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# The search for Neutrinoless double beta decay in Ge

PIKIMO 15 - Fall 2023

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INDIANA UNIVERSITY

# Outline

- Neutrinos: Known and Unknown
- Neutrinoless double beta decay, in
- LEGEND - a neutrinoless double beta decay (in Ge) experiment
- Work of IU group: investigating a small part of the detectors called ‘passivated surface’

# What we know & don’t know about Neutrinos

(so far, among other things)

We know: Neutrinos

At least, very tiny, since so many
of them can escape the Sun

- Are only electric chargeless (charge conservation in beta decays, Cowan-Reines, 1953) fermions (have spin ½, from many experiments, by angular momentum conservation)
- Interact ~only through Weak interactions!
- Violate parity! (And ~maximally, ~100% LH!!) [Wu, 1958]

$$\psi_L \to (1 - i\theta \cdot \tfrac{\sigma}{2} - \beta \cdot \tfrac{\sigma}{2})\psi_L; \checkmark$$

$$\psi_R \to (1 - i\theta \cdot \tfrac{\sigma}{2} + \beta \cdot \tfrac{\sigma}{2})\psi_R. \text{ X}$$

- Have mass $\gtrsim$ 0.01 eV (from $\nu$-flavor oscillation experiments)

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  $\psi_L \to (1 - i\theta\cdot\frac{\sigma}{2} - \beta\cdot\frac{\sigma}{2})\psi_L;$ ✓

  $\psi_R \to (1 - i\theta\cdot\frac{\sigma}{2} + \beta\cdot\frac{\sigma}{2})\psi_R.$ X
- Have mass $\gtrsim$ 0.01 eV (from $\nu$-flavor oscillation experiments)

We don’t know: Origin of their masses.

Two possible ways:

Dirac Way: Two handedness of leptons + coupling with Higgs field → Conserves Lepton Number → Leads to $y_\nu \sim O(10^{-12})$ (meh)

Right handed neutrino

Higgs

Left handed lepton

Both same handed,
No Higgs field needed.

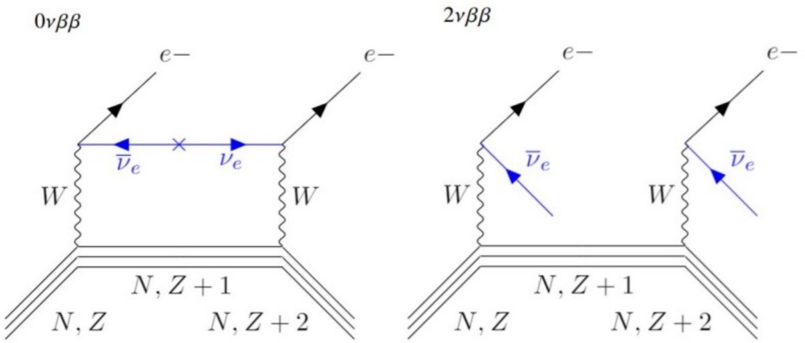
$$\mathcal{L}_N^{\mathrm{M}} = \frac{\mathrm{i}}{2}\overline{N_I^{\mathrm{R}}}\not\partial N_I^{\mathrm{R}} \underbrace{\boxed{-y_{I\alpha}\overline{N_I^{\mathrm{R}}}\tilde{\phi}^\dagger L_\alpha}}_{\text{Dirac-like term}} \underbrace{\boxed{-\frac{1}{2}\overline{N_I^{\mathrm{L}}}M_{IJ}(N_J^{\mathrm{L}})^{\mathrm{C}}}}_{\text{Majorana-like term}} + \mathrm{H.c.}$$

Majorana Way: Charglessness + being fermion → No Higgs coupling needed → Lets same handed fermionic fields be coupled together → Violates Lepton number, No need for RH neutrinos

$\psi^C = (\psi_L + \psi_L^C)^C = \psi_L^C + \psi_L = \psi$ : Particle = Anti-particle

# Neutrinoless double beta decay

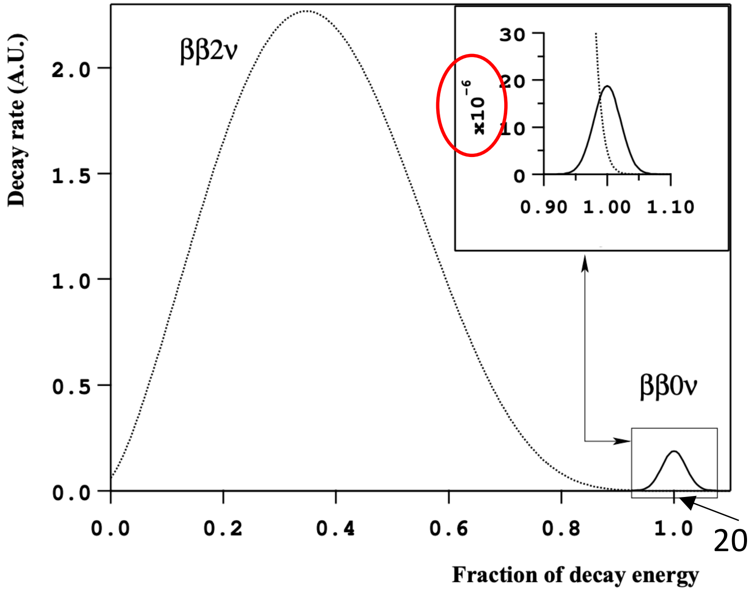
$\beta^-$ decay: $n \rightarrow p^+ + e^- + \bar{\nu}_e$
$2\nu\beta\beta$ decay: $2n \rightarrow 2p^+ + 2e^- + 2\bar{\nu}_e$ ($T_{\frac{1}{2}}$ ($^{76}$Ge) $= 10^{21}$yr)
$0\nu\beta\beta$ decay: $2n \rightarrow 2p^+ + 2e^- + 0\bar{\nu}_e$ ($T_{\frac{1}{2}}$ =??, Current: >$10^{25}$yr)



**Experimental signature of $0\nu\beta\beta$**

No neutrinos in this case to take away any energy → very sharp peak at the $Q_{\beta\beta}$ of $2\nu\beta\beta$

$Q_{\beta\beta}$ = Total energy of 2e$^-$ (2.039 MeV for $^{76}$Ge)

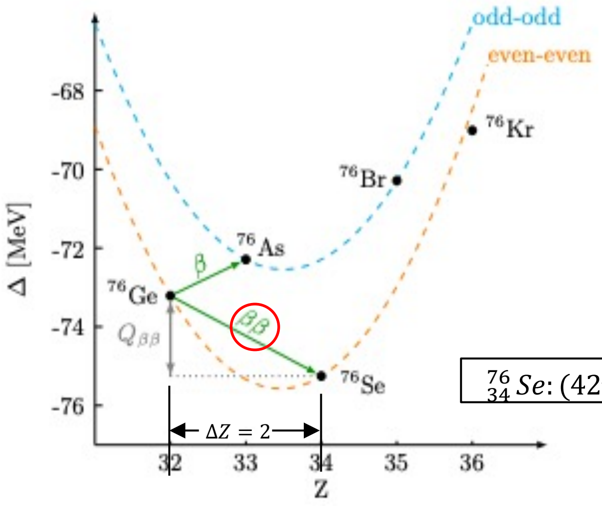


2039 keV for Ge

# What isotopes can actually go through $\beta\beta$?

**Spin paring** makes even-even nuclei more strongly bound than its nearby ones.

**Binding energy** of parent and daughter nuclei decides if that nucleus can go through a $\beta\beta$ decay instead of $\beta$ decay!



$^{76}_{34}Se: (42n, 34p)$

- ~100 isotopes calculated to be able to go through $\beta\beta$.
- 9 nuclei directly observed to do this.

| Nuclide | Half-life, $10^{21}$ years | Mode | Transition | Method | Experiment |
|---|---|---|---|---|---|
| $^{48}$Ca | $0.064^{+0.007}_{-0.006} \pm ^{+0.012}_{-0.009}$ | $\beta^-\beta^-$ | | direct | NEMO-3[11] |
| $^{76}$Ge | $1.926 \pm 0.094$ | $\beta^-\beta^-$ | | direct | GERDA[10] |
| $^{78}$Kr | $9.2^{+5.5}_{-2.6} \pm 1.3$ | εε | | direct | BAKSAN[10] |
| $^{82}$Se | $0.096 \pm 0.003 \pm 0.010$ | $\beta^-\beta^-$ | | direct | NEMO-3[10] |
| $^{96}$Zr | $0.0235 \pm 0.0014 \pm 0.0016$ | $\beta^-\beta^-$ | | direct | NEMO-3[10] |
| $^{100}$Mo | $0.00693 \pm 0.00004$ | $\beta^-\beta^-$ | | direct | NEMO-3[10] |
| | $0.69^{+0.10}_{-0.08} \pm 0.07$ | $\beta^-\beta^-$ | $0^+ \rightarrow 0^+_1$ | | Ge coincidence[10] |
| $^{116}$Cd | $0.028 \pm 0.001 \pm 0.003$<br>$0.026^{+0.009}_{-0.005}$ | $\beta^-\beta^-$ | | direct | NEMO-3[10]<br>ELEGANT IV[10] |
| $^{128}$Te | $7200 \pm 400$<br>$1800 \pm 700$ | $\beta^-\beta^-$ | | geochemical | [10] |
| $^{130}$Te | $0.82 \pm 0.02 \pm 0.06$ | $\beta^-\beta^-$ | | direct | CUORE-0[12] |
| $^{124}$Xe | $18 \pm 5 \pm 1$ | εε | | direct | XENON1T[13] |
| $^{136}$Xe | $2.165 \pm 0.016 \pm 0.059$ | $\beta^-\beta^-$ | | direct | EXO-200[10] |
| $^{130}$Ba | (0.5 – 2.7) | εε | | geochemical | [14][15] |
| $^{150}$Nd | $0.00911^{+0.00025}_{-0.00022} \pm 0.00063$ | $\beta^-\beta^-$ | | direct | NEMO-3[10] |
| | $0.107^{+0.046}_{-0.026}$ | $\beta^-\beta^-$ | $0^+ \rightarrow 0^+_1$ | | Ge coincidence[10] |
| $^{238}$U | $2.0 \pm 0.6$ | $\beta^-\beta^-$ | | radiochemical | [10] |

# Why Ge?

Ge detectors are semiconductors

→ Big number of electron-hole pairs for even small amount of energy deposition

→ Greater energy resolution

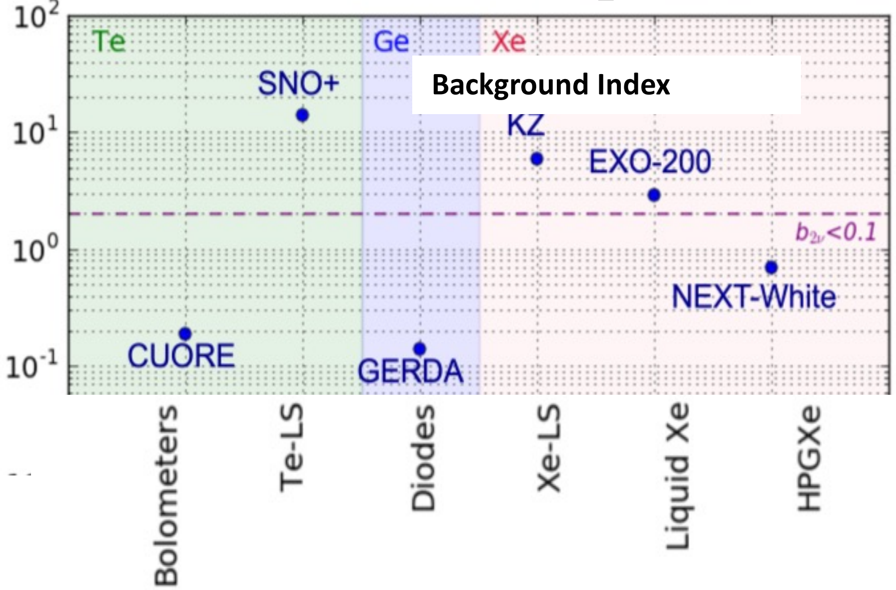
→ Makes it possible to remove more background

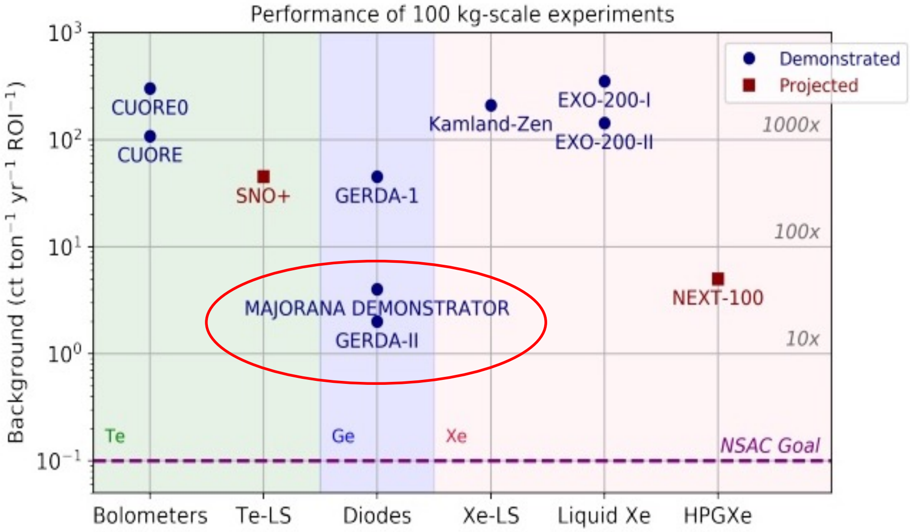
From Majorana Demonstrator and GERDA:

**Energy resolution** 0.12% FWHM at $Q_{\beta\beta}$;

**Bkg Index** $10^{-3}$ counts/keV-kg-yr at ROI

**Resolution (%FWHM) at Q_BB**

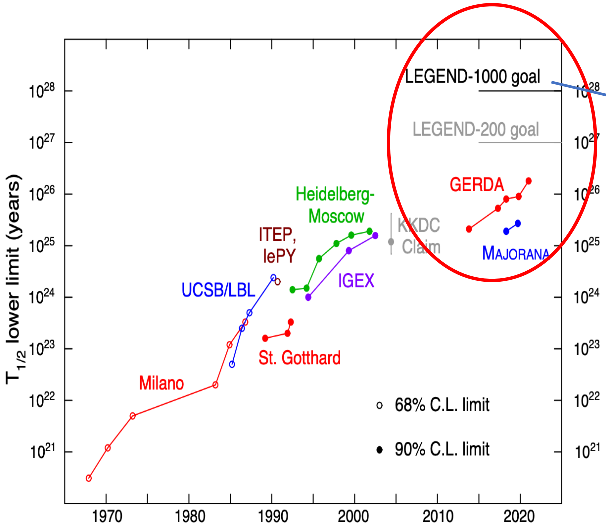


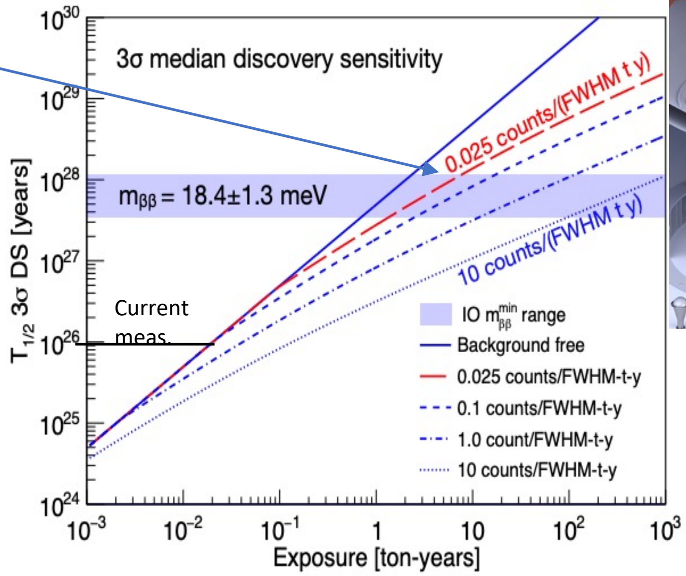


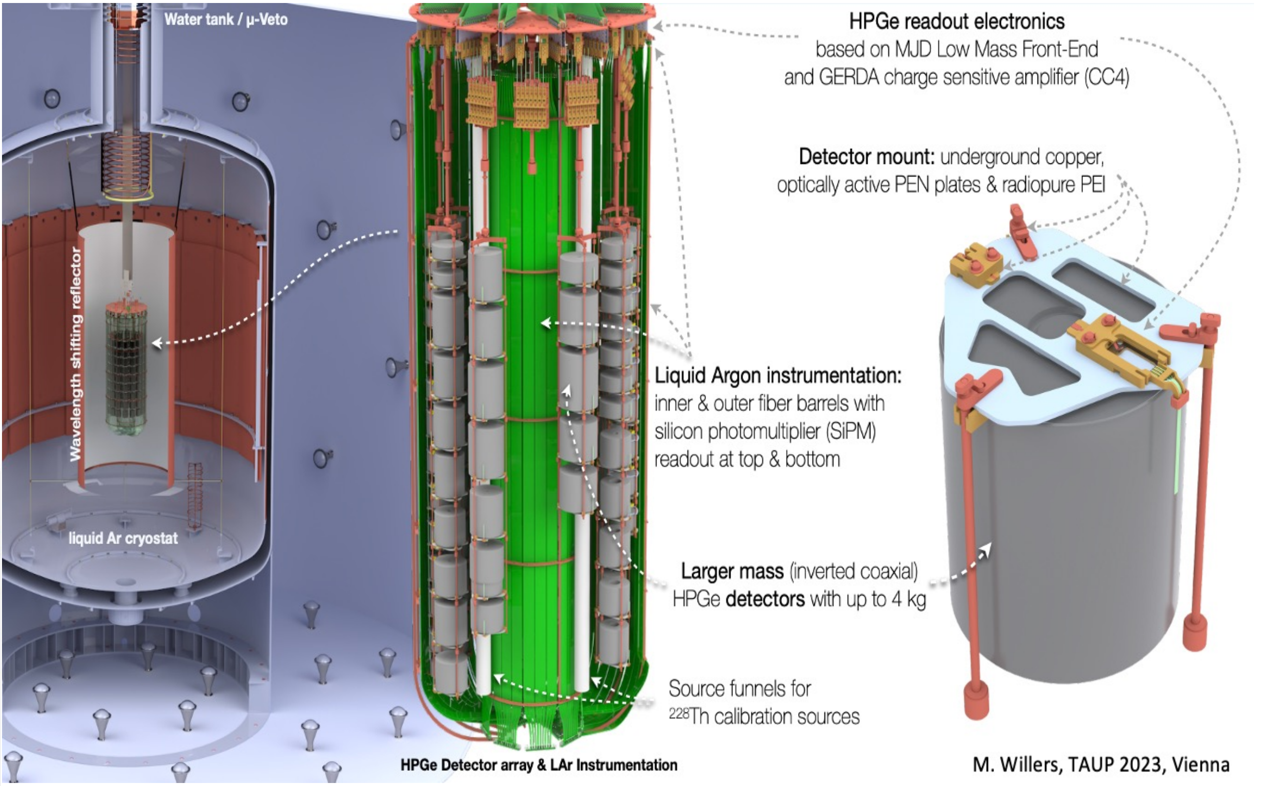
~300 members, 55 institutions, 12 countries

# LEGEND (Large Enriched Ge Experiment for Neutrinoless $\beta\beta$ Decay)

- ~1 mile underground in Gran Sasso, Italy.
- Modular form, arrays of ~10 detectors hung on strings.
- LAr in the cryostat below detector strings. SiPMs basically make it an ‘active detector for backgrounds’.



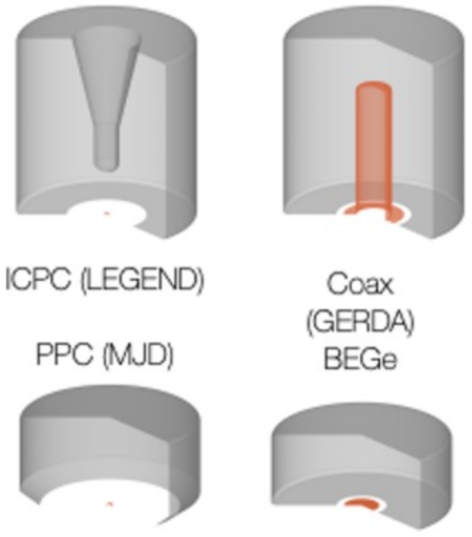


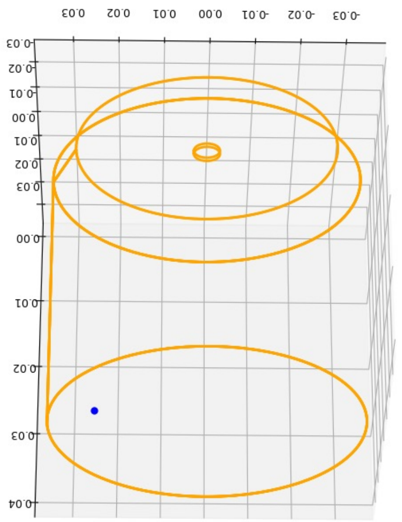


M. Willers, TAUP 2023, Vienna

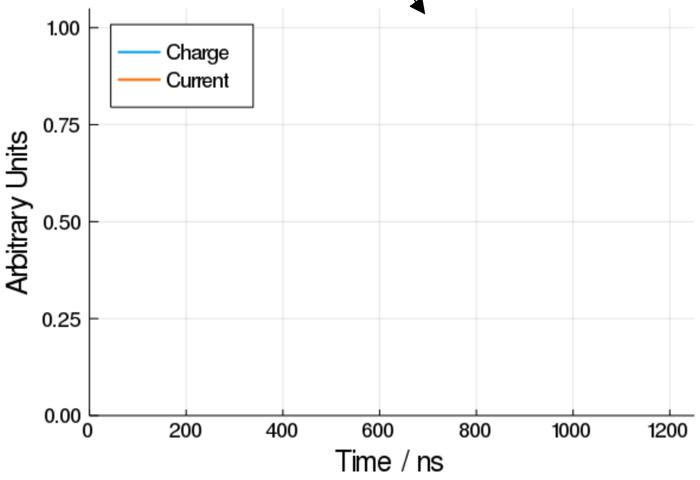
# Detectors of LEGEND

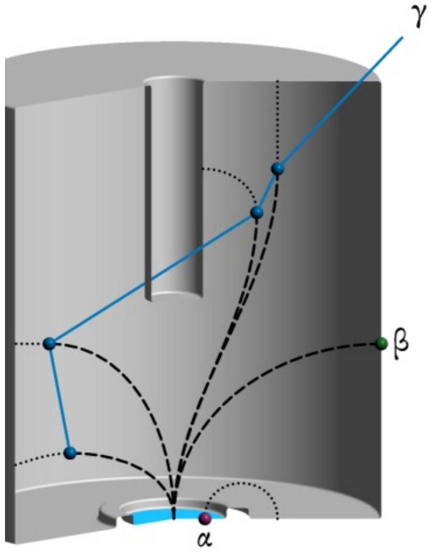
Chunks of highly pure Ge. Connected in reverse bias of 2-5 kV.
Broadly two types:
- The ones that collect charge through a point (good for analysis later): PPC (repurposed from MJD), BEGe (from GERDA) , ICPC.
- The ones with larger contact for charge collection: Coaxial.





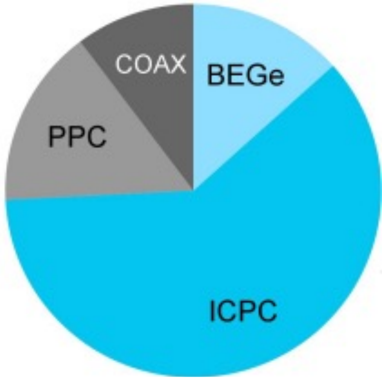
pulse





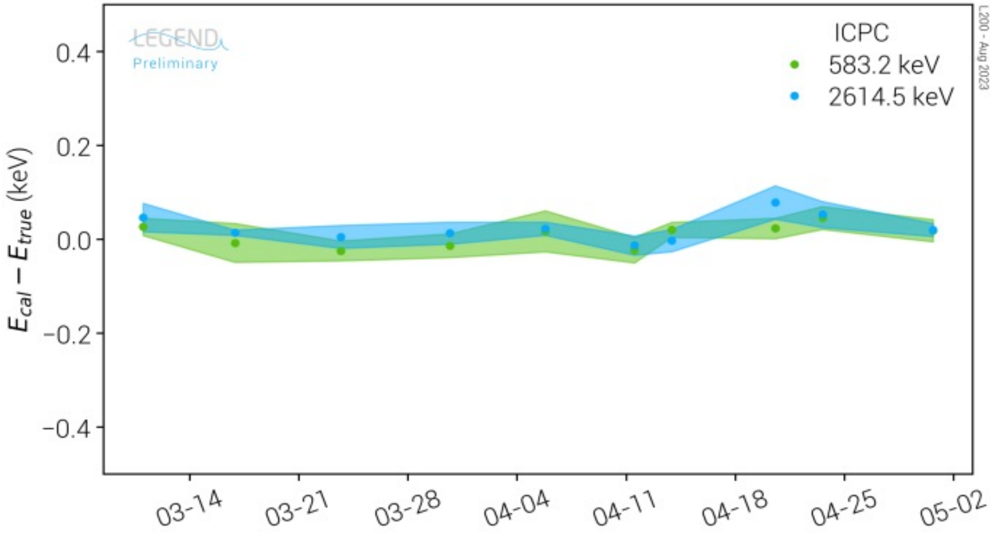
# LEGEND-200 : Detector performances

- 101 detectors = ~140 kg (14% of total goal)
- Mostly ICPC. PPC and BEGe from MJD and GERDA repurposed
- Weekly energy calibration using $^{228}$Th sources.
- Currently collecting data. Recent result on 10.1 kg-yr.

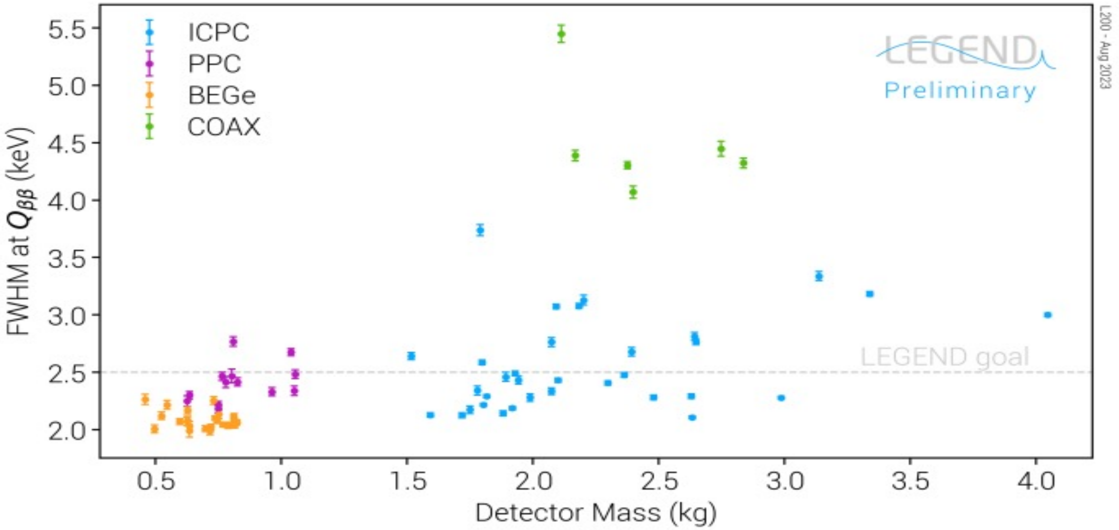


L-200 Detector composition
(By mass)

Energy calibration stable over months



FWHM ~ 0.1% of $Q_{\beta\beta}$, even better than expected!



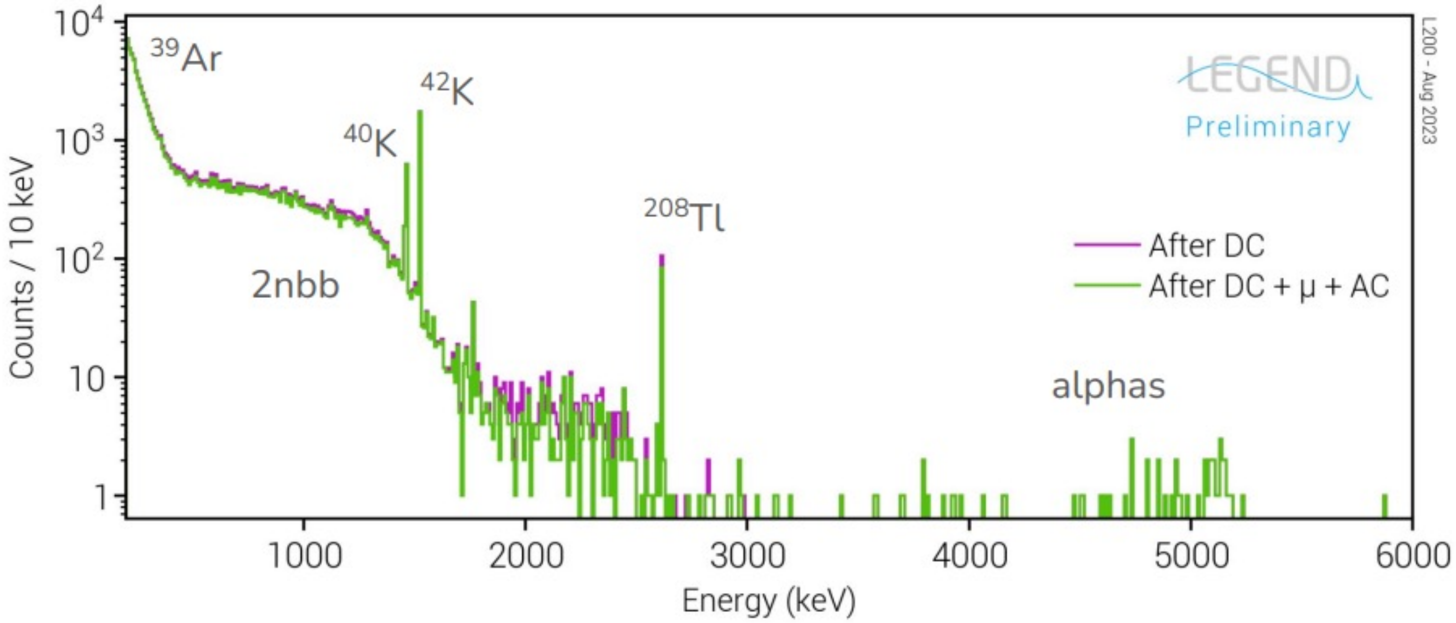
# LEGEND-200 : Energy spectrum and background index

Energy spectrum of L200. Nothing surprising.

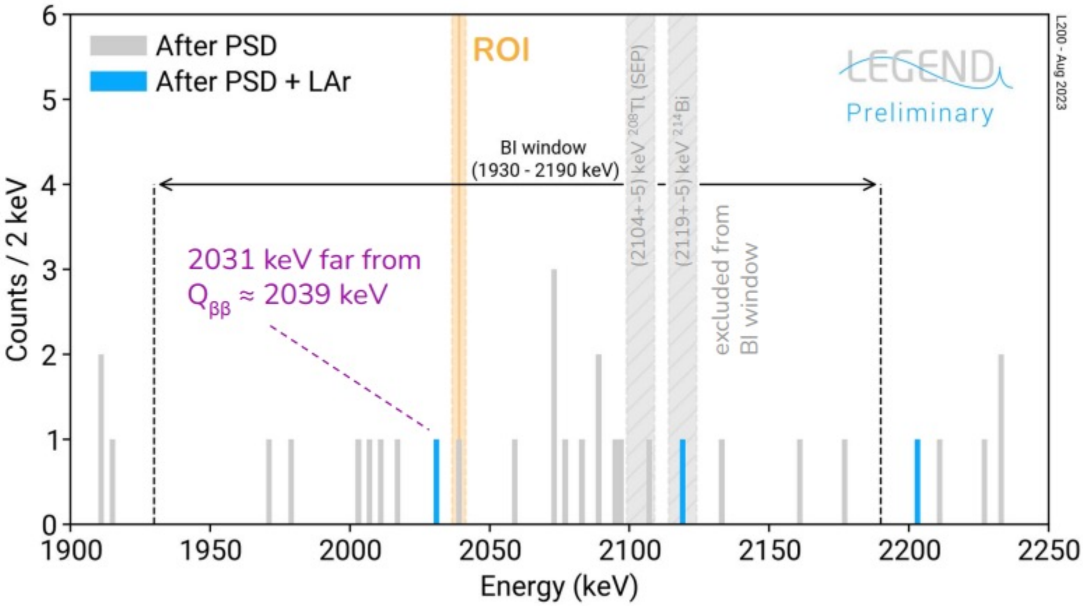
- ${}^{42}$K, ${}^{40}$K from Liquid Ar
- ${}^{208}$Tl from ${}^{232}$Th chain (residual Thoriums in the detector components)
- $2\nu\beta\beta$ spectrum visible with thousands of them detected already!
  ($T_{\frac{1}{2}, {}^{76}\mathrm{Ge}\rightarrow 2\nu\beta\beta} = 10^{21} yr$, so already very very rare!)
- Some 'high energy' (~5 MeV) $\alpha$ particles, originated from ${}^{210}$Po and ${}^{210}$Pb.

Bkg Index = 2x$10^{-4}$ cts/keV-kg-yr

(< $10^{-3}$ of previous best)

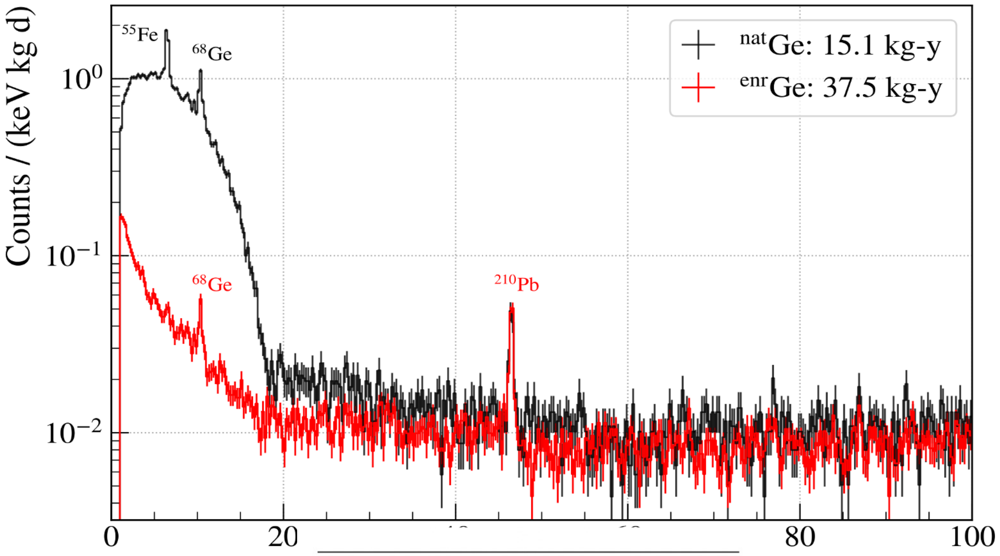


Background subtracted spectrum of L200 in ROI



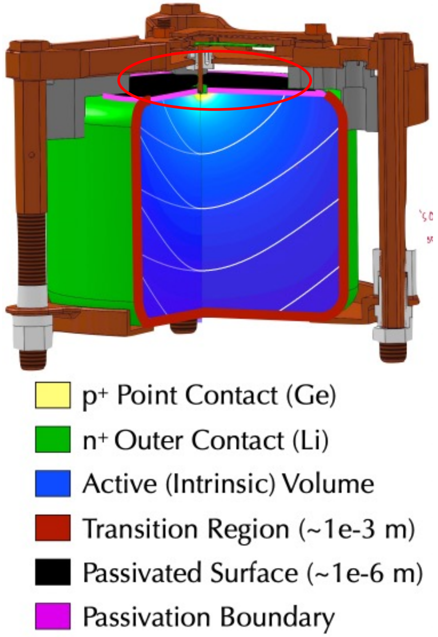
# Can those alphas be problematic? Possibly!

Majorana Demonstrator’s low energy spectrum reveals some missing peaks from $^{210}$Pb → Energy degraded in the passivated surface of the detectors?



| Transition Energy | Attenuation Length in crystal Ge | |
|---|---|---|
| 10.8 keV X-ray ($^{210}$Pb) | 60 microns | x |
| 13.0 keV X-ray ($^{210}$Pb) | 14 microns | x |
| 46.5 keV $\gamma$ ($^{210}$Pb) | 460 microns | √ |
| 30.0 keV electron ($^{210}$Pb) | 5 microns | x |

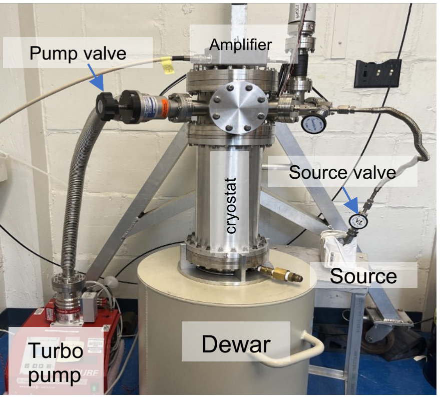
* this is not a comprehensive list, just a quick copy-paste



~5 MeV $\alpha$ particles can get degraded to ~2 MeV, which is ROI!!!

# IU+UW joint effort to solve the issue!

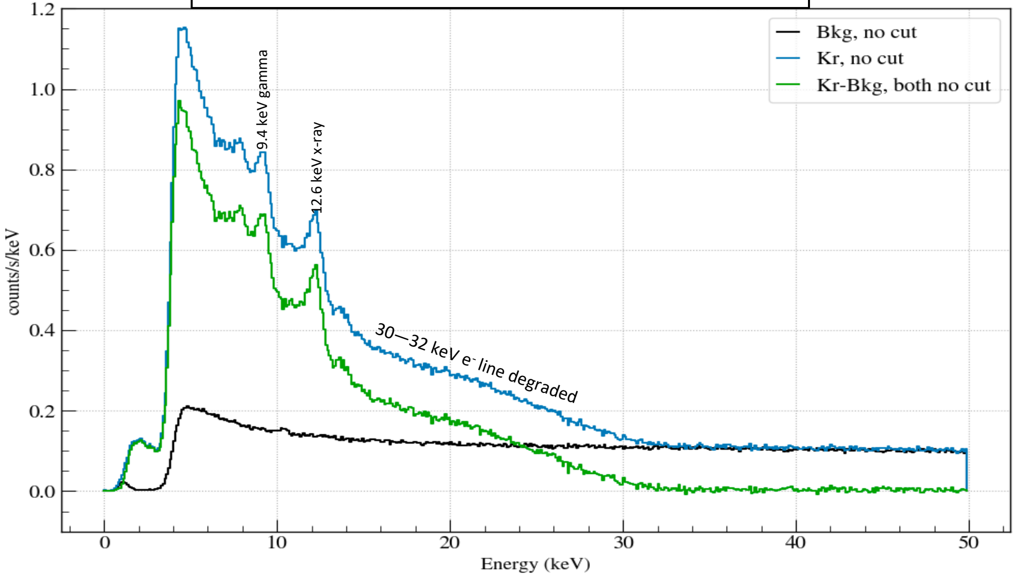
- A PPC detector from Majorana Demonstrator
- Shoot Kr towards it
- Look for 32 keV electron peak



Copper can inside cryostat

Inside the copper can

Typical energy spectra for the Kr source



**Expected signals:**

**Conversion electrons***

**17-18 keV (25%)**

**30-31 keV (63%)**

Gammas

**9.4 keV (5.5%),**

**32.15 keV (< 0.1%)**

**X-rays**

**(requires atomic excitation)**

**12 keV (~13%)**

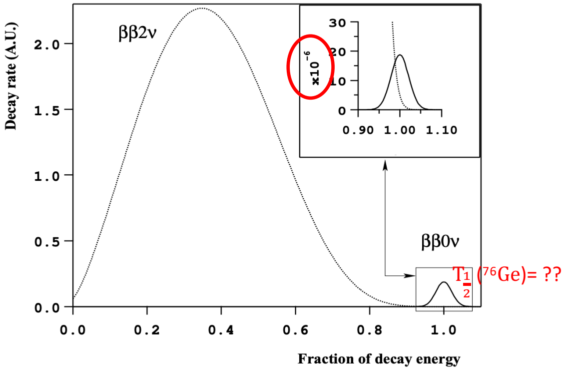
*monoenergetic

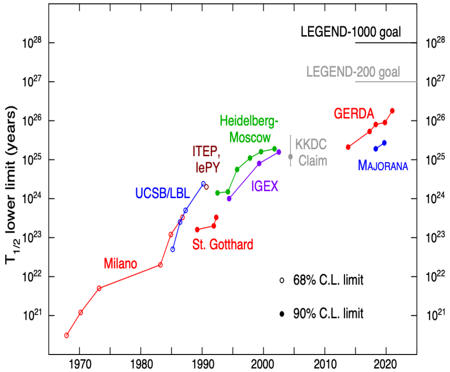
32 keV line of Kr is clearly degraded, and possibly in the passivated surface.

How do we quantify it?

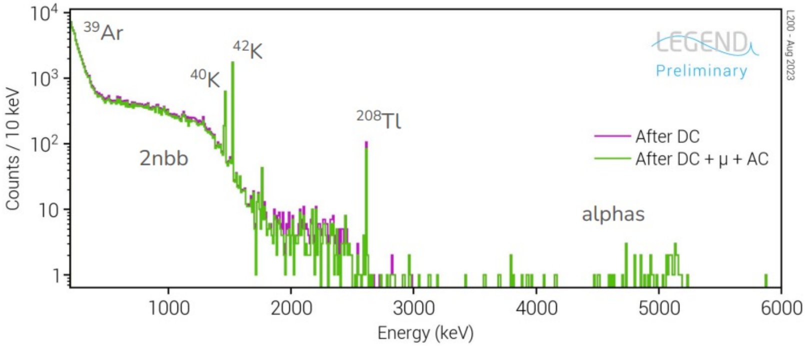
WORK IN PROGRESS

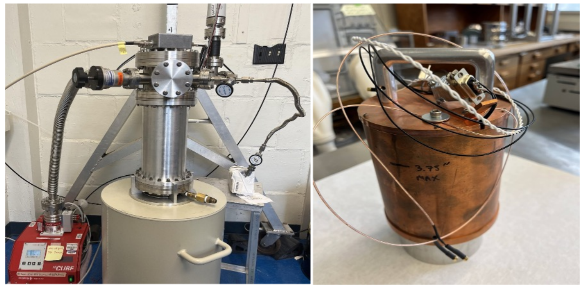
# Summary





- Set out to measure $T_{\frac{1}{2}}(^{76}Ge \rightarrow 0\nu\beta\beta)$, Currently: >$10^{25}$yr
- LEGEND: A ton scale experiment looking for 0vBB in 76Ge, Built on success of Majorana Demonstrator and GERDA
- LEGEND 200: 15% deployed, currently taking physics data
  - better both FWHM and Bkg Index so far
  - Already seeing thousands of $2\nu\beta\beta$
- Some 'high energy' $\alpha$s are expected to be problematic. IU+UW groups are working on it.





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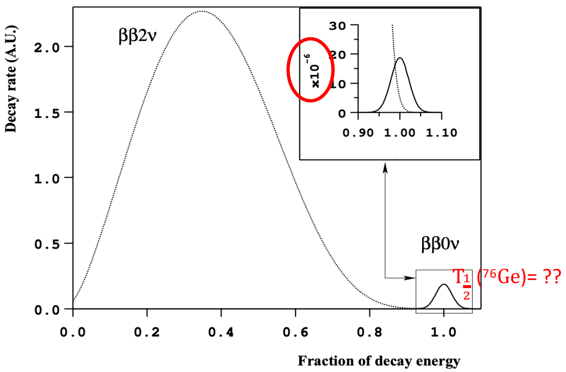
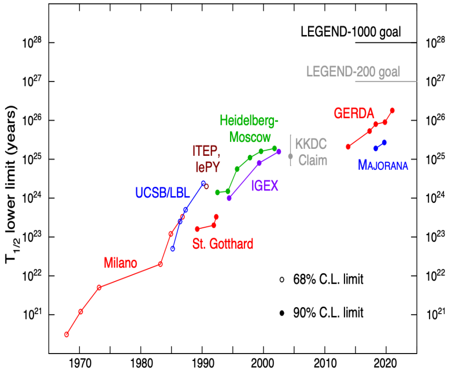
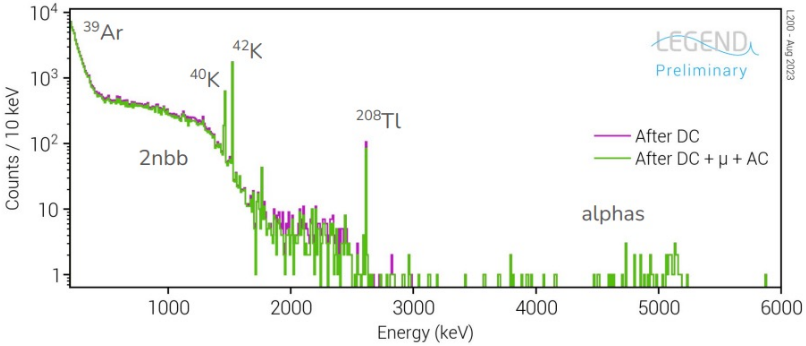
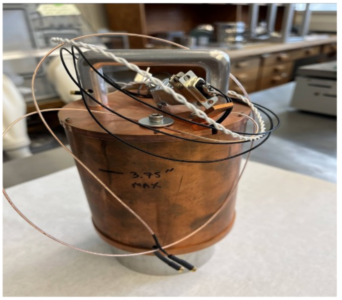






## Thanks everyone for listening!

## Questions?

# Backup slides

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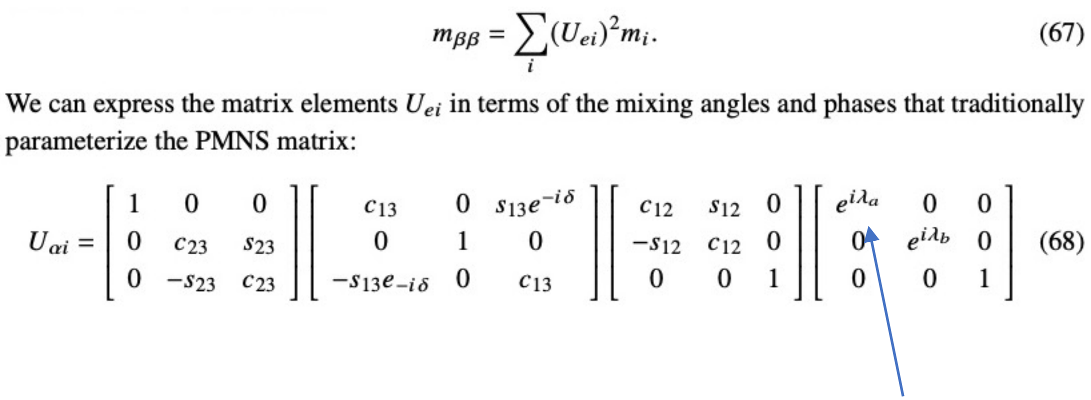


$$m_{\beta\beta} = \sum_i (U_{ei})^2 m_i. \tag{67}$$

We can express the matrix elements $U_{ei}$ in terms of the mixing angles and phases that traditionally parameterize the PMNS matrix:

$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e_{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\lambda_a} & 0 & 0 \\ 0 & e^{i\lambda_b} & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{68}$$

Majorana phases

Inverted and normal order hierarchy comes into play when calculating m_BB from T_1/2, not before that.

# But Standard Model tries to understand them

Leads to ElectroWeak theory: SU(2)xU(1), [G,W,S,…,1970s]
[all fermions starts with 0 Dirac mass and only gets mass later through SSBreaking]

No evidence of RH neutrino + Only evidence of Higgs doublet

↓

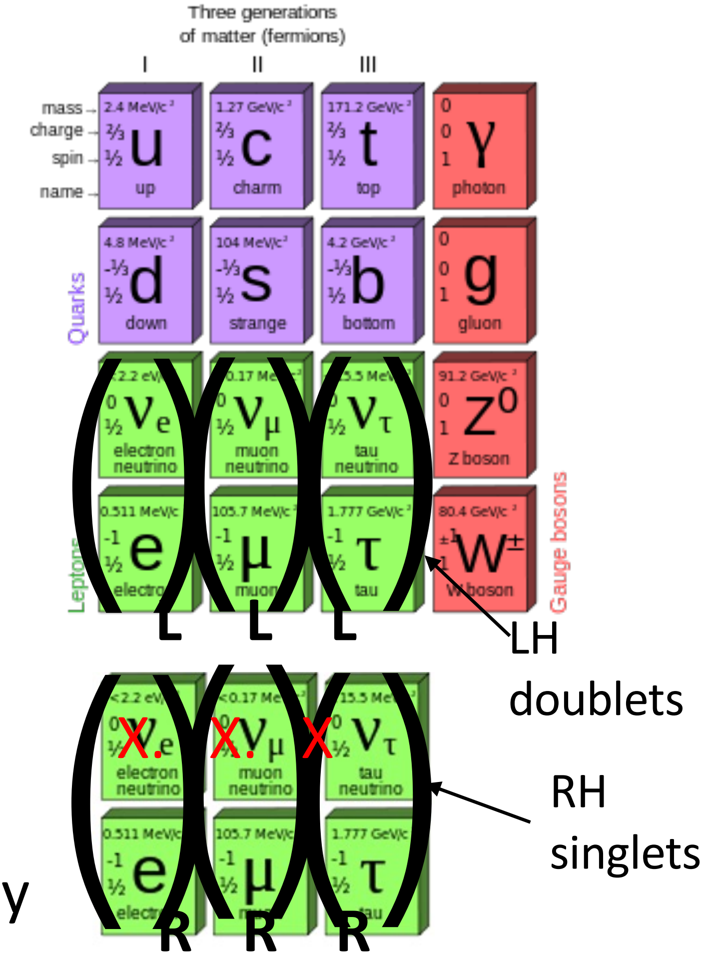
LH doublet + RH singlet

↓

Neutrinos are massless

(i.e. no coupling with Higgs)

1998: Neutrinos have mass! (=all mass eigenvalues can't be 0), but very tiny!(~0.1 eV) [Super-Kamiokande]



$$\Delta\mathcal{L} = -\frac{y_e v}{\sqrt{2}} e_L^\dagger e_R - \frac{y_d v}{\sqrt{2}} d_L^\dagger d_R \longrightarrow m_f = y_f \frac{v}{\sqrt{2}}$$

# Worth to look for $0\nu\beta\beta$?

** ~'Anything that can happen, should happen.'*(Good enough?)

Majorana nature of neutrino → 'Tunable' origin of $\nu$ masses → Leptogenesis

↓

All the good stuff…

↓

Only 3 phases can be absorbed in leptonic fields
(i.e. only charged lepton fields can do that now)

↓

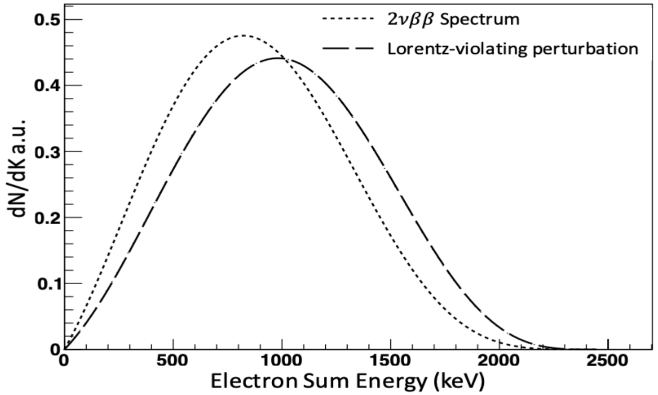
$$U_{PMNS} = U_{CKM}(\delta) \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

[Just two more ways to explain the observed 'big' amount of CP violation]

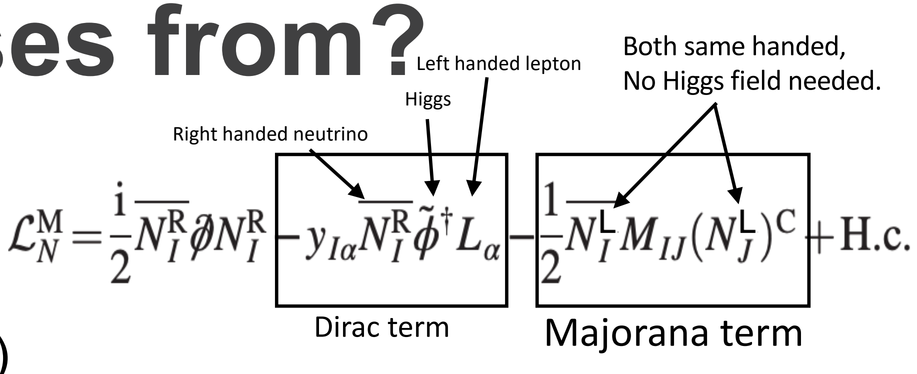
Schechter-Valle[1982] : 'Any diagram of $0\nu\beta\beta$ → Majorana $\nu$'

Possible Lorentz violation: shifts $2\nu\beta\beta$ spectrum

[Checked on 136Xe, null result.]



# Where could neutrinos gain masses from?



$$\mathcal{L}_N^{\mathrm{M}} = \frac{\mathrm{i}}{2}\overline{N_I^{\mathrm{R}}}\partial\!\!\!/ N_I^{\mathrm{R}} \boxed{- y_{I\alpha}\overline{N_I^{\mathrm{R}}}\tilde{\phi}^{\dagger} L_\alpha} - \boxed{\frac{1}{2}\overline{N_I^{\mathrm{L}}} M_{IJ} (N_J^{\mathrm{L}})^{\mathrm{C}}} + \mathrm{H.c.}$$

<ins>Dirac way</ins>: coupling with Higgs field (just like other leptons gets mass through SSB.

→ conserves lepton number (like all other known interactions)

Leads to $y_\nu \sim O(10^{-12})$, based on limits of $m_{\nu[exp]}$ and VEV. Existence of heavy RH $\nu$ could make this better.

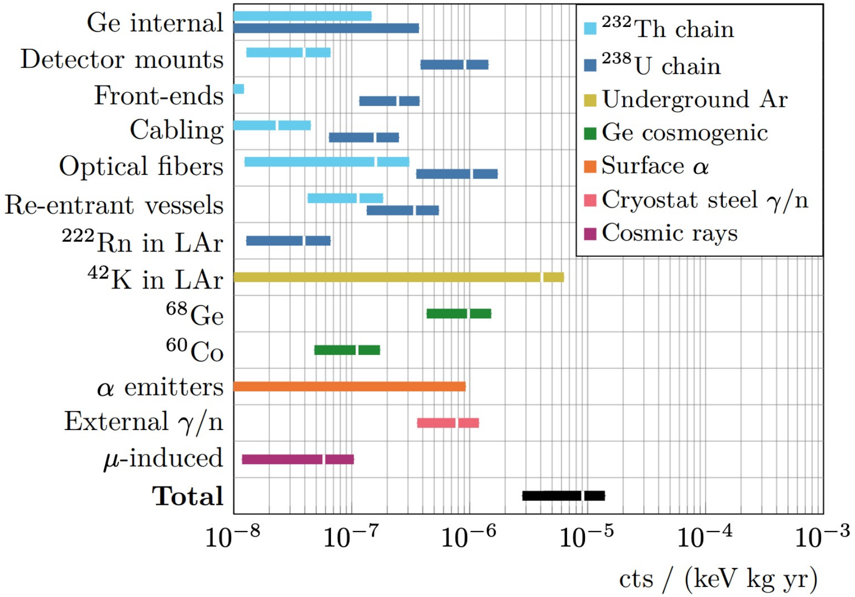
(But other ones (e.g. electrons') are ~O(1) 🤔)

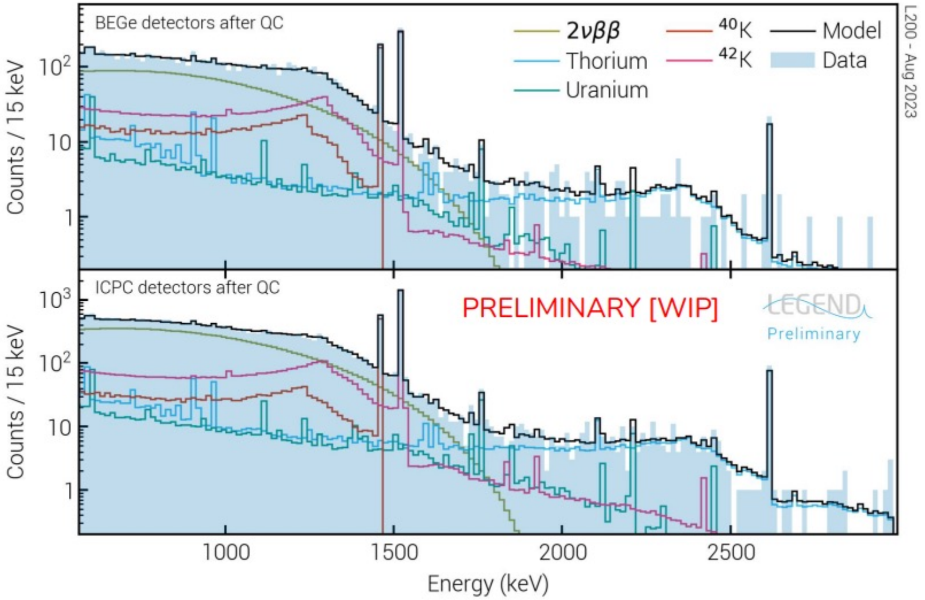
<ins>Majorana way</ins>: No Higgs coupling required, so can explain ~any value of $m_\nu$!

$\bar{\nu}_L \nu_L^C$ can be $\neq 0$, since $\boldsymbol{\nu_L^C} = \mathrm{CP}(\nu_L) = C(\nu_R) = \boldsymbol{\nu_R}$ (since $\nu$s are chargeless. So no *need* of $\nu_R$, but can accommodate that if needed.)

Violates Lepton number conservation 😬 (no known interaction does that, but not prohibited either! 🤔)

Majorana →. $\psi^C = (\psi_L + \psi_L^C)^C = \psi_L^C + \psi_L = \psi$ → particle = anti-particle





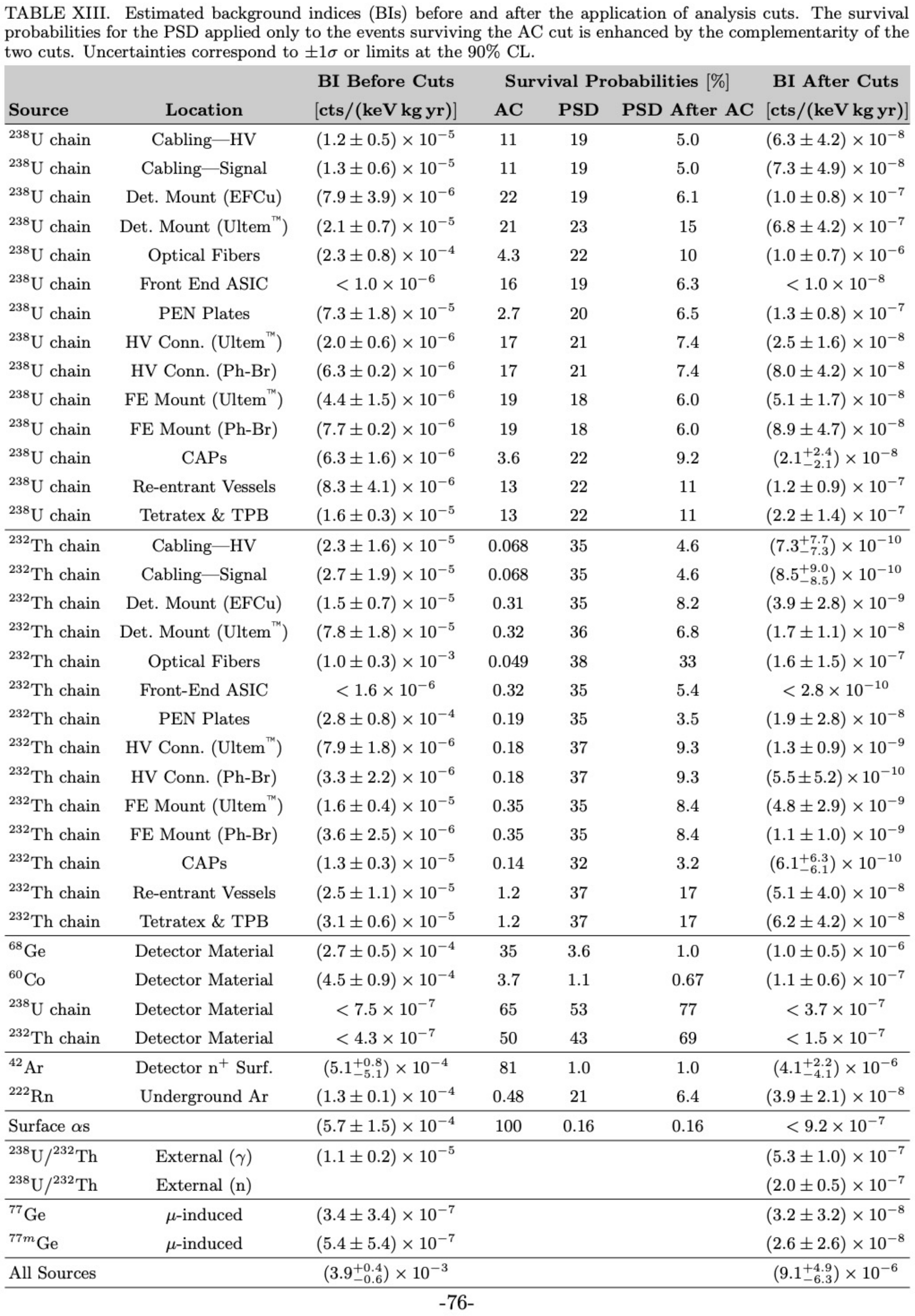


TABLE XIII. Estimated background indices (BIs) before and after the application of analysis cuts. The survival probabilities for the PSD applied only to the events surviving the AC cut is enhanced by the complementarity of the two cuts. Uncertainties correspond to ±1$\sigma$ or limits at the 90% CL.

| | | **BI Before Cuts** | **Survival Probabilities [%]** | | | **BI After Cuts** |
|---|---|---|---|---|---|---|
| **Source** | **Location** | **[cts/(keV kg yr)]** | **AC** | **PSD** | **PSD After AC** | **[cts/(keV kg yr)]** |
| $^{238}$U chain | Cabling—HV | $(1.2 \pm 0.5) \times 10^{-5}$ | 11 | 19 | 5.0 | $(6.3 \pm 4.2) \times 10^{-8}$ |
| $^{238}$U chain | Cabling—Signal | $(1.3 \pm 0.6) \times 10^{-5}$ | 11 | 19 | 5.0 | $(7.3 \pm 4.9) \times 10^{-8}$ |
| $^{238}$U chain | Det. Mount (EFCu) | $(7.9 \pm 3.9) \times 10^{-6}$ | 22 | 19 | 6.1 | $(1.0 \pm 0.8) \times 10^{-7}$ |
| $^{238}$U chain | Det. Mount (Ultem™) | $(2.1 \pm 0.7) \times 10^{-5}$ | 21 | 23 | 15 | $(6.8 \pm 4.2) \times 10^{-7}$ |
| $^{238}$U chain | Optical Fibers | $(2.3 \pm 0.8) \times 10^{-4}$ | 4.3 | 22 | 10 | $(1.0 \pm 0.7) \times 10^{-6}$ |
| $^{238}$U chain | Front End ASIC | $< 1.0 \times 10^{-6}$ | 16 | 19 | 6.3 | $< 1.0 \times 10^{-8}$ |
| $^{238}$U chain | PEN Plates | $(7.3 \pm 1.8) \times 10^{-5}$ | 2.7 | 20 | 6.5 | $(1.3 \pm 0.8) \times 10^{-7}$ |
| $^{238}$U chain | HV Conn. (Ultem™) | $(2.0 \pm 0.6) \times 10^{-6}$ | 17 | 21 | 7.4 | $(2.5 \pm 1.6) \times 10^{-8}$ |
| $^{238}$U chain | HV Conn. (Ph-Br) | $(6.3 \pm 0.2) \times 10^{-6}$ | 17 | 21 | 7.4 | $(8.0 \pm 4.2) \times 10^{-8}$ |
| $^{238}$U chain | FE Mount (Ultem™) | $(4.4 \pm 1.5) \times 10^{-6}$ | 19 | 18 | 6.0 | $(5.1 \pm 1.7) \times 10^{-8}$ |
| $^{238}$U chain | FE Mount (Ph-Br) | $(7.7 \pm 0.2) \times 10^{-6}$ | 19 | 18 | 6.0 | $(8.9 \pm 4.7) \times 10^{-8}$ |
| $^{238}$U chain | CAPs | $(6.3 \pm 1.6) \times 10^{-6}$ | 3.6 | 22 | 9.2 | $(2.1^{+2.4}_{-2.1}) \times 10^{-8}$ |
| $^{238}$U chain | Re-entrant Vessels | $(8.3 \pm 4.1) \times 10^{-6}$ | 13 | 22 | 11 | $(1.2 \pm 0.9) \times 10^{-7}$ |
| $^{238}$U chain | Tetratex & TPB | $(1.6 \pm 0.3) \times 10^{-5}$ | 13 | 22 | 11 | $(2.2 \pm 1.4) \times 10^{-7}$ |
| $^{232}$Th chain | Cabling—HV | $(2.3 \pm 1.6) \times 10^{-5}$ | 0.068 | 35 | 4.6 | $(7.3^{+7.7}_{-7.3}) \times 10^{-10}$ |
| $^{232}$Th chain | Cabling—Signal | $(2.7 \pm 1.9) \times 10^{-5}$ | 0.068 | 35 | 4.6 | $(8.5^{+9.0}_{-8.5}) \times 10^{-10}$ |
| $^{232}$Th chain | Det. Mount (EFCu) | $(1.5 \pm 0.7) \times 10^{-5}$ | 0.31 | 35 | 8.2 | $(3.9 \pm 2.8) \times 10^{-9}$ |
| $^{232}$Th chain | Det. Mount (Ultem™) | $(7.8 \pm 1.8) \times 10^{-5}$ | 0.32 | 36 | 6.8 | $(1.7 \pm 1.1) \times 10^{-8}$ |
| $^{232}$Th chain | Optical Fibers | $(1.0 \pm 0.3) \times 10^{-3}$ | 0.049 | 38 | 33 | $(1.6 \pm 1.5) \times 10^{-7}$ |
| $^{232}$Th chain | Front-End ASIC | $< 1.6 \times 10^{-6}$ | 0.32 | 35 | 5.4 | $< 2.8 \times 10^{-10}$ |
| $^{232}$Th chain | PEN Plates | $(2.8 \pm 0.8) \times 10^{-4}$ | 0.19 | 35 | 3.5 | $(1.9 \pm 2.8) \times 10^{-8}$ |
| $^{232}$Th chain | HV Conn. (Ultem™) | $(7.9 \pm 1.8) \times 10^{-6}$ | 0.18 | 37 | 9.3 | $(1.3 \pm 0.9) \times 10^{-9}$ |
| $^{232}$Th chain | HV Conn. (Ph-Br) | $(3.3 \pm 2.2) \times 10^{-6}$ | 0.18 | 37 | 9.3 | $(5.5 \pm 5.2) \times 10^{-10}$ |
| $^{232}$Th chain | FE Mount (Ultem™) | $(1.6 \pm 0.4) \times 10^{-5}$ | 0.35 | 35 | 8.4 | $(4.8 \pm 2.9) \times 10^{-9}$ |
| $^{232}$Th chain | FE Mount (Ph-Br) | $(3.6 \pm 2.5) \times 10^{-6}$ | 0.35 | 35 | 8.4 | $(1.1 \pm 1.0) \times 10^{-9}$ |
| $^{232}$Th chain | CAPs | $(1.3 \pm 0.3) \times 10^{-5}$ | 0.14 | 32 | 3.2 | $(6.1^{+6.3}_{-6.1}) \times 10^{-10}$ |
| $^{232}$Th chain | Re-entrant Vessels | $(2.5 \pm 1.1) \times 10^{-5}$ | 1.2 | 37 | 17 | $(5.1 \pm 4.0) \times 10^{-8}$ |
| $^{232}$Th chain | Tetratex & TPB | $(3.1 \pm 0.6) \times 10^{-5}$ | 1.2 | 37 | 17 | $(6.2 \pm 4.2) \times 10^{-8}$ |
| $^{68}$Ge | Detector Material | $(2.7 \pm 0.5) \times 10^{-4}$ | 35 | 3.6 | 1.0 | $(1.0 \pm 0.5) \times 10^{-6}$ |
| $^{60}$Co | Detector Material | $(4.5 \pm 0.9) \times 10^{-4}$ | 3.7 | 1.1 | 0.67 | $(1.1 \pm 0.6) \times 10^{-7}$ |
| $^{238}$U chain | Detector Material | $< 7.5 \times 10^{-7}$ | 65 | 53 | 77 | $< 3.7 \times 10^{-7}$ |
| $^{232}$Th chain | Detector Material | $< 4.3 \times 10^{-7}$ | 50 | 43 | 69 | $< 1.5 \times 10^{-7}$ |
| $^{42}$Ar | Detector n$^+$ Surf. | $(5.1^{+0.8}_{-5.1}) \times 10^{-4}$ | 81 | 1.0 | 1.0 | $(4.1^{+2.2}_{-4.1}) \times 10^{-6}$ |
| $^{222}$Rn | Underground Ar | $(1.3 \pm 0.1) \times 10^{-4}$ | 0.48 | 21 | 6.4 | $(3.9 \pm 2.1) \times 10^{-8}$ |
| Surface $\alpha$s | | $(5.7 \pm 1.5) \times 10^{-4}$ | 100 | 0.16 | 0.16 | $< 9.2 \times 10^{-7}$ |
| $^{238}$U/$^{232}$Th | External ($\gamma$) | $(1.1 \pm 0.2) \times 10^{-5}$ | | | | $(5.3 \pm 1.0) \times 10^{-7}$ |
| $^{238}$U/$^{232}$Th | External (n) | | | | | $(2.0 \pm 0.5) \times 10^{-7}$ |
| $^{77}$Ge | $\mu$-induced | $(3.4 \pm 3.4) \times 10^{-7}$ | | | | $(3.2 \pm 3.2) \times 10^{-8}$ |
| $^{77m}$Ge | $\mu$-induced | $(5.4 \pm 5.4) \times 10^{-7}$ | | | | $(2.6 \pm 2.6) \times 10^{-8}$ |
| All Sources | | $(3.9^{+0.4}_{-0.6}) \times 10^{-3}$ | | | | $(9.1^{+4.9}_{-6.3}) \times 10^{-6}$ |

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