Neutrino Physics: The Long Baseline project

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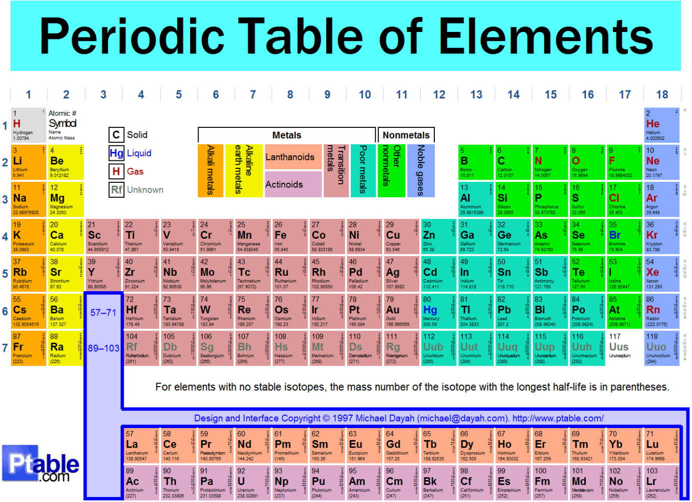
UNICAMP

INFIERI, 30 de January de 2017


Periodic Table of Elements
Atomic #
Symbol
Name
Atomic Mass
C Solid
Hg Liquid
H Gas
Rf Unknown
Metals
Nonmetals
Alkali metals
Alkaline earth metals
Lanthanoids
Actinoids
Transition metals
Poor metals
Other nonmetals
Noble gases
57–71
89–103
For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.
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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*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	−1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	−1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	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, ...

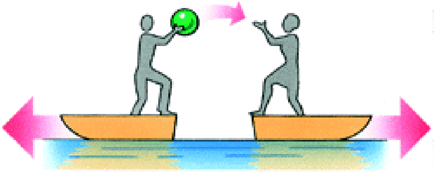
Unified Electroweak spin = 1

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

Interaction: exchange forces



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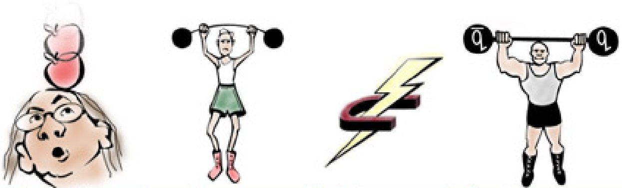
Forces in nature



	Gravity	Weak	Electromagnetic	Strong
		(Electroweak)		
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

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

Symmetry matters in particle physics!!

Particle physics: gauge symmetries fix the interactions

Standard Model of particle physics

Proposed by Weinberg, Salam and Glashow in 1967

Nobel prize for them in 1979

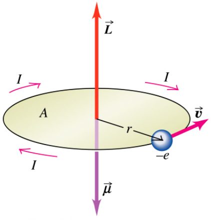
In 2013 LHC confirmed one fundamental prediction: the Higgs boson
Nobel prize for P. Higgs em 2013

LHC physics : Ian Shipsey talk

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

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

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



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

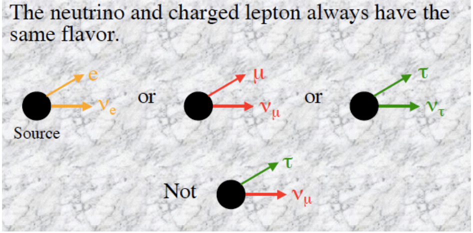
Arthur B. McDonald

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"*

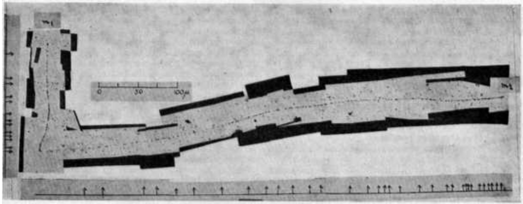
What we know about neutrinos at the end of 20th Century?

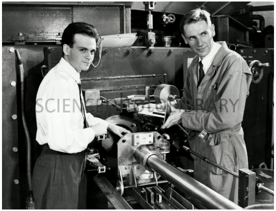
- There are 3 types of neutrinos: ν flavor: ν_e ν_μ ν_τ
- have ZERO mass e ZERO charge
- interact only by weak interactions:



Neutrino Physics

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



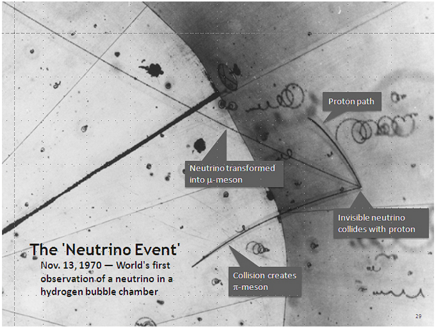


Example to produce neutrinos

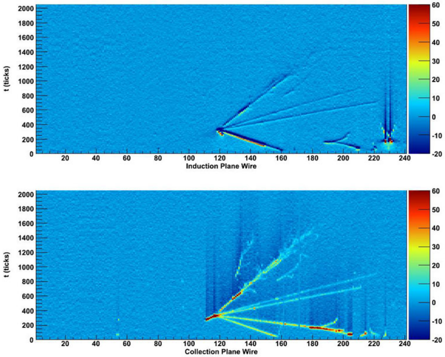
β decay : $n \rightarrow p + e + \bar{\nu}_e$

π decay : : $\pi^{-} \rightarrow \mu^{+} + \nu_{\mu}$.

Neutrino interaction: past



Neutrino interaction: present



ARGONEUT experiment

see next talks by Sebastien Murphy and Ettore Segretto

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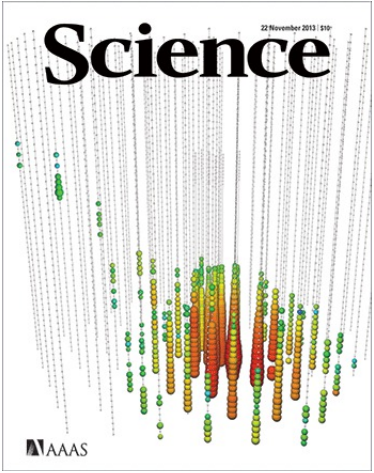
Neutrinos from unknow sources: 2015 in ICECUBE experiment



First time that it was detected high energy neutrinos from space

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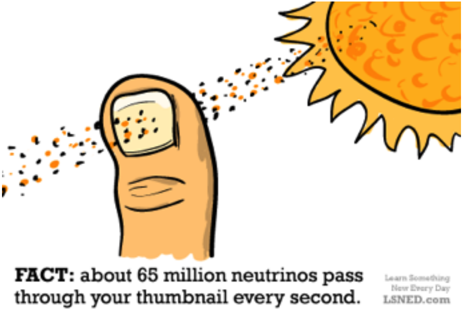
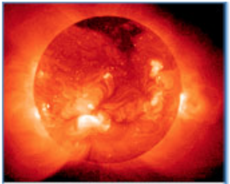
Neutrino are feeble

Big detectors are necessary





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 :

Chain pp: ${}^1_1\mathrm{H} +^1_1 \mathrm{H} \to^2_2 \mathrm{He} + \gamma,\ {}^2_2\mathrm{He} \to^2_1 \mathrm{H} + e^+ + \nu_e.$

↑ Sun luminosity

First measurement of neutrinos from the Sun

Nobel Prize in 2008 for R. Davis.

Puzzle: the number of neutrinos was small then expected,

Possible explanations

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

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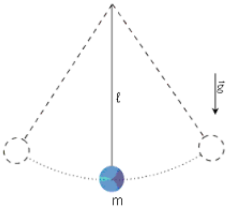
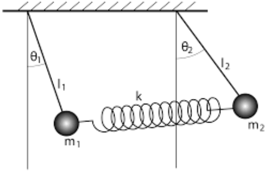
Let's take a break

Classical analogy

Simple Pendulum

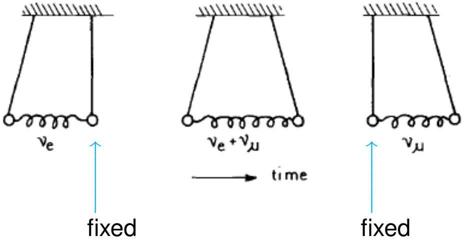


Two Pendulums connected by an spring



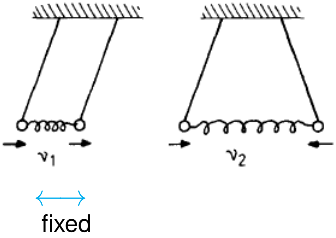
Classical analogy

Possible oscillations



Classical analogy

Two possible joint movements:



Two type of descriptions:
Isolated movement: ν_e, ν_μ or global movement: ν_1, ν_2

Neutrino oscillation

- Pontecorvo(1958) :

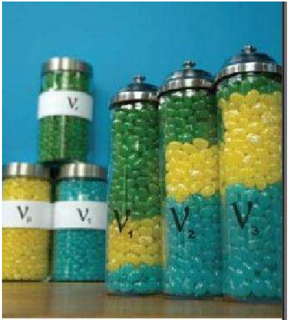
Flavor of Neutrinos, ν_e ν_μ ν_τ are a linear combination of states with well defined mass, ν_1 ν_2 ν_3

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

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

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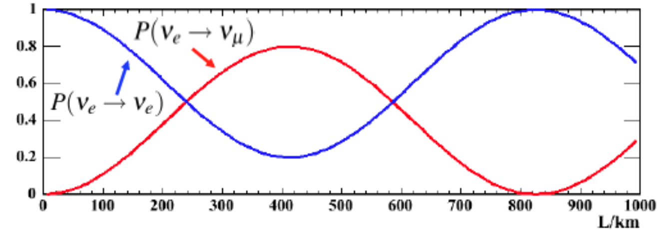
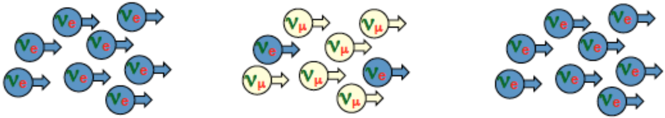
Neutrino oscillation

The conversion probability of electronic neutrinos is

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

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

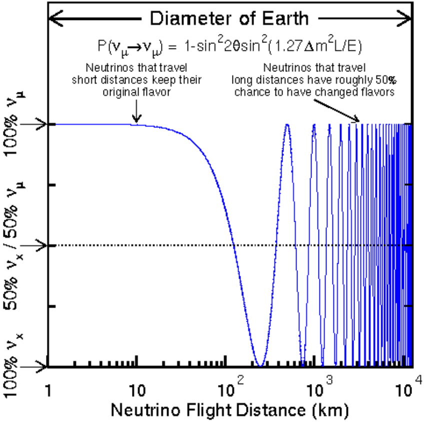


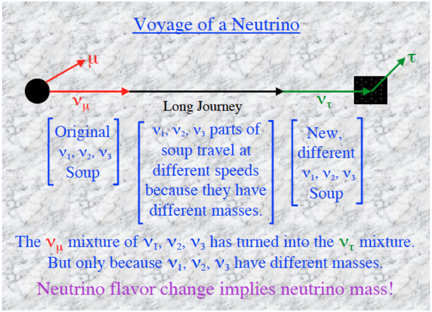


Neutrino oscillation

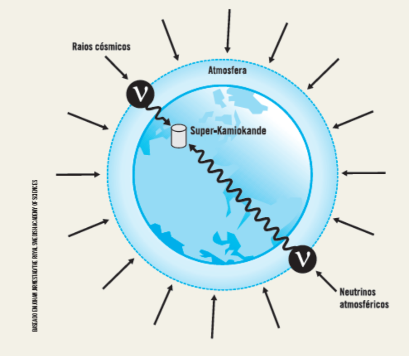
We can write down the survival probability of muon neutrino as

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

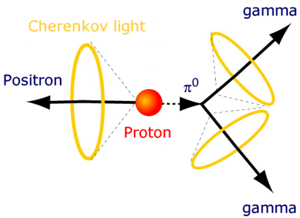




Atmospheric neutrinos

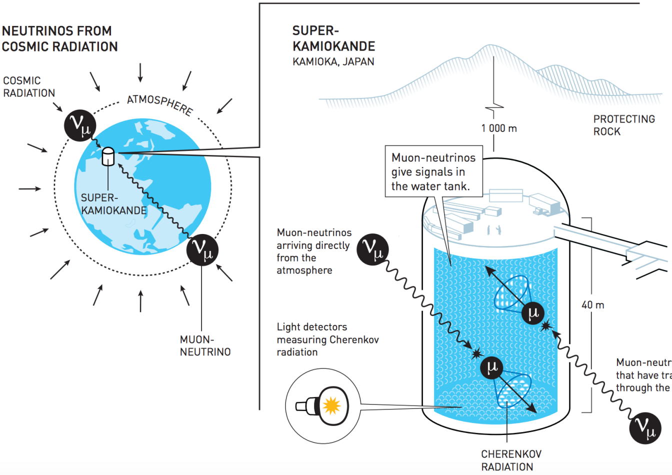


Noise for the search of proton decay

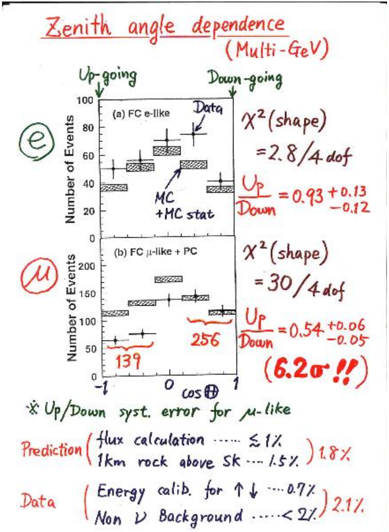


Ciência Hoje de Dezembro de 2015: Metaformose Fantasmagórica

Atmospheric neutrinos



Atmospheric neutrinos

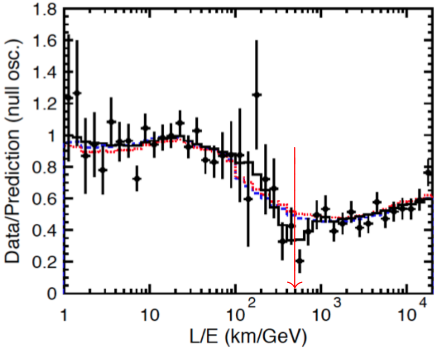


In 1998, Kajita show this slide:

Muonic Neutrinos change flavor: neutrinos are disappearing.

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

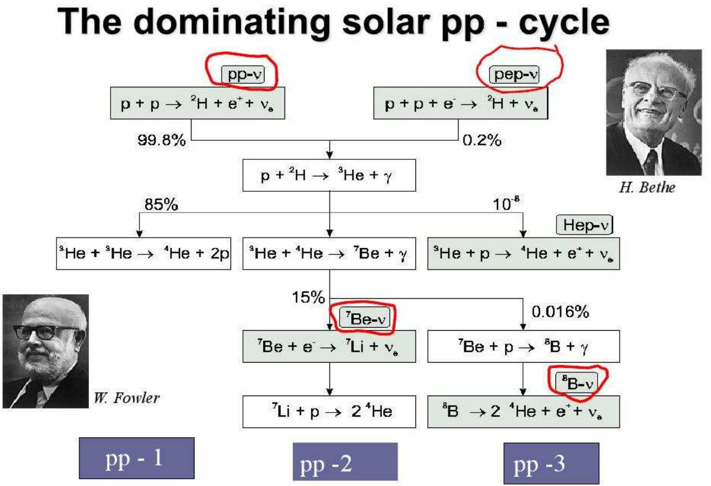
For neutrinos $E = 1$GeV, $L \sim 500$ km macroscropic distance!!



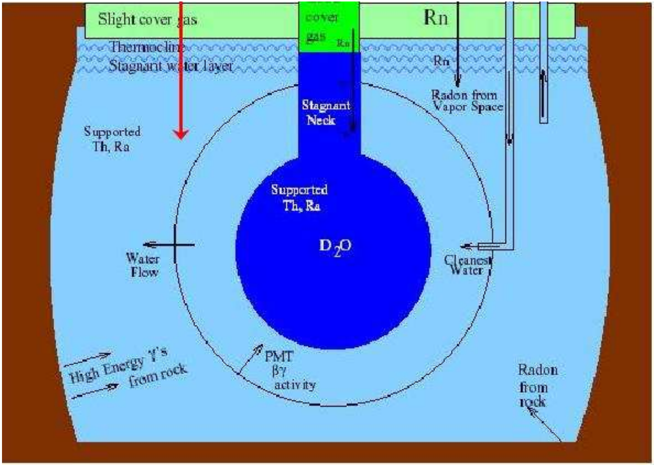
Disappearance of ν_μ

Neutrinos solares

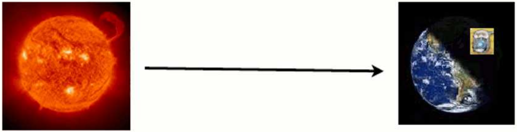
- Sun as neutrino lamp



- SNO Experiment: Arthur B. McDonald, Canadá



- Detection method



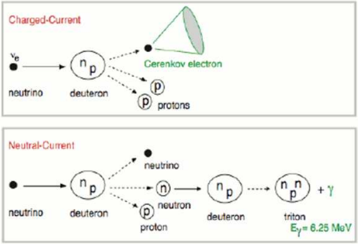
a pure ν_e source — a ν_x detector

Charged-Current (CC)

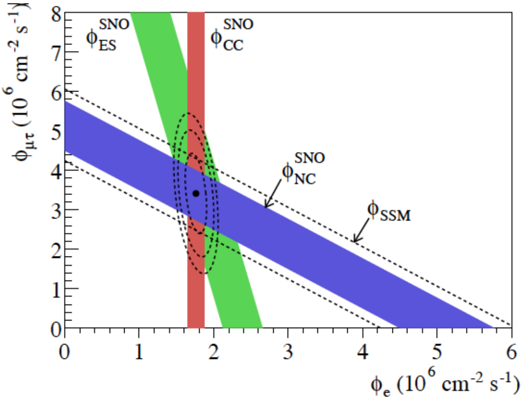
$\nu_e + d \rightarrow e^- + p + p$

Neutral-Current (NC)

$\nu_x + d \rightarrow \nu_x + n + p$



In 2003 SNO measure different reactions of neutrinos from sun



CC: $\nu_e + {}^2_1\mathrm{H} \rightarrow p + p + e^-$

NC: $\nu + {}^2_1\mathrm{H} \rightarrow p + n + \nu$

ES: $\nu + e^- \rightarrow \nu + e^-$

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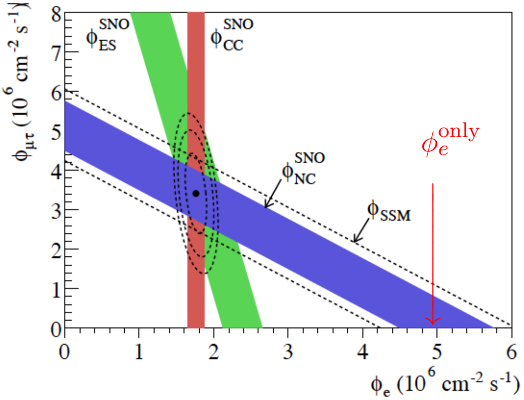

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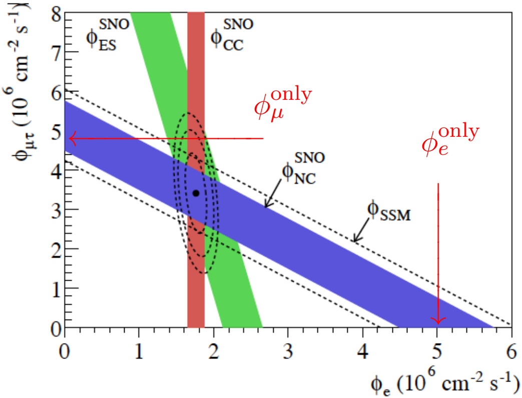

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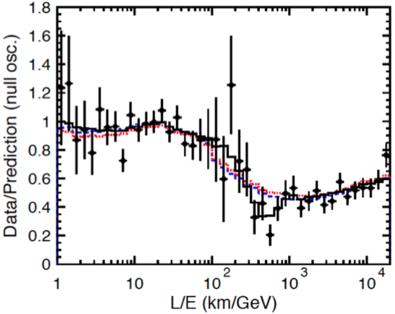
NC: $\nu + {}^2_1\mathrm{H} \to p + n + \nu$

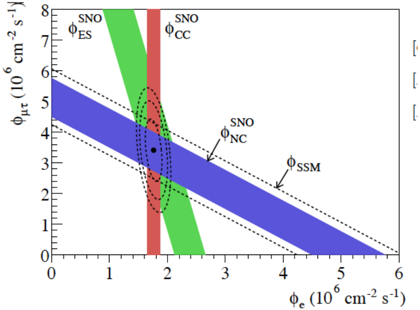
ES: $\nu + e^- \to \nu + e^-$

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

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

We saw neutrino oscillation!!





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

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

How to explain neutrino oscillations? Pontecorvo + Refraction effect

Pontecorvo mechanism: mixing

The survival probability of electron neutrino is in vacuum

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

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

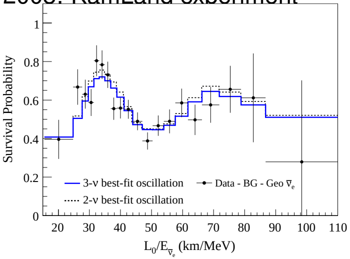
Refraction for neutrinos: effective mass in matter

Wolfestein -Mikheyev-Smirnov 1986:

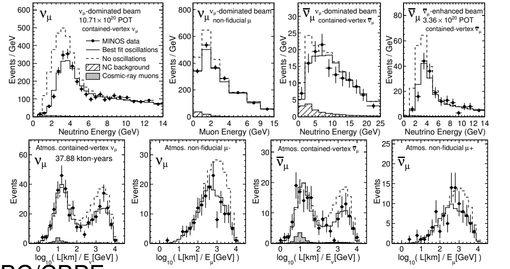
The neutrino get different mass and mixing angle that are function of medium density

Oscillation discover in other expts

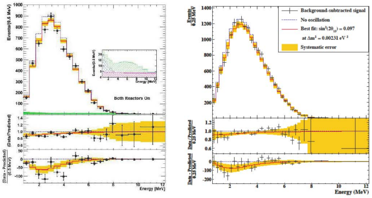
2008: KamLand experiment



MINOS experiment 2010: UFG/USP/UNICAMP

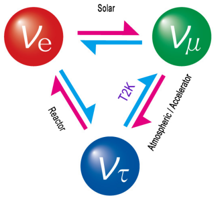


Double Chooz 2013: UNICAMP/UFABC/CBPF



Gd-capture

H-capture



Neutrino oscillation between three generations

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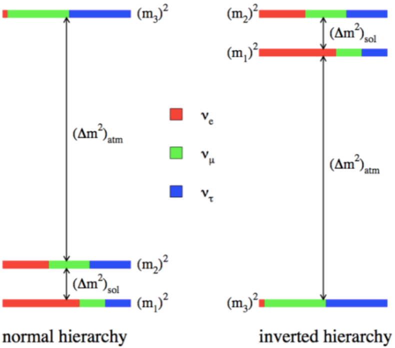
Paradigm of 3ν oscillation



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

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

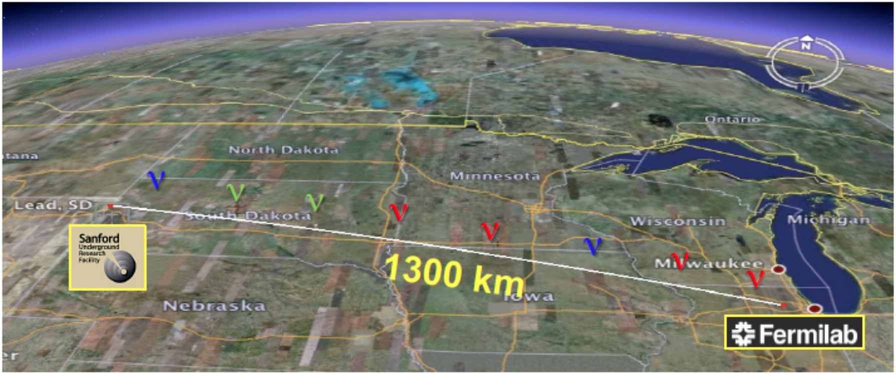
and one CP violation phase, δ_{CP}

Unknowns: Mass hierarchy (ordering), CP violation

DUNE Experiment

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

DEEP UNDERGROUND NEUTRINO EXPERIMENT

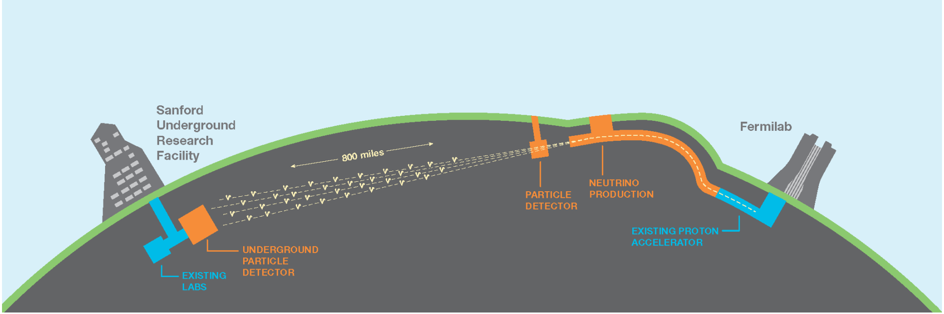


DUNE Experiment

- Muon neutrinos/anti-neutrinos from high-power proton: 1.2 MW
- Large underground Liquid Argon Time Projection Chamber

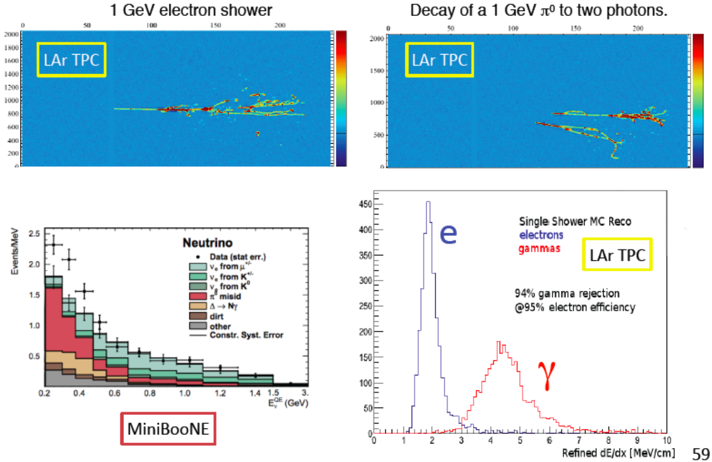
  Mass of 40 kton

- Near detector to characterize the beam



- Good separation of electron/γ : ν_e appearence

Electron/photon Separation with LAr TPCs



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DUNE Experiment

- Why L=1300Km?

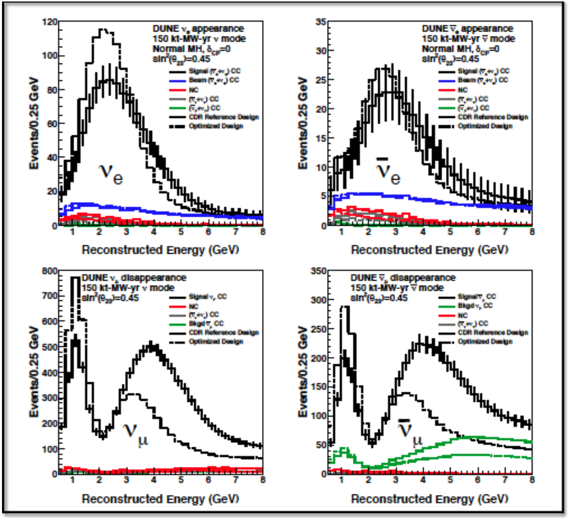
$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31} + \delta_{CP})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

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

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

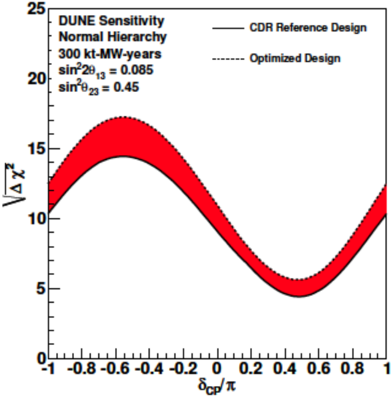
For anti-neutrinos $a \to -a$.

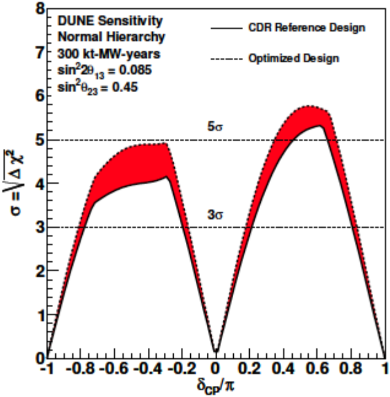
- Dependence on θ_{23},a, CP violaton phase δ_{CP}
- Present Range for $\sin^2\theta_{23}$ for one octante : 0.03 : With DUNE 0.005.
- Present Range : Any value for δ_{CP}
- At the present we did not know if $\Delta_{31} > 0$ or < 0.


DUNE νe appearance
150 kt-MW-yr ν mode
Normal MH, δCP=0
sin²(θ23)=0.45
DUNE ν̄e appearance
150 kt-MW-yr ν̄ mode
DUNE νμ disappearance
DUNE ν̄μ disappearance
NC
CDR Reference Design
Optimized Design
Events/0.25 GeV
Reconstructed Energy (GeV)

DUNE Experiment

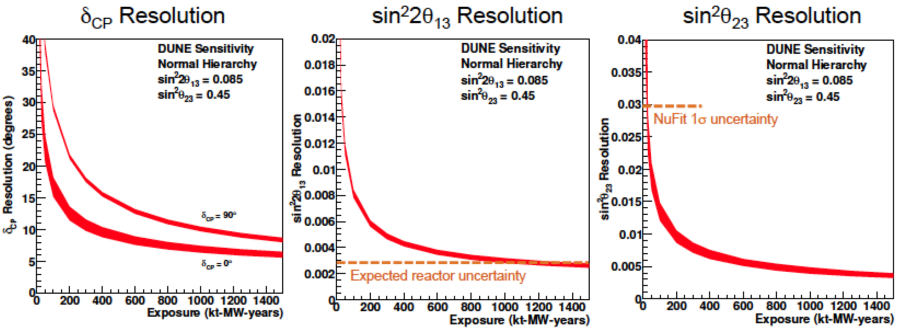
DUNE CDR: Mass Hierarchy CP Violation





DUNE Experiment

DUNE CDR:



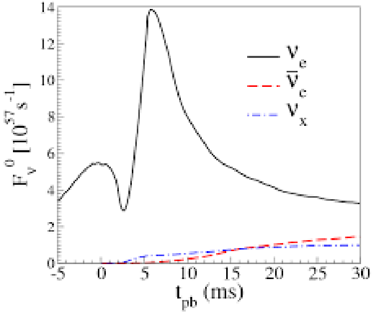
Other physics topics for DUNE

- Neutrinos from stelar core colapse

Core colapse produce neutrinos from all types.

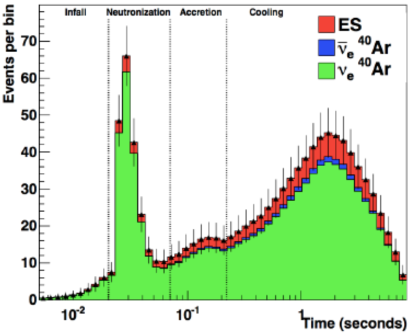
Previous experiments mainly sensitive to $\bar{\nu}_e$

DUNE experiment can see the ν_e component

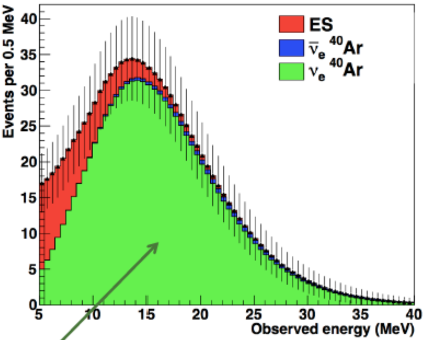


Supernova 1987A

Flavor composition as function of time:



Energy spectra integrated over time:



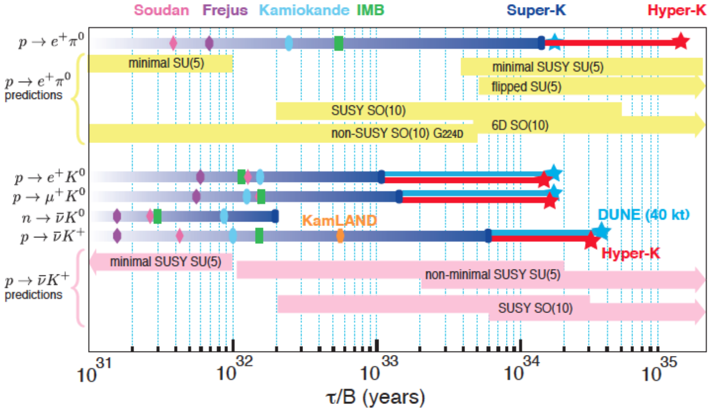
Electron flavor dominant

Other physics topics for DUNE

- Test of fundamental symmetries: proton decay

Baryon number conservation so far

Well motivated models suggest proton decay



GEFAN UNICAMP

DUNE physics symmary

- 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 stelar core colapse 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