Perspectives on neutrino physics

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FERMILAB

focused on accelerator based long-baseline neutrino experiments…


To plan where we are going, let’s see where we have been

OUTLINE

- Who am I
- A Little History of Neutrinos
- Accelerator Neutrino Experiments
- Focus on Neutrino Oscillations
- Long Baseline Experiments
- Summary and Outlook

WHO AM I

- I am an EXPERIMENTAL Physicist
- I have worked at Fermilab for my entire career (1978 – present)
- I have been working on Neutrino Experiments since 1993
  - *Before that I studied Hyperon Polarization and Magnetic Moments*
- In the early '90's I worked on the development, operation and analysis of the Fermilab MINOS and DONUT Experiments
- I have also worked on NOvA, MicroBooNE
- I am currently the Co-spokesperson of DUNE (Deep Underground Neutrino Experiment)

A LITTLE HISTORY OF NEUTRINOS

- The existence of a neutrino was hypothesized in 1930 as a ZERO MASS elementary particle to concerve the concept of conservation of energy in the beta decay process
- The first detection of neutrinos occurred in 1956 in the landmark experiment of Reines and Cowen at the Savannah River nuclear power plant
- In 1957 Bruno Pontecorvo hypothesized that neutrinos may oscillate, or change from one *type* to another
- In 1962 a second *type* or *flavor* of neutrino was identified in a Brookhaven Laboratory experiment led by Lederman, Swartz and Steinberger; the charged current neutrino interaction produced a MUON (rather than electron)
- In 1973 NEUTRAL CURRENT interactions were detected at CERN by the Gargamelle experiment
- In 1975 the first detection of TAU Leptons at SLAC lead to the prediction of a third flavor of neutrino : the TAU Neutrino

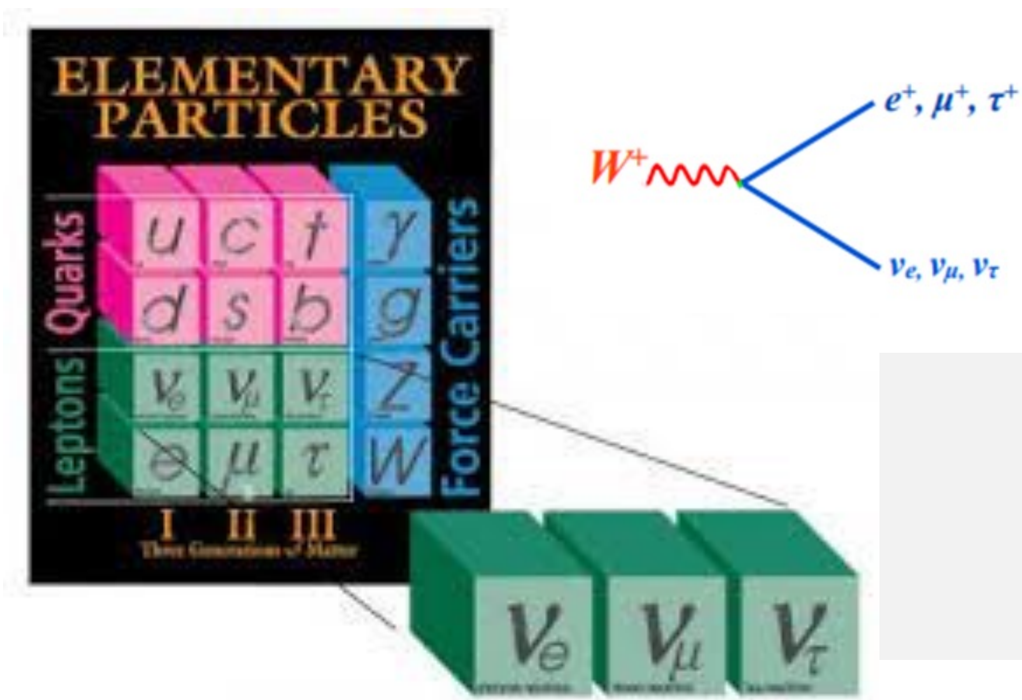
A LITTLE HISTORY OF NEUTRINOS : SMOKING GUNS

- In 1957 Bruno Pontecorvo hypothesized that neutrinos may oscillate, or change from one *type* to another !
- In 1968 neutrinos from the sun were detected in a huge tank of perchloroethylene (dry cleaning fluid) located in the Homestake Gold Mine in South Dakota; the team was led by Ray Davis, and the detected number of neutrinos was low compared to theoretical predictions!!
- In 1983 studies of atmospheric neutrinos in the Kamiokande (Japan) and IMB (Irvine, Michigan, Brookhaven) Collaborations measured an anomaly in the muon to electron neutrino interaction rates!!!

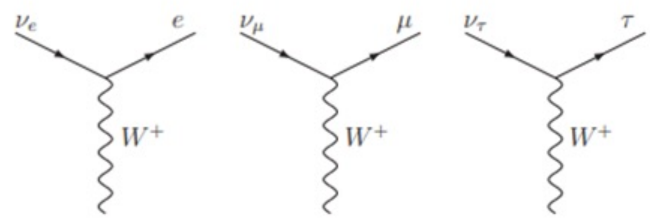
A LITTLE HISTORY OF NEUTRINOS : MYSTERY SOLVED

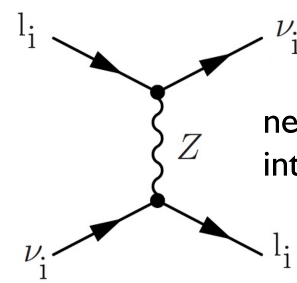
- In 1998 the Super-Kamiokande experiment determined that atmospheric muon neutrinos were "disappearing" as they traveled from their production to interaction point; as predicted by PONTECORVO more than 20 years earlier : flavor changing neutrinos have MASS!!!
  - *The hypothesis by now was that MUON neutrinos were oscillating into TAU neutrinos; HOWEVER, no one had yet detected a TAU neutrino interaction.*
- In 2000, scientists from the DONUT collaboration announced the recording of 4 TAU neutrino interactions (a total of 9 interactions were published in the final data analysis)
- In 2002, the SNO experiment (Canada) announced conclusive evidence that THREE flavors of solar neutrinos were accounted for.
- In 2010 the OPERA experiment, using the same detector technique in DONUT, searched for TAU neutrino appearance using a neutrino beam from CERN. In 2015 they announced the detection of 5 TAU neutrino interactions.

NEUTRINOS IN THE STANDARD MODEL



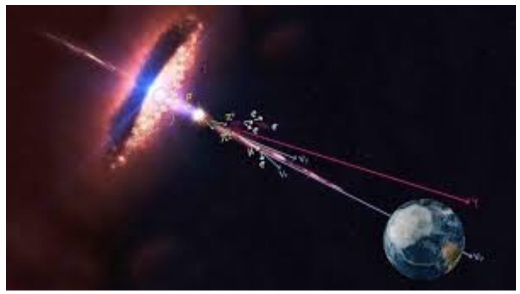
charged current interactions

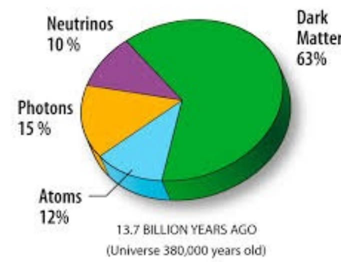


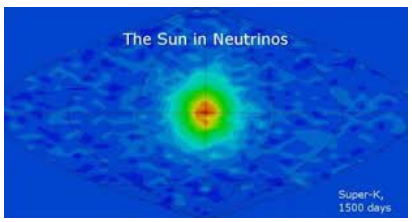


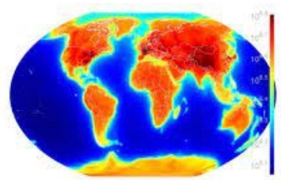
neutral current interactions

NEUTRINOS IN OUR UNIVERSE









DETECTING NEUTRINOS

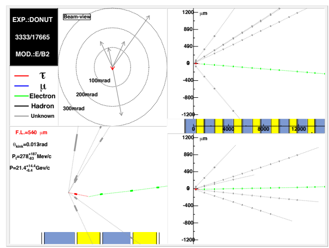
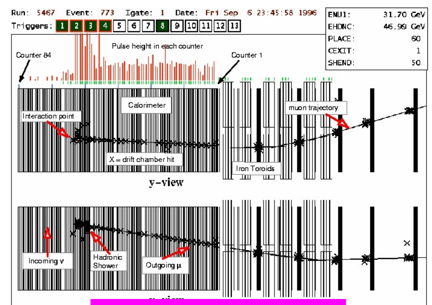
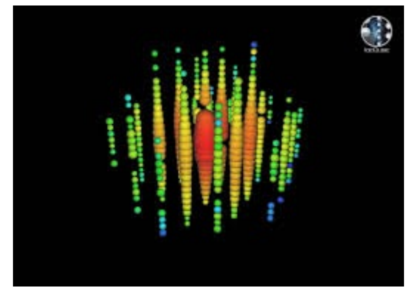


Fig. 15. Event 3333-17665: $\tau \to e + \nu_\tau + \nu_e$

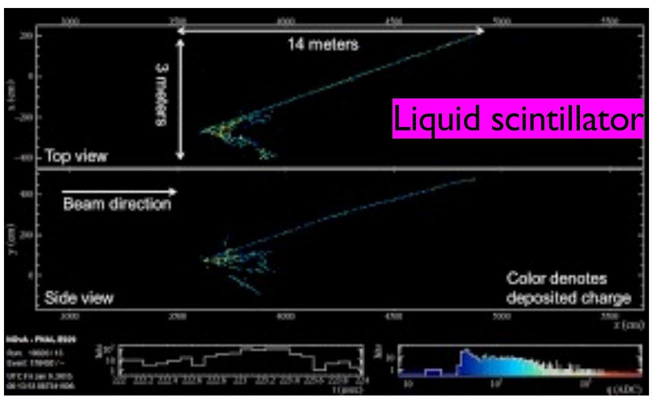
Emulsion

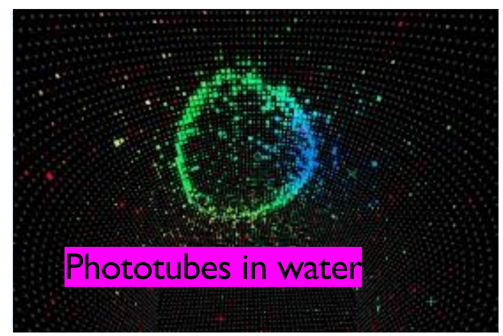


Iron & scintillator



Phototubes in ice





NEUTRINO OSCILLATIONS

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

$$\begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13}\end{bmatrix}\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}$$

$$= \begin{bmatrix}c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\rm CP}}\\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\rm CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\rm CP}} & s_{23}c_{13}\\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\rm CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{\rm CP}} & c_{23}c_{13}\end{bmatrix}$$

Features : Mixing angles and CP phase

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\,|\nu_i\rangle\,,$$

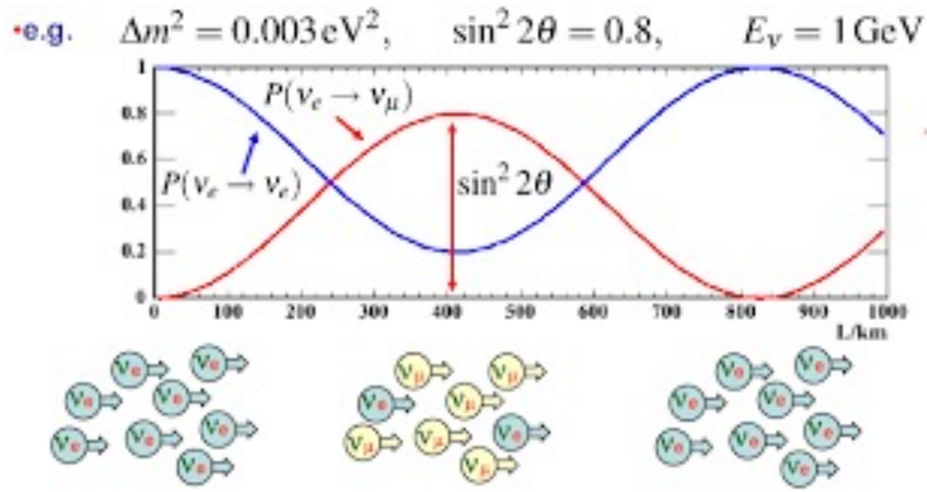
$$|\nu_i\rangle = \sum_\alpha U_{\alpha i}\,|\nu_\alpha\rangle\,,$$

where

- $|\nu_\alpha\rangle$ is a neutrino with definite flavor α = e (electron), μ (muon) or τ (tauon),
- $|\nu_i\rangle$ is a neutrino with definite mass m_i, $i = 1, 2, 3$,

A FOCUS ON NEUTRINO OSCILLATIONS

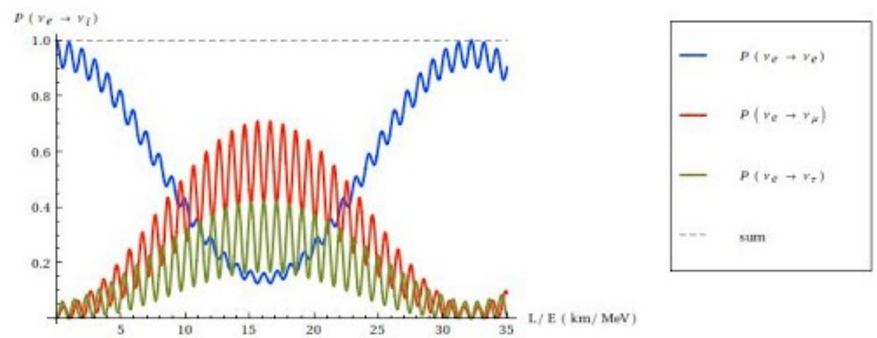
Two flavor approximation

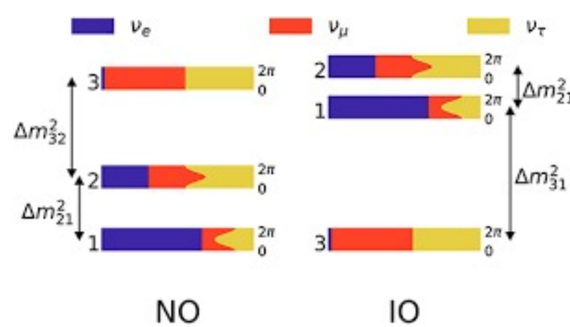


$$P\left(\nu_\alpha \to \nu_\beta\right) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\Delta m_{ij}^2 \frac{L}{E}\right)$$

Mass difference

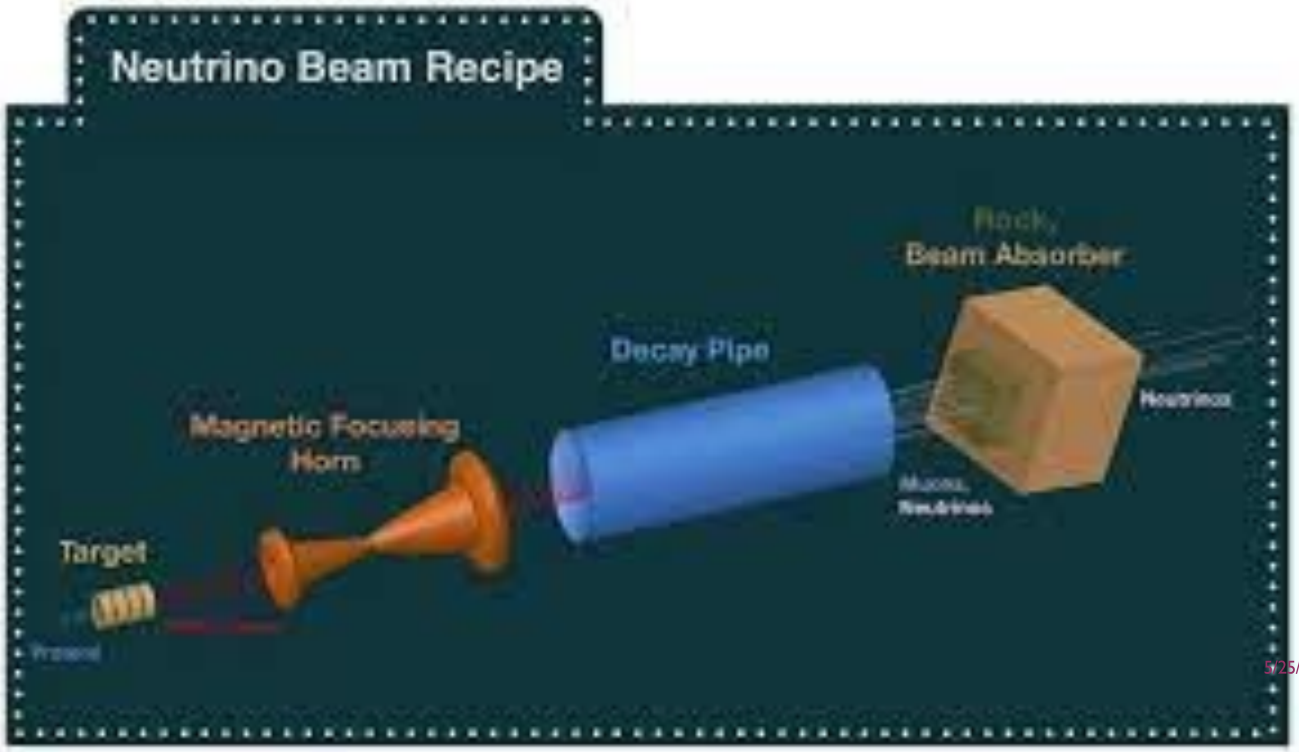
Three flavors



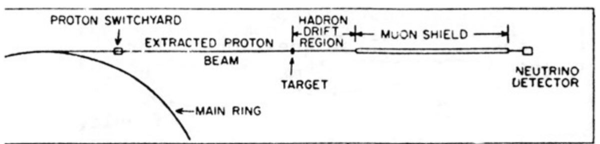


Two distinct mass differences

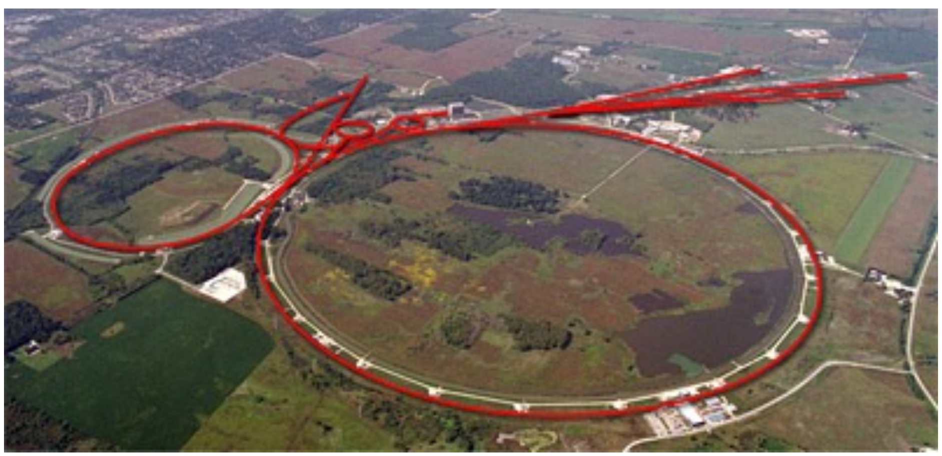
ACCELERATOR NEUTRINO EXPERIMENTS

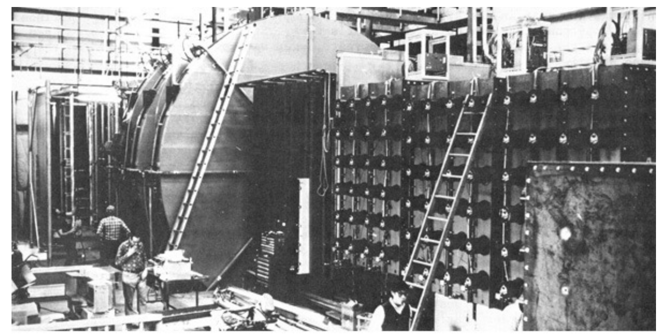


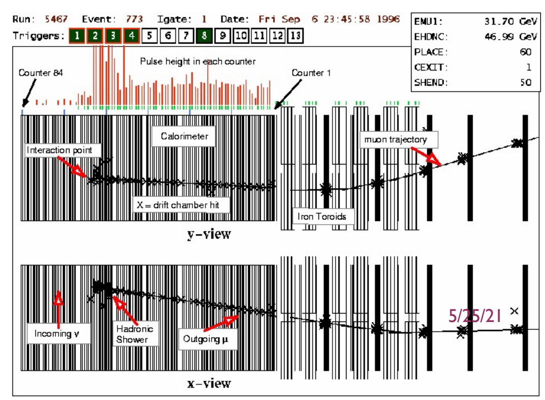
ACCELERATOR NEUTRINO EXPERIMENTS



First experiment approved
at Fermilab : E1A
1972







NuTeV :
~2000

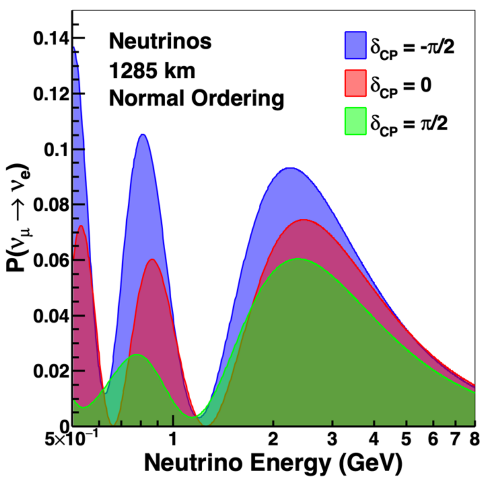
WHY LONG BASELINE?

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP})$$
$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

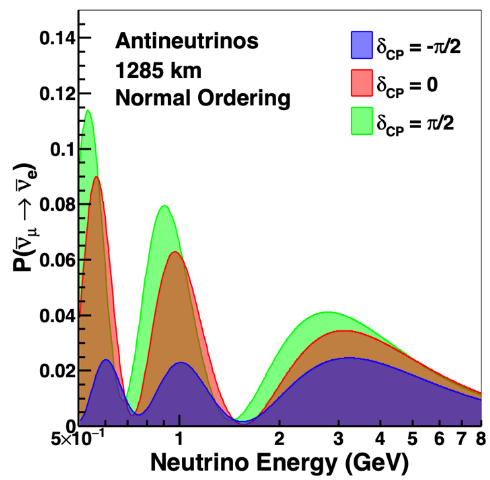
$$a = G_F N_e / \sqrt{2}$$

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

Neutrinos



Antineutrinos



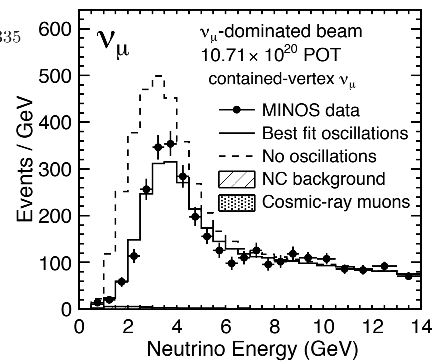
Neutrino and anti-neutrino oscillation probabilities are moderated by the matter through which they pass

For a normal mass hierarchy, neutrinos are enhanced and anti-neutrinos are suppressed

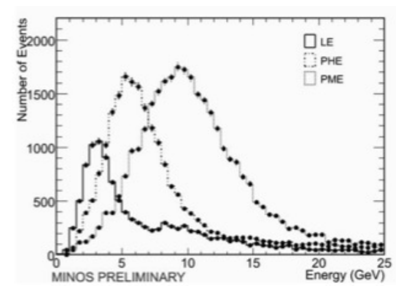
In an inverted hierarchy, the effect is reversed

THE MINOS EXPERIMENT (2005 – 2016)

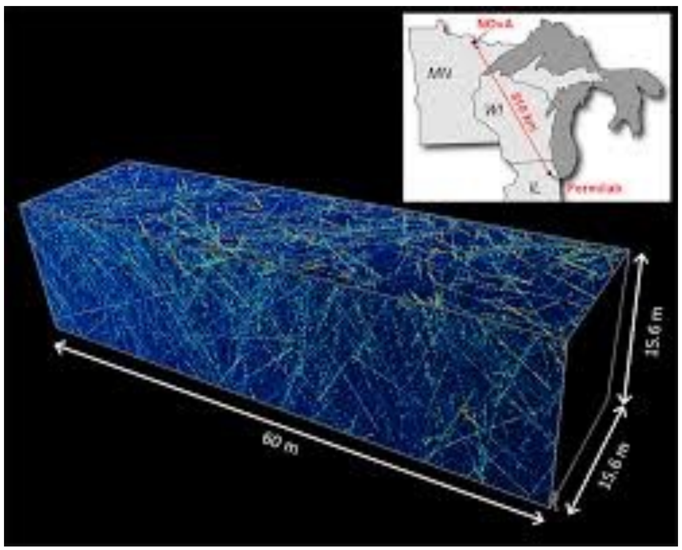
arXiv:hep-ex/1304.6335



Nuclear Physics B (Proc. Suppl.) 159 (2006) 63–68

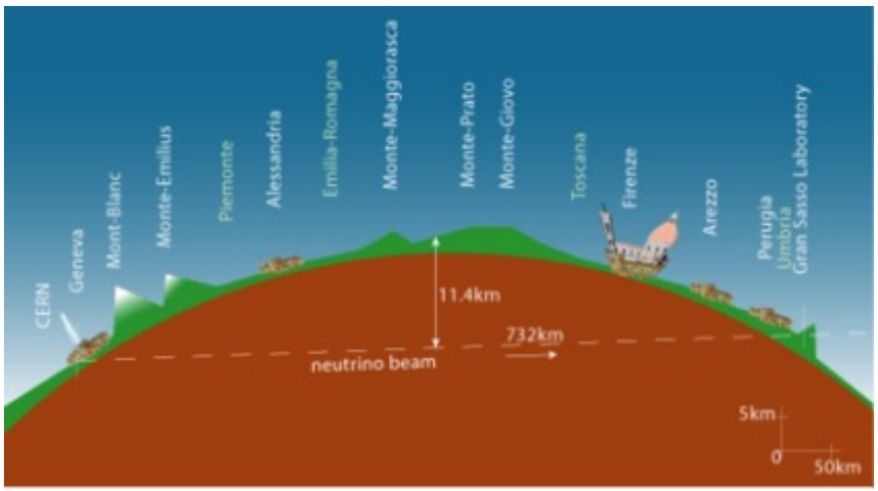


NOVA (NUMI OFF-AXIS NEUTRINO APPARATUS)

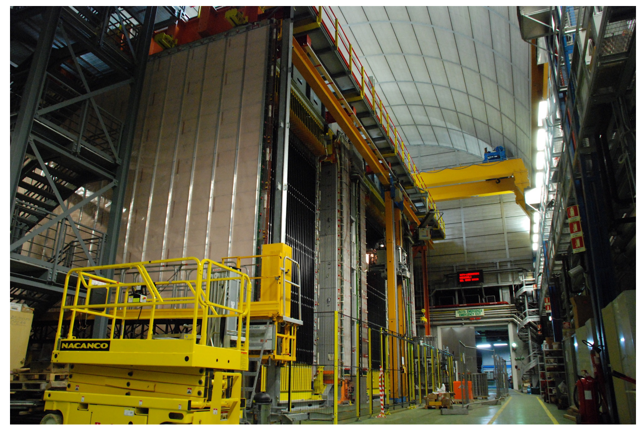


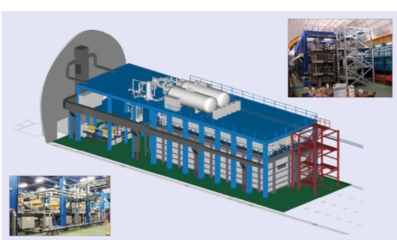
Very large detector – located on the surface

CERN BEAM TO GRAN SASSO

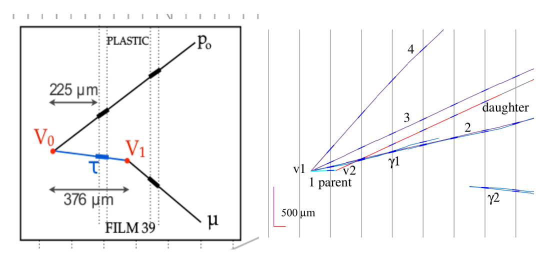


OPERA Detector





ICARUS Liquid Argon Detector (now at FNAL for short baseline experiment)



Tau neutrino events in OPERA

LONG-BASELINE NEUTRINO EXPERIMENTS TO DATE

Table 14.3: List of long-baseline neutrino oscillation experiments

Name	Beamline	Far Detector	L (km)	E_ν (GeV)	Year
K2K	KEK-PS	Water Cherenkov	250	1.3	1999–2004
MINOS	NuMI	Iron-scintillator	735	3	2005–2013
MINOS+	NuMI	Iron-scintillator	735	7	2013–2016
OPERA	CNGS	Emulsion	730	17	2008–2012
ICARUS	CNGS	Liquid argon TPC	730	17	2010–2012
T2K	J-PARC	Water Cherenkov	295	0.6	2010–
NOvA	NuMI	Liquid scint. tracking calorimeter	810	2	2014–

Written August 2019 by M.C. Gonzalez-Garcia (YITP, Stony Brook; ICREA, Barcelona; ICC, U. of Barcelona) and M. Yokoyama (Tokyo U.; Kavli IPMU (WPI), U. Tokyo).

In addition to LBL experiments a program of measurements using reactor neutrinos has contributed to the global knowledge of neutrino mass and mixing parameters ….

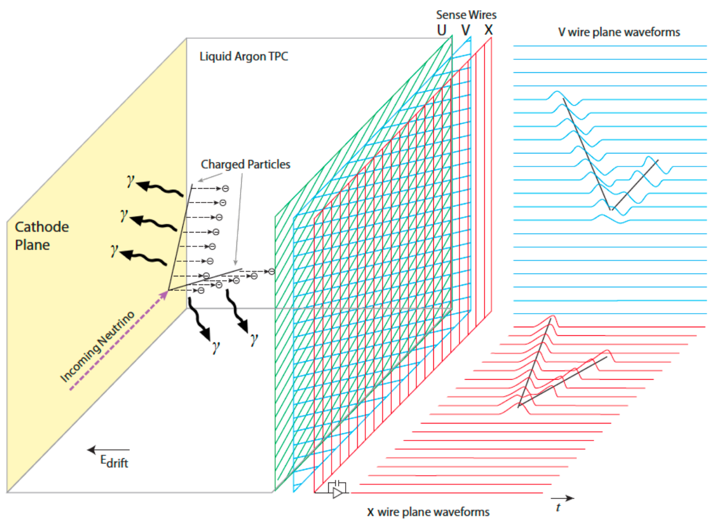
THE RESULTS SO FAR

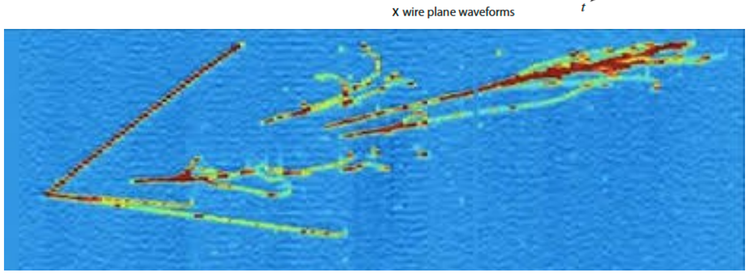
From PDG 2020

- In general, the data show consistent results for the better known parameters : θ_{12}, θ_{13} , Δm^2_{21}, and $|\Delta m^2_{32}|$
- The issues which still require clarification are : the mass ordering discrimination, the determination of θ_{23} and the leptonic CP phase δ_{CP} .
  - In all analyses the best fit is for the NORMAL mass ordering
  - All analyses find some preference for the second octant of θ_{23} but with statistical significance still well below 3σ.
  - The best fit for in NORMAL ordering is at δ_{CP} ~120° but CP conservation (for δ_{CP} = 180°) is still allowed at a 1-2σ confidence level
  - The significance of CP violation in the global analysis is reduced with respect to that reported by T2K because NOvA data does not show a significant indication of CP violation

- So what's next?

LIQUID ARGON DETECTORS

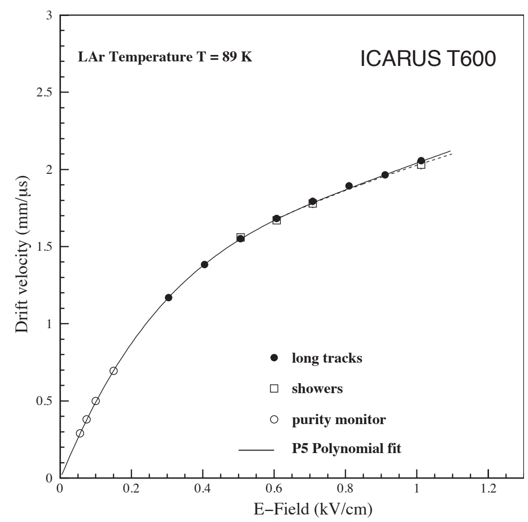


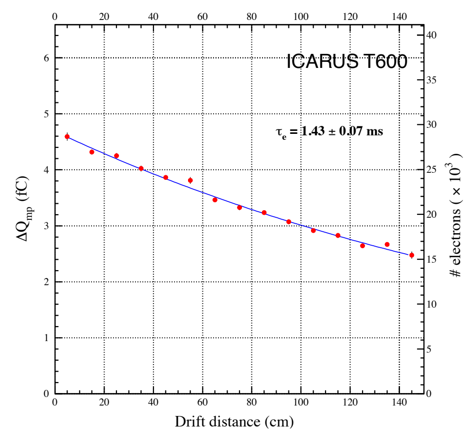


- Drift ionization charge : High Voltage
  - HV power supply and feed-through
  - Cathode Plane
  - Field Cages
    - Resistive dividers
- Collect ionization charge : Sense wires, electronics
  - Anode Planes
  - Front-end amplification, digitization, readout
- Collect scintillation light : wavelength shifters, light guides, light collection electronics

LIQUID ARGON DETECTORS

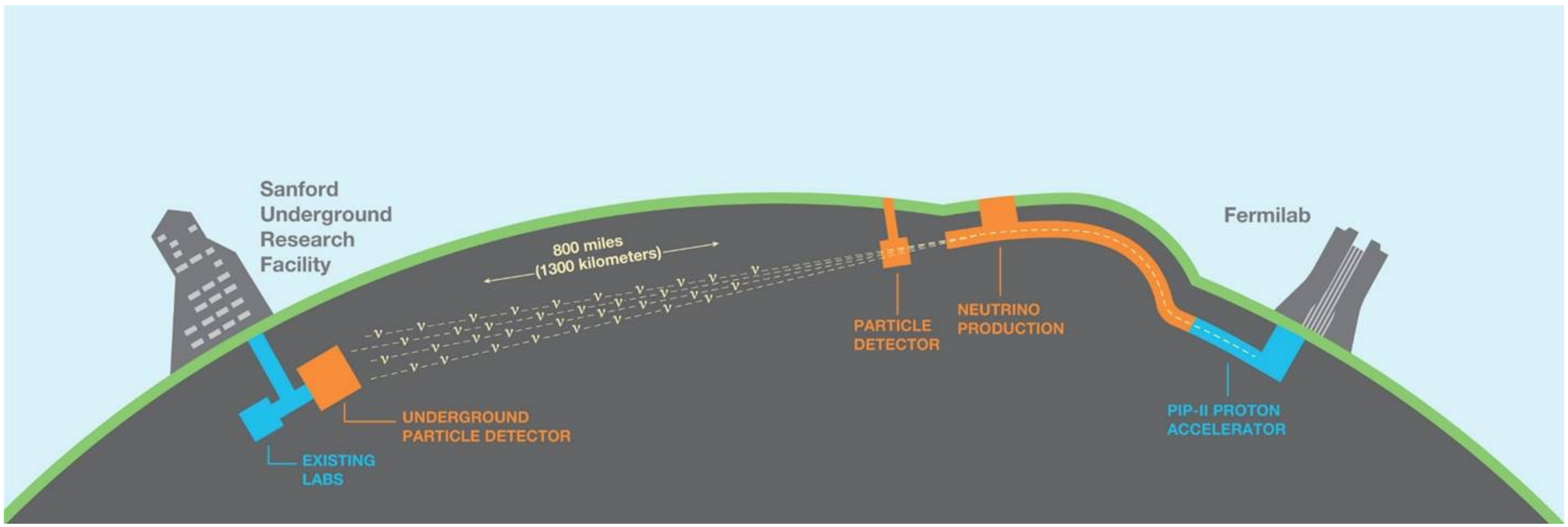
- Ionization
  - Electron drift velocity
  - Electron lifetime – argon purity
  - Diffusion
  - Recombination
- Scintillation light
  - Nitrogen content in the argon





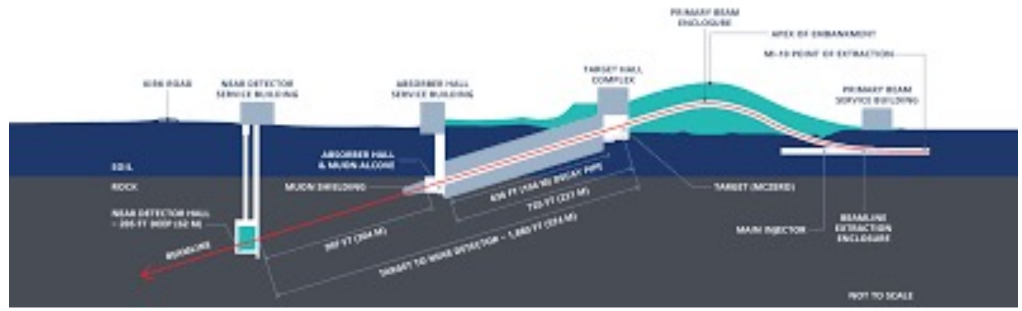
Nuclear Instruments and Methods in Physics Research A 516 (2004) 68–79

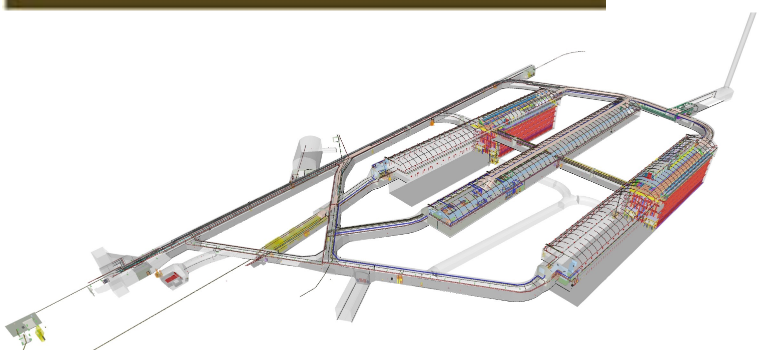
DEEP UNDERGROUND NEUTRINO EXPERIMENT (DUNE)

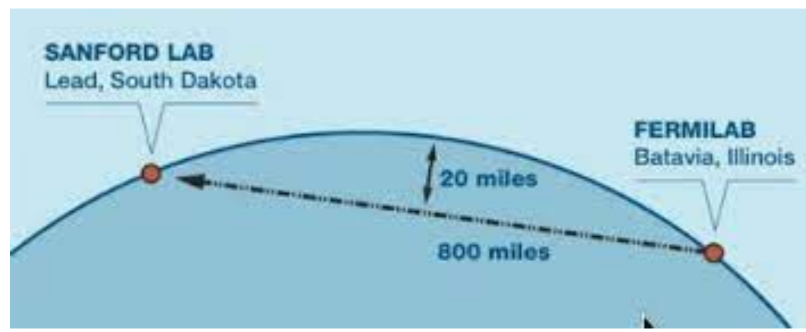


1300 kilometer baseline

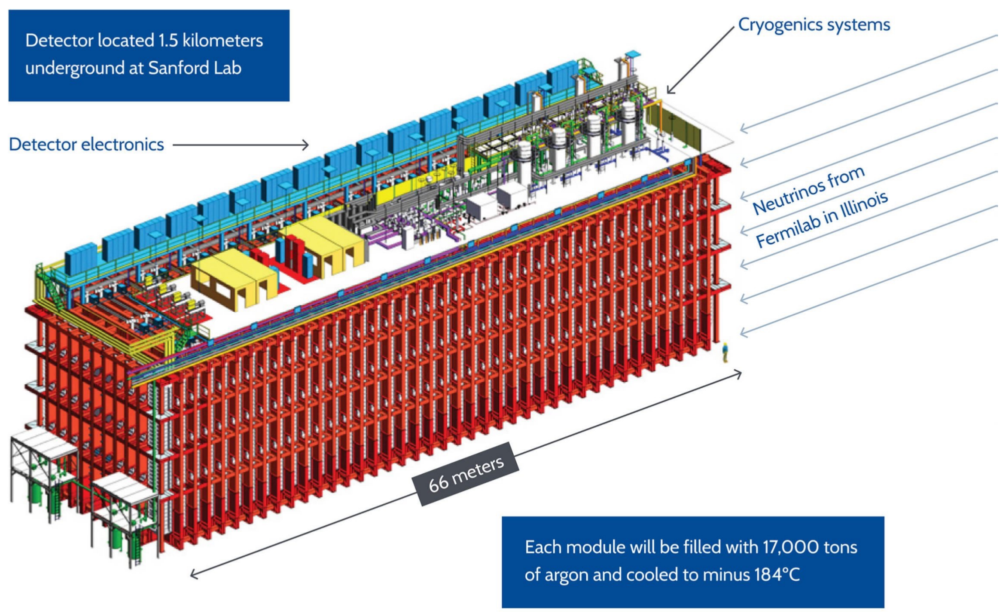
Sanford Underground Research Facility is located at the old Homestake Mine in Lead, South Dakota





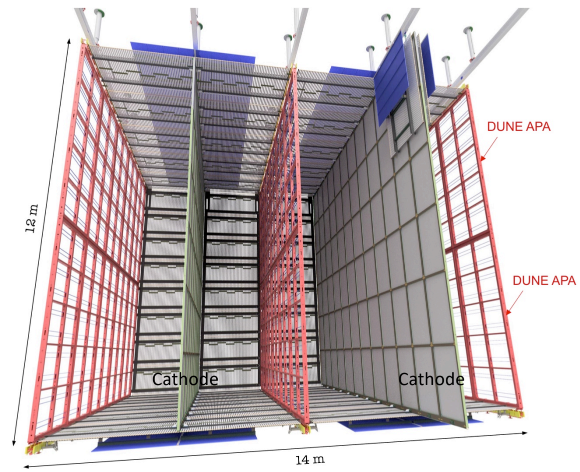


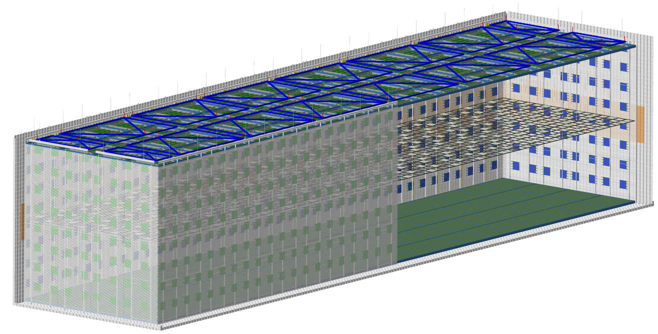
Underground cavern space for 4 detector modules



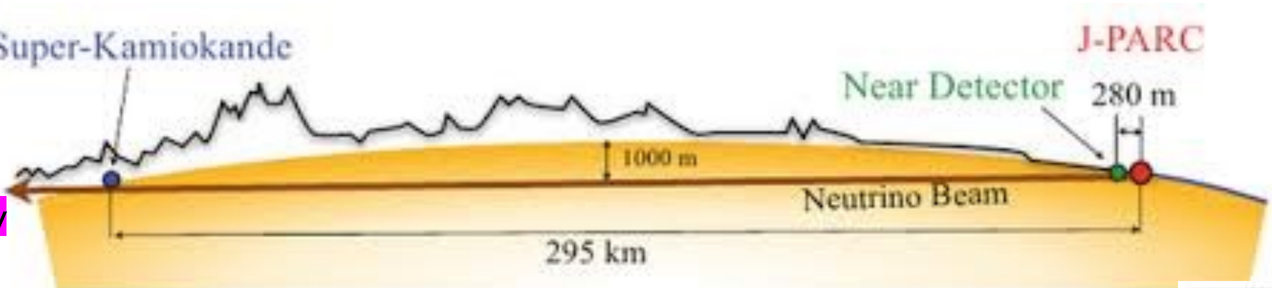
Liquid argon cryostat

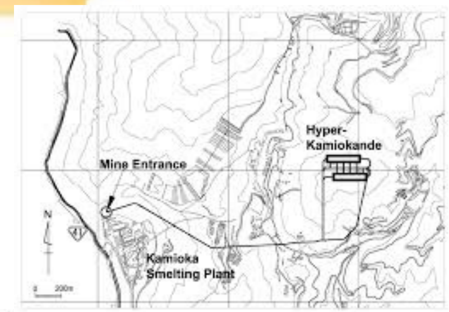
Horizontal and Vertical Drift TPCs for 1st and 2nd modules

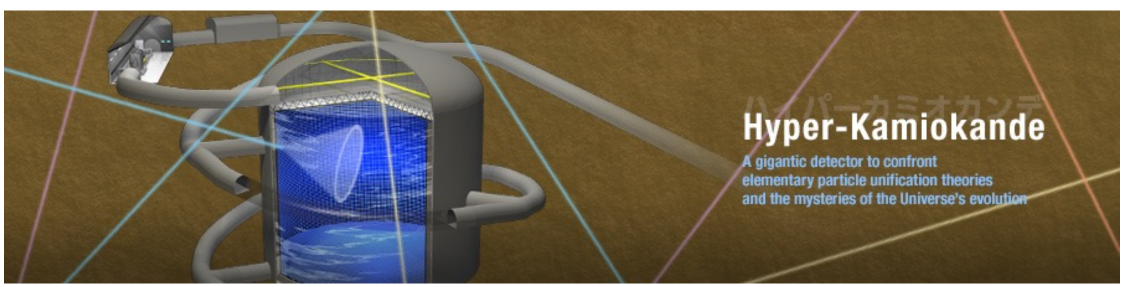


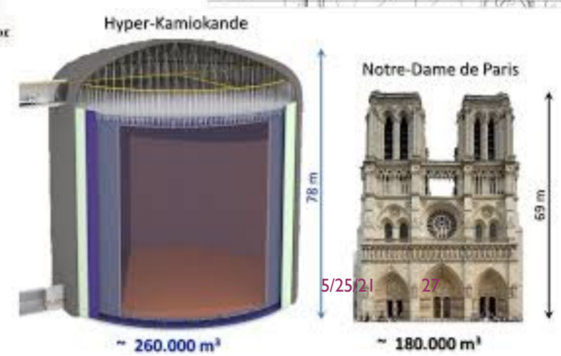


Shorter baseline
Lower Energy
Water Cerenkov









SUMMARY AND OUTLOOK

- For the next several years the NOvA and T2K experiments will continue to make world class measurements to confirm our understanding of the neutrino mass and mixing parameters
- The DUNE and Hyper-K experiments are beginning construction and once operating will offer unprecedented data sets to refine the parameters
- The long baseline of the DUNE experiment will enable a definitive measurement of the Mass Ordering within just a couple of years of operation
- The DUNE and Hyper-K experiments offer complimentary approaches to measuring the challenging parameter, δ_{CP}
- Both experiments will also provide laboratories which are sensitive to supernova, solar neutrinos and nucleon decay
- **The future is bright for neutrino enthusiasts**