GERDA: Phase I results & status of Phase II upgrade

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Neutrinos in Astro- and Particle Physics (NIAPP) workshop
Munich, 30 Jun - 25 Jul 2014

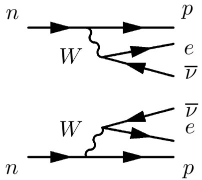
Outline

- Neutrinoless double-β decay
- The GERDA experiment
- Phase I: analysis and results
- Upgrade for Phase II

Double-β decays

2-neutrino double-β decay ($2\nu\beta\beta$):

- $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$
- allowed in the Standard Model
- measured in several isotopes
- $T_{1/2}^{2\nu}$ in the range $10^{19} - 10^{24}$ yr



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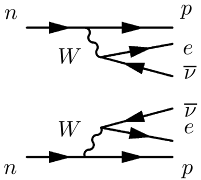
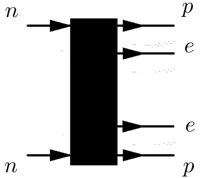


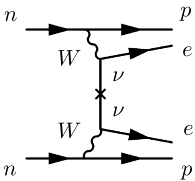
Neutrinoless double-β decay ($0\nu\beta\beta$):

- $(A, Z) \rightarrow (A, Z+2) + 2e^-$
- lepton number violation ($\Delta L = 2$)
- physics beyond the Standard Model (e.g. light Majorana ν, R-handed weak currents, SUSY particles)
- ν has non-null Majorana mass component
- $T_{1/2}^{0\nu}$ limits in the range $10^{21} - 10^{26}$ yr (10^{25} yr for ^{76}Ge)
- claim for a signal (subgroup of HdM experiment)

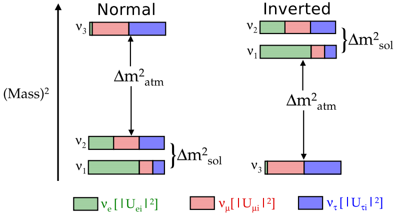


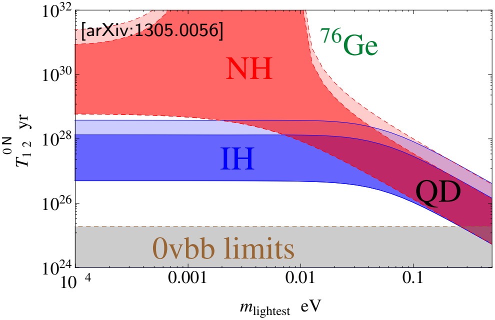
Neutrinoless double-β decay & neutrino physics

Assuming light-Majorana neutrino exchange as dominant $0\nu\beta\beta$ channel:

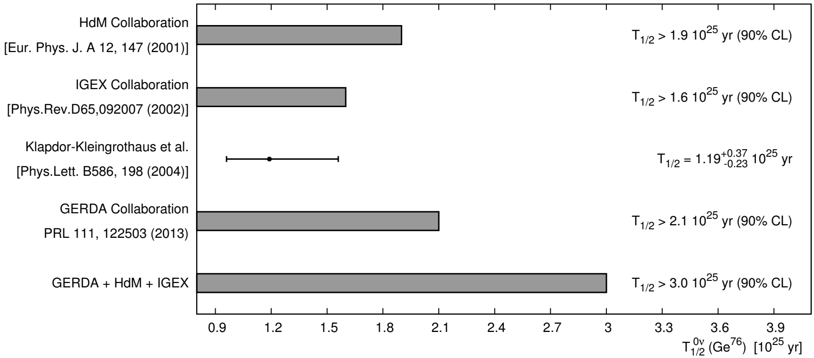


- $(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|\mathcal{M}_{0\nu}(A, Z)|^2 \langle m_{\beta\beta}\rangle^2$
- effective Majorana mass:
  $\langle m_{\beta\beta}\rangle \equiv \left|\sum_i U^2_{ei} m_i\right| = \left|c^2_{12}\, c^2_{13}\, m_1 + s^2_{12}\, c^2_{13}\, m_2\, e^{i2\alpha} + s^2_{13}\, m_3\, e^{i2\beta}\right|$
- ν mass spectrum (inverted/normal hierarchy, absolute mass scale)





State of the art of $0\nu\beta\beta$ search with ^{76}Ge



KK claim 2004 [Phys.Lett. B586 198]

- 71.7 kg·yr
- 28.75±6.86 signal events
- $T^{0\nu}_{1/2} = 1.19^{+0.37}_{-0.23} \cdot 10^{25}$ yr

KK claim 2006 [Mod Phys Lett A21]

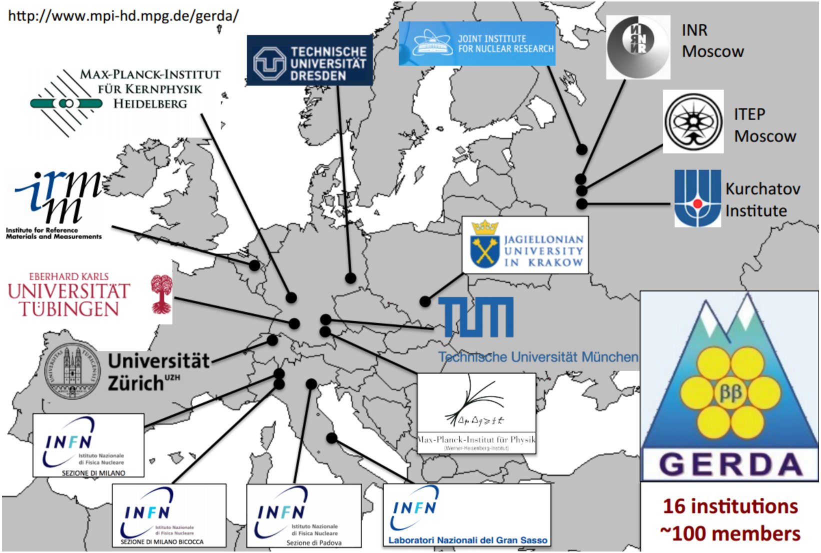
$T^{0\nu}_{1/2}$ central value and errors incorrect:

- missing efficiency corrections
- signal cts uncertainties < Poisson error

[Ann. Phys. 525 (2013) 269]

Collaboration

Institutions



16 institutions

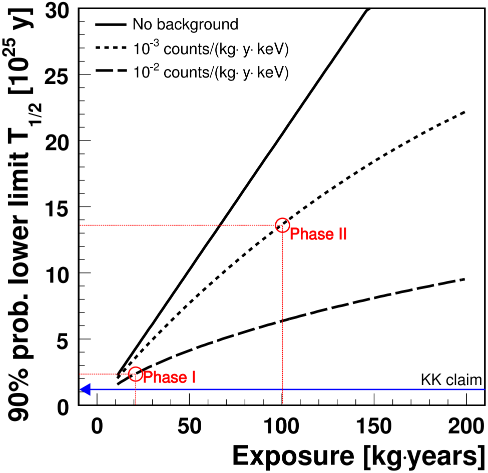
~100 members

Sensitivity and background goals

Phase I (Nov 2011 - May 2013):

- 15 – 20 kg of target mass (87% ^{76}Ge)
- bkg ∼ 10^{-2} cts/(keV· kg· yr) at $Q_{\beta\beta}$
- exposure 21.6 kg·yr
- sensitivity to scrutinize KK claim

[Phys.Rev.D75, 092003 (2006)]



Sensitivity and background goals

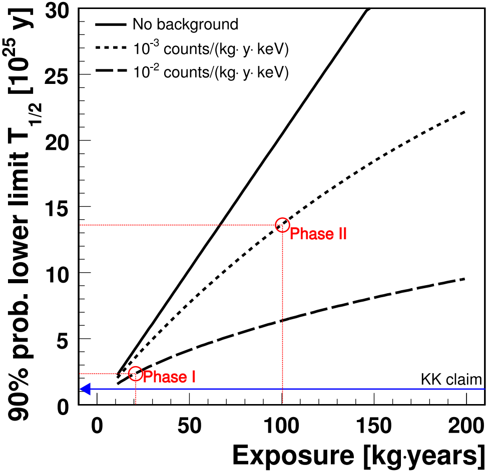
Phase I (Nov 2011 - May 2013):

- 15 – 20 kg of target mass (87% ^{76}Ge)
- bkg $\sim 10^{-2}$ cts/(keV· kg· yr) at $Q_{\beta\beta}$
- exposure 21.6 kg·yr
- sensitivity to scrutinize KK claim

Phase II (migration ongoing):

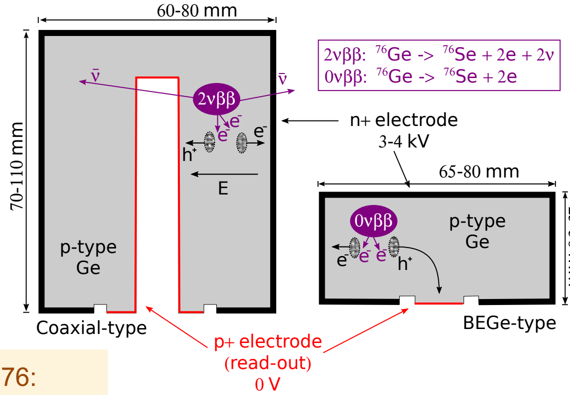
- new custom-produced BEGe detectors (additional 20 kg, 87% ^{76}Ge)
- bkg $\lesssim 10^{-3}$ cts/(keV· kg· yr) at $Q_{\beta\beta}$ (active techniques for bkg suppression)
- exposure $\gtrsim$ 100 kg·yr
- start exploring $T_{1/2}^{0\nu}$ in the 10^{26} yr range

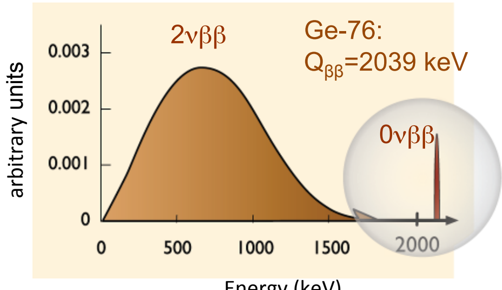
[Phys.Rev.D75, 092003 (2006)]



Detectors

- HPGe detectors from material enriched in ^{76}Ge ($\sim$87%)
- detectors well established technology
- optimal spectroscopy performance:
  - long-term stability
  - $\Delta E \approx 0.1\%$ at $Q_{\beta\beta}$
  - radio purity

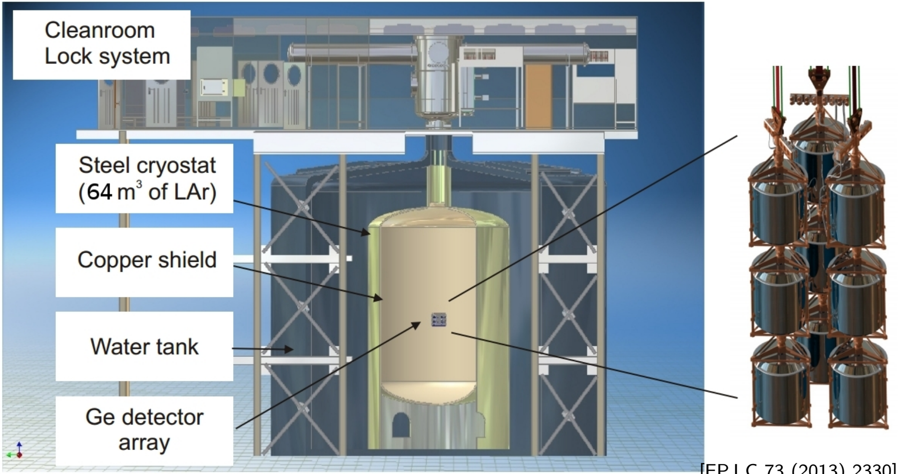




Calorimeter detectors:
- source=detector
- high detection efficiency
- peak at Q-value ($Q_{\beta\beta}$)

Shielding strategy and apparatus

- bare Ge detectors in liquid Argon (LAr)
- shield: high-purity LAr/H_2O
- radio-pure material selection
- deep underground (LNGS, 3800 m.w.e.)

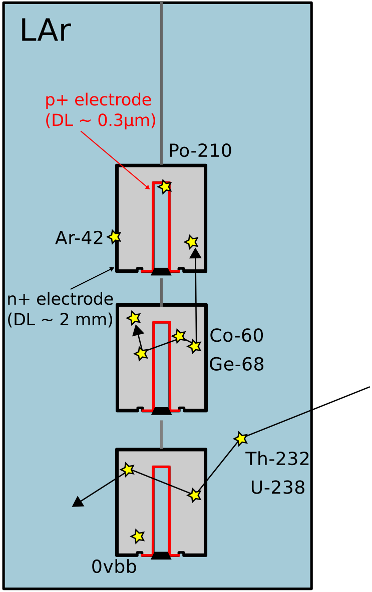


[EPJ C 73 (2013) 2330]

Backgrounds and mitigation techniques

Background sources:

- natural radioactivity (^{232}Th and ^{238}U chains):
  - γ-rays (e.g. ^{208}Tl, ^{214}Bi)
  - α-emitting isotopes from surface contamination (e.g. ^{210}Po) or ^{222}Rn in LAr
- long-lived cosmogenic Ar isotopes (^{39}Ar,^{42}Ar)
- cosmogenic isotopes activated in Ge (^{68}Ge, ^{60}Co)



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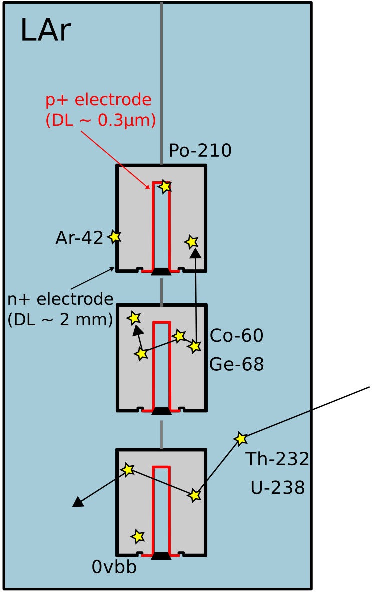
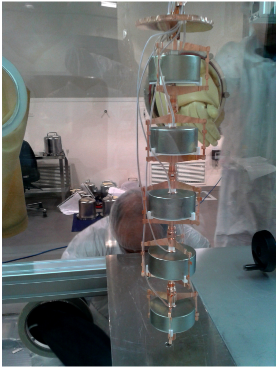
Mitigation strategy:

- detector anti-coincidence
- time-coincidence (Bi-Po or ^{68}Ge)
- pulse shape analysis
- detection of LAr-scintillation light



Detector array assembly



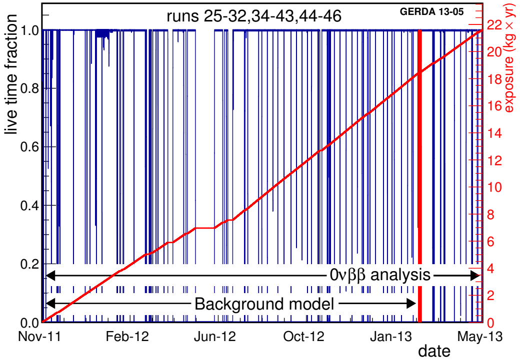


- $3 + 1$ strings
- 8 ^{enr}Ge coaxial detectors (2 not considered in the analysis)
- 5 ^{enr}Ge BEGe detectors (1 not considered in the analysis)
- 1 ^{nat}Ge coaxial detectors

^{enr}Ge mass for physics analysis: 14.6 kg (coaxial) + 3.0 kg (BEGe)

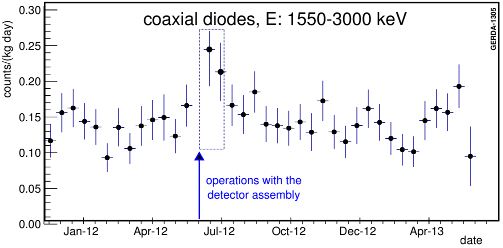
Overview of the data taking

- data taking Nov11 - May13 (492 d)
- average duty cycle 88%
- total exposure 21.6 kg·yr
- (bi)weekly calibration with Th-228 (blue spikes)



- BEGe detectors from Jul12
- 3 data sets:

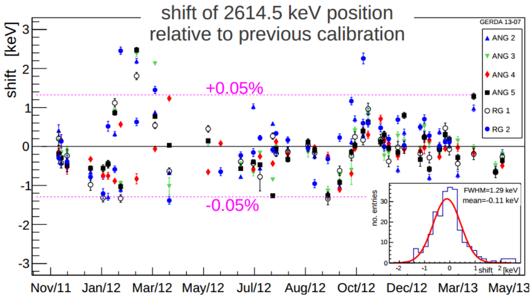
dataset	exposure
coaxial (golden)	17.9 kg·yr
coaxial (silver)	1.3 kg·yr
BEGe	2.4 kg·yr



Stability of the energy scale and resolution

Calibration runs:

- (bi)weekly calibration with Th-228
- off-line energy reconstruction (semi-Gaussian filter)
- energy resolution stable
- energy shift between successive calibrations $\lesssim 1$ keV @ $Q_{\beta\beta}$

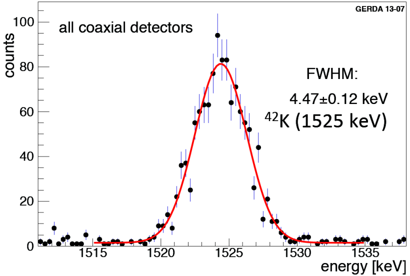


$0\nu\beta\beta$ data set:

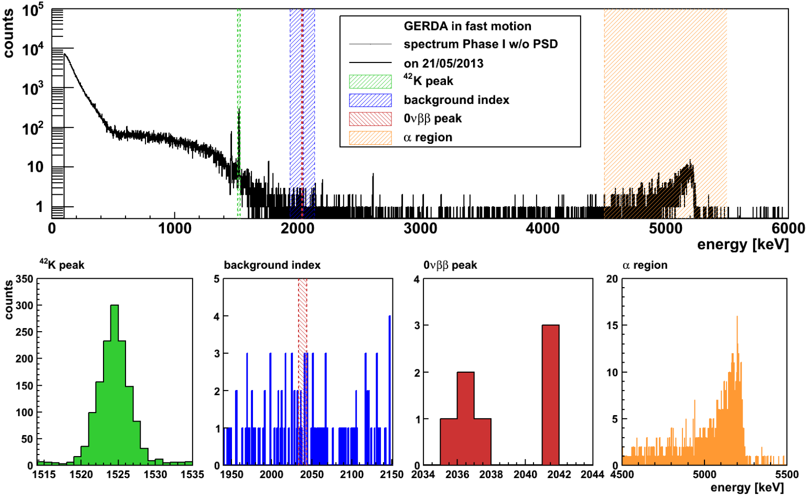
- peak position within 0.3 keV at correct position
- resolution 4% larger than in calibration runs
- mean FWHM at $Q_{\beta\beta}$ (mass/exposure weighted):

  coax —> 4.8±0.2 keV

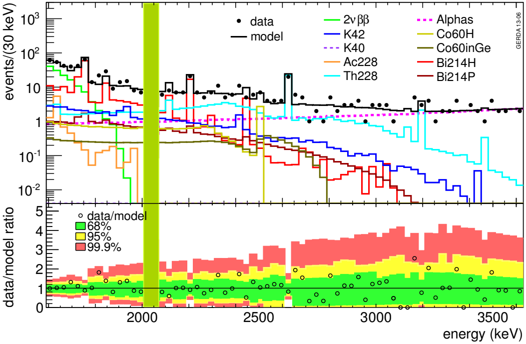
  BEGe —> 3.2±0.2 keV



Prominent structures in the energy spectrum



Background modeling

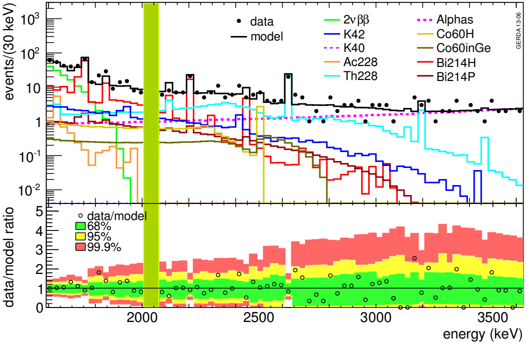


Contribution at $Q_{\beta\beta}$:

- γ-rays (close sources):
  Bi-214, Tl-208, K-42
- α- and β-rays (surface decays):
  Ra-226 daughter, Po-210, K-42

more details in [EPJ C74 (2014) 2764]

Background modeling



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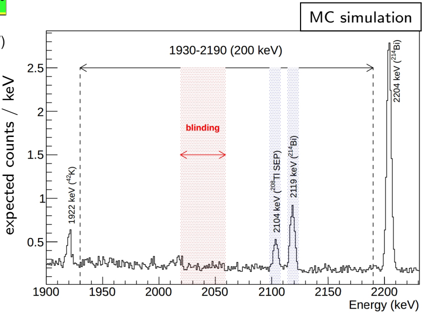


- no line expected in the blinded window
- background flat between 1930-2190 keV (excluding peaks at 2104 and 2119 keV)
- extrapolated background at $Q_{\beta\beta}$ before pulse shape analysis in units of 10^{-2} cts/(keV· kg· yr):
  - coaxial (golden): $1.75^{+0.26}_{-0.24}$
  - BEGe: $3.6^{+1.3}_{-1.0}$

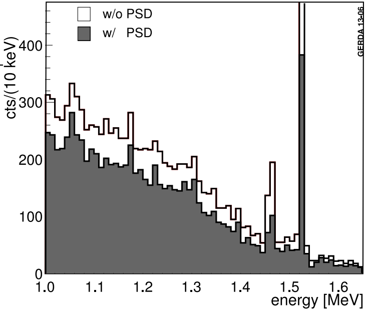
Pulse shape discrimination

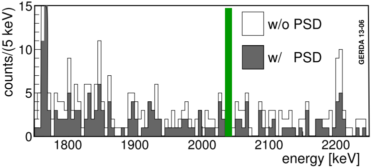
Coaxial detectors:

- artificial neural network
- cut defined using ^{228}Th calibration data
  cut fixed to 90% acceptance of 2.6 MeV DEP
- cross checks:
  - $2\nu\beta\beta$ acc. = (85±2)%
  - 2.6 MeV γ-line compton-edge acc. = 85-94%
  - Co-56 DEP (1576 & 2231 keV) acc. = 83-95%

$0\nu\beta\beta$ acceptance $= 90^{+5}_{-9}\%$

background acc at $Q_{\beta\beta} = \sim 45\%$





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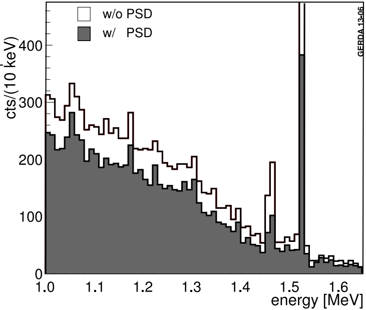

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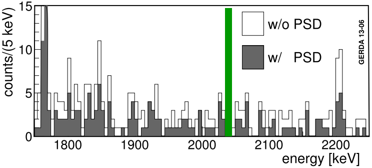
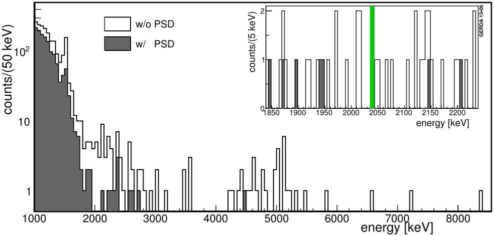
$0\nu\beta\beta$ acceptance = 90^{+5}_{-9}%

background acc at $Q_{\beta\beta}$= ∼45%



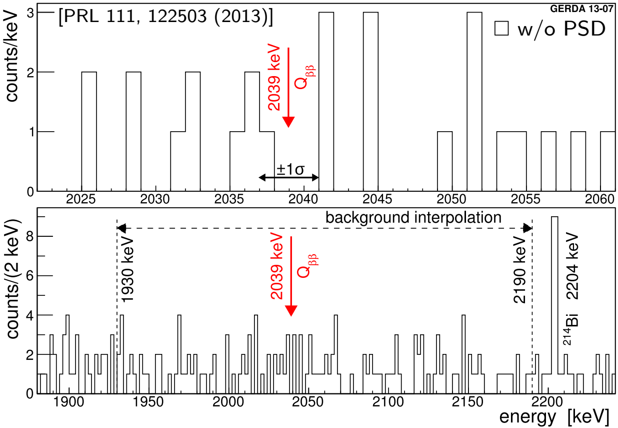


BEGe detectors:

- A/E parameter (mono-parametric PSD)
- $0\nu\beta\beta$ acc (DEP and simulations) (92±2)%
- $2\nu\beta\beta$ acc (91±5)%
- background acc at $Q_{\beta\beta}$≤20%

more details in [Eur.Phys.J C73 (2013) 2583]

Unblinding: spectrum around $Q_{\beta\beta}$



Analysis cuts applied:

1) signals quality cuts
2) detector anti-coincidence
3) muon-veto anti-coincidence
4) single-detectors time coincidence (BiPo cut)

Survival fraction at $Q_{\beta\beta}$:

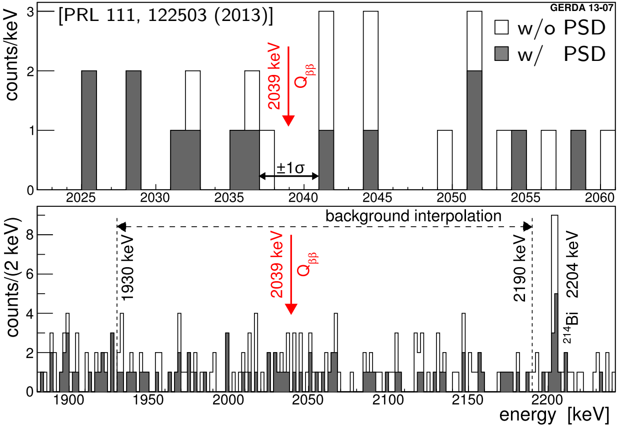
1	∼99%
2+3	∼60%
4	∼100%

w/o PSD

w/ PSD

data set	exposure [kg·yr]	background 10^{-2} cts/(keV· kg· yr)	expected cts ($Q_{\beta\beta}$±5 keV)	observed cts ($Q_{\beta\beta}$±5 keV)
golden	17.3	1.8	3.3	5
silver	1.3	6.3	0.8	1
BEGe	2.4	4.2	1.0	1

Unblinding: spectrum around $Q_{\beta\beta}$



Analysis cuts applied:

1) signals quality cuts
2) detector anti-coincidence
3) muon-veto anti-coincidence
4) single-detectors time coincidence (BiPo cut)
5) **PSD**

Survival fraction at $Q_{\beta\beta}$:

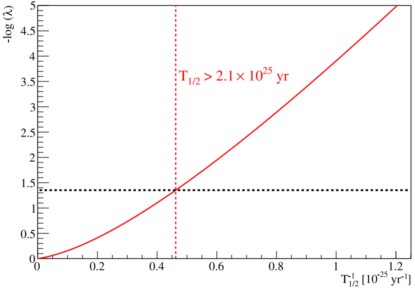
1	∼99%
2+3	∼60%
4	∼100%
5	**∼50%**

w/o PSD

w/ PSD

data set	exposure [kg·yr]	background 10^{-2} cts/(keV· kg· yr) w/o PSD	background w/ PSD	expected cts ($Q_{\beta\beta}\pm5$ keV) w/o PSD	expected cts w/ PSD	observed cts ($Q_{\beta\beta}\pm5$ keV) w/o PSD	observed cts w/ PSD
golden	17.3	1.8	1.1	3.3	2.0	5	2
silver	1.3	6.3	3.0	0.8	0.4	1	1
BEGe	2.4	4.2	0.5	1.0	0.1	1	0

Statistical analysis



Baseline analysis (profile likelihood):

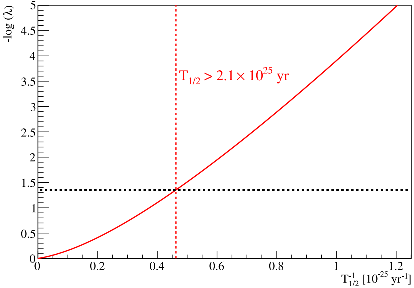
- likelihood fit
 (constant+Gauss in 1930-2190 keV range)
- multiple data sets (common $T^{0\nu}_{1/2}$)
- $T^{0\nu}_{1/2} \geq 0$ (coverage tested)

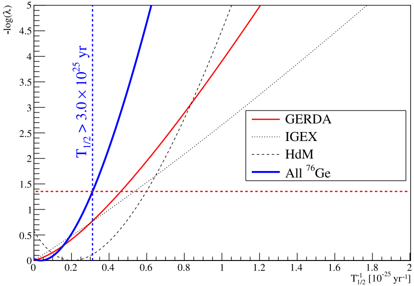
Results (GERDA only):

- best fit for $N_{0\nu\beta\beta} = 0$ signal cts
- $N_{0\nu\beta\beta} < 3.5$ cts at 90% C.L.
- $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.)
- MC Median sensitivity (for no signal):
  $T^{0\nu}_{1/2} > 2.4 \cdot 10^{25}$ yr (90% C.L.)

PRL 111, 122503 (2013); [1] Phys.Rev. D65, 092007 (2002); [2] Eur.Phys.J. A12, 147 (2001)

Statistical analysis





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- $N_{0\nu\beta\beta} < 3.5$ cts at 90% C.L.
- $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.)
- MC Median sensitivity (for no signal): $T^{0\nu}_{1/2} > 2.4 \cdot 10^{25}$ yr (90% C.L.)

Results (GERDA + IGEX [1] + HdM [2]):

- best fit for $N_{0\nu\beta\beta} = 0$ signal cts
- $T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}$ yr (90% C.L.)

PRL 111, 122503 (2013); [1] Phys.Rev. D65, 092007 (2002); [2] Eur.Phys.J. A12, 147 (2001)

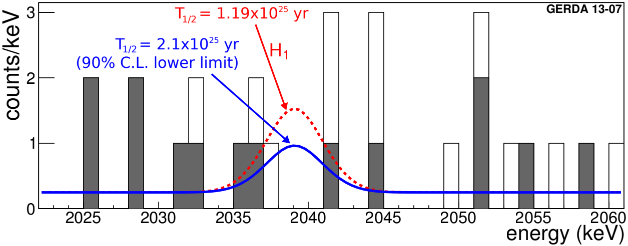
Comparison with Phys.Lett. B586 198 (2004)

Hypothesis test: H_0 (bkg only) vs H_1 ($T^{0\nu}_{1/2} = 1.19^{+0.37}_{-0.23} \cdot 10^{25}$ yr + bkg)

In $Q_{\beta\beta} \pm 2\sigma_E$ (after PSD):

- expected 2.0±0.3 bkg cts
- expected 5.9±1.4 signal cts (assuming H1)
- observed 3 cts

[PRL 111, 122503 (2013)]



GERDA only:

- Frequentist p-value ($N_{0\nu\beta\beta} = 0 | H_1$) = 0.01
- Bayes factor $P(H_1)/P(H_0) = 2.4 \cdot 10^{-2}$

GERDA + IGEX + HdM:

- Bayes factor $P(H_1)/P(H_0) = 2 \cdot 10^{-4}$

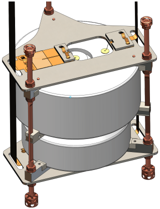
Long standing claim strongly disfavoured!

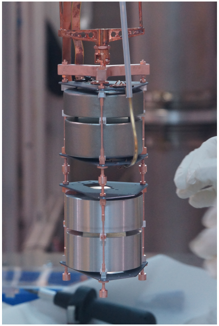
Phase II challenges and goals

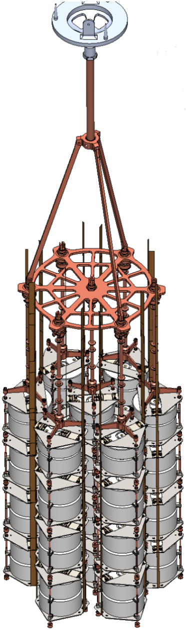
Goal: starting exploration of $T_{1/2}^{0\nu}$ values in the range of 10^{26} yr

Ongoing upgrades:

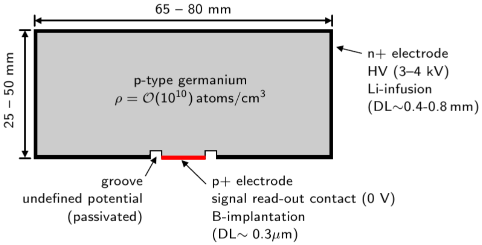
- Installation of additional 20 kg of BEGe detectors:
  - increased array granularity (anti-coincidence cut)
  - enhanced pulse shape discrimination performance
  - excellent energy resolution
- PMT and fibers+SiPM
  to detect LAr scintillation light
- lower-mass holders

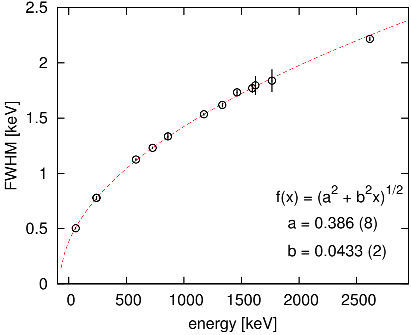


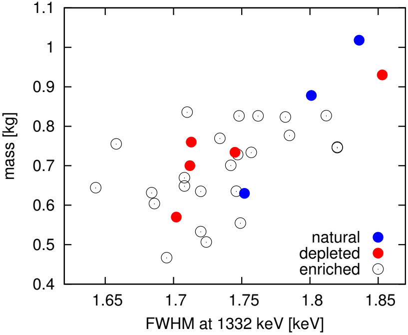




Broad Energy Germanium (BEGe) detectors



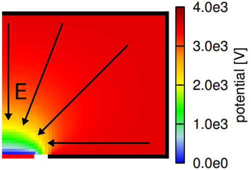




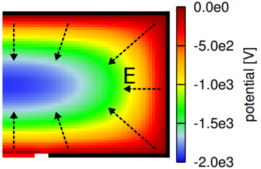
Electric field and charge collection

Contributions to the electric field (E):

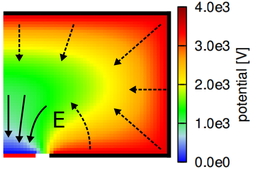
1) electrodes potentials:
   $\phi_{p+} = 0\,\mathrm{V}$, $\phi_{n+} = 4\,\mathrm{kV}$



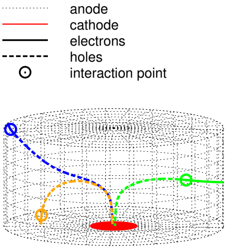
2) impurity concentration:
   negative charges for depleted p-type Ge



Total field (1+2):
holes are pushed to the detector central slice (2) and then collected to the p+ electrode (1)



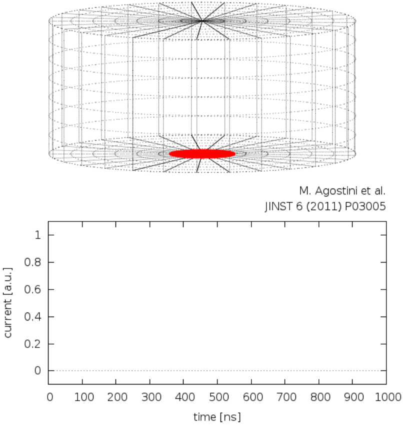
Interplay between (1) and (2) results in the **funnel effect**:

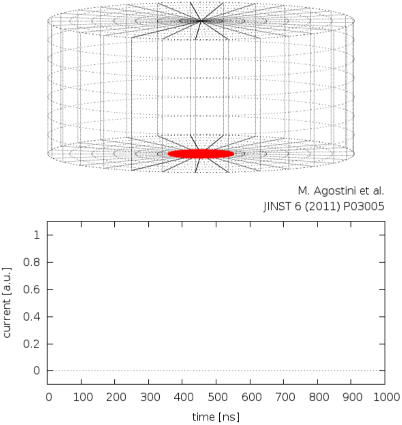


final part of hole trajectories independent of interaction positions

[JINST 6 (2011) P03005]

Signal formation and development

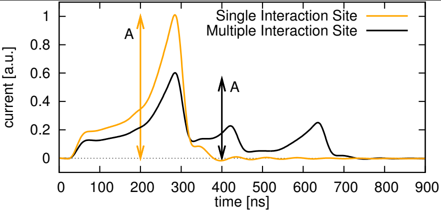


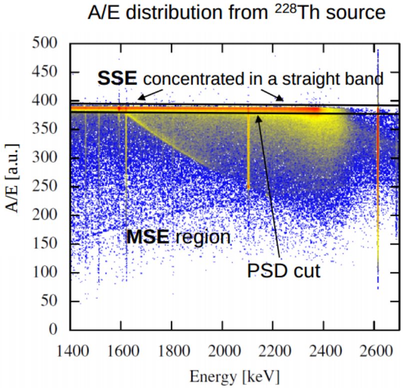


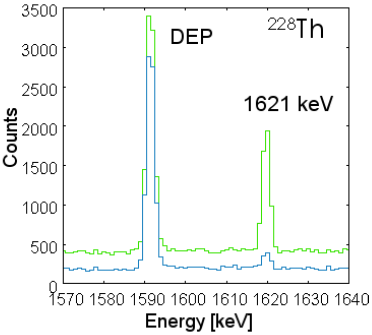
Pulse shape discrimination technique

A/E method:

E: integral of the current signal (energy)
A: maximum of the current signal

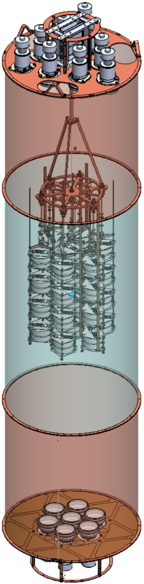


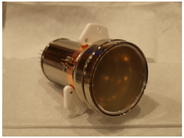




[Budjas et al. JINST 4 P10007]
[M.A et al. JINST 6 P03005]

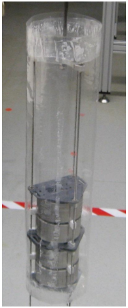
Detection of LAr scintillation light



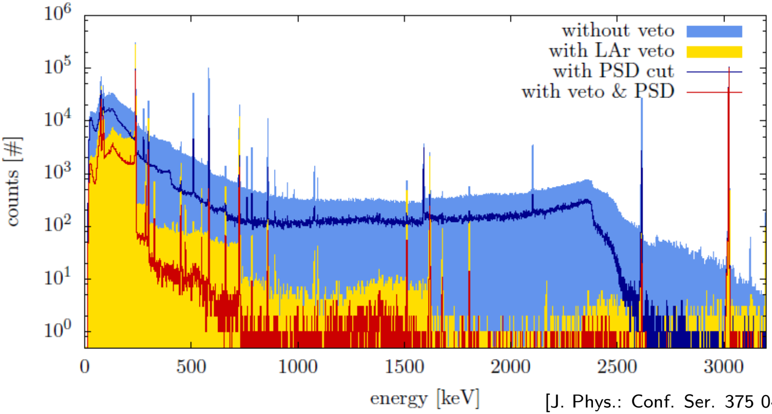


Design:

- low-background photo-multipliers (9 top, 7 bottom)
- wave-length-shifting fibers read-out by SiPMs
- wave-length-shifting nylon mini-shroud



Combined used of PSD and LAr scintillation signal

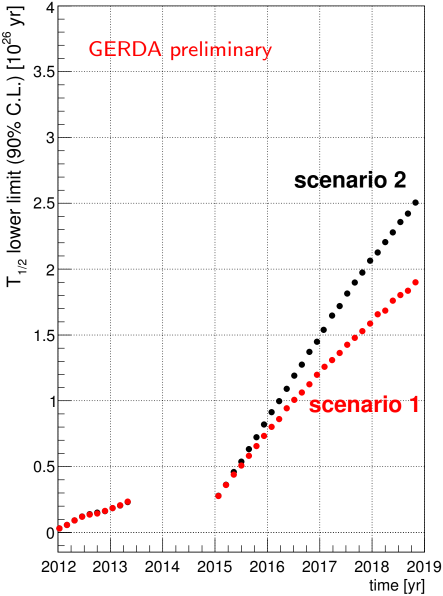


[J. Phys.: Conf. Ser. 375 042009]

Pulse shape analysis combined with LAr-scintillation (in LArGe setup): measured suppression factor of $(5.2 \pm 1.3) \cdot 10^3$ at $Q_{\beta\beta}$ for close Th-228

Phase II median sensitivity for limit setting

- profile likelihood analysis
- global analyis (Phase I+II data sets)
- beginning of Phase II set to Jan 2015
- scenario 1:
  - $BI_{\mathrm{coax}} = 5 \cdot 10^{-3}$ cts/(keV· kg· yr)
  - $BI_{\mathrm{bege}} = 1 \cdot 10^{-3}$ cts/(keV· kg· yr)
- scenario 2:
  - $BI_{\mathrm{coax}} = 1 \cdot 10^{-3}$ cts/(keV· kg· yr)
  - $BI_{\mathrm{bege}} = 0.5 \cdot 10^{-3}$ cts/(keV· kg· yr)



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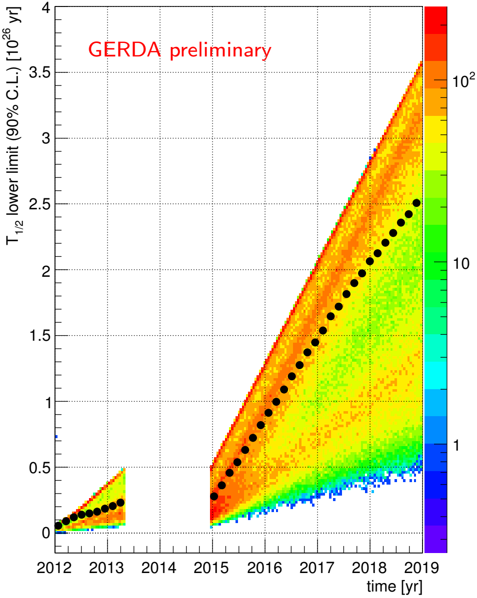

Conclusions

GERDA Phase I (21.6 kg·yr of exposure):

- background order of magnitude lower than previous Ge experiments:

  $\sim$0.01 cts/(keV· kg· yr) at $Q_{\beta\beta}$ (after PSD)

- blind analysis —> no positive $0\nu\beta\beta$ signal:

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

- Long standing claim excluded at 99% C.L. (model-independent result)

GERDA Phase II:

- transition ongoing
- quasi background-free experiment
- start exploration of $T^{0\nu}_{1/2} > 10^{26}$ yr in a $\leq$2 yr of data taking