Neutrino physics (theory & phenomenology)

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Niels Bohr Institute, July 2023

ν_I

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Universitat de València · Generalitat Valenciana · IFIC · CSIC

Why ν's ?

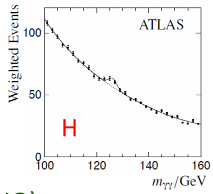
Neutrinos are so far the ONLY evidence beyond the SM

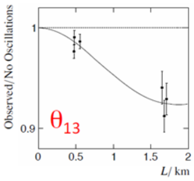
Neutrinos are rewarding

- Fermi: formulation of β decay theory
- Reines: detection electron antineutrinos
- Lederman, Schwartz and Steinberger: ν_μ
- Davis and Koshiba: solar ν interactions
- Kajita and McDonald: ν oscillations

2012 ~~One~~ two major discovery ~~in~~ ies particle physics

- A SM-like Higgs boson (ATLAS, CMS)
  The key to EWSB and a possible window to





- θ_{13} ~ 10^o (T2K, MINOS, Daya Bay, RENO)
  about as large as it could have been !
  The door to CP Violation in the leptonic sector

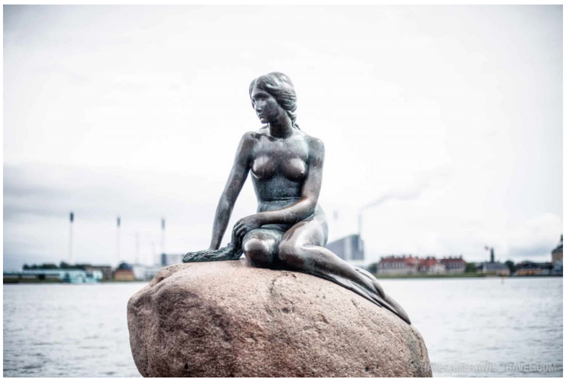
Is The Whole Universe made of—
Electrons Protons Neutrons ?

NO!

Electrons Protons Neutrons
are rareties!

For every one of them, the universe contains a billion neutrinos ν!

Within each cubic centimeter of space
~ 360 neutrinos from the Big Bang



8 million
neutrinos !!!!

Passing through each person on earth every second:
One hundred trillion neutrinos from the sun.

The sun shines because of nuclear fusion in its core.

This fusion produces—

- Energy, including visible light
- Neutrinos
- The atoms more complicated than hydrogen

Our view

ν View

Almost all neutrinos zipping through us do nothing at all.

Typically, a solar neutrino would have to zip through 10,000,000,000,000,000,000 people before doing anything.

The probability that a particular solar neutrino will interact as it zips through one of us is 1 / 10,000,000,000,000,000,000 .

Are Neutrinos Important to Our Lives?

If there were no νs, the sun and stars would not shine.

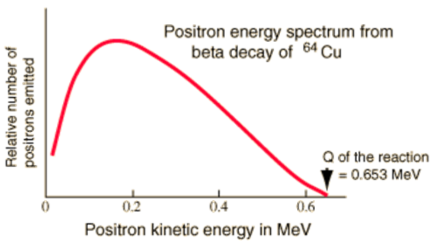
- No energy from the sun to keep us warm.
- No atoms more complicated than hydrogen. No carbon. No oxygen. No water. No earth. No moon. No us.

No νs is very BAD news.

Summer Schools (if existed) were VERY short …..

$$E_e = \frac{m_n^2 + m_e^2 - m_p^2}{2\, m_n}$$

Studies of β decay revealed a continuous energy spectrum.



Another anomaly was the fact that the nuclear recoil was not in the direction opposite to the momentum of the electron.

The emission of another particle was a probable explanation of this behaviour, but searches found no evidence of either mass or charge.

...desperate remedy to save the law of conservation of energy...

Neutron Decay:

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

Fermi postulated a theory for β decay in terms of spinors

$$H_{ew} = \frac{G_F}{\sqrt{2}} \overline{\Psi}_p \; \gamma_\mu \, \Psi_n \quad \overline{\Psi}_e \gamma^\mu \; \psi_\nu$$

A Dirac field is described by a four component spinor

$$\begin{pmatrix} e_L \\ e_R \\ \widehat{e_L} \\ \widehat{e_R} \end{pmatrix}$$

Standard Model of Particle Physics

Gauge Theory based on the group:

$$SU(3) \times SU(2) \times U(1)$$

$SU(3) \Rightarrow$ Quantum Chromodynamics

Strong Force (Quarks and Gluons)

$SU_L(2) \times U(1) \Rightarrow$ ElectroWeak Interactions broken to $U_{EM}(1)$

by HIGGS

$SU_L(2) \times U_Y(1) \Rightarrow U_{EM}(1)$

Force Carriers: $W^{\pm}$, Z^0 and γ masses: 80, 91 and 0 GeV

quark, SU(2) doublets: $\begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} c \\ s \end{pmatrix}_L, \begin{pmatrix} t \\ b \end{pmatrix}_L$

up-quark, SU(2) singlets: u_R, c_R, t_R

down-quark, SU(2) singlets: d_R, s_R, b_R

lepton, SU(2) doublets: $\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$

neutrino, SU(2) singlets: $- - -$

charge lepton, SU(2) singlets: e_R, μ_R, τ_R

Electron mass

comes from a term of the form

$\bar{L}\phi e_R$

Absence of ν_R

forbids such a mass term (dim 4)

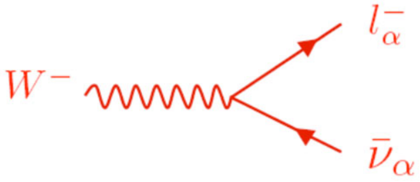
for the Neutrino

Therefore in the SM neutrinos are massless

and hence travel at speed of light.

Interactions:

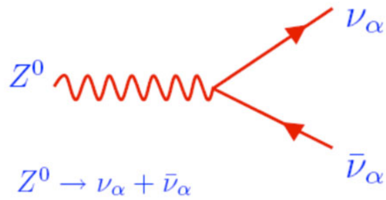
Charge Current (CC)



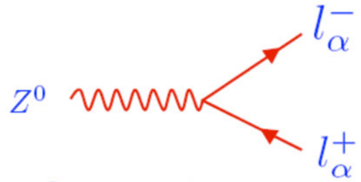
$W^- \to l_\alpha^- + \bar{\nu}_\alpha$

$$\Gamma(Z^0 \to f + \bar{f}) = K \frac{g_Z^2 M_Z}{48\pi}[|c_V^f|^2 + |c_A^f|^2]$$

Neutral Current (NC)



$Z^0 \to \nu_\alpha + \bar{\nu}_\alpha$



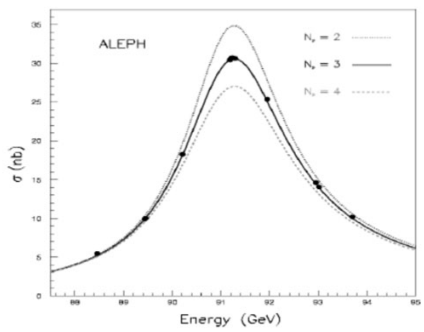
$Z^0 \to l_\alpha^- + l_\alpha^+$

$\alpha = e, \mu,\ or\ \tau$

Invisible width of Z plus other data from LEP:

$Z^0 \to \nu\bar{\nu}$

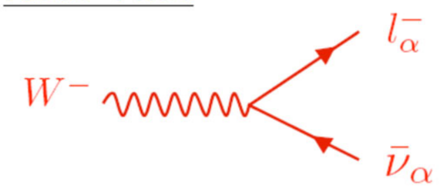
Implies $N_\nu = 2.99 \pm 0.01$



Three Active Neutrinos!!!

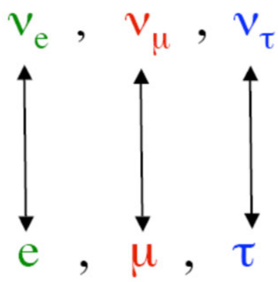
Sterile Neutrinos don't couple to Z^0

Note That

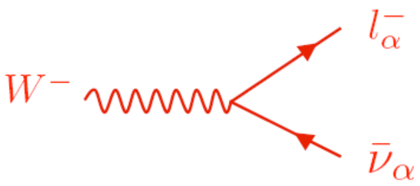


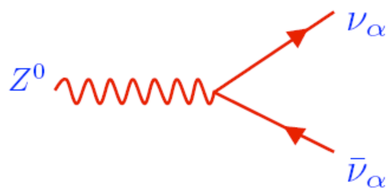
$W^- \to l_\alpha^- + \bar{\nu}_\alpha$

Implies



Standard Model



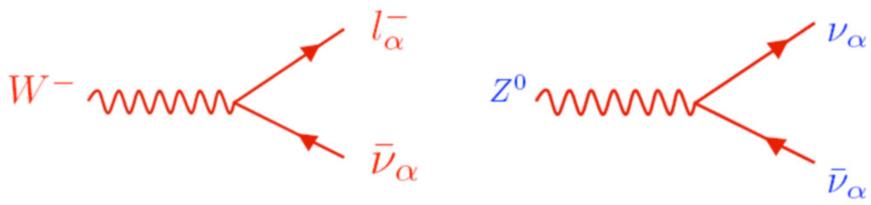


couplings conserve the Lepton Number L
defined by—

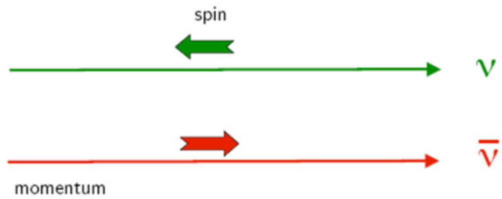
$L(\nu) = L(\ell^-) = -L(\bar{\nu}) = -L(\ell^+) = 1.$

Actually L_e, L_μ, and L_τ
separately

Left Handed Nature of The Neutrino



Produce Left-Handed Neutrinos
and Right-Handed Anti-Neutrinos



What about the RH neutrinos and LH anti-neutrino ????

There exist three fundamental and discrete transformations in nature:

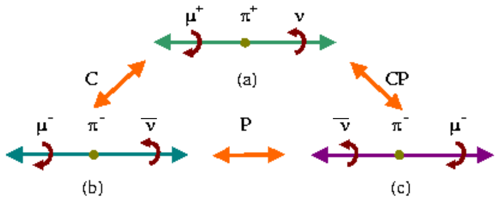
- **Parity** $\mathcal{P}$ $\vec{x} \to -\vec{x}$
- **Time reversal** $\mathcal{T}$ $t \to -t$
- **Charge conjugation** $\mathcal{C}$ $q \to -q$

$\mathcal{P}$, $\mathcal{T}$ and $\mathcal{C}$ are conserved in the classical theories of mechanics and electrodynamics!

$\mathcal{CPT} \leftrightarrow$ Lorentz invariance $\oplus$ unitarity: is an essential building block of field theory

$\mathcal{CPT}$: L particle $\leftrightarrow$ R antiparticle

Neutrinos in the MSM are massless and exist only in two states: particle with negative helicity and antiparticle with positive one: Weyl fermion



$\mathcal{P}$: L particle ↔ R particle

Parity violation is nowhere more obvious than in the neutrino sector: the reflection of a left-handed neutrino in a mirror is nothing !

Summary of ν's in SM:

Three flavors of massless neutrinos

$$W^- \rightarrow l_\alpha^- + \bar{\nu}_\alpha$$

$$W^+ \rightarrow l_\alpha^+ + \nu_\alpha$$

$$\alpha = e, \mu, \ or \ \tau$$

Anti-neutrino, $\bar{\nu}_\alpha$, has +ve helicity, Right Handed

Neutrino, ν_α, has -ve helicity, Left Handed

ν_L and $\bar{\nu}_R$ are CPT conjugates

massless implies helicity = chirality

Beyond the SM

What if Neutrino have a MASS?

speed is less than c therefore time can pass

and

Neutrinos can change character!!!

What are the stationary states?

How are they related to the interaction states?

NEUTRINO OSCILLATIONS:

Two Flavors

flavor eigenstates $\neq$ mass eigenestates

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

W's produce ν_μ and/or ν_τ's

but ν_1 and ν_2 are the states that change by a phase over time, mass eigenstates.

$$|\nu_j\rangle \rightarrow e^{-ip_j \cdot x}|\nu_j\rangle \qquad p_j^2 = m_j^2$$

$\alpha, \beta \ldots$ flavor index $\qquad i, j \ldots$ mass index

Production:

$$|\nu_\mu\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

Propogation:

$$\cos\theta e^{-ip_1\cdot x}|\nu_1\rangle + \sin\theta e^{-ip_2\cdot x}|\nu_2\rangle$$

Detection:

$$|\nu_1\rangle = \cos\theta|\nu_\mu\rangle - \sin\theta|\nu_\tau\rangle$$

$$|\nu_2\rangle = \sin\theta|\nu_\mu\rangle + \cos\theta|\nu_\tau\rangle$$

$$\begin{pmatrix}\nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

$$P(\nu_\mu \to \nu_\tau) = |\cos\theta(e^{-ip_1\cdot x})(-\sin\theta) + \sin\theta(e^{-ip_2\cdot x})\cos\theta|^2$$

$$P(\nu_\mu \to \nu_\tau) = |\cos\theta(e^{-ip_1\cdot x})(-\sin\theta) + \sin\theta(e^{-ip_2\cdot x})\cos\theta|^2$$

Same E, therefore $p_j = \sqrt{E^2 - m_j^2} \approx E - \frac{m_j^2}{2E}$

$$e^{-ip_j\cdot x} = e^{-iEt}e^{-ip_jL} \approx e^{-i(Et-EL)} \quad e^{-im_j^2L/2E}$$

$$P(\nu_\mu \to \nu_\tau) = \sin^2\theta\cos^2\theta|e^{-im_2^2L/2E} - e^{-im_1^2L/2E}|^2$$

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\frac{\delta m^2 L}{4E}$$

$\delta m^2 = m_2^2 - m_1^2$ and $\frac{\delta m^2 L}{4E} \equiv \Delta$ kinematic phase:

$$P(\nu_\mu \to \nu_\tau) = |\cos\theta(e^{-ip_1\cdot x})(-\sin\theta) + \sin\theta(e^{-ip_2\cdot x})\cos\theta|^2$$

Same E, therefore $p_j = \sqrt{E^2 - m_j^2} \approx E - \frac{m_j^2}{2E}$

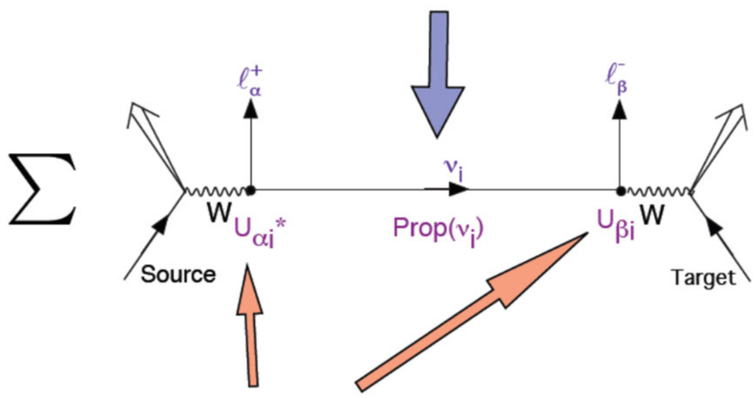
$$e^{-ip_j\cdot x} = e^{-iEt}e^{-ip_jL} \approx e^{-i(Et-EL)} \quad e^{-im_j^2 L/2E}$$

$$P(\nu_\mu \to \nu_\tau) = \sin^2\theta\cos^2\theta|e^{-im_2^2 L/2E} - e^{-im_1^2 L/2E}|^2$$

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{\delta m^2 L}{4E}\frac{c^4}{hc}\right)$$

Amplitude

$$e^{-im_j^2 L/2E}$$



$$U_{\alpha j} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Appearance:

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2 \frac{\delta m^2 L}{4E}$$

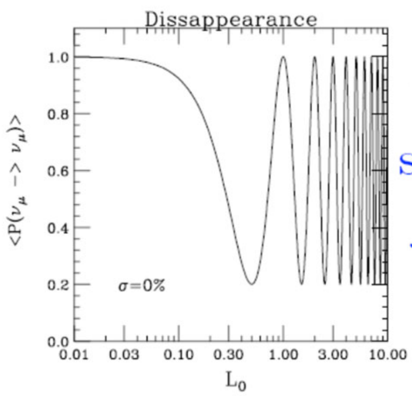
Disappearance:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \frac{\delta m^2 L}{4E}$$

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \frac{\delta m^2 L}{4E}$$

Oscillation Length $L_0 = 4\pi E/\delta m^2$

Fixed E_ν

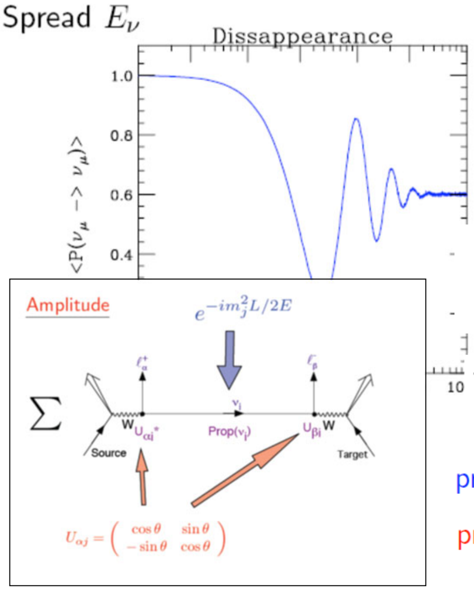


Amplitude of Oscillation

$\Uparrow$ $\sin^2 2\theta$ $\Downarrow$

$$\langle P(\nu_\mu \to \nu_\mu)\rangle = 1 - \sin^2 2\theta \left\langle \sin^2 \frac{\delta m^2 L}{4E} \right\rangle$$

Spread E_ν



effectively incoherent mass eigenstates

$$1 - \sin^2 2\theta(\tfrac{1}{2}) = \cos^4\theta + \sin^4\theta$$

- $W^+ \to \mu^+ + \nu_1$ probability $\cos^2\theta$
- $W^+ \to \mu^+ + \nu_2$ probability $\sin^2\theta$

flavour fractions $|\nu_1\rangle$ and $|\nu_2\rangle$ during propagation remain unchanged

probability ν_1 contains ν_μ is $\cos^2\theta$

probability ν_2 contains ν_μ is $\sin^2\theta$

$$x = 0 \quad |\nu_\alpha\rangle = \sum_j V_{\alpha j}|\nu_j\rangle = \sum_j V_{\alpha j} \int \frac{d^3k}{(2\pi)^3} f_j(k)|\nu_j(k)\rangle$$

where $k_0^{j\,2} = \vec{k}^2 + m_j^2$ and $|\nu_j(k)\rangle = e^{-ik_0^j}|\nu_j\rangle$

The wave packets $f_j(k)$ depend on the production process (uncertainty in momentum of the inicial states, kinematics), but we do not need to know the specific form:

$$f_i(k) \sim e^{-(\vec{k}-\vec{k}^i)^2/(2\sigma_i^2)}$$

We expect that

$$f_i(k) \sim f(k) + O\left(m_i/|\bar{k}|\right) \sim e^{-(\vec{k}-\vec{\bar{k}})^2/(2\sigma^2)}$$

$$\int d^3k |f(k)|^2 = 1$$

We have a dectector located at some distance down the beam line $x = L$:

$$x = L \quad |\nu_\alpha(x)\rangle = \sum_j \int \frac{d^3k}{(2\pi)^2}\, e^{-i\sqrt{m_j^2+\vec{k}^2}t} e^{i\vec{x}\vec{k}} f_j(k)\; V_{\alpha j}|\nu_j\rangle$$

where neutrino can interact producing a given flavour. The probability that the flavour we measured is β is: $|\langle\nu_\beta|\nu_\alpha(x)\rangle|^2$:

We can safely neglect terms of $O(m_i/|\bar{k}|)$ except in the phase factor because they are enhanced by L:

$$P(\nu_\alpha \to \nu_\beta) = \sum_{i,j} V_{\beta j}^* V_{\alpha j} V_{\beta i} V_{\alpha i}^* \int d^3k\; e^{-i\frac{\Delta_{ij}L}{2|k_x|}} |f(\vec{k})|^2$$

$$\simeq \sum_{i,j} V_{\beta j}^* V_{\alpha j} V_{\beta i} V_{\alpha i}^* e^{-i\frac{\Delta_{ij}L}{2|k_x|}}$$

with $\Delta_{ij} = m_j^2 - m_i^2$.

There is an intrinsic limit to coherence, because $\sigma \neq 0$!

$$\left|\frac{\Delta_{ij}L_D}{2}\left(\frac{1}{|\bar{k}|} - \frac{1}{|\bar{k}|+\sigma}\right)\right| \sim 2\pi \Rightarrow L_D \sim L_{osc}\frac{|\bar{k}|}{\sigma}$$

If $L \gg L_D$:

$$P\left(\nu_\alpha \to \nu_\beta\right) = \sum_i |V_{\alpha i} V_{\beta i}|^2 = 2\cos^2\theta \sin^2\theta = \frac{1}{2}\sin^2 2\theta$$

In practice, the smearing in L and E_ν produces the same effect when $L \gg L_{osc}$: averaged oscillations

$$\langle P\left(\nu_\alpha \to \nu_\beta\right)\rangle = \frac{1}{2}\sin^2 2\theta$$

Using the unitarity of the mixing matrix: ($W^{jk}_{\alpha\beta} \equiv [V_{\alpha j} V^*_{\beta j} V^*_{\alpha k} V_{\beta k}]$)

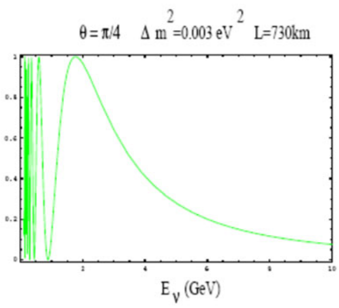
$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{k>j} \mathrm{Re}[\mathrm{W}^{\mathrm{jk}}_{\alpha\beta}] \sin^2\left(\frac{\Delta \mathrm{m}^2_{\mathrm{jk}} \mathrm{L}}{4\mathrm{E}_\nu}\right)$$

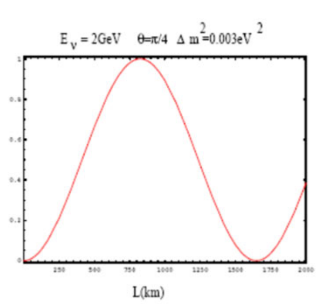
$$\pm \quad 2 \sum_{k>j} \mathrm{Im}[\mathrm{W}^{\mathrm{jk}}_{\alpha\beta}] \sin\left(\frac{\Delta \mathrm{m}^2_{\mathrm{jk}} \mathrm{L}}{2\mathrm{E}_\nu}\right)$$

For 2 families: $V_{MNS} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$

$P_{\alpha\beta} = \sin^2 2\theta \ \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right) \to$ appearance

$P_{\alpha\alpha} = 1 - P_{\alpha\beta} < 1 \to$ disappearance





Oscillation probabilities show the expected GIM suppression of any flavour changing process: they vanish if the neutrinos are degenerate

Probability for Neutrino Oscillation in Vacuum

$$P(\nu_\alpha \to \nu_\beta) = |\mathrm{Amp}(\nu_\alpha \to \nu_\beta)|^2 =$$

$$P_{\alpha\beta} = \sin^2 2\theta \ \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right) \to \text{appearance}$$

$$P_{\alpha\alpha} = 1 - P_{\alpha\beta} < 1 \to \text{disappearance}$$

Probability for Neutrino Oscillation in Vacuum

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$$P_{\alpha\alpha} = 1 - P_{\alpha\beta} < 1 \to \text{disappearance}$$

$$\left(\frac{\Delta m^2\, L}{4\, E}\right)$$

$$\left(1.27\ \frac{\Delta m^2\,(eV^2)\ L(km)}{E(GeV)}\right)$$

L/E becomes crucial !!!

Evidence for Flavor Change:

⋆⋆⋆ Atmospheric and Accelerator Neutrinos with L/E = 500 km/GeV

⋆⋆⋆ Solar and Reactor Neutrinos with L/E = 15 km/MeV

Neutrinos from Stopped muons L/E= 2m/MeV (Unconfirmed)

Atmospheric neutrinos

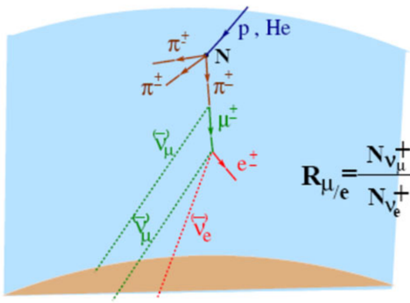
- Atmospheric neutrinos are produced by the interaction of *cosmic rays* (p, He, ...) with the Earth's atmosphere:

[1] $A_{cr} + A_{air} \rightarrow \pi^{\pm}, K^{\pm}, K^0, \ldots$

[2] $\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$,

[3] $\mu^{\pm} \rightarrow e^{\pm} + \nu_e + \nu_{\mu}$;

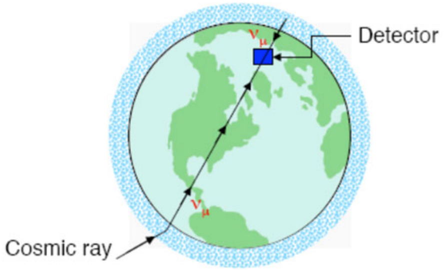
- at the detector, some ν interacts and produces a **charged lepton**, which is observed.



$$R_{\mu/e} = \frac{N_{\nu_\mu} + N_{\bar{\nu}_\mu}}{N_{\nu_e} + N_{\bar{\nu}_e}} \sim 2$$

A deficit was observed in the ratio μ/e events: Soudan2, IMB, Kamiokande

Atmospheric Neutrinos

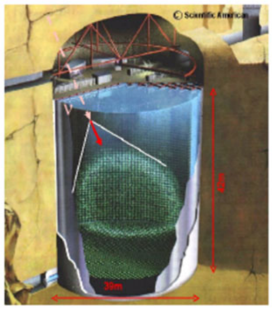


Isotropy of the $\gtrsim 2$ GeV cosmic rays + Gauss' Law + No ν_μ disappearance

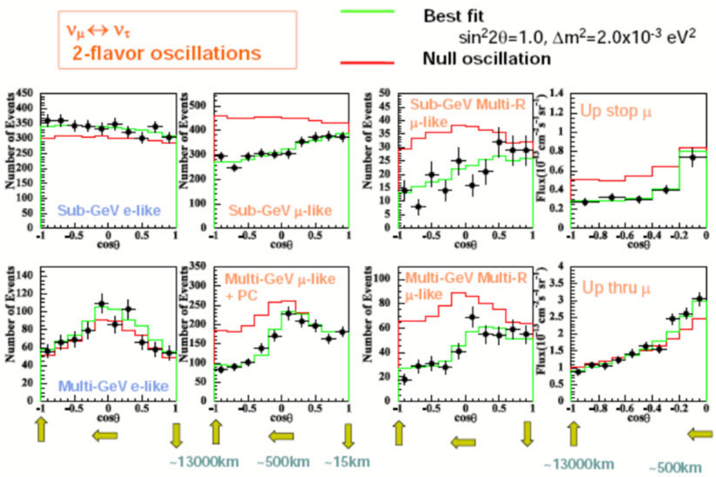
$$\Rightarrow \quad \frac{\phi_{\nu_\mu}(\text{Up})}{\phi_{\nu_\mu}(\text{Down})} = 1 \ .$$

But Super-Kamiokande finds for $E_\nu > 1.3$ GeV

$$\frac{\phi_{\nu_\mu}(\text{Up})}{\phi_{\nu_\mu}(\text{Down})} = 0.54 \pm 0.04 \ .$$



Zenith angle distributions



Half of the upward-going, long-distance-traveling ν_μ are disappearing.

Voluminous atmospheric neutrino data are well described by —

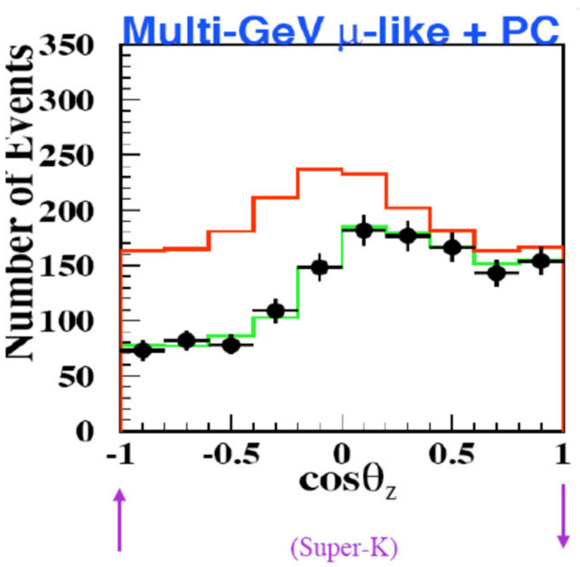
$$\nu_\mu \longrightarrow \nu_\tau$$

with —

$$\Delta m_{atm}^2 \cong 2.4\ 10^{-3}\ eV^2$$

and —

$$\sin^2 2\theta_{atm} \cong 1$$

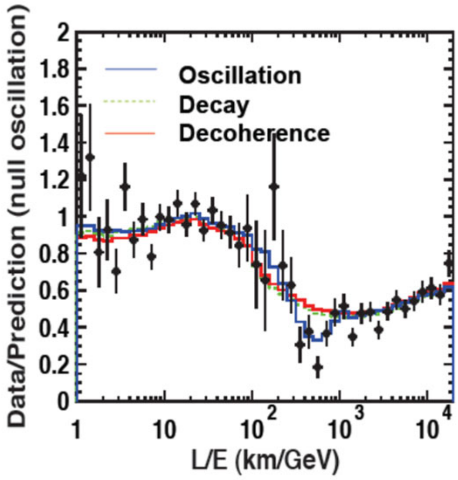


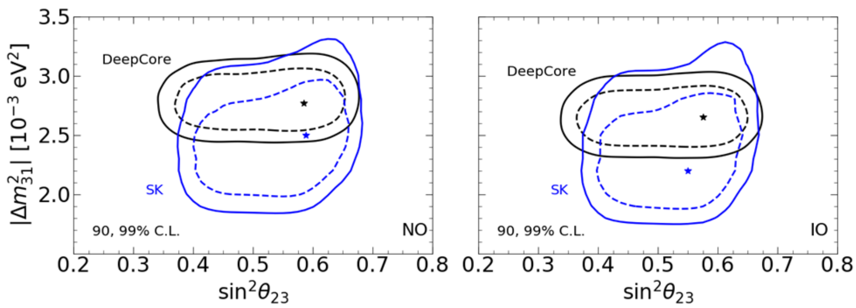
(Super-K)

L/E Analysis

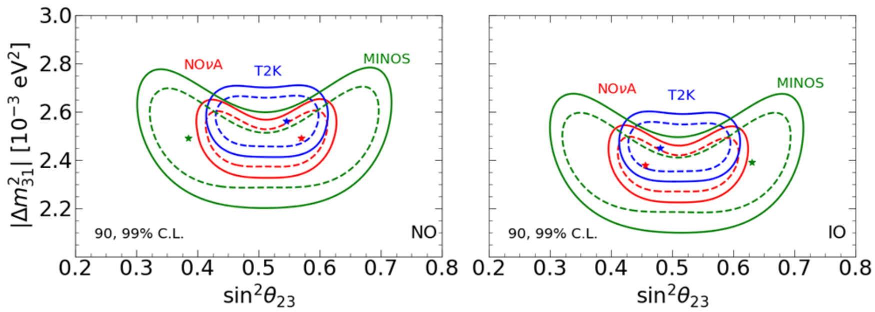
- Oscillation, decay and decoherence models tested

χ^2_{osc} = 83.9/83
χ^2_{dcy} = 107.1/83, $\Delta\chi^2$ = 23.2(**4.8σ**)
χ^2_{dec} = 112.5/83, $\Delta\chi^2$ = 27.6(**5.3σ**)

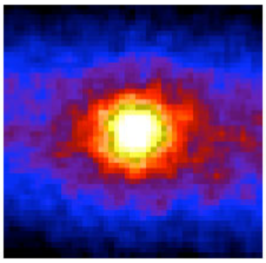




https://globalfit.astroparticles.es/



Solar δm^2



Solar Engine:

$$4p + 2e^- \rightarrow ^4He + 2\nu_e + 26.7MeV$$

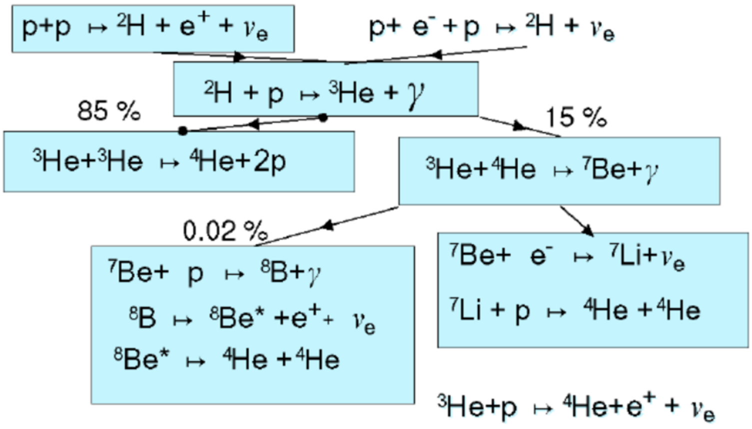
$E = mc^2$

1 ν_e for every 13.4 MeV (=2.1 $\times 10^{-12}$ J)

$\mathcal{L}_\odot$ at earth's surface 0.13 watts/cm^2

$$\phi_\nu = \frac{0.13}{2.1\times10^{-12}} = 6 \times 10^{10}/cm^2/sec$$

This corresponds to an average of 2 ν's per cm^3
since they are going at speed c.



Solar Spectrum:

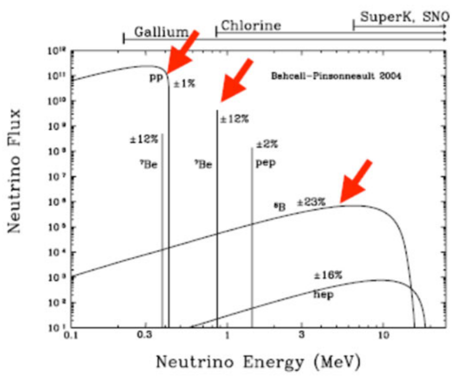


Figure 1. The predicted solar neutrino energy spectrum. The figure shows the energy spectrum of solar neutrinos predicted by the BP04 solar model [22]. For continuum sources, the neutrino fluxes are given in number of neutrinos $cm^{-2} s^{-1} MeV^{-1}$ at the Earth's surface. For line sources, the units are number of neutrinos $cm^{-2} s^{-1}$. Total theoretical uncertainties taken from column 2 of table 1 are shown for each source. To avoid complication in the figure, we have omitted the difficult-to-detect CNO neutrino fluxes (see table 1).

$$p + p \rightarrow {}^2H + e^+ + \nu_e$$

$$\phi_{pp} = 5.94(1 \pm 0.01) \times 10^{10} cm^{-2} sec^{-1}$$

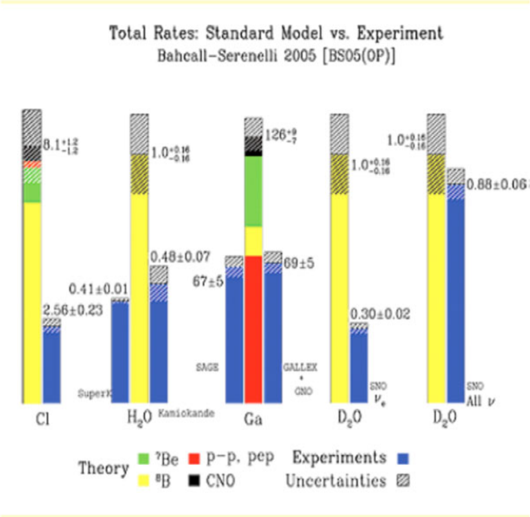
$$^7Be + e^- \rightarrow {}^7Li + \nu_e$$

$$\phi_{^7Be} = 4.86(1 \pm 0.12) \times 10^{9} cm^{-2} sec^{-1}$$

$$^7Be + p \rightarrow {}^8B \rightarrow {}^8Be^* + e^- + \nu_e$$

$$\phi_{^8B} = 5.82(1 \pm 0.23) \times 10^{6} cm^{-2} sec^{-1}$$

Ray Davis & John Bahcall



Theory v Exp.

Neutrino Flavor Transistions!!!

Kinematical Phase:

$$\delta m^2_{\odot} = 8.0 \times 10^{-5} eV^2$$

$$\sin^2\theta_{\odot} = 0.31$$

$$\Delta_{\odot} = \frac{\delta m^2_{\odot} L}{4E} = 1.27 \; \frac{8\times10^{-5}\; eV^2 \;\cdot\; 1.5\times10^{11}\; m}{0.1-10\; MeV}$$

$$\Delta_{\odot} \approx 10^{7\pm1}$$

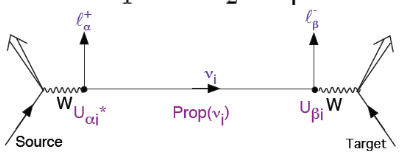
Effectively Incoherent !!!

Vacuum ν_e Survival Probability:

$$\langle P_{ee}\rangle = f_1 \cos^2\theta_\odot + f_2 \sin^2\theta_\odot$$

where f_1 and f_2 are the fraction of ν_1 and ν_2 at production.

In vacuum $f_1 = $ co $\sum$

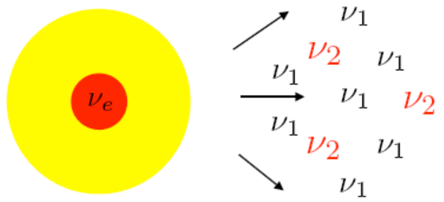


$$\langle P_{ee}\rangle = \cos^4\theta_\odot + \sin^4\theta_\odot = 1 - \tfrac{1}{2}\sin^2 2\theta_\odot$$

for pp and ^{7}Be this is approximately THE ANSWER.

$f_1 \sim 69\%$ and $f_2 \sim 31\%$ and $\langle P_{ee}\rangle \approx 0.6$

pp and ^{7}Be



$f_1 \sim 69\%$

$f_2 \sim 31\%$

$$\langle P_{ee}\rangle \approx 0.6$$

$f_3 = \sin^2\theta_{13} < 4\%$

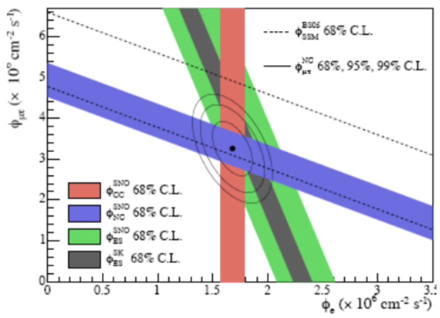
What about ^8B ?

SNO's CC/NC

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

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

ES: $\nu_\alpha + e^- \rightarrow \nu_\alpha + e^-$

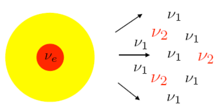


$$\frac{CC}{NC} = \langle P_{ee} \rangle = f_1 \cos^2\theta_\odot + f_2 \sin^2\theta_\odot$$

$$f_1 = \left(\frac{CC}{NC} - \sin^2\theta_\odot\right) / \cos 2\theta_\odot$$

$$= (0.35 - 0.31)/0.4 \approx 10$$

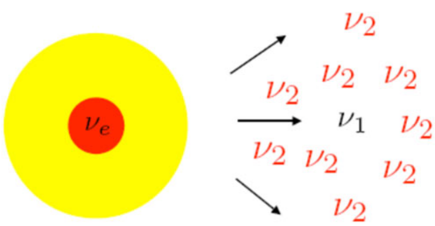
pp and ^{7}Be



$f_1 \sim 69\%$

$f_2 \sim 31\%$

^8B



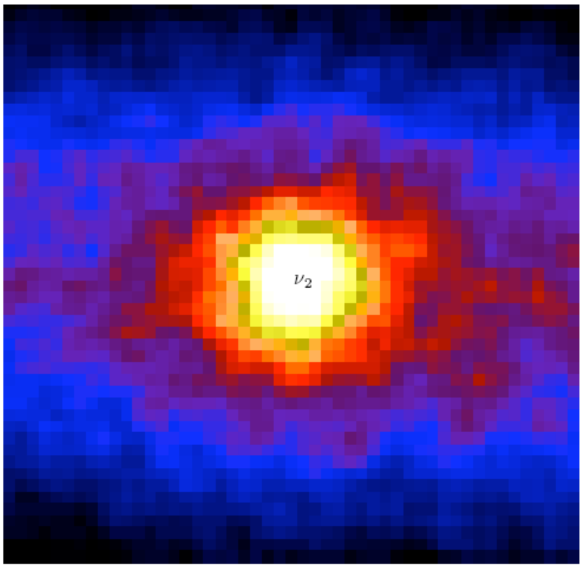
$f_2 \sim 90\%$

$f_1 \sim 10\%$

$$\langle P_{ee} \rangle = \sin^2\theta + f_1 \cos 2\theta_\odot \approx \sin^2\theta_\odot = 0.31$$

Wow!!! How did that happen???

energy dependence!!!



These are ν_2 Neutrinos !!!