LONG BASELINE NEUTRINO EXPERIMENTS
the next generation: Hyper-Kamiokande and DUNE

H. A. Tanaka (SLAC, Stanford)

NEUTRINO OSCILLATIONS

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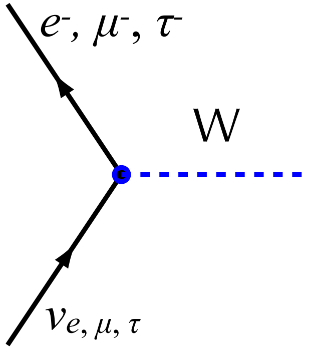
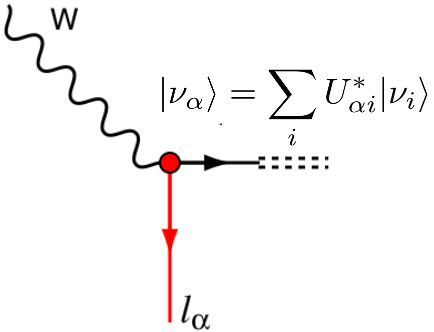
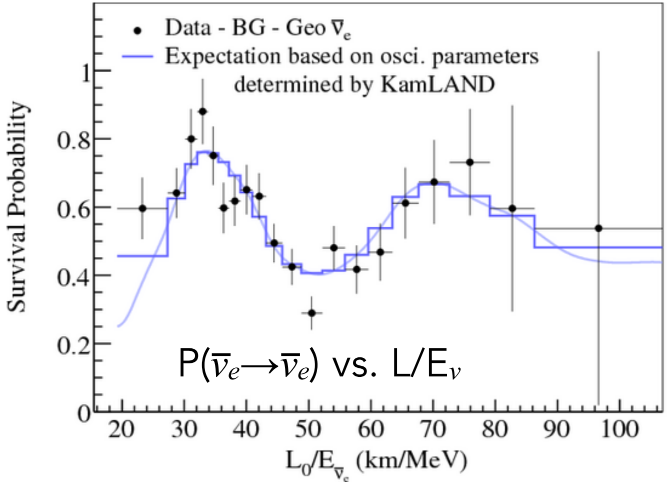
- Neutrino come in three "flavor" eigenstates (ν_e, ν_μ, ν_τ)
- Likewise, neutrinos come in three mass eigenstates (ν_1, ν_2, ν_3)
- The mass and flavor eigenstates "mix" (summarized in unitary matrix U)
  - Neutrinos are produced in flavor eigenstates by weak interaction
  - Mass eigenstates evolve differently in proper time (L/E).
  - New flavor components appear → "neutrino oscillations"







- **Amplitudes:** mixing matrix U
- **Wavelength** in L/E_ν: mass^2 splittings.

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin^2[1.27\Delta m^2_{ij}(L/E)] + 2\sum_{i>j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin[2.54\Delta m^2_{ij}(L/E)] .$$

in vacuo

Δm^2_{ij} (eV^2)
L (km)
E (GeV)

THREE FLAVORS/MASS STATES

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

$$\begin{array}{c} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{array}\begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}\end{array}$$

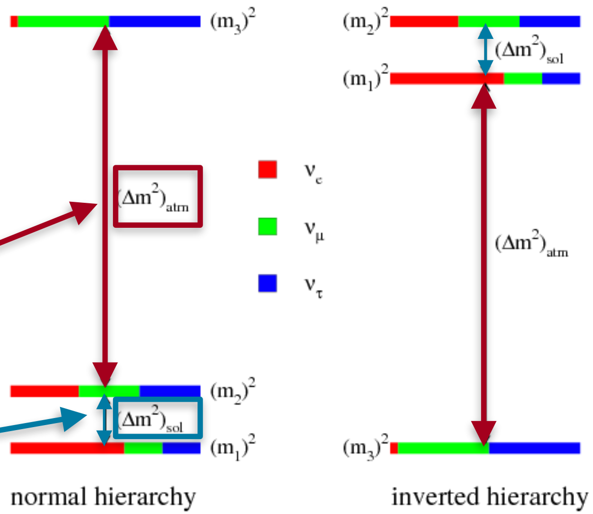
$$\times\, \mathrm{diag}(e^{i\alpha_1/2},\ e^{i\,\alpha_2/2},\ 1)\ .$$

- Three rotation angles (θ_{12}, θ_{13}, θ_{23})
- One complex phase δ_{CP}
  - additional phases possible if neutrinos are "Majorana"
  - changes sign for antineutrino oscillations ("CP odd")

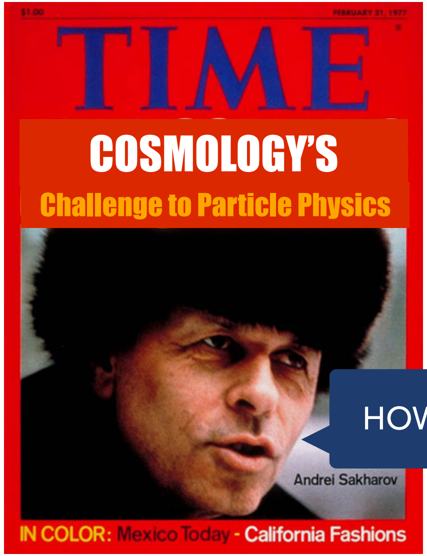
$s_{ij} = \sin\theta_{ij}$

$c_{ij} = \cos\theta_{ij}$

- Neutrino oscillations in atmospheric neutrinos:
  - mass² splitting of 2.5x10⁻³ eV² (**$\Delta m^2_{atm} \sim \Delta m^2_{31}, \Delta m^2_{32}$**)
  - first maximum at 500 km/GeV
- Solar neutrinos, reactor:
  - mass² splitting of ~7.8x10⁻⁵ eV² (**$\Delta m^2_{sol} = \Delta m^2_{21}$**)



THE MATTER-DOMINATED UNIVERSE



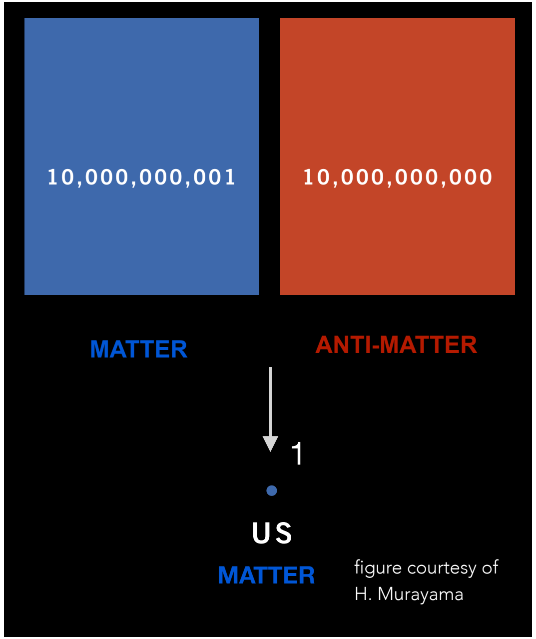
SAKHAROV CONDITIONS:

- BARYON NUMBER (B) VIOLATION
- VIOLATION OF C, CP SYMMETRY (CPV)
- DEPARTURE FROM THERMAL EQUILIBRIUM

HOW DID THIS HAPPEN?

$$\frac{\Delta B}{N_\gamma} \sim \mathcal{O}(10^{-10})$$

- Extremely small?
- Extremely large?
  - This asymmetry remains a mystery



Further **exploration** and **elucidation** of possible CPV sources is critical

THE MYSTERY OF FLAVOR

see talk from J. Renner on 0v2β

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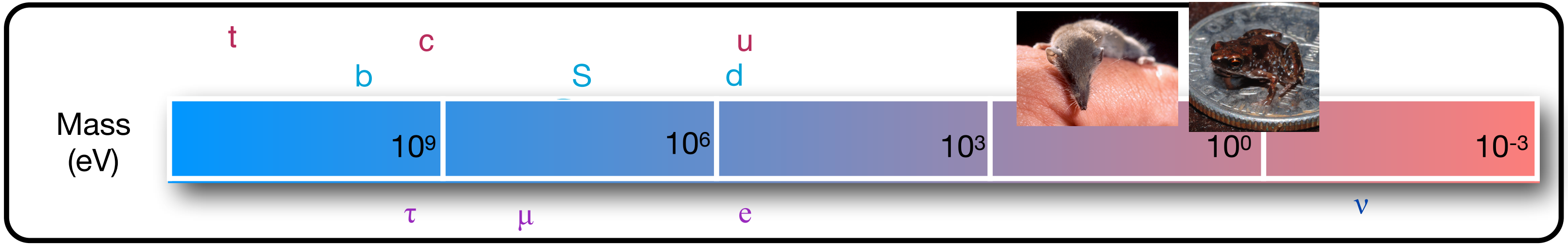
u	c	t
d	s	b
ν_e	ν_μ	ν_τ
e^-	μ^-	τ^-

$$|U_{QUARK}| \sim \begin{pmatrix} 0.97428 & 0.2253 & 0.0034 \\ 0.2252 & 0.93745 & 0.0410 \\ 0.00862 & 0.0403 & 0.99915 \end{pmatrix}$$

$$|U_{LEPTON}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

- Unexplained physics in the Standard Model . .
- Whence mixing and mass parameters?
- Do neutrinos have a different origin?



NEUTRINO BEAMS IN A NUTSHELL

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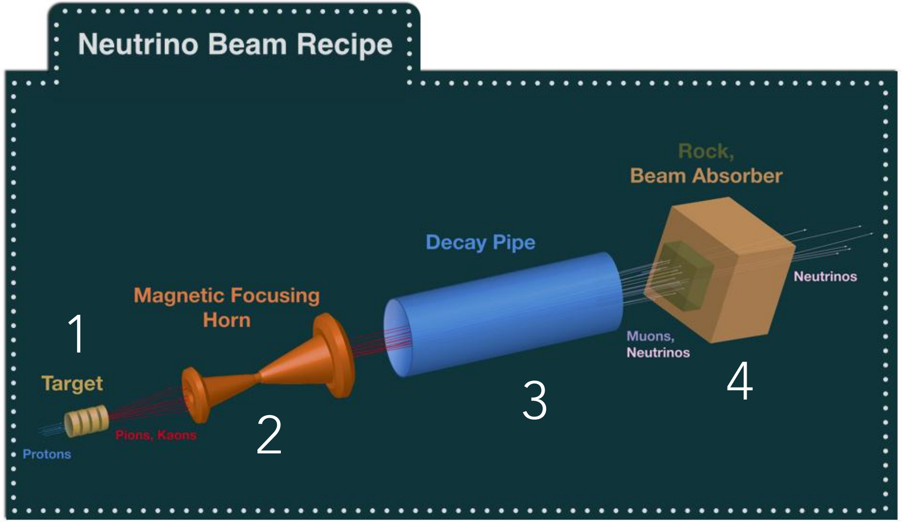
- To first order, accelerator-based neutrino beams operate on the same basic principles

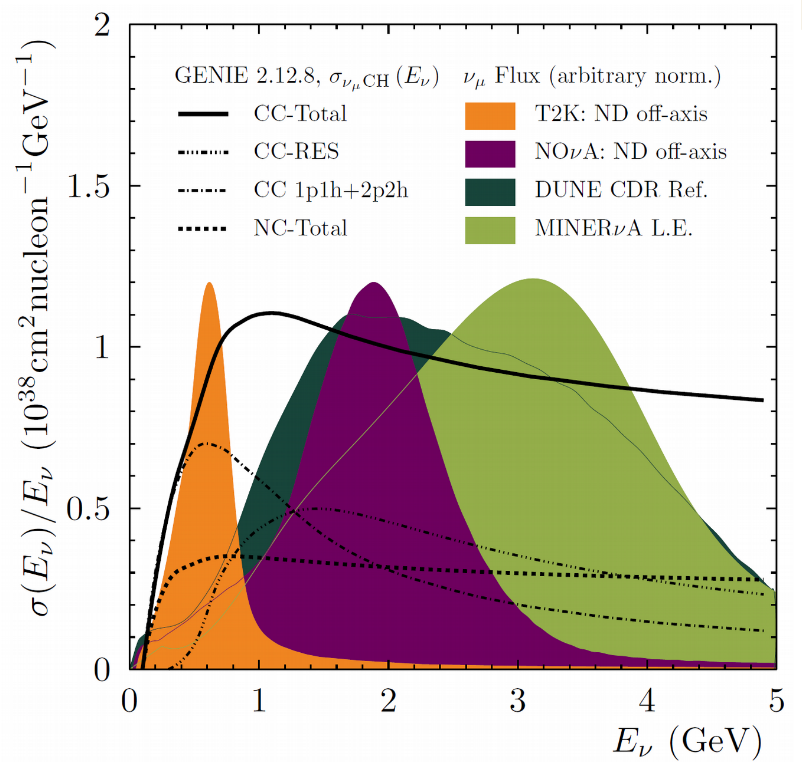


1. High energy protons impinge on a target
   - pions are produced
2. Electromagnets focus pions into a decay region
   - one sign is focussed, the other defocussed
3. The pions decay in a decay pipe
   - muon (anti)neutrinos are produced (sign selection)
4. Beam absorber stops all other remaining particles
   - some muons penetrate and can be monitored.
   - neutrinos go on to the experiment

- Each step represents an enormous technical challenge
  - Primary proton beams approaching 1 MW in power
  - Hundreds of kA of current to focus the beam

Currency: "protons-on-target"
n.b. Non-trivial exchange rate when comparing different beams

LONG BASELINE EXPERIMENTS



Accelerator-based beams are typically E_ν ~ few GeV

- "on-axis" beams provide the highest rate, width of spectrum
- "off-axis" beams can be tuned to maximize the oscillation probability, reduce background

Maximize oscillations for Δm^2_{atm} → 500 km/GeV

Since the beam is ν_μ or $\bar{\nu}_\mu$, a critical measurement is the "disappearance" of $\nu_\mu/\bar{\nu}_\mu$ into other flavors

- Primarily sensitive to $\sin^2 2\theta_{23}$

$$P(\nu_\mu \to \nu_\mu) \sim 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2(1.27\Delta m^2_{31} L/E)$$

$\nu_\mu \rightarrow \nu_e$ OSCILLATION PROBABILITY

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$$P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta_{13} \times \sin^2\theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$
$$-\alpha \sin\delta \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$
$$+\alpha \cos\delta \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \cos\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$
$$+\mathcal{O}(\alpha^2)$$

M. Freund, Phys.Rev. D64 (2001) 053003

$$\alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad x = \pm\frac{2\sqrt{2}G_F N_e E_\nu}{\Delta m^2_{31}}$$

- θ_{13} may be constrained by reactor measurements
- θ_{23} (as opposed to $2\theta_{23}$) dependence → "octant" dependence if $\theta_{23} \neq 45°$
  - Joint analysis with ν_μ disappearance
- CP odd phase δ_{CP} can result in
  - asymmetry of oscillation probabilities $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$, distortion of $\nu_e/\bar{\nu}_e$ appearance spectrum
- Mass ordering sensitivity through x: $\nu_e/\bar{\nu}_e$ enhanced in normal/inverted hierarchy

QUICK SUMMARY

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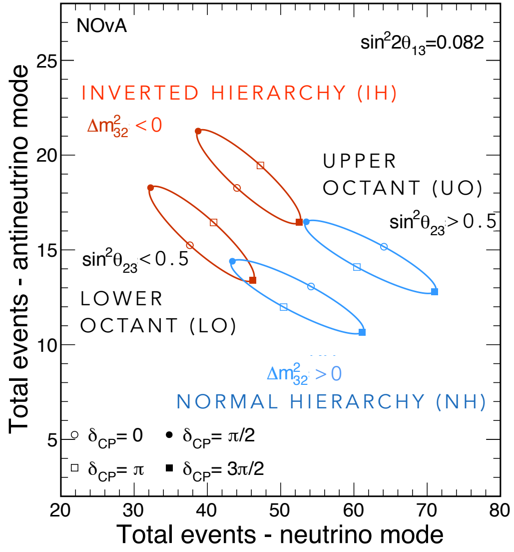
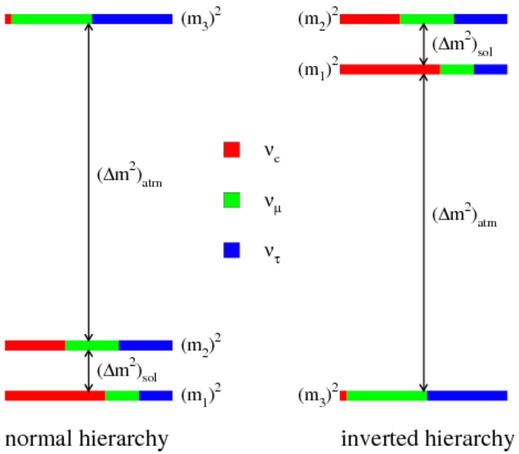
- increase $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$
    - enhance both $\nu_\mu\rightarrow\nu_e$ and $\bar{\nu}_\mu\rightarrow\bar{\nu}_e$
- CP violating parameter δ_{CP}
    - δ_{CP} =0,π: no CP violation: vacuum oscillation probabilities equal
    - δ_{CP} ~-π/2: enhance $\nu_\mu\rightarrow\nu_e$, suppress $\bar{\nu}_\mu\rightarrow\bar{\nu}_e$
    - δ_{CP} ~+π/2: suppress $\nu_\mu\rightarrow\nu_e$, enhance $\bar{\nu}_\mu\rightarrow\bar{\nu}_e$

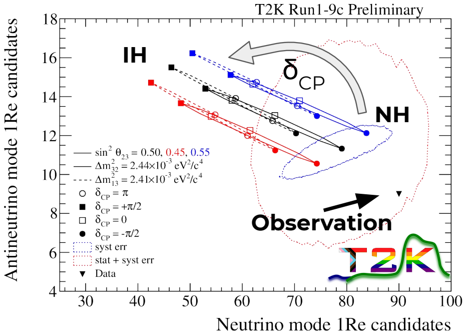


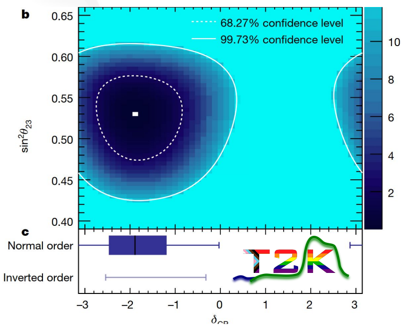


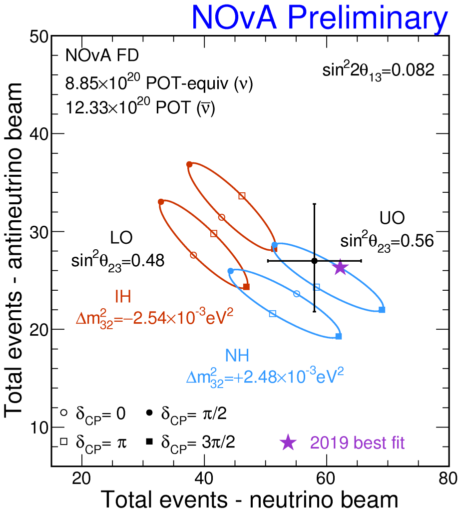
- "normal" ordering:
    - enhance $\nu_\mu\rightarrow\nu_e$
    - suppresses $\bar{\nu}_\mu\rightarrow\bar{\nu}_e$
- "inverted" ordering:
    - suppress $\nu_\mu\rightarrow\nu_e$
    - enhance $\bar{\nu}_\mu\rightarrow\bar{\nu}_e$

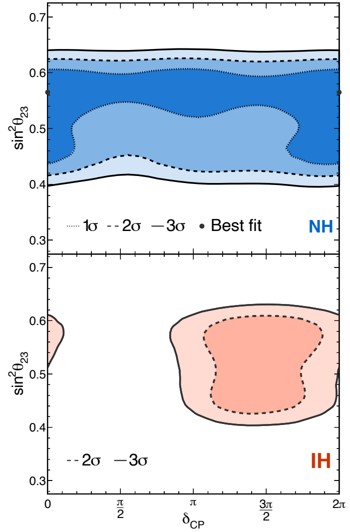
CURRENT STATUS:

see talk from L. Pickering on T2K/NOvA





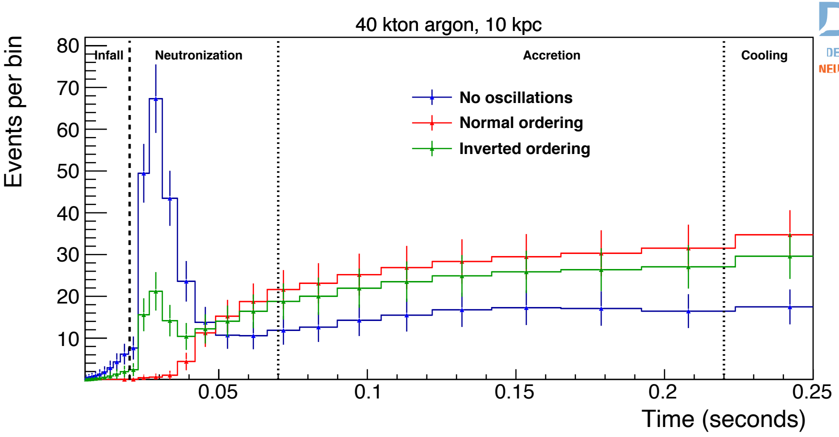


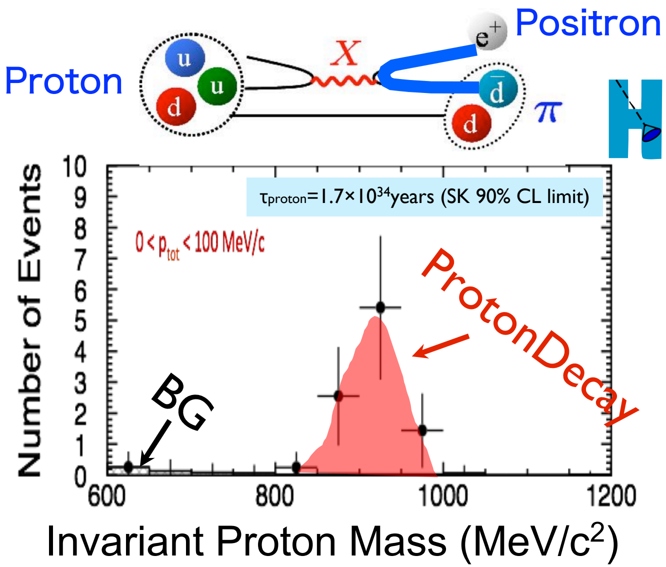


- T2K and NOvA have somewhat different best fit parameters:
  - note differing conventions on range of δ_{CP}
- T2K:
  - maximal θ_{23} ($\sin^2\theta_{23}$ ~0.5), δ_{CP} ~-π/2
- NOvA:
  - θ_{23} slightly in second octant, δ_{CP} ~0 though broad range of values allowed.
- Both experiments prefer normal ordering.

TO THE FUTURE

- n.b.
  - Both DUNE/LBNF and Hyper-Kamiokande have a rich and wide scientific program
    - they also have important complementarities in key physics measurements
  - nucleon decay, atmospheric neutrinos, neutrino astrophysics
  - sterile and exotic properties of neutrinos
  - exotic particle production in the neutrino beam line
- Here, I will focus on the "long-baseline" program at each detector



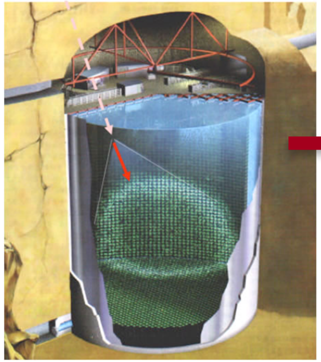


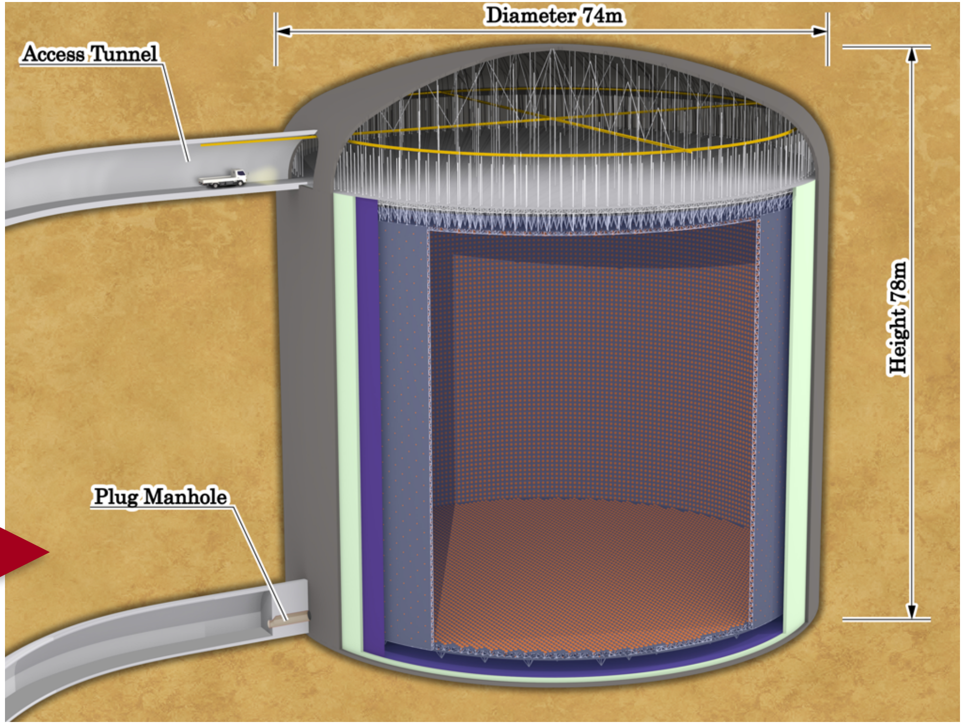
HYPER-KAMIOKANDE:

- 8.4x larger fiducial volume than Super-Kamiokande
- Equivalent photo coverage with 2x sensitive PMTs

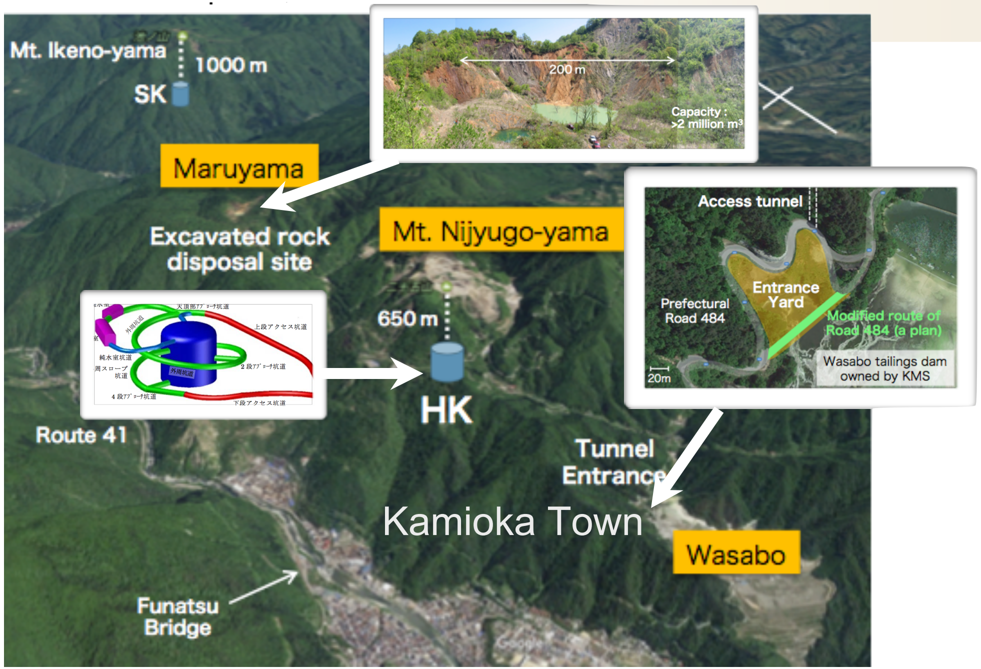
	SK	HK
overburden	Mozumi, 1000 m	Tochibora, 650 m
Inner PMTs	11,129 20"	40,000 20"
Photocoverage	40%	40% (x2 sensitivity)
Total/Fiducial mass	50/22.5 kaon	260/187 kton

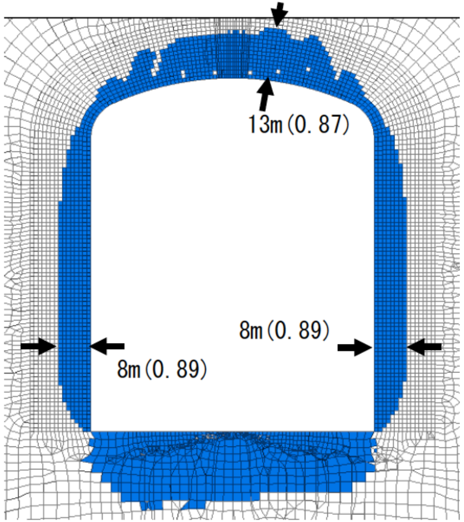
- Proto-collaboration:
  - 340 members
  - 17 countries
- Host institutions:
  - University of Tokyo, KEK





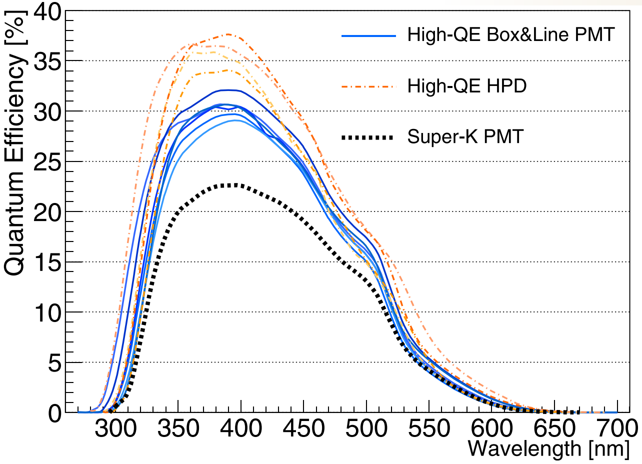
FAR DETECTOR SITE:

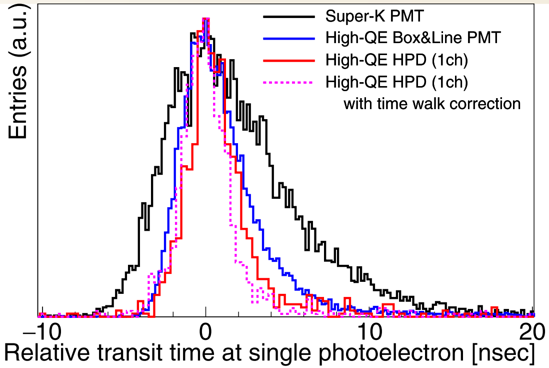


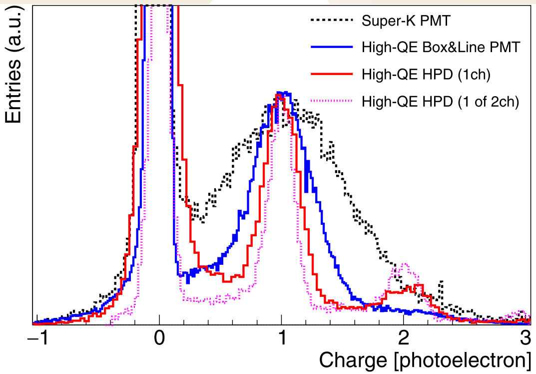


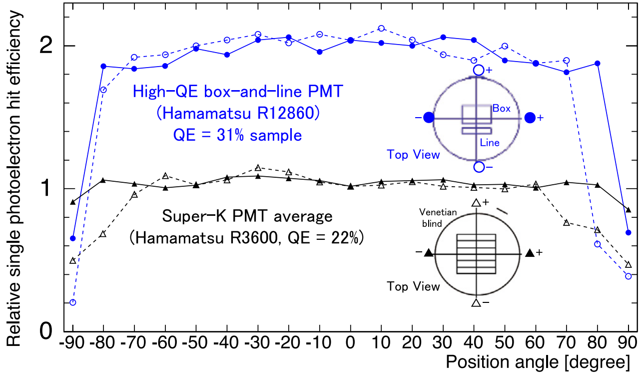
- Site is 8 km south from SK
- Geological survey indicates that 68 m diameter x 71 m height cavern can be excavated with conventional techniques
- **Same off-axis angle as Super-Kamiokande in the J-PARC neutrino beam**

PHOTOSENSORS:

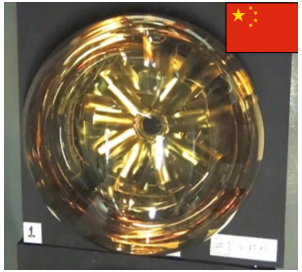


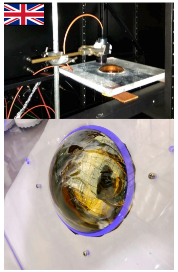




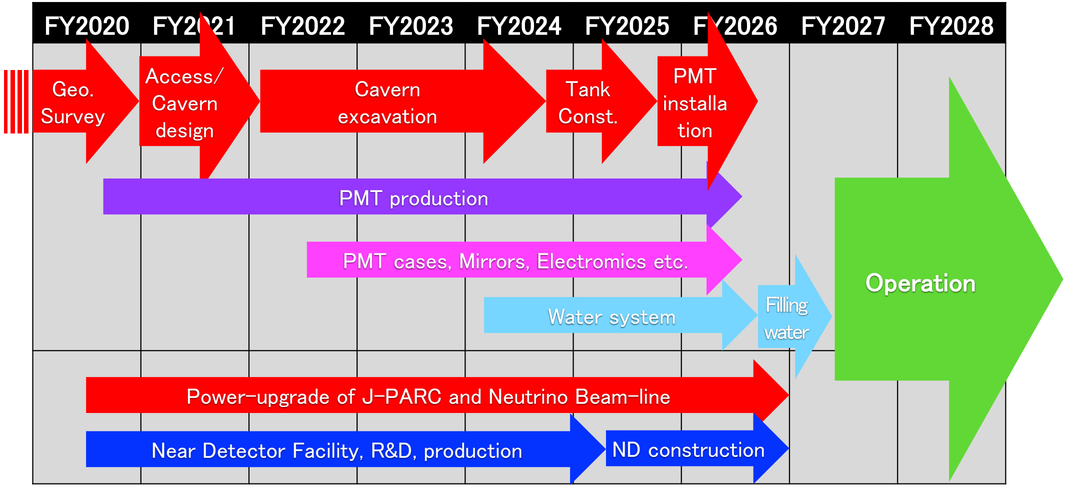


- New Hamamatsu R12860 50 cm PMT:
  - ~2 x photodetector efficiency relative to R3600 used in SK
    - combination of photocathode and collection efficiency
  - Improved charge and time resolution
- Additional technologies (MCP-PMT, mPMT, etc.) under investigation





SCHEDULE



J-PARC Mid-term plan of MR

PAC January 16,

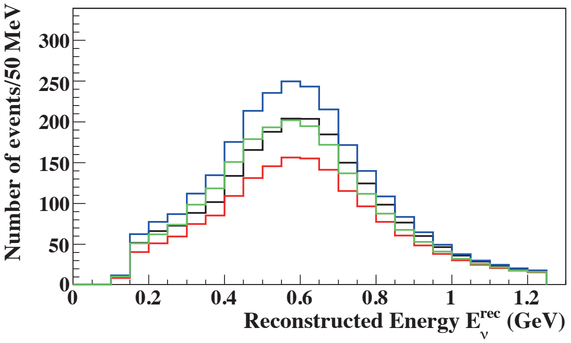
FX: The higher repetition rate scheme : Period 2.48 s —> 1.3 s for 750 kW.
(= shorter repetition period) —> 1.16 s for 1.3 MW
SX: Mitigation of the residual activity for 100kW

JFY	2017	2018	2019	2020	2021	2022	2023	2024
Event	New buildings →		HD target		Long shutdown			
FX power [kW] SX power [kW]	475 50	>480 50	>480 50	>480 70		>700 >80	800 >80	900 >80
Cycle time of main magnet PS New magnet PS	2.48 s	2.48 s Mass production installation/test →	2.48s	2.48s		1.32s	<1.32 s	<1.32 s
High gradient rf system 2nd harmonic rf system	Manufacture, installation/test →							
Ring collimators	Add.collimators (2 kW)				Add.colli. (3.5kW)			
Injection system FX system	Kicker PS improvement, Septa manufacture /test → Kicker PS improvement, FX septa manufacture /test →							
SX collimator / Local shields					Local shields →			
Ti ducts and SX devices with Ti chamber	Ti-ESS-1	(Ti-ESS-2)						

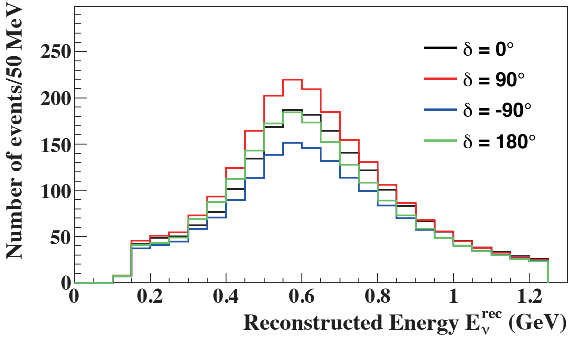
- Funding for Hyper-Kamiokande was approved December 2019
- Construction has started with the aim to start operations in 2027.
- Meanwhile, J-PARC plans a series of upgrades to the Main Ring which supplies the neutrino beam line
  - ~500 kW now → 1.3 MW

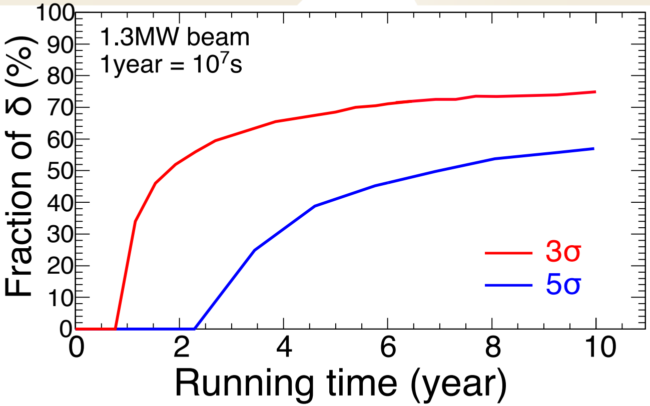
PHYSICS SENSITIVITY

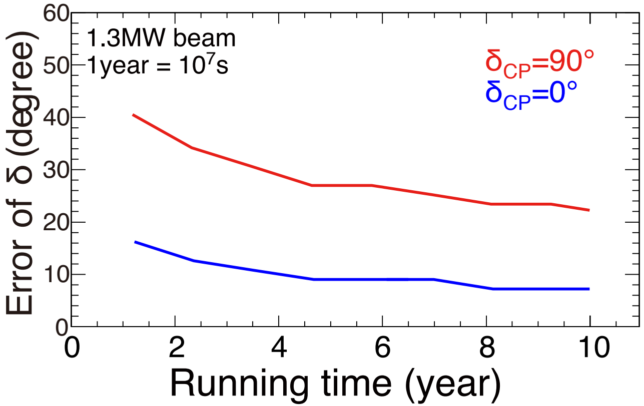
Neutrino mode: appearance



Antineutrino mode: appearance

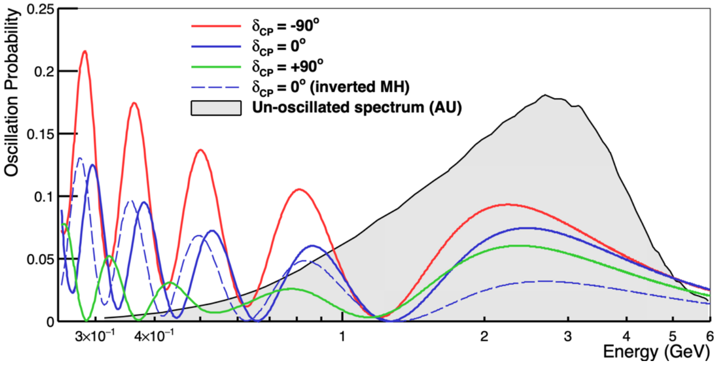


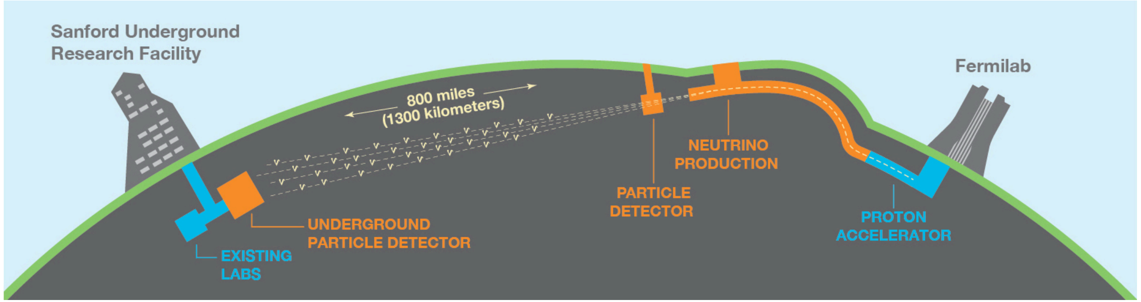


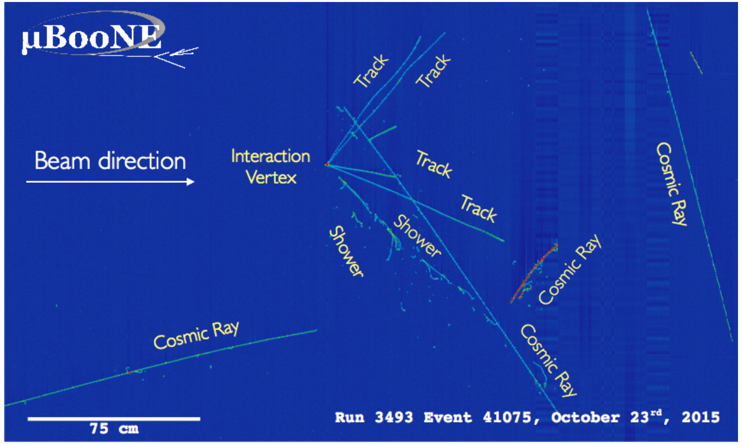


- Over 10 years of beam operation ~ 2000 $\nu_\mu \rightarrow \nu_e, \bar{\nu}_\mu \rightarrow \bar{\nu}_e$ candidates are expected, allowing a high statistics test of CP asymmetry
  - 3:1 mix of neutrino vs. antineutrino beam running to get roughly equal statistics in both modes.
- Precision of ~7-20° can be achieved depending on the value of dCP

DUNE/LBNF

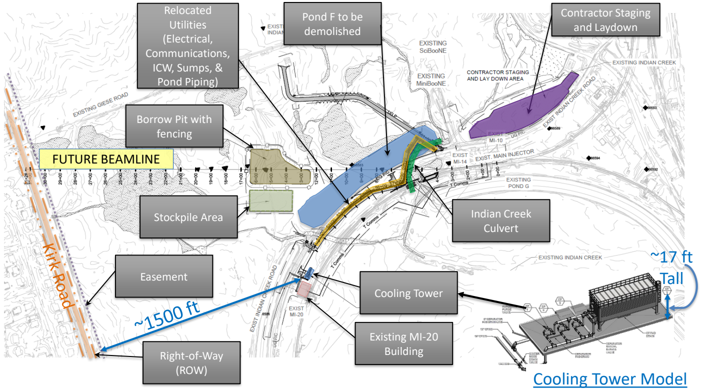


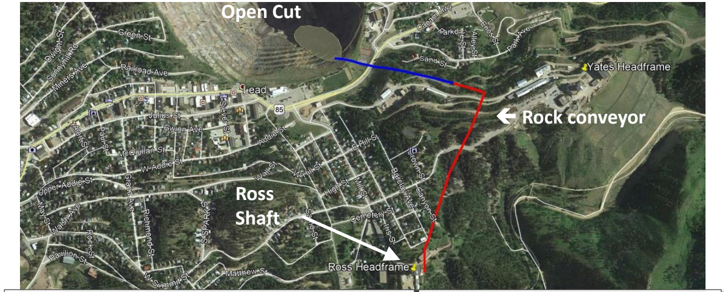




- 1.2 MW beam from FNAL to SURF (1300 km)
  - upgrade to 2.4 MW planned
- 4 x 10 kT Liquid Argon Time Projection detectors
- Broad beam, higher energy, longer baseline
  - very powerful capability to resolve mass ordering
  - broad beam may probe additional oscillation maxima

LONG BASELINE NEUTRINO FACILITY

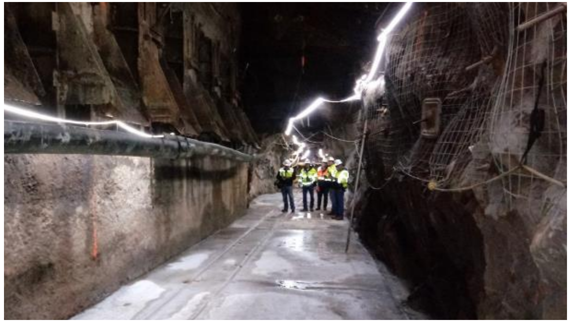




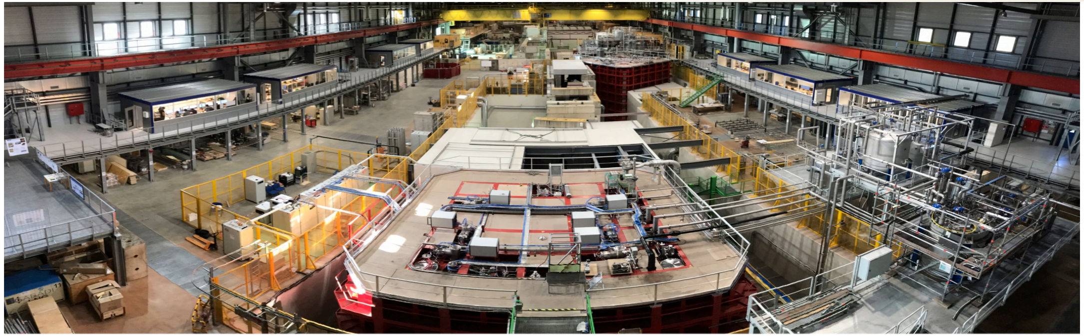
- Underground rock handling systems (ore passes, skip loading, temporary grizzly, rock spill collection system)
- Rock crushing system at Ross Headframe
- Installing 4200' surface rock conveyor to open cut

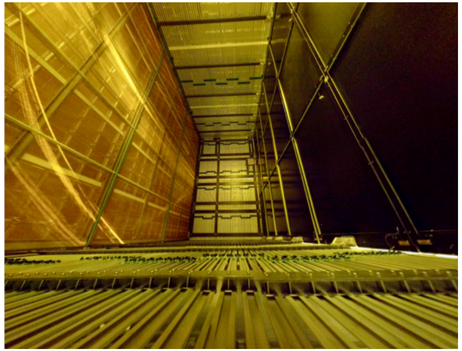
- Ross headframe reinforcement
- Shaft utilities: fiber optic and power cables, water and gas piping
- Electrical service on the surface to the shaft

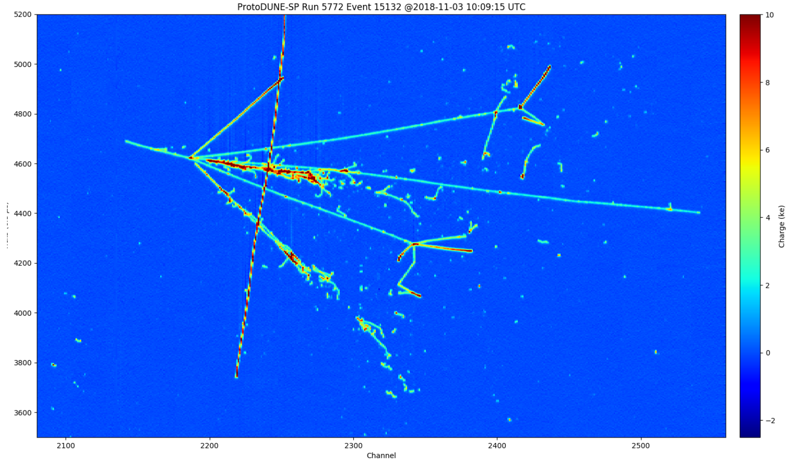
- Pre-excavation activities underway at Sanford Underground Research Facility (SURF)
  - Need to transport 800k tons of rock out of the ground
- Site preparation at near site (beam line + near detector hall) underway
  - main construction expected to start in 2020

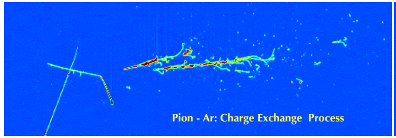


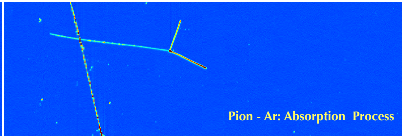
PROTODUNE

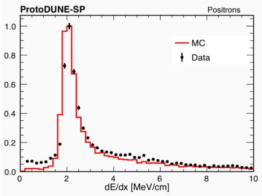


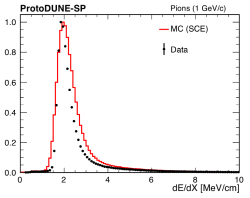


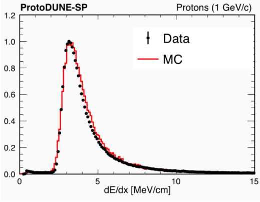






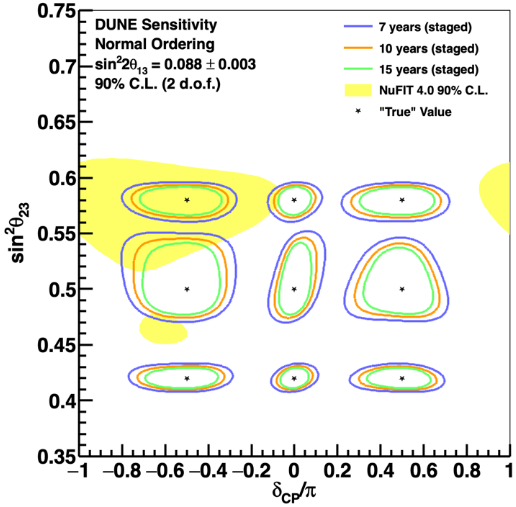


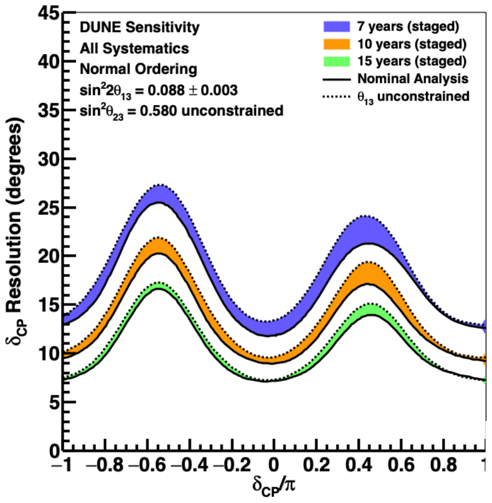




- ProtoDUNE: 7 x 6 x 3.6 m^3 demonstrator of DUNE design operated at the CERN Neutrino Platform with a tagged charged particle test beam
  - 500 days of operation in 2018-2019
- Second run planned for 2022 with production components

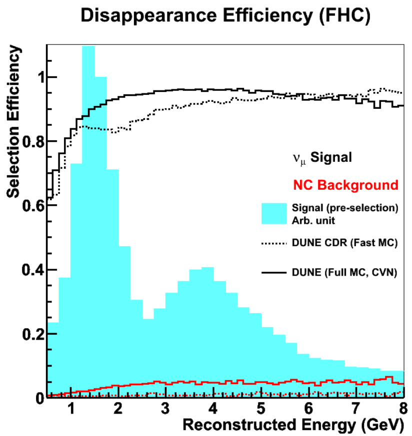
PHYSICS SENSITIVITY

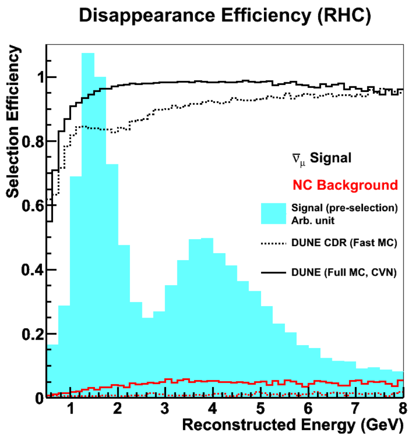




- Large matter effects allow DUNE to definitively resolve the mass ordering within the first years
- Detecting CP violation occurs in the context of simultaneously probing all other parameters

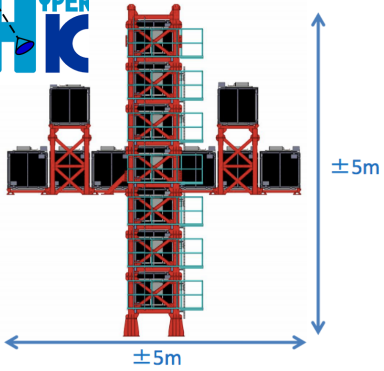
- ν_μ/ν_e CC events are identified with high (~90% and higher) and purity (~95% and higher)
- DUNE will achieve 7-17° precision in δ_{CP} depending on its value



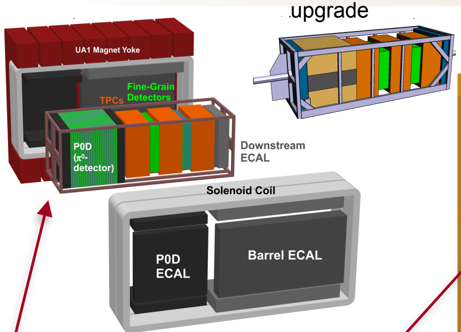


NEAR DETECTORS

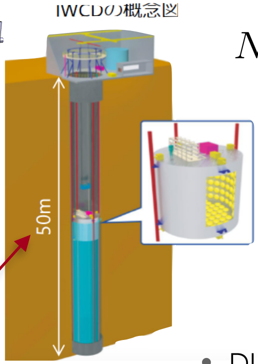
SLAC



on-axis monitor



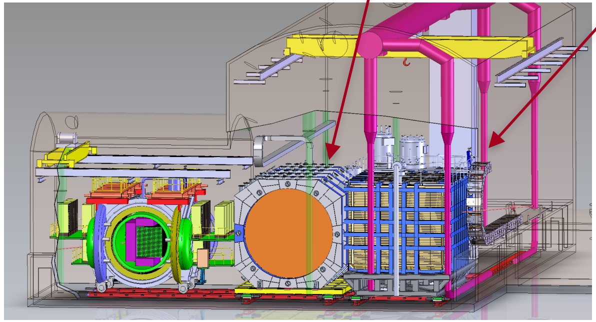
magnetized tracking spectrometer with calorimetry

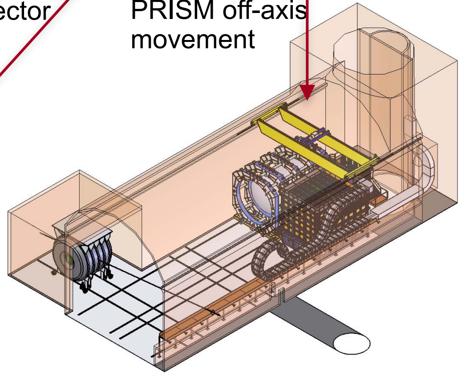


DEEP UNDERGROUND NEUTRINO EXPERIMENT

FD-like detector

PRISM off-axis movement



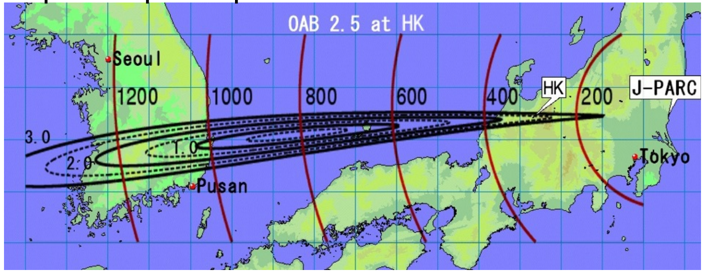


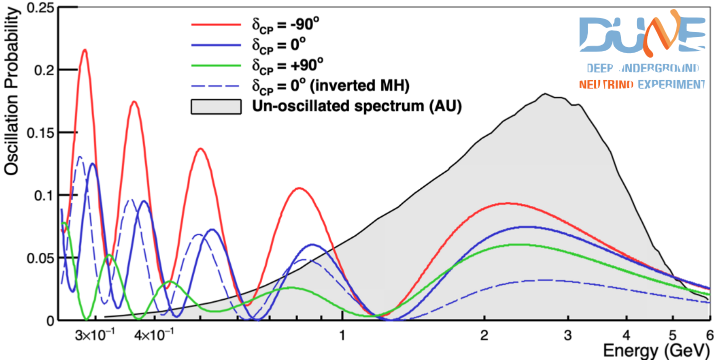
$$N_{FD}(\nu_\alpha \to \nu_\beta, E_{REC}) = \int dE_\nu \times \Phi(\nu_\alpha, E_\nu) \times P(\nu_\alpha \to \nu_\beta, E_\nu) \sigma(\nu_\beta, E_\nu) \times V \times n \times R(\nu_\beta, E_{REC}, E_\nu)$$

- DUNE and HK confront unprecedented challenges in reducing systematic uncertainties to observe CP violation
    - the Near Detector is the principal means to reduce uncertainties
- Both DUNE and HK employ:
    - On-axis beam monitoring system
    - Detectors with functionally identical methods as the far detector (FD)
    - Detectors with capabilities beyond the far detector
        - e.g. magnetization, lower thresholds, calorimetry
    - Movement off-axis (PRISM) to intercept neutrinos with different spectra

SECOND OSCILLATION MAXIMUM

https://inspirehep.net/literature/1499045





The interference which gives rise to CP violation grows as the neutrinos continue to oscillate

- "Second oscillation maximum": neutrinos have oscillated ~twice from their initial state
- kinematic phase ~π/2 → ~3π/2
- Recall that the kinematic phase of the oscillation goes as L/E
  - For fixed energy, go 3x the distance
  - For fixed distance, look at 1/3 the energy

- Both programs have the opportunity to study the 2nd oscillation maximum
  - HK: Same E_ν ~600 MeV with a 2nd detector at ~1100 km
  - DUNE: E_ν ~800 MeV at the same 1285 km distance

CONCLUSIONS:

The future long-baseline neutrino program is "on shell"

- CP violation, mass ordering, next level of precision in neutrino oscillation parameters
- Hyper-Kamiokande :
  - project is now approved!
  - construction phase is starting
  - based on proven Water Cherenkov technique enhanced with new photosensor technology
- DUNE/LBNF:
  - successful large scale demonstration with ProtoDUNE @ CERN
    - Technical design report for the far detector published!
  - pre-excavation activities ongoing at SURF, preparatory activities at FNAL
- Both experiments have a wide-ranging physics program beyond the long baseline physics
- Both experiments require near detectors that will control systematic errors well beyond the state of the art.

Meanwhile, enjoy the exciting "completition" between T2K and NOvA

- The fun will continue with HK and DUNE!