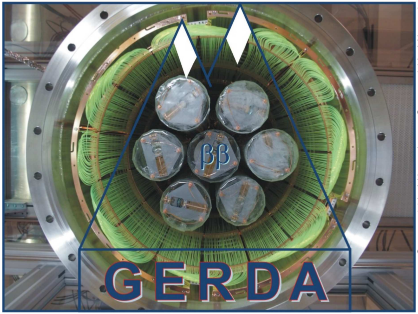
University of Zurich[UZH]

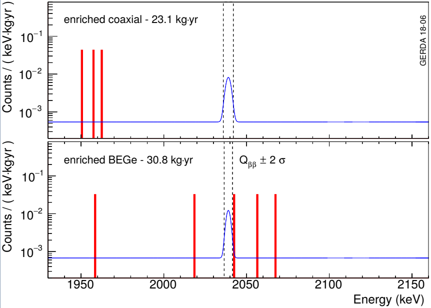
Physik-Institut

Searching $0\nu\beta\beta$-decay up to 10^{26} yr lifetime with GERDA

Roman Hiller for the GERDA collaboration

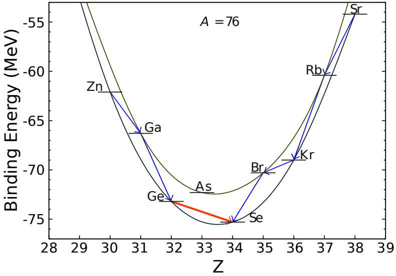
TeV Particle Astrophysics 2018, Berlin

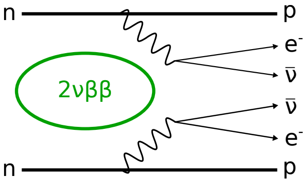


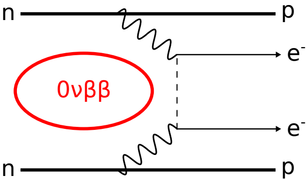


$0\nu\beta\beta$ Motivation

- Hypoth. process in even-even nuclei, e.g., (Z, N)$\rightarrow$(Z+2, N) + 2e$^-$
- Relation to $2\nu\beta\beta$
  (Ge: $T_{1/2} = 1.926 \pm 0.095 \times 10^{21}$ yr)
  Eur. Phys. J. C 75 (2015) 416
- Theory: Dirac vs. Majorana fermion
- Lepton number violation
- Potentially sensitive to other ν properties



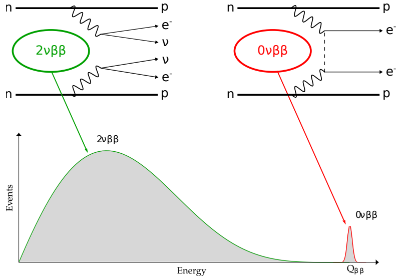




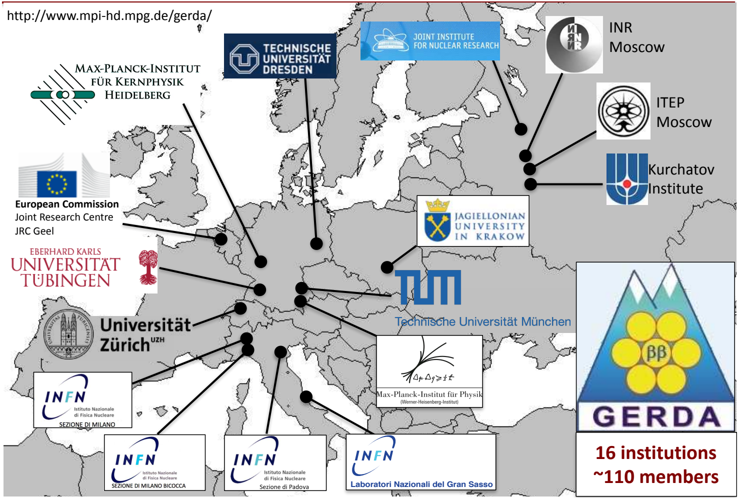
$0\nu\beta\beta$ Detection

- $0\nu\beta\beta$ signature = peak at $Q_{\beta\beta}$ in e^- spectrum
- $\mathcal{O}(10)$ experimentally interesting isotopes
- No clear favorite ($G\,|M|^2$ ~const.) $T_{1/2}^{-1} = G\,|M|^2 \left|\sum_{i=1}^{3} m_i U_{ei}\right|^2$
  G phase space integral, M nuclear matrix element
- Sensitivity $\sim$ abundance$\cdot$efficiency$\cdot\sqrt{\frac{\text{exposure}}{BI\cdot\Delta E}}$
  BI=background index, ΔE= energy resolution
- advatages of Ge: ΔE, detector tech. (purity, efficiency, enrichment)

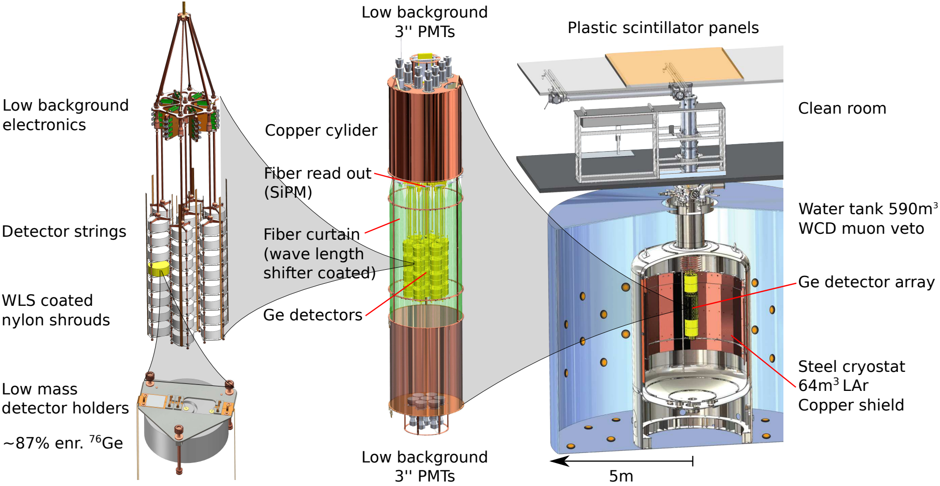
isotope	nat. ab.	$Q_{\beta\beta}$ (keV)
^{48}Ca	0.2%	4263
^{76}Ge	7.6%	2039
^{82}Se	9.2%	2998
^{96}Zr	2.8%	3348
^{100}Mo	9.6%	3035
^{116}Cd	7.6%	2813
^{130}Te	34.1%	2527
^{136}Xe	8.9%	2459
^{150}Nd	5.6%	3371



The GERDA Collaboration



GERmanium Detector Array

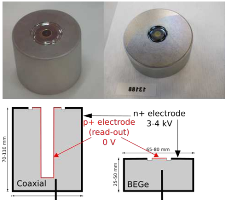


GERDA experiment

- LNGS, Italy, 3500 m.w.e., Muons $10^6 \rightarrow 1$ per m^2 h
- Coaxial and BEGe type detectors
- 36 kg total Ge mass

Goals:

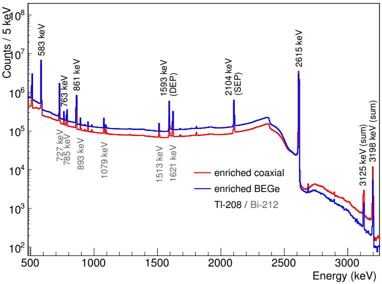
- BI$\sim 10^{-3}$ $\frac{\mathrm{cts}}{\mathrm{keV\ kg\ yr}}$
- 100 kg yr exposure $\rightarrow$ sensitivity $\sim 10^{26}$yr
- Demonstrate LAr veto concept

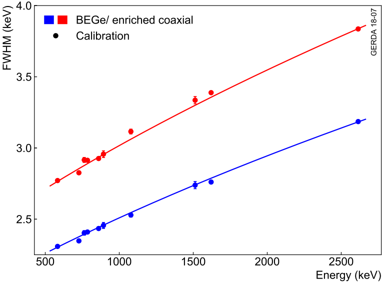


Eur. Phys. J. C 73 (2013) 2330

Energy calibration

– Weekly calibrations with low neutron emission Th-228 sources
– Energy scale and resolution monitoring
– FWHM Energy resolution at $Q_{\beta\beta}$
  Coax $\rightarrow$ 3.6(1) keV
  BEGe $\rightarrow$ 3.0(1) keV

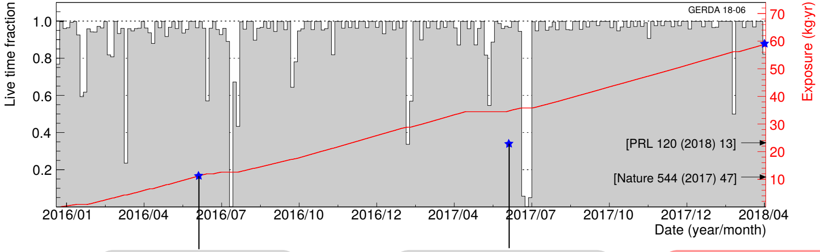




Data taking

Phase II (Dec 2015-present):

- Blind analysis: Events at 2039±25 keV released after analysis frozen
- Latest release June 2018, total 82.4 kg yr
- 35.7 kg yr fresh release (Phase IIc)
  + 23.2 kg yr from 2016/2017 (Phase IIa/b) + 23.5 kg yr from Phase I



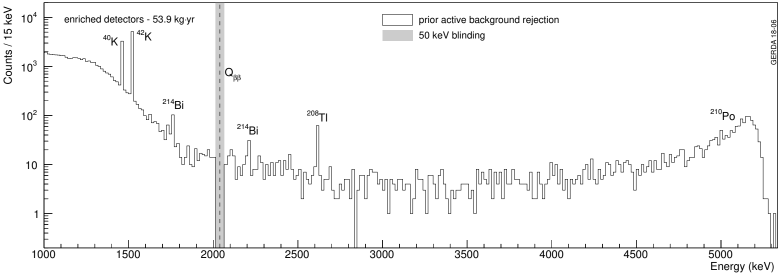
June 2016
10.8 kg yr
Nature 554, 47

June 2017
23.2 kg yr
PRL 120, 132503

June 2018
58.9 kg yr

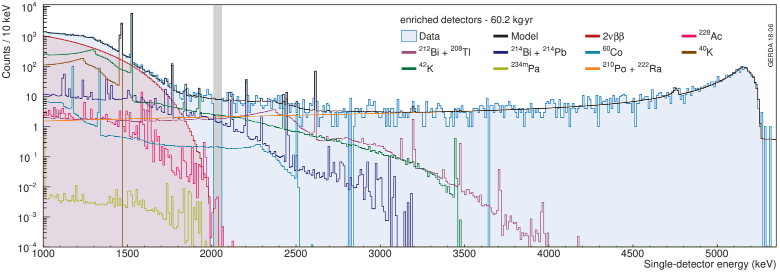
(Raw) Energy spectrum Phase II

– Spectral features after muon veto and detector anti-concidence:
  – $2\nu\beta\beta$ continuum
  – ^{40}K, ^{42}K lines
  – Lines from U/Th chains
  – Degraded α continuum
  – (^{39}Ar, ^{85}Kr)



Background model

- Fit individual sources from GEANT4 sim. to background data
- Screening measurements, coincidence rate, spacial info. K-lines
- Dominating backgrounds at $Q_{\beta\beta}$
  - degraded α
  - β from ^{42}K
  - γ from U/Th chains

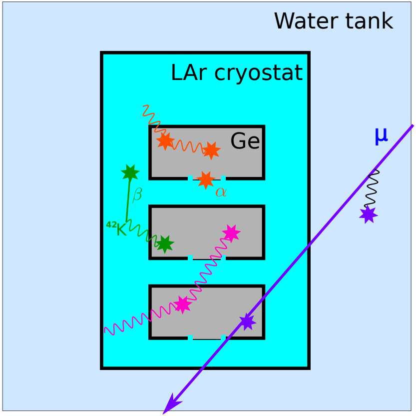


Background reduction

The signal signature is a point-like energy deposition of 2039 keV in a single detector.

Pulse shape discrimination vs. multi-site and surface events

LAr scintillation light from external sources



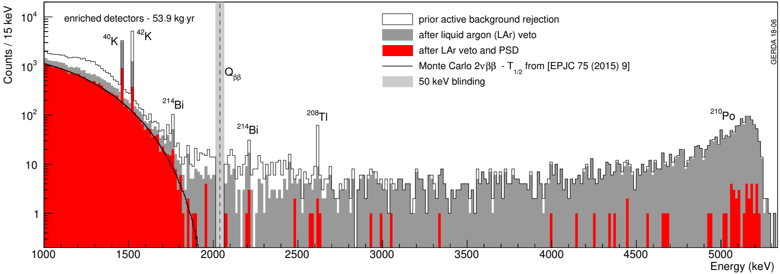
Muon veto via Cherenkov radiation

Detector anti-coincidence

Spectrum after cuts

– after background rejection cuts background rate in ROI reduced to $0.6 \cdot 10^{-3}$ cts/(keV kg yr)

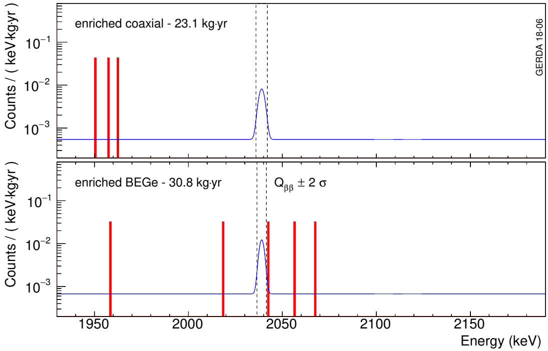
– background rejection$\sim$ 95% at signal efficiency of $\sim$86/70% BEGe/Coax (only LAr veto, PSD)



ROI statistical analysis

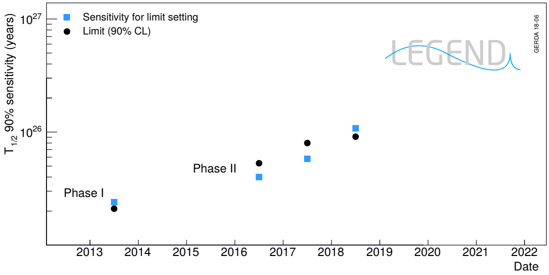
Combined unbinned maximum likelihood fit (7 datasets PI + PII)
Details on method: Agostini et al., Nature 544, 47-52, 2017

- 1 new event "close" ($>2\sigma$) to $Q_{\beta\beta}$
- Best fit for no signal
- $T_{1/2} > 0.9 \cdot 10^{26}$ yr @ 90% CL
- Median sensitivity (limit) $1.1 \cdot 10^{26}$ yr



Conclusion and Outlook

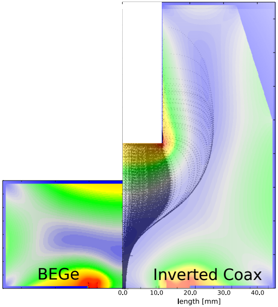
- GERDA has reached 10^{26} yr sensitivity for $0\nu\beta\beta$ half-life in ^{76}Ge
- Highest in the field, achieved due to unprecedented low background and with an exposure of 82.4 kg yr, approaching the target 100 kg yr
- GERDA was upgraded recently $\rightarrow$ continue data taking until 2019
- ...after which we will transition to a bigger experiment in a bigger collaboration, LEGEND200 at LNGS



Backup

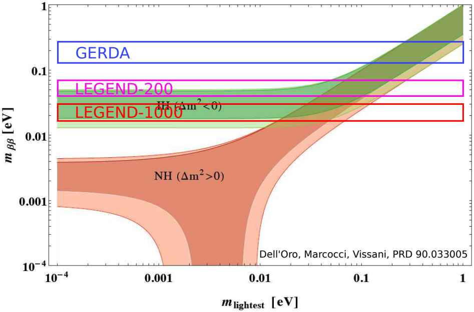
GERDA upgrade

- Replace natural coax with $\sim$9 kg enriched inverted coax type
- Install denser fibre curtain, middle string curtain
- Repair electronics to recover the 3 lost channels
- Etch a few detectors to reduce their leakage current
- Replace cables with lower activity version



Beyond GERDA

- GERDA current limit $m_{\beta\beta} < 120 - 260\,\text{meV}$
- $\sim 10\,\text{meV}$ sensitivity to cover IH region (light Majorana-ν exchange)
- $T_{1/2} \sim 10^{27} - 10^{28}\,\text{yr} \rightarrow$ Background-free ton scale experiment



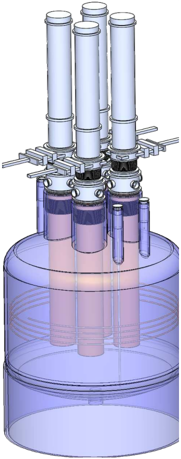
LEGEND

– Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay
– Collaboration formed October 2016 (GERDA, Majorana, others)
– 1 t scale experiment to reach 10^{28} yr sensitivity ($10^{-5}\,\frac{\mathrm{cts}}{\mathrm{keV\,kg\,yr}}$)

237 Members   47 Institutions   16 Countries

LEGEND-200

- First 200 kg stage LEGEND-200 at LNGS (2021?)
- Reuse modified GERDA infrastructure
- Obtain 1 t yr exposure
- 10^{27} yr$\hat{=}$30 $-$ 70 meV discovery sensitivity
- Background 0.2 cts/keV t yr (x 1/5 rel. to GERDA/Majorana):



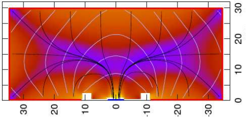
Germanium detectors in LEGEND-200

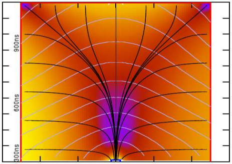
20 kg GERDA BEGes, 30 kg Majorana PPCs

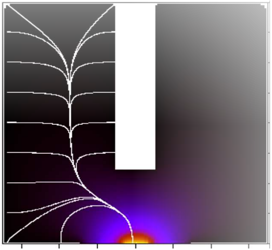
- Excellent energy resolution ~3 keV FWHM
- Pulse shape discrimination capability (SSE, MSE, surface)
- Small mass, 0.66/0.85 kg on average

New design Inverted-Coaxial Point Contact detectors

- Similar energy resolution and PSD capabilities
- Mass 1.5-2.0 kg→ less cables, electronics, cost
- Deployed and tested in GERDA upgrade ~9 kg

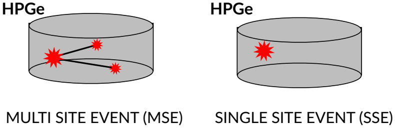


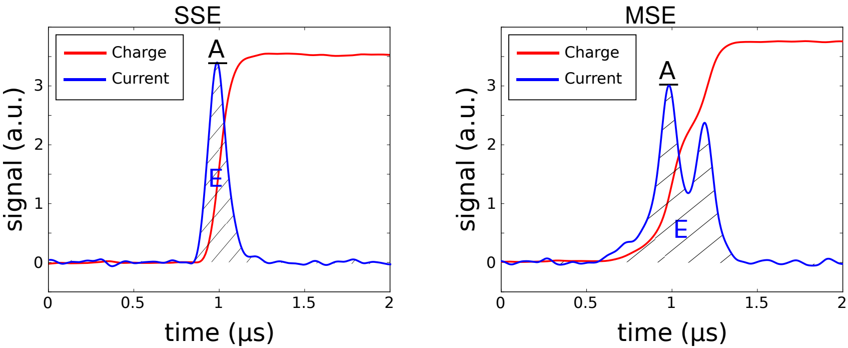




Pulse shape discrimination

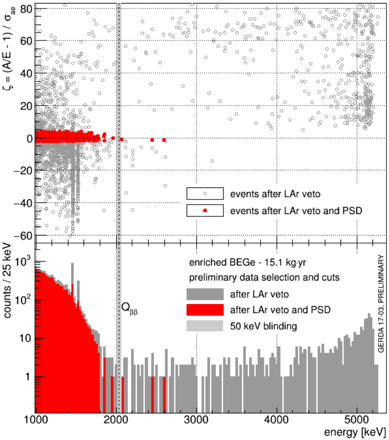
- Discrimination of SSE/MSE, surface events
- Charge drift time $\rightarrow$ pulse shape
- Current trace amplitude/energy = amplitude/area

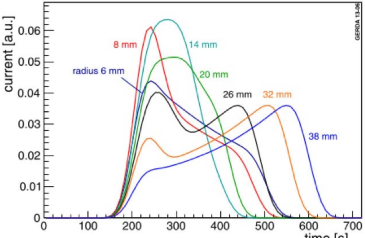




AoE vs. ANN

- Current amplitude/energy very efficient PSD parameter for BEGes
- 87% acceptance of single site events (e.g. $2\nu\beta\beta$, $0\nu\beta\beta$)
- 80-90% rejection of multi site events (gamma)
- all $\sim$500 alpha events so far rejected
- For Coax waveform more dependent on hit position
  $\rightarrow$ artificial neural network, dedicated cut for MSE and alpha





LEGEND-200 vs. GERDA

- Review lock design (550→ 610 mm)
- 11 additional strings
- Reduce nylon shroud volume
- Improved LAr veto efficiency
- Optimized material selection
- Larger detector channels
- Tweaked electronics (PSD)
- Feasibility of most improvements has been demonstrated in the laboratory