Neutrinoless Double Beta Decay: Current results and future outlook

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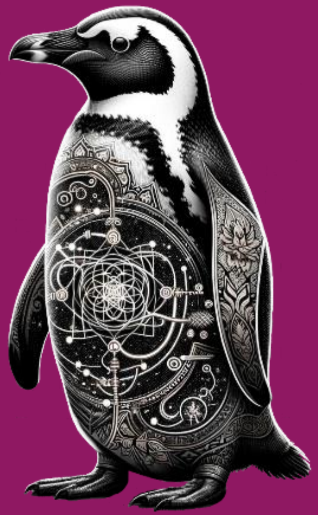

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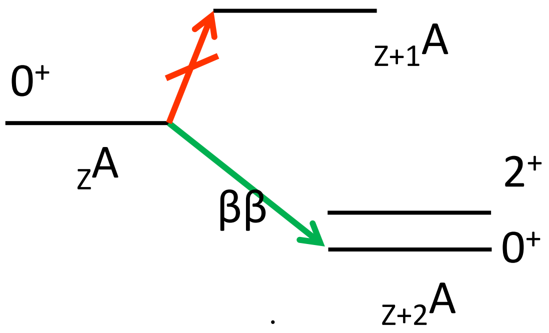
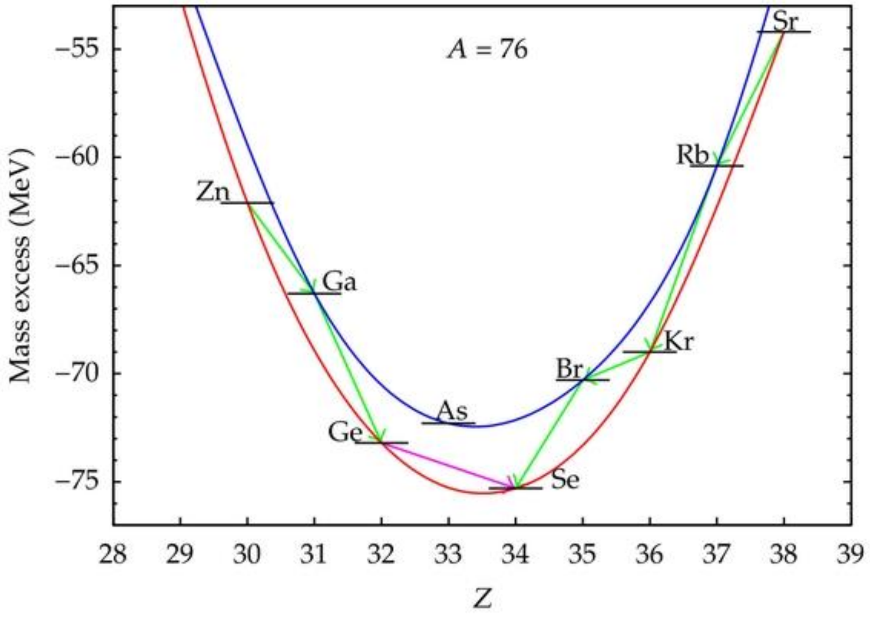
Double Beta Decays

In 1935, Maria Geoppert-Mayer first proposed the idea of 2^{nd} order weak decays known as Double Beta ($\beta\beta$) decays

Possible in 35 even – even nuclei, where β decay is energy/spin suppressed.

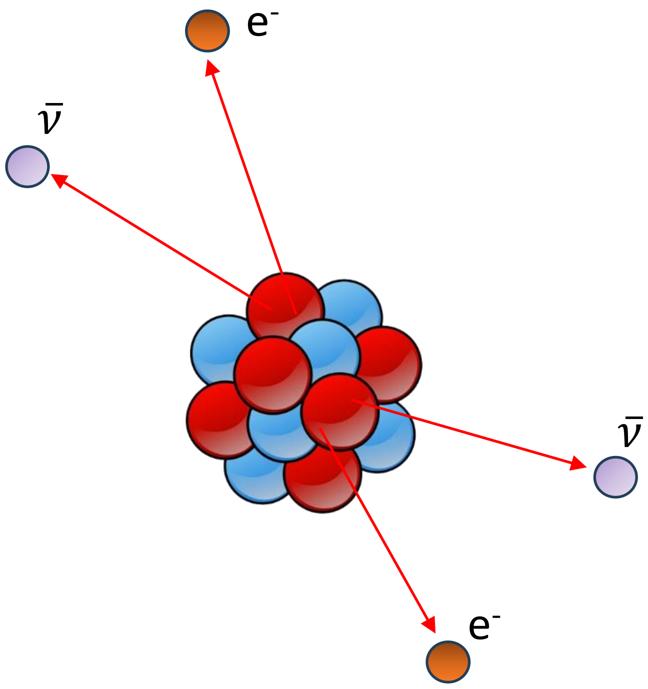


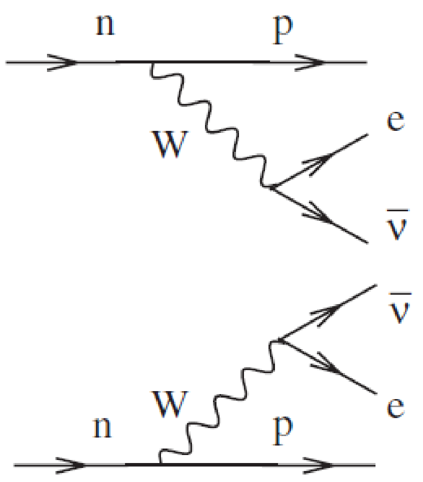
From J. Menendez's thesis



Double Beta Decays

2νββ
A rare decay, allowed by the standard model





2νββ has been **observed** in 12 nuclei, $T_{1/2}^{2\nu}$ ranges from $10^{18} - 10^{24}$y.

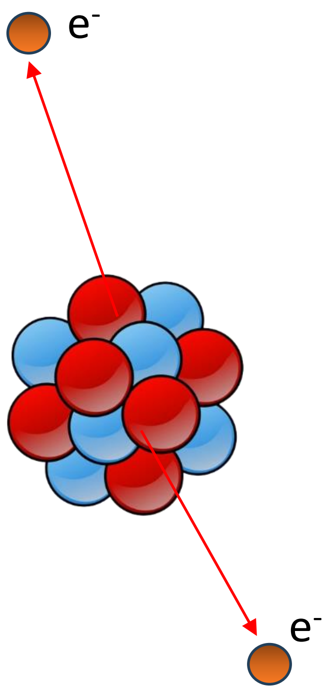
^{48}Ca, ^{76}Ge, ^{82}Se , ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128,130}Te, ^{136}Xe, ^{130}Ba, ^{150}Nd, ^{238}U

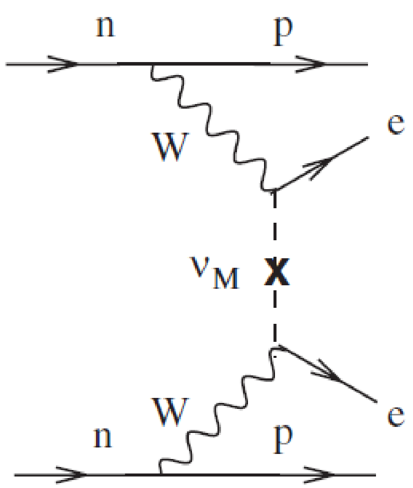
Neutrinoless Double Beta Decay

Neutrinos are the only known standard model particles, which can potentially be Majorana fermions (i.e., the neutrino could be its own antiparticle). In 1939, W. H. Furry proposed a fascinating variant of ββ decays in which **no neutrinos** are emitted, possible due to its Majorana nature.

0νββ

A rare lepton number violating process, **not allowed** by the standard model



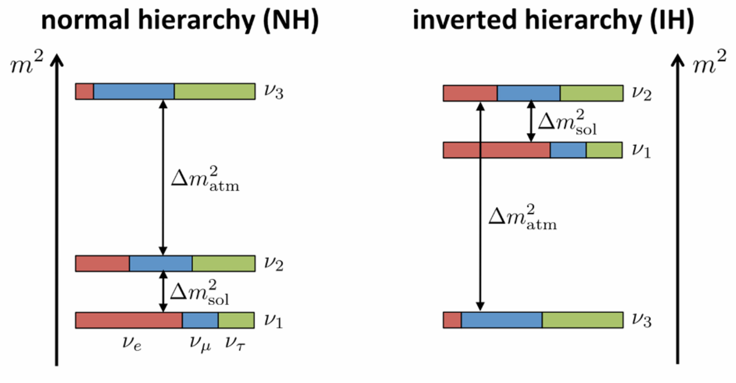


Yet to be observed!

A window to physics beyond the standard model

Implications, if 0νββ is observed:

- Smoking gun evidence for the Majorana nature of the neutrino (i.e., the neutrino is its own antiparticle).
- Lepton Number violation $\Delta L = 2$.
- Can tell us more about the matter-antimatter asymmetry of the universe.
- Sensitive to the absolute mass of the neutrino.

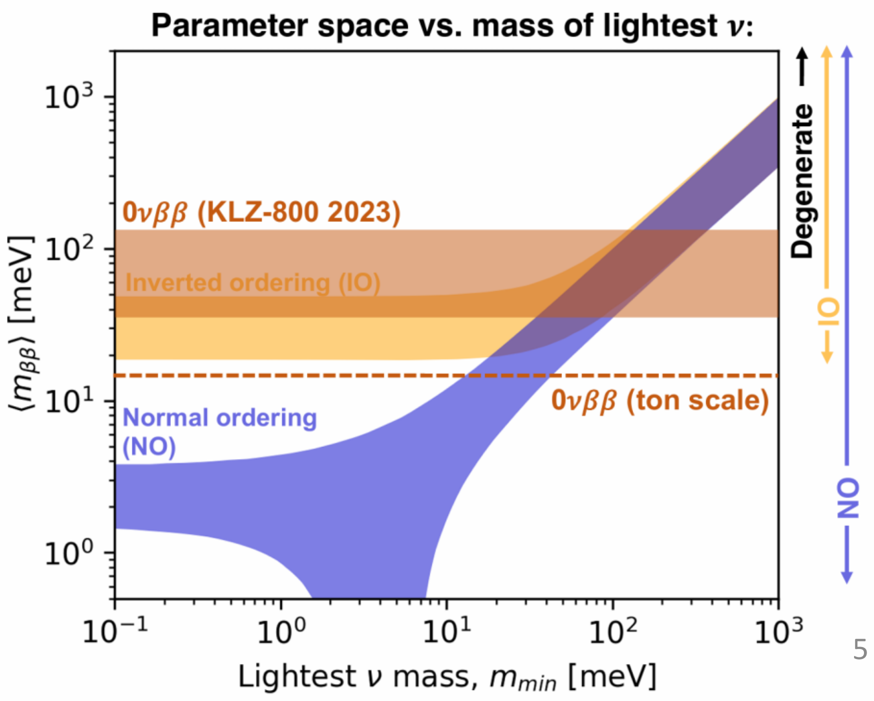


Best sensitivity limits at (90% C.L.) for current 0νββ experiments:

KamLANDZen (^{136}Xe): $T_{1/2}^{0\nu\beta\beta} > 2.3 \times 10^{26}\ y$,
$< m > < 0.036 - 0.156$ eV

GERDA (^{76}Ge): $T_{1/2}^{0\nu\beta\beta} > 1.8 \times 10^{26}\ y$,
$< \mathrm{m} > < 0.08 - 0.182$ eV

CUORE (^{130}Te): $T_{1/2}^{0\nu\beta\beta} > 3.3 \times 10^{25}\ y$,
$< m > < 0.075 - 0.255$ eV



Interpreting the half life

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q,Z) g_A^4 |M_{0\nu}|^2 \frac{< m_{\beta\beta} >^2}{m_e^2}$$

Phase Space NME Mass

$$\langle m_{\beta\beta} \rangle = \left| \sum |U_{ei}|^2 e^{i\phi_i} m_i \right|$$

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix elements

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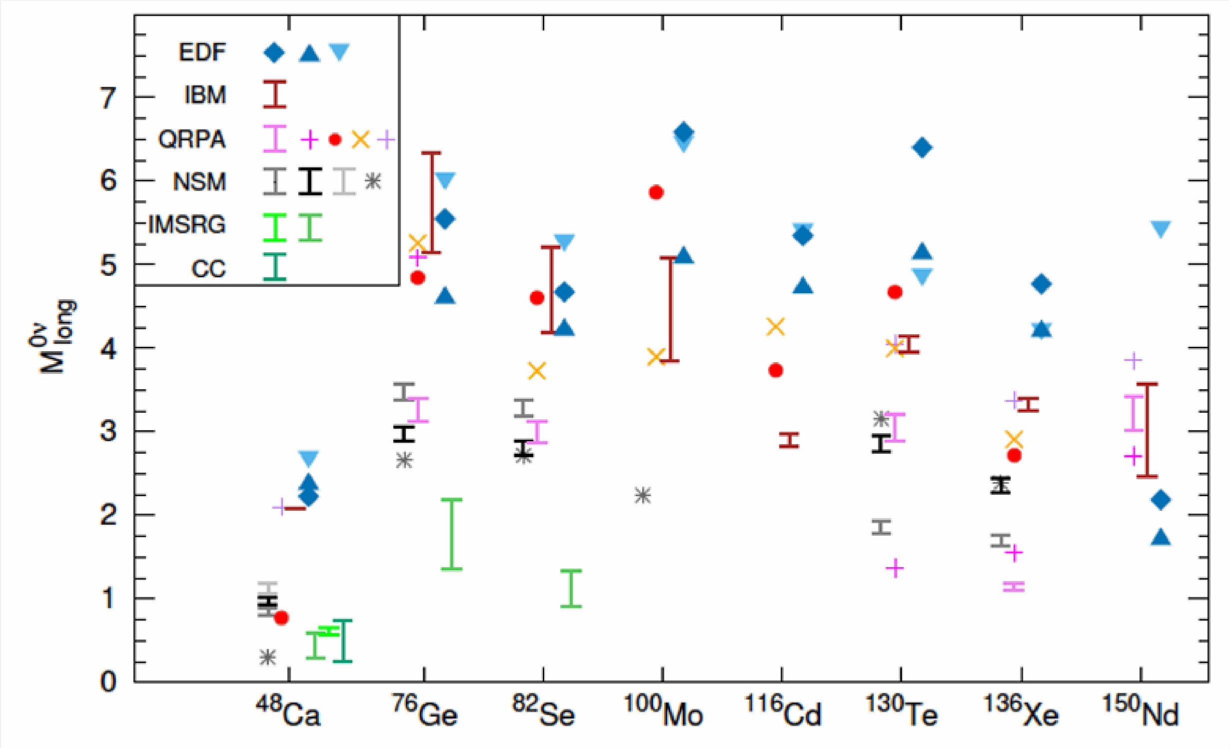
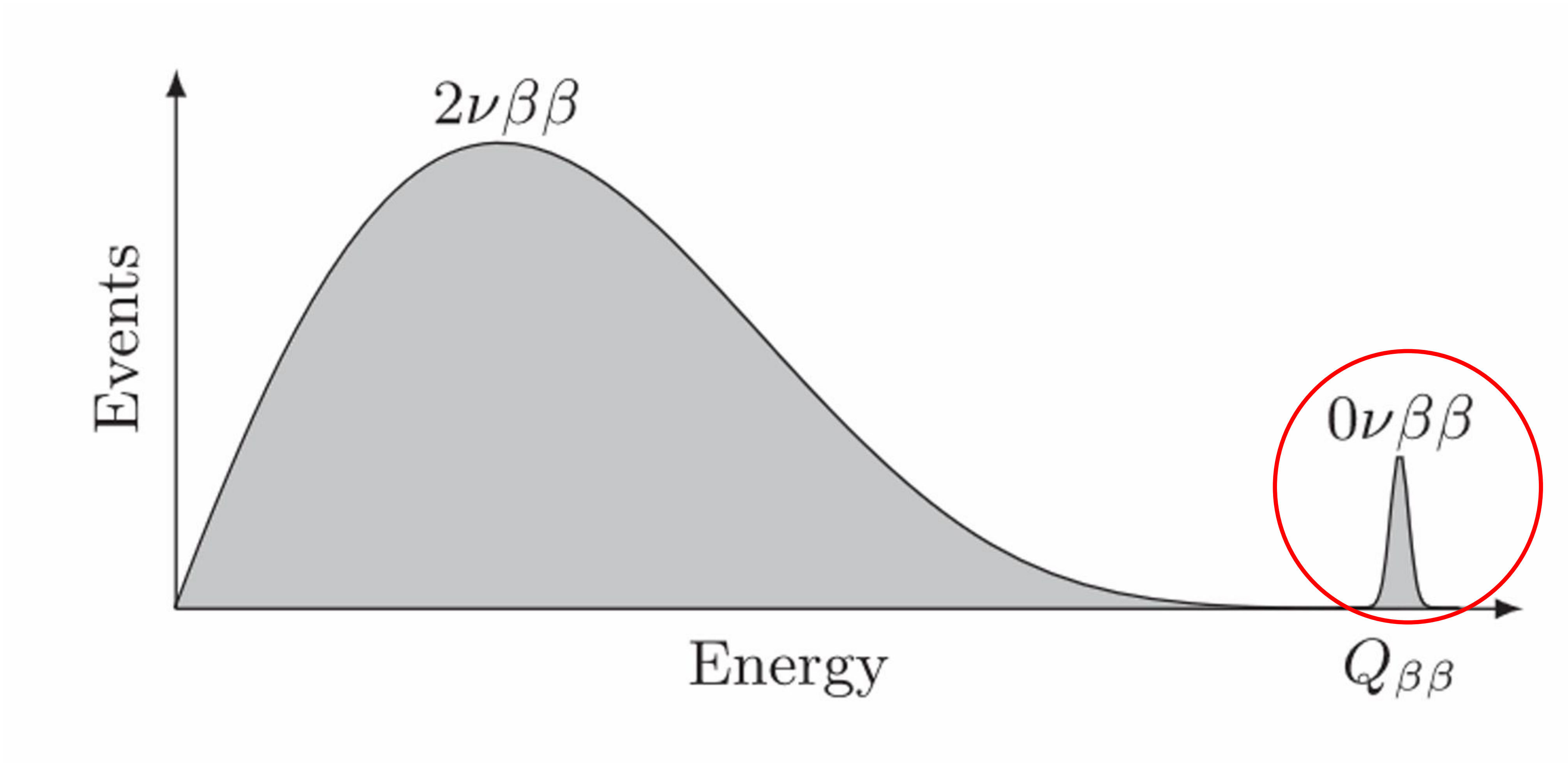


- Nuclear Matrix Element (NME) is a model dependent input to the result, required to interpret the results of the experiment.
- Historically, the nuclear matrix element (NME) has large uncertainty, having a scatter of 2 – 3x between different models.
- A lot of recent progress on the theoretical front to better constrain the value!

Experimental Design Considerations

Experimental signature: peak at $Q_{\beta\beta}$.



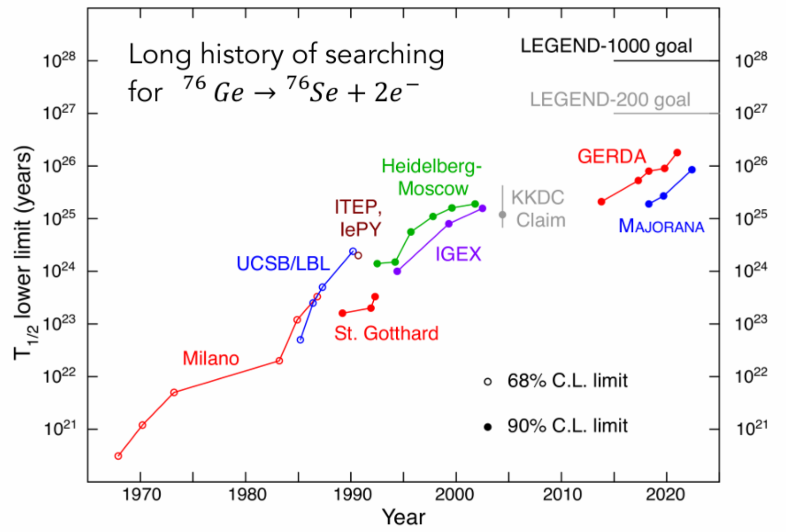
Sum electron energy spectrum

Experimental Design Considerations

Finite background $T^{0\nu}_{1/2} > \frac{\ln 2 \, N_A \varepsilon i}{A k_{CL}} \sqrt{\frac{Mt}{BI \, \Delta E}}$

Mass Livetime

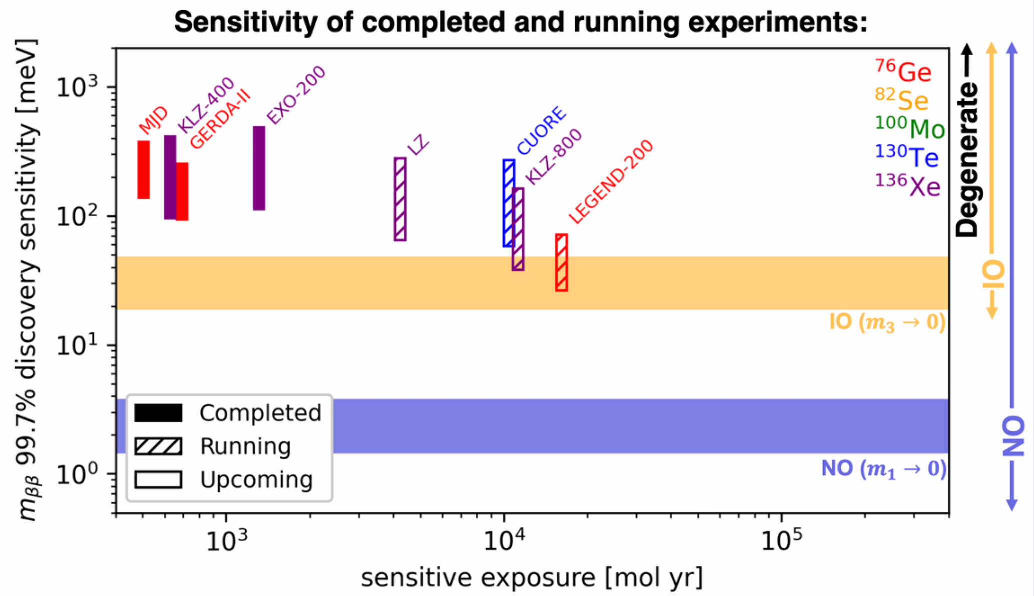
For e.g.,



Maximizing exposure:

- Large mass
- Long operational time

Aside from the innovations, one of the main factors driving the sensitivity of the experiment.



Experimental Design Considerations

Finite background $T_{1/2}^{0\nu} > \frac{ln2\, N_A \varepsilon i}{A k_{CL}} \sqrt{\frac{Mt}{BI\, \Delta E}}$

Isotopic abundance

Isotope considerations:

- Large isotopic abundance, either naturally available or through accessible isotopic enrichment
- Large $Q_{\beta\beta}$
- Bonus points if the $Q_{\beta\beta}$ > 2614 keV, since it is above the prominent gamma lines in the natural radioactive backgrounds.

$\beta\beta$ decay $^{A}X \rightarrow {}^{A}Y$	$Q_{\beta\beta}$ keV	i %
$^{48}Ca \rightarrow {}^{48}Ti$	4268.1 ± 0.1	0.2
$^{76}Ge \rightarrow {}^{76}Se$	2039.06 ± 0.02	7.7
$^{82}Se \rightarrow {}^{82}Kr$	2997.9 ± 0.5	8.7
$^{96}Zr \rightarrow {}^{96}Mo$	3356.0 ± 0.2	2.8
$^{100}Mo \rightarrow {}^{100}Ru$	3034.4 ± 0.5	9.8
$^{110}Pd \rightarrow {}^{110}Cd$	2017.1 ± 0.7	11.7
$^{116}Cd \rightarrow {}^{116}Sn$	2813.5 ± 0.2	7.5
$^{124}Sn \rightarrow {}^{124}Te$	2291.1 ± 1.8	5.8
$^{130}Te \rightarrow {}^{130}Xe$	2527.51 ± 0.01	34.1
$^{136}Xe \rightarrow {}^{136}Ba$	2457.8 ± 0.3	8.9
$^{150}Nd \rightarrow {}^{150}Sn$	3371.4 ± 1.8	5.6

Experimental Design Considerations

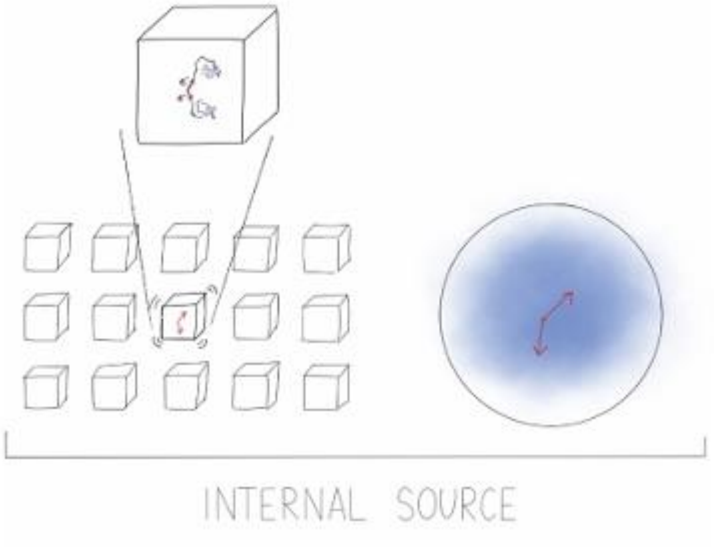
Finite background $$T_{1/2}^{0\nu} > \frac{\ln 2\, N_A \varepsilon i}{A k_{CL}} \sqrt{\frac{Mt}{B I \Delta E}}$$

Efficiency

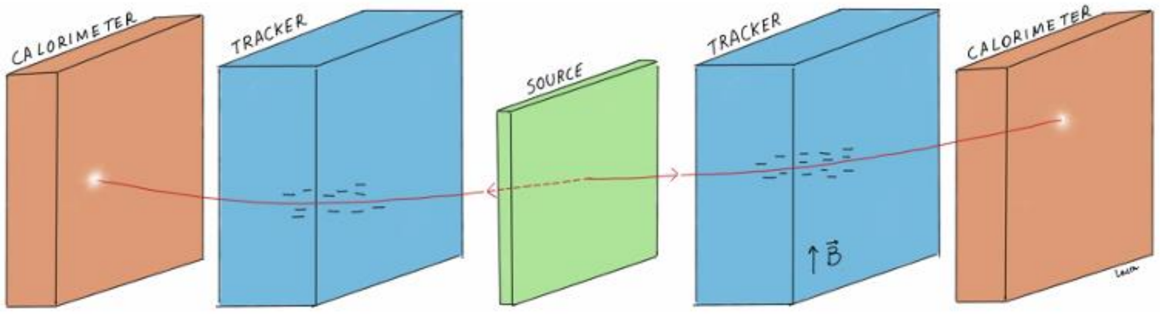
Energy resolution

Detector properties:

- High detection efficiency for the electrons
- Good energy resolution of the detector



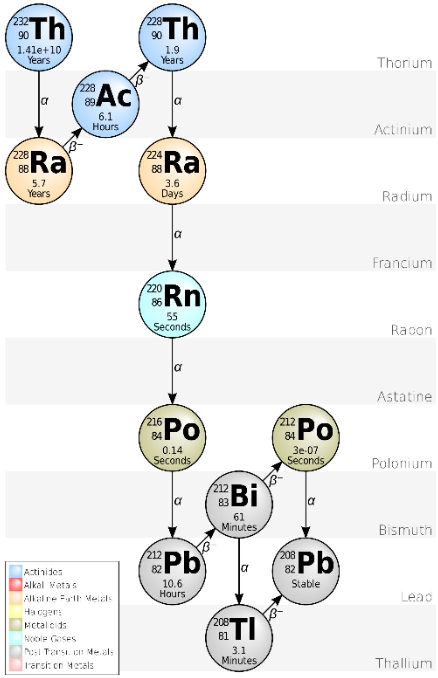
Preferred for its higher efficiency

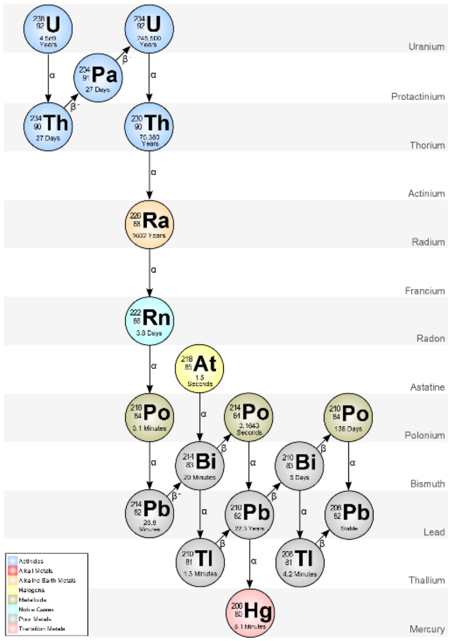


External source not preferable due to lower efficiency, but has its own advantages (can be used to study the topology)

Background sources

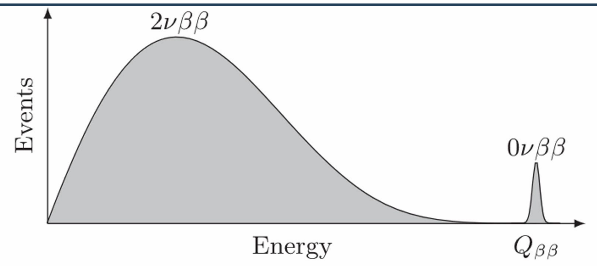
Natural Radioactive Backgrounds (Th, U, K, …)





Cosmogenics

Alpha and Neutron Activation



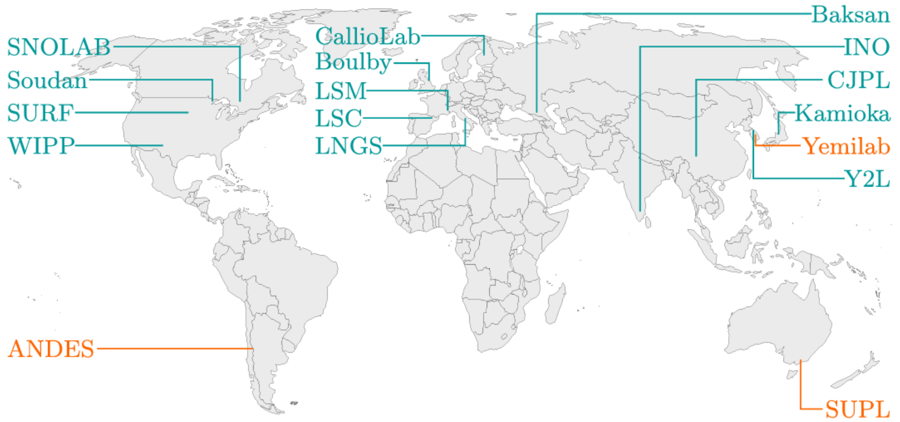
Even the rare process ββ will be a background for 0νββ

$$\frac{dN}{dt}_{0\nu\beta\beta} \propto Q_{\beta\beta}{}^{5} \qquad \frac{dN}{dt}_{2\nu\beta\beta} \propto Q_{\beta\beta}{}^{11}$$

Experimental Design Considerations

Finite background $$T^{0\nu}_{1/2} > \frac{\ln 2\, N_A \varepsilon i}{A k_{CL}} \sqrt{\frac{Mt}{BI\,\Delta E}}$$

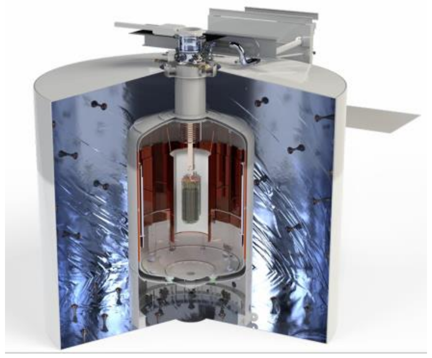
Background Index



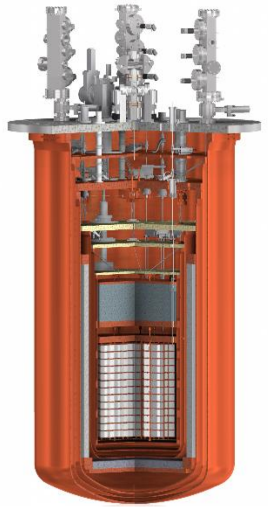
Background reduction efforts:

- Underground labs to reduce the cosmogenic backgrounds.
- Careful materials transport, to avoid activation.

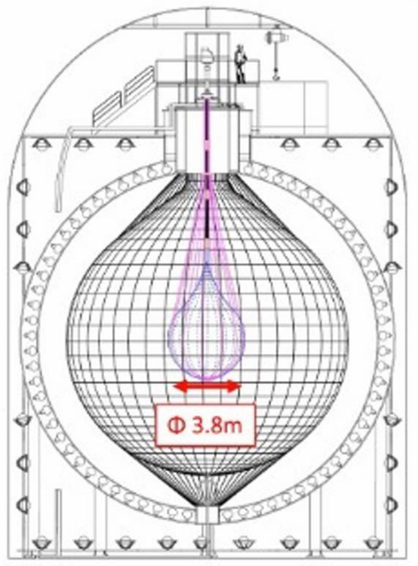
- Materials handling and cleanliness
- Strict radiopurity constraints



LAr (high Z, active)



Pb (high Z)



Fiducialization

Shielding and active materials

Signal Discrimination Techniques

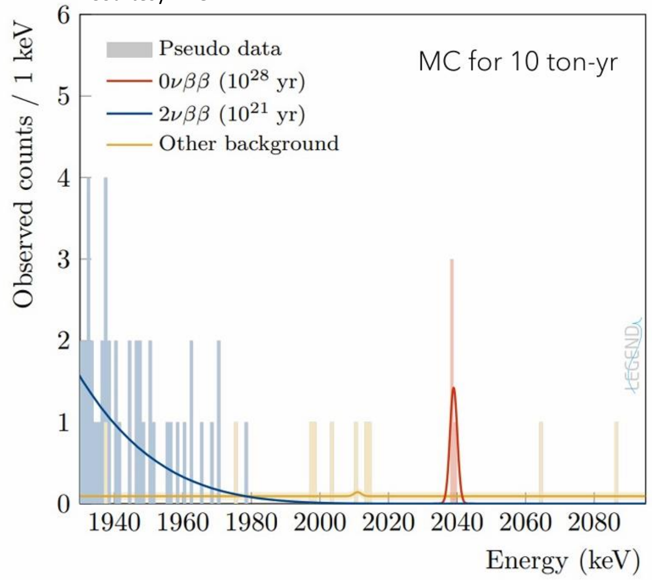
Experimental Design Considerations

"Background-free" $$T^{0\nu}_{1/2} = \frac{\ln 2\, N_A \varepsilon i M t}{A N_{obs}}$$

Finite background $$T^{0\nu}_{1/2} > \frac{\ln 2\, N_A \varepsilon i}{A k_{CL}} \sqrt{\frac{Mt}{BI\ \Delta E}}$$

Sensitivity scales linearly with exposure in the scenario in the background-free regime

Courtesy: LEGEND



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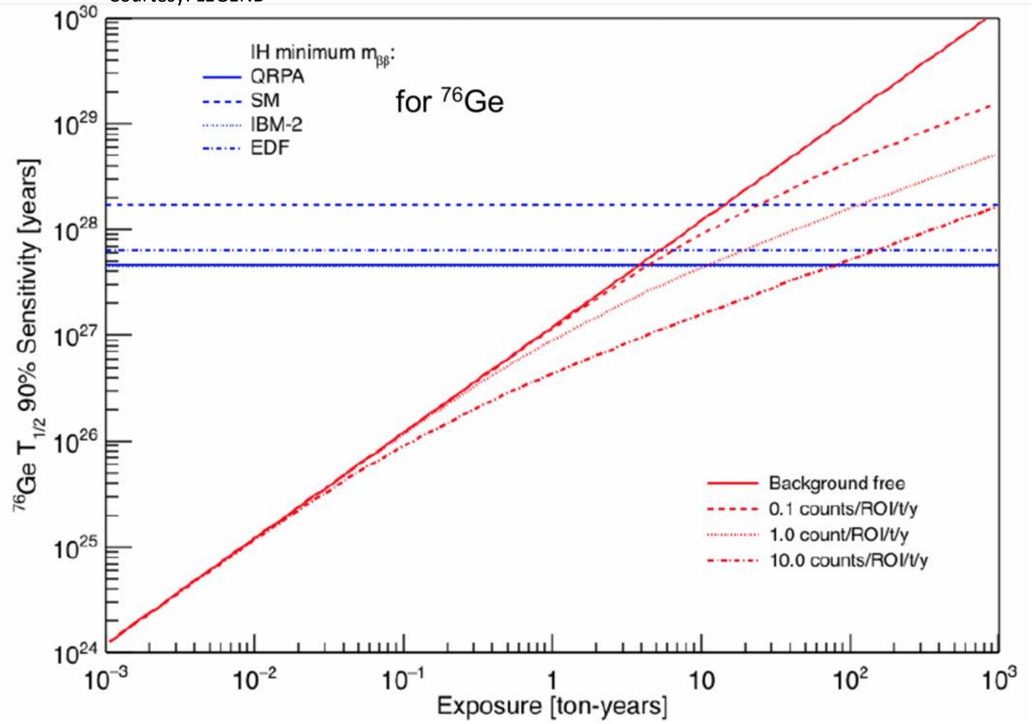
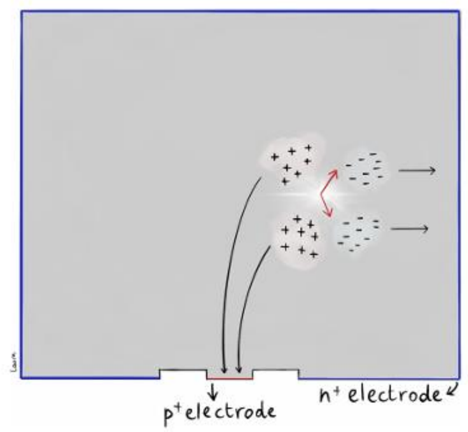
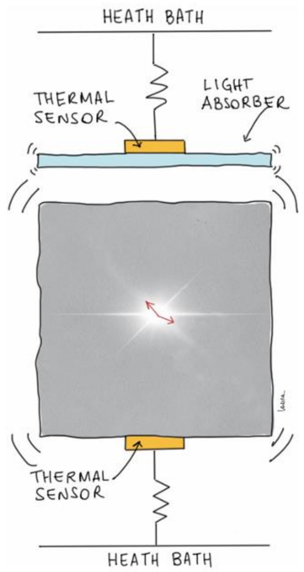
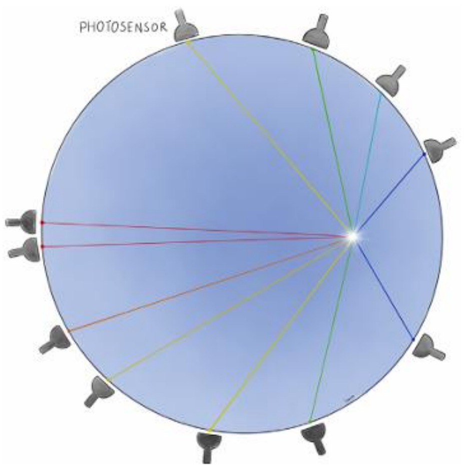


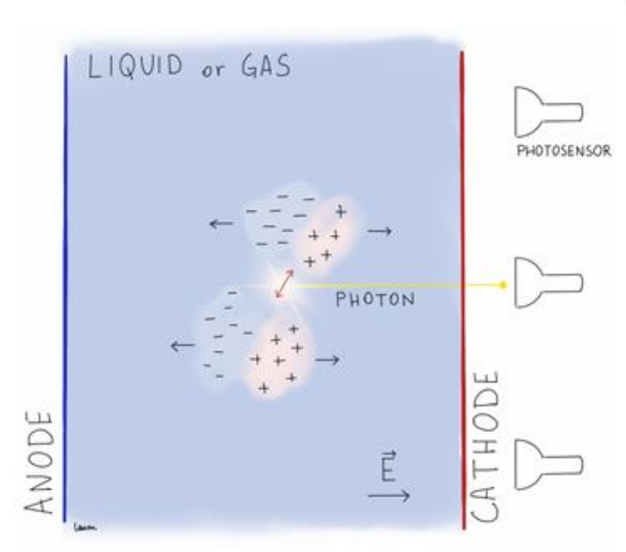
Would be capable of a discovery with just a handful of counts!!

Landscape of NDBD experiments









Ionization detector

Semiconducting material (e.g. Ge)

Notable Pros:

- Great energy resolution.
- Modular and scalable to large masses.

Cryogenic Bolometer

Insulator (e.g. TeO_2, LMO, etc.) or superconductor (Sn)

Notable Pros:

- Good energy resolution.
- Modular and scalable to large masses.

Scintillation detector

Should be feasible to load in liquid scintillator

Notable Pros:

- Large mass and often a large loading fraction, leading to large exposures.
- Extremely radiopure.

Time Projection Chamber (TPC)

Liquid or gas should produce both scintillation light + ionization signal

Notable Pros:

- 3D position and energy reconstruction + particle identification

\+ ...

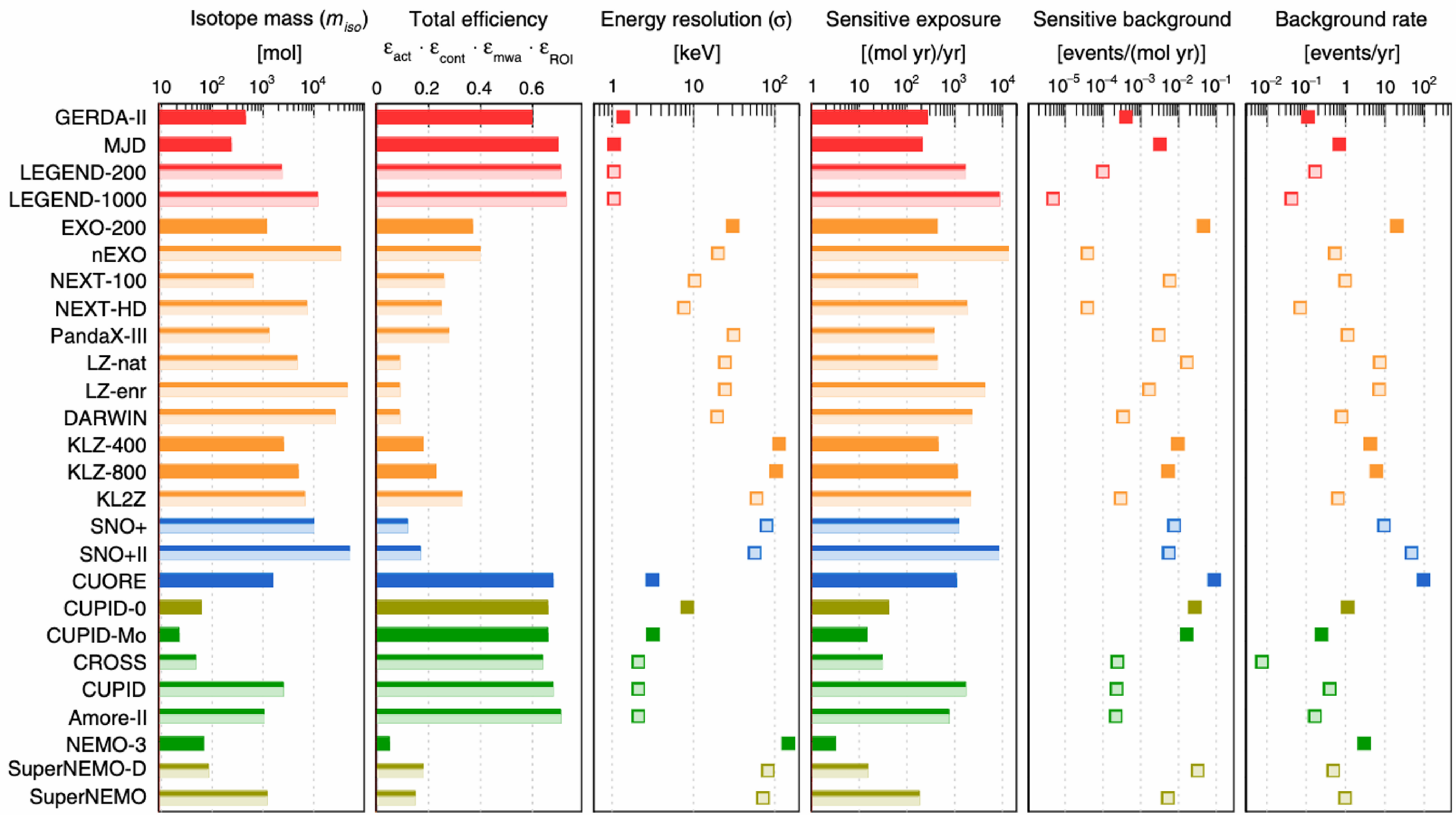
Choice of the isotope and adaptability to a detector technology is a major driving force for the choice of technology used in an experiment.

TABLE IV. Fundamental parameters driving the sensitive background and exposure of recent and future phases of existing experiments. The last two columns report the discovery sensitivity on the $0\nu\beta\beta$-decay half-life for 10 yr of live time and the corresponding sensitivity on $m_{\beta\beta}$ for the range of NMEs specified in Table I. For completed experiments, sensitivities are computed using the reported final exposure. MJD, KLZ, and SuperNEMO-D refer to the MAJORANA DEMONSTRATOR, KamLAND-Zen, and the SuperNEMO Demonstrator, respectively.

Experiment	Isotope	Status	Lab	m_{iso} (mol)	ε_{act} (%)	ε_{cont} (%)	ε_{mva} (%)	σ (keV)	ROI (σ)	ε_{ROI} (%)	$\mathcal{E}$ (mol yr/yr)	$\mathcal{B}$ (events/ mol yr)	λ_b (events/yr)	$T_{1/2}$ (yr)	$m_{\beta\beta}$ (meV)
High-purity Ge detectors (Sec. VI.B)															
GERDA-II	^{76}Ge	Completed	LNGS	4.5×10^2	88	91	79	1.4	−2, 2	95	273	4.2×10^{-4}	1.1×10^{-1}	1.2×10^{26}	93–222
MJD	^{76}Ge	Completed	SURF	3.1×10^2	91	91	86	1.1	−2, 2	95	212	3.3×10^{-3}	7.1×10^{-1}	4.7×10^{25}	149–355
LEGEND-200	^{76}Ge	Construction	LNGS	2.4×10^3	91	91	90	1.1	−2, 2	95	1684	1.0×10^{-4}	1.7×10^{-1}	1.5×10^{27}	27–63
LEGEND-1000	^{76}Ge	Proposed		1.2×10^4	92	92	90	1.1	−2, 2	95	8736	4.9×10^{-6}	4.3×10^{-2}	1.3×10^{28}	9.0–21
Xe time-projection chambers (Sec. VI.C)															
EXO-200	^{136}Xe	Completed	WIPP	1.2×10^3	46	100	84	31	−2, 2	95	438	4.7×10^{-2}	$2.1\times10^{+1}$	2.4×10^{25}	111–477
nEXO	^{136}Xe	Proposed	SNOLAB	3.4×10^4	64	100	66	20	−2, 2	95	13 700	4.0×10^{-5}	5.5×10^{-1}	7.4×10^{27}	6.1–27
NEXT-100	^{136}Xe	Construction	LSC	6.4×10^2	88	76	49	10	−1.0, 1.8	80	167	5.9×10^{-3}	9.9×10^{-1}	7.0×10^{25}	66–281
NEXT-HD	^{136}Xe	Proposed		7.4×10^3	95	89	44	7.7	−0.5, 1.7	65	1809	4.0×10^{-5}	7.2×10^{-2}	2.2×10^{27}	12–50
PandaX-III-200	^{136}Xe	Construction	CJPL	1.3×10^3	77	74	65	31	−1.2, 1.2	76	374	3.0×10^{-3}	$1.1\times10^{+0}$	1.5×10^{26}	45–194
LZ-nat	^{136}Xe	Construction	SURF	4.7×10^3	14	100	80	25	−1.4, 1.4	84	440	1.7×10^{-2}	$7.5\times10^{+0}$	7.2×10^{25}	64–277
LZ-enr	^{136}Xe	Proposed	SURF	4.6×10^4	14	100	80	25	−1.4, 1.4	84	4302	1.7×10^{-3}	$7.3\times10^{+0}$	7.1×10^{26}	20–87
Darwin	^{136}Xe	Proposed		2.7×10^4	13	100	90	20	−1.2, 1.2	76	2312	3.5×10^{-4}	8.0×10^{-1}	1.1×10^{27}	17–72
Large liquid scintillators (Sec. VI.D)															
KLZ-400	^{136}Xe	Completed	Kamioka	2.5×10^3	44	100	97	114	−0.0, 1.4	42	450	9.8×10^{-3}	$4.4\times10^{+0}$	3.3×10^{25}	95–408
KLZ-800	^{136}Xe	Taking data	Kamioka	5.0×10^3	55	100	100	105	−0.0, 1.4	42	1143	5.5×10^{-3}	$6.2\times10^{+0}$	2.0×10^{26}	38–164
KL2Z	^{136}Xe	Proposed	Kamioka	6.7×10^3	80	100	97	60	−0.0, 1.4	42	2176	3.0×10^{-4}	6.5×10^{-1}	1.1×10^{27}	17–71
SNO + I	^{130}Te	Construction	SNOLAB	1.0×10^4	20	100	97	74	−0.5, 1.5	62	1232	7.8×10^{-3}	$9.7\times10^{+0}$	1.8×10^{26}	31–144
SNO + II	^{130}Te	Proposed	SNOLAB	5.1×10^4	27	100	97	57	−0.5, 1.5	62	8521	5.7×10^{-3}	$4.8\times10^{+1}$	5.7×10^{26}	17–81
Cryogenic calorimeters (Sec. VI.E)															
CUORE	^{130}Te	Taking data	LNGS	1.6×10^3	100	88	92	3.2	−1.4, 1.4	84	1088	9.1×10^{-2}	$9.9\times10^{+1}$	5.1×10^{25}	58–270
CUPID-0	^{82}Se	Completed	LNGS	6.2×10	100	81	86	8.5	−2, 2	95	41	2.8×10^{-2}	$1.2\times10^{+0}$	4.4×10^{24}	283–551
CUPID-Mo	^{100}Mo	Completed	LSM	2.3×10	100	76	91	3.2	−2, 2	95	15	1.7×10^{-2}	2.5×10^{-1}	1.7×10^{24}	293–858
CROSS	^{100}Mo	Construction	LSC	4.8×10	100	75	90	2.1	−2, 2	95	31	2.5×10^{-4}	7.6×10^{-3}	4.9×10^{25}	54–160
CUPID	^{100}Mo	Proposed	LNGS	2.5×10^3	100	79	90	2.1	−2, 2	95	1717	2.3×10^{-4}	4.0×10^{-1}	1.1×10^{27}	12–34
AMoRE-II	^{100}Mo	Proposed	Yemilab	1.1×10^3	100	82	91	2.1	−2, 2	95	760	2.2×10^{-4}	1.7×10^{-1}	6.7×10^{26}	15–43
Tracking calorimeters (Sec. VI.F)															
NEMO-3	^{100}Mo	Completed	LSM	6.9×10	100	100	11	148	−1.6, 1.1	42	3	9.4×10^{-1}	$3.0\times10^{+0}$	5.6×10^{23}	505–1485
SuperNEMO-D	^{82}Se	Construction	LSM	8.5×10	100	100	28	83	−4.2, 2.4	64	15	3.3×10^{-2}	5.0×10^{-1}	8.6×10^{24}	201–391
SuperNEMO	^{82}Se	Proposed	LSM	1.2×10^3	100	100	28	72	−4.1, 2.8	54	185	5.3×10^{-3}	9.8×10^{-1}	7.8×10^{25}	67–131

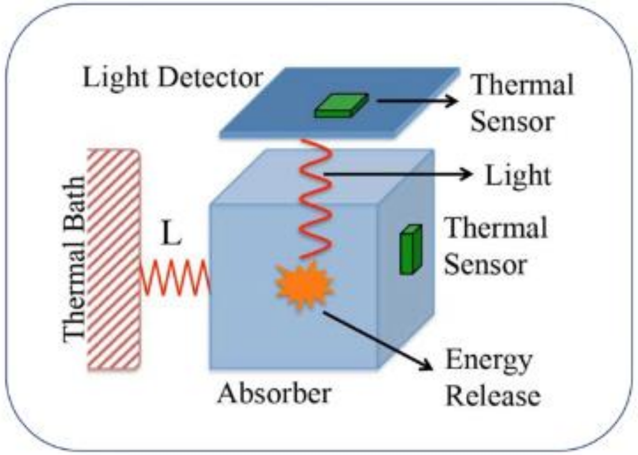
Not a complete list

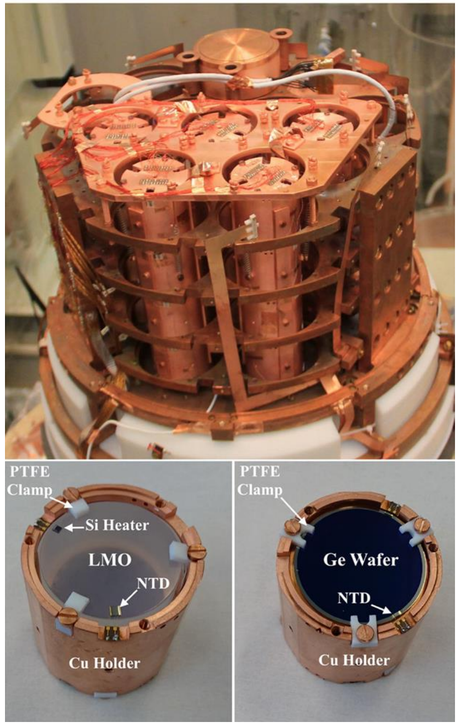
Landscape of NDBD experiments

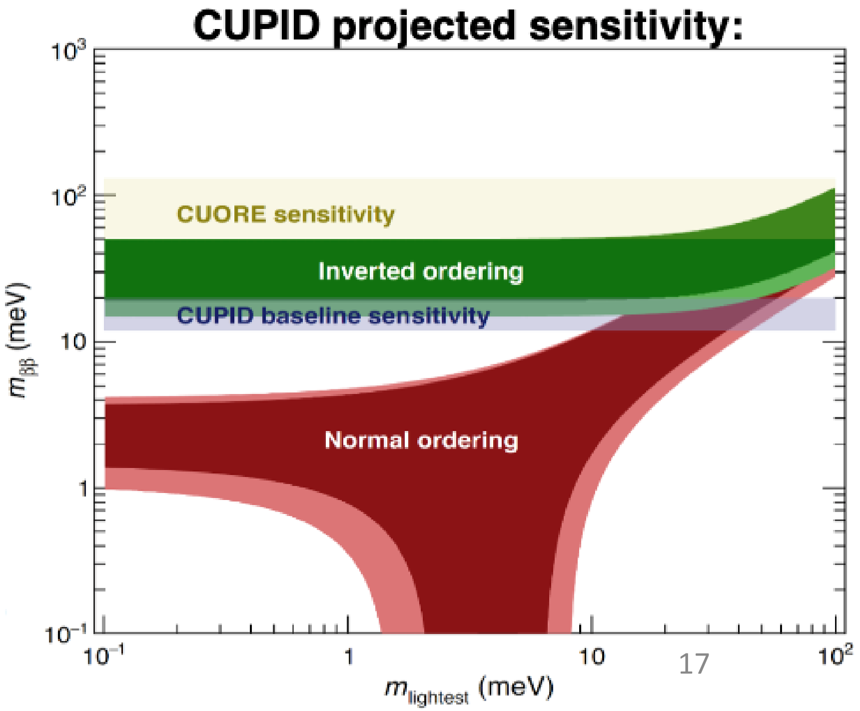


Tonne scale effort – CUPID (^{100}Mo)

- Scintillating Bolometer (heat and light) so discrimination possible
- Makes use of the existing CUORE facility
- High efficiency (detector = source)
- ^{100}Mo has high Q-value above U/Th backgrounds
- CUPID demonstrator complete
- Projected sensitivity
    - $m_{\beta\beta}$ 12-34 meV
    - 10^{27} years







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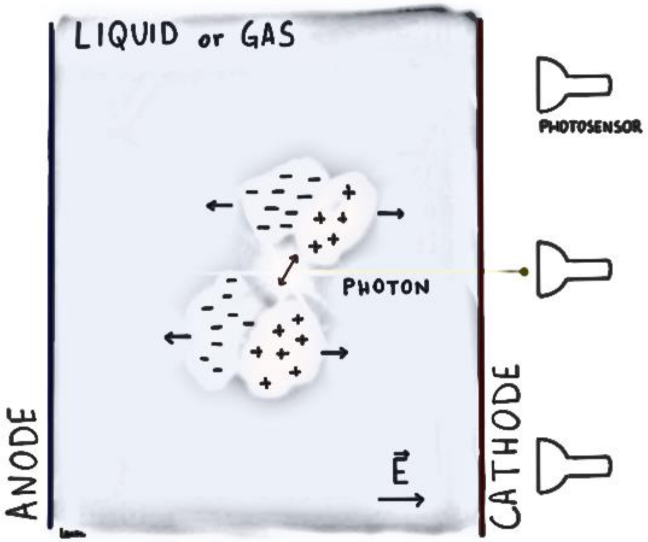
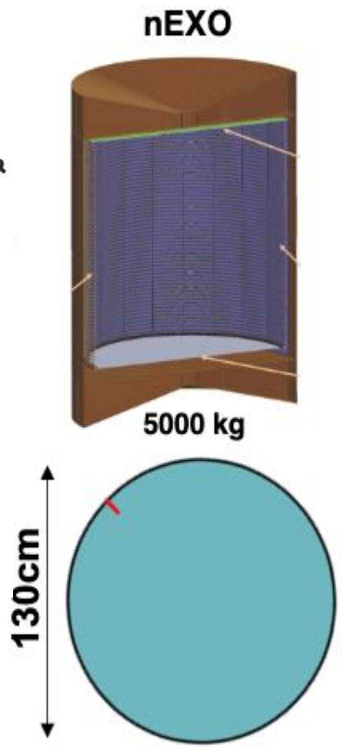
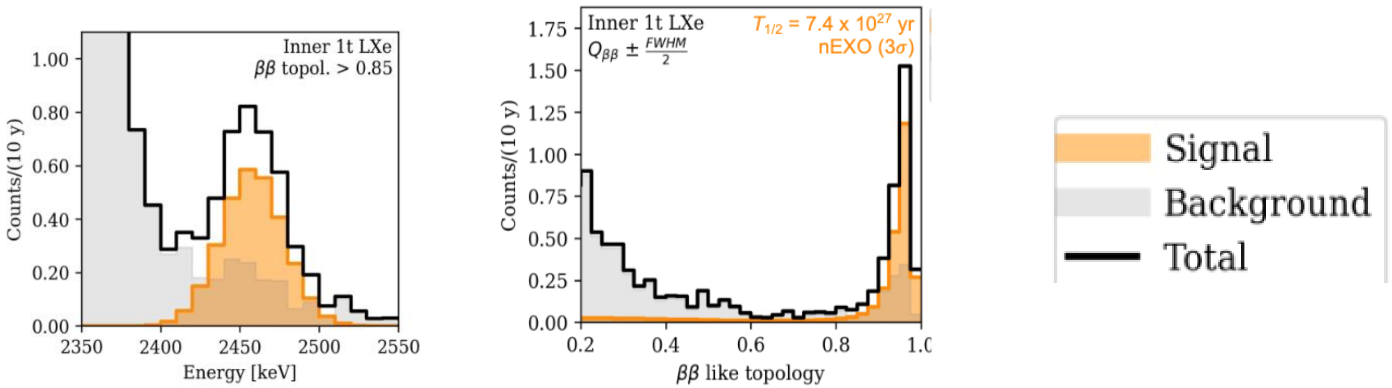
Tonne scale effort – nEXO (^{136}Xe)

- Homogenous liquid ^{enr}Xe TPC
- 5-ton mass
- Large detector backgrounds attenuated in the center
- Powerful background restriction via topology
- Conceptual design in progress
- Projected sensitivity
  - $m_{\beta\beta}$ 6-27 meV
  - 0.7 x 10^{28} years

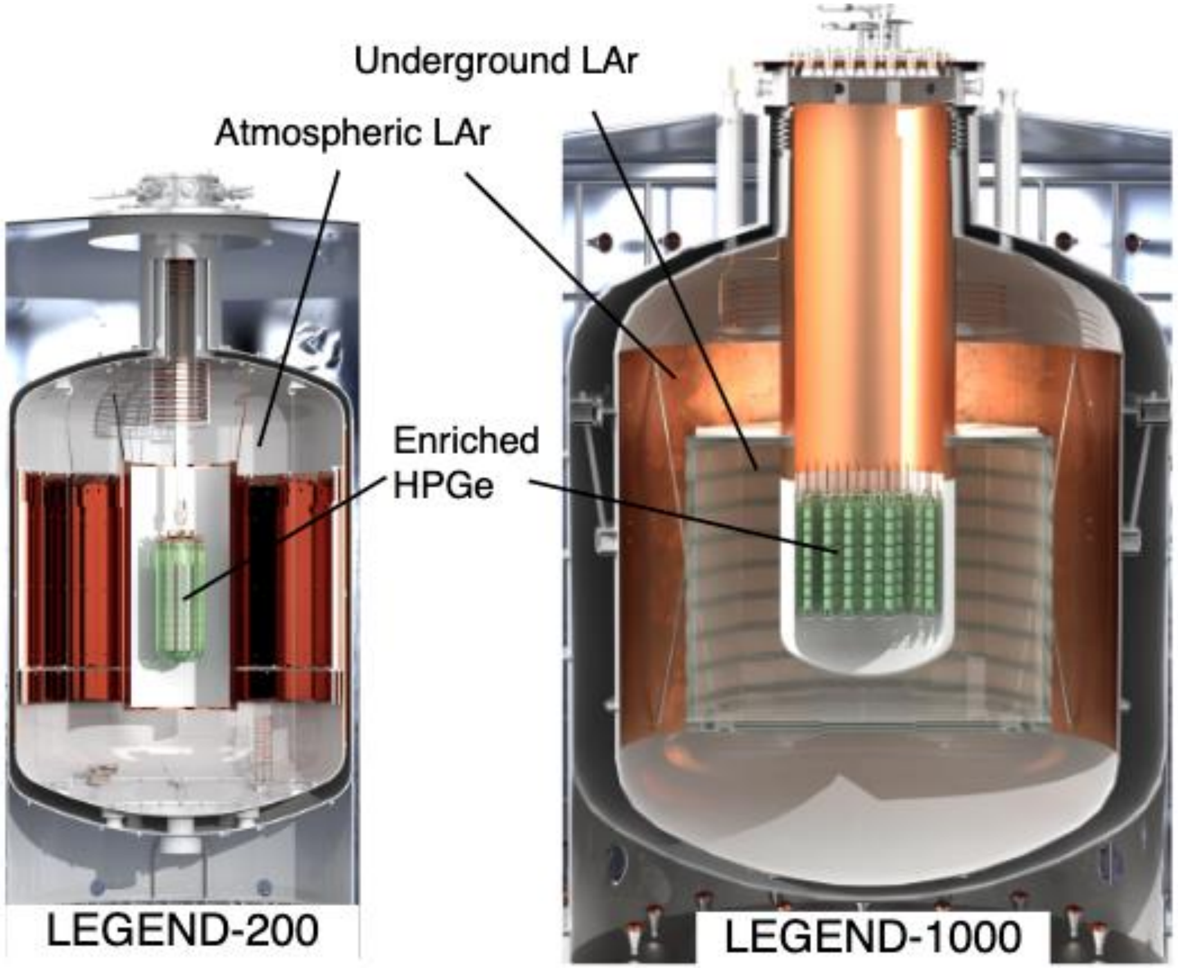




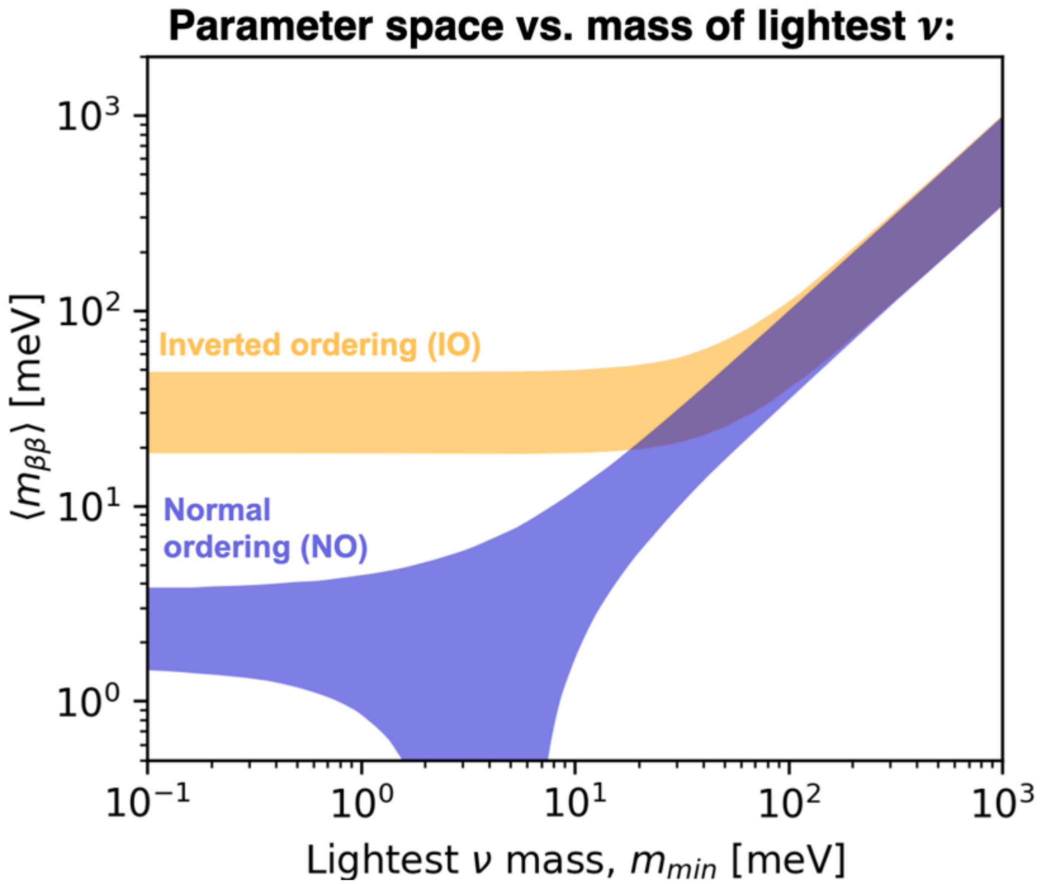


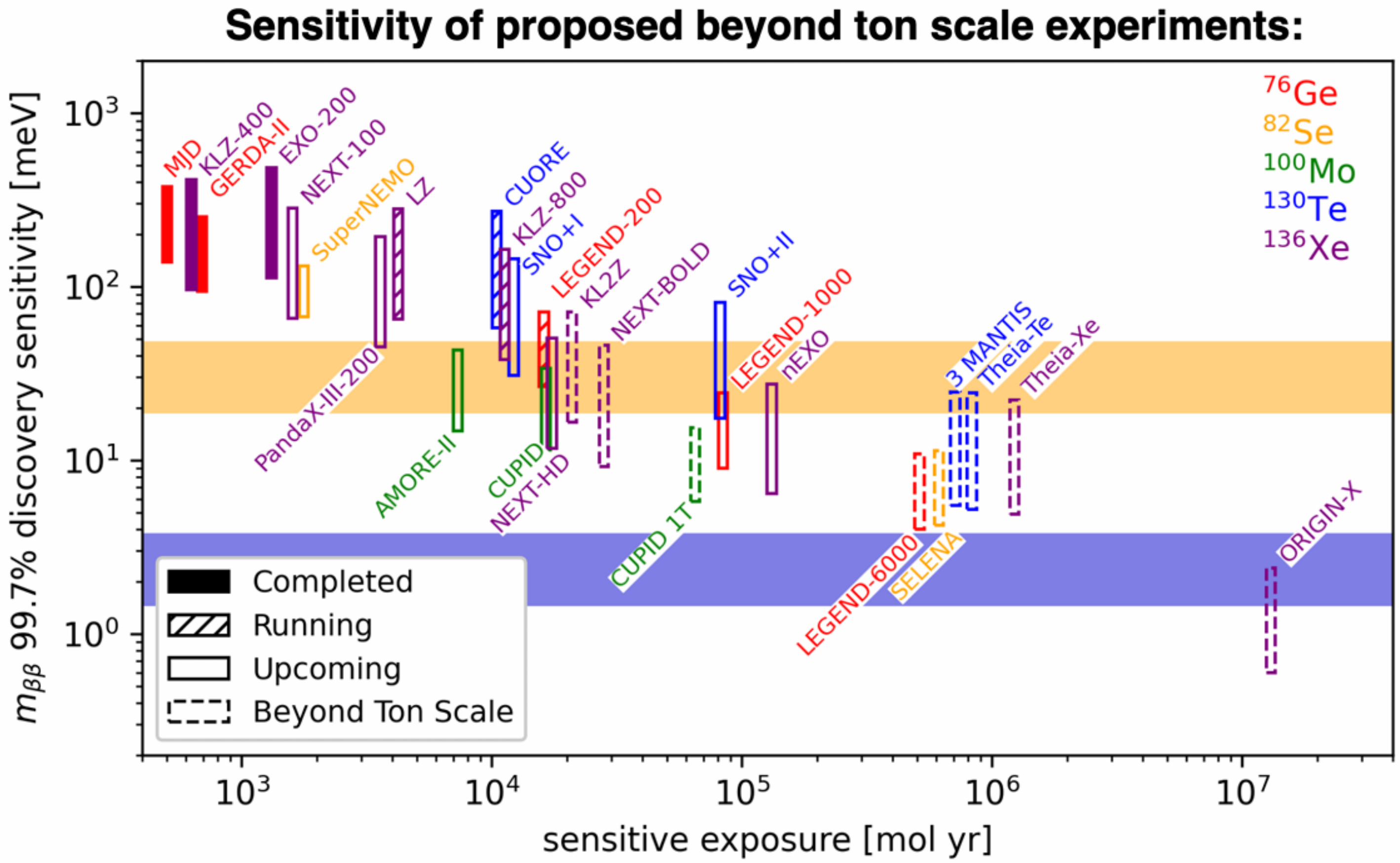
Tonne scale effort – LEGEND (^{76}Ge)

- ^{enr}Ge crystals
- High efficiency and excellent energy resolution
- Background suppression via active shielding and signal analysis
- Staged from 200-kg (operating since 2023) to 1000 kg
- Most favorable concept in DOE design review 2022
- Projected sensitivity
  - $m_{\beta\beta}$ 9 – 21 meV
  - 1.3 x 10^{28} years



The Future Outlook





- The next generation experiments cover the entire IH region, and could even possibly usher in an era of discovery!
- New ideas would be needed in order to push beyond the IH region.

https://nuclearsciencefuture.org/

As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.

Thank you for listening!