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A background veto system for GERDA based on scintillation of liquid argon

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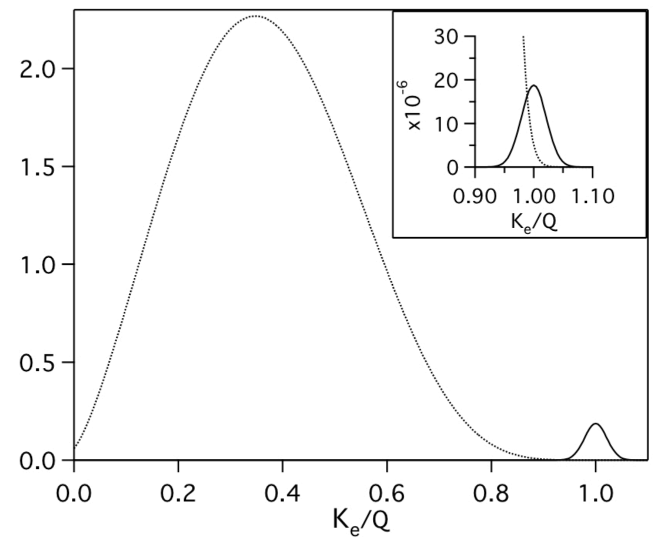
DPG Frühjahrstagung, March 4, 2013

DRESDEN concept
Exzellenz aus Wissenschaft und Kultur

ββ decay

- **2νββ**: $(\mathbf{A}, \mathbf{Z}) \rightarrow (\mathbf{A}, \mathbf{Z}+\mathbf{2}) + \mathbf{2e}^{-} + \mathbf{2}\overline{\nu_{\mathbf{e}}}$
  - Predicted by the SM
  - Observed in more than 10 isotopes
- **0νββ**: $(\mathbf{A}, \mathbf{Z}) \rightarrow (\mathbf{A}, \mathbf{Z}+\mathbf{2}) + \mathbf{2e}^{-} + \mathbf{0}\overline{\nu_{\mathbf{e}}}$
  - $\Delta L = 2$
  - One claim and many limits…
  - $\left[T^{0\nu}_{1/2}\right]^{-1} = F^{0\nu} \cdot \left|M^{0\nu}\right|^2 \cdot {m_{\beta\beta}}^2$



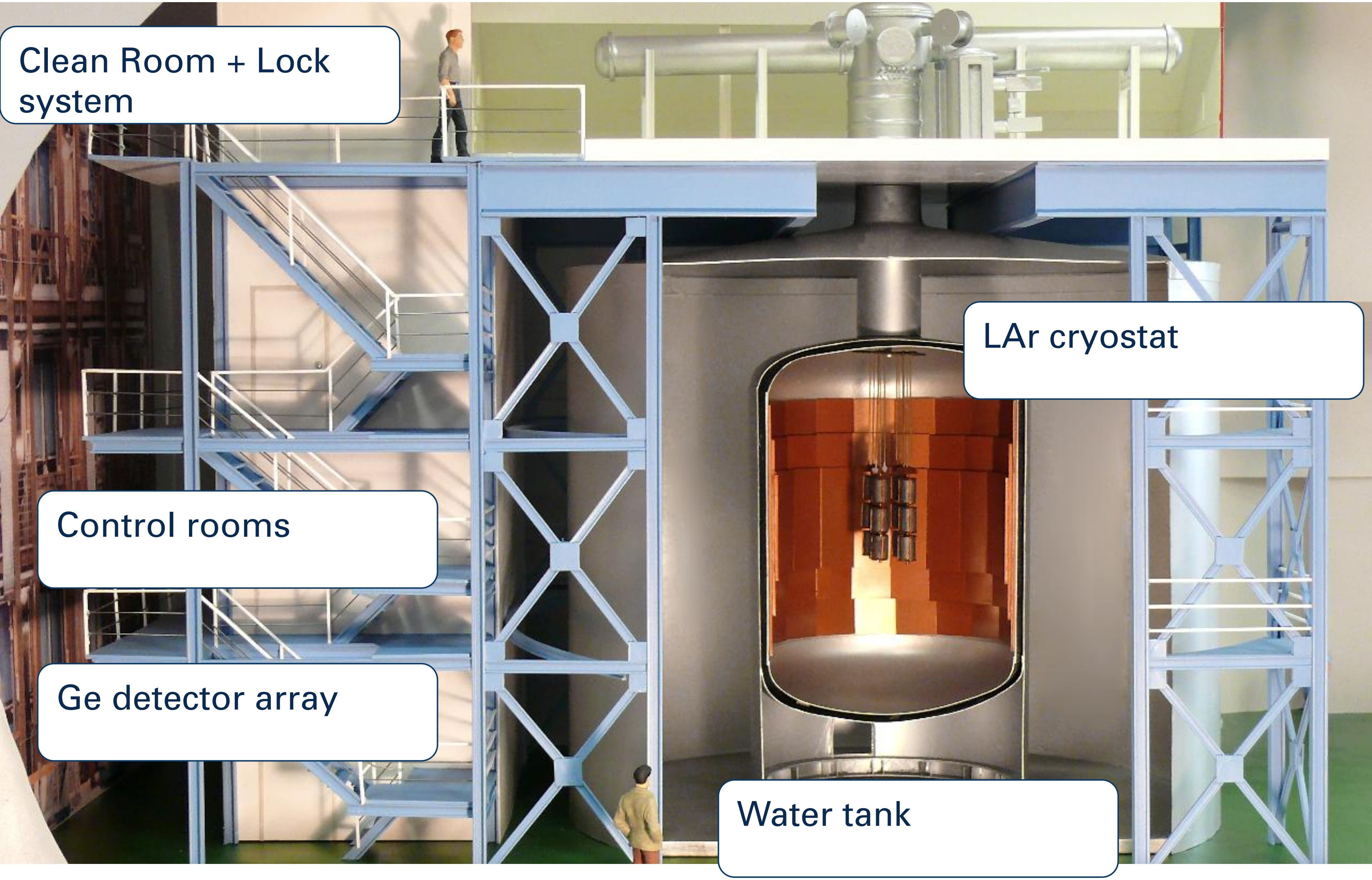
$$T^{0\nu}_{1/2} \approx \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

- **M** – mass of the isotope
- **t** – time
- **B** – background
- **ΔE** – energy resolution

Ways to improve sensitivity

- More mass
- Better energy resolution
- Longer measurement
- **Lower background**

Germanium Detector Array



Germanium Detector Array

$$T_{1/2}^{0\nu} \approx \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

Double beta decay in Ge:

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

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

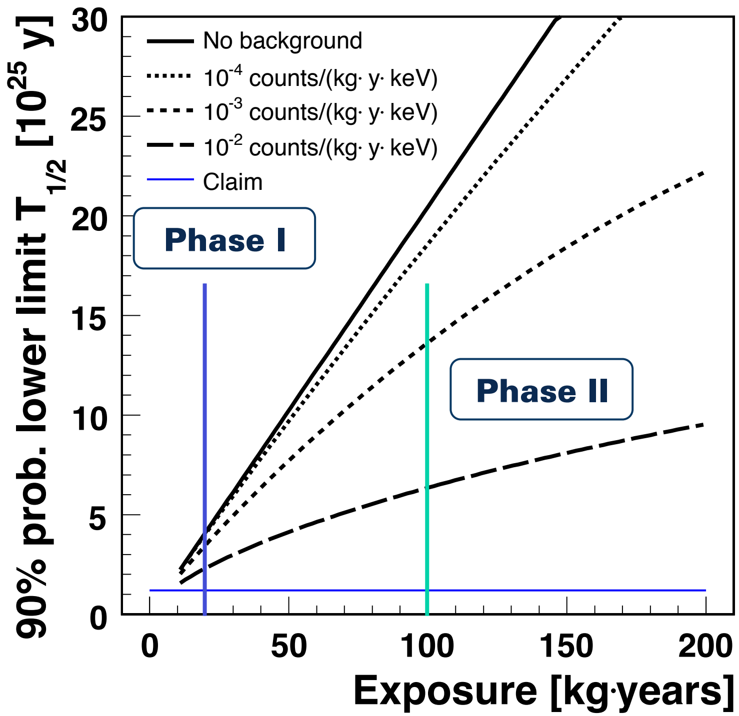
Phase I

- Check existing claim with HPGe
  - Exposure : ~20 kg yr
  - **BI : 2.43 x 10^{-2} cts/(keV kg yr)**

Phase II

- Expand sensitivity with enriched BEGe (+20 kg)
  - Exposure : ~100 kg yr
  - **BI: ≤ 1.0 x 10^{-3} cts/(keV kg yr)**

Background reduction in the ROI around $Q_{\beta\beta}$ crucial for GERDA objectives



A. Caldwell et al. Phys. Rev. D 74 (2006) 092003

Reducing the background in GERDA

- **Background index (BI)**
  - present (Phase I) : 2.43 x 10^{-2} cts/(keV kg yr)
  - aspired (Phase II) : ≲ 1.0 x 10^{-3} cts/(keV kg yr)

- Employed background suppression techniques:
  - Water Cherenkov veto (muons)
  - Detector anti-coincidence
  - Pulse shape discrimination (PSD)

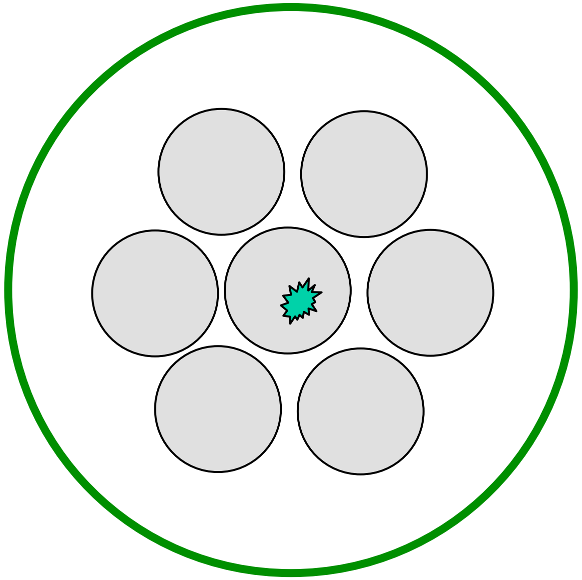
LAr scintillation veto

- Tag background events by detecting light from scintillation of argon

Background suppression in GERDA

- **ββ-event**
  - Single site event (energy deposited in a single crystal)
  - **Not vetoed**

Events in ROI around 2039 keV

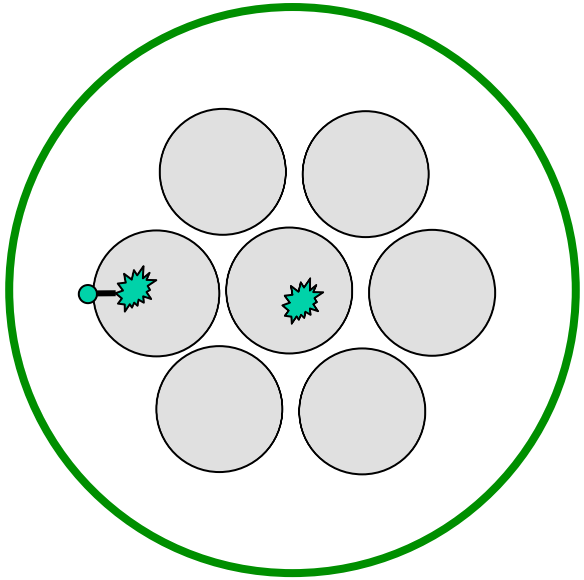


Background suppression in GERDA

- **ββ-event**
  - Single site event (energy deposited in a single point)
  - **Not vetoed**

- **Surface event (^{214}Bi, ^{42}K)**
  - Often not vetoed by LAr instrumentation
    - **High veto efficiency from PSD**

Events in ROI around 2039 keV



Background suppression in GERDA

- **ββ-event**
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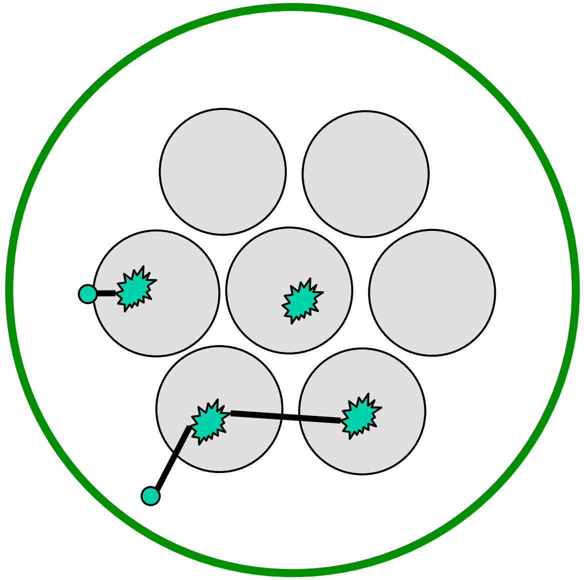
- **Surface event (^{214}Bi, ^{42}K)**
  - Often not vetoed by LAr instrumentation
- **External event (^{208}Tl, ^{214}Bi)**
  - Energy deposited in multiple crystals
    - **Detector anti-coincidence veto**

Events in ROI around 2039 keV



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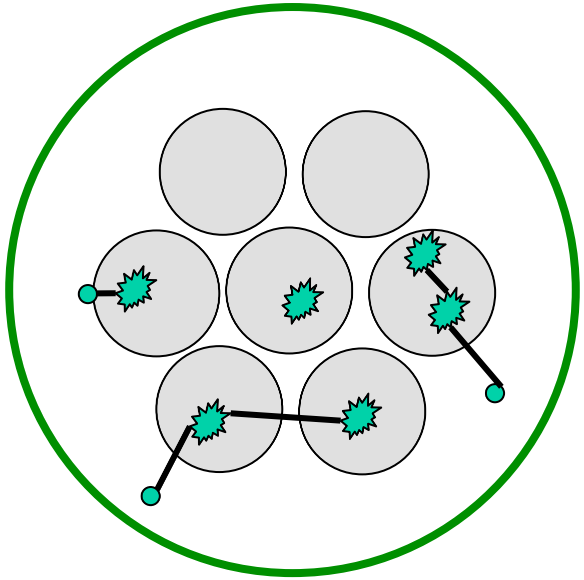
    - Detector anti-coincidence veto
  - Multi site events
    - **PSD veto**

Events in ROI around 2039 keV



Background suppression in GERDA

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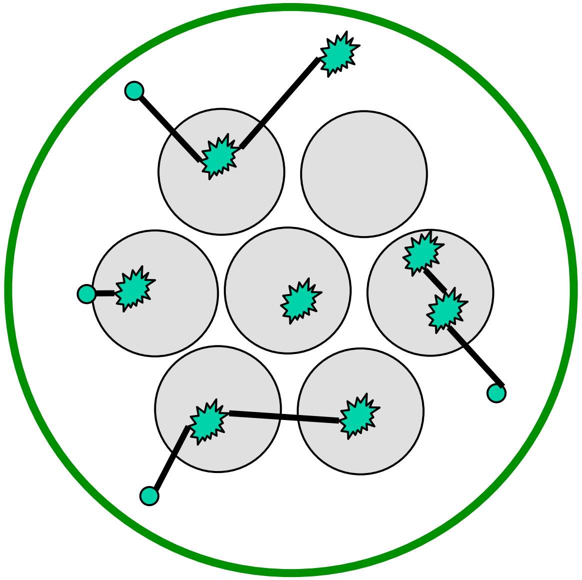
  - Not vetoed
- **Surface event (^{214}Bi, ^{42}K)**
  - Often not vetoed by LAr instrumentation
- **External event (^{208}Tl, ^{214}Bi)**
  - Energy deposited in multiple crystals
    - Detector anti-coincidence veto
  - Multi site events
    - PSD veto
  - Energy deposited both in the detector and in the surrounding LAr
    - **Often vetoed by LAr instrumentation**

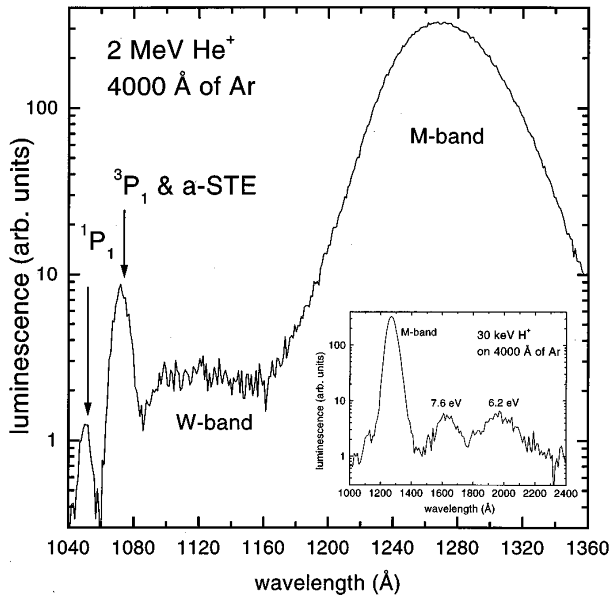
Events in ROI around 2039 keV



LAr veto efficiency highly dependent of background type.

LAr scintillation for background suppression

- Advantages:
  - Very high light yield : ~4 x 10^4 γ/MeV
  - Single re-emission peak: λ = 128 nm (XUV)
  - Very distinctive short and long decay times
    - T_s ~ 6 ns
    - T_l ~ 1200 – 1500 ns



- Challenges:
  - Hard to measure optical properties
    - Very dependent on impurities
  - Light cannot be detected directly (XUV)
    - Need to use WLS

LArGe test facility

lock system

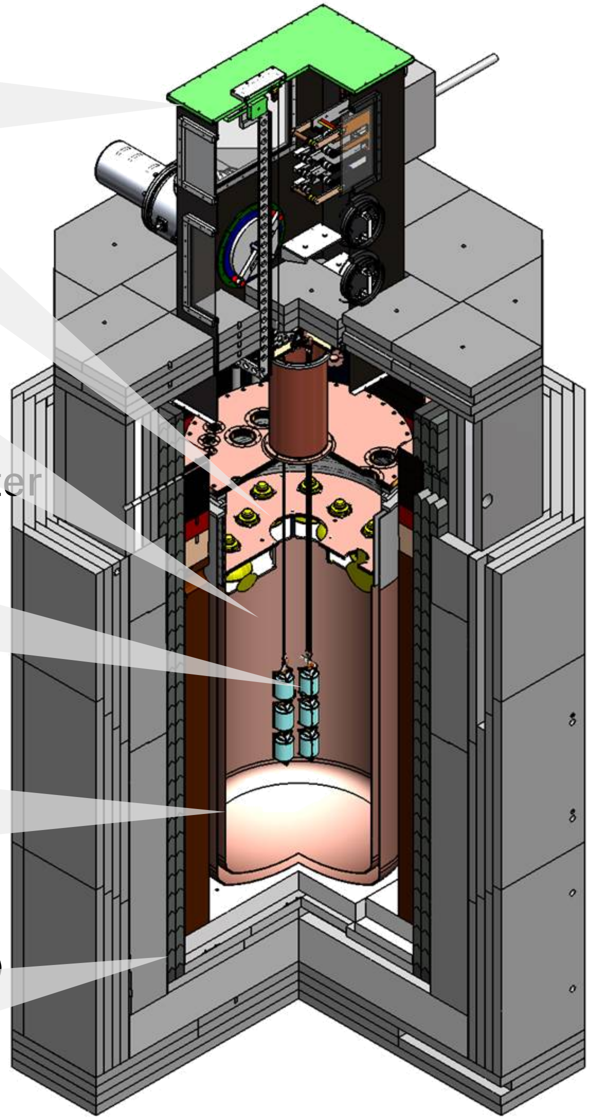
9x 8“ PMTs

reflector foil
& wavelength shifter

bare Ge-detector

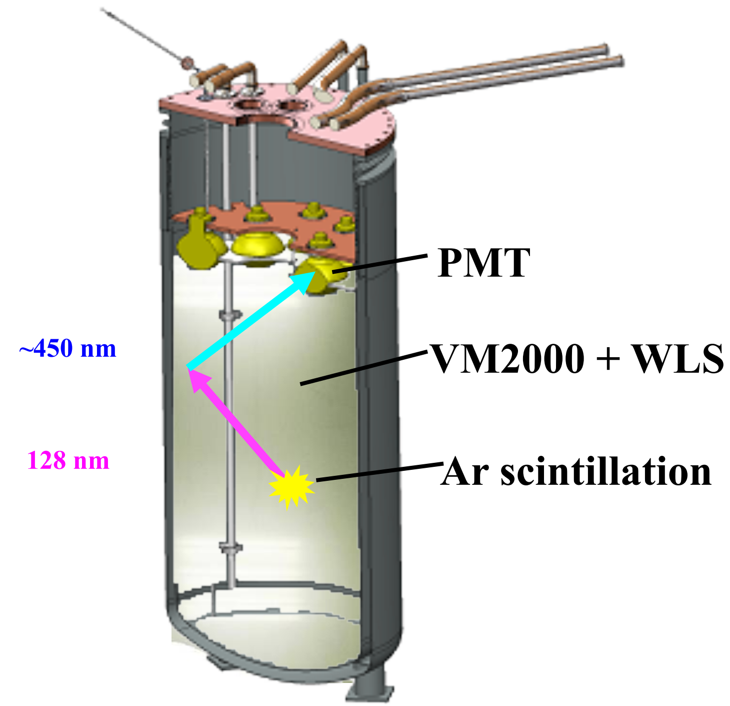
cryostat with LAr
- volume 1000 l

Shield (unfinished)
- Cu 15 cm,
- Pb 10 cm,
- Steel 23 cm,
- PE 20 cm



Location: Germanium detector lab
LNGS @ 3800 m w.e.

[arXiV: 0701001, TAUP 2011 proc.]



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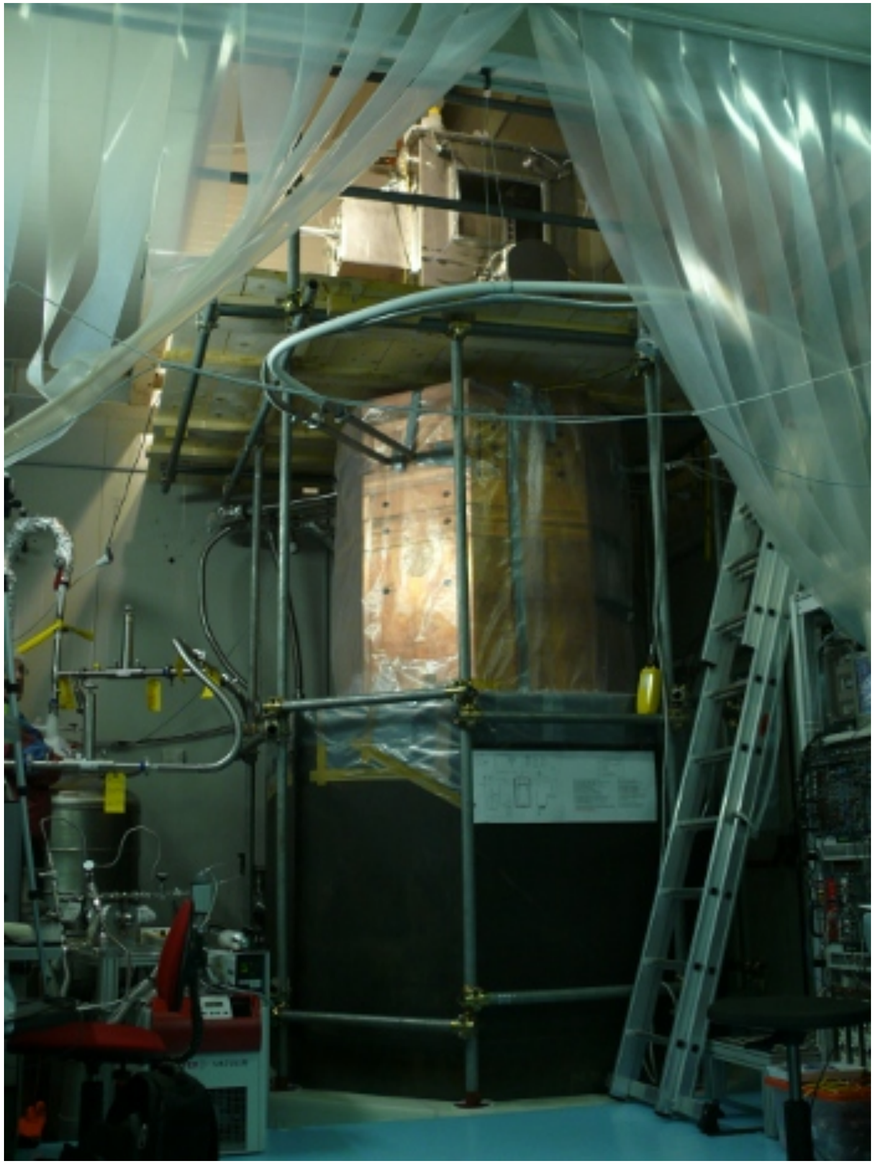
LArGe test facility



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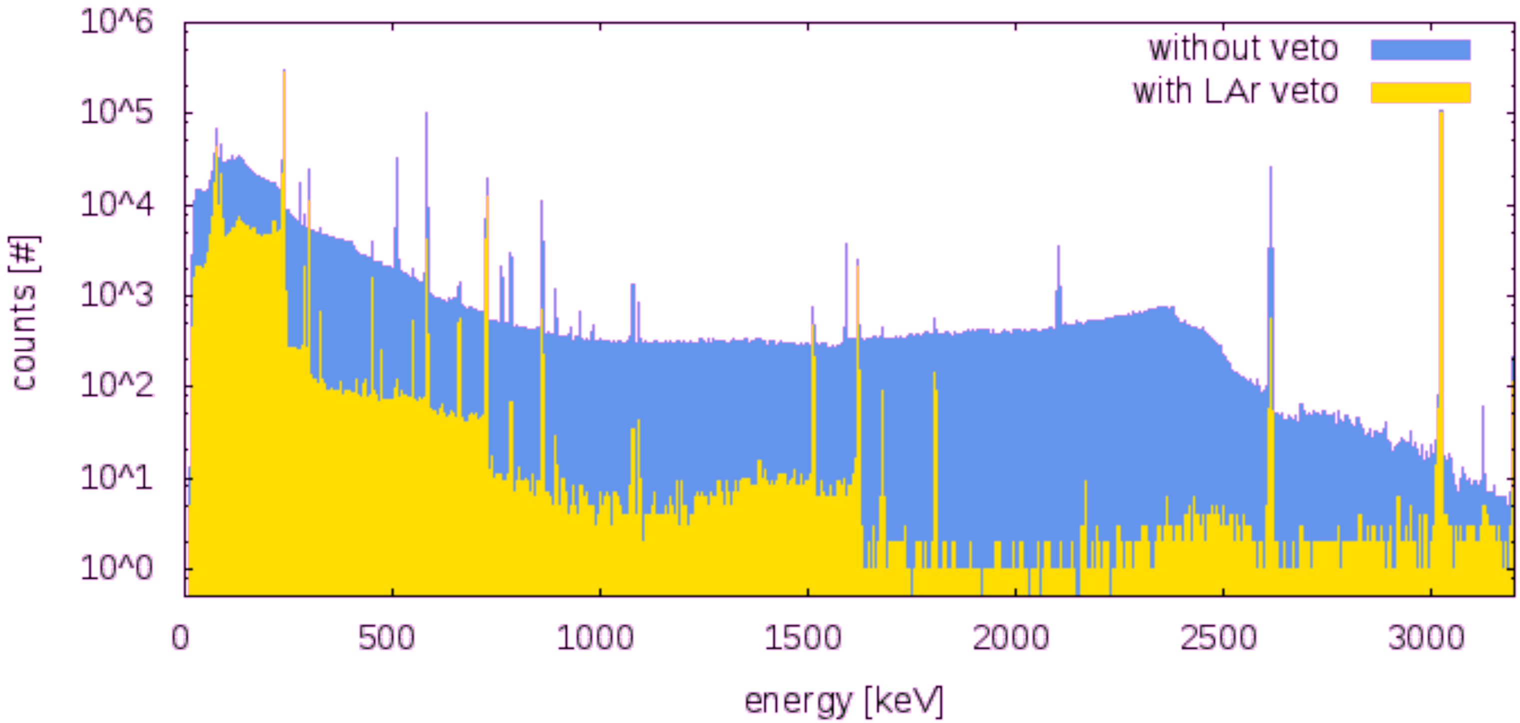
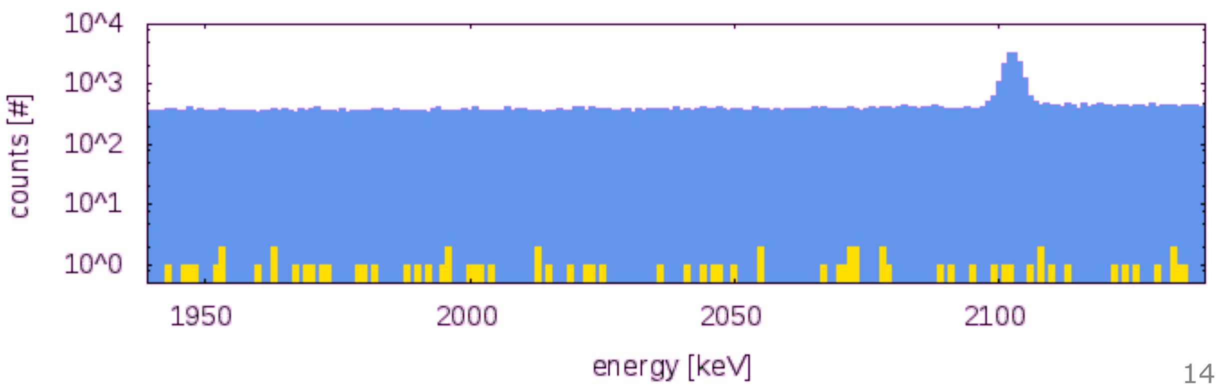
LArGe : suppression of internal ^{228}Th



- Suppression factor at $Q_{\beta\beta}$±35keV
  - LAr veto : ~1200



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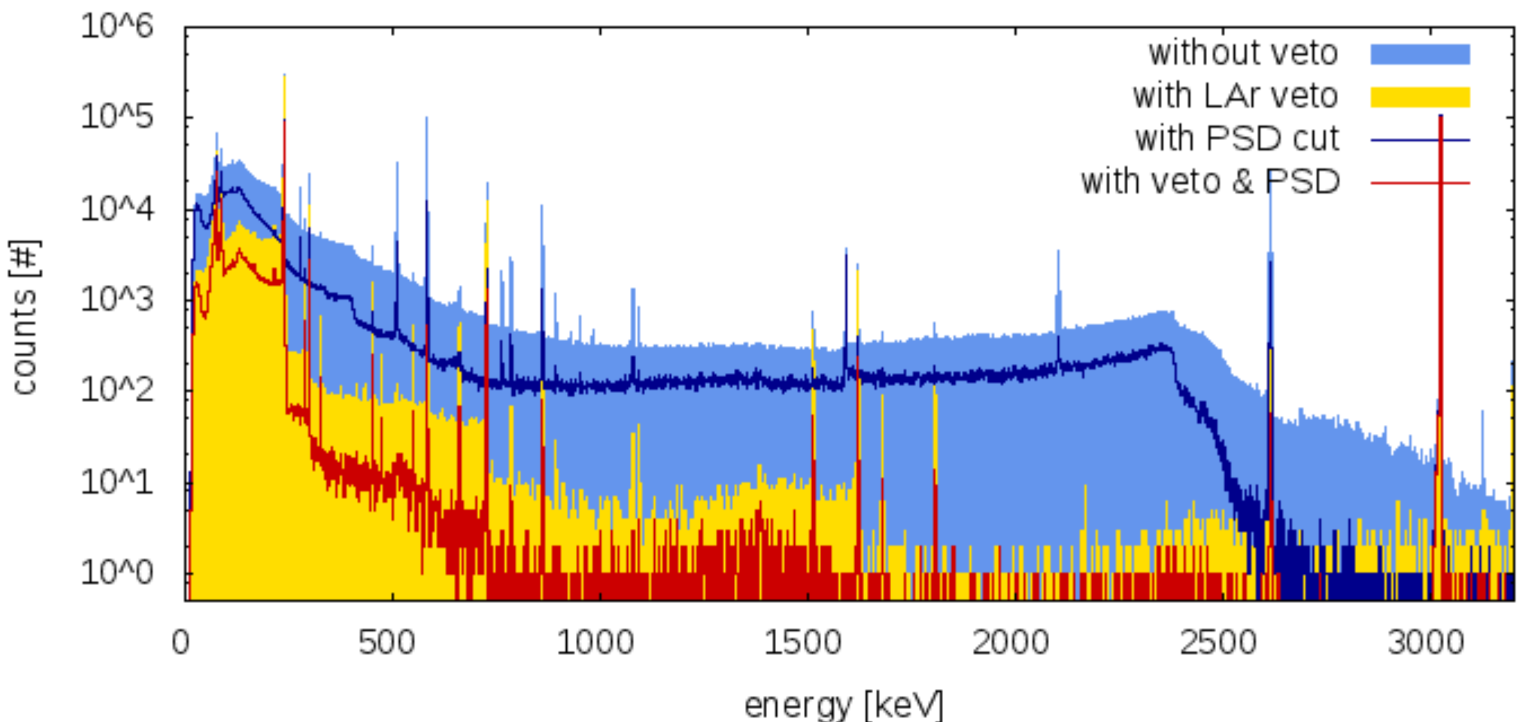
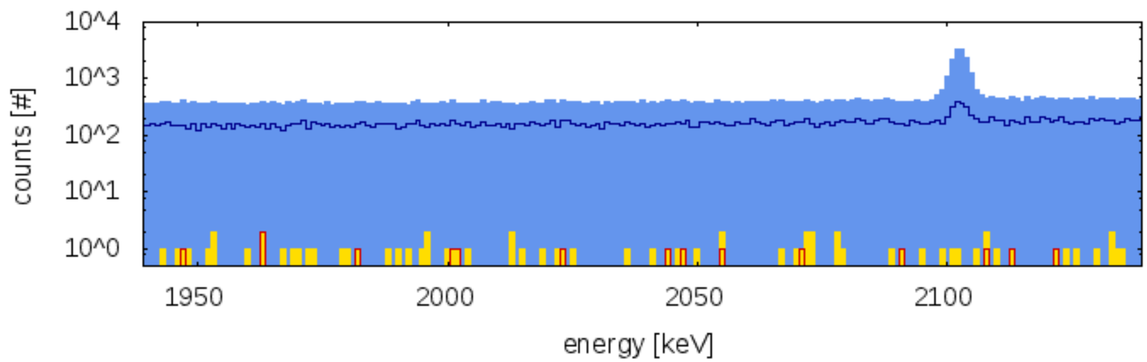
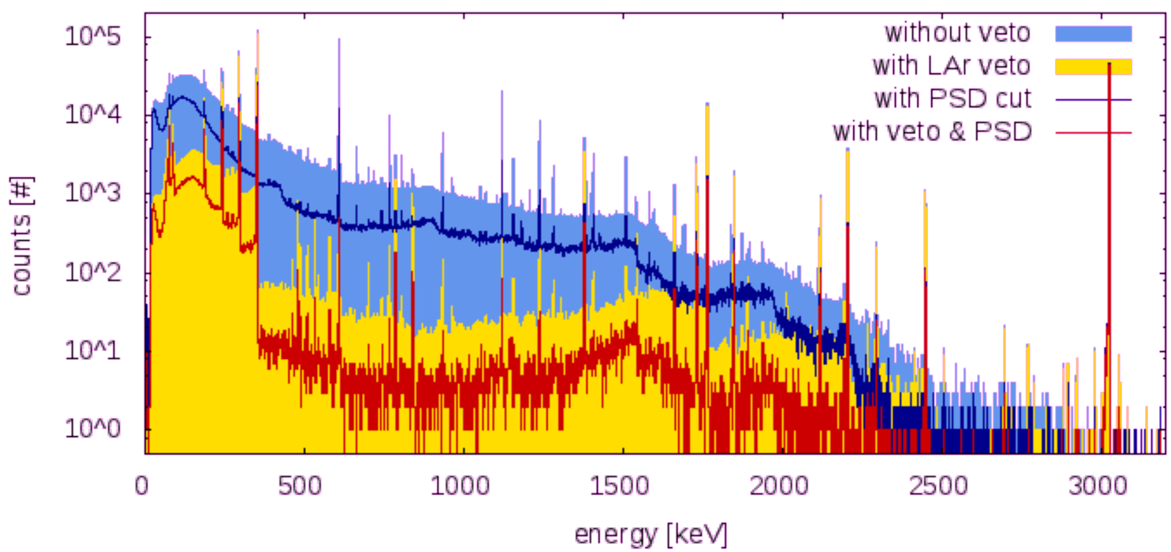


- Suppression factor at $Q_{\beta\beta}$±35keV
  - LAr veto : ~1200
  - PSD : ~2.4
  - **LAr + PSD: ~5200**



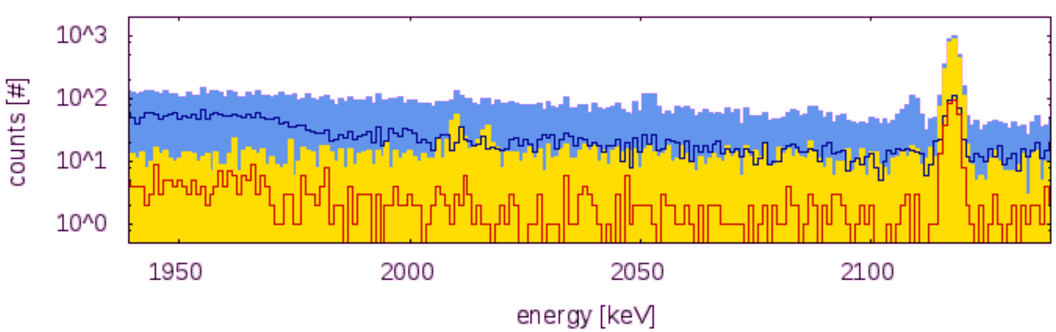
LArGe : suppression of internal ^{226}Ra

- Suppression factor at $Q_{\beta\beta}$±35keV
  - LAr veto : ~4.6
  - PSD : ~4.1
  - LAr + PSD: ~45



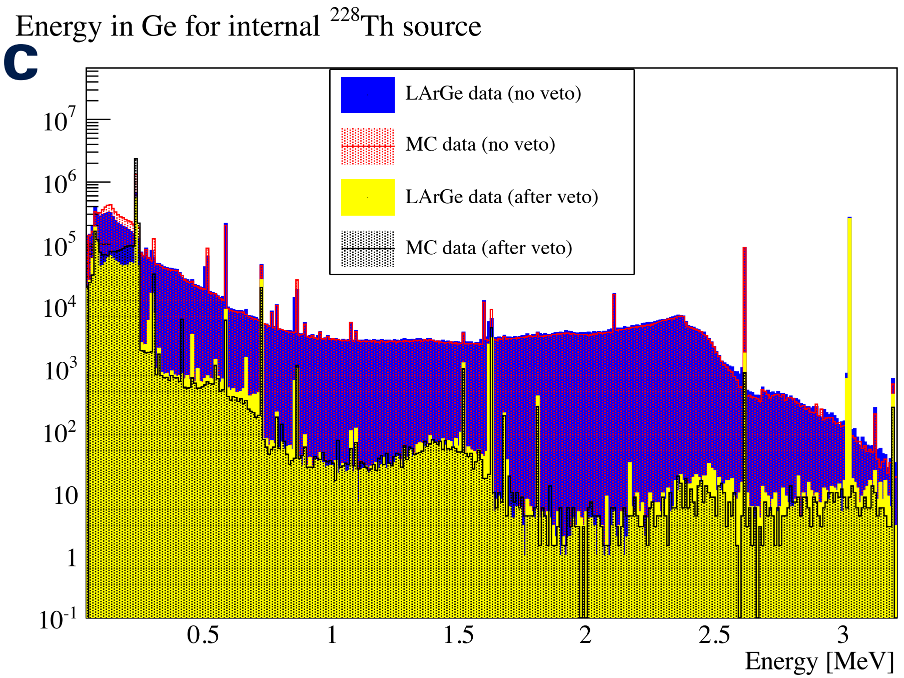
Demonstrated by LArGe:

- **Concept works**
- Complementarity with PSD
- Efficient background suppression for select backgrounds



LArGe test facility – Validation of MC

- **LArGe results used to validate MC model**
  - Simpler geometry
  - Measurements available



Tuning of optical properties:

- Material reflectivities
  - Cu, Ge, teflon,…
- LAr properties:
  - Attenuation length, light yield, triplet lifetime
- WLS properties
  - Absorption and re-emission spectra

Background	LArGe data	MC
^{208}Tl	1180 ± 250	**909 ± 235**
^{214}Bi	4.6 ± 0.2	**3.8 ± 0.1**
^{60}Co	27 ± 1.7	**16.1 ± 1.3**
External Sources		
^{208}Tl	25 ± 1.2	**17.2 ± 1.6**
^{214}Bi	3.2 ± 0.2	**3.2 ± 0.4**

Unknown accurate source geometry affects fraction of escaped betas.

LAr instrumentation in GERDA

- Combination of technologies for maximized veto efficiency.
  - PMTs (as verified in LArGe)
  - Scintillation fibers [T 109.2].

Requirements

- Large instrumented volume
- Low background contribution
  - After self-veto
- Low mass
  - Instrumentation deployed with Ge crystals

The hybrid design

top PMTs
(9 x 3″ Hamamatsu R11065-10/-20)

600 x 490 mm
- Cu coated with Tetratex + TPB [HK 46.8]

Scintillating fibers + WLS (1000 x 490 mm)
- BCF-91A fibers coated with TPB
- Light readout by SiPMs at upper end

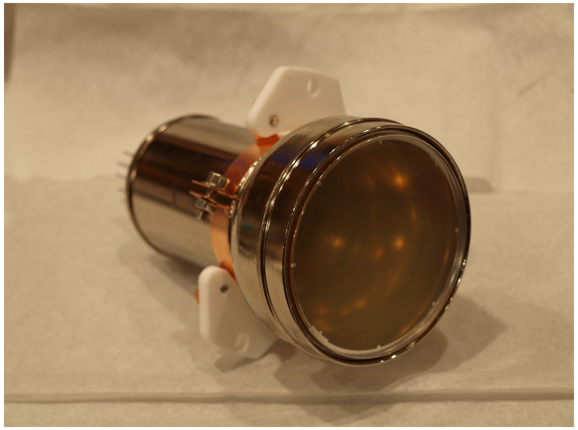
600 x 490 mm
- Cu coated with Tetratex + TPB

bottom PMTs
(7 x 3″ Hamamatsu R11065-10/-20)

Breakdown of the designs

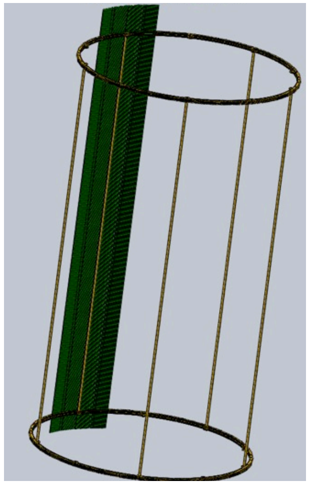
PMTs

- Proven technology (LArGe)
- Low background contribution
  - Clean PMTs
  - Distance from the crystals



Scintillating fibers

- Sensitive LAr volume not confined
- High solid angle coverage
- Low background contribution
  - Can afford to place fibers closer to detectors

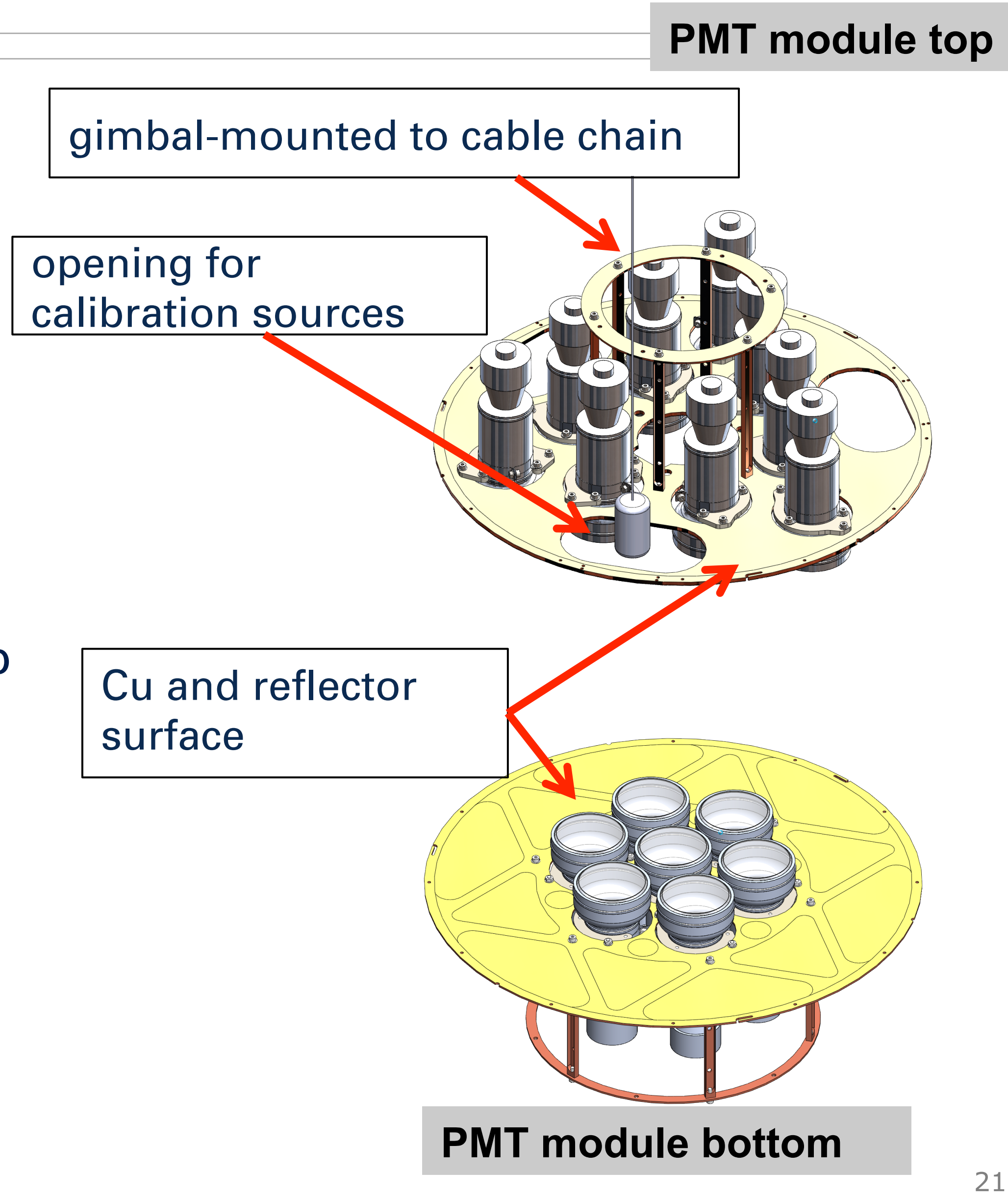


Hardware : PMTs [T 109.1]

- 18 low background PMTs
  - 9 x R11065-10
  - 9 x R11065-20
- Custom made voltage dividers
  - Encapsulation to prevent discharges/flashing
- Tight control on weight of setup
  - Share same cable chain as detectors

Screening results

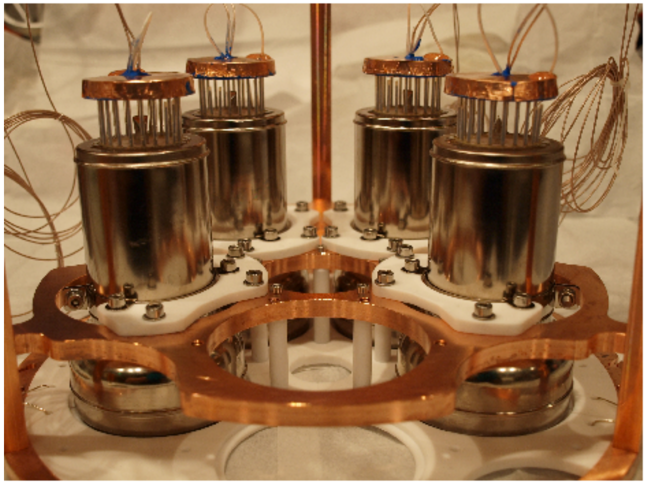
- ^{228}Th : ≲ 1.94 mBq/PMT
- ^{226}Ra : ≲ 1.7 mBq/PMT

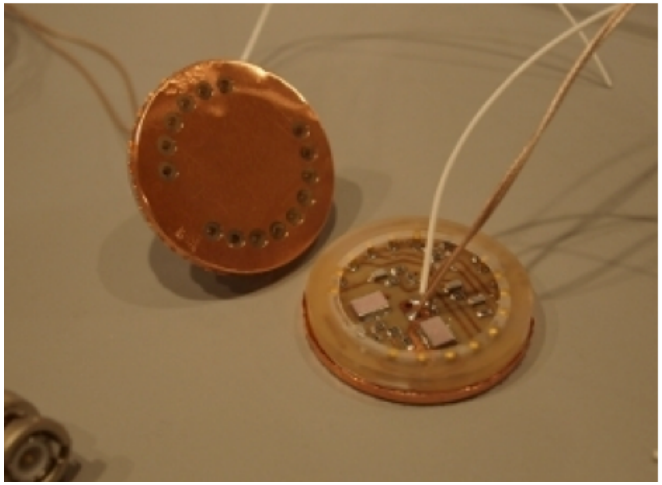


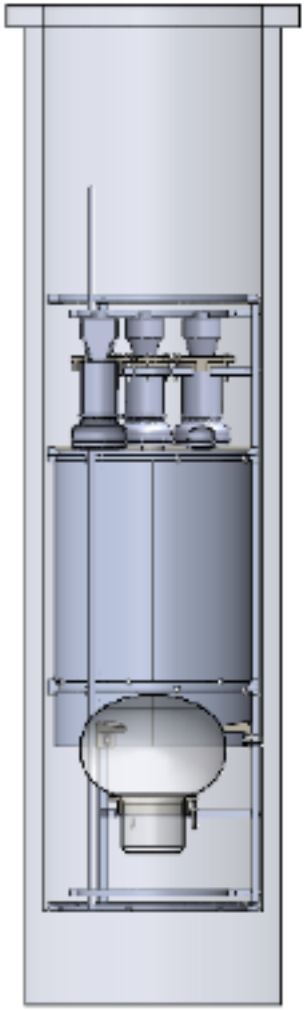
Hardware : PMTs [T 109.1]

- Intensive tests of all parts
  - Tight control of background
- Run in test stand with in MPIK
  - 4 PMTs with negative voltage dividers
  - So far no flashing occurred

test stand at MPIK

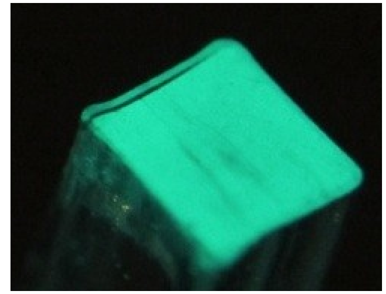






PMT support successfully tested

Hardware : Fibers [T 109.2]

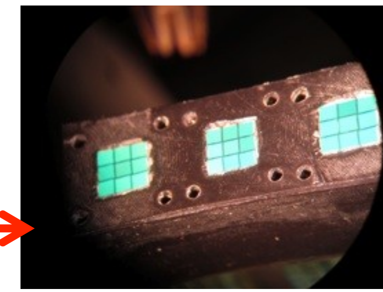


BCF-91A green + WLS multiclad fiber

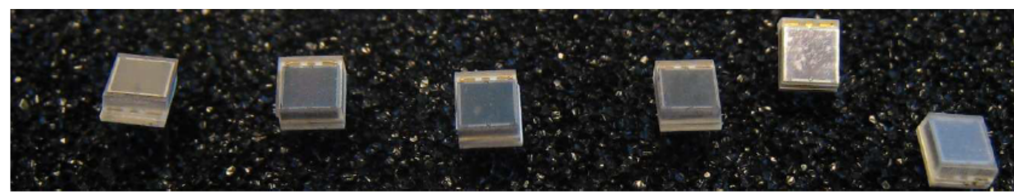
- Coupling 9 fibres per SiPM
  - Readout on one end
  - Reflective surface on other end

- "Dirtiest" parts far from detectors

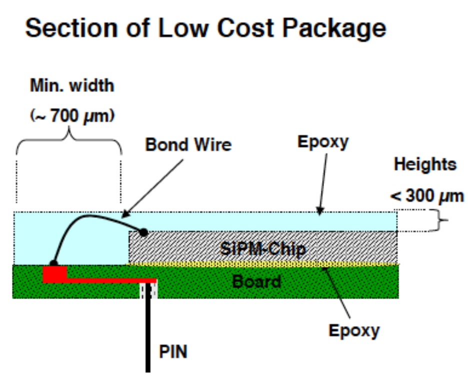
coupled fibers in holder



- Fibers coated with TPB
  - Fibers themselves are WLS



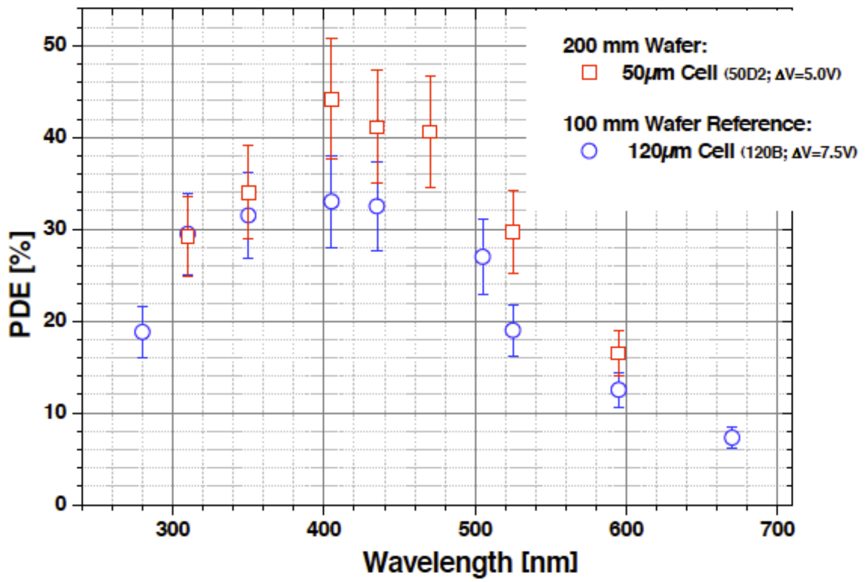
- Large solid angle coverage maximizes detection efficiency
  - Does not penalize PMTs



Size 3.9 mm x 4.4 mm x 2.0 mm
(Active chip area: 3 mm x 3 mm)

Hardware : Fibers [T 109.2]

- SiPMs
  - Work at LN temperature
  - Good QE, negligible Dark Rate
  - Candidates: Hamamatsu and Ketek SiPMs

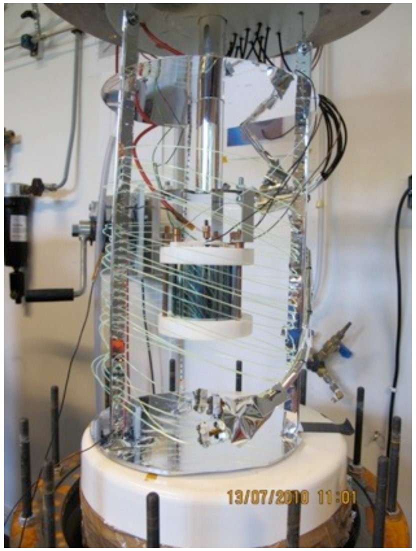


- **TPB coated WLS fiber concept already demonstrated**

Screening results

- ^{228}Th : 0.058 mBq/kg
- ^{226}Ra : 0.042 mBq/kg
- ^{40}K : 0.46 mBq/kg

Concept tested in small scale (< 20 l)



LAr Instrumentation : MC simulations

- **Extensive MC simulation campaign of designs:**
  - Implemented in MaGe
    - GERDA simulation software based on Geant4
  - Tuned with LArGe data

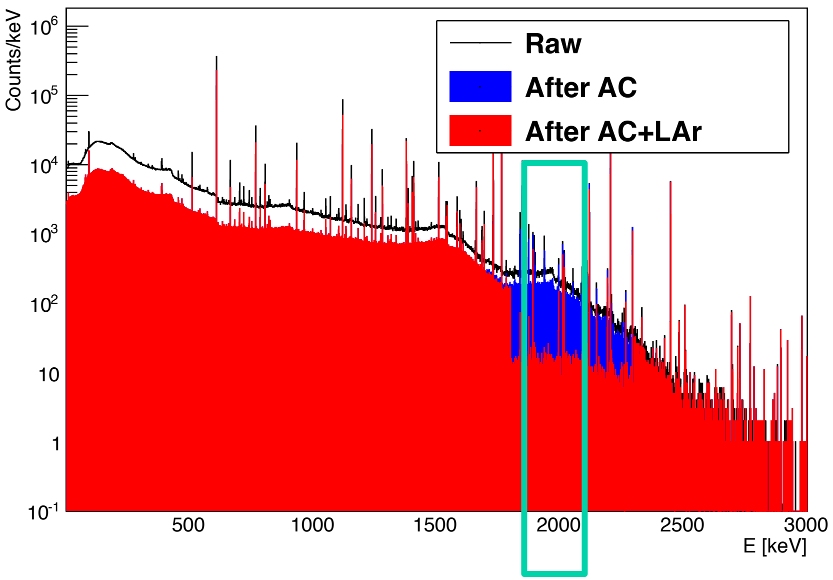
- Two-fold objective:
  - **Initial comparison of technologies**
  - **Optimization of geometries (detectors and instrumentation)**

- Simulation details:
  - Simulation of known nuclear decays in detector parts
    - LAr, detector holders, LAr instrumentation, Ge crystals
    - Most relevant simulated decays: ^{214}Bi, ^{208}Tl

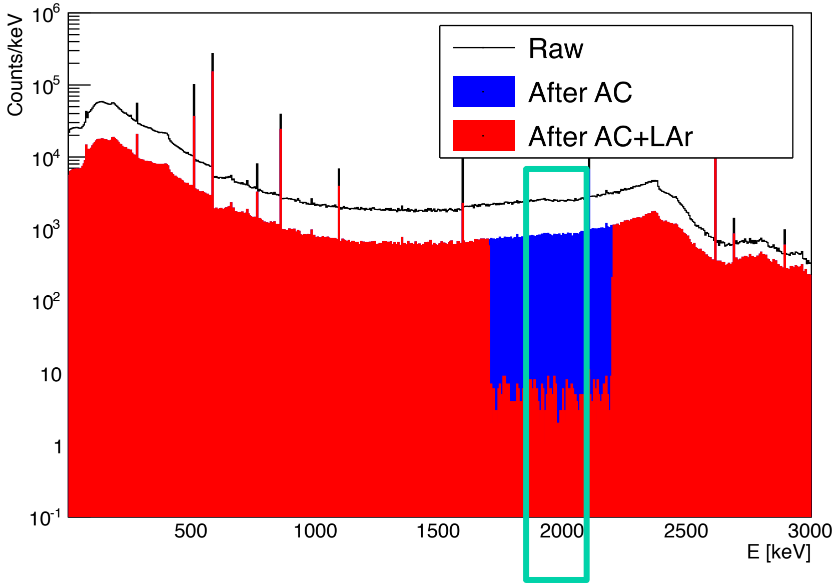
  - Photon tracking only if event deposits energy in Ge inside the ROI
    - Performance optimization

MC simulations

^{214}Bi in detector holders



^{208}Tl in detector holders



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

- ROI : $Q_{\beta\beta} \pm 100$ keV
  - Same window used to determine the BI.

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MC simulations : results

	Location	SF
^{208}Tl	holders	320 ± 34
	external	112 ± 39
^{214}Bi	surface	3.5 ± 0.1
	holders	10.3 ± 0.3
	homogeneous in LAr	54.8 ± 7.9
Sources simulated in earlier designs (approximate values)		
^{60}Co	detectors	10
^{42}K	homogeneous in LAr	10
	crystal surface	1

- Simulation campaign was iterative process
  - Designs evolved/improved with results from simulations

MC simulations : systematics studies

- Some parameters hard to measure
  - Literature values used
  - Systematic studies of their effect performed

Systematic	SF
Nominal	10.3 ± 0.3
0.2 * Attenuation	8.9 ± 0.3
0.1 * Reflectivity	9.4 ± 0.3

- **Attenuation of XUV light**
  - Absorption highly dependent on purity of LAr
  - Literature value : 60 cm [NIM A 384 (1997)]
  - **Major systematic uncertainty**

- **Reflectivity of materials**
  - Measurements in visible range performed at MPIK
  - Literature values used for XUV range

Global suppression slightly reduced

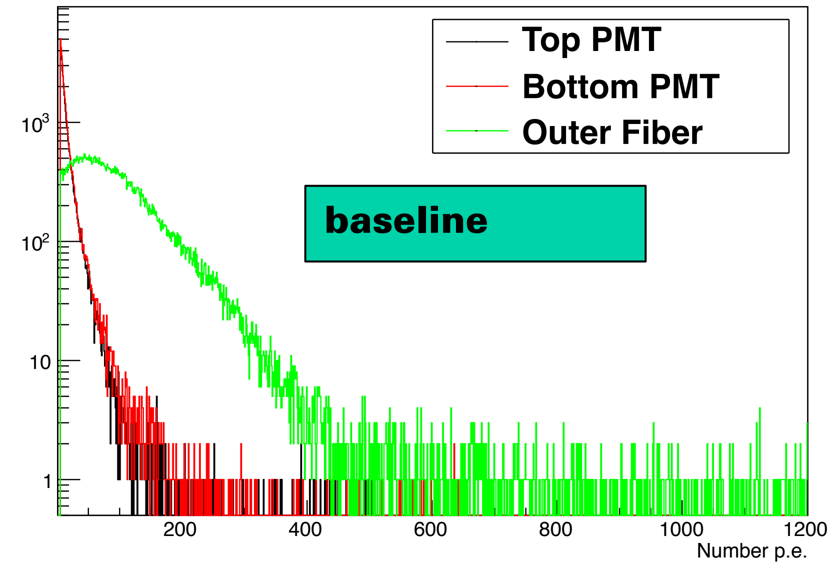
MC simulations : systematics studies (II)

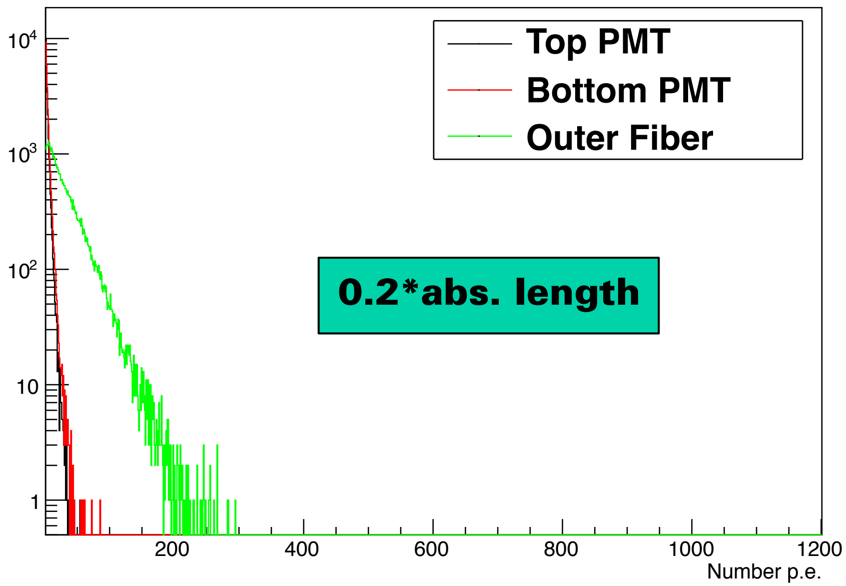
- **Effect in p.e. yield more clear**

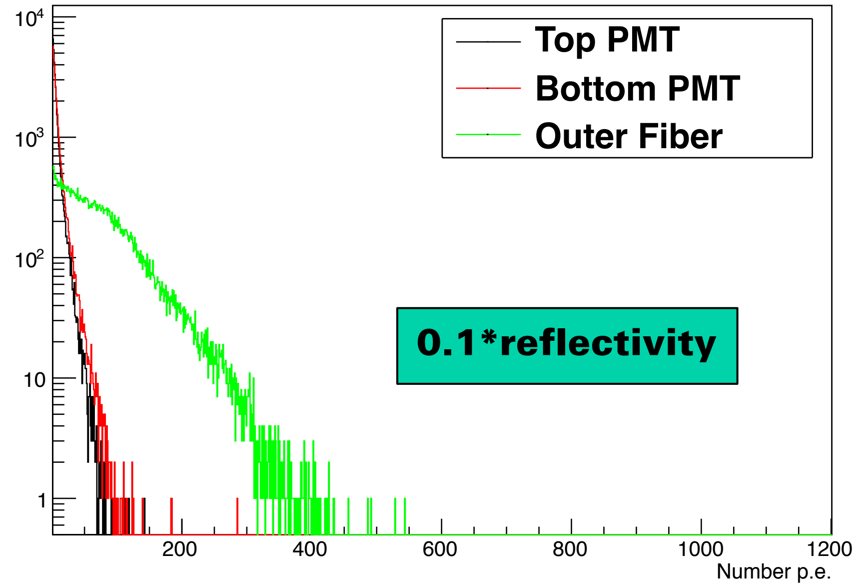
  •**Attenuation:** Reduction of p.e. yield of factor ~2

  •**Reflectivity :** Elimination of high p.e. tails.

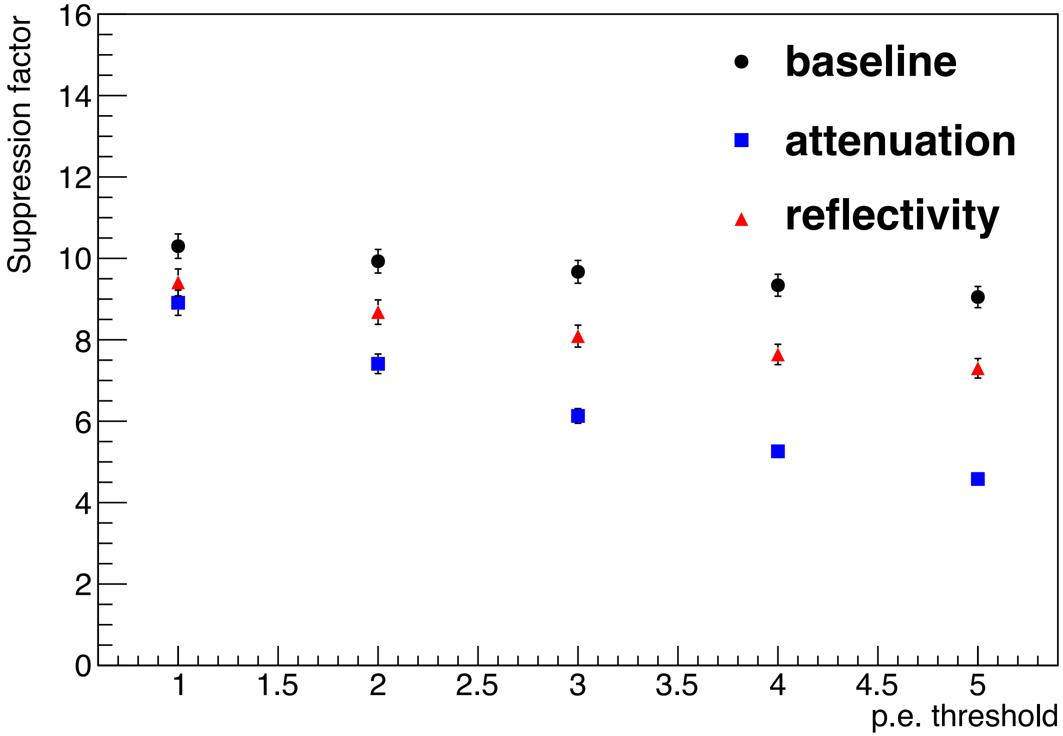
    - Reflectivity has small effect in the simulations.







MC simulations : systematics studies



- Effect of increased attenuation highly dependent on p.e. threshold
  - Other systematics not so critical
- **Purity of argon and threshold of instrumentation critical for its efficiency**

Summary

- **A LAr scintillation veto is planned for phase II of GERDA**
  - Principle demonstrated in LArGe
- **Favored design of combination of PMTs and scintillating fibers**
  - Hardware tests ongoing
  - Both technologies demonstrated on smaller scale
  - Construction has started
- **Extensive MC simulation campaign performed**
  - Used LArGe results for validation and tuning
  - Provided optimizations to the hardware designs.
- **LAr veto suppression factors look promising:**
  - > 10^2 for ^{228}Th (~300 close by, ~100 far from detectors)
  - ~ 10 for nearby ^{226}Rn backgrounds
- **Instrumentation induced BI within allowed budget**
  - Counting self-veto