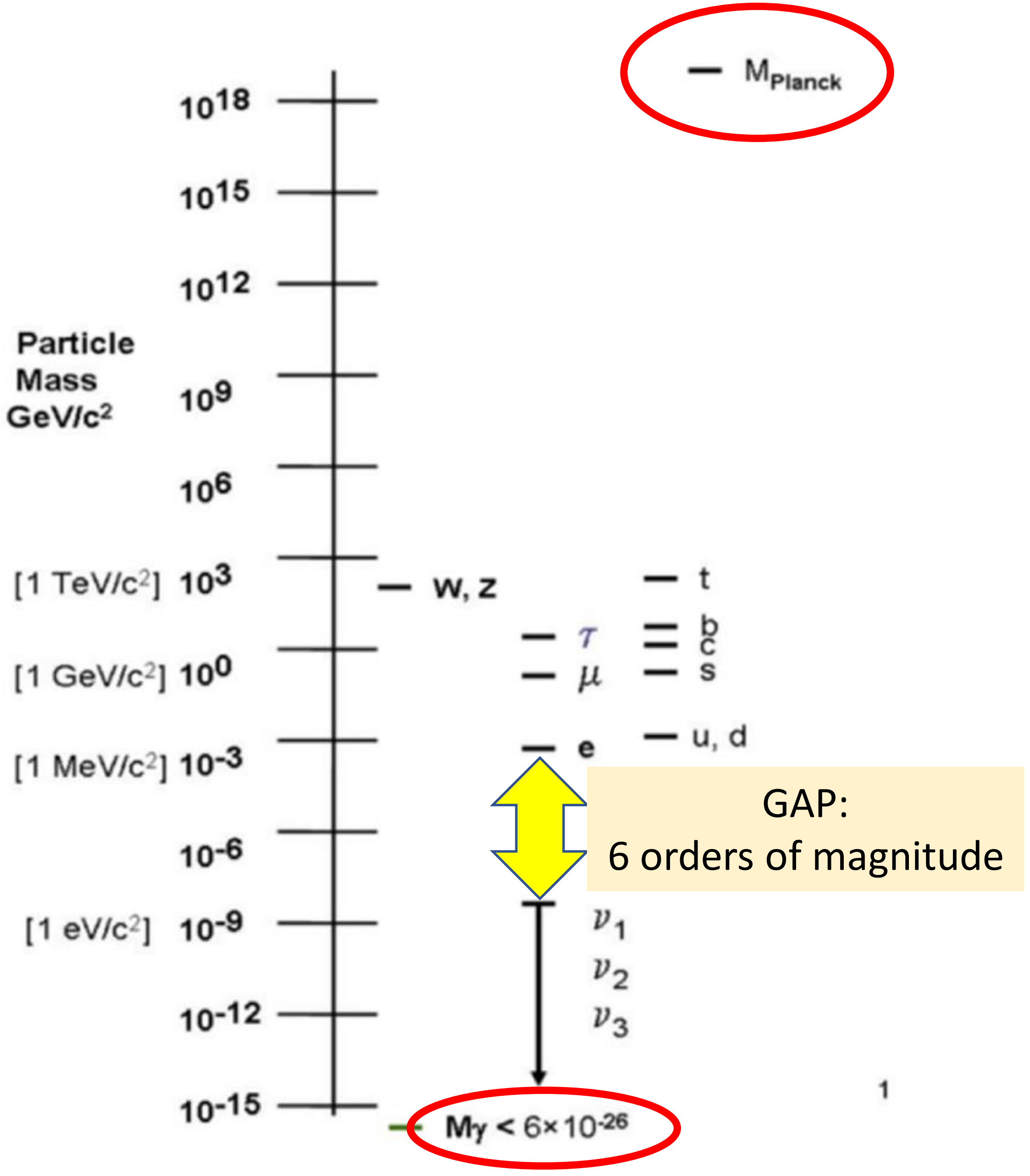
Why neutrino masses are so small?

$m_t = 174.3 \pm 5.1$ GeV
$m_b = (4.0\text{-}4.5)$ GeV
$m_\tau = 1776.99 \pm 0.29$ MeV

neutrinos: 50meV < m_3 < 1eV

Mass generation in SM:
Charged (and Z^0) particles aquire mass via coupling to Higgs boson

Is this true for neutrinos?
The different order of magnitude of their masses might hint to other nature of mass generation



Ettore Majorana
1906 – 1938?

Majorana Particles

Because neutrinos carry no electric charge
(and no color charge), there is the possibility:

particle ≡ anti-particle

Majorana particle

particle ψ

anti-particle (charge conjugate field): $\psi^c = C\overline{\psi}^T$

for a Majorana particle: $\psi_M^c = \pm\psi_M$

But what about experiments?

Neutrinos (solar): $\nu_{eL} + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + \mathrm{e}^-$ observed!

Anti-neutrinos(reactor): $\nu_{eR} + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + \mathrm{e}^-$ not observed!

There are two different states per flavor
but the difference could be due to left-handed and right-handed states!

Very mysterious biographie, see for example:
Antonino Zichichi: Ettore Majorana: genius and mystery. Cern *Courier*, 24. Juli 2006 (englisch)

Nature of Neutrino Mass

Neutrino fields ν(x) with mass m are described by the Dirac equation:

$$(i\gamma^\alpha \partial_\alpha - m)\nu(x) = 0$$

4 component spinor

The left-handed and right-handed components are:

$$\nu_L(x) = \frac{1-\gamma_5}{2}\nu(x) \qquad \nu_R(x) = \frac{1+\gamma_5}{2}\nu(x)$$

2 components each

This leads to a system of two coupled equations:

$$i\gamma^\alpha \partial_\alpha \nu_L - m\nu_R = 0 \qquad i\gamma^\alpha \partial_\alpha \nu_R - m\nu_L = 0$$

With m=0 one obtains the decoupled Weyl equations:

$$i\gamma^\alpha \partial_\alpha \nu_{L,R} = 0$$

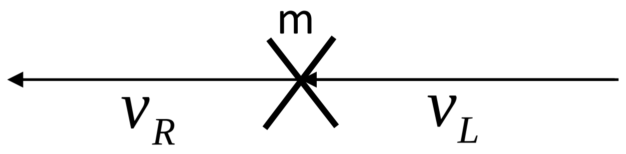
From Goldhaber experiment one knows that ν_L is realized.
With m=0 there is no need to have ν_R.
Therefore, there were no ν_R in the Standard Model.

Dirac Mass Term

The neutrino mass term in L could have exactly the same form as the mass term of the quarks and charged leptons:

$$L_D = -m\bar{\nu}_R \nu_L + h.c.$$

Dirac mass term



Lepton number is conserved!

Must add ν_R (right handed SU(2) singlets) to standard model!

Problem: When the mechanism is the same,
why are the masses so small?
Or: why should couplings to Higgs be so different?

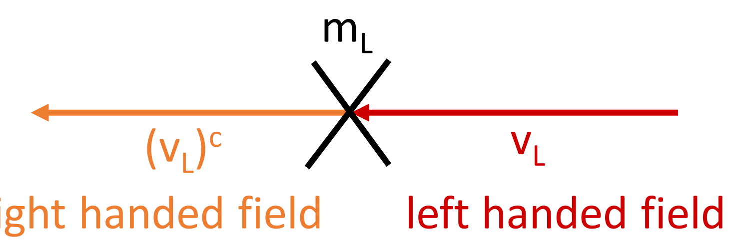
Footnote: A Lorentz invariant mass term must link a chirally left-handed field with a chirally right handed field

Majorana Mass Term

Note that $(\nu_R)^c = (\nu^c)_L$ is a left-handed field

and $(\nu_L)^c = (\nu^c)_R$ is a right-handed field

Let's try $$L_{M_L} = -\frac{m_L}{2}\left(\overline{(\nu_L)^c}\nu_L + \overline{\nu_L}(\nu_L)^c\right)$$ ok!



Lepton number violation!

$$L_{M_R} = -\frac{m_R}{2}\left(\overline{(\nu_R)^c}\nu_R + \overline{\nu_R}(\nu_R)^c\right)$$ works too!

<u>Footnote</u>: A Lorentz invariant mass term must link a chirally left-handed field with a chirally right handed field

$$L_{M_L} = -\frac{m_L}{2}\left(\overline{(\nu_L)^c}\nu_L + \overline{\nu_L}(\nu_L)^c\right)$$

$$L_{M_R} = -\frac{m_R}{2}\left(\overline{(\nu_R)^c}\nu_R + \overline{\nu_R}(\nu_R)^c\right)$$

Construct the Majorana fields:

$$\phi_1 = \nu_L + (\nu_L)^c \qquad \phi_2 = \nu_R + (\nu_R)^c$$

$$\phi_{1,2} = (\phi_{1,2})^c$$

$$-2L_{M_L} = m_L\bar{\phi}_1\phi_1$$
$$-2L_{M_R} = m_R\bar{\phi}_2\phi_2$$

Eigenstates of the interaction: ν_L and ν_R

Mass eigenstates: Φ_1 (mass m_L), Φ_2 (mass m_R)

Most general case: Dirac-Majorana Mass Term

mass term for each flavor:

$$-2L_{DM} = \left(\overline{\nu_L}, \overline{(\nu_R)^c}\right) \cdot \underbrace{\begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}}_{\text{mass matrix M}} \cdot \begin{pmatrix} (\nu_L)^c \\ \nu_R \end{pmatrix} + \text{h.c.}$$

In order to obtain the mass eigenstates one must diagonalize M:

find unitary U with $\tilde{M} = U^+ M U = \begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix}$

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \quad \text{with} \quad \tan 2\theta = \frac{2m_D}{m_R - m_L}$$

with the mass eigenstates:

$$\begin{pmatrix} \nu_{1L} \\ \nu_{2L} \end{pmatrix} = U^+ \begin{pmatrix} \nu_L \\ (\nu_R)^c \end{pmatrix}$$

and mass eigenvalues:

$$m_{1,2} = \frac{1}{2}\left[(m_R + m_L) \pm \sqrt{(m_L - m_R)^2 + 4m_D^2}\right]$$

What if...

1. $m_L = m_R = 0$: pure Dirac case

   $\theta = 45$, $m_1 = m_2 = m_D$.

   2 degenerate Majorana states

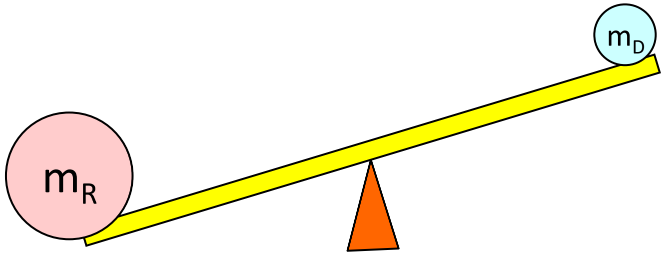
   can be combined to form 1 Dirac state.

2. $m_D = 0$: pure Majorana case

   $\theta = 0$, $m_1 = m_L$ $m_2 = m_R$

3. $m_R \gg m_D$, $m_L = 0$: seesaw model

   $\theta = m_D/m_R \ll 1$



$$m_1 = \frac{m_D^2}{m_R}, \qquad m_2 \approx m_R$$

per neutrino flavor: one very light Majorana neutrino $\nu_{1L} = \nu_L$

one very heavy Majorana neutrino $\nu_{2L} = (\nu_R)^c$

m_D of the order of lepton masses, m_R reflects scale of new physics

⇒ explains small neutrino masses!

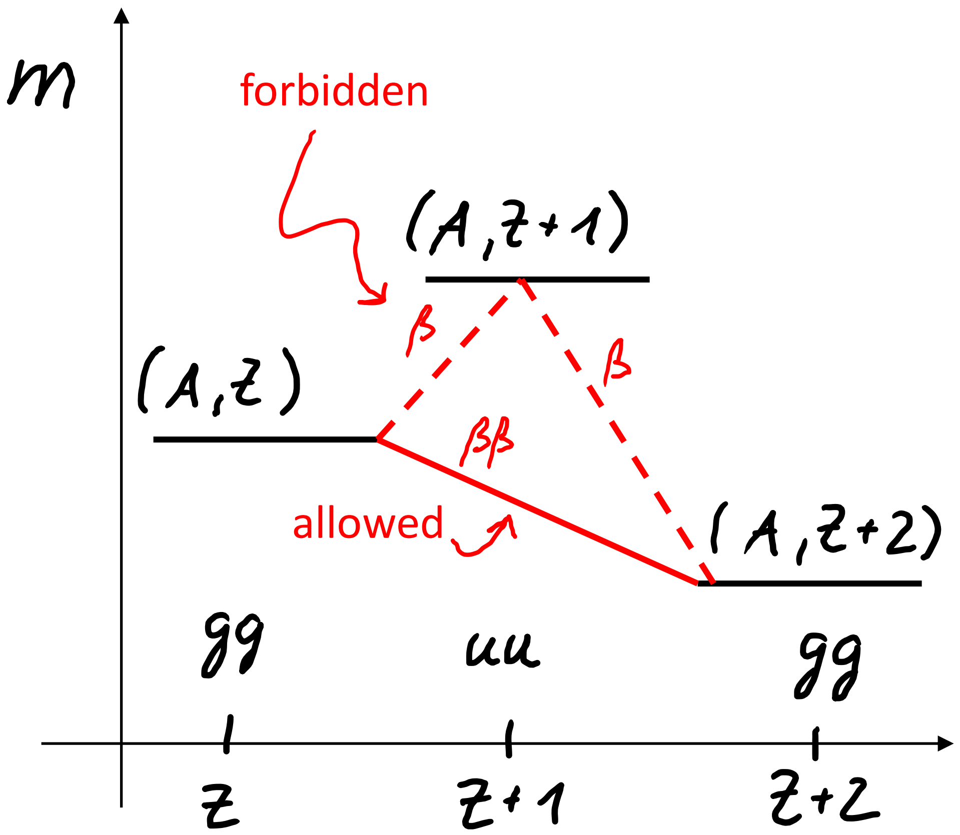
Consequences / Motivation for Majorana neutrinos

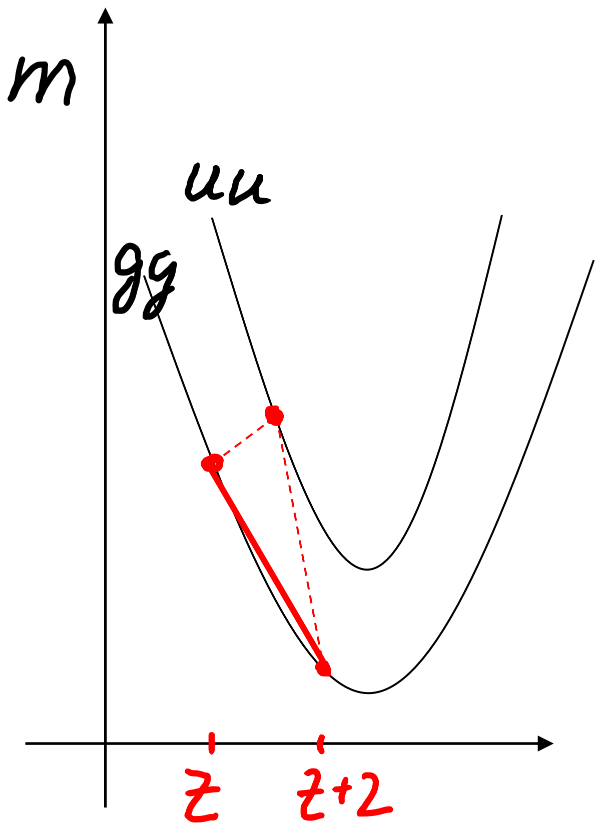
- See-saw mechanism could „explain"
  (introduce scale of new physics)
  smallness of neutrino masses
- m_R could be $\approx$ keV $\Rightarrow$ candidate for warm dark matter
- Could have Majorana CP-phases in mixing matrix $\Rightarrow$ lead to Leptogenesis
  ↳ creation of matter-antimatter asymmetry in universe
- Lepton flavour number is violated

$$\Delta L = 2 \quad \text{if} \quad \underset{L=+1}{\nu} \equiv \underset{L=-1}{\bar{\nu}}$$

→ How to test Majorana nature of ν?

Which isotopes can do ββ-decays?

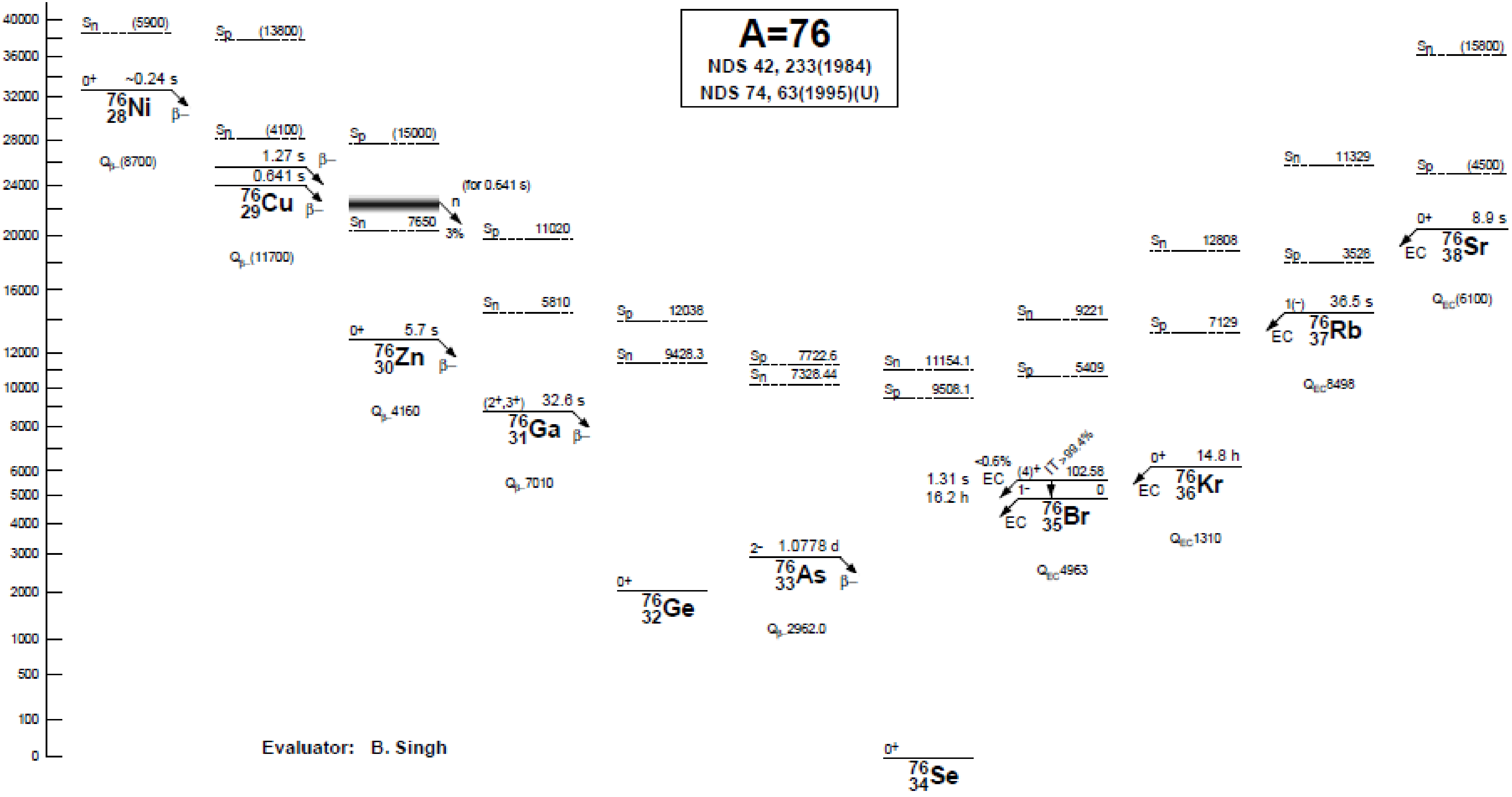




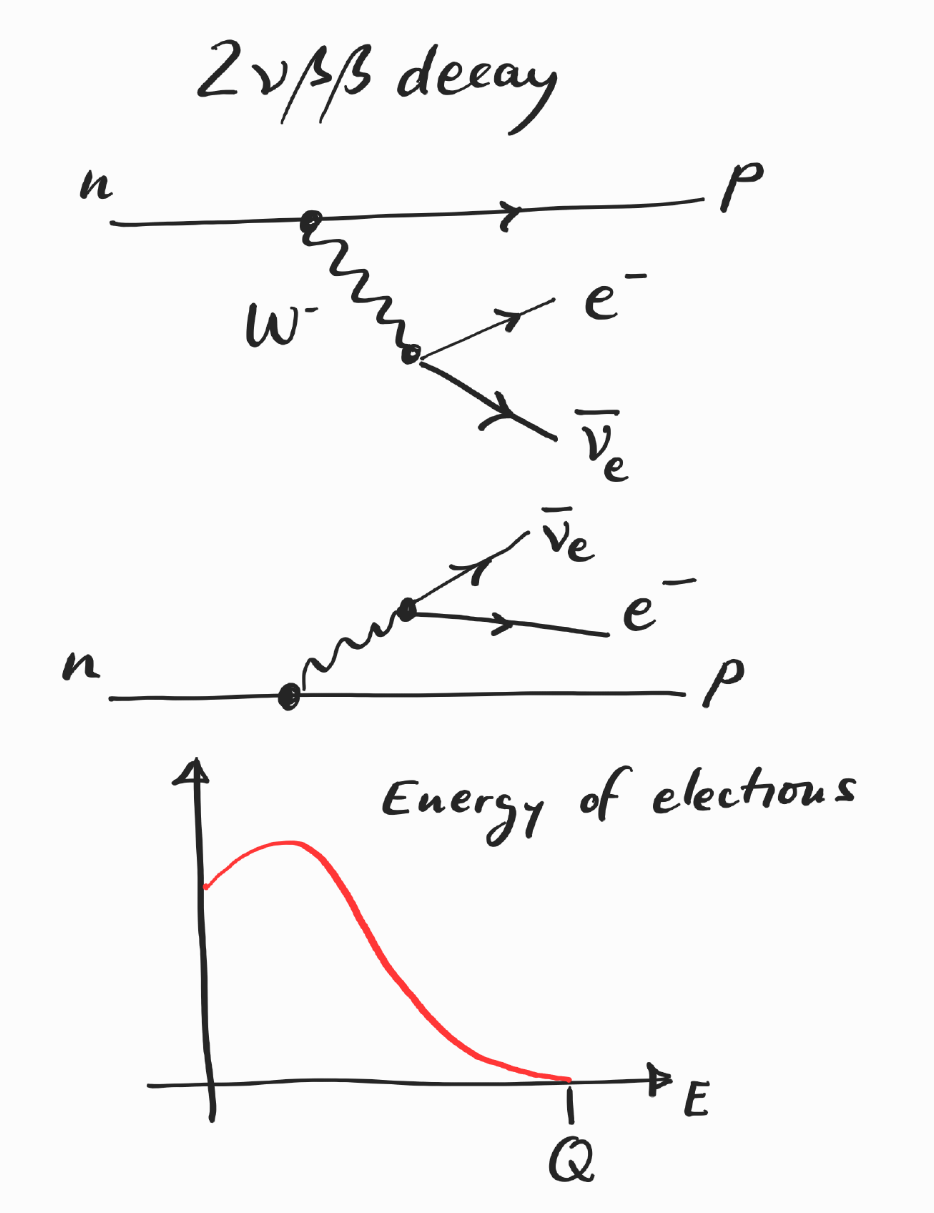
Examples: ^{76}Ge, ^{100}Mo, ^{130}Te, ^{150}Nd, ^{116}Cd

A=76

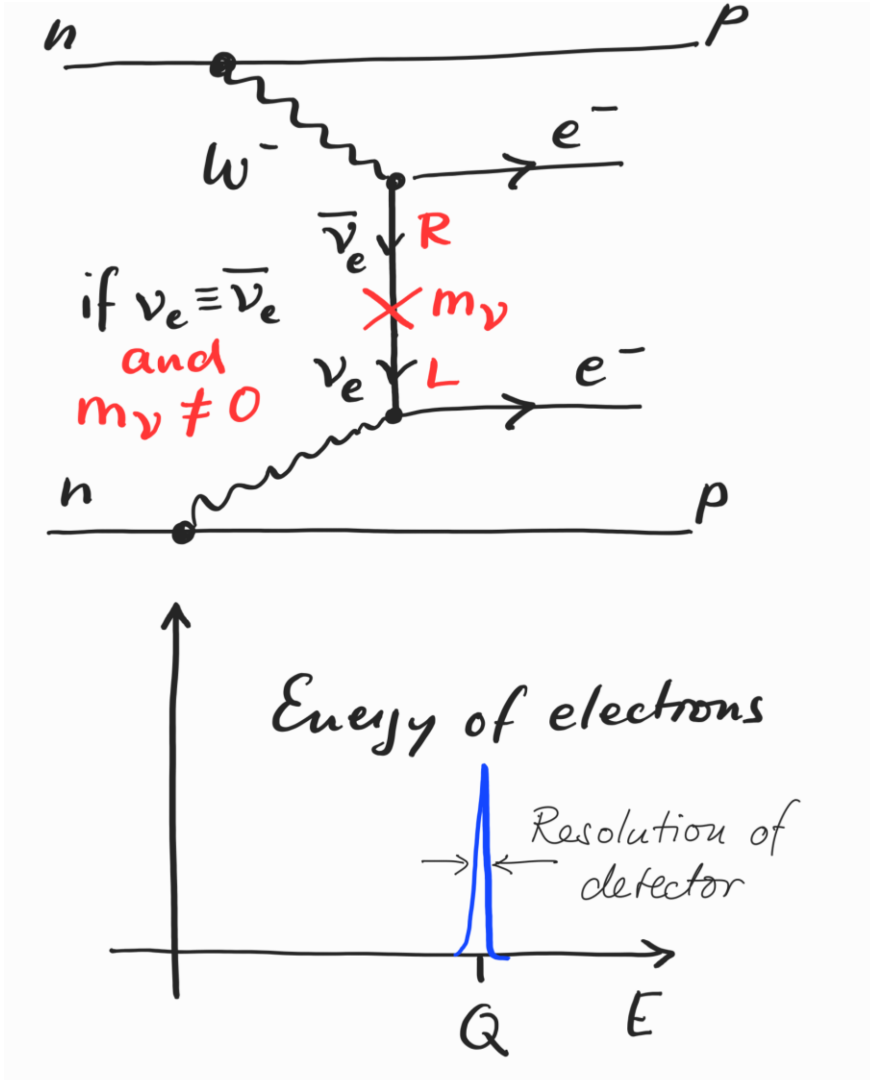
NDS 42, 233(1984)
NDS 74, 63(1995)(U)



Evaluator: B. Singh



Neutrinoless Double Beta Decay
0νββ decay



Neutrinoless Double Beta Decay: Rate and Neutrino mass

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu}(E_0, Z) \left| M_{GT}^{0\nu} - \frac{g_V^2}{g_A^2} M_F^{0\nu} \right|^2 \langle m_\nu \rangle_{\beta\beta}^2$$

Phase space factor

Transition matrix element

Effective neutrino mass

Effective neutrino mass in 0νββ-decay:

$$\langle m \rangle_{\beta\beta} \equiv \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|$$

Compare to β-decay:

$$\langle m^2 \rangle_{\beta} = \sum_i m_i^2 |U_{ei}|^2$$

Double Beta Decay Candidates:

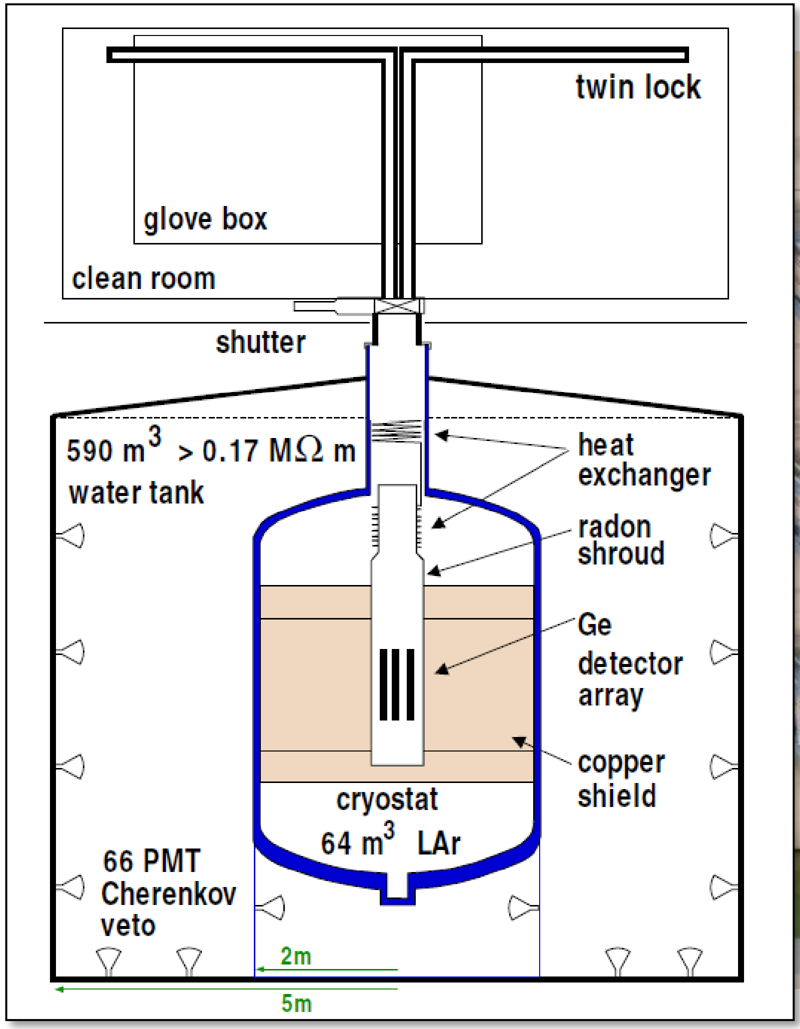
Decay candidate	Q value (MeV)	natural abundance (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

Meanwhile measured:
2v Double Beta Decay

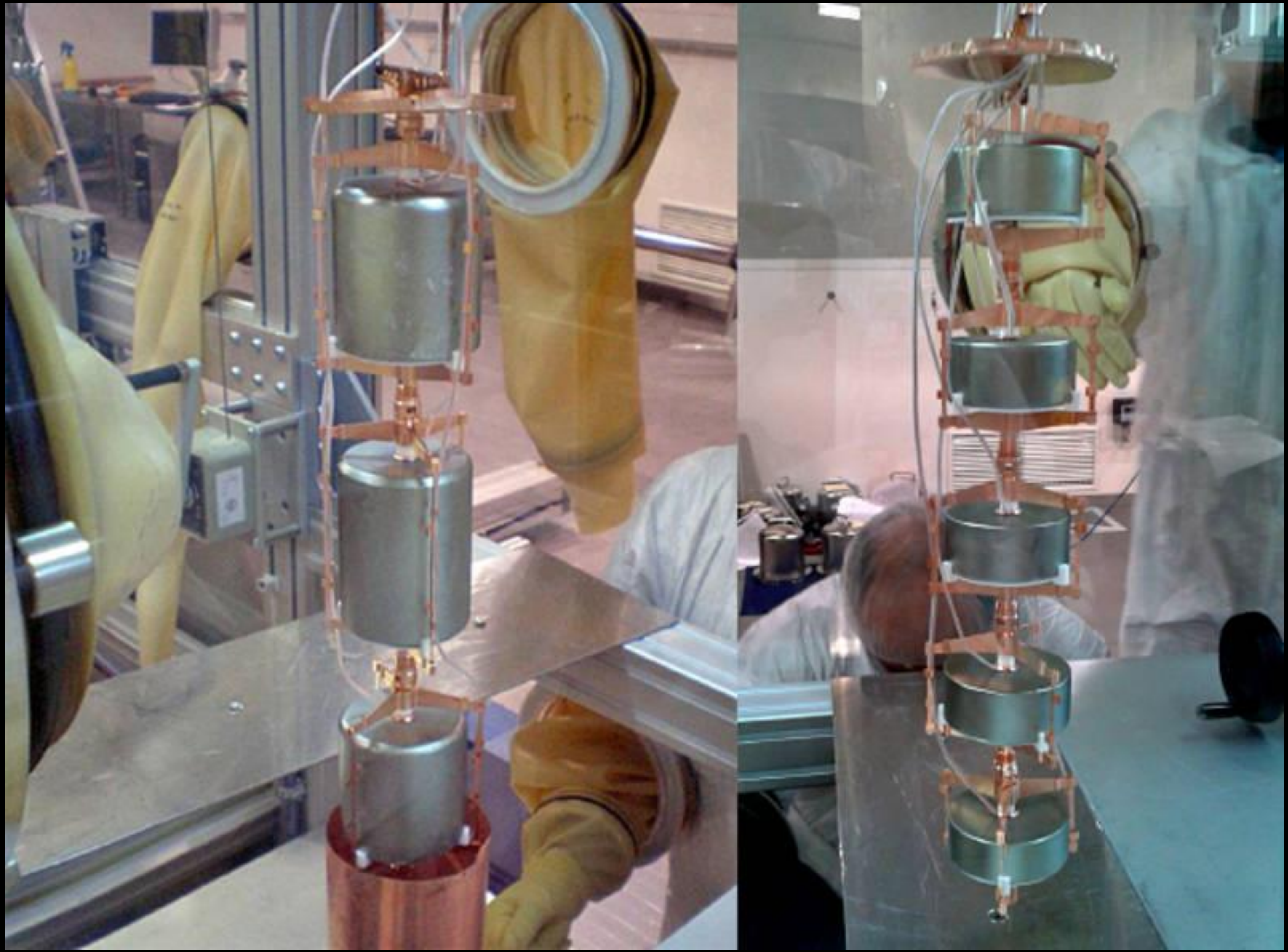
Isotope	$T_{1/2}(2\nu)$, yr
^{48}Ca	$4.4^{+0.6}_{-0.5} \cdot 10^{19}$
^{76}Ge	$(1.5 \pm 0.1) \cdot 10^{21}$
^{82}Se	$(0.92 \pm 0.07) \cdot 10^{20}$
^{96}Zr	$(2.3 \pm 0.2) \cdot 10^{19}$
^{100}Mo	$(7.1 \pm 0.4) \cdot 10^{18}$
^{100}Mo-$^{100}Ru(0^+_1)$	$5.9^{+0.8}_{-0.6} \cdot 10^{20}$
^{116}Cd	$(2.8 \pm 0.2) \cdot 10^{19}$
^{128}Te	$(1.9 \pm 0.4) \cdot 10^{24}$
^{130}Te	$(6.8^{+1.2}_{-1.1}) \cdot 10^{20}$
^{150}Nd	$(8.2 \pm 0.9) \cdot 10^{18}$
^{150}Nd-$^{150}Sm(0^+_1)$	$1.33^{+0.45}_{-0.26} \cdot 10^{20}$
^{238}U	$(2.0 \pm 0.6) \cdot 10^{21}$
^{130}Ba; ECEC(2ν)	$(2.2 \pm 0.5) \cdot 10^{21}$

from A.S.Barabash arXiv:1003.1005

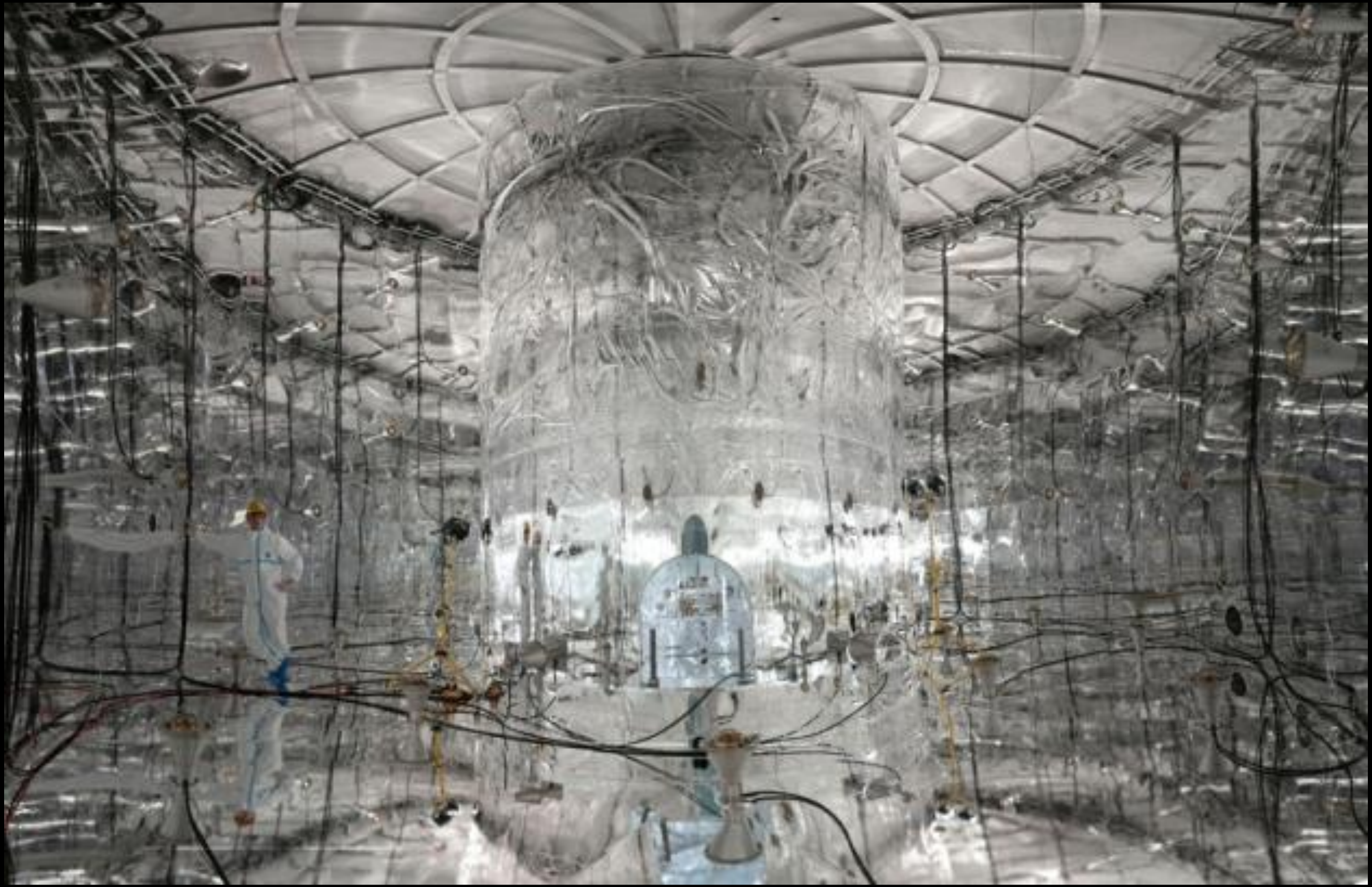
GERDA at LNGS



Ge Detectors of GERDA (enriched in ^{76}Ge)

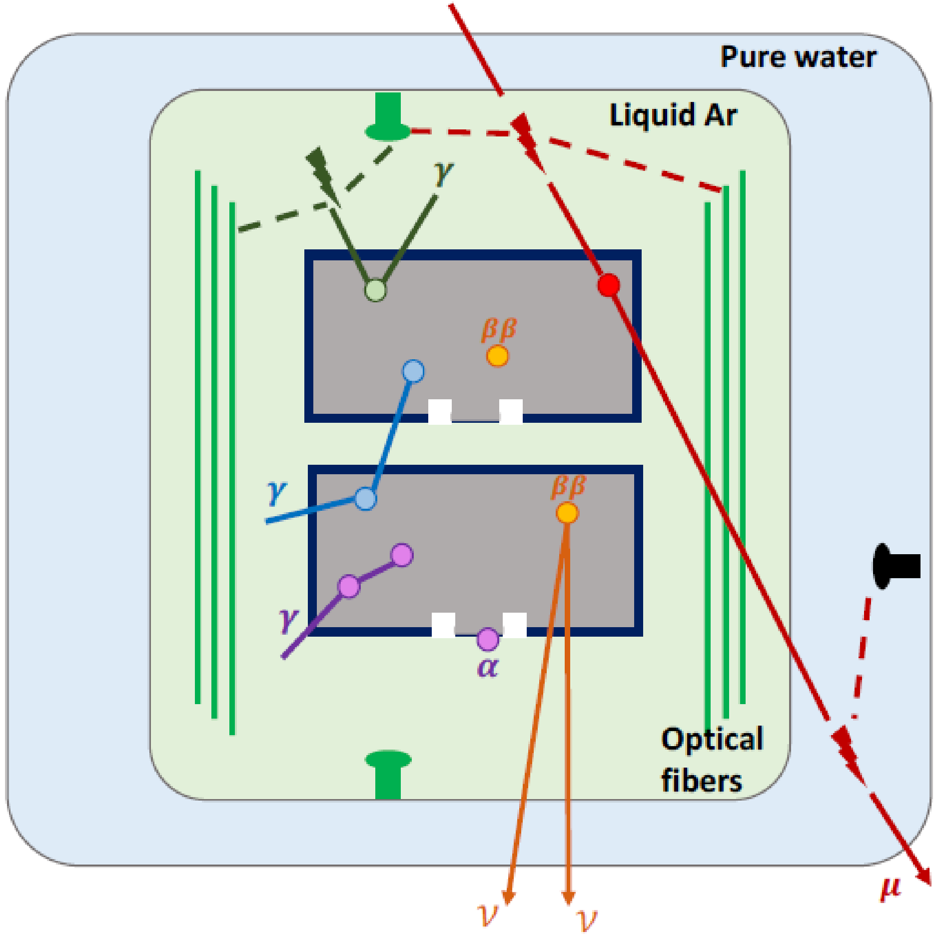


Water Tank for GERDA Muon Veto



Fighting the background

$\beta\beta$ decay signal: single energy deposition in a 1 mm^3 volume



Pulse shape discrimination (PSD) for multi-site and surface α events

Ge detector anti-coincidence

LAr veto based on Ar scintillation light read by fibers and PMT

Muon veto based on Cherenkov light and plastic scintillator

GERDA Phase II final results on 0νββ-decay

PHYSICAL REVIEW LETTERS **125,** 252502 (2020)

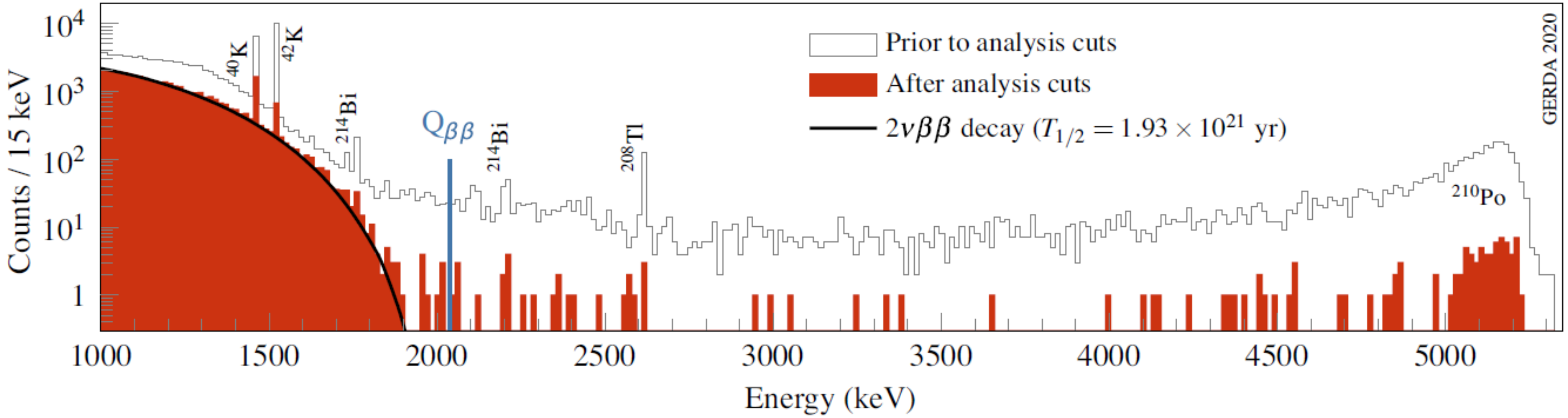


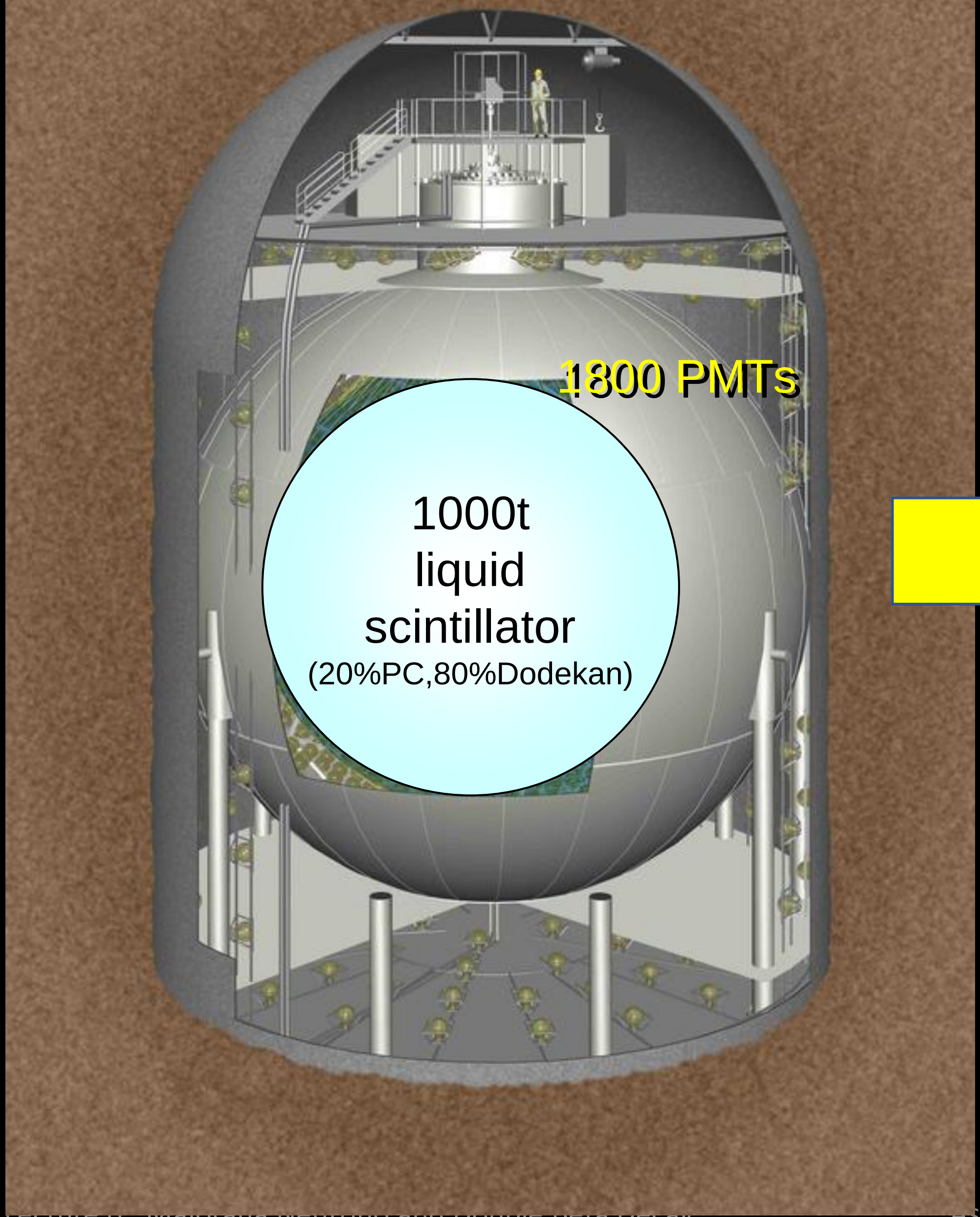
FIG. 1. Energy distribution of GERDA Phase II events between 1.0 and 5.3 MeV before and after analysis cuts; the exposure is 103.7 kg yr. The expected distribution of $2\nu\beta\beta$ decay events is shown assuming the half-life measured by GERDA [31]. The prominent γ lines and the α population around 5.2 MeV are also labeled.

127.2 kg yr of total exposure. background index of 5.2×10^{-4} counts/(keV kg yr)

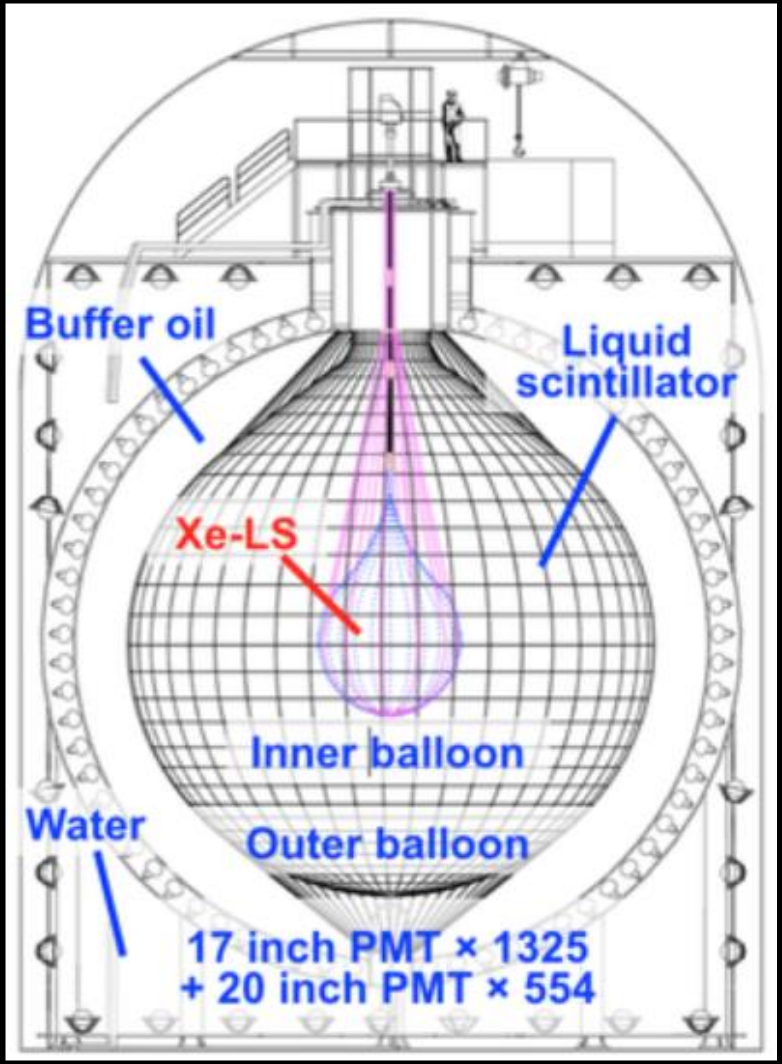
$$T_{1/2} > 1.8 \times 10^{26} \text{ yr at } 90\% \text{ C.L.}$$

$$m_{\beta\beta} < 79\text{–}180 \text{ meV}$$

KAMLAND



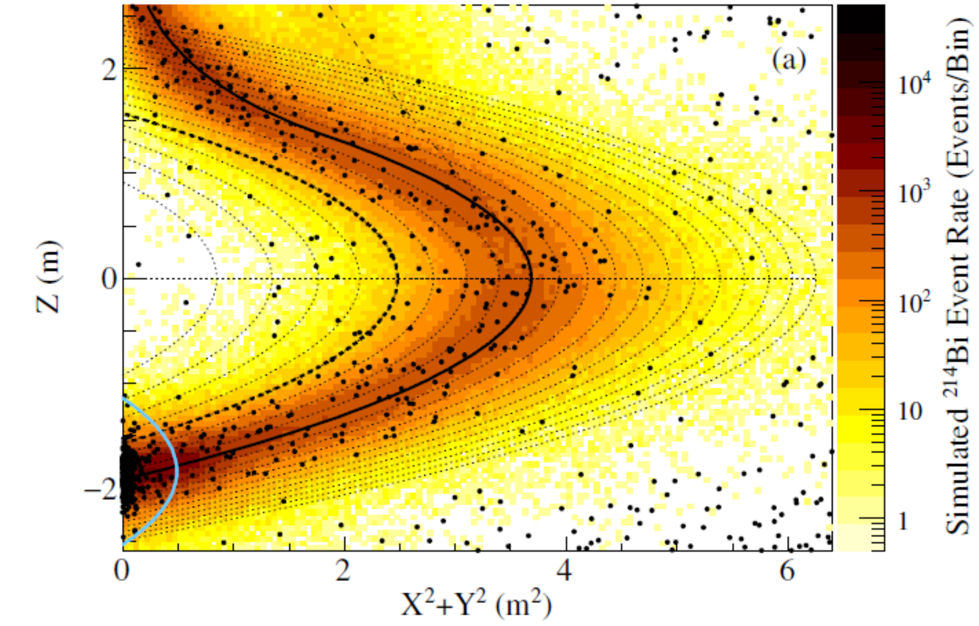
KAMLAND - ZEN

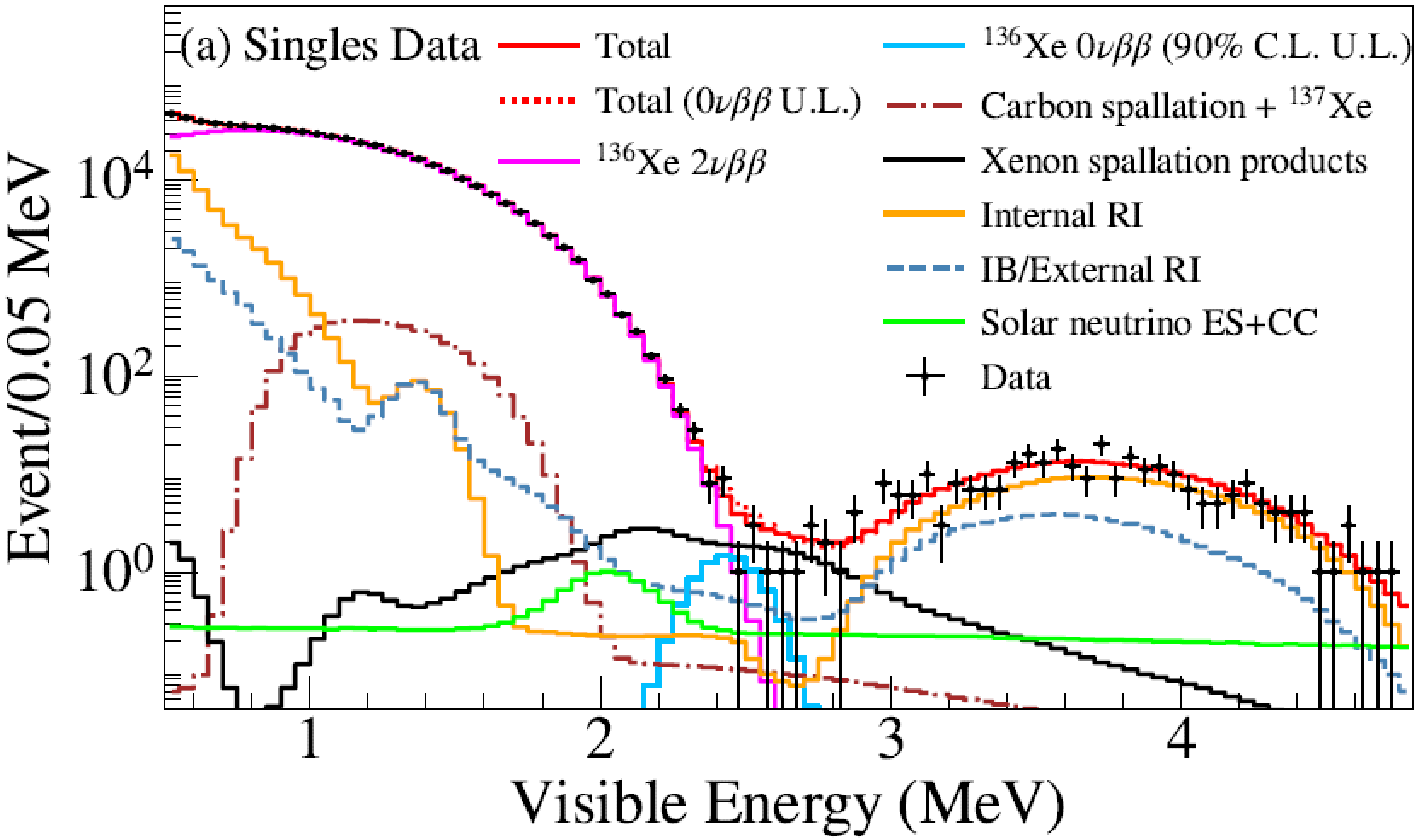


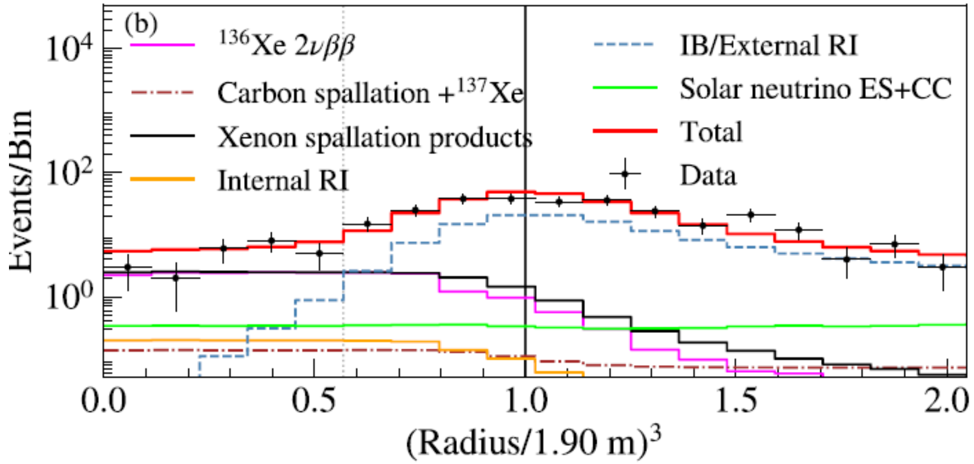
KamLAND-Zen 800: 745kg enriched Xe (90% ^{136}Xe)
started 2019

KamLAND-Zen: recent results

exposure of 970 kg yr of ^{136}Xe





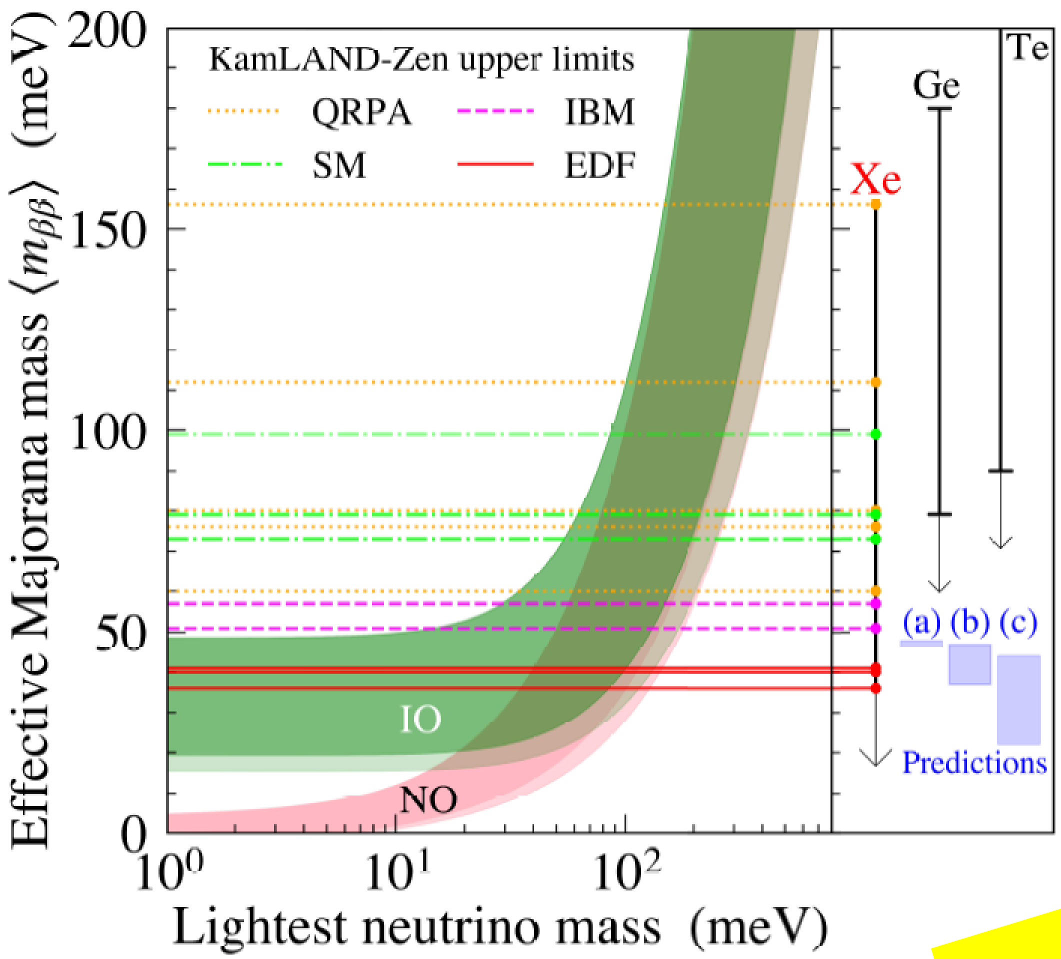


$$T^{0\nu}_{1/2} > 2.3 \times 10^{26}\ \text{yr at } 90\%\ \text{C.L.}$$

$$\langle m_{\beta\beta} \rangle \equiv \left| \Sigma_i U_{ei}^2 m_{\nu_i} \right| < 36\text{–}156\ \text{meV}$$

arXiv:2203.02139v2: „Search for the Majorana Nature of Neutrinos in the Inverted Mass Ordering Region with KamLAND-Zen“

Status of 0νββ experiments: Kamland-Zen(Xe), Gerda(Ge), Cuore(Te)



It starts to get really interesting!

Thank you!