theta_{23}, \sin^2 2\theta_{13}$

Motivation: A general purpose detector

Tau neutrino appearance

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

- additional probe to neutrino properties and BSM
- verify the standard solar model, measure sun's core temperature, characterize neutrino floor, resolve tension between global solar neutrino measurements & KamLAND, characterize MSW affect

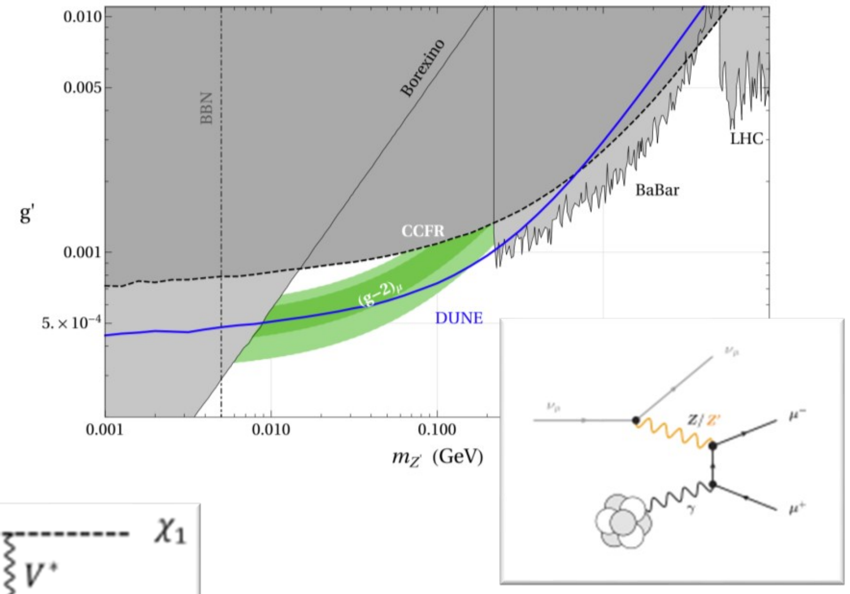
Supernova neutrinos: Core collapses expected to occur few times per century (at 10-15 kpc), ~ 10^{58} of ~ 10 MeV ν emitted for few seconds.

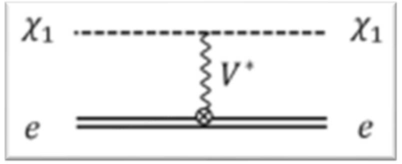
- Test astrophysical theories, probe new physics
- DUNE uniquely sensitive to ν_e ($\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$)

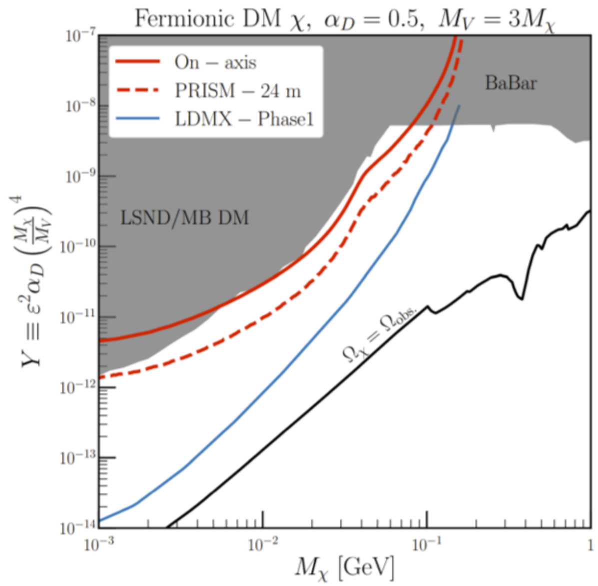
Beyond standard Model

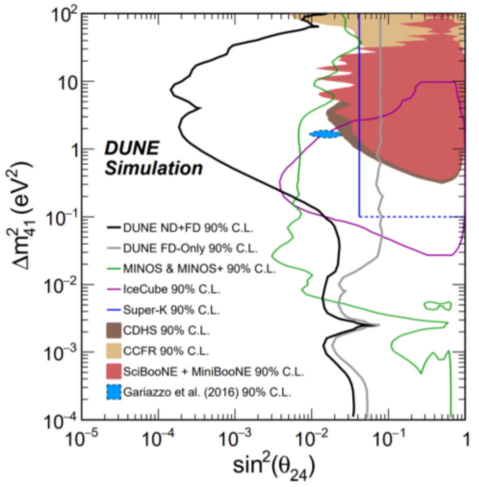
- Light Sterile ν (could explain short baseline/ gallium/reactor anomalies, hints of CKM non-unitarity and LFV)
- Neutrino tridents (Z' in gauged $L_\mu - L_\tau$ can explain g-2/B-anomalies)
- Non-standard interactions (could explain B-anomalies)
- Dark Matter, Heavy Leptons, Non-PMNS unitarity, Lorentz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

Proto Decay, Baryon Number Violation



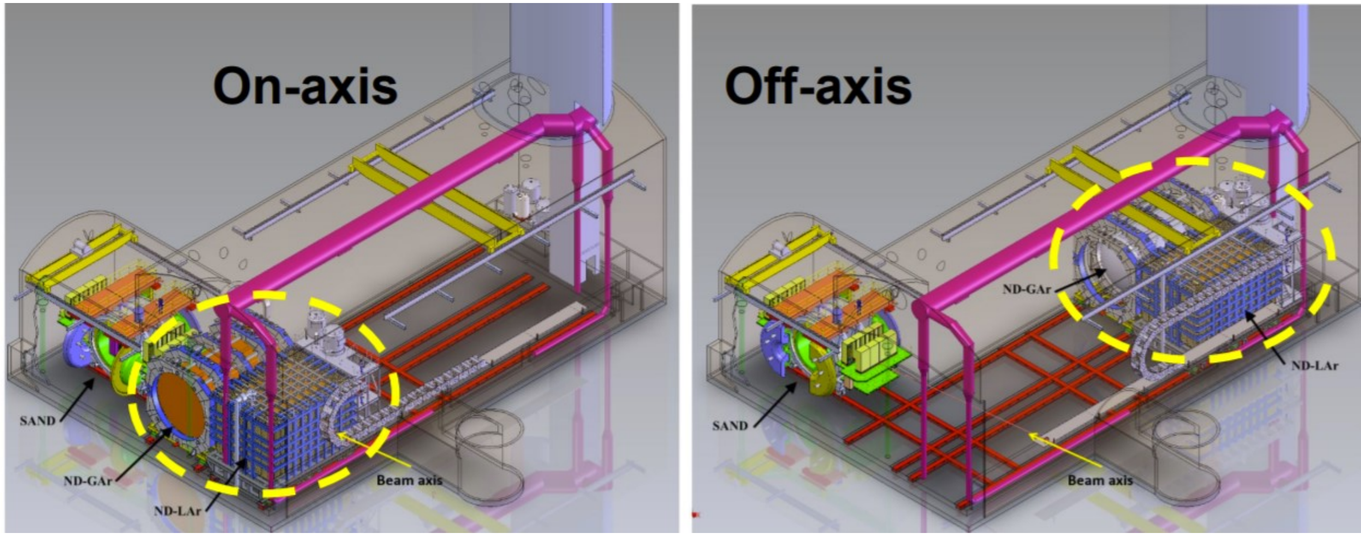




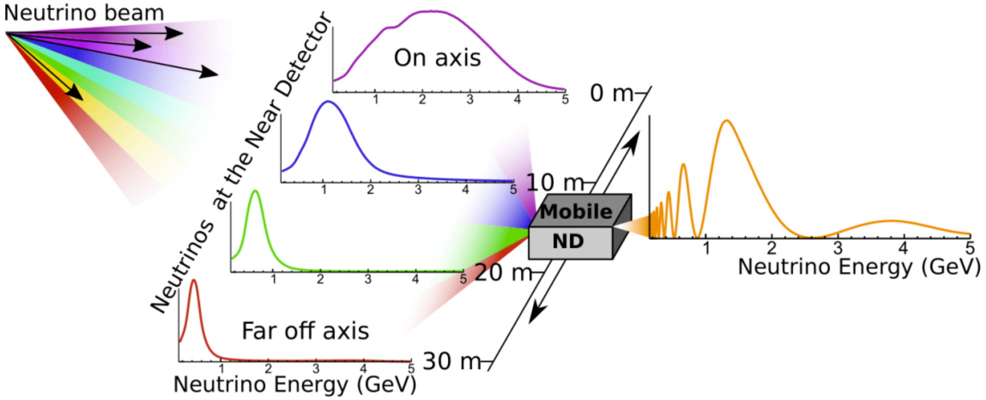


DUNE Near Detector

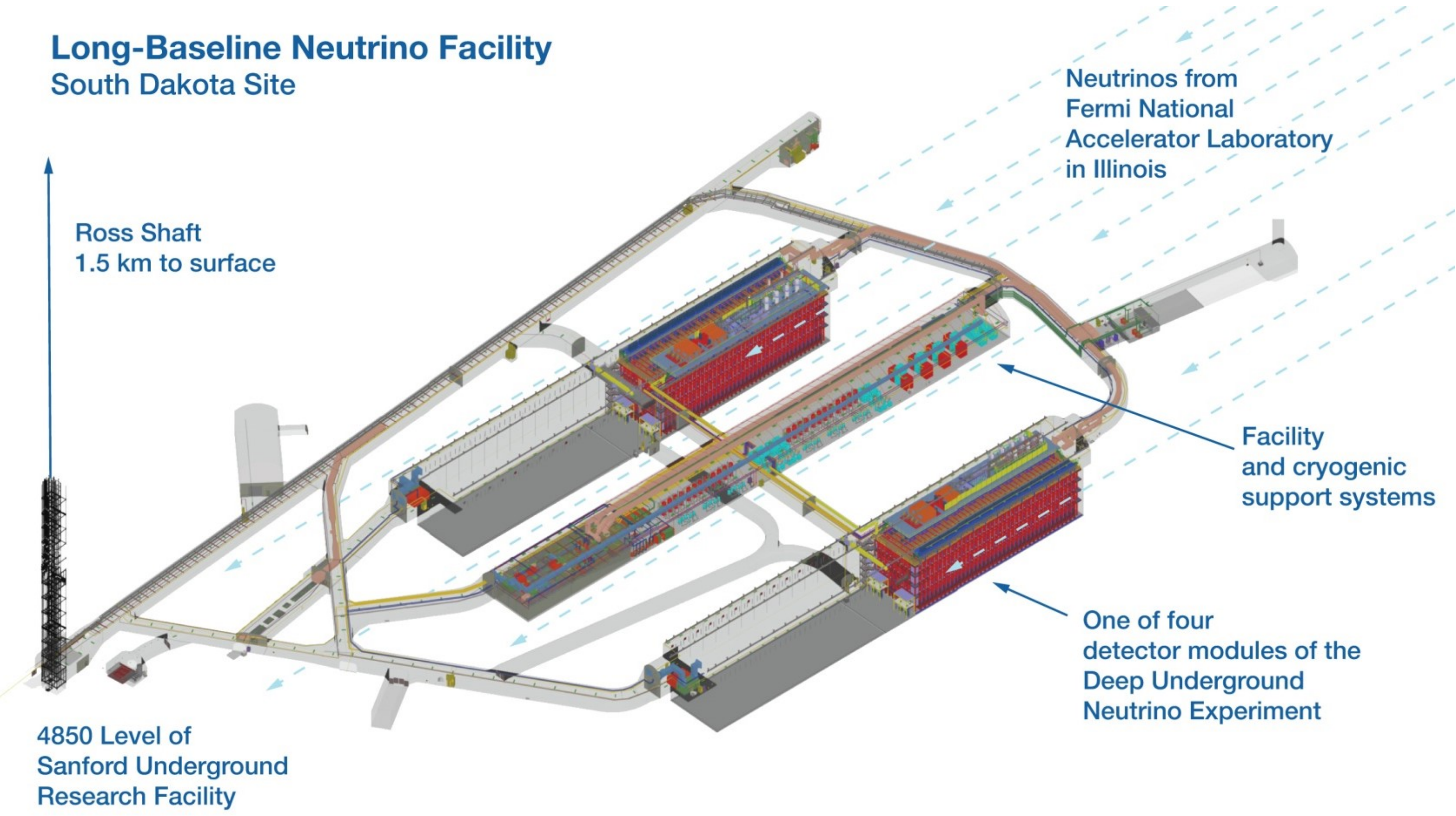
- **ND-LAR:** liquid argon TPC with muon spectrometer (TMS) 50t fiducial mass, modular detector with pixel readout to reduce pileup
  - Similar to FD to characterize beam flux and neutrino interactions
- **ND-GAr**: Gaseous argon detector
  - surrounded by ECAL and muon system in magnetic field
  - good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



DUNE PRISM



DUNE Far Detector



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

Phase I

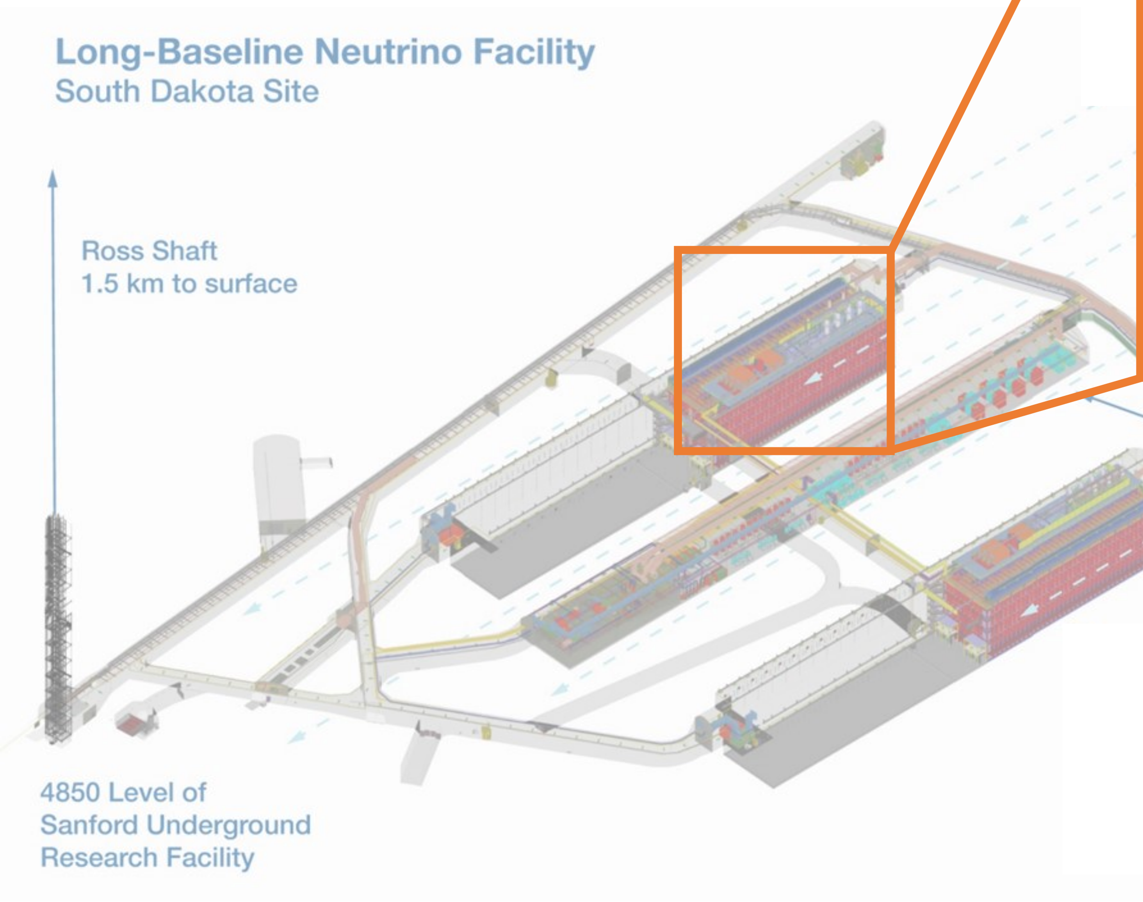
- 1st module - Single Phase (SP), horizontal drift, LAr Time Projection Chamber (LArTPC) Installed mid 2020s
- 2nd module - SP vertical drift LAr TPC
- ND: NDLAr+TMS+SAND
- 1.2 MW beam power

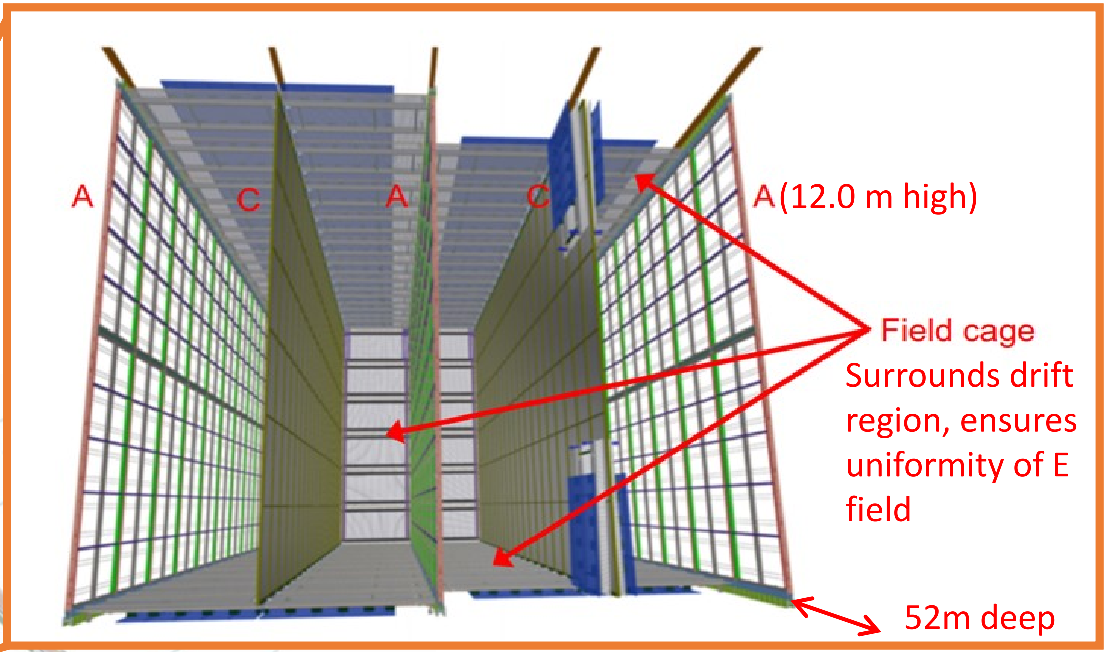
Phase II

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

Excavation started!

DUNE 1st Module

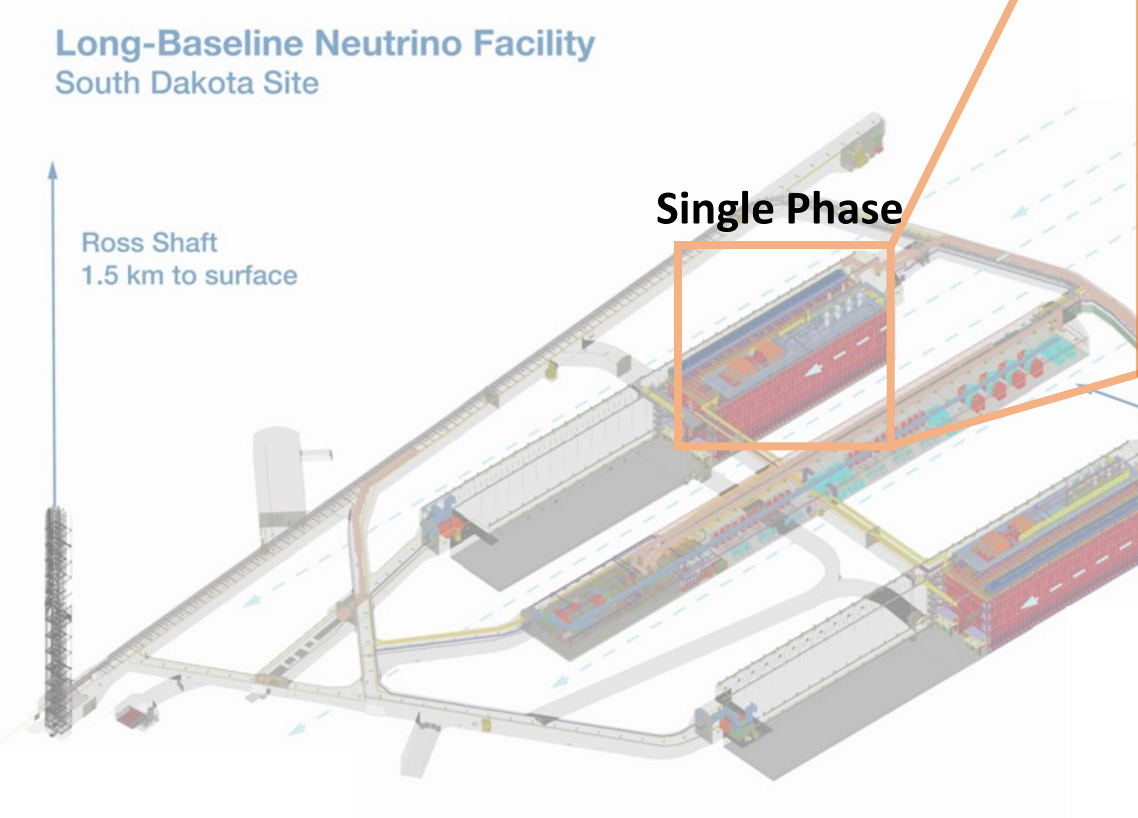


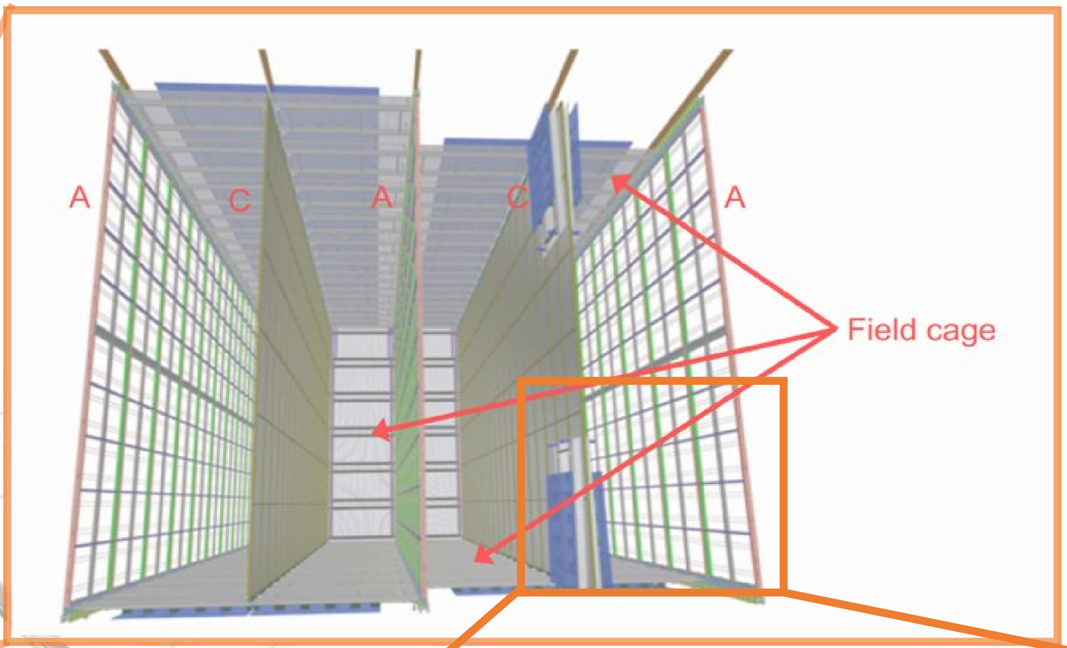


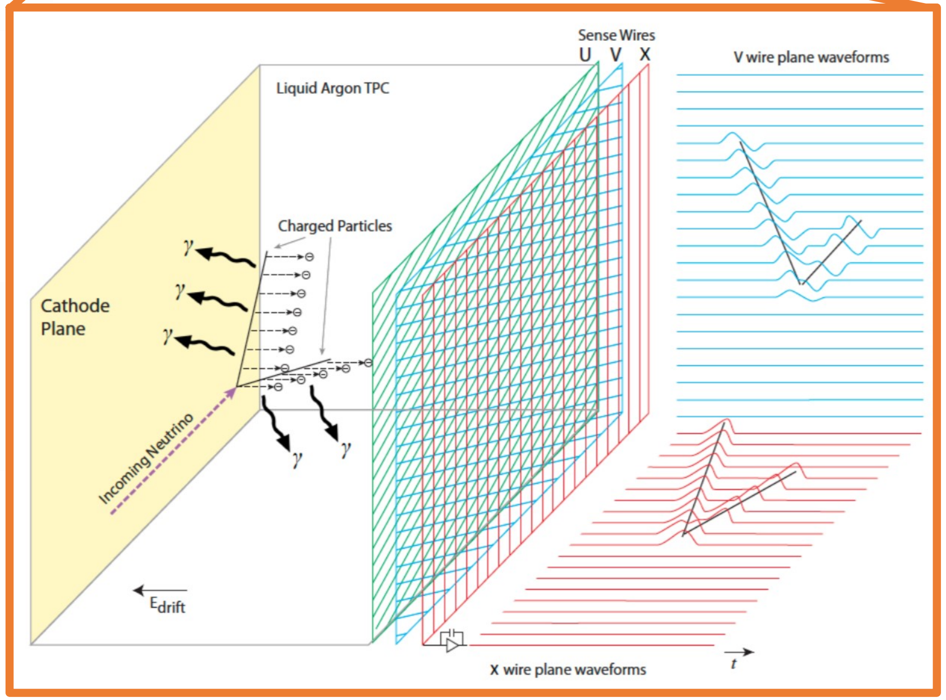
Field cage
Surrounds drift region, ensures uniformity of E field

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

DUNE 1st Module

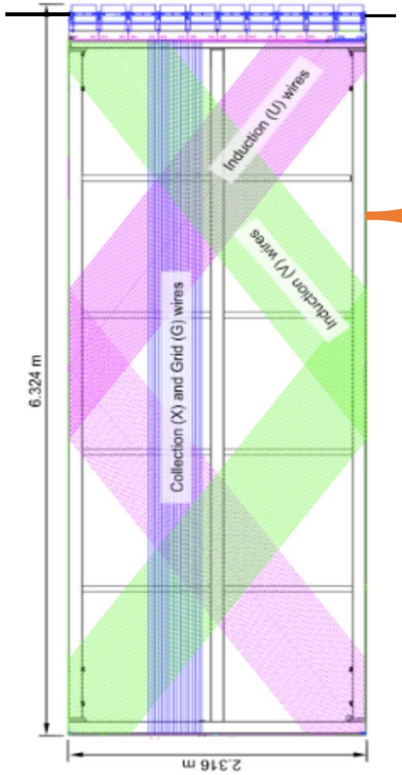


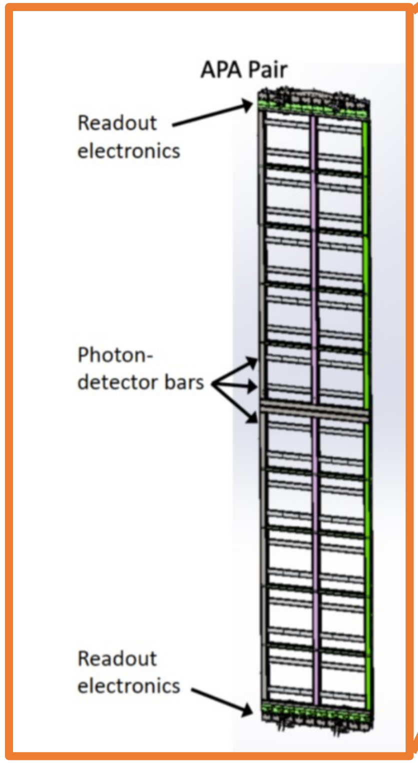


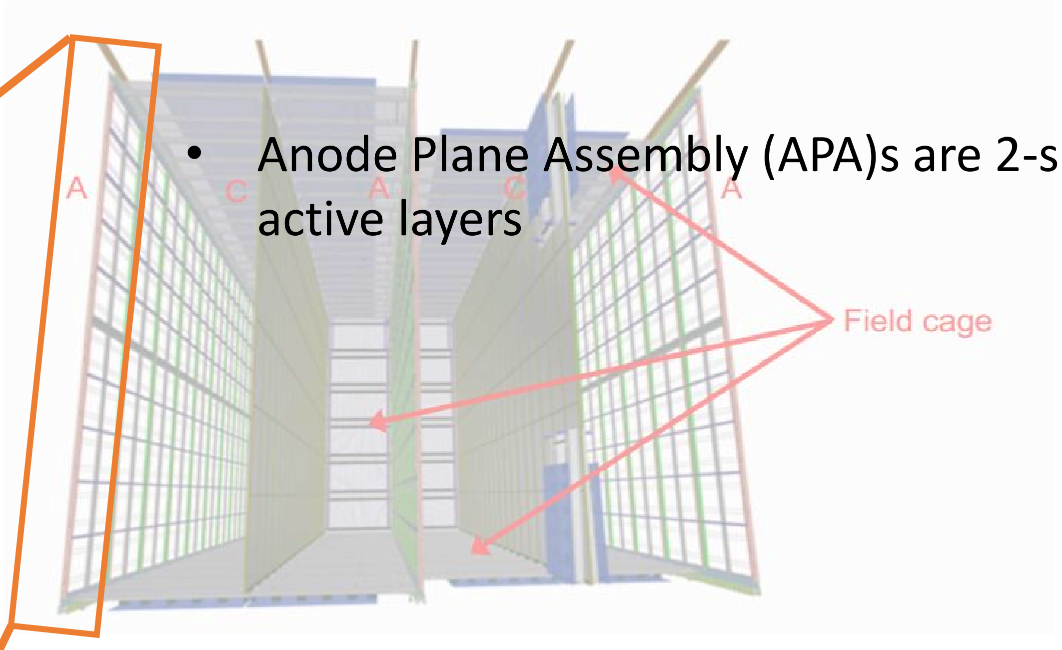


- 3D image of neutrino interactions with mm resolution
  - 3.5m drift region, E field of 500 V/cm, Cathode HV 180 kV
- LAr is good scintillator ⇒ provide t_0 (non-beam trigger)

DUNE 1st Module

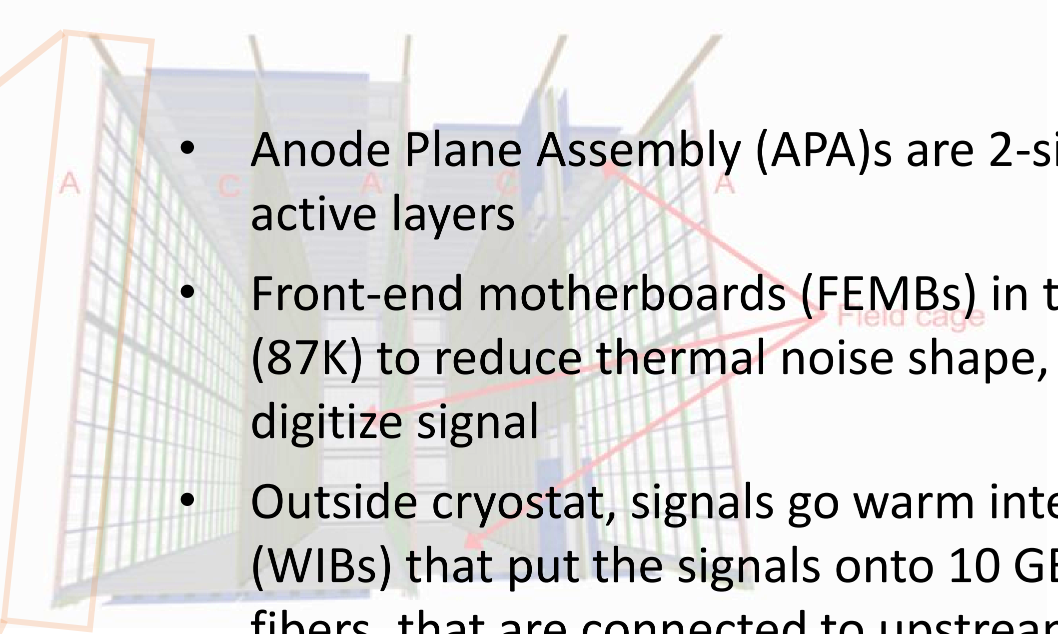




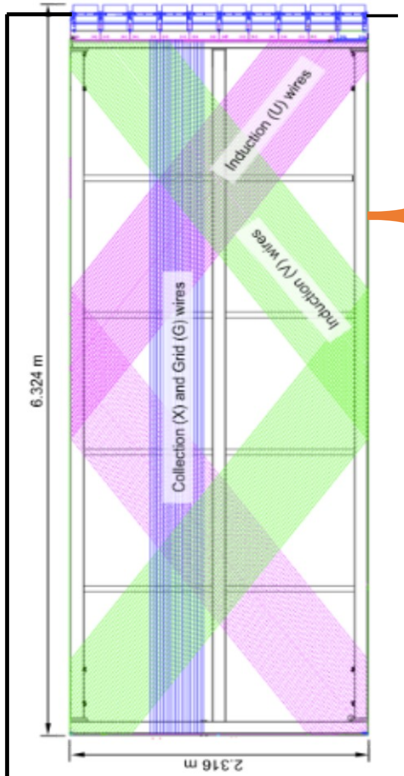


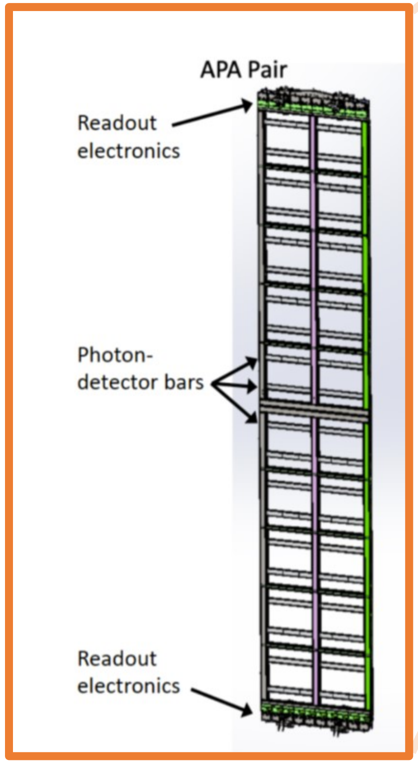
- Anode Plane Assembly (APA)s are 2-sided, with 3 active layers

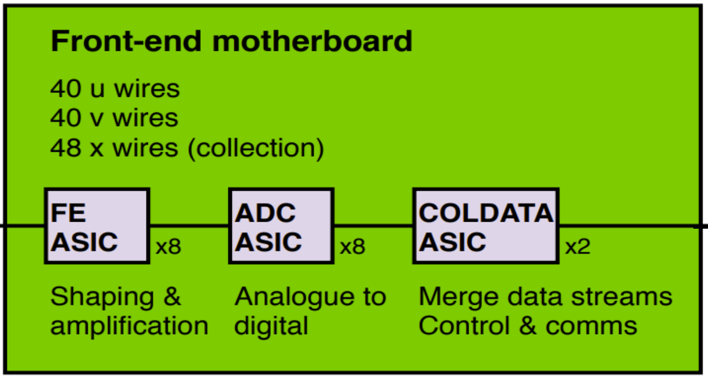
DUNE 1st Module



- 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







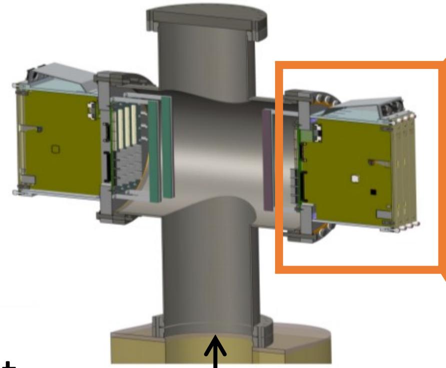
Front-end motherboard

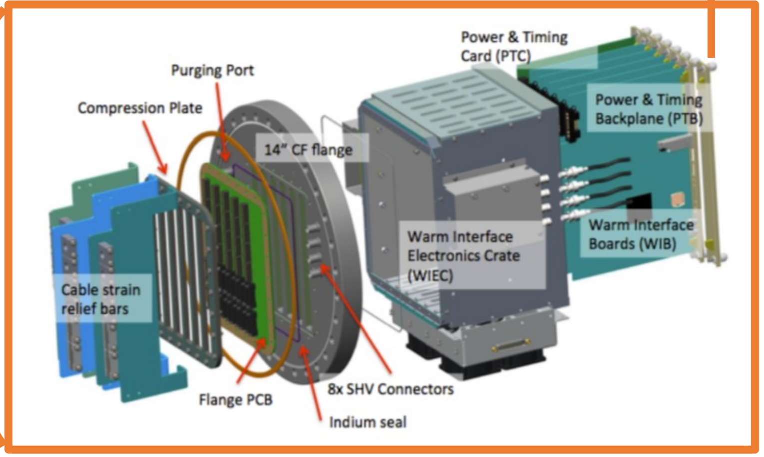
40 u wires
40 v wires
48 x wires (collection)

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

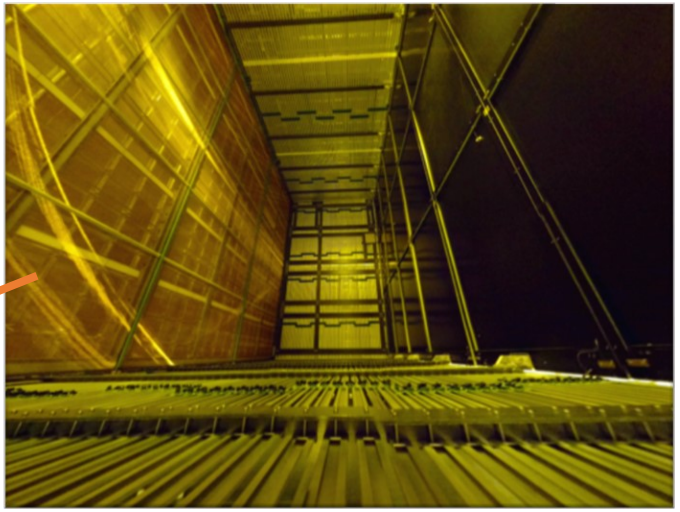
x 20 per APA

Outside Cryostat





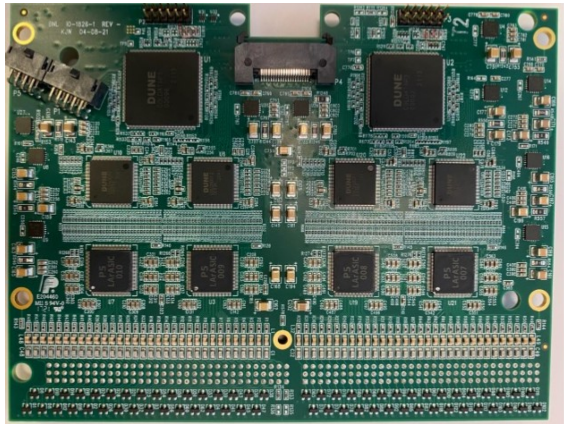
ProtoDUNE



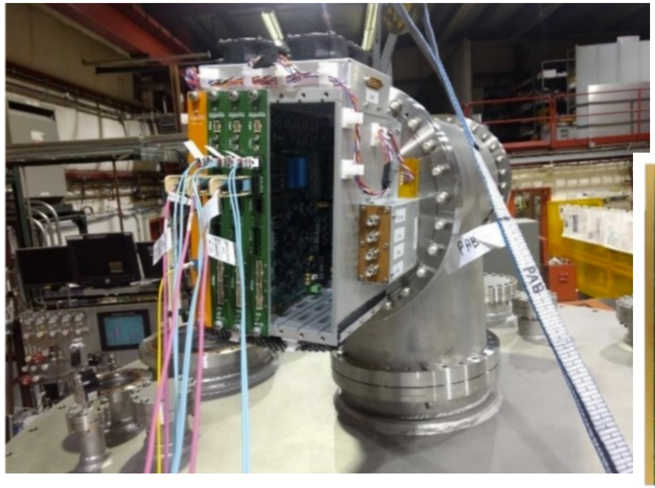
ProtoDUNE SP Drift Region

APA

FEMB

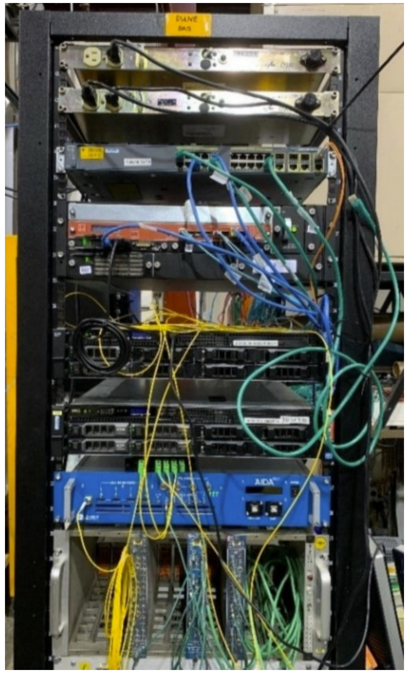


Outside Cryostat

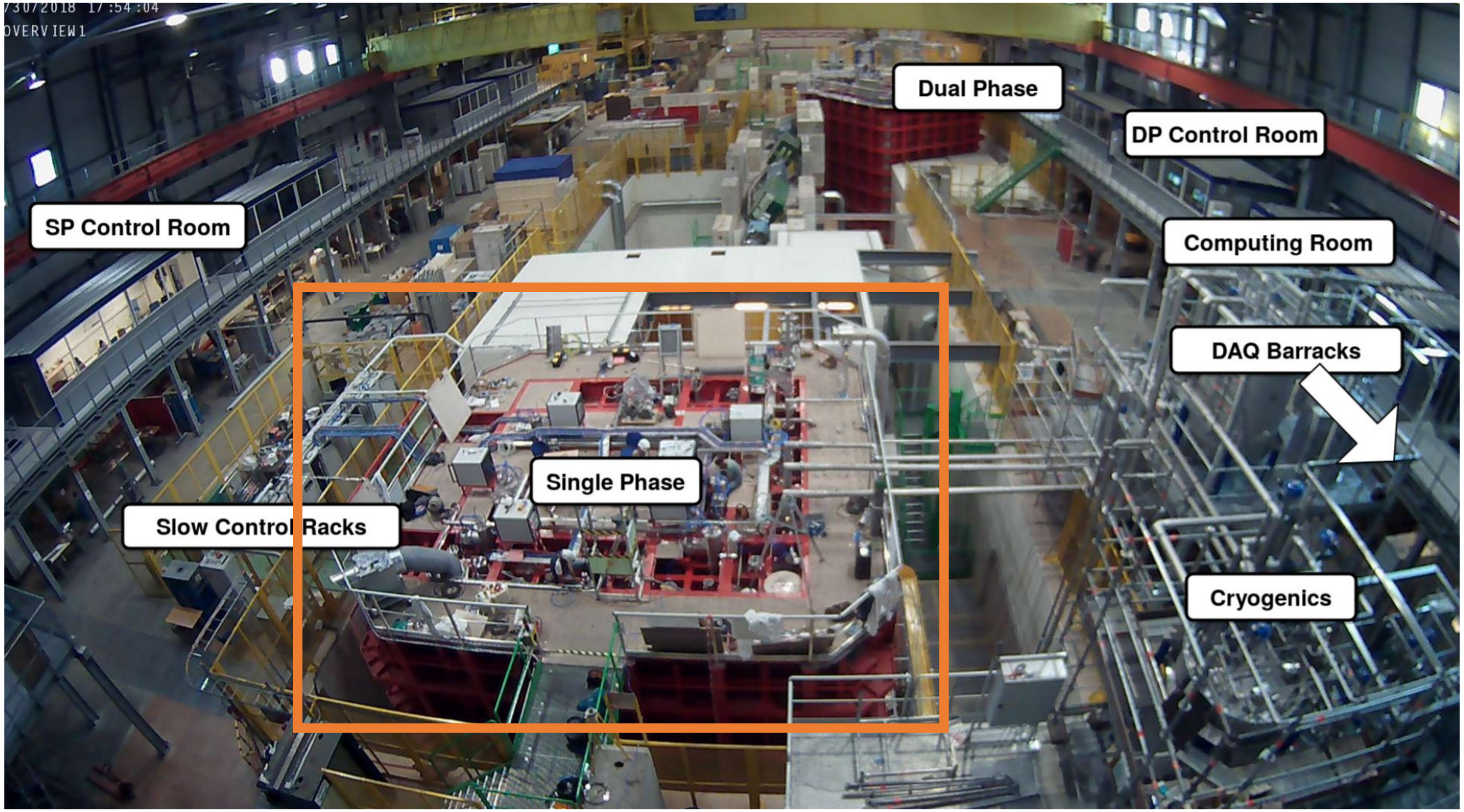


WIB

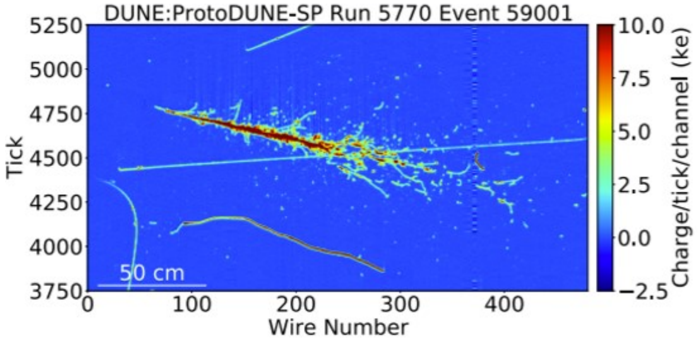
DAQ



ProtoDUNE



- At CERN neutrino platform, have built 2 prototypes, 1/20th the size of planned DUNE (15K sense wires)
- Collected hadron data 2018-2020, excellent performance!
  - 99.7% of electronics responsive, 99% HV uptime, high purity
- Will run again this year with vertical drift design!



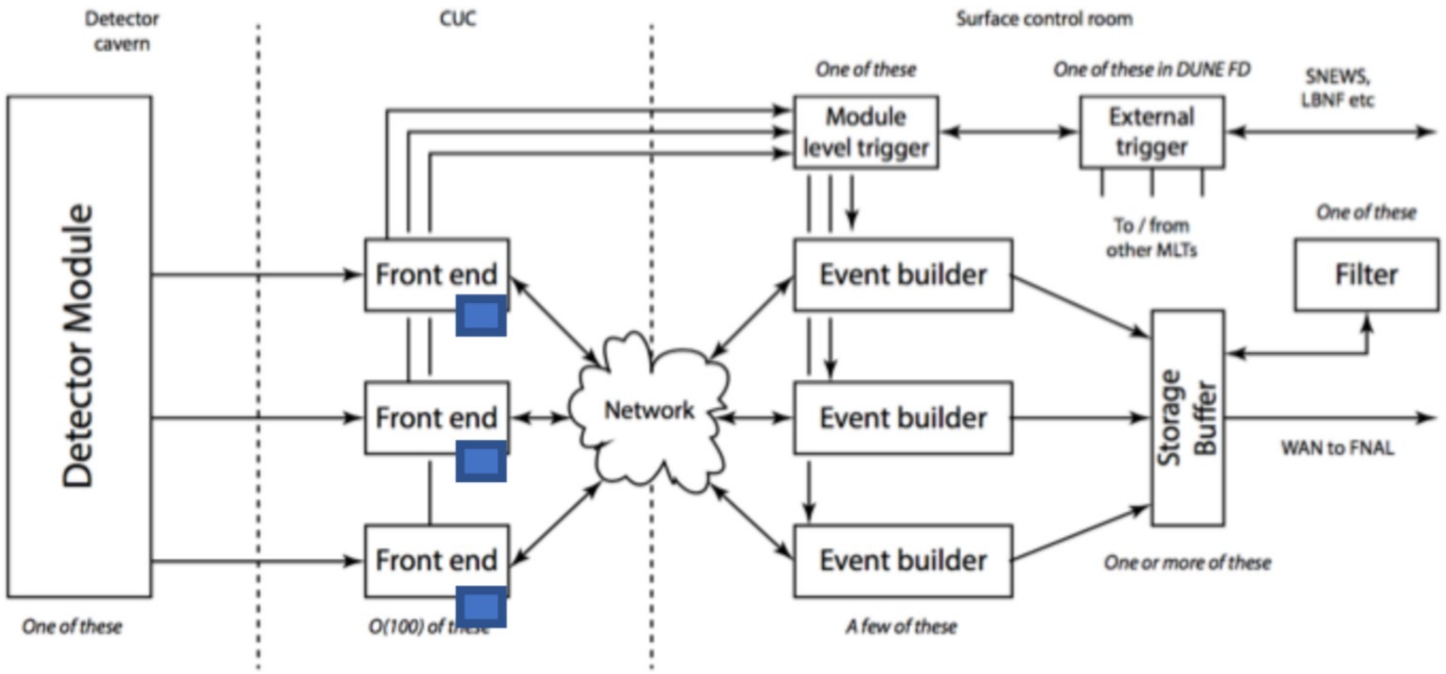
6 GeV electron

Data Acquisition (DAQ)

- High performance I/O and compute system - Detector input (~1.5 TB/s). Data rate to tape 30 PB/year

- FPGA-based readout board deals data reception from detectors, data exchange with server

- On receipt of supernova trigger must be able to record 100s of full waveform data including O(10s) before the trigger signal



DUNE

CANADA

YORK UNIVERSITÉ UNIVERSITY

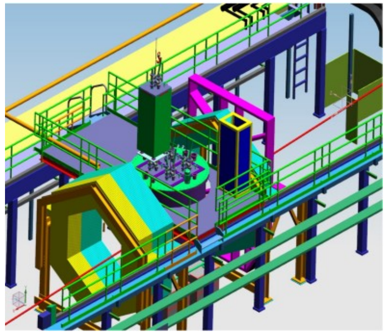
INSTITUTE OF PARTICLE PHYSICS

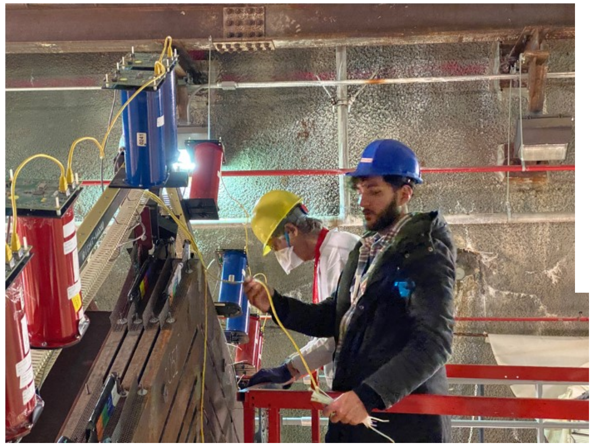
UNIVERSITY OF TORONTO

Testing DUNE’s ND Technology

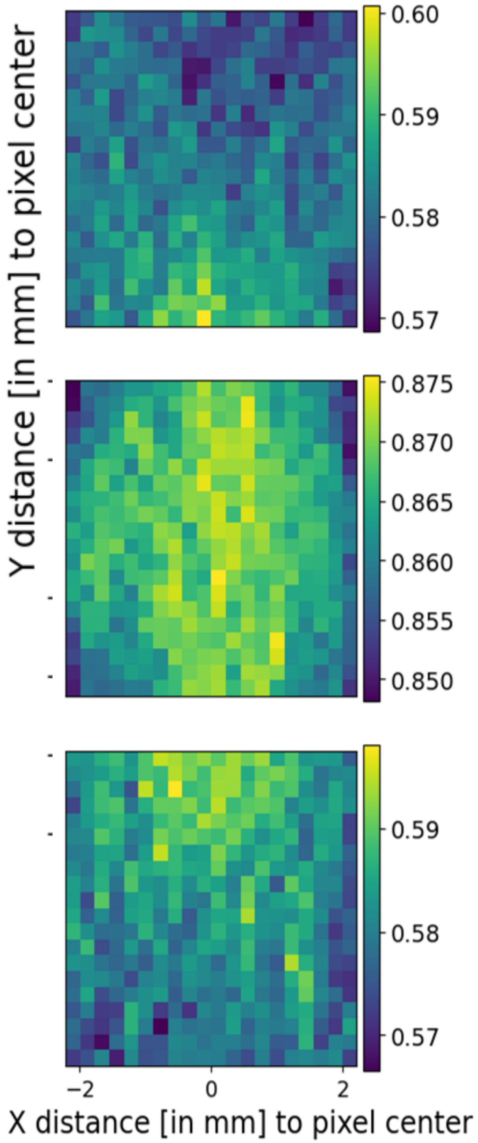
ND want same detector technology to withstand 10^6 x rate, need prototypes:

- planned at York U. single cube (30 cm^3 pixelated LAr TPC) (CFI Grant at York)
- Modules 0/1 tested (elongated single cubes) on cosmic ray at Bern
- 2x2 module tests in real neutrino beam





response maps of pixels



Deborah Harris
(faculty)

Rowan Zaki
(PhD student)

Computing

C. David is contributing author of DUNE Computing CDR (under review)

- DUNE computing training (Jan/May/Dec 2021 & May 2022), co-convener of training & documentation group
- Compute-Canada resource allocation (VCPU and cloud storage) successful in 2021/22, fast track extension of initial resource allocation competition (RAC) 2022/23
- collaboration with HEP software foundation and IRIS-HEP

Claire David, faculty

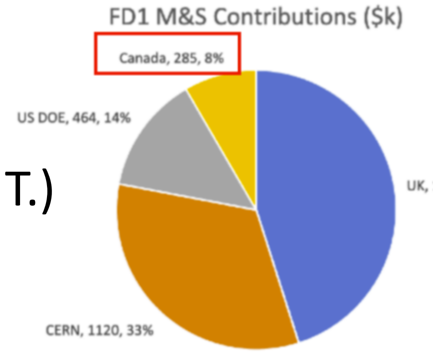
T. Cai leading effort to develop analysis facility with Jupyterlab on Compute Canada Arbutus cloud

- Lead study on advanced computing methods, such as routing machine learning segments of ProtoDUNE data processing to external GPU farm
- Developing algorithms to supernova neutrino directions using the in-storage computing elements at the FD

Tejin Cai, postdoc

Data Acquisition (DAQ)

- Ilic is on DUNE DAQ Management board, coordinating/writing of FDR
  - Contributing 8% to DAQ FD hardware + ProtoDUNE (CFI JELF/ORF/U of T.)
  - Planned collaboration with U of Montreal as MRS co-PI

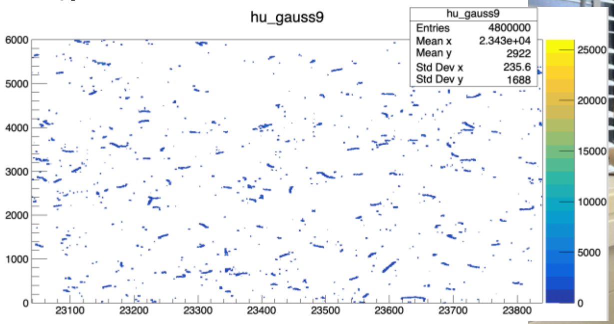


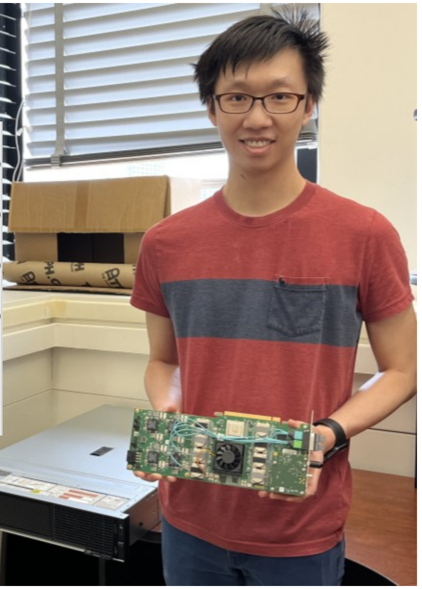
Nikolina Ilic (faculty)

Danaisis Vargas (Postdoc)

At CERN: DAQ testing/integration in ProtoDUNE

- For the last 3 years, postdoc was one of few people based at CERN responsible for all hardware/software & integration/commissioning activities (published in TDR/ProtoDUNE papers)





Mathew Man (PhD Student)

U of Toronto lab: testing high performance servers with FELIX

- tests on several server/SSD/adapter combinations to ensure DUNE can handle readout requirements for beam physics, calibrations, supernova etc.
- Optimizing DAQ for low energy physics such Supernova & Boron 8 neutrinos (paper in progress)

Improving DUNE’s description of Neutrino Interactions

- Measurements of $\bar{\nu}$+p → μ + n, probe weak charge distribution in free protons
  - Previously only done on deuterium with bubble chambers
  - Critical input for DUNE neutrino-nucleus generator
  - T. Cai pioneered new technique pioneered using MINERvA data (submitted for publication)

Tejin Cai, postdoc

- Improved model of pion production by neutrinos
  - M. Kabirnezhad authored model currently in use, superior due to its sophisticated treatment of different channels with same final state
  - Using electron-scatering measurements of pion production to constrain the model parameters (submitted for publication https://arxiv.org/abs/2203.15594)

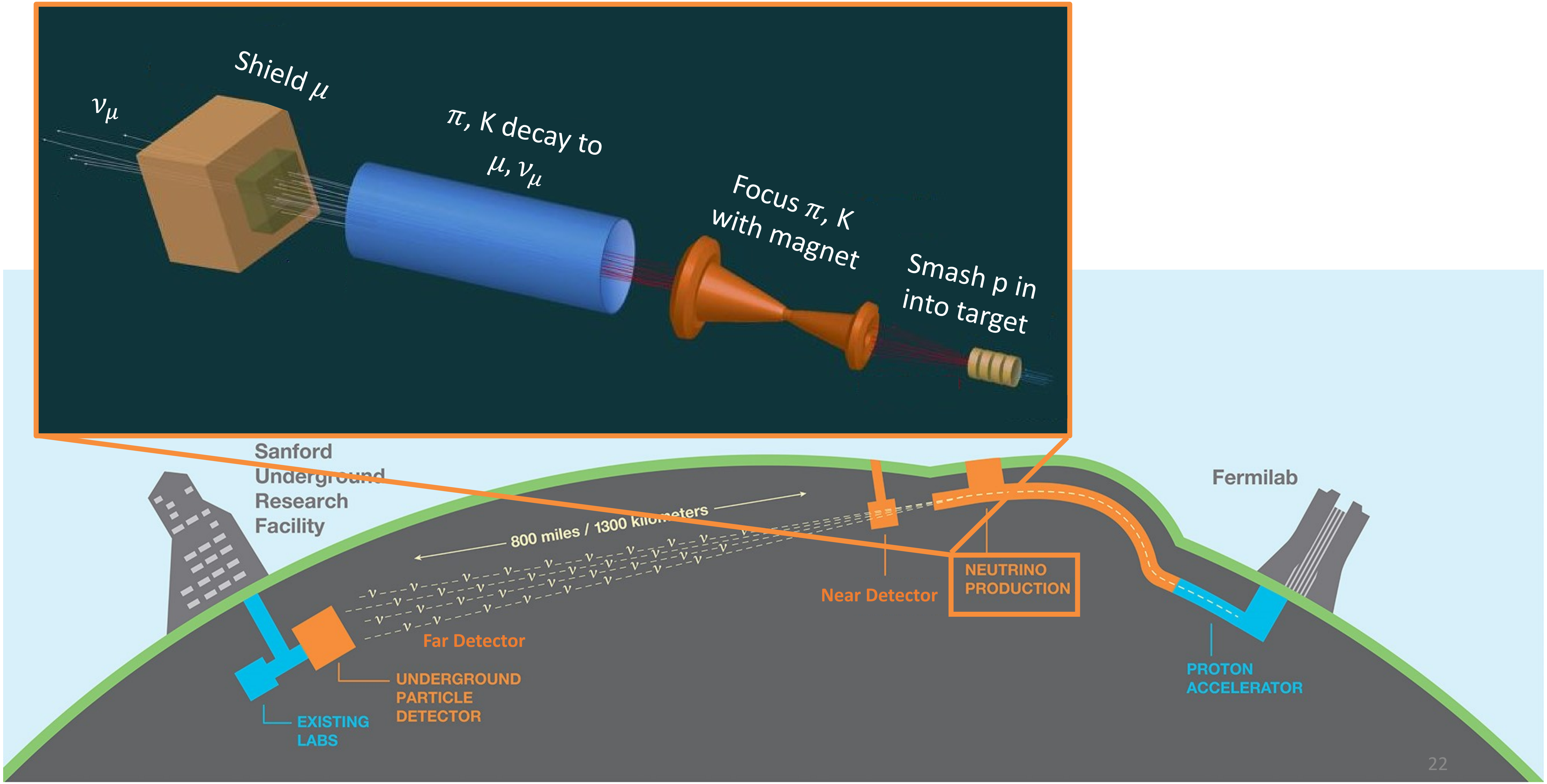
Monireh Kabirnezhad
(postdoc, theory)

Summary & Outlook

- DUNE is a broad band energy neutrino experiment (TDRs completed: JINST 15 (2020) 08, T08008, T08009, T08010, FERMILAB-PUB-20-025-ND)
- DUNE will have a large physics program: unprecedent 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, this year will run again to test vertical drift technology
- Far detector construction is underway
- Near site construction is underway
- Far detector expected to take physics data in late 2020s
- Neutrino beam expected on similar time scale
- Canadian contributions on ND, DAQ, Computing, Neutrino Interactions, JOIN US!

BACKUP

LBNF DUNE Facility



ν_μ

Shield μ

π, K decay to μ, ν_μ

Focus π, K with magnet

Smash p in into target

Sanford Underground Research Facility

800 miles / 1300 kilometers

Fermilab

Near Detector

NEUTRINO PRODUCTION

Far Detector

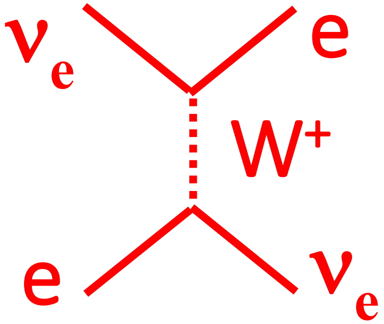
UNDERGROUND PARTICLE DETECTOR

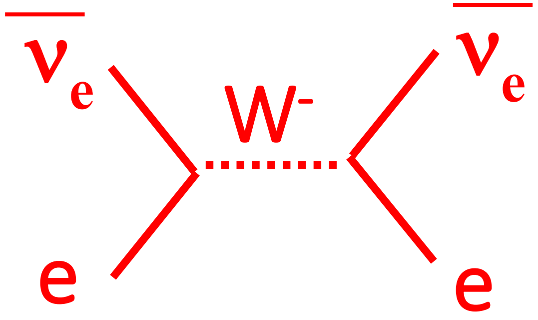
EXISTING LABS

PROTON ACCELERATOR

DUNE Sensitivity to Mass Ordering and CP violation

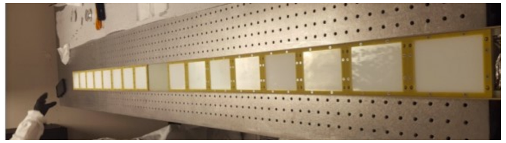
- In DUNE, L = 1300km, lots of chances to interact with matter!
- Since matter acts differently on ν_e and $\bar{\nu}_e$, there is asymmetry in $\mathrm{P}(\nu_\mu \rightarrow \nu_\mathrm{e})$ versus $\mathrm{P}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- Sign of asymmetry depends on mass ordering!

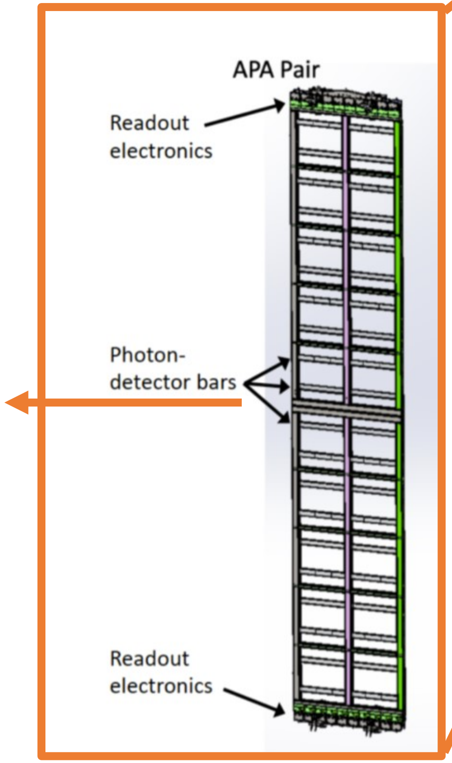


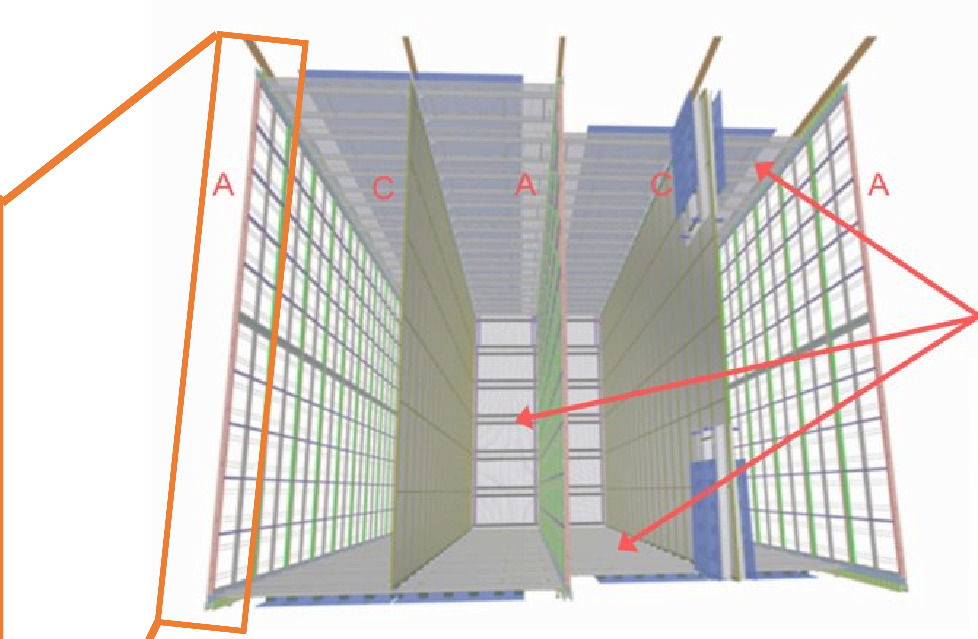


- This complicates CP measurement, BUT matter effects and direct CP violation have different *E* and *L* dependences – and DUNE can get CP violation as function of E!

DUNE 1st Module



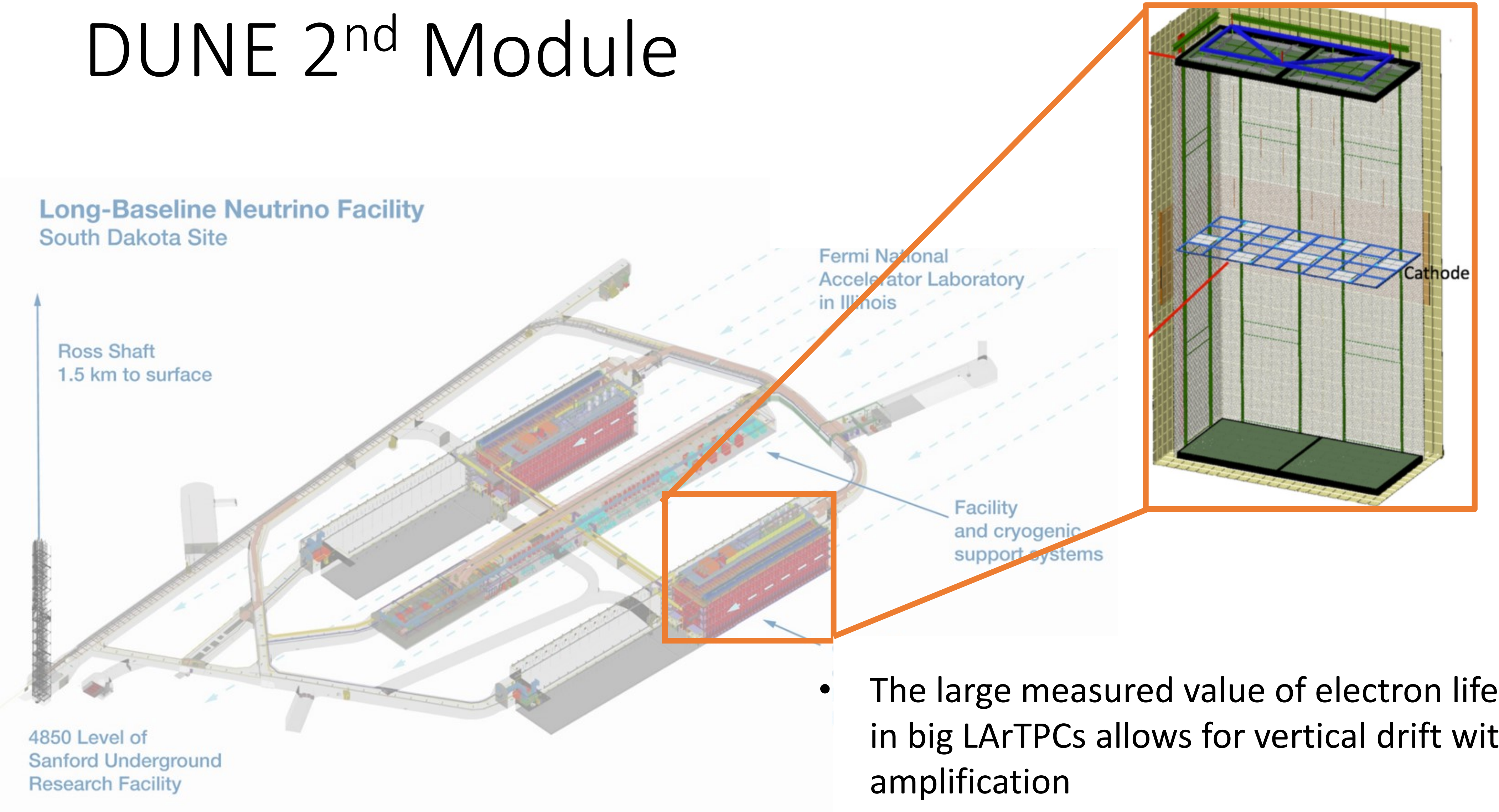




aluminum with white polyethylene caps on the ends to prevent discharges

- 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 2nd Module



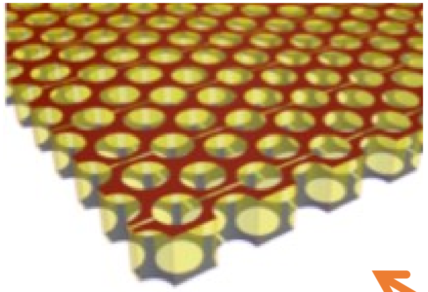
- The large measured value of electron lifetime (> few ms) in big LArTPCs allows for vertical drift without signal amplification

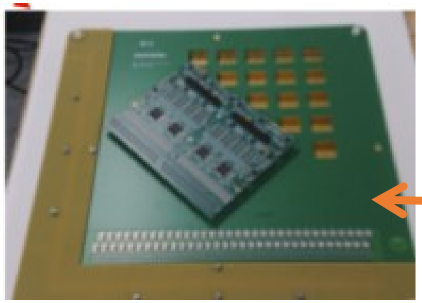
- Ionized charges drift vertically, read out on horizontal PCB anode and cathode planes (two 6.5 m drift volumes). E field 450 V/cm
- This design simplifies construction/installation and reduces cost

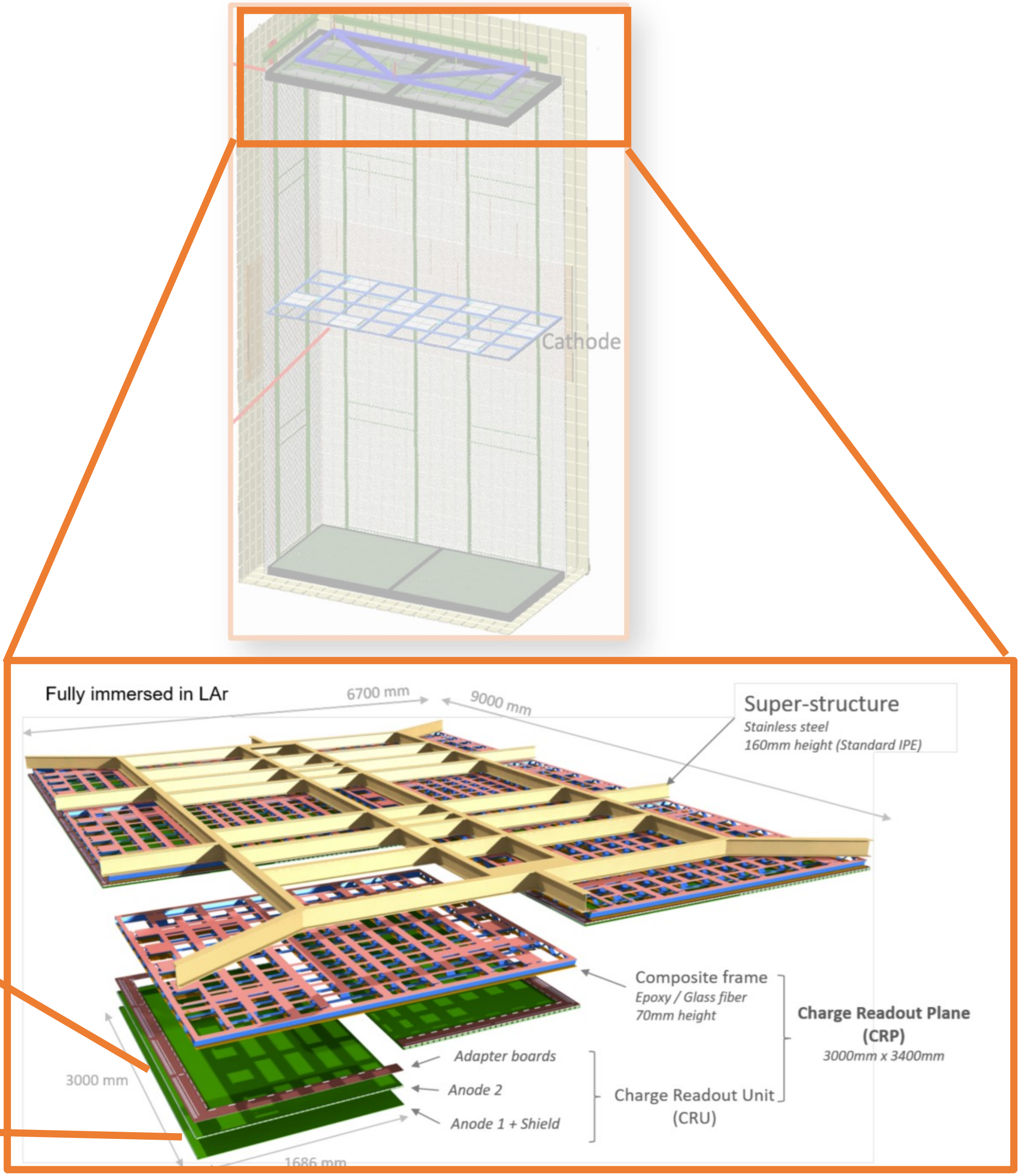
DUNE 2nd Module

- 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

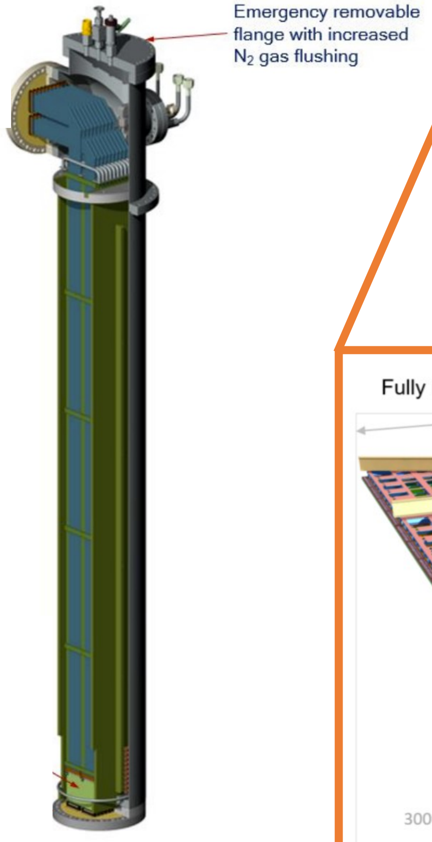




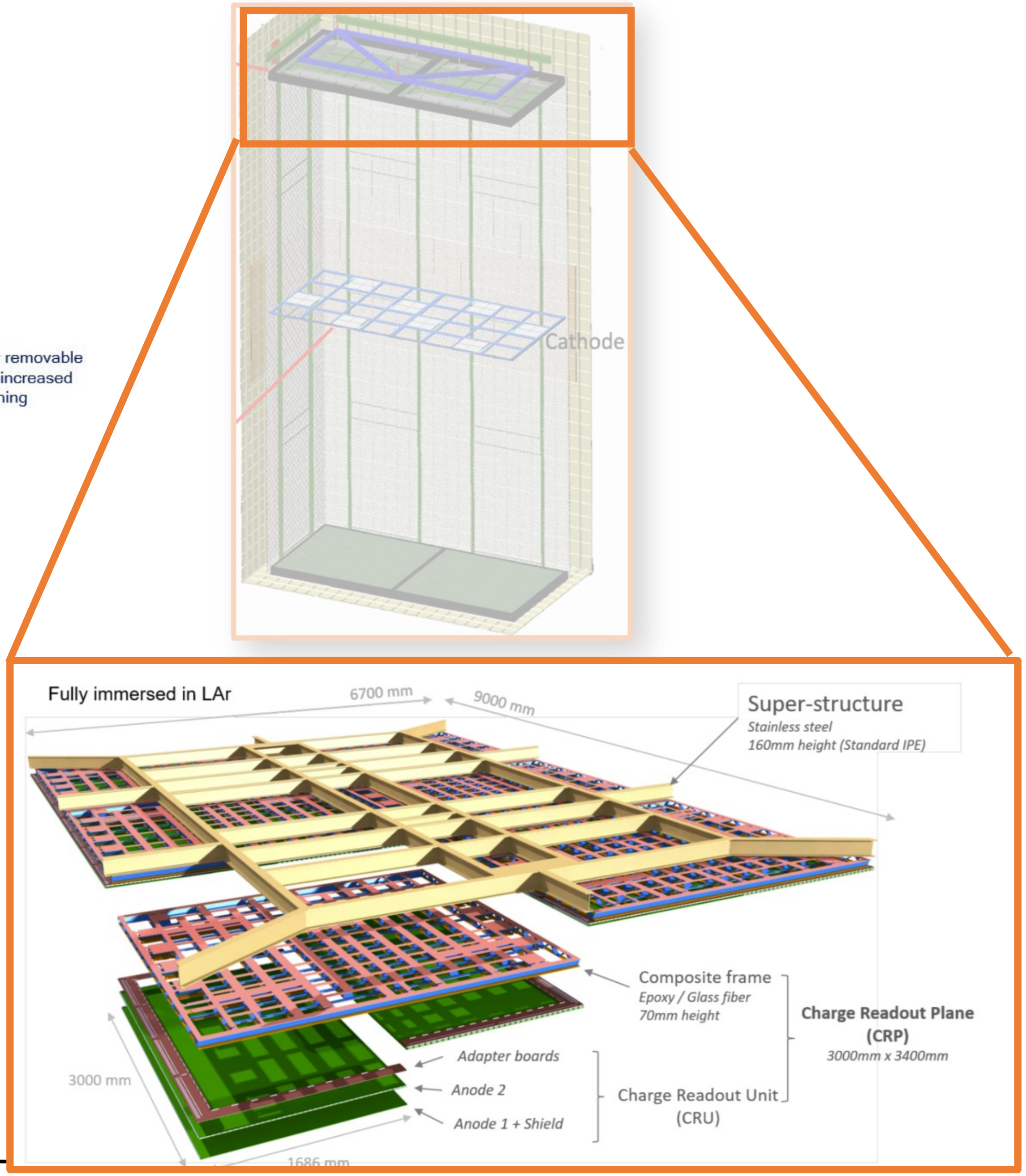


DUNE 2nd Module

- 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
  - 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

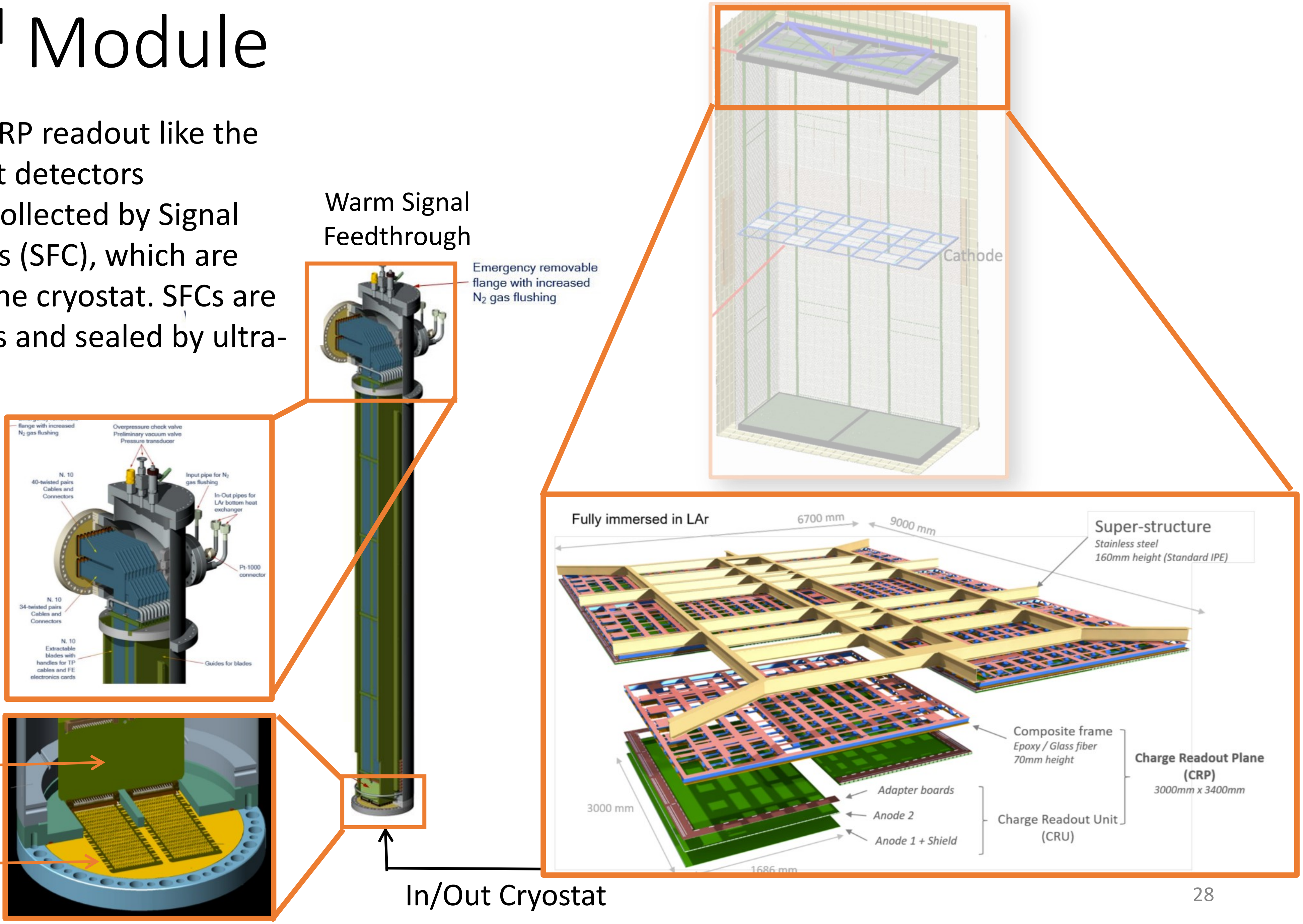


In/Out Cryostat



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



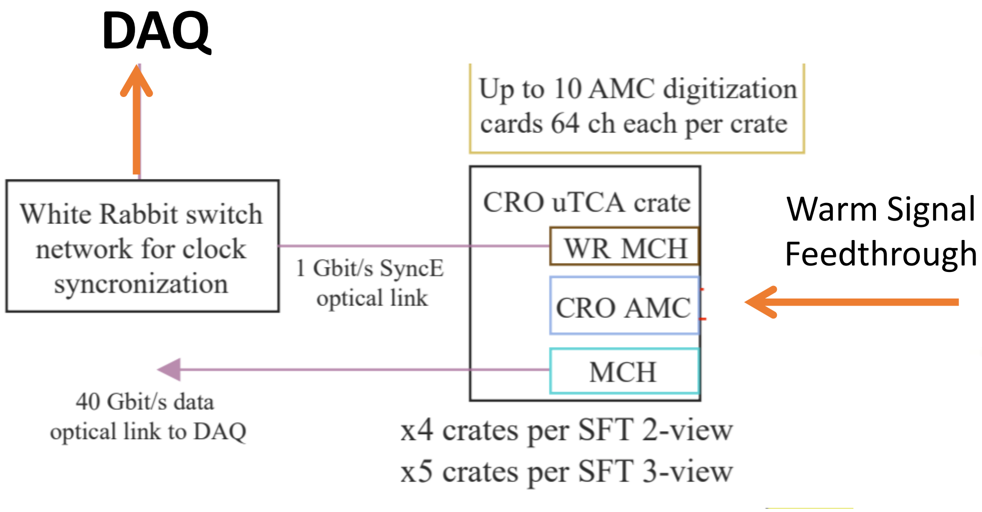
Warm Signal Feedthrough

Cold FE Analogue Acquisition Card

Cold Signal Feedthrough

In/Out Cryostat

DUNE 2^{nd} Module


DAQ

White Rabbit switch network for clock syncronization

1 Gbit/s SyncE optical link

40 Gbit/s data optical link to DAQ

Up to 10 AMC digitization cards 64 ch each per crate

CRO uTCA crate

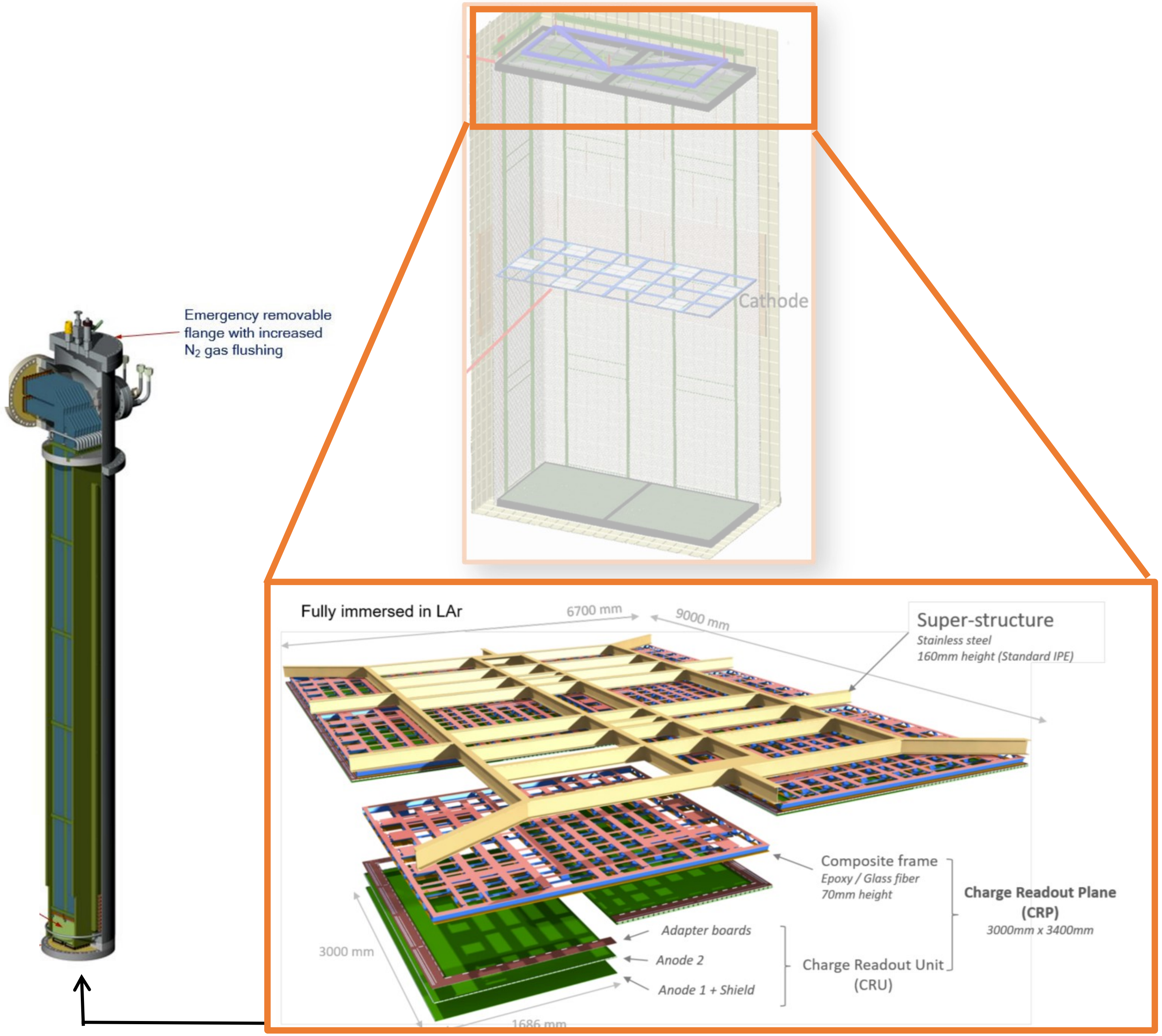
WR MCH

CRO AMC

MCH

x4 crates per SFT 2-view
x5 crates per SFT 3-view

Warm Signal Feedthrough



In/Out Cryostat

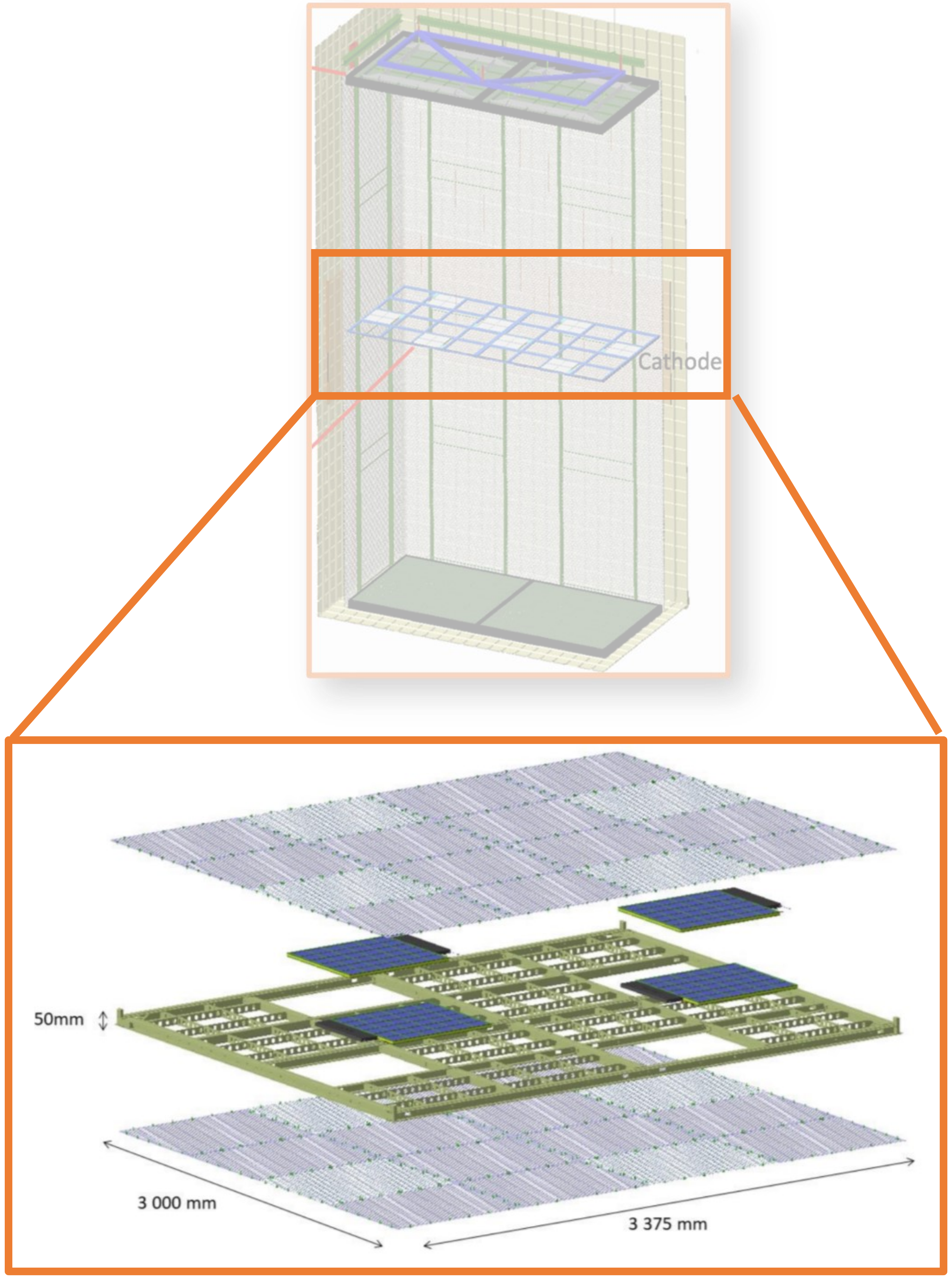
- Each SFT chimney sends data to Micro Telecommunications Computing Architecture (µTCA) crate, containing AMC cards.
- AMC cards read and digitizes signal and sends to White Rabbit switch and DAQ via optical fiber. AMCs have ADC chips and FGPA (Alterra6 Cyclone V)

DUNE 2nd Module

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

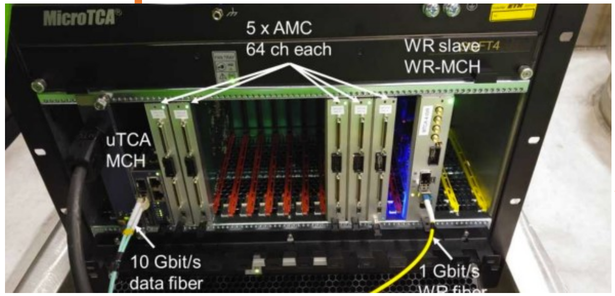
- Although CRP is perforated, opaque to light and therefore PDs can't be installed at anode. Thus each cathode module holds 4 double-sided X-ARAPUCA PD modules, exposed to top and bottom drift volumes. Frame has openings for PDs (blue)
  - Wavelength-shifted photons converted to electrical signals by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

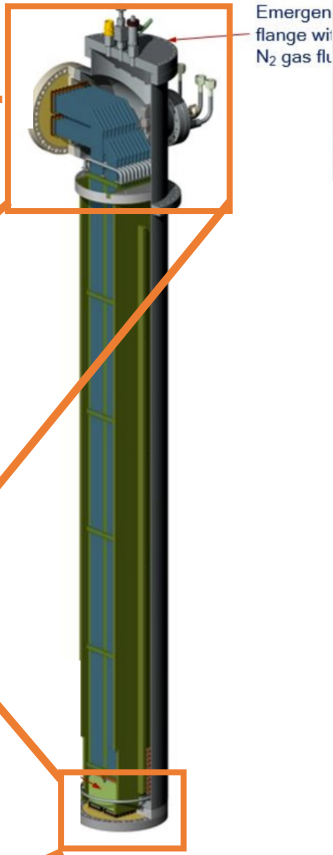


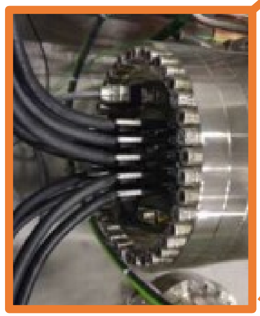
Prototypes

DAQ

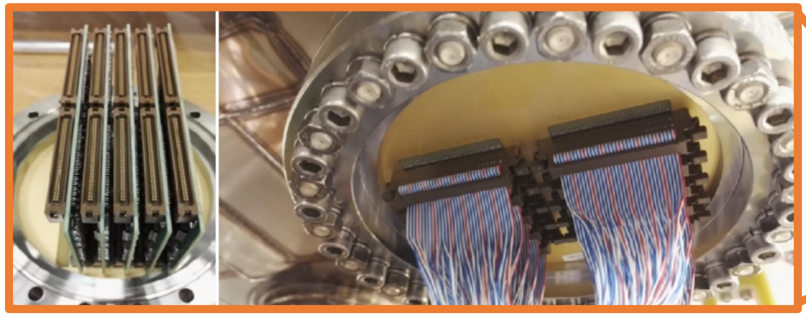


μTCA with AMCs





Warm Signal Feedthrough



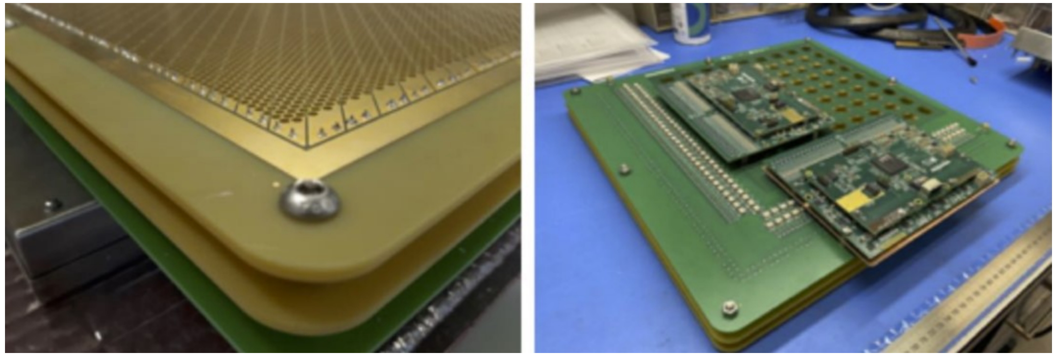
Cold FE Analogue Acquisition Card

Vertical Drift Chamber

(from ProtoDUNE)

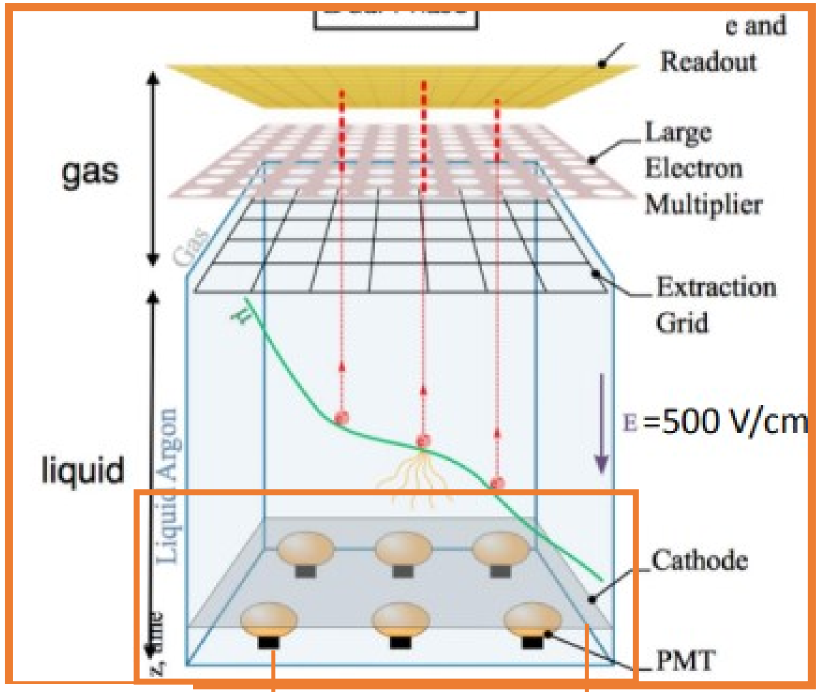
ANODE & Cold FEMBs

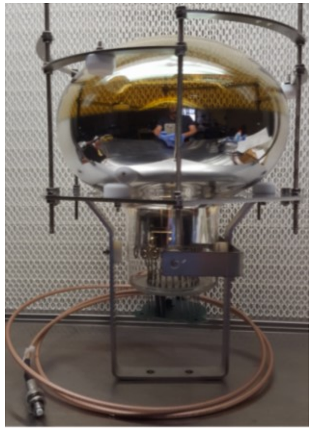
(from test stand)

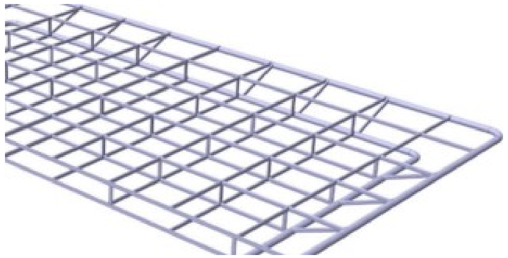


Dual Phase

- 1 PMT (Hamamatsu R5912- MOD20) per m^2 anchored to bottom of cryostat
- PMT coated with tetra-phenyl butadiene (TPB) to provide wavelength shifting to read out 127 nm light from LAr
- The stainless steel cathode plane (eighty 3 m × 3 m modules) held at – 600 kV located 2 m above the bottom of the cryostat

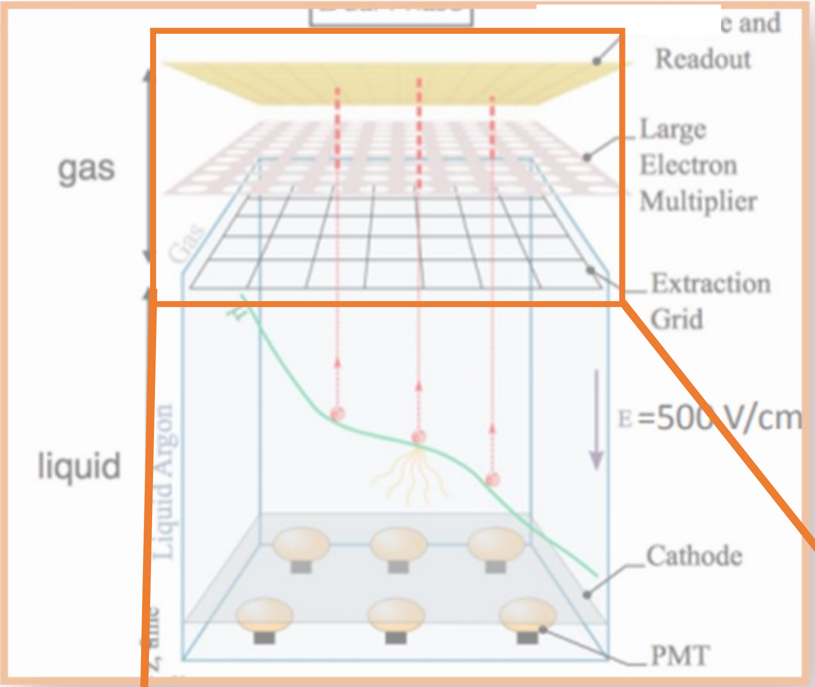


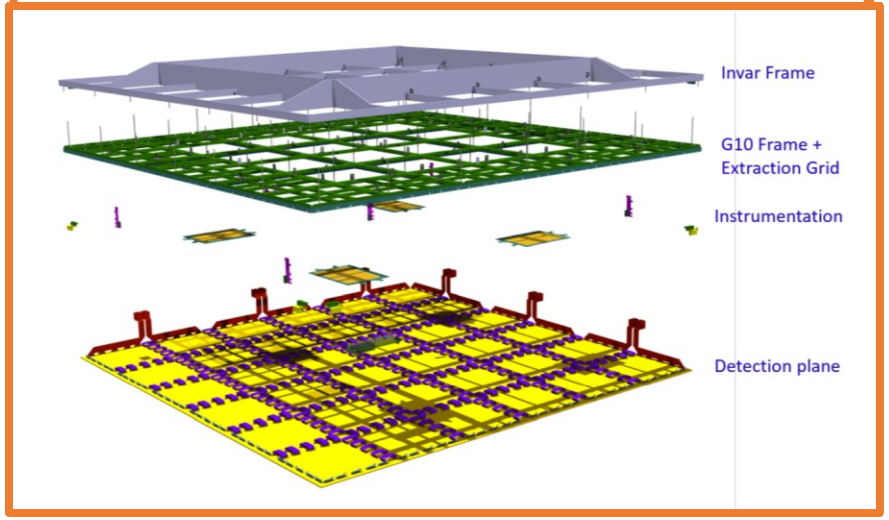




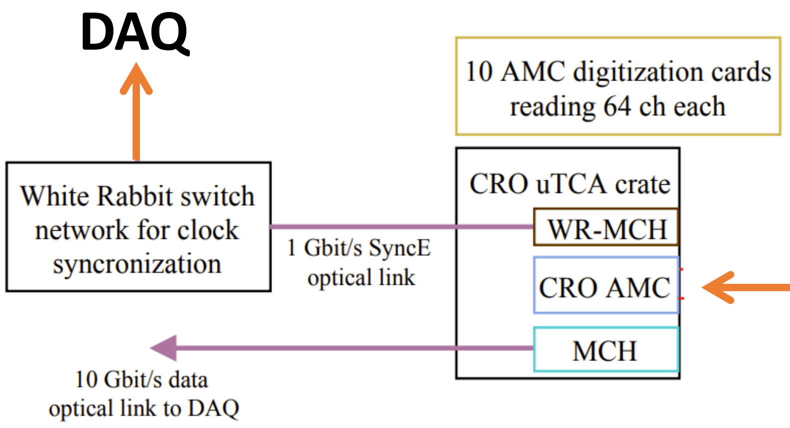
Dual Phase

- Charge readout plates (CRPs) are three layer sandwich (extraction grid, LEM, Anodes) sandwich that perform the collection, amplification and readout of charges
- LEMs and anodes form the detection plane, attached to the fiberglass grid (G10 Frame)
- LEM: is a 1 mm-thick, 50×50 cm^2 copper-clad PCB with electrodes on top and bottom. It contains holes of 500 µm diameter, through which electrons undergo amplification
- Anode: 2D PCB with gold-platted copper strips that provide x and y views of event (moving toward 3). Pattern of readout strips optimized so that charge is evenly spilt between both views

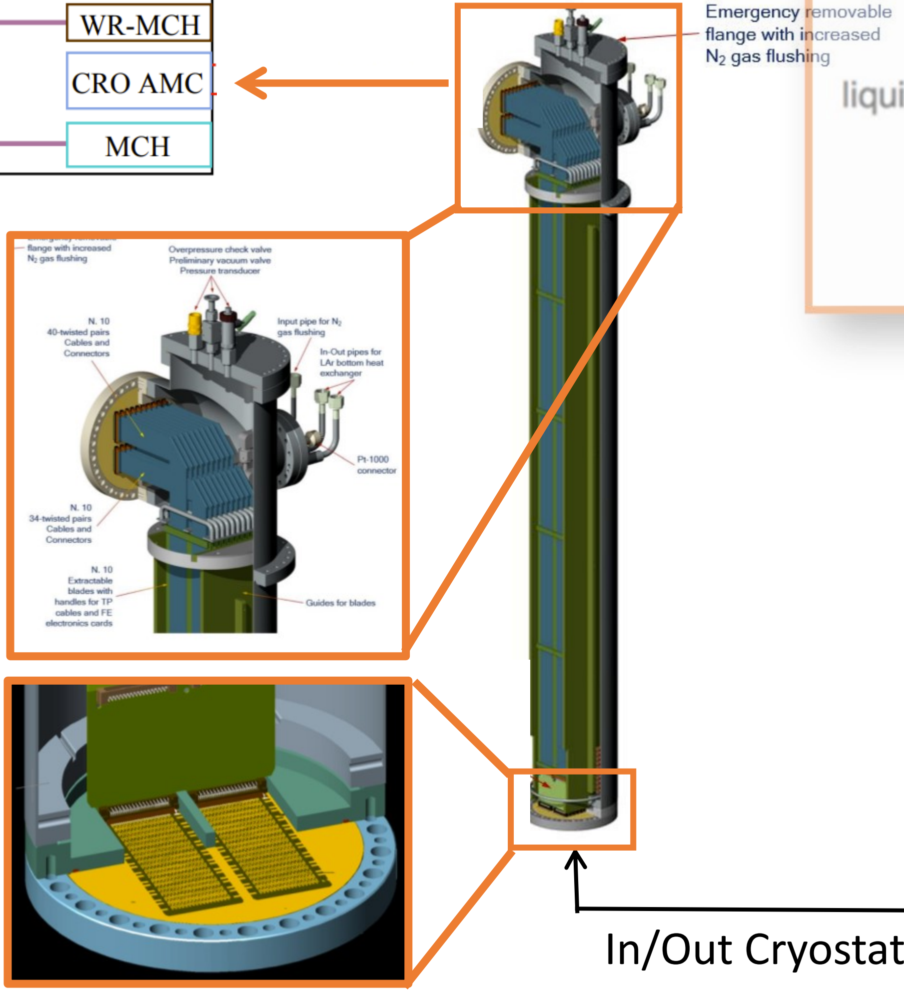


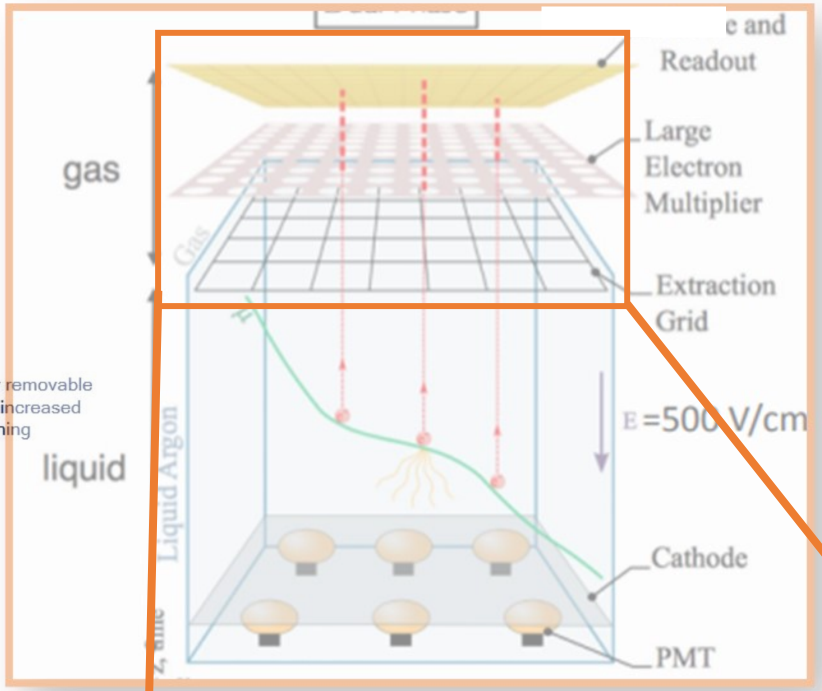


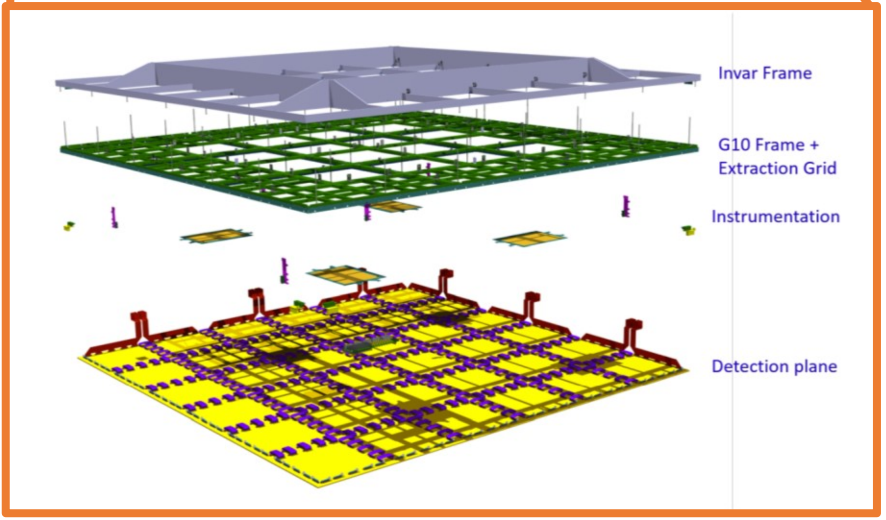
Dual Phase



- Same readout as Single Phase Vertical Drift

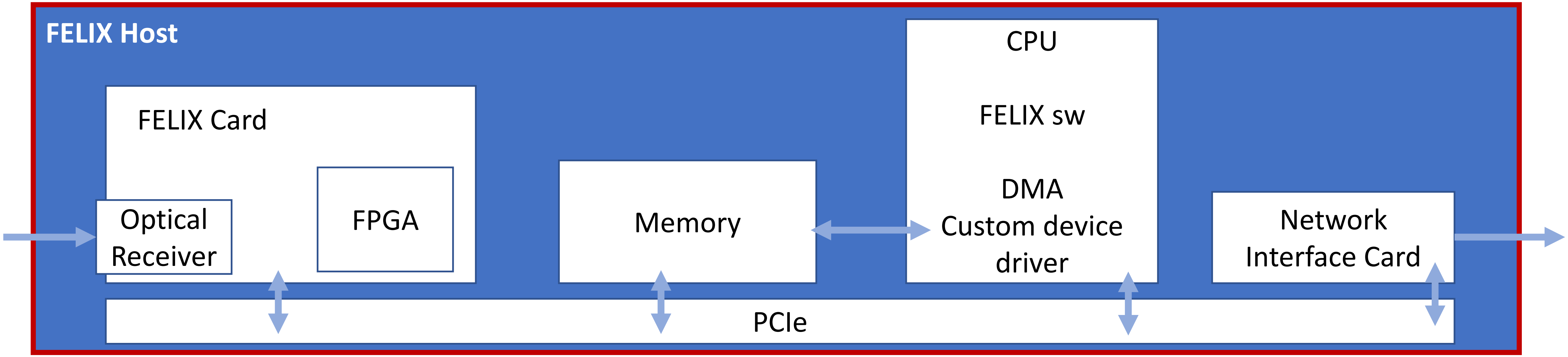






In/Out Cryostat

DAQ: FELIX Readout



FELIX Host

FELIX Card

Optical Receiver

FPGA

Memory

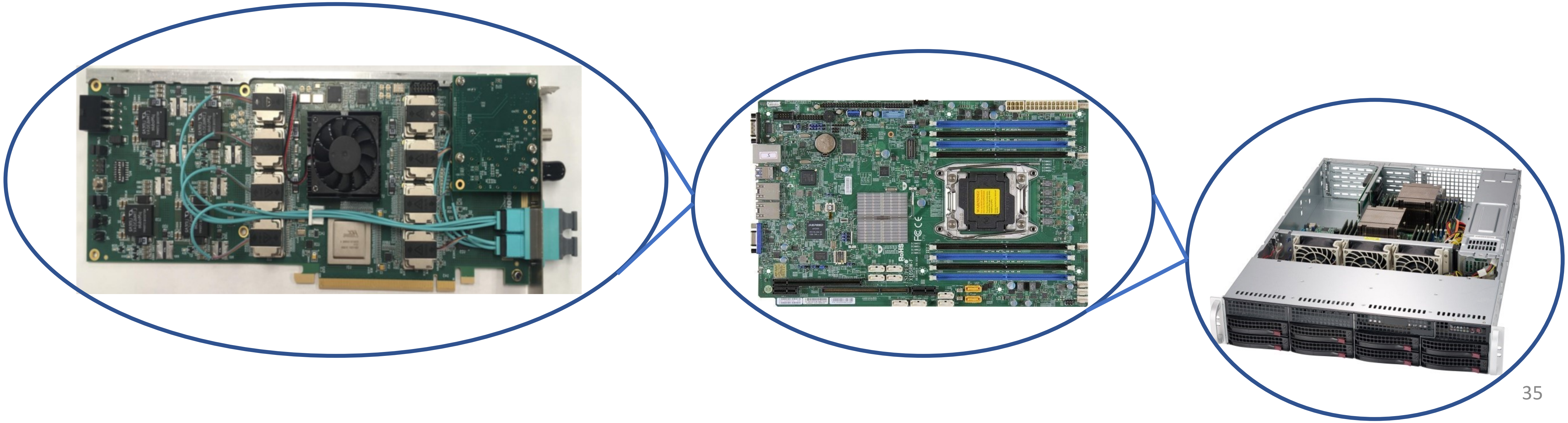
CPU

FELIX sw

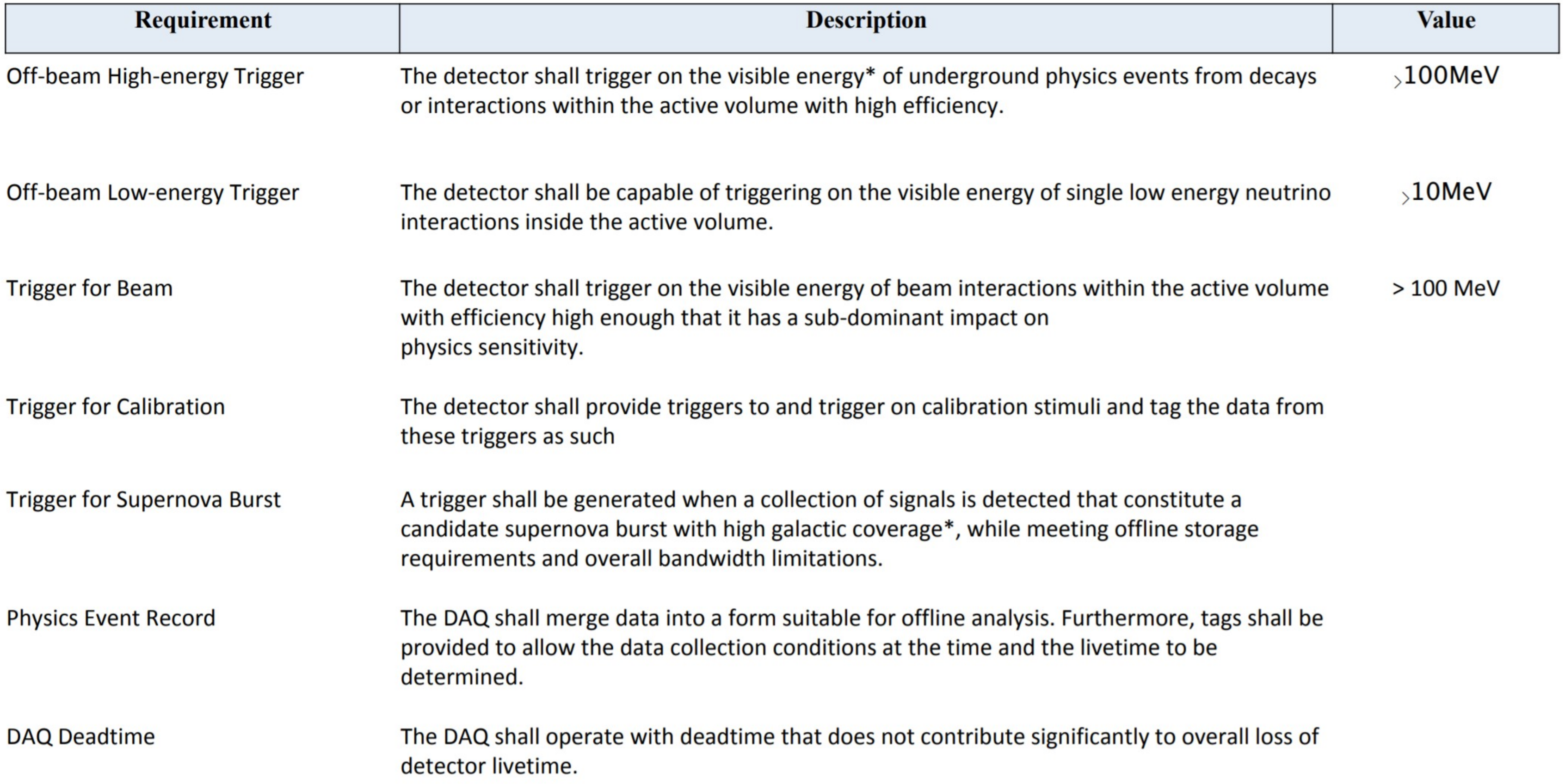
DMA
Custom device driver

Network Interface Card

PCIe



DUNE Readout Requirements



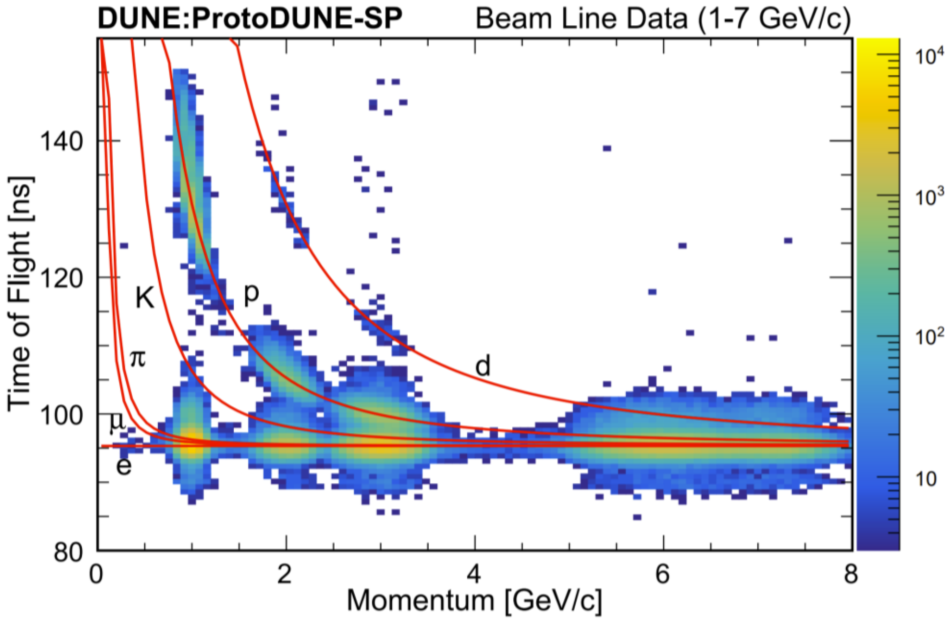
Requirement	Description	Value
Off-beam High-energy Trigger	The detector shall trigger on the visible energy* of underground physics events from decays or interactions within the active volume with high efficiency.	>100MeV
Off-beam Low-energy Trigger	The detector shall be capable of triggering on the visible energy of single low energy neutrino interactions inside the active volume.	>10MeV
Trigger for Beam	The detector shall trigger on the visible energy of beam interactions within the active volume with efficiency high enough that it has a sub-dominant impact on physics sensitivity.	> 100 MeV
Trigger for Calibration	The detector shall provide triggers to and trigger on calibration stimuli and tag the data from these triggers as such	
Trigger for Supernova Burst	A trigger shall be generated when a collection of signals is detected that constitute a candidate supernova burst with high galactic coverage*, while meeting offline storage requirements and overall bandwidth limitations.	
Physics Event Record	The DAQ shall merge data into a form suitable for offline analysis. Furthermore, tags shall be provided to allow the data collection conditions at the time and the livetime to be determined.	
DAQ Deadtime	The DAQ shall operate with deadtime that does not contribute significantly to overall loss of detector livetime.	

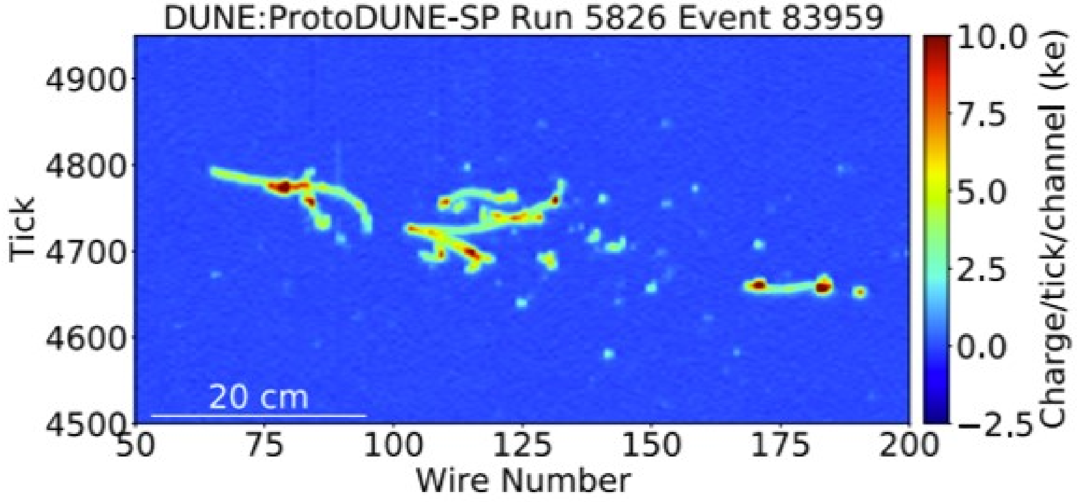
*Visible energy = deposited energy in the active volume as ionization and/or scintillation

*Galactic coverage = SBN probability-weighted efficiency, integrated over the physical extent of the Milkyway

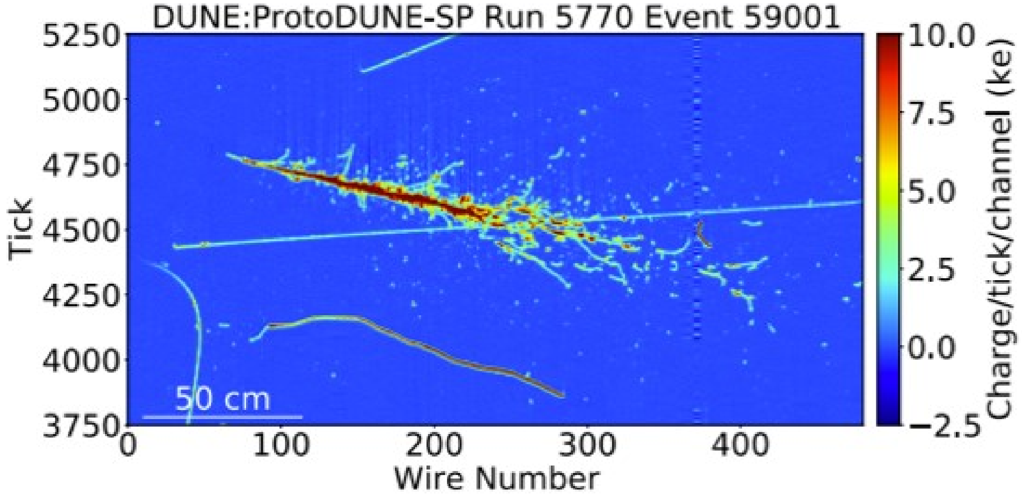
ProtoDUNE SP Performance

- 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





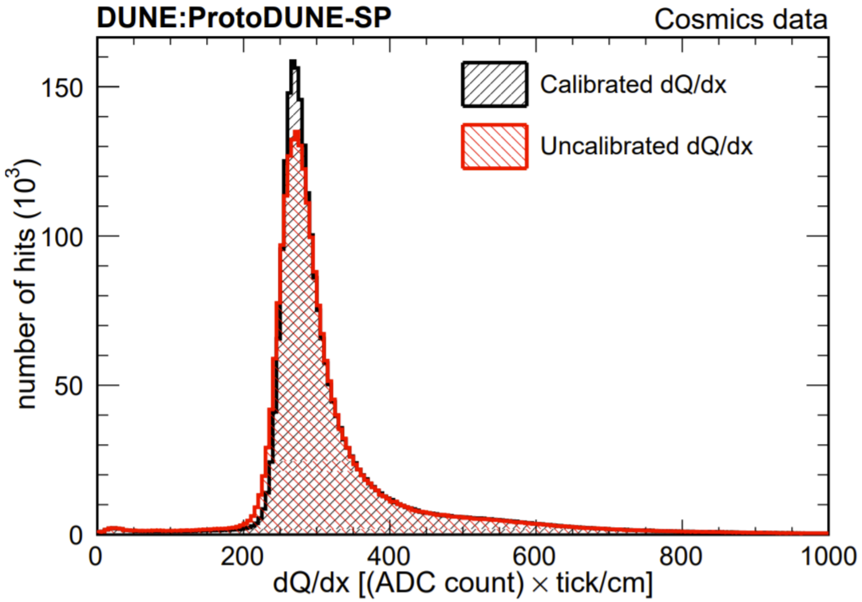
0.5 GeV electron

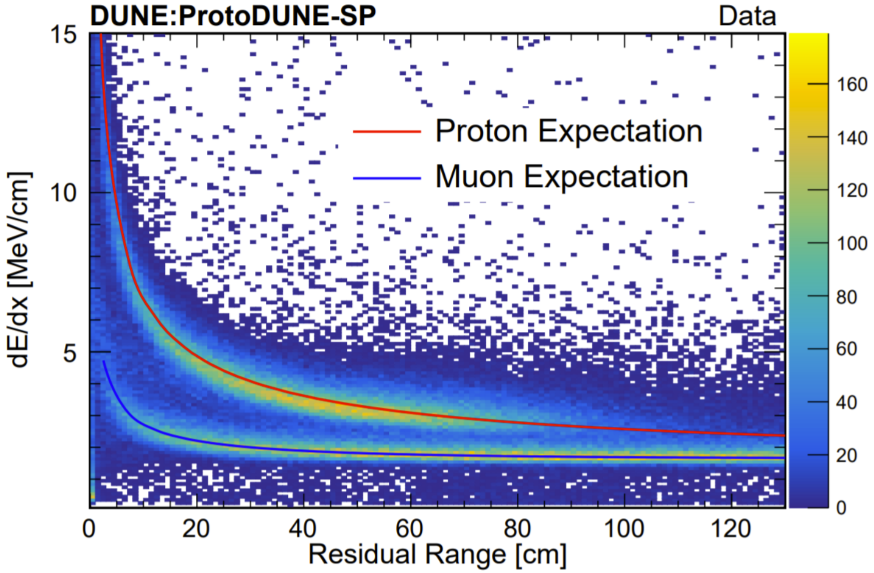


6 GeV electron

ProtoDUNE SP Performance

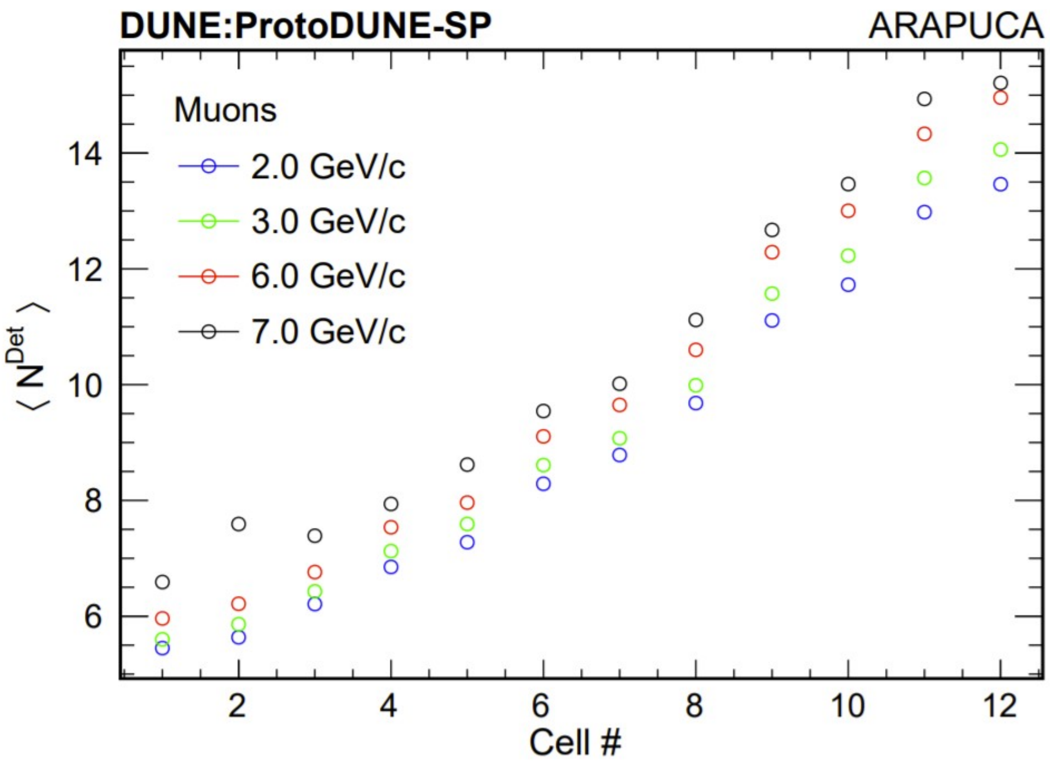
- Charge deposited along track converted energy loss (dE/dx) using stopping cosmic ray muons
- Calibration constants derived and applied to beam particles (muons, pions, protons, positrons)
- Charge deposition per unit length (dQ/dx) affected by space-charge effect, recombination effect, electron attenuation, 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

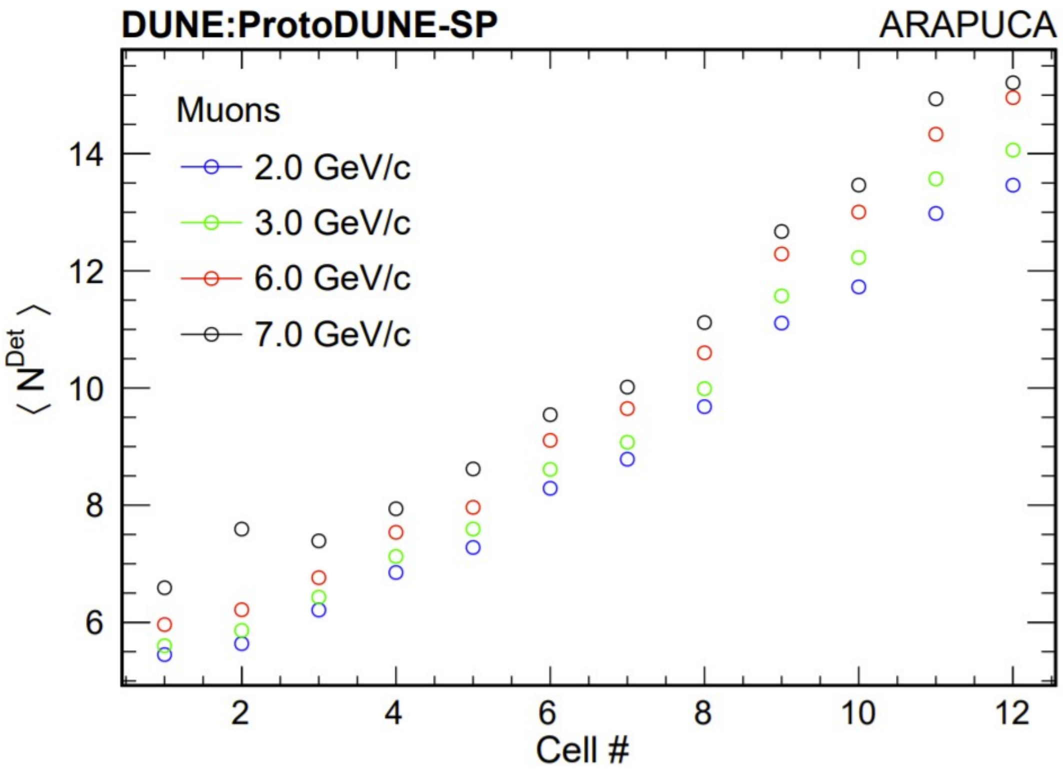




ProtoDUNE SP Performance

- Photon system performed well

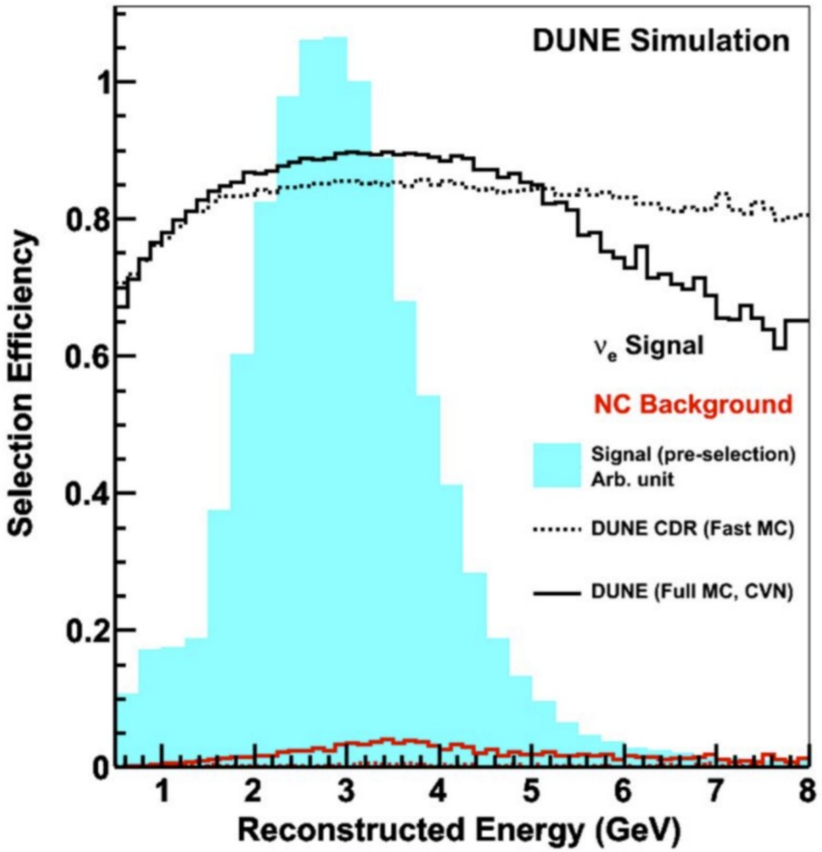


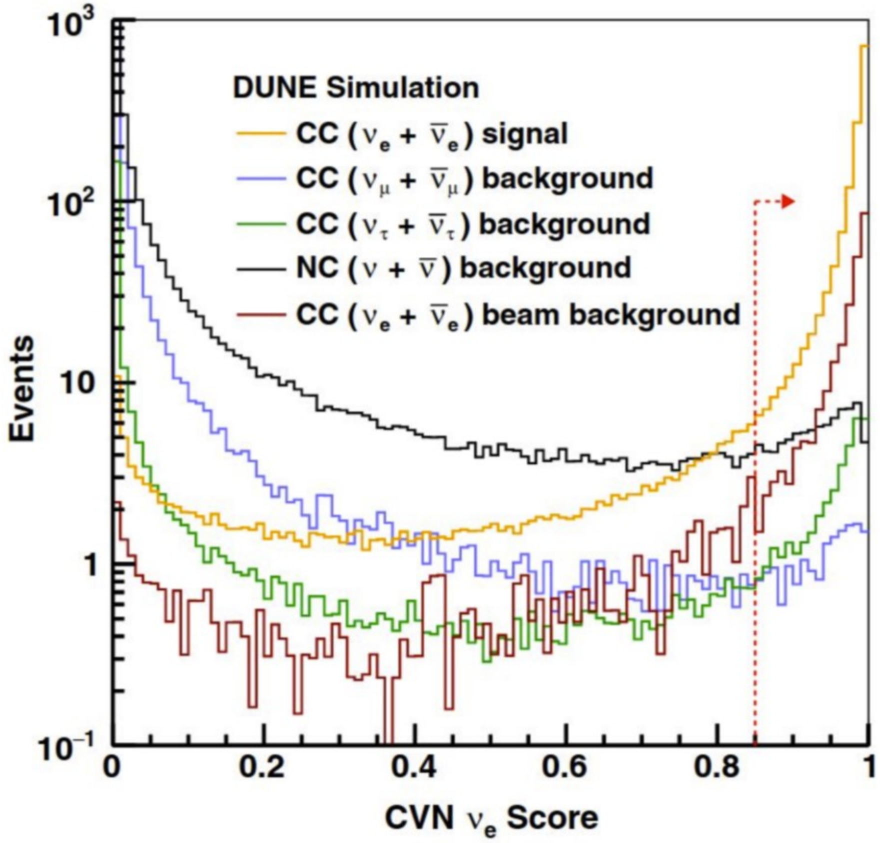


average number of detected photons with beams at different momenta

DUNE Far Detector Event Reconstruction

- Many Algorithms being explored: 2D clustering per plane, 3D hit clustering, convolutional visual networks



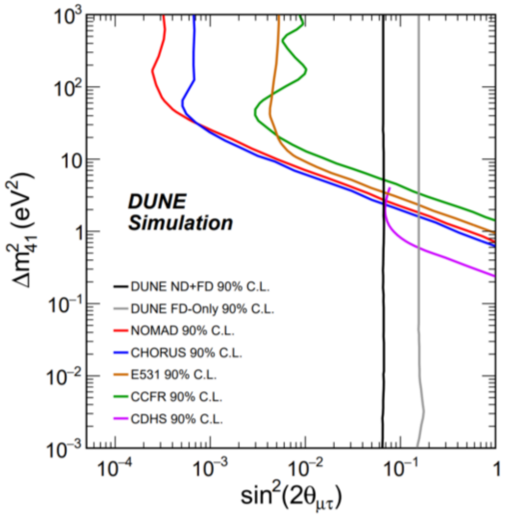


Sensitivity to Sterile Neutrinos

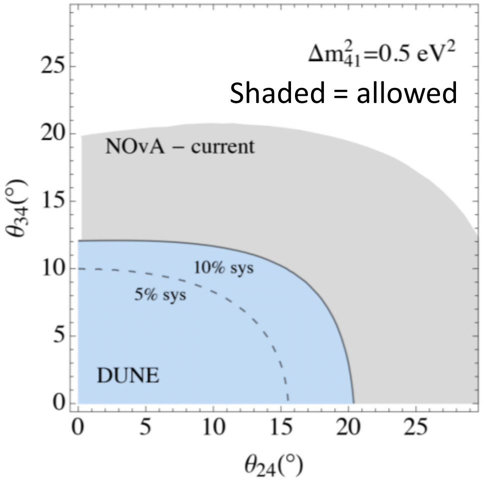
Case 1 ($\Delta m_{14}^2 \sim 0.1 - 1\ eV^2$): slow light-sterile neutrino oscillations, underdeveloped in ND, averaged out in FD

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

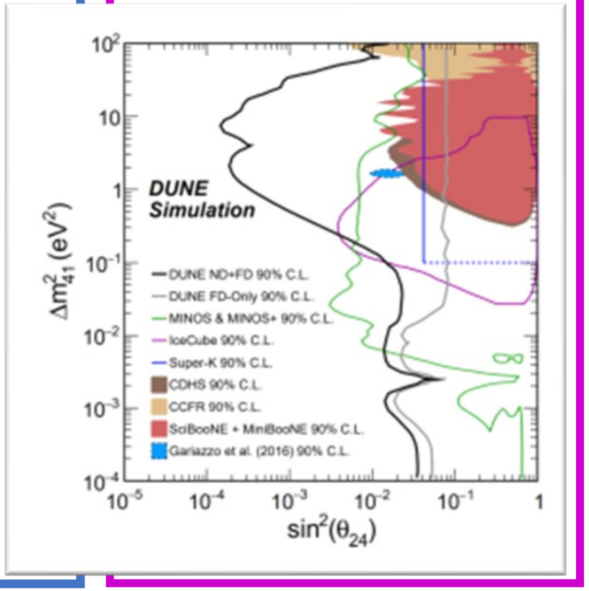
3+1



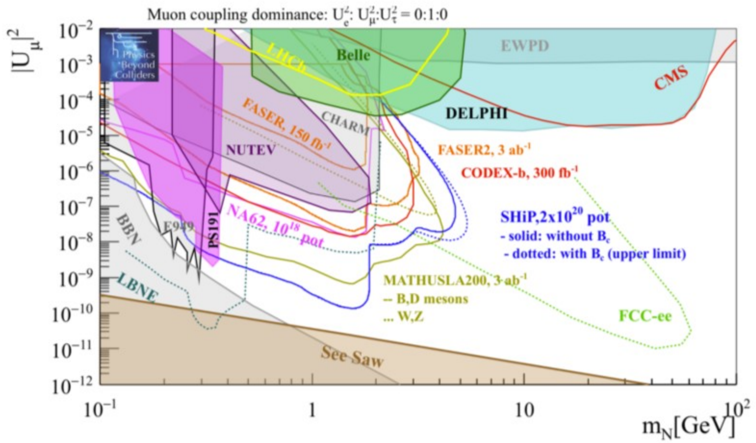
arXiv:1707.05348v1



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)



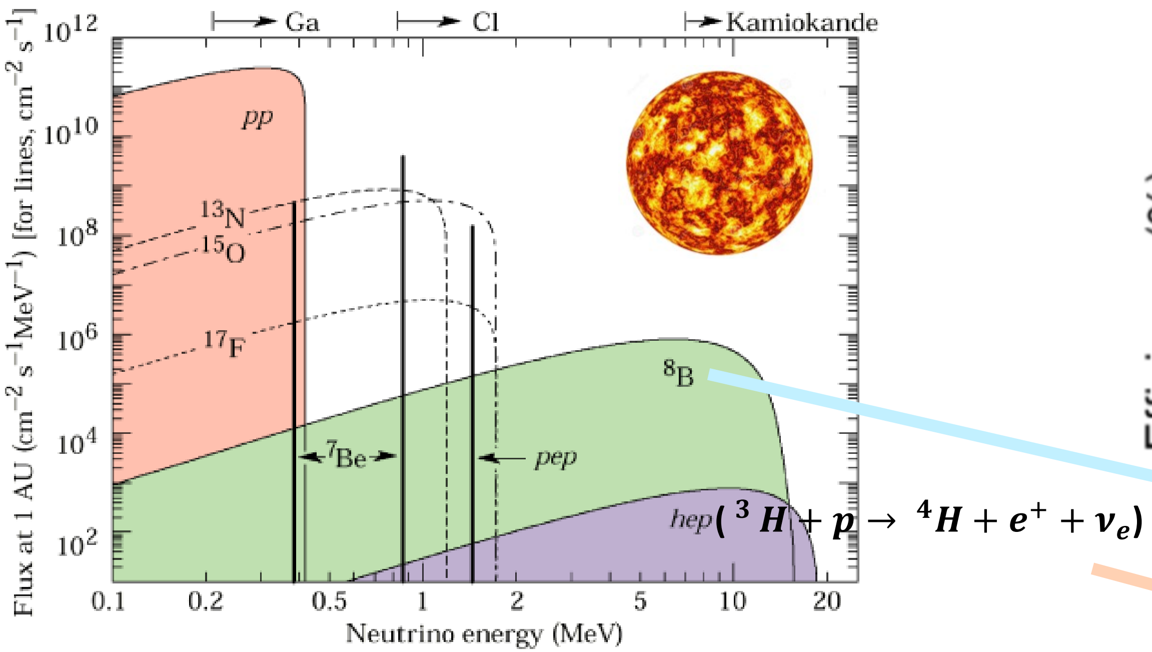
Case 3 ($\Delta m_{14}^2 > 100\ eV^2$) : fast sterile neutrino oscillations, averaged out in ND and FD (same as PMNS non-unitarity from heavy neutrinos)



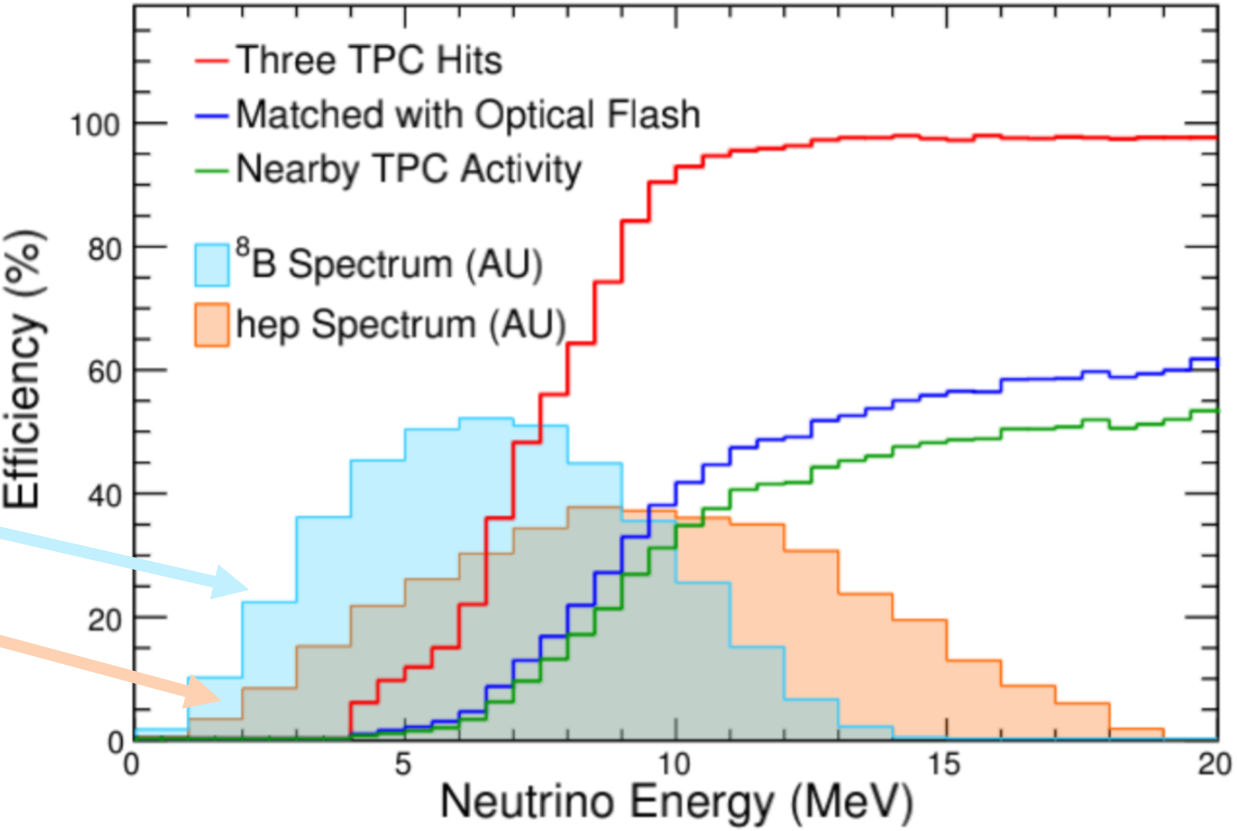
10^{-3}eV 10^{-2}eV 10^{-1}eV eV KeV MeV GeV 100 GeV

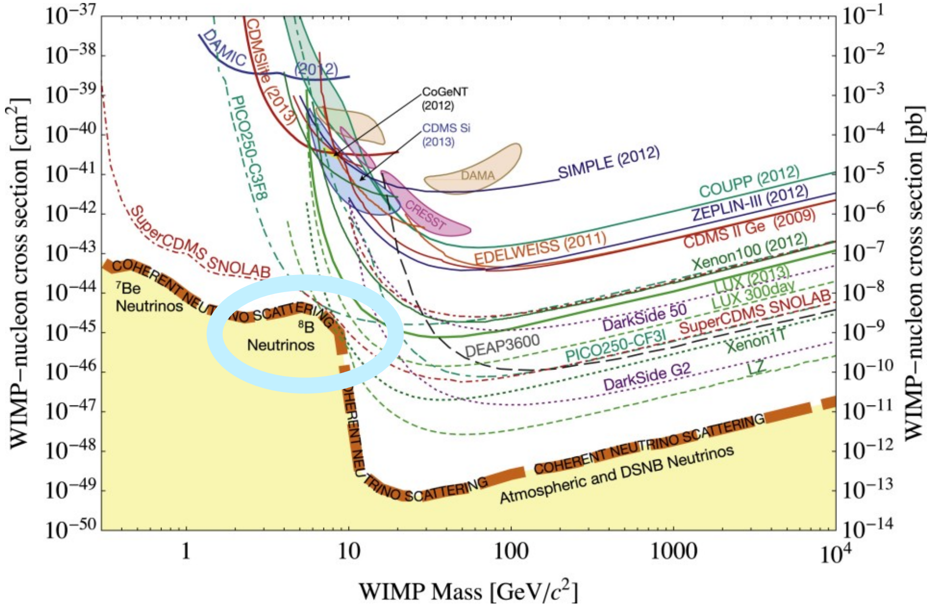
Extra Neutrino mass

Solar Neutrinos



$hep(\,^3H + p \rightarrow \,^4H + e^+ + \nu_e)$





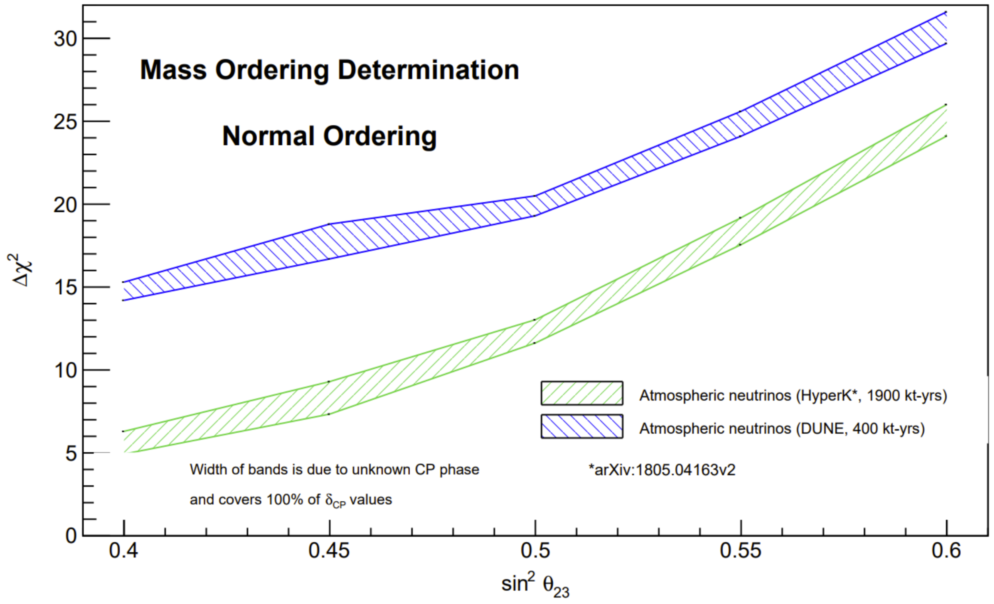
- DUNE can measure solar neutrinos to help verify the standard solar model, measure sun's core temperature, characterize neutrino floor, resolve tension between global solar neutrino measurements & KamLAND (arXiv:1808.08232), characterize MSW affect

Atmospheric & SuperNova Neutrinos

- Can use atmospheric neutrinos to extract neutrino properties

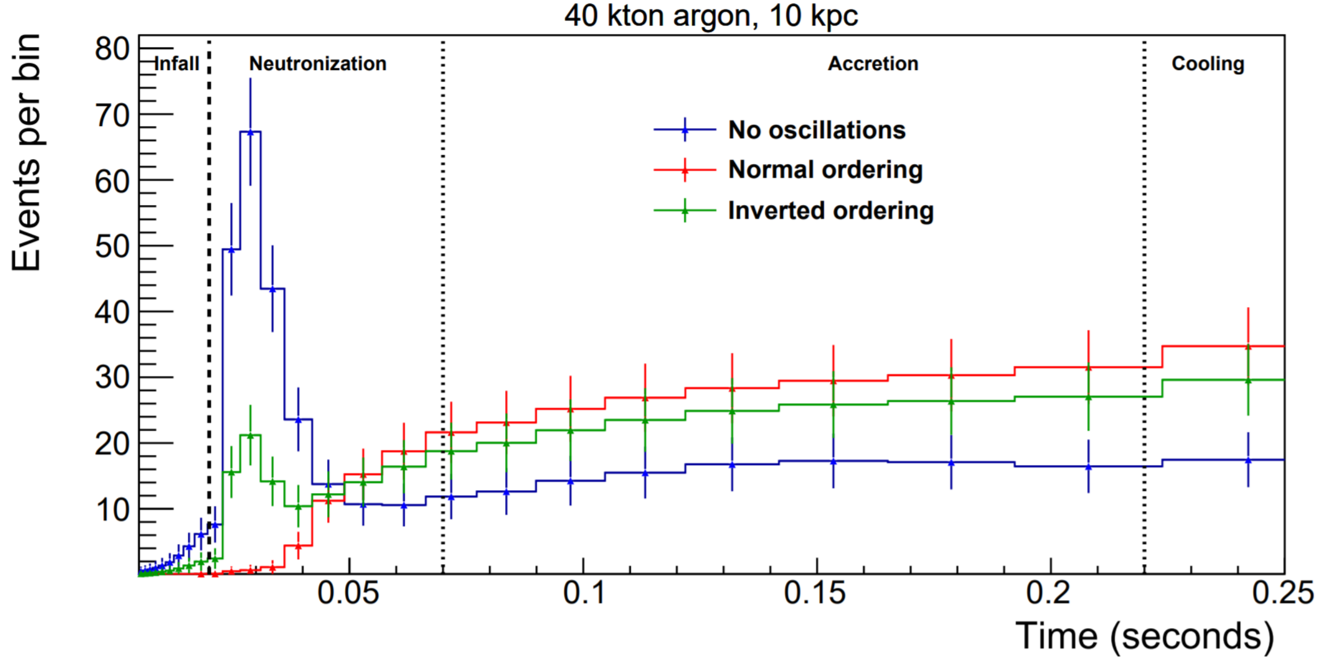
- Core collapses expected to occur few times per century (at 10-15 kpc): test astrophysical theories, probe new physics
- When massive star collapses to neutron star/black hole, $\sim 10^{58}$ of ~ 10 MeV ν emitted for a few seconds.
- DUNE sensitive to ν_e supernova neutrinos- this is unique among supernova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

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



Width of bands is due to unknown CP phase and covers 100% of δ_{CP} values

*arXiv:1805.04163v2



Non Standard Interactions

DUNE will improve current constraints on τe and μe, the magnitude of the NSI relative to standard weak interactions, by a factor of 2 to 5.

$$H = U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21}/2E & \\ & & \Delta m^2_{31}/2E \end{pmatrix} U^\dagger + \tilde{V}_{\mathrm{MSW}}$$

$$\tilde{V}_{\mathrm{MSW}} = \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix}$$

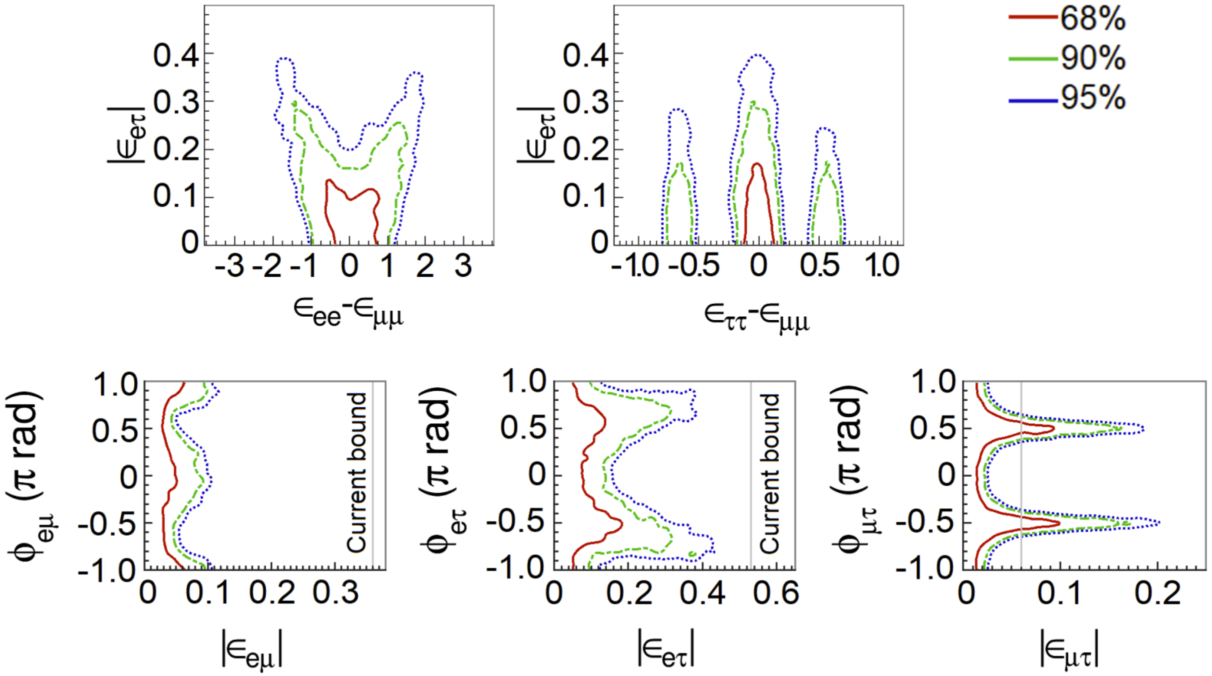


Figure 8.7: Allowed regions of the non-standard oscillation parameters in which we see important degeneracies (top) and the complex non-diagonal ones (bottom). We conduct the analysis considering all the NSI parameters as non-negligible. The sensitivity regions are for 68% CL [red line (left)], 90% CL [green dashed line (middle)], and 95% CL [blue dotted line (right)]. Current bounds are taken from [397].

Tau Neutrino

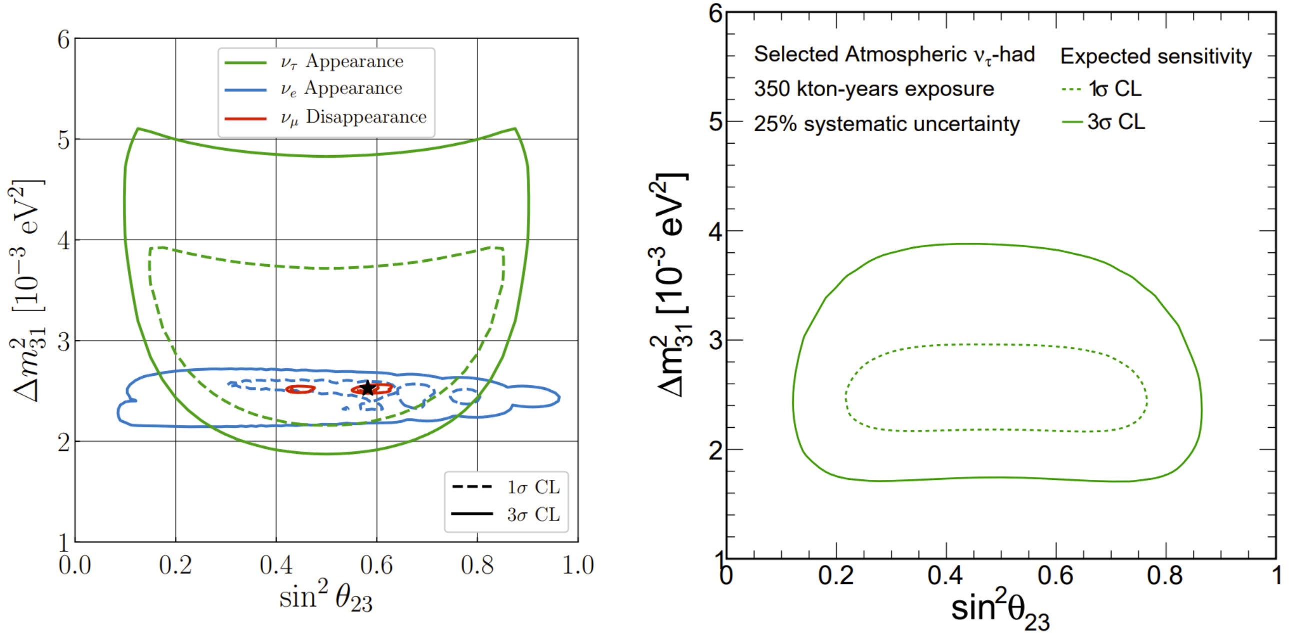


Figure 8.26: The 1σ (dashed) and 3σ (solid) expected sensitivity for measuring Δm^2_{31} and $\sin^2\theta_{23}$ using a variety of samples. Left: The expected sensitivity for seven years of beam data collection, assuming 3.5 years each in neutrino and antineutrino modes, measured independently using 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

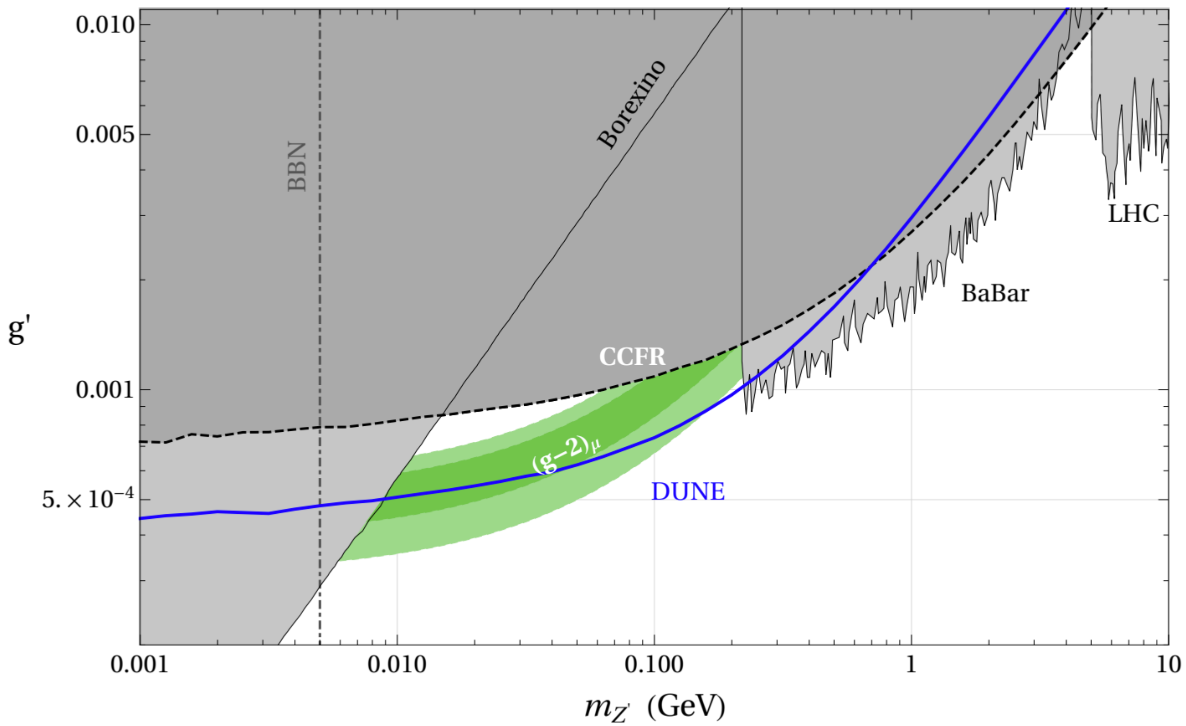
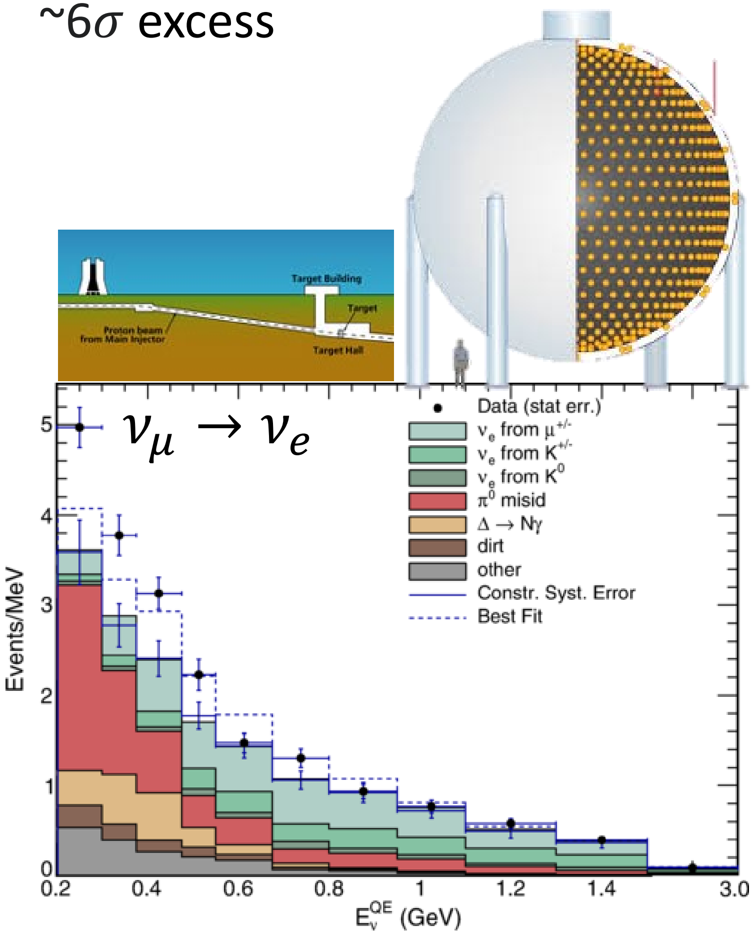


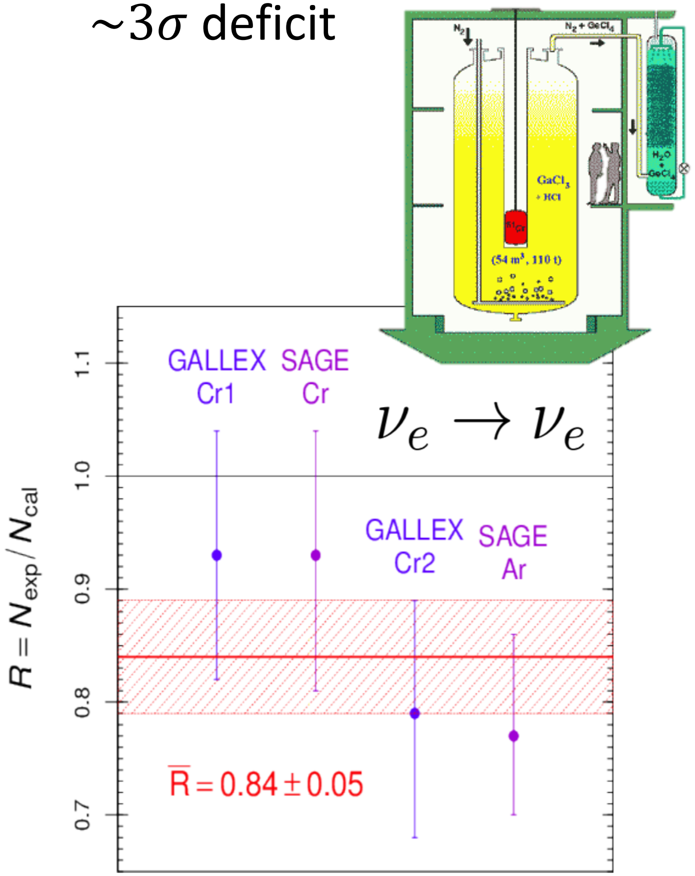
Figure 8.15: Existing constraints and projected DUNE sensitivity in the $L_\mu - L_\tau$ parameter space. Shown in green is the region where the $(g-2)_\mu$ anomaly can be explained at the 2σ level. The parameter regions already excluded by existing constraints are shaded in gray and correspond to a 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.

Modern Neutrino Mysteries?

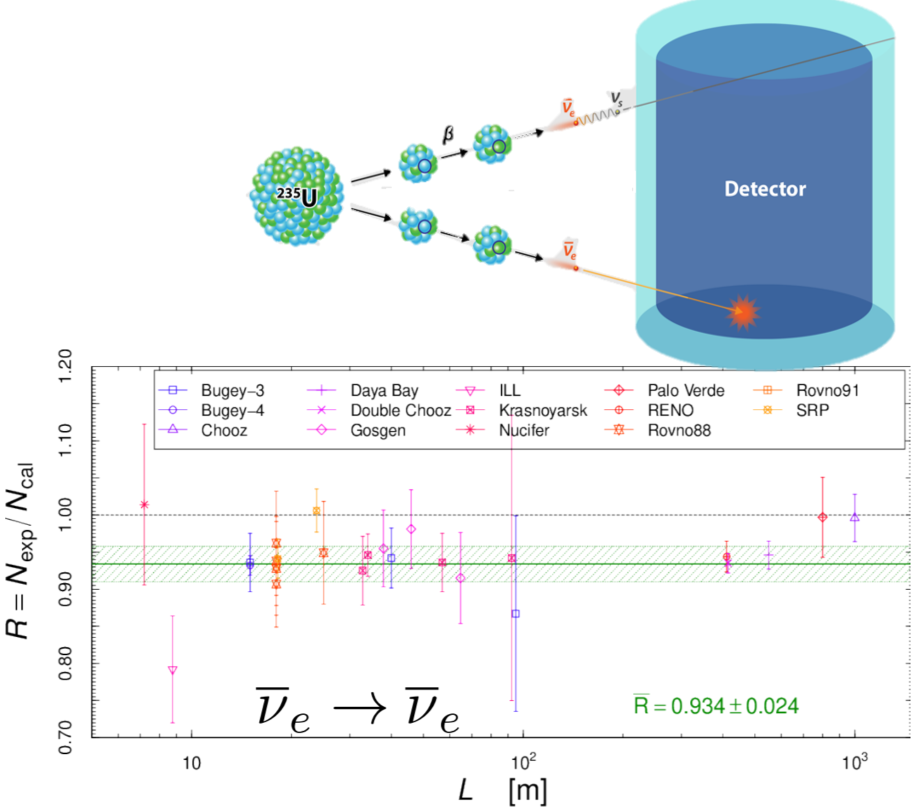
MiniBooNE & LSND
~6σ excess



Gallium anomaly
~3σ deficit



Reactor anomalies
~3σ deficit



Extra Neutrino Searches & NSI

$$\mathcal{L} = \mathcal{L}_{SM} + \ldots$$

$+ \delta\mathcal{L}^{d=5}$

Neutrino mass generation (if mass hierarchy too big, naturally get light 3ν), but other dimensions suppressed – and get no observable phenomena at energies we can reach (**Seesaw I/II/III**)

$+\delta\mathcal{L}^{d=6}$

Non Standard Neutrino Interactions (NSI)
Minimal Unitarity violation (MUV)
After EW symmetry breaking ->PMNS non-unitarity induced by mixing with heavy neutrinos. Implies breaking lepton universality and lepton flavor violation
(**inverse or linear seesaw**)

$$H = \frac{1}{2E}\left[U_{\text{PMNS}}\begin{pmatrix}0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31}\end{pmatrix}U^\dagger_{\text{PMNS}} + a\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]$$

$+\delta\mathcal{L}^{d=8}$

NSI – strong matter effects. Not sensitive at Colliders, but are at neutrino facilities

$+\delta\mathcal{L}^{d=9}$

Dark photon & extra neutrino motivated by LNSD/ MiniBoone

$$P^{\text{SBL}}_{\alpha\beta} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$+ \phi$

Add new Scaler - Radiative models. (some type 1 radiative models have NSI, all type II radiative models don't have NSI)

10^{-3}eV .1 eV ⋮ eV KeV MeV ⋮ GeV ⋮ 10^2GeV TeV 10 TeV 10^2 TeV 10^3 TeV 10^{12} TeV

Extra neutrinos can participate in oscillations

accessible at osc. Exp

Accessible at B-factories

Accessible at LHC

Parameterizations for Extra Neutrinos Searches

$$\mathcal{U} = \begin{array}{c} \text{3x3 active } \nu \quad \text{Active-heavy mix} \\ \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix} \\ \text{Active-sterile mix} \quad \text{Sterile-heavy mix} \end{array}$$

$\epsilon, \alpha, \eta, \theta$ can be related to each other: **arXiv:1609.08637v3**

R allowed at % level since it can only be probed at osc exp.

If sterile ν would participate in neutrino oscillations – ie: $P_{\alpha\beta}$ depends on $\mathcal{U}$

3+1, 3+N scenarios : $\theta_{14}, \theta_{24}, \delta_{14}$

$$\mathcal{U} = \begin{pmatrix} c_{12}c_{13}c_{14} & s_{12}c_{13}c_{14} & c_{14}s_{13}e^{-i\delta_{13}} & s_{14}e^{-i\delta_{14}} \\ \cdots & \cdots & \begin{matrix} c_{13}c_{24}s_{23} \\ -s_{13}s_{14}s_{24}e^{i(\delta_{14}-\delta_{13})} \end{matrix} & c_{14}s_{24} \\ \cdots & \cdots & \cdots & c_{14}c_{24}s_{34}e^{-i\delta_{34}} \end{pmatrix}$$

arXiv:1901.08330v1

Direct Heavy Neutrino Searches at LHC

Here N is not unitary – 2 common parametrizations

Triangular

$$\boldsymbol{N} = (I - \underset{\downarrow}{\alpha})\underset{\downarrow}{U}$$

Unitary PMNS

$$\begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{pmatrix}$$

Hermitian

$$\boldsymbol{N} = (I - \underset{\downarrow}{\eta})U'$$

$$\begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta^*_{e\mu} & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta^*_{e\tau} & \eta^*_{\mu\tau} & \eta_{\tau\tau} \end{pmatrix}$$

10^{-3}eV .1 eV | eV KeV MeV | GeV | 10^2GeV TeV 10 TeV 10^2 TeV 10^3 TeV 10^{12} TeV

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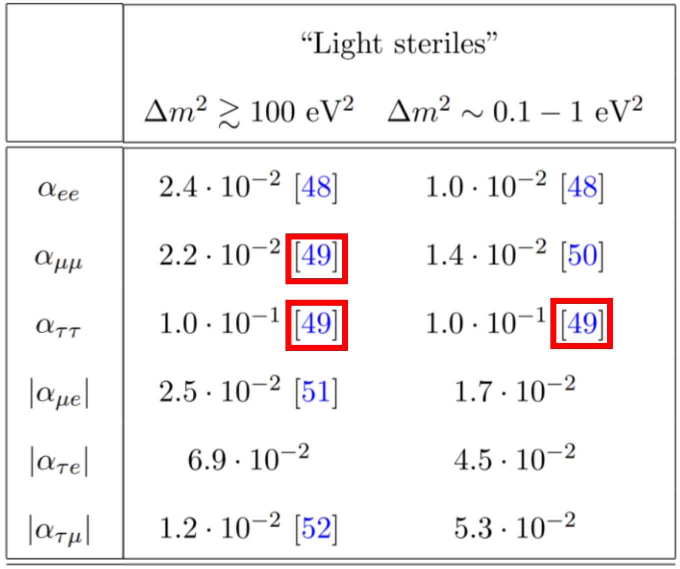
Accessible at LHC

Limits on Extra Neutrinos

For neutrinos with masses below the electroweak scale, best limits from oscillation data. BUT most future experiments (DUNE) won't add too much here (see arXiv:1609.08637v3) – maybe Hyper-K can?

PMNS non-unitarity bounded at per mil level from Lepton Universality, Lepton Flavor Violation EW observables, (B-factories ,MEG, LHC)

arXiv:1609.08637v3



	"Light steriles" $\Delta m^2 \gtrsim 100$ eV^2	$\Delta m^2 \sim 0.1 - 1$ eV^2
α_{ee}	$2.4 \cdot 10^{-2}$ [48]	$1.0 \cdot 10^{-2}$ [48]
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-2}$ [49]	$1.4 \cdot 10^{-2}$ [50]
$\alpha_{\tau\tau}$	$1.0 \cdot 10^{-1}$ [49]	$1.0 \cdot 10^{-1}$ [49]
$\lvert\alpha_{\mu e}\rvert$	$2.5 \cdot 10^{-2}$ [51]	$1.7 \cdot 10^{-2}$
$\lvert\alpha_{\tau e}\rvert$	$6.9 \cdot 10^{-2}$	$4.5 \cdot 10^{-2}$
$\lvert\alpha_{\tau\mu}\rvert$	$1.2 \cdot 10^{-2}$ [52]	$5.3 \cdot 10^{-2}$

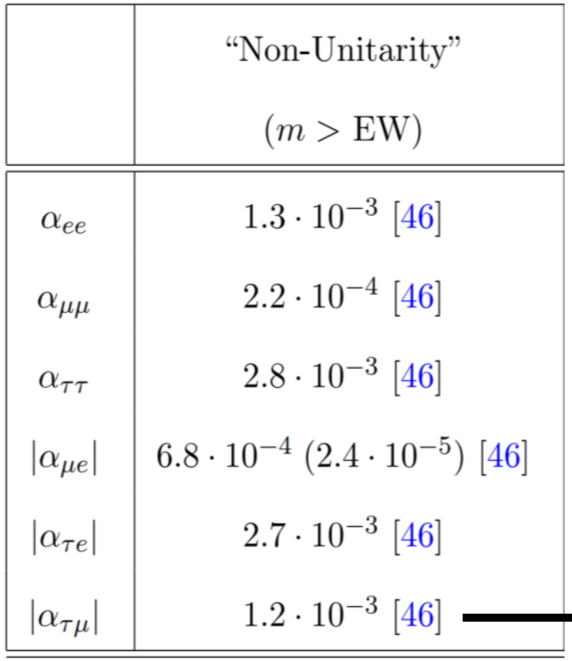
48: Buggy

49: SuperK atmospheric

51/52: Nomad

50: Minos

arXiv:1609.08637v3

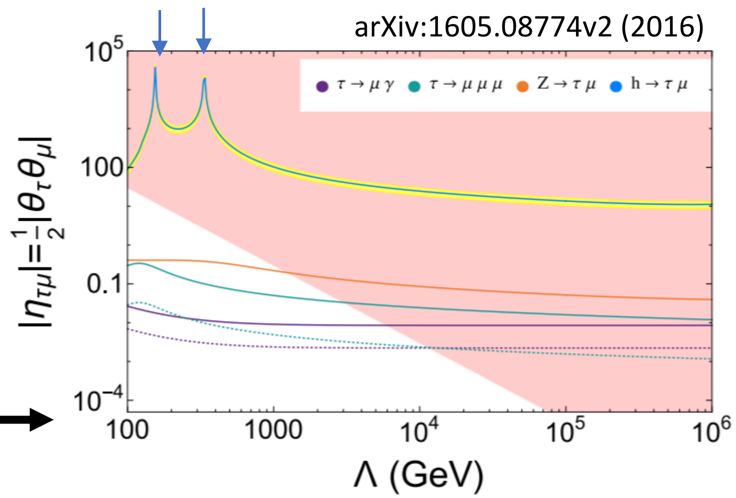


	"Non-Unitarity" $(m > \text{EW})$
α_{ee}	$1.3 \cdot 10^{-3}$ [46]
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$ [46]
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$ [46]
$\lvert\alpha_{\mu e}\rvert$	$6.8 \cdot 10^{-4}$ $(2.4 \cdot 10^{-5})$ [46]
$\lvert\alpha_{\tau e}\rvert$	$2.7 \cdot 10^{-3}$ [46]
$\lvert\alpha_{\tau\mu}\rvert$	$1.2 \cdot 10^{-3}$ [46]

LFV: best limits from $\alpha \rightarrow \gamma\alpha$ & $\alpha \rightarrow 3\beta$ for 3 extra neutrino model

$H \rightarrow \tau\mu$ has small preference for non zero (arXiv:1502.07400, arXiv:1508.03372)

arXiv:1605.08774v2 (2016)



10^{-3}eV .1 eV eV KeV MeV GeV 10^2GeV TeV 10 TeV 10^2 TeV 10^3 TeV 10^{12} TeV

Extra neutrinos can participate in oscillations

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Accessible at B-factories

Accessible at LHC

Lepton Flavor Violation & non Unitarity of PMNS

arXiv:1407.6607v2 [hep-ph] 6 Aug 2014

$$\Gamma_{W,\alpha} = \sum_i \Gamma(W \to \ell_\alpha \nu_i) = \frac{G_\mu M_W^3}{6\sqrt{2}\pi} \frac{(NN^\dagger)_{\alpha\alpha} F_W(m_{\ell_\alpha})}{\sqrt{(NN^\dagger)_{ee}(NN^\dagger)_{\mu\mu}}}$$

$$F_W(m_{\ell_\alpha}) = \left(1 - \frac{m_{\ell_\alpha}^2}{m_W^2}\right)^2 \left(1 + \frac{m_{\ell_\alpha}^2}{m_W^2}\right) .$$

$$R_{\alpha\beta}^W = \sqrt{\frac{\Gamma_{W,\alpha} F(m_{\ell_\beta})}{\Gamma_{W,\beta} F(m_{\ell_\alpha})}} = \sqrt{\frac{(NN^\dagger)_{\alpha\alpha}}{(NN^\dagger)_{\beta\beta}}}$$

arXiv:1605.08774v2, 21 Dec 2016

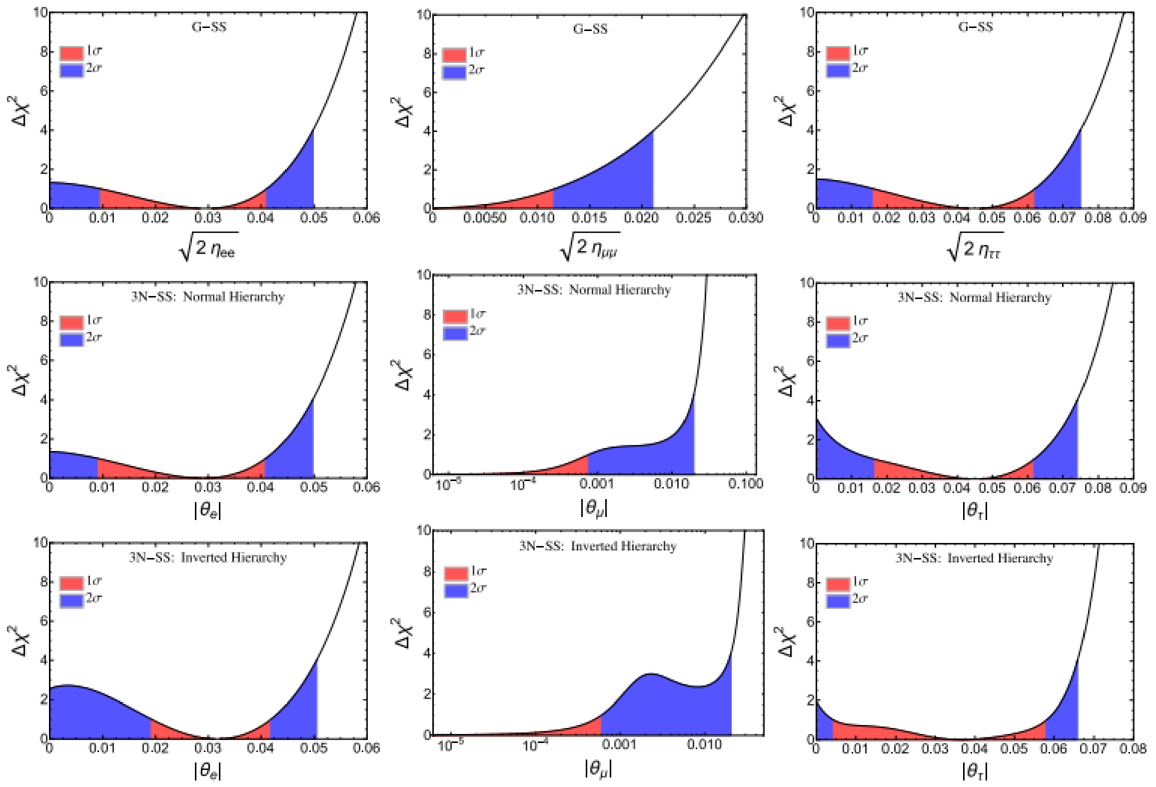


FIG. 3: $\Delta\chi^2$ profile minimized over all fit variables except for one θ_α (or $\sqrt{2\eta_{\alpha\alpha}}$) in the case of the G-SS) at a time. The upper panels are for the G-SS, and the middle and lower panels for the 3N-SS for a normal and inverted hierarchy respectively.

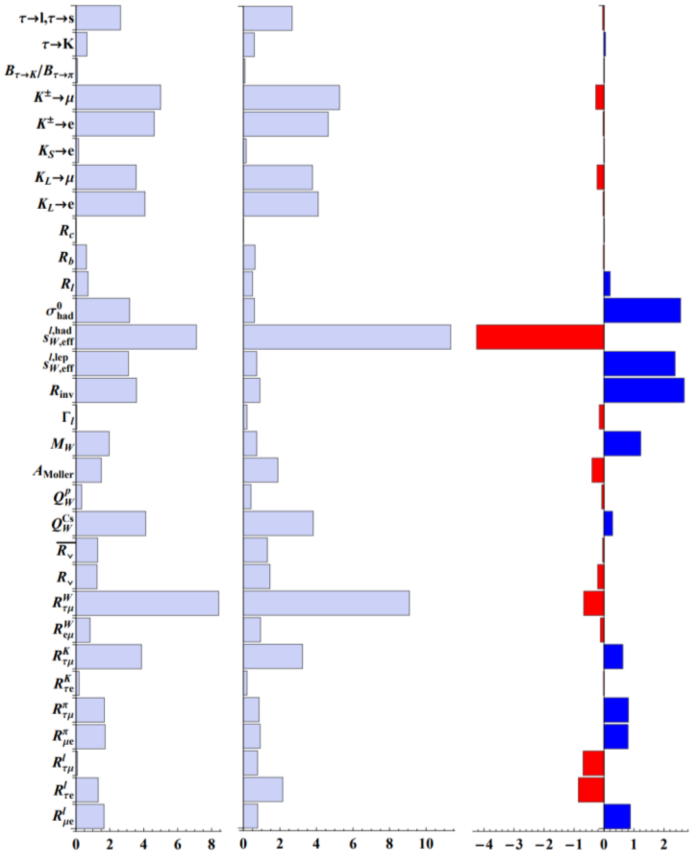
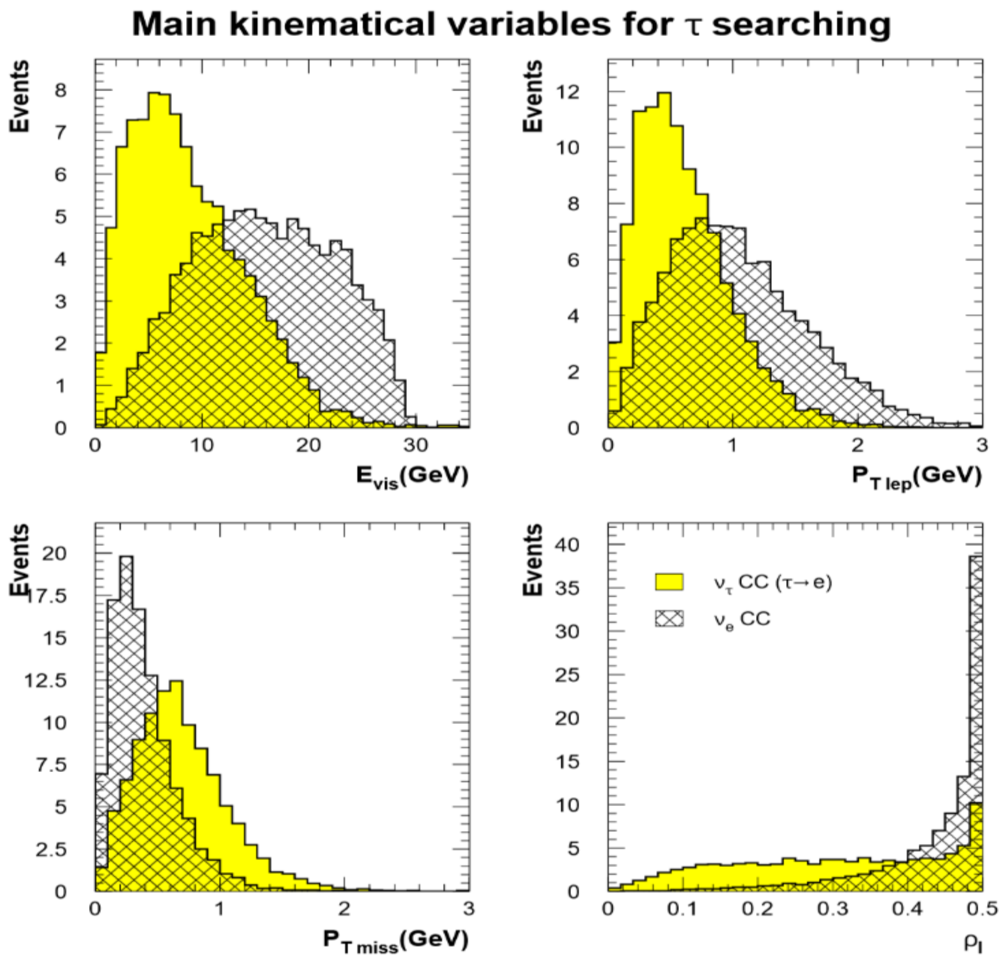


Figure 1: Individual contributions to the total χ^2 from the considered observables. The left column shows the SM and the middle column the MUV scheme with best-fit parameters. The right column shows $\chi^2_i(SM) - \chi^2_i(MUV)$ for the observable i. The positive blue (negative red) bars indicate an improvement (worsening) of the MUV scheme best fit compared to the SM.

Tau Neutrinos in DUNE

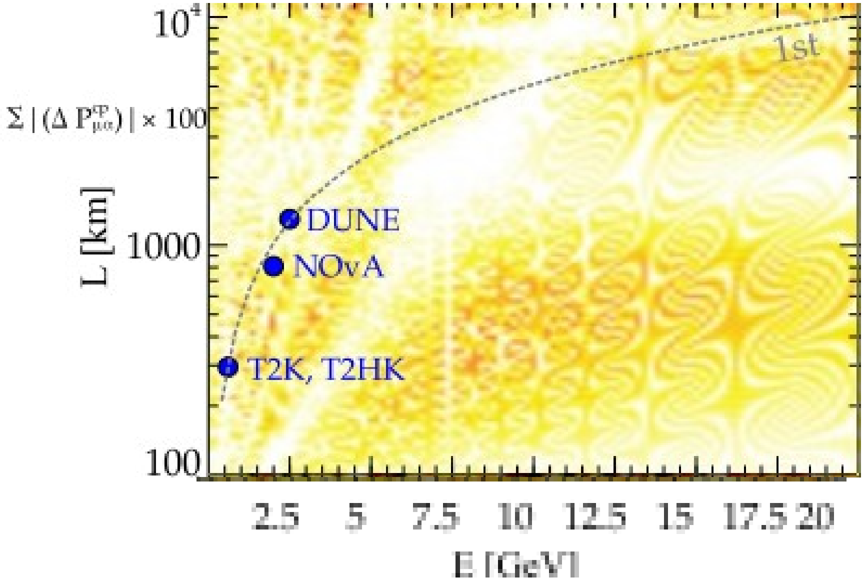


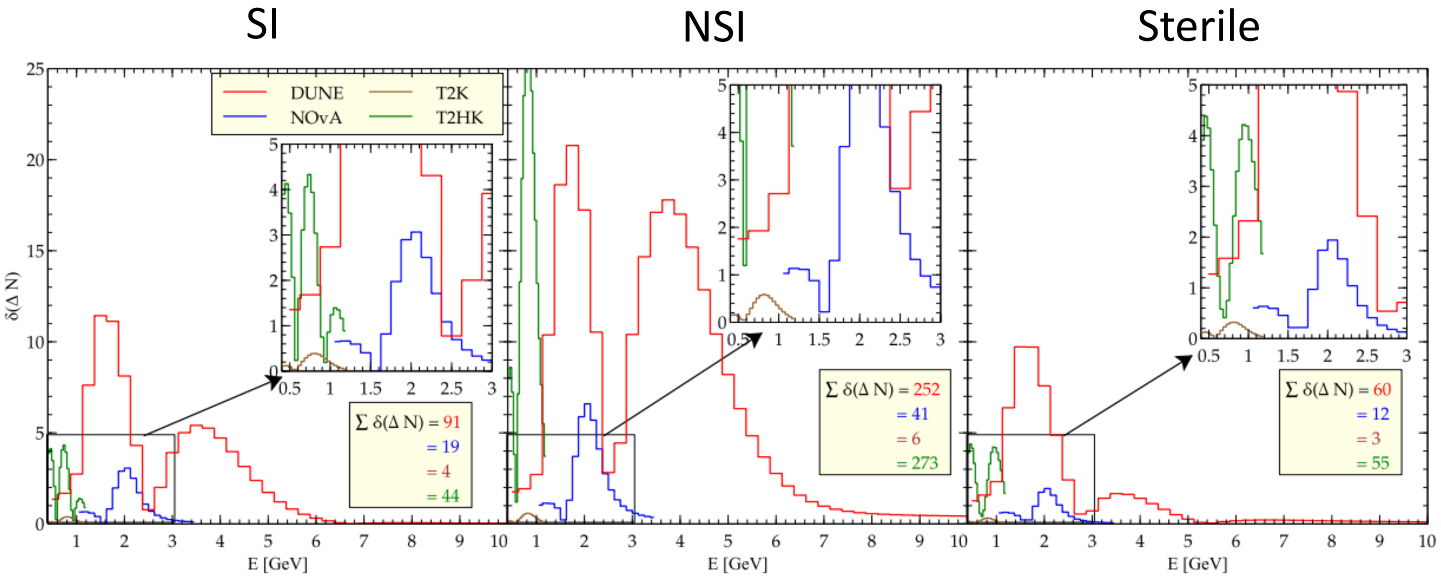
$$\rho = \frac{P_T^{lepton}}{P_T^{lepton} + P_T^{hadron} + P_T^{miss}}$$

The discriminating power of E_{vis}, P_T, P_T^{miss}, ρ between ν_τ induced interactions, represented by the filled yellow distributions, and the ν_e background events represented by the hashed distribution.

Sensitivity to Extra Neutrinos and NSI

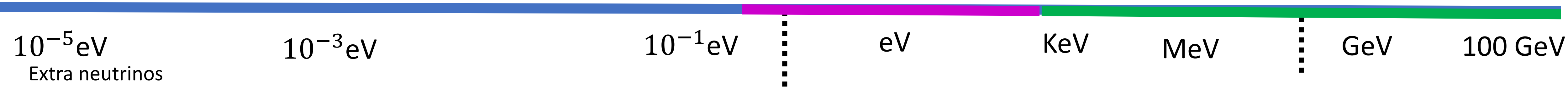
Darker regions = larger amount of non-unitarity in sterile
Can't probe non-unitarity at better than 6%





$$\delta[\Delta N^{CP}_{\alpha\beta}] = [\Delta N^{CP}_{\alpha\beta}](\delta_{13} = \pi/2) - [\Delta N^{CP}_{\alpha\beta}](\delta_{13} = 0)$$

- NSI with matter gives rise to NSI at source and/or detector (arXiv:0807.1003v3). Bounds on source & detector NSI an order of magnitude more strict than matter NSI. DUNE can probe matter (dim 8), Hyper – K source & detector NSI (dim 6)
- NSI can be probed with supernova neutrinos in Hyper-K : arXiv:1907.01059v2

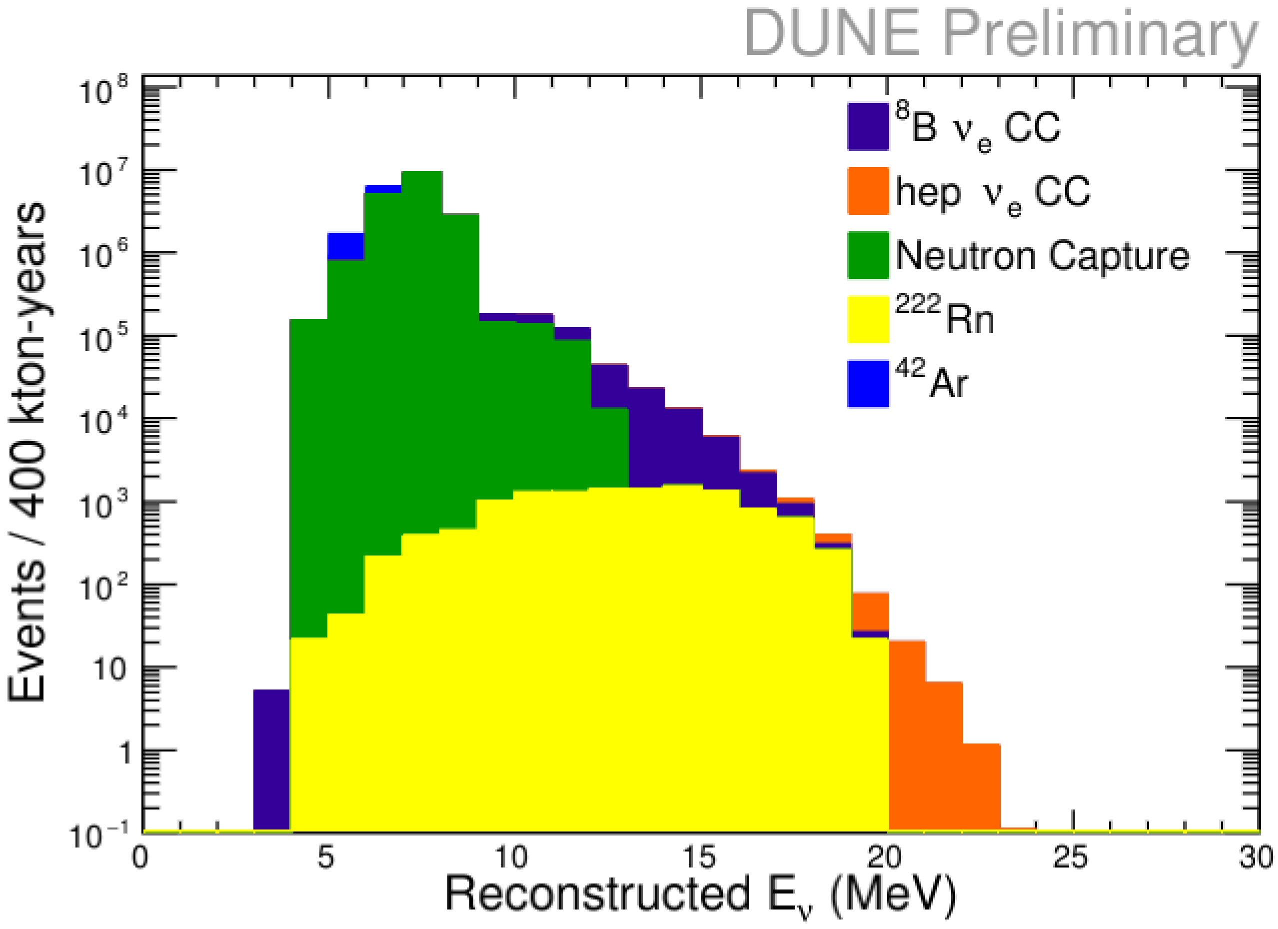


Extra neutrinos can participate in oscillations

accessible at osc. Exp

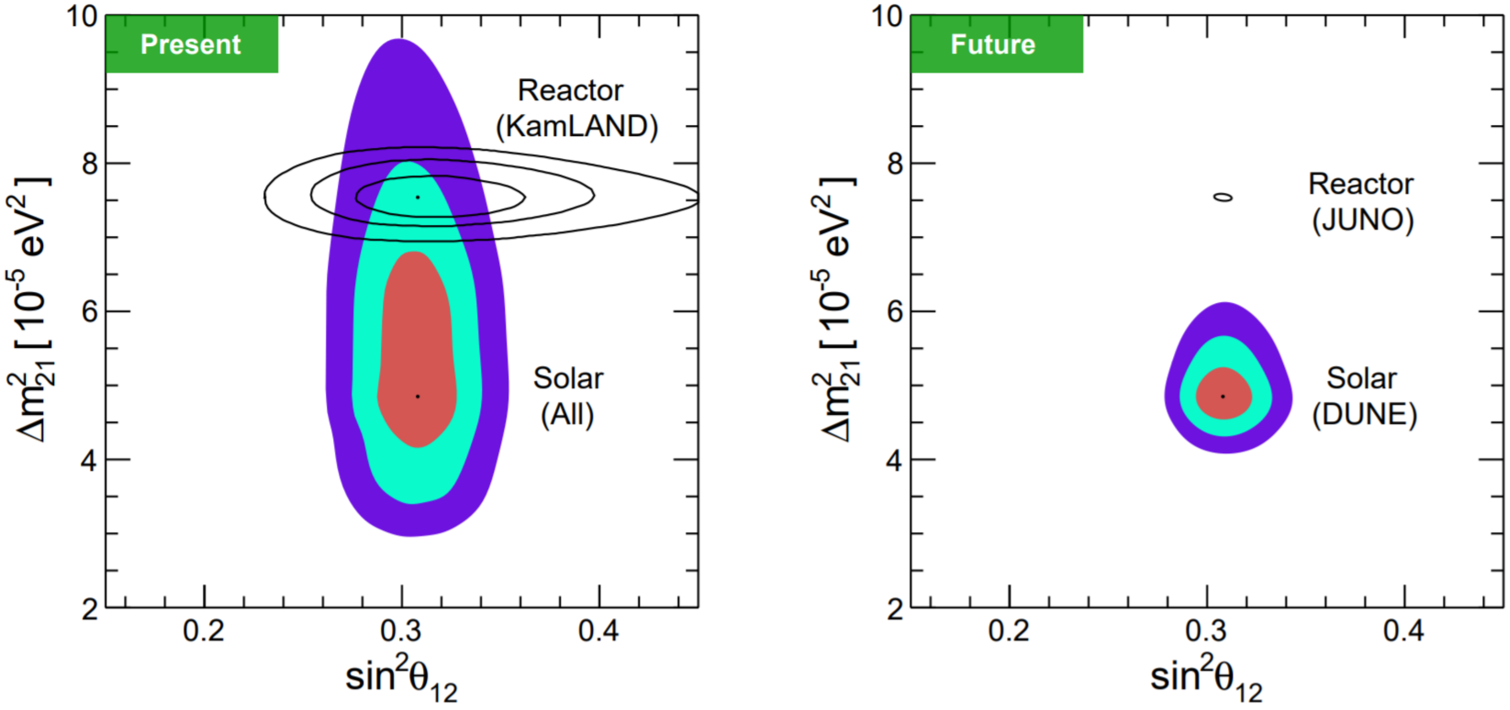
Accessible at B-factories

Solar Neutrino Backgrounds

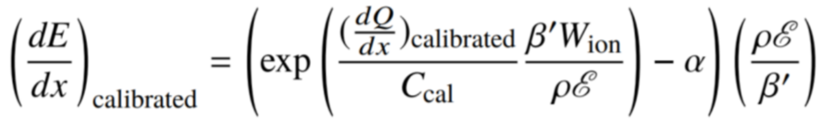


DUNE as the Next-Generation Solar Neutrino Experiment

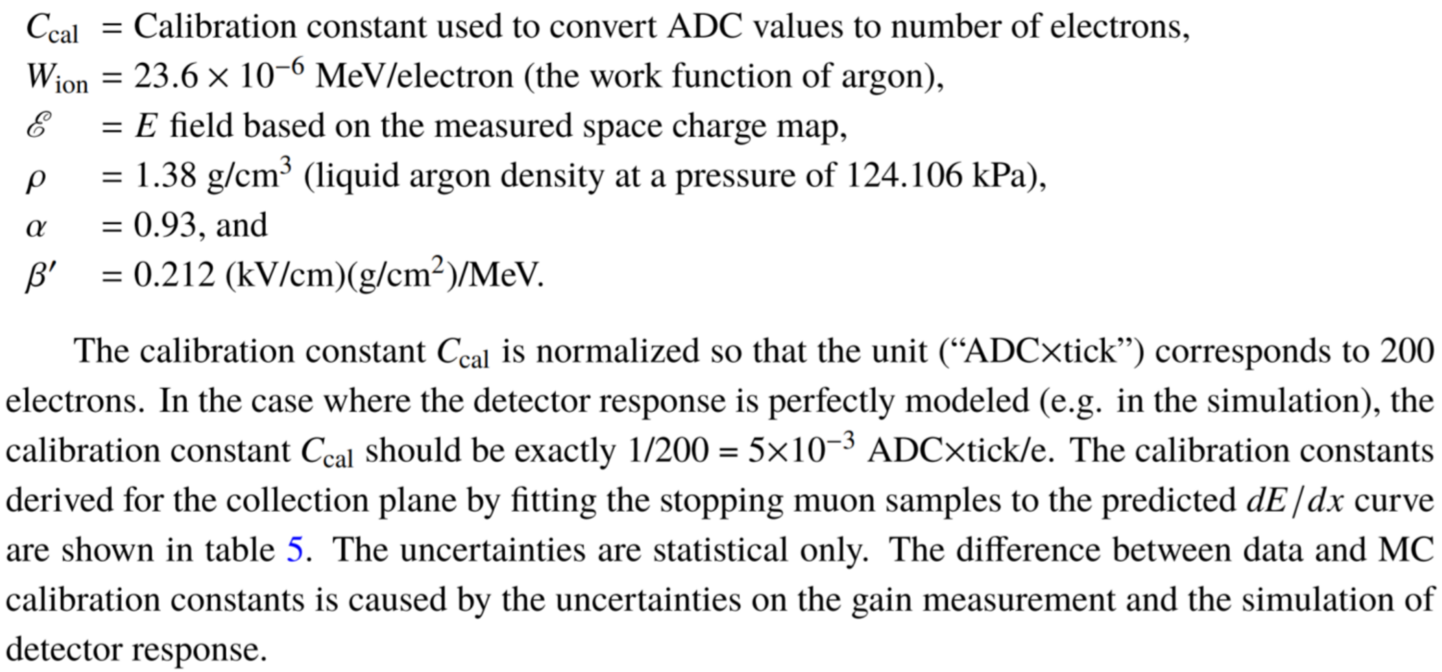
- https://arxiv.org/pdf/1808.08232.pdf



ProtoDUNE calibration



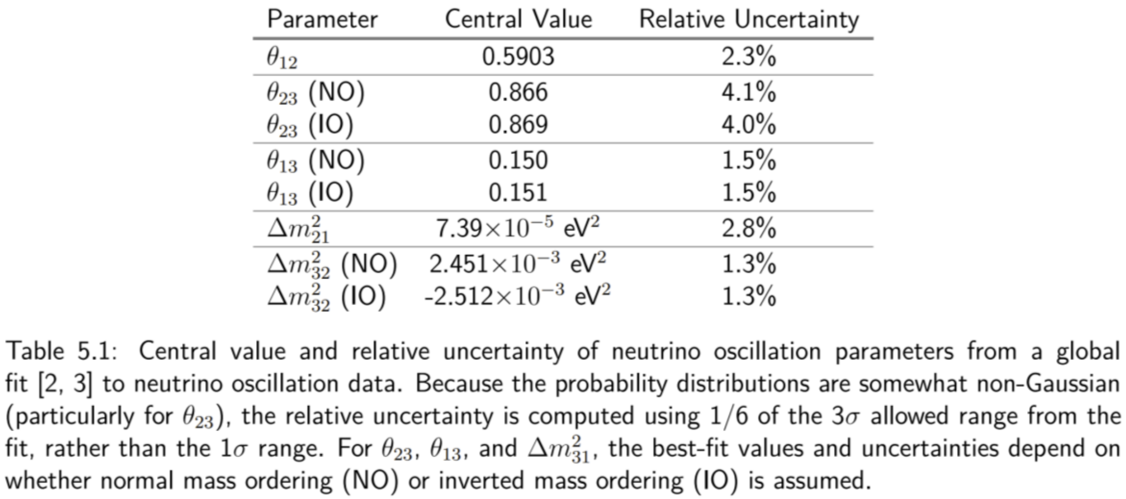
$$\left(\frac{dE}{dx}\right)_{\text{calibrated}} = \left(\exp\left(\frac{(\frac{dQ}{dx})_{\text{calibrated}}}{C_{\text{cal}}}\frac{\beta' W_{\text{ion}}}{\rho\mathscr{E}}\right) - \alpha\right)\left(\frac{\rho\mathscr{E}}{\beta'}\right)$$



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.

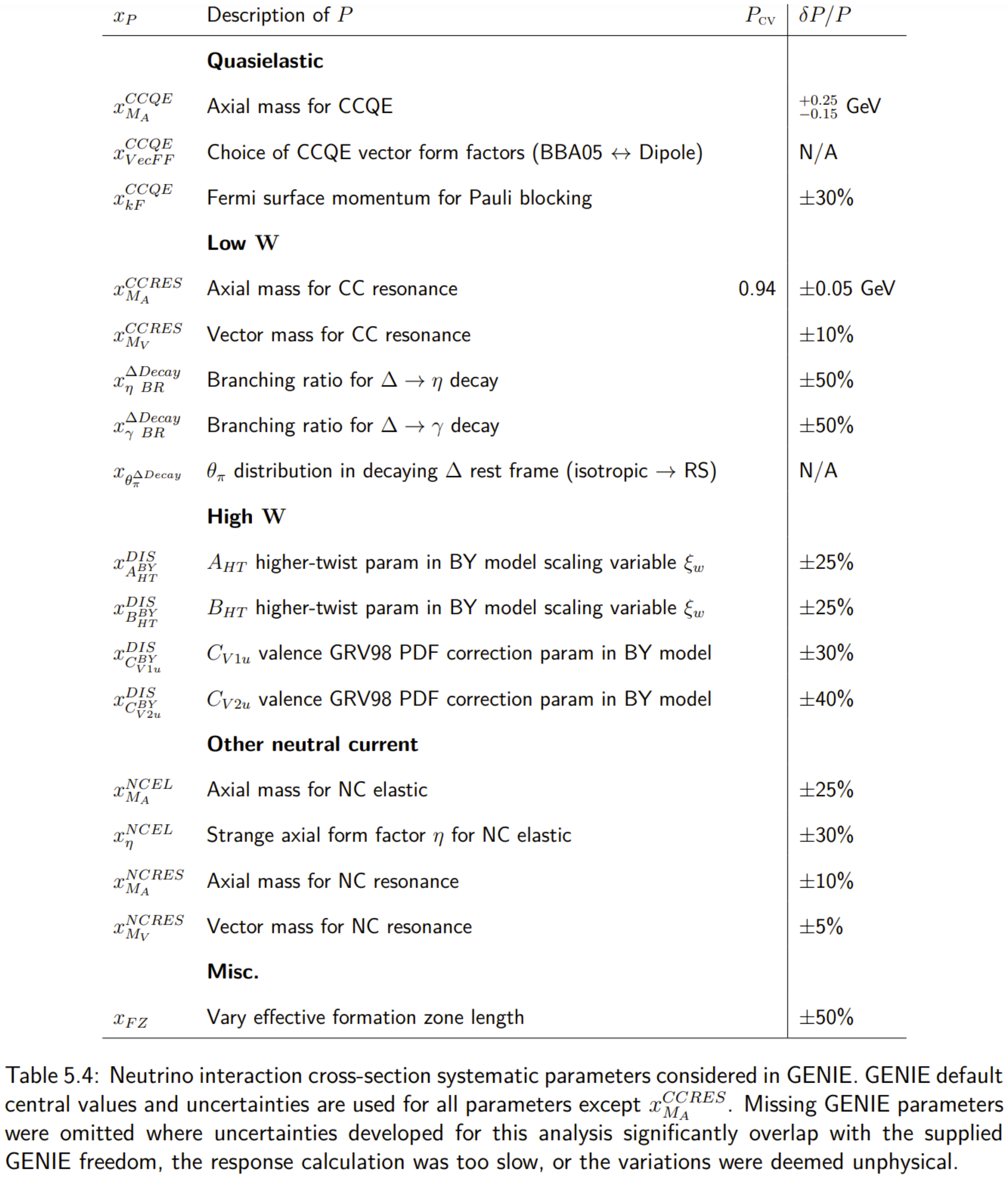
The calibration constant C_{cal} is normalized so that the unit ("ADC×tick") corresponds to 200 electrons. In the case where the detector response is perfectly modeled (e.g. in the simulation), the calibration constant C_{cal} should be exactly 1/200 = 5×10^{-3} ADC×tick/e. The calibration constants 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 $\Delta \rightarrow \eta$ decay		$\pm$50%
$x^{\Delta Decay}_{\gamma\ BR}$	Branching ratio for $\Delta \rightarrow \gamma$ decay		$\pm$50%
$x_{\theta_\pi^{\Delta Decay}}$	θ_π distribution in decaying Δ rest frame (isotropic $\rightarrow$ 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.

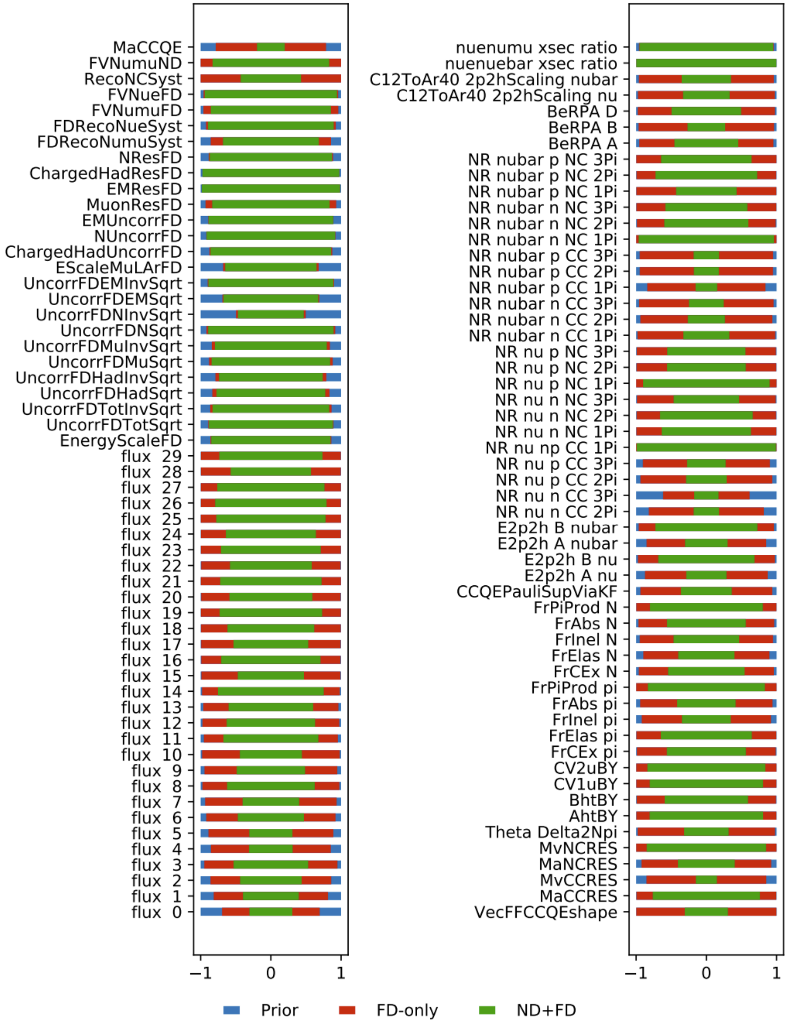


Figure 5.34: The ratio of post-fit to pre-fit uncertainties for various systematic parameters for a 15-year staged exposure. The red band shows the constraint from the FD only in 15 years, while the green shows the ND+FD constraints. Systematic parameter names are defined in Table 5.12.

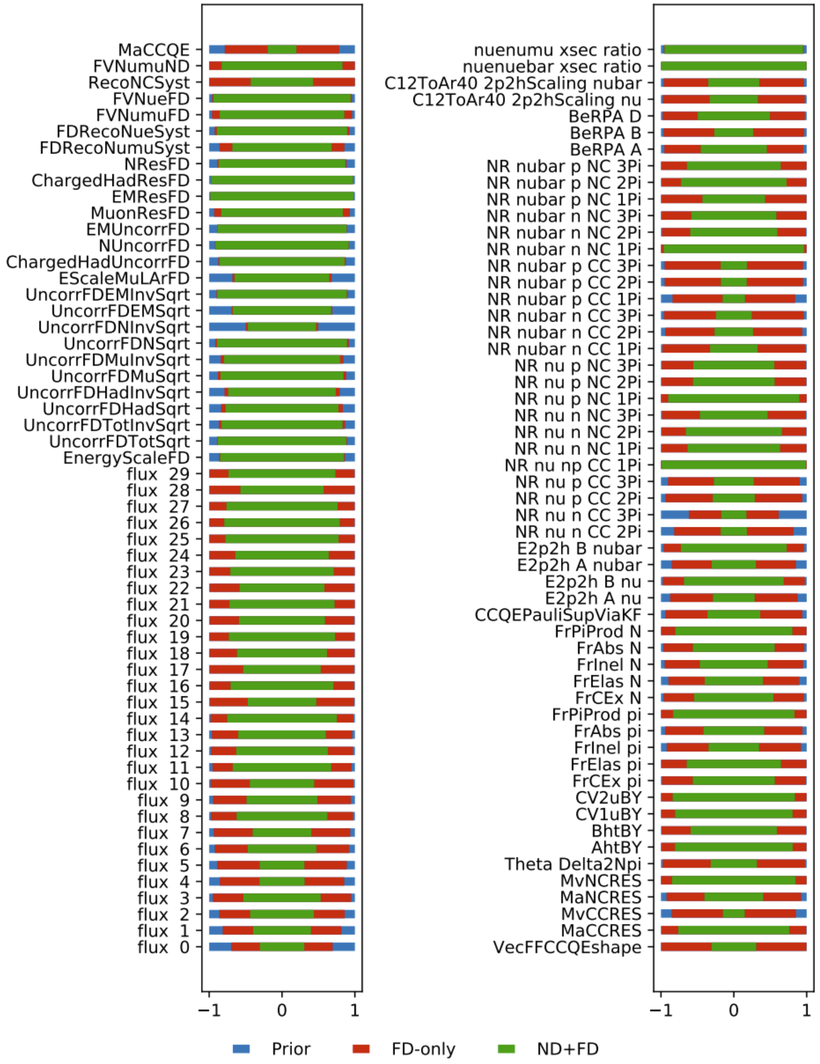


Figure 5.34: The ratio of post-fit to pre-fit uncertainties for various systematic parameters for a 15-year staged exposure. The red band shows the constraint from the FD only in 15 years, while the green shows the ND+FD constraints. Systematic parameter names are defined in Table 5.12.

SuperNova Neutrinos

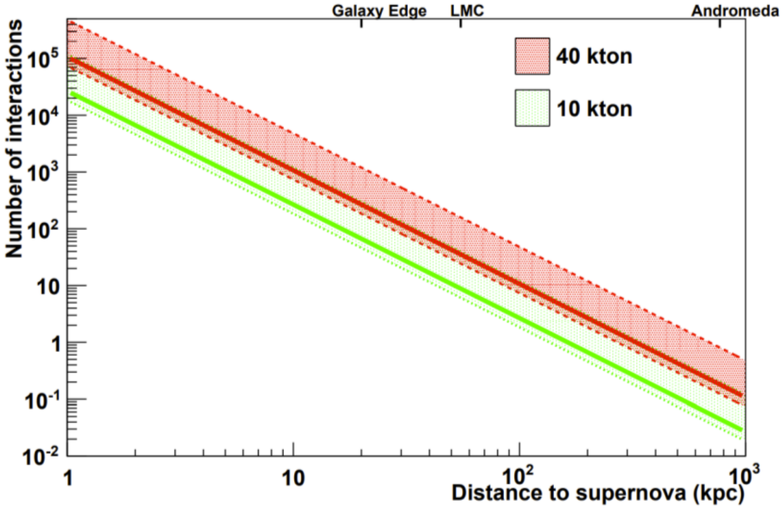
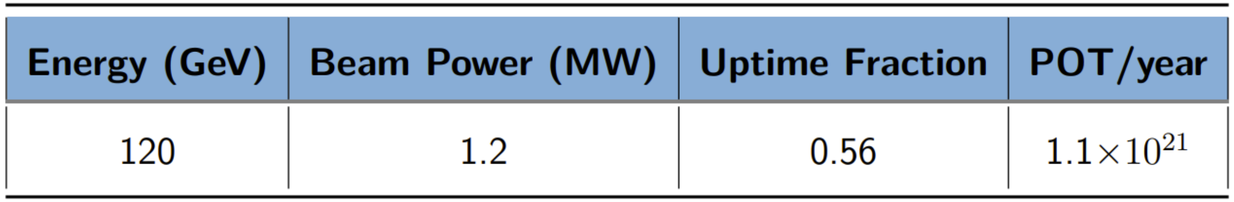


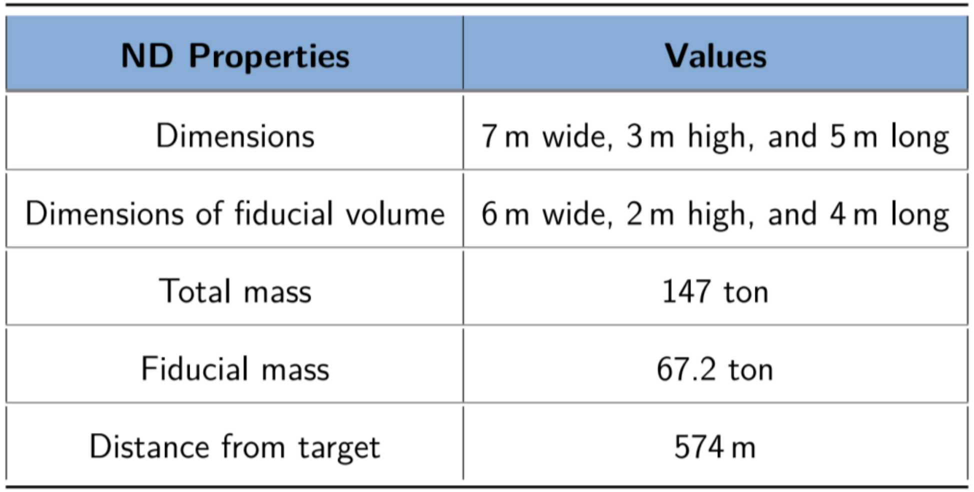
Figure 7.7: Estimated numbers of supernova neutrino interactions in DUNE as a function of distance to the supernova, for different detector masses (ν_e events dominate). The red dashed lines represent expected events for a 40-kton detector and the green dotted lines represent expected events for a 10-kton 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



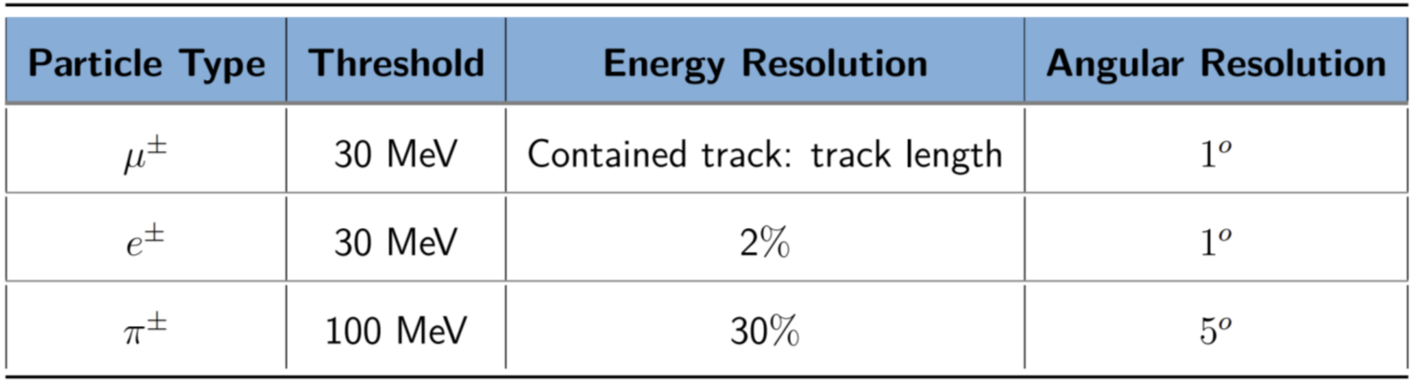
Energy (GeV)	Beam Power (MW)	Uptime Fraction	POT/year
120	1.2	0.56	1.1×10^{21}

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



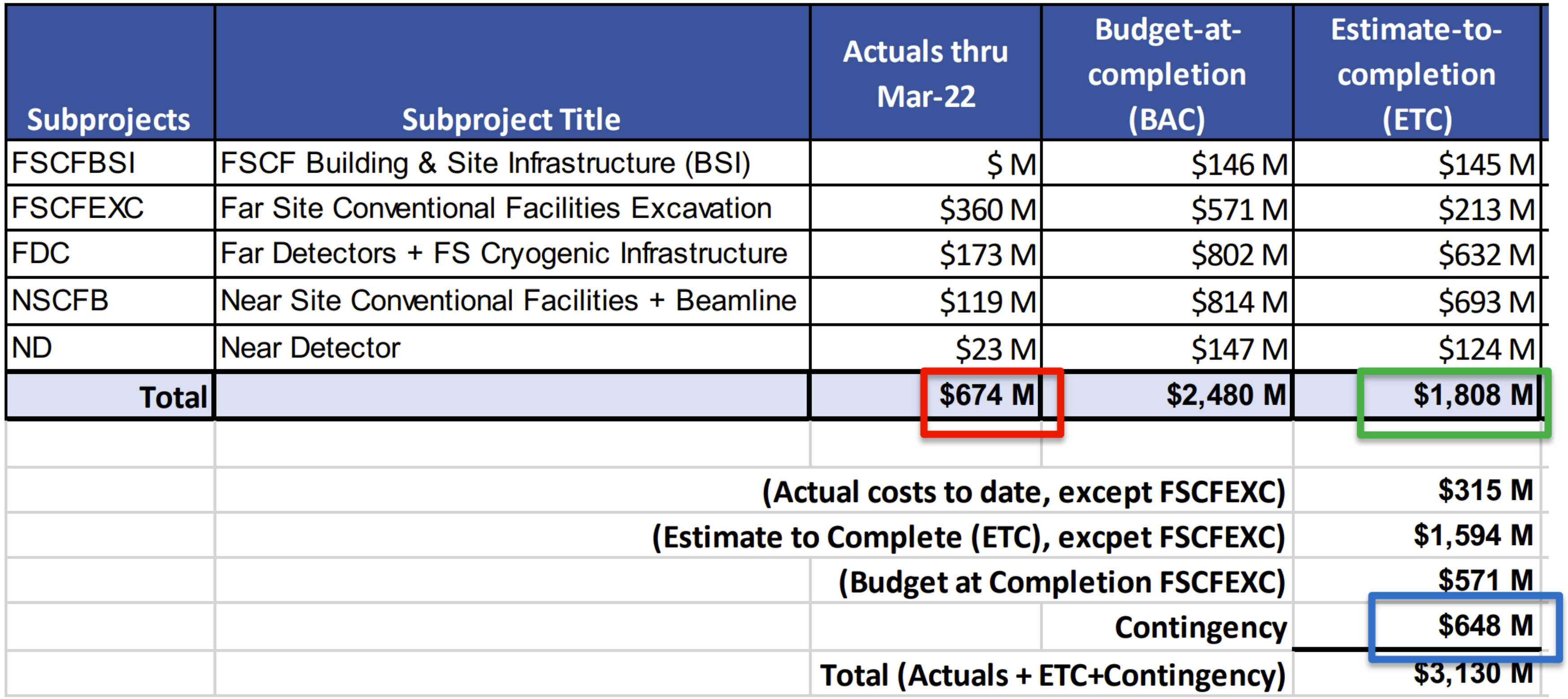
ND Properties	Values
Dimensions	7 m wide, 3 m high, and 5 m long
Dimensions of fiducial volume	6 m wide, 2 m high, and 4 m long
Total mass	147 ton
Fiducial mass	67.2 ton
Distance from target	574 m

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^o
$e^\pm$	30 MeV	2%	1^o
$\pi^\pm$	100 MeV	30%	5^o

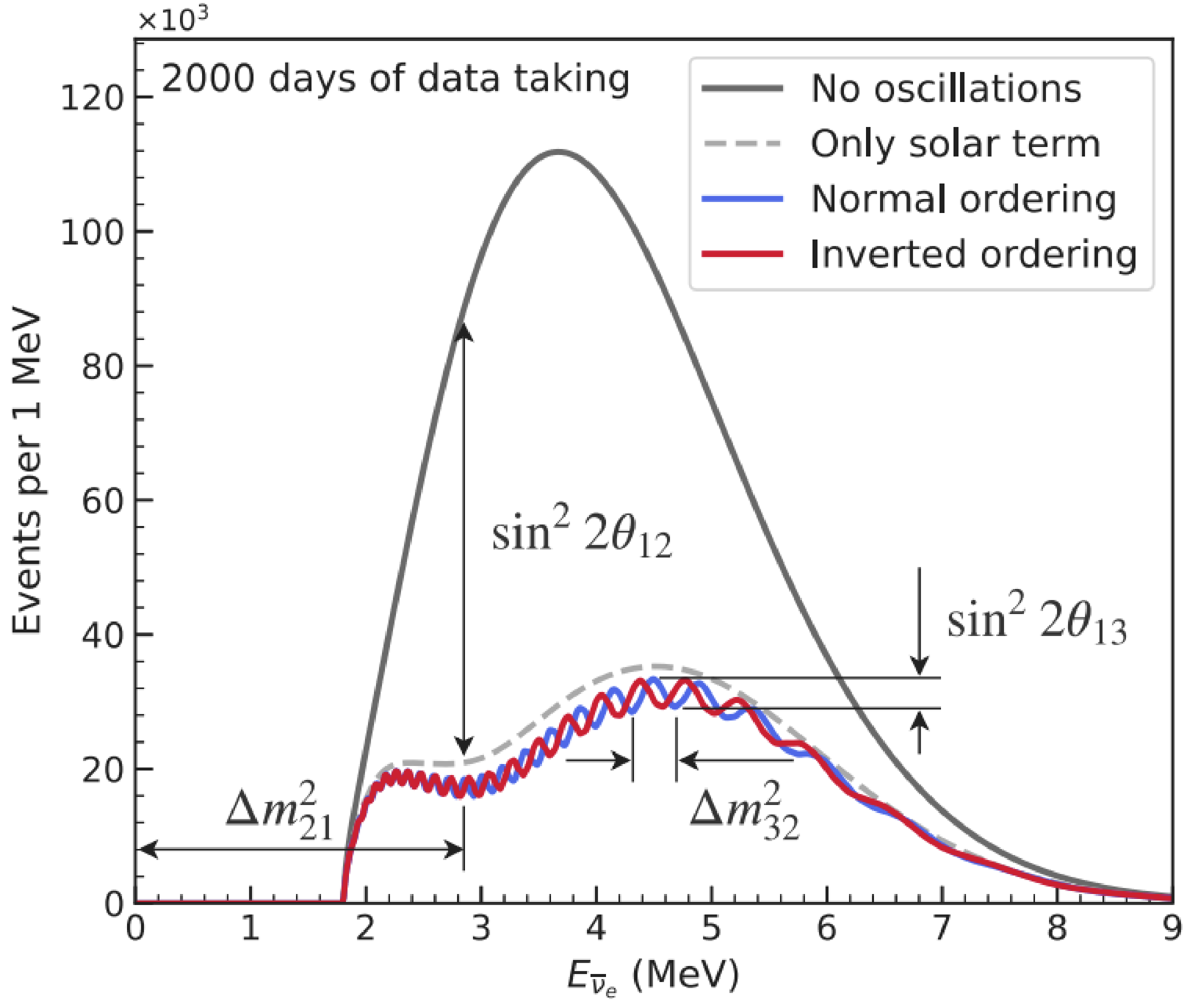
LBNF/DUNE Cost Phase I



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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