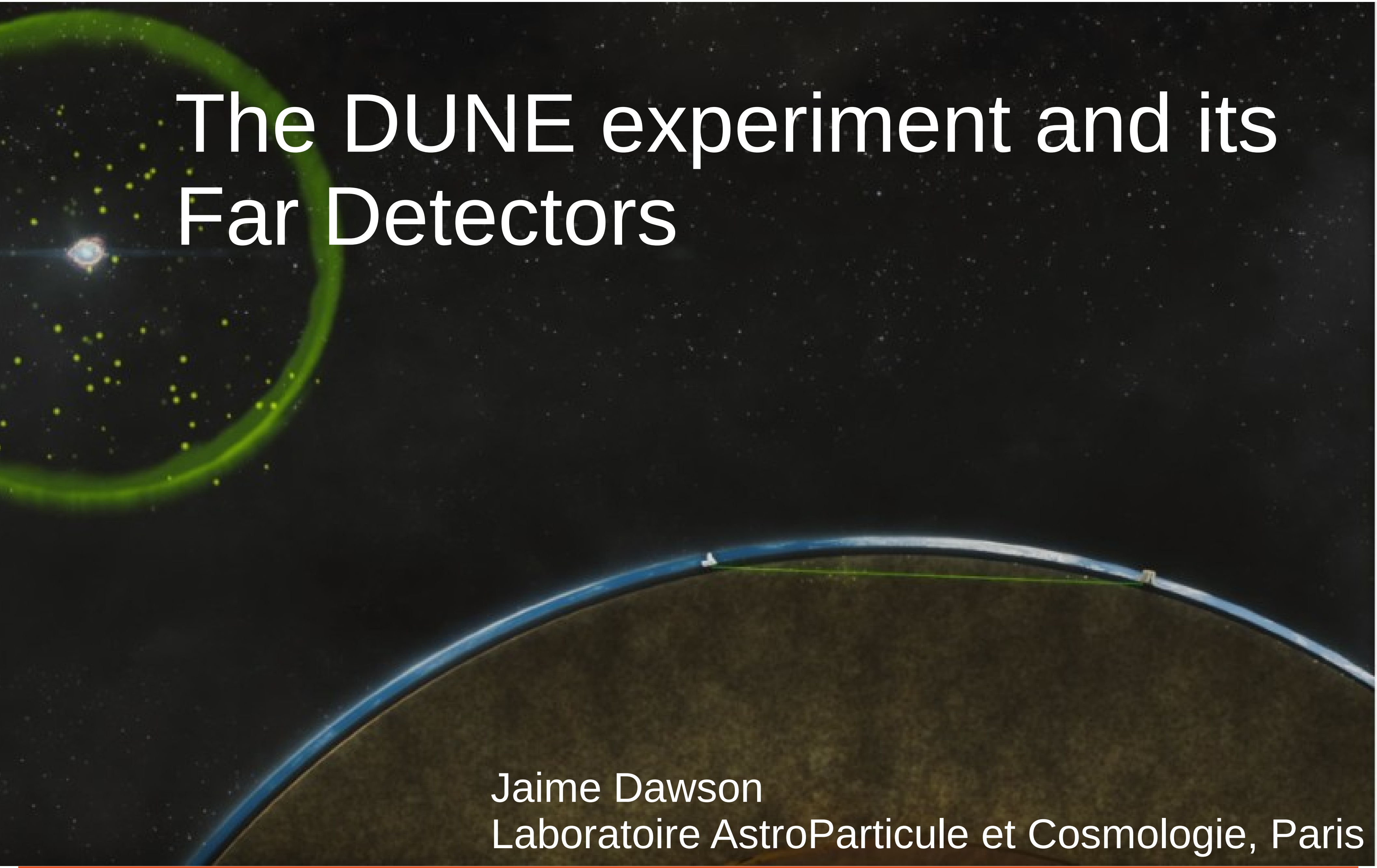

The DUNE experiment and its Far Detectors

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Contents

Illustration by Sandbox Studio/Symmetry Magazine

Neutrino Oscillation

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

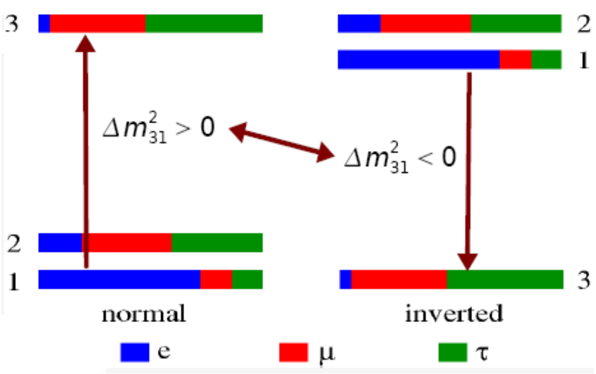
Pontecorvo – Maki – Nakagawa – Sakata (PMNS) matrix

- 3 mixing angles
- 1 CP phase

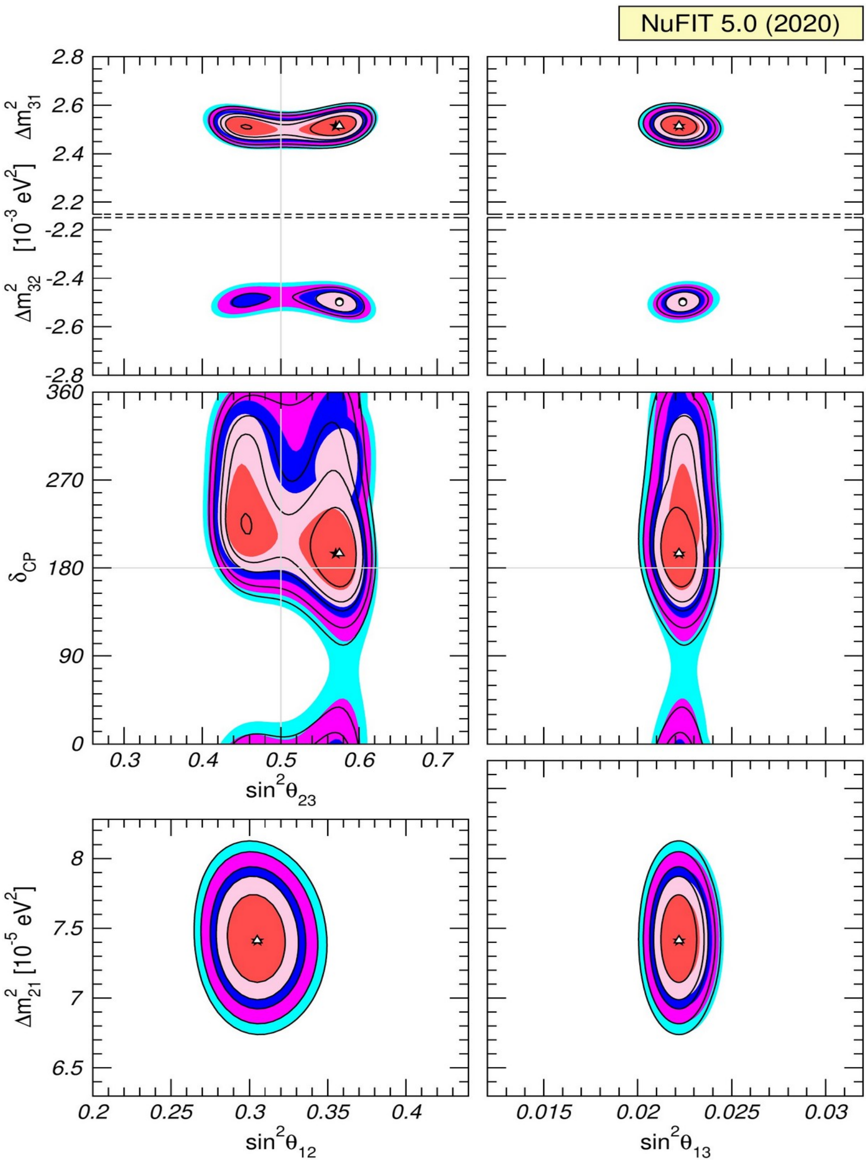
$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 &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

solar atmospheric

- 2 mass splittings Δm^2_{ij}
- θ_{13} → δ_{cp} and sign of Δm^2_{31}



Global Fits



		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

JHEP 09 (2020) 178 [arXiv:2007.14792]   NuFIT 5.0 (2020), www.nu-fit.org.

$$|U_{\mathrm{PMNS}}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.5 & 0.6 & 0.7 \\ 0.3 & 0.6 & 0.7 \end{pmatrix}$$

Long Baseline Experiments

Beam of ν_μ
or $\bar{\nu}_\mu$

hundreds of km through
the Earth

Detect ν_μ ($\bar{\nu}_\mu$)
ν_e ($\bar{\nu}_e$)
and if you can
ν_τ ($\bar{\nu}_\tau$)

ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

$$+ \; 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$$- \; 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \Delta = \frac{\Delta m^2_{31} L}{4E} \qquad A = +G_f N_e \frac{L}{\sqrt{2}\Delta}$$

- ν_e appearance: mass hierarchy, δ_{CP} and octant of θ_{23}
- ν_μ disappearance: high precision $|\Delta m_{32}|$ and $\sin^2 2\theta_{23}$, constrain octant

From T. Patzak

Long Baseline Experiments

Beam of ν_μ
or $\bar{\nu}_\mu$

hundreds of km through the Earth

Detect ν_μ ($\bar{\nu}_\mu$)
ν_e ($\bar{\nu}_e$)
and if you can
ν_τ ($\bar{\nu}_\tau$)

Compare oscillation probabilities P($\nu_\mu \rightarrow \nu_e$) to P($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)

They are not the same due to:

1) δCP $\neq$0 or π (CP violation!!)
2) asymmetry due to matter effects (the Earth is made of matter)

- ν_e appearance: mass hierarchy, δ_{CP} and octant of θ_{23}
- ν_μ disappearance: high precision $|\Delta m_{32}|$ and $\sin^2 2\theta_{23}$, constrain octant

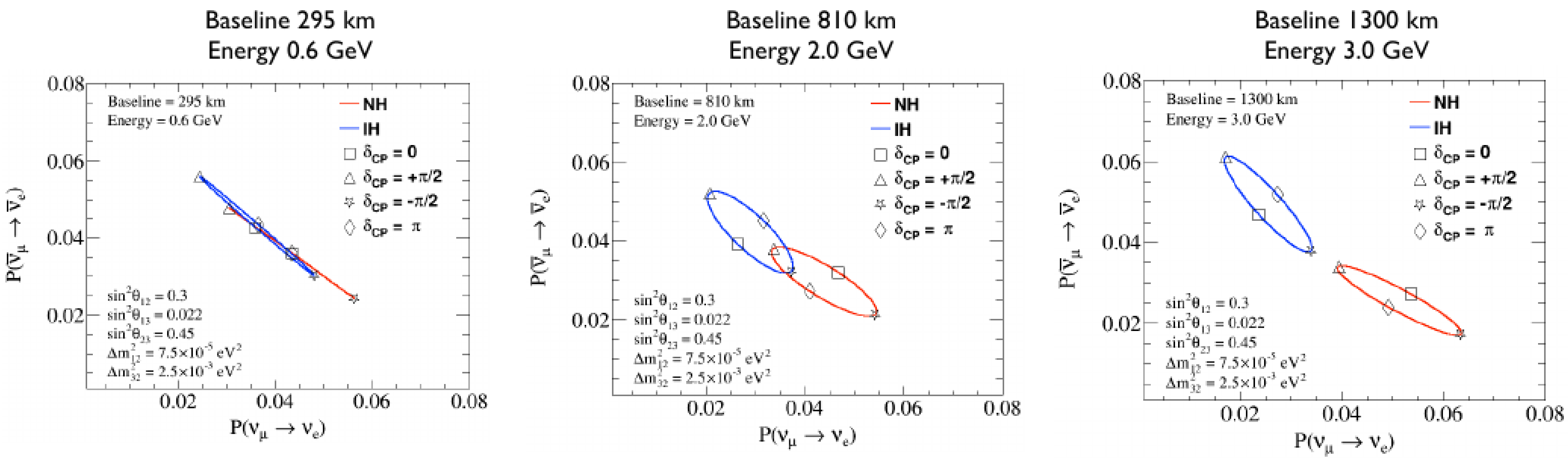
Long Baseline Experiments

Beam of ν_μ
or $\bar{\nu}_\mu$

hundreds of km through the Earth

Detect ν_μ ($\bar{\nu}_\mu$)
ν_e ($\bar{\nu}_e$)
and if you can
ν_τ ($\bar{\nu}_\tau$)

If the baseline is long enough, the matter effect dominates, and δCP and neutrino mass ordering disentangle.

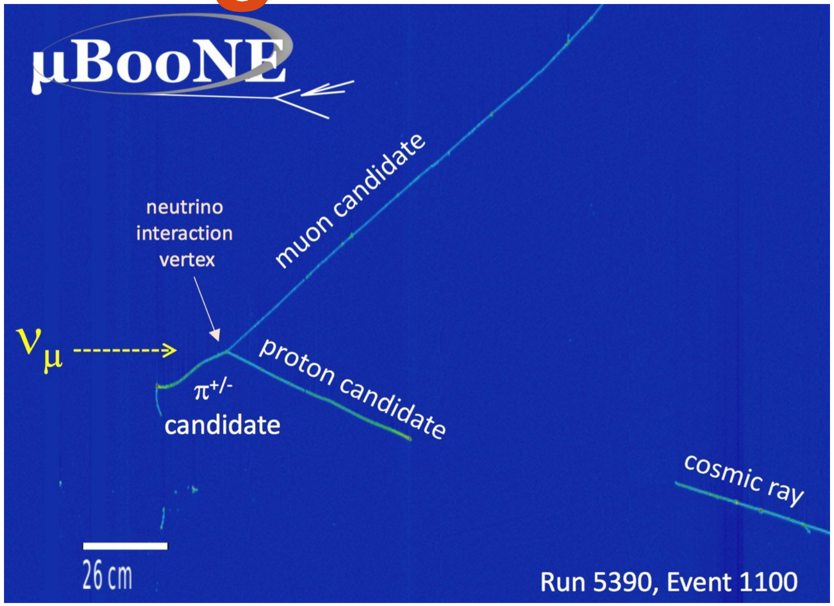


Long Baseline Experiments – Neutrino Signal

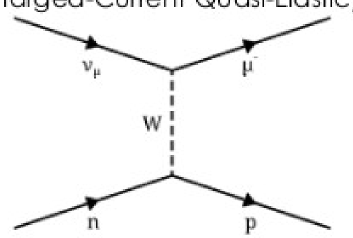
Real ν_μ as seen by µBooNE

Neutrino flavour determined by outgoing lepton

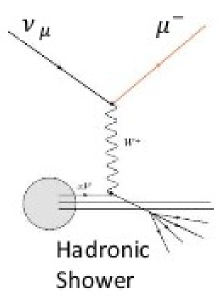
Depending on neutrino energy, interactions can be quite complex (multiple products and showers)



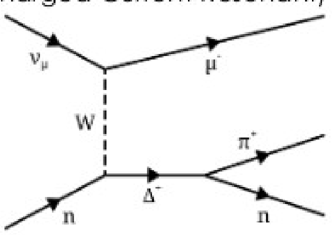
CCQE (1p1h)
(Charged-Current Quasi-Elastic)



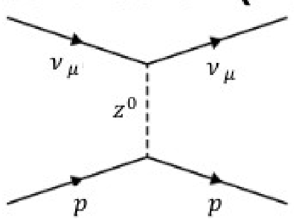
CCDIS
(Deep Inelastic Scattering)



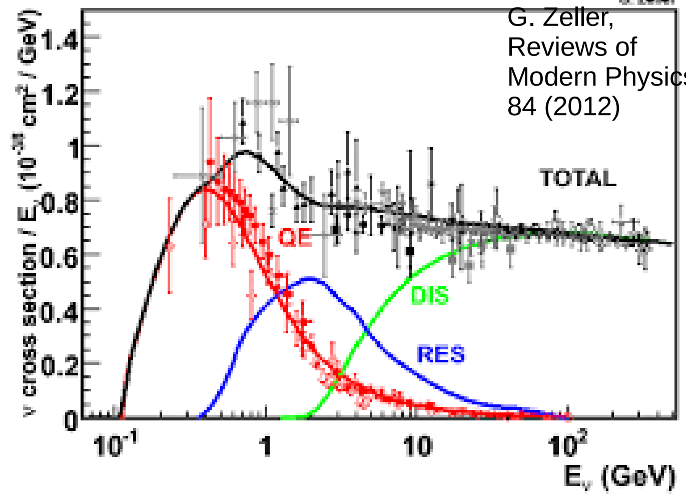
CCRES
(Charged-Current Resonant)



Neutral Current (NC)

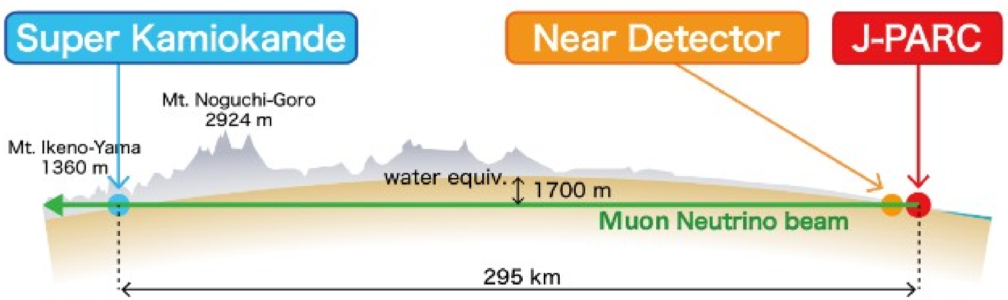


J. A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

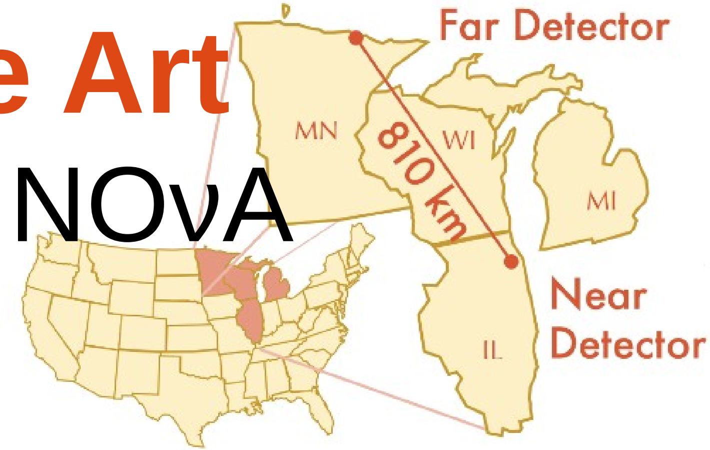


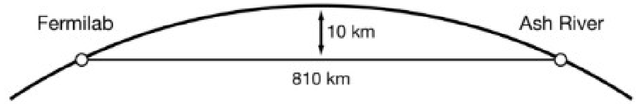
Long Baseline Experiments – State of the Art

T2K



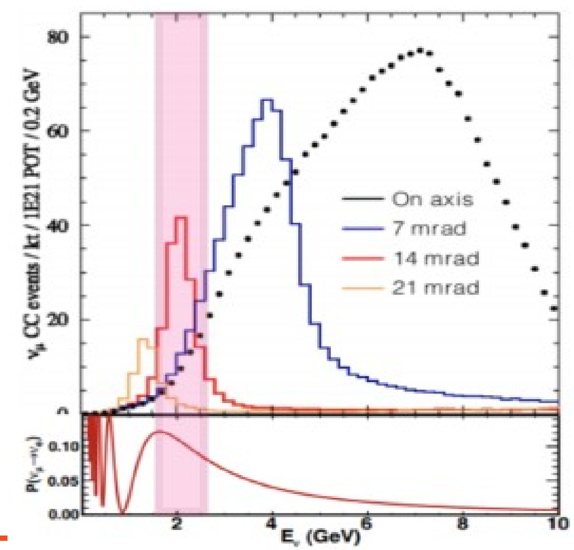
NOνA





- T2K Far Detector is Water Cherenkov (SuperK 50 ktons)
- Baseline is 295 km
- Both have narrow-band beams (off-axis) peaked at 0.6 GeV (T2K) and 1.9 GeV (NOVA)
- Most events are CCQE

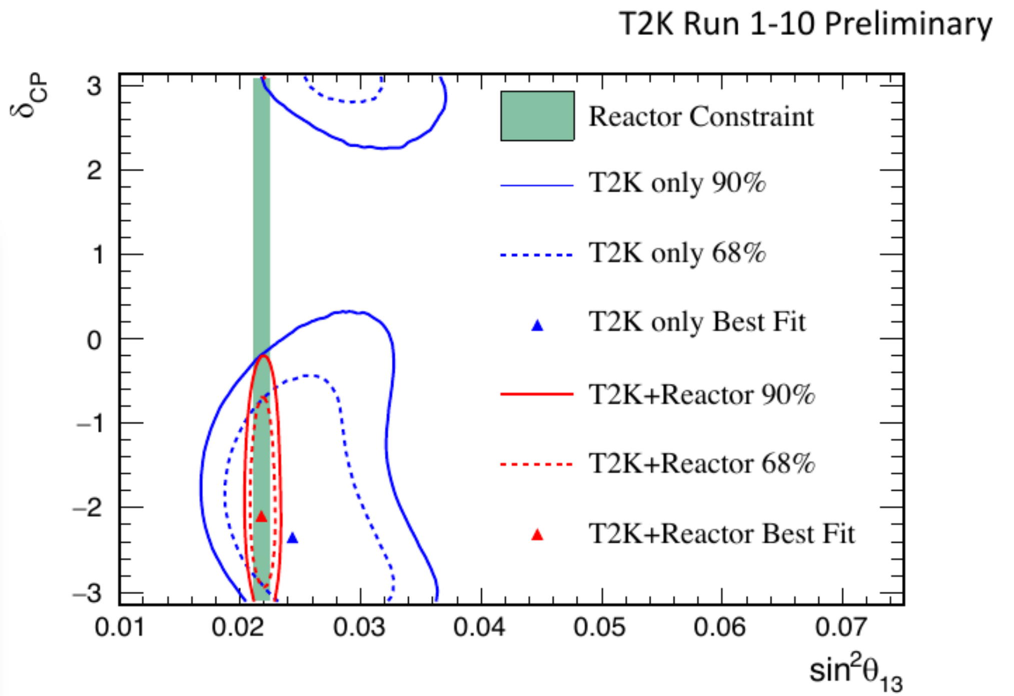
- NOVA has functionally identical Near and Far detectors (finely grained liquid scintillator; 14kton far)
- Baseline is 810km
- Higher neutrino energy
  - DIS occurs



Long Baseline Experiments – State of the Art

T2K

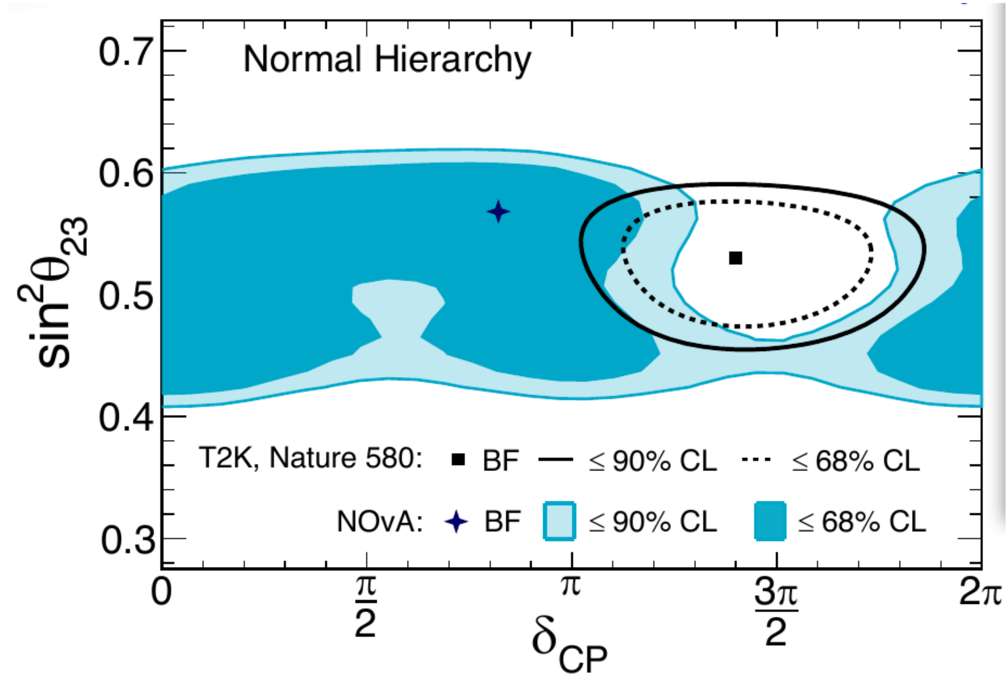
- Preference for Normal Ordering



P. Dunne Neutrino2020 -
https://zenodo.org/record/4154355#.YHA6zxKxVH4

NOνA

- Also prefers Normal Ordering
- Clear tension with T2K on deltaCP!

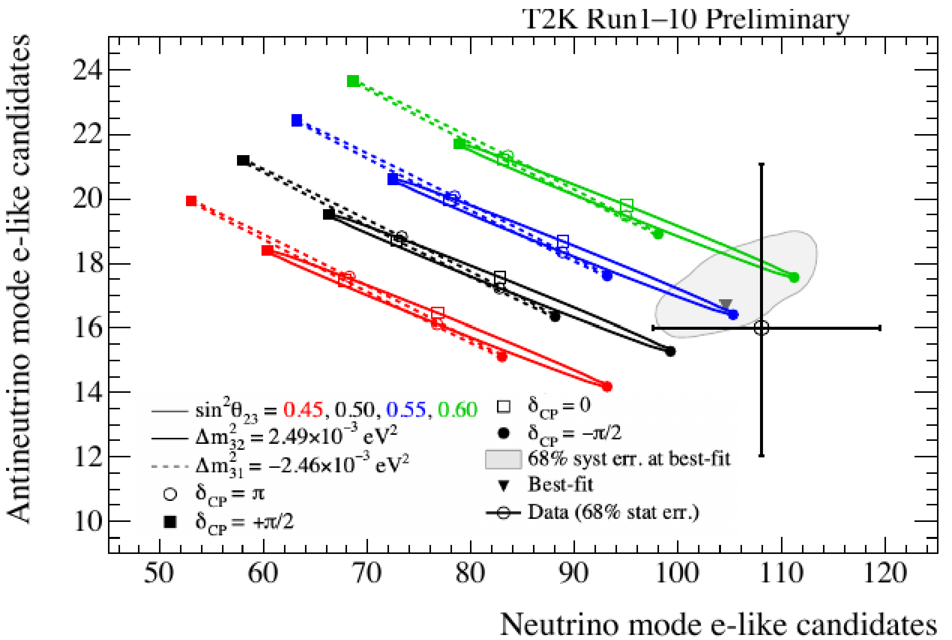


A. Himmel Neutrino2020

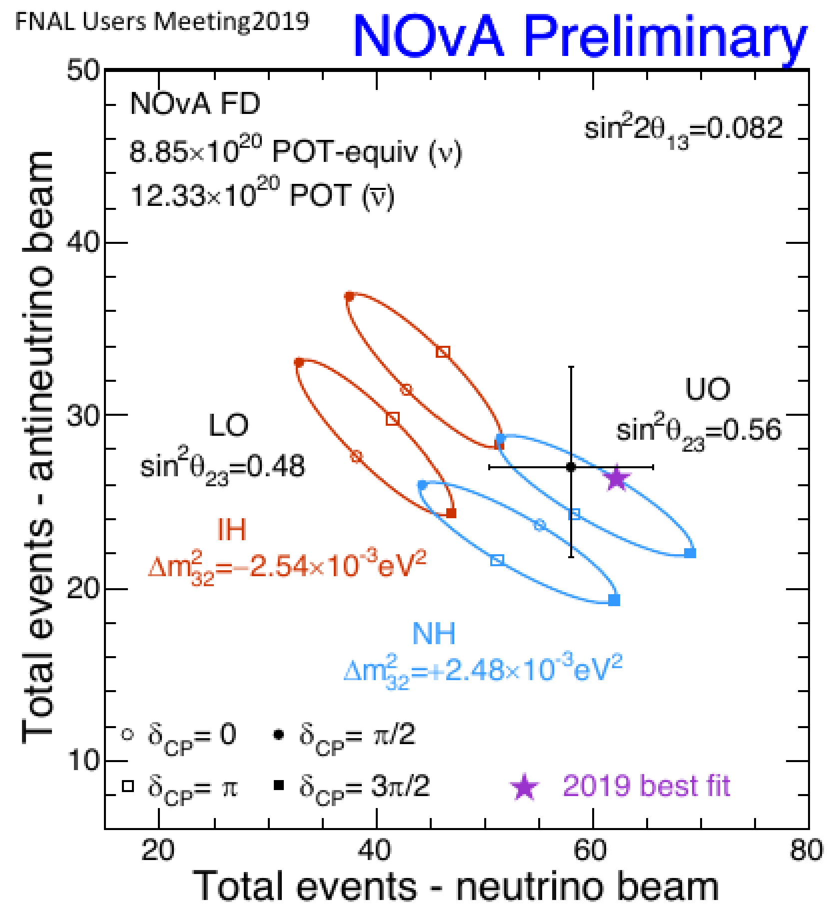
Collaborations are working towards a joint analysis

Long Baseline Experiments – State of the Art

T2K



NOνA

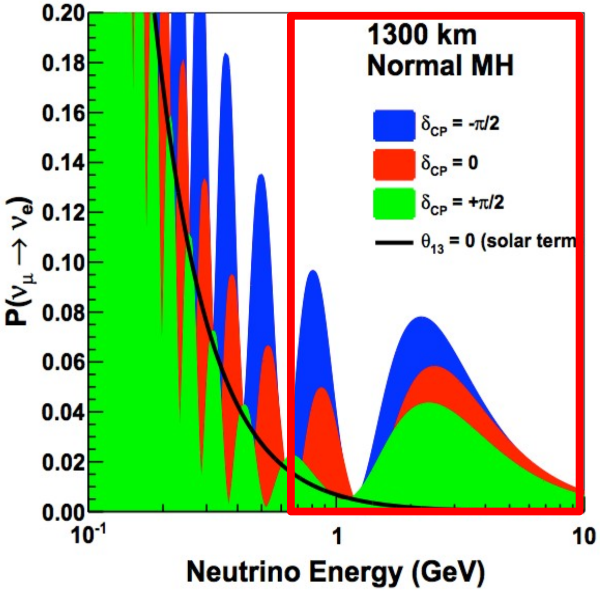


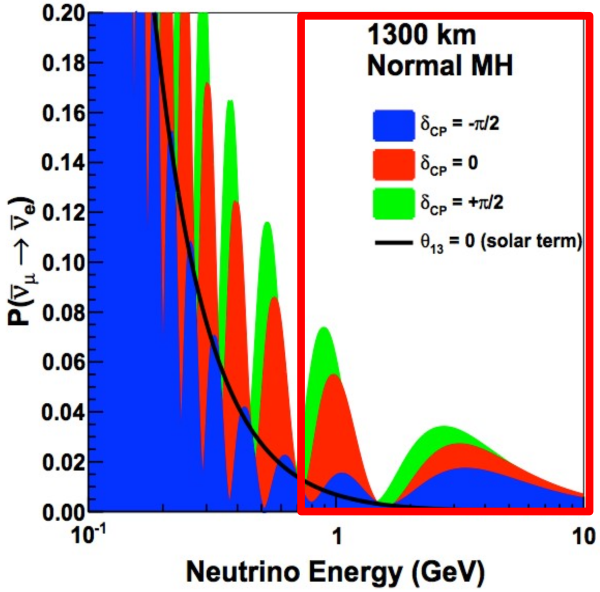
P. Dunne Neutrino2020 -
https://zenodo.org/record/4154355#.YHA6zxKxVH4

Collaborations are working towards a joint analysis

Long Baseline Experiments – Future

Higher power beam (more stats)
Make a spectral measurement – use a wide band beam
And a longer baseline (completely disentangle mass ordering and CP violation)
Make a spectral measurement
 use a wide band beam
 highly performing detectors





Measurement range spans 2 oscillation peaks
Gain additional power on deltaCP

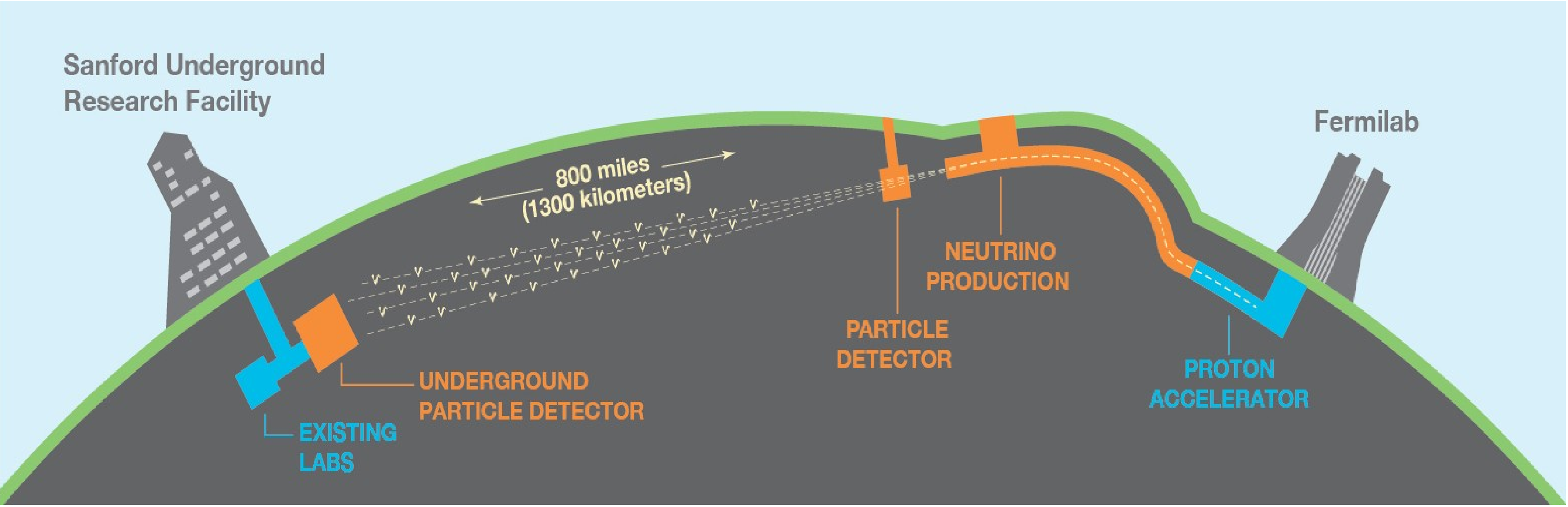
Downside – hit all forms of neutrino interactions.
Need highly performing Near Detectors...

DUNE: international collaboration

DUNE Virtual Collaboration Meeting
January 2021

- 1298 collaborators
- 205 institutions
- 32 countries (plus CERN)

DUNE is next generation neutrino oscillation experiment



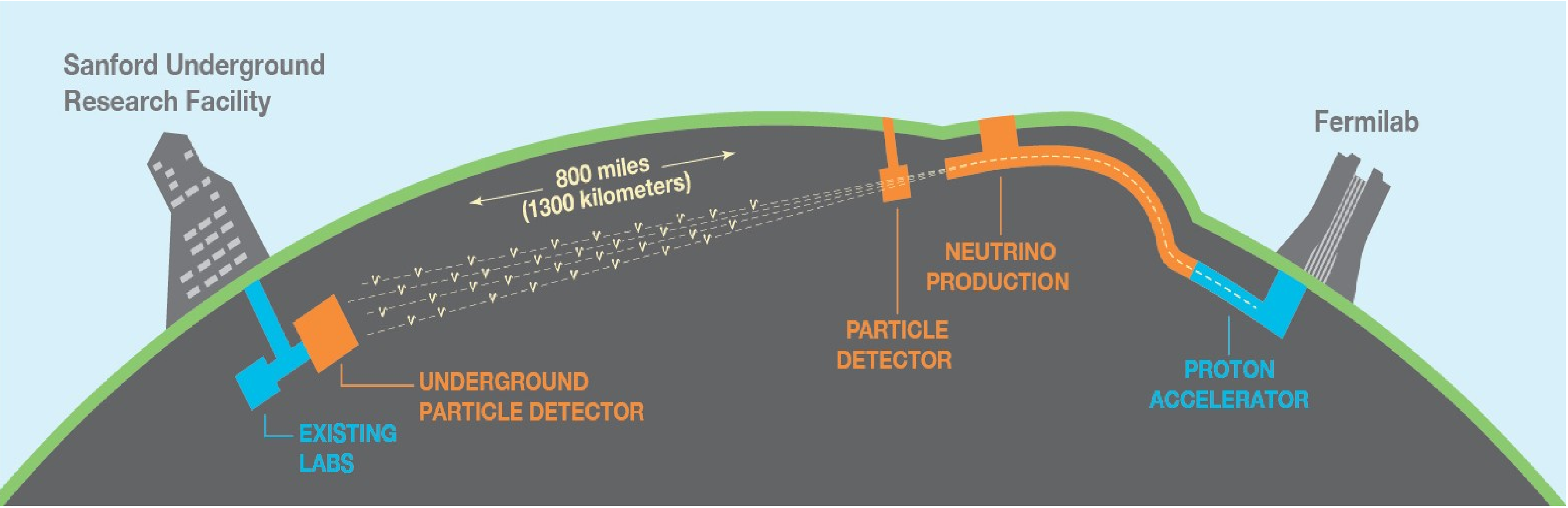
Physics goals :

Neutrino oscillations : measure ν_μ disappearance + ν_e and ν_τ appearance (both neutrino and anti-neutrino modes)

Mass Ordering, leptonic CP Violation discovery, θ_{23} octant and more in a single experiment + physics beyond the Standard Model

Large underground detectors : Nucleon Decay searches, SuperNovae core collapse etc

DUNE is next generation neutrino oscillation experiment

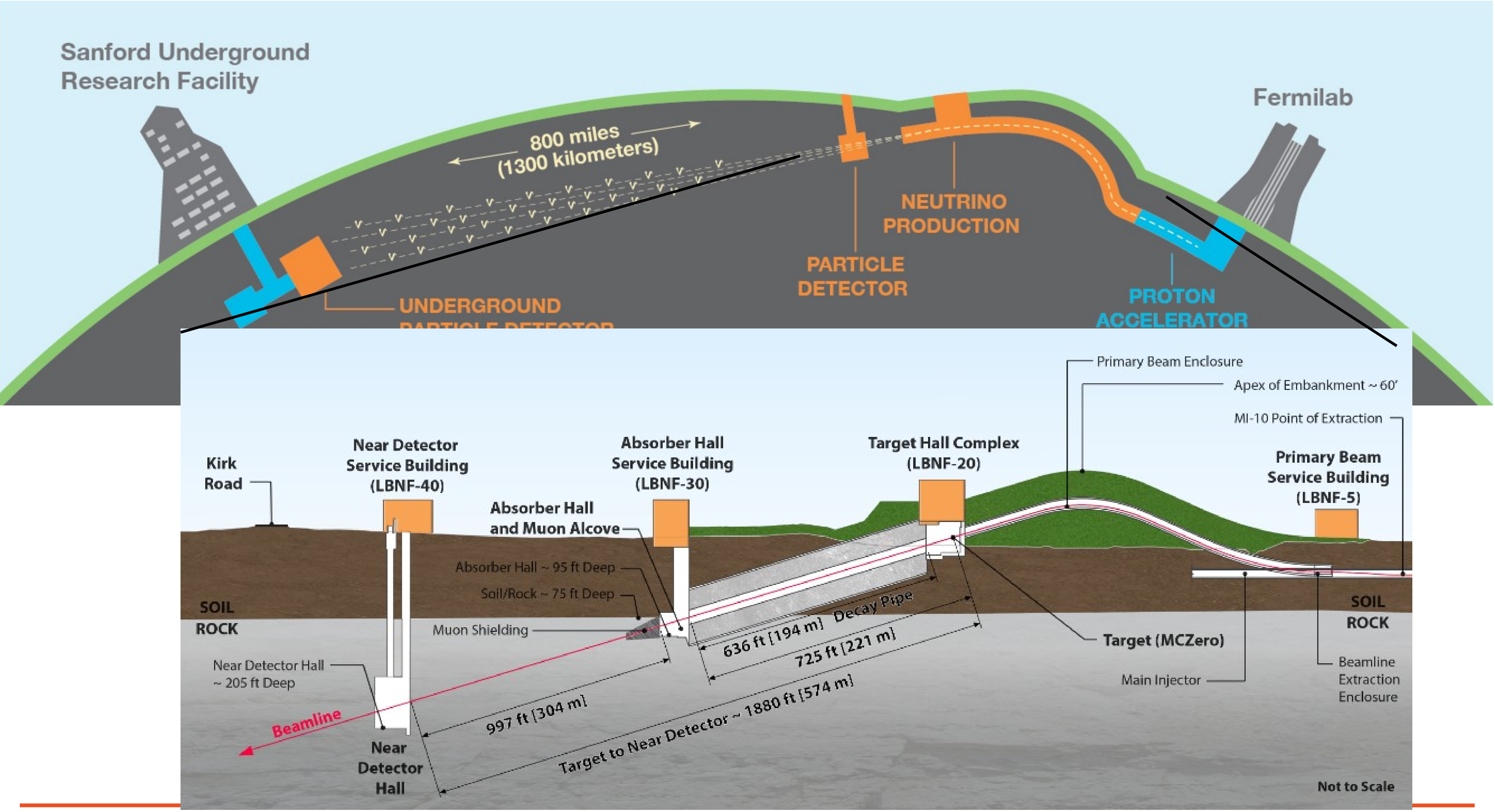


Far detectors at SURF:
4 x 17 kt Liquid Argon TPCs
1.5 km underground

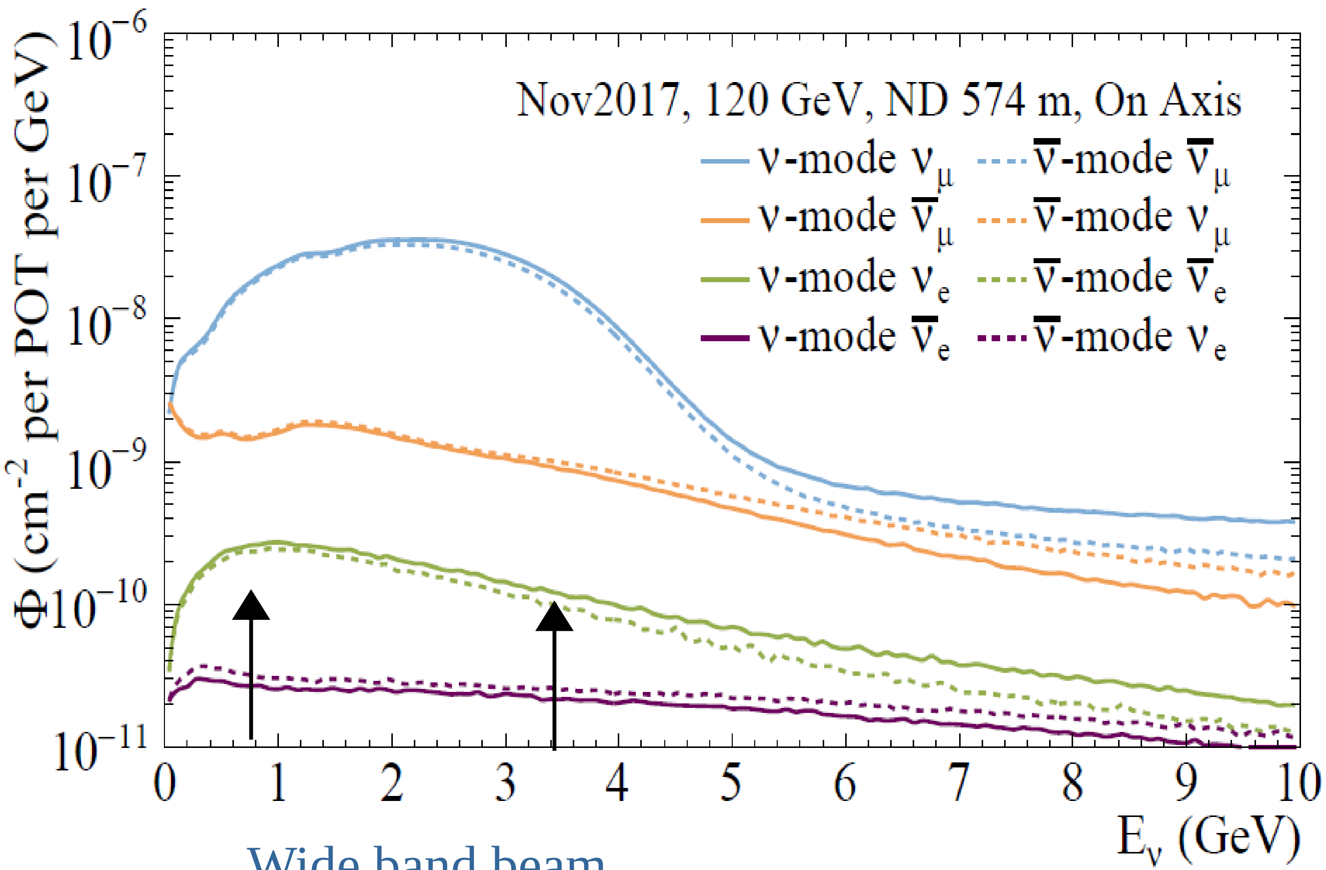
1.2 MW wide-band beam from Fermilab (upgradable to 2.4 MW)

Near Detector to measure initial composition

Long Baseline Neutrino Facility



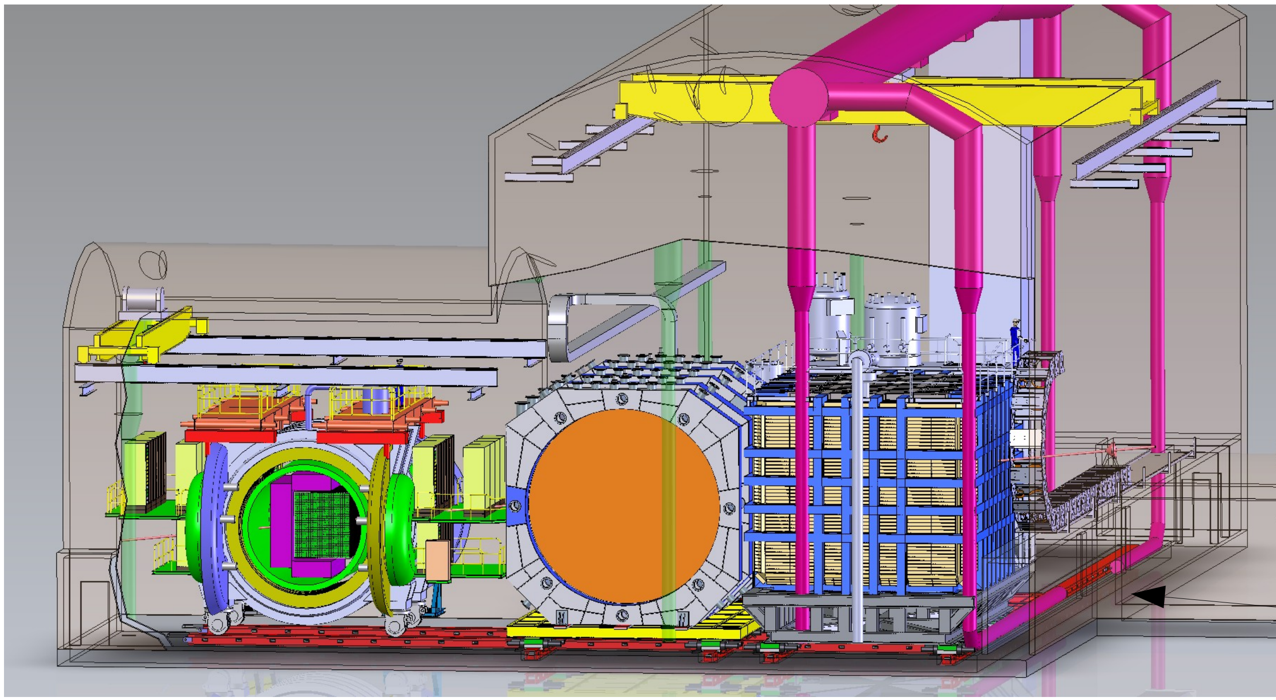
LBNF beam



Wide band beam
2 oscillation maxima

- 120 GeV Main Injector proton beam
- 1.2 MW initial beam power, upgradeable to 2.4 MW
- Beamline and focusing system optimized for CP violation sensitivity

Near detector system at Fermilab



ν

SAND MPD LAr

Predict the neutrino spectrum at the FD

Measure interactions on Ar

Measure neutrino energy

Constrain x-section model

Measure neutrino flux

Obtain data with different fluxes

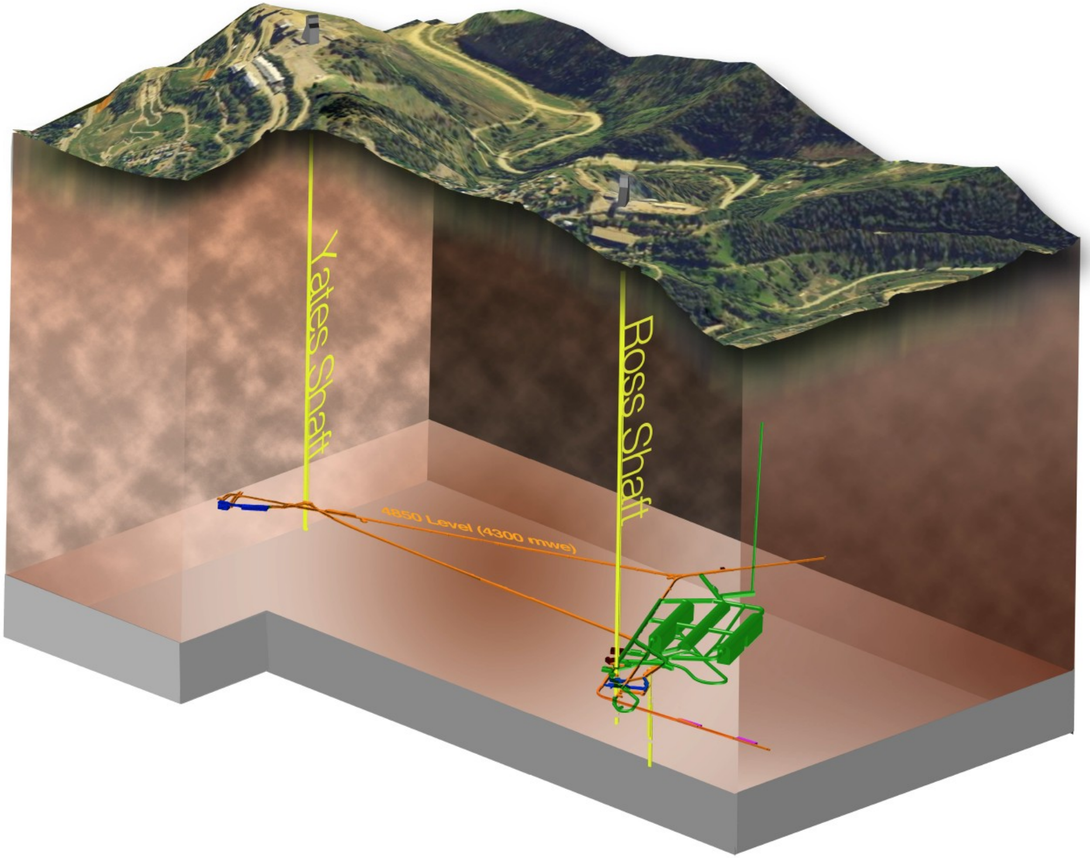
Monitor the neutrino beam

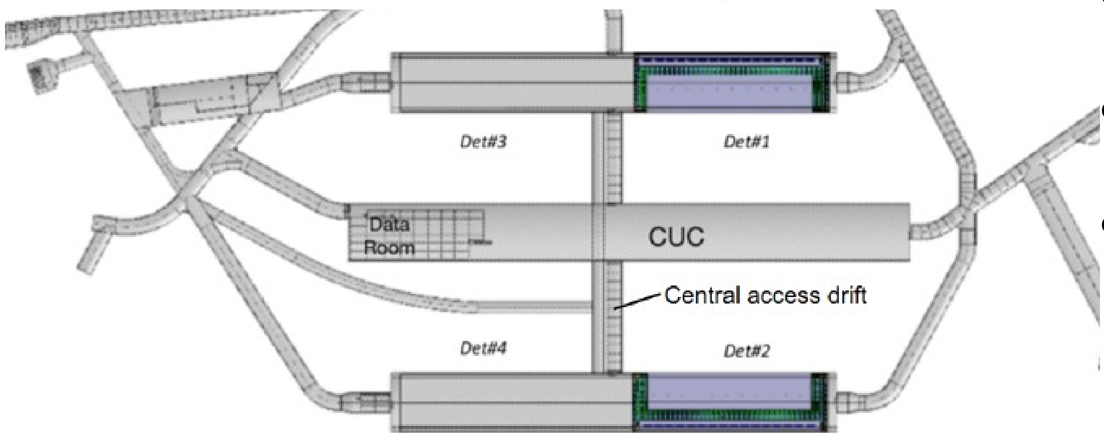
Liquid Argon TPC

Multi-Purpose Detector - HP gaseous Argon TPC + ECAL + Magnet

3D Scintillating Tracking Spectrometer

Far detector at SURF





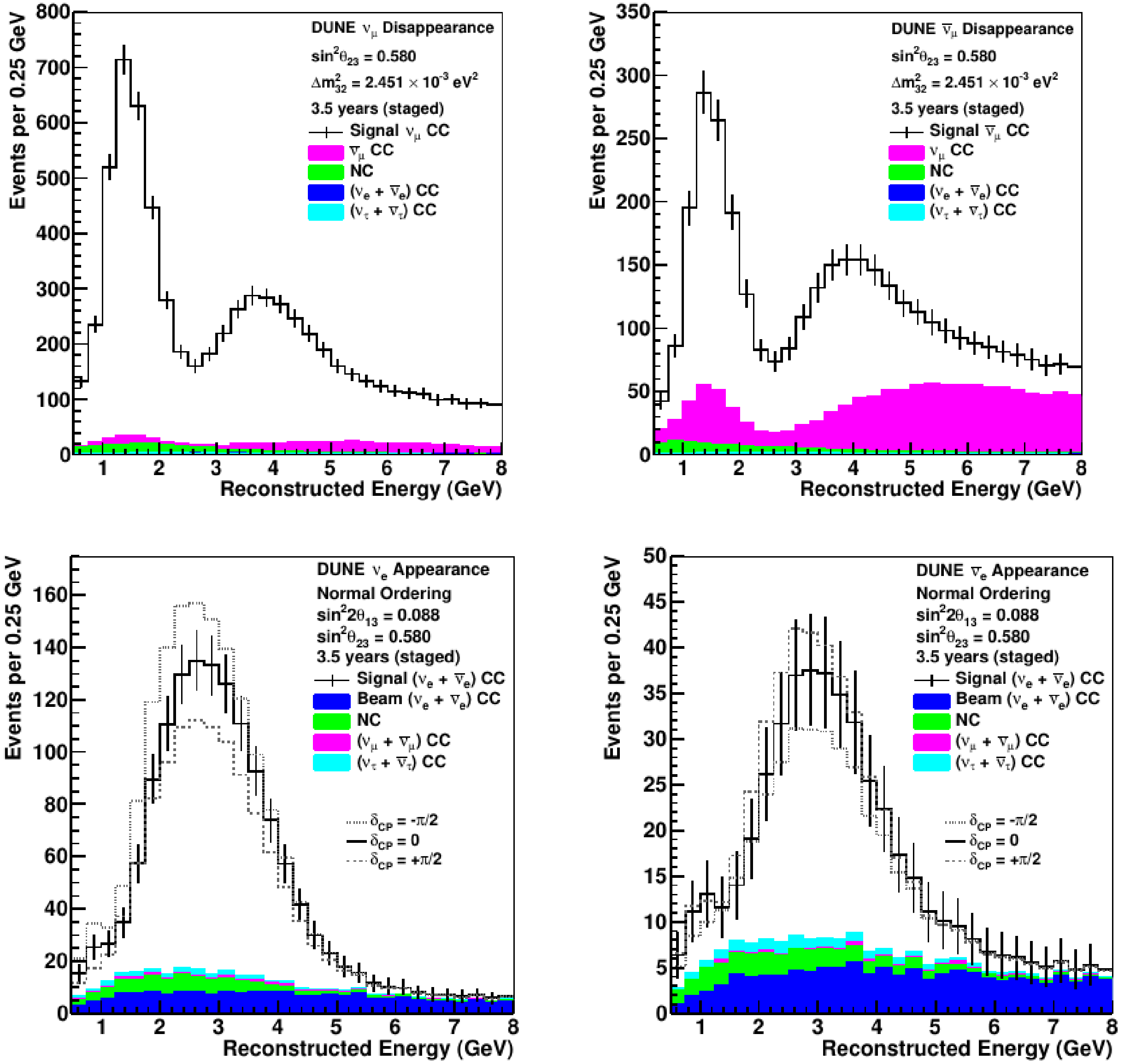
- Sanford Underground Research Facility in Lead, South Dakota
- Four 17-kt LAr TPC modules, located 1.48 km underground
- Excavation
- first module operational in 2024
- Start of run: 2 FD modules, 1.2 MW beam power, with ND
- +1 year: 3 FD modules
- +3 years: 4 FD modules
- +6 years: upgrade to 2.4 MW beam

Neutrino Oscillations

Measure appearance and disappearance for both neutrino and anti-neutrinos

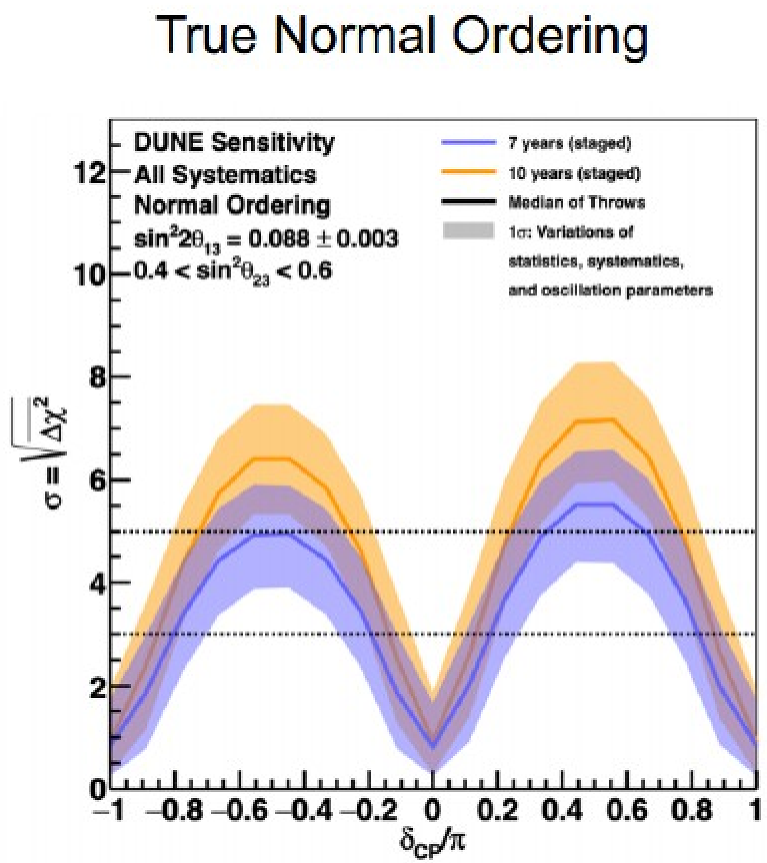
disentangle Mass Ordering and CP effects

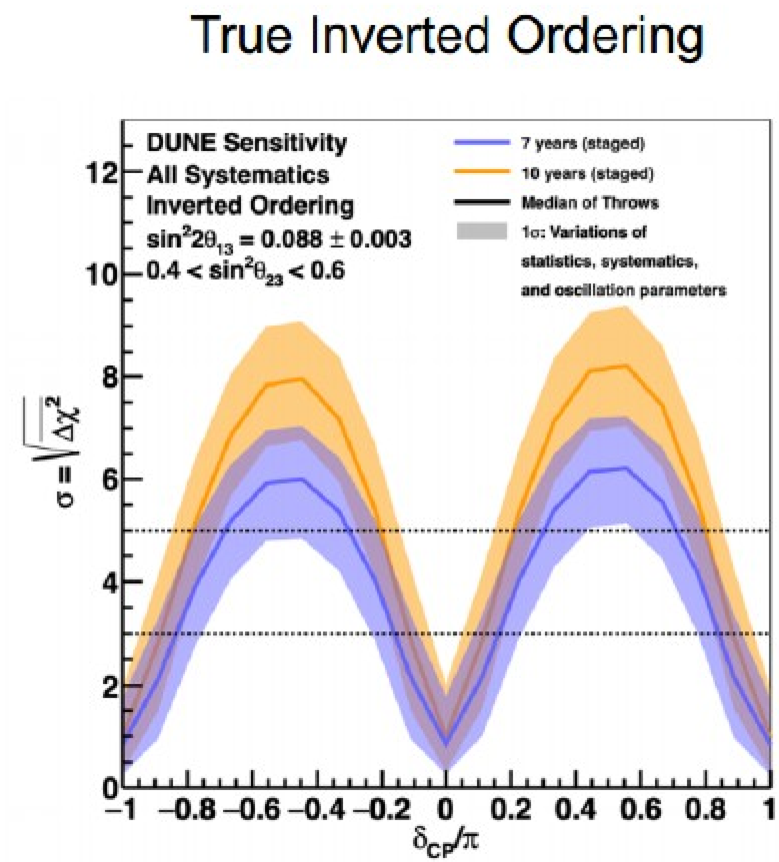
Spectral measurement - 1st and 2nd maxima



DUNE Technical Design Report (TDR) arXiv:2002.03005 EPJC (2020) 10, 97

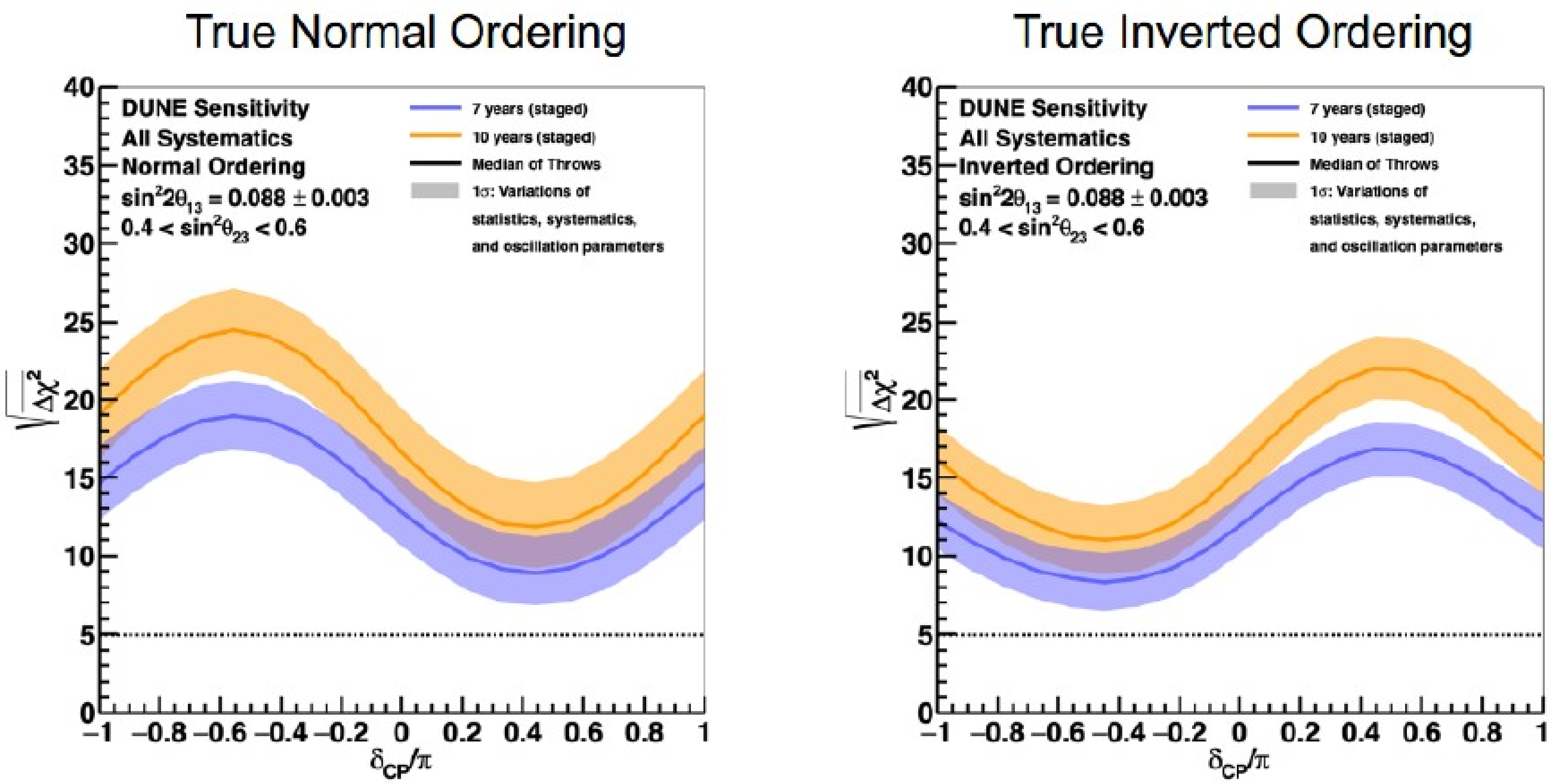
Sensitivity to CPV





Significant discovery potential over a large range of possible true δCP values in 7-10 years of (staged) running

Sensitivity to Mass Ordering

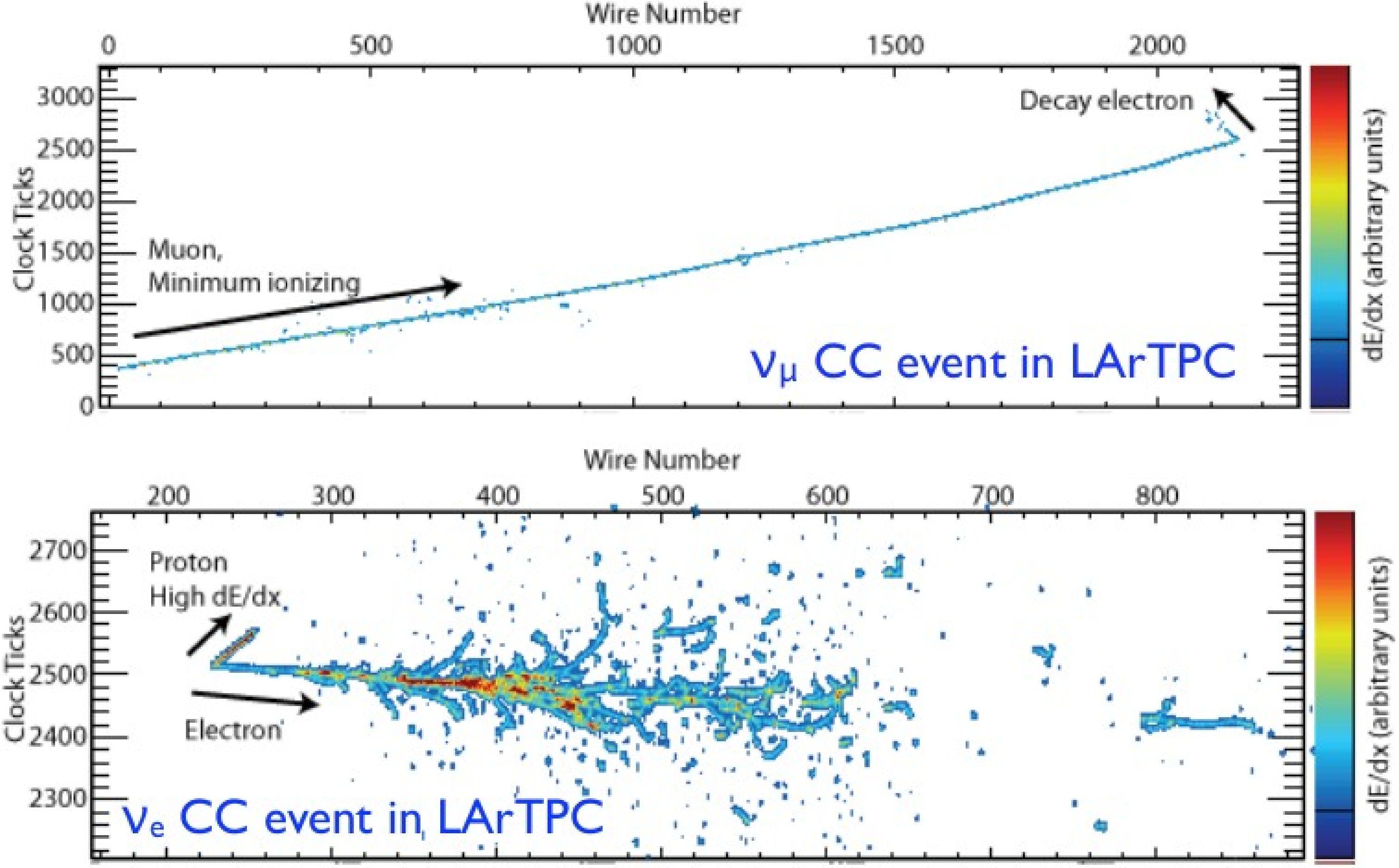


Definitive determination of neutrino mass ordering (normal or inverted) for all possible parameters

LAr TPCs

- Gigantic detectors deep underground with excellent calorimetric and spatial resolution
- Wide off-beam physics program

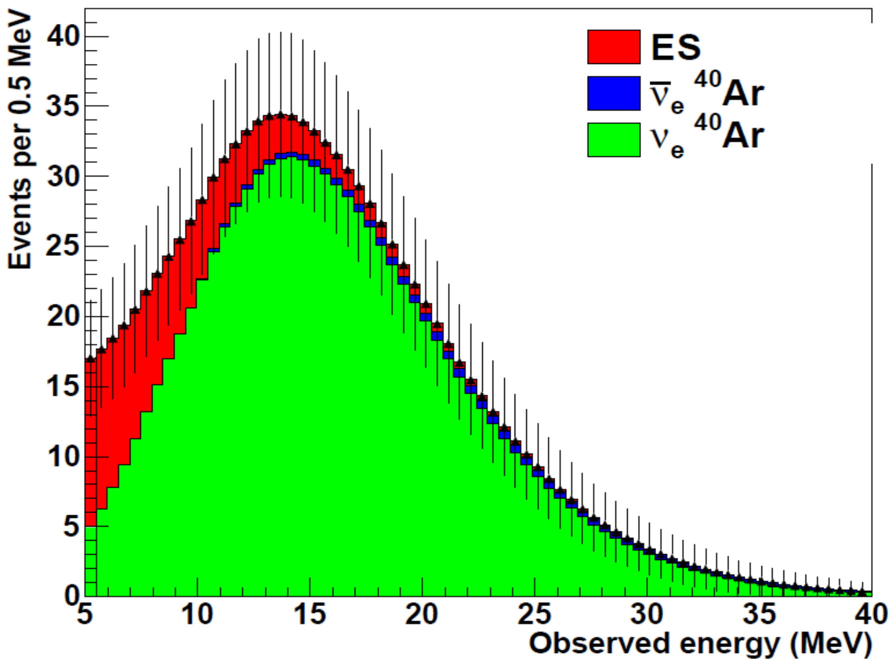
Simulation

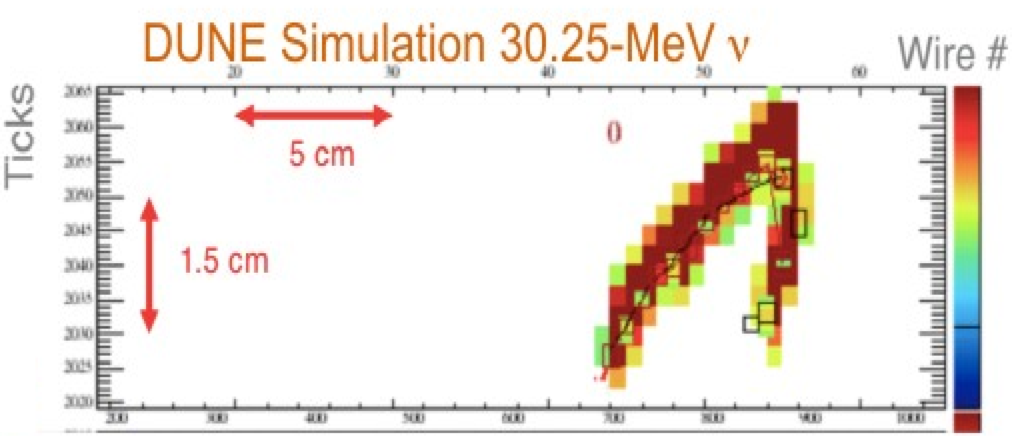


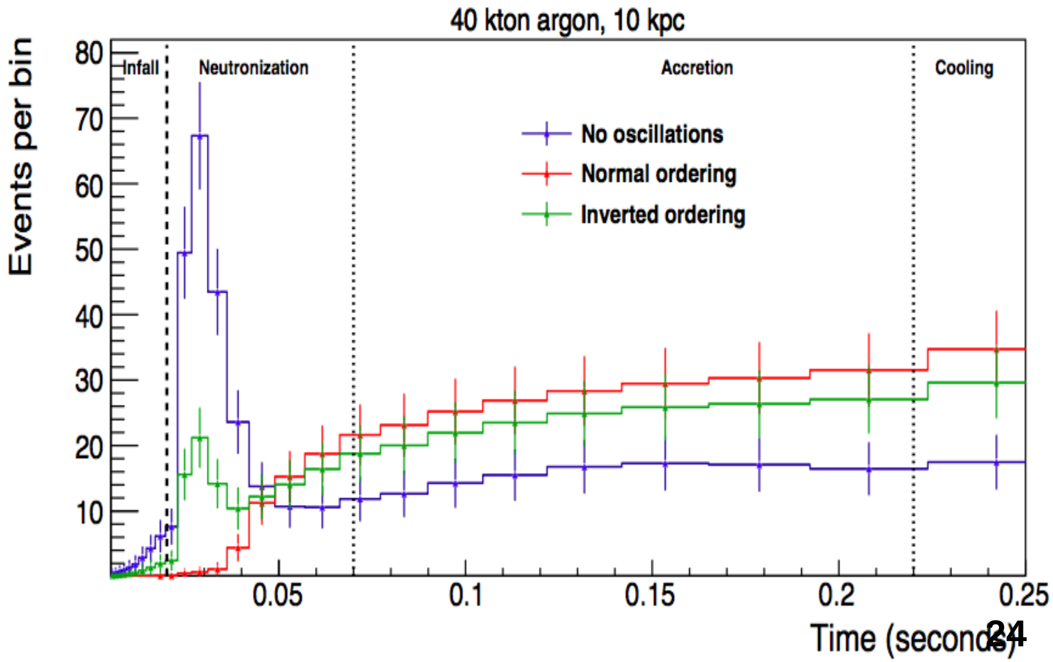
non-beam physics: SuperNova burst

Uniquely DUNE is sensitive to ve
ve + ^{40}Ar $\rightarrow$ e^{-} + ^{40}K*

5-50 MeV signals: efficient triggering + continuous data collection







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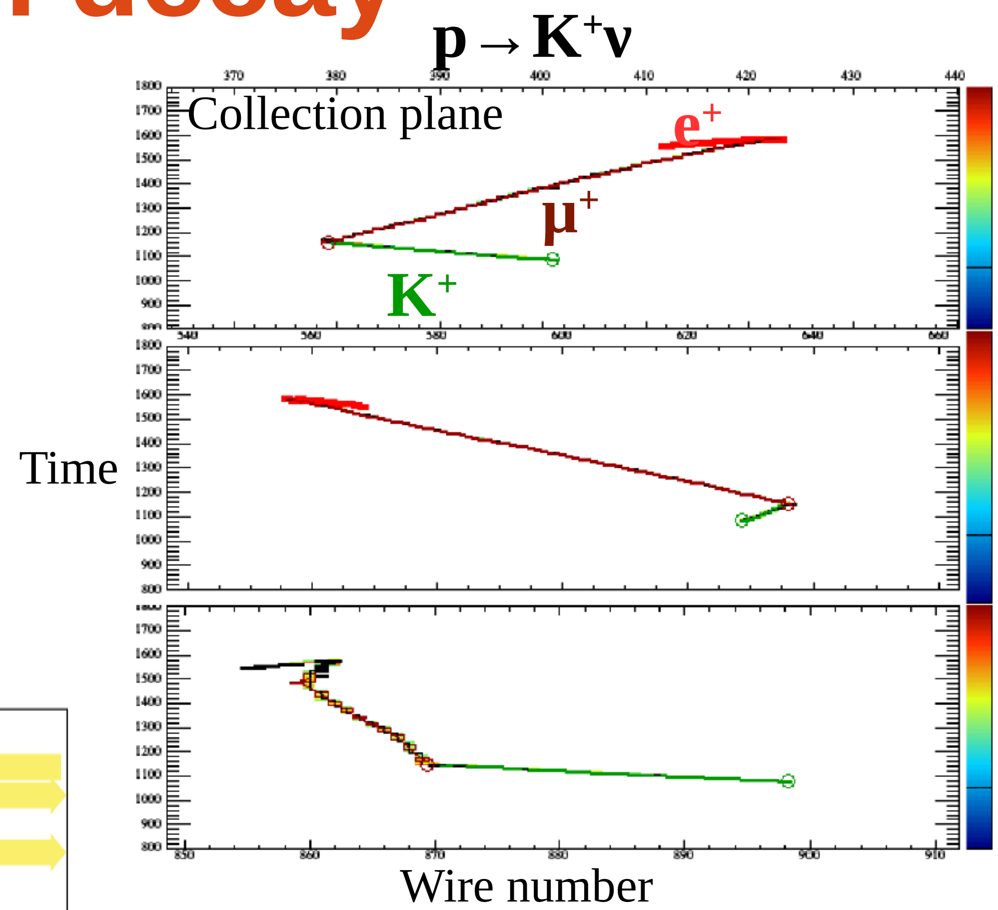
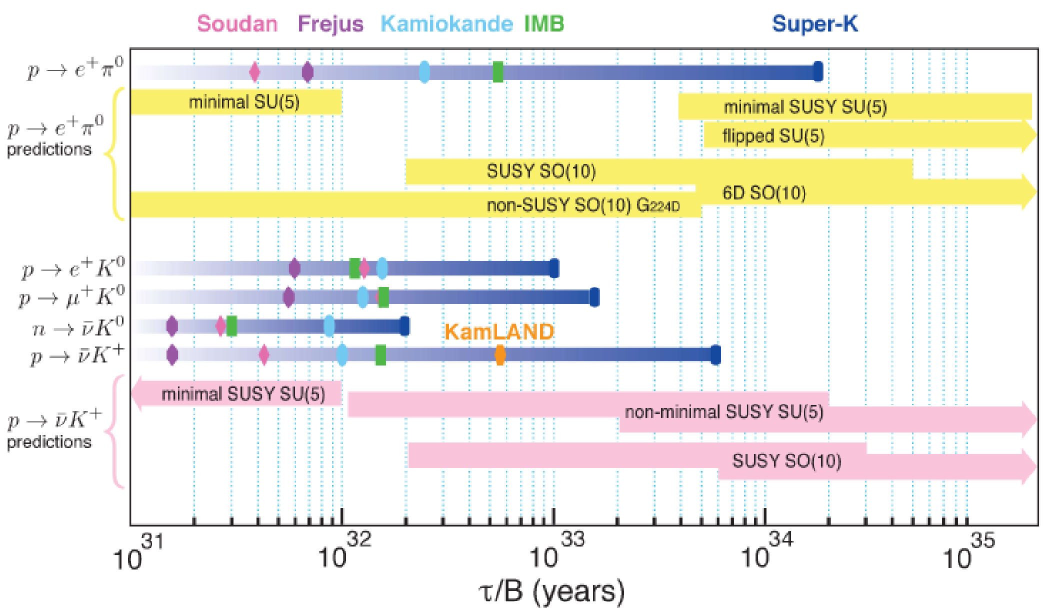
Nucleon decay

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

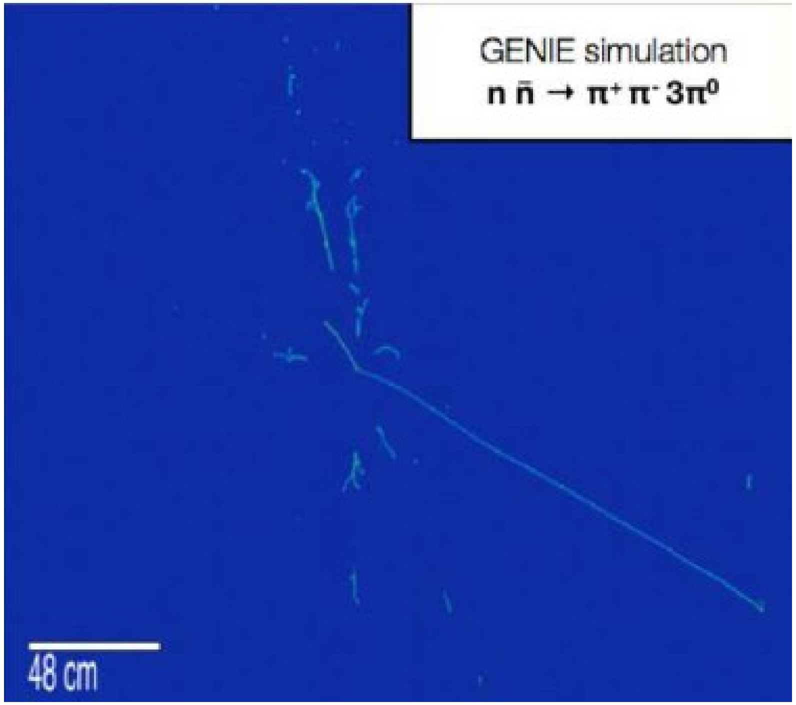


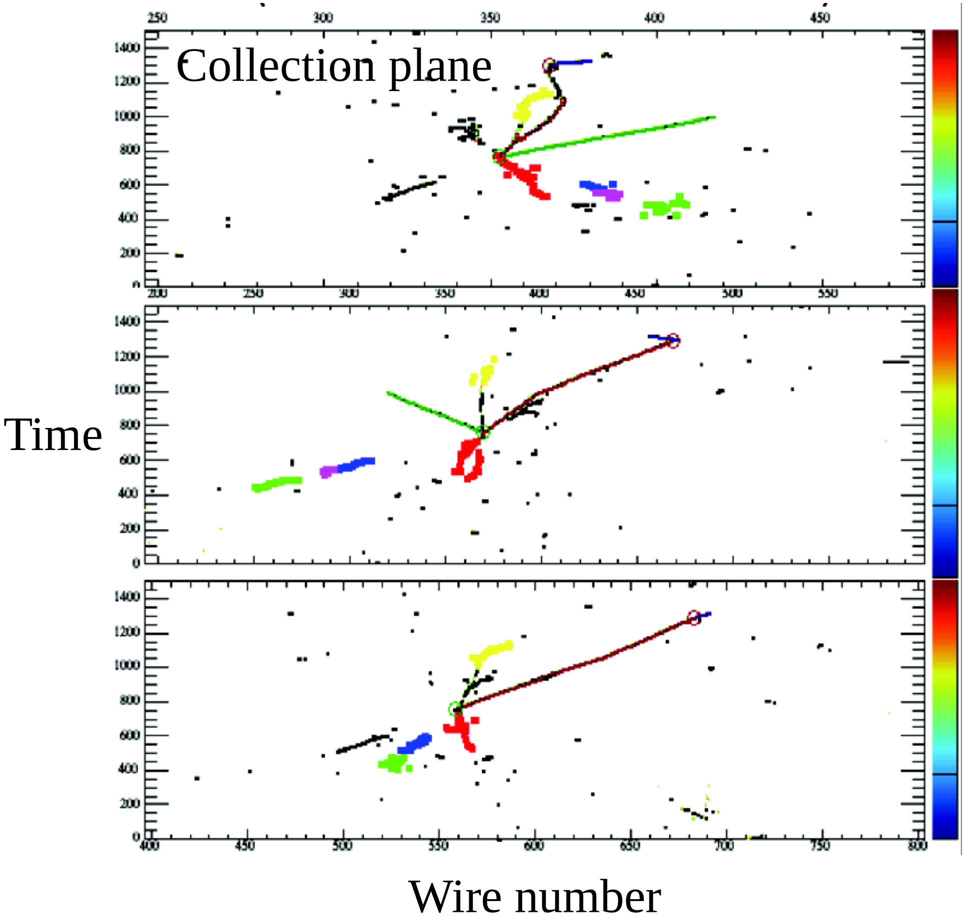


More details in TDR arXiv: 2002.03005

neutron-antineutron oscillations

Baryon number violating BSM process
Signature is a ‘star’ of charged and neutral pions

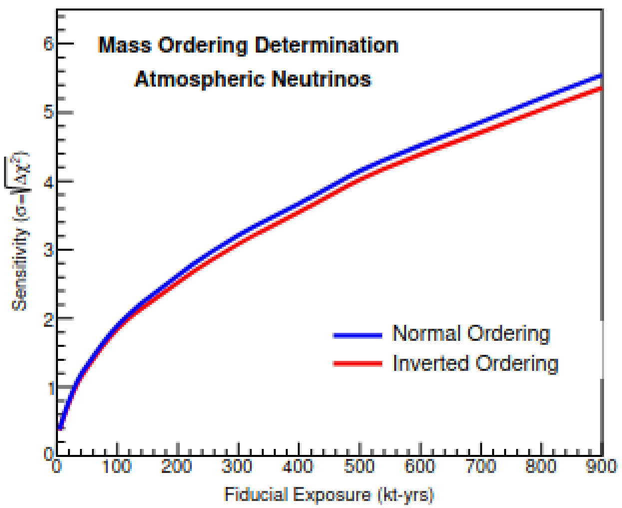




More details in TDR arXiv: 2002.03005

and more..

Atmospheric Neutrinos



Other **BSM physics**

New particles:

light dark matter, boosted dark matter, heavy neutral leptons

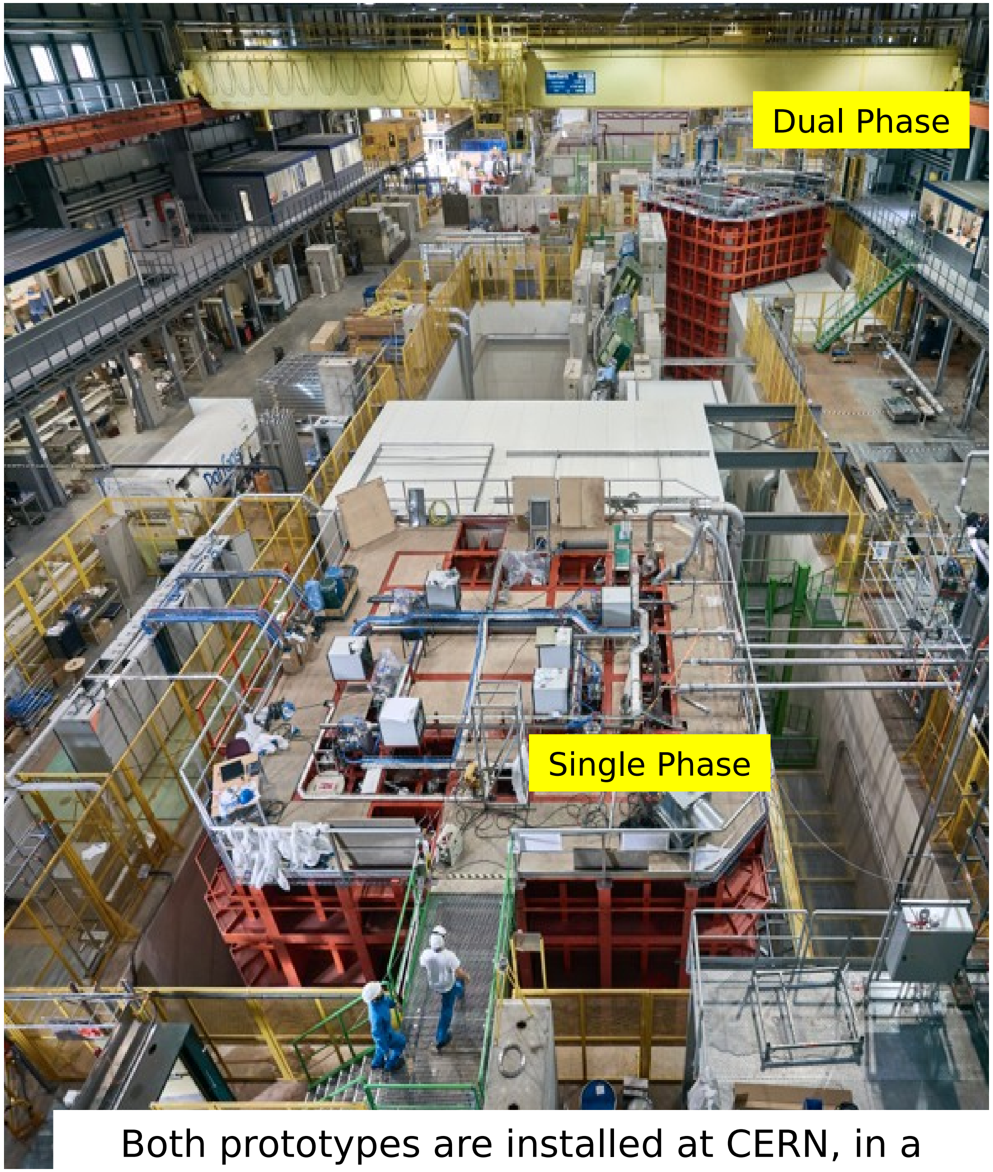
Deviations from PNMS ν mixing paradigm:

non-standard ν interactions, non-unitarity, CPT or Lorentz violation

… etc...

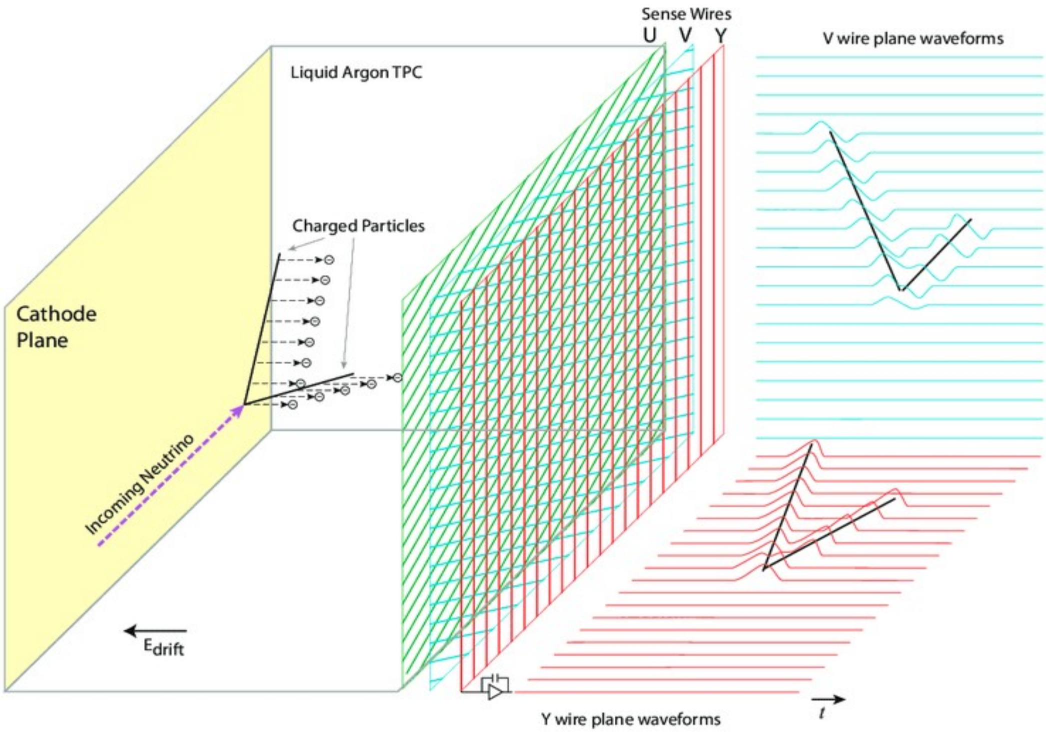
protoDUNEs

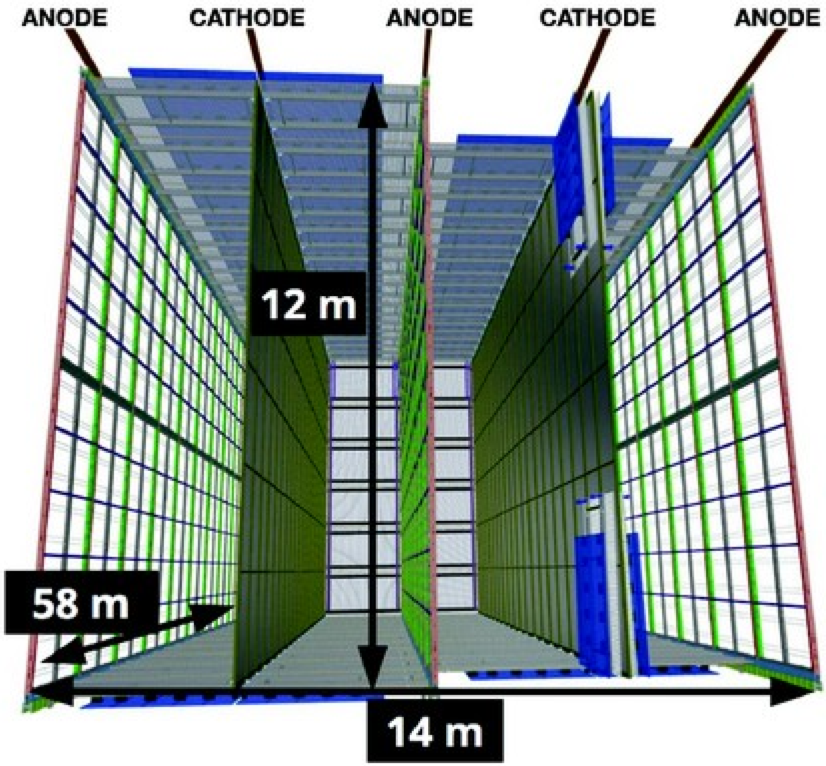
- Giant Liquid Argon TPCs (LArTPC) – one Single-Phase, one Dual-Phase hosted at the CERN neutrino platform
- Necessary R&D step towards the DUNE Far Detectors
  - Tests of all engineering solutions and installation procedures
  - Use full-size components identical to those planned for DUNE FD
- 300t fiducial mass of LAr
  - Technology demonstrators
  - Demonstrate long term performance and stability
- Charged particle test beams to characterise detector response over the energy range of interest for DUNE (~0.5 GeV to 8 GeV)



Both prototypes are installed at CERN, in a dedicated extension of the North Area

Single Phase



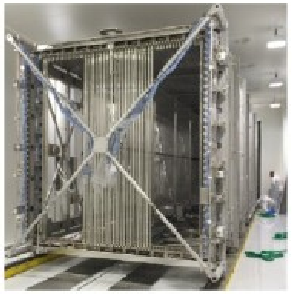


Horizontal drift, distance 3.6 m
Anode wires immersed in LAr
Vertical Anode and Cathode Plane Assemblies (APA,CPA)
1 collection, 2 induction wires at 37.7^{o}, wire pitch 5 mm
Photon detectors: light guides + SiPM,embedded in APAs

- Single Phase is modular
- Shorter drift lengths (and distance to photodetectors)
- Immersed cold electronics (inaccessible)

A history of Single Phase LAr TPCs

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



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

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

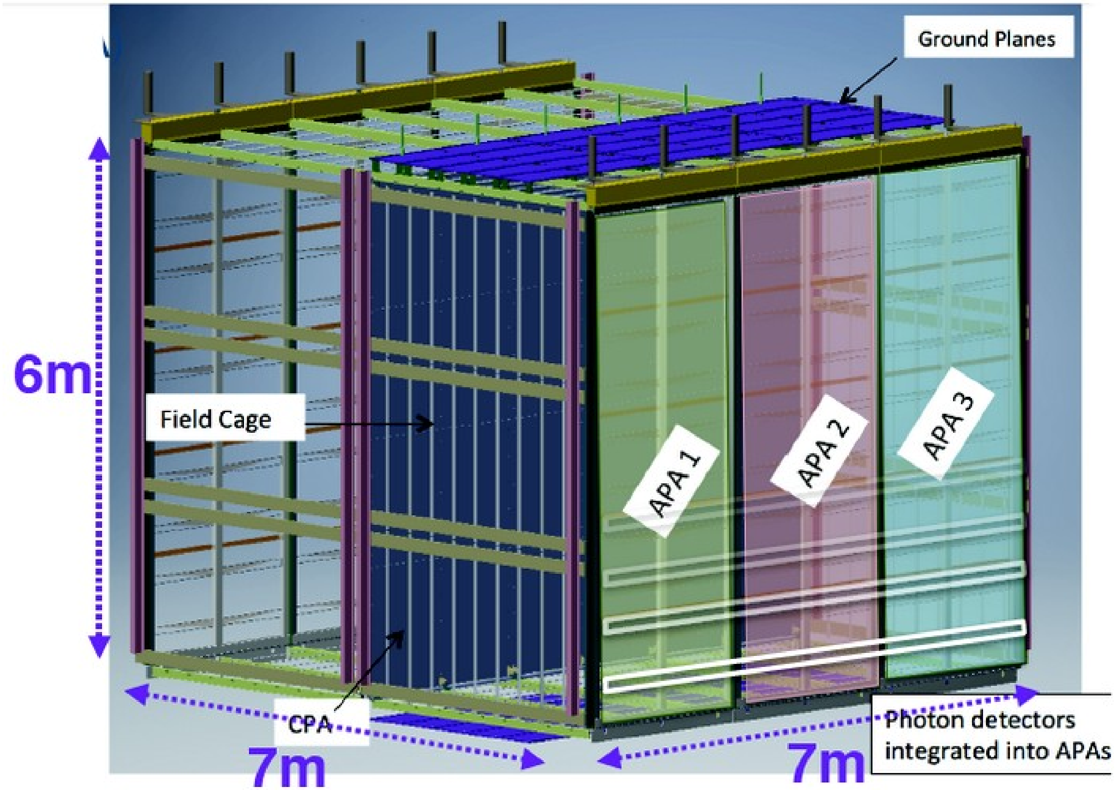
Small TPC, precise measurements of cross-sections and neutrino interactions

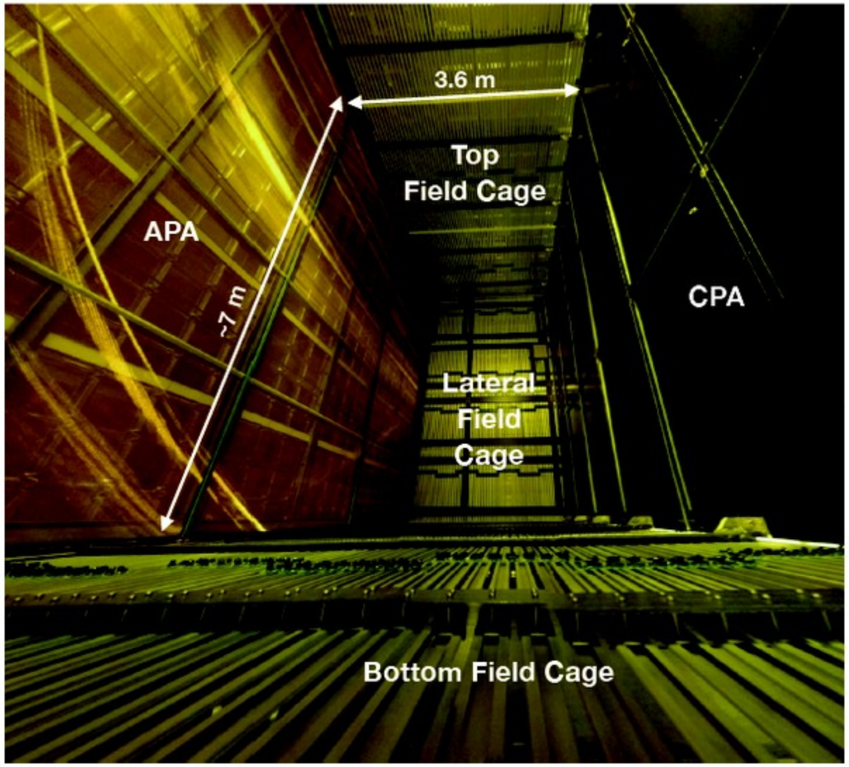
MicroBooNE @ FNAL (2015-ongoing , 170 tons LAr)

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

taken from A. Chatterjee

Single Phase protoDUNE





Successful Beam test in 2018 (Sept-Nov) – pions, protons, kaons from 0.3-7GeV (~4M triggers)
Achieved stable running, >5ms electron lifetime,S/N > 20

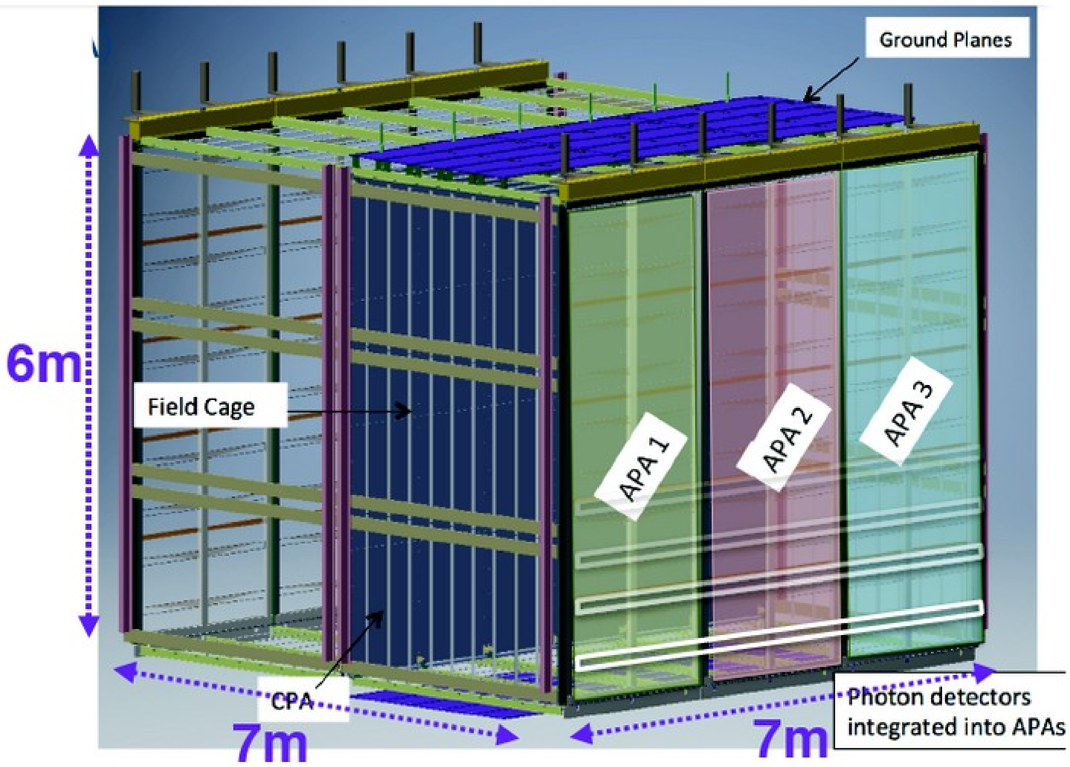
Single Phase protoDUNE

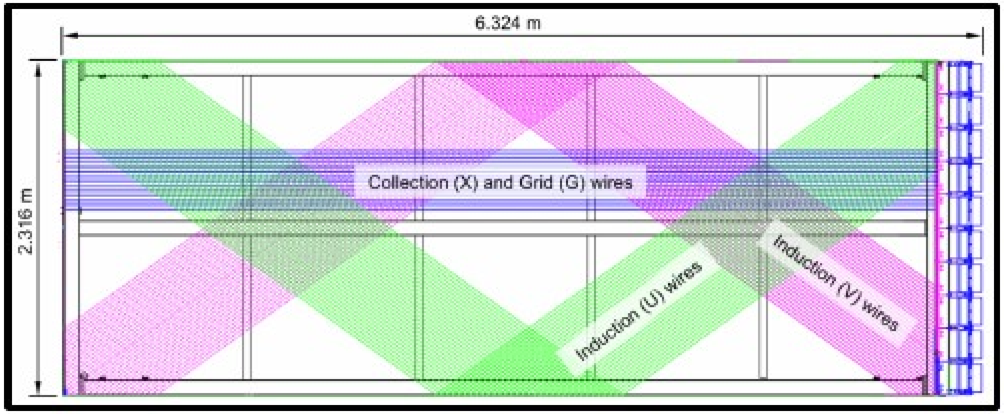
2 drift volumes,
each with a 3.6 m drift distance

6 anode plane assemblies (APAs)
(one far detector module has 150
APAs)

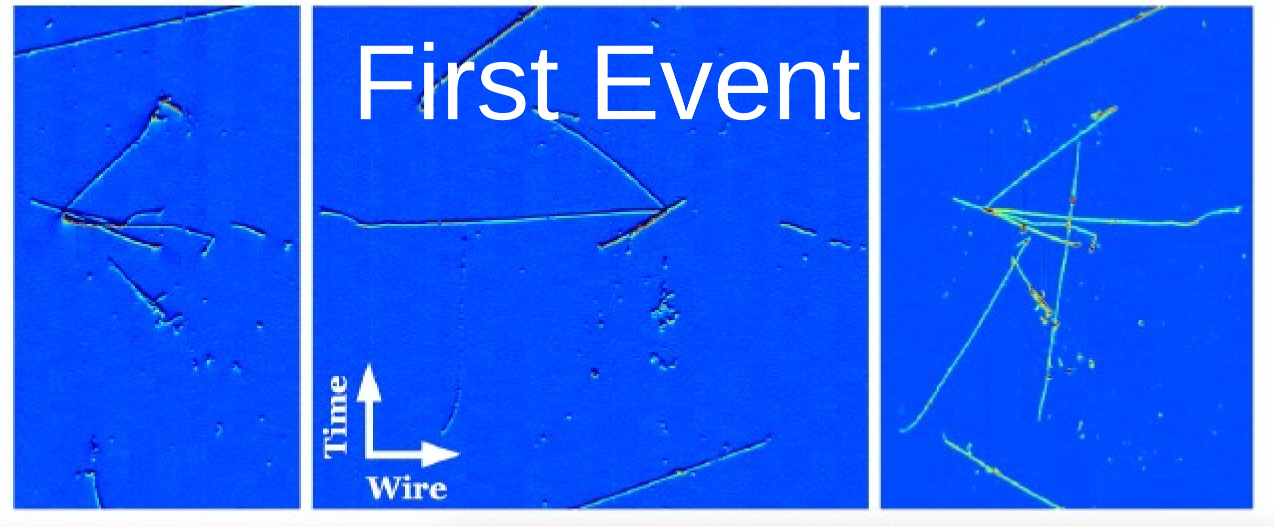
Cold electronics (preamplifier +
digitizer) with 15360 channels.

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



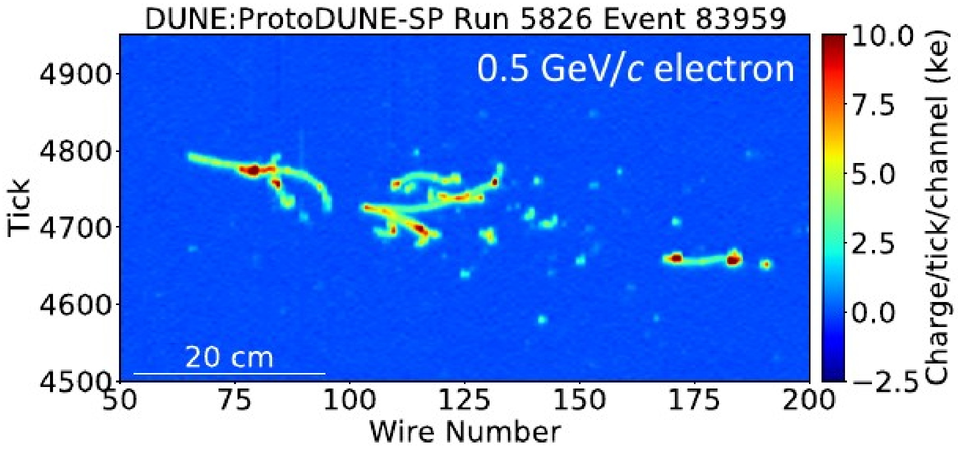


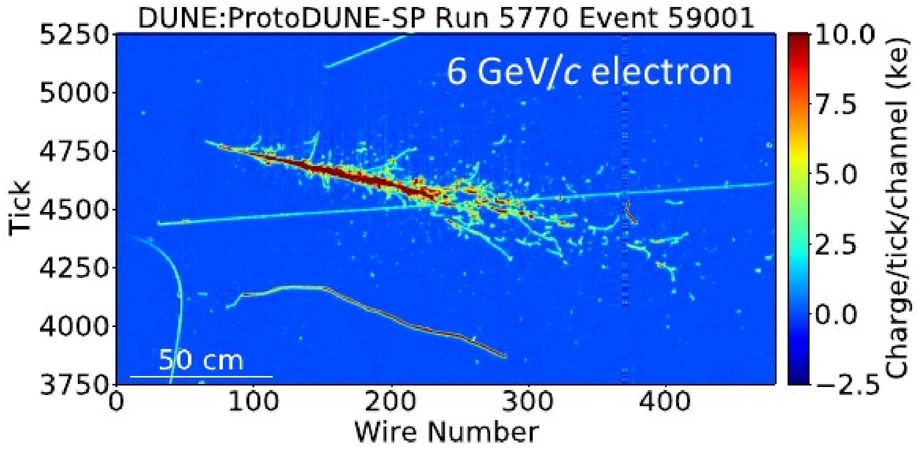
Single Phase protoDUNE



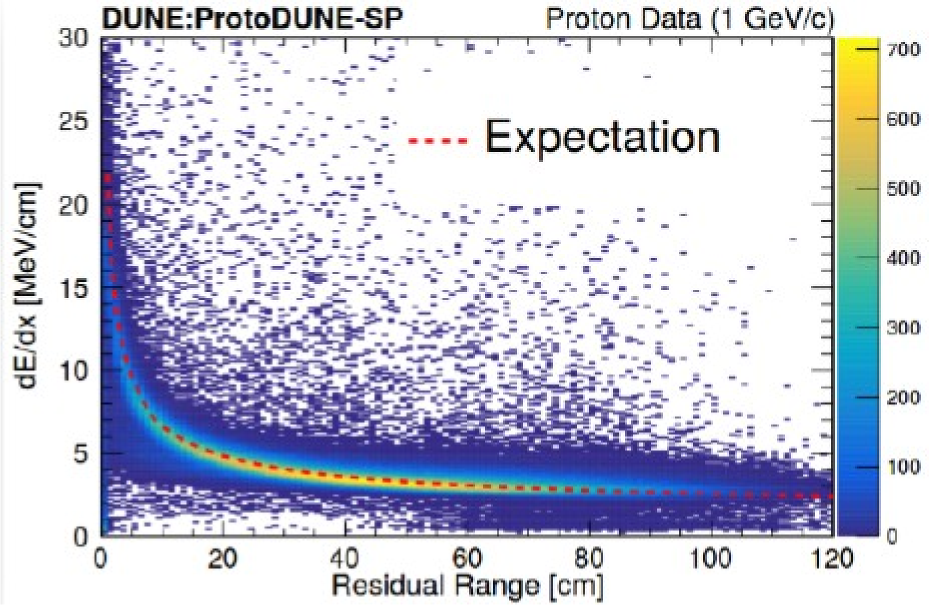
S/N ratio > 10 in all cases
(> 40 for collection plane)

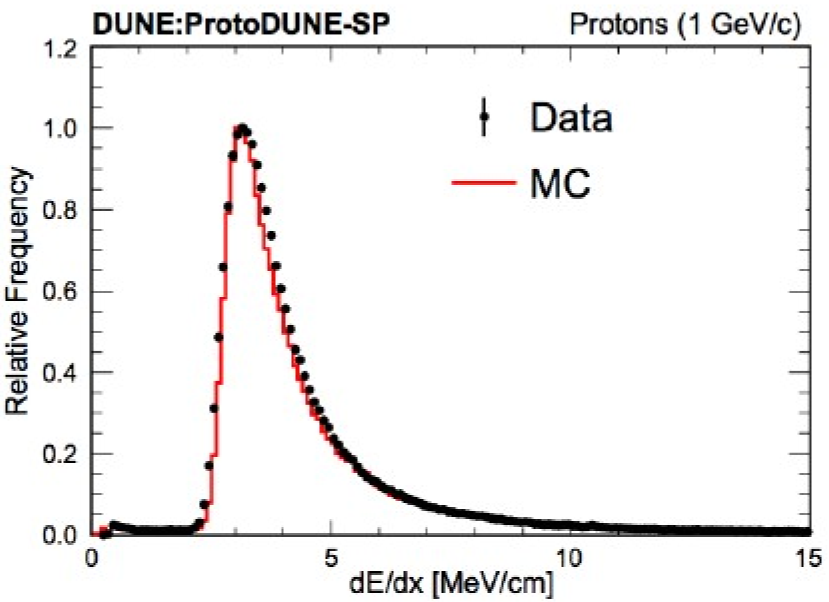
First results in Performance paper:
JINST 15 (2020) 12, P12004

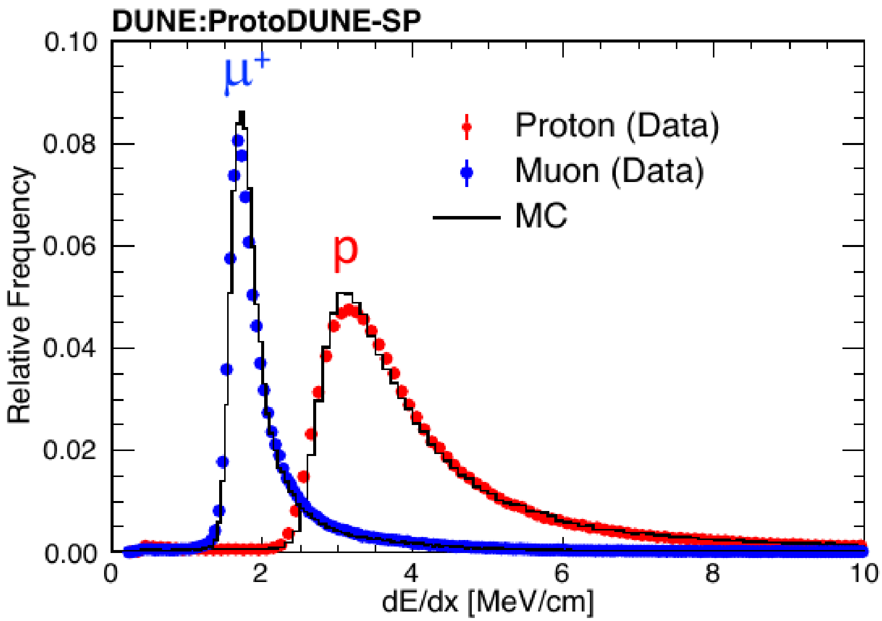


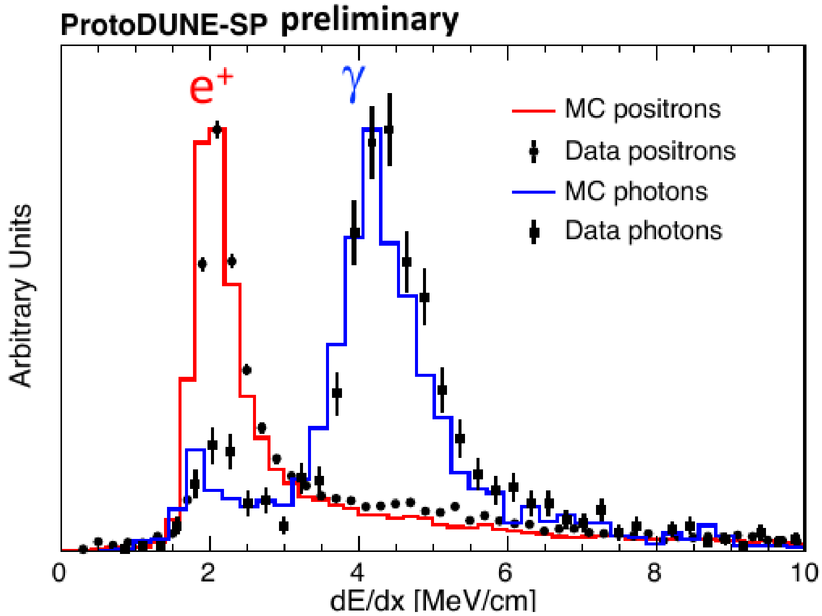


Single Phase protoDUNE



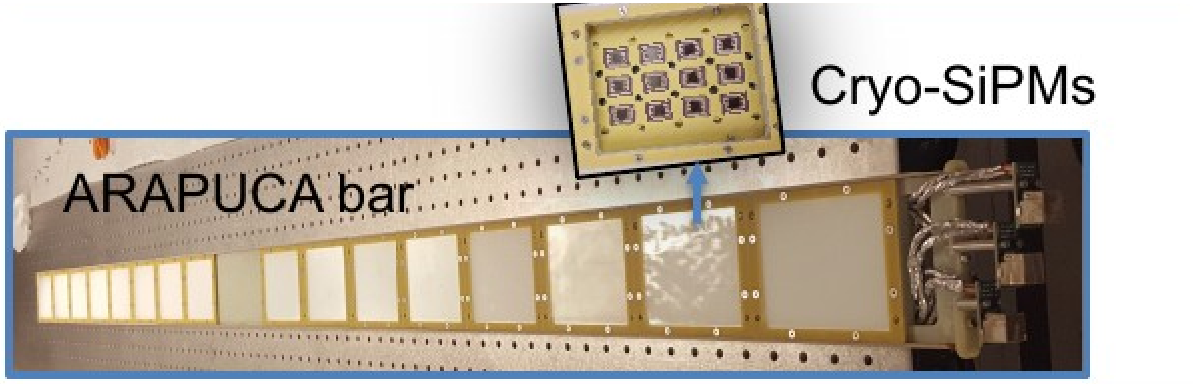


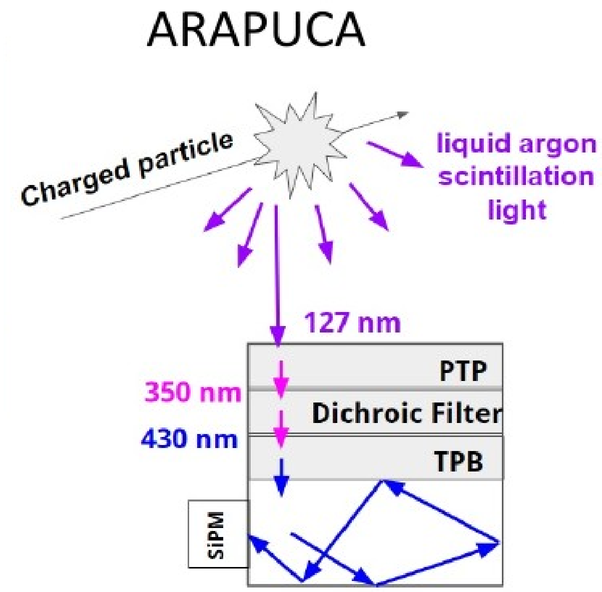




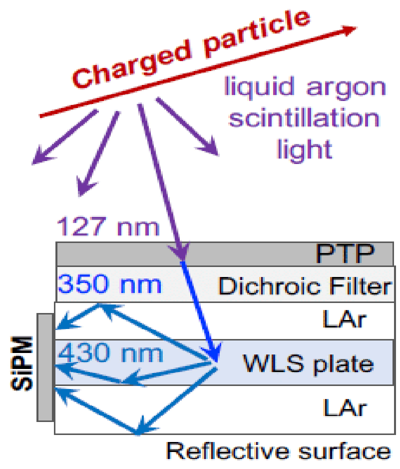
Photon Detectors

- 60 light collecting bars (10 per APA)
- 3 photodetector technologies tested – one is ARAPUCA

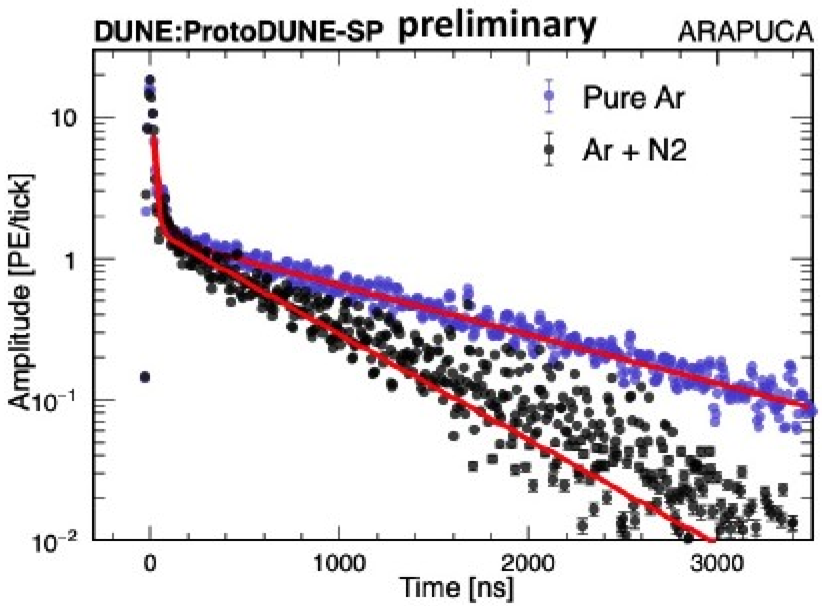




- Improved X-ARAPUCA



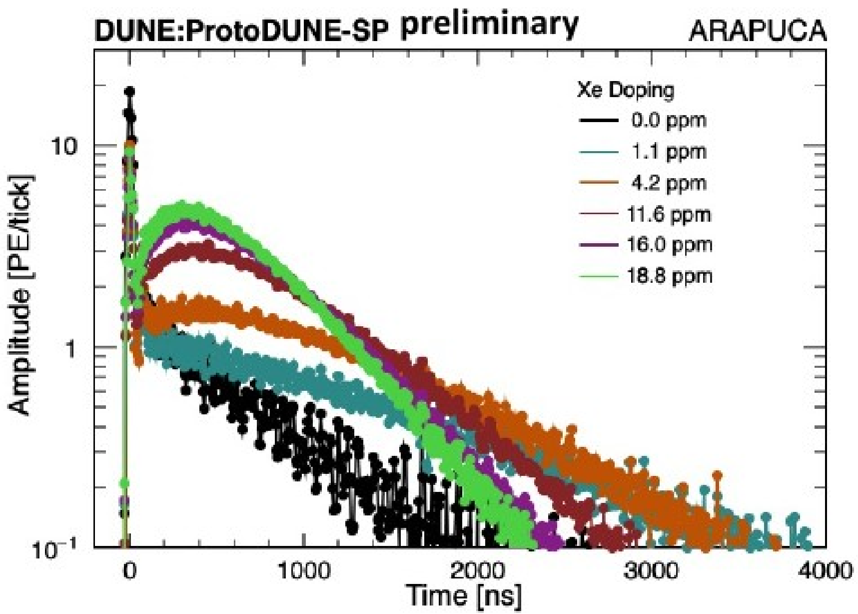
Xe-doping

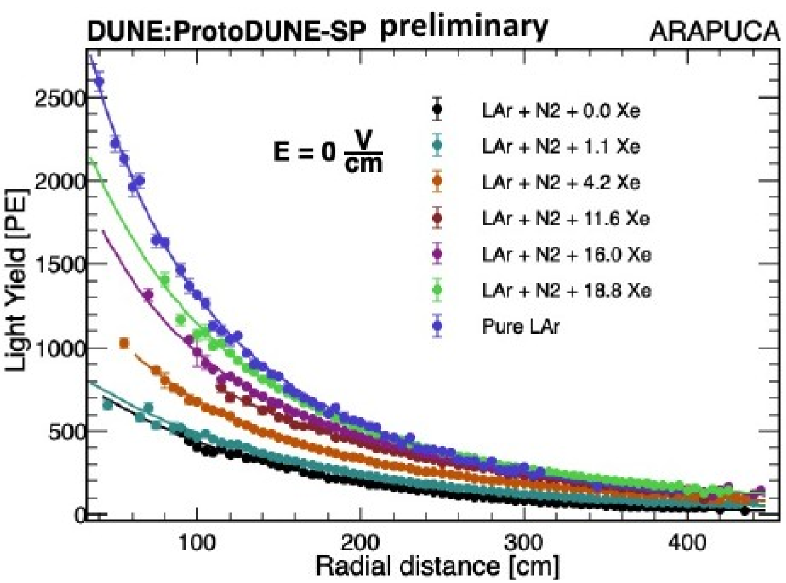


Gas recirculation pump failure in July 2019

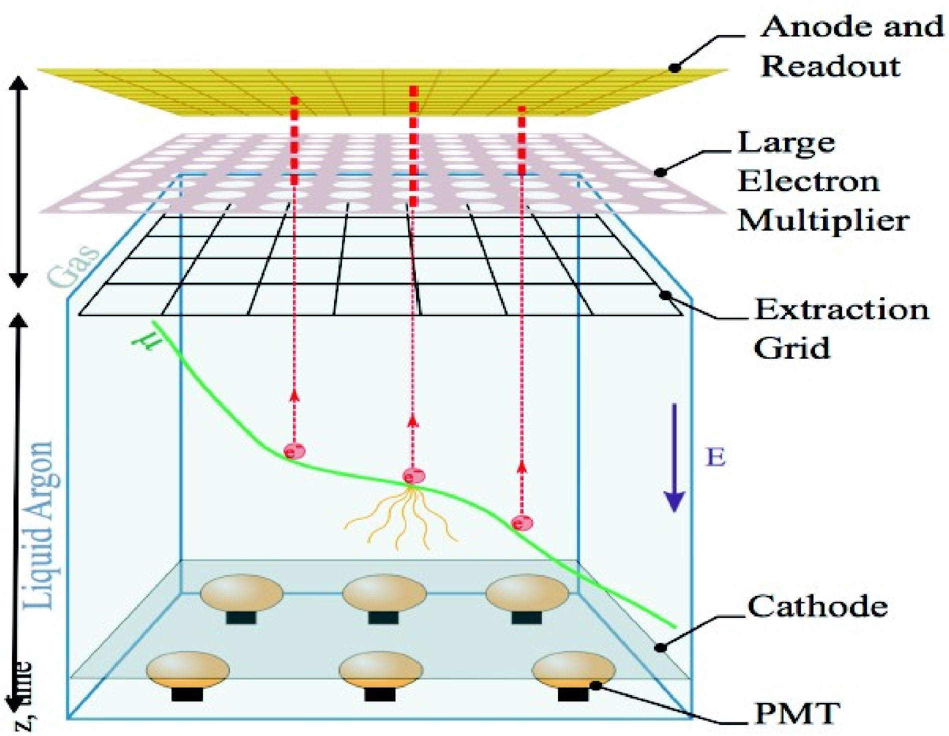
- N2 concentration increased from 0.2 ppm to 5.4 ppm and cannot be removed.
- Scintillation light yield reduced by 70%.
- Slow light component largely quenched.

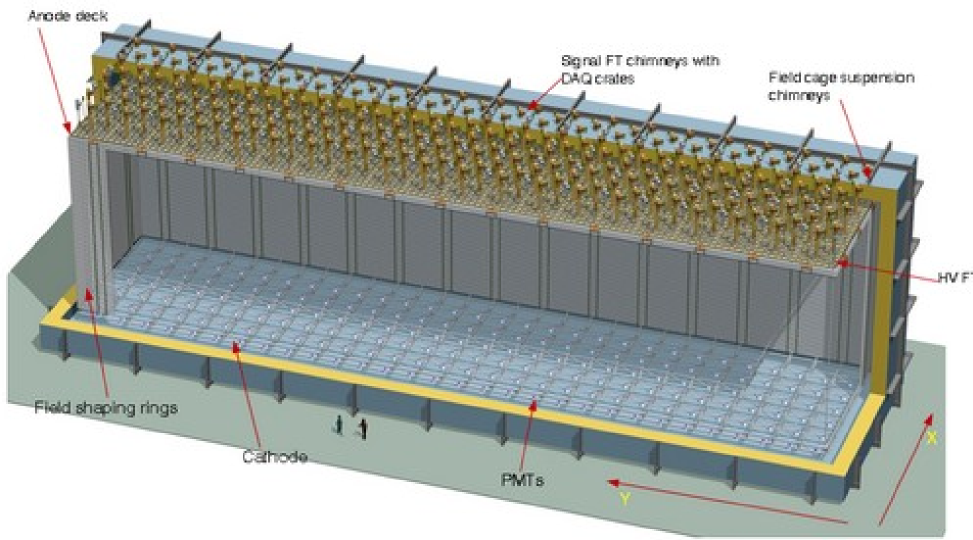
18.9 ppm Xe was injected into LAr over 5 months
95% of light recovered





Dual Phase



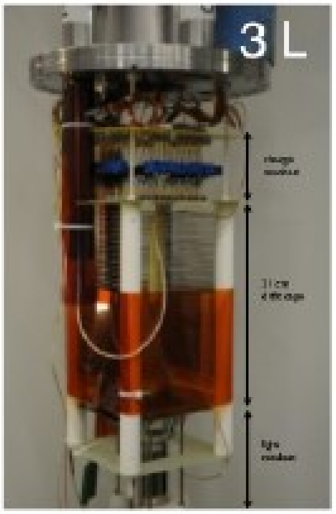


Vertical drift, distance 12 m
Ionization electrons extracted from LAr to gas
Signal amplified in GAr by Large Electron Multiplier (LEM)
Charge collected on 2 orthogonal views, 3mm pitch
Photon detectors: PMTs below the cathode

- Dual Phase is homogeneous
- Drift is long (12m) (and distance to photodetectors)
- Cold Electronics at the top of the detector (accessible)

A history of Dual Phase LAr TPCs

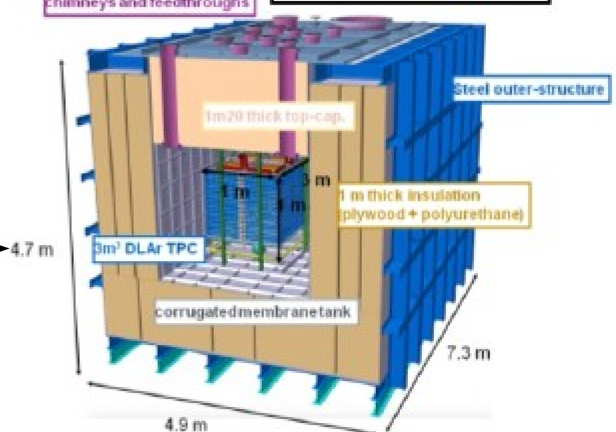
Small R&D TPCs



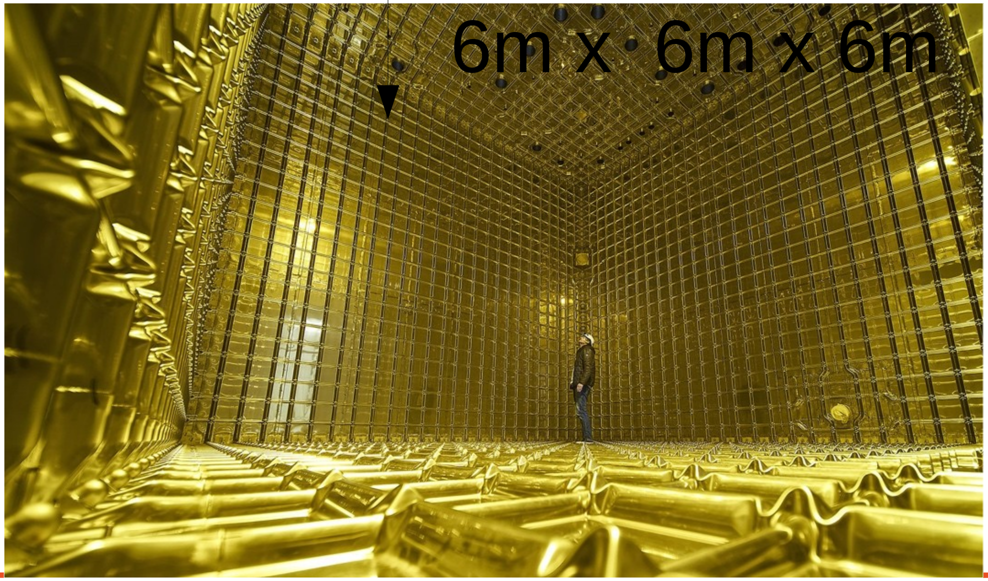
2007 ~ 2014

2014 ~ 2017

3x1x1 m^3 demonstrator



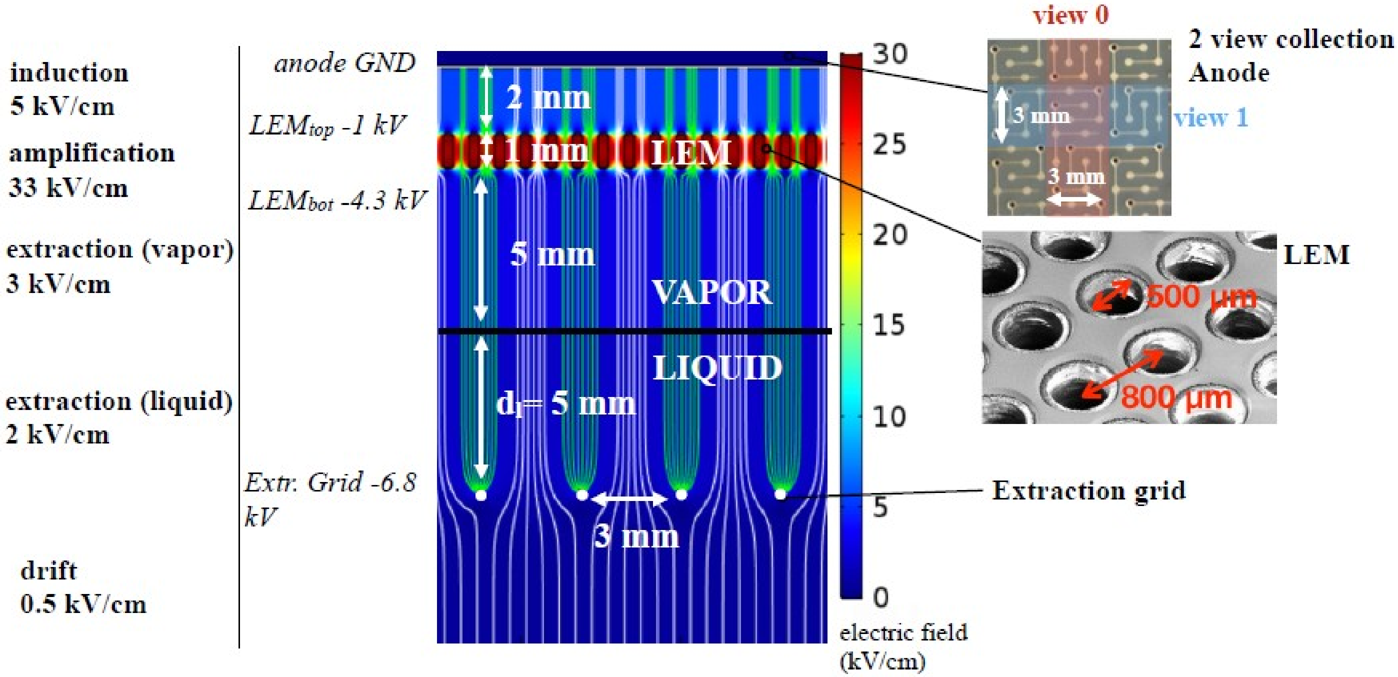
ProtoDUNE DP
6m x 6m x 6m

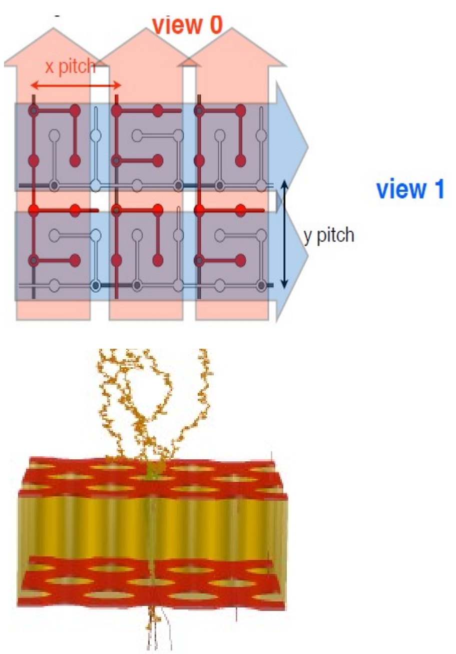


Charge Read Out Planes

Each CRP is 3m x 3m and contains:

1 x Extraction Grid
36 x Large Electron Multipliers (0.5m x 0.5m)
36 x Anodes





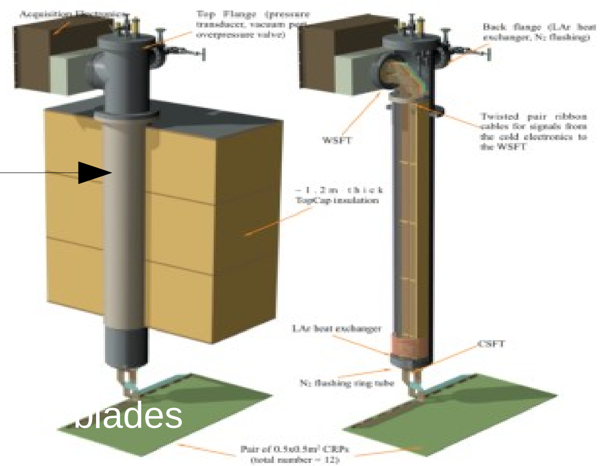
Accessible Cold Electronics

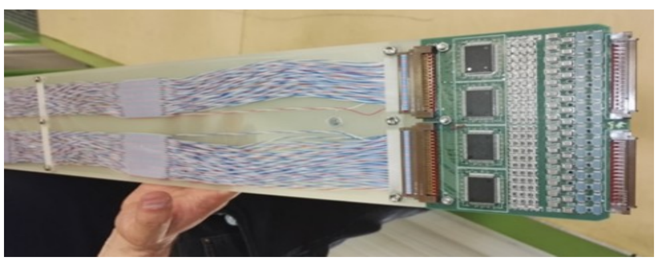
Specially developed signal chimneys

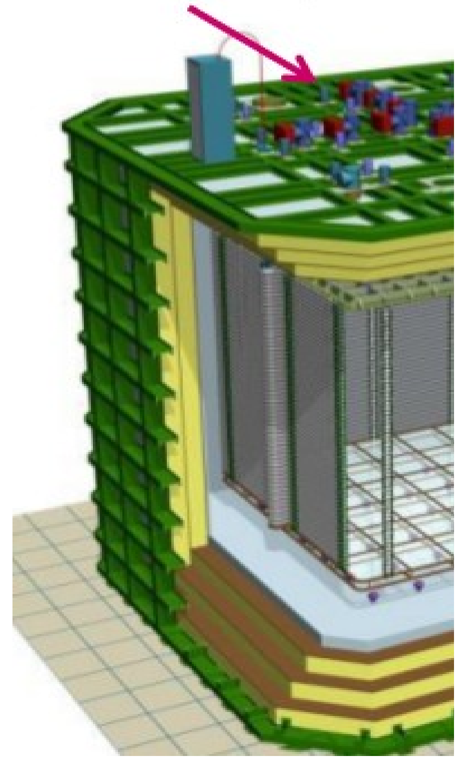
- 16-channel Cryogenic ASIC amplifiers close to the anodes but are also externally accessible!

On the tank deck (warm): digital electronics

- Based on uTCA standard
- 1 uTCA crate/ signal chimney
- AMC card – 64 channels, 12 bit ADC, 2.5 MHz
- 10 AMC cards (64 channels/card)
- Total of 12 uTCA crates (7,680 channels)

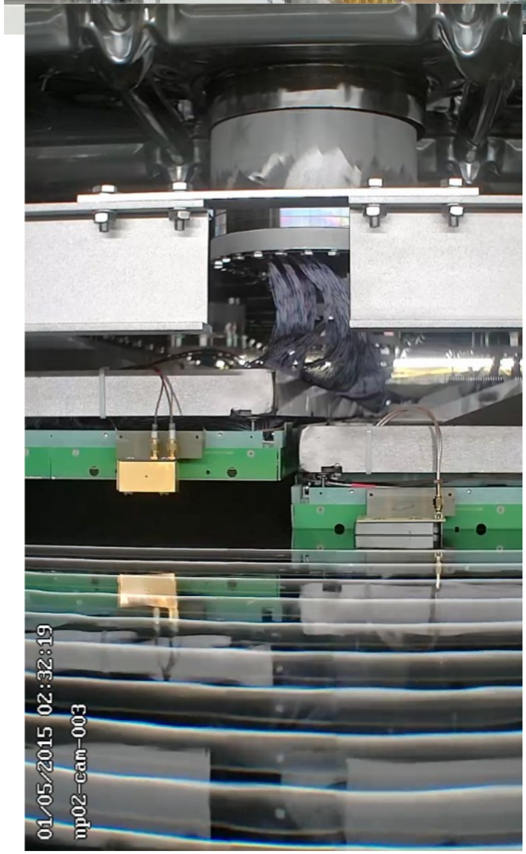






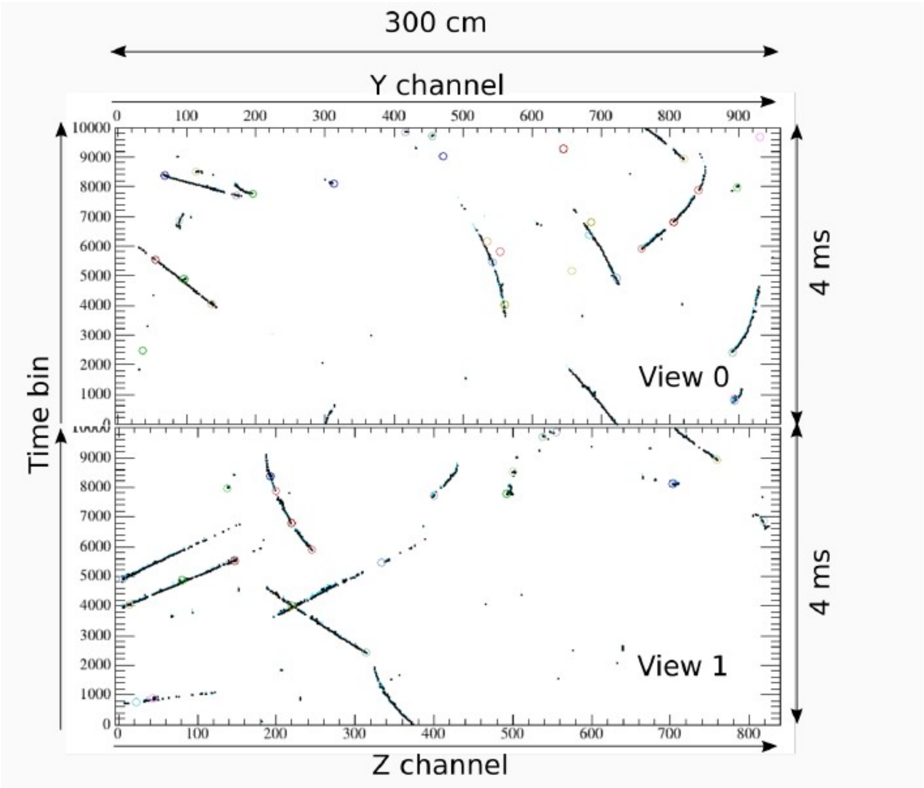
Dual Phase Status

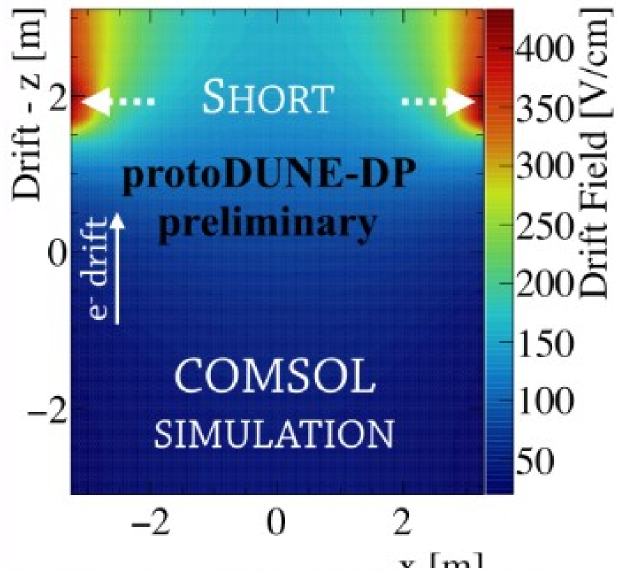
- Two runs of operation of ProtoDUNE Dual Phase (September 2019-spring 2020, and a short run during August 2020)
  - Experienced some technical issues
    - Short on Field cage (inhomogenous field)
    - Cryogenic issues – bubbling
    - Reduced gain on charge readout
- Runs of Cosmic Ray muon data (~7 kHz muon rate)
- With CR muons
  - We can explore 3D response of detector
  - Determine operational parameters such as gain, purity etc
  - Demonstrate track reconstruction

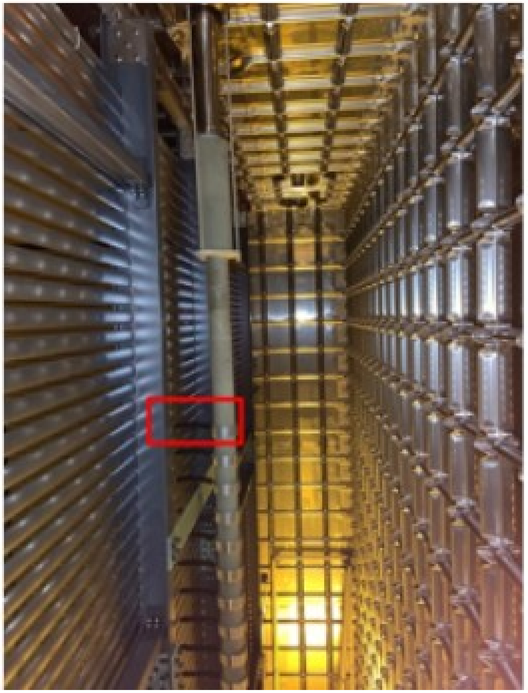


Dual Phase - HV

- Short between field cage and HV extender (08/19)
- Attempt to repair June 2020
- However situation not improved
- Cosmic Muon tracks appear curved due to inhomogenous Efield

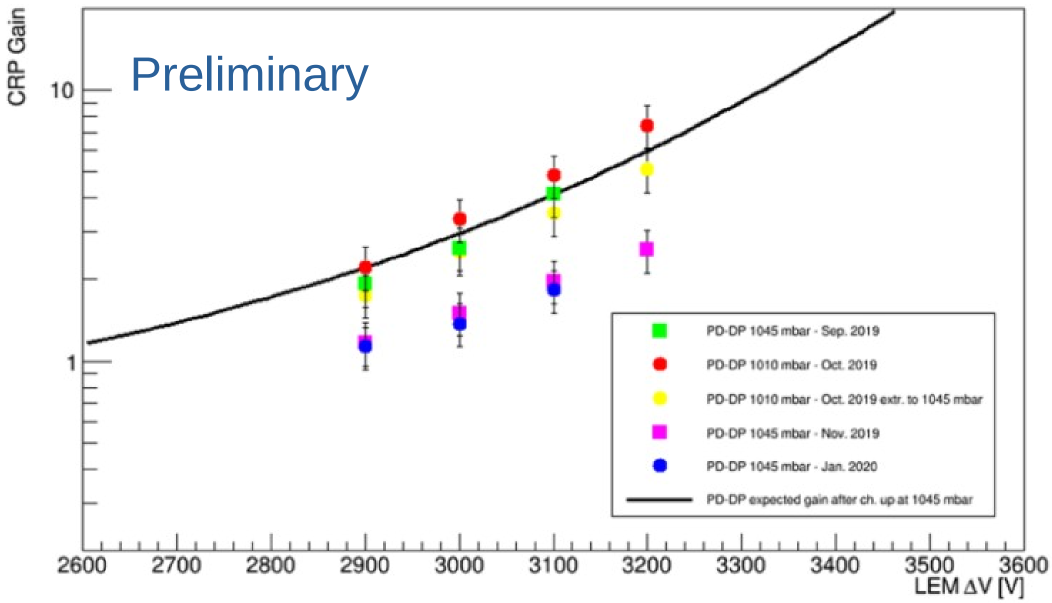


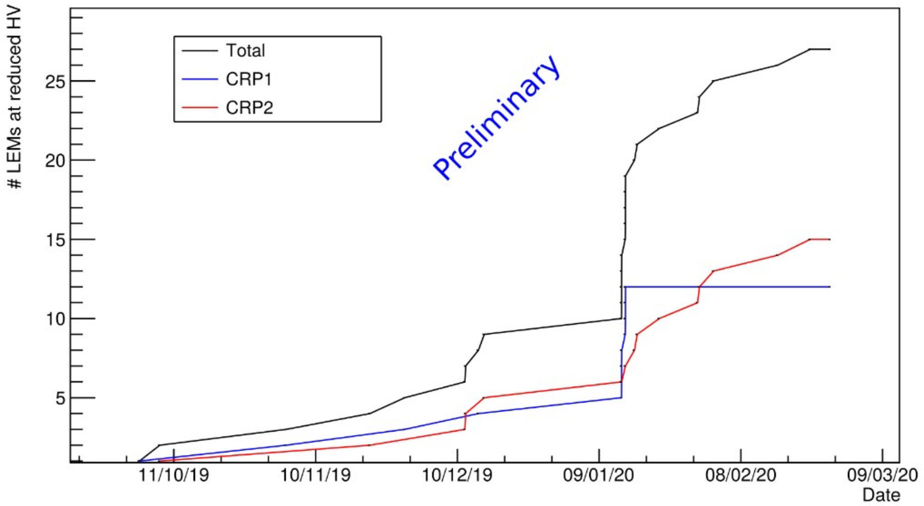




Dual Phase - CRP

- Data taken between September 2019 and January 2020
- LEM ‘charging up’ effect reduces gain
- However, gain is factor 2 lower than expected
- LEMs appear to ‘age’ during the run
- Voltage was reduced on many of them to reduce sparking rate

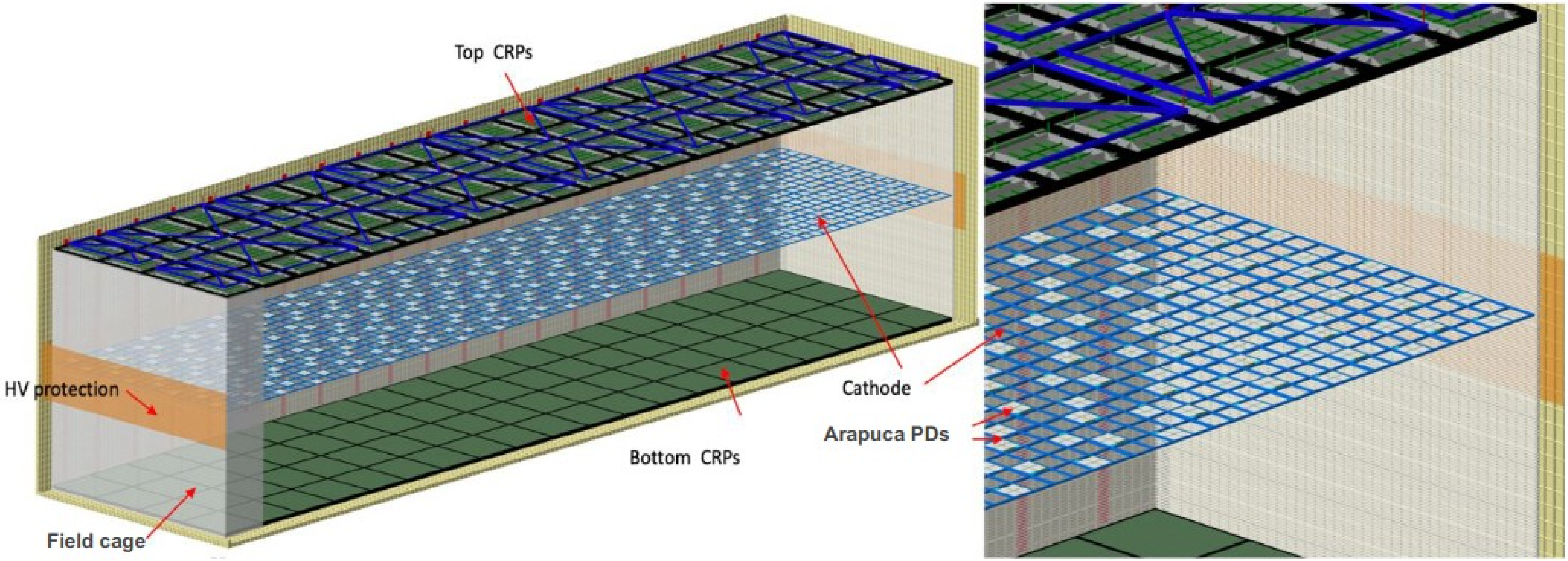




Vertical Drift

New ‘Single Phase’ concept - Synergy of Single and Dual Phase

Replace Wire Planes for Charge Readout with perforated PCB
Photodetectors embedded in Cathode

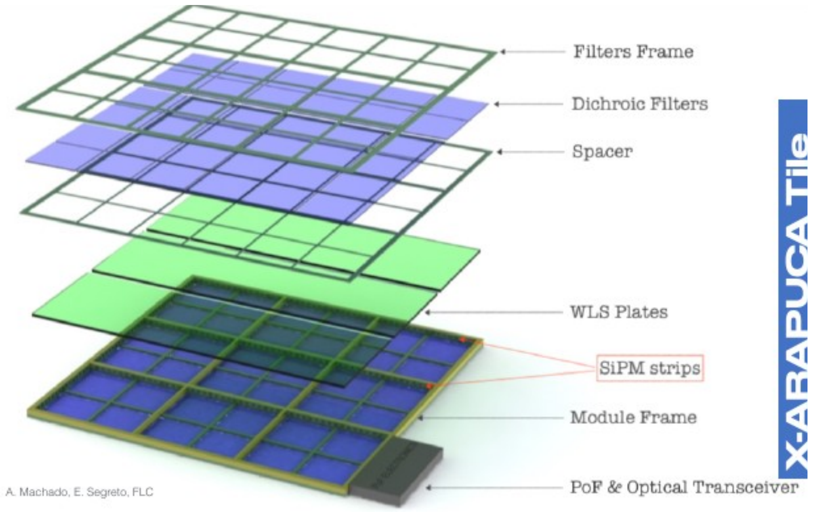


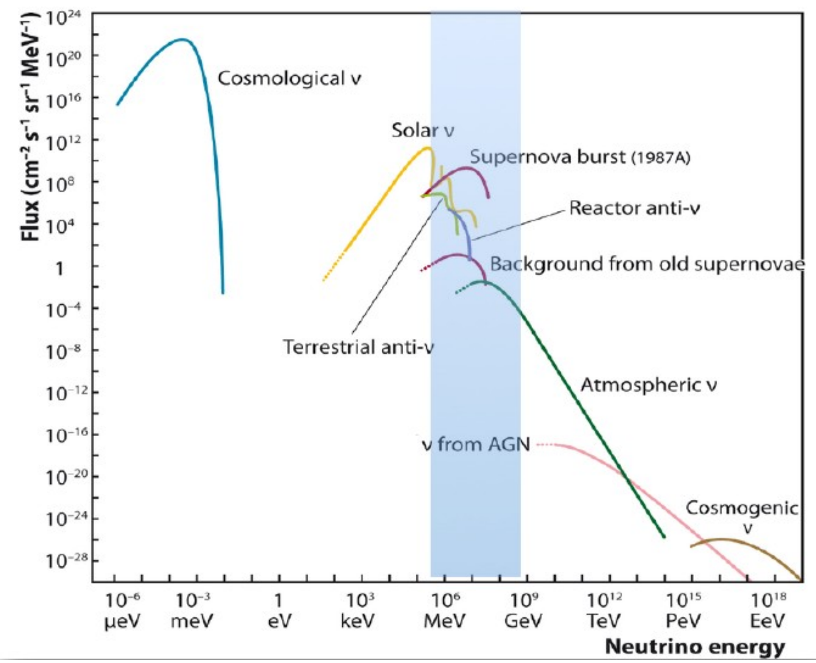
Vertical Drift - PhotoDetectors

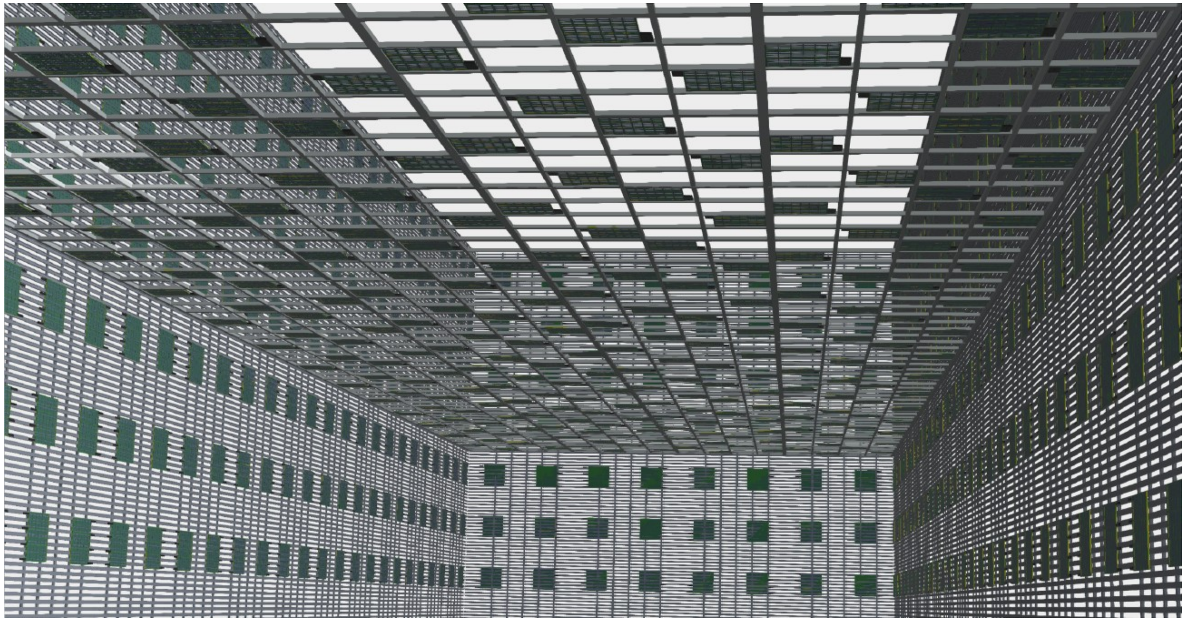
Square Arapuca Tiles embedded in Cathode

But … why not ...
Cover field cage and cathode…
..and..
Increase Light Output by Xe-doping

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





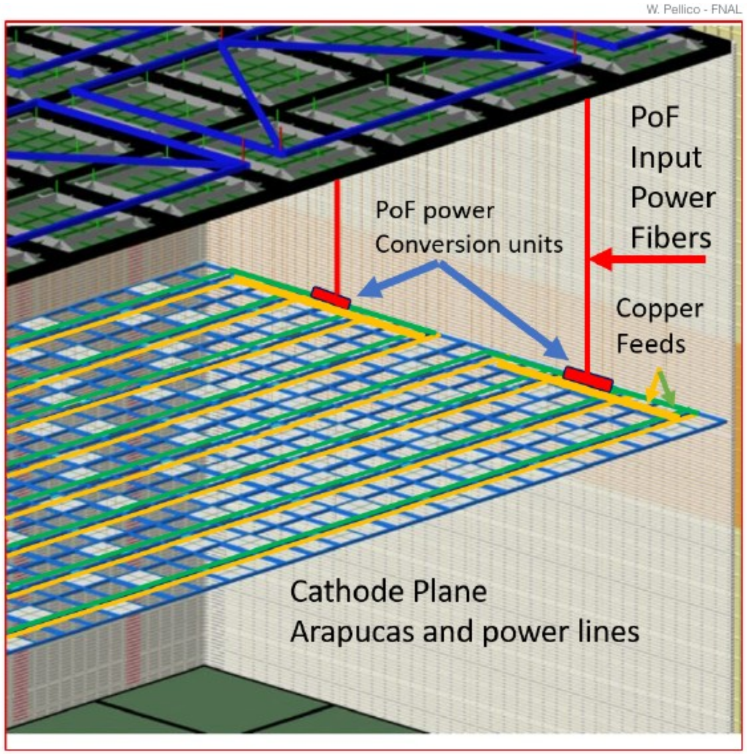


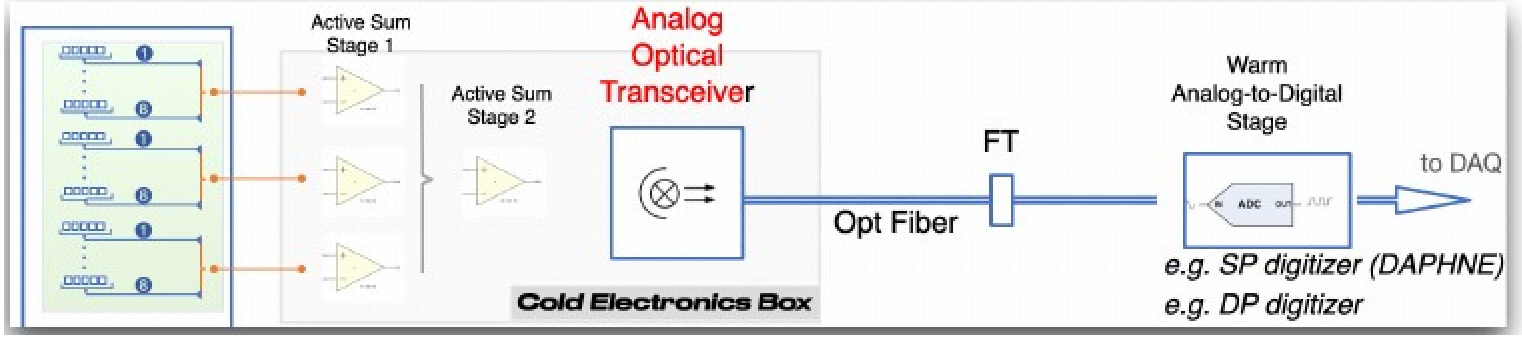
Vertical Drift

Challenge – SiPMs embedded in cathode (at -300 kV)

Power and Signal Read-out via optical fiber

Two solutions being explored:
- Complete Digital solution (ADCs, FPGA, digital transmission)
- **Analog Optical Transceiver**





Summary

- DUNE will measure neutrino and anti-neutrino oscillations over a 1300 km baseline with four 17kt LAr TPCs deployed in stages
- Two far detector designs – **Horizontal** and **Vertical Drift**
- First detector module will be **Horizontal Drift**
- Large underground detectors can do other interesting physics searches (BSM such as Nucleon decay, detect galactic Core-Collapse SN etc)