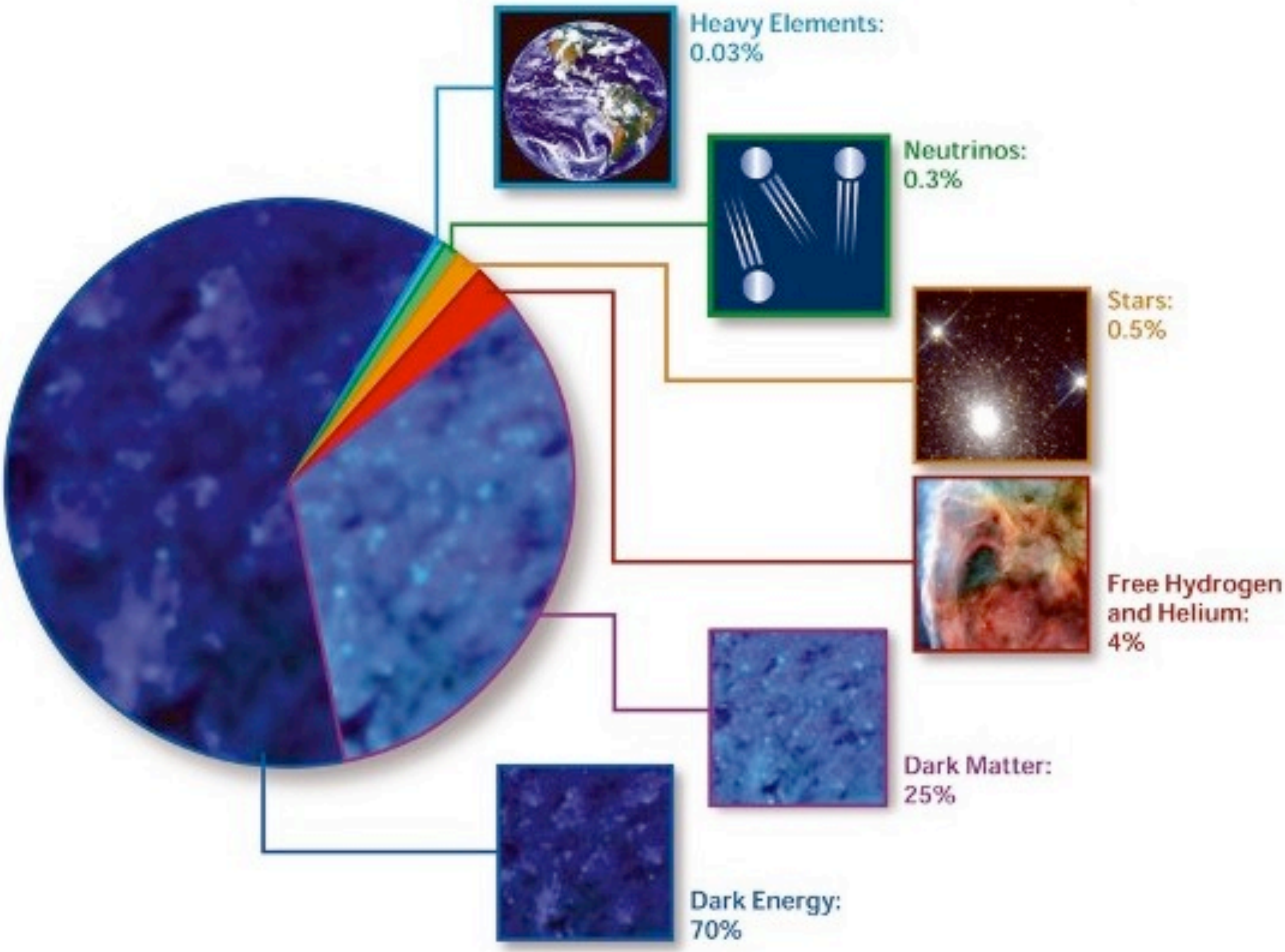
Composition of Present Universe



Some Neutrino Physics

陆锦标 Kam-Biu Luk

Tsinghua University

and

University of California, Berkeley

and

Lawrence Berkeley National Laboratory

Outline

- Some historic findings about neutrinos
- Standard Model of Particle Physics
- Neutrino Oscillation
- Possible modifications of Standard Model
- Open questions in neutrino physics

References

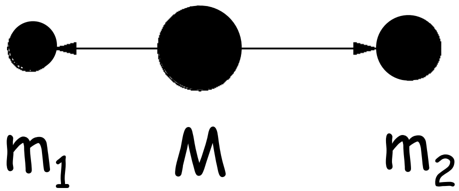
- ‘Physics of Massive Neutrinos’, F. Boehm and P. Vogel, Cambridge University Press (1992).
- ‘Weak Interaction of Leptons and Quarks’, E. D. Commins and P.H. Bucksbaum, Cambridge University Press (1983).
- M.C. Gonzalex-Garcia and M. Maltoni, Phys. Rep. **460**(2008)1.
- S.F. Novaes, arXiv:hep-ph/0001283 (2000).
- R. Barbieri, arXiv:0706.0684 [hep-ph] (2007).

Beta Decay

Prior to 1930, beta decay was assumed to be a 2-body decay:

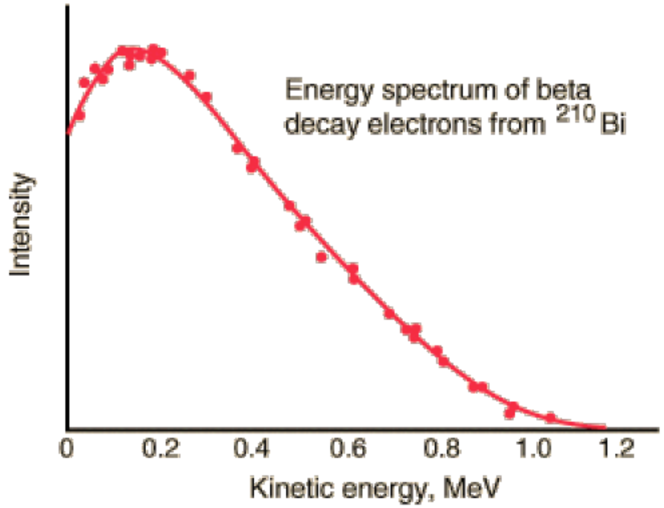
$$ {}^{A}_{Z}N \rightarrow {}^{A}_{Z+1}N + \beta $$

For two-body decay:



$$E_2 = \sqrt{m_2^2 + p^2} = \frac{M^2 + m_2^2 - m_1^2}{2M}$$

But observed continuous energy spectra for β particles :

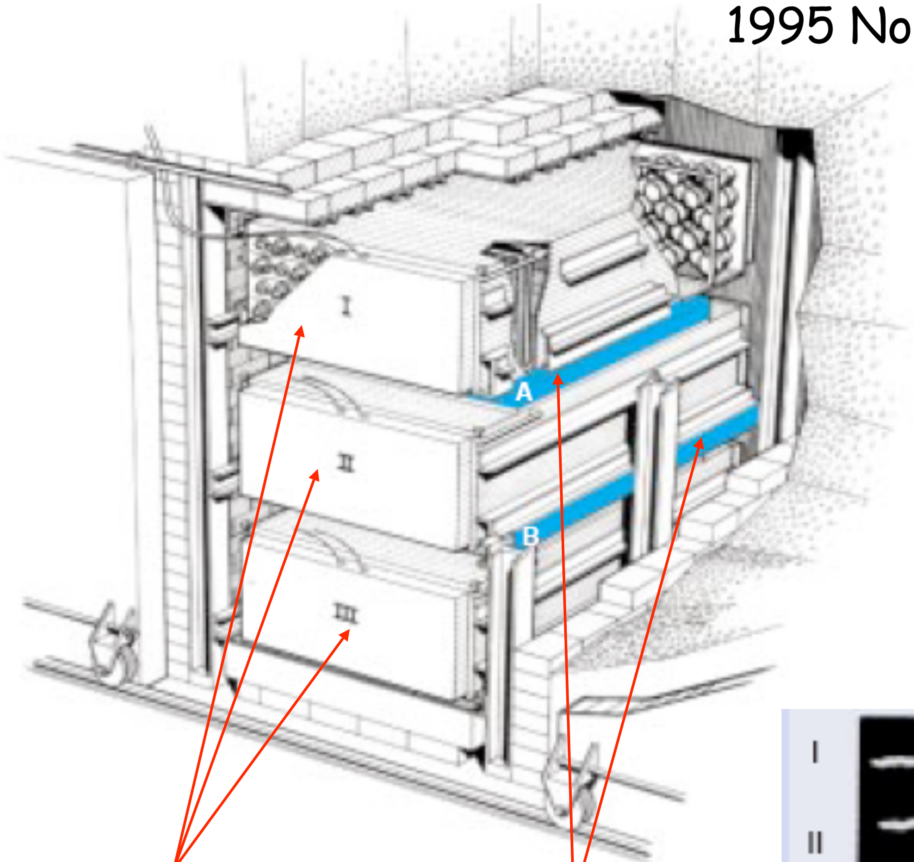


Pauli's solution : there exists a neutral particle - neutrino.

Discovery of Antineutrino

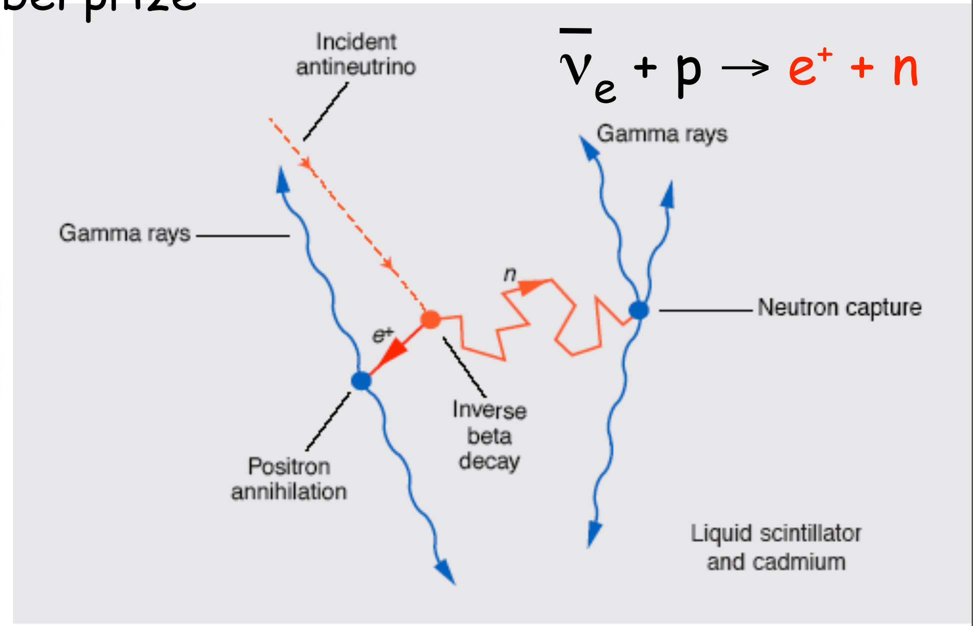
Reines-Cowan Experiment with reactor $\bar{\nu}_e$ at Savannah River (1953-1956)

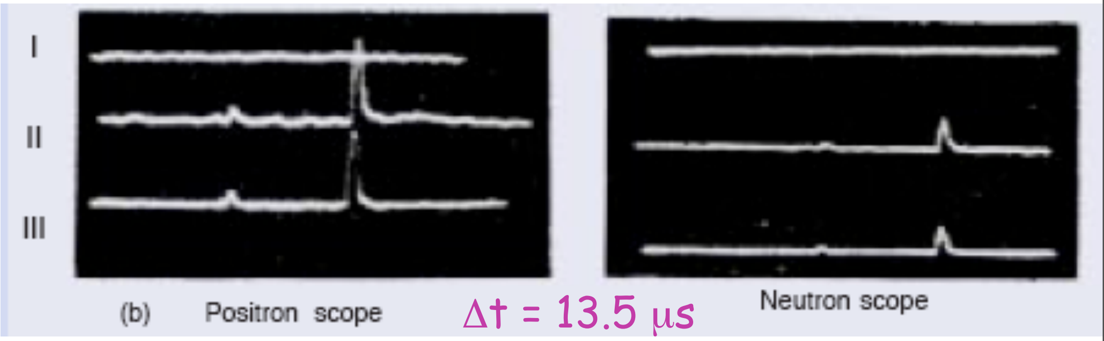
1995 Nobel prize



Each with 1000 l of liquid scintillator viewed with PMTs

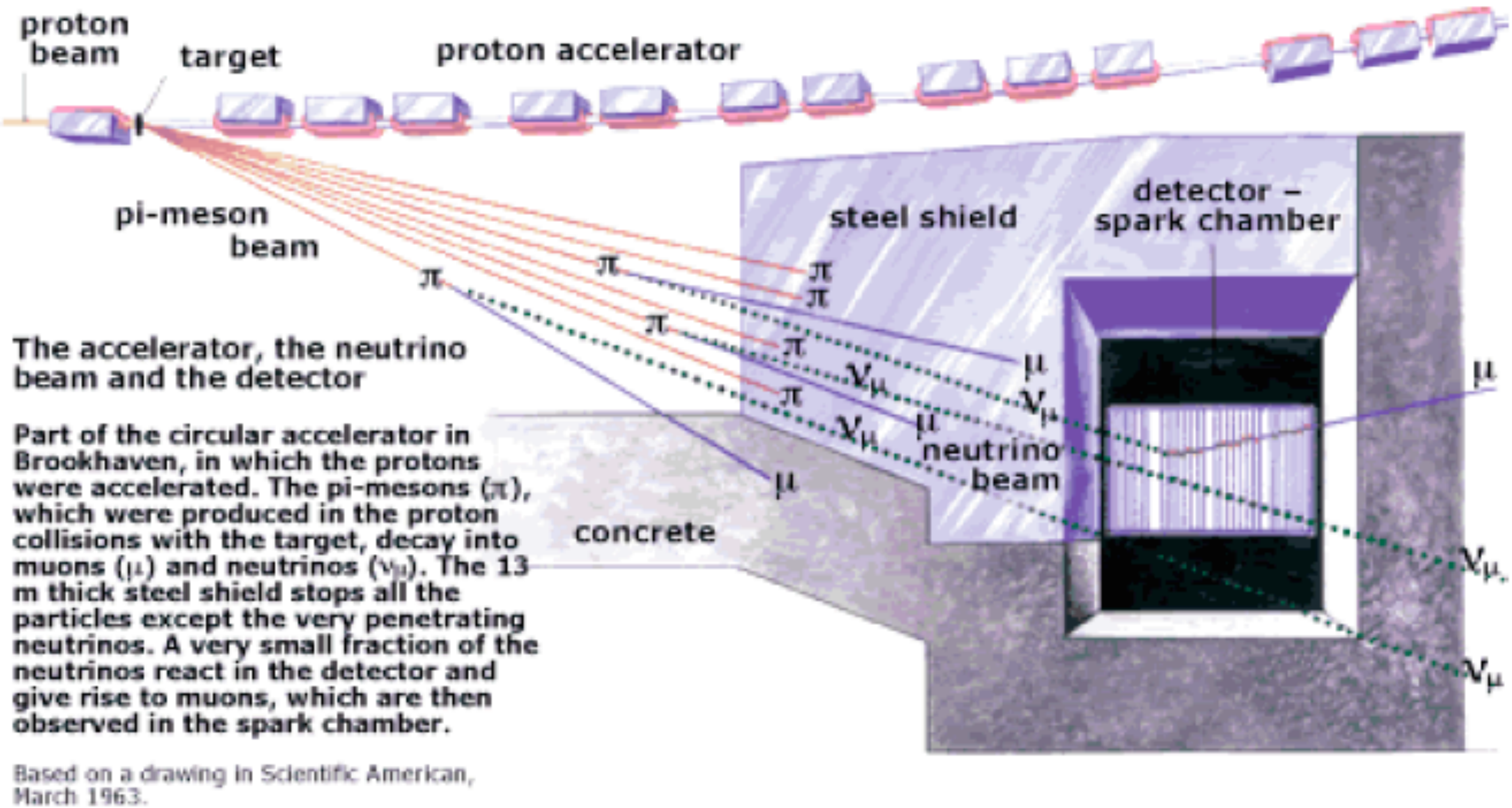
Each with 200 l of water with $CdCl_2$





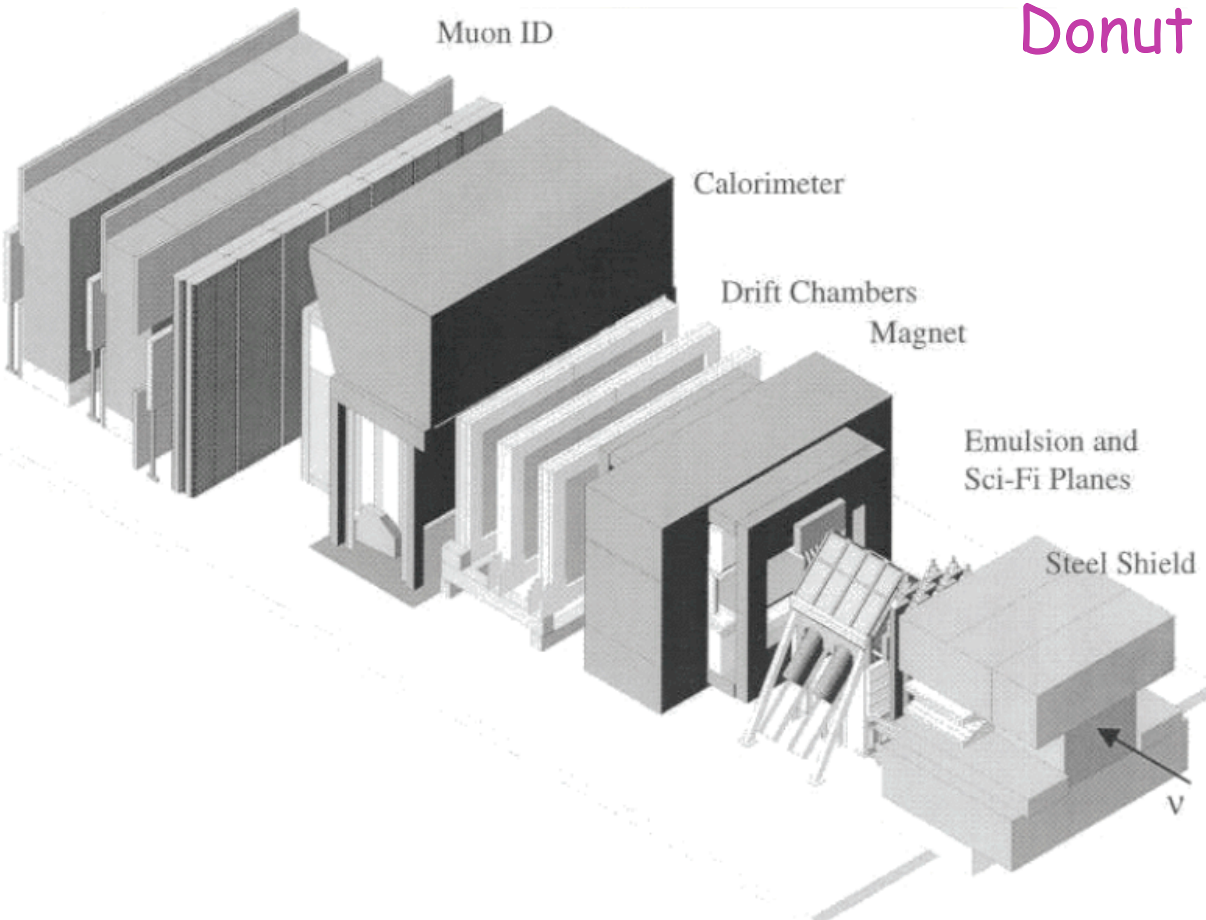
$\bar{\nu}_e$ **is seen !**

Not Just One, But Two types !



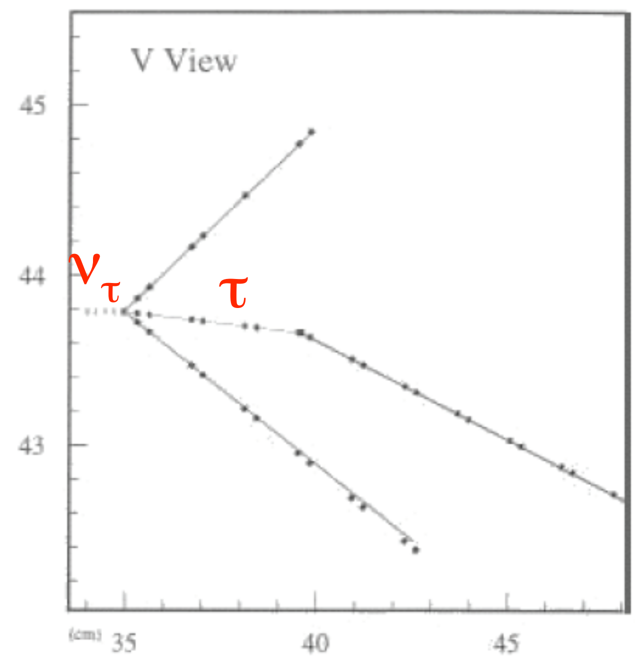
1988 Nobel prize

Wait, History Repeats Itself !



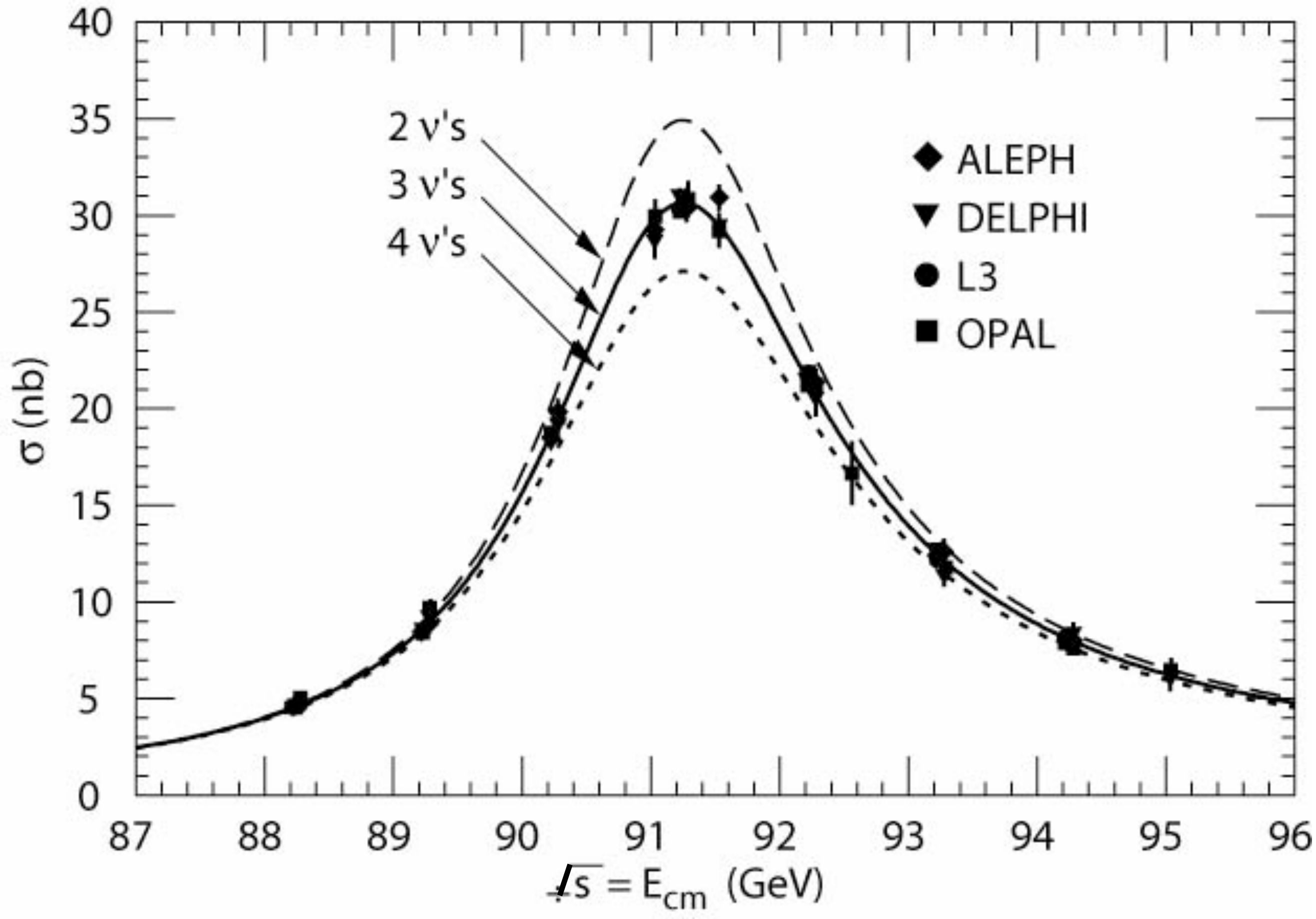
Donut at Fermilab (2000):

$D_s \to \tau + \nu_\tau$



$\nu_\tau + N \to \tau + \text{hadrons}$

Three and No More



Lepton Numbers

	e^-	ν_e	μ^-	ν_μ	τ^-	ν_τ	e^+	$\bar{\nu}_e$	μ^+	$\bar{\nu}_\mu$	τ^+	$\bar{\nu}_\tau$
L_e	1	1	0	0	0	0	-1	-1	0	0	0	0
L_μ	0	0	1	1	0	0	0	0	-1	-1	0	0
L_τ	0	0	0	0	1	1	0	0	0	0	-1	-1

Total lepton number: $L = L_e + L_\mu + L_\tau$

Conservation of lepton numbers can explain why

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

(b) $\mu^- \not\rightarrow e^- + \bar{\nu}_e + \nu_\mu$

(c) $\tau^- \not\rightarrow e^- + \gamma$ $(< 2.6 \times 10^{-6}, 90\%\ CL)$

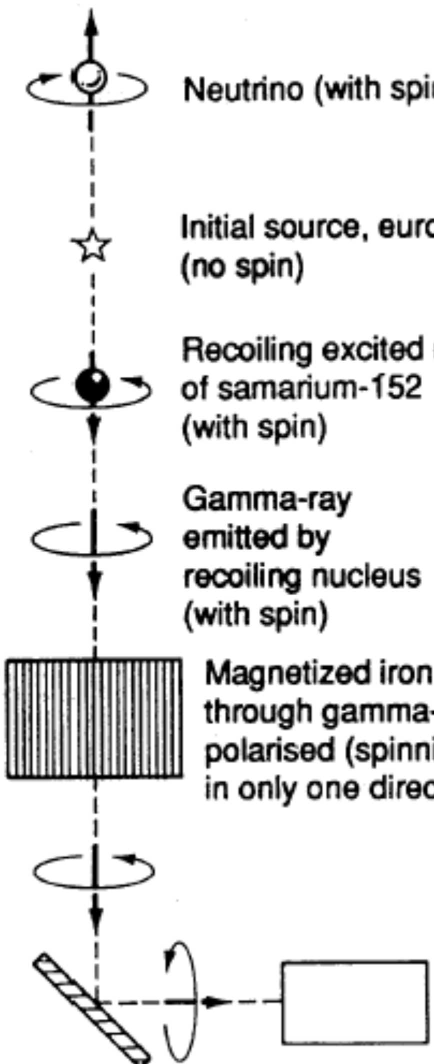
(d) $\mu^- \rightarrow e^- + e^- + e^+$ $(< 1 \times 10^{-12}, 90\%\ CL)$

Neutrinos Are Left-handed

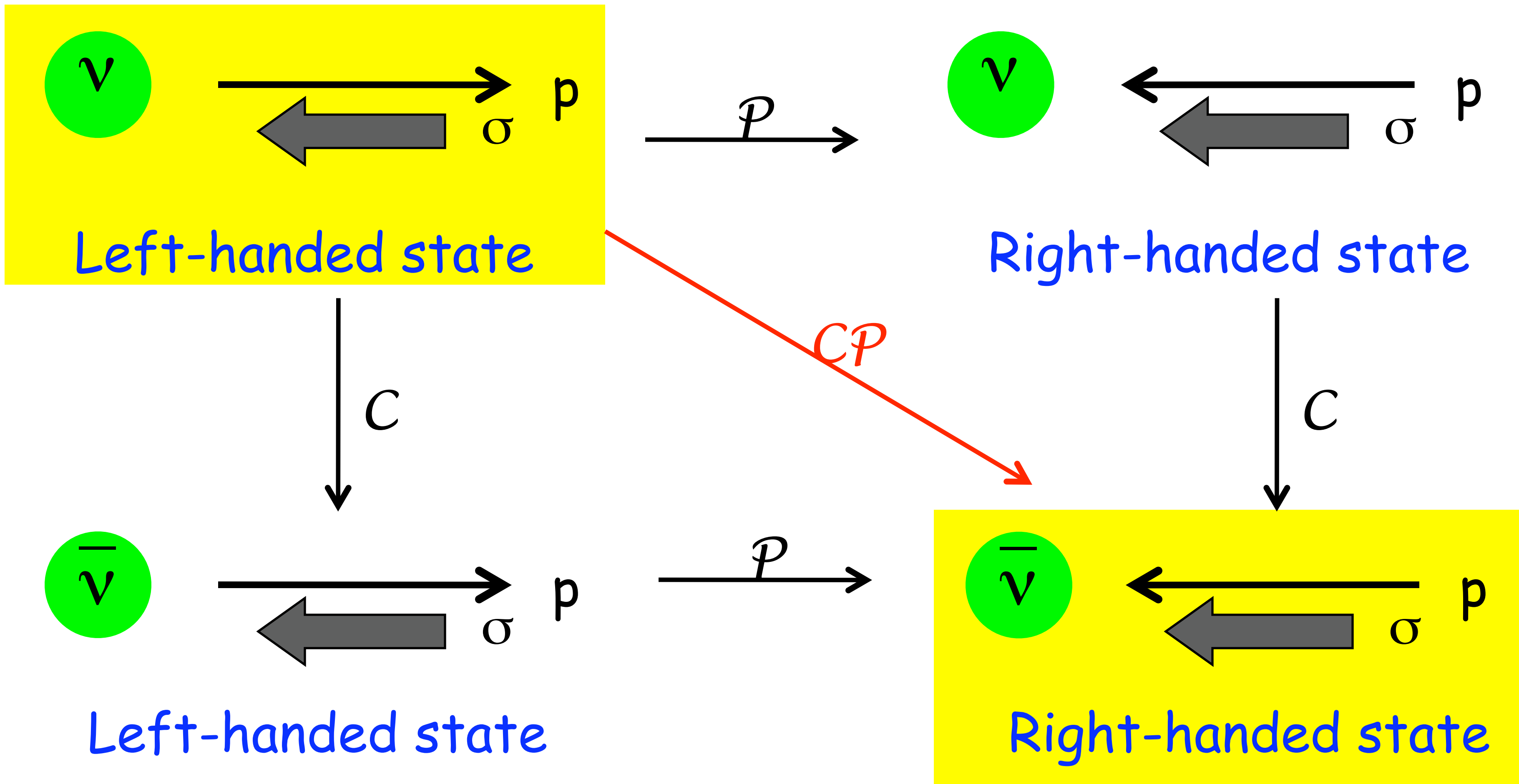
Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] $0-$, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

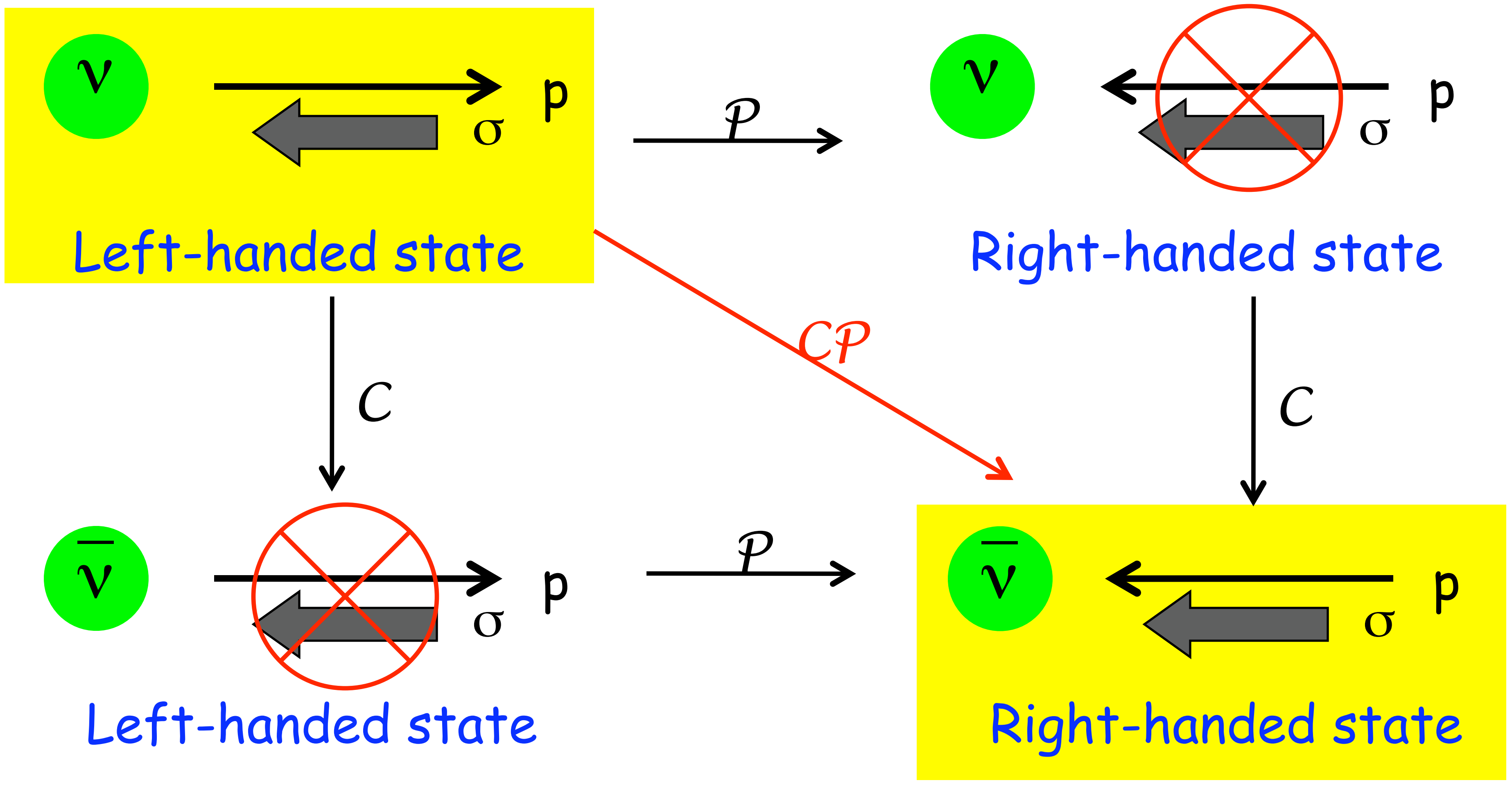


CP Transformation



Left-handed neutrino implies right-handed antineutrino

CP Transformation



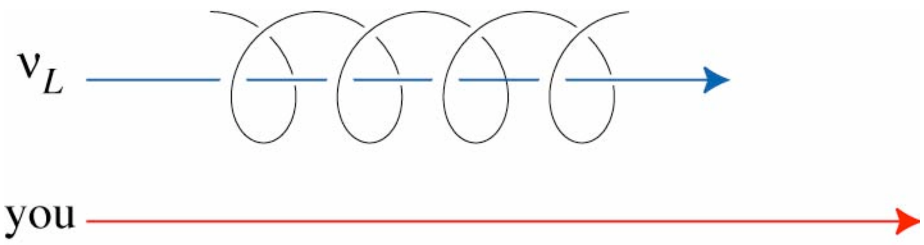
Right-handed neutrino and left-handed antineutrino do not exist.

Neutrinos Believed To Be Massless

- All neutrinos are left-handed $\Rightarrow$ massless
- If they have mass, can't go at speed of light:

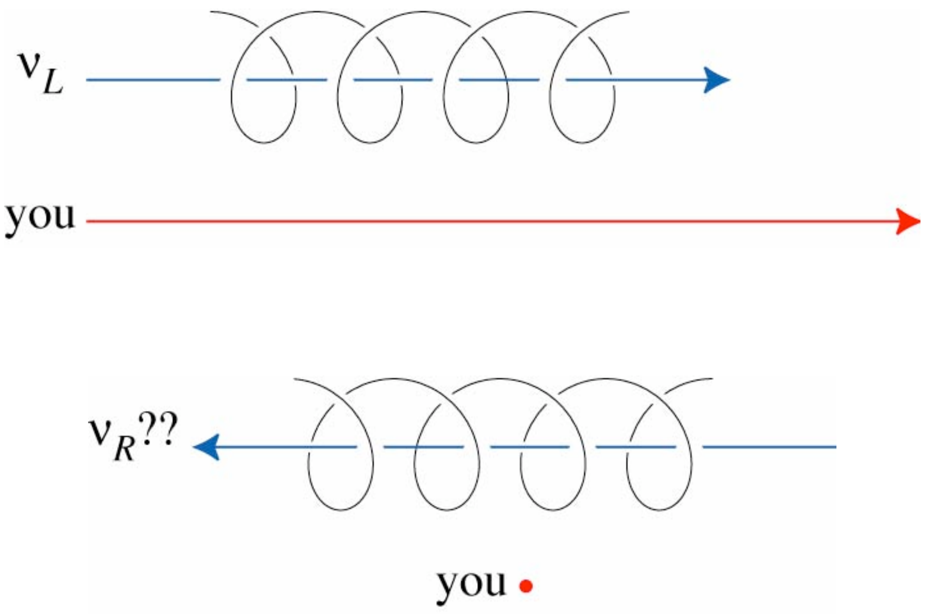
Neutrinos Believed To Be Massless

- All neutrinos are left-handed $\Rightarrow$ massless
- If they have mass, can't go at speed of light:



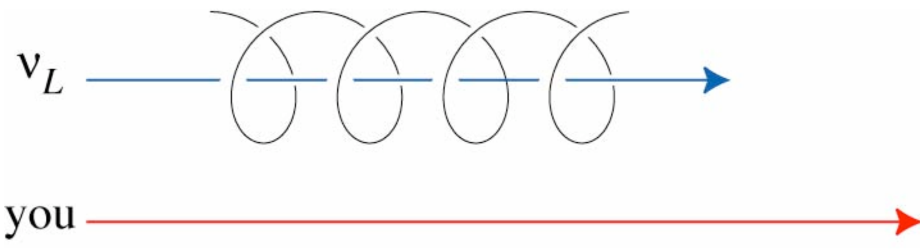
Neutrinos Believed To Be Massless

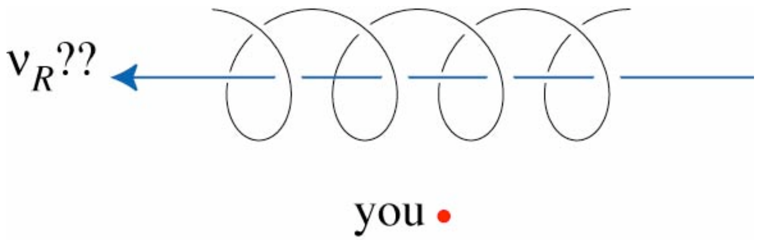
- All neutrinos are left-handed $\Rightarrow$ massless
- If they have mass, can't go at speed of light:



Neutrinos Believed To Be Massless

- All neutrinos are left-handed $\Rightarrow$ massless
- If they have mass, can't go at speed of light:





- Now the neutrino becomes right-handed??

  $\Rightarrow$ contradicts experimental findings

  $\Rightarrow$ neutrino can't be massive

Standard Model of Particle Physics

Fermions are grouped into weak-isospin doublets or singlets:

$$\text{Quarks}: \quad \begin{pmatrix} u \\ d' \end{pmatrix}_L \; u_R \; d_R \qquad \begin{pmatrix} c \\ s' \end{pmatrix}_L \; c_R \; s_R \qquad \begin{pmatrix} t \\ b' \end{pmatrix}_L \; t_R \; b_R$$

$$\text{Leptons}: \quad \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \; e_R^- \qquad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \; \mu_R^- \qquad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \; \tau_R^-$$

Gauge bosons : $W^{\pm}, Z, \gamma, g_i$

Coupling constants : α_s, g, g' such that $g = |q_e|/\sin\theta_W$, $\quad g' = g\tan\theta_W$

where $\sin^2\theta_W \approx 0.231$

Higgs : $H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$ with vacuum expectation value $\langle H \rangle_0 = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$ $\quad v \approx 246$ GeV

Some Remarks About Standard Model

- All fermions are Dirac particles
  - ν and $\bar{\nu}$ are not identical
- Mass of a Dirac particle arises from its interaction with the Higgs field in the vacuum:
  - mass operator, $m = \lambda_f \langle H \rangle_0 f^c f \quad \Rightarrow \quad m_e = \lambda_e \langle H \rangle_0$

Yukawa coupling

annihilates f_L/ creates f_R

annihilates $\bar{f}_L$/ creates $\bar{f}_R$

- No ν_R (no ν^c).
  - neutrinos are massless
- W and Z only couple to the left-handed states.

Quark Mixing

- The weak eigenstates of quarks are related to the mass eigenstates via the Cabibbo-Kobayashi-Maskawa (CKM) matrix:

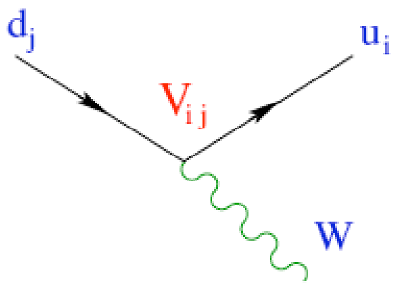
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

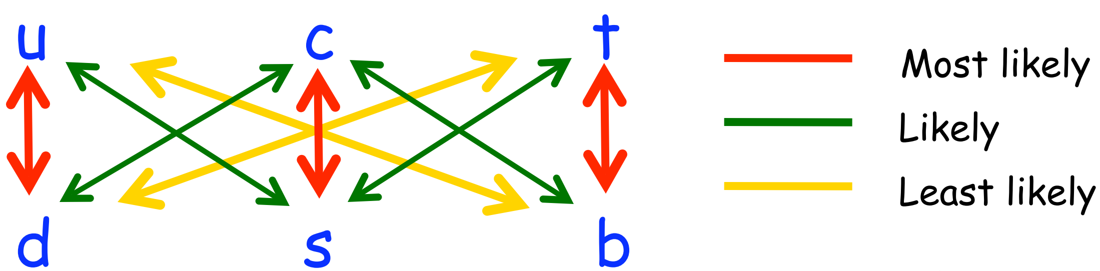
where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ with i, j = 1, 2, 3

- Measured: $\theta_{12} = 13°$, $\theta_{23} = 2.4°$, $\theta_{13} = 0.21°$, $\delta = 60° \pm 14°$. This yields

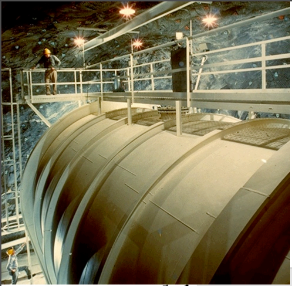
$$V = \begin{pmatrix} 0.9742 & 0.2257 & 0.00359 \\ 0.2256 & 0.9733 & 0.0415 \\ 0.00874 & 0.0407 & 0.9991 \end{pmatrix}$$

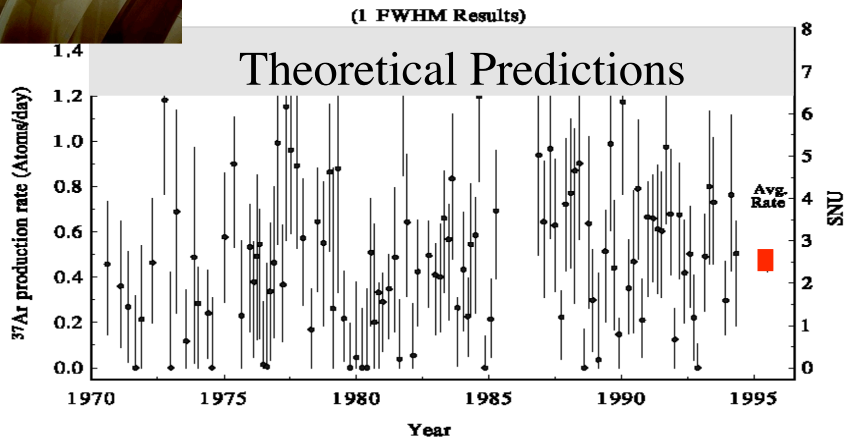
- Transition between quarks:



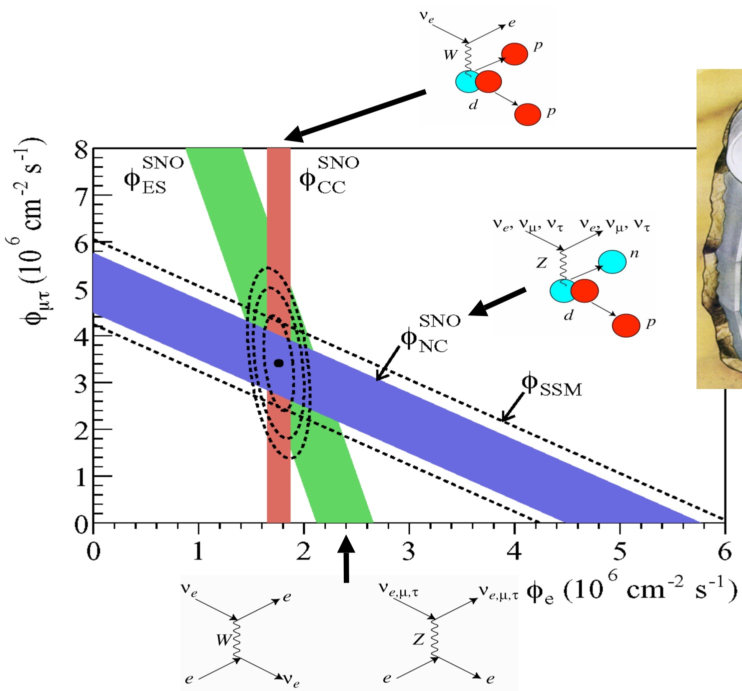


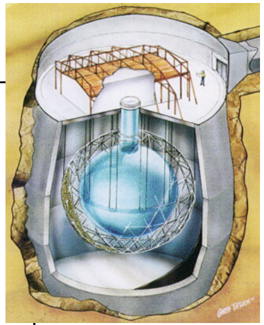
Discoveries of Neutrino Oscillation

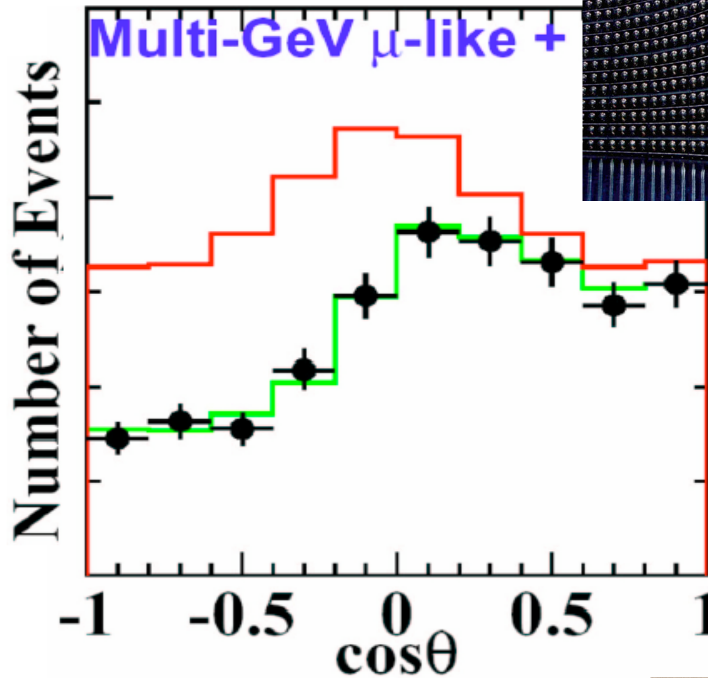


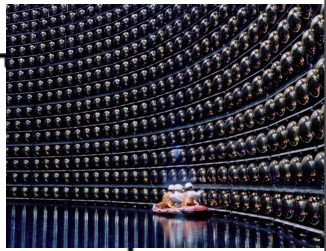


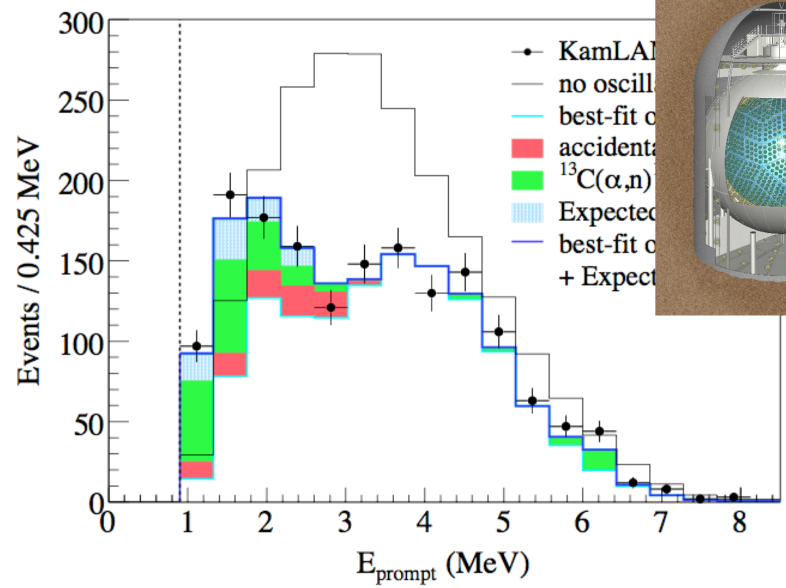
1 SNU = 10^{-36} interaction/atom/s

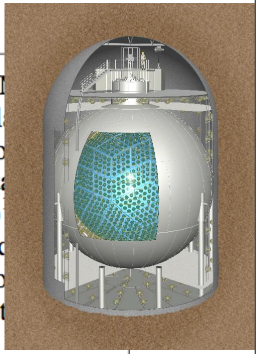












Neutrino Mixing

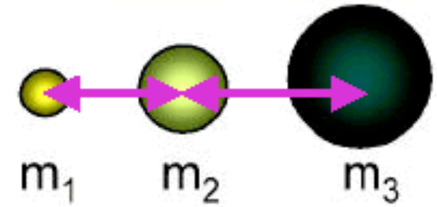
- If neutrinos are massive, it is possible that the weak eigenstates are not the same as the mass eigenstates:

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Weak eigenstates
„flavor eigenstates"

Mass eigenstates



$$\Delta m_{ij}^2 = \left| m_i^2 - m_j^2 \right| \rightarrow \Delta m^2{}_{12}, \Delta m^2{}_{23}$$

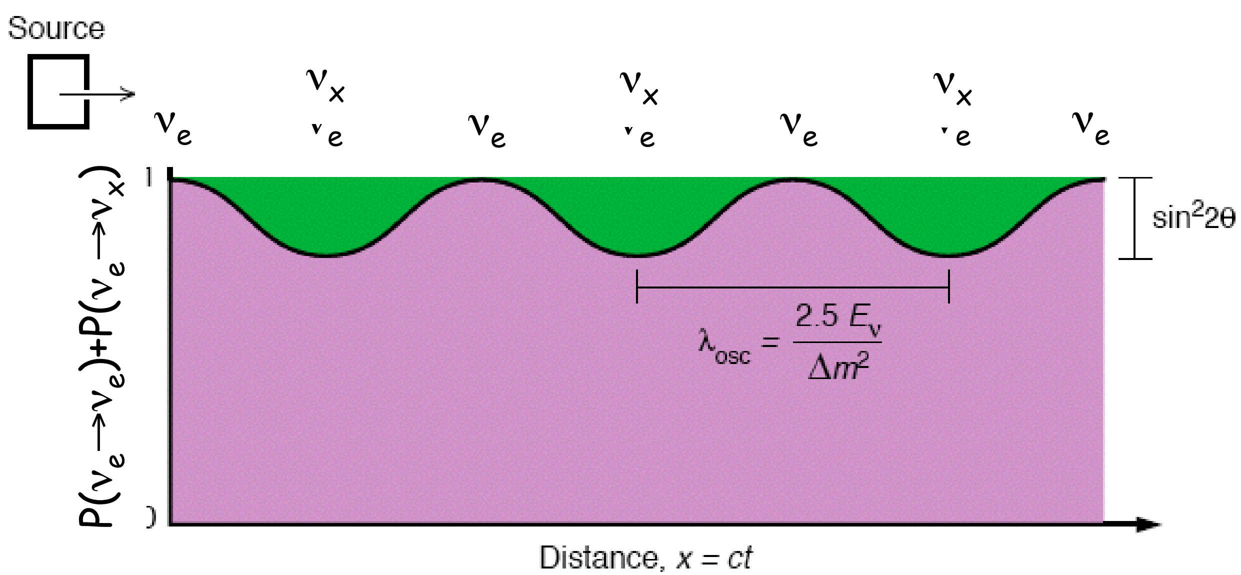
More On Neutrino Mixing

- Parametrize the mixing matrix as:

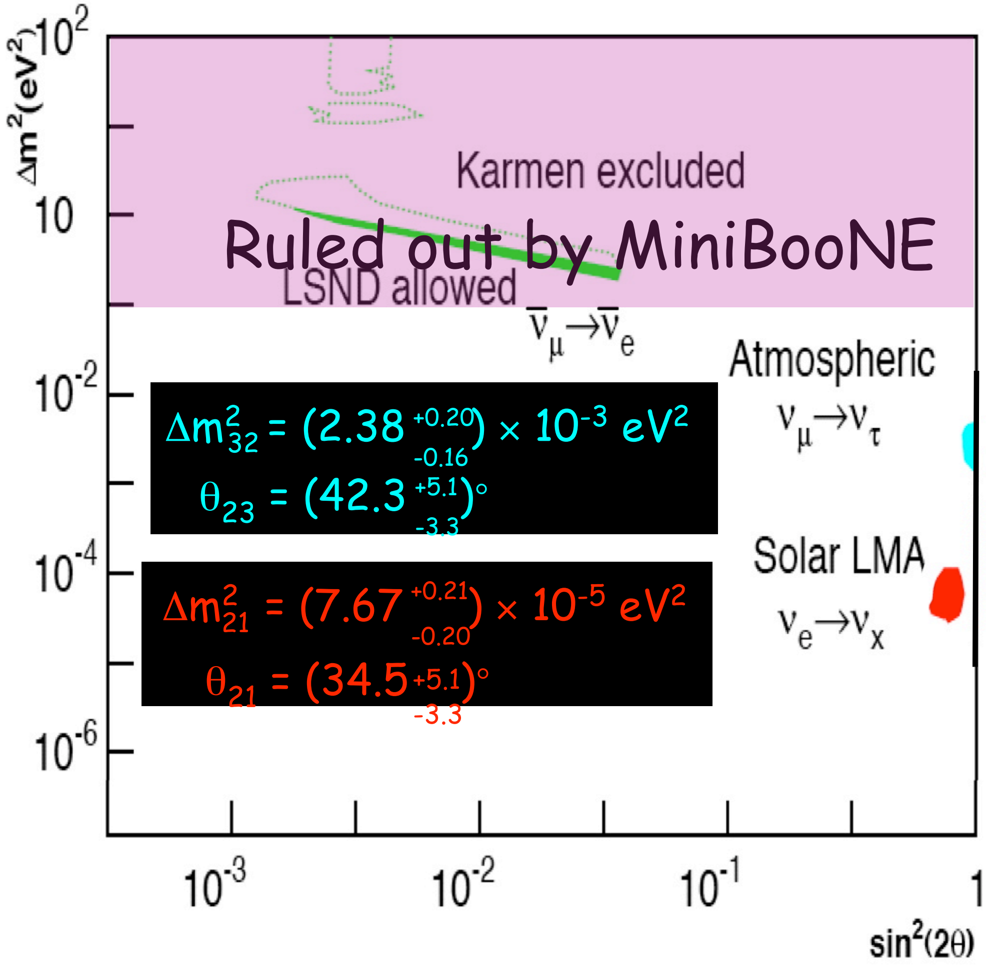
$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

- The survival probability of $\nu_e \rightarrow \nu_e$ is:

$$P(\nu_e \rightarrow \nu_e) = \langle \nu_e | \nu_e(t) \rangle^2 \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

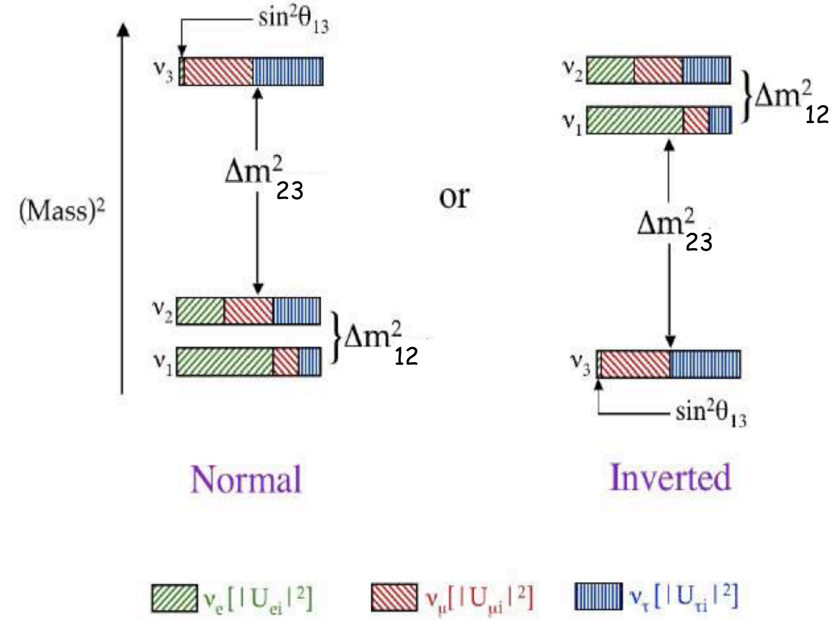


Current Status of Mixing Parameters



Unknowns:

- θ_{13}, δ,
- sign of Δm^2_{32} (mass hierarchy)



$$U_{bf} \approx \begin{pmatrix} 0.82 & 0.56 & 0.09 \\ 0.37-0.47 & 0.58-0.65 & 0.67 \\ 0.32-0.43 & 0.52-0.59 & 0.74 \end{pmatrix}$$

Implications of Neutrino Oscillation

- Lepton number is not conserved:

$$\Rightarrow \Delta L_i \neq 0, \qquad i = e, \mu, \tau$$

$$\Rightarrow \Delta L = 0$$

$$\Rightarrow \mu \rightarrow e + \gamma \text{ could exist}$$

- Neutrinos possess small but finite mass:

$\Rightarrow$ From the measured Δm^2 values and assume normal mass hierarchy:

taking $m_1 \approx 0$, then

$$m_2 \approx 9 \text{ meV}$$

$$m_3 \approx 50 \text{ meV}$$

$\Rightarrow$ Standard Model is incomplete

Fixing Standard Model: Majorana Mass

- Introduce a new effective interaction:

$$\frac{1}{M_{eff}}\left(h^0\nu_e - h^+e\right)^2$$

yields a Majorana mass operator

$$\frac{1}{M_{eff}}\langle H\rangle_0^2\nu_e\nu_e \qquad \text{with } \bar{\nu}_e = \nu_e$$

that, in general, generates a neutrino mass

$$m_\nu = \frac{2\langle H\rangle_0^2}{M_{eff}} = \frac{v^2}{M_{eff}}$$

Remarks:

(1) the Majorana operator violates lepton-number conservation.

(2) M_{eff} must be large to make m_ν small

- Seesaw mechanism

Fixing Standard Model: Sterile Neutrinos

- Introduce right-handed neutrino fields ν^c such that

$$\lambda_\nu \nu_e^c \left(\nu_e h^0 - e h^+\right)$$

which yields, in general, a Dirac mass for each neutrino:

$$m_\nu = \frac{\lambda_\nu v}{\sqrt{2}}$$

Remarks:

(1) why $m_\nu \ll m_e$?

(2) the field ν^c and its states ν_R and $\overline{\nu}_L$ are weak isospin singlets with

- zero weak hypercharge
- no coupling to W, Z, and γ.

They are called sterile neutrinos.

(3) If the ν_L has mass, it may oscillate into a

What Lie Ahead in Neutrino Physics?

- What is the nature of a neutrino?

  - a Dirac particle?

$$\nu \neq \bar{\nu}$$

  - a Majorana particle?

$$\nu = \bar{\nu}$$

- What is the absolute mass of the neutrinos?
- How do the neutrinos get their mass?
- What is the magnetic moment a neutrino?
- What is the size of the neutrino mixing angle θ_{13}?
- What is the order of the neutrino masses?
- Is there CP violation in the neutrino sector?
- Are there heavy active neutrinos?

Charge Conjugation and Bar

Bar operator :

$$\overline{\psi} = (\psi^{*\mathbf{T}})\gamma_0$$

Charge cojugation :

$$\psi^C = C\,\overline{\psi}^{\mathbf{T}} = i\gamma_0\gamma_2\,\overline{\psi}^{\mathbf{T}}$$

$$(\psi_R)^C = (\psi^C)_L\,;$$

Dirac Neutrino

Dirac equation for electrons:

$$(i\gamma^{\mu}\frac{\partial}{\partial x_{\mu}} - m)\psi = 0;$$

$$L = \frac{1}{2}(\overline{\psi}(i\gamma^{\mu}\partial_{\mu})\psi - m_D^2\overline{\psi}\psi) + h.c.$$

it is convinient to work with R and L projections:

$$\psi_{\mathrm{R,L}} = \frac{1}{2}(1 \pm \gamma_5)\psi = P_{R,L}\psi;\ P_{\mathrm{R,L}} = \frac{1}{2}(1 \pm \gamma_5)$$

$$\psi = \psi_R + \psi_L;$$

$$\overline{\psi_R}\psi_R = \overline{\psi_L}\psi_L = 0$$

$$L_D^M = -\frac{1}{2}m_D^2(\overline{\psi}_L\psi_R + \overline{\psi}_R\psi_L)$$

electron is charged, thus no other mass terms allowed.

Applying the same for neutrino, one comes to Dirac neutrino description. In SM ν_{R} doesn't exist, hence $\mathrm{m}_{\nu} = 0!$

Majorana neutrino

ν is neutral $\Rightarrow$ $\overline{\psi}\psi^C$ and $\overline{\psi}^C\psi$ terms are allowed ($\psi^C = \mathrm{C}\psi\mathrm{C}^{-1}$)

$$L_M^M = -\frac{1}{2}\left[m_{ML}^2(\overline{\psi}_L(\psi^C)_R + \overline{(\psi^C)_R}\psi_L) + m_{MR}^2(\overline{\psi}_R(\psi^C)_L + \overline{(\psi^C)_L}\psi_R)\right]$$

introduce: $\nu_1 = \nu_L + (\nu^C)_R; \nu_2 = \nu_R + (\nu^C)_L$

$$L_M^M = -\frac{1}{2}\left[m_{ML}^2\overline{\nu}_1\nu_1 + m_{MR}^2\overline{\nu}_2\nu_2\right]$$

${\nu_{1,2}}^C = \nu_{1,2} \Rightarrow$ particle $\equiv$ anti-particle

Majorana description assumes 2-component neutrino.

In case of $\mathrm{m}_\nu = 0$, second one is sterile in SM, thus

Dirac and Majorana descriptions are identical.

See-Saw Mechanism

In the general case :

$$L_M = L_M^D + L_M^M$$

$$L_M = -\frac{1}{2}\begin{pmatrix}\overline{\nu_L} & \overline{\nu^C{}_L}\end{pmatrix}\begin{pmatrix} m_{ML} & m_D \\ m_D & m_{MR}\end{pmatrix}\begin{pmatrix}\nu^C{}_R \\ \nu_R\end{pmatrix}$$

$$L_M = -\frac{1}{2}(m_1\overline{\nu_1}\nu_1 + m_2\overline{\nu_2}\nu_2)$$

$$m_{1,2} = \frac{m_{MR}+m_{ML}}{2} \pm \sqrt{\frac{(m_{MR}-m_{ML})^2}{4} + m_D^2}$$

if $m_{MR} >> m_D, m_{ML}$:

$$m_1 \cong m_{MR};\, m_2 \cong \frac{m_D^2}{m_{MR}}$$

This can explain smallness of m_ν .