Search for neutrinoless double beta decay with germanium detectors

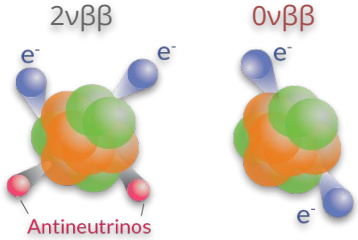
Anna Julia Zsigmond
(Max Planck Institute for Physics)

for the GERDA Collaboration

BLV 2019

Neutrinoless double beta decay search with ^{76}Ge

- $^{76}Ge \rightarrow {}^{76}Se + 2e^-$ with $Q_{\beta\beta} = 2039$ keV



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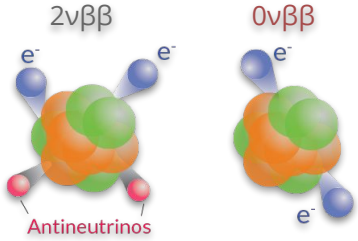

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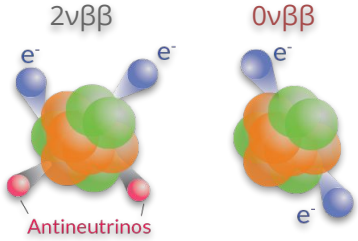

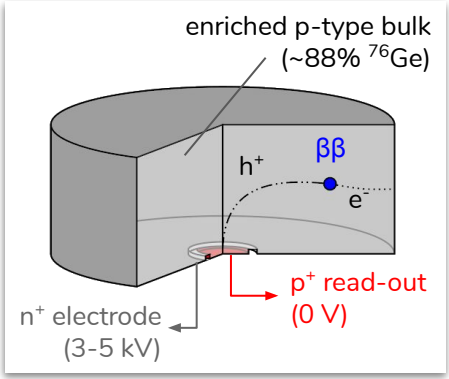

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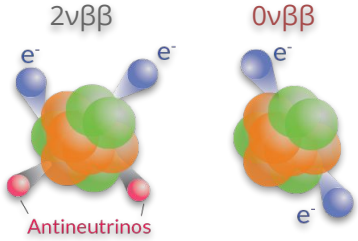

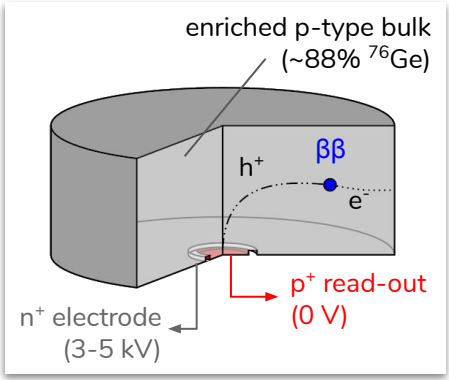

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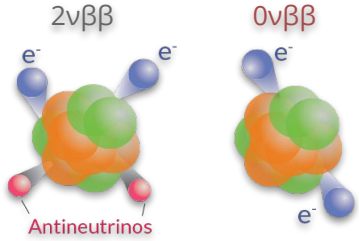
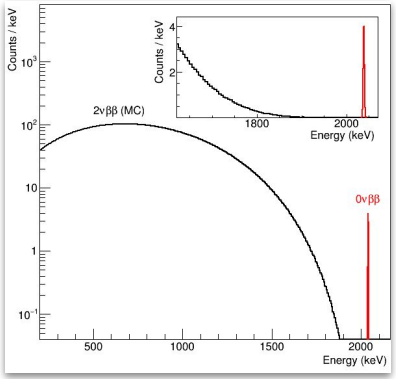
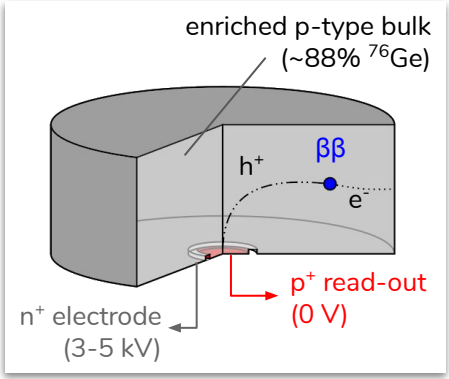
- Excellent energy resolution 0.1% @ $Q_{\beta\beta}$
  → 2νββ background suppressed







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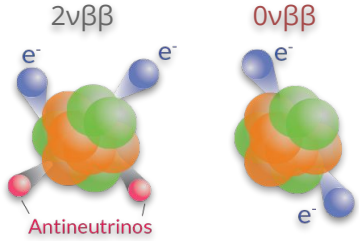
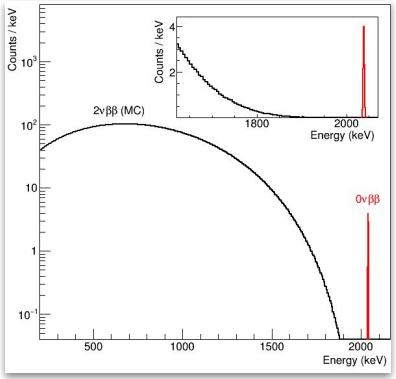
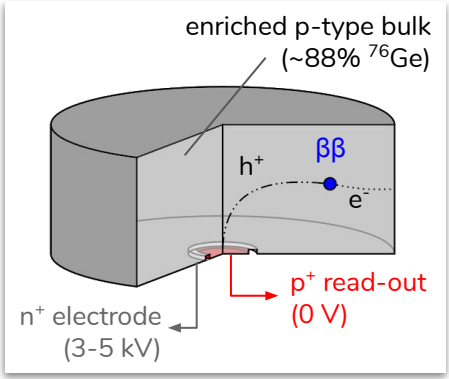
- Excellent energy resolution 0.1% @ $Q_{\beta\beta}$
  → 2νββ background suppressed
- High density material → ββ point-like
  → backgrounds can be discriminated and rejected

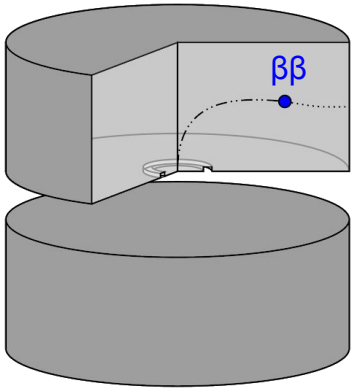






Background reduction concept

ββ signal

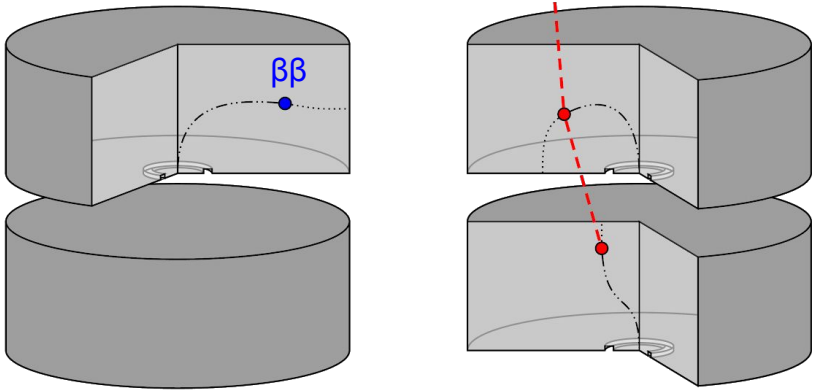


point-like: single-detector, single-site topology

Background reduction concept

ββ signal

Detector
anti-coincidence



point-like: single-detector,
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multi-detector
interactions

Background reduction concept

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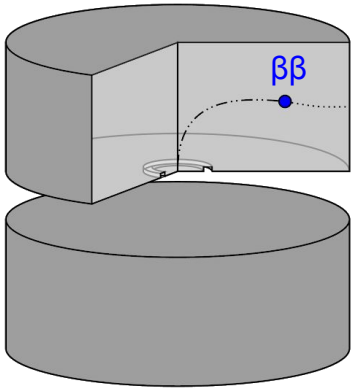

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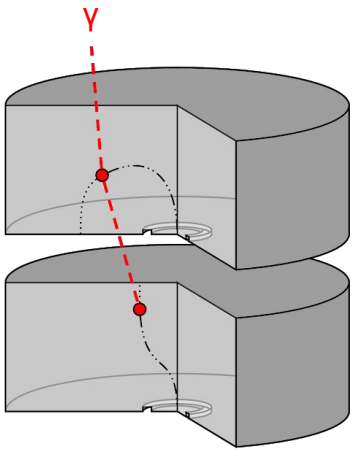
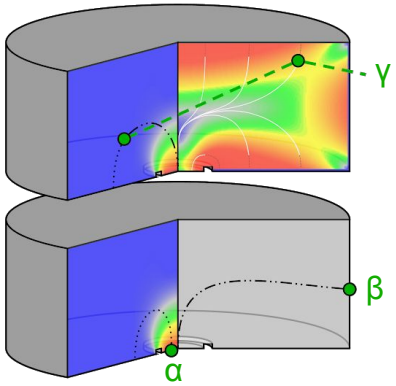
Detector anti-coincidence



multi-detector interactions

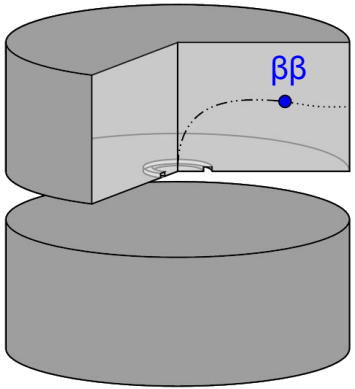
Pulse shape discrimination (PSD)



multi-site / surface interactions

Background reduction concept

ββ signal



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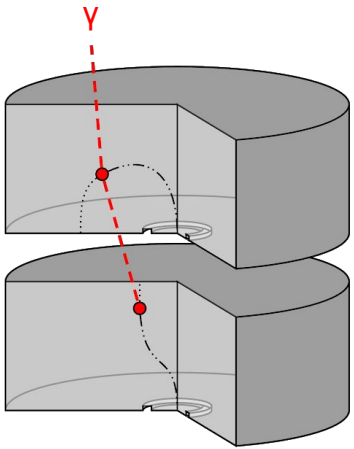

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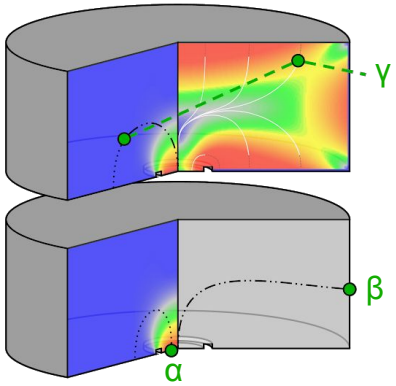
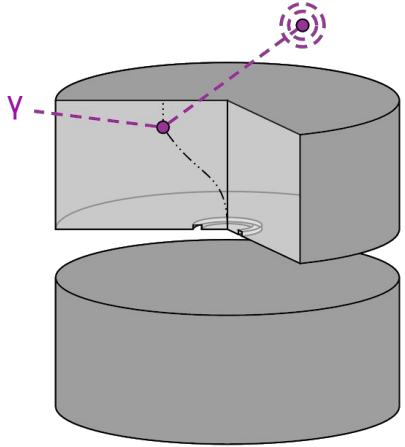


multi-site / surface interactions

Liquid argon (LAr) veto

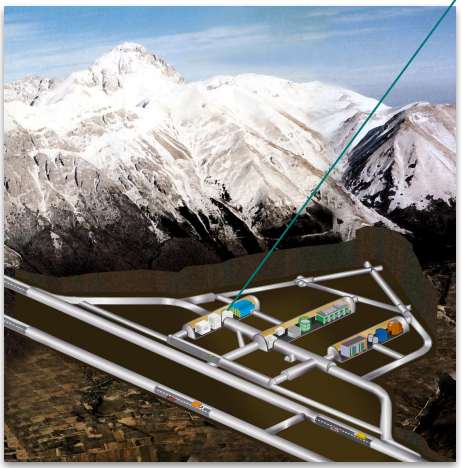


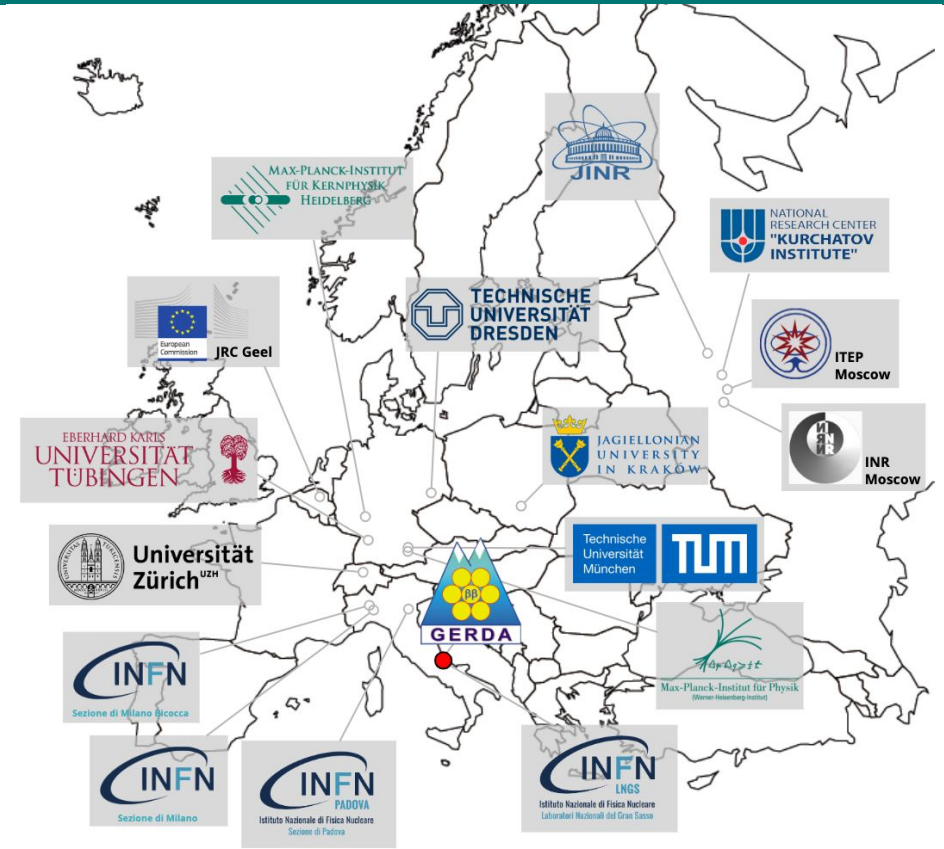
interactions with coincident energy deposition in surroundings

GERDA Collaboration

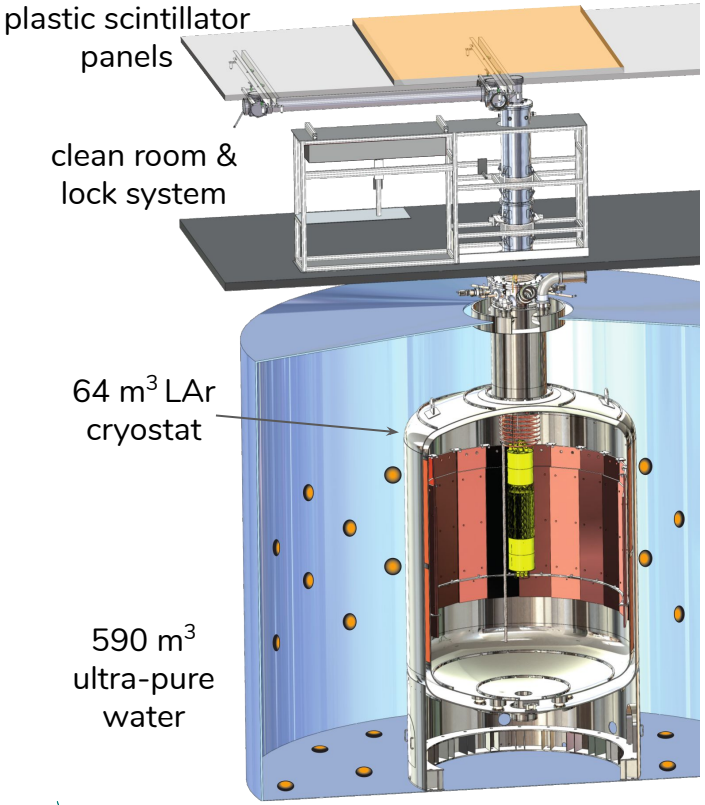
16 institutions
~110 members

LNGS Hall A





GERDA Phase II



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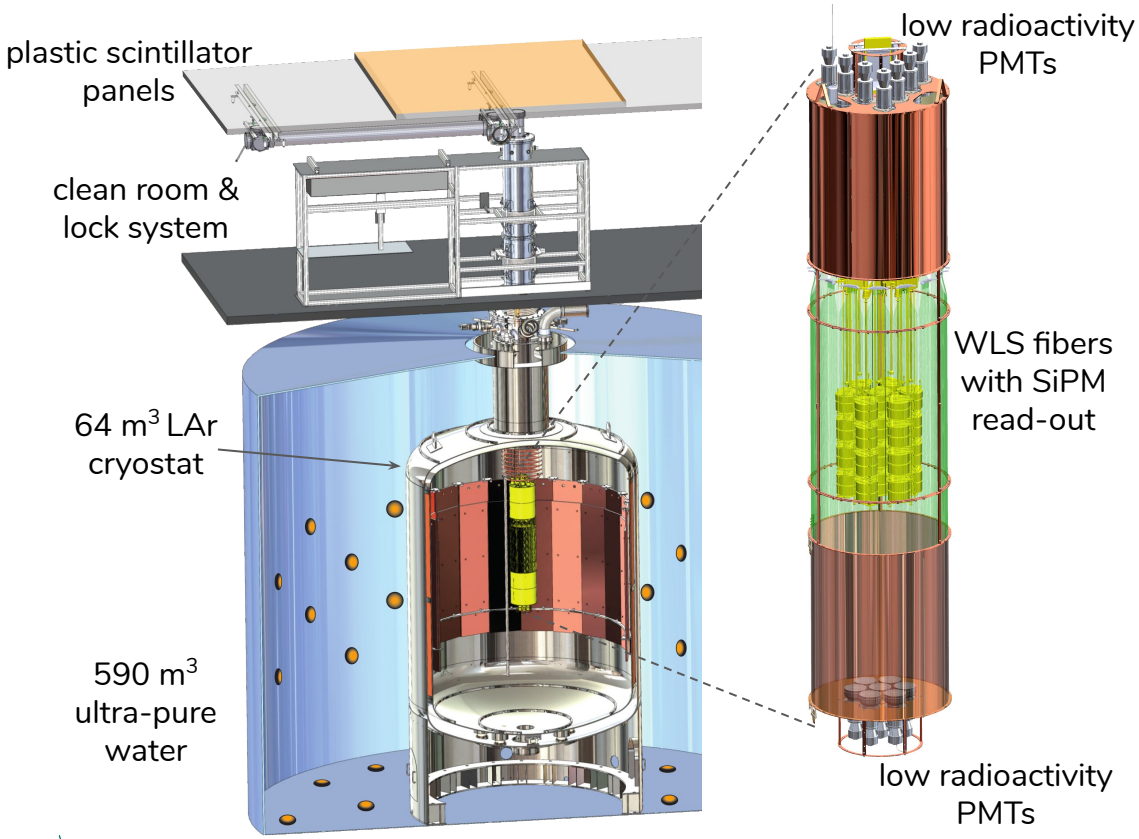

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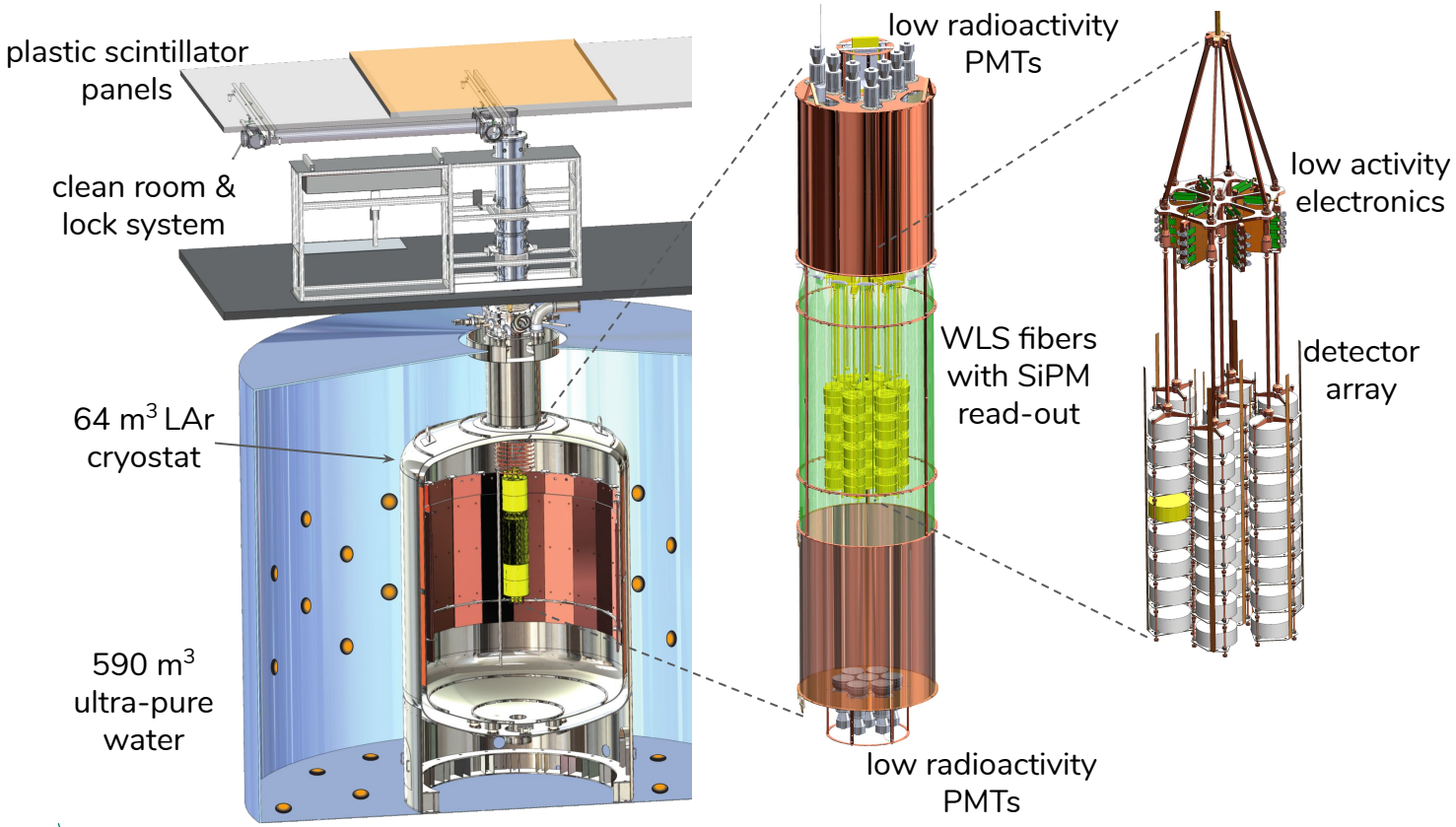

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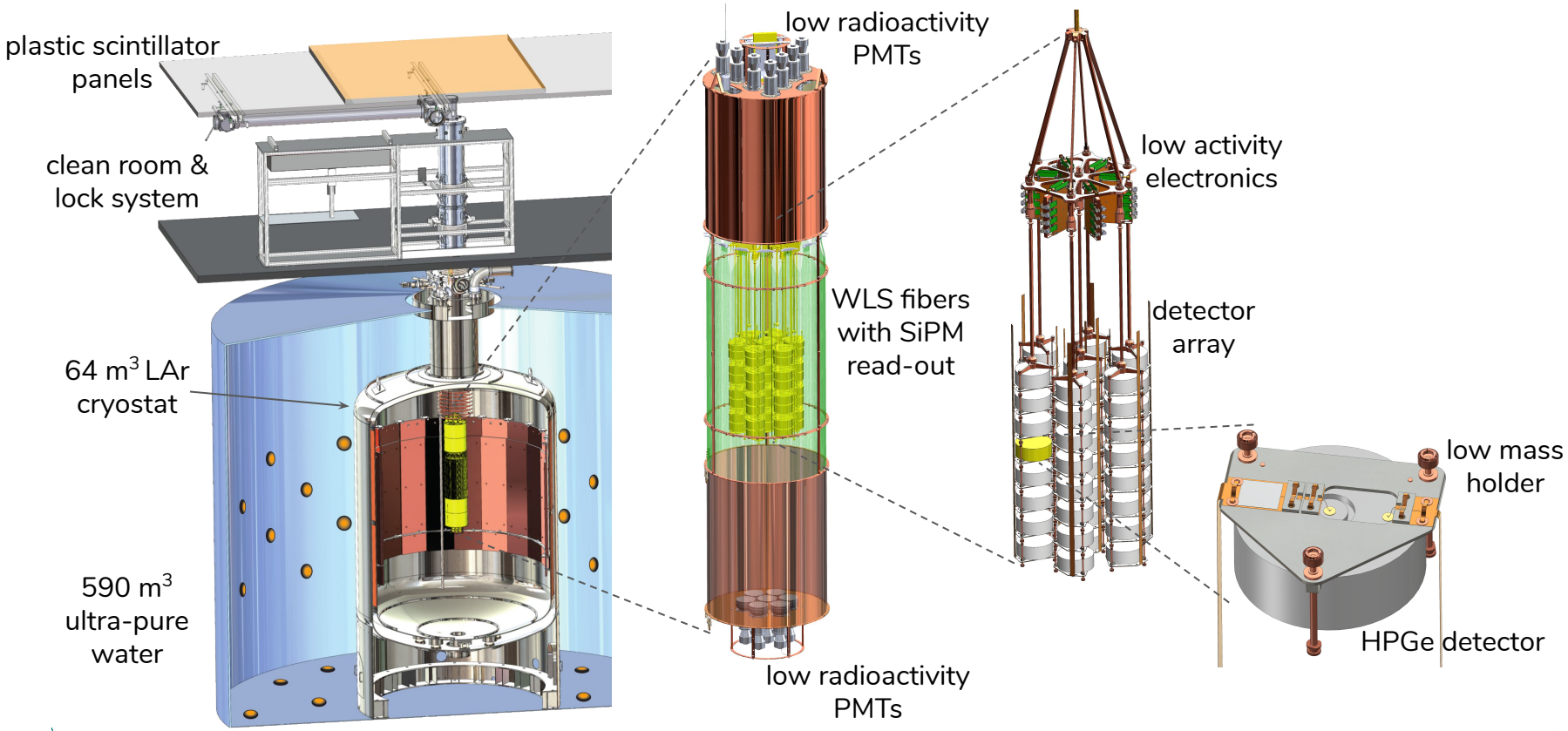
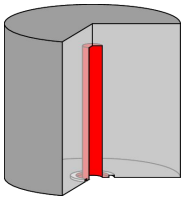
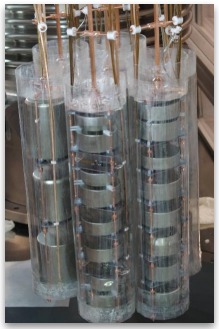


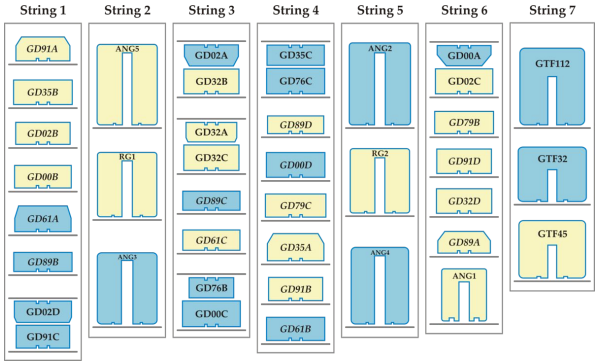
Germanium detectors

Phase II: 7 strings with 40 detectors

- 7 enriched (semi-)coaxial (15.6 kg)
- 30 enriched BEGe (20.0 kg)
- 3 natural coaxial (7.6 kg)







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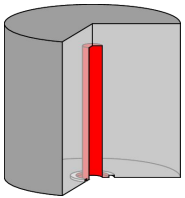
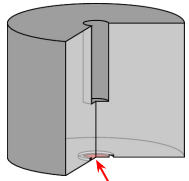
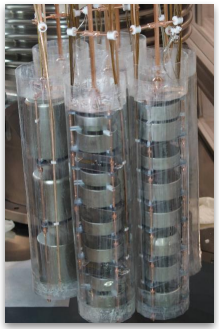
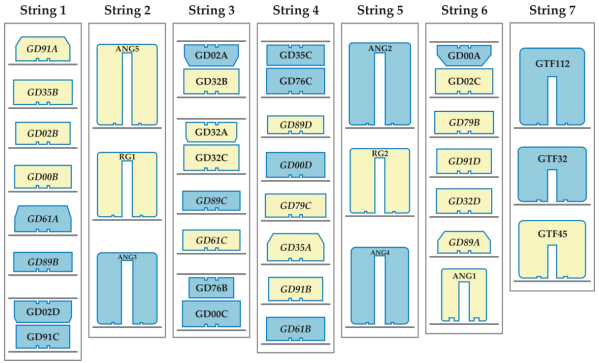


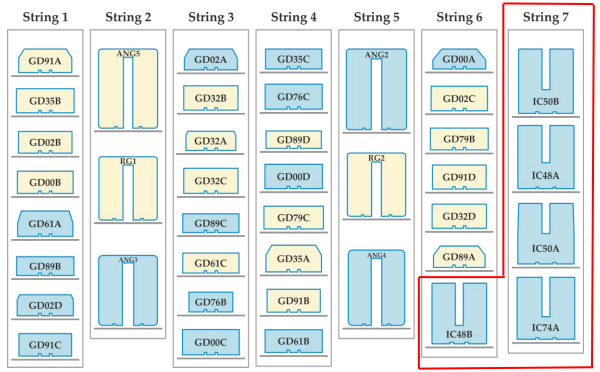
Upgrade in summer 2018: 41 enriched detectors

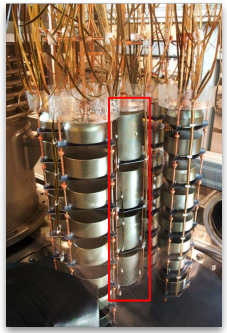
- 6 enriched coaxial (14.6 kg)
- 30 enriched BEGe (20.0 kg)
- 4 enriched inverted coaxial (9 kg)



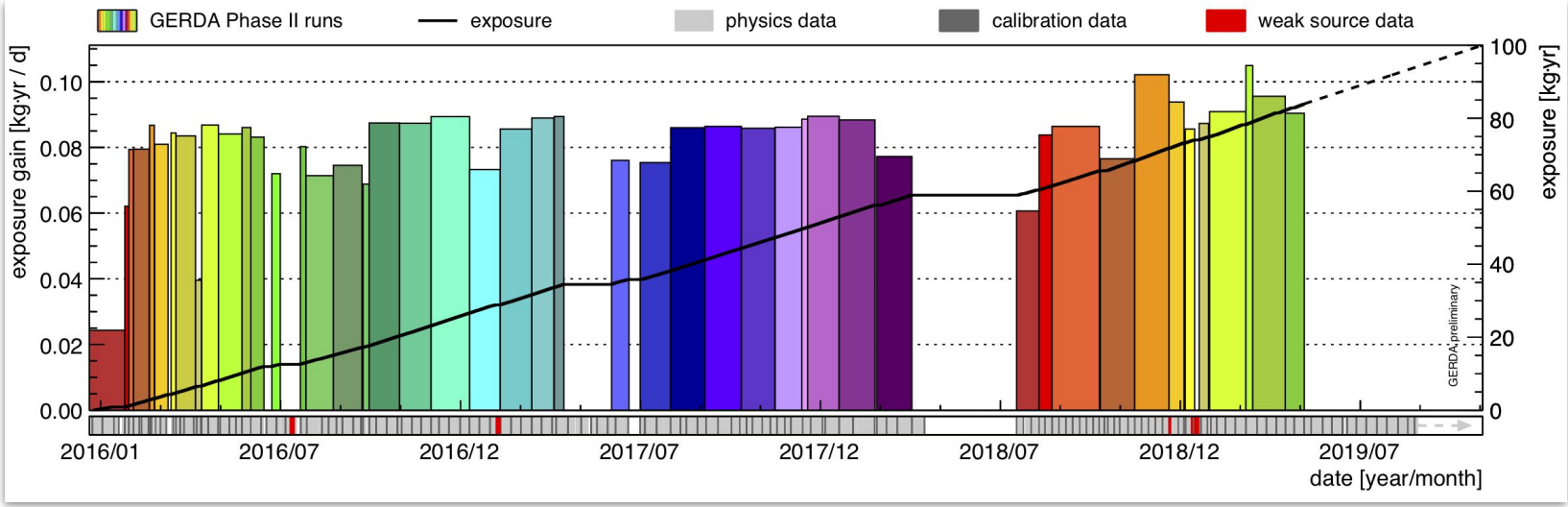








Phase II data taking



June 2016
10.8 kg · yr
Nature **554** (2017) 47

June 2017
+12.4 kg · yr BEGe data
PRL **120** (2018) 132503

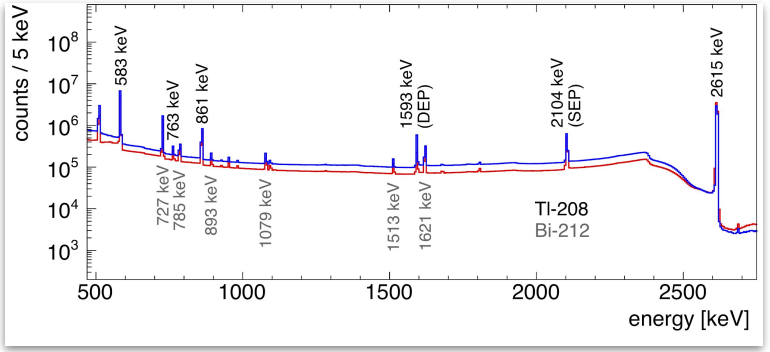
June 2018
+35.7 kg · yr BEGe and Coax data
Science **365** (2019) 1445

June 2019
+24.9 kg · yr BEGe, Coax and IC data

- Blind analysis: events with energy $Q_{\beta\beta}$ ± 25 keV not processed until all analysis cuts finalized

Energy resolution

- Weekly calibrations with ^{228}Th sources
- Optimized zero area cusp (ZAC) filter for energy reconstruction



Energy resolution

- Weekly calibrations with ^{228}Th sources
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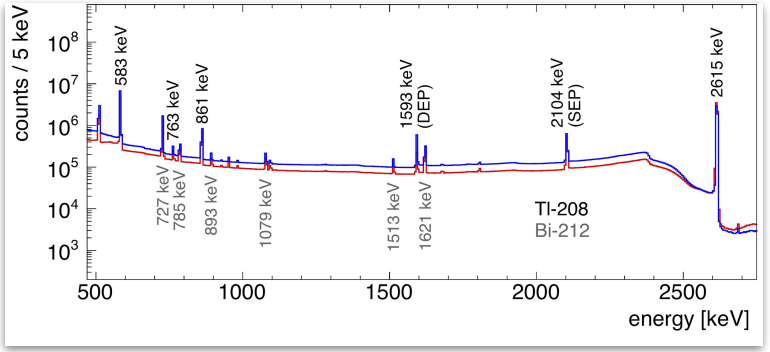
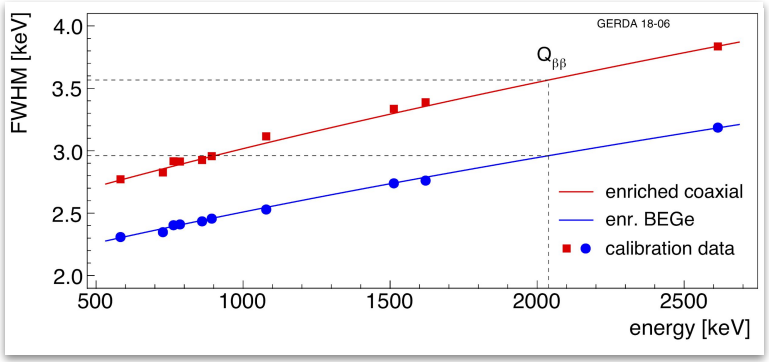
- Energy resolution FWHM at $Q_{\beta\beta}$

coaxial	3.6±0.1 keV
BEGe	3.0±0.1 keV





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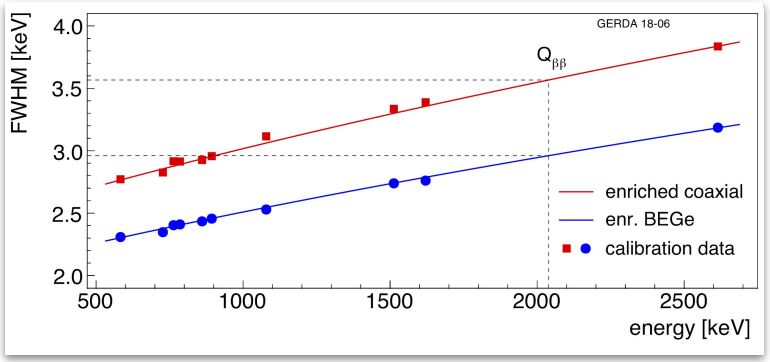
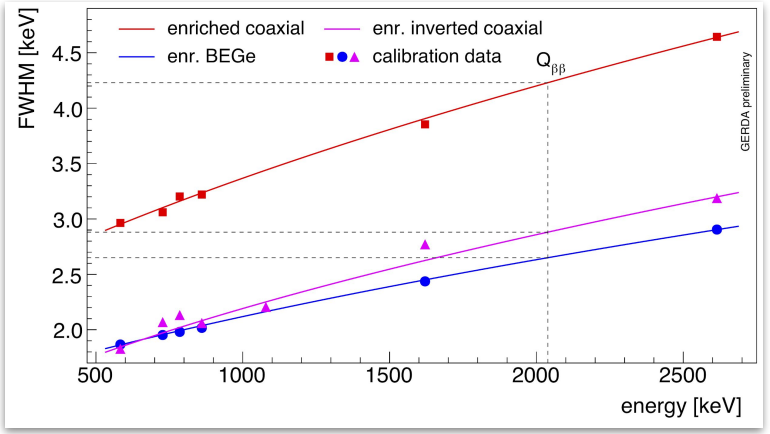
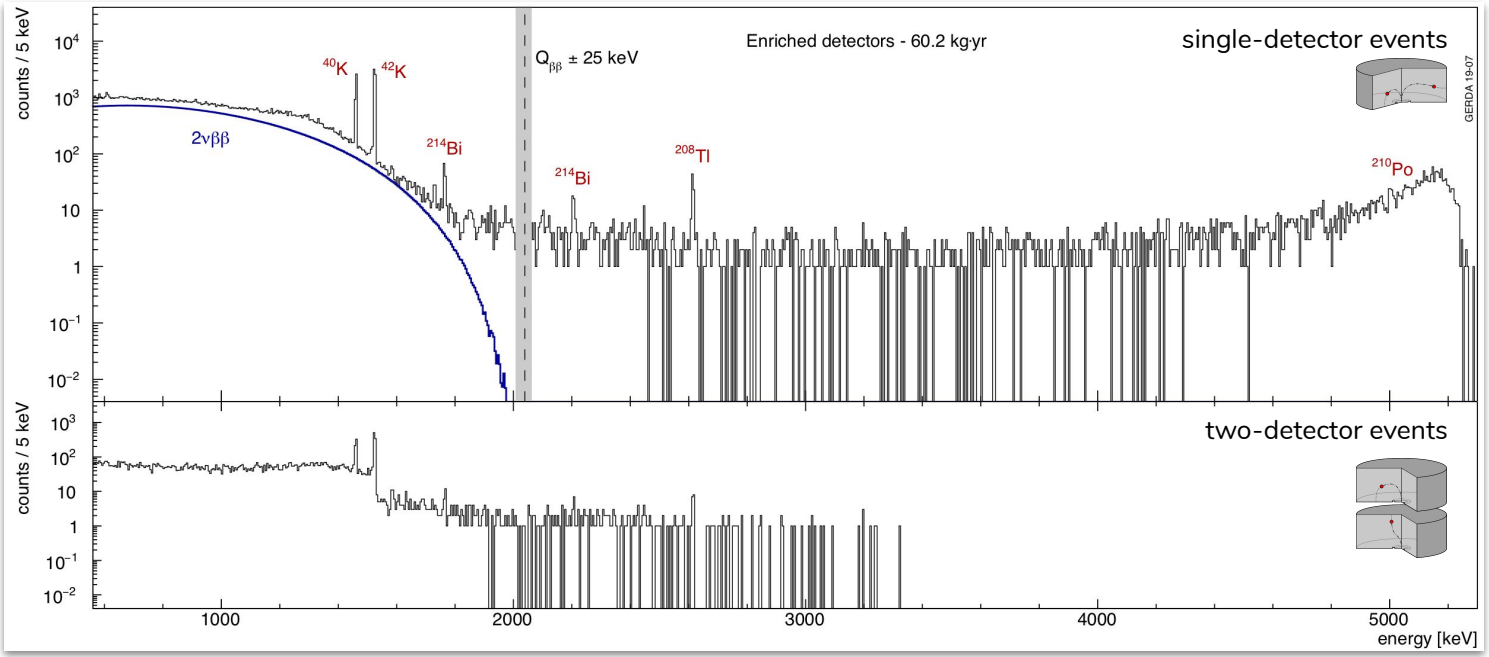


- Performance stable after upgrade
- Energy resolution FWHM at $Q_{\beta\beta}$

coaxial	4.2±0.1 keV
BEGe	2.7±0.1 keV
inverted coaxial	2.9±0.1 keV

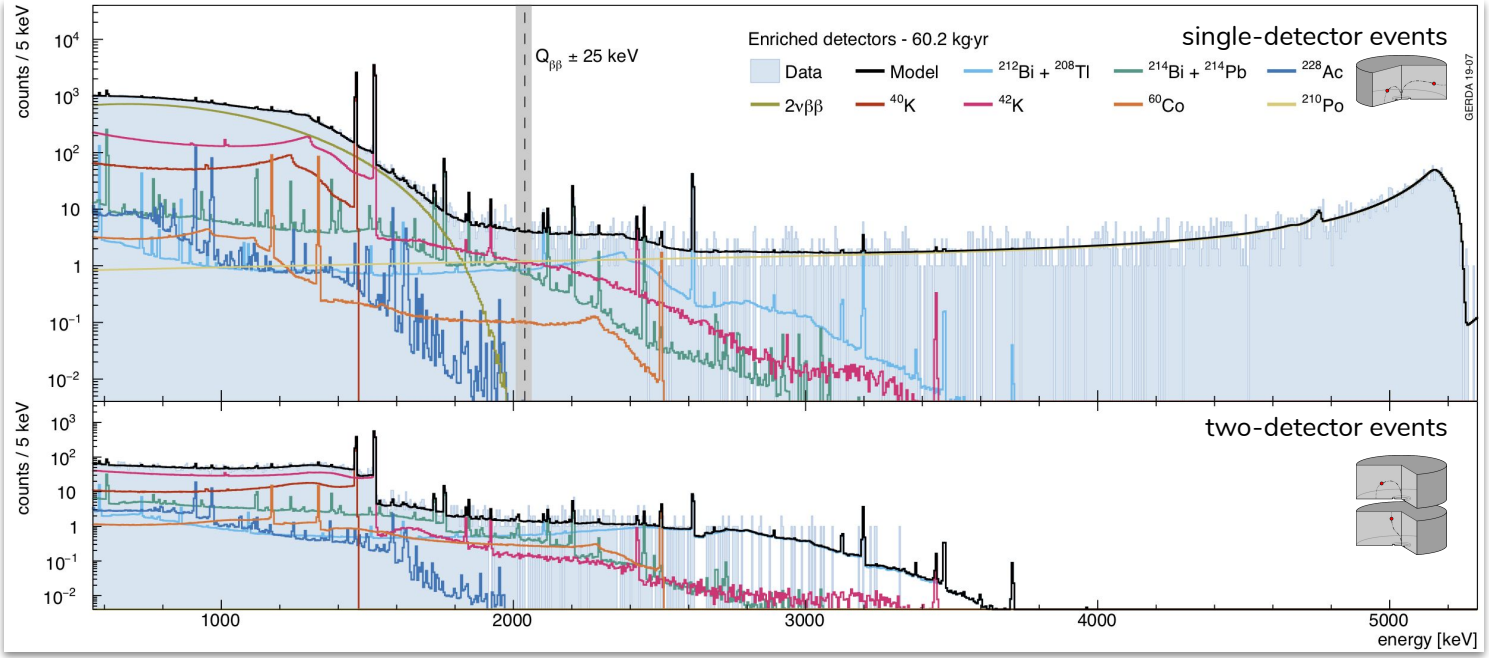


Physics spectrum



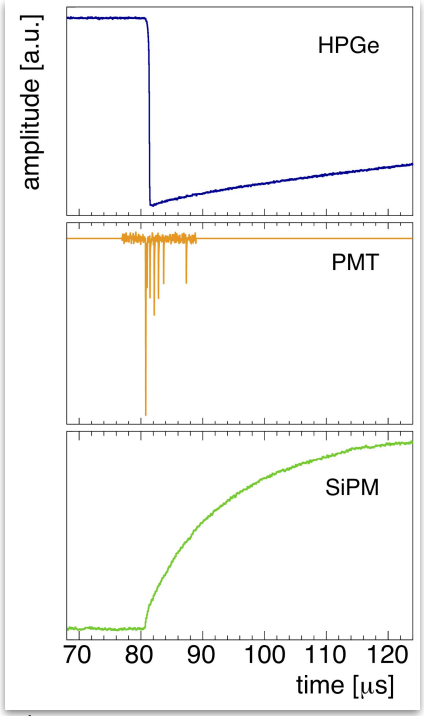
- After muon veto and detector anti-coincidence cuts
- 2νββ events and natural radioactivity: γ lines from ^{40}K, ^{42}K, U/Th decay chains and αs at high energies

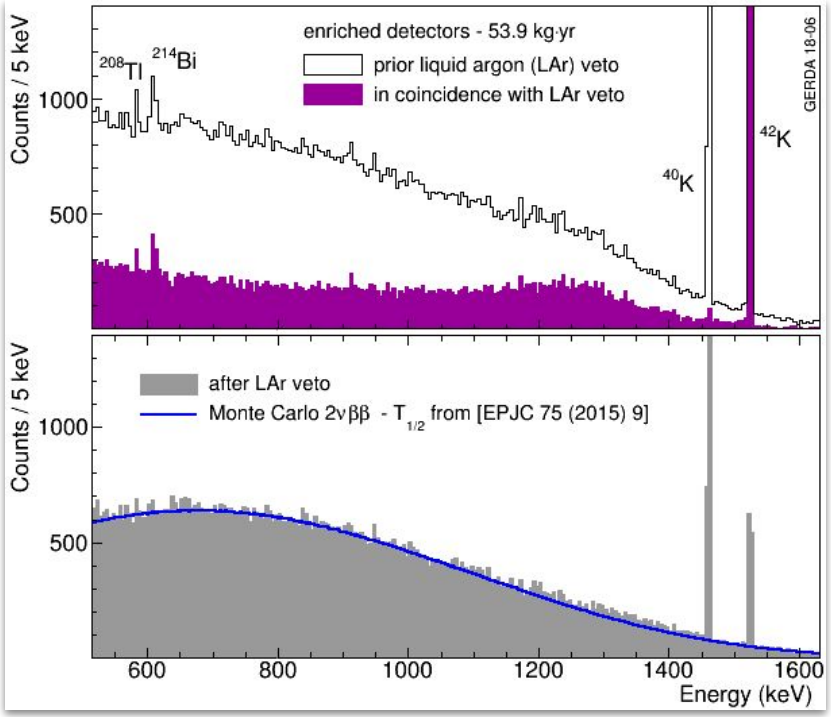
Background model



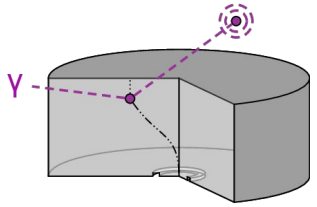
- Bayesian fit to multiple datasets with Monte Carlo PDFs for nearby components and screening measurements as priors

Background suppression with LAr veto





Channelwise (PMT/SiPM) anti-coincidence condition (threshold ~0.5 PE)

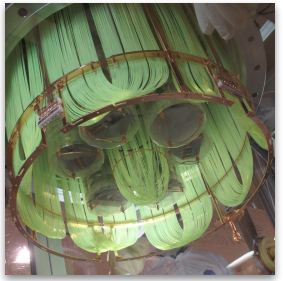


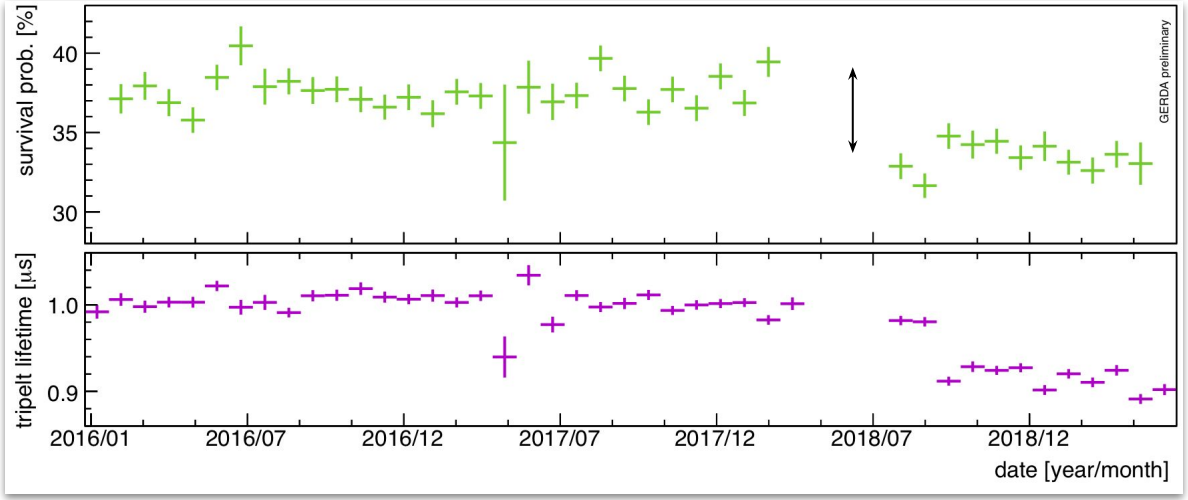
- Almost pure 2νββ spectrum after LAr veto cut
- 0νββ signal acceptance **(97.7±0.1)%** from random triggered events

LAr veto upgrade

~800 m of TPB coated WLS fibers,
15 SiPM channels

increased fiber density,
~1400 m WLS fibers,
added central read-out,
15+2 SiPM channels





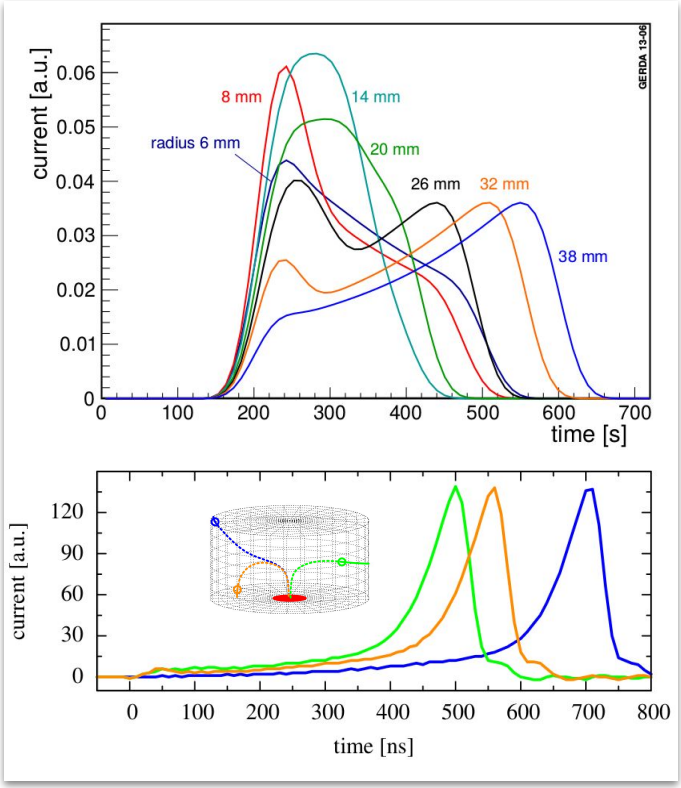
improved **light collection** based on ^{39}Ar events at 200-400 keV

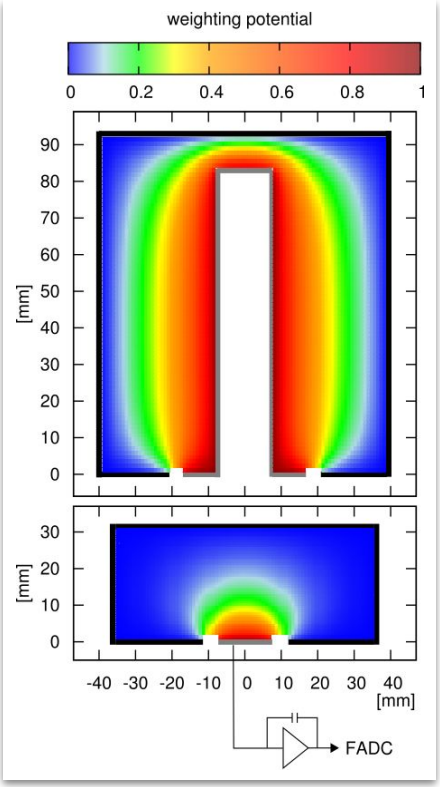
stable **LAr quality** over > 2 yr of Phase II data taking

Pulse shape discrimination

SSEs in **coaxial detectors**:
both holes and electrons
contribute to the signal
→ complicated pulse shapes

SSEs in **BEGe detectors**:
strong weighting field around
contact
→ very similar pulse shapes

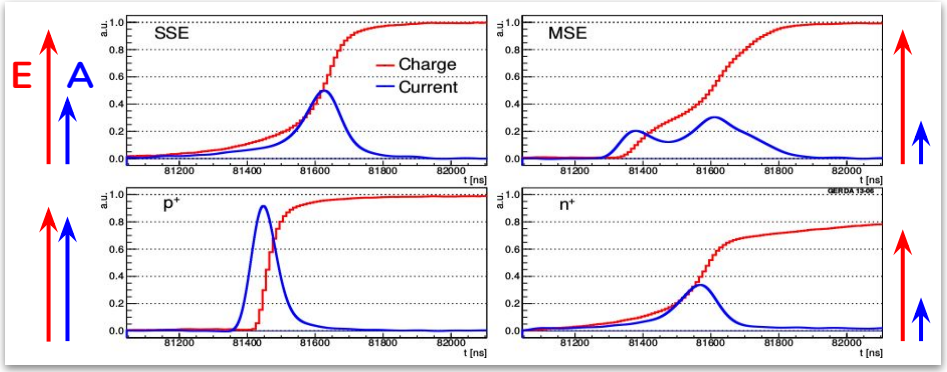




Pulse shape discrimination

BEGe

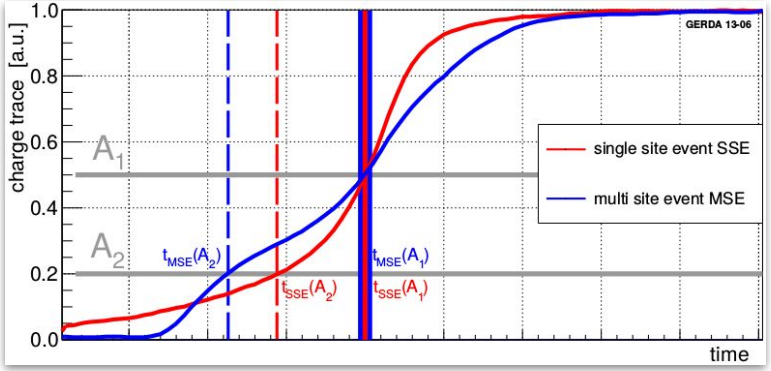
→ A/E parameter



- A = current amplitude
- E = energy
- Multi-site events have lower A/E than single-site events

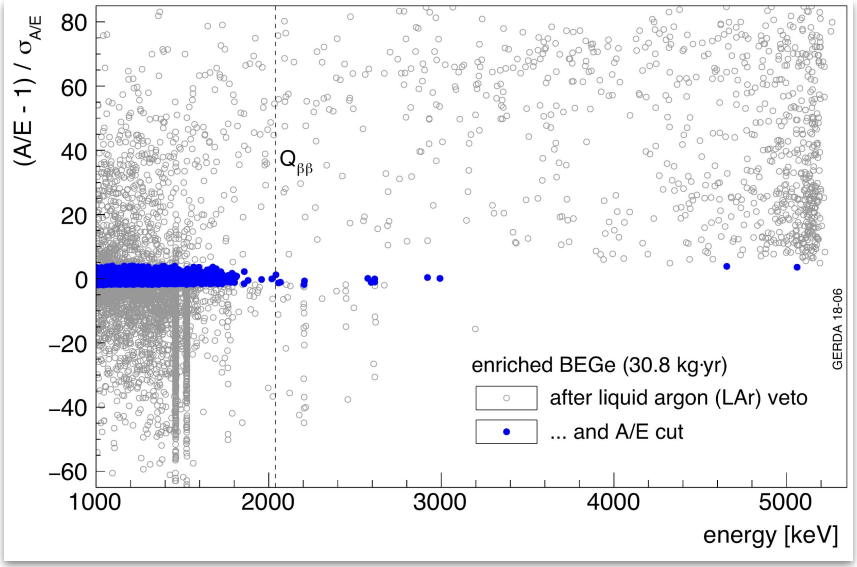
Coaxial

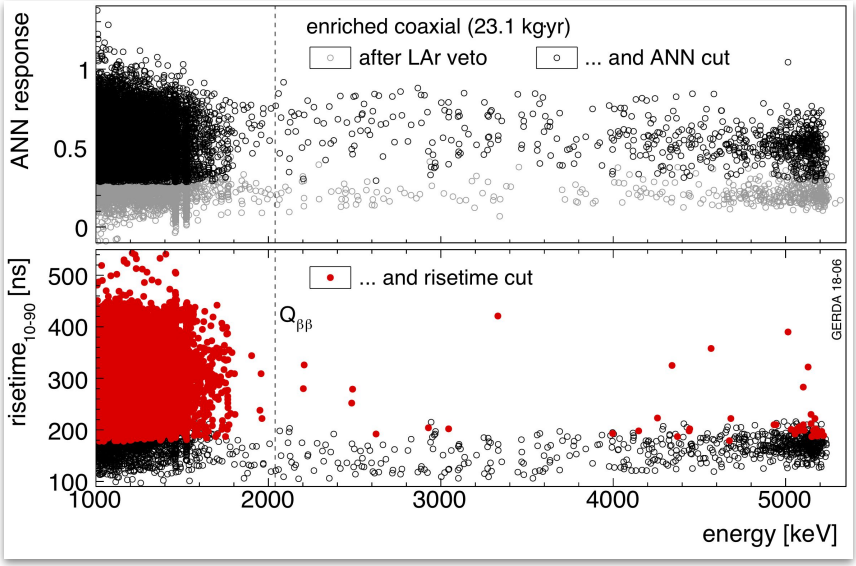
→ Neural Network (ANN) + Rise time



- Input variables: times when the pulse reaches a given relative height (1% … 99%)
- Trained on calibration data
- Additional cut on rise time for surface events

Pulse shape discrimination

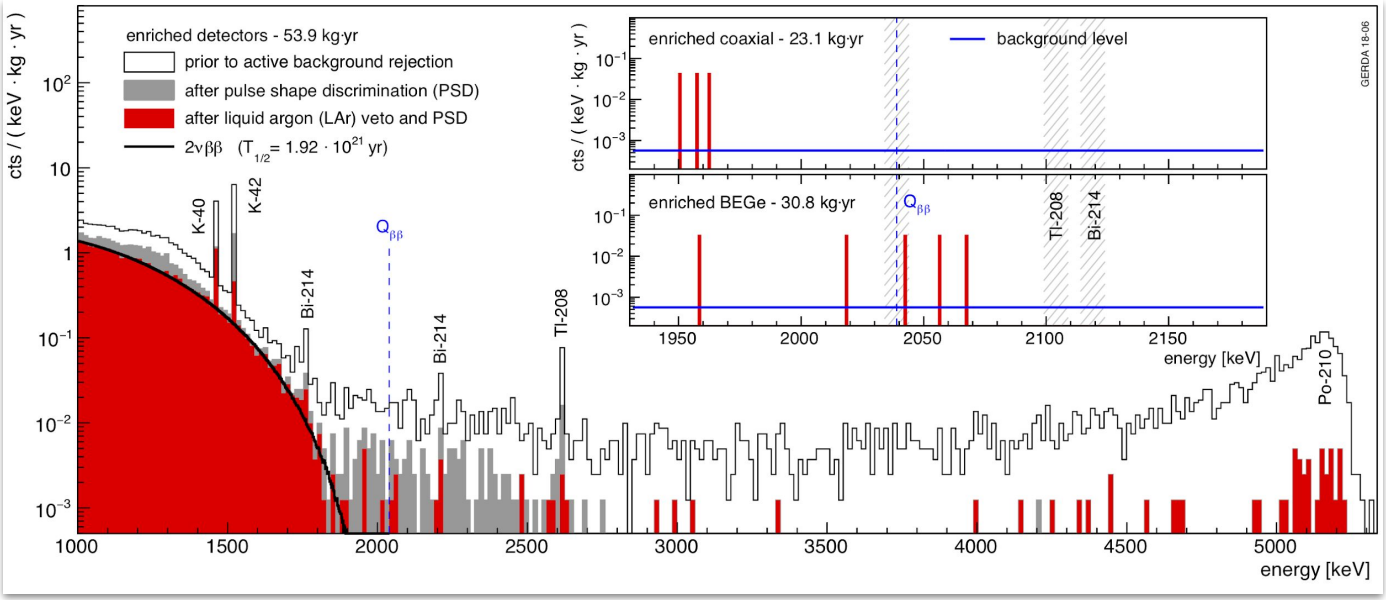




- A/E cut value determined from calibration data at 90% ^{208}Tl DEP acceptance and high cut at 4σ
- 0νββ acceptance: (87.6±2.5)%

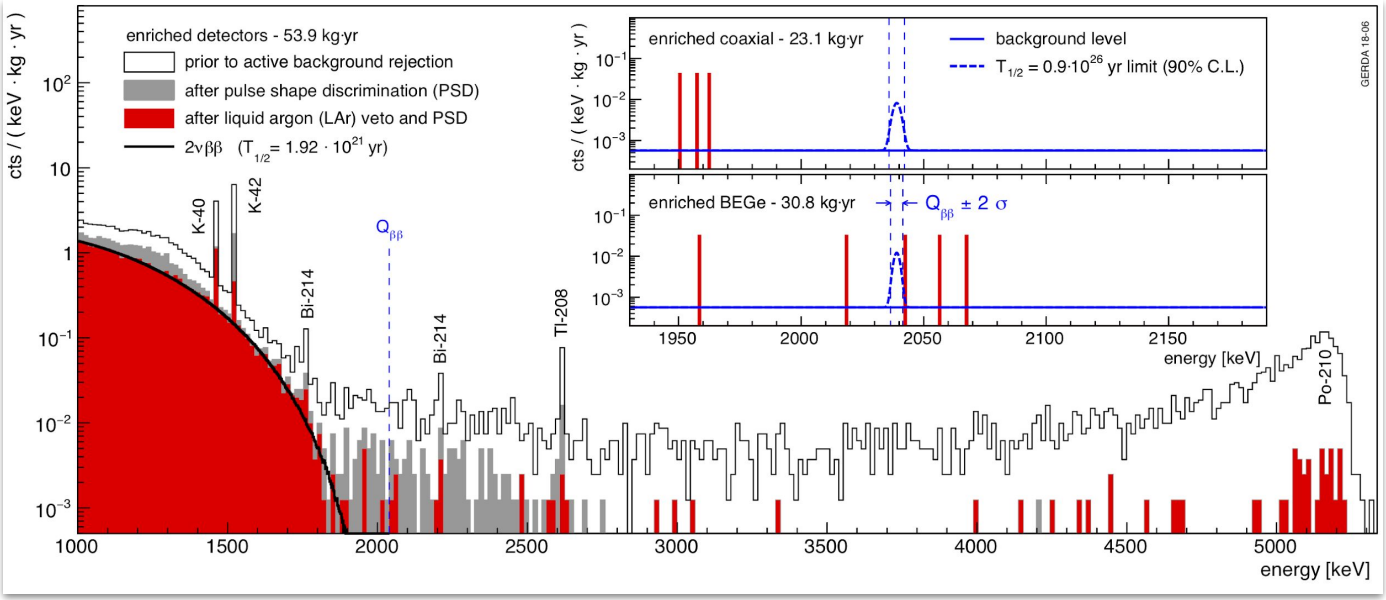
- ANN cut set 90% ^{208}Tl DEP acceptance and rise time cut optimized on high-energy α events
- 0νββ acceptance: (84±5)% x (85±1)%

Background index



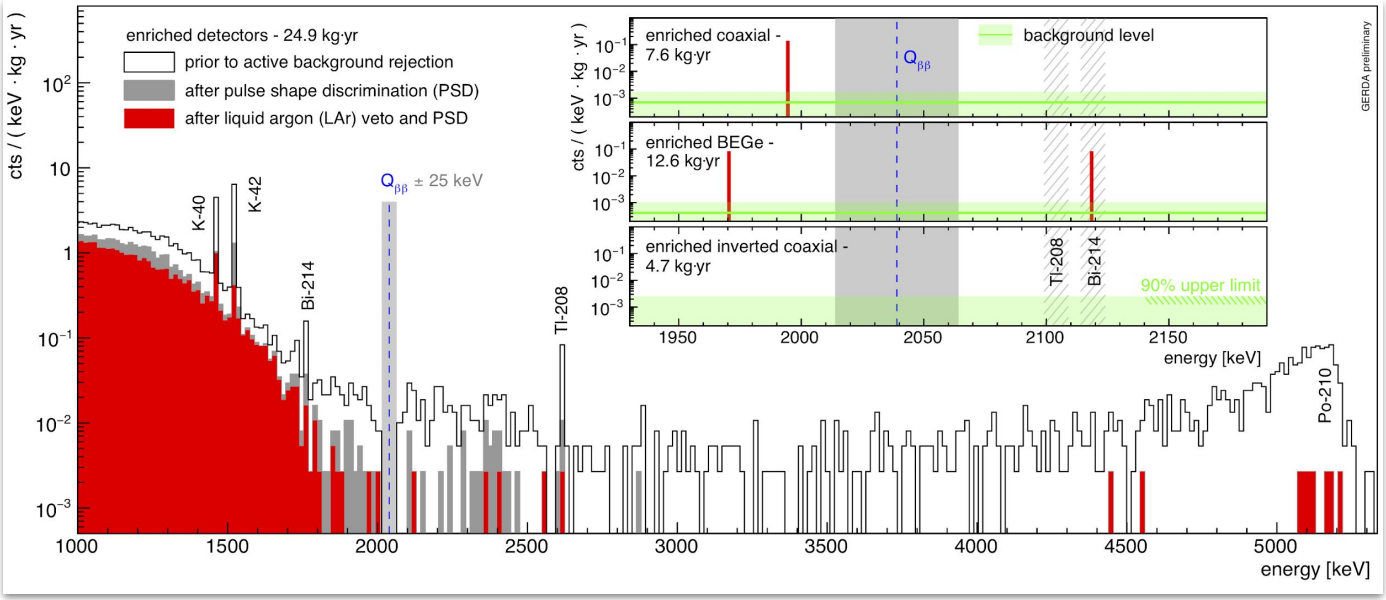
- Background index window: 1930-2190 keV, excl. ±5 keV around two known γ lines and around $Q_{\beta\beta}$
- Background index $\mathbf{0.6^{+0.4}_{-0.3} \times 10^{-3}}$ **cts/(keV·kg·yr)** and $\mathbf{0.6^{+0.3}_{-0.2} \times 10^{-3}}$ **cts/(keV·kg·yr)** for coaxial and BEGe

Statistical analysis



- Combined (including Phase I) unbinned maximum likelihood fit
- Best fit: no signal → $\mathbf{T^{0\nu}_{1/2} > 0.9\times10^{26}}$ **yr (median sensitivity** $\mathbf{1.1\times10^{26}}$ **yr) @ 90% C.L.**

Background index after upgrade



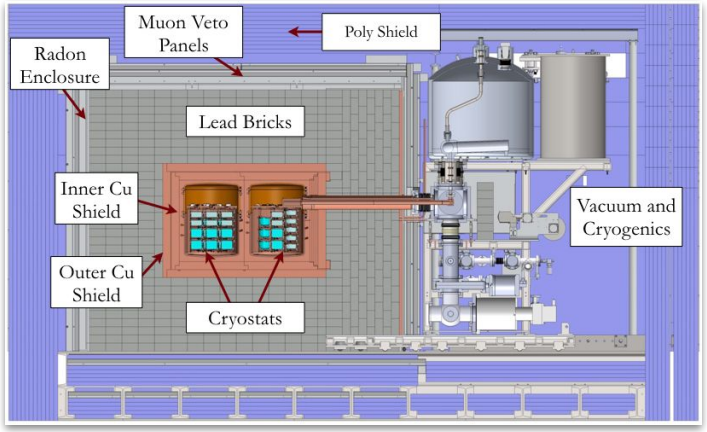
- Background index $0.7^{+1.0}_{-0.5} \times 10^{-3}$ cts/(keV·kg·yr) for coaxial

  $0.4^{+0.6}_{-0.3} \times 10^{-3}$ cts/(keV·kg·yr) for BEGe

  $< 2.7 \times 10^{-3}$ cts/(keV·kg·yr) (90% C.L.) for inverted coaxial

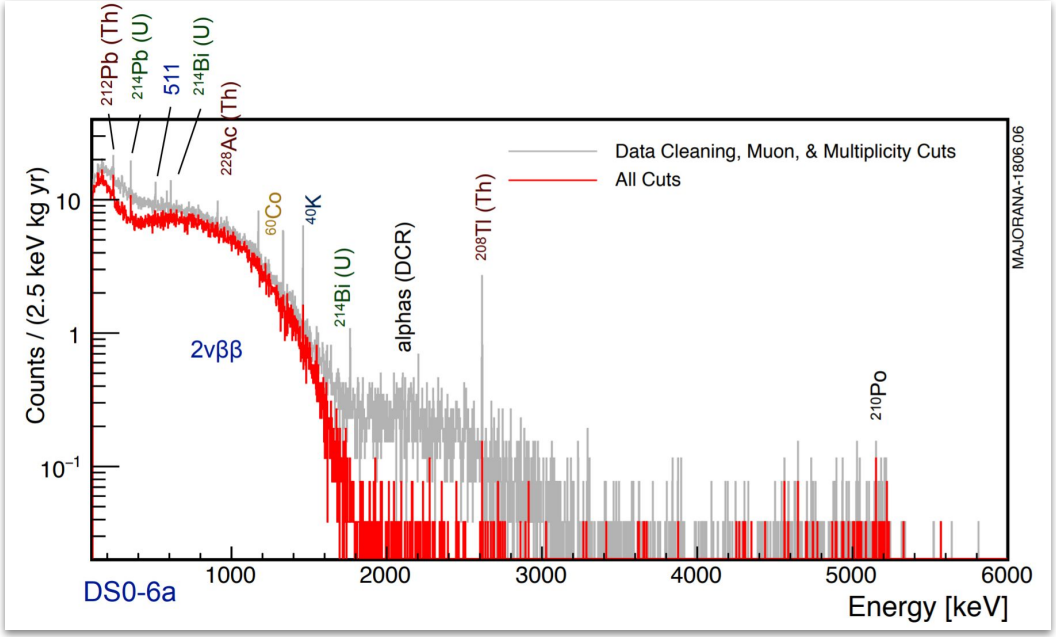
Majorana Demonstrator

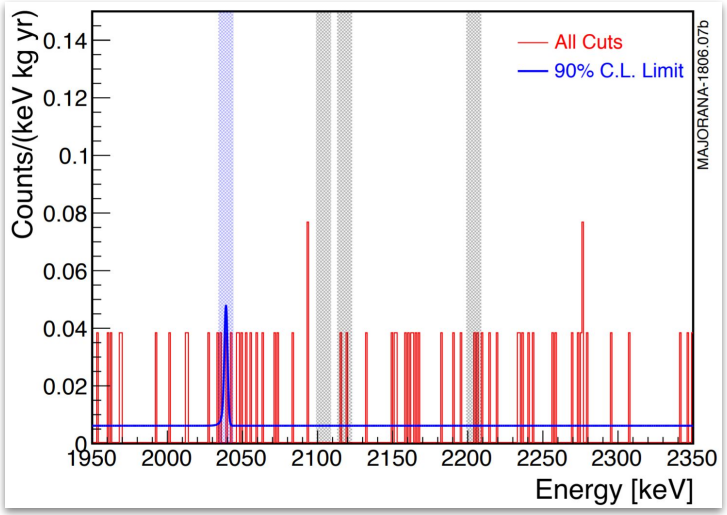
- 29.7 kg of 88% ^{76}Ge enriched crystals
- p-type point contact (PPC) detectors with 2.5 keV FWHM energy resolution
- 2 modules within a compact graded shield and active muon veto using ultra-clean materials
- Low noise and low energy threshold allows searches for dark matter, axions, etc.



- Background rejection based on array anti-coincidence and pulse shape discrimination (A/E and α surface events)

MAJORANA DEMONSTRATOR





- **26 kg · yr** of exposure unblinded
- **(4.8±0.8) × 10^{-3} cts/(keV · kg · yr)** background index
- $T^{0\nu}_{1/2} > 2.7 \times 10^{25}$ yr (90% C.L.)
- median sensitivity **$T^{0\nu}_{1/2} > 4.8 \times 10^{25}$ yr**

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

53 institutions, ~250 scientists

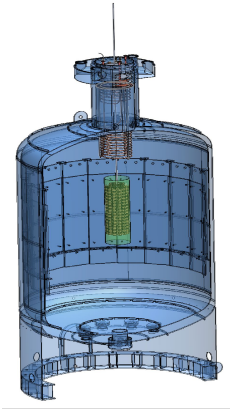
LEGEND mission: “The collaboration aims to develop a phased, ^{76}Ge based double-beta decay experimental program with **discovery potential** at a half-life beyond **10^{28} years**, using existing resources as appropriate to expedite physics results.”

LEGEND strategy

- Best technologies based on experience in GERDA and MAJORANA and from other experiments in a phased approach

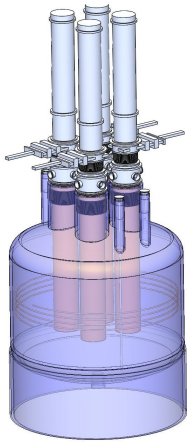
LEGEND-200

- 200 kg in upgrade of existing infrastructure at LNGS
- Background goal
  ~0.2×10^{-3} cts/(keV · kg · yr)



LEGEND-1000

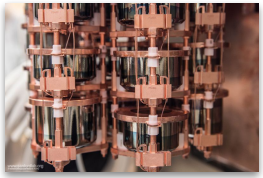
- 1000 kg staged via individual payloads
- Requirements for location under investigation
- Background goal
  <0.04×10^{-3} cts/(keV · kg · yr)



LEGEND strategy

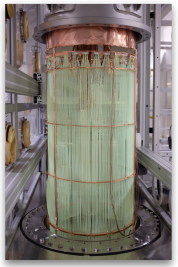
Majorana

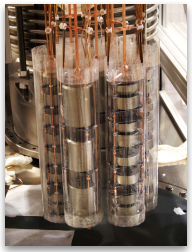
- Radiopurity of nearby parts (cables, copper mounts, etc.)
- Low noise electronics
- Low energy threshold



Gerda

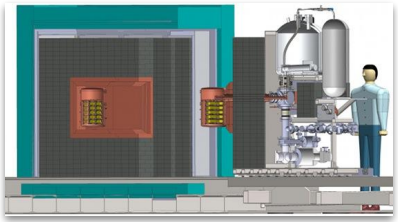
- Liquid argon (LAr) veto
- Low A shield, no lead





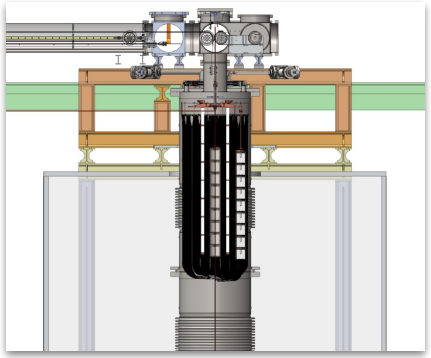
Both

- Clean fabrication techniques
- Control of surface exposure
- Development of large point-contact detectors
- Lowest background and best resolution experiments

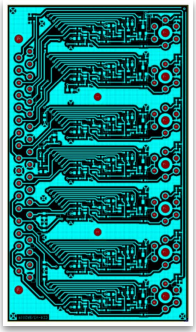


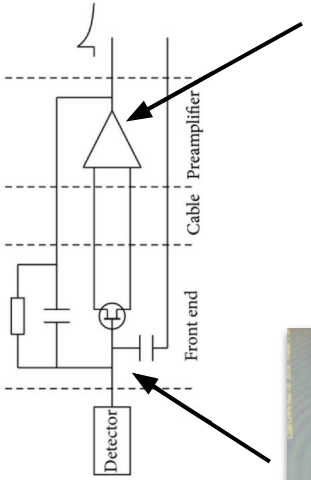
LEGEND-200 status

- New lock system, enriched detectors, new LAr veto system under production
- Electronics, cables under study
- Plan to start data taking in 2021

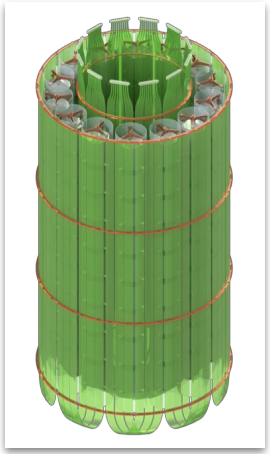


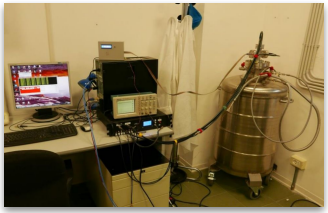
Preamplifier (CC4) with 7 channels

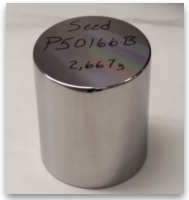


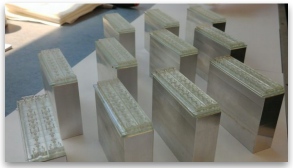


Low Mass Front End

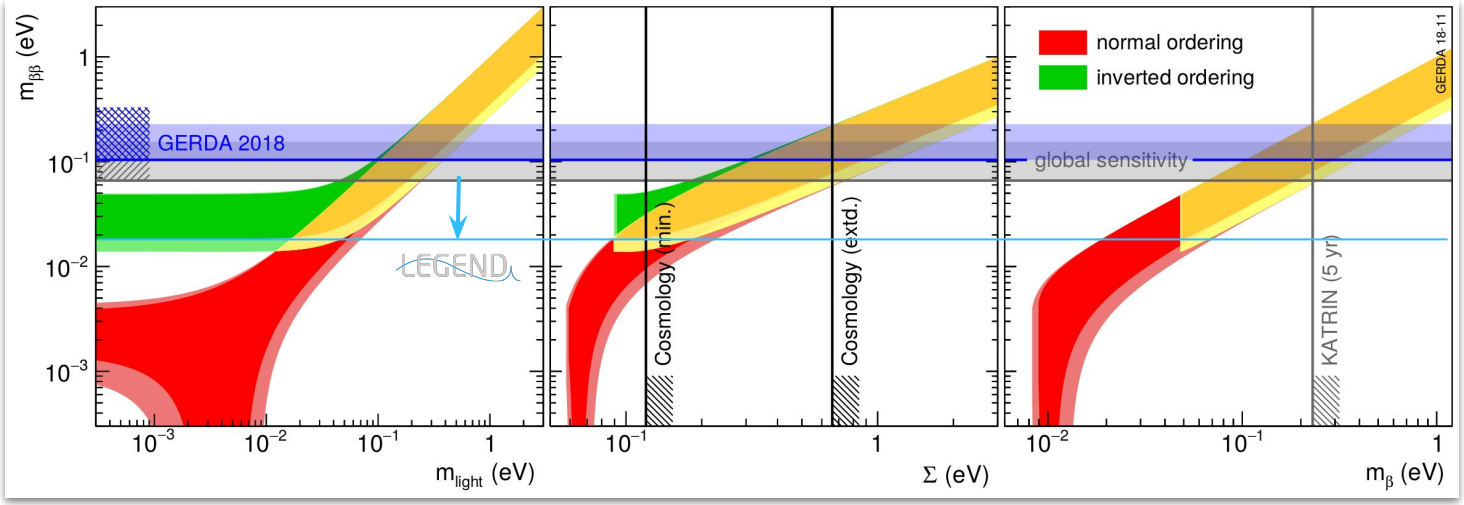








Mass observables



- GERDA constrains $m_{\beta\beta}$ < (0.10-0.23) eV taking into account the range of nuclear matrix elements
- Current global 0νββ sensitivity $m_{\beta\beta}$ < (0.07-0.16) eV (90% C.L.)
- LEGEND-1000 plans to reach a sensitivity down to 0.017 eV to cover the range of inverted ordering

Summary

- GERDA background model allows a detailed decomposition of the Phase II data
- With a background of **$<10^{-3}$ cts/(keV·kg·yr)** GERDA Phase II surpassed **10^{26} yr sensitivity**
- GERDA has been successfully upgraded
- Continue data taking until **100 kg·yr** exposure at the end of this year
- MAJORANA is taking data with lowest background conditions until 75 kg·yr exposure
- MAJORANA competitive in other searches, like dark matter and excited states
- LEGEND-200 will take over the GERDA infrastructure in 2020 with the goal to reach 10^{27} yr sensitivity
- LEGEND-1000 has the goal of 10^{28} yr sensitivity to cover inverted mass ordering region