# GERDA: Phase I results & upgrade for Phase II

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- on behalf of the GERDA collaboration -

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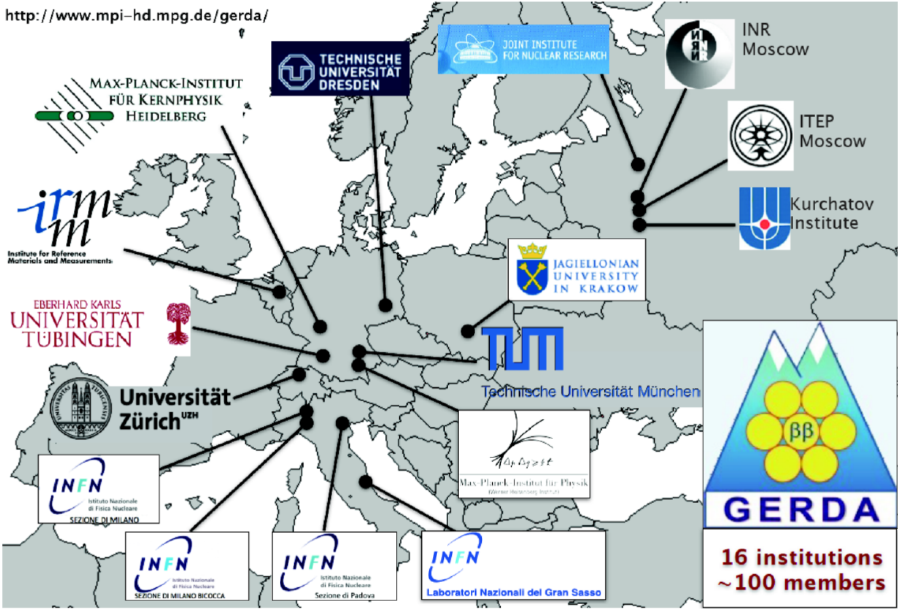
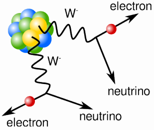
**PANIC**, August 25 2014, Hamburg

# The GERDA collaboration



# Double beta decays

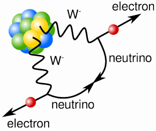
## $2\nu\beta\beta$: $(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\nu_e$




- so far observed in 12 nuclei
- half lifes in the range of $10^{18}$ - $10^{24}$ *yr* with $T^{2\nu}_{1/2}(^{76}Ge) = (1.84^{+0.14}_{-0.08})\,10^{21}$ yr
  J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110
- $\Delta L = 0$: lepton number conserved
- allowed by the standard model

## $0\nu\beta\beta$: $(A, Z) \rightarrow (A, Z + 2) + 2e^-$

- only if $\nu$ has Majorana mass component
- still hunted process




- note: one claim by subgroup of HdM with $T^{0\nu}_{1/2} = (1.19^{+0.37}_{-0.23})\,10^{25}$ yr
  Phys. Rev. Lett. B 586, 198-212 (2004)
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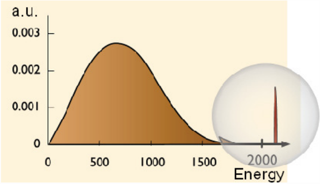
- not allowed by standard model

## experimental signatures

- measure the electrons sum energy spectrum




- continuum $\rightarrow 2\nu\beta\beta$
- monoenergetic peak @ $Q_{\beta\beta} \rightarrow 0\nu\beta\beta$

# Double beta decays

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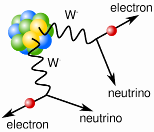


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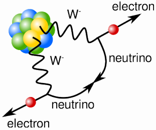


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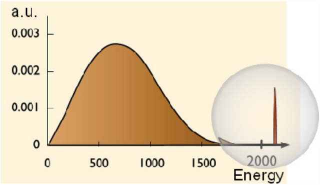
## why to search in $^{76}Ge$?

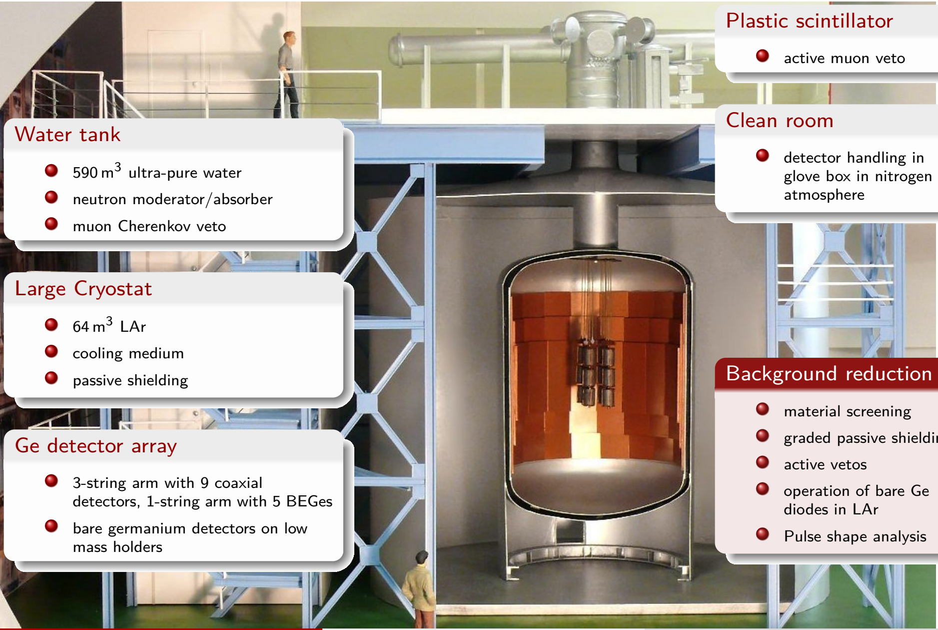
- high purity Ge detectors (enriched in $^{76}Ge$ to $\approx 87\%$) $\rightarrow$ low intrinsic $BI$
- detectors well established technology
- FWHM @ $Q_{\beta\beta} \approx 0.2\%$




calorimeter detectors:

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

# The GERDA experiment



## Water tank

- 590 $m^3$ ultra-pure water
- neutron moderator/absorber
- muon Cherenkov veto

## Large Cryostat

- 64 $m^3$ LAr
- cooling medium
- passive shielding

## Ge detector array

- 3-string arm with 9 coaxial detectors, 1-string arm with 5 BEGes
- bare germanium detectors on low mass holders

## Plastic scintillator

- active muon veto

## Clean room

- detector handling in glove box in nitrogen atmosphere

## Background reduction

- material screening
- graded passive shielding
- active vetos
- operation of bare Ge diodes in LAr
- Pulse shape analysis

# Phase I data

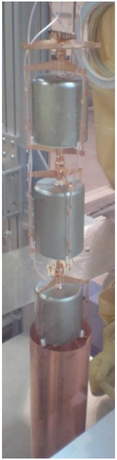
| phase | mass | aspired BI | livetime | $T^{0\nu}_{1/2}$ sensitivity |
|---|---|---|---|---|
| | [kg] | $[cts/(keV \cdot kg \cdot yr]$ | [yr] | [yr] |
| I | 15 | $10^{-2}$ | 1 | $2.4 \cdot 10^{25}$ |

## 8 x semi-coaxial detectors

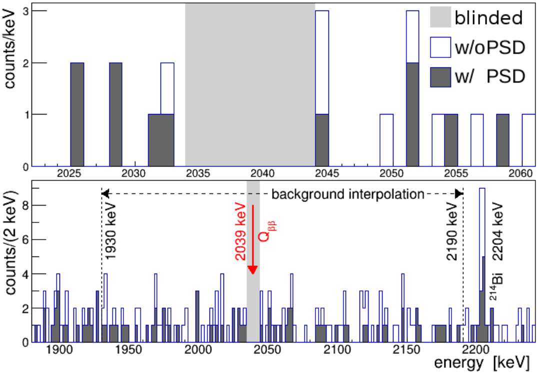
- reprocessed detectors formerly used by HdM & IGEX experiments
- enrichment fraction of $^{76}Ge$: $\approx 86\%$
- data taking: November 2011 - May 2013
- 2 detectors not considered (high leakage current)
- total mass used for analysis: 14.6 kg

## 5 x Broad Energy Germanium (BEGe) detectors

- from $\approx$ 30 newly processed Phase II detectors
- enrichment fraction of $^{76}Ge$: $\approx 88\%$
- data taking (first test): July 2012 - May 2013
- 1 detector not considered (unstable behaviour)
- total mass used for analysis: 3.0 kg



# Phase I results

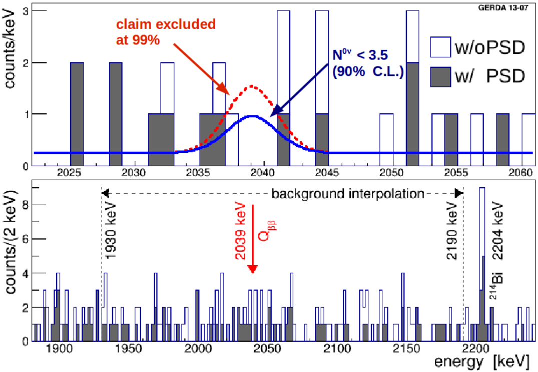



data at $Q_{\beta\beta} \pm 5\,\mathrm{keV}$ was blinded

## before unblinding

- energy calibration
- data selection
- analysis method
- background model
- pulse shape discrimination (PSD) cuts

# Phase I results




## result

- total exposure:
  $M \cdot t = 21.6\,\mathrm{kg\,yr}$
- no peak in spectrum @ $Q_{\beta\beta}$
- $N_{obs} = 7$ (w/o) $\leftrightarrow$ 3 (w/ PSD)
- $N_{exp} = 5.1$ (w/o) $\leftrightarrow$ 2.5 (w/ PSD)
- event count $N_{obs}$ consistent with expected background $N_{exp}$

## result on $T_{1/2}^{0\nu}$

frequentist profile likelihood fit

- best fit $N^{0\nu} = 0$
- $T_{1/2}^{0\nu}(90\% C.L.) > 2.1 \cdot 10^{25} yr$
- median sensitivity: $2.4 \cdot 10^{25} yr$

Bayes: $T_{1/2}^{0\nu}(90\% C.L.) > 1.9 \cdot 10^{25} yr$

# Phase II goal

| phase | mass [kg] | aspired BI $[cts/(keV \cdot kg \cdot yr]$ | livetime [yr] | $T_{1/2}^{0\nu}$ sensitivity [yr] |
|---|---|---|---|---|
| I | 15 | $10^{-2}$ | 1 | $2.4 \cdot 10^{25}$ |
| II | 35 | $10^{-3}$ | 3 | $1.4 \cdot 10^{26}$ |

## experimental sensitivity (if background « 1)

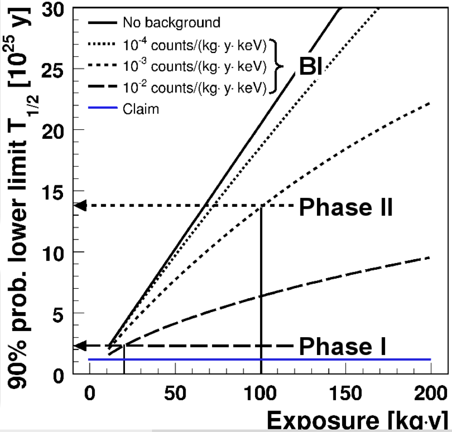
$$T_{1/2}^{0\nu} \propto \epsilon \cdot a \cdot M \cdot t$$

$\epsilon$: detection efficiency,
$a$: abundance of $^{76}$Ge
$Mt$: exposure [kg yr],
$BI$: background index $[\mathrm{cts/(keV\,kg\,yr)}]$,
$\Delta(E)$: energy resolution in ROI at $Q_{\beta\beta}$

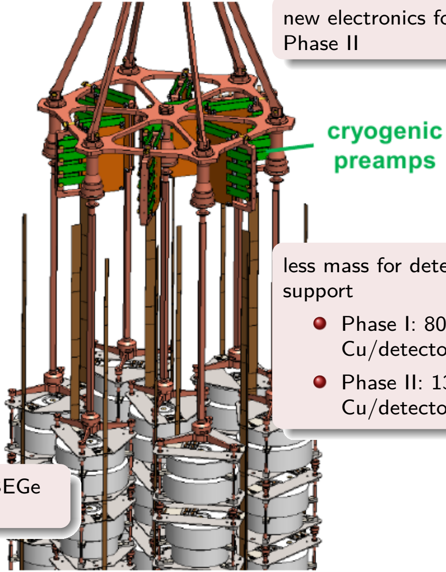
## upgrade strategy

- stay as long as possible in background-free regime

⇔ increase mass / exposure & resolution and reduce BI



## Upgrade



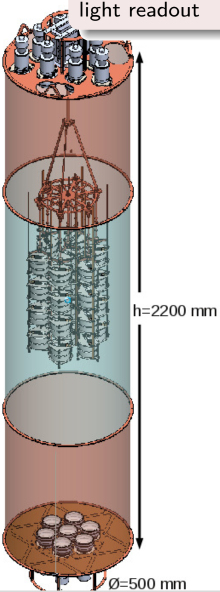

new electronics for Phase II

less mass for detector support

- Phase I: 80g Cu/detector
- Phase II: 13 g Cu/detector

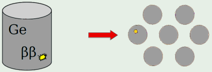
30 new BEGe detectors

LAr scintillation light readout



# More and better enr Ge-diodes

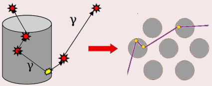
## signal




- $\beta\beta$ events: range for $1\,\mathrm{MeV}$ electrons in Ge about $1\,\mathrm{mm}$

$\Rightarrow$ single-site event (SSE)

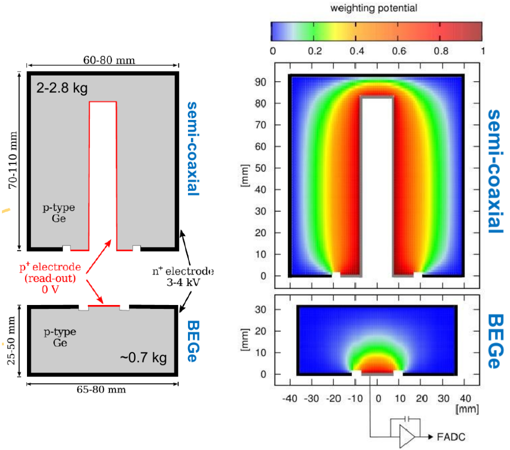
## background




- $\gamma$ events: range of $1\,\mathrm{MeV}$ $\gamma$'s in Ge $> 1\,\mathrm{cm}$

$\Rightarrow$ multi-site event (MSE)

- surface events: $\beta$-particles on $n^+$ surface, $\alpha$-particles on $p^+$ contact




- significantly better PSD for BEGe detectors

- BEGe: smaller capacitance

$\Rightarrow$ better energy resolution: 0.1% at $Q_{\beta\beta}$

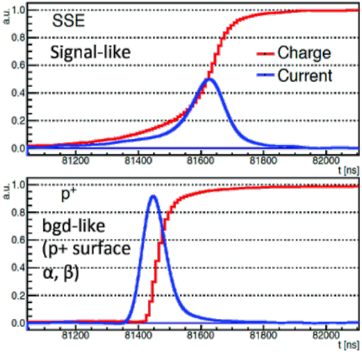
# PSD for BEGe's

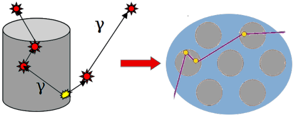
## mono-parametric $A/E$ cut

- $A$ = amplitude of current pulse
- $E$ = energy
- high capability of distinguishing SSE from MSE and surface $p^+/n^+$ events
- well tested and understood method

## Phase I

- tuned using $^{208}$Tl DEP (per definition $A/E = 1$) $\rightarrow$ keep $0.965 < A/E < 1.07$
- $0\nu\beta\beta$ acceptance $= (92 \pm 2)\%$ (determined from $^{208}$Tl DEP and MC); background acceptance @ $Q_{\beta\beta} \leq 20\%$






## LAr scintillation

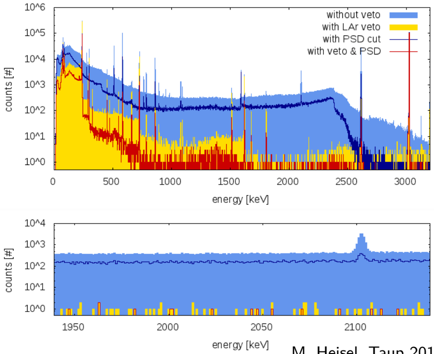
- energy deposition in LAr creates scintillation light @ $\lambda = 128\,\mathrm{nm}$, 40000 pe/MeV
- can be used as anticoincidence veto

## LAr instrumentation

- detect scintillation light with photomultipliers and scintillating fibers coupled to SiPMs
- shift the XUV scintillation light into the visible range

## Proof of LAr-veto concept in low background environment

energy spectrum for an internal Th228 source:




M. Heisel, Taup 2011

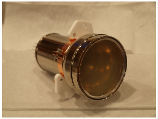
| source | suppression factor | | |
|---|---|---|---|
| | LAr veto | PSD | total |
| $^{228}Th$ | 1180 ± 250 | 2.4 ± 0.1 | 5200 ± 1300 |

# "Hybrid" LAr veto design

- MC simulations (including photon propagation) of important backgrounds conducted
  - suppression factors: $^{214}Bi \approx 10$, $^{208}Tl > 100$
  - validated with data of existing low background facility

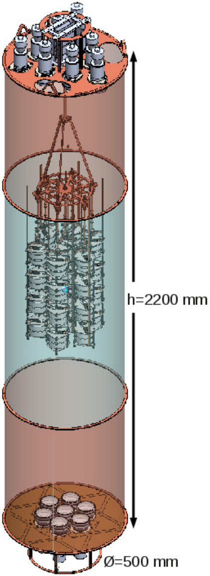
**photomultipliers**

- type: 3 " R 11065-20 MOD
- 9* top, 7* bottom



**scintillating fibers and SiPMs**

- build the middle shroud
- type: BCF-91A coated with TPB
- light readout at both ends by SiPMs on top



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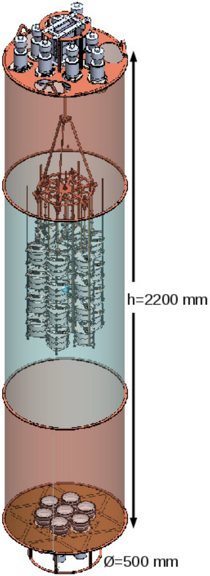
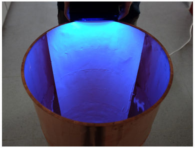
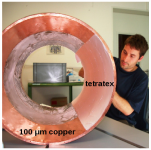



## top/bottom copper shroud + reflective foil

- Tetratex coated with TPB as wavelength shifter
- installed on inner side of copper shrouds





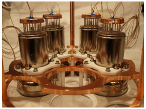
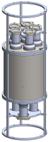

## nylon mini-shrouds

- around each detector string
- transparent & WLS

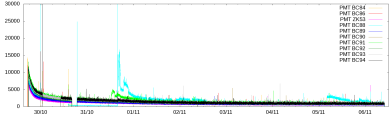
⇒ usable together with light instrumentation

# Current status - LAr veto integration

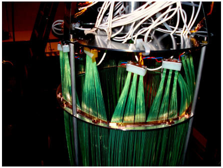
- PMTs and scintillating fibers are tested in dedicated teststands


- longterm tests of PMTs successful

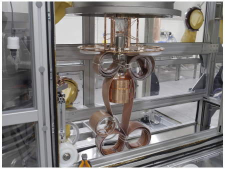



- final production of fiber modules started

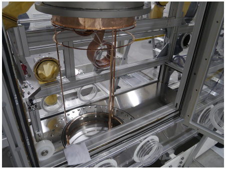



## Mechanical test of the hybrid design in GERDA

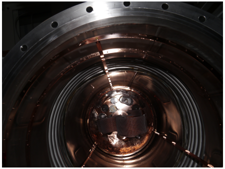
top PMT plate:



top PMT plate & middle fiber shroud:



bottom Cu shroud with bottom PMT plate:



whole setup immersed in GERDA cryostat:

# Conclusion

**GERDA Phase I design goals reached:**

- background index after PSD: 0.01 $\mathrm{cts/(keV\,kg\,yr)}$
- exposure: 21.6 $\mathrm{kg\,yr}$

**No $0\nu\beta\beta$ signal observed at $Q_{\beta\beta} = 2039\,\mathrm{keV}$**

- best fit: $N_{0\nu} = 0$
- limit on half-life: $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}\,\mathrm{yr}$ (90% C.L.)

**Transition to Phase II ongoing:**

- increase of target mass: $\approx 40\,\mathrm{kg}$ of Ge detectors
- new custom made BEGe detectors with enhanced pulse shape discrimination
- liquid argon instrumentation

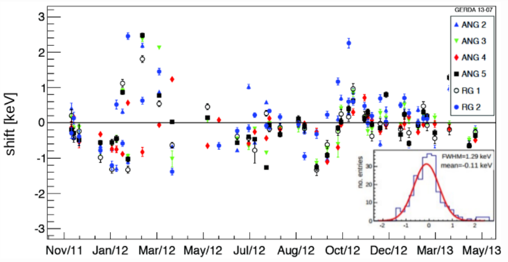
⇒ background $\lesssim 10^{-3}\,\mathrm{(cts/(keV\,kg\,yr)}$

⇒ explore $T_{1/2}^{0\nu}$ values in the range of $10^{26}\,\mathrm{yr}$

Bonus slides

# Calibration, time stability and energy resolution

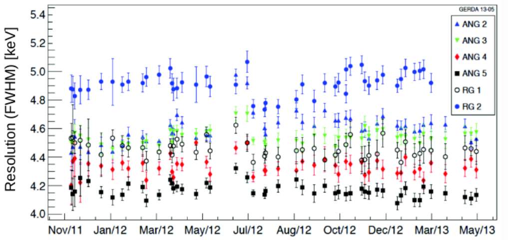
## Shift of $^{208}$Tl FEP @ 2614.5 keV




- (bi-) weekly calibration with movable $^{228}$Th sources
- offline energy reconstruction (semi-Gaussian filter)
- stability monitored with test pulser (0.05 Hz)

drift of 2614.5 keV $\gamma$-line small ($\pm$0.05%) compared to FWHM @ $Q_{\beta\beta}$ of $\sim$0.2%

## Energy resolution @ $Q_{\beta\beta} = 2039$ keV

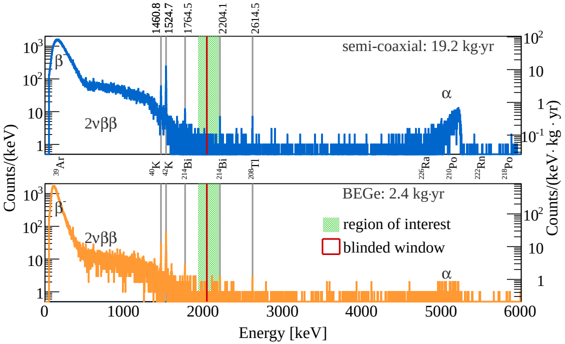


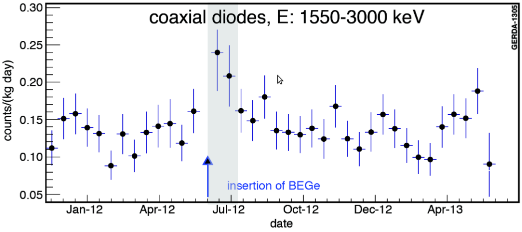

## Mean FWHM of detectors @ $Q_{\beta\beta}$

1. semi-coaxial: $(4.8 \pm 0.2)$ keV
2. BEGe: $(3.2 \pm 0.2)$ keV

automatic blinding of the $Q_{\beta\beta}\pm$20 keV (later $\pm$5 keV) region applied to allow for an unbiased data analysis; validated background model and PSD before perform unblinding

# Blinded physics spectrum




Region Of Interest (ROI) = interval [1930 – 2190] keV

## Main background components:

- $\beta$-spectrum of $^{39}$Ar (with $Q = 565$ keV)
- $2\nu\beta\beta$-spectrum of $^{76}$Ge
- $\gamma$-lines from $^{40}$K, $^{42}$K, $^{60}$Co, $^{214}$Bi, $^{212}$Bi, $^{208}$Tl & $^{228}$Ac
- $\alpha$-spectrum of $^{238}$U chain (in semi-coaxial detectors)

## Division in 3 data sets:

- semi-coaxial data splitted in two sets ("golden", "silver") according to *BI*
- "BEGe" set kept seperated due to different resolution and background

| data set | Exposure [kg·yr] | FWHM @ $Q_{\beta\beta}$ [keV] |
|---|---|---|
| golden | 17.9 | $4.8 \pm 0.2$ |
| silver | 1.3 | $4.8 \pm 0.2$ |
| BEGe | 2.4 | $3.2 \pm 0.2$ |

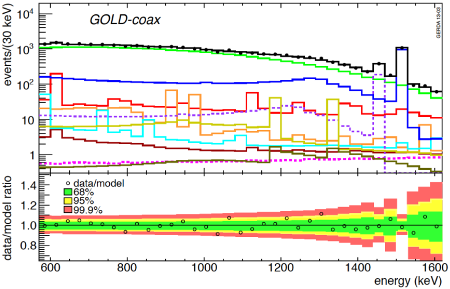
# Background model Eur. Phys. J. C74 (2014) 2764

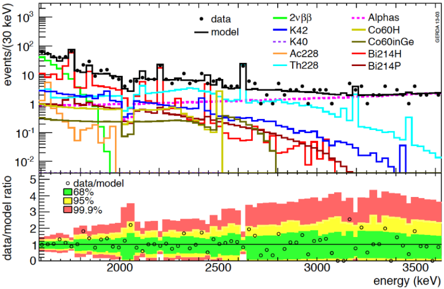
## General procedure:

- simulation of known (from material screening) and observed (from detector operation) background sources
- spectral fit with combination of all components in the energy region between 570 keV and 7500 keV on the 3 data sets
- 2 extremes: "minimum" (all known + visible contributions) & "maximum" (additional contributions from other possible locations)

## Results:

- no $\gamma$-line expected in the blinded window around $Q_{\beta\beta}$
- flat background between 1930 keV and 2190 keV (= ROI) excluding known peaks @ 2103 keV ($^{208}$Tl) as well as 2119 keV ($^{214}$Bi)
- $BI = (1.76 - 2.38) \cdot 10^{-2}\ \frac{\mathrm{cts}}{\mathrm{kg \cdot keV \cdot yr}}$ (depending on assumption of source location)



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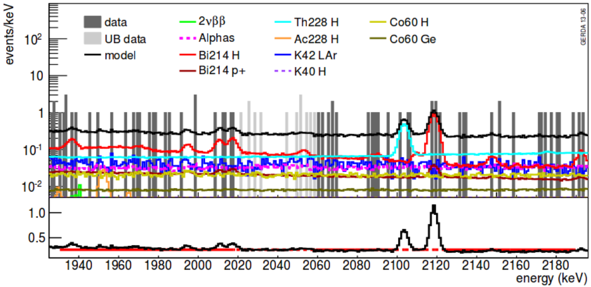
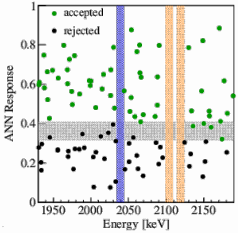
Partial unblinding @ $Q_{\beta\beta}$ $\pm$20 keV $\rightarrow$ $\pm$5 keV with 8.6 $-$ 10.3 expected and 13 observed events



# Pulse shape discrimination (PSD) Eur. Phys. J. C73 (2013) 2583

## semi-coaxial: artificial neural network (ANN)

- TMVA / TMlpANN with 2 hidden layers of $n_{\mathrm{var}}$ and $n_{\mathrm{var}}+1$ nodes
- Input: time when charge pulse reaches 1%, 3%,...,90% of maximum ($n_{\mathrm{var}}=50$)
- training using $^{228}$Th calibration data
  $\rightarrow$ SSE: $^{208}$Tl DEP @ 1620.7 keV
  $\rightarrow$ MSE: $^{212}$Bi FEP @ 1592.5 keV
- cut defined such that the acceptance of $^{208}$Tl DEP is fixed to 90%
- $0\nu\beta\beta$ acceptance $= 90^{+5}_{-9}$%; background acceptance @ $Q_{\beta\beta}$ ~55%





cross checks

$2\nu\beta\beta$: $(85 \pm 2)$%

compton edge: (85-94)%

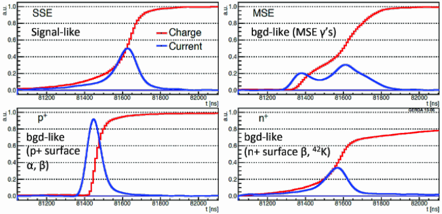
$^{56}$Co DEP: (83-95)%

2 alternative PSD

## BEGe: mono-parametric $A/E$

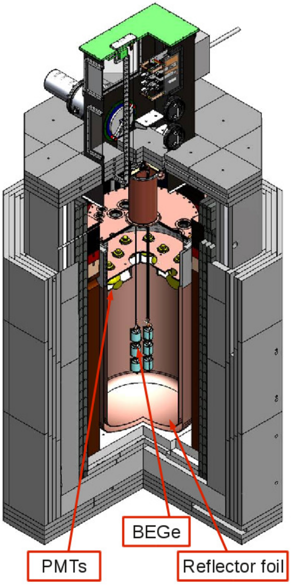
- $A$ = amplitude of current pulse
- $E$ = energy

- high capability of distinguising SSE from MSE and surface p$^+$/n$^+$ events
- tuned using $^{208}$Tl DEP (per definition $A/E=1$) $\rightarrow$ keep $0.965 < A/E < 1.07$
- well tested and understood method
- $0\nu\beta\beta$ acceptance $= (92 \pm 2)$% (determined from $^{208}$Tl DEP and MC); background acceptance @ $Q_{\beta\beta}$ $\leq$20%

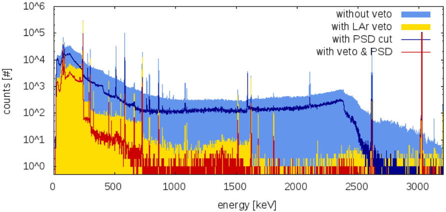


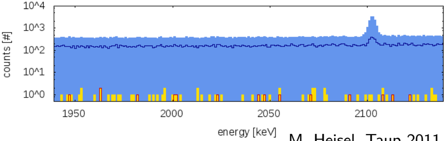
# LArGe - a test facility for GERDA

## Proof of LAr-veto concept in low background environment




energy spectrum for an internal Th228 source:

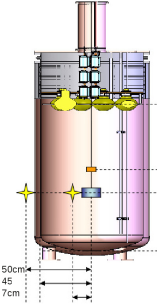


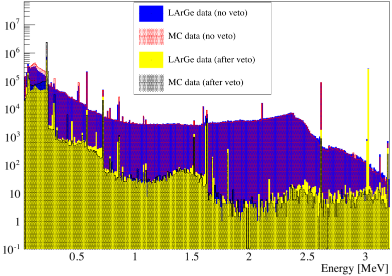

M. Heisel, Taup 2011

| source | position | suppression factor LAr veto | PSD | total |
|---|---|---|---|---|
| $^{228}Th$ | int | 1180 ± 250 | 2.4 ± 0.1 | 5200 ± 1300 |
| | ext | 25 ± 1.2 | 2.8 ± 0.1 | 129 ± 15 |
| $^{226}Ra$ | int | 4.6 ± 0.2 | 4.1 ± 0.2 | 45 ± 5 |
| | ext | 3.2 ± 0.2 | 4.4 ± 0.4 | 18 ± 3 |
| $^{60}Co$ | int | 27 ± 1.7 | 76 ± 8.7 | 3900 ± 1300 |

# Physics validation of Monte Carlo using photon tracking
## Comparison to LArGe data




- simple geometry
- data with various sources in different locations available




- tuning of optical properties
  - material reflectivities (Ge, Cu, VM2000, ... )
  - absorption and emission spectra
  - LAr attenuation length, light yield and triplet lifetime
- good MC description after tuning

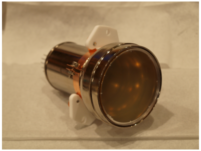
⇒ can be used to design the LAr veto for GERDA

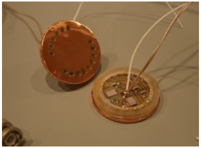
| bg | LArGe data | MC |
|---|---|---|
| | internal | |
| $^{208}Tl$ | $1180 \pm 250$ | $909 \pm 235$ |
| $^{214}Bi$ | $4.6 \pm 0.2$ | $3.8 \pm 0.1$ |
| $^{60}Co$ | $27 \pm 2$ | $16.1 \pm 1.3$ |
| | external | |
| $^{208}Tl$ | $25 \pm 1.2$ | $17.2 \pm 1.6$ |
| $^{214}Bi$ | $3.2 \pm 0.2$ | $3.2 \pm 0.4$ |

# “Hybrid” LAr veto design
## Instrumentation induced BI [cts/(keV kg yr)]

| background source | | activity | BI w/o LAr veto | BI with LAr veto * |
|---|---|---|---|---|
| PMTs + VD | $^{228}Th$ | $< 2.44\,\mathrm{mBq/PMT}$ | $< 3.1(1) * 10^{-4}$ | $< 3.1(5) * 10^{-6}$ |
| | $^{226}Ra$ | $< 2.84\,\mathrm{mBq/PMT}$ | $< 5.5(2) * 10^{-5}$ | $< 2.7(5) * 10^{-6}$ |
| cable | $^{228}Th$ | $< 14.4\,\mu\mathrm{Bq/m}$ | $< 2.4(1) * 10^{-4}$ | $< 7.0(2) * 10^{-6}$ |
| | $^{226}Ra$ | $< 11.2\,\mu\mathrm{Bq/m}$ | $< 3.9(1) * 10^{-5}$ | $< 5.5(2) * 10^{-6}$ |
| top & bottom shroud (Tetratex & copper) | $^{228}Th$ | $< 103\,\mu\mathrm{Bq/m^2}$ | $< 2.7(1) * 10^{-5}$ | $< 9.9(5) * 10^{-7}$ |
| | $^{226}Ra$ | $< 282\,\mu\mathrm{Bq/m^2}$ | $< 1.2(1) * 10^{-5}$ | $< 1.5(1) * 10^{-6}$ |
| sum | $^{228}Th$ | | $< 5.8(1) * 10^{-4}$ | $< 1.1(1) * 10^{-5}$ |
| | $^{226}Ra$ | | $< 1.1(1) * 10^{-4}$ | $< 9.8(6) * 10^{-6}$ |
| | total | | $< 6.8(1) * 10^{-4}$ | $< 2.1(1) * 10^{-5}$ |

# Photomultiplier - Hardware



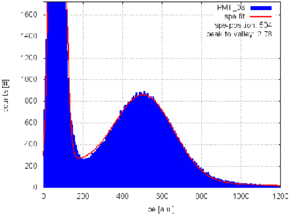


screening results [mBq/pc]

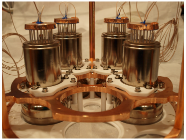
| | $^{228}Th$ | $^{226}Ra$ |
|---|---|---|
| PMT * | $< 1.94$ | $< 1.7$ |
| VD | $< 0.5$ | $< 1.14$ |

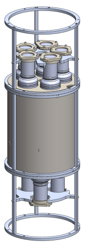
* calculated from component screening

peak-to-valley: 4:1



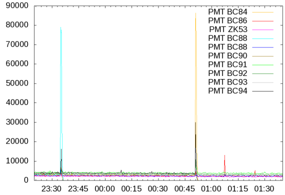

## teststand

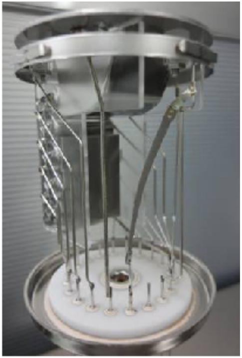




test of up to 10 PMTs in LAr

- ➢ light yield measurements with internal sources
- ➢ gain calibration with LED
- ➢ signal rate monitoring
- ➢ longterm test up to 6 weeks performed



DM2014 on February 28, 2014, Yuji Hotta, Hamamatsu

some of the PMTs exhibited light production when operated in LAr

likely cause: discharges of electron surface charges on ceramic stem

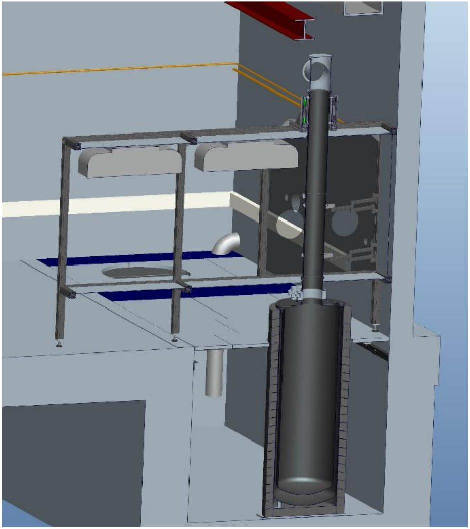
iterative process in close cooperation with Hamamatsu to solve flashing of PMTs

several countermeasures investigated:

- reduce supply voltage between pins
- enlarge distance between pins
- put metal or quartz plate on ceramic stem

⇒ significant improvement of PMT stability in later modifications

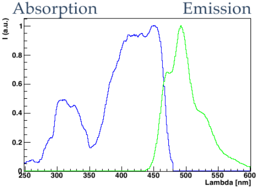
# Fibers - Hardware
## TUM cryostat

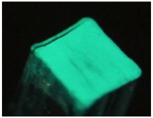


## Fibers - Hardware

scintillating fibers coated with TPB

- fibers themselve are WLS



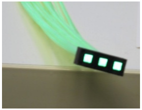
- screening results
  $^{228}Th$: $0.058\,\mathrm{Bq/kg}$

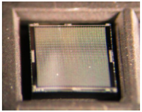
  $^{226}Ra$: $0.042\,\mathrm{Bq/kg}$

9 fibers per SiPM

- readout at the top

⇒ far from detectors





SiPMs at LN temperature

- good QE, negligible dark rate
- Ketek SiPMs in 'die' → low background packaging