Neutrinos in physics, astrophysics and cosmology

Mariam Tórtola
IFIC, CSIC/Universitat de València

The Galileo Galilei Institute For Theoretical Physics

Centro Nazionale di Studi Avanzati dell'Istituto Nazionale di Fisica Nucleare

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Theoretical Aspects of Astroparticle Physics, Cosmology and Gravitation - 2025

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Course outline

Lecture 1

Historical introduction and Neutrinos in the Standard Model

Lecture 2

Neutrino oscillations in vacuum and in matter

Lecture 3

Three-Neutrino phenomenology

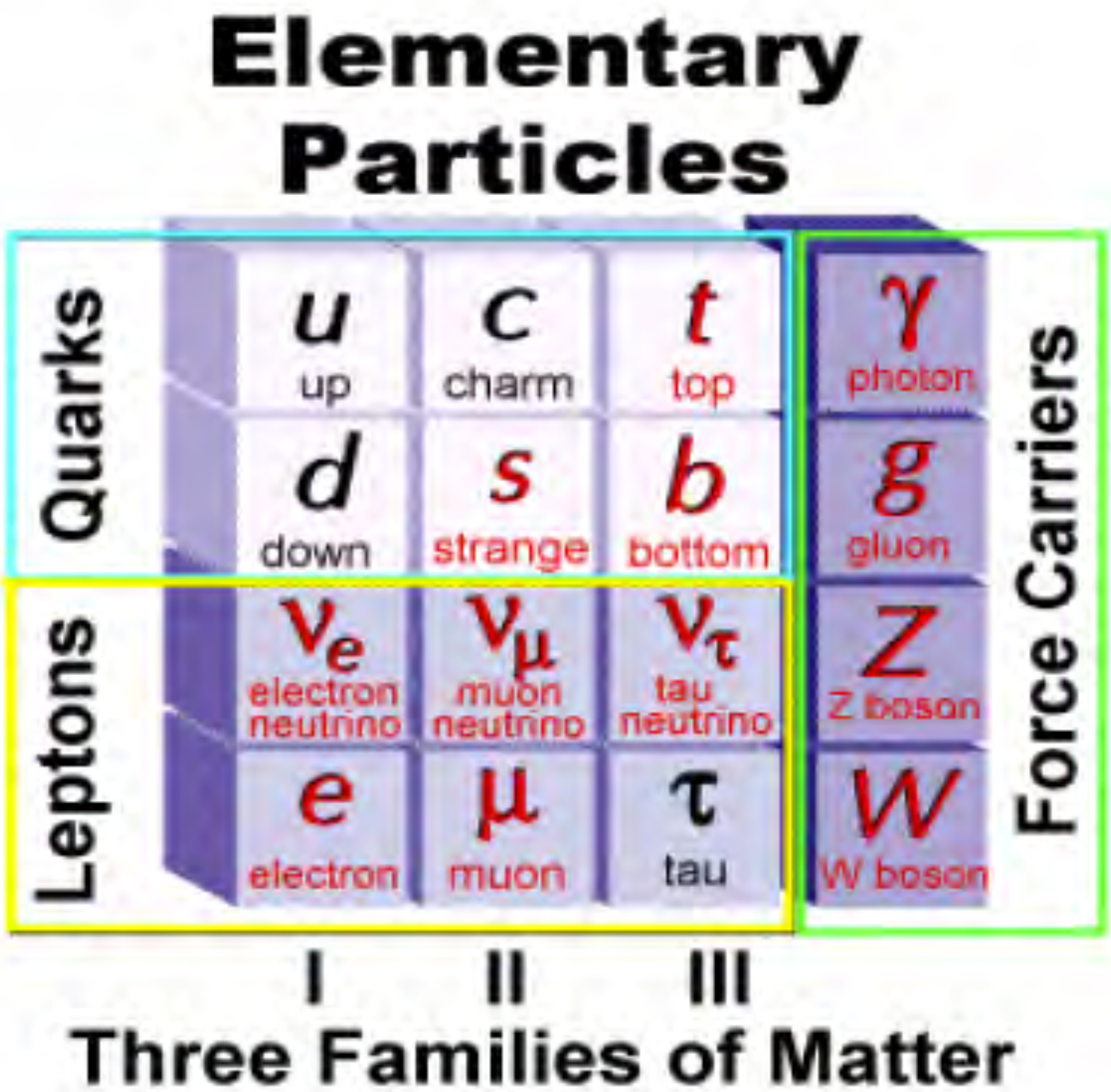
Lecture 4

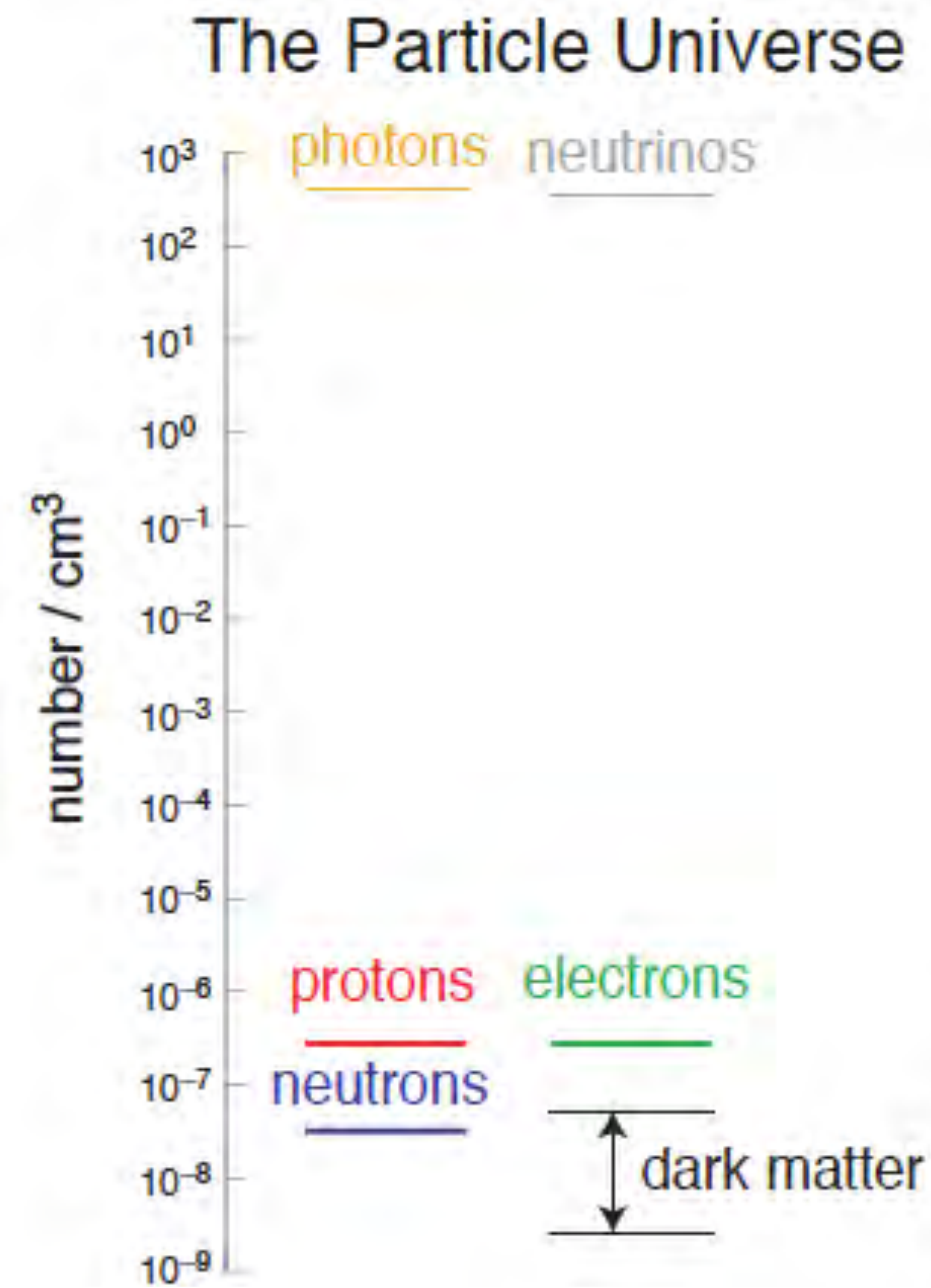
Neutrino physics beyond the Standard Model

Lecture 5

Neutrino mass searches, Neutrinos in Astrophysics & Cosmology

What is a neutrino?



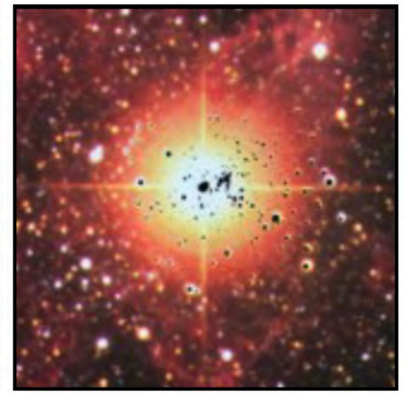


Neutrino sources

✓ Nuclear reactors

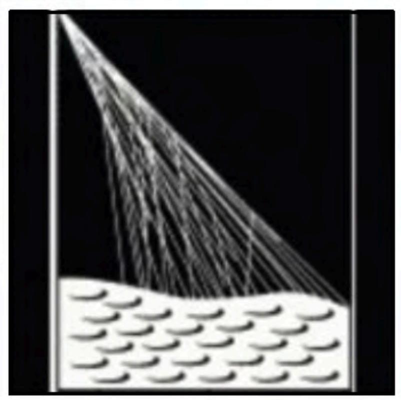
Sun ✓

✓ Particle accelerators



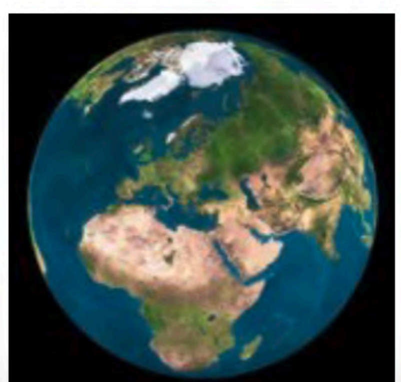
Supernovae
SN 1987A ✓

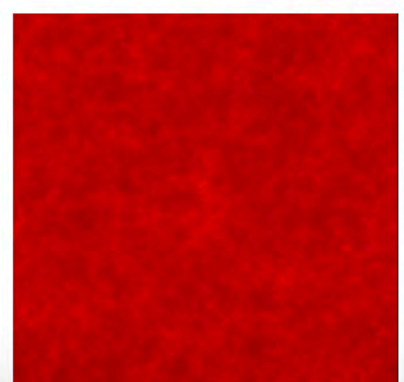
✓ Earth Atmosphere
(Cosmic rays)



Accelerators in
astrophysical sources ?✓

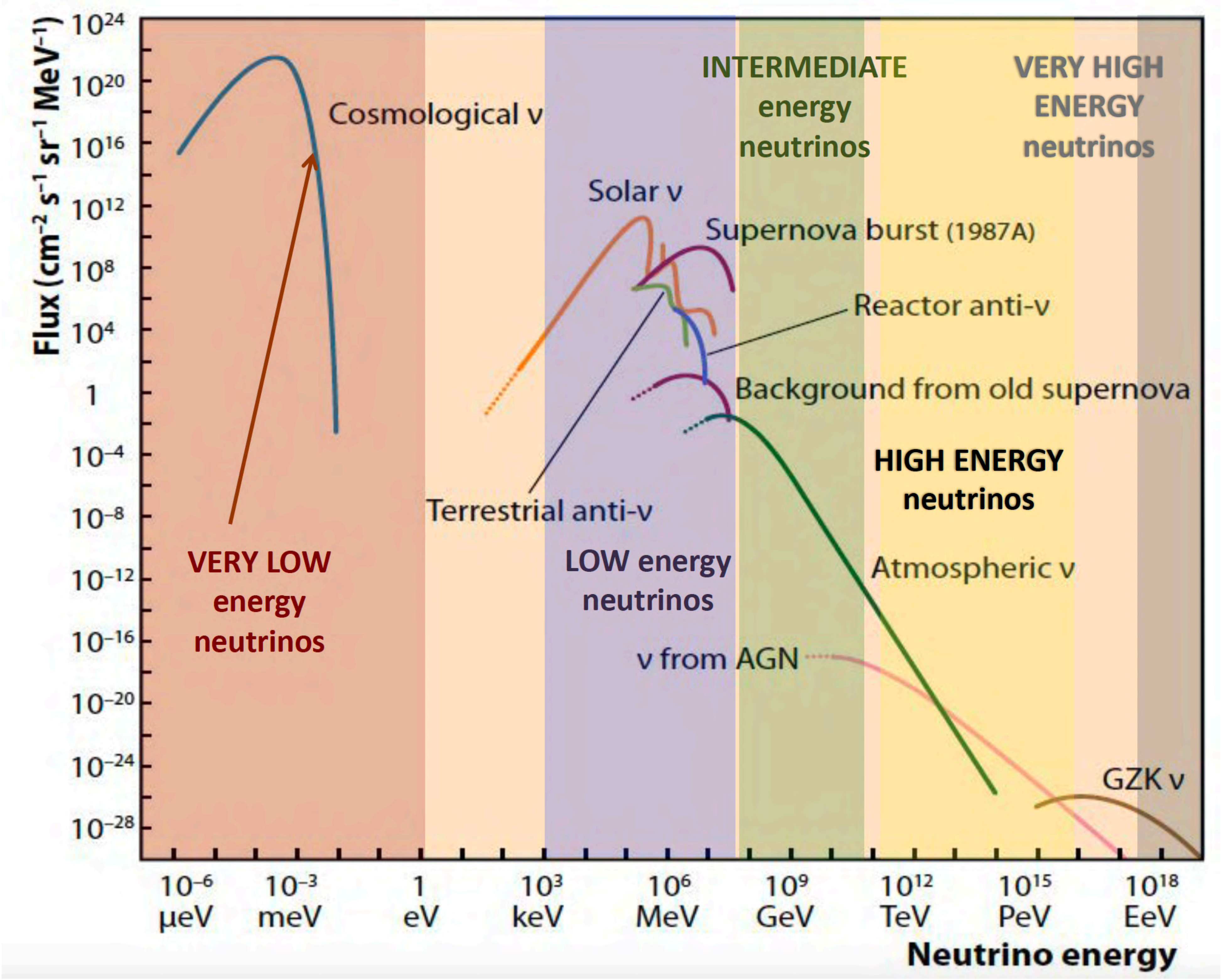
✓ Earth interior
(Natural Radioactivity)





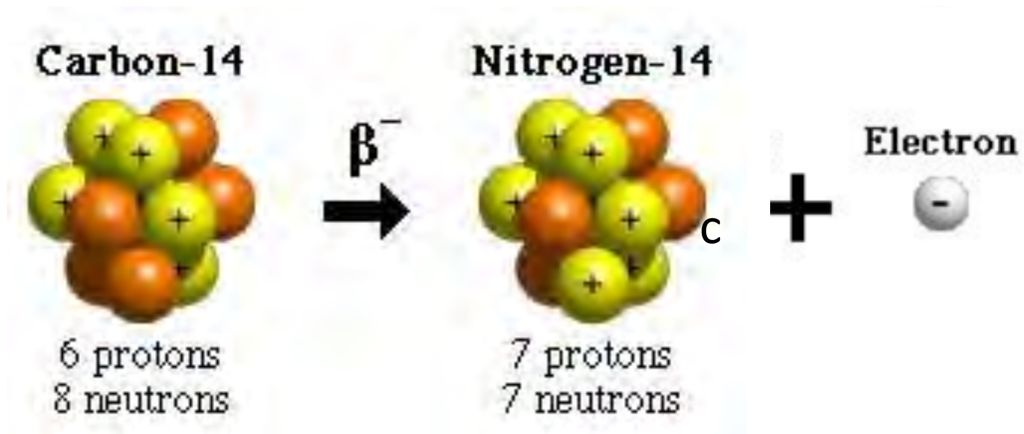
EARLY UNIVERSE
(today 336 ν/cm^3)
Indirect evidence

Neutrino sources



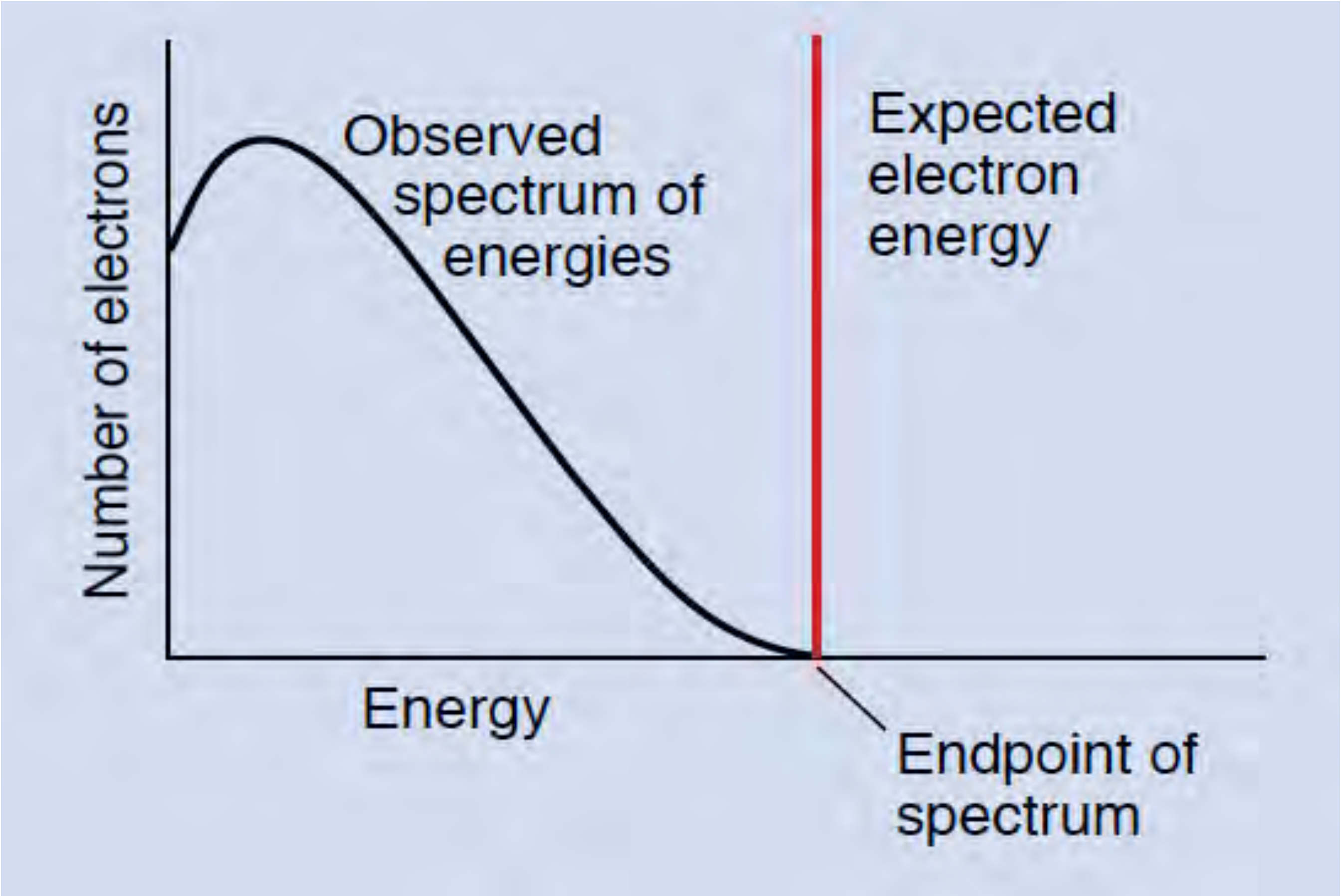
Historical introduction to neutrino physics

The proposal of the neutrino

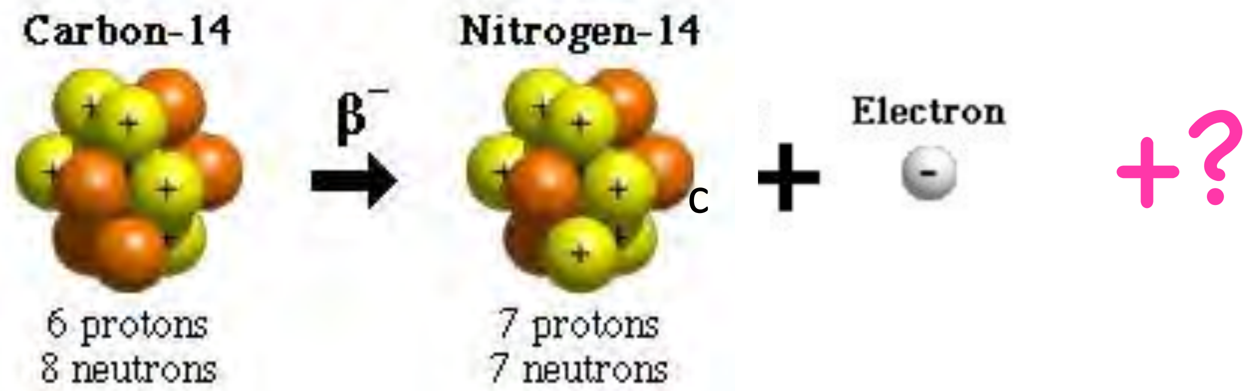


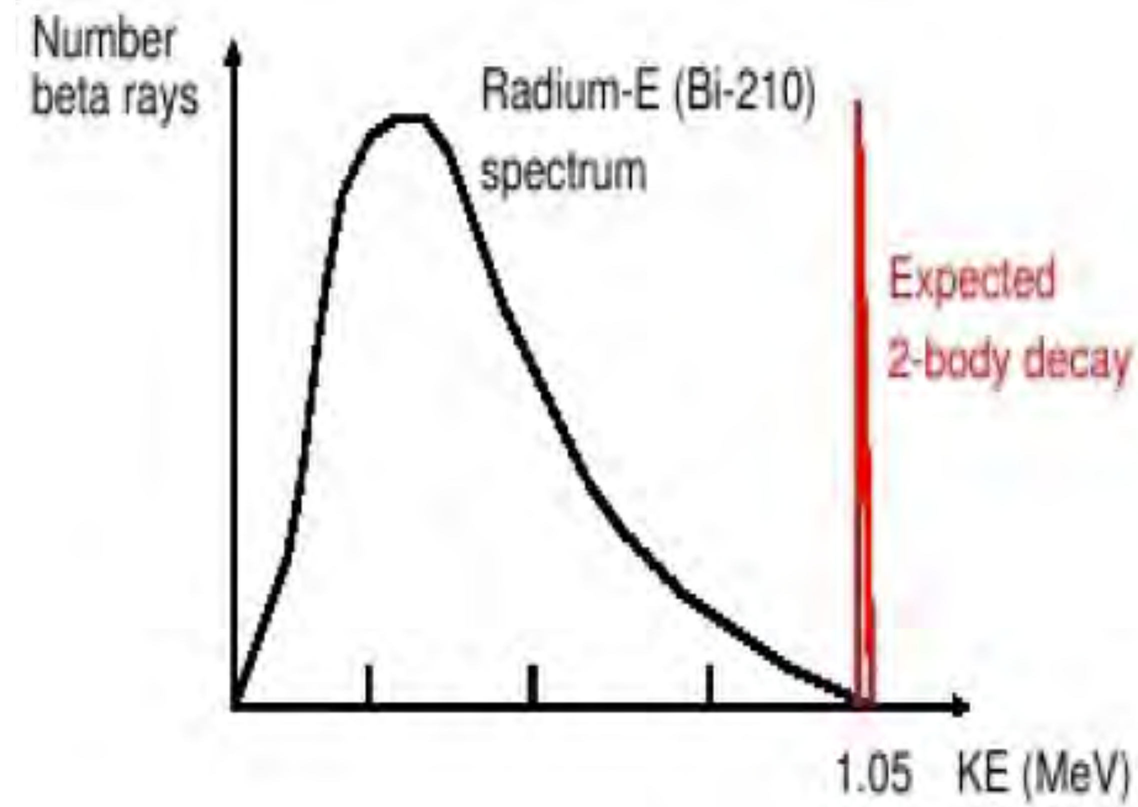
Chadwick

Meitner and Hahn



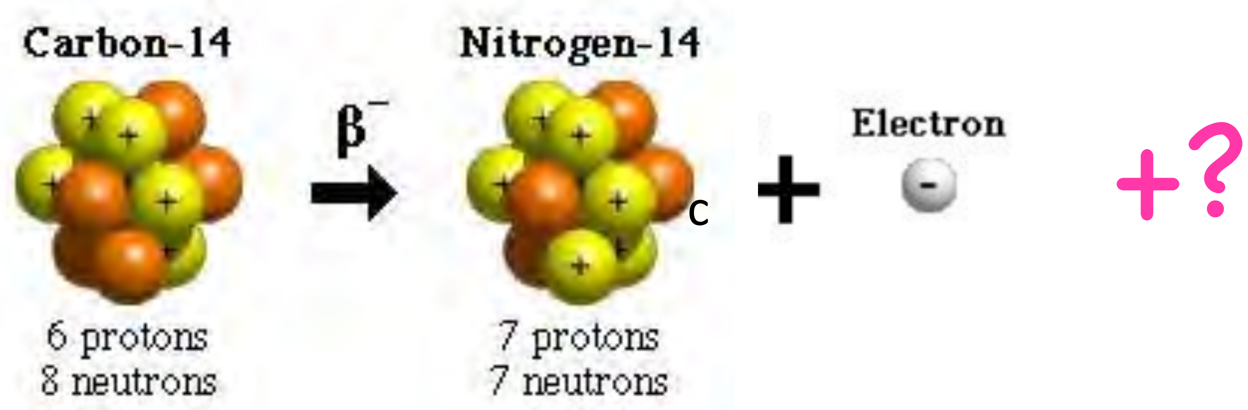
The proposal of the neutrino

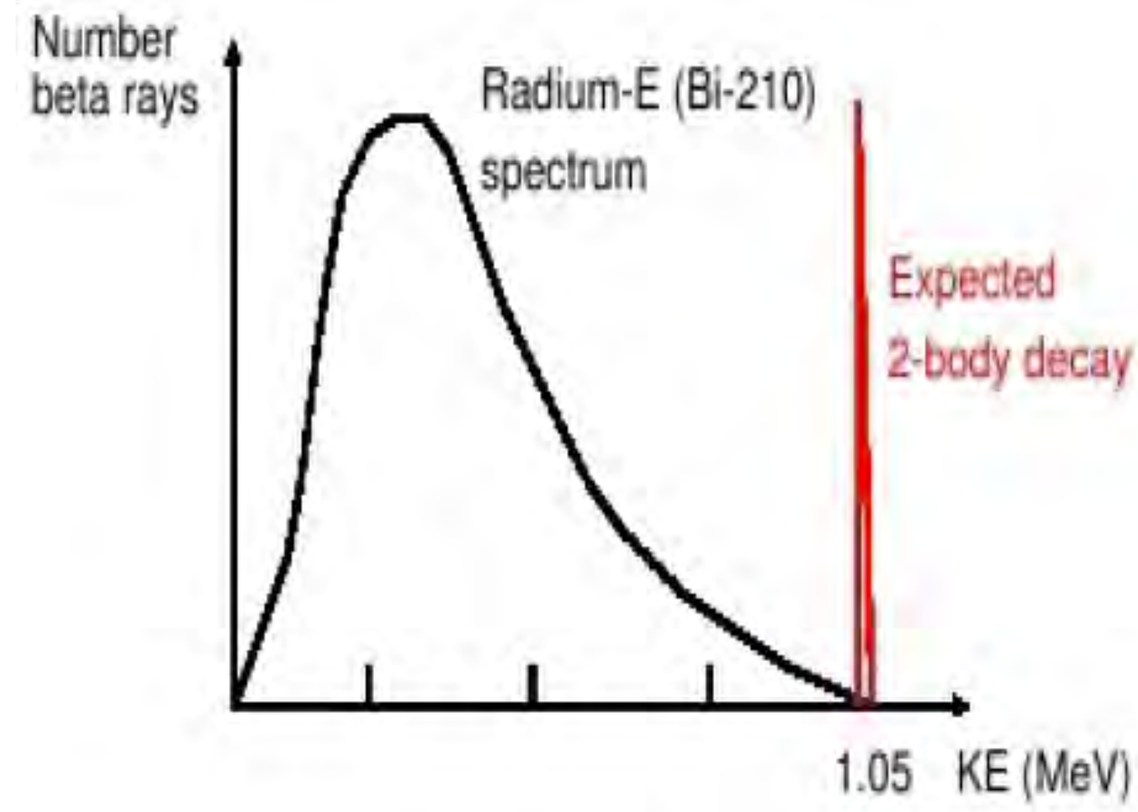




"*Dear radioactive ladies and gentlemen,*
I have come upon a desperate way out regarding . . . [some fairly obscure data], as well as to the continuous β-spectrum, in order to save . . . The energy law. To wit, the possibility that there could exist in the nucleus electrically neutral particles, which 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."

The proposal of the neutrino



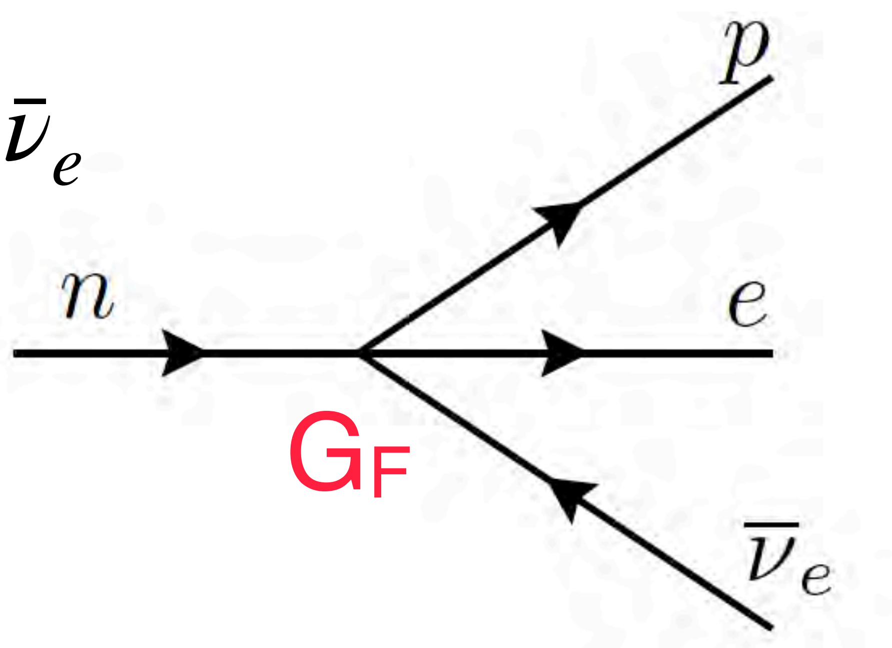


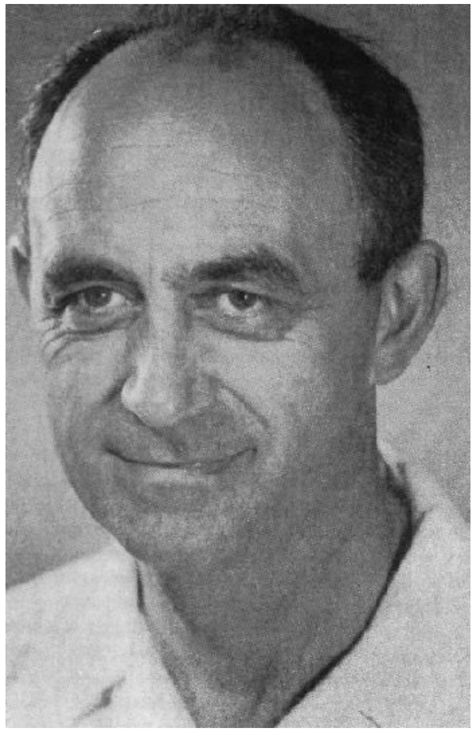
"I have done something very bad today by proposing a particle that cannot be detected. It is something that no theorist should ever do."

Fermi theory for weak interactions

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

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





Enrico Fermi

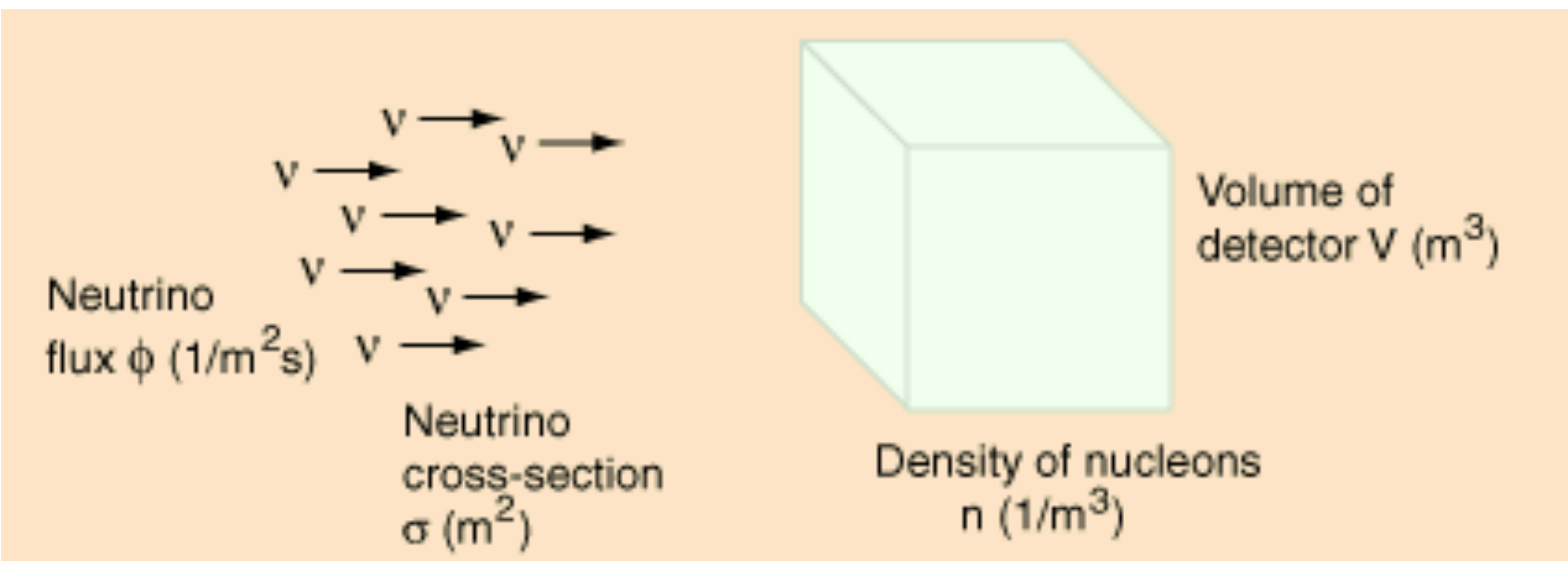
➡ new name for particle: **neutrino**

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

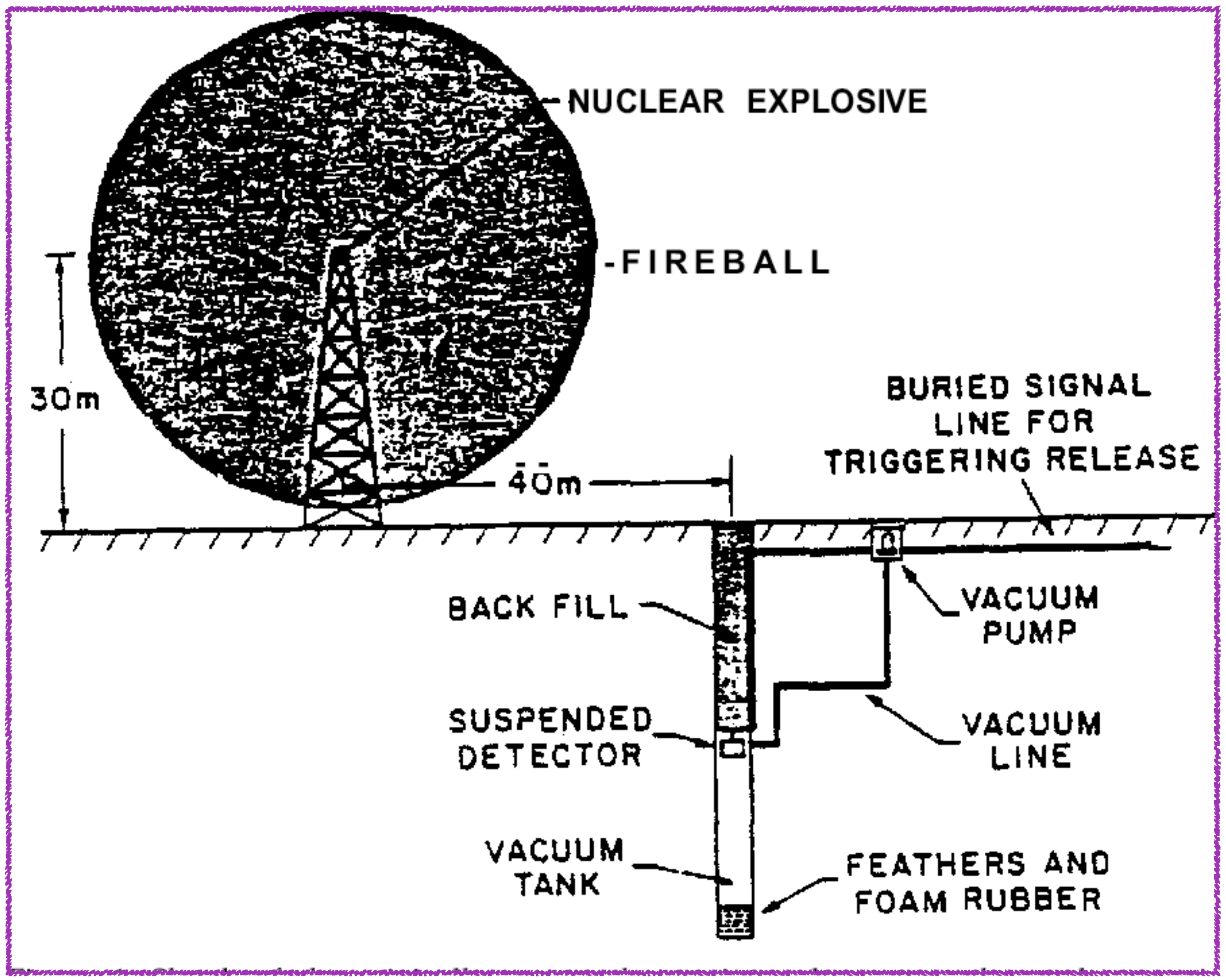
Event number in a neutrino experiment:



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

First proposals for neutrino detection

1951: Detection after a nuclear explosion

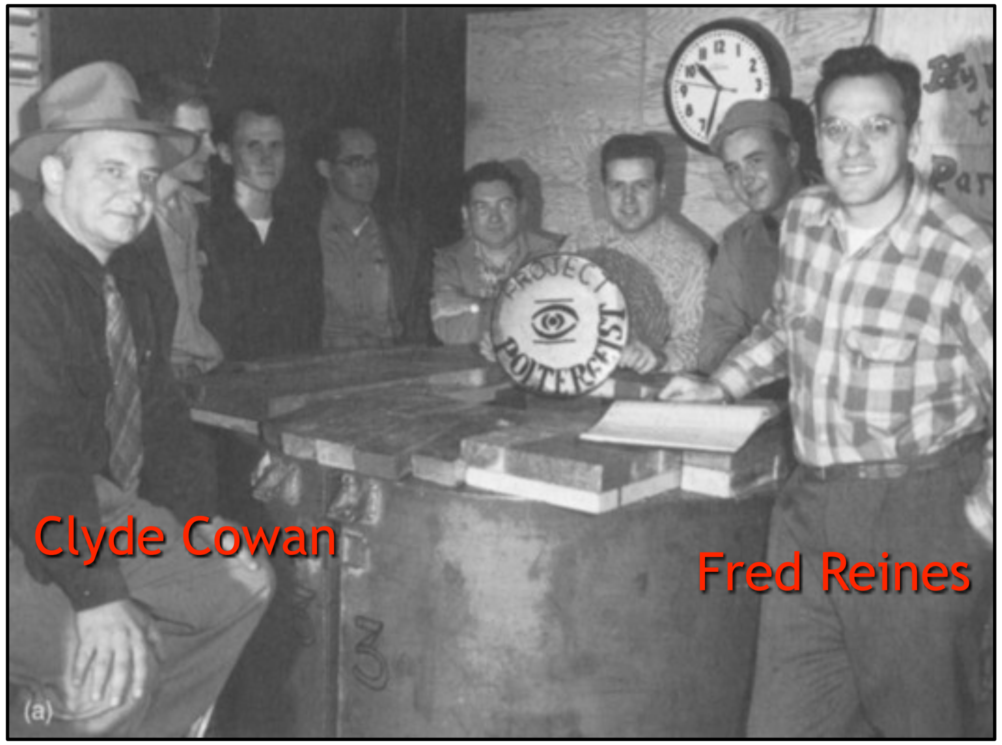


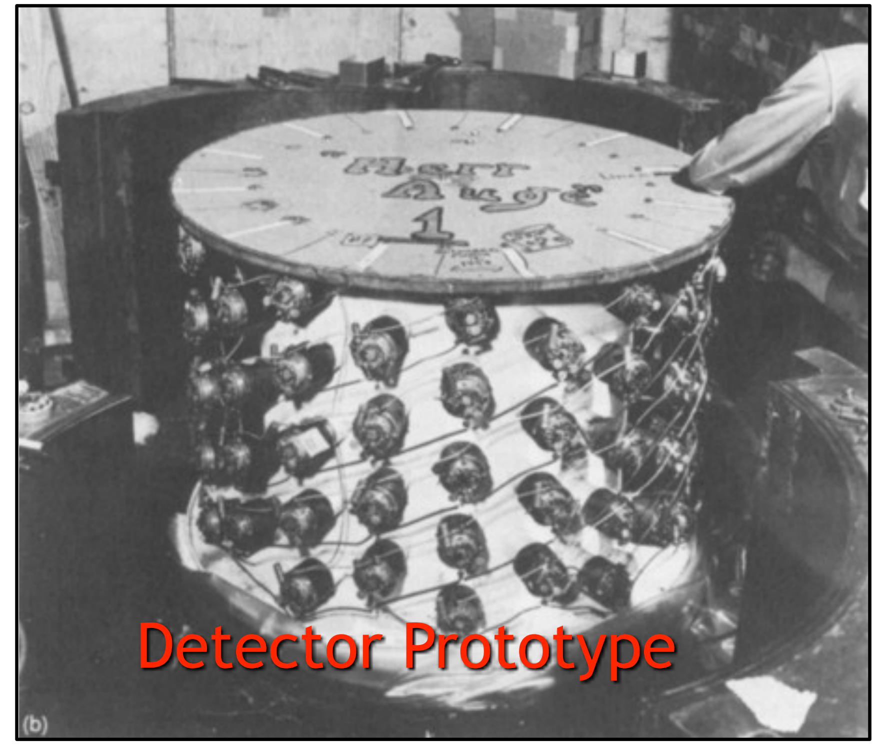
1953: Prototype at Hanford reactor

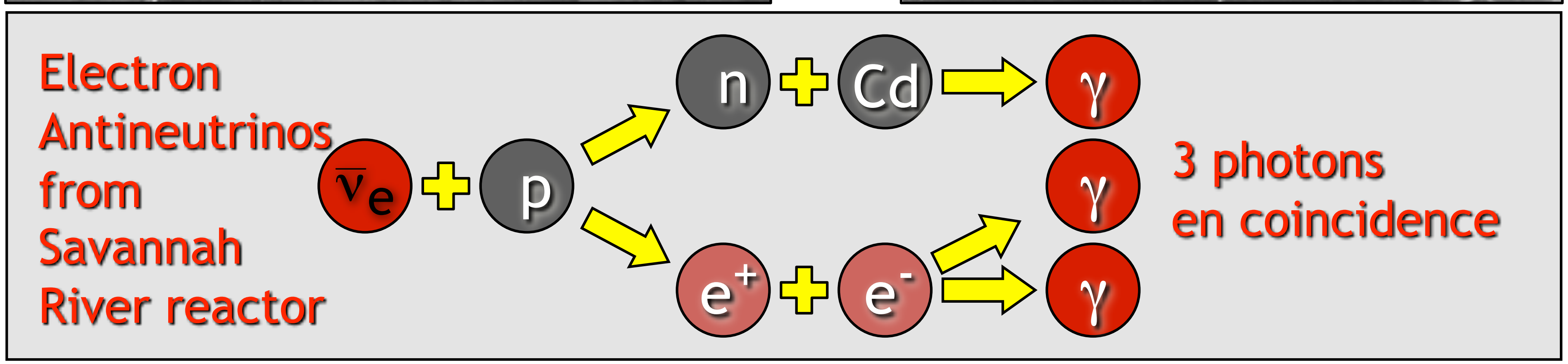
Poltergeist Project

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

Discovery of the neutrino

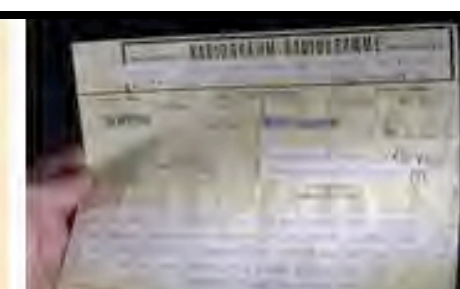






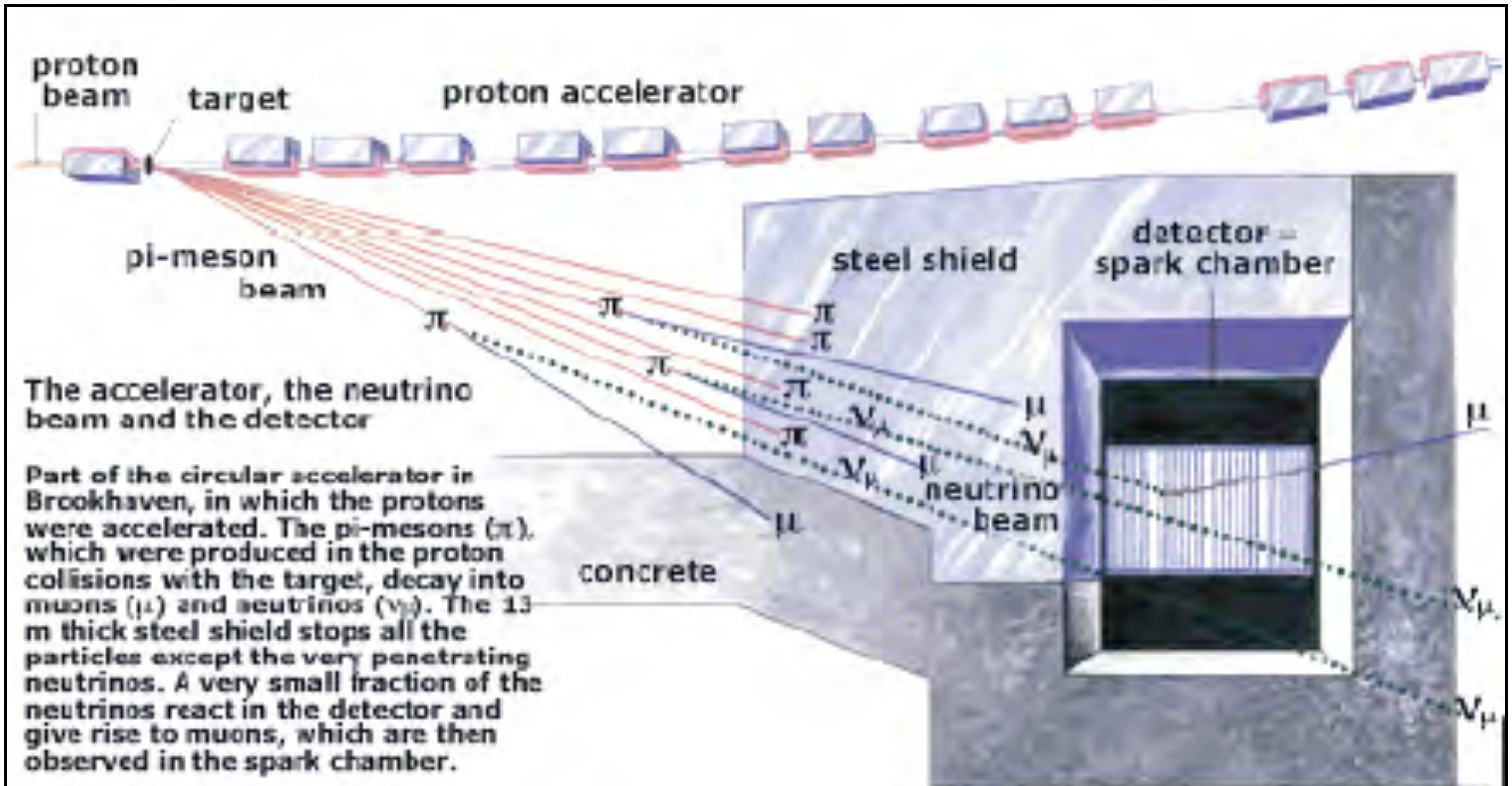
Telegram to Pauli on 12/06/1956

"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"



More than one neutrino flavour?

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



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

not e-

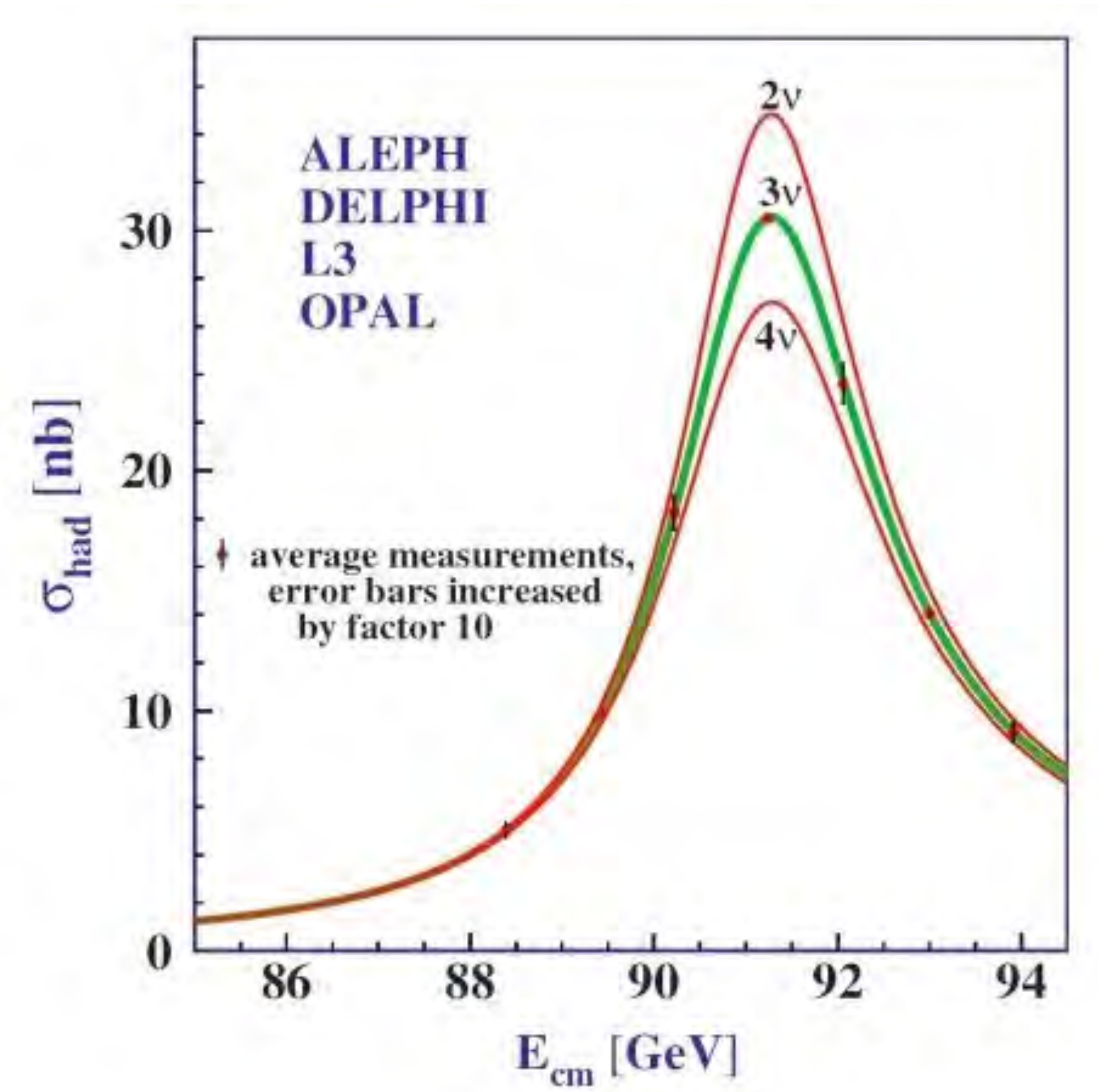
$$\nu_\mu + n \to p + \mu^-$$


Leon M. Lederman


Melvin Schwartz


Jack Steinberger

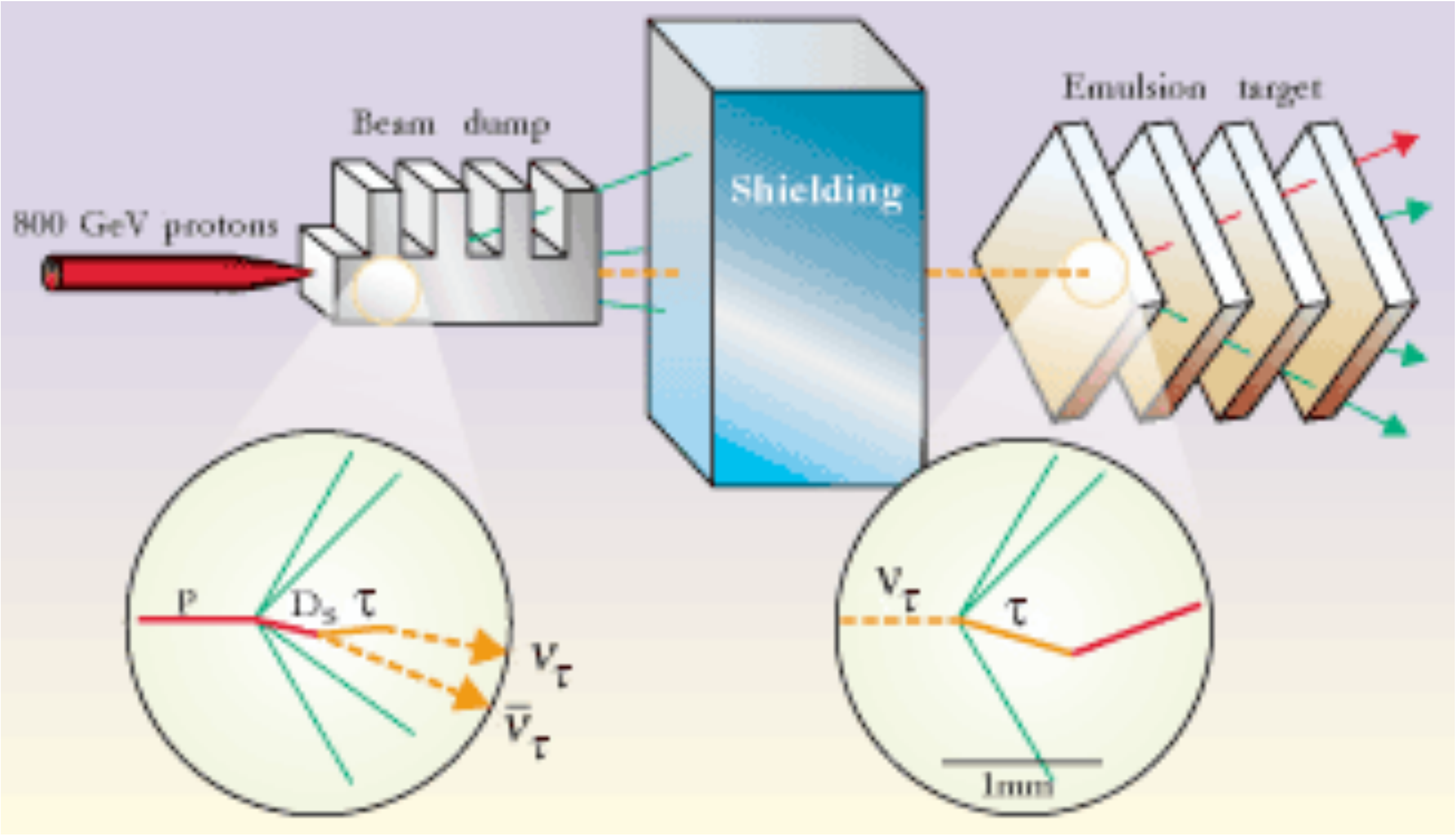
More than two neutrino flavours?



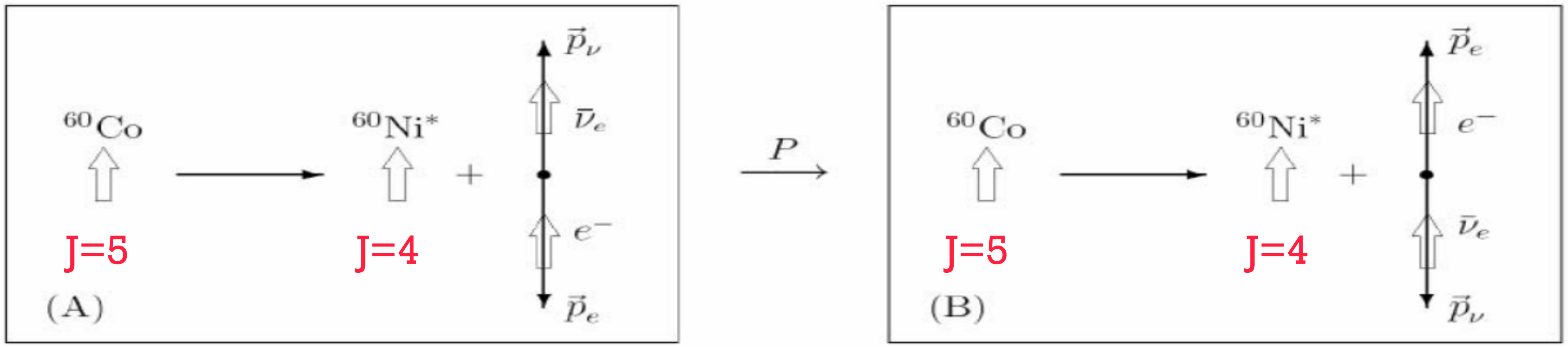
$N_\nu = 2.984 \pm 0.008$

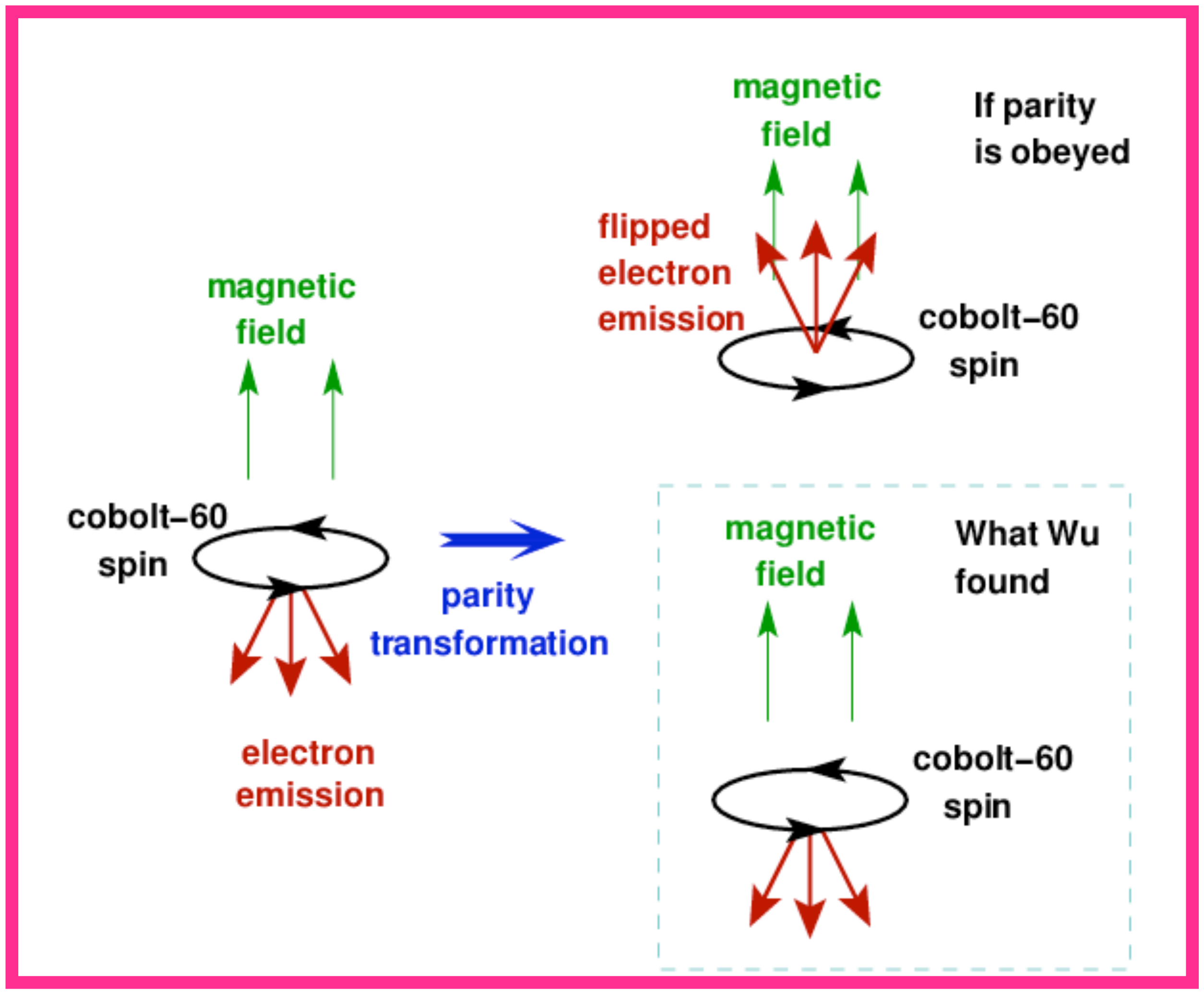
More than two neutrino flavours?

DONUT (**D**irect **O**bservation of the **N**e**U**trino **T**au) detector



Parity violation in Wu experiment





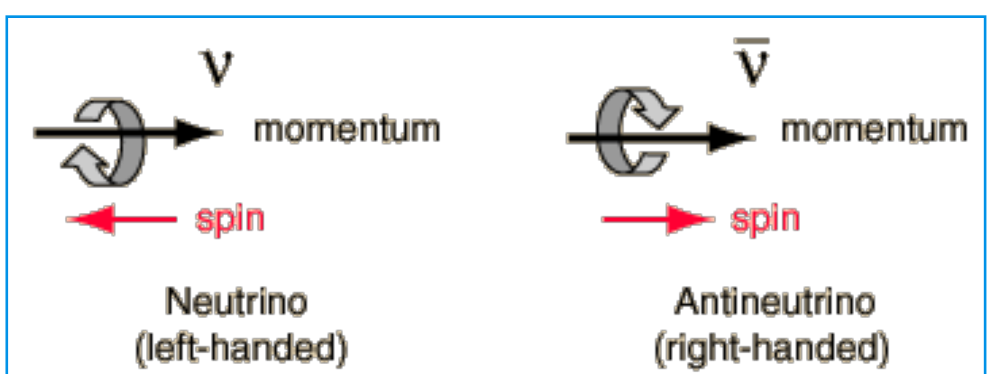
Wu et al, Phys. Rev. 105 (1957)1413

Neutrinos in the Standard Model

Neutrinos in the Standard Model

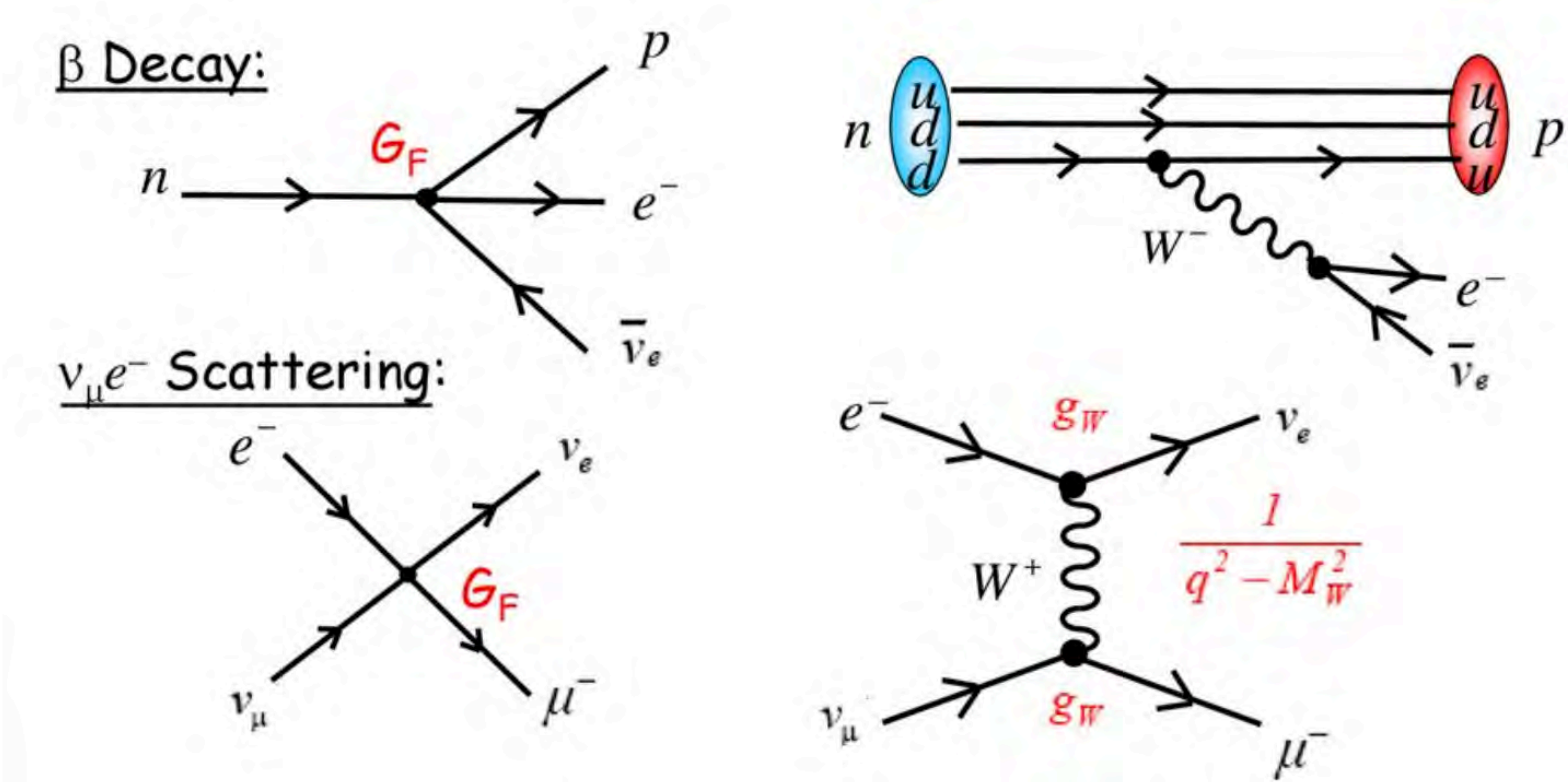
$$SU(3) \times SU(2) \times U(1)_Y$$

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{-\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{-\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	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



no SU(2) neutrino singlets in the SM

Neutrino interactions with charged leptons

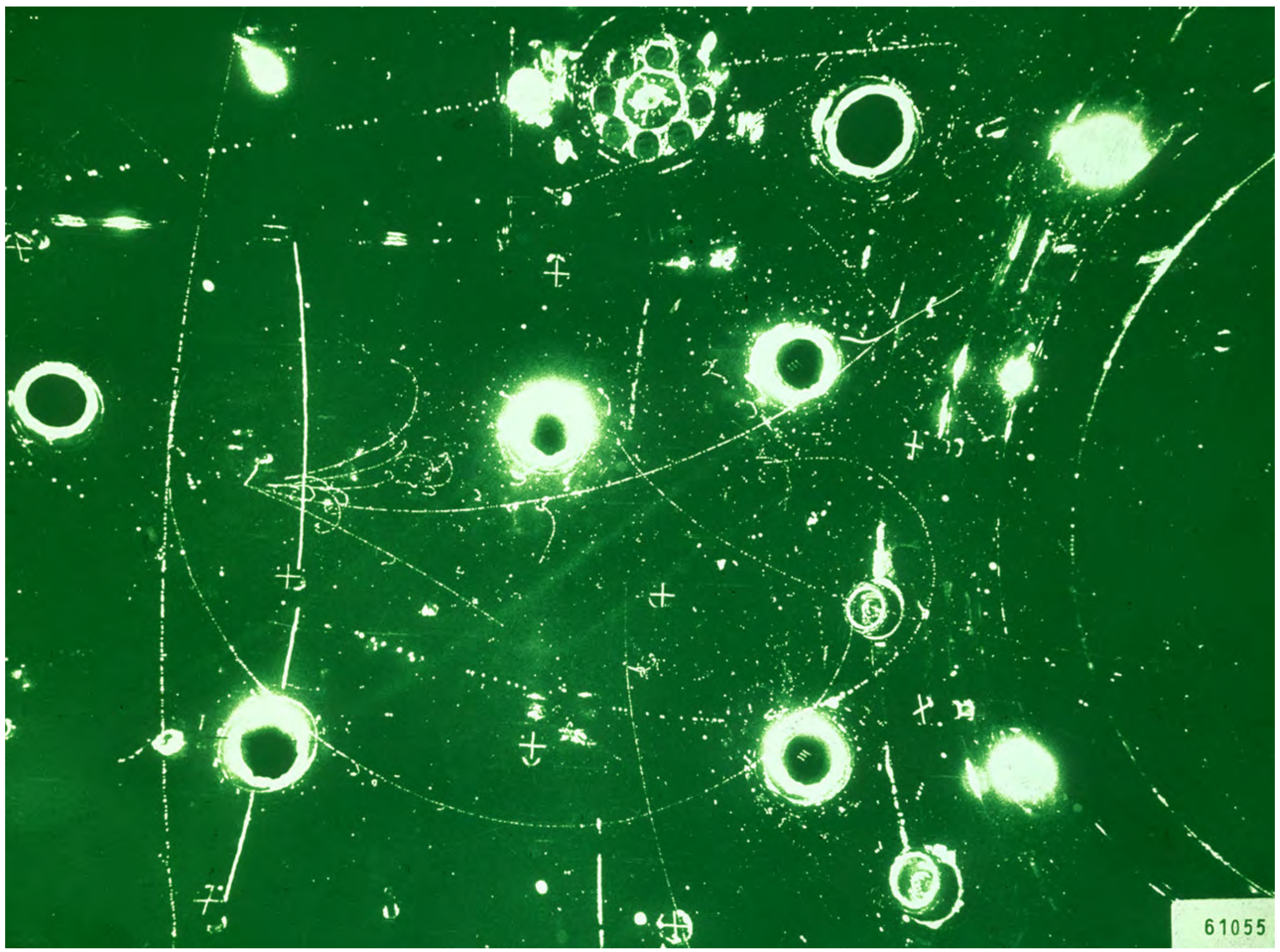


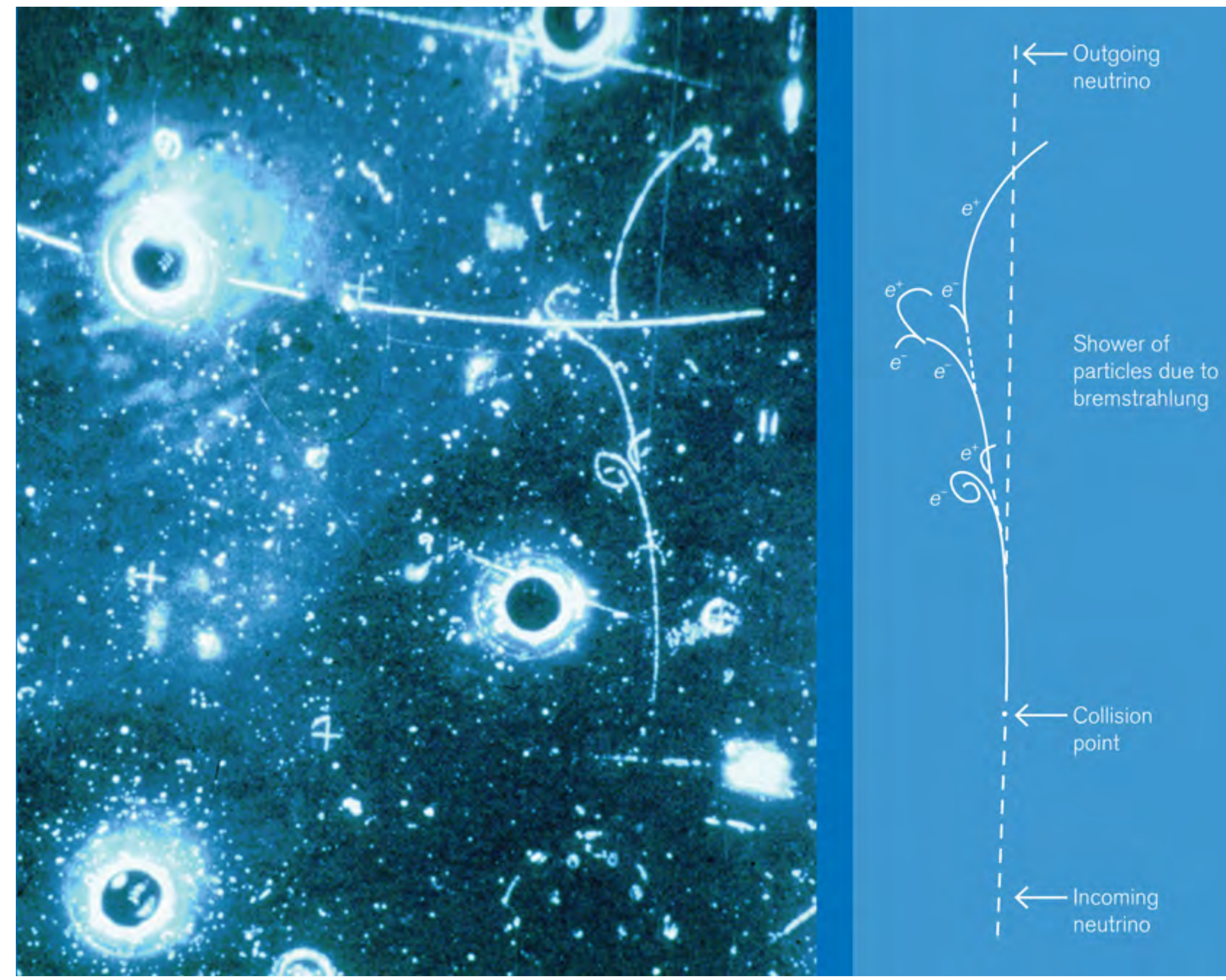
W's couple to leptons in the same doublet

Discovery of Neutral Currents

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

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



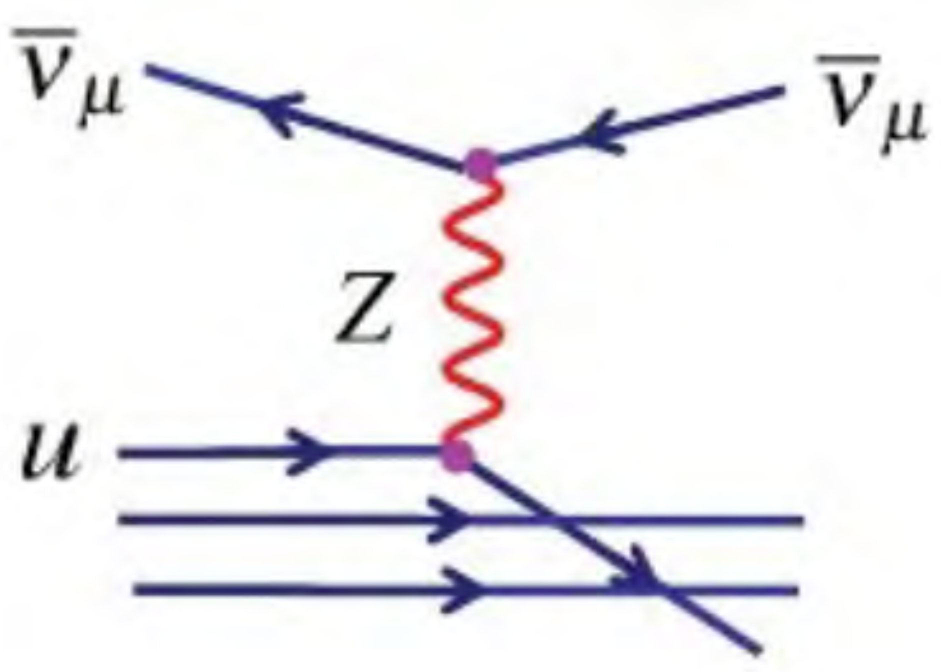


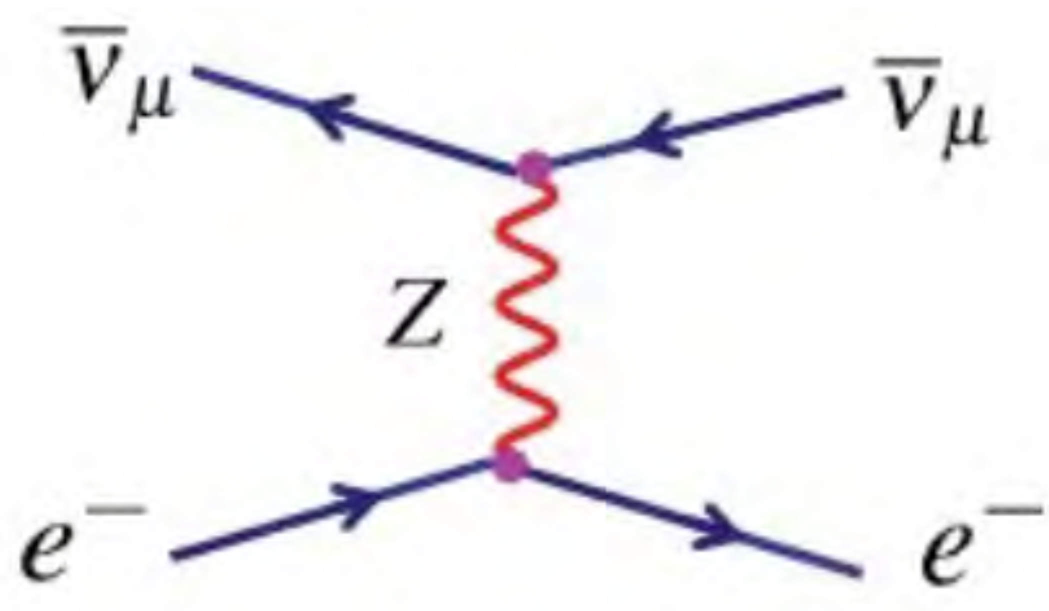
Hasert et al, Phys. Lett. B 46 (1973) 138

Neutral Currents

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

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

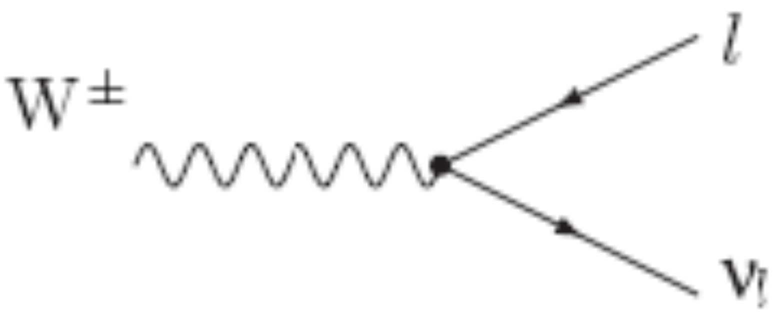




Hasert et al, Phys. Lett. B 46 (1973) 138

Neutrino interactions in the SM

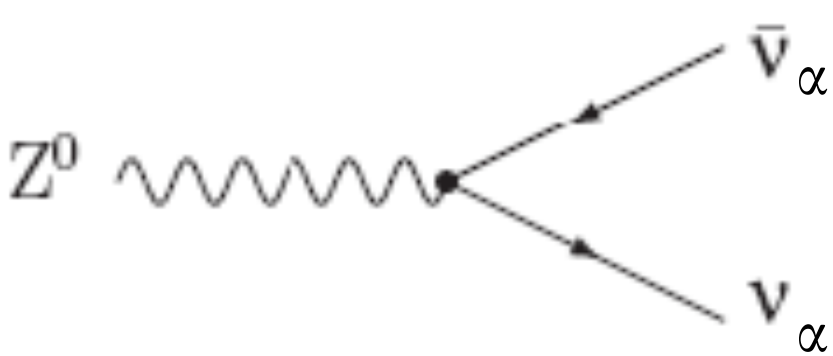
Charged Current Interactions



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

$$W^- \to l_\alpha^- + \overline{\nu}_\alpha \qquad (\alpha = e, \mu, \tau)$$
$$W^+ \to l_\alpha^+ + \nu_\alpha$$

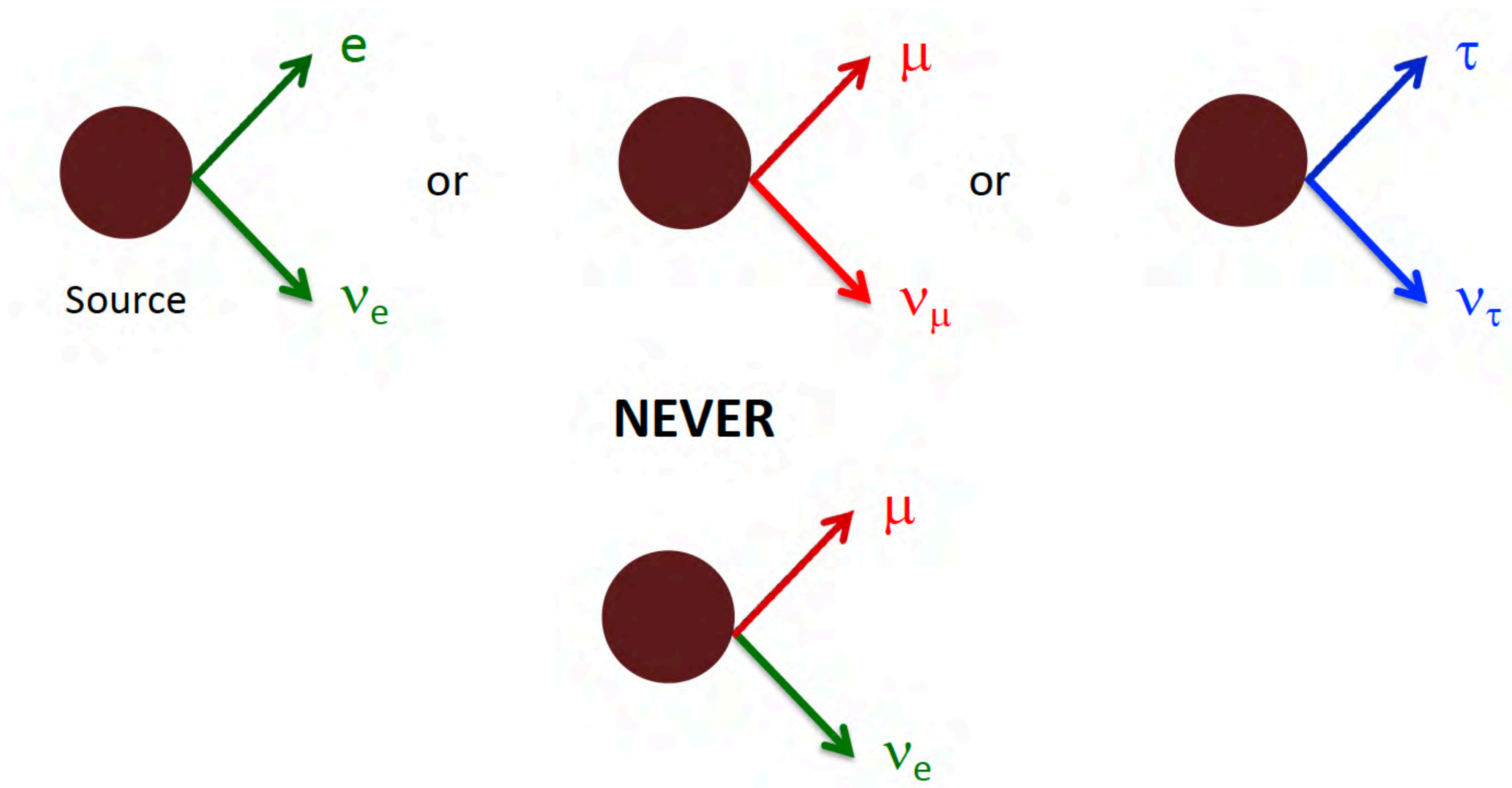
Neutral Current Interactions



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

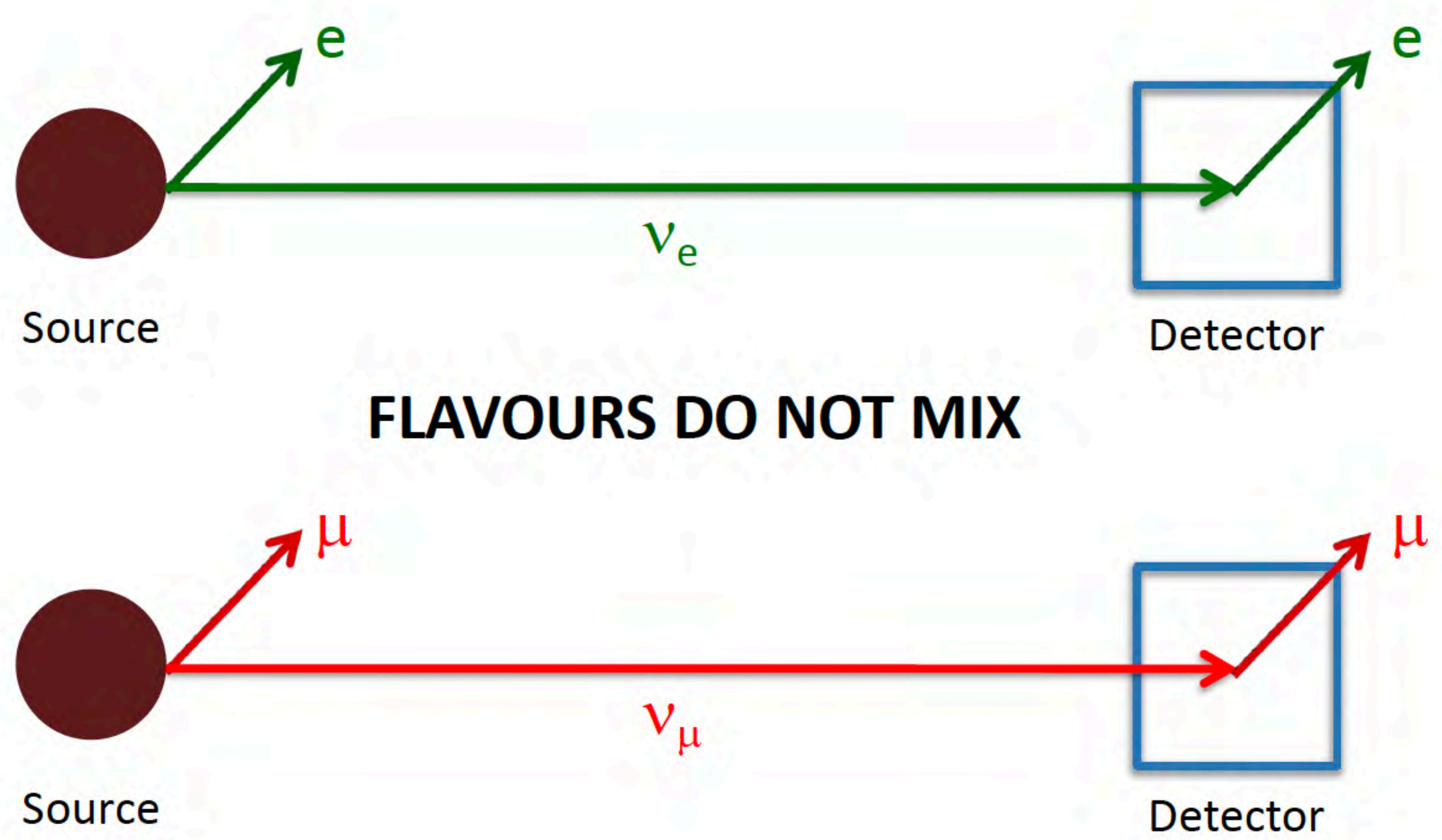
Neutrino production in the SM

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

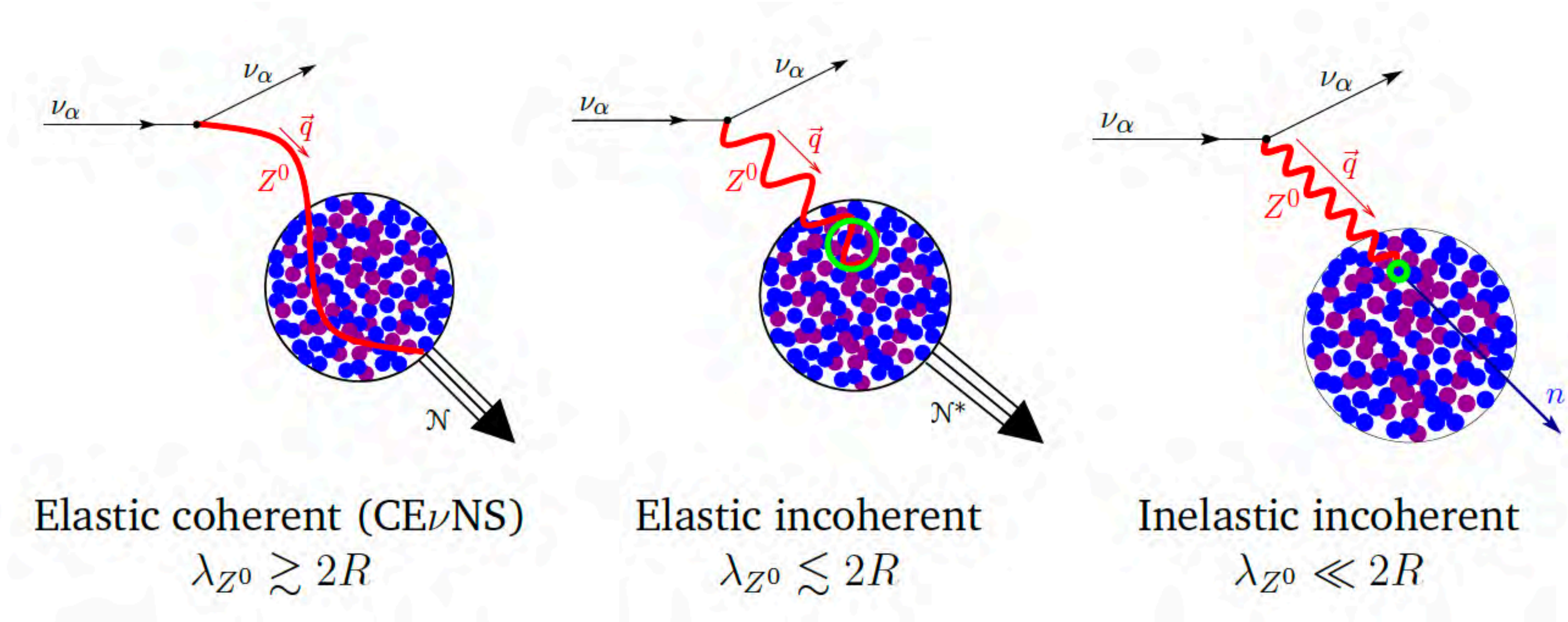


Neutrino detection

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



Coherent Elastic ν Nucleus Scattering (CEνNS)

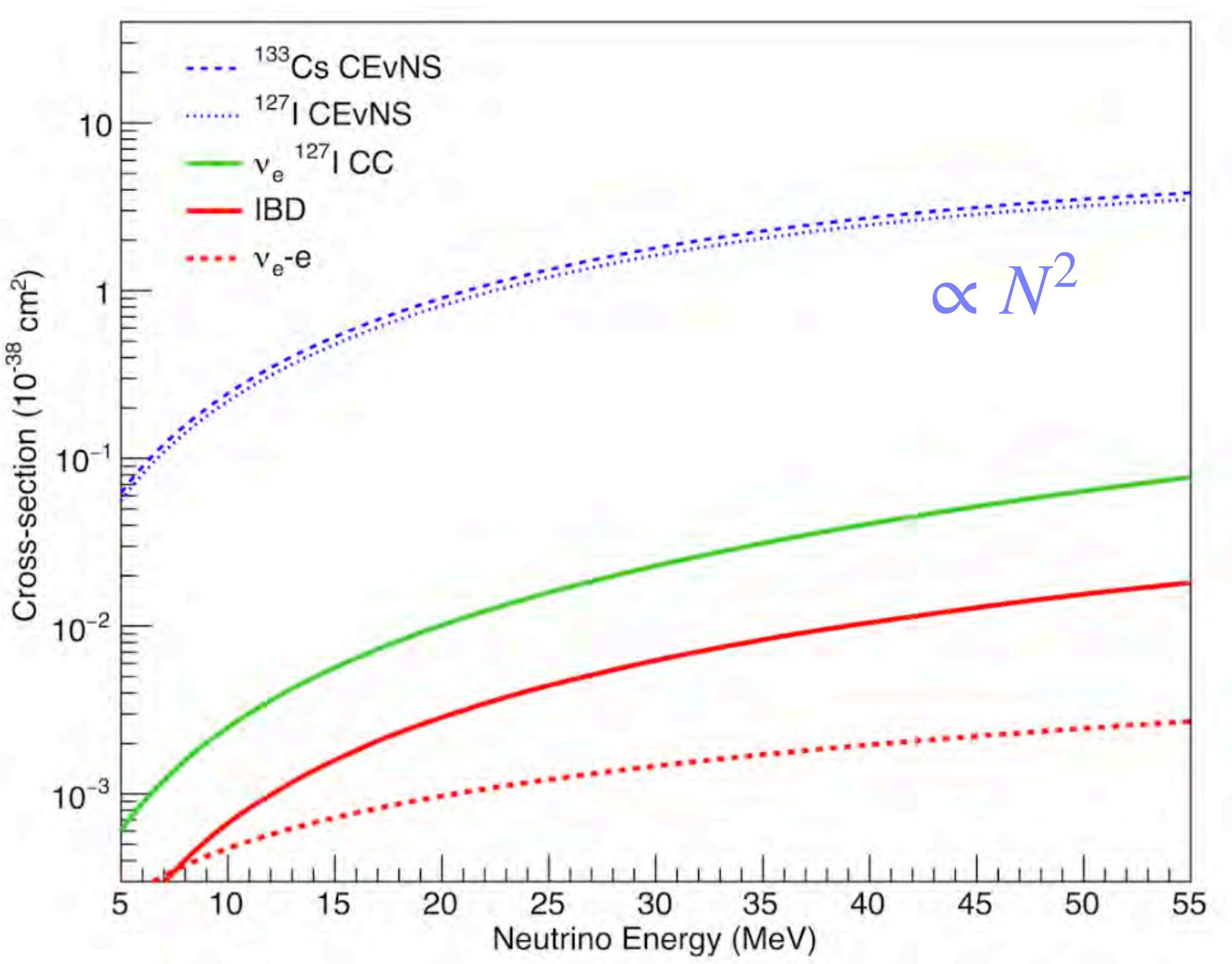


Freedman, PRD 1974

Cadeddu et al, EPL 143 (2023) 3

Coherent Elastic ν Nucleus Scattering (CEνNS)

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

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

Weak nuclear charge

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

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

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

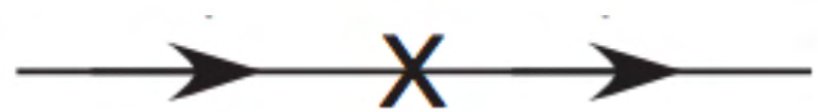
✦ **New physics** may affect the nuclear form factor, weak nuclear charge or add new terms to the cross section

Fermion masses in the SM

Dirac mass term

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

$$\psi_L \qquad\qquad \psi_R$$



→ forbidden: not invariant under SU(2)x U(1) gauge invariance

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

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

→ no R-chiral neutrino state in the SM!

Majorana neutrino mass

R-chiral field from charge conjugation of L-chiral field by (Majorana, 1930)

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

only for neutral particles

$$\psi = \psi_L + \psi_R = \psi_L + \psi_L^C$$

$$\psi^C = (\psi_L + \psi_R)^C = \psi_L^C + \psi_L = \psi$$

Majorana neutrino mass: $\psi = \nu = \nu_L + \nu_L^C$

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

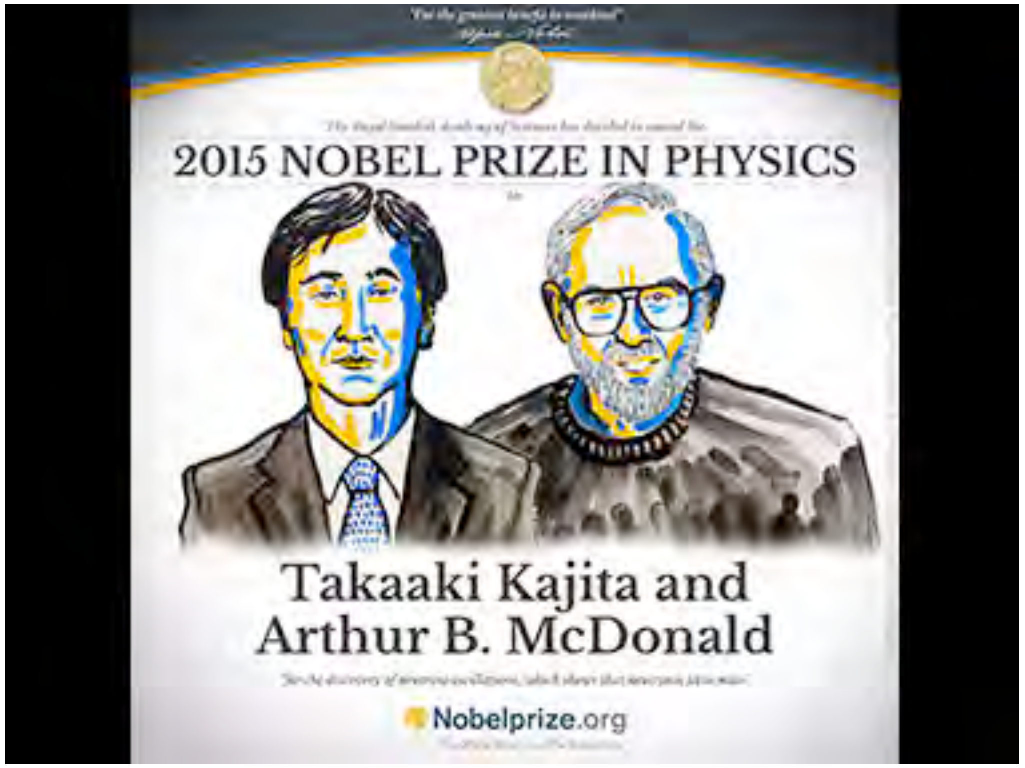
→ forbidden: not invariant under gauge invariance

→ not invariant under global symmetries either

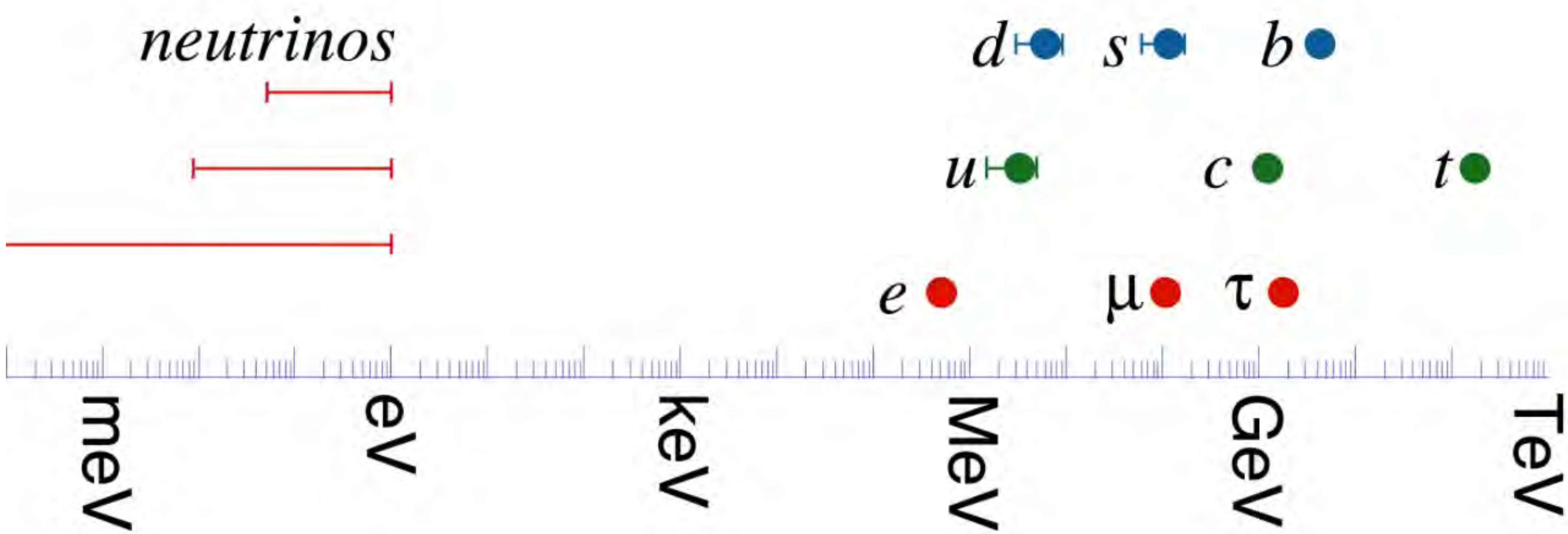
Neutrino mass in the SM

- 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: $\nu_L\,,\overline{\nu_L}\,,N_R\,,\overline{N_R}$

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

✦ Higgs mechanism:

$$\mathcal{L}_{\text{Yukawa}} = Y_\nu\,(\overline{\nu_l}\,\overline{l})\begin{pmatrix}\phi^0\\ \phi^-\end{pmatrix}N_R + \text{h.c.} \quad \xrightarrow{\text{SSB}} \quad m_D = Y_\nu\frac{v}{\sqrt{2}}$$

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

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

Minimal seesaw mechanism

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

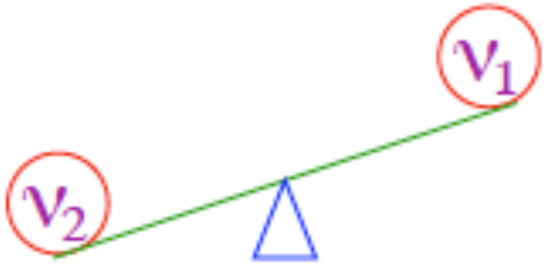
✦ Most general mass term:

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

$(m_D \simeq v Y_\nu)$

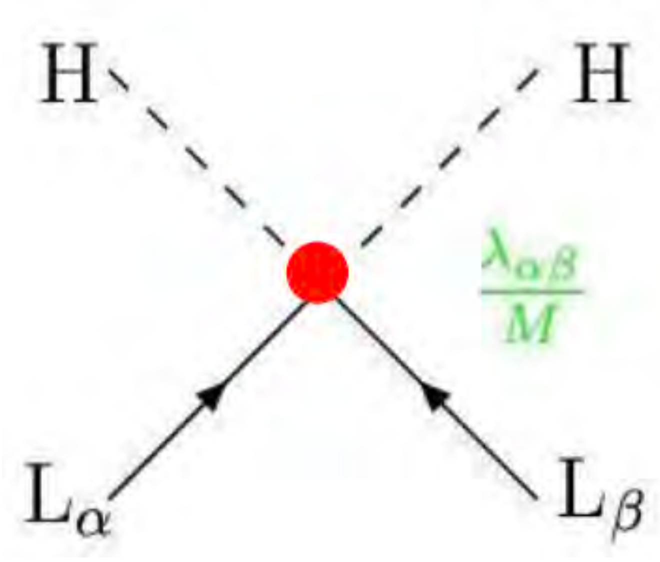
→ Diagonalization: $$\frac{1}{2}\left(\overline{\nu} \quad \overline{N}\right)\begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix}\begin{pmatrix} \nu \\ N \end{pmatrix}$$

for $M_R \gg m_D :$ $\quad M_1 \simeq \dfrac{m_D^2}{M_R}, \quad M_2 \simeq M_R$

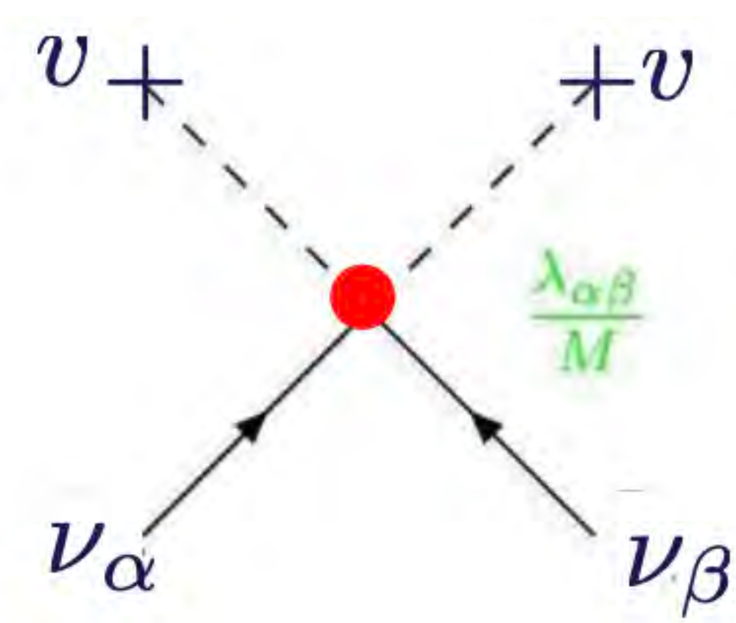


Weinberg operator

Effective dim-5 operator for Majorana neutrino mass



$\Longrightarrow$



$$\mathcal{L} \ni \frac{\lambda}{M}(LLHH) \Longrightarrow m_\nu = \frac{\lambda}{M}v^2$$

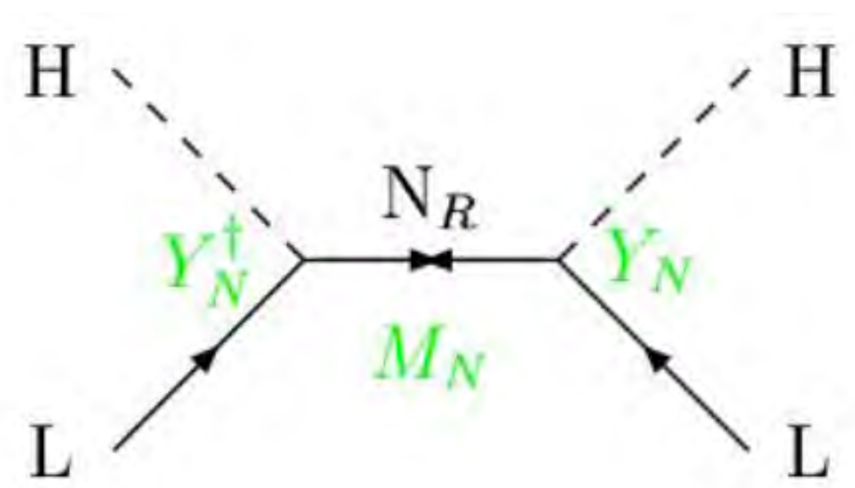
Majorana mass

$$(\Delta L = 2)$$

S. Weinberg PRL 43 (1979) 1566

Seesaw mass models

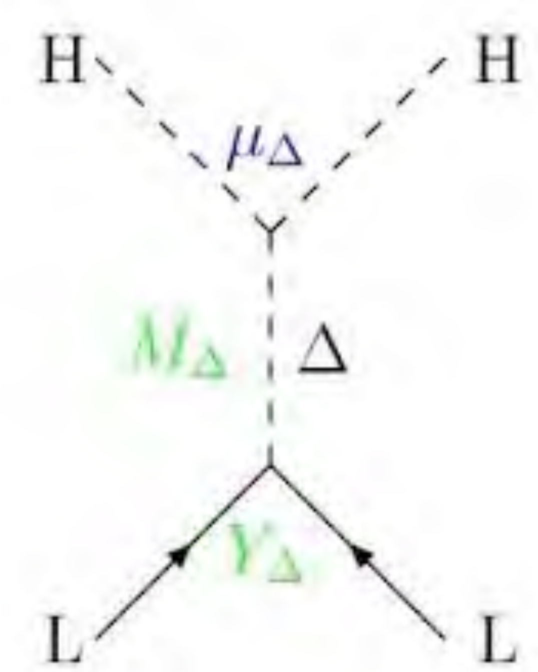
Type-I seesaw
(right-handed singlet N_R)



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

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

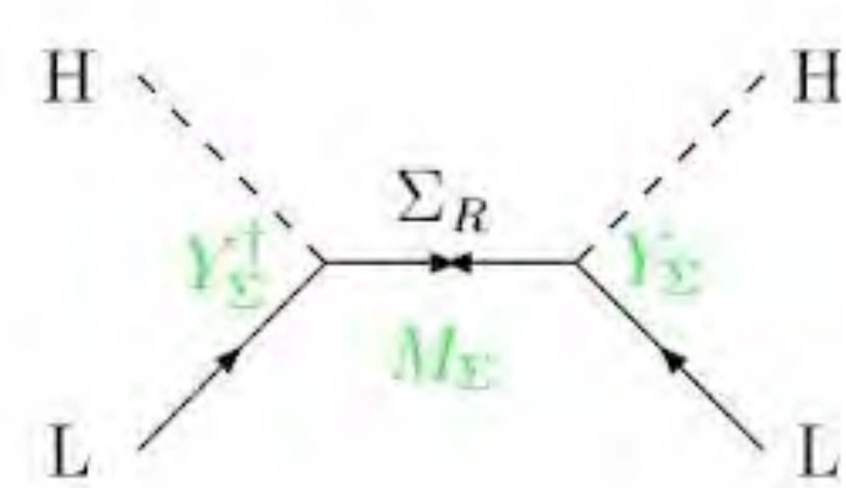
Type-II seesaw
(Scalar triplet Δ)



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

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

Type-III seesaw
(Fermion triplet Σ_R)



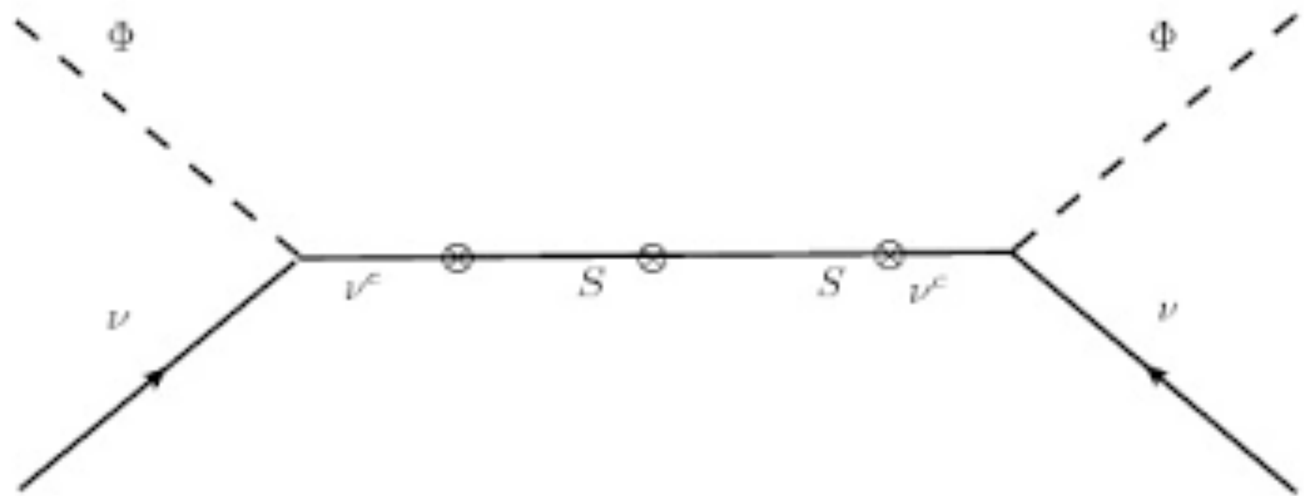
$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

Foot, Lew, He, Joshi; …

Low energy seesaw models

Inverse seesaw model

Mohapatra and Valle, PRD 34 (1986) 1642



Extended lepton content:

(ν, ν^c, S) L=(+1,-1,+1)

SU(2) singlets

$$M_\nu = \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

$$m_\nu = M_D (M^T)^{-1} \mu M^{-1} M_D^T$$

- 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:

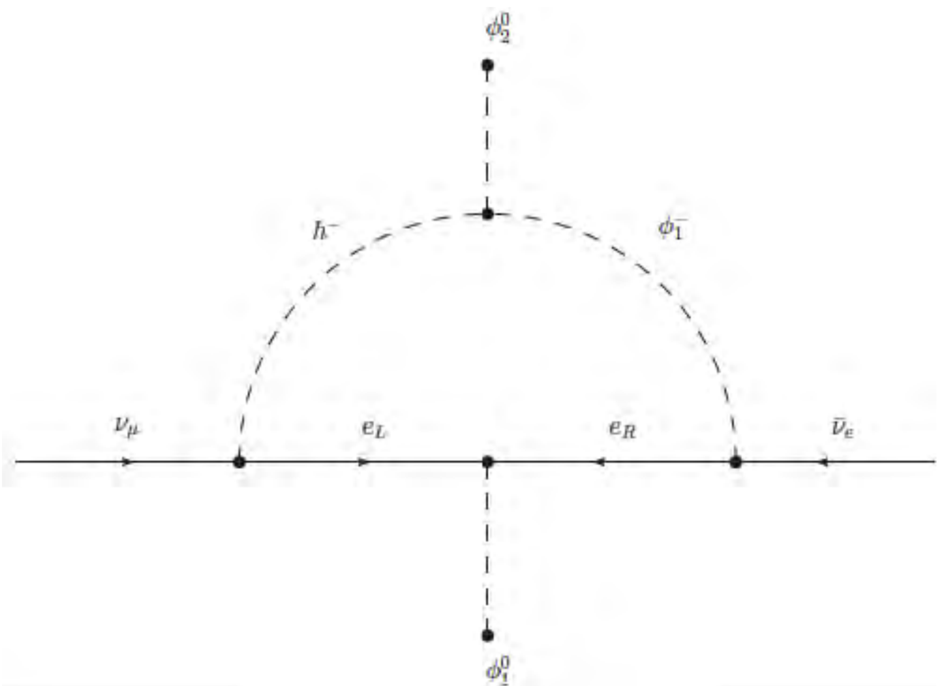
with $\mu \sim$ keV and M $\sim 10^3$ GeV $\rightarrow m_\nu \sim$ eV

Radiative models

- ✦ extension of scalar sector of the SM
- ✦ neutrino masses can be generated through loops

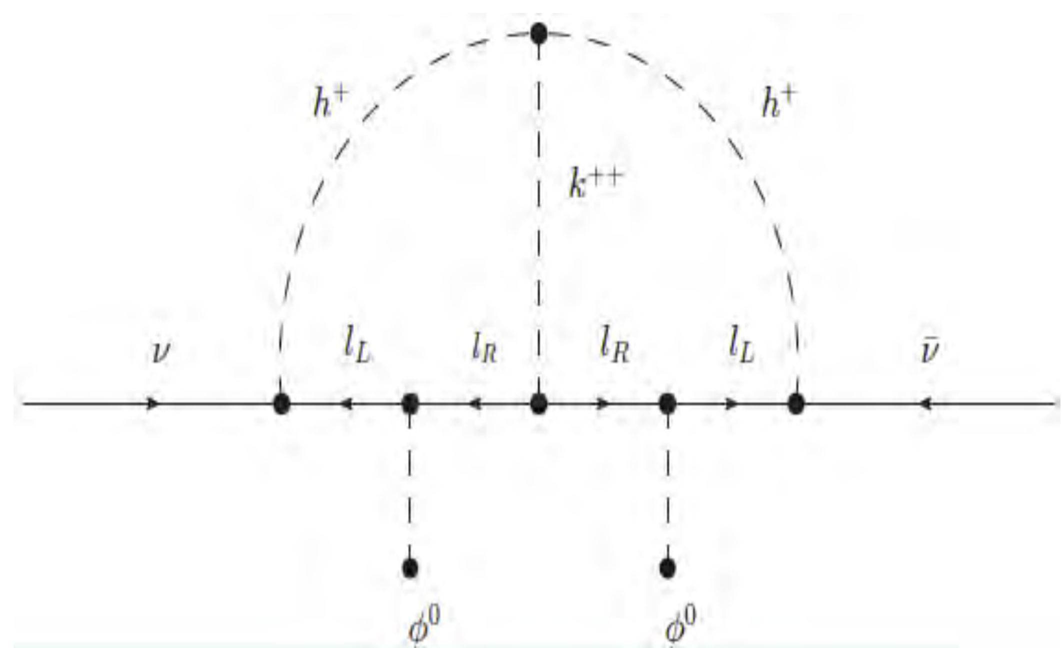
Zee model Zee, PLB 93 (1980) 389

+ singlet scalar h^+
+ extra Higgs doublet H



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

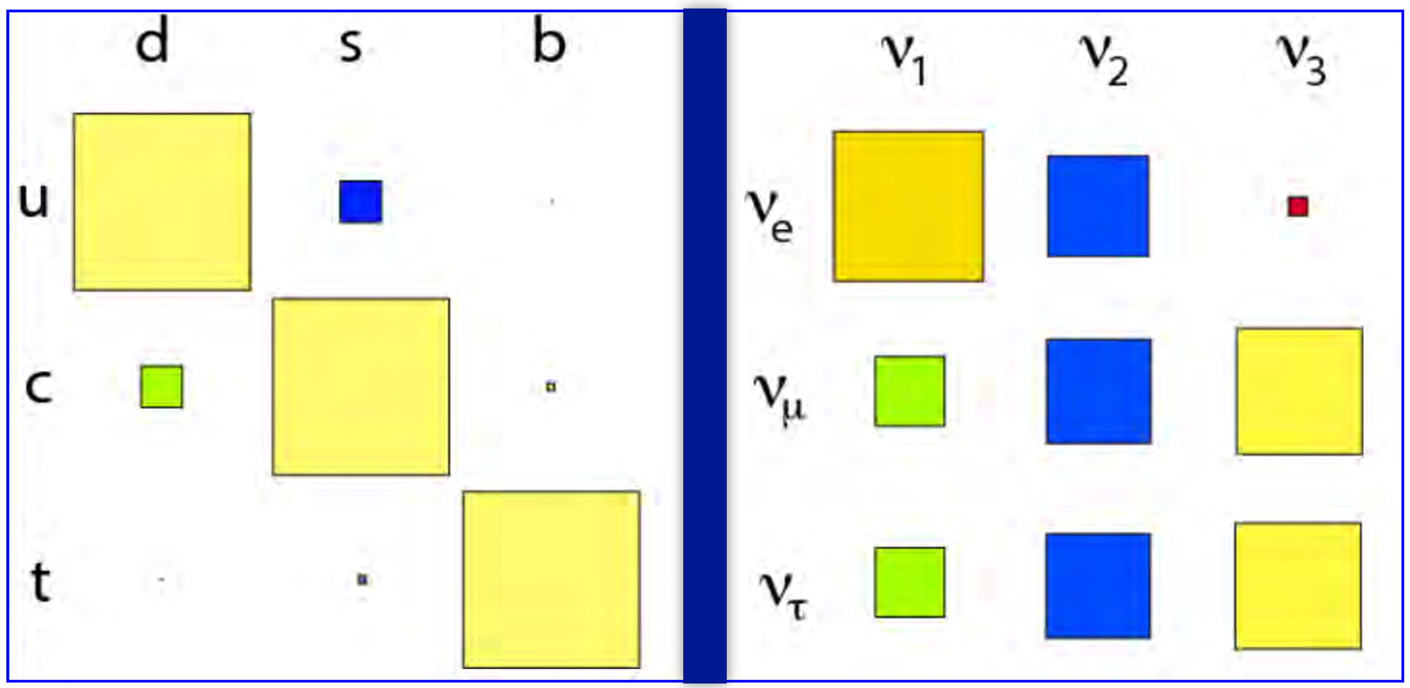
+ singlet scalar h^+
+ singlet scalar k^{++}



The flavour problem

Why quark and lepton mixings are so different?

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



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

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

$\Rightarrow$ New symmetries can be added to the Standard Model

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