Majorana ν's hidden in 0ν2β decays

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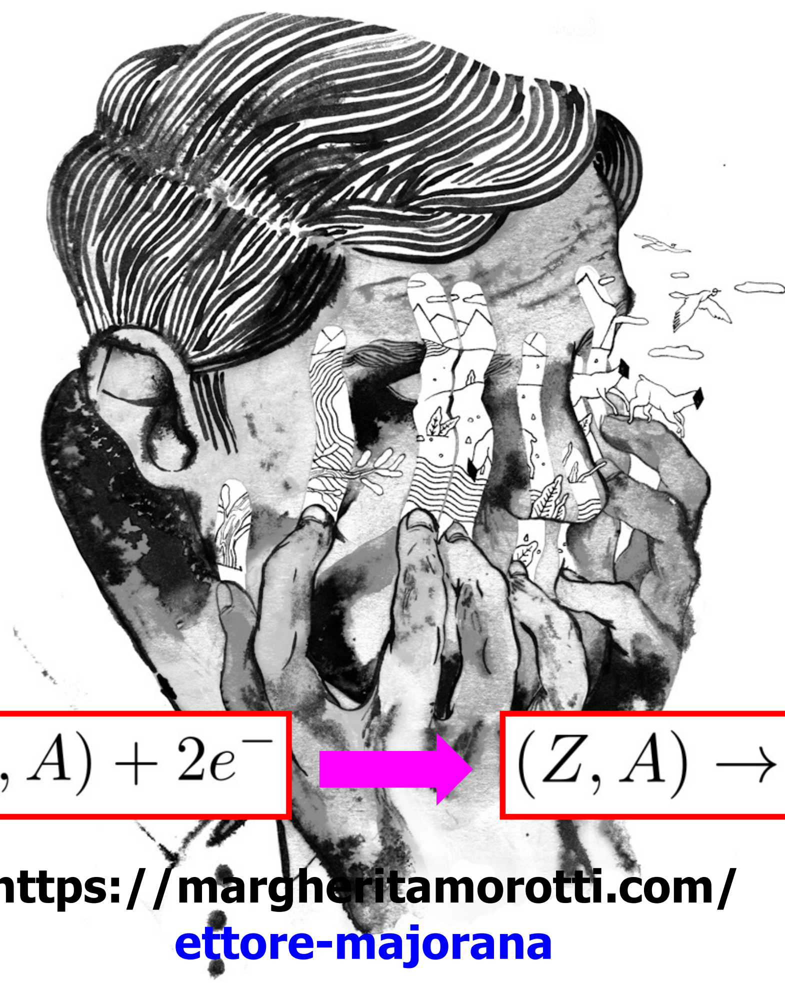


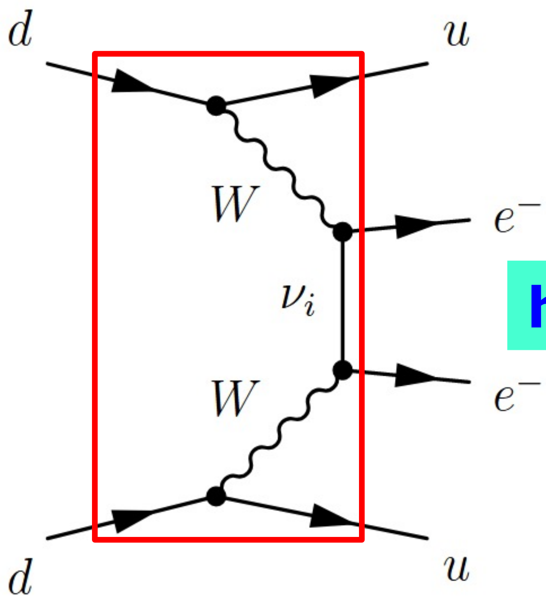
$$(Z, A) \to (Z+2, A) + 2e^- \quad \Rightarrow \quad (Z, A) \to (Z+2, A) + 2\nu_e$$

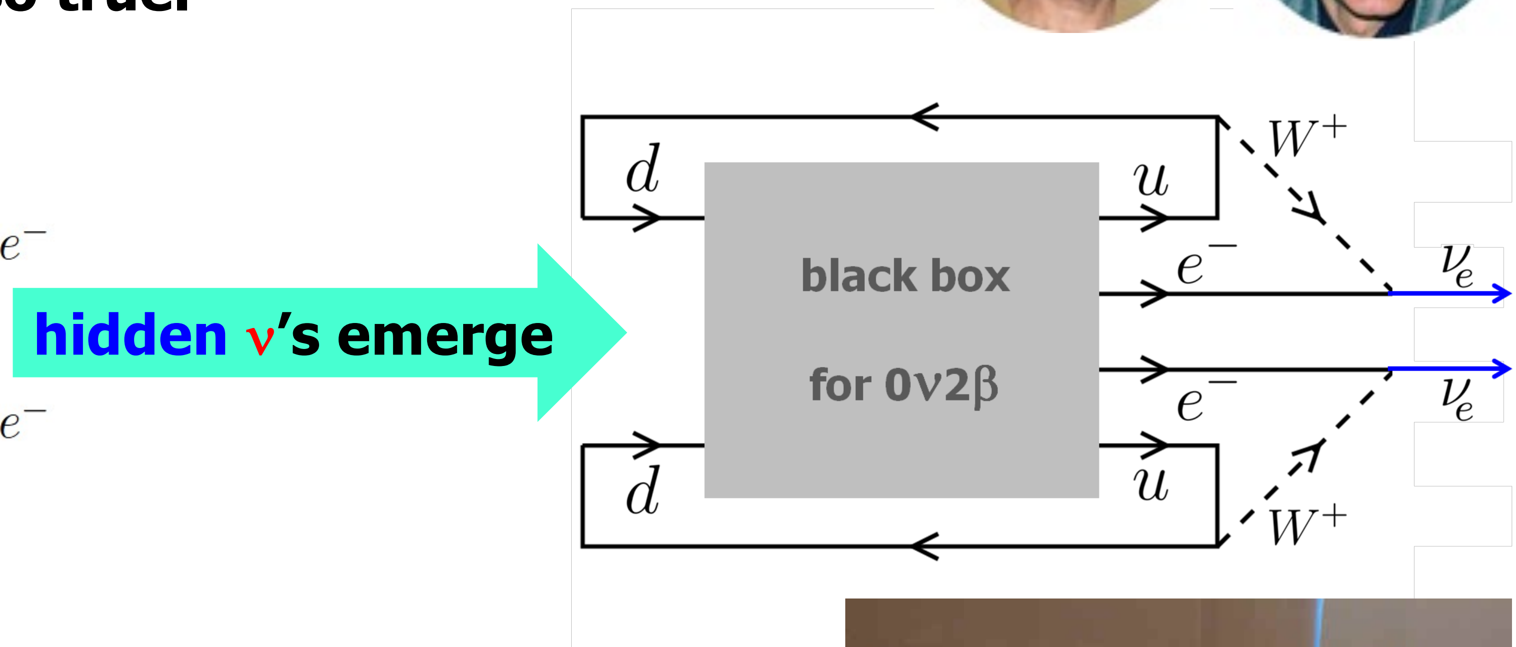
https://margheritamorotti.com/ettore-majorana

无中微子衰变研讨会，中山大学珠海校区，2021.5.19—23

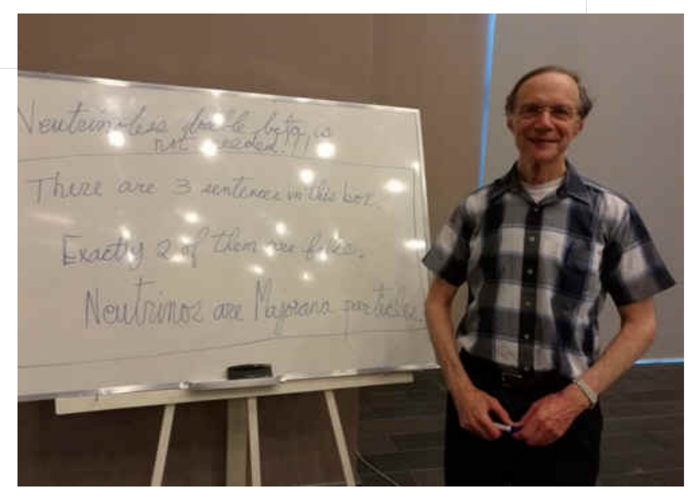
Two theorems

★ **Joseph Schechter** and **Jose Valle** suggested a theorem in **June 1982**: if a **0ν2β** decay happens, there must be an effective **Majorana** mass term. The reverse is also true.



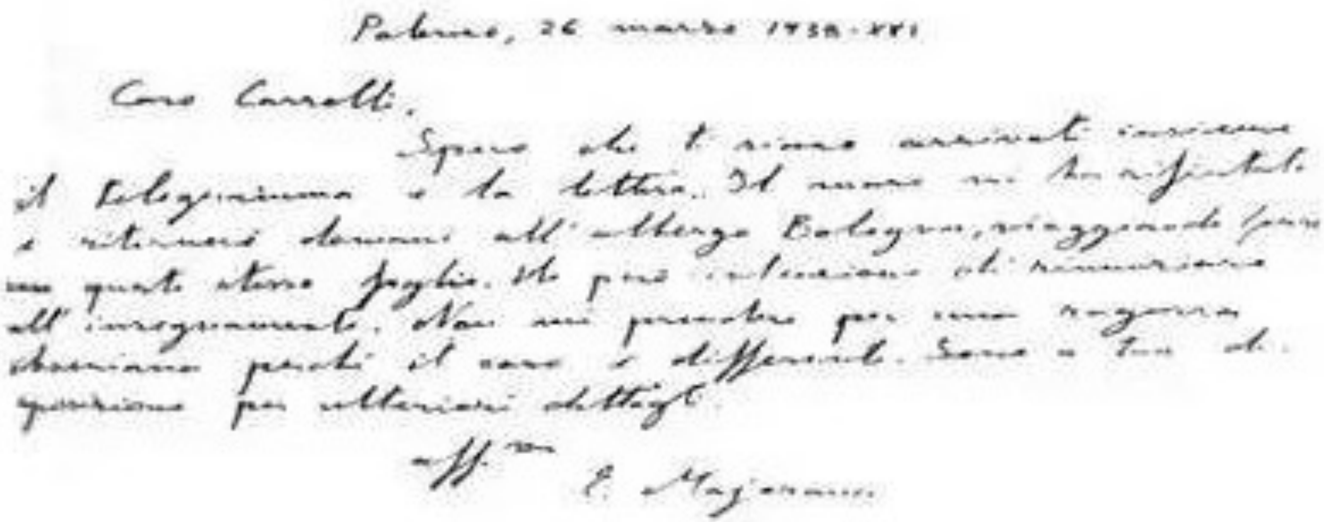


★ The **Majorana**-**Dirac** **confusion theorem** by **Boris Kayser** in **October 1982**: If there're no right-handed currents and the ν-masses are very small compared with the experimental energy scale, then it is impossible to tell the difference between **Dirac** and **Majorana** ν's.

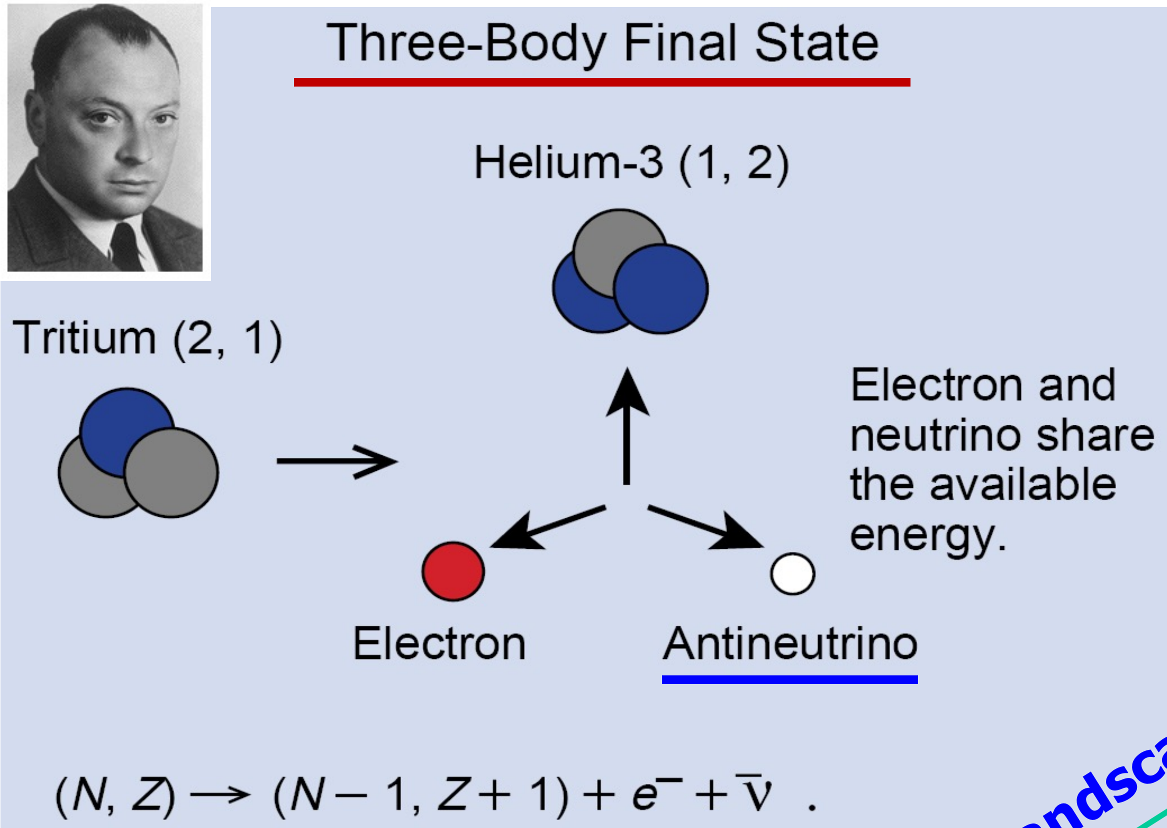


OUTLINE

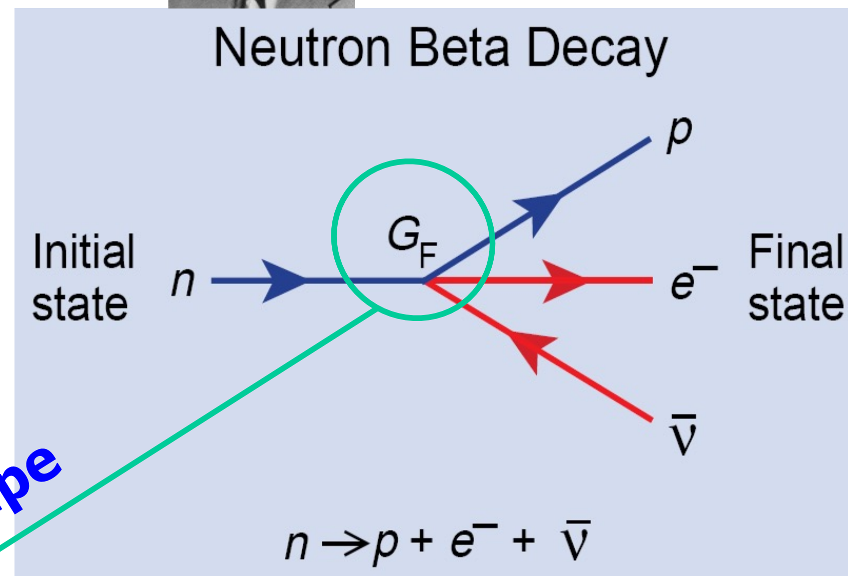
- **A brief history: ideas and facts oscillated**
- **Salient properties of Majorana neutrinos**

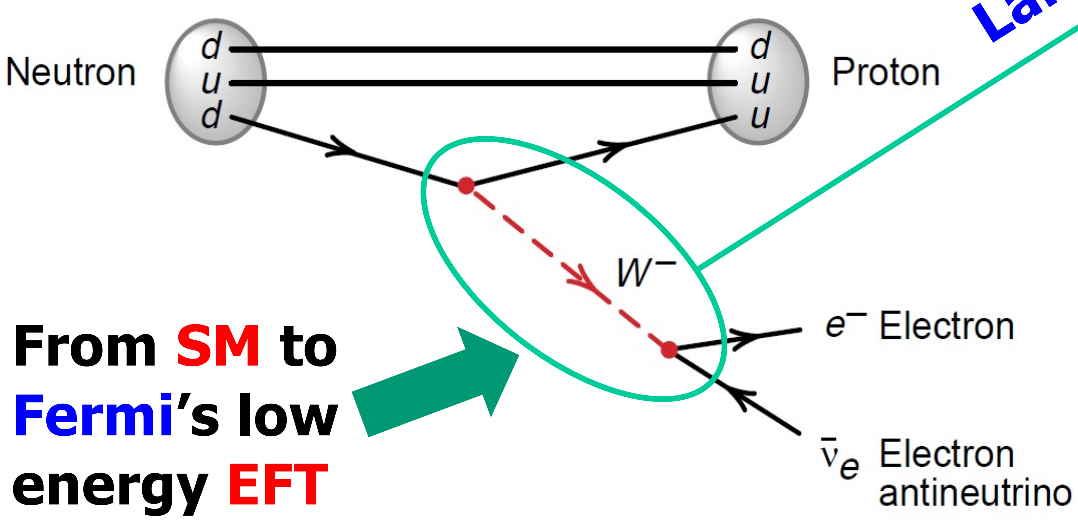


Pauli (1930) and Fermi (1933)



I will be remembered for this paper





From SM to Fermi's low energy EFT

The seesaw-like relation:

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} \Rightarrow g \simeq 0.65$$

$$M_W \simeq 80.4 \text{ GeV}$$

$$G_F \simeq 1.166 \times 10^{-5} \text{ GeV}^{-2}$$

Goeppert-Mayer (1935)

★ 2ν2β decay: some even-even nuclei have an opportunity to decay to the 2nd nearest neighbor via 2 simultaneous β decays (equivalent to the β decays of two neutrons).

$$(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\bar{\nu}_e.$$

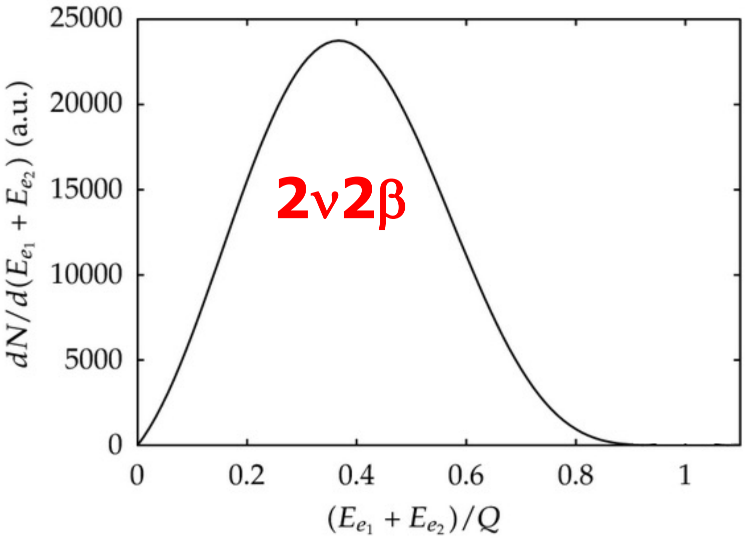
Maria Goeppert-Mayer

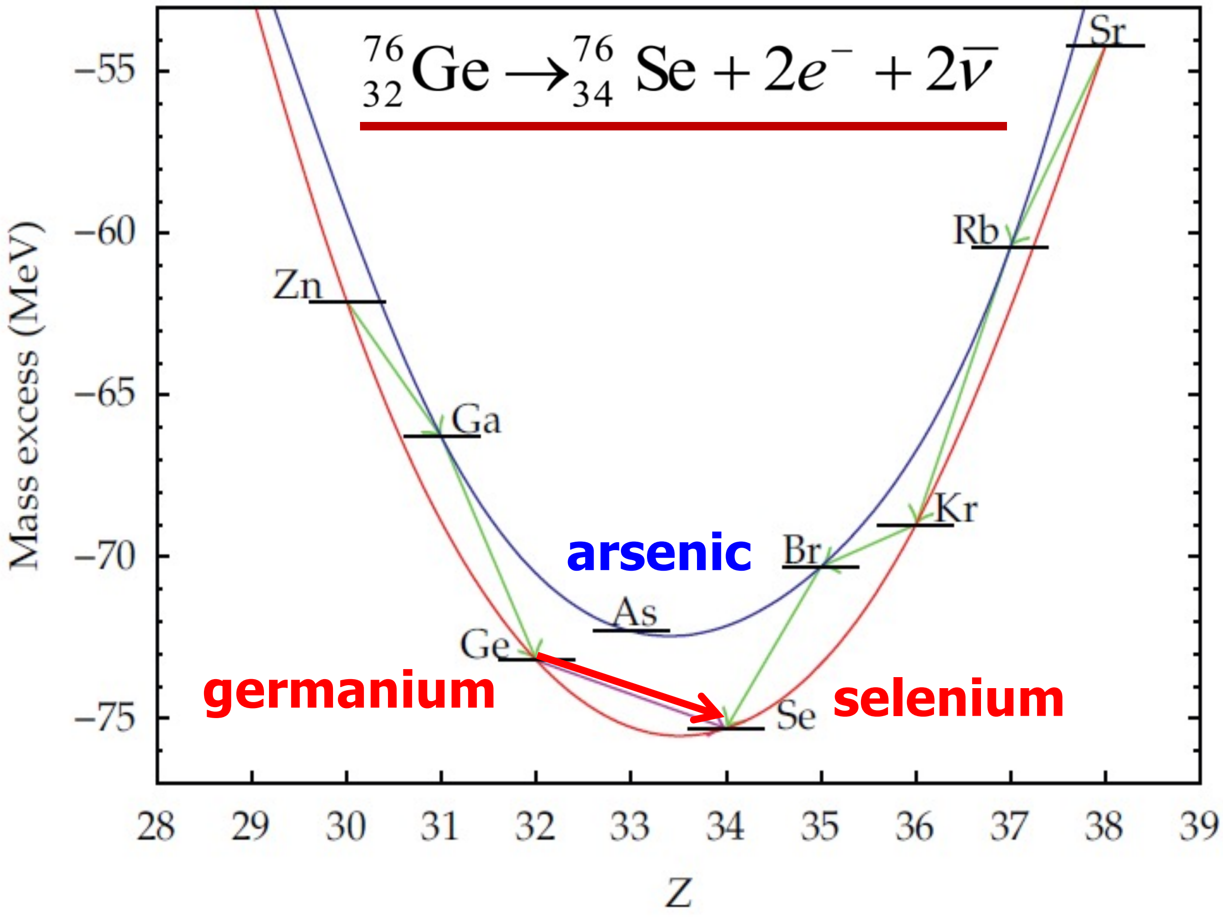
necessary conditions:

$$m(Z,A) > m(Z+2,A)$$

$$m(Z,A) < m(Z+1,A)$$

Electron energy spectrum





Majorana (1937)

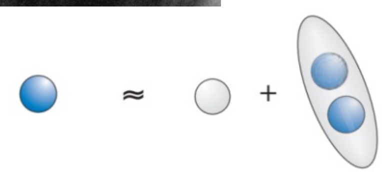
★ **Ettore Majorana: theory of the symmetry of electrons and positrons —— an idea as mysterious as Majorana's personality.**

"…there is now no need to assume the existence of antineutron or antineutrinos. The latter particles are indeed introduced in the theory of positive beta-ray emission; the theory, however, can be obviously modified so that the beta-emission, both positive and negative, is always accompanied by the emission of a neutrino."

Our judgement today:

- **No, antineutron ≠ neutron (100%)**
- **Ja, antineutrinos = neutrinos (99%?)**

★ **Majorana fermions are a new form of matter.**



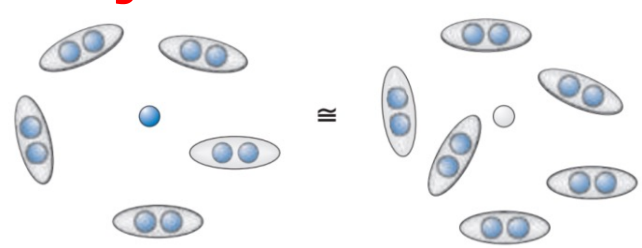
★ **Majorana neutrinos are truly *New Physics* beyond SM, and have profound implications for the Universe.**

"Majorana returns"

—— Frank Wilczek

Nature Physics 2009

Majorana zero mode

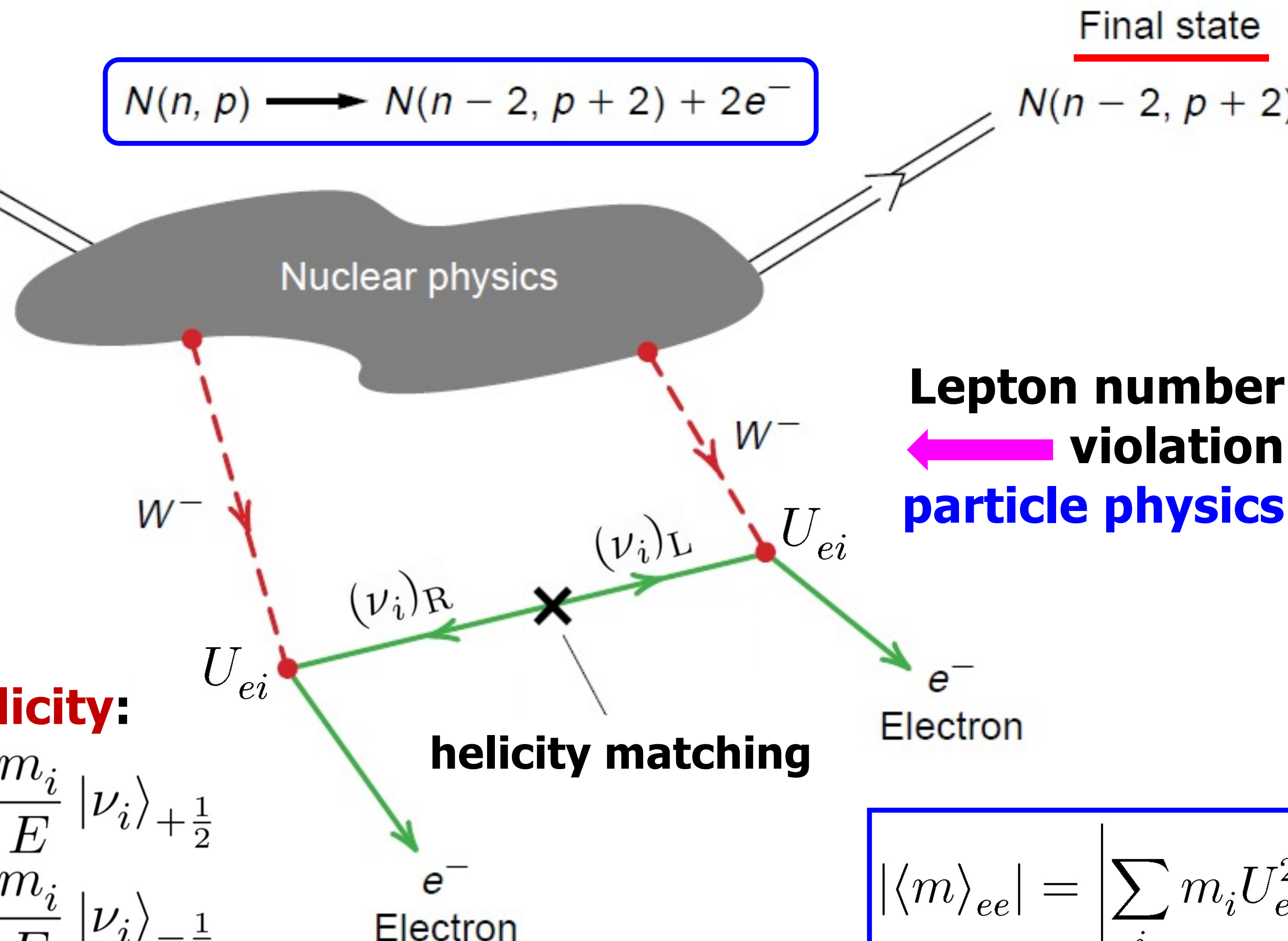


Furry (1939)

★ A *0ν2β* decay may occur if massive ν's have the **Majorana** nature, as first pointed out by **Furry** in 1939.

$$T^{0\nu}_{1/2} = \left(G^{0\nu}\right)^{-1} \left|M^{0\nu}\right|^{-2} \left|\langle m\rangle_{ee}\right|^{-2}$$

Wendell Furry



Lepton number violation ⟵ **particle physics**

Chirality and Helicity:

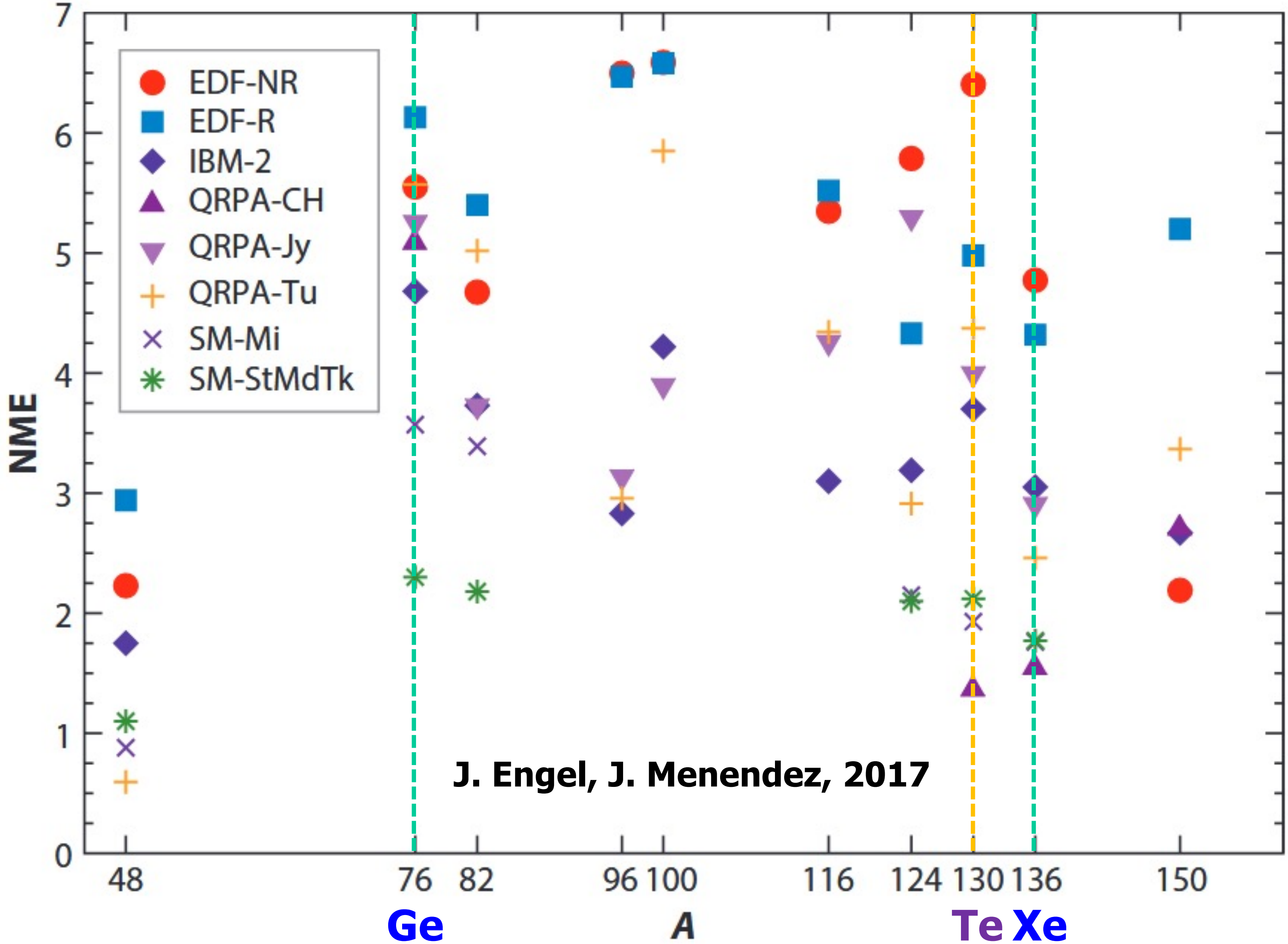
$$|\nu_i\rangle_{\rm L} \propto |\nu_i\rangle_{-\frac{1}{2}} + \frac{m_i}{E}\,|\nu_i\rangle_{+\frac{1}{2}}$$

$$|\nu_i\rangle_{\rm R} \propto |\nu_i\rangle_{+\frac{1}{2}} - \frac{m_i}{E}\,|\nu_i\rangle_{-\frac{1}{2}}$$

$$\left|\langle m\rangle_{ee}\right| = \left|\sum_i m_i U^2_{ei}\right|$$

Nuclear matrix elements

★ **Big uncertainties associated with nuclear matrix elements (NMEs):**



Half-life lower limits

★ **Current experimental constraints on the half-life of the 0ν2β decay.**

$$T_{1/2}^{0\nu} = \left(G\,|\mathcal{M}|^2\,\langle m_{\beta\beta}\rangle^2\right)^{-1} \simeq 10^{27-28}\left(\frac{0.01\,\text{eV}}{\langle m_{\beta\beta}\rangle}\right)^2\ \text{years}$$

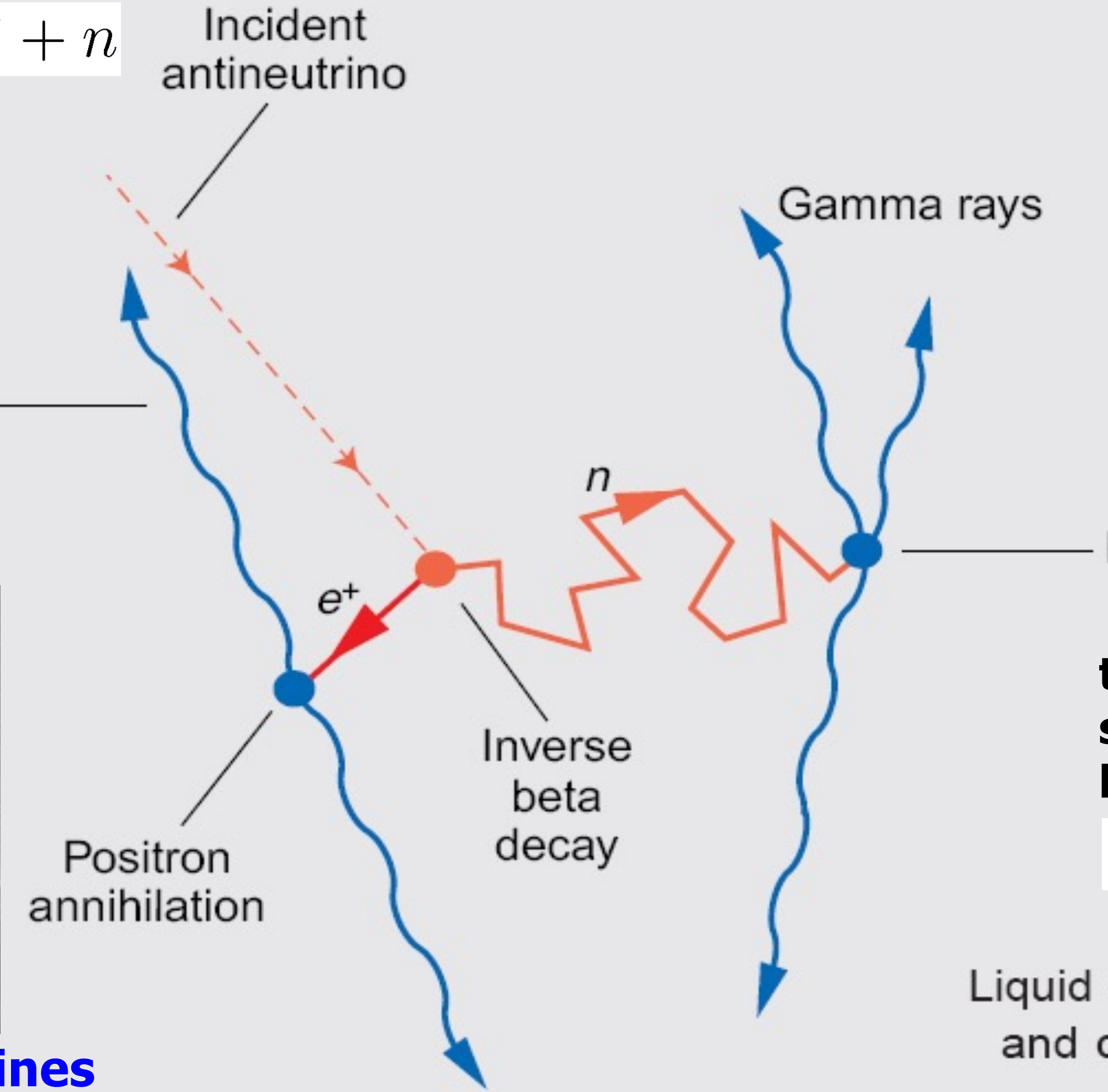
Isotope	$T_{1/2}^{0\nu}$ (x10^{25} years)	$\langle m_{\beta\beta}\rangle$ (eV)	Experiment	Reference
^{48}Ca	$>5.8\times10^{-3}$	<3.5–22	ELEGANT-IV	159
^{76}Ge	>8.0 ★	<0.12–0.26	GERDA	160
GERDA 2020	$T_{1/2} > 1.8\times10^{26}$ yr at 90% C.L.		MAJORANA DEMONSTRATOR	161
^{82}Se	$>3.6\times10^{-2}$	<0.89–2.43	NEMO-3	162
^{96}Zr	$>9.2\times10^{-4}$	<7.2–19.5	NEMO-3	163
^{100}Mo	$>1.1\times10^{-1}$	<0.33–0.62	NEMO-3	164
^{116}Cd	$>2.2\times10^{-2}$	<1.0–1.7	Aurora	165
^{128}Te	$>1.1\times10^{-2}$	NE	C. Arnaboldi et al.	166
^{130}Te	>1.5	<0.11–0.52	CUORE	126
^{136}Xe	>10.7 ★	<0.061–0.165	KamLAND-Zen	167
	>1.8	<0.15–0.40	EXO-200	168
^{150}Nd	$>2.0\times10^{-3}$	<1.6–5.3	NEMO-3	169

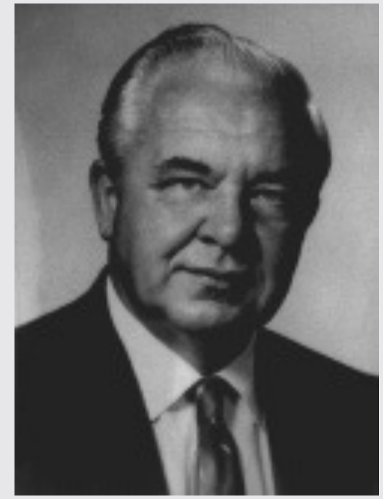
M. Dolinski, A. Poon, W. Rodejohann, 2019

Reines and Cowan (1956)

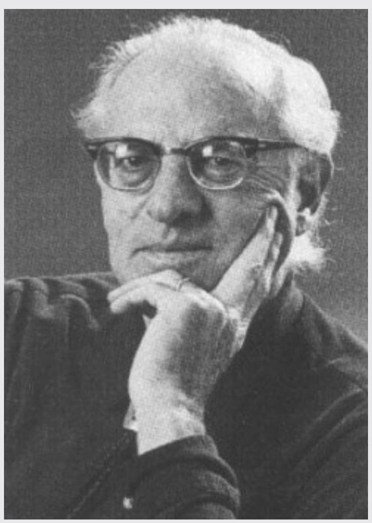
★ **The 1st good news: electron antineutrinos were discovered in 1956.**

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





Clyde Cowan



Frederick Reines

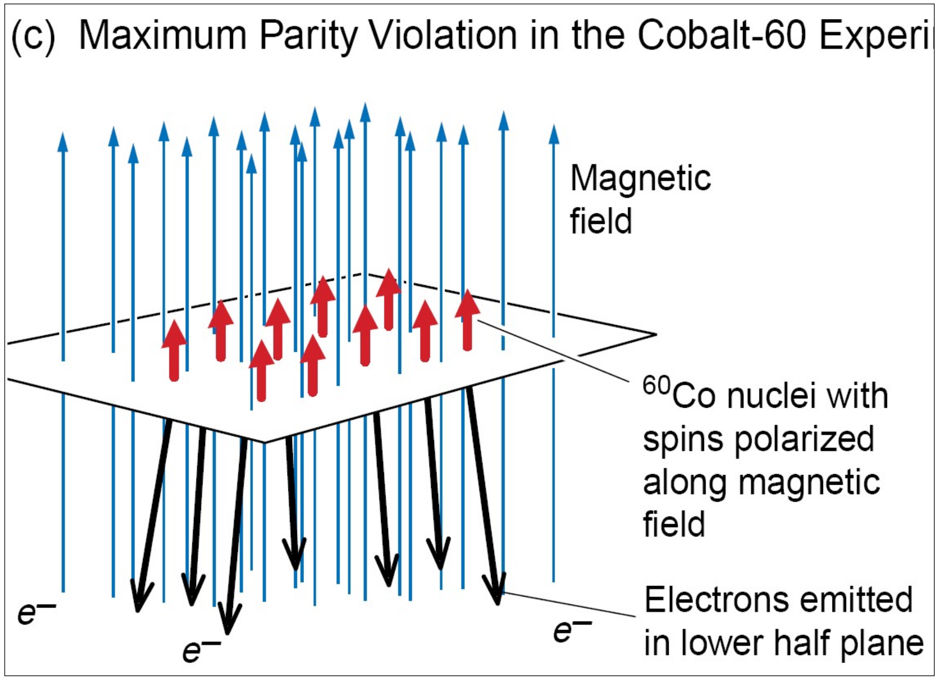
two flashes separated by some μs

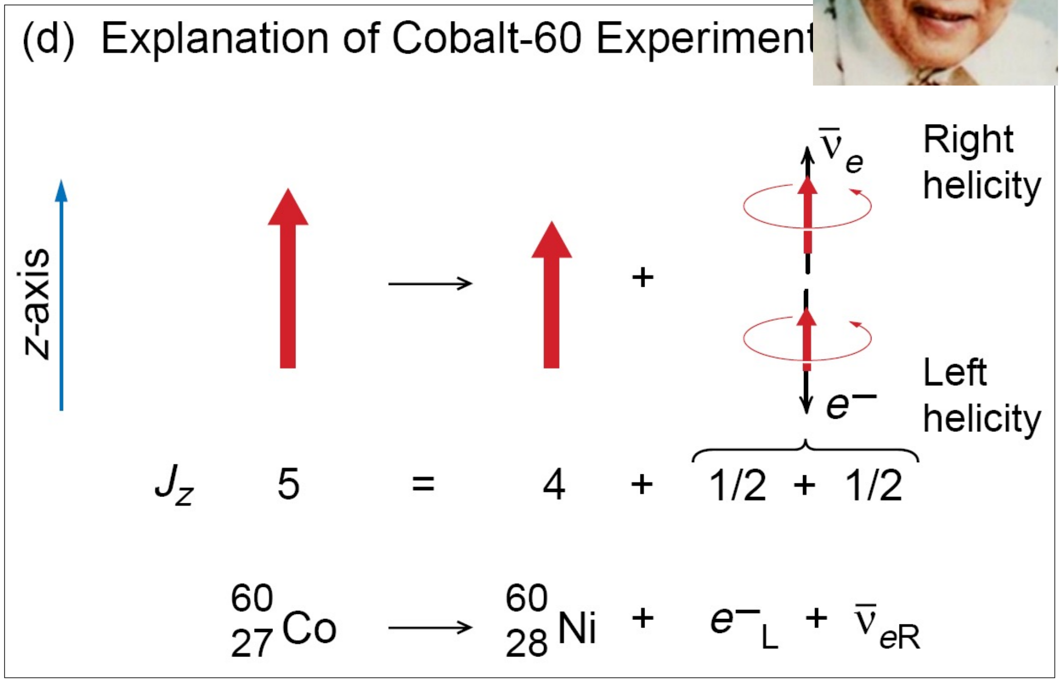
$$\mu\mathrm{s} = 10^{-6}\mathrm{s}$$

Wu, Lee and Yang (1957)

★ **The 1st bad news: neutrinos seemed to have no mass (left-handed).**

Chien-shiung Wu *et al* aligned the spins of Cobalt-60 nuclei along external magnetic field and then measured directions of the emitted electrons. They saw maximal parity violation.





(Leon Lederman *et al* observed similar effects in leptonic pion decays).

Tsung-Dao Lee and Chen-Ning Yang proposed the two-component theory: neutrinos are left-handed and exactly massless!

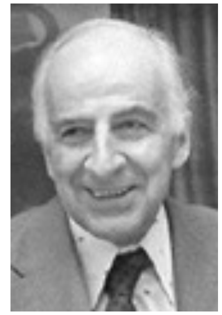
Pontecorvo (1957) and V–A (1958)

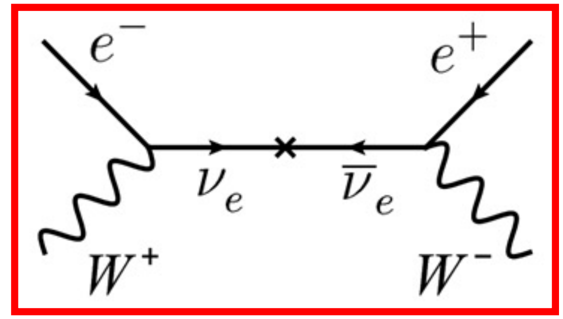
★ **Bruno Pontecorvo's conjecture in 1957:**

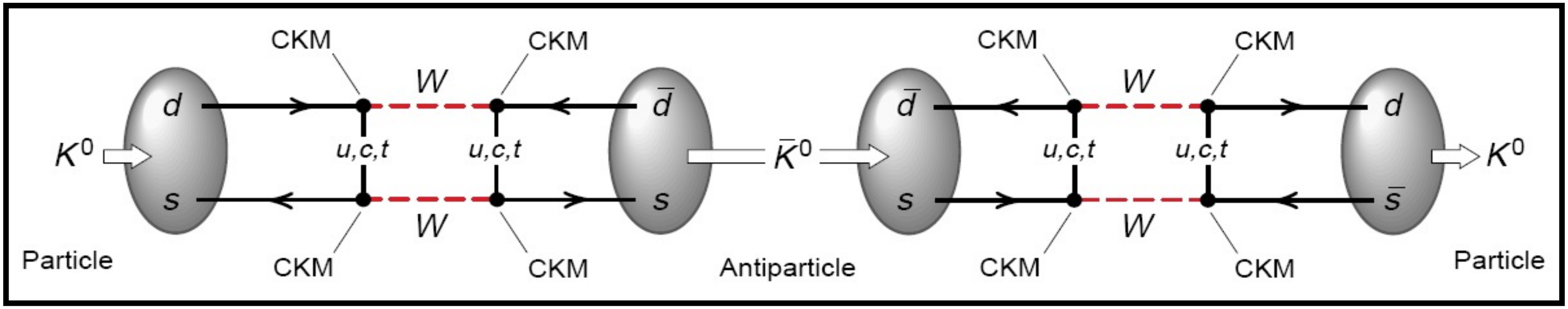
— The two-component ν-theory is wrong.

— Lepton number is violated (Majorana).

— Transition between electron ν & anti-ν.







Murray Gell-mann and **Abraham Pais** 1955

$$P(\nu_e \to \overline{\nu}_e) = \frac{m_\nu^2}{E^2}|K|^2$$

Note: a single leptonic flavor cannot oscillate!

★ The **V–A** structure of weak interactions was formulated in 1958, inspired by measurement of **maximal parity violation**:

—— **George Sudarshan** and **Robert Marshak**

—— **Richard Feynman** and **Murray Gell-Mann**

Goldhaber (1958) and Sakata (1962)

★ **The 2nd bad news: a neutrino did have the negative helicity and thus should have no mass. A proof of this was first done by Maurice Goldhaber et al in 1958.**

$$^{152}_{63}\mathrm{Eu}(0^-) + e^- \rightarrow \, ^{152}_{62}\mathrm{Sm}^*(1^-) + \nu_e \qquad \lambda \equiv \vec{s}\cdot\vec{p}/|\vec{p}| = -1/2$$

★ **The Nagoya school's conjectures: neutrinos are massive and mixed.**

Progress of Theoretical Physics, Vol. 28, No. 5, November 1962

Remarks on the Unified Model of Elementary Particles

Ziro MAKI, Masami NAKAGAWA and Shoichi SAKATA

Institute for Theoretical Physics
Nagoya University, Nagoya

(Received June 25, 1962)

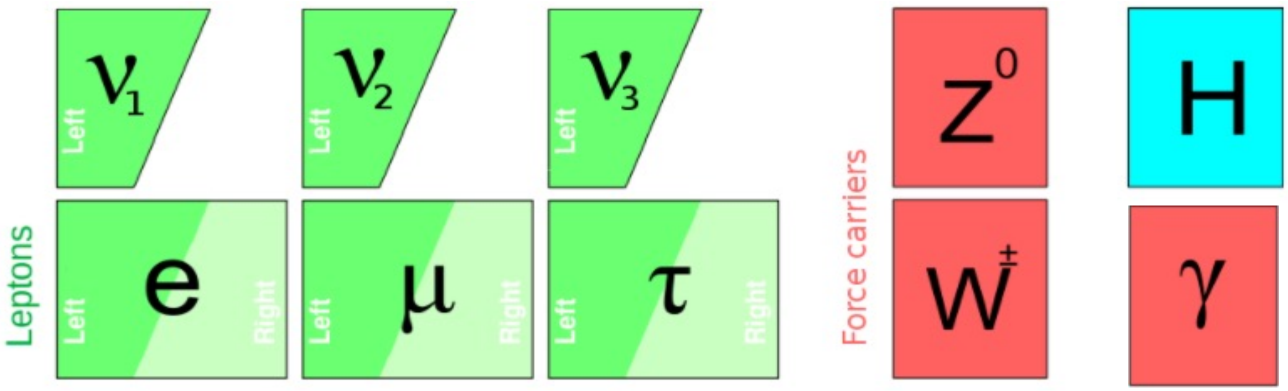
their original notation:

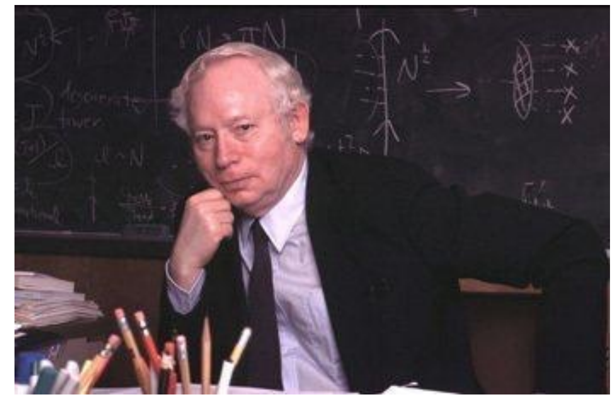
$$\nu_e = \nu_1 \cos\delta - \nu_2 \sin\delta,$$
$$\nu_\mu = \nu_1 \sin\delta + \nu_2 \cos\delta.$$

Inspired by Murray Gell-Mann + Maurice Levy 1960

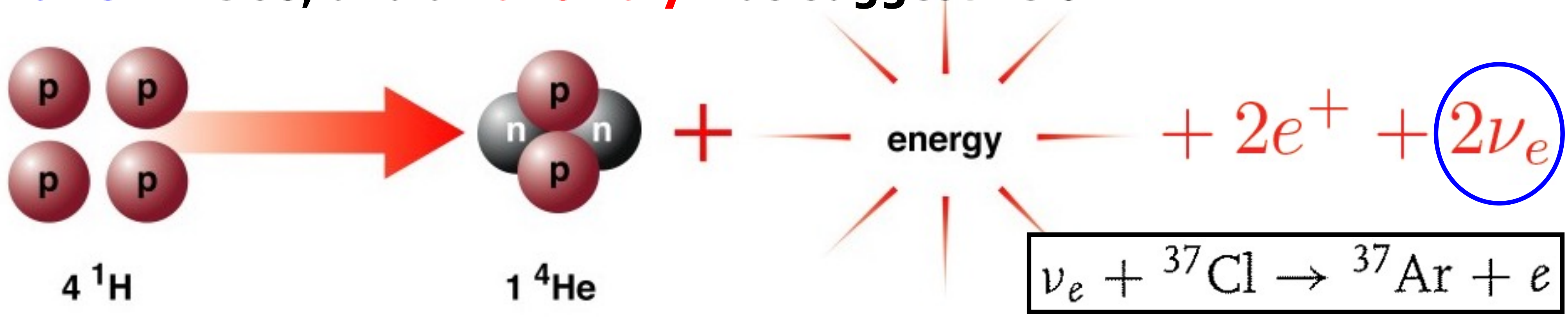
Weinberg (1967) and Davis (1968)

★ **Steven Weinberg built a rigid framework for the electroweak theory in 1967 by putting aside right-handed neutrinos.**





★ **The 2nd good news: the solar neutrinos were observed by Raymond Davis in 1968, and an anomaly was suggestive of ....**



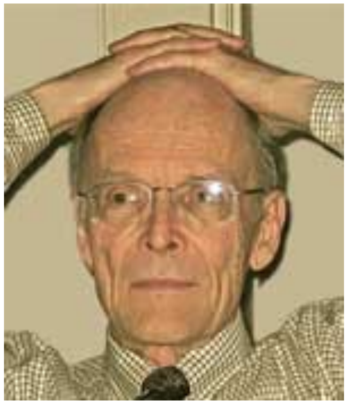
How can we tell what is going on inside the Sun? Photons take 1000 years to work their way out from the center to the surface, and what we see from the earth does not tell us much about the interior.

Moe (1987)

★ **The 3rd good news: the double-beta decay of Se-82 was first observed by Michael Moe et al in 1987.**

$$^{82}_{34}\mathrm{Se} \rightarrow {}^{82}_{36}\mathrm{Kr} + 2e^- + 2\overline{\nu}_e$$

Tom Bonner Prize **in nuclear physics 2013**



VOLUME 59, NUMBER 18 PHYSICAL REVIEW LETTERS 2 NOVEMBER 1987

Direct Evidence for Two-Neutrino Double-Beta Decay in ^{82}Se

S. R. Elliott, A. A. Hahn, and M. K. Moe

Department of Physics, University of California, Irvine, Irvine, California 92717

(Received 31 August 1987)

The two-neutrino mode of double-beta decay in ^{82}Se has been observed in a time-projection chamber at a half-life of $(1.1^{+0.8}_{-0.3})\times 10^{20}$ yr (68% confidence level). This result from direct counting confirms the earlier geochemical measurements and helps provide a standard by which to test the double-beta-decay matrix elements of nuclear theory. It is the rarest natural decay process ever observed directly in the laboratory.

The introduction of this paper is very informative:

- **The 2ν2β transition was first suggested by Eugene Wigner in 1930.**
- **Wendell Furry remarked that 2ν2β could never be observed, but 0ν2β could.**
- **Ironically 2ν2β instead of 0ν2β was seen. Neutrino could be of Dirac nature.**

Super-Kamiokande (1998)

★ **The 4th good news: neutrinos do oscillate, so they must be massive.**

Sun: Yoichiro Suzuki (4/6) **Atmosphere: Takaaki Kajita (5/6)**

"Modest" Conclusions

(1) Flux: $\phi^{8B} = 2.44 \pm 0.05(\text{stat.})^{+0.09}_{-0.07}(\text{syst.}) \times 10^6/\text{cm}^2/\text{s}$

(0.368 for BP95, 0.474 for BP98)

(2) No seasonal variations.

(3) $(D-N)/(D+N) = -0.023 \pm 0.020(\text{stat}) \pm 0.014(\text{syst})$

no difference:

excluded regions extended into "small angle sol."

No core enhancement found.

(4) Day-Night + E-shape analysis.

(a) "No oscillation" is disfavoured @ 1~5% C.L.

(b) L.A. solution is disfavoured @ 1~5% C.L.

(c) V.O. regions are favoured (than MSW regions) @ 95% C.L.

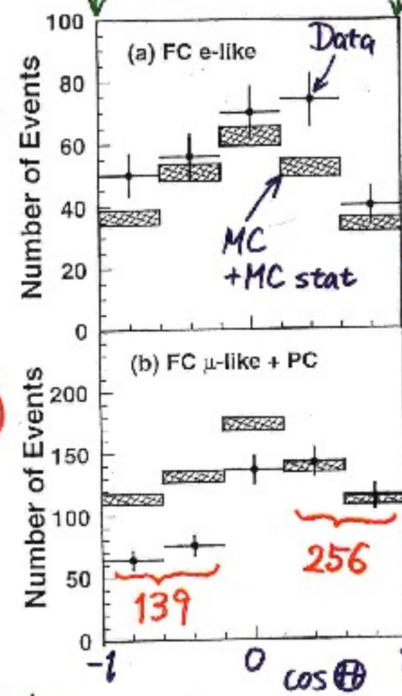
(MSW is ok for 99% C.L.)

Neutrino98
TAKAYAMA

last question:
MAJORANA

Zenith angle dependence (Multi-GeV)

Up-going Down-going



(e): $\chi^2(\text{shape}) = 2.8/4$ dof, $\frac{Up}{Down} = 0.93^{+0.13}_{-0.12}$

(μ): $\chi^2(\text{shape}) = 30/4$ dof, $\frac{Up}{Down} = 0.54^{+0.06}_{-0.05}$

(6.2σ!!)

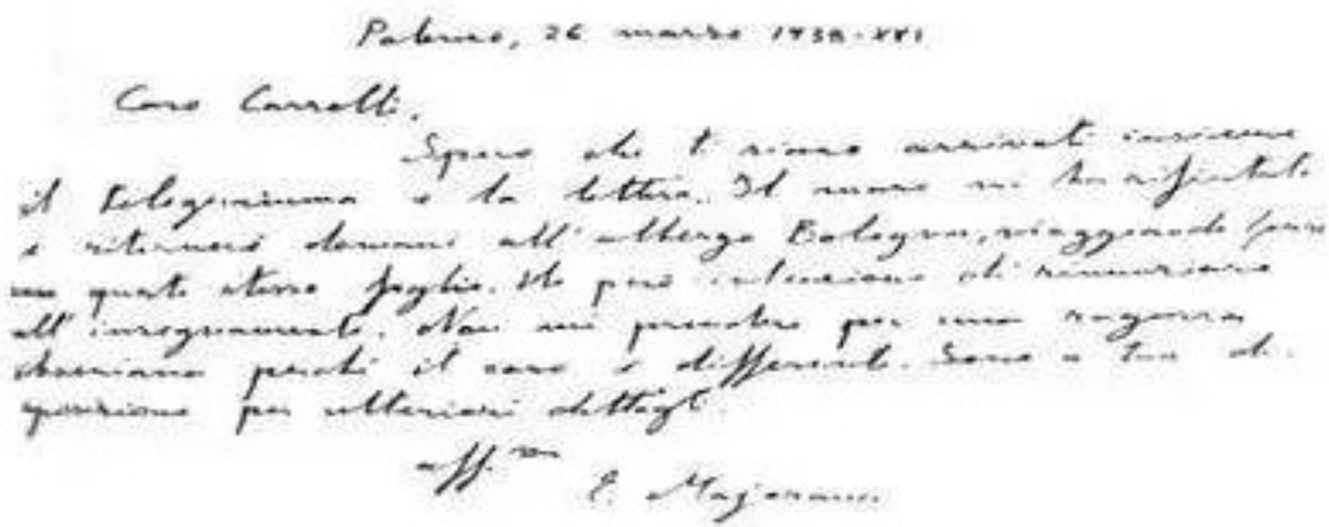
※ Up/Down syst. error for μ-like

Prediction (flux calculation …… ≲ 1%; 1km rock above SK …… 1.5%) 1.8%

Data (Energy calib. for ↑↓ …… 0.7%; Non ν Background …… < 2%) 2.1%

OUTLINE

- **A brief history: ideas and facts oscillated**
- **Salient properties of Majorana neutrinos**



Palermo, 26 marzo 1938-XVI

Caro Carrelli,
Spero che ti siano arrivati insieme il telegramma e la lettera. Il mare mi ha rifiutato e ritornerò domani all'albergo Bologna, viaggiando forse con questo stesso foglio. Ho però intenzione di rinunziare all'insegnamento. Non mi prendere per una ragazza ibseniana perché il caso è differente. Sono a tua disposizione per ulteriori dettagli.

Aff.mo
E. Majorana

Weinberg's taste

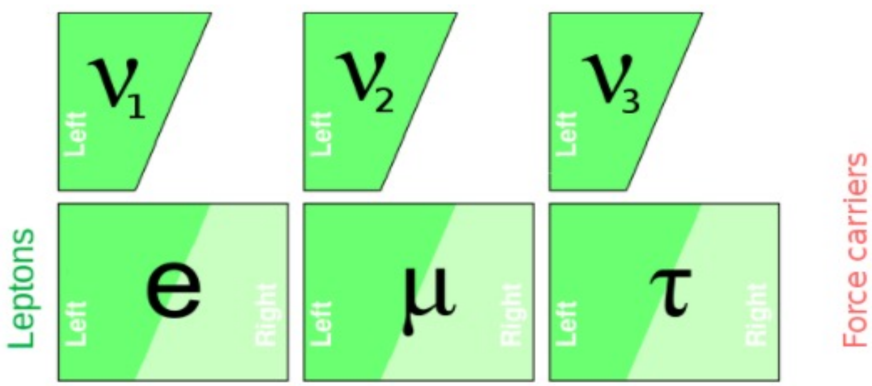
VOLUME 19, NUMBER 21 PHYSICAL REVIEW LETTERS 20 NOVEMBER 1967

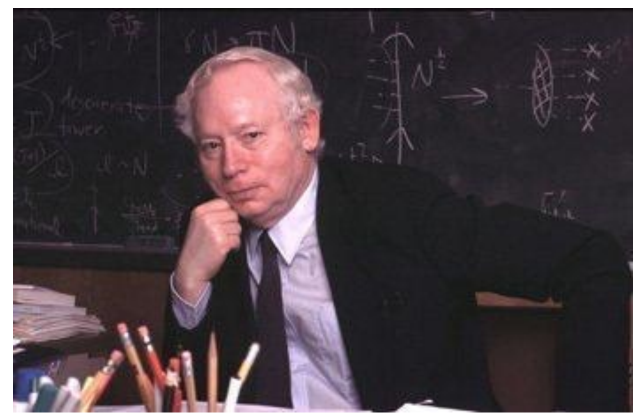
A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Theoretical ingredients: it's got what it matters（五脏俱全）

Particle content: no neutrino mass, no quarks, no flavor mixing & CPV

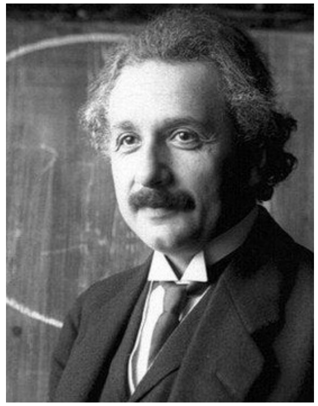




My style is usually not to propose specific models that will lead to specific experimental predictions, but rather to interpret in a broad way what is going on and make very general remarks, like with the development of the point of view associated with effective field theory ---- Weinberg 2021@CERN Courier

Go beyond the SM

Albert Einstein: **Everything should be made as simple as possible, but not simpler!**

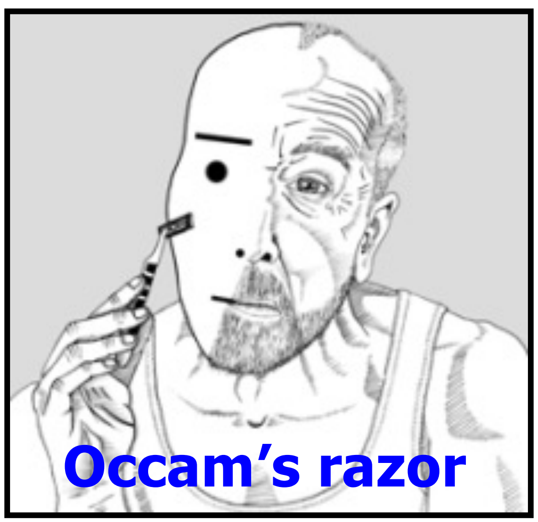


maximal P violation

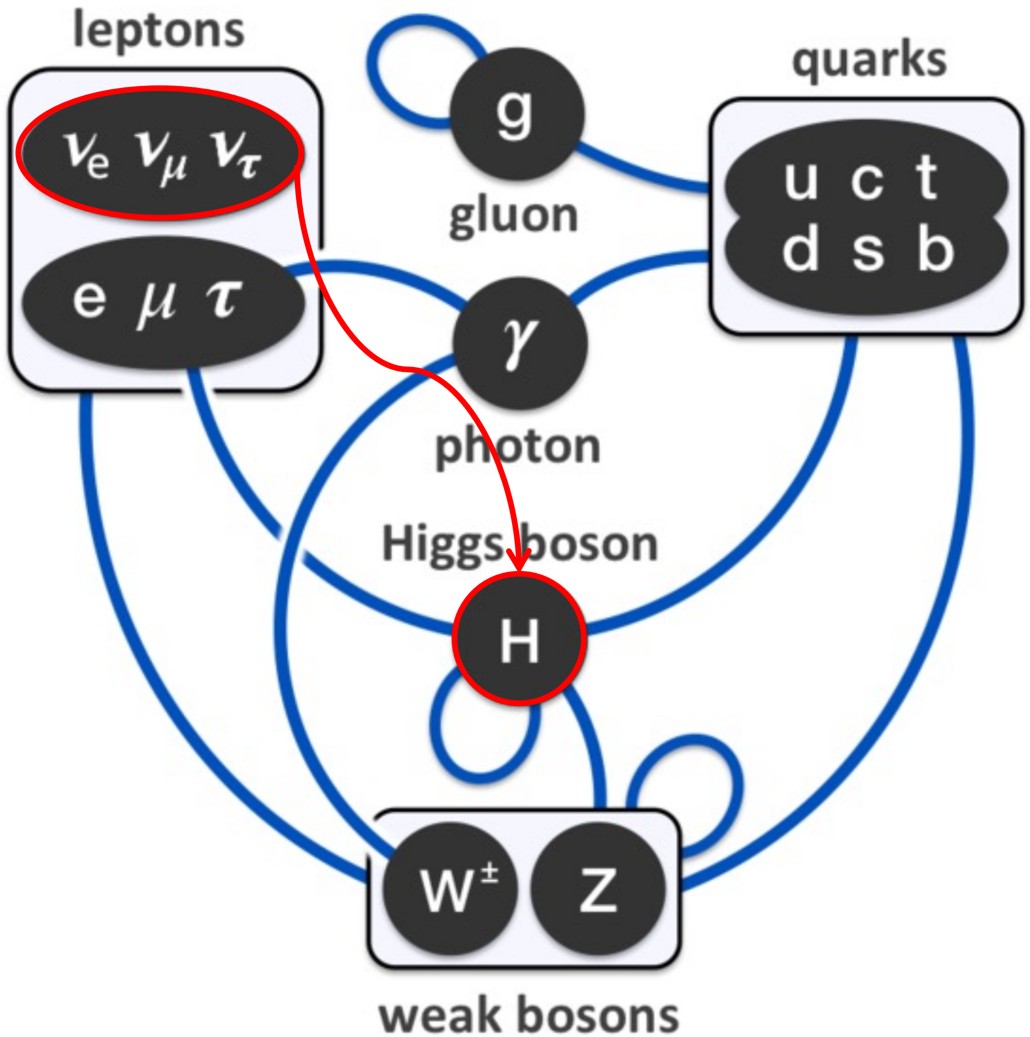
$$\begin{pmatrix} u_{\rm L} \\ d_{\rm L} \end{pmatrix} \longleftrightarrow \begin{matrix} u_{\rm R} \\ d_{\rm R} \end{matrix}$$

$$\begin{pmatrix} \nu_{e\rm L} \\ e_{\rm L} \end{pmatrix} \longleftrightarrow \begin{matrix} \bigcirc \\ e_{\rm R} \end{matrix}$$

- **Theoretically unnatural**
- **Experimentally natural**



cut off 7 physical parameters



★ **The least cost to generate ν-mass is a Yukawa coupling**

★ **Use charge-conjugated fields of left-handed ν’s? Pay with the scalar fields**

Majorana is more natural

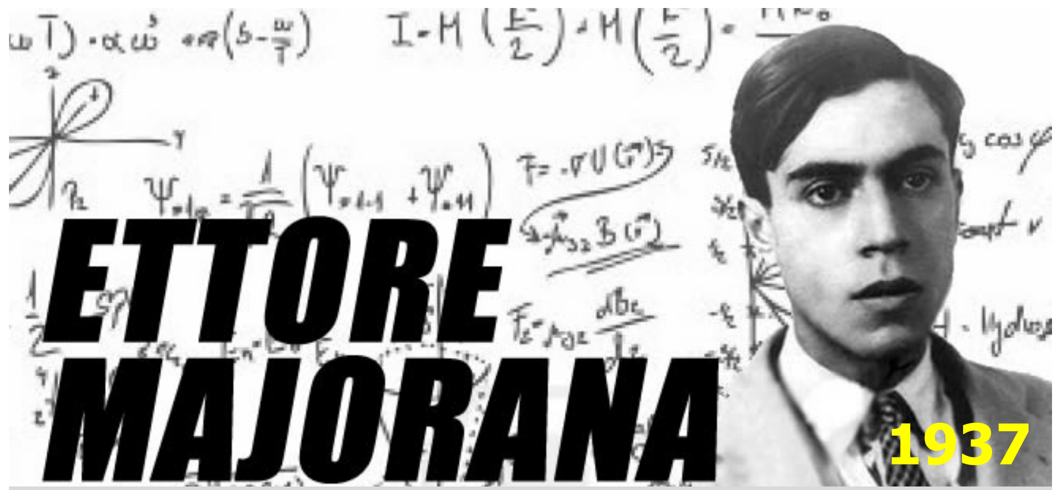
★ The simplest way to extend the SM is to introduce the right-handed neutrino fields and write out a Dirac mass term.

Dirac mass $\overline{\ell_{\rm L}} Y_\nu \widetilde{H} N_{\rm R} \longrightarrow M_{\rm D} = Y_\nu \langle H \rangle$

Murray Gell-Mann: everything not forbidden is compulsory!

Majorana mass $\frac{1}{2}\overline{N^c_{\rm R}} M_{\rm R} N_{\rm R}$

It is lepton-number-violating.



mass state: antineutrino=neutrino

In the SM, L and B are violated by instantons, only B − L is conserved.

$$-\mathcal{L}_{\nu+N} = \overline{\nu_{\rm L}} M_{\rm D} N_{\rm R} + \frac{1}{2}\overline{(N_{\rm R})^c} M_{\rm R} N_{\rm R} + {\rm h.c.} = \frac{1}{2}\overline{[\nu_{\rm L} \quad (N_{\rm R})^c]} \begin{pmatrix} 0 & M_{\rm D} \\ M_{\rm D}^T & M_{\rm R} \end{pmatrix} \begin{bmatrix} (\nu_{\rm L})^c \\ N_{\rm R} \end{bmatrix} + {\rm h.c.}$$

P. Minkowski 1977, T. Yanagida 1979: $M_\nu \simeq -M_{\rm D} M_{\rm R}^{-1} M_{\rm D}^T = -\langle H \rangle^2 Y_\nu M_{\rm R}^{-1} Y_\nu^T$

★ This **seesaw** picture is consistent with the **Weinberg** operator (1979):

$$\mathcal{O}_{\rm Weinberg} = \frac{\kappa_{\alpha\beta}}{2}\left[\overline{\ell_{\alpha \rm L}} \widetilde{H} \widetilde{H}^T \ell^c_{\beta \rm L}\right]$$

LFV and LNV

★ **Diagonalizing the 6×6 neutrino mass matrix by a 6×6 unitary matrix**

$$\begin{pmatrix} U & R \\ S & U' \end{pmatrix}^{\dagger} \begin{pmatrix} 0 & M_{\rm D} \\ M_{\rm D}^{T} & M_{\rm R} \end{pmatrix} \begin{pmatrix} U & R \\ S & U' \end{pmatrix}^{*} = \begin{pmatrix} D_{\nu} & 0 \\ 0 & D_{N} \end{pmatrix}$$

$$D_{\nu} \equiv {\rm Diag}\{m_1, m_2, m_3\}, \; D_{N} \equiv {\rm Diag}\{M_1, M_2, M_3\}$$

$$\overline{(N_{\rm R})^c} M_{\rm D}^{T} (\nu_{\rm L})^c = \left[(N_{\rm R})^T \mathcal{C} M_{\rm D}^{T} \mathcal{C} \overline{\nu_{\rm L}}^{T} \right]^T = \overline{\nu_{\rm L}} M_{\rm D} N_{\rm R}$$

Majorana mass states:

$$\nu' = \begin{bmatrix} \nu'_{\rm L} \\ (N'_{\rm R})^c \end{bmatrix} + \begin{bmatrix} (\nu'_{\rm L})^c \\ N'_{\rm R} \end{bmatrix} = \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ N_1 \\ N_2 \\ N_3 \end{pmatrix}$$

$$(\nu')^c = \nu'$$

Three flavor states are linear combinations of six mass states (LFV):

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_{\rm L} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_{\rm L} + R \begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix}_{\rm L}$$

$$UU^{\dagger} + RR^{\dagger} = I$$

★ **The standard weak charged-current interactions:**

$$-\mathcal{L}_{\rm cc} = \frac{g}{\sqrt{2}} \overline{(e \;\; \mu \;\; \tau)_{\rm L}} \, \gamma^{\mu} \left[U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_{\rm L} + R \begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix}_{\rm L} \right] W_{\mu}^{-} + {\rm h.c.}$$

global rephasing

$$\ell_{\rm L}(x) \to e^{{\rm i}\phi} \ell_{\rm L}(x)$$

$$\nu'_{\rm L}(x) \to e^{{\rm i}\phi} \nu'_{\rm L}(x)$$

LNV

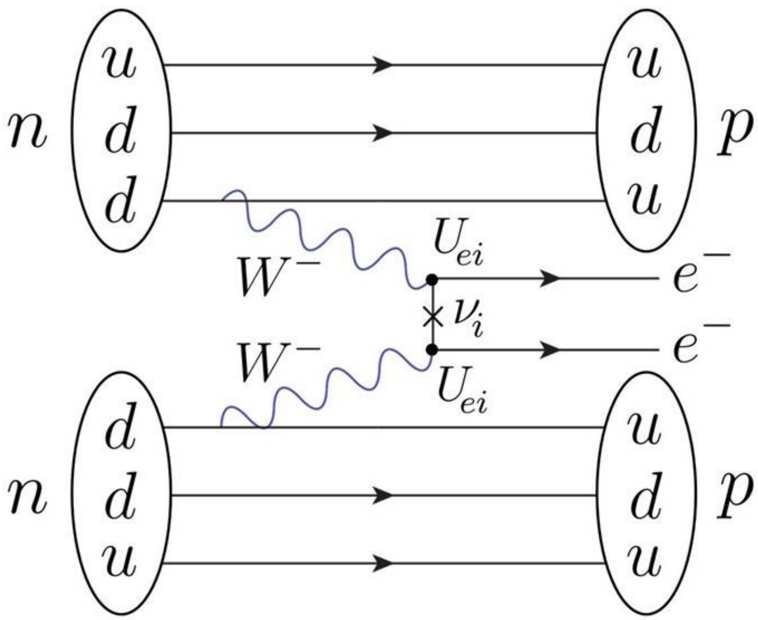
$$-\mathcal{L}'_{\nu} = \frac{1}{2} \overline{\nu'_{\rm L}} \, D_{\nu} \, (\nu'_{\rm L})^c + {\rm h.c.}$$

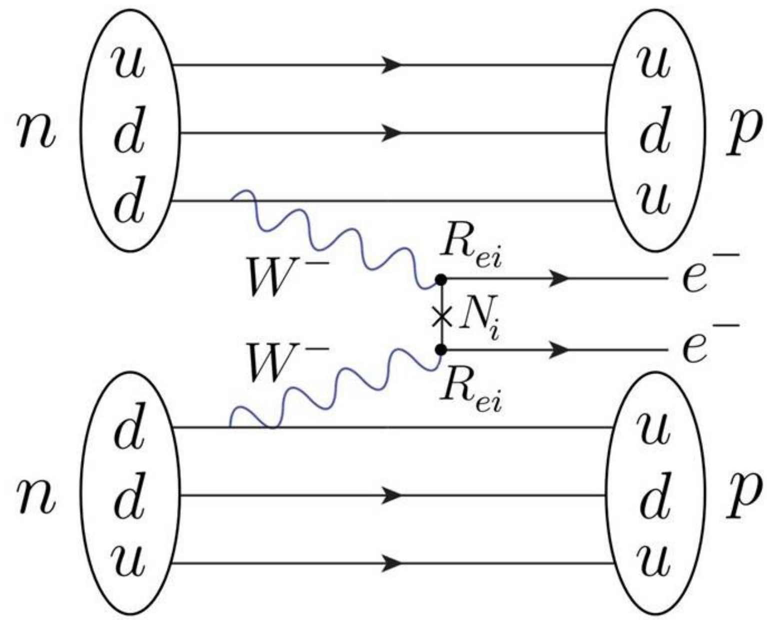
U **= non-unitary light neutrino mixing.**

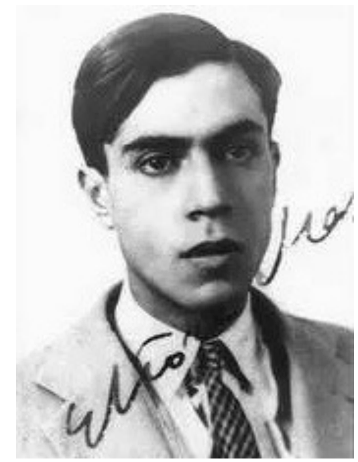
R **= small light-heavy neutrino mixing.**

$0\nu2\beta$ decays

★ **Lepton number violation (neutrinoless double-beta decays):**







★ **In most cases the contribution of heavy Majorana neutrinos to $0\nu2\beta$ is negligible in the canonical type-one seesaw.**

ZZX, arXiv:0907.3014; W. Rodejohann, 0912.3388.

$$U D_\nu U^T = -R D_N R^T$$

$$\Gamma_{0\nu2\beta} \propto \left| \sum_{i=1}^{3} m_i U_{ei}^2 - M_A^2 \sum_{i=1}^{3} \frac{R_{ei}^2}{M_i} \mathcal{F}(A, M_i) \right|^2 = \left| \sum_{i=1}^{3} M_i R_{ei}^2 \left[1 + \frac{M_A^2}{M_i^2} \mathcal{F}(A, M_i) \right] \right|^2$$

★ **There're many different lepton-number-violating scenarios for $0\nu2\beta$.**

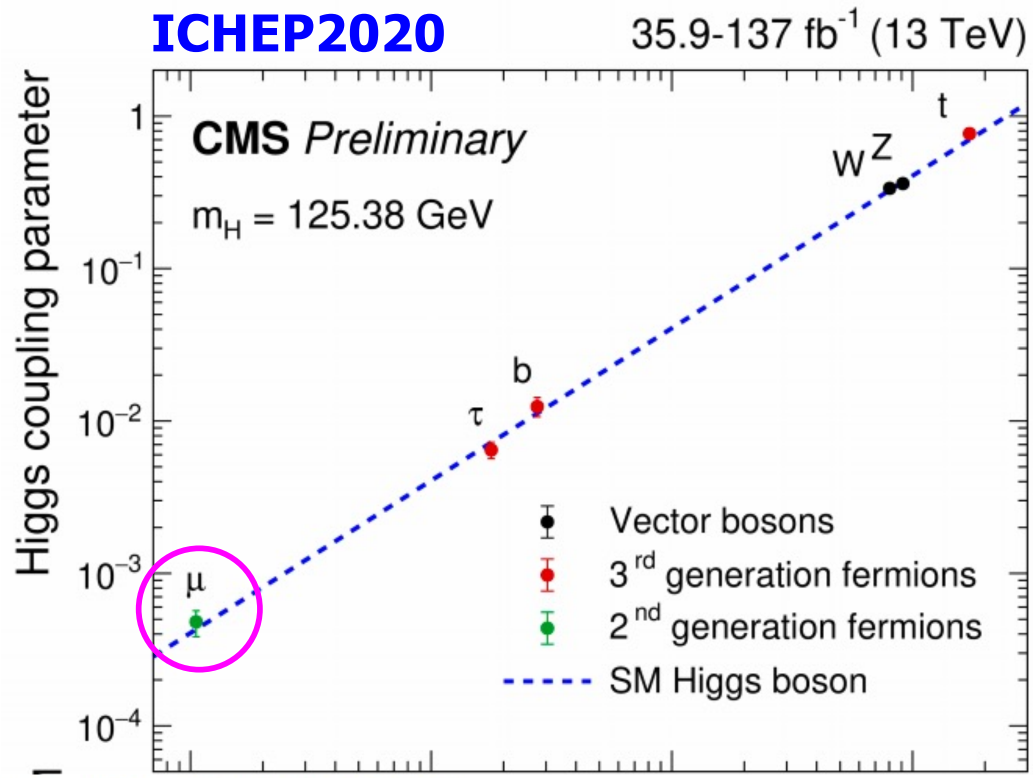
Bet on the simplest seesaw?

★ **New experimental evidence for Yukawa interactions at tree level:**

★ **So Steven Weinberg's model in 2020 seems invalid.**

★ **There is no good reason for ν's not to have a Yukawa interaction at tree level.**

★ **But it is the poor's philosophy! Many *new physics* models ...**



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Models of lepton and quark masses

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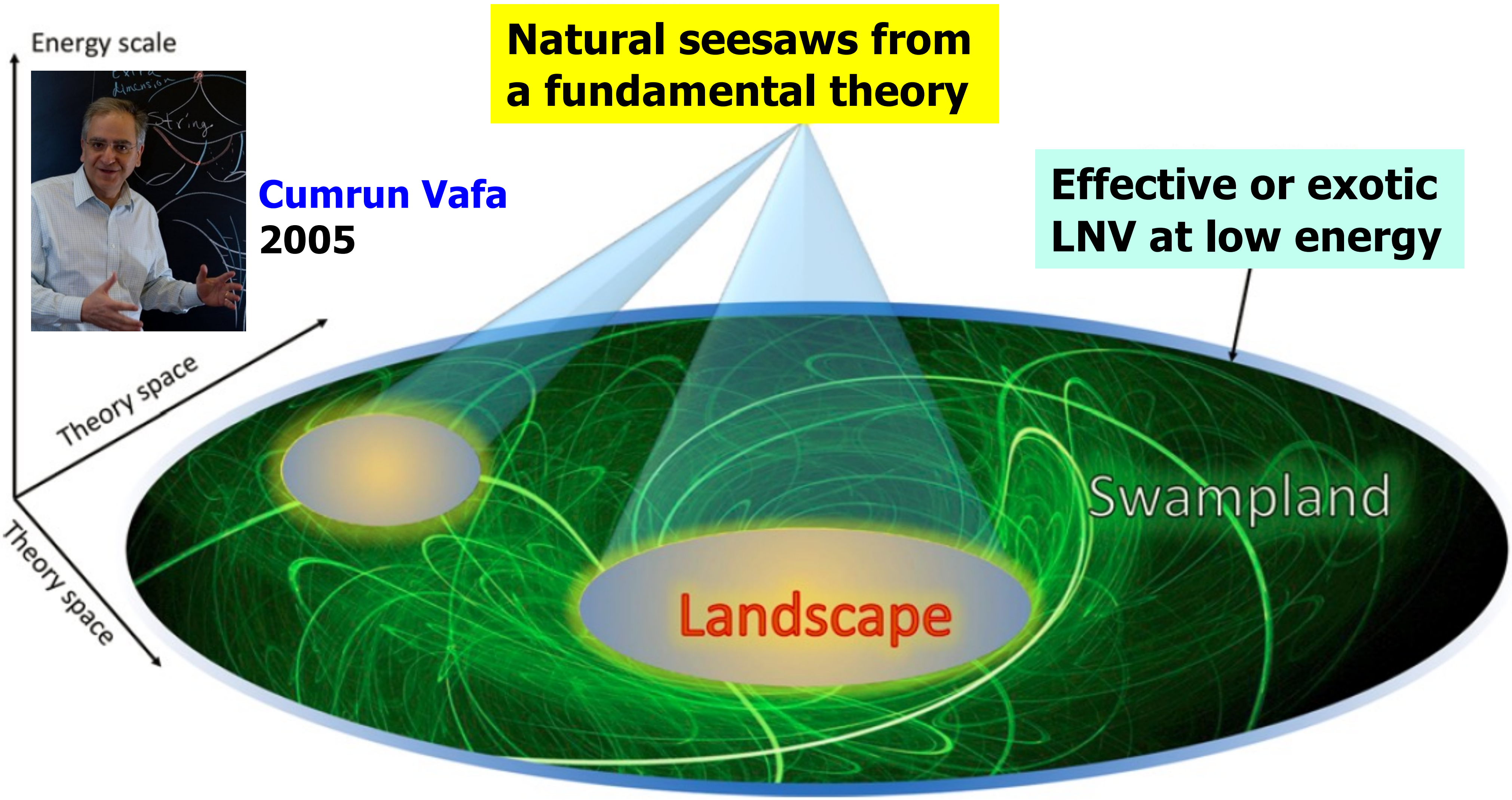
at age of 87

A class of models is considered in which the masses only of the third generation of quarks and leptons arise in the tree approximation, while masses for the second and first generations are produced respectively by one-loop and two-loop radiative corrections. So far, for various reasons, these models are not realistic.

A 0ν2β landscape or swampland

★ **Landscape**: ν-mass models originate from a complete flavor theory.

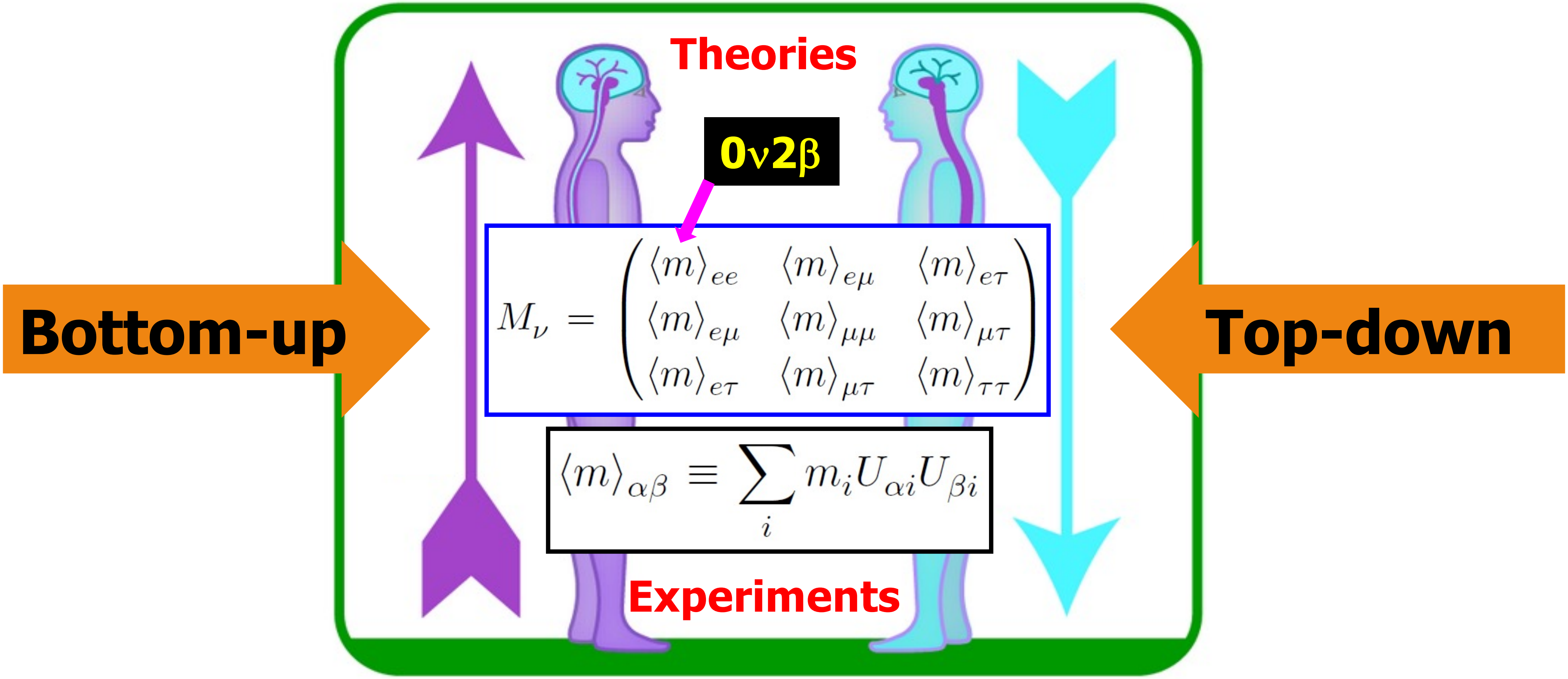
★ **Swampland**: ***new physics*** which has nothing or little to do with ν's.



★ Imprints of **new physics** models on the low-energy 0ν2β processes.

Concluding remarks

Without information on the nature of massive neutrinos (Majorana or not) and all the CP-violating phases, one will have no way to establish a full theory of ν masses and flavor mixing. Give 0ν2β a chance!

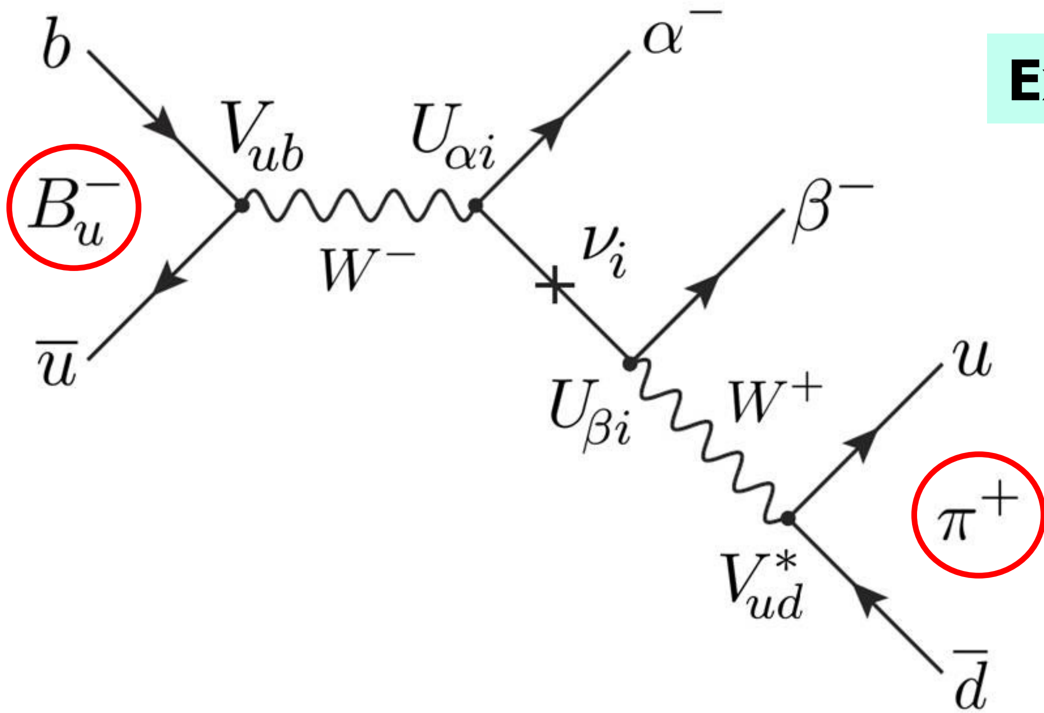


Within about 10 years, after both the neutrino mass ordering and the Dirac CP-violating phase are measured, one has to try all the possible ways to determine the absolute mass scale and two Majorana phases.

Hopeless at low energies?

There are many LNV processes, but none of them are observable?

Example



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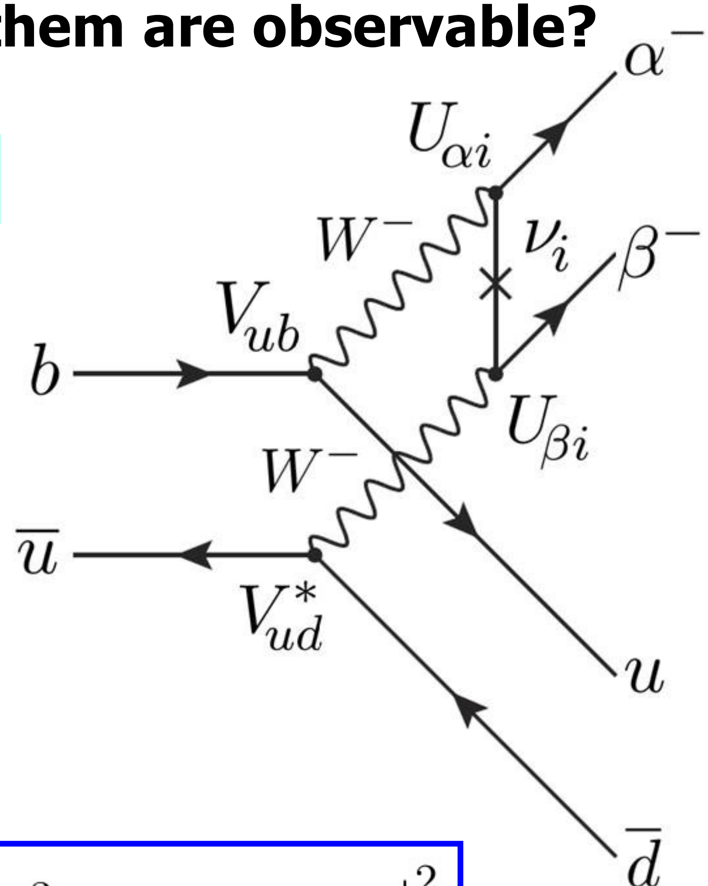

decay rates suppressed

$$\Gamma(B_u^- \to \pi^+ \alpha^- \beta^-) \propto \left|\langle m \rangle_{\alpha\beta}\right|^2 = \left|\sum_{i=1}^{3} (m_i U_{\alpha i} U_{\beta i})\right|^2$$

$$\mathcal{B}(B_u^- \to \pi^+ e^- e^-) < 2.3 \times 10^{-8} \;(\mathrm{CL} = 90\%)$$

$$\mathcal{B}(B_u^- \to \pi^+ e^- \mu^-) < 1.5 \times 10^{-7} \;(\mathrm{CL} = 90\%)$$

$$\mathcal{B}(B_u^- \to \pi^+ \mu^- \mu^-) < 4.0 \times 10^{-9} \;(\mathrm{CL} = 95\%)$$

History tells us: the fool didn't know it's impossible, so he did it and sometimes succeeded…


Majorana’s poetry and distance
Wind blow blow
Water cold cold
Strongman go go
Come back no no
风萧萧兮，易水寒，壮士一去兮，不复还