Neutrinoless double beta decay searches with the LEGEND experiment

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

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Università degli Studi di Padova

INFN

Overview

- Introduction to 0vbb decay
- Experimental search for 0vbb decay
- The LEGEND project
- First results and future goals
- Conclusions

Introduction to 0vββ decay

Concepts of neutrino physics

Neutrinos in the Standard Model: massless neutral fermions

Concepts of neutrino physics

Neutrinos in the Standard Model: **massless** neutral fermions

↑

Experimental observation of
neutrino oscillations

Concepts of neutrino physics

Neutrinos in the Standard Model: ~~massless~~ neutral fermions

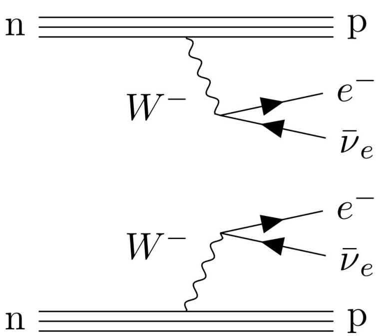
Experimental observation of
neutrino oscillations

BUT still no clue to understand their nature:

- **Dirac fermions** -> Particles and antiparticles are different
- **Majorana fermions** -> Particles and antiparticles coincide

Double beta decay

2VBB

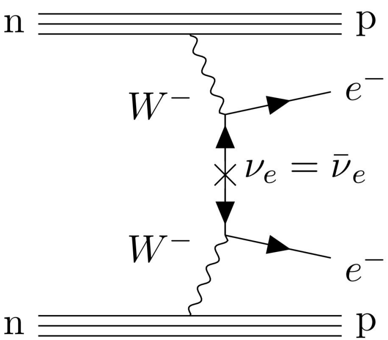


$\Delta L = 0$

Allowed by SM and observed

But strongly suppressed:
second order weak process!

0VBB



$\Delta L = 2$

Forbidden by SM and not observed yet

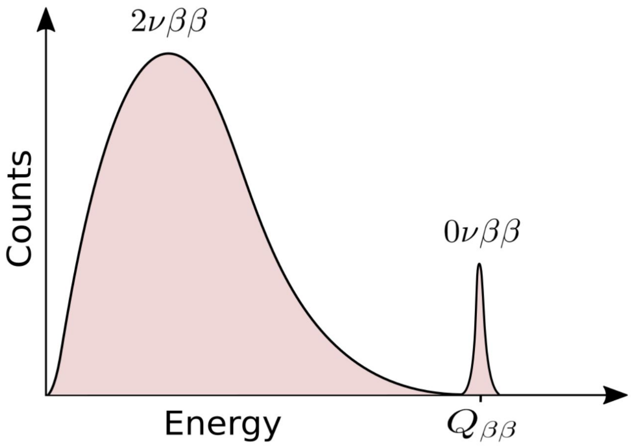
Can only take place if neutrinos
are Majorana fermions!

NEUTRINOLESS DOUBLE BETA DECAY

If 0vbb is observed -> Evidence for New Physics Beyond the Standard Model:

- Unambiguous evidence for **lepton number violation:** it is not a fundamental symmetry of the universe
- Proof that neutrino is a **Majorana fermion**
- **Cosmological implications**: information to explain the matter-antimatter asymmetry in the Universe (leptogenesis)

0VBB DECAY SIGNATURE



0vbb is a three-body decay: its signature is a **monoenergetic peak** at the endpoint of the double beta spectrum!

$$Q_{\beta\beta} = M(Z) - M(Z+2) - 2m_e$$

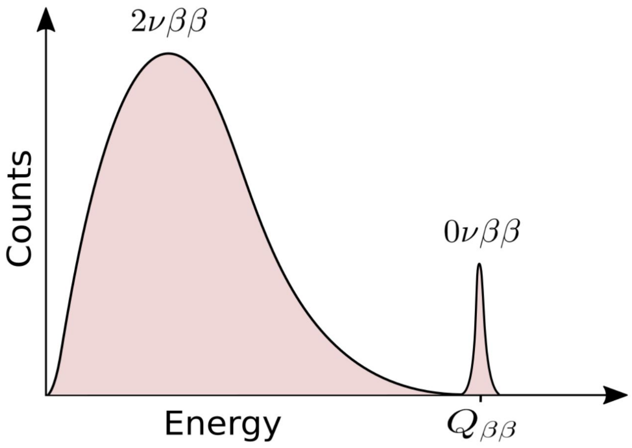
Its **half-life** is given by:

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}(\mathrm{Q}_{\beta\beta}, Z)\ |M^{0\nu}|^2\ \frac{|m_{\beta\beta}|^2}{m_e^2}$$

in which $m_{\beta\beta} = \sum_{i=1}^{3} U_{1i}^2 m_i = (c_{12}^2 c_{13}^2 e^{2i\kappa})\, m_1 + (s_{12}^2 c_{13}^2 e^{2i\lambda})\, m_2 + (s_{13}^2 e^{-2i\delta})\, m_3$

is the **effective Majorana mass,** G is the phase space factor and M the nuclear matrix element.

0VBB DECAY SIGNATURE



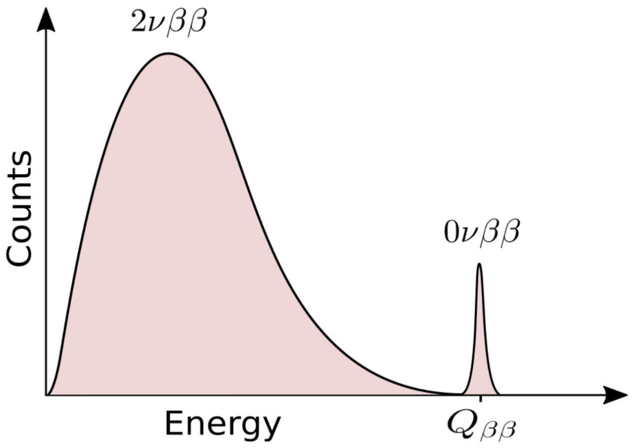
Experimental sensitivity:

$$T_{1/2}^{0\nu} \propto \begin{cases} M \cdot t & \text{-> Bkg free} \\ \sqrt{\frac{M \cdot t}{B \cdot \sigma}} & \text{-> With bkg} \end{cases}$$

In which:

- M = total active mass
- t = duration of the data taking
- B = background fraction
- σ = energy resolution at Qbb

0VBB DECAY SIGNATURE



Experimental sensitivity:

$$T^{0\nu}_{1/2} \propto \begin{cases} M \cdot t & \cdot\ \boldsymbol{f} \cdot \boldsymbol{\varepsilon} \text{ -> Bkg free} \\ \sqrt{\frac{M \cdot t}{B \cdot \sigma}} & \cdot\ \boldsymbol{f} \cdot \boldsymbol{\varepsilon} \text{ -> With bkg} \end{cases}$$

In which:

- M = total active mass
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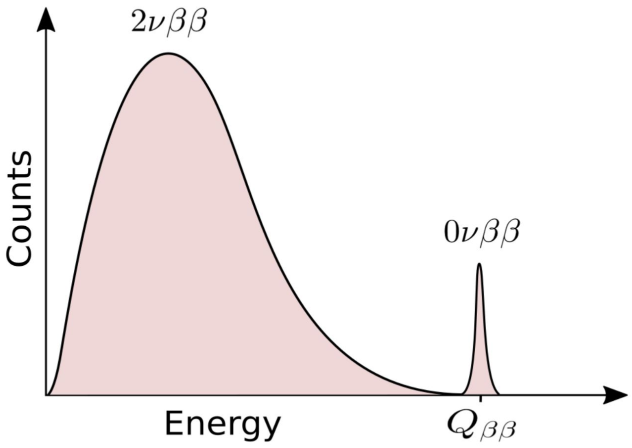
- ***f*** = fraction of 0vbb decaying isotope
- ***ε*** = efficiency

0VBB DECAY SIGNATURE



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In which:

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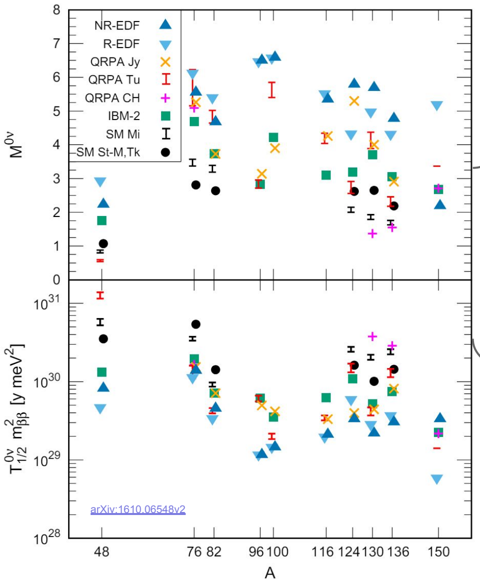
⇒ Goal:

- Reduce the background
- Increase the exposure E = M·t

Experimental search for 0vbb decay

Issues

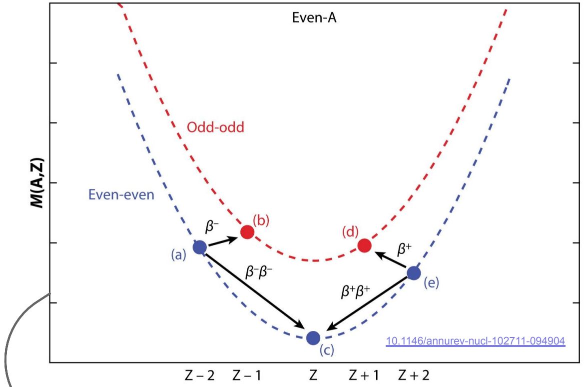
Large **theoretical uncertainties** on the phase space factor and on the Nuclear Matrix Elements (NME)



NME for 0vbb decaying candidates as a function of the mass number A, from different nuclear models

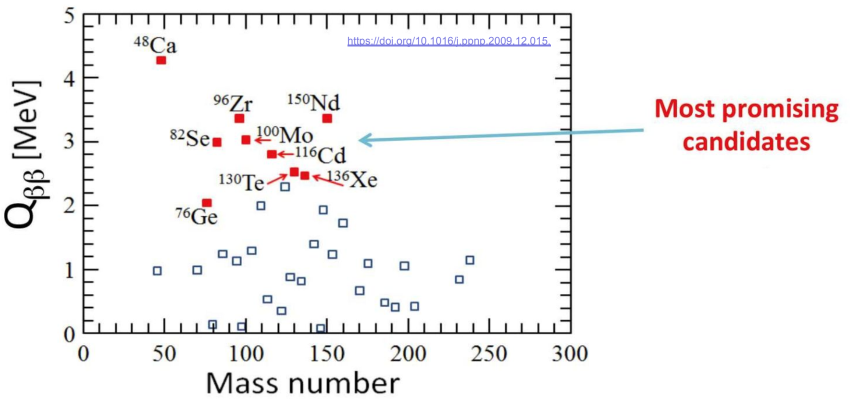
Corresponding 0vbb half lives, scaled by the unknown mββ parameter

Extremely **rare process**:
2vbb is a second order weak process -> its probability is strongly suppressed



2vbb is allowed for even-even nuclei in which the single β decay is energetically forbidden

Choosing the best isotope



- **High Qββ**
  - bigger phase space → shorter half-life
  - less background → easier to achieve bkg-free regime
- High natural **isotopic abundance** / easy enrichment → higher active mass
- **Scalability** → higher mass
- **Compatibility with detection techniques**

Choosing the best detection technique

Semiconductor detectors

GERDA/MJD/**LEGEND** (76Ge)

Bolometers

CUORE/CUPID (130Te+100Mo)

Scintillators

KamLAND-Zen(136Xe)

Time Projection Chambers

EXO/NEXT (136Xe)

LEGEND CHOICES

Active 76Ge-enriched HPGe detectors

LEGEND CHOICES

Active 76Ge-enriched HPGe detectors

Active

Source = Detector

76Ge-enriched

The ββ decaying isotope of Germanium is 76Ge:

76Ge → 76Se + 2e [+ 2ν]

- *f(76Ge, nat) ~ 8%*
  ⇒ Low natural isotopic abundance
  ⇒ Enrichment needed
  → ***f(76Ge, enr) ~ 92%***
- **Qββ(76Ge) = 2039.061 ± 0.007 keV**

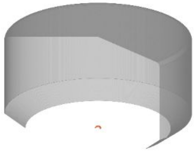
HPGe detectors

- Well established technology
- High Purity
  ⇒ Intrinsic low background
- **Superior energy resolution: FWHM ~ 0.1% @Qββ**

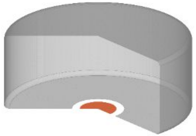
LEGEND CHOICES

Active 76Ge-enriched HPGe detectors

Different geometries:

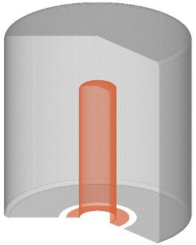


BEGe
Broad Energy
Germanium



PPC
P-type Point
Contact

ICPC
Inverted
Coaxial
Point
Contact



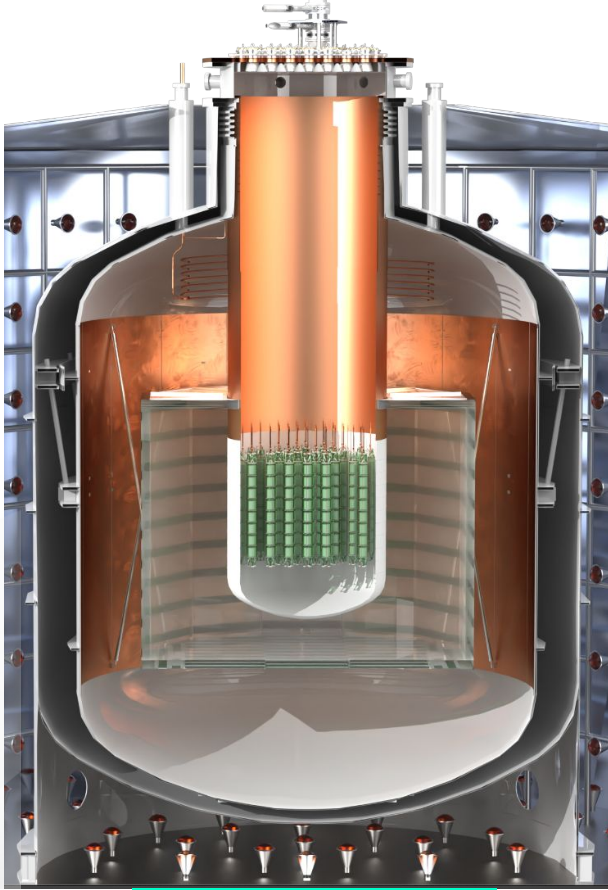
COAX
Coaxials

The LEGEND Project

A STAGED APPROACH

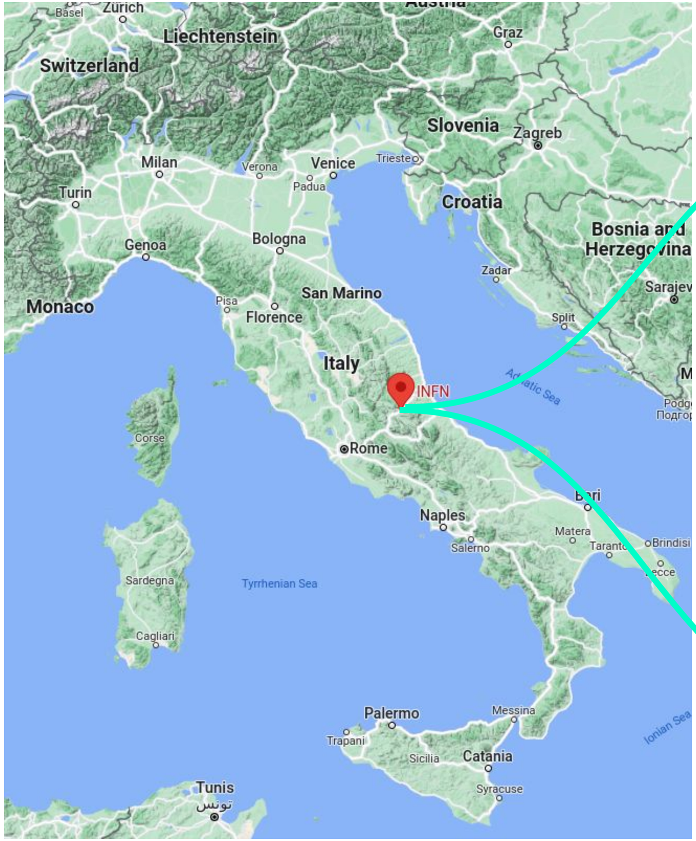
LEGEND-200	
Mass [kg]	200
Exposure [kg yr]	1 000
BI [cts/(keV kg yr)]	$2 \cdot 10^{-4}$
Half-life sensitivity [yr]	10^{27}
mββ sensitivity [meV]	34 - 78

LEGEND-1000	
Mass [kg]	1 000
Exposure [kg yr]	10 000
BI [cts/(keV kg yr)]	10^{-5}
Half-life sensitivity [yr]	10^{28}
mββ sensitivity [meV]	9 - 21



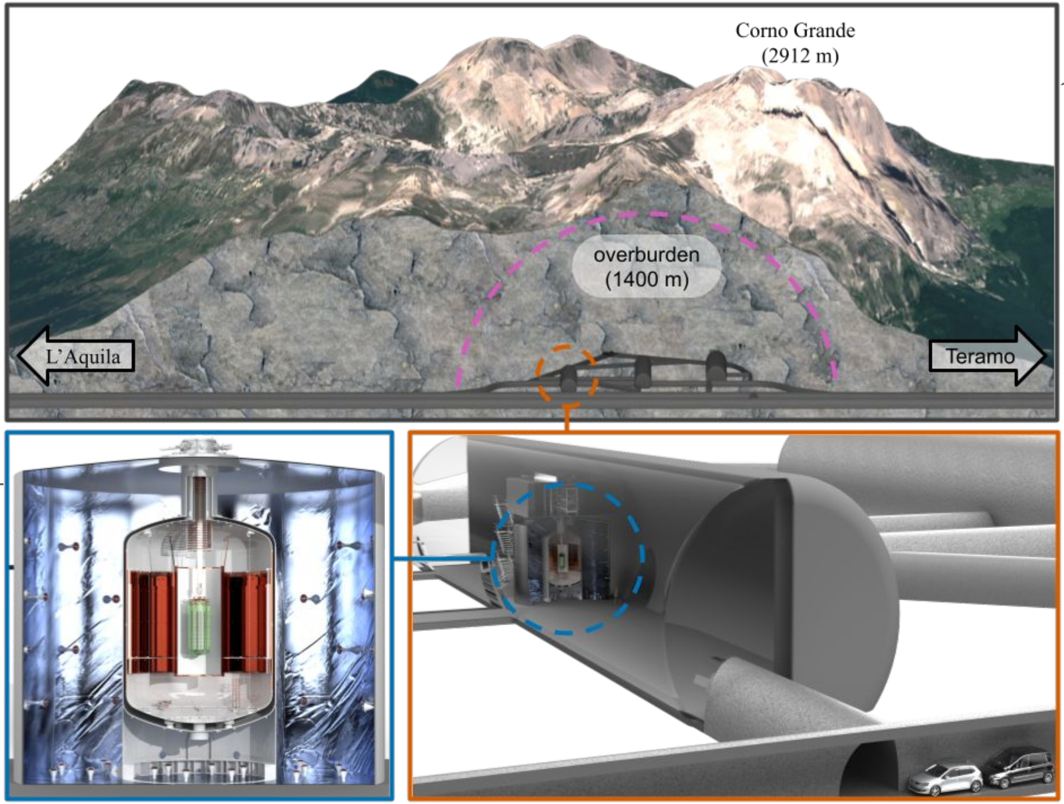
LEGEND-200 → LEGEND-1000

Location



Gran Sasso National Laboratories
(LNGS-INFN)
Assergi, Italy

The experimental site



Outside the laboratories

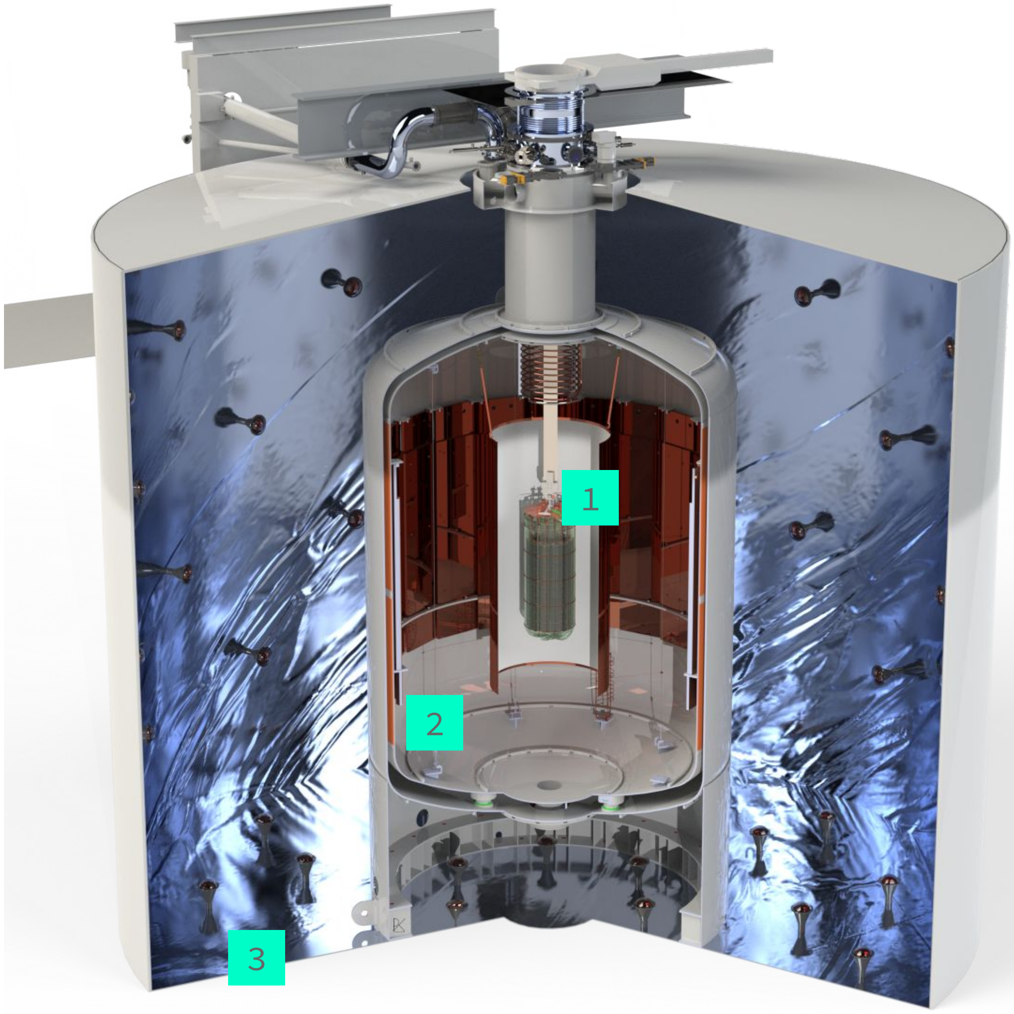
Inside the experiment

The LEGEND-200 experiment

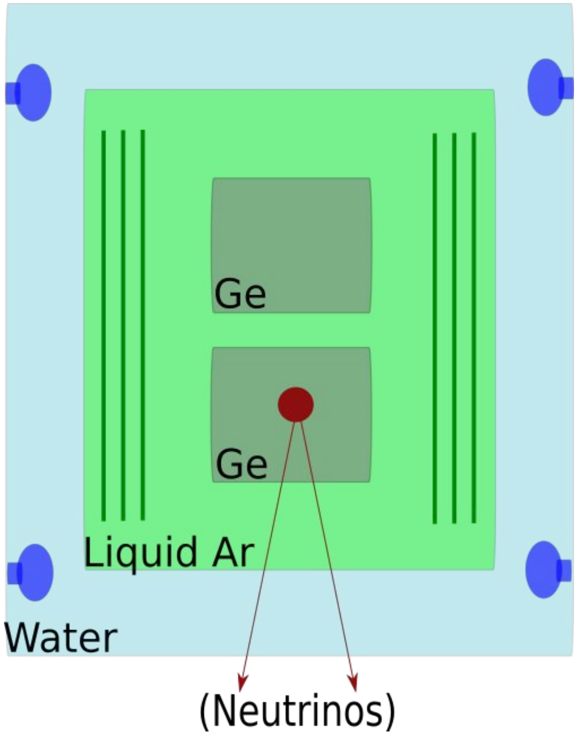
1. **HPGe detectors strings**

2. **Liquid Argon cryostat:**
   → Volume = 64 m^3
   → Cooler for the HPGe
   → Active veto with 58 SiPMs read-out modules and WLS fibers

3. **Water tank:**
   → Volume = 590 m^3
   → Active muon veto with 66 PMTs for Cherenkov radiation

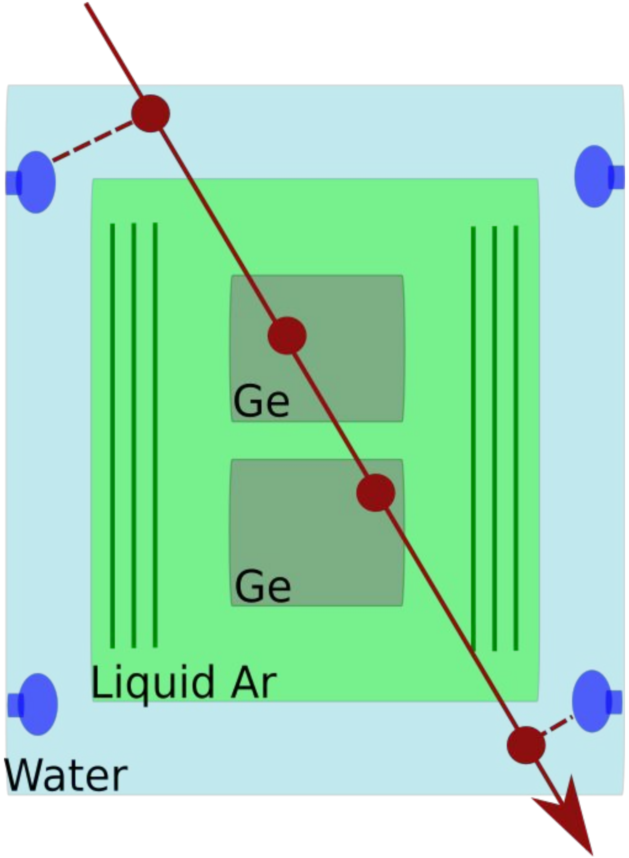


The detection strategy: good ββ candidates

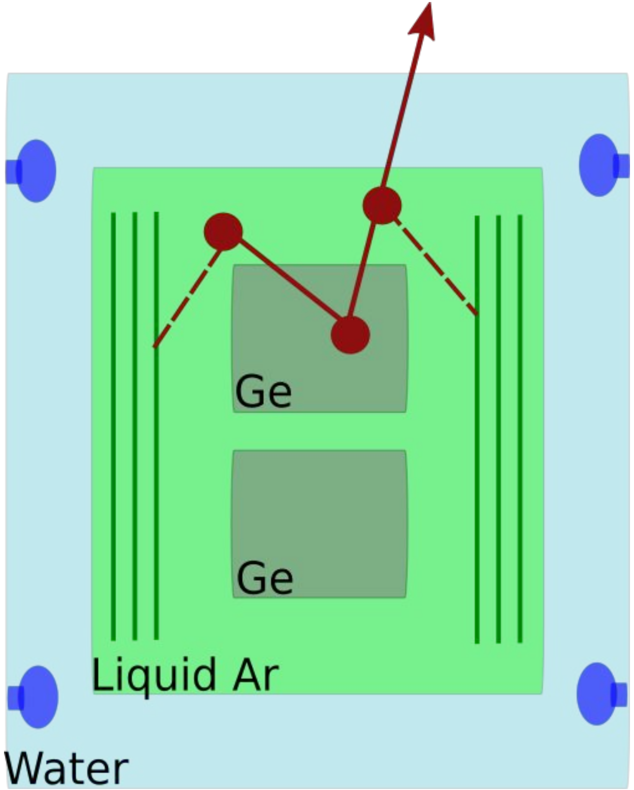


Signature of the ββ events:
energy release is highly localized (≈ 1 mm^3)
⇓
All the other types of events are **not** good 0vbb candidates!

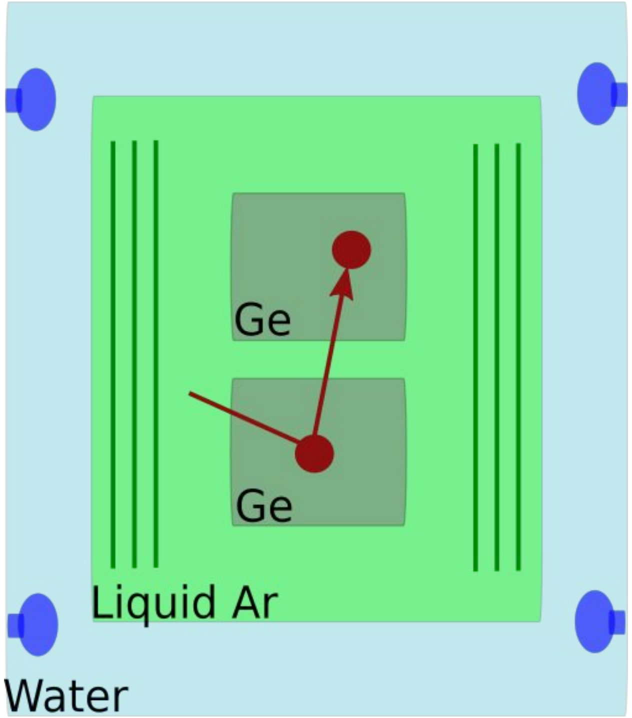
The detection strategy: Muon veto



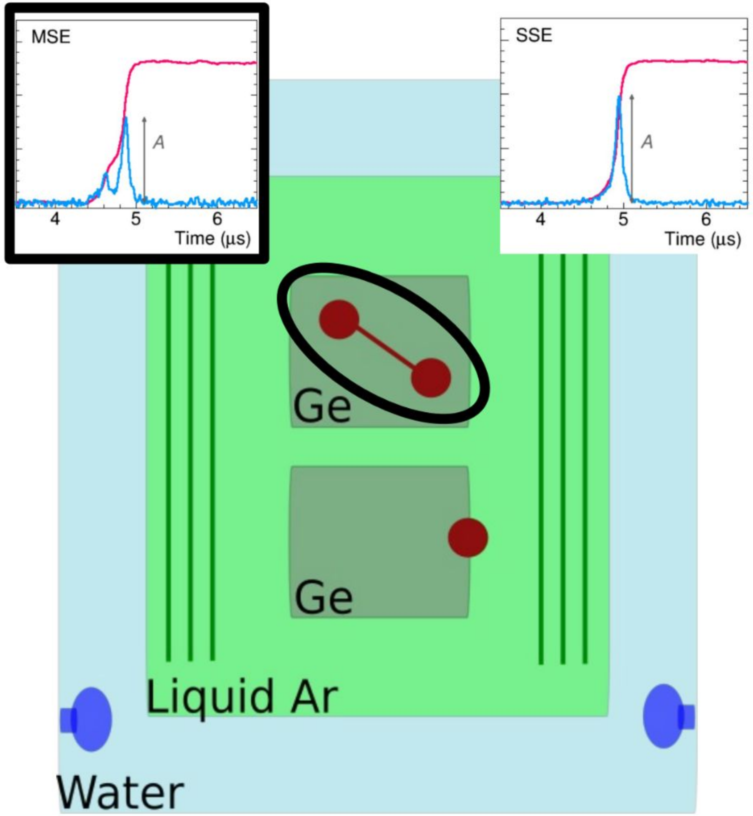
The detection strategy: Liquid Argon veto



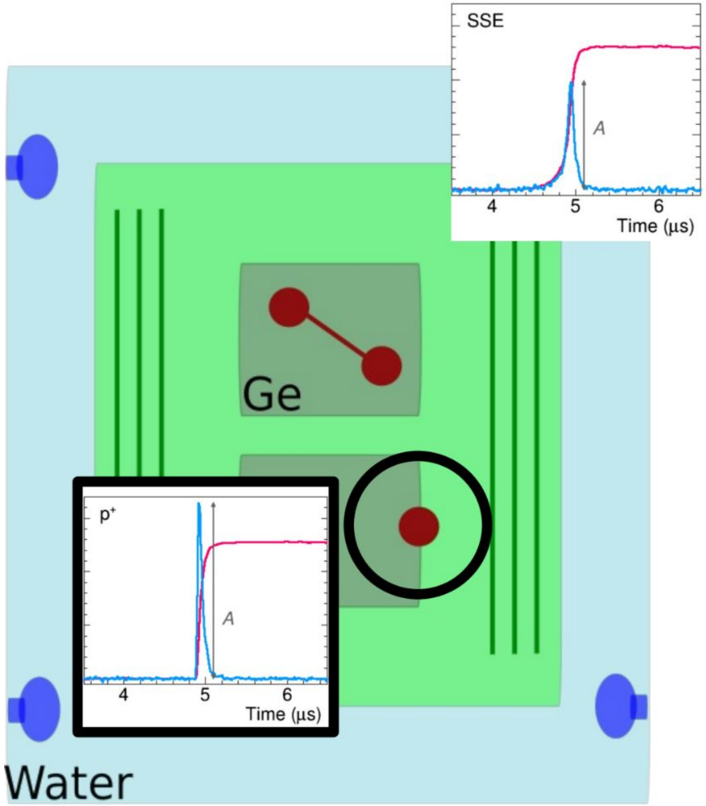
The detection strategy: Anti-coincidence



The detection strategy: Pulse Shape Discrimination (PSD)

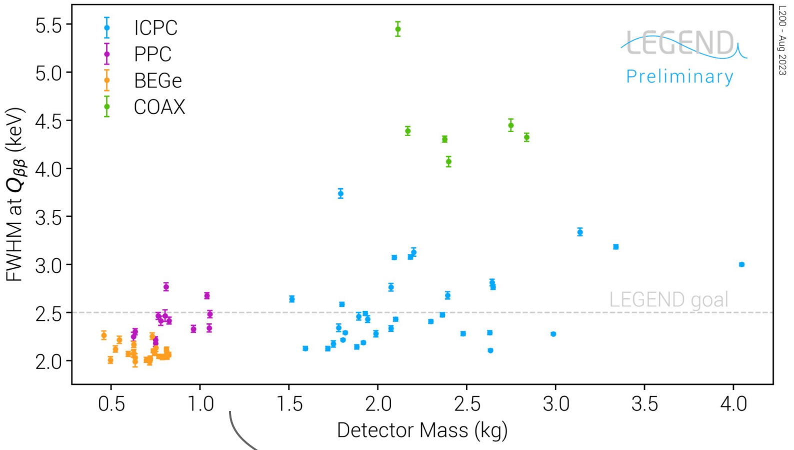


The detection strategy: Pulse Shape Discrimination (PSD)

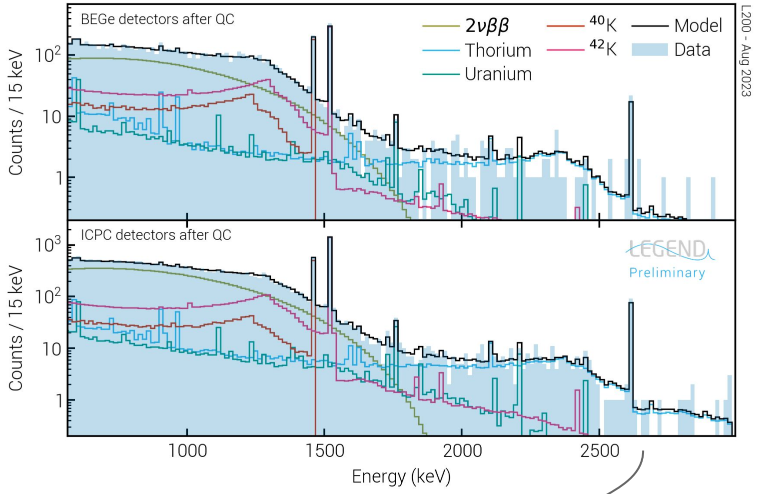


First results and future goals

Performances

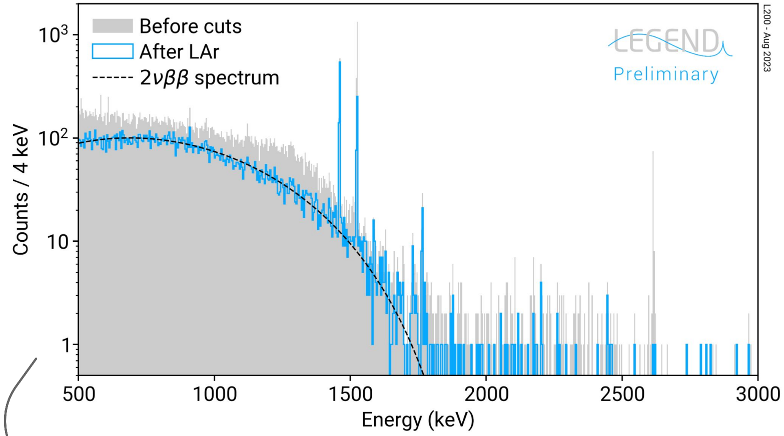


FWHM at $Q\beta\beta$
as function of the detector mass



Background decomposition for BEGes (top panel) and ICPCs (bottom panel). The model includes 30 independent components, here grouped by physics process.

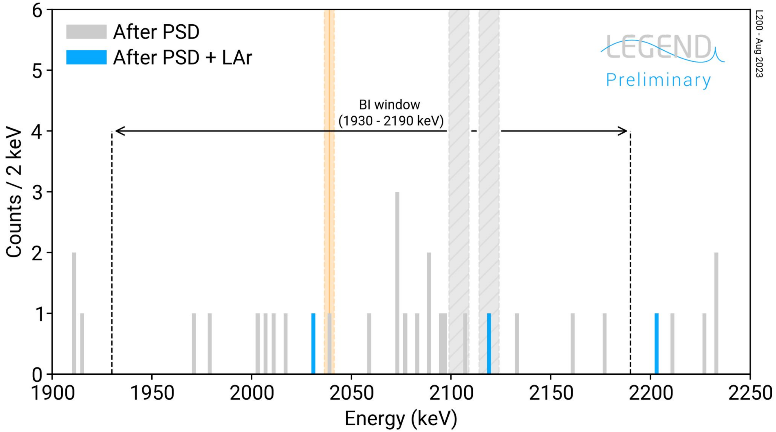
Preliminary results



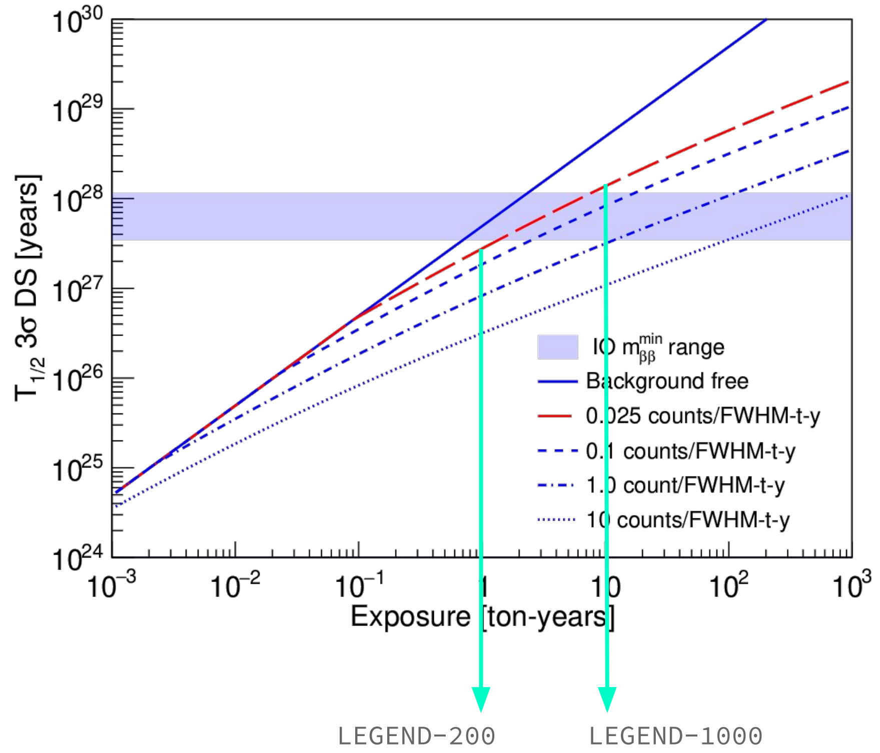
Energy spectrum compatible with 2vbb
after Liquid Argon (LAr) veto

First data release in August 2023 (TAUP):
10.1 kg yr of exposure
↓
Stay tuned for the next release!

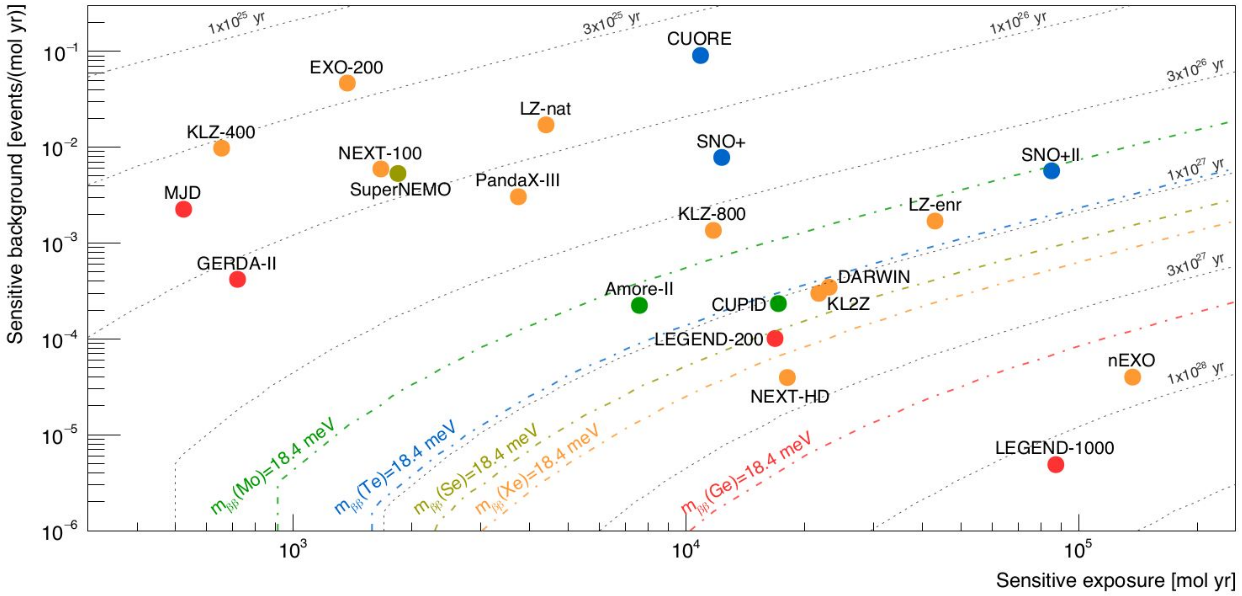
Background Index achieved in a
260 keV analysis window around Qββ:
B.I.=4.1[1.5, 11.4]x10^{-4} cts/(keV kg yr) at 68% CL



Long term plan: discovery potential



The experimental panorama



Sensitive background and exposure for recent and future experiments.

→ Grey dashed lines: discovery sensitivity values on the 0νββ-decay half-life.

→ Colored dashed line: half-life sensitivities required to test the the inverted ordering scenario for 76Ge, 136Xe, 130Te 100Mo, 82Se.

A livetime of 10 yr is assumed for all the experiments except for completed ones, for which the final reported exposure is used.

Conclusions

Conclusions

- Huge ongoing experimental effort to investigate Neutrino nature:
  - Dirac fermion?
  - Majorana fermion?
- Different experimental approaches and detection techniques being employed
- LEGEND experiment designed and built to discover 0vbb decay:
  - HPGe detectors + ancillary instrumentation
  - First data being taken → Background compatible with goal
  - New data release upcoming → Stay tuned!
- Beyond 0vbb → LEGEND-1000 has wide Beyond Standard Model Physics program:
  - Dark Matter Candidates
  - Spectral Effects
  - Tracklike Signatures
  - Tests of Fundamental Physics
  - Astrophysical Neutrinos

The LEGEND Collaboration

Centre for Energy, Environmental and Technological Research
Comenius University
Czech Technical University in Prague and IEAP
Daresbury Laboratory
Duke University and Triangle Universities Nuclear Laboratory
Gran Sasso Science Institute
Indiana University Bloomington
Institute for Nuclear Research Russian Academy of Sciences
Jagiellonian University
Joint Institute for Nuclear Research
Joint Research Centre Geel
Laboratori Nazionali del Gran Sasso
Lancaster University
Leibniz Institute for Crystal Growth
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