Pulse shape discrimination for GERDA Phase I

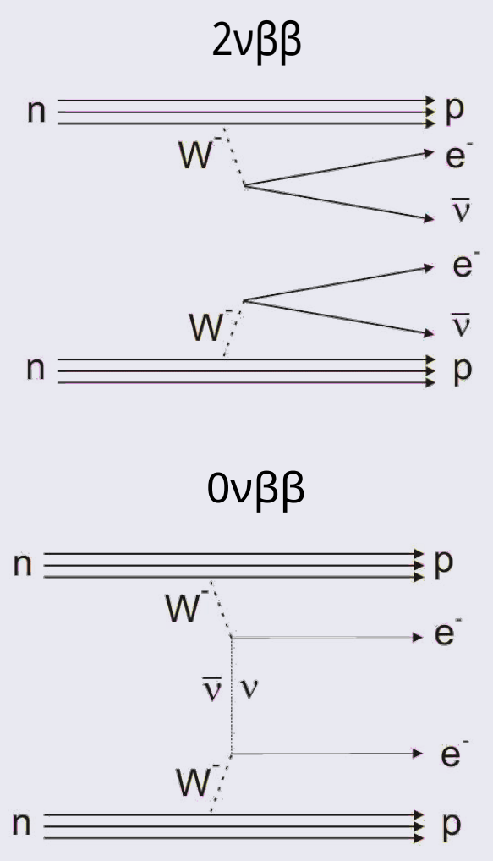
Victoria Wagner for the GERDA Collaboration
Max-Planck-Institut für Kernphysik

Motivation

Double beta decay (2νββ):

- If single beta decay is energetically forbidden certain isotopes decay via double beta decay (2νββ)
- (A,Z) → (A,Z+2) + $2e^-$ + $2\bar{\nu}_e$
- Observed in 11 isotopes, e.g. ^{76}Ge, ^{136}Xe ^{130}Te
- 2νββ half-life of ^{76}Ge [1]

$$T^{2\nu}_{1/2} = 1.84^{+0.14}_{-0.10} \times 10^{21}\mathrm{yr}$$



Neutrinoless double beta decay (0νββ):

- In the standard interpretation the 0νββ is realized via the exchange of two light Majorana neutrinos
- (A,Z) → (A,Z+2) + $2e^-$
- Lepton number is violated by ΔL=2

  ⇨ **physics beyond Standard Model**

What else do we learn from 0νββ ?

- Effective Majorana neutrino mass

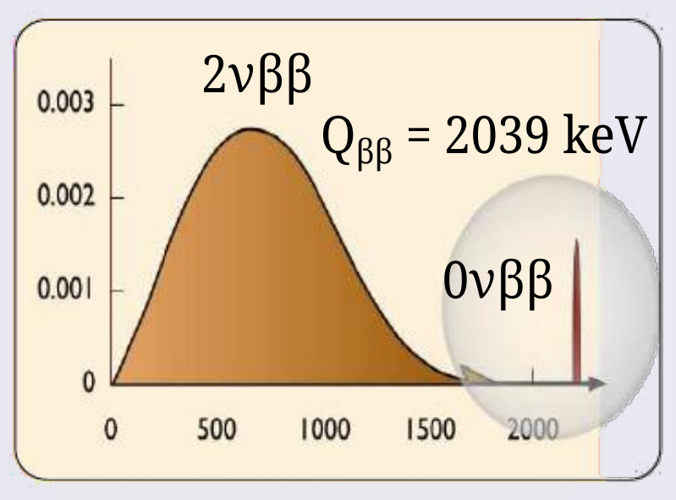
$$m_{\beta\beta} = |\Sigma_i U^2_{ei} m_i|$$
$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 m^2_{\beta\beta}$$

- The neutrino mass hierarchy

Signature & Method

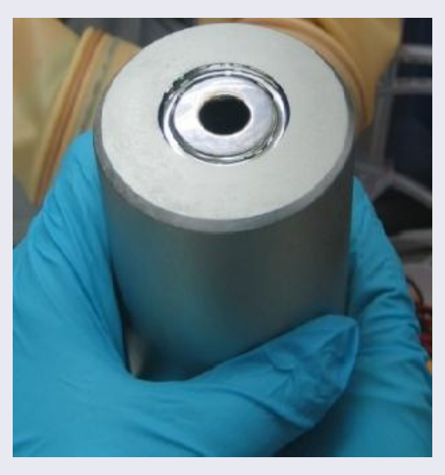
Measure the sum energy of the two electrons:

- 2νββ is a continuous spectrum as both neutrinos escape the detection
- 0νββ gives a peak at $Q_{\beta\beta}$ = 2039 keV
- In the presence of background the sensitivity to the lower limit of the half-life scales as



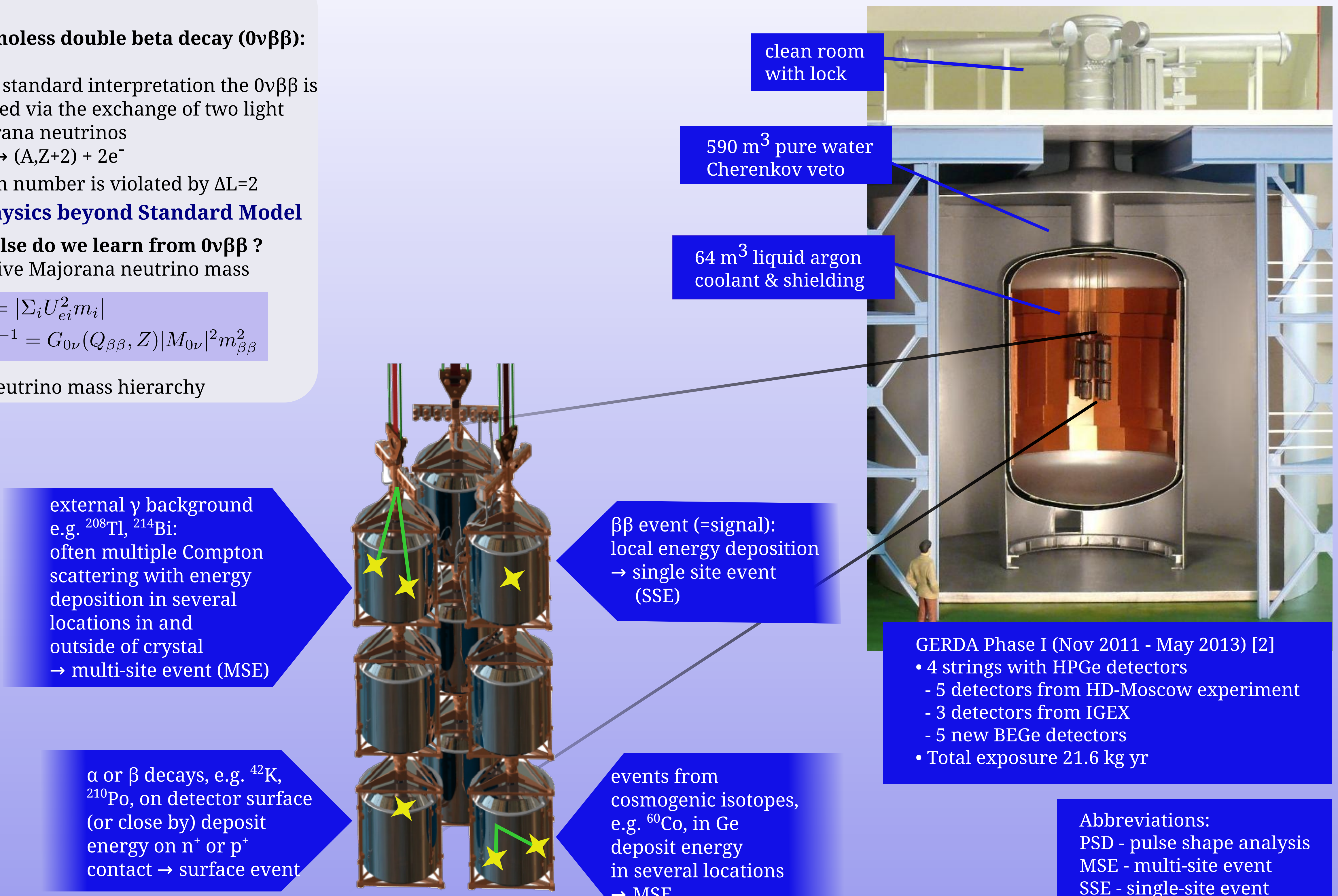
$$T^{0\nu}_{1/2} \propto \epsilon a \sqrt{\frac{M \cdot t}{BI \cdot \Delta E}}$$

ε: detection efficiency, a: active volume, Mt: exposure [kg yr], ΔE: energy resolution, BI : background index [counts/(keV kg yr)]



Concept: Source = Detector

- Concept provides a high detection efficiency
- HPGe detectors are isotopically enriched in ^{76}Ge (~ 87%)
- Germanium detectors have an excellent energy resolution (0.1% FWHM)
- $Q_{\beta\beta}$ = 2039 keV is low compared to possible background
  → passive and active background reduction techniques are required



clean room with lock

590 m^3 pure water Cherenkov veto

64 m^3 liquid argon coolant & shielding

external γ background e.g. ^{208}Tl, ^{214}Bi: often multiple Compton scattering with energy deposition in several locations in and outside of crystal → multi-site event (MSE)

ββ event (=signal): local energy deposition → single site event (SSE)

α or β decays, e.g. ^{42}K, ^{210}Po, on detector surface (or close by) deposit energy on n^+ or p^+ contact → surface event

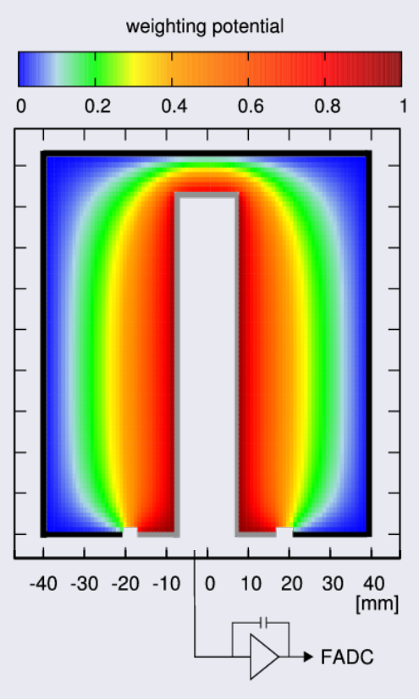
events from cosmogenic isotopes, e.g. ^{60}Co, in Ge deposit energy in several locations → MSE

GERDA Phase I (Nov 2011 - May 2013) [2]

- 4 strings with HPGe detectors
  - 5 detectors from HD-Moscow experiment
  - 3 detectors from IGEX
  - 5 new BEGe detectors
- Total exposure 21.6 kg yr

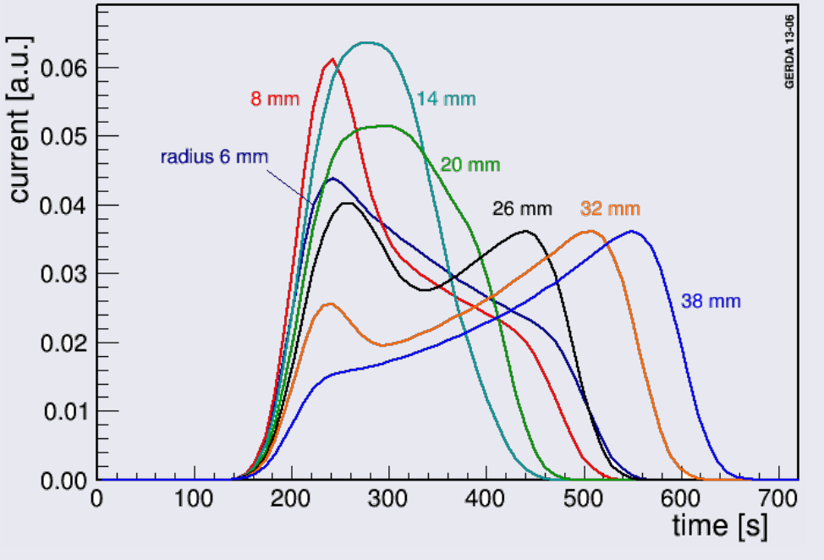
Abbreviations:
PSD - pulse shape analysis
MSE - multi-site event
SSE - single-site event
FEP - full energy peak
SEP - single escape peak
DEP - double escape peak

Pulse shape discrimination for semi-coaxial detectors

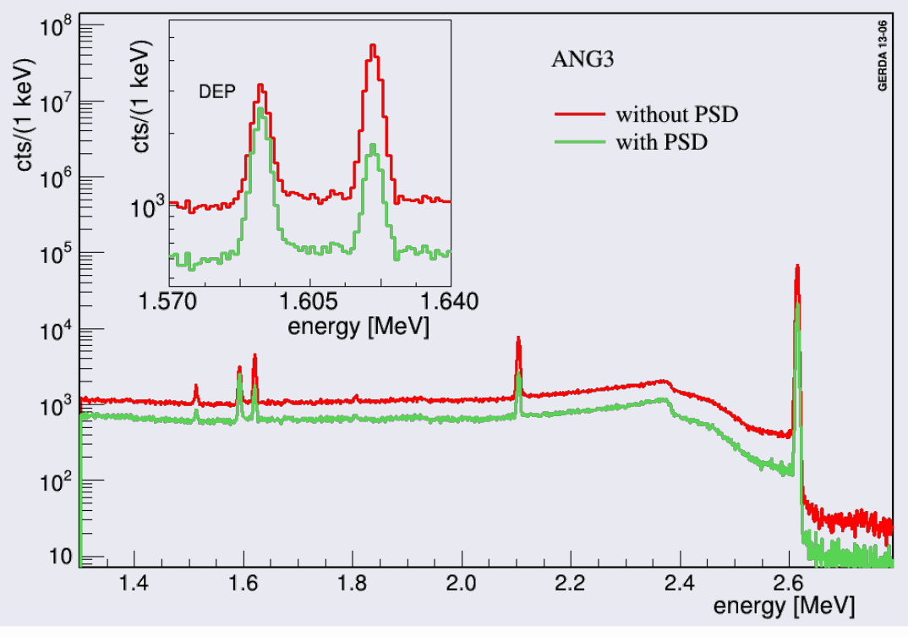


- The weighting potential determines the induced signal on the read-out electrode for drifting charges at a given position in the crystal
- The figure on the right shows current pulses of SSE at different radii
- The signal of a MSE is a superposition of such SSE signals
- The pulse shapes of different event types are analyzed with the aim to discriminate signal-like events from background events
- SSE are signal-like events whereas MSE are typical background events

current signal for different r

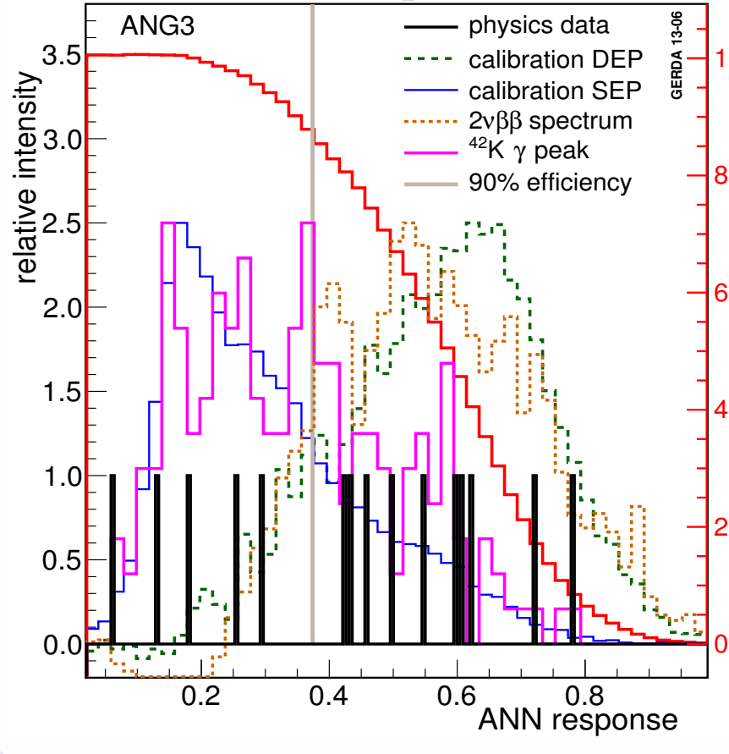


^{228}Th spectrum before and after cut



- To identify signal-like events an artificial neural network (ANN) TMlpANN from the TMVA package is used
- The input variables for the ANN are the times when the charge pulse is at 1%, 3%, ..., 99% of its maximum amplitude
- The algorithm is trained with ^{228}Th calibration data:
  - DEP of the 2.6 MeV γ-line of ^{208}Tl is used as a proxy for SSE
  - FEP and SEP typically contain a high fraction of MSE
- The qualifier is set to 90% survival fraction in the DEP
- DEP survival efficiency is taken as the 0νββ efficiency

neural network output for different event classes

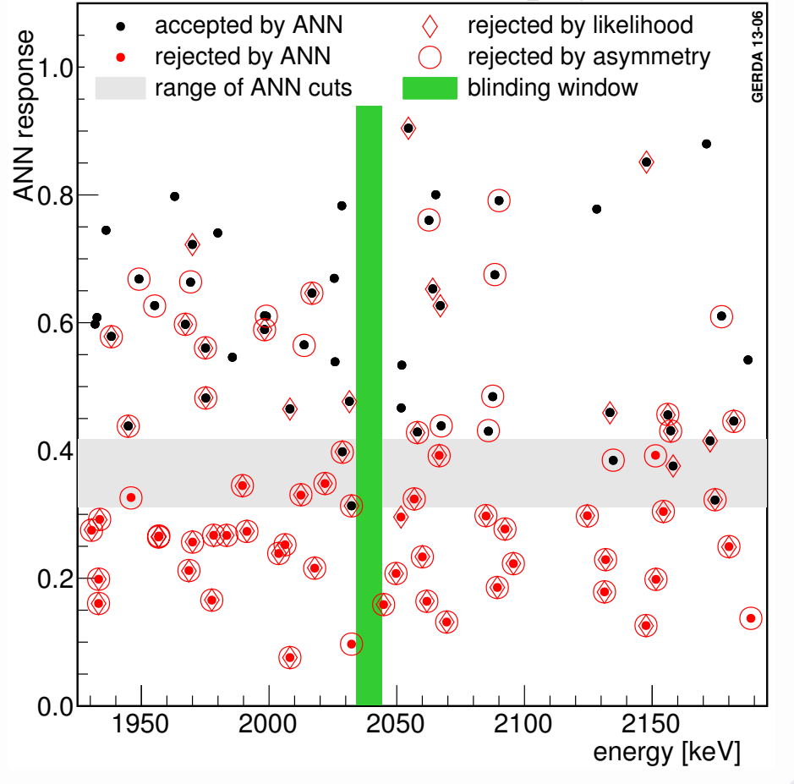


⇨ **45% of the background is rejected at $Q_{\beta\beta}$ with a 0νββ efficiency of 90^{+5}_{-9} %**

Efficiency cross-check with signal like events:

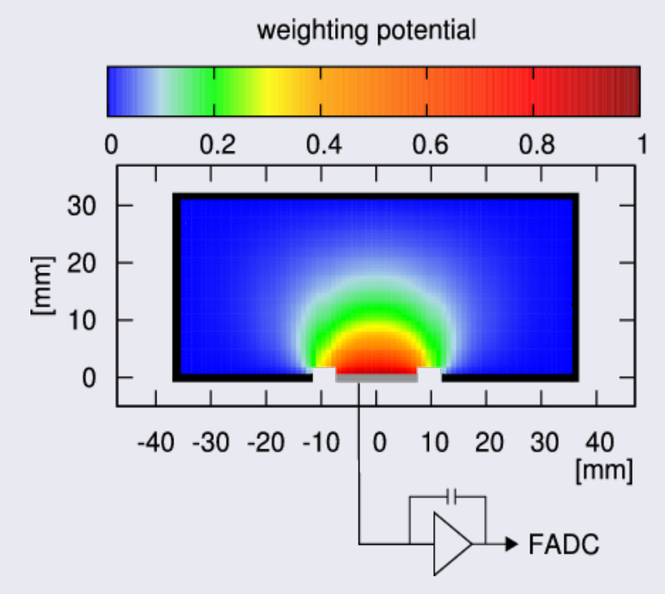
- 2νββ efficiency = 85 ± 2%
- Pulse shape simulation for DEP and ββ events give an efficiency of ~ 83%
- Survival efficiency for DEP events from ^{56}Co (1.1 and 2.2 MeV) 83-95%

event classification of physics data

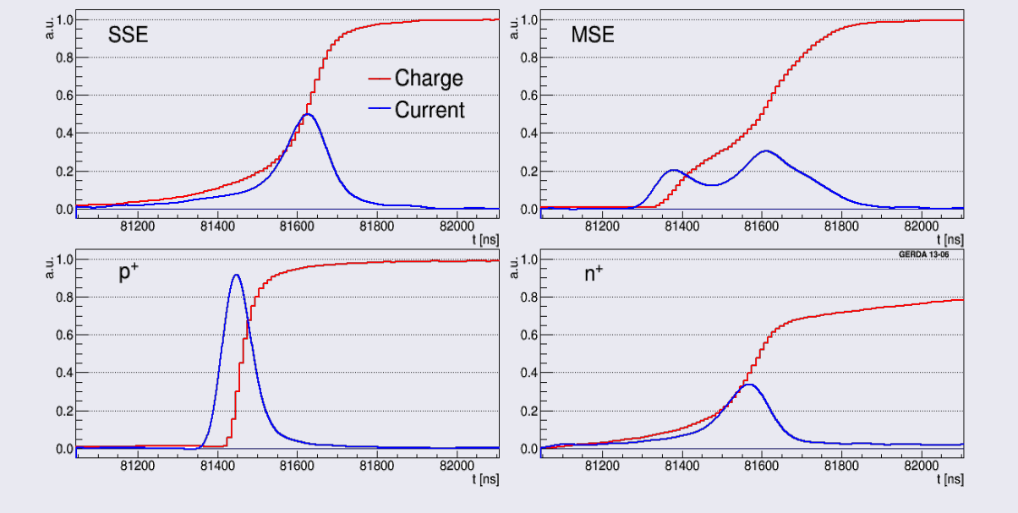


Pulse shape discrimination for BEGe detectors

- The induced signal is determined by the weighting potential
- In PSD the signals for different event types are analyzed to discriminate signal-like events (=SSE) from background events (=MSE and surface events)
- The PSD method for BEGe detectors is based on the ratio of the maximum of the current pulse A over the energy E: the A/E parameter
- Most **SSE (= signal-like events)** have similar pulse shapes independent of the interaction point
- **MSE** are a superposition of such SSE. Thus, the amplitude of the current pulse is lower than for a SSE with the same energy → smaller A/E
- **p^+ contact events**: in a small volume close to the read-out electrode the maximum of the current pulse is larger compared to a SSE with the same energy → larger A/E
- **n^+ surface events**: signals from events penetrating through the outer detector surface have longer rise times due to diffusion in the transition layer compared to bulk events → smaller A/E
- DEP events from 2.6 MeV γ-line of ^{208}Tl are used as a proxy for SSE



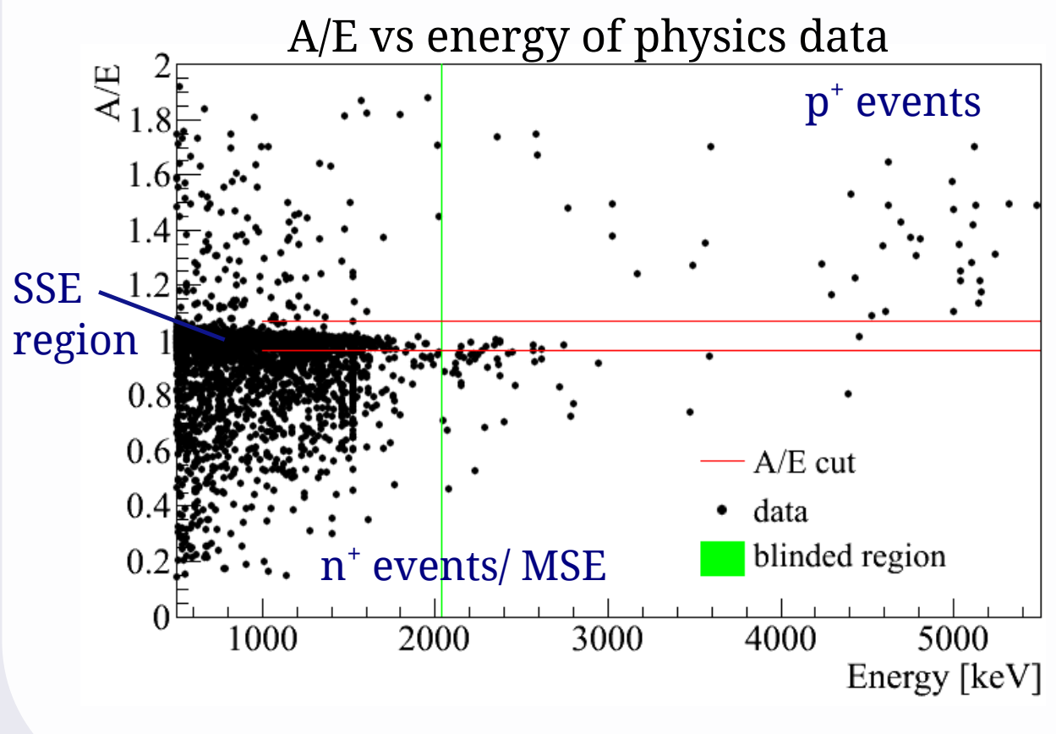
current and charge pulse for different event types

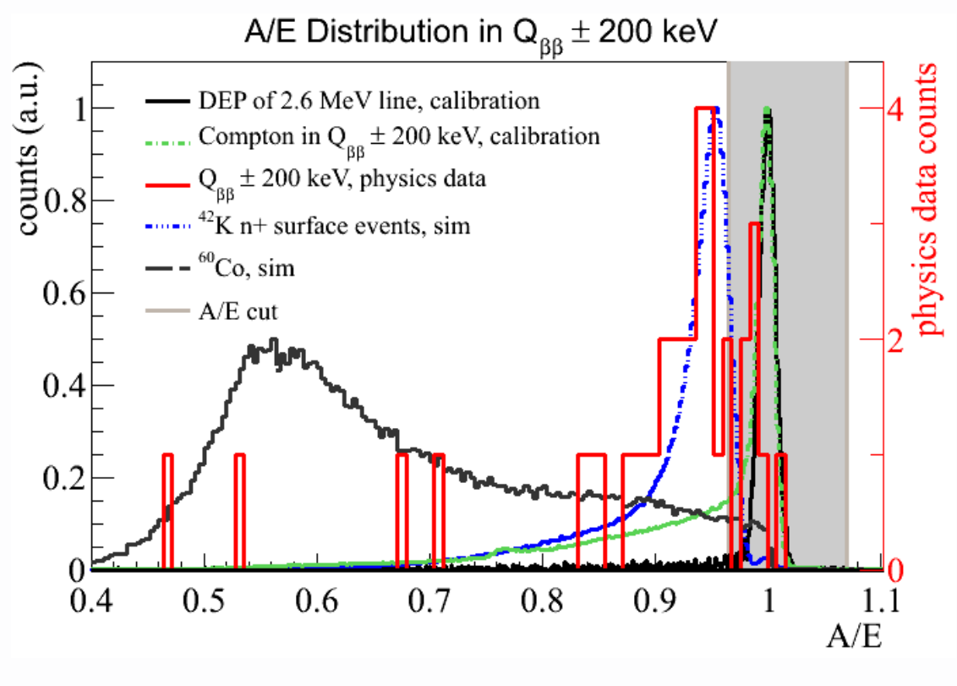


⇨ **more than 80% of the background is rejected at $Q_{\beta\beta}$ with a 0νββ efficiency of 92±2 %**

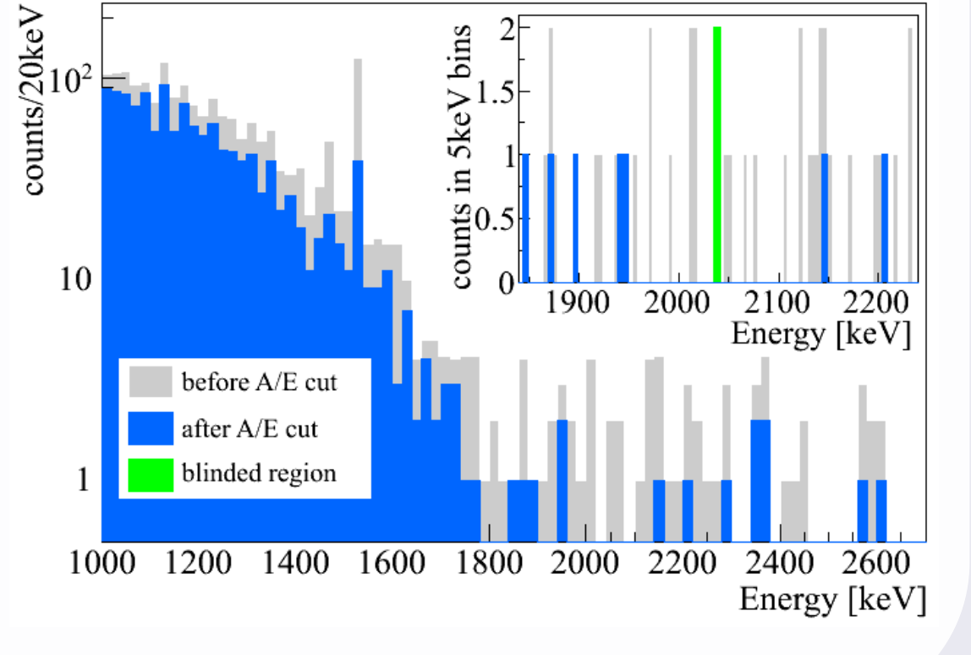
- 0νββ efficiency determined with events from pulse shape simulation and DEP events from calibration.
- The 2νββ efficiency = 91±5 % is in good agreement with the derived 0νββ efficiency.

A/E vs energy of physics data





energy distr. of physics data w and w/o cut



Results for 0νββ

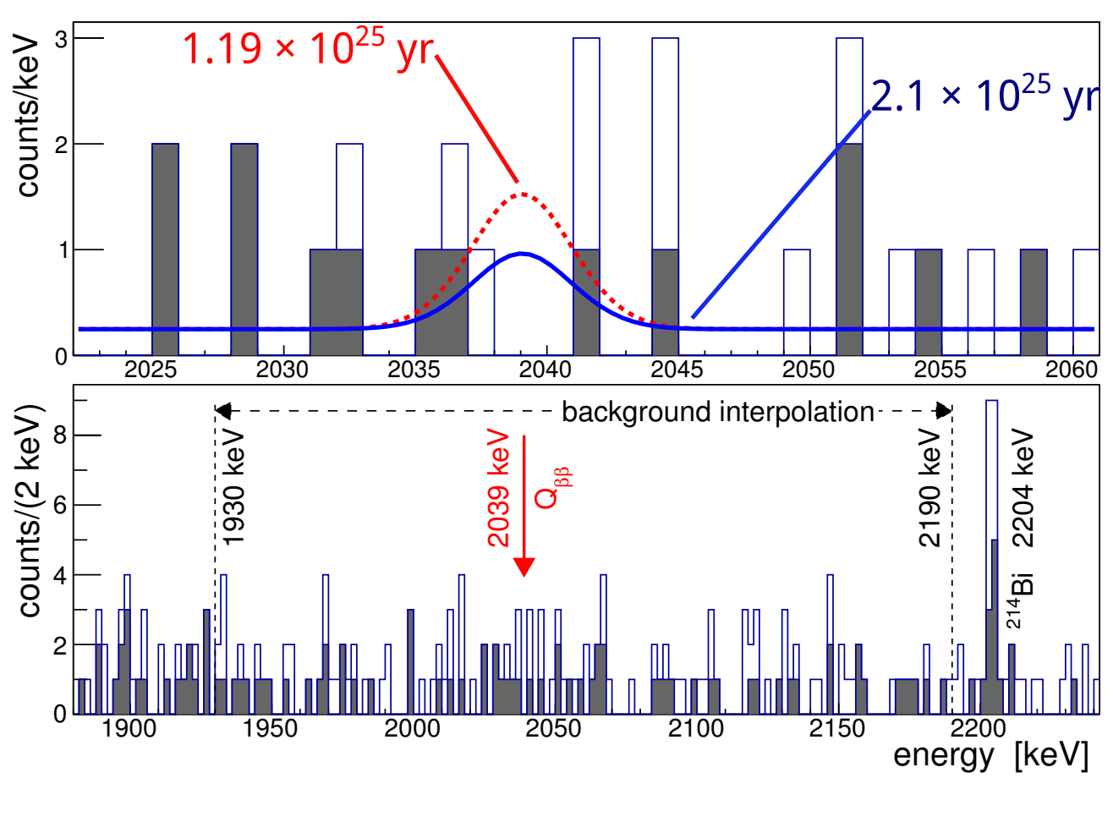
0νββ analysis:

- In a blind analysis the background model [3] as well as the quality and PSD cuts [4] were fixed prior to opening the ROI at $Q_{\beta\beta}$.
- After cuts the background index is 1.0(1) × 10^{-2} counts/(keV kg yr)
- **No peak is spectrum at $Q_{\beta\beta}$ ± $2\sigma_E$**, the number of observed events is consistent with background

$$T^{0\nu}_{1/2} = \frac{ln2 \cdot N_A}{m_{enr} \cdot N^{0\nu}} M \cdot t \cdot f_{76} \cdot f_{av} \cdot \epsilon_{FEP} \cdot \epsilon_{PSD}$$

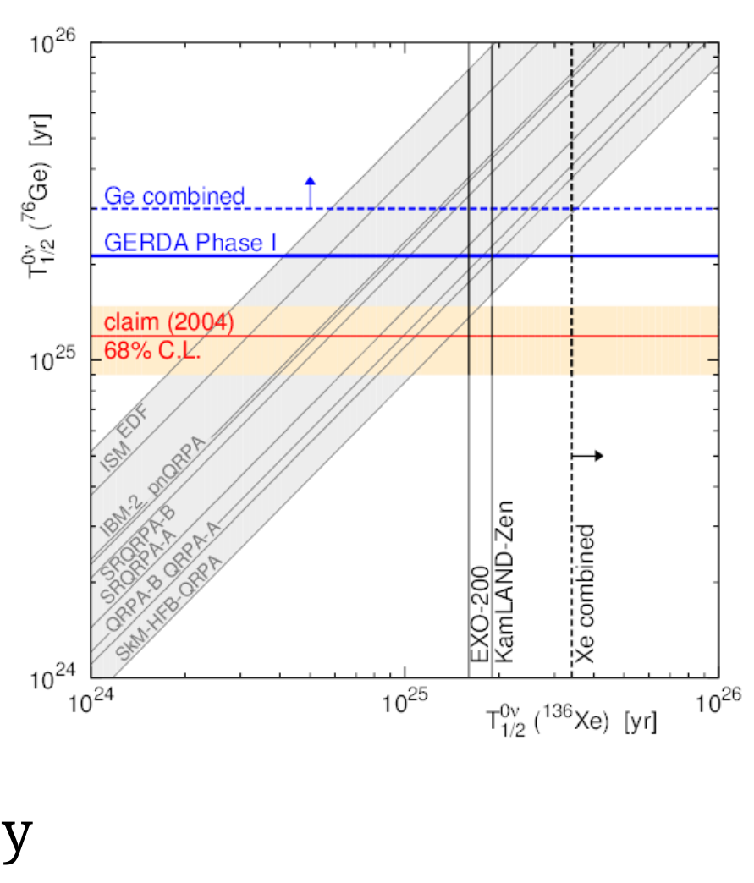
N_A: Avogadro's constant, Mt: total exposure, m_{enr}:75.6 g molar mass, $N^{0\nu}$: observed signal strength, f_{76}: fraction of ^{76}Ge, f_{av}: active volume fraction, ϵ_{PSD}: signal acceptance by PSD, ϵ_{FEP}: efficiency to detect full energy peak

- To derive $N^{0\nu}$ a profile likelihood fit of the data is performed
  → flat background + Gaussian in 1930-2190 keV range with mean at $Q_{\beta\beta}$ and standard deviation σ_E
- Background of the data sets and $1/T^{0\nu}_{1/2}$ are free parameters in the fit
- Best fit value is $N^{0\nu}$ = 0



Number of events in $Q_{\beta\beta}$ ± $2\sigma_E$ after cuts (gray):

- ~ 2 bck counts expected
- observed 3 counts
- expect ~ 6 counts for a half-life of 1.19 × 10^{25} yr

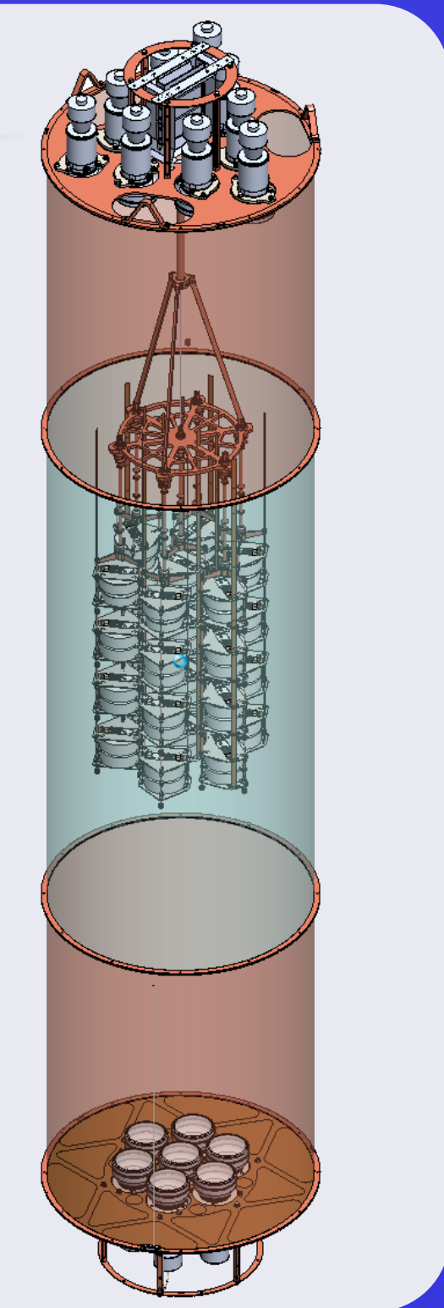


⇨ **No signal observed at $Q_{\beta\beta}$**
The limit on the half-life is [5]

$$T^{0\nu}_{1/2} > 2.1 \times 10^{25}\mathrm{yr}\ (90\%\ \mathrm{C.L.})$$

- The claim [6] of a 4.2σ signal for 0νββ decay of ^{76}Ge with half-life of 1.19 × 10^{25} yr is ruled out by GERDA with 99% probability

Outlook Phase II



Transition to GERDA Phase II is ongoing. The upgrade includes:

- Additional 25 BEGe detectors with
  - an additional target mass of ~ 20 kg
  - a better energy resolution compared to coaxial detectors
  - an enhanced pulse shape discrimination of signal and background (see PSD for BEGe)
- Specially designed low mass detector holders and electronics
- A light instrumentation of the LAr cryostat to use the scintillation light produced in LAr by background events as anti-coincidence veto

The PSD has proven to be an efficient active background reduction technique. Together with the LAr veto we expect to reach

- a background ≤ 10^{-3} counts/(keV kg yr)
- and $T^{0\nu}_{1/2}$ values in the range of 10^{26} yr

References

[1] M Agostini et al. (GERDA Collaboration), J. Phys. G: Nucl. Part. Phys. 40, 035110 (2013)
[2] K.-H. Ackermann et al. (GERDA Collaboration), Eur. Phys. J. C 73, 2330 (2013)
[3] M. Agostini et al. (GERDA Collaboration), Eur. Phys. J. C 74, 2764 (2014)
[4] M. Agostini et al. (GERDA Collaboration), Eur. Phys. J. C 73, 2583 (2013)
[5] M. Agostini et al. (GERDA Collaboration), Phys. Rev. Lett 111, 122503 (2013)
[6] K. V. Klapdor-Kleingrothaus, I. V. Krivosheina, A. Dietz and O. Chkvorets, Phys. Lett. B 586, 198 (2004)