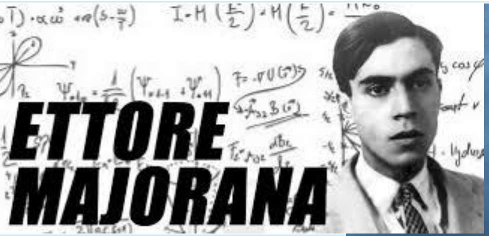
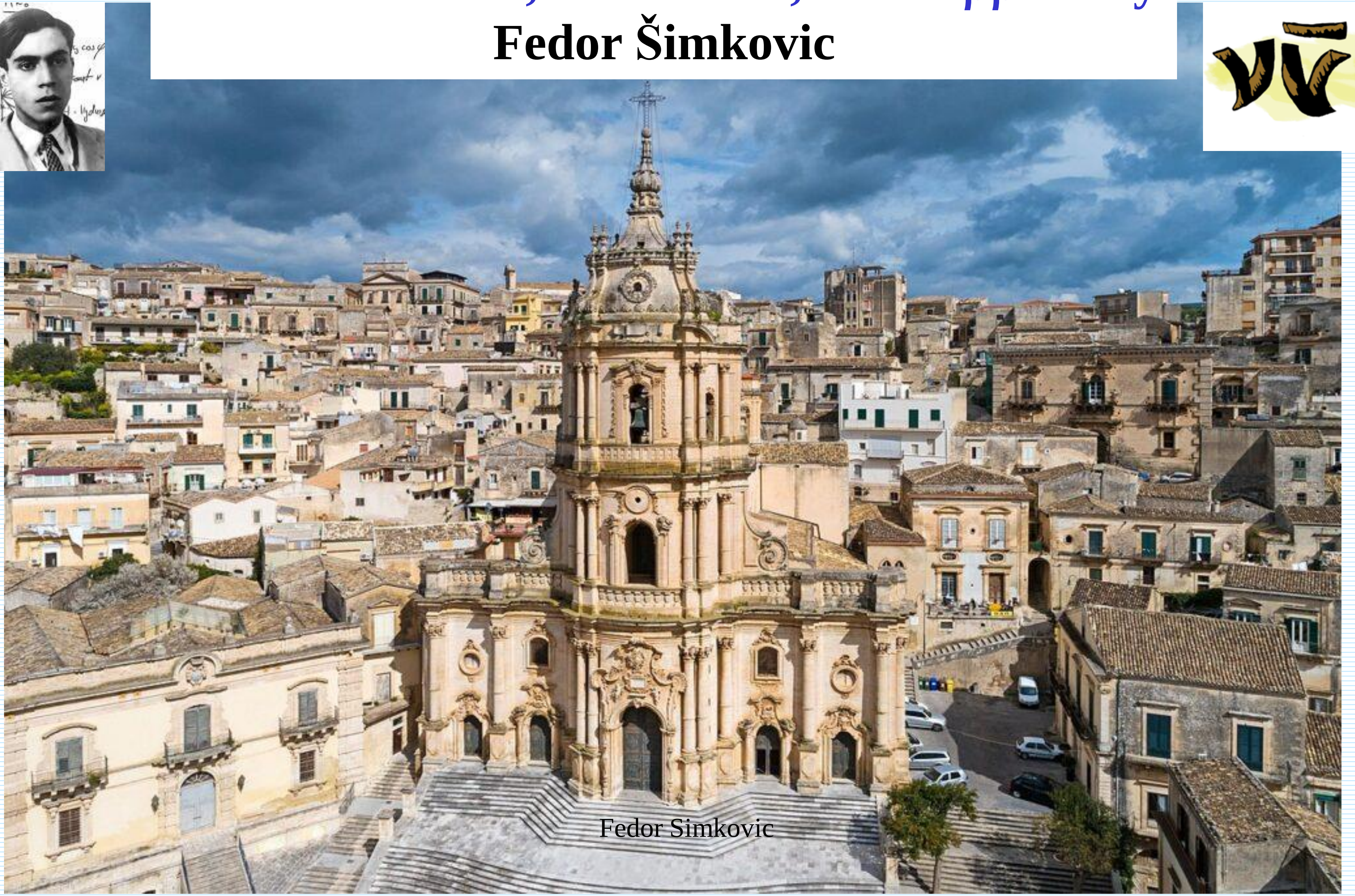
MAYORANA workshop, Modica, Sicily
July 12-14, 2023

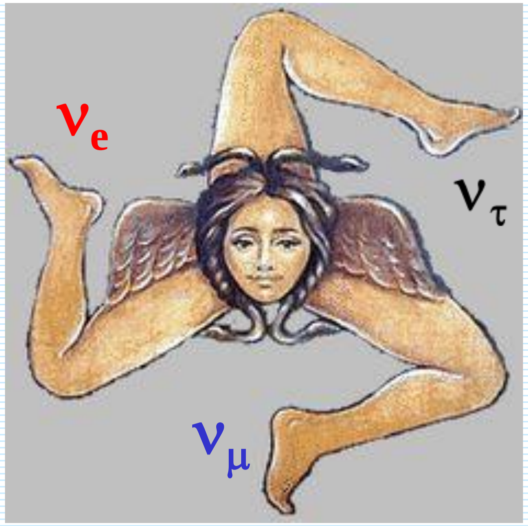
Neutrino masses, oscillations, and 0νββ-decay

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. *The $0\nu\beta\beta$-decay NME, effective gA, and supporting nuclear physics experiments*

(muon capture, DCE)

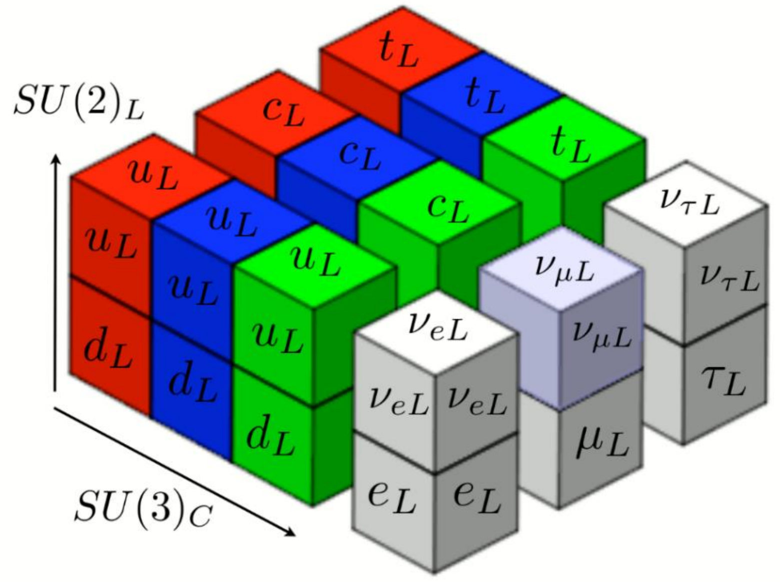
V. *The $2\nu\beta\beta$-decay and new physics*

(sterile heavy ν, right-handed ν)

V. *Outlook*

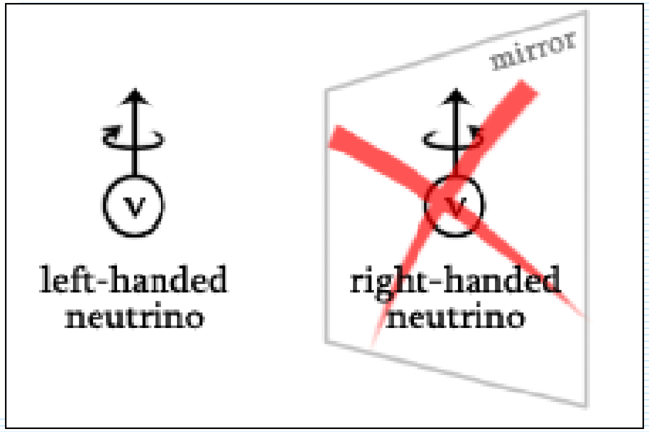
Acknowledgements: F. Deppisch, R. Dvornický, L. Graf,A. Khatun, S. Kovalenko, M. Krivoruchenko, A. Smetana, P. Vogel, and other colleagues and friends.

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
$\Rightarrow$ tiny neutrino masses (!)
$\Rightarrow$ Beyond SM physics (!)

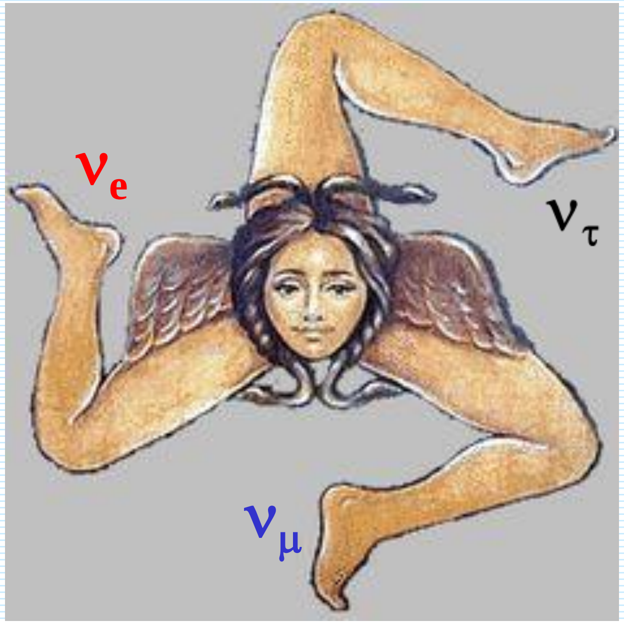
, etc

After 93/67 years we know

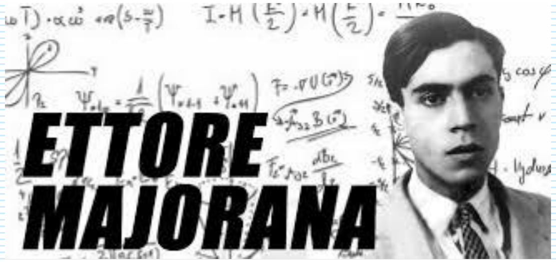
Fundamental ν properties

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)

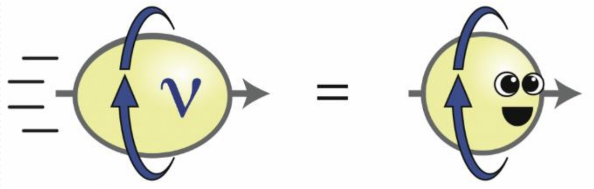


- Are ν Dirac or Majorana?
- Is there a CP violation in ν sector?
- Are neutrinos stable?
- What is the magnetic moment of ν?
- Sterile neutrinos?
- Statistical properties of ν? Fermionic or partly bosonic?



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

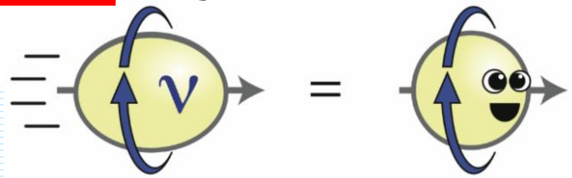
It follows from the above assumptions that in vacuum a neutrino can be transformed into an antineutrino and vice versa. This means that the neutrino and antineutrino are "mixed" particles, i.e., a symmetric and antisymmetric combination of two truly neutral Majorana particles ν_1 and ν_2 of different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

Bruno Pontecorvo

Inverse beta processes and nonconservation of lepton charge

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

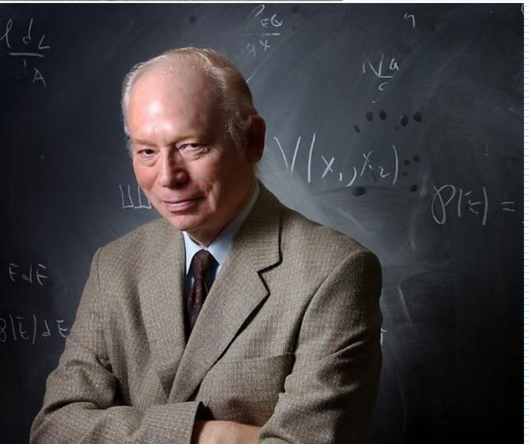
ν ↔ anti-ν oscillation



INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERNCOURIER

VOLUME 57 NUMBER 9 NOVEMBER 2017



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

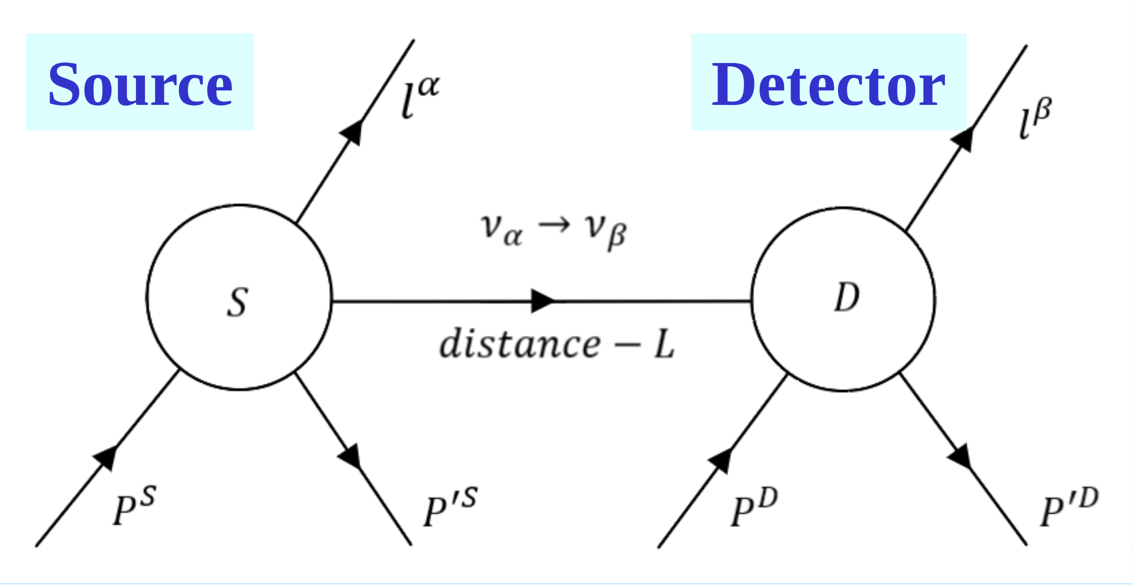
$$|\nu_\alpha\rangle = \sum_{j=1}^{3} U^*_{\alpha j} |\nu_j\rangle$$

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

	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	4.60-5.82	4.39-5.96
		$\oplus$ 5.31-6.10		
δ/π	1.52	1.37-1.65	1.23-1.78	1.09-1.90

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

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

$$S + D \to \ell^+_\alpha + \ell^-_\beta + S' + D'$$

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

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

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

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

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.

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

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

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

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

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

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

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

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

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

Replacement:

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

Particular process:

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

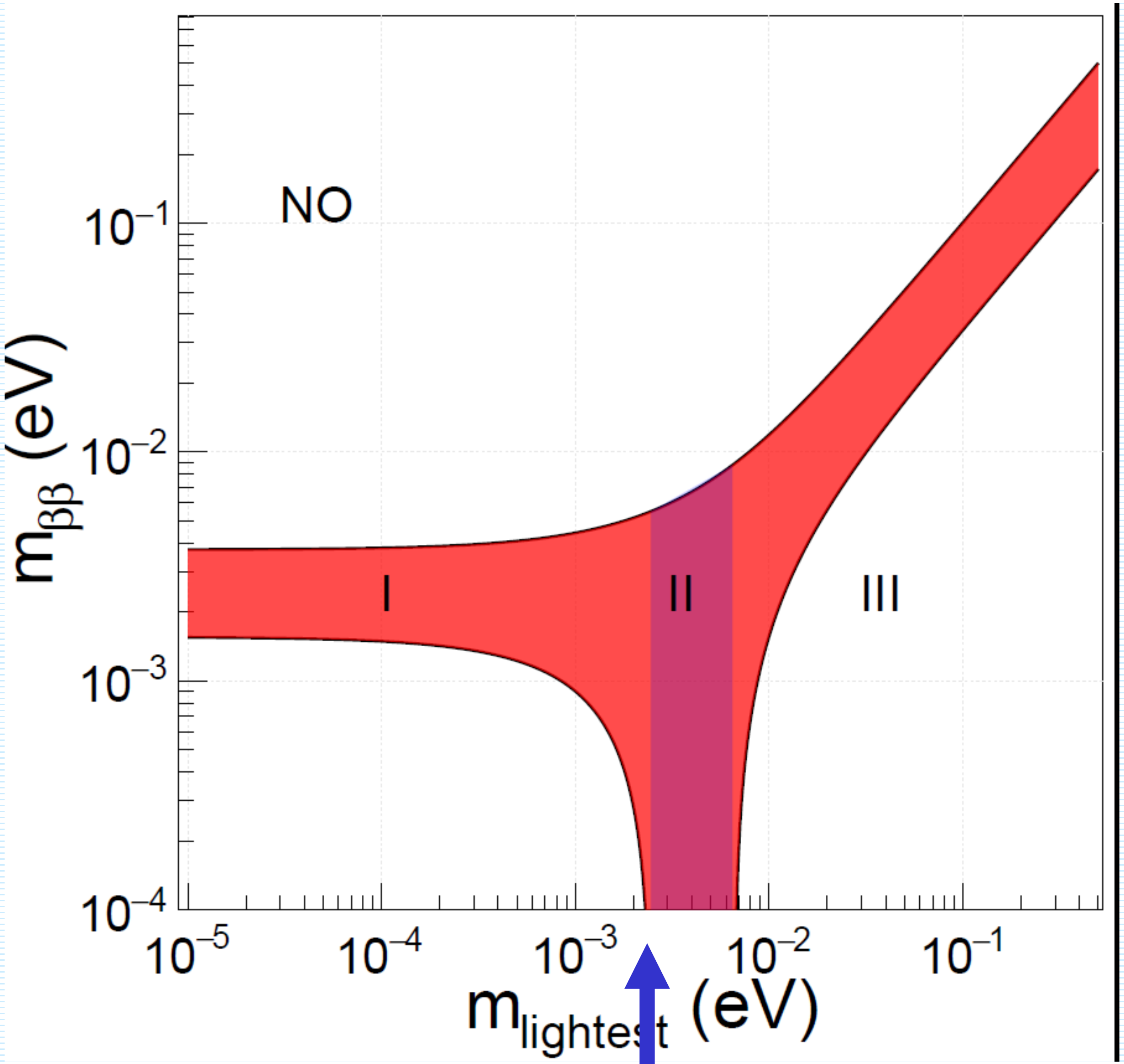
Production rate

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

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

For L=0

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

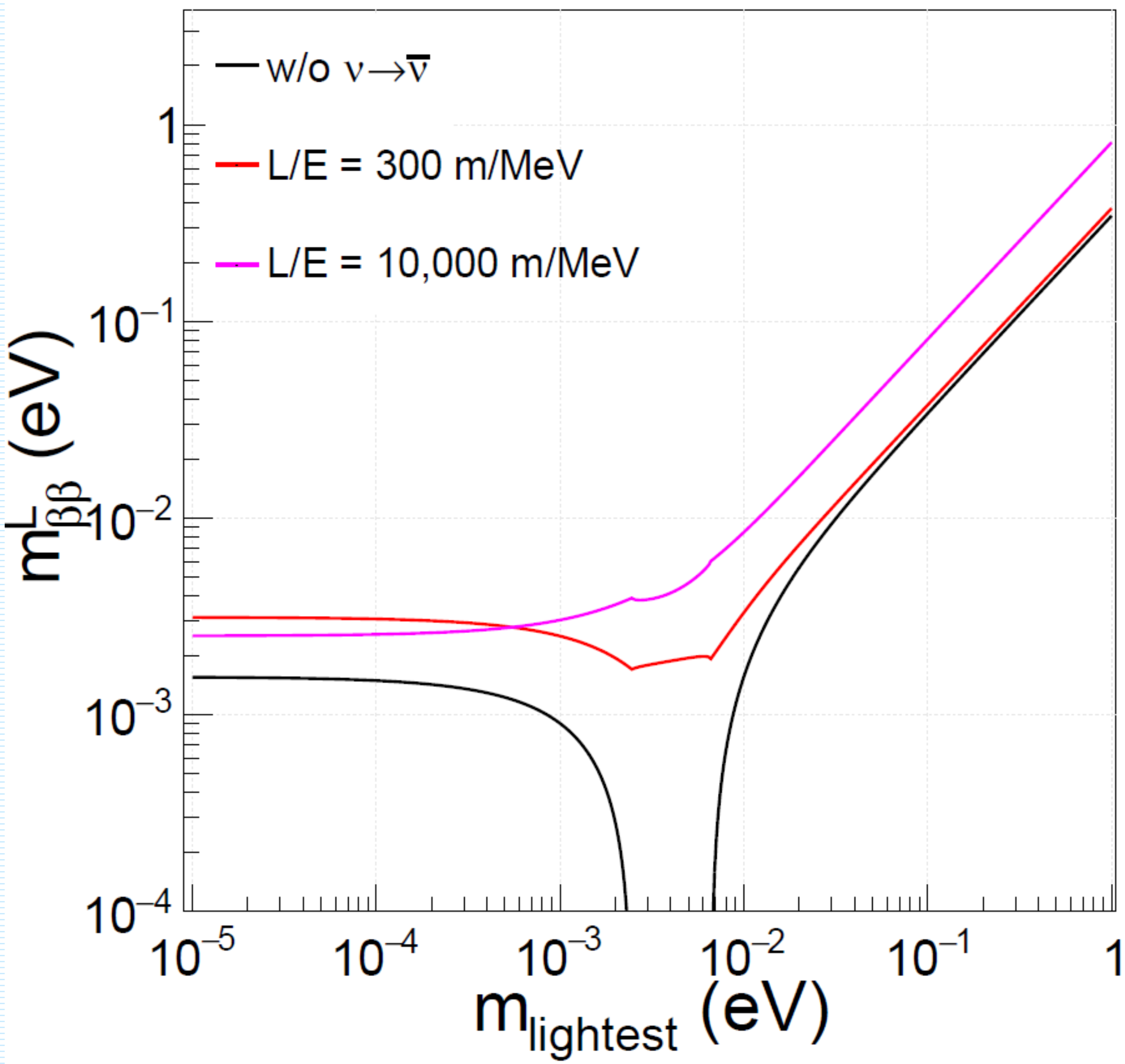


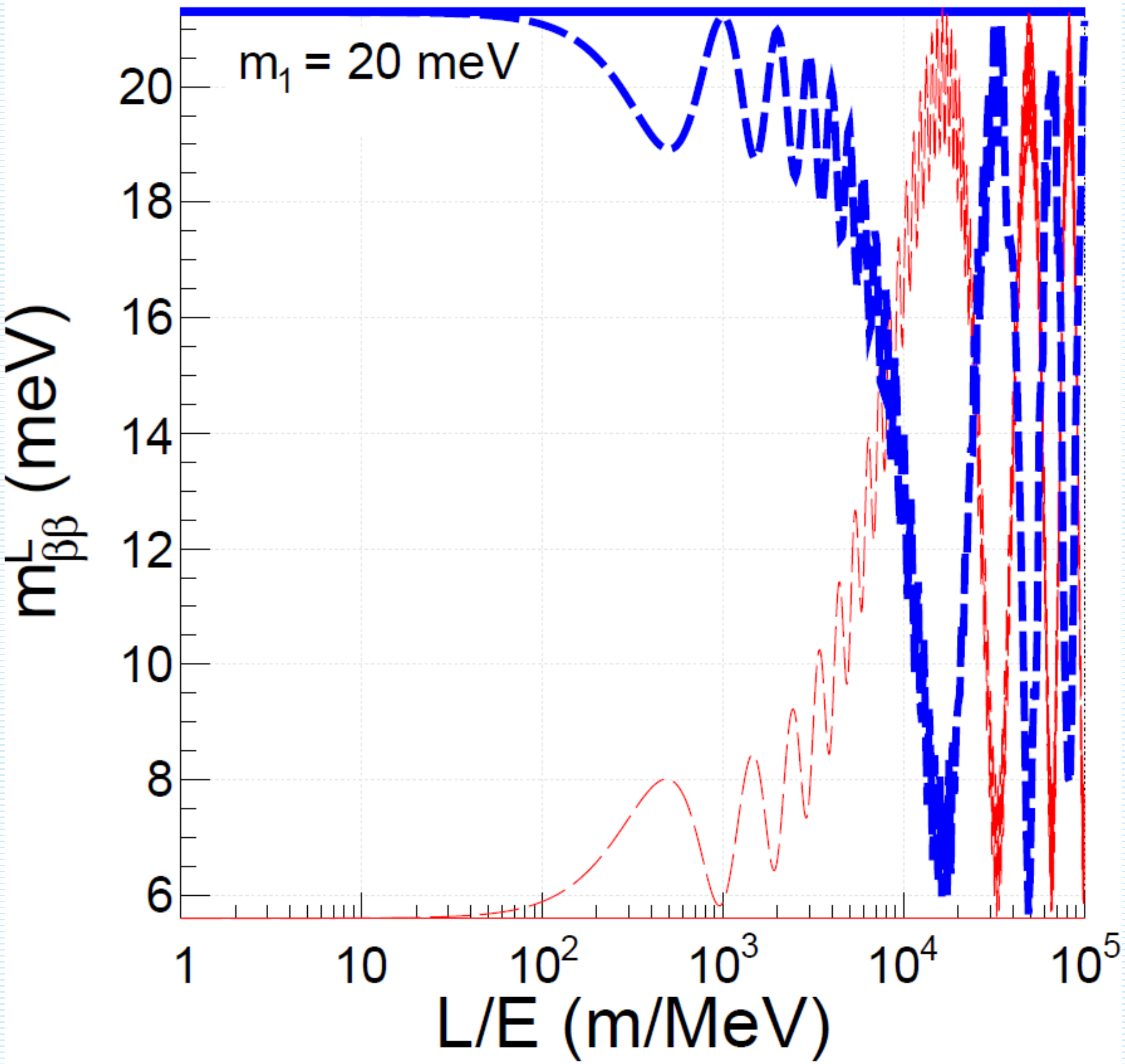
$$m_{\beta\beta} = |\rho_1 e^{2i\phi_1} + \rho_2 e^{2i\phi_2} + \rho_3|$$

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

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

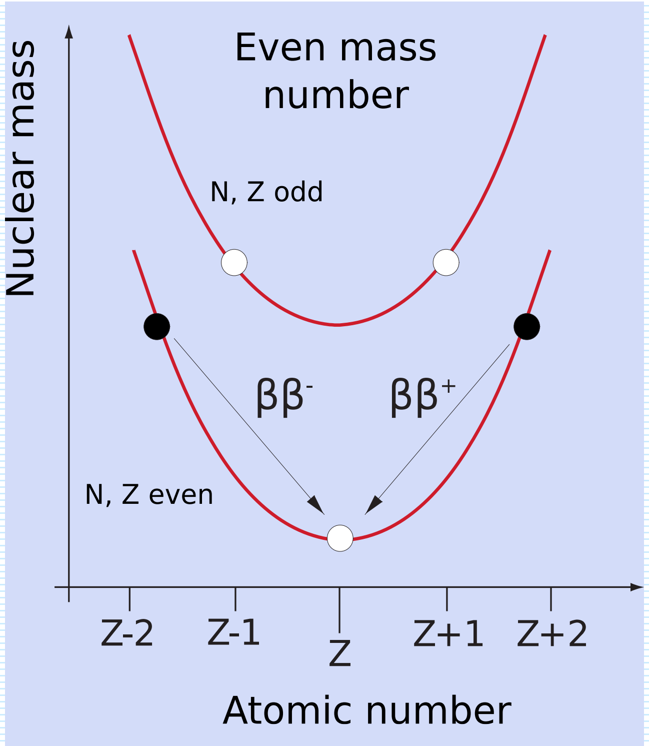
Dependence of m^L_{ee} on $m_{lightest}$ and L/E

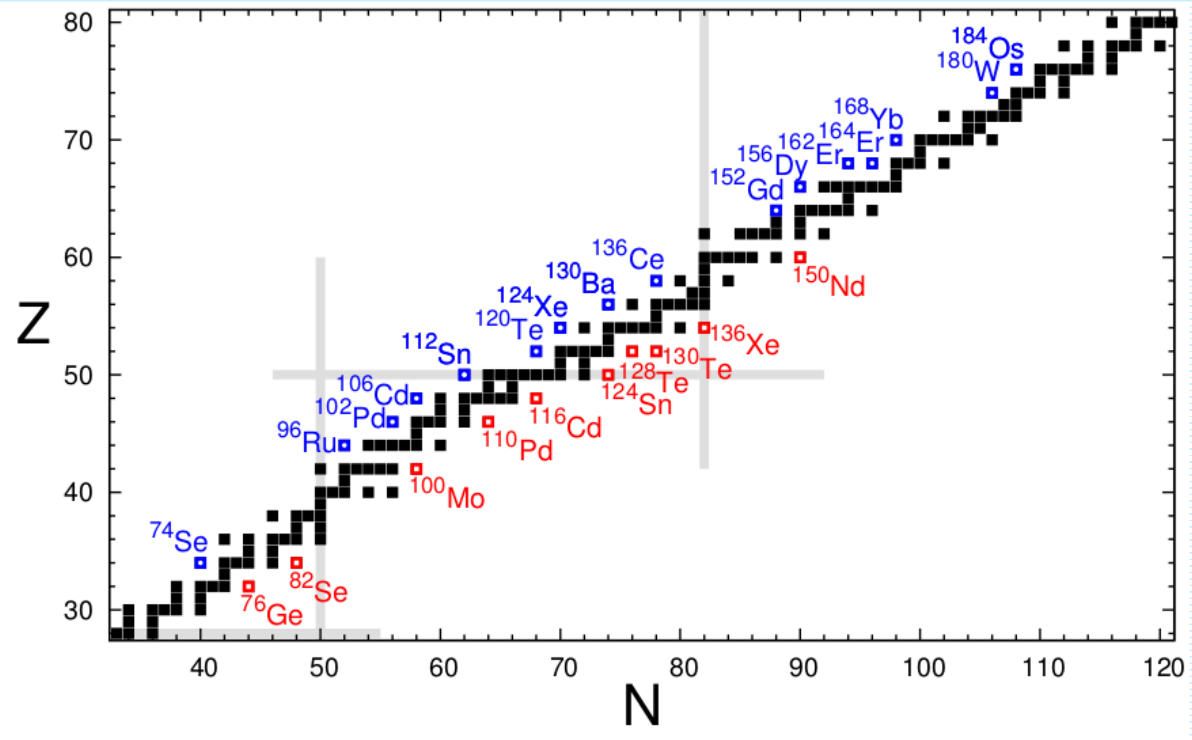




Symmetry 14, 1383 (2022)

Nuclear double-β decay
(even-even nuclei, pairing int.)





Phys. Rev. 48, 512 (1935)

Two-neutrino double-β decay – LN conserved

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

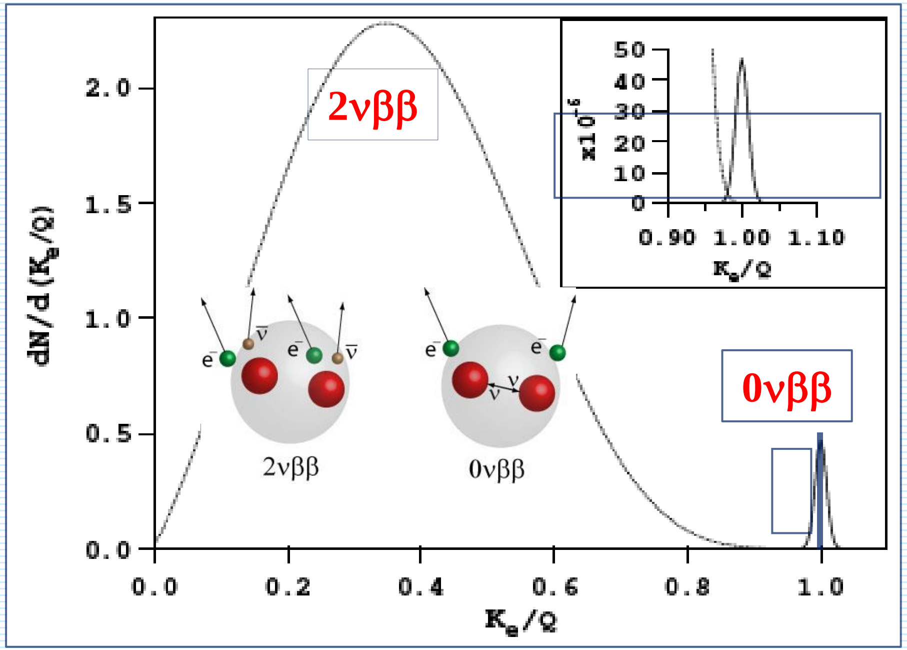
Goepert-Mayer – 1935. 1st observation in 1987

Phys. Rev. 56, 1184 (1939)

Neutrinoless double-β decay – LN violated

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

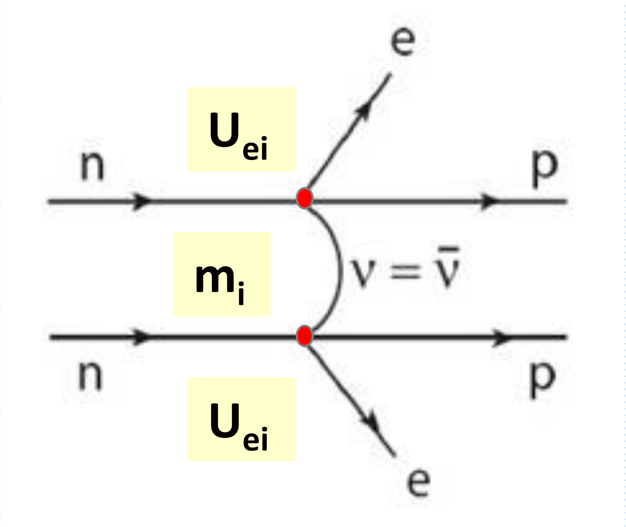
Not observed yet. Requires massive Majorana ν's



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

$0\nu\beta\beta$-decay

(LNV at ≈GUT scale, exchange of three light ν)



$$\left(T^{0\nu}_{1/2}\right)^{-1} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 g_A^4 \left|M^{0\nu}_{\nu}\right|^2 G^{0\nu}$$

?

Phase space factor well understood

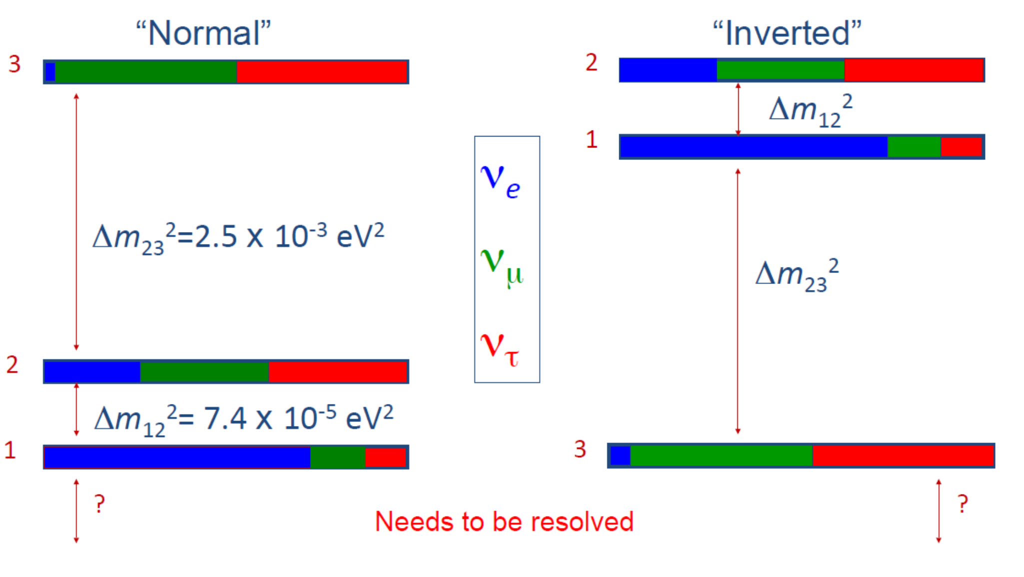
NME must be evaluated using tools of nuclear theory

Effective Majorana mass can be evaluated. It depends on

$m_1, m_2, m_3, \theta_{12}, \theta_{13}, \alpha_1, \alpha_2$

(3 unknown parameters: $m_1/m_3, \alpha_1, \alpha_2$ and ν-mass hierarchy)

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 e^{i\alpha_1} m_1 + c_{13}^2 s_{12}^2 e^{i\alpha_2} m_2 + s_{13}^2 m_3\right|$$

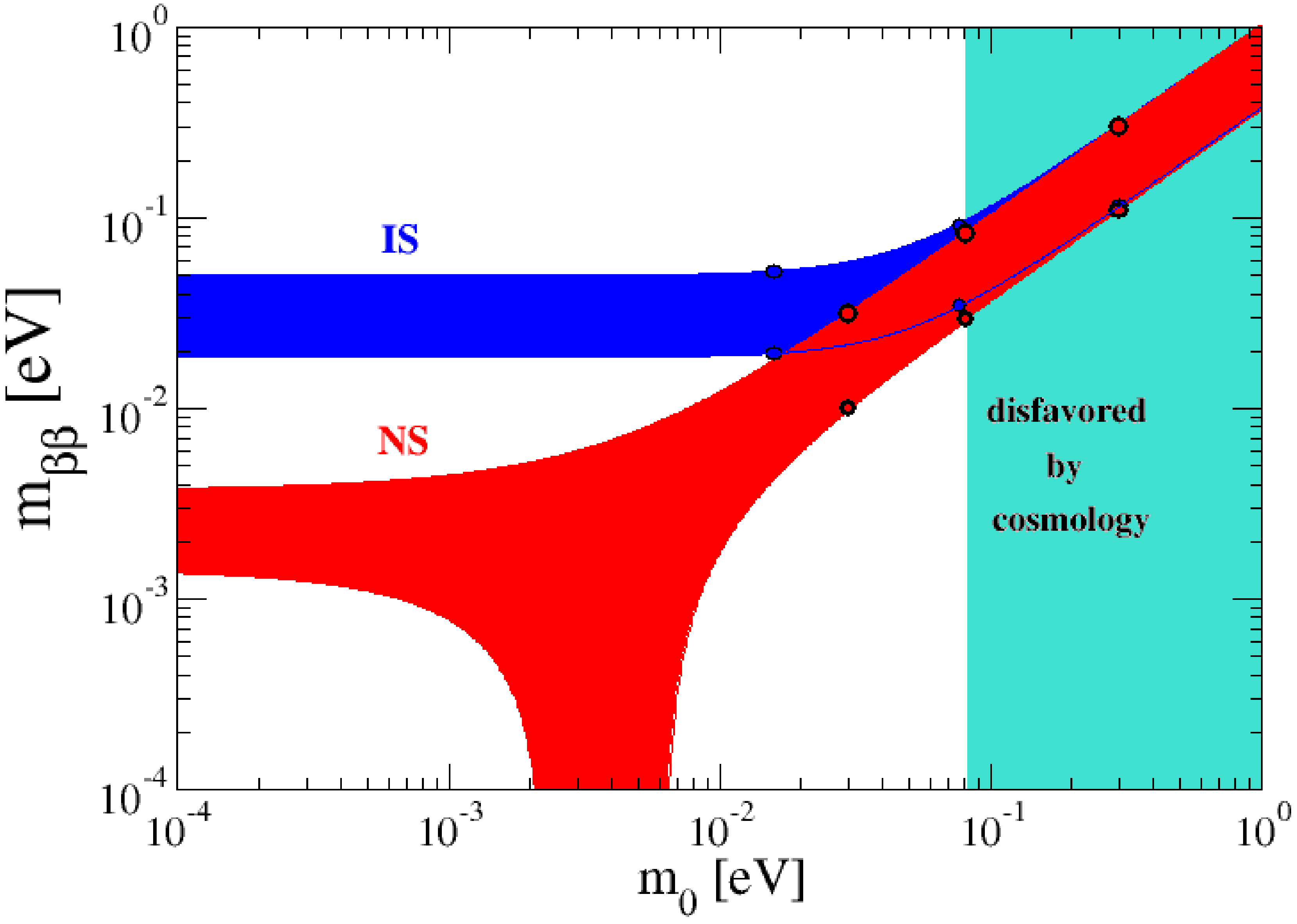


$$U^{PMNS} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\ -c_{23}s_{12} - e^{i\delta}c_{12}s_{13}s_{23} & c_{12}c_{23} - e^{i\delta}s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - e^{i\delta}c_{12}c_{23}s_{13} & -e^{i\delta}c_{23}s_{12}s_{13} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Effective Majorana ν-mass $m_{\beta\beta}$
(prediction due ν-oscillations)

Constraint from cosmology
$\Sigma = m_1 + m_2 + m_3$
< 0.90 eV
< 0.26 eV (Planck coll.)
< 0.12 eV

Contrary, the constraint from $0\nu\beta\beta$-decay (KLZ)
$m_{\beta\beta} < 0.036\text{-}0.156$ eV
implies
$\Sigma < 0.12$ eV



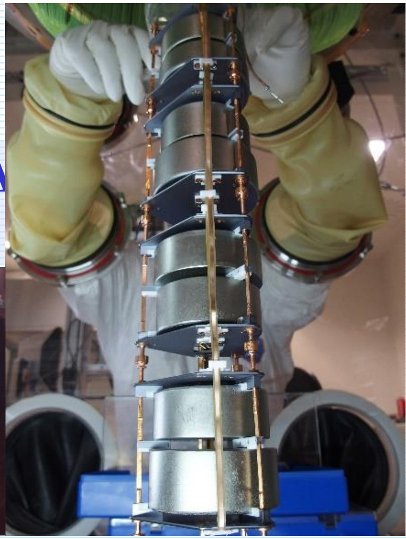
$0\nu\beta\beta$ decay isotopes and experiments

【Current CANDLES detector】

CANDLE
CaF scintillating crystal

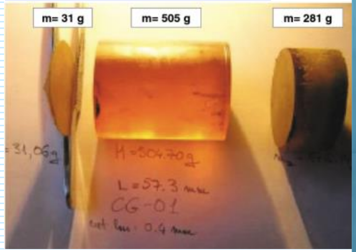
SuperNEMO
Se source foil

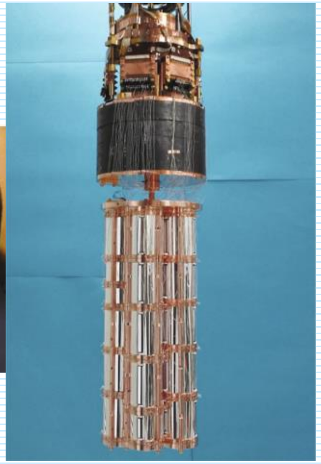
GERDA, MAJORANA
Ge crystal

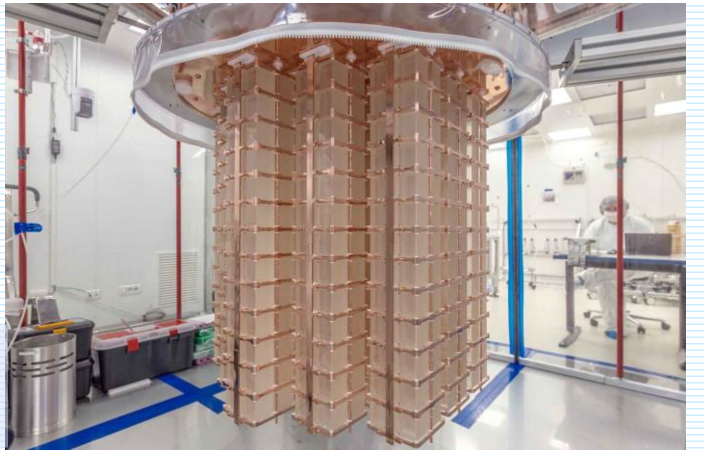


Candidates	$Q_{\beta\beta}$(MeV)	N.A. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.268	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.039	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.998	8.8
$^{96}Zr \rightarrow ^{96}Mo$	3.356	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.7
$^{110}Pd \rightarrow ^{110}Cd$	2.017	11.7
$^{116}Cd \rightarrow ^{116}Sn$	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

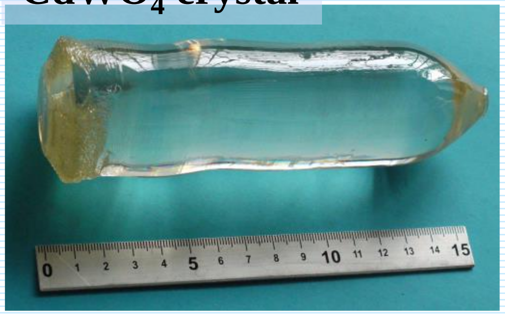
CUPID-0
ZnSe scintillating crystal





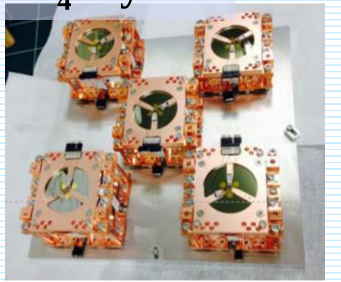


Aurora
$CdWO_4$ crystal



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)

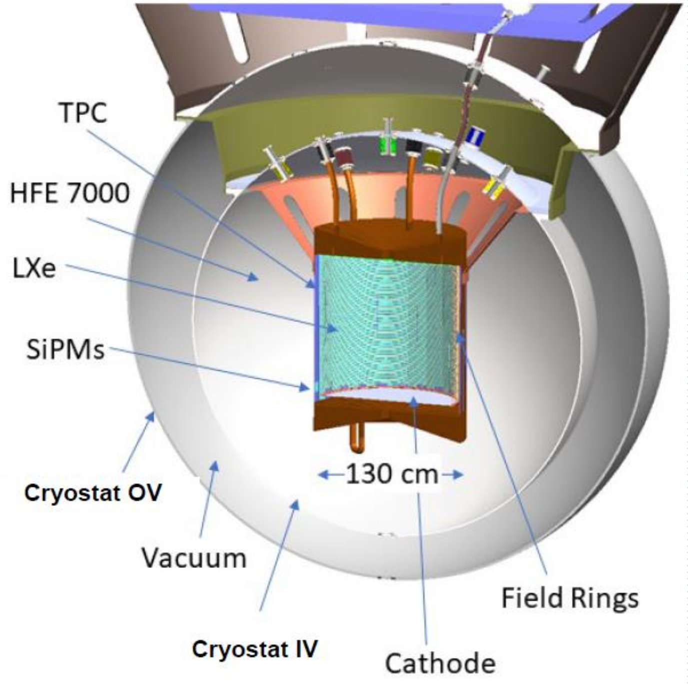
A monoenergetic peak at the Q-value is searched for.
Need a large amount of decay isotope and low radioactive environment

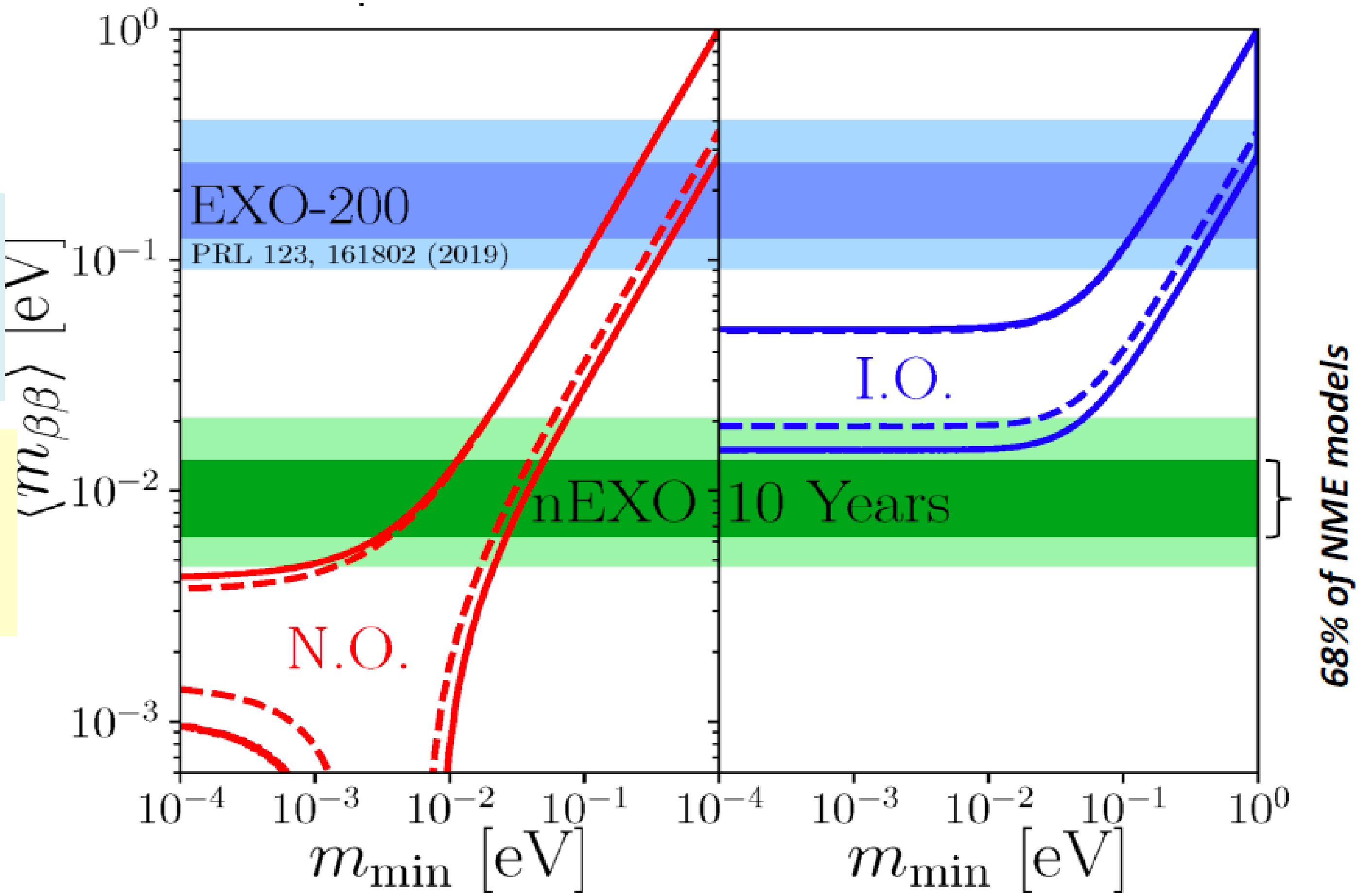
Experiment	Isotope	Exposure [kg yr]	$T^{0\nu}_{1/2}[10^{25}$ yr]	$m_{\beta\beta}$ [meV]
Gerda	^{76}Ge	127.2	18	79-180
Majorana	^{76}Ge	26	2.7	200-433
CUPID-0	^{82}Se	5.29	0.47	276-570
NEMO3	^{100}Mo	34.3	0.15	620-1000
CUPID-Mo	^{100}Mo	2.71	0.18	280-490
Amore	^{100}Mo	111	0.095	1200-2100
CUORE	^{130}Te	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.

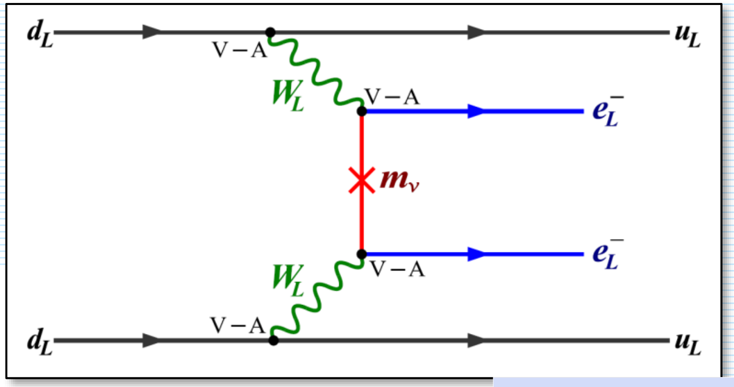
nEXO, discovery 0νββ experiment, reaches sensitivity of 10^{28} yr in 6.5 yr data taking, probes $m_{\beta\beta}$ down to 15 meV, scalable experiment.

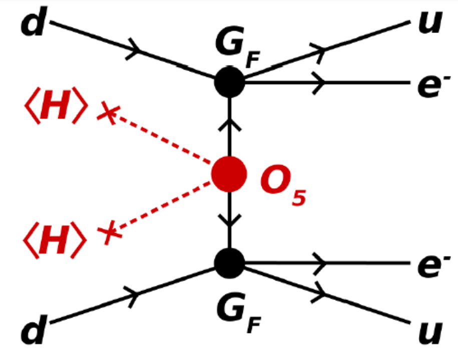




	isotope	$m_{\beta\beta}$ [meV] 90% excl. sensitivity	$m_{\beta\beta}$ [meV] 3 σ discovery potential
Legend	^{76}Se	8.2	11.1
CUPID	^{100}Mo	11.1	12.0
nEXO	^{136}Xe	12.9	15.0

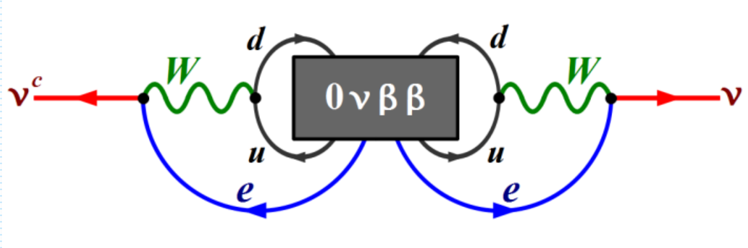
$0\nu\beta\beta$ governed by exotic mechanisms





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

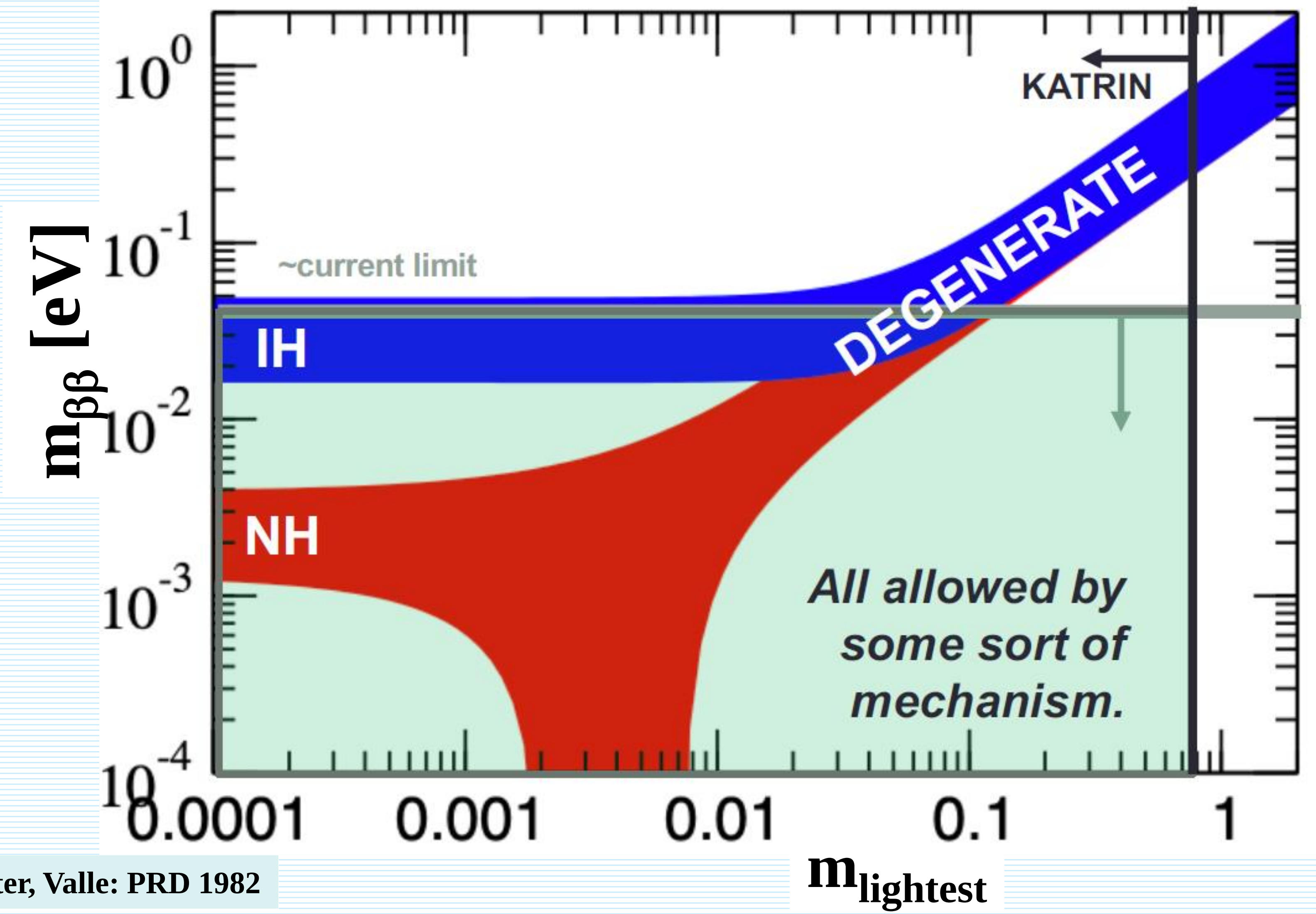
Any $0\nu\beta\beta$ mech. generates a small correction to ν-mass



Schechter, Valle: PRD 1982

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

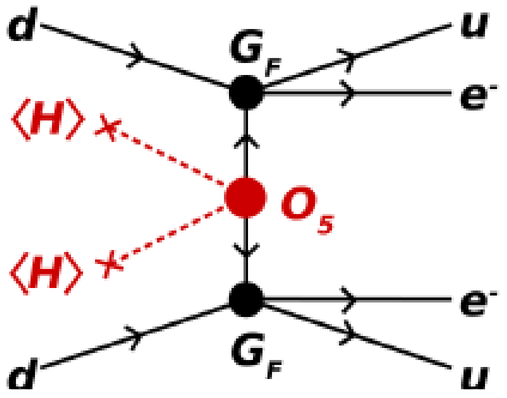


Beyond the SM physics

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

Amplitude for $(A,Z)\rightarrow(A,Z+2)+2e^-$ can be divided into:

mass mechanism: d=5

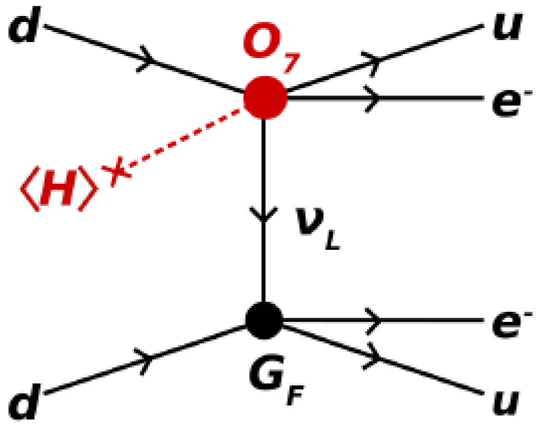


$$\mathcal{O}_W \propto \frac{c_{ij}}{\Lambda}(L_i H)(L_j H)$$

Weinberg, 1979

+

long range: d=7

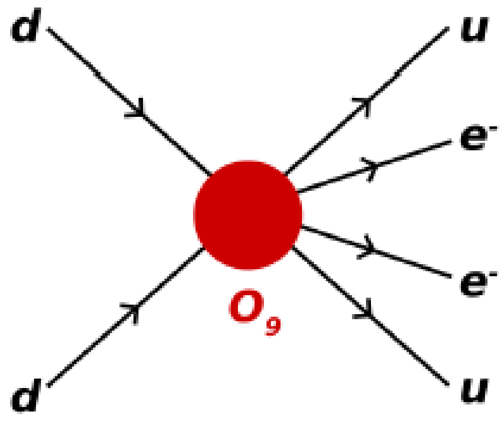


$$\mathcal{O}_2 \propto LLLe^cH$$
$$\mathcal{O}_3 \propto LLQd^cH$$
$$\mathcal{O}_4 \propto LL\bar{Q}\bar{u}^cH$$
$$\mathcal{O}_8 \propto L\bar{e}^c\bar{u}^cd^cH$$

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**.

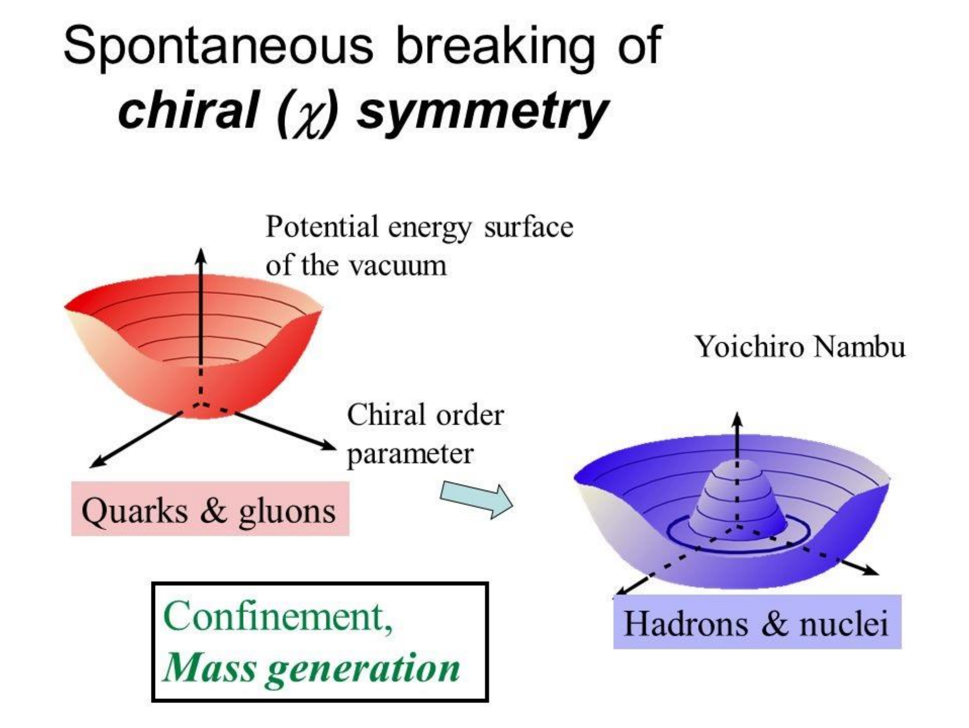
The SM gauge-invariant effective operators

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

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

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

$$\begin{aligned} g_{\alpha\beta} &= g^u_{\alpha\beta} + g^d_{\alpha\beta}, \quad v/\sqrt{2} = \langle H^0 \rangle \\ \omega &= -\langle \overline{q} q \rangle^{1/3}, \quad \langle \overline{q} q \rangle^{1/3} \approx -283\ \mathrm{MeV} \end{aligned}$$



$\Lambda \sim$ **a few TeV**
we get the neutrino mass in the **sub-eV** ballpark

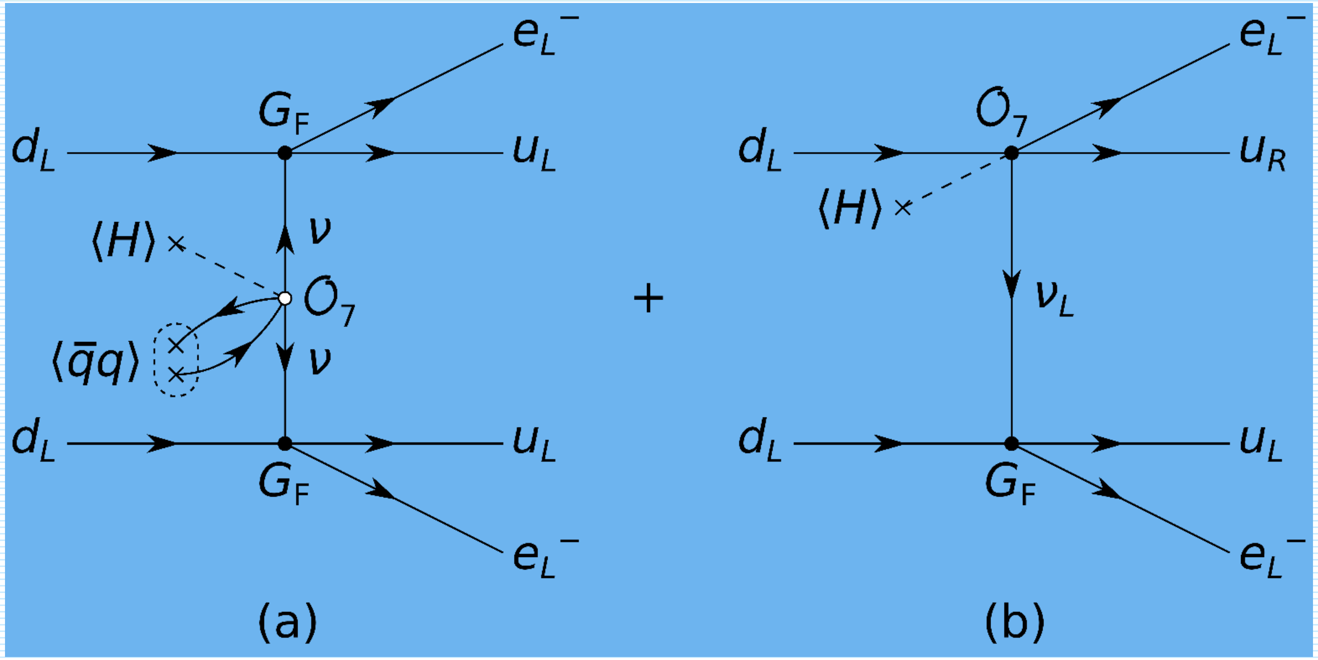
The genuine QCSS scenario
(predicts NH and ν-mass spectrum)

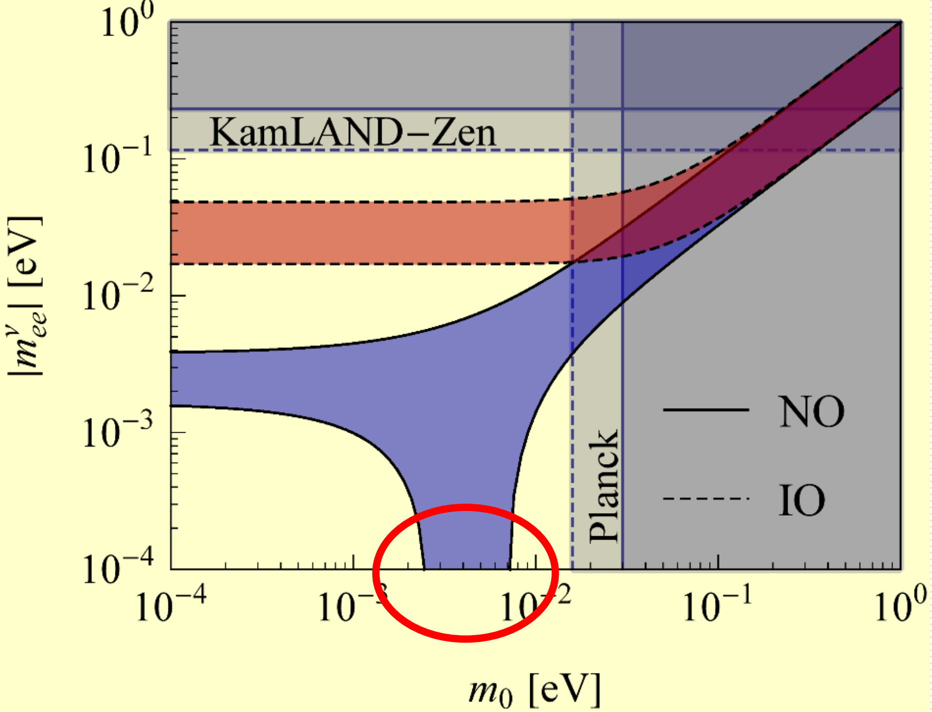
$$\mathcal{L}_7 = \frac{1}{\sqrt{2}} \sum_{\alpha\beta} \frac{v}{\Lambda^3} \overline{\nu^C_{\alpha L}} \nu_{\beta L} (g^u_{\alpha\beta} \overline{u_L} u_R + g^d_{\alpha\beta} \overline{d_R} d_L) + \text{H.c.}$$

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

(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)

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

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

3 Dirac masses and 1 universal Majorana mass splitting ε

Oscillation probabilities among active neutrinos

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

The survival probability of electron antineutrinos

Quasi-Dirac neutrinos and constraints on neutrino masses

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

Tritium β-decay

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

Cosmology

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

Restriction from Daya-Bay data (3σ):

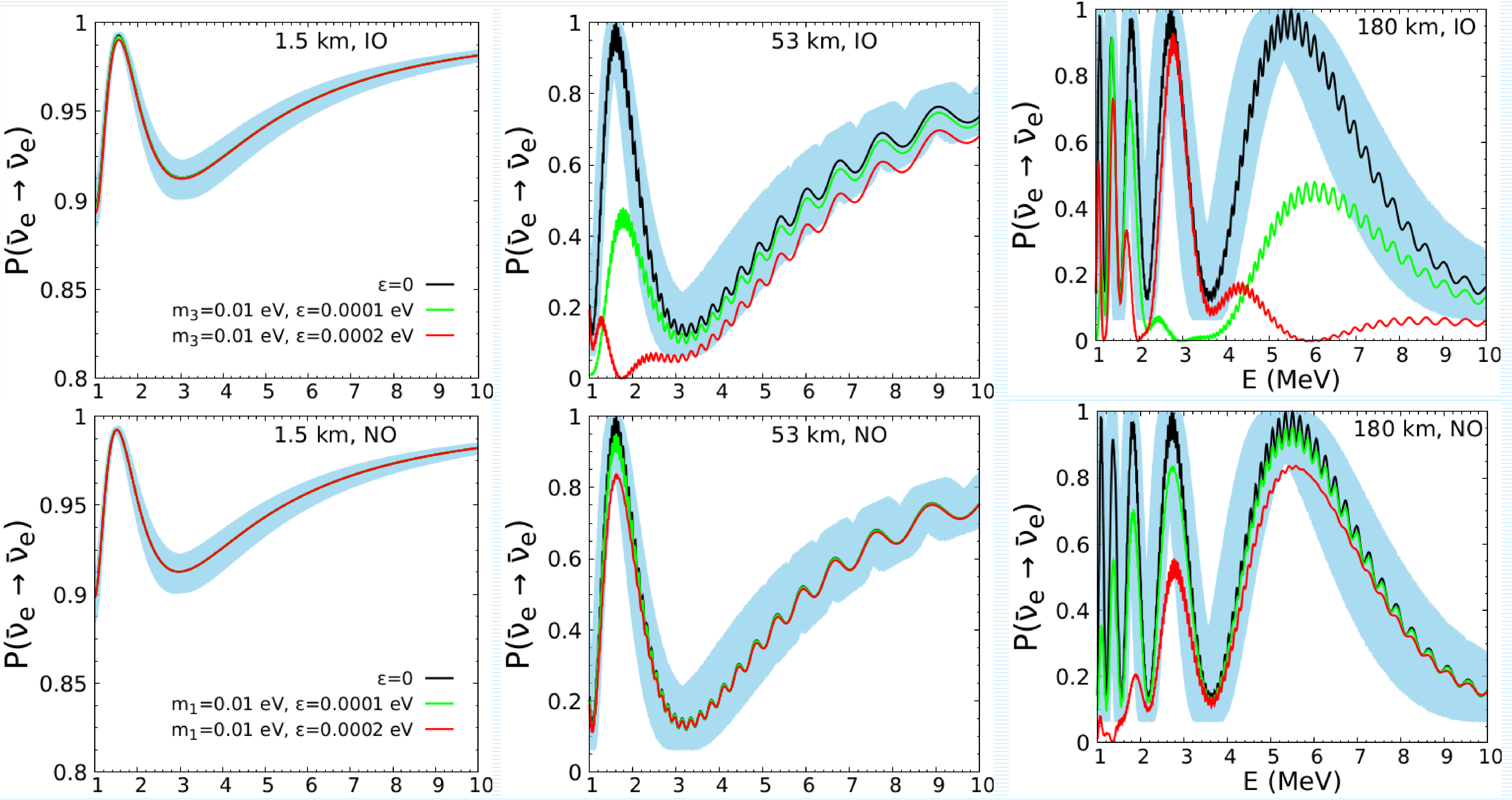
Survival probabilities with non-zero ε are the same 3ν cases.

0νββ-decay

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

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

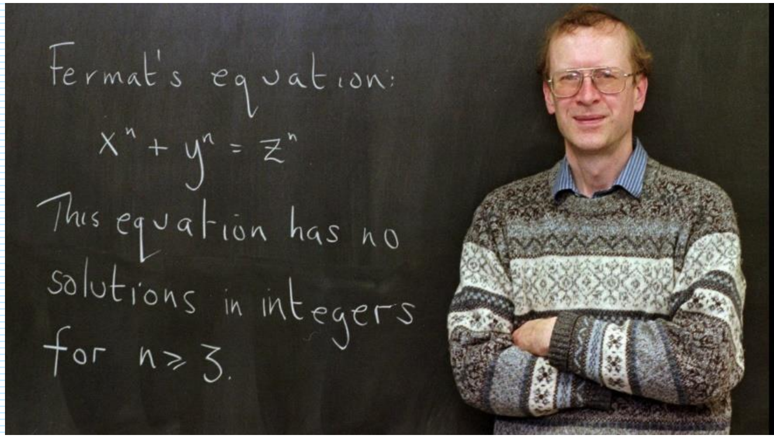
Quasi-Dirac neutrino oscillations at different distances



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

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

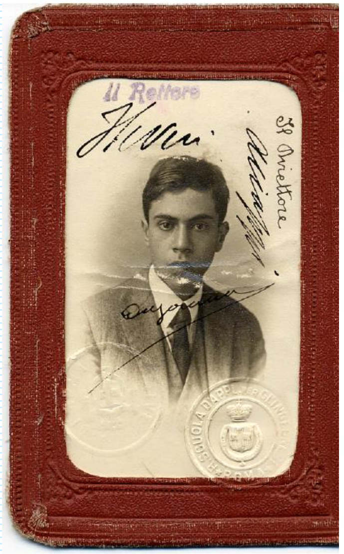
had no solutions in positive integers if n is an integer greater than 2.

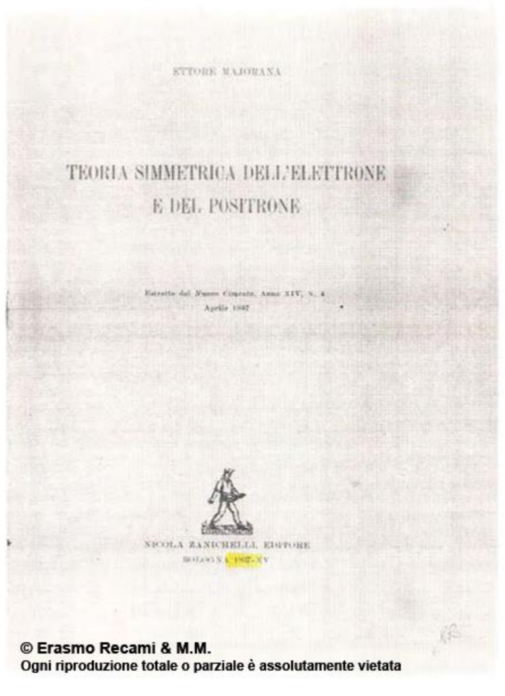


After **358** years

The proof was published by Andrew Wiles in 1995.

Some long-standing tasks of humanity …





1937

After **85** years

n-ton-class $0\nu\beta\beta$ 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 $0\nu\beta\beta$?

Evaluation of the $0\nu\beta\beta$-decay NMEs calculation - Approximations needed

The nuclear w. f. of
(A,Z), (A,Z+1)*, (A,Z+2)
Many-body methods
of choice:

Nuclear Shell Model (Madrid-Strasbourg, Michigan, Tokyo): Relatively small model space (1 shell), all correlations included, solved by direct diagonalization

QRPA (Tuebingen-Bratislava-Calltech, Jyvaskyla, Chapel Hill, Lanzhou): Several major shells, only simple correlations included

Interacting Boson Method (Yale-Concepcion): Small space, important proton-neutron Pairing correlations missing

Projected Hartree-Fock-Bogoliubov Method (Lucknow): Several major shells, missing GT proton-neutron residual interaction.

Energy Density Functional theory (Madrid, Beijing): >10 shells, important proton-neutron pairing missing

An initio approaches:

The $0\nu\beta\beta$ nuclear transition operators
(F, GT, and tensor type):

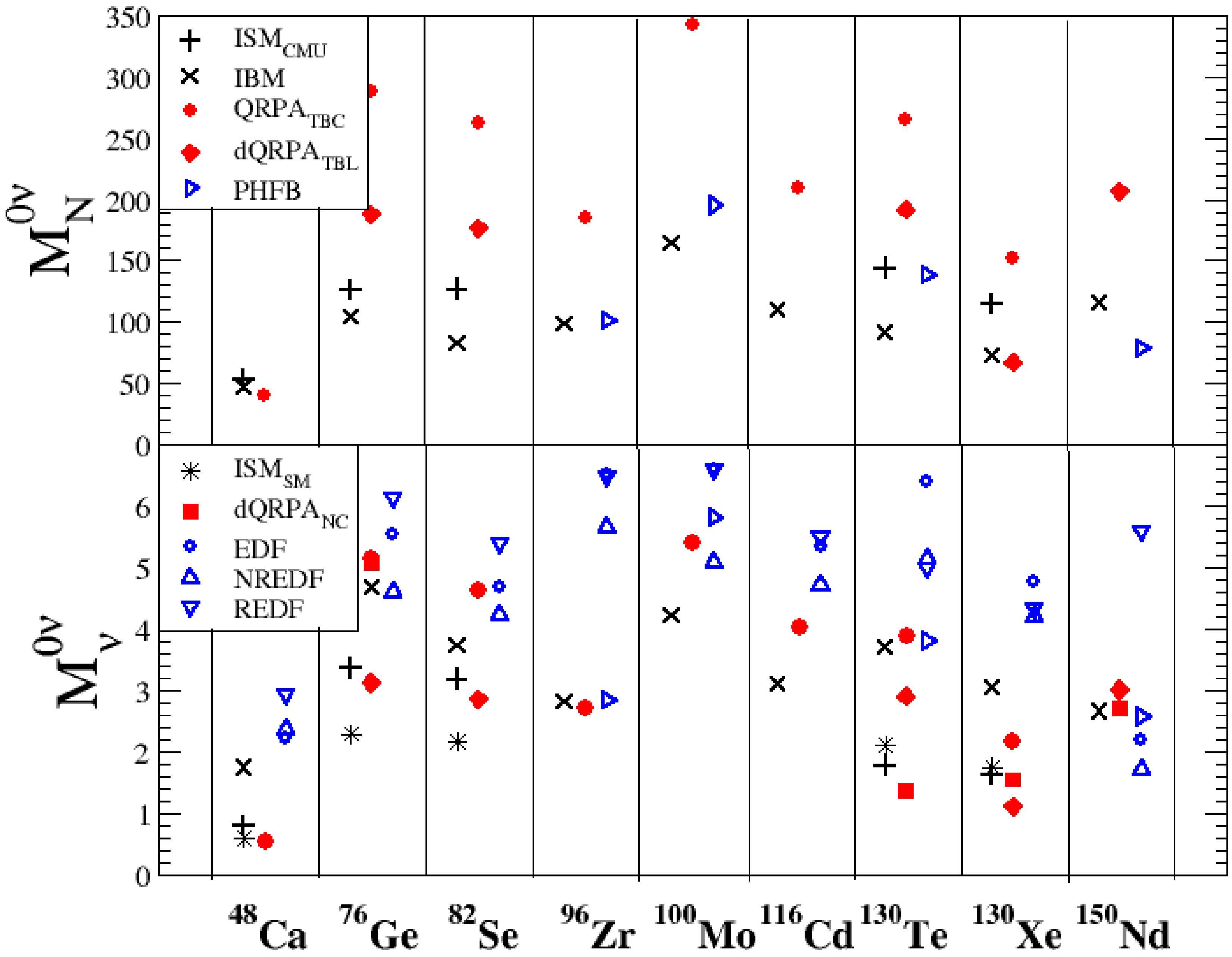
+ Transiton operators involving complete set of states of intermediate nucleus
+ Transition operators in closure approximation – just two-body operators
+ Chiral effective field theory two-body transition operators with contact term

! Isospin, and spin-isospin symmetries
($M_{Fcl}\approx 0$, M_{GTcl} strongly suppressed):

Initial 0^+ g.s.: (T, T)
Final 0^+ g.s.: (T-2, T-2) $\Rightarrow$ $\Delta T = 2$ (!)

Till now, this issue addressed only within the QRPA
PRC 98, 064325 (2018)

$0\nu\beta\beta$-decay NME status 2022



unquenched g_A

All models missing essential physics

Impossible to assign rigorous uncertainties

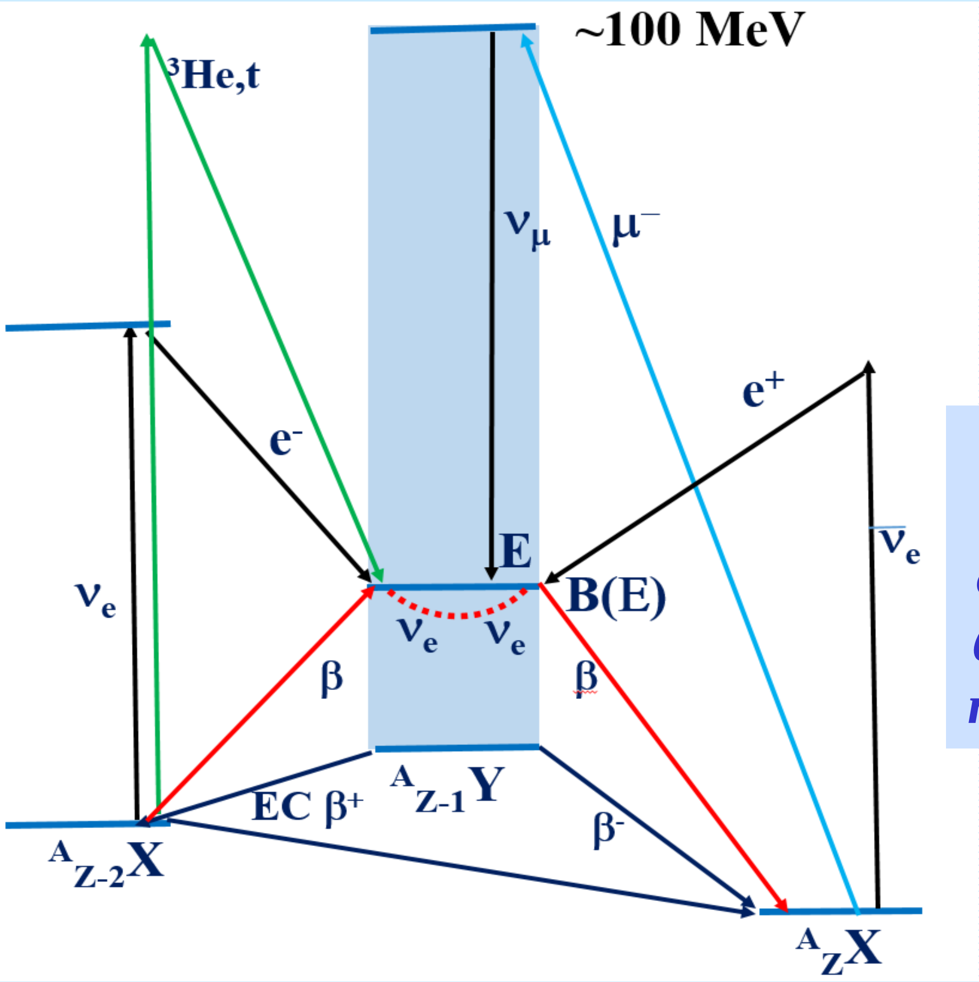
Differencies:

- **Many-body approxim.**
- **Size of the m.s.**
- **Residual interactions**

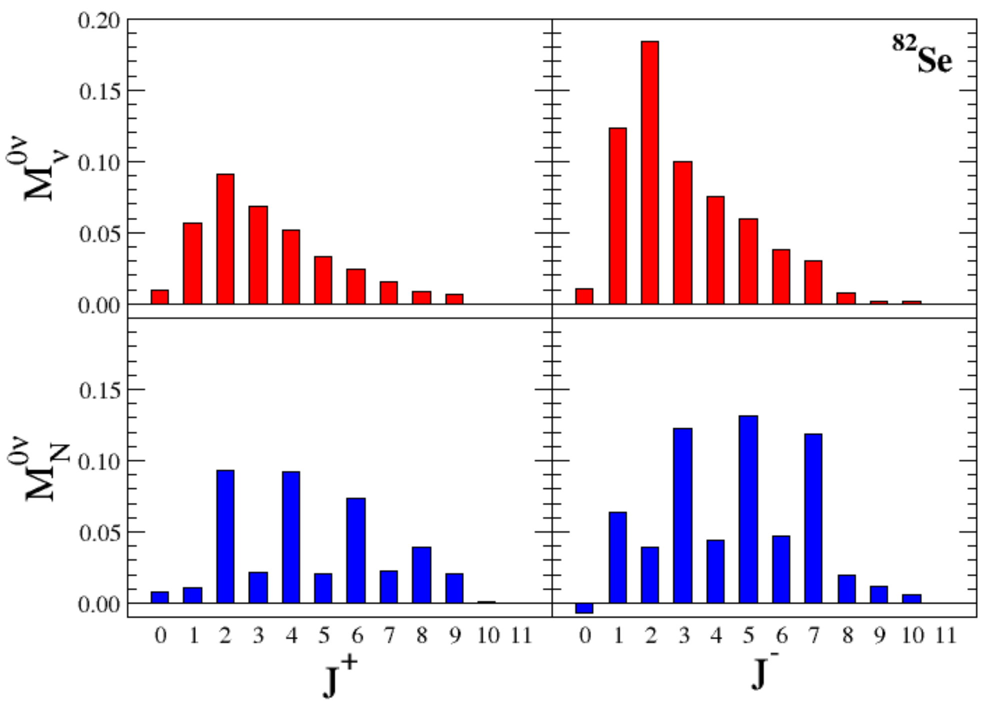
Supporting nuclear physics experiments

(Measurements still not conclusive for 0νββ NME)

- ✓β-decay, EC and 2νββ decay
- ✓μ-capture
- ✓(π+, π-), single charge exchange
- ✓ (3He,t), (d,2He), transfer reactions
- ✓γ-ray spectroscopy, γγ-decay
- ✓A promising experimental tool: **Heavy-Ion Double Charge-Exchange**



Multipole decomposition of light and heavy 0νββ-decay NMEs normalized to unity

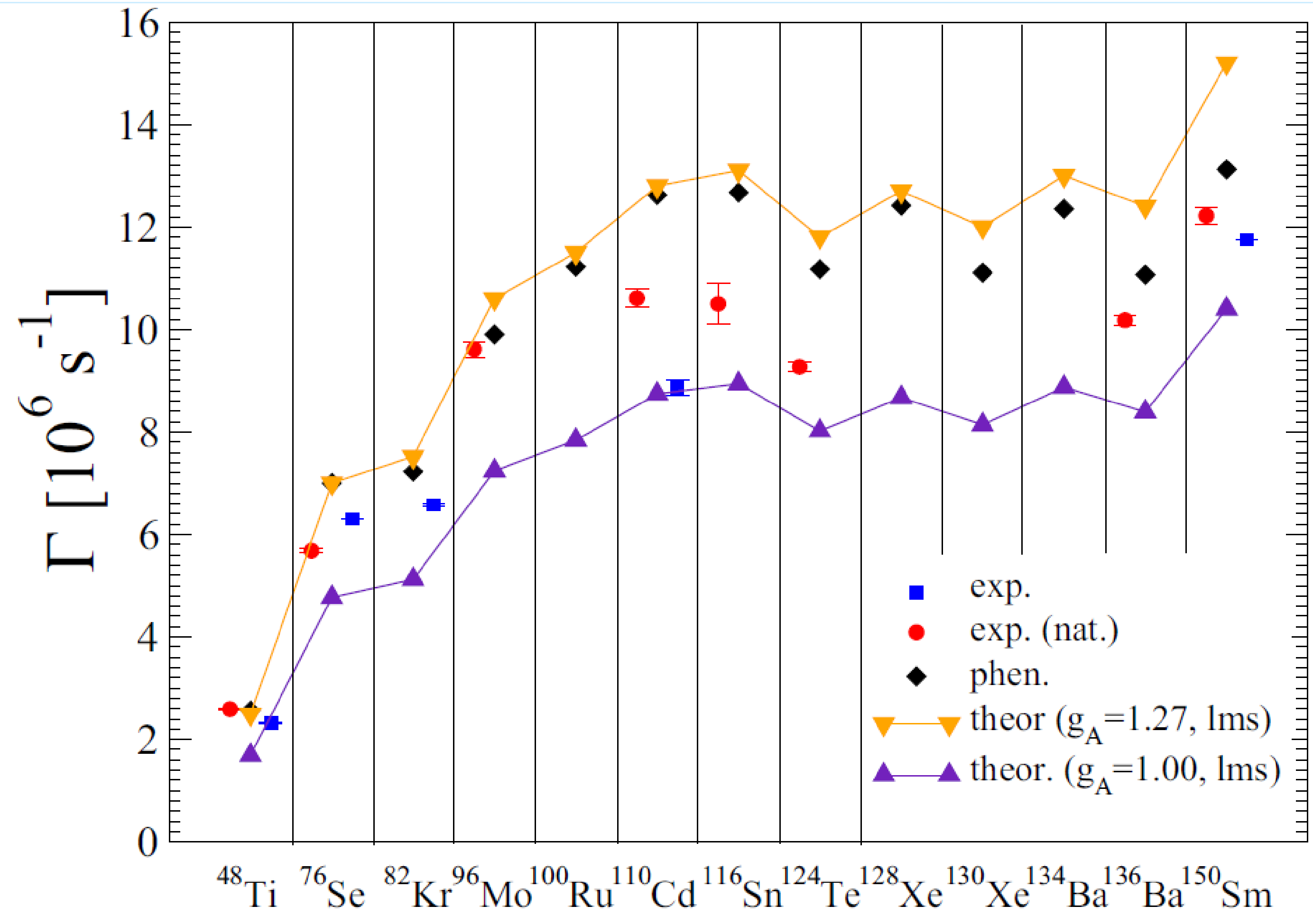


Higher multiploles are populated mostly due large ν-momenta transfer

Fedor Simkovic

Muon capture rates evaluated within QRPA

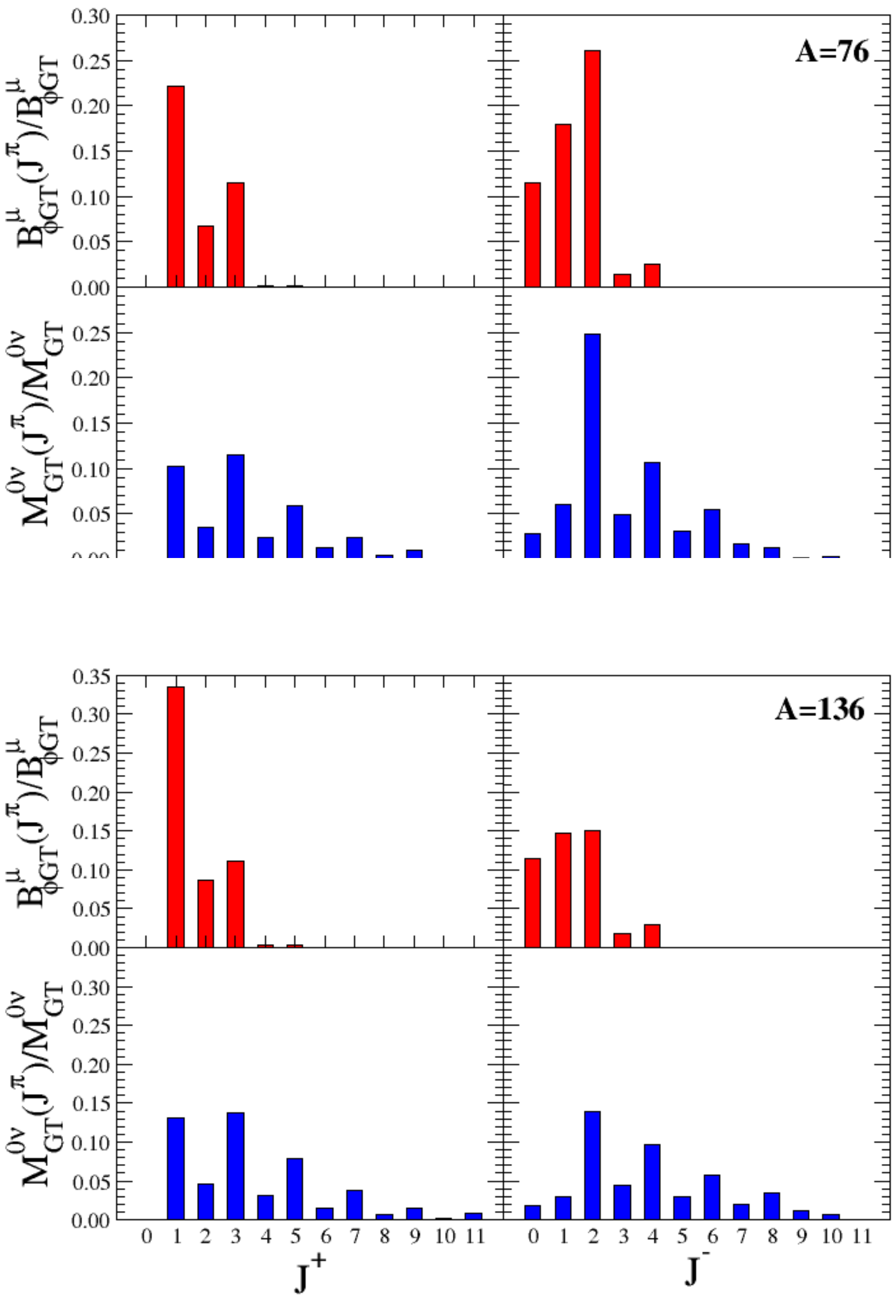
In agreement with soft quenching ($g_A \approx 1.1$)



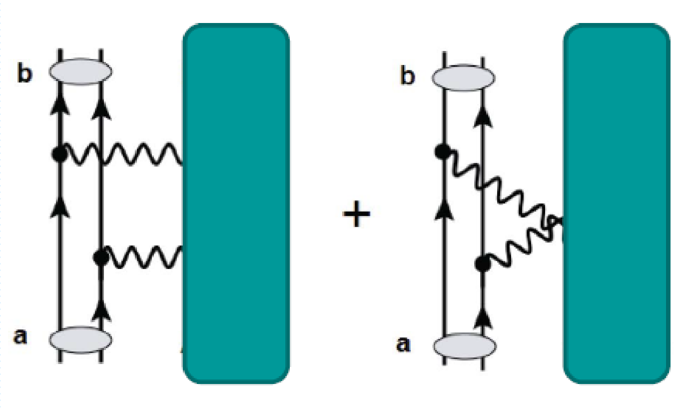
PRC 102, 034301 (2020).

7/13/2023

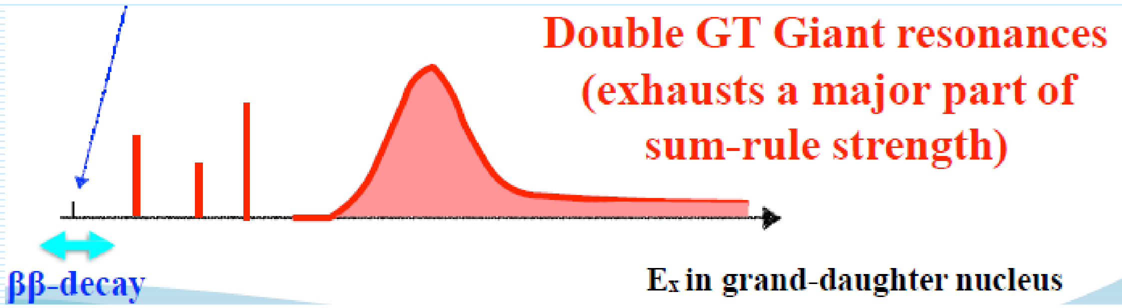
Experiment Monument at PSI will study contributions from all multipoles



Multipole decomposition of B^{μ}_{GT} and $M^{0\nu}_{GT}$

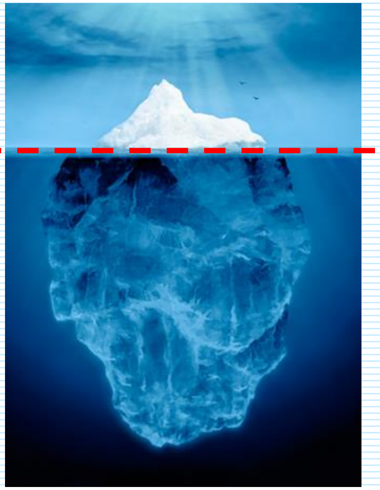


Heavy-ion DCE as surrogate processes of ββ-decay



- ✓ Induced by strong interaction
- ✓ Sequential nucleon transfer mechanism 4th order: Kinematical matching
- ✓ Meson exchange mechanism 1st or 2nd order
- ✓ Possibility to go in both directions
- ✓ Low cross section

Tiny amount of DGT strenght for low lying states



NUMEN

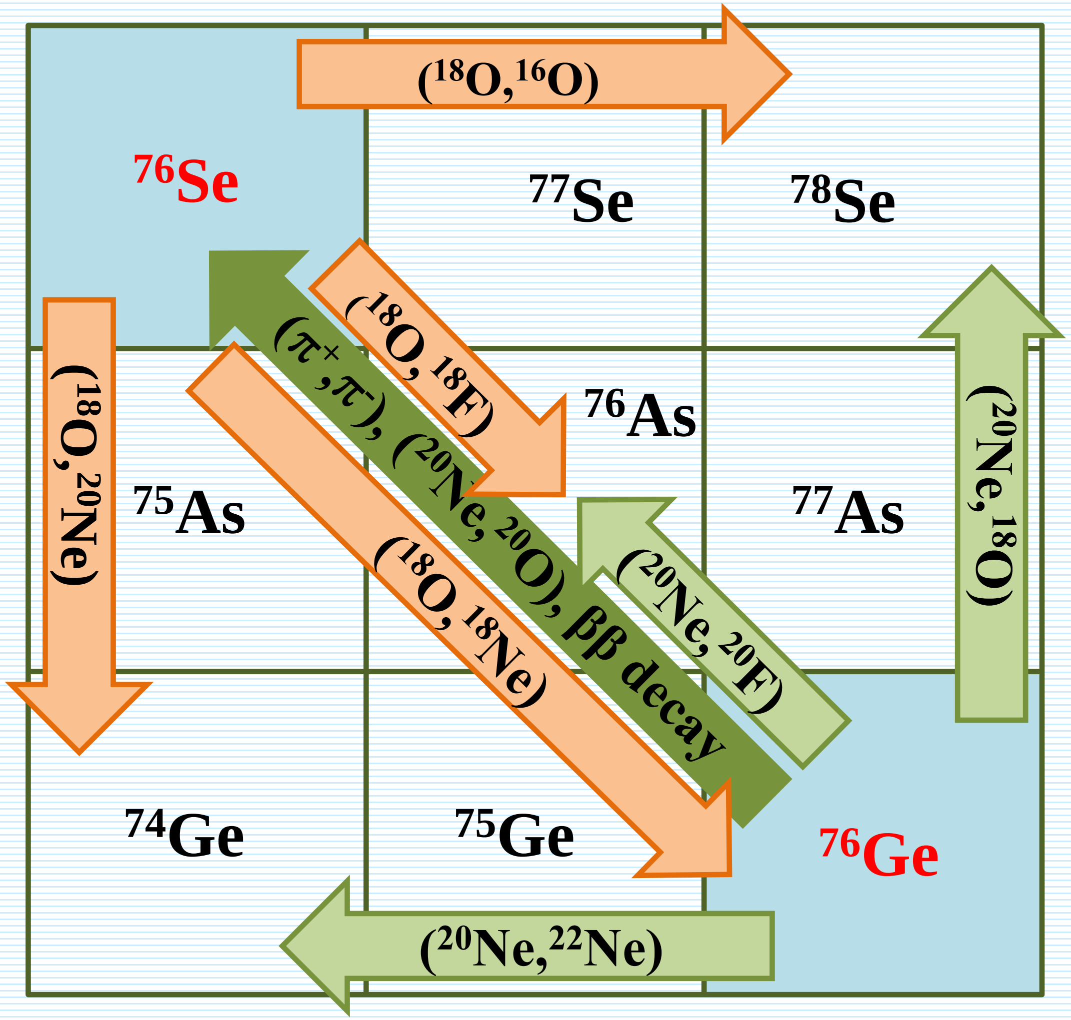
erc NURE

Sum rule almost exhausted by DGT Giant Mode, still not observed

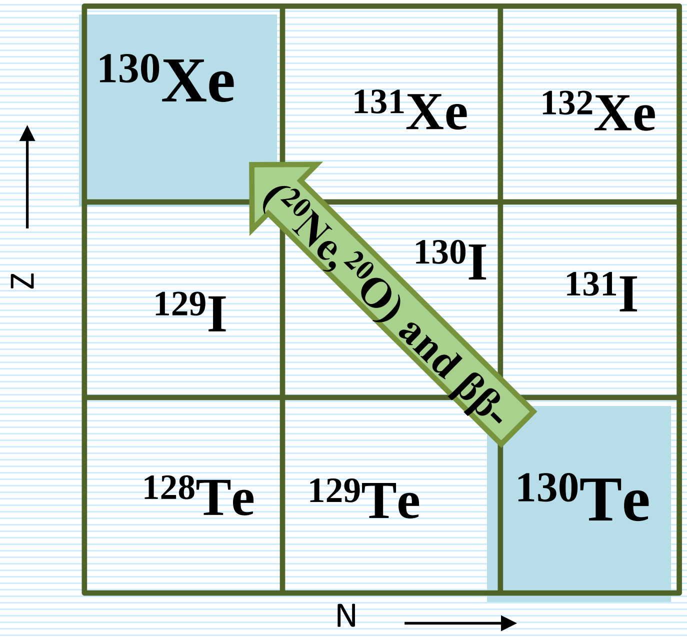
RIKEN

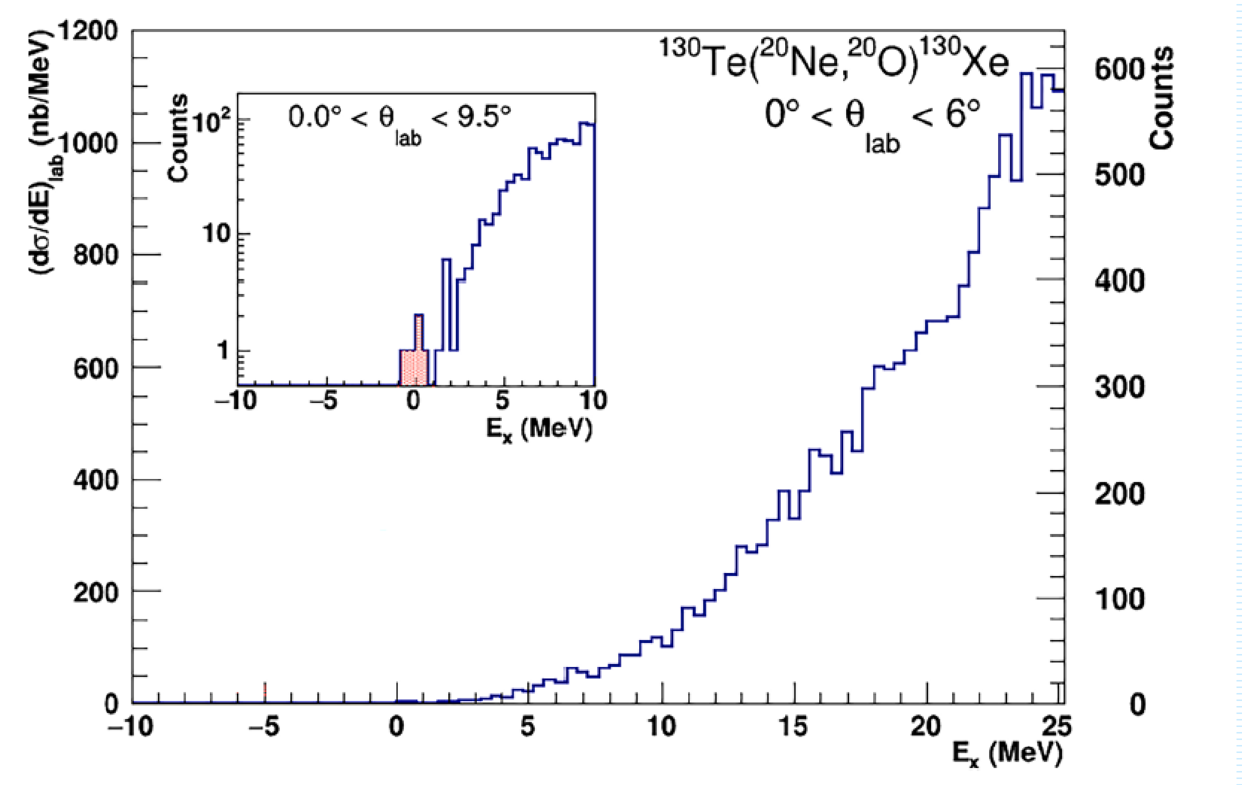
RCNP

Future: INFN-LNS



The $^{130}Te(^{20}Ne,^{20}O)^{130}Xe$ DCE reaction





- g.s. → g.s. transition maybe isolated
- Absolute cross section measured

Resolution ~ 500 keV FWHM

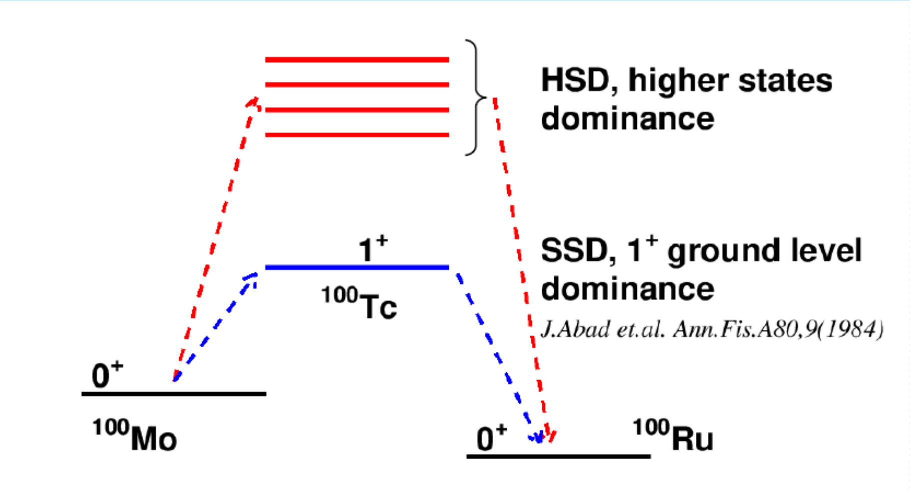
No spurious counts at $-10 < E_x < -2$ MeV

State (MeV)	Counts	Absolute coss section (nb)	Cross section 95% limit (nb)
g.s. (0^+) + 2^+ (536 keV)	5	13	[3--18]

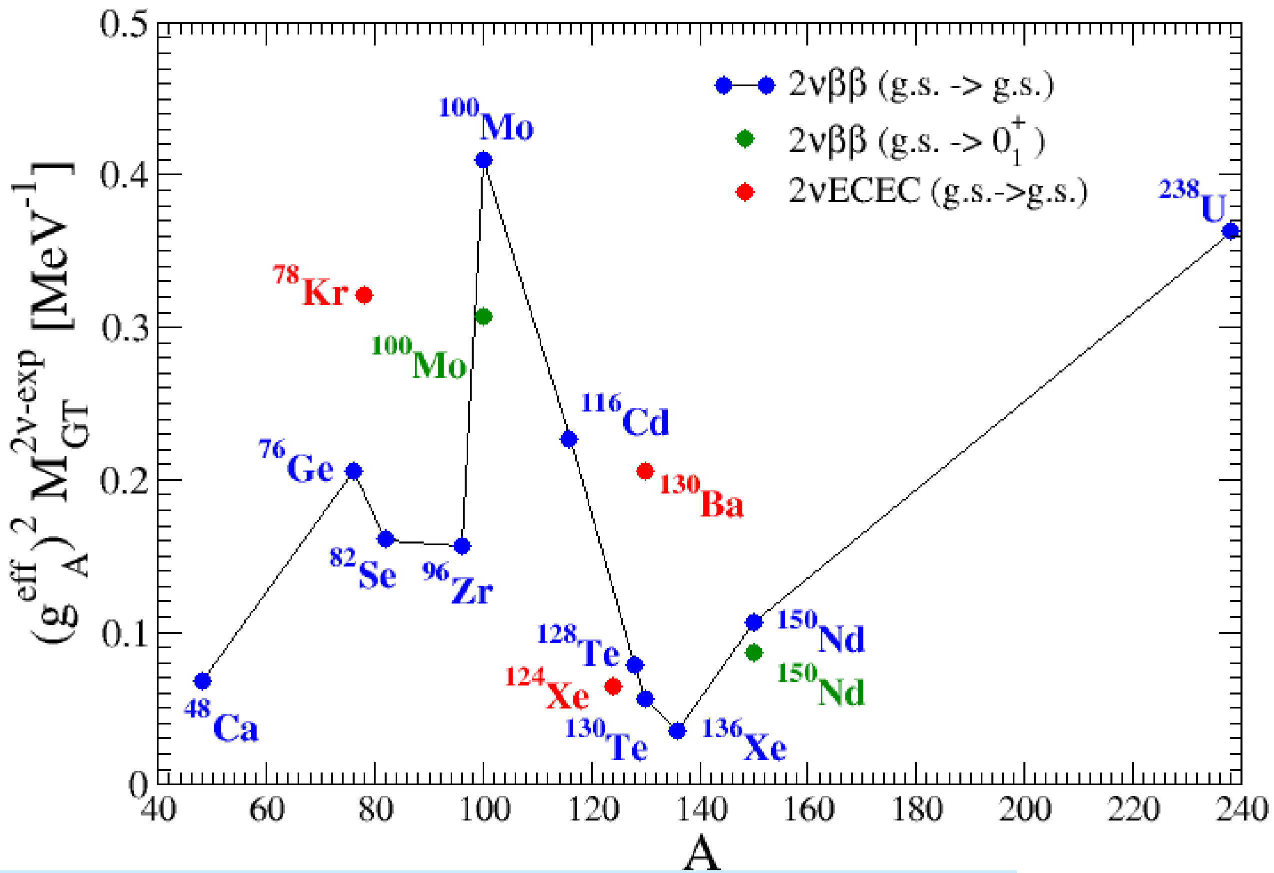
Analysis of cross-section sensitivity < 0.1 nb in the Region Of Interest

Understanding of the 2νββ-decay NMEs is of crucial importance for correct evaluation of the 0νββ-decay NMEs

There is no reliable calculation of the *2νββ-decay NMEs yet*



$$M_{GT}^{2\nu} = \sum_m \frac{< 0_f^+ ||\tau^+\sigma|| 1_m^+ >< 1_m^+ ||\tau^+\sigma|| 0_i^+ >}{E_m - E_i + \Delta}$$



The spread of 2νββ and 0νββ NMEs is large and small, respectively.
Reasons:

- **2νββ NMEs governed by contribution from single (1^+) multipole unlike 0νββ NMEs by contributions from all multipoles (J^π) of int. nucl.**
- **Neutrino potential vs 2νββ potential**

Both 2νββ and 0νββ operators connect the same states. Both change two neutrons into two protons. Explaining 2νββ-decay is necessary but not sufficient

Improved description of the 0νββ–decay rate (a way to fix g_A^{eff})

PRC 97, 034315 (2018)

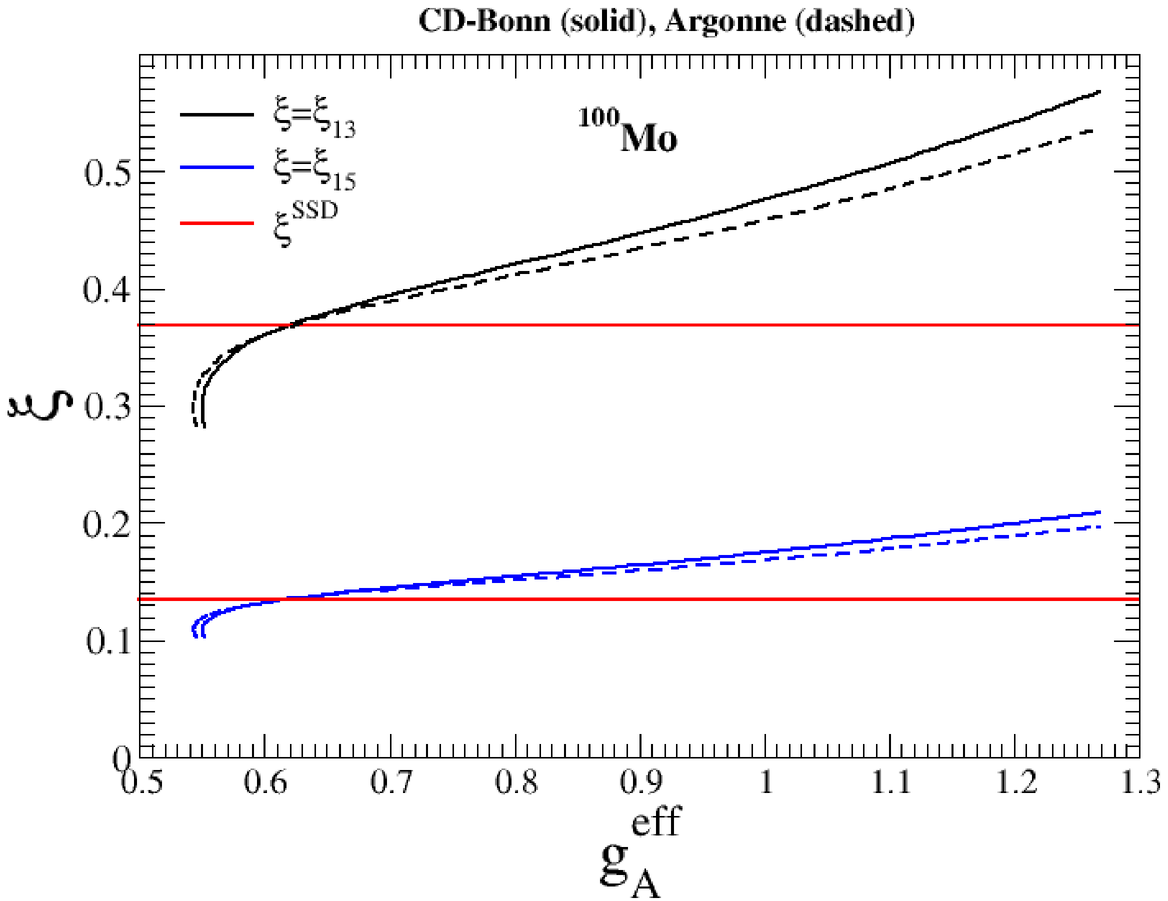
$$\left[T_{1/2}^{2\nu\beta\beta}\right]^{-1} \simeq \left(g_A^{\rm eff}\right)^4 \left|M_{GT-3}^{2\nu}\right|^2 \frac{1}{\left|\xi_{13}^{2\nu}\right|^2}\left(G_0^{2\nu} + \xi_{13}^{2\nu} G_2^{2\nu}\right)$$

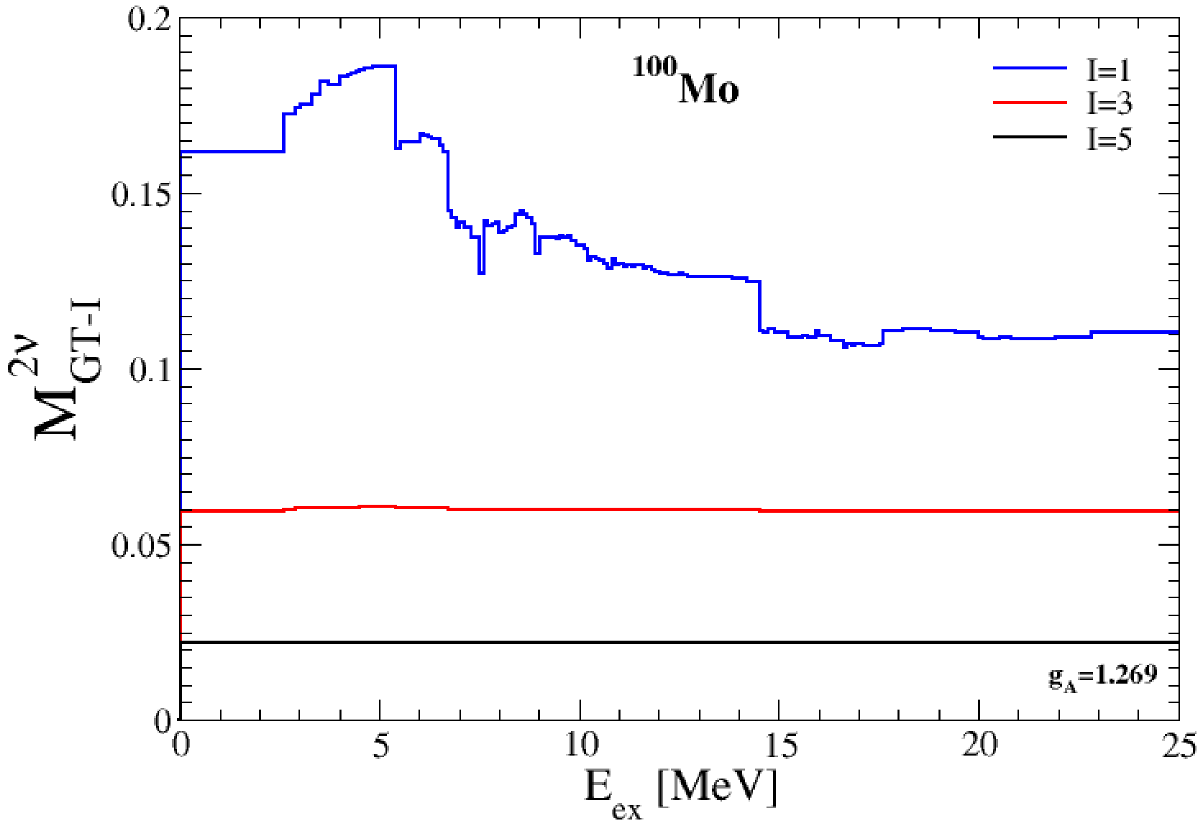
$$M_{GT}^{K,L} = m_e \sum_n M_n \frac{E_n - (E_i+E_f)/2}{[E_n - (E_i+E_f)/2]^2 - \varepsilon_{K,L}^2}$$

$$M_{GT-1}^{2\nu} = \sum_n M_n \frac{1}{(E_n - (E_i+E_f)/2}$$

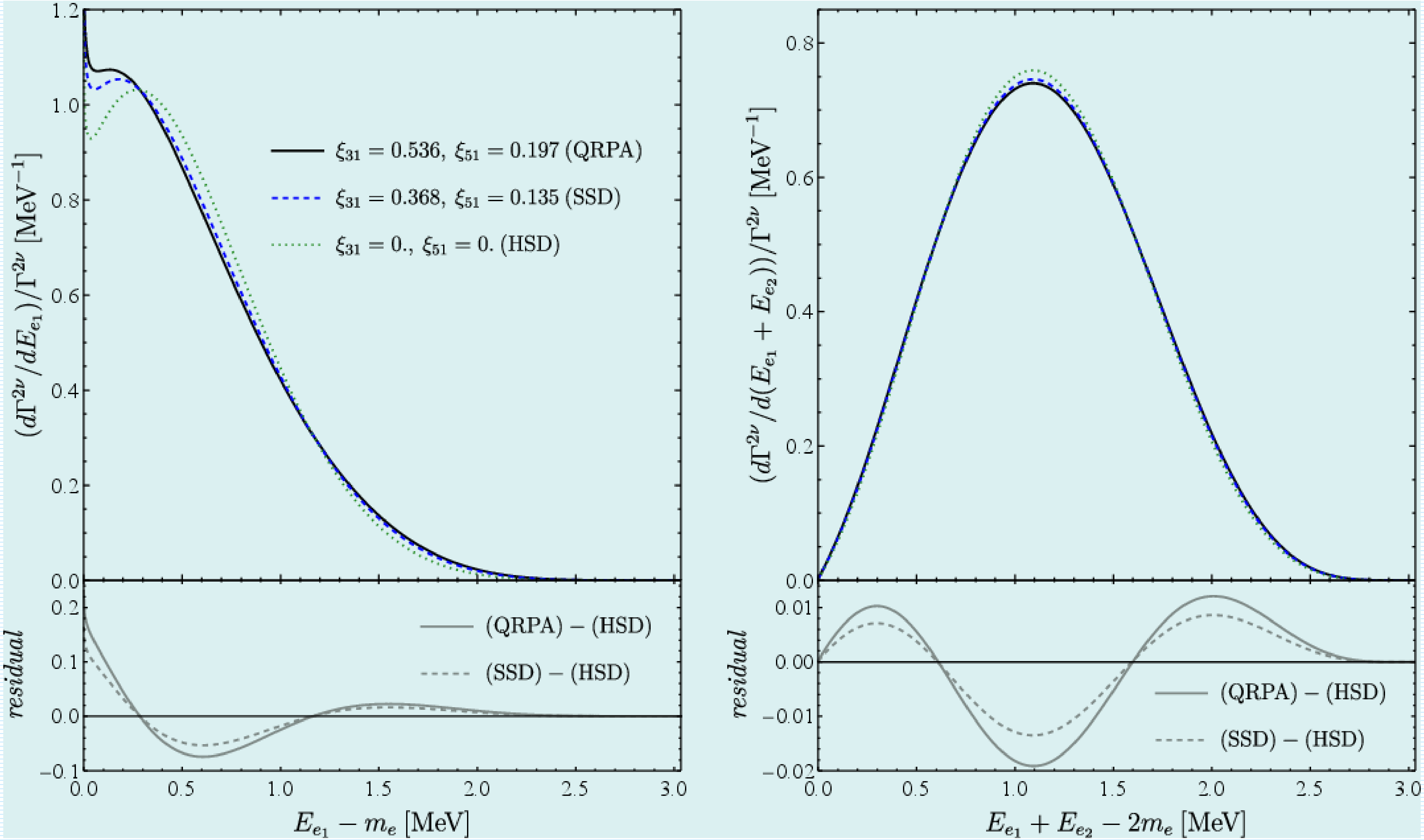
$$M_{GT-3}^{2\nu} = \sum_n M_n \frac{4\ m_e^3}{(E_n - (E_i+E_f)/2)^3}$$

$$\xi_{13}^{2\nu} = \frac{M_{GT-3}^{2\nu}}{M_{GT-1}^{2\nu}} \qquad \xi_{15}^{2\nu} = \frac{M_{GT-5}^{2\nu}}{M_{GT-1}^{2\nu}}$$





Determining g_A from the $2\nu\beta\beta$ differential characteristics



$2\nu\beta\beta$ is sensitive to New Physics as well

All 100 kg- and ton-class $0\nu\beta\beta$ experiments can also study a diverse range of exotic phenomena, e.g. through spectral distortion in $2\nu\beta\beta$.
Future searches will probe the $2\nu\beta\beta$ with high statistics about 10^5-10^6 events.

Common subjects:

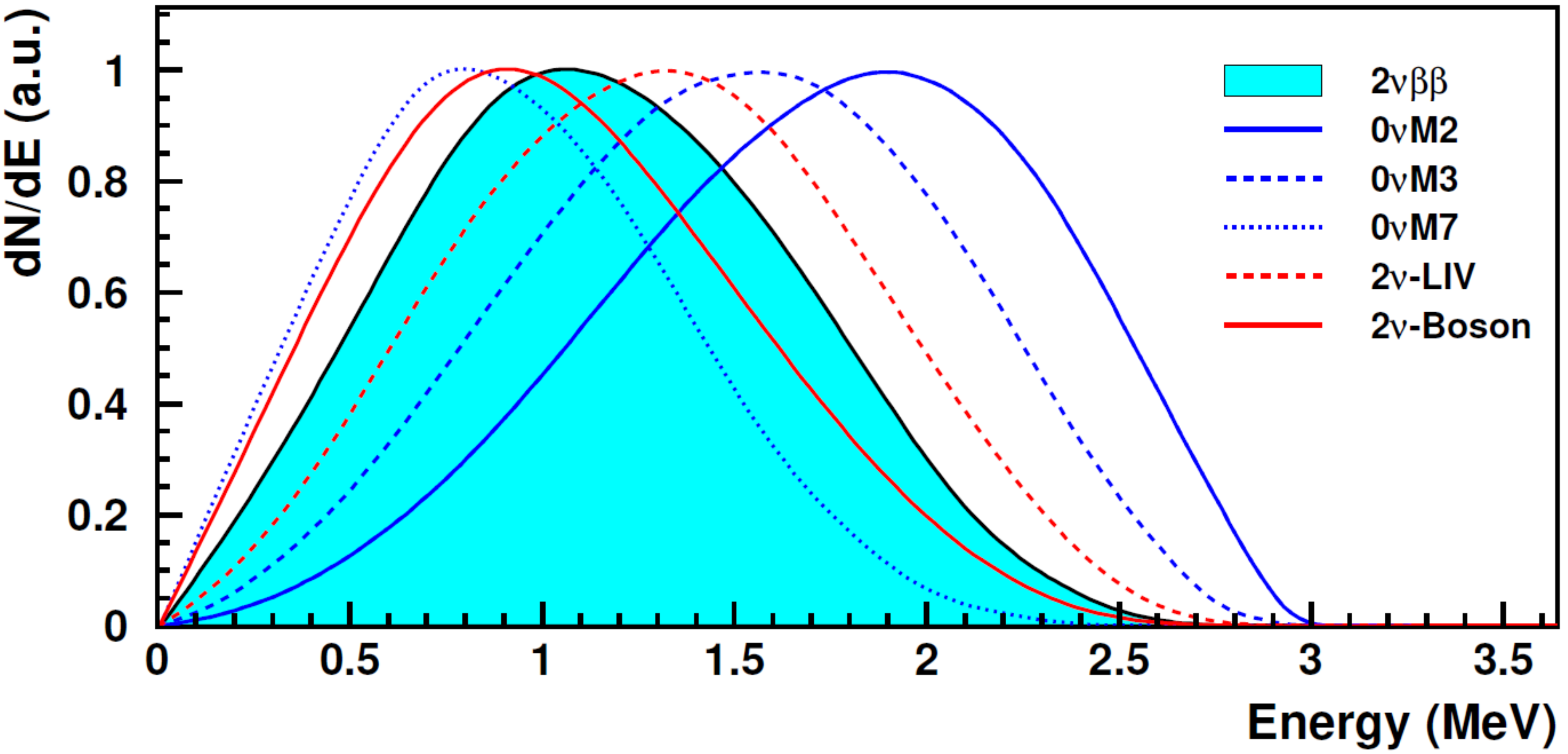
Majoron(s) emission
(partly)bosonic neutrinos,
Lorentz invariance violation

Recent subjects:

Lepton-number conserving right-handed currents
(PRL 125 (2020) 17, 171801)

Neutrino self-interactions
(PRD 102 (2020) 5, 051701)

Sterile neutrino and light fermion searches through energy end point
(PRD 103 (2021) 5, 055019; PLB 815 (2021) 136127)



$$\frac{d\Gamma}{d\varepsilon_1 d\varepsilon_2} = C(Q - \varepsilon_1 - \varepsilon_2)^n \left[p_1\varepsilon_1 F(\varepsilon_1)\right] \left[p_2\varepsilon_2 F(\varepsilon_2)\right]$$

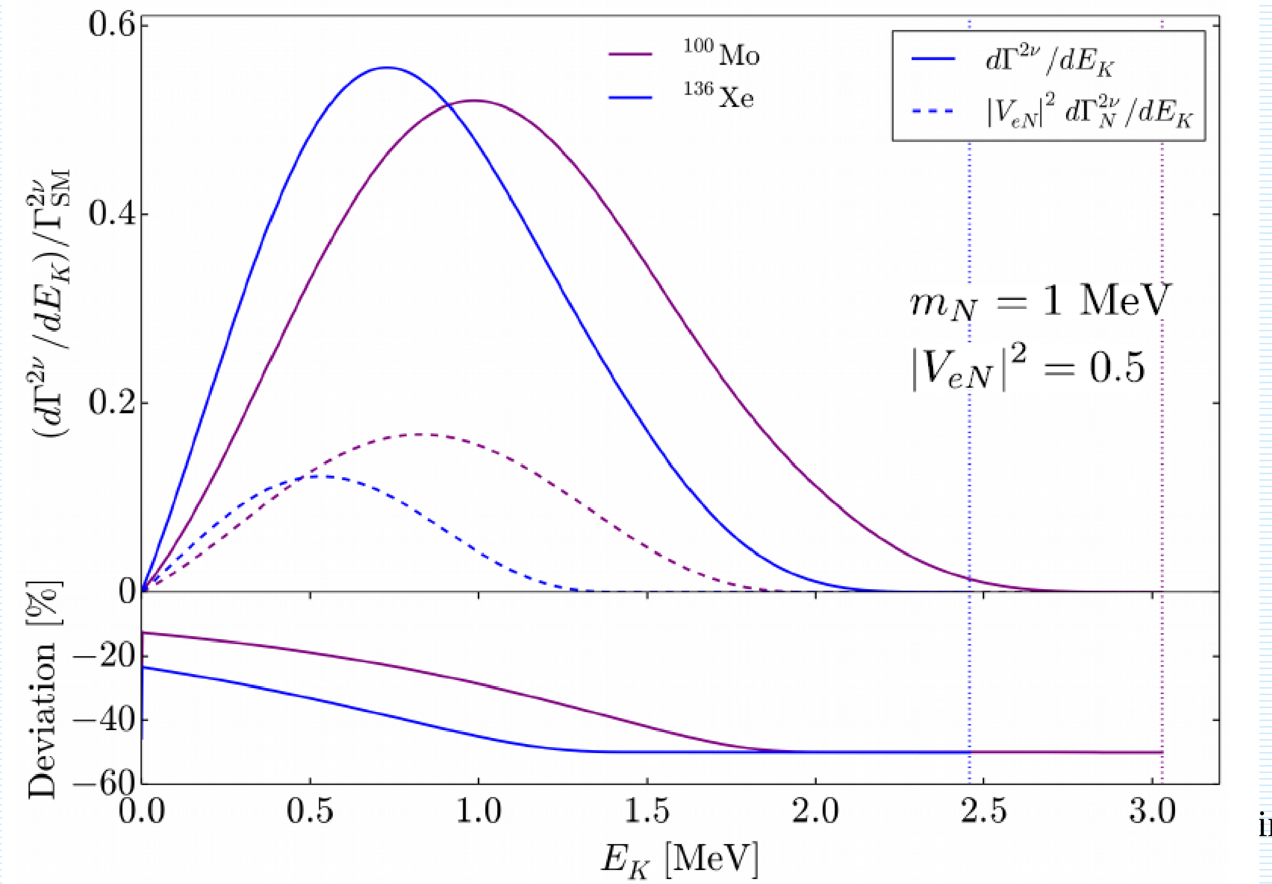
Spectral index n

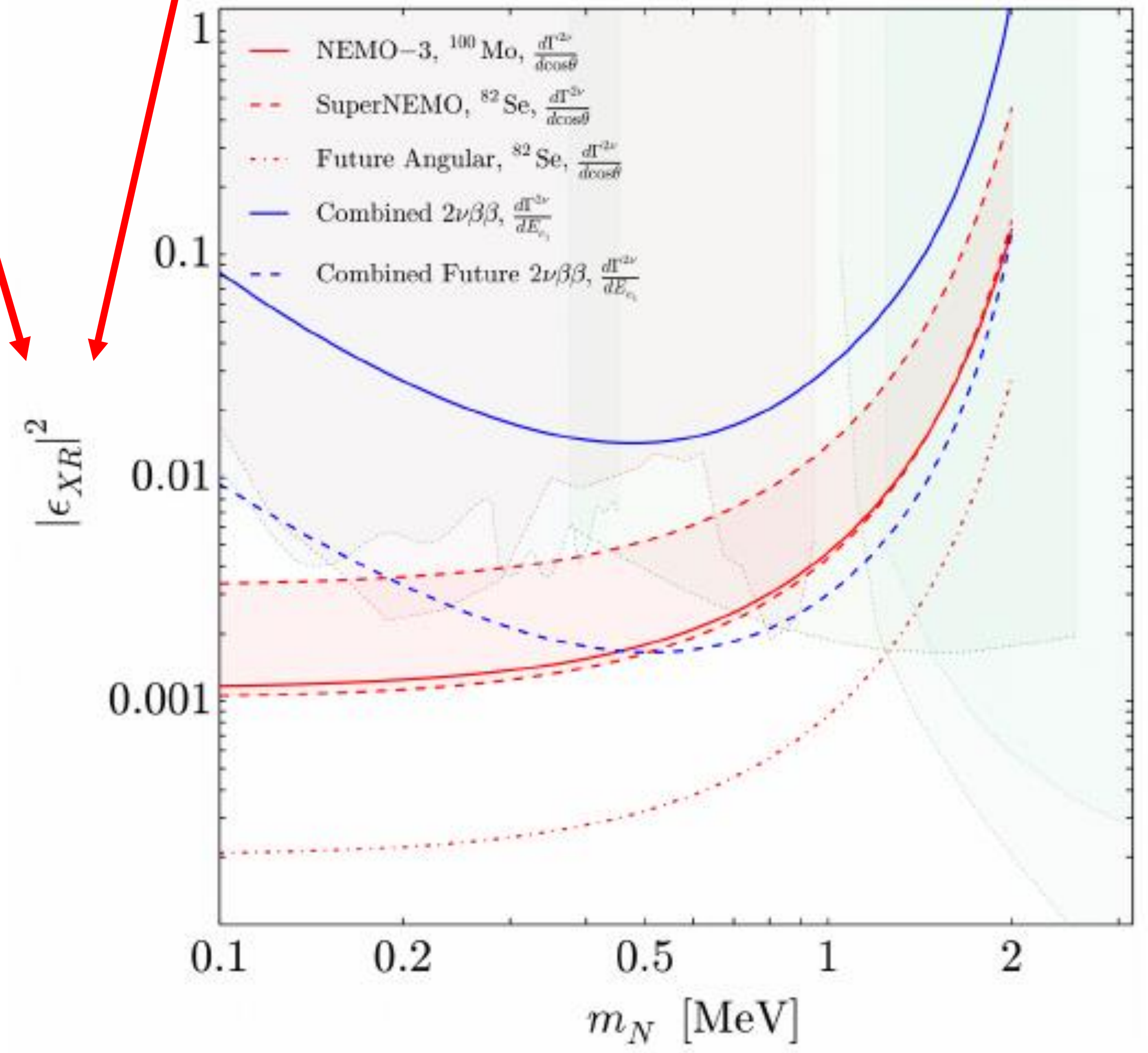
$$\mathcal{L} = \frac{G_F \cos\theta_C}{\sqrt{2}} \left[(1+\delta_{\mathrm{SM}}) j_L^{\mu} J_{L\mu} + V_{eN} j_L^{N\mu} J_{L\mu} + \epsilon_{LR} j_R^{N\mu} J_{L\mu} + \epsilon_{RR} j_R^{N\mu} J_{R\mu}\right] + \text{h.c.}$$

Exotic 2νββ Sterile Neutrino (or HNL)

Consider either mixing of sterile ν with active ν, or right-handed currents

Phys.Rev.D 103 (2021) 055019



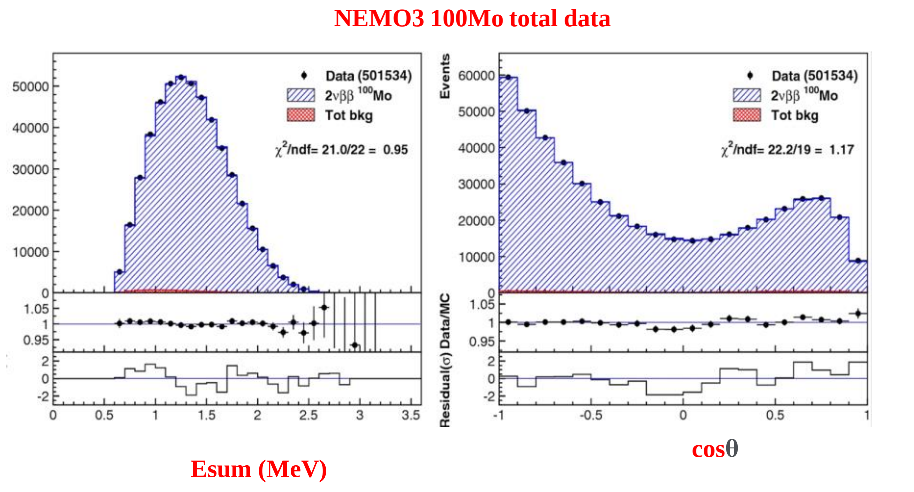


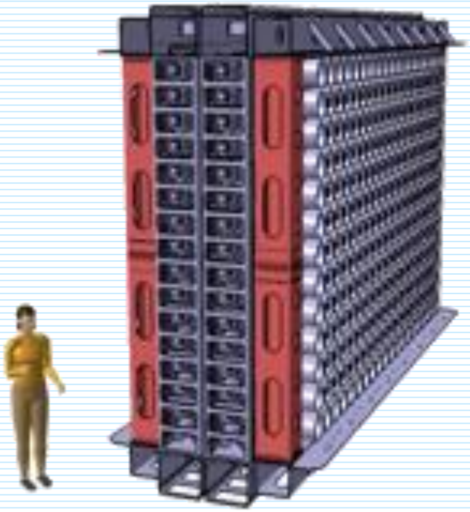
SuperNEMO Double-Beta Decay Experiment

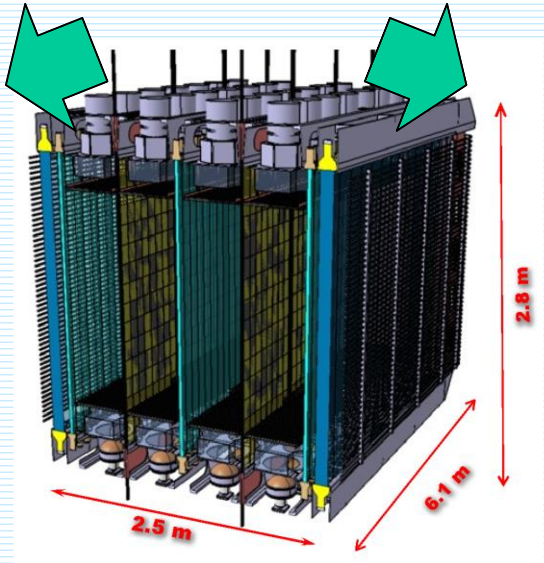
Full kinematics and precision measurements of *2νββ*

- Nuclear model constraints
- g_A quenching constraints
- Sterile neutrinos
- Right-handed currents
- *2νββ* with emission of single e$^-$, etc

(NEMO-3 analysis in preparation)







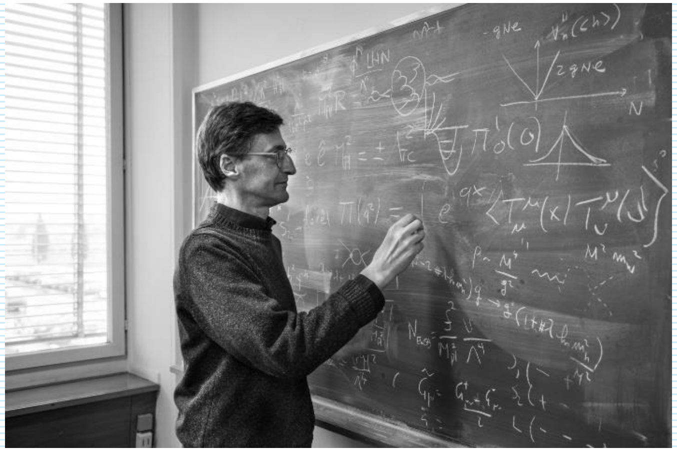
Understanding the Ultimate Reach of the Tracker-Calorimeter Technique

- Can the technique be used to confirm & probe a signal found in the next generation of *0νββ* experiments?
- Explore alternative tracker-calorimeter technologies & different isotopes

SuperNEMO Collaboration

AI can not solve ν-physics problems!

ν-physics problems can be solved
only by ν-experiments (and ν-theory),
i.e., by skilled experimentalists and theorists



Thank you for your attention!