Neutrino Oscillation Experiments

IOP Institute of Physics

HEPP & APP Annual Conference 2022
3–6 April 2022, Rutherford Appleton Laboratory STFC, Oxfordshire, UK

Stefan Söldner-Rembold, University of Manchester

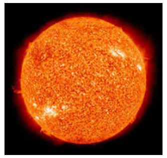
Pontecorvo–Maki–Nakagawa–Sakata Matrix

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

See talk by Melissa Uchida this morning

$$U_{\mathrm{PMNS}} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

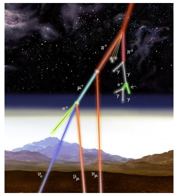
$$c_{ij} = \cos\theta_{ij};\, s_{ij} = \sin\theta_{ij}$$



- θ_{12}: “solar mixing angle”
- mixes ν_e with ν_1 and ν_2

θ_{13}: mixes ν_e with ν_3

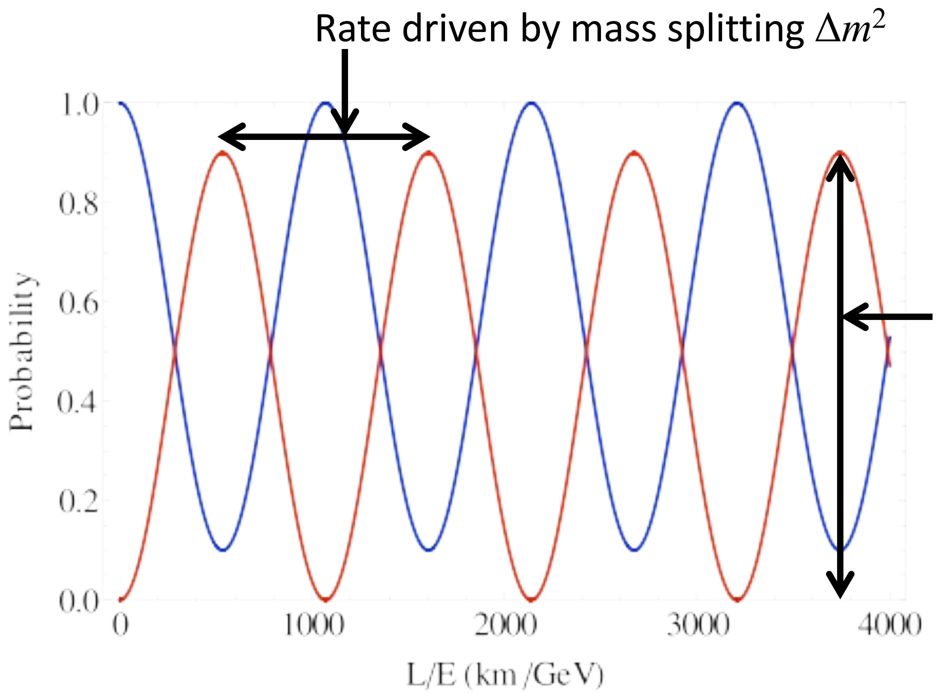
δ: complex phase



- θ_{23}: “atmospheric mixing angle”
- mixes ν_μ with ν_τ

Neutrino flavour oscillations

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2_{21}[\text{eV}^2]L[\text{km}]}{E[\text{GeV}]}\right)$$



ν_α component

ν_β component

The PMNS Matrix and CP violation

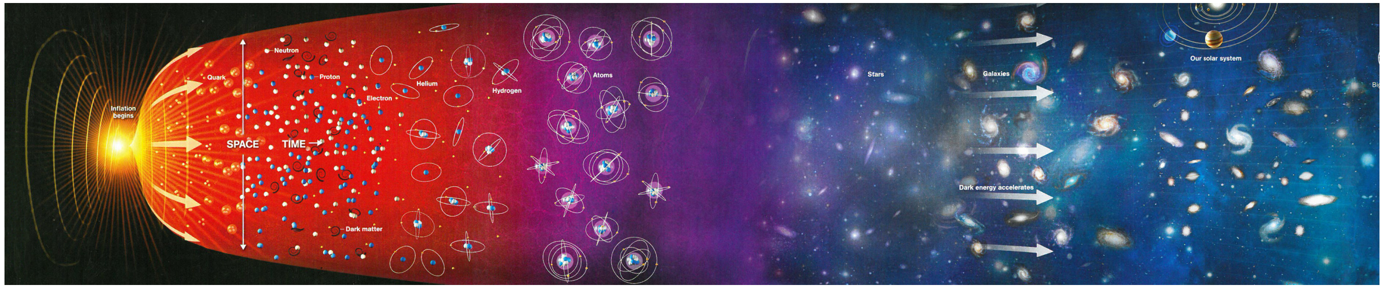
complex CP phase

$$U_{\mathrm{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

$$\delta \neq \{0, \pi\}$$

CP Violation involving neutrinos might provide support for *Leptogenesis* as mechanism to generate the Universe's matter-antimatter asymmetry.

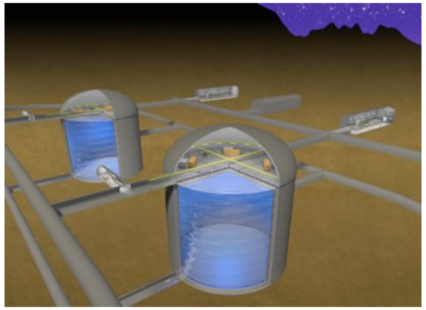


Optimizing detectors for neutrino oscillations

L/E(1st max) = 500 km/GeV
L/E (2nd max) = 1700 km/GeV

L ≈ 300 km

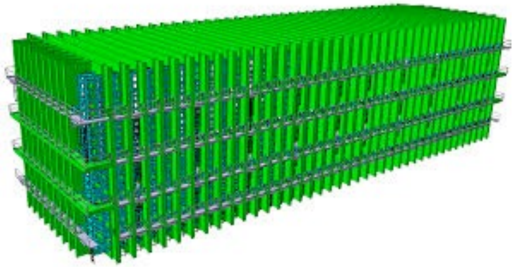
- no matter effects.
- use narrow width neutrino beam (off axis) with E < 1 GeV
- observe first oscillation maximum
- "counting experiment"



Water Cherenkov (HK)

L = 1300 km

- matter effects
- use broad-band neutrino beam (on axis).
- observe first and second oscillation maximum.
- unfold CP and MO effects through energy dependence



Liquid argon (DUNE)

$\nu_\mu \longrightarrow \nu_e$ appearance sensitive to δ

$$\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) \approx\; & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\
& + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{aL}\Delta_{21}\cos(\Delta_{31}-\delta) \\
& + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin(aL)}{aL}\Delta_{21}^2
\end{aligned}$$

$$a = \frac{G_F N_e}{\sqrt{2}}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

$\nu_\mu \longrightarrow \nu_e$ appearance sensitive to δ

$$
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\end{aligned}
$$

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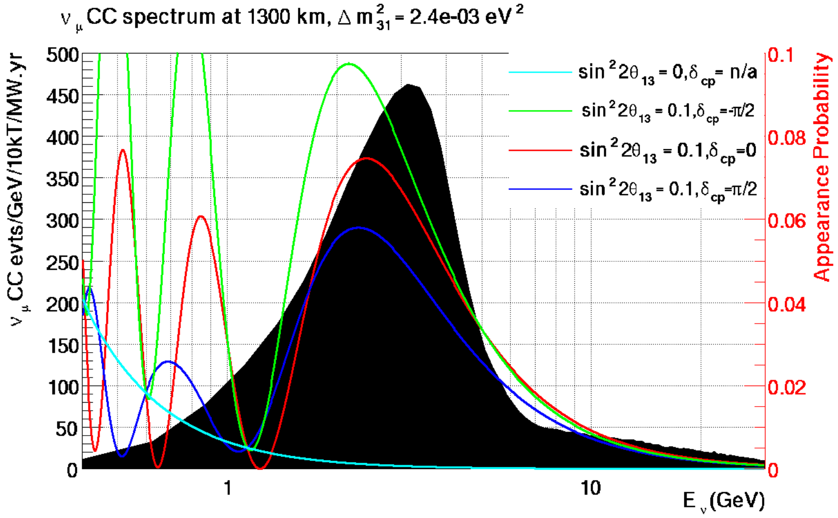

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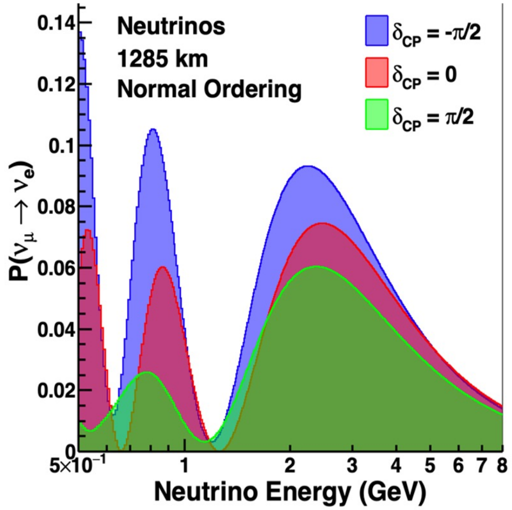
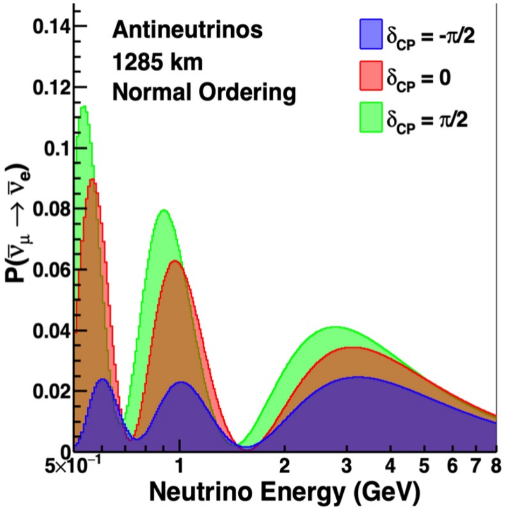
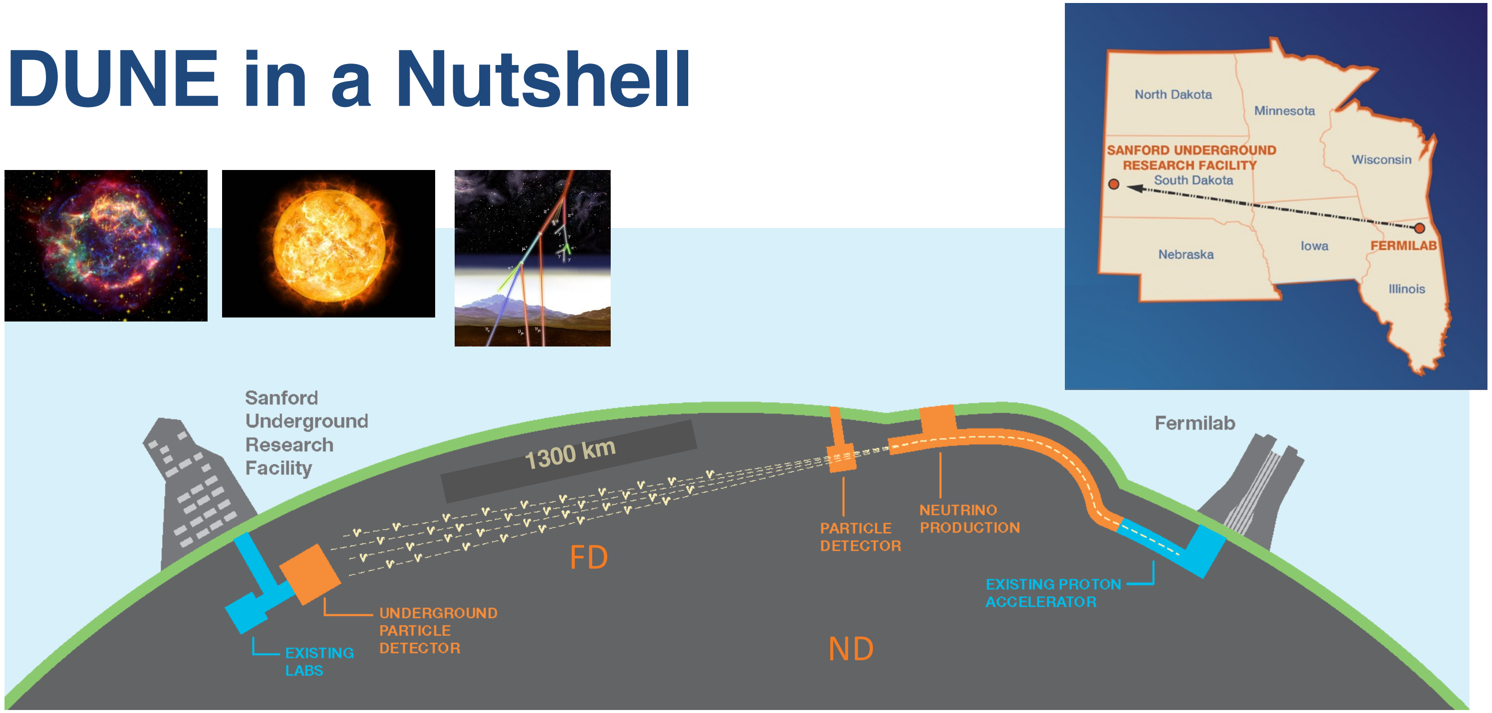


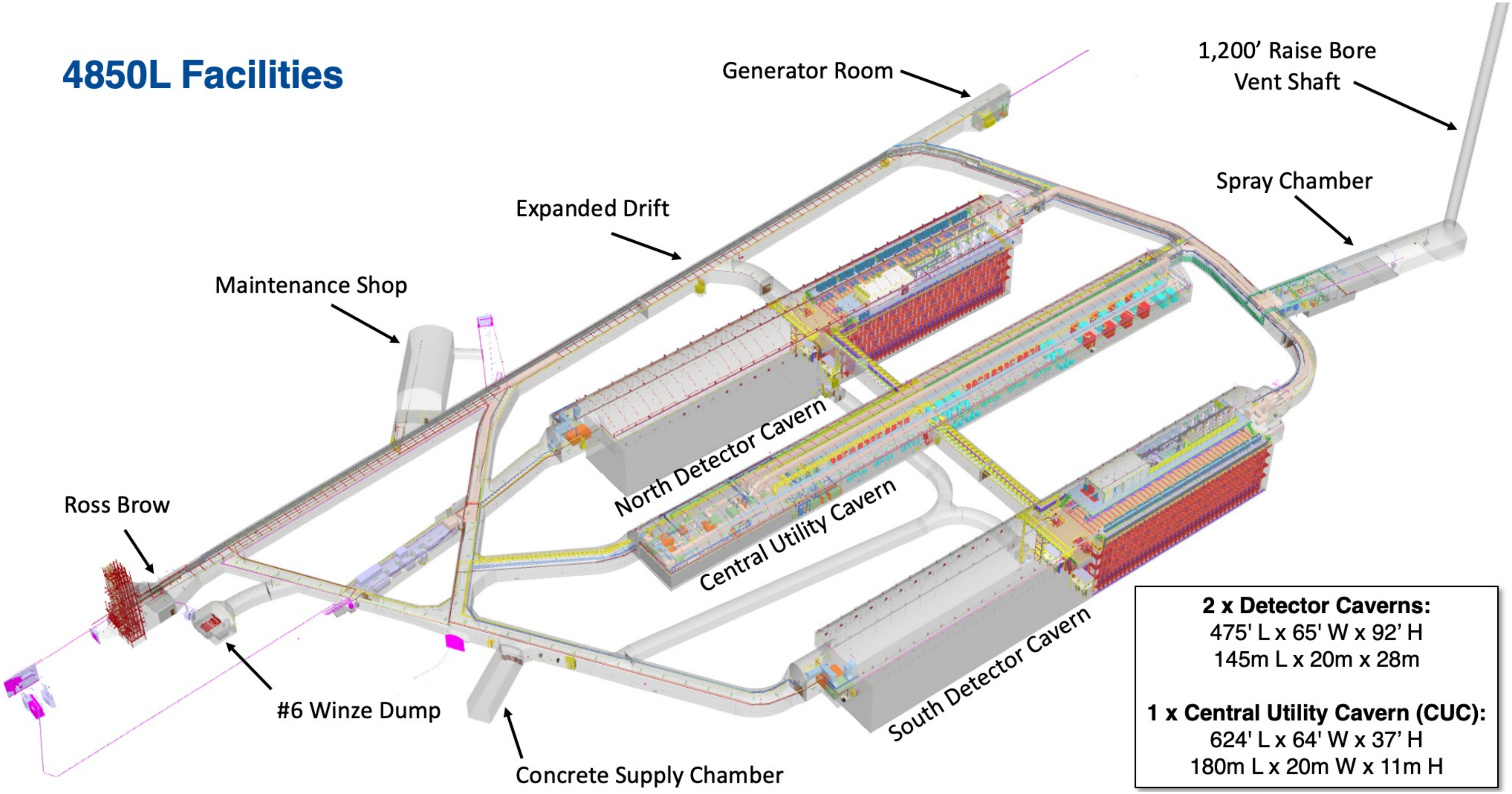


DUNE in a Nutshell



1. A high-power, wide-band **neutrino beam** (~ GeV energy range).
2. A ≈ 70 kt **liquid-argon Far Detector** in South Dakota, located 1478 m underground in a former gold mine.
3. A **Near Detector** located approximately 575 m from the neutrino source at Fermilab close to Chicago.

4850L Facilities



2 x Detector Caverns:
475' L x 65' W x 92' H
145m L x 20m x 28m

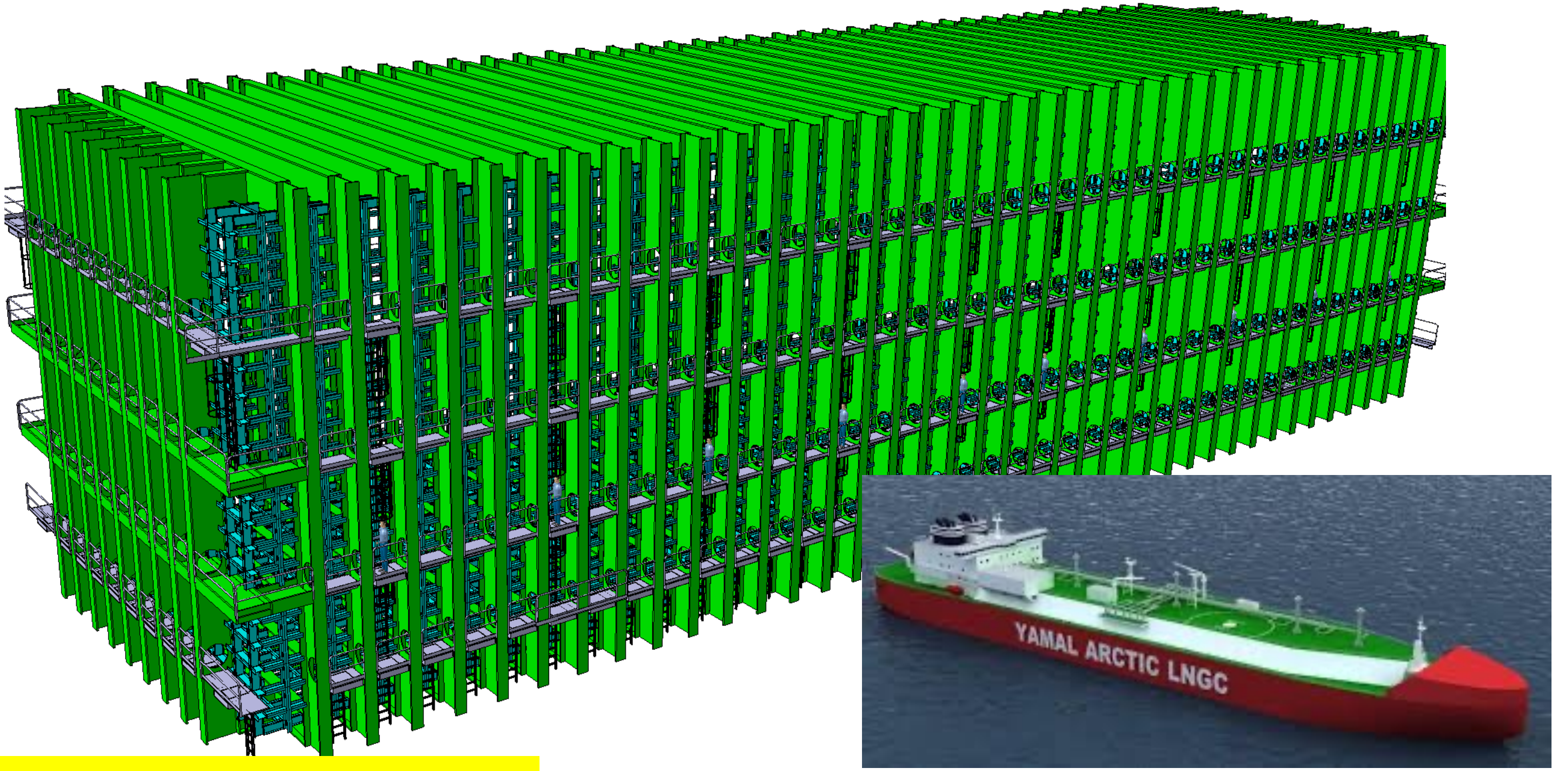
1 x Central Utility Cavern (CUC):
624' L x 64' W x 37' H
180m L x 20m W x 11m H

12 Feb 2022

Central Utility Cavern Pilot Drift Breakthrough

Four cryostats filled with liquid argon

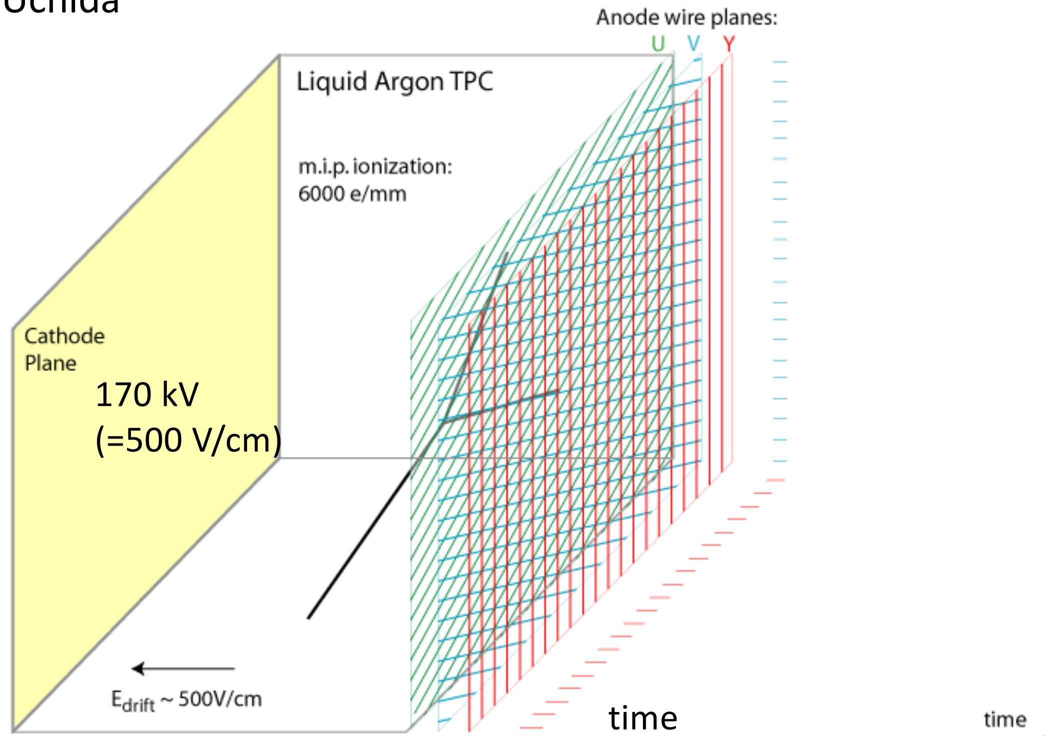
Each of the four cryostats contains 17,000 tons of liquid argon at 89 K (-184°C or -299°F)



<u>External Dimensions:</u> 19 m x 18 m x 66 m

DUNE: Liquid-argon Time Projection Chamber

See talk by Melissa Uchida

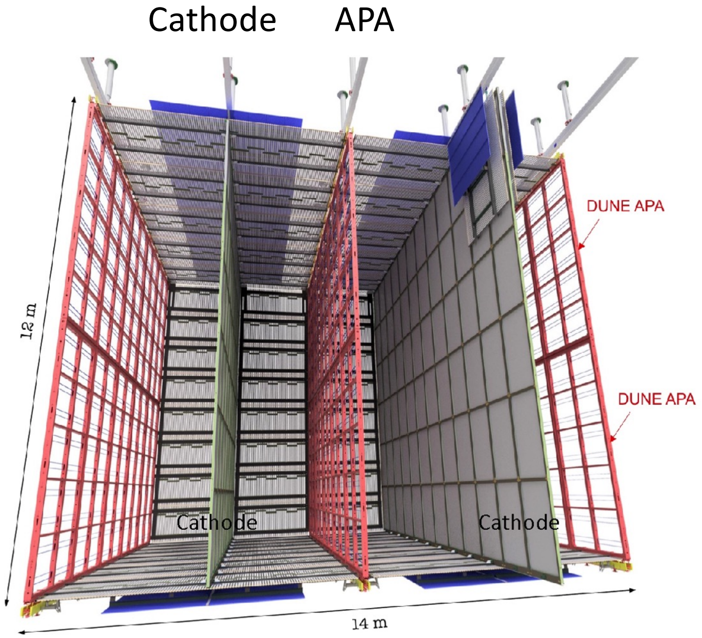


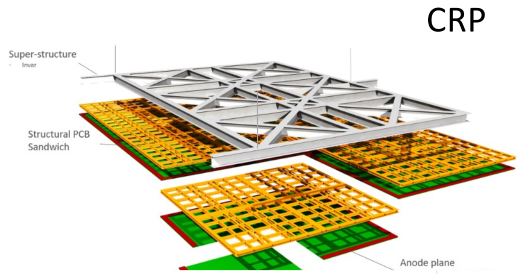
170 kV
(=500 V/cm)

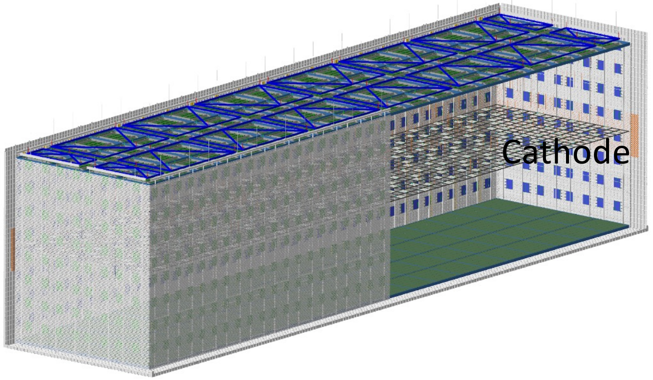
time

3.4 m → 2.13 ms

Horizontal and Vertical Drift



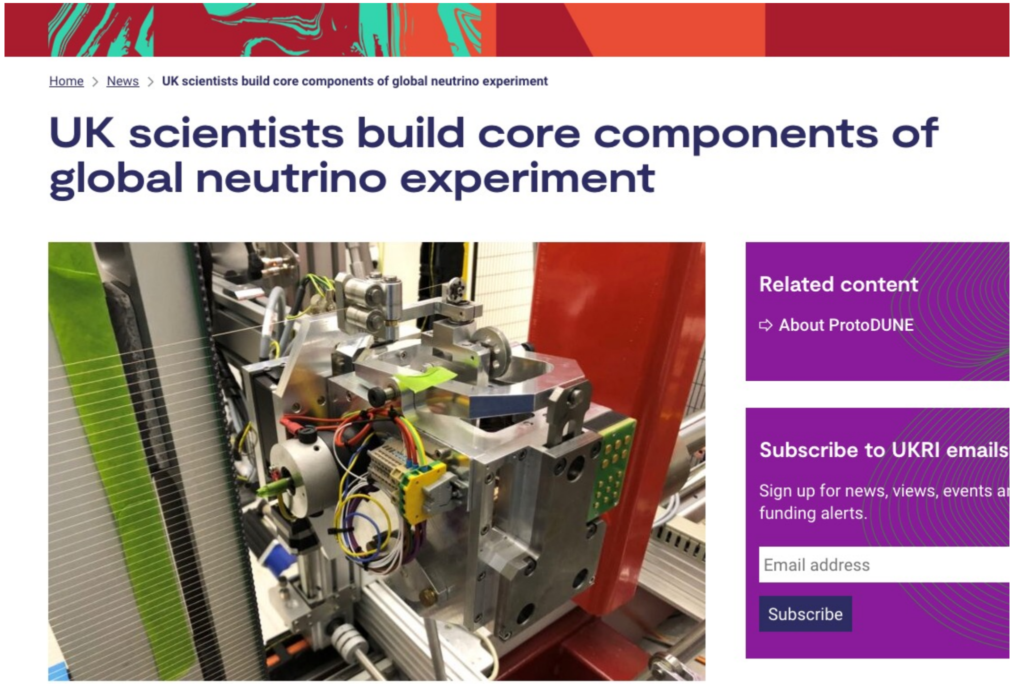




Charge produced in neutrino interaction drifts horizontally and is read out by large wire planes (APAs).

Charge produced in neutrino interaction drifts vertically and is read out by strips on printed circuit boards mounted on a charge readout plane (CRP).

Module 1: Horizontal Drift



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UK scientists build core components of global neutrino experiment

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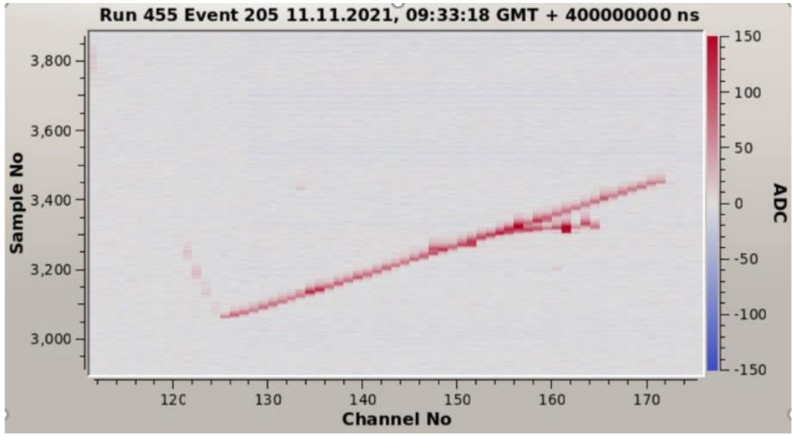
- 150 Anode Plane Assemblies (APA)
- 130 in UK and 20 in US

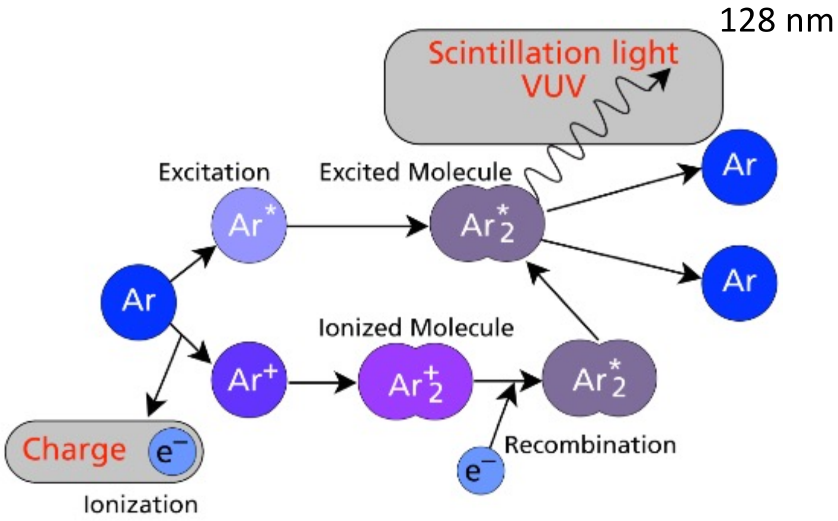
ProtoDUNE at CERN

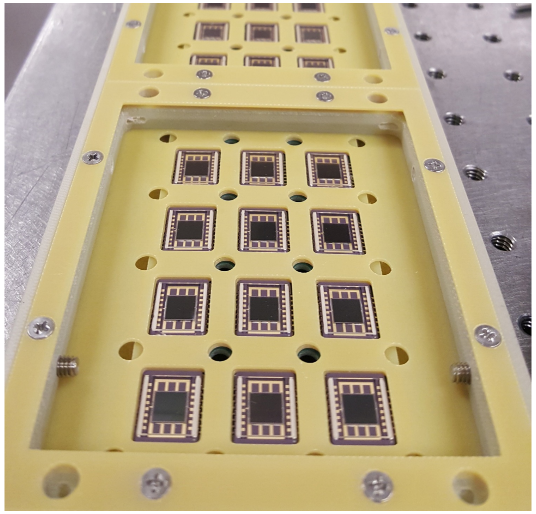
Module 2: Vertical Drift

Successful tests at CERN,
leading to design of ProtoDUNE
Module-0 for Vertical Drift.



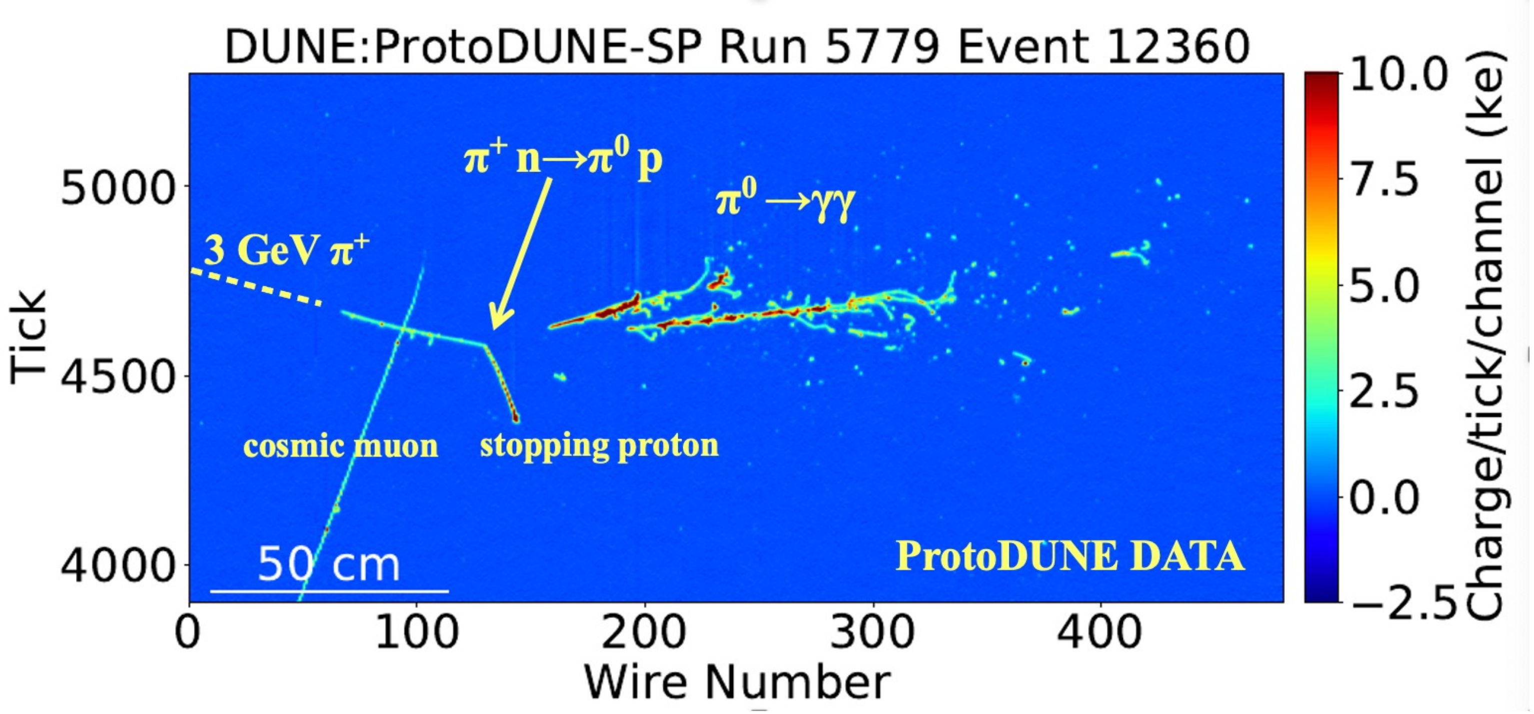
Photon Detection





- LArTPCs rely on light for event reconstruction and timing.
- “Arapuca” light trap technology developed by Brazilian groups.

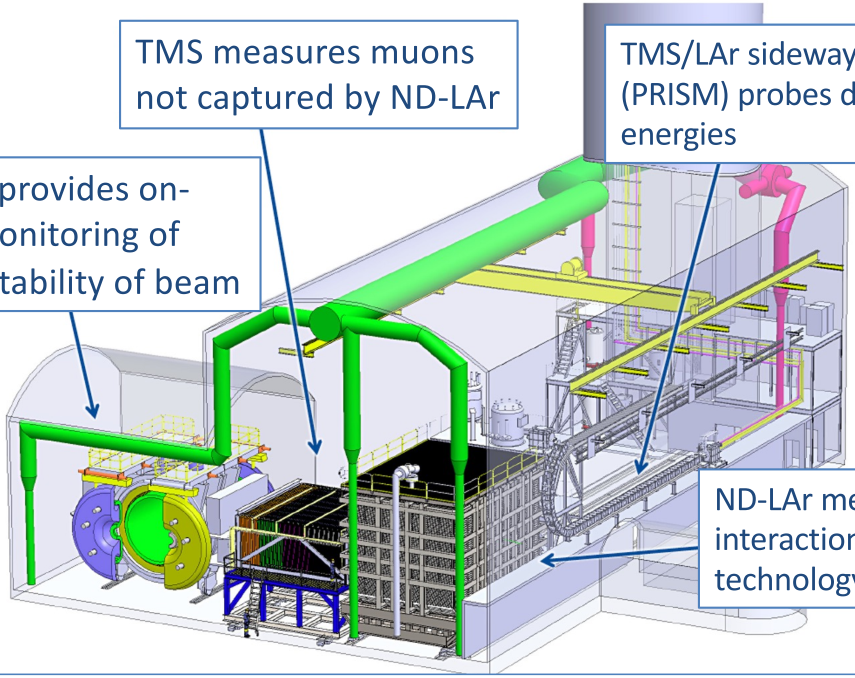
A ProtoDUNE-HD Data Event



Reconstruction of events performed by PANDORA framework with the use of Grid computing resources, both areas UK-led.

DUNE Phase I Near Detector

We expect to replace TMS by a gas-argon TPC for Phase-II.



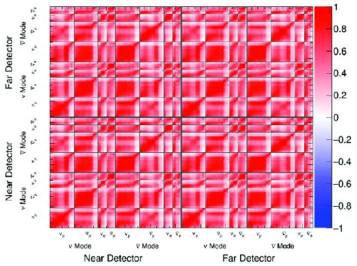
TMS measures muons not captured by ND-LAr

TMS/LAr sideways movement (PRISM) probes different neutrino energies

SAND provides on-axis monitoring of time-stability of beam

ND-LAr measures neutrino interactions on argon using TPC technology (equivalent to FD).

Systematics

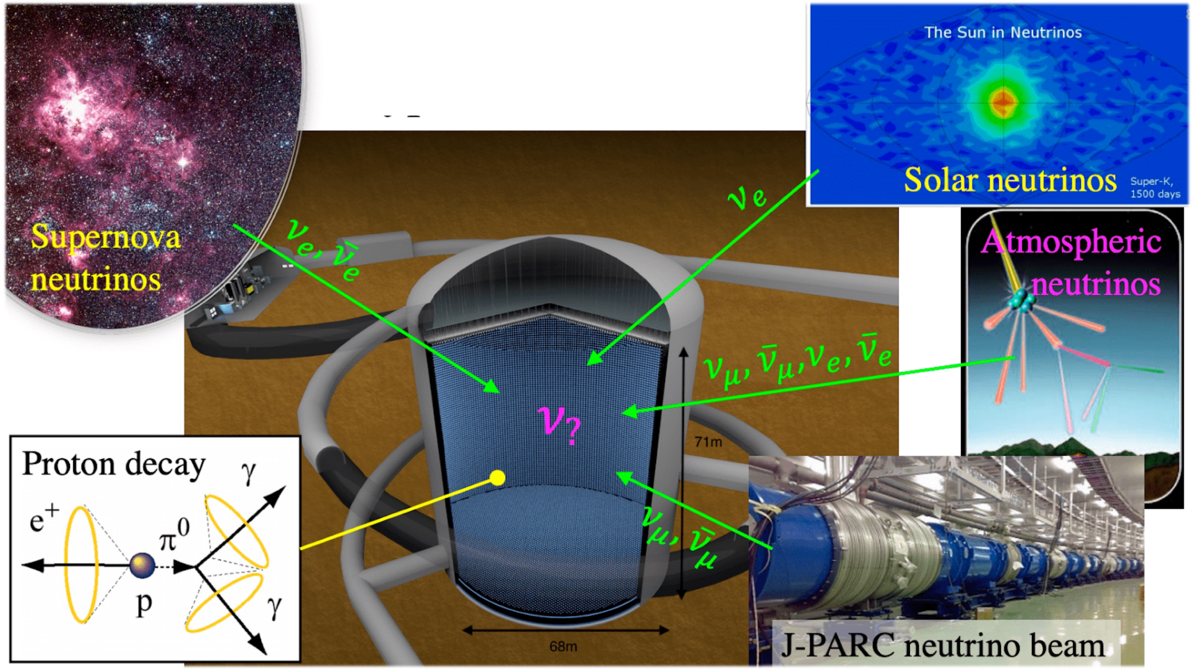


- Near Detectors constrain systematic uncertainties for long-baseline oscillation analysis

  Neutrino flux & cross-section, and detector systematics
- In addition, >100 million interactions will also enable a rich non-oscillation physics programme (e.g. BSM).

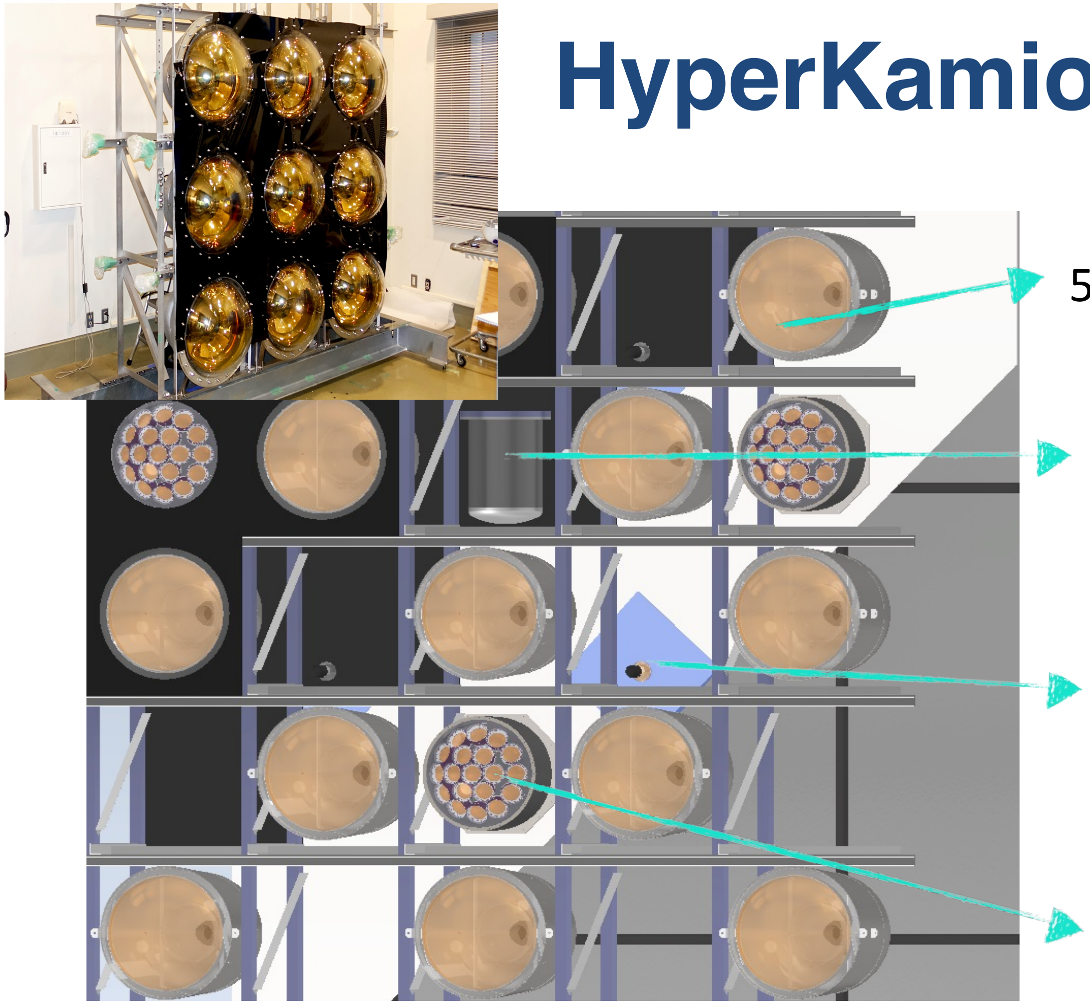
HyperKamiokande in a Nutshell

Thanks to
Francesca Di Lodovico



- **8.4 times larger fiducial mass** (190 kiloton) than SK with **double-sensitivity PMTs**
- New (IWCD) and upgraded (@280m) Near Detectors to control systematic uncertainties.
- J-PARC neutrino beam to be upgraded from 0.5 to 1.3 MW

HyperKamiokande

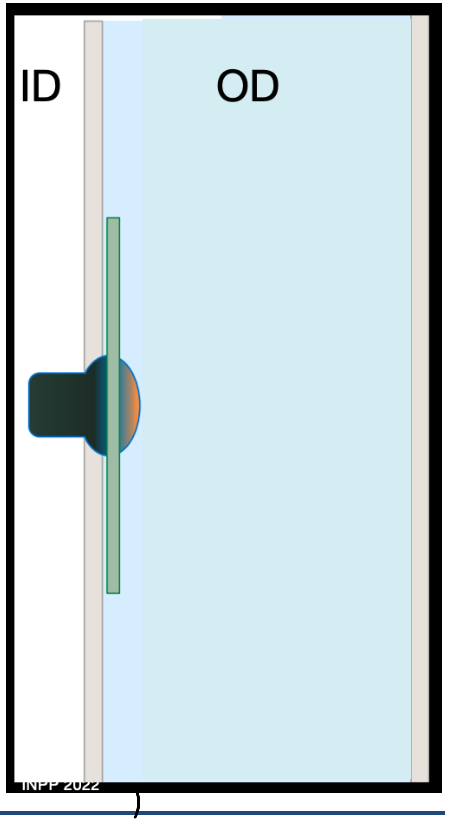


50 cm PMTs

Electronics

Outer Detector

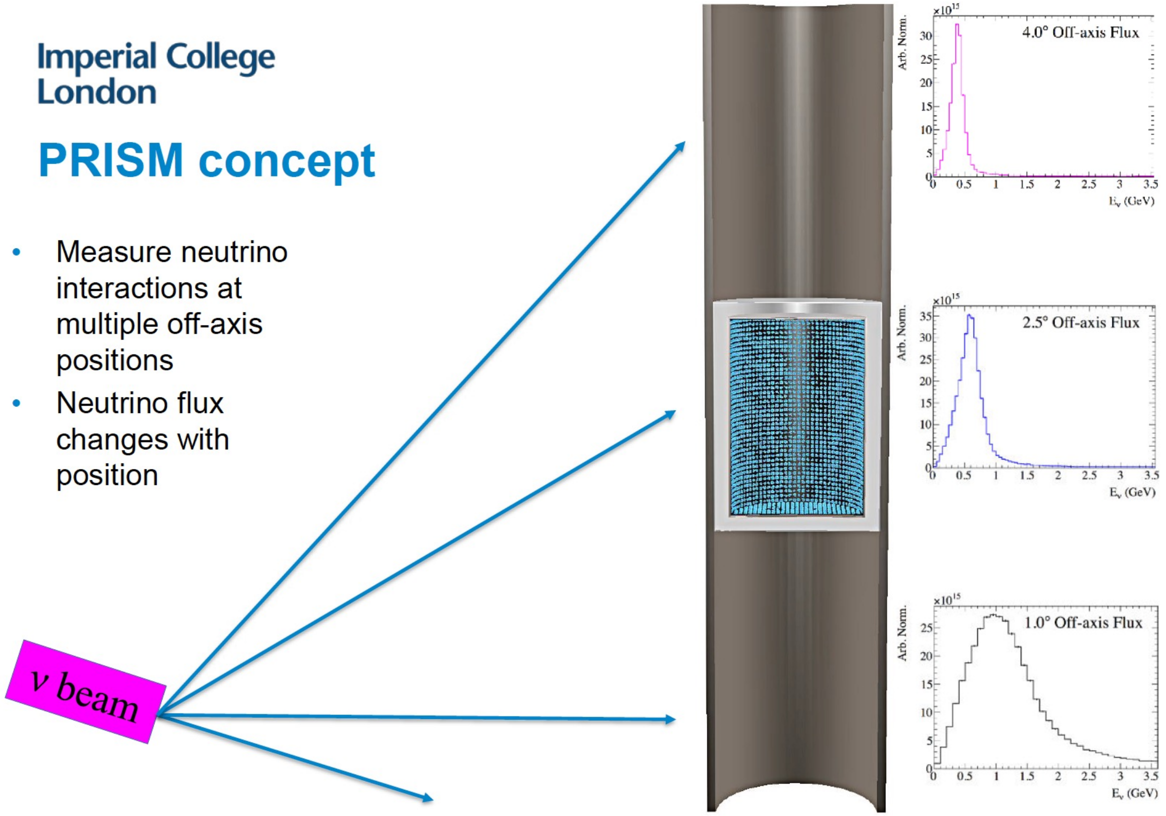
mPMT

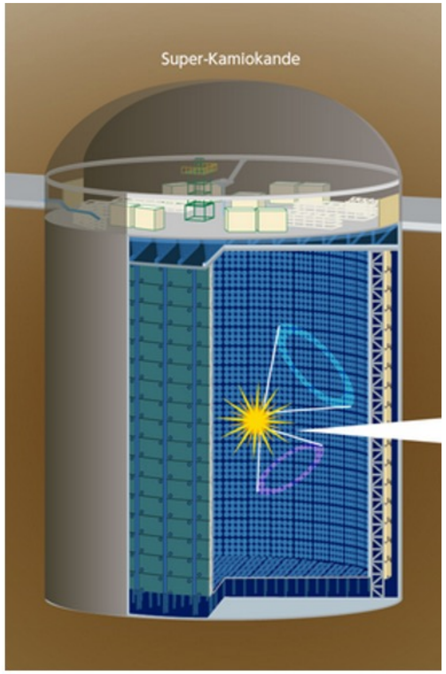


Imperial College London

PRISM concept

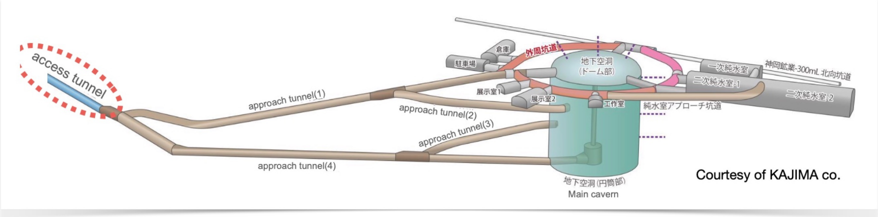
- Measure neutrino interactions at multiple off-axis positions
- Neutrino flux changes with position



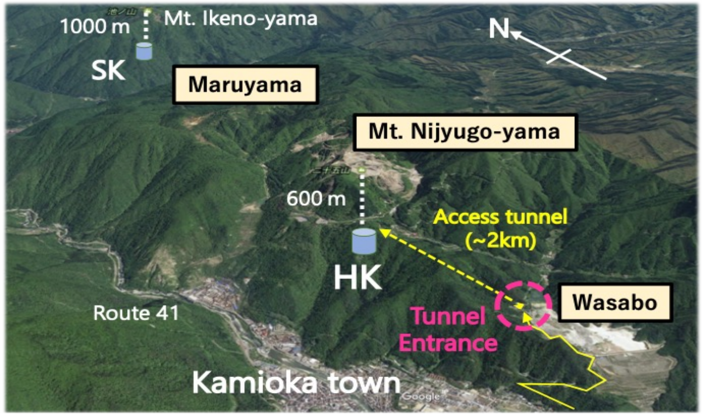


- PMT frame moving inside 10 m wide and 50 m high cylinder with water
- ICWD located at ~1-2 km, scanning the beam from 1˚ to 4˚ off-axis angle

HK Access Tunnel

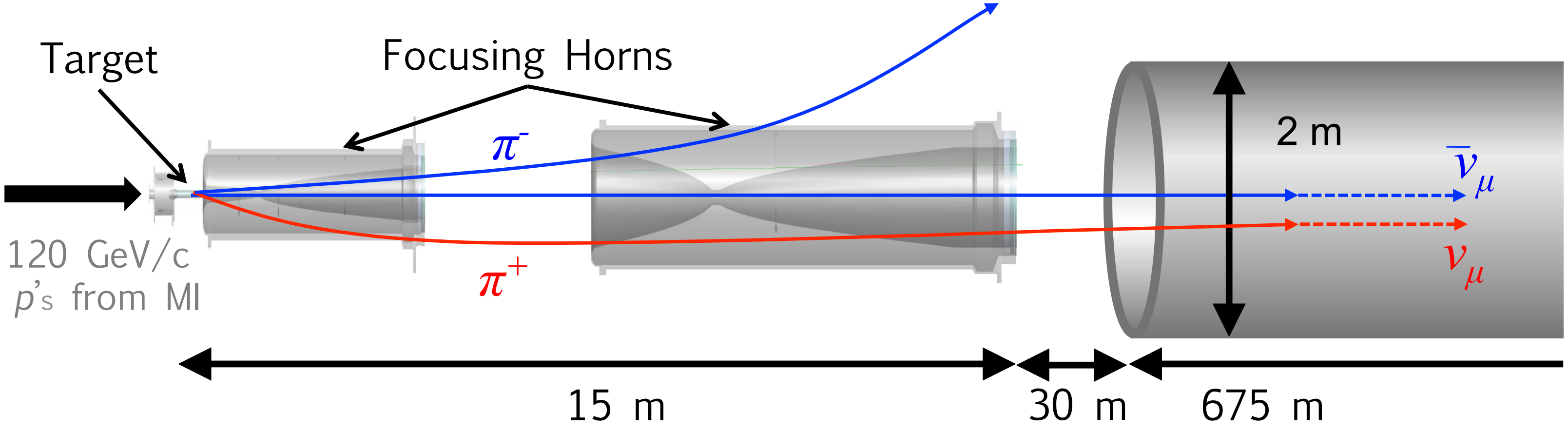


Courtesy of KAJIMA co.



Access tunnel (1873 m) completed in February 2022 and work on approach tunnel has started.

How to make a neutrino beam



- Protons on target → charged pions → neutrinos
- Since neutrinos cannot be focused, we focus the charged pions so that the decay products travel forwards, using a magnetic focusing horn.
- Neutrino flux depends on hadronic cross sections, description of beam line..
- Major UK contributions (through STFC/RAL) to PIP-II, neutrino beam targets.

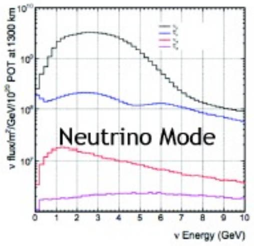
How to make a neutrino beam

- T2K 1.3 MW prototype target production
- All graphite and titanium parts ready for final assembly and welding.

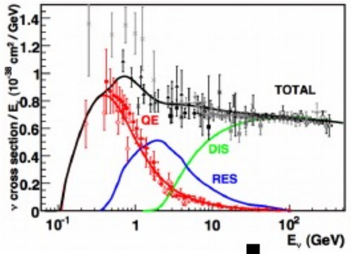
Schedules

- DUNE Phase I:
  - Far Detectors (first two modules) operation in 2029
  - Beam (1.2 MW) in 2030
  - Near Detector (SAND, TMS+NDLAr, PRISM) in 2031
- DUNE Phase II:
  - Modules 3 and 4
  - Beam upgraded to 2.4 MW
  - Upgrade to Near Detector (gas-argon)
- HyperKamiokande:
  - Commissioning 2026
  - Far Detector operation in 2026

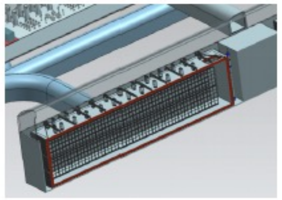
ν Flux



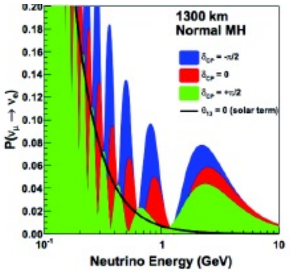
ν-Ar Interactions



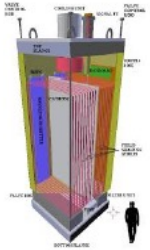
Far Detector



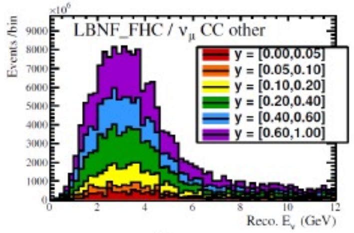
Oscillations

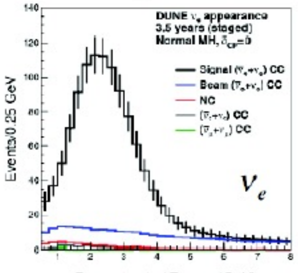


Near Detector

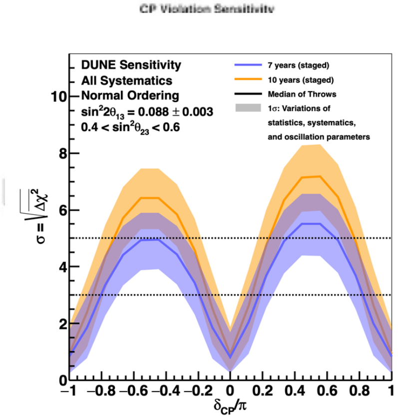


ND and FD Spectra





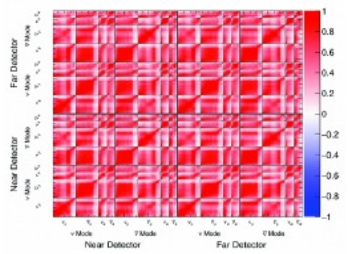
Final Sensitivity



Statistical Test

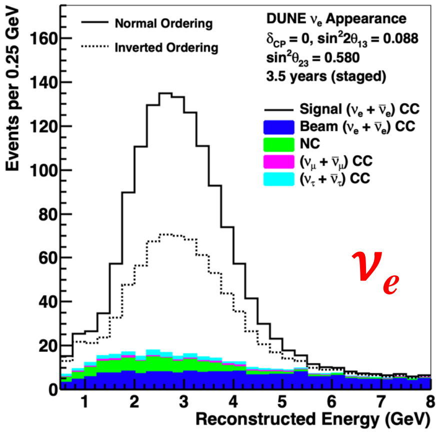
$$\boxed{\sqrt{\Delta\chi^2}}$$

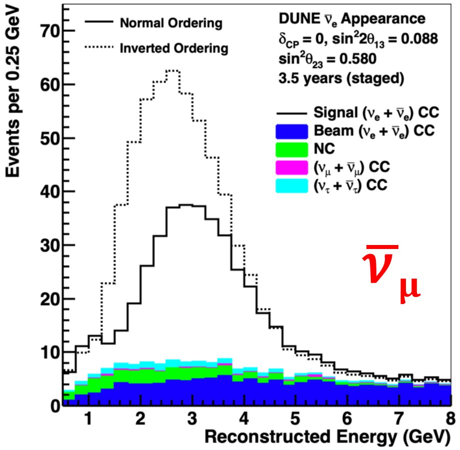
Systematics



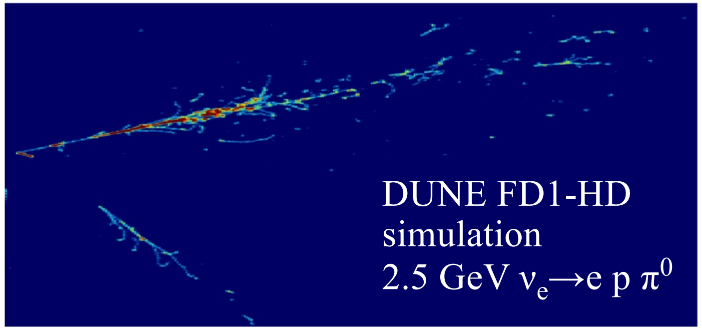
7 years

DUNE simulation

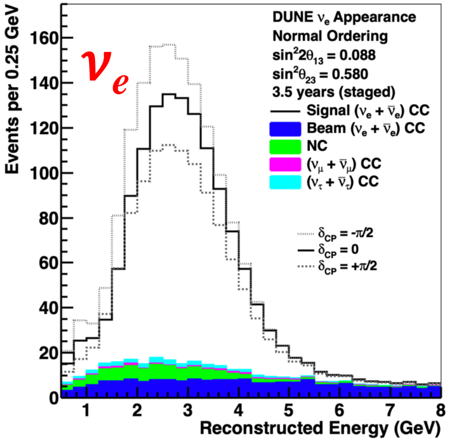


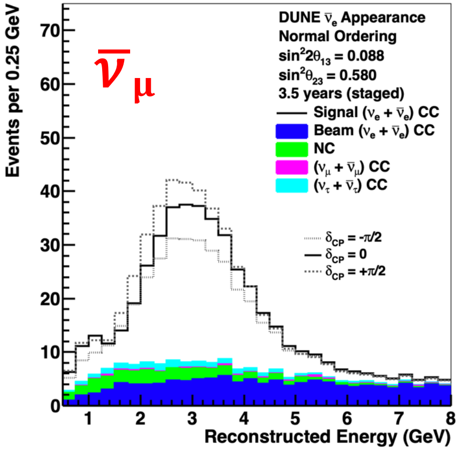


variation with mass ordering



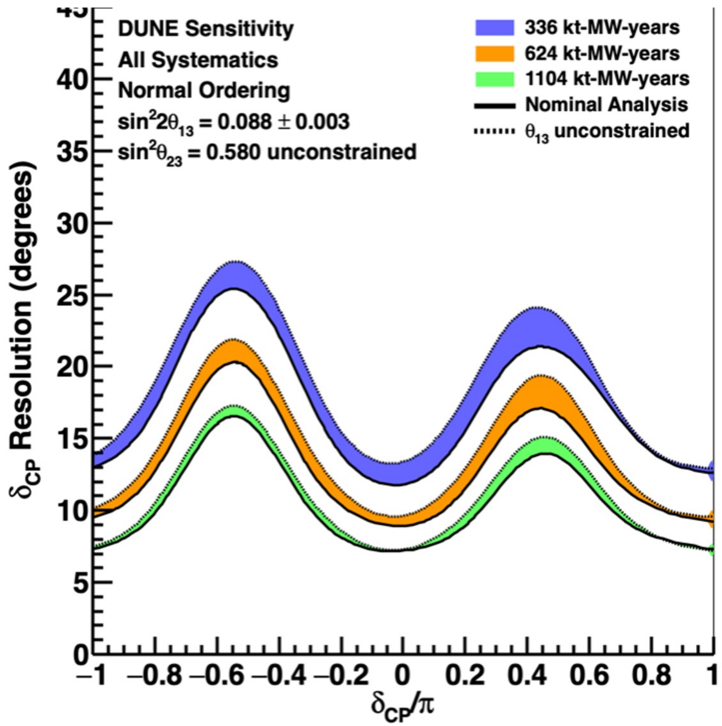
DUNE FD1-HD simulation
2.5 GeV $\nu_e \rightarrow e\, p\, \pi^0$

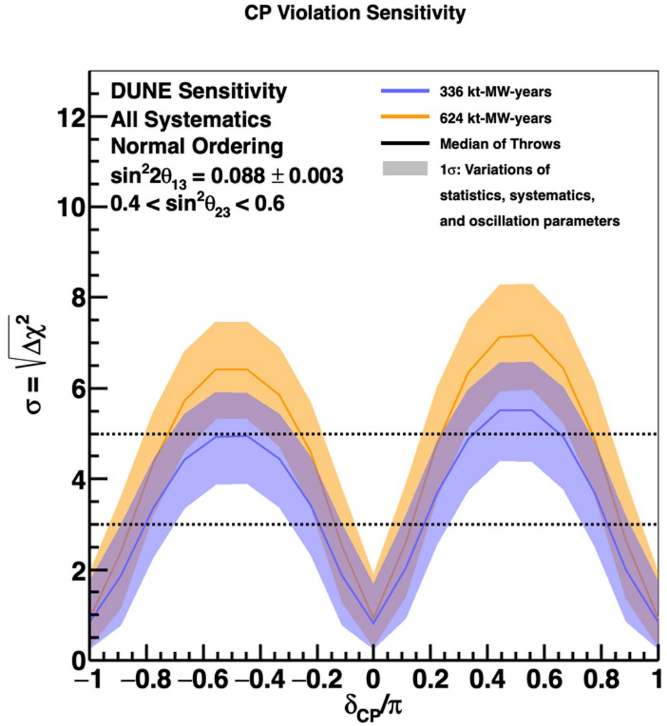




variation with δ_{CP}

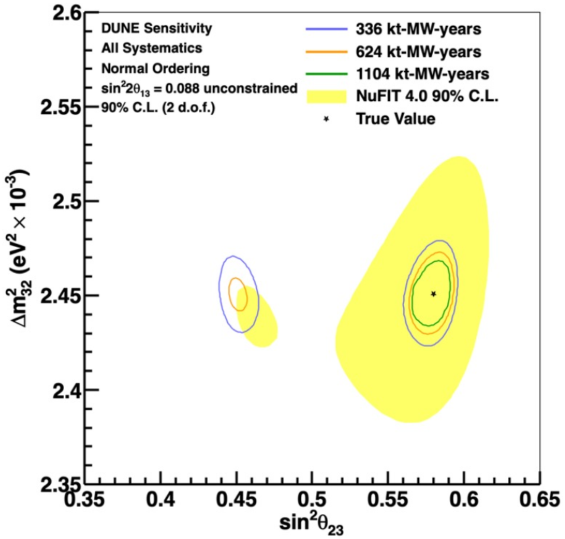
DUNE: Sensitivity to CP Violation

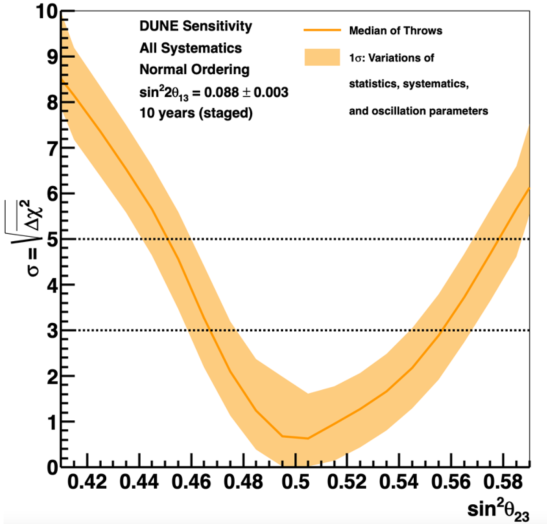


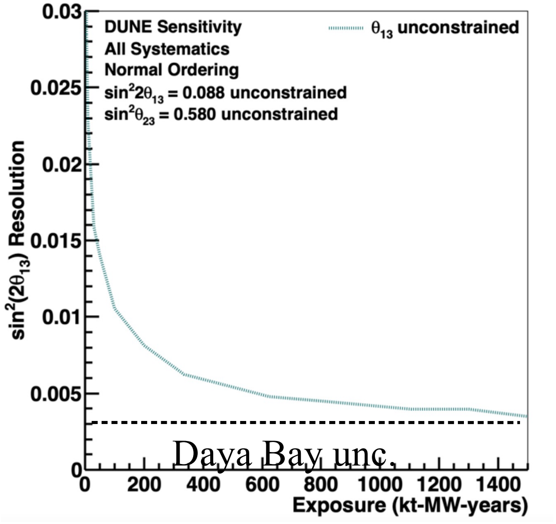


- 5σ discovery potential for CP violation over >50% of δ_{CP} values
- 7-16° resolution to δ_{CP}, *without reliance on other experiments*

DUNE: Unitarity tests

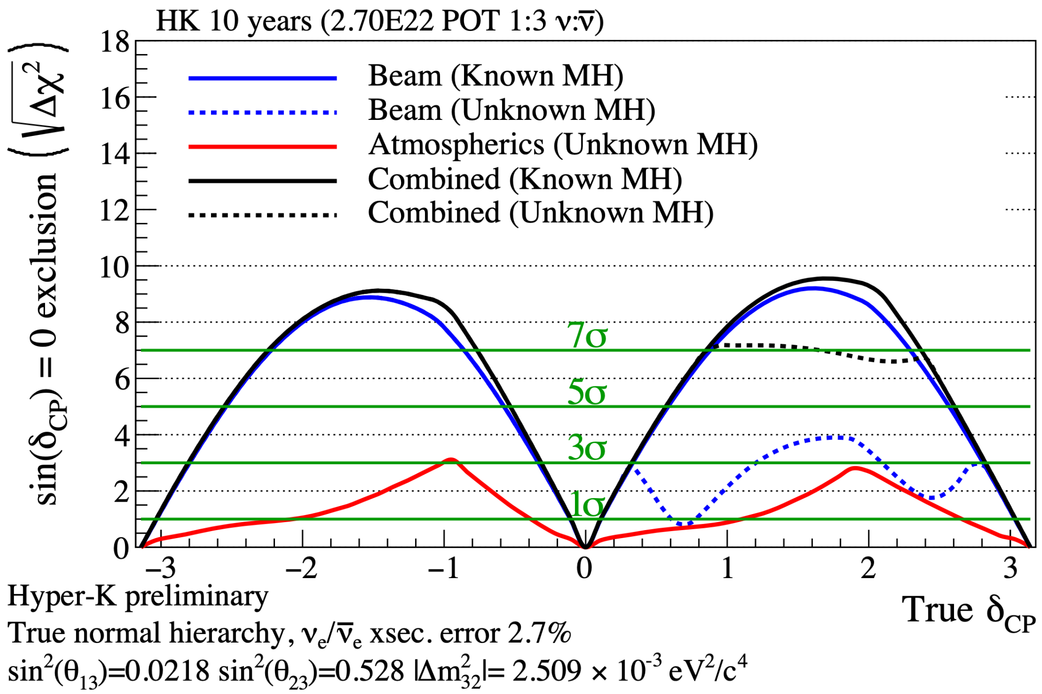






- World-leading precision on Δm^2_{32} and θ_{23}, including octant, and novel PRISM technique that is less sensitive to systematic effects
- Ultimate reach does not depend on external θ_{13} measurements, and comparison with reactor data directly tests PMNS unitarity

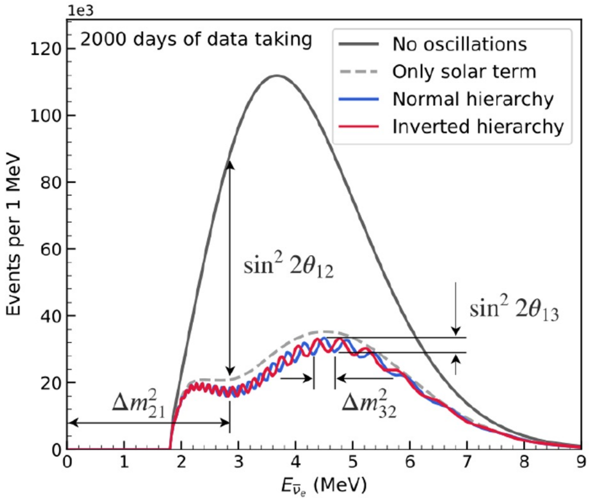
HK: Sensitivity to CP Violation



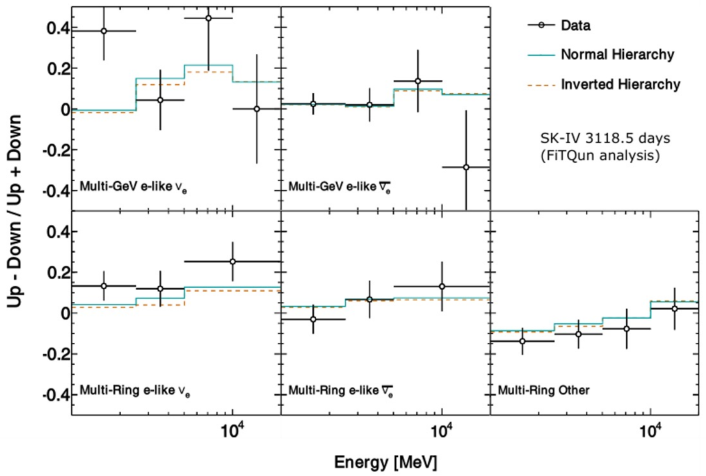
- Due to short baseline HK cannot resolve MO/CP degeneracy.
- If MO unknown, beam analysis less sensitive for some values of δ.
- Joint atmospheric and beam analysis increases sensitivity.

Other mass hierarchy measurements

JUNO: Snowmass2021 JUNO LOI



Super-K: PTEP Vol. 2019, Iss. 5 (2019)

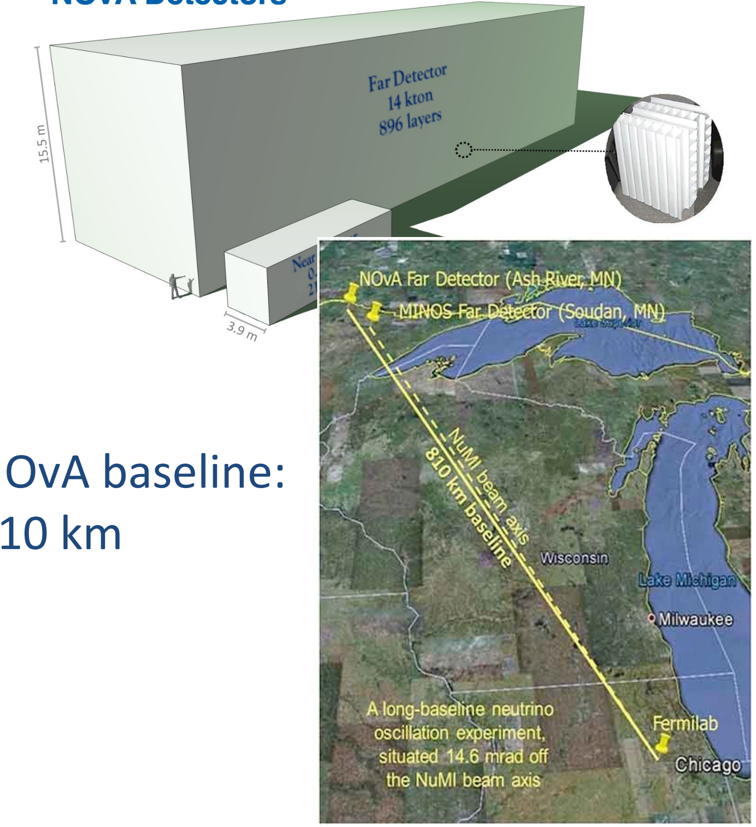


- JUNO can determine mass ordering by differentiating rapid wiggle with unprecedented energy resolution.
- Large water Cherenkov detectors can model ν_e/ν_e flux and cross sections and look for a small differences in the up/down asymmetry

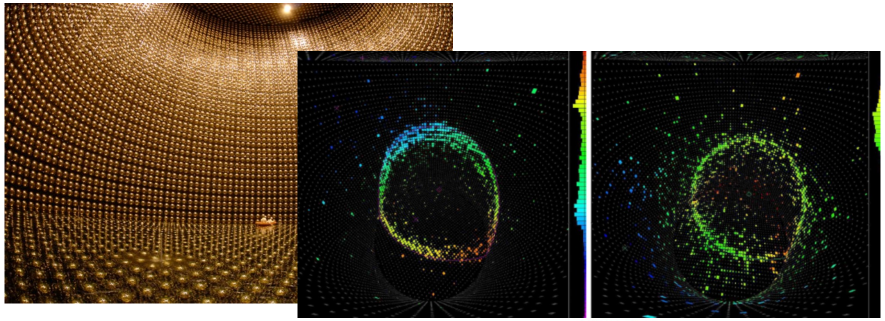
Operating Long-baseline experiments

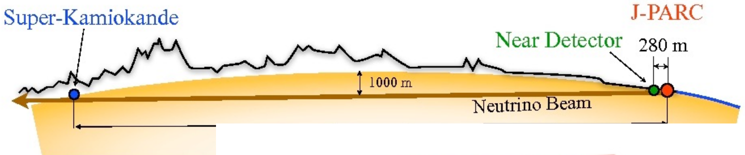
T2K baseline:
295 km

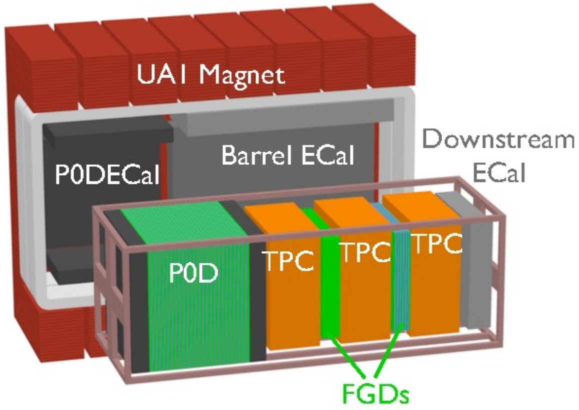
NOvA Detectors



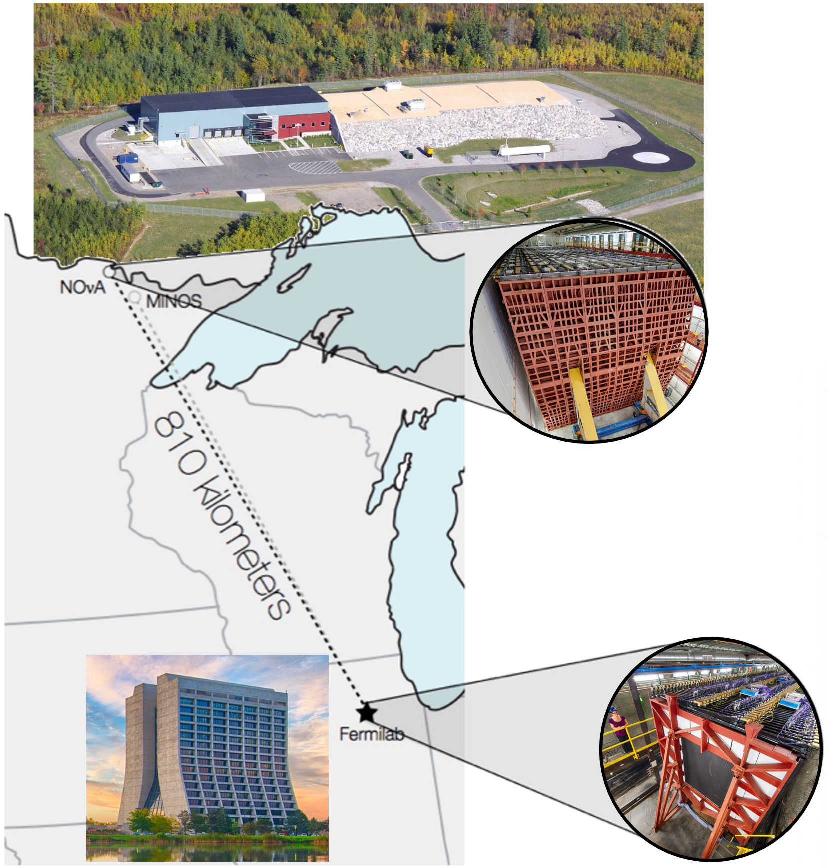
NOvA baseline:
810 km



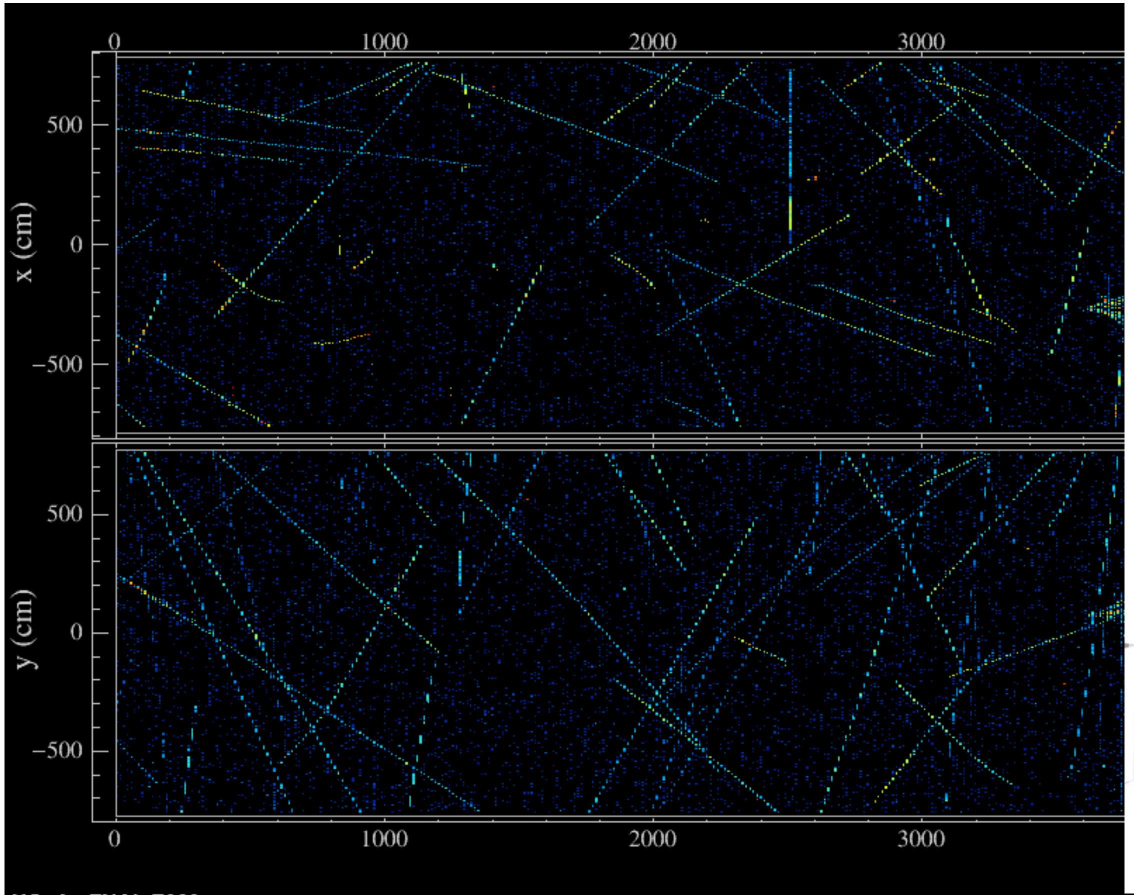


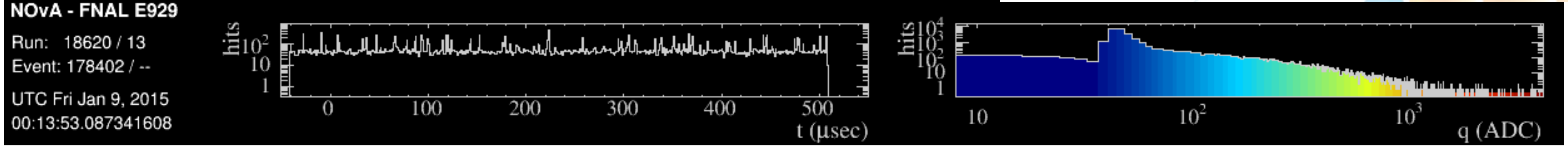


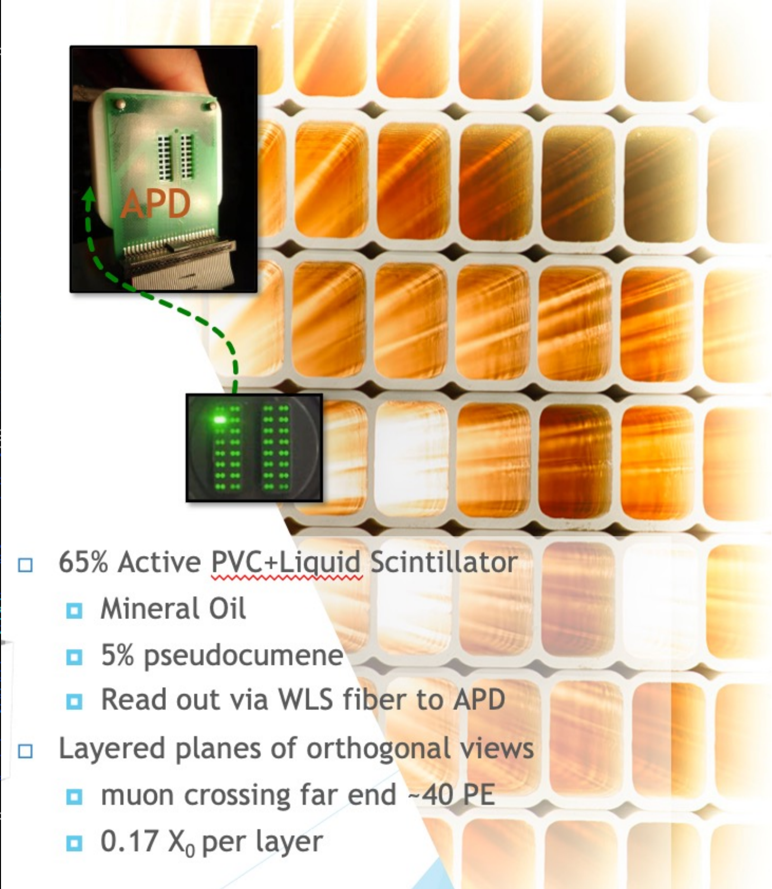
NOvA Experiment



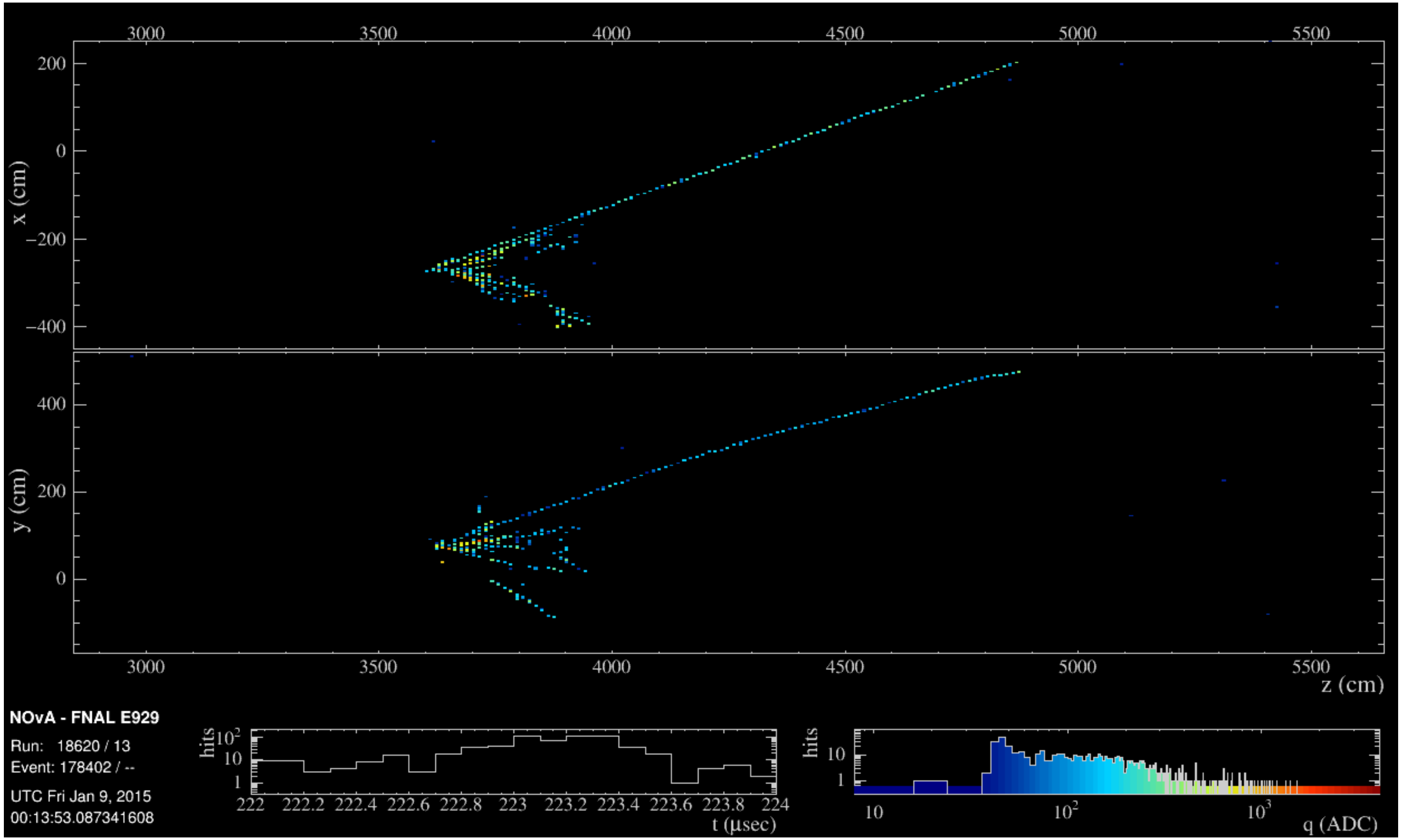
- NuMI beam: ν_μ or $\bar{\nu}_\mu$
- Two functionally identical, tracking calorimeter detectors
  - Near: 300 T underground
  - Far: 14 kT on the surface
  - Placed 14 mrad off-axis to produce a narrow-band spectrum (peak at 2 GeV)
- 810 km baseline
  - Longest baseline of current experiments.



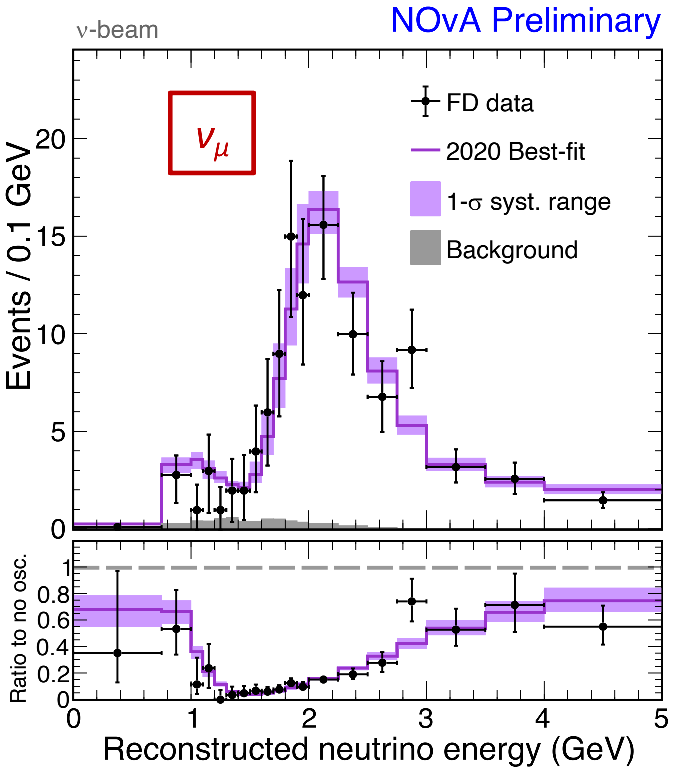




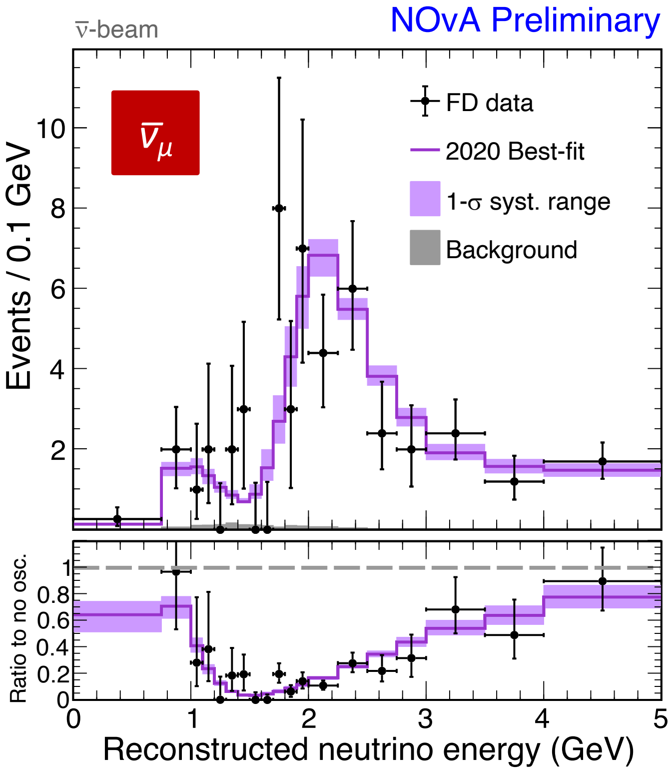
- 65% Active PVC+Liquid Scintillator
  - Mineral Oil
  - 5% pseudocumene
  - Read out via WLS fiber to APD
- Layered planes of orthogonal views
  - muon crossing far end ~40 PE
  - 0.17 X_0 per layer


3000
3500
4000
4500
5000
5500
200
0
−200
−400
x (cm)
400
200
0
y (cm)
3000
3500
4000
4500
5000
5500
z (cm)
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
hits
10^2
10
1
222
222.2
222.4
222.6
222.8
223
223.2
223.4
223.6
223.8
224
t (µsec)
hits
10
1
10
10^2
10^3
q (ADC)

ν_μ and $\bar{\nu}_\mu$ disappearance at the NOvA Far Detector

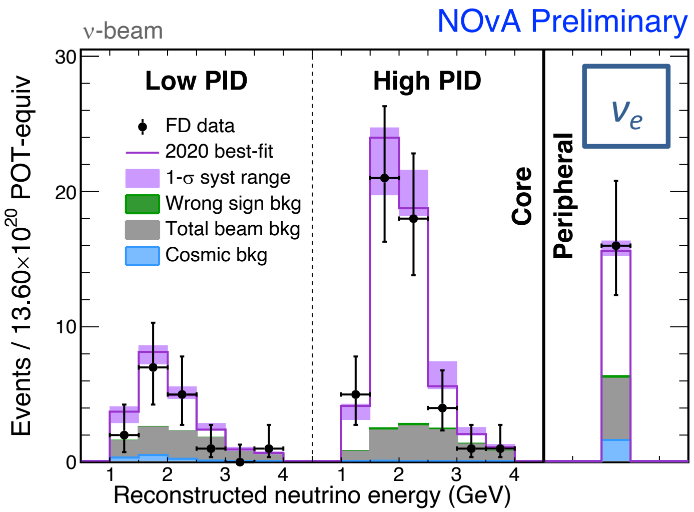


211 events, 8.2 background

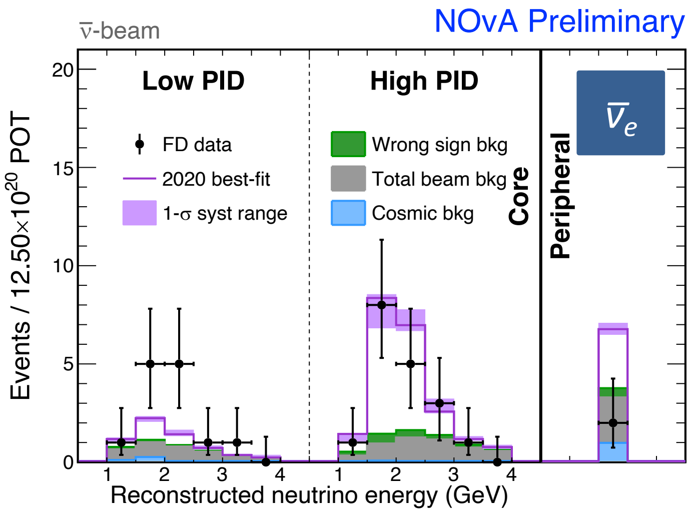


105 events, 2.1 background

ν_e and $\bar{\nu}_e$ appearance at the NOvA Far Detector



Total Observed	82	Range
Total Prediction	85.8	52-110
Wrong-sign	1.0	0.6-1.7
Beam Bkgd.	22.7	
Cosmic Bkgd.	3.1	
Total Bkgd.	26.8	26-28



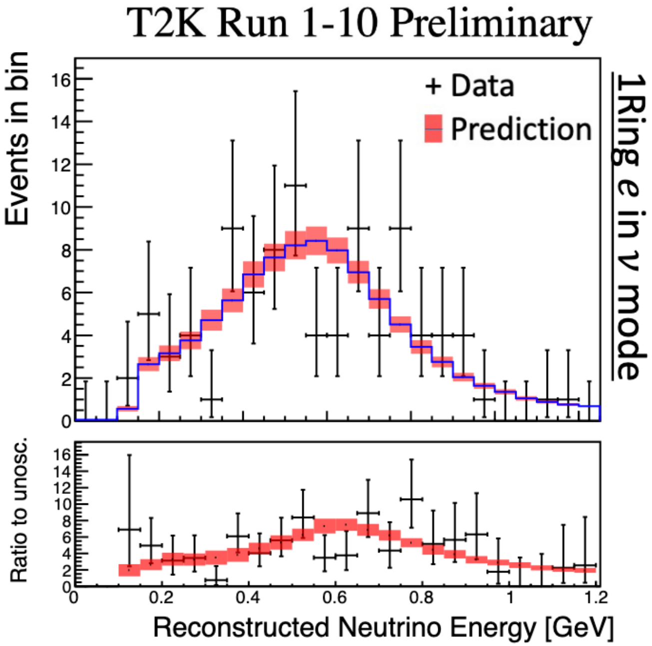
Total Observed	33	Range
Total Prediction	33.2	25-45
Wrong-sign	2.3	1.0-3.2
Beam Bkgd.	10.2	
Cosmic Bkgd.	1.6	
Total Bkgd.	14.0	13-15

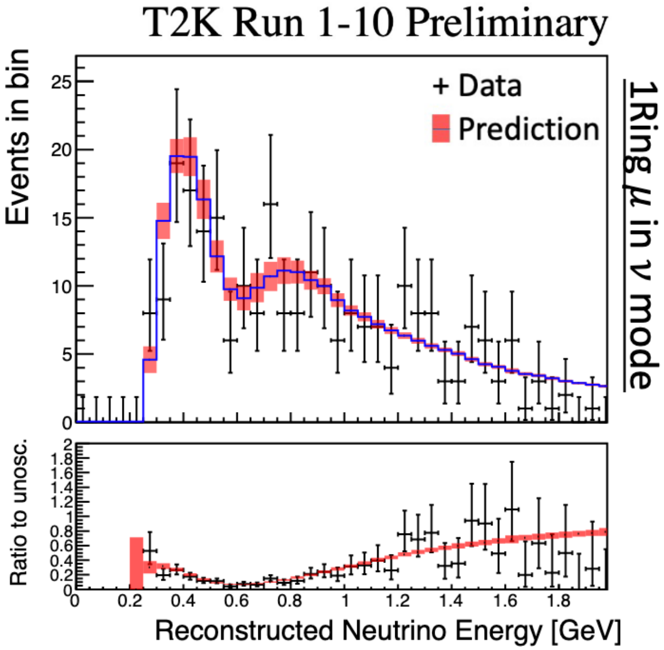
>4σ evidence of $\bar{\nu}_e$ appearance

Oscillation Samples in T2K Far Detector (SK)

Five oscillation samples:

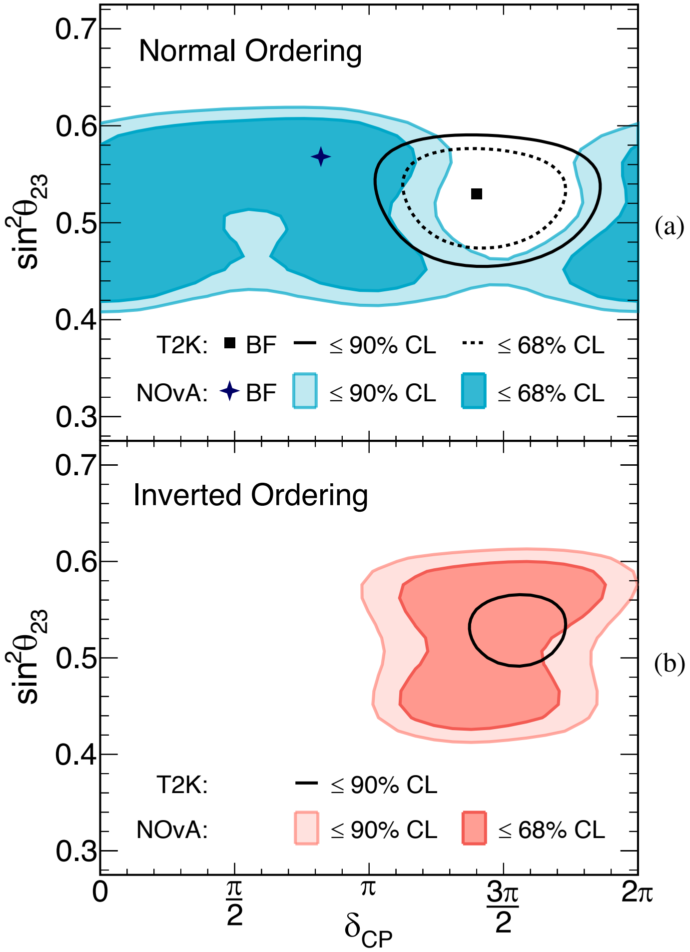
- 1 μ-like ring in ν and $\bar{\nu}$ modes
- 1 e-like ring in ν and $\bar{\nu}$ modes
- 1 e-like ring + Michel electron ring in ν mode





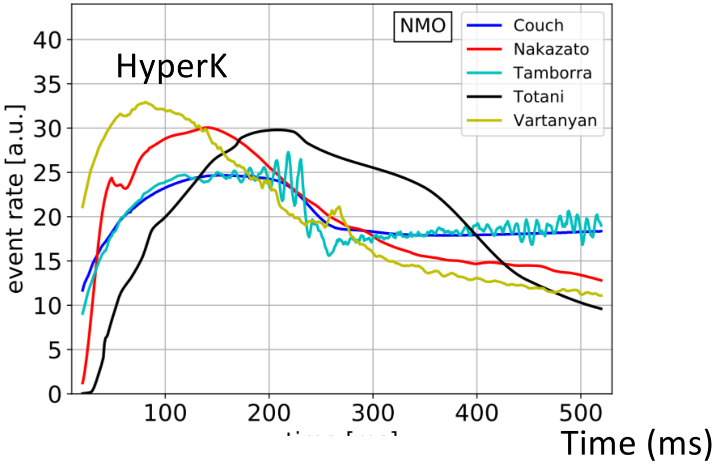
NOvA and T2K

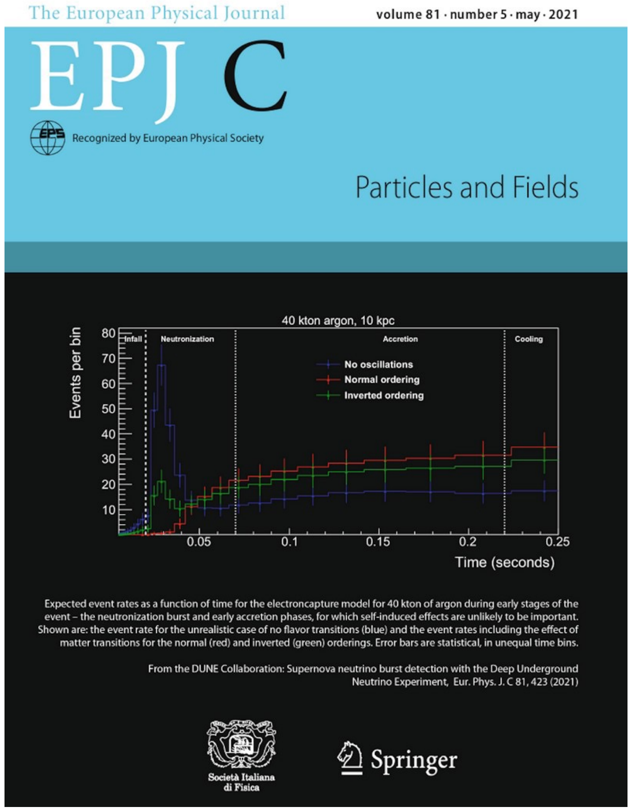
- NOvA does not see strong neutrino/antineutrino asymmetry in electron neutrino appearance.
- T2K observes more electron neutrino appearance than electron antineutrino appearance.
- Current data are inconclusive – expect some improvements with further running.
- Need next-generation experiments to discover CPV and resolve mass ordering.



Neutrino Observatories

- Rich non-accelerator physics programme studying neutrinos from a supernova, solar, atmospheric neutrinos..
- Measurement at early times tests mass ordering and supernova burst model.
- HK and DUNE are complementary in their sensitivity.
- Detector requirements different from beam physics.





The European Physical Journal

volume 81 · number 5 · may · 2021

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Particles and Fields

Expected event rates as a function of time for the electroncapture model for 40 kton of argon during early stages of the event – the neutronization burst and early accretion phases, for which self-induced effects are unlikely to be important. Shown are: the event rate for the unrealistic case of no flavor transitions (blue) and the event rates including the effect of matter transitions for the normal (red) and inverted (green) orderings. Error bars are statistical, in unequal time bins.

From the DUNE Collaboration: Supernova neutrino burst detection with the Deep Underground Neutrino Experiment, Eur. Phys. J. C 81, 423 (2021)

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European Strategy Update

European Particle Physics Strategy Update 2018 – 2020

- …the Neutrino Platform was established by CERN in response to the recommendation in the 2013 Strategy and has successfully acted as a hub for European neutrino research at accelerator-based projects outside Europe.
- Europe, and CERN through the Neutrino Platform, should continue to support long baseline experiments in Japan and the United States.
- In particular, they should continue to collaborate with the United States and other international partners towards the successful implementation of the Long-Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE).