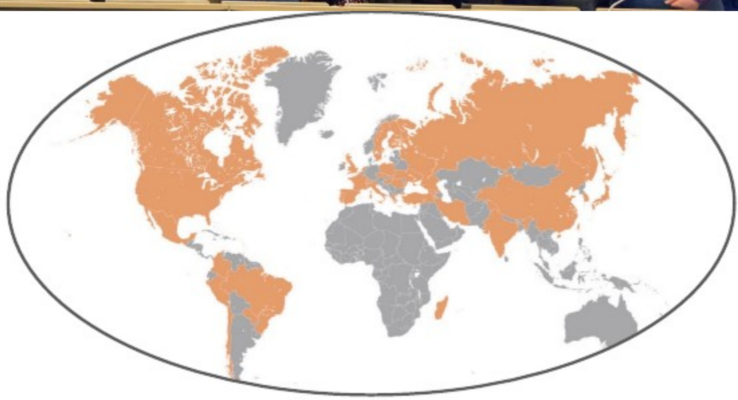
The Horizontal and Vertical Drift detectors in DUNE

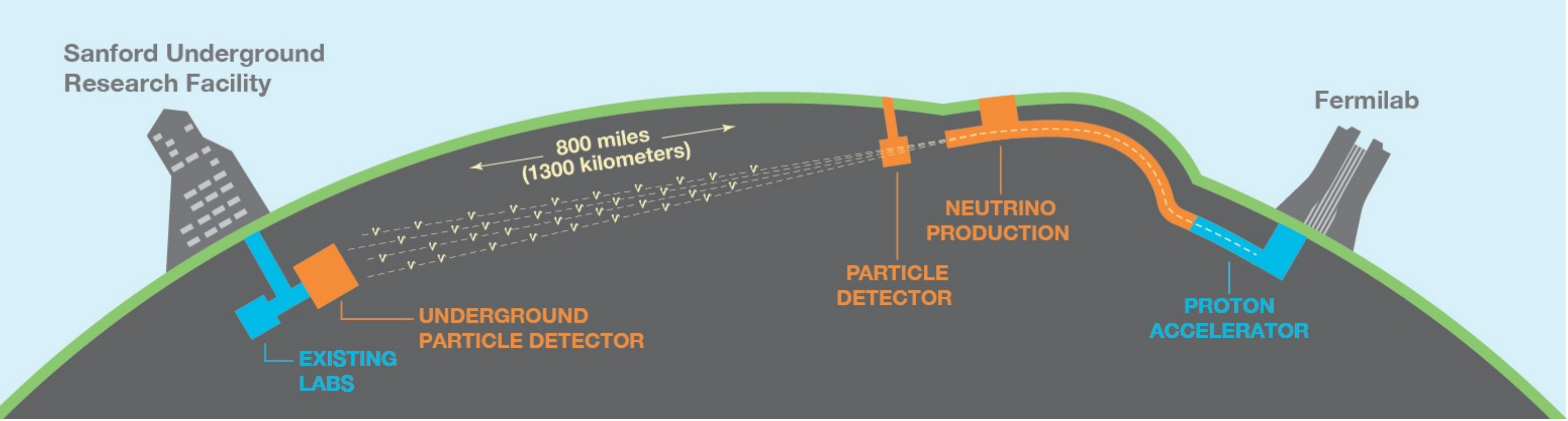
Jaime Dawson on behalf of the DUNE collaboration
Laboratoire AstroParticule et Cosmologie, Paris

DUNE: international collaboration

1400+ collaborators
200+ institutions
37 countries (including CERN)



DUNE is next generation neutrino oscillation experiment



Far detectors at SURF:
4 x 17 kt Liquid Argon TPCs
1.5 km underground

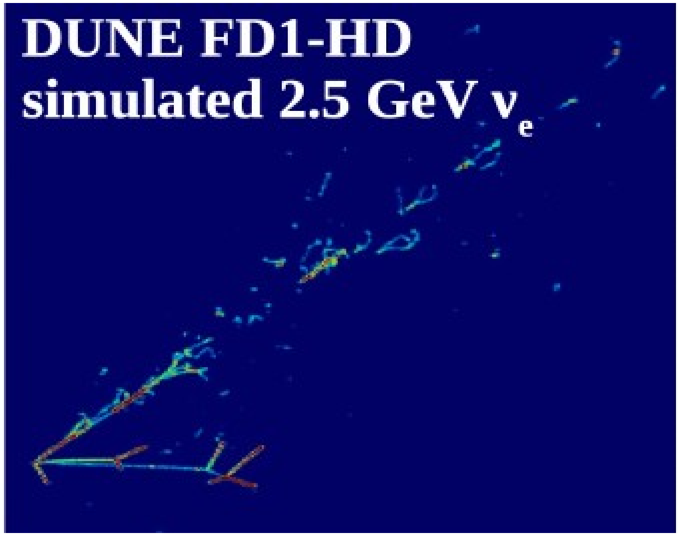
Long baseline: 1300km

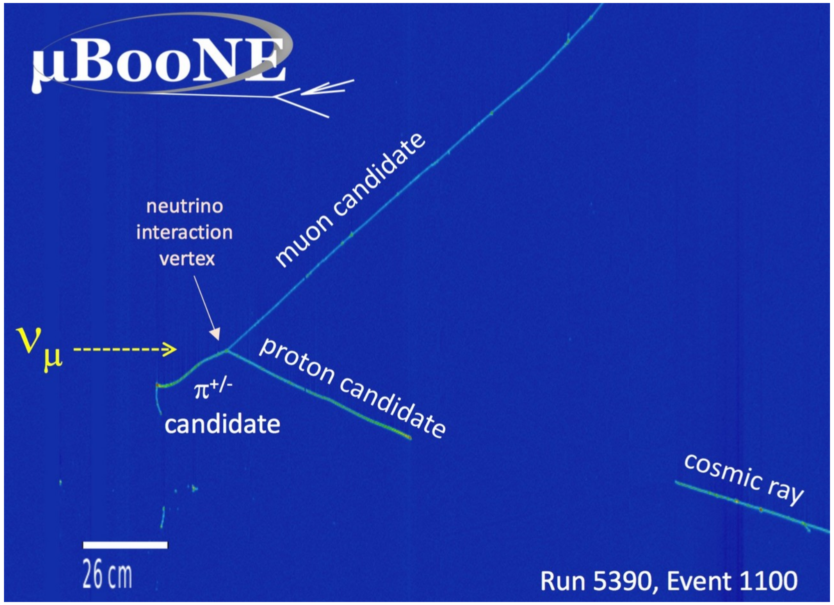
1.2 MW wide-band beam from Fermilab (upgradable to 2.4 MW)

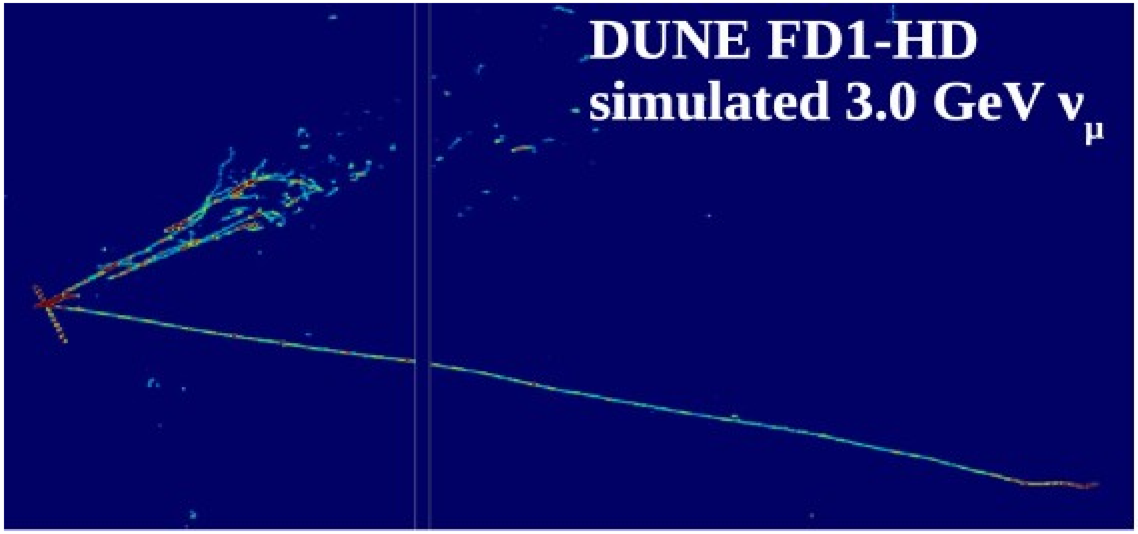
Near Detector to measure initial composition

LAr TPCs

- Massive detectors (17 ktons Far Detectors)
- Fine-grain 'images' of neutrino interactions
- Separation ν_μ/ν_e
- Good energy reconstruction
- Low energy threshold







LAr TPCs

- Supernova signals
  - DUNE is sensitive to ν_e

    $\nu e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$
  - Also elastic-scattering
  - 5-50 MeV signals

- Proton decay
  - DUNE sensitive to:

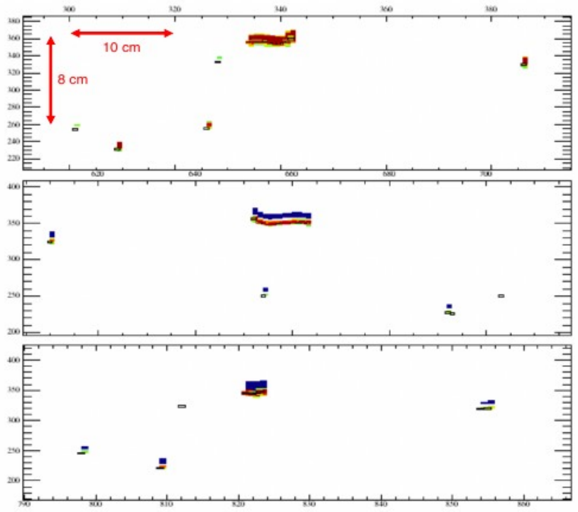
    $p \rightarrow K^+ \nu$
  - and other channels:

    $n \rightarrow K^+ e^-$

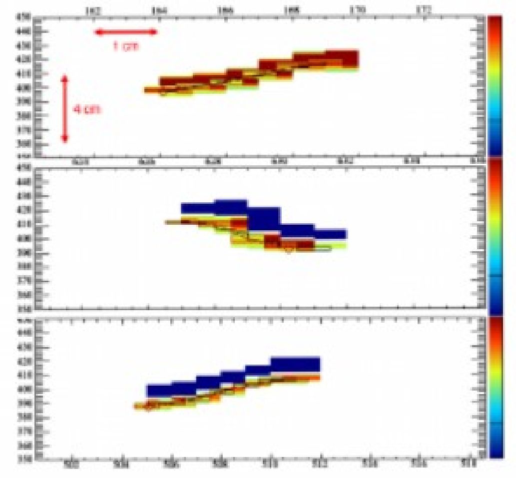
    $p \rightarrow l^+ K^0$

    $p \rightarrow \pi^0 e^+$

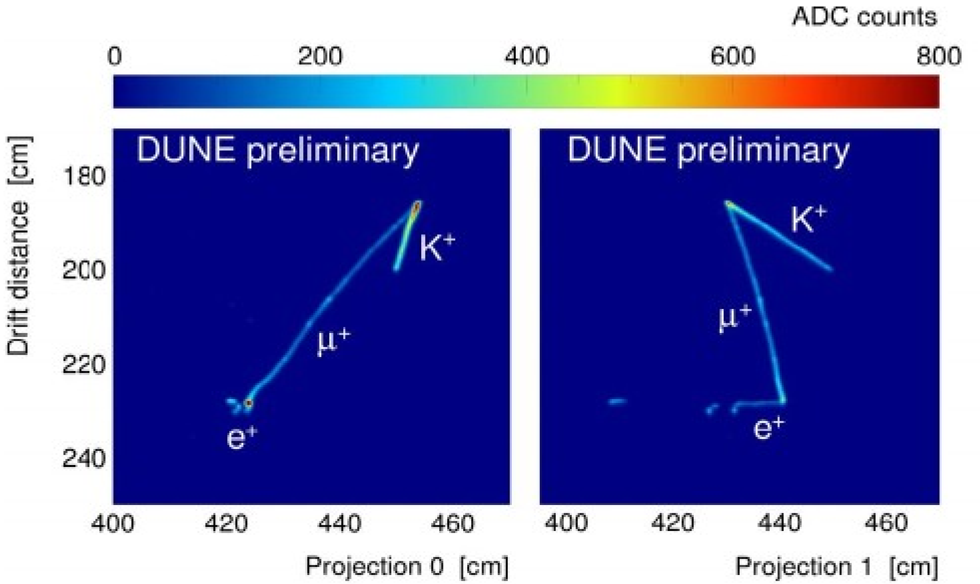
2008.06647



20.25 MeV νeCC

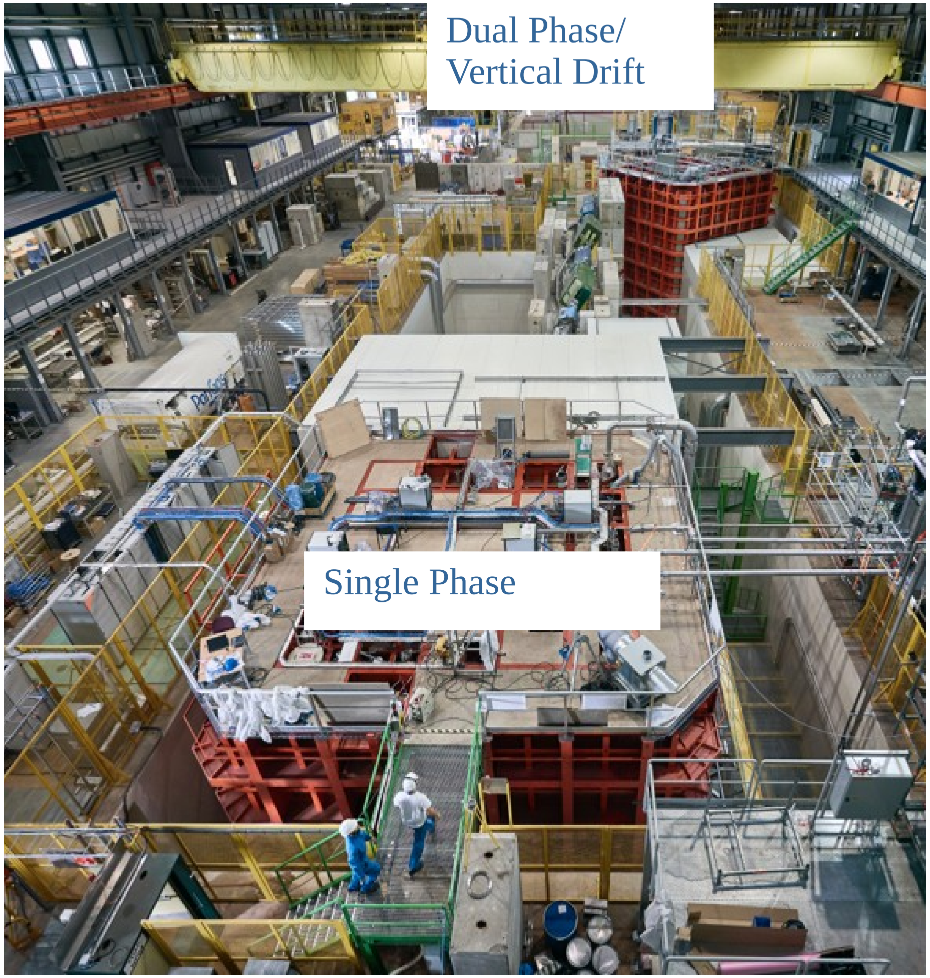


10.25 MeV νES

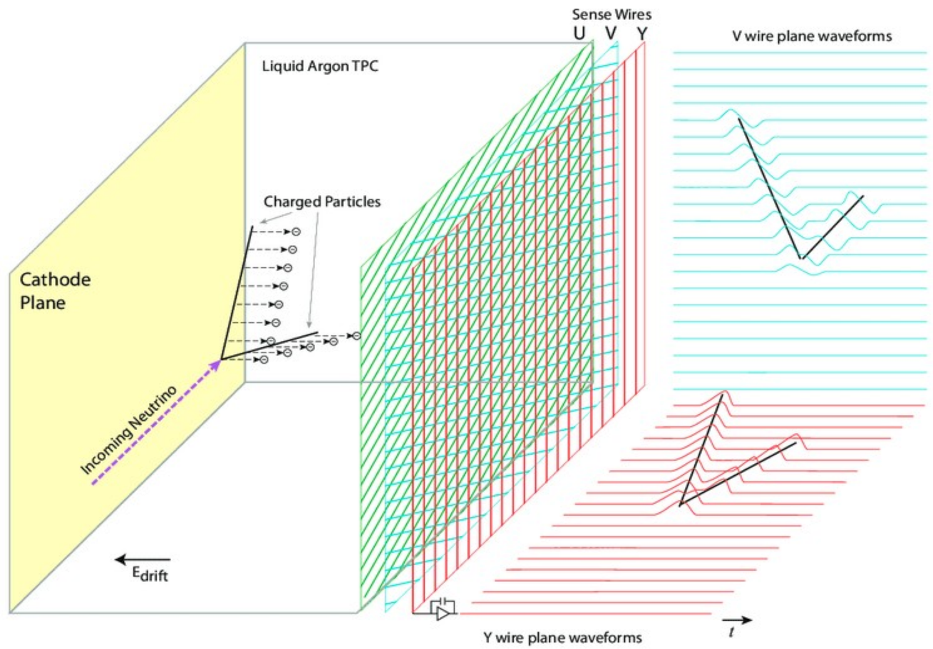


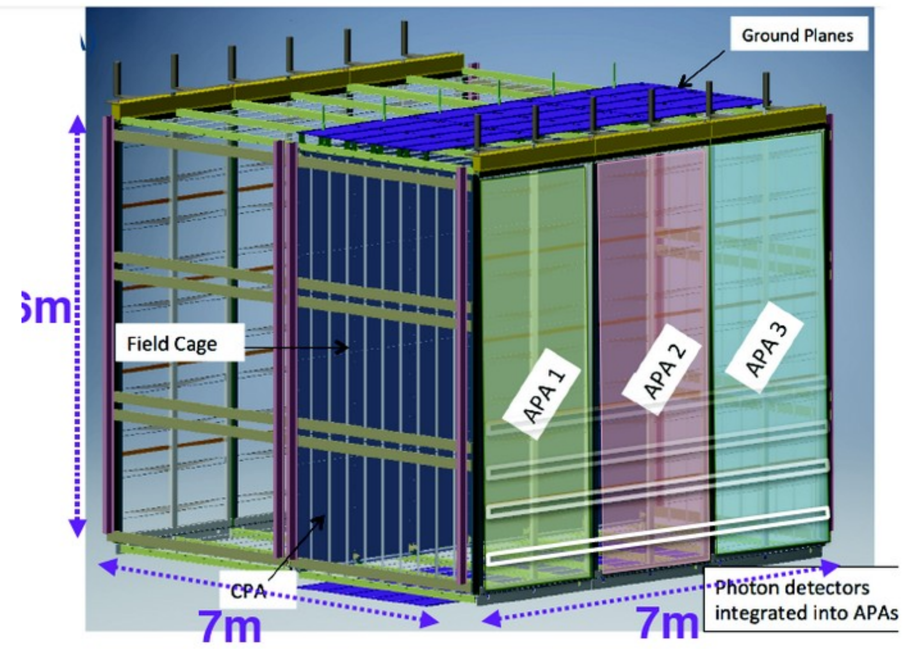
ProtoDUNEs

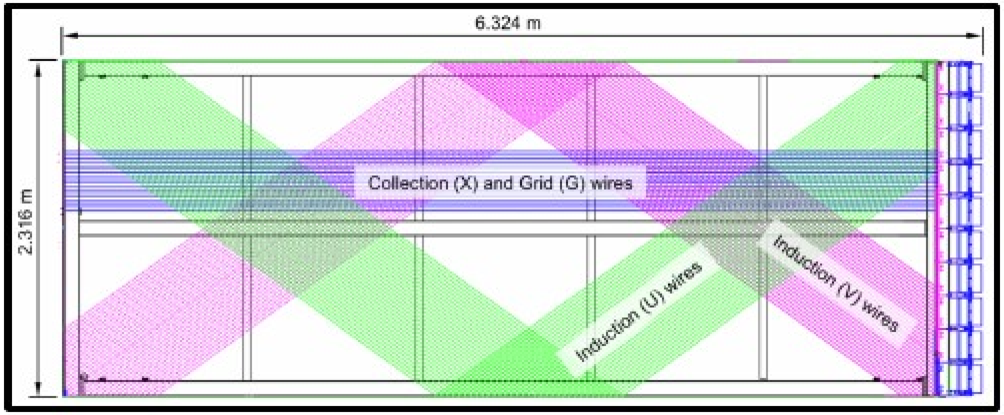
- TPC technologies tested with full-size components at the CERN neutrino platform – protoDUNEs
- Each cryostat holds 720 tons LAr
- Single Phase [August 2018 -]
  - 3rd run this year (Horizontal Drift)
- Dual Phase [2019-]
- Experience with ProtoDUNE Dual Phase led to Vertical Drift



ProtoDUNE Single Phase







2 drift volumes,
each with a 3.6 m drift distance

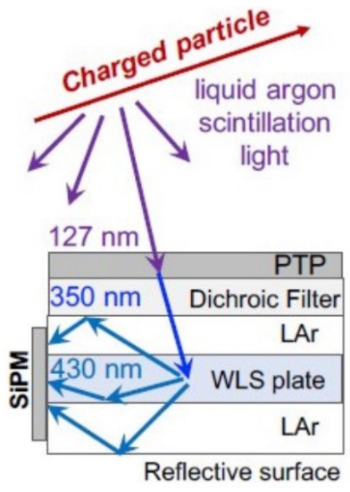
6 anode plane assemblies (APAs)
Charge Read-out electronics in LAr:
2560 channels/APA

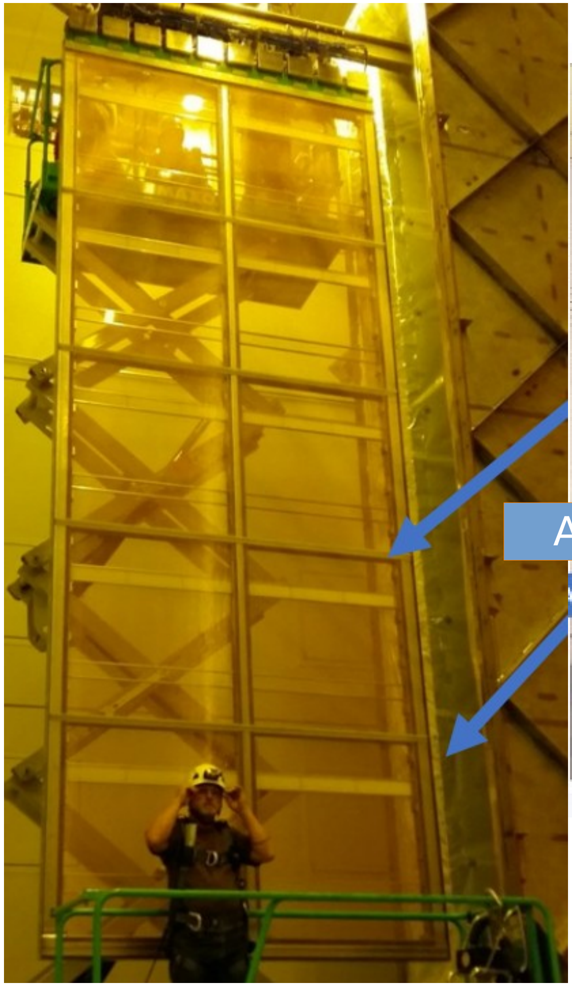
HV at -180 kV,
nominal E-field 500 V/cm

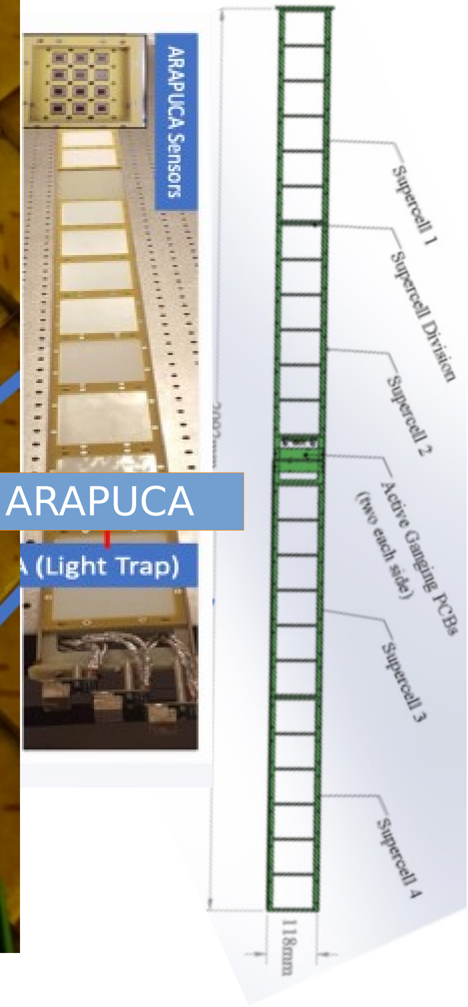
ProtoDUNE Single Phase

ARAPUCA photon detector modules
mounted inside Anode Plane Assemblies (10 per APA)

ARAPUCAs: light traps coupled to SiPM readout

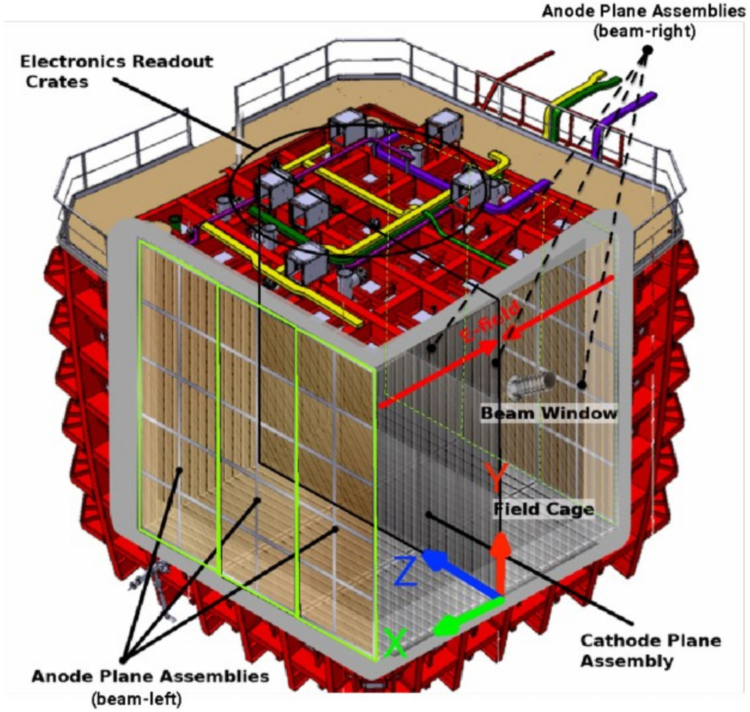


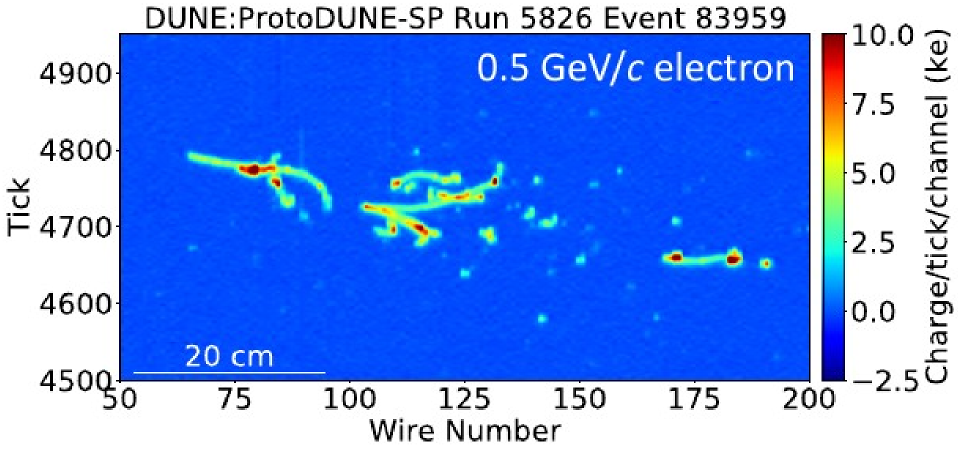


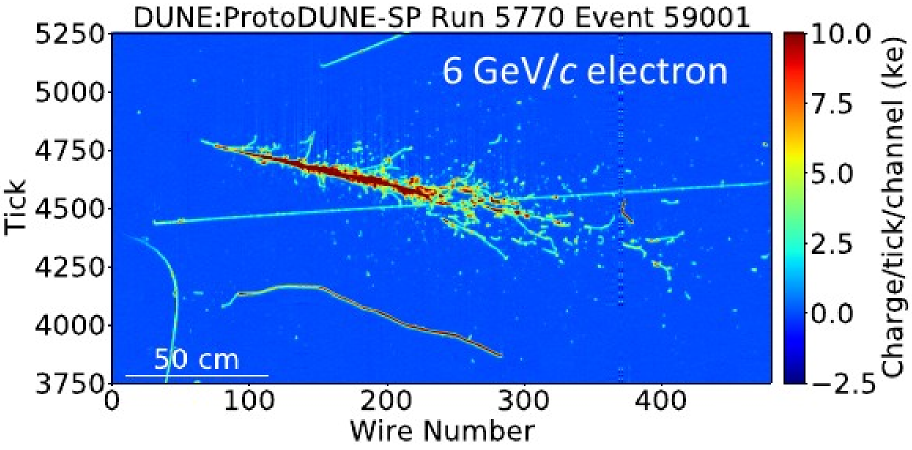


ProtoDUNE Single-Phase

- First run charged-particle test beam
- Operated from August 2018 – July 2020
- Instrumented Beamline
- Known incident particle momentum - 300 MeV/c to 7 GeV/c
- First results paper: JINST 15 P12004



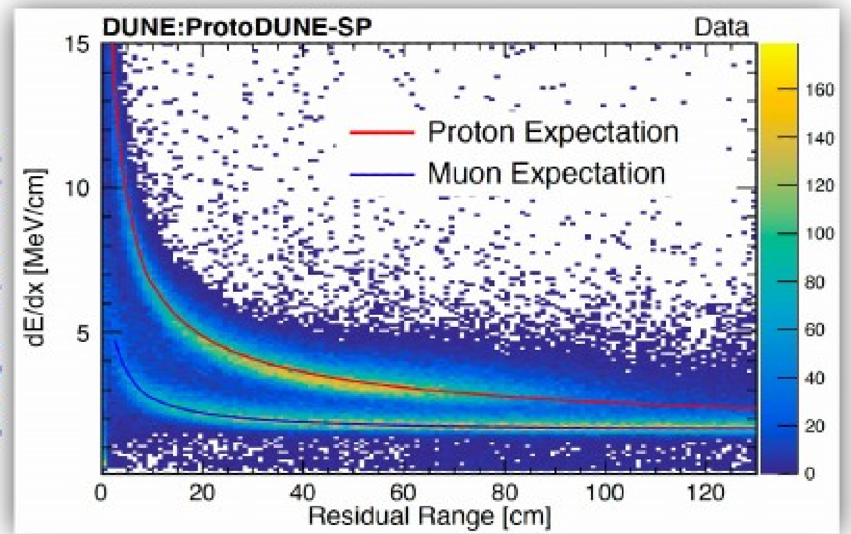




ProtoDUNE Single-Phase

- First run charged-particle test beam
- Operated from August 2018 – July 2020
- Instrumented Beamline
- Known incident particle momentum - 30 MeV/c to 7 GeV/c
- First results paper: JINST 15 P12004

JINST 15 P12004

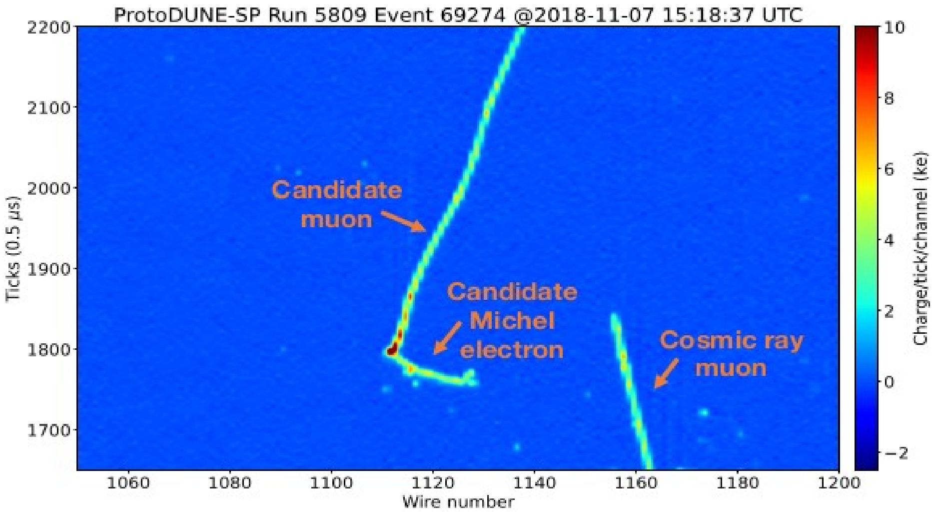


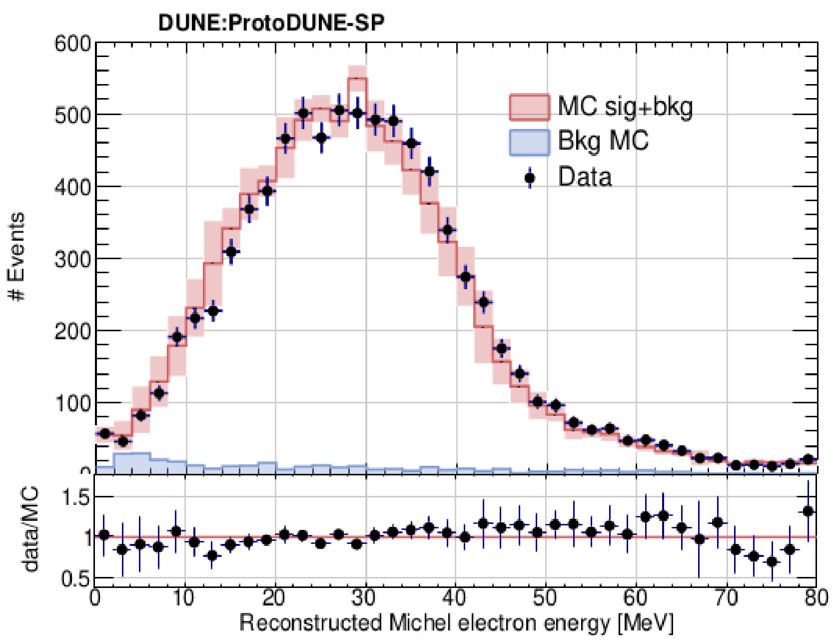
Stopping muon and proton dE/dx vs. residual range in ProtoDUNE-SP.

Detector Parameter	Specification	Goal	ProtoDUNE Performance
Electric Drift Field	> 250 V/cm	500 V/cm	500 V/cm *
Electron Lifetime *Impurity Concentration*	> 3 ms *(<100 ppt [O_2-equiv])*	10 ms *(<30 ppt [O_2-equiv])*	> ~30 ms in TPC ** *< 10 ppt*
TPC Electronics Noise	< 1000 e ENC	ALARA	550-650 e ENC (raw) 450-560 e ENC (cnr)***
TPC dead channels	< 1%	ALARA	0.2 % (of ~15,360 channels over 1.5 yr operation)
PhotoDetector Light Yield	> 0.5 Ph/MeV (at cathode plane - 3.6 m distance)		1.9 Ph/MeV ++ (at 3.3 m distance)
PhotoDetector Time Resolution	< 1μs	< 100 ns	14 ns ^^

* 99.5% uptime. ** in TPC EF=500 V/cm, in PurMon EF=20 V/cm - (< 10 ppt [O_2-equiv] during beam run).
*** coherent noise removed. ++ from extrapolation based on actual ARAPUCA data. ^^ two pulse separation.

ProtoDUNE Single Phase



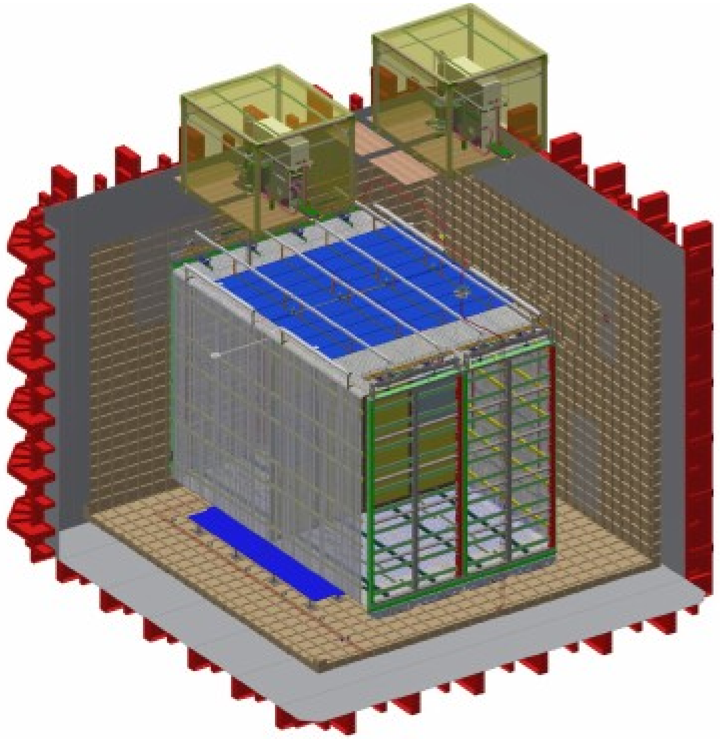


Charge response to low energy signals

Michel electrons arXiv: 2211.01166

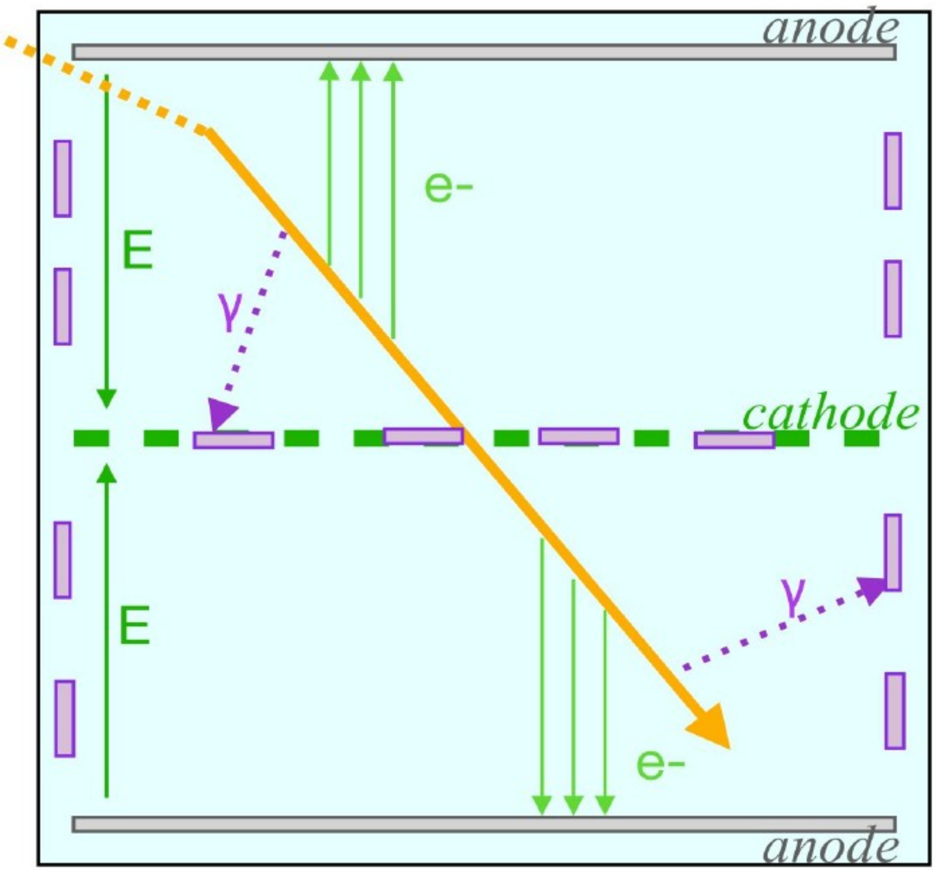
ProtoDUNE Horizontal-Drift

- 4 APAs – two with readout on the bottom
- New versions of TPC and PDS electronics
- Test of calibration systems for DUNE
  - Ionization Laser System (IoLS) calibration
  - Pulse Neutron Source (PNS)
  - Radioactive Source Deployment System (RSDS)
- LAr filling begins soon



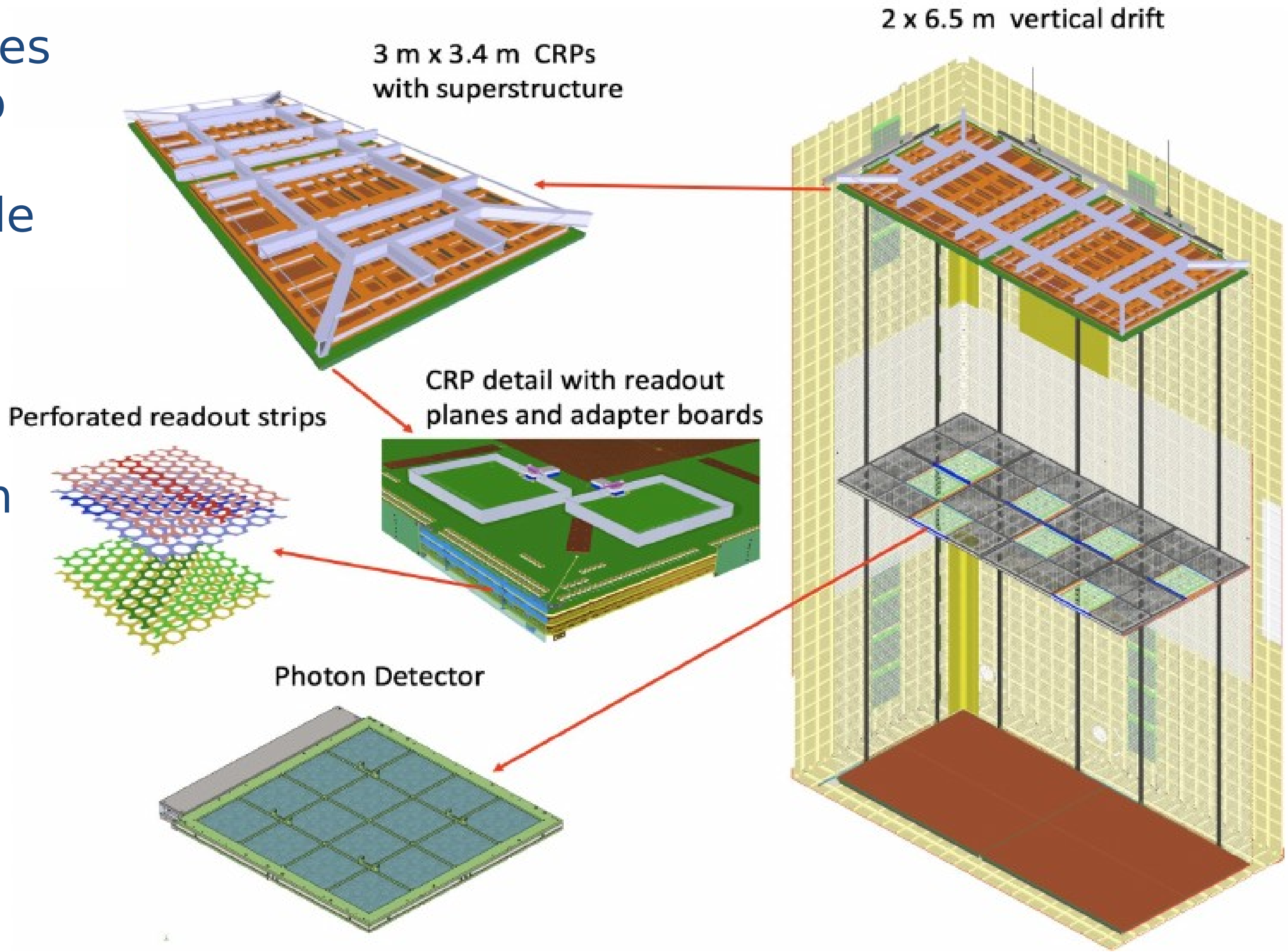
ProtoDUNE Vertical-Drift

- New concept merging positive features of Dual Phase with successful Single Phase LArTPC
- HV delivery allows large drift volumes
  - Top and Bottom
  - Top volume electronics is accessible
- PCB-based charge read-out
  - 3-views
  - Advantageous for manufacturing and installation
- Single-Phase



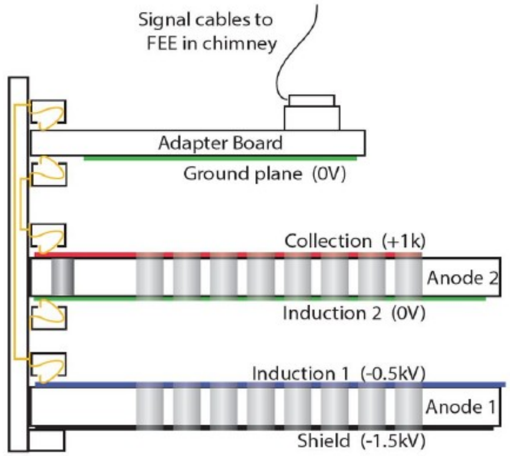
ProtoDUNE Vertical-Drift

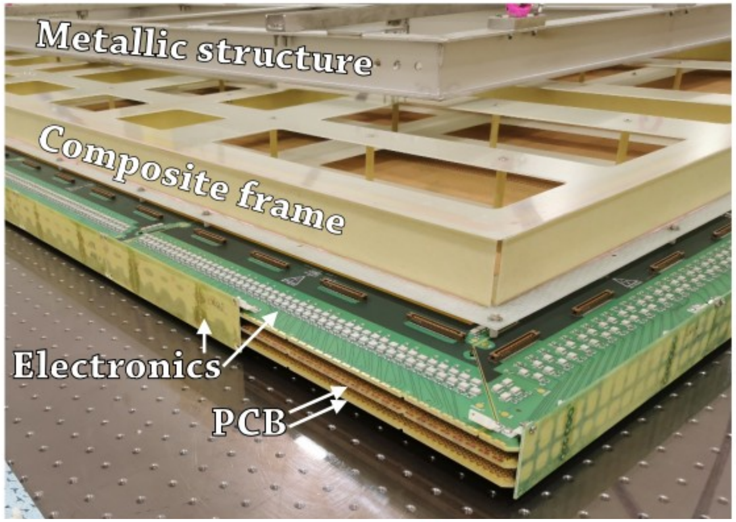
- Charge-readout planes (CRP) (anode) on top and bottom.
- Cathode in the middle at -300 kV
- 6,5 m drift distance
- Photon detectors
  - X-arapuca
  - Behind field cage (on cryostat walls)
  - Embedded in cathode !!

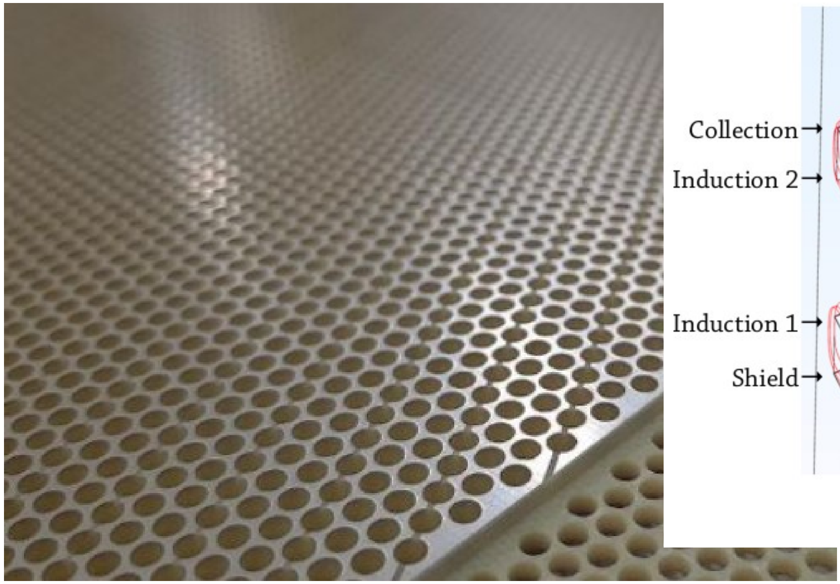


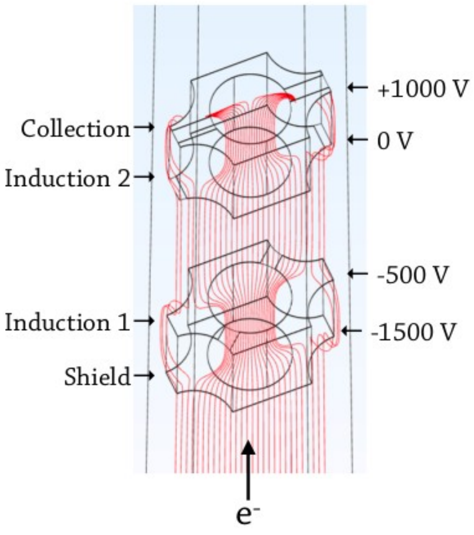
ProtoDUNE Vertical-Drift

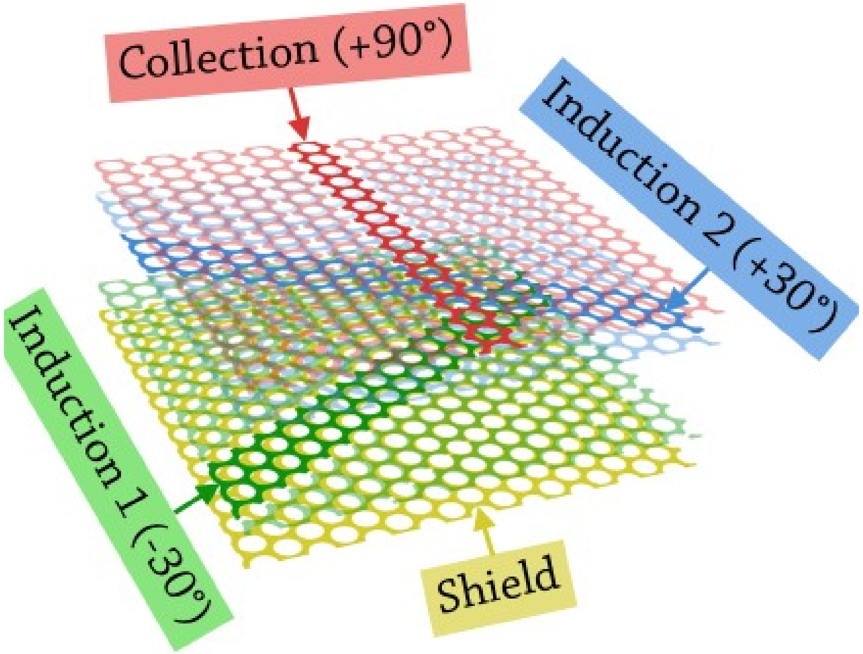
- 3-views with different strip orientation
- 3072 channels/CRP
  - 2 induction
    - Bipolar signals
    - 7.65mm wide strips
    - 952/view/CRP
  - 1 collection
    - Unipolar signals
    - 5.1 mm wide strips, total of 1168 strips/CRP





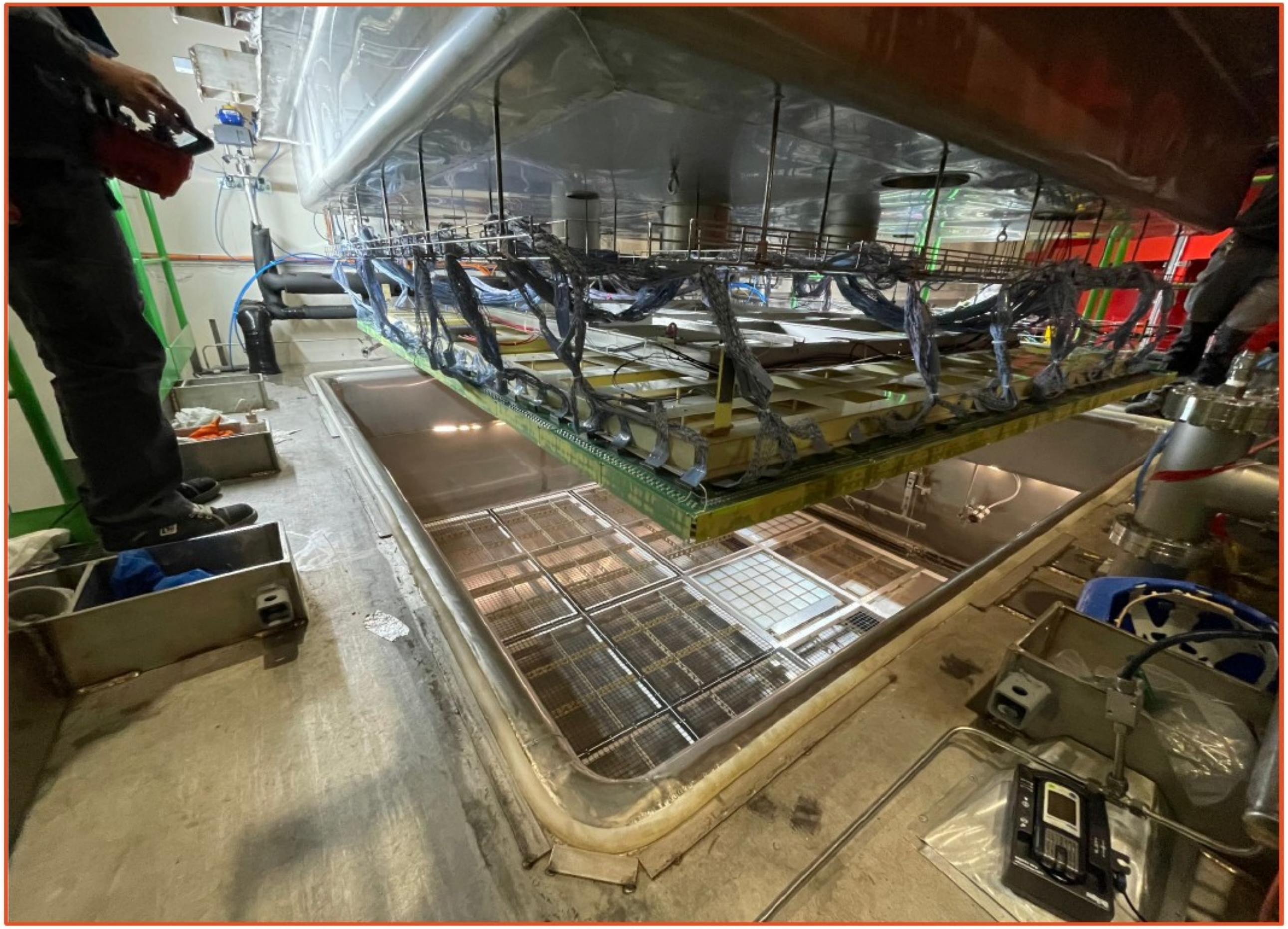






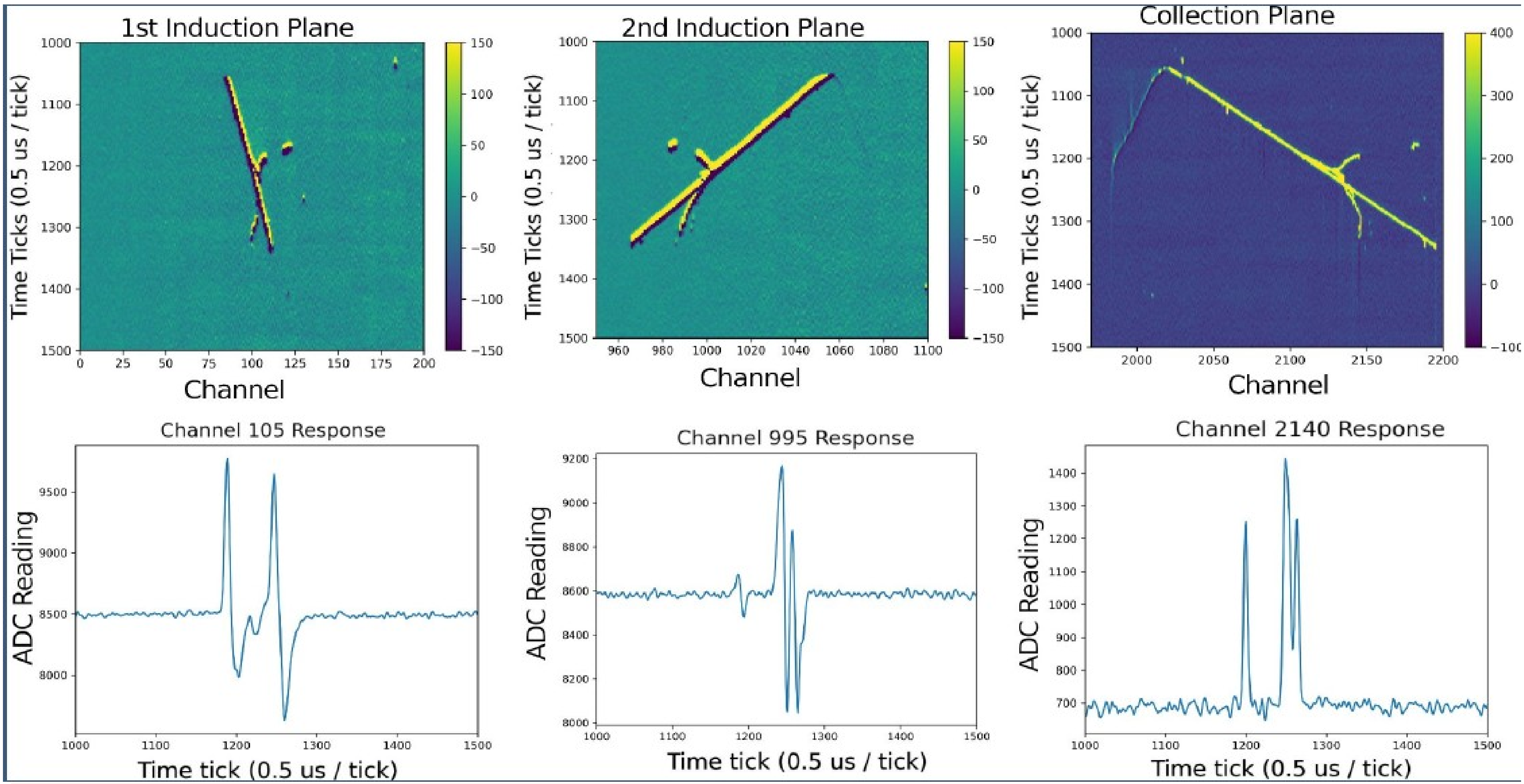
ProtoDUNE Vertical-Drift

- Test of the Vertical Drift design in the coldbox facility at the Neutrino Platform at CERN
- 3×3×1 m3 cryostat
- 23cm drift
- Testing Nov 2021 – present



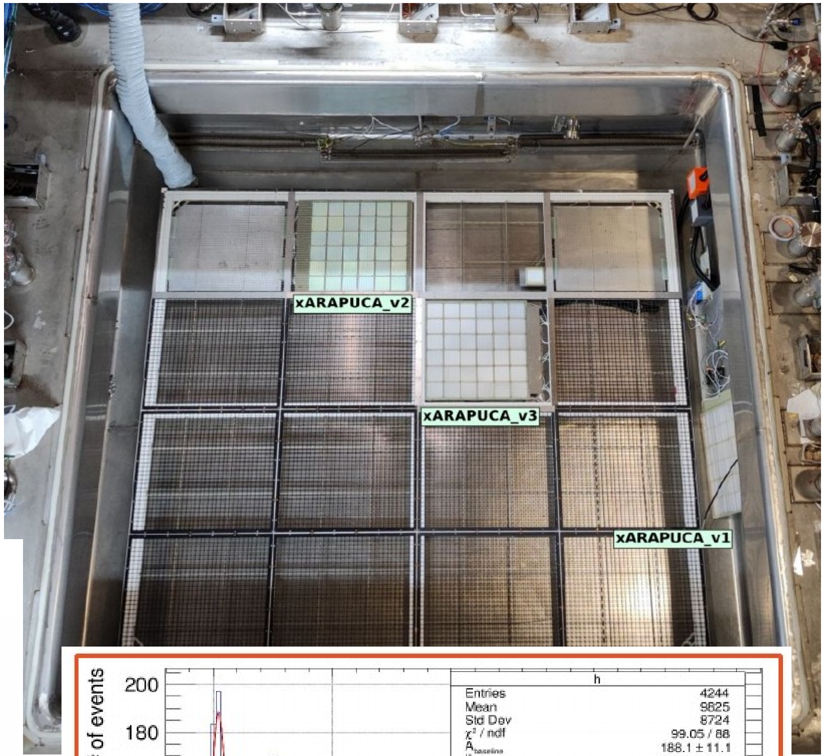
ProtoDUNE Vertical-Drift

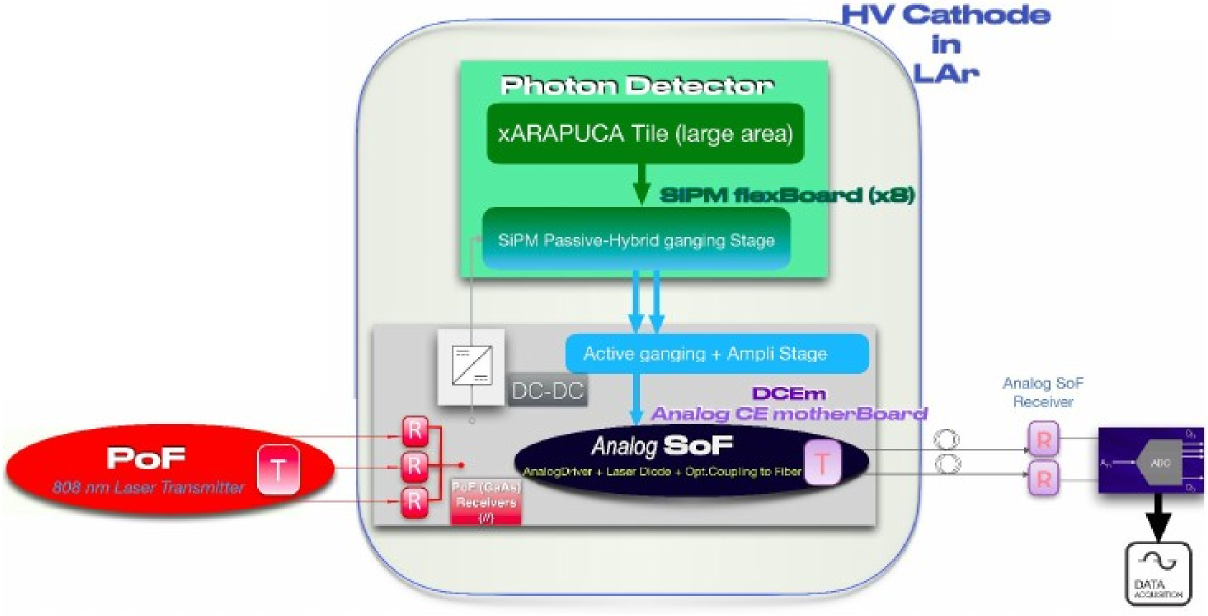
- Charge Read-Out Planes testing
- Successfully operated
- Less than 1% channel failure

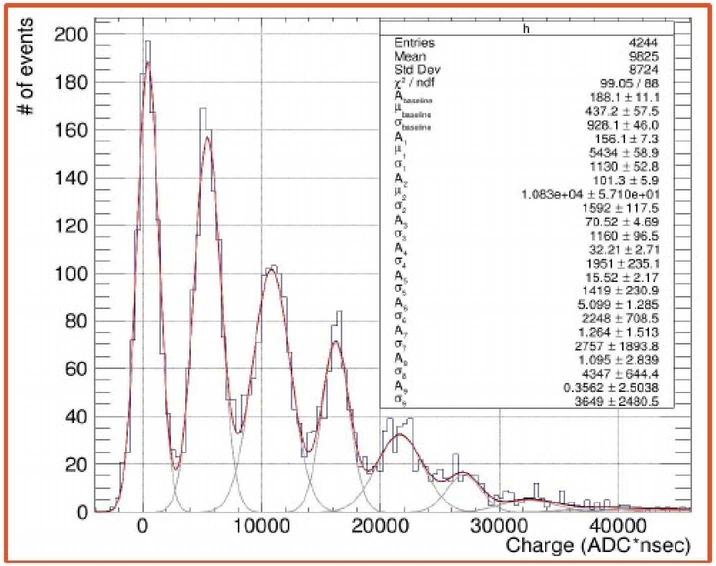


ProtoDUNE Vertical-Drift

- Photon Detectors embedded in Cathode
- One module: 65x65cm², 2x80 SiPMs
- Electronics and SiPMs powered and signals read-out by optical fiber

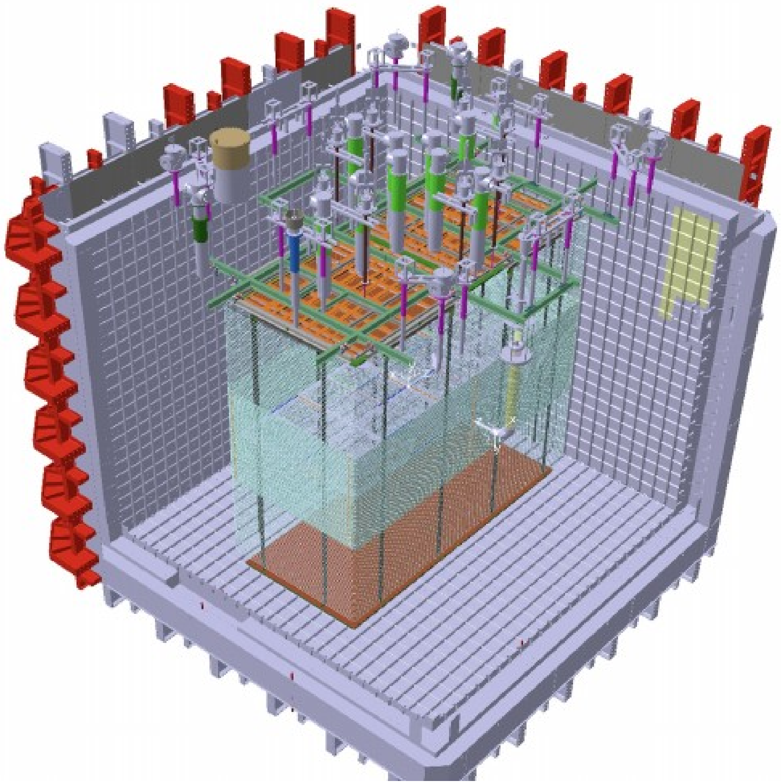






ProtoDUNE Vertical-Drift

- Large-scale test of the Vertical Drift design in the NP02 cryostat in the Neutrino Platform at CERN
- Active volume: 3 × 6.8 × 7 m2
  - 2 CRPs top
  - 2 CRPs bottom
  - 2 Cathode modules
- Operated at -175 kV



Top volume

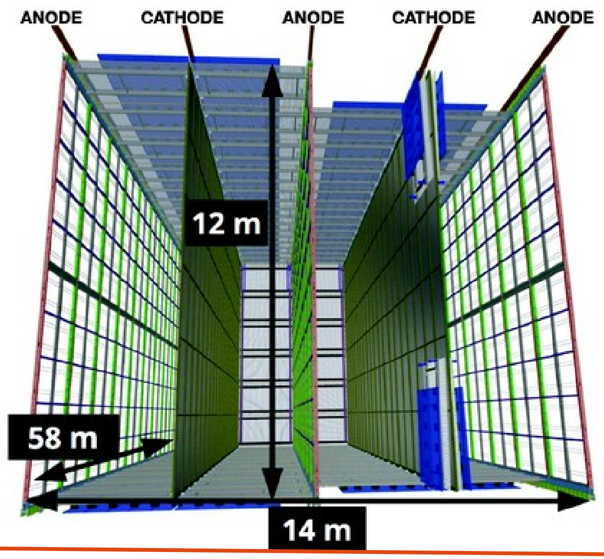
Bottom volume

Installation complete
Operation in Autumn 2024

Far detector at SURF

Horizontal Drift

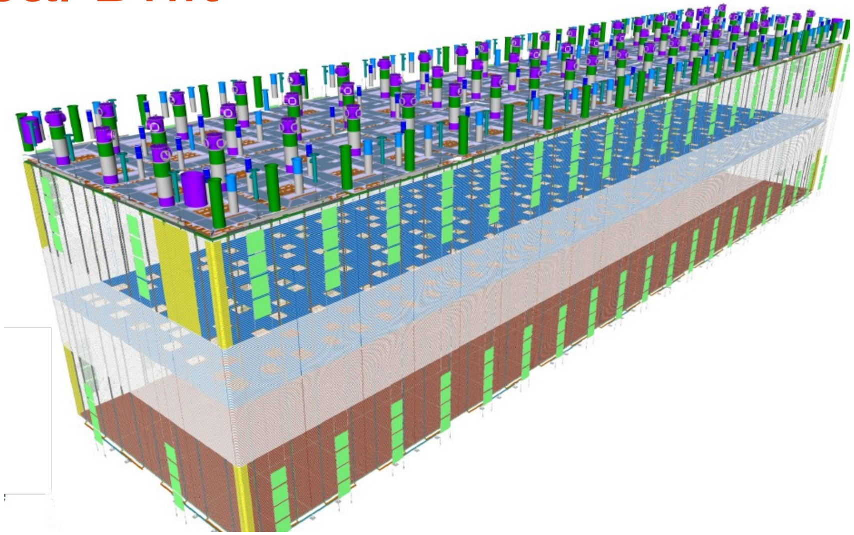
FD1



- Modular design
  - 500 V/cm horizontal-drift (HD) field
  - 3.5-meter drift length
- Wire plane charge read-out
  - 150 APAs (2560 channels/APA)
- Photodetectors (Arapuca) embedded in Anode Plane Assemblies

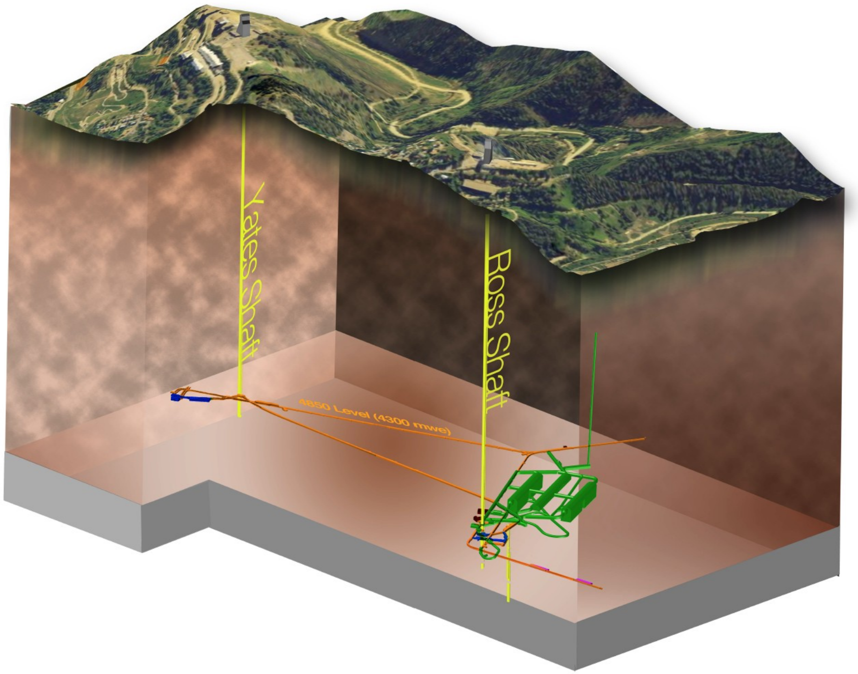
Vertical Drift

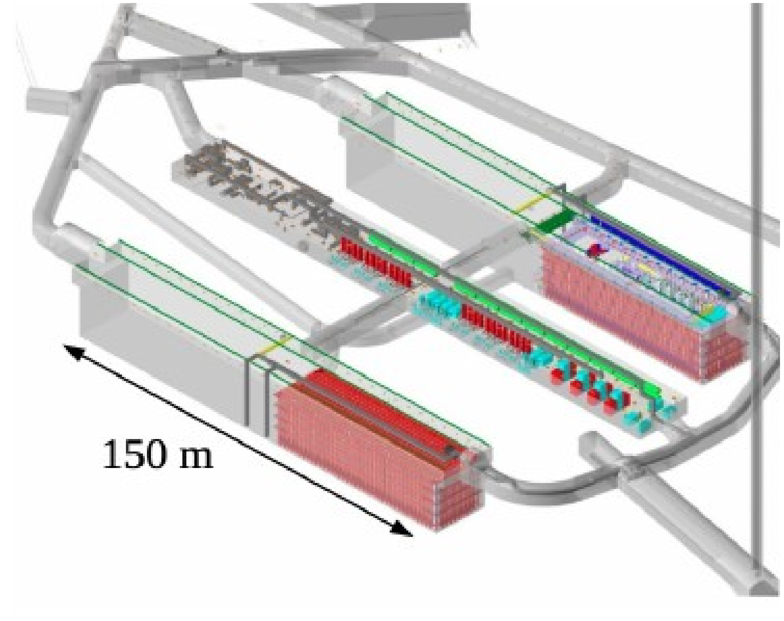
FD2



- Two volumes
  - 500 V/cm vertical-drift (VD) field
  - 6-meter drift length
- PCB charge read-out
  - 160 CRPs (3072 channels/CRP)
- Top electronics replaceable
- Xe-doping
- Photodetectors (Arapuca) embedded in Cathode and on membrane

Far detector at SURF

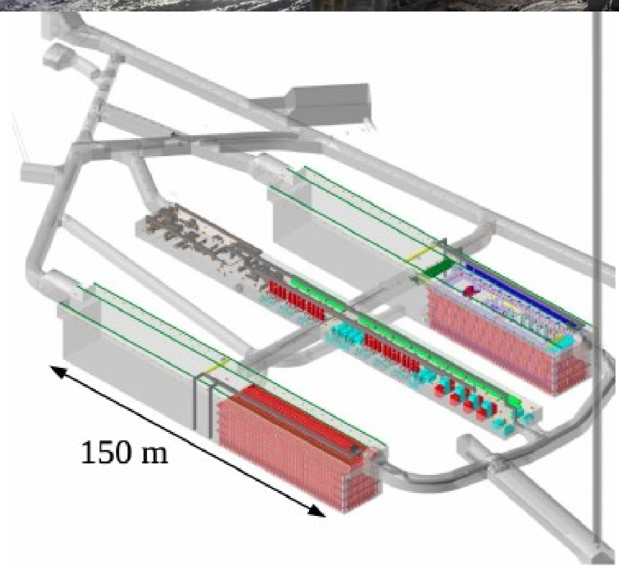




- Sanford Underground Research Facility in Lead, South Dakota
- Four 17-kt LAr TPC modules, located 1.48 km underground (4850 mwe)
- Excavation complete
- FD1 – Horizontal Drift LArTPC
- FD2 – Vertical Drift LArTPC

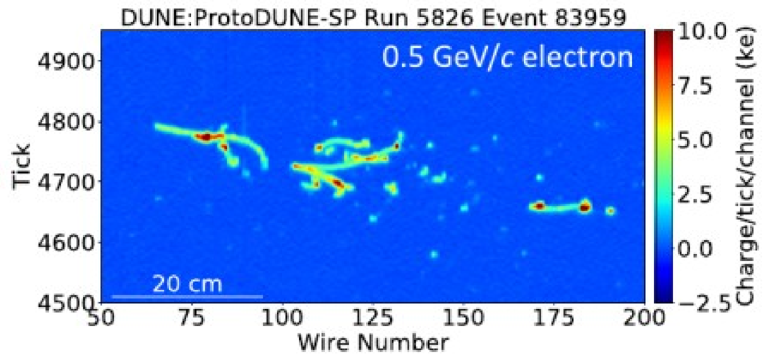
Phase-2
- FD3 (decision 2027)
- FD4 module of opportunity (decision 2028)

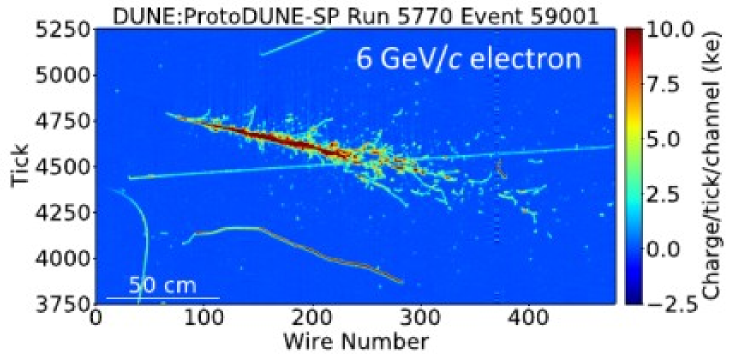
Far detector at SURF

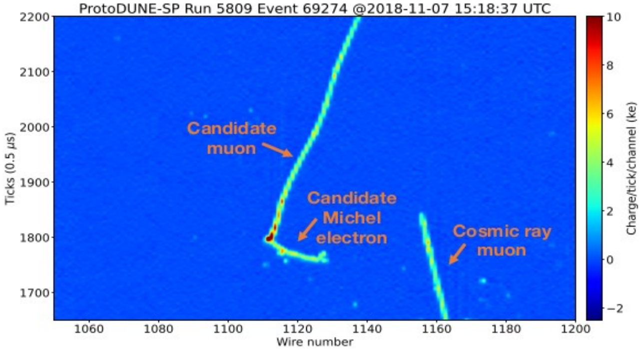


Summary

- DUNE's ambitious program based on high Performance TPCs
- decadal US Particle Physics Project Prioritization Panel (P5) - DUNE received strong endorsement of Phase 1 and 2
- Construction of the experiment underway
- At CERN neutrino platform
  - Testing of Vertical Drift in the cold-box continues
  - ProtoDUNEs (HD and VD) to run 2024
- R&D continues preparing for Phase 2
- Running FDs expected from 2028
- Beam and ND from 2031







Backups

A history of Single Phase LAr TPCs

ICARUS T-600 @ CNGS (2010-2012, 760 tons LAr)

Argoneut @ FNAL (2009-2010, 240 kg LAr)

MicroBooNE @ FNAL (2015-ongoing , 170 tons LAr)

taken from A. Chatterjee

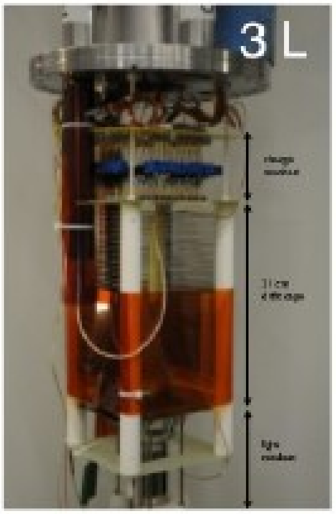
Successfully reconstructed neutrino events from CNGS beam (~17 GeV)

Small TPC, precise measurements of cross-sections and neutrino interactions

Sterile neutrino search. Neutrino event selection and reconstruction. Leads to protoDUNE Single Phase

A history of Dual Phase LAr TPCs

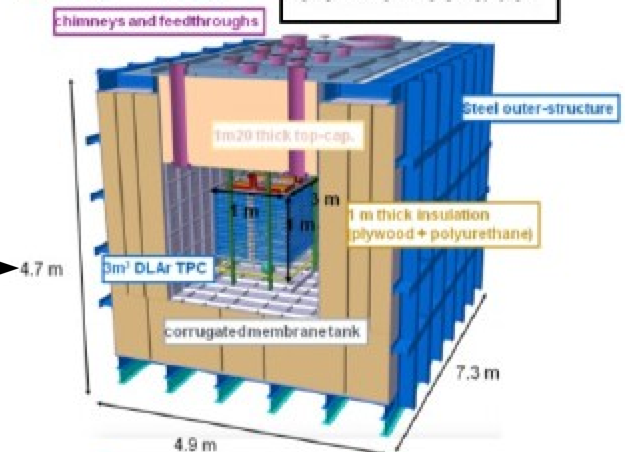
Small R&D TPCs



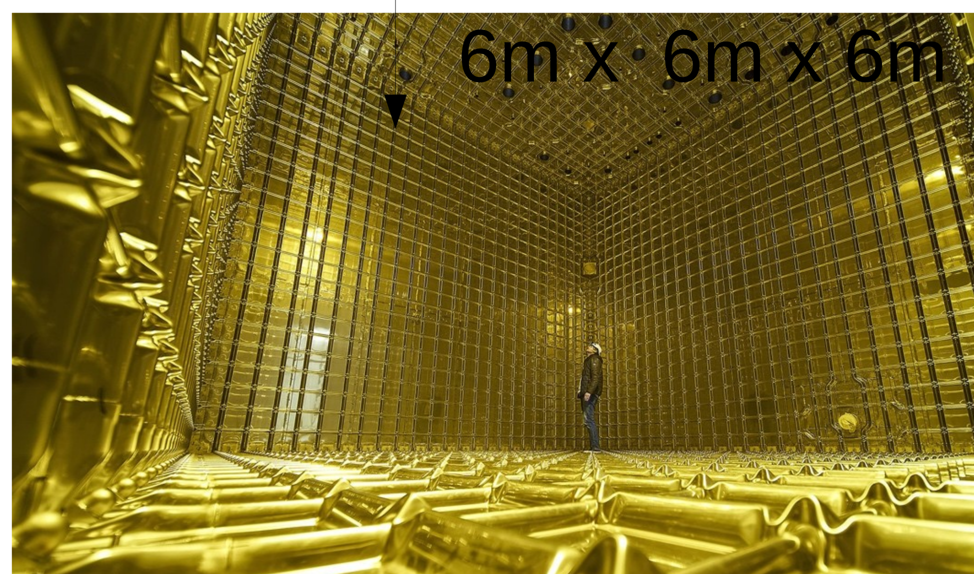
2007 ~ 2014

2014 ~ 2017

3x1x1 m^3 demonstrator



ProtoDUNE DP
6m x 6m x 6m

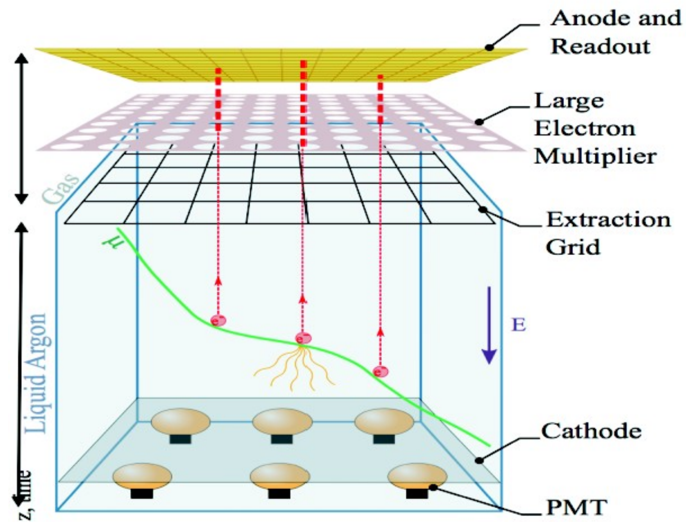


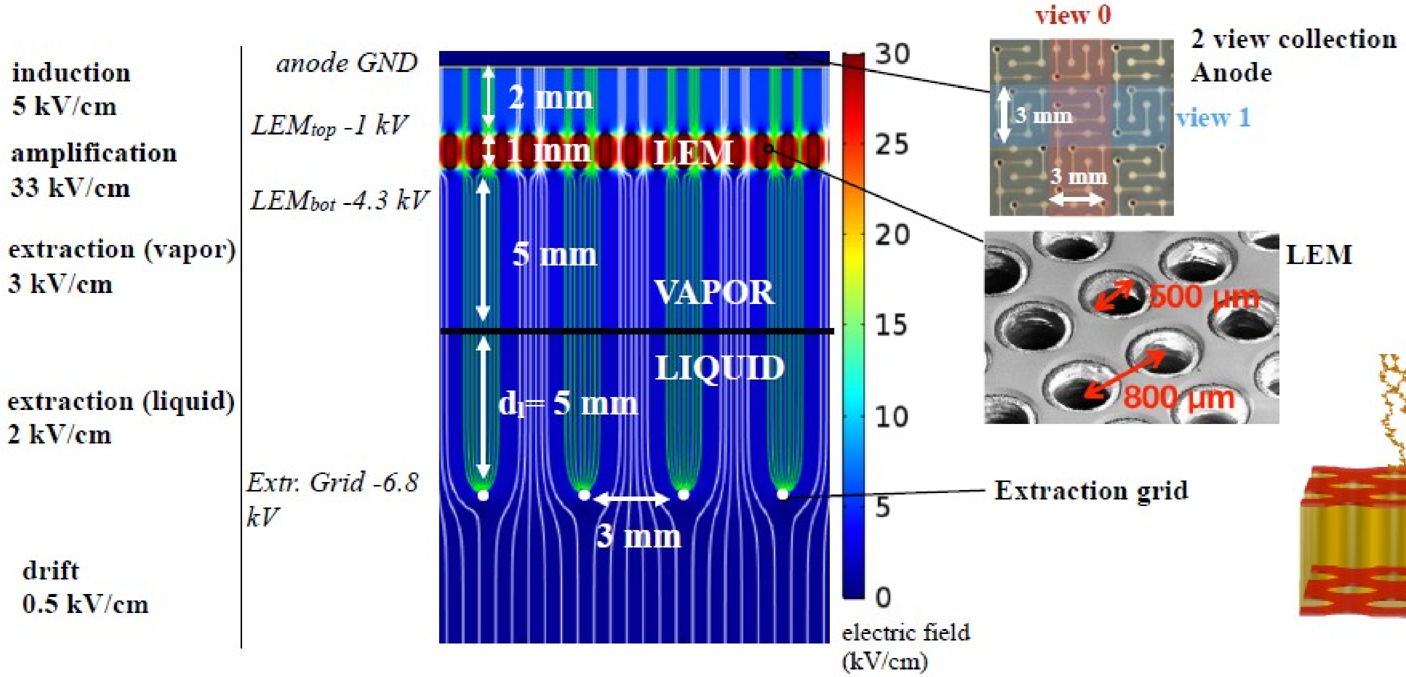
ProtoDUNE Dual Phase

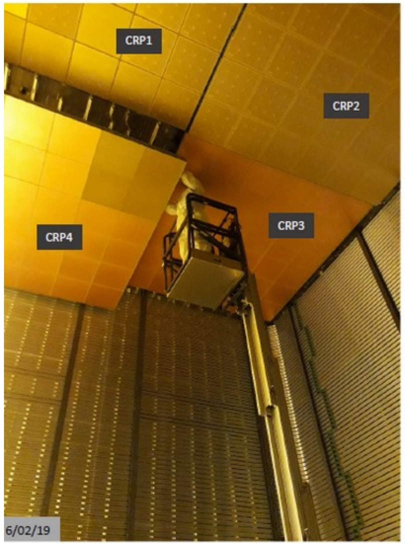
PCB-based Charge Read-Out in gas phase
LEM and Anode

Replaceable charge read-out electronics

Homogeneous
Large drift volume (6m) requires -300 kV on cathode





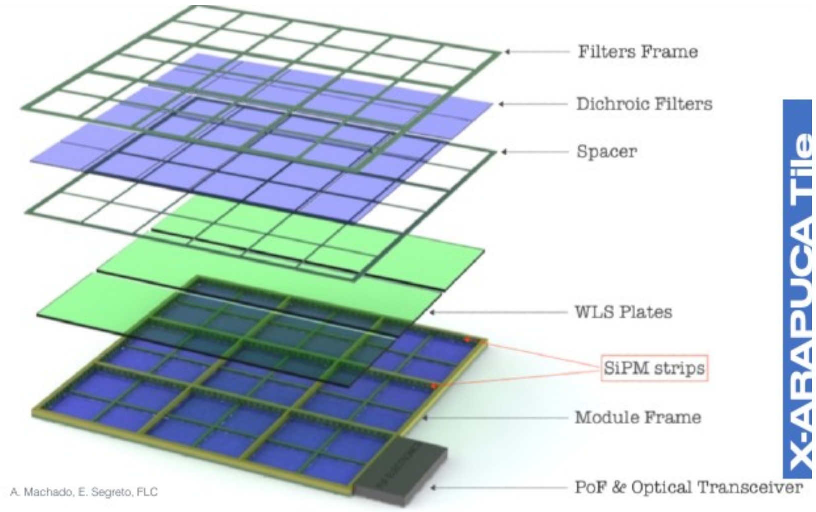


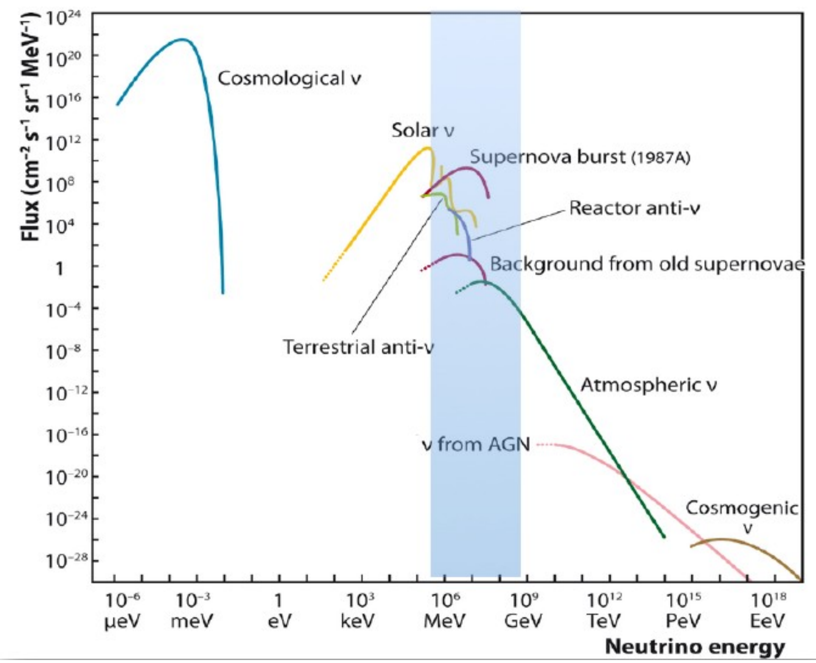
PhotoDetectors

Square Arapuca Tiles embedded in Cathode

Increase Light Output by Xe-doping

Lowers **SN** threshold and **solar** neutrinos





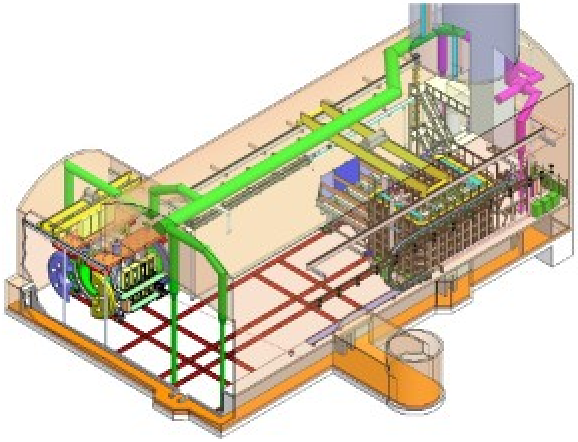
Schedule

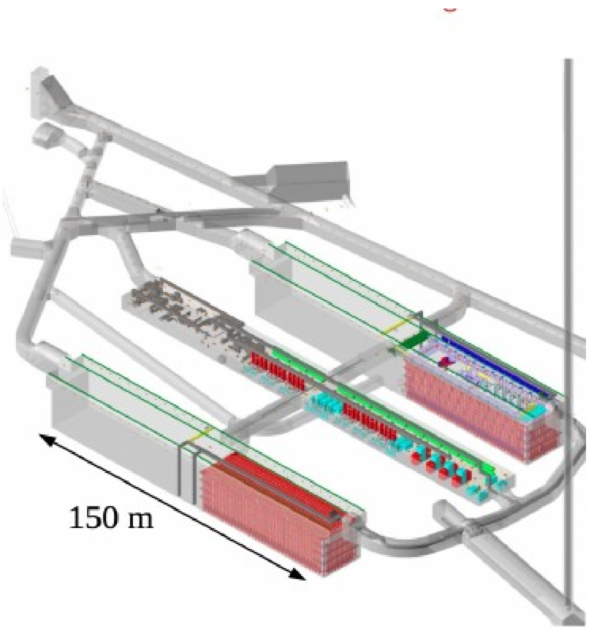
Phase 1

- Excavation complete 2024
- Far Detector
  - FD1 installation begins 2026
  - Running by 2028
  - FD2 installation begins 2029
- New neutrino beam 2031
- Near Detector System 2031
  - Moveable NDLAr + TMS
  - On-axis Near detector (SAND)

Phase 2

- Far Detector
  - +FD3 FD4
    - Increased physics scope
  - Neutrino beam upgrade (2.4 MW)
- Near Detector upgrade





Neutrino Oscillation

Pontecorvo – Maki – Nakagawa – Sakata (PMNS) matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- 3 mixing angles
- 1 CP phase

- Oscillation also governed by 2 mass splittings Δm^2_{ij}

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$\theta_{12} \sim 33^o$ $\theta_{13} \sim 9^o$ $\theta_{23} \sim 45^o$

Still to discover

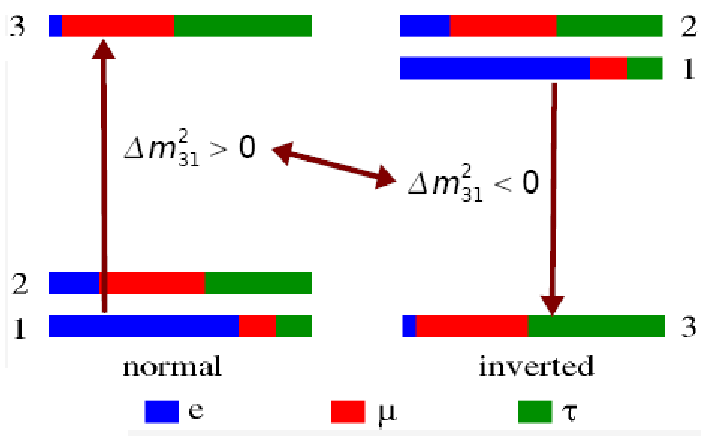
- Mass ordering (sign of Δm^2_{31})
- CP violation ($\delta_{cp} \neq 0$ or π)
- Octant θ_{23} ($\theta_{23}=45^o$?)

Precision measurements

Complete picture of neutrino oscillation

3 flavour mixing

PMNS unitarity



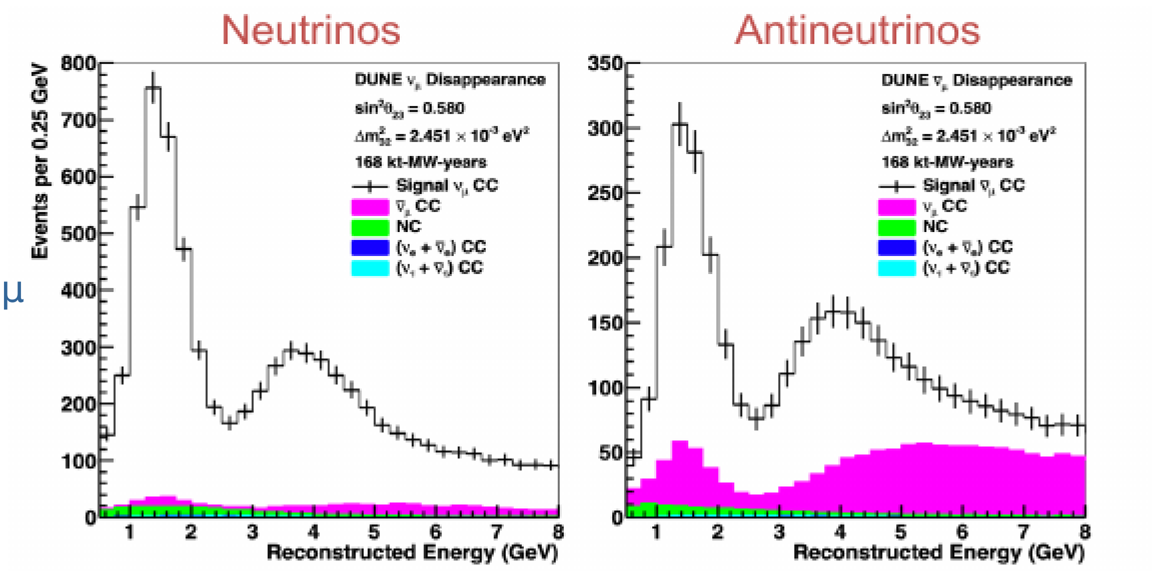
Neutrino Oscillations

~7 years running

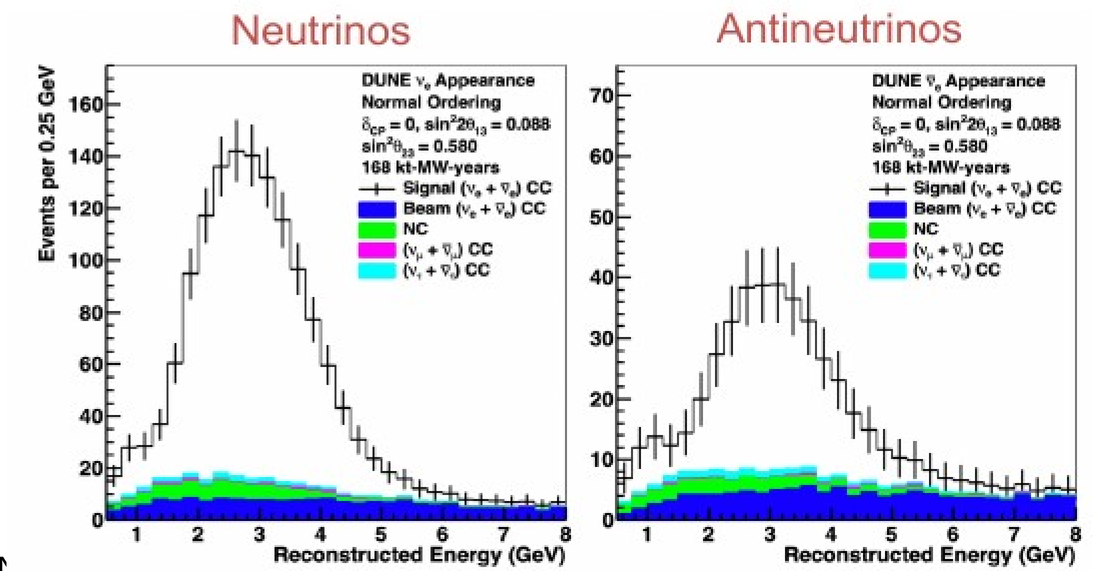
Measure appearance and disappearance for both neutrino and anti-neutrinos

Order of 10,000 ν_μ and 1,000 ν_e

ν_μ



ν_e



DUN

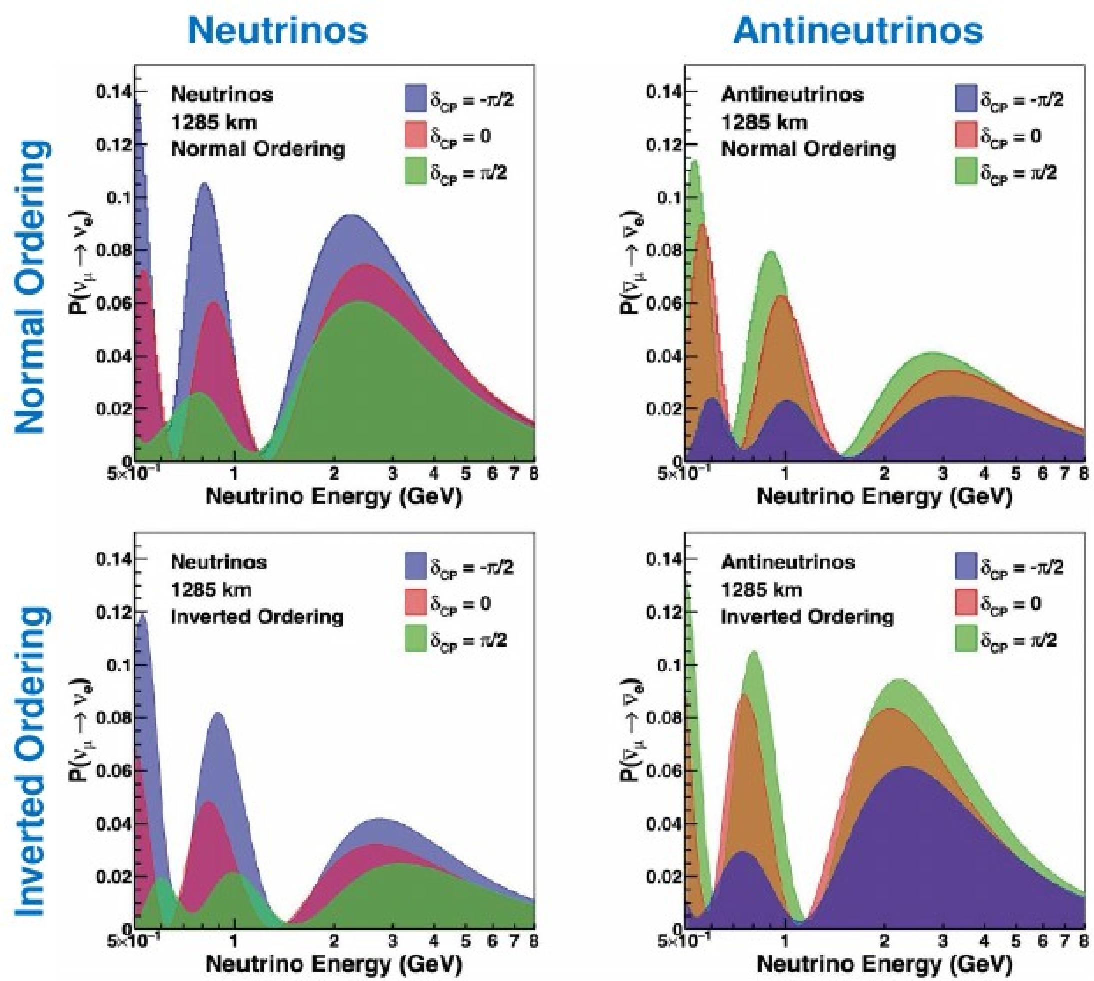
DUNE

Long baseline (completely disentangle mass ordering and CP violation)
High power beam and gigantic far detectors (more stats)

Make a spectral measurement
use a wide band beam
(neutrino/anti-neutrino mode)

Measurement range spans 2 oscillation peaks

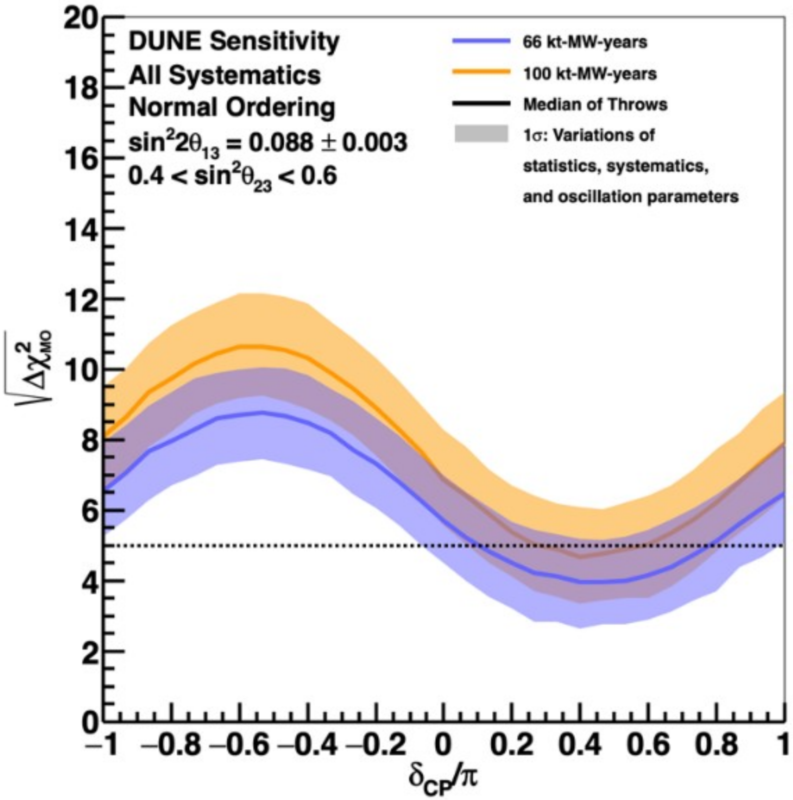
Gain additional power on deltaCP



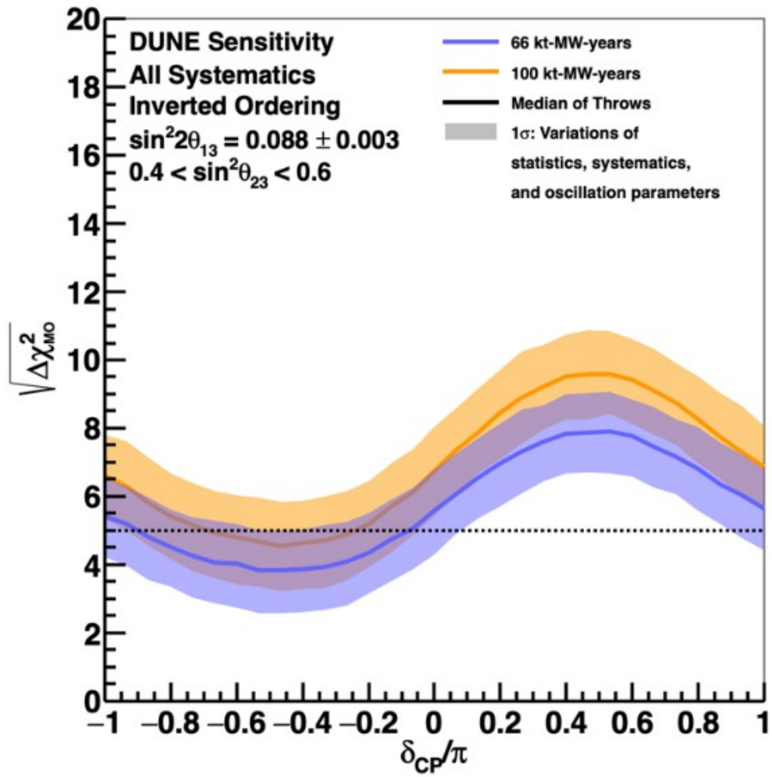
Sensitivity – Phase 1

Determine neutrino mass ordering at 3σ (5σ) with 66 (100) kt-MW-yr exposure

Normal ordering



Inverted ordering

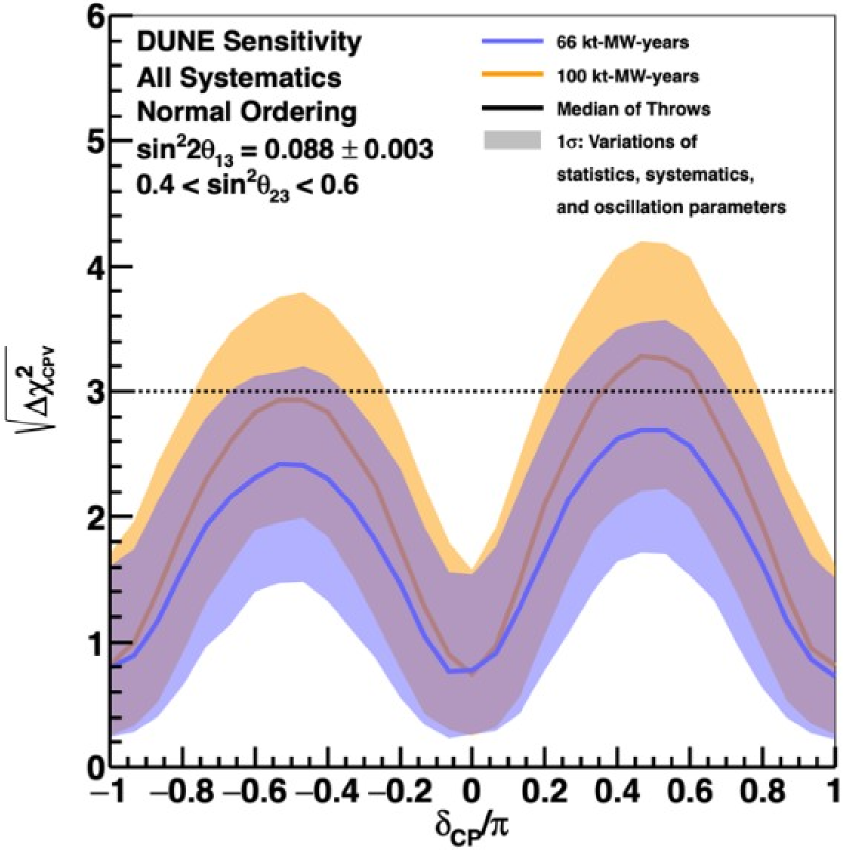


Phys. Rev D 105 (2022) 072006

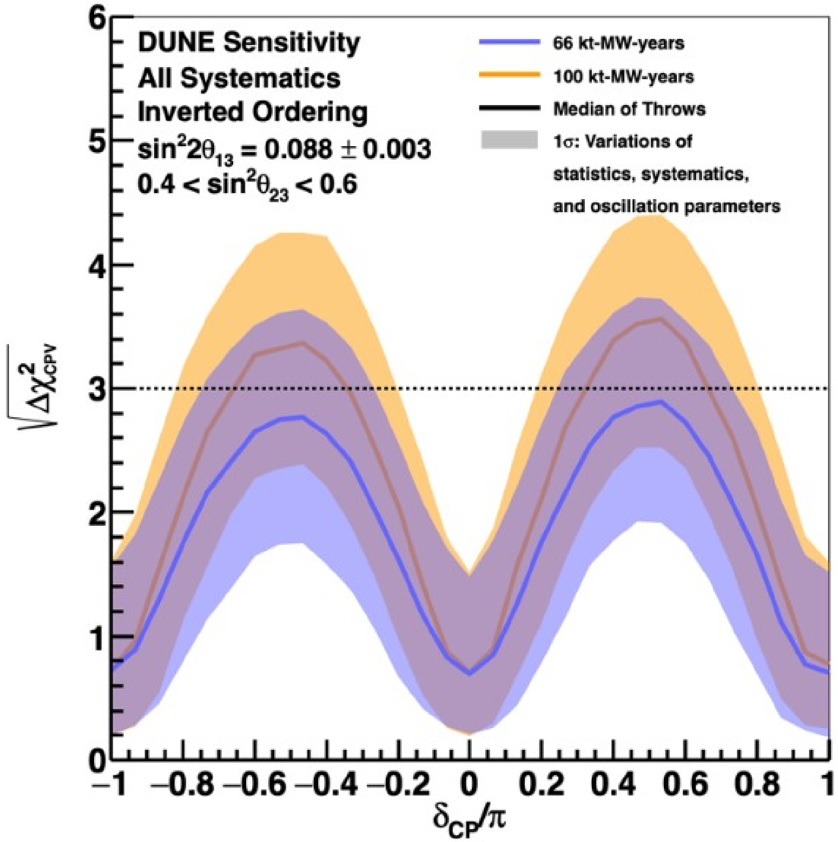
Sensitivity – Phase 1

δ_{CP} = ±90°, CPV at 3σ

Normal ordering



Inverted ordering



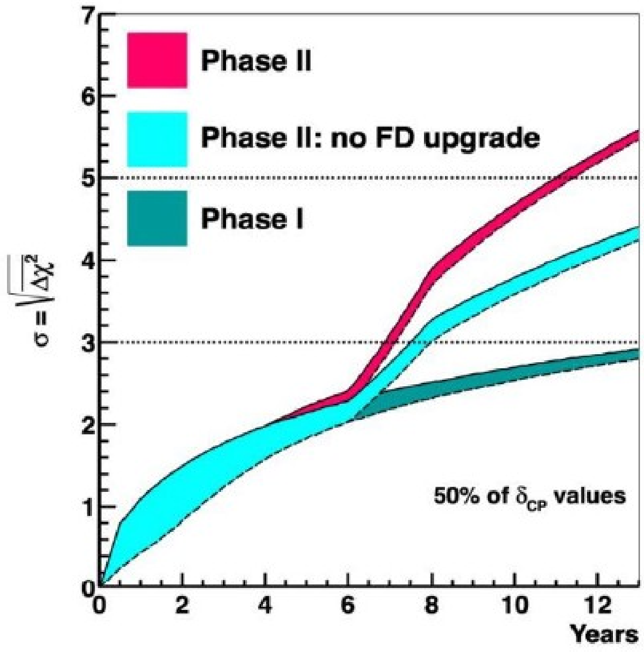
Phys. Rev D 105 (2022) 072006

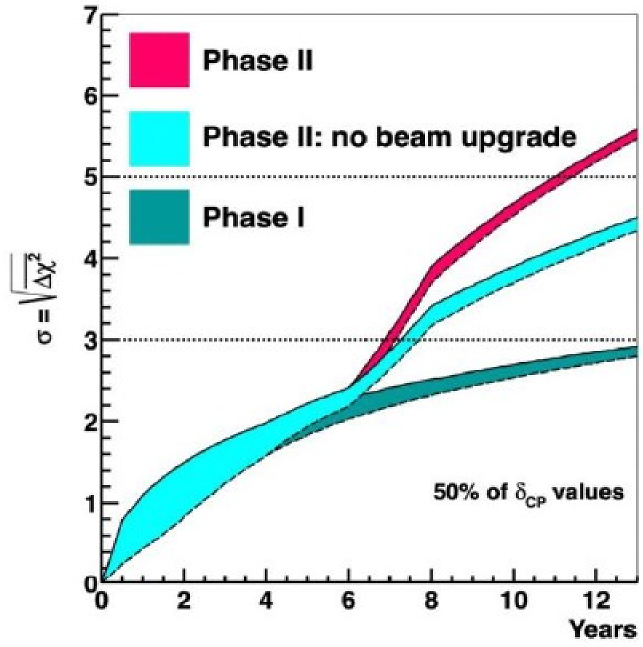
Sensitivity – Phase 2

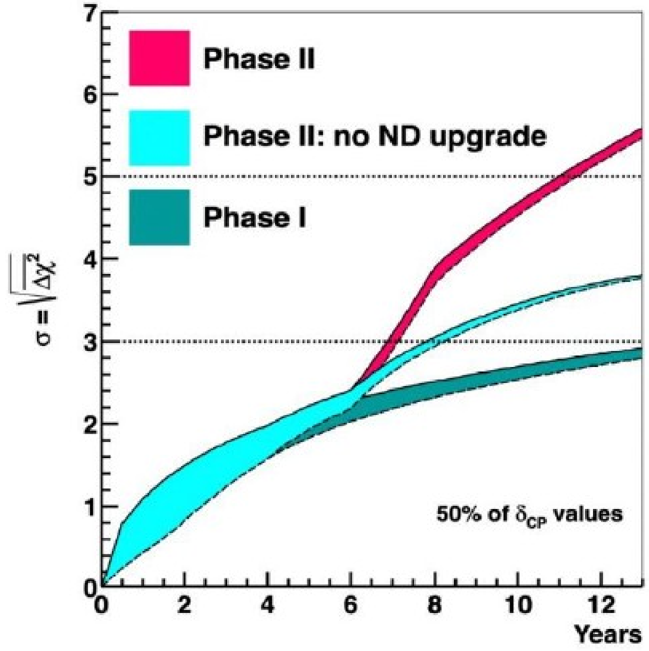
- 4 FD
- ND upgrade
- 2.4 MW beam

If $\delta_{CP} = \pm 90°$, 5σ in 7 years

For 50% of δ_{CP} values 5σ CPV in 12 years

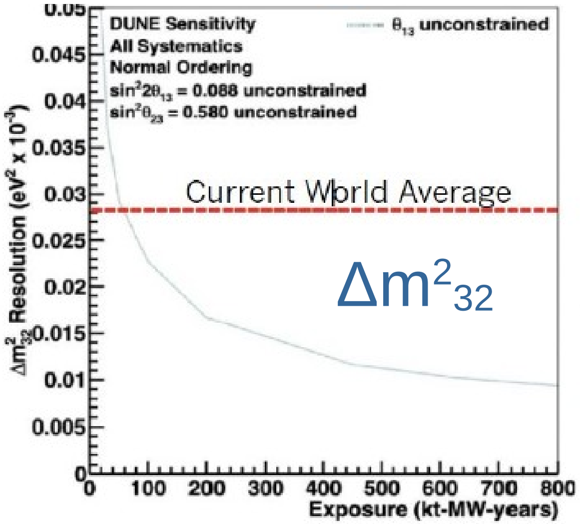


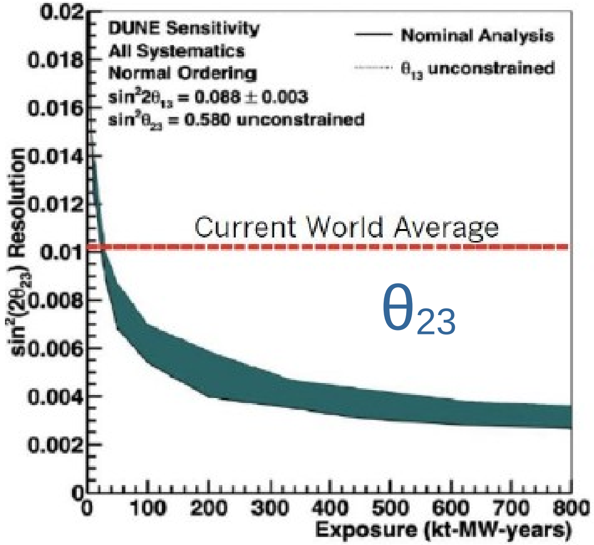




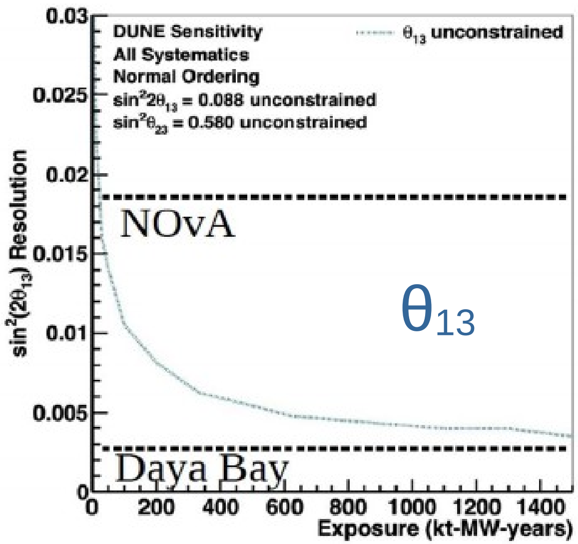
Phys. Rev D 105 (2022) 072006

Precision Measurements

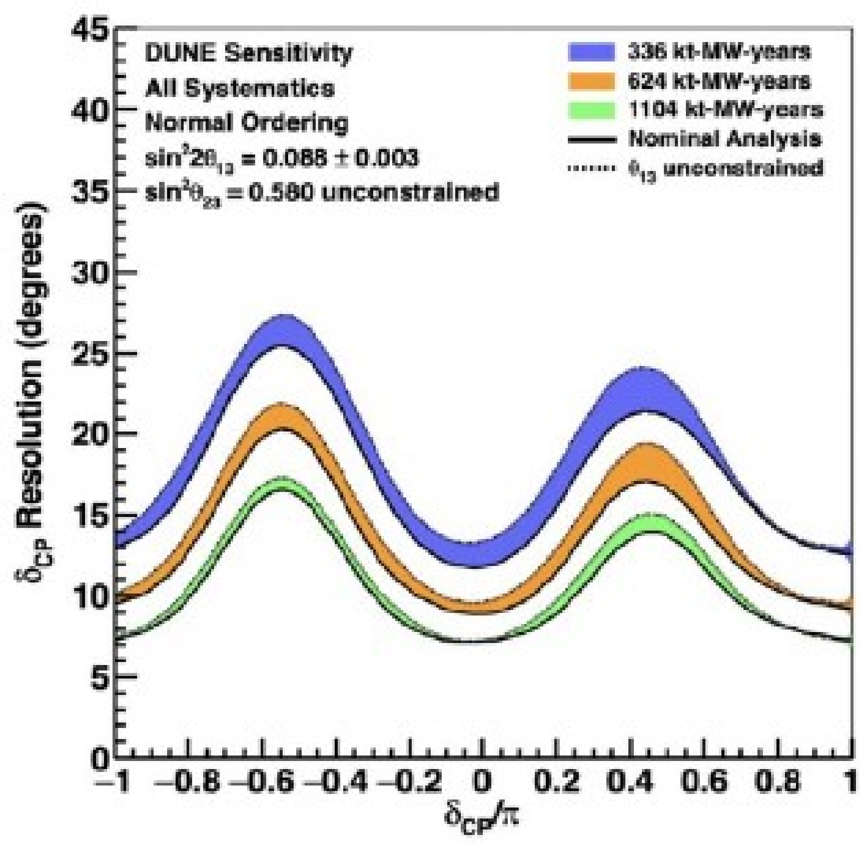




Oscillation parameters:
Δm^2_{32}, δ_{CP}, θ_{23}, θ_{13}



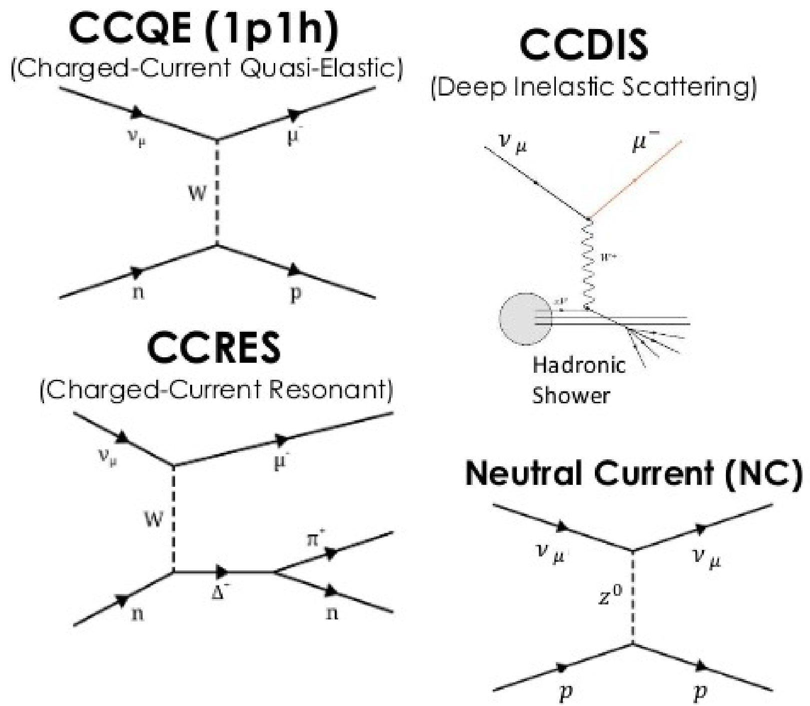
Precision Measurements



Precision δ_{CP} : 6 – 16°

Neutrino Signal

Neutrino interactions can be quite complex (multiple products and showers)

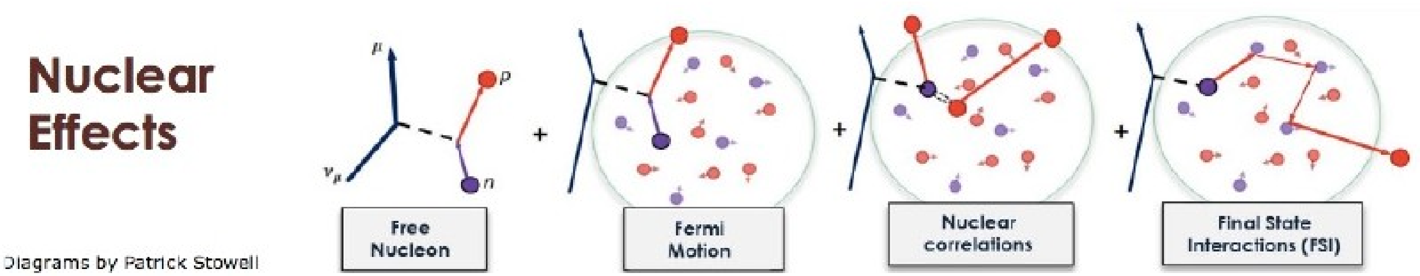


Neutrino flavour determined by outgoing lepton

Neutrino Energy Reconstruction dependent on Interaction Model

Not all products may be visible (neutrons)

Need highly performing Near and Far detectors!



Off-beam program

Astrophysical Neutrinos
Galactic supernova
Solar

Atmospheric Neutrinos

BSM physics (at Near and Far)

Deviations from 3-flavour oscillation (sterile ν, NSI, PMNS non-unitarity, CPT violation etc)

Other new physics: Neutrino trident rate, dark matter, baryon number violation

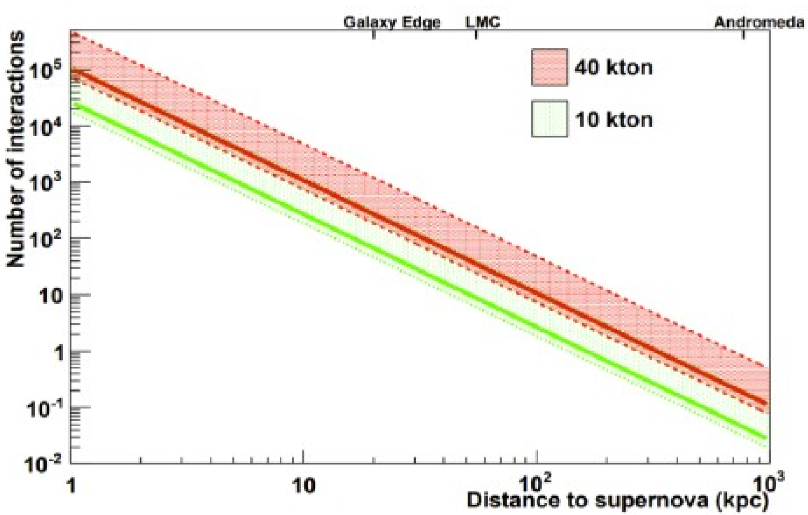
and more !

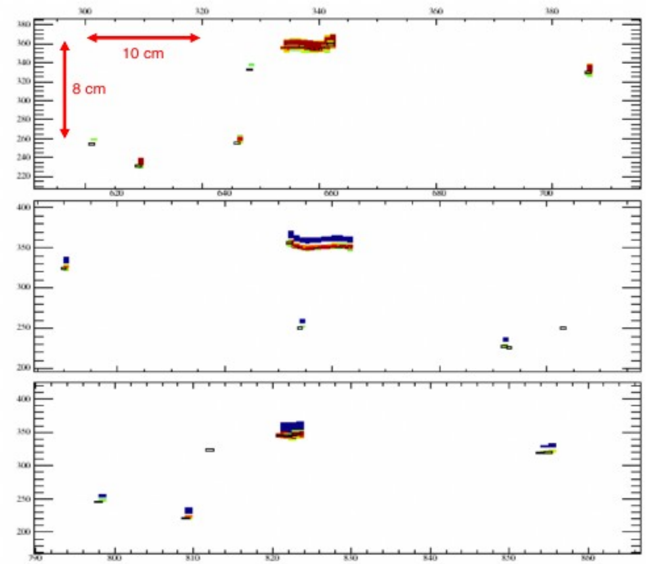
Galactic SuperNova

Uniquely DUNE is sensitive to ν_e

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

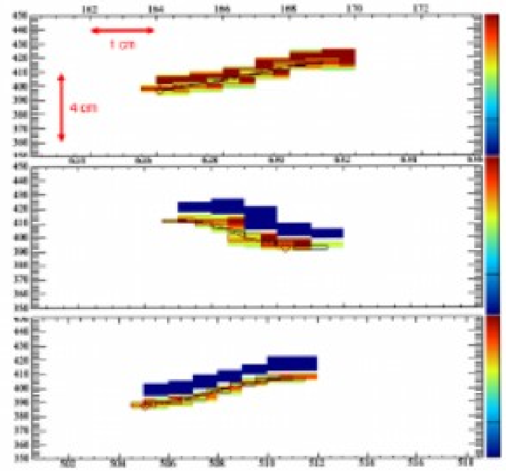
Also elastic-scattering
5-50 MeV signals





20.25 MeV νeCC

10 MeV electron
(Simulation+Reconstruction)



10.25 MeV νES

2008.06647

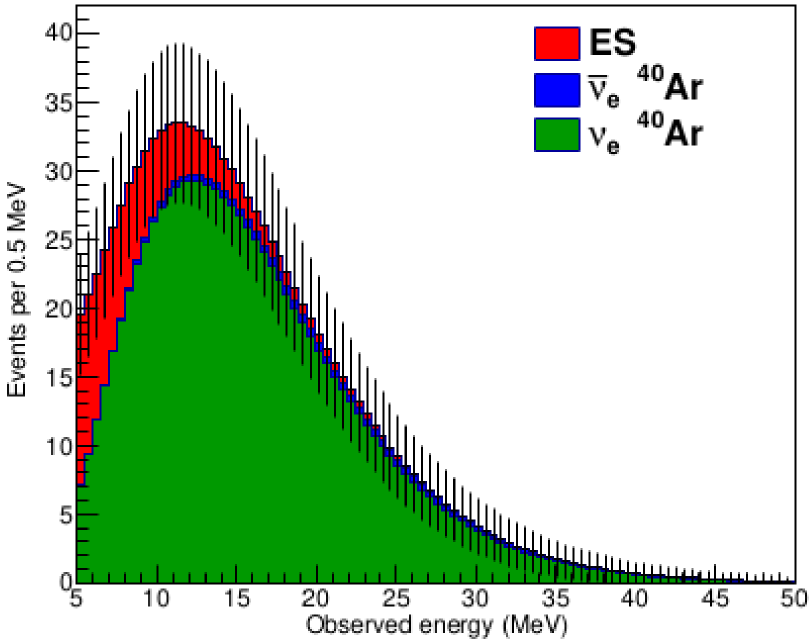
Galactic SuperNova

SN trigger – (Light and Charge signals)
Continuous data-taking, all waveforms stored for 100s (with 10s pre-trigger)

Light signal provides:

- SN signal arrival times
  - Global triangulation (SuperNova Early Warning System)
- Position in drift direction needed to correct of electron drift loss (Energy estimate)

ES short tracks – forward scattering allows direction estimate

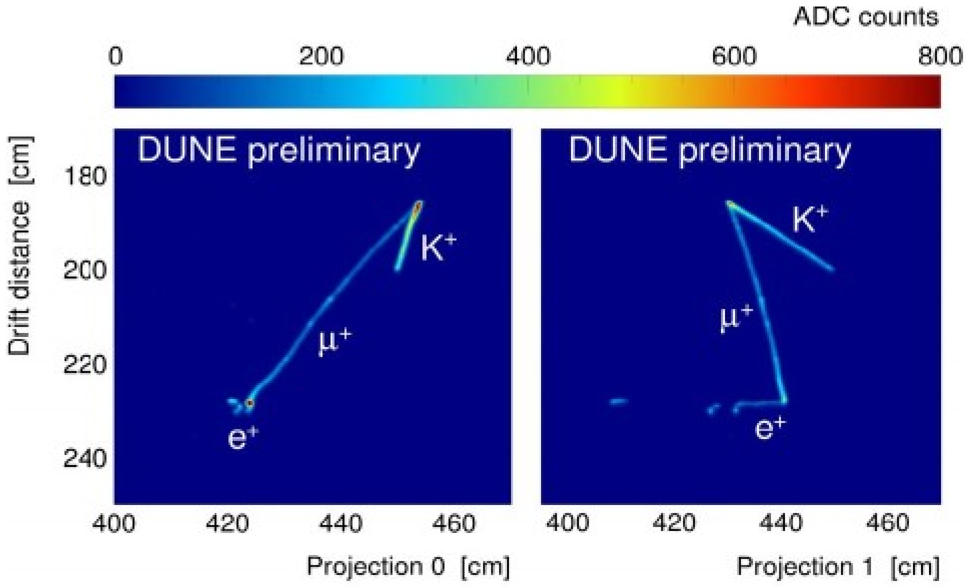


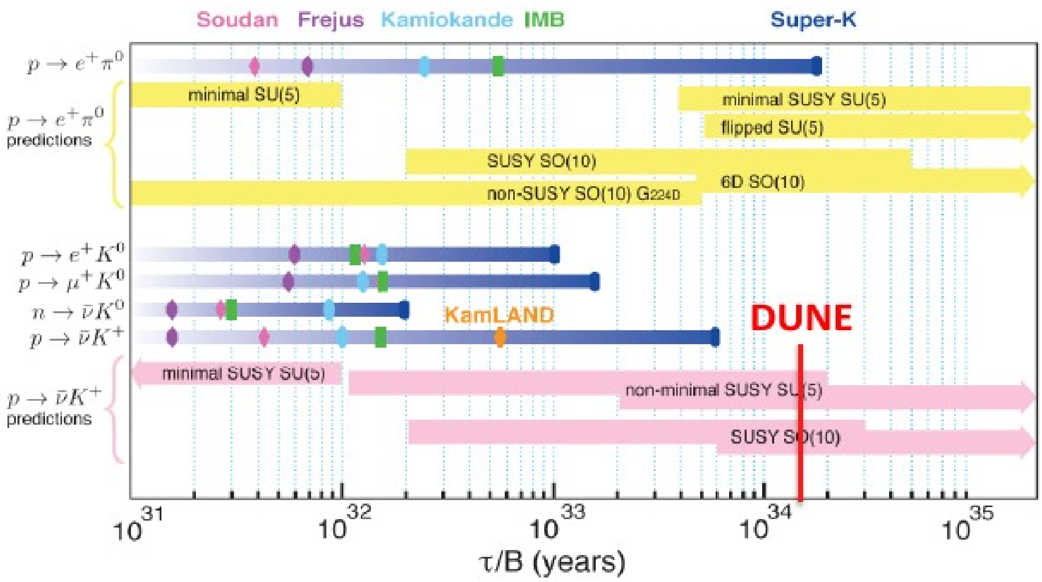
'Garching' model SN as seen by 40 ktons DUNE (inc detector response)

2008.06647

Nucleon decay

- DUNE sensitive to:
  - $p \rightarrow K^+ \nu$
- and other channels:
  - $n \rightarrow K^+ e^-$
  - $p \rightarrow l^+ K^0$
  - $p \rightarrow \pi^0 e^+$





Assuming no signal in 10 years, FV of 40 ktons and 30% signal efficiency
1.3×10^{34} years (90% C.L.)