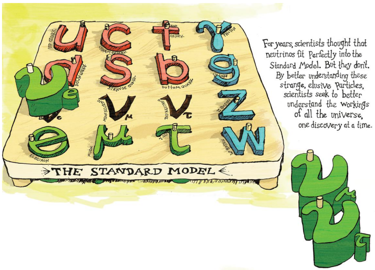
The Little νeutral One

ASP Teachers Program, July 22, 2021

Mary Bishai
Brookhaven National Laboratory

July 8^{th}, 2021

About Neutrinos



From Symmetry Magazine, Feb 2013

Cosmic Gall

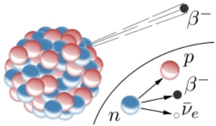
by John Updike

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed—you call
It wonderful; I call it crass.

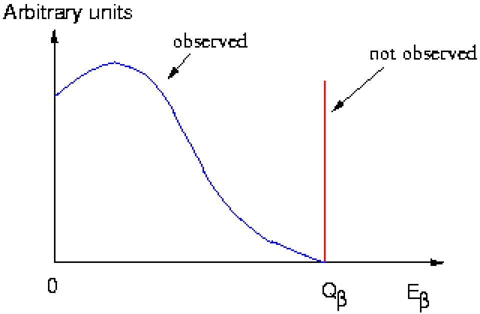
Credit: "Cosmic Gall" from Collected Poems 1953–1993, by John Updike. Copyright John Updike. Used by permission of Alfred A. Knopf, a division of Random House, Inc.

A BRIEF HISTORY OF THE NEUTRINO

Neutrino Conception



Before 1930's: beta decay spectrum continuous - is this energy non-conservation?



Neutrino Conception

Dec 1930: Wolfgang Pauli's letter to physicists at a workshop in Tubingen:

Wolfgang Pauli

Dear Radioactive Ladies and Gentlemen,

.........., I have hit upon a desparate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons.... The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant..........

Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

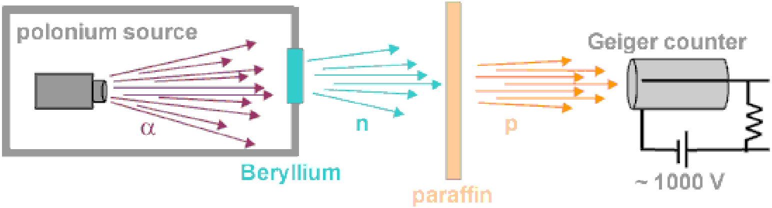
Your humble servant

. W. Pauli

Neutrino Conception

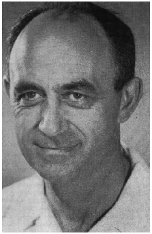
1932: James Chadwick discovers the neutron, mass$_{\text{neutron}}$ $= 1.0014 \times$ mass$_{\text{proton}}$ **- its too heavy - cant be Pauli's particle**

James Chadwick



Neutrino Conception

Solvay Conference, Bruxelles 1933: Enrico Fermi proposes to name Pauli's particle the "neutrino".

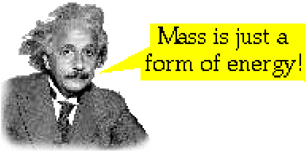


Enrico Fermi

Particle physics units and symbols

Symbols used for some common particles:

Symbol	Particle
ν, $\bar{\nu}$	**Neutrino and anti-neutrino**
γ	**Photon**
e^-	**Electron**
e^+	**Anti-electron (positron)**
p	**proton**
n	**neutron**
N	**nucleon - proton or neutron**



Particle physicists express masses in terms of energy, $E = mc^2$
Mass of proton $= 1.67 \times 10^{-24}$ **g** ≈ 1 **billion (Giga) electron-volts (GeV)**
1 thousand GeV = energy of a flying mosquito

The Theory of Weak Interactions

$\geq$ **1933: Fermi builds his theory of weak interactions and beta decay**

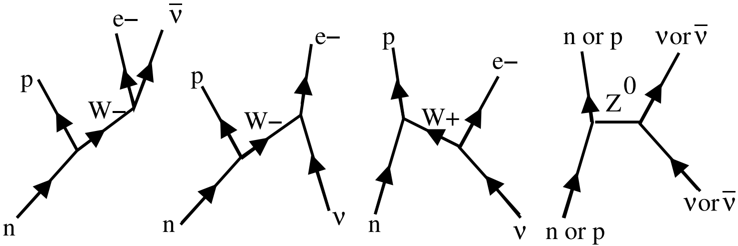
Charged current interactions

Decay of neutron

Neutrino interacts with neutron

Neutral current interactions

n or p interacts with neutrino or antineutrino



$n \rightarrow p + e^- + \bar{\nu}$

$n + \nu \rightarrow p + e^-$

A little exercise:

$$n \rightarrow p^{+} + e^{-} + \bar{\nu}$$

A little exercise:

$$\begin{aligned} \mathrm{n} &\rightarrow \mathrm{p}^+ + \mathrm{e}^- + \bar{\nu} \\ \mathrm{n} + \nu &\rightarrow \mathrm{p}^+ + \mathrm{e}^- \end{aligned}$$

The Theory of Weak Interactions

A little exercise:

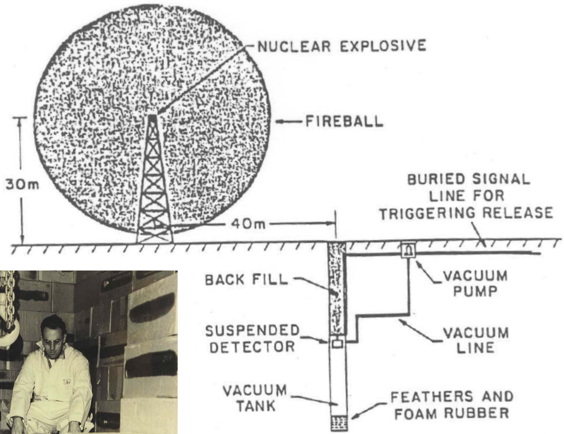
$$\begin{aligned} n &\rightarrow p^+ + e^- + \bar{\nu} \\ n + \nu &\rightarrow p^+ + e^- \\ p^+ + \bar{\nu} &\rightarrow \end{aligned}$$

A little exercise:

$$\begin{aligned} n &\rightarrow p^+ + e^- + \bar{\nu} \\ n + \nu &\rightarrow p^+ + e^- \\ p^+ + \bar{\nu} &\rightarrow n + e^+ \end{aligned}$$

Finding Neutrinos.... 1st attempt

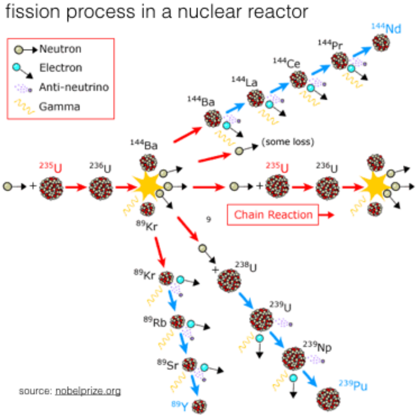
1950's: Fredrick Reines, protege of Richard Feynman proposes to find neutrinos

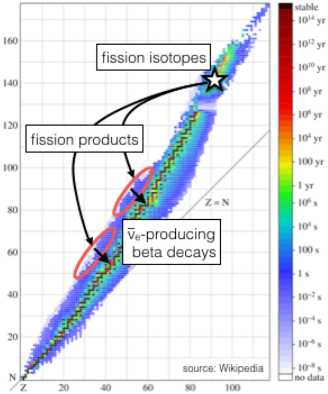


NOT ATTEMPTED

Finding Neutrinos.... 2^{nd} attempt

<u>1950's:</u> Fred Reines at Los Alamos and Clyde Cowan propose to use the Hanford nuclear reactor (1953) and the new Savannah River nuclear reactor (1955) to find neutrinos.



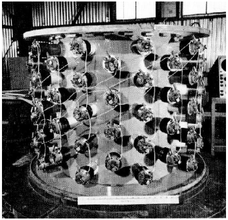


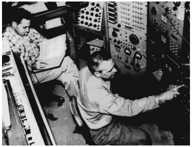
Finding Neutrinos.... 2^{nd} attempt

1950's: Fred Reines at Los Alamos and Clyde Cowan propose to use the Hanford nuclear reactor (1953) and the new Savannah River nuclear reactor (1955) to find neutrinos.
A detector filled with water with $CdCl_2$ in solution was located 11 meters from the reactor center and 12 meters underground.

The detection sequence was as follows:

1. $\bar{\nu}_e + p \rightarrow n + e^+$
2. $e^+ + e^- \rightarrow \gamma\gamma$
3. $n + ^{108}Cd \rightarrow ^{109}Cd* \rightarrow ^{109}Cd + \gamma$ ($\tau = 5\mu s$).





Neutrinos first detected using a nuclear reactor!

Reines shared 1995 Nobel for work on neutrino physics.

ν: A Truly Elusive Particle!

Reines and Cowan were the first to estimate the interaction strength of neutrinos. **The cross-section is $\sigma \sim 10^{-43}\mathrm{cm}^2$ per nucleon (N = n or p).**

$$\nu \text{ mean free path} = \frac{1}{\sigma \times \text{number of nucleons per cm}^3}$$

ν Exercise: What is the mean free path of a neutrino in lead?

(use Table of atomic and nuclear properties)

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$$= \frac{1}{10^{-43}\text{cm}^2 \times 11.4\text{g/cm}^3 \times 6.02 \times 10^{23}\text{nucleons/g}}$$

$$\approx 1.5 \times 10^{16}\text{m}$$

How many light years is that? How does it compare to the distance from the sun to the moon?

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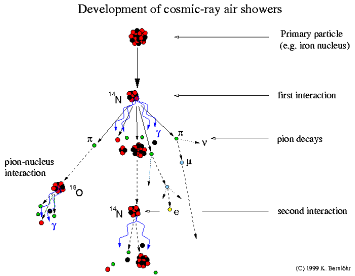
How many light years is that? How does it compare to the distance from the sun to the moon?

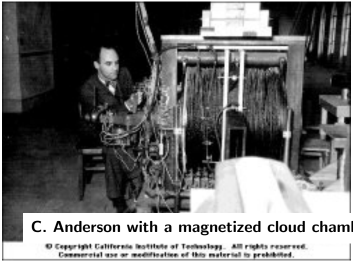
$$= \text{1.6 LIGHT YEARS OF LEAD}$$
$$= 100,000 \text{ distance earth to sun}$$

A proton has a mean free path of 10cm in lead

Discovery of the Muon (μ)

1936: Carl Andersen, Seth Neddermeyer observed an unknown charged particle in cosmic rays with mass between that of the electron and the proton - called it the μ meson (now muons).




C. Anderson with a magnetized cloud chamber

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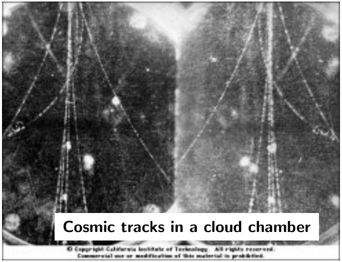
Cosmic tracks in a cloud chamber

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I. I Rabbi (founder of BNL): Who ordered THAT?

The Lepton Family and Flavors

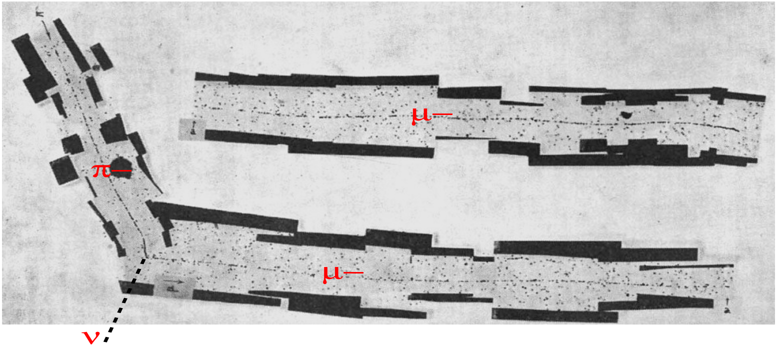
The muon and the electron are *different "flavors" of the same family of elementary particles called leptons*.

Generation	**I**	**II**	**III**
Lepton	e^-	μ	τ
Mass (GeV)	**0.000511**	**0.1057**	**1.78**
Lifetime (sec)	**stable**	2.2×10^{-6}	2.9×10^{-13}

Neutrinos are neutral leptons.

Discovery of the Pion: 1947

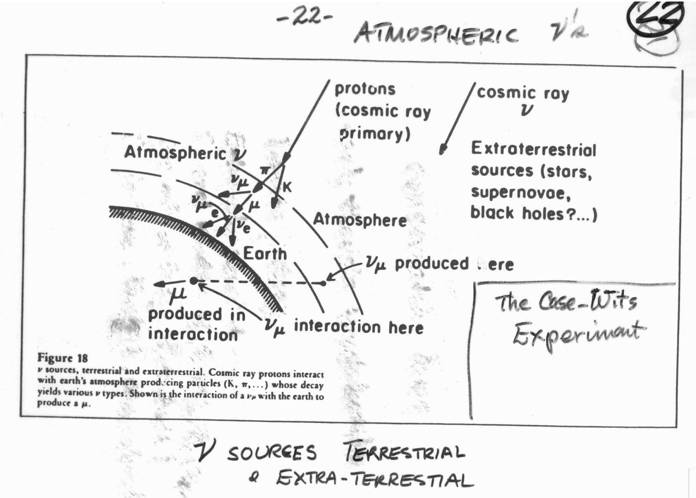
Cecil Powell takes emulsion photos aboard high altitude RAF flights. A charged particle is found decaying to a muon:



mass$_{\pi^-}$ = 0.1396 GeV/c^2 , $\tau = 26$ nano-second (ns).
Pions are composite particles from the "hadron" family which includes protons and neutrons.

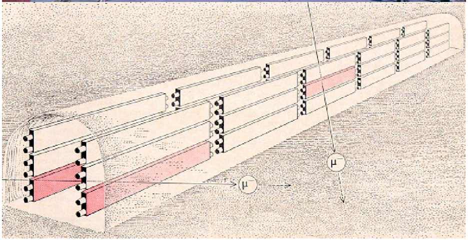
Proposal to find Atmospheric Neutrinos

Slide to find atmospheri neutrinos by Fred Reines (Case Western Institute):



The CWI-SAND Experiment

1964: The Case Western Institute-South Africa Neutrino Detector (CWI-SAND) and a search for atmospheric ν_μ at the East Rand gold mine in South Africa at 3585m depth



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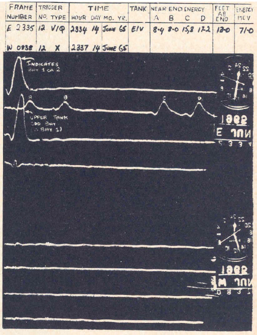
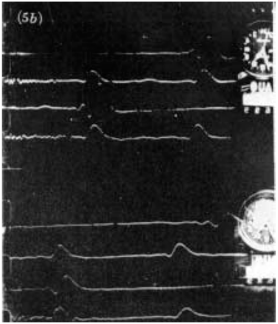


Downward-going Muon
(background)

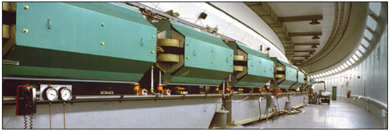


Horizontal Muon
(neutrino signal)

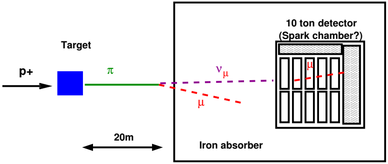
Detection of the first neutrino in nature!

Producing Neutrinos from an Accelerator

1962: Leon Lederman, Melvin Schwartz and Jack Steinberger use a proton beam from BNL's Alternating Gradient Synchrotron (AGS) to produce a beam of neutrinos using the decay $\pi \rightarrow \mu\nu_x$

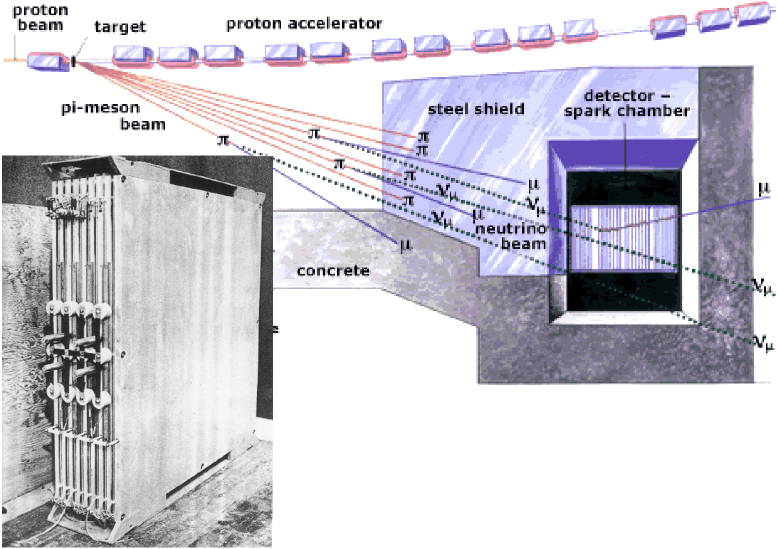


The AGS

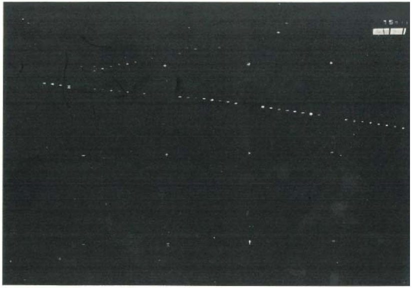


Making ν's

The Two-Neutrino Experiment

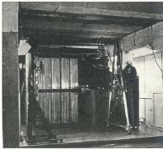


The Two-Neutrino Experiment



Neutrino Event

Columbia (News)



BNL

Classification of "Events"

Single Tracks

p_μ < 300 MeV/c[a]	49
p_μ > 300	34
> 400	19
> 500	8
> 600	3
> 700	2
Total "single Muon Events"	34

Vertex Events

Visible Energy Released < 1 BeV	15
Visible Energy Released > 1 BeV	7
Total vertex events	22

"Shower" Events

Energy of "electron" = 200 ± 100 MeV	3
220	1
240	1
280	1
Total "shower events"[b]	6

[a] These are not included in the "event" count.

[b] The two shower events which are so located that their potential energy release in the chamber corresponds to muons of less than 300 MeV/c are not included here.

The first event!

The Two-Neutrino Experiment

Result: 40 neutrino interactions recorded in the detector, 6 of the resultant particles where identified as background and 34 identified as $\mu \Rightarrow \nu_x = \nu_\mu$

The first successful accelerator neutrino experiment was at Brookhaven Lab.

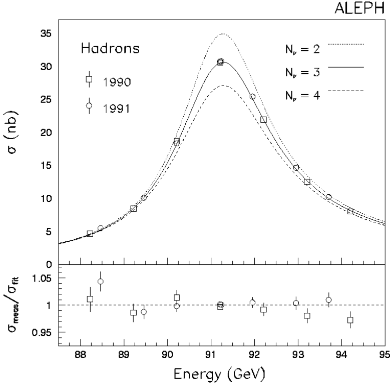
1988 NOBEL PRIZE

Number of Neutrino Flavors: Particle Colliders

1980's - 90's: The number of neutrino types is precisely determined from studies of Z^0 boson properties produced in e^+e^- colliders.

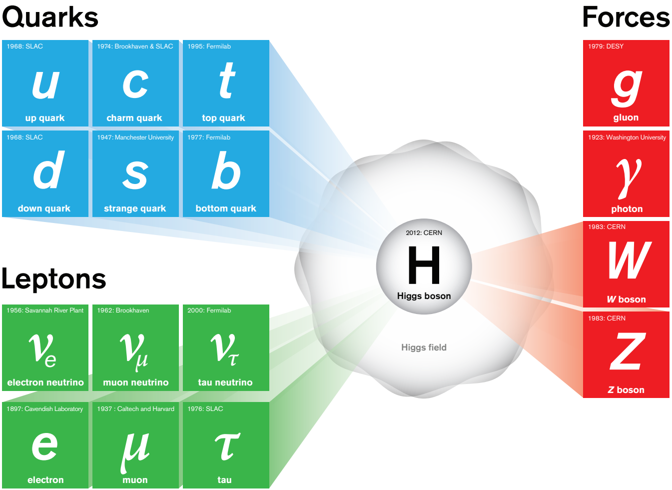
The LEP e^+e^- collider at CERN, Switzerland

The 27km LEP ring was reused to build the Large Hadron Collider

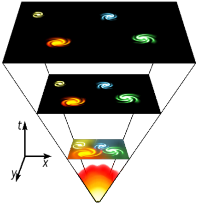
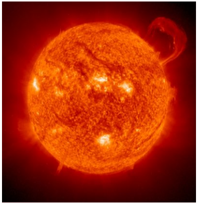
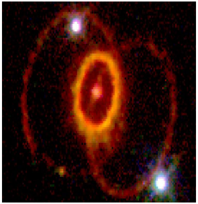


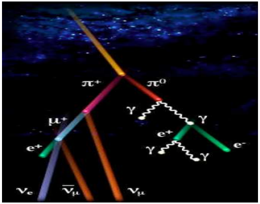
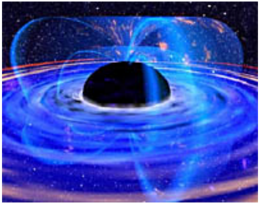
$N_\nu = 2.984 \pm 0.008$

The Particle Zoo



Sources of Neutrinos

Big Bang	Reactors	Sun	SuperNova
			
10^{-4} eV	few MeV	0.1-14 MeV	$\sim$ 10 MeV
$300/\text{cm}^3$	$10^{21}/\text{GW}_{th}/\text{s}$	$10^{10}/\text{cm}^2/\text{s}$	$10^{9}/\text{cm}^2/\text{s}$

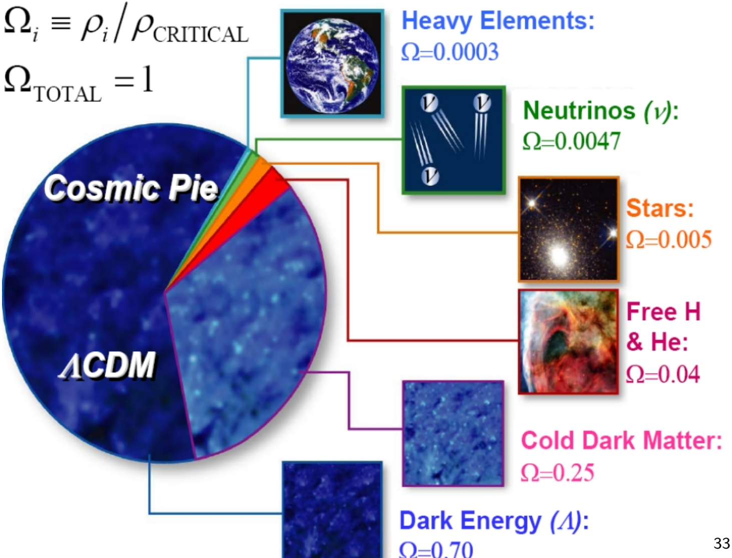
Atmosphere	Accelerators	Extragalactic
		
$\sim$ 1 GeV	1-20 GeV	TeV-PeV
$\text{few}/\text{cm}^2/\text{s}$	$10^{6}/\text{MW}/\text{cm}^2/\text{s}$ (at 1km)	varies

Neutrinos and Todays Universe

Neutrino mass < 2 eV (beta-decay limits)

$$\Omega_i \equiv \rho_i / \rho_{\text{CRITICAL}}$$

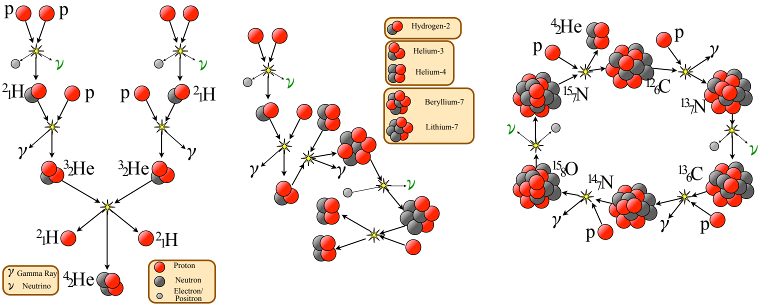
$$\Omega_{\text{TOTAL}} = 1$$



NEUTRINO MIXING AND OSCILLATIONS

Solar Neutrinos

Fusion of nuclei in the Sun produces solar energy and neutrinos

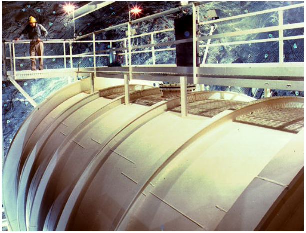


The Homestake Experiment

1967: Ray Davis from BNL installs a large detector, containing 615 tons of tetrachloroethylene (cleaning fluid), 1.6km underground in Homestake mine, SD.

1. $\nu_e^{sun} + ^{37}\mathrm{CL} \rightarrow e^- + ^{37}\mathrm{Ar}, \; \tau(^{37}\mathrm{Ar}) = 35$ **days.**
2. **Number of** Ar **atoms** $\approx$ **number of** ν_e^{sun} **interactions.**

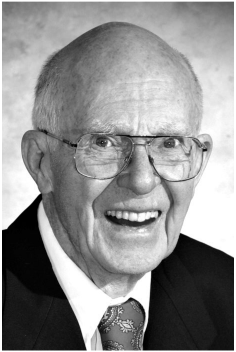
Ray Davis



Results: 1969 - 1993 Measured 2.5 $\pm$ 0.2 SNU (1 SNU = 1 neutrino interaction per second for 10^{36} target atoms) while theory predicts 8 SNU. This is a ν_e^{sun} deficit of 69%.

Where did the suns ν_e's go?

2002 Nobel Prize

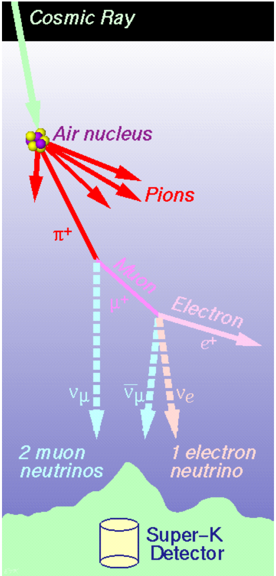


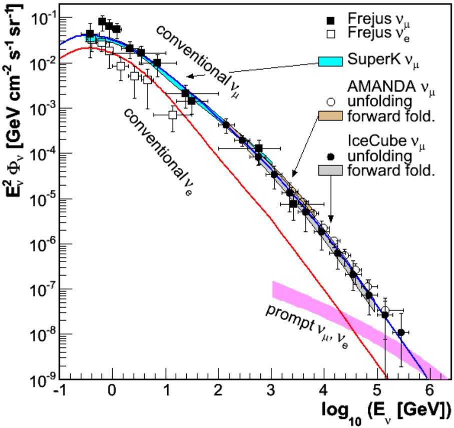
Ray Davis
Brookhaven Lab, USA
(Homestake experiment)

Masatoshi Koshiba
University of Tokyo, USA
(Kamiokande experiment)

The Nobel Prize in Physics 2002 was awarded 1/4 to Ray Davis and 1/4 Masatoshi Koshiba *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos."*

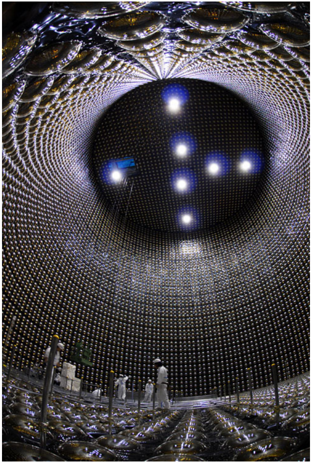
The Super-Kamiokande Experiment. Kamioka Mine, Japan





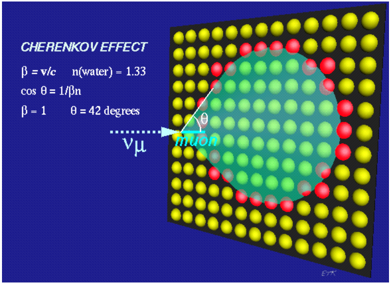
Many decades in E

The Super-Kamiokande Experiment. Kamioka Mine, Japan

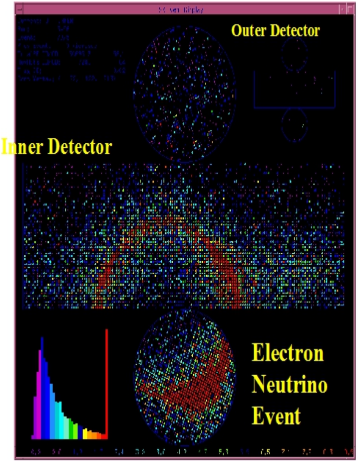


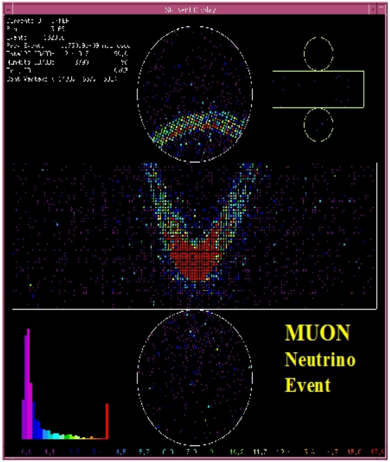
50kT double layered tank of ultra pure water surrounded by 11,146 20" diameter photomultiplier tubes.

Neutrinos are identified by using CC interaction $\nu_{\mu,e} \rightarrow e^{\pm}, \mu^{\pm}X$. The lepton produces Cherenkov light as it goes through the detector:

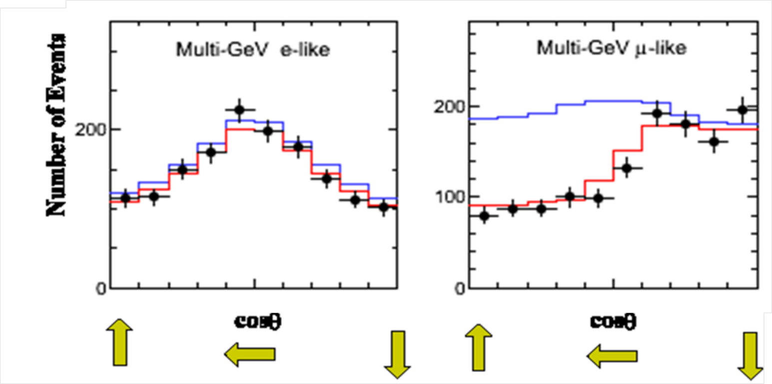


The Super-Kamiokande Experiment. Kamioka Mine, Japan





More Disappearing Neutrinos!!



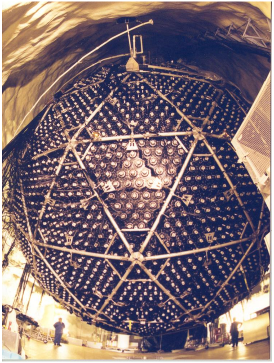
All the ν_e are there! But what happened to the ν_μ ??

SNO Experiment: Solar ν Measurments

$1 \leftrightarrow 2$ mix ing

2001-02: Sudbury Neutrino Observatory. Water Čerenkov detector with 1 kT heavy water (0.5 B$ worth on loan from Atomic Energy of Canada Ltd.) located 2Km below ground in INCO's Creighton nickel mine near Sudbury, Ontario. Can detect the following ν^{sun} interactions:

1) $\nu_e + d \rightarrow e^- + p + p$ **(CC).**
2) $\nu_{e,x} + e^- \rightarrow e^- + \nu_x, \quad \nu_e : \nu_x = 6 : 1$ **(ES).**
3) $\nu_x + d \rightarrow p + n + \nu_x, \quad x = e, \mu, \tau$ **(NC).**



SNO measured:

$$\phi^{CC}_{SNO}(\nu_e) = 1.75 \pm 0.07(\text{stat})^{+0.12}_{-0.11}(\text{sys.}) \pm 0.05(\text{theor}) \times 10^6 \text{cm}^{-2}\text{s}^{-1}$$
$$\phi^{ES}_{SNO}(\nu_x) = 2.39 \pm 0.34(\text{stat})^{+0.16}_{-0.14}(\text{sys.}) \pm \times 10^6 \text{cm}^{-2}\text{s}^{-1}$$
$$\phi^{NC}_{SNO}(\nu_x) = 5.09 \pm 0.44(\text{stat})^{+0.46}_{-0.43}(\text{sys.}) \pm \times 10^6 \text{cm}^{-2}\text{s}^{-1}$$

All the solar ν's are there but ν_e appears as ν_x!

Some Quantum Mechanics

1924: Louis-Victor-Pierre-Raymond, 7th duc de Broglie proposes in his doctoral thesis that all matter has wave-like and particle-like properties.

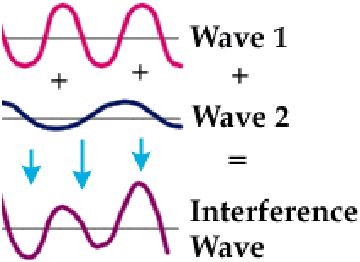
For highly relativistic particles : energy ≈ momentum

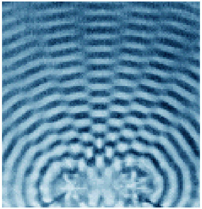
De Broglie

$$\textbf{Wavelength (nm)} \approx \frac{1.24 \times 10^{-6}\ \textbf{GeV.nm}}{\textbf{Energy (GeV)}}$$

Neutrino Mixing

1957,1967: B. Pontecorvo proposes that neutrinos of a particular flavor are a mix of quantum states with different masses that propagate with different phases:





The interference of water waves coming from two sources.

The inteference pattern depends on the difference in masses

Neutrino Mixing ⇒ Oscillations

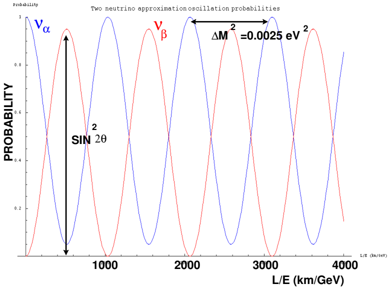
$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2t} - e^{-iE_1t}|^2 \end{aligned}$$

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2_{21} L}{E}$$

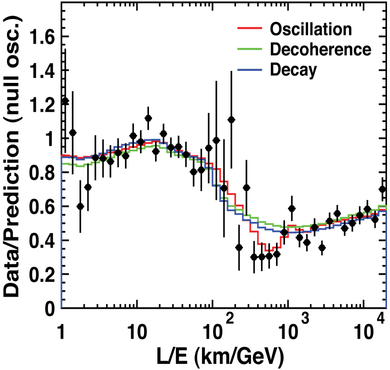
where $\Delta m^2_{21} = (m^2_2 - m^2_1)$ **in** eV^2**, L (km) and E (GeV).**

Observation of oscillations
implies non-zero mass eigenstates

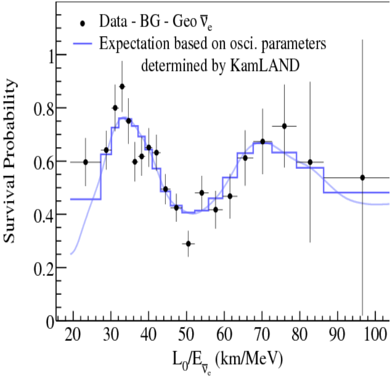


Two Different Mass Scales!

Super-K, atmospheric ν_μ



KamLAND, reactor $\bar{\nu}_e$



Global fit 2013:

$$\Delta m^2_{atm} = 2.43^{+0.06}_{-0.10} \times 10^{-3}\ \mathbf{eV^2}$$
$$\sin^2\theta_{atm} = 0.386^{+0.24}_{-0.21}$$

Atmospheric L/E ∼ 500 km/GeV

Global fit 2013:

$$\Delta m^2_{solar} = 7.54^{+0.26}_{-0.22} \times 10^{-5}\ \mathbf{eV^2}$$
$$\sin^2\theta_{solar} = 0.307^{+0.18}_{-0.16}$$

Solar L/E ∼ 15,000 km/GeV

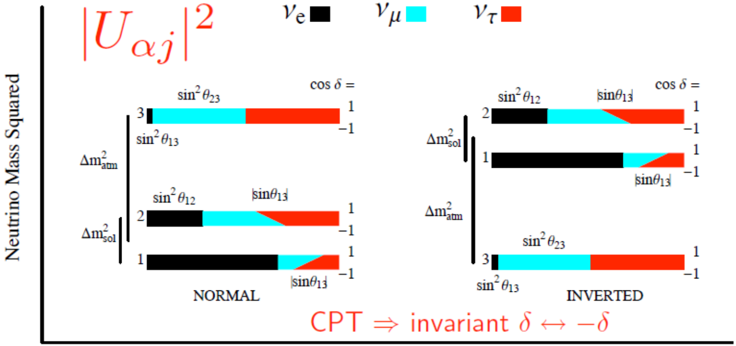
2015 Nobel Prize

Takaaki Kajita
University of Tokyo, Japan
(SuperKamiokande)

Arthur B. MacDonald
Queens University, Canada
(SNO)

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Neutrino Mixing: 3 flavors, 3 amplitudes, 2 mass scales



Fractional Flavor Content varying cos δ

The "mixing angles" $(\theta_{13}, \theta_{12}, \theta_{23})$ represent the fraction of ν_e, ν_μ in the 3 mass states. They determine the probability of oscillation from one flavor to the other

$\sin^2\theta_{12} \approx \sin^2\theta_{\text{solar}}$, $\sin^2\theta_{23} \approx \sin^2\theta_{\text{atmospheric}}$

3 quantum states interfering $\Rightarrow$ phase δ

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

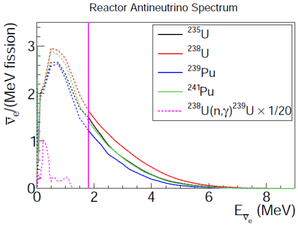
Reactor power and neutrinos

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**
γ**s and** β**s 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?

Reactor power and neutrinos

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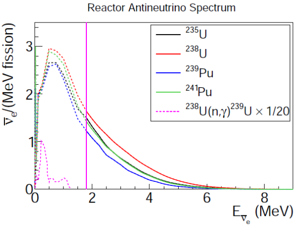
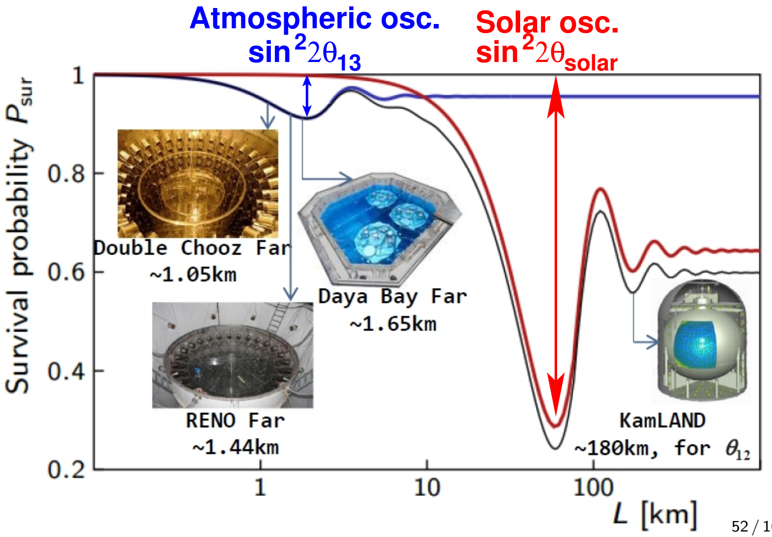


How many neutrinos are emitted per second from a 1 Gigawatt (thermal) reactor?

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

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 GW_{th}

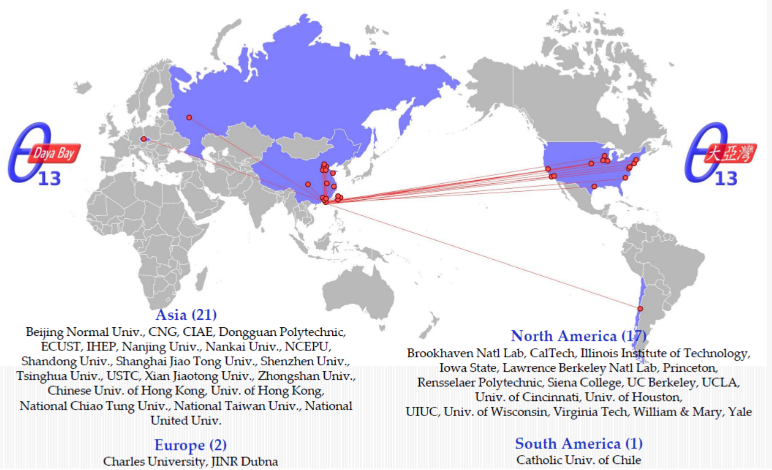
By 2011: 2 more cores at Ling Ao II site = 17.4 GW_{th} $\Rightarrow$ top five worldwide

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

Deploy multiple near and far detectors

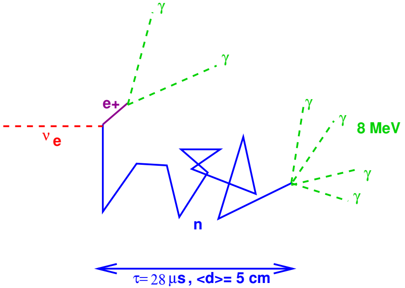
Reactor power uncertainties $< 0.1\%$

The Daya Bay Collaboration : 231 Collaborators



Detecting Neutrinos from the Daya Bay Reactors

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

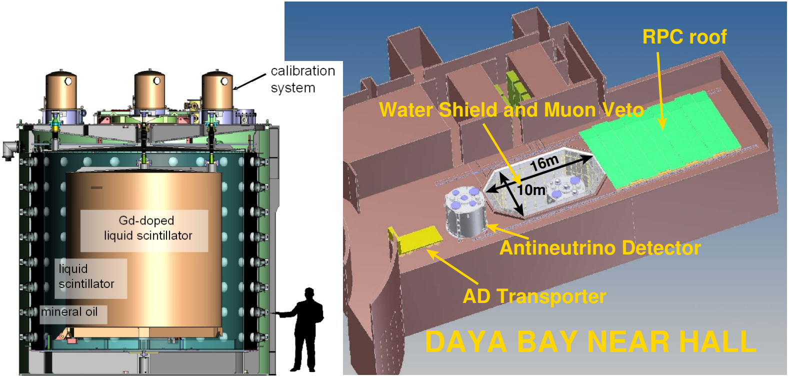


- $\bar{\nu}_e + p \rightarrow n + e^+$
- $e^+ + e^- \rightarrow \gamma\gamma$ **(2X 0.511 MeV $+T_{e^+}$, prompt)**
- $n + p \rightarrow D + \gamma$ **(2.2 MeV, $\tau \sim$ 180μs). OR**
- $n + Gd \rightarrow Gd* \rightarrow Gd + \gamma$'s **(8 MeV, $\tau \sim 28\mu$s).**

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

with a specfic energy signature

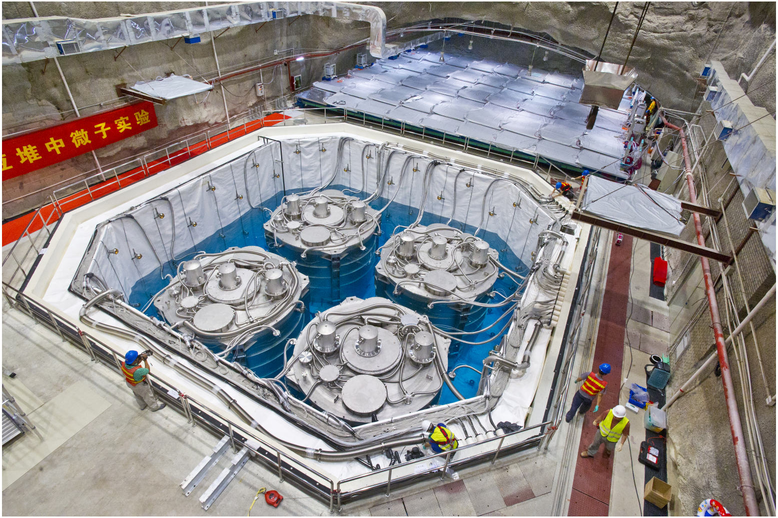
The Daya Bay Experimental Apparatus



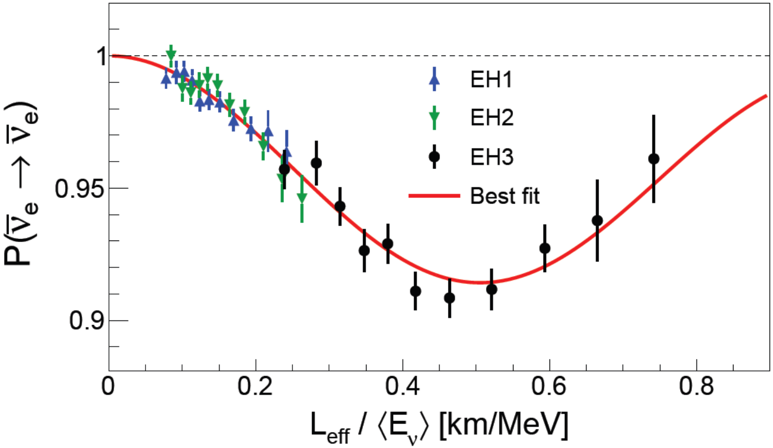
- **Multiple "identical" detectors at each site.**
- **Manual and multiple automated calibration systems per detector.**
- **Thick water shield to reduce cosmogenic and radiation bkgds.**

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

The Daya Bay Experimental Apparatus



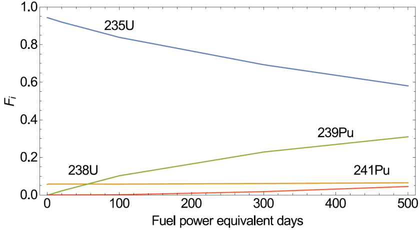
Daya Bay Measurement of Non-zero θ_{13}

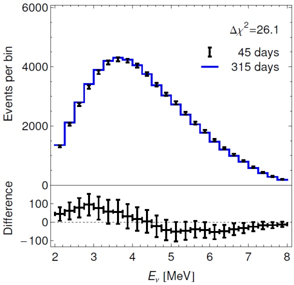


First to discover non-zero θ_{13} (2012) and currently most precise result (2018):

$$\sin^2 2\theta_{13} = 0.086 \pm 0.003 \Rightarrow \sin^2 \theta_{13} = 0.0219 \pm 0.0008$$

Fuel burnup in a typical 3.5 GW commercial reactor:





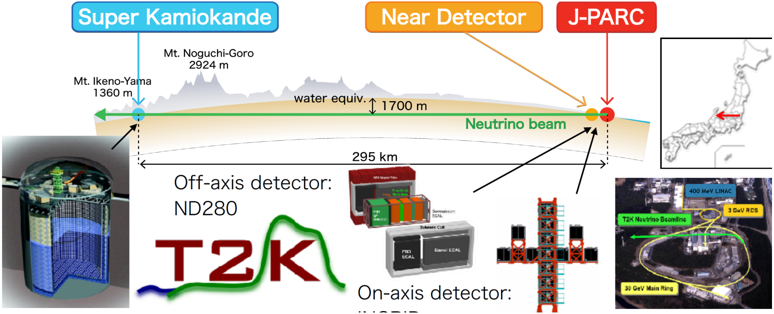
A neutrino detector in a standard ISO shipping container with 4.3E29 target protons (10-20metric tons). Difference in reactor ν spectrum at 45 days vs 315days.

Corresponds to difference in plutonium content of about 7kg

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

Confirming $\nu_\mu \rightarrow \nu_e$ 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:



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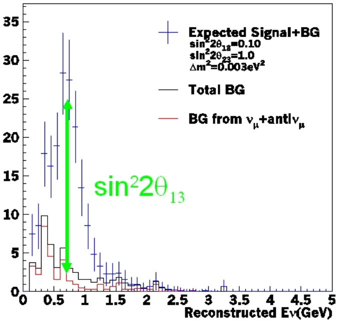
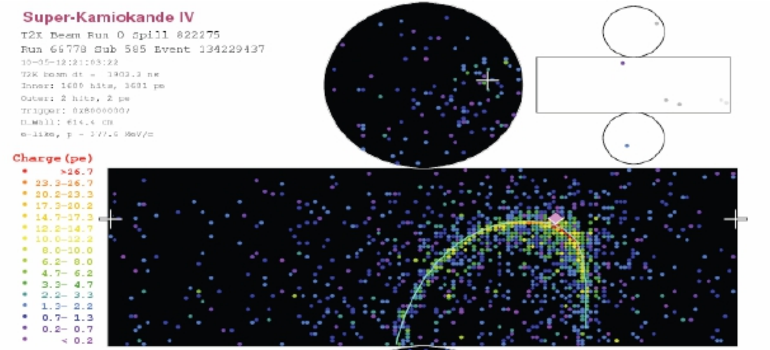
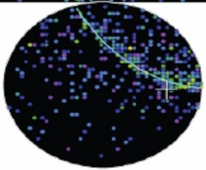
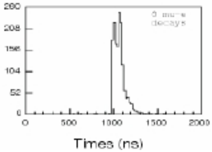


T2K beam ν_e Candidate Event 2010

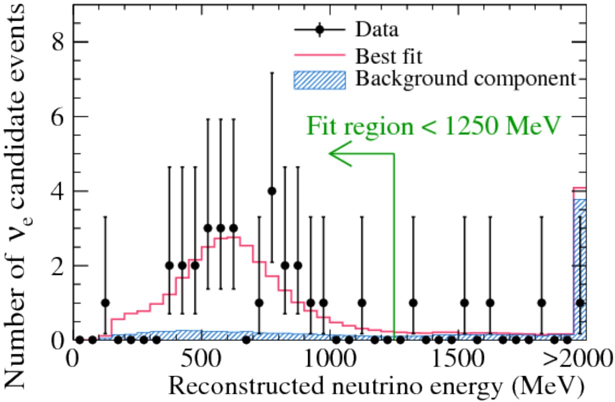


Item	Event	T2K cut
Date (JST)	2010 May 12th 21:3:22	
Ring, PID	1-Ring electron-like	OK
Momentum	378 MeV	>100
N_{dcy}	0	0
$\cos(\theta_{\nu e})$	0.55 (57 degree)	N/A
$Mass$	0.13 MeV	<105
E_{rec}	496 MeV	<1250





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 $\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$.

2016 Breakthrough Prize in Fundamental Physics

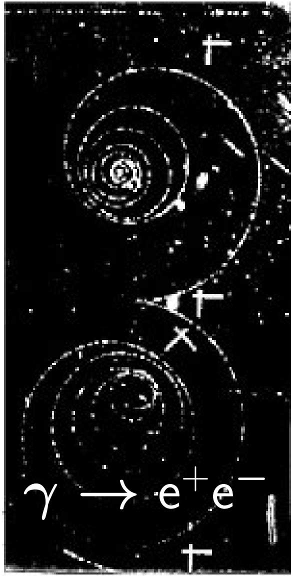
The 2016 Breakthrough Prize in Fundamental Physics awarded to 7 leaders and 1370 members of 5 experiments investigating neutrino oscillation: Daya Bay (China); KamLAND (Japan); K2K / T2K (Japan); Sudbury Neutrino Observatory (Canada); and Super-Kamiokande (Japan)

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.

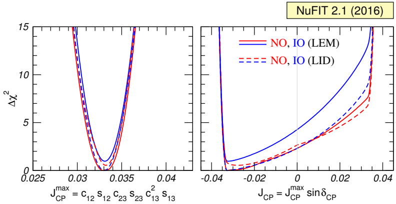
A violation of CP ⇒ matter/anti-matter asymmetry.



CP Violation in Particle Physics

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

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



(JHEP 11 (2014) 052, arXiv:1409.5439)

Given the current best-fit values of the ν mixing angles (see here)

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

Mixing has already been observed between the 3 quark generations):

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

despite the large value of $\delta_{CP}^{\mathrm{quarks}} \approx 70^{\circ}$.

$\nu_\mu \to \nu_e$ Oscillations

$\nu_\mu \to \nu_e$ oscillations are sensitive to all mixing parameters contributing to the Jarlskog invariant. With terms up to second order in $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} = 0.03$ and $\sin^2\theta_{13} = 0.02$, (M. Freund. Phys. Rev. D 64, 053003):

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

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 $\Delta = 1.27\Delta m^2_{31}L/E$

For $\bar{\nu}_\mu \to \bar{\nu}_e$, $\underbrace{P_{\sin\delta} \to -P_{\sin\delta}}_{\text{CP asymmetry } (\delta \neq 0)}$,

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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 $\Delta = 1.27\Delta m^2_{31}L/E$ and $A = \sqrt{2}G_F N_e 2E/\Delta m^2_{31}$

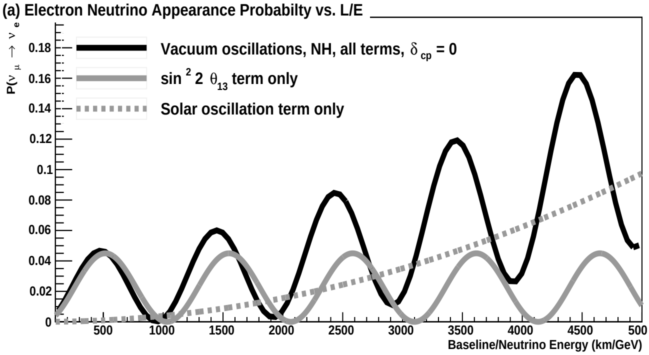
For $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\underbrace{P_{\sin\delta} \rightarrow -P_{\sin\delta}}_{\text{CP asymmetry } (\delta\neq 0)}$, $\underbrace{A \rightarrow -A}_{\text{matter asymmetry}}$

ν Exercise: Use ROOT or Jupyter and reproduce the plots shown below

G_F = **Fermi coupling constant, Multiply by** $(\hbar c)^3$ **to get units in GeV.m^3.**

N_e = **electron number density in the earth per** m^3**. Assume density of crust = 2.8 g/cm^3**

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



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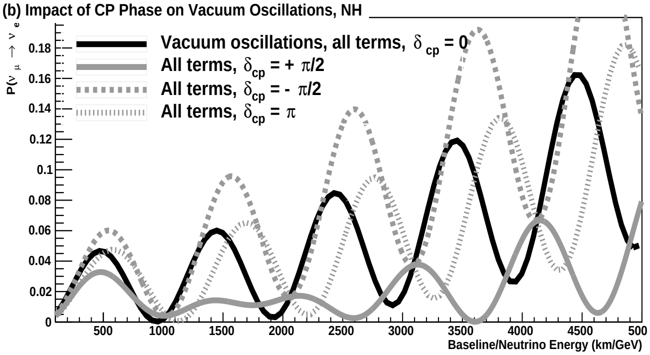
Impact of δ_{CP} on oscillations in vacuum, $\Delta m^2_{31} > 0$ (NH)



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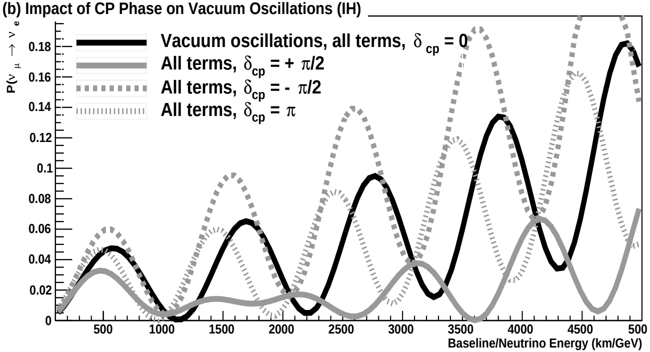
Impact of δ_{CP} on oscillations in vacuum, $\Delta m^2_{31} < 0$ (IH)



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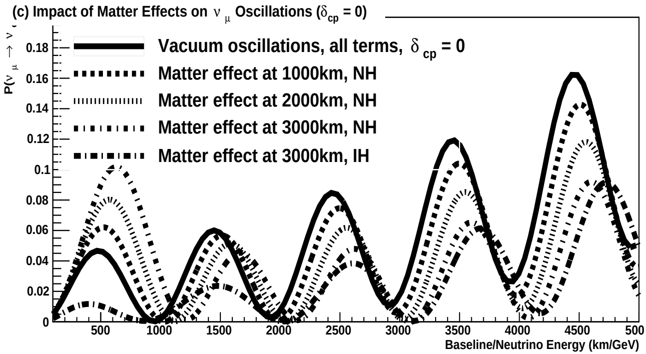
Impact of matter effect on ν_μ oscillations ($\delta_{CP} = 0$)



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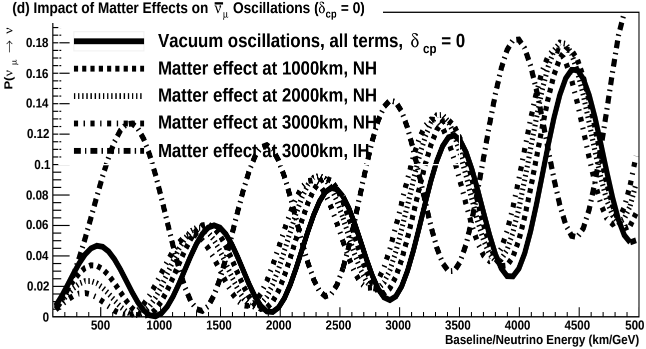
Impact of matter effect on $\bar{\nu}_\mu$ oscillations ($\delta_{CP} = 0$)



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

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

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

$$\begin{aligned}
\Phi^{\nu_\mu}(E_\nu, L) &\approx \frac{C}{L^2}, \quad C = \textbf{number of } \nu_\mu/\mathbf{m}^2/\mathbf{GeV}/\mathbf{sec \ at \ 1 \ km} \\
P^{\nu_\mu \to \nu_e}(E_\nu, L) &\approx \underbrace{\sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E_\nu)}_{P_0} \\
\sigma^{\nu_e}(E_\nu) &= 0.7 \times 10^{-42} (\mathbf{m}^2/\mathbf{GeV}/N) \times E_\nu, \quad E_\nu > 1 \ \mathbf{GeV}
\end{aligned}$$

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

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

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

ν Exercise:

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

Calculate the rate of ν_e events observed per kton of detector integrating over the region $x = 100$ km/GeV to 2000 km/GeV. Use ROOT to do the integral!

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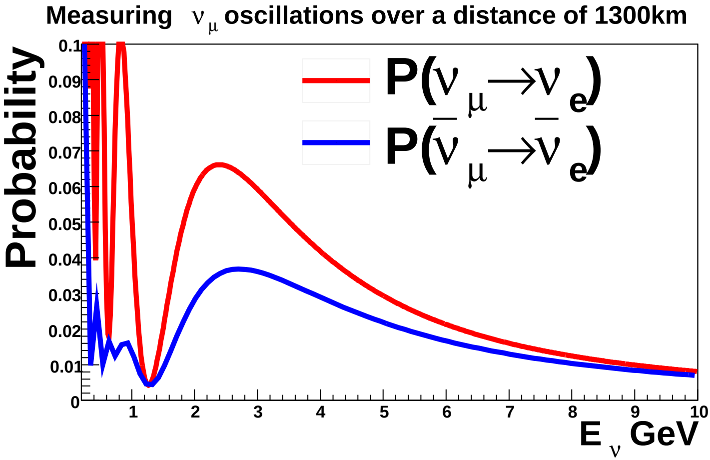
Calculate the rate of ν_e events observed per kton of detector integrating over the region $x = 100$ km/GeV to 2000 km/GeV. Use ROOT to do the integral!

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

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

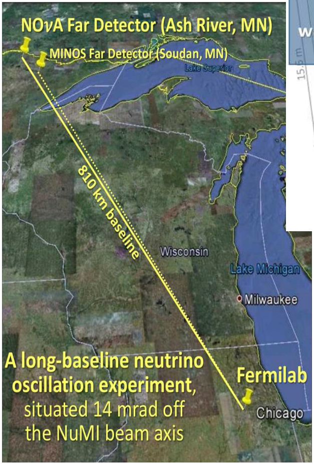
Charge-parity Symmetry and Neutrino Mixing

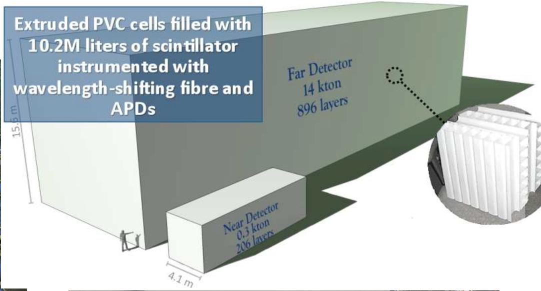
Could neutrinos and anti-neutrinos oscillate differently?

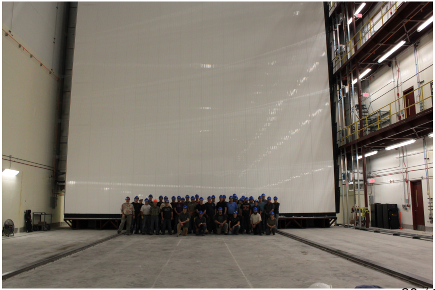


Could this explain the excess of matter in the Universe?

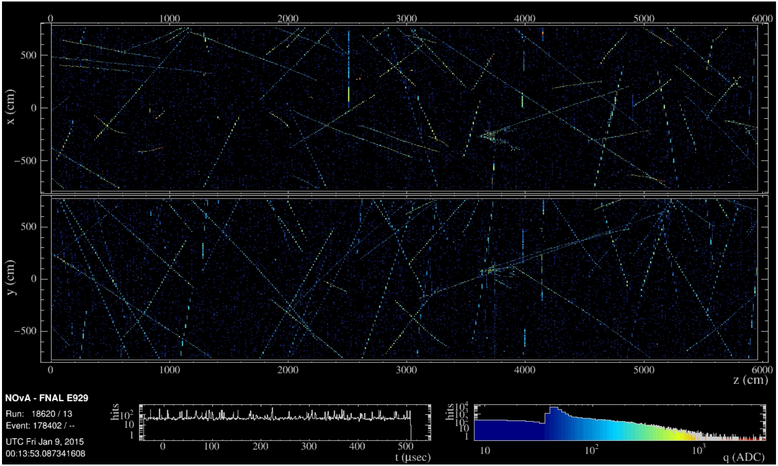
The NOνA Experiment



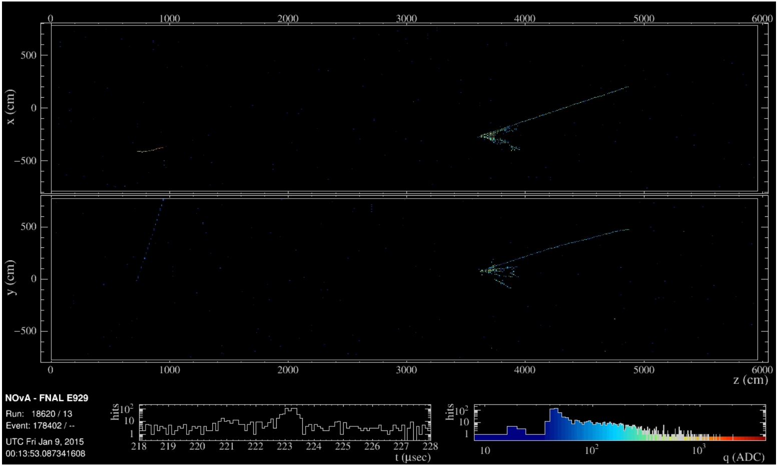




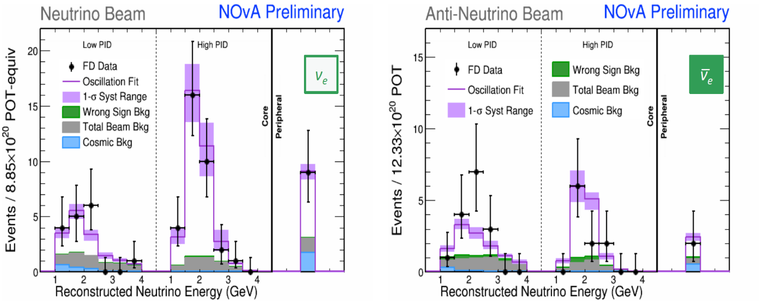
Neutrino Events in NOνA



Neutrino Events in NOνA



NOνA ν_e and $\bar{\nu}_e$ Appearance - 2019



Total Observed	58
Total Prediction	59.0
Wrong-sign	0.7
Beam Bkgd.	11.1
Cosmic Bkgd.	3.3
Total Bkgd.	15.1

4.4σ evidence of $\bar{\nu}_e$ appearance

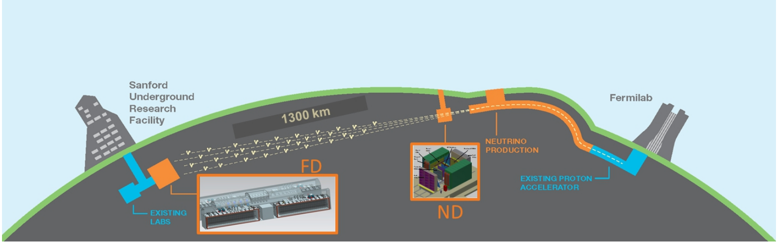
Erika Catano-Mur (William & Mary, NOvA)

Total Observed	27
Total Prediction	27
Wrong-sign	2.2
Beam Bkgd.	7.0
Cosmic Bkgd.	1.1
Total Bkgd.	10.3

Strong evidence of $\bar{\nu}_e$ appearance

Future Neutrino Experiments

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 at Fermilab.**
- **A very deep (1 mile underground) far detector: massive 40-kton Liquid Argon Time-Projection-Chamber with state-of-the-art instrumentation.**
- **High intensity *tunable* wide-band neutrino beam from LBNF produced from upgraded MW-class proton accelerator at Fermilab.**

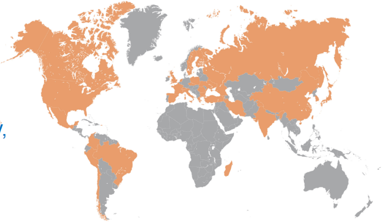
The DUNE Scientific Collaboration

As of Jan 2018:

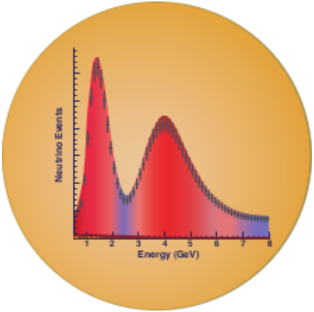
60 % non-US

1061 collaborators from 175 institutions in 31 nations

Armenia, Brazil, Bulgaria, Canada, CERN, Chile, China, Colombia, Czech Republic, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Paraguay, Peru, Poland, Romania, Russia, South Korea, Spain, Sweden, Switzerland, Turkey, UK, Ukraine, USA

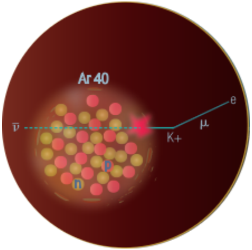


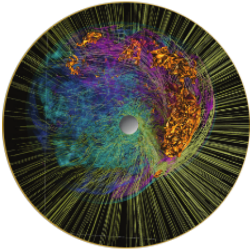
Scientific Objectives of DUNE



1. **precision measurements of the parameters that govern $\nu_\mu \rightarrow \nu_e$ 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**
2. **precision measurements of the mixing angle θ_{23}, including the determination of the octant in which this angle lies, and the value of the mass difference, —Δm^2_{32}—, in $\nu_\mu \rightarrow \nu_{e,\mu}$ oscillations**

Scientific Objectives of DUNE

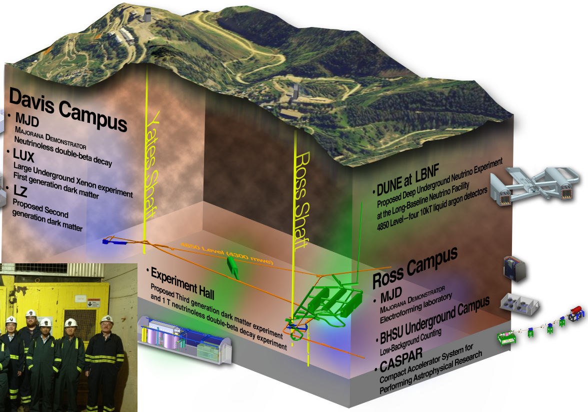




3. **search for proton decay, yielding significant improvement in the current limits on the partial lifetime of the proton (τ/BR) in one or more important candidate decay modes, e.g., $p \rightarrow K^{+}\overline{\nu}$**

4. **detection and measurement of the neutrino flux from a core-collapse supernova within our galaxy, should one occur during the lifetime of DUNE**

The Sanford Underground Research Facility

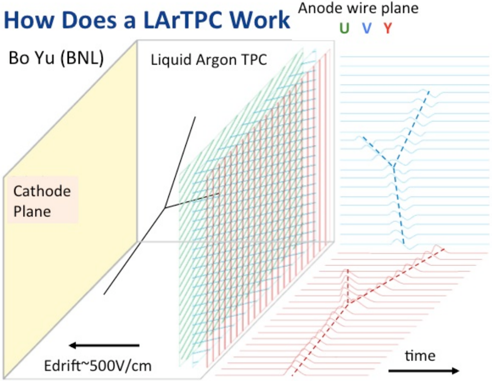


Experimental facility operated by the state of South Dakota. LUX/LZ (dark matter), Majorana ($0\nu-2\beta$) demonstrator and CASPER (accelerator for astrophysical research) operational expts at 4850-ft level.

The DUNE Far Detector

A large cryogenic liquid Argon detector located a mile underground in the former Homestake Mine with a mass of at least 40 kilo-tons is used to image neutrino interactions with unprecedented precision:

Single Phase LArTPC



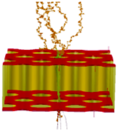
The DUNE prototype wireplane

The DUNE Far Detector

Dual Phase LArTPC

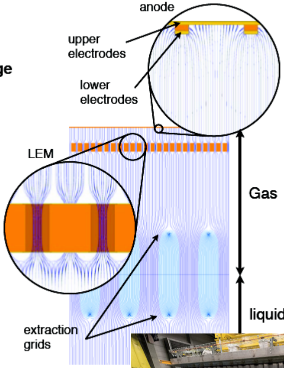
4.) Charge collection on a **2D anode readout** (symmetric unipolar signals with two orthogonal views)

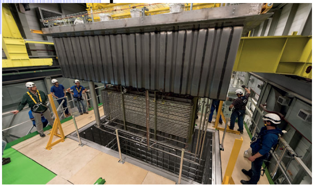
3.) Charge multiplication in the holes of the **Large Electron Multiplier (LEM)**



2.) Drift electrons are efficiently emitted into the gas phase

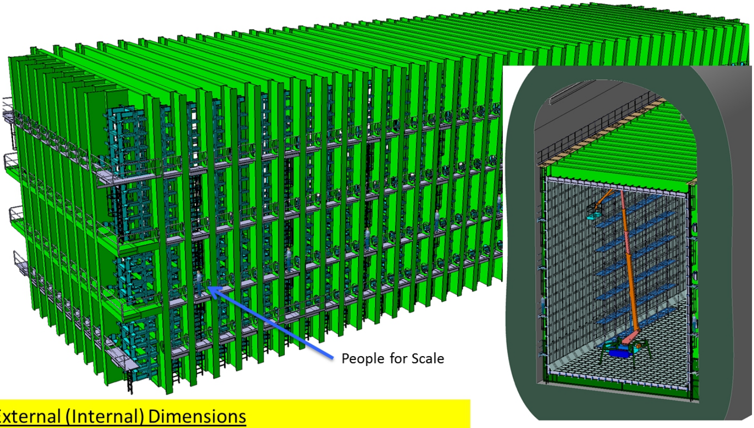
1.) Ionization electrons drift towards the liquid argon surface





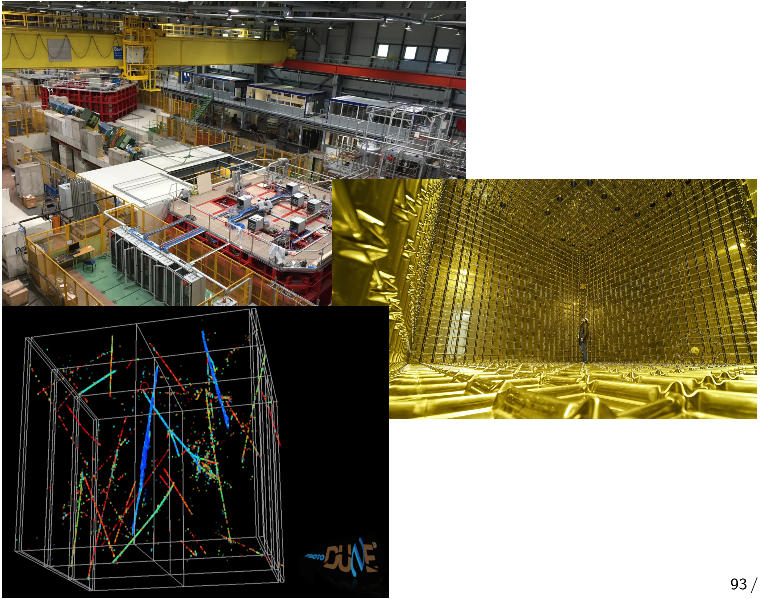
The DUNE Far Detector

The 40-kton (fiducial) detector is constructed of four modules with a total mass of 17.4 kton each.

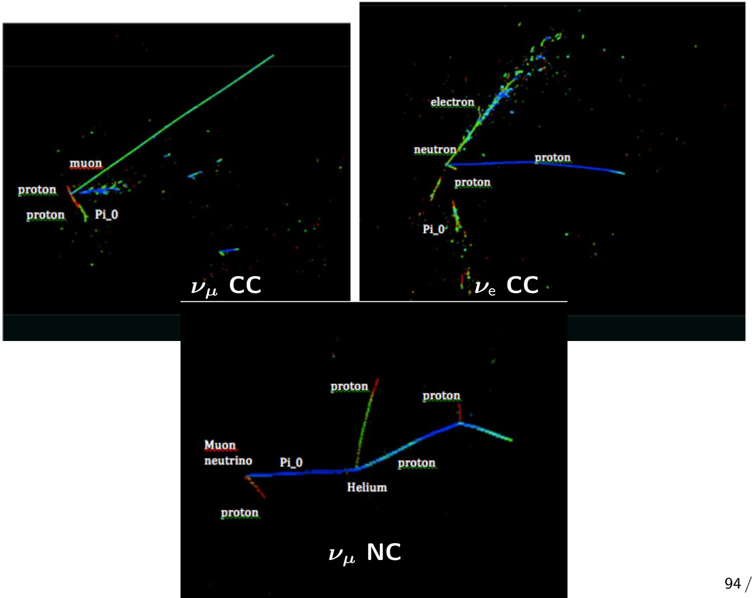


<u>External (Internal) Dimensions</u>
19.1m (16.9m) W x 18.0m (15.8m) H x 66.0m (63.8m) L

DUNE Prototypes ($\sim 5\%$) in charged particle beam at CERN

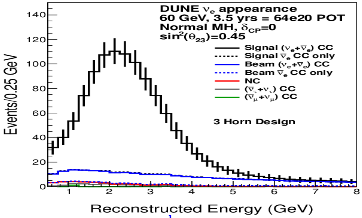


Reconstructed Neutrino Interactions in a LArTPC

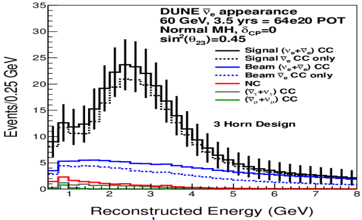


DUNE Event Spectra

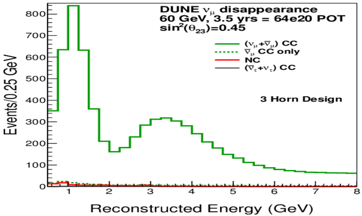
Exposure: 150 kT.MW.yr (equal $\nu/\bar{\nu}$) 1MW.yr = 1×10^{21} p.o.t at 120 GeV. ($\sin^2 2\theta_{13} = 0.085,\ \sin^2\theta_{23} = 0.45,\ \delta m^2_{31} = 2.46 \times 10^{-3}\ \mathrm{eV}^2$)



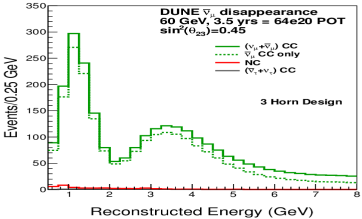
930 ν_e, 5 $\bar{\nu}_e$, 204 ν_e^{beam}, 17 NC, 19 ν_τ, 3 ν_μ



154 $\bar{\nu}_e$, 32 ν_e, 98 ν_e^{beam}, 7 NC, 8 ν_τ, 1 ν_μ



8329 ν_μ, 192 $\bar{\nu}_\mu$, 72 NC, 29 ν_τ



2420 $\bar{\nu}_\mu$, 791 ν_μ, 33 NC, 13 ν_τ

Simultaneous fit to all four samples. Richness of spectral information in both ν_μ and $\bar{\nu}_\mu$ $\Rightarrow$ explicit demonstration of CPV

DUNE Event Spectra

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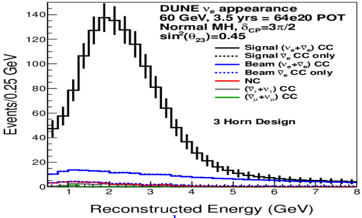
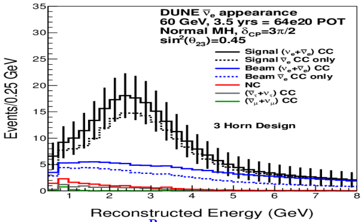
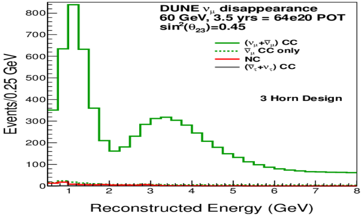


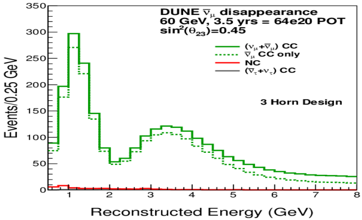
1171 ν_e,3 $\bar{\nu}_e$, 204 ν_e^{beam}, 17 NC, 19 ν_τ, 3 ν_μ



94 $\bar{\nu}_e$,39 ν_e, 98 ν_e^{Beam}, 7 NC, 8 ν_τ, 1 ν_μ



8329 ν_μ, 192 $\bar{\nu}_\mu$, 72 NC, 29 ν_τ



2420 $\bar{\nu}_\mu$, 791 ν_μ, 33 NC, 13 ν_τ

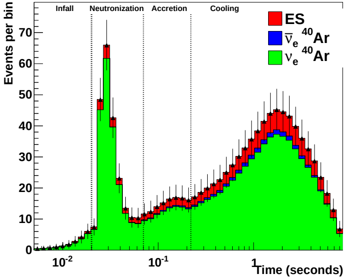
Simultaneous fit to all four samples. Richness of spectral information in both ν_μ and $\bar{\nu}_\mu$ $\Rightarrow$ explicit demonstration of CPV

Possible Supernova Signature in DUNE

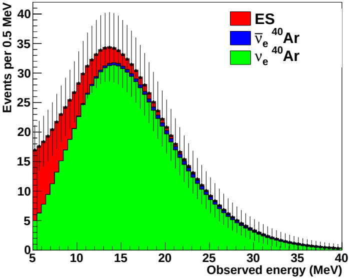
Liquid argon is particularly sensitive to the ν_e component of a supernova neutrino burst:

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*, \qquad (1)$$

Expected time-dependent signal in 40 kton of liquid argon for a Supernova at 10 kpc:



Time distribution



Energy spectrum (time integrated)

LBNF/DUNE Schedule

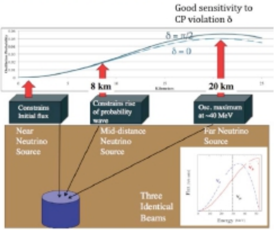
- **2017: Far site pre-excavation begins**
- **2018: DUNE prototypes (single & dual phase) operational in test beam at CERN**
- **2022: Technical design review (beam and far detectors) by US-DOE and international funding energies. Conceptual design for near detector ready.**
- **2026: First 10kton FD module (single phase) installation begins**
- **2028: Second FD module (single phase) installation begins**
- **2029-2030: First beam operations at 1.2 MW**

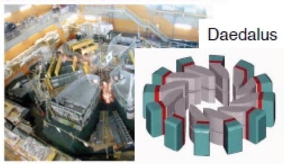
PRACTICAL APPLICATIONS of ν

Practical Applications of Technologies for ν Experiments

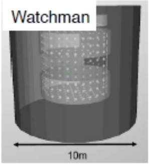
Synergies and Applications - Examples

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

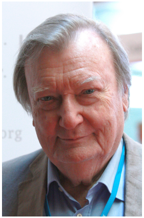
US Short-Baseline Experiment

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)



Global energy resources in ZetaJoules

Resource	*Type*	*Yearly consumption (1999) ZJ*	*Resources ZJ*	*Consumed until 1999 (ZJ)*
Oil	Conventional	0.13	12.08	4.85
	Unconventional	0.01	20.35	0.29
	Total oil	0.14	32.42	5.14
Natural gas	Conventional	0.08	16.56	2.35
	Unconventional	0.00	33.23	0.03
	Total gas	0.08	49.79	2.38
Coal	Total coal	0.09	199.67	5.99
Total Fossils		0.31	281.88	13.51
Uranium	Thermal reactors	0.04	5.41 (2'000, sw)	
	Breeder	0	324 (120'000, sw)	
Thorium			1'300'000	

sw: including sea water
1 ZJ (ZetaJoule)= 10^3 EJ(ExaJoule)= 10^{21} J(Joule)

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

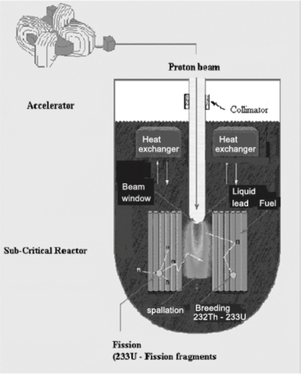
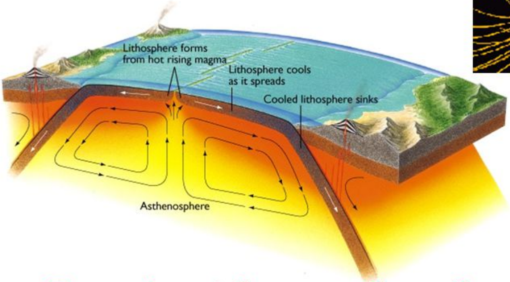
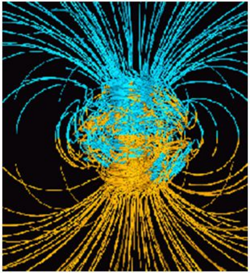


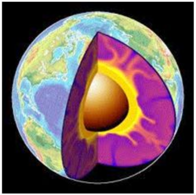
Figure 1. Schematic representation of Energy Amplifier proposed by Rubbia [4]

Neutrinos and Earth's Geology

Plate Tectonics, Convection, Geodynamo



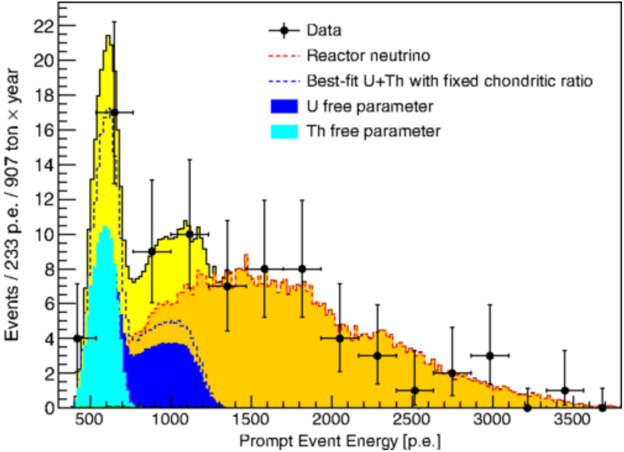




Does heat from radioactive decay drive the Earth's engine?

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

Click for Neutrino rap!!