

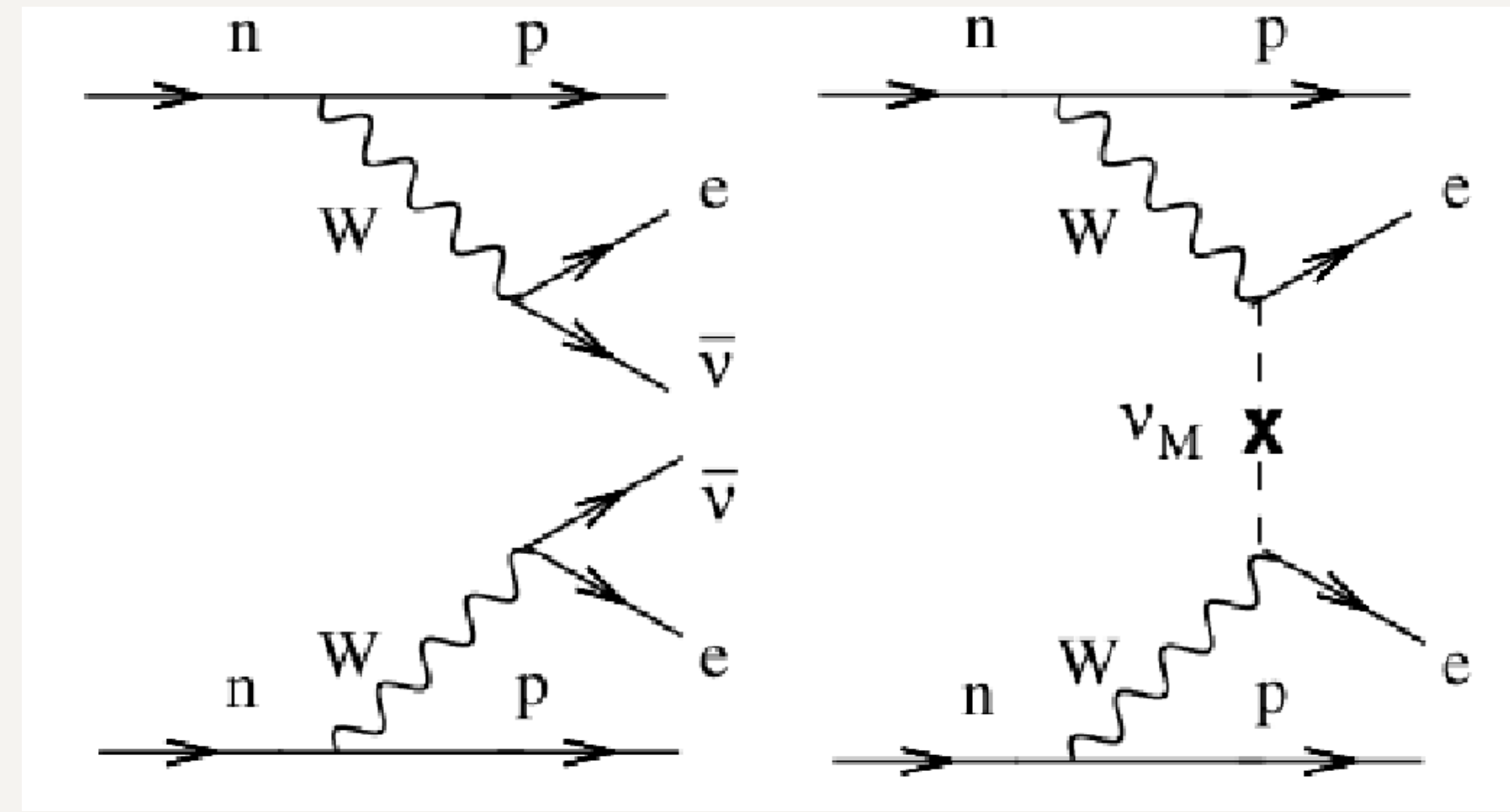
3rd Summit on the Future of Neutrinoless Double Beta Decay, Heidelberg

# ~~Why~~ How are we here?

# 0νββ by light Majorana neutrinos\*



This meeting is focused on 0νββ experiments.



The search for neutrinoless double beta decay addresses the question: Are the right-handed components of neutrinos new degrees of freedom (Dirac fermions) or are they related to the degrees of freedom in antineutrinos (Majorana fermions)?

The second choice involves a Majorana mass term, which breaks the phase symmetry, therefore the number symmetry, and leads to neutrinoless double beta decay.

0νββ is suppressed by  $O[(m/E)^2]$  and difficult to observe. Are there other observables searching for the nature of neutrinos competitive with 0νββ? Not quite (recent discussion by [Akhmedov, 2410.11940](#))

\* Other theoretical (less minimal) alternatives have been proposed.

# Standard Model of Particle Physics



$$\begin{aligned} & \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2} \partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[ \frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - igc_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\mu W_\nu^- - W_\nu^- \partial_\mu W_\nu^+)] - igs_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - \frac{1}{2} g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2} g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \frac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - gMW_\mu^+ W_\mu^- H - \frac{1}{2} g \frac{M}{c_w} Z_\mu^0 Z_\mu^0 H - \frac{1}{2} ig [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2} g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2} g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + igs_w MA_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4} g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \frac{1}{4} g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2} g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2} ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) + \frac{1}{2} ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + igs_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3} (\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3} (\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \frac{ig}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_e^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda)] + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + igs_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + igs_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2} gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \end{aligned}$$

An SU(3)xSU(2)xU(1) gauge symmetry theory of chiral fermions with spontaneous symmetry by the Higgs mechanism. **What else is missing?**

**Two extra terms respect gauge symmetries but yet to be uncovered:**

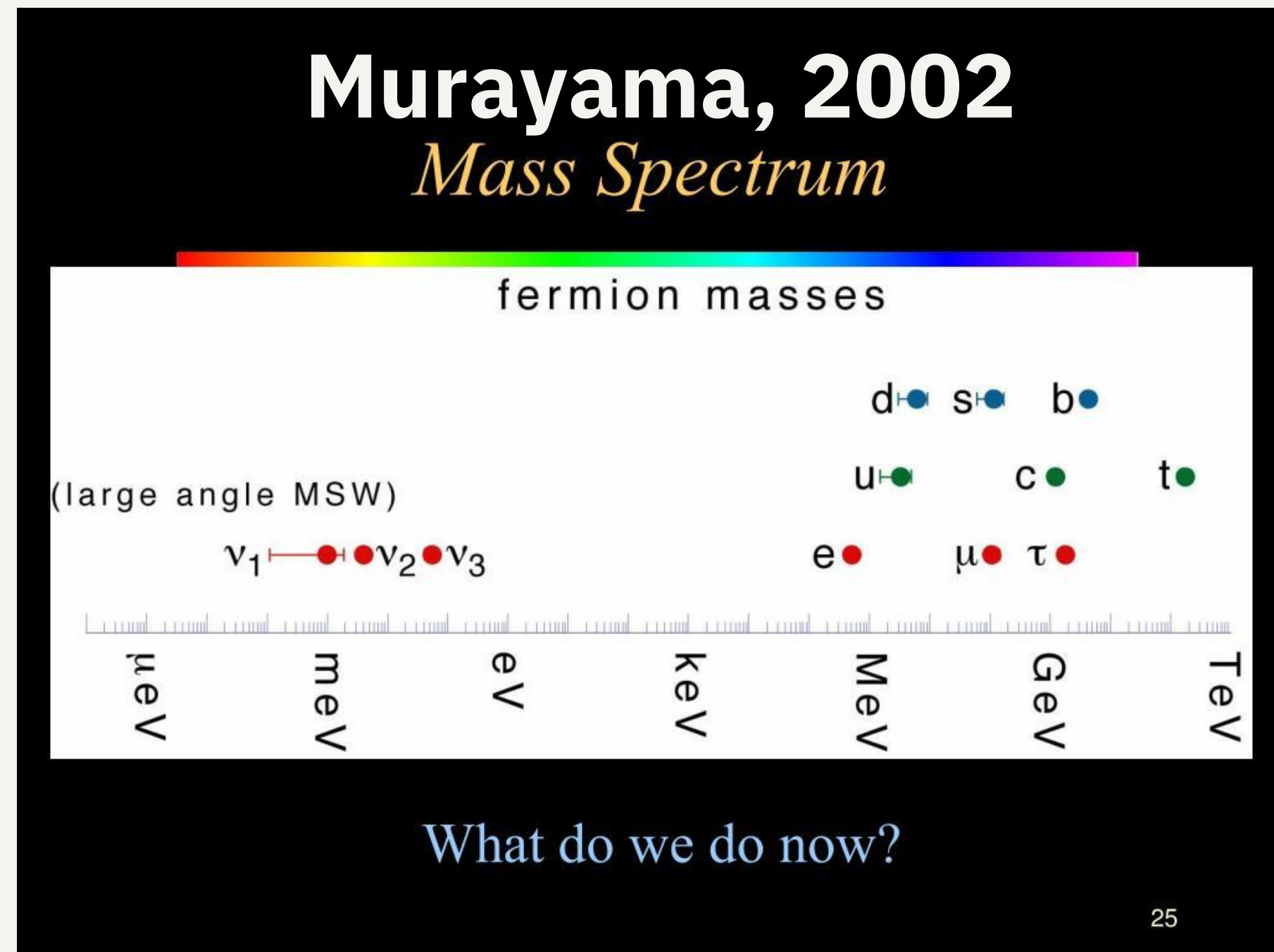
- **Majorana mass term:** Neutrinos have masses, so you could build a term with singlets and a Mass (M hides new physics). This term changes lepton number by two units. Proposed solution: Neutrinos are Majorana particles.

- **Theta term or strong CP problem:** CP violating term, FxFdual, is permitted by gauge symmetries but strongly constrained to very small by limits on the neutron electric dipole moment. Proposed solution: theta is promoted to scalar field - axion

# The quest of mass: new hints



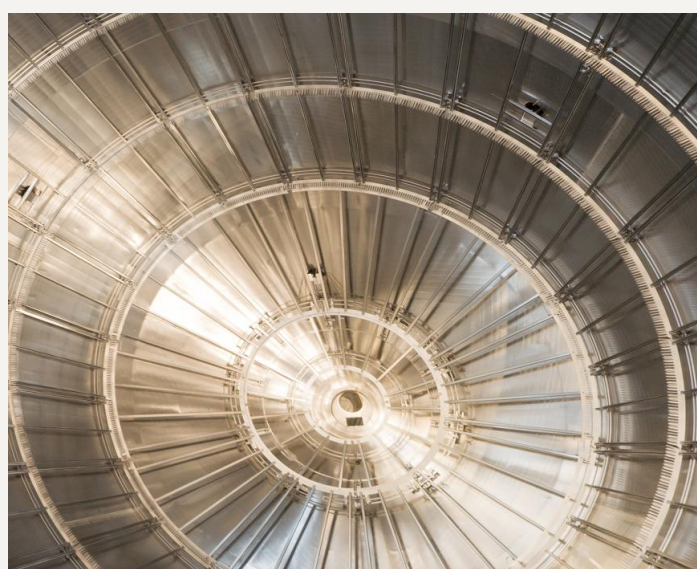
**Do we need something more than the Higgs mechanism for neutral fermions?** Hints: very different mass and mixing patterns.



**PDG, 2024**

$$V_{\text{CKM}} = \begin{pmatrix} 0.97401 \pm 0.00011 & 0.22650 \pm 0.00048 & 0.00361^{+0.00011}_{-0.00009} \\ 0.22636 \pm 0.00048 & 0.97320 \pm 0.00011 & 0.04053^{+0.00083}_{-0.00061} \\ 0.00854^{+0.00023}_{-0.00016} & 0.03978^{+0.00082}_{-0.00060} & 0.999172^{+0.000024}_{-0.000035} \end{pmatrix}$$

$$|U|_{3\sigma}^{\text{wSK atm}} = \begin{pmatrix} 0.797 \rightarrow 0.842 & 0.518 \rightarrow 0.585 & 0.143 \rightarrow 0.156 \\ 0.235 \rightarrow 0.484 & 0.458 \rightarrow 0.671 & 0.647 \rightarrow 0.781 \\ 0.304 \rightarrow 0.531 & 0.497 \rightarrow 0.699 & 0.607 \rightarrow 0.747 \end{pmatrix}$$

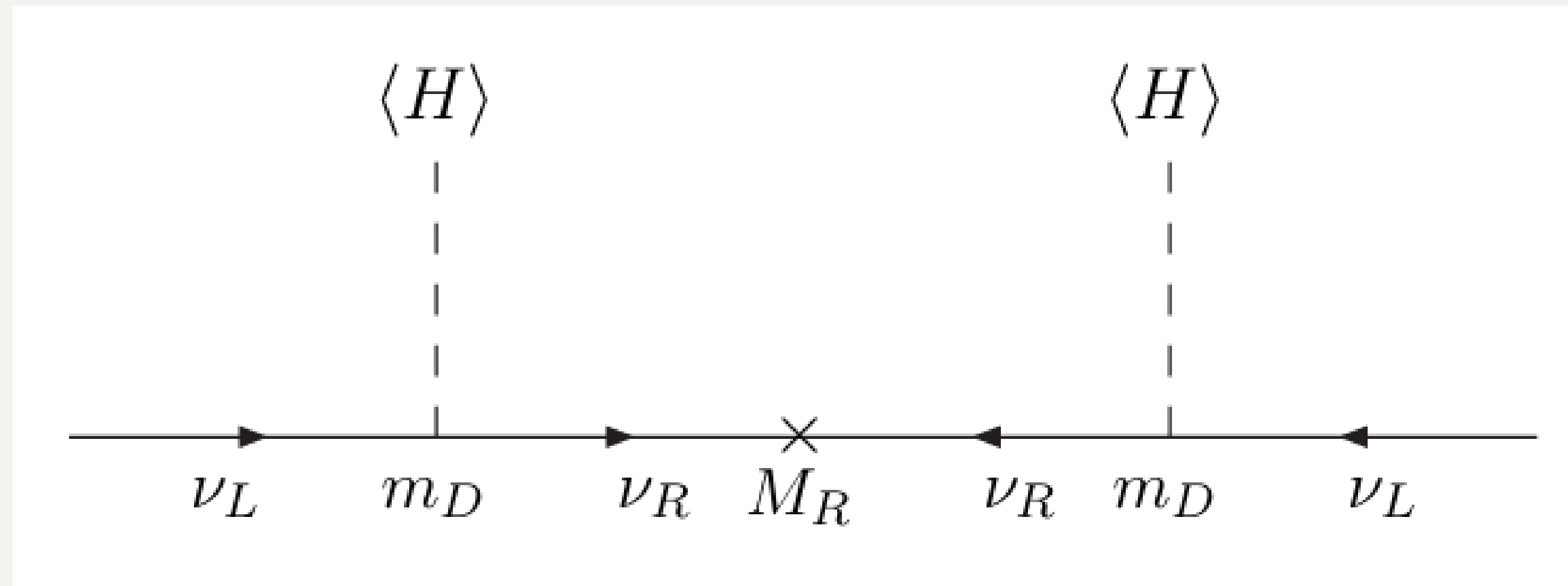


**KATRIN** new result:  
 $m\beta < 0.45 \text{ eV} - 90\% \text{CL}$ .  
Sub-eV neutrino mass.

**JUNO** water filling started:  
it will improve the precision  
of the neutrino mixings.



# Light neutrinos: Hints to a new physics scale?



Minkowski, 1977; Yanagida, 1979; Gell-Mann, Ramond and Slansky, 1979; Glashow, 1979; Mohapatra, Senjanovic, 1980

Seesaw mechanism (Type I): as sketched in the diagram for one generation, light neutrinos get masses, even if they do not have SM masses, of  $O[(m_D)^2/M_R]$  by the interaction with the Higgs and the mass of the right handed neutrinos. Other seesaw mechanisms exist for a variety of intermediate states.

Physics scale of  $M_R$  is unknown. It could run from light to heavy depending on the Yukawa couplings to the Higgs times the vacuum expectation ( $m_D$ ).

# Baryogenesis via leptogenesis and Majorana mass



The observed asymmetry of matter and antimatter in the Universe can not be explained by the SM due to the insufficient CP violating contribution and the very small deviation from thermal equilibrium.

The heavy Majorana neutrinos introduced in the seesaw type I\*, can account for the asymmetry. The singlet heavy neutrino can decay due to its Yukawa coupling with the Higgs and the lepton doublet. If CP is violated (complex couplings), the decay rates to matter and antimatter are different, producing lepton asymmetry. Deviation from thermal equilibrium is produced by the expansion of the Universe at T comparable to M.

[Fukugita, Yanagida, 1986](#)

\*A large number of leptogenesis models have been proposed.

Baryon asymmetry generation: In the SM, non-perturbative effects (chiral anomaly) violate Baryon number, but not B-L number. Non-linear solutions of the fields (sphalerons) can wash out the B+L number and reprocess the L into B number, at Temperatures of  $(10^2-10^{12})$  GeV, at times when T is larger than H.

All Sakharov conditions are satisfied [Sakharov, 1967](#)

[Kuzmin, Rubakov, Shaposhnikov, 1985](#)

# Is $0\nu\beta\beta$ decay within reach?



$$|\langle m_{ee}^\nu \rangle| = m_e \frac{1}{\sqrt{T_{1/2} F_N}}$$

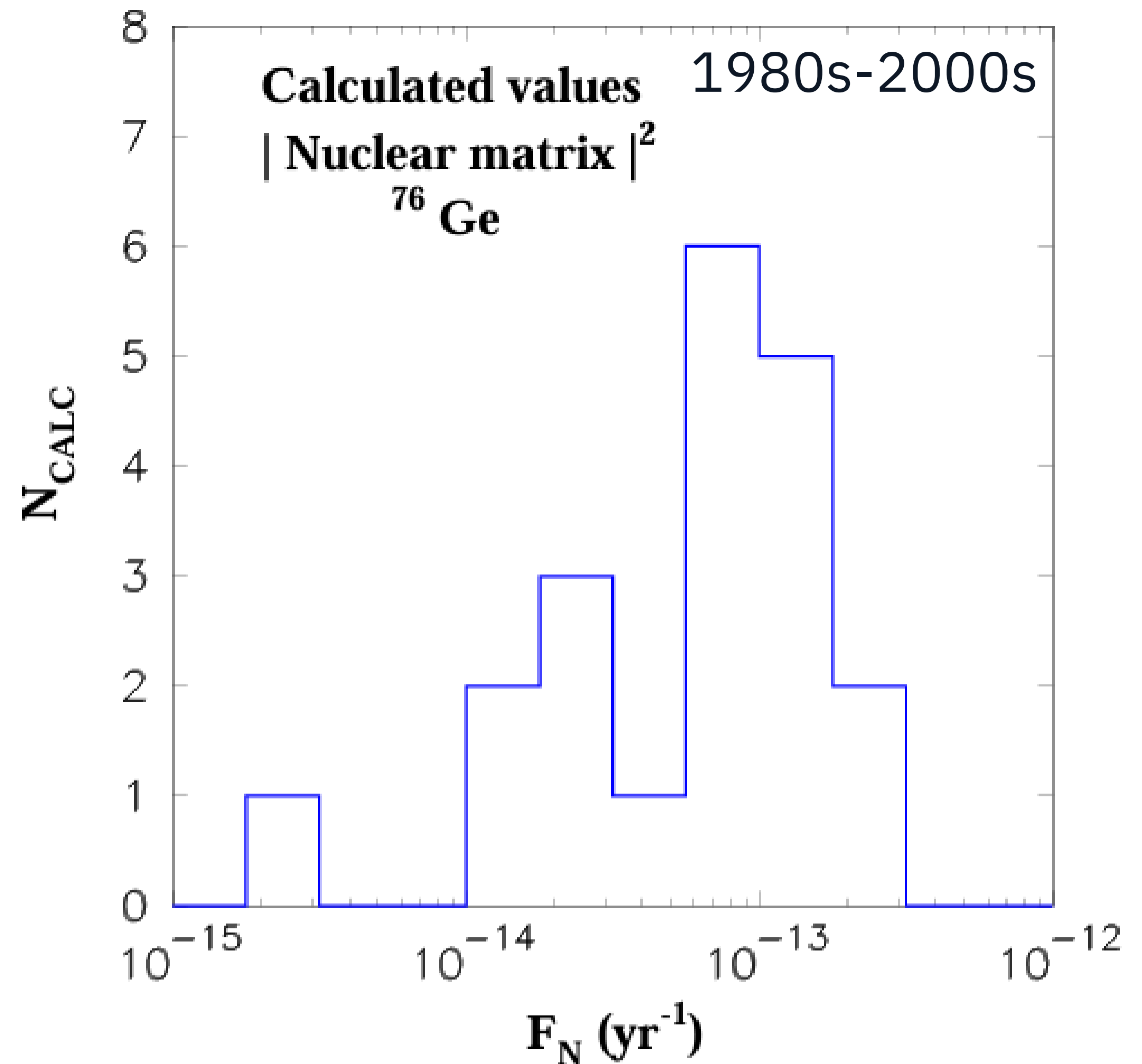
$$|\langle m_{ee}^\nu \rangle| = |m_1 |U_{e1}^2| e^{i\phi_1} + m_2 |U_{e2}^2| e^{i\phi_2} + m_3 |U_{e3}^2| |$$

$F_N$ - nuclear structure parameter

Using *Katrin* and oscillation exp. data,  $1 \text{ meV} < m_{ee} < 450 \text{ meV}$  (if no accidental cancellation),

we expect  $T_{1/2} > 10^{25} - 10^{30} \text{ yr}$

## Bahcall, Murayama, CPG 2004



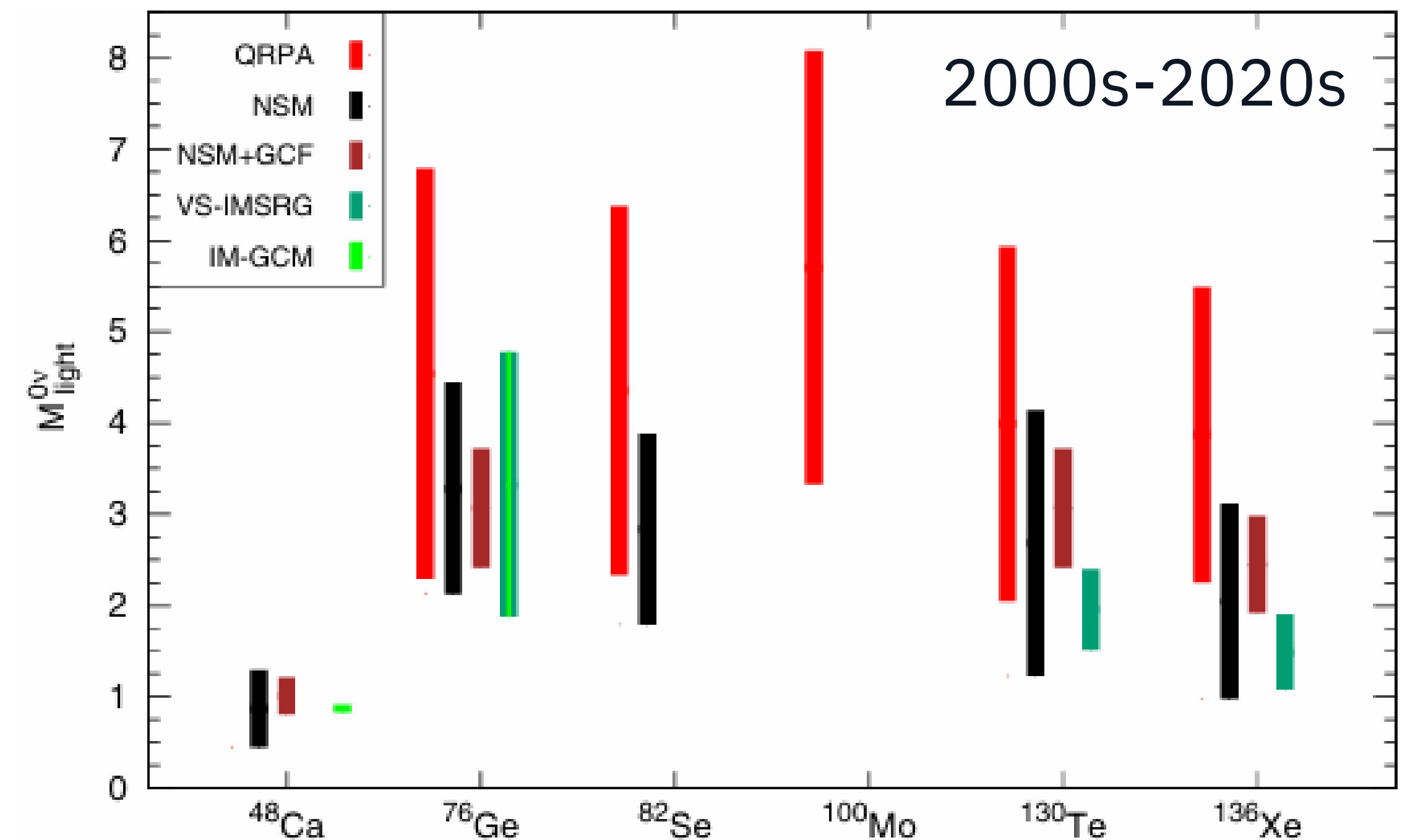
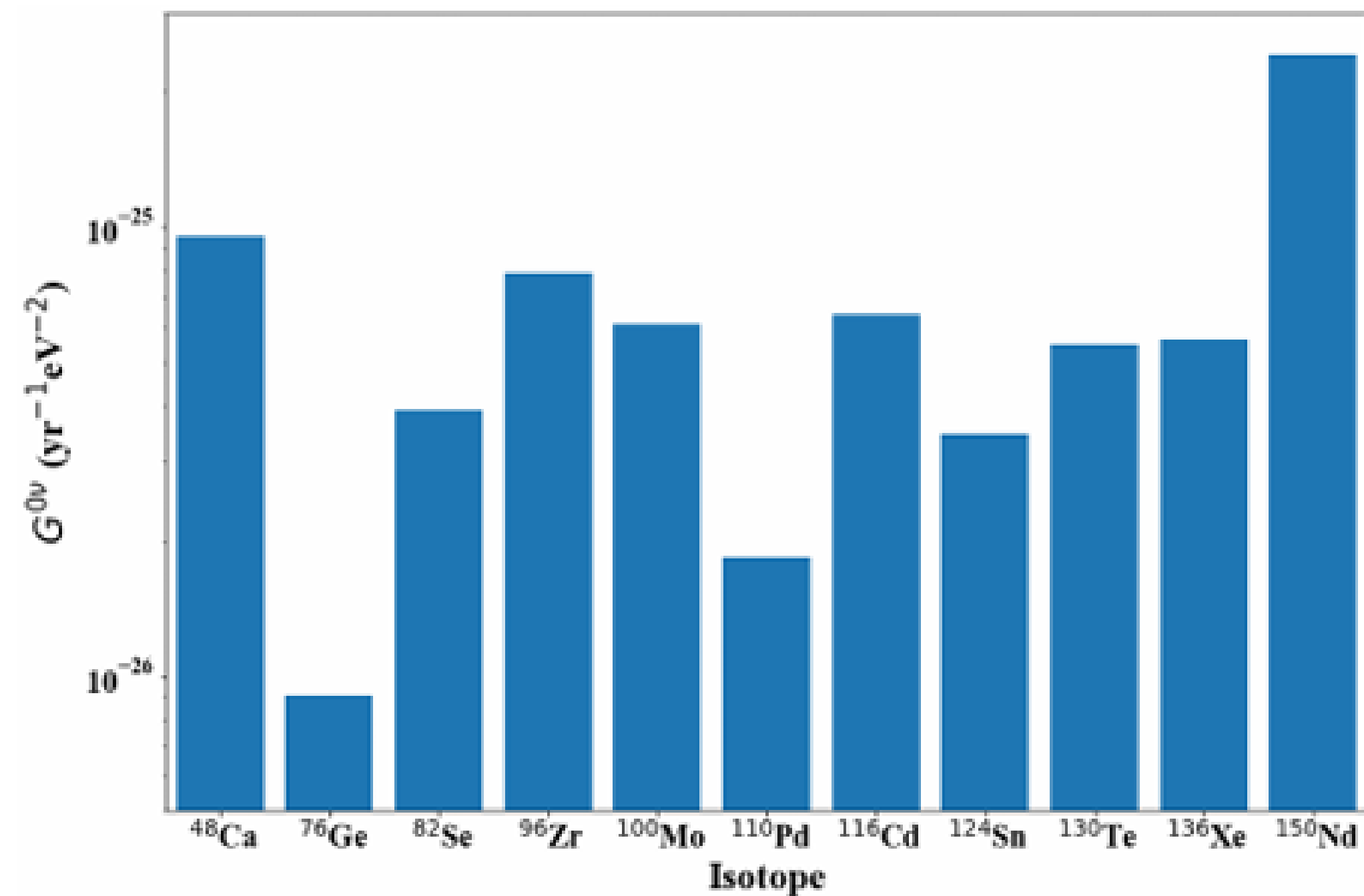
# Recent improvements in NME



$$T_{1/2}^{-1} = G^{0\nu}(Q, Z) g_A^4 \left| M_{\text{light}}^{0\nu} \right|^2 m_{\beta\beta}^2$$

Kotila, Iachelo, 2012; Stoica, Mirea, 2013

Compiled in Gomez-Cadenas et al, 2023



$F_N$  - nuclear factor varies from nucleus to nucleus (within one order of magnitude), reduced theoretical uncertainties with tendency to predict larger half-lives.



Are the new calculations of NME converging to the correct values and with reduced theoretical uncertainties?

Deficiencies in our understanding of many-body systems under the conditions of high order isospin dynamics can be addressed by improving the nuclear calculations and applying the structure models to a variety of independent physical observables.

- Development of nuclear methods to better address the truncation of the space of nuclear wavefunctions, improved description of the effective interactions, ...
- Exploration of the correlations of observables due to the common spin-isospin nature of the SM interactions: double Gamow-Teller transitions, heavy-ion double charge exchange reactions, double-gamma decay, ...



Neutrinoless double decay searches address the quest to discover the nature of neutrinos. Best observable to make a discovery.

In the simplest scenario of light neutrinos exchange, half-life of the decays are uncertain due to the unknown neutrino mass effective parameter and the uncertain nuclear matrix elements calculations. Unless accidental cancelation, there is a maximum value for the half-life. In my opinion, these elements point to the need to :

- Search for the decay with more than one nucleus.
- Continue the scaling up of the detector sensitivity.

Implications of the discovery will provide hints to a new physics scale that could explain the lightness of neutrinos by the Seesaw mechanism and a source of baryon asymmetry by leptogenesis.

# LSC



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