

Neutrino Physics: The Long Baseline project

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INFIERI, 30 de January de 2017



Periodic Table of Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H Hydrogen (1.00794)	Atomic # Name Symbol Atomic Mass																2 He Helium (4.002602)
3 Li Lithium (6.941)	4 Be Beryllium (9.012182)	<div style="display: flex; justify-content: space-around;"> <div style="border: 1px solid black; padding: 2px;">C Solid</div> <div style="border: 1px solid black; padding: 2px;">Hg Liquid</div> <div style="border: 1px solid black; padding: 2px;">H Gas</div> <div style="border: 1px solid black; padding: 2px;">Rf Unknown</div> </div>										10 Ne Neon (20.1797)					
11 Na Sodium (22.98976928)	12 Mg Magnesium (24.304)	<div style="display: flex; justify-content: space-around;"> <div style="border: 1px solid black; padding: 2px;">Alkali metals</div> <div style="border: 1px solid black; padding: 2px;">Alkaline earth metals</div> <div style="border: 1px solid black; padding: 2px;">Metals</div> <div style="border: 1px solid black; padding: 2px;">Transition metals</div> <div style="border: 1px solid black; padding: 2px;">Poor metals</div> <div style="border: 1px solid black; padding: 2px;">Other nonmetals</div> <div style="border: 1px solid black; padding: 2px;">Noble gases</div> </div>										16 S Sulfur (32.06)					
19 K Potassium (39.0983)	20 Ca Calcium (40.078)	21 Sc Scandium (44.955912)	22 Ti Titanium (47.88)	23 V Vanadium (50.9415)	24 Cr Chromium (51.9961)	25 Mn Manganese (54.938045)	26 Fe Iron (55.845)	27 Co Cobalt (58.933195)	28 Ni Nickel (58.6934)	29 Cu Copper (63.546)	30 Zn Zinc (65.38)	31 Ga Gallium (69.723)	32 Ge Germanium (72.64)	33 As Arsenic (74.9216)	34 Se Selenium (78.96)	35 Br Bromine (79.904)	36 Kr Krypton (83.798)
37 Rb Rubidium (85.4678)	38 Sr Strontium (87.62)	39 Y Yttrium (88.90584)	40 Zr Zirconium (91.224)	41 Nb Niobium (92.90638)	42 Mo Molybdenum (95.94)	43 Tc Technetium (97.90631)	44 Ru Ruthenium (101.07)	45 Rh Rhodium (102.9055)	46 Pd Palladium (106.3676)	47 Ag Silver (107.8682)	48 Cd Cadmium (112.411)	49 In Indium (114.818)	50 Sn Tin (118.710)	51 Sb Antimony (121.757)	52 Te Tellurium (127.6)	53 I Iodine (126.90545)	54 Xe Xenon (131.29)
55 Cs Cesium (132.90545196)	56 Ba Barium (137.327)	57-71 Lanthanides	72 Hf Hafnium (178.49)	73 Ta Tantalum (180.94788)	74 W Tungsten (183.84)	75 Re Rhenium (186.207)	76 Os Osmium (190.23)	77 Ir Iridium (192.222)	78 Pt Platinum (195.084)	79 Au Gold (196.966569)	80 Hg Mercury (200.59)	81 Tl Thallium (204.38)	82 Pb Lead (207.2)	83 Bi Bismuth (208.9804)	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222.01757)
87 Fr Francium (223)	88 Ra Radium (226)	89-103 Actinides	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (264)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 Ds Darmstadtium (267)	111 Rg Roentgenium (268)	112 Cu Copernicium (269)	113 Nh Nihonium (270)	114 Fl Flerovium (271)	115 Uu Uup (272)	116 Uuh Uuq (273)	117 Uus Uus (274)	118 Uuo Uuo (276)

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

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57 La Lanthanum (138.90547)	58 Ce Cerium (140.12)	59 Pr Praseodymium (140.90766)	60 Nd Neodymium (144.242)	61 Pm Promethium (145)	62 Sm Samarium (150.36)	63 Eu Europium (151.964)	64 Gd Gadolinium (157.25)	65 Tb Terbium (158.92535)	66 Dy Dysprosium (162.50015)	67 Ho Holmium (164.93033)	68 Er Erbium (167.2593)	69 Tm Thulium (168.93402)	70 Yb Ytterbium (173.054)	71 Lu Lutetium (174.967)
89 Ac Actinium (227)	90 Th Thorium (232.0376)	91 Pa Protactinium (231.03688)	92 U Uranium (238.02891)	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)



Particle Physics

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c ²	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times 10^{-9}$	0
e electron	0.000511	-1
ν_M middle neutrino*	$(0.009-0.13)\times 10^{-9}$	0
μ muon	0.106	-1
ν_H heaviest neutrino*	$(0.04-0.14)\times 10^{-9}$	0
τ tau	1.777	-1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c ²	Electric charge
u up	0.002	2/3
d down	0.005	-1/3
c charm	1.3	2/3
s strange	0.1	-1/3
t top	173	2/3
b bottom	4.2	-1/3

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c ²	Electric charge
γ photon	0	0
W^-	80.4	-1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c ²	Electric charge
g gluon	0	0



Particle Physics

Interaction: exchange forces



BOSONS			force carriers spin = 0, 1, 2, ...		
Unified Electroweak spin = 1			Strong (color) spin = 1		
Name	Mass GeV/c ²	Electric charge	Name	Mass GeV/c ²	Electric charge
γ photon	0	0	g gluon	0	0
W^-	80.4	-1			
W^+	80.4	+1			
Z^0	91.187	0			

Particle Physics

Forces in nature



	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	$W^+ W^- Z^0$	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and $W^+ W^-$	Quarks and Gluons

Particle Physics

Gravitational force=weaker force for particles not for humans...



Particle Physics

Symmetry matters in particle physics!!



Particle physics: gauge symmetries fix the interactions

Particle Physics

Standard Model of particle physics

Proposed by Weinberg, Salam and Glashow in 1967



Nobel prize for them in 1979

In 2013 LHC confirmed one fundamental prediction: [the Higgs boson](#)
Nobel prize for P. Higgs em 2013

LHC physics : [Ian Shipsey talk](#)



Particle Physics

Magnetic dipole momentum: $B = \frac{\mu}{r^2}$; $\mu = IA$

classically $\vec{\mu} = \frac{q}{2m} \vec{L}$

Interaction: $\vec{\mu} \cdot \vec{B} \propto \vec{L} \cdot \vec{B}$

Stern-Gerlach experiment: quantized deflection

In Quantum Mechanics $\vec{\mu} \propto g \vec{S}$ S=spin g giromagnetic factor

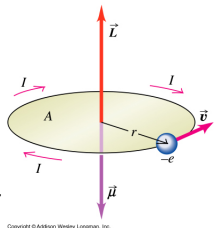
QM cannot predicted the giromagnetic factor, it is put by hand $g=2$.

The value predicted by the Standard Model is $g_{\mu}^{theo} = 2.0023318418$.

It is measured

$$g_{\mu}^{exp} = 2.0023318418(13).$$

The Standard Model of elementary particles is the most successful theories in Physics!!



The Nobel Prize in Physics 2015



Photo: A. Mahmoud
Takaaki Kajita
Prize share: 1/2

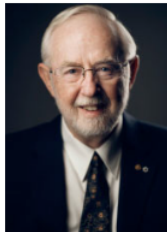


Photo: A. Mahmoud
Arthur B. McDonald
Prize share: 1/2

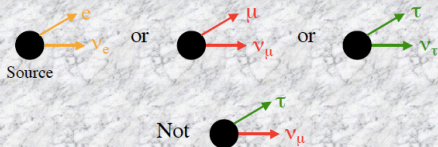
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Photos: Copyright © The Nobel Foundation

What we know about neutrinos at the end of 20th Century?

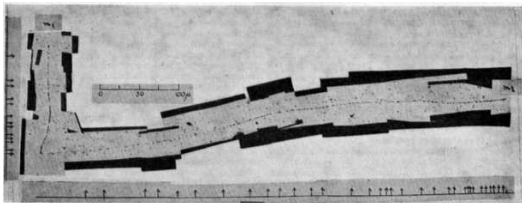
- There are 3 types of neutrinos: ν flavor: $\nu_e \nu_\mu \nu_\tau$
- have ZERO mass e ZERO charge
- interact **only** by weak interactions:

The neutrino and charged lepton always have the same flavor.

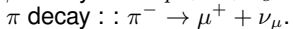
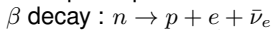


Neutrino Physics

Pion discovery: Cesar Lattes (Raios Cosmicos e Cronologia) and Cecil Powell

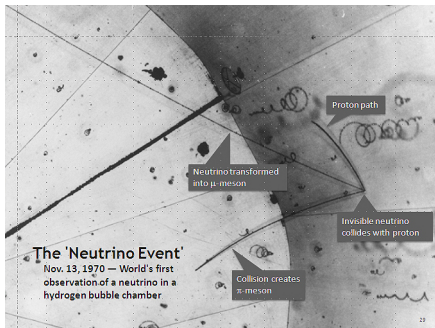


Example to produce neutrinos

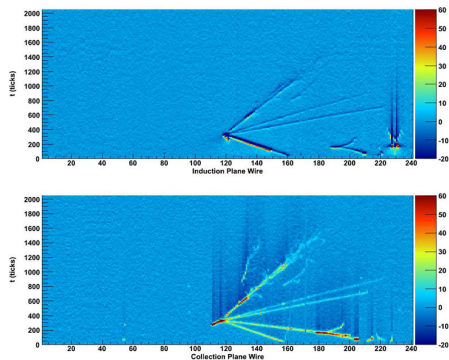


Neutrino Physics

Neutrino interaction: past



Neutrino interaction: present



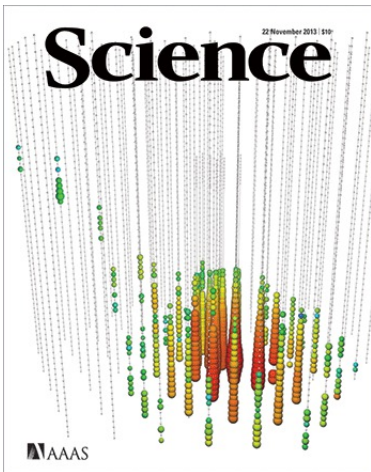
ARGONEUT experiment

see next talks by Sebastien Murphy and Ettore Segretto



Neutrino Physics

Neutrinos from **unknown sources**: 2015 in ICECUBE experiment



First time that it was detected high energy neutrinos from space



Neutrino Physics

Neutrino are feeble

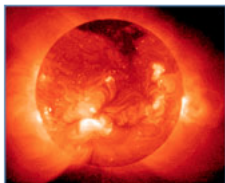


FACT: about 65 million neutrinos pass through your thumbnail every second.

Learn Something
New Every Day
LSNED.com

Big detectors are necessary

Neutrino Physics



FIRST STEPS
1920–1956



GRAND EXPERIMENT
1964–1968

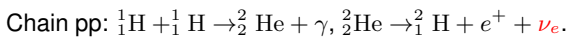


DECADES OF DOUBT
1969–1985



MYSTERY SOLVED
1998–2002

Eddington, Bethe: Sun luminosity is due atomic fusion :



↑
Sun luminosity



First measurement of neutrinos from the Sun

Nobel Prize in 2008 for R. Davis.

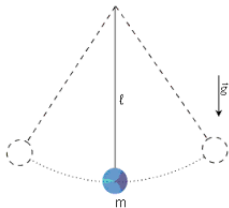
Puzzle: the number of neutrinos was small than expected,

Possible explanations

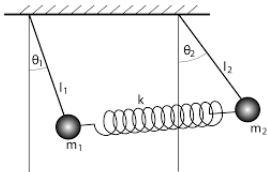
- sun hydrodynamics: convection ??
- nuclear physics?
- We are counting **electron neutrinos**. Maybe the problem are the neutrinos.

Classical analogy

Simple Pendulum

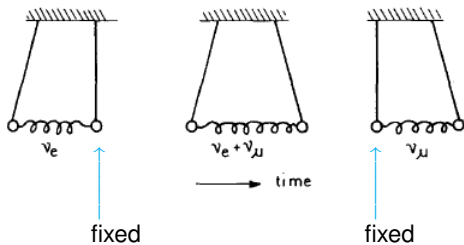


Two Pendulums connected by a spring



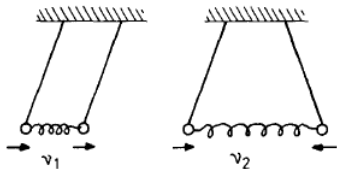
Classical analogy

Possible oscillations



Classical analogy

Two possible joint movements:



←→
fixed

Two type of descriptions:

Isolated movement: ν_e, ν_μ or global movement: ν_1, ν_2

Neutrino oscillation

- Pontecorvo(1958) :

Flavor of Neutrinos, ν_e ν_μ ν_τ are a linear combination of states with well defined mass,

ν_1 ν_2 ν_3

we have

$$\nu_e = +\cos\theta \nu_1 + \sin\theta \nu_2$$

$$\nu_\mu = -\sin\theta \nu_1 + \cos\theta \nu_2$$

the states ν_1 e ν_2 are mass eigenstates



Symmetry Magazine

Neutrino oscillation

Using the Pontecorvo mechanism

$$\underbrace{\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}}_{\text{flavor}} = \underbrace{\begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}}_{\text{mixing: } U} \underbrace{\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}}_{\text{mass}}$$

The evolution equation is in the shape of Schroendinger equation

$$\frac{\partial}{\partial t} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = U \begin{pmatrix} E_1 & 0 \\ 0 & E_2 \end{pmatrix} U^\dagger \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

With relativistic energies : $E_1 \sim p + \frac{m_1^2}{2p}$ $E_2 \sim p + \frac{m_2^2}{2p}$.

Correspondence between Pontecorvo mechanism and the classical analogy

Normal modes \longleftrightarrow mass eigenstates

Non-normal Modes \longleftrightarrow flavor eigenstates

frequency w_i \longleftrightarrow $E = \sqrt{p^2 + m_i^2}$

spring coupling k \longleftrightarrow mixing angle θ

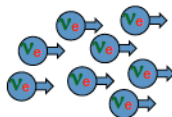
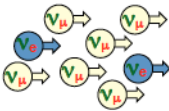
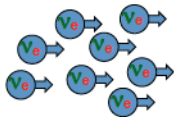
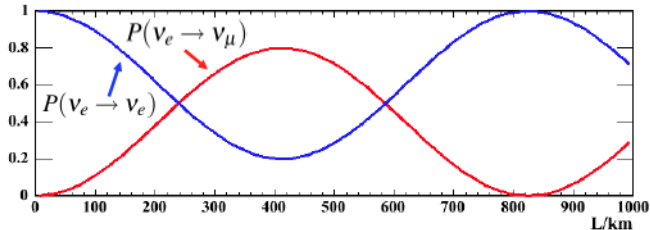


Neutrino oscillation

The conversion probability of electronic neutrinos is

$$P(\nu_e \rightarrow \nu_\mu) \equiv \sin^2 2\theta_{e\mu} \sin^2 \left(\frac{\Delta m^2 L}{4p} \right)$$

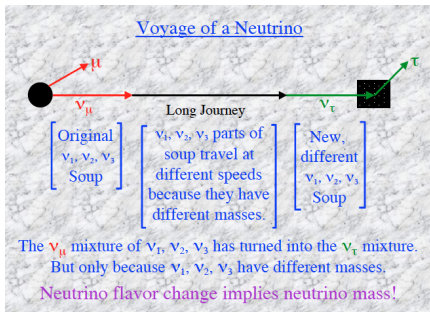
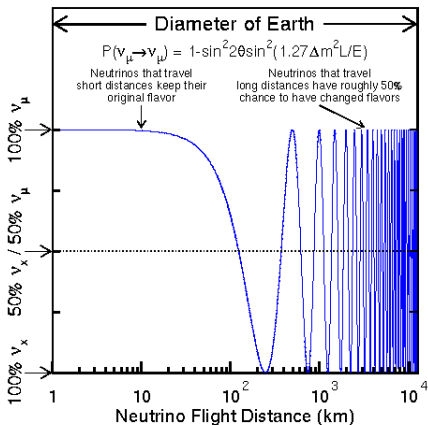
Definition: $\Delta m^2 = m_2^2 - m_1^2$



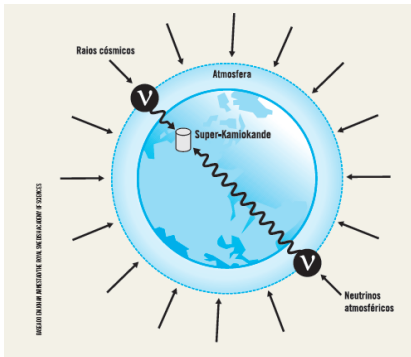
Neutrino oscillation

We can write down the survival probability of muon neutrino as

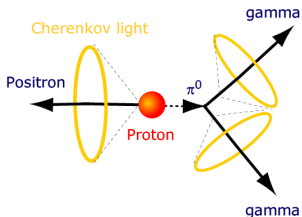
$$P(\nu_\mu \rightarrow \nu_\mu) \equiv 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \left(\frac{\Delta m^2 L}{4p} \right)$$



Atmospheric neutrinos



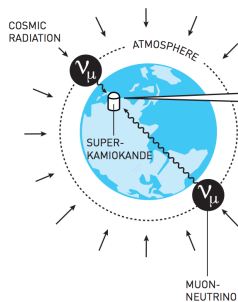
Noise for the search of **proton decay**



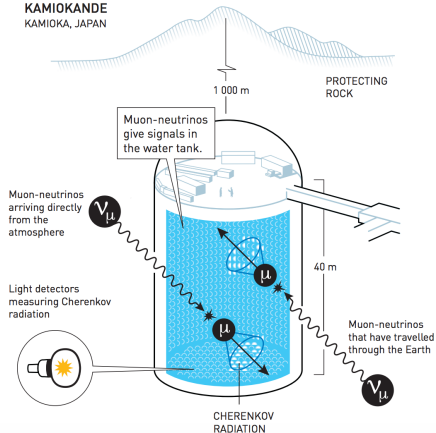
Ciência Hoje de Dezembro de 2015: Metaformose Fantasmagórica

Atmospheric neutrinos

NEUTRINOS FROM COSMIC RADIATION

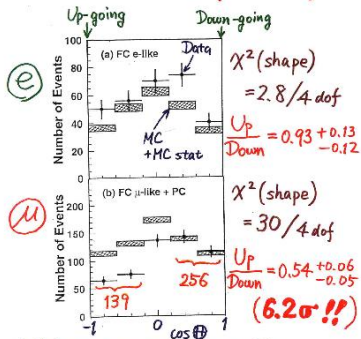


SUPER-KAMIOKANDE KAMIOKA, JAPAN



Atmospheric neutrinos

Zenith angle dependence (Multi-GeV)



* Up/Down syst. error for μ -like

Prediction (flux calculation $\lesssim 1\%$
1km rock above SK 1.5%) 1.8%

Data (Energy calib. for $\uparrow \downarrow$ 0.7%
Non ν Background < 2%) 2.1%

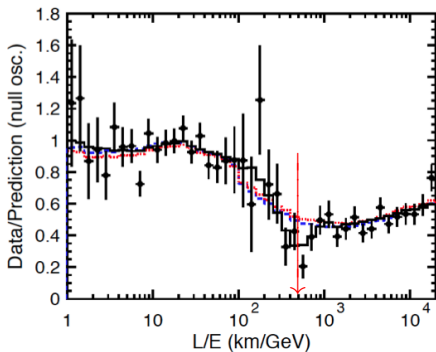
In 1998, Kajita show this slide:

Muonic Neutrinos change flavor:
neutrinos are disappearing.

Atmospheric neutrinos

A better way to look is the dependence of L/E , distance over energy

For neutrinos $E = 1\text{ GeV}$, $L \sim 500\text{ km}$ macroscopic distance!!

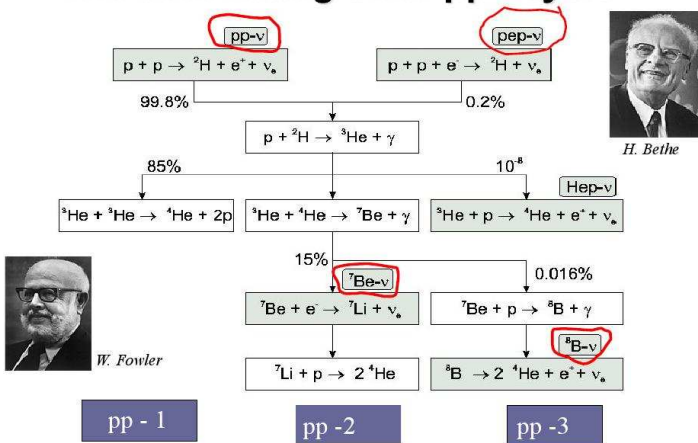


Disappearance of ν_μ

Neutrinos solares

- Sun as neutrino lamp

The dominating solar pp - cycle



Experimento SNO

- Detection method

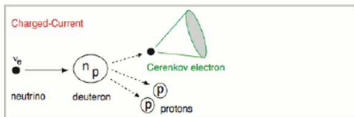
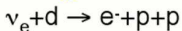


a pure ν_e source

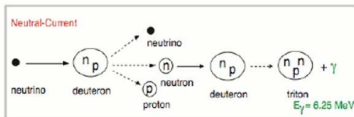
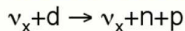


a ν_x detector

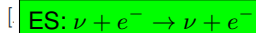
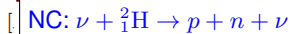
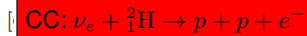
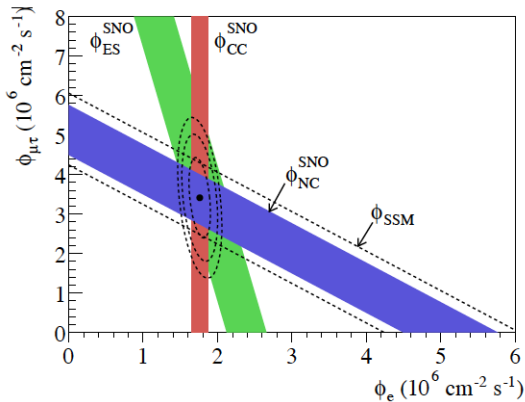
Charged-Current (CC)



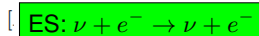
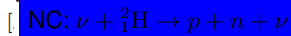
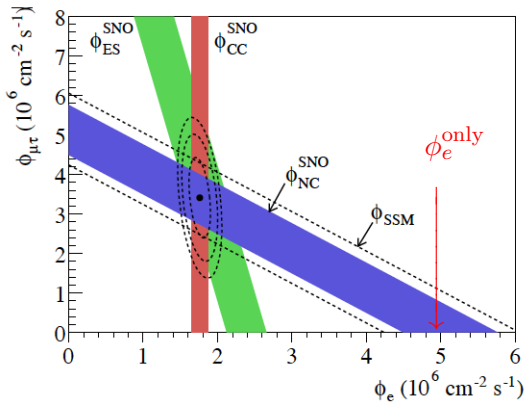
Neutral-Current (NC)



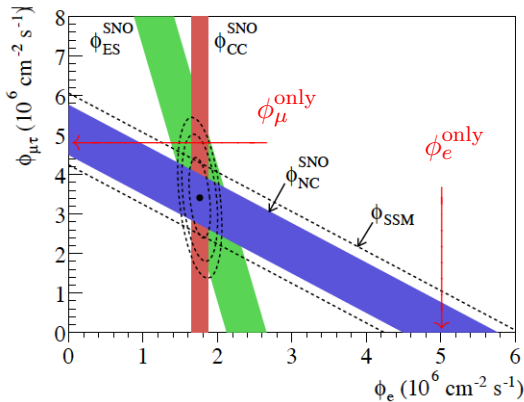
In 2003 SNO measure different reactions of neutrinos from sun



In 2003 SNO measure different reactions of neutrinos from sun



In 2003 SNO measure different reactions of neutrinos from sun

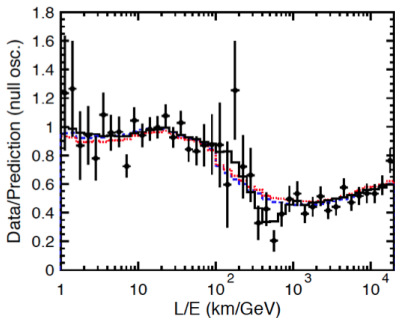


- [CC: $\nu_e + {}^2_1\text{H} \rightarrow p + p + e^-$
- [NC: $\nu + {}^2_1\text{H} \rightarrow p + n + \nu$
- [ES: $\nu + e^- \rightarrow \nu + e^-$

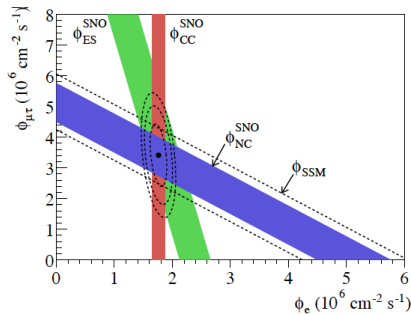
• Best fit for : $\phi_{\mu\tau} \neq 0$

Oscillation signal $\nu_e \rightarrow \nu_\mu$.

We saw neutrino oscillation!!



Oscillation signal $\nu_\mu \rightarrow \nu_\tau$.



Oscillation signal $\nu_e \rightarrow \nu_\mu$.

How to explain neutrino oscillations? Pontecorvo + Refraction effect

Pontecorvo mechanism: mixing

The survival probability of electron neutrino is **in vacuum**

$$P(\nu_e \rightarrow \nu_e) \equiv 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4p} \right)$$

Light refraction: $v \equiv \frac{c}{n}$



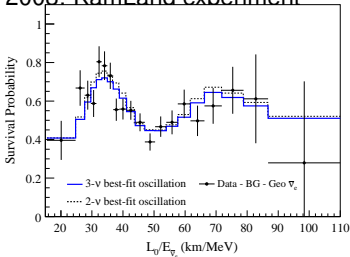
Refraction for neutrinos: effective mass in matter

Wolfenstein -Mikheyev-Smirnov 1986:

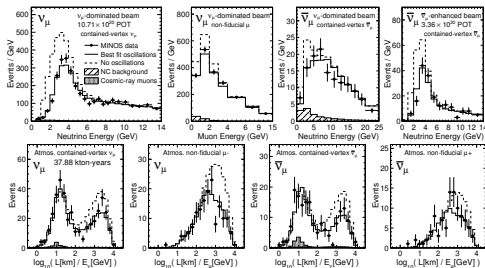
The neutrino get different mass and mixing angle that are function of medium density

Oscillation discover in other expts

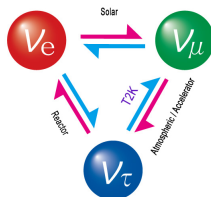
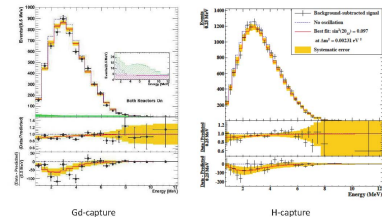
2008: KamLand experiment



MINOS experiment 2010: UFG/USP/UNICAMP



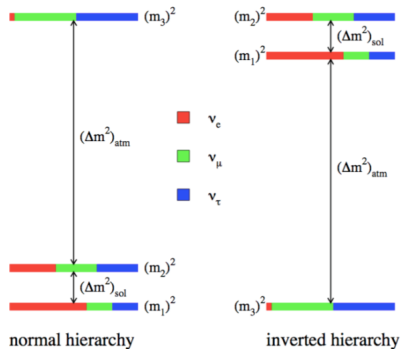
Double Chooz 2013: UNICAMP/UFABC/CBPF



Neutrino oscillation between three generations



Paradigm of 3ν oscillation



$$U_{\text{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Described by three mixing angles: $\theta_{23}, \theta_{13}, \theta_{21}$

and one CP violation phase, δ_{CP}

Unknowns: Mass hierarchy (ordering), CP violation

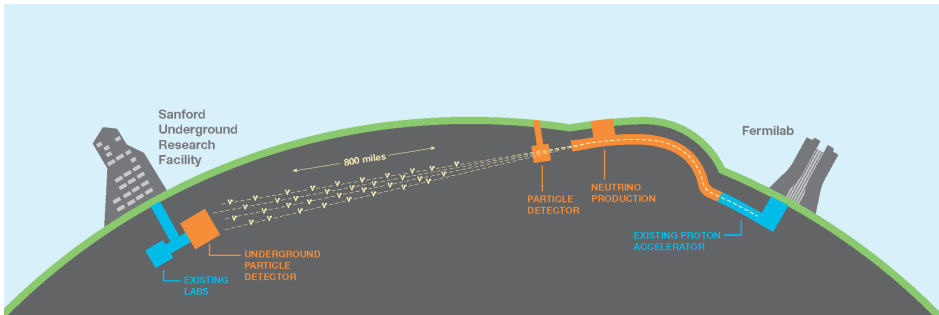
DUNE Experiment

- Intense beam of ν_μ ($\bar{\nu}_\mu$) fired 1300km at large detector
- Compare $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
- Probe fundamental differences between matter and antimatter



DUNE Experiment

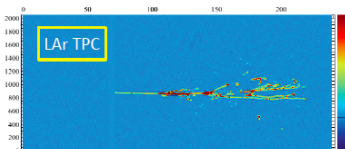
- Muon neutrinos/anti-neutrinos from high-power proton: 1.2 MW
- Large underground Liquid Argon Time Projection Chamber
Mass of 40 kton
- Near detector to characterize the beam



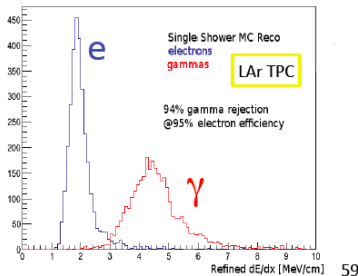
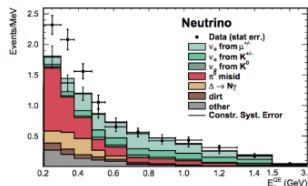
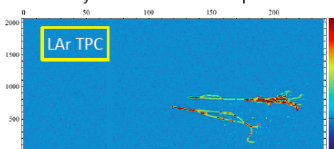
- Good separation of electron/ γ : ν_e appearance

Electron/photon Separation with LAr TPCs

1 GeV electron shower



Decay of a 1 GeV π^0 to two photons.



59

DUNE Experiment

- Why $L=1300\text{Km}$?

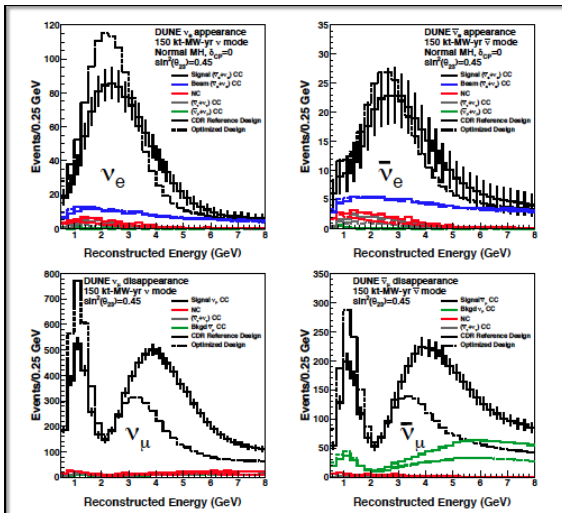
$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) \simeq & \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 \\
 & + \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin aL}{aL}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

$$\begin{aligned}
 a &= G_F N_e / \sqrt{2} \\
 \Delta_{ij} &= \frac{\Delta m_{ij}^2 L}{4E}
 \end{aligned}$$

For anti-neutrinos $a \rightarrow -a$.

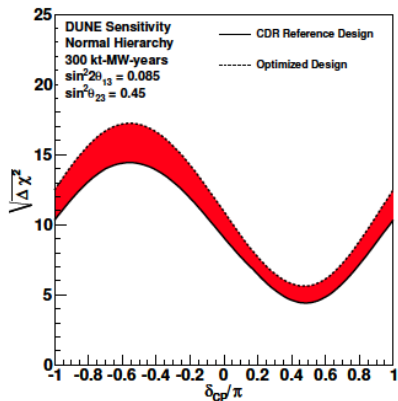
- Dependence on θ_{23}, a , CP violation phase δ_{CP}
- Present Range for $\sin^2 \theta_{23}$ for one octante : 0.03 : With DUNE 0.005.
- Present Range : Any value for δ_{CP}
- At the present we did not know if $\Delta_{31} > 0$ or < 0 .

DUNE Experiment

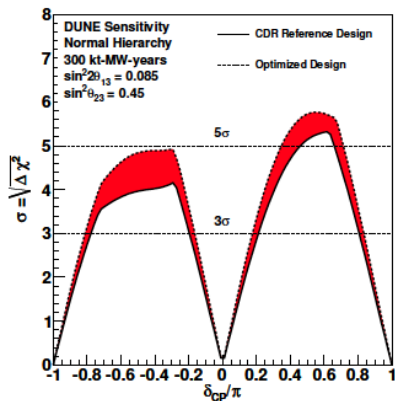


DUNE Experiment

DUNE CDR: Mass Hierarchy



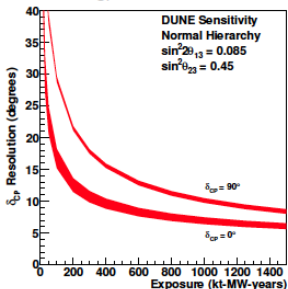
CP Violation



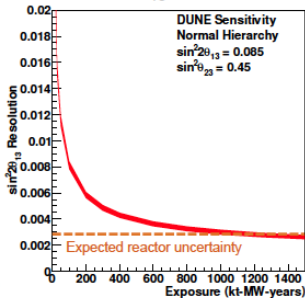
DUNE Experiment

DUNE CDR:

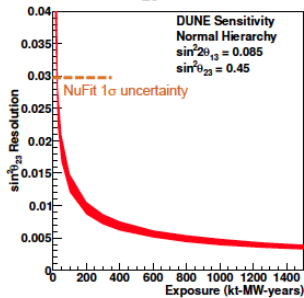
δ_{CP} Resolution



$\sin^2 2\theta_{13}$ Resolution



$\sin^2 \theta_{23}$ Resolution



Other physics topics for DUNE

- Neutrinos from stellar core collapse

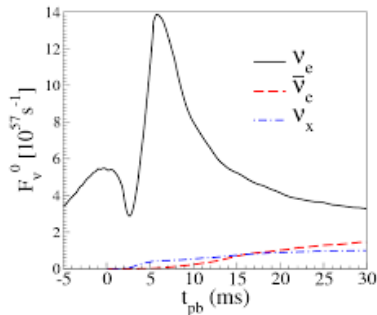
Core collapse produce neutrinos from all types.

Previous experiments mainly sensitive to $\bar{\nu}_e$

DUNE experiment can see the ν_e component

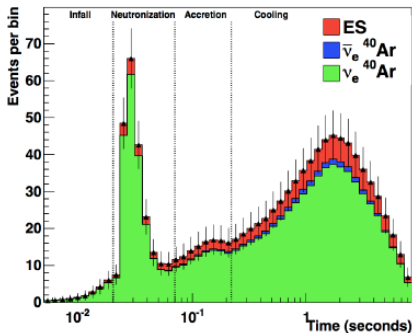


Supernova 1987A

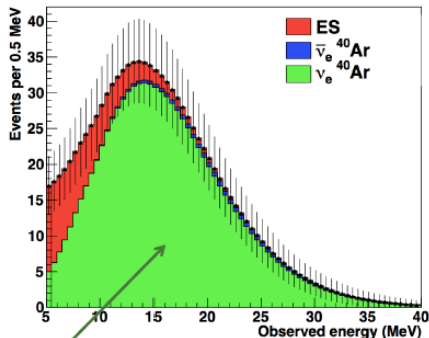


Other physics topics for DUNE

Flavor composition as function of time:



Energy spectra integrated over time:



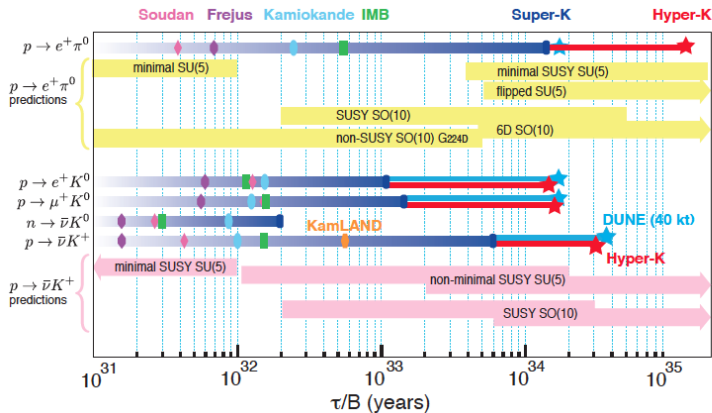
Electron flavor dominant

Other physics topics for DUNE

- Test of fundamental symmetries: proton decay

Baryon number conservation so far

Well motivated models suggest proton decay



DUNE physics summary

- Determination of mass hierarchy: 5σ
- Probe CP violation with neutrinos: $(3 - 5)\sigma$
- Precise test of 3ν paradigm
- Sensitivity to nucleon decay: $\tau/b > 10^{34}$ yr
- Unique test of stellar core collapse fluxes: ν_e sensitivity



Final symmary

- Neutrino physics have surprised us: neutrino oscillations
 - Paradigm of three ν neutrinos in different experiments
 - DUNE experiment: new generation neutrino experiment: tracking, flavor tag
- It is possible to test mass hierarchy and CP violation: implications for particle physics
- Proton decay : fundamental symmetries
- Neutrino astrophysics: understand neutrino production

