Background free search for Neutrinoless Double Beta Decay of Ge-76 in GERDA Phase II

Andrea Kirsch

Max-Planck Institut für Kernphysik, Heidelberg

International Workshop on Baryon and Lepton Number Violation
May 15-18 2017

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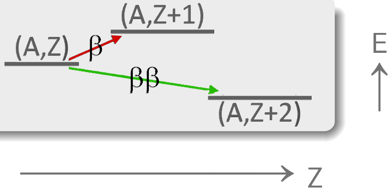
1. Motivation for $0\nu\beta\beta$ search
2. The GERDA Experiment
3. Phase II & first results

Double Beta Decay

Only if Single Beta Decay is energetically forbidden!



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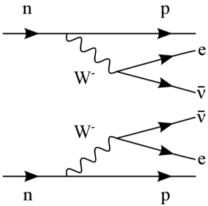

$2\nu\beta\beta$ (A,Z) → (A,Z+2) + $2e^-$ + $2\overline{\nu}$

- weak second order process is allowed by SM
- observed in 12 isotopes $T^{2\nu}_{1/2} \approx (10^{18}\text{ - }10^{24})\ \mathrm{yr}$
- half-life of ^{76}Ge measured by GERDA

$$T^{2\nu}_{1/2} = 1.926 \pm 0.095 \times 10^{21}\ \mathrm{yr}$$

EPJC 75 (2015) 416

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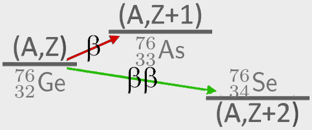
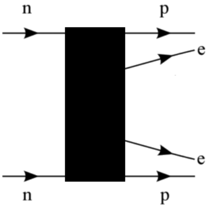


$0\nu\beta\beta$ (A,Z) → (A,Z+2) + $2e^-$

- Lepton number violating
  → $\Delta L = 2$ operator → physics beyond SM
- predicted in many theoretical scenarios
- still hunted and, if existing, extremely rare



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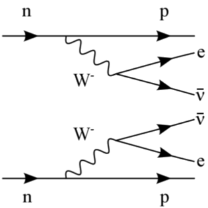

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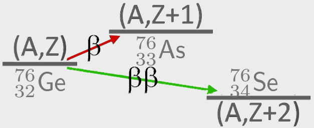

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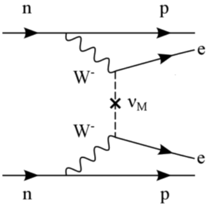
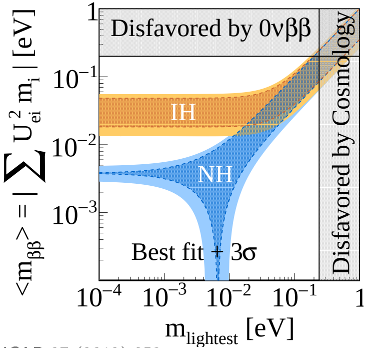


Why / How to search for $0\nu\beta\beta$?



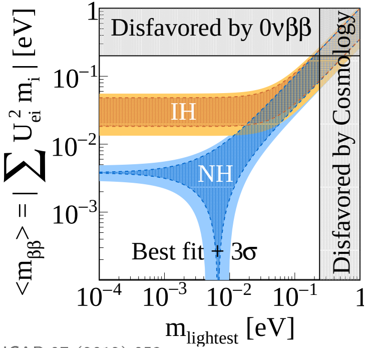
JCAP 07 (2012) 053
Phys. Rev. D86 (2012) 013012

if decay is dominated by light Majorana neutrino exchange:

$$\overbrace{(T_{1/2}^{0\nu})^{-1}}^{\text{decay rate}} = \underbrace{G(Q^5_{\beta\beta})}_{\text{phase space integral}}\ \overbrace{|M_{\text{nucl}}|}^{\text{nuclear matrix element}}{}^2\ \underbrace{\langle m_{\beta\beta}\rangle}_{\text{effective } \nu \text{ mass}}{}^2$$

- Majorana nature of the neutrino
- Matter / anti-matter asymmetry
- constraints on lightest neutrino mass eigenstate + mass hierarchy

Why / How to search for $0\nu\beta\beta$?



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- Majorana nature of the neutrino
- Matter / anti-matter asymmetry
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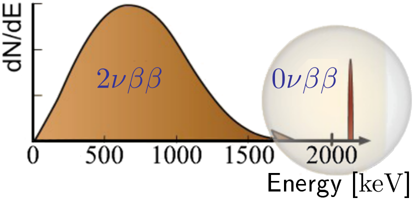
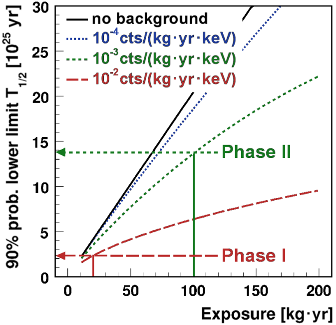
Sum energy of electrons:

- two neutrinos escape the detector
  $2\nu\beta\beta \rightarrow$ continuous spectrum
- total energy deposited in detector
  $0\nu\beta\beta \rightarrow$ peak @ $Q_{\beta\beta} = 2039\,\text{keV}$ for ^{76}Ge



Sensitivity & Method



Background $\ll 1$

$$T_{1/2}^{0\nu} \propto \epsilon \cdot a \cdot M \cdot t$$

Background $\gg 1$

$$T_{1/2}^{0\nu} \propto \epsilon \cdot a \cdot \sqrt{M \cdot t / (\Delta E \cdot BI)}$$

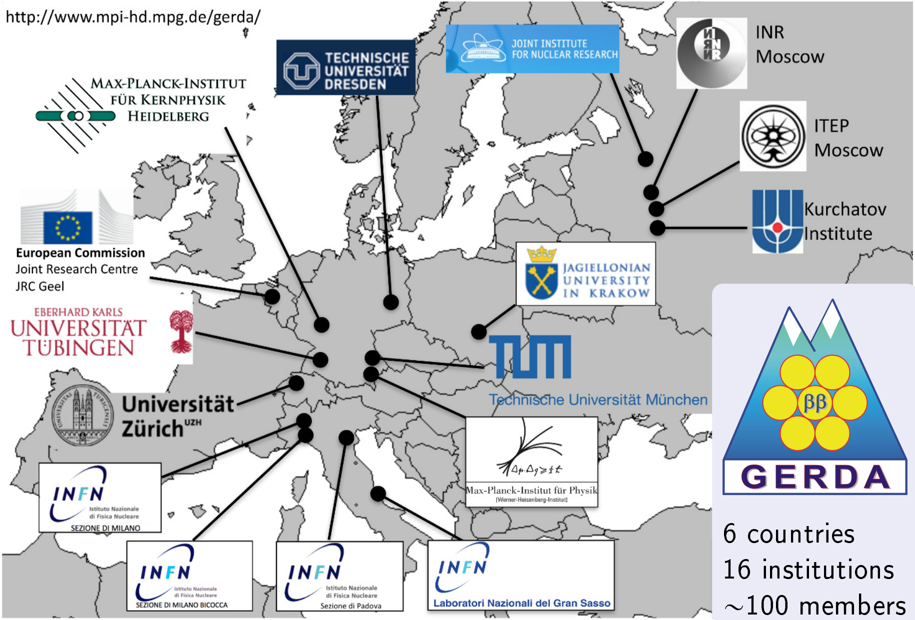
ϵ	detection efficiency
a	abundance of $0\nu\beta\beta$ isotope
$M \cdot t$	active mass × time of measurement
ΔE	energy resolution
BI	background index $[\frac{\text{cts}}{(\text{keV}\cdot\text{kg}\cdot\text{yr})}]$

Well established semiconductor technology:

e	source = detector → optimal detection efficiency
a	isotopically enriched in ^{76}Ge up to $\approx 87\,\%$
M	material is expensive and capacity is limited
t	stable performance and long measurment periods
ΔE	excellent resolution of $\sim 0.1\,\%$ $FWHM$ @ $Q_{\beta\beta}$
BI	selection of radio-pure materials (screening), passive / active background rejection

The GERDA Collaboration

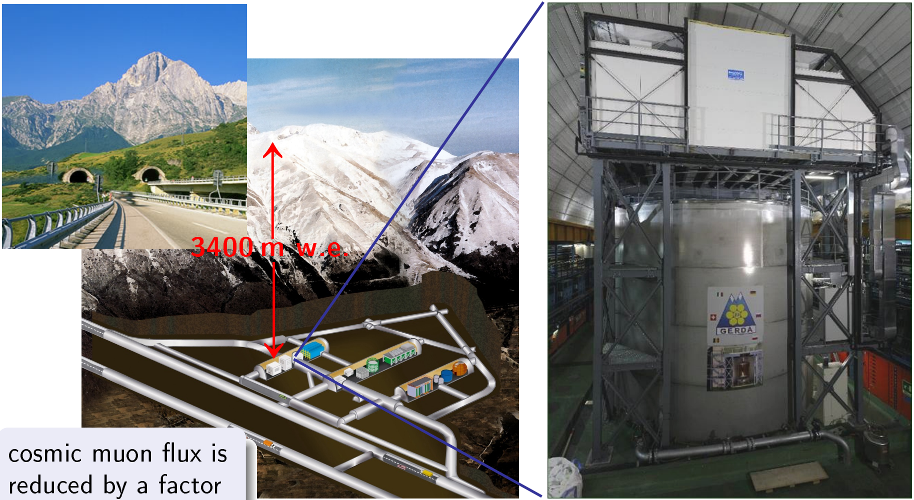
http://www.mpi-hd.mpg.de/gerda/



GERDA

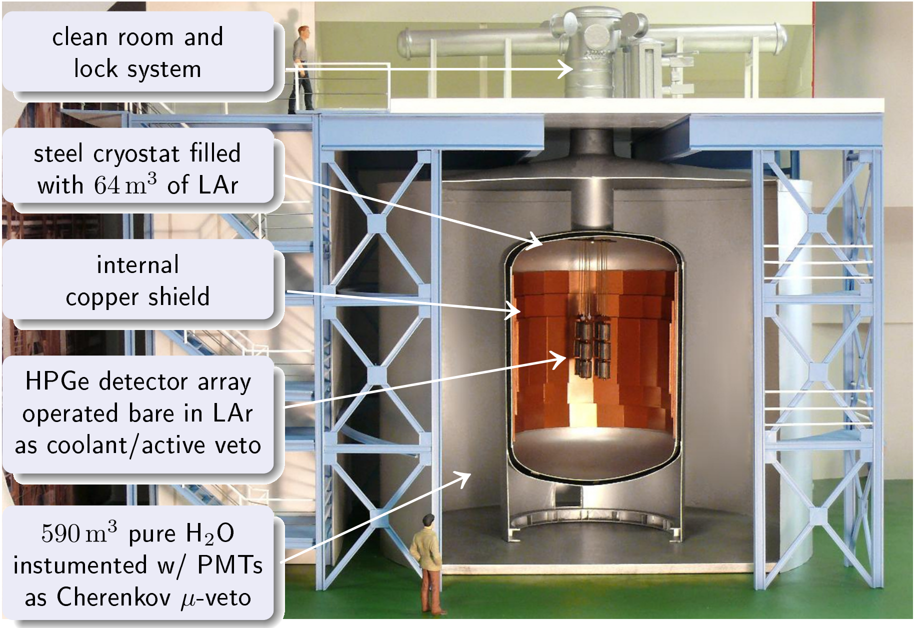
6 countries
16 institutions
~100 members

The GERDA Experiment @ LNGS, Italy



cosmic muon flux is reduced by a factor $10^{-6} \rightarrow 1\ \mu/(\mathrm{m}^2{\cdot}\mathrm{h})$

The GERmanium Detector Array



clean room and lock system

steel cryostat filled with $64\,\mathrm{m}^3$ of LAr

internal copper shield

HPGe detector array operated bare in LAr as coolant/active veto

$590\,\mathrm{m}^3$ pure H_2O instumented w/ PMTs as Cherenkov μ-veto

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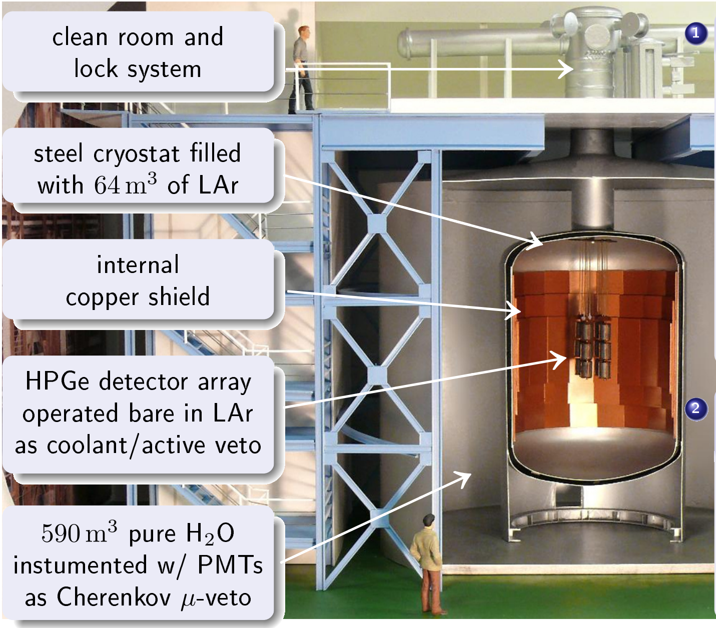

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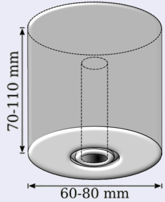
$590\,\mathrm{m}^3$ pure H_2O instumented w/ PMTs as Cherenkov μ-veto

① semi-coaxial

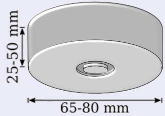


5× from HdM

3× from IGEX

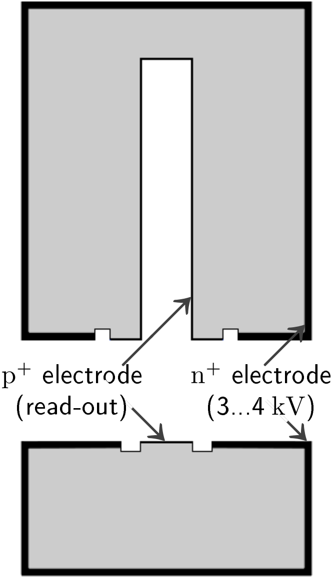
3× ^{nat}Ge GTF

② **BEGe** = Broad Energy Germanium



30× newly made

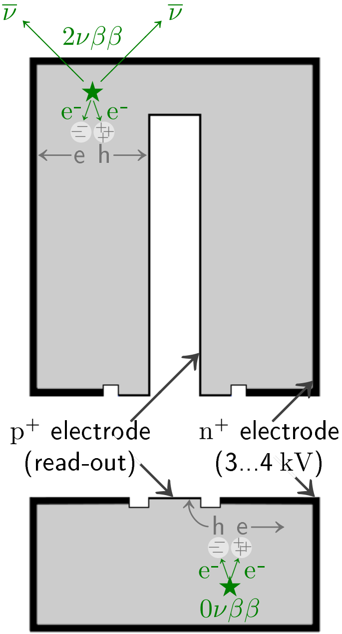
Signal vs. Background



Signal vs. Background

Signal = $\beta\beta$ events *good*

- localized energy deposition within $\approx 1\,\mathrm{mm}$ in only one, single detector (SSE)



Signal vs. Background

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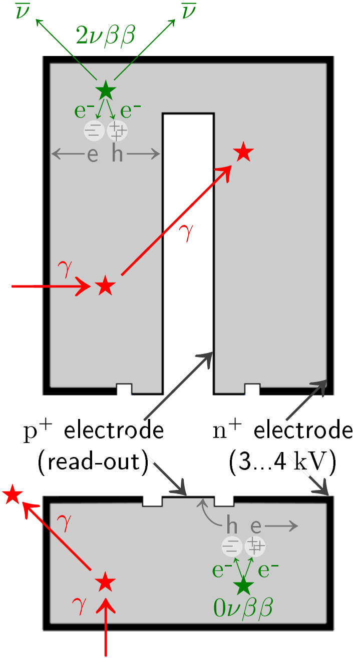
Background = γ events *bad*

- energy deposition @ multiple locations $\sim\mathcal{O}(1\,\mathrm{cm})$ in detector (MSE) → PSD
- simultaneous energy deposition in more than one detector → anti-coincidence
- additional energy deposition outside in liquid argon → LAr veto (since Phase II)



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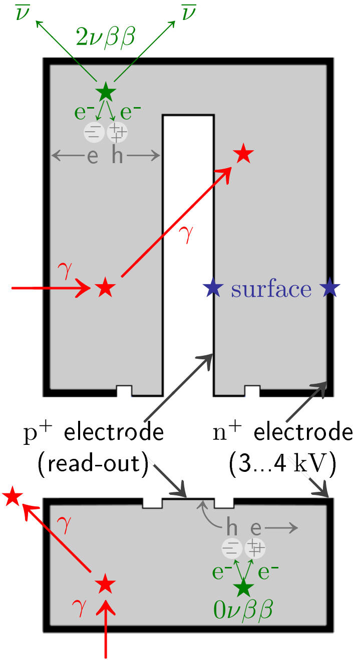
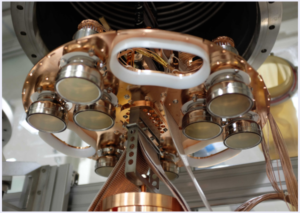
Surface = β and α events *ugly*

- energy deposited "on" or "close by" the detector surface contacts → traces are either very fast (p^+) or very slow (n^+)

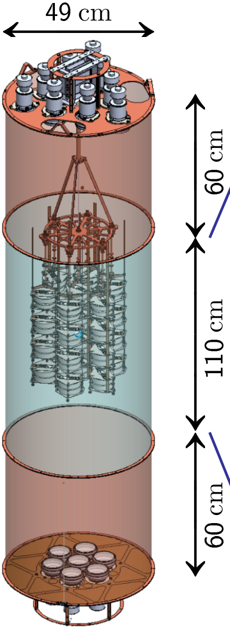


Phase II: LAr veto

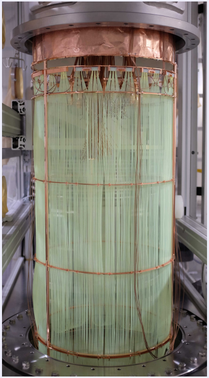
9× top and 7× bottom photomultiplier tube (PMT)



Cu cylinder w/ wavelength shifting reflector foil



810× scintillating fiber coupled to SiPMs



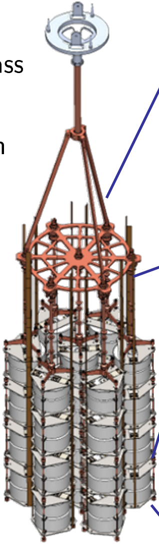
Phase II: Detector array

① increase exposure to 100 $\mathrm{kg \cdot yr}$
- long / stable data aquisition
- add "BEGe" type to double mass

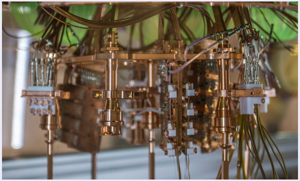
② avoid close-by background
- special care in crystal production
- aluminum bonding contacts, reduce material of holders
- nylon shroud as ^{42}Ar barrier
- new front-end readout
- screening measurements

③ reject residual background
- Pulse Shape Discrimination
- dense packing of detectors (enhanced anti-coincidence)
- LAr scintillation light veto

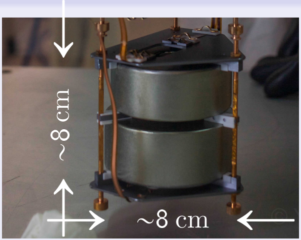
④ improve energy resolution
- Zero Area Cusp (ZAC) filter EPJC 75 (2015) ,255



low radioactivity electronics and cabling



detector holders w/ reduced mass & Cu → Si

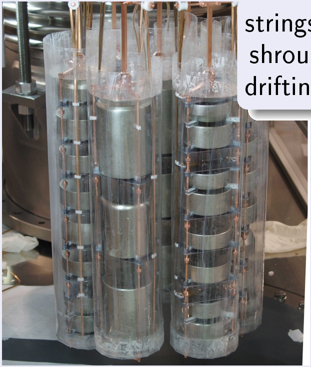


Phase II: Final Integration … in Dec 2015

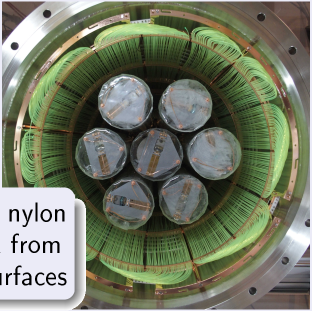
40 detectors (all working) in 7 strings:

1. 30× ${}^{\mathrm{enr}}$BEGe (20.0 kg)
2. 7× ${}^{\mathrm{enr}}$semi-coaxial (15.8 kg)
3. 3× ${}^{\mathrm{nat}}$semi-coaxial (7.6 kg)

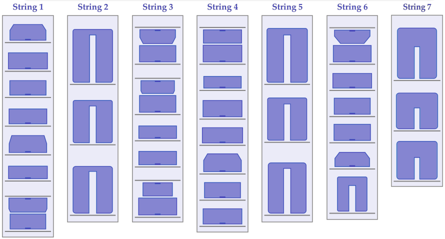
side view



bottom view

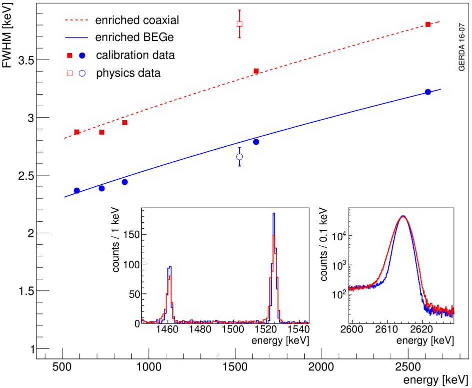


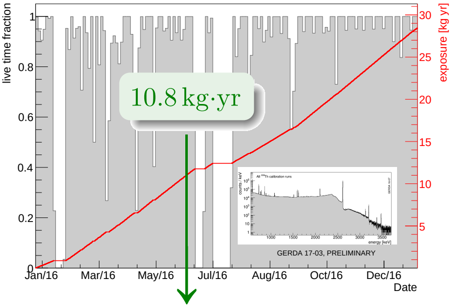
strings surrounded by nylon shroud to reduce ^{42}K from drifting to detector surfaces



Continuous data-taking … since Dec 2015

- $85\,\%$ average duty cycle
- weekly ^{228}Th calibrations
- $\leqslant 1\,\mathrm{keV}$ between successive runs
- data removed from analysis if energy scale uncertain
- blinding window @ $Q_{\beta\beta} \pm 25\,\mathrm{keV}$





$10.8\,\mathrm{kg{\cdot}yr}$

Neutrino 2016 data release

- Dec 2015 - May 2016
- exposure used for analysis

$5.0\mathrm{kg{\cdot}yr}$ for coaxial

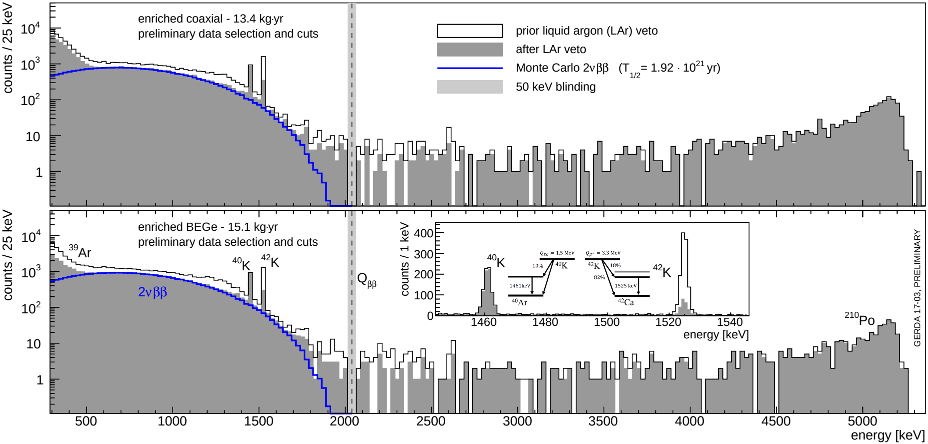
$5.8\mathrm{kg{\cdot}yr}$ for BEGe

- $FWHM$ @ $Q_{\beta\beta}$

$4.0(2)\mathrm{keV}$ for coaxial

$3.2(2)\mathrm{keV}$ for BEGe

Newest physics spectra … from Mar 2017



	exposure [kg·yr]	BI^{*} $[10^{-3}\cdot\frac{\text{cts}}{\text{keV}\cdot\text{kg}\cdot\text{yr}}]$ (cts)	…after LAr veto**
coaxial	13.4	$16.7^{+2.7}_{-2.3}$ (46)	$8.0^{+1.9}_{-1.6}$ (22)
BEGe	15.1	$12.3^{+2.3}_{-1.8}$ (38)	$3.9^{+1.3}_{-1.0}$ (12)

* for ROI = (1930 - 2190) keV w/o (2104 ± 5) keV and (2119 ± 5) keV and ($Q_{\beta\beta}$ ± 25) keV ⇒ 190 keV

** LAr veto acceptance from test pulser measurements = (97.7 ± 0.1) %

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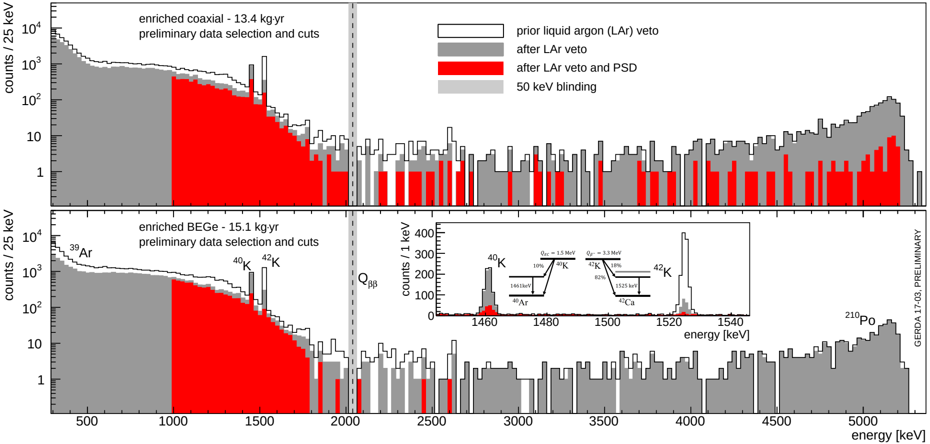


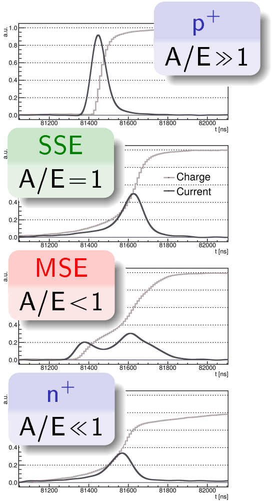
	exposure [kg·yr]	BI^* $[10^{-3}\cdot\frac{\text{cts}}{\text{keV}\cdot\text{kg}\cdot\text{yr}}]$ (cts)	…after LAr veto**	…after PSD	…after LAr + PSD
coaxial	13.4	$16.7^{+2.7}_{-2.3}$ (46)	$8.0^{+1.9}_{-1.6}$ (22)	$8.0^{+1.9}_{-1.6}$ (22)	$2.2^{+1.1}_{-0.8}$ (6)
BEGe	15.1	$12.3^{+2.3}_{-1.8}$ (38)	$3.9^{+1.3}_{-1.0}$ (12)	$3.2^{+1.2}_{-0.9}$ (10)	$0.6^{+0.6}_{-0.4}$ (2)

* for ROI = (1930 - 2190) keV w/o (2104 ± 5) keV and (2119 ± 5) keV and ($Q_{\beta\beta}$ ± 25) keV ⇒ 190 keV

** LAr veto acceptance from test pulser measurements = (97.7 ± 0.1) %

Pulse Shape Discrimination for BEGe

A/E = Amplitude of current pulse over Energy

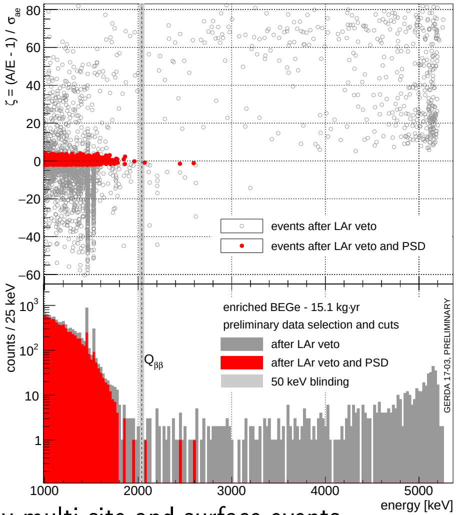


p^+
$A/E \gg 1$

SSE
$A/E = 1$

MSE
$A/E < 1$

n^+
$A/E \ll 1$



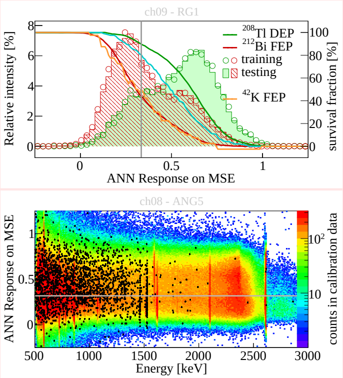
- two sided cut rejects efficiently multi-site and surface events
- high signal efficiency: $\epsilon_{\mathrm{DEP}} = 87(2)\,\%$ and $\epsilon_{2\nu\beta\beta} = 85^{+2}_{-1}\,\%$

Pulse Shape Discrimination for semi-coaxial

Artificial Neural Network

- ROOT integrated TMVA toolkit (i.e. TMlpANN)
- 50 input variables: times where charge pulse is at $1\,\%$, $3\,\%$, ..., $99\,\%$ of maximum height

ANN on MSE



training / testing of supervised learning algorithm

^{228}Th calibration ←

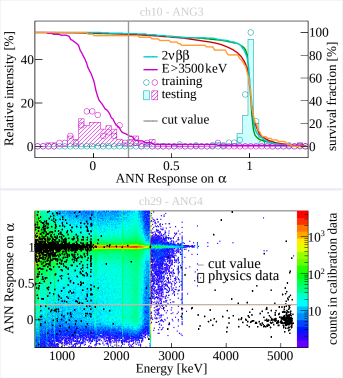
physics data →

adjust cut to survival fraction

$90\,\%$ @ DEP ←

$10\,\%$ @ $\geqslant 3500\,$keV →

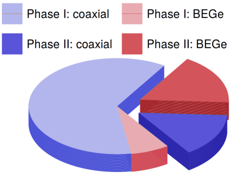
ANN on α



- signal efficiency determined by MC simulation: $\epsilon_{0\nu\beta\beta} = (79 \pm 5)\,\%$

First Phase II Result

from Neutrino 2016 data release



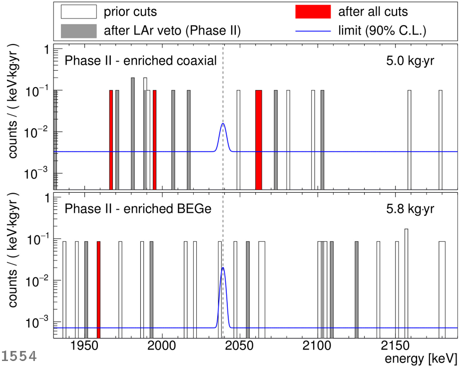
data	exposure	$FWHM$	efficiency		BI
set	$[\mathrm{kg \cdot yr}]$	$[\mathrm{keV}]$	PSD	total*	$[10^{-3}\,\frac{\mathrm{cts}}{\mathrm{keV \cdot kg \cdot yr}}]$
PI golden	17.9	4.3(1)	0.85	0.57(3)	11 ± 2
PI silver	1.3	4.3(1)	0.85	0.57(3)	30 ± 10
PI BEGe	2.4	2.7(2)	0.92	0.66(2)	5^{+4}_{-3}
PI extra	1.9	4.2(2)	0.85	0.58(4)	5^{+4}_{-3}
PIIa coaxial	5.0	4.0(2)	0.79	0.53(5)	$3.5^{+2.1}_{-1.5}$
PIIa BEGE	5.8	3.0(2)	0.87	0.60(2)	$0.7^{+1.1}_{-0.5}$

* including enrichment, active mass, reconstruction efficiencies, dead time

- unbinned profile likelihood:
  6× flat background @ $1930\text{-}2190\,\mathrm{keV}$
  1× common Gaussian signal at $Q_{\beta\beta}$

	profile likelihood 2-side test-stat**	Bayesian flat prior
$0\nu\beta\beta$ cts best fit value $[\mathrm{cts}]$	0	0
$T^{0\nu}_{1/2}$ lower limit $[10^{25}\mathrm{yr}]$	>5.3 (90% CL)	>3.5 (90% CI)
$T^{0\nu}_{1/2}$ median sensitivity $[10^{25}\mathrm{yr}]$	>4.0 (90% CL)	>3.0 (90% CI)

** frequentist test-statisitics & methods EPJC 71 (2011) 1554



Conclusions

- GERDA Phase II is running stable
- 3-4 keV energy resolution @ $Q_{\beta\beta}$
- blind analysis on first $10.8\,\mathrm{kg{\cdot}yr}$ of data
- published in Nature 544 (2017) 47

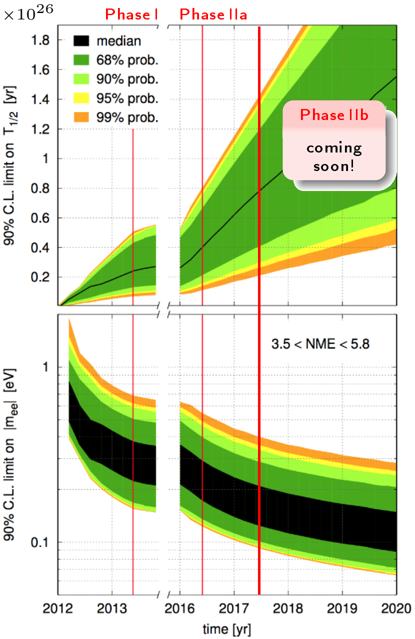
new limit on $0\nu\beta\beta$ decay in ^{76}Ge		
$T_{1/2}^{0\nu}$	$>$	$5.3 \cdot 10^{25}\,\mathrm{yr}$ (90% CL)
$m_{\beta\beta}$	$<$	$(0.15 - 0.33)\,\mathrm{eV}$ (90% CL)

- exposure further increased to $28.5\,\mathrm{kg{\cdot}yr}$

background index @ $Q_{\beta\beta}$	
coaxial	$2.2^{+1.1}_{-0.8} \cdot 10^{-3}\,\mathrm{cts/(keV{\cdot}kg{\cdot}yr)}$
BEGe	$0.6^{+1.1}_{-0.8} \cdot 10^{-3}\,\mathrm{cts/(keV{\cdot}kg{\cdot}yr)}$

GERDA Phase II is "the" high-resolution and background-free $0\nu\beta\beta$ experiment!

GERDA Phase II goals		
background	$\sim 10^{-3}\,\mathrm{cts/(keV{\cdot}kg{\cdot}yr)}$	✓
exposure	$> 100\,\mathrm{kg{\cdot}yr}$	🕒
sensitivity	$T_{1/2}^{0\nu} > 10^{26}\,\mathrm{yr}$	🕒



Phase IIb

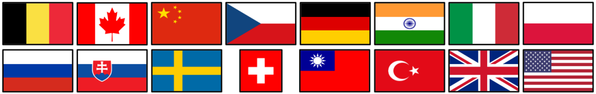
coming soon!

… and beyond

LEGEND @ www.legend-exp.org

Large Enriched Germanium Experiment
for Neutrinoless $\beta\beta$ Decay

- collaboration formed in Oct 2016
- phased approach towards $1000\,\mathrm{kg}$
- 1^{st} phase: $200\,\mathrm{kg}$ in existing infrastructure at LNGS

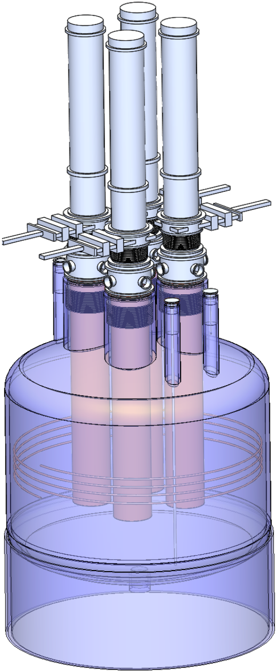


216 members, 48 institutions, 16 countries

LEGEND-200 goals	
background	$2{\cdot}10^{-4}\ \frac{\mathrm{cts}}{\mathrm{keV{\cdot}kg{\cdot}yr}}$
exposure	$10^{3}\ \mathrm{kg{\cdot}yr}$
sensitivity	$T^{0\nu}_{1/2}\ {\sim}10^{27}\mathrm{yr}$

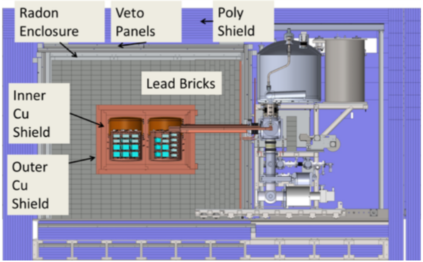
LEGEND-1000 goals	
background	$3{\cdot}10^{-5}\ \frac{\mathrm{cts}}{\mathrm{keV{\cdot}kg{\cdot}yr}}$
exposure	$10^{4}\ \mathrm{kg{\cdot}yr}$
sensitivity	$T^{0\nu}_{1/2}\ {\sim}10^{28}\mathrm{yr}$

- forseen start: end of 2020
- discovery potential (!) for light Majorana neutrino exchange & inverted mass ordering!



Majorana Demonstrator

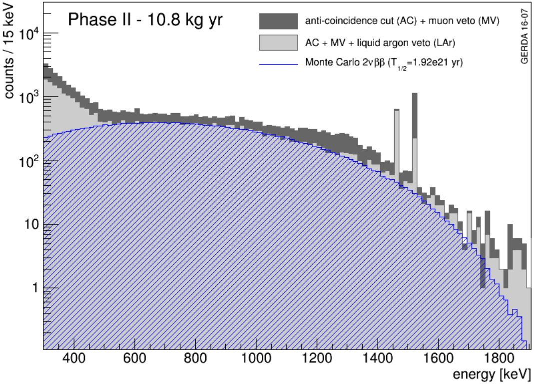
www.npl.washington.edu/majorana/



proto-type module, 2014-2015
7.0kg (10) ^{nat}Ge
Module 1, since Jan 2016
16.8kg (20) ^{enr}Ge + 5.7kg (9) ^{nat}Ge
Module 2, since summer 2016
12.8kg (14) ^{enr}Ge + 9.4kg (15) ^{nat}Ge

- located @ Sanford Underground Research Facility (SURF) in Lead, SD
- $29\,\mathrm{kg}$ ^{enr}Ge + $15\,\mathrm{kg}$ ^{nat}Ge in cryostat
- conventional copper/lead shield
- ultra-clean (home made) electroformed copper
- point-contact detectors
  → rejection of multi-site and surface events
- goal: prove design for ton scale with BI of $\sim 1\,\mathrm{cts/(t \cdot yr)}$ @ $4\,\mathrm{keV}$ region of interest

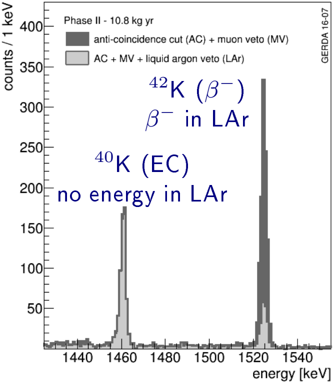
LAr veto background suppression



$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ar} + \gamma\,(1.461\,\mathrm{MeV})$$

$$^{42}\mathrm{K} \rightarrow {}^{42}\mathrm{Ca} + \gamma\,(1.525\,\mathrm{MeV})$$

$$+\ e^{-}\ \text{up to}\ 2\,\mathrm{MeV}$$

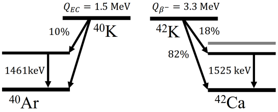


^{42}K (β^-)

β^- in LAr

^{40}K (EC)

no energy in LAr



(600-1300) keV

"pure" $2\nu\beta\beta$ spectrum

^{40}K / ^{42}K Compton continuum fully suppressed

at $Q_{\beta\beta}$

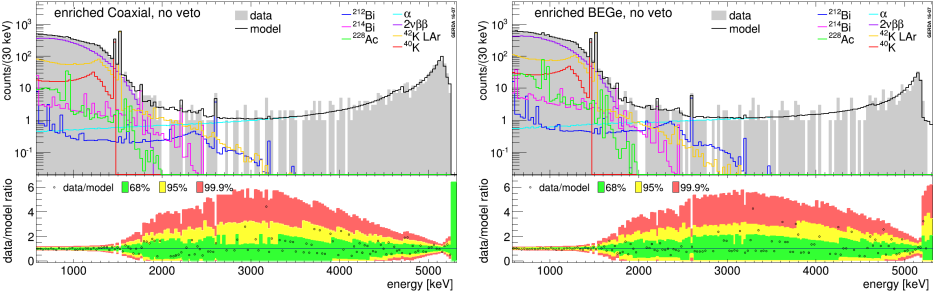
background reduced by a factor 2

high energies

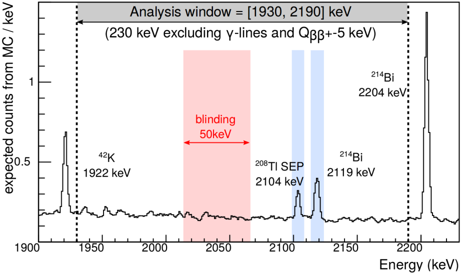
(quasi) no reduction of α's

- signal (test pulser) acceptance: $(97.7 \pm 0.1)\,\%$

Background Model before LAr veto/PSD



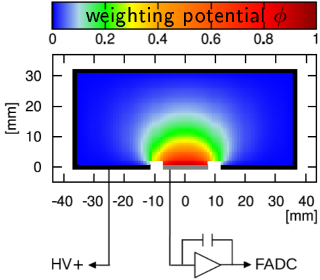
- fit between 570-5300 keV with 30 keV binning
- main components
  1. α from ^{210}Po, ^{226}Ra
  2. β from ^{42}K
  3. γ from ^{214}Bi, ^{208}Tl
- flat background in ROI @ $Q_{\beta\beta}$



Pulse shape: BEGe

Ramo-Shockley theorem

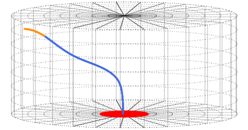
- Charge $Q(t)$
  $= -q \times [\phi(\boldsymbol{r}_\mathrm{h}(t)) - \phi(\boldsymbol{r}_\mathrm{e}(t))]$
- Current $I(t) = \mathrm{d}Q(t)/\mathrm{d}t$
  $= q \times [\mathcal{E}(\boldsymbol{r}_\mathrm{h}(t))\cdot\boldsymbol{v}_\mathrm{h}(t) - \mathcal{E}(\boldsymbol{r}_\mathrm{e}(t))\cdot\boldsymbol{v}_\mathrm{e}(t)]$

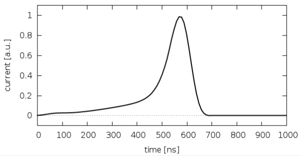


→ mostly holes (but hardly any electrons) do contribute to the signal formation!

Signal-like single-site event (SSE)

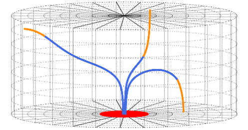
$A \propto E$

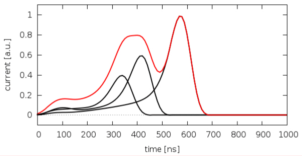




Background-like multi-site event (MSE)

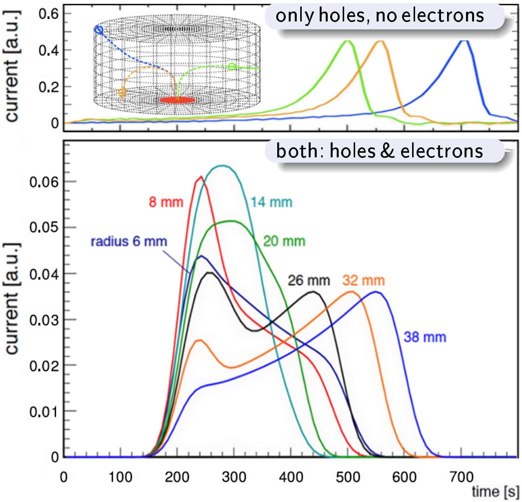
$A \not\propto E$

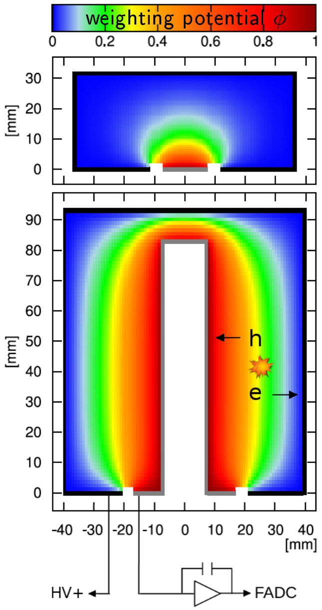




Pulse shape: semi-coaxial vs. BEGe

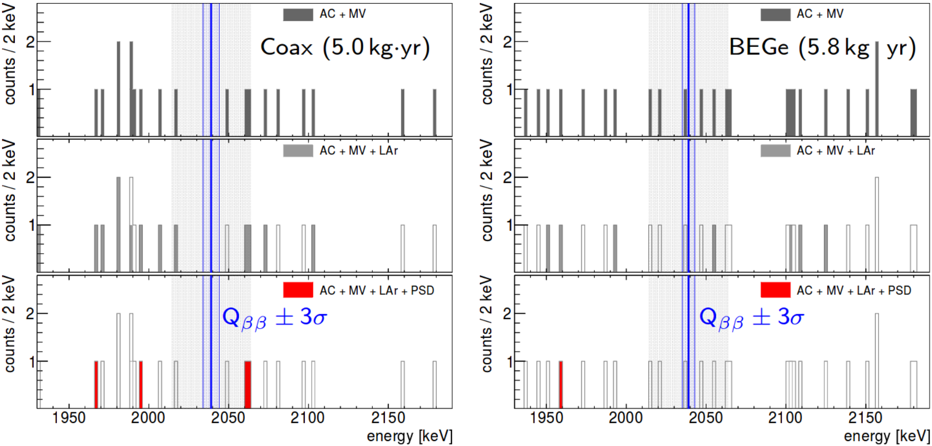
simulated current pulses for SSEs





Different PSD method than mono-parametric A/E needed for semi-coaxial detector type!

unblinding the spectrum



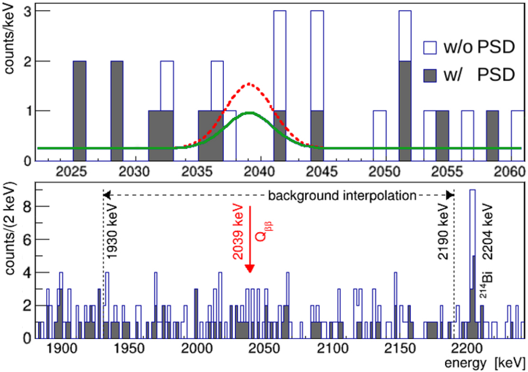
	counts expected from BM		counts observed in data	
	$Q_{\beta\beta} \pm 25\,\mathrm{keV}$	$(1930-2190)\,\mathrm{keV}$	$Q_{\beta\beta} \pm 25\,\mathrm{keV}$	$(1930-2190)\,\mathrm{keV}$
coaxial	0.8	3.6	2	4
BEGe	0.3	1.2	0	1

Phase I $0\nu\beta\beta$ result (Nov 2011 - May 2013)

- 21.6 $\mathrm{kg{\cdot}yr}$ exposure
- 8× semi-coaxial and 5× BEGe detectors
- blind analysis @ ROI $= Q_{\beta\beta} \pm 5\ \mathrm{keV}$
- background index after pulse shape cut:

$$BI = 1.0(1) \cdot 10^{-2}\ \mathrm{cts/(keV{\cdot}kg{\cdot}yr)}$$

(10× better than previous experiments)



number of events in $Q_{\beta\beta} \pm 2\sigma_\mathrm{E}$

- N_exp = 2.0 ± 0.3
  from background model
- N_obs = 3
  after opening blinded region
- profile likelihood: best fit for $N_{0\nu}$ = 0

→ GERDA sees no $0\nu\beta\beta$-signal

90% C.L. on half-live

- $T^{0\nu}_{1/2} > 2.1 \times 10^{25}\ \mathrm{yr}$
  (Frequentist analysis)

Phys. Rev. Lett. 111 (2013) 122503

Claim: $T^{0\nu}_{1/2} = 1.19 \times 10^{25}\ \mathrm{yr}$

- rejected w/ 99% probability

Phys. Lett. B 586 (2004) 198-212

Phase I $2\nu\beta\beta$ result (Nov 2011 - May 2013)

- Run $25\text{-}46$ with $17.2\,\mathrm{kg{\cdot}yr}$ exposure from "golden" data set to evaluate $2\nu\beta\beta$ half-life
- fit range: $(570\text{-}7500)$ keV
- binned maximum likelihood
- minimum background model

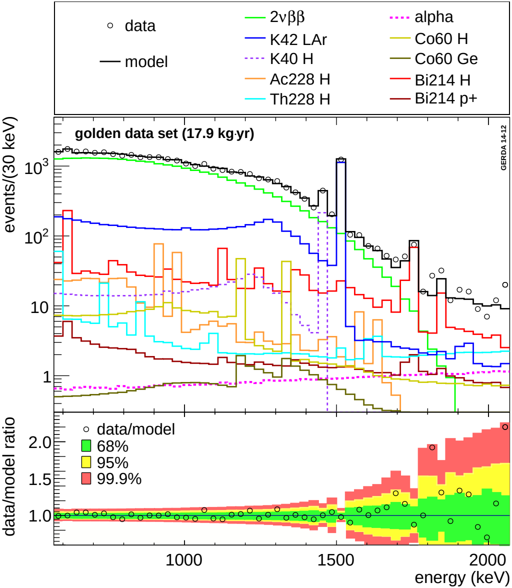
- important for understanding of $0\nu\beta\beta$ decay (e.g. nuclear matrix element)

half-life:

$$T_{1/2}^{2\nu} = 1.926 \pm 0.095 \cdot 10^{21}\ \mathrm{yr}$$

(unprecedented precision)

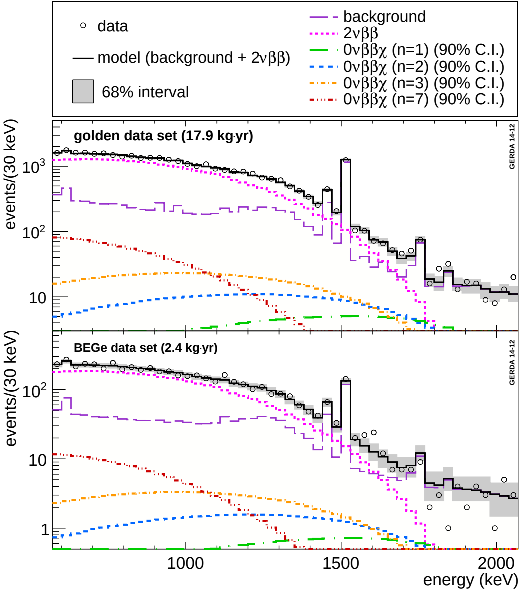
- published in EPJC 75 (2015) 416



Phase I $0\nu\beta\beta\chi$ result (Nov 2011 - May 2013)

- search for Majoron accompanied $0\nu\beta\beta$ decay
- Run 25-46 with data sets of 17.2 kg·yr from "golden" & 2.4 kg·yr from "BEGe"

Model	n	Mode	L	$T^{0\nu\chi}_{1/2}$ [10^{23} yr]
IB	1	χ	0	>4.15
IC	1	χ	0	>4.15
ID	3	$\chi\chi$	0	>0.89
IE	3	$\chi\chi$	0	>0.89
IF (bulk)	2	χ	0	>1.82
IIB	1	χ	-2	>4.15
IIC	3	χ	-2	>0.89
IID	3	$\chi\chi$	-1	>0.89
IIE	7	$\chi\chi$	-1	>0.33
IIF	3	χ	-2	>0.89



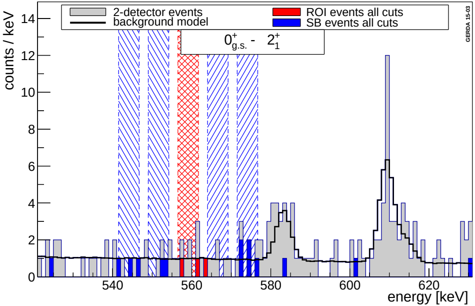
Most stringent limits for ^{76}Ge:

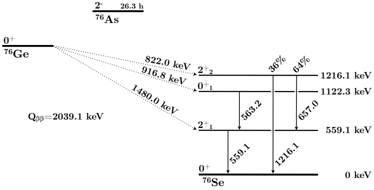
- $n=1$, 3 improved by factor 6
- $n=2$ reported for first time
- $n=7$ improved by factor 5

- published in EPJC 75 (2015) 416

Phase I $2\nu\beta\beta$ to exited states (Nov 2011 - May 2013)

decay mode	Frequentist 90% C.L.		Bayesian 90% C.I.	
	$T_{1/2}$ $[10^{23}$ yr$]$	$T_{1/2}$ $[10^{23}$ yr$]$	$T_{1/2}$ $[10^{23}$ yr$]$	$T_{1/2}$ $[10^{23}$ yr$]$
$0^+_{\rm g.s.} - 2^+_1$	> 1.6	> 1.3	> 1.3	> 1.2
$0^+_{\rm g.s.} - 0^+_1$	> 3.7	> 1.9	> 2.7	> 1.8
$0^+_{\rm g.s.} - 2^+_2$	> 2.3	> 1.4	> 1.8	> 1.3





- coincident deexcitation γ with the right energy in a second detector

coincidence signature:

- Det. 1: $\beta\beta$ energy
- Det. 2: γ full energy

- published in J. Phys. G Nucl. Part. Phys. 42 (2015) 115201

- benchmark for NME calculations

Phase I $2\nu\beta\beta$ to exited states (Nov 2011 - May 2013)

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	$T_{1/2}$ $[10^{23}$ yr$]$	$T_{1/2}$ $[10^{23}$ yr$]$	$T_{1/2}$ $[10^{23}$ yr$]$	$T_{1/2}$ $[10^{23}$ yr$]$
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$0^+_{\rm g.s.} - 0^+_1$	> 3.7	> 1.9	> 2.7	> 1.8
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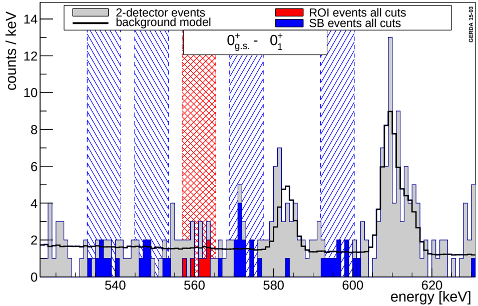

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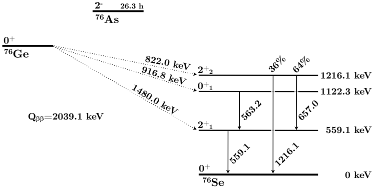

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Phase I $2\nu\beta\beta$ to exited states (Nov 2011 - May 2013)

decay mode	Frequentist 90% C.L.		Bayesian 90% C.I.	
	$T_{1/2}$ $[10^{23}$ yr$]$	$T_{1/2}$ $[10^{23}$ yr$]$	$T_{1/2}$ $[10^{23}$ yr$]$	$T_{1/2}$ $[10^{23}$ yr$]$
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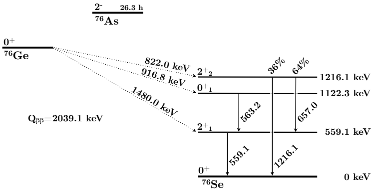

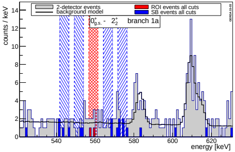

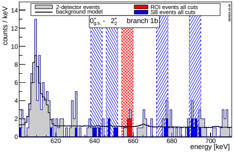

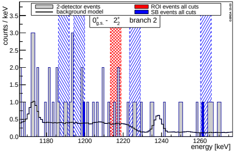

- coincident deexcitation γ with the right energy in a second detector

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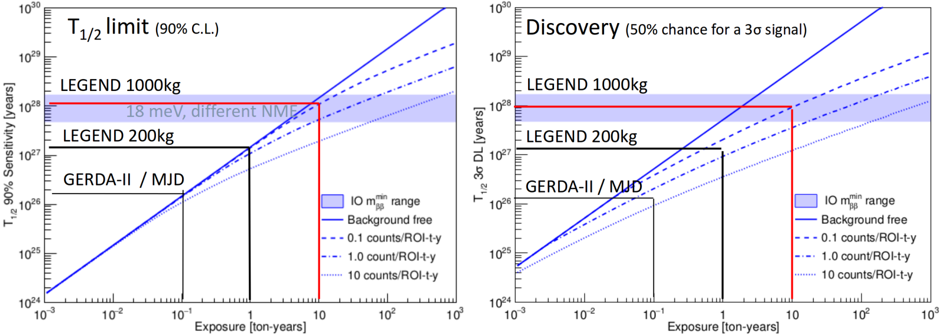
- benchmark for NME calculations

LEGEND: sensitivity for limit setting / discovery



- assuming 60% "efficiency"
  which includes isotope fraction, active volume fraction, analysis cuts
- GERDA-II / MJD: $3\,\mathrm{cts/(ROI \cdot t \cdot yr)}$
- LEGEND-200: $0.6\,\mathrm{cts/(ROI \cdot t \cdot yr)}$
- LEGEND-1000: $0.1\,\mathrm{cts/(ROI \cdot t \cdot yr)}$

- "background-free" operation is a prerequisite for a discovery