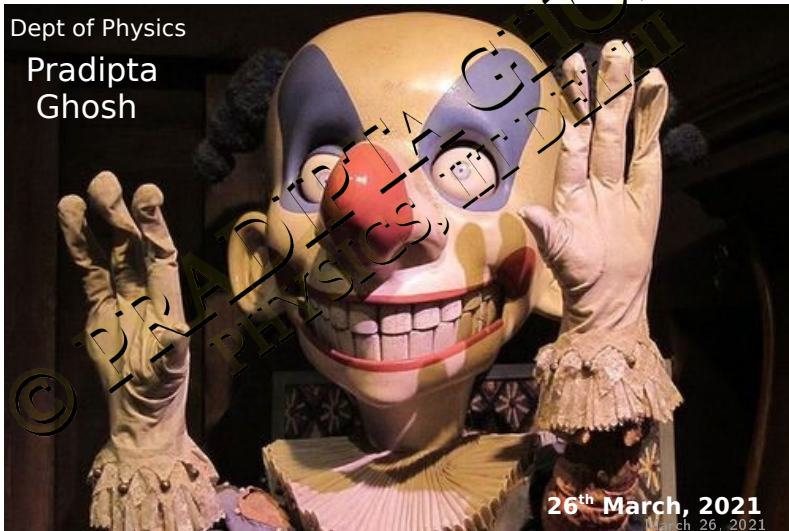




The “Boggart” of Particle Physics

Dept of Physics

Pradipta
Ghosh



26th March, 2021

March 26, 2021



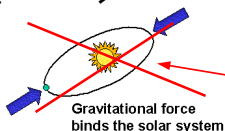
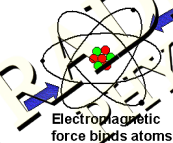
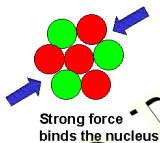
"Hogwarts" of the Particle Physics

The Standard Model

The Inmates and Laws

Elementary Particles

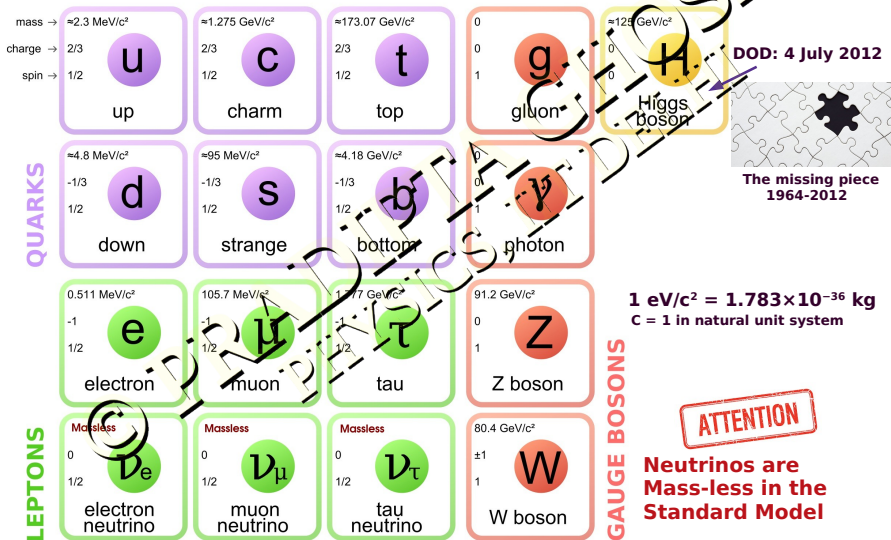
Basic Interactions
and mediators



Not included in
the Standard Model

Hogwarts of the Particle Physics: The inmates

Elementary Particles and Mediators



Theory: Glashow, 1961, Weinberg, 1967, Salam, 1968



Sheldon Glashow Steven Weinberg Abdus Salam



Theory: Greenberg, 1964, Han, Nambu, 1964, Bardeen, Fritzsche, Gell-Mann, 1973



David Gross H. D. Politzer F. Wilczek

Theory: 1973

C. R. Hagen Tom Kibble Gerald Guralnik



Theory: Nambu, Jona-Lasinio 1961



Yoichiro Nambu



Gerard 't Hooft Martinus J. G. Veltman

Peter Englert



Theory: Brout, Englert, Higgs, Guralnik, Hagen, Kibble, 1964



Robert Brout

Electron (1897)



J. J. Thomson

Muon (1936)



S. Neddermeyer

C. D. Anderson

μ -Neutrino (1962)

Theory: 1940



Leon M.
Lederman

Melvin
Schwartz

Jack
Steinberger

Light quarks (up, down, strange) SLAC (1968)



Murray
Gell-Mann

George
Zweig

Theory: 1964

Tau (1975)



Martin
Lewis Perl

τ -Neutrino (2000)

DONUT Coll.

Theory: 1970



The Seekers

Theory: Pauli, 1930

e-Neutrino (1956)

Clyde
Cowan



Frederick
Reines

Carlo Rubbia,



Simon van
der Meer

W^+ , W^- , Z UA1, UA2 (1983) CERN

Theory: Glashow, Weinberg, Salam, 1968



T. Maskawa M. Kobayashi

Bottom quark Top quark FermiLAB CDF & D0 (1977) (1995)



Burton
Richter

Samuel
Ting

Charm quark SLAC, BNL (1974)

Theory: Glashow,
Iliopoulos, Maiani, 1970

Gluons DORIS (1978) PETRA (1979) DESY

Theory: Gell-Mann, 1962



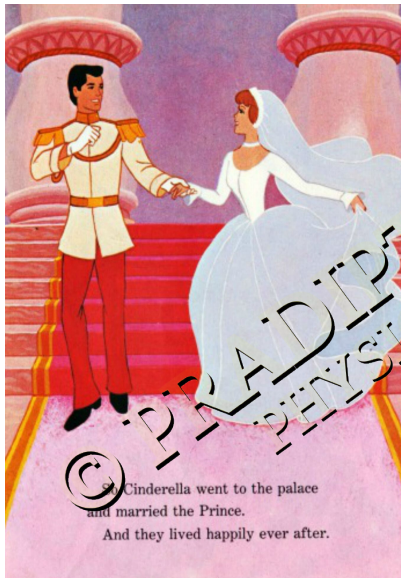
Peter
Higgs

François
Englert

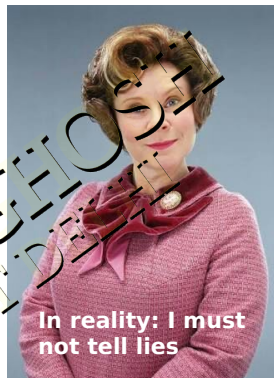
Higgs boson ATLAS, CMS (2012) LHC-CERN

Theory: Brout, Englert, Higgs, Guralnik, Hagen, Kibble, 1964

Life after Higgs discovery



© 2013
So Cinderella went to the palace
and married the Prince.
And they lived happily ever after.



In reality: I must
not tell lies

Unanswered questions:

1. Massive Neutrinos?
2. Why Higgs mass is only 125 GeV?
3. What is dark matter?
4. Why so much matter?
- 5.....
- 6.....

**We NEED to move beyond the
Standard Model**



Massive Neutrinos !!!!!

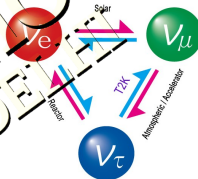
Neutrinos are Massless within the SM

Neutrinos oscillate in nature: Observed

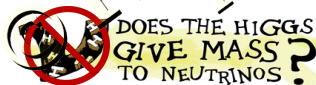
Arthur McDonald Takaaki Kajita



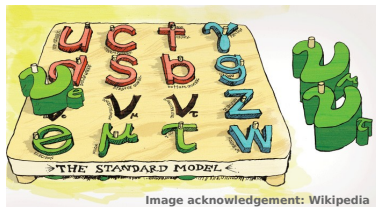
Theory: Pontecorvo, 1957, 1967,
Maki, Nakagawa, Sakata, 1962



Oscillation impossible
WITHOUT Neutrino mass



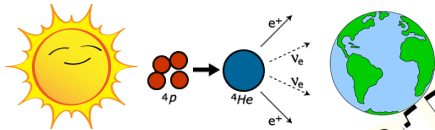
Not within the SM





Neutrinos oscillate in nature: Observed

Neutrinos are Massless within the SM

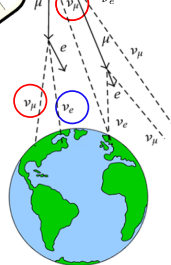


Detection via $\nu_e + X \rightarrow e^- + Y$ process

X, Y are nuclei. **Detected only 1/3 of the expected event:**
Solar neutrino problem



$$\frac{\nu_\mu}{\nu_e} \approx 2 \text{ expected}$$



Not observed:
Atmospheric neutrino problem

Why we are losing certain types?

The “Boggart”: Neutrinos

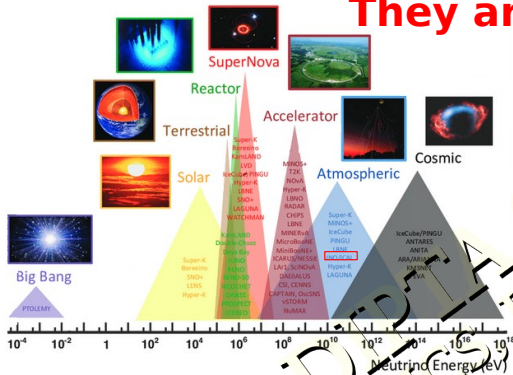
A **Boggart** is a shapeshifter (Harry Potter wiki)



For Particle Physics:

Boggart (shape): *Neutrinos (Flavours)*
Poor Wizards: *The Physicists*

They are everywhere!



Only 1 interacts on average out of 10^{22} !!
It is indeed a



Trillions (10^{12}) of neutrinos pass through Your body / second !





Why we are losing certain types?

Are they changing their types in motion? How?

Basic idea with a silly example: Consider vectors in 2-dimension

$$\vec{r} = x\hat{i} + y\hat{j}$$

Linear Superposition to construct type "a" and "b" vectors→

$$\vec{a} = \cos\theta\hat{i} + \sin\theta\hat{j} \text{ and } \vec{b} = -\sin\theta\hat{i} + \cos\theta\hat{j}$$

At $\theta = 60^\circ$, $\theta \Rightarrow \omega t$

$$\vec{a} = \frac{1}{2}\hat{i} + \frac{\sqrt{3}}{2}\hat{j}, \text{ and } \vec{b} = -\frac{\sqrt{3}}{2}\hat{i} + \frac{1}{2}\hat{j}$$

At $\theta = 150^\circ$,

$$\vec{a} = -\frac{\sqrt{3}}{2}\hat{i} + \frac{1}{2}\hat{j} \equiv \vec{b}, \text{ and } \vec{b} = -\frac{1}{2}\hat{i} - \frac{\sqrt{3}}{2}\hat{j} \equiv -\vec{a}$$



Why we are losing certain types?

Another trivial but rather realistic example:

Consider a two-level quantum mechanical system:

Solutions of Schrödinger equation:

Energy Eigenvalues E_1 and E_2 and Eigen Wave functions ν_1 and ν_2

Time evolutions of Eigen Wave functions $\nu_i(t) = e^{-iE_it}\nu_i$

Natural Unit System $\rightarrow \hbar = 1, c = 1$

Linear Superposition to construct type "a" and "b" wave functions $\rightarrow$

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

$$\nu_b = -\sin \theta \nu_1 + \cos \theta \nu_2$$

After a time span of "t", we can write $\rightarrow$

$$\nu_a(t) = \cos \theta e^{-iE_1t} \nu_1 + \sin \theta e^{-iE_2t} \nu_2$$



If we start with “a”, can we get “b” after some time?

Yes: The corresponding quantity is

$$|\nu_b^* \nu_a(t)|^2 = \frac{\sin^2 2\theta}{2} [1 - \cos(E_2 - E_1)t] \neq 0$$

Vanishes for massless neutrinos

We have used Euler's formula $e^{\pm i\theta} = \cos \theta \pm i \sin \theta$

We have used Orthonormality conditions $\rightarrow \nu_i^* \nu_j = 0$ for $i \neq j$
 $\nu_i^* \nu_j = 1$ for $i = j$

Remember the vector dot products: $\hat{i} \cdot \hat{i} = 1$ but $\hat{i} \cdot \hat{j} = 0$



How non-zero $|\nu_b^* \nu_a(t)|^2$ is connected with neutrino mass?

Neutrinos have tiny masses:

$$\sum m_{\nu_i} \approx 0.1 \text{ eV} - 0.2 \text{ eV} \text{ (Cosmological Probe)}$$

They are “almost” massless and thus, travel with great speed $\sim c$

Neglecting mass contribution to the energy:

Which gives $\rightarrow$

$$E_i = \sqrt{\vec{p} \cdot \vec{p} + m_i^2} \approx E + \frac{m_i^2}{2E}$$

$$|\nu_b^* \nu_a(t)|^2 = \frac{\sin^2 2\theta}{2} \left[1 - \cos \left(\frac{m_2^2 - m_1^2}{2E} t \right) \right] \neq 0$$

Lesson 1: Non-zero masses are needed for neutrino oscillations

Lesson 2: Neutrino oscillations can probe squared mass differences, but not the mass scale !!!!!



The reality: Three flavours oscillations

For three flavours:

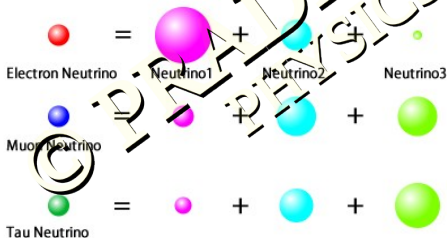
$$\nu_\alpha = \sum_{j=1,2,3} U_{\alpha j}^* \nu_j$$

e, μ, τ

$$|\nu_\beta^* \nu_\alpha(t)|^2 = \sum_j \sum_k U_{\alpha j}^* U_{\alpha k} U_{\beta j} U_{\beta k} \exp\left[\frac{i(m_j^2 - m_k^2)t}{2E}\right]$$

squared mass differences

The "real" picture



Entries of the "U" matrix varies a lot !!!!!

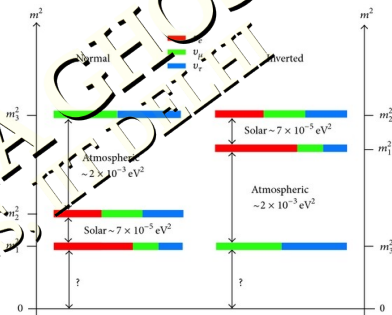
Flavour states

Massive states



The “U” matrix: in-homogeneous mixing

We can probe squared mass differences
What about orderings?



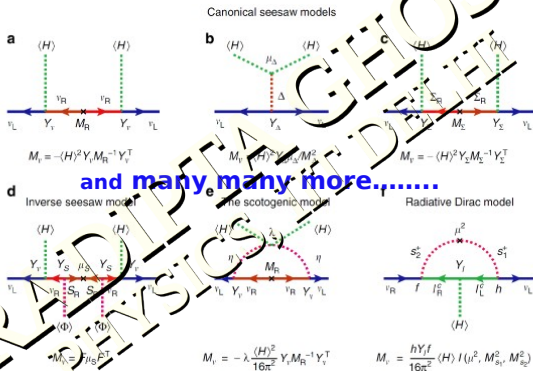
Questions to answer: (food for thought)

1. Why the mixings are so in-homogeneous?
2. How to extend the Standard Model to generate neutrino masses?
3. How to assure tiny neutrino masses?
4. Can we treat neutrinos as dark matter?
5. Can a neutrino act as its anti-particle?

•
•
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Models for neutrino masses and mixings



and many many more.....

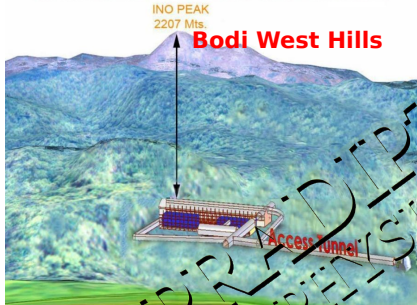
Which one is the “chosen one”?
Time will answer



What we Indians are doing....

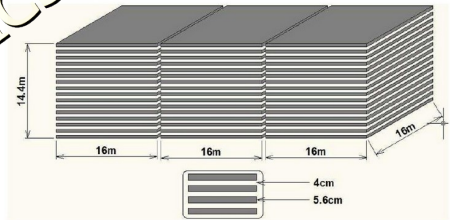


INDIA BASED NEUTRINO OBSERVATORY



INO site is located 115 km west of the temple city Madurai in the Theni district of Tamil Nadu close to the border the between Tamil Nadu & Kerala.

INO-ICAL Detector



Today is gone,
what's done is done.
Embrace your
dreams
through
the night,
Tomorrow comes with
a whole new light!



Thanks!