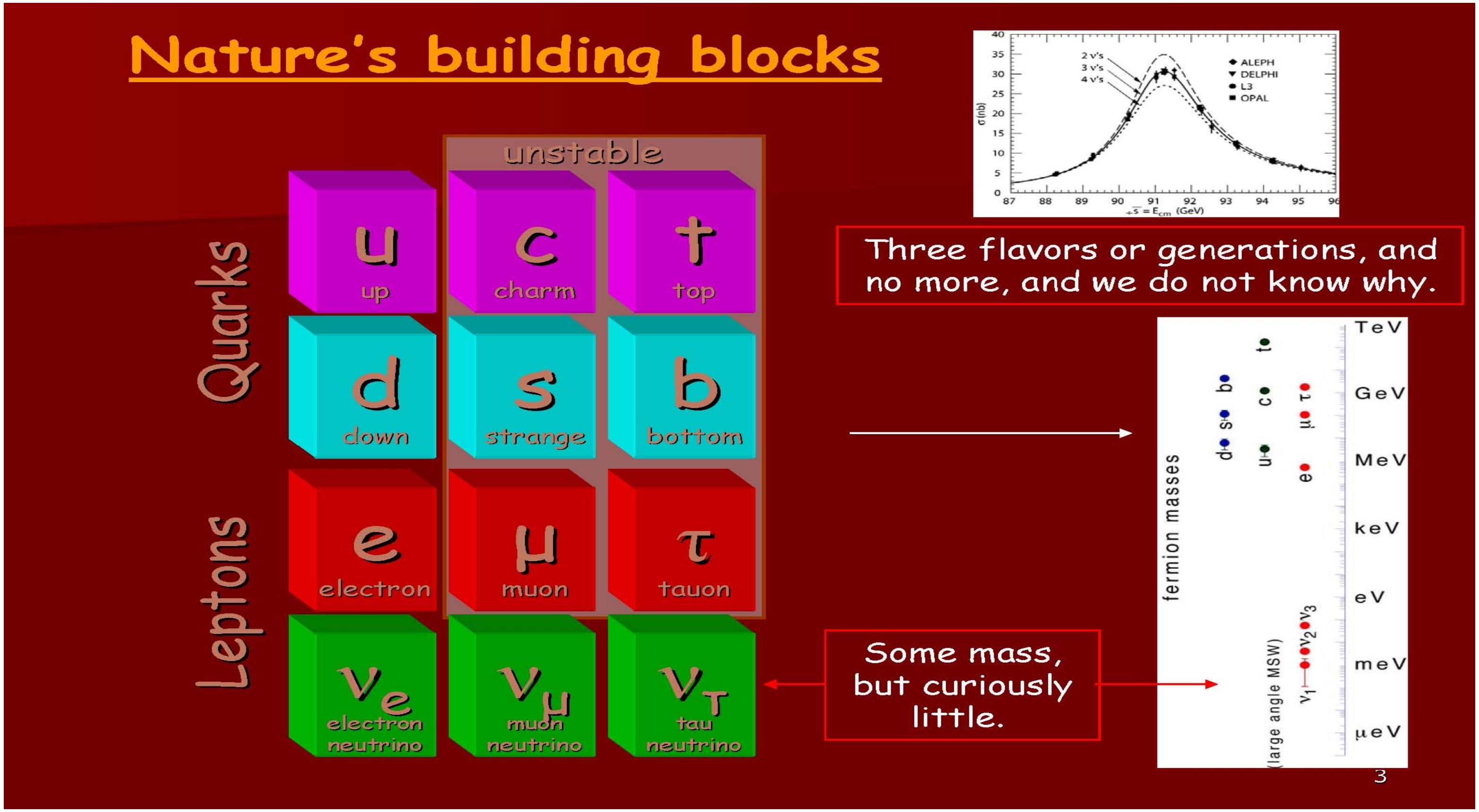
ν physics
in deep underground laboratories …

1. Double beta decay
2. Solar and atmospheric neutrinos
3. Neutrino oscillations
4. Neutrino astronomy
5. Neutrino from supernovae
6. Neutrinos from reactors
7. Neutrinos from beams
8. Geoneutrinos
9. …

… and in under-ice,
under-water experiments

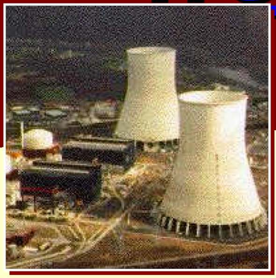
What is a neutrino?

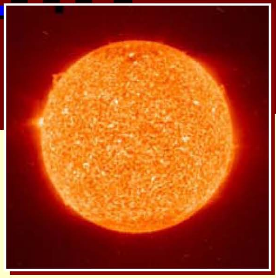
- **Stable Elementary Particle** – *3 over 6 constituents of (stable) matter*
- **No electric charge** – *cannot see it*
- **Very little interaction with matter** – *goes through the Earth unscathed*
- **Has very little mass** – *less than 1 millionth of electron's mass*
- **Lots of them throughout** – *100 million in your body any time!*



Where do Neutrinos come from?

✓ Nuclear Reactors (power stations, ships)



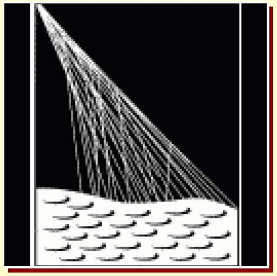


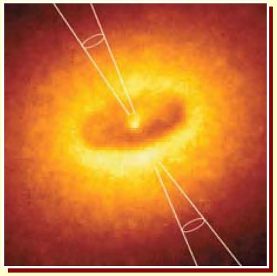
Sun ✓

✓ Particle Accelerator

Supernovae (star collapse)
SN 1987A ✓

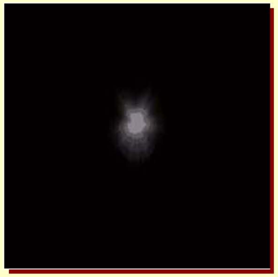
✓ Earth's Atmosphere (Cosmic Rays)





Astrophysical Accelerators
Soon ?

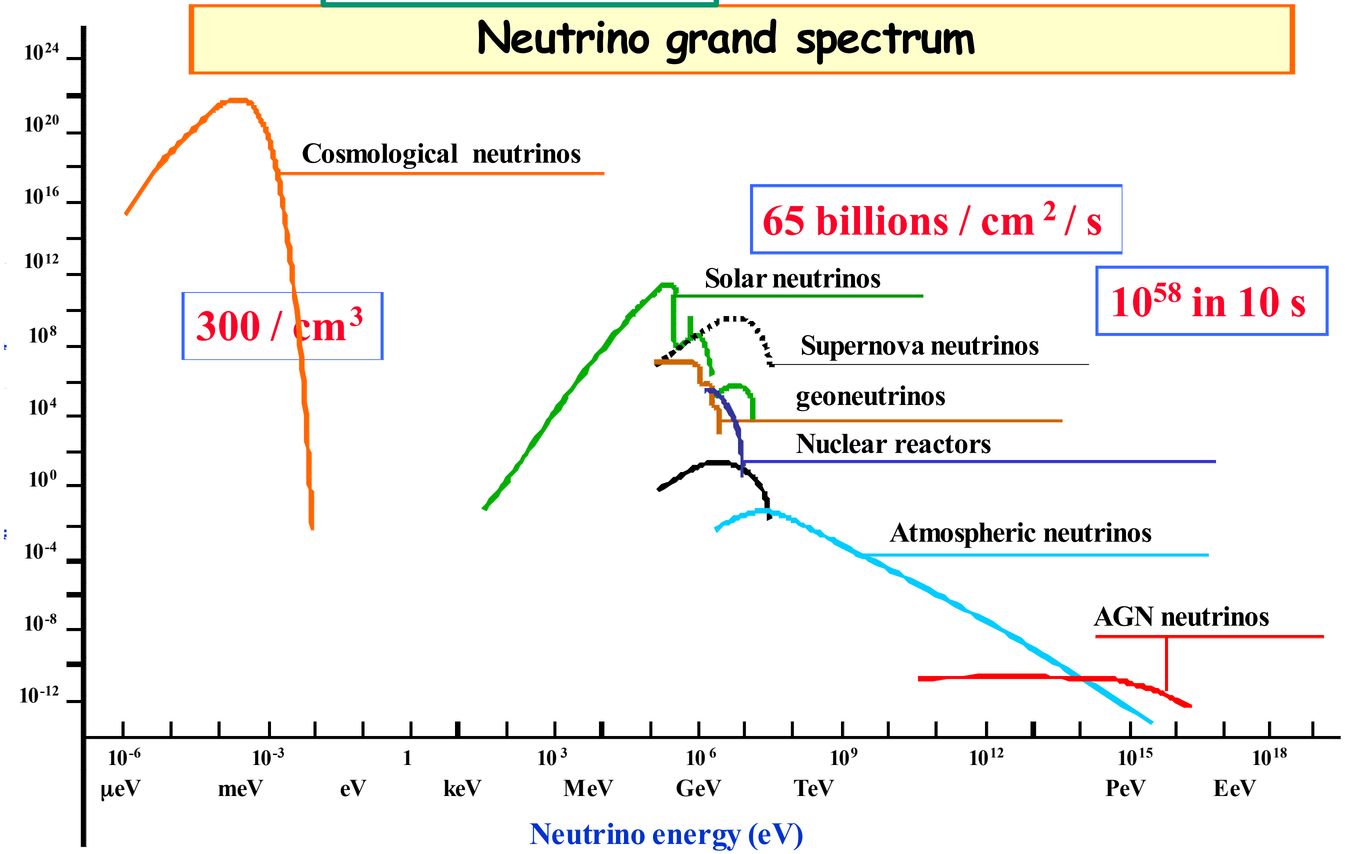
✓ Earth's Crust (Natural Radioactivity)



Big Bang (here 330 ν/cm^3)
Indirect Evidence

Sources of ν

& other information from: β and ββ decays



Sources of Neutrinos:

Natural:

(i) Atmospheric (10^{-4} s),
(ii) Solar (8 min),
(iii) Supernova (>10^4 yr),
(iv) Other astrophysical sources (GRB, AGN) (10^6 yr),
(v) Early Universe (10^{12} yr),
(vi) Earth's Interior (0.01 s).

- Artificial (Man-made):
  - (i)Reactors (10^{-4} s)
  - (ii)Accelrators (0.001 s)

(iii) Sources from β/EC decay isotopes

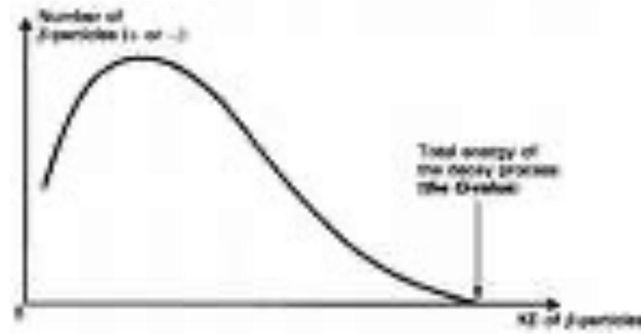
Early History:

November 1895 :William Roentgen discovers X-rays from Cathode Ray Tubes (Wuerzburg)

- January 1896: Henri Becquerel (Paris) hears about the X-rays in a lecture by Poincare
- February 1896: H.B. discovers Radioactivity(in Uranium ore) while trying to find natural sources for X-rays!
- 1898: Ernest Rutherford and Marie (and Pierre) Curie start working on Radioactivity and studying its properties
- Rutherford found: (a) the exponential decay law; (b) three types of Activity. Beta (penetrating and easily so easily) and Gamma (undeflected and most penetrating). Thus alphas and betas were charged and gammas were neutral.
- Curies found other stronger radioactive substances(Thorium, Radium, Polonium etc) and showed alphas were much heavier than betas(turned out to be electrons).

The beginning of ν…

1914 - Chadwick: Two-body decay would give monoenergetic electrons. Continuous energy spectrum of β inconsistent with 2-body decay!



1929 - Bohr: Goes as far as to suggest that energy is not conserved in beta decay!

Puzzle with Beta Spectrum

- Three-types of radioactivity: α, β, γ
- Both α, γ discrete spectrum because $E_{\alpha,\gamma} = E_i - E_f$
- But β spectrum continuous

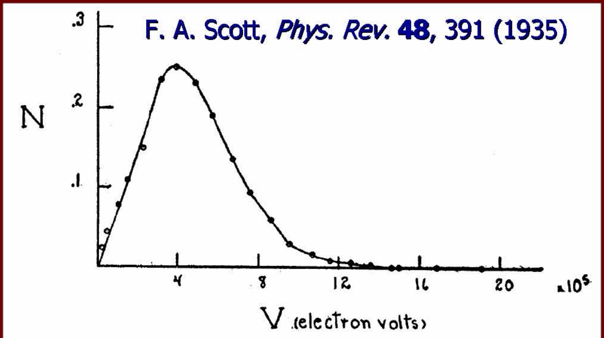


FIG. 5. Energy distribution curve of the beta-rays.

Bohr: *At the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β-ray disintegrations*

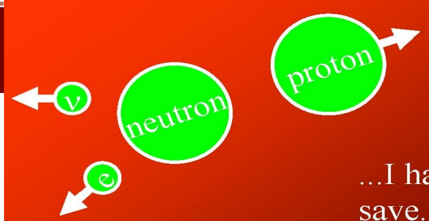
Desperate Idea of Pauli

4th December 1930

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

β decay



December 4, 1930

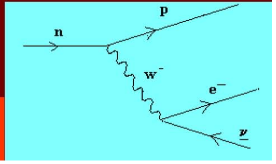
Dear radioactive ladies and gentlemen,

...I have hit upon a ‘desperate remedy’ to save...the law of conservation of energy. Namely the possibility that there exists in the nuclei electrically neutral particles, that I call neutrons...I agree that my remedy could seem incredible...but only the one who dare can win...

Unfortunately I cannot appear in person, since I am indispensable at a ball here in Zurich.

Your humble servant
W. Pauli

Note: this was before the discovery of the real neutron



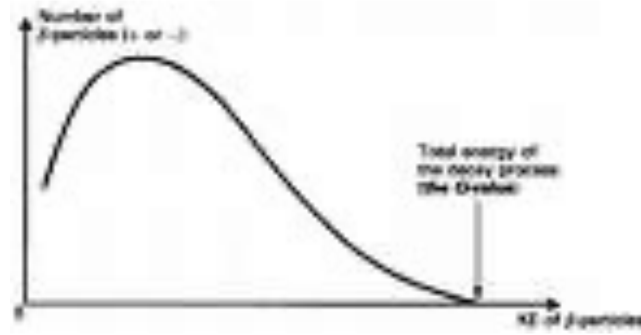
December 1933: Enrico Fermi

submits a paper to Nature: “Tentativo di Una Teoria Della Emissione di raggi Beta”

It was rejected:”speculations too remote from reality to be of interest to the readers”.

Eventually published in Nuovo Cimento This paper laid out the essential theory of beta decay that has survived almost unchanged until now, with “small” modifications. It predicted the spectrum, obtained the correct value for the coupling etc………

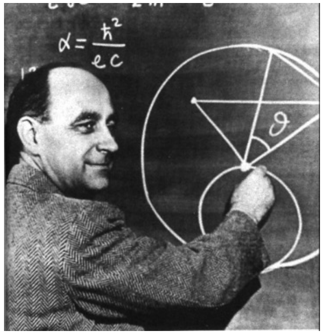
The beginning of ν…



1914 - Chadwick: Two-body decay would give monoenergetic electrons. Continuous energy spectrum of β inconsistent with 2-body decay!

1929 - Bohr: Goes as far as to suggest that energy is not conserved in beta decay!

1930 - W. Pauli postulates a new invisible particle



1933 E. Fermi defines it the neutrino ν

1956 Reines and Cowan gave experimental proof

Savannah River Reactor

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

$$e^+ + e^- \rightarrow 2 * \gamma(511[keV])$$

$$delayed: \; Gd(n, \sum \gamma' s = 8MeV)$$

Antineutrino Detection

inverse beta decay:

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

$$Q_{thr} = M_n + m_e - M_p \approx 1.8 \text{ MeV}$$

$$E_{vis} \cong E_\nu - E_n - 0.8\text{MeV}$$
$$\approx 1-8 \text{ MeV}$$
prompt event

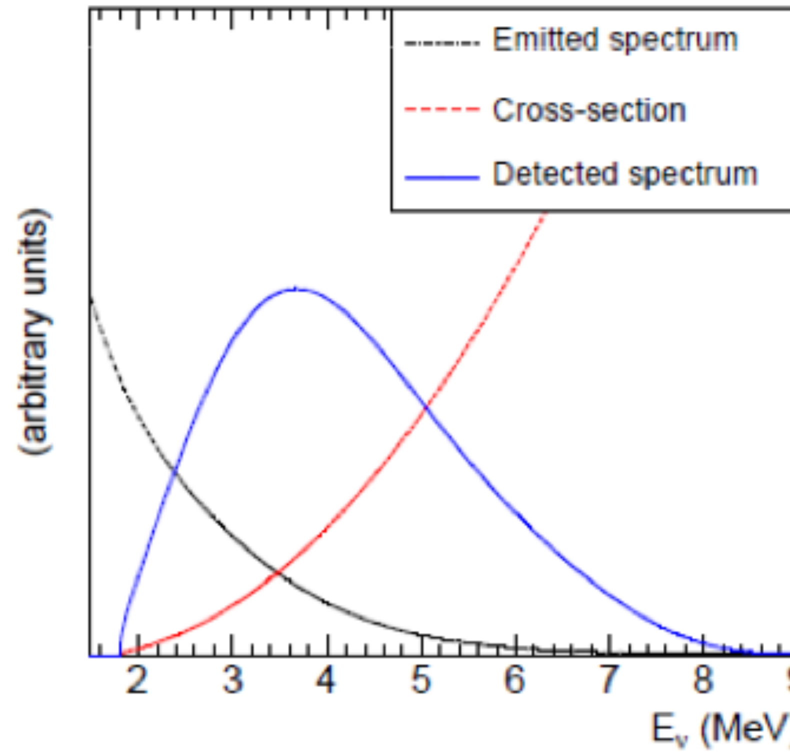
$$n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma\text{'s } (\sim 8\text{MeV}), \tau \sim 30\mu s$$
$$n + H \rightarrow d + \gamma\,(2.2\text{MeV}),\ \tau \sim 230\mu s$$
delayed event

Detection in Gd-loaded liquid organic scintillator

^{157}Gd, ^{155}Gd highest cross section for thermal n

release of total ~8 MeV γs

⇒ distinctive signature, well above radioactive background



Antineutrino Signal

inverse beta decay:

$$Q_{thr} = M_n + m_e - M_p \approx 1.8 \text{ MeV}$$

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

$$E_{vis} \cong E_\nu - E_n - 0.8\text{MeV}$$
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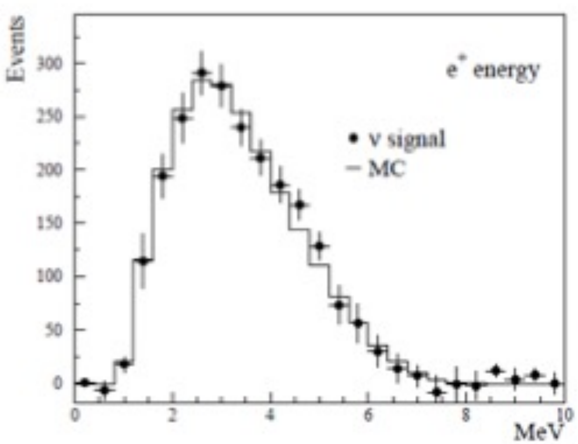
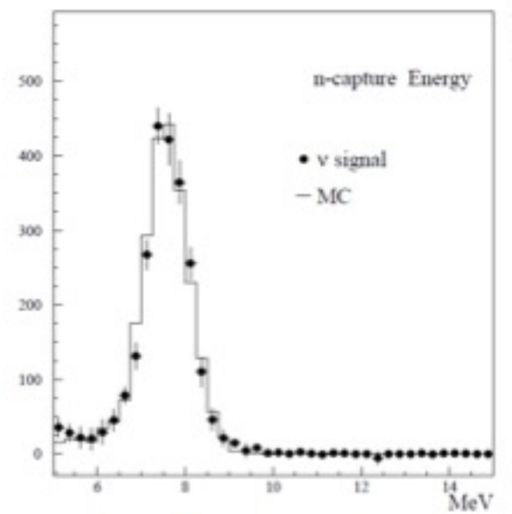
delayed event

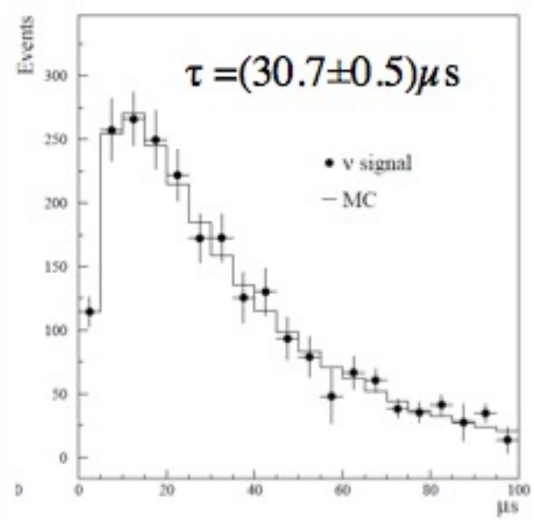
Detection in Gd-loaded liquid scintillator



e+ energy



n capture energy



e+-n time delay

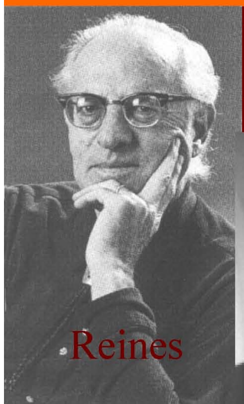
Apollonio et al. (2003)

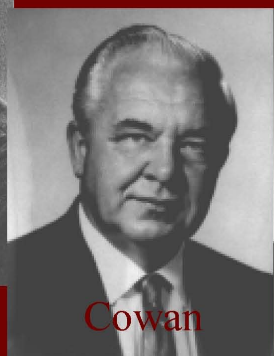
Project Poltergeist 1956

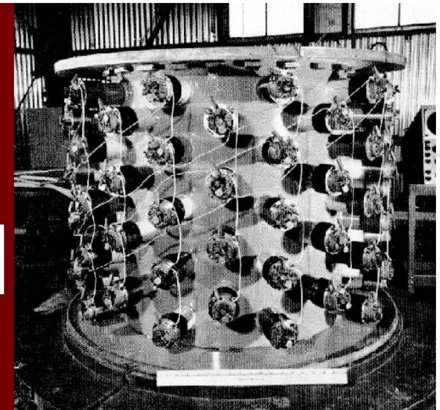
$$\nu + p^+ \rightarrow n^o + e^+$$

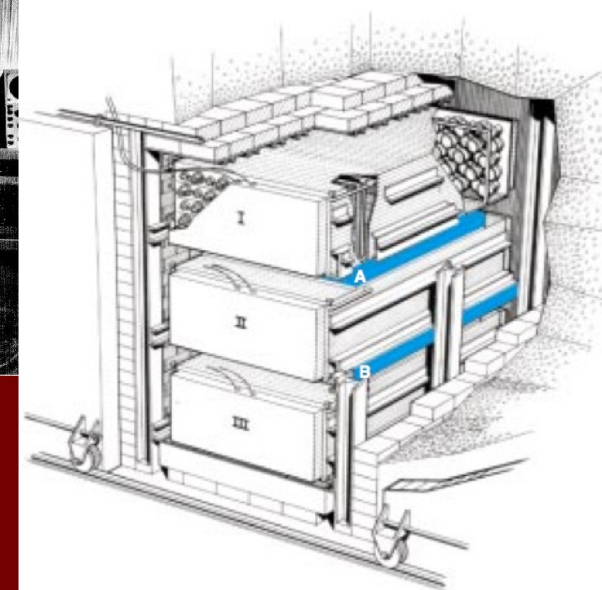
$$e^+ + e^- \rightarrow 2\gamma$$

$$n^o + \text{Cd} \rightarrow (\text{several})\,\gamma$$

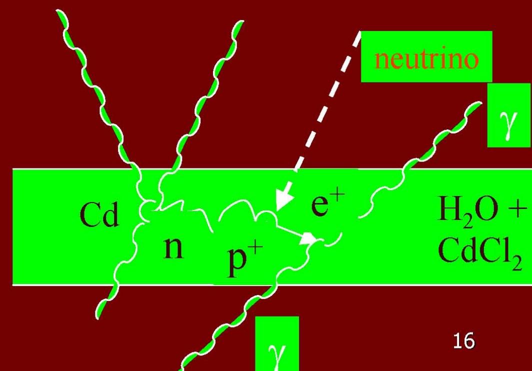




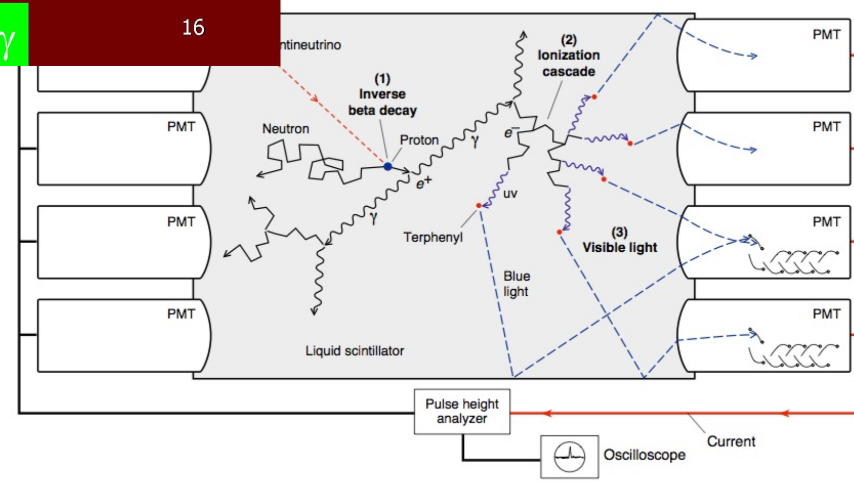




Signal 2γ, then several γ ~few μs later

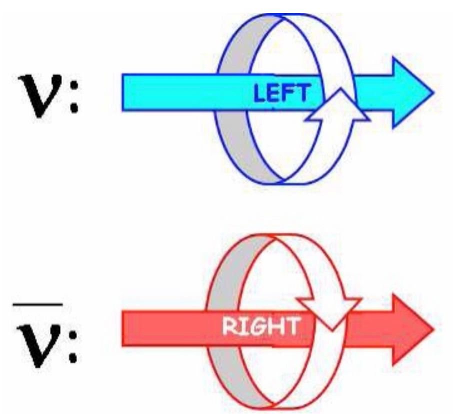


Experiment attempted at Hanford in 1953, too much background. Repeated at Savannah River in 1955. [Flux: 10^{13} neutrinos/(cm^2 s)]



ν is a Dirac or a Majorana Particle?

Teoria simmetrica dell'elettrone e del positrone **(1937).**
Majorana trova una particolare formulazione delle matrici di Dirac che gli permette di identificare una nuova particella priva di carica elettrica che non è fisicamente distinguibile dalla sua antiparticella
→ fanno la loro apparizione i ν di Majorana. Una loro proprietà fondamentale è che la sua massa a riposo $\neq$ zero.



$$\nu = \bar{\nu} \quad \text{(Majorana, 1937)}$$

- Dirac equation: $i\hbar\eth\psi - m\psi = 0$
- Majorana equation: $i\hbar\eth\psi - m\psi_c = 0$

  $i\hbar\eth\psi_c + m\psi = 0$

$$A\!\!\!/ \stackrel{\text{def}}{=} \gamma^\mu A_\mu$$

In this equation, ψ_c, is the charge conjugate of ψ, which can be defined in the Majorana basis as: $\psi_c = i\psi^*$

- The appearance of both ψ and ψ_c in the Majorana equation means that the field ψ cannot be coupled to a charged electromagnetic field without violating charge conservation, since particles have the opposite charge to their own antiparticles.
- To satisfy this restriction, ψ must be taken to be **neutral**.
- The quanta of the Majorana equation allow for two classes of particles, a neutral particle and its neutral antiparticle.
- The frequently applied supplemental condition ψ results in a single **neutral particle**, in which case ψ is known as a **Majorana spinor.**

Neutrinos are Left-handed

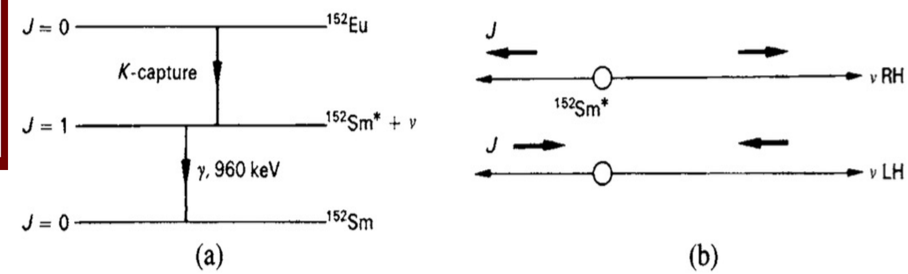
Helicity of Neutrinos*

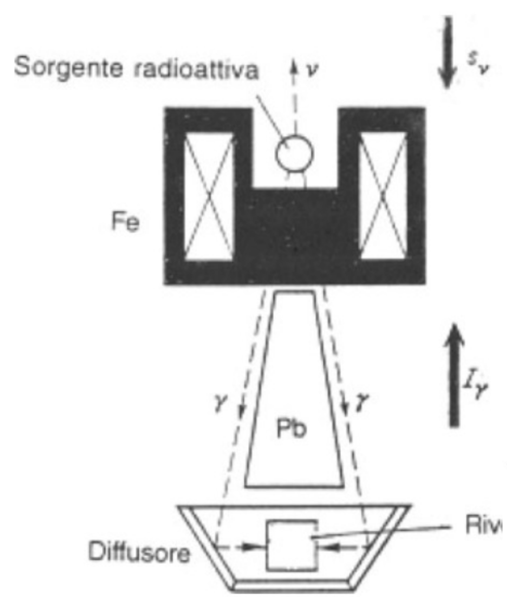
M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

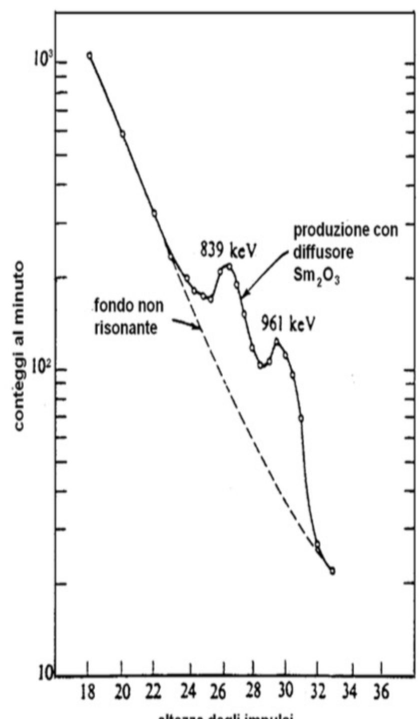
A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment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

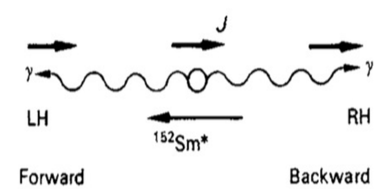
This result that neutrino is left-handed is exactly what was expected in the 1957 V - A theory of Sudarshan and Marshak and in the two component theory of Lee, Yang and Landau and Salam, so this was a confirmation of it.

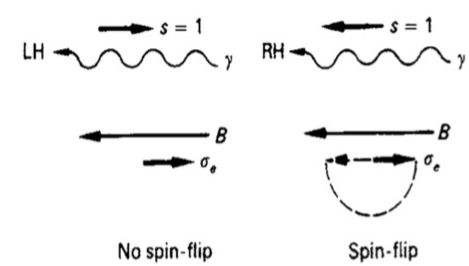
The fact that weak interactions are V – A was crucial in constructing the Standard Model of electroweak interactions a la Glashow, Salam and Weinberg.









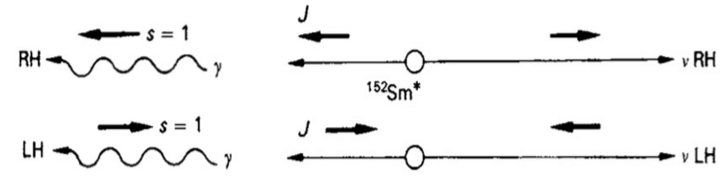


Distribuzione energetica dei gamma osservati dal rivelatore. La radiazione prodotta dalla cattura elettronica del ^{152}Eu eccita lo stato di 964 keV del ^{152}Sm; questo si diseccita emettendo gamma di 961 e 839 keV.

… in more details

$$^{152}\mathrm{Eu}(J=0) + e^- \rightarrow {}^{152}\mathrm{Sm}^*(J=1) + \nu_e.$$

$$^{152}\mathrm{Sm}^*(J=1) \rightarrow {}^{152}\mathrm{Sm}(J=0) + \gamma.$$



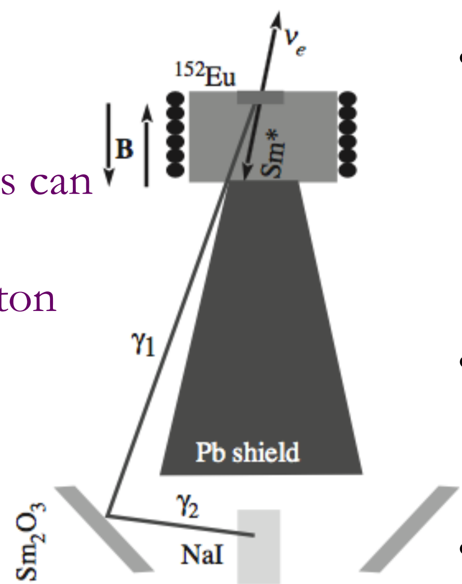
$s_z(e)$	$s_z(\mathrm{Sm}^*)$	$s_z(\nu)$	h_ν	$s_z(\gamma)$	h_γ
+1/2	1	−1/2	−	1	−
+1/2	0	+1/2	+	0	×
−1/2	−1	+1/2	+	−1	+
−1/2	0	−1/2	−	0	×

If the ν and γ are anti-parallel, they have the same helicity

The spins of the electrons responsible for the ferromagnetism are oriented opposite to B. These electrons can easily absorb the photons, by flipping their spin, if the photon spin has the direction of B.

The measured quantity is the asymmetry:

$$R = \frac{I_+ - I_-}{I_+ + I_-}.$$

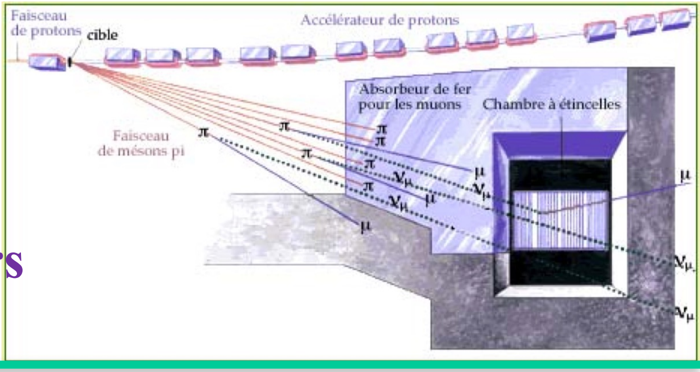


- Because the directions of the photon and neutrino momenta are nearly **uncorrelated**, the problem is to select only those photons that happen to be emitted opposite to the neutrino.
- This is done by scattering the photons in a sample of ^{152}Sm before they enter the detector.
- Only photons emitted opposite to the direction of the neutrino have sufficient energy to be **resonantly** scattered

ν_μ

New missing energy problems in π and μ decays, observed in cosmic rays

1964 Lederman, Schwartz & Steinberger First ν beam built at Brookhaven accelerator

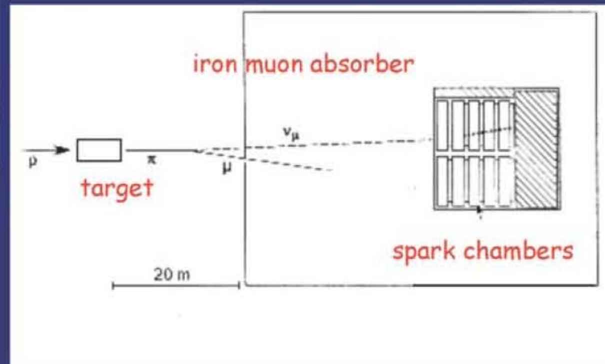


29 interactions showing a muon, none with an electron

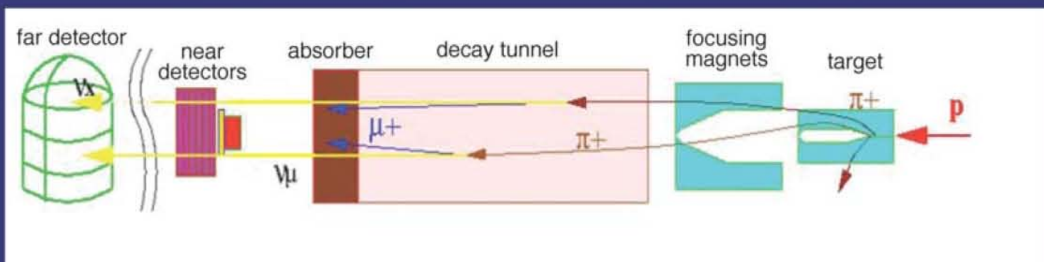
ν_μ *with* μ ν_e *with* e

⇒ **two different conserved leptonic numbers**

Schwartz Lederman Steinberger



Brookhaven experiment (1962)



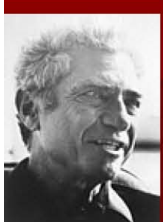
Conceptual layout of an accelerator neutrino beam

Confirmation that the second neutrino is different from the first!

Expectation: Since neutrinos are created with muons and electrons, the neutrino beam should create both electrons and muons in the detector.

Result: No electrons produced, only muons

Conclusion: There must be two kinds of neutrinos.



More than one kind of neutrino?

Date: 1962

Intent: Measure weak force at high energies

ν_μ

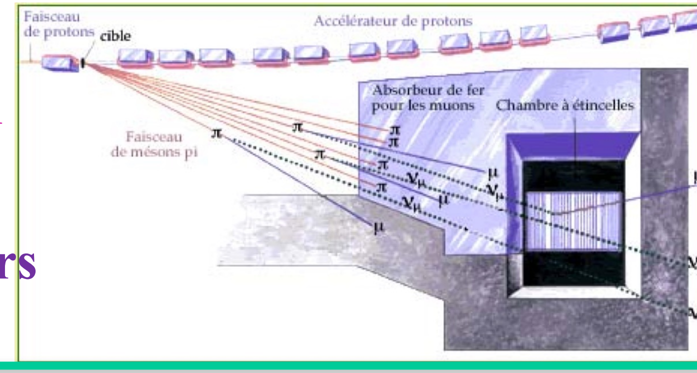
New missing energy problems in π and μ decays, observed in cosmic rays

1964 Lederman, Schwartz & Steinberger First ν beam built at Brookhaven accelerator

29 interactions showing a muon, none with an electron

ν_μ *with* μ ν_e *with e*

$\Rightarrow$ two different conserved leptonic numbers

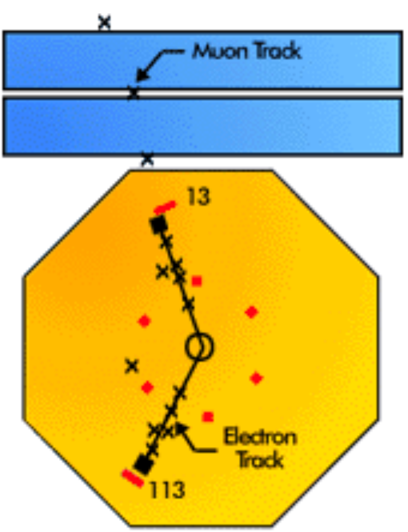


1975 Mark 1 detector at SPEAR: ~ 20 « anomalous events »

$$e^+ + e^- \Rightarrow e + \mu + X$$

The 3rd family

$$e^+ + e^- \Rightarrow \tau^+ + \tau^-$$



Three conserved lepton numbers

$$\tau \Rightarrow e + \nu_\tau + \nu_e$$

$$\tau \Rightarrow \mu + \nu_\tau + \nu_\mu$$

Direct proof: few events in the Donut exp

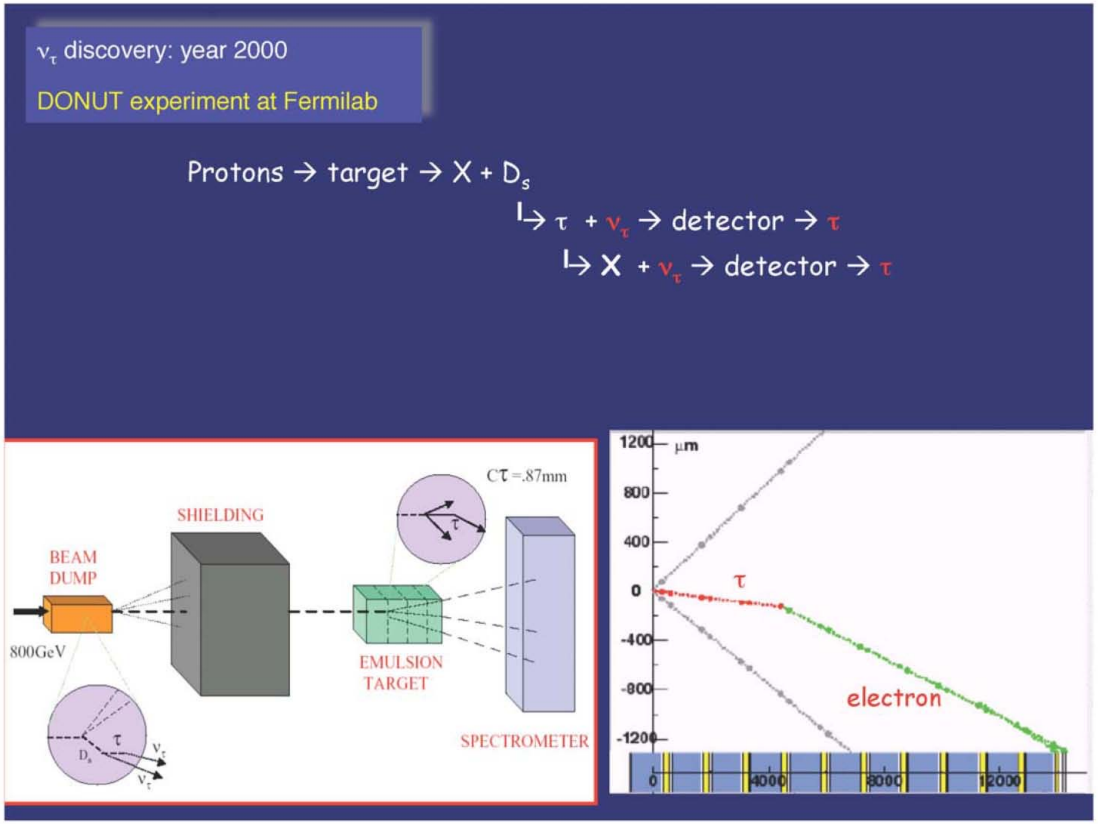
2000 Beam-dump at Fermilab: $D_s \Rightarrow \tau + \nu_\tau$

ν_τ

In 1975 Martin Perl et al. observed events at SLAC in e^+-e^- collisions which suggested the existence of a third lepton, christened the Tau(τ).

There was a third neutrino expected to be associated with this charged lepton.

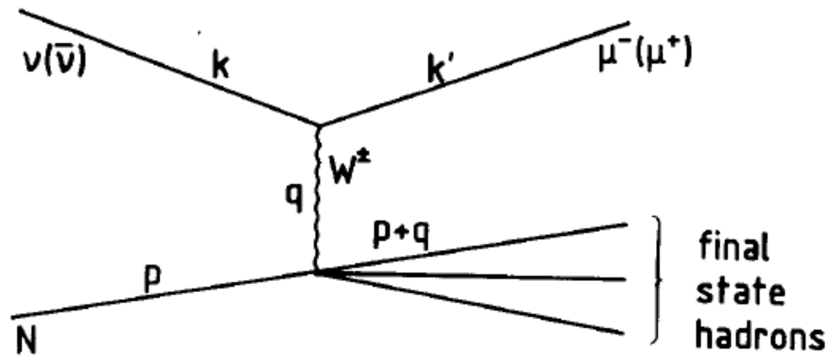
It required 25 years (2000) to confirm the existence of ν_τ by direct detection (Fermilab)!



Neutrino interactions

- Weak interactions only, high energy ν

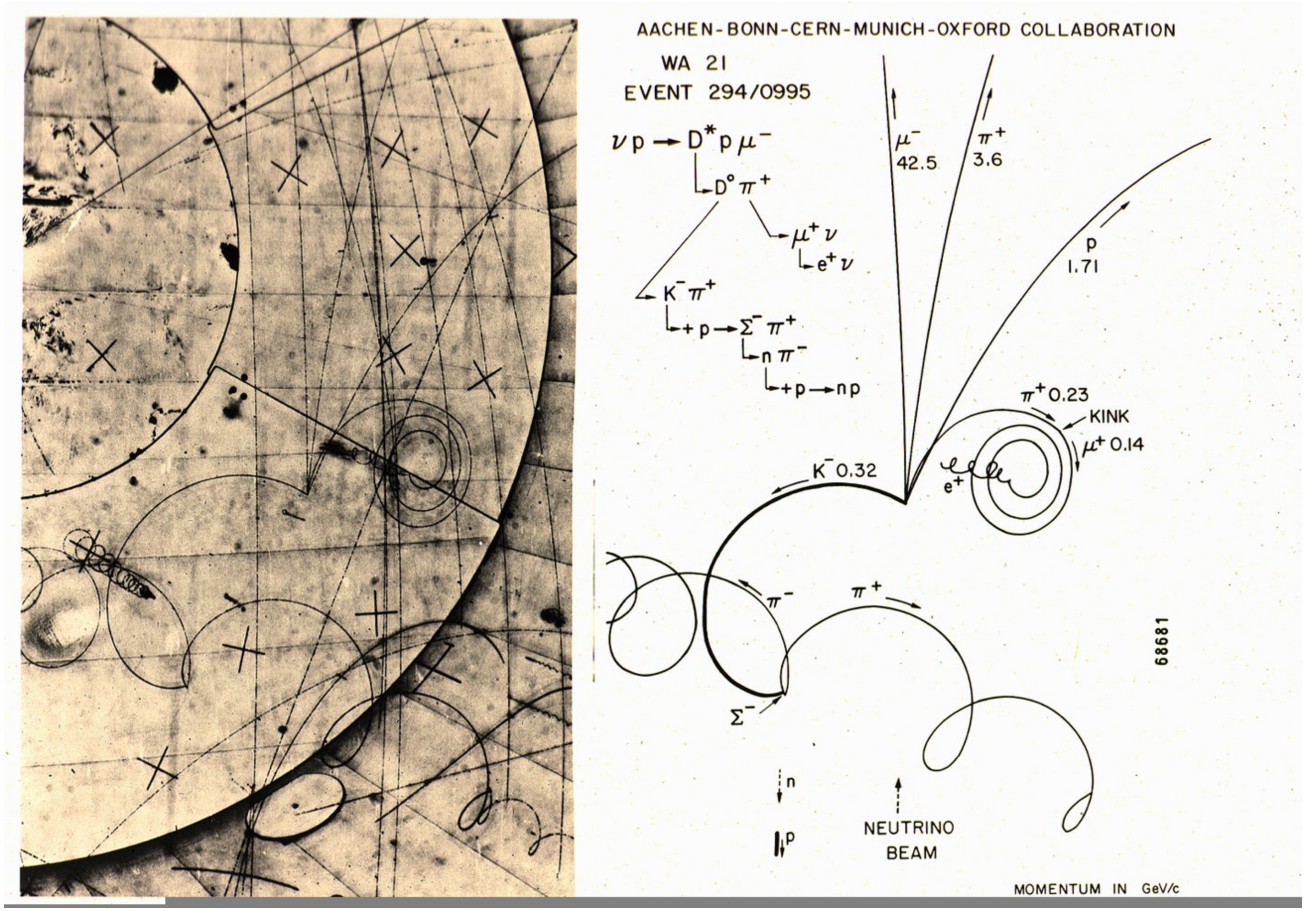
$$\nu_\mu + N \Rightarrow \mu + hadrons$$



- Nuclear reactions used in experiments:

1.	$\bar{\nu}_e + p \rightarrow e^+ + n$	**CC**	($E_{thr} \simeq 1.8$ MeV, reactor and geoch. expts)
2.	$\nu_e + (A,Z) \rightarrow e^- + (A,Z+1)$	**CC**	(E_{thr}, radiochemical and geoch. expts)
3.	$\nu_X + e^- \rightarrow \nu_X + e^-$	**NC (CC)**	(real time, e^- direction Sun-Earth; ν energy dist.; ν flavour sensitivity)
4.	$\nu_X + (A,Z) \rightarrow \nu_X + (A,Z)^*$	**NC**	(Recoil energy + E_γ; ν flavour)
5.	$\nu_e + d \rightarrow e^- + p + p$	**CC**	(real time, anti-correlation with Sun direction)
6.	$\nu_X + d \rightarrow \nu_X + p + n$	**NC**	(ν flavour sensitivity)
7.	$\nu_X + N \rightarrow \mu, e, \tau + hadrons$	**CC**	(HE ν)
8.	$\nu_X + N \rightarrow \nu_X + hadrons$	**NC**	(HE ν)

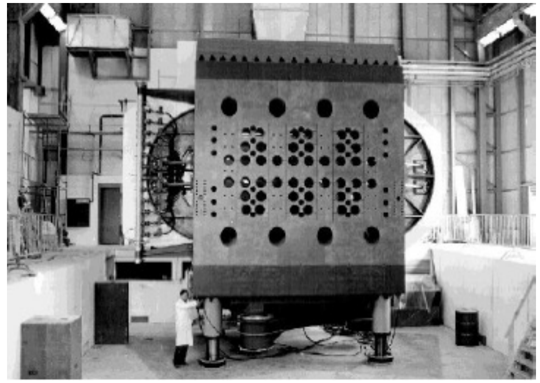
A textbook picture



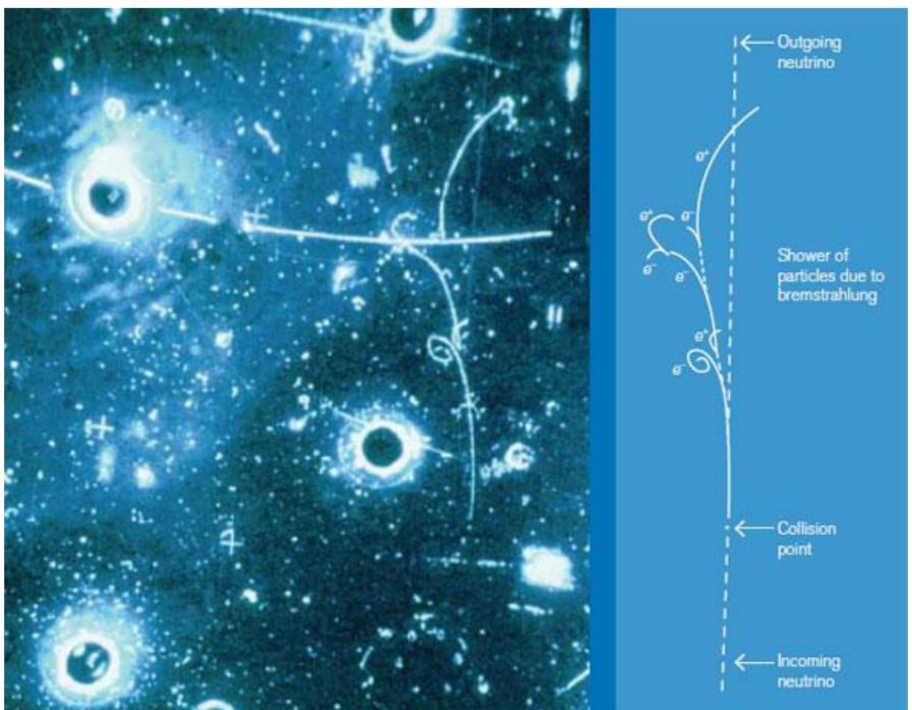
Gargamelle

Discovery of neutral currents

(1973)



Gargamelle bubble chamber: leptonic neutral current



$$\nu_\mu + N \rightarrow \nu_\mu + hadrons$$

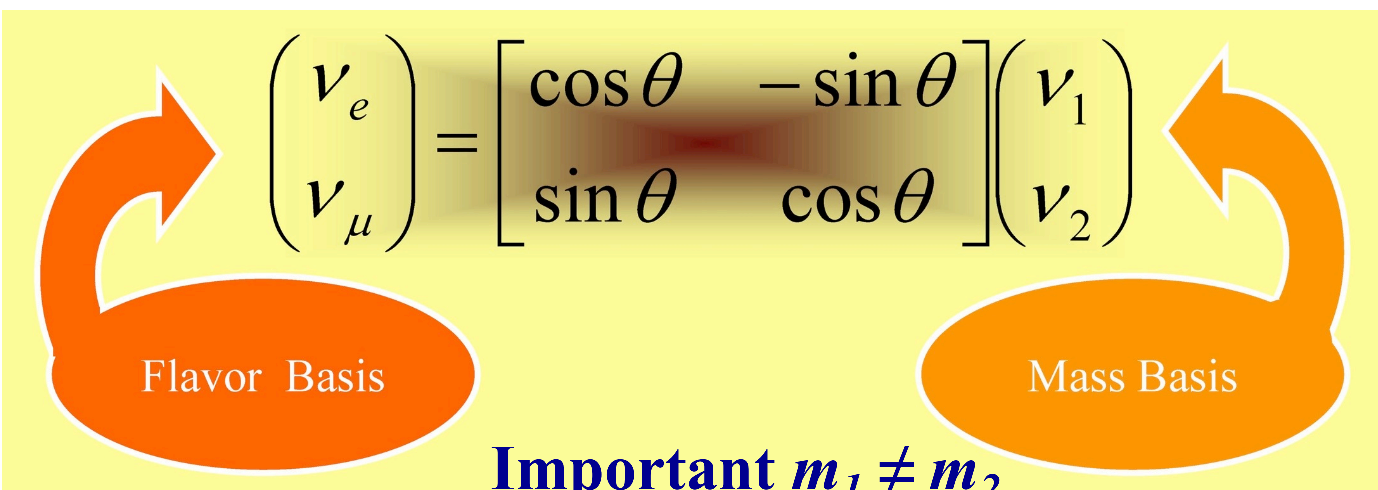
$$\boxed{\nu_\mu + e^- \rightarrow \nu_\mu + e^-}$$

Neutrino masses, mixings and oscillations

- When neutrinos have masses, the "flavor" states, such as ν_e and ν_μ, do **NOT** have well defined mass states.
- So the production is in these states, whereas the propagation afterwards is in terms of states with well defined masses.

  - B. Pontecorvo invented the concept of neutrino oscillation (1957)
  - Z. Maki, M. Nakagawa and S.Sakata (1962)
  - V. Gribov and B. Pontecorvo (1968)

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



Important $m_1 \neq m_2$

Bruno Pontecorvo
(1913–1993)
Invented ν oscillations

Neutrino oscillations

basics: flavor and mass eigenstates

- 1957: Bruno Pontecorvo proposed neutrino oscillations in analogy with $K^0 \rightleftarrows \overline{K}^0$ oscillations (Gell-Mann and Pais, 1955)
- Flavor Neutrinos: ν_e, ν_μ, ν_τ produced in weak interactions
- Massive Neutrinos: ν_1, ν_2, ν_3 propagate from source to detector
- A Flavor Neutrino is a linear superposition of Massive Neutrinos

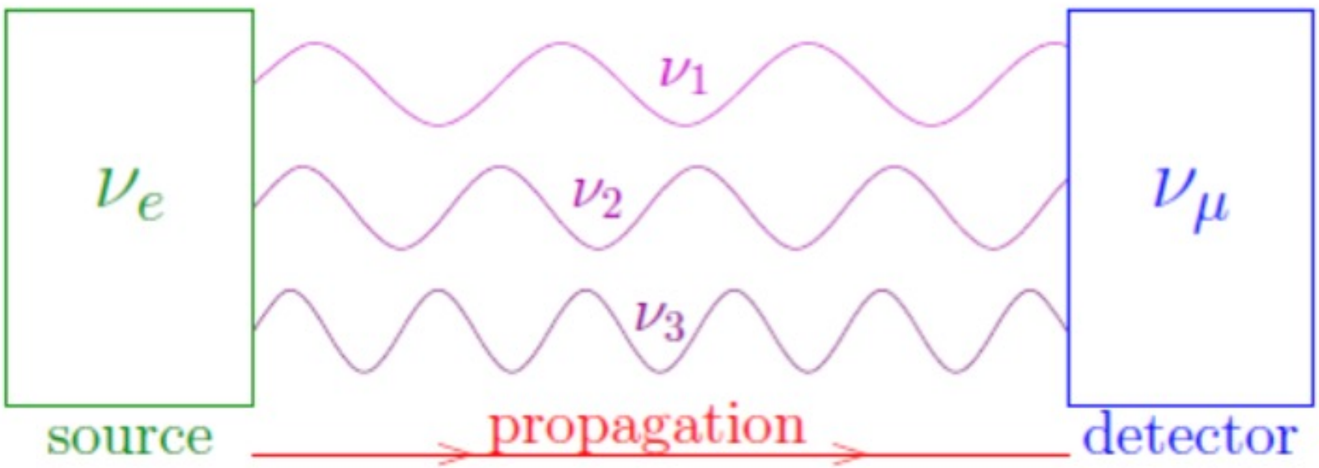
$$
\begin{aligned}
|\nu_e\rangle &= U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle \\
|\nu_\mu\rangle &= U_{\mu 1}|\nu_1\rangle + U_{\mu 2}|\nu_2\rangle + U_{\mu 3}|\nu_3\rangle \\
|\nu_\tau\rangle &= U_{\tau 1}|\nu_1\rangle + U_{\tau 2}|\nu_2\rangle + U_{\tau 3}|\nu_3\rangle
\end{aligned}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

- U is the 3×3 Neutrino Mixing Matrix
- It is called Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix.

Neutrino oscillations

basic of neutrino oscillations: change of ν flavor due to propagation

$$|\nu(t=0)\rangle = |\nu_e\rangle = U_{e1}\,|\nu_1\rangle + U_{e2}\,|\nu_2\rangle + U_{e3}\,|\nu_3\rangle$$



$$|\nu(t>0)\rangle = U_{e1}\,e^{-iE_1 t}\,|\nu_1\rangle + U_{e2}\,e^{-iE_2 t}\,|\nu_2\rangle + U_{e3}\,e^{-iE_3 t}\,|\nu_3\rangle \neq |\nu_e\rangle$$

at the detector there is a probability > 0 to see the neutrino as a ν_μ

Simplest case: two flavour neutrino oscillation

- Interaction eigenstates are linear combination of mass eigenstates:

$$
\begin{aligned}
|\nu_e\rangle &= \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle \\
|\nu_\mu\rangle &= -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle
\end{aligned}
$$

- An electron neutrino evolves in time into the state

$$|\nu_e(t)\rangle = \cos\theta\, e^{iE_1 t}|\nu_1\rangle + \sin\theta\, e^{iE_2 t}|\nu_2\rangle$$

- Probability amplitude for ν_e to ν_μ conversion

$$A(\nu_e \to \nu_\mu) = \langle \nu_\mu | \nu_e(t)\rangle = -\sin\theta\cos\theta\, e^{iE_1 t} + \cos\theta\sin\theta\, e^{iE_2 t}$$

$$A(\nu_e \to \nu_\mu) = \sin 2\theta\, \frac{e^{iE_2 t} - e^{iE_1 t}}{2}$$

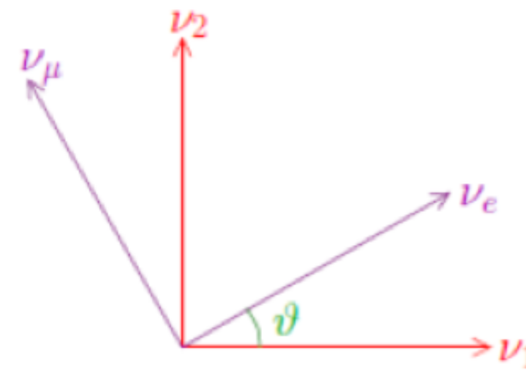
- Probability of ν_e to convert into ν_μ
  - $P(\nu_e \to \nu_\mu) = |A(\nu_e \to \nu_\mu)|^2 = \sin^2 2\theta \frac{|e^{iE_2t} - e^{iE_1t}|^2}{4}$
  - $P(\nu_e \to \nu_\mu) = \sin^2 2\theta \frac{2 - (e^{i(E_2-E_1)t} + e^{-i(E_2-E_1)t})}{4}$
  - $P(\nu_e \to \nu_\mu) = \sin^2 2\theta \frac{1 - \cos(E_2-E_1)t}{2}$
  - $P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2 \frac{(E_2-E_1)t}{2}$
- When neutrinos are relativistic
  - $(E_2 - E_1) = \sqrt{p^2 + m_2^2} - \sqrt{p^2 + m_1^2} \simeq \frac{\Delta m_{21}^2}{2p}$; where $\Delta m_{21}^2 = m_2^2 - m_1^2$
- Neutrinos can change flavour during propagation with a probability
  - $P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E}\right)$; where $L = ct$ is the distance
  - $P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m_{21}^2 L}{E}\right)$

Δm_{21}^2 in eV^2; L in km; E in GeV

Neutrino oscillations

basic of neutrino oscillations: practical case: two ν mixing and oscillation

$$|\nu_\alpha\rangle = \sum_{k=1}^{2} U_{\alpha k} |\nu_k\rangle \qquad (\alpha = e, \mu)$$



$$U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix}$$

$$|\nu_e\rangle = \cos\vartheta\, |\nu_1\rangle + \sin\vartheta\, |\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\vartheta\, |\nu_1\rangle + \cos\vartheta\, |\nu_2\rangle$$

$$\Delta m^2 \equiv \Delta m^2_{21} \equiv m_2^2 - m_1^2$$

Transition Probability: $$P_{\nu_e \to \nu_\mu} = P_{\nu_\mu \to \nu_e} = \sin^2 2\vartheta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

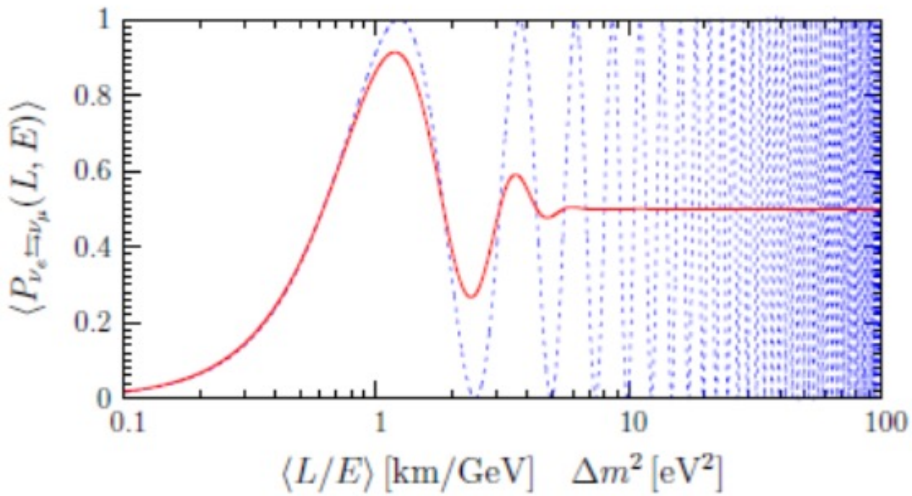
Survival Probabilities: $$P_{\nu_e \to \nu_e} = P_{\nu_\mu \to \nu_\mu} = 1 - P_{\nu_e \to \nu_\mu}$$

Neutrino oscillations

basic of neutrino oscillations: dependence of flux from distance

$$P_{\nu_e \leftrightarrows \nu_\mu}(L/E) = \sin^2 2\vartheta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right) = \sin^2 2\vartheta \, \frac{1}{2}\left[1 - \cos\left(\frac{\Delta m^2 L}{2E}\right)\right]$$

$$\langle P_{\nu_e \leftrightarrows \nu_\mu} \rangle = \int \mathrm{d}\left(\frac{L}{E}\right) \phi\left(\frac{L}{E}\right) P_{\nu_e \leftrightarrows \nu_\mu}(L/E)$$



$$\phi(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(\frac{(x - \langle x \rangle)^2}{2\sigma^2}\right)$$

$$\sin^2 2\vartheta = 1$$

$$\sigma_{L/E} = 0.2 \langle L/E \rangle$$

Suppose neutrinos have non-zero masses.

Mass eigenstates are distinct from weak interaction eigenstates.

Weak interaction eigenstates

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

Mass eigenstates

- It is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix.

Neutrino flavor oscillations

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix}$$

Flavor eigenstates ≠ Mass eigenstates

$$\begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Weak interaction

Propagation

Neutrino flavor oscillations

what we presently know from neutrino flavor oscillations

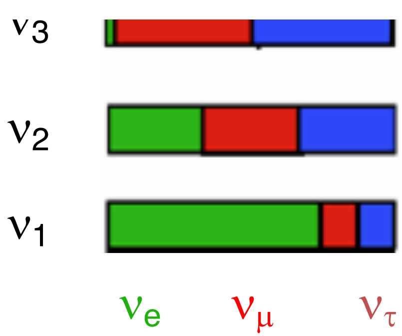
oscillations do occur → neutrinos are massive

Neutrino mixing and masses

given the three ν mass eigenvalues m_1, m_2, m_3 we have approximate measurements of two Δm_{ij}:

$\Delta M_{21}{}^2 \sim (9\ \text{meV})^2$ Solar $\qquad |\Delta M_{31}{}^2| \sim (50\ \text{meV})^2$ Atmospheric

The current neutrino oscillation data has been fitted well in terms of two mass squared differences namely, the solar mass splitting, ($\Delta m^2_{21} = 7.6\times10^{-5} eV^2$) and the atmospheric mass splitting ($|\Delta m_{31}|^2 = 2.5\times10^{-3} eV^2$). In the case of solar mass splitting, due to the presence of matter effects in the sun, it is known that



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

Exactly, $\Delta M^2_{21} \simeq 7.6\times10^{-5}\ \text{eV}^2$; $|\Delta M^2_{31}| \simeq 2.5\times10^{-3}\ \text{eV}^2$

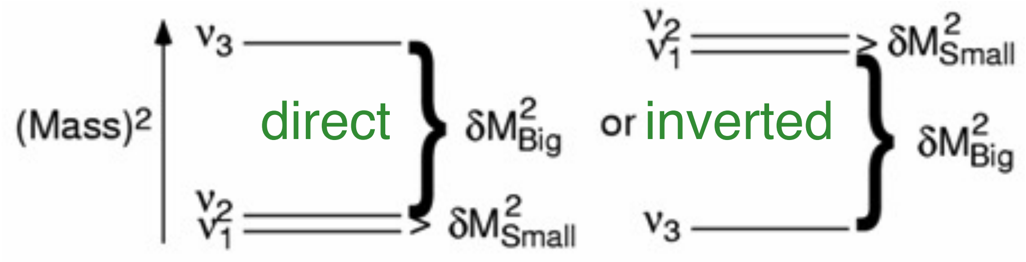
Neutrino flavor oscillations and mass scale

Since $\Delta M^2_{21} \simeq 7.6\times10^{-5}$ eV^2; $|\Delta M^2_{31}| \simeq 2.5\times10^{-3}$ eV^2

$\Longrightarrow$ $m_2>m_1$ but we don't know if either $m_3>m_1$ or $m_3<m_1$

what we do not know from neutrino flavor oscillations:

- neutrino mass hierarchy



- absolute neutrino mass scale --> degeneracy ? ($m_1 \sim m_2 \sim m_3$)

- DIRAC or MAJORANA nature of neutrinos

$\nu \neq$ anti-ν $\qquad$ $\nu \equiv$ anti-ν

Neutrinos Are Left-Handed (chirality is left-handed) … and Helicity

- Helicity is projection of spin along the particle direction
  - Frame dependent (if massive)

The operator: $\sigma \cdot \mathbf{p}$

- Handedness (or chirality) is Lorentz-invariant
  - Only same as helicity for massless particles.

- If neutrinos have mass, then left-handed neutrino is:
  - Mainly left-helicity
  - But also, small right-helicity component ∝ *m/E*

- Only left-handed charged-leptons (e^-,μ^-,τ^-) interact weakly but those with mass bring right-helicity:

$$R_{theory} = \frac{\Gamma(\pi^\pm \to e^\pm \nu_e)}{\Gamma(\pi^\pm \to \mu^\pm \nu_\mu)} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{{m_\pi}^2 - {m_e}^2}{{m_\pi}^2 - {m_\mu}^2}\right)^2 = 1.23 \times 10^{-4}$$

Neutrinos only interact weakly with a (V-A) interaction

- All **neutrinos** are **left-handed**
- All **antineutrinos** are **right-handed**

Neutrino di Dirac e di Majorana

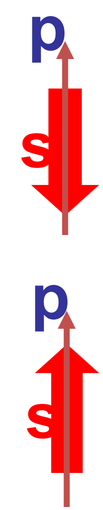
Domanda: qual è la differenza tra un neutrino ν e un antineutrino $\bar{\nu}$?

Fenomenologicamente:

$$\nu_e + \text{materia} \longrightarrow e^-$$
$$\bar{\nu}_e + \text{materia} \longrightarrow e^+$$

due modi per spiegare questo comportamento

numero leptonico differente	differente elicità
$L(\nu_e, e^-) = -1$	$H(\nu_e) = -1$
$L(\bar{\nu}_e, e^+) = +1$	$H(\bar{\nu}_e) = +1$
Il numero leptonico, come una **carica**, è strettamente conservata	Il comportamento del ν è determinato solo dalla elicità
Dirac $\nu_e \neq \bar{\nu}_e$	**Majorana** $\nu_e = \bar{\nu}_e$



Se $m_\nu = 0$ ⇒

L = H
DIRAC = MAJORANA

Ma esperimenti indicano che il ν ha massa

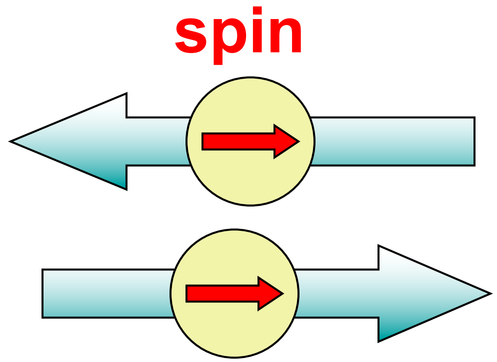
Massive Neutrinos: Majorana or Dirac?

Lorentz Invariance:

massive particle velocity < speed of light c

Helicity: H = -1 ν_L

Helicity: H = 1 ν_R



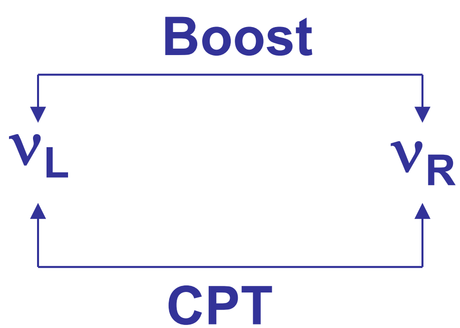
(Lab)

(Speed-of-light Frame)

If m<<E, chirality ≃ helicity

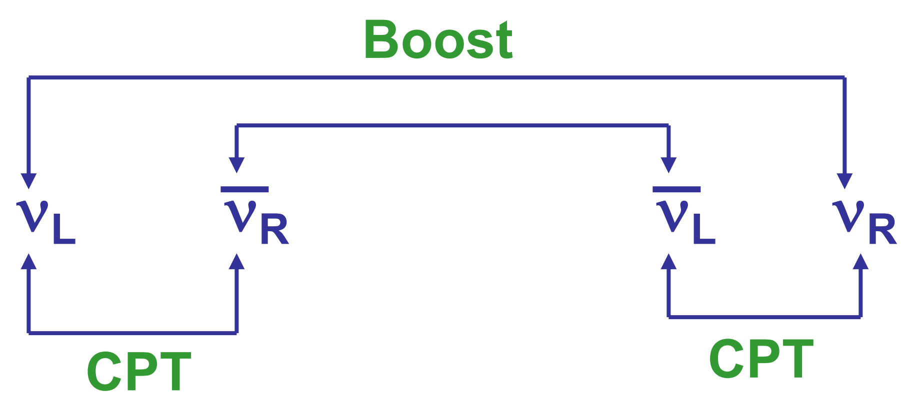
Majorana Neutrino

Neutrino=anti-neutrino



Dirac Neutrino

Neutrino and anti-neut distinct



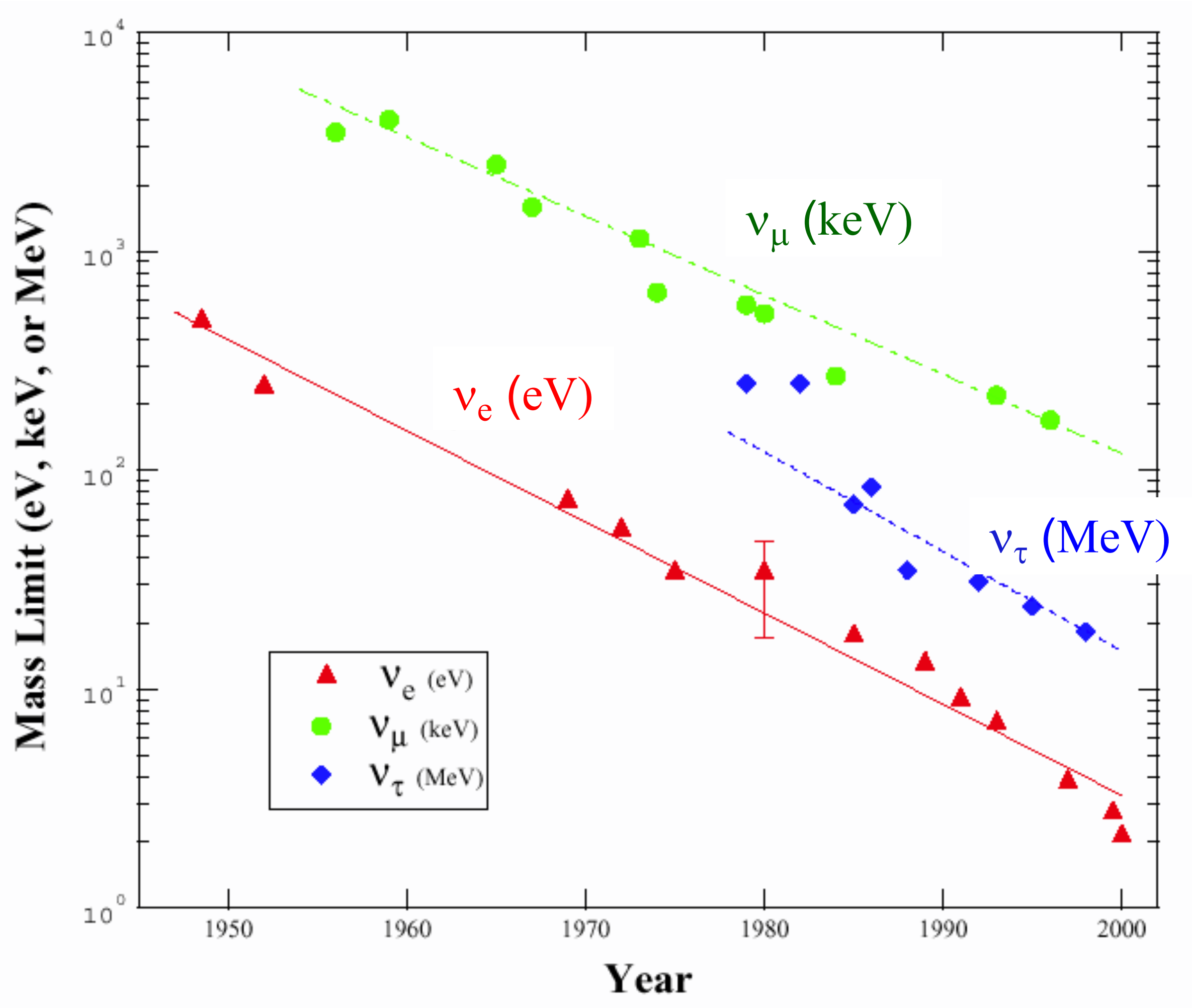
Neutrino Properties

- Neutrino Mass Phenomenology
- Direct Neutrino Mass Experiments
- Double Beta Decay Experiments
- Neutrino Oscillations

Direct Neutrino Mass Experiments

- Techniques
  - Electron neutrino:
    - Study E_e end point for $^3H \to {}^3He + \nu_e + e^-$
  - Muon neutrino:
    - Measure P_μ in $\pi \to \mu \nu_\mu$ decays
  - Tau neutrino:
    - Study $n\pi$ mass in $\tau \to (n\pi)\, \nu_\tau$ decays

(Also, information from Supernova time-of-flight)



Three and only three neutrinos

LEP = Z factory

Z decays democratically to all pairs of constituents (m<45 GeV)

11 constituents: 2.7 GeV width

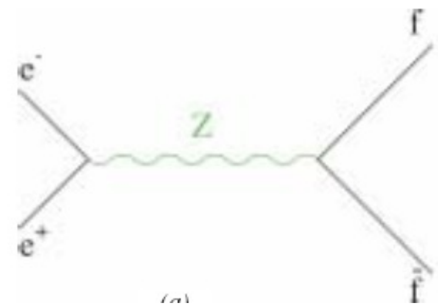
New ν flavor adds 167 MeV to the width

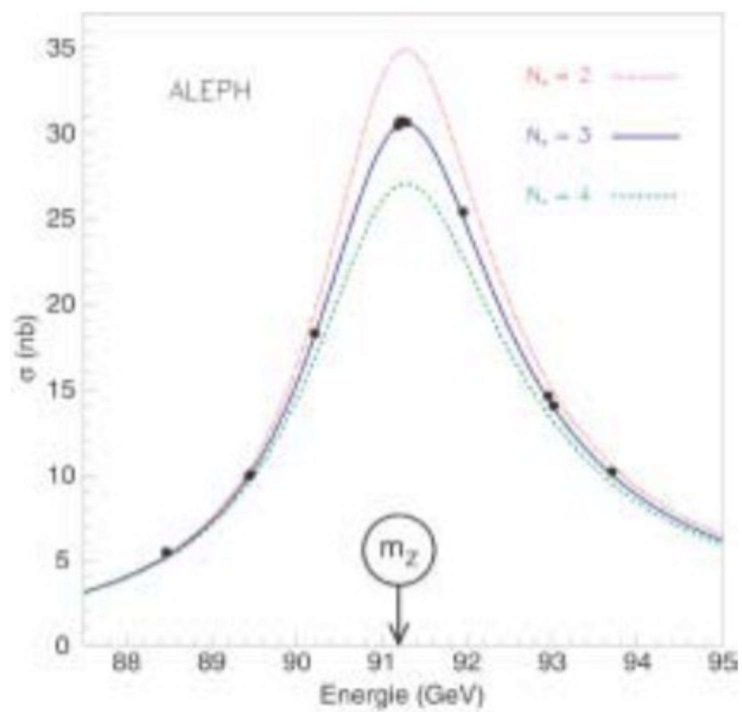
First LEP result (1989)

$$N(\nu) = 3.00 \pm 0.01$$

⇒ Three families of constituents

+ infos from cosmology





The Fundamental Particles in the Standard Model

Neutrinos

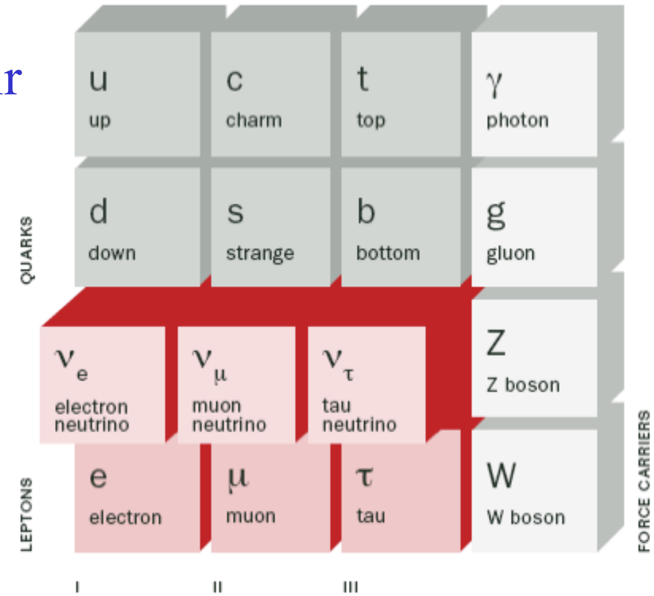
There exist 3 and only 3 “active” neutrinos, with their antineutrinos

$\nu + N \Rightarrow l^- + hadrons$ *cc*

$anti\text{-}\nu + N \Rightarrow l^+ + hadrons$ *cc*

$\nu + N \Rightarrow \nu + hadrons$ *nc*

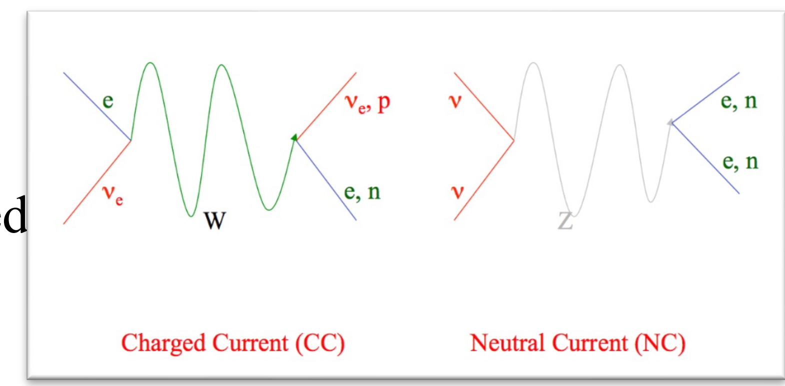
$anti\text{-}\nu + N \Rightarrow anti\text{-}\nu + hadrons$ *nc*



They only feel weak interactions:

couplings to $W^{\pm}$ (CC) and Z^0 (NC)

Neutrino interactions



In the MSM, SU(2)xU(1)

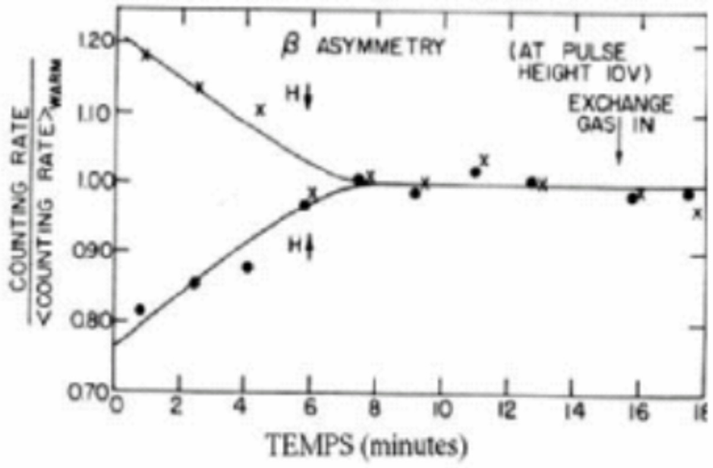
leptons appear as left-handed doublets + right-handed singlets $(\, l^- , \nu \,)_L \quad (\, l^- \,)_R$

No right-handed ν (or left-handed anti-ν) ⇒ ν are massless

Electroweak Theory

Parity violation and V-A

- Parity violation in weak decays postulated by Lee & Yang in 1956
- Parity violation confirmed through forward-backward asymmetry of polarized ^{60}Co (Wu, 1957).



$$^{60}Co \rightarrow {}^{60}Ni^* + e^- + \bar{\nu}_e$$

More electrons emitted in direction opposite to ^{60}Co spins, implying maximal parity violation

- Helicity operator: $$H = \frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|} \xrightarrow{P} \frac{\vec{\sigma}\cdot(-\vec{p})}{|\vec{p}|} = -H$$

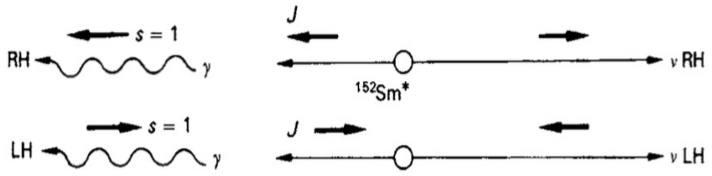
Projects spin along direction of motion

Electroweak Theory

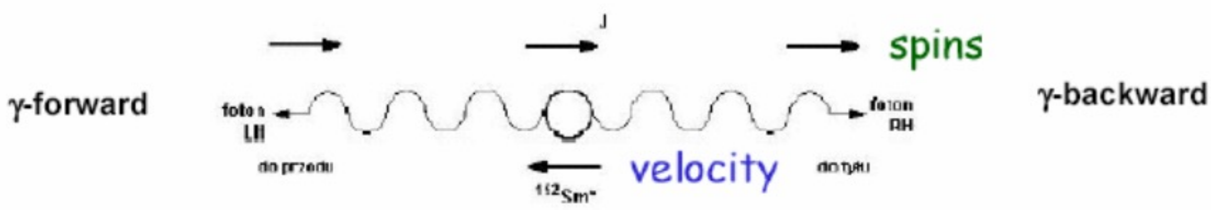
Parity violation and V-A

- Goldhaber, Grodzins, Sunyar (1958) measure helicity of neutrino from K capture of ^{152}Eu:

$$^{152}Eu(0^-) + e^- \rightarrow {}^{152}Sm^*(1^-) + \nu_e$$
$$^{152}Sm^*(1^-) \rightarrow {}^{152}Sm^*(0^+) + \gamma$$



$p_\gamma = -p_\nu$
$\sigma_\gamma = -\sigma_\nu$
$H_\gamma = H_\nu$



Asymmetry of photon spectrum in magnetic field determines helicity of ν_e:

$$H(\nu_e) = -1 \Rightarrow H(\bar{\nu}_e) = +1$$

Neutrinos are “left-handed” ↓ Antineutrinos are “right-handed” ↑

Electroweak Theory

Parity violation and V-A

- Left and right handed projection operators:

$$\nu_L = P_L \nu = \frac{1}{2}(1-\gamma_5)\nu \qquad \nu_R = P_R \nu = \frac{1}{2}(1+\gamma_5)\nu$$

- Chirality operator: $\gamma_5 = i\gamma^0\gamma^1\gamma^2\gamma^3$
  same as helicity operator for massless neutrinos (E=p).

$$\gamma_5 \nu_L = H\nu_L = -\nu_L \qquad \gamma_5 \nu_R = H\nu_R = +\nu_R$$

- If only ν_L interact and ν_R do not interact, then Γ_i have to transform as: $\bar{e}\Gamma_i\nu \rightarrow \overline{(P_L e)}\Gamma_i(P_L\nu) = \bar{e}P_R\Gamma_i P_L\nu$

$$V: P_R\gamma^\mu P_L = \frac{1}{2}\gamma^\mu(1-\gamma_5) \qquad A: P_R\gamma^\mu\gamma_5 P_L = -\frac{1}{2}\gamma^\mu(1-\gamma_5)$$

- The only possible coupling is V-A, due to maximal parity violation in weak interactions (Feynman, Gell-Mann, 1958):

$$L_{V-A} = -\frac{G_F}{\sqrt{2}}\left[\bar{\psi}_p\gamma^\mu(1-g_A\gamma_5)\psi_n\right]\left[\bar{\psi}_e\gamma_\mu(1-\gamma_5)\psi_\nu\right]$$

with $g_A = -1.2573 \pm 0.0028$ (determined empirically)

Electroweak Theory

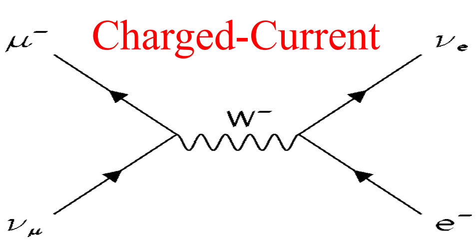
- Standard Model
  - SU(2) ⊗ U(1) gauge theory unifying weak/EM
    - ⇒ weak Neutral Current interaction
  - Measured physical parameters related to mixing parameter for the couplings, $g' = g \tan\theta_W$

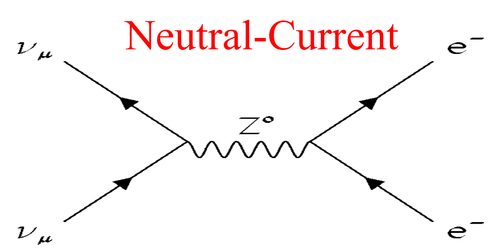
$$\mathcal{H}_{weak} = \frac{4G_F}{\sqrt{2}}\left[\bar{\ell}/\bar{\nu}\gamma_\mu \frac{(1-\gamma_5)}{2}\nu\right]\left[\bar{f}'\gamma^\mu\left(g_L\frac{1-\gamma_5}{2} + g_R\frac{1+\gamma_5}{2}\right)f\right] + \text{h.c.}$$

Z coupling	g_L	g_R
ν	$1/2$	0
e,μ,τ	$-1/2+\sin^2\theta_W$	$\sin^2\theta_W$
u,c,t	$1/2-(2/3)\sin^2\theta_W$	$-(2/3)\sin^2\theta_W$
d,s,b	$-1/2+(1/3)\sin^2\theta_W$	$(1/3)\sin^2\theta_W$

$$e = g\sin\theta_W,\ G_F = \frac{g^2\sqrt{2}}{8M_W^2},\ \frac{M_W}{M_Z} = \cos\theta_W$$

- Neutrinos are special in SM
  - Only have left-handed weak interactions
    - ⇒ $W^\pm$ and Z boson exchange





Electroweak Theory

- Lagrangian for electroweak interactions:

$$L_{\text{int}} = i\frac{g}{\sqrt{2}}\left[j_\mu^{(+)}W^\mu + j_\mu^{(-)}W^{\mu+}\right] + i\left[g\cos\theta_W\, j_\mu^{(3)} - g'\sin\theta_W\, j_\mu^{(Y/2)}\right]Z^\mu +$$
$$+ i\left[g\sin\theta_W\, j_\mu^{(3)} + g'\cos\theta_W\, j_\mu^{(Y/2)}\right]A^\mu$$

- 1st term: charged current interactions (W^+, W^- exchange)
- 2nd term: neutral current interactions (Z^0 exchange)
- 3rd term:electromagnetic interactions (photon exchange)

- Electron charge: $e = g\sin\theta_W = g'\cos\theta_W$

- 3rd term: $e j_\mu^{e.m.} = e(j_\mu^{(3)} + j_\mu^{(Y/2)})$

  (neutrinos only couple to $W^\pm$ and Z^0)

Electroweak Theory

- A) Neutrino electron interaction

$$L_{\text{int}} = i\frac{g}{\sqrt{2}}\left[j_\mu^{(+)} W^\mu + j_\mu^{(-)} W^{\mu +}\right] + i\frac{g}{2\cos\theta_W} j_\mu^{(Z)} Z^\mu + iej_\mu^{e.m}$$

- Where: $j_\mu^{(+)} = \bar{\nu}_{e,L}\gamma_\mu e_L = \frac{1}{2}\bar{\nu}_e\gamma_\mu(1-\gamma_5)e$

$$j_\mu^{(-)} = \bar{e}_L\gamma_\mu \nu_{e,L} = \frac{1}{2}\bar{e}\gamma_\mu(1-\gamma_5)\nu_e$$

$$j_\mu^{(Z)} = 2(j_\mu^{(3)} - \sin^2\theta_W j_\mu^{e.m}) =$$

$$= \bar{\nu}_{e,L}\gamma_\mu \nu_{e,L} - \bar{e}_L\gamma_\mu e_L + 2\sin^2\theta_W \bar{e}\gamma_\mu e =$$

$$= \frac{1}{2}\bar{\nu}_e\gamma_\mu(1-\gamma_5)\nu_e - \frac{1}{2}\bar{e}\gamma_\mu(1-\gamma_5)e + 2\sin^2\theta_W \bar{e}\gamma_\mu e$$

$$\Rightarrow j_\mu^{(Z)} = \frac{1}{2}\bar{\nu}_e\gamma_\mu(1-\gamma_5)\nu_e + \bar{e}\gamma_\mu(g_V - g_A\gamma_5)e$$

- With: $g_V = -\frac{1}{2} + 2\sin^2\theta_W \qquad g_A = -\frac{1}{2}$

Electroweak Theory

- B) Quark weak interactions

$$L_{\text{int}} = i\frac{g}{\sqrt{2}}\left[j_\mu^{(+)}W^\mu + j_\mu^{(-)}W^{\mu+}\right] + i\frac{g}{2\cos\theta_W} j_\mu^{(Z)}Z^\mu + iej_\mu^{e.m}$$

- Where:

$$j_\mu^{(+)} = \frac{1}{2}\bar{u}\gamma_\mu(1-\gamma_5)d$$

$$j_\mu^{(-)} = \frac{1}{2}\bar{d}\gamma_\mu(1-\gamma_5)u$$

$$j_\mu^{(Z)} = \bar{u}\gamma_\mu(A_u - B_u\gamma_5)u + \bar{d}\gamma_\mu(A_d - B_d\gamma_5)d$$

- With:

$$A_u = \frac{1}{2} - \frac{4}{3}\sin^2\theta_W \qquad B_u = \frac{1}{2}$$

$$A_d = -\frac{1}{2} + \frac{2}{3}\sin^2\theta_W \qquad B_d = -\frac{1}{2}$$

Electroweak Theory

- After introducing Higgs field and spontaneous symmetry breaking:

$$L_{Higgs} = -\left|D_\mu \phi\right| - \mu^2 \left|\phi\right|^2 - \lambda \left|\phi\right|^4$$

- Masses: $m_H = \sqrt{2\lambda} v$

$$m_{W^\pm} = \frac{gv}{2} \qquad \left(\frac{m_{W^\pm}}{m_{Z^0}}\right)^2 = \frac{g^2}{g^2 + g'^2} = \cos^2\theta_W$$

$$m_{Z^0} = \frac{\sqrt{g^2 + g'^2}}{2} v$$

- Vacuum expectation value: $v = \left(\sqrt{2} G_F\right)^{-1/2} \approx 246\ GeV$
- Effective Hamiltonian:

$$H_{eff} = \frac{g^2}{4 m_W{}^2}\left[j^{(+)\mu} j_\mu^{(-)} + h.c.\right] + \frac{g^2}{8 m_Z{}^2 \cos^2\theta_W} j^{(Z)\mu} j_\mu^{(Z)} =$$

$$= \frac{G_F}{\sqrt{2}}\left[2 j^{(+)\mu} j_\mu^{(-)} + h.c. + j^{(Z)\mu} j_\mu^{(Z)}\right]$$

- The vector boson masses are then predicted:

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8 m_W{}^2} = \frac{e^2}{8 m_W{}^2 \sin^2\theta_W} = \frac{4\pi\alpha}{8 m_W{}^2 \sin^2\theta_W} \qquad \alpha = 1/137.036$$

- Masses:

$$m_W{}^2 = \left(\frac{37.2805}{\sin\theta_W}\right)^2$$

$$m_W = 80.450 \pm 0.058\ GeV$$
$$m_Z = 91.1876 \pm 0.0021\ GeV$$
$$\sin^2\theta_W = 0.22280 \pm 0.00035$$

- Need radiative corrections:

$$m_W = \frac{37.2805}{\sin\theta_W (1 - \Delta r)^{1/2}}$$

with $\Delta r \approx 0.03630 \pm 0.0011$ for $m_t = 172.7\ GeV$ $m_H = 117\ GeV$

yields: $m_W = 80.51 \pm 0.11\ GeV$

Neutrino cross-section

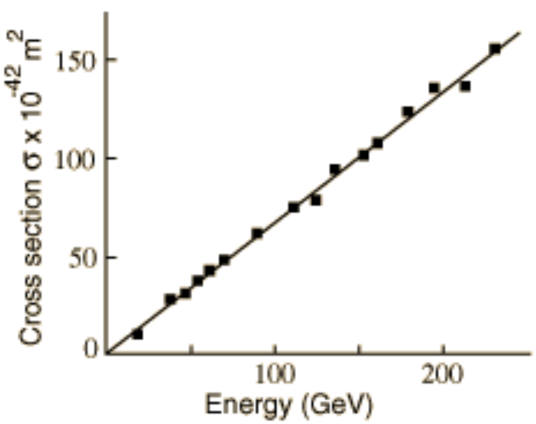
Total cross-section (ignoring mass terms) on electrons:

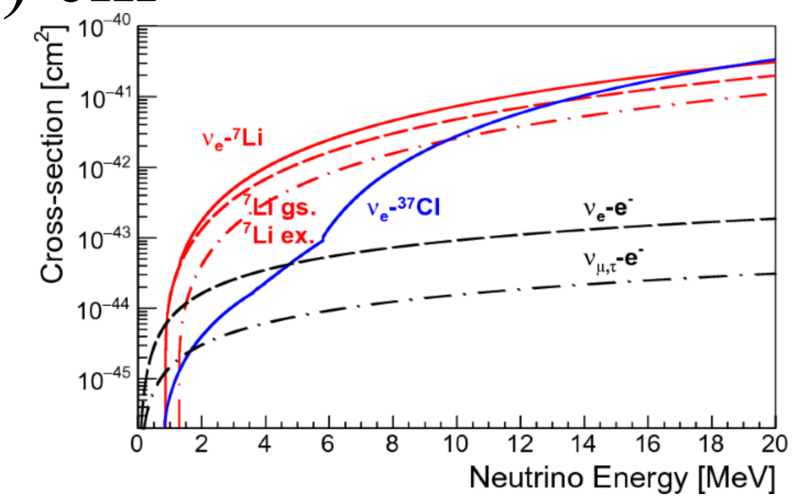
$$\sigma \approx \frac{G_F^2 s}{\pi} = \frac{2G_F^2 m_e}{\pi} E_\nu \text{ (LAB)}$$

The squared energy in CM:
$s = (p_\nu + p_e)^2 \approx 2m_e E_\nu$

Total cross-section on nucleus:

$$\sigma = 0{,}7\ 10^{-38} * E\ (\text{GeV})\ \text{cm}^2$$





Solar ν: only 1/1 billion interacts in crossing the earth

But Earth becomes opaque above 10^{15} eV

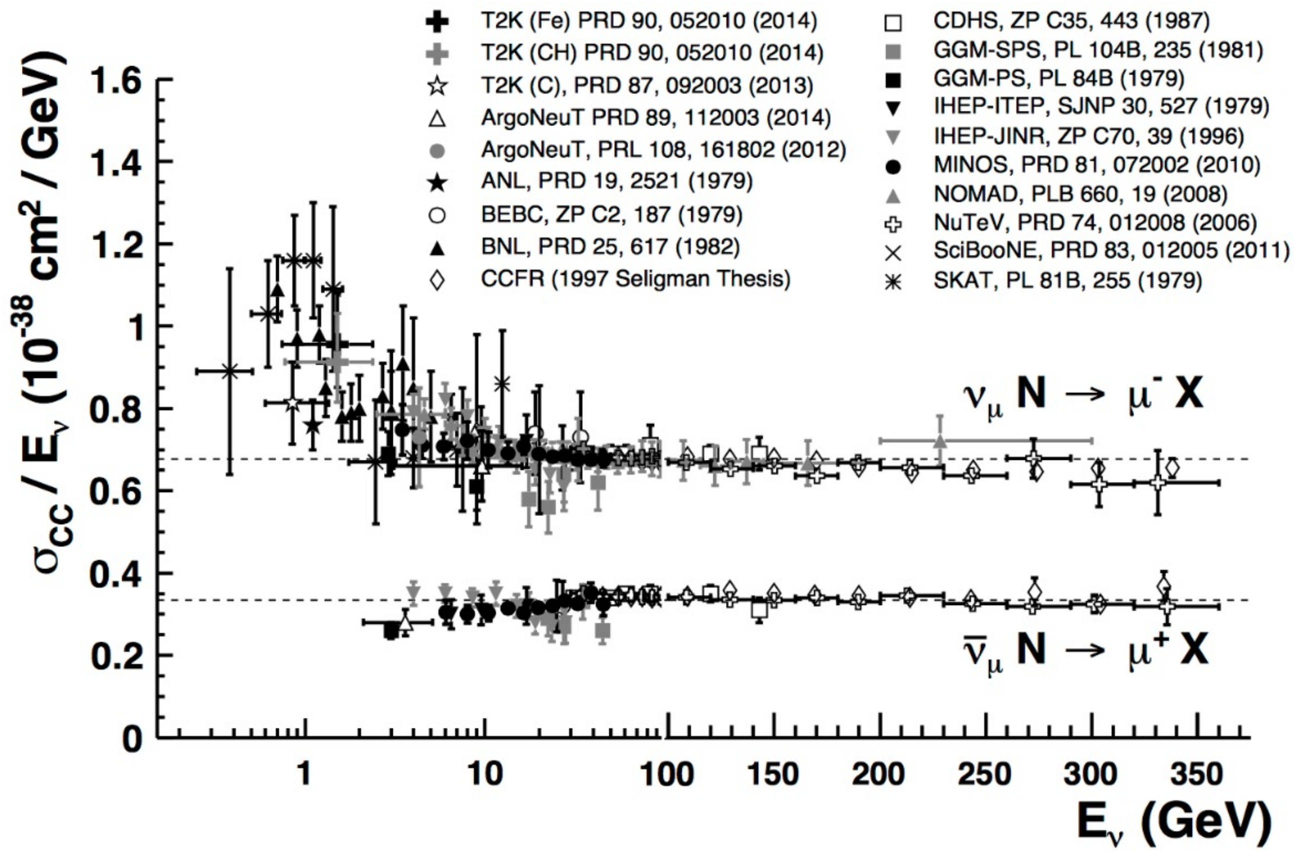
- ⟹ Neutrino physics: need of huge fluxes and gigantic detectors

Total cross section:

$$\sigma_{CC}(\nu_\mu N) = \frac{G_F^2 s}{2\pi}\left[\langle Q\rangle + \frac{1}{3}\langle \overline{Q}\rangle\right] = (0.677 \pm 0.014)\times 10^{-38}\, cm^2/GeV \times E(GeV)$$

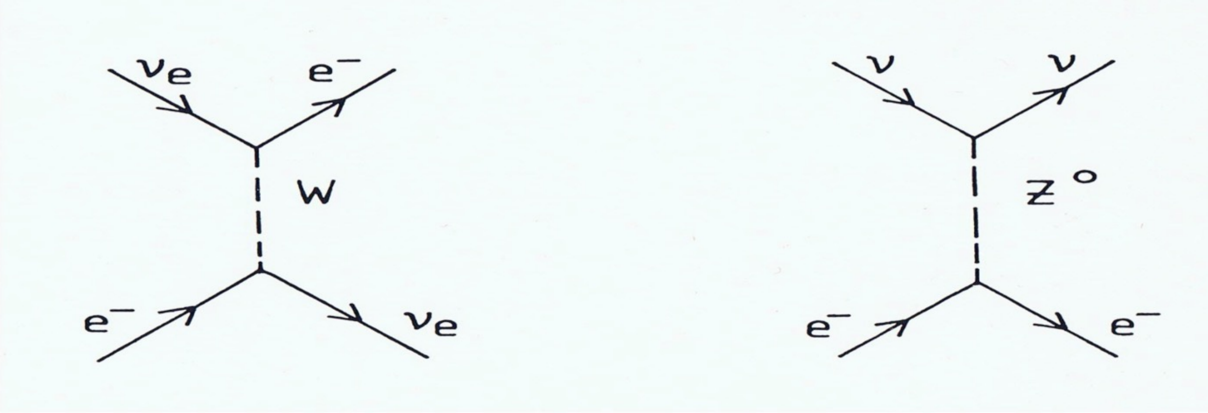
$$\sigma_{CC}(\overline{\nu}_\mu N) = \frac{G_F^2 s}{2\pi}\left[\frac{1}{3}\langle Q\rangle + \langle \overline{Q}\rangle\right] = (0.334 \pm 0.008)\times 10^{-38}\, cm^2/GeV \times E(GeV)$$

Different quark content in the nucleus: $\langle Q\rangle$, $\langle \bar{Q}\rangle$



Interactions on electrons

- *Purely leptonic process, simple in principle*



$\sigma \approx \frac{G_F^2 s}{\pi} = \frac{2G_F^2 m}{\pi} E_\nu$ (LAB)

But experimentally difficult

$\sigma(\nu+e)/\sigma(\nu+N) \sim m_e/m_N \sim 1/2000$

Neutrino Mass: Theoretical Ideas

- No fundamental reason why neutrinos are much lighter than other particles?

➢ **Grand Unified Theories**
  - Dirac and Majorana Mass
    $\Rightarrow$ See-saw Mechanism

➢ **Modified Higgs sector to accommodate neutrino mass**

➢ **Extra Dimensions**
  - Neutrinos live outside of 3 + 1 space

Many of these models have at least one Electroweak iso-singlet ν
  - Right-handed partner of the left-handed ν
  - Mass uncertain from light (< 1 eV) to heavy ($>10^{16}$ eV)
  - Would be "sterile" – Doesn't couple to standard W and Z bosons

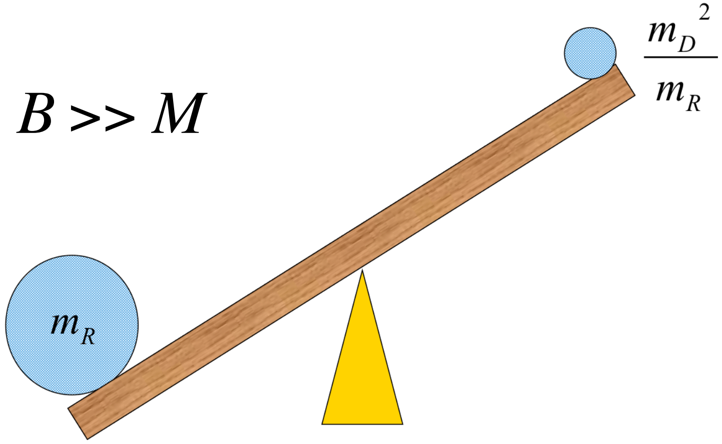
Seesaw mechanism

This model produces a light neutrino, corresponding to the three known neutrino flavours, and a very heavy, undiscovered neutrino.

$$L_M = -\frac{1}{2}\begin{pmatrix} \bar{\nu}_L & \bar{\nu}_L^C \end{pmatrix}\begin{pmatrix} 0 & M \\ M & B \end{pmatrix}\begin{pmatrix} \nu_R^C \\ \nu_R \end{pmatrix}$$

$$A = \begin{pmatrix} 0 & M \\ M & B \end{pmatrix},$$

$$B >> M$$



A is essentially the mass matrix for the right-handed neutrino.

The Majorana mass *B* is comparable to the GUT scale
The Dirac mass *M* is of order of the electroweak scale.

The matrix A has the following eigenvalues:

$$\lambda_\pm = \frac{B \pm \sqrt{B^2 + 4M^2}}{2}.$$

m_D Dirac mass will be the same order as the others. (0.1~10 GeV)

m_R Right handed Majorana mass will be at GUT scale 10^{15} GeV

The larger eigenvalue is approximately equal to *B* while the smaller eigenvalue is approximately equal to

$$\lambda_- \approx -\frac{M^2}{B}. \qquad \lambda_+ \approx B$$

If one of the eigenvalues goes up, the other goes down, and viceversa. This is the reason why the name seesaw was given to the mechanism.

This mechanism is used to explain why the neutrino masses are so small.

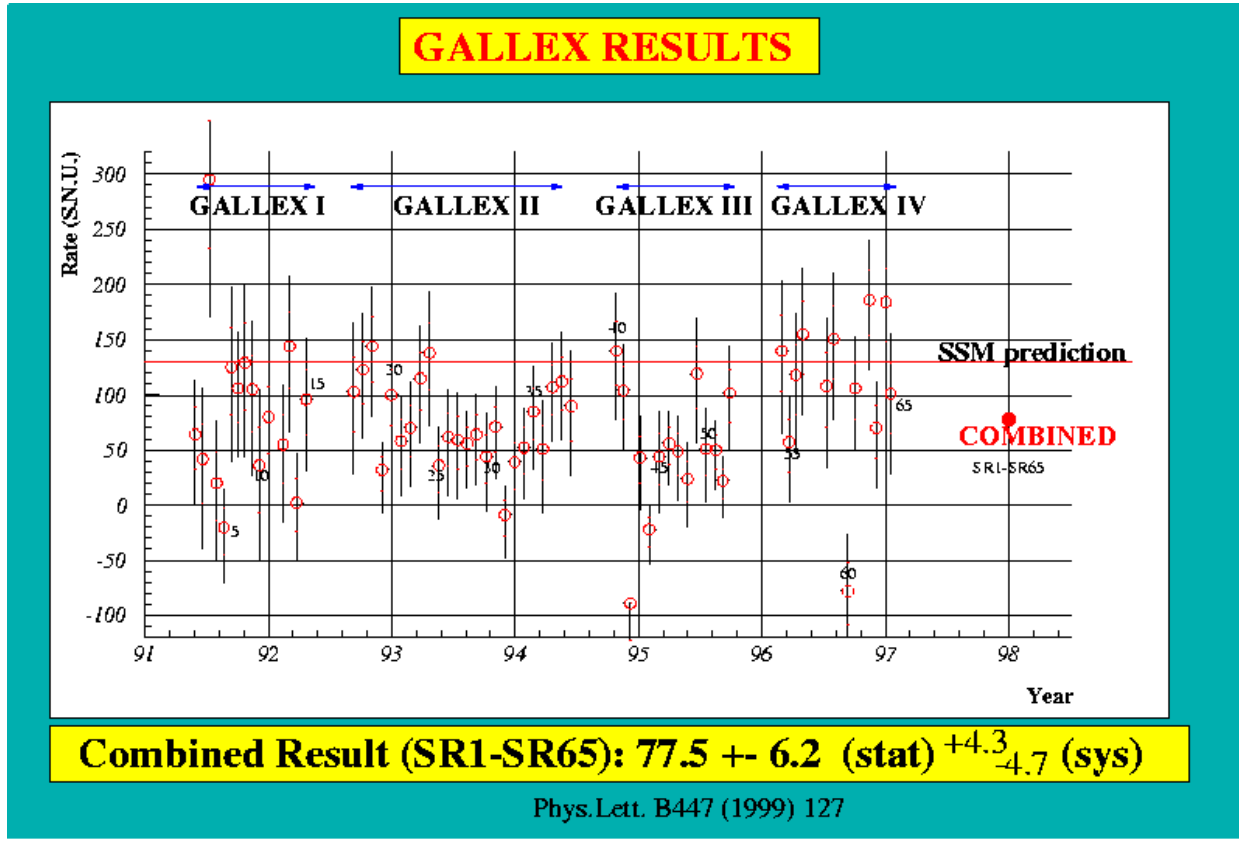
The smaller eigenvalue then leads to a very small neutrino mass comparable to 1 eV which qualitatively agrees with the experiments. Such an agreement may be interpreted as an experimentally confirmed qualitative prediction of Grand Unified Theories.

Prime evidenze di oscillazioni di neutrino: esperimenti con neutrini solari (vedi prossime lezioni)

Example: GALLEX results
(Low energy ν measurements)

Capture Rate expected in SSM for ^{71}Ga *

Source	Rate (SNU)
pp	**70.8**
pep	**3.0**
hep	**0.06**
^{7}Be	**34.3**
^{8}B	**14.0**
^{13}N	**3.8**
^{15}O	**6.1**
^{17}F	**0.06**
TOTAL	**132 SNU**



$$\textbf{Data/SSM} = 0.59 \pm 0.06$$

*Bahcall 1990

The first observations of Atmospheric Neutrinos made in Kolar Gold Fields near Bangalore, and in South Africa in 1965.

- The Indian team was led by
  M. G. K. Menon et al
- The South African team was led by
  F. Reines et al.

KGF – The 1st reported Atmospheric ν

- Several detectors in KGF mine at various depths.
- 3 ν evts published 15 Aug 65

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

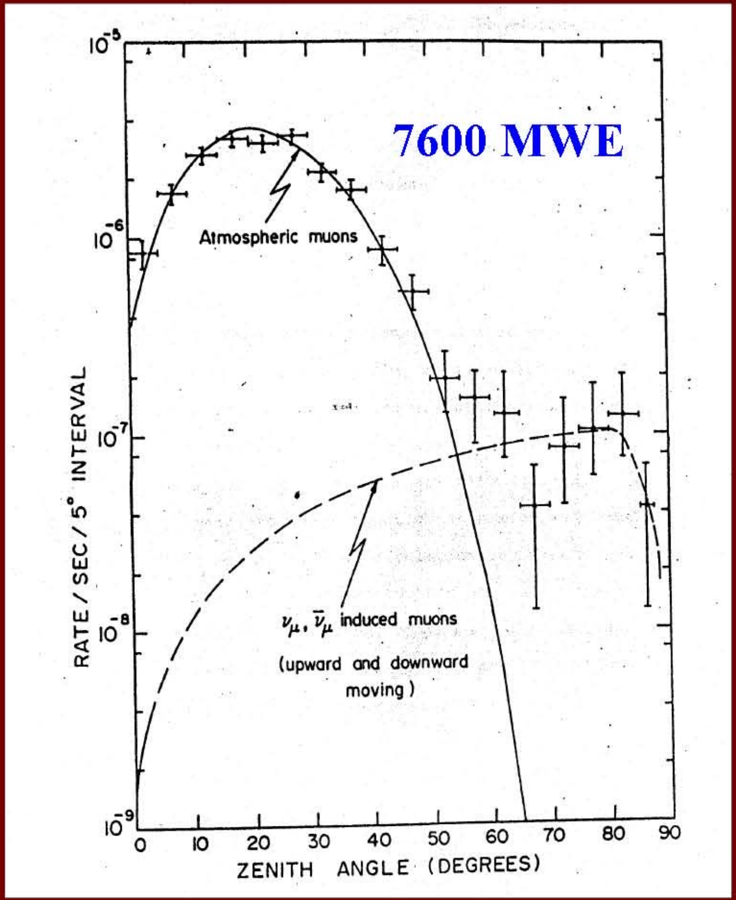
K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

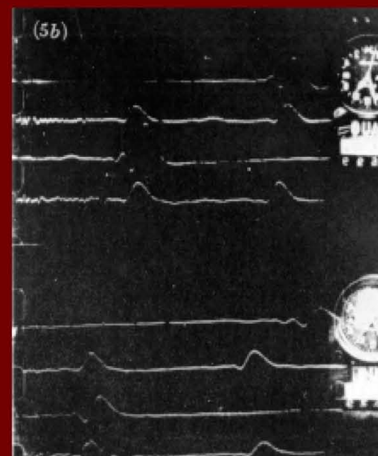
Table 1

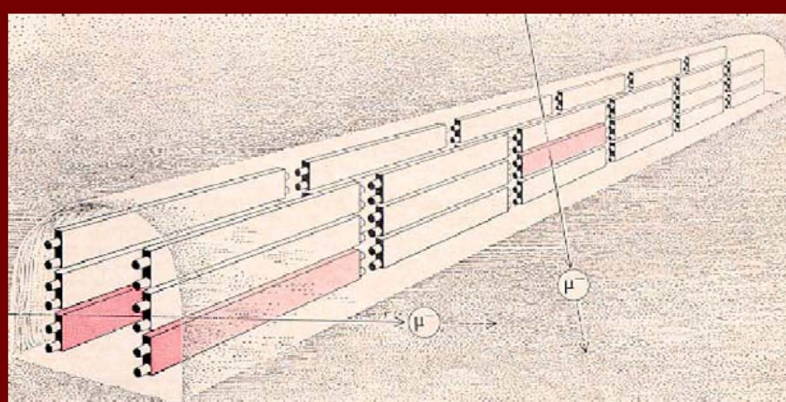
Event number	Type of coincidence	Projected zenith angle	Date	Time
1	TEL.2 N_4+S_4	37°	30.3	20.04
2	TEL.1 N_1+S_1	48 ± 1°	27.4	18.26
3	TEL.2 N_6+S_6	75 ± 10°	25.5	20.03

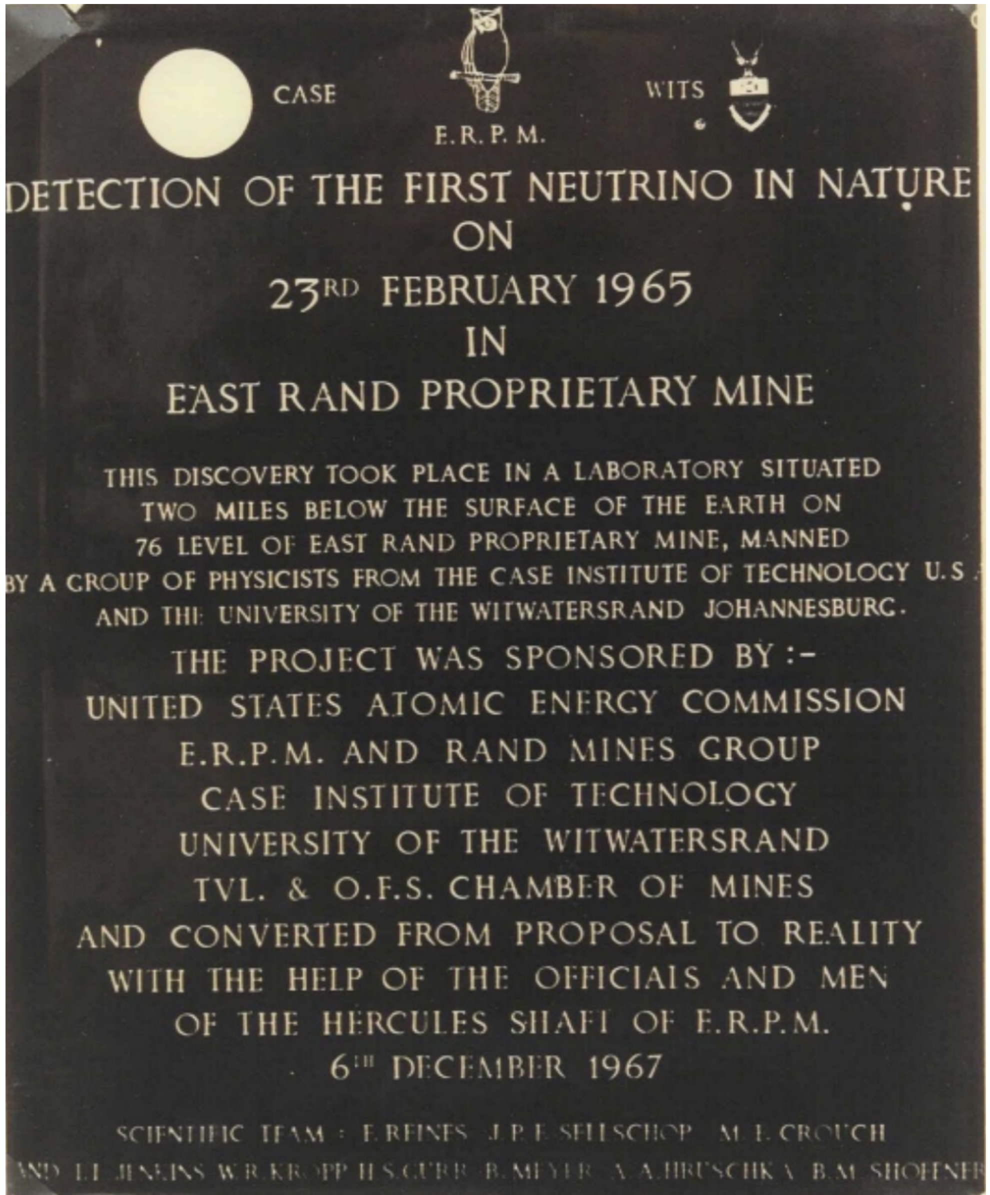


CWI – The 1st recorded Atmospheric ν

First ν
February 29, 1965
Recorded 100 (1/month)



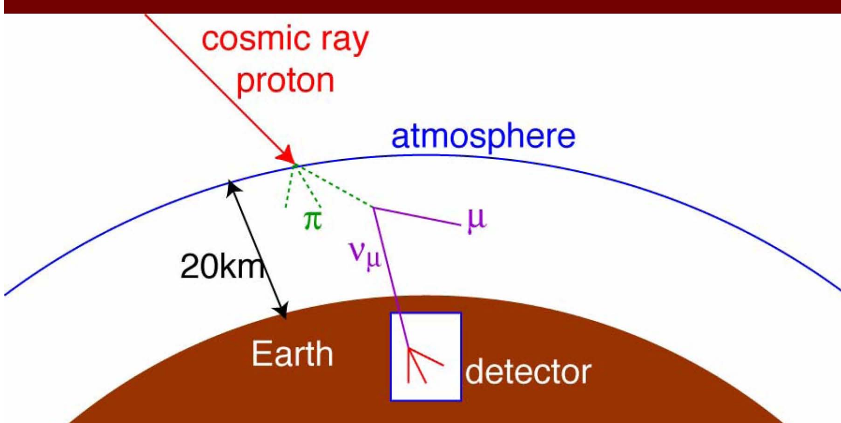


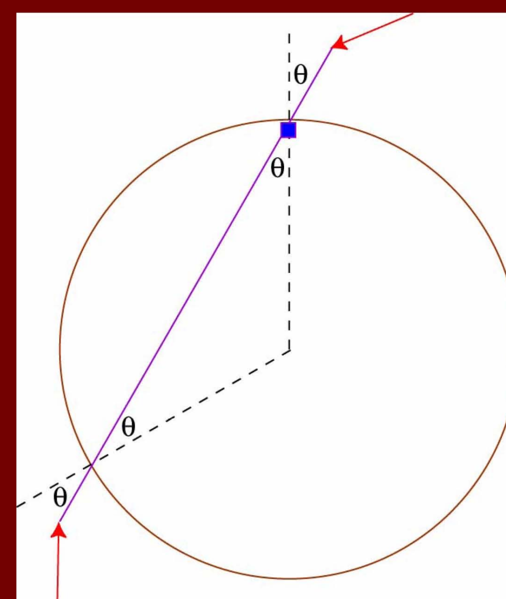

CASE
E.R.P.M.
WITS
DETECTION OF THE FIRST NEUTRINO IN NATURE
ON
23RD FEBRUARY 1965
IN
EAST RAND PROPRIETARY MINE
THIS DISCOVERY TOOK PLACE IN A LABORATORY SITUATED
TWO MILES BELOW THE SURFACE OF THE EARTH ON
76 LEVEL OF EAST RAND PROPRIETARY MINE, MANNED
BY A GROUP OF PHYSICISTS FROM THE CASE INSTITUTE OF TECHNOLOGY U.S.
AND THE UNIVERSITY OF THE WITWATERSRAND JOHANNESBURG.
THE PROJECT WAS SPONSORED BY :-
UNITED STATES ATOMIC ENERGY COMMISSION
E.R.P.M. AND RAND MINES GROUP
CASE INSTITUTE OF TECHNOLOGY
UNIVERSITY OF THE WITWATERSRAND
TVL. & O.F.S. CHAMBER OF MINES
AND CONVERTED FROM PROPOSAL TO REALITY
WITH THE HELP OF THE OFFICIALS AND MEN
OF THE HERCULES SHAFT OF E.R.P.M.
6TH DECEMBER 1967
SCIENTIFIC TEAM : F. REINES J.P.F. SELLSCHOP M.F. CROUCH
AND T.L. JENKINS W.R. KROPP H.S. GURR B. MEYER A.A. HRUSCHKA B.M.

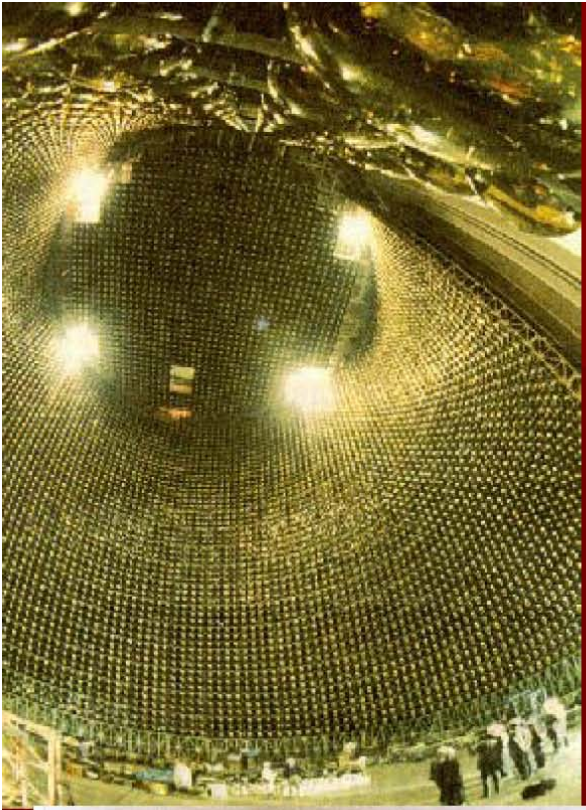
1998: Super-Kamiokande announces observation of Neutrino oscillations

Super-Kamiokande Nucleon Decay Experiment

- $p \to e^+ \pi^0$, $K^+ \nu$, etc
  - So far not seen
  - Atmospheric neutrino main background
- Cosmic rays isotropic
  - Atmospheric neutrino up-down symmetric

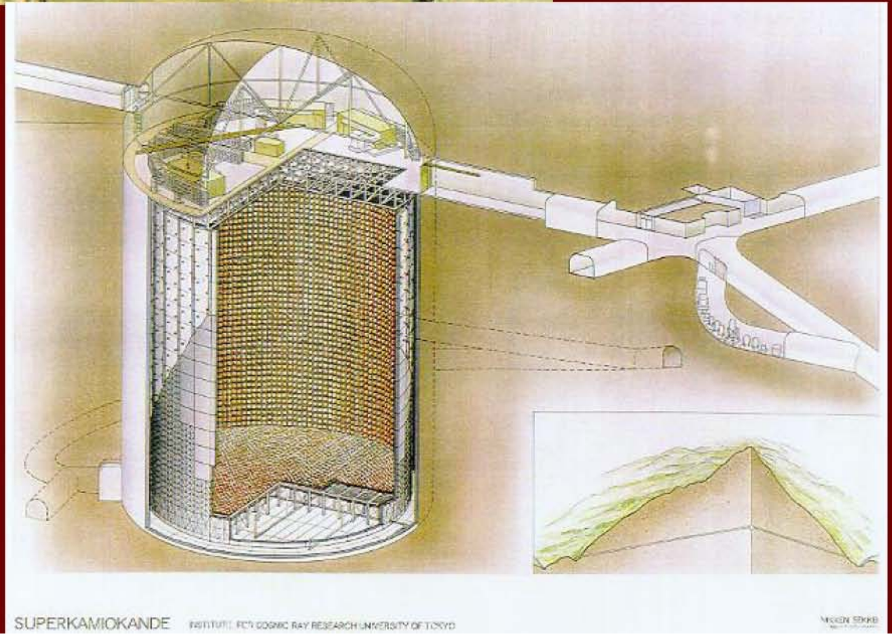


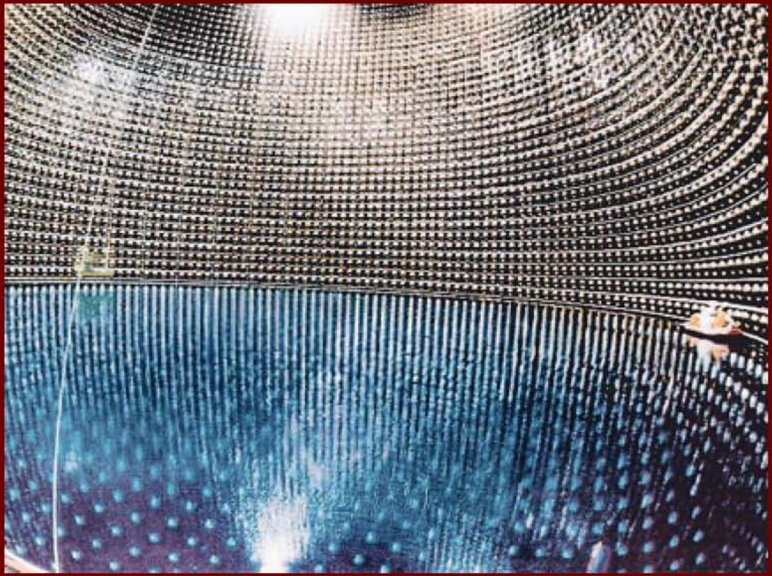




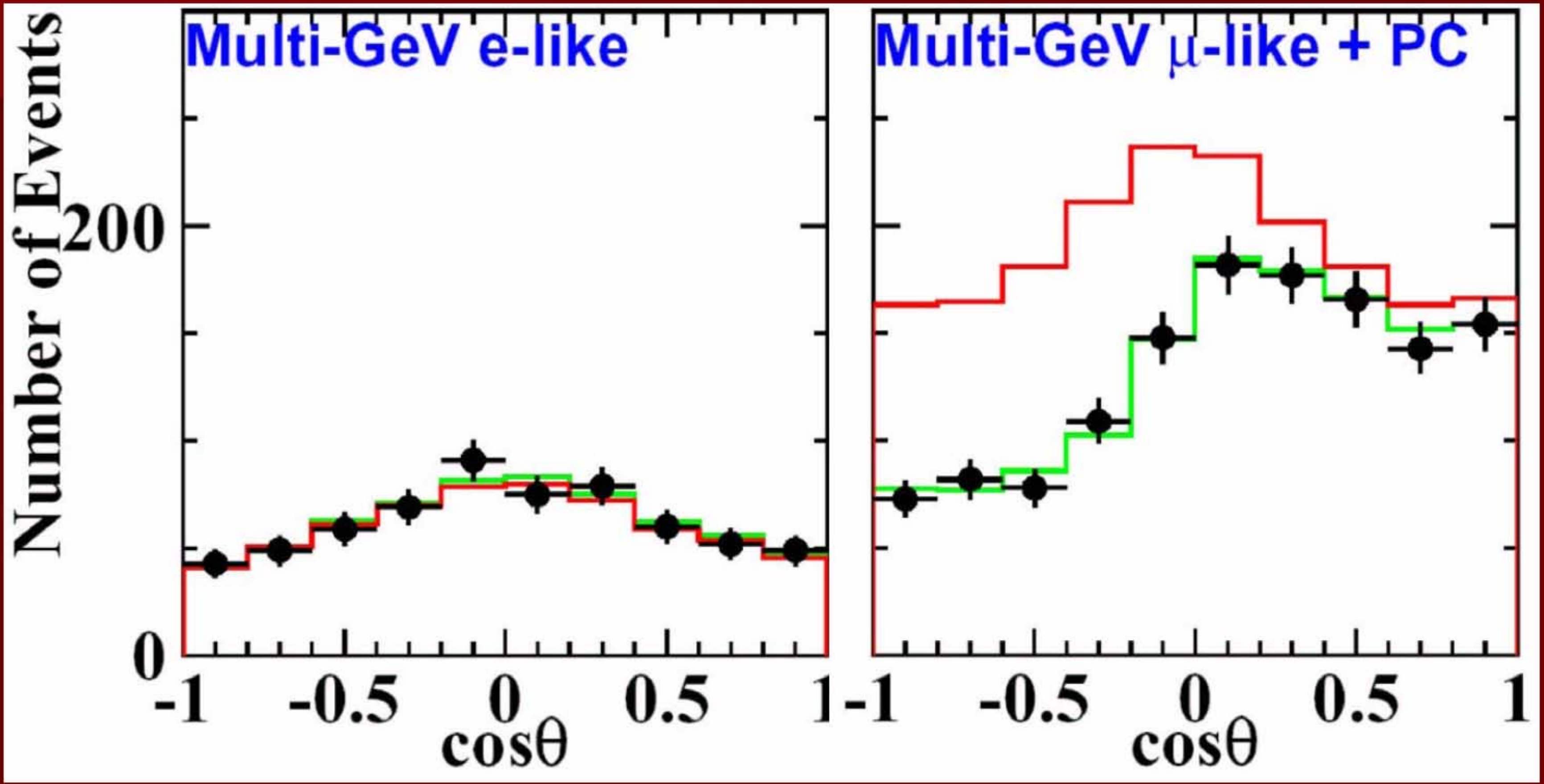
Super-Kamiokande

11 stories high
1,000 meters underground
50,000 tons of water
22,500 tons fiducial volume
11,200 photomultipliers
0.5 meter photomultiplier diameter
(old copper and zinc mine)





Half of ν_μ lost!



Critical Questions for Future Neutrino Physics Program

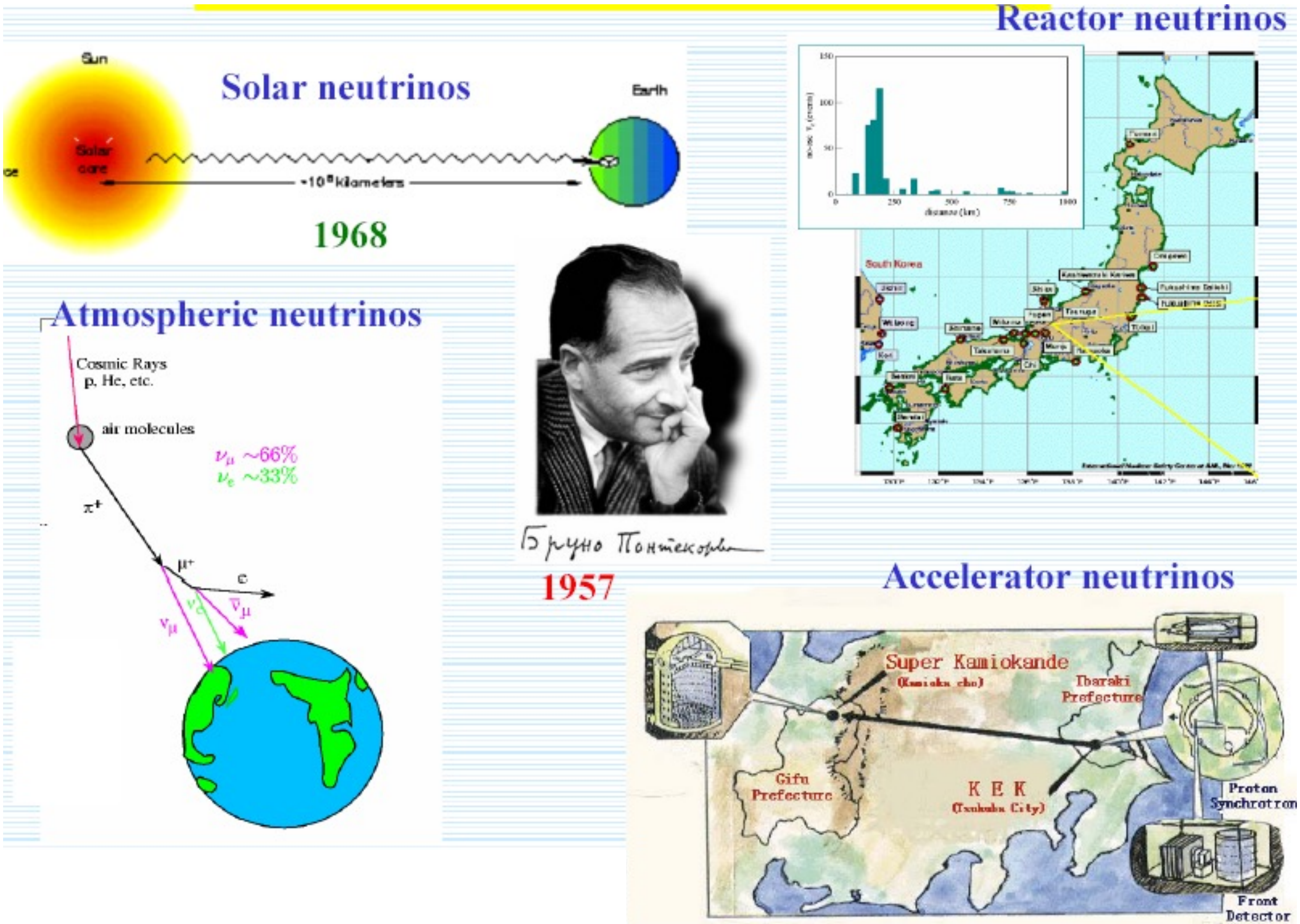
1) Are neutrinos their own anti-particles? Dirac or Majorana neutrinos

2) What are the scale of neutrino masses and the hierarchy of the neutrino mass ordering?

3) What is the remaining neutrino mixing angle θ_{13}? Now it has been measured

4) Do neutrinos violate the CP symmetry and contribute to the matter-antimatter asymmetry?

Oscillations indicate $\Delta m^2 \neq 0$, but unable to determine $\langle m_\nu \rangle$



How to weight neutrinos?

- Neutrino Oscillations
- Cosmology
- Direct Beta Decay Endpoint
- Double Beta Decay