Probing the Nature of Neutrinos: the Search for Neutrinoless Double-β Decay

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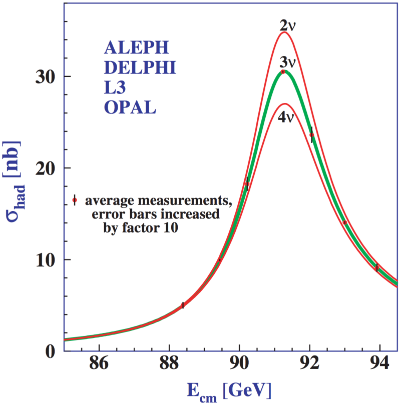
Table of Contents

Neutrinos in the Standard Model

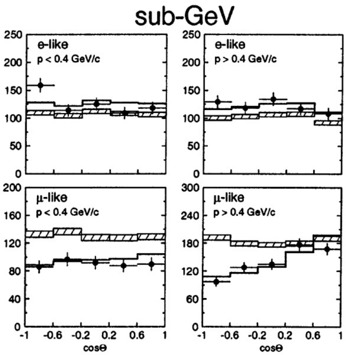
- proposed in 1930, Pauli
- discovered in 1956, reactor $\overline{\nu}_e$, Cowan and Reines
- Lee, Yang, Wu in 1956–1957: parity violation
- Goldhaber in 1957: neutrinos are left-handed
- three light active neutrinos ν_e, ν_μ, and ν_τ
- $N = 2.9840 \pm 0.0082$ from Z boson decay
- neutrinos were considered massless in Standard Model



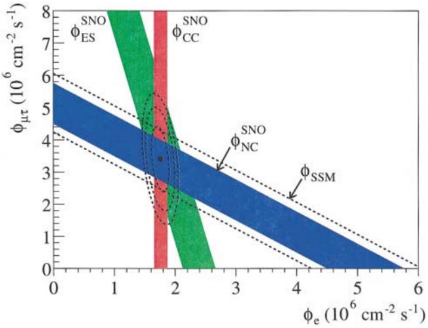
Number of active neutrino flavors from Z decay in LEP experiments.

Discovery of Neutrino Oscillations

- Super-Kamiokande: atmospheric ν_μ disappearance
- SNO: ν_e flux and total neutrino $\nu_{e,\mu,\tau}$ flux from the Sun
- neutrinos have non-zero mass, 2015 Nobel Prize



(a) Super-Kamiokande, 1998 [1]



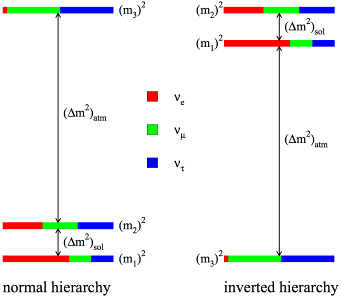
(b) SNO, 2002 [2]

Neutrino Oscillation Measurements

- ν_α: state with specific flavor (ν_e, ν_μ, ν_τ)
- ν_i: state with specific mass (m_1, m_2, m_3)
- $|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$, matrix U is unitary, called PMNS matrix

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & -s_{13}e^{i\delta_{CP}} \\ & 1 & \\ -s_{13}e^{i\delta_{CP}} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

- θ_{ij}, δ_{CP}, $\Delta m^2_{ij} = m^2_i - m^2_j$
- θ_{12}, Δm^2_{21} (solar, reactor)
- θ_{23}, $\left|\Delta m^2_{32}\right|$ (atmo., beam)
- θ_{13} (reactor)
- $\left|\Delta m^2_{32}\right| = 2.5 \times 10^{-3}\,\mathrm{eV}^2$
  $\Delta m^2_{21} = 7.5 \times 10^{-5}\,\mathrm{eV}^2$
- mass ordering and absolute masses remain unknown

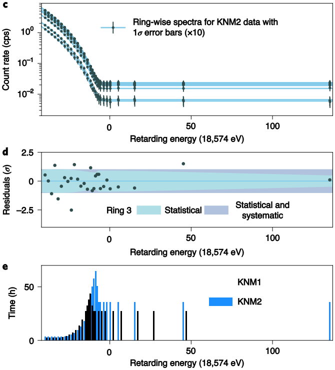


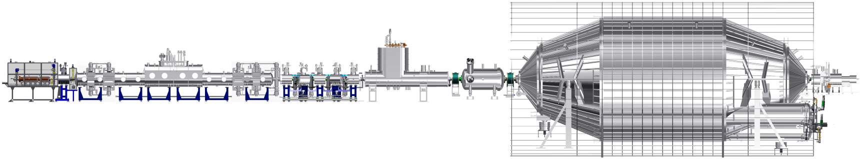
normal hierarchy

inverted hierarchy

Absolute Neutrino Masses

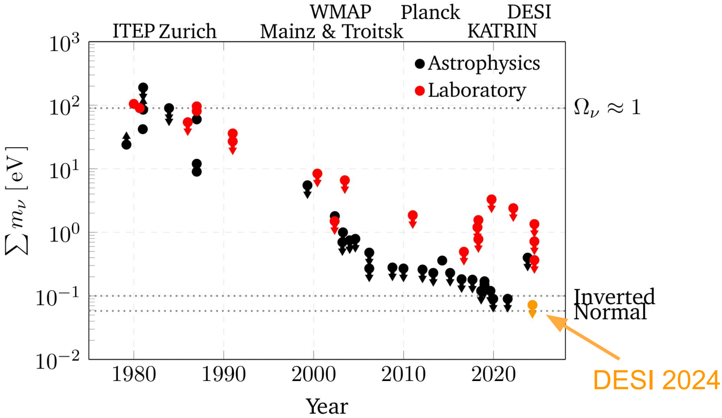
- KATRIN experiment [3]
  - end point of tritium β decay at 18.574 keV
  - $m_\beta^2 = \sum |U_{ei}|^2 m_i^2$
  - $m_\beta < 1.1\,\mathrm{eV}$, 2019 [3]
  - $m_\beta < 0.8\,\mathrm{eV}$, 2021 [4]
  - $m_\beta < 0.45\,\mathrm{eV}$, 2024, [5]
- cosmology, Planck data
  - e.g. $\sum m_i < 0.28\,\mathrm{eV}$ [6]
  - cosmological model dependent





New constraints from DESI

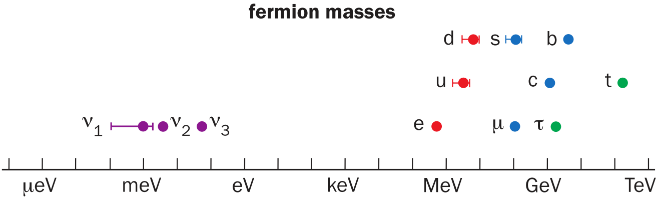
- Dark Energy Spectroscopic Instrument (DESI): spectra of > 6 million extragalactic objects, precision measurements of large-scale distribution of matter in the Universe
- CMB + DESI BAO limit in 2024: $\sum m_\nu < 0.072\,\mathrm{eV}$ [7]



Where Do Neutrino Masses Come from? [13]

- neutrinos can be Dirac particles: $m\overline{\psi}_R\psi_L$, need ψ_R

- why are neutrino masses so small?



- a different possible source: seesaw mechanism [8–12]

- seesaw requires that neutrinos are Majorana particles

Majorana Neutrinos

- Majorana in 1937: $\nu = \overline{\nu}$ [14]

$$(i\widetilde{\gamma}^{\mu}\partial_{\mu} - m)\widetilde{\psi} = 0,$$

where $\widetilde{\gamma}^{\mu}$ are purely imaginary satisfying Clifford Algebra, $i\widetilde{\gamma}^{\mu}$ is real, $\widetilde{\psi}$ is a real field [15]

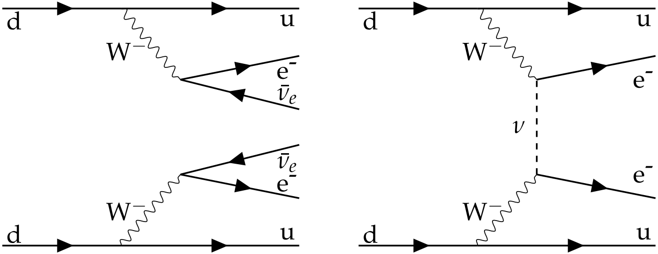
> *"The theory, however, can be obviously modified so that the β-emission, both positive and negative, is always accompanied by the emission of a neutrino."*
> — E. Majorana [14]

- besides neutrino mass, may also help explain baryon asymmetry: leptogenesis [16], L violation induces B violation
- most promising probe: neutrinoless double-β decay

Neutrinoless Double-β Decay

- double-β ($2\nu\beta\beta$) decay
  - first calculated by Goeppert-Mayer in 1935
  - first direct observation: $^{82}\mathrm{Se} \to {}^{82}\mathrm{Kr} + 2e^- + 2\overline{\nu}$ in a time projection chamber (TPC), Elliott, Hahn, and Moe, 1987
- neutrinoless double-β ($0\nu\beta\beta$) decay, Furry, 1939, lepton number violation process, Majorana ↔ $0\nu\beta\beta$ decay [17]

$$^{A}_{Z}\mathrm{X} \to {}^{\ \ A}_{Z+2}\mathrm{X} + 2e^-$$



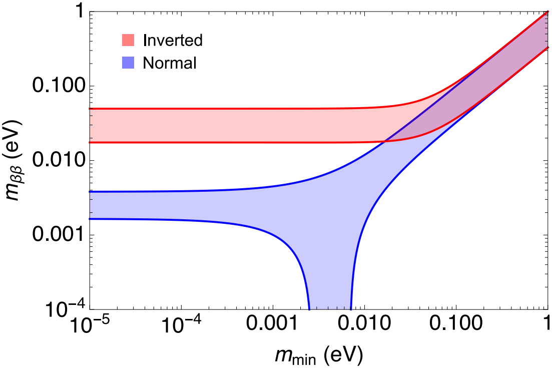
Feynman diagrams of $2\nu\beta\beta$ and $0\nu\beta\beta$ decays.

Decay Half-Life

- decay half-life

$$\frac{1}{T_{1/2}} = G^{0\nu}\left|M^{0\nu}\right|^2 \frac{m_{\beta\beta}^2}{m_e^2}.$$

  - phase factor $G^{0\nu}$, nuclear matrix element $M^{0\nu}$
  - effective Majorana mass $m_{\beta\beta} = \left|\sum_k U_{ek}^2 m_k\right|$
- $m_{\beta\beta}$ vs. mass ordering and absolute neutrino mass



Experimental Design

Signal Signature

- mono-energetic peak at $Q_{\beta\beta}$
- background free

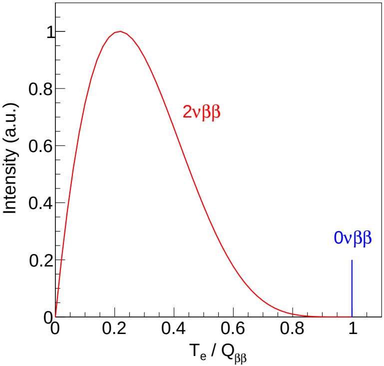
$$T_{1/2} \propto \epsilon M t$$

where M is mass, t is running time, ϵ is efficiency

- with background

$$T_{1/2} \propto \epsilon \sqrt{\frac{Mt}{B\Delta E}}$$

  - B: background index, in $\mathrm{keV}^{-1}\,\mathrm{kg}^{-1}\,\mathrm{yr}^{-1}$
  - ΔE: energy resolution

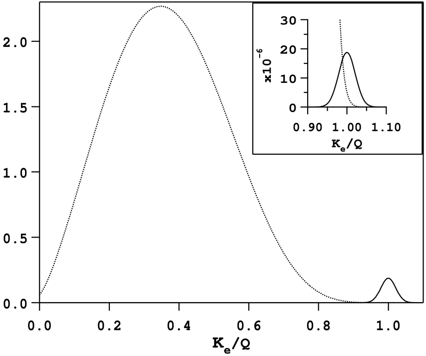


The two-electron energy spectrum for the $2\nu\beta\beta$ and $0\nu\beta\beta$ decays. For example, $Q_{\beta\beta} = 2039\,\mathrm{keV}$ for ^{76}Ge, and 2458 keV for ^{136}Xe.

Intrinsic $2\nu\beta\beta$ Background

- $T^{2\nu}_{1/2} \ll T^{0\nu}_{1/2}$, $2\nu\beta\beta$ decay is a potential ultimate background
- the fraction of the $2\nu\beta\beta$ counts in the peak region [18]

$$F \propto (\Delta E/Q_{\beta\beta})^6$$



Signature of $0\nu\beta\beta$ decay in the observed spectrum of electron energy normalized by the Q value ($Q_{\beta\beta}$) [18].

Choice of Isotopes

- high abundance: lower cost in enrichment, or without enrichment, e.g. ^{130}Te
- high $Q_{\beta\beta}$: low intrinsic $2\nu\beta\beta$ background, low background of radioactivity

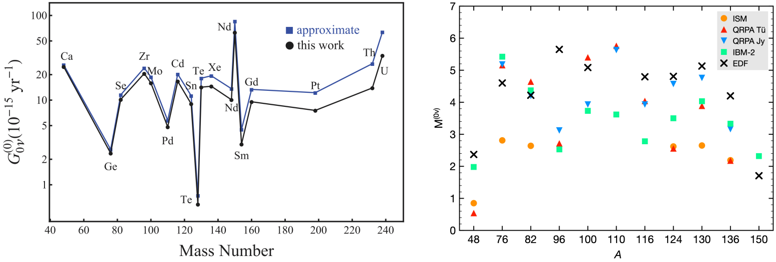
isotope	natural abundance (%)	$Q_{\beta\beta}$(MeV)
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	8.7	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.8	3.035
^{116}Cd	7.5	2.813
^{130}Te	34.08	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371

Nuclear Matrix Element and Phase Space Factor

- larger $\left|M^{0\nu}\right|^2$ and $G^{0\nu}$, easier for $0\nu\beta\beta$ decay to happen

$$1/T_{1/2} = G^{0\nu}\left|M^{0\nu}\right|^2 m_{\beta\beta}^2/m_e^2$$

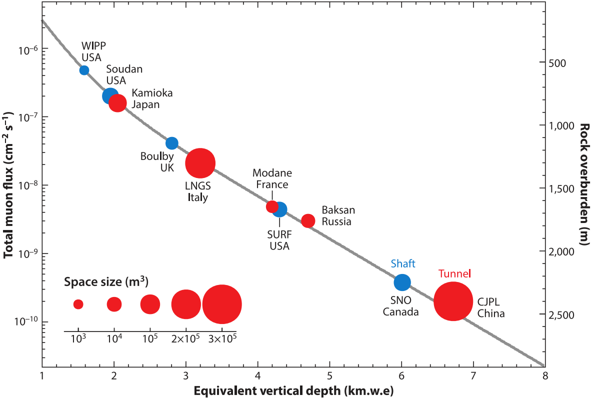
- uncertainty in $\left|M^{0\nu}\right|^2$ due to nuclear models



Phase factors [19] and nuclear matrix elements [20].

Background Challenges

- cosmic rays and cosmogenic activation, e.g. ^{77}Ge, ^{137}Xe
- radioactivity of detector materials, e.g. ^{235}U, ^{238}U, ^{232}Th
- anthropogenic, e.g. ^{60}Co, ^{137}Cs, ^{110m}Ag
- neutrinos: $\nu + e^- \to \nu + e^-$

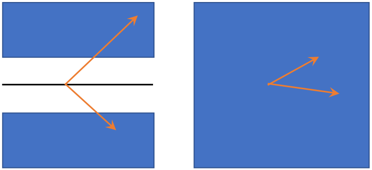


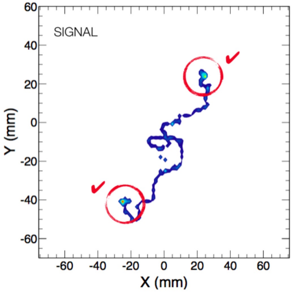
World underground laboratories [21].

Experimental Programs

Main Approaches

- source $\neq$ detector
  - source on a foil
  - event energy and topology
  - low resolution and efficiency
- source $=$ calorimeter
  - measure double-β energy
  - high resolution and efficiency
  - no event topology
- source $=$ calorimeter $=$ tracker
  - high pressure gas TPC
  - high efficiency and resolution, event topology
  - large volume, weak self-shielding

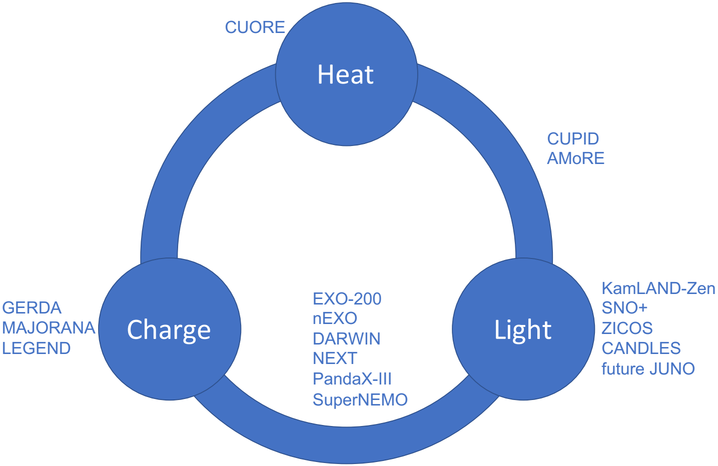




Bottom figure taken from [22] based on simulation.

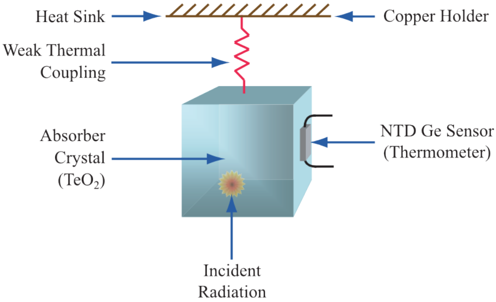
Detector Signals

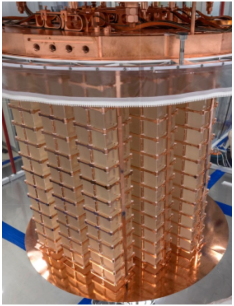
- signals come in form of heat (bolometer), light (scintillator), and charge (semiconductor, etc.)
- non-exhaustive list, selectively introduce them clockwise



CUORE Experiment

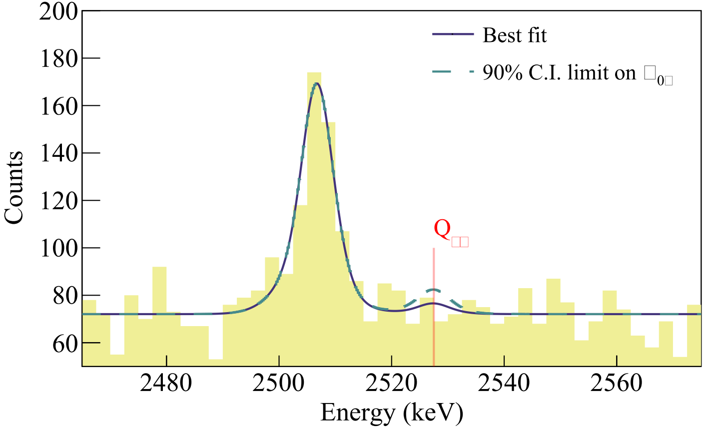
- Cryogenic Underground Observatory for Rare Events, at LNGS
- bolometers, ultra-cold $^{130}\mathrm{TeO}_2$
- 988 TeO_2 crystals, 206 kg of $^{130}\mathrm{Te}$, 11.8 mK
- 7 keV FWHM at $Q_{\beta\beta}$, taking data since 2019





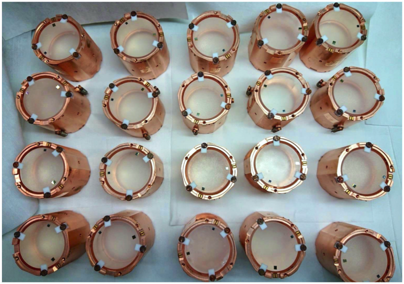
CUORE 2024 Results

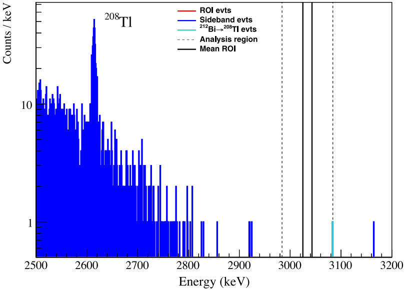
- 2024 new result: $T_{1/2} > 2.2 \times 10^{25}$ yr at 90% C.L. [23]
- about 2 t yr TeO_2 exposure (plan to stop at 3 t yr), background $1.42 \times 10^{-2}\,\mathrm{keV^{-1}\,kg^{-1}\,yr^{-1}}$
- 90% background near $Q_{\beta\beta}$ from α, ^{60}Co peak at 2505.7 keV



CUPID Experiment

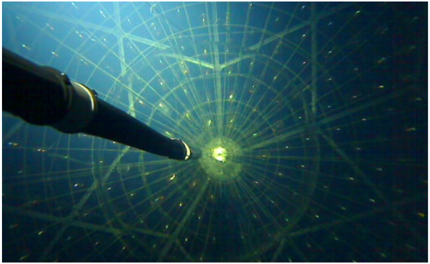
- CUPID: CUORE Upgrade with Particle Identification
- separate α from β/γ with the same energy
- CUPID-0: scintillating bolometers Zn^{82}Se crystals
- CUPID-Mo: Li$_2$ ^{100}MoO$_4$, chosen for CUPID ton-scale
- PRL 126, 181802 (2021), 1.17 kg yr, 7.6 keV FWHM [24]

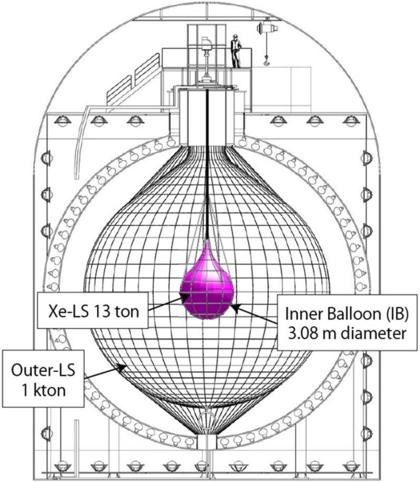




KamLAND-Zen

- multi-ton scale experiment, light from liquid scintillator
- liquid scintillator loaded with 3.1% Xe, 745 kg, 91% enriched
- ^{110m}Ag from Fukushima (2011)
- 270 keV FWHM

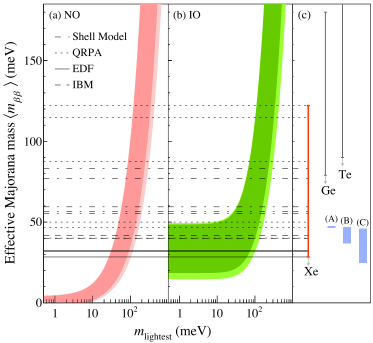


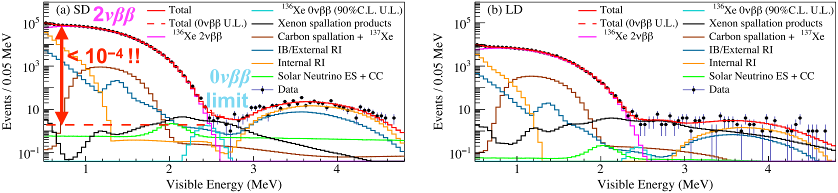


1879 17-inch and 20-inch PMTs

Kamland-Zen 2024 Results [25]

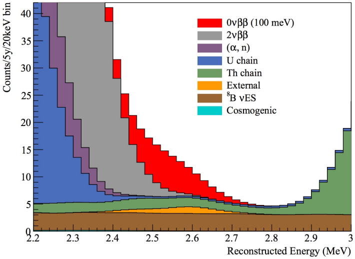
- Zen 400: $T_{1/2} > 0.9 \times 10^{26}$ yr
- Zen 800: $T_{1/2} > 3.4 \times 10^{26}$ yr
- combined: $T_{1/2} > 3.8 \times 10^{26}$ yr
- most stringent in the inverted mass ordering region!
- future: KamLAND2, more light yield, new electronics, etc. cover inverted region



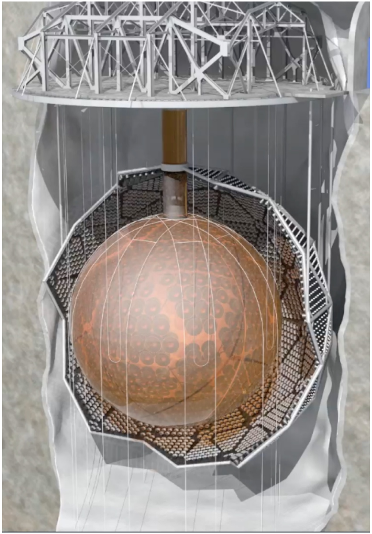


SNO+

- SNOLAB, 5890 mwe
- 780 tons liquid scintillator is in, will be loaded with 0.5% natural Te, 1300 kg ^{130}Te
- 7000 tons water for shielding, $\sim$ 9300 PMTs

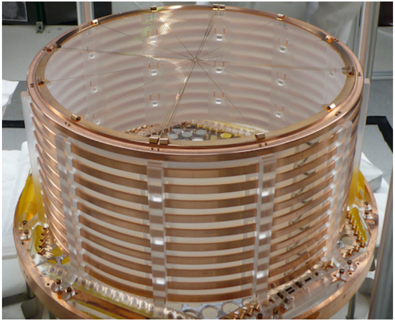


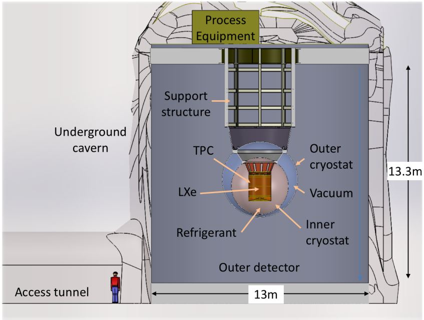
Expected spectrum [26].



EXO-200, nEXO

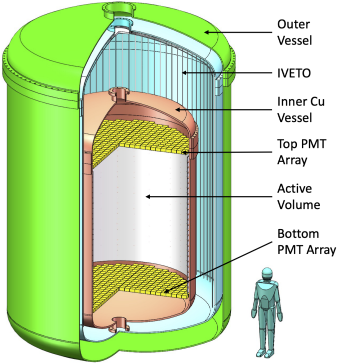
- liquid Xe TPC, single phase, enriched
- EXO-200 (Enriched Xenon Observatory)
  - 110 kg of Xe, enriched to 80.6% in ^{136}Xe
  - PRL 123, 161802 (2019), 67 keV FWHM ($\sigma/E = 1.15\%$)
- nEXO (next EXO), plann to use 5 ton of Xe, barium tagging

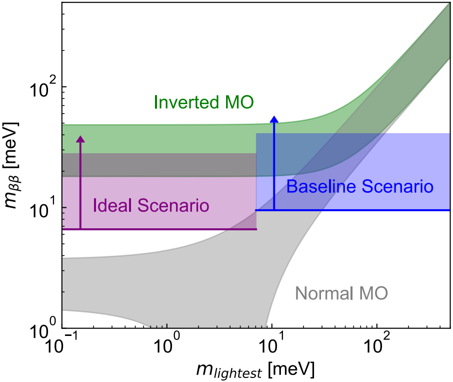




DARWIN, XLZD, PandaX-xT

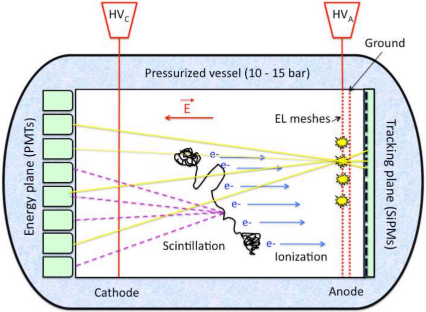
- liquid Xe duel phase TPC for dark matter WIMP searches
- $\sigma/E = 0.8\%$ resolution at $Q_{\beta\beta}$ achieved in XENON1T [27]
- DARWIN: 50t Xe for dark matter searches, 3.6t of ^{136}Xe [28]
- PandaX-xT, expect sensitivity below inverted ordering [29]

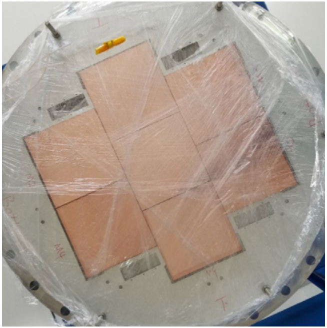




NEXT, AXEL, PandaX-III

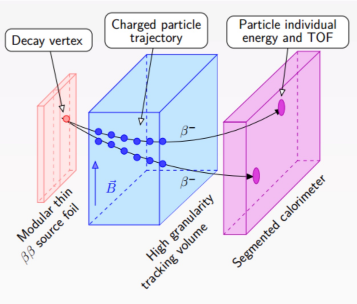
- high pressure gas Xe TPC: high resolution ($< 1\%$ FWHM [30], $\sigma/E < 0.4\%$), topology to reject α, β and γ
- NEXT: electroluminescent amplification + PMTs, NEXT-100: 100 kg, under comissioning
- PandaX-III: fine-pitch Micromegas [31]
- AXEL: cellular photosensors, electroluminescence (ELCC) [32]

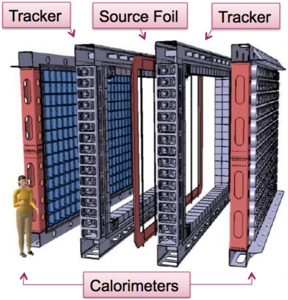




SuperNEMO

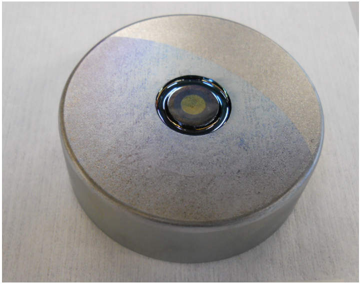
- built upon the success of NEMO-3
- thin foil enriched in double-β isotope, flexibility in isotope type
- wire-chamber tracker: measure particles' trajectories, background rejection
- segmented calorimeter: energy and timing

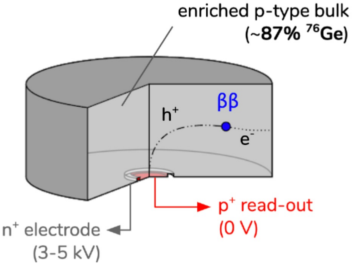




GERDA, MAJORANA, and LEGEND

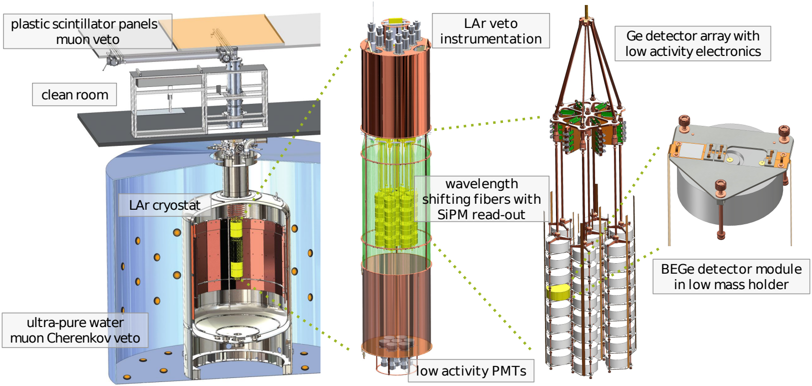
- $^{76}\mathrm{Ge} \to {}^{76}\mathrm{Se} + 2e^-$
- source is also detector, high efficiency
- best energy resolution and lowest background index in all $0\nu\beta\beta$ decay experiments
- commercial technology, modest cryogenic requirements





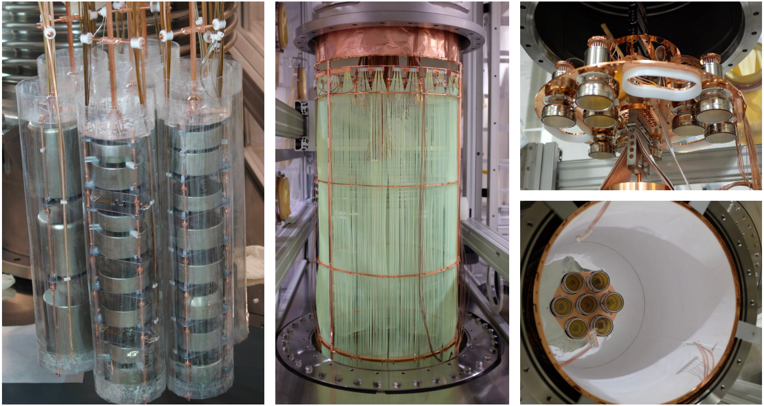
GERDA Experiment

- LNGS, Italy, 3500 wme, 10^6 reduction of cosmic rays
- water tank: 10 m diameter, muon veto, shielding
- LAr veto: 0.5 m diameter, 2 m high, veto, shielding, cooling
- about 40 detectors, enriched to about 87%, 35.6 kg



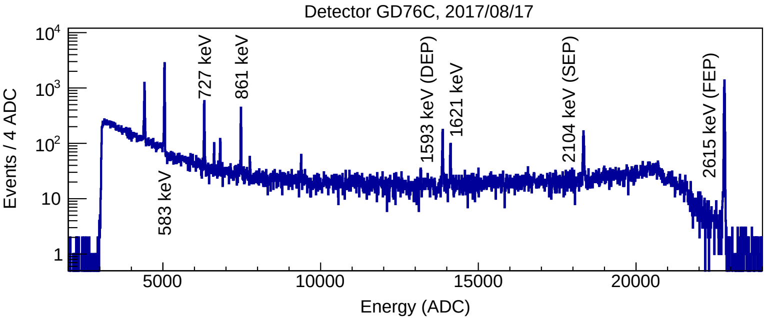
Detector Array and Liquid Argon Veto Instrumentation

- detectors mounted on 6 strings, nylon cylinder
- liquid argon veto: TPB reflector, PMTs, wavelength shifting fibers + SiPMs



Energy Calibration

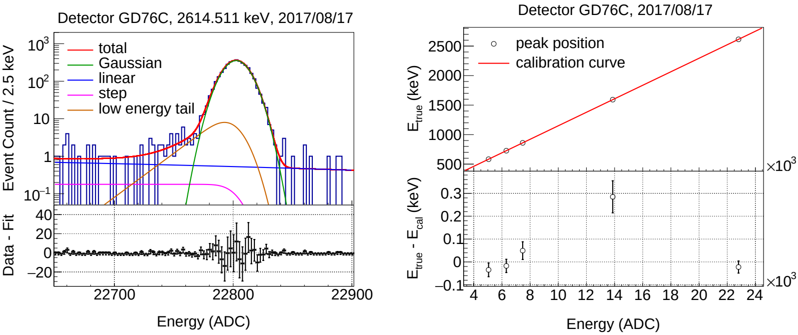
- ^{228}Th, weekly calibration
- between calibrations: test pulses injected every 20 s, stable operating conditions for physics analysis is about 80%



An example of the GERDA Phase II calibration data.

Calibration Curve

- after each calibration, find the position of the gamma lines
- fit a linear function as the calibration curve (ADC to keV)
- energy resolution determined from width of Gaussian

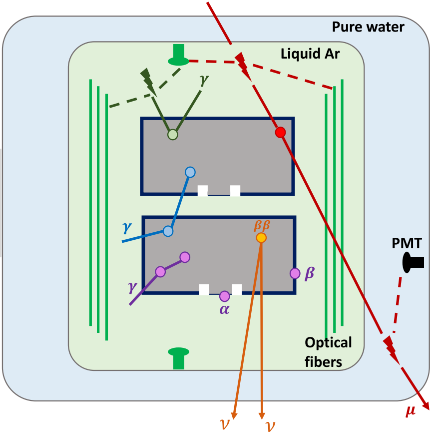


(a) fit to full energy peak

(b) calibration curve

Background Reduction

- liquid argon veto + pulse shape discrimination + cosmic veto
- first in the field to operate in background-free regime
- signal efficiency: 46% for coaxial, 61% for BEGe, 66% for IC



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

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

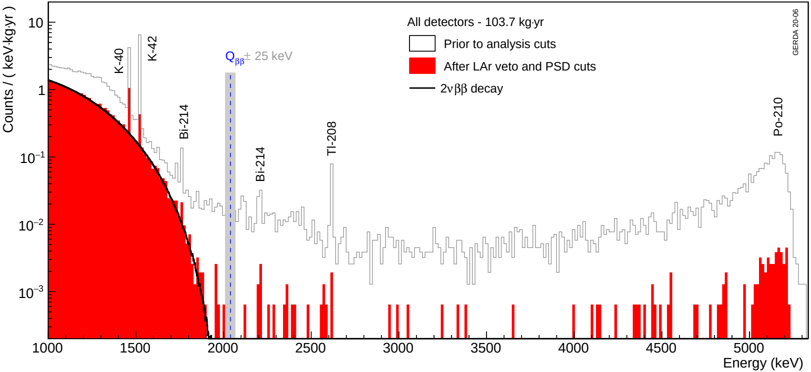
Ge detector anti-coincidence

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

Muon veto based on Cherenkov light and plastic scintillator

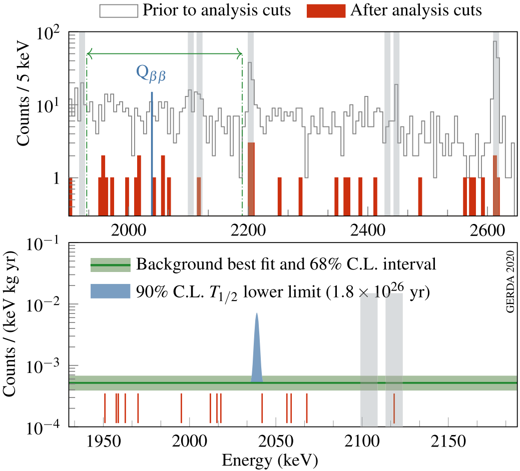
Energy Spectrum

- analysis cut: liquid argon veto, pulse shape discrimination
- at low energy, dominated by $2\nu\beta\beta$ decay of ^{76}Ge
- $Q_{\beta\beta} \pm 25\,\text{keV}$ for blind analysis



Calibrated energy spectrum after all event selections.

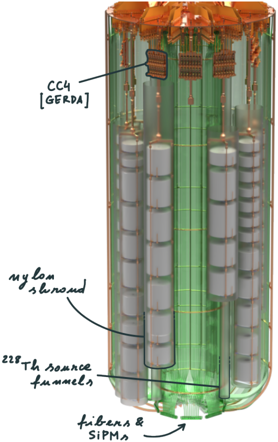
Final GERDA Results: PRL 125 (2020), 252502

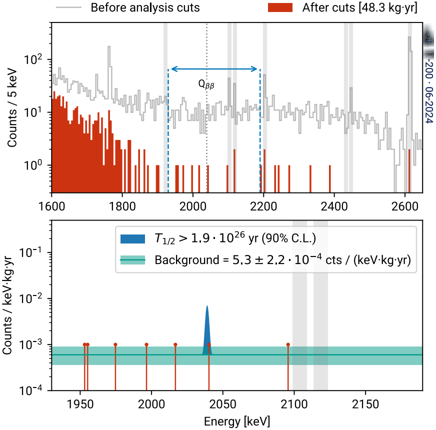


- half-life limit: $T_{1/2} > 1.8 \times 10^{26}$ yr at 90% C.L.
- world's lowest background: $B = 5.2 \times 10^{-4}$ cts/(keV kg yr)

LEGEND-200 Detector and New Results

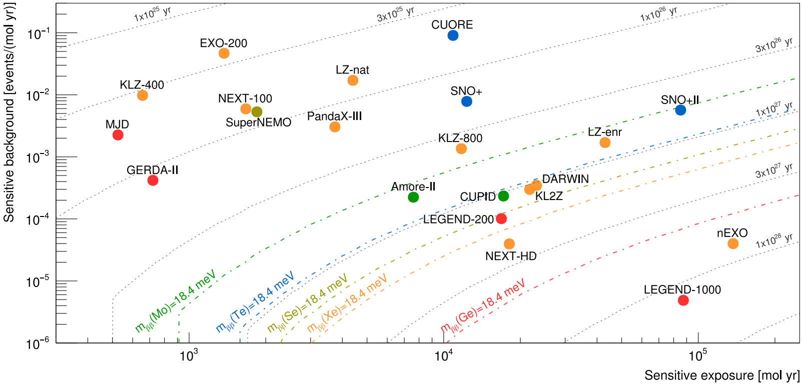
- about 130kg of Ge, a year data taking since early 2023, new results in Neutrino 2024 (talk by Luigi Pertoldi)
- background index: BI $= 5.3 \times 10^{-4}\,\mathrm{cts}/(\mathrm{keV\,kg\,yr})$, $T_{1/2} > 1.9 \times 10^{-26}\,\mathrm{yr}$





Comparison: Background vs. Exposure

- keys to $0\nu\beta\beta$ experiments: background and exposure
- extreme background requirements for LEGEND, nEXO, etc.

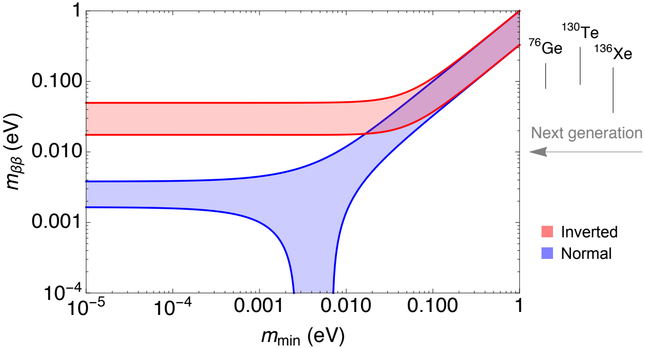


A summary of background and exposure for various experiments [33].

Current Status

- leading constraints on $m_{\beta\beta}$ comes from ^{76}Ge, ^{130}Te, and ^{136}Xe
- region above the inverted mass ordering is mostly excluded

isotope	experiment	year	half-life limit (yr)	$m_{\beta\beta}$ (meV)	reference
^{76}Ge	LEGEND-200	2024	1.9×10^{26}	~79-180	[34]
^{136}Xe	KamLAND-Zen	2024	3.8×10^{26}	28-122	[25]
^{130}Te	CUORE	2024	3.8×10^{25}	70-240	[23]



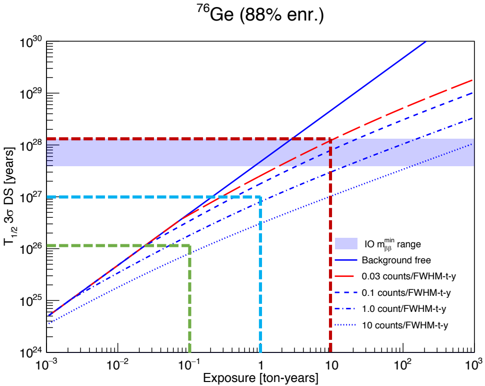
Future Prospect

- cover inverted ordering region: $m_{\beta\beta} \sim 10\,\text{meV}$, use larger mass, further reduce background
- CUPID, nEXO, KamLAND2-Zen, NEXT, etc.
- LEGEND: 1 ton of ^{76}Ge, run for 10 yr, 10^{28} yr
- dark matter experiments (XLZD/DARWIN/PandaX, CDEX), future JUNO, new ideas (NvDEx, etc.)

LEGEND-1000
1000 kg, $T_{1/2} > 10^{28}$

LEGEND-200
200 kg, $T_{1/2} > 10^{27}$

GERDA/MAJORANA
30 kg, $T_{1/2} > 10^{26}$



Relation with Other Neutrino Experiments

- mass ordering measurement
  - NOvA + T2K: no preference with 2024 joint analysis [35]
  - JUNO: data taking starts in 2025, 6 years, 3-4σ
  - next generation beam experiments: DUNE, T2HK
- precision measurement of mixing parameters [36]
- absolute mass from beta decay, sum of neutrino masses

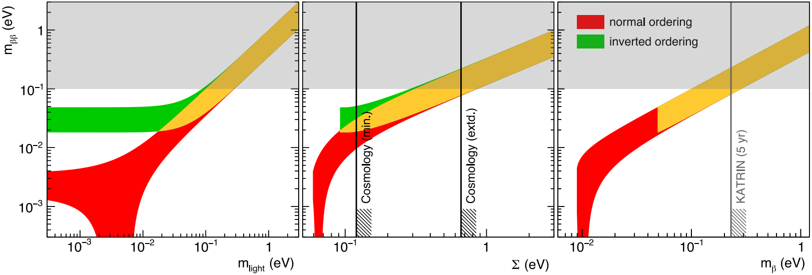


Figure adapted from [37].

Summary and Outlook

- Majorana neutrinos may solve several fundamental issues in particle physics and cosmology
  - origin of neutrino mass, why it is small
  - why the universe is dominated by matter
- neutrinoless double-β decay is the most promising probe
  - keys: exposure, energy resolution, and background
  - technologies: bolometers, scintillators, TPCs, semiconductors
- most of the parameter space above the inverted mass ordering region are excluded, results led by ^{76}Ge, ^{130}Te, and ^{136}Xe
- the goal of next generation experiment is to reach below the inverted mass ordering region, ton-scale, lower background

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