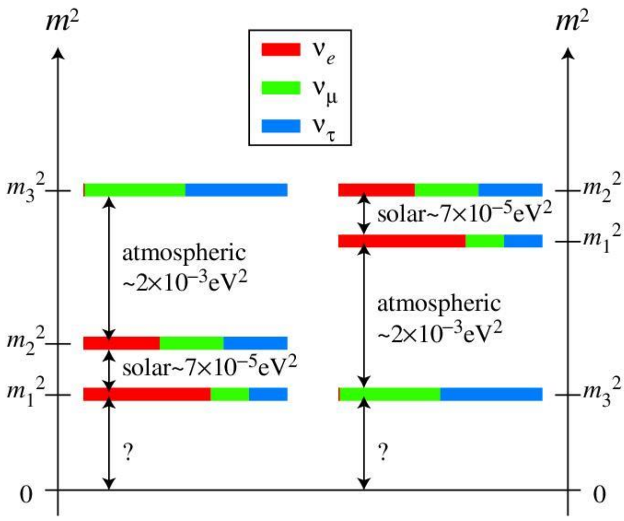
Massive Neutrinos:

What we know about neutrinos:

- Neutrino flavors mix with each other
  → At least two neutrino flavors must have a small mass
  → Contain CP violating phase
- They have no electric charge
- Weak interaction couples only to left handed (Chirality=-1) neutrinos and right handed (Chirality=+1)anti-neutrinos (V-A) structure of the interaction

What we would like to know about neutrinos:

- What is the mass scale of neutrinos?
  So far: limits from
  - cosmology on sum of neutrino masses (structure formation)
  - end point measurements of electron spectrum (KATRIN,…)
- Why are neutrino masses so small?
- Which mass hierarchy do neutrinos obey, i.e. which flavor is the lightest?



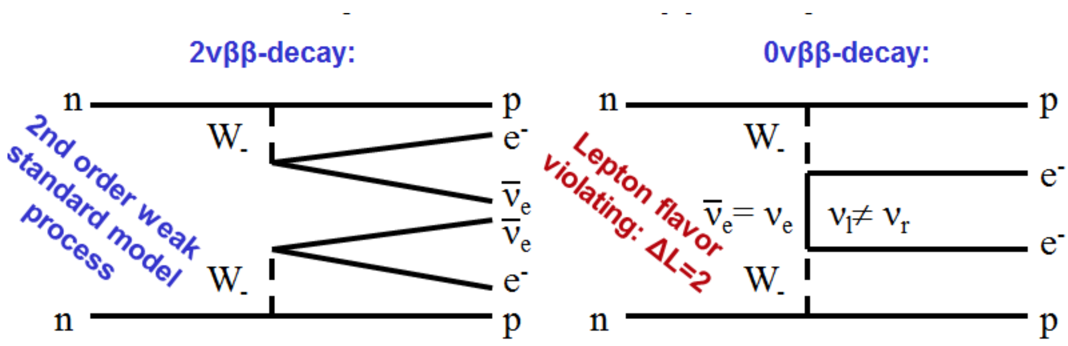
- As neutrinos have no charge: what does CPT-conjugation do to neutrinos?
  Are neutrinos and anti-neutrinos identical? I.e. is the neutrino a Majorana particle?
  ➔ This would imply Lepton number violation!

Also remember: Majorana neutrino could help in BAU (decay of heavy neutrions CP violating)!

Neutrinoless Double Beta Deacay:

To tackle these questions → Neutrinoless double beta decay with $|\Delta L| = 2$:

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



$2\nu\beta\beta$ − decay can be observed if single β − decay is energetically forbidden, while coherent decay of two neutrons into two protons is allowed as 2nd order weak process
→ $2\nu\beta\beta$ Half-lives of isotopes are of the order $10^{18} - 10^{21} yr$.

$0\nu\beta\beta$ −decay can only occur if:

- Neutrino has Majorana nature → Lepton number violation!
- Helicity flip occurs in the vertex Standard assumption: if decay exists: dominated by exchange of Majorana neutrino. In general: all Lepton flavor violating processes leading to helicity flip can induce $0\nu\beta\beta$ −decay.

Observation is possible for even even nuclei due to pair binding term in Weizsäcker formula: Two parabolas of binding energy vs. Z:

Half-life limits: ~10^{26} yr!

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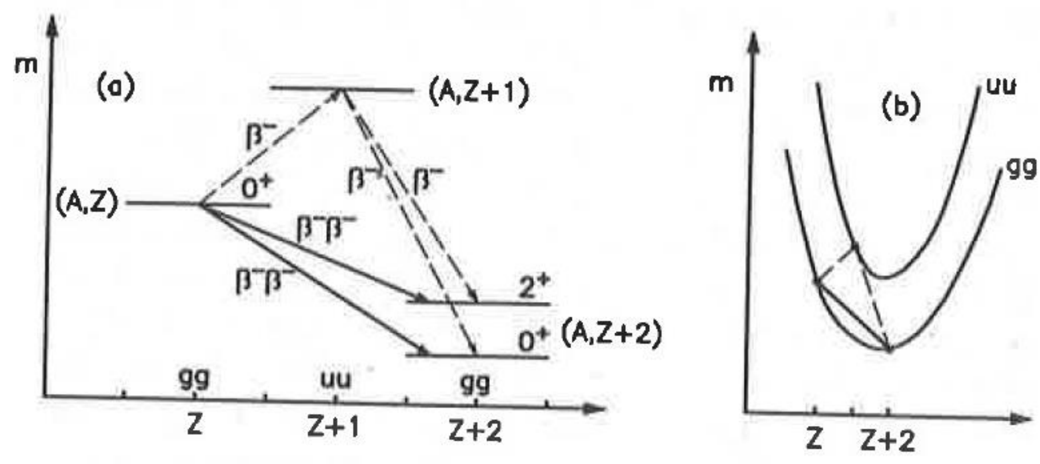


Left: Scheme for decay of a gg nucleus- single beta decay is forbidden

Candidate isotopes (among others): ^{48}Ca, ^{76}Ge, ^{130}Te, ^{100}Mo, ^{136}Xe, ^{150}Nd

For exchange of light Majorana neutrino:

$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G(Q^5)|\mathcal{M}_{Nucl}|^2\langle m_{ee}\rangle^2$$

with $G(Q^5)$ the phase space factor of the decay, $\mathcal{M}_{Nucl}$ the nuclear matrix element and

$$\langle m_{ee}\rangle = \left|\sum_i U_{ei}{}^2\, m_i\right|$$

Nuclear matrix element calculations uncertain to factor of ~2! Phase space factor uncertainty due to axial vector coupling…..

The effective Majorana electron neutrino mass (note that phases appear in U_{ei}):

$$\begin{aligned}|{<}m{>}| &= \left|m_1 U_{e1}^2 + m_2 U_{e2}^2 + m_3 U_{e3}^2\right| \\ &= \left|\left(m_1 c_{12}^2 + m_2 s_{12}^2 e^{i\alpha_{21}}\right) c_{13}^2 + m_3 s_{13}^2 e^{i(\alpha_{31}-2\delta)}\right|.\end{aligned}$$

→ Can express this in terms of neutrino mixin parameters
$\Delta m_{21}^2,\ \sin^2\theta_{12},\ \Delta m_{31}^2$ and $\sin^2\theta_{13}$

→ $|<m>|$ related to effective mass of lightest neutrino (assessed with beta-end point measurements):

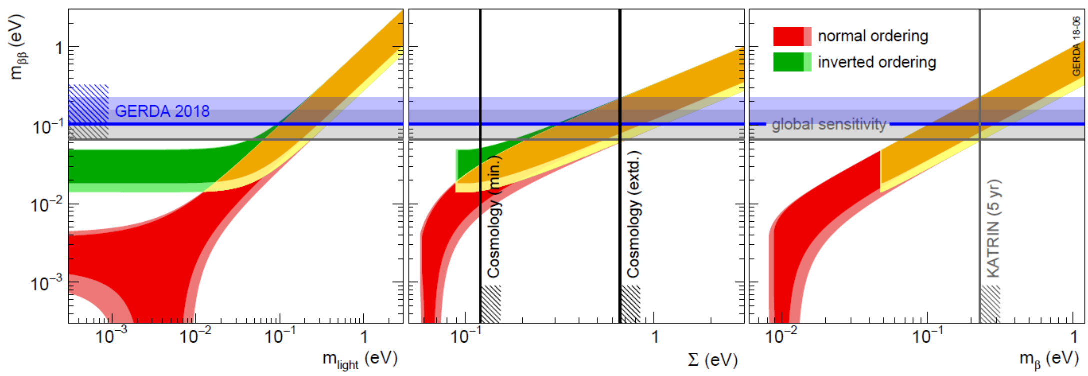
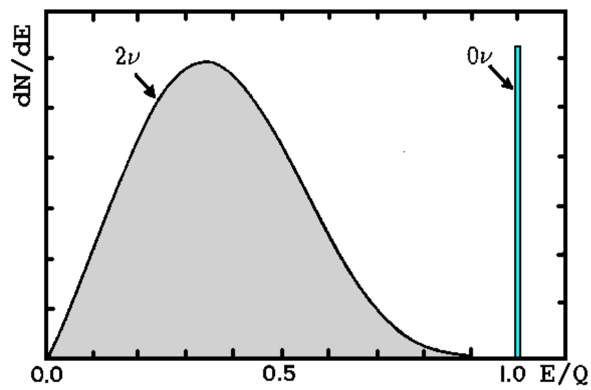


Figure 3: Constraints of the parameter space for $m_{\beta\beta}$ in the scenario of three light Majorana neutrinos as function of the lightest neutrino mass m_{light}, the sum of neutrino masses Σ, and the effective neutrino mass m_β. Contours follow from a scan of the Majorana phases (dark colors) and the 3σ intervals of the neutrino oscillation data (light colours) within NuFIT (*4*). The blue horizontal band shows the upper limits on $m_{\beta\beta}$ obtained by GERDA, the grey band those from combining sensitivities of all leading experiments in the field (see Table 1). Vertical lines denote $\Sigma = 0.12$ eV and $\Sigma = 0.66$ eV, a stringent limit from cosmology (*18*) and an extended model bound (*7*), as well as $m_\beta = 0.23$ eV, the 5 yr sensitivity of the KATRIN experiment (*17*).

Effective Majorana neutrino mass vs. mass of lightest neutrino allowed regions for different hierarchies

Experimental search: "Signature":



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Schematic sketch of energy spectrum of 2vββ- and 0vββ decays. While for the neutrino accompanied mode the spectrum is continuous, for the neutrinoless mode a sharp peak at the Q-value of the decay is expected. Peak height not to scale!

Expected rates are extremely low: for $\langle m_{ee}\rangle \;\; = 10\ meV$ expect $\lesssim 1\ Events/(ton\ yr)$!

Half life [years]	~Signal [cts/(t·yr)]
$1\cdot10^{26}$	50
$5\cdot10^{27}$	1
$1\cdot10^{29}$	0.05

Figure of merit for an experiment: Limit setting sensitivity for an experiment with, abundance a of the double beta emitting isotope signal detection efficiency ε, total detector mass m, measuring time t, background index B and energy resolution Δ in the energy region of interest :

$$T_{1/2}^{0\nu\beta\beta} \propto a\varepsilon\sqrt{\frac{mt}{\Delta\, B}}$$

a:Enrichment fraction, ε:detection efficiency, m:mass of the detector, Δ:RoI used (realted to energy resolution), B:Background index.

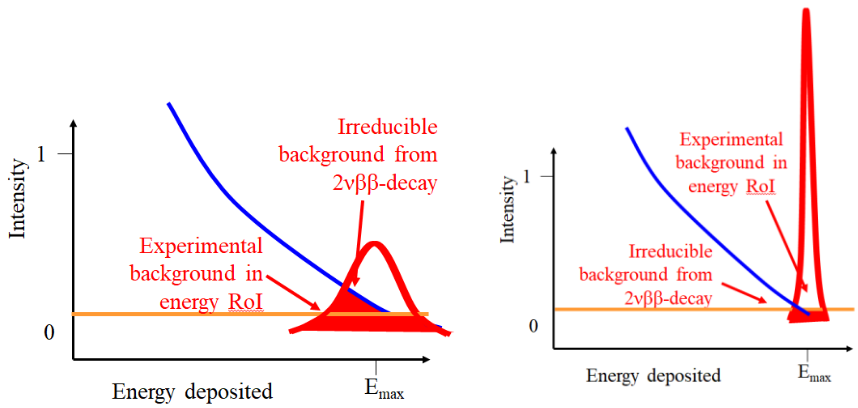
Strategy: look for peak at the Q-value of the decay.

- avoid and identify backgrounds:
- excellent energy resolution (background)
- Detector made from double beta emitting isotope (detection efficiency)
- Maximize detector mass → isotopically enrich material

Example: The GERDA experiments:

Use high purity germanium radiation detectors: reverse biased diode:
energy deposition create electron-hole pairs that can drift in E-field to contacts. Read- out using charge sensitive preamplifiers (Field Emission transistors – FETs):

- Excellent energy resolution (0.15% @ Q-value),



In order to deplete large volumes: very clean material needed (no electrically active impurities) → Only around 10^{10} impurities per cm³ allowed (one in $5*10^{12}$)

- Intrinsically low in long lived radioactive isotopes

Germanium material can be enriched in isotope ^{76}Ge to ~87%. Centrifugationof germanium tetra fluorid (same process as for uranium enrichment)

→ Detector from source material → high detection efficiency

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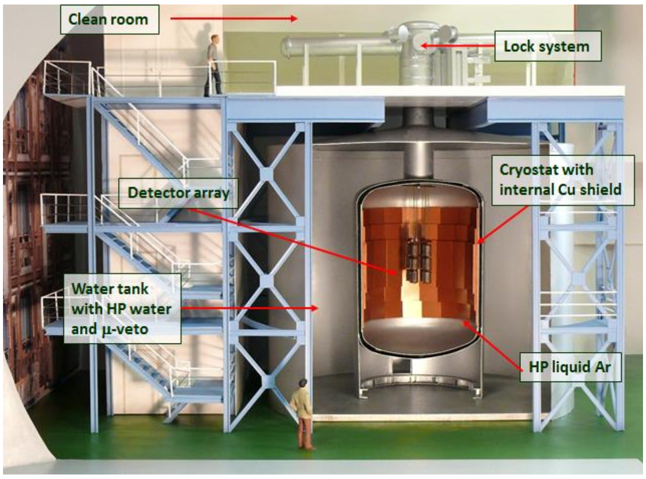


Schematic of GERDA experiment at LNGS.

The GERD experiment is located at LNGS underground laboratory in Italy.
→ Shiel cosmic rays by 1.4km of rock overburden: ~3400 mwe. Hard component (neutrons, protons, pions,…) shielded completely, μ- component reduced by factor ~10^6.

- Avoid background:

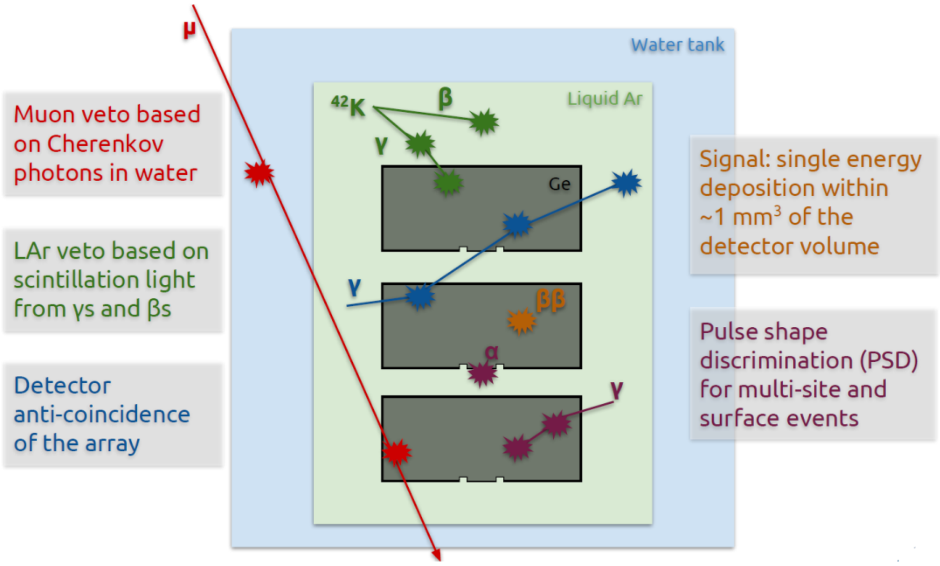
All materials used selected for very natural low background: ^{238}U, ^{232}Th chains + ^{222}Rn from ^{226}Ra sub-chain: Use HPGe screening, ICPMS characteriozation, Rn emanation measurements.
Germanium and copper stored underground, careful logistics: Avoid cosmogenically produced long lived isotopes: ^{60}Co, ^{68}Ge, …

Water tank to shield external natural radioactivity + thermalize and capture neutrons. 10m tank of ultra clean water: equipped with PMTs to detect Čerenkov light from through-giong muons.

LAr Cryostat with 4m diameter placed inside. LAr for shielding of natural radioactivity from steel walls (specially selected)

Deploy array of 40 detectors (10 coaxial – 20kg, and 30 BEGe detectors – 20kg) directly in liquid argon (Aar): Use liquid argon as cooling medium for detectors and as ultra clean shield against background radiation.

Identification of background:



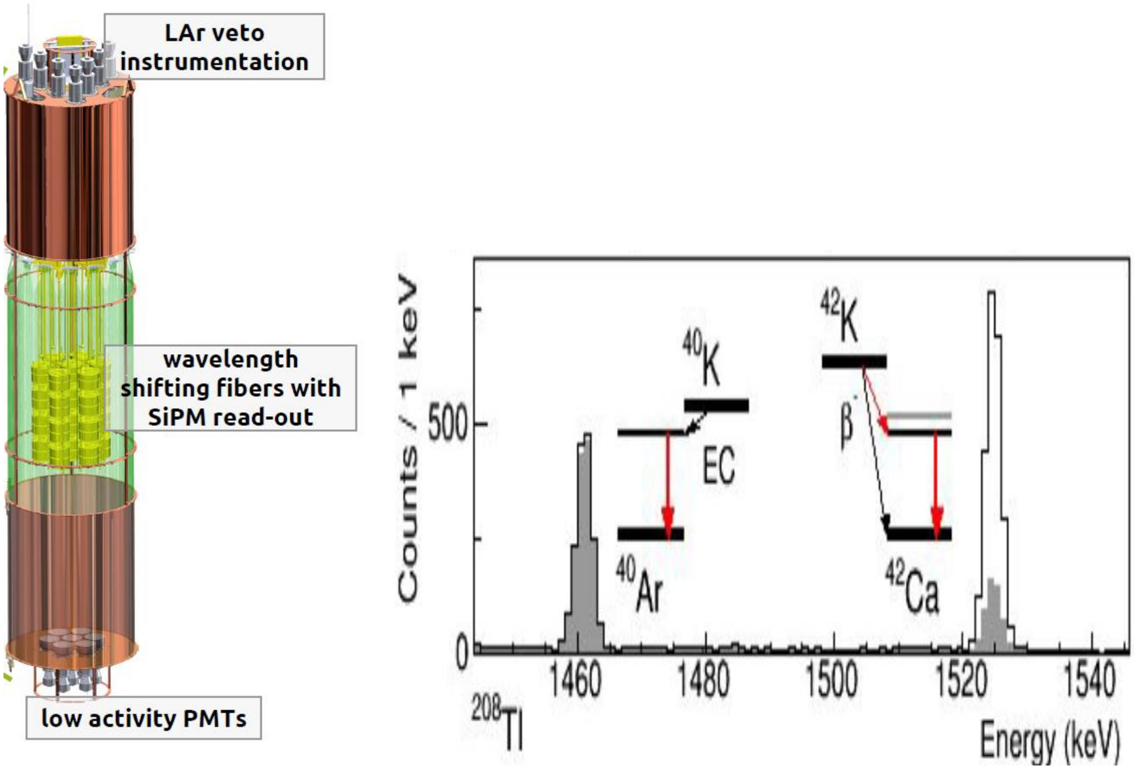
- *Myon veto:*

Cerenkov light detection in water around LAr tank
→ Water tank is equipped with PMTs → >99% myon detection probability

- *LAr veto:*

LAr scintillates at ~128nm → Detect scintillation light for Bkg tagging!

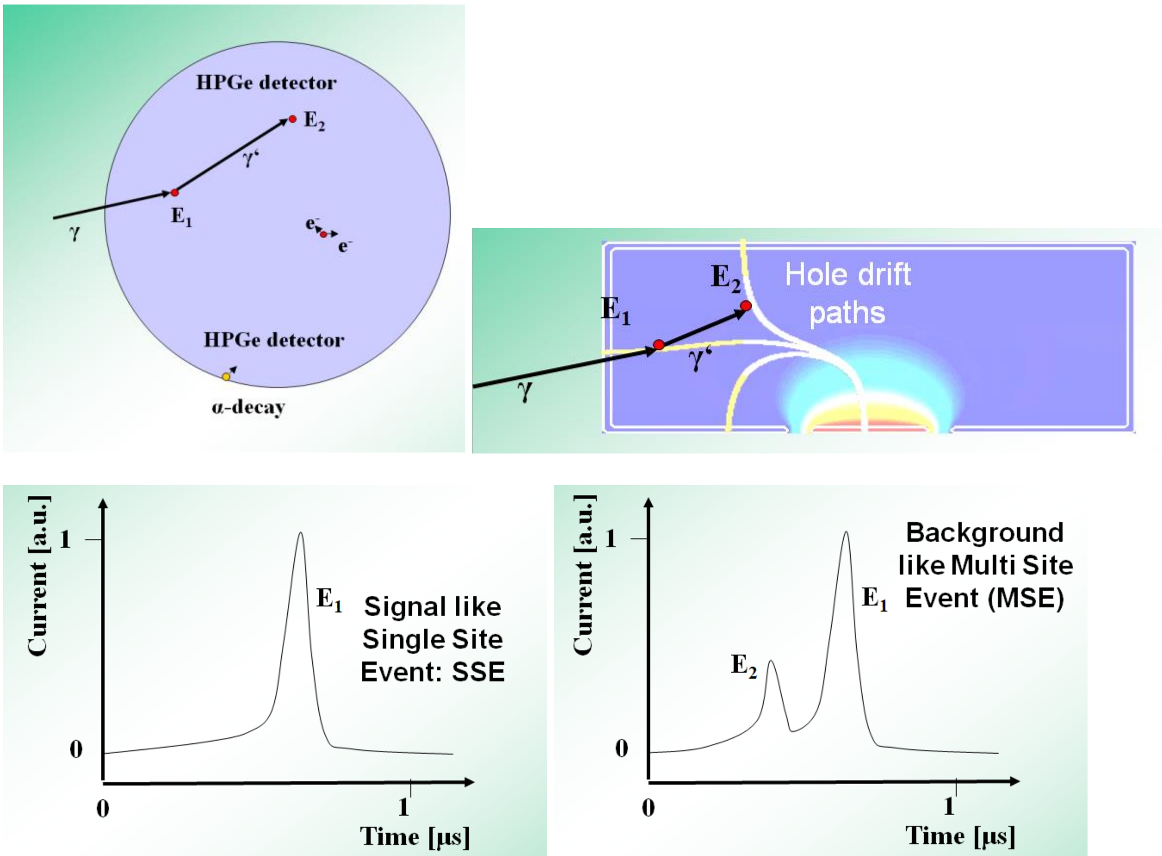
→ Deploy optical fibre curtain equipped with SiPMs around detector array + view array from top and bottom using PMTs



Left: Conceptual drawing of GERDA detector string inside LAr veto system. Right: Spectrum around the two peaks from decay of ^{40}K and ^{42}K measured in the GERDA setup. While the^{42}K is reduced considerably be the LAr veto cut, the ^{40}K is not, as expected.

- *Pulse shapes to distinguish background from signal*:

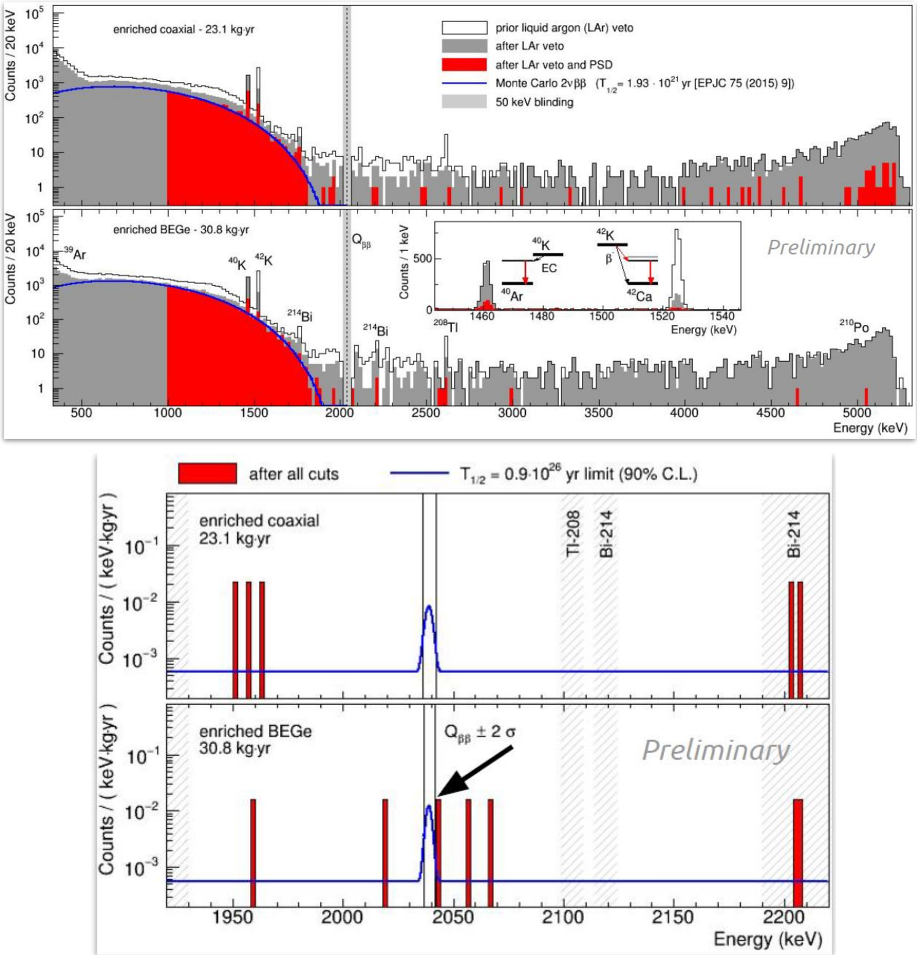
Distinction between
- signal like Single Site Events: two betas deposit energy within ~1mm³
- background from gamma rays: 2 MeV gammas mean free path after Compton scattering ~cm) → multiple energy depositions within detector
- p+ surface events: very fast,
- n+ surface: slow due to low field region and partly diffusion into active volume



Differences in event topologies can lead to differences in pulse shapes of events: γ –rays at 2 MeV are most likely to interact vie Compton scattering with mean free path of few cm in germanium → events with more than one energy deposit inside detector can be identified as background events (mean free path of electrons with 1 MeV around mm).

GERDA Results:

Took data from Nov 2011 to June 2019 (without LAr veto): BI in RoI: 0.01 Cts/(kg yr keV) with Δ@RoI: 4.8 keV for coaxial detectors, 3.2 keV for BEGe detectors.



Top: Overall spectrum of Phase II measurement Result from Phase II showing the low background and the efficiency of the background identification. Bottom zoom into the region around the Q-value of ^{76}Ge at 2040 keV of the GERDA experiment. No peak like structure could be found.

World record low background for 0vbb decay experiments:
~0.5 Counts/(ton keV yr)

No peak observed

→ $T_{1/2}^{0\nu\beta\beta} > 9 \cdot 10^{25} yr$ (90% C.L.) , $\langle m_{ee} \rangle < 0.1 - 0.2\ eV$ (depending on matrix element).

Phase II data taking resumes in December 2019.
→ follow up experiment: LEGEND 200 with ~200kg germanium detectors

Sensitivity estimate: ~10^{27} yr

Final goal: LEGEND 1000 with 1ton of enriched germanium detectors

Sensitivity reach: ~10^{28} yr → Discovery if IH!

Other 0νββ decay experiments:

Majorana (^{76}Ge), use germanium detectors (~40kg) in "conventional" copper cryostat with copper shield, use ultra-pure copper for cryostat and shield. Started measueremnts end of 2015

Expected sensitivity: $\sim 10^{26}\ yr$ until 2019

- ➔ Afterwards merging with GERDA (and others) → LEGEND

CUORE: $^{130}TeO_2$ crystals in low temperature bolometry. Energy resolution expected ~ 6keV at RoI, BI expected: total detector mass: 741kg → ~200kg of ^{130}Te.

Started data taking with full mass at 20mK!

Expected sensitivity: $\sim 10^{26}\ yr$ until 2020

EXO, nEXO, NEXT, Kamland ZEN all use ^{136}Xe (nobel gas)

EXO, EXO200 and nEXO: LAr TPC. Energy reolution ~2-3% at RoI
NEXT: pressurized Xe TPC: improved energy resolution
KamlandZEN: ^{136}Xe doped liquid scintillator
→ large mass, moderate energy resolution
Latest results: limit: $T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{26} yr$ with sensitivity $3.7 - 4.9 \cdot 10^{25} yr$
→ background underfluctuation seems to help (?)

Had problems with background from man-made anthropogenic isotope ^{110m}Ag

Now resolved. Taking data. Expecting results at TAUP conference in September with sensitivity ~3· $10^{26} yr$!

…..

Helicity is defined as the expectation value of spin in the direction of momentum:

$$\hat{h} = \frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|}$$

For massive particles this operator is NOT invariant under Lorentz transformation! This means that you can always find a Lorentz boost into an inertial system that is changing the helicity of a particle. This means that helicity is not a good quantum number!

Chirality describes the "handedness" of a particle, i.e. the asymmetry of an object (wave function) under reflection.
Every wave function can be separated in left- and right handed components:

$$|\psi> = |\psi_R> + |\psi_L> = \widehat{P_R}\,|\psi> + \widehat{P_L}|\psi>$$

with the projection operators $\widehat{P_L} = \frac{1}{2}(1 + \gamma_5)$ and $\widehat{P_R} = \frac{1}{2}(1 - \gamma_5)$.

$\widehat{P_L}$ and $\widehat{P_R}$ have the following properties:

$$\widehat{P_L} \cdot \widehat{P_R} = \widehat{P_R} \cdot \widehat{P_L} = 0, \qquad \widehat{P_L} \cdot \widehat{P_L} = \widehat{P_L}, \qquad \widehat{P_L} \cdot \widehat{P_R} = \widehat{P_R}$$

Chirality is invariant under Lorentz transformation, i.e. there is no Lorentz boost that can change the chirality of a system.

Charge conjugation transformation does not alter chirality of a particle, i.e. $\hat{C}|\nu_L> = |\bar{\nu}_L>$.
So far no observation of right-handed neutrinos or left handed anti-neutrinos could be made. This means that the weak interaction couples only to left handed particles and right handed anti-particles → Charge conjugation is maximally broken in weak interaction!