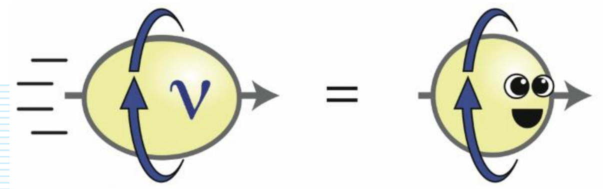
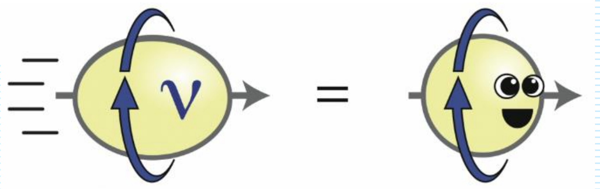
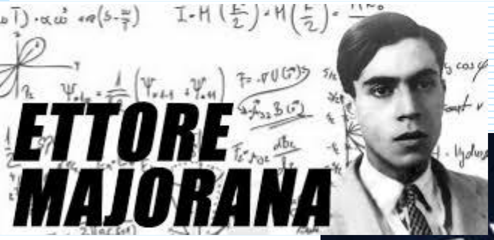


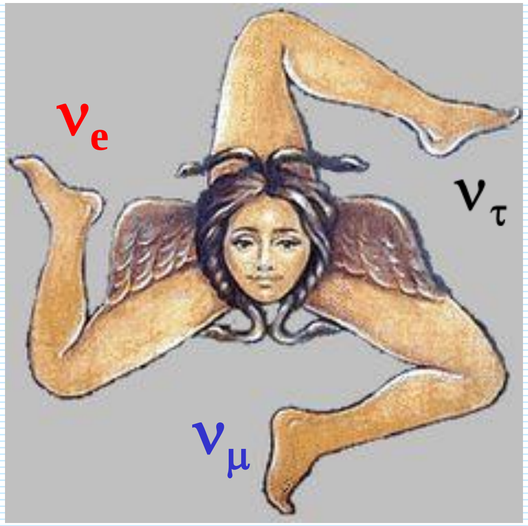
ν-oscillations revisited and 0νββ-decay

Fedor Šimkovic





OUTLINE



I. ***Introduction***

II. ***Neutrino oscillations as a single Feynman diagram***

(QFT formalism, nu-antinu oscil.)

III. ***$0\nu\beta\beta$-decay mechanisms***

(QCSS scenario, Quasi-Dirac ν)

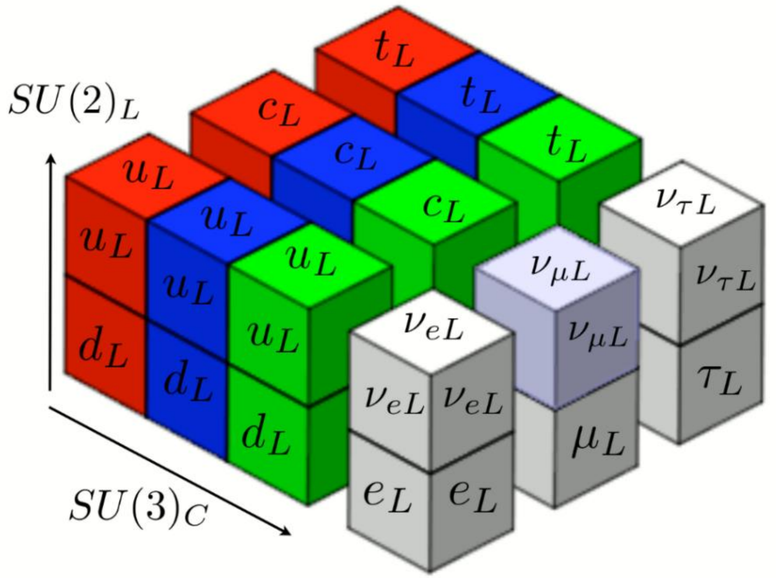
IV. ~~**Towards fixing parameters of the ν-mass matrix**~~

(2305.12378 [hep-ph], 2306.10638 [hep-ph])

V. ***Outlook***

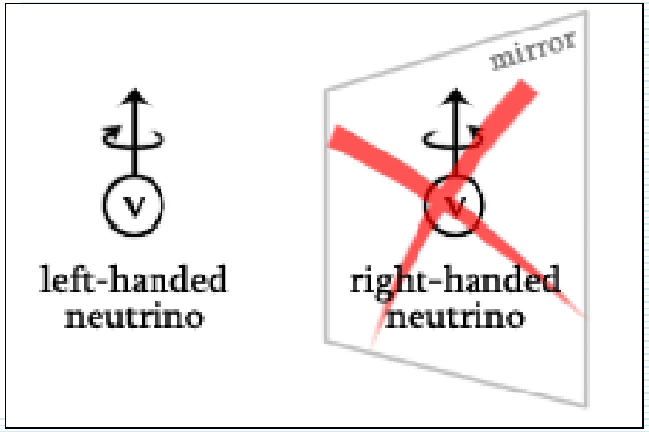
Acknowledgments: A. Khatun, S. Kovalenko, M. Krivoruchenko, A. Smetana, and other colleagues and friends.

Standard Model
(an astonishing successful theory,
based on few principles)



ν is a special particle in SM:

- **It is the only fermion that does not carry electric charge (like γ, g, H^0)**
- **There are only left-handed ν's (ν_{eL}, $\nu_{\mu L}$, $\nu_{\tau L}$)**
- **ν-mass can not be generated with any renormalizable coupling with the Higgs fields through SSB**



ν's oscillations experiments
⇒ tiny neutrino masses (!)
⇒ Beyond SM physics (!)

Super-K, SNO, KamLAND, Double Chooz, Daya Bay, RENO, T2K, NOvA

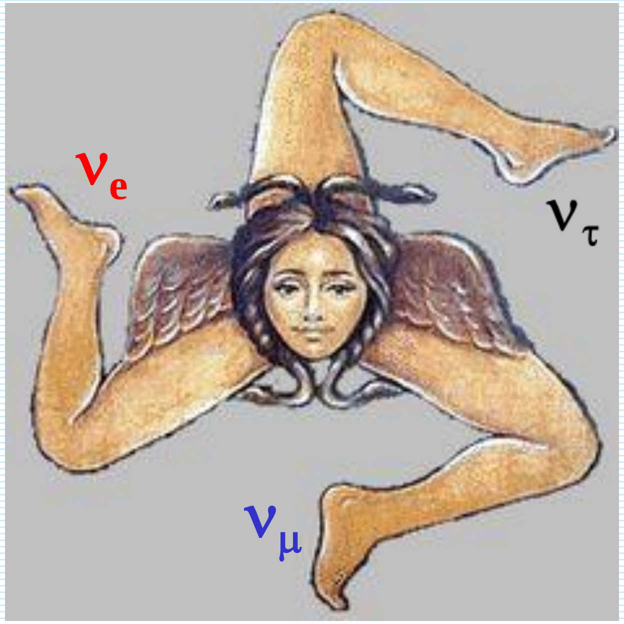
, etc

After 93/67 years we know

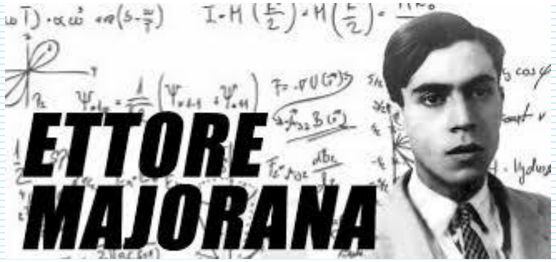
Fundamental ν properties

No answer yet

- 3 families of light (V-A) neutrinos: ν_e, ν_μ, ν_τ
- ν are massive: we know mass squared differences
- relation between flavor states and mass states (neutrino mixing)

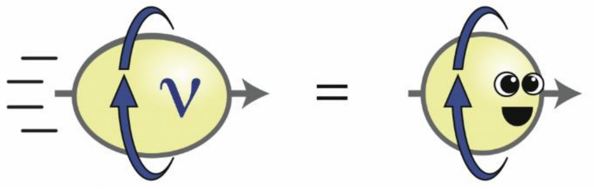


- Are ν Dirac or Majorana?
- Is there a CP violation in ν sector?
- Are neutrinos stable?
- What is the magnetic moment of ν?
- Sterile neutrinos?
- Statistical properties of ν? Fermionic or partly bosonic?



Currently main issue

Nature, Mass hierarchy,
CP-properties, sterile ν



The observation of neutrino oscillations has opened a new excited era in neutrino physics and represents a big step forward in our knowledge of neutrino properties

Majorana fermions

Ettore Majorana

Teoria simmetrica dell'elettrone e del positrone (A symmetric theory of electrons and positrons).

Il Nuovo Cimento, 14: 171–184, 1937.) 171

ν is its own antiparticle

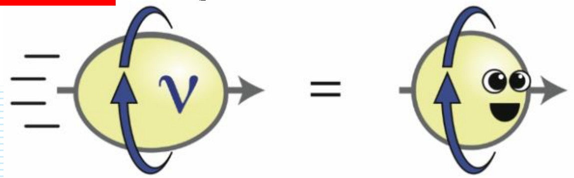
It follows from the above assumptions that in vacuum a neutrino can be transformed into an antineutrino and vice versa. This means that the neutrino and antineutrino are "mixed" particles, i.e., a symmetric and antisymmetric combination of two truly neutral Majorana particles ν_1 and ν_2 of different combined parity.[5]

Bruno Pontecorvo

Inverse beta processes and nonconservation of lepton charge

Zhur. Eksptl'. i Teoret. Fiz. 34, 247 (1958)

ν ↔ anti-ν oscillation



INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

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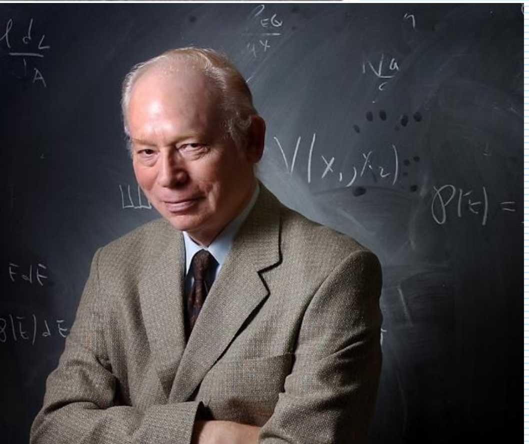


Steve Weinberg

ν-mass generation via d=5 eff. oper. related to unknown high energy scale (GUT?)

thought massless back in 1979. Weinberg does not take credit for predicting neutrino masses, but he thinks it's the right interpretation. What's more, he says, the non-renormalisable interaction that produces the neutrino masses is probably also accompanied with non-renormalisable interactions that produce proton decay and other things that haven't been observed, such as violation of baryon-number conservations. "We don't know anything about the details of those terms, but I'll swear they are there."

$$R_{12} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad R_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{12} & s_{12} \\ 0 & -s_{12} & c_{12} \end{pmatrix}$$

$$\tilde{R}_{13} = \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta} & 0 & c_{13} \end{pmatrix}$$

3 neutrino masses, 2 mass squared differences

$$\delta m^2 = m_2^2 - m_1^2, \quad \Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$$

$$U = R_{23} \tilde{R}_{13} R_{12}$$

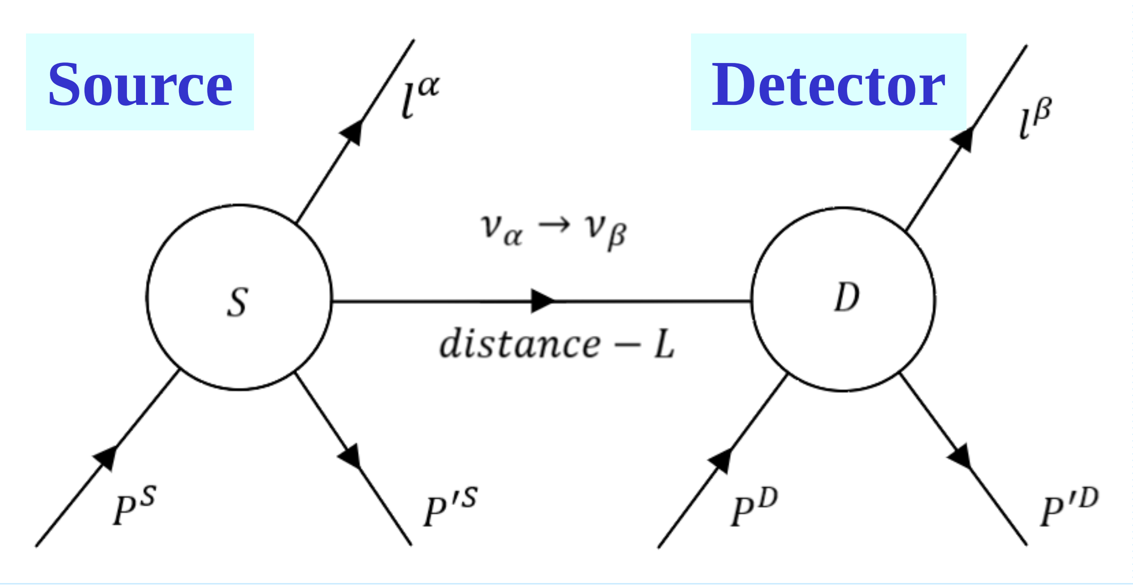
3 mixing angles
CP-phase

$$|\nu_\alpha\rangle = \sum_{j=1}^{3} U^*_{\alpha j} |\nu_j\rangle \quad (\alpha = e,\ \mu, \tau)$$

Global neutrino oscillations analysis
(PRD 101, 116013 (2020))

	best − fit	1σ	2σ	3σ
Normal hierarchy (NH)				
$\delta m^2/10^{-5}$ eV^2	7.34	7.20-7.51	7.05-7.69	6.92-7.90
$\Delta m^2/10^{-3}$ eV^2	2.485	2.453-2.514	2.419-2.547	2.2389-2.578
$\sin^2\theta_{12}/10^{-1}$	3.05	2.92-3.19	2.78-3.32	2.65-3.47
$\sin^2\theta_{13}/10^{-2}$	2.22	2.14-2.28	2.07-2.34	2.01-2.41
$\sin^2\theta_{23}/10^{-1}$	5.45	4.98-5.65	4.54-5.81	4.36-5.95
δ/π	1.28	1.10-1.66	0.95-1.90	0-0.07 $\oplus$ 0.81-2.00
Inverted hierarchy (IH)				
$\delta m^2/10^{-5}$ eV^2	7.34	7.20-7.51	7.05-7.69	6.92-7.91
$-\Delta m^2/10^{-3}$ eV^2	2.465	2.434-2.495	2.404-2.526	2.374-2.556
$\sin^2\theta_{12}/10^{-1}$	3.03	2.90-3.17	2.77-3.31	2.64-3.45
$\sin^2\theta_{13}/10^{-2}$	2.23	2.17-2.30	2.10-2.37	2.03-2.43
$\sin^2\theta_{23}/10^{-1}$	5.51	5.17-5.67 $\oplus$ 5.31-6.10	4.60-5.82	4.39-5.96
δ/π	1.52	1.37-1.65	1.23-1.78	1.09-1.90

Neutrino oscillations
(Quantum Mechanics Approach)



Massive neutrinos and neutrino oscillations

S. M. Bilenky

Joint Institute of Nuclear Research, Dubna, Union of Soviet Socialist Republics

S. T. Petcov

Institute of Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, 1784 Sofia, People's Republic of Bulgaria

The theory of neutrino mixing and neutrino oscillations, as well as the properties of massive neutrinos (Dirac and Majorana), are reviewed. More specifically, the following topics are discussed in detail: (i) the possible types of neutrino mass terms; (ii) oscillations of neutrinos (iii) the implications of *CP* invariance for the mixing and oscillations of neutrinos in vacuum; (iv) possible varieties of massive neutrinos (Dirac, Majorana, pseudo-Dirac); (v) the physical differences between massive Dirac and massive Majorana neutrinos and the possibilities of distinguishing experimentally between them; (vi) the electromagnetic properties of massive neutrinos. Some of the proposed mechanisms of neutrino mass generation in gauge theories of the electroweak interaction and in grand unified theories are also discussed. The lepton number nonconserving processes $\mu \to e\gamma$ and $\mu \to 3e$ in theories with massive neutrinos are considered. The basic elements of the theory of neutrinoless double-β decay are discussed as well. Finally, the existing data on neutrino masses, oscillations of neutrinos, and neutrinoless double-β decay are briefly reviewed. The main emphasis in the review is on the general model-independent results of the theory. Detailed derivations of these are presented.

$$S \to S' + \ell_\alpha^+ + \nu_\alpha$$

$$\nu_\alpha \to \nu_\beta$$

$$\nu_\beta + D \to D' + \ell_\beta^-$$

$$\Gamma_{osc} = \int \frac{d\Phi_\nu(E_\nu)}{dE_\nu} \frac{\mathcal{P}_{\alpha\beta}(E_\nu, L)}{4\pi L^2} \sigma(E_\nu)\, dE_\nu$$

Rev. Mod. Phys. 59, 671 (1987)
961 citations (inspire hep)

Process is governed by the oscillation probability

$$S + D \to \ell_\alpha^+ + \ell_\beta^- + S' + D'$$

$$\mathcal{P}_{\alpha\beta}(E_\nu, L) = \left| \sum_{j=1}^{3} U_{\alpha j}^* U_{\beta j} e^{-i\, m_j^2\, L/(2E_\nu)} \right|^2$$

$$\langle f|S^{(2)}|i\rangle = -i \int d^4x_1 J_S^{\mu}(P'_S, P_S) e^{i(P_\alpha + P'_S - P_S)\cdot x_1} \times$$

$$\int d^4x_2 J_D^{\mu}(P'_D, P_D) e^{i(P_\beta + P'_D - P_D)\cdot x_2} \sum_{k=1}^{3} U^*_{\alpha k} U_{\beta k} \times$$

$$\overline{v}(P_\alpha;\lambda_\alpha)\gamma_\mu(1-\gamma_5)\ D(x_2 - x_1, m_k)\ (1-\gamma_5)\gamma_\nu u(P_\beta;\lambda_\beta)$$

Neutrino oscillations as a single Feynman diagram

(within QFT, Walter Grimus approach revisited)

e-Print: *2212.13635* [hep-ph]

The neutrino emission and detection are identified with the charged-current vertices of a single second-order Feynman diagram for the underlying process, enclosing neutrino propagation between these two points.

$$D(x;m) = \theta(x_0) D^-(x;m) + \theta(-x_0) D^+(x;m),$$

$$D^{\pm}(x;m) = \int \frac{d\mathbf{q}}{(2\pi)^3} \frac{\mp(-\mathbf{q}\cdot\vec{\gamma} + \omega\gamma^0) + m}{2\omega} e^{\pm i(-\mathbf{q}\cdot\mathbf{x} + \omega x_0)}$$

Integration over time variables results in energy conservation and energy denominator

$$2\pi i \frac{\delta(E_\beta + E'_D - E_D + E_\alpha + E'_S - E_S)}{\omega + E_\alpha + E'_S - E_S + i\varepsilon}.$$

Neutrino propagation

$$\int \frac{d\mathbf{q}}{(2\pi)^3} \frac{\not{p} + m_k}{2\omega(\omega + E_\alpha + E'_S - E_S + i\varepsilon)} e^{i\mathbf{q}\cdot(\mathbf{x}_2 - \mathbf{x}_1)}$$

$$\simeq \frac{1}{4\pi} \frac{e^{ip_k|\mathbf{x}_2 - \mathbf{x}_1|}}{|\mathbf{x}_2 - \mathbf{x}_1|} \ (\not{Q}_k + m_k) \simeq e^{i\mathbf{p}_k\cdot\mathbf{x}_D} \ e^{-i\mathbf{p}_k\cdot\mathbf{x}_S} \ \frac{e^{ip_k L}}{L} \ (\not{Q}_k + m_k)$$

$$Q_k \equiv (E_\nu, \mathbf{p}_k), \quad \mathbf{p}_k = p_k\,(\mathbf{x}_2 - \mathbf{x}_1)\,/|\mathbf{x}_2 - \mathbf{x}_1|, \quad p_k = \sqrt{E_\nu^2 - m_k^2}$$

$$E_\nu = E_S - E'_S - E_\alpha \ (source) = E_\beta + E'_D - E_D \ (detector)$$

Energy conservation

Amplitude (there is no factorization of source and detector!)

Momentum conservation at source

Momentum conservation at detector

Energy conservation

$$\langle f|S^{(2)}|i\rangle = (2\pi)^7 \delta(E_f - E_i) \sum_k U_{\alpha k} U^*_{\beta k} \frac{e^{ip_k L}}{4\pi L} \times$$

$$T_k^{\alpha\beta} \; \delta^3_{V_S}(\mathbf{p}_k + \mathbf{p}_\alpha + \mathbf{p}'_S - \mathbf{p}_S) \; \delta^3_{V_D}(\mathbf{p}_\beta + \mathbf{p}'_D - \mathbf{p}_D - \mathbf{p}_k)$$

with

$$E_f - E_i = E_\beta + E'_D - E_D + E_\alpha + E'_S - E_S$$

$$T_k^{\alpha\beta} = J^\mu_S(P'_S, P_S) J^\nu_D(P'_D, P_D) \; \overline{v}(P_\alpha; \lambda_\alpha)\gamma_\mu(1-\gamma_5) \; \not{Q}_k \; \gamma_\nu u(P_\beta; \lambda_\beta)$$

Lepton current

Master formula

$$d\Gamma^{\alpha\beta}(L) = \sum_{km} U_{\alpha k} U^*_{\beta k} U_{\alpha m} U^*_{\beta m} \frac{e^{i(p_k - p_m)L}}{4\pi L^2} \times \mathcal{F}^{\alpha\beta}_{km}$$

$$\delta(\mathbf{p}_k + \mathbf{p}_\alpha + \mathbf{p}'_S - \mathbf{p}_S)\delta(\mathbf{p}_\beta + \mathbf{p}'_D - \mathbf{p}_D - \mathbf{p}_m)$$

$$\frac{(2\pi)^7}{4E_S E_D} \delta(E_\beta + E'_D - E_D + E_\alpha + E'_S - E_S)\times$$

$$\frac{1}{\hat{J}_S \hat{J}_D} \frac{d\mathbf{p}_\alpha}{2E_\alpha\ (2\pi)^3} \frac{d\mathbf{p}_\beta}{2E_\beta\ (2\pi)^3} \frac{d\mathbf{p}'_S}{2E'_S\ (2\pi)^3} \frac{d\mathbf{p}'_D}{2E'_D\ (2\pi)^3}$$

with

$$\mathcal{F}^{\alpha\beta}_{km} = 4\pi \sum_{\text{spin}} \frac{1}{2} \left(T^{\alpha\beta}_k \left(T^{\alpha\beta}_m\right)^* + T^{\alpha\beta}_m \left(T^{\alpha\beta}_k\right)^* \right)$$

$$\langle \Phi^{S,D}(\mathbf{P}_i) | \Phi^{S,D}(\mathbf{P}_k) \rangle = (2\pi)^3\ 2E_k\ \delta^3_{V_{S,D}}\ (\mathbf{P}_i - \mathbf{P}_k)$$

Two normalization volumes:

i) source;

ii) Detector.

$$\delta^3_V(\mathbf{Q}_n - \mathbf{P})\ \delta^3_V(\mathbf{Q}_m - \mathbf{P}) \simeq \frac{V}{(2\pi)^3} \frac{1}{2} \left(\delta^3_V(\mathbf{Q}_n - \mathbf{P}) + \delta^3_V(\mathbf{Q}_m - \mathbf{P}) \right)$$

An example:

e-Print: 2212.13635 [hep-ph]

$$\pi^+ + n \to \mu^+ + e^- + p$$

$$\pi^+ \to \mu^+ + \nu_\mu, \quad \nu_\mu \to \nu_e, \quad \nu_e + n \to p + e^-$$

$$\Gamma^{\pi^+ n}_{osc} = \int \frac{d\Phi_\nu(E'_\nu)}{dE'_\nu} \frac{\mathcal{P}_{\nu_\mu \nu_e}(E'_\nu)}{4\pi L^2} \sigma(E'_\nu)\, dE'_\nu$$

$$= \frac{1}{2\pi^2} G_\beta^2 \left(\frac{f_\pi}{\sqrt{2}}\right)^2 \frac{m_\mu^2}{m_\pi} E_\nu^2 \frac{P_{\nu_\mu \nu_e}(E_\nu)}{4\pi L^2} (g_V^2 + 3g_A^2)\ p_e E_e$$

with

$$\mathcal{P}_{\alpha\beta}(E_\nu, L) = \left|\sum_{j=1}^{3} U^*_{\alpha j} U_{\beta j} e^{-i m_j^2 L/(2E_\nu)}\right|^2$$

Standard QM approach

New QFT approach (no decoherence, no factorization of two processes)

$$\Gamma^{\pi^+ n}_{QFT} = \frac{1}{2\pi^2} G_\beta^2 \left(\frac{f_\pi}{\sqrt{2}}\right)^2 \frac{m_\mu^2}{m_\pi} E_\nu^2 \frac{\mathcal{P}^{QFT}_{\mu e}(E_\nu)}{4\pi L^2} (g_V^2 + 3g_A^2)\ p_e E_e$$

with

$$\mathcal{P}^{QFT}_{\alpha\beta}(E_\nu) = \frac{1}{2} \sum_{km} U_{\beta k} U^*_{\alpha k}\ U^*_{\beta k} U_{\alpha k}\ e^{i(p_m - p_k)L} \left(1 + \frac{p_k p_m}{E_\nu^2}\right)$$

Nuovo Cim. 14, 322 (1937)

neutrino ↔ antineutrinos oscillations

Second order process with real intermediate neutrinos

$$S + D \to \ell_\alpha^+ + \ell_\beta^+ + S' + D'$$

$$S \to S' + \ell_\alpha^+ + \nu_\alpha, \;\; \nu_\alpha \to \overline{\nu}_\beta, \;\; \overline{\nu}_\beta + D \to D' + \ell_\beta^+$$

Amplitude proportional to ν–mass

$$T_k^{\alpha\beta} = J_S^\mu(P'_S, P_S) J_D^\nu(P'_D, P_D) \times \overline{v}(P_\alpha;\lambda_\alpha)\gamma_\mu(1-\gamma_5) m_k \gamma_\nu u(P_\beta;\lambda_\beta)$$

Oscillation probability

$$\mathcal{P}_{\alpha\bar{\beta}}^{\text{QFT}}(E_\nu, L) \equiv |\langle \nu_\beta | \overline{\nu}_\alpha \rangle|^2 = \left| \sum_{j=1}^{3} U_{\alpha j}^* U_{\beta j}^* \frac{m_j}{E_\nu} e^{-i m_j^2 L/(2E_\nu)} \right|^2$$

Replacement:

$$U_{\alpha k} \to U_{\alpha k}^*$$
$$U_{\beta m}^* \to U_{\beta m}$$

Particular process:

$$\pi^+ + p \to \mu^+ + e^+ + n$$

Production rate

$$\Gamma_{QFT}^{\pi^+ p} = \frac{1}{2\pi^2} G_\beta^2 \left(\frac{f_\pi}{\sqrt{2}} \right)^2 \frac{m_\mu^2}{m_\pi} E_\nu^2 \frac{P_{\nu_\mu \overline{\nu}_e}^{\text{QFT}}(E_\nu, L)}{4\pi L^2} (g_V^2 + 3g_A^2) \; p_e E_e$$

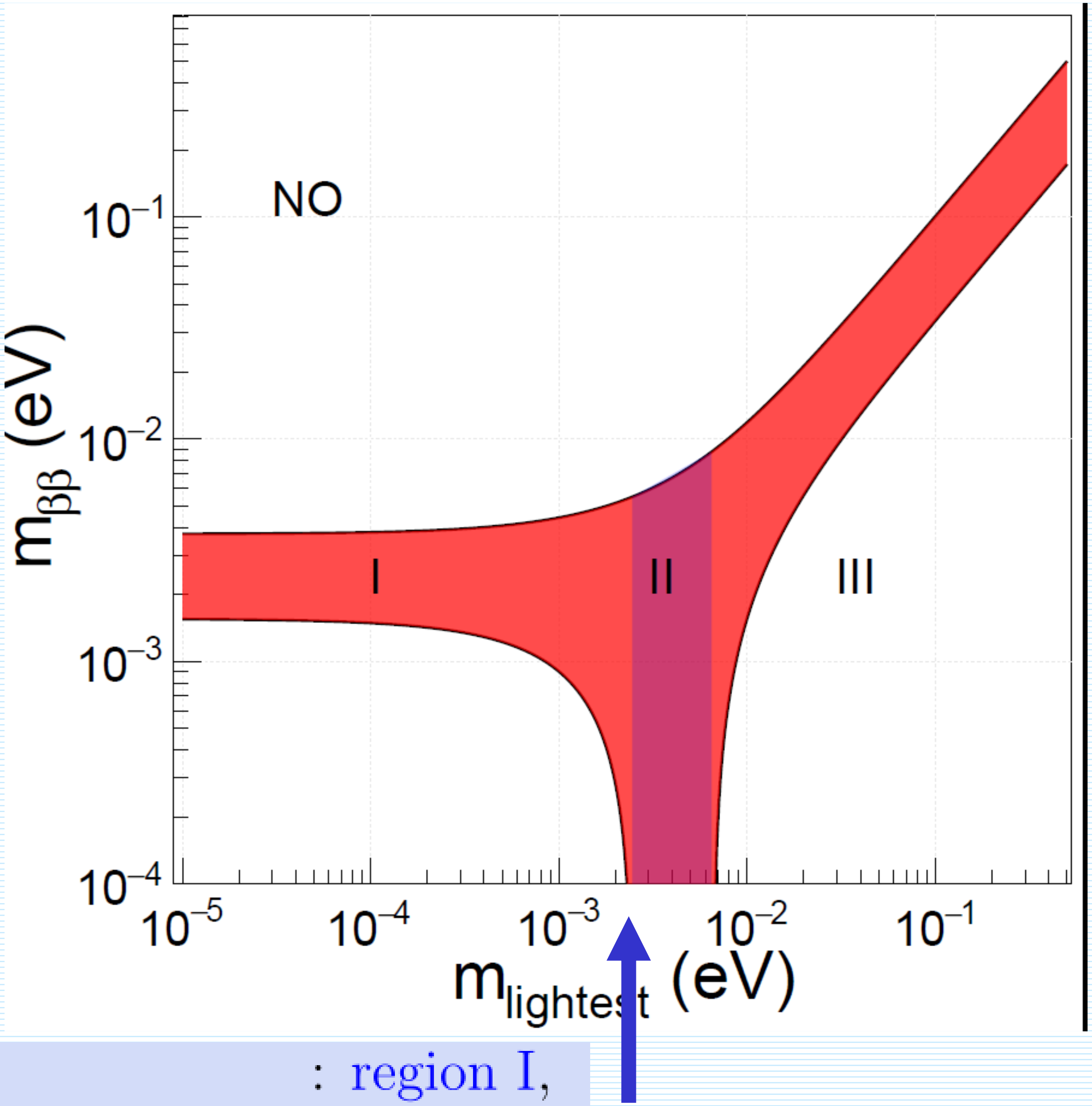
Effective Majorana mass $m_{\beta\beta}$ can be strongly suppressed (?!) …

For L=0

$$\mathcal{P}_{\alpha\bar{\beta}}(E_\nu, L=0) = \frac{m_{\beta\beta}^2}{E_\nu^2} = \frac{1}{E_\nu^2}\left|\sum_{j=1}^{3} U_{\alpha j}U_{\beta j}m_j\right|^2$$

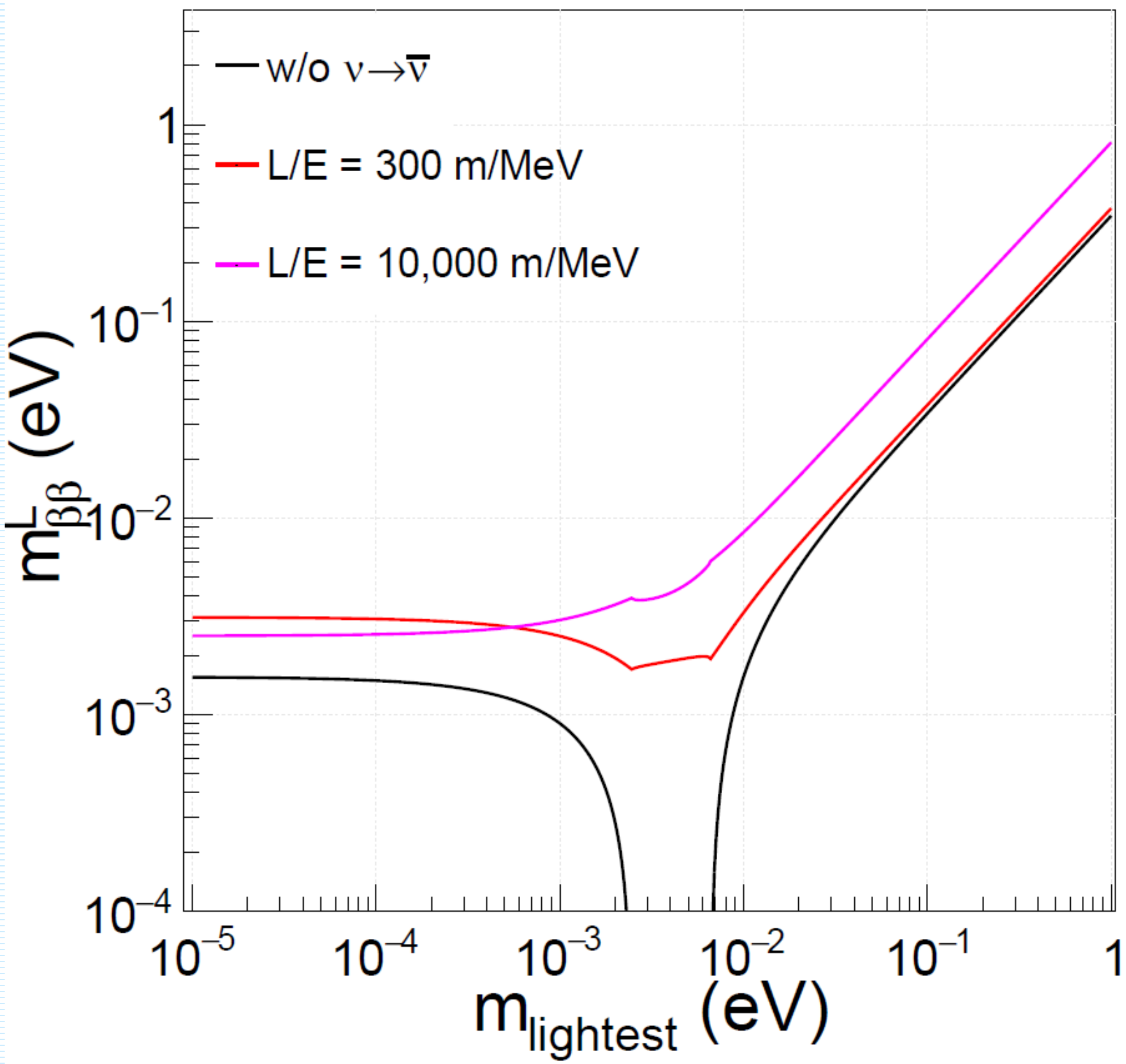
$$m_{\beta\beta} = |\rho_1 e^{2i\phi_1} + \rho_2 e^{2i\phi_2} + \rho_3|$$

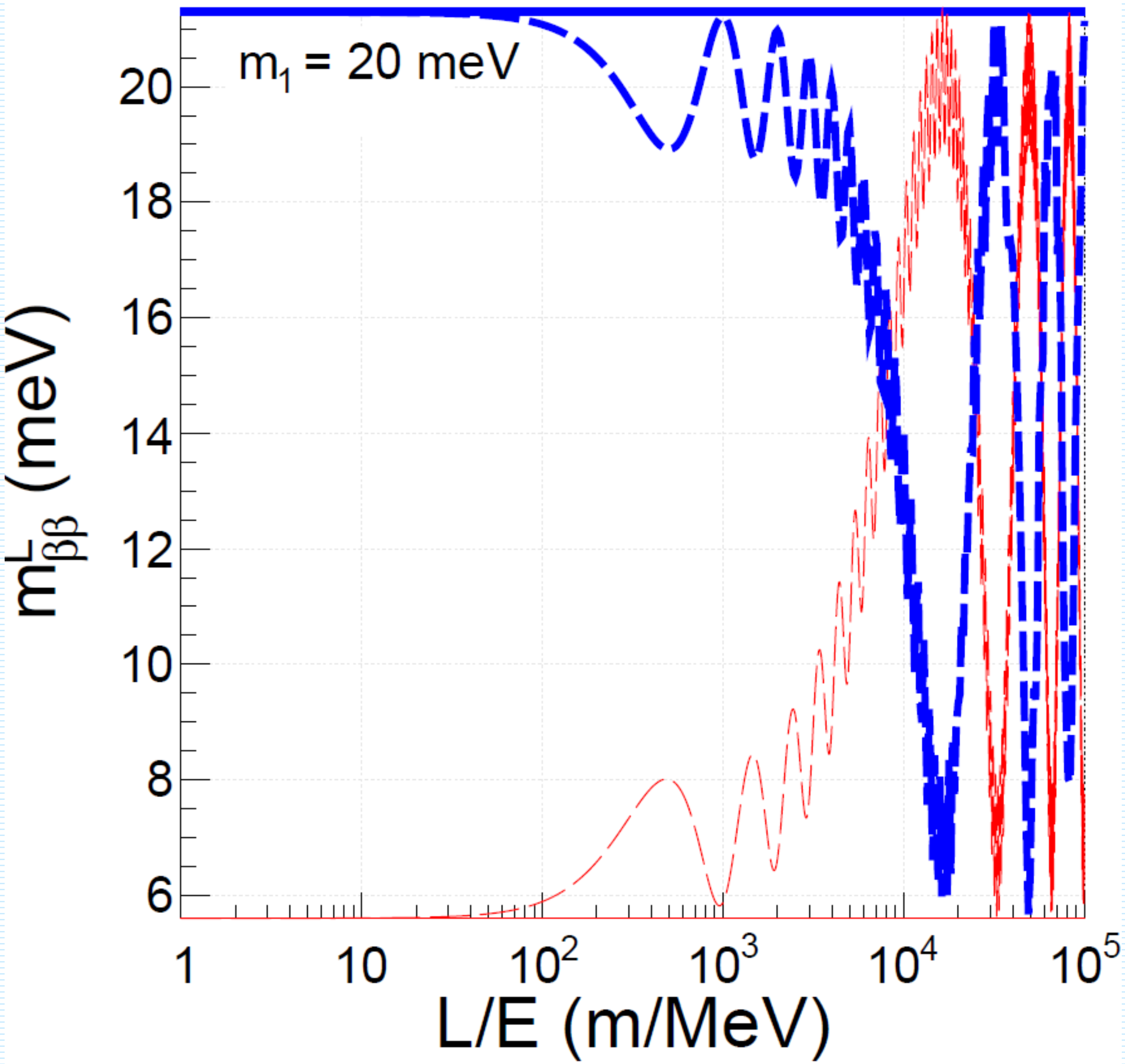
$$\rho_1 = c_{12}^2 c_{13}^2 m_1,\ \rho_2 = s_{12}^2 c_{13}^2 m_2,\ \rho_3 = s_{13}^2 m_3$$



$$\min_{\phi_1,\phi_2} m_{\beta\beta} = \begin{cases} |\rho_2-\rho_3|-\rho_1, & \text{if } \rho_1 < |\rho_2-\rho_3| \quad : \text{region I}, \\ 0, & \text{if } |\rho_2-\rho_3| \le \rho_1 \le \rho_2+\rho_3 \quad : \text{region II}, \\ \rho_1-(\rho_2+\rho_3), & \text{if } \rho_2+\rho_3 < \rho_1 \quad : \text{region III}. \end{cases}$$

Dependence of m^L_{ee} on $m_{lightest}$ and L/E

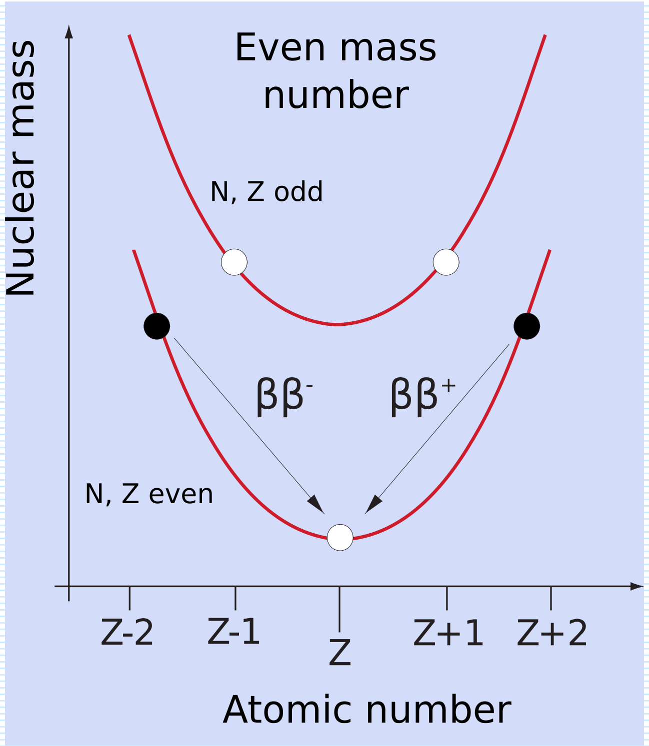


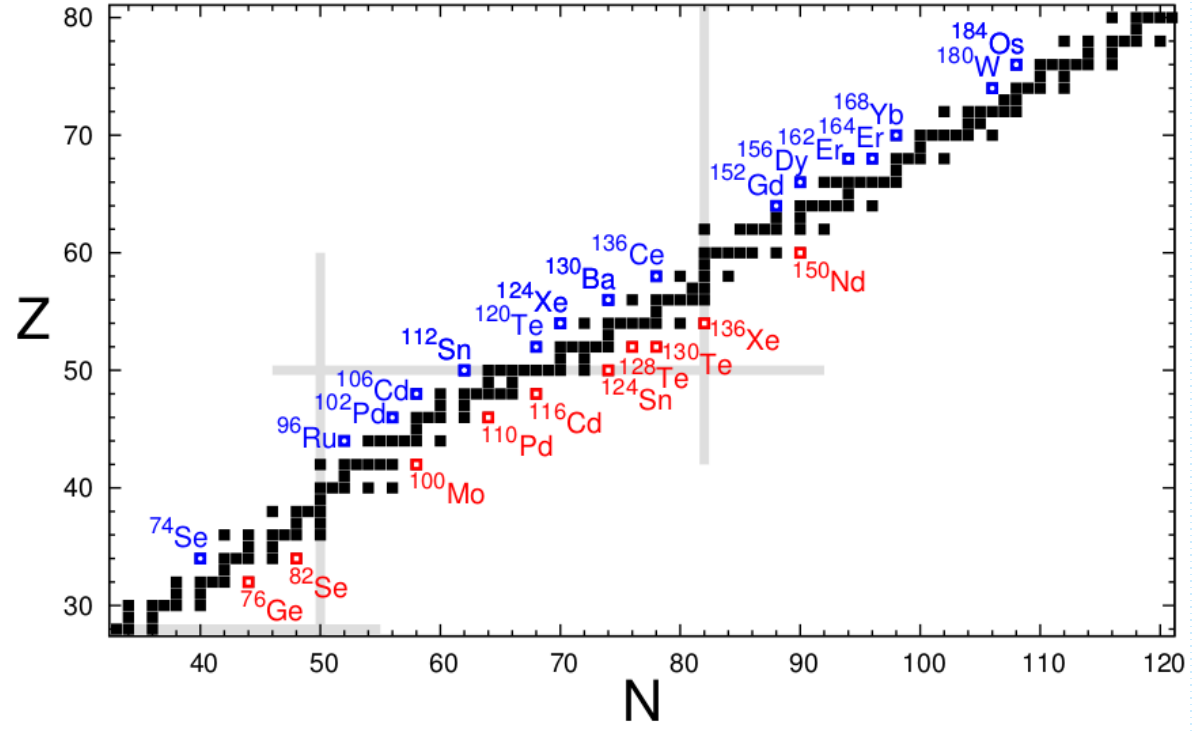


Symmetry 14, 1383 (2022)

Nuclear double-β decay

(even-even nuclei, pairing int.)





Phys. Rev. 48, 512 (1935)

Two-neutrino double-β decay – LN conserved

$$(A,Z) \rightarrow (A,Z+2) + e^- + e^- + \nu_e + \nu_e$$

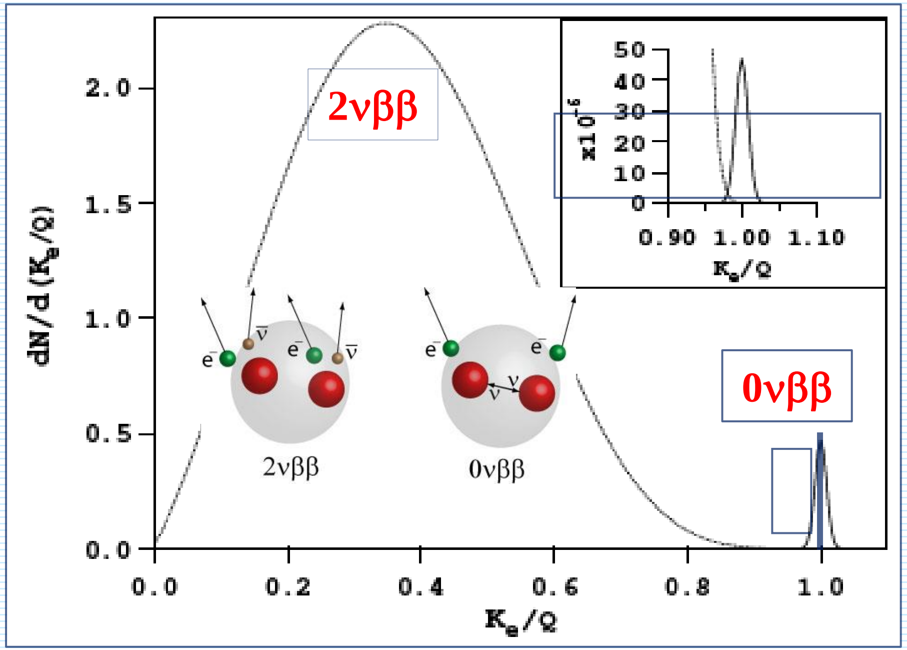
Goepert-Mayer – 1935. 1st observation in 1987

Phys. Rev. 56, 1184 (1939)

Neutrinoless double-β decay – LN violated

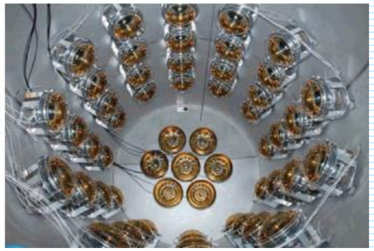
$$(A,Z) \rightarrow (A,Z+2) + e^- + e^- \quad \text{(Furry 1937)}$$

Not observed yet. Requires massive Majorana ν's



$0\nu\beta\beta$ decay isotopes and experiments

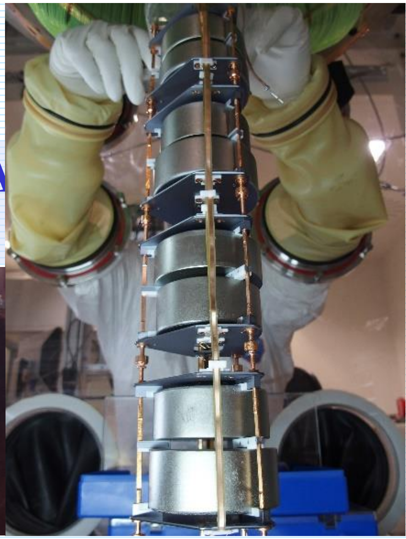
【Current CANDLES detector】



CANDLE
CaF scintillating crystal

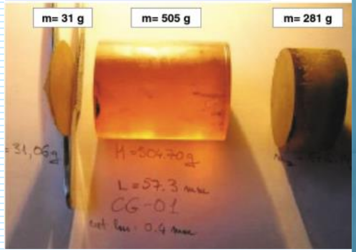
SuperNEMO
Se source foil

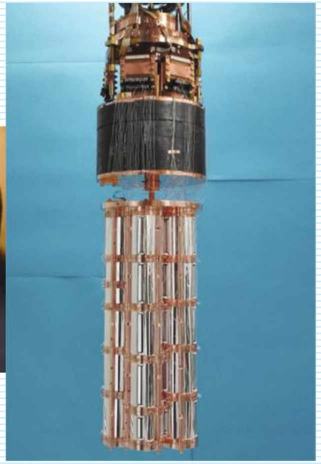
GERDA, MAJORANA
Ge crystal

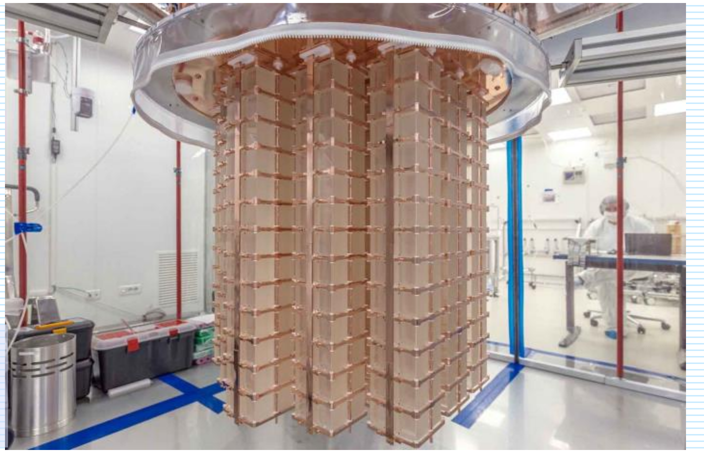


Candidates	$Q_{\beta\beta}$(MeV)	N.A. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.268	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.039	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.998	8.8
$^{96}Zr \rightarrow ^{96}Mo$	3.356	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.7
$^{110}Pd \rightarrow ^{110}Cd$	2.017	11.7
$^{116}Cd \rightarrow ^{116}Sn$	2.813	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.293	5.8
$^{130}Te \rightarrow ^{130}Xe$	2.528	34.1
$^{136}Xe \rightarrow ^{136}Ba$	2.458	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.371	5.6

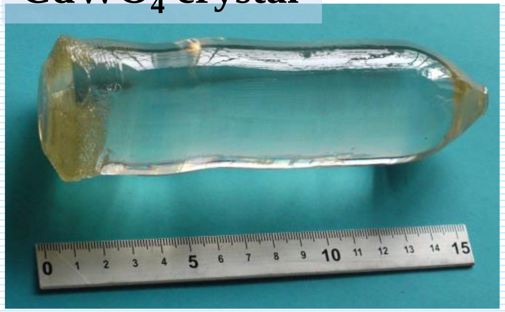
CUPID-0
ZnSe scintillating crystal





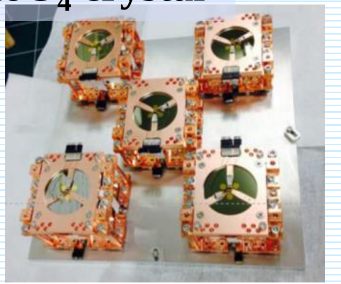


Aurora
$CdWO_4$ crystal



CUORE
TeO_2 crystal

Amore
$CaMoO_4$ crystal



EXO, KamLAND-Zen
Liquid Xe

Leading limits in each $0\nu\beta\beta$ isotope (unquenched g_A)

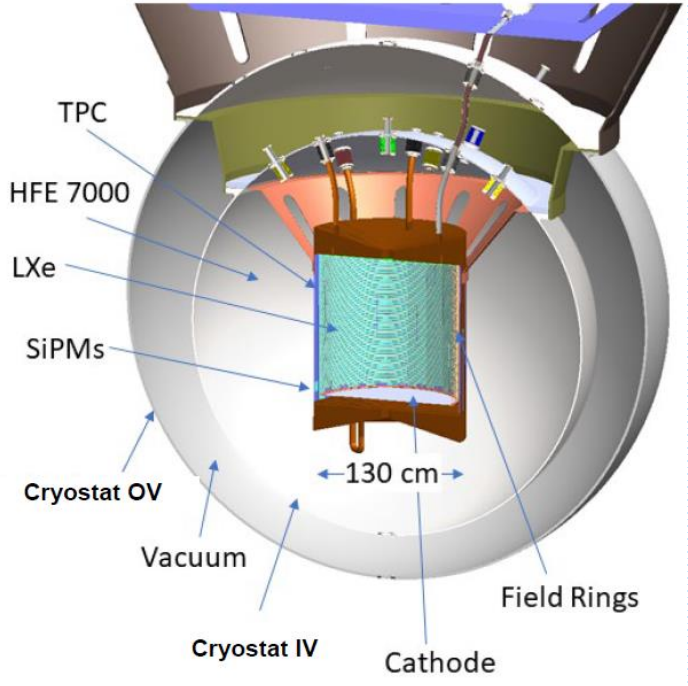
A monoenergetic peak at the Q-value is searched for.
Need a large amount of decay isotope and low radioactive environment

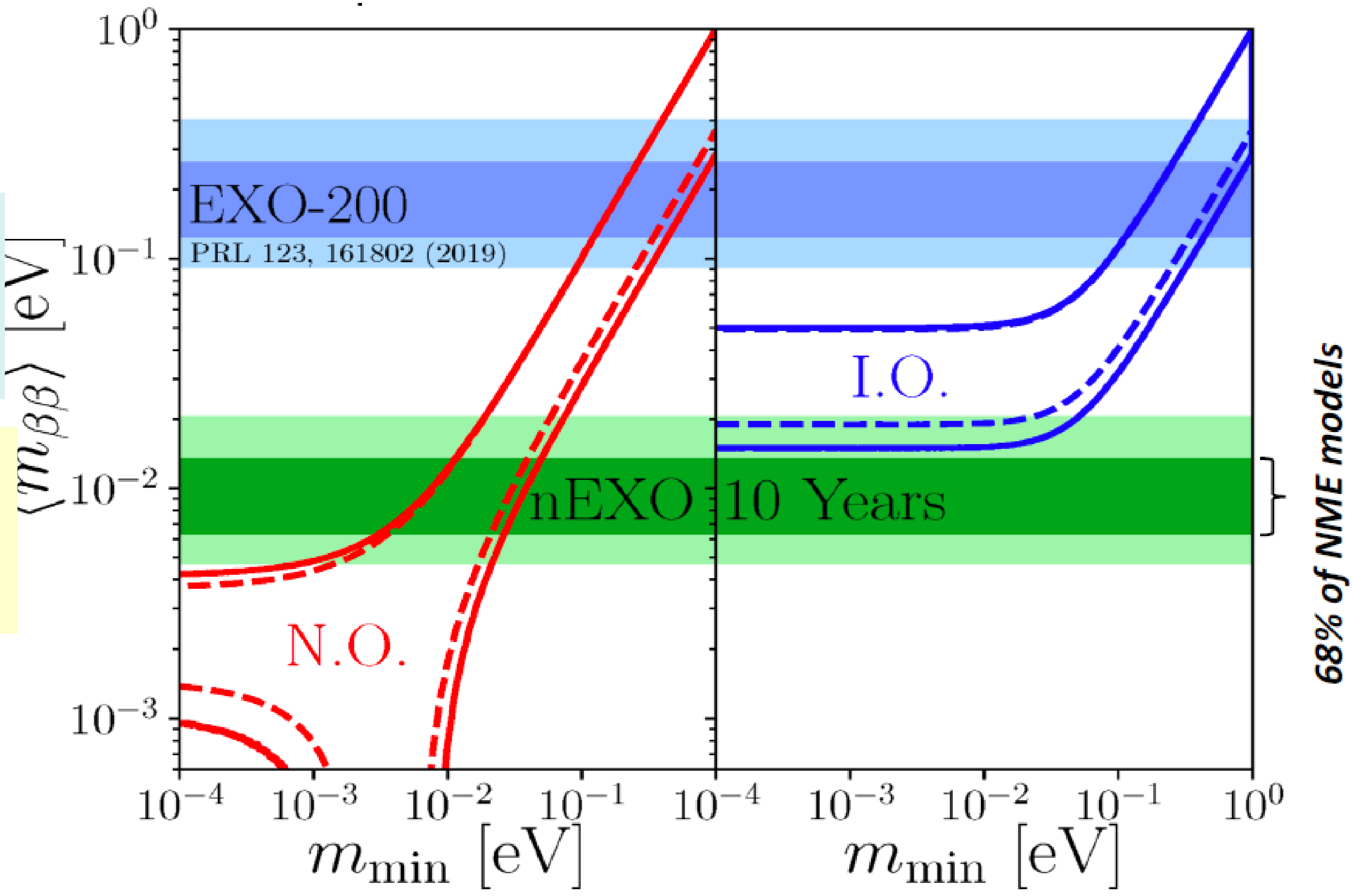
Experiment	Isotope	Exposure [kg yr]	$T^{0\nu}_{1/2}[10^{25}$ yr]	$m_{\beta\beta}$ [meV]
Gerda	^{76}Ge	127.2	18	79-180
Majorana	^{76}Ge	26	2.7	200-433
CUPID-0	^{82}Se	5.29	0.47	276-570
NEMO3	^{100}Mo	34.3	0.15	620-1000
CUPID-Mo	^{100}Mo	2.71	0.18	280-490
Amore	^{100}Mo	111	0.095	1200-2100
CUORE	^{130}Te	1038.4	2.2	90-305
EXO-200	^{136}Xe	234.1	3.5	93-286
KamLAND-Zen	^{136}Xe	970	23	36-156

nEXO
5 ton-class ^{136}Xe 0νββ experiment

EXO-200, 1st 100 kg-class 0νββ-experiment, excellent background-essential for nEXO design, Sensitivity increased linearly with exposure.

nEXO, discovery 0νββ experiment, reaches sensitivity of 10^{28} yr in 6.5 yr data taking, probes $m_{\beta\beta}$ down to 15 meV, scalable experiment.



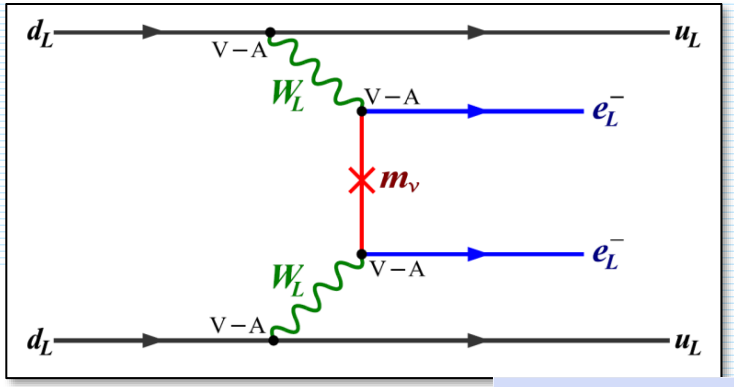


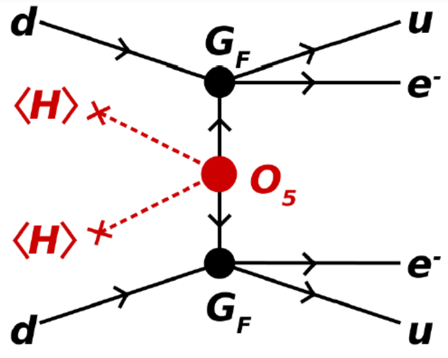
	isotope	$m_{\beta\beta}$ [meV] 90% excl. sensitivity	$m_{\beta\beta}$ [meV] 3 σ discovery potential
Legend	^{76}Se	**8.2**	**11.1**
CUPID	^{100}Mo	**11.1**	**12.0**
nEXO	^{136}Xe	**12.9**	**15.0**

$0\nu\beta\beta$ governed by exotic mechanisms

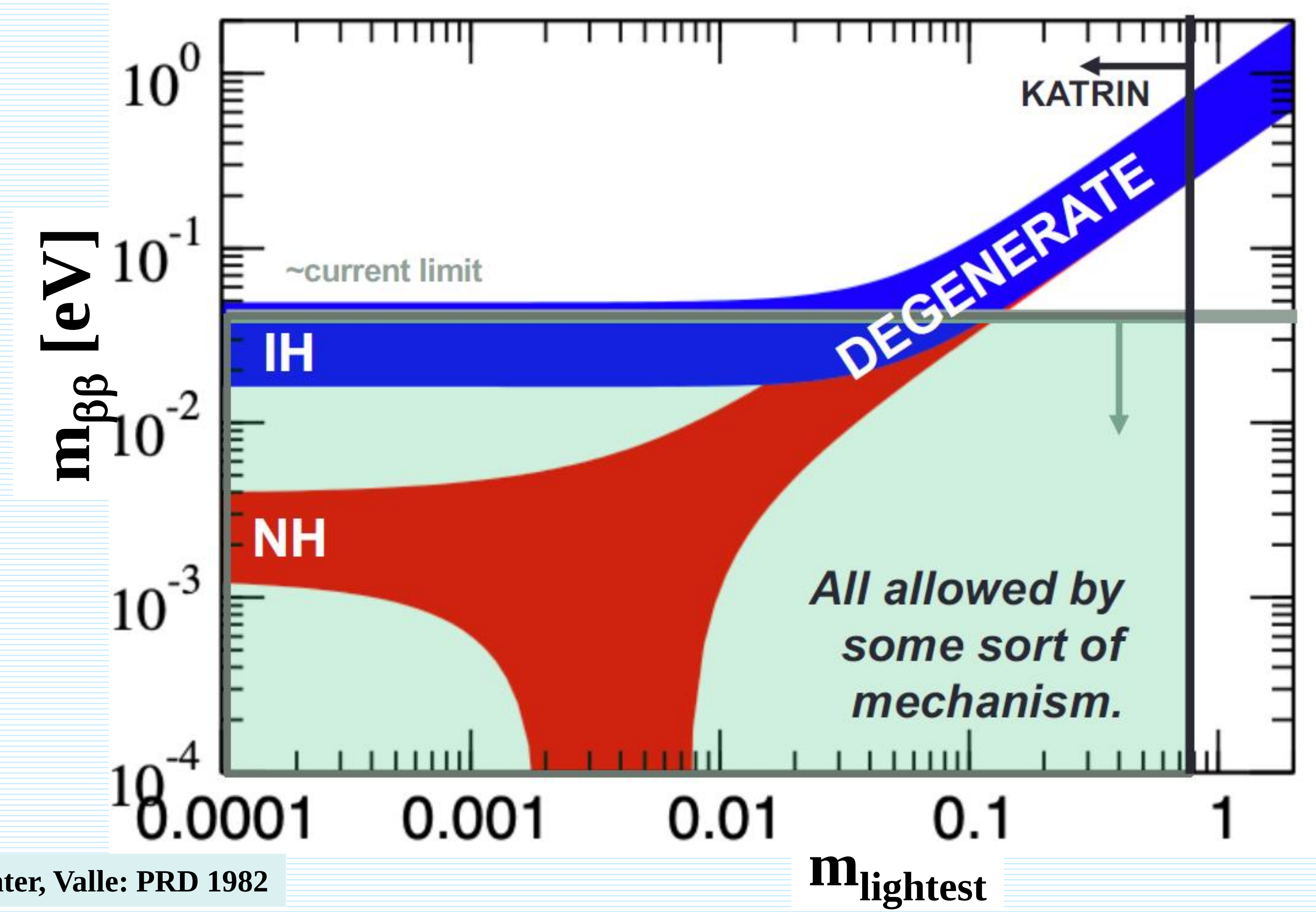
Light ν-mass mechanism can be strongly suppressed: $m_{\beta\beta} < 1$ meV

- It is not possible to discover $0\nu\beta\beta$ with **10-100 ton-class** experiment
- It should be a **subject of theory** to justify it
- There might be a dominance of other $0\nu\beta\beta$ mechanisms

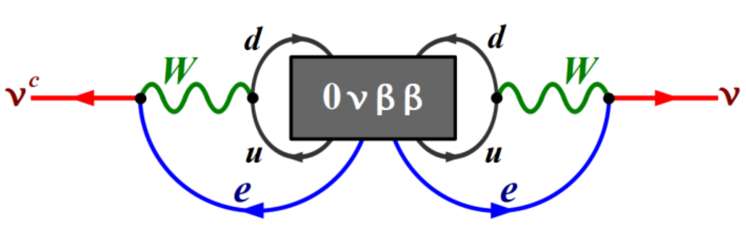




$m_{\beta\beta}$ mech. strongly suppressed



Any $0\nu\beta\beta$ mech. generates a small correction to ν-mass



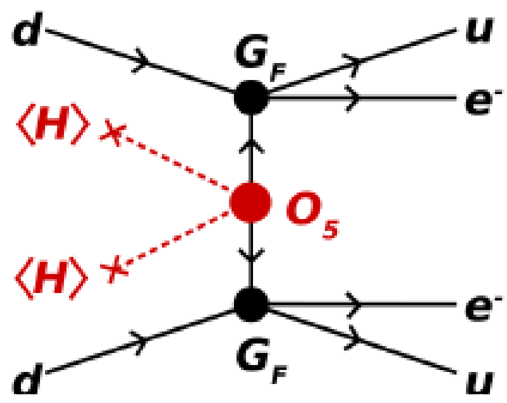
Schechter, Valle: PRD 1982

Beyond the SM physics

$$\mathcal{L} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_i c_i^{(5)}\mathcal{O}_i^{(5)} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)}\mathcal{O}_i^{(6)} + O\left(\frac{1}{\Lambda^3}\right)$$

Amplitude for (A,Z)→(A,Z+2)+2e⁻ can be divided into:

mass mechanism: d=5

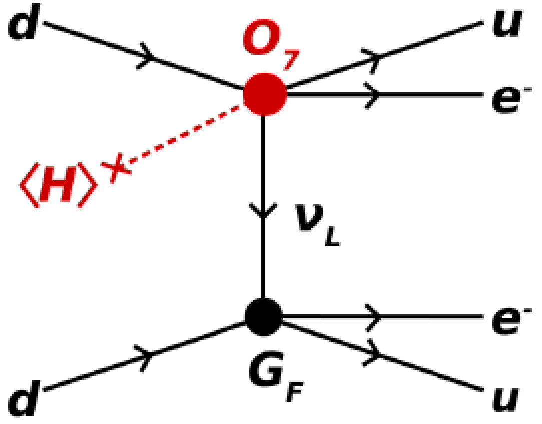


$$\mathcal{O}_W \propto \frac{c_{ij}}{\Lambda}(L_i H)(L_j H)$$

Weinberg, 1979

\+

long range: d=7

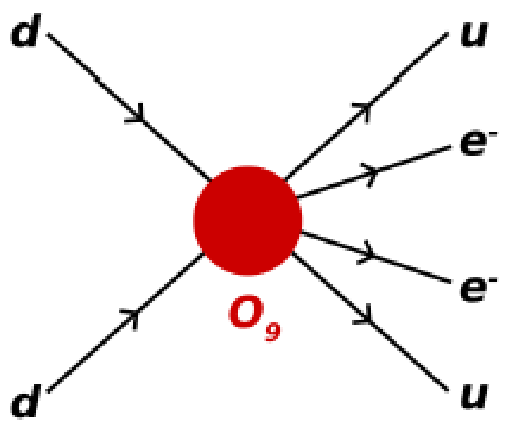


$$\mathcal{O}_2 \propto LLLe^cH$$
$$\mathcal{O}_3 \propto LLQd^cH$$
$$\mathcal{O}_4 \propto LL\bar{Q}\bar{u}^cH$$
$$\mathcal{O}_8 \propto L\bar{e}^c\bar{u}^cd^cH$$

Babu, Leung: 2001
de Gouvea, Jenkins: 2007

\+

short range: d=9 (d=11)



$$\mathcal{O}_5 \propto LLQd^cHHH^\dagger$$
$$\mathcal{O}_6 \propto LL\bar{Q}\bar{u}^cHH^\dagger H$$
$$\mathcal{O}_7 \propto LQ\bar{e}^c\bar{Q}HHH^\dagger$$

$$\mathcal{O}_9 \propto LLLe^cLe^c$$
$$\mathcal{O}_{10} \propto LLLe^cQd^c$$
$$\mathcal{O}_{11} \propto LLQd^cQd^c$$

$\cdots\cdots$

Valle

Quark Condensate Seesaw Mechanism for Neutrino Mass

PRD 103, 015007 (2021).

This operator contributes to the Majorana-neutrino mass matrix due to chiral symmetry breaking via the light-quark condensate.

The SM gauge-invariant effective operators

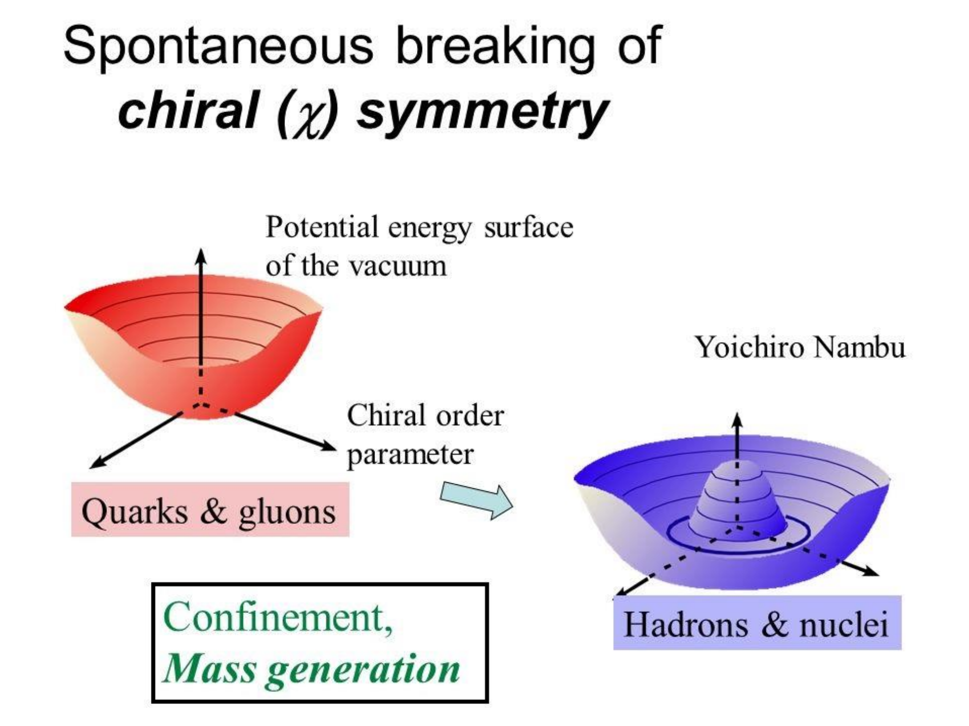
$$\mathcal{O}_7^{u,d} = \frac{\tilde{g}^{u,d}_{\alpha\beta}}{\Lambda^3}\, \overline{L^C_\alpha}\, L_\beta\, H \left\{(\overline{Q}\, u_R),\ (\overline{d_R}\, Q)\right\}$$

After the EWSB and ChSB one arrives at the Majorana mass matrix of active neutrinos

$$m_{\alpha\beta}{}^{\nu} = g_{\alpha\beta}\, v\, \frac{\langle \overline{q} q\rangle}{\Lambda^3} = g_{\alpha\beta}\, v \left(\frac{\omega}{\Lambda}\right)^3$$

$$g_{\alpha\beta} = g^u_{\alpha\beta} + g^d_{\alpha\beta}, \quad v/\sqrt{2} = \langle H^0\rangle$$

$$\omega = -\langle \overline{q} q\rangle^{1/3}, \quad \langle \overline{q} q\rangle^{1/3} \approx -283\ \mathrm{MeV}$$



Λ ~ a few TeV
we get the neutrino mass in the sub-eV ballpark

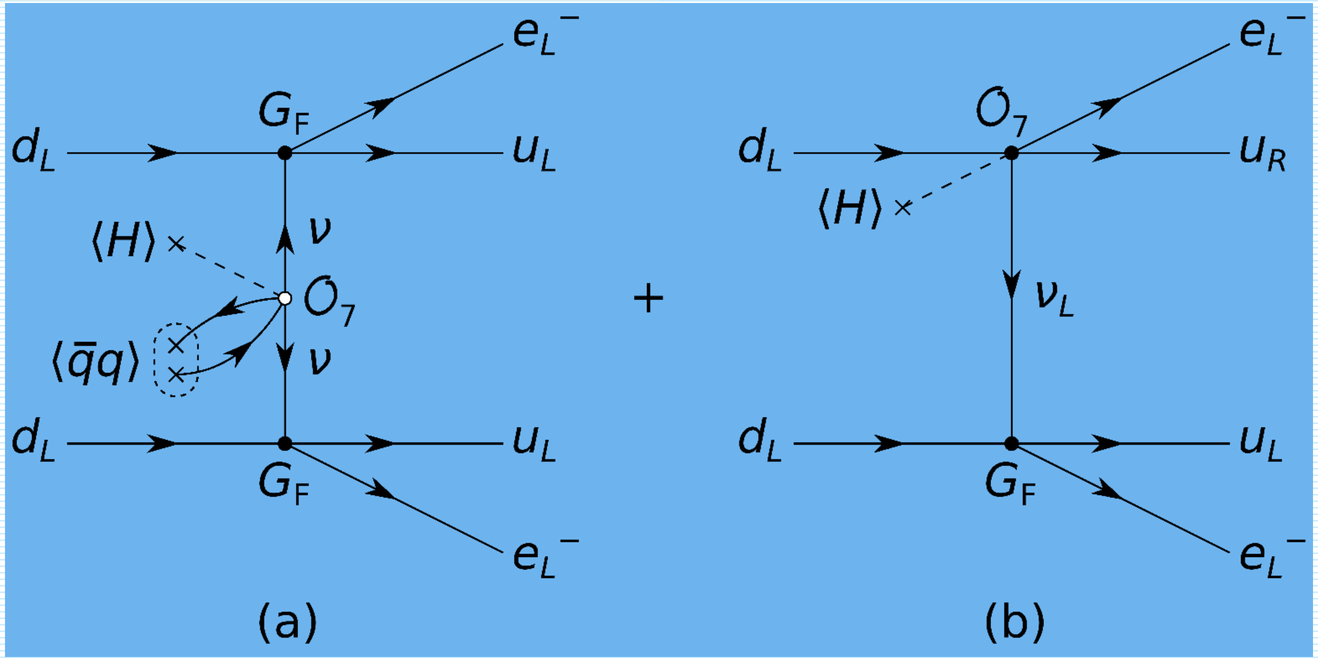
The genuine QCSS scenario
(predicts NH and ν-mass spectrum)

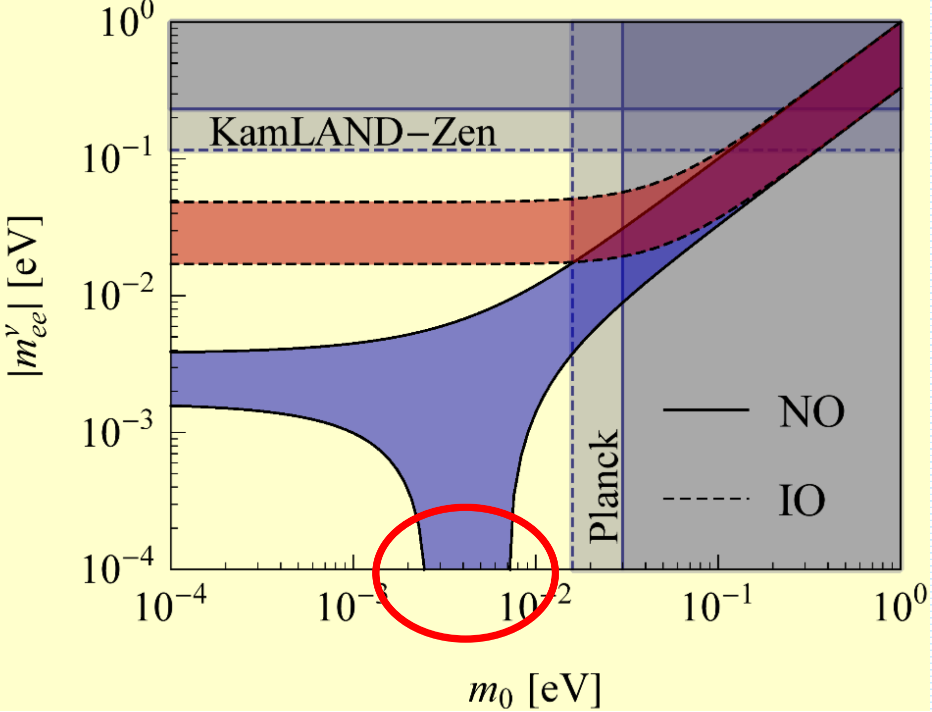
$$\mathcal{L}_7 = \frac{1}{\sqrt{2}} \sum_{\alpha\beta} \frac{v}{\Lambda^3} \overline{\nu^C_{\alpha L}} \nu_{\beta L} (g^u_{\alpha\beta} \overline{u_L} u_R + g^d_{\alpha\beta} \overline{d_R} d_L) + \text{H.c.}$$

$$m^\nu_{\alpha\beta} = -\frac{g_{\alpha\beta}}{\sqrt{2}} v \frac{\langle \bar{q} q \rangle}{\Lambda^3} = \frac{g_{\alpha\beta}}{\sqrt{2}} v \left(\frac{\omega}{\Lambda}\right)^3$$

(a) PRL 112, 142503 (2014).

(b) PLB 453, 194 (1999).





Neutrino spectrum (NH) !!!

2 meV < m_1 < 7 meV

9 meV < m_2 < 11 meV

50 meV < m_2 < 51 meV

Prediction for m_β

9 meV < m_β < 12 meV

Prediction for cosmology (Σ)

62 meV < $m_1 + m_2 + m_3$ < 69 meV

Six Quasi-Dirac neutrinos and 0νββ-decay

Symmetry 12, 1310 (2020).

M_D - 3x3 complex matrix (18 real numb.)
$M_{L,R}$ - 3x3 symmetric matrix (12 real numb.)
(42 parameters)

Dirac-Majorana mass term

$$\mathcal{L}_m = \frac{1}{2} \left(\overline{\nu_L} \quad \overline{\nu^c_R} \right) \mathcal{M} \begin{pmatrix} \nu^c_L \\ \nu_R \end{pmatrix} + h.c.$$

$$\mathcal{M} = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix}$$

$|M_{L,R}| \ll |M_D|$

$$\mathcal{U}^T \, \tilde{\mathcal{M}} \, \mathcal{U} = \mathcal{M}$$

6 eigenvalues:
3 Dirac masses $m_{1,2,3}$, 3 mass splitting $\varepsilon_{1,2,3}$

$$m_i^{\pm} = \pm m_i + \epsilon_i$$

Diagonalization: 6x6 unitary mixing matrix (15 mixing angles plus 15 phases)

$$\mathcal{U} = \mathcal{X} \cdot \mathcal{A} \cdot \mathcal{S}$$

$$\mathcal{A} \equiv \begin{pmatrix} U^T & 0 \\ 0 & 1 \end{pmatrix}$$

$$\mathcal{S} \equiv \begin{pmatrix} 1 & 0 \\ 0 & V^\dagger \end{pmatrix}$$

$$\mathcal{X} = \begin{pmatrix} 1 & X^\dagger \\ -X & 1 \end{pmatrix} + O(X^2)$$

Product of 3 unitary matrices. A and S mix exclusively active and sterile neutrino flavors, each given by 3 angles and 3 phases.

X given by 9 angles and 9 phases, small parameters.

Simplified Quasi-Dirac neutrino mixing scheme

(6x6 generalization of the PMNS matrix)

$$\mathcal{U}_{\rm QD} = \frac{1}{\sqrt{2}} \begin{pmatrix} U & U \\ -V^* & V^* \end{pmatrix}$$

$$m_i^{\pm} = \pm m_i + \epsilon \quad (\epsilon > 0)$$

3 Dirac masses and 1 universal Majorana mass splitting ε

Oscillation probabilities among active neutrinos

$$\begin{aligned} P_{\alpha\beta} = \; & \delta_{\alpha\beta} - \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2 \sin^2 \frac{m_i \epsilon}{E} L - \sum_{i>j=1}^{3} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \Big(\sin^2 \frac{\Delta m^2_{ij} + 2\epsilon \Delta m_{ij}}{4E} L \\ & + \sin^2 \frac{\Delta m^2_{ij} - 2\epsilon \Sigma m_{ij}}{4E} L + \sin^2 \frac{\Delta m^2_{ij} + 2\epsilon \Sigma m_{ij}}{4E} L + \sin^2 \frac{\Delta m^2_{ij} - 2\epsilon \Delta m_{ij}}{4E} L \Big) \\ & + \frac{1}{2} \sum_{i>j=1}^{3} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \Big(\sin \frac{\Delta m^2_{ij} + 2\epsilon \Delta m_{ij}}{2E} L + \sin \frac{\Delta m^2_{ij} - 2\epsilon \Sigma m_{ij}}{2E} L \\ & + \sin \frac{\Delta m^2_{ij} + 2\epsilon \Sigma m_{ij}}{2E} L + \sin \frac{\Delta m^2_{ij} - 2\epsilon \Delta m_{ij}}{2E} L \Big) \end{aligned}$$

Quasi-Dirac neutrinos and constraints on neutrino masses

The survival probability of electron antineutrinos

$$P_{\bar\nu_e\to\bar\nu_e}(\epsilon\neq 0) = P_{\bar\nu_e\to\bar\nu_e}(\epsilon = 0) - \frac{\epsilon^2 L^2}{E^2}\left[c_{13}^4 c_{12}^4 m_1^2 + c_{13}^4 s_{12}^4 m_2^2 + s_{13}^4 m_3^2\right]$$
$$- \frac{\epsilon^2 L^2}{4E^2}\Big[4\, c_{13}^4 s_{12}^2 c_{12}^2 \Sigma m_{21}^2 \cos\frac{\Delta m_{21}^2 L}{2E} + 4 s_{13}^2 c_{13}^2 c_{12}^2 \Sigma m_{31}^2 \cos\frac{\Delta m_{31}^2 L}{2E}$$
$$+ 4\, s_{13}^2 c_{13}^2 s_{12}^2 \Sigma m_{32}^2 \cos\frac{\Delta m_{32}^2 L}{2E}\Big] + \mathcal{O}(\epsilon^4)\,,$$

Tritium β-decay

$$m_\beta = \sqrt{m_1^2 c_{12}^2 c_{13}^2 + m_2^2 c_{13}^2 s_{12}^2 + m_3^2 s_{13}^2 + \epsilon^2}$$
$$= m_\beta^{(0)}\left(1 + \frac{1}{2}\left(\epsilon/m_\beta^{(0)}\right)^2 + \dots\right)$$

Cosmology

$$\frac{1}{2}\sum_{i=1}^{6}\left|\tilde{\mathcal{M}}_{ii}\right| = \sum_{i=1}^{3} m_i$$

0νββ-decay

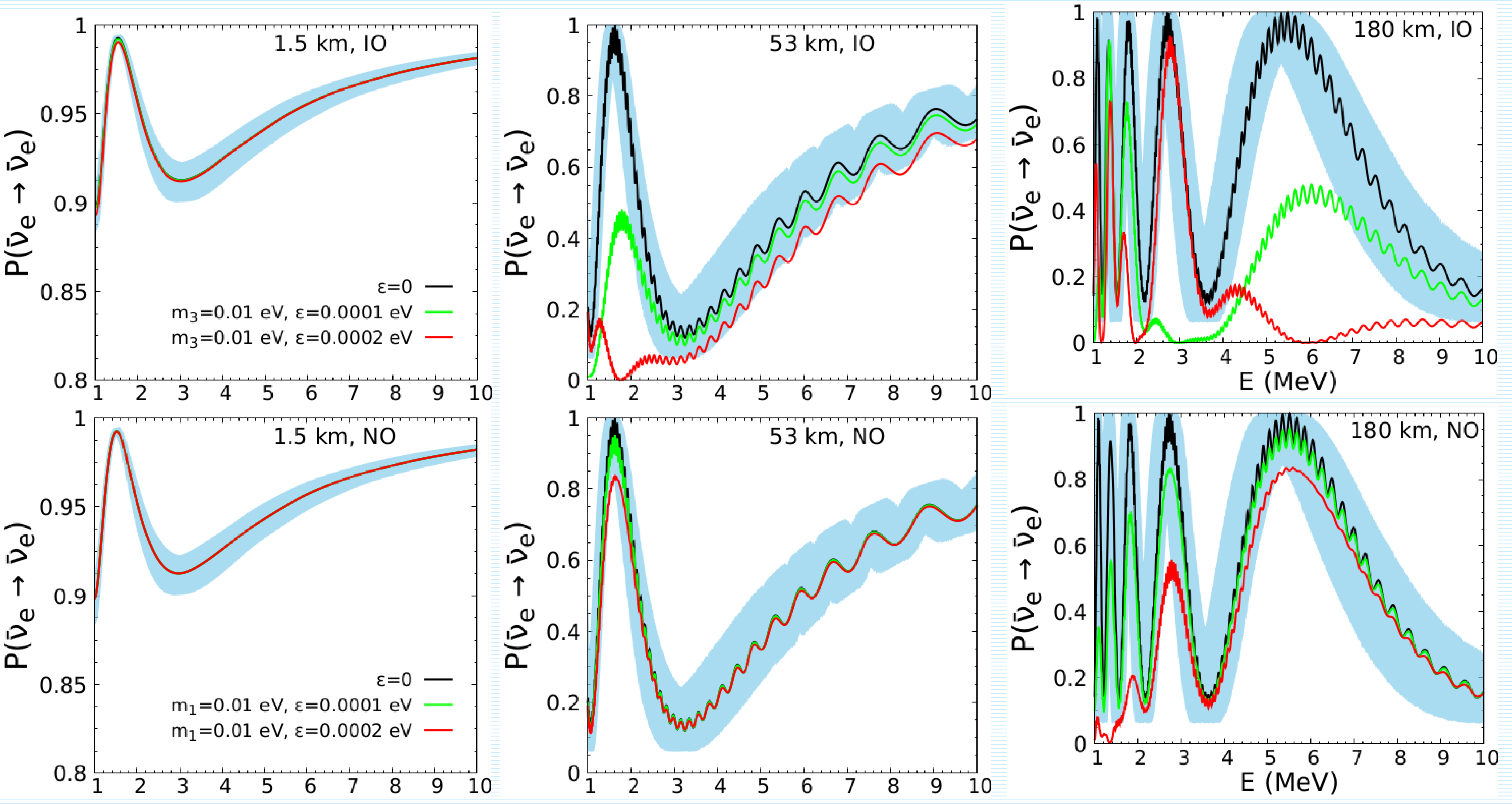
$$m_{\beta\beta} = \left|M_L\right|_{ee}$$
$$= \epsilon\,\left|c_{12}^2 c_{13}^2 + e^{2i\alpha_{21}}\, c_{13}^2 s_{12}^2 + e^{2i\alpha_{31}}\, s_{13}^2\right|$$

Restriction from Daya-Bay data (3σ):

Survival probabilities with non-zero ε are the same 3ν cases.

$$m_{\beta\beta} \lesssim 30 \text{ meV} \quad \text{for NO}$$
$$\lesssim 1 \text{ meV} \quad \text{for IO}$$

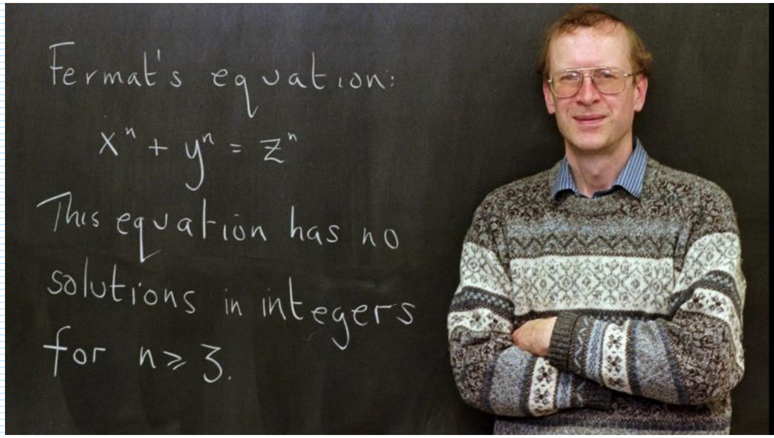
Quasi-Dirac neutrino oscillations at different distances



Around 1637, Pierre de Fermat wrote in the margin of a book that the more general equation

$$a^n + b^n = c^n$$

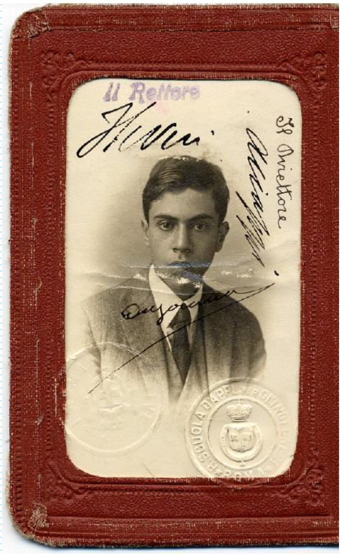
had no solutions in positive integers if n is an integer greater than 2.



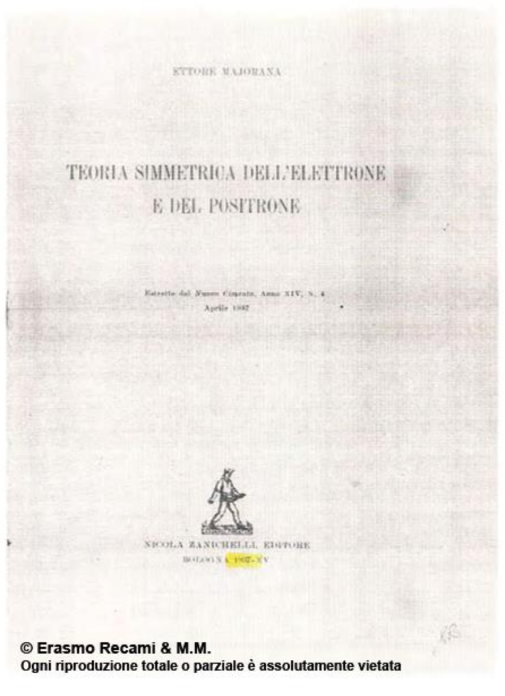
After **358** years

The proof was published by Andrew Wiles in 1995.

Some long-standing tasks of humanity …



1937



After **85** years

n-ton-class 0νββ exp.
with discovery potential
KamLAND-Zen 800
SNO+
LEGEND
nEXO
NEXT
CUPID
etc

After **?** years

If $m_{\beta\beta}$ < 1 meV, what technology is needed for observation of 0νββ?