Lepton Number Violation

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Outline

- Standard Model and beyond
- (Charged) lepton flavor violation
    - Muon to electron conversion
- (Total) lepton number violation
    - Neutrino-less double beta decay
- Conclusions

Physics beyond the Standard Model

- In the Standard Model:
  - neutrinos are massless
  - Lagrangian is invariant under global $U(1)_e \times U(1)_\mu \times U(1)_\tau$
  - individual lepton-flavor numbers are conserved.

- However a variety of neutrino oscillation experiments proved that neutrino flavours are not conserved

- Only consistent picture:
  - (some of the) neutrino masses are non-zero and distinct
  - the weakly interacting flavour neutrinos ν_e,ν_μ and ν_τ are non-trivial superpositions of mass eigenstates ν_1,ν_2 and ν_3 described by a 3 × 3 unitary mixing matrix.

Current neutrino picture

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

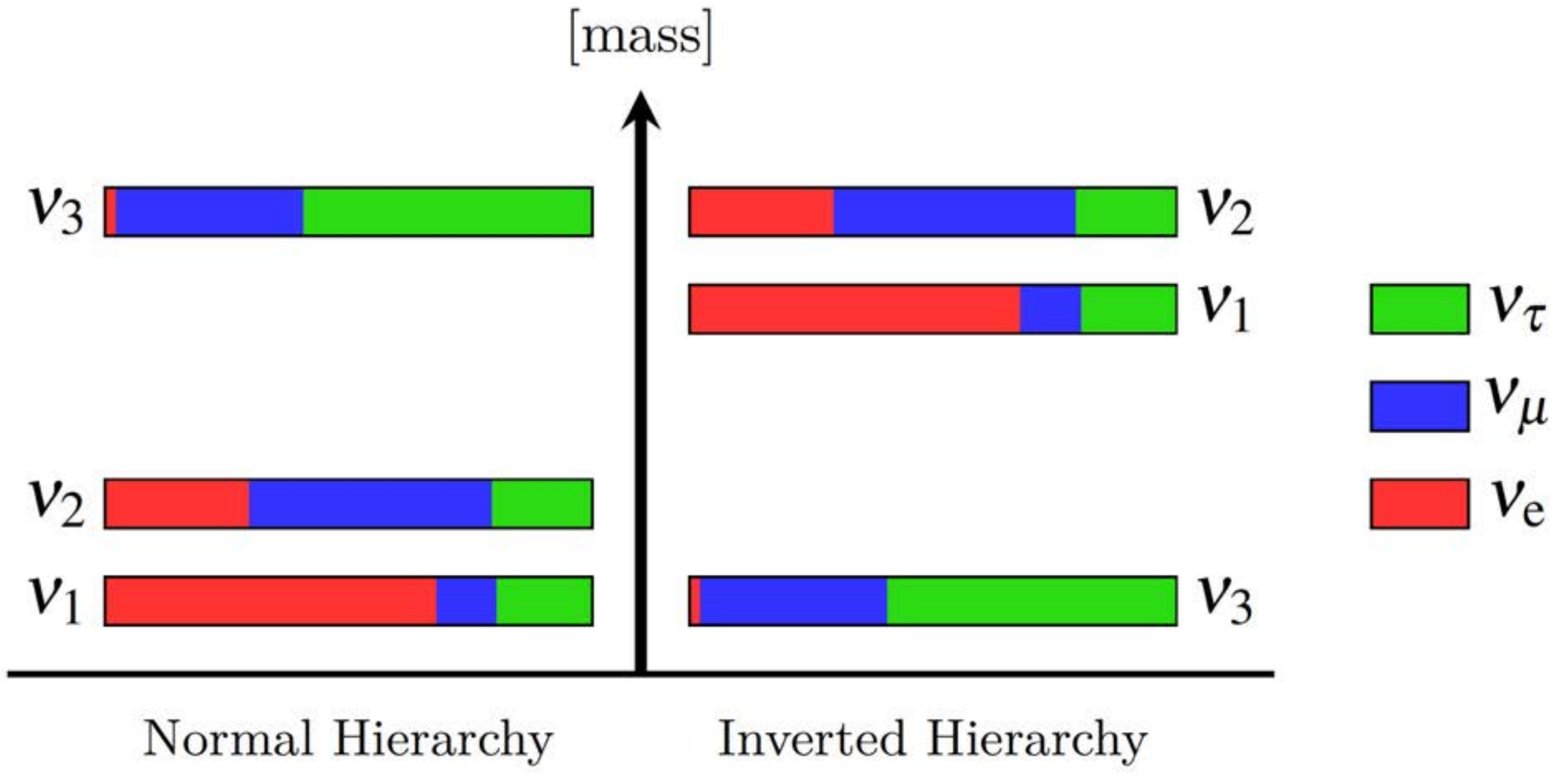
$$\delta m^2 = m_2^2 - m_1^2$$

$$\Delta m^2 = |m_3^2 - (m_2^2 + m_1^2)/2|$$

$$\left\{ \begin{array}{lll|l} m_1 & = m & & (= \sqrt{m^2 + \Delta m^2 - \delta m^2/2}) \\ m_2 & = \sqrt{m^2 + \delta m^2} & & (= \sqrt{m^2 + \Delta m^2 + \delta m^2/2}) \\ m_3 & = \sqrt{m^2 + \Delta m^2 + \delta m^2/2} & & (= m) \end{array} \right.$$

	Normal (Inverted)	Error	Units
Δm^2	2.50 (2.46)	18 %	10^{-3} eV^2
δm^2	7.37 (7.37)	2.4 %	10^{-5} eV^2
$\sin^2\theta_{13}$	2.17 (2.19)	4.8 %	10^{-2}
$\sin^2\theta_{12}$	2.97 (2.97)	6.2 %	10^{-1}
$\sin^2\theta_{23}$	4.43 (5.75)	16 %	10^{-1}
δ	1.39 (1.39)	19%	π

Particle Data Group



Physics beyond the Standard Model

- Neutrino oscillations violate lepton flavour conservation
    - **Standard Model is incomplete and needs generalization**.
    - All lepton flavour violating processes are in principle allowed and should occur at some order in perturbation theory.
- The new physics responsible for neutrino masses and mixing remains unknown
- The rates are model-dependent and can provide non-trivial information concerning the nature of new physics.

Neutrino masses and LNV

- Neutrino masses are six or more orders of magnitude smaller than the masses of other charged fermions.
- Mass ordering is unknown and could be also different with respect to other fermions

- **Weinberg finding**: there exists only one lowest order (dimension 5, suppressed by only one inverse power of the corresponding high energy scale Λ) gauge-invariant operator given the content of the Standard Model. After spontaneous symmetry breaking it provides the **Majorana mass** which violates L by 2 units

$$\mathcal{L}^{(M)} = \frac{C^{(5)}}{\Lambda}\frac{v^2}{2}(\bar{\nu}^c\nu) + h.c.$$

- Large enough scale Λ → arbitrarily small neutrino masses
- Large number of physics realisations of this basic idea: all imply that neutrinos are Majorana fermions and that the total lepton number is not exactly conserved quantity.

See-saw mechanisms

Type I see-saw mechanism

- Assume the existence of very heavy right-handed neutrinos N_R then diagonalise the mass matrix

$$m_\nu = \frac{m_D^2}{M_N}$$

- Type I seesaw template scenario particularly attractive:
  - $m_\nu \sim 0.1$ eV means that M_N (or Λ) is ~ 10^{14-15} GeV, i.e. near the GUT scale.
- Direct observation of the gauge-singlet neutrinos N_R, if they exist, is not possible.

Effective theory

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \ldots + \frac{1}{\Lambda^5}\mathcal{L}_9$$

dim 4

dim 5

dim 6

dim 9

- Standard Model

- Majorana mass terms LNV

- Proton decay

- LNV
- Seesaw Light Majorana ν_L
- Heavy Majorana N_R

See-saw mechanisms

Type II see-saw

- add a Higgs triplet (ξ++,ξ+,ξ0) which couples directly to the symmetric triplet combination of two (ℓ, ν)L doublets.
- $m_\nu = h_\nu \langle \xi_0 \rangle$ can be small provided that the $\langle \xi_0 \rangle$ is very small,
- If the mass of the ξ++, Mξ ~ 1 TeV then its decay into $\ell_i^+ \ell_j^+$ could be observable

Type III see- saw

- N_R are replaced by a fermion triplet Σ+, Σ0, Σ− and small neutrino Majorana masses are again obtained.

- See-saw mechanisms offer an explanation of the smallness of neutrino masses, and suggest that neutrinos are likely massive Majorana fermions
- Lepton number violating processes.

CLFV: Charged Lepton Flavor Violation

- Neutrino oscillations imply that lepton flavour is violated.
- Naive massive-neutrino expectations bring too small rates for CLFV
  - GIM mechanism and too tiny neutrino masses
- However:
  - new degrees of freedom at the TeV scale → possibly large CLFV processes
  - CLFV experimental bounds → constraints on the new physics sector (TeV scale)
- $\mu \to e\gamma$ and $\mu \to e$ conversion are the most promising scenarios

- CLFV should be investigated in all channels (especially if CLFV is observed in some channel)
  - Results from different probes may help to:
    - ✦ discover the nature of the new physics.
    - ✦ understand the origin of neutrino masses.
- CLVF can play a key role in our understanding of the see-saw mechanism, grand unified theories, and the physics behind the matter–antimatter asymmetry of the universe

CLFV

- Most stringent current bounds on CLFV
  - $\mu^+ \rightarrow e^+\gamma$

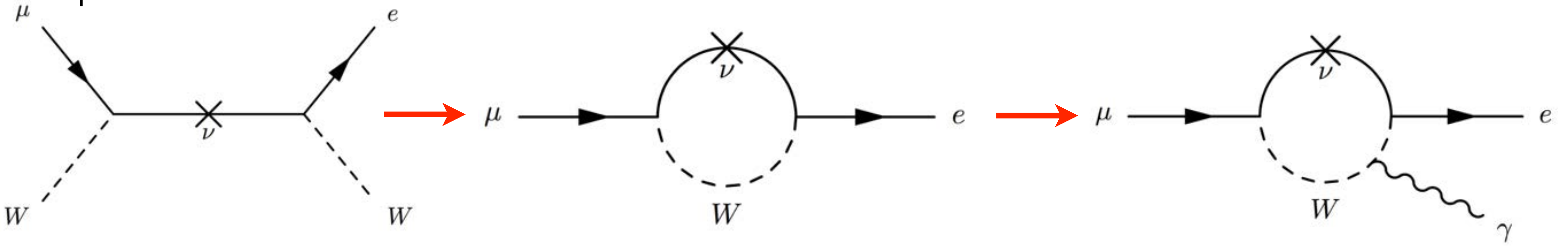
$\Gamma(\mu^+ \rightarrow e^+\gamma)/\Gamma(\text{Total})$	$<4.2\times10^{-13}$	MEG 2016 (EPJC 2016, 76:434)

- Two other promise improved near-future sensitivity:
  - $\mu^+ \rightarrow e^+e^-e^+$
  - $\mu^- \rightarrow e^-$ conversion in nuclei $[\Gamma(\mu N \rightarrow eN)/\Gamma(\text{Capture})]$

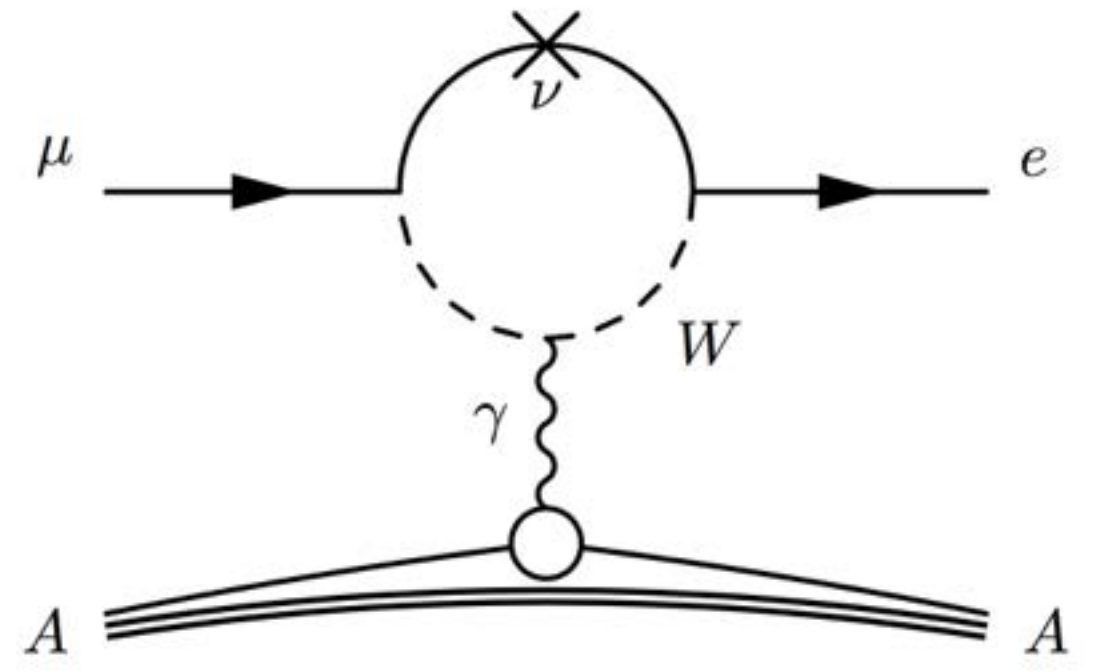
- Other processes include mesons rare decays:
  - e.g. $K_L \rightarrow \mu^\pm e^\mp$, $K \rightarrow \pi\mu^\pm e^\mp$ (opposite sign di-leptons)
- and muonium – anti-muonium oscillations,
  - $\mu^+e^- \leftrightarrow \mu^-e^+$

muon to electron conversion

- Existence of neutrino oscillations suggests that similar processes are possible also for charged leptons



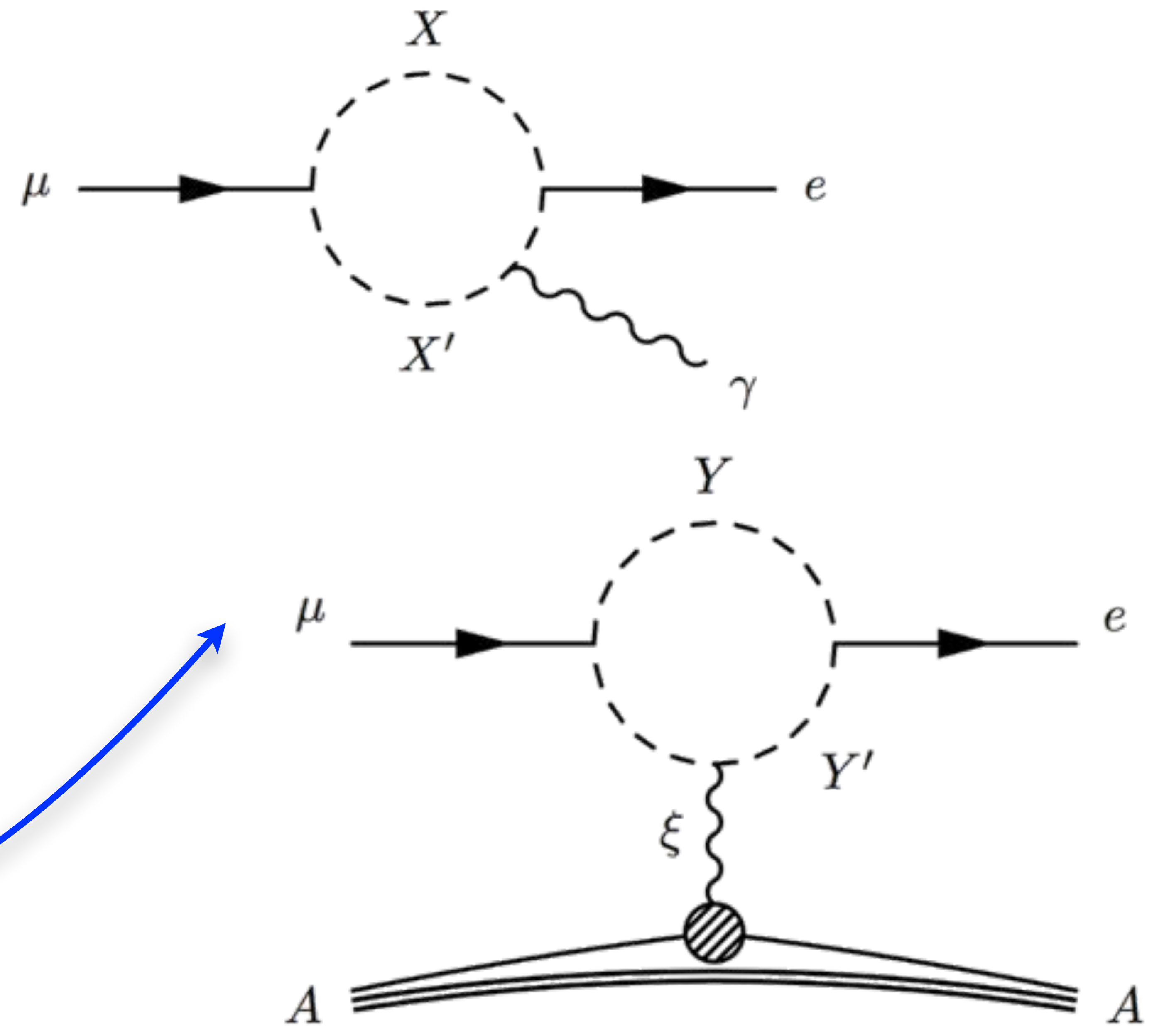
or



- Three kinematically allowed flavor variations: one involving a muon decaying to an electron, other two being decays of the tau
- **Muon to electron process is by far the easiest to study**
- Extremely rare in the Standard Model because of the large mass difference of the particles in the loop.

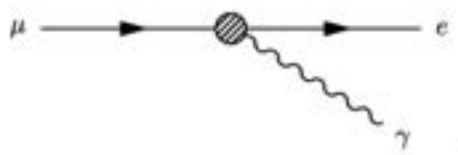
$$\frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\nu)} \propto \left| \sum_i \frac{m_i^2}{m_W^2} U_{\mu i}^* U_{ei} \right|^2 \sim 10^{-54}$$

- Many new physics scenarios provide fields that can take the place of the W and neutrino in the internal loop. Thus charged lepton flavor violation has good sensitivity to a very broad range of models

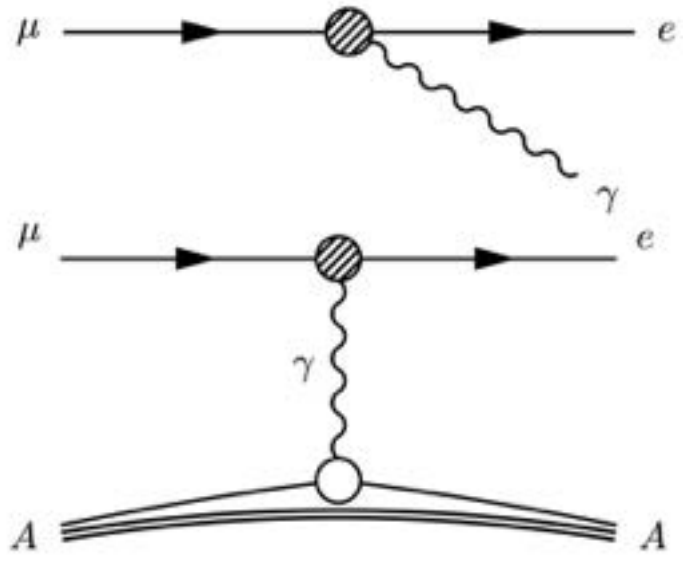


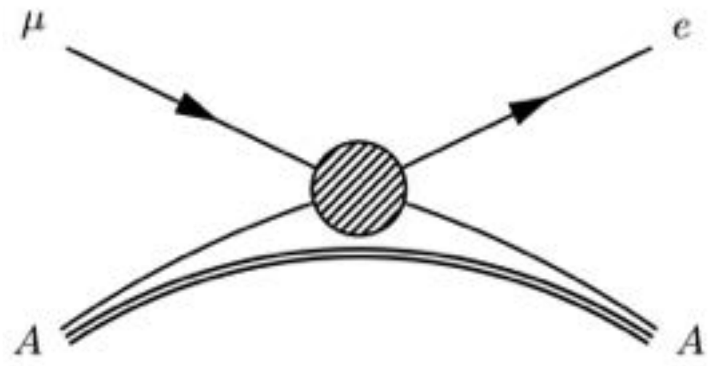
muon to electron conversion

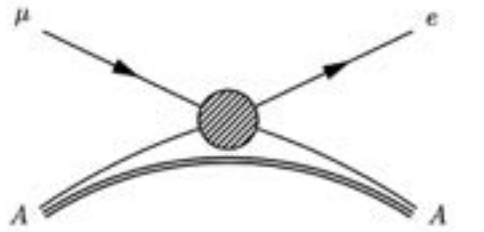
- The new physics mediators (X, X′, Y , Y ′ and ξ) are unspecified and can be assumed heavier than the muon.
- Therefore we can reduce the diagrams to effective field theories, with a mass scale Λ
- General Lagrangian including both terms:



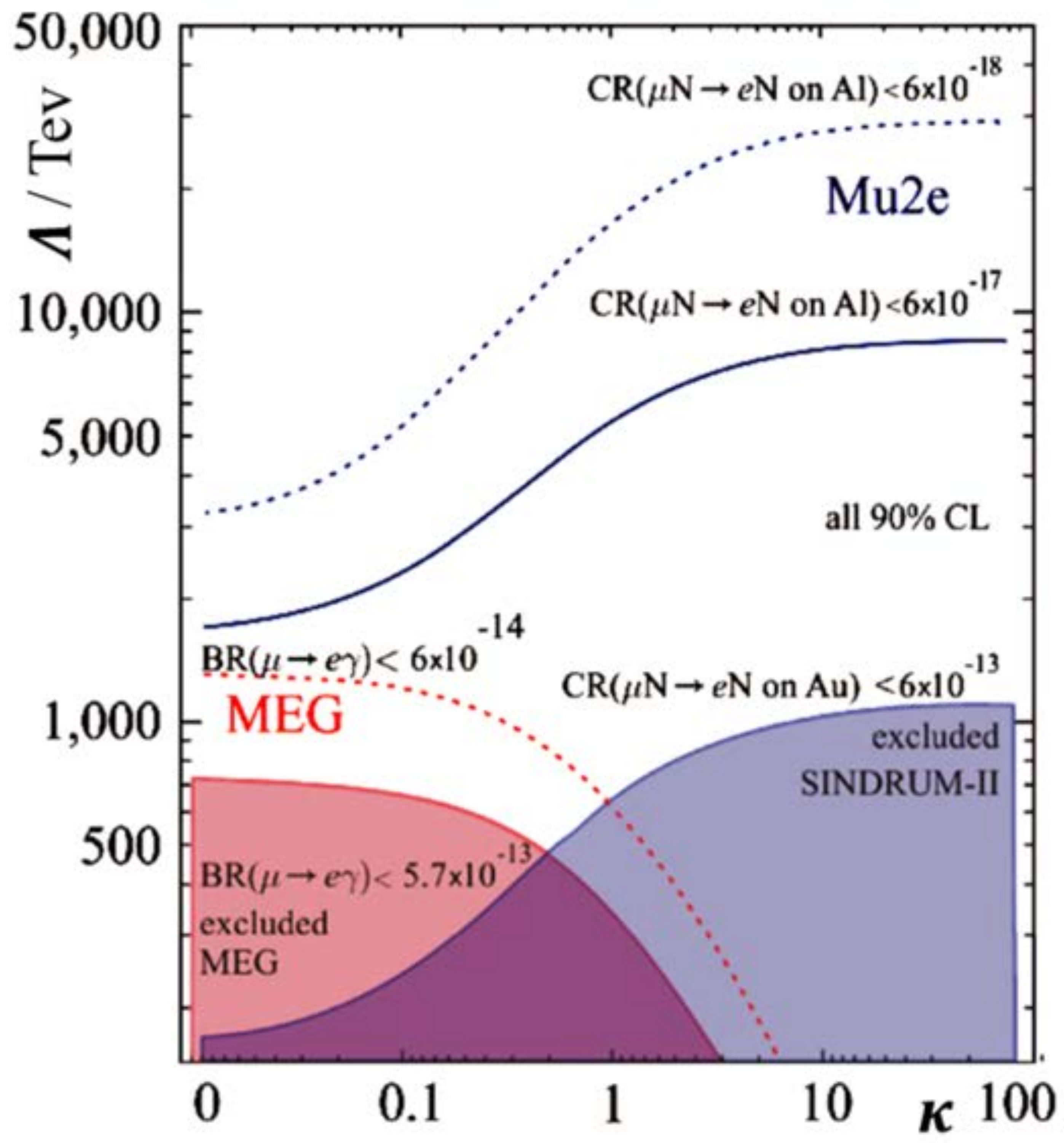
$$\mathcal{L}_{\mu e} \sim \frac{1}{\Lambda^2}\left[\frac{1}{1+\kappa}\, m_\mu\, \bar{\mu}_L \sigma_{\mu\nu} e_R\, F^{\mu\nu} + \frac{\kappa}{1+\kappa}\, \bar{\mu}_L \gamma_\mu e_L \,\left(\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L\right)\right]$$





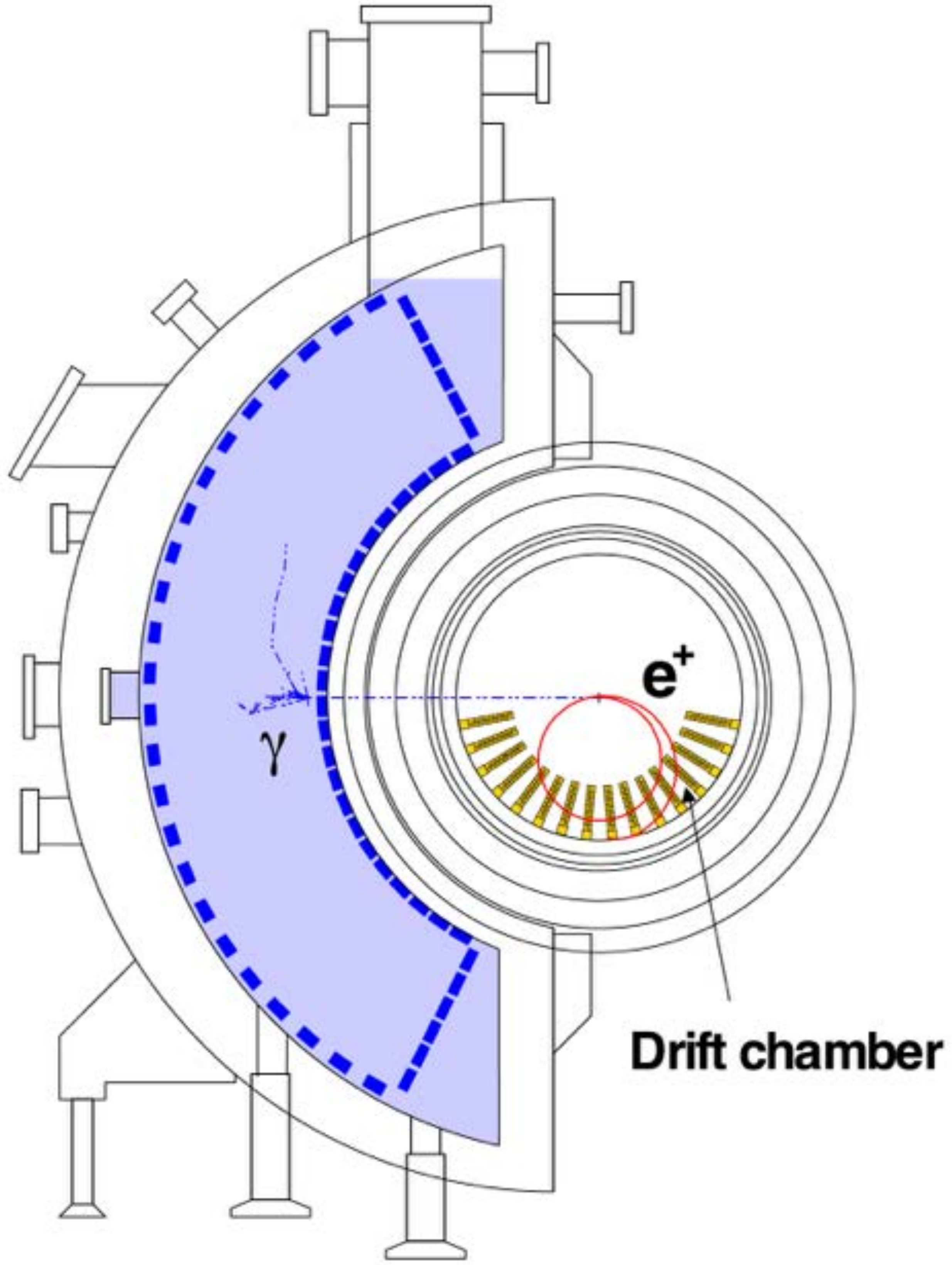


- $L_{\mu e}$ incorporates the physics for from both μ → eγ and μ–e conversion, κ being the new physics parameter.
- The comparison between the two channels can be used to measure κ and narrow down the possible models

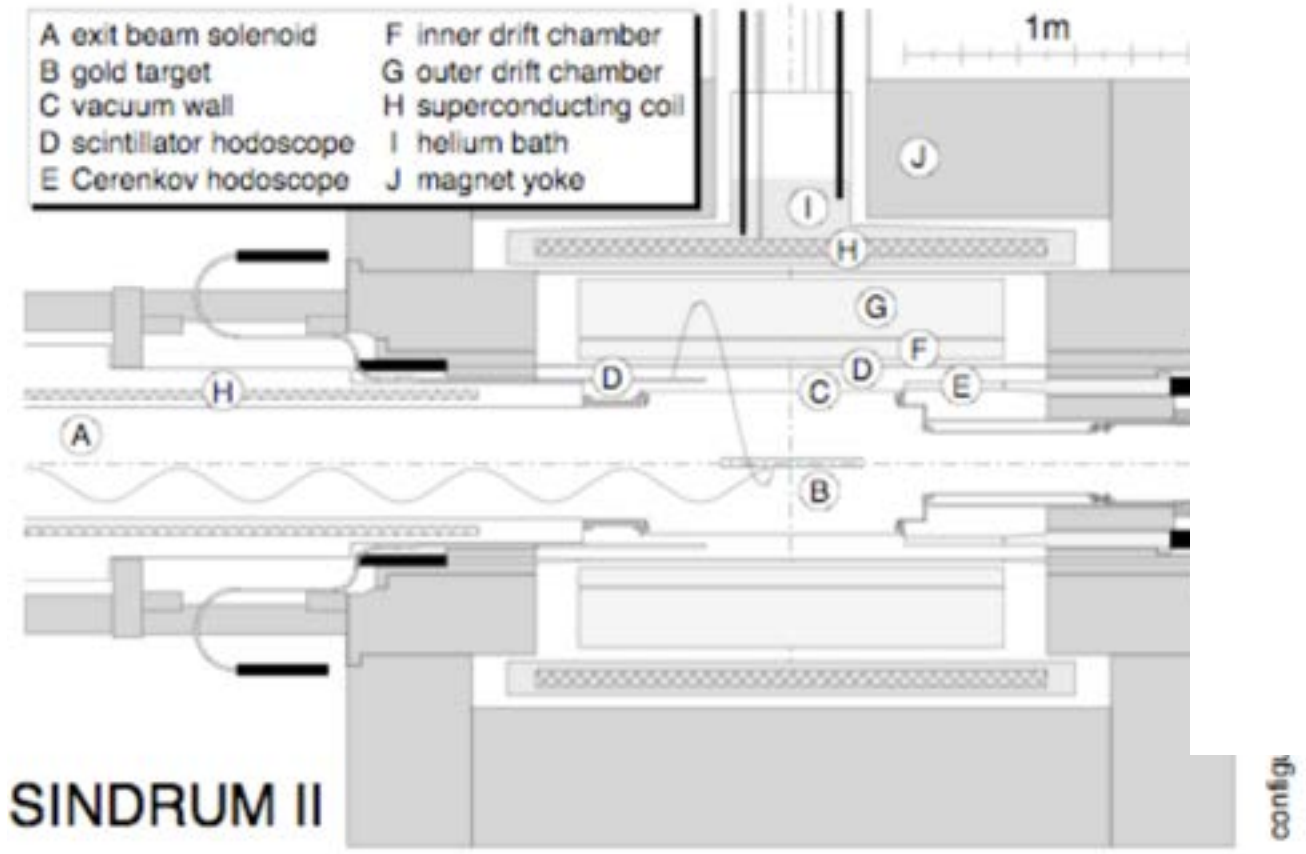


Current limits and future sensitivities as a function of κ

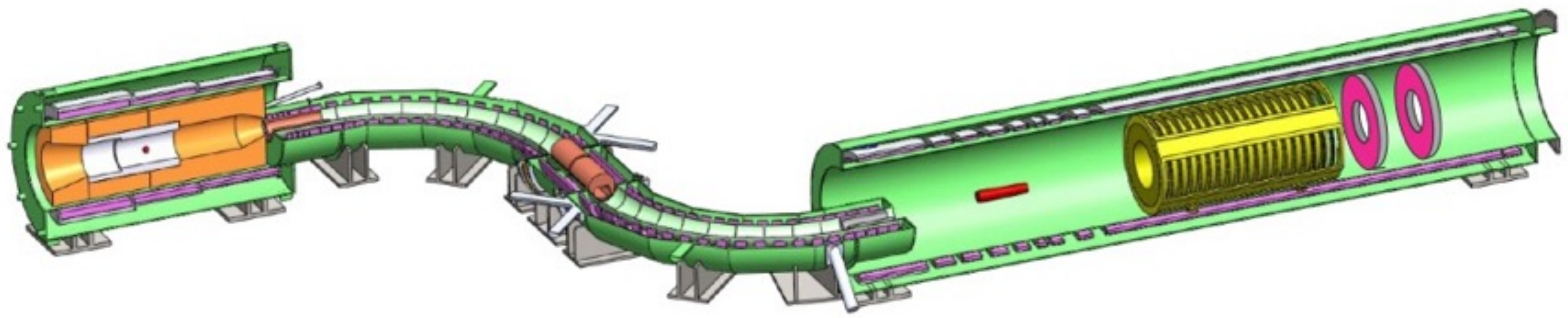
μ→e experiments



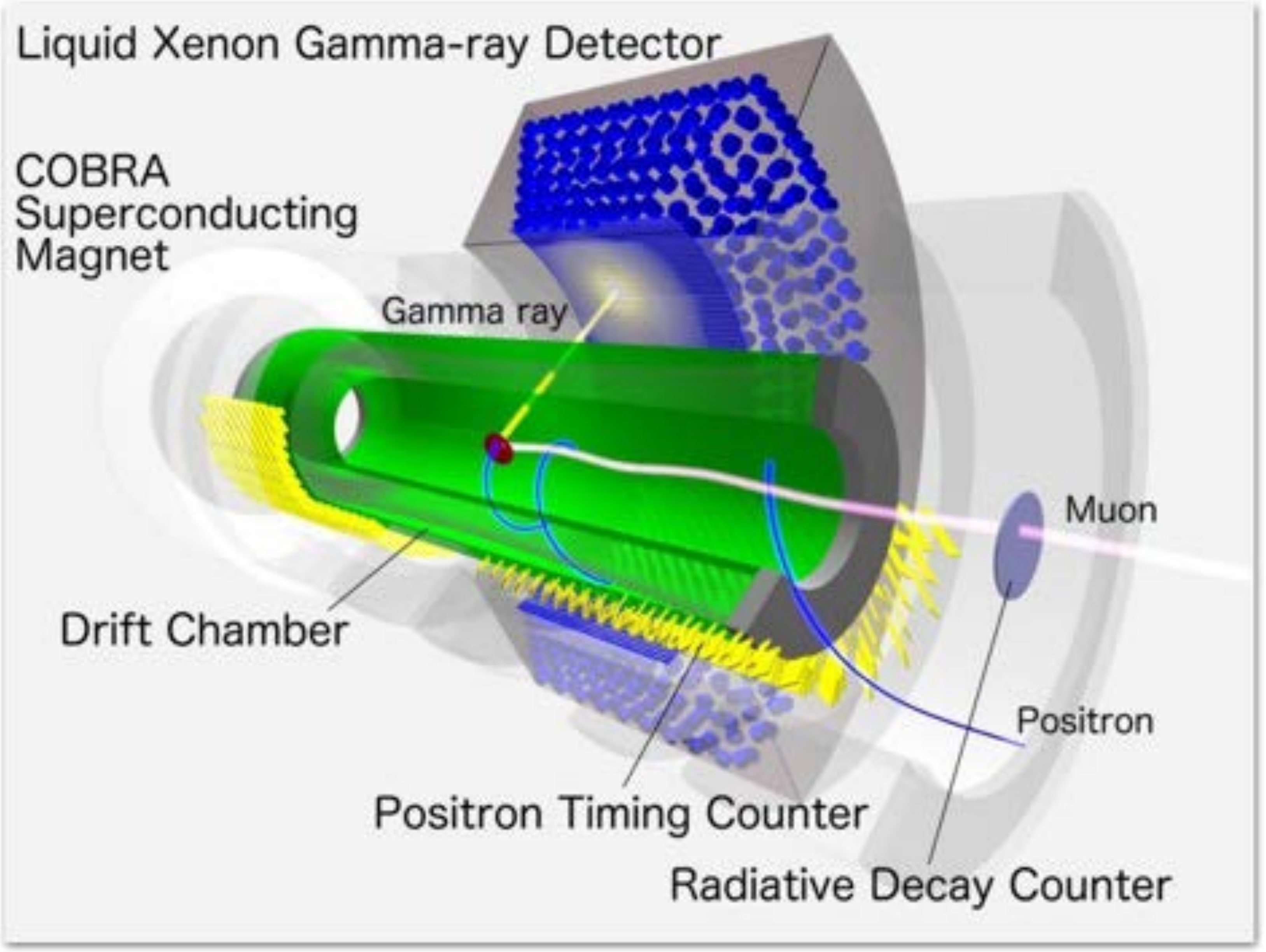
MEG @ PSI



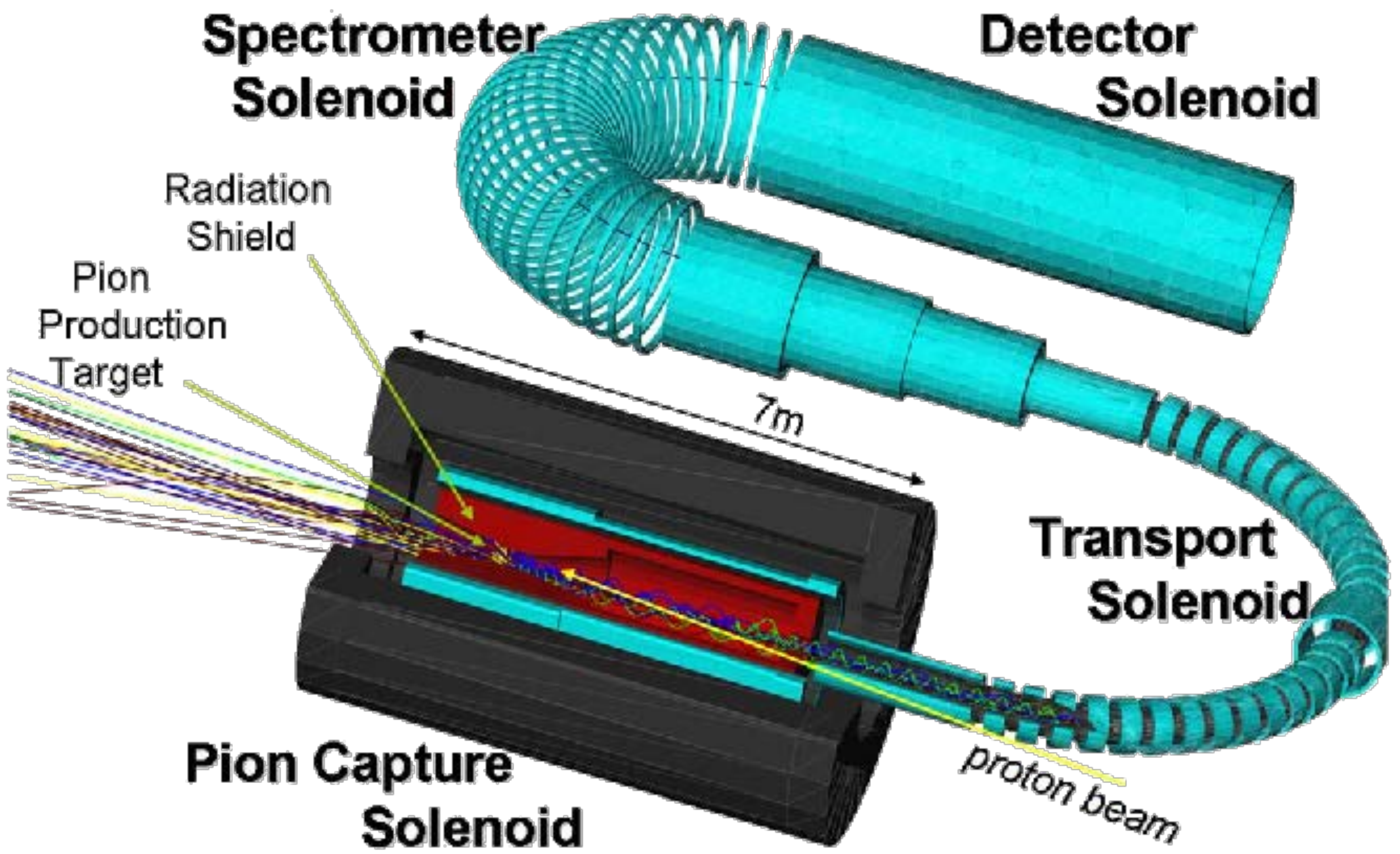
SINDRUM II
@ PSI



Mu2e @ FermiLab



MEG2 @ PSI



COMET @ JPARC

$\mu \rightarrow e\gamma$ experiments

- $\mu \rightarrow e\gamma$ has historically provided the best sensitivity for many models
- However …
  - experiments rely on a coincidence between electron and photon
  - increasing the muon intensity raises the combinatoric background, making improvements beyond the next MEG upgrade infeasible with current technology

MEG @ PSI

- Signature: coincidence e^+-γ
- Five observables (E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg}) to characterize $\mu \rightarrow e\gamma$ events
- **BR sensitivity: 10^{-13}**
- Correlated background: $\mu^+ \rightarrow e^+ \nu \bar{\nu} \gamma$ (BR~10^{-15})
- Accidental background: $\mu^+ \rightarrow e^+ \nu \bar{\nu} + \gamma$ (BR~10^{-14})

- The most intense DC muon beam:~10^8 muon/s (28 MeV/c) → 1.2 MW Pp cyclotron @ PSI
- e^+: very precise momentum and time resolutions
- γ: High energy and time resolutions
- High efficiency event selection and frequency signal digitization
- Complementary calibration and monitoring methods

Final result: BR($\mu \rightarrow e\gamma$) < $4.2\ 10^{-13}$

PSI program

MEG II

- An upgrade of MEG approved by PSI and funding agencies
  - **Design sensitivity: 5 x 10^{-14}**
  - Larger LXe volume with finer photon detector granularity
  - Higher beam intensity
  - Pixelated TC
  - Unique volume drift chamber

Construction ongoing

Mu3e

Current best result: BR($\mu^+ \rightarrow e^+ e^+ e^-$) ≤ 1. x 10^{-12} @90 C.L. by the SINDRUM experiment)

- Signature: $\mu^+ \rightarrow e^+ e^+ e^-$ (3 charged particle in the final state)
- **Design sensitivity of ~10^{-16}**
- Main backgrounds:
  - $\mu^+ \rightarrow e^+ e^+ e^- \nu \nu$
  - combinatorial e.g. $\mu^+ \rightarrow e^+ \nu \nu$, $\mu^+ \rightarrow e^+ \nu \nu$, e^+e^-

- Excellent momentum resolution
- Good vertex resolution
- Good timing resolution

- **Same beam as MEG II**

muon to electron conversion experiments

- μ–e conversion does not require a coincidence and combinatoric background is not an issue
- A new generation of μ–e conversion experiments, **COMET** and **Mu2e** take advantage of new high intensity pulsed muon beams available at J-PARC and Fermilab, respectively.

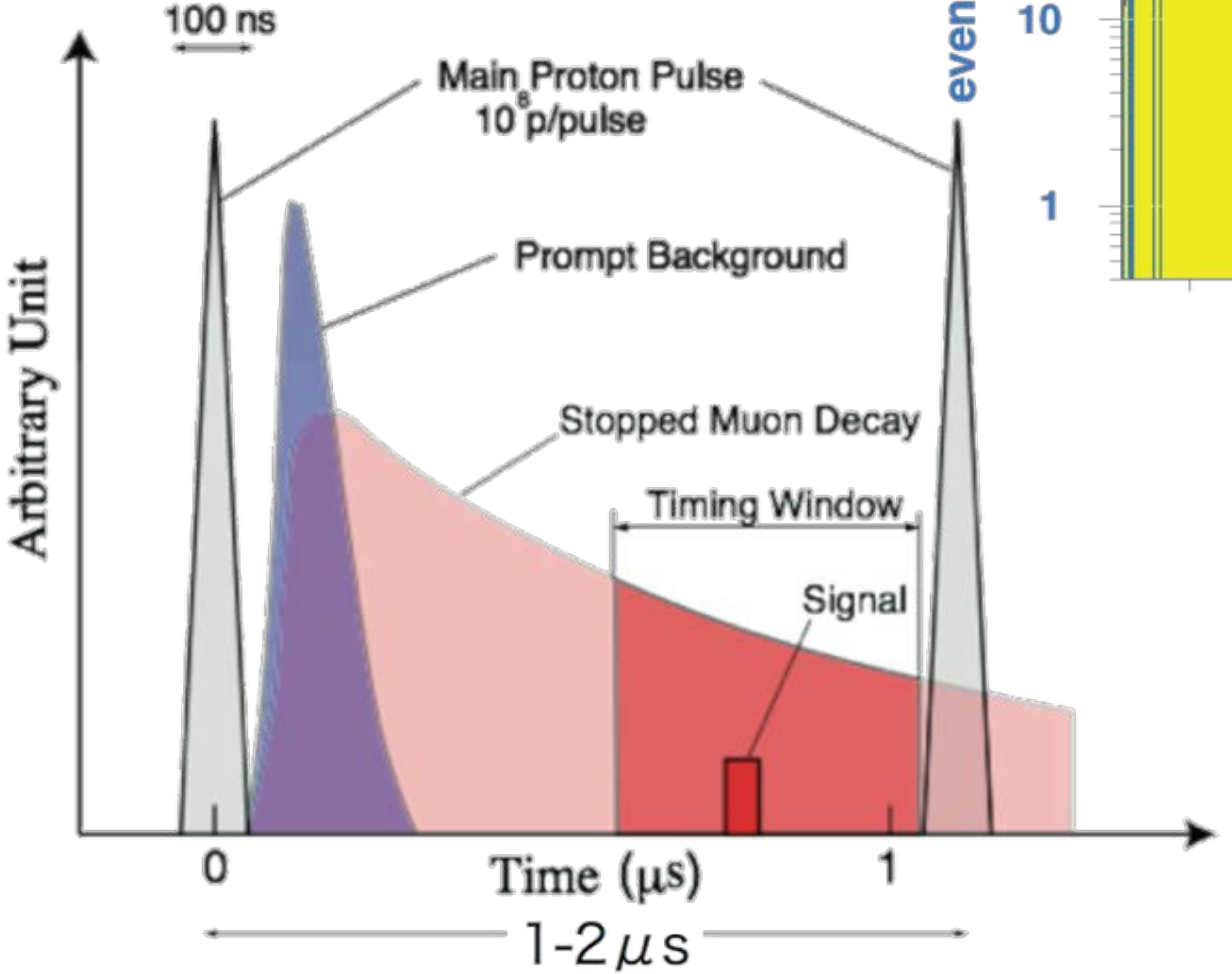
Concept:

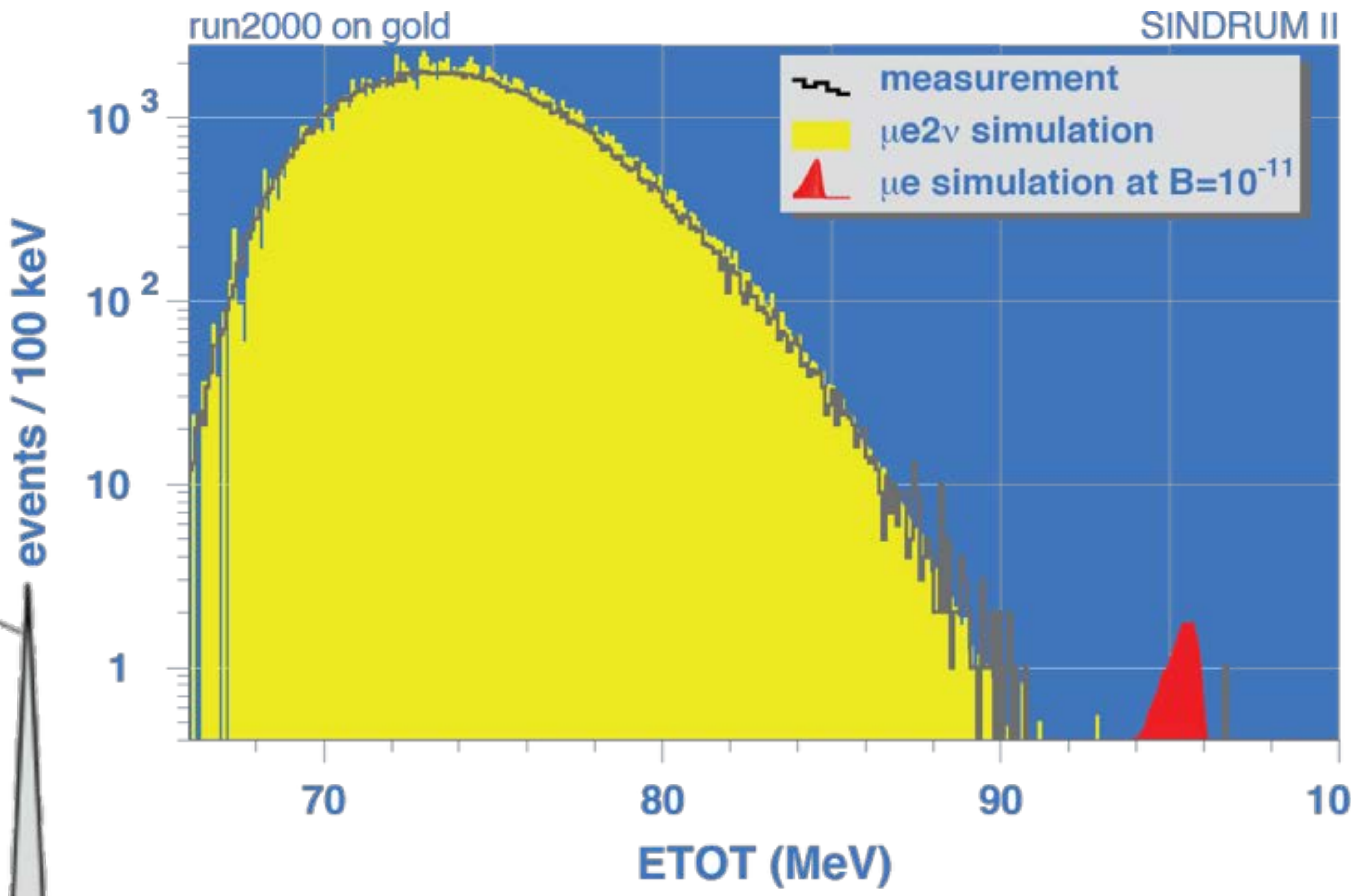
- Process : μ- +(A,Z) → e- +(A,Z)
- A single ~mono-energetic electron
- $E_{\mu e} \sim m_{\mu}-B_{\mu}$:105 MeV
- Delayed： ~1μS

Backgrounds:

- No accidental backgrounds
- Physics backgrounds
- Muon Decay in Orbit (DIO)
- Particles produced directly from the muon production target

Good energy resolution





Mu2e (FermiLab) and COMET (JPARC)

- Aluminium (Z = 13) targets: lifetime (τ_μ = 880 ns) to better match their pulsed beams (SINDRUM-II: used continuous beam and gold target)
- **Design sensitivities: 10^{-16} in 5-10 yr (SINDRUM II result $7 \cdot 10^{-12}$)**

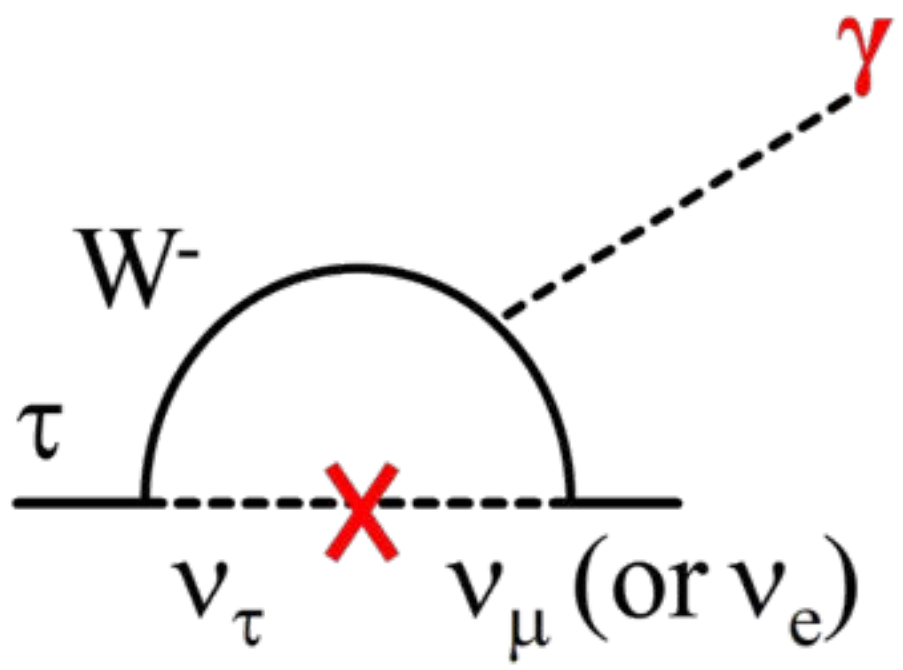
- Main constraint
  - control of the background
  - large number of low energy muons
- Dedicated high-power beam lines that can provide pulses of protons at around 8 GeV.
- Resonant slow extraction scheme is used to take a small fraction of the circulating pulses in each cycle.
- Low-Z production target, inside a powerful superconducting solenoid.
- Effective collection of low-energy pions into the secondary beam transport.
- **Characteristic transport lines**: curved solenoids that keep the low energy muons on helical trajectories while deflecting them through 90○ in the horizontal plane.
  - No direct line of sight from the production target
  - Neutron shield

Timeline

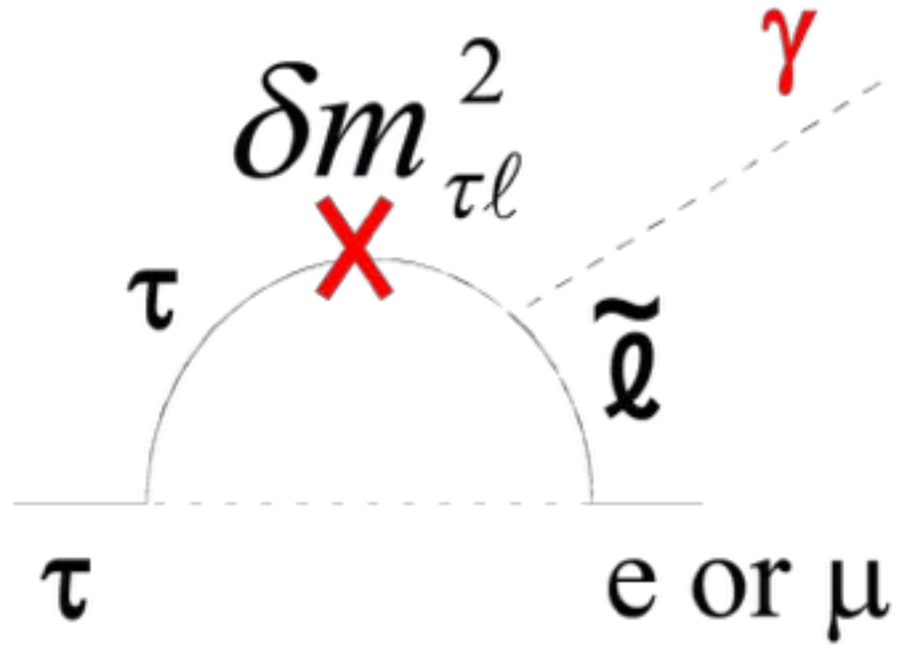
- Mu2e: expected start is early 2020
- COMET: phase I start in 2018, in parallel to phase II construction. phase II start: 2019

CLFV in τ decays

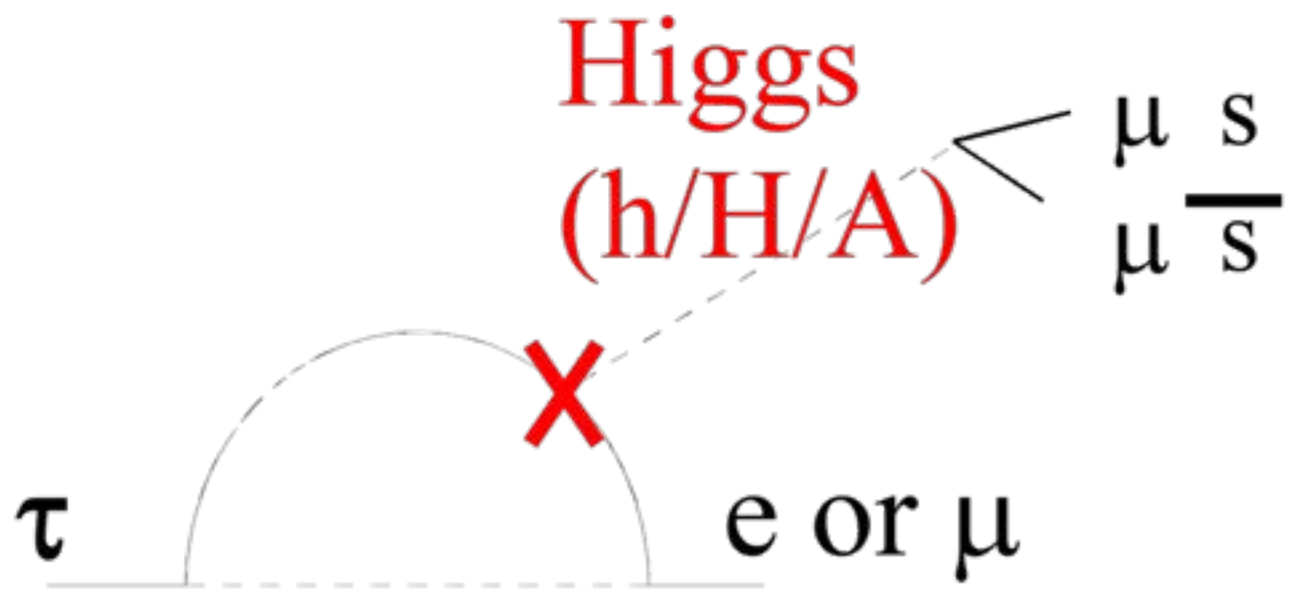
SM



SUSY-seesaw or SUSY-GUT



Heavier s-leptons (mass > mW)



- Full analogy with muon to electron but many more possibilities
- SUSY is the most popular candidate among various NP models; it naturally induces LFV at one-loop level due to the s-lepton mixing
- To distinguish which model is preferred, we need to search for all possible CLFV decays

Current results: PDG (1/2)

$\sigma(\mu^{-32}S\to e^{+32}Si^*)/\sigma(\mu^{-32}S\to \nu_\mu{}^{32}P^*)$	$<9\times10^{-10}$
$\sigma(\mu^{-127}I\to e^{+127}Sb^*)/\sigma(\mu^{-127}I\to \text{anything})$	$<3\times10^{-10}$
$\sigma(\mu^- Ti\to e^+ Ca)/\sigma(\mu^- Ti\to \text{capture})$	$<3.6\times10^{-11}$

$\Gamma(\tau^-\to\bar{p}\mu^+\mu^-)/\Gamma(\text{total})$	$<3.3\times10^{-7}$
$\Gamma(\tau^-\to p\mu^-\mu^-)/\Gamma(\text{total})$	$<4.4\times10^{-7}$
$\Gamma(\tau^-\to\bar{\Lambda}\pi^-)/\Gamma(\text{total})$	$<1.4\times10^{-7}$
$\Gamma(\tau^-\to\Lambda\pi^-)/\Gamma(\text{total})$	$<7.2\times10^{-8}$
$\Gamma(\tau^-\to\bar{p}\pi^0\eta)/\Gamma(\text{total})$	$<2.7\times10^{-5}$
$\Gamma(\tau^-\to\bar{p}2\pi^0)/\Gamma(\text{total})$	$<3.3\times10^{-5}$
$\Gamma(\tau^-\to\mu^+K^-K^-)/\Gamma(\text{total})$	$<4.7\times10^{-8}$
$\Gamma(\tau^-\to e^+K^-K^-)/\Gamma(\text{total})$	$<3.3\times10^{-8}$
$\Gamma(\tau^-\to\bar{p}\eta)/\Gamma(\text{total})$	$<8.9\times10^{-6}$
$\Gamma(\tau^-\to\bar{p}\pi^0)/\Gamma(\text{total})$	$<1.5\times10^{-5}$
$\Gamma(\tau^-\to\bar{p}\gamma)/\Gamma(\text{total})$	$<3.5\times10^{-6}$
$\Gamma(\tau^-\to\mu^+\pi^-K^-)/\Gamma(\text{total})$	$<4.8\times10^{-8}$
$\Gamma(\tau^-\to e^+\pi^-K^-)/\Gamma(\text{total})$	$<3.2\times10^{-8}$
$\Gamma(\tau^-\to\mu^+\pi^-\pi^-)/\Gamma(\text{total})$	$<3.9\times10^{-8}$
$\Gamma(\tau^-\to e^+\pi^-\pi^-)/\Gamma(\text{total})$	$<2.0\times10^{-8}$

$\Gamma(Z\to p\mu)/\Gamma(\text{total})$	$<1.8\times10^{-6}$
$\Gamma(Z\to pe)/\Gamma(\text{total})$	$<1.8\times10^{-6}$

$\Gamma(\pi^+\to\mu^+\bar{\nu}_{\bar{e}})/\Gamma(\text{total})$	$<1.5\times10^{-3}$
$\Gamma(K^+\to\pi^-\mu^+\mu^+)/\Gamma(\text{total})$	$<1.1\times10^{-9}$
$\Gamma(K^+\to\pi^-\mu^+e^+)/\Gamma(\text{total})$	$<5.0\times10^{-10}$
$\Gamma(K^+\to\pi^0e^+\bar{\nu}_{\bar{e}}\})/\Gamma(\text{total})$	$<3\times10^{-3}$
$\Gamma(K^+\to\mu\bar{\nu}_{\bar{e}e}\})/\Gamma(\text{total})$	$<3.3\times10^{-3}$
$\Gamma(K^+\to\pi^-e^+e^+)/\Gamma(\text{total})$	$<6.4\times10^{-10}$

$\Gamma(\Lambda\to K_S^0\nu)/\Gamma(\text{total})$	$<2\times10^{-5}$
$\Gamma(\Lambda\to K^-\mu^+)/\Gamma(\text{total})$	$<3\times10^{-6}$
$\Gamma(\Lambda\to K^-e^+)/\Gamma(\text{total})$	$<2\times10^{-6}$
$\Gamma(\Lambda\to K^+\mu^-)/\Gamma(\text{total})$	$<3\times10^{-6}$
$\Gamma(\Lambda\to K^+e^-)/\Gamma(\text{total})$	$<2\times10^{-6}$
$\Gamma(\Lambda\to\pi^-\mu^+)/\Gamma(\text{total})$	$<6\times10^{-7}$
$\Gamma(\Lambda\to\pi^-e^+)/\Gamma(\text{total})$	$<4\times10^{-7}$
$\Gamma(\Lambda\to\pi^+\mu^-)/\Gamma(\text{total})$	$<6\times10^{-7}$
$\Gamma(\Lambda\to\pi^+e^-)/\Gamma(\text{total})$	$<6\times10^{-7}$
$\Gamma(\Xi^-\to p\mu^-\mu^-)/\Gamma(\text{total})$	$<4\times10^{-8}$
$\Gamma(\Lambda_c{}^+\to\bar{p}e^+\mu^+)/\Gamma(\text{total})$	$<1.6\times10^{-5}$
$\Gamma(\Lambda_c{}^+\to\bar{p}2\mu^+)/\Gamma(\text{total})$	$<9.4\times10^{-6}$
$\Gamma(\Lambda_c{}^+\to\bar{p}\{p\}2e^+)/\Gamma(\text{total})$	$<2.7\times10^{-6}$
$\Gamma(\Lambda_c{}^+\to\Sigma^-\mu^+\mu^+)/\Gamma(\text{total})$	$<7.0\times10^{-4}$

Current results: PDG (2/2)

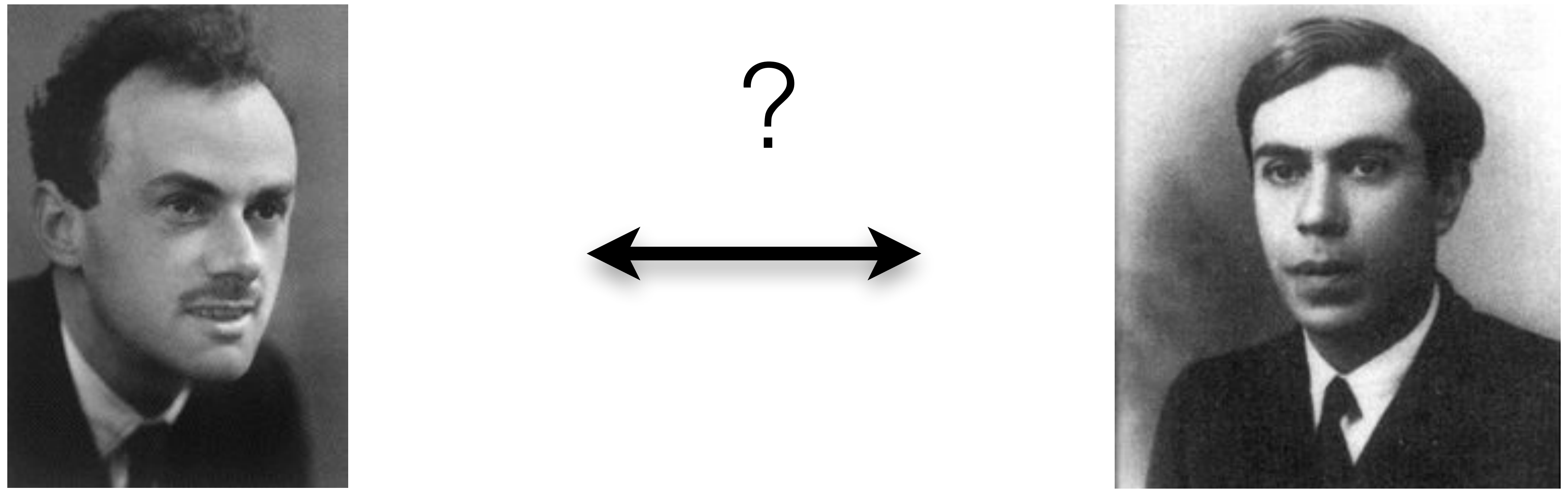
$\Gamma(D^+ \to K^*(892)^- 2\mu^+)/\Gamma(\text{total})$	$<8.5\times10^{-4}$
$\Gamma(D^+ \to \rho^- 2\mu^+)/\Gamma(\text{total})$	$<5.6\times10^{-4}$
$\Gamma(D^+ \to K^- e^+ \mu^+)/\Gamma(\text{total})$	$<1.9\times10^{-6}$
$\Gamma(D^+ \to K^- 2\mu^+)/\Gamma(\text{total})$	$<1.0\times10^{-5}$
$\Gamma(D^+ \to K^- 2e^+)/\Gamma(\text{total})$	$<9\times10^{-7}$
$\Gamma(D^+ \to \pi^- e^+ \mu^+)/\Gamma(\text{total})$	$<2.0\times10^{-6}$
$\Gamma(D^+ \to \pi^- 2\mu^+)/\Gamma(\text{total})$	$<2.2\times10^{-8}$
$\Gamma(D^+ \to \pi^- 2e^+)/\Gamma(\text{total})$	$<1.1\times10^{-6}$
$\Gamma(D^0 \to \bar{p} e^+)/\Gamma(\text{total})$	$<1.1\times10^{-5}$
$\Gamma(D^0 \to p e^-)/\Gamma(\text{total})$	$<1.0\times10^{-5}$
$\Gamma(D^0 \to 2K^- e^+ \mu^+ + \text{c.c.})/\Gamma(\text{total})$	$<5.7\times10^{-5}$
$\Gamma(D^0 \to K^- \pi^- e^+ \mu^+ + \text{c.c.})/\Gamma(\text{total})$	$<2.18\times10^{-4}$
$\Gamma(D^0 \to \pi^- \pi^- e^+ \mu^+ + \text{c.c.})/\Gamma(\text{total})$	$<7.9\times10^{-5}$
$\Gamma(D^0 \to 2K^- 2\mu^+ + \text{c.c.})/\Gamma(\text{total})$	$<9.4\times10^{-5}$
$\Gamma(D^0 \to 2K^- 2e^+ + \text{c.c.})/\Gamma(\text{total})$	$<1.52\times10^{-4}$
$\Gamma(D^0 \to K^- \pi^- 2\mu^+ + \text{c.c.})/\Gamma(\text{total})$	$<3.9\times10^{-4}$
$\Gamma(D^0 \to K^- \pi^- 2e^+ + \text{c.c.})/\Gamma(\text{total})$	$<2.06\times10^{-4}$
$\Gamma(D^0 \to 2\pi^- 2\mu^+ + \text{c.c.})/\Gamma(\text{total})$	$<2.9\times10^{-5}$
$\Gamma(D^0 \to 2\pi^- 2e^+ + \text{c.c.})/\Gamma(\text{total})$	$<1.12\times10^{-4}$

$\Gamma(D_s^+ \to K^- e^+ \mu^+)/\Gamma(\text{total})$	$<6.1\times10^{-6}$
$\Gamma(D_s^+ \to K^- 2e^+)/\Gamma(\text{total})$	$<5.2\times10^{-6}$
$\Gamma(D_s^+ \to \pi^- e^+ \mu^+)/\Gamma(\text{total})$	$<8.4\times10^{-6}$
$\Gamma(D_s^+ \to \pi^- 2e^+)/\Gamma(\text{total})$	$<4.1\times10^{-6}$
$\Gamma(D_s^+ \to K^*(892)^- 2\mu^+)/\Gamma(\text{total})$	$<1.4\times10^{-3}$
$\Gamma(D_s^+ \to K^- 2\mu^+)/\Gamma(\text{total})$	$<1.3\times10^{-5}$
$\Gamma(D_s^+ \to \pi^- 2\mu^+)/\Gamma(\text{total})$	$<1.2\times10^{-7}$

$\Gamma(B^+ \to \bar{D}^0 \pi^- \mu^+ \mu^+)/\Gamma(\text{total})$	$<1.5\times10^{-6}$
$\Gamma(B^+ \to D_s^- \mu^+ \mu^+)/\Gamma(\text{total})$	$<5.8\times10^{-7}$
$\Gamma(B^+ \to D^*\text{-} \mu^+ \mu^+)/\Gamma(\text{total})$	$<2.4\times10^{-6}$
$\Gamma(B^+ \to D^- \mu^+ \mu^+)/\Gamma(\text{total})$	$<6.9\times10^{-7}$
$\Gamma(B^+ \to D^- e^+ \mu^+)/\Gamma(\text{total})$	$<1.8\times10^{-6}$
$\Gamma(B^+ \to D^- e^+ e^+)/\Gamma(\text{total})$	$<2.6\times10^{-6}$
$\Gamma(B^+ \to \bar{\Lambda}\{\Lambda\}^0 e^+)/\Gamma(\text{total})$	$<8\times10^{-8}$
$\Gamma(B^+ \to \bar{\Lambda}\{\Lambda\}^0 \mu^+)/\Gamma(\text{total})$	$<6\times10^{-8}$
$\Gamma(B^+ \to \Lambda^0 e^+)/\Gamma(\text{total})$	$<3.2\times10^{-8}$
$\Gamma(B^+ \to \Lambda^0 \mu^+)/\Gamma(\text{total})$	$<6\times10^{-8}$
$\Gamma(B^+ \to \rho^- \mu^+ \mu^+)/\Gamma(\text{total})$	$<4.2\times10^{-7}$
$\Gamma(B^+ \to \rho^- e^+ \mu^+)/\Gamma(\text{total})$	$<4.7\times10^{-7}$
$\Gamma(B^+ \to K^*(892)^- e^+ \mu^+)/\Gamma(\text{total})$	$<3.0\times10^{-7}$
$\Gamma(B^+ \to K^*(892)^- \mu^+ \mu^+)/\Gamma(\text{total})$	$<5.9\times10^{-7}$
$\Gamma(B^+ \to \rho^- e^+ e^+)/\Gamma(\text{total})$	$<1.7\times10^{-7}$
$\Gamma(B^+ \to K^*(892)^- e^+ e^+)/\Gamma(\text{total})$	$<4.0\times10^{-7}$
$\Gamma(B^+ \to K^- \mu^+ \mu^+)/\Gamma(\text{total})$	$<4.1\times10^{-8}$
$\Gamma(B^+ \to K^- e^+ \mu^+)/\Gamma(\text{total})$	$<1.6\times10^{-7}$
$\Gamma(B^+ \to K^- e^+ e^+)/\Gamma(\text{total})$	$<3.0\times10^{-8}$
$\Gamma(B^+ \to \pi^- \mu^+ \mu^+)/\Gamma(\text{total})$	$<4.0\times10^{-9}$
$\Gamma(B^+ \to \pi^- e^+ \mu^+)/\Gamma(\text{total})$	$<1.5\times10^{-7}$
$\Gamma(B^+ \to \pi^- e^+ e^+)/\Gamma(\text{total})$	$<2.3\times10^{-8}$
$\Gamma(B^0 \to \Lambda\_c^+ e^-)/\Gamma(\text{total})$	$<4\times10^{-6}$
$\Gamma(B^0 \to \Lambda\_c^+ \mu^-)/\Gamma(\text{total})$	$<1.4\times10^{-6}$

(Total) Lepton Number L

- Neutrino oscillations have no direct implications on total lepton number
- Therefore $U(1)_L$ could be an exact global symmetry also in the NP Lagrangian:
  → L is conserved and neutrino's are Dirac massive particles
- However ... if neutrinos are Majorana fermions → $U(1)_L$ is not a good symmetry and L is violated (by 2 units)
- **So far … no experimental indication concerning the Majorana/Dirac nature of the massive neutrinos.**
- Different models for non-zero neutrino masses: either Dirac or Majorana fermions.



Testing Lepton Number

- Experiments involving purely Majorana neutrino processes can provide the seeded answer:
  - Rare τ, meson and hyperon decays at accelerators
  - Nuclear processes (neutrinoless double beta decay)

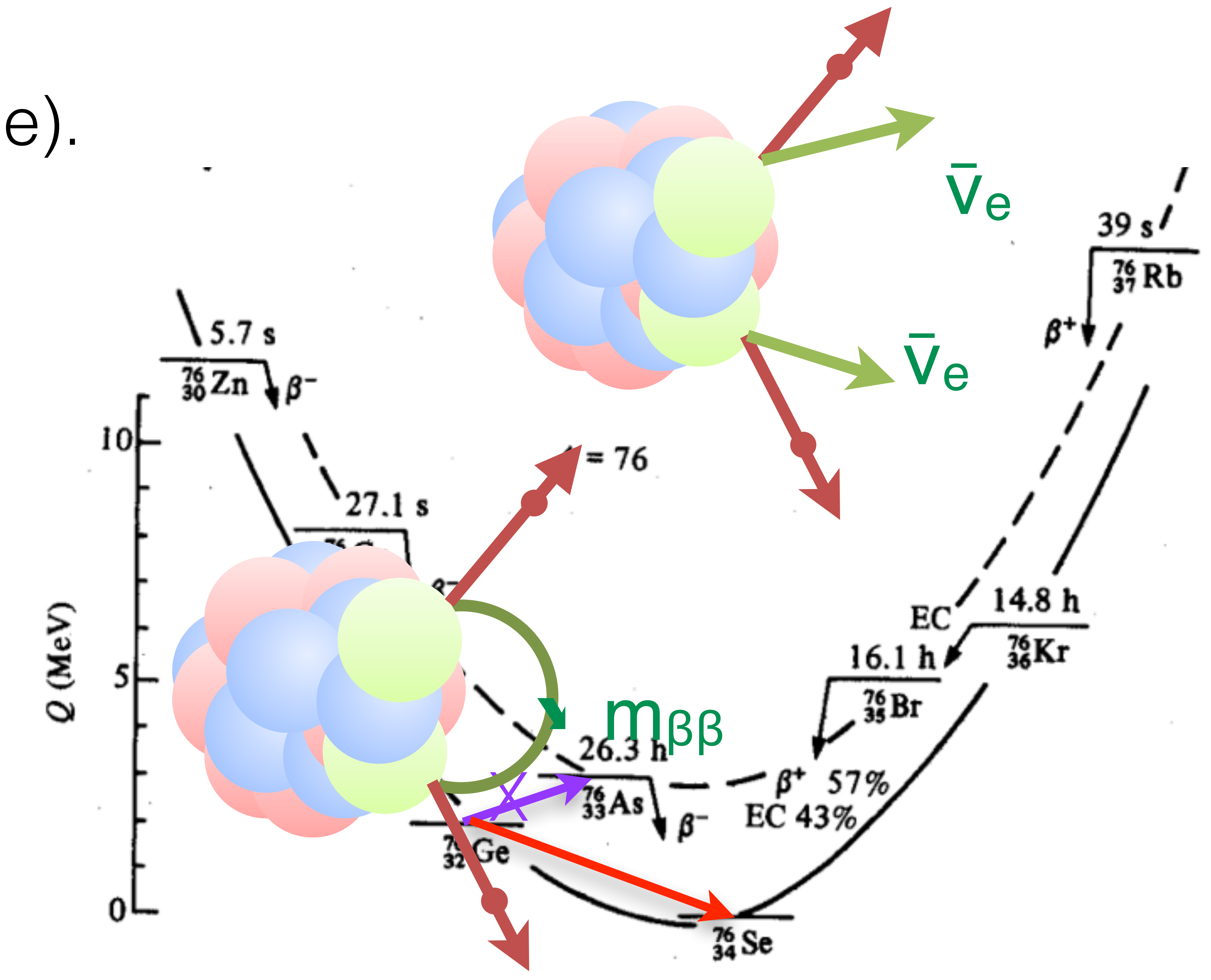
- 0νββ decay is by far the most sensitive test
- Just compare the amount of tries one can make:
  - 100 kg 0νββ decay source contains ~ 10^{27} nuclei that can be observed for a long time (several years)
  - At an accelerator: first produce muons or kaons, and then search for the unusual decay channels

typically ~10^{20} pot / year and correspondingly smaller numbers of muons or kaons

ββ decays

Even-even nuclei: only direct $0^+ \rightarrow 0^+$ transition (e.g. ^{76}Ge → ^{76}Se).

- 2n → 2p + 2e– + $2\bar{\nu}$ (2νββ)
  - Standard 2nd order weak nuclear transition
  - Long lifetime, but always occurring
- **2n → 2p + 2e– [(Z,A) → (Z + 2,A)] (0νββ)**
- **Lepton number violation (LNV): physics beyond the SM**



LNV and neutrino masses

- Majorana neutrinos
- absolute neutrino mass scale
- Majorana phases

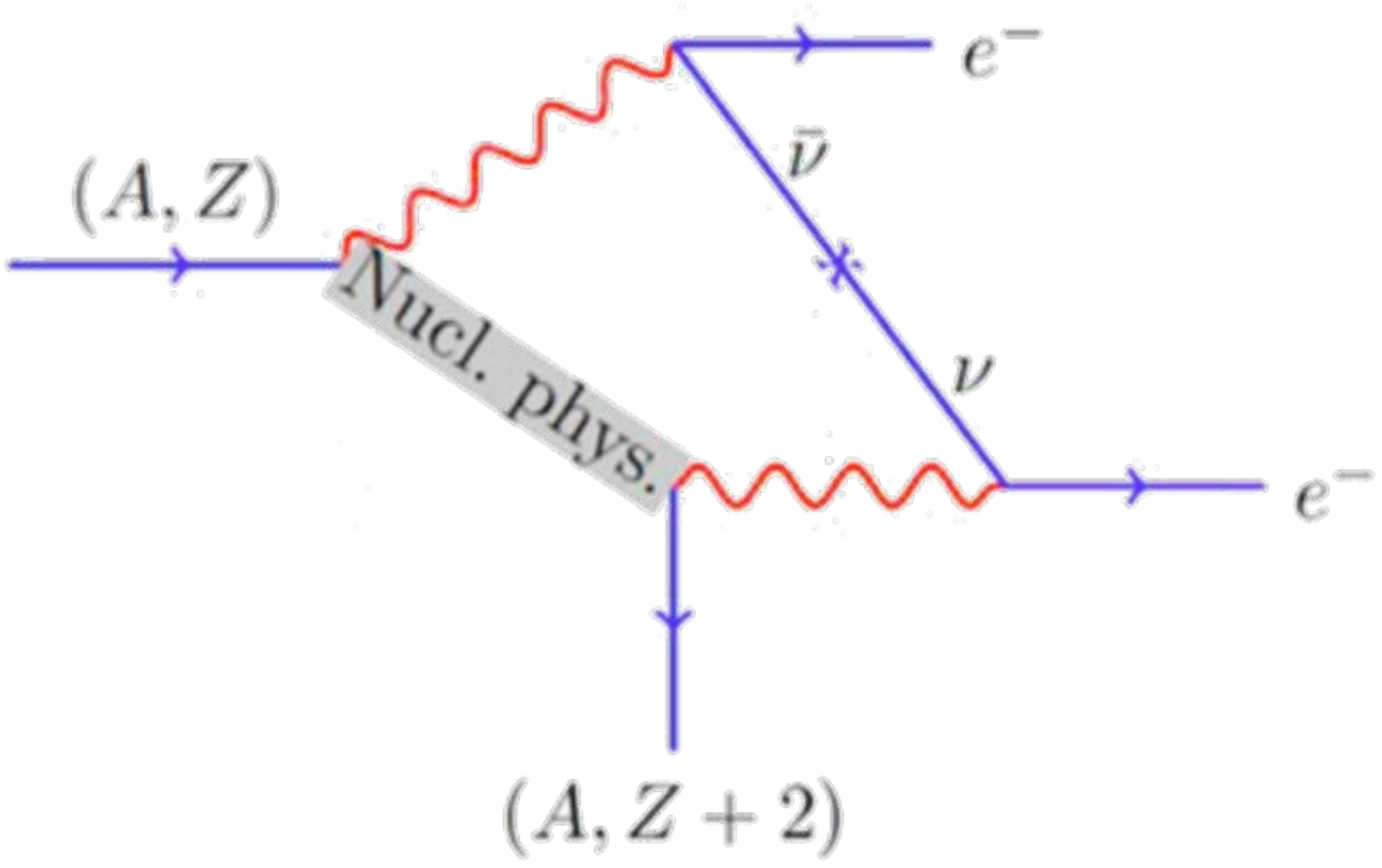
Other new physics

0νββ provides stringent constraints to many LNV models

Experiments

Under non trivial approximations it is possible to separate atomic, nuclear and particle contributions

$$\Gamma^{0\nu} = G_x(Q,Z)|M_x(A,Z)|^2|\eta_x|^2$$

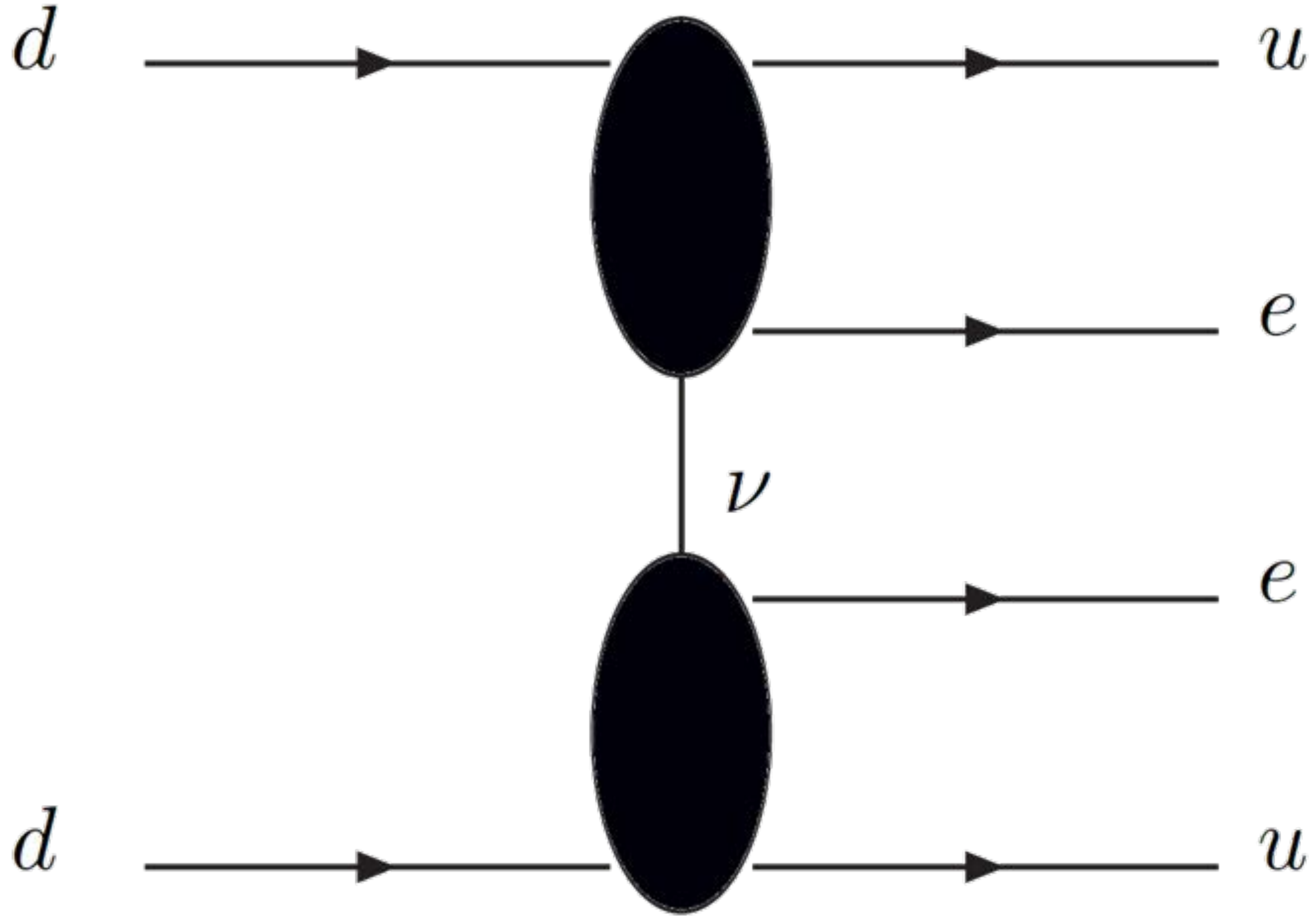


$G_x(Q,Z)$ = phase space factor ➞ calculable

$M_x(A,Z)$ = nuclear matrix element ➞ problematic

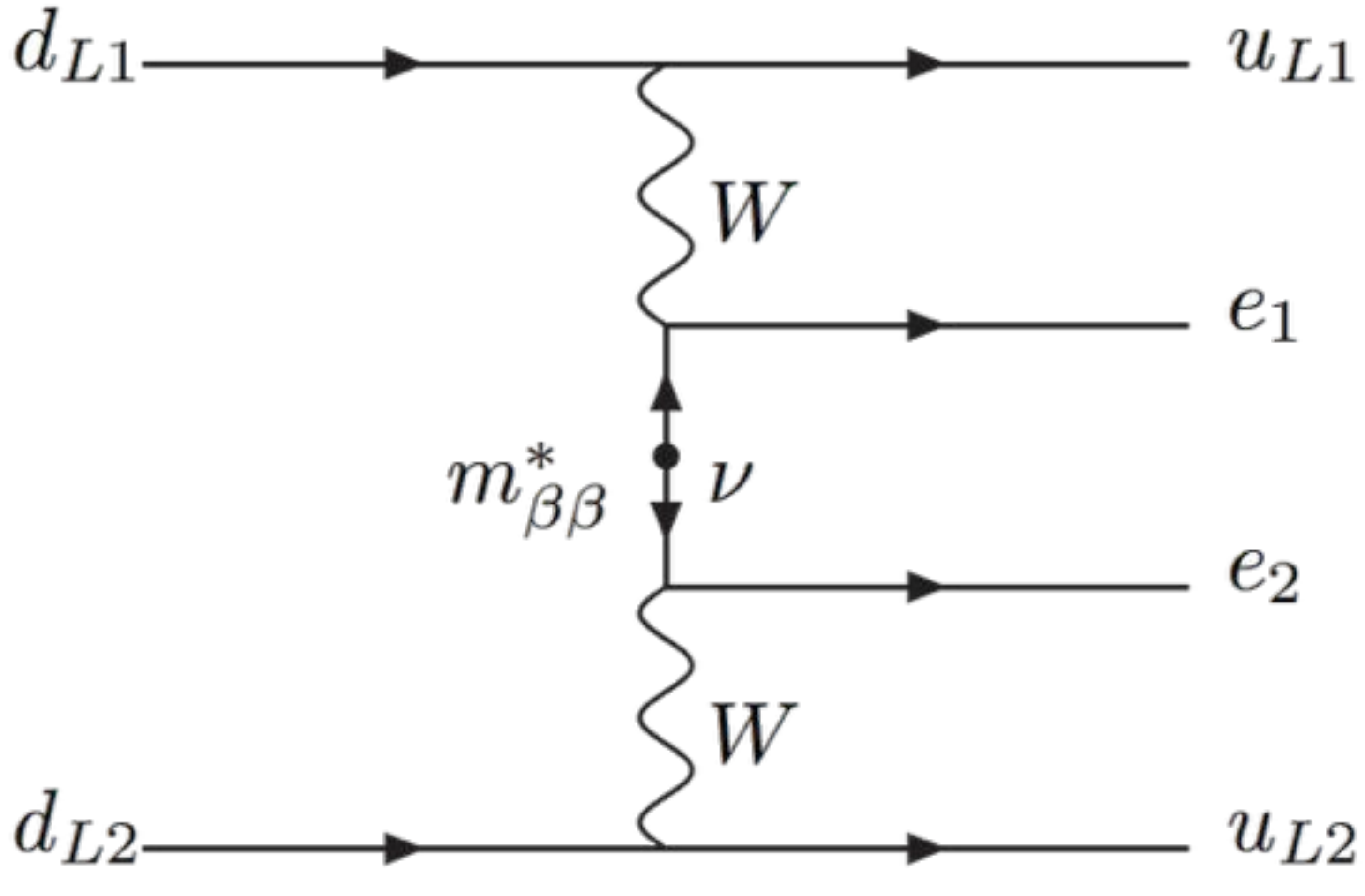
η_x = particle physics parameter ➞ model dependent

0νββ mechanisms: Majorana ν's



Long range interactions: light Majorana ν exchange between 2 point like vertices

$$
\begin{aligned}
\mathcal{L} &= \frac{G_F}{\sqrt{2}}\left(j^{SM}_{V-A} J^{SM}_{V-A} + \sum \epsilon_{NP} j_{NP} J_{NP}\right) \\
J &= \bar{u}\mathcal{O}_\beta d, \qquad j = \bar{e}\mathcal{O}_\beta \nu, \qquad \beta = V \pm A, PS, T
\end{aligned}
$$



$$
\mathcal{L}_{EW}^{eff,\,\Delta L_e=2}(x) = \frac{G_F^2}{2}\left[\bar{e}_1\gamma_\mu(1-\gamma_5)\frac{m_{\beta\beta}}{q^2}\gamma_\nu e_2^c\right]
$$

$$
\times\left[J^{\mu}_{1,\,V-A}(q)\,J^{\nu}_{2,\,V-A}(-q)\right]
$$

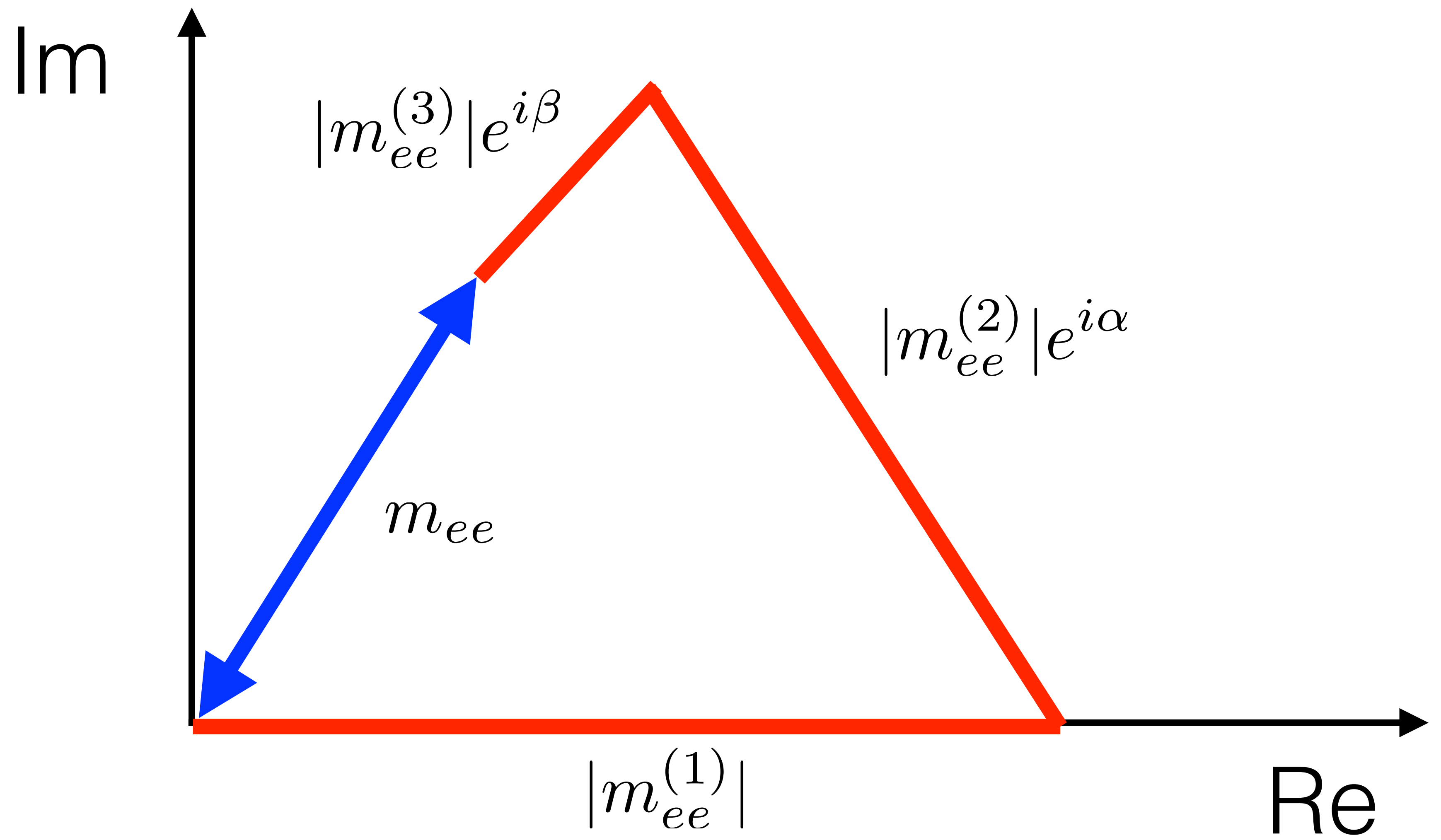
ββ0ν standard interpretation: light Majorana neutrino

- Neutrinoless Double Beta Decay is mediated by light massive Majorana neutrinos and all other potential mechanisms give negligible or no contribution

$$\eta_x = < m_{ee} >= \sum_k U_{ek}^2 m_k$$

$$= c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3$$

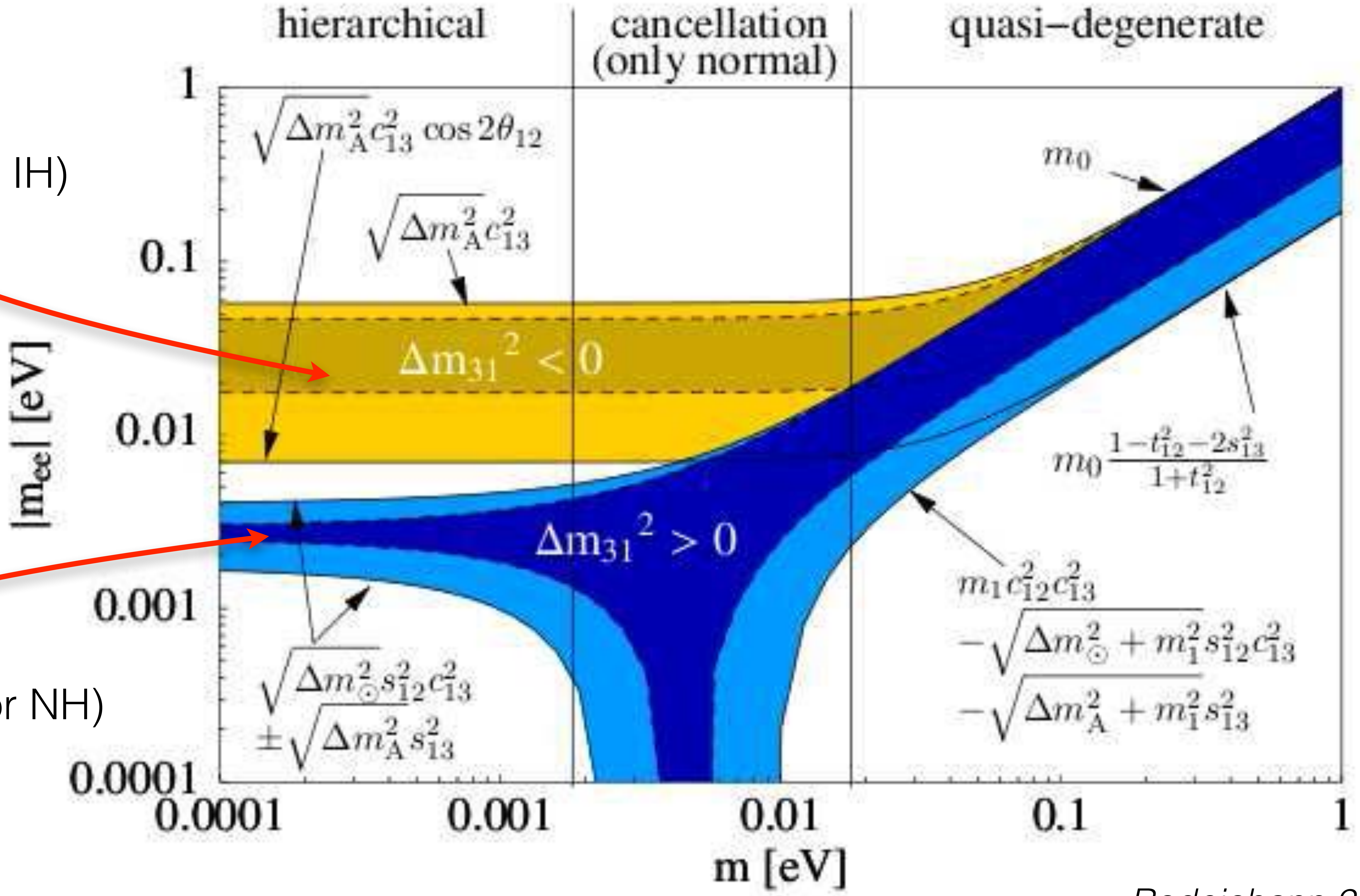
- The transition amplitude is proportional to coherent sum of neutrino masses
- Majorana phases play a crucial role: possible cancellations



Light Majorana neutrino

Inverse Ordering (IO or IH)

Normal Ordering (NO or NH)

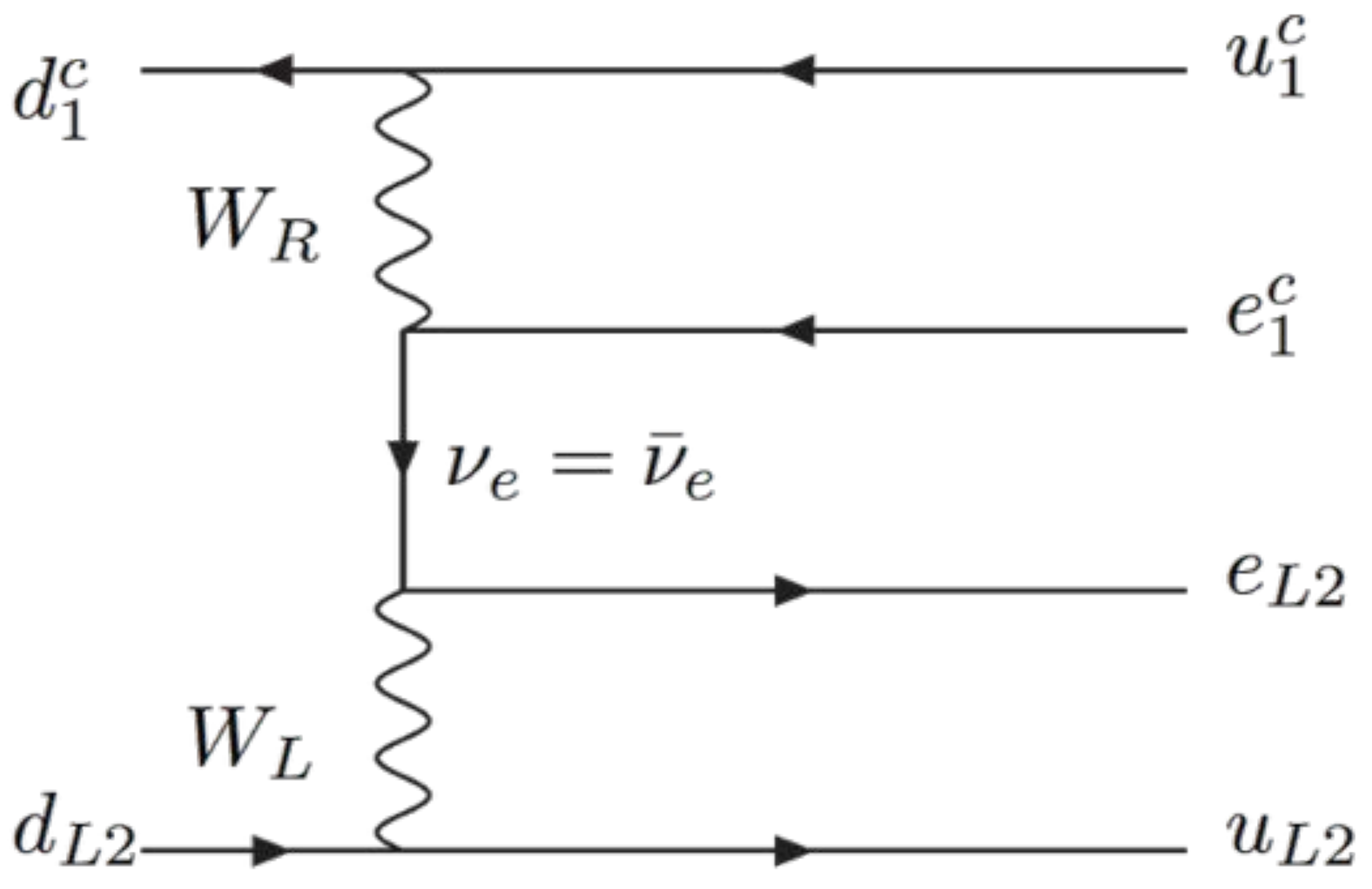


Rodejohann 2015

ββ0ν in SM extensions

Long range interactions:

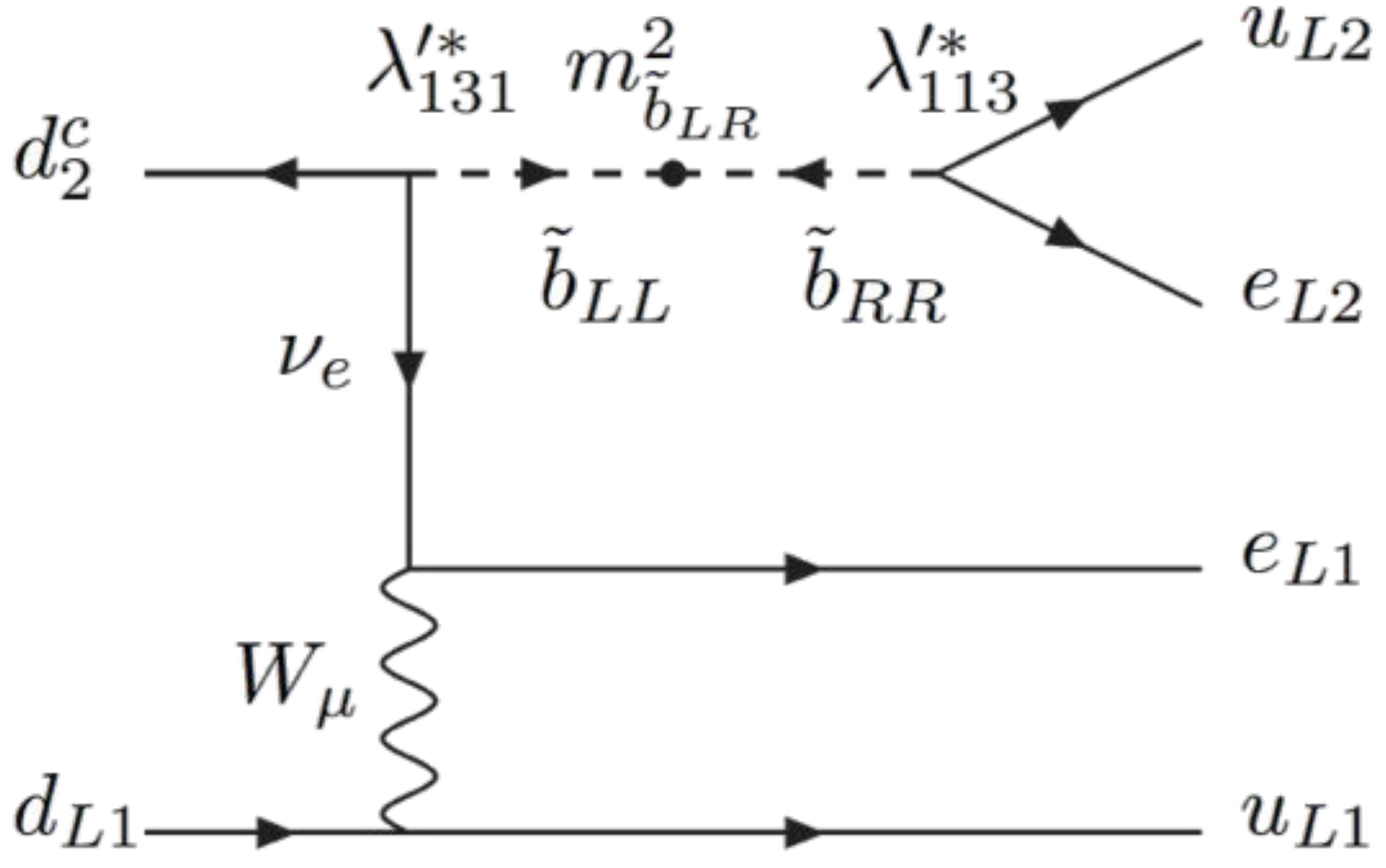
LR symmetric Model



$$\mathcal{L} \propto \left[\bar{e}_1\gamma_\mu(1+\gamma_5)\frac{\gamma\cdot q}{q^2}\gamma_\nu e_2^c\right] \times \left[J^\mu_{1,V+A}(q)\,J^\nu_{2,V-A}(-q)\right]$$

W_R-W_L contributions

s-bottom exchange in LNV SUSY



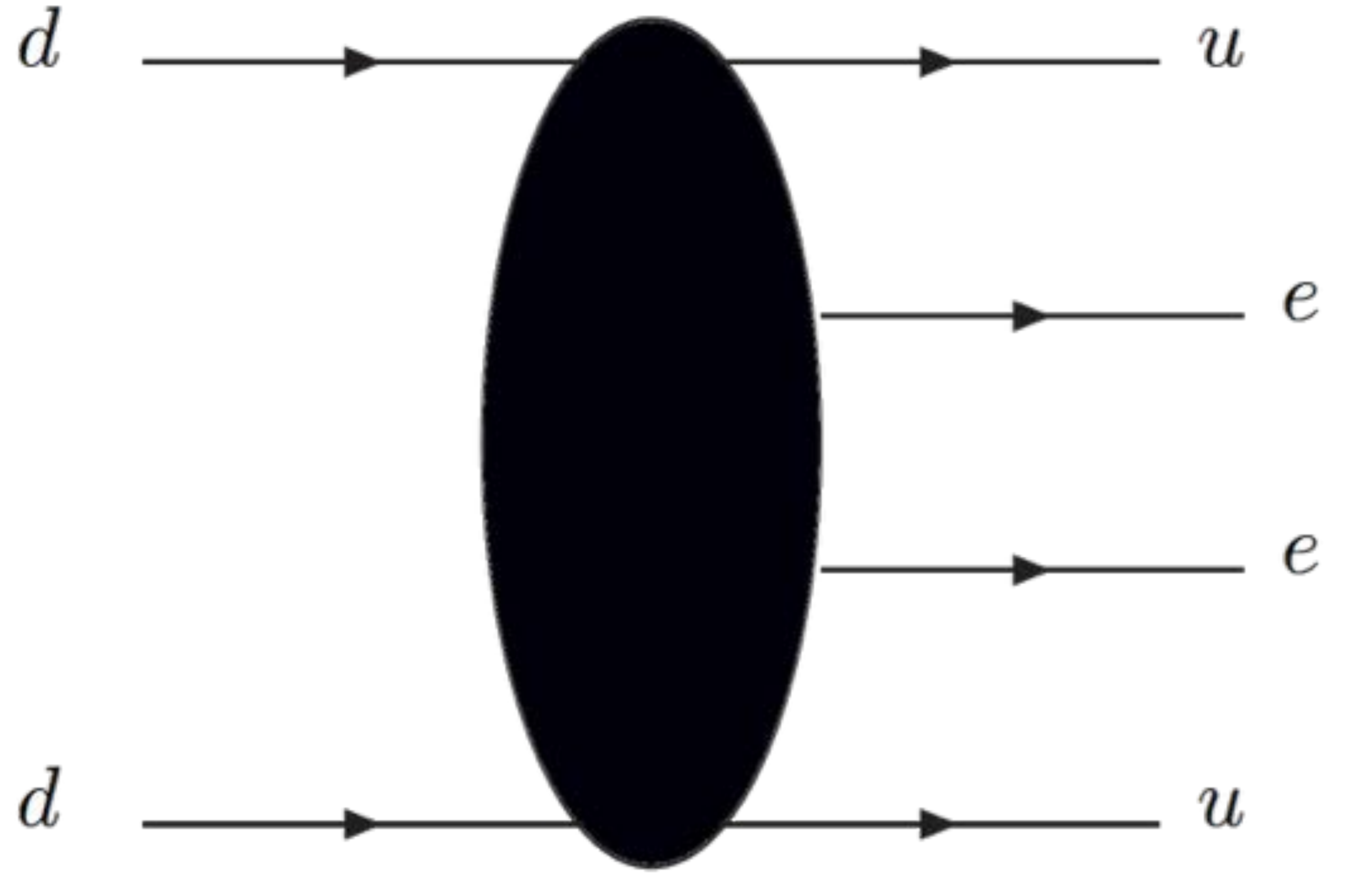
$$\mathcal{L} \propto \frac{1}{2}\left[\bar{e}_1\gamma_\rho(1-\gamma_5)\frac{1}{\not{q}} e_2^c\right]\left[J^\rho_{1,V-A}(q)\,J_{2,PS}(-q)\right] + \frac{1}{8}\left[\bar{e}_1\gamma_\rho(1-\gamma_5)\frac{1}{\not{q}}\sigma_{\mu\nu}e_2^c\right]\left[J^\rho_{1,V-A}(q)\,J^{\mu\nu}_{2,T}(-q)\right]$$

(Scalar) lepto-quark contributions

$$T_{1/2}^{0\nu\beta\beta} \approx 10^{25} yr \rightarrow \langle m_{\beta\beta}\rangle \approx 0.1 eV$$

Short range interactions:

Single point-like interactions



$$\mathcal{L} = \frac{G_F^2}{2} m_P^{-1} \sum \epsilon_{NP}\, j_{NP}\, J_{NP}\, J_{NP}$$

SUSY with gaugino exchange, [O(TeV)] heavy neutrinos...

$$T_{1/2}^{0\nu\beta\beta} \approx 10^{25} yr \rightarrow \Lambda_{LNV} \approx 1 TeV$$

Distinguishing 0νββ mechanisms

A single measurement of total rate cannot pin down underlying 0νββ mechanisms.

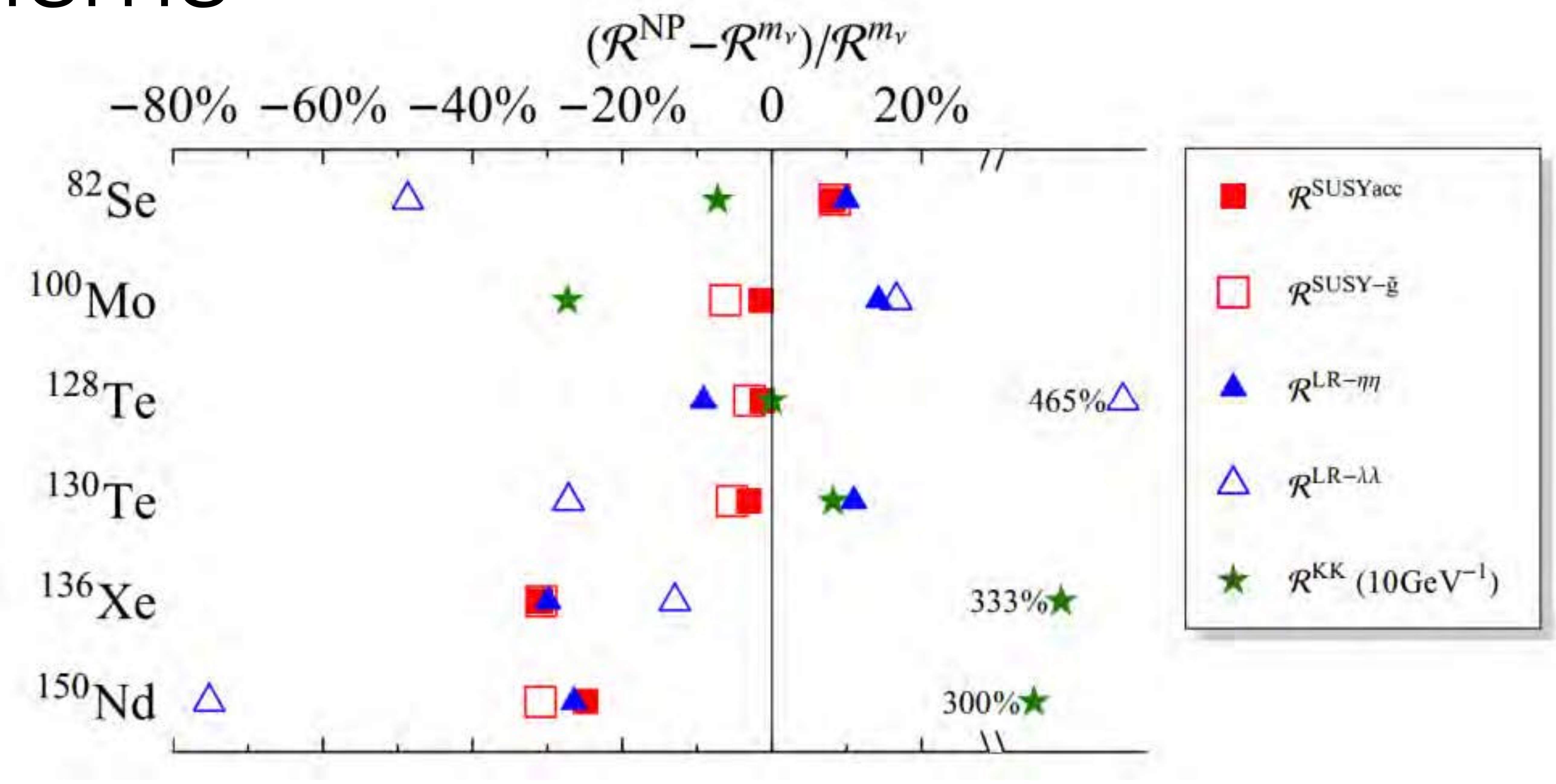
- Half life ratios of different isotopes

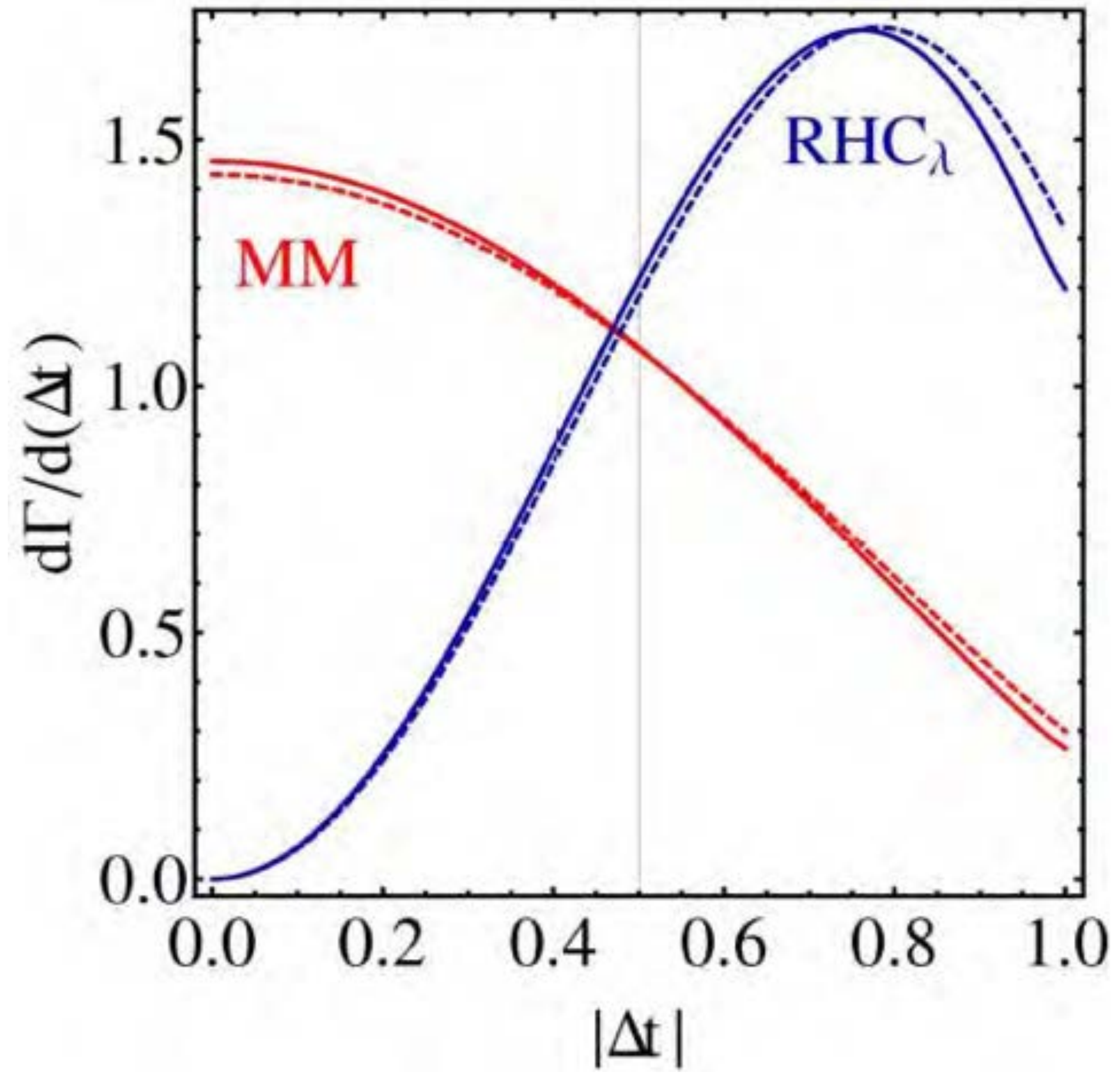
  Deppisch,Päs 06 , Gehman,Elliot 07 , Fogli,Lisi,Rotunno 09
- Electron angular correlations

  Ali,Borisov,Zhuridov 07
- Decay to excited states and other rare decays

  Faessler et.al. 94
- LNV processes at the LHC

  Allanach,CHK,Päs 09





Schechter-Valle theorem ("black box")

[Schechter and Valle, 1982]

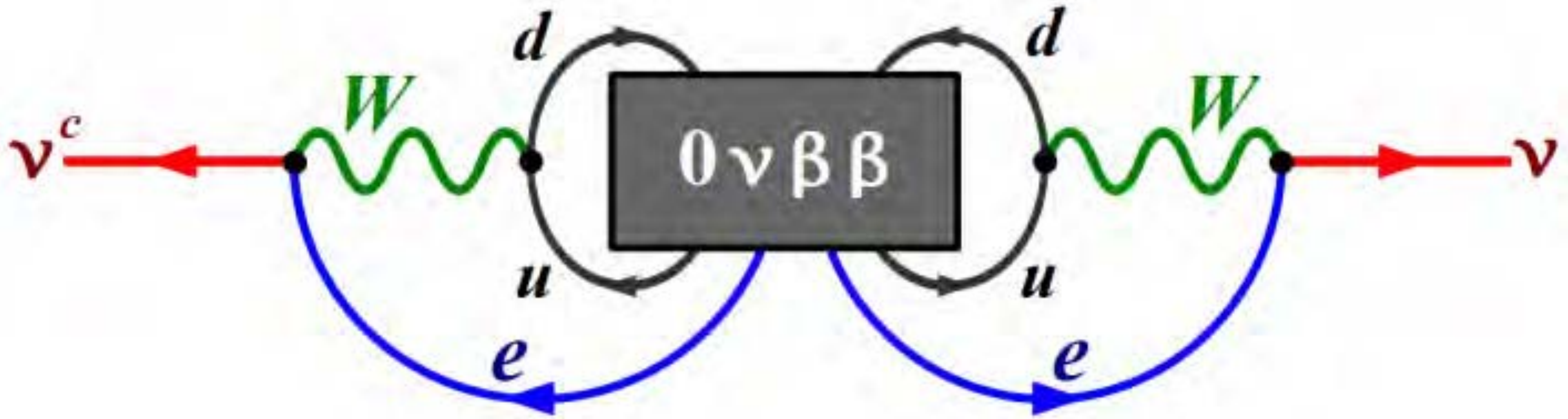
A non-zero *0vββ* amplitude implies a non vanishing Majorana neutrino mass

Basic assumptions:

- massive electron and u and d quarks
- standard left-handed interactions

Taking into account present 0vββ upper limits the conclusion is that the Feynman graph below corresponds to an unobservably small neutrino Majorana mass: $\mathbf{m_{bb} \sim 10^{-25}\ eV}$

[Duerr M., Lindner M. & Merle A. J. High Energ. Phys. (2011) 2011:9; arXiv:11105.0901]



Lepton number violation (LNV) and *0νββ*

- Let's estimate the relative size of heavy (A_H) versus light particle (A_L) exchange contributions

$$A_L \sim G_F^2 \frac{\langle m_{\beta\beta}\rangle}{\langle k^2\rangle} \qquad A_H \sim G_F^2 \frac{M_W^4}{\Lambda^5} \qquad \frac{A_H}{A_L} \sim \frac{M_W^4 \langle k^2\rangle}{\Lambda^5 \langle m_{\beta\beta}\rangle}$$

where ⟨m_{ee}⟩ is the effective neutrino Majorana mass, ⟨k^2⟩ ~ $(100\text{ MeV})^2$ is the typical light neutrino energy scale, and Λ is the heavy LNV scale

- For ⟨m_{ee}⟩ ~ 0.1–0.5 eV and Λ ~ 1 TeV: A_H/A_L ~ O(1) and LNV dynamics at the TeV scale would provide comparable effects

- Main difference is the range:
  - light neutrino: exchange between 2 vertices at distance r~1/q (q~100 MeV)
  - heavy particle: single vertex (6 fermions, i.e. dimension 9)

$$\mathcal{L}_{0\nu\beta\beta} = \sum_i \frac{\tilde{c}_i}{\Lambda^5}\,\tilde{O}_i \qquad \tilde{O}_i = \bar{q}\Gamma_1 q\;\; \bar{q}\Gamma_2 q\; \bar{e}\Gamma_3 e^c$$

Experimental signature

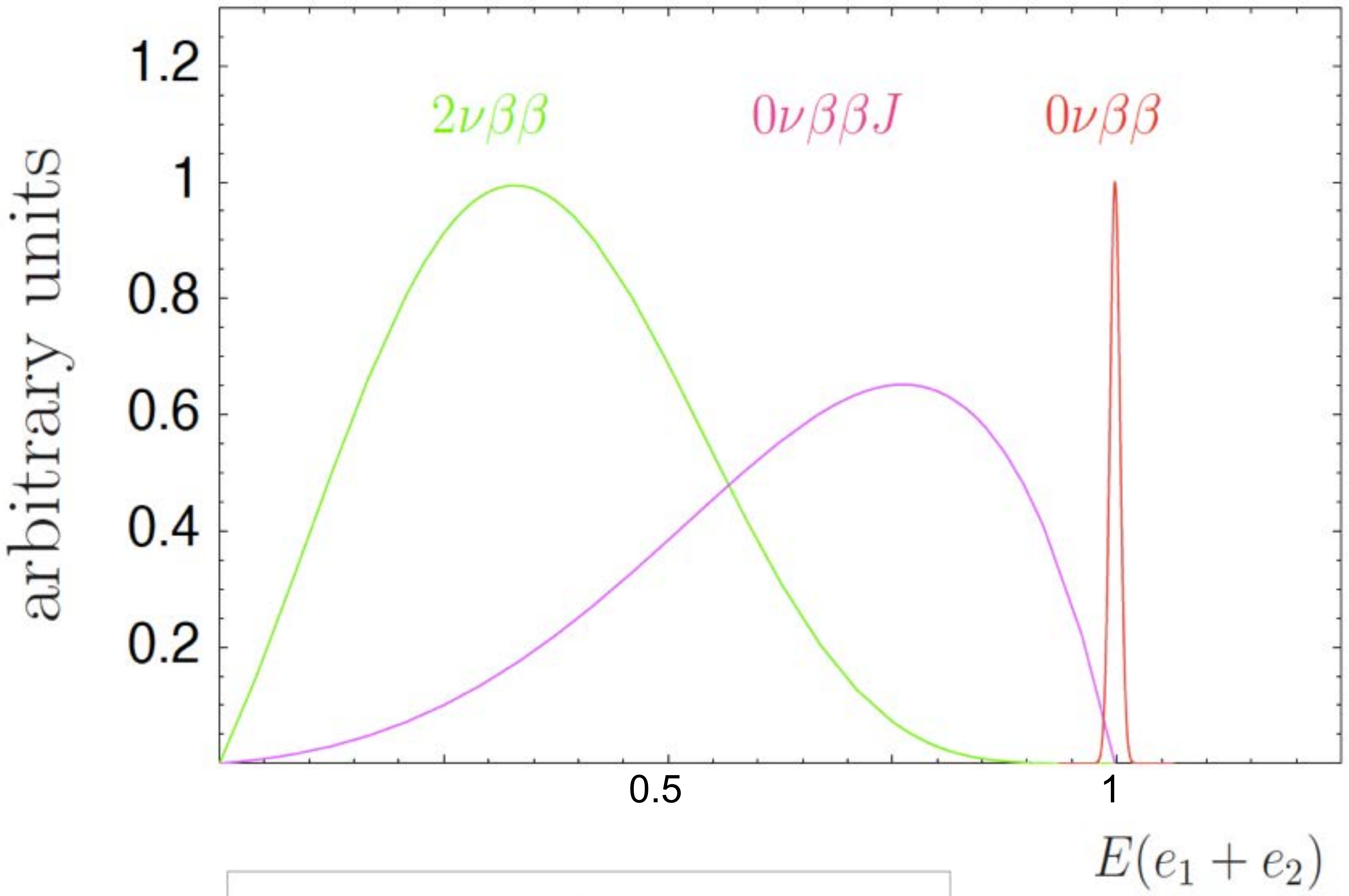
(A,Z) → $(A,Z+2)^{++}$ + 2 e-

- A new (ionised) isotope
- Two electrons

Minimal information:

- two e^- energy sum spectrum

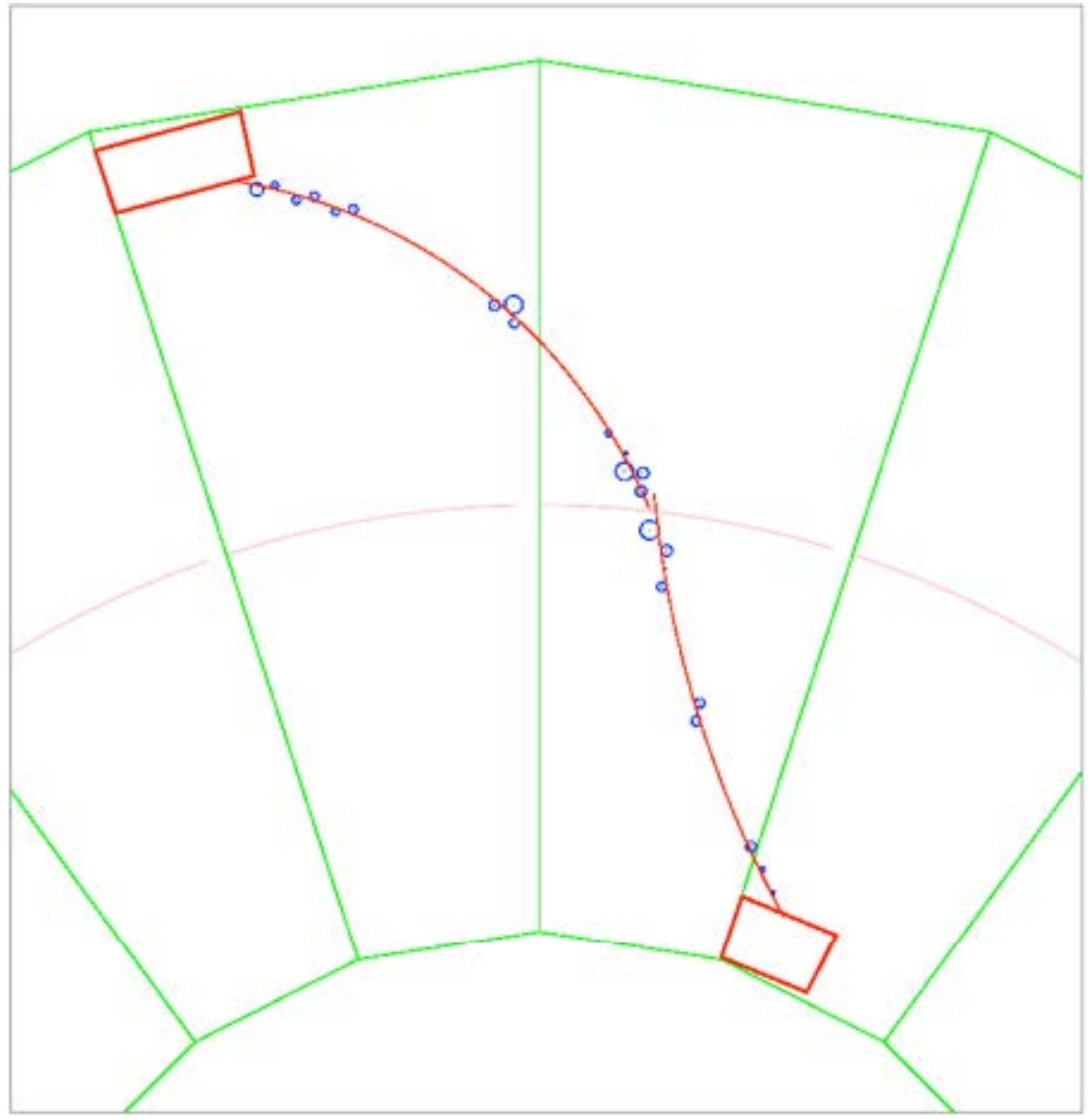
0νββ exhibits a peak at Q over 2νββ tail
(and background contributions)



Additional signatures:

- Single electron energy spectrum
- Angular correlation between the two electrons
- Daughter nuclear species

→ Track and event topology
→ Time Of Flight



Experimental sensitivity

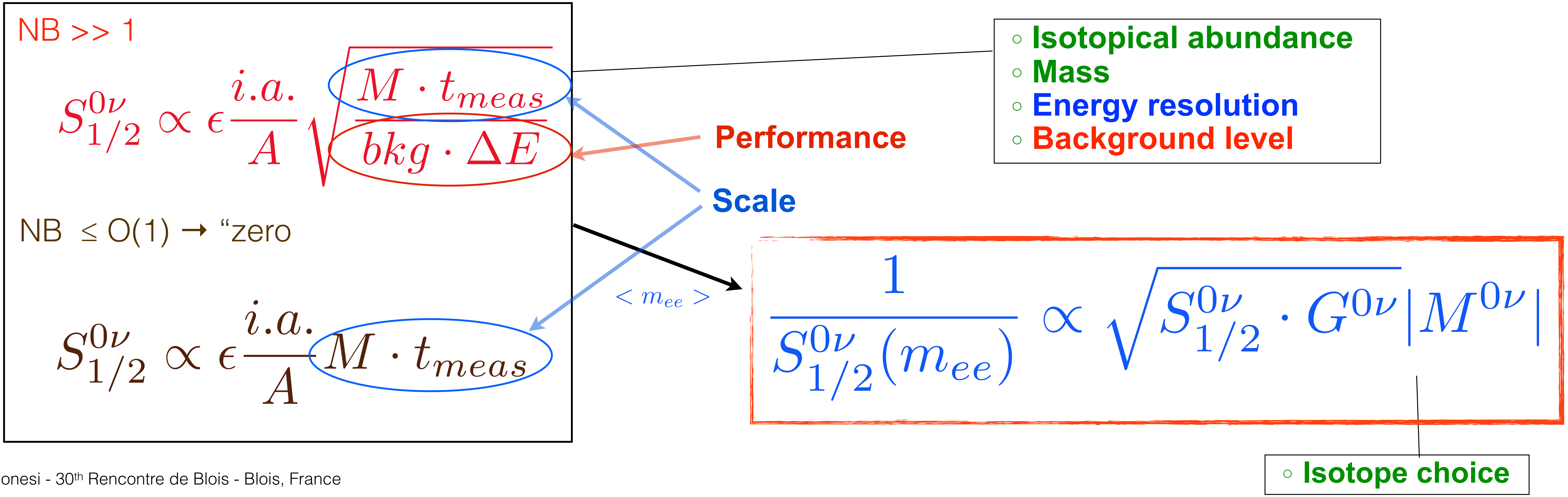
$$\tau^{0\nu}_{1/2} = ln2\frac{\epsilon N_{nuclei} t_{meas}}{N_{\beta\beta}}$$

Lifetime corresponding to the minimum detectable number of events over background at a given confidence level

$$N_{\beta\beta} \leq \sqrt{bkg \cdot \Delta E \cdot M \cdot t_{meas}}$$

N_{nuclei}	number of active nuclei in the experiment
t_{meas}	measuring time [y]
M	detector mass [kg]
ε	detector efficiency
i.a.	isotopic abundance
A	atomic number
ΔE	energy resolution [keV]
bkg	background [c/keV/y/kg]

NB = bkg·ΔE·T·M number of background events expected along the experiment lifetime



NB >> 1

$$S^{0\nu}_{1/2} \propto \epsilon\frac{i.a.}{A}\sqrt{\frac{M \cdot t_{meas}}{bkg \cdot \Delta E}}$$

NB ≤ O(1) → “zero

$$S^{0\nu}_{1/2} \propto \epsilon\frac{i.a.}{A} M \cdot t_{meas}$$

Performance

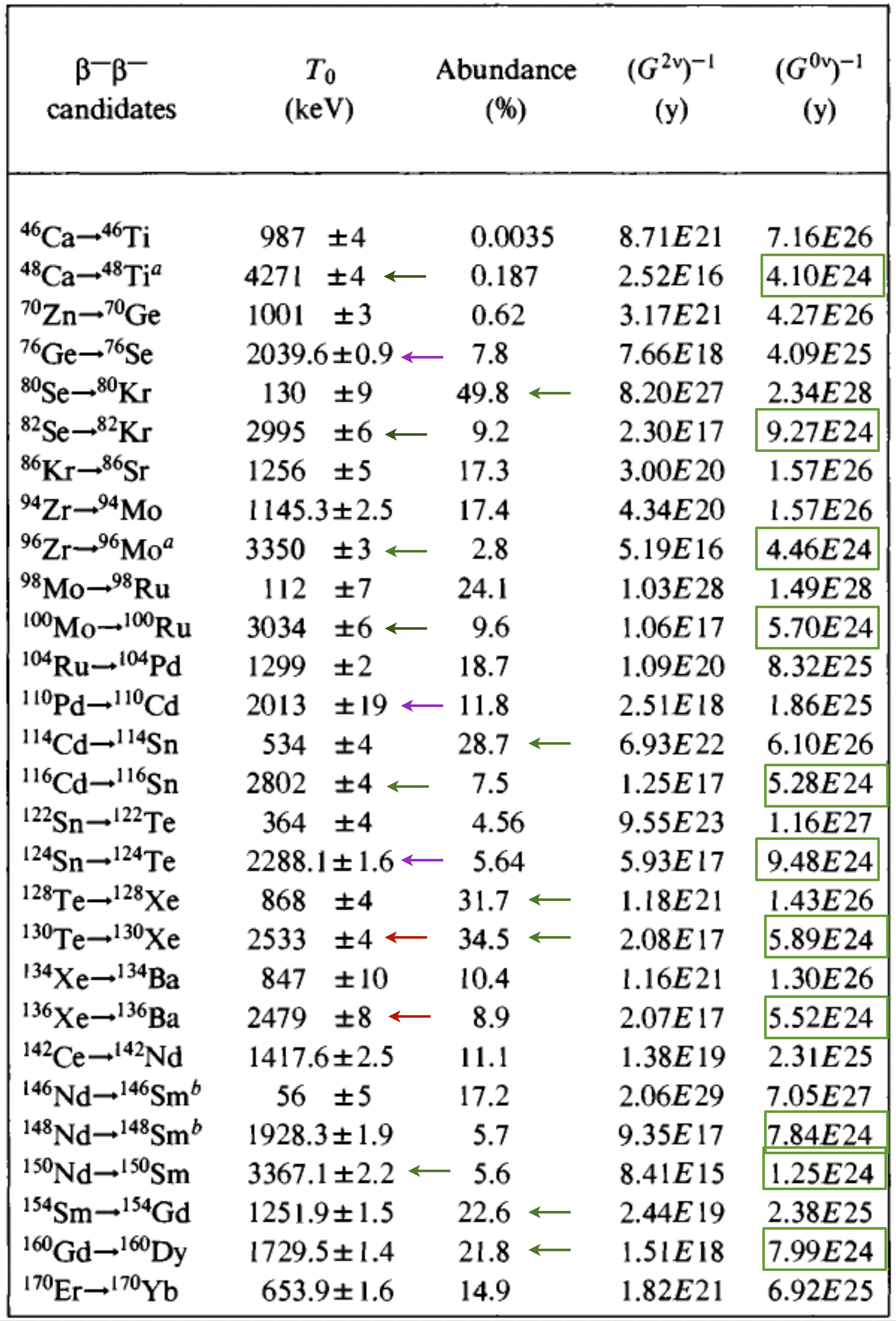
Scale

$< m_{ee} >$

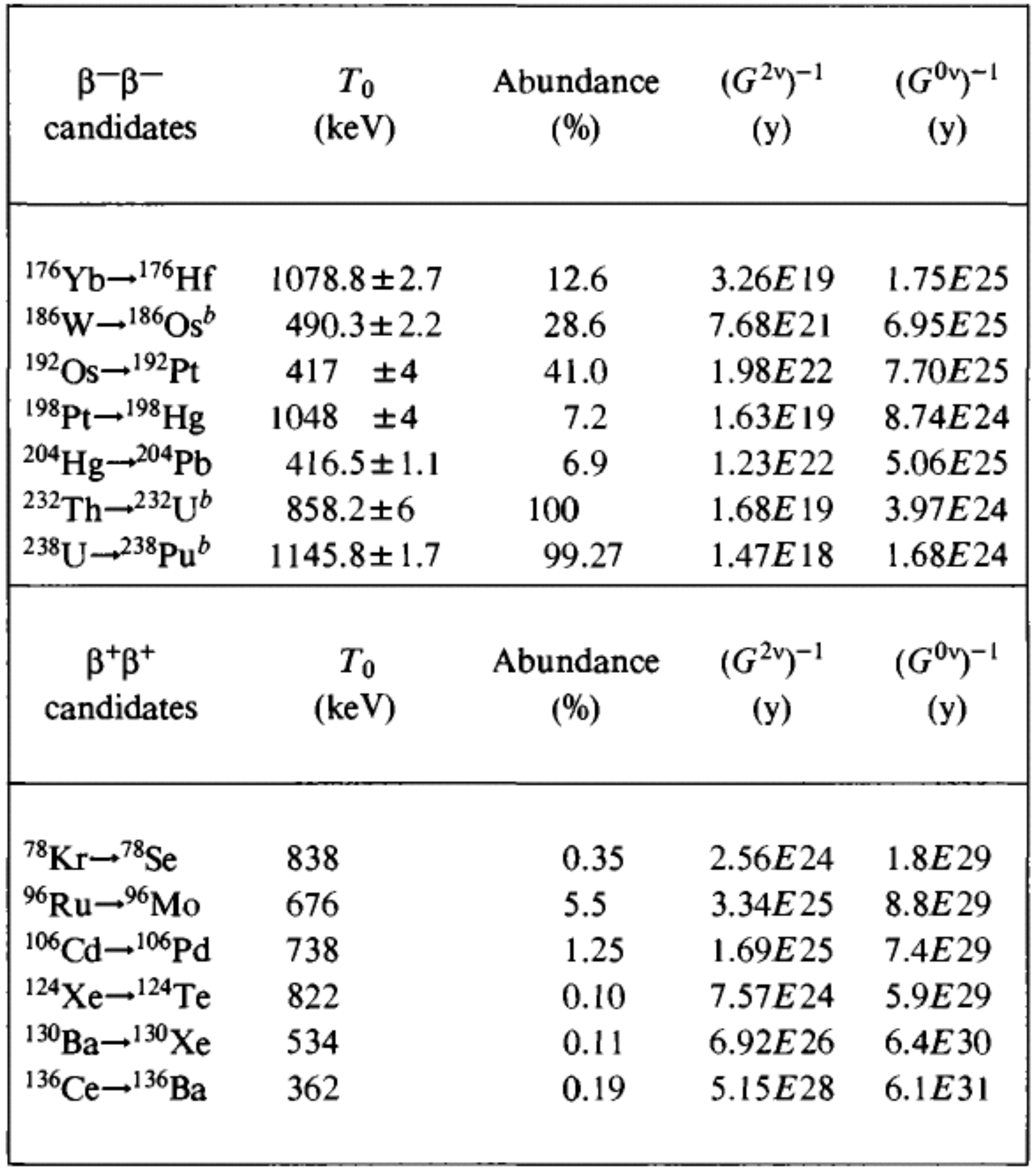
$$\frac{1}{S^{0\nu}_{1/2}(m_{ee})} \propto \sqrt{S^{0\nu}_{1/2} \cdot G^{0\nu}} |M^{0\nu}|$$

- **Isotopical abundance**
- **Mass**
- **Energy resolution**
- **Background level**

- **Isotope choice**



$\beta^-\beta^-$ candidates	T_0 (keV)	Abundance (%)	$(G^{2\nu})^{-1}$ (y)	$(G^{0\nu})^{-1}$ (y)
^{46}Ca→^{46}Ti	987 ±4	0.0035	8.71E21	7.16E26
^{48}Ca→^{48}Ti^{a}	4271 ±4 ←	0.187	2.52E16	$\boxed{4.10E24}$
^{70}Zn→^{70}Ge	1001 ±3	0.62	3.17E21	4.27E26
^{76}Ge→^{76}Se	2039.6±0.9 ←	7.8	7.66E18	4.09E25
^{80}Se→^{80}Kr	130 ±9	49.8 ←	8.20E27	2.34E28
^{82}Se→^{82}Kr	2995 ±6 ←	9.2	2.30E17	$\boxed{9.27E24}$
^{86}Kr→^{86}Sr	1256 ±5	17.3	3.00E20	1.57E26
^{94}Zr→^{94}Mo	1145.3±2.5	17.4	4.34E20	1.57E26
^{96}Zr→^{96}Mo^{a}	3350 ±3 ←	2.8	5.19E16	$\boxed{4.46E24}$
^{98}Mo→^{98}Ru	112 ±7	24.1	1.03E28	1.49E28
^{100}Mo→^{100}Ru	3034 ±6 ←	9.6	1.06E17	$\boxed{5.70E24}$
^{104}Ru→^{104}Pd	1299 ±2	18.7	1.09E20	8.32E25
^{110}Pd→^{110}Cd	2013 ±19 ←	11.8	2.51E18	1.86E25
^{114}Cd→^{114}Sn	534 ±4	28.7 ←	6.93E22	6.10E26
^{116}Cd→^{116}Sn	2802 ±4 ←	7.5	1.25E17	$\boxed{5.28E24}$
^{122}Sn→^{122}Te	364 ±4	4.56	9.55E23	1.16E27
^{124}Sn→^{124}Te	2288.1±1.6 ←	5.64	5.93E17	$\boxed{9.48E24}$
^{128}Te→^{128}Xe	868 ±4	31.7 ←	1.18E21	1.43E26
^{130}Te→^{130}Xe	2533 ±4 ←	34.5 ←	2.08E17	$\boxed{5.89E24}$
^{134}Xe→^{134}Ba	847 ±10	10.4	1.16E21	1.30E26
^{136}Xe→^{136}Ba	2479 ±8 ←	8.9	2.07E17	$\boxed{5.52E24}$
^{142}Ce→^{142}Nd	1417.6±2.5	11.1	1.38E19	2.31E25
^{146}Nd→^{146}Sm^{b}	56 ±5	17.2	2.06E29	7.05E27
^{148}Nd→^{148}Sm^{b}	1928.3±1.9	5.7	9.35E17	$\boxed{7.84E24}$
^{150}Nd→^{150}Sm	3367.1±2.2 ←	5.6	8.41E15	$\boxed{1.25E24}$
^{154}Sm→^{154}Gd	1251.9±1.5	22.6 ←	2.44E19	2.38E25
^{160}Gd→^{160}Dy	1729.5±1.4	21.8 ←	1.51E18	$\boxed{7.99E24}$
^{170}Er→^{170}Yb	653.9±1.6	14.9	1.82E21	6.92E25



$\beta^-\beta^-$ candidates	T_0 (keV)	Abundance (%)	$(G^{2\nu})^{-1}$ (y)	$(G^{0\nu})^{-1}$ (y)
^{176}Yb→^{176}Hf	1078.8±2.7	12.6	3.26E19	1.75E25
^{186}W→^{186}Os^{b}	490.3±2.2	28.6	7.68E21	6.95E25
^{192}Os→^{192}Pt	417 ±4	41.0	1.98E22	7.70E25
^{198}Pt→^{198}Hg	1048 ±4	7.2	1.63E19	8.74E24
^{204}Hg→^{204}Pb	416.5±1.1	6.9	1.23E22	5.06E25
^{232}Th→^{232}U^{b}	858.2±6	100	1.68E19	3.97E24
^{238}U→^{238}Pu^{b}	1145.8±1.7	99.27	1.47E18	1.68E24

$\beta^+\beta^+$ candidates	T_0 (keV)	Abundance (%)	$(G^{2\nu})^{-1}$ (y)	$(G^{0\nu})^{-1}$ (y)
^{78}Kr→^{78}Se	838	0.35	2.56E24	1.8E29
^{96}Ru→^{96}Mo	676	5.5	3.34E25	8.8E29
^{106}Cd→^{106}Pd	738	1.25	1.69E25	7.4E29
^{124}Xe→^{124}Te	822	0.10	7.57E24	5.9E29
^{130}Ba→^{130}Xe	534	0.11	6.92E26	6.4E30
^{136}Ce→^{136}Ba	362	0.19	5.15E28	6.1E31

EX signifies 10^x

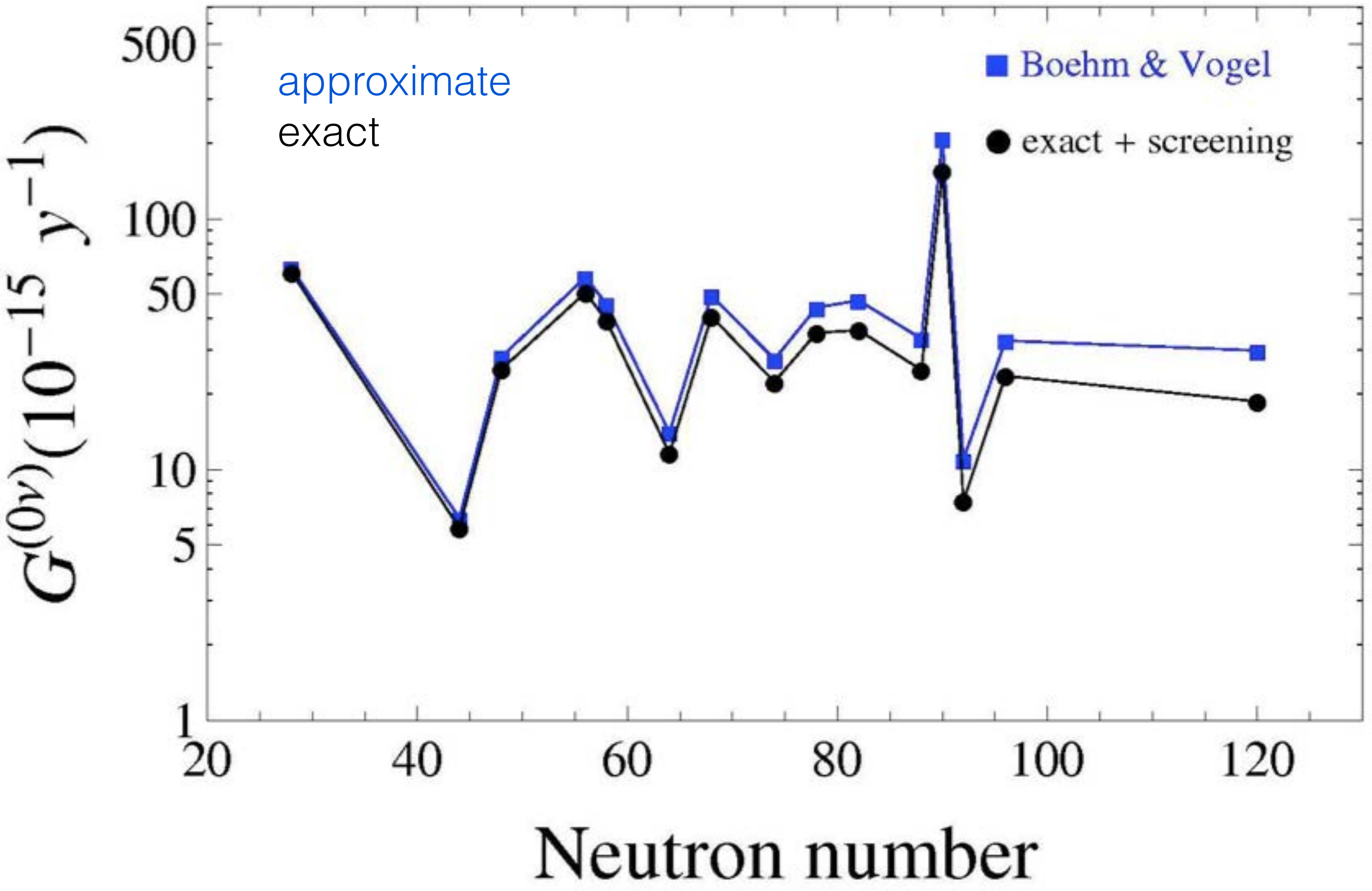
[a] The single beta decay is kinematically allowed.

[b] The daughter nucleus is unstable against alpha decay.

W. C. Haxton and G. J. Stephenson Jr., Prog. in Part. Nucl. Phys. 12, 409 (1984).

Extract m_{ee} from data: a hard job

$$\Gamma^{0\nu} = G_{0\nu}(Q,Z)|M_{0\nu}(A,Z)|^2|m_{ee}|^2$$



The easy part:
phase space factor
→ precisely calculable

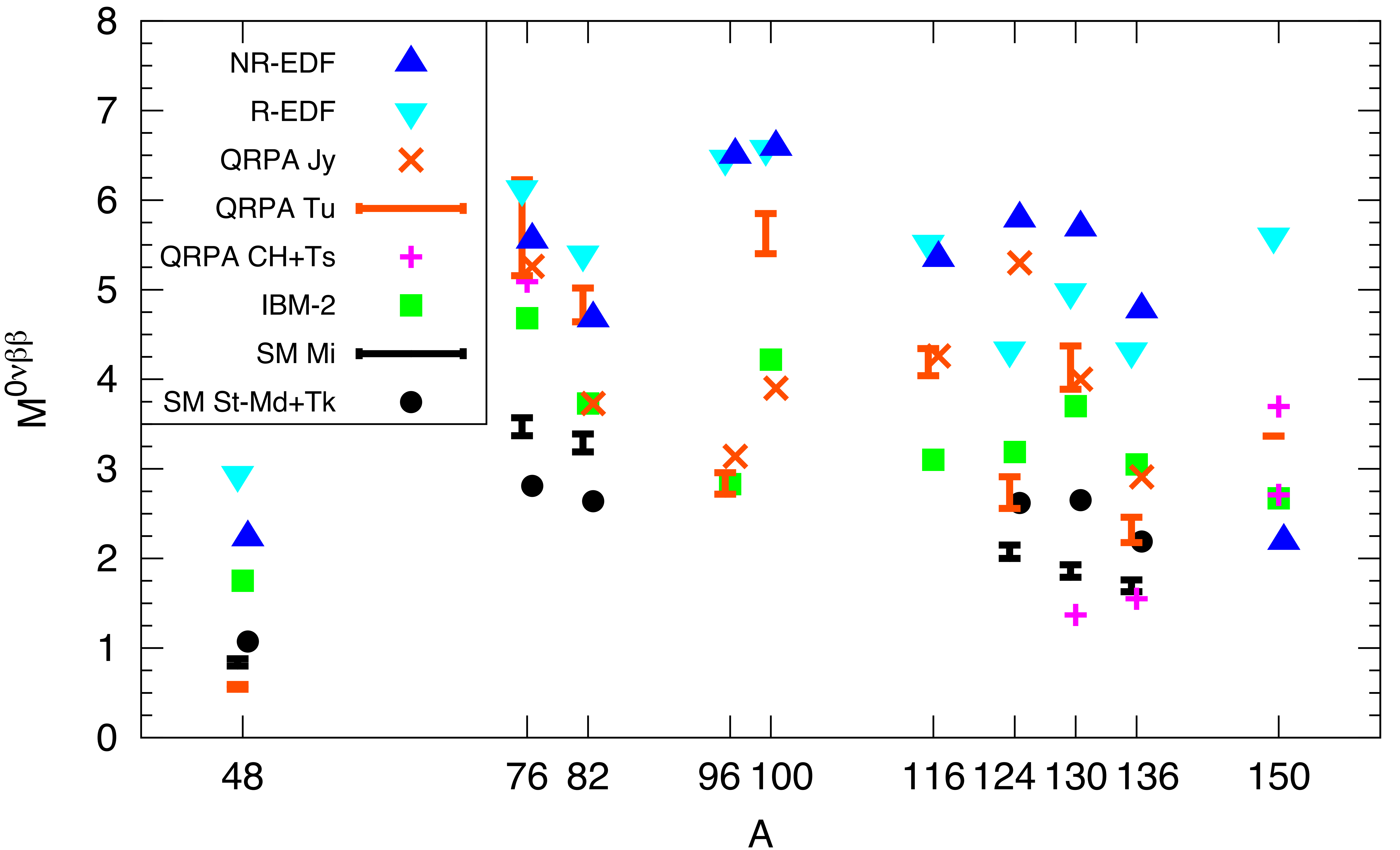
F. Böhm and P. Vogel, *loc. cit.*

J. Kotila and F. Iachello, Phys. Rev. C 85, 034316 (2012)

Extract m_{ee} from data: a hard job

Full estimated range of $M^{0\nu}$ within different calculation methods

$$\Gamma^{0\nu} = G_{0\nu}(Q,Z)|M_{0\nu}(A,Z)|^2|m_{ee}|^2$$



Jonathan Engel and Javier Menéndez 2017 *Rep. Prog. Phys.* **80**

Much more problematic: nuclear matrix elements

- Significant spread
- Absolute values inaccuracy

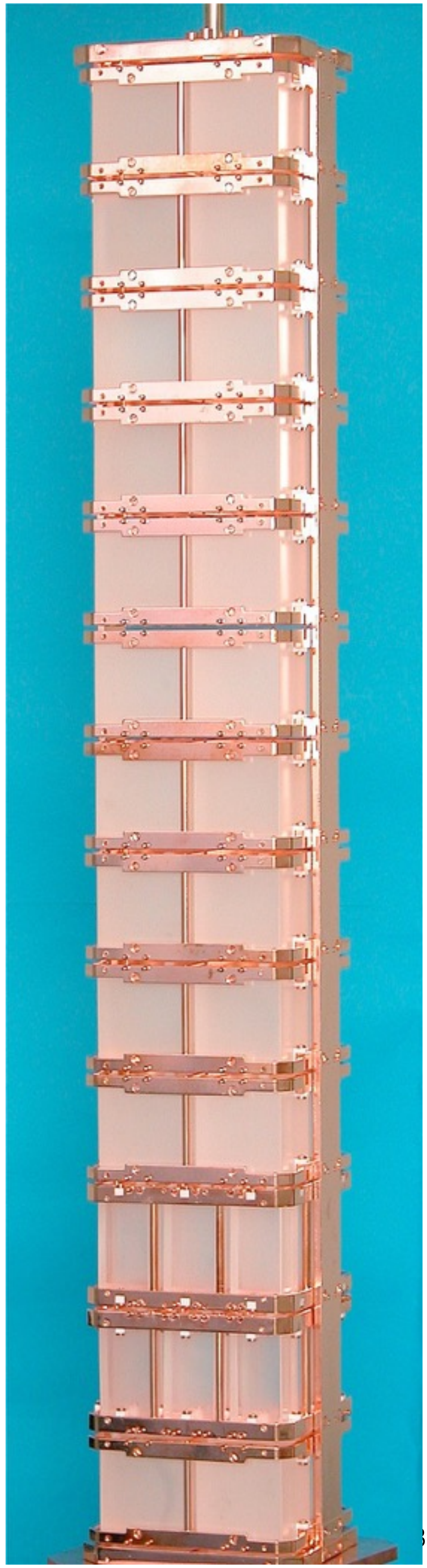
quenching of g_A?

DBD experiments summary

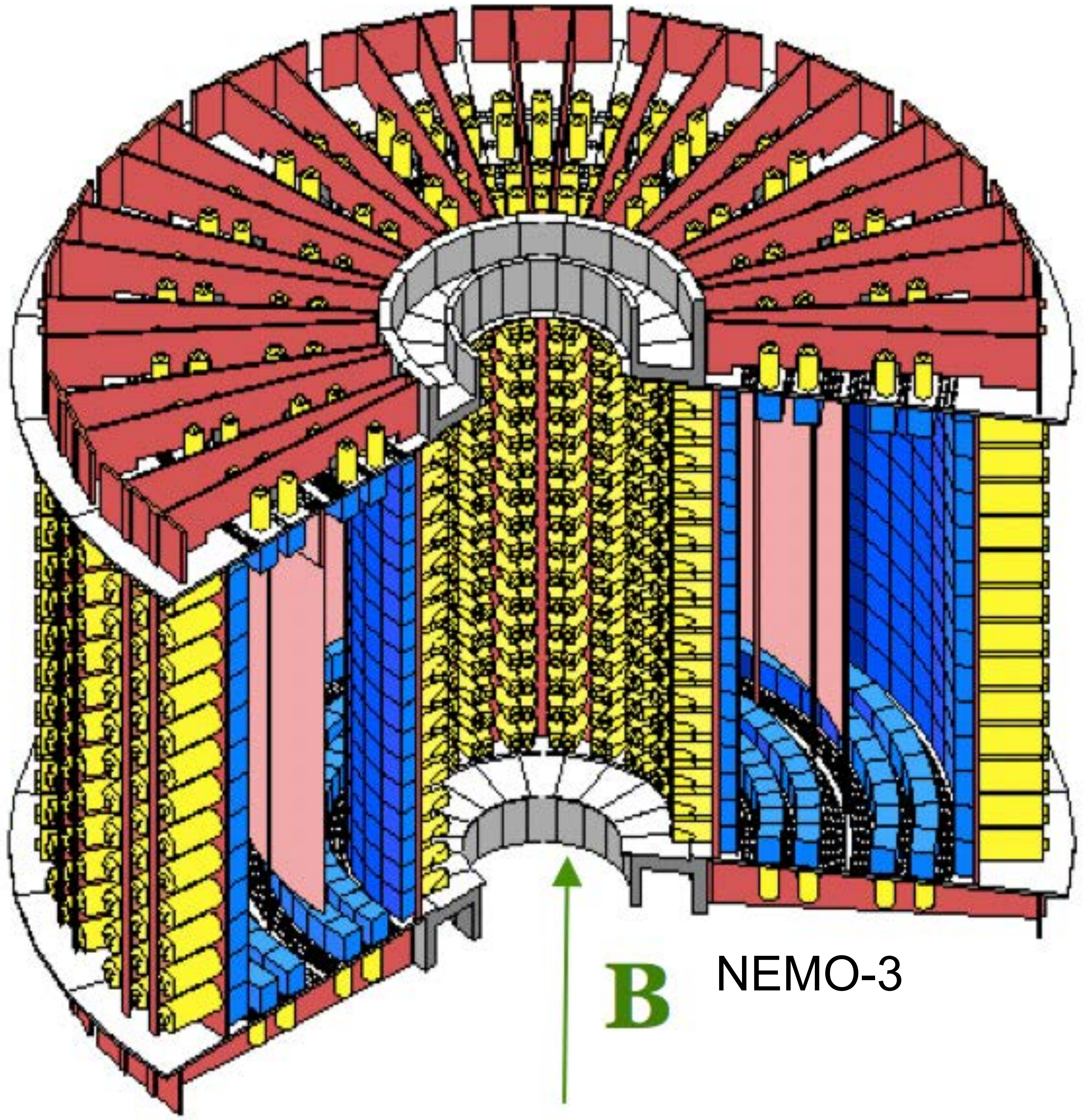
Experiment	Isotope	m_{fid}(ßß) [kg]	Technique	Laboratory	Status
CANDLES	48Ca	305	CaF2 crystals - liq. scintillator	Kamioka	Construction
CARVEL	48Ca		48CaWO4 crystal scint.		R&D
GERDA I	76Ge	14	Ge diodes in LAr	LNGS	Complete
GERDA II	76Ge	31	Point contact Ge in LAr	LNGS	Operating
Majorana D	76Ge	26	Point contact Ge	SURF	Operating
LEGEND-200	76Ge	172	Best technology from GERDA and MAJORANA	LNGS	R&D
NEMO3	100Mo/82Se	6.9/0.9	Foils with tracking	LSM	Complete
SuperNEMO D	82Se	6.3	Foils with tracking	LSM	Construction
SuperNEMO	82Se	126	Foils with tracking		R&D
CUPID-0	82Se	5	ZnSe scint. bolometer	LNGS	Operating
AMoRE	100Mo	50	CaMoO4 scint. bolometer		R&D
MOON	100Mo	200	Mo sheets		R&D
COBRA	116Cd	10/183	CdZnTe detectors	LNGS	R&D
CUORICINO	130Te	10	TeO2 Bolometer	LNGS	Complete
CUORE-0	130Te	11	TeO2 Bolometer	LNGS	Complete
CUORE	130Te	206	TeO2 Bolometer	LNGS	Operating
SNO+	130Te	55	0.1% natNd suspended in Scint	SNOlab	Commissioning
KamLAND-ZEN	136Xe	380	2.7% in liquid scint.	Kamioka	Operating
NEXT-100	136Xe	90	High pressure Xe TPC	LSC	Construction
EXO-200	136Xe	60	Xe liquid TPC	WIPP	Operating
nEXO	136Xe	450/3330	Xe liquid TPC	SNOlab	R&D
DCBA	150Nd		Nd foils & tracking chambers		R&D

Near past

Cuoricino
CUORE0



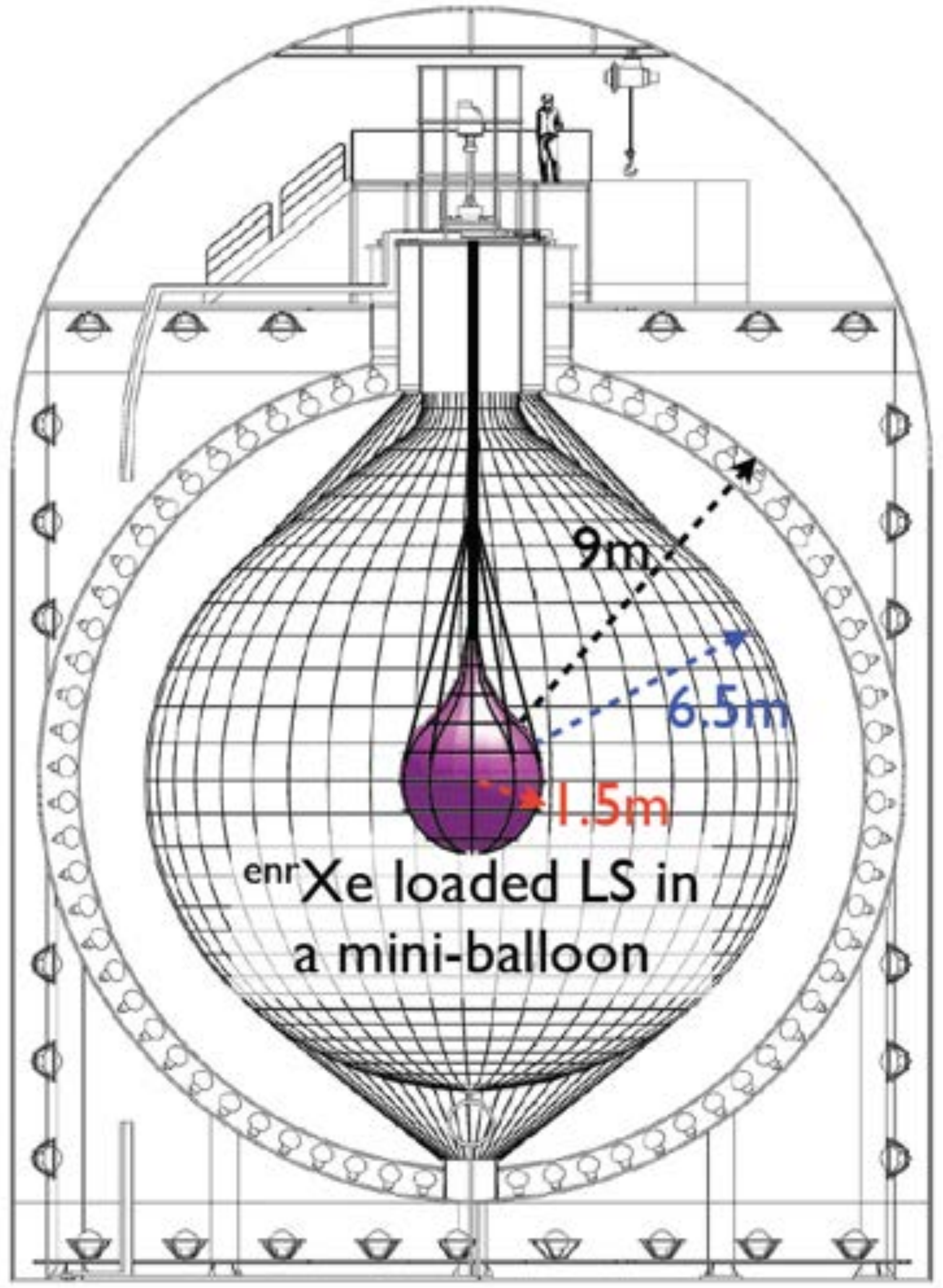
HDM & IGEX → GERDA-I



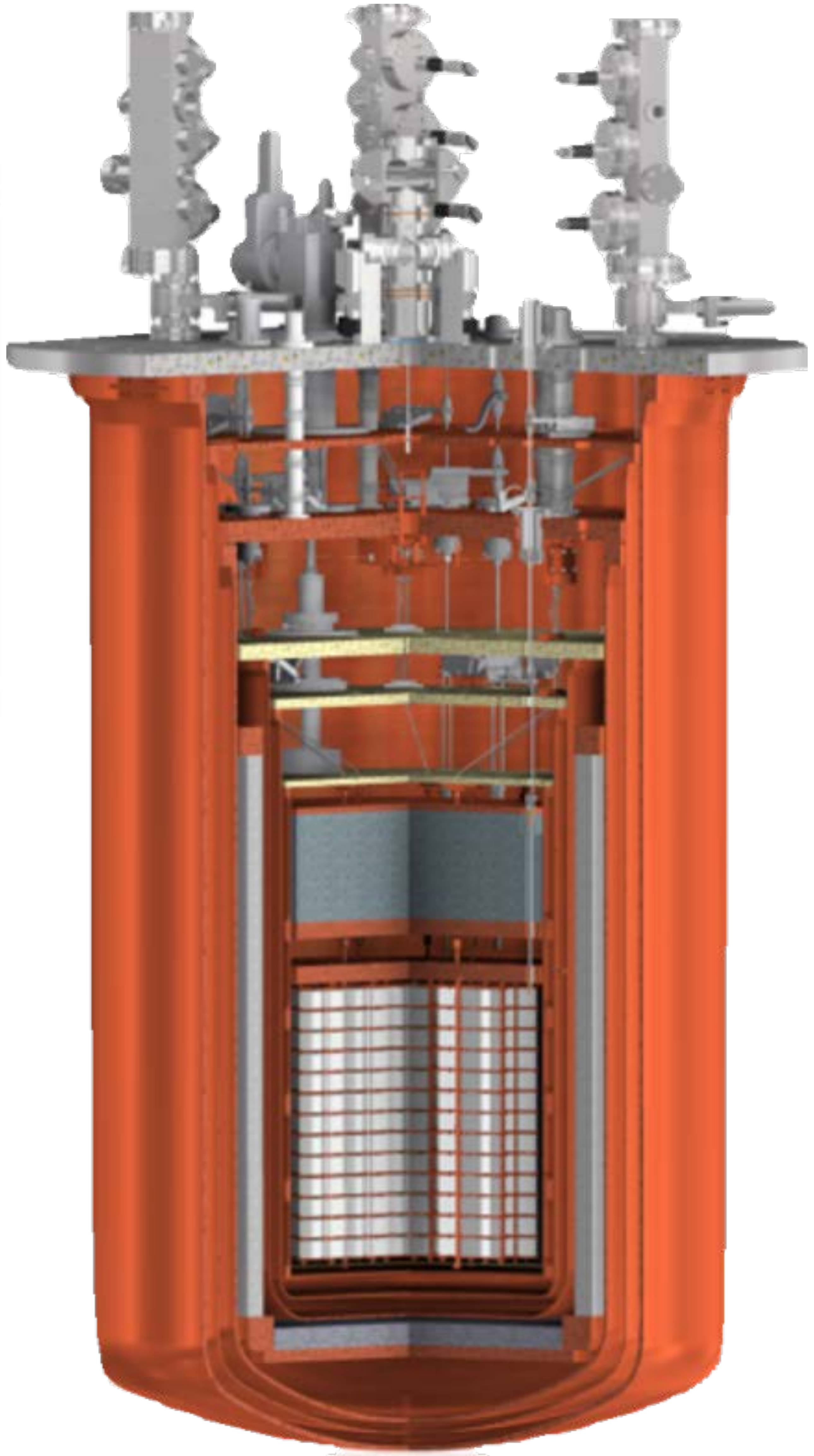
NEMO-3

Present

GERDA-II

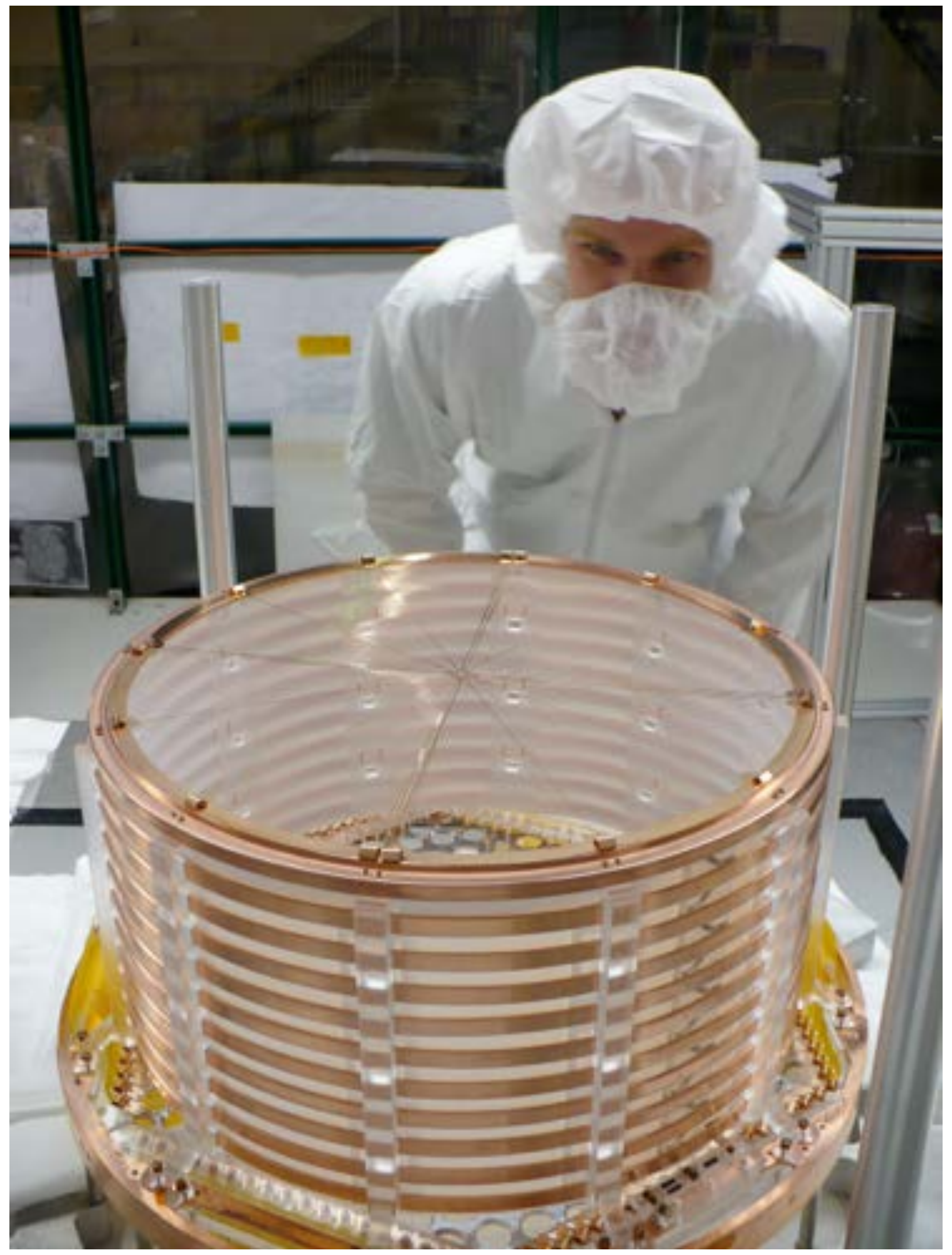


KamLAND-ZEN

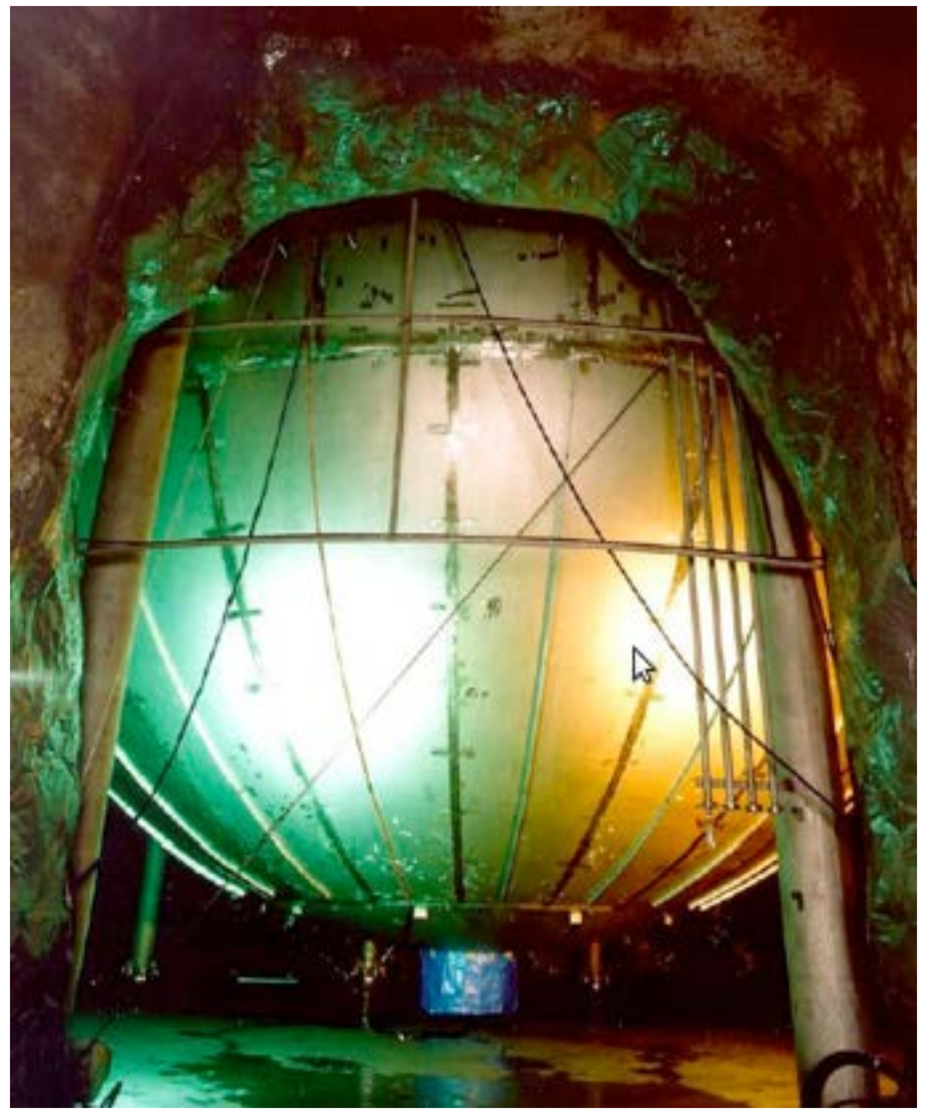


CUORE

EXO-200

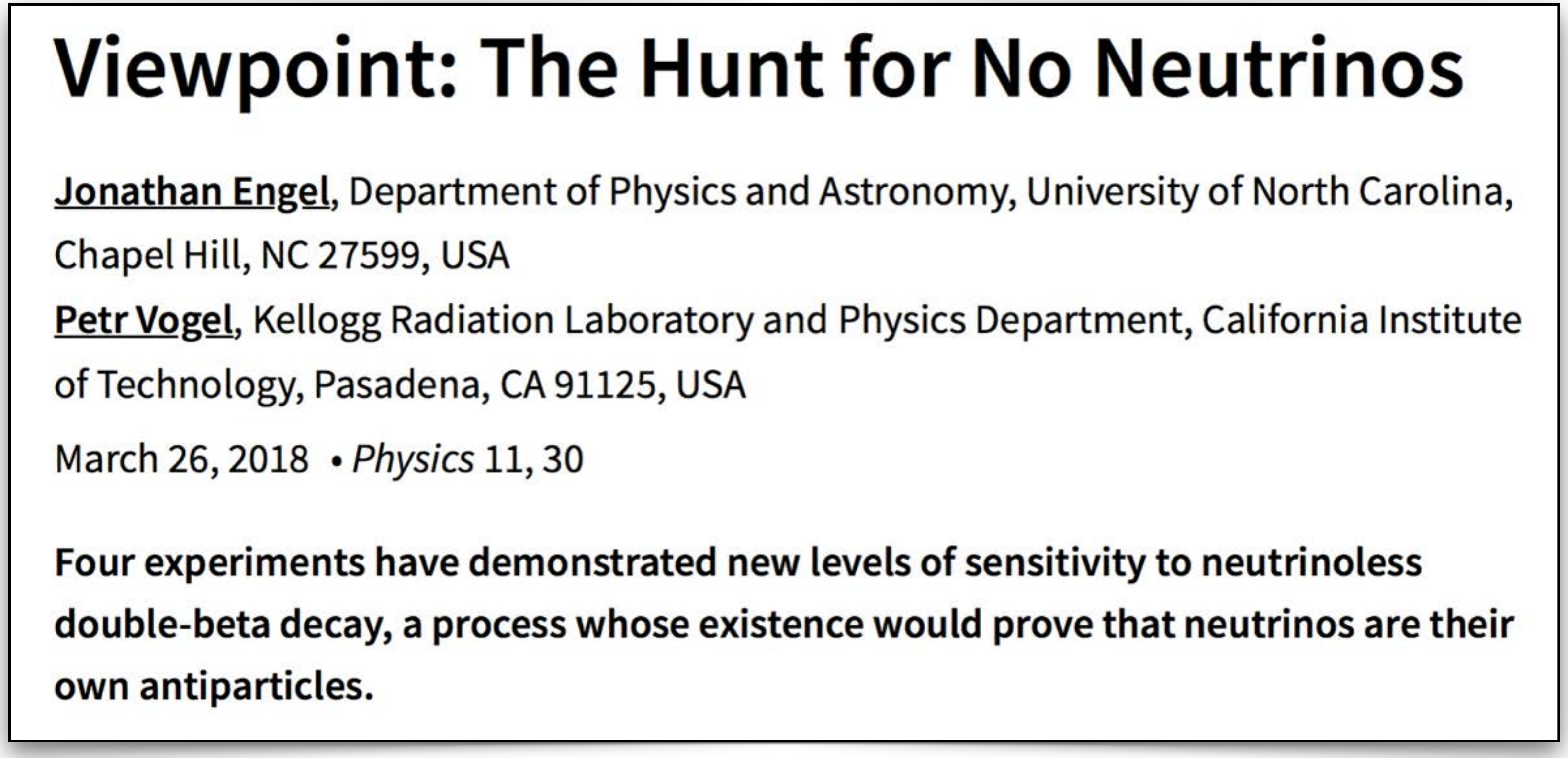


MAJORANA DEM.



An exciting moment for 0νββ

- After a long construction and commissioning period a number of next generation experiments have eventually started data taking and produced excellent results
- 4 papers summarising the results from the most sensitive experiments have been published back-to-back on the same PRL volume in March and another has followed soon later



Viewpoint: The Hunt for No Neutrinos

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March 26, 2018 • *Physics* 11, 30

Four experiments have demonstrated new levels of sensitivity to neutrinoless double-beta decay, a process whose existence would prove that neutrinos are their own antiparticles.

Latest results

Experiment	**Isotope**	**S^{0v} (90%C.L.) [yr]**	**Lower bound for m_1^3 [eV]**			
			$g_{A,nucleon}$	**$g_{A,quark}$**	**$g_{A,phen}$**	
GERDA-(I+II)	^{76}Ge	8.00E+25	0.15	0.25	0.74	Agostini M et al, PRL 120 132503 (2018)
MJD	^{76}Ge	1.90E+25	0.32	0.52	1.52	Aalseth C E et al, PRL 120 132502 (2018)
CUORE (+CUORE-0+Cuoricino)	^{130}Te	1.50E+25	0.186	0.3	1	Alduino C et al, PRL 120 132501 (2018)
KamLAND-ZEN	^{136}Xe	1.11E+26	0.083	0.13	0.49	Gando A et al, PRL 117 082503 (2016)
CUPID-0	^{82}Se	2.40E+24	0.55	0.88	2.66	Azzolini O et al, PRL (2018)
EXO-200	^{136}Xe	1.80E+25	0.206	0.32	1.21	Albert J B et al, PRL 120 072701 (2018)

NME from J. Barea, J. Kotila and F. Iachello, Phys. Rev. C 91, 034304 (2015)

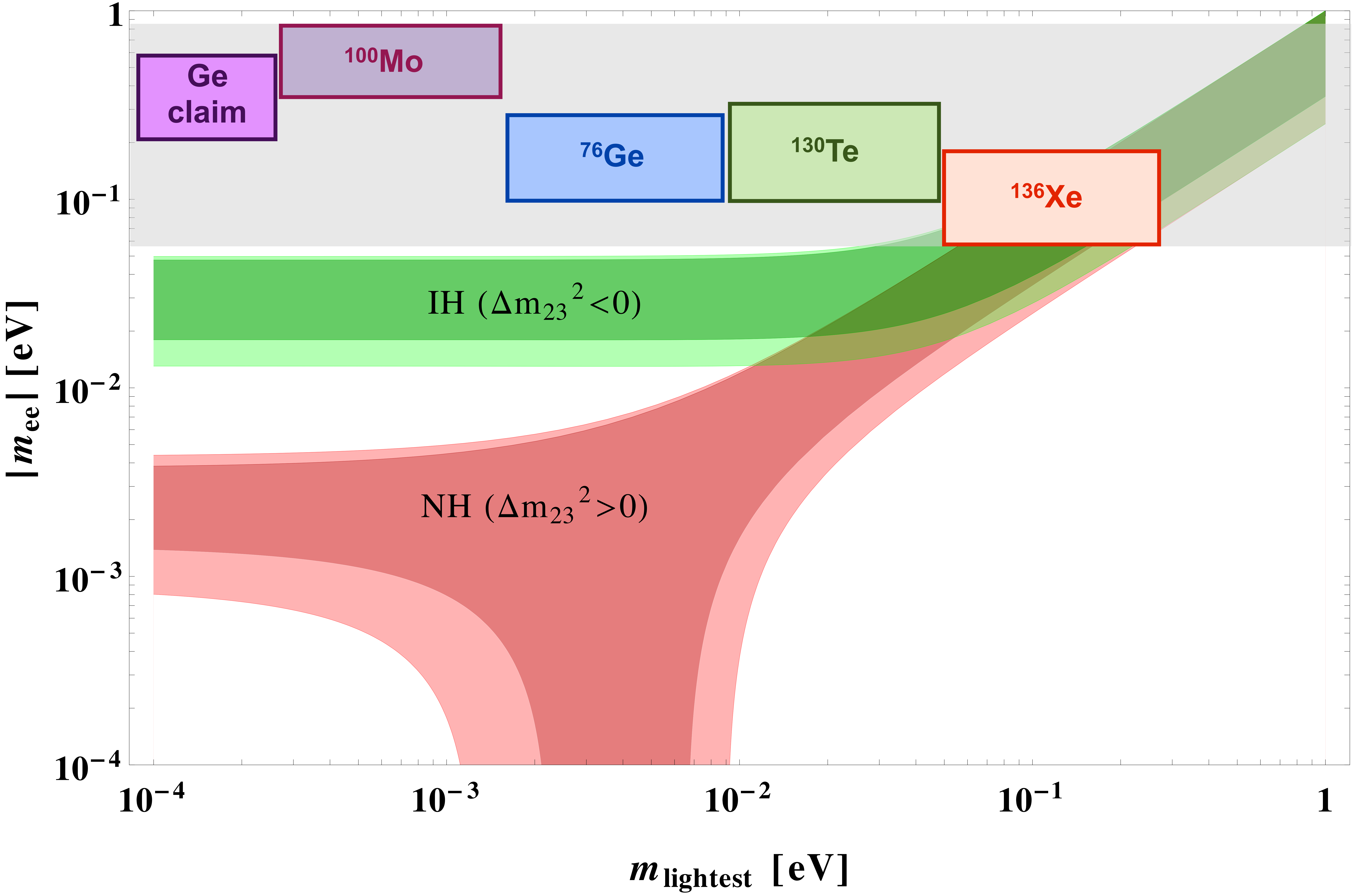
An exciting moment for 0νββ

- Current experiments are characterised by sensitivities O(10^{26} yr) on the half lifetime
- Depending on the evolution of the discussion on NME’s and g_A quenching they will approach or enter the IH band of neutrino masses
- Most of them are developments of previous experiments (or demonstrators)

Status

no gA quenching assumed

Present results



Sensitivities

	Ref	Isotope	$S^{0\nu}$(90% CL)	$m_{\beta\beta}$ ($g_{A,nucleon}$)	$m_{\beta\beta}$ ($g_{A,quark}$)	$m_{\beta\beta}$ ($g_{A,phen}$)
GERDA-II	1	^{76}Ge	1.50E+26	0.11±0.01	0.18±0.02	0.54±0.05
MJD	2	^{76}Ge	3.01E+25	0.25±0.02	0.41±0.04	1.2±0.1
CUPID-0	3	^{82}Se	1.81E+25	0.20±0.02	0.32±0.03	0.97±0.09
SuperNEMO	4	^{82}Se	1.01E+26	0.084±0.008	0.14±0.01	0.41±0.04
AMoRE	5	^{100}Mo	1.11E+27	0.018±0.002	0.029±0.003	0.094±0.009
CUORE	6	^{130}Te	9.51E+25	0.074±0.007	0.12±0.01	0.43±0.04
SNO+(II)	7	^{130}Te	2.01E+26	0.051±0.005	0.083±0.008	0.30±0.03
EX0-200	8	^{136}Xe	5.70E+25	0.11±0.01	0.18±0.02	0.67±0.07
KamLAND2-Zen	9	^{136}Xe	1.00E+27	0.027±0.003	0.044±0.005	0.16±0.02
nEXO	10	^{136}Xe	5.01E+27	0.012±0.001	0.019±0.002	0.071±0.008
NEXT-100	11	^{136}Xe	6.01E+25	0.11±0.01	0.18±0.02	0.65±0.07
PandaX (III)	7	^{136}Xe	1.00E+26	0.087±0.010	0.14±0.02	0.50±0.06

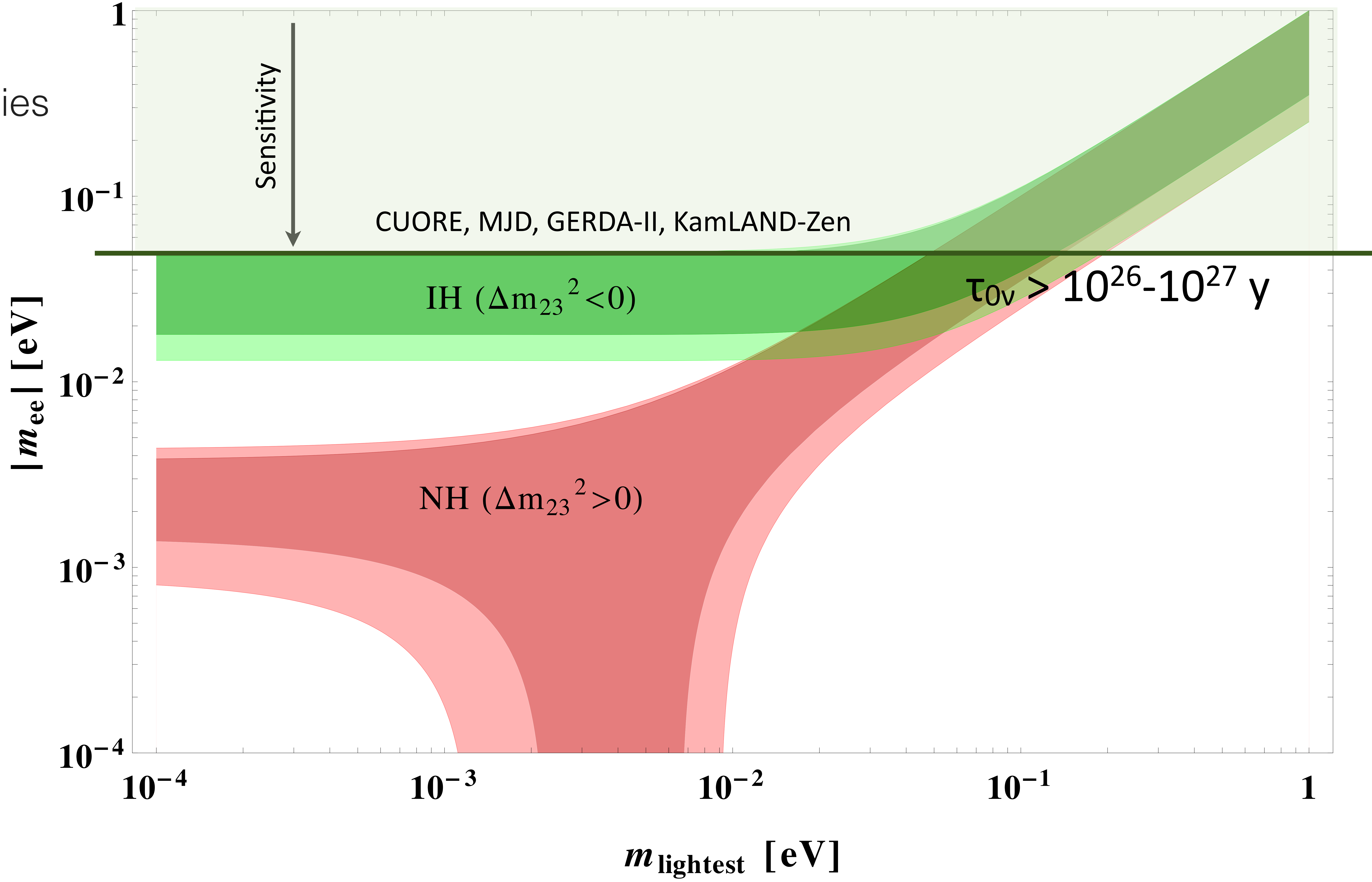
Some references

[1]	M. Agostini et al. (GERDA Collaboration)	Nature 544, 5 (2017).
[2]	K. Alfonso et al. (CUORE Collaboration)	Phys. Rev. Lett. 115, 102502 (2015).
[3]	A. Gando et al. (KamLAND-Zen Collaboration)	Phys. Rev. Lett. 117, 082503 (2016) .
[1]	R. Brugnera and A. Garfagnini	Adv High Energy Phys. 2013, 506186 (2013).
[2]	S.R. Elliott et al	J. Phys.: Conf. Ser. 888 012035 (2017)
[3]	L. Pattavina (LUCIFER Collaboration)	J Phys. Conf. Ser. 718, 062048 (2016).
[4]	R. Arnold et al. (NEM0-3 Collaboration)	Phys. Rev. D 92, 072011 (2015).
[5]	V. Alenkov et al. (AMoRE Collaboration)	arXiv:I512.05957 (physics.ins-det]
[6]	D. R. Artusa et al. (CUORE Collaboration)	Adv. High Energy Phys. 2015, 879871 (2015).
[7]	A. Wright	J. Phys.: Conf. Ser. 888 012036 (2017)
[8]	L. Yang and EXO-200 and nEXO Collaborations	J. Phys.: Conf. Ser.888 012032 (2017)
[9]	K. Asakura et al. (KamLAND-Zen Collaboration)	AIP Conf. Proc. 1666, 170003 (2015)
[10]	C. Licciardi and nEXO Collaboration	J. Phys.: Conf. Ser. 888 012237 (2017)
[11]	J. MartIn-Albo et al. (NEXT Collaboration)	J. High Energy Phys. 05, 159 (2016)

Status

no gA quenching assumed

Present Sensitivities



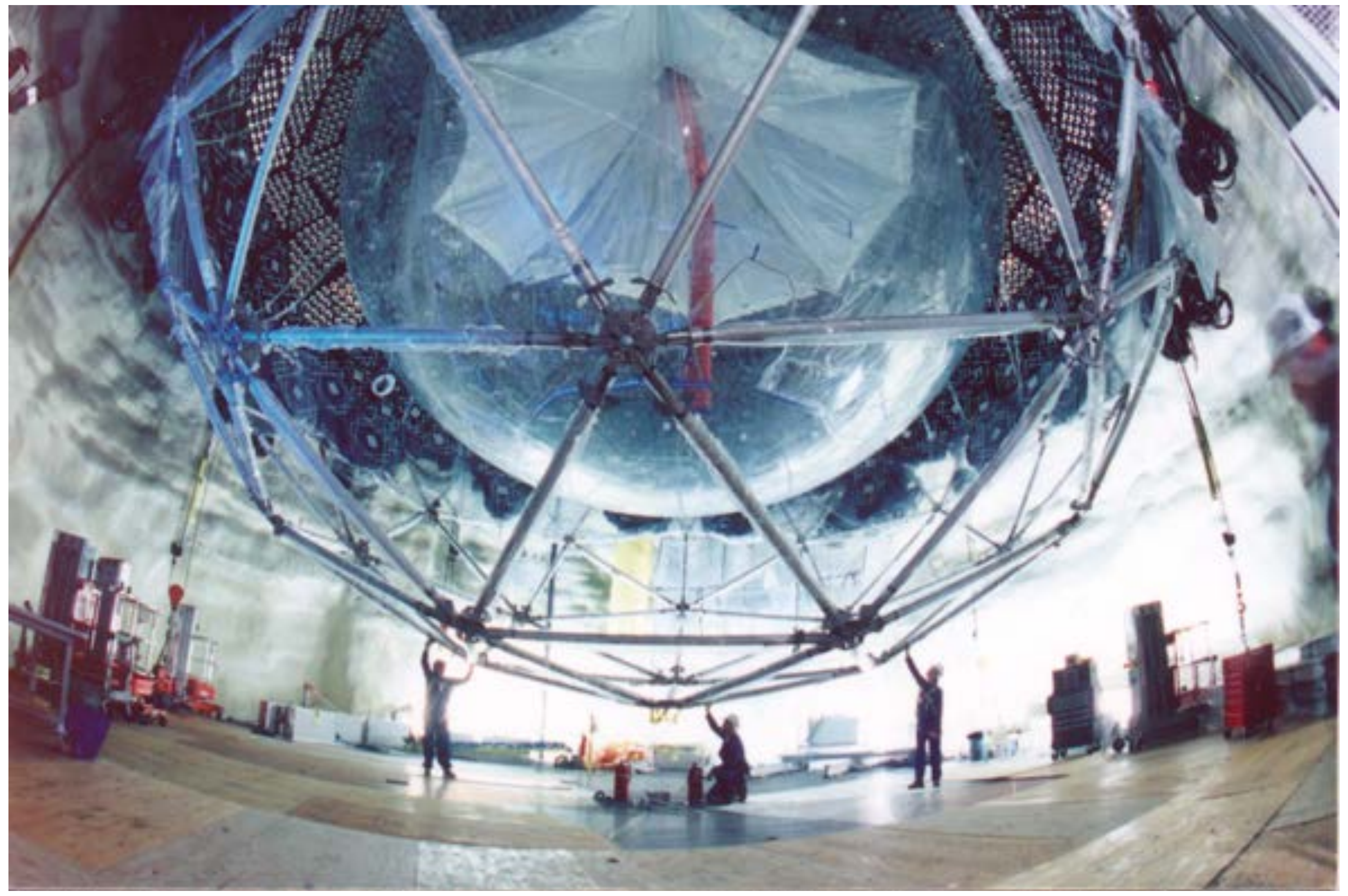
An exciting moment for 0νββ

- Current experiments are characterised by sensitivities O(10^{26} yr) on the half lifetime
- Depending on the evolution of the discussion on NME's and g_A quenching they will approach or enter the IH band of neutrino masses
- Most of them are developments of previous experiments (or demonstrators)

- R&D's to improve sensitivity (performance or scale) have already produced a number of successful results
- Plans for developments aiming at sensitivities O($10^{27\text{-}28}$ yr), i.e. at least one order of magnitude better than present have been already developed and projects proposed
- Next generation experiments will be able to sound the IH region of neutrino masses

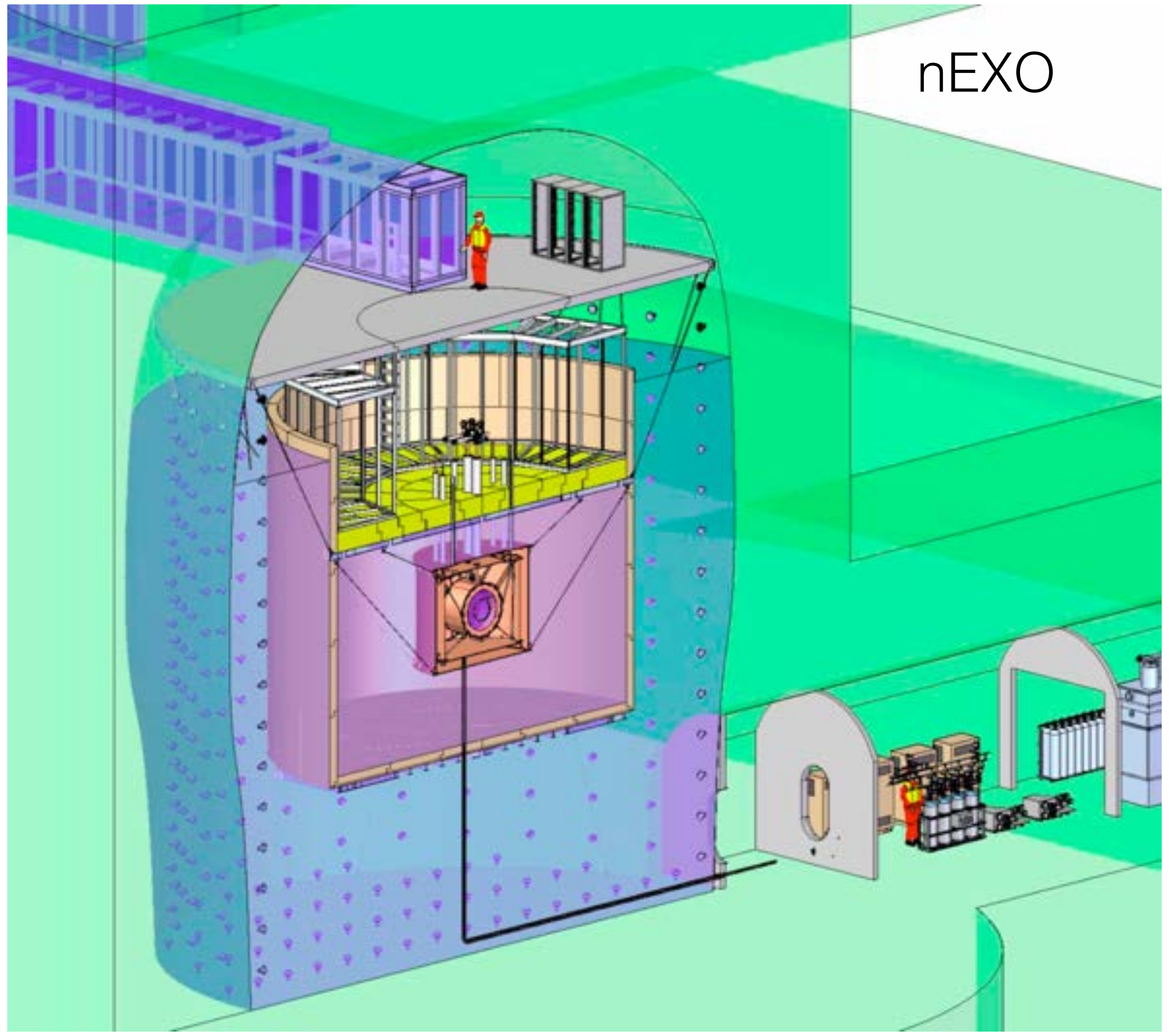
Future

SNO+



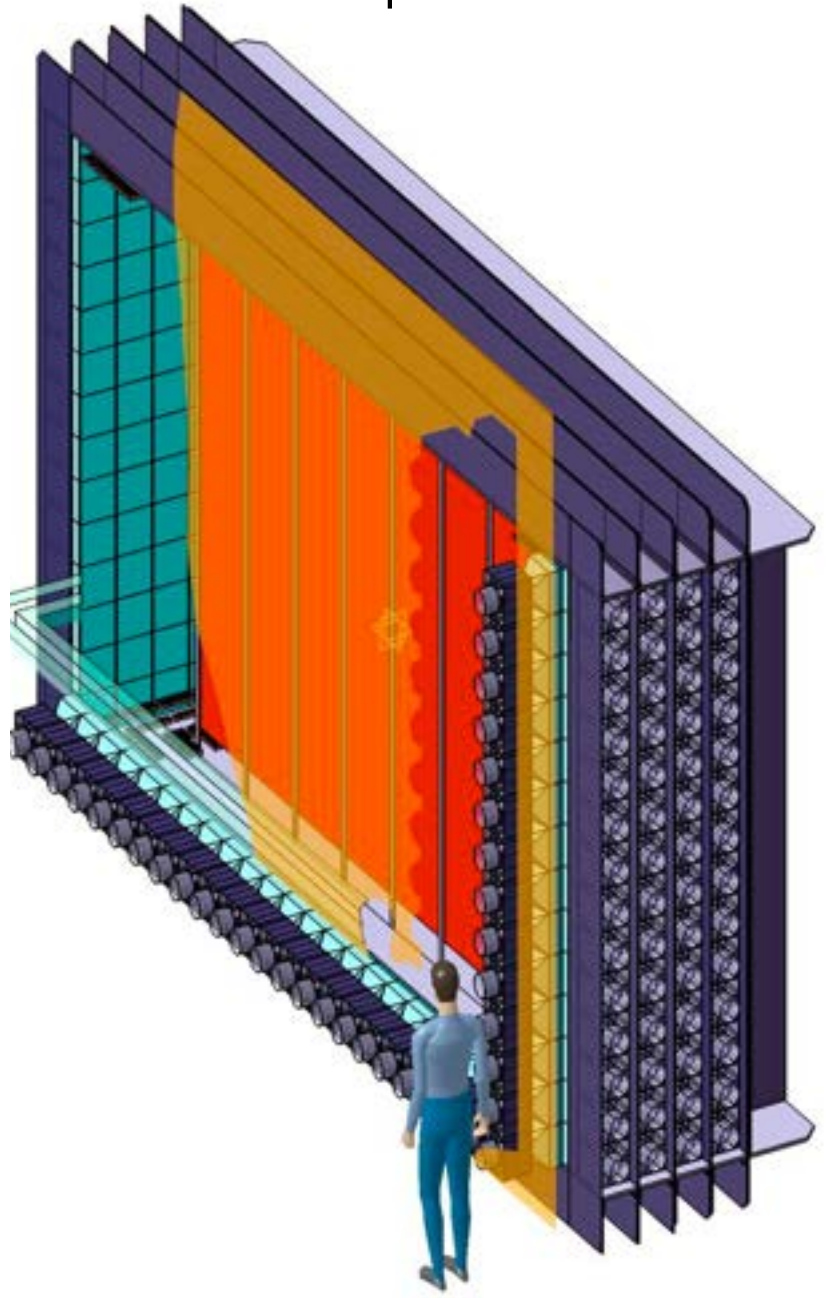
CUPID

nEXO

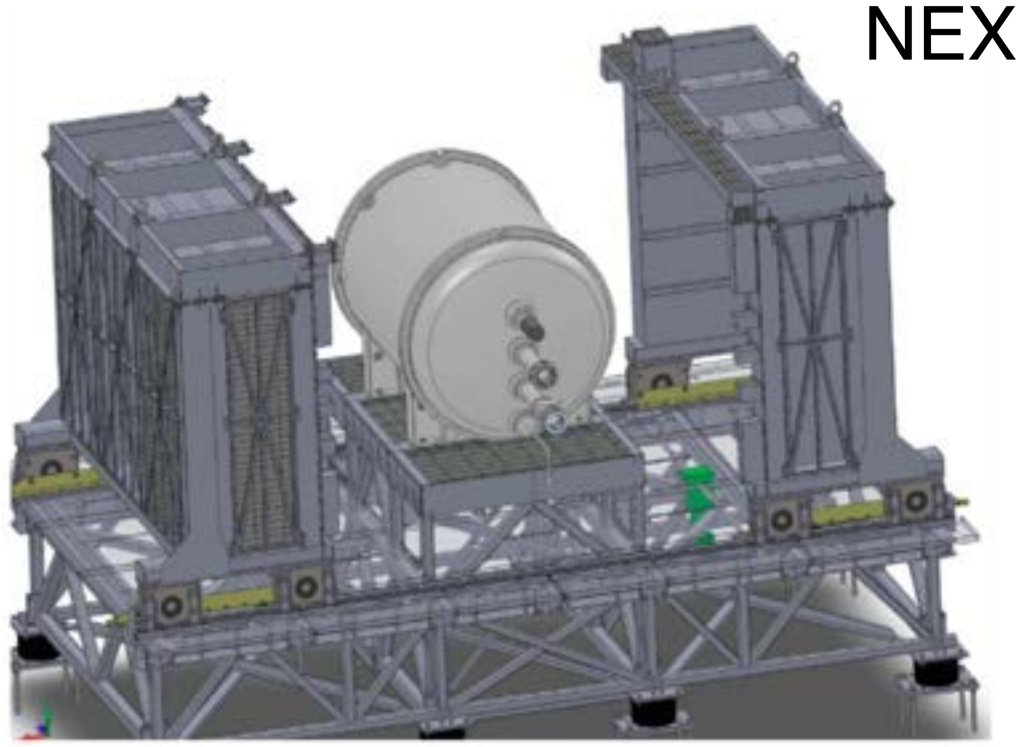


KamLAND-ZEN

SuperNEMO



NEXT

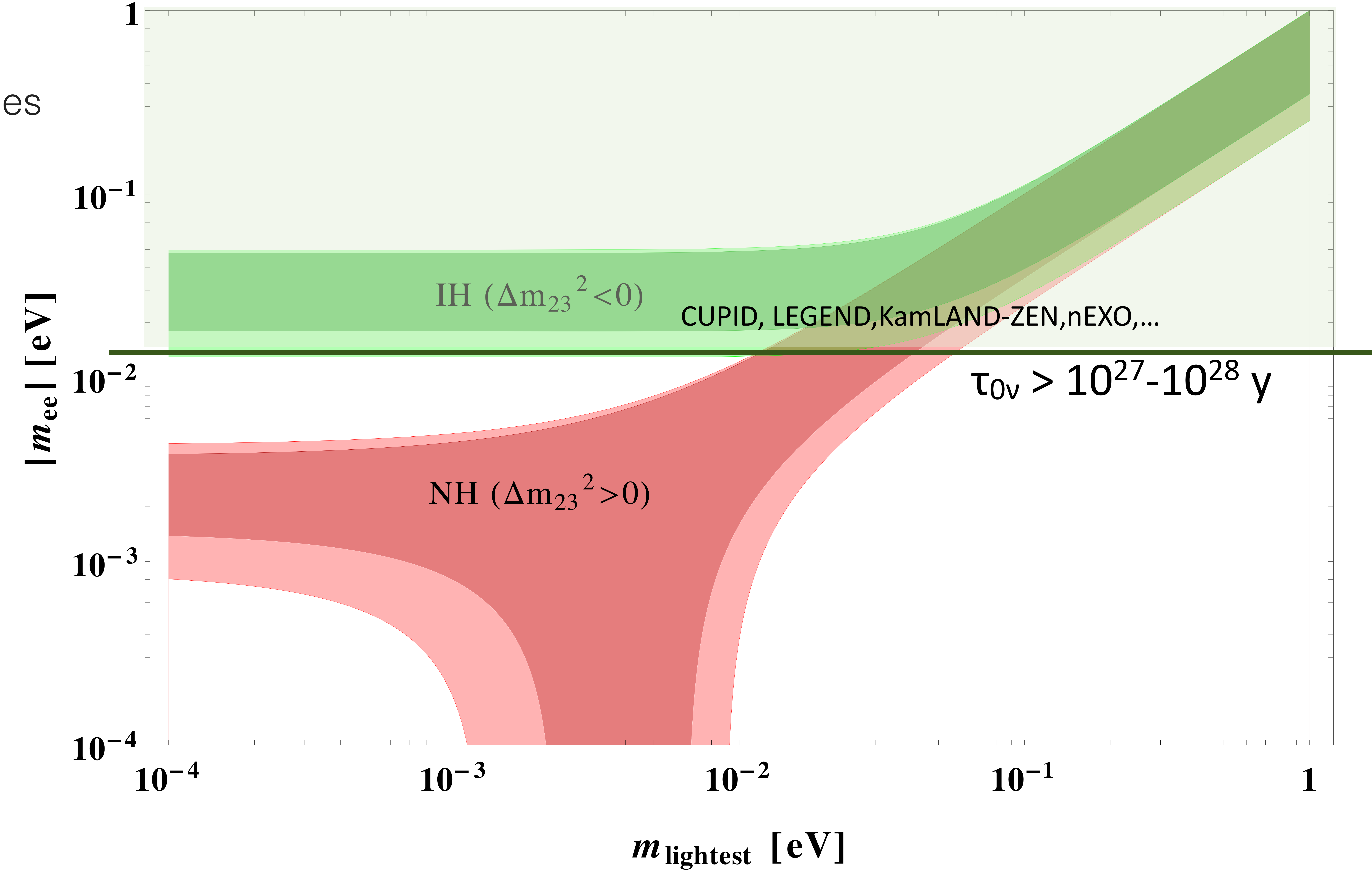


LEGEND

Status

no gA quenching assumed

Future Sensitivities



Conclusions

- Despite the incredible list of successful verifications, the Standard Model is incomplete
- The nature of the new physics is still unknown and many extensions are possible
- Neutrino has still a number of open questions whose answers require SM extensions
- In particular neutrino mass and nature can play a decisive role
- The conservation of lepton numbers is questioned in most extended models and tests of its validity can help disentangling different expectations
- A number of experiments aiming at observing CLFV and/or LNV have been realised
- Muon to electron conversion and neutrino-less double beta decay are presently the most sensitive probes
- No evidence has been so far signalled and new experiments are bringing sensitivities to the limits of current technology
- If observed, LNV would have an incredible impact on future developments of particle physics