GERDA searches for 0νββ and other ββ decay modes of ^{76}Ge

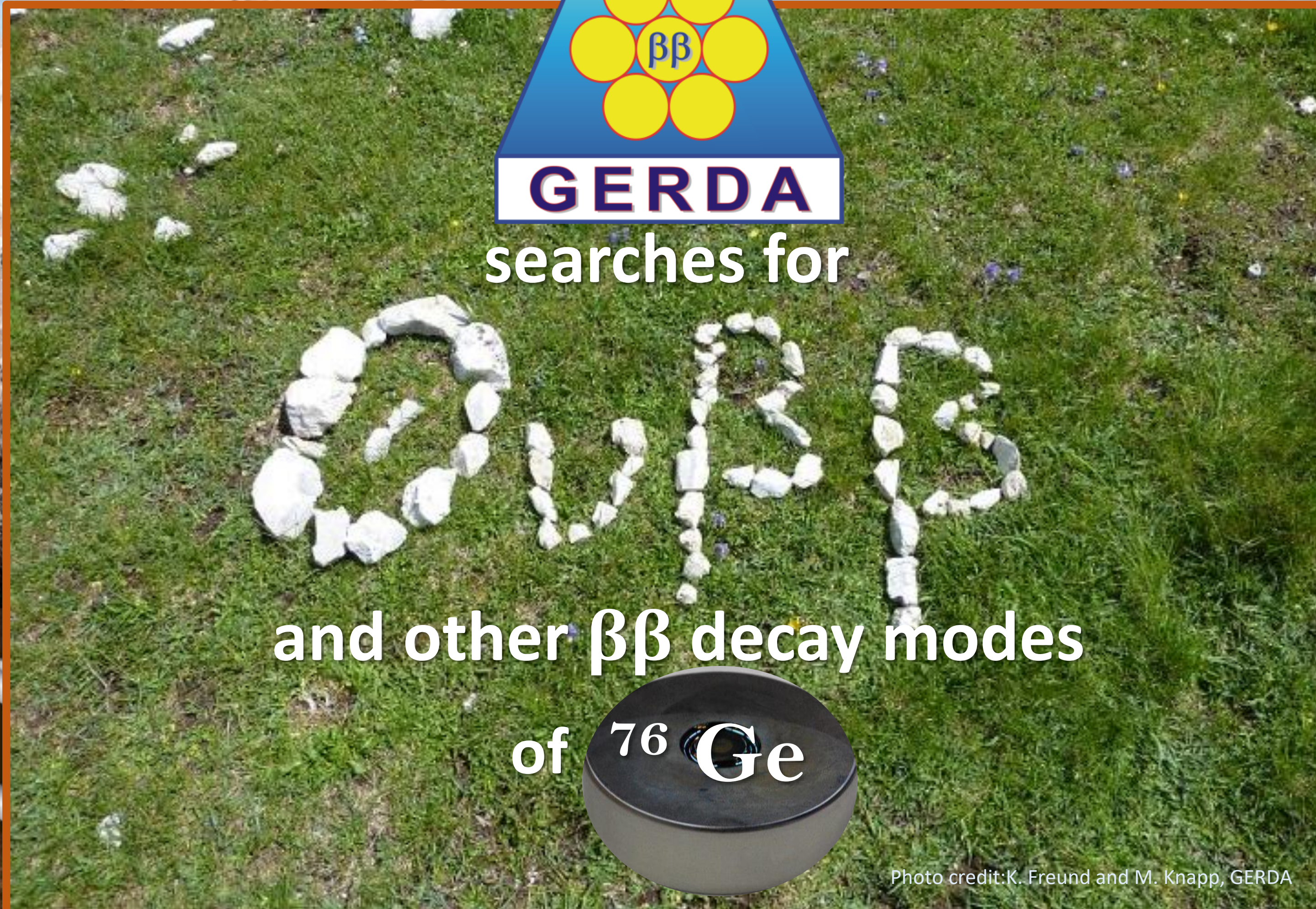
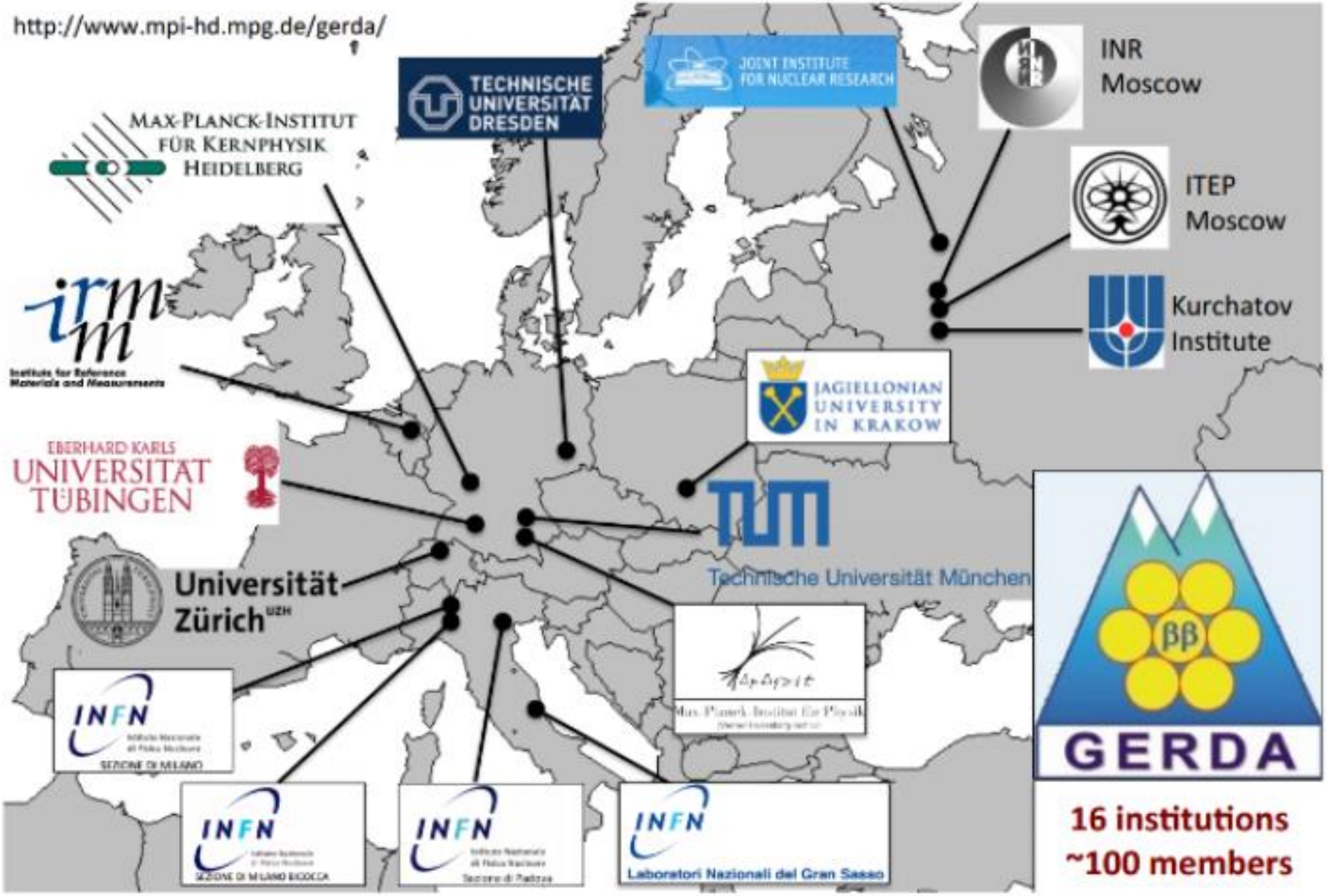


Photo credit:K. Freund and M. Knapp, GERDA

Anatoly Smolnikov for the GERDA collaboration
MPIK, Heidelberg / JINR, Dubna

MEDEX'19, Prague, 27-31 May 2019

The GERDA Collaboration

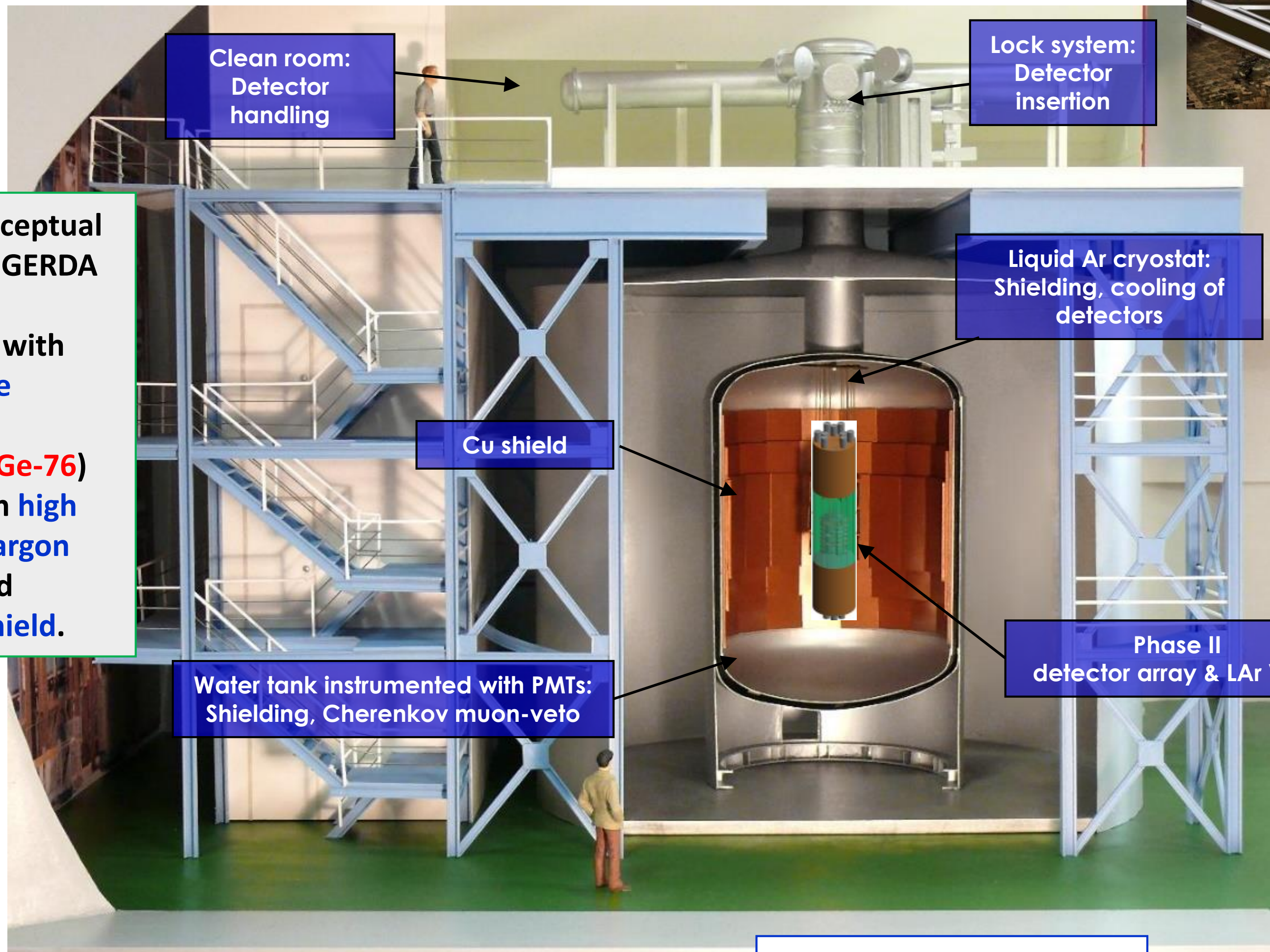


GERDA: the GERmanium Detector Array

Double Beta Decay Experiment

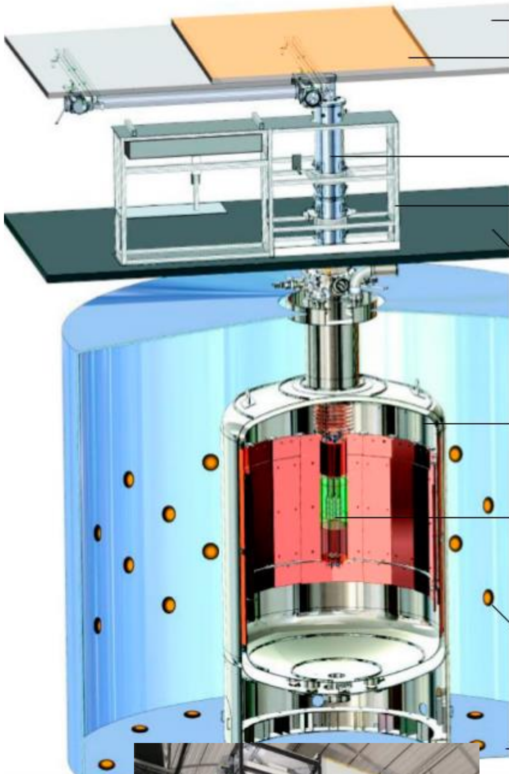
http://www.mpi-hd.mpg.de/gerda/

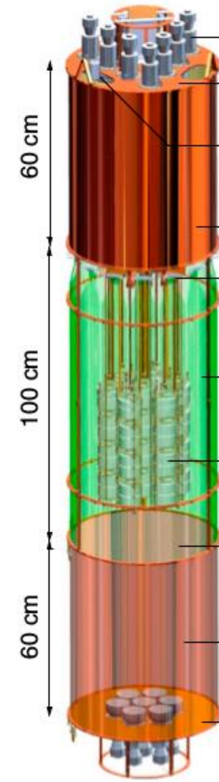
The main conceptual design of the GERDA experiment is to operate with “naked” HPGe detectors (enriched in Ge-76) submerged in high purity liquid argon supplemented by a water shield.



Eur. Phys. J. C (2013) 73:2330
Eur. Phys. J. C (2018) 78:388

GERDA Phase II: design and main components

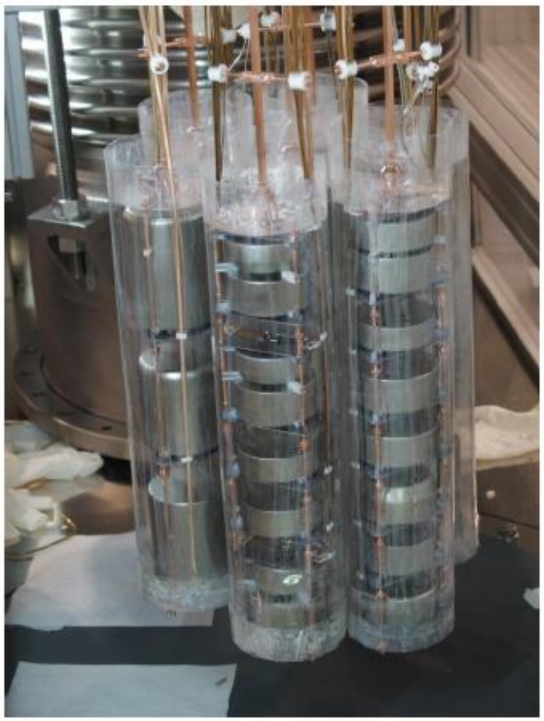




Eur. Phys. J. C (2018) 78:388

GERDA Phase II – started December 2015

7 strings of HPGe detectors deployed:
37 detectors enriched in 76Ge (**35.8 kg**)
3 natural detectors (7.6 kg)

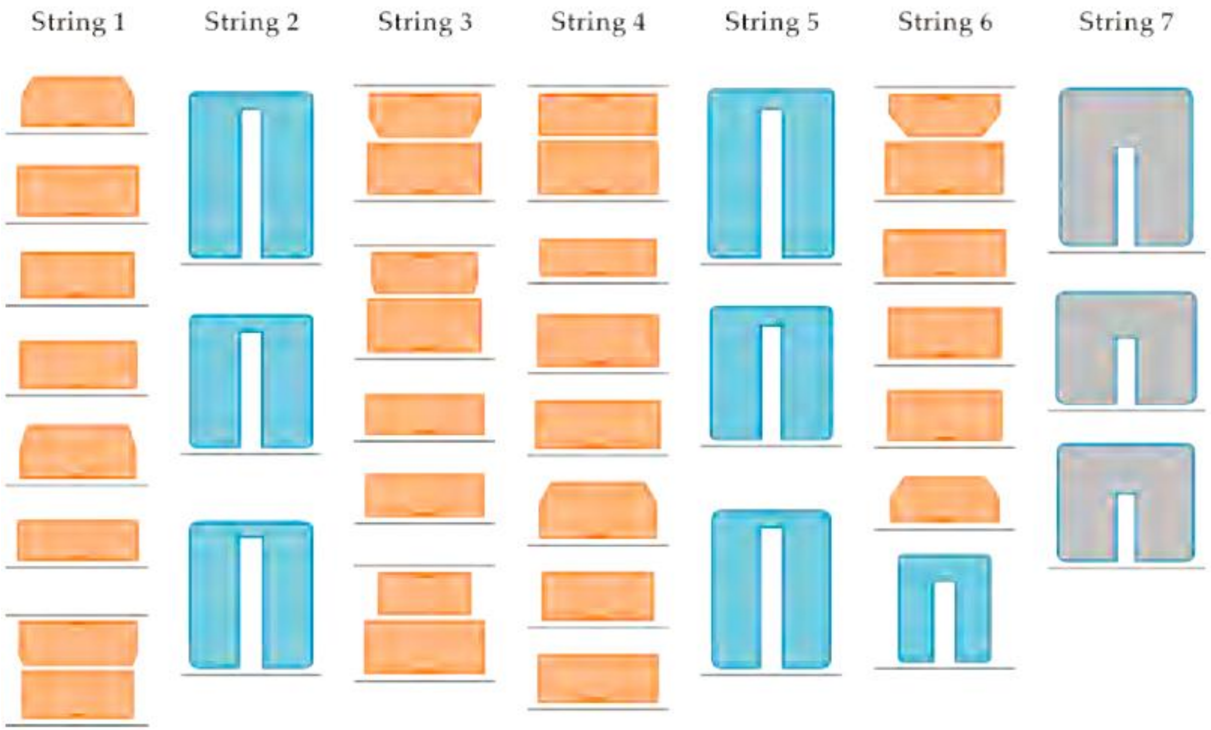


GERDA Phase II: 40 detectors in 7 strings

30 BEGe, enriched in ^{76}Ge

7 Semi-coaxial det-s enriched in ^{76}Ge

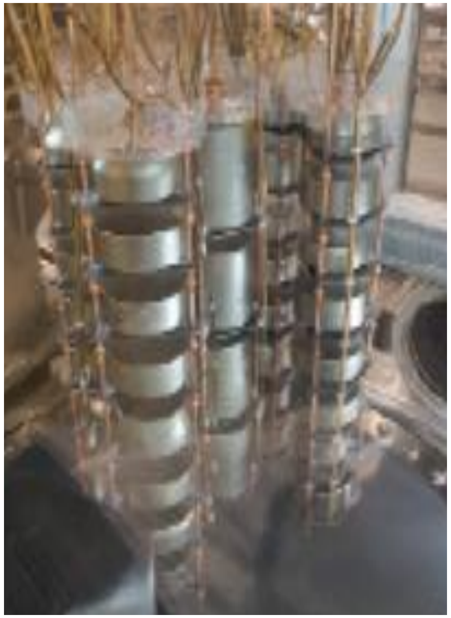
3 Semi-coaxial det-s from ^{Nat}Ge



GERDA Phase II – Upgrade in Summer 2018

5 new inverted semi-coaxial detectors enriched in ^{76}Ge **added** (+9.5 kg)
3 Semi-coaxial detectors from ^{Nat}Ge **removed**

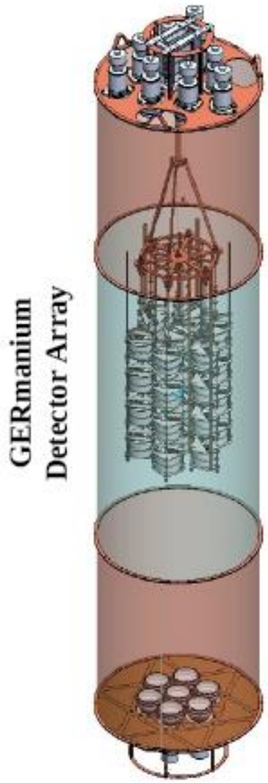
To increase LAr light collection:
New LAr fiber curtain with higher density and additional new central module

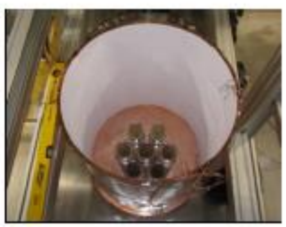


Liquid Argon veto for GERDA Phase II

LAr veto

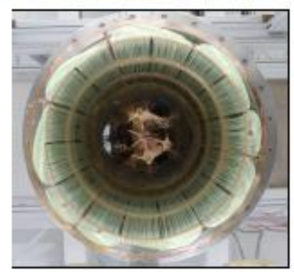
9 off 3” PMTs



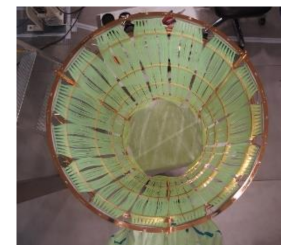


7 off 3” PMTs

copper shroud lined with reflecting TPB coated Tetratex

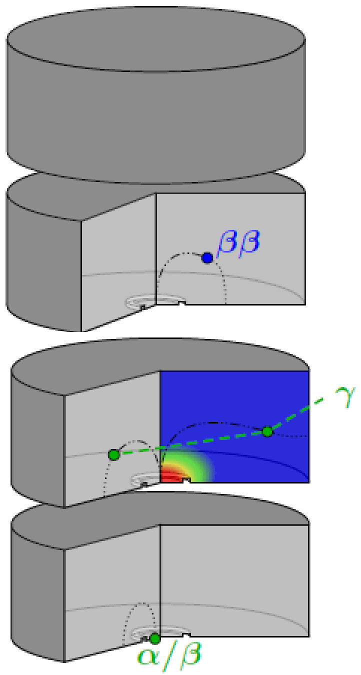


TPB coated fiber shroud with SiPMs

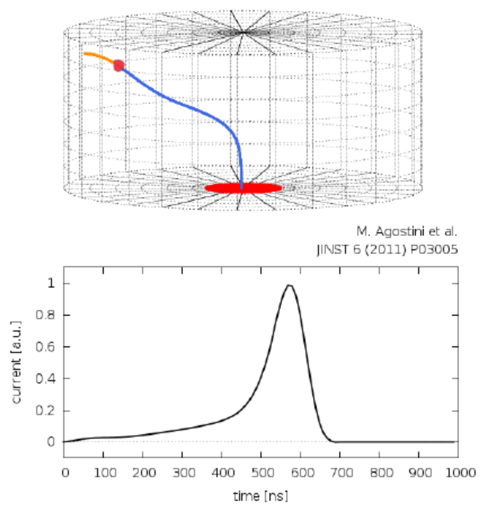


After upgrade in Summer 2018

Pulse-Shape Discrimination

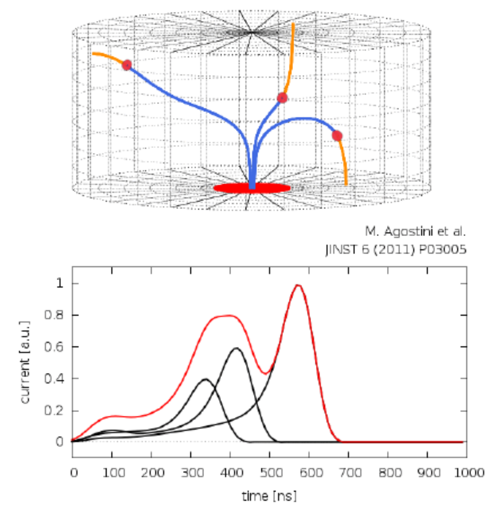


Single Site Event



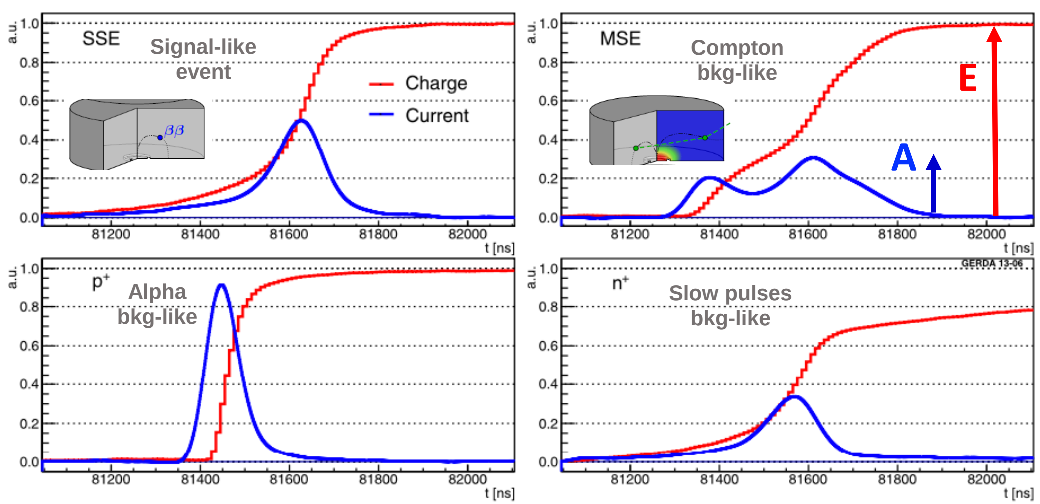
M. Agostini et al.
JINST 6 (2011) P03005

Multiple Site Event



M. Agostini et al.
JINST 6 (2011) P03005

PSD parameter for BEGe : A/E



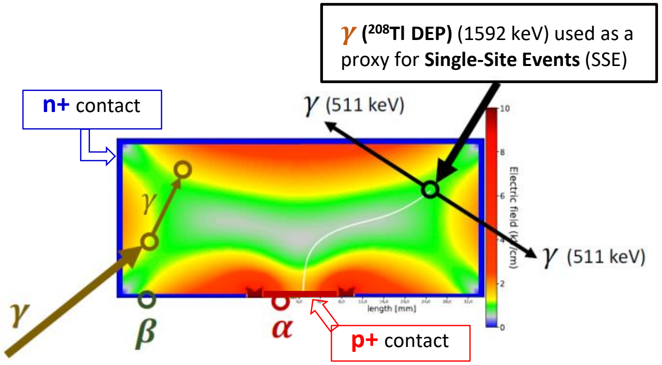
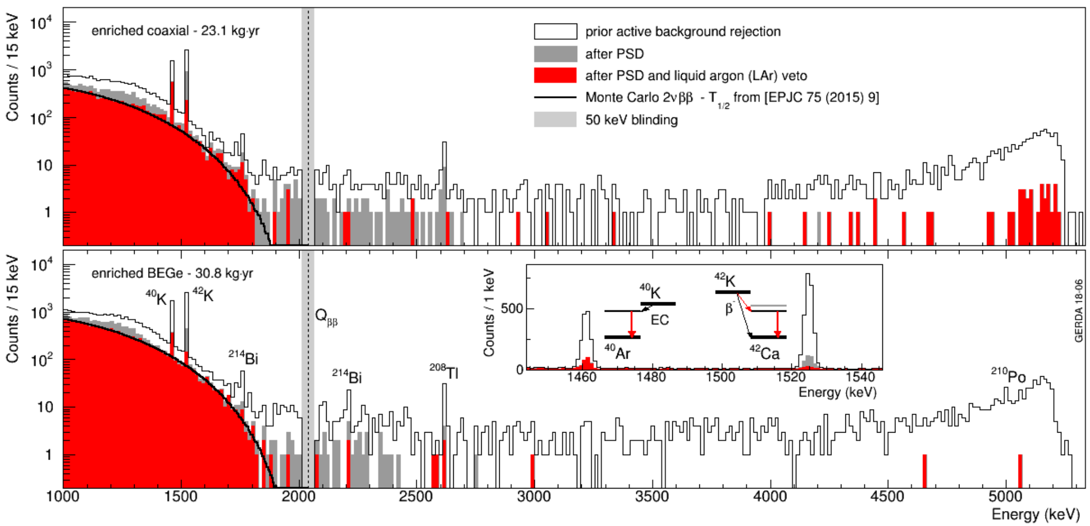


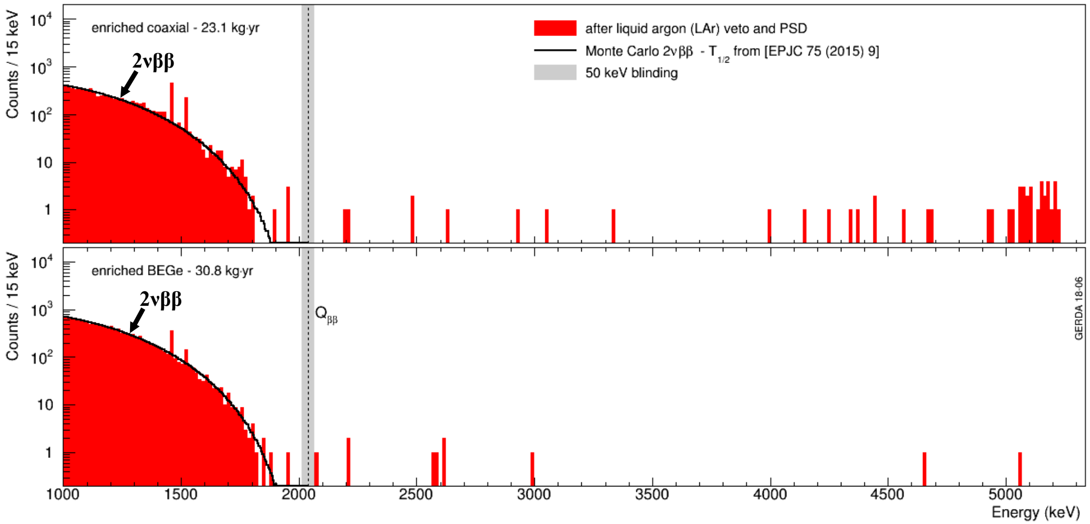
Image credit: from Yoann Kermaпdic, GERDA

Phase exposures and BI-s

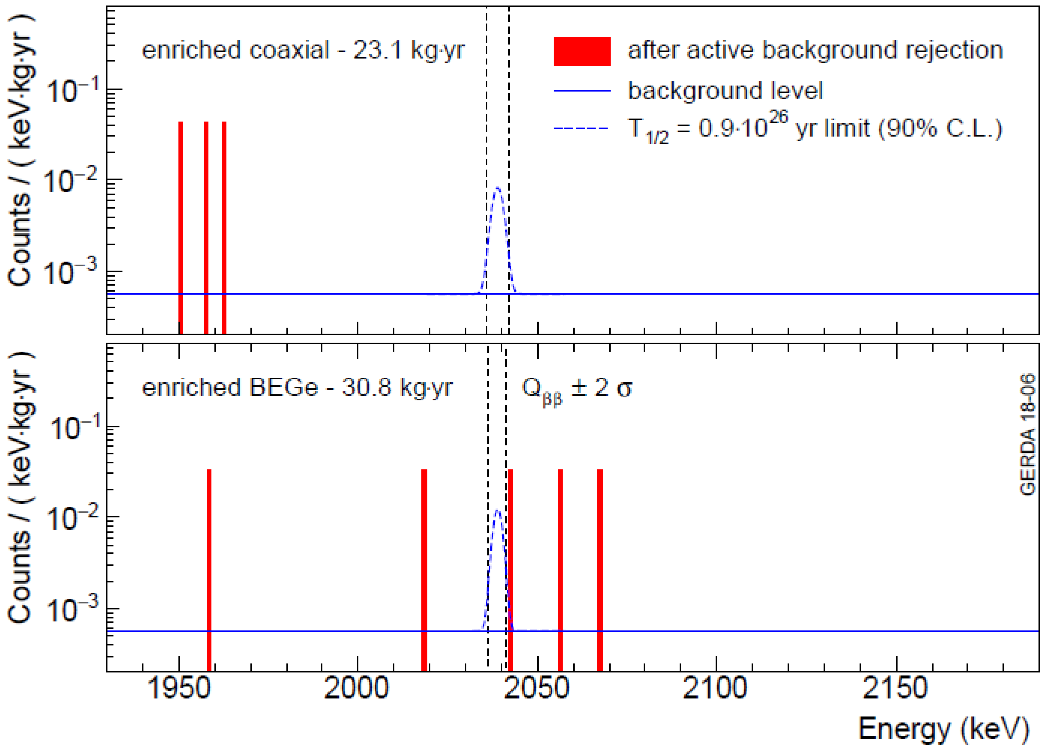
Dataset	Exposure [kg.yr]	FWHM [keV]	ε	BI [10^{-3} cts/kev.kg.yr]
Phase I golden	17.9	4.3 ± 0.1	0.57 ± 0.03	11 ± 2
Phase I silver	1.3	4.3 ± 0.1	0.57 ± 0.03	30 ± 10
Phase I BEGe	2.4	2.7 ± 0.1	0.66 ± 0.02	5^{+4}_{-3}
Phase I extra	1.9	4.2 ± 0.1	0.58 ± 0.04	5^{+4}_{-3}
Phase II coax-1	5.0	3.6 ± 0.1	0.52 ± 0.04	$3.5^{+2.1}_{-1.5}$
Phase II coax-2	**23.1**	$\mathbf{3.6 \pm 0.1}$	$\mathbf{0.48 \pm 0.04}$	$\mathbf{0.6^{+0.4}_{-0.3}}$
Phase II BEGe	**30.8**	$\mathbf{3.0 \pm 0.1}$	$\mathbf{0.60 \pm 0.02}$	$\mathbf{0.6^{+0.4}_{-0.3}}$

GERDA Phase II: Last 0νββ data release





GERDA Phase II: $0\nu\beta\beta$ current result



Phase I + Phase II:

Total exposure: **82.4 kg yr**

$T_{1/2}$(0v2β) > 0.9 x 10^{26} yr (Frequentist)

$T_{1/2}$(0v2β) > 0.8 x 10^{26} yr (Bayesian)

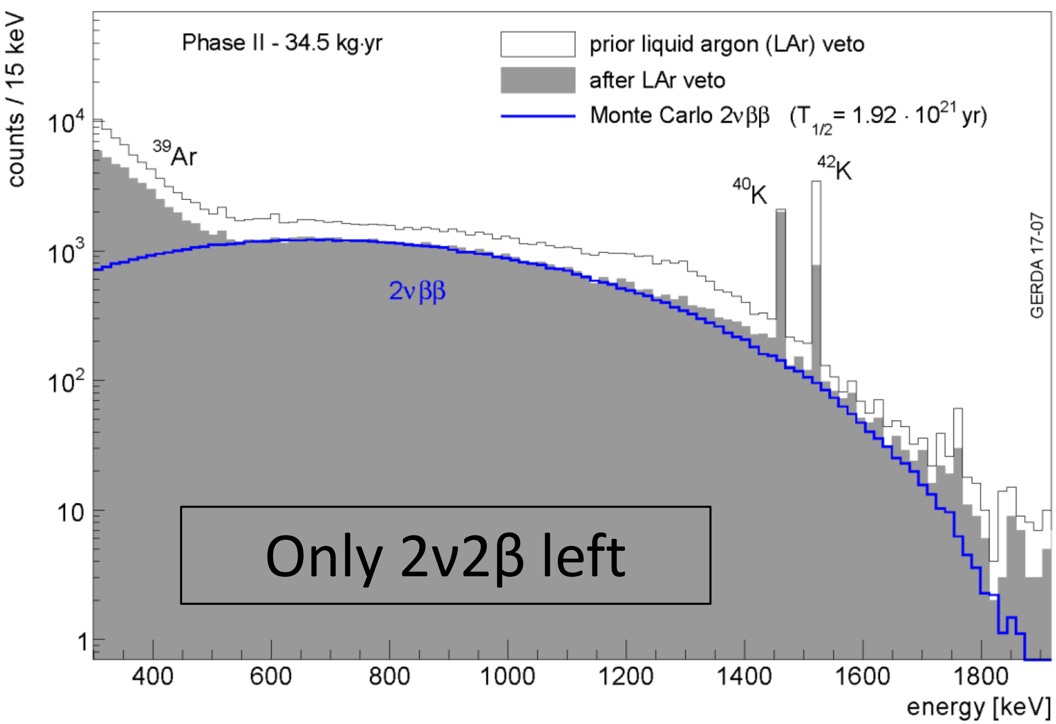
Background in ROI ~ 6 x10^{-4} cts/(keV kg yr)

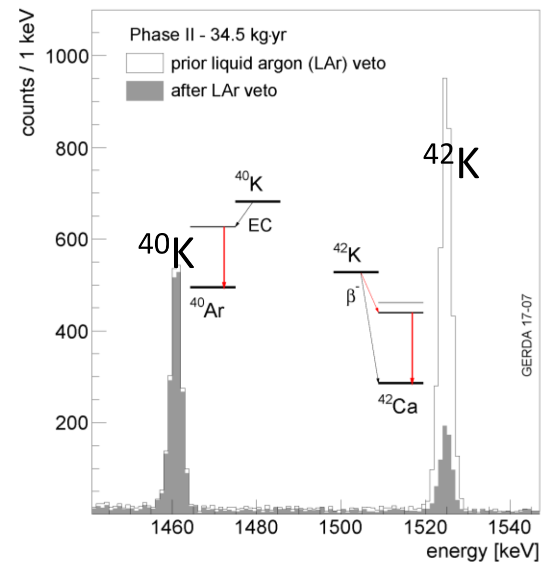
Sensitivity **1.0 x 10^{26}** yr

Presented at NEUTRINO 2018 conf., to be published

Half-life of 2νββ decay of 76Ge

After LAr Veto performance





Survival fraction between 0.6 and 1.3 MeV:

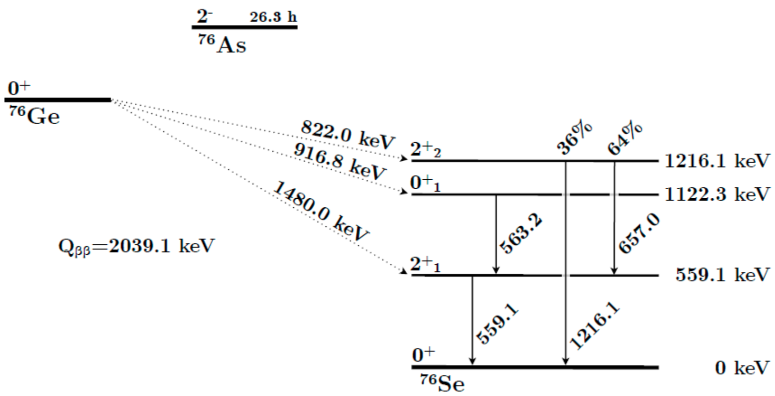
(68.6 ± 0.3)%

$T_{1/2}$(2ν2β) fixed as 1.92 10^{21} yr

^{40}K and ^{42}K continua

strongly suppressed

GERDA Phase I : 2νββ decay of ^{76}Ge to excited states of ^{76}Se

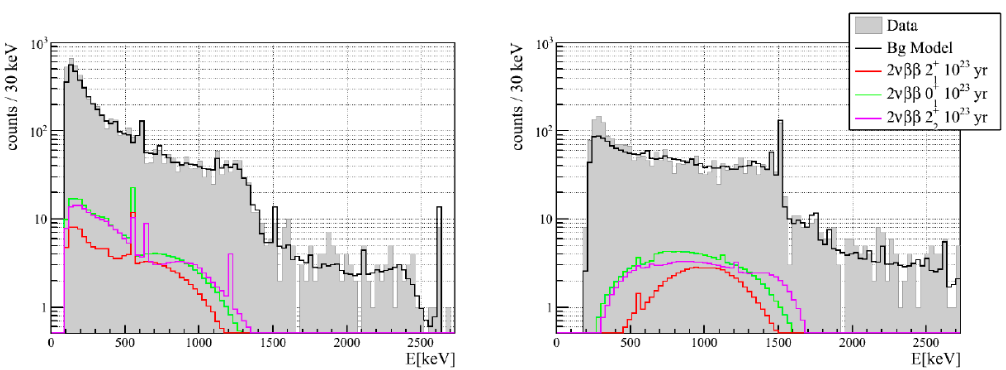


Three decay modes are investigated: 2^+_1, 0^+_1, 2^+_2

0^+_1 most likely, sensitivity in the range of predictions
2^+_2 has two branches for de-excitation

Large uncertainties in matrix elements
→ predicted half-lives range
over several orders of magnitude

$2\nu\beta\beta$ decay mode	$T^{2\nu}_{1/2}$ (yr)	Model/exp.	References	Year
$0^+_{g.s.} - 2^+_1$ (559.1 keV)	$>6.3 \times 10^{20}$ (68% C.L.)	Exp.	[19]	1992
	$>1.1 \times 10^{21}$ (90% C.L.)	Exp.	[20]	1995
	1.2×10^{30}	SM	[21]	1984
	5.8×10^{23}	HFB	[22]	1994
	5.0×10^{26}	QRPA	[23]	1994
	2.4×10^{24}	QRPA	[24]	1996
	7.8×10^{25}	MCM-QRPA	[25]	1996
	1.0×10^{26}	RQRPA	[26]	1997
	$(2.4{-}4.3) \times 10^{26}$	RQRPA	[27]	1998
	2.0×10^{27}	RQRPA	[28]	2014
$0^+_{g.s.} - 0^+_1$ (1122.3 keV)	$>6.3 \times 10^{20}$ (68% C.L.)	Exp.	[19]	1992
	$>1.7 \times 10^{21}$ (90% C.L.)	Exp.	[20]	1995
	$>6.2 \times 10^{21}$ (90% C.L.)	Exp.	[29]	2000
	1.32×10^{21}	HFB	[22]	1994
	4.0×10^{22}	QRPA	[23]	1994
	4.5×10^{22}	QRPA	[24]	1996
	7.5×10^{21}	MCM-QRPA	[25]	1996
	$(1.0{-}3.1) \times 10^{23}$	RQRPA	[26]	1997
	$(1.2{-}5.8) \times 10^{23}$	RQRPA	[11]	2014
	6.4×10^{24}	IBM-2	[14, 15]	2014
	$(2.3{-}2.6) \times 10^{24}$	SM	[16]	2014
$0^+_{g.s.} - 2^+_2$ (1216.1 keV)	$>1.4 \times 10^{21}$ (90% C.L.)	Exp.	[20]	1995
	1.0×10^{29}	QRPA	[23]	1994
	1.3×10^{29}	MCM-QRPA	[25]	1996
	$(0.7{-}2.2) \times 10^{28}$	RQRPA	[26]	1997



Single detector spectrum Sum detector spectrum

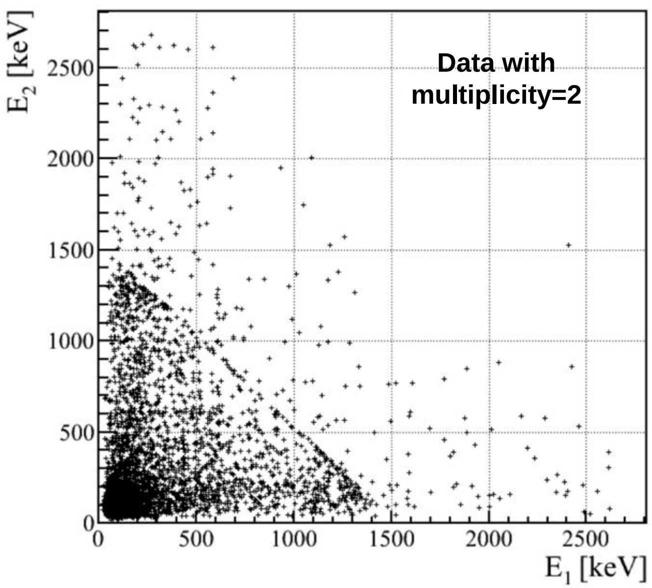
Spectra of 2-detector events in the GERDA Phase I data set scaled to a half-life of 10^{23} yr. Shown are the individual detector energy spectra (left) and as their sum energy spectra(right). Also shown is the background model (black line) and data events (gray)

J. Phys. G: Nucl. Part. Phys. 42 (2015) 115201

GERDA Phase I: data with multiplicity=2

Data taken:
from November 2011 to May 2013
Exposure ε ($Ge76$) = **22.3 kg · yr**

Two detector configurations:
– until March 2012: **11 detectors**
– from July 2012: **14 detectors**



Multiplicity	**1**	**2**	**3**	**4**	**5**
N events	7 · 10^5	2710	82	2	1

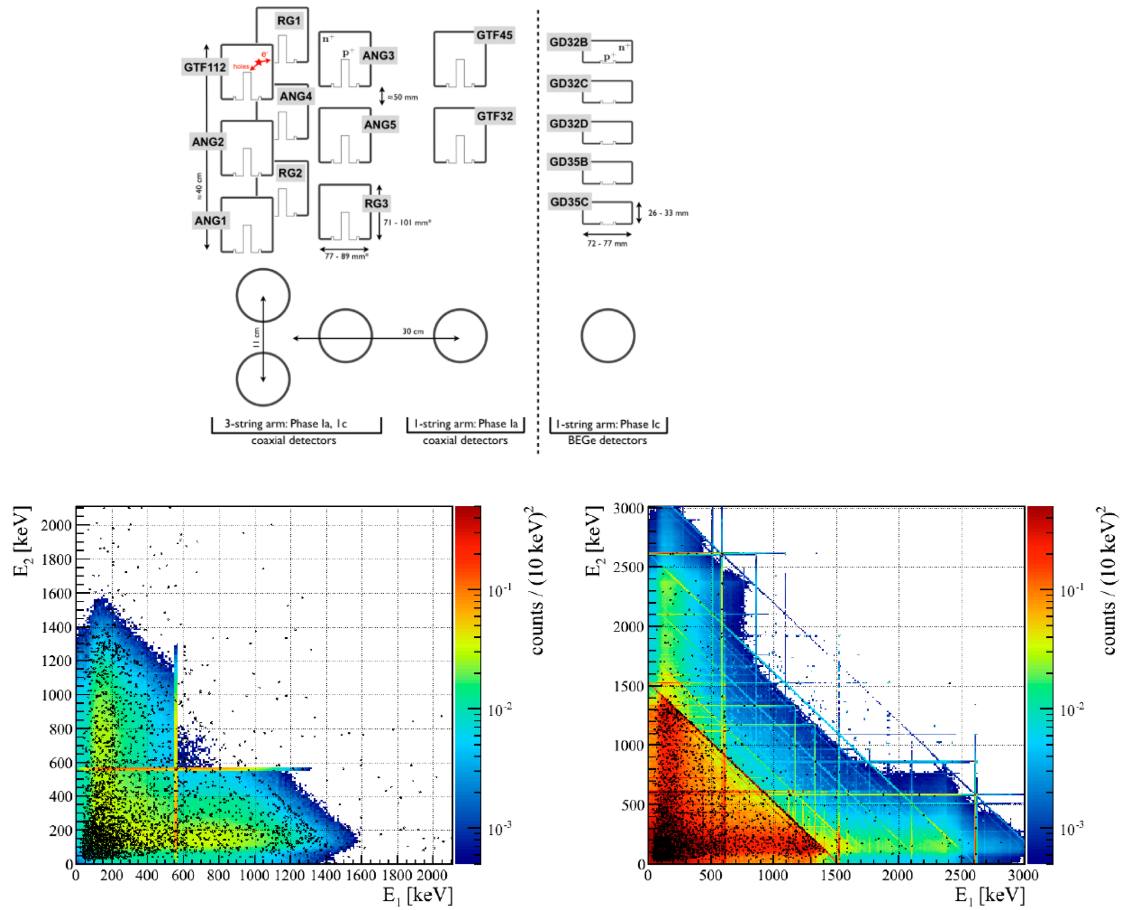
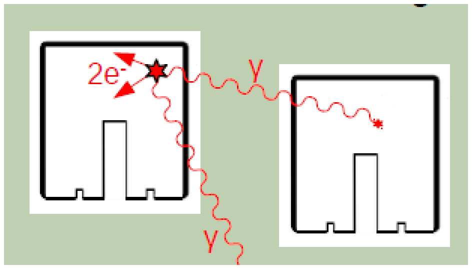
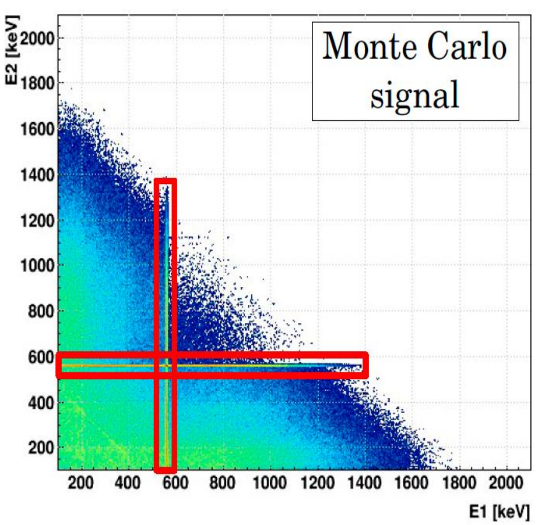


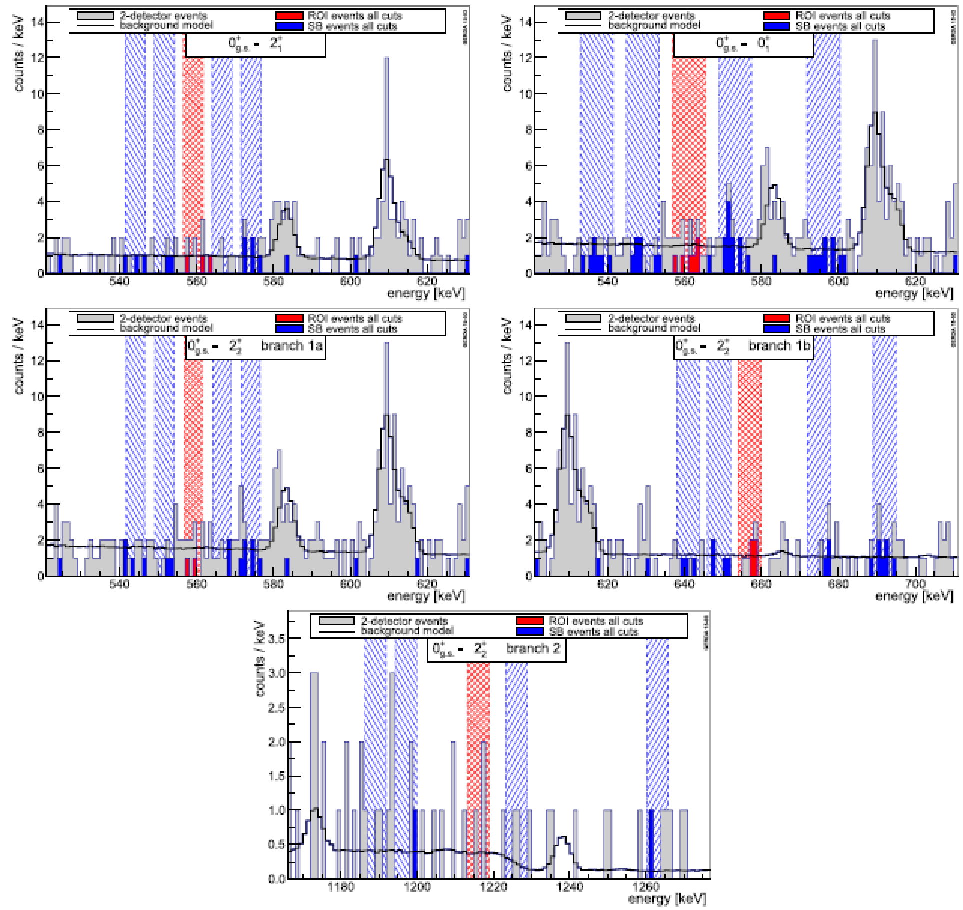
Figure : 2-detector event energy-energy correlations showing the simulated **2νββ** signal process for the decay mode $\mathbf{0^+_1}$ scaled to 10^{23} yr half-life (left) and the simulated background model (right). Simulated events are shown in color and GERDA Phase I data events in black. The number of MC events is scaled to the Phase I data

GERDA



Decay mode specific coincidence cut – includes signal peak + background SB sidebands to estimate background





Single-energy spectra around the respective ROI for all decay modes. Two-detector events (light gray) and the corresponding background curves (black), the ROI (shaded red) and SB region (shaded blue). Highlighted are events that are tagged as ROI (red) and SB (blue) after all cuts and that are used for the limit setting. The histograms contain two entries per event and that one entry maylie outside the tagging region

GERDA Phase I : 2$\nu\beta\beta$ decay of ^{76}Ge to excited states of ^{76}Se

Results

Decay mode	n	m	ϵ [%]	Frequentist 90 % CL $T_{1/2}$ [10^{23} yr]	Frequentist 90 % CL $T_{1/2}^{\text{sensitivity}}$ [10^{23} yr]	Bayesian 90 % CI $T_{1/2}$ [10^{23} yr]	Bayesian 90 % CI $T_{1/2}^{\text{sensitivity}}$ [10^{23} yr]
$0^+_{\text{g.s.}} - 2^+_1$	2	10	0.389	> 1.56	> 1.22	> 1.26	> 1.09
$0^+_{\text{g.s.}} - 0^+_1$	5	34	0.919	> 3.72	> 1.72	> 2.67	> 1.65
$0^+_{\text{g.s.}} - 2^+_2$ branch 1	6	29	0.594	> 1.68	> 1.19	> 1.38	> 1.14
$0^+_{\text{g.s.}} - 2^+_2$ branch 2	0	2	0.092	> 0.74	> 0.48	> 0.49	> 0.38
$0^+_{\text{g.s.}} - 2^+_2$ combined	-	-	-	> 2.31	> 1.31	> 1.75	> 1.32

n - number of events with ROI tag, m - number of background events with a SB tag, ε- detection efficiency.
The lower half-life limits and sensitivities are given for the frequentist and Bayesian analysis.

No signal has been observed and an event counting prole likelihood analysis yields lower half-life limits:

$$0^+_{\text{g.s.}} - 2^+_1\text{: } T_{1/2} > 1.6\cdot10^{23}\text{ yr,}$$

$$0^+_{\text{g.s.}} - 0^+_1\text{: } T_{1/2} > 3.7\cdot10^{23}$$

$$0^+_{\text{g.s.}} - 2^+_2\text{: } T_{1/2} > 2.3\cdot10^{23}\text{ yr (90 \% C.L.)}$$

$0^+_{\text{g.s.}} - 0^+_1$ (1122.3 keV)	$>6.3 \times 10^{20}$ (68% C.L.)	Exp.	[19]	1992
	$>1.7 \times 10^{21}$ (90% C.L.)	Exp.	[20]	1995
	$>6.2 \times 10^{21}$ (90% C.L.)	Exp.	[29]	2000
	1.32×10^{21}	HFB	[22]	1994
	4.0×10^{22}	QRPA	[23]	1994
	4.5×10^{22}	QRPA	[24]	1996
	7.5×10^{21}	MCM-QRPA	[25]	1996
	$(1.0–3.1) \times 10^{23}$	RQRPA	[26]	1997
	$(1.2–5.8) \times 10^{23}$	RQRPA	[11]	2014
	6.4×10^{24}	IBM-2	[14, 15]	2014
	$(2.3–2.6) \times 10^{24}$	SM	[16]	2014

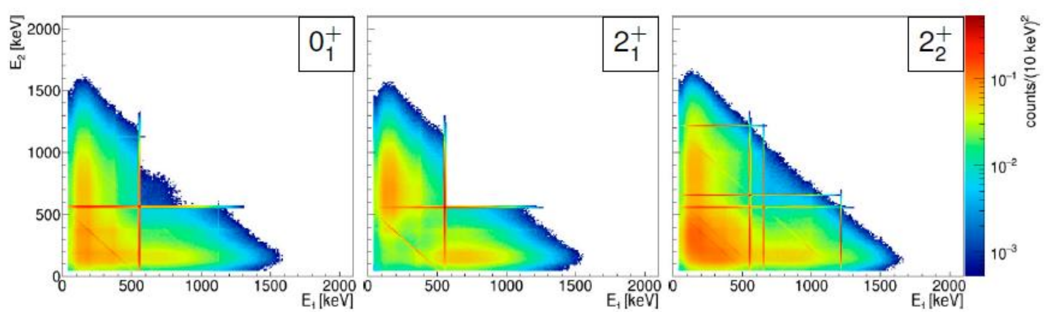
ruled out

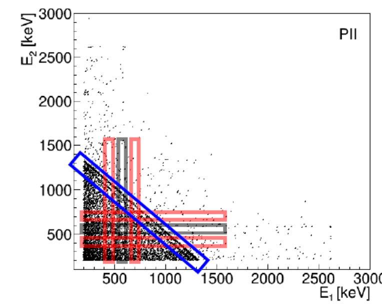
This is an improvement by more than Two orders of magnitude compared to the best previous results with ^{76}Ge.

J. Phys. G: Nucl. Part. Phys. 42 (2015)

GERDA Phase II : Estimated sensitivity for $2\nu\beta\beta$ decay of ^{76}Ge to excited states of ^{76}Se

MC simulation





Phase II data

Integrated efficiency (>200 keV):

Phase I: 6.4% (0_1^+), 3.5% (2_1^+), 6.3% (2_2^+)

Phase II: 16.9% (0_1^+), 10.0% (2_1^+), 16.2% (2_2^+)

Factor 2.5 to 3 increase due to more efficient array

decay mode	ε [%]	N_{MC}^{ROI}	$\overline{N}_{MC}^{SB}$	N^{ROI}	$\overline{N}^{SB}$	S [10^{23} yr]
Phase I						
$0^+_{g.s.} \rightarrow 0^+_1$	0.899	7.6	7.3	5	8.0	>1.8
$0^+_{g.s.} \rightarrow 2^+_1$	0.406	2.4	2.3	3	2.75	>1.2
$0^+_{g.s.} \rightarrow 2^+_2$ B1	0.591	8.3	8.3	8	6.25	>1.1
$0^+_{g.s.} \rightarrow 2^+_2$ B2	0.096	0.4	0.5	0	0.5	
Phase II						
$0^+_{g.s.} \rightarrow 0^+_1$	2.167	45.1	44.6	50	41.3	>3.6
$0^+_{g.s.} \rightarrow 2^+_1$	1.136	11.7	11.9	17	10.1	
$0^+_{g.s.} \rightarrow 2^+_1$ +LAr	1.136	-	-	4	1.4	>6.7
$0^+_{g.s.} \rightarrow 2^+_2$ B1	1.255	32.7	32.8	38	31.9	
$0^+_{g.s.} \rightarrow 2^+_2$ B2	0.288	3.0	3.1	4	4.4	>3.5
$0^+_{g.s.} \rightarrow 2^+_2$ B2 +LAr	0.288	-	-	1	1.4	

PRELIMINARY

See talk: B.Schneider and Th. Wester "Investigation of the double beta decay of 76Ge into excited states of 76Se with GERDA" (T 32.6) at DPG spring conference Aachen 26 March 2019

GERDA Phase I : Results on $\beta\beta$ decay with emission of Majorons

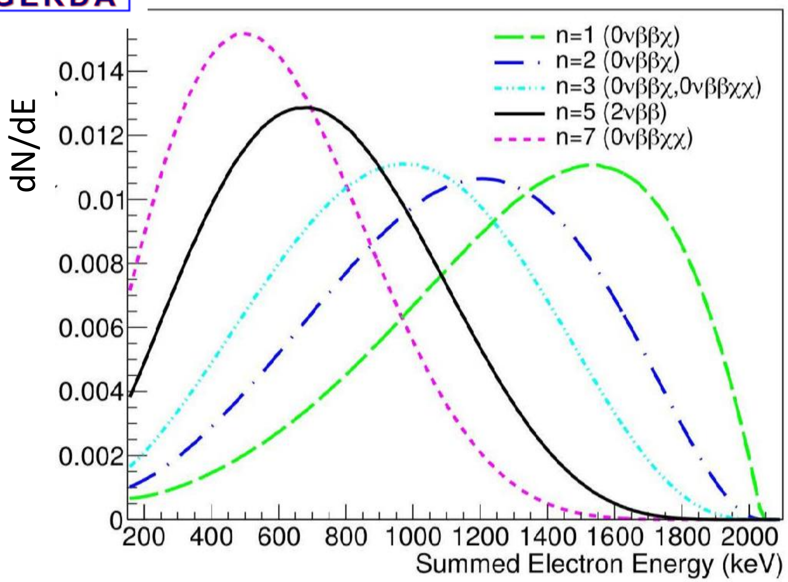


Fig.1. Spectra of the sum kinetic energy of the two electrons for spectral index n = 5 ($2\nu\beta\beta$ decay of ^{76}Ge) and n = 1, 2, 3, 7 ($0\nu\beta\beta\chi(\chi)$ decay modes of ^{76}Ge). *

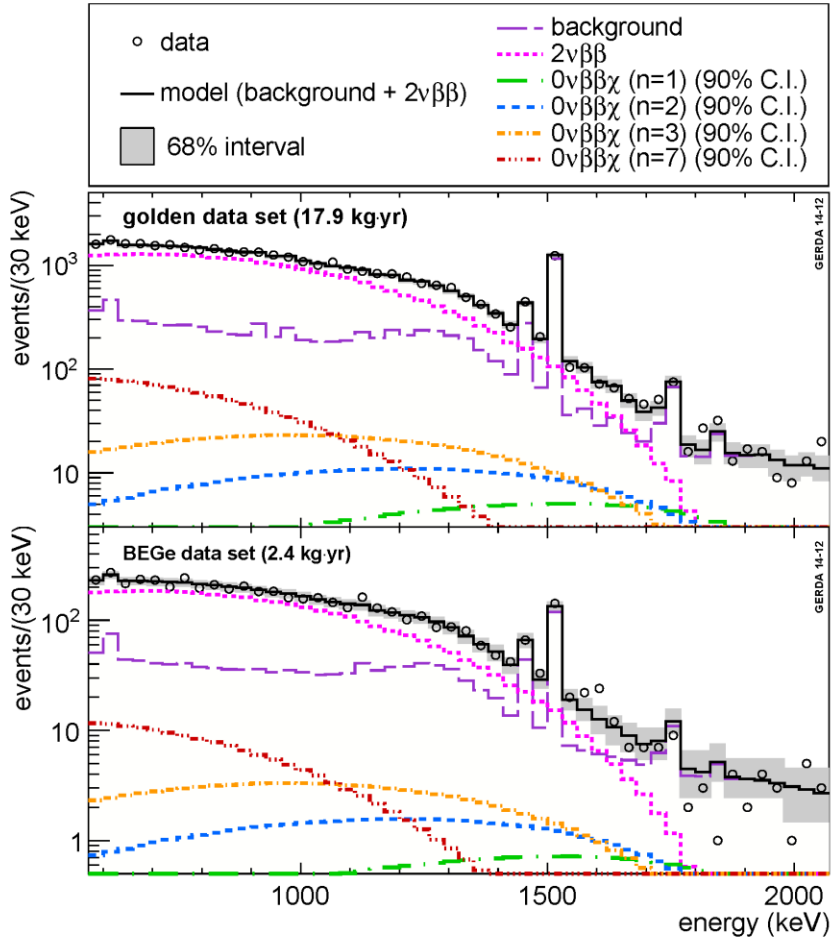


Fig. 2. Best-fit energy spectrum model for the coaxial and BEGe Phase I data sets. The interval of 68% probability for the model expectation is indicated. The contribution from $2\nu\beta\beta$ decay of ^{76}Ge are shown. The spectra corresponding to the upper limits on $T_{1/2}$ at 90% C.L. for $0\nu\beta\beta\chi$ decays of ^{76}Ge with the spectral indices n = 1, 2, 3, 7, are shown too.

* The spectra are based on the functions provided in [1, 2]. Figure adapted from [3].

*1. V.I. Tretyak, Yu.G. Zdesenko, At. Data Nucl. Data Tables **61**, 43 (1995).*

*2. V.I. Tretyak, Yu.G. Zdesenko, At. Data Nucl. Data Tables **80**, 83 (2002).*

3. S. Hemmer, Study of Lepton Number Conserving and Non-Conserving Processes using GERDA Phase I data, PhD thesis, Universit`a degli Studi di Padova (2014).

Eur. Phys. J. C (2015) **75**:416,
Eur. Phys. J. Plus (2015) **130**: 139

GERDA Phase I : Results on $\beta\beta$ decay with emission of Majorons

Model	n	Mode	Goldstone boson	L	$T_{1/2}^{0\nu\chi}$ (10^{23} yr)	$\mathcal{M}^{0\nu\chi(\chi)}$	$G^{0\nu\chi(\chi)}$ (yr^{-1})	$\langle g \rangle$
IB	1	χ	No	0	>4.2	(2.30–5.82)	5.86×10^{-17}	$<(3.4–8.7) \times 10^{-5}$
IC	1	χ	Yes	0	>4.2	(2.30–5.82)	5.86×10^{-17}	$<(3.4–8.7) \times 10^{-5}$
ID	3	$\chi\chi$	No	0	>0.8	$10^{-3\pm1}$	6.32×10^{-19}	$<2.1^{+4.5}_{-1.4}$
IE	3	$\chi\chi$	Yes	0	>0.8	$10^{-3\pm1}$	6.32×10^{-19}	$<2.1^{+4.5}_{-1.4}$
IF	2	χ	Bulk field	0	>1.8	–	–	–
IIB	1	χ	No	−2	>4.2	(2.30–5.82)	5.86×10^{-17}	$<(3.4–8.7) \times 10^{-5}$
IIC	3	χ	Yes	−2	>0.8	0.16	2.07×10^{-19}	$<4.7 \times 10^{-2}$
IID	3	$\chi\chi$	No	−1	>0.8	$10^{-3\pm1}$	6.32×10^{-19}	$<2.1^{+4.5}_{-1.4}$
IIE	7	$\chi\chi$	Yes	−1	>0.3	$10^{-3\pm1}$	1.21×10^{-18}	$<2.2^{+4.9}_{-1.4}$
IIF	3	χ	Gauge boson	−2	>0.8	0.16	2.07×10^{-19}	$<4.7 \times 10^{-2}$

Eur. Phys. J. C (2015) **75**:416,
Eur. Phys. J. Plus (2015) **130**: 139

GERDA Phase II: Estimated sensitivities for *ββ* decay with emission of Majorons & Lorentz violating double beta decay

Data after the Liquid Argon (LAr) cut in the region of two-neutrino double-beta decay are almost background-free

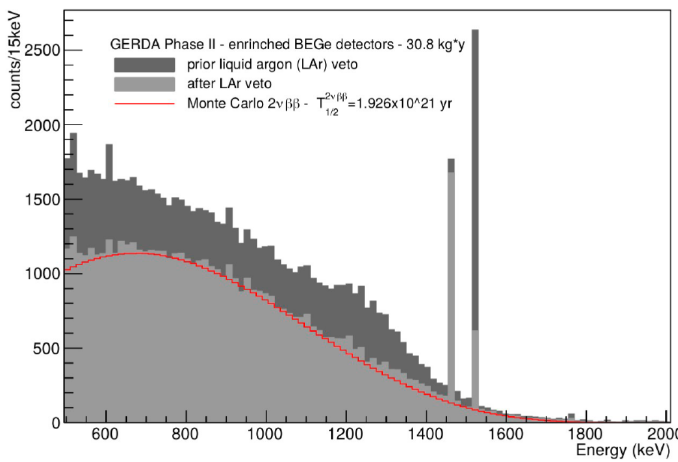
-> to look for distortion of the spectral shape due to exotic physics

Only BEGe dataset, exposure 30.8 kg*yr, LAr cut, not yet Pulse Shape Discrim

Before LAr cut

Large uncertainties due to background modelling (source position)

Uncertainties related to detector physics are subdominant



After LAr cut

The expected residual background is very low (signal-to-background ratio ~11:1 in 500-2000keV)

-> small uncertainties due to background modelling

other source of uncertainties ->

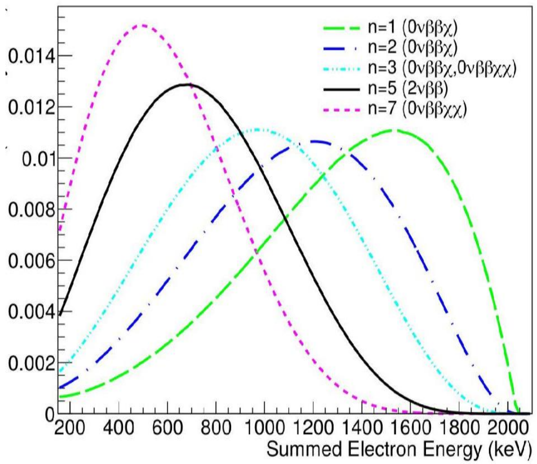
Need to model the LAr efficiency

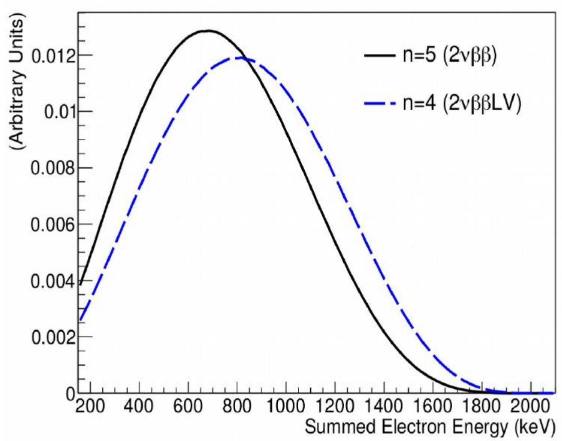
Detector physics: surface effect

Ongoing studies

E. Bossio, "Probing new physics with double-beta decay in GERDA Phase II",
Talk at DPG Spring Meeting – Matter and Cosmos Section (SMuK), Munich, 17-22 March 2019

GERDA Phase II: *ββ* **decay with emission of Majorons & Lorentz violating double beta decay**





Lorentz violating double beta decay

Standard Model Extension (SME)

"Countershaded effects" → four independent components of the coefficient $\left(a_{of}^{(3)}\right)^{\alpha}$

Distortion of shape of the conventional two electron sum spectrum due to the $\mathring{a}_{of}^{(3)}$

Jorge S. Diaz, Phys.Rev. D89 (2014) 036002

$$d\Gamma/dE = C\left(E^5+10E^4+40E^3+60E^2+30E\right) \times\left[\left(Q_{\beta\beta}-E\right)^5+10\,\mathring{a}_{of}^{(3)}\left(Q_{\beta\beta}-E\right)^4\right]$$

The total decay rate can be expressed as a sum of two rates through a perturbation

$\Gamma=\Gamma_0+\delta\,\Gamma_{LV}$

Model	$T_{1/2}$
n=1, 0νββχ	$1\cdot10^{24}$
n=2, 0νββχ	$4\cdot10^{23}$
n=3, 0νββχ,0νββχχ	$2\cdot10^{23}$
n=7, 0νββχχ	$0.7\cdot10^{23}$
2νββLV	$0.7\cdot10^{23}$

PRELIMINARY

E. Bossio, "**Probing new physics with double-beta decay in GERDA Phase II**",
Talk at DPG Spring Meeting – Matter and Cosmos Section (SMuK), Munich, 17-22 March 2019

Instead of Conclusion - Future perspectives

Predecessors, GERDA phases, progeny and next generation in search for 0vββ of ^{76} Ge