Searching for extremely rare events with the GERDA experiment

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GERDA

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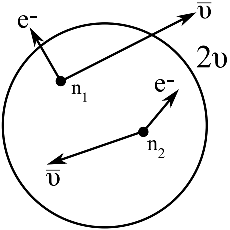
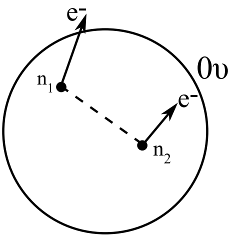
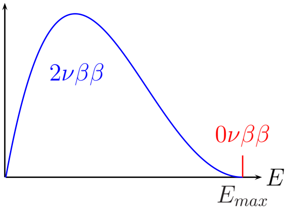
Interdisciplinary Cluster Workshop
"Detectors and Instrumentation",
May 31th, 2016

$0\nu\beta\beta$-Decay

- Single β-decay not allowed for some isotopes, only double β-decay
- If $0\nu\beta\beta$-decay exists, ν must be a Majorana Particle ($\nu = \bar{\nu}$)



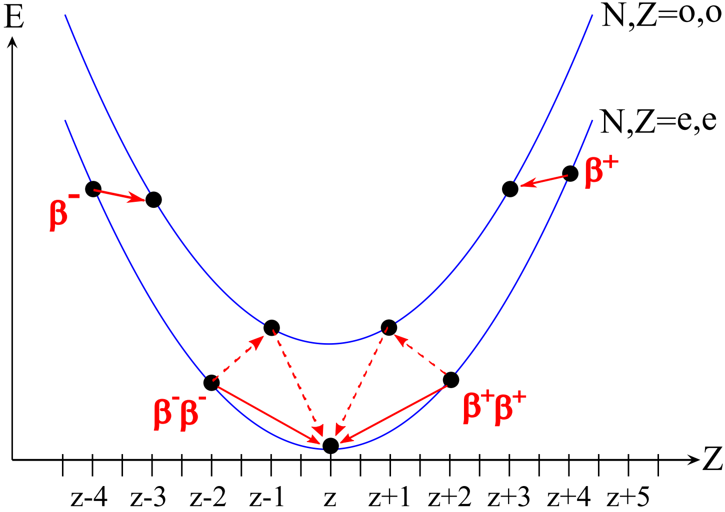




$$\left(T_{1/2}^{0\nu}\right)^{-1} = G(Q,Z)\,\left|M_{\mathrm{nucl}}\right|^2 \langle m_{ee}\rangle^2$$

- Discovery of $0\nu\beta\beta$-decay would
  - Imply lepton-number violation
  - Determine nature of ν (Majorana or Dirac).
  - Give information about absolute Neutrino mass / hierarchy?

Single and Double Beta Decay



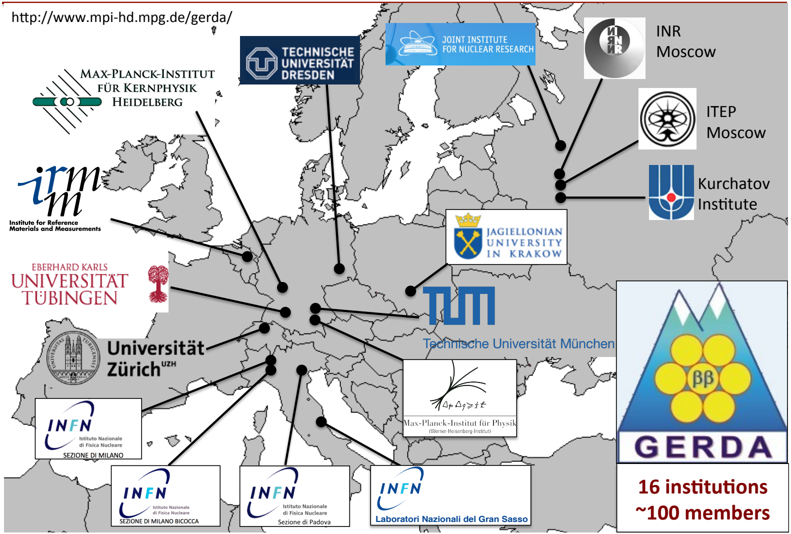
Low-Background Challenge

- Expected $0\nu\beta\beta$-decay half lives very long ($>= 10^{26}$ years): Background must be almost zero
- Need enough active material
  $\rightarrow$ Isotope enrichment
- Need to get rid of radioactive background:
  - Cosmic background
    $\rightarrow$ Need underground location
  - Environmental radiation
    $\rightarrow$ Need excellent shielding
  - Radiation from materials used in setup
    $\rightarrow$ Need very radio-pure materials
  - Intrinsic $2\nu\beta\beta$-Background
    $\rightarrow$ Need good energy resolution

The GERDA Experiment

- Search for $0\nu\beta\beta$-Decay in $^{76}\mathrm{Ge}$ at $Q_{\beta\beta} = 2039 keV$
- Array of isotopically enriched HPGe detectors, suspended in liquid Argon
- Ultra-low background setup, located underground at LNGS
- Phase-I completed very successfully, world-best limit for $^{76}\mathrm{Ge}$ $0\nu\beta\beta$-Decay
- Phase-II will go beyond: Increased total detector mass, even lower background
- Current status: Phase-II data taking

The GERDA Collaboration



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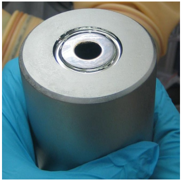
Why use $^{76}\mathrm{Ge}$?



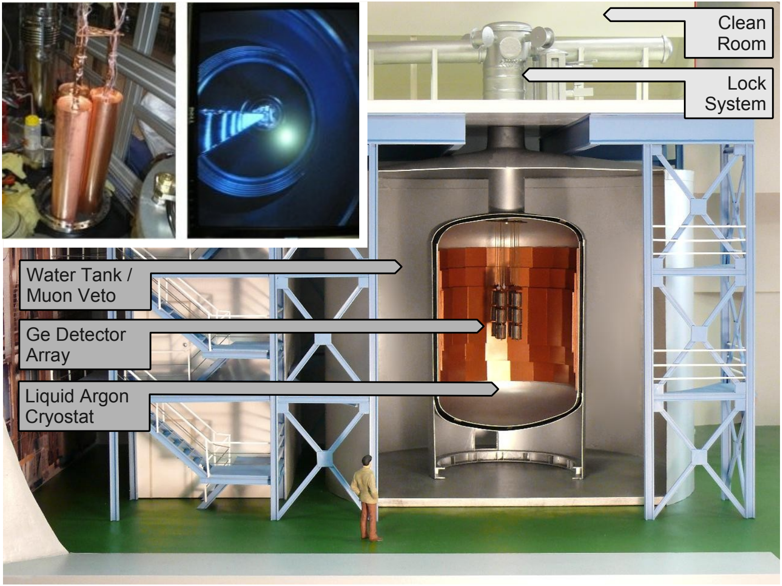
Advantages:

- Source = Detector
- Production of enriched detectors up to 86% well established (though expensive)
- HPGe has excellent energy resolution, important since:
  $T_{1/2} \propto \epsilon \cdot A\sqrt{\frac{M \cdot T}{b \cdot \Delta E}}$
- Intrinsically pure

Challenges:

- As for all $0\nu\beta\beta$ experiments:
  - Must be well shielded from cosmics and external radiation
  - Radio-pure setup, carefully select and screen all materials
- Detector operation under cryogenic conditions
- Cosmic activation of detector material ($\rightarrow$ $^{60}\mathrm{Co}$ and $^{68}\mathrm{Ge}$)

The Gerda Setup



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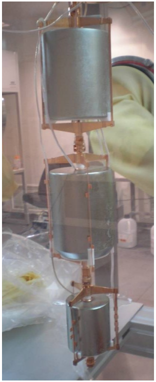
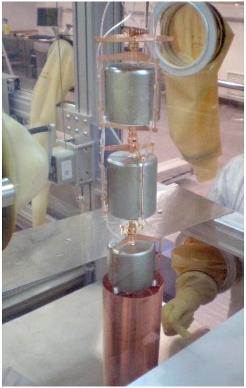
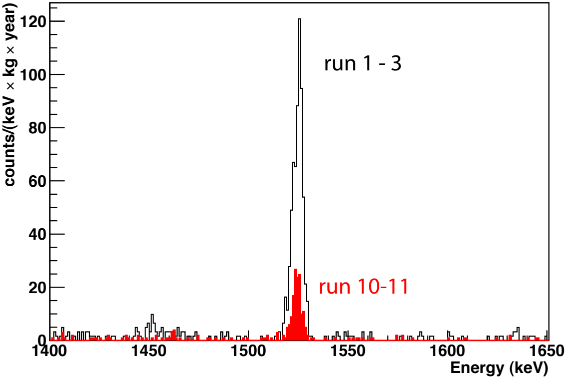
Gerda Phase-I Detectors



- 8 enriched coaxial detectors from HDM and IGEX (17.7 kg, Nov. 2011 - June 2013)
- 1 non-enriched coaxial detector (3.0 kg)
- May 2012 to June 2013: 5 enriched Phase-II BEGe detectors (3.6 kg)

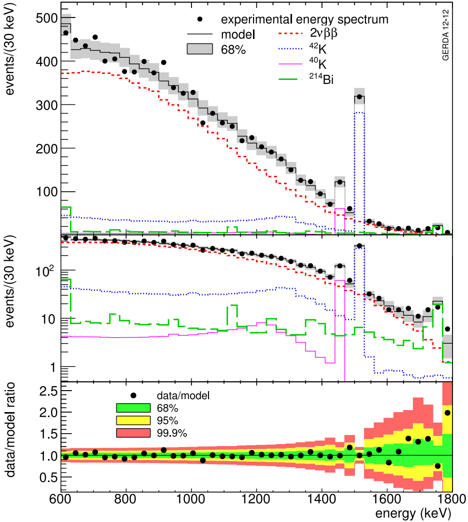
An Unexpected Background





- Observed background 10 $\times$ higher than expected
- $^{42}\mathrm{Ar} \rightarrow {}^{42}\mathrm{K}$, charged $^{42}\mathrm{K}$ drift in E-field of detectors and decay there
- Copper mini-shrouds shield detector strings

Measurement of $^{76}\mathrm{Ge}$ $2\nu\beta\beta$ Half-Life



$$T_{1/2}^{2\nu} = \left(1.84^{+0.09}_{-0.08\ \mathrm{fit}}\ {}^{+0.11}_{-0.06\ \mathrm{syst}}\right) \times 10^{21}\mathrm{yr} = \left(1.84^{+0.14}_{-0.10}\right) \times 10^{21}\mathrm{yr}$$

J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110

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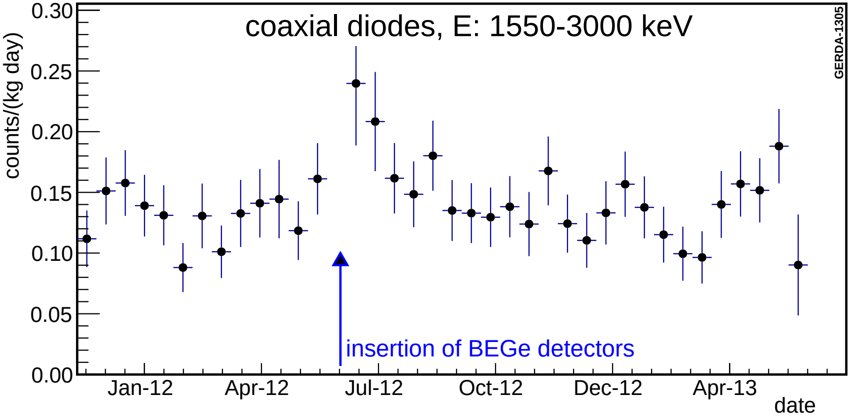
Phase-I Background Stability



- Background index (1550 to 3000 keV) stable over time, temporary increase due to BEGe detector insertion

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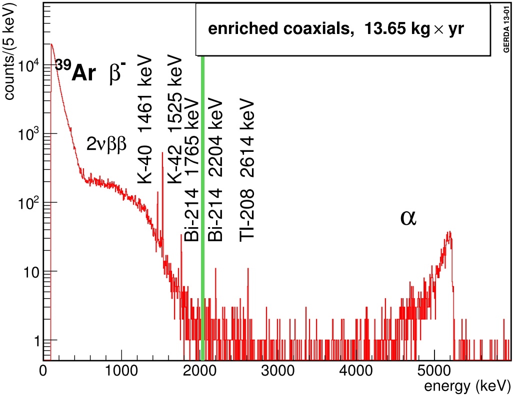
Phase-I Background



No contribution at $Q_{\beta\beta}$:
^{39}Ar (Q_β = 565 keV), **^{40}K**, **^{228}Ac**

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

- **^{42}K** (^{42}Ar) → Q_β = 3.5 MeV, E_γ = 2.4 MeV
- **^{214}Bi** (^{238}U) → Q_β = 3.3 MeV, E_γ = 2.1, 2.2, 2.4 MeV
- **^{208}Tl** (^{232}Th) → E_γ = 2.6 MeV
- **^{60}Co** → Q_β = 2.8 MeV
- **α-induced events** (from isotopes in ^{238}U chain)

- Blinded window: 40 keV around $Q_{\beta\beta} = 2039$ keV
- Achieved background index: 0.02 cts/(keV kg yr) in ROI: 10 × better than HdM and IGEX

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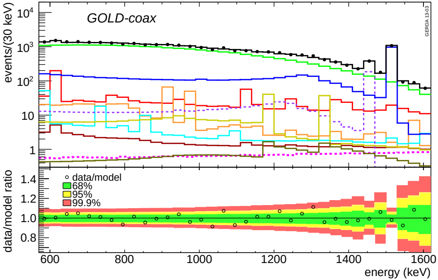
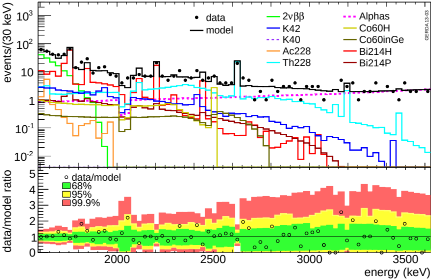
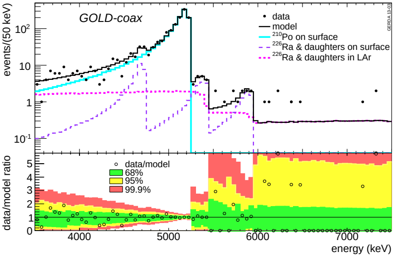
Phase-I Background Decomposition







Background index:

- 2×10^{-2} cts/(keV·kg·yr) [EPJC 74 (2014) 2764]
- 1×10^{-2} cts/(keV·kg·yr) after PSD
- Design goal reached

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Pulse-Shape Discrimination

- Use the cleanest materials, build the best way you possibly can, some background always remains
- Need to reduce background further during data analysis
- Separate signal events (e.g. $0\nu\beta\beta$-decay) from certain background events (e.g. Compton-scattering) by analysing shape of detector signal?
- Pulse shape discrimination (PSD)!

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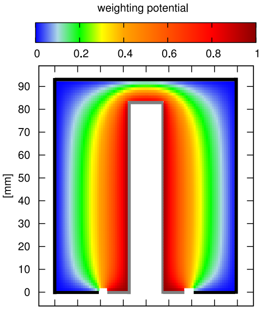
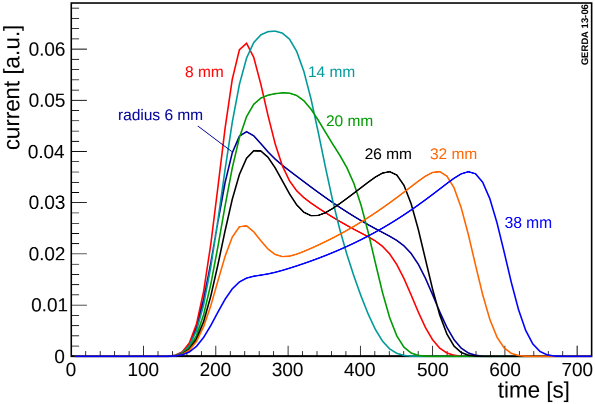
Coaxial Detector PSD





- Very complex issue
- New PSD algorithm used in Phase-I [EPJC 73 (2013) 2583]
- Easier for BeGe detectors (discussed later on)

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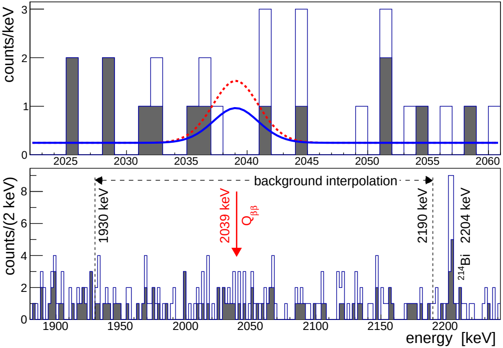
Phase-I Result



- Blind analysis: Everything frozen before unblinding of last ± 5 keV window around 2039 keV in June 2013
- 7 events in blinded region, 3 remain after PSD
- Phase-I Result: $T^{0\nu}_{1/2} > 2.1 \times 10^{25}$ yr (90% C.L.), $T^{0\nu}_{1/2} > 3.0 \times 10^{25}$ yr in combination HDM and IGEX results [Phys. Rev. Lett. 111 (2013) 122503]

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GERDA Phase-II

- GERDA Phase-I completed successfully - now taking data in GERDA Phase-II
- Design goals:
  - Sensitive to half-life of 10^{26} yr with exposure of 100 kg yr
  - Understand whether technology is suitable for ton-scale
- Increased active mass: 18 kg $\rightarrow$ 38 kg
  - 28 new BEGe-type HPGe detectors, additional mass of 20 kg
  - Phase-I coaxial detectors (18 kg) will be re-used in Phase-II
- Lower background: $1 \times 10^{-2} \rightarrow 1 \times 10^{-3}$ cts/(keV·kg·yr)
  - New detector technology: BEGe detectors (already tested a few in Phase-I)
  - Active veto around detectors: LAr instrumentation
  - Cleaner/less material: detector holders, electronics, cables

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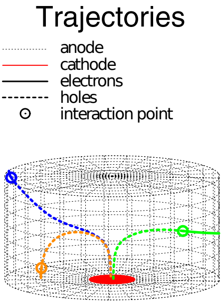
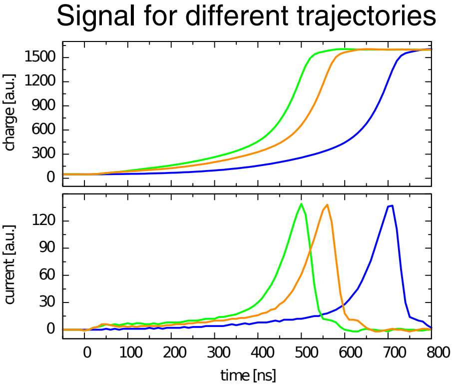
BeGe Detectors for Phase-II





- BeGe: Broad-Energy Germanium Detector (Canberra)
- No bore-hole, small contact:
  - Small capacitance, higher energy resolution
  - Strong weighting field
- Charges from different points $\rightarrow$ signals at different times

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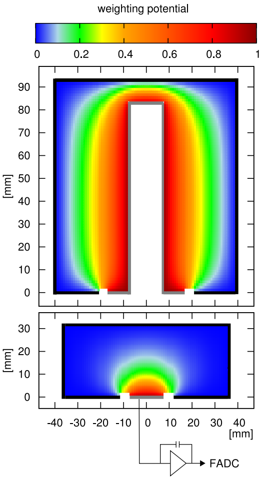
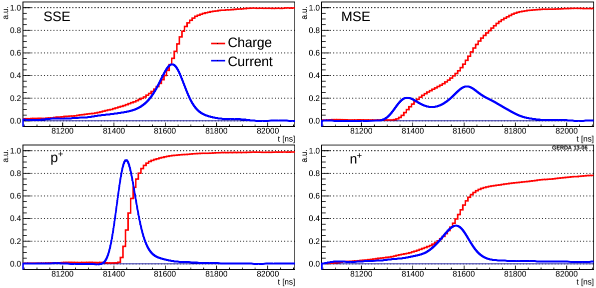
BEGe Detector PSD





- BEGe detectors have steep weighting potential
  → PSD more effective
- Also rejection of surface backgrounds

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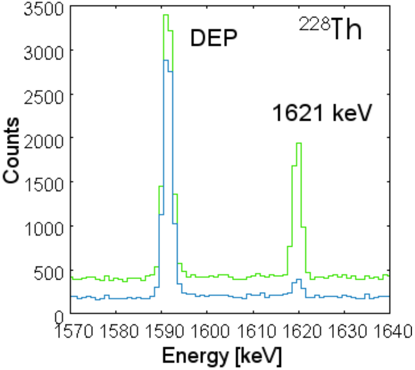
MSE Suppression with BeGe Detectors



D. Budjas et al., JINST 4P10007 (2009)

green: before PSA, blue: after PSA

- Double-escape peak (DEP): Mostly single-site events (simulates $0\nu\beta\beta$-decay)
- $^{212}\mathrm{Bi}$ γ-line at $1621\mathrm{keV}$: Mostly multi-site events (simulates γ-background)

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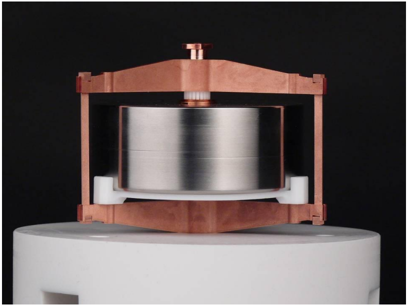
BeGe Detector Production



- 2005: 37.5 kg GeO_2 produced by ECP, Zelengorsk, Russia
- 2010: Reduction and zone refinement, PPM Metals GmbH, Rammelsberg, Germany
- 2011-12: Crystal pulling and cutting, Canberra, Oak Ridge
- 2012: Detector production at Canberra, Olen (Belgium) & testing (HADES underground lab, Mol (Belgium).
- All Ge transport in shielded shipping container (Water plus Steel shield)

[JINST 8 P04018, JINST 8 P06012]

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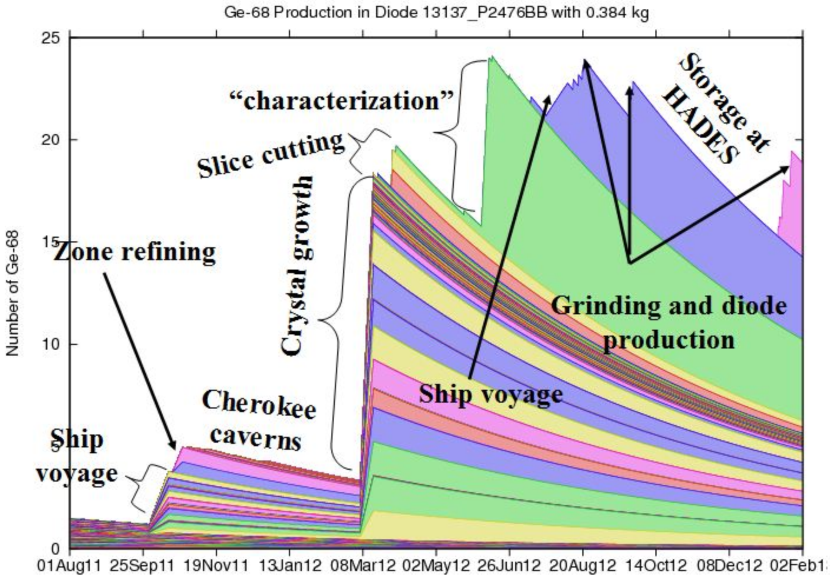
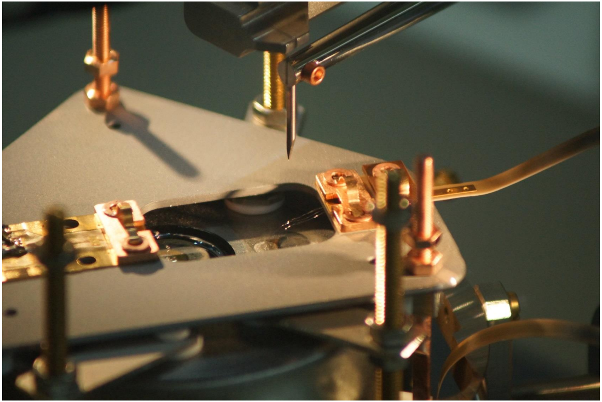
^{68}Ge Activation During Production

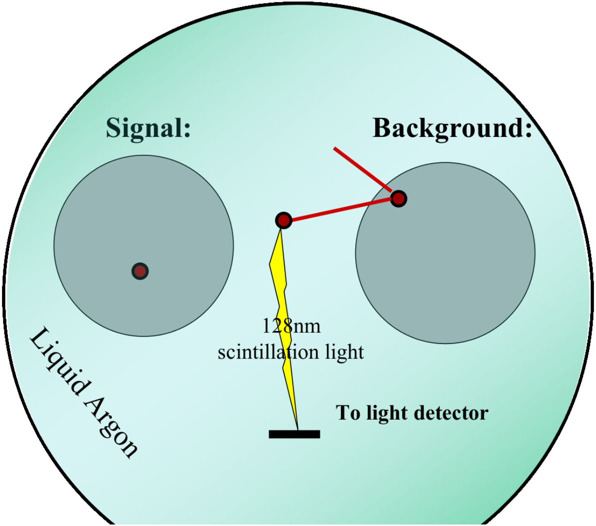


Phase-II Detector Holders



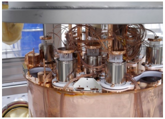
- Built from semiconductor-grade silicon and e-copper
- Detectors contacted by wire-bonding

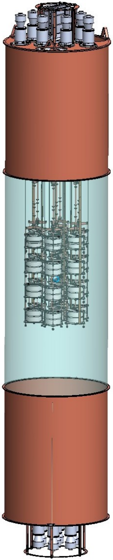
LAr Scintillation as Background Veto



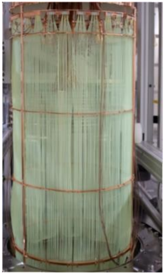
LAr Instrumentation

Top PMTs

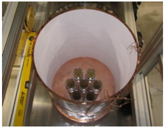


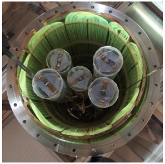


Fiber Cylinder



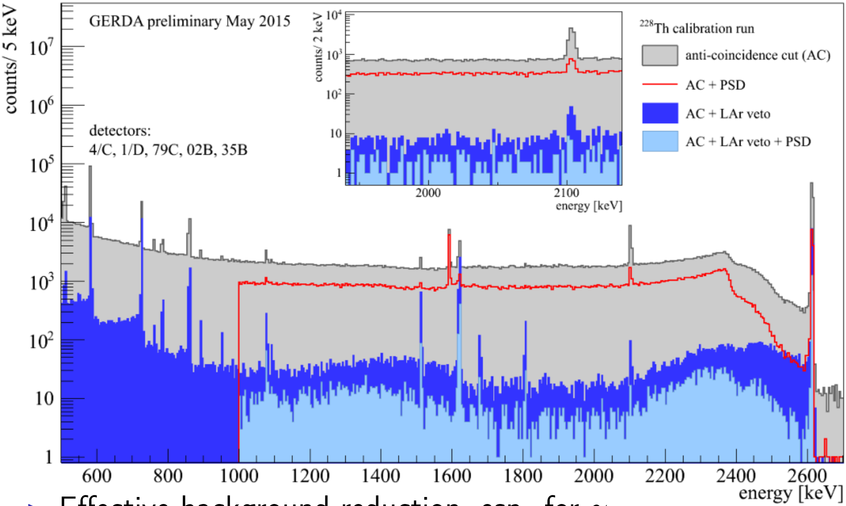
Bottom PMTs





- Liquid Argon scintillates: High potential for background reduction (esp. γ)
- Instrumentation of LAr volume around detectors as background veto

LAr Veto Background Reduction



- Effective background reduction, esp. for γ

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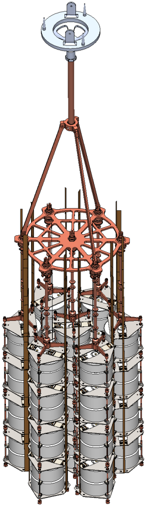
Phase-II Detector Array



- Phase-II array is very different:
  - Single array with 7 strings → large diameter
  - Increased weight:
    More detectors and LAr instrumentation
  - A lot more channels → a lot more cables
- Needed new lock system and cabling solution

- It's a tight fit!

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Phase-II Integration

- First insertion Phase-II-type multi-string array in July
- Improvement of detector reliability during commisioning
- Integration is teamwork!
- Installed last detectors end of 2016

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Phase-II Background Expectations

background [10^{-3} cts/(keV·kg·yr)]	without cuts	after PSD cuts	after PSD & veto († opaque MS)
^{228}Th (near)	≤ 5 *	≤ 2.3	≤ 0.01
^{228}Th (1 m away)	< 3	< 1.3	< 0.01
^{228}Th (distant)	< 3 ?	< 1.2 ?	< 0.1 ?
^{214}Bi (holder/MS)	≤ 5 *	≤ 1.7	≤ 0.13 († 0.5)
^{214}Bi (near p+)	< 6	< 0.13	< 0.03 († 0.07)
^{214}Bi (n+)	< 7 ?	< 0.7 ?	< 0.15 († 0.4)
^{214}Bi (1 m away)	< 3	< 1	< 0.08 († 0.2)
^{60}Co (near)	1	0.02	0.001
^{60}Co (in Ge)	≤ 0.3	≤ 0.006	≤ 0.0004
^{68}Ga (in Ge)	≤ 2.3	≤ 0.21	≤ 0.04
^{226}Ra (α near p+)	1.5	< 0.03	< 0.03
^{42}K (β on n+)	~ 20	< 1	< 0.86
unknown (n?)	?	?	?

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Conclusions and Outlook

- Searching for such rare events is very, very hard!
- Gerda Phase-I:
  - Achieved background index of 1×10^{-2} cts/(keV·kg·yr)
  - New limit on $0\nu\beta\beta$ decay: $T_{1/2}^{0\nu} > 2.1 \times 10^{25}$ yr
- Gerda Phase-II:
  - Additional 20 kg of detector mass (new technology)
  - New materials and techniques for lower background
  - Design goal: 1×10^{-3} cts/(keV·kg·yr)
- Next step on the road:
  A one-ton $^{76}\mathrm{Ge}$ experiment?

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