The GERDA experiment in the search for neutrinoless double-beta decay

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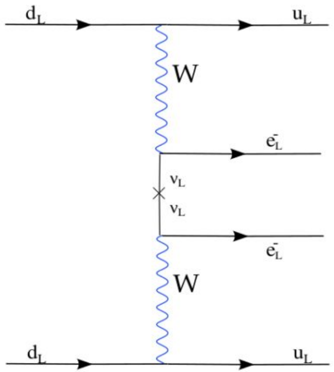
Double-beta decay without neutrinos

The neutrinoless double-beta (0νββ) decay is a hypothetical nuclear transition.

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

For the standard interpretations, 0νββ can be mediated by the exchange of two massive Majorana neutrinos.



$$\frac{1}{T_{1/2}^{0\nu}} = |M^{0\nu}|^2 G^{0\nu}(Q,Z) \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

nuclear matrix element

phase space factor

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

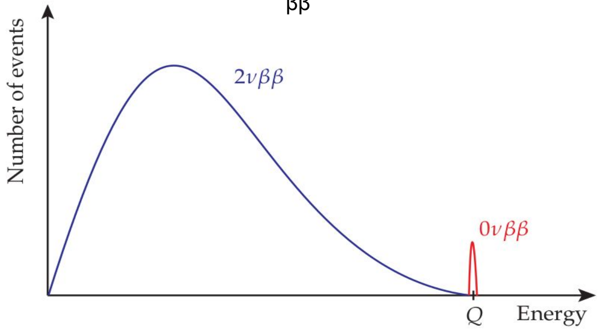
effective neutrino mass

Motivation for 0νββ decay searches

- Establish **lepton number violation** (LNV) → ΔL=2
- Only way to determine **if neutrino is its own antiparticle** ($\nu = \bar{\nu}$)
- Important to understand the **origin of the neutrino mass**
- Probe the a**bsolute neutrino mass scale** and **neutrino mass ordering**
- Provide important **input to cosmology**

0νββ signature and half-life

$Q_{\beta\beta}$ = 2039 keV for ^{76}Ge



0νββ signal = monoenergetic peak

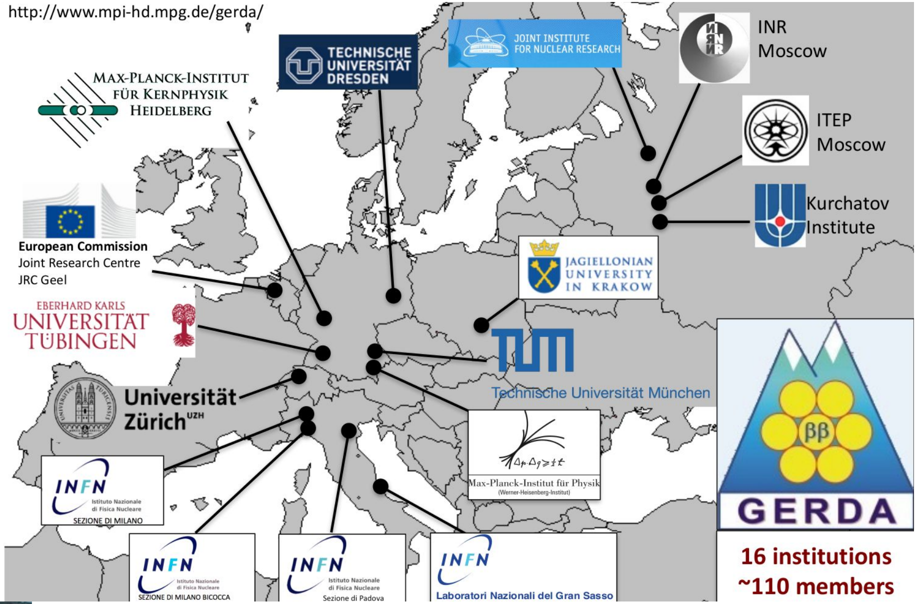
$$T_{1/2}^{0\nu} \propto \begin{cases} \epsilon \cdot a \cdot \sqrt{\dfrac{M \cdot t}{BI \cdot \Delta E}} & \textit{with background} \\ \epsilon \cdot a \cdot M \cdot t & \textit{without background} \end{cases}$$

ϵ: detection efficiency
a: isotopic abundance
M: total detector mass
t: run time
BI: background index
ΔE: energy resolution at $Q_{\beta\beta}$

low background level and good energy resolution

The GERDA collaboration

The **GERDA** experiment (**GER**manium **D**etector **A**rray) is searching for the neutrinoless double beta decay of ^{76}Ge.

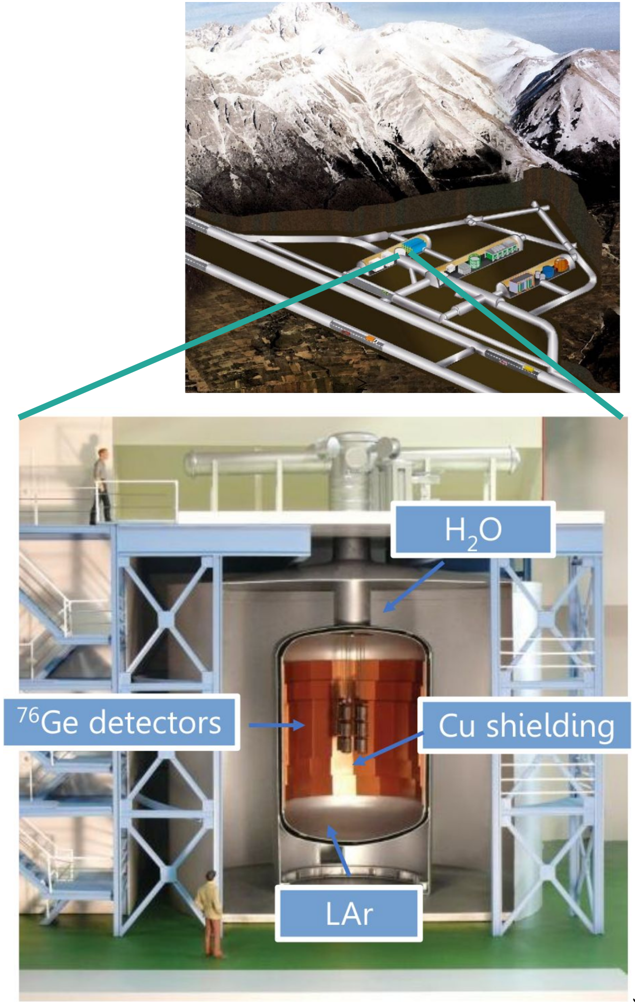


Collaboration meeting in Zurich (2019)

GERDA experiment

- The GERDA experiment has been proposed in 2004 as a new ^{76}Ge double-beta decay experiment at LNGS (Italy).
- Up to 41 enriched detectors deployed from Dec 2015 to Dec 2019.
- Two data taking periods with an upgrade in May 2018 in between.

- The array of germanium detectors was placed in a liquid argon (LAr) cryostat.
- A tank filled with 590 m^3 pure water surrounded the cryostat.
- Water tank equipped with PMTs detecting Cherenkov light.



^{76}Ge Detectors

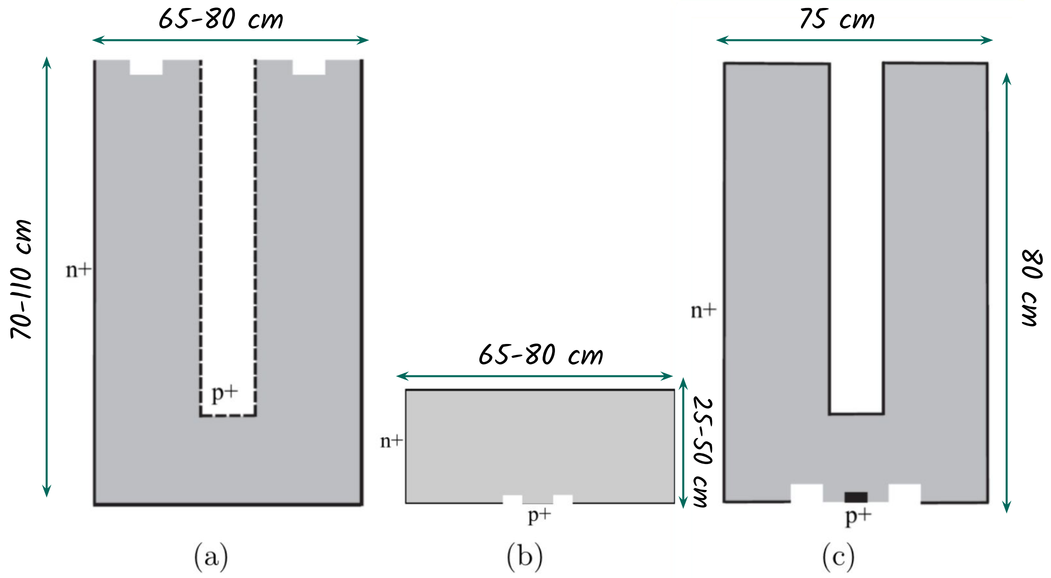
Why germanium?

- High detection efficiency (detector = ββ source)
- Enrichment from 7.7% to ~88%
- Best proved energy resolution at the Q-value (0.13% FWHM)
- Lowest background per FWHM energy resolution in the field

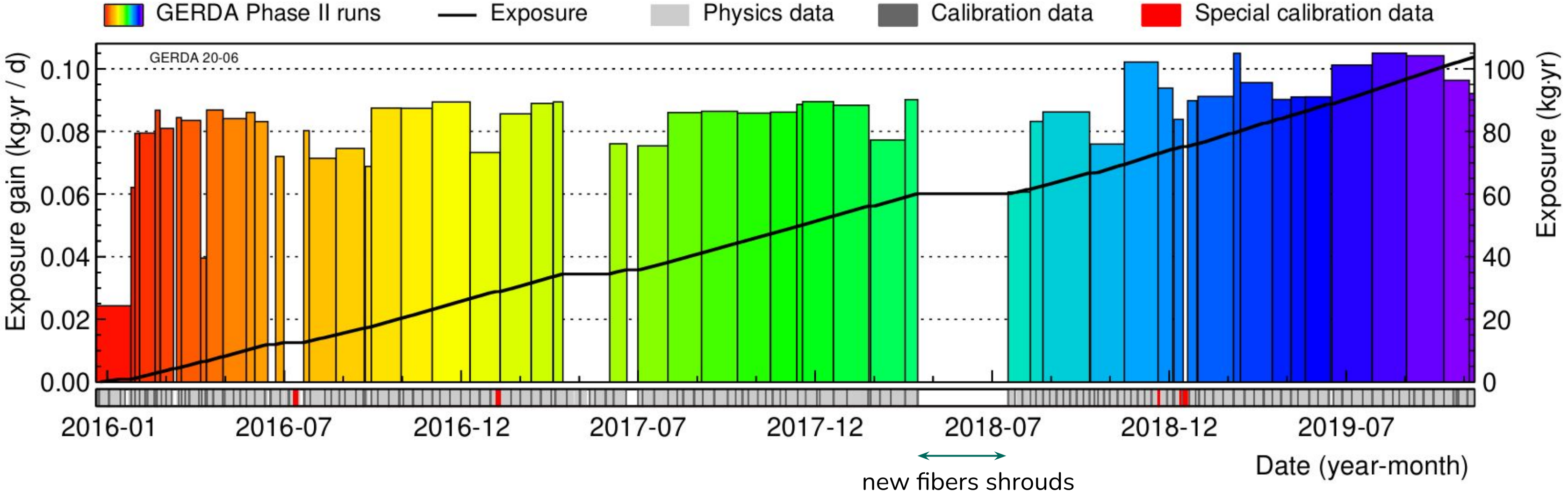
(a) **Semi-coaxial** detectors:
  A. typically mass 2~3 kg
  B. enriched to ~87% in ^{76}Ge

(b) **BEGe**(Broad Energy Germanium) detectors:
  A. average mass 670 g
  B. small p+ contact at the bottom side
  C. excellent energy resolution

(c) **Inverted-coaxial** detectors:
  A. same advantageous characteristics of BEGe
  B. larger mass

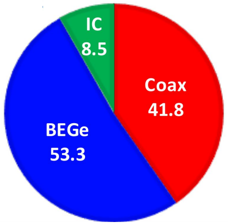


Data taking



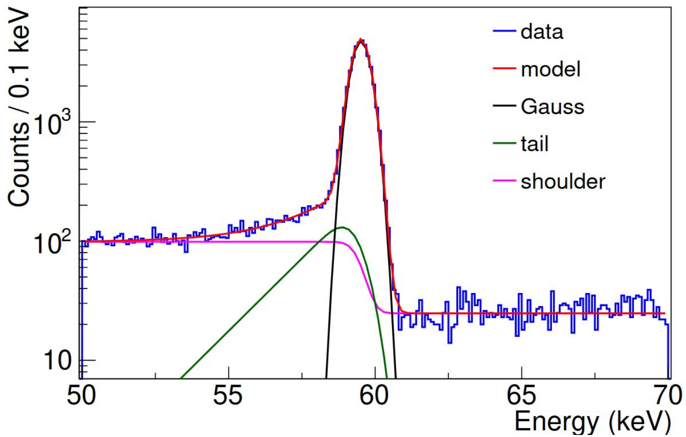
new fibers shrouds
5 new IC detectors

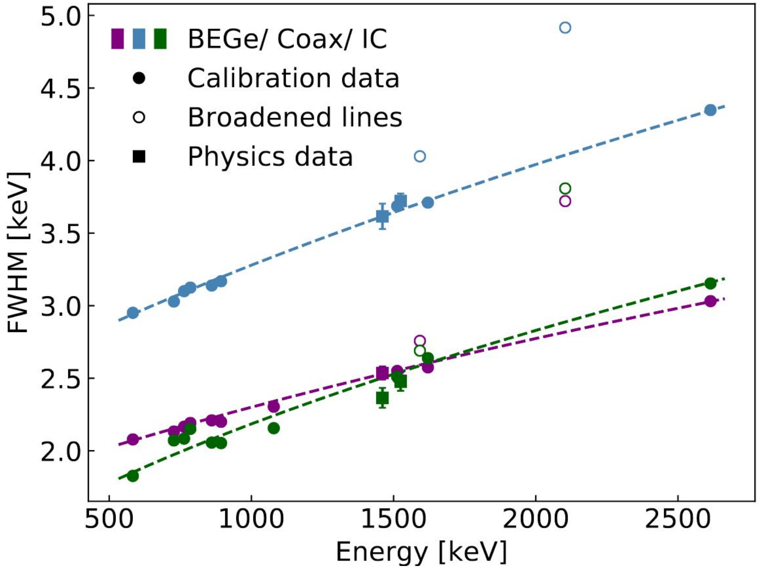
- 2011-2013: Phase I, 23.5 kg yr exposure
- 2015-2019: Phase II, 103.7 kg yr exposure, installation of LAr veto, upgrade with IC detectors in 2018, operation in background-free regime



Energy resolution

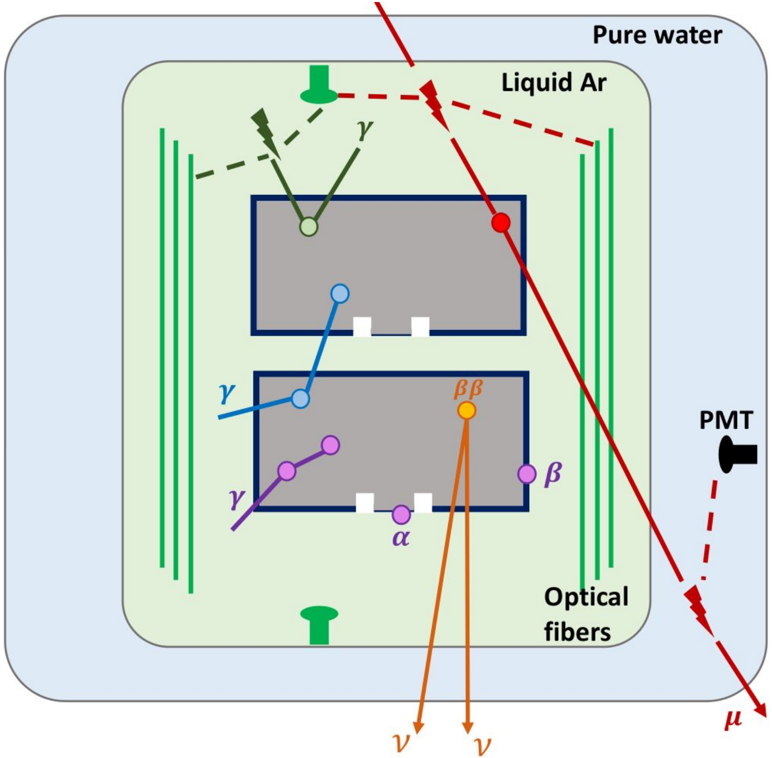
- Peak fitting algorithm to determine each detector's resolution
- Gaussian mixture models to determine resolutions per detector type
- Excellent energy resolution leads to lower backgrounds and higher discovery potential
- Well-understood peak shape, energy scale stability, and linearity lead to improved confidence in results



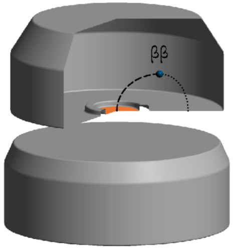


[GERDA, Eur. Phys. J. C (2021) 81, 682]

Active background reduction tools

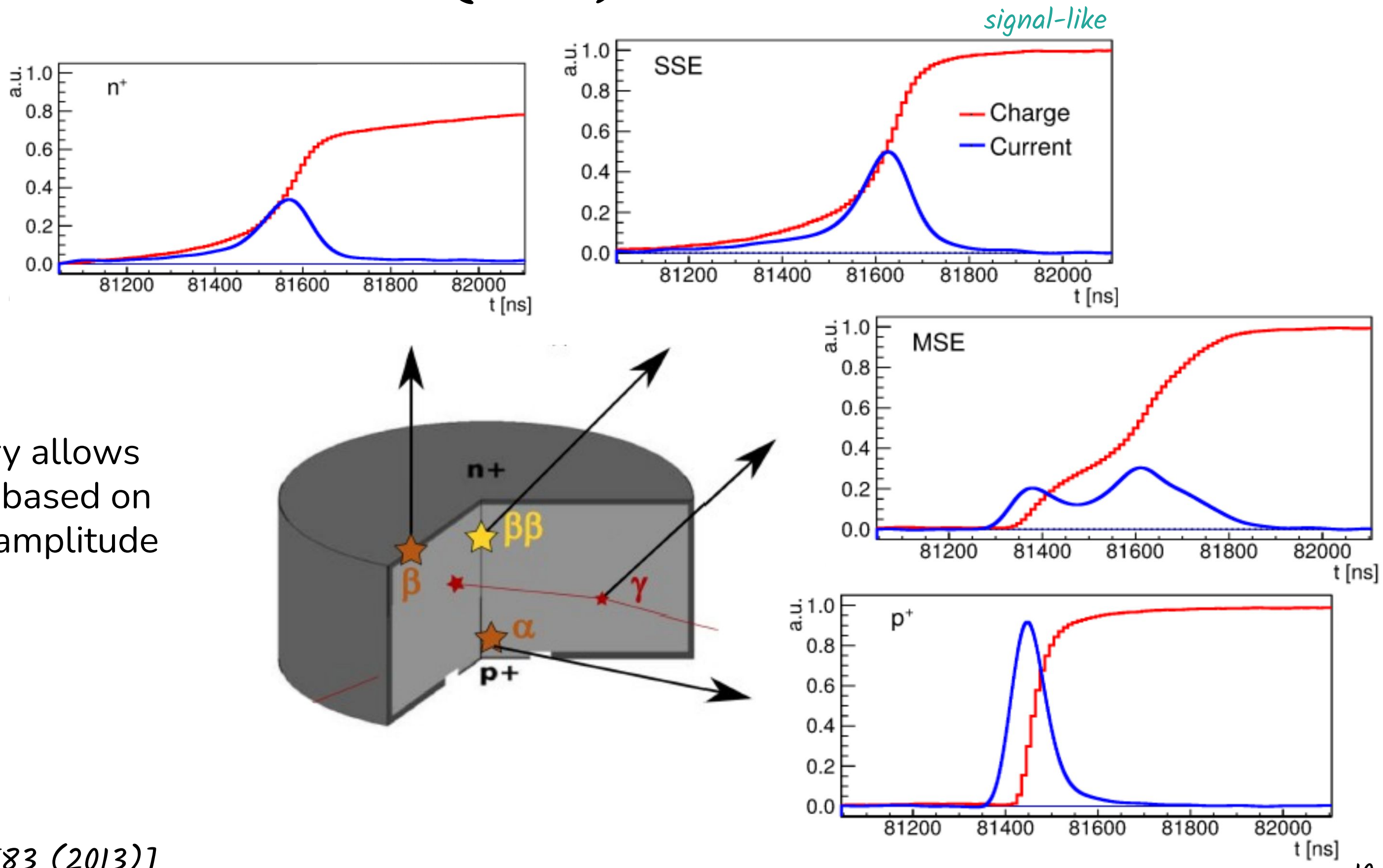


- ββ decay signal: single-site event energy deposition in a 1 mm^3 volume



- Anti-coincidence with the muon veto
- Anti-coincidence between detectors (cuts multi-site)
- Active veto using LAr scintillation (LAr Veto)
- Pulse shape discrimination (PSD)

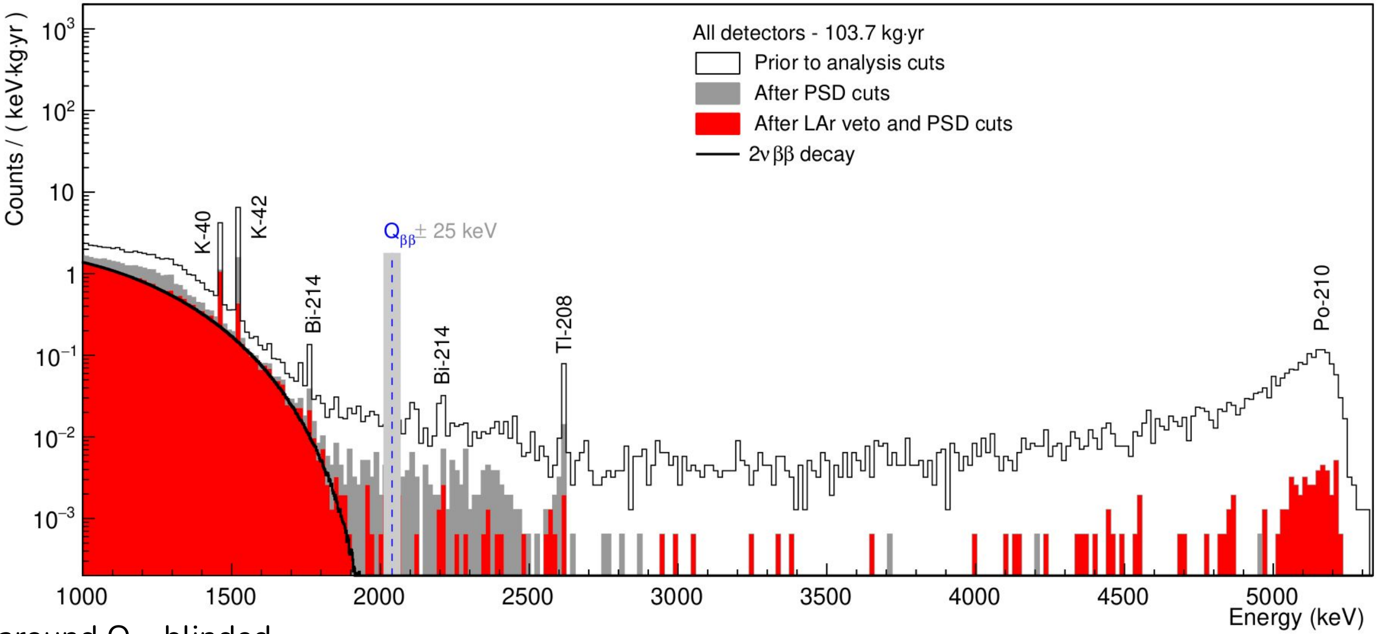
Pulse Shape Discrimination (PSD)



- Point-contact geometry allows for MS event rejection based on pulse shapes, current amplitude over energy (A/E)

[GERDA, Eur. Phys. J. C 73 2583 (2013)]

Total active background suppression



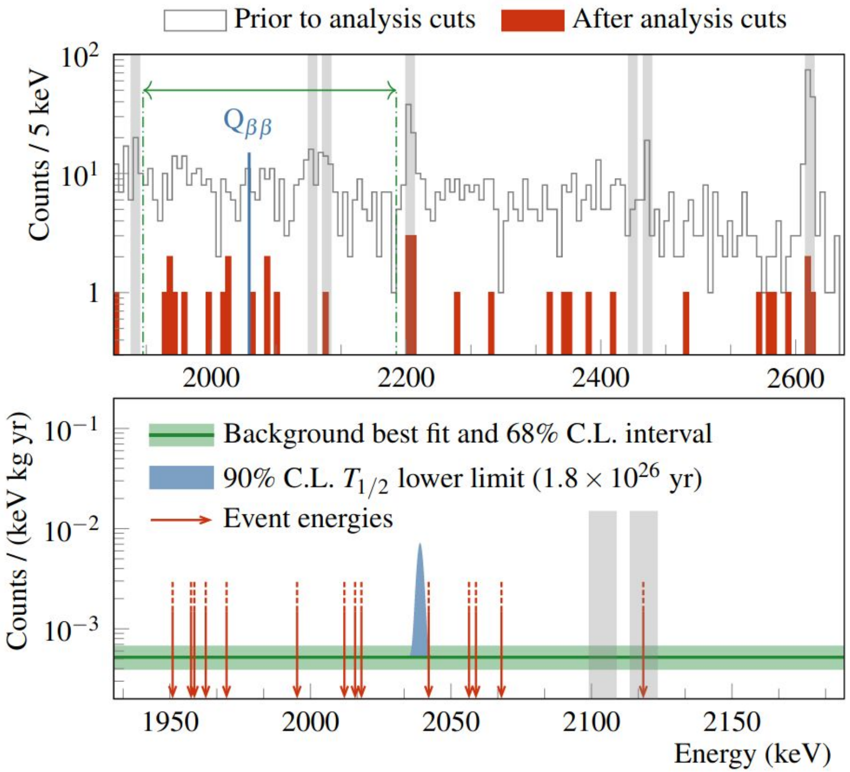
- ±25 keV around $Q_{\beta\beta}$ blinded
- Spectrum well understood:
  - ≲ 0.5 MeV: ^{39}Ar
  - ~ [0.5 - 2] MeV: 2νββ
  - ≳4 MeV: α
- Flat background in 0νββ signal region

GERDA, Science 365, 1445-1448 (2019)

Results

- Combined unbinned maximum likelihood fit
  - Combined fit of Gaussian signal & uniform background
- Best fit for null signal strength

	Goals	Achievements
Background	10^{-3} cts/(keV kg yr)	$5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ cts/(keV kg yr)
Exposure	≥ 100 kg yr	103.7 kg yr (footnote Phase I)
Sensitivity	$T^{0\nu\beta\beta}_{1/2} \geq 10^{26}$ yr	$T^{0\nu\beta\beta}_{1/2} > 1.8 \cdot 10^{26}$ yr

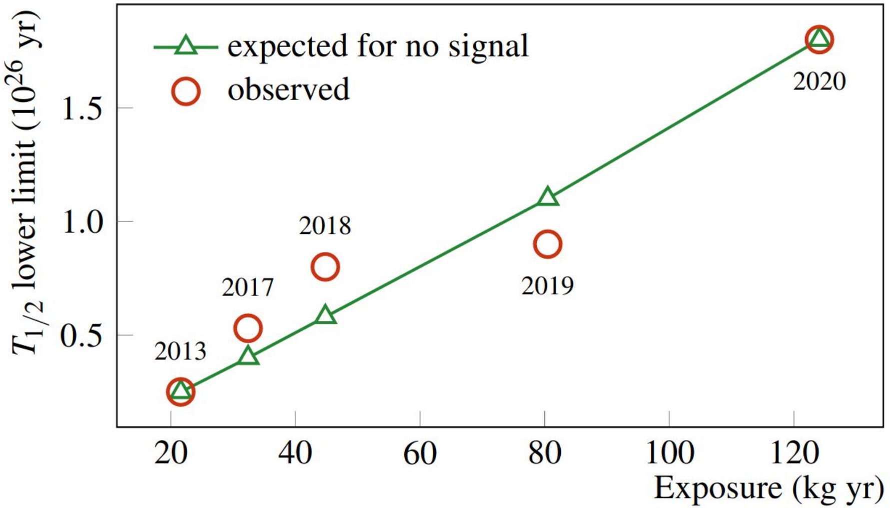


[GERDA , Nature 544 (2017), 47-52]

Conclusion

- GERDA employed an array of HPGe detectors enriched in ^{76}Ge to search for $0\nu\beta\beta$
- GERDA ran in background-free regime for the entire duration of its data taking.
- Provides the most stringent constraints on the half-life of $0\nu\beta\beta$ decay:

  $T_{1/2} > 1.8 \times 10^{26}$ yr $\rightarrow$ $|m_{\beta\beta}| \lesssim 79 - 180$ meV



- Next step... LEGEND

stay tuned!

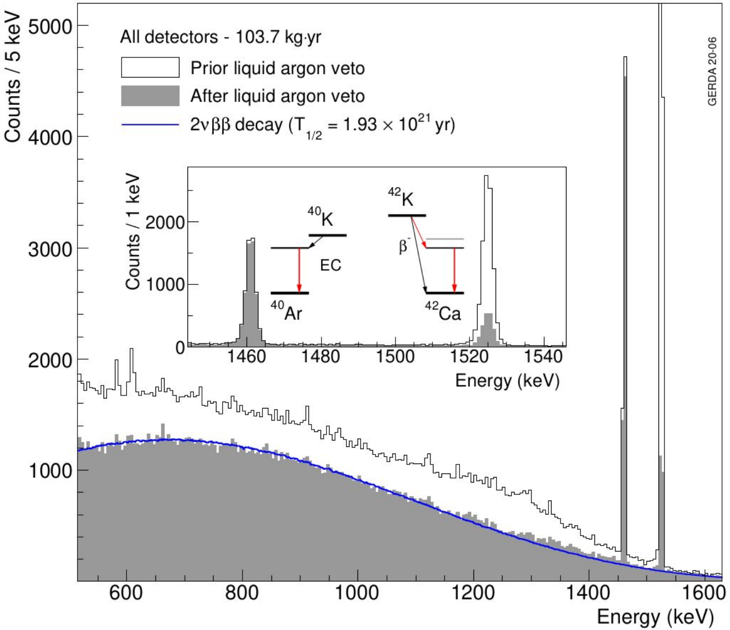
[GERDA , Nature 544 (2017), 47-52]

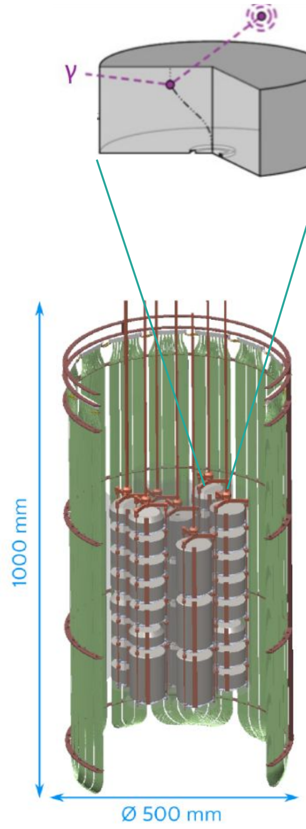
backup

Liquid Argon Veto

- Stable operations over 4 years of data taking:
    - 16 PMts
    - 1.5 km light guiding fibers + SiPM readout
    - Vetoes events in coincidence with Germanium

- Acceptance ($0\nu\beta\beta$) ~ 98%
- Crucial role in background suppression after PSD: ÷ 6 in the ROI



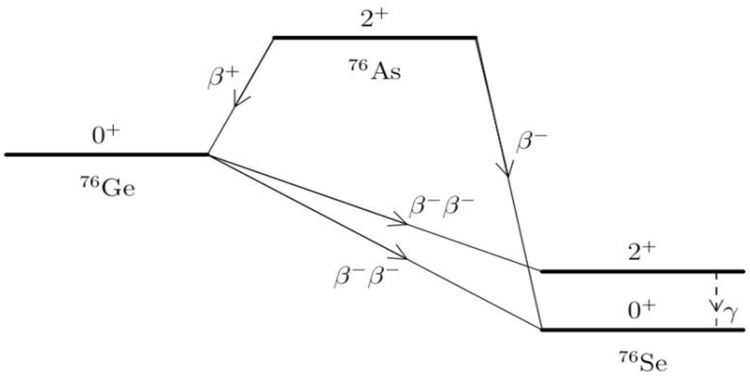


[GERDA, European Phys J C 78 (2018), 388]

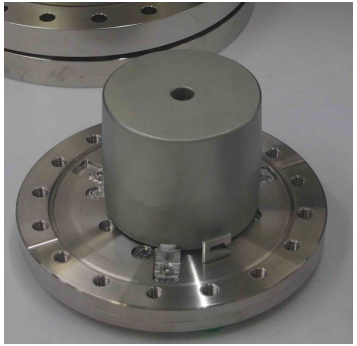
Searching in ^{76}Ge

Why using Germanium?

Advantage
- High efficiency → Source=Detector
- Small intrinsic BI = high purity Ge
- Excellent ΔE
- Well-established technology



Disadvantages
- Small Q-value
- Small $G^{0\nu}(Q,Z)$
- Small abundance 0νββ of isotope

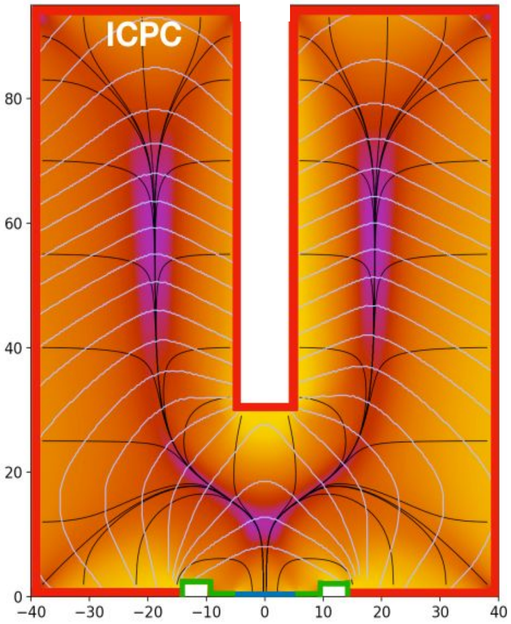


HPGe detector

HPGe detectors

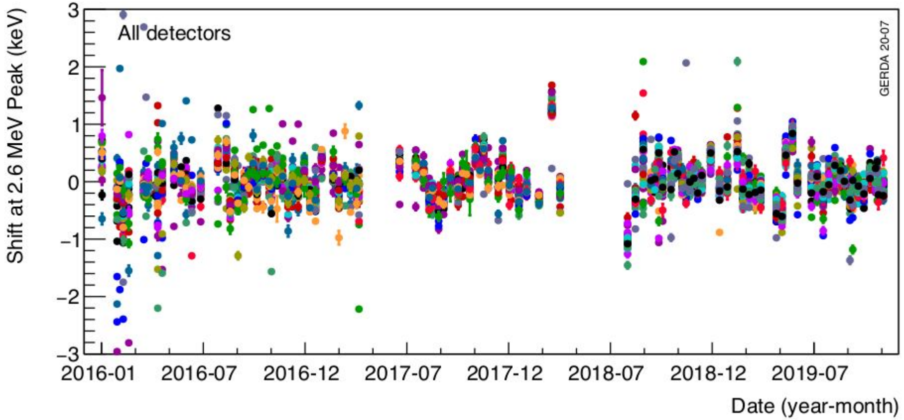
Advantages of Inverted Coaxial Point Contact (ICPC) detectors:

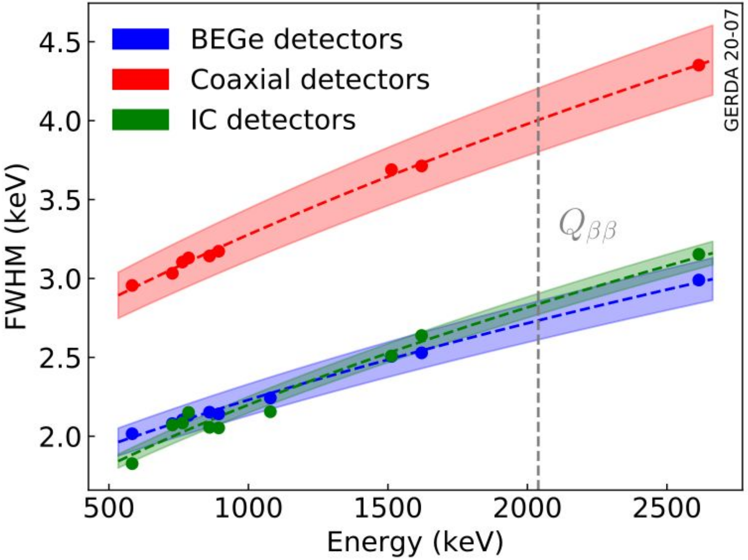
- Enriched detectors, 92% of detector material is ^{76}Ge
- Excellent resolution and pulse shape discrimination
- Significantly larger w.r.t. BEGe or PPC (up to 3 kg)
- Less channels, less background
- Better surface to volume-ratio (30-40%)
- Production started early 2019
- About 60 detectors expected by fall 2021



n+ electrode
p+ electrode
passivation

Performance on the energy scale

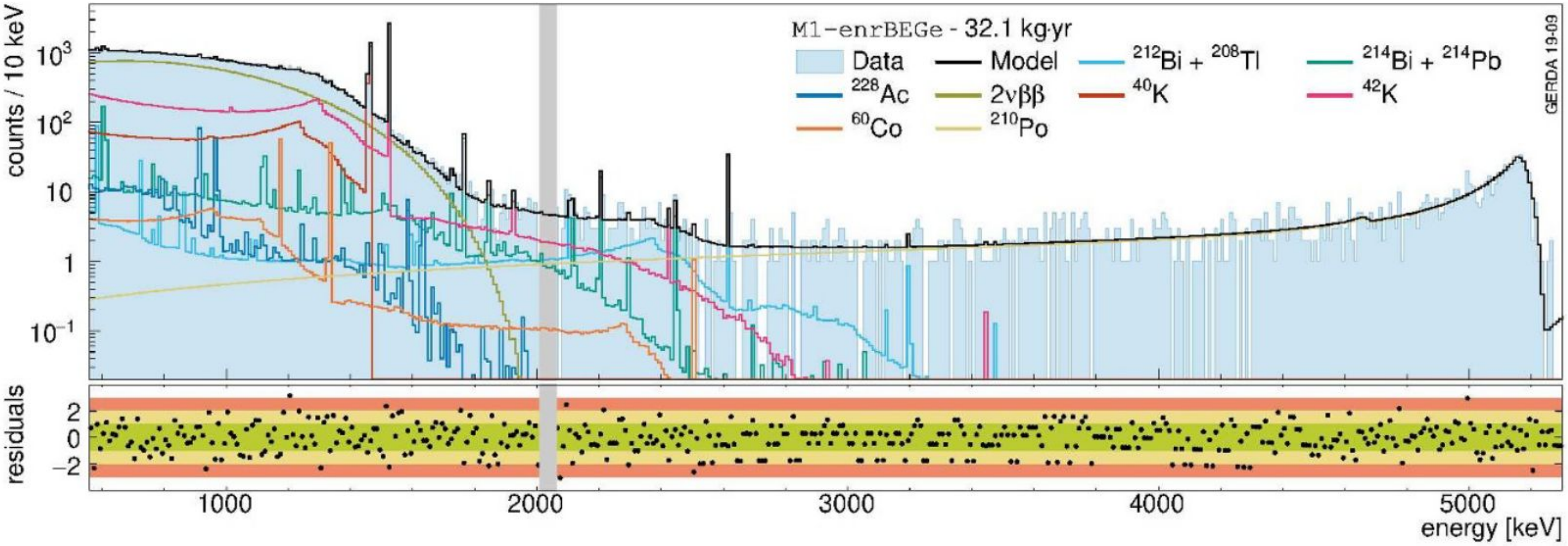




- Detectors calibrated weekly with ^{228}Th
- Energy shifts between calibrations < 1 keV
- Zero Area Cusp energy filter [*European Phys J C* 75 (2015), 255]

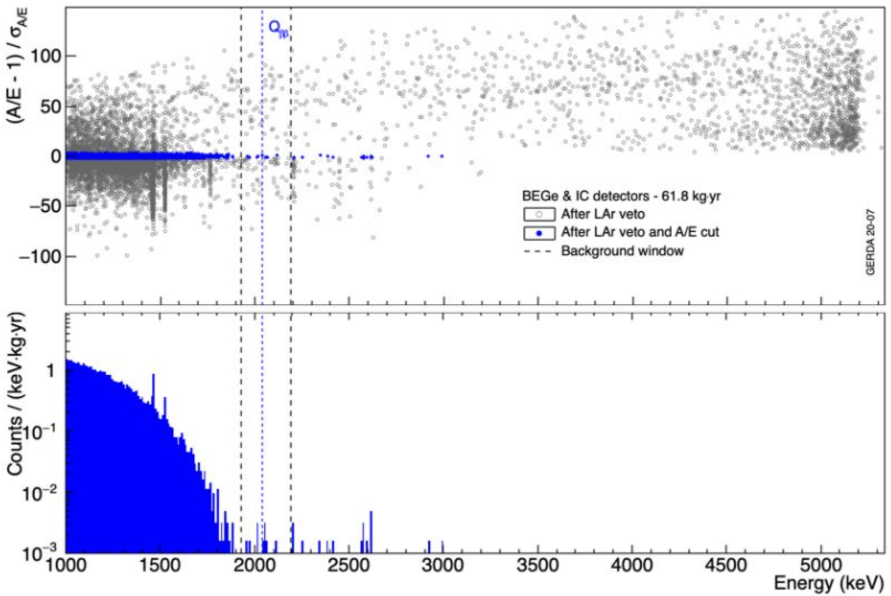
Background model

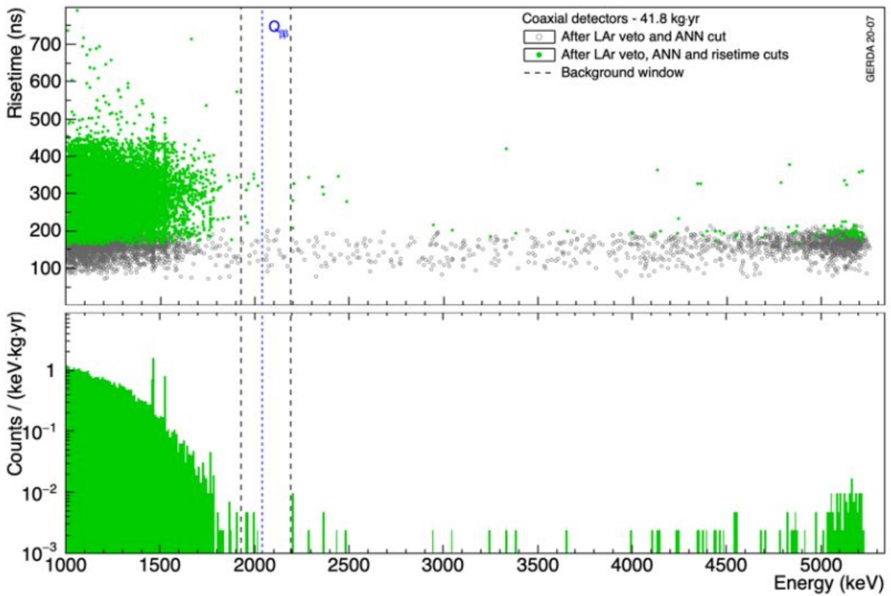
[GERDA , J High Energy Phys, 2020 (2020), no. 3, 139]



All the background components are well known

Details on PSD





LEGEND experiment

First Stage (**LEGEND-200**):

- Upgrade of the existing infrastructure of GERDA experiment
- Reduction of the BI of a factor 5 w.r.t. GERDA Phase II goal
- ~200 kg of detector mass: 35 kg from GERDA + 30 kg from MJD + 140 kg which are new.

Further Stage (**LEGEND-1000**):

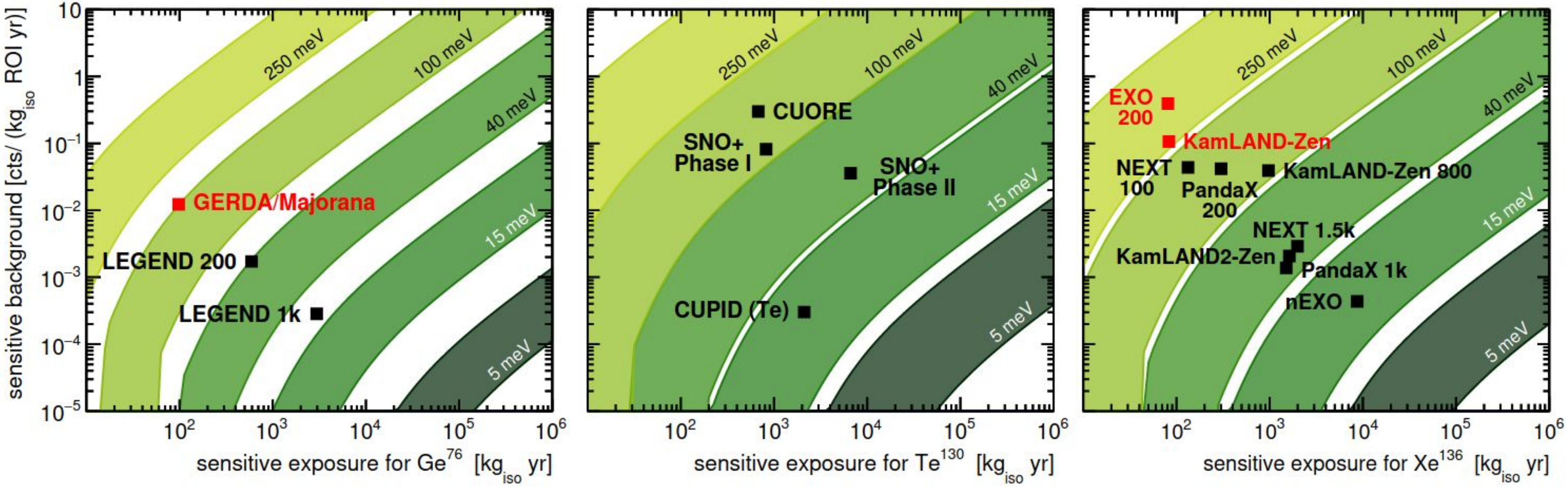
- 1000 kg detector mass (staged)
- Background reduction of a factor 20 w.r.t. LEGEND-200
- To reach beyond 10^{28} yrs half-life discovery sensitivity
- Location to be defined (SNOLAB or LNGS)

L200 Goals

half life discovery sensitivity	10^{27} yrs
mass sensitivity	30-70 meV
background index	$2 \cdot 10^{-4}$ cts/(keV $\cdot$ kg $\cdot$ yr)

Discovery sensitivity for ^{76}Ge, ^{130}Te, and ^{136}Xe

Comparison of rough sensitivity between ongoing & planned experiments



Agostini, Benato, Detwiler, Phys. Rev. D 96 053001 (2017)