The Little Neutral One: Neutrinos in the 21^{st} Century

African School of Fundamental Physics and Applications (ASP2024), Marrakech, Morocco, July 2024

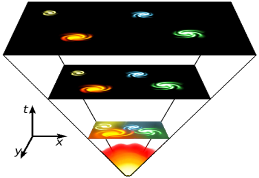
Mary Bishai
Brookhaven National Laboratory

July 19^{th}, 2024

The Neutrino Experimental Landscape

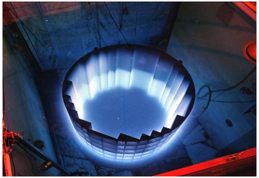
Sources of Neutrinos

Big Bang



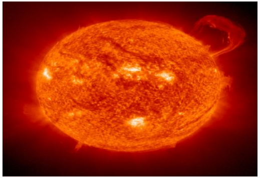
10^{-4} eV
300/cm^3

Reactors



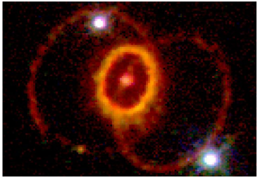
few MeV
10^{21}/GW$_{\text{th}}$/s

Sun



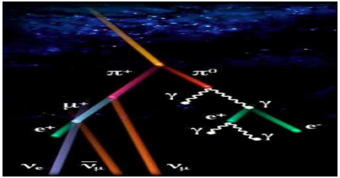
0.1-14 MeV
10^{10}/cm^2/s

SuperNova



$\sim$ 10 MeV
10^9/cm^2/s

Atmosphere

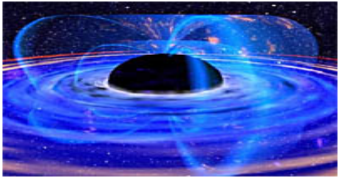


$\sim$ 1 GeV
few/cm^2/s

Accelerators

1-20 GeV
10^6/cm^2/s/MW (at 1km)

Extragalactic

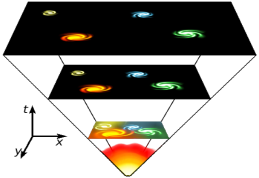


TeV-PeV
varies

The Neutrino Experimental Landscape

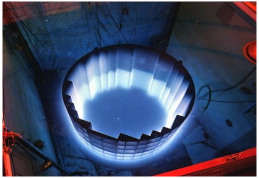
Examples of Neutrino Experiments (current, future)

Big Bang



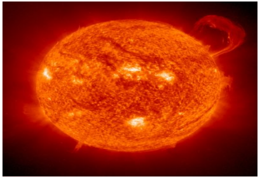
PTOLEMY

Reactors



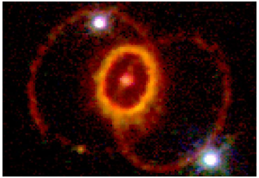
Daya Bay
JUNO

Sun



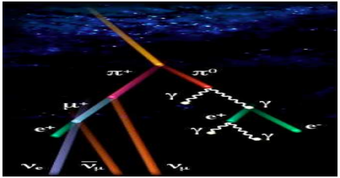
BOREXINO
SNO+/JUNO

SuperNova



SuperK-GD
DUNE/HK/JUNO

Atmosphere

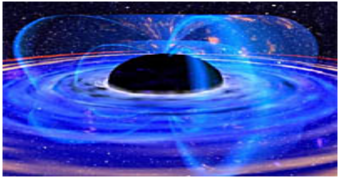


SuperK/IC-DeepCore
HyperK/KM3NeT/ORCA

Accelerators

T2K/NoVA
T2HK/DUNE/ESSνSB

Extragalactic



IceCUBE/KM3NeT
IceCUBE-Gen2

Current Neutrino Experiments: Reactor experiments and measuring the ν_e content of ν_3

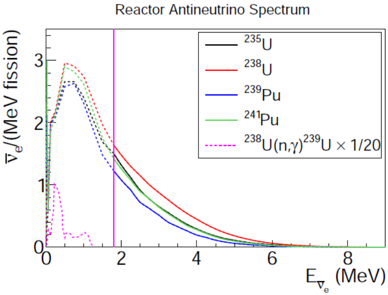
Reactor power and neutrinos

ν Exercise:

The following table shows the breakdown of energy released per fission from ^{235}U:

Fission fragment	Energy (MeV)
Fission products	175
$\langle 2.44 \rangle$ neutrons	5
γ from fission	7
γs and βs from beta decay	13
$\langle 6 \rangle$ neutrinos	10
Total	210

5% of a reactor's power is in neutrinos !



How many neutrinos are emitted per second from a 1 Gigawatt (thermal) reactor? 1 Joule $= 6.242 \times 10^{9}$GeV

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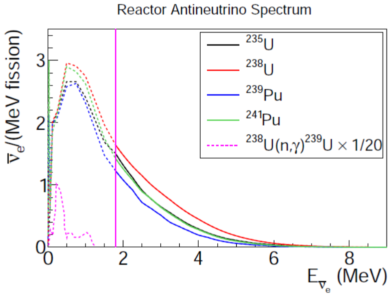
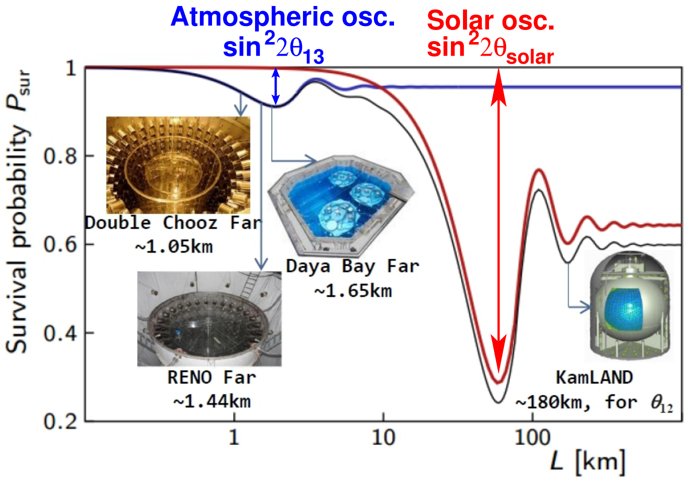


How many neutrinos are emitted per second from a 1 Gigawatt (thermal) reactor? 1 Joule $= 6.242 \times 10^9$GeV

$$
\begin{aligned}
1 \times 10^9 \ \textbf{Joules/sec} &= 6.242 \times 10^{18} \ \textbf{GeV/sec} \\
&= 3 \times 10^{19} \ \textbf{fissions/sec} \\
&\sim 2 \times 10^{20} \ \boldsymbol{\nu}\textbf{/sec} \\
&= 1.6 \times 10^{13}/\textbf{m}^2/\textbf{sec at 1 km}
\end{aligned}
$$

Reactor Experiments and Neutrino Mixing Parameters

$\sin^2\theta_{13}$ = fraction of ν_e in ν_3 state, $\sin^2\theta_{12}$ = fraction of ν_e in ν_2 state



The Daya Bay Reactor Complex

Reactor Specs:

Located 55km north-east of Hong Kong.

Initially: 2 cores at Daya Bay site + 2 cores at Ling Ao site $= 11.6\ \mathrm{GW_{th}}$

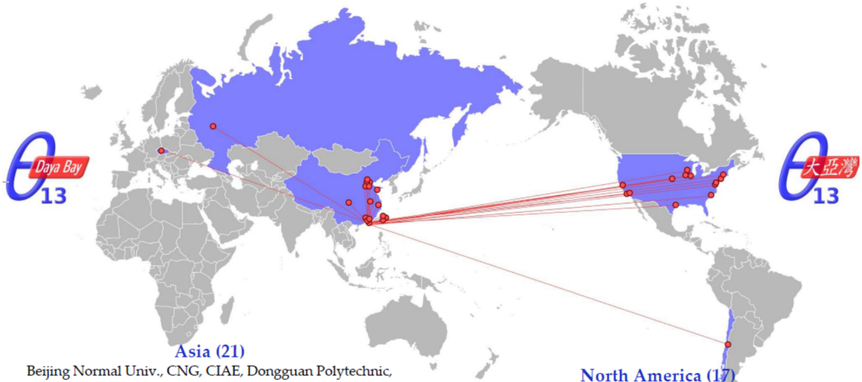
By 2011: 2 more cores at Ling Ao II site $= 17.4\ \mathrm{GW_{th}} \Rightarrow$ top five worldwide

$1\ \mathrm{GW_{th}} = 2 \times 10^{20} \bar{\nu}_e/\mathrm{second}$

Deploy multiple near and far detectors

Reactor power uncertainties $< 0.1\%$

The Daya Bay Collaboration : 231 Collaborators



Asia (21)

Beijing Normal Univ., CNG, CIAE, Dongguan Polytechnic, ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

Europe (2)

Charles University, JINR Dubna

North America (17)

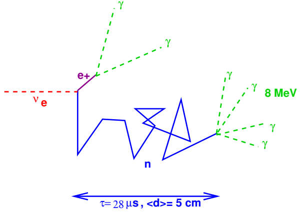
Brookhaven Natl Lab, CalTech, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Rensselaer Polytechnic, Siena College, UC Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

South America (1)

Catholic Univ. of Chile

Detecting Neutrinos from the Daya Bay Reactors

The active target in each detector is liquid scintillator loaded with 0.1% Gd

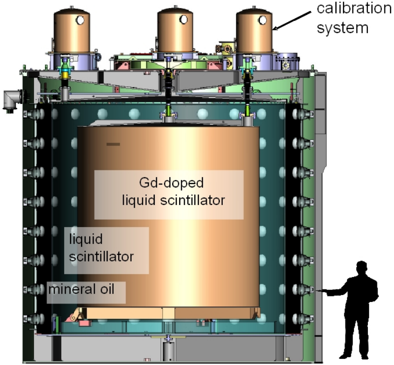


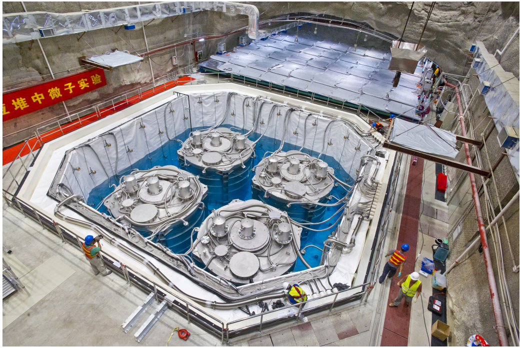
- $\bar{\nu}_e + p \rightarrow n + e^+$
- $e^+ + e^- \rightarrow \gamma\gamma$ **(2X 0.511 MeV** $+T_{e+}$**, prompt)**
- $n + p \rightarrow D + \gamma$ **(2.2 MeV,** $\tau \sim 180\mu s$**). OR**
- $n + Gd \rightarrow Gd* \rightarrow Gd + \gamma$**'s (8 MeV,** $\tau \sim 28\mu s$**).**

$\Rightarrow$ delayed co-incidence of e^+ conversion and n-capture (> 6 MeV)

with a specfic energy signature

The Daya Bay Experimental Apparatus

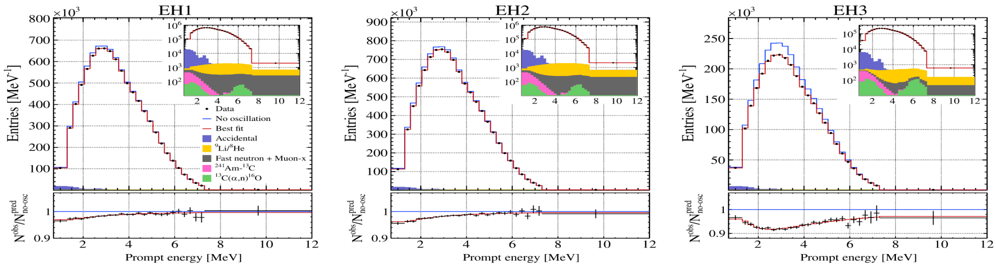


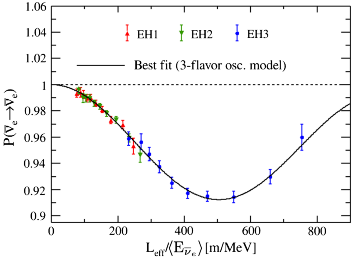


- **Multiple "identical" detectors at each site.**
- **Thick water shield to reduce cosmogenic and radiation bkgds.**

	DYB	LA	Far
Event rates/20T/day	840	740	90

Daya Bay Measurement of Non-zero θ_{13}





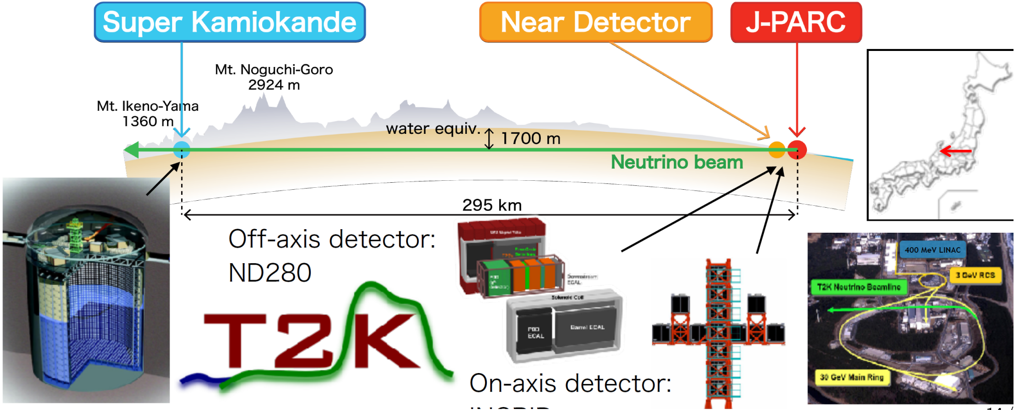
First to discover non-zero θ_{13} (2012) and currently most precise result (2023):

$$\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$$

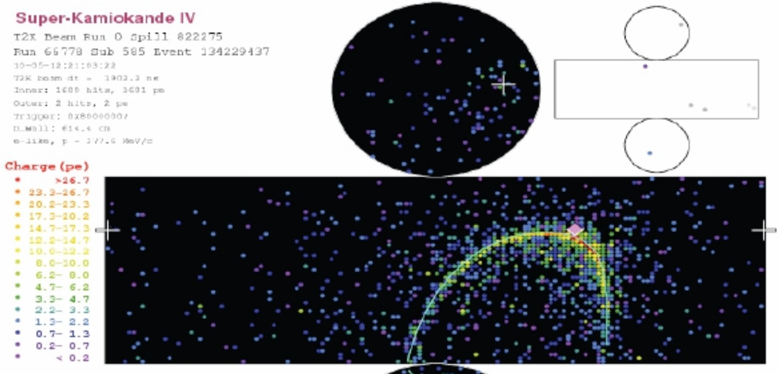
Current Neutrino Experiments: Accelerator ν_μ beams and observing $\nu_\mu \rightarrow \nu_e$

Confirming $\nu_\mu \to \nu_e$ flavor change

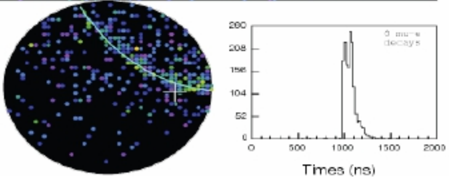
The T2K experiment: a beam of ν_μ neutrinos generated from the decay of pions produced at the Japan Proton Accelerator Complex (JPARC) located in Tokai, Japan travels 295km to the SuperKamiokande neutrino detector:



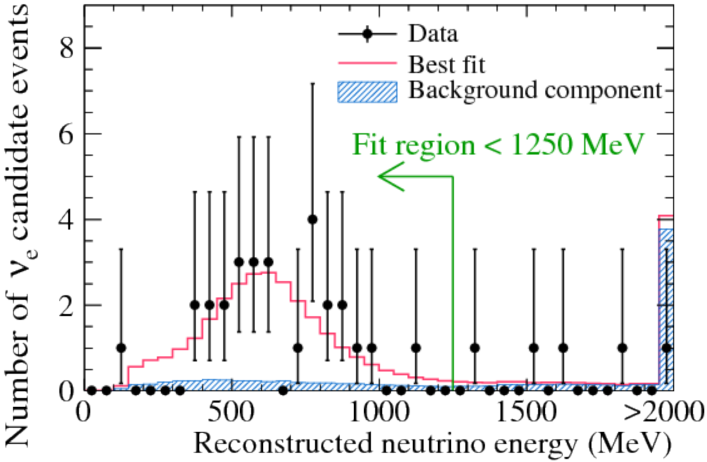
T2K beam ν_e Candidate Event 2010



Item	Event	T2K cut
Date (JST)	2010 May 12th 21:3:22	
Ring, PID	1-Ring electron-like	OK
Momentum	378 MeV	>100
N_{dcy}	0	0
$\cos(\theta_{\nu e})$	0.55 (57 degree)	N/A
$Mass$	0.13 MeV	<105
E_{rec}	496 MeV	<1250



T2K: First Observation of $\nu_\mu \to \nu_e$ APPEARANCE



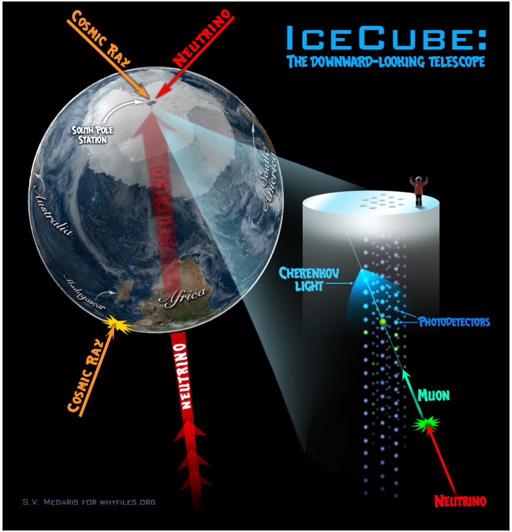
In 2014 T2K observes conversion of ν_μ to ν_e (atmospheric oscillation scale) with an amplitude of (2023 results) $\sin^2 2\theta_{13} = 0.109^{+0.011}_{-0.025}$.

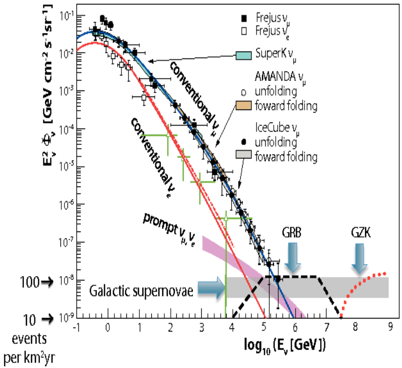
2016 Breakthrough Prize in Fundamental Physics

The 2016 Breakthrough Prize in Fundamental Physics awarded to 7 leaders and 1370 members of 5 experiments investigating neutrino oscillation: Daya Bay (China); KamLAND (Japan); K2K / T2K (Japan); Sudbury Neutrino Observatory (Canada); and Super-Kamiokande (Japan)

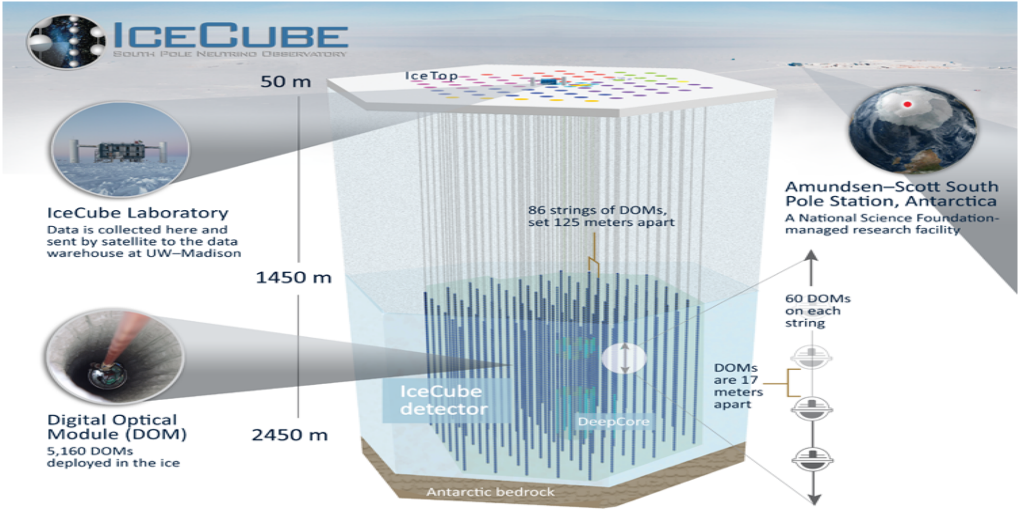
Current Neutrino Experiments: Neutrino Telescopes

The IceCUBE Experiment



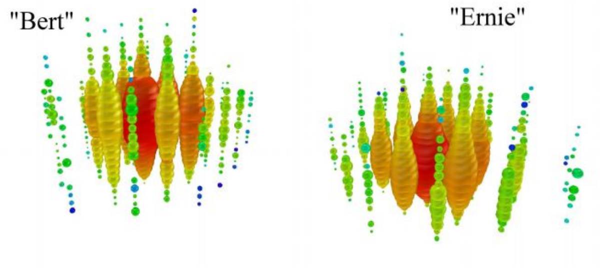


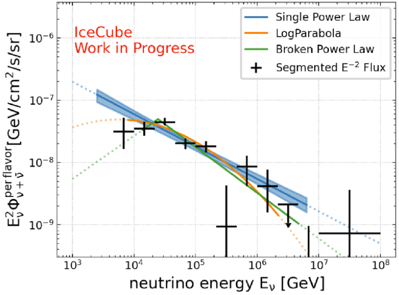
The IceCUBE Experiment



The Highest Energy Neutrinos (Gamma Ray Bursts)

Neutrino events with energies > PeV (10^{15}eV)





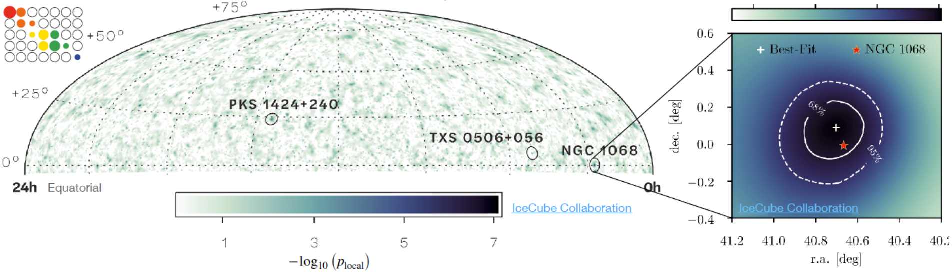
IceCUBE detects neutrinos from a known active sources

https://youtu.be/QkBAL3yvXBg

Hunting for Neutrino Sources

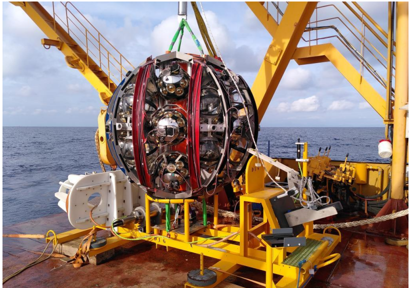
Search of northern-sky, track data set with three searches

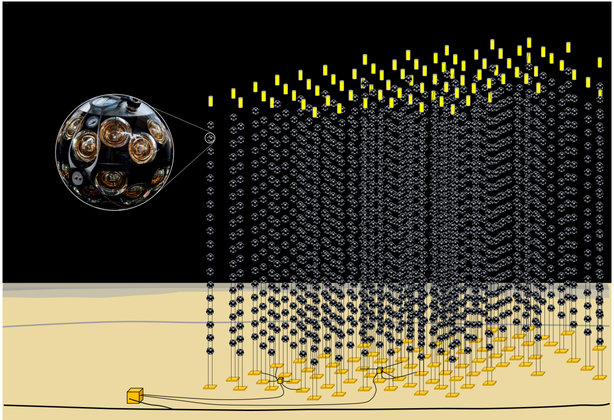
1. General clustering of neutrinos in the northern sky
2. An excess of events from known γ-ray emitters
3. An excess of events from k known γ-ray emitters



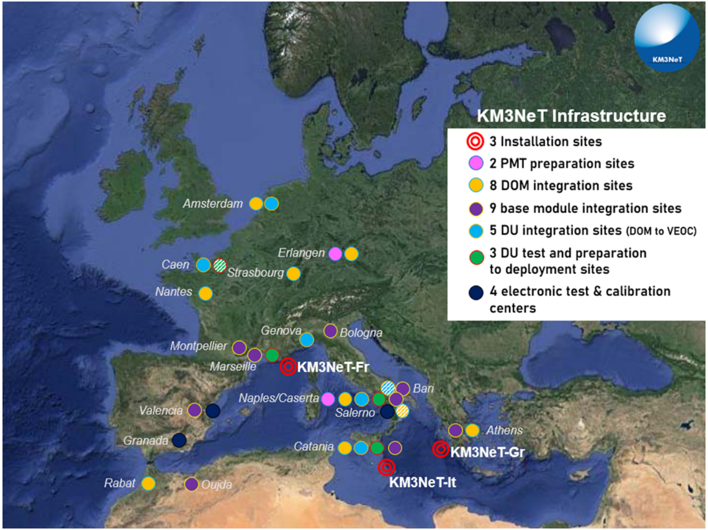
KM3NeT: Neutrino Telescope in the Mediterrenean

KM3NeT is a research infrastructure deployed in deep sea locations in the Mediterranean that houses the next generation kilometer scale neutrino water Cherenkov telescopes. Ultimately the detector will have volumes between a megaton and several cubic kilometers of clear sea water.





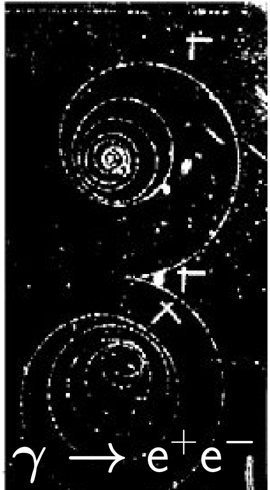
KM3NeT Infrastructure



Neutrinos and matter/anti-matter asymmetry of the Universe

Charge-Parity Symmetry

Charge-parity symmetry: laws of physics are the same if a particle is interchanged with its anti-particle and left and right are swapped.
A violation of CP ⇒ matter/anti-matter asymmetry.



CP Violation in PMNS (leptons) and CKM (quarks)

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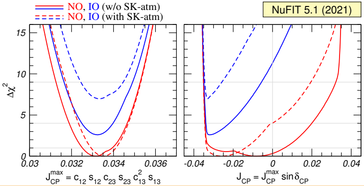
In 3-flavor mixing the degree of CP violation is determined by the Jarlskog invariant:

$$J_{CP}^{PMNS} \equiv \frac{1}{8}\sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\theta_{13} \sin\delta_{CP}.$$



Given the current best-fit values of the ν mixing angles :

$$J_{CP}^{PMNS} \approx 3 \times 10^{-2} \sin\delta_{CP}.$$

For CKM (mixing among the 3 quark generations):

$$J_{CP}^{CKM} \approx 3 \times 10^{-5},$$

despite the large value of $\delta_{CP}^{CKM} \approx 70°$.

$\nu_\mu \rightarrow \nu_e$ Oscillations in the 3-flavor ν SM

Matter/anti-matter asymmetries in neutrinos are best probed using $\nu_\mu/\bar{\nu}_\mu \rightarrow \nu_e/\bar{\nu}_e$ oscillations. **With terms up to second order in $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} = 0.03$ (M. Freund. Phys. Rev. D 64, 053003):**

$$P(\nu_\mu \rightarrow \nu_e) \cong P(\nu_e \rightarrow \nu_\mu) \cong \underbrace{P_0}_{\theta_{13}} + \underbrace{P_{\sin\delta}}_{\text{CP violating}} + \underbrace{P_{\cos\delta}}_{\text{CP conserving}} + \underbrace{P_3}_{\text{solar oscillation}}$$

where for oscillations in vacuum:

$$P_0 = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(\Delta),$$

$$P_{\sin\delta} = \alpha\, 8J_{cp}\sin^3(\Delta),$$

$$P_{\cos\delta} = \alpha\, 8J_{cp}\cot\delta_{CP}\cos\Delta\sin^2(\Delta),$$

$$P_3 = \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2(\Delta),$$

where $\Delta = 1.27\Delta m^2_{31}(eV^2)L(km)/E(GeV)$

For $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\underbrace{P_{\sin\delta} \rightarrow -P_{\sin\delta}}_{\text{CP asymmetry}}$,

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where **for oscillations in matter with constant density:**

$$P_0 = \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta],$$

$$P_{\sin\delta} = \alpha\frac{8J_{cp}}{A(1-A)}\sin\Delta\sin(A\Delta)\sin[(1-A)\Delta],$$

$$P_{\cos\delta} = \alpha\frac{8J_{cp}\cot\delta_{CP}}{A(1-A)}\cos\Delta\sin(A\Delta)\sin[(1-A)\Delta],$$

$$P_3 = \alpha^2\cos^2\theta_{23}\frac{\sin^2 2\theta_{12}}{A^2}\sin^2(A\Delta),$$

where $\Delta = 1.27\Delta m^2_{31}(eV^2)L(km)/E(GeV)$ and $A = \sqrt{2}G_F N_e 2E/\Delta m^2_{31}$.

For $\bar{\nu}_\mu \to \bar{\nu}_e$, $\underbrace{P_{\sin\delta} \to -P_{\sin\delta}}_{\text{CP asymmetry}}$, $\underbrace{A \to -A}_{\text{matter asymmetry}}$

Osc. vs L/E

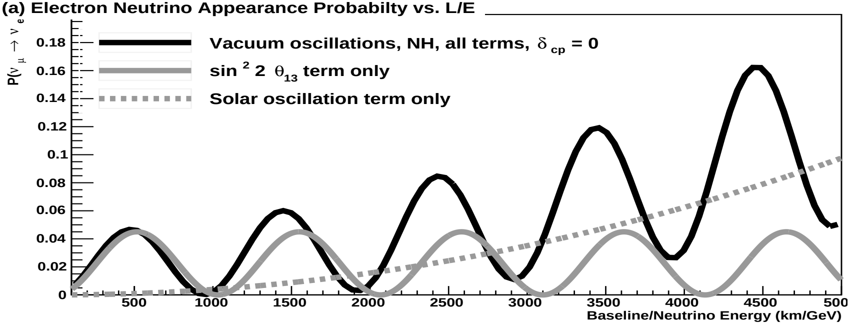
$\sin^2 2\theta_{13} = 0.09, \sin^2\theta_{23} = 0.5, \Delta m^2_{31} = \pm 2.4 \times 10^{-3}\mathrm{eV}^2$

ν Exercise: reproduce the plots shown below

The $\nu_\mu \rightarrow \nu_e$ oscillation probability maxima occur at

$$\frac{L\ (\mathrm{km})}{E_n(\mathrm{GeV})} = \left(\frac{\pi}{2}\right)\frac{(2n-1)}{1.27 \times \Delta m^2_{31}(\mathrm{eV}^2)} \approx (2n-1) \times \frac{515\ \mathrm{km}}{\mathrm{GeV}}$$

Oscillations in vacuum - different terms ($\delta_{CP} = 0$)



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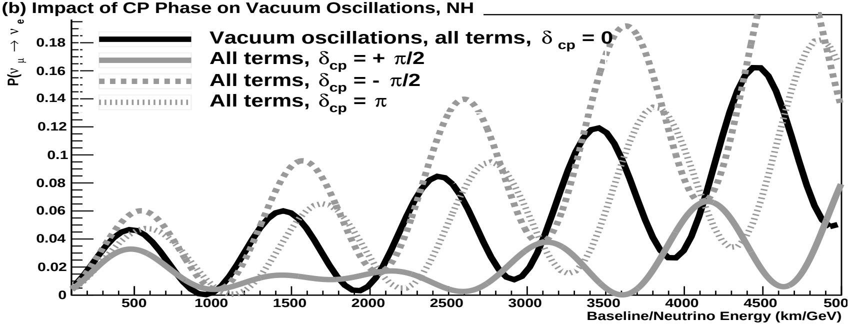
Impact of δ_{CP} on oscillations in vacuum, $\Delta m^2_{31} > 0$ (NH)



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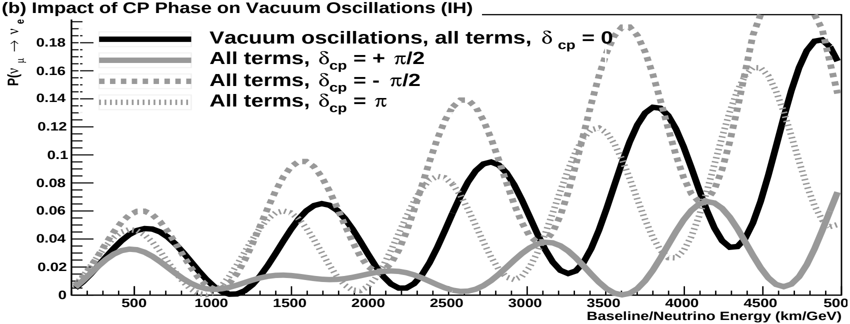
Impact of δ_{CP} on oscillations in vacuum, $\Delta m^2_{31} < 0$ (IH)



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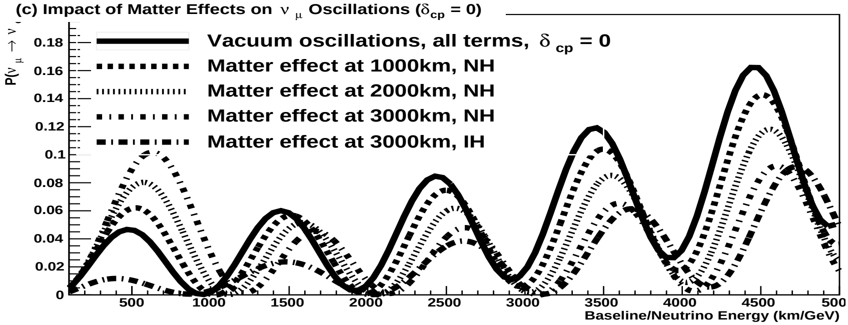
$$\frac{L\ (\mathrm{km})}{E_n(\mathrm{GeV})} = \left(\frac{\pi}{2}\right) \frac{(2n-1)}{1.27 \times \Delta m^2_{31}(\mathrm{eV}^2)} \approx (2n-1) \times \frac{515\ \mathrm{km}}{\mathrm{GeV}}$$

Impact of matter effect on ν_μ oscillations ($\delta_{CP} = 0$)

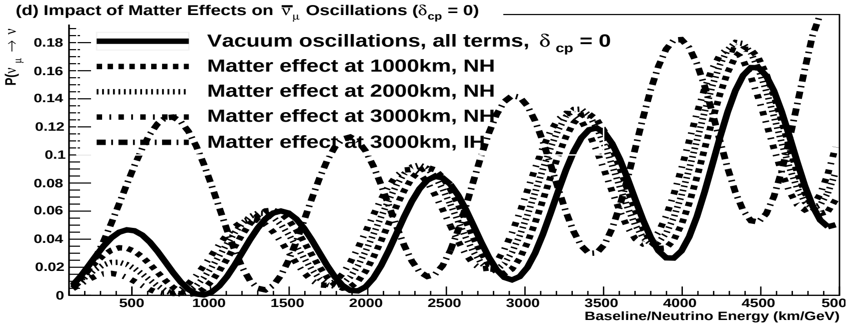


ν Exercise: reproduce the plots shown below

The $\nu_\mu \to \nu_e$ oscillation probability maxima occur at

$$\frac{L\ (km)}{E_n (GeV)} = \left(\frac{\pi}{2}\right) \frac{(2n-1)}{1.27 \times \Delta m^2_{31} (eV^2)} \approx (2n-1) \times \frac{515\ km}{GeV}$$

Impact of matter effect on $\bar{\nu}_\mu$ oscillations ($\delta_{CP} = 0$)



Expected Appearance Signal Event Rates

ν Exercise: The total number of electron neutrino appearance events expected for a given exposure from a muon neutrino source as a function of baseline is given as

$$N_{\nu_e}^{\text{appear}}(L) = \int \Phi^{\nu_\mu}(E_\nu, L) \times P^{\nu_\mu \to \nu_e}(E_\nu, L) \times \sigma^{\nu_e}(E_\nu) dE_\nu$$

Assume the neutrino source produces a flux that is constant in energy and using only the dominant term in the probability(no matter effect)

$$\Phi^{\nu_\mu}(E_\nu, L) \approx \frac{C}{L^2}, \quad C = \text{number of } \nu_\mu/\text{m}^2/\text{GeV}/\text{sec at 1 km}$$

$$P^{\nu_\mu \to \nu_e}(E_\nu, L) \approx \underbrace{\sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.27\Delta m^2_{31}L/E_\nu)}_{P_0}$$

$$\sigma^{\nu_e}(E_\nu) = 0.7 \times 10^{-42}(\text{m}^2/\text{GeV}/\text{N}) \times E_\nu, \quad E_\nu > 1\ \text{GeV}$$

Prove that the rate of ν_e appearing integrated over a constant range of L/E is independent of baseline for $L > 500$ km!

Expected Appearance Signal Event Rates

$$N^{\text{appear}}_{\nu_e}(L) \propto \textbf{constant term} \times \int \frac{\sin^2(ax)}{x^3} dx,$$

$$x \equiv L/E_\nu, \quad a \equiv 1.27\Delta m^2_{31}\ \textbf{GeV/(eV}^2\textbf{.km)}$$

ν Exercise:

$C \approx 1 \times 10^{17}\ \nu_\mu/\text{m}^2/\text{GeV/yr}$ **at 1 km (from 1MW accelerator)**
$\sin^2 2\theta_{13} = 0.084$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{31} = 2.4 \times 10^{-3}\text{eV}^2$

Calculate the rate of ν_e events observed per kton of detector integrating over the region $x = 100$ km/GeV to 2000 km/GeV:

Expected Appearance Signal Event Rates

$$N^{\rm appear}_{\nu_e}(L) \propto \textbf{constant term} \times \int \frac{\sin^2(ax)}{x^3} dx,$$

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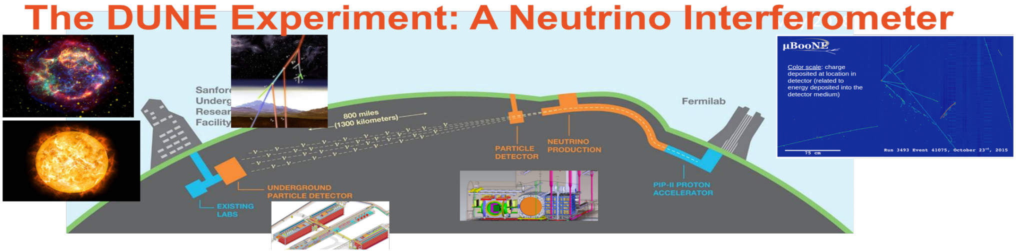
Calculate the rate of ν_e events observed per kton of detector integrating over the region $x = 100$ km/GeV to 2000 km/GeV:

$$N^{\rm appear}_{\nu_e}(L) \approx (2 \times 10^6 \mathbf{events/kton/yr}) \cdot (\mathbf{km/GeV})^2 \int_{x_0}^{x_1} \frac{\sin^2(ax)}{x^3} dx,$$

$$N^{\rm appear}_{\nu_e}(L) \sim \mathcal{O}(20 - 30)\ \mathbf{events/kton.MW.yr}$$

Hunting for CP violation: LBNF/DUNE

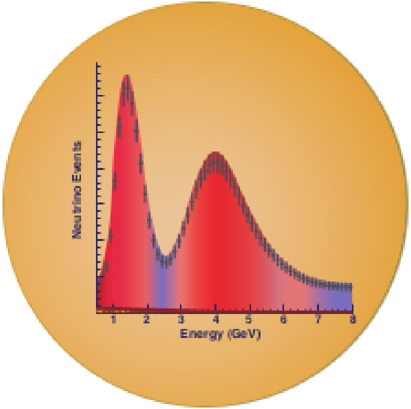
The Deep Underground Neutrino Experiment



- A very long baseline experiment: 1300km from Fermilab in Batavia, IL to the Sanford Underground Research Facility (former Homestake Mine) in Lead, SD.
- A highly capable near detector facility at Fermilab.
- Very deep (1 mile underground) far detectors: $4 \times$ 10-kiloton fiducial (17 kt total) Liquid-Argon Time-Projection-Chambers with state-of-the-art instrumentation.
- High intensity *tunable* wide-band neutrino beam produced from 120 GeV Main Injector proton accelerator at Fermilab upgraded to 2MW.

Scientific Objectives of DUNE (4 experiments-in-one)

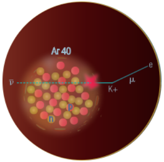
A long-baseline neutrino oscillation experiment:



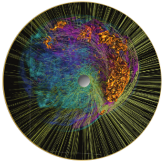
- **precision measurements of the parameters that govern $\nu_\mu \to \nu_e$ oscillations; this includes precision measurement of the third mixing angle θ_{13}, measurement of the charge-parity (CP) violating phase δ_{CP}, and determination of the neutrino mass ordering (the sign of $\Delta m^2_{31} = m^2_3 - m^2_1$), the so-called mass hierarchy**
- **precision measurements of the mixing angle θ_{23}, including the determination of the octant in which this angle lies.**
- **Searches for physics beyond the 3 flavor model using neutrino oscillations**

Scientific Objectives of DUNE (4 experiments-in-one)

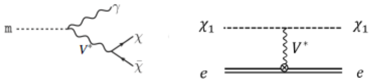
A proton decay experiment:



A neutrino telescope:

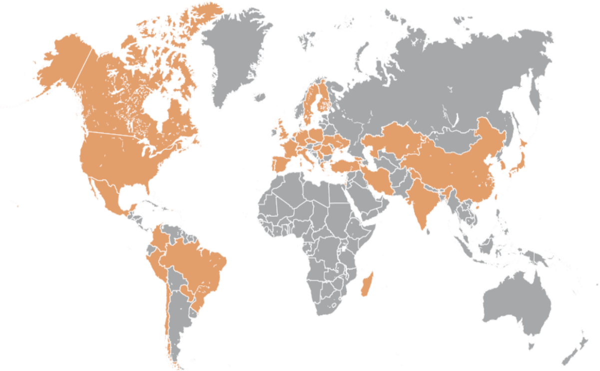


A fixed target experiment:



- complemantary searches for proton decay in several important candidate decay modes, e.g., $p \to K^+\overline{\nu}$ as well as other baryon number violating signals.
- detection and measurement of the neutrino flux, spectrum and time evolution from a core-collapse supernova within our galaxy, should one occur during the lifetime of DUNE
- Unique searches for heavy neutral leptons, dark matter scattering, precision electroweak measurements, nuclear form factors and other measurements made possible by the high power proton beam and neutrino scattering in the near detector

The DUNE Scientific Collaboration



As of Oct 2023

- **1508 members**
- **1419 active collaborators (657 US + 762 non-US)**
- **37 active countries including CERN**
- **209 active institutions**

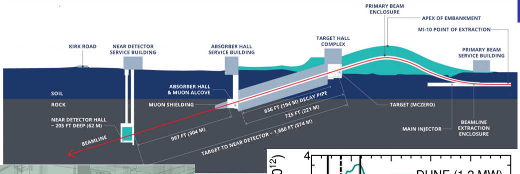
The DUNE Scientific Collaboration

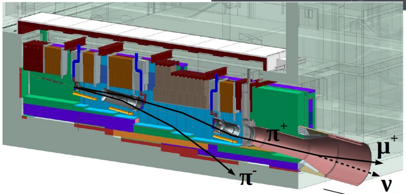
DUNE Coll. Meet. at CERN, Jan 2023

Total participants : 581 **In person: 354 (largest on record)** **Zoom:227**

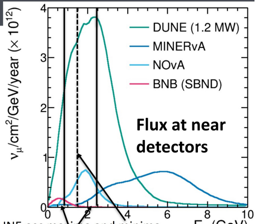
Overview of the LBNF Beamline

LBNF/DUNE Beamline





Pions decay into neutrinos



- **Primary proton beam 60-120 GeV with initial 1.2 MW beam power (Phase I), upgradable to 2.4 MW (Phase II). Embankement allows target complex to be at grade (BNL concept)**
- **Wide-band beam (on-axis) optimized for CP violation sensitivity - uses 3 focusing horns to select neutrino beam with a decay pipe 194m long x 4m diameter, He filled**

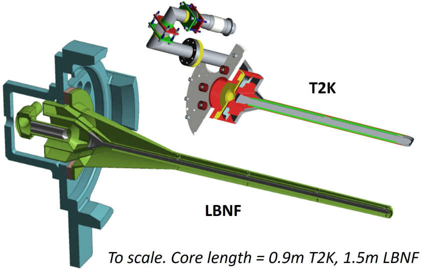
The LBNF Beamline Target Challenges

Advanced engineering and material science challenges

Comparison with T2K

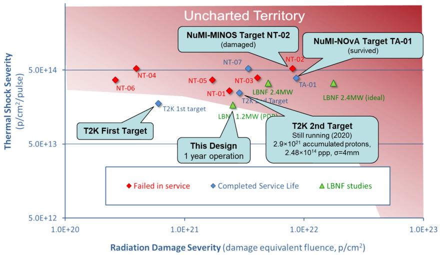
- Higher beam power but lower current and smaller beam spot = lower proton fluence and thermal shock than T2K
- Longer target will require optimised design of cantilever support

Parameter	LBNF Design (1 Year Design Life)	T2K Experience (Target 2 History)
Beam Power (MW)	1.2	0.51
Proton Energy (GeV)	120	30
Beam Current (μA)	10	17
Beam Sigma (mm)	2.7	4
Radiation Damage Severity (p/cm^2)	2.5E+21	3.1E+21
Thermal Shock Severity (p/cm^2/pulse)	1.7E+14	2.6E+14

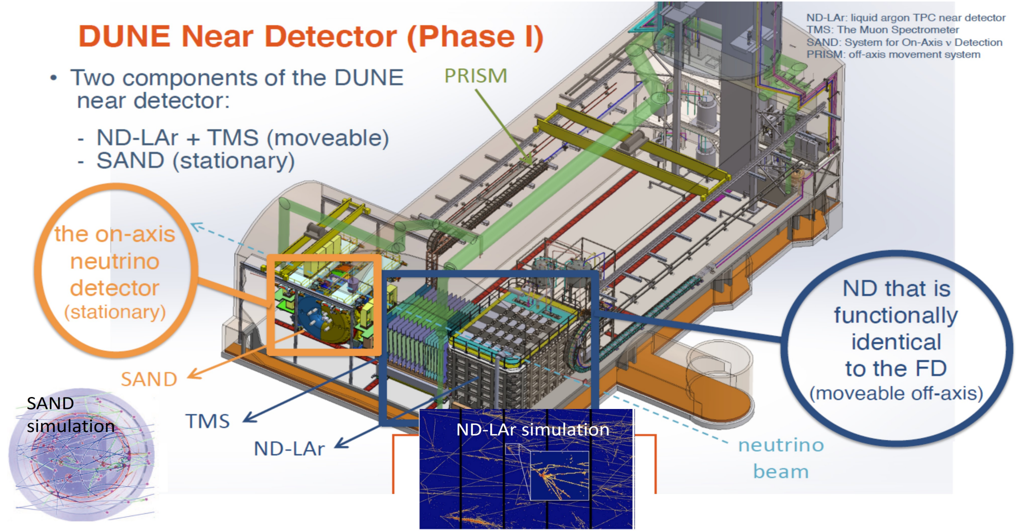


To scale. Core length = 0.9m T2K, 1.5m LBNF

Graphite Neutrino Targets Exploratory Map

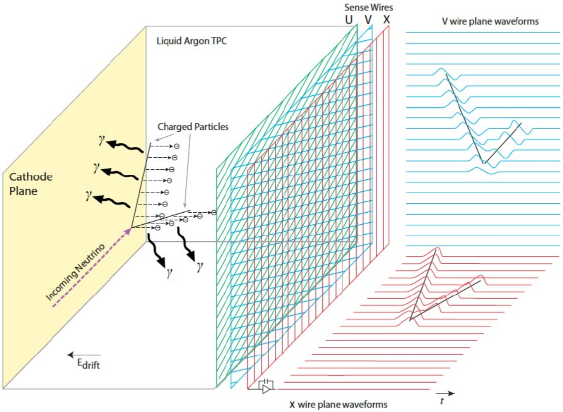


DUNE Near Detectors



The DUNE Far Detectors: Liquid-Argon Time-Projection Chambers

Single Phase "horizontal drift" LArTPC with 3 anode wire planes



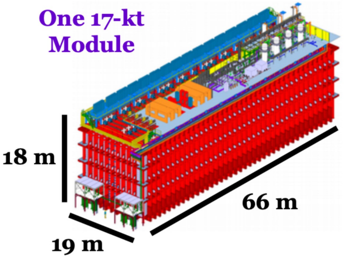
DUNE "horizontal drift" TPC design by Bo Yu (BNL)

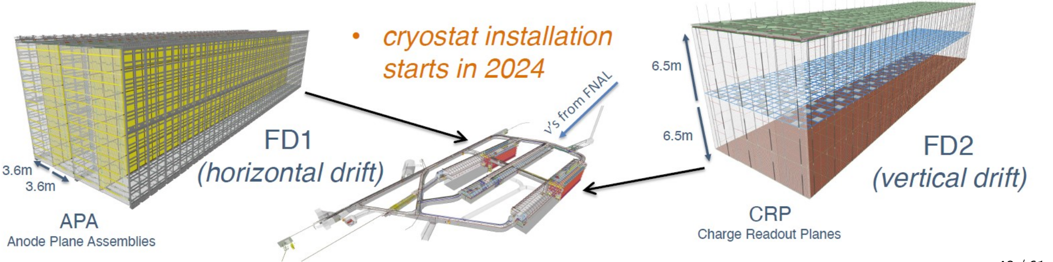
The DUNE anode wireplane assembly

The DUNE Far Detectors: Liquid-Argon Time-Projection Chambers

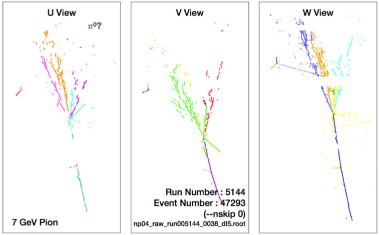
The DUNE LArTPCs

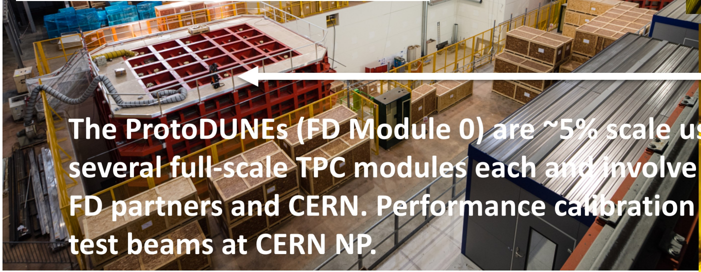
- **Both FD1 and FD2 are LArTPCs using highly modularized TPC design comprising $\mathcal{O}(100)$ identical TPC modules**
- **FD1 is a "horizontal drift" detector using 3 layers of wire planes vertical and $\pm 36^\circ$ - goes in the NE cavern**
- **FD2 is a "vertical drift" detector that uses 3 layers of strips on PCBs as the charge plane readout.**

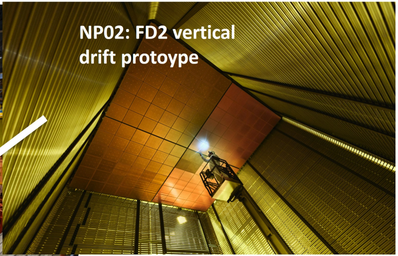


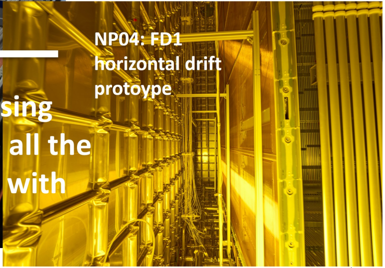


DUNE Prototypes @ CERN Neutrino Platform



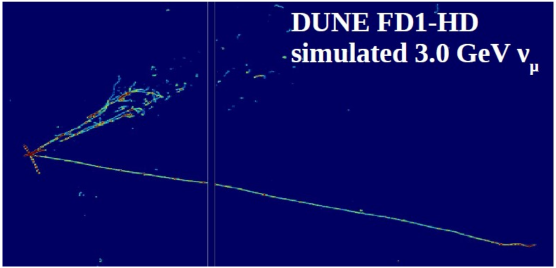


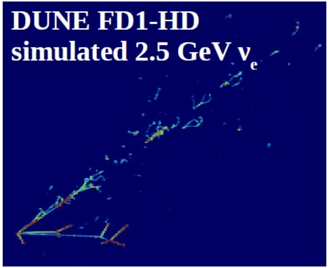


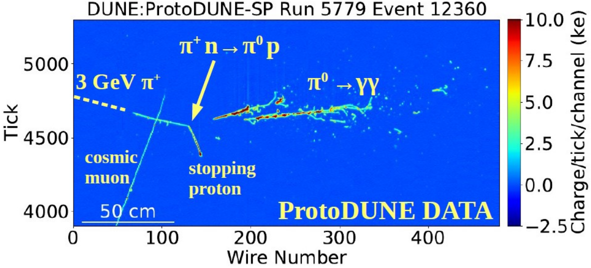


The ProtoDUNEs (FD Module 0) are ~5% scale using several full-scale TPC modules each and involve all the FD partners and CERN. Performance calibration with test beams at CERN NP.

Neutrino Interactions in DUNE Far Detectors

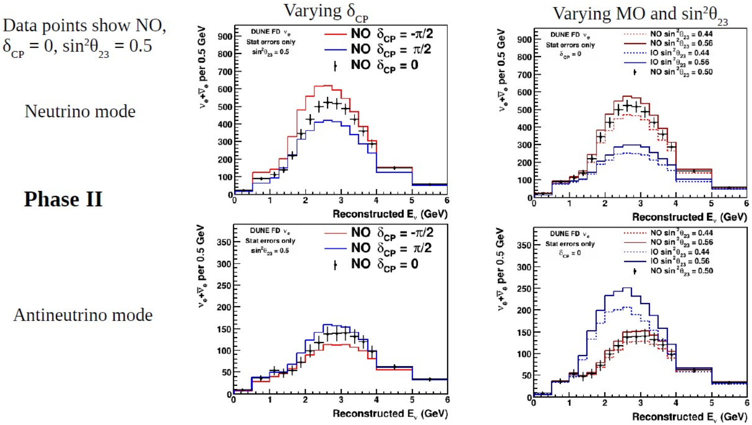






DUNE Long-Baseline Oscillation Measurements

DUNE Phase I+II measures δ_{cp}, θ_{23} octant

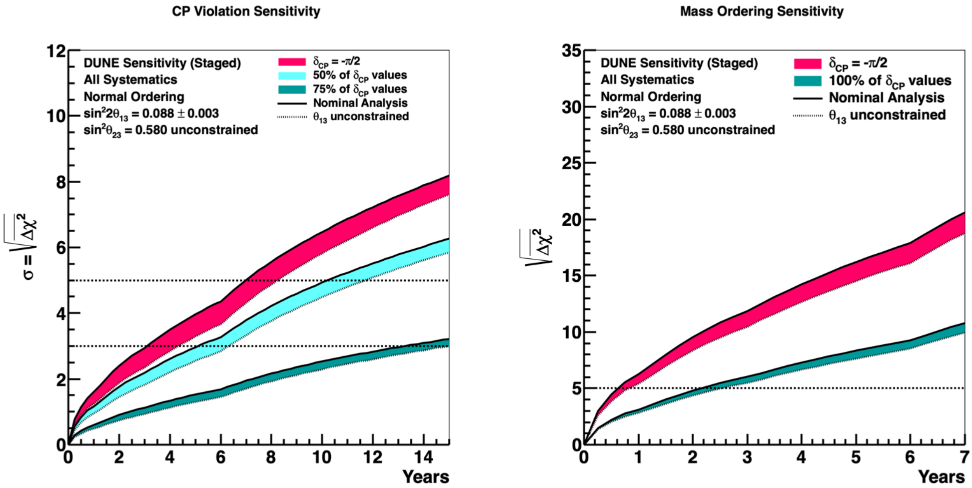


Rich spectral information = unmatched sensitivity to osc. parameters

DUNE Sensitivities to ν 3-flavor Oscillations

The Little Neutral One: Neutrinos in the 21st Century

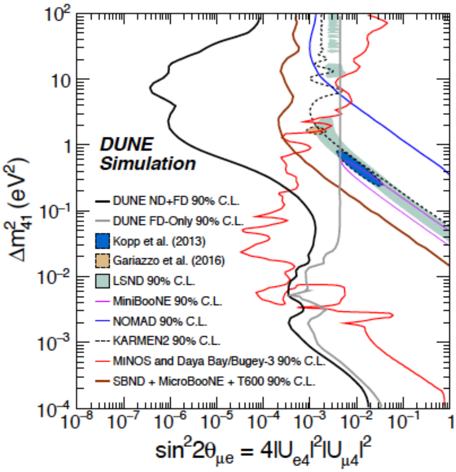
Mary Bishai Brookhaven National Laboratory



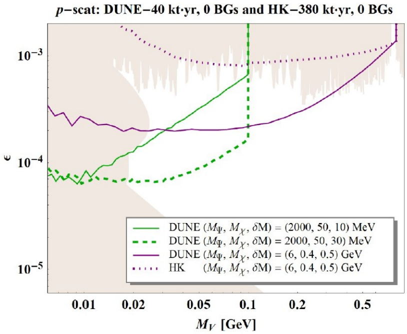
DUNE will determine mass ordering unambigously and CPV to 5σ (50% of δ_{cp})

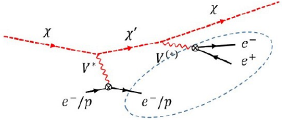
BSM Searches with DUNE

Sterile ν Searches



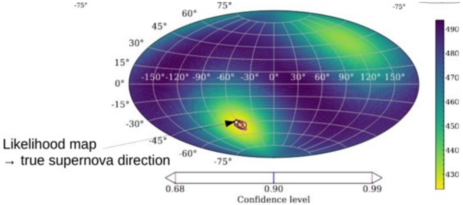
Inelastic Dark Matter Scattering



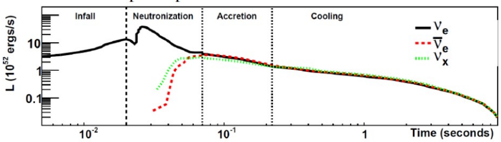


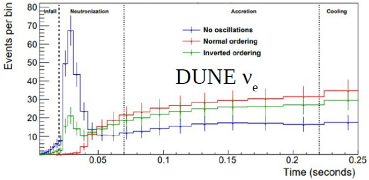
Supernova Burst Neutrinos in DUNE

- **Time (and energy) profile is rich in Supernova astrophysics.**
- **DUNE has unique sensitivity to the ν_e flux**
- **Studies using ν_e electron scattering indicate 5% pointing resolution**



10 kpc supernova burst





	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK[1]	10%	87%	3%
JUNO[2]	1%	72%	27%

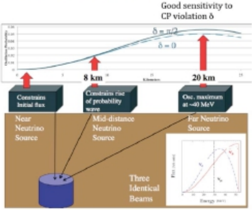
[1]Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)
[2]Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)

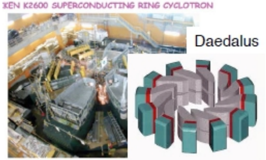
PRACTICAL APPLICATIONS of ν

Practical Applications of Technologies for ν Experiments

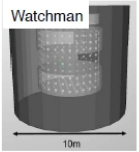
Synergies and Applications - Examples

Cyclotrons for neutrino physics (and industrial applications)





Neutrino detectors for reactor monitoring and non-proliferation



remote discovery of undeclared nuclear reactors with large detectors at km scale

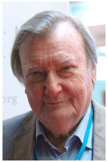
US Short-Baseline Experiment

reactor antineutrino studies at short baselines

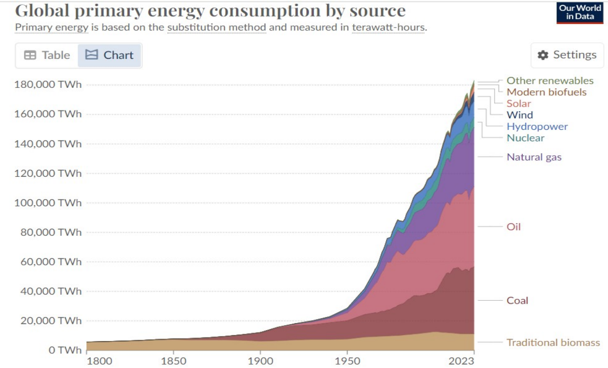
Karsten Heeger, Yale University   Snowmass, July 31, 2013   21

Multi-MW Accelerators Driving Thorium Reactors

First proposed by Carlo Rubbia in 1995 (1984 Nobel Prize winner)



Requires proton accelerators with powers of 10 MW. Currently neutrino and neutron experiments are driving the technology of high power MW class proton beams.



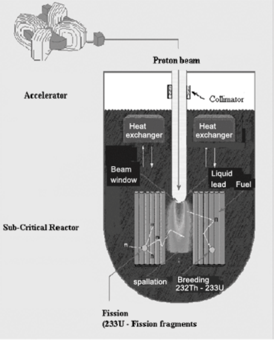
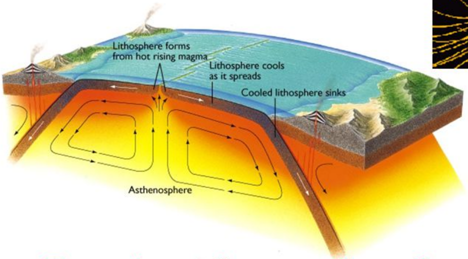
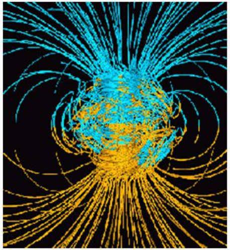


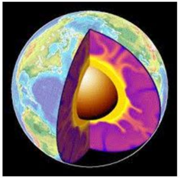
Figure 1. Schematic representation of Energy Amplifier proposed by Rubbia [4].

Neutrinos and Earth's Geology

Plate Tectonics, Convection, Geodynamo



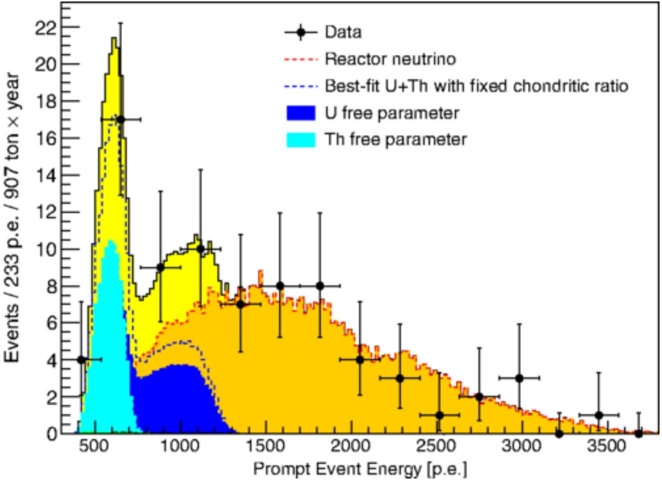




Does heat from radioactive decay drive the Earth's engine?

Neutrinos and Earth's Geology

Signal of $\bar{\nu}_e$ from radioactive decays of U/TH in the earth observed in the BOREXINO solar neutrino experiment:



Summary

- **Neutrinos have been at the forefront of fundamental discoveries in particle physics for decades.**
- **Discoveries of neutrino properties like the very small mass, large almost maximal mixing, are the** *ONLY direct evidence for physics beyond the Standard Model of particle physics, and new hidden symmetries.*
- **Results from the current generation of accelerator based neutrino experiments hint (inconclusively) at large matter/anti-matter asymmetries.**
- **The future T2HK and LBNF/DUNE project are ambitious multi-national neutrino experiments designed to probe matter/anti-matter asymmetries, neutrino oscillations and cosmological neutrinos with unprecedented precision.**
- **Studying neutrinos is advancing new technologies in accelerators, non-proliferation, geology...etc**


THANK YOU