Search for the neutrinoless double-β decay

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TECHNISCHE UNIVERSITÄT MÜNCHEN

SFB 1258 | Neutrinos Dark Matter Messengers

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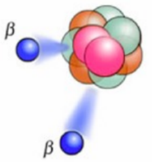
Double-β decays

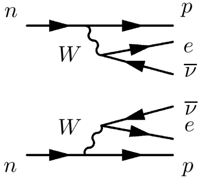
Second order nuclear transitions $\rightarrow$ decay of two neutrons into two protons:

$$(A, Z) \rightarrow (A, Z+2) + 2e^- + \ldots$$



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 (^{48}Ca, ^{76}Ge, ^{82}Se...)
- $T_{1/2}^{2\nu}$ in the range $10^{19} - 10^{24}$ yr



Double-β decays

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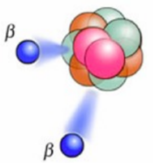
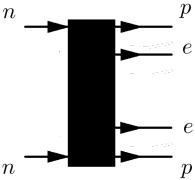


<u>Neutrinoless double-β decay ($0\nu\beta\beta$):</u>

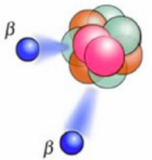
- $(A, Z) \rightarrow (A, Z+2) + 2e^-$
- foreseen by many extensions of the Standard Model
- possible for several isotopes (^{48}Ca, ^{76}Ge, ^{82}Se...)
- $T_{1/2}^{0\nu}$ limits in the range $10^{21} - 10^{26}$ yr



Double-β decays

Second order nuclear transitions → decay of two neutrons into two protons:

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + \dots$$



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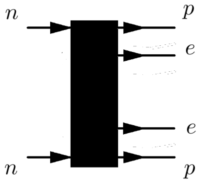


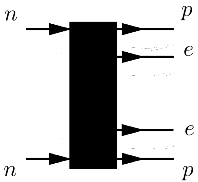
< 50% chance for an atom to decay

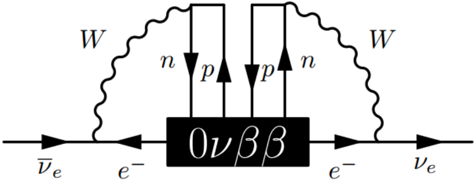
in a hundred trillion times the age of the universe

Why to look for neutrinoless double-β decay?

Independently from underlying physics:

- matter-creating process measurable in lab
  $\Rightarrow$ lepton-number is not conserved ($\Delta L = 2$)
- neutrinos are Majorana particles
  $\Rightarrow$ see-saw models to explain ν mass scale





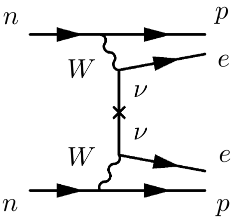
"Black Box" theorem (Schechter, Valle, PR D25 (1982) 2951):

- non-null Majorana mass component
- bulk of neutrino mass not given by black-box operator (Duerr et al., JHEP 1106 091,2011)

Why to look for neutrinoless double-β decay?

Exchange of light-Majorana ν

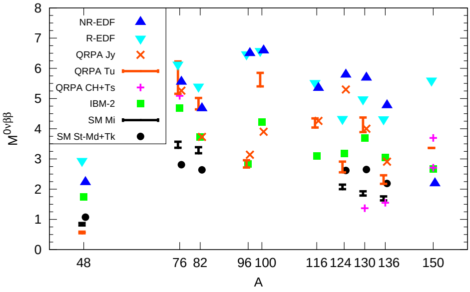
- possible in a minimal extension of the SM (massive + majorana ν)
- dominant channel for most of the models



Assuming the exchange of light ν:

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu} \cdot |\mathcal{M}_{0\nu}(A,Z)|^2 \cdot |m_{\beta\beta}|^2$$

- $G_{0\nu}$ phase space factor
- $\mathcal{M}_{0\nu}$ nuclear matrix element
- $|m_{\beta\beta}|$ effective Majorana mass
- additional uncertainty from quenching of axial vector coupling (g_a)



[Engel, Menendez, 1610.06548]

Neutrino phenomenology

9 parameters:

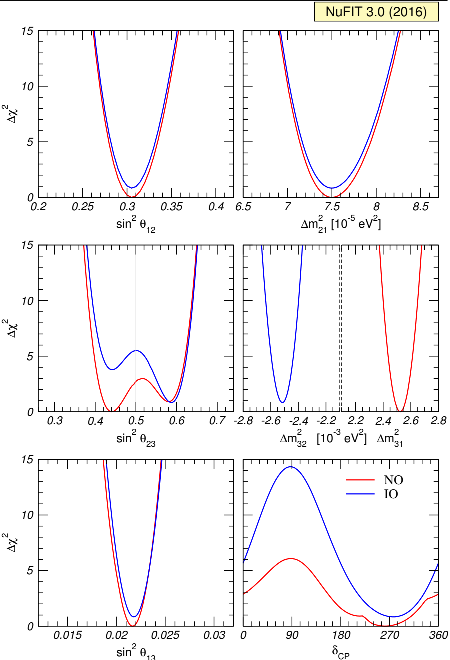
- 3 mixing angle: $\theta_{12}, \theta_{13}, \theta_{23}$
- 3 mass eigenstates: m_1, m_2, m_3
- 1+2 phases: $\delta, \alpha_1, \alpha_2$

Oscillations observables:

- 3 mixing angle: $\theta_{12}, \theta_{13}, \theta_{23}$
- Δm^2_{12} and Δm^2_{13}
- δ CP-violating phase

Open questions:

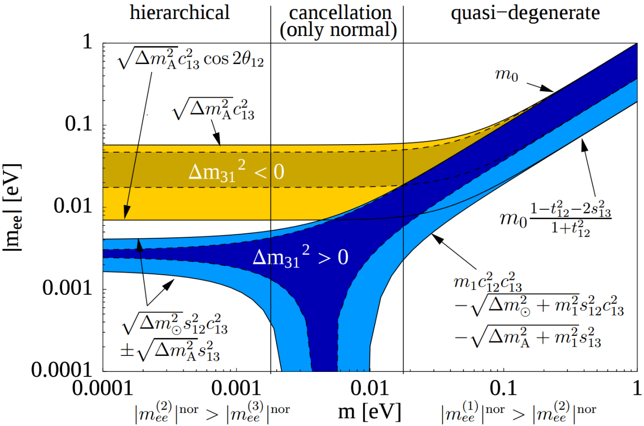
- ordering: is $m_1 < m_2 < m_3$ or $m_3 < m_1 < m_2$?
- mass scale: what is the mass of the lightest eigenstate m_{lightes}?
- nature: dirac or Majorana?
- additional sterile mass states?



ν oscillations and neutrinoless double-β decay

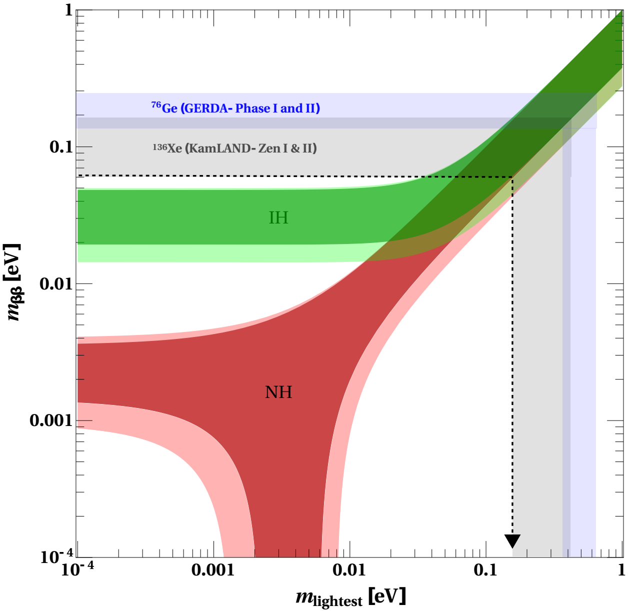
Effective majorana mass:

$$|m_{\beta\beta}| = \left|\cos^2\theta_{12}\,\cos^2\theta_{13}\,m_1 + \sin^2\theta_{12}\,\cos^2\theta_{13}\,m_2\,e^{i2\alpha_1} + \sin^2\theta_{13}\,m_3\,e^{i2\alpha_2}\right|$$



[Phys. Rev. D 73, 053005]

Current constrains



Most stringent limits (SM-EDF):

$T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 8.0 \cdot 10^{25}$ yr

$\Rightarrow |m_{\beta\beta}| < (147 - 279)$ meV

$T^{0\nu}_{1/2}(^{136}\mathrm{Xe}) > 10.7 \cdot 10^{25}\ yr$

$\Rightarrow |m_{\beta\beta}| < (77 - 183)$ meV

$\Rightarrow |m_{\mathrm{light}}| < (180 - 480)$ meV

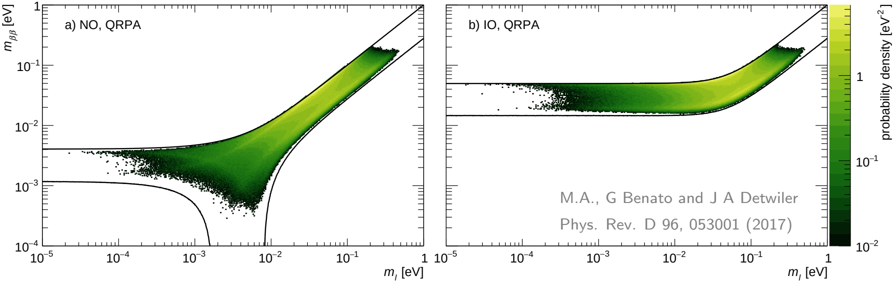
Next generation experiments:

$|m_{\beta\beta}|$ down to $\mathcal{O}(10)$ meV

[Adapted from Dell'Oro et al, Adv.High Energy Phys. 2016 (2016)]

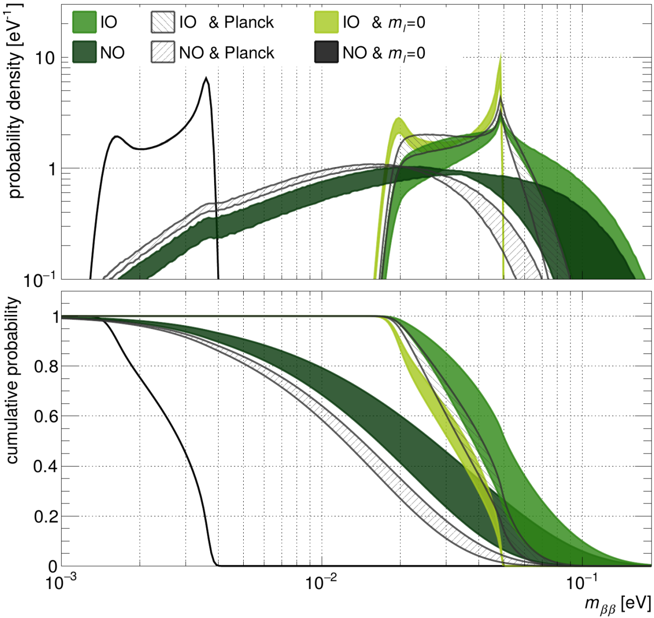
Discovery probability

In the absence of neutrino mass mechanisms or flavour symmetries that fix the value of the Majorana phases and drive $m_{\beta\beta}$ or $m_{lightest}$ to zero, the probability distribution for $m_{\beta\beta}$ is pushed to large values:



- flat prior for the Majorana phases
- small $m_{\beta\beta}$ values require a fine tuning of the parameters
- discovery probability for the next experiments even assuming NO
- see also arXiv:1705.01945 (Caldwell, Merle, Schulz, Totzauer) and arXiv:1707.07904 (Ge, Rodejohann, Zuber)

Discovery probability



- data in the analysis: osc, $0\nu\beta\beta$, m_β, (cosmology)
- bands shows deformation due to NME uncertainty
- $0\nu\beta\beta$ constraints on $m_{lightest}$ competitive with cosmology
- what if there are flavour symmetries?

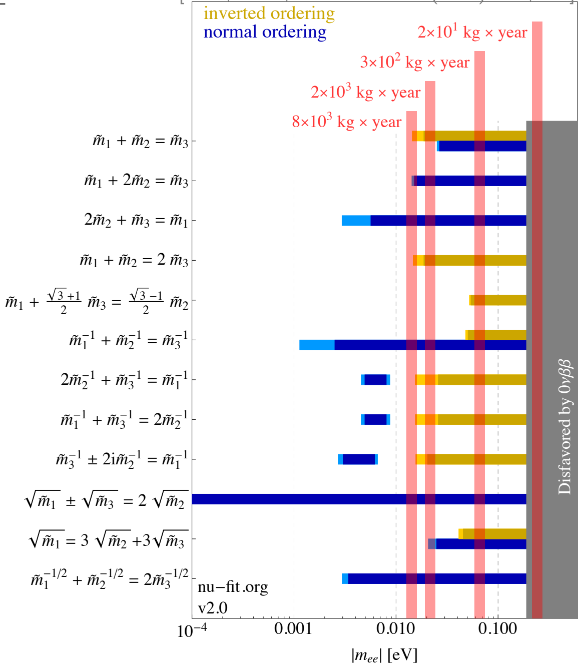
Discovery probability

Some flavor models predict correlations between observables (neutrino mass sum rules) that decrease the range allowed for $m_{\beta\beta}$

Such models will be probed with early stages of next-generation experiments

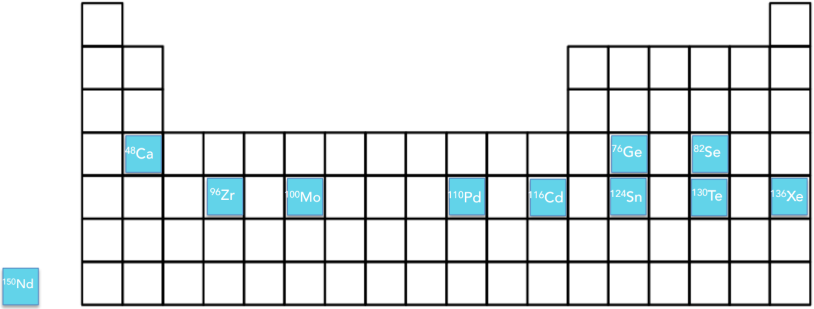
High discovery probability for some scenarios: a discovery could be around the corner!

[King, Merle, Stuart, JHEP 1312, 005 (2013)]
[M.A., Merle, Zuber EPJ C76 (2016) no.4, 176]



Double-β decaying isotopes

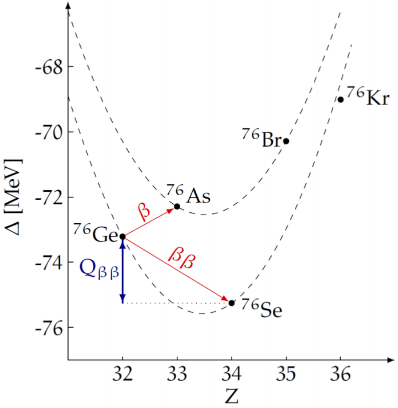
35 isotopes available, ~ 9 used for $0\nu\beta\beta$ searches:



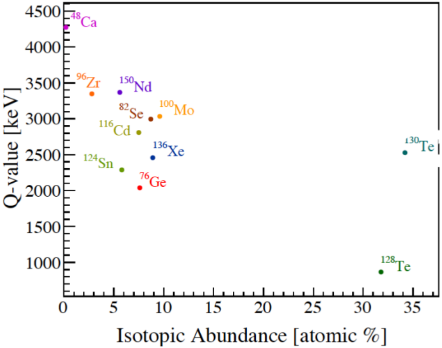
[from K. Schäffner]

Double-β decaying isotopes

Single β-decay must be energetically forbidden:



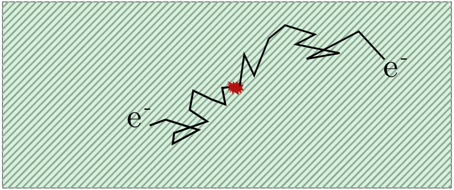
[From G Benato]



- $(T^{0\nu}_{1/2})^{-1} \propto G_{0\nu}(Q_{\beta\beta}, Z) \propto (Q_{\beta\beta})^5$
- isotopic enrichment
- different detection techniques for different isotopes

Detection approaches

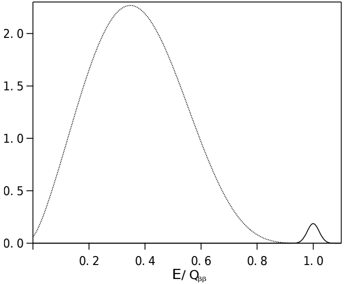
source=detector
high efficiency & good resolution



Most of the experiments have also other handles, however energy is the one observable that is both **necessary and sufficient for discovery.**

Measuring of the electron energy sum:

- $(A, Z) \to (A, Z+2) + 2e^- + 2\nu$
  $\Rightarrow$ continuum energy distribution
- $(A, Z) \to (A, Z+2) + 2e^-$
  $\Rightarrow$ energy $= Q_{\beta\beta}$

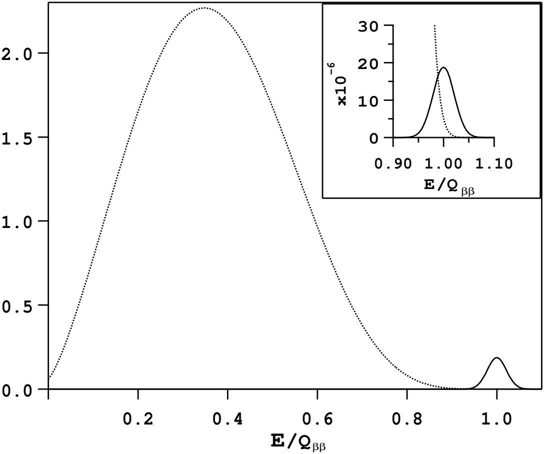


[S. Elliot et al., Ann.Rev.Nucl.Part.Sci. 52 (2002)]

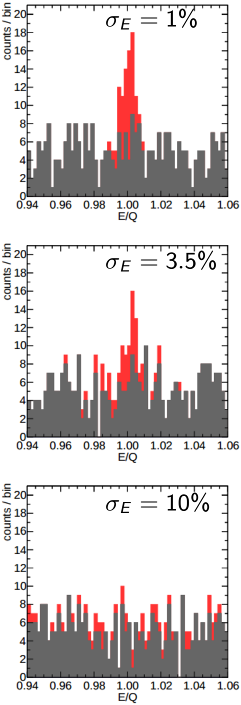
Energy resolution and background

Good energy resolution needed

$\rightarrow$ mitigation of $2\nu\beta\beta$ and other backgrounds



[Ann.Rev.Nucl.Part.Sci. 52 (2002)]



[J. J. Gòmez-Cadenas et al., PoS (GSSI2014), 004 (2015)]

Experimental sensitivity for signal discovery

ROI background free:

$$T_{1/2}^{0\nu} > \ln 2 \cdot \varepsilon \cdot (mass \cdot time)$$

$$mass \cdot time = exposure$$

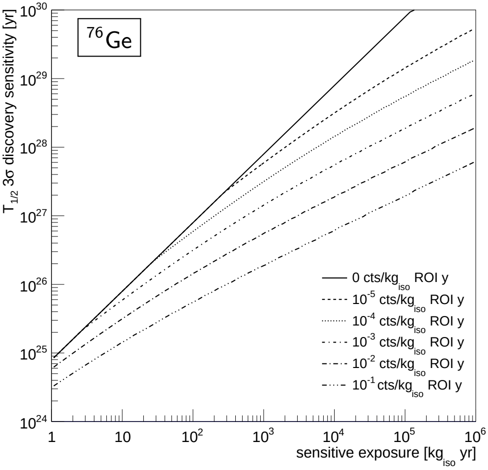
ROI background limited:

$$T_{1/2}^{0\nu} > \ln 2 \cdot \varepsilon \cdot \sqrt{\frac{mass \cdot time}{\Delta E \cdot \mathrm{BI}}}$$

ΔE energy resolution

BI: background level at $Q_{\beta\beta}$

[M.A., G Benato and J A Detwiler, Phys. Rev. D 96, 053001 (2017)]



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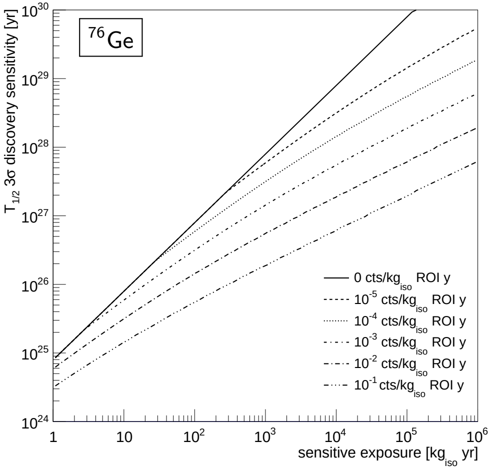


important parameters:	mass	energy resolution	background at $Q_{\beta\beta}$
current experiments:	10-1000 kg	0.1-10%	10^{-3}-10^{-2} cts/(keV· kg· yr)

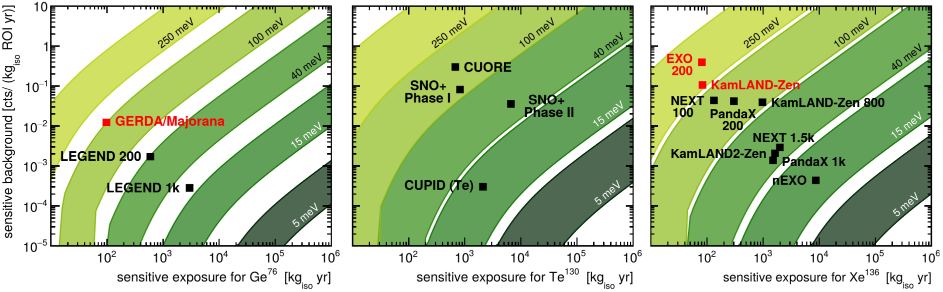
Experimental approaches

Isotope	past generation	future generation	type
^{76}Ge	GERDA / MAJORANA	LEGEND	semiconductor detectors
^{82}Se	NEMO-3	SuperNEMO	tracking calorimeters
^{130}Te	CUORE	CUPID	bolometers/scintillators (diff isot considerd for CUPID)
^{130}Te		SNO+	liquid scintillator
^{136}Xe	KamLAND-Zen	KamLAND2-Zen	liquid scintillator
^{136}Xe	EXO-200	nEXO	liquid TPC
^{136}Xe		NEXT/PANDA-X III	gas TPC

- Many other project in the R&D phase
- see dedicated talks on nEXO, CUORE, COBRA, MAJORANA...

Discovery potential (5 yr data taking)

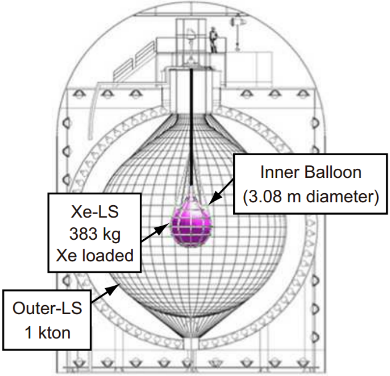
- 3σ discovery sensitivity as a function of the background and exposure (normalized over the efficiencies and ROI)
- bands are contours in $m_{\beta\beta}$ covering NME uncertainties
- most projects adopt a staged approach
- various project reaching 18 meV (min of $m_{\beta\beta}$ for IO)



[M.A., G Benato and J A Detwiler, Phys. Rev. D 96, 053001 (2017)]

KamLAND-Zen Phase II @ Kamioka (Japan)

Isotope:	^{136}Xe ($Q_{\beta\beta}$=2458 keV)
Resolution:	240-270 keV FWHM
Mass:	350 kg
Technology:	Xe-loaded liquid scintillator
Status:	completed/upgrading

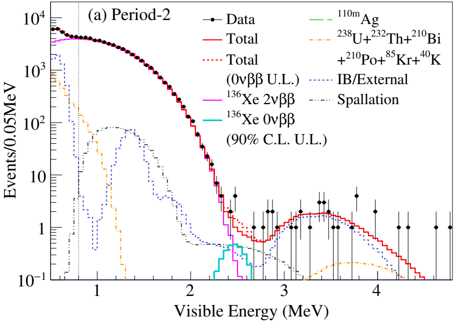


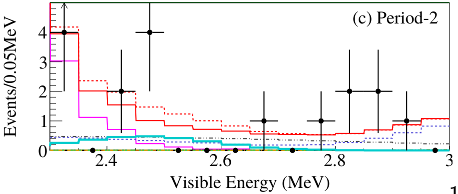
[Phys.Rev.Lett. 117 (2016) no.10, 109903]

Latest result with 504 kg·yr + old data:

$T^{0\nu}_{1/2} > 10.7 \cdot 10^{25}$ yr (90% C.L.)

$T^{0\nu}_{1/2} > 5.6 \cdot 10^{25}$ yr (sensitivity)

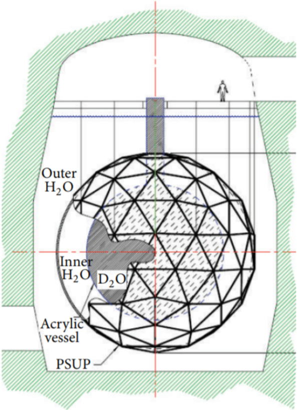


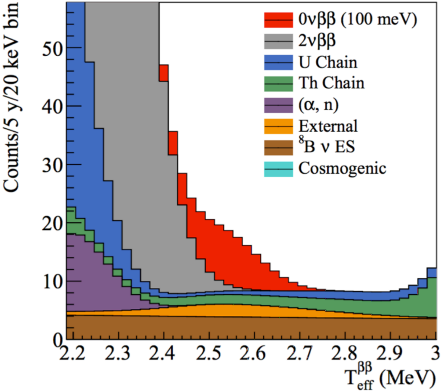


SNO+ @ SNOLAB (Canada)

Isototope:	^{130}Te ($Q_{\beta\beta}$=2527 kev)
Resolution:	130-190 keV FWHM
Mass:	3.9 ton of Te
Technology:	Te-loaded liquid scintillator
Status:	commissioning

- 780 t LAB(+PPO+Te-ButaneDiol)
- 0.5% loading → 1300 kg ^{130}Te
- currently filled with water
- Filling with unloaded liquid scintillator later this year





SuperNEMO

Isototope:	^{82}Se ($Q_{\beta\beta}$=2995 kev)
Resolution:	~120 keV FWHM
Mass:	100 kg
Technology:	particle charge identification + track
Status:	demonstrator module in construction

Results from NEMO-3 (90% C.L.):

$T_{1/2}^{0\nu}(^{150}\mathrm{Nd}) > 2.0 \cdot 10^{22}$ yr

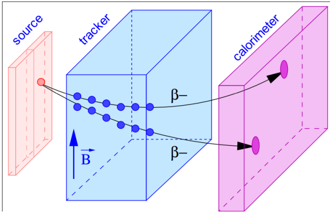
$T_{1/2}^{0\nu}(^{116}\mathrm{Cd}) > 2.5 \cdot 10^{23}$ yr

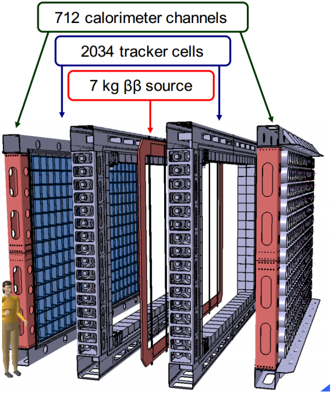
$T_{1/2}^{0\nu}(^{110}\mathrm{Mo}) > 1.1 \cdot 10^{24}$ yr

$T_{1/2}^{0\nu}(^{82}\mathrm{Se}) > 2.5 \cdot 10^{23}$ yr

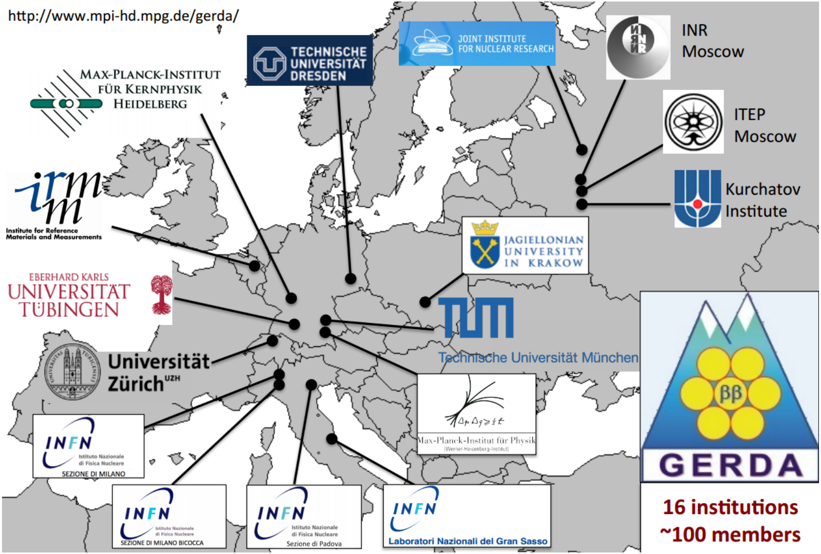
$T_{1/2}^{0\nu 4\beta}(^{150}\mathrm{Nd}) > [1.0, 3.2] \cdot 10^{21}$ yr

[PRD 94 (2016) 072003,
PRD 95 (2017) 012007,
PRD 92, 072011 (2015)]





GERDA collaboration



ARTICLE

doi:10.1038/nature21717

Background-free search for neutrinoless double-β decay of ^{76}Ge with GERDA

The GERDA Collaboration*

Many extensions of the Standard Model of particle physics explain the dominance of matter over antimatter in our Universe by neutrinos being their own antiparticles. This would imply the existence of neutrinoless double-β decay, which is an extremely rare lepton-number-violating radioactive decay process whose detection requires the utmost background suppression. Among the programmes that aim to detect this decay, the GERDA Collaboration is searching for neutrinoless double-β decay of ^{76}Ge by operating bare detectors, made of germanium with an enriched ^{76}Ge fraction, in liquid argon. After having completed Phase I of data taking, we have recently launched Phase II. Here we report that in GERDA Phase II we have achieved a background level of approximately 10^{-3} counts keV^{-1} kg^{-1} yr^{-1}. This implies that the experiment is background-free, even when increasing the exposure up to design level. This is achieved by use of an active veto system, superior germanium detector energy resolution and improved background recognition of our new detectors. No signal of neutrinoless double-β decay was found when Phase I and Phase II data were combined, and we deduce a lower-limit half-life of 5.3×10^{25} years at the 90 per cent confidence level. Our half-life sensitivity of 4.0×10^{25} years is competitive with the best experiments that use a substantially larger isotope mass. The potential of an essentially background-free search for neutrinoless double-β decay will facilitate a larger germanium experiment with sensitivity levels that will bring us closer to clarifying whether neutrinos are their own antiparticles.

[Nature 544 (2017) 47]

Sensitivity and prospects

Phase I:

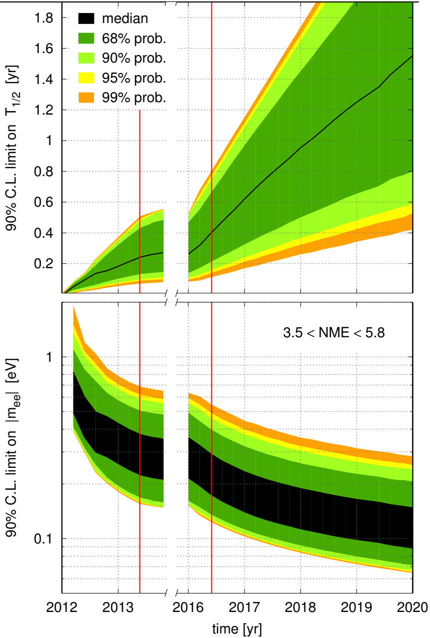
- background $\sim 10^{-2}$ cts/(keV$\cdot$ kg$\cdot$ yr)
- exposure 21.6 kg·yr
- result $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr (90% CL)
  [PRL 111, 122503 (2013)]

Upgrade & commissioning (2013 ->2015):

- doubled target mass
- reduced background by factor $\sim$10

Phase II:

- background $\lesssim 10^{-3}$ cts/(keV$\cdot$ kg$\cdot$ yr)
- exposure $\gtrsim$ 100 kg·yr
- first result $T_{1/2}^{0\nu} > 5.3 \cdot 10^{25}$ yr (90% CL)
  [Nature 544 (2017) 47]



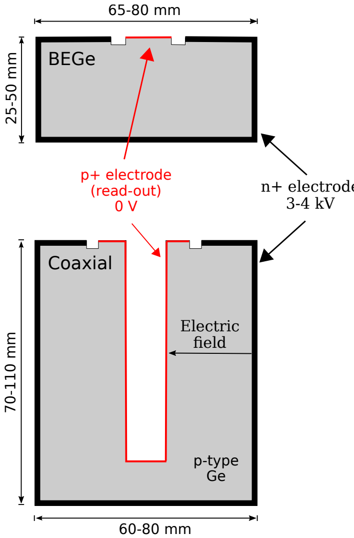
The detectors of GERDA

- Search for neutrinoless double beta decay of ^{76}Ge:

$$^{76}\text{Ge} \longrightarrow {}^{76}\text{Se} + 2e^-$$

- Q-value of ^{76}Ge: $Q_{\beta\beta}$=2039 keV

- High purity Ge detectors (87% ^{76}Ge):
  - source=detector ⇒ high detection efficiency
  - ultra radio-pure ⇒ no intrinsic background
  - high density ⇒ $0\nu\beta\beta$ point like events
  - semiconductor ⇒ $\Delta E \approx 0.2\%$ at $Q_{\beta\beta}$
  - pulse shape ⇒ signal/bkg discrimination



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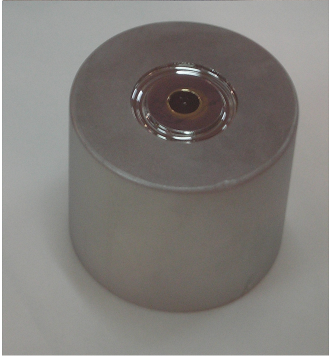
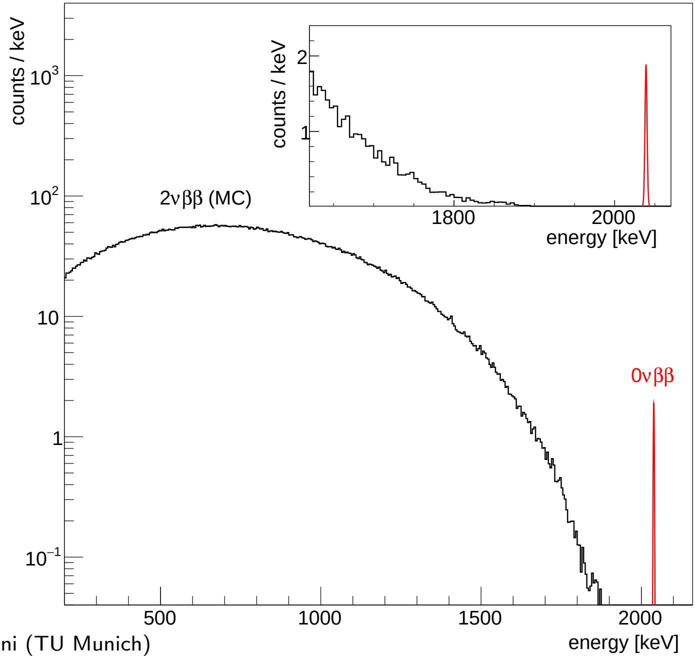
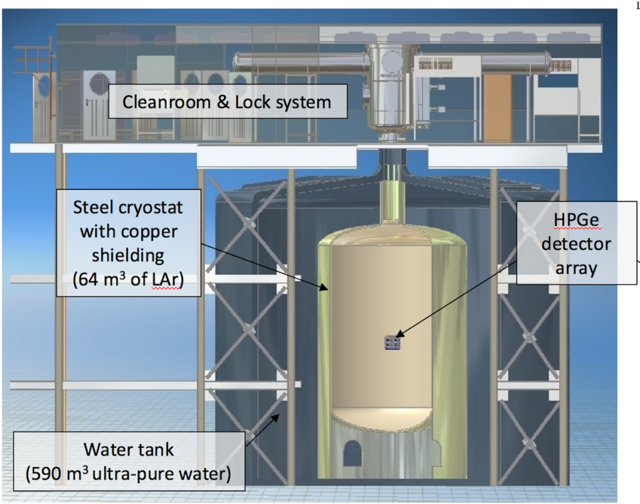
  - semiconductor ⇒ $\Delta E \approx 0.2\%$ at $Q_{\beta\beta}$
  - pulse shape ⇒ signal/bkg discrimination

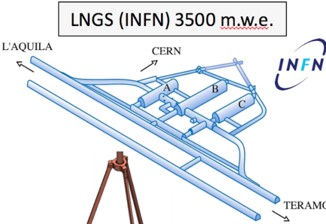


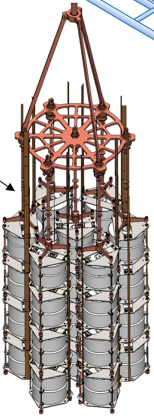
The double-β decay signal in GERDA



Shielding strategy and apparatus



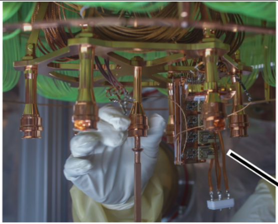


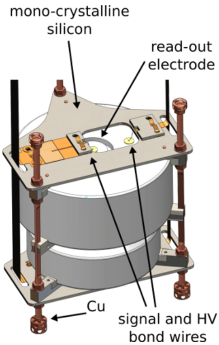


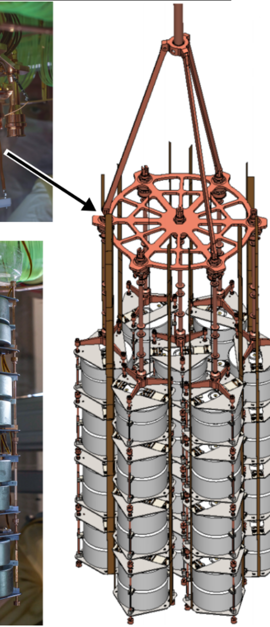
[EPJC 73 (2013) 2330]

Phase II upgrade: detector array

- 30 custom-designed BEGe-type detectors (20 kg)
- low mass holders and contacting solution (wire bonding)
- low-mass low-activity electronics and detector-to-FE contacts







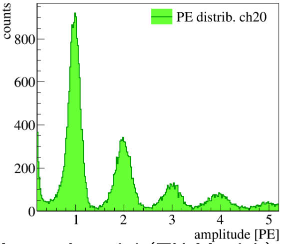
Phase II upgrade: LAr scintillation light veto

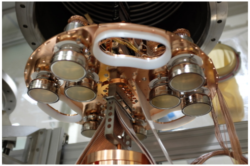
Hybrid veto instrumentation:

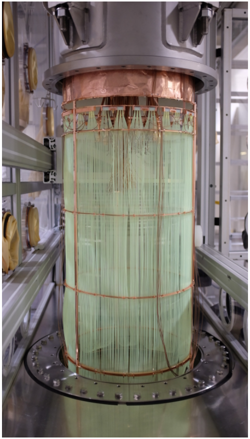
- 16 PMTs (9 top / 7 btm)
- 800 m fibers coated with WLS + 90 SiPMs
- nylon mini-shroud around each string coated with WLS

Parameters optimized for each channel:

- ~0.5 PE threshold
- $\sim 5-6\,\mu$s anti-coincidence window





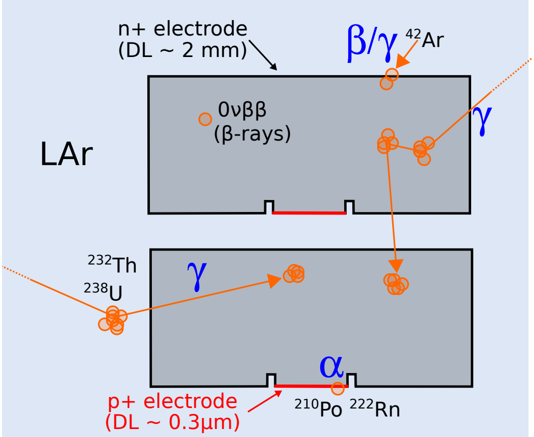


Background

- natural radioactivity: γ-rays from ^{208}Tl, ^{214}Bi + α-rays from ^{210}Po or ^{222}Rn
- long-lived cosmogenic Ar isotopes (^{39}Ar,^{42}Ar)
- cosmogenic isotopes activated in Ge (^{68}Ge, ^{60}Co)

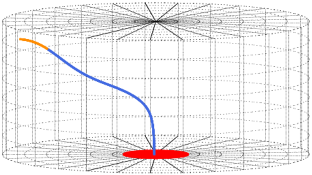
Mitigation strategy:

- time-coincidence
- detector-detector anti-coincidence
- detector-LAr anti-coincidence
- pulse shape discrimination

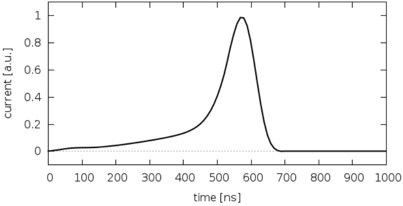


Pulse shape discrimination (BEGe)

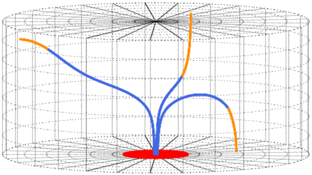
$0\nu\beta\beta$-like event (SSE):



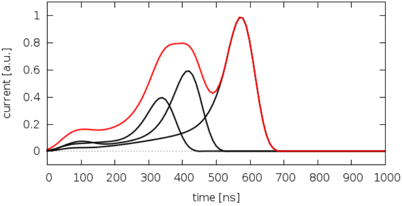
M. Agostini et al.
JINST 6 (2011) P03005



γ-ray event (MSE):

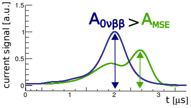


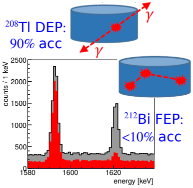
M. Agostini et al.
JINST 6 (2011) P03005

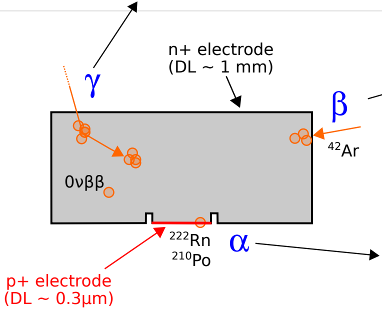


Pulse shape discrimination (BEGe)

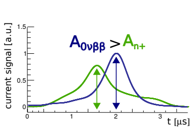
γ interactions:
- multiple Compton scattering (MSE)
- sequence of peaks in current signal
- Double escpape peak (DEP): proxy for 0νββ events



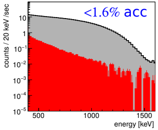




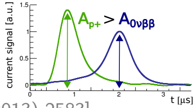
events on n+ surface:
- semiconductor junction -> weak E field
- slow current signal



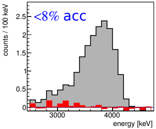
β-rays from ^{90}Sr:



events on p+ electrode:
- electron drift faster then holes
- faster charge signal



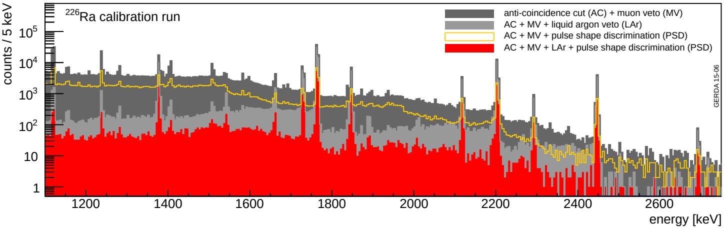
α-rays from ^{241}Am

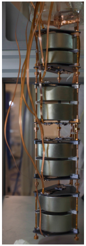


[JINST 6 2011 P03005, JINST 4 2009 P10007, EPJC 73 (2013) 2583]

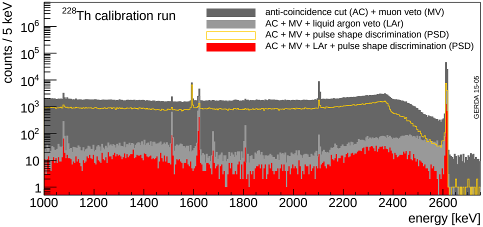
PSD and LAr veto during Phase II commissioning

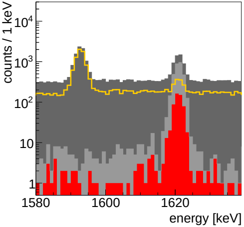
^{226}Ra calibration run (single BEGe string in GERDA):

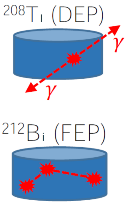




^{228}Th calibration run:







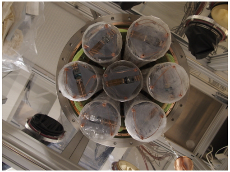
Combined suppression factors: 27±2 (for ^{226}Ra) and 300±28 (for ^{228}Th)

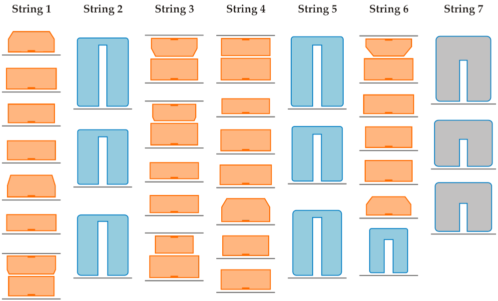
Suppression depends on isotope, location and detector configuration

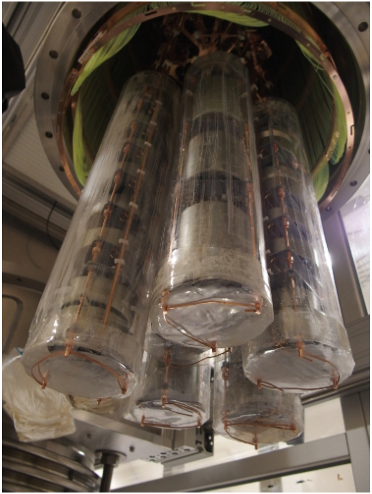
Phase II array configuration

- Deployed in Dec 2015
- 30 enriched BEGe (20 kg)
- 7 enriched Coax (15 kg)
- 3 natural Coax (8 kg)

⇒ 36 kg of enr detectors





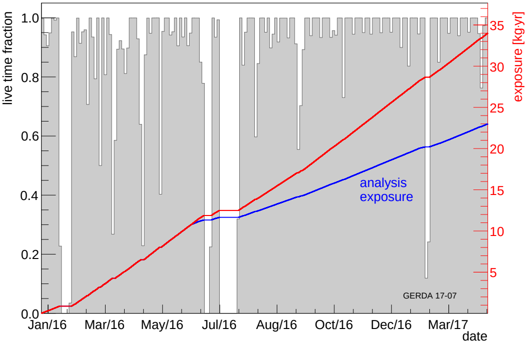


Phase II data taking

- ongoing since Dec 2015
- blinding window $Q_{\beta\beta} \pm 25\,\mathrm{keV}$
- exposure accumulated till Apr 17:

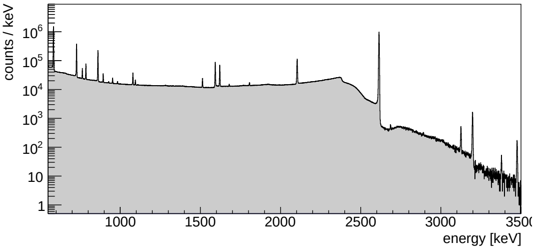
  18.2 kg·yr for enriched BEGe

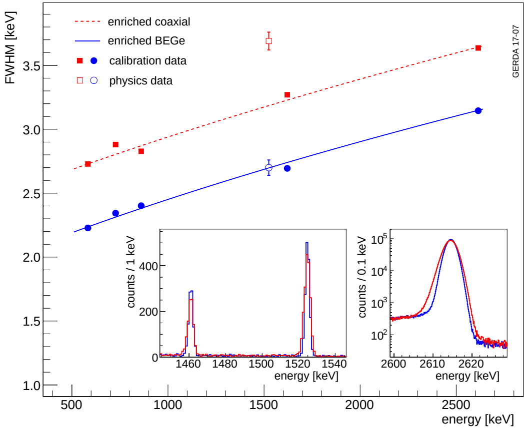
  16.2 kg·yr for enriched coax
- analysis finalized for 23.3 kg·yr



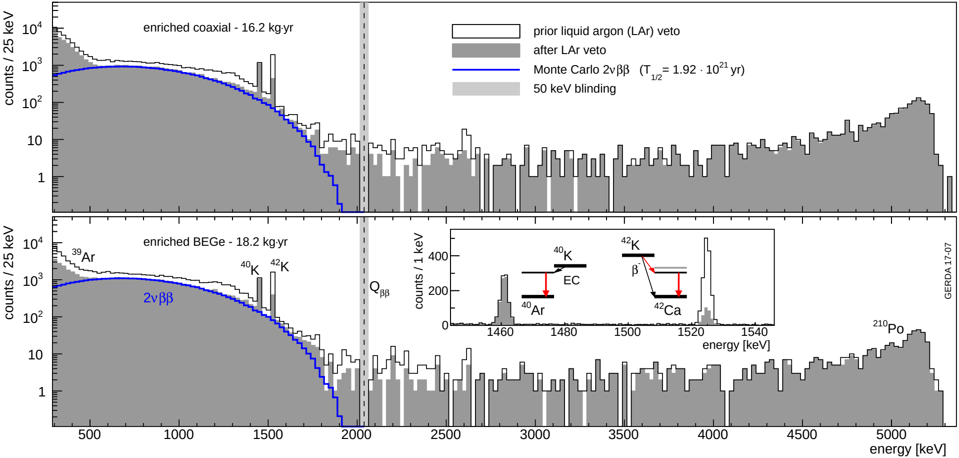
Energy scale

- weekly calibration runs with ^{228}Th
- energy scale monitored with pulser
- $\lesssim$1 keV changes between successive calibrations
- energy reconstructed with "zero area cusp" filter [EPJC 75 (2015) 255]
- data removed from $0\nu\beta\beta$ analysis if energy scale uncertain





LAr veto background suppression



- ^{40}K/^{42}K Compton continuum fully suppressed
- LAr veto generates 2.3% dead time
- $T^{2\nu}_{1/2} = 1.9 \cdot 10^{21}$ yr taken from Phase I [EPJC 75 (2015) 416]

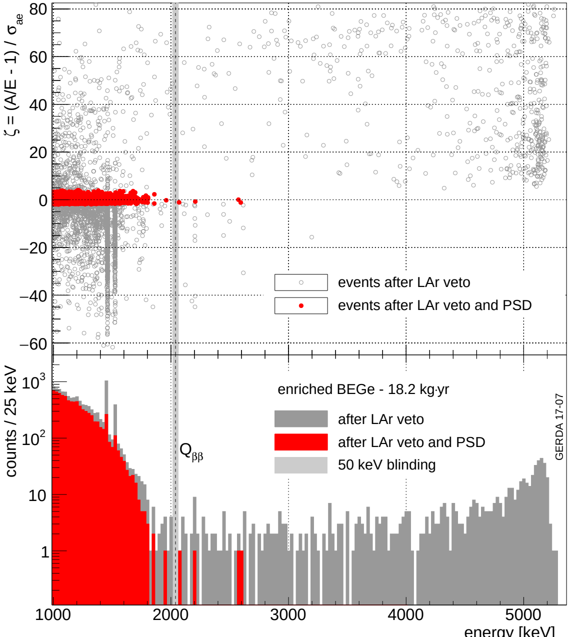
PSD for BEGe detectors

All events at high energy are efficiently classified as alpha and rejected

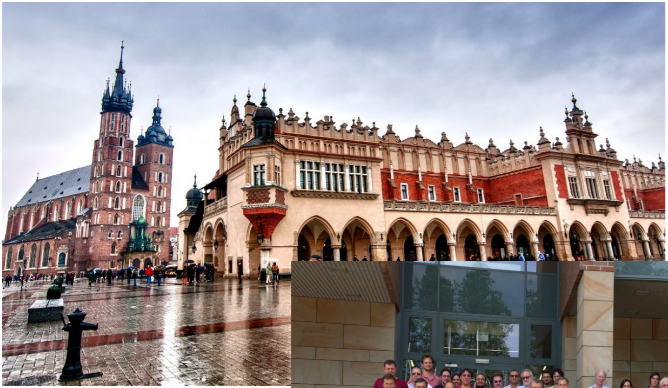
$0\nu\beta\beta$ acceptance from ^{228}Th calibrations (DEP):

$$\epsilon^{PSD}_{BEGe} = (87 \pm 3)\%$$

Cross check at lower energy with $2\nu\beta\beta$ LAr cut (1-1.3 MeV) gives consistent results



Unblinding in Cracow (30th of June 2016)



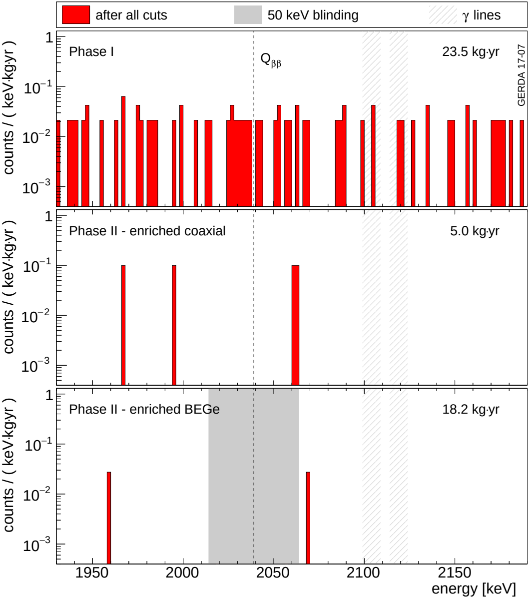
$0\nu\beta\beta$ decay analysis

Combined analysis of:

- 23.5 kg·yr Phase I
- 5.0 kg·yr Phase II coax
- 5.8+12.4 (new) kg·yr Phase II BEGe

Phase II BEGe data set:

- 2 conts before unblinding



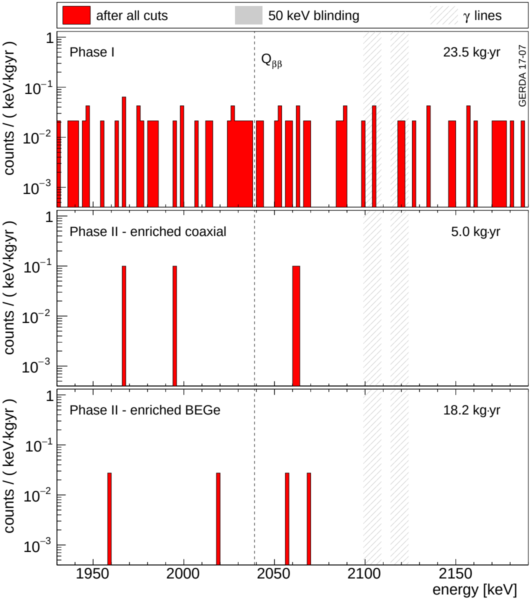
$0\nu\beta\beta$ decay analysis

Combined analysis of:

- 23.5 kg·yr Phase I
- 5.0 kg·yr Phase II coax
- 5.8+12.4 (new) kg·yr Phase II BEGe

Phase II BEGe data set:

- 4 conts after unblinding
- BI= $1.0^{+0.6}_{-0.4} \cdot 10^{3}$cts/(keV· kg· yr)
- no signal at $Q_{\beta\beta}$



$0\nu\beta\beta$ decay analysis

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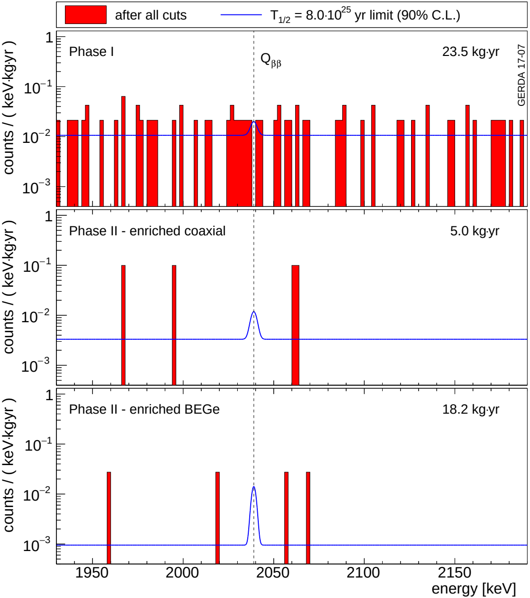
- 4 conts after unblinding
- BI= $1.0^{+0.6}_{-0.4} \cdot 10^{3}$cts/(keV· kg· yr)
- no signal at $Q_{\beta\beta}$

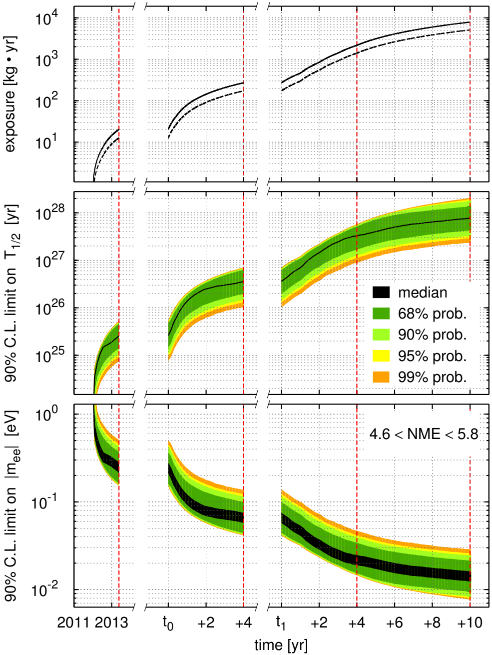
	Frequentist profile likelihood	Bayesian flat prior on cts
$0\nu\beta\beta$ cts best fit value [cts]	0	0
$T^{0\nu}_{1/2}$ lower limit	>8.0·10^{25} (90% CL)	>5.1·10^{25} (90% CI)
$T^{0\nu}_{1/2}$ median sensitivity	>5.8·10^{25} (90% CL)	>4.5·10^{25} (90% CI)



Prospects for ^{76}Ge-based experiments

LEGEND:

- GERDA and Majorana collaborations plus new gruops
- 200 kg stage in existing GERDA infrastructure
- final target mass of 1 t
- sensitive to all IO parameter space



Conclusions - I

- $0\nu\beta\beta$: matter creating process measureble in the lab with strong implications for neutrino physics and cosmology
- huge experimental effort, many ton-scale experiments in preparation
- very high discovery potential for IO
- significant discovery potential also for NO assuming the absence of mechanism or flavour symmetries driving $m_{\beta\beta}$ or $m_{lightest}$ to zero

Conclusions - II

- GERDA pursues a background-free search for $0\nu\beta\beta$ decay (lowest background in the ROI ever achieved by a $0\nu\beta\beta$-decay experiment)
- New data released in Aug (unblinded 12.4 kg·yr)
$\Rightarrow T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 8.0 \cdot 10^{25}$ yr at 90% C.L. ($5.3 \cdot 10^{25}$ yr sensitivity)
- data taking continue: sensitivity above 10^{26} yr next year
- LEGEND collaboration formed, 200-kg stage at LNGS after GERDA, reaching sensitivity up to almost 10^{27} yr in 5 yr of data taking

Our work in a nutshell – part I

Experiment	Iso.	Iso. Mass [kg_{iso}]	σ [keV]	ROI [σ]	ϵ_{FV} [%]	ϵ_{sig} [%]	$\mathcal{E}$ $\left[\frac{kg_{iso}\,yr}{yr}\right]$	$\mathcal{B}$ $\left[\frac{cts}{kg_{iso}\,ROI\,yr}\right]$	3σ disc. sens. $\hat{T}_{1/2}$ [yr]	3σ disc. sens. $\hat{m}_{\beta\beta}$ [meV]	Required Improvement: Bkg	Required Improvement: σ	Required Improvement: Iso. Mass
LEGEND 200 [63, 64]	^{76}Ge	175	1.3	[-2, 2]	93	77	119	$1.7 \cdot 10^{-3}$	$8.4 \cdot 10^{26}$	40–73	3	1	5.7
LEGEND 1k [63, 64]	^{76}Ge	873	1.3	[-2, 2]	93	77	593	$2.8 \cdot 10^{-4}$	$4.5 \cdot 10^{27}$	17–31	18	1	29
SuperNEMO [70, 71]	^{82}Se	100	51	[-4, 2]	100	16	16.5	$4.9 \cdot 10^{-2}$	$6.1 \cdot 10^{25}$	82–138	49	2	14
CUPID [60, 61, 72]	^{82}Se	336	2.1	[-2, 2]	100	69	221	$5.2 \cdot 10^{-4}$	$1.8 \cdot 10^{27}$	15–25	n/a	6	n/a
CUORE [54, 55]	^{130}Te	206	2.1	[-1.4, 1.4]	100	81	141	$3.1 \cdot 10^{-1}$	$5.4 \cdot 10^{25}$	66–164	6	1	19
CUPID [60, 61, 72]	^{130}Te	543	2.1	[-2, 2]	100	81	422	$3.0 \cdot 10^{-4}$	$2.1 \cdot 10^{27}$	11–26	3000	1	50
SNO+ Phase I [68, 73]	^{130}Te	1357	82	[-0.5, 1.5]	20	97	164	$8.2 \cdot 10^{-2}$	$1.1 \cdot 10^{26}$	46–115	n/a	n/a	n/a
SNO+ Phase II [69]	^{130}Te	7960	57	[-0.5, 1.5]	28	97	1326	$3.6 \cdot 10^{-2}$	$4.8 \cdot 10^{26}$	22–54	n/a	n/a	n/a
KamLAND-Zen 800 [62]	^{136}Xe	750	114	[0, 1.4]	64	97	194	$3.9 \cdot 10^{-2}$	$1.6 \cdot 10^{26}$	47–108	1.5	1	2.1
KamLAND2-Zen [62]	^{136}Xe	1000	60	[0, 1.4]	80	97	325	$2.1 \cdot 10^{-3}$	$8.0 \cdot 10^{26}$	21–49	15	2	2.9
nEXO [74]	^{136}Xe	4507	25	[-1.2, 1.2]	60	85	1741	$4.4 \cdot 10^{-4}$	$4.1 \cdot 10^{27}$	9–22	400	1.2	30
NEXT 100 [66, 75]	^{136}Xe	91	7.8	[-1.3, 2.4]	88	37	26.5	$4.4 \cdot 10^{-2}$	$5.3 \cdot 10^{25}$	82–189	n/a	1	20
NEXT 1.5k [76]	^{136}Xe	1367	5.2	[-1.3, 2.4]	88	37	398	$2.9 \cdot 10^{-3}$	$7.9 \cdot 10^{26}$	21–49	n/a	1	300
PandaX-III 200 [67]	^{136}Xe	180	31	[-2, 2]	100	35	60.2	$4.2 \cdot 10^{-2}$	$8.3 \cdot 10^{25}$	65–150	n/a	n/a	n/a
PandaX-III 1k [67]	^{136}Xe	901	10	[-2, 2]	100	35	301	$1.4 \cdot 10^{-3}$	$9.0 \cdot 10^{26}$	20–46	n/a	n/a	n/a

sensitivity for signal discovery derived with heuristic counting analysis
Note: sensitivity for limit setting would be different!