A liquid Argon scintillation veto for the GERDA experiment

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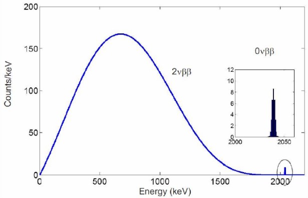
The GERDA experiment

double beta decay

$^{76}\text{Ge} \rightarrow {}^{76}\text{Se} + 2e^- + 2\bar{\nu}_e$
$^{76}\text{Ge} \rightarrow {}^{76}\text{Se} + 2e^-$

energy spectrum



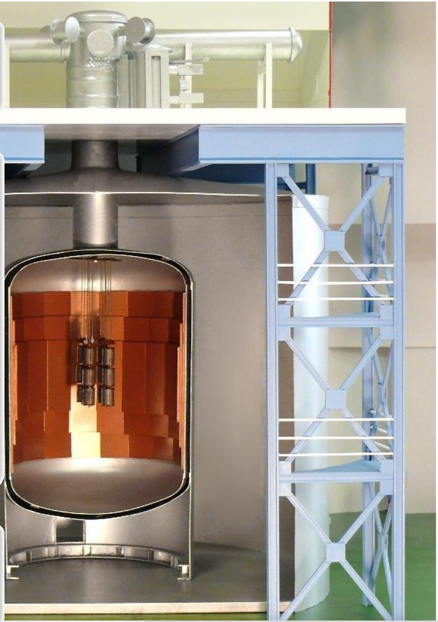
$T^{2\nu}_{1/2} = (1.84^{+0.14}_{-0.08})\, 10^{21}\,\text{yr}$ — J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110

$T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}\,\text{yr}\ (90\%\,C.L.)$ — Phys. Rev. Lett 111 (2013) 122503

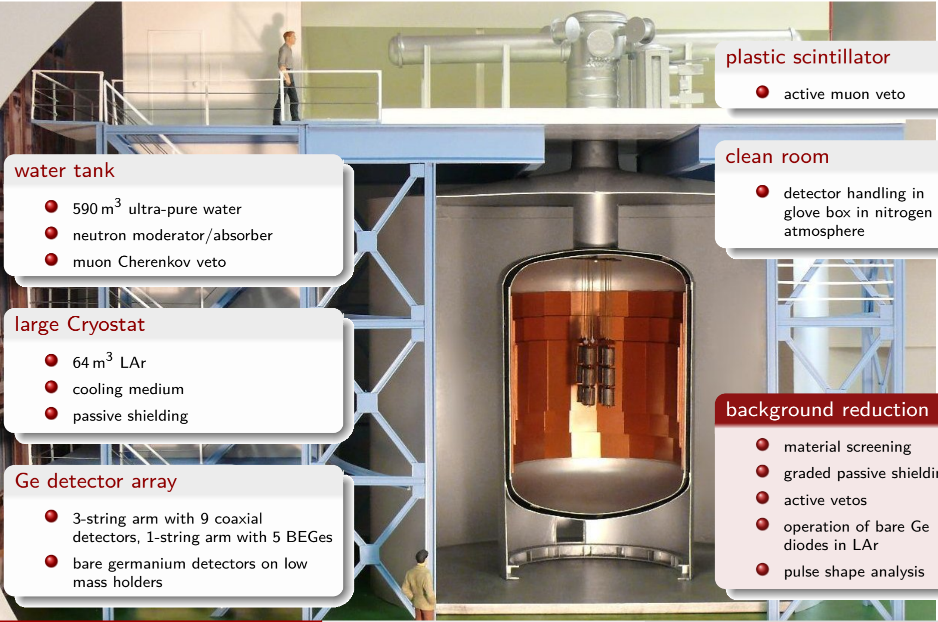
main challenge

fight and understand background at

$Q_{\beta\beta} = 2039\,\text{keV}$



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

The GERDA experiment

sensitivity to the lower limit of the half life scale of $0\nu\beta\beta$ decay

$$T_{1/2} \propto \epsilon a \sqrt{\frac{Mt}{BI \cdot \Delta E}}$$

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

Phase I:

- November 2011 - May 2013
- mass of operational detectors:
  $M_{\mathrm{coaxial,\ enr}} = 14.63\,\mathrm{kg}$
  $M_{\mathrm{coaxial,\ nat}} = 2.96\,\mathrm{kg}$
  $M_{\mathrm{BEGe}} = 3.00\,\mathrm{kg}$
- energy resolution @ 2.6 MeV (FWHM):
  $\Delta E_{\mathrm{coaxial}} \approx 4.2 - 5.8\,\mathrm{keV}$
  $\Delta E_{\mathrm{BEGe}} \approx 2.6 - 4.0\,\mathrm{keV}$
- BI $\approx 0.01\,\mathrm{cts/(keV\,kg\,yr)}$ after PSD

Phase II

- additional 20 kg of enr Ge detectors (BEGe)
- cleaner and lighter detector holders, cables, ...

aspired BI $\leqslant 10^{-3}\,\mathrm{cts/(keV\,kg\,yr)}$

$\Rightarrow$ active background suppression methods are needed

- ➢ detector anticoincidence
- ➢ water cherenkov veto
- ➢ pulse shape analysis
- ➢ **LAr scintillation veto** will be installed

LAr scintillation veto for background suppression

How does an active LAr veto work?

signal

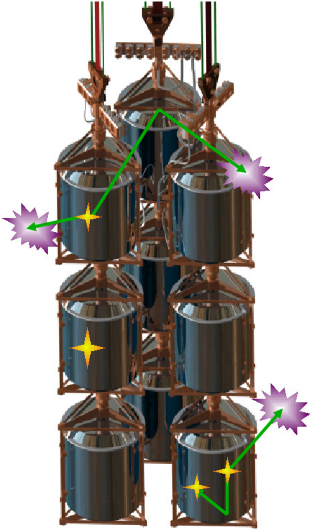
$0\nu\beta\beta$ event deposits its energy at a single point in the Ge-crystal $\rightarrow$ single site event

backgrounds

- γ background: mainly compton scattered events from natural decay chains (^{228}Th, ^{226}Ra)
- α and β decays near/on detector surface (^{226}Ra, ^{42}K)

γ background

1. two compton scatterings in one Ge detector: $\rightarrow$ multi site event, vetoed by PSD
2. compton scattering in two different Ge detectors: $\rightarrow$ vetoed by detector anticoincidence
3. compton scattering in one Ge detector and in LAr: $\rightarrow$ can be vetoed by a LAr scintillation veto



LAr scintillation veto for background suppression

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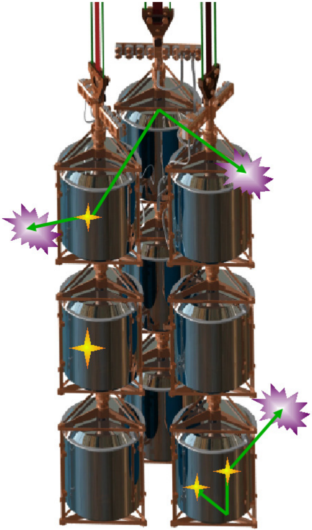

LAr instrumentation

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

LAr scintillation veto for background suppression

How does an active LAr veto work?

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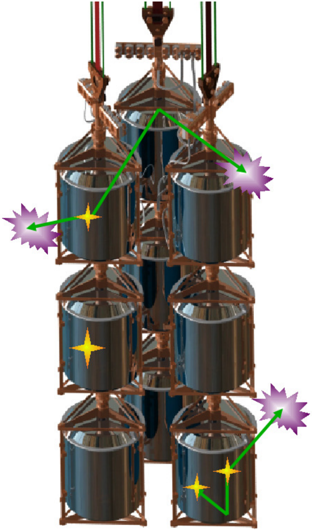
- γ background: mainly compton scattered events from natural decay chains (^{228}Th, ^{226}Ra)
- α and β decays near/on detector surface (^{226}Ra, ^{42}K)

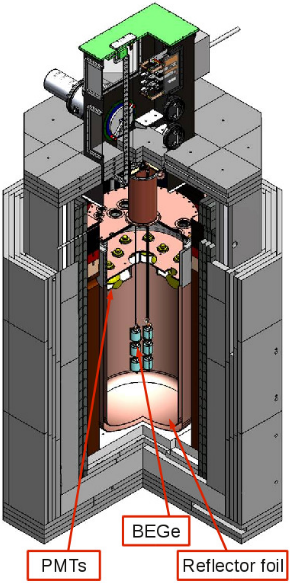
surface β, α background

1. single site events but modified pulse shape due to energy deposition in dead layer $\rightarrow$ PSD
2. part of energy deposition can be in LAr $\rightarrow$ LAr scintillation veto

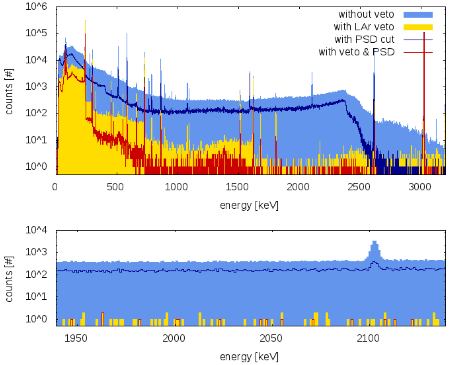


LArGe - a test facility for GERDA

Experimental verification



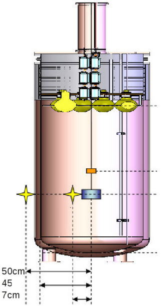
energy spectrum for an internal Th228 source:



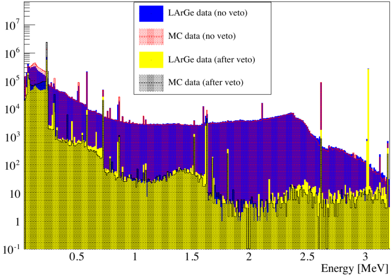
suppression factors at $Q_{\beta\beta} \pm 35\,\mathrm{keV}$:
LAr $\approx$ 1200; PSD $\approx$ 2.4

LArGe - a test facility for GERDA

Monte Carlo validation & tuning of optical parameters



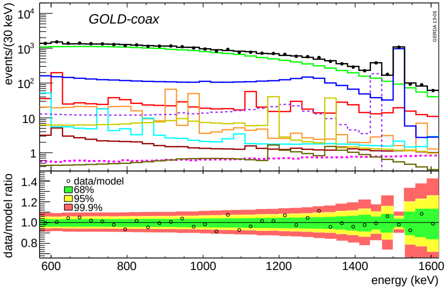
- simple geometry
- measurements available

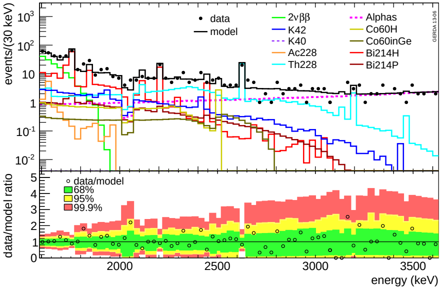


- tuning of optical properties
  - ➢ material reflectivities (Ge, Cu, VM2000, ...)
  - ➢ absorption and emission spectra
  - ➢ LAr attenuation length, light yield and triplet lifetime
- good MC description after tuning

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

Phase I background





Phase I background contributions for enriched coaxial detectors

component	location	BI in $Q_{\beta\beta} \pm 5\,\mathrm{keV}$ $[10^{-3}\,\mathrm{cts/(keV\,kg\,yr)}]$	relative contribution
total		18.5	
^{42}K	LAr homogenous	3.0	16.2 %
^{60}Co	det. assembly	1.4	7.6 %
^{60}Co	germanium	0.6	3.2 %
^{214}Bi	det. assembly	5.2	28.1 %
^{214}Bi	p^+ surface	1.4	7.6 %
^{228}Th	det. assembly	4.5	24.3 %
α model	p^+ surface	2.4	13.0 %

background in BEGe data set

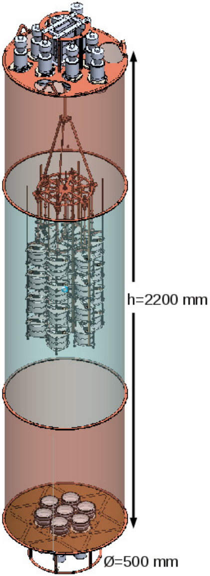
- additional contribution from ^{42}K on n^+ surface
- 50 % of total background

Light instrumentation for GERDA

- result of MC simulation optimization campaign
- uses combination of PMTs and scintillation fibers to read-out the scintillation light

requirements on light instrumentation

- big instrumented volume
- low instrumentation-induced background
  - ➢ photomultiplier
  - ➢ wavelength shifting fibers
  - ➢ wavelength shifting and reflective foil
- applicable without LAr drainage



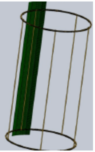
“Hybrid” LAr veto design

photomultiplier

- type: 3 “ R 11065-10/-20
- 9* top, 7* bottom

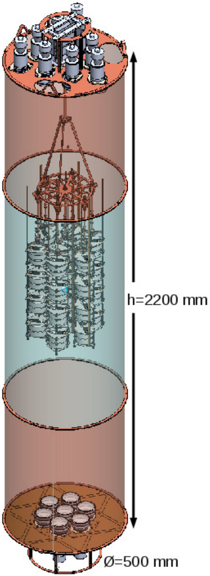
scintillating fibers

- build the middle shroud
- type: BCF-91A coated with TPB
- light readout at upper end by SiPMs

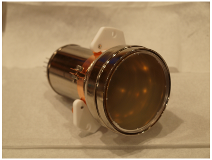


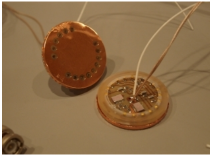
copper shroud + reflective foil

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



Photomultiplier - Hardware





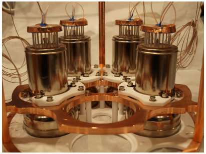
screening results [mBq/pc]

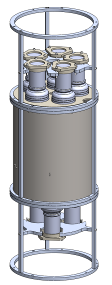
	^{228}Th	^{226}Ra
PMT *	< 1.94	< 1.7
VD	< 0.5	< 1.14

* calculated from component screening

currently screening of 6 R11065-10 PMTs

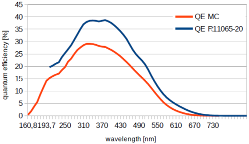
teststand



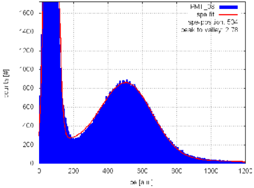


- test of up to 10 PMTs in LAr
- light yield measurements
- gain measurements

R11065-20 has higher QE than R11065-10



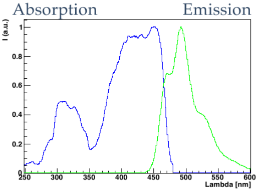
peak-to-valley:

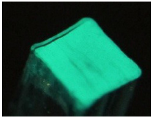


Fibers - Hardware

scintillating fibers coated with TPB

- fibers themselve are WLS





- screening results

  ^{228}Th: 0.058 Bq/kg

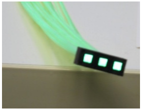
  ^{226}Ra: 0.042 Bq/kg

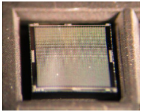
9 fibers per SiPM

- readout on one end

⇒ dirtiest parts far from detector

- reflective surface on other end

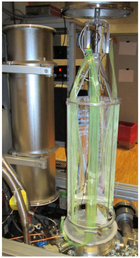


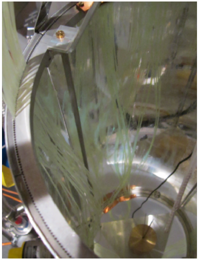


SiPMs

- work at LN temperature
- good QE, negligible dark rate
- candidates: Ketek and Hamamatsu SiPMs

teststand @ TUM



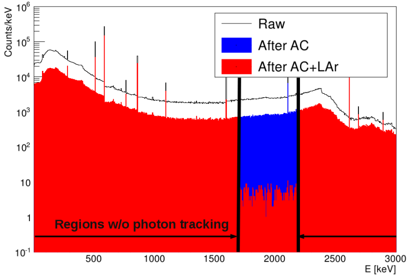


- first tests have been done
- scintillation light seen

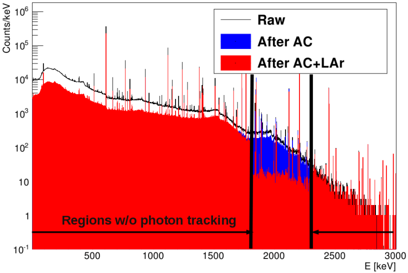
"Hybrid" LAr veto design - MC simulations

- veto efficiencies for different background sources are estimated by MC simulations (Geant4)
- photon propagation in LAr if energy deposition in Ge crystal is in ROI

^{208}Tl in holders:



^{214}Bi in holders:



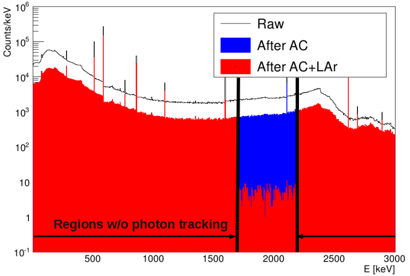
suppression factors

$$SF = \frac{\text{total events in ROI}}{\text{unvetoed events in ROI}}$$

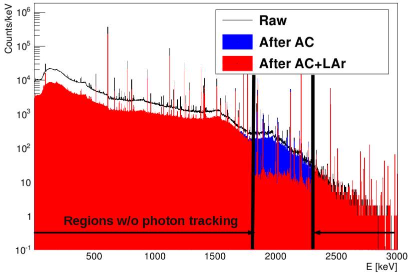
ROI: $Q_{\beta\beta} \pm 100\,\mathrm{keV}$

“Hybrid” LAr veto design - MC simulations

^{208}Tl in holders:



^{214}Bi in holders:



suppression factors

	holders	surface	homogenous	external	detector
^{214}Bi	10.3 ± 0.3	3.5 ± 0.1	54.8 ± 7.9	-	-
^{208}Tl	320 ± 34	-	-	112.1 ± 38.8	-
^{60}Co	-	-	-	-	10*
^{42}K	-	1*	5.3 ± 0.6	-	-

* suppression factors calculated for older designs (approximate values)

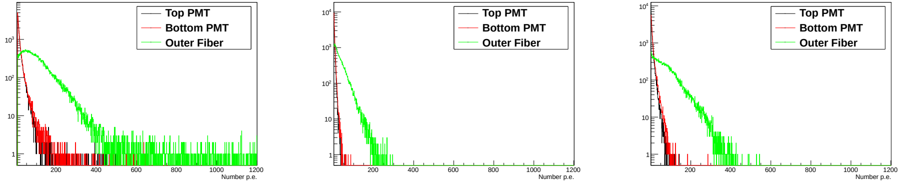
"Hybrid" LAr veto design - MC simulations

systematics studies

- changed attenuation for XUV light and metal reflectivities dramatically

	baseline	attenuation * 0.2	reflectivity * 0.1
^{214}Bi in holders	10.3 ± 0.3	8.9 ± 0.3	9.4 ± 0.3

$\Rightarrow$ LAr veto gives still good suppression factors
but p.e. yield drops



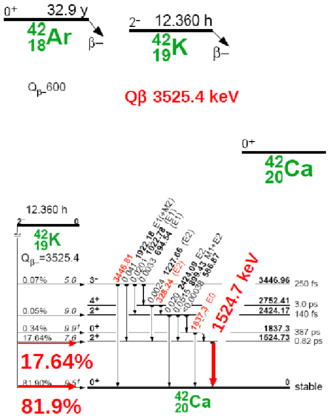
“Hybrid” LAr veto design

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		$< 6.8(1) * 10^{-4}$	$< 2.1(1) * 10^{-5}$

* determined with older geometry, will improve a bit

^{42}K mitigation: Mini-shroud and LAr instrumentation



^{42}Ar activity in proposal:
$< 41\ \mu\mathrm{Bq/kg}$ at 90% C.L. [Barabash et al., 2002]

measured in GERDA:
$< 93.0 \pm 6.4\ \mu\mathrm{Bq/kg}$ [preliminary result]

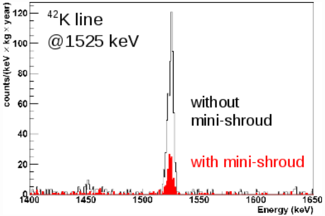
^{42}K mitigation in GERDA

- electric field
- mini-shroud
- LAr veto
- pulse shape discrimination

Phase I

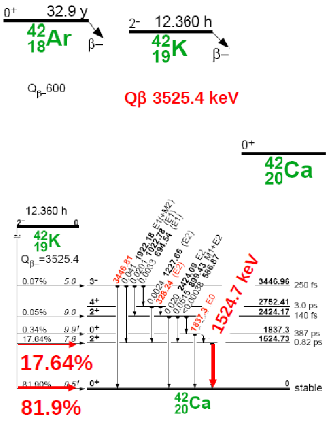
- background enhanced by collection of ^{42}K ions via E-Field

⇒ E-field & convection free configuration in 'mini-shroud'



⇒ **copper 'mini-shroud' cannot be used together with baseline hybrid LAr instrumentation**
e.g. SF (Bi214 on holders): $10.3 \pm 0.3 \rightarrow 2.4 \pm 0.1$

^{42}K mitigation: Mini-shroud and LAr instrumentation



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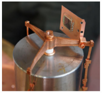
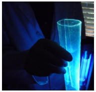
Phase II

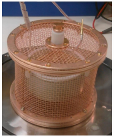
- different options under investigation:
  - AC readout
  - SiPMs/APDs inside the copper mini-shroud



  - nylon mini-shroud




  - copper mesh mini-shroud



- currently tests of the different options ongoing in LArGe
- MC simulations performed

Summary

- installation of LAr scintillation veto is planned for PhaseII of GERDA
- hybrid design using scintillating fibers and PMTs is the baseline option
  - hardware tests are ongoing
  - construction has started
- extensive MC simulation campaign performed
  - used LArGe for validation and tuning
  - provided optimizations to the hardware design
- LAr veto suppression factors look promising:
  - ➢ $> 10^2$ for ^{228}Th ($\approx$ 300 close by, $\approx$ 100 far from detectors)
  - ➢ $\approx$ 10 for nearby ^{226}Ra background source
- instrumentation-induced BI within the budget
- ^{42}K most critical known background in Phase II
- work on ^{42}K mitigation is ongoing (different mini-shroud options)

Thanks for your attention !

“Hybrid” LAr veto design - MC simulations

Veto efficiencies for different background sources are estimated by Monte Carlo simulations

- MaGe (Geant4) based simulation of nuclear decays
- If event passes cuts on energy deposition in the Ge crystals, optical photons created in the LAr are propagated. Otherwise event is discarded
  - ➢ photons are tracked inside the wls fiber
  - ➢ green shifted photons in the fiber can reach the PMTs
- reflectivity and surface roughness of the surrounding materials are implemented