A liquid Argon scintillation veto for the GERDA experiment

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Max-Planck Institut für Kernphysik

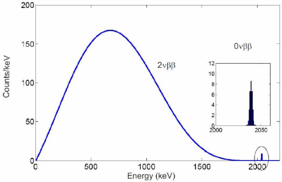
DPG Frühjahrstagung, Frankfurt, 17 March 2014

The GERDA experiment

double beta decay

$2\nu\beta\beta$: $^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se} + 2e^- + 2\bar{\nu}_e$
$0\nu\beta\beta$: $^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se} + 2e^-$

energy spectrum



GERDA Phase I results:

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

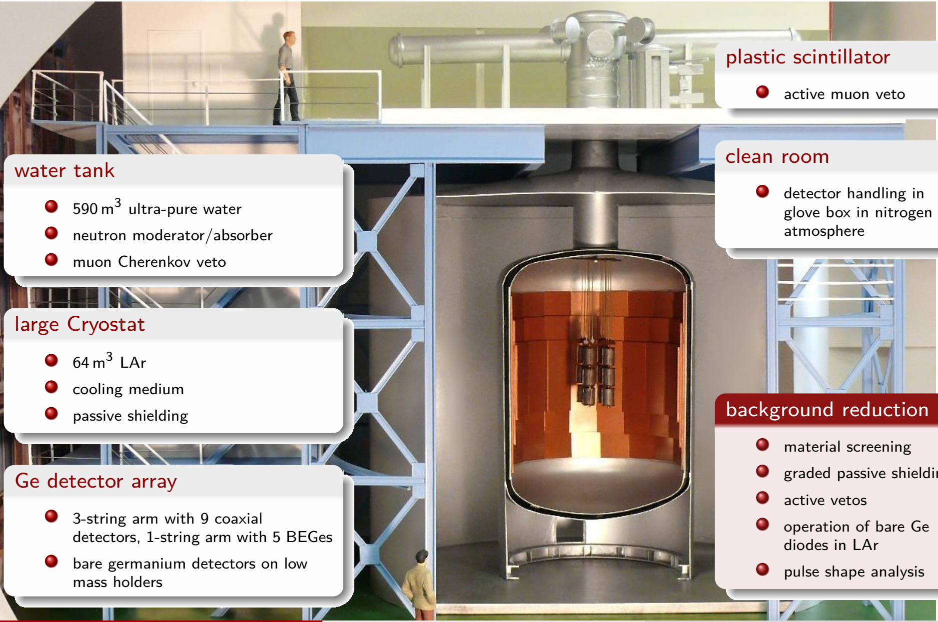
$T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}\,\mathrm{yr}\,(90\% C.L.)$ — Phys. Rev. Lett 111 (2013) 122503

main challenge

fight and understand background at

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

The GERDA experiment



plastic scintillator

- active muon veto

water tank

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

clean room

- detector handling in glove box in nitrogen atmosphere

large Cryostat

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

background reduction

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

Ge detector array

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

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 [$\mathrm{cts/(keV\,kg\,yr)}$],
$\Delta(E)$: energy resolution in ROI at $Q_{\beta\beta}$

Phase I:

- data taking: 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 @ $2.6\,\mathrm{MeV}$ (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 $20\,\mathrm{kg}$ of enr Ge detectors (BEGe)
- cleaner and lighter detector holders, cables, ...

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

⇒ 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

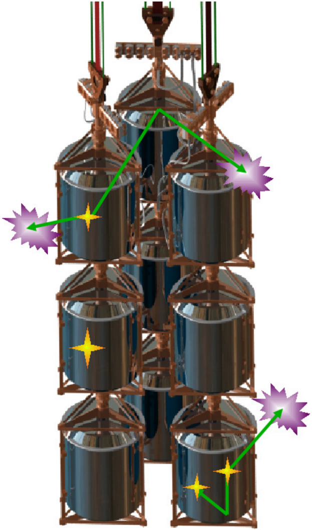
How does an active LAr veto work?

signal

$0\nu\beta\beta$ event deposits its energy locally in the Ge-crystal
→ 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 energy depositions in one Ge detector:
   → multi site event, vetoed by PSD
2. energy deposition in two different Ge detectors:
   → vetoed by detector anticoincidence
3. energy deposition in one Ge detector and in LAr:
   → can be vetoed by a LAr scintillation veto

LAr scintillation veto for background suppression

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$\rightarrow$ single site event

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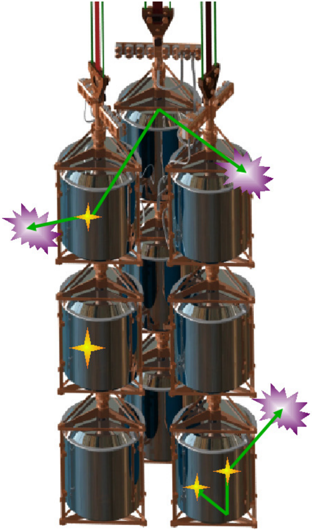
- α and β decays near/on detector surface (^{226}Ra, ^{42}K)

LAr instrumentation

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



LAr scintillation veto for background suppression

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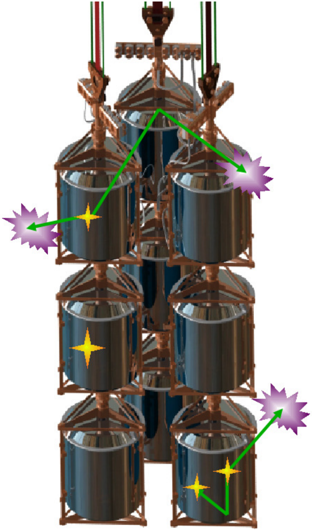
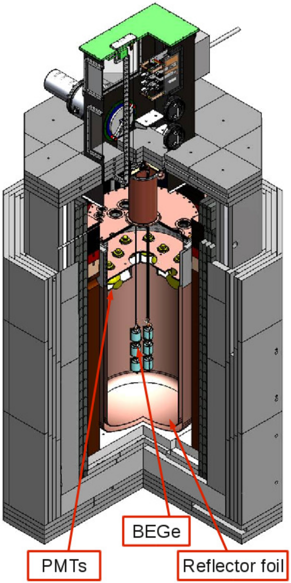
surface β, α background

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

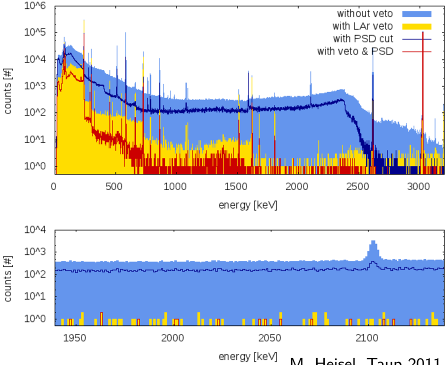


LArGe - a test facility for GERDA

Proof of LAr-veto concept in low background environment



energy spectrum for an internal Th228 source:

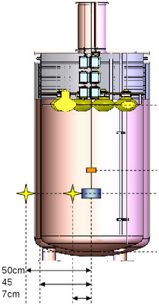


M. Heisel, Taup 2011

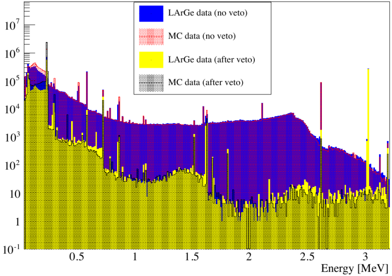
source	position	suppression factor LAr veto	PSD	total
^{228}Th	int	1180 ± 250	2.4 ± 0.1	5200 ± 1300
	ext	25 ± 1.2	2.8 ± 0.1	129 ± 15
^{226}Ra	int	4.6 ± 0.2	4.1 ± 0.2	45 ± 5
	ext	3.2 ± 0.2	4.4 ± 0.4	18 ± 3
^{60}Co	int	27 ± 1.7	76 ± 8.7	3900 ± 1300

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 ± 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

Design criteria for light instrumentation for GERDA

"Hybrid" LAr veto design

general constraint:

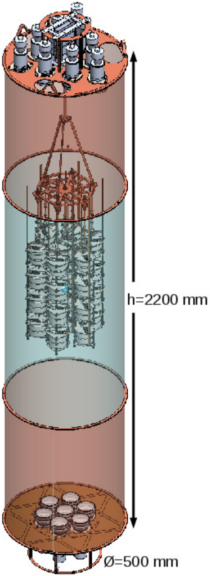
- limited Ø $< 500\,\mathrm{mm}$

MC helps to answer the following questions...

- two technologies: PMTs vs. Fibers
  which is better? use both?

⇒ baseline design is hybrid

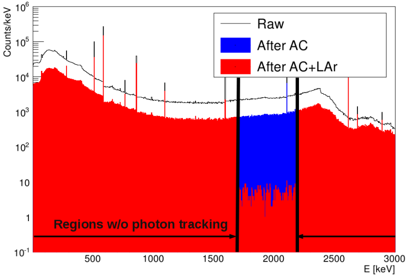
- optimize geometry (dimensions) with respect to suppression factors and self-induced background
  - ➢ vertical distance and number of PMTs
  - ➢ loose/dense packing of detector array
  - ➢ vertical position of array



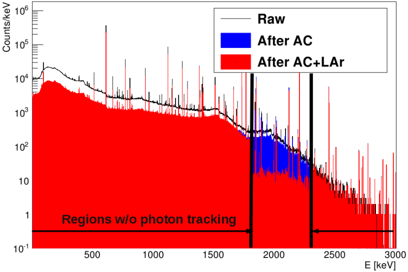
“Hybrid” LAr veto design - MC simulations

- 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:



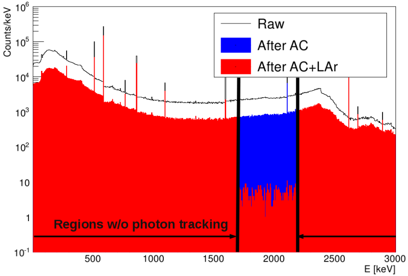
suppression factors for different backgrounds

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

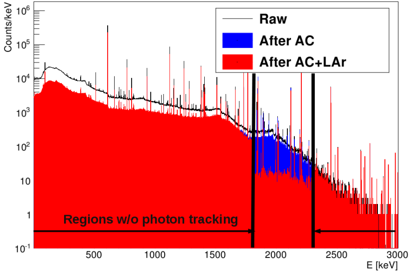
ROI: $Q_{\beta\beta} \pm 100\,\mathrm{keV}$

“Hybrid” LAr veto design - MC simulations

^{208}Tl in holders:



^{214}Bi in holders:



suppression factors for different backgrounds

	Ge detector holders	Ge detector surface	inside detector	homogenous in LAr	source far away
^{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

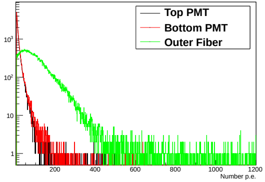
systematics in optical parameters

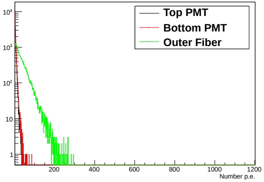
- large variations of attenuation for XUV light and metal reflectivities have small impact

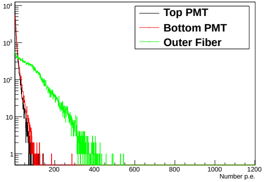
	baseline	attenuation * 0.2	reflectivity * 0.1
^{214}Bi in holders	10.3 ± 0.3	8.9 ± 0.3	9.4 ± 0.3

⇒ LAr veto gives still good suppression factors
but p.e. yield drops

- in-situ measurement of the light extinction of LAr in GERDA foreseen [T 65.2]







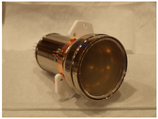
“Hybrid” LAr veto design

Instrumentation induced BI $[\mathrm{cts/(keV\,kg\,yr)}]$

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

“Hybrid” LAr veto design

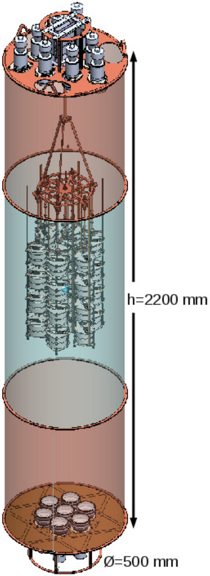
photomultipliers



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

scintillating fibers and SiPMs

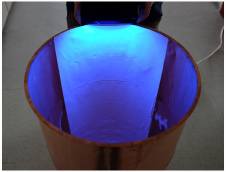
- build the middle shroud
- type: BCF-91A coated with TPB
- light readout at both ends by SiPMs on top



“Hybrid” LAr veto design

top/bottom copper shroud + reflective foil

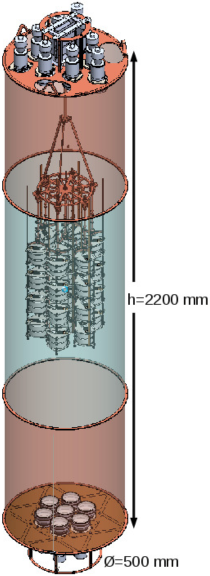
- Tetratex coated with TPB as wavelength shifter
- installed on inner side of copper shrouds



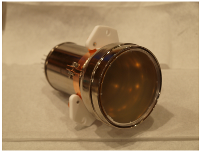
nylon mini-shrouds

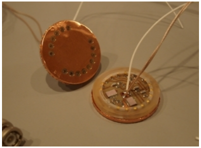
- around each detector string
- transparent & WLS

⇒ usable together with light instrumentation



Photomultiplier - Hardware



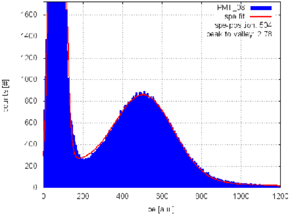


screening results [mBq/pc]

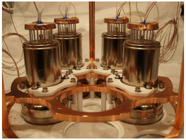
	^{228}Th	^{226}Ra
PMT *	< 1.94	< 1.7
VD	< 0.5	< 1.14

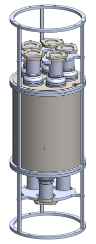
* calculated from component screening

peak-to-valley: 4:1



teststand

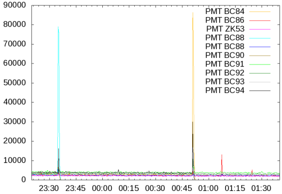


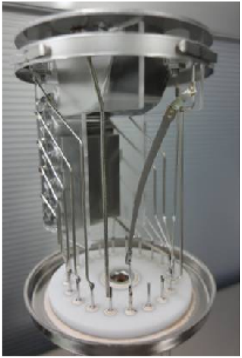


test of up to 10 PMTs in LAr

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

Photomultiplier - Hardware





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

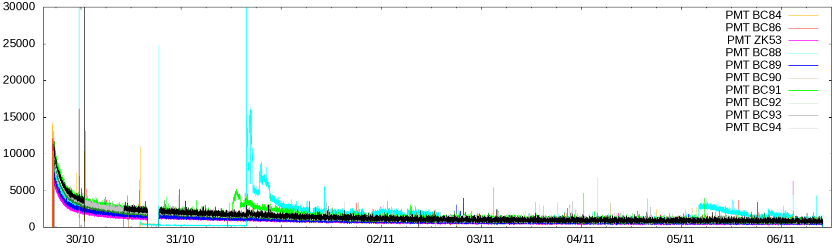
iterative process in close cooperation with Hamamatsu to solve flashing of PMTs

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

Photomultiplier - Longterm test

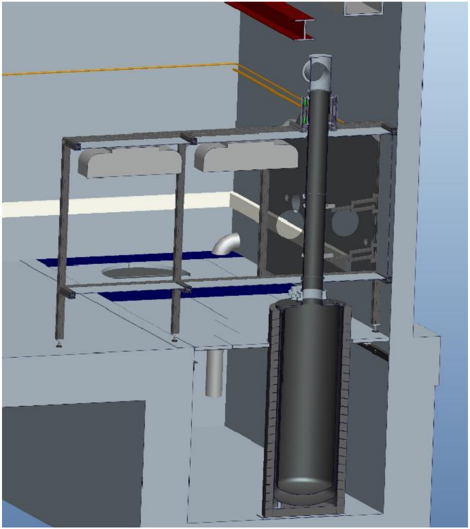


- 29 PMTs tested so far for > 40 d
- > 12 good enough for operation in GERDA
- 17 to come

⇒ by summer we should have enough PMTs suitable for operation in GERDA

Fibers - Hardware

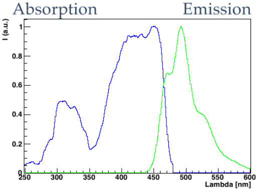
TUM cryostat

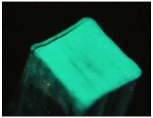


Fibers - Hardware

scintillating fibers coated with TPB

- fibers themselve are WLS





- screening results

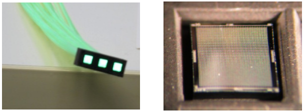
^{228}Th: 0.058 Bq/kg

^{226}Ra: 0.042 Bq/kg

9 fibers per SiPM

- readout at the top

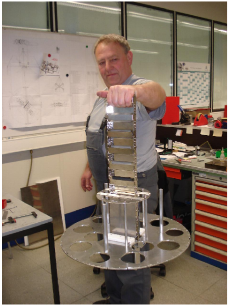
⇒ far from detectors



SiPMs at LN temperature

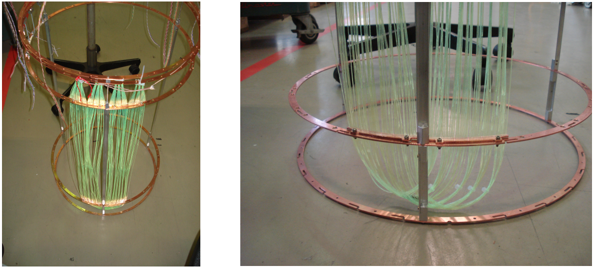
- good QE, negligible dark rate
- Ketek SiPMs in 'die' → low background packaging

Current status - LAr veto integration



aluminium dummy of top PMT plate in first integration test with GERDA lock

mock-Up of fiber middle shroud



Summary

- LAr light instrumentation with PMTs and Fibers/SiPMs is being prepared for Phase II of GERDA:
- using scintillating fibers/SiPMs and PMTs is the baseline option
  - hardware tests are being completed (PMTs & SiPMs/Fibers)
  - construction and integration tests are conducted
- extensive MC simulation campaign performed
  - photon tracking successfully added to simulation framework MaGe (validation with LArGe data)
  - provided optimizations to the hardware design with respect to suppression factors
    - ➢ $> 10^2$ for nearby ^{228}Th sources
    - ➢ ≈ 10 for nearby ^{226}Ra background source
- instrumentation-induced BI is much smaller than benefit from background suppression

Thank you 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