Neutrino physics (phenomenology)

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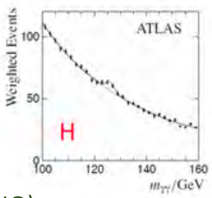
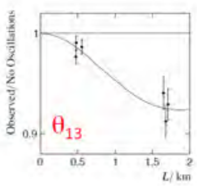
TAE 2022
Benasque - September 12, 2022

2012 ~~One~~ *two* major discover~~y in~~ *ies* particle physics

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





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

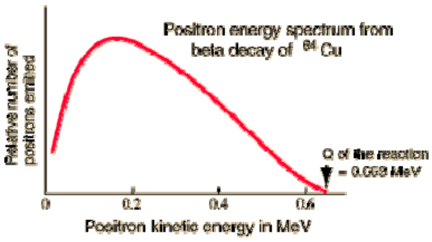
Summer Schools (if existed) were VERY short …..

β decay was supposed to be a two body decay

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

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

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

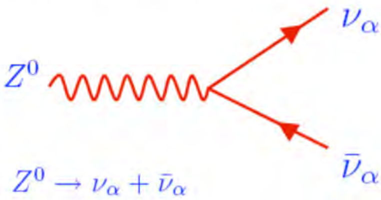
Therefore in the SM neutrinos are massless

and hence travel at speed of light.

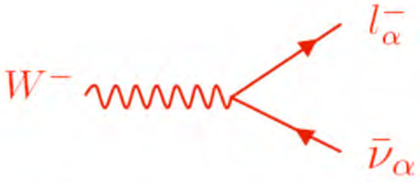
Interactions:

Charge Current (CC)

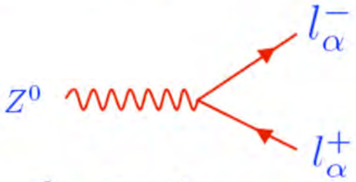
Neutral Current (NC)



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



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



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

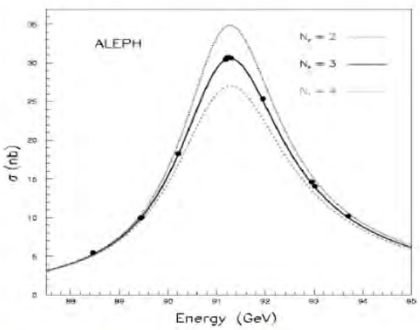
$$\Gamma(Z^0 \rightarrow f + \bar{f}) = K \frac{g_Z^2 M_Z}{48\pi}[|c_V^f|^2 + |c_A^f|^2]$$

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

Invisible width of Z plus other data from LEP:

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

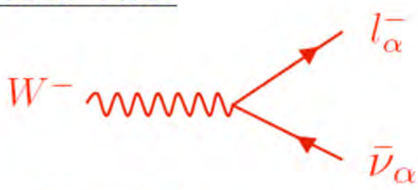
Implies $N_\nu = 2.99 \pm 0.01$



Three Active Neutrinos!!!

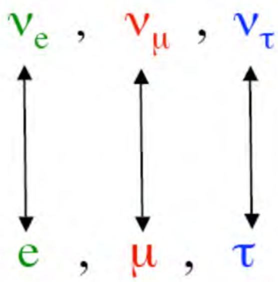
Sterile Neutrinos don't couple to Z^0

Note That

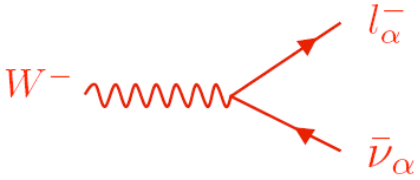


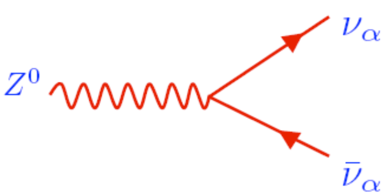
$W^- \rightarrow l_\alpha^- + \bar{\nu}_\alpha$

Implies



Standard Model



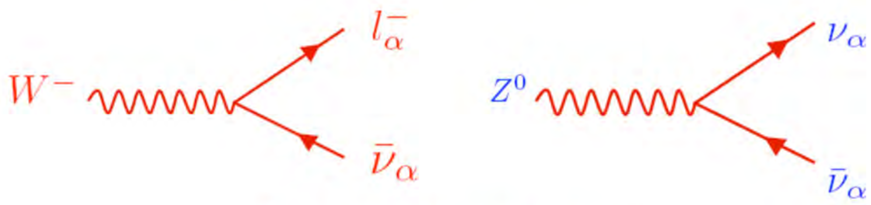


couplings conserve the Lepton Number L
defined by—

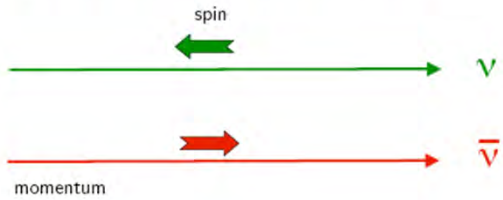
$L(\nu) = L(\ell^-) = -L(\bar{\nu}) = -L(\ell^+) = 1.$

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

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.

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

$\alpha, \beta \dots$ flavor index $\qquad$ $i, j \dots$ 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:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Appearance:

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

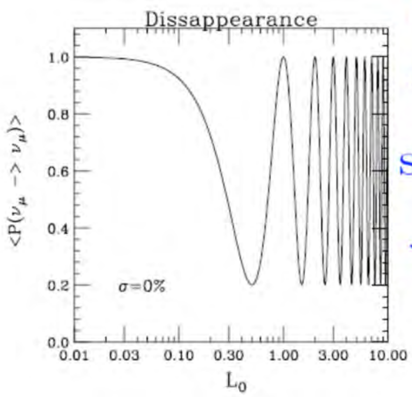
Disappearance:

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

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

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

Fixed E_ν

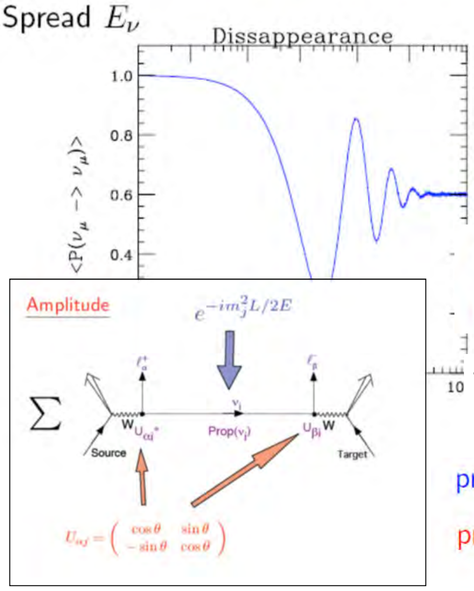


Amplitude of Oscillation

$\sin^2 2\theta$

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

Spread E_ν



effectively incoherent mass eigenstates

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

$W^+ \to \mu^+ + \nu_1$ 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 $\sin^2\theta$

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

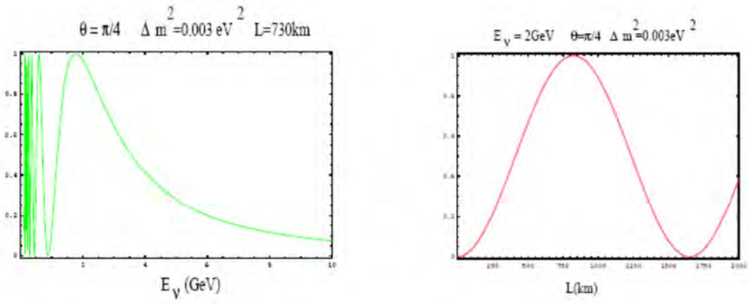
$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{k>j} \mathrm{Re}[W_{\alpha\beta}^{jk}] \sin^2\left(\frac{\Delta m_{jk}^2 L}{4E_\nu}\right)$$

$$\pm \; 2 \sum_{k>j} \mathrm{Im}[W_{\alpha\beta}^{jk}] \sin\left(\frac{\Delta m_{jk}^2 L}{2E_\nu}\right)$$

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

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

$P_{\alpha\beta} = \sin^2 2\theta$ ... pearance

$P_{\alpha\alpha} = 1 - P_{\alpha\beta}$ ... nce

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

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

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

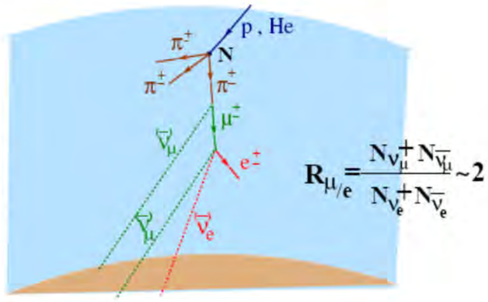
Neutrinos from Stopped muons L/E= 2m/MeV (Unconfirmed)

Atmospheric neutrinos

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

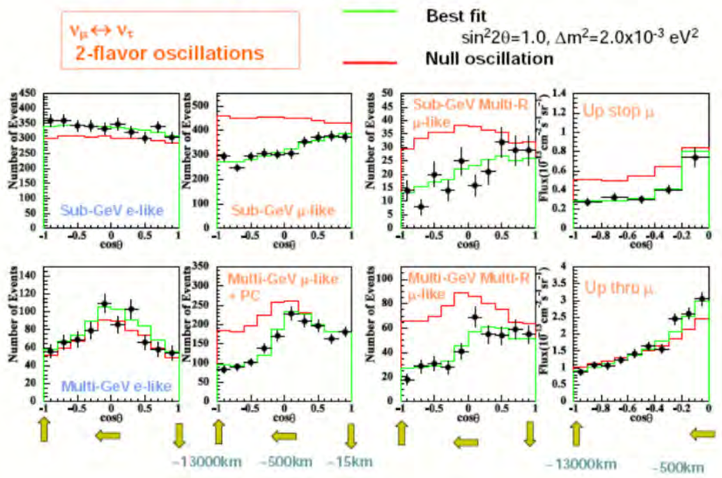
1. $A_{cr} + A_{air} \to \pi^{\pm}, K^{\pm}, K^0, \ldots$
2. $\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}$,
3. $\mu^{\pm} \to e^{\pm} + \nu_e + \nu_{\mu}$;

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



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

Zenith angle distributions



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

Voluminous atmospheric neutrino data are well described by —

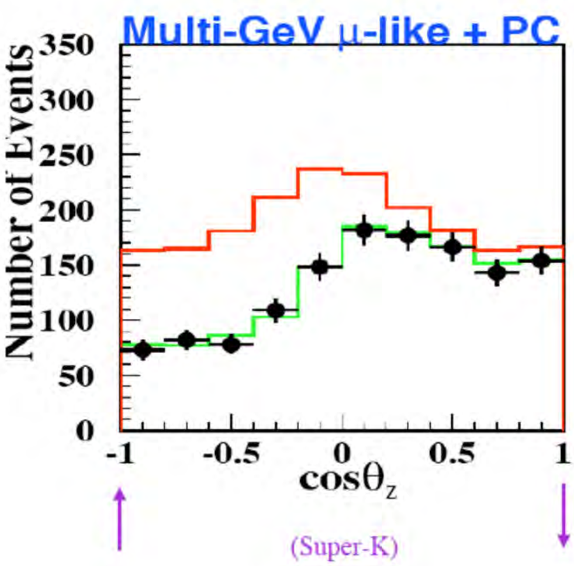
$$\nu_\mu \longrightarrow \nu_\tau$$

with —

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

and —

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

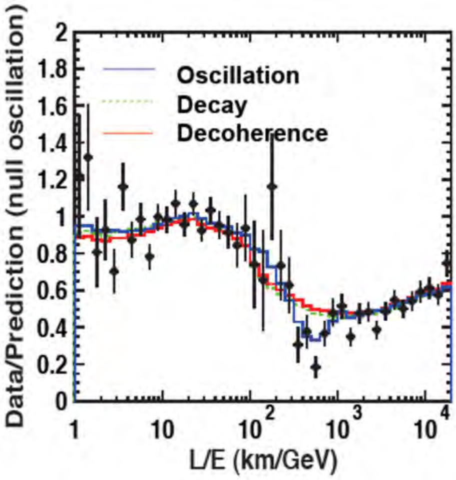


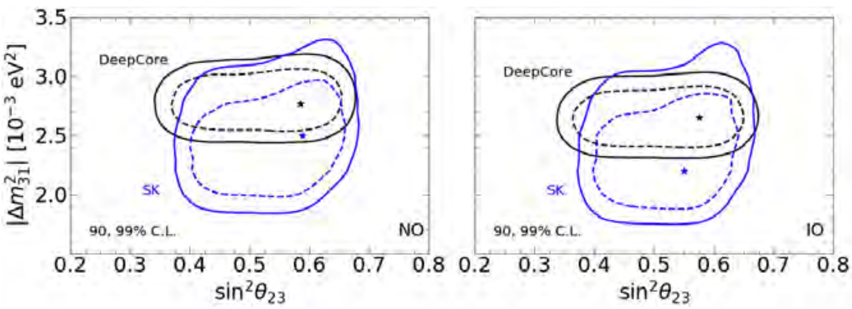
(Super-K)

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**)





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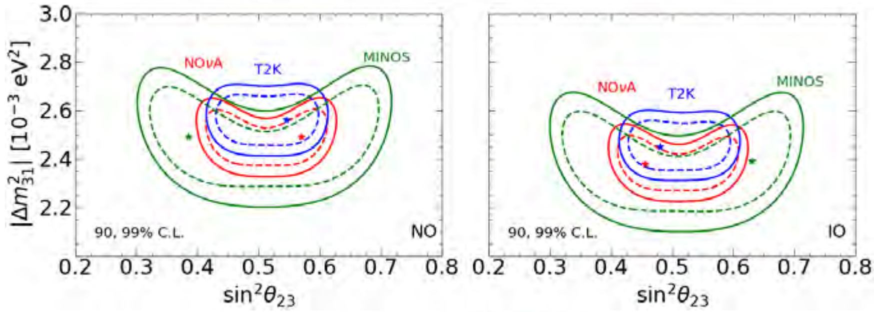
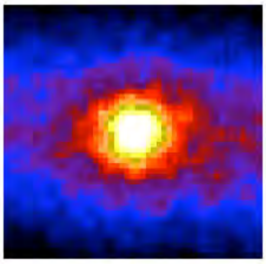
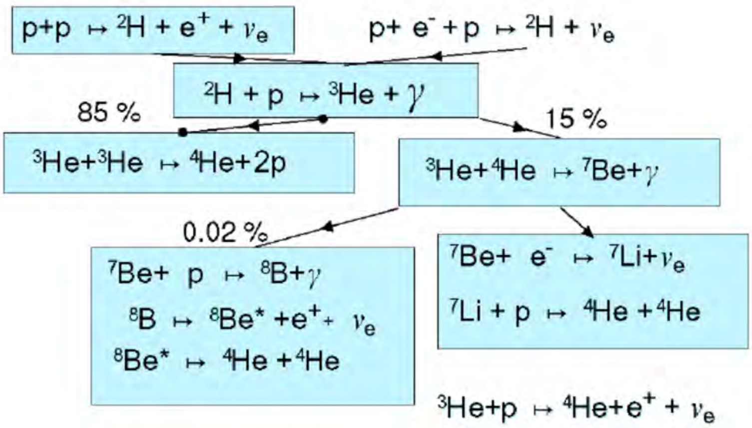


Solar δm^2





Solar Spectrum:

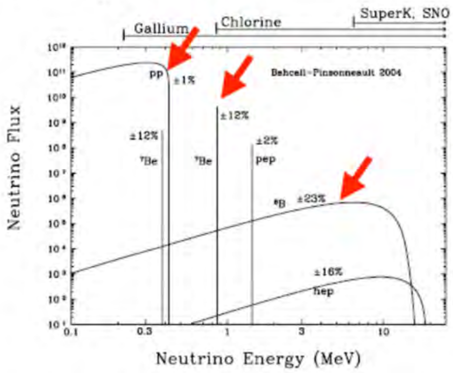


Figure 1. The predicted solar neutrino energy spectrum. The figure shows the energy spectrum of solar neutrinos predicted by the BP04 solar model [22]. For continuum sources, the neutrino fluxes are given in number of neutrinos $cm^{-2}\,s^{-1}\,MeV^{-1}$ at the Earth's surface. For line sources, the 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).

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

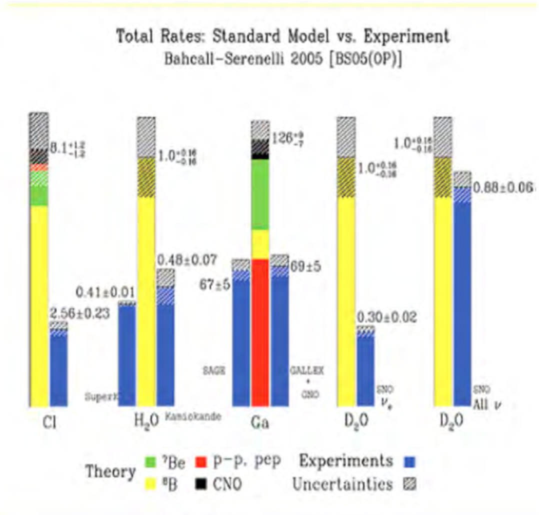
$$\phi_{pp} = 5.94(1 \pm 0.01) \times 10^{10} cm^{-2} sec^{-1}$$

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

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

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

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



Ray Davis & John Bahcall

Theory v Exp.

Neutrino Flavor Transistions!!!

Kinematical Phase:

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

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

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

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

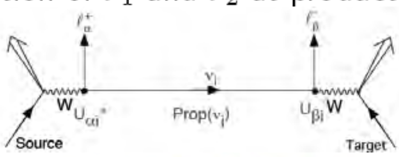
Effectively Incoherent !!!

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 $\sum$

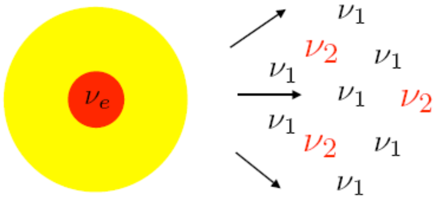


$$\langle P_{ee}\rangle = \cos^4\theta_\odot + \sin^4\theta_\odot = 1 - \frac{1}{2}\sin^2 2\theta_\odot$$

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



$f_1 \sim 69\%$

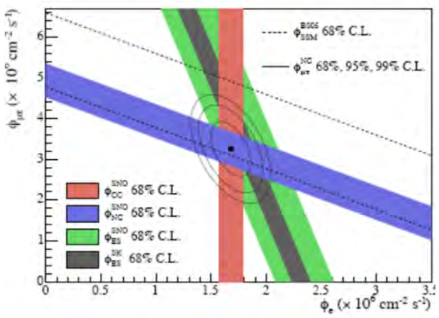
$f_2 \sim 31\%$

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

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

What about ^8B ?

SNO's CC/NC



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

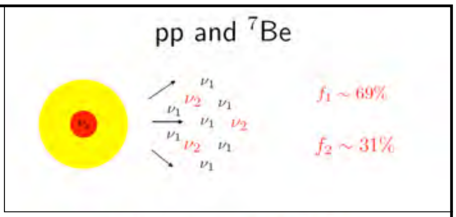
NC : $\nu_x + d \to \nu_x + p + n$

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

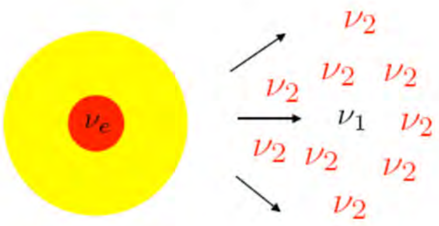
$\frac{CC}{NC} = \langle P_{ee} \rangle = f_1 \cos^2\theta_\odot + f_2 \sin^2\theta_\odot$

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

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



^8B



$f_2 \sim 90\%$

$f_1 \sim 10\%$

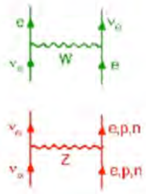
$$\langle P_{ee} \rangle = \sin^2\theta + f_1 \cos 2\theta_\odot \approx \sin^2\theta_\odot = 0.31$$

Wow!!! How did that happen???

energy dependence!!!

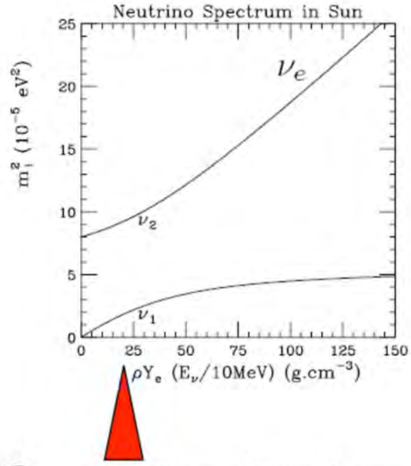
MSW

Coherent Forward Scattering:



Wolfenstein '78

MATTER EFFECTS CHANGE THE NEUTRINO MASSES AND MIXINGS



Mikheyev + Smirnov Resonance WIN '85

Neutrino Evolution:

$$-i\frac{\partial}{\partial t}\nu = H\nu$$

in the mass eigenstate basis

$$\nu = \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \text{ and } H = \begin{pmatrix} \sqrt{p^2+m_1^2} & 0 \\ 0 & \sqrt{p^2+m_2^2} \end{pmatrix}$$

$$E = \sqrt{p^2+m^2}$$

$$H = (p + \frac{m_1^2+m_2^2}{4p})I + \frac{1}{4E}\begin{pmatrix} -\delta m^2 & 0 \\ 0 & \delta m^2 \end{pmatrix}$$

$$\delta m^2 = m_2^2 - m_1^2 > 0$$

in the flavor basis

$$\nu \rightarrow U\nu \text{ and } H \rightarrow UHU^\dagger$$

$$\text{where } \nu = \begin{pmatrix} \nu_e \\ \nu_\sigma \end{pmatrix} \text{ and } U = \begin{pmatrix} \cos\theta_\odot & \sin\theta_\odot \\ -\sin\theta_\odot & \cos\theta_\odot \end{pmatrix}$$

and therefore in flavor basis

$$0 < \theta_\odot < \frac{\pi}{2}$$

$$H = \frac{\delta m^2}{4E}\begin{pmatrix} -\cos 2\theta_\odot & \sin 2\theta_\odot \\ \sin 2\theta_\odot & \cos 2\theta_\odot \end{pmatrix}$$

i.e.

$$\begin{pmatrix} E_1 & 0 \\ 0 & E_2 \end{pmatrix}_{mass} \Rightarrow \frac{\delta m^2}{4E}\begin{pmatrix} -\cos 2\theta_\odot & \sin 2\theta_\odot \\ \sin 2\theta_\odot & \cos 2\theta_\odot \end{pmatrix}_{flavor}$$

Coherent Forward Scattering:

dimensions $[G_F N_e] = M^{-2}L^{-3} = M$

$$\pm\sqrt{2}G_F N_e \;\delta_{ee}$$

N_e is number density of electrons

+(-) for neutrinos (anti-neutrinos)

Wolfenstein '78

Same for all active flavors, therefore overall phases

$$\begin{pmatrix} +\sqrt{2}G_F N_e & 0 \\ 0 & 0 \end{pmatrix} \rightarrow \frac{G_F N_e}{\sqrt{2}} I_2 + \frac{1}{2}\begin{pmatrix} +\sqrt{2}G_F N_e & 0 \\ 0 & -\sqrt{2}G_F N_e \end{pmatrix}$$

Including Matter Effects in the Flavor Basis:

$$H_{flavor} = \frac{1}{4E_\nu}\begin{pmatrix} -\delta m^2 \cos 2\theta_\odot + 2\sqrt{2}G_F N_e E_\nu & \delta m^2 \sin 2\theta_\odot \\ \delta m^2 \sin 2\theta_\odot & \delta m^2 \cos 2\theta_\odot - 2\sqrt{2}G_F N_e E_\nu \end{pmatrix}$$

Diagonalize by identifying with

$$H_{flavor} = \frac{1}{4E_\nu}\begin{pmatrix} -\delta m_N^2 \cos 2\theta_\odot^N & \delta m_N^2 \sin 2\theta_\odot^N \\ \delta m_N^2 \sin 2\theta_\odot^N & \delta m_N^2 \cos 2\theta_\odot^N \end{pmatrix}$$

Masses and Mixings in MATTER: δm_N^2 and $\theta_\odot^N$

$$\begin{aligned} \delta m_N^2 \cos 2\theta_\odot^N &= \delta m^2 \cos 2\theta_\odot - 2\sqrt{2}G_F N_e E_\nu \\ \delta m_N^2 \sin 2\theta_\odot^N &= \delta m^2 \sin 2\theta_\odot \end{aligned}$$

Notice:
(1) Possible zero when $\delta m^2 \cos 2\theta_\odot = 2\sqrt{2}G_F N_e E_\nu$
(2) the invariance of the product $\delta m^2 \sin 2\theta_\odot$

ν_e disappearance in Loooong Block of Lead:

$$1 - P(\nu_e \to \nu_e) = \sin^2 2\theta_\odot^N \sin^2 \Delta_N$$

$$\Delta_N = \frac{\delta m_N^2 L}{4E}$$

same form as vacuum

The Solution:

$$\delta m_N^2 = \sqrt{(\delta m^2 \cos 2\theta_\odot - 2\sqrt{2} G_F N_e E_\nu)^2 + (\delta m^2 \sin 2\theta_\odot)^2}$$

$$\sin^2 \theta_\odot^N = \frac{1}{2}\left(1 - \frac{(\delta m^2 \cos 2\theta_\odot - 2\sqrt{2} G_F N_e E_\nu)}{\delta m_N^2}\right) \qquad \theta_\odot^N > \theta_\odot$$

Quasi-Vacuum: $2\sqrt{2} G_F N_e E_\nu \ll \delta m^2 \cos 2\theta_\odot$ — pp and ^{7}Be

$\delta m_N^2 = \delta m^2$ and $\theta_\odot^N = \theta_\odot$

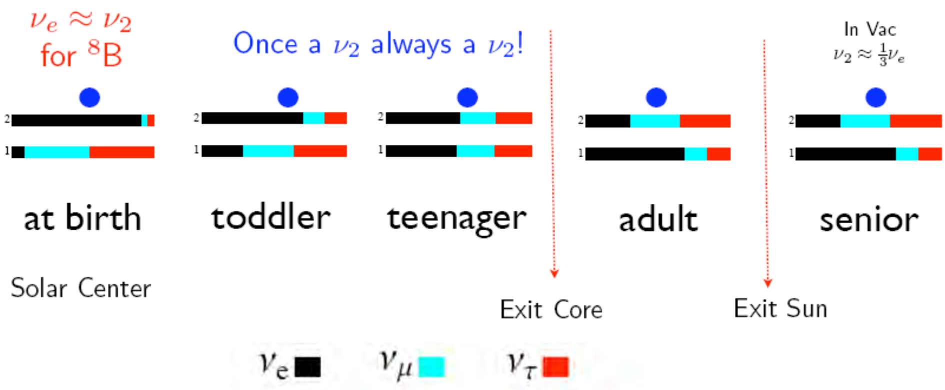
Resonance (Mikheyev + Smirnov '85): $2\sqrt{2} G_F N_e E_\nu = \delta m^2 \cos 2\theta_\odot$

$\delta m_N^2 = \delta m^2 \sin 2\theta_\odot$ and $\theta_\odot^N = \pi/4$

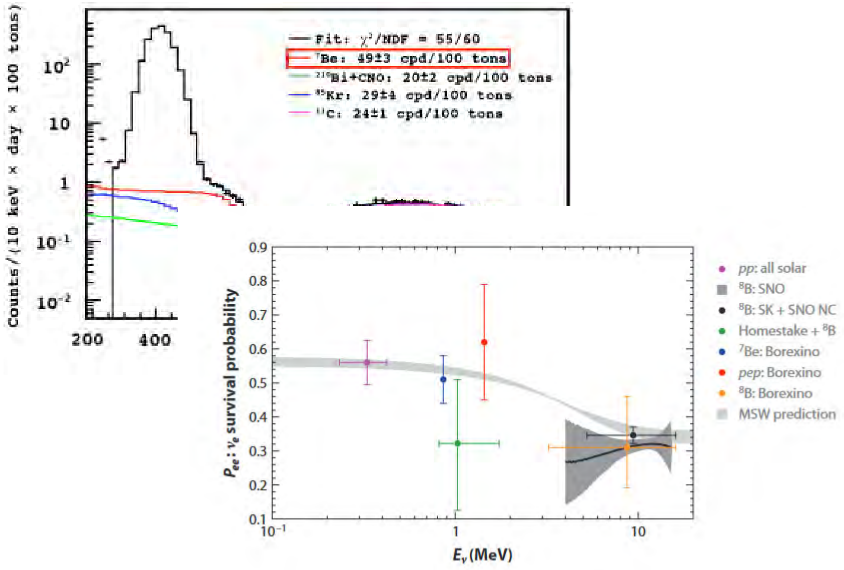
Matter Dominated: $2\sqrt{2} G_F N_e E_\nu \gg \delta m^2 \cos 2\theta_\odot$ — ^8B

$\delta m_N^2 \to 2\sqrt{2} G_F N_e E_\nu$ and $\theta_\odot^N \to \pi/2$

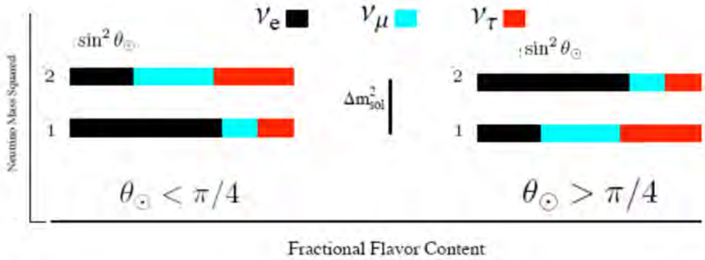
Life of a Boron-8 Solar Neutrino:



Borexino results



Solar Pair Mass Hierarchy:



Who cares ?
SNO does !!!

for neutrino in matter
$\theta_\odot^N > \theta_\odot$

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

if $\theta_\odot < \pi/4$
$\langle P_{ee}\rangle \geq \sin^2\theta_\odot$

if $\theta_\odot > \pi/4$
$\langle P_{ee}\rangle \geq \tfrac{1}{2}(1+\cos^2 2\theta_\odot) \geq \tfrac{1}{2}$

SNO: $\langle P_{ee}\rangle_{day} = 0.347 \pm 0.038$

Solar Hierarchy Determined !!!

Day/Night Asymmetry:

$\sin^2\theta_\odot \to \sin^2\theta_\oplus = \sin^2\theta_\odot + \tfrac{1}{2}\sin^2 2\theta_\odot \left(\frac{A_\oplus}{\delta m^2_\odot}\right)$ in the earth.

A=2(D-N)/(D+N) expected to be few %

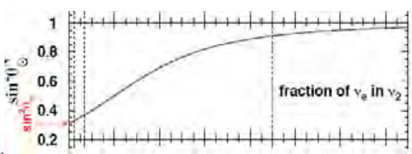
	Amplitude fit		separate D, N:
	Δm	Δm	(D-N)/((D+N)/2)
SK-I	-2.0±1.8±1.0%	-1.9±1.7±1.0%	-2.1±2.0±1.3%
SK-II	-4.4±3.8±1.0%	-4.4±3.6±1.0%	-5.5±4.2±3.7%
SK-III	-4.2±2.7±0.7%	-3.8±2.6±0.7%	-5.9±3.2±1.3%
SK-IV	-3.6±1.6±0.6%	-3.3±1.5±0.6%	-4.9±1.8±1.4%
comb	-3.3±1.0±0.5%	-3.1±1.0±0.5%	-4.1±1.2±0.8%
non-zero signif.	3.0σ	2.8σ	2.8σ

Spectral Distortion:

A characteristic of matter effects is that the Fraction of ν_2 is energy dependent .

Smaller at smaller E.

Implies an increase in P_{ee} near threshold.



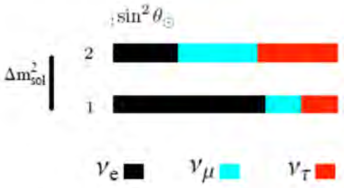
Summary:

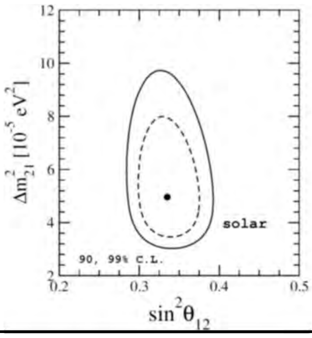
The low energy pp and ^{7}Be Solar Neutrinos exit the sun as two thirds ν_1 and one third ν_2 due to (quasi-) vacuum oscillations.

$f_1 = 65 \pm 2\%$, $f_2 = 35 \mp 2\%$ with $P_{ee} \approx 0.56$

The high energy ^{8}B Solar Neutrinos exit the sun as "PURE" ν_2 mass eigenstates due to matter effects.

$f_2 = 91 \pm 2\%$ and $f_1 = 9 \mp 2\%$ with $P_{ee} \approx 0.35$.





Testing solar neutrino oscillations with reactors

$$1 - P(\nu_e \to \nu_e) = \sin^2 2\theta_\odot \sin^2 \Delta$$

10^{-5} eV^2

10^5m = 100 km

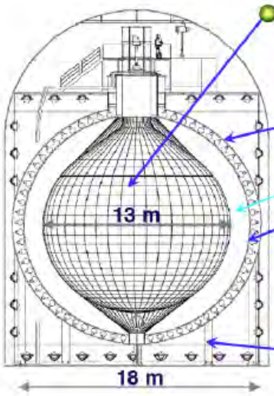
$$\Delta = \frac{\delta m^2 L}{4E}$$

1 MeV

Reactor Neutrinos

KamLAND Detector

- detector location: old Kamiokande site
  : 2700 m.w.e.



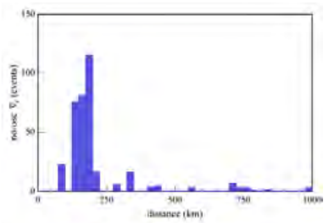
- 1000 ton liquid scintillator
  : 80% (dodecane) + 20% (pseudocumene)
  + 1.52 g/l PPO
  : housed in spherical plastic balloon
- 3000 m³ stainless steel vessel
  : filled with a mixture of paraffin oil
  and dodecane ($\Delta\rho = 0.04\%$)
- 1325 17-inch + 554 20-inch PMT's

commissioned in February, 2003

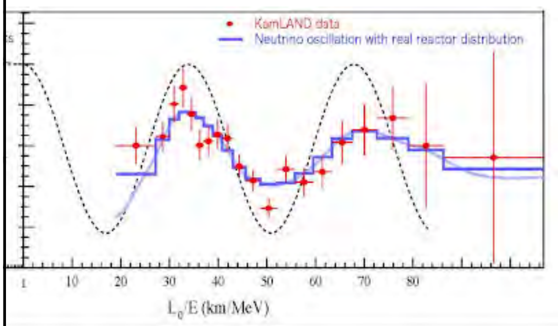
photocathode coverage : 22% → 34%
energy resolution at 1 MeV : 7.3% → 6.3%

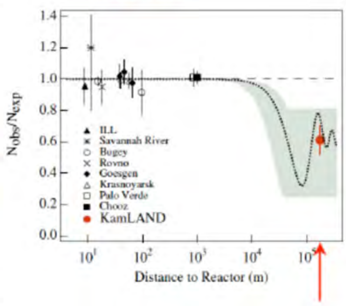
- water Cerenkov outer detector

expected no-oscillation neutrino event rate at KamLAND



180 km





180 km

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The low energy pp and ^{7}Be Solar Neutrinos exit the sun as two thirds ν_1 and one third ν_2 due to (quasi-) vacuum oscillations.

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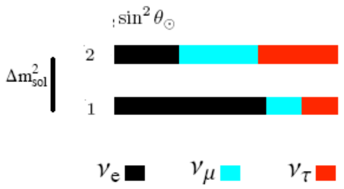
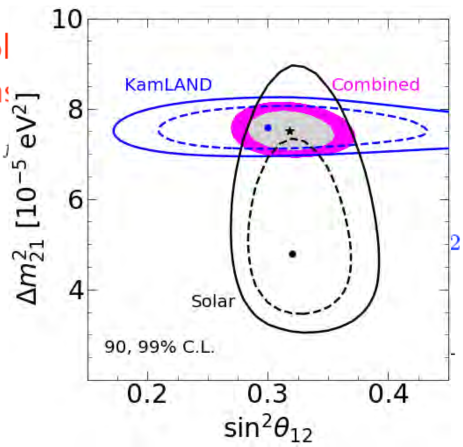
The high energy ^{8}B Sol
"PURE" ν_2 mass eigen

$f_2 = 91 \pm 2\%$ and j

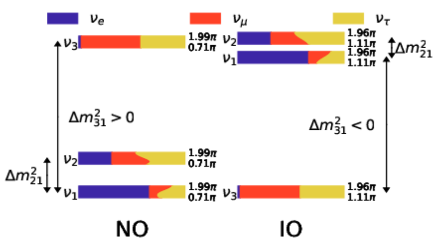




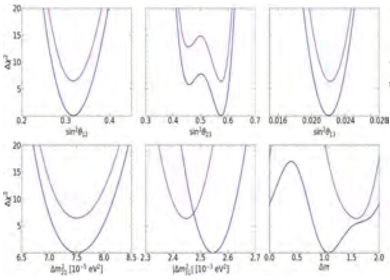
Three-neutrino oscillations

Neutrino mixing matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



https://globalfit.astroparticles.es/



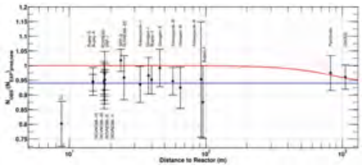
de Salas et al, JHEP 02 (2021) 071[arXiv:2006.11237]

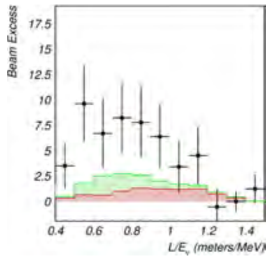
parameter	best fit ± 1σ	2σ range	3σ range	Relative 1σ uncertainty
$\Delta m^2_{21} [10^{-5}\mathrm{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14	2.7% PRECISION
$\|\Delta m^2_{31}\| [10^{-3}\mathrm{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63	1.1% ORDERING?
$\|\Delta m^2_{31}\| [10^{-3}\mathrm{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53	
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69	5.2% PRECISION
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14	5.41–5.99	4.34–6.10	5.1% OCTANT?
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08	
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405	3.0% PRECISION
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424	
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99	20% CPV?
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96	9.0%

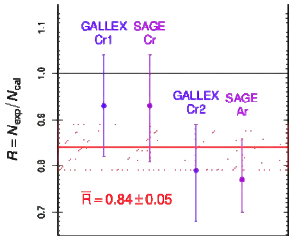
Parameter	Main contribution	Other contributions
θ_{12}	SOL	KamLAND
θ_{13}	REAC	ATM+LBL and SOL+KamLAND
θ_{23}	ATM+LBL	-
δ_{CP}	LBL	ATM
Δm^2_{21}	KamLAND	SOL
$\|\Delta m^2_{31}\|$	LBL+ATM+REAC	-
MO	LBL+REAC and ATM	-

SOL: Solar
ATM: Amtopsheric neutrinos
LBL: Long baseline accelerator experiments
REAC: Short-baseline reactor experiments

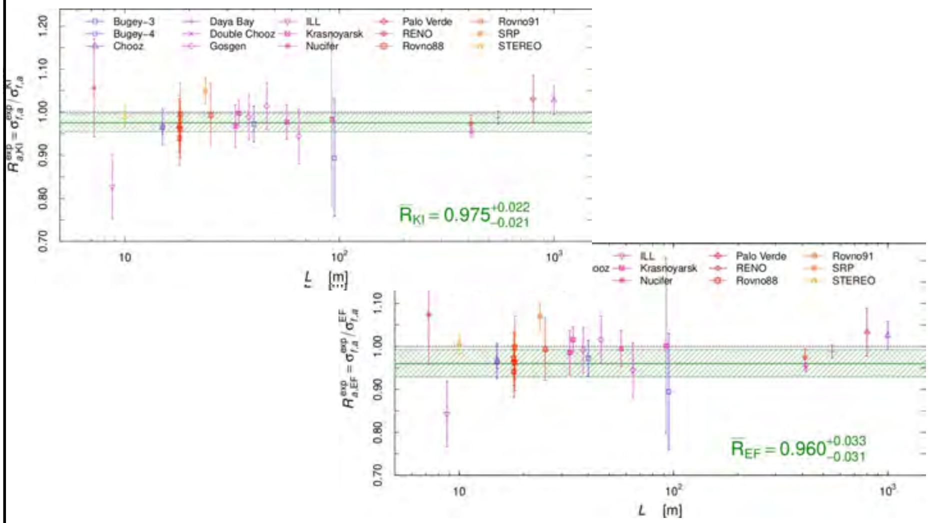
Anomalies







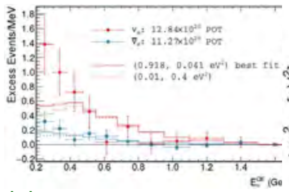
Need extra states !!!



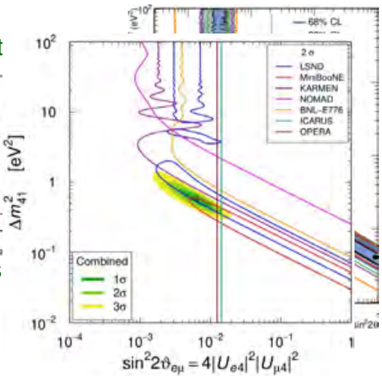
MiniBooNE

MiniBooNE was built to check the LSND results with a different baseline, but similar L/E

MiniBooNE has no near det



MiniBooNE sees an excess at ~5σ at low energies



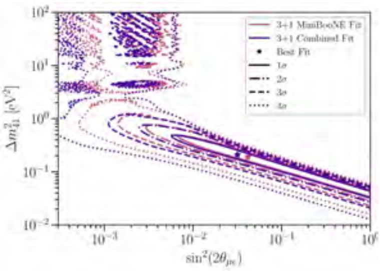
MicroBooNE

MicroBooNE was built to check the Mir results!

Looking for signals using several final s channels

The collaboration did not perform an os analysis

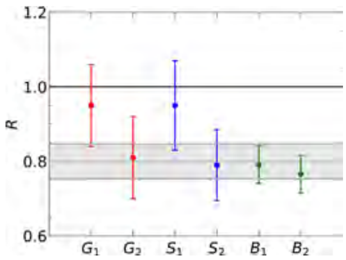
A combined analysis shows that MicroI not exclude the region of parameter sp preferred by MiniBooNE

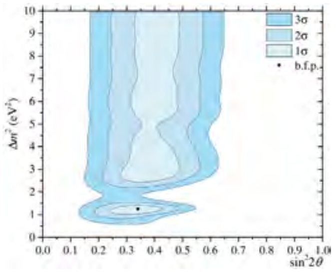


2201.01724

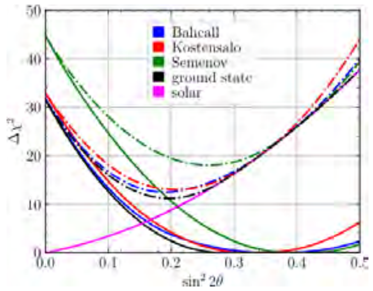
The Gallium anomaly

BEST coll., 2109.11482





The Gallium anomaly is now at more than 5σ significance



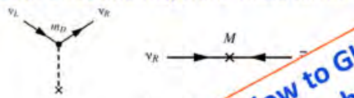
Berryman et al, 2111.12530, JHEP 2022

Can not be explained due to cross section mistakes

a connection to BSM physics

★ **Is there a connection to the GUT scale?**

- If both Dirac and Majorana mass terms are pres…



⇨ $\mathcal{L} \sim -\frac{1}{2}\left(\overline{\nu_L}\ \ldots\right) \ldots \left(\nu_R\right)$

- The seesaw m… …ysical "mass eigenstates" are thos… …e the mass matrix is diagonal

…ino $m_\nu \approx \frac{m_D^2}{M}$ + heavy RH neutrino $m_N \approx M$

…$m_D \sim m_\ell$ to get to right range of small neutrino masses:

$$M \sim 10^{12} - 10^{16}\,\text{GeV}$$

Neutrinos may provide a window to GUT-scale physics argues for a precision neutrino physics program

The Known Unknowns

★ **Next generation Long-Baseline experiments (such as DUNE) can address three of these questions:**

- **Are neutrinos Dirac or Majorana ?**
  - Is there a connection to the GUT scale?
- **Are there light sterile neutrino states ?** → Breaks 3-flavor paradigm
  - No clear theoretical guidance on mass scale, M, …
- **What is the neutrino mass hierarchy ?**
  - An important question in flavor physics, e.g. CKM vs. PNMS

- **Is CP violated in the leptonic sector ?**
  - Are νs key to understanding the matter-antimatter asymmetry?

We determined that $m(K_L) > m(K_S)$ by

•Passing kaons through matter (regenerator)

•Beating the unknown sign[$m(K_L) - m(K_S)$] against the known sign[reg. ampl.]

We will determine the sign(Δm^2_{31}) by

•Passing neutrinos through matter (Earth)

•Beating the unknown sign(Δm^2_{31}) against the known sign[forward $\nu_e\, e \longrightarrow \nu_e\, e$ ampl]

$$L \approx \frac{2\,\pi}{G_F n_e} \approx 1.16\ 10^4\ \text{km} \left(\frac{1.69\ 10^{24}\ cm^3}{n_e}\right)$$

The Known Unknowns

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  - Is there a connection to the GUT scale?
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- Is CP violated in the leptonic sector ?
  - Are νs key to understanding the matter-antimatter asymmetry?

In principle, it is straightforward

★ CPV ⇨ different oscillation rates for νs and $\overline{\nu}$s

$$P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e) = 4 s_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \times \left[\sin\left(\frac{\Delta m_{21}^2 L}{4E}\right) \times \sin\left(\frac{\Delta m_{23}^2 L}{4E}\right) \times \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right)\right]$$

vacuum osc.

★ Requires $\{\theta_{12}, \theta_{13}, \theta_{23}\} \neq \{0, \pi\}$

- now know that this is true, $\theta_{13} \approx 9^\circ$
- but, despite hints, don't yet know "much" about δ

★ So "just" measure $P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)$?

★ Not quite, there is a complication…

Neutrino Oscillations in Matter

★ Accounting for this potential term, gives a Hamiltonian that is not diagonal in the basis of the mass eigenstates

$$\mathcal{H}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix} = i\frac{d}{dt}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix} = \begin{pmatrix}E_1 & 0 & 0\\0 & E_2 & 0\\0 & 0 & E_3\end{pmatrix}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix} + V|\nu_e\rangle$$

← ME

★ Complicates the simple picture !!!!

$$P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e) =$$

ME $$\frac{16A}{\Delta m_{31}^2}\sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2)$$

ME $$-\frac{2AL}{E}\sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2)$$

CPV $$-8\frac{\Delta m_{21}^2 L}{2E}\sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)\sin\delta \; s_{13} c_{13}^2 c_{23} s_{23} c_{12} s_{12}$$

with $A = 2\sqrt{2} G_F n_e E = 7.6 \times 10^{-5}\,\mathrm{eV}^2 \cdot \frac{\rho}{\mathrm{g\,cm^{-3}}} \cdot \frac{E}{\mathrm{GeV}}$

Experimental Strategy

EITHER:

- ★ Keep L small (~200 km): so that matter effects are insignificant
  - First oscillation maximum:

    $$\frac{\Delta m_{31}^2 L}{4E} \sim \frac{\pi}{2} \;\Rightarrow\; E_\nu < 1\,\mathrm{GeV}$$
  - Want high flux at oscillation maximum

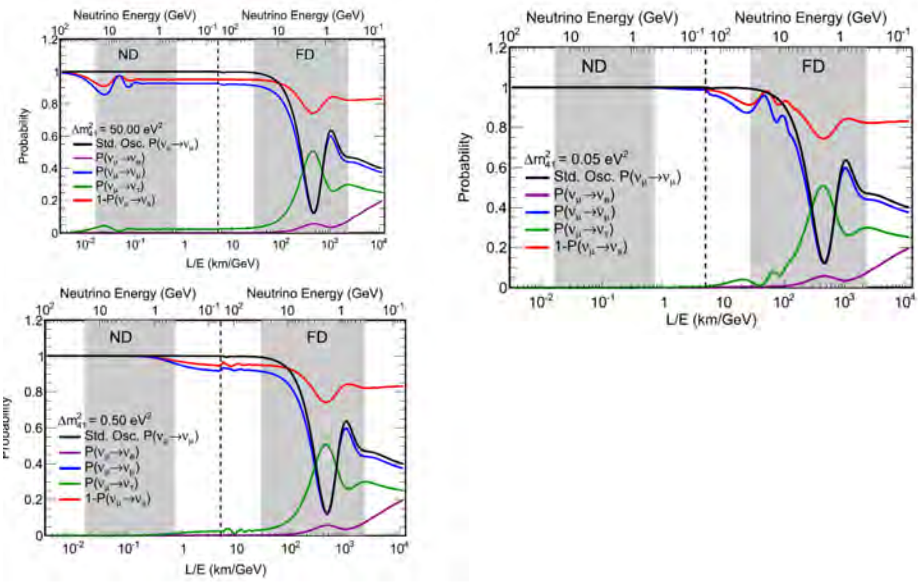
    ⇨ **Off-axis beam:** narrow range of neutrino energies

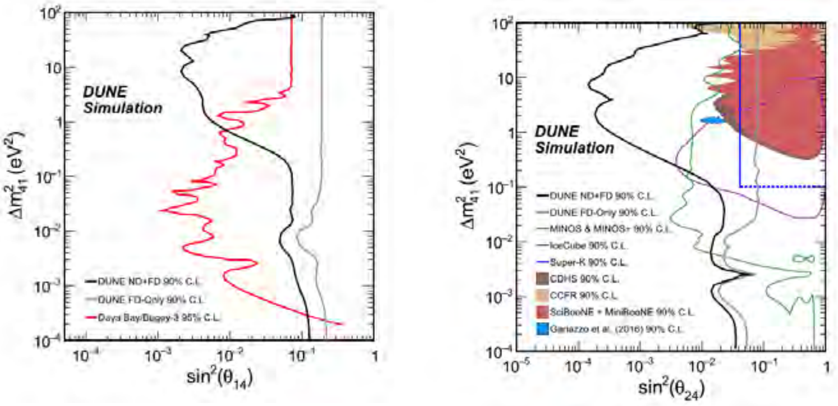
OR:

- ★ Make L large (>1000 km): measure the matter effects (i.e. MH)
  - First oscillation maximum:

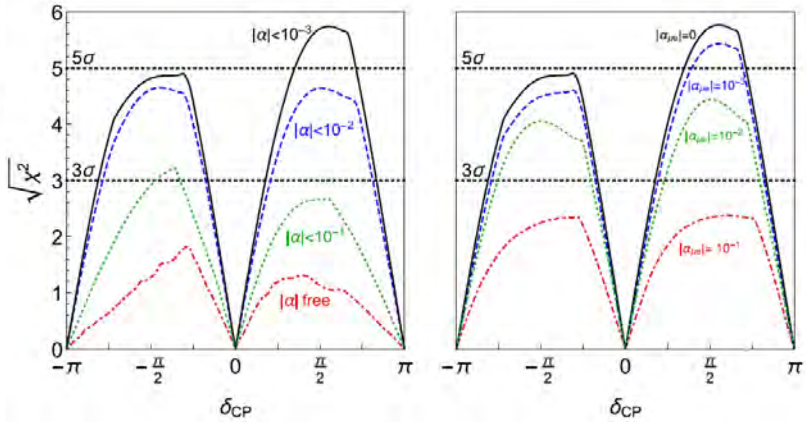
    $$\frac{\Delta m_{31}^2 L}{4E} \sim \frac{\pi}{2} \;\Rightarrow\; E_\nu > 2\,\mathrm{GeV}$$
  - **Unfold CPV from Matter Effects through E dependence**

    ⇨ **On-axis beam:** wide range of neutrino energies





Non unitarity



Neutrinos,

In and Beyond the Standard Model:

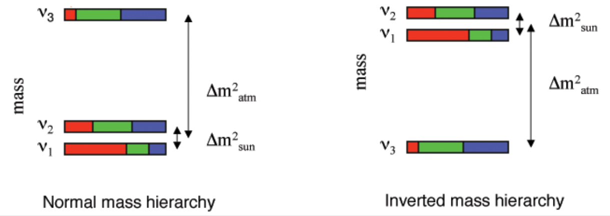
NEUTRINO MASS:

$\delta m^2_{atm} = 2.7^{+0.4}_{-0.3} \times 10^{-3} eV^2$ $L/E = 500\ km/GeV$

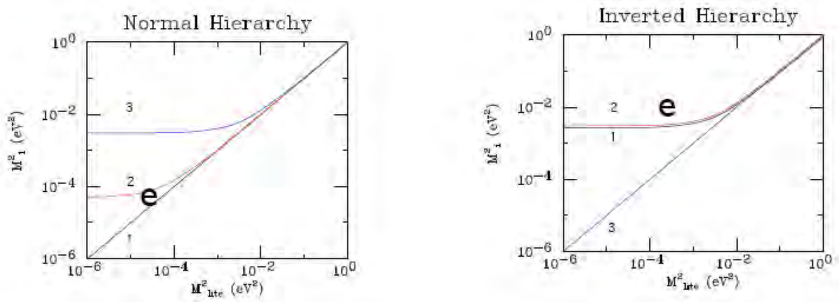
$\delta m^2_{solar} = 8.0 \pm 0.4 \times 10^{-5} eV^2$ $L/E = 15\ km/MeV$

$$\Downarrow$$

$$m_\nu^{Heavy} > \sqrt{\delta m^2_{atm}} = 50 meV$$

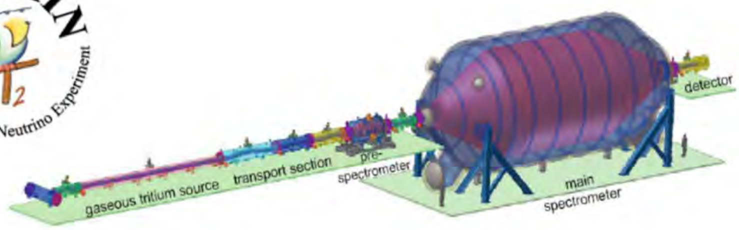


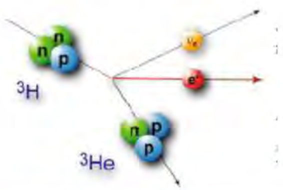
Masses:



States 1 and 2 are ν_e rich.

KATRIN
Karlsruhe Tritium Neutrino Experiment



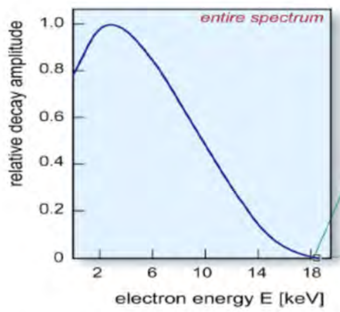


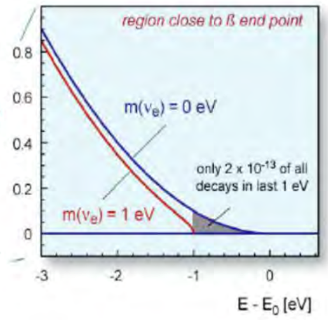
Requirements:

- Strong source
- Excellent energy resolution
- Small endpoint energy E_0
- Long term stability
- Low background rate

KATRIN Task:
Investigate Tritium endpoint with sub-eV precision

KATRIN Aim:
Improve m_ν sensitivity 10 x (2eV → 0.2eV)





Decay Rate:

$$|\langle {}^3He + e^- + \bar{\nu}|T|{}^3H\rangle|^2 \sim pE(E_0 - E)\sum_k |U_{ek}|^2\sqrt{(E_0 - E)^2 - m_k^2}$$

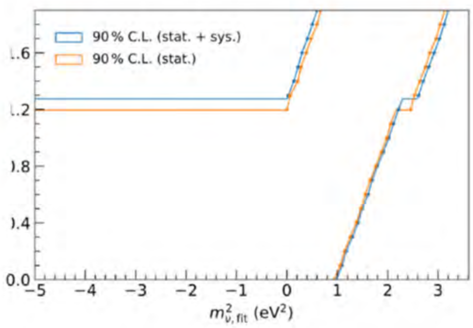
if ν's quasi-degenerate: $m_1 \approx m_2 \approx m_3$

$$|\langle {}^3He + e^- + \bar{\nu}|T|{}^3H\rangle|^2 \sim pE(E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}$$

- **KATRIN upper limit on neutrino mass:**

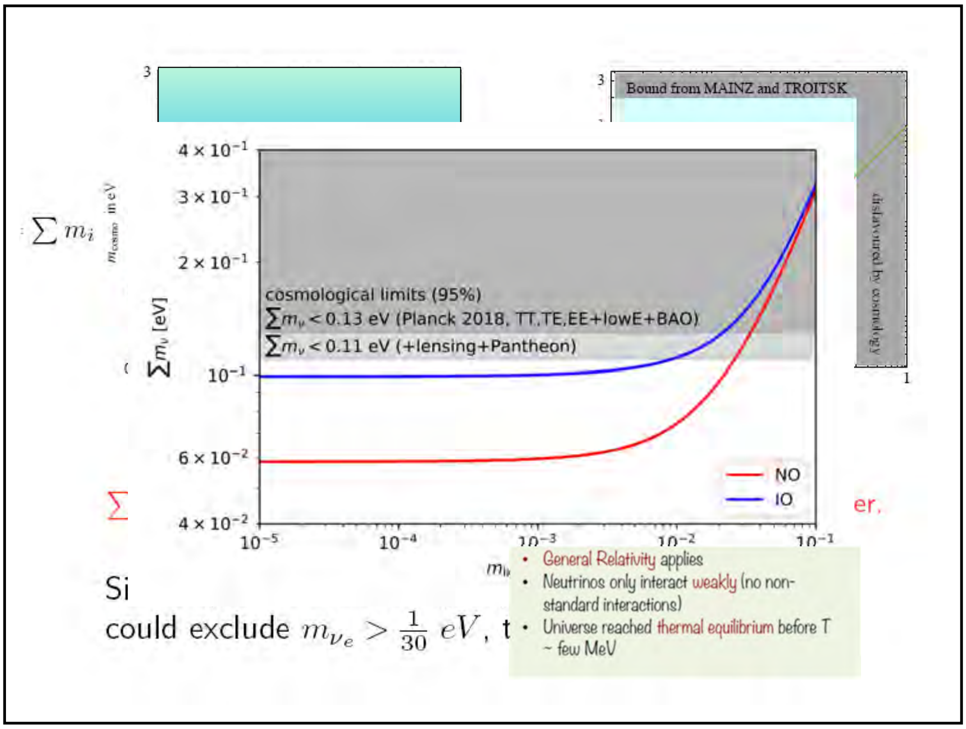
LT m(ν) < 1.1 eV (90% CL)

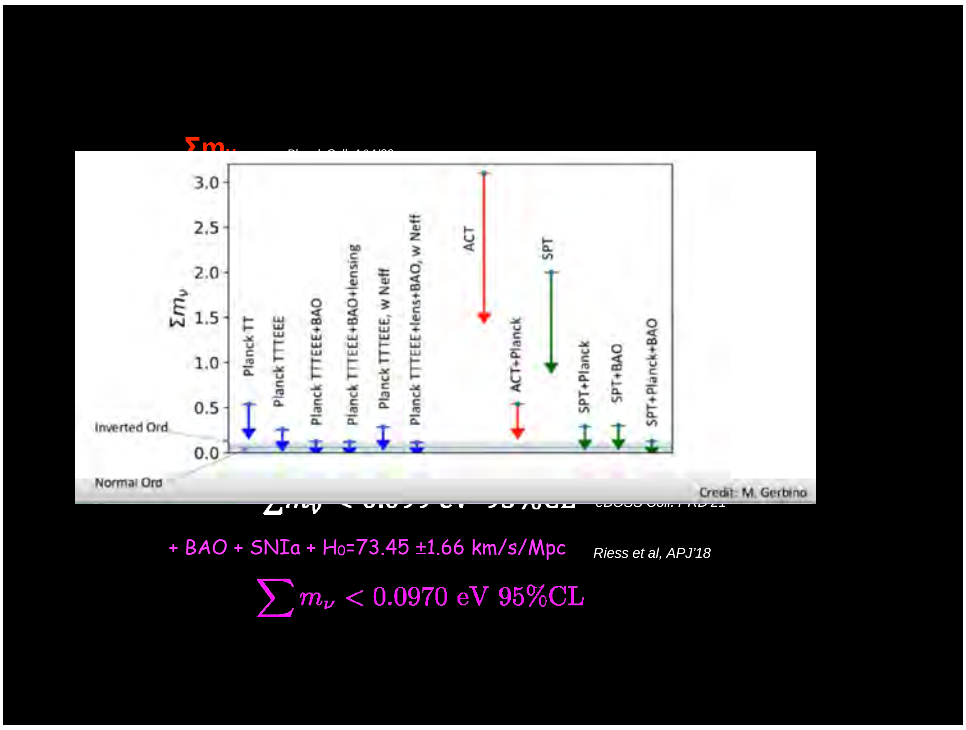
FC m(ν) < 0.8 eV (90% CL)
< 0.9 eV (95% CL)



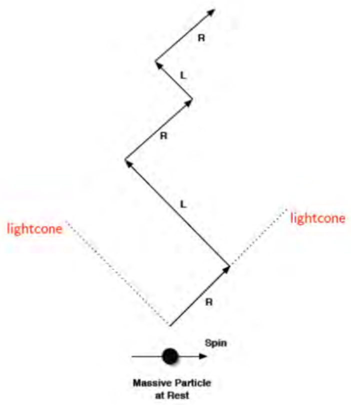
- **1000 days of measurements** at nominal ρd ($5 \cdot 10^{17}$ molecules cm^{-2}) 3 tritium campaigns (65 days each) per calendar year

sensitivity $m(\nu_e)$ = 0.2 eV (90% CL)
0.35 eV (5σ)


Bound from MAINZ and TROITSK
disfavoured by cosmology
$\sum m_i$
$\sum m_\nu$ [eV]
cosmological limits (95%)
$\sum m_\nu < 0.13$ eV (Planck 2018, TT,TE,EE+lowE+BAO)
$\sum m_\nu < 0.11$ eV (+lensing+Pantheon)
NO
IO
m_ν
er.
Si
could exclude $m_{\nu_e} > \frac{1}{30}\, eV$, t
• General Relativity applies
• Neutrinos only interact weakly (no non-standard interactions)
• Universe reached thermal equilibrium before T ~ few MeV


Σm_ν
Planck TT
Planck TTTEEE
Planck TTTEEE+BAO
Planck TTTEEE+BAO+lensing
Planck TTTEEE, w Neff
Planck TTTEEE+lens+BAO, w Neff
ACT
ACT+Planck
SPT
SPT+Planck
SPT+BAO
SPT+Planck+BAO
Inverted Ord
Normal Ord
Credit: M. Gerbino
+ BAO + SNIa + H0=73.45 ±1.66 km/s/Mpc
Riess et al, APJ'18
$\sum m_\nu < 0.0970$ eV 95%CL

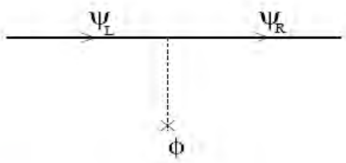
What is Fermion Mass ???



A mass can be thought of as a $L \leftrightarrow R$ transition:

$$m\,\overline{\psi_L}\psi_R + h.c.$$

In the SM fermion masses originate in the interaction with the Higgs field:



$$\lambda_f\,\overline{\psi_L}\,\Phi\,\psi_R + h.c. \rightarrow m_f = \lambda_f\,v$$

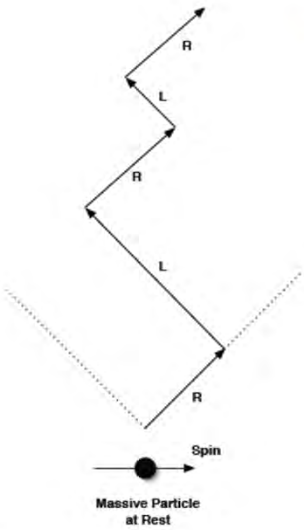
Fermion Masses:

	electron	positron	
Left Chiral	e_L	$\bar{e}_R$	SU(2)×U(1)
Right Chiral	e_R	$\bar{e}_L$	U(1)

CPT: $e_L \leftrightarrow \bar{e}_R$ and $e_R \leftrightarrow \bar{e}_L$

Mass couples L to R:

e_L to e_R AND also $\bar{e}_R$ to $\bar{e}_L$ Dirac Mass terms.



Mass couples L to R:

$$P^2 = M^2, \quad P \cdot S = 0 \quad and \quad S^2 = -1$$

$$u(P,S) = \frac{(1+\gamma_5)}{2} u(\frac{P+MS}{2}) + e^{i\phi} \frac{(1-\gamma_5)}{2} u(\frac{P-MS}{2})$$

right massless   left massless

A coupling of
e_L to $\bar{e}_R$ OR e_R to $\bar{e}_L$ would be (Majorana) mass term
but this violates conservation of electric charge!

Seesaw / Dirac Neutrinos / Light Sterile Neutrinos

	Nu	CPT:	Anti-Nu	
Left Chiral	$\boldsymbol{\nu_L}$	$\Leftrightarrow$	$\boldsymbol{\bar{\nu}_R}$	
	$\Updownarrow$		$\Updownarrow$	Dirac Masses
Right Chiral	$\boldsymbol{\nu_R}$	$\Leftrightarrow$	$\boldsymbol{\bar{\nu}_L}$	
		Majorana Masses		

Coupling of

- ν_L to ν_R AND $\bar{\nu}_R$ to $\bar{\nu}_L$ are the Dirac masses.
- ν_L to $\bar{\nu}_R$ forbidden by weak isospin.
- ν_R to $\bar{\nu}_L$ allowed and coefficient is unprotected. $(\rightarrow M)$

ν_L to $\bar{\nu}_R$ $\quad$ ν_L to ν_R

$$\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}$$

$\bar{\nu}_R$ to $\bar{\nu}_L$ $\quad$ ν_R to $\bar{\nu}_L$

Two Majorana neutrinos with masses m_D^2/M and M

Seesaw: Yanagida, Gell-man-Ramond-Slansky

- Coupling of ν_R to $\bar{\nu}_L$ allowed and coefficient is unprotected. $(\rightarrow M)$

Also applies to sterile neutrinos.

Light Sterile Neutrinos and/or Dirac Neutrinos Unexpected!!!

The consequences of this alternative are profound:

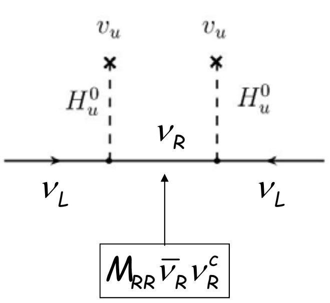
- Physics beyond the SM at a scale M!
- Majorana fermions carry no conserved charge: L is violated !

$$\nu_L \to e^{i\alpha}\nu_L$$

does not leave the Majorana mass term invariant.
$\to$ Most welcome for baryogenesis: a mechanism to understand the matter-antimatter asymmetry in the Universe emerges naturally
$\to$ Most welcome by string theory: it is difficult to get global $U(1)$ charges conserved

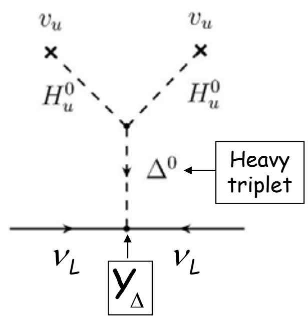
Types of see-saw mechanism

Type I see-saw mechanism



$$m_{LL}^{I} \approx -m_{LR}M_{RR}^{-1}m_{LR}^{T}$$

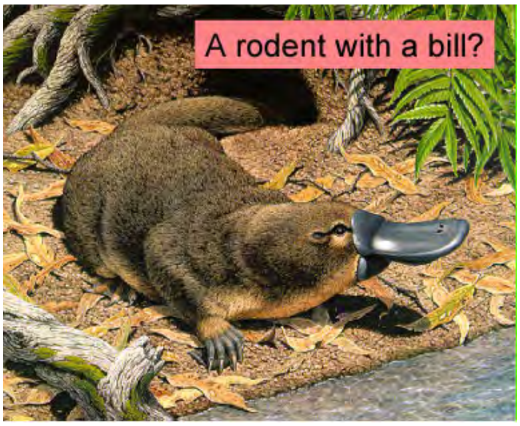
Type II see-saw mechanism



$$m_{LL}^{II}\bar{\nu}_L\nu_L^c \approx Y_\Delta \frac{v_u^2}{M_\Delta}$$

Naturalness may be over rated …

Does this look natural ??

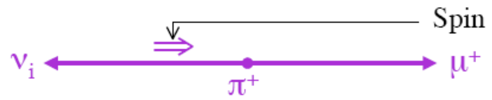


How Can We Demonstrate That $\overline{\nu}_i = \nu_i$?

We assume neutrino interactions are correctly described by the SM. Then the interactions conserve L ($\nu \to \ell^-$; $\overline{\nu} \to \ell^+$).

An Idea that Does Not Work
[and illustrates why most ideas do not work]

Produce a ν_i via—



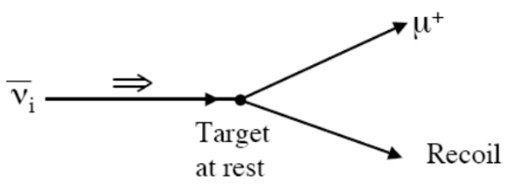
Pion Rest Frame

Give the neutrino a Boost:

$\beta_\pi(\text{Lab}) > \beta_\nu(\pi \text{ Rest Frame})$

Lab. Frame

The SM weak interaction causes—



$\nu_i = \overline{\nu}_i$ means that $\nu_i(h) = \overline{\nu}_i(h)$.

↑ helicity

If $\nu_i \xrightarrow{\Rightarrow} = \overline{\nu}_i \xrightarrow{\Rightarrow}$,

our $\nu_i \xrightarrow{\Rightarrow}$ will make μ^+ too.

Minor Technical Difficulties

$$\beta_\pi(\text{Lab}) > \beta_\nu(\pi \text{ Rest Frame})$$

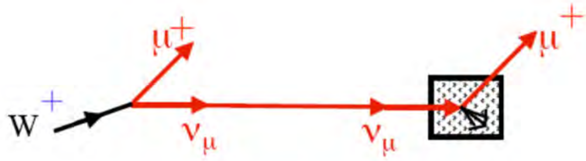
$$\Rightarrow \frac{E_\pi(\text{Lab})}{m_\pi} > \frac{E_\nu(\pi \text{ Rest Frame})}{m_{\nu_i}}$$

$$\Rightarrow E_\pi \text{ (Lab)} > 10^4 \text{ TeV} \quad \text{if } m_\nu \sim 1 \text{ eV}$$

Fraction of all π–decay that get helicity flipped

$$\approx \left(\frac{m_\nu}{E_\nu(\pi \text{ Rest Frame})} \right)^2 \sim 10^{-16} \quad \text{if } m_\nu \sim 1 \text{ eV}$$

For Majorana Neutrinos

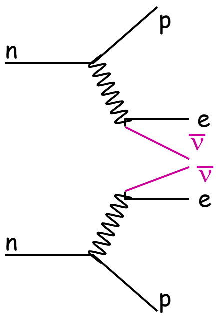


Not Observed

Allowed

BUT Suppressed by $\frac{m_\nu^2}{E^2} \sim 10^{-20}$!!!

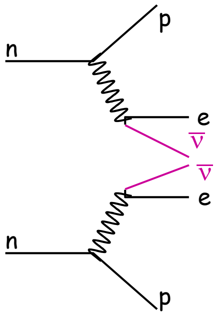
➢ How we can find out ?



SM double weak process

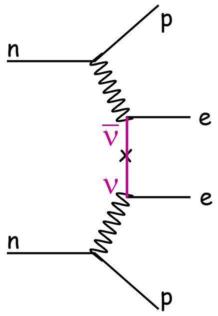
4 body decay: continuos spectrum for the e energy sum

➢ How we can find out ?



SM double weak process

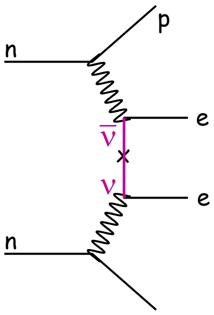
4 body decay: continuos spectrum for the e energy sum



Only allowed for Majorana ν

2 body decay: e energy sum is a delta

$\bar{\nu}_i$ is emitted (RH + 0(m_i/E) LH)



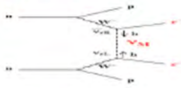
Amp[ν_i contribution] ~ m_i

$$\mathrm{Amp}[0\nu\beta\beta] \propto \left| \sum m_i U_{ei}^2 \right|$$

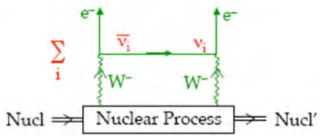
effective mass

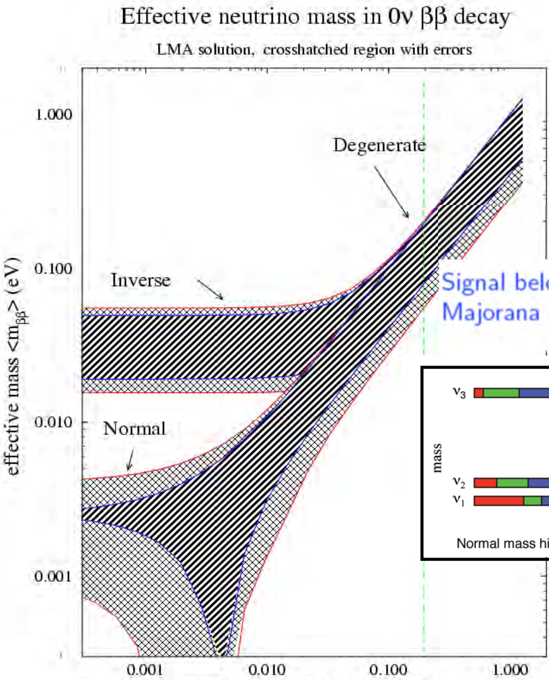
Neutrinoless double beta decay

- Most sensitive (terrestrial) probe of the absolute neutrino mass
- Unique way of proving Majorana nature of ν
- If Majorana ν is the only mechanism, ===>



$$\langle m \rangle_{\beta\beta} \equiv \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|$$
$$= \left| m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\beta} + m_3 s_{13}^2 e^{2i(\gamma-\delta)} \right|$$

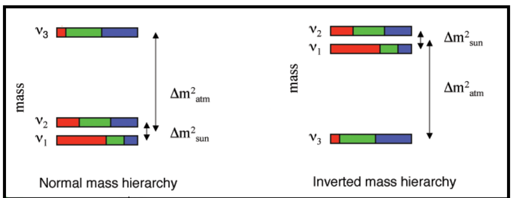




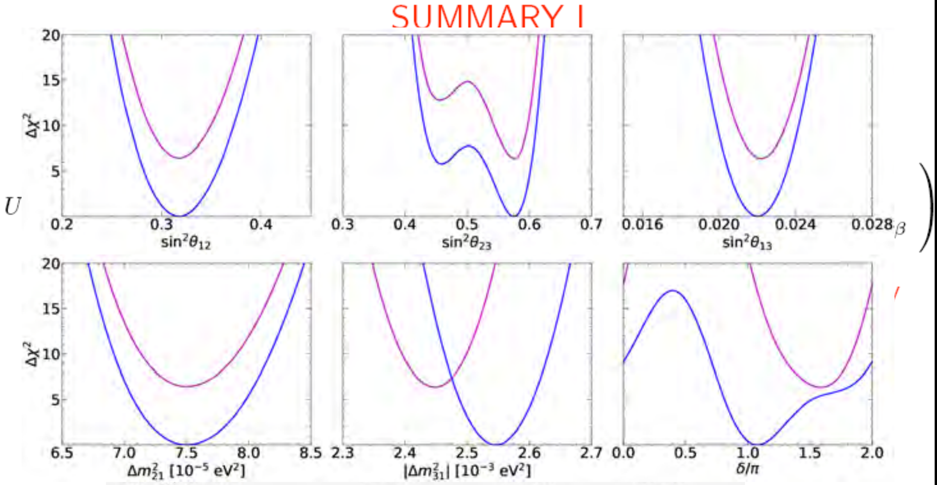
$m_{\beta\beta} = |\sum m_i U_{ei}^2|$

dividing point $m_{\beta\beta} \approx 10 meV$

Signal below ~ 10 meV would imply Majorana and Normal Hierarchy!



SUMMARY I



$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424
δ_{CP}/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
δ_{CP}/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96