Neutrino Theory & Phenomenology (I)

Mariam Tórtola
IFIC (CSIC/Universitat de València)

Niehls Bohr Institute, Copenhagen, 7-11 July 2025

Course outline

Historical introduction and Neutrinos in the Standard Model

Neutrino oscillations in vacuum and in matter

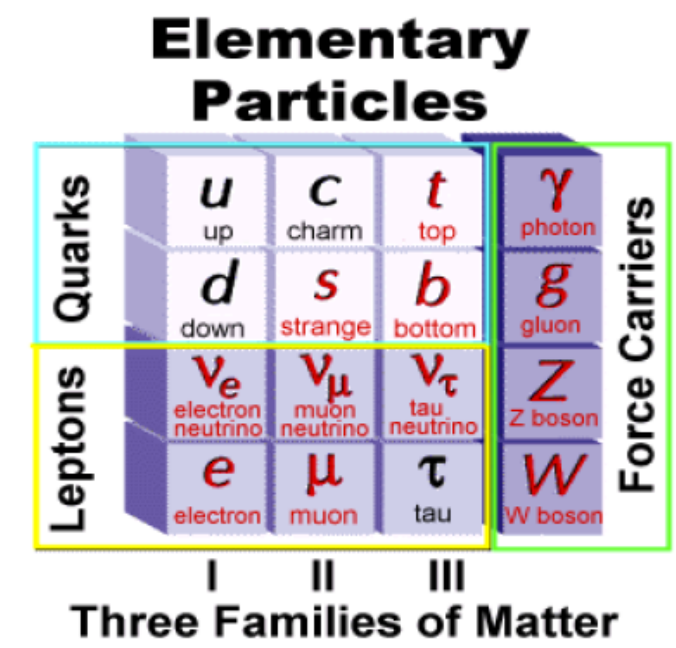
Three-Neutrino phenomenology

Neutrino physics beyond the Standard Model

Historical introduction and Neutrinos in the Standard Model

What is a neutrino?

- spin 1/2 particle
- neutral
- massless particle (almost)
- 3 flavors (mixing)



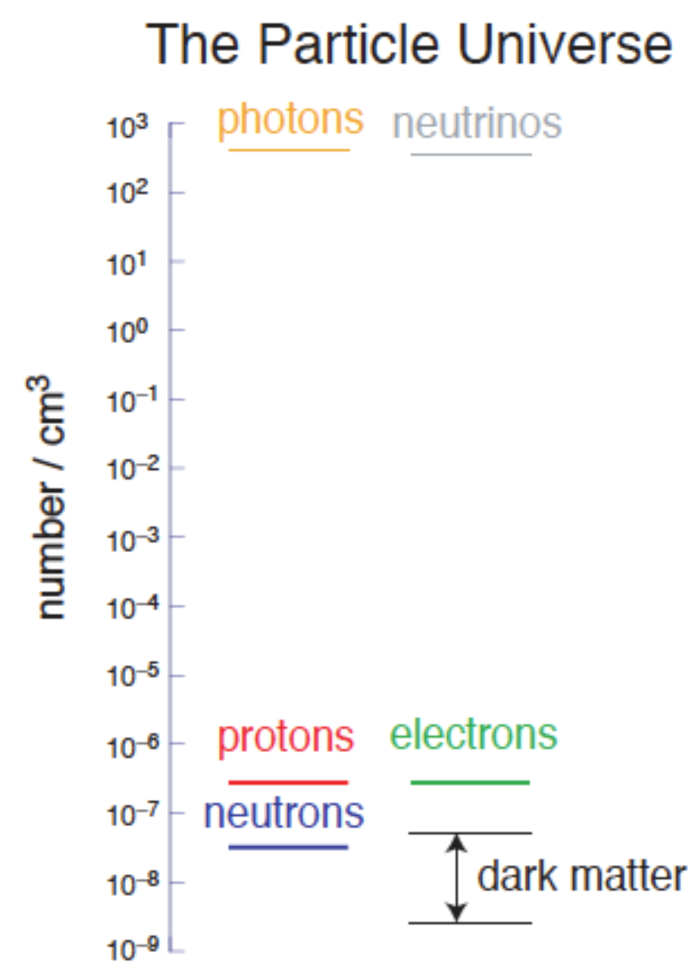
Anything else?

Every second we are traversed by:

- 400×10^{12} neutrinos from the Sun
- 50×10^{9} neutrinos from natural radioactivity
- 10×10^{9} neutrinos from nuclear power plants

Moreover:

- our body emits 4000 neutrinos/s (^{40}K decay)
- the Universe contains ~ 330×10^{6} neutrinos/m^3

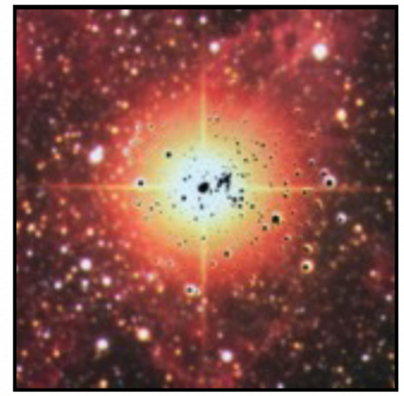


Neutrino sources

✓ Nuclear reactors

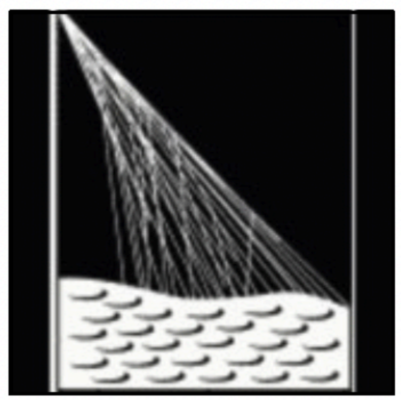
Sun ✓

✓ Particle accelerators



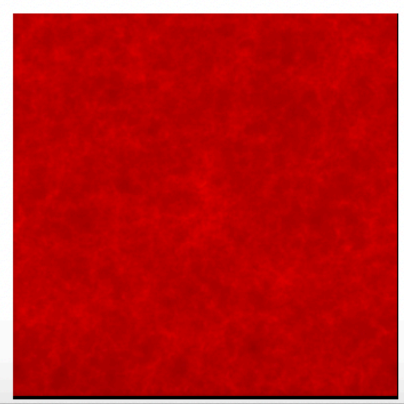
Supernovae
SN 1987A ✓

✓ Earth Atmosphere (Cosmic rays)



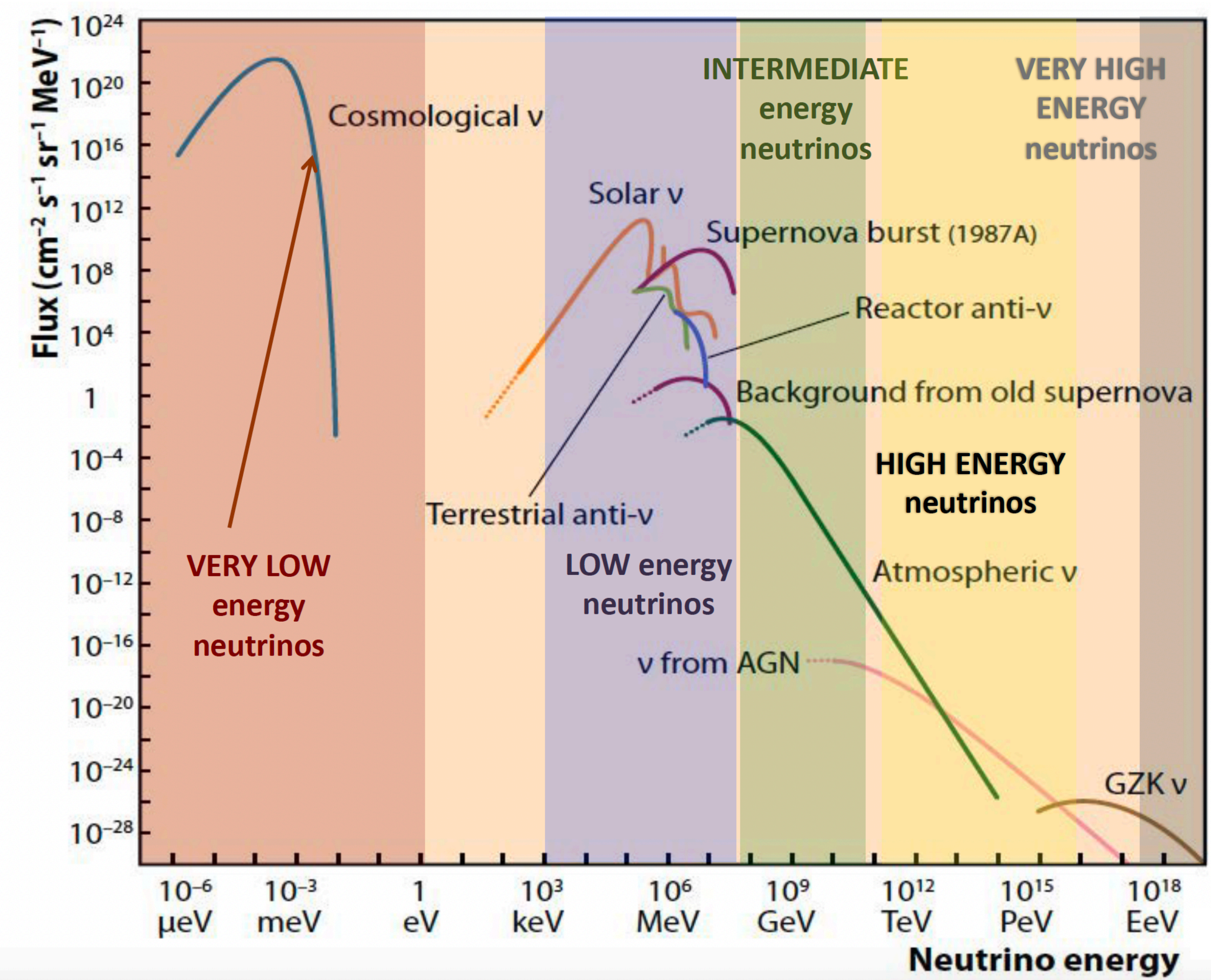
Accelerators in astrophysical sources ?✓

✓ Earth interior (Natural Radioactivity)



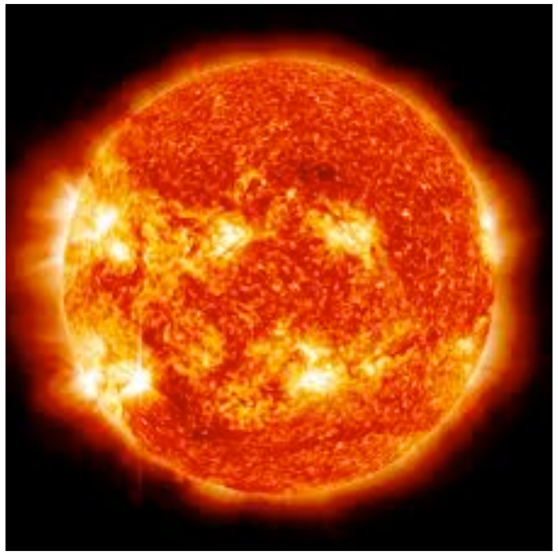
EARLY UNIVERSE
(today 336 ν/cm^3)
Indirect evidence

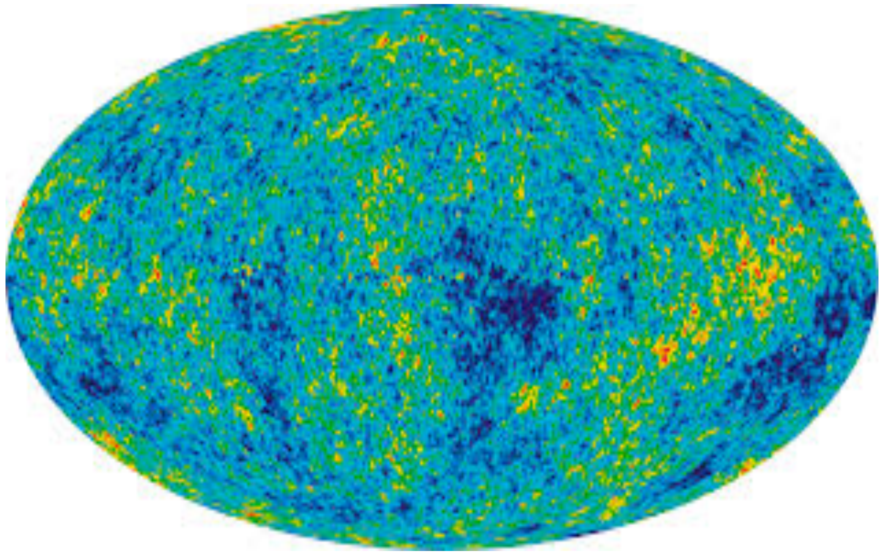
Neutrino sources



Why neutrinos are so important?

- They can probe environments that other techniques cannot: SN explosions, the core of the Sun,...
- Their role is crucial for the evolution of the universe (Big Bang Nucleosynthesis, structure formation).
- They could help explaining the matter-antimatter asymmetry of the Universe (leptogenesis mechanism).
- They could be a component of the dark matter of the universe.
- They provide the first evidence for physics beyond the SM!!!






Why neutrinos are so important?

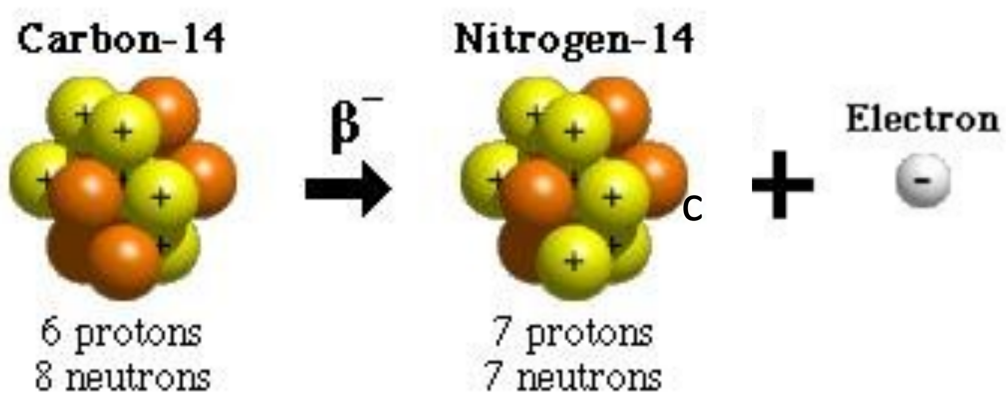
- They can probe environments that other techniques cannot: SN explosions, the core of the Sun,…
- Their role is crucial for the evolution of the universe (Big Bang Nucleosynthesis, structure formation)
- They could help explaining the matter-antimatter asymmetry of the Universe (leptogenesis mechanism)
- They could be a component of the dark matter of the universe.
- They provide the first evidence for physics beyond the SM!!!

However: there are still many open questions in neutrino physics

Historical introduction to neutrino physics

The proposal of the neutrino

1910-1920: Experiments on radioactive decay of atomic nuclei

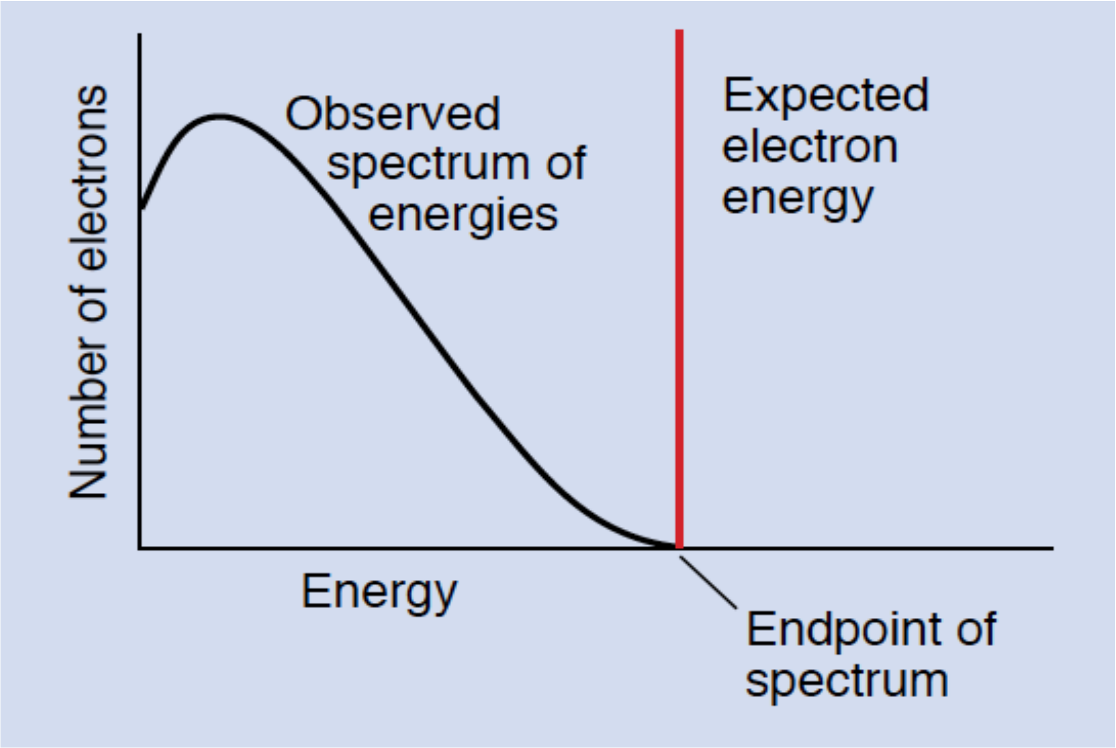



Chadwick


Meitner and Hahn

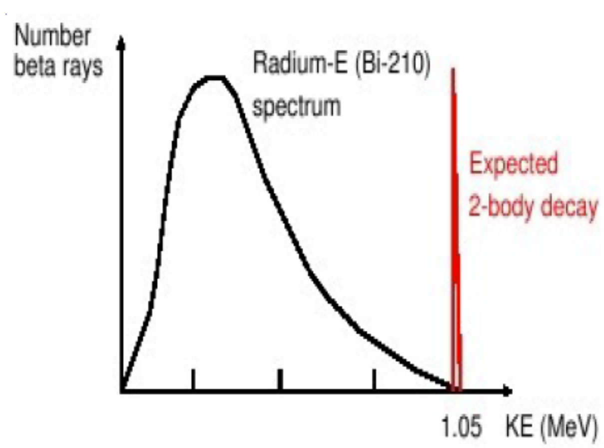
Energy and momentum conservation
⇒ emitted electrons should have a fixed energy

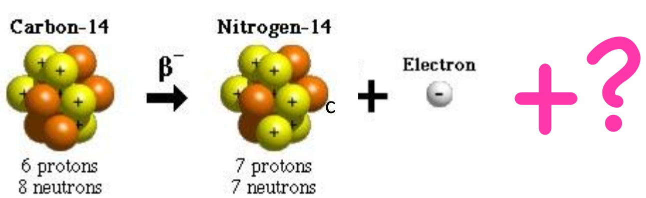
Niels Bohr suggested that energy may not be conserved in individual nuclear processes



The proposal of the neutrino

1930: Pauli introduced the neutrino to explain the continuous electron spectrum





"Dear radioactive ladies and gentlemen,
I have come upon a desperate way out regarding . . . [some fairly obscure data], as well as to the continuous β-spectrum, in order to save . . . The energy law. To wit, the possibility that there could exist in the nucleus electrically neutral particles, which I shall call neutrons, which have spin 1/2 and satisfy the exclusion principle and which are further distinct from light-quanta in that they do not move with light velocity. . . . The continuous β-spectrum would then become understandable from the assumption that in β-decay a neutron is emitted along with the electron, in such a way that the sum of the energies of the neutron and the electron is constant."

➡ from conservation of angular momentum: spin 1/2

The **new particle** would interact very weakly with matter, which explains why it had not been observed, and would carry part of the decay energy, so that the energy spectrum of electrons is continuous.

Fisrt proposal of a **new part**icle that is **NOT** part of ordinary matter

"I have done something very bad today by proposing a particle that cannot be detected. It is something that no theorist should ever do."

Pauli (1930)

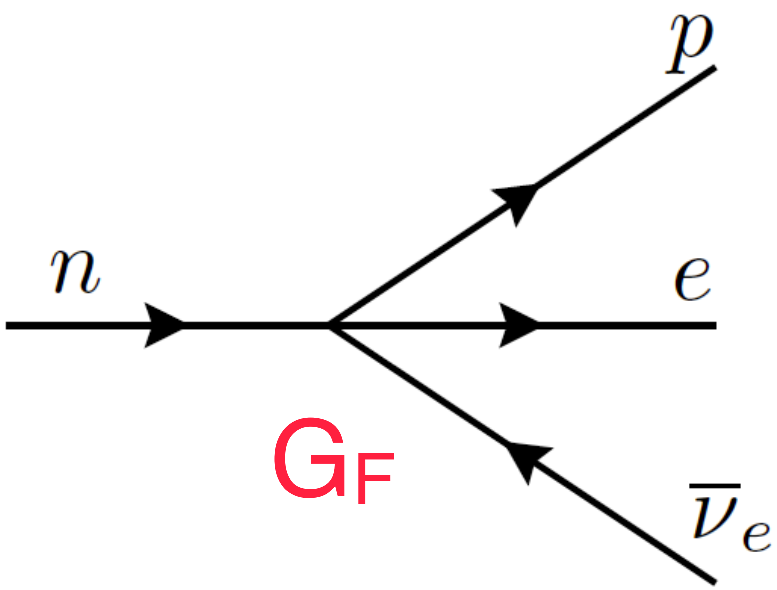
13

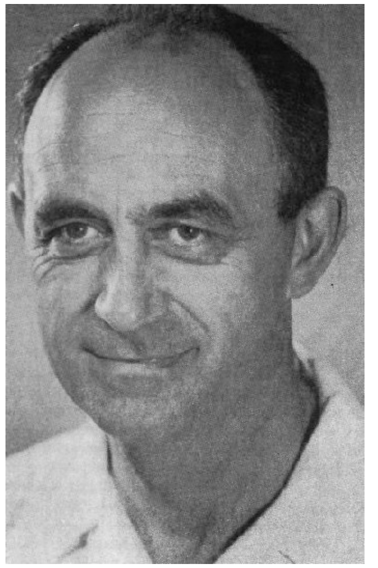
Fermi theory for weak interactions

1933: Fermi postulated the first theory of nuclear beta decay, the theory of weak interactions (in analogy with QED Lagrangian)

$$\mathscr{L}_\beta = \frac{G_\beta}{\sqrt{2}} \overline{\psi}_p \gamma_\alpha \psi_n \overline{\psi}_e \gamma^\alpha \psi_\nu + \mathrm{h.c.}$$

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





Enrico Fermi

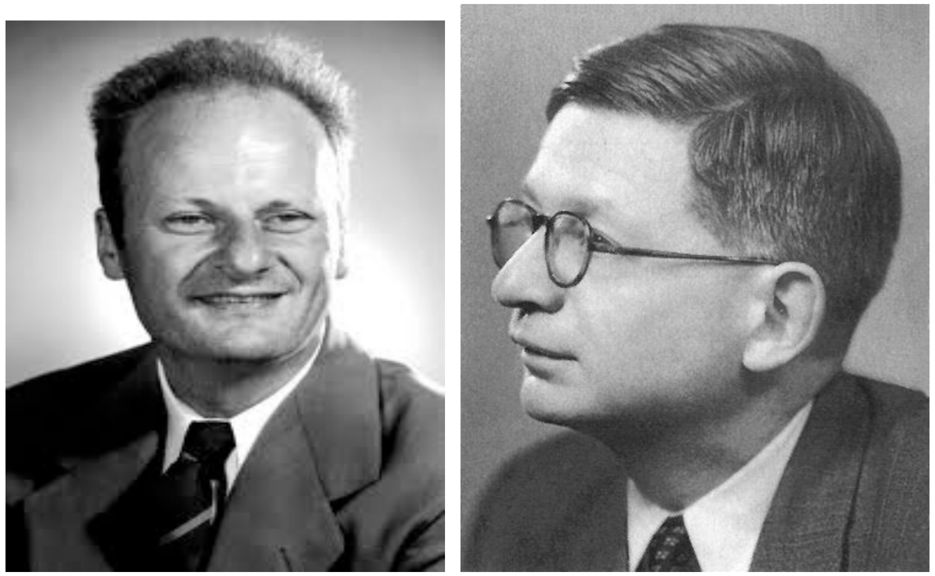
1932: **James Chadwick** discovers the neutron (mass similar to proton)

➡ new name for particle: **neutrino**

Where was the neutrino?

1934: Bethe and Peierls used Fermi theory to calculate the cross section σ for the processes:

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



$$\sigma(\bar{\nu}p \rightarrow e^+ n) \simeq \frac{2\pi^2}{\tau_n m_e^5 f} E_e p_e = \frac{2\pi^2 (hc)^3}{\tau_n c (m_e c^2)^5 f} E_e c p_e$$

$f = 1.715$ phase space factor (for $E_{\bar{\nu}}$ close to threshold)
$\tau_n = 886 \pm 8\text{s}$ neutron lifetime

$$\sigma(\bar{\nu}p \rightarrow e^+ n) \simeq 10^{-43} \left(\frac{E_e p_e}{\text{MeV}^2}\right) \times \left(\frac{\tau_n}{886\text{s}}\right) \text{cm}^2$$

Tiny compared with $\sigma_{\gamma p} \sim 10^{-25}$ cm^2) !!!

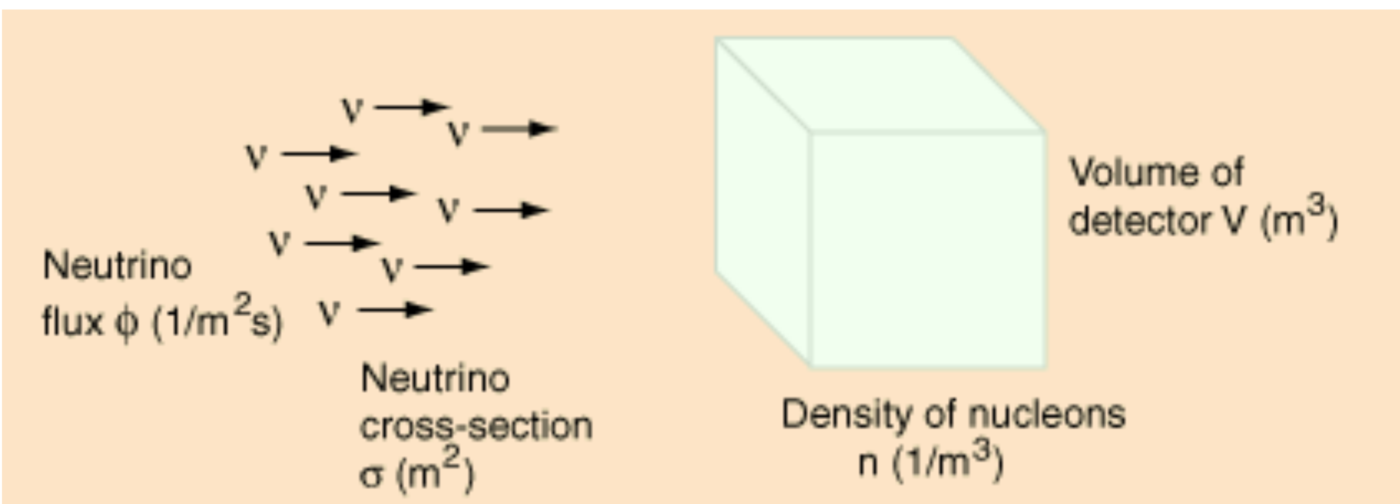
Exercises → mean free path of neutrinos in **water** and **lead**

Neutrino: impossible to detect?

> *"I have done something very bad today by proposing a particle that cannot be detected. It is something that no theorist should ever do."*

Pauli, 1930

Event number in a neutrino experiment:



$$N = \phi\, \sigma\, N_{targ}\, \Delta t$$

Exercises

with a 1000 kg detector and a flux of 10^{10} ν/s: few ν events/day

→ solar neutrino flux ~ 7×10^{10} ν/cm^2/s

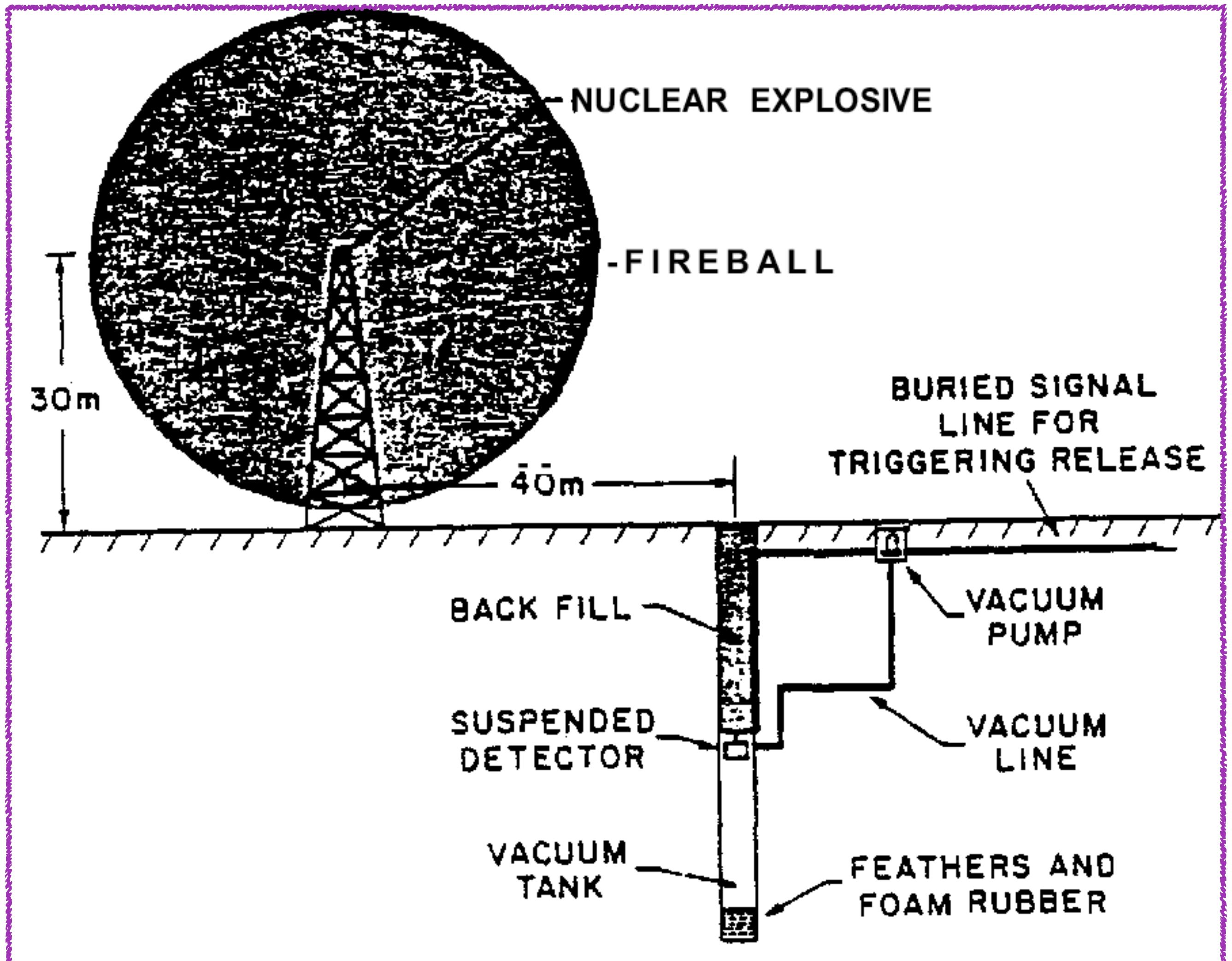
→ reactor neutrino flux ~ 10^{20} ν/s

Difficult but not impossible!

First proposals for neutrino detection

Fred Reines and Clyde Cowan

1951: Detection after a nuclear explosion



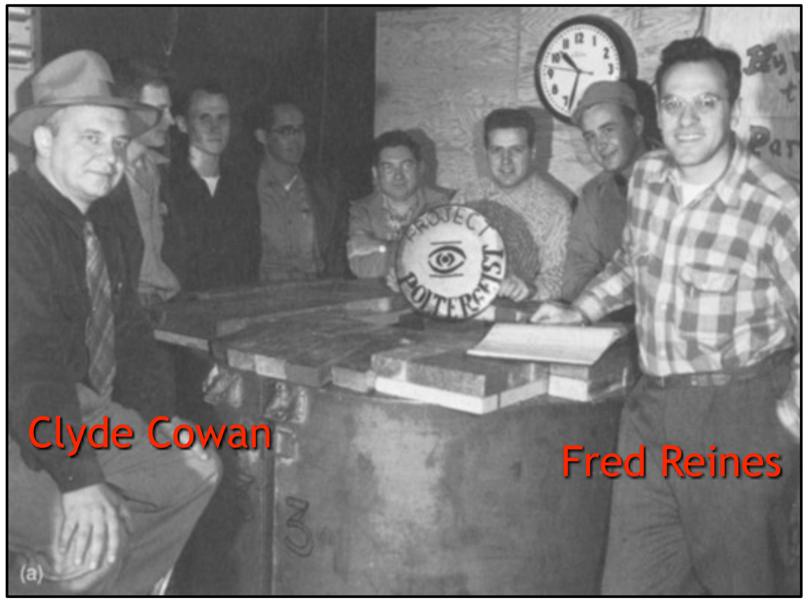
1953: Prototype at Hanford reactor

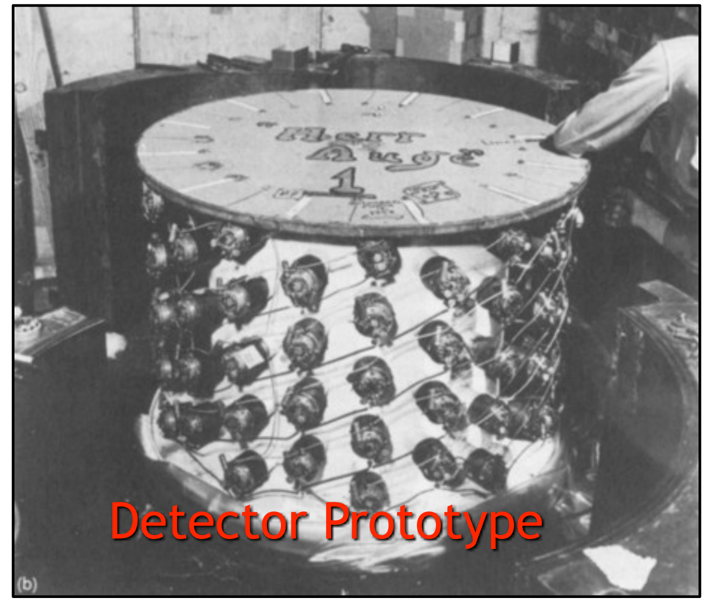
Poltergeist Project

“The Reines-Cowan Experiments-Detecting the Poltergeist”
Los Alamos Science Number 25 1997

Discovery of the neutrino

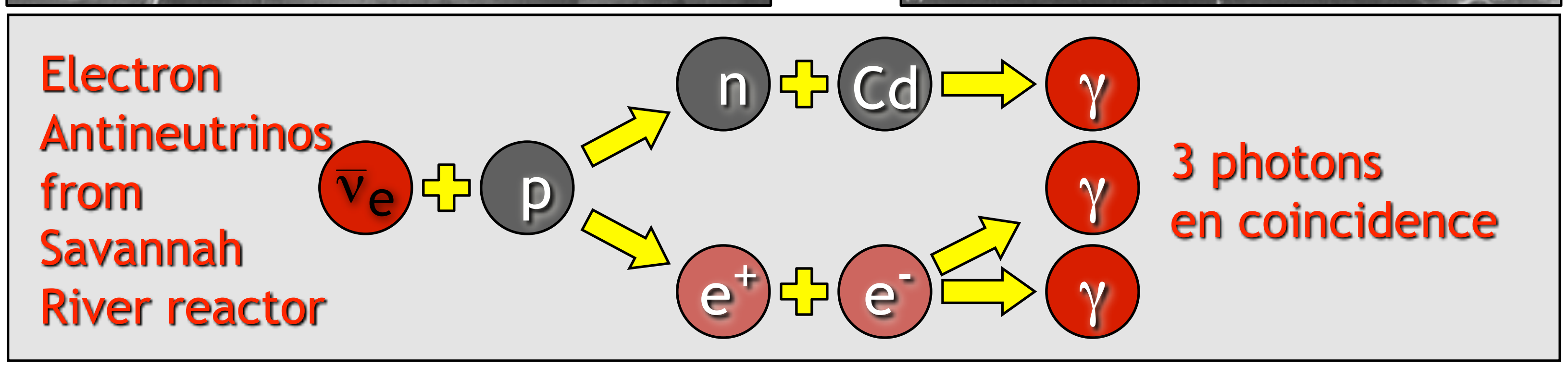
1956: First observation of reactor ν_e by Reines and Cowan.





2 tanks with
200 liters H_2O
+
40 kg $CdCl_2$

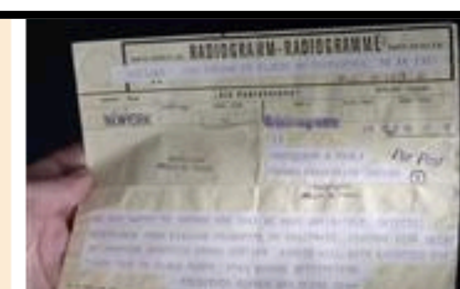
3 scintillator
layers with PMTs



1995: Nobel
Prize in Physics
to Reines

Telegram to Pauli on 12/06/1956

"We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected six times ten to minus forty-four square centimeters"



Beyond Fermi theory

- 1933: Fermi theory for β-decay: $\mathscr{L}_\beta = \frac{G_\beta}{\sqrt{2}} \overline{\Psi}_p \gamma_\alpha \Psi_n \overline{\Psi}_e \gamma^\alpha \Psi_\nu + \mathrm{h.c.}$

  Applied to other decays? with the currents $J_N^\alpha = \overline{\Psi}_p \gamma^\alpha \Psi_n$ and $J_e^\alpha = \overline{\Psi}_e \gamma^\alpha \Psi_\nu$

  vectors under Lorentz transformations

  $\rightarrow \mathscr{L}_\beta = \frac{G_\beta}{\sqrt{2}} J_N^\alpha J_{e\alpha} + \mathrm{h.c.}$ → Lorentz scalar

- 1936: Gamow & Teller proposed the more general $\mathscr{L}$ (Lorentz scalar)

$$\mathscr{L} = c_1 \overline{\Psi}_p \Psi_n \overline{\Psi}_e \Psi_\nu + c_2 \overline{\Psi}_p \gamma^\alpha \Psi_n \overline{\Psi}_e \gamma_\alpha \Psi_\nu + c_3 \overline{\Psi}_p \sigma^{\alpha\beta} \Psi_n \overline{\Psi}_e \sigma_{\alpha\beta} \Psi_\nu$$

SxS VxV TxT

$$+ c_4 \overline{\Psi}_p \gamma^\alpha \gamma_5 \Psi_n \overline{\Psi}_e \gamma_\alpha \gamma_5 \Psi_\nu + c_5 \overline{\Psi}_p \gamma_5 \Psi_n \overline{\Psi}_e \gamma_5 \Psi_\nu$$

AxA PxP

Assuming parity was conserved in weak interactions

Parity violation in weak interactions

τ-θ puzzle:

$$\Theta^+ \to \pi^+ + \pi^0$$ $P = (-1)(-1) = +1$

$$\tau^+ \to \pi^+ + \pi^+ + \pi^-$$ $P = (-1)(-1)(-1) = -1$

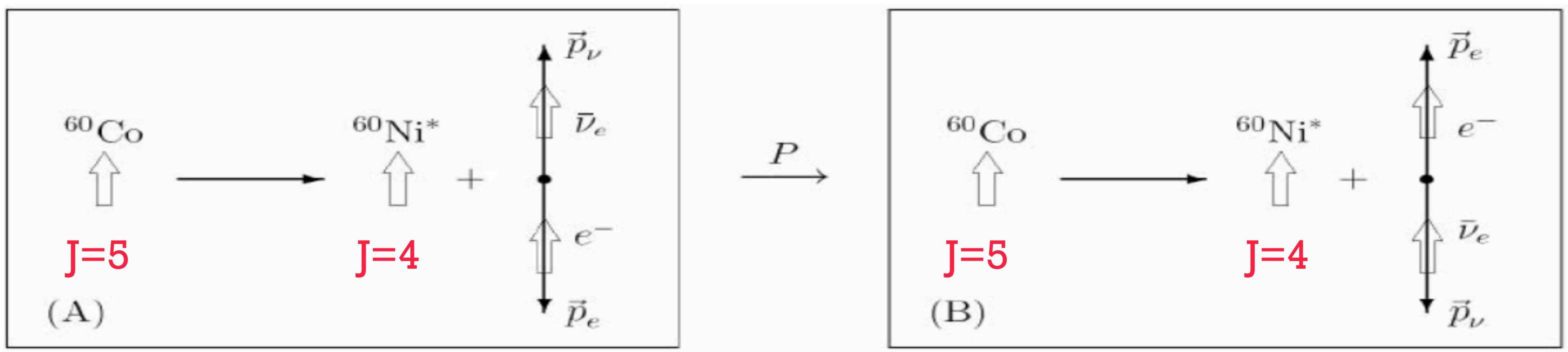
$(\tau^+ = \theta^+ = K^+)$

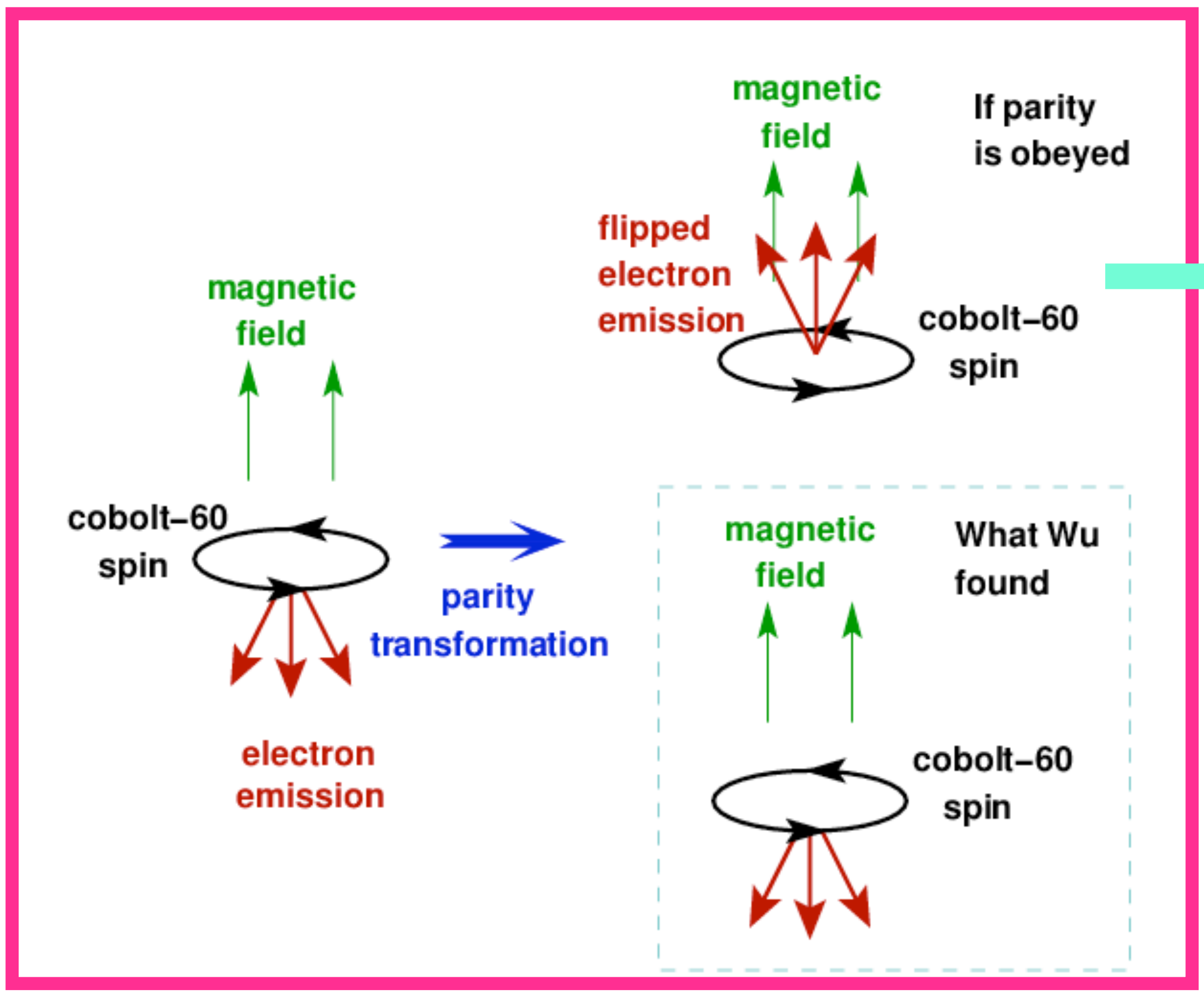
1956: Lee and Yang proposed parity violation in weak interactions

Lee and Yang, Phys. Rev. 104 (1956) 254.

1957: using a radioactive source of ^{60}Co, Chien-Shiung Wu et al. determined that weak interaction violates parity conservation maximally.

Parity violation in Wu experiment





Fewer electrons emitted in the direction of the magnetic field!

Antineutrinos are preferably emitted in the direction of the field (in parallel to their spin)

Wu et al, Phys. Rev. 105 (1957)1413.

Parity violation in weak interactions

τ-θ puzzle:

$$\theta^+ \to \pi^+ + \pi^0 \qquad P = (-1)(-1) = +1$$

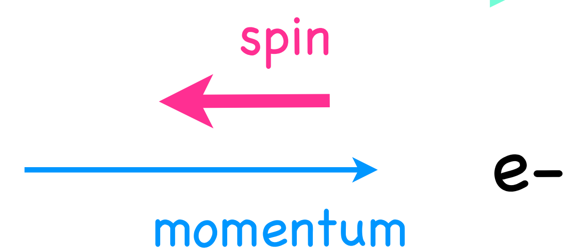
$$\tau^+ \to \pi^+ + \pi^+ + \pi^- \qquad P = (-1)(-1)(-1) = -1$$

$(\tau^+ = \theta^+ = K^+)$

1956: Lee and Yang proposed parity violation in weak interactions

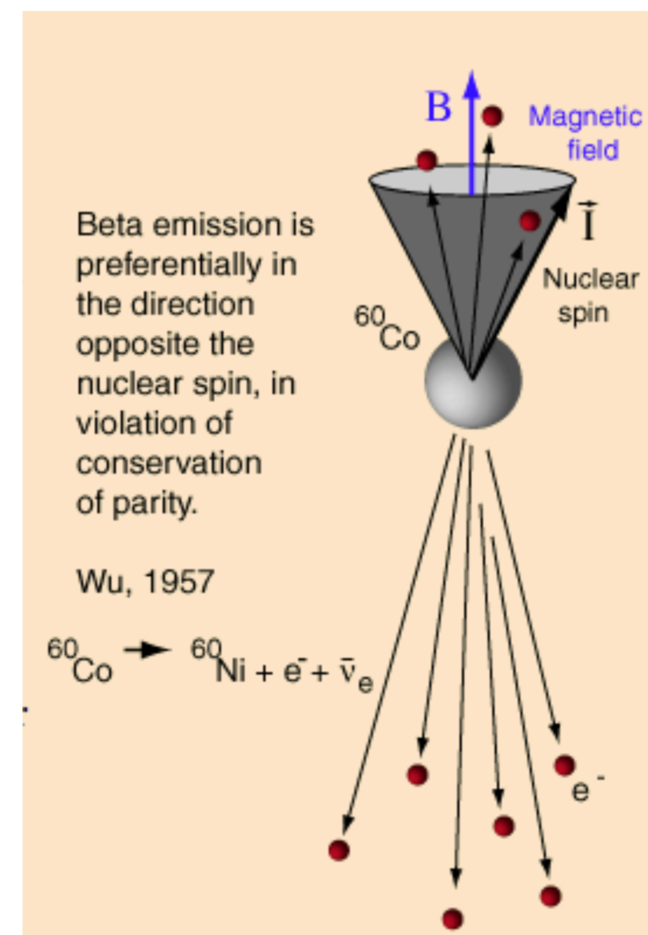
Lee and Yang, Phys. Rev. 104 (1956) 254.

1957: using a radioactive source of ^{60}Co, Chien-Shiung Wu et al. determined that weak interaction violates parity conservation maximally:



1957: Nobel Prize in Physics (Lee & Yang)

1978: Wolf Prize in Physics (C.S. Wu)



1958: Goldhaber et al. showed that neutrinos can only be emitted with their spin anti-parallel to their momentum direction.

Goldhaber experiment

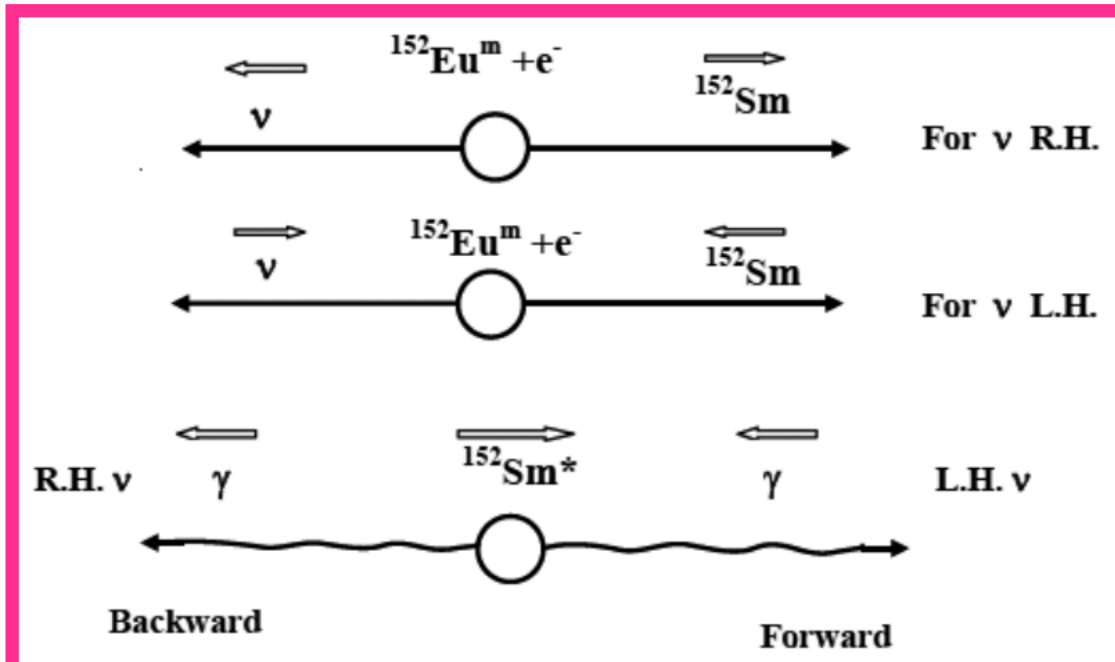
- Indirect measurement of neutrino helicity in an electron capture experiment

$$^{152m}Eu + e^- \to {}^{152}Sm^* + \nu_e \to {}^{152}Sm + \gamma + \nu_e$$

0	½	1	- ½	0	1	- ½
0	- ½	-1	½	0	-1	½

- By angular momentum conservation: the spin of the photon and the neutrino are always opposite
- By momentum conservation: they are also emitted back to back

→ H(γ) = H(ν)



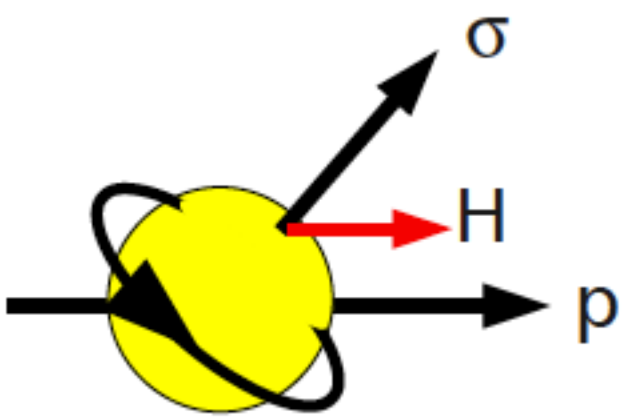
→ They measured photon polarization (=helicity)

H(γ) = -1 → H(ν)=-1 → neutrino always left-handed

Goldhaber, Grodzins and Sunyar, Phys. Rev. 109 (1958) 1015.

Helicity and Chirality

Helicity is the projection of spin along the momentum direction



$$\hat{H} = \frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|}$$

→ Lorentz-invariant only for massless particles

→ directly measurable

Chirality is an asymmetry property: a chiral object is not identical to its mirror image, cannot be superimposed on it.

$$P_{\mathrm{L,R}} = \frac{1 \mp \gamma_5}{2}\,, \ \psi_{\mathrm{L,R}} = P_{\mathrm{L,R}}\psi$$

→ Handedness = Chirality

→ Lorentz-invariant although not directly measurable

Massless particles: Helicity = Chirality

Massive particles: Chiral states contain contributions from both helicity states

Ultra-relativistic particles: LH (RH) chiral projection dominated by a - (+) helicity state

The V-A theory

Parity violation in weak interactions: Gamow and Teller construction had to be modified to include terms of the form V x A

$$\overline{\psi}_p \gamma^\alpha \psi_n \overline{\psi}_e \gamma_\alpha \gamma_5 \psi_\nu$$

Besides, these results proved that neutrinos have negative helicity (small mass):

$$\psi_\nu = P_L \psi_\nu = \frac{1-\gamma_5}{2}\psi_\nu$$

Leptonic current: $J_e^\alpha = \overline{\psi_e}\gamma^\alpha \psi_\nu \rightarrow J_e^\alpha = \overline{\psi_e}\gamma^\alpha (1-\gamma_5)\psi_\nu$

And: $\overline{\psi_e}\gamma^\alpha P_L \psi_\nu = \overline{(P_L \psi_e)}\gamma^\alpha P_L \psi_\nu$

Only LH part of electron field participates in weak interactions!!

✦ In general, the **V-A current**: $\overline{\psi}\gamma^\alpha (g_v - g_A \gamma_5)\psi$

In general: $\psi = P_L \psi + P_R \psi \quad \rightarrow \overline{\psi_L}\gamma^\alpha (g_v - g_A\gamma_5)\psi_L + \overline{\psi_R}\gamma^\alpha (g_v - g_A \gamma_5)\psi_R$

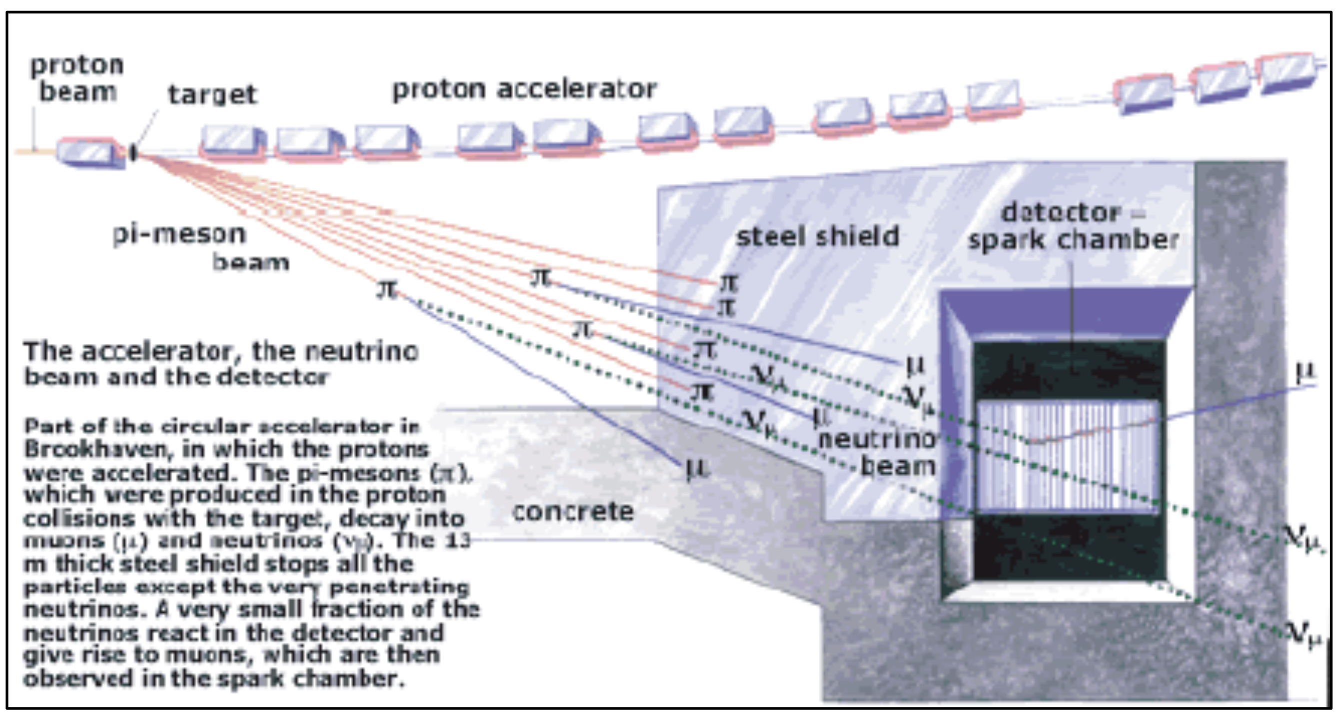
V and AV currents preserve chirality

More than one neutrino flavour?

1959: Pontecorvo suggested the existence of a different neutrino, associated to muon decay and proposed an experiment to check it.

$$\nu_{\rm acc} + n \to p + (e^- \text{ or } \mu^- ?)$$

1962: Discovery of ν_μ by Lederman, Schwartz and Steinberger



$$\pi^+ \to \mu^+ + \nu_\mu$$

not e⁻

$$\nu_\mu + n \to p + \mu^-$$


Leon M. Lederman


Melvin Schwartz

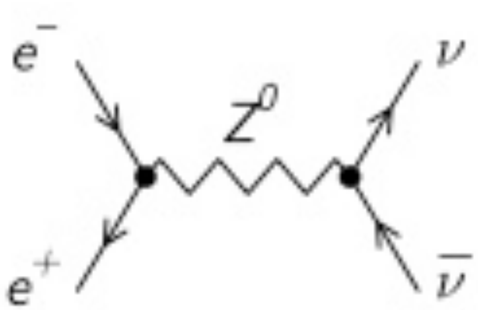

Jack Steinberger

1988: Nobel Prize in Physics

More than two neutrino flavours?

1978: Discovery of τ at SLAC → imbalance of energy in τ decay suggests the existence of a third neutrino.

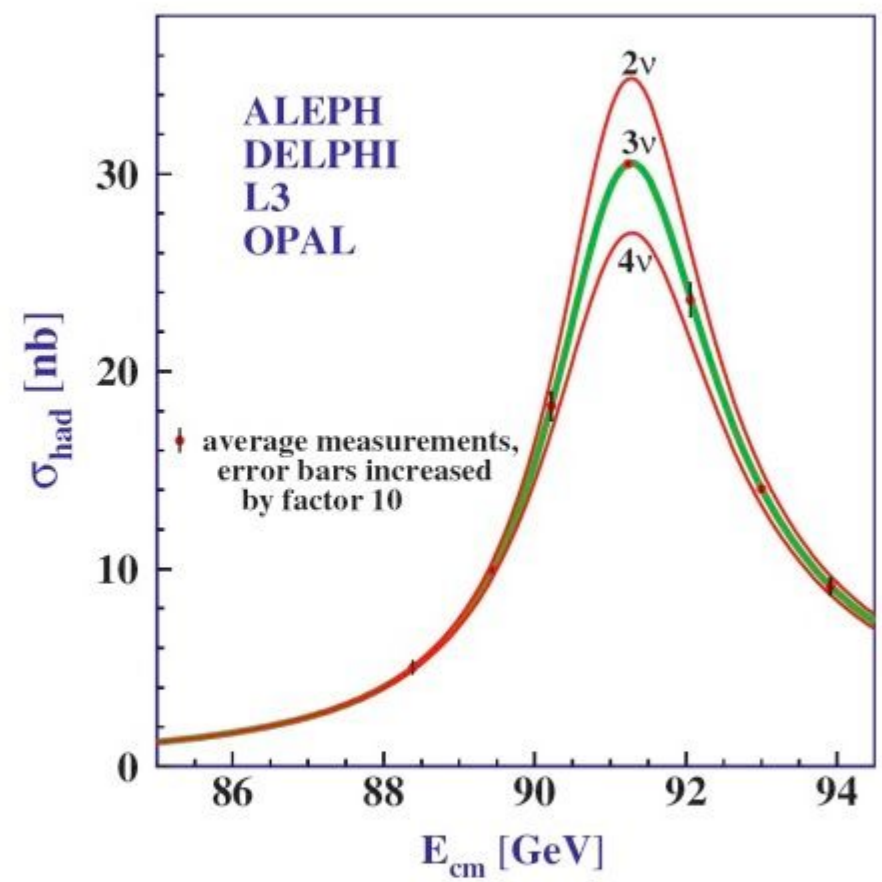
1989: LEP measurements of the invisible decay width of Z boson



$$\Gamma_{\rm inv} \equiv \Gamma_Z - \Gamma_{\rm had} - 3\Gamma_{\rm lep}$$

$$N_\nu = \Gamma_{\rm inv}/\Gamma_{\rm SM}(Z \to \nu_i \overline{\nu}_i)$$

→ $N_\nu = 2.984 \pm 0.008$

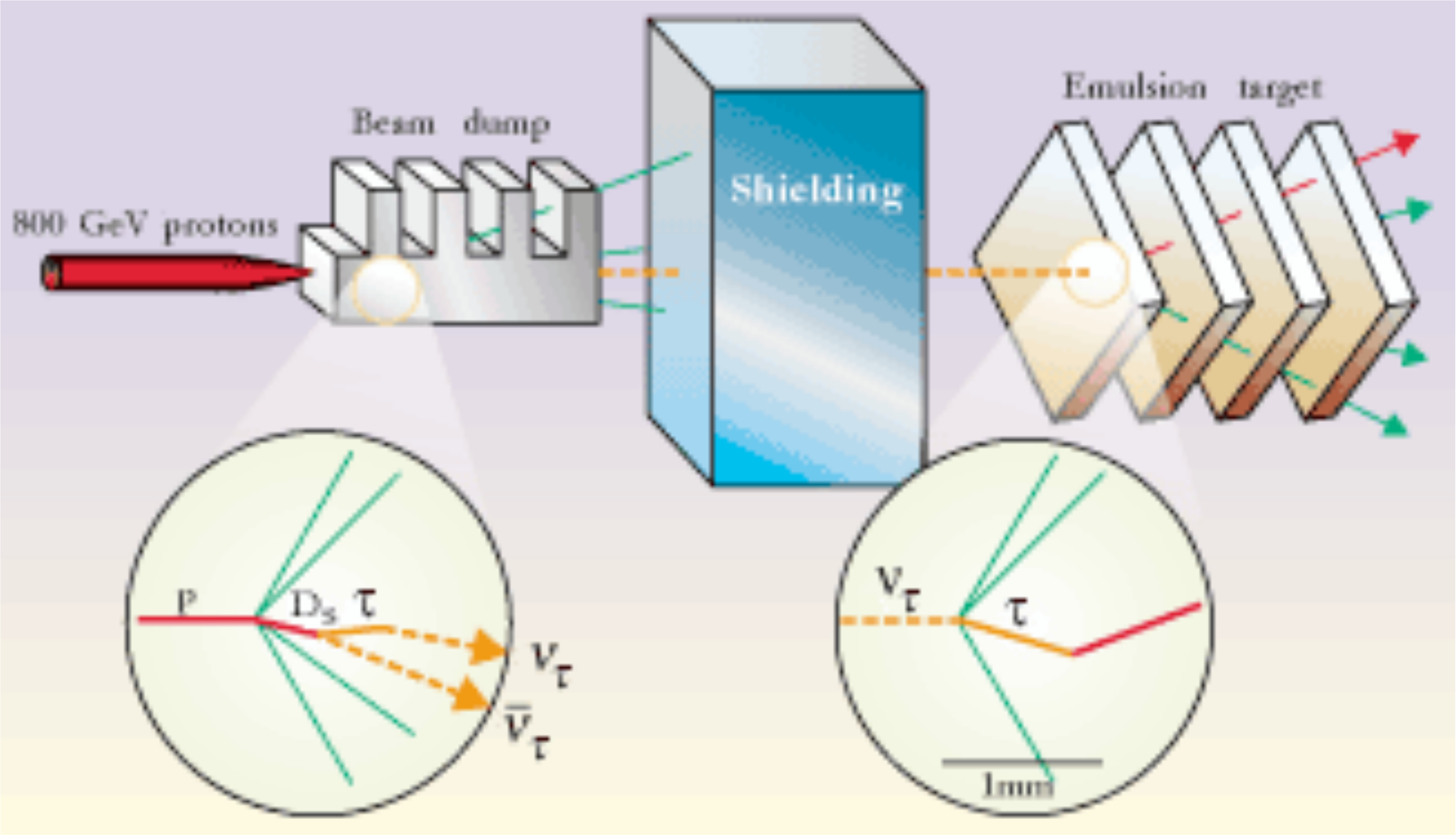


-

More than two neutrino flavours?

2000: Discovery of ν_τ by the DONUT Collaboration.

800 GeV p ⇒ Ds meson (≡cs) → ν_τ τ ⇒ τ detected



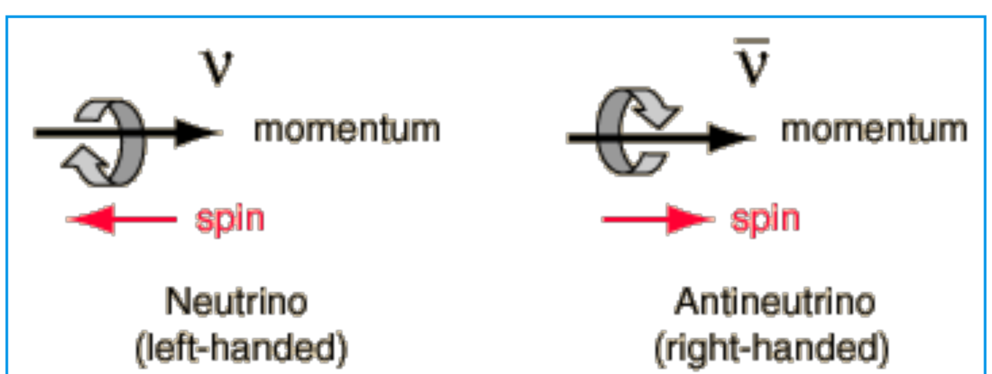
Neutrinos in the Standard Model

Neutrinos in the Standard Model

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

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{-\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{-\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

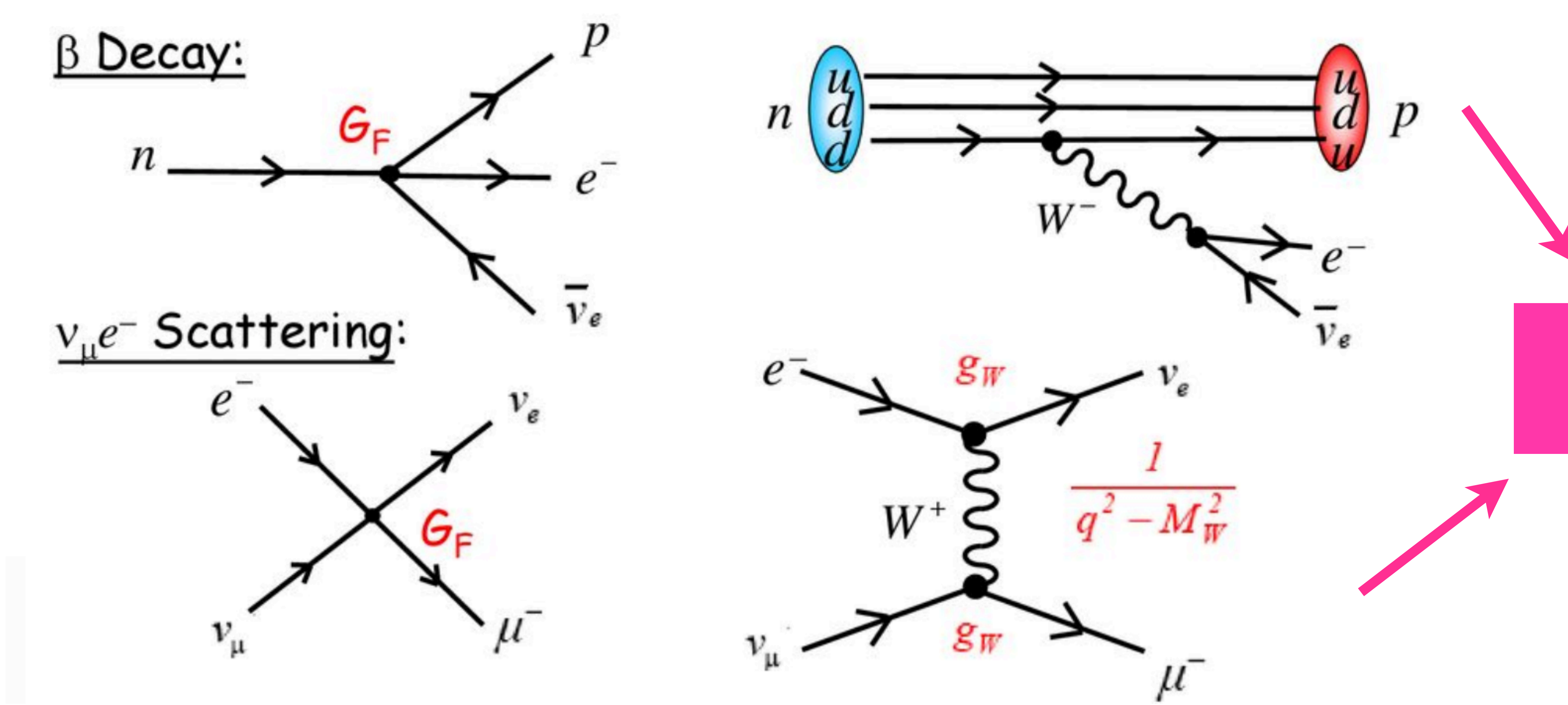
$Y = Q - I_3$



no SU(2) neutrino singlets in the SM

Neutrino interactions with charged leptons

- Neutrinos were first detected through their weak interactions with charged leptons, known as Charged Current (CC) interactions.
- CC weak interactions first described by Fermi as point-like 4-fermion vertex.
- SM: CC interactions are mediated by the vector boson W (W^-, W^+)

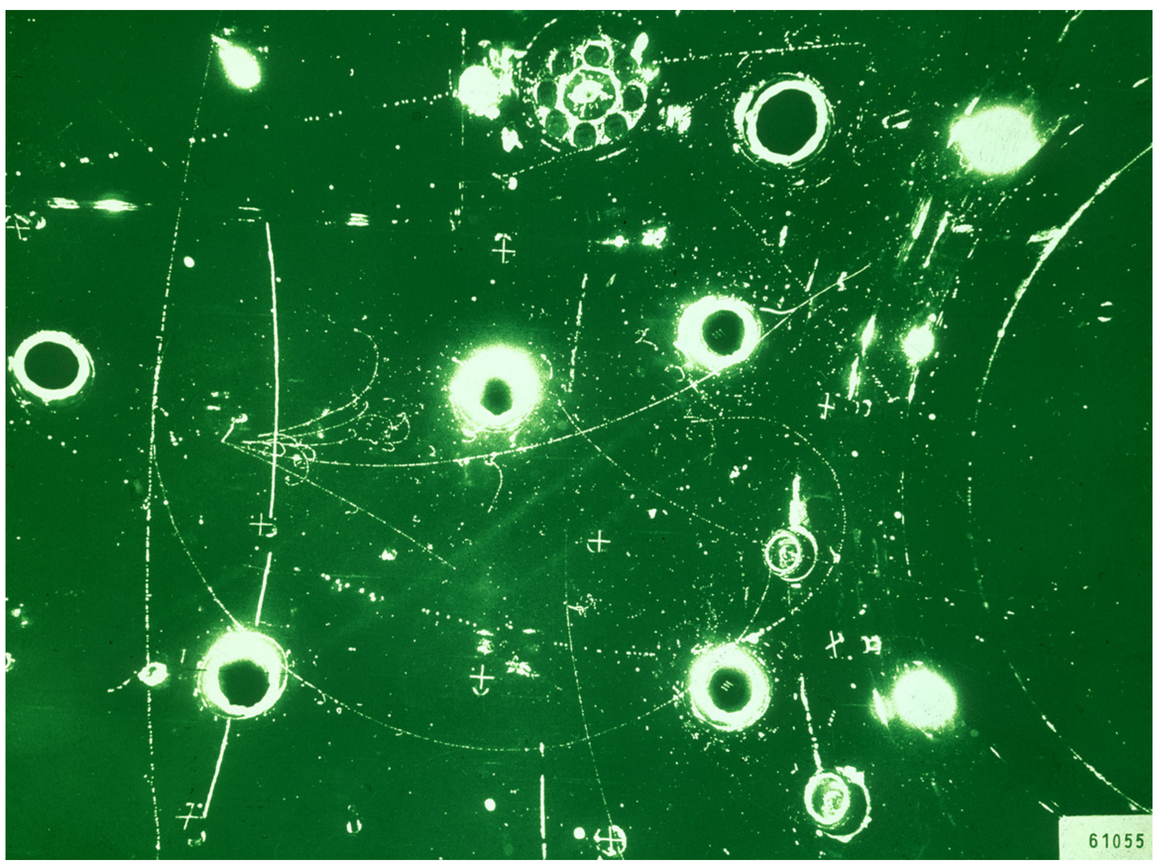


W's couple to leptons in the same doublet

Discovery of Neutral Currents

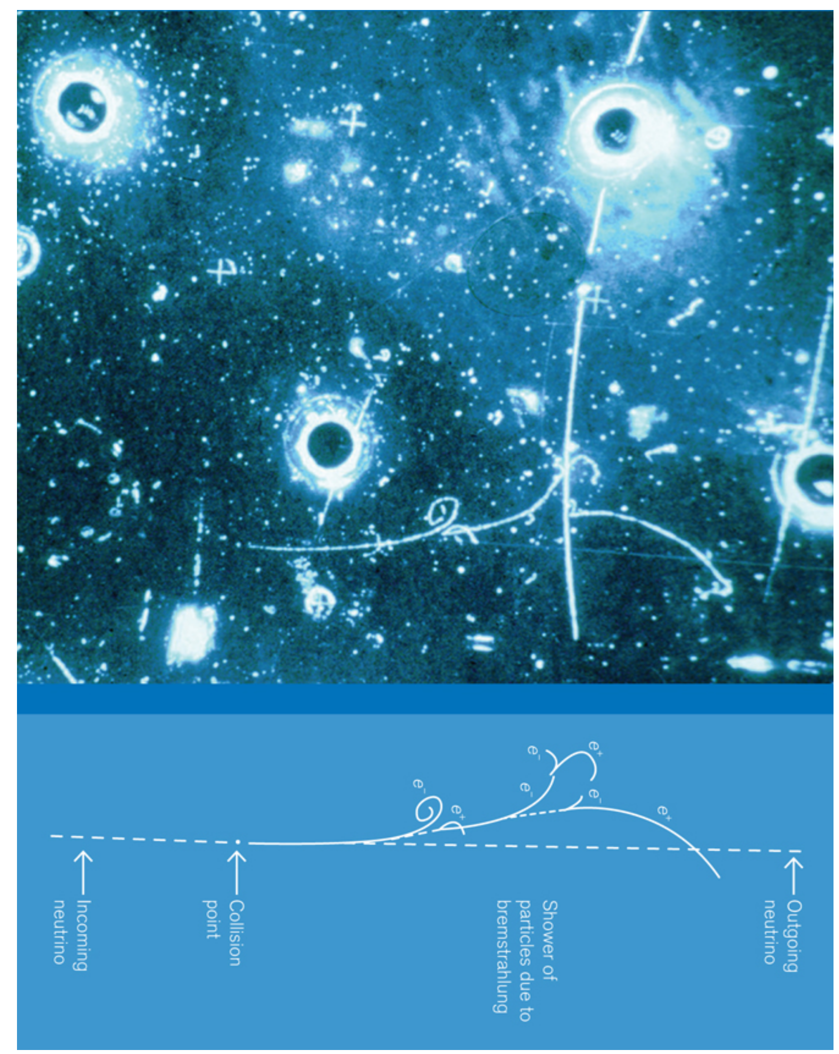
- ✦ The Glashow-Weinberg-Salam model predicted the existence of weak interactions mediated by a neutral vector boson, the Z^0
- ✦ Neutral Current interactions were first observed in 1973 with Gargamelle bubble chamber

$$\overline{\nu}_\mu + N \to \overline{\nu}_\mu + \text{hadrons}$$



Hasert et al, Phys. Lett. B 46 (1973) 138.

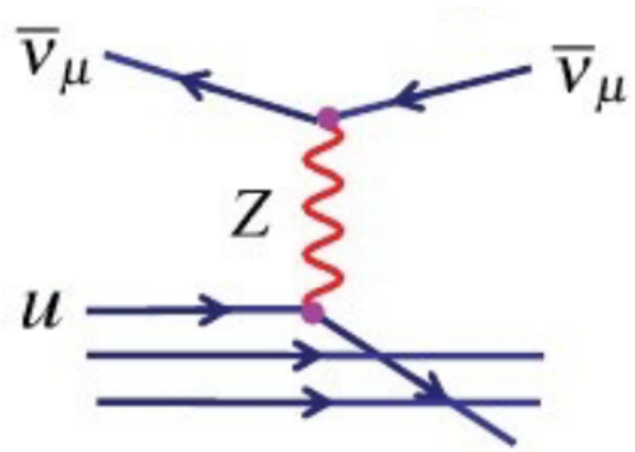
$$\overline{\nu}_\mu + e^- \to \overline{\nu}_\mu + e^-$$



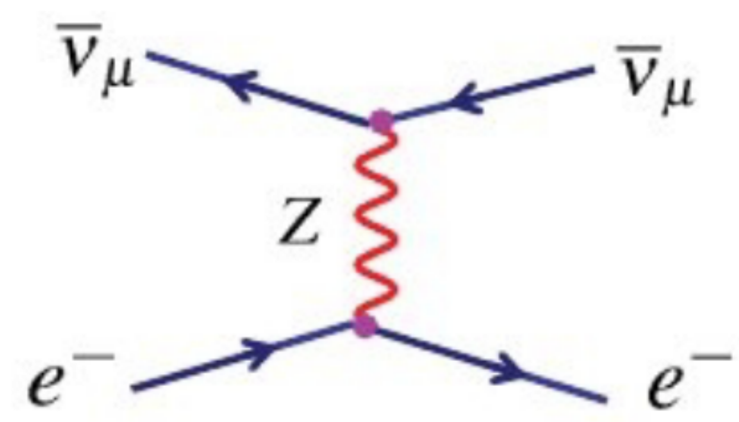
Discovery of Neutral Currents

- The Glashow-Weinberg-Salam model predicted the existence of weak interactions mediated by a neutral vector boson, the Z^0
- Neutral Current interactions were first observed in 1973 with Gargamelle bubble chamber

$$\overline{\nu}_\mu + N \to \overline{\nu}_\mu + \text{hadrons}$$



$$\overline{\nu}_\mu + e^- \to \overline{\nu}_\mu + e^-$$

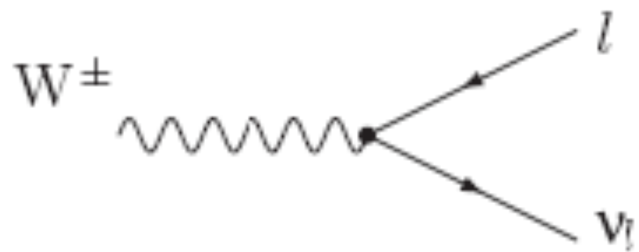


→ First evidence for Z boson

Hasert et al, Phys. Lett. B 46 (1973) 138.

Neutrino interactions in the SM

Charged Current (CC):



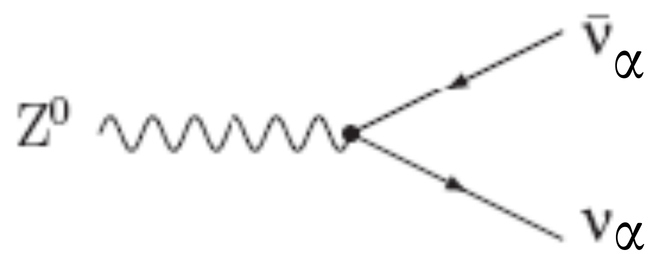
$$W^- \to l_\alpha^- + \overline{\nu}_\alpha$$

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

$$(\alpha = e, \mu, \tau)$$

$$\mathcal{L}_{\rm CC} = -\frac{g}{\sqrt{2}} \sum_\alpha \overline{\nu}_{\alpha L} \gamma^\mu l_{\alpha L} W_\mu + {\rm h.c.}$$

Neutral Current (NC):



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

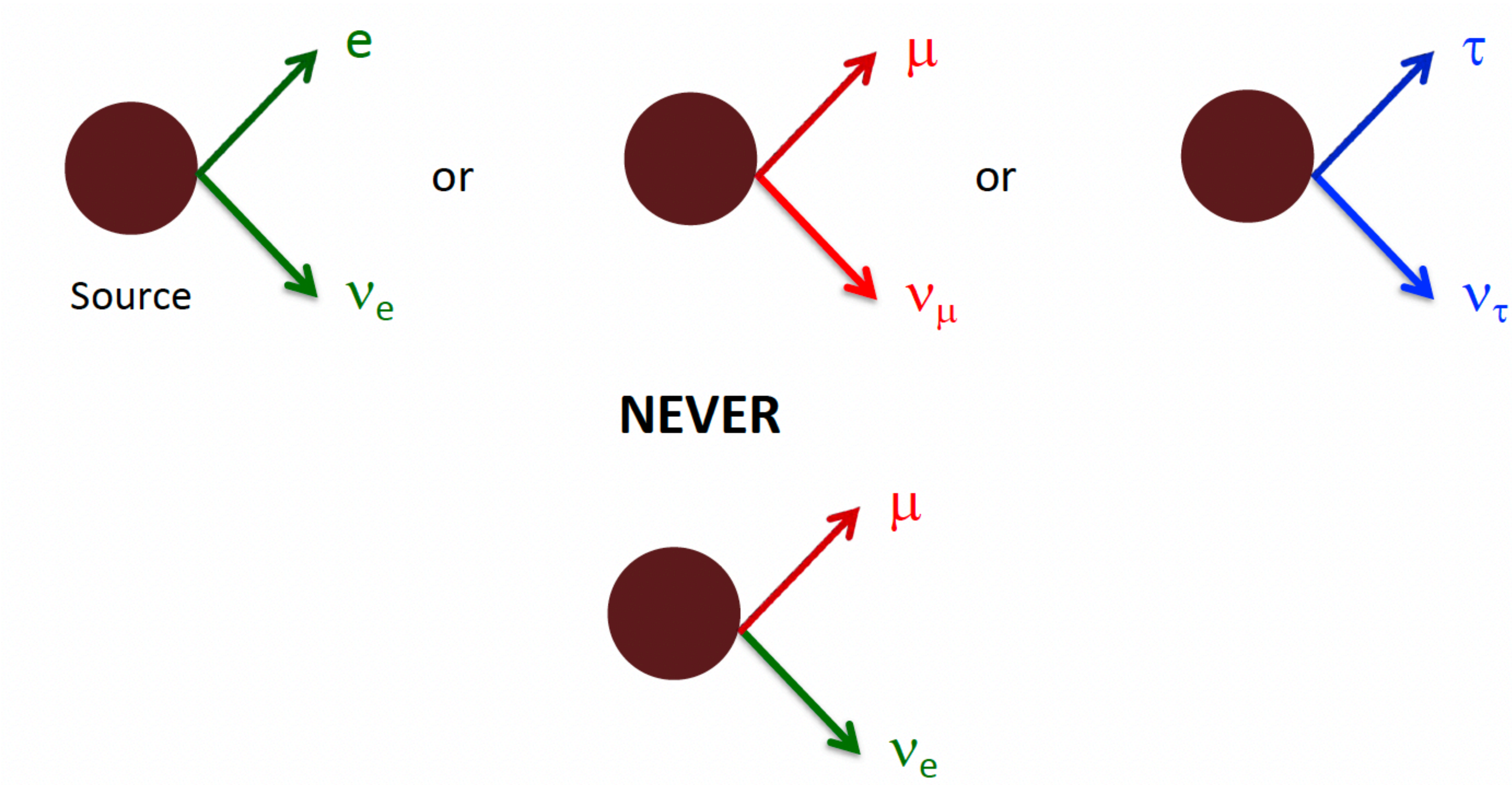
$$\mathcal{L}_{\rm NC} = -\frac{g}{2\cos\theta_W} \sum_\alpha \overline{\nu}_{\alpha L} \gamma^\mu \nu_{\alpha L} Z_\mu^0$$

in the SM, only LH neutrinos and RH antineutrinos participate in weak interactions

- ✦ Interactions conserve total Lepton Number L: $L(l^-) = L(\nu) = -L(l^+) = -L(\overline{\nu}) = 1$
- ✦ Family lepton numbers L_e, L_μ, L_τ are also conserved.

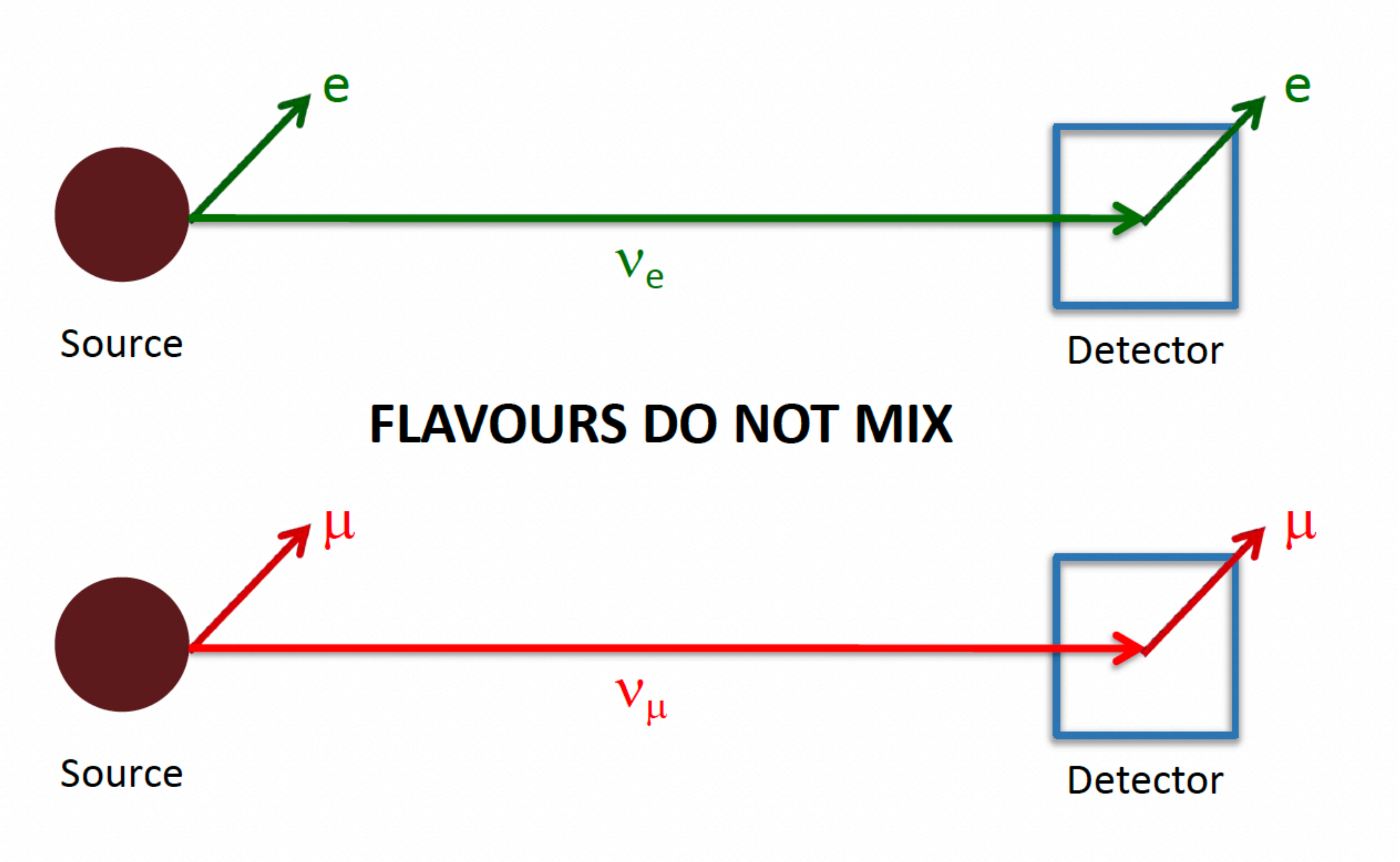
Neutrino production in the SM

✦ Weak interactions conserve flavour: neutrinos are always produced together with their associated charged lepton (e, μ, τ)

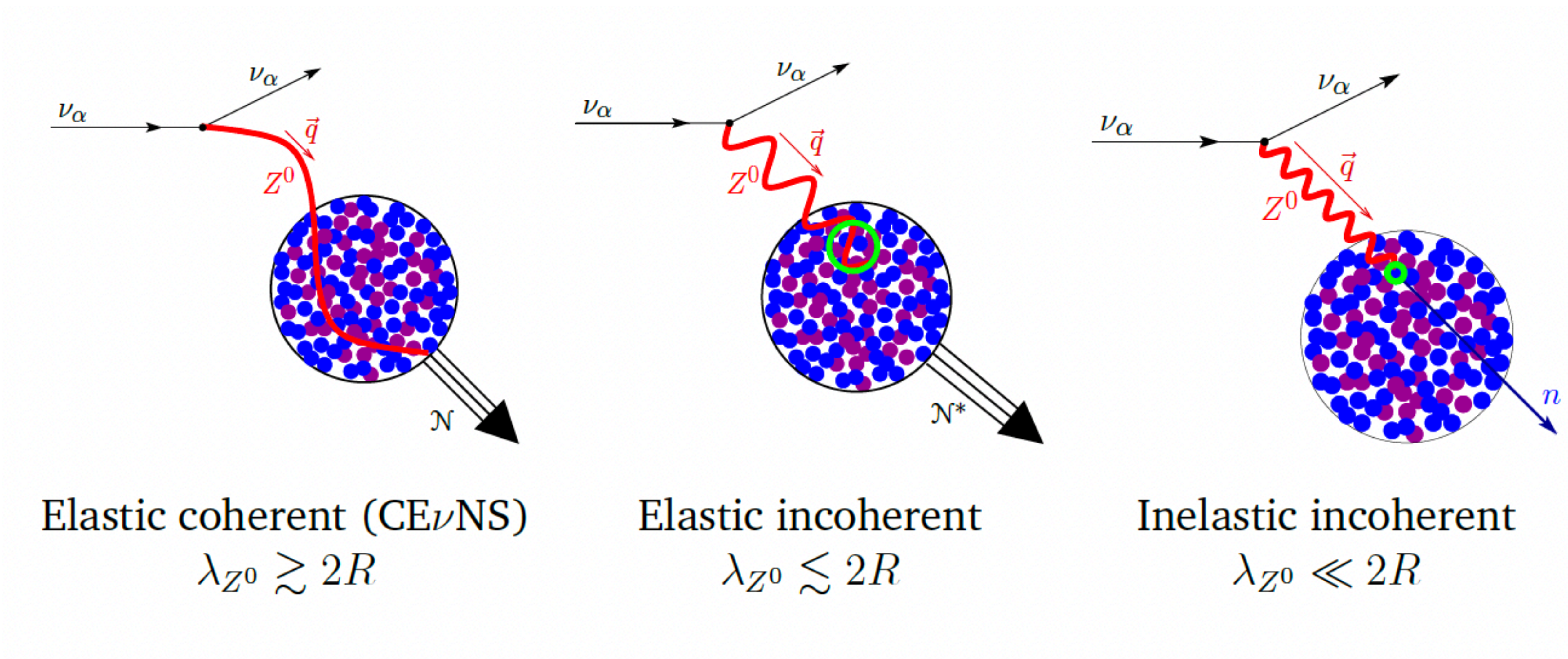


Neutrino detection

✦ Neutrinos are indirectly detected through the detection of their associated charged lepton



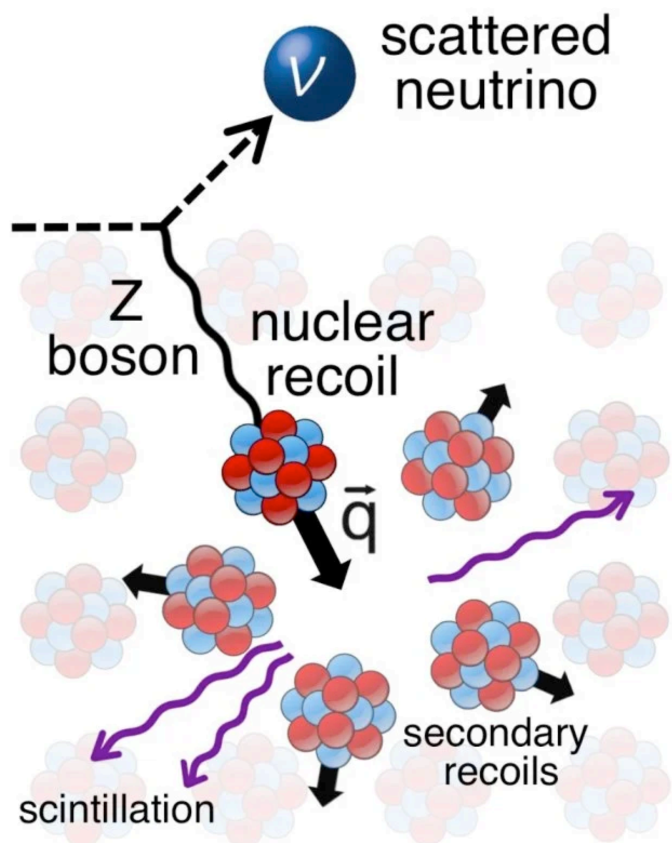
Coherent Elastic ν Nucleus Scattering (CEνNS)



Freedman, PRD 1974

Cadeddu et al, EPL 143.3 (2023)

Coherent Elastic ν Nucleus Scattering (CEνNS)



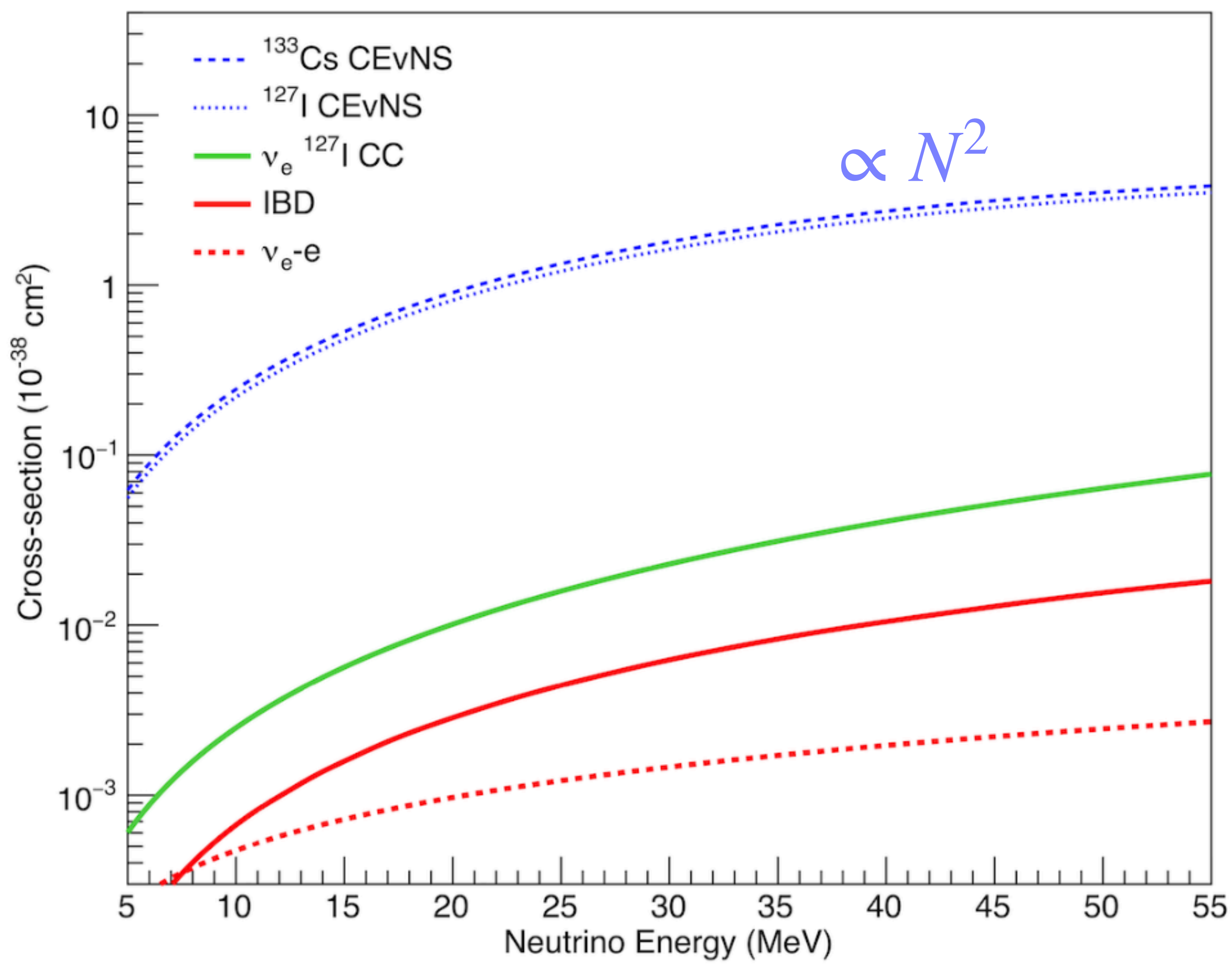
- Neutral-current process: ν + N(A,Z) → ν + N(A,Z)
- Low neutrino energies ($|q| \lesssim 1/R_{nucleus}$) such that nucleon amplitudes sum up coherently (E≲100MeV)
  - ➡ cross section is enhanced as $(N_{target})^2$
  - ➡ up to 2 times larger than IBD: one can use kg-size detectors!

Freedman, PRD 1974

$$\left.\frac{d\sigma_{\nu N}}{dE_{nr}}\right|_{\rm SM}^{\rm CE\nu NS} = \frac{G_F^2 m_N}{\pi} F_W^2\left(|\vec{q}|^2\right)\left(1 - \frac{m_N E_{nr}}{2E_\nu^2}\right)\left(Q_V^{\rm SM}\right)^2$$

$$Q_V^{SM} = g_V^p Z + g_\nu^n N \sim g_V^n N$$

Coherent Elastic ν Nucleus Scattering (CEνNS)



⇒ smaller detectors!

2017: First observed at the Spallation Neutron Source (Oak Ridge National Lab)

COHERENT Coll. Science 357 (2017) 1123

Physics potential of CEvNS

Freedman, PRD 1974

Barranco et al, JHEP 2005

✦ Standard Model CEvNS cross section:

Nuclear form factor

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi}\left(1 - \frac{MT}{2E_\nu^2} - \frac{T}{E_\nu}\right) Q_W^2 [F_W(q^2)]^2 + \frac{G_F^2 M}{4\pi}\left(1 + \frac{MT}{2E_\nu^2} - \frac{T}{E_\nu}\right) F_A(q^2)$$

Weak nuclear charge

Axial contribution: small for most nuclei, it cancels out for nuclei with even number of p and n

$$Q_W = [Z(1 - 4\sin^2\theta_W) - N]$$

$\sin^2\theta_W \sim 0.23$ → neutron contribution dominates

✦ **New physics** may affect the nuclear form factor, weak nuclear charge or add new terms to the cross section

Neutrino masses

Fermion masses in the SM

- In the SM, fermion masses appear in the lagrangian with terms like:

$$m\overline{\psi}\psi \qquad \rightarrow \textbf{Dirac mass term}$$

decomposing into its chiral states: $\psi \equiv \psi_L + \psi_R$

$$-\mathcal{L}_D = m\overline{\psi}\psi = m\overline{(\psi_L + \psi_R)}(\psi_L + \psi_R) = m\overline{\psi_L}\psi_R + m\overline{\psi_R}\psi_L$$

→ not invariant under SU(2)x U(1) gauge invariance: it couples ψ_L with ψ_R

- Solved by Higgs mechanism: after SSB, Dirac mass terms appear from Yukawa couplings:

$$\tilde{\phi} \equiv \sigma_2 \phi^*, \quad \tilde{\phi} : (1, 2)_{-1/2}, \quad \langle \tilde{\phi} \rangle = \begin{pmatrix} \frac{v}{\sqrt{2}} \\ 0 \end{pmatrix}$$

$$-\mathcal{L}_{\text{Yukawa}} = Y \underbrace{\overline{\psi_L}}_{(1,1,0)} \tilde{\phi} \underbrace{\psi_R}_{(1,1,0)} + \text{h.c.} \quad \xrightarrow{\text{SSB}} \quad \frac{v}{\sqrt{2}} Y \overline{\psi_L} \psi_R$$

→ OK for most of particles but SM neutrino has only a L-chiral state (no ψ_R)

→ a Dirac mass term for neutrinos can not be built in the Standard Model

Majorana neutrino mass

Majorana, ~1930

✦ We build a R-chiral field from a L-chiral field by charge conjugation:

$$\psi_R \equiv \psi_L^C = \hat{C}\overline{\psi}^T \qquad \hat{C} = i\gamma^2\gamma^0$$

only for neutral particles

→ the total neutrino field is: $\psi = \psi_L + \psi_R = \psi_L + \psi_L^C$

→ taking the charge conjugate: $\psi^C = (\psi_L + \psi_R)^C = \psi_L^C + \psi_L = \psi$

$$\psi = \nu = \nu_L + \nu_L^C$$

neutrino = antineutrino

Majorana mass term:
$$-\mathcal{L}_M = \frac{1}{2} m \left(\overline{\nu_L^C} \nu_L + \overline{\nu_L} \nu_L^C \right)$$

Not invariant under U(1) transformations

However: this mass term not invariant under weak isospin (I_W=1)

→ solved with a Higgs triplet BUT it is not included in the SM.

→ solved with a dim-5 operator (Weinberg operator) BUT non-renormalizable

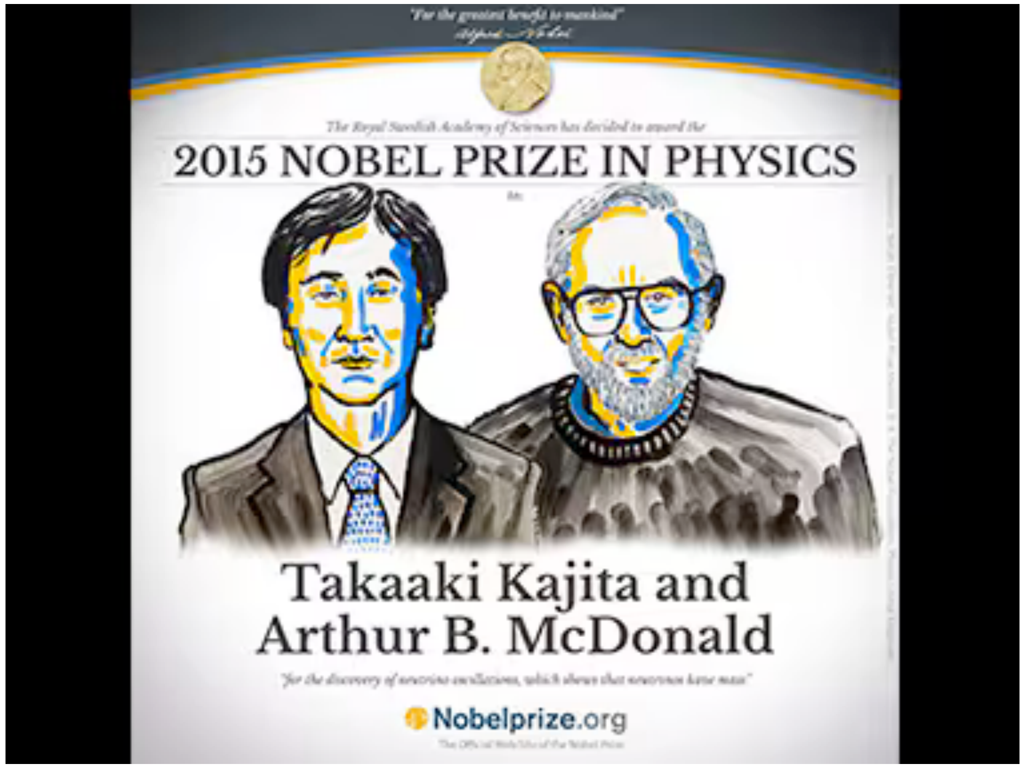
Neutrino mass in the SM

- Since the SM does not contain right-handed neutrinos: a Dirac mass term as for the rest of fermions is not allowed.

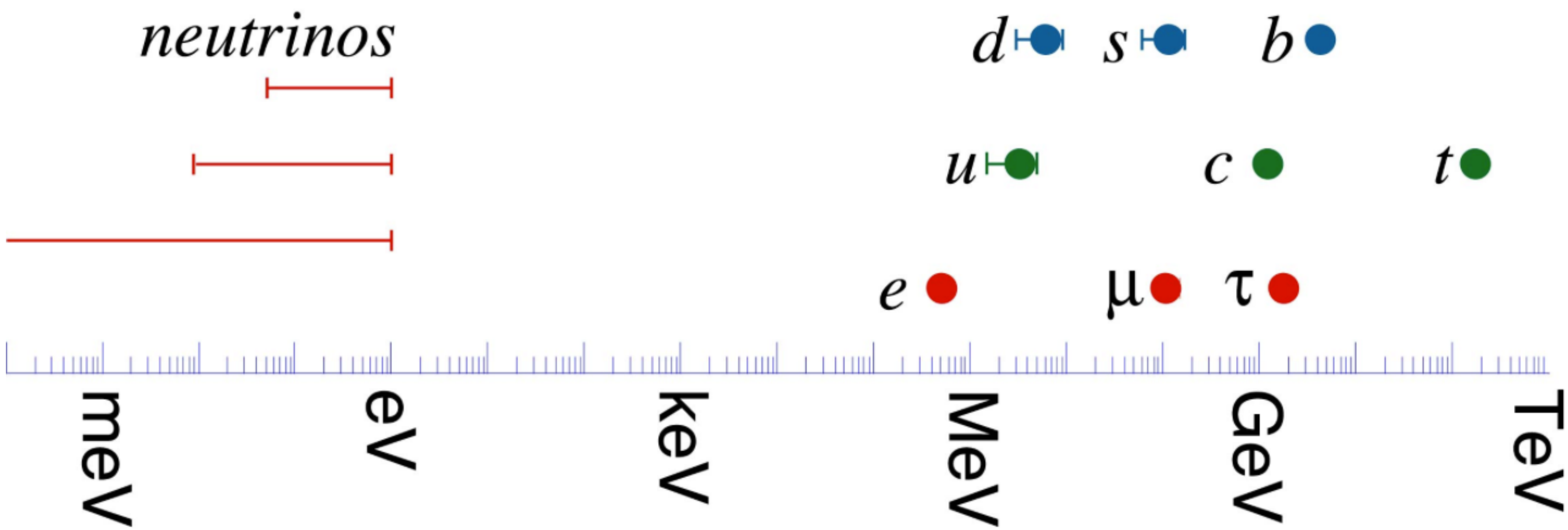
- The SM only contains one Higgs doublet: no Higgs triplet to build a Majorana mass term

- The SM is renomalizable and, therefore, dim-5 terms as the Weinberg operator are not allowed.

→ **Neutrinos are strictly massless in the Standard Model!**



"For the discovery of neutrino oscillations, which shows that neutrinos have mass"



$m_\nu \sim 0 - 1$ eV

Dirac neutrino mass term

Minimal extension SM: add N_R → "sterile" neutrino (singlet under SU(2)xU(1))

✦ 4 components Dirac neutrino: $\nu_L \, , \overline{\nu_L} \, , N_R \, , \overline{N_R}$

→ decomposing into its chiral states: $\psi = \nu = \nu_L + \nu_L^C$

$$-\mathcal{L}_D = m_D \overline{\nu} \nu = m_D (\overline{\nu_L} + \overline{N_R})(\nu_L + N_R) = m_D \left(\overline{\nu_L} N_R + \overline{N_R} \nu_L \right)$$

✦ Higgs mechanism:

$$\mathcal{L}_{\rm Yukawa} = Y_\nu \left(\overline{\nu_l} \, \overline{l} \right) \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} N_R + \text{h.c.}$$

→ after SSB: $\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v \\ 0 \end{pmatrix}$ $\qquad m_D = Y_\nu \frac{v}{\sqrt{2}}$

✦ From ν oscillations: $m_\nu \geq \sqrt{\Delta m^2_{31}} = 0.05 \, \text{eV}$ $\quad \rightarrow Y_\nu \simeq 10^{-13}$

much smaller than other Yukawas !!! $\quad Y_e \simeq 10^{-5}$

Minimal seesaw mechanism

Minimal extension SM: add N_R $N = N_R + N_R^C$ $\nu = \nu_L + \nu_L^C$

✦ Most general mass term:

≠0 if we add a coupling with Higgs triplet

$$\mathcal{L} = \mathcal{L}_D + \mathcal{L}_M = \frac{1}{2}\left(\overline{\nu_L}\,\overline{N_R^C}\right)\begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}\begin{pmatrix} \nu_L^C \\ N_R \end{pmatrix} + \text{h.c.}$$

$(m_D \simeq v Y_\nu)$

not mass eigenstates

→ Dirac & Majorana terms appear simultaneously:

→ Diagonalization:

$$\frac{1}{2}\left(\overline{\nu} \quad \overline{N}\right)\begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix}\begin{pmatrix} \nu \\ N \end{pmatrix}$$

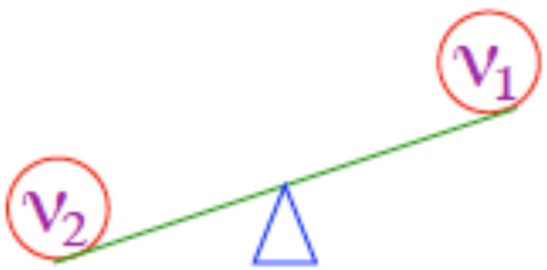
for $M_R \gg m_D$: $\quad M_1 \simeq \dfrac{m_D^2}{M_R}$

$M_2 \simeq M_R$

→ seesaw mechanism

Minimal seesaw mechanism

✦ Provides a “natural” explanation for **smallness** of neutrino mass:



$$M_1 \simeq \frac{m_D^2}{M_R}\,, \quad M_2 \simeq M_R$$

for $m_D \sim$ 100 GeV and $m_\nu \sim$ 0.01 - 1 eV $\rightarrow$ $M_R \sim 10^{13}$ - 10^{15} GeV !!!

✦ Can explain baryon asymmetry of the Universe through **leptogenesis**:

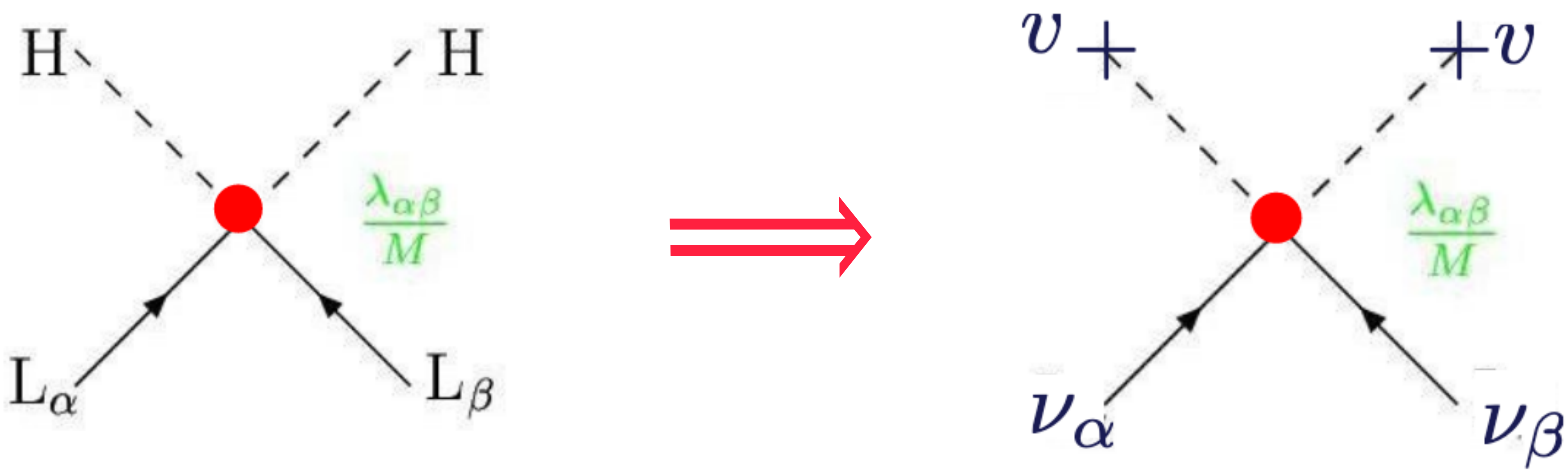
if heavy neutrino decay violates CP: $\Gamma(N \rightarrow l + H) \neq \Gamma(N \rightarrow \bar{l} + \overline{H})$

$\rightarrow$ thanks to (B-L) conservation, the lepton asymmetry generated, L, may be transformed into a B asymmetry:

$$B \neq \overline{B}$$

Weinberg operator

- ✦ If **Majorana** ⇒ masses can be generated via the Weinberg operator
- ✦ Effective dim-5 operator for Majorana neutrino mass



$$\mathcal{L} \ni \frac{\lambda}{M}(LLHH)$$

SSB ⟹

$$m_\nu = \frac{\lambda}{M} v^2$$

Majorana mass

M = new physics scale

S. Weinberg PRL 43 (1979) 1566

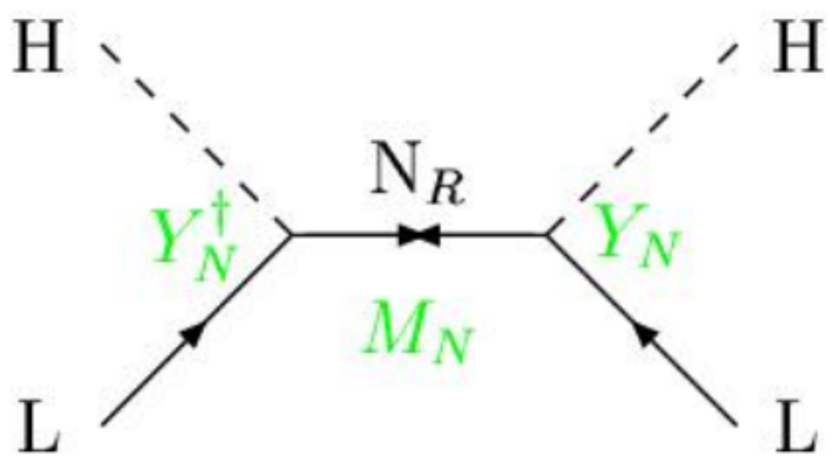
ΔL=2 ⇒ opens the possibility for 0νββ

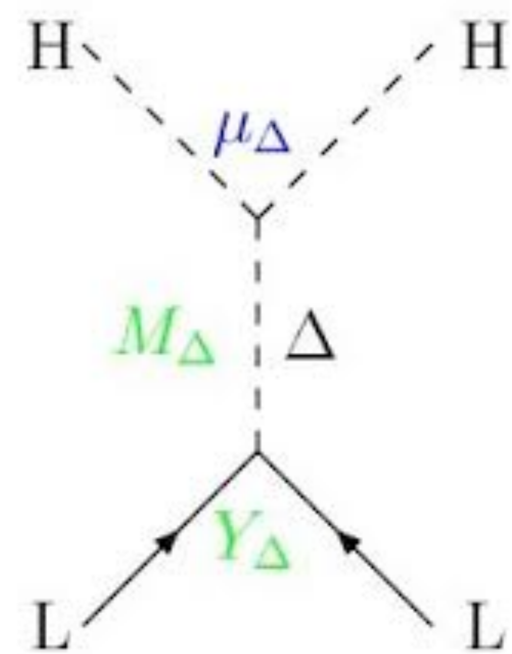
Seesaw mass models

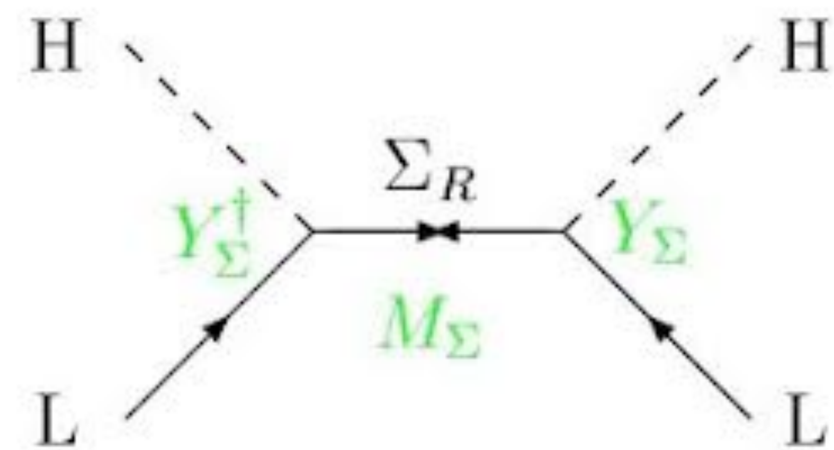
⇒ They are tree level realizations of the Weinberg operator.

⇒ ν masses are generated through mixing with heavy particles.

Type-I seesaw (right-handed singlet N_R)	Type-II seesaw (Scalar triplet Δ)	Type-III seesaw (Fermion triplet Σ_R)







$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

Minkovski; Gellman, Ramond, Slansky; Yanagida; Mohapatra, Senjanovic.

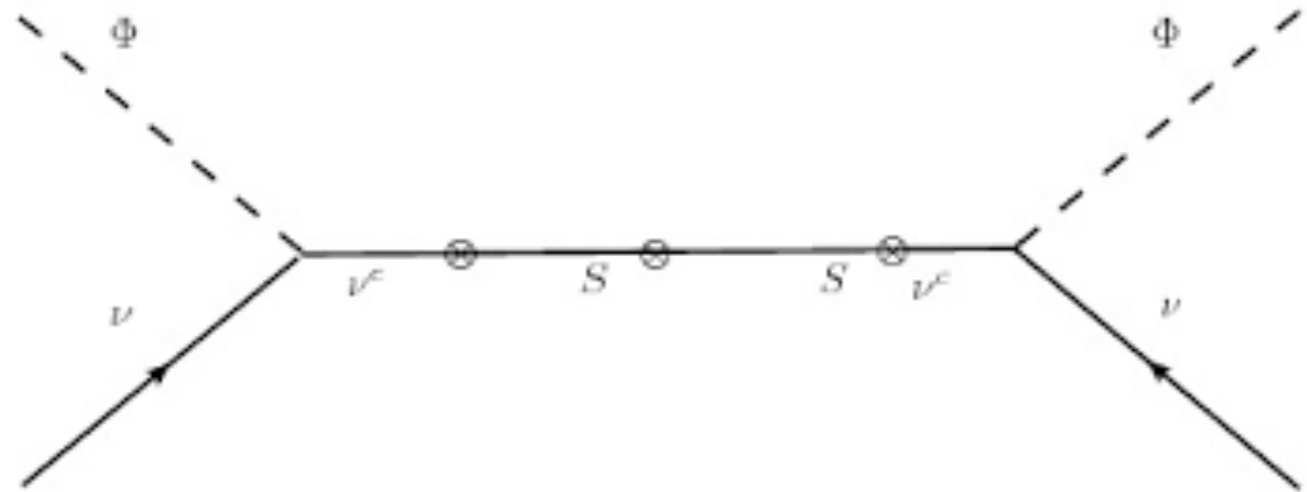
Schechter, Valle; Lazarides, Shafi, Wetterich; Cheng, Li; Mohapatra,…

Foot, Lew, He, Joshi; …

Low energy seesaw models

Mohapatra and Valle, PRD 34 (1986) 1642

Inverse seesaw model



Extended lepton content:

(ν, ν^c, S) L=(+1,-1,+1)

SU(2) singlets

$$M_\nu = \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix} \rightarrow m_\nu = M_D (M^T)^{-1} \mu M^{-1} M_D^T$$

- μ breaks L and generates neutrino mass (massless for μ=0)
- m_ν can be very light even if M is far below GUT scale:

with $\mu \sim$ keV and M $\sim 10^3$ GeV $\rightarrow m_\nu \sim$ eV

Radiative models

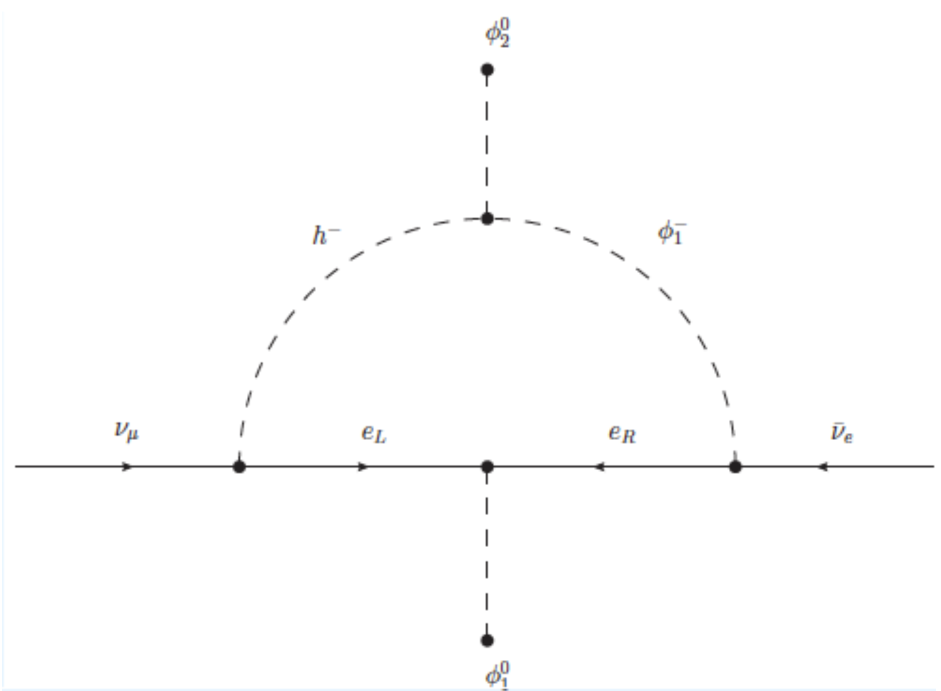
✦ extension of scalar sector of the SM

✦ neutrino masses can be generated through loops

⇒ loop suppression accounts for the smallness of m_ν

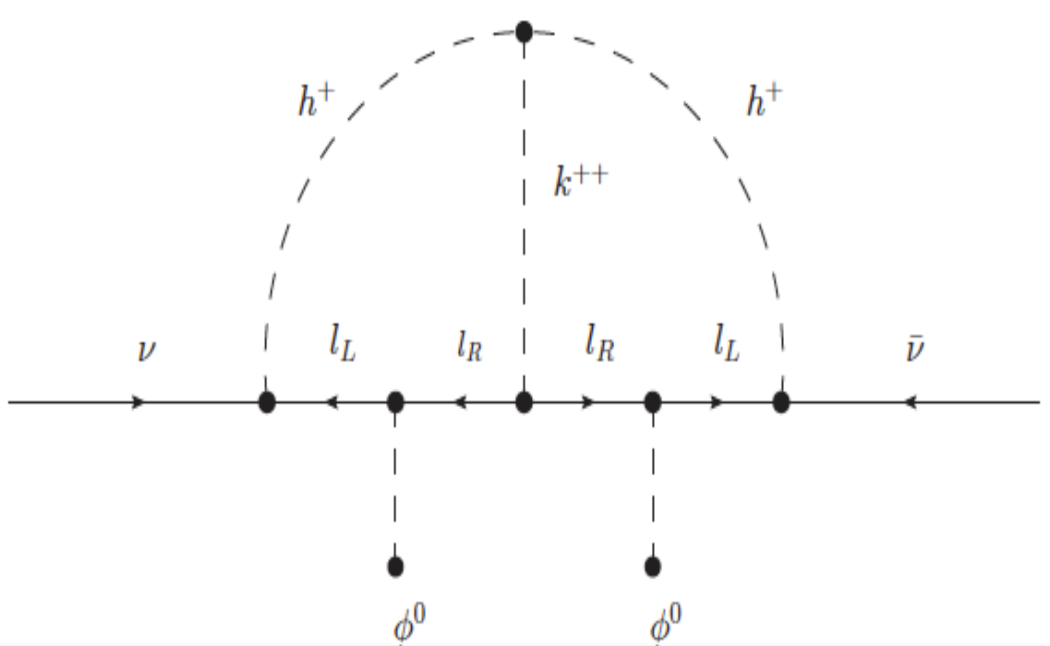
Zee model Zee, PLB 93 (1980) 389

+ singlet scalar h^+
+ extra Higgs doublet H



Zee-Babu model Zee, NPB 264 (1986) 99; Babu, PLB 203 (1988) 132

+ singlet scalar h^+
+ singlet scalar k^{++}



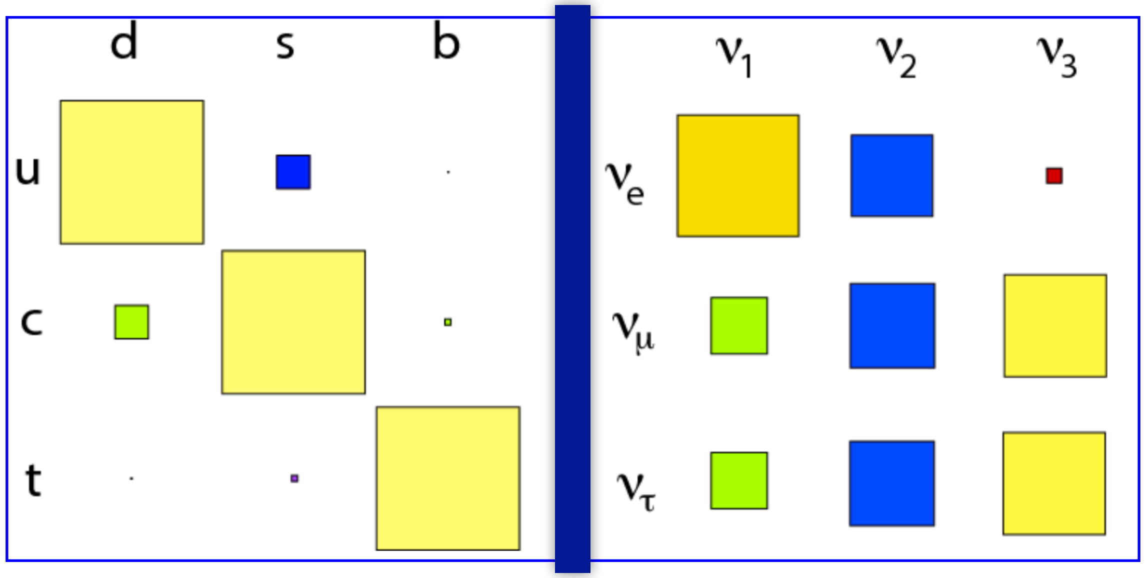
The flavour problem

✦ seesaw models explain the smallness of neutrino masses

However, they can not explain:

✦ Why quark and lepton mixings are so different?

$\theta_{12} \simeq 13°$
$\theta_{13} \simeq 0.2°$
$\theta_{23} \simeq 2.4°$



$\theta_{12} \simeq 34°$
$\theta_{13} \simeq 9°$
$\theta_{23} \simeq 49°$

✦ Why do fermion masses show these hierarchical relations?

$$m_e \ll m_\mu \ll m_\tau \qquad m_u, m_d \ll m_c, m_s \ll m_t, m_b$$

⇒ One can add new symmetries of leptons to the Standard Model

$$SU_c(3) \times SU_L(2) \times U_Y(1) \times G_f$$