Neutrinoless double beta decay and inference on neutrino mass and nature

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Contents

- Neutrinos and open questions
- Dirac and Majorana nature of the neutrinos
- Double beta decay
- Neutrinoless double beta decay and implications
- Experimental 0νββ sensitivity
- 0νββ experimental searches

What do we know about neutrinos

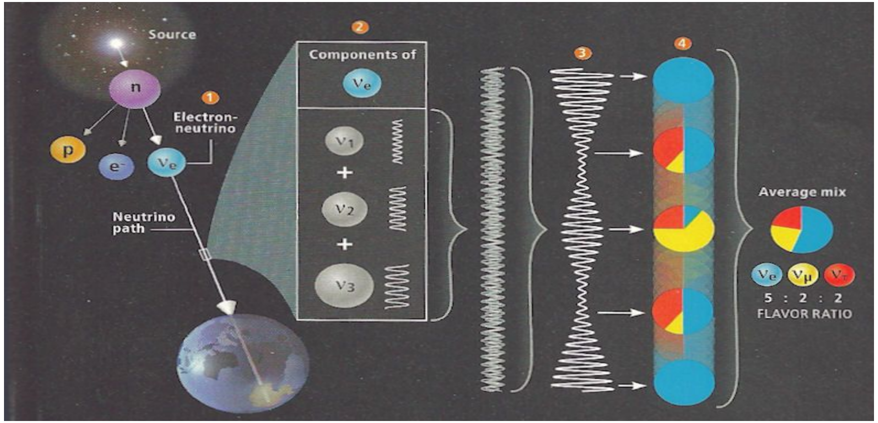
Neutrinos are the lightest known elementary fermions. They do not carry electric or color charge, and are observable only via weak interactions (v_L - negative chirality neutrino).

Neutrinos are massless particles in the (Minimal) Standard Model (MSM).

3 neutrino flavours (v_e, v_μ, v_τ) participating in weak interactions

Neutrino flavour oscillations
Neutrinos propagating in space can be detected with a flavour different from the original one

- Hypothesis - Pauli (1957)
- Mixing theory - Pontecorvo, Maki, Nakagawa, Sakata (1962) → **3 neutrino mass eigenstates (v_1, v_2, v_2)**



Review of Particle Physics (for PDG 2024): Sec. 14." Neutrino Masses, Mixing, and Oscillations"

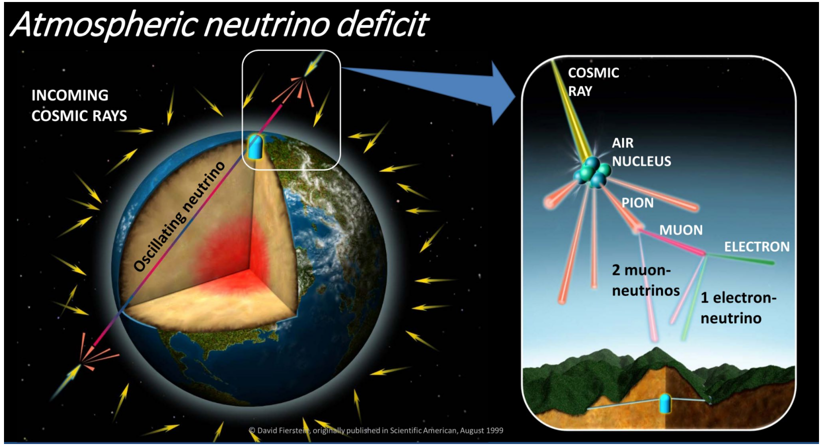
What do we know about neutrinos

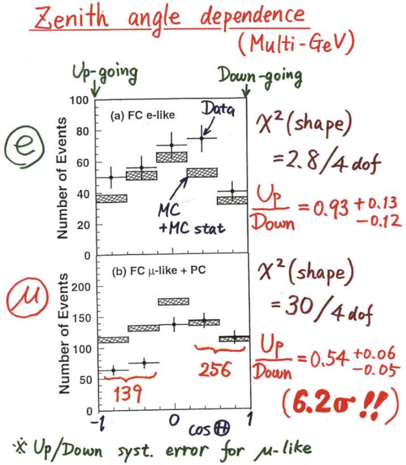
Neutrino flavour oscillations:

- Detection of neutrino flavour oscillations by SNO and Super-Kamiokande experiments for solar and atmospheric neutrinos (1998-2001)

Neutrinos are not mass-less!
It is necessary to extend the MSM to accommodate for massive neutrinos

2015 - Nobel Prize Physics - Neutrino Oscillations





※ Up/Down syst. error for μ-like

Prediction (flux calculation …… ≲ 1%
1km rock above SK …. 1.5%) 1.8%

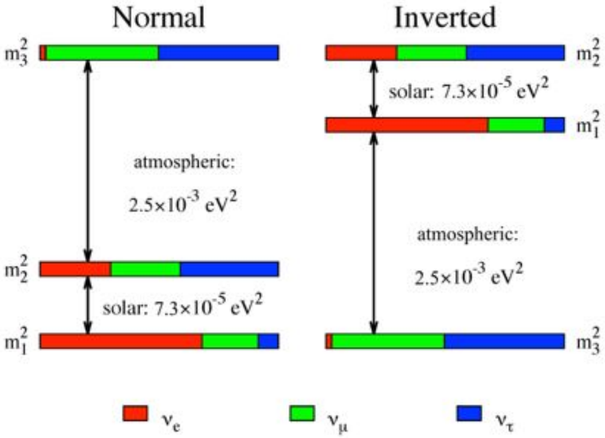
Data (Energy calib. for ↑↓ …. 0.7%
Non ν Background ….. < 2%) 2.1%

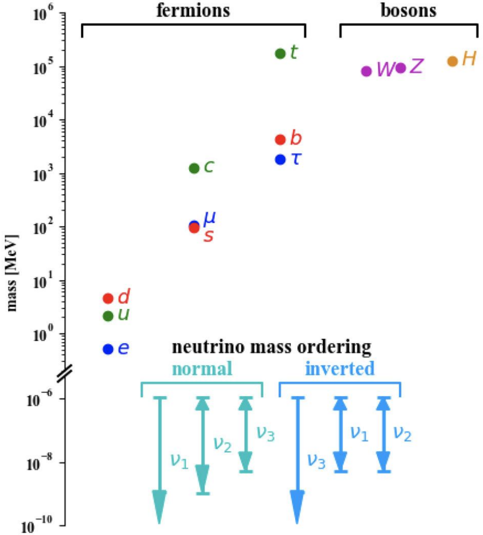
Takaaki Kajita - Nobel Lecture: Discovery of Atmospheric Neutrino Oscillations (Nobel Prize Lecture, 2015)

What do we know about neutrinos: open questions

Open questions about the neutrino mass:

- How the neutrino mass eigenstates are ordered (normal/inverted hierarchy) ?
- Which are the neutrino mass absolute values?
- Why the neutrino mass is so small wrt to the other SM particles ($m_\nu < 10^{-6}\, m_e$)?
- The neutrinos - neutral leptons - are Dirac or Majorana particles?





Review of Particle Physics (for PDG 2024): Sec. 14." Neutrino Masses, Mixing, and Oscillations"
Phenomenology with massive neutrinos (2008), pp 4-9;
Neutrino masses, mixing and ... (2011), Ch 2, pp 10-20

What do we know about neutrinos: open questions

Experimental searches

Neutrino flavour oscillations	Precision measurement of ν flavour oscillation parameters (solar, atmospheric, accelerator and reactor neutrinos): T2K, Nova, Daya-Bay, Super-K; DUNE, Hyper-K, JUNO
Neutrino interactions	Neutrino interactions with matter: different targets, different mechanisms (eg. COHERENT), probes of astrophysical sources (eg. BOREXINO)
Sum of neutrino masses	Cosmological and astrophysical data: CMB - PLANCK, BAO - SDSS and large scale structures
Direct mass measurement	β-decay or Electron Capture: KATRIN, PROJECT-8 and PTOLEMY (^{3}H), HOLMES and ECHO (^{163}Ho)
Majorana nature of neutrino	**Neutrinoless double beta decay (0νββ)** CUORE/CUPID, LEGEND, nEXO, NEMO; Kamland-Zen, SNO+; AMoRE; NEXT
Sterile neutrino searches	eV/keV-scale sterile neutrino: FNAL SBN program (MicroBoone, ICARUS, SBND), PROSPECT, NEOS, DANSS, Neutrino-4

Neutrino mass: Dirac or Majorana

Neutrinos are the only particles in the SM that could be *Majorana fermions*, that is, completely neutral fermions not carrying any other charge-like conserved quantum number, that are their own antiparticles.
Whether neutrinos are Majorana or Dirac particles depends on the nature of the physics that give them mass

Dirac neutrino

- Adding ν_R to the neutrino field
- ν_L active, ν_R sterile for weak interactions
- Yukawa coupling with Higgs doublet for ν mass
- 4 ν states with same mass
- Impose the lepton number conservation

$$-\mathcal{L}_D = m_D(\overline{\nu_L}\nu_R + \overline{\nu_R}\nu_L)$$

where $m_\nu = y_\nu v$

Majorana neutrino

- *Majorana condition* (valid only for neutral fermions): $\nu^c = \nu$, where $\nu^c = C\bar{\nu}^T$
- ν_R for a Majorana ν, obtained from ν_L: $\nu_R = (\nu_L)^c$
- Majorana mass term: converts particles into their antiparticles; **lepton number violating term (ΔL =2)**

$$-\mathcal{L}_L = \frac{1}{2}m_L(\overline{\nu_L}(\nu_L)^c + \overline{(\nu_L)^c}\nu_L).$$

- See-Saw mechanism: Light active ν_i; Heavy sterile N_i

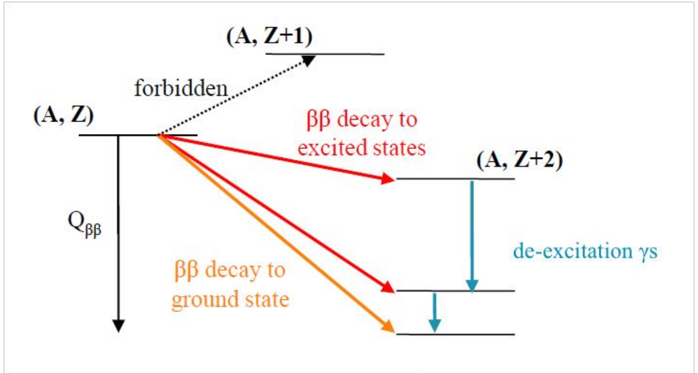
Neutrino mass nature: probing the Majorana nature

- *Scattering of non-relativistic neutrinos: CνB* (Cosmic Neutrino Background)
  - Indirect evidence of CνB from cosmological probes
  - CνB:
    - if Dirac ν: ν_R population absent
    - if Majorana ν: both ν_L and ν_R populations present
    - ν capture on beta decaying nuclei: capture rate is double for Majorana neutrinos
  - Current experiments for CνB detection: PTOLEMY

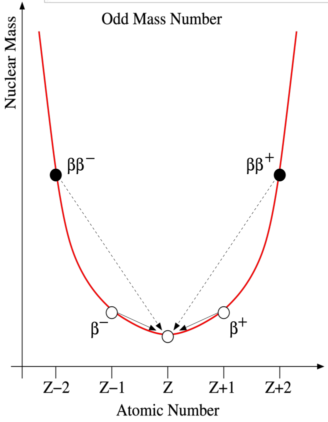
- *Lepton number violating processes*
  - **Neutrinoless double beta decay (0νββ)**
    - Nuclear process involving *relativistic neutrinos*
    - Physical phenomenon violating the total lepton number L (ΔL =2)
    - Matter creation process mediated by: $W^-W^- \to l_\alpha^- l_\beta^-$, via light Majorana neutrino exchange

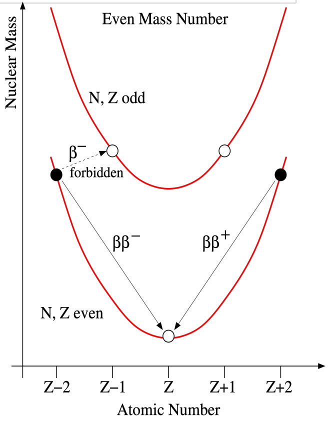
Double beta decay

Double beta decay is a rare nuclear transition, a second-order weak decay where a nucleus (A, Z) undergoes two beta decays to its isobar (A, Z+2), in a single step emitting two electrons in the process.



35 suitable nuclei in nature for double-beta decay: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te,^{128}Te,^{136}Xe ..., which are all even-even nuclei and the beta transition to the intermediate nucleus is forbidden. Q-value ~ MeV





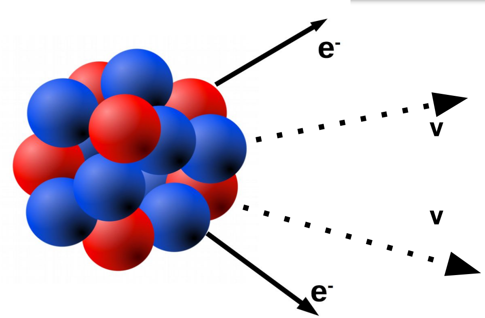
Two-neutrino double beta decay (2νββ)

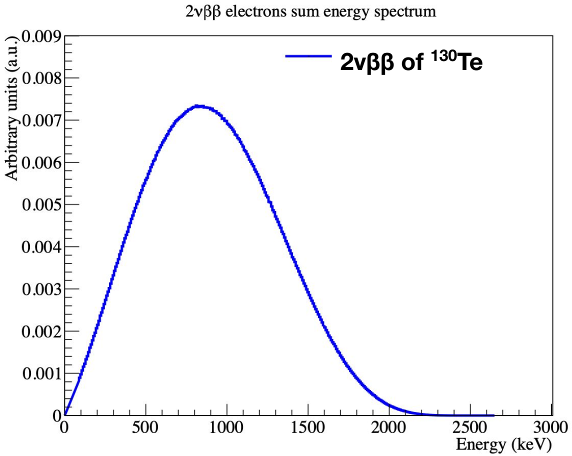
$$(A,Z) \longrightarrow (A,Z+2) + 2e^- + 2\overline{\nu}_e$$

- 2^{nd} order process allowed in Standard Model ($\Delta L = 0$)
- Proposed in 1935 by M.Goeppert-Mayer
- Observed in several nuclei: $T^{1/2}_{2\nu\beta\beta} \sim 10^{19\text{-}21}$ yr

(among the longest ever observed among radioactive decay processes)

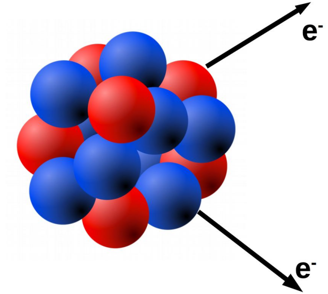
Most relevant measurable quantity:
sum of the kinetic energy of the electrons produced in the decay
- continuous spectrum with endpoint at $Q_{\beta\beta}$





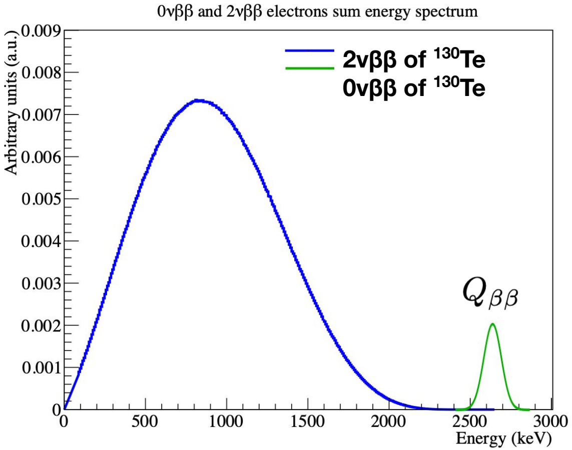
Neutrinoless double beta decay (0νββ)

$$(A, Z) \longrightarrow (A, Z+2) + 2e^-$$



- Beyond Standard Model process: violation of lepton number ($\Delta L = 2$)
- Proposed by W.H.Furry in 1939 as a method to test the Majorana theory applied to neutrinos
- Not yet observed: $\boxed{T^{1/2}_{0\nu\beta\beta} > 10^{22\text{-}26}\ \text{yr}}$

Experimental signature of 0νββ decay:
a peak in the summed energy spectrum of the final state electrons at the Q-value of the ββ decay ($Q_{\beta\beta}$)



Comparing 0νββ and 2νββ

Similarities

- The electrons carry essentially all the available energy
- The transition involves 0^+(gnd) → 0^+(gnd) states. Transitions to excited states are suppressed due to smaller phase space
- 2nd order weak processes: $\Gamma \sim G_F^4$, with $G_F = 1.166\ 3787 \times 10^{-5}$ GeV

Differences

- 2νββ: sum e^- kinetic energy spectrum - continuous

  vs 0νββ: sum e^- kinetic energy spectrum - peak
- 2νββ: low momentum transfer ~ $Q_{\beta\beta}$(MeV)

  vs 0νββ: high momentum transfer ~ 100 MeV
- Phase-space preference to the 0νββ mode, which is, however, forbidden by total lepton number conservation.

Other lepton number violating rare decays

There are other three 2nd order rare decays, with a lepton number violating counterpart, that can also be investigated:

$$\beta^+\beta^+0\nu: \quad (Z, A) \rightarrow (Z-2, A) + 2\, e^+$$

$$\beta^+\mathrm{EC}0\nu: e^- + (Z, A) \rightarrow (Z-2, A) + e^+$$

$$\mathrm{ECEC}0\nu: \; 2\, e^- + (Z, A) \rightarrow (Z-2, A)^*.$$

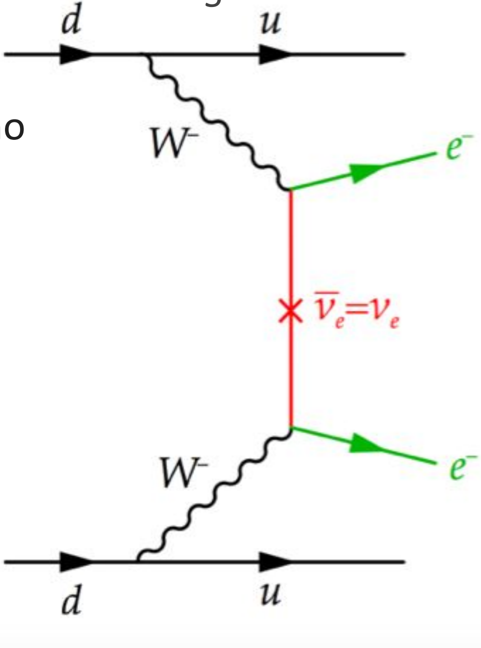
All three involve transitions where the nuclear charge decreases (as opposed to increasing, as in ββ) by two units.

- From the theoretical point of view, the physics probed by β+β+0ν, β+EC0ν and ECEC0ν is identical to the one probed by ββ0ν.
- From the experimental point of view, however, β+β+0ν and β+EC0ν are less favorable than ββ0ν because of the smaller phase space available. On the other hand, the process ECEC0ν is gaining some attention recently as a promising (but still much less developed) alternative to ββ0ν, since a resonant enhancement of its rate can in principle occur

0νββ decay and inference on neutrino mass

The standard neutrinoless double-beta decay mechanism: light Majorana neutrino exchange

The parent nucleus emits a pair of virtual W bosons. The W exchange a Majorana neutrino to produce the outgoing electrons. The exchanged neutrino can be seen as emitted (in association with an electron) with almost total positive helicity. For a massive Majorana neutrino, it has a small, O(m/E), negative helicity component which is absorbed in the other vertex by the Standard Model electroweak current.



From the decay rate it is possible to infer the effective neutrino mass

$$\frac{1}{T^{0\nu}_{1/2}} \propto G(Q_{\beta\beta}, Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

Phase space integral
$G(Q_{\beta\beta},Z) \sim Q_{\beta\beta}^5$

Nuclear matrix element
(NME)

Effective neutrino mass term

0νββ decay and inference on neutrino mass

The standard neutrinoless double-beta decay mechanism: light Majorana neutrino exchange

$$\frac{1}{T^{0\nu}_{1/2}} \propto G(Q_{\beta\beta}, Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

Effective neutrino mass term |$m_{\beta\beta}|^2$

Neutrino mass matrix M_ν can be decomposed as $M_\nu = U \ \mathrm{diag}(\mathrm{m}_1,\mathrm{m}_2,\mathrm{m}_3) \ U^t$
where $m_i>0$ are the masses of the neutrinos and U is the PMNS mixing matrix

Define the effective Majorana mass $m_{\beta\beta}$ where φ_i are called Majorana phases and cannot be probed by oscillation experiments.
$m_{\beta\beta}$ is the ee-element of the mass matrix $|(M_\nu)_{ee}|$

$$m_{\beta\beta} = \left|\sum_{i=1}^{3} |U^2_{\mathrm{ei}}| \ e^{i\varphi_{\mathrm{i}}} \ m_{\mathrm{i}}\right|$$

0νββ decay and inference on neutrino mass

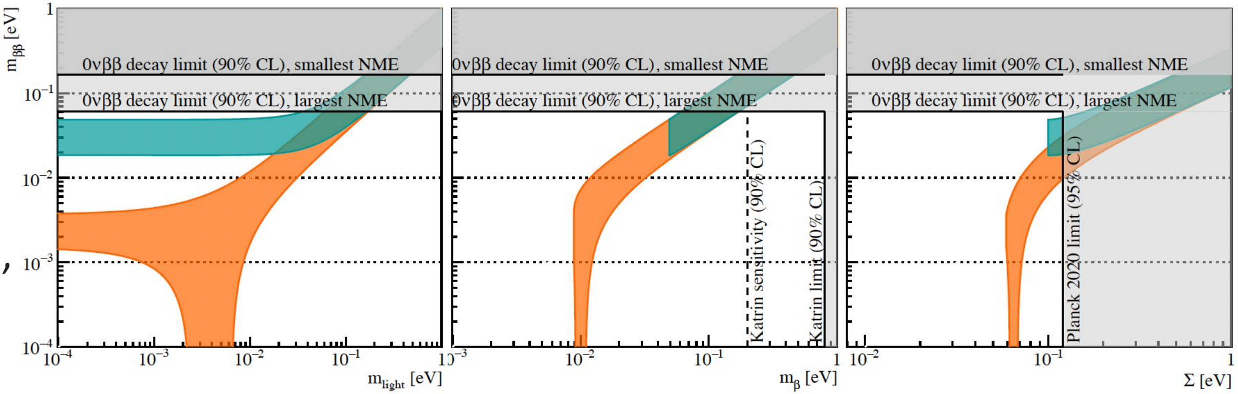
The standard neutrinoless double-beta decay mechanism: light Majorana neutrino exchange

$$\frac{1}{T_{1/2}^{0\nu}} \propto G(Q_{\beta\beta}, Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

Effective neutrino mass term $|m_{\beta\beta}|^2$

0νββ is directly connected to neutrino oscillations phenomenology, and that it also provides direct information on the absolute neutrino mass scale, as cosmology and decay experiments do.

Rev. Mod. Phys. ***95****, 025002;*
https://doi.org/10.1103/RevModPhys.95.025002



0νββ decay and inference on neutrino mass

The standard neutrinoless double-beta decay mechanism: light Majorana neutrino exchange

$$\frac{1}{T^{0\nu}_{1/2}} \propto G(Q_{\beta\beta}, Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

Nuclear Matrix Elements

Factoring out the hadron coupling g_A wrt to just the nuclear many-body part and to light neutrino exchange

$$|M_{nucl}|^2 = g_A^4|M^{0\nu}_{light}|^2$$

$$M^{0\nu}_{light} = M^{0\nu}_{long} + M^{0\nu}_{short}$$

All nuclear methods used to study 0νββ decay make a significant effort to describe with high quality the structure of the initial and final nuclei and the relative long and short-term interactions among nucleons.
Models: *Shell model, QRPA, EDF theory, IBM, Ab-initio methods*

0νββ decay and inference on neutrino mass

The standard neutrinoless double-beta decay mechanism: light Majorana neutrino exchange

$$\frac{1}{T^{0\nu}_{1/2}} \propto G(Q_{\beta\beta}, Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

Nuclear Matrix Elements

The variation of the NME about a factor three for a given isotope, highlights the uncertainties introduced by the approximate solutions of the nuclear many-body problem.

Current strong effort to improve the nuclear models for multiple isotopes and quantify the NMEs theoretical uncertainties

Rev. Mod. Phys. ***95****, 025002;*
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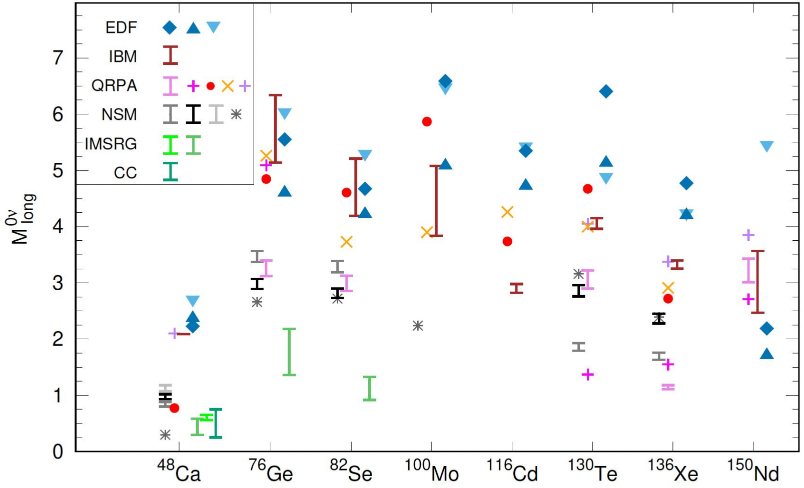


0νββ decay and implications

Observation of 0νββ decay would imply:

Lepton number violation

Presence of a Majorana term for the neutrino mass

Constraints on neutrino mass hierarchy and scale

Hint on origin of matter/anti-matter asymmetry (baryogenesis via leptogenesis involving Majorana neutrinos)

The importance of 0νββ decay has triggered a continuously evolving line of research with dedicated experiments spanning several isotopes and a rich selection of detector techniques

Experimental 0νββ sensitivity

The number of observable 0νββ decays is limited by the fluctuations of the background counts around $Q_{\beta\beta}$ (region of interest, ROI)

'Finite background' $S_{0\nu} \propto \eta \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta \cdot B}}$

'Zero background' $S_{0\nu} \propto \eta \cdot \epsilon \cdot M \cdot T$

$(B \cdot \Delta \cdot M \cdot T) << 1$

Ingredients for 0νββ decay experiments

Isotope choice
- High isotope natural abundance or enrichment, η
- High Q-value, $Q_{\beta\beta}$

Detection technology
- Good detection efficiency (ε): ββ source embedded into the absorber
- Excellent energy resolution (Δ)
- Low backgrounds (B)

Exposure
- Large active mass (M) detector
- Long live-time (T)

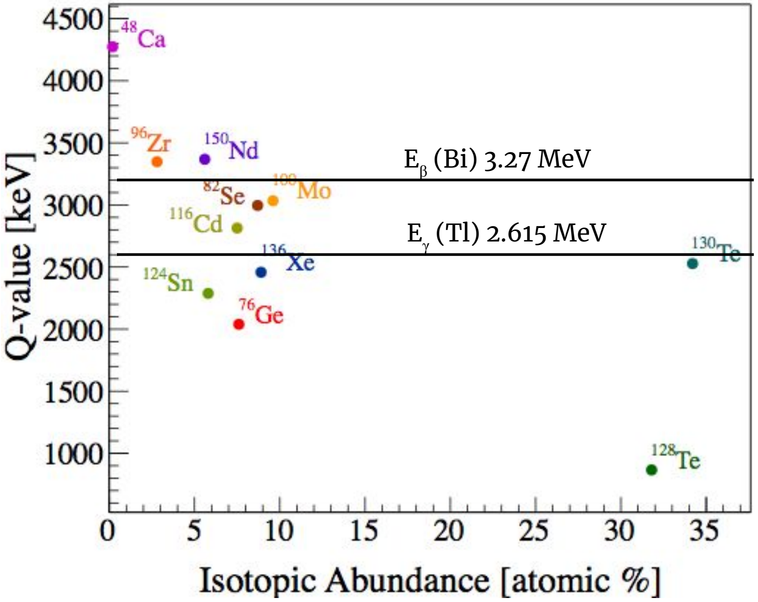
Experimental 0νββ sensitivity: isotope choice

The candidate isotopes for 0νββ experimental search are those readily available at the level of thousands of moles (i.e., hundreds of kg) or more, with a high Q-value and thus a large decay rate, and compatible with existing detection technologies.

Large source: ton-scale, > 10^{27} nuclei

- Isotopes with high natural η
- Enrichment of the isotope

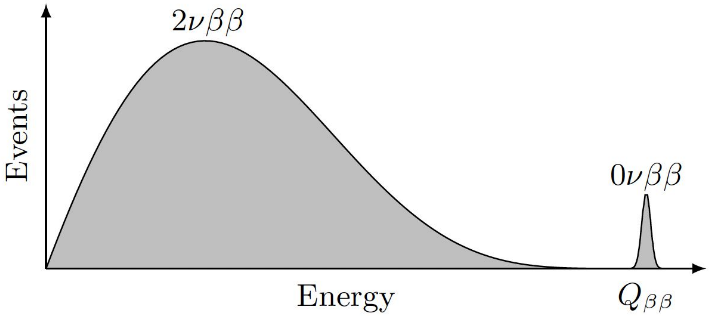
High Q-value preferred for larger phase-space and lower potential backgrounds

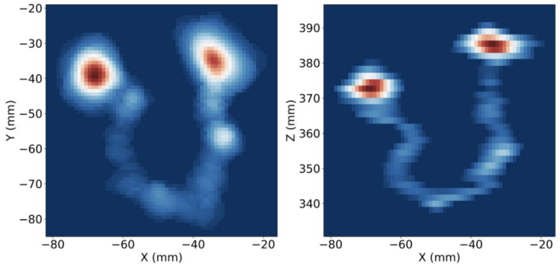


Experimental 0νββ sensitivity: detection technique

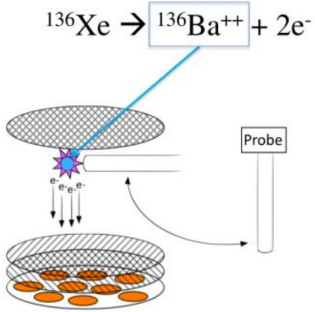
Signal detection and experimental observables

- Cinematic parameters of the two emitted electrons
  - Summed (kinetic) energy of the two electrons - Track reconstruction of the single electrons
- Detection of the daughter nucleus, as ion++
- Gamma rays emitted in decay to excited states





JHEP01(2021)189, https://doi.org/10.1007/JHEP01(2021)189

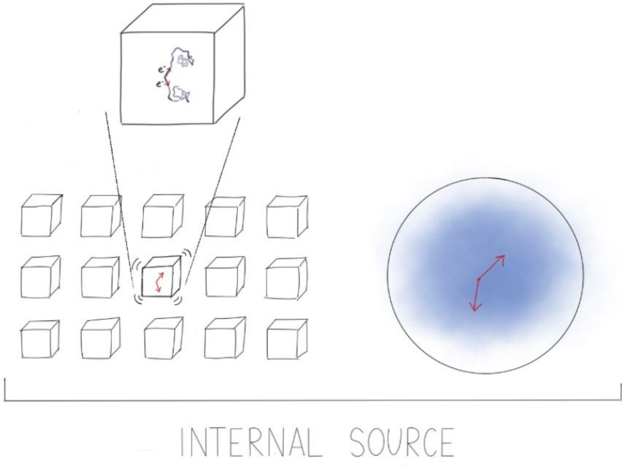


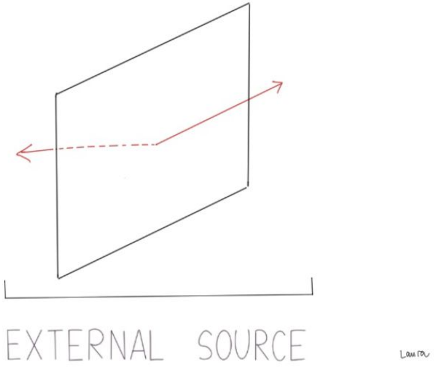
Nucl. Phys. B - Proc. Suppl., Vol. 229–232 (2012), https://doi.org/10.1016/j.nuclphysbps.2012.09.020

Experimental $0\nu\beta\beta$ sensitivity: detection technique

Signal detection and detector concepts

Solid state detectors with an embedded source	Monolithic liquid or gas detectors with an embedded or dissolved source	Composite detectors with external sources





Rev. Mod. Phys. **95**, 025002;
https://doi.org/10.1103/RevModPhys.95.025002

Experimental 0νββ sensitivity: detection technique

Signal detection and detector concepts

Solid state detectors with an embedded source	**Monolithic liquid or gas detectors with an embedded or dissolved source**	**Composite detectors with external sources**
Single crystals: ~kg, 100cm^3, high granularity, up to ton-scale	Linear dimensions 1-10m, volumes ton-kton	Isotope mass and number of readout detectors proportional to the foil area
ε ~ 70-95% for MeV e-	ε ~ 75-100% for MeV e-	ε ~ 30 % for MeV e-
Only calorimetric meas	Calorimetric meas + if good spatial reso, event topology	Calorimetric meas + track reconstruction of single e-
Δ~0.1% @MeV	Δ~10-30% @MeV	Δ~1-3% @MeV but energy reco limited by energy losses

Experimental 0νββ sensitivity: backgrounds

Natural radioactivity (α, β, γ radiation from ^{238}U and ^{232}Th chains)

Levels < 1 μBq/kg are required ⟵ ⟶ Ordinary materials 1-100 Bq/kg

- Material selection and cleaning procedures for all the detector components
- Strict radiopurity controls during detector assembly
- Radon abatement systems

Identification and suppression of backgrounds via the study of event topology or particle identification techniques

CUORE tower assembly in glove-box

Experimental 0νββ sensitivity: backgrounds

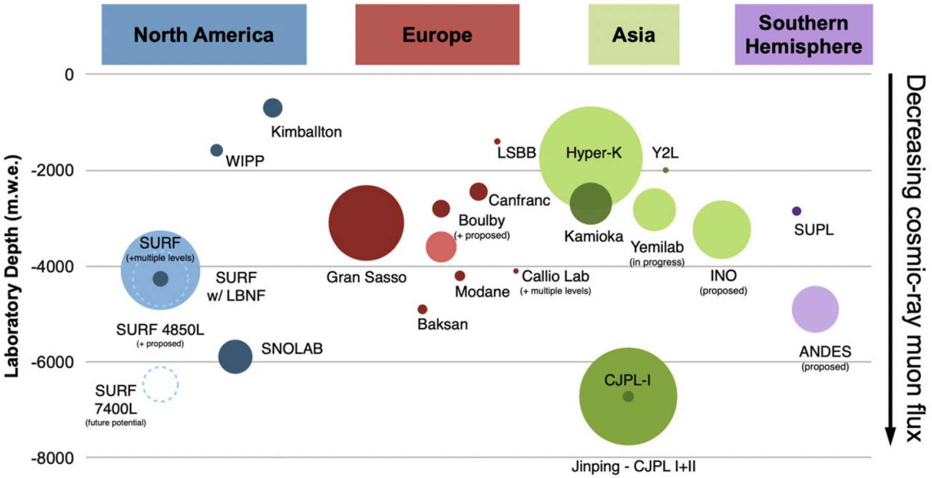
Cosmic rays

Underground laboratory → Muon flux reduction by > 10^6

- Reconstruction of residual muons crossing the detector active volume

Cosmic rays induced spallation processes:

- Activate unstable cosmogenic nuclei
  → minimize above ground exposure;
  delayed time coincidence with primary muon
- Produce high energy neutrons



La Rivista del Nuovo Cimento (2023) 46:619–692
https://doi.org/10.1007/s40766-023-00049-2

Neutrons

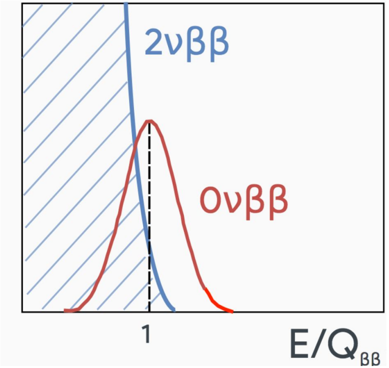
Generated by rock radioactivity and muons
→ Quality and depth of the underground laboratory
→ Dedicated shieldings are often required

Experimental 0νββ sensitivity: backgrounds

2νββ decay

Intrinsic and irreducible background.

- Detector finite resolution: some of the highest energy 2νββ decay events reconstructing with energies at $Q_{\beta\beta}$.
- If the 2νββ decay rate is high compared to the desired 0νββ decay sensitivity, 2νββ decay events can pile-up and contribute to the background at $Q_{\beta\beta}$

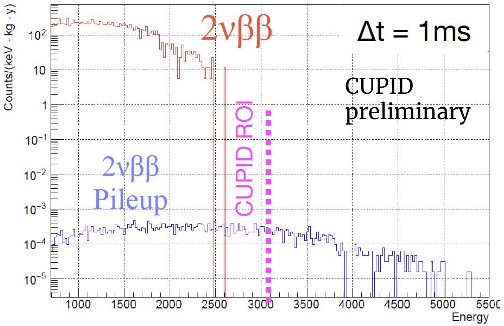


Anthropogenic radioactive isotopes

Result of nuclear accidents or nuclear weapon tests. Potential background source if Q-value > $Q_{\beta\beta}$, and half-life ~ experiment's lifetime

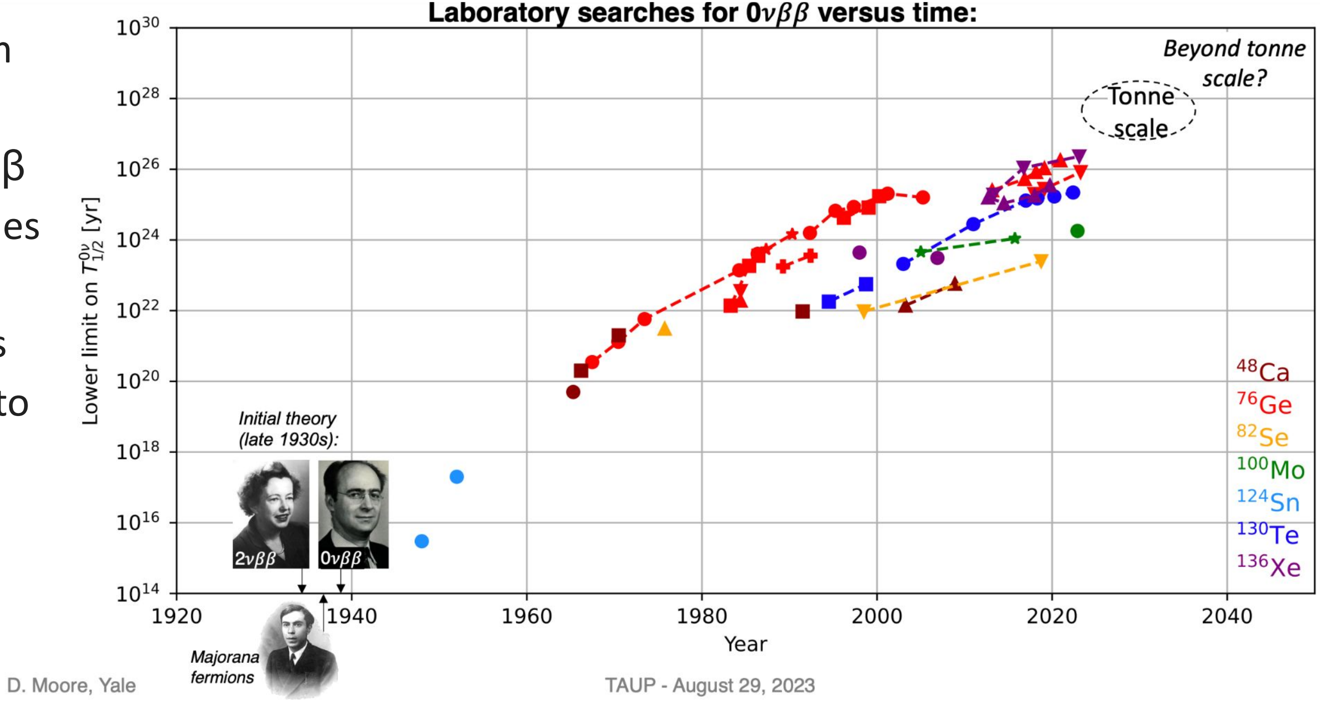
Neutrinos

Irreducible background. Negligible if active material is mostly made of the ββ isotope, but becomes significant for liquid scintillator experiments with dissolved sources



0νββ experimental searches: yesterday and today

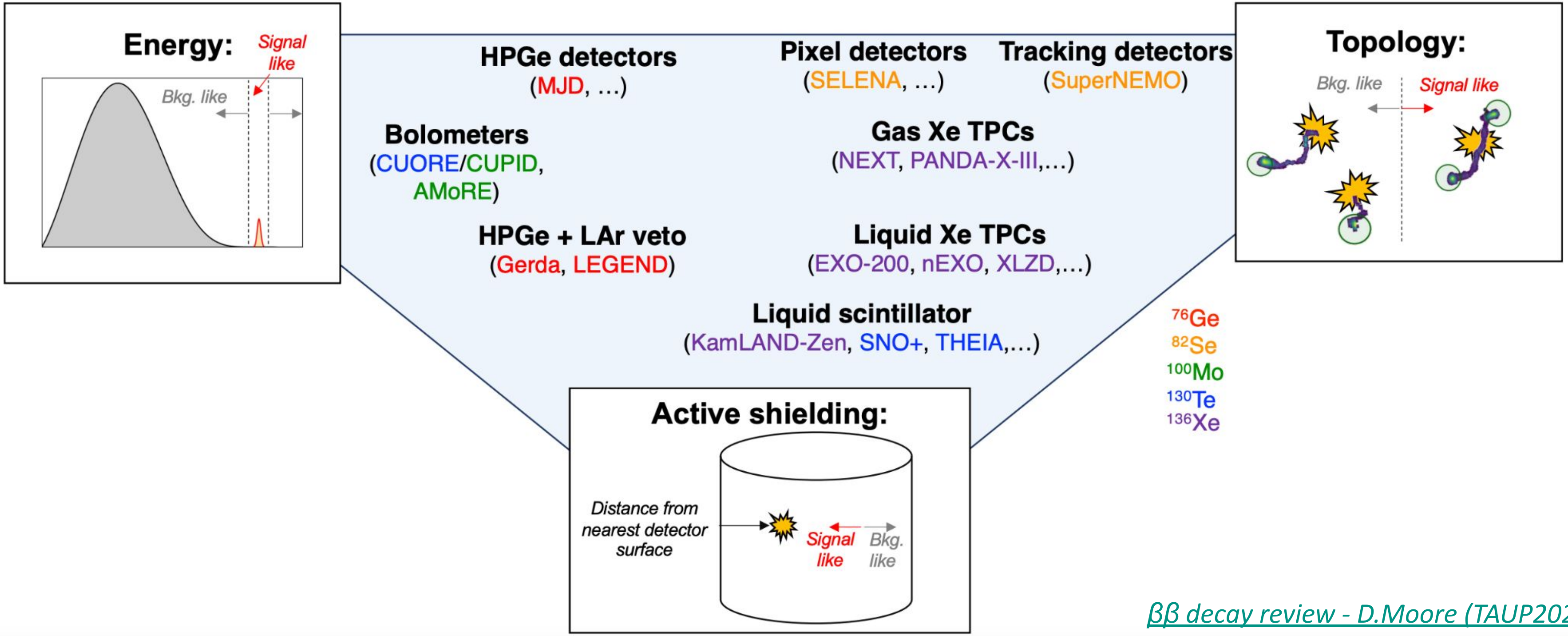
A broad experimental program has been mounted in the last few decades to search for 0νββ decay. Very diverse technologies have been developed and tested, leading to experiments with setting half-life limits up to 10^{26} years.



[ββ decay review - D.Moore (TAUP2023)](#)

0νββ experimental landscape

Different detection approaches and background suppression techniques



HPGe detectors
(MJD, …)

Bolometers
(CUORE/CUPID, AMoRE)

HPGe + LAr veto
(Gerda, LEGEND)

Pixel detectors
(SELENA, …)

Tracking detectors
(SuperNEMO)

Gas Xe TPCs
(NEXT, PANDA-X-III,…)

Liquid Xe TPCs
(EXO-200, nEXO, XLZD,…)

Liquid scintillator
(KamLAND-Zen, SNO+, THEIA,…)

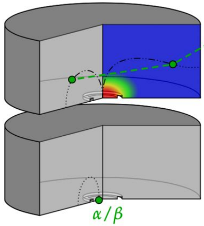
^{76}Ge
^{82}Se
^{100}Mo
^{130}Te
^{136}Xe

ββ decay review - D.Moore (TAUP2023)

0νββ experimental landscape

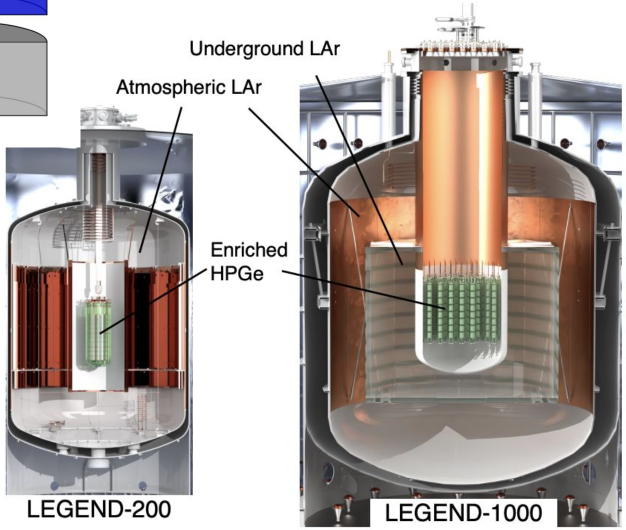
High-purity Ge semiconductor detectors

Germanium can be enriched in the ββ isotope ^{76}Ge and transformed into high-purity germanium (HPGe) detectors, devices characterized by superb energy resolution (2-3 keV at $Q_{\beta\beta}$), high efficiency (80-90%) and particle ID tagging.



LEGEND (^{76}Ge):

- Builds on the completed MJD and GERDA experiments
- Pulse shape discrimination: multi site vs. single site events
- Anticoincidence with LAr active shield
- Project:
  - LEGEND-200: up to 200 kg of ^{76}Ge, @LNGS (Italy)
    bkg goal 0.6 cts/(FWHM·t·yr)= 2 x 10^{-4} cts/(keV kg yr)
  - LEGEND-1000:
    1000 kg of ^{76}Ge, bkg goal <0.03 cts/(FWHM·t·yr)

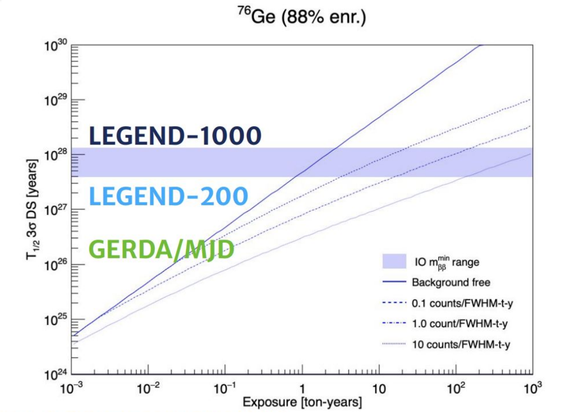


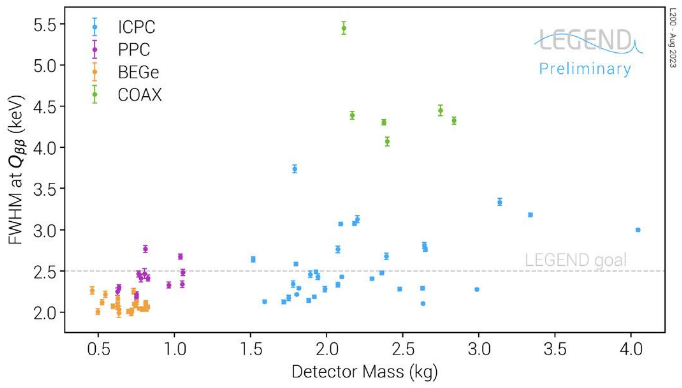
0νββ experimental landscape

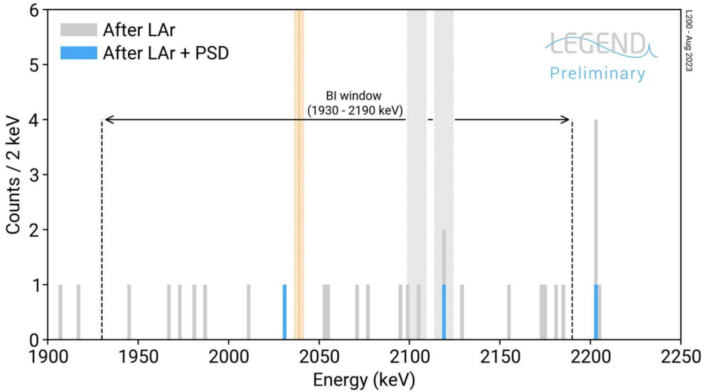
High-purity Ge semiconductor detectors

LEGEND (^{76}Ge):

- LEGEND-200: Began stable data taking March 2023 (140 kg), with complete 200 kg array planned early 2024
- LEGEND-1000: Conceptual design in progress, projected 3σ discovery sensitivity $m_{\beta\beta}$ = 9-21 meV ($T_{1/2}$ = 1.3 x 10^{28} yr)







First 10.1 kg yr from LEGEND-200.
Bkg index after LAr and PSD: 4.1 x 10^{-4} cts/(keV kg yr)

LEGEND-200 results @TAUP2023
Look at background data (K.V.Sturm)
From construction to data-taking (M.Willers)

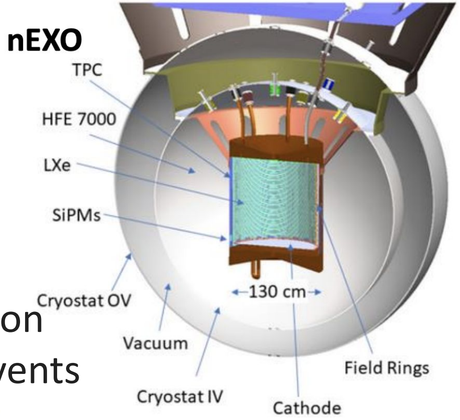
0νββ experimental landscape

Xenon time-projection chambers

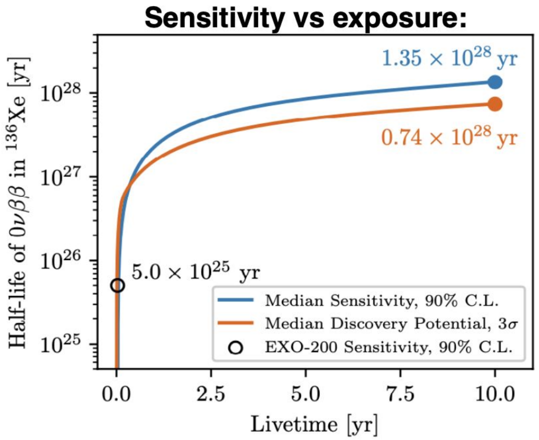
TPCs are particularly well-suited to searches for the 0νββ decay of ^{136}Xe. Xe inert noble element, can be used directly in TPCs; it exhibits VUV scintillation emitted promptly with an energy deposition.
Xe TPCs also potentially lend themselves to techniques for observation of the daughter Ba ion.

nEXO (^{136}Xe)

- Homogeneous, liquid ^{enr}Xe single-phase TPC scaled to 5 tonne total mass
- Built on the successful EXO-200, @SNO-Lab
  - Energy resolution ΔE(s) 0.8%@Qbb
  - Measurement of both charge and scintillation
  - Single site (including signal) vs. multi site events (background)
- Status: Conceptual design in progress, projected 3σ discovery sensitivity $m_{\beta\beta}$ =6-27 meV ($T_{1/2}$ = 0.74 x 10^{28} yr)



nEXO 0νββ search (S.Sangiorgio) @TAUP2023



0νββ experimental landscape

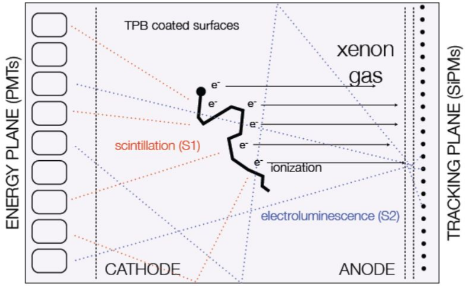
Xenon time-projection chambers

NEXT (^{136}Xe)

High pressure (10-15 bar) enriched Xe TPC @LSC

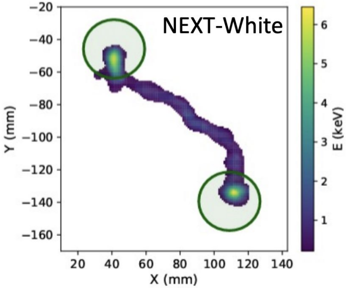
- Primary scintillation (t_0 → z coordinate)
- Electroluminescence for energy resolution (PMT plane) and for tracking (SiPMs plane) → only light detection, also for the charge readout

- Energy resolution (0.7% FWHM)
- Topological separation (ββ vs β)
- Status:
  - NEXT-White (10 kg) @LSC - completed
  - NEXT-100 (100 kg) - construction underway @LSC
  - NEXT-HD proposed to extend to 1t
  - R&D towards tagging ^{136}Ba daughter (NEXT-BOLD)



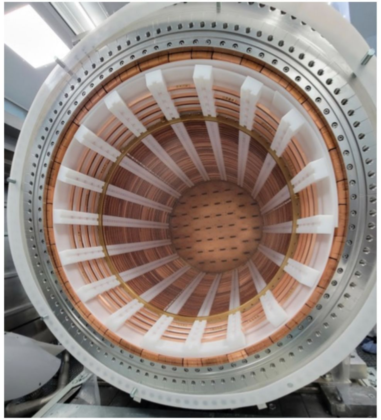
NEXT results (P.Novella) @TAUP2023

Reconstruction of $\beta\beta$ event:



Phys. Rev. C 105, 055501 (2022)

Photo of NEXT-100 TPC:



0νββ experimental landscape

Large liquid scintillators

Large liquid-scintillator detectors, have a successful track record in low-background searches in neutrino physics. Loading them with large amounts of ββ isotopes represents a cost-effective way to search for 0νββ. → Active isotope mass > 1 ton, high radio purity, limitations in energy resolution

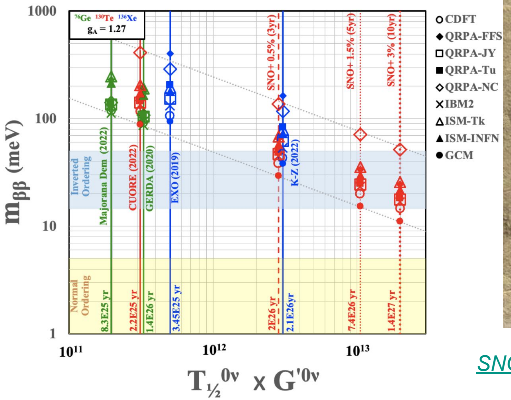
SNO+ (^{130}Te)

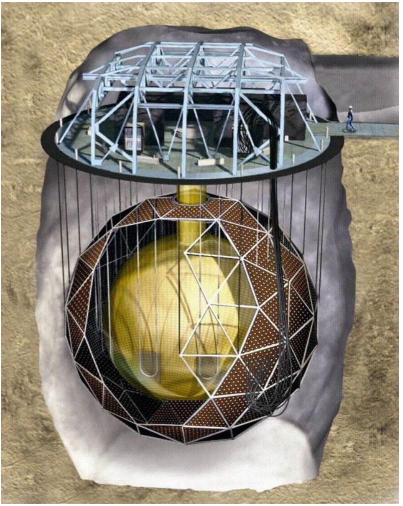
Reuse the acrylic vessel, the PMT array and the electronics of the SNO detector @SNO-Lab: Te-loaded liquid scintillator

→ Scintillator purification system & optical properties

→ Novel metal loading technique

- Status:
  - Water phase complete
  - Pure scintillator phase in progress (780 t)
  - Phase I - Te loading to start in 2024:
    0.5% ^{nat}Te → 1.3 t ^{130}Te
  - Planned Phase II with 3% Te





SNO+ 0νββ updates (V.Lozza) @TAUP2023

0νββ experimental landscape

Large liquid scintillators

Kamland-Zen (^{136}Xe)

Enriched Xenon diluted (3 wt%) in liquid scintillator exploiting the existing KamLAND detector with the addition of a nylon balloon

→ *Most sensitive search to date for 0νββ: $m_{\beta\beta} < 36–156$ meV*

Project @Kamioka:

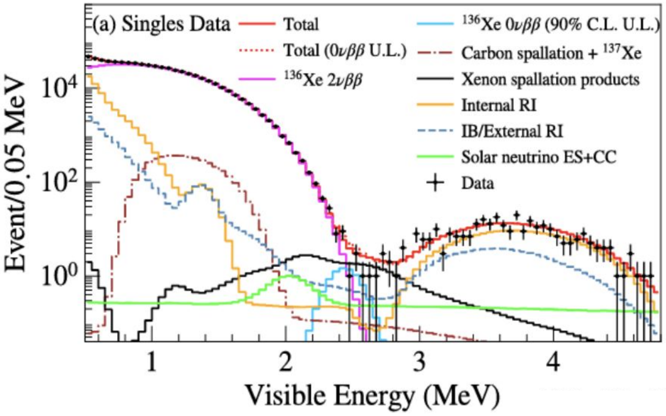
- KLZ-800:

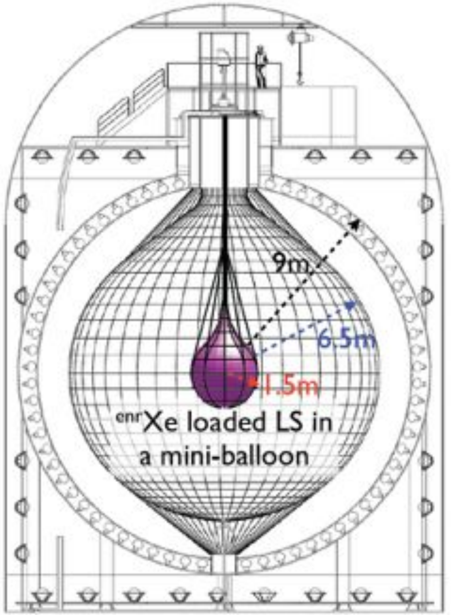
Mini-balloon with 745 kg of ^{136}Xe, currently in operation

- KamLAND2-Zen:

Proposed to improve energy resolution, 1t ^{136}Xe mass

KLZ-800 observed spectrum:



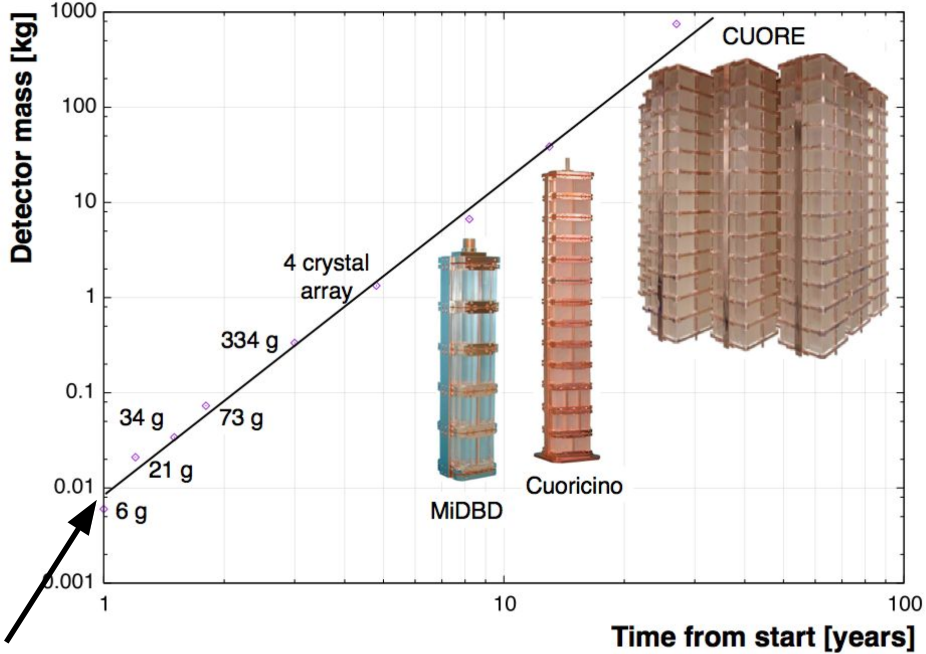


Phys. Rev. Lett. 130, 051801 (2023)

0νββ experimental landscape

Cryogenic calorimeters
Cryogenic calorimeters, often referred to as bolometers, are one of the most *versatile* types of detectors for rare events searches.
Crystals typically used in 0νββ decay experiments: masses ~ (0.2-0.8) kg; operated at **10-20 mK**; energy resolutions ~ 2-10 keV at $Q_{\beta\beta}$; containment efficiency varies 70-90%

CUORE (^{130}Te)
From few g to 1 tonne TeO_2 cryogenic calorimeters for ββ-decay search



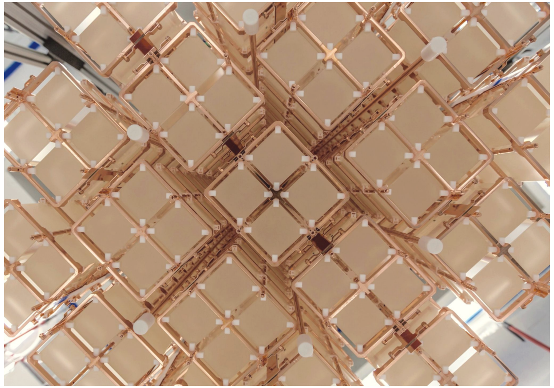
Pioneering experiments:
E.Fiorini group in Milano in the 1980s

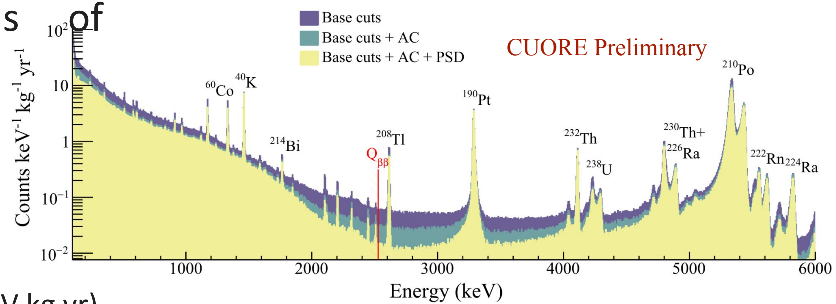
0νββ experimental landscape

Cryogenic calorimeters

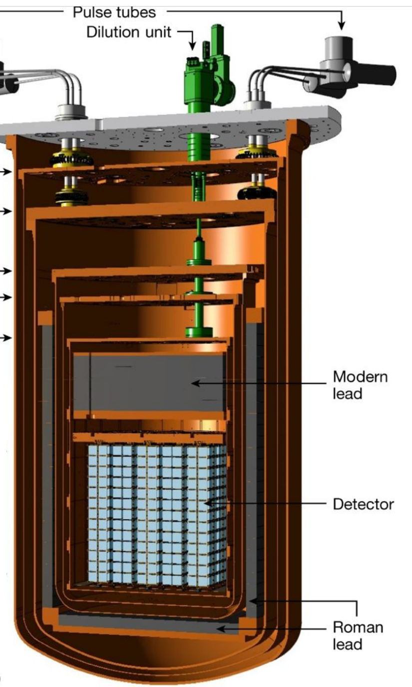
CUORE (^{130}Te)

- *Technological challenge*: 988 detectors (742 kg TeO_2) read out with NTD thermistors, operated at 15mK continuously for > 5 years with > 90% uptime, @LNGS (Italy)
- Acquired > 2.5 TY TeO_2 exposure as of today
- 2025 - Planned final exposure for CUORE: 3 TY TeO2 (1 TY ^{130}Te)





[CUORE 0νββ updates (I.Nutini) @MoriondEW2024](#)



Nature 604 (2022) 7904, 53-58, https://www.nature.com/articles/s41586-022-04497-4

CUORE 2024 2TY release:

$\Delta E(Q_{\beta\beta}, 2TY)$ ~ 7.32 keV, Bkg ~ 1.4 x 10^{-2} cts/(keV kg yr)

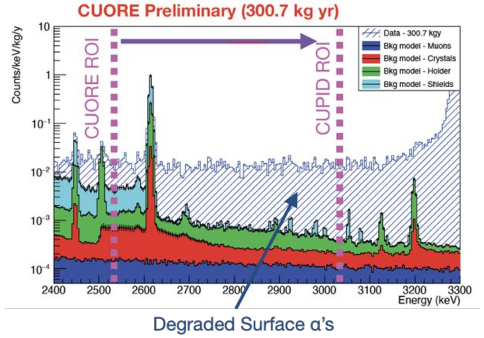
$T_{0\nu,1/2} > 3.8 \times 10^{25}$ yr (90% C.I.) – $m_{\beta\beta} <$ 70-240 meV

0νββ experimental landscape

Cryogenic calorimeters

CUORE: what's next?

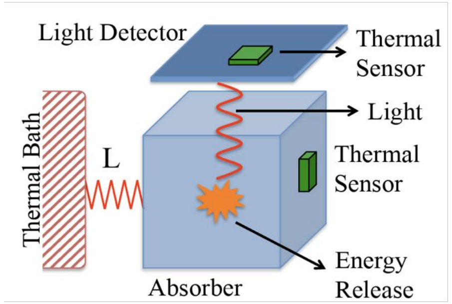
- CUORE is an ideal calorimeter. TeO_2 detectors measure only heat → no discrimination of α vs β/γ events in the ROI.
- Need for *hybrid approaches* to discriminate/reduce the α contribution in the ROI. Use other ββ candidates (^{48}Ca, ^{82}Se, ^{100}Mo) with high $Q_{\beta\beta}$ and/or scintillating compounds

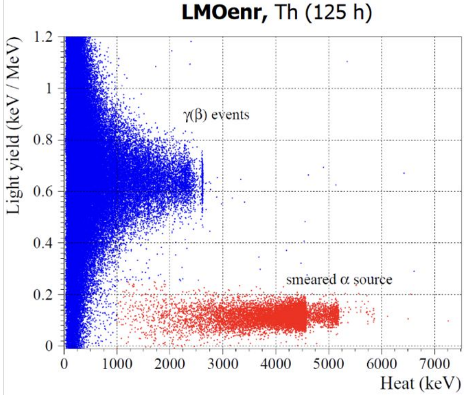


CUPID (CUORE Upgrade with Particle IDentification)

$Li_2{}^{100}MoO_4$ scintillating crystals
(CUPID-Mo, successful proof of concept)

- Readout of both heat and scintillation light
- Alpha-particle and ββ pileup rejection using light signal
- ^{100}Mo ββ decay candidate: $Q_{\beta\beta}$ ~3034 keV



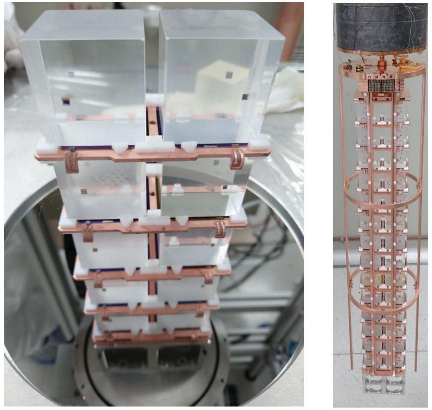


0νββ experimental landscape

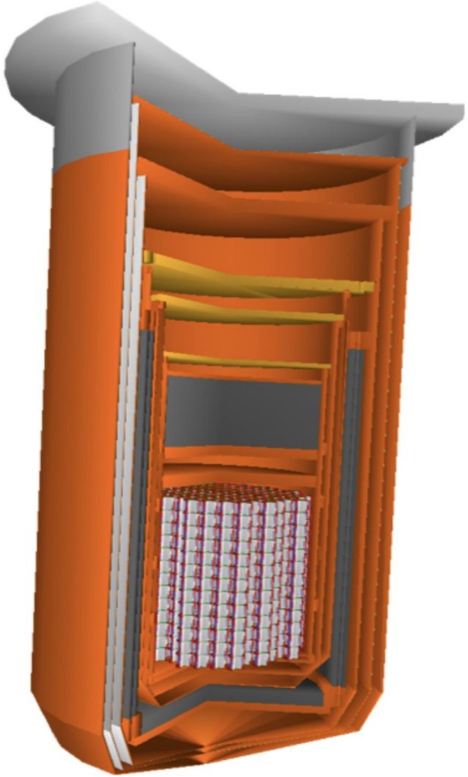
Cryogenic calorimeters

CUPID (^{100}Mo)

- Reusing CUORE cryogenic infrastructure @LNGS (Italy)
- Detector array with 1596 Li_2MoO_4 scintillating crystals, enriched > 95% in ^{100}Mo (~250 kg of ^{100}Mo), paired with Ge-light detectors
- Bkg goal < 10^{-4} cts/(keV kg yr),
- Nominal resolution $\Delta E(Q_{\beta\beta})$ ~ 5 keV
- Status:
  - CUPID tower design demonstrators in progress
  - Conceptual design in progress, projected 3σ discovery sensitivity $m_{\beta\beta}$=12-20 meV ($T_{1/2} = 1 \times 10^{27}$ yr)



CUPID updates (C.Nones) @TAUP2023

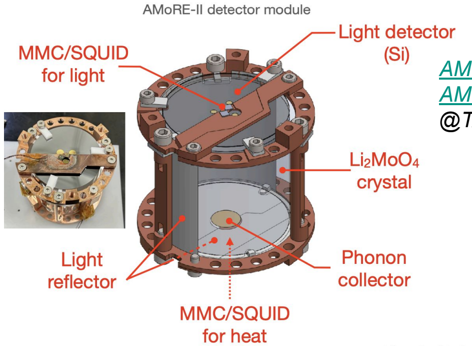


0νββ experimental landscape

Cryogenic calorimeters

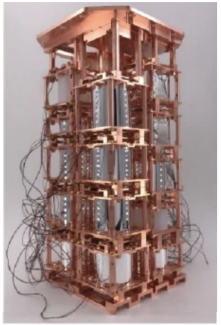
AMoRE (^{100}Mo)

- Scintillating bolometers with ^{enr}Mo: ^{48depl}CaMoO$_4$ and Li$_2$MoO$_4$, read out with MMCs thermal sensors
- Status:
  - AMoRE-I (2020-2023, 6.2 kg ^{100}Mo) @Y2L(Corea)
    Physics data at 12mK;
    Bkg 0.03 cts/(keV kg yr), ΔE($Q_{\beta\beta}$) ~ 9.5-28 keV
  - AMoRE-II (from 2024) @Yemilab (Corea)
    Stage 1: 90 LMOs (27 kg ^{100}Mo);
    Stage 2: 360 crystals (157 kg ^{100}Mo)
    Over 100 kg of enriched ^{100}MoO$_3$ powder has been purified

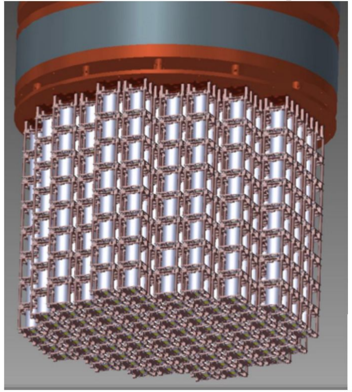


AMoRE-I updates (K.Hanbeom)
AMoRE-II plans (Y.Oh)
@TAUP2023

AMoRE-I tower:



AMoRE-II concept:



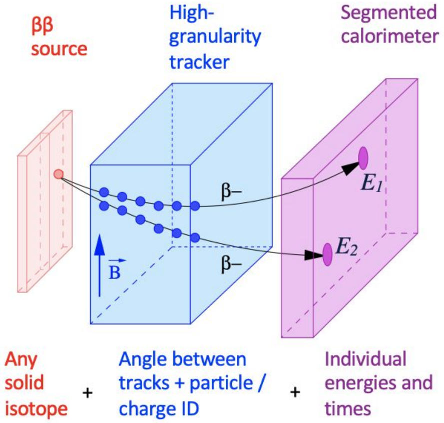
0νββ experimental landscape

Tracking calorimeters

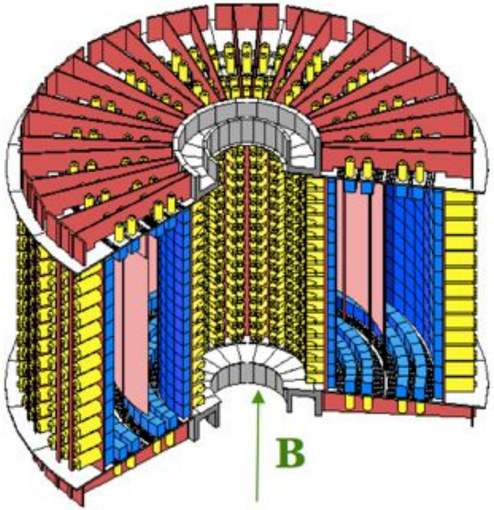
The 0νββ source is in the form of a foil sandwiched by drift chambers with an applied magnetic field for discriminating electrons and positrons, beyond which lie calorimeters for measuring energy. Capability of precisely measuring properties of the decay kinematics: single-energy spectra and opening angle distributions.

SuperNEMO (^{82}Se and other ββ isotopes)

- Full topological reconstruction
- Background rejection
- Unique 2νββ measurements (nuclear effects, new physics)
- Ability to probe 0νββ mechanism if discovered
- Status: Demonstrator currently taking data (~6 kg ^{82}Se) @Modane



Status of SuperNEMO (C.Patrick) @TAUP2023



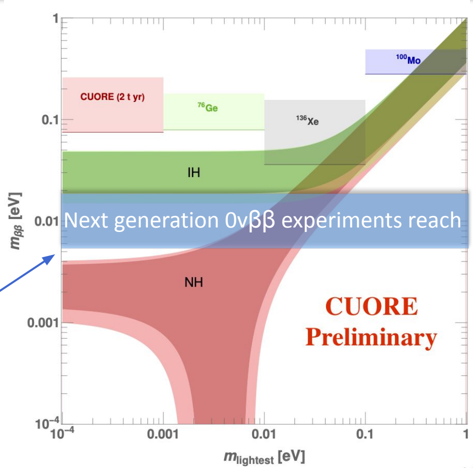
0νββ experimental landscape: summary

Current 0νββ decay experiments:
Exploring multiple isotopes and technologies; pushing to reach the upper part of Inverted Hierarchy in the $m_{\beta\beta}$ plot

Next generation of 0νββ decay experiments seek to be sensitive to the full Inverted Hierarchy region:
$S_{0\nu} > 10^{27}$ yr, $m_{\beta\beta} \sim 6$ - 20 meV

Key ingredients:

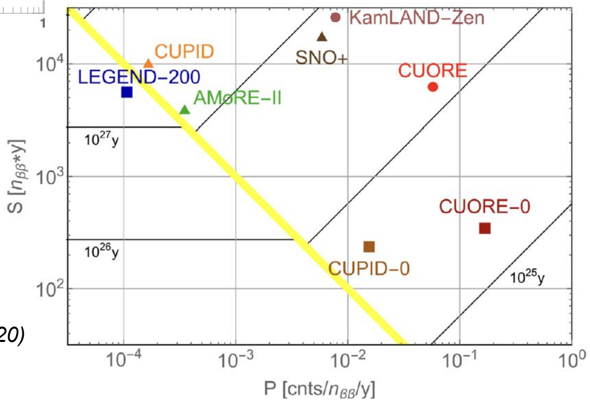
- Reach the ‘zero background’ regime: lower the background (and improve energy resolution) in the ROI
- Larger active masses



Next generation 0νββ experiments reach

CUORE 0νββ updates (K.Alfonso) @TAUP2023

Width of the mββ intervals due to large uncertainties on NMEs



iso-sensitivity $S_{0\nu}$ lines

S = scale,
P = performance

Progr. Part. Nucl. Phys.Vol. 114,103803 (2020)
https://doi.org/10.1016/j.ppnp.2020.103803

Conclusions

Searches for 0νββ are a powerful probe of lepton number violation in nature and the most sensitive experimental test of whether neutrinos are Majorana particles.

There is at present a diverse and healthy competition among a variety of experimental techniques.
Many projects aim at extending the present sensitivity.
Continuous theoretical progress on determining accurate NMEs and LNV phenomenology for 0νββ decay.

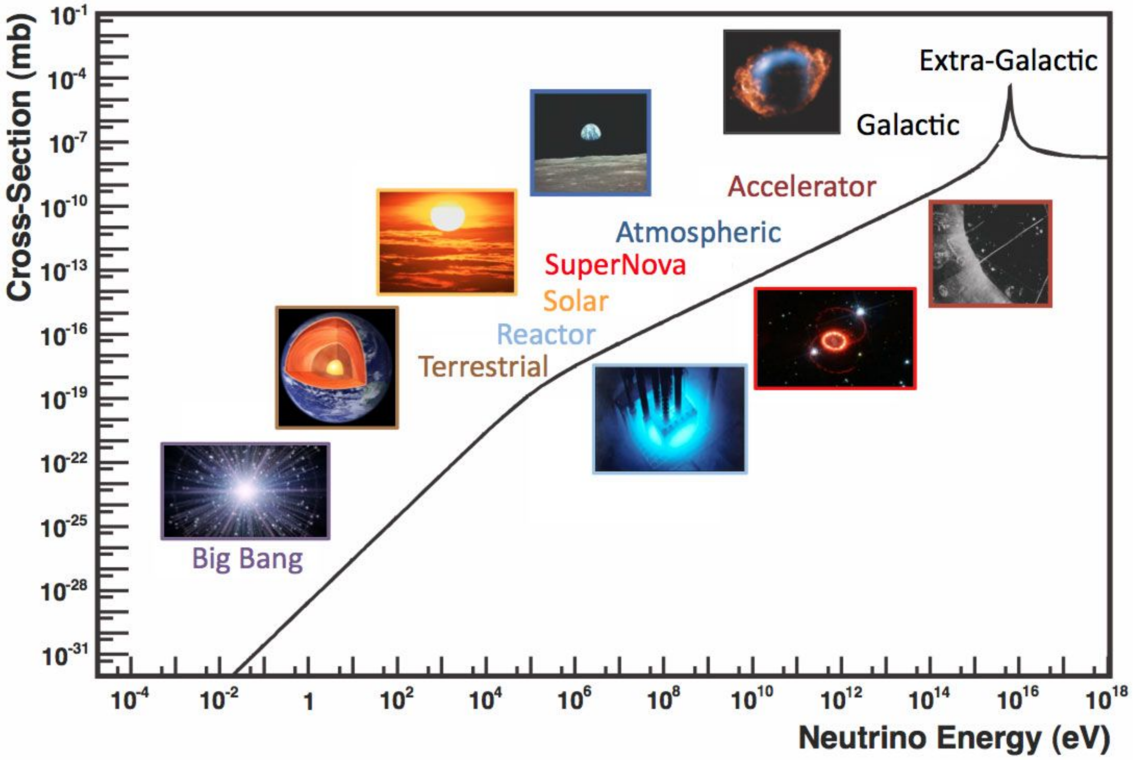
Next-generation experiments have a good discovery potential!

Image from ββ decay review - A.Giuliani (TAUP2021)

Backup

What do we know about neutrinos: neutrino sources

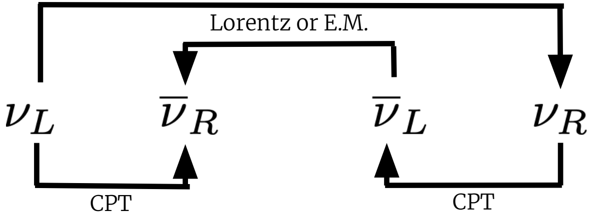
Neutrinos are produced by many mechanisms with energies spanning several orders of magnitude (from sub-eV to >10^{15} eV).



Neutrino mass nature: Dirac or Majorana

Neutrinos are the only particles in the SM that could be Majorana fermions, that is, completely neutral fermions that are their own antiparticles.

Dirac neutrino

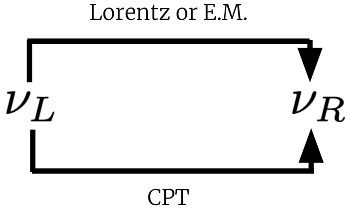


- 4 ν states with same mass
- Impose the lepton number conservation
- Yukawa coupling with Higgs doublet for ν mass
- Degenerate states
- ν_L active, ν_R sterile

$$\mathcal{L}^D_{mass,\nu} = m_{D}{}'\overline{\nu}_L\nu_R + h.c.)$$

where $m_\nu = y_\nu v$

Majorana neutrino



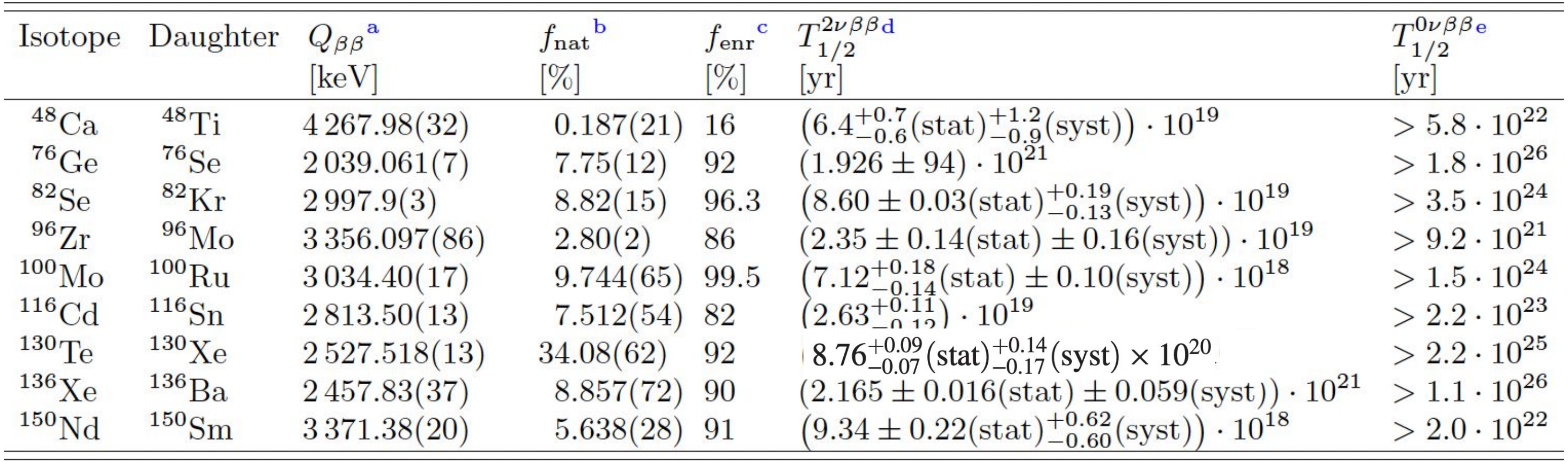
Neutrinos are charge-less (apart from L), a neutrino could be its own anti-particle: $\nu_i = \overline{\nu}_i$

- 2 ν states with same mass
- **Lepton number violating mass term** $\mathcal{L}^M_{mass,\nu} = m_\nu \overline{\nu}_L \nu^c_L$
- See-Saw: Recover 4 nu states
  - Light active neutrinos ν_i
  - Heavy sterile partners N_i

Neutrinoless double beta decay is an unique tool to probe the majorana Nature of the neutrino

2νββ and 0νββ: current measurements/limits

Target isotopes currently being pursued by 0νββ leading experiments

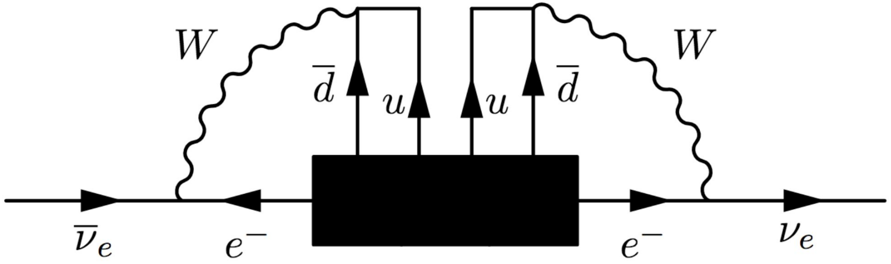


Isotope	Daughter	$Q_{\beta\beta}$ [a] [keV]	f_{nat} [b] [%]	f_{enr} [c] [%]	$T_{1/2}^{2\nu\beta\beta}$ [d] [yr]	$T_{1/2}^{0\nu\beta\beta}$ [e] [yr]
^{48}Ca	^{48}Ti	4 267.98(32)	0.187(21)	16	$(6.4^{+0.7}_{-0.6}(\mathrm{stat})^{+1.2}_{-0.9}(\mathrm{syst}))\cdot 10^{19}$	$> 5.8 \cdot 10^{22}$
^{76}Ge	^{76}Se	2 039.061(7)	7.75(12)	92	$(1.926 \pm 94)\cdot 10^{21}$	$> 1.8 \cdot 10^{26}$
^{82}Se	^{82}Kr	2 997.9(3)	8.82(15)	96.3	$(8.60 \pm 0.03(\mathrm{stat})^{+0.19}_{-0.13}(\mathrm{syst}))\cdot 10^{19}$	$> 3.5 \cdot 10^{24}$
^{96}Zr	^{96}Mo	3 356.097(86)	2.80(2)	86	$(2.35 \pm 0.14(\mathrm{stat}) \pm 0.16(\mathrm{syst}))\cdot 10^{19}$	$> 9.2 \cdot 10^{21}$
^{100}Mo	^{100}Ru	3 034.40(17)	9.744(65)	99.5	$(7.12^{+0.18}_{-0.14}(\mathrm{stat}) \pm 0.10(\mathrm{syst}))\cdot 10^{18}$	$> 1.5 \cdot 10^{24}$
^{116}Cd	^{116}Sn	2 813.50(13)	7.512(54)	82	$(2.63^{+0.11}_{-0.12})\cdot 10^{19}$	$> 2.2 \cdot 10^{23}$
^{130}Te	^{130}Xe	2 527.518(13)	34.08(62)	92	$(8.76^{+0.09}_{-0.07}(\mathrm{stat})^{+0.14}_{-0.17}(\mathrm{syst}) \times 10^{20}$	$> 2.2 \cdot 10^{25}$
^{136}Xe	^{136}Ba	2 457.83(37)	8.857(72)	90	$(2.165 \pm 0.016(\mathrm{stat}) \pm 0.059(\mathrm{syst}))\cdot 10^{21}$	$> 1.1 \cdot 10^{26}$
^{150}Nd	^{150}Sm	3 371.38(20)	5.638(28)	91	$(9.34 \pm 0.22(\mathrm{stat})^{+0.62}_{-0.60}(\mathrm{syst}))\cdot 10^{18}$	$> 2.0 \cdot 10^{22}$

0νββ decay and inference on neutrino mass

In theories beyond the Standard Model, there may be several sources of total lepton number violation which can lead to 0νββ. Nevertheless, irrespective of the mechanism, 0νββ necessarily implies Majorana neutrinos.

Black box (or Schechter–Valle) theorem



0vββ decay and inference on neutrino mass

The standard neutrinoless double-beta decay mechanism: light Majorana neutrino exchange

$$\frac{1}{T_{1/2}^{0\nu}} \propto G(Q_{\beta\beta}, Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

Effective neutrino mass term |$m_{\beta\beta}|^2$

0vββ is directly connected to neutrino oscillations phenomenology, and that it also provides direct information on the absolute neutrino mass scale, as cosmology and decay experiments do.

The relationship between $m_{\beta\beta}$ and the actual neutrino masses m_i is affected by:

1. the uncertainties in the measured oscillation parameters;
2. the unknown neutrino mass ordering (normal or inverted);
3. the unknown phases in the neutrino mixing matrix (both Dirac and Majorana).

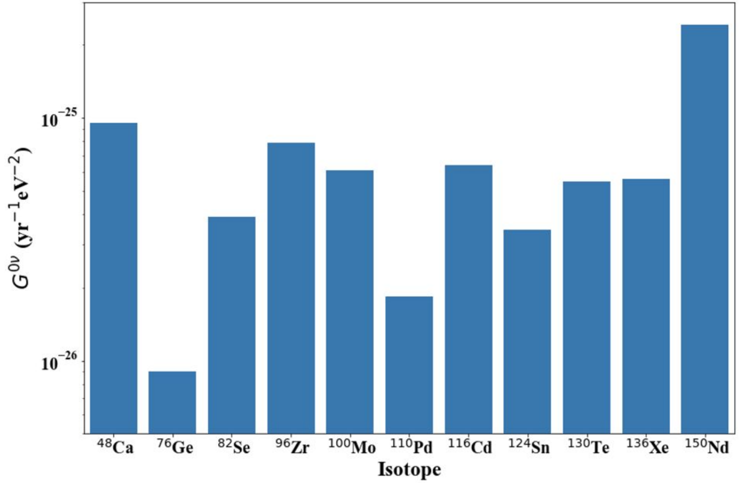
0νββ decay and inference on neutrino mass

The standard neutrinoless double-beta decay mechanism: light Majorana neutrino exchange

$$\frac{1}{T_{1/2}^{0\nu}} \propto G(Q_{\beta\beta}, Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

Phase space integral

Phase-space factors are calculated analytically and are quite accurately known for all relevant nuclei used in 0νββ decay experiments



La Rivista del Nuovo Cimento (2023) 46:619–692
https://doi.org/10.1007/s40766-023-00049-2

0νββ decay and inference on neutrino mass

The standard neutrinoless double-beta decay mechanism: light Majorana neutrino exchange

$$\frac{1}{T^{0\nu}_{1/2}} \propto G(Q_{\beta\beta}, Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

Nuclear Matrix Elements

$$|M_{nucl}|^2 = g_A^4|M^{0\nu}_{light}|^2$$

The “gA quenching" is a potential source of uncertainty in 0νββ-decay NMEs. Most calculations systematically overestimate β-decay Gamow–Teller matrix elements.

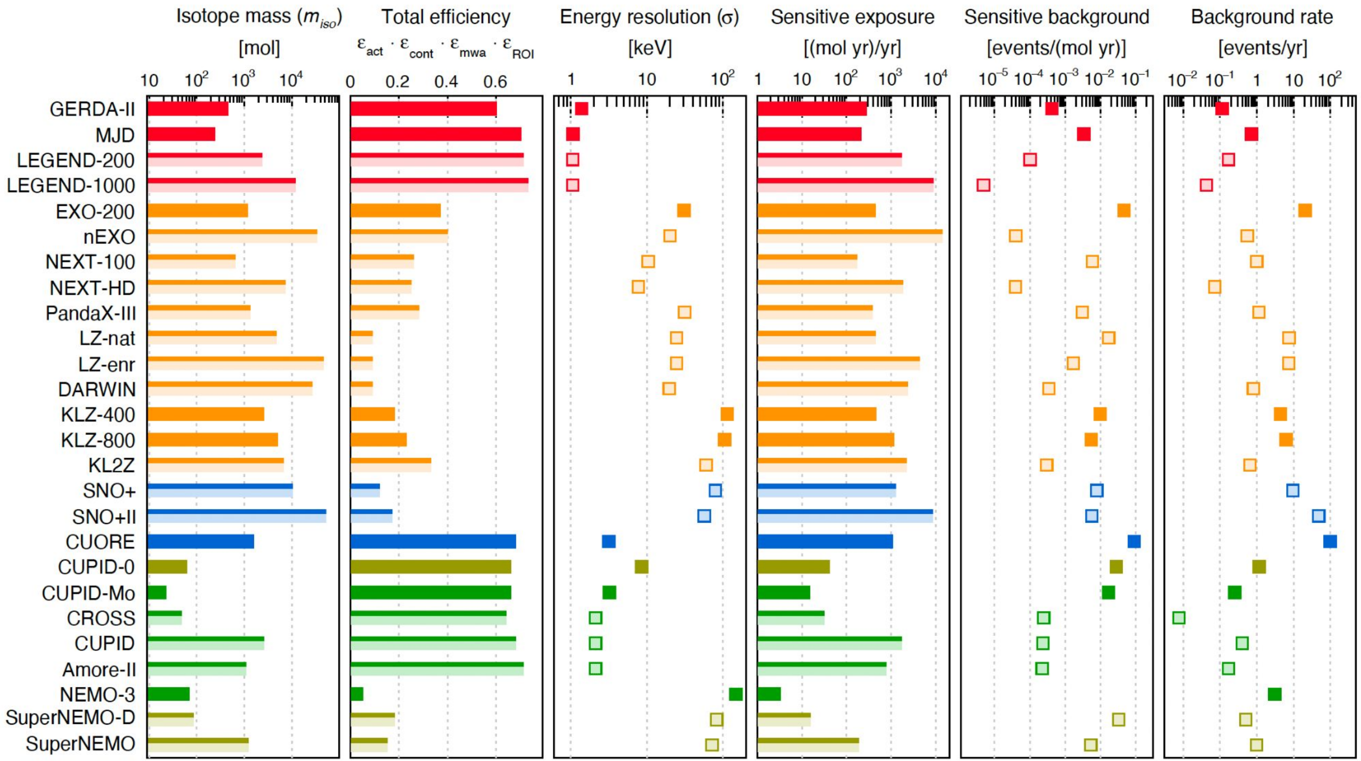
This implies the need of a correction, by quenching the value of the axial coupling g_A ($g_A' = q\, g_A$ with q ~0.7-0.8).

Very recently decay β-decay has been studied with the ab initio methods.

These calculations suggest that the overprediction of matrix elements is more likely related to the GT β-decay operator than to g_A.

0νββ experimental landscape

Each detection concept is characterized by specific parameter combinations.



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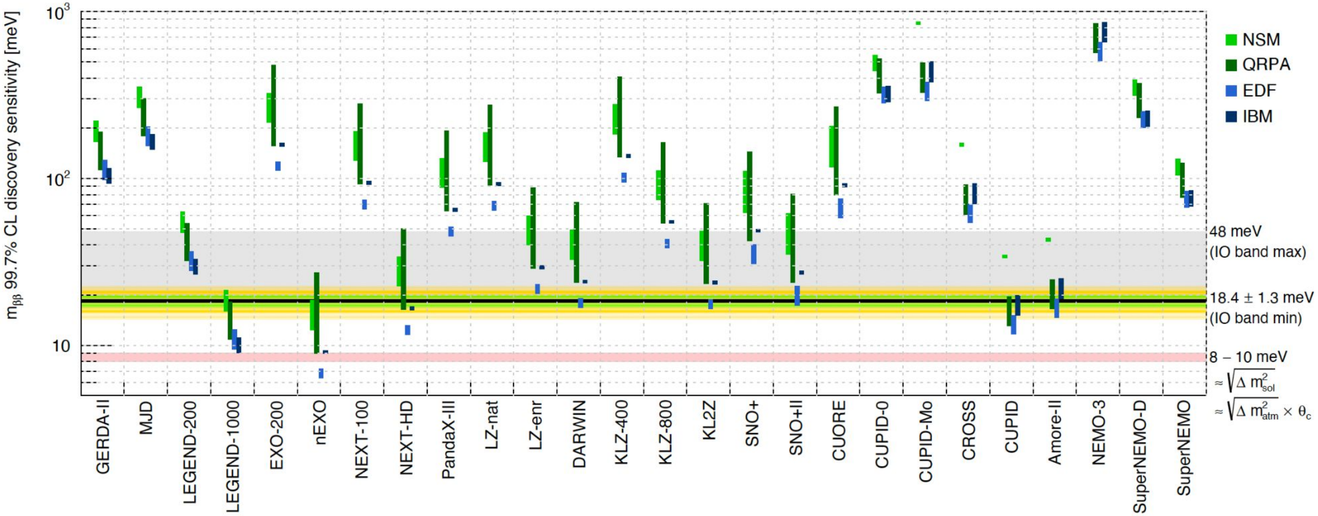
0νββ experimental landscape: summary

Discovery sensitivities of current- and next-generation *0νββ* decay experiments for exchange dominated by the light neutrino exchange, and effect of the NMEs.



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