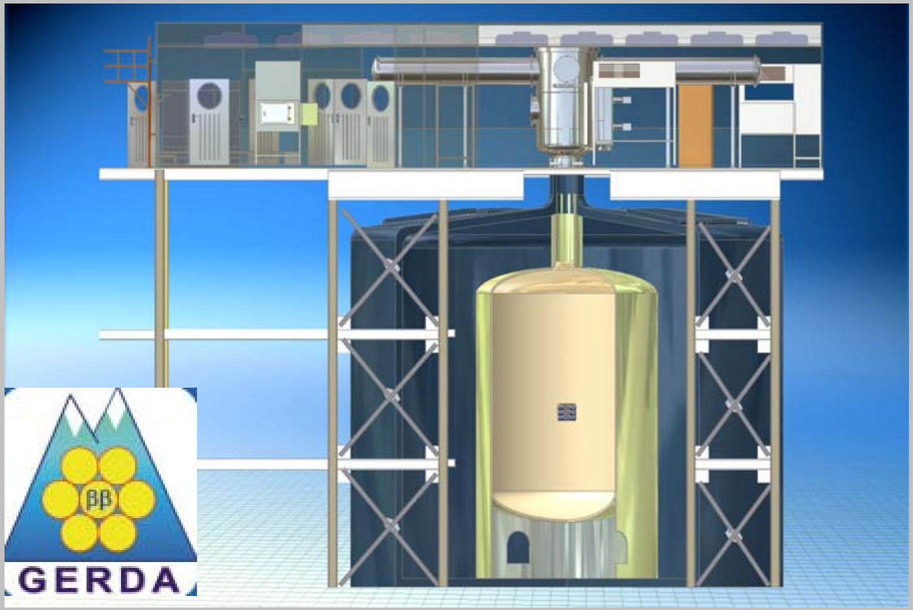
GERDA: GERmanium Detector Array
a search for 0νββ decay in ^{76}Ge

http://www.mpi-hd.mpg.de/gerda/

- Previous experiments
- GERDA design
- Phase-I and –II detectors
- Phase-III R&D
- Summary

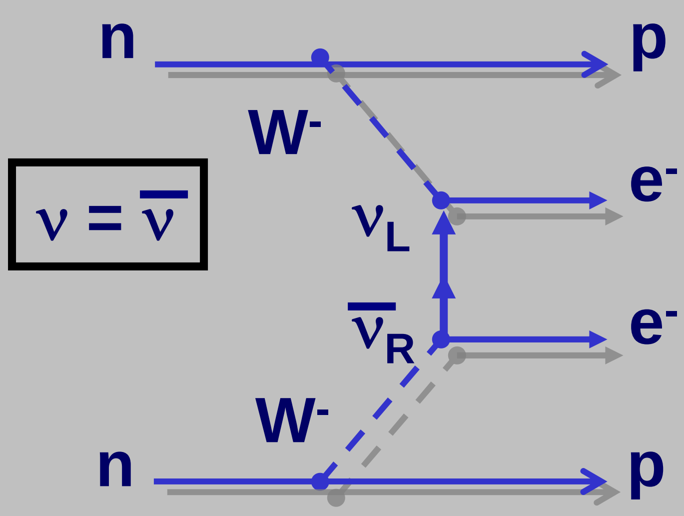


Xiang Liu 刘湘
Max-Planck-Institut für Physik
Munich, Germany

IWDD, Shanghai Jiao Tong Univerisity
June 15-16th, 2009

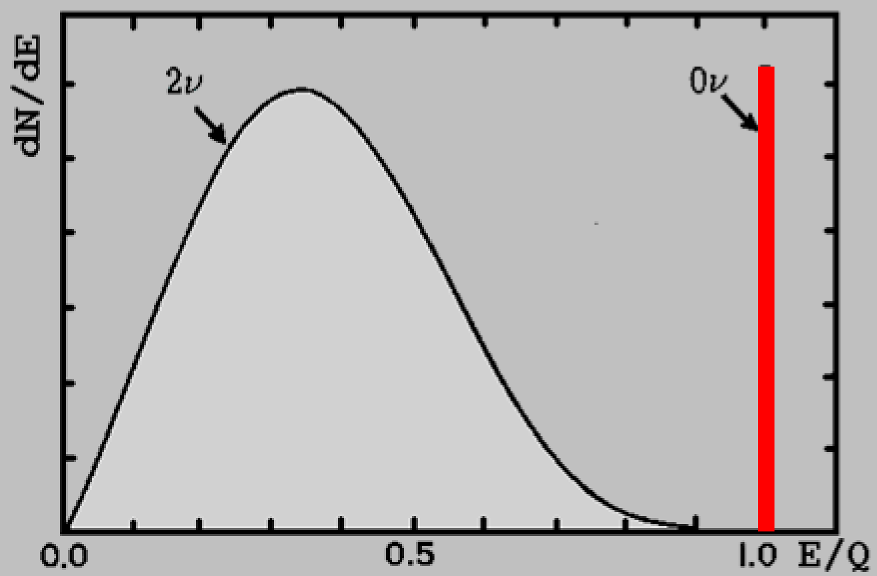
$0\nu\beta\beta$ decay → effective Majorana neutrino mass $\langle m_{\beta\beta}\rangle$

- $2\nu\beta\beta$ decay:
  $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}$
  SM allowed & observed.
- $0\nu\beta\beta$ decay: $\Delta L=2$
  $(A,Z) \rightarrow (A,Z+2) + 2e^-$
  if νs Majorana & $\langle m_{\beta\beta}\rangle > 0$.



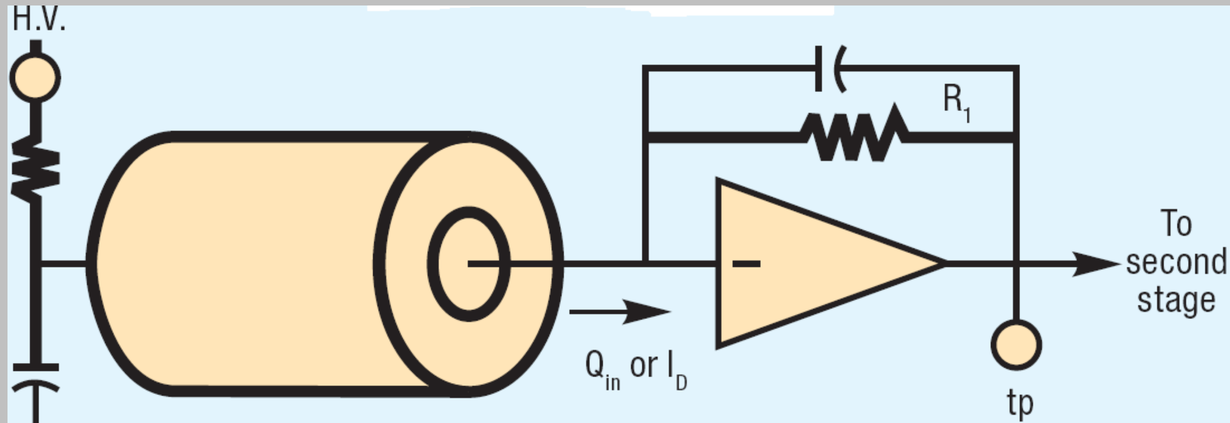
- many isotopes can be used to search for $0\nu\beta\beta$.
- Search ΔL=0 process and measure half-life $T_{1/2}$:

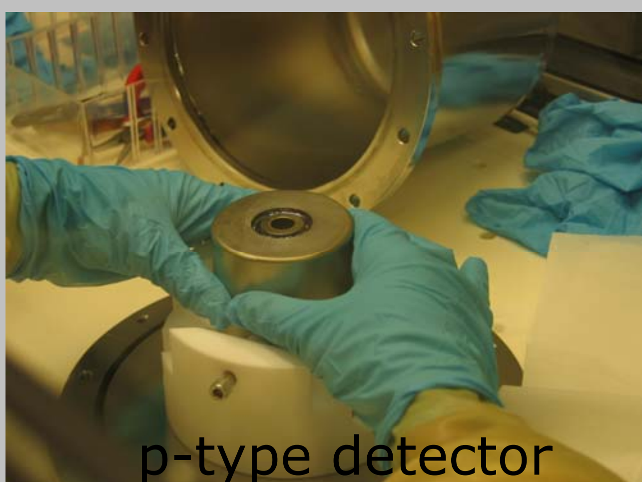
$$T_{1/2}^{-1} = G^{0\nu}(E_0, Z)\left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$



$G^{0\nu}$: phase space integral
$M^{0\nu}$: nuclear matrix element
$\langle m_{\beta\beta}\rangle = \left| \Sigma U_{ei}^2 m_i \right|$
(U_{ei}: PMNS matrix)

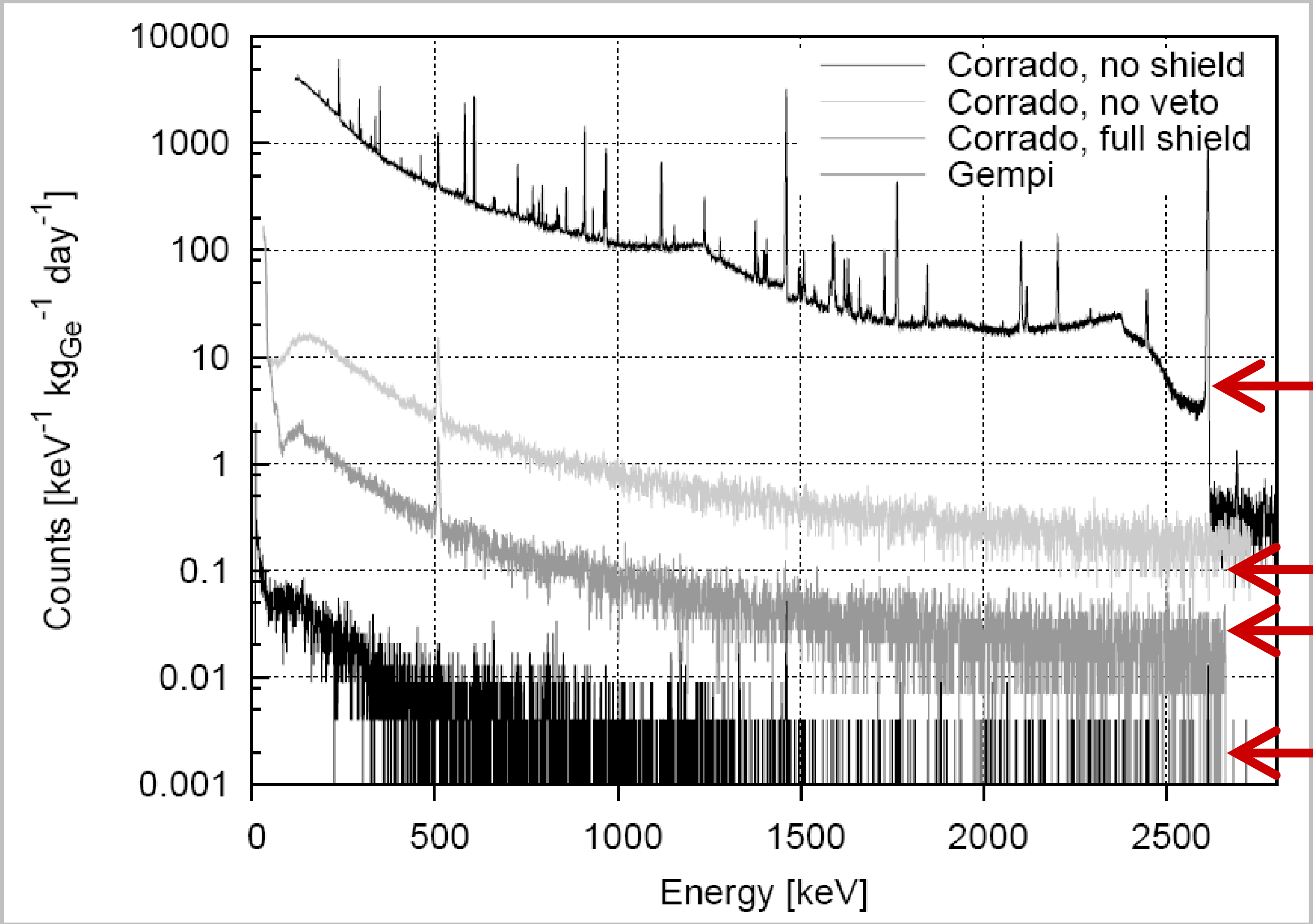
Germanium detector is a “simple” semi-conductor detector





- ~3eV to create one e-h pair
- FWHM 0.14% (at 1.3MeV with Canberra REGe detector)

Energy spectra of a p-type high purity Ge detector (HPGe)



above ground

passive shield

shield + μ-veto

underground at LNGS

D. Budjáš, et al. arXiv.0812.0768

Why choose Ge76

$$\text{sensitivity on } T_{1/2} \propto \varepsilon \bullet A \bullet \sqrt{\frac{M \bullet T}{b \bullet \sigma}}$$

$$T_{1/2} \propto \varepsilon MTA \text{ if } b = 0$$

challenge	
large amount isotope **M** long exposure **T**	
high signal efficiency ε	
extremely low level background rate b: background rate σ: energy resolution	

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challenge	Ge76 advantage
large amount isotope **M** long exposure **T**	existing IGEX & HdMo detectors
high signal efficiency ε	source=detector, 85~95% ε
extremely low level background rate b: background rate σ: energy resolution	ultrapure material (HPGe) excellent energy resolution → FWHM ~3keV at 2MeV, small search window → reduce background, including $2\nu\beta\beta$ new development → segmentation, new type of Ge detector etc…

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☹need enrichment (A=7.6%, most bg scale with target mass)

☹$Q_{\beta\beta}$=2039keV (<2614keV)

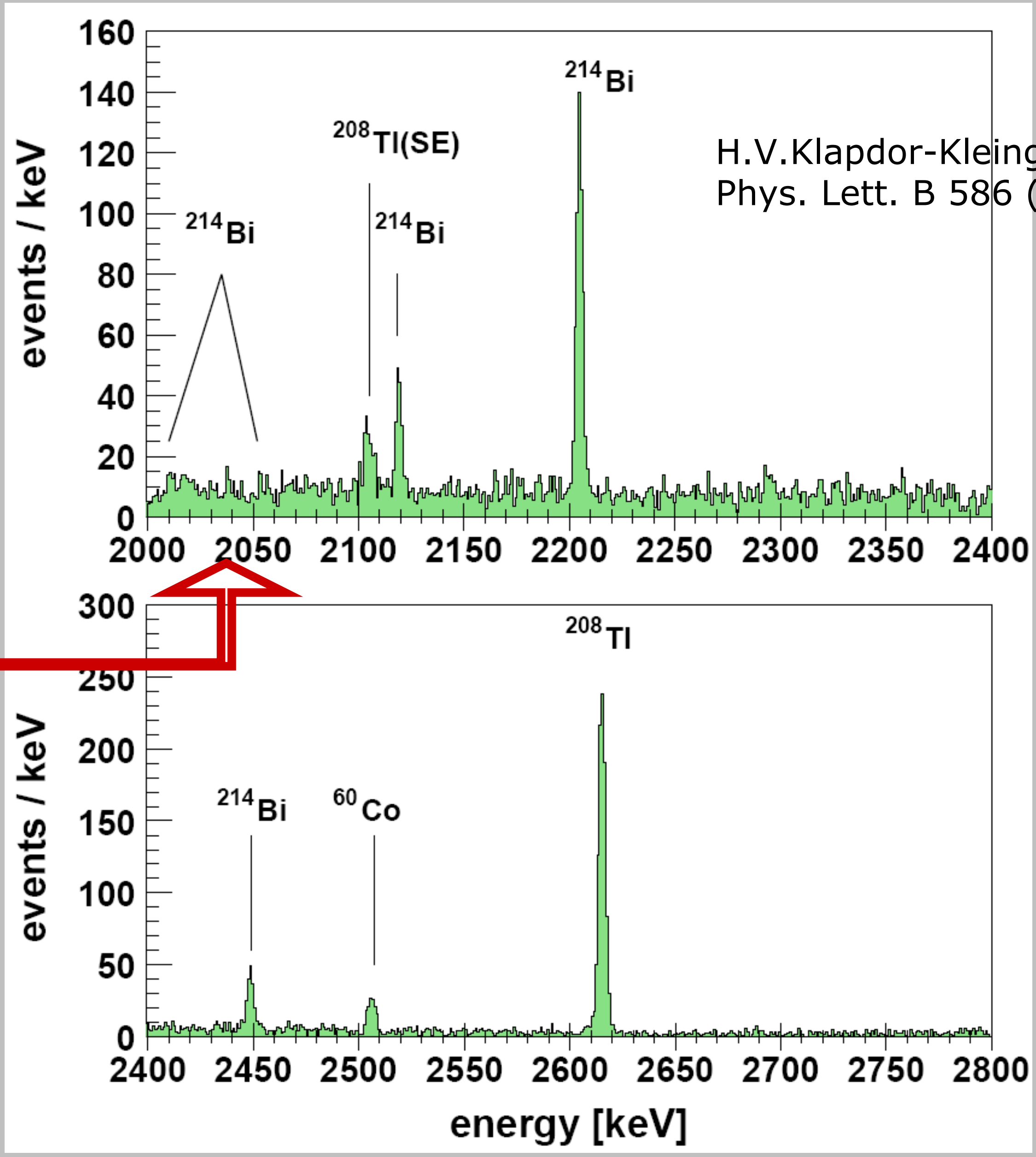
Previous 0νββ Ge76 experiment: Heidelberg-Moscow

	Th	U
Cu	58.1	116.0 μBq/kg
Pb	12.3	26.6 μBq/kg

5 Ge76-enriched (86%) detectors

- at LNGS 1990-2003
- total 11.5kg, 71.1kg·year exposure
- operated in vacuum
- shielded with pure Pb & Cu

Previous 0νββ Ge76 experiment: Heidelberg-Moscow



H.V.Klapdor-Kleingrothaus, et al.,
Phys. Lett. B 586 (2004) 198-212

Ge76 Q-value:
2039keV

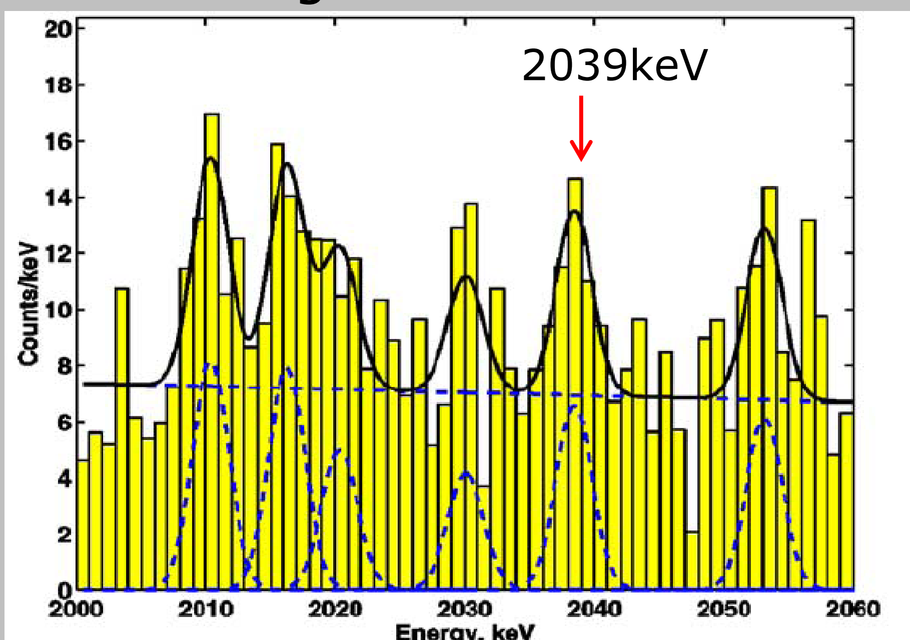
Previous Ge76 experiments

	HdMo	IGEX
exposure[kg·year]	71.1	8.87
B [counts/(keV·kg·year)]	0.11	0.2
$T_{1/2}$ limit (90%CL)[year]	$1.9 \cdot 10^{25}$	$1.6 \cdot 10^{25}$

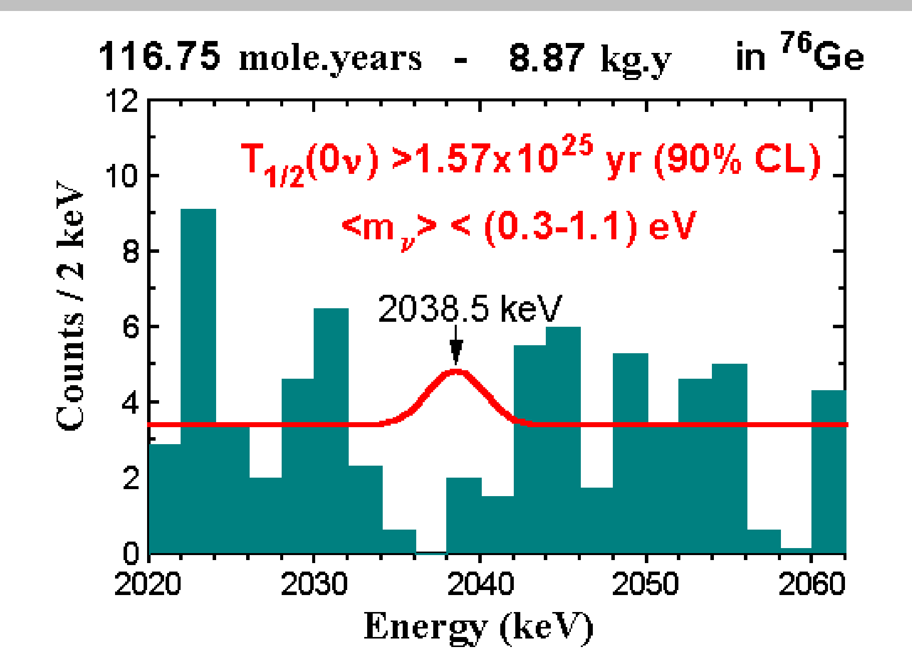
"Evidence for $0\nu\beta\beta$" $1.2 \cdot 10^{25}$
H.V.Klapdor-Kleingrothaus, et al., Phys. Lett. B 586 (2004) 198-212 (0.69-4.18 3σ)

Background index B:
counts/(keV·kg·year)
keV: energy window
kg: Ge mass
year: exposure time

Heidelberg-Moscow



IGEX



GERDA goal

phase	I	II	"III"
detector [kg]	17.9 existing	~25 more	ton-scale
exposure[kg·year]	30	100	>1000
bg [counts/(keV·kg·year)]	10^{-2}	10^{-3}	10^{-4}
limit on $T_{1/2}$ [10^{25} year](90%C.L.)	2	15	>280
limit on $m_{\beta\beta}$ [eV]*	0.27	0.13	<0.03

*Assuming $<M^{0\nu}>=3.92$
(Erratum: Nucl. Phys. A766 (2006) 107)

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Phase-I fact

Claim of evidence
signal: 28.75±6.86 events
bg level: 0.11 counts/ keV·kg·year
H.V.Klapdor-Kleingrothaus, et al.,
Phys. Lett. B 586 (2004) 198-212

If claim true, phase-I will see:
signal: 13 events
bg: 3 events

in 10keV window at 2MeV
assume 4keV FWHM at 2MeV

*Assuming $\langle M^{0\nu} \rangle = 3.92$
(Erratum: Nucl. Phys. A766 (2006) 107)

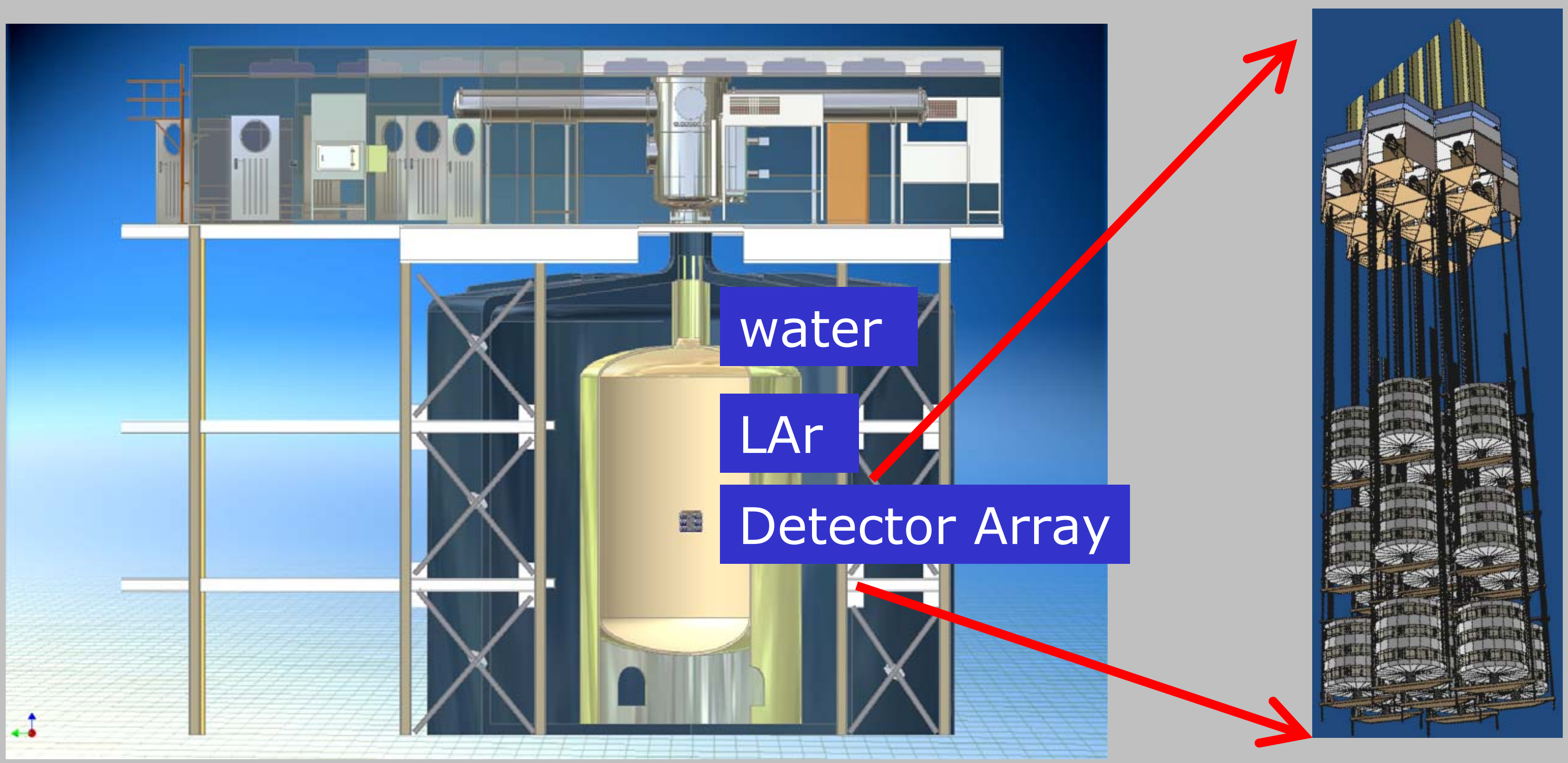
GERDA concept

naked Ge detectors submerged in liquid argon

- ✓LAr as cooling and shielding*
- ✓Th & U in LAr <7·10^{-4} μBq/kg
- ✓minimum surrounding materials

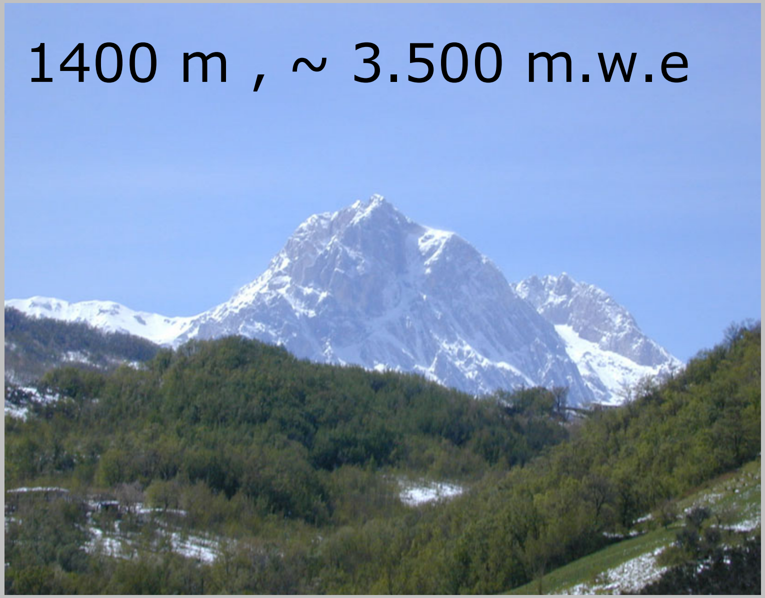
phased approach with existing and new detectors

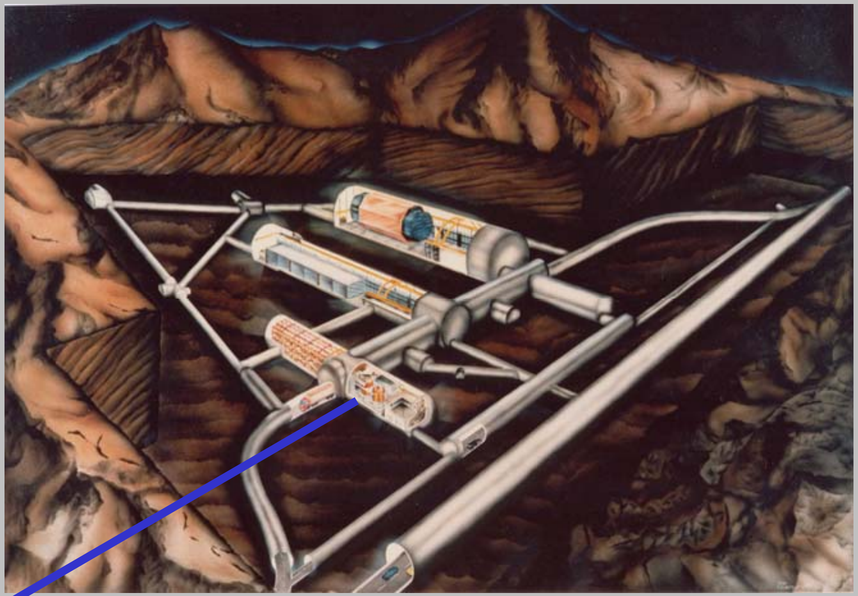
- ✓increase target mass
- ✓new bg-reduction techniques

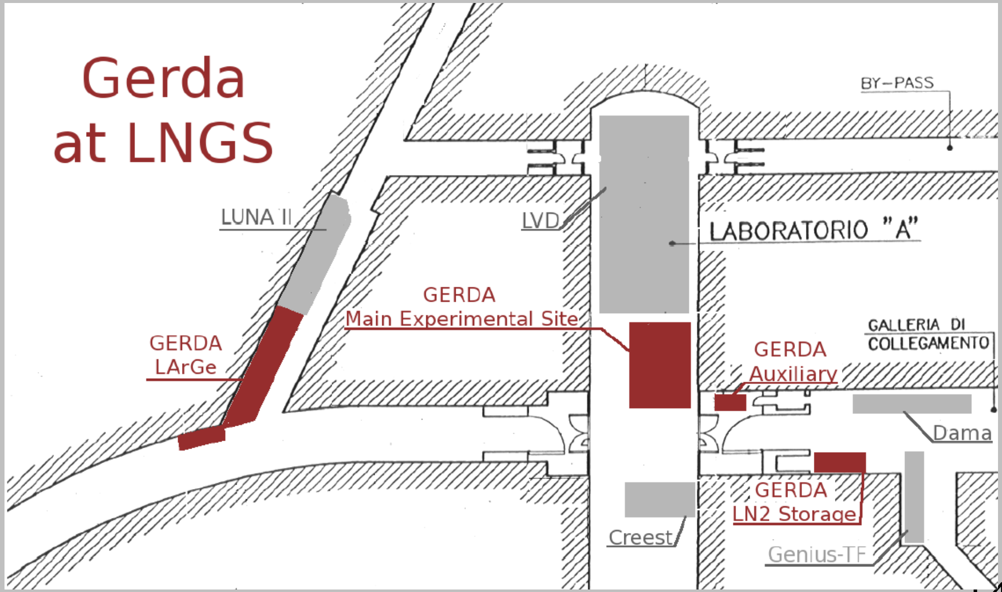


* G. Heusser, Ann. Rev. Nucl. Part. Sci. 45 (1995) 543.

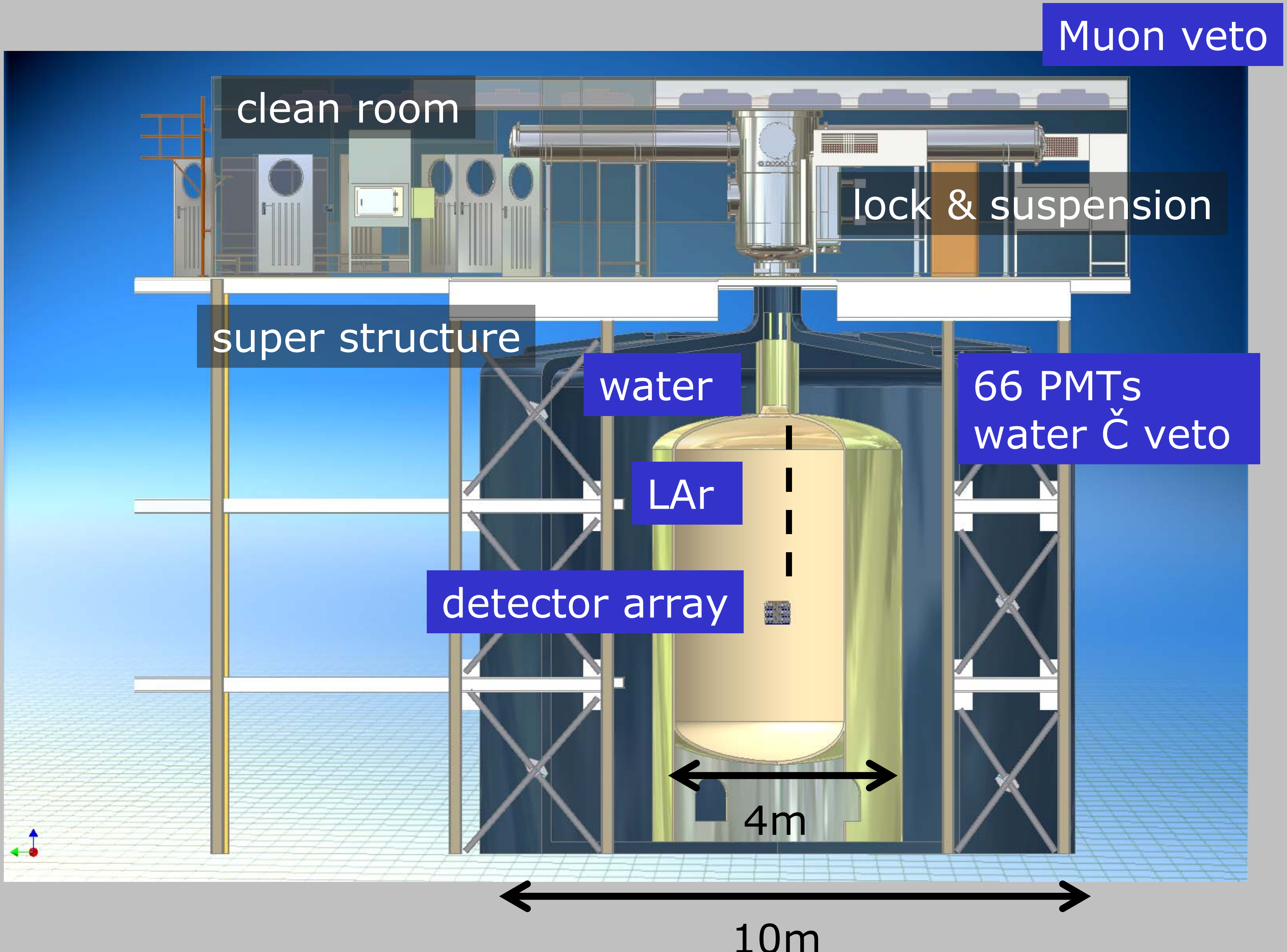
GERDA experiment at LNGS



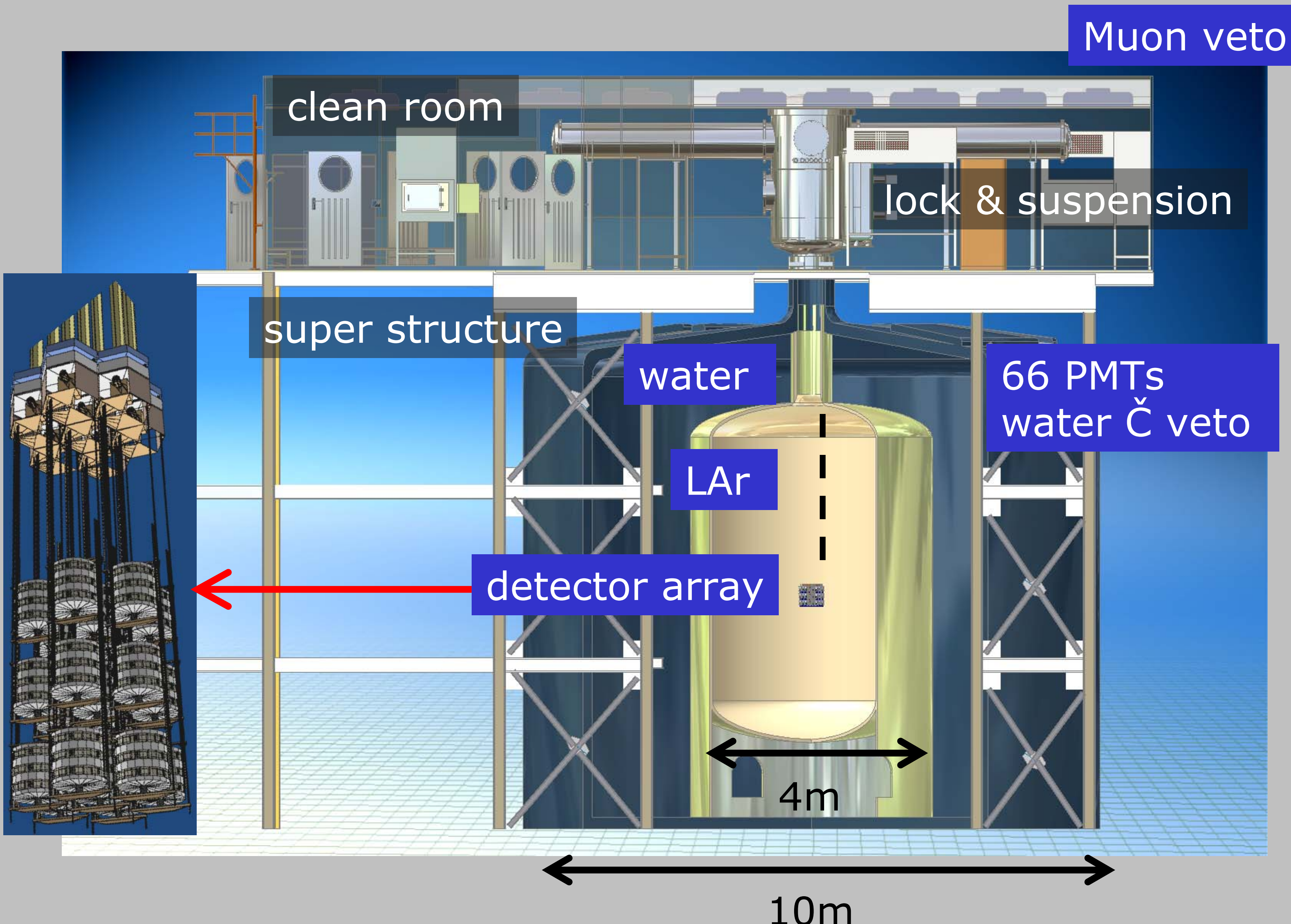




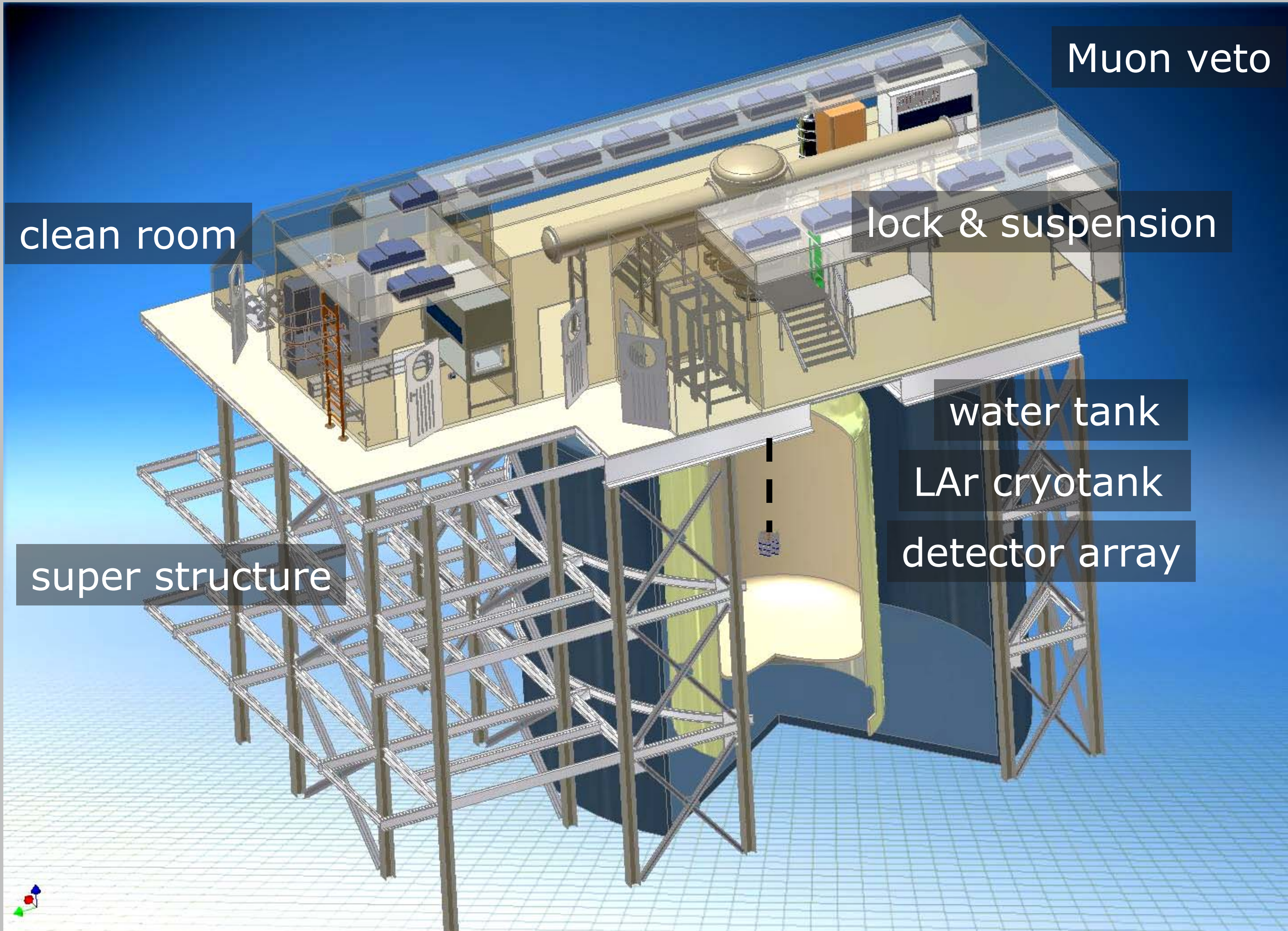
GERDA design



GERDA design



GERDA design



Cryotank and water tank constructed

cryotank (Mar. 2008)

water tank (Aug. 2008)

Clean room and PMT in water tank almost ready

cleanroom
May. 2009

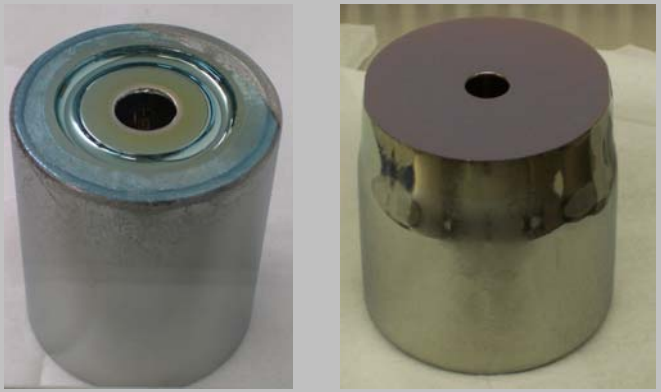
mounting PMTs in watertank
May. 2009

Phase-I detector status

Phase I: 3 IGEX & 5 HdMo detectors, in total 17.9 kg,
30g Cu, 6.3g PTFE, 1g Si per detector

	ANG1	ANG2	ANG3	ANG4	ANG5	RG1	RG2	RG3
FWHM [keV]	2.54	2.29	2.93	2.47	2.59	2.21	2.31	2.26
Mass [kg]	0.980	2.906	2.446	2.400	2.781	2.150	2.194	2.121

(at 1.3MeV)



Heidelberg-Moscow & IGEX
(before reprocessing)

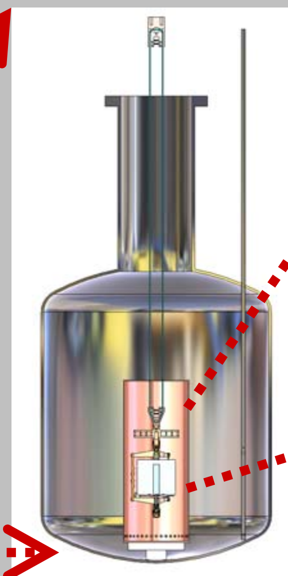
reprocessed detectors
tested in LAr

All detectors reprocessed and tested in liquid Argon
FWHM ~2.5keV (at 1332keV), leakage current (LC) stable

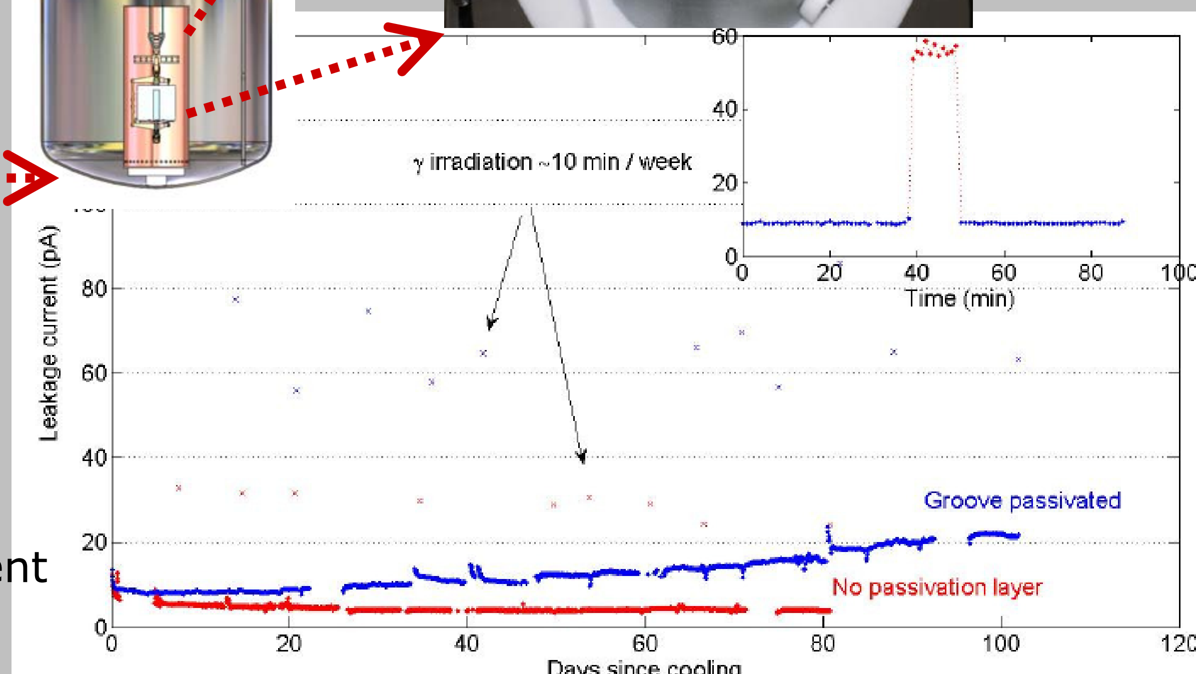
Phase-I prototype detector performance in liquid argon

- A well tested procedure for handling detectors defined.
- Observed increase of LC well understood,
  due to charge trapping above passivation layer (PL)
- Detector without PL inside groove, long term performance stable.

detector test bench

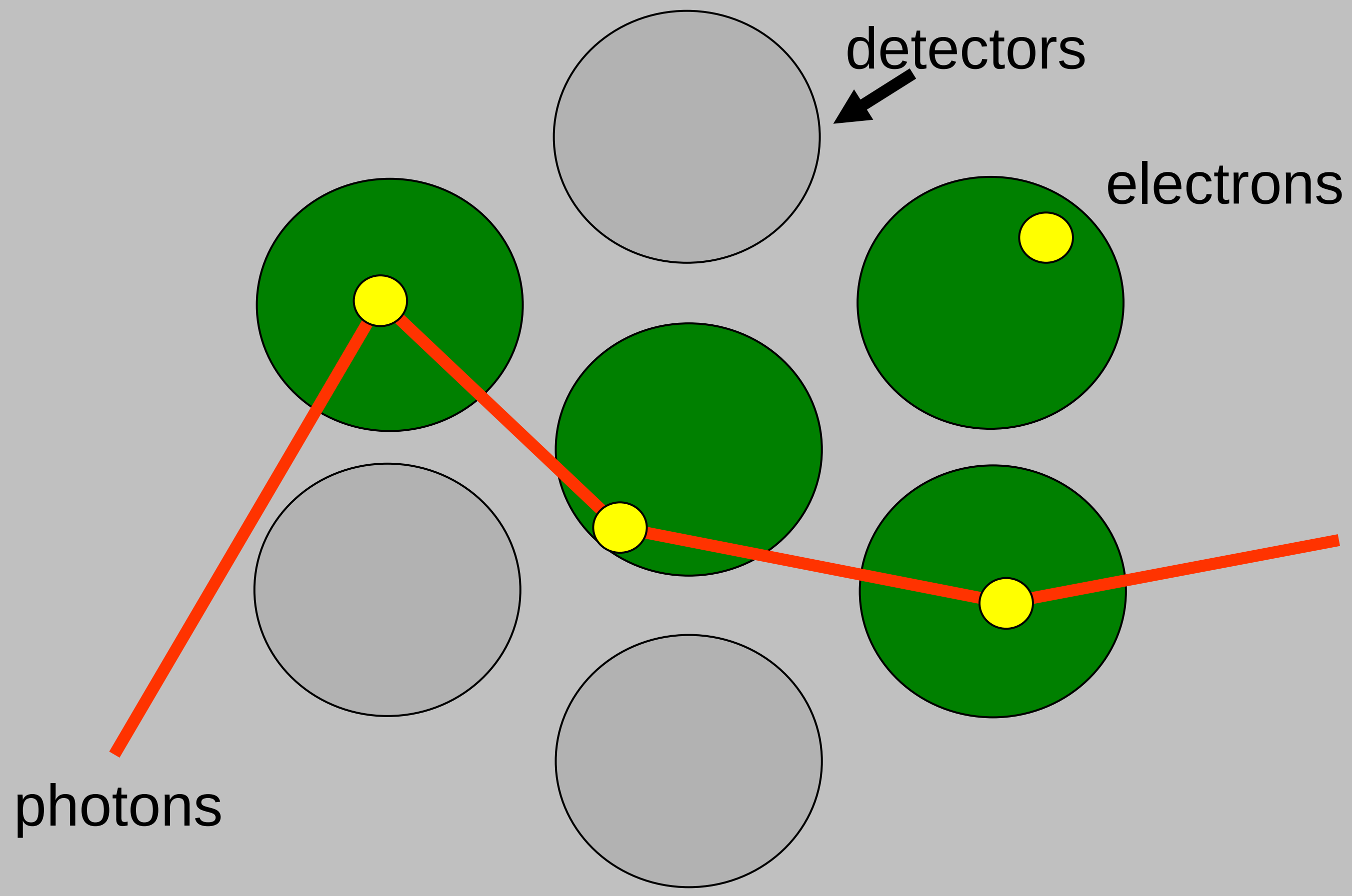


passivation layer in groove



detector leakage current with & without PL

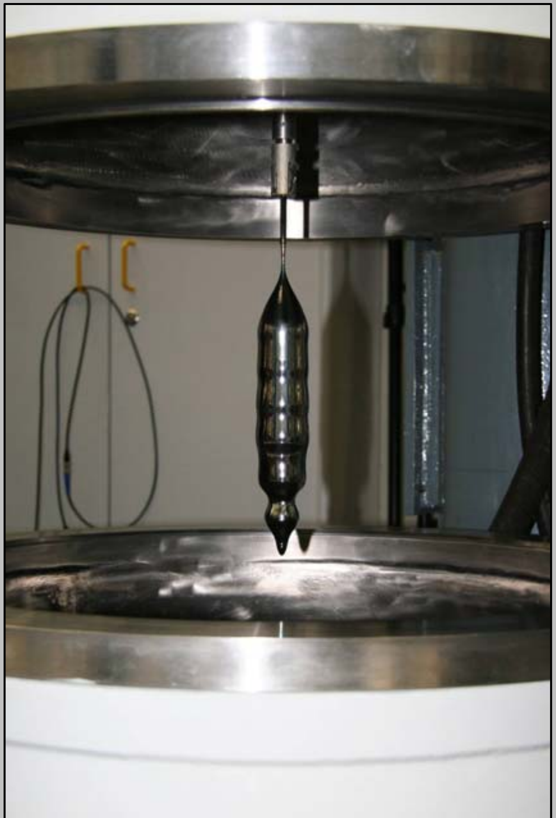
Remove photon background by detector anti-coincidence



2 electrons : energy deposit range in germanium <1mm
2MeV photon: several Compton scattering, cm range

Phase-II enriched detector status

- 37.5 kg Ge with 88% enrichment, stored underground.
- 50kg ${}^{dep}GeO_2$ delivered, for testing metal reduction and 6N purification.
- Several ^{dep}Ge crystals pulled with dedicated Czochralski puller at Institut für Kristallzüchtung (IKZ) Berlin .
- Charge carrier density: 10^{11} cm^{-3} to 10^{13} cm^{-3} (required: 10^{10} cm^{-3})

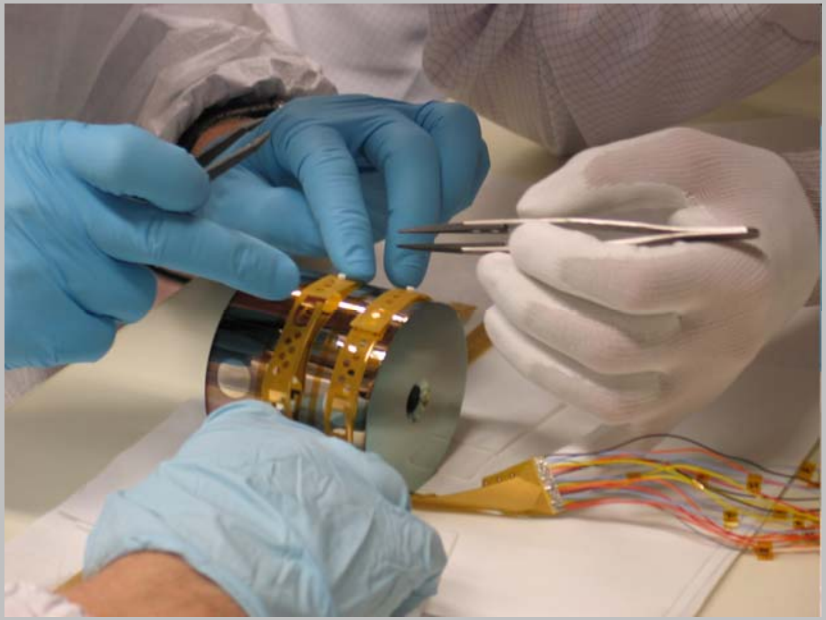


Phase-II detector candidate: 18-fold segmented detector

expect ~25kg, ~15 detectors

prototype

- novel "snap contact"
- small amount of extra material
  19g Cu, 7g PTFE, 2.5g Kapton per 1.62kg detector

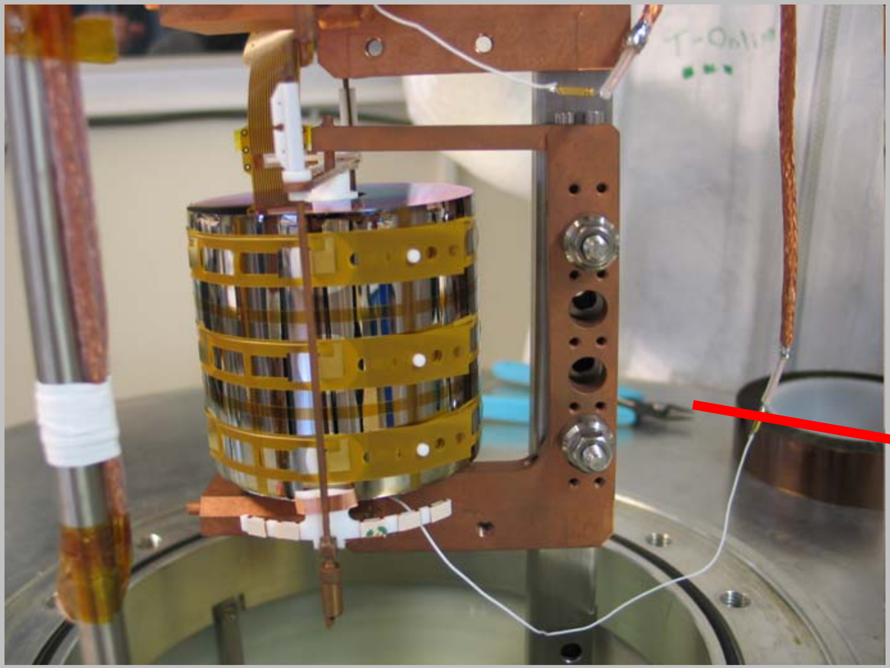


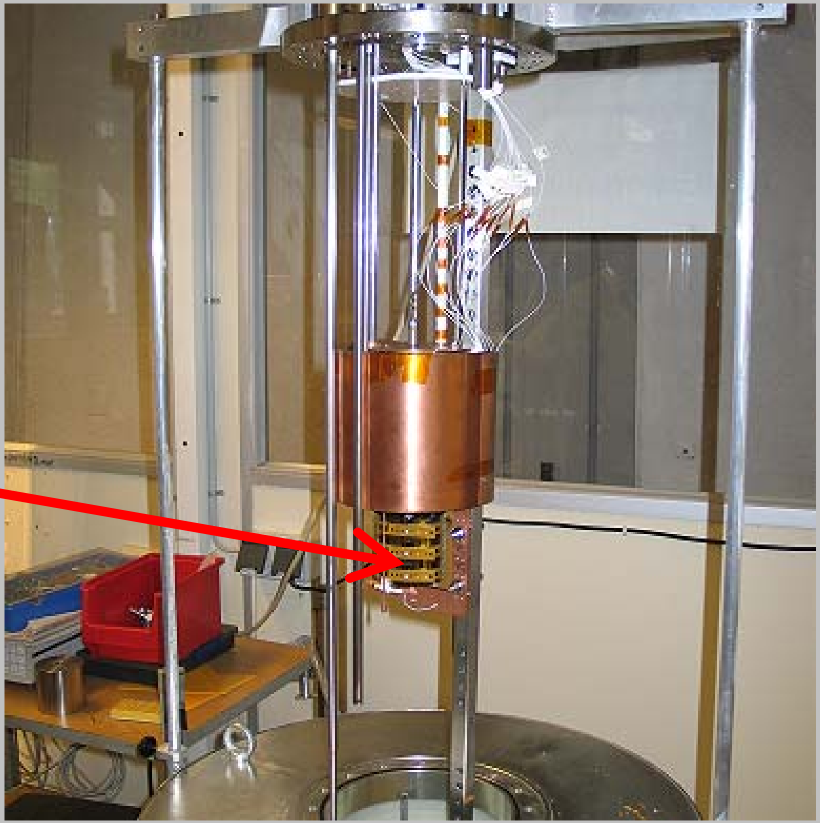
Contact by mechanical pressure

Segmented prototype detector (non-enriched) tested in LN2

Detector works in liquid nitrogen

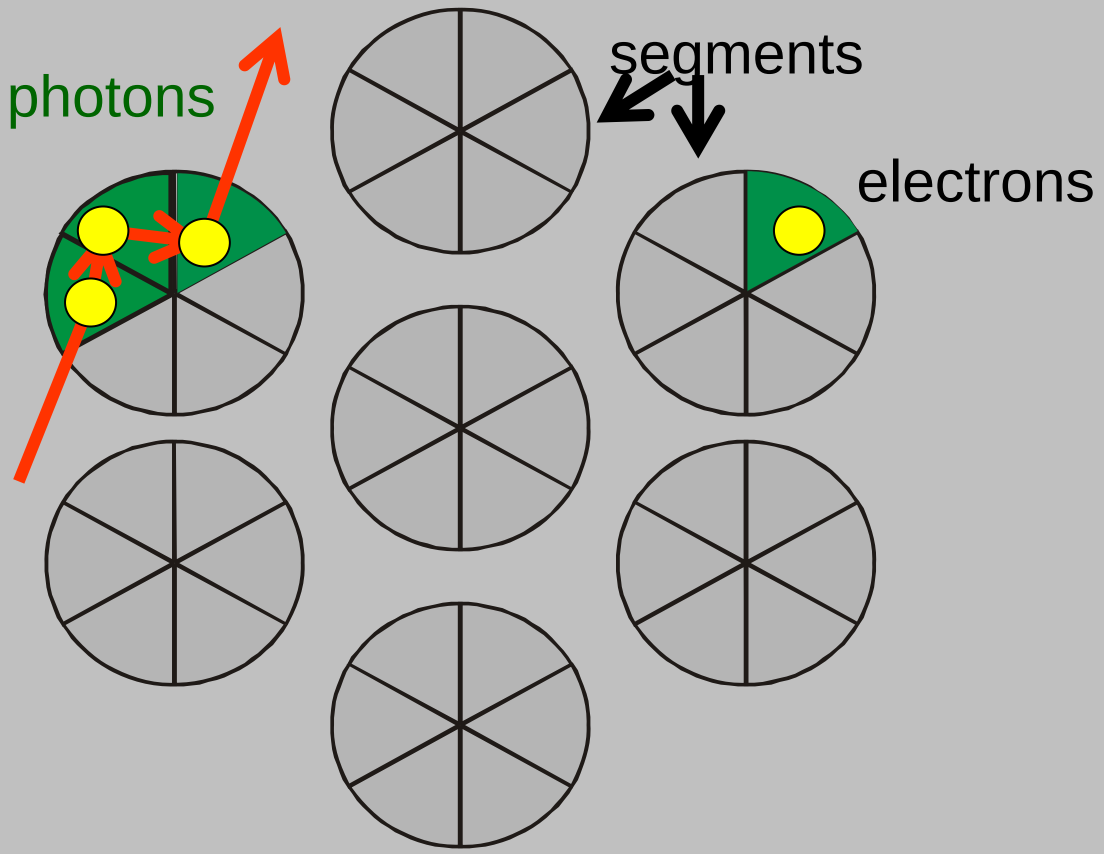
- FWHM core 4.1 keV, segments 3.6 - 5.7 keV
- leakage current 30 ± 5 pA
- stable performance for 5 months
- currently being tested in liquid argon





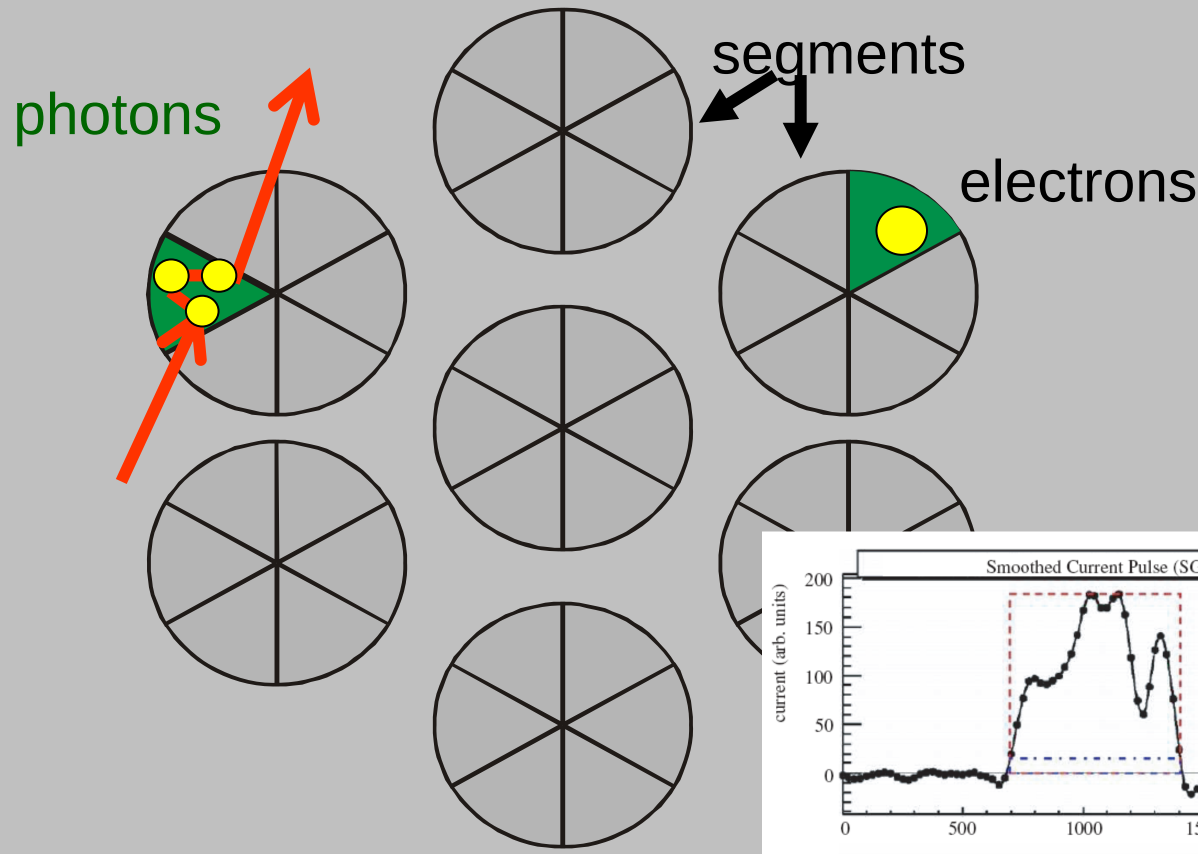
prototype in liquid nitrogen

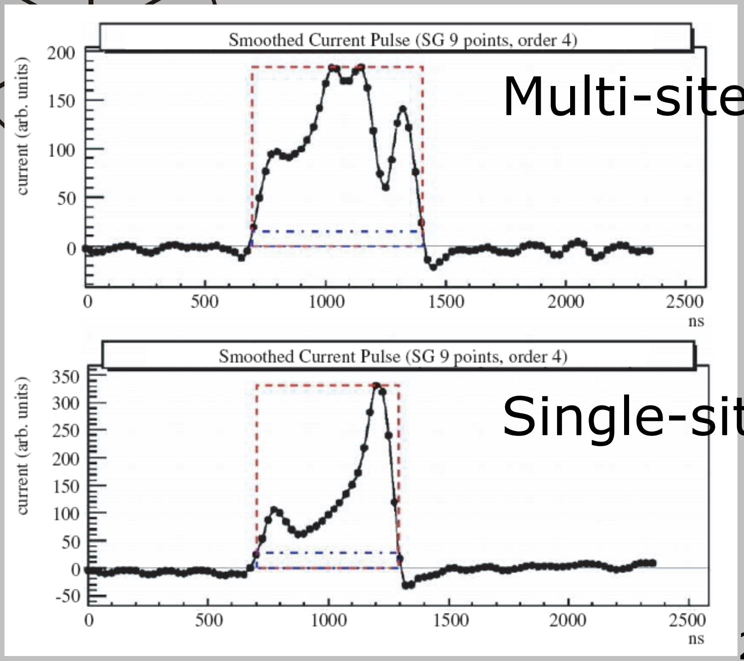
Remove multi-segment background: segmentation



Signal (2 electron): single-segment event
Photon background: multi-segment event

Remove single-segment background: pulse shape analysis

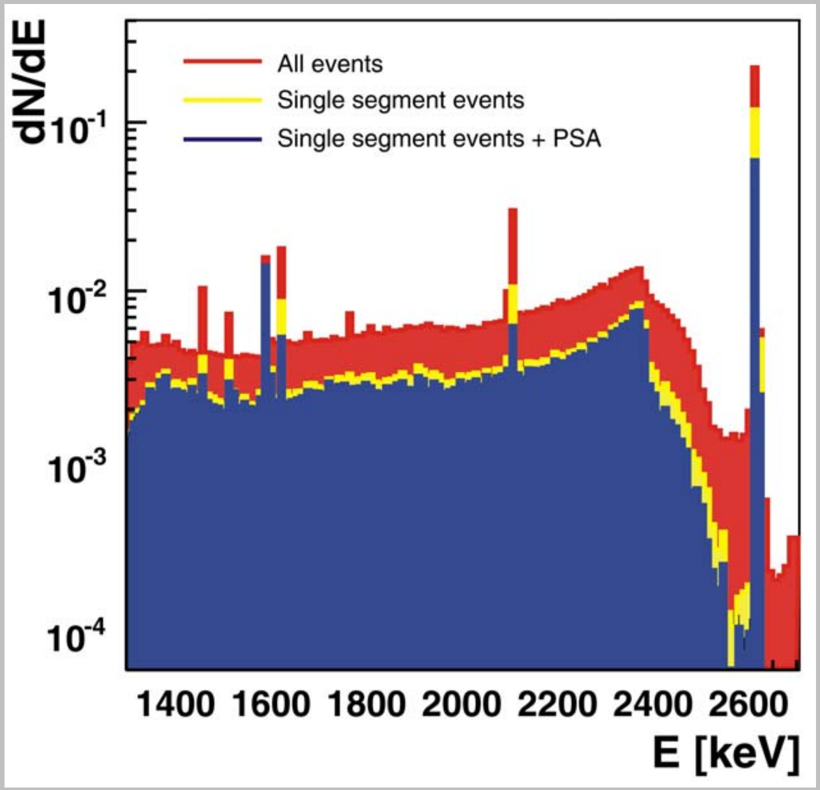


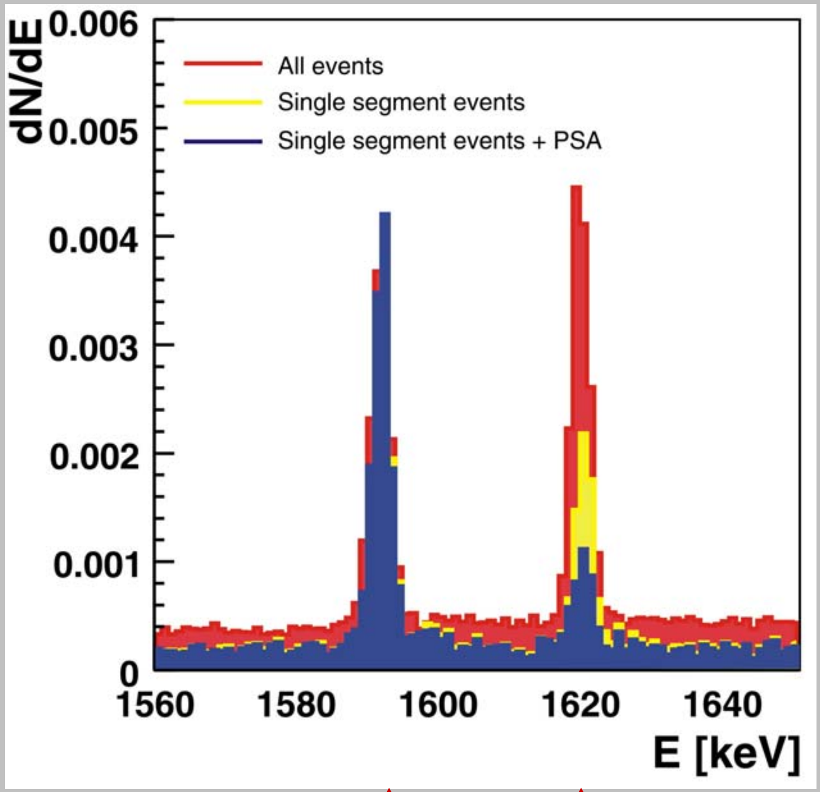


Signal (2 electron): single-segment event
Photon background: multi-segment event

R&D: photon background reduction with segmented detector

Detector in vacuum exposed to Th228 source





Double-escape peak
(single-site dominant)

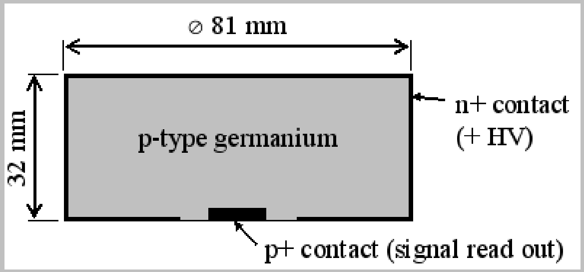
1620keV Bi212
(multi-site dominant)

segment reduction factor in RoI

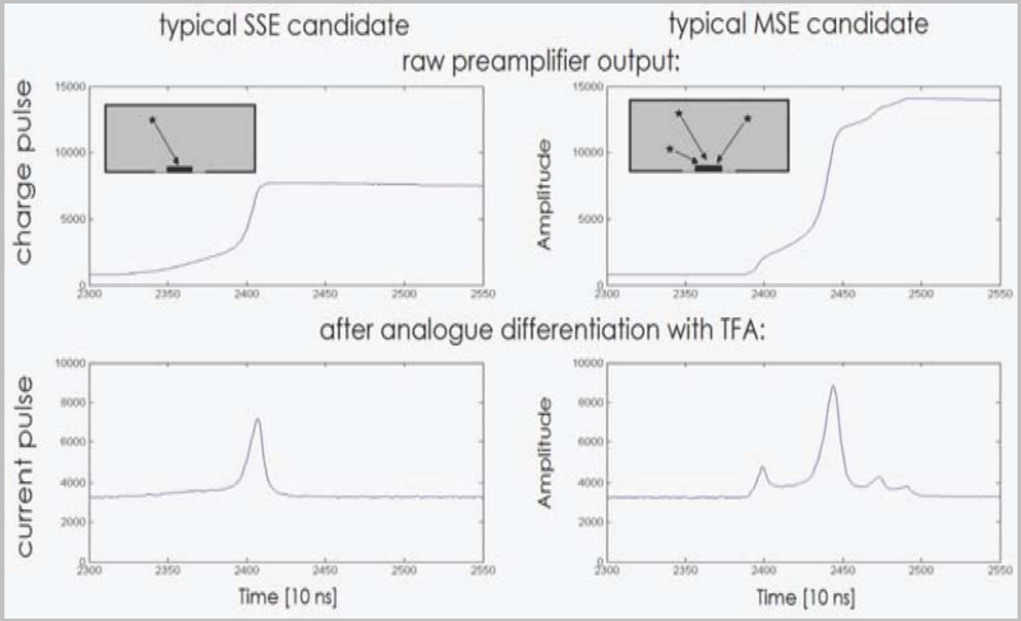
sample	data	MC
Co60	14.2 ± 2.1	12.5 ± 2.1
Th228	1.68 ± 0.02	1.66 ± 0.05

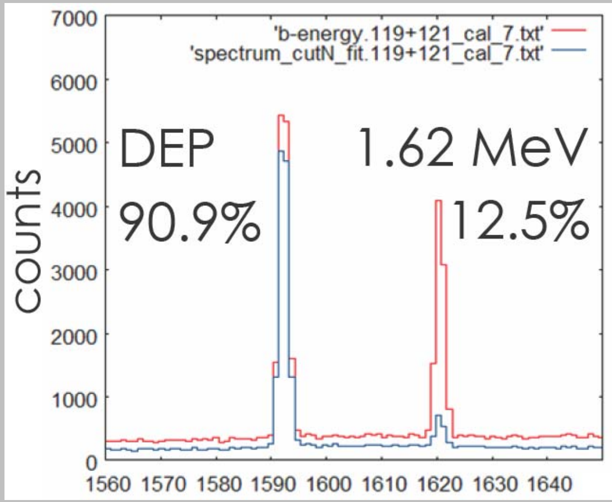
(depend on source position)

Phase-II detector candidate: point-contact detector



Canberra thick window broad energy detector (BEGe, 878g)

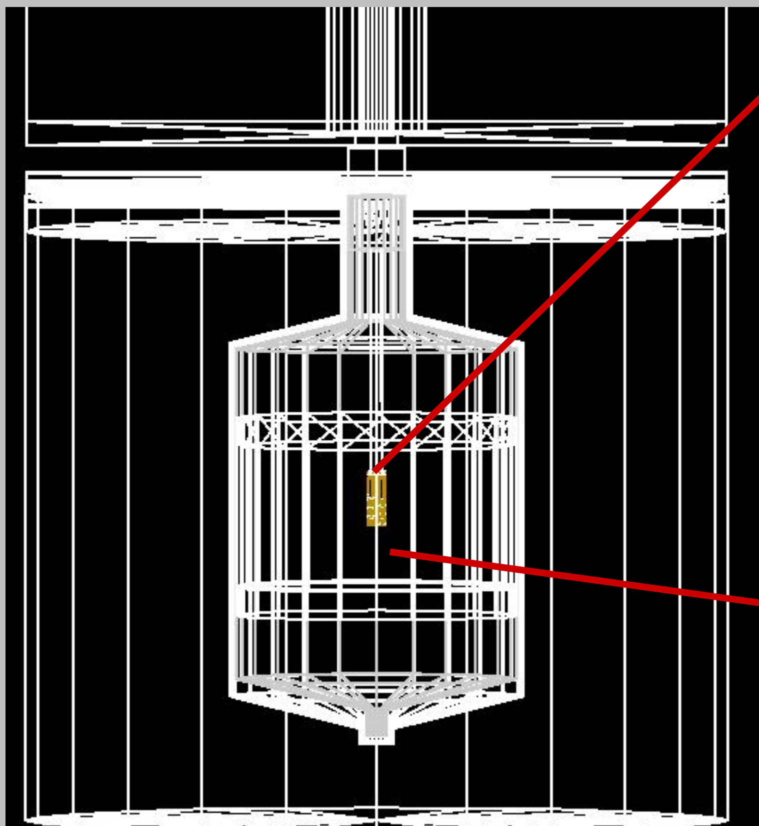


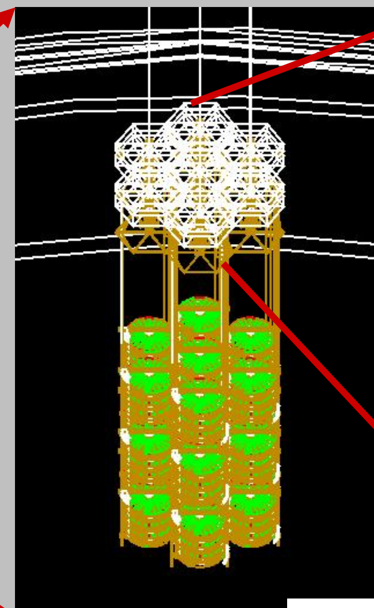


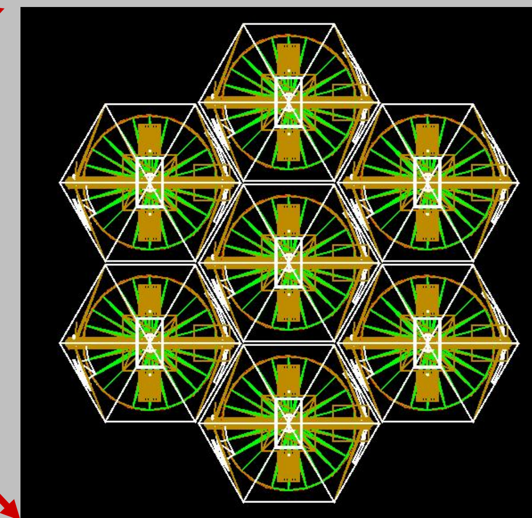
- Successful R&D
  - ✓Observed complete charge collection from full detector volume.
  - ✓No position dependence of pulse heigh and resolution.
  - ✓Similar reduction factor achieved.
- BEGe production yield under investigation.

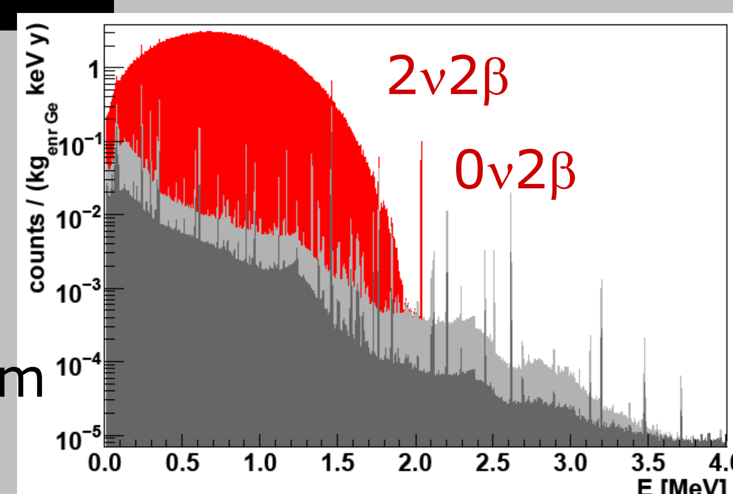
Monte Carlo package MaGe (Majorana-Gerda)

- Geant4-based, developed together with Majorana.
- optimized for low energy & low bg.
- code sharing & physics verification.



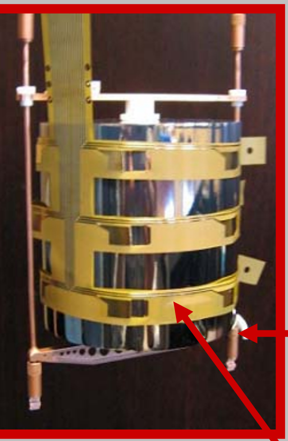






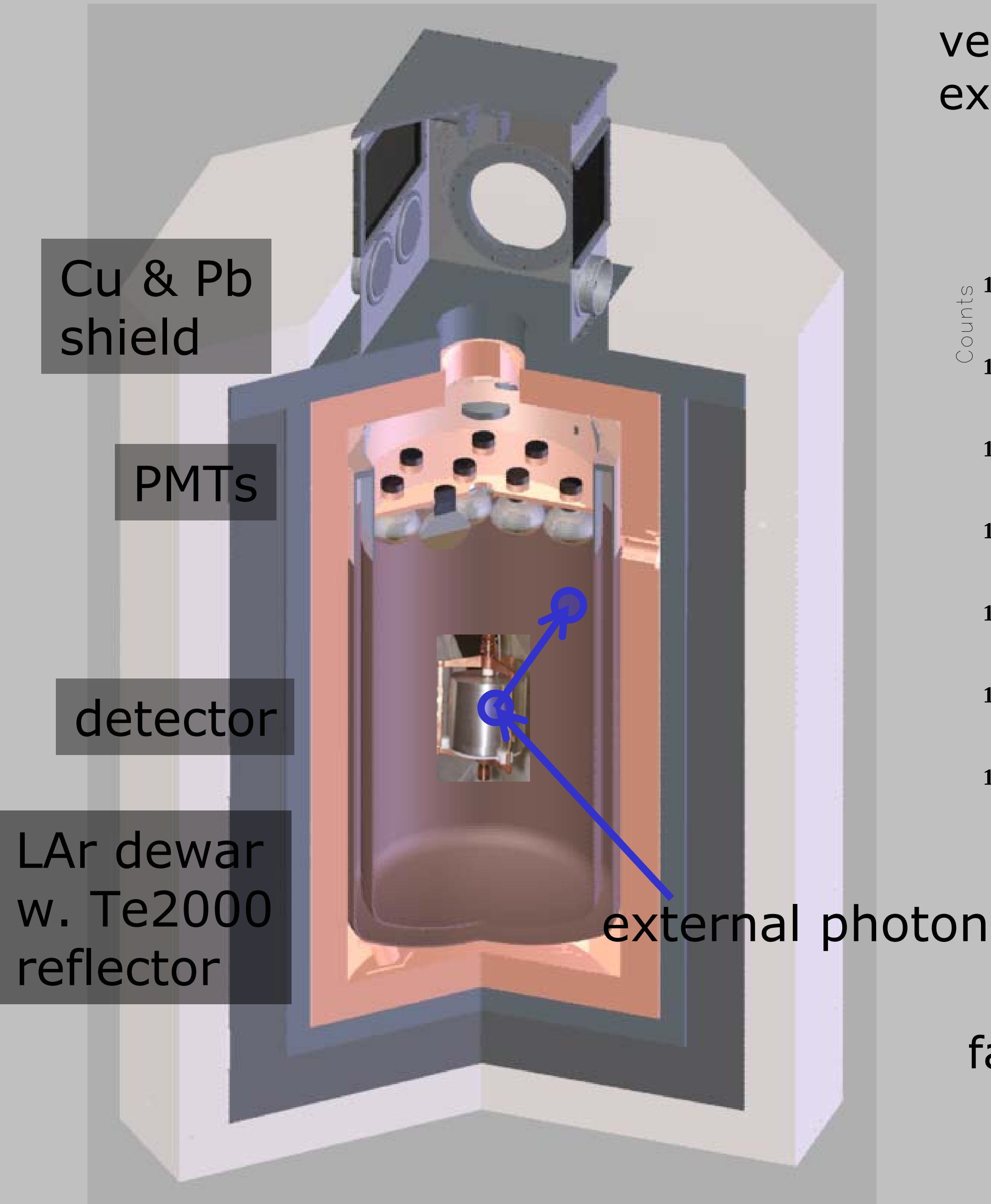
background from detector holder

MC simulation of background (phase II)



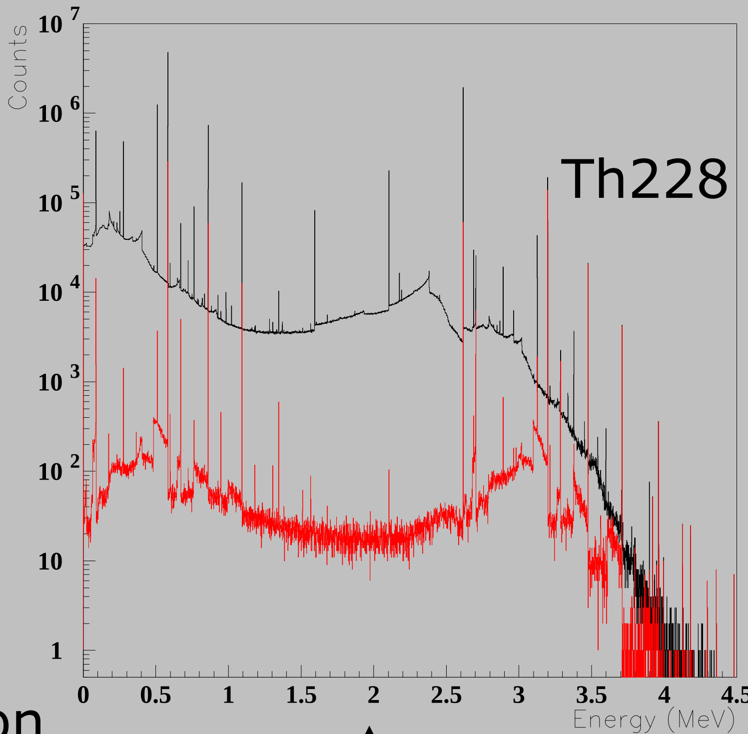
Part		Background contribution [10^{-4} counts/(kg·keV·y)]	
Detector	**^{68}Ge**	**4.3**	→ after 2 years
	^{60}Co	0.3	
	Bulk	3.0	
	Surf.	**3.5**	→ further reduction expected from PSA
Holder		3.3	
Cabling		4.8	
Electronics		**6.8**	
LAr		1.0	
Infrastructure		0.2	
Muons and neutrons		2.0	
Total		29.2	

Phase-III R&D: LArGe (liquid Argon scintillation veto)



veto background by tagging extra energy in LAr

P. Peiffer *et al.*, Nucl. Phys. B. Proc. Supp. **143** (2005) 511



factor 300 reduction in ROI

Summary

Open questions about neutrino :
absolute mass? hierarchy? Majorana or Dirac?
→ GERDA (searching $0\nu\beta\beta$ in Ge76) might address all.

- Phase-I detectors ready.
- Successful R&D with Phase-II prototype detectors.
- R&D on Ge metal purification and crystal pulling.
- R&D on LAr scintillation for Phase-III.

- Phase-I commissioning 2009!

GERDA collaboration

Institute for Reference Materials and Measurements, Geel, Belgium
Institut für Kernphysik, Universität Köln, Germany
Max-Planck-Institut für Kernphysik, Heidelberg, Germany
Max-Planck-Institut für Physik (Werner-Heisenberg-Insititut), München, Germany
Physikalisches Institut, Universität Tübingen, Germany
Technische Universität Dresden, Germany
Dipartimento di Fisica dell'Univeristá; di Padova e INFN Padova, Padova, Italy
INFN Laboratori Nazionali del Gran Sasso, Assergi, Italy
Universitá; di Milano Bicocca e INFN Milano, Milano, Italy
Jagiellonian University, Cracow, Poland
Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics, Moscow, Russia
Joint Institute for Nuclear Research, Dubna, Russia
Russian Research Center Kurchatov Institute, Moscow, Russia
University Zurich, Switzerland

~97 scientists.

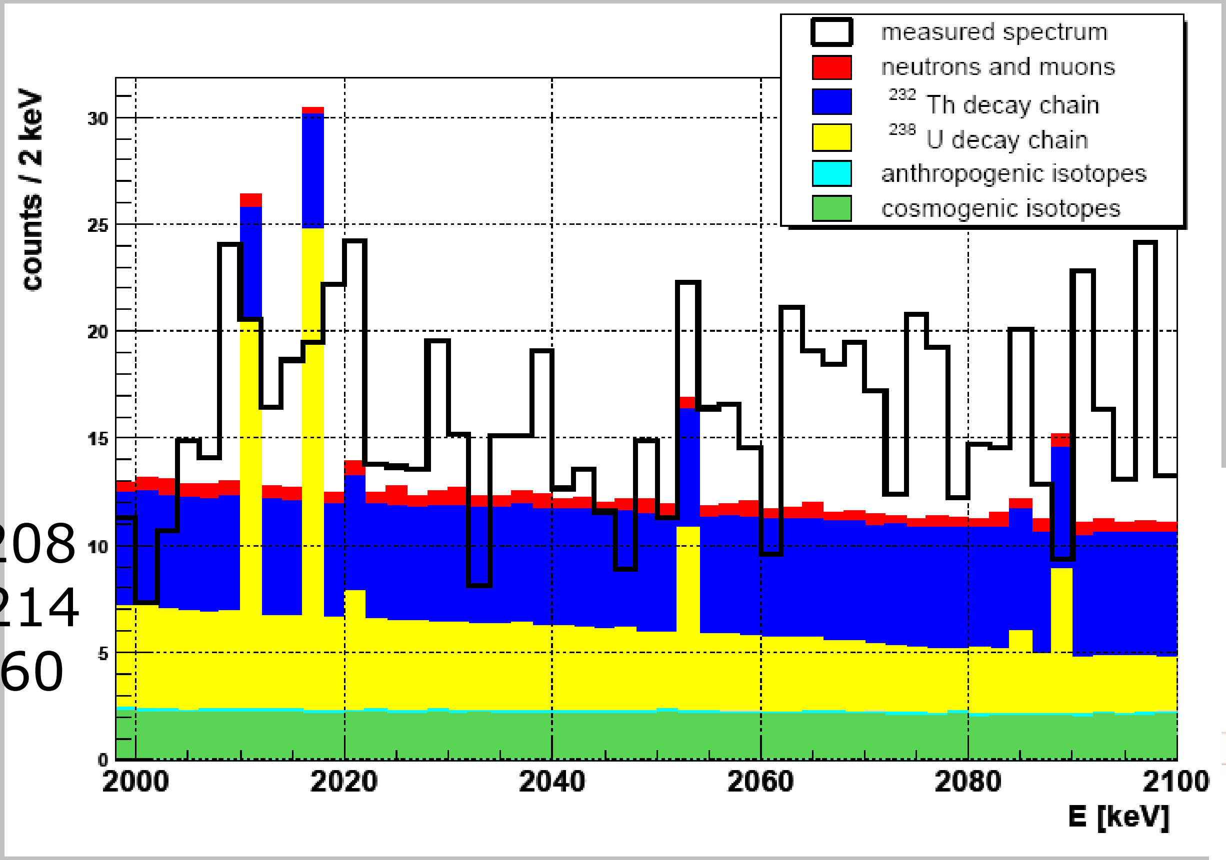
Backup

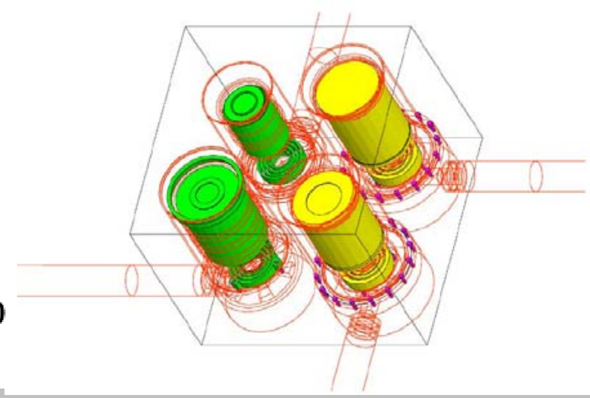
Background in HdMo experiment

- lead shield and copper cryostat: Th232, U238, K40
- cosmogenic activation: Co60
- muon and neutron

	Th232	U238
Cu	58.1	116.0
Pb	12.3	26.6
		μBq/kg

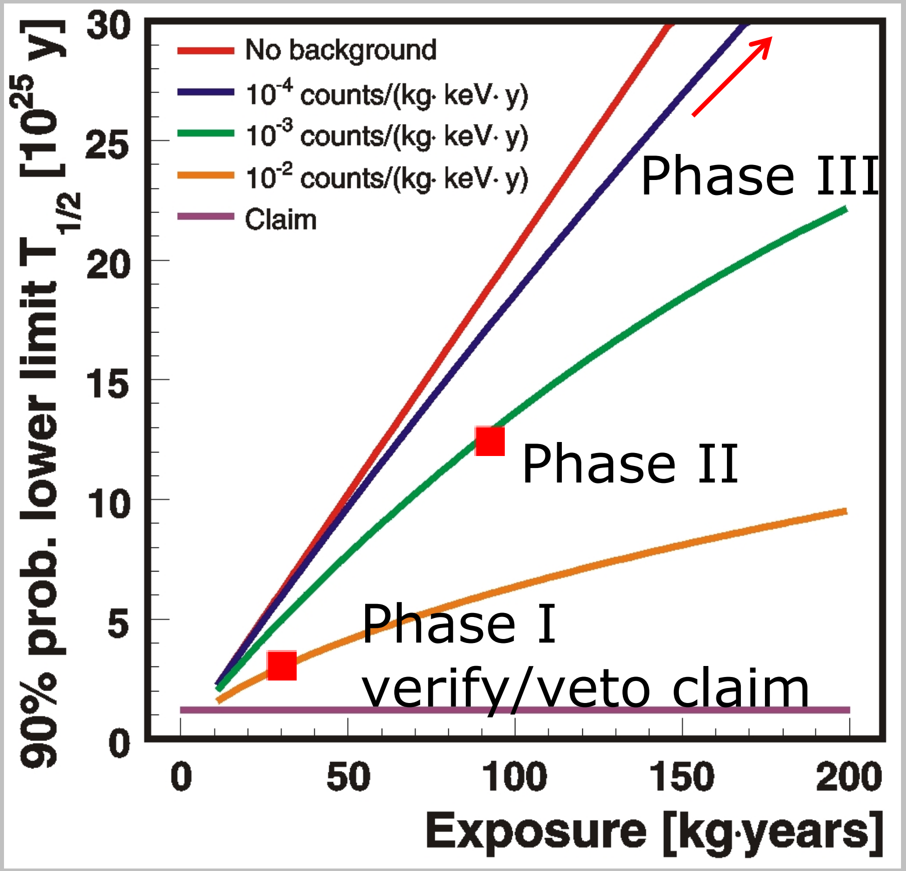
Tl208
Bi214
Co60

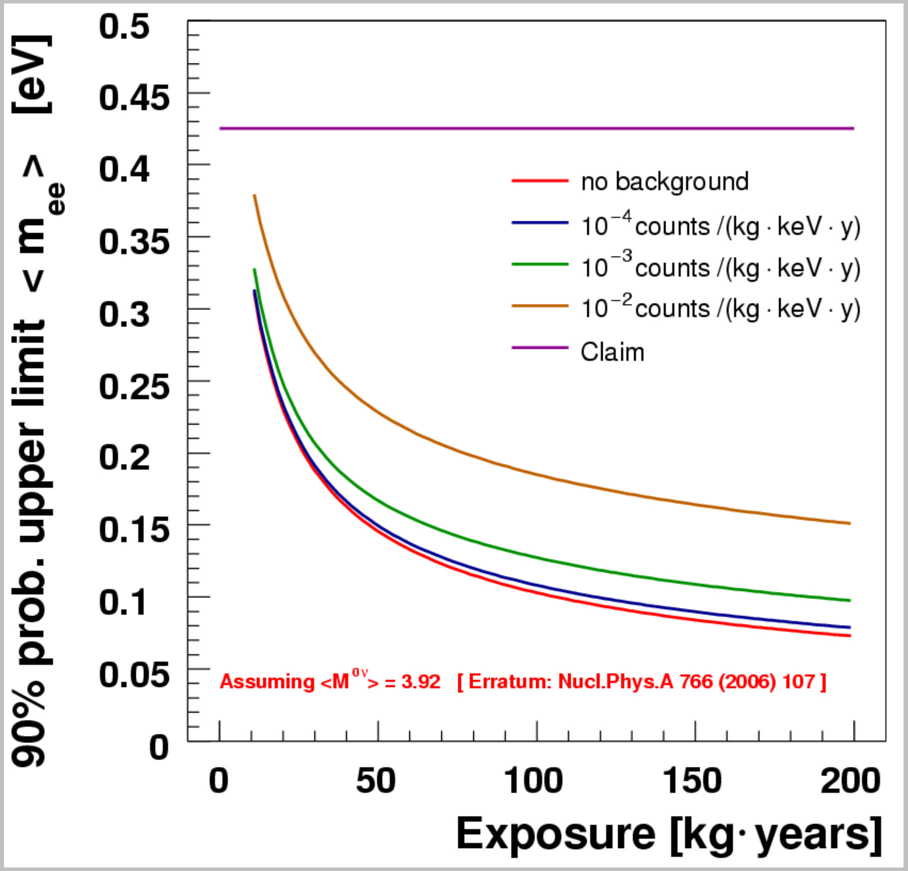




C, Dörr, H.V.Klapdor-Kleingrothaus, etc., NIM A 513 (2003) 596-621

sensitivity



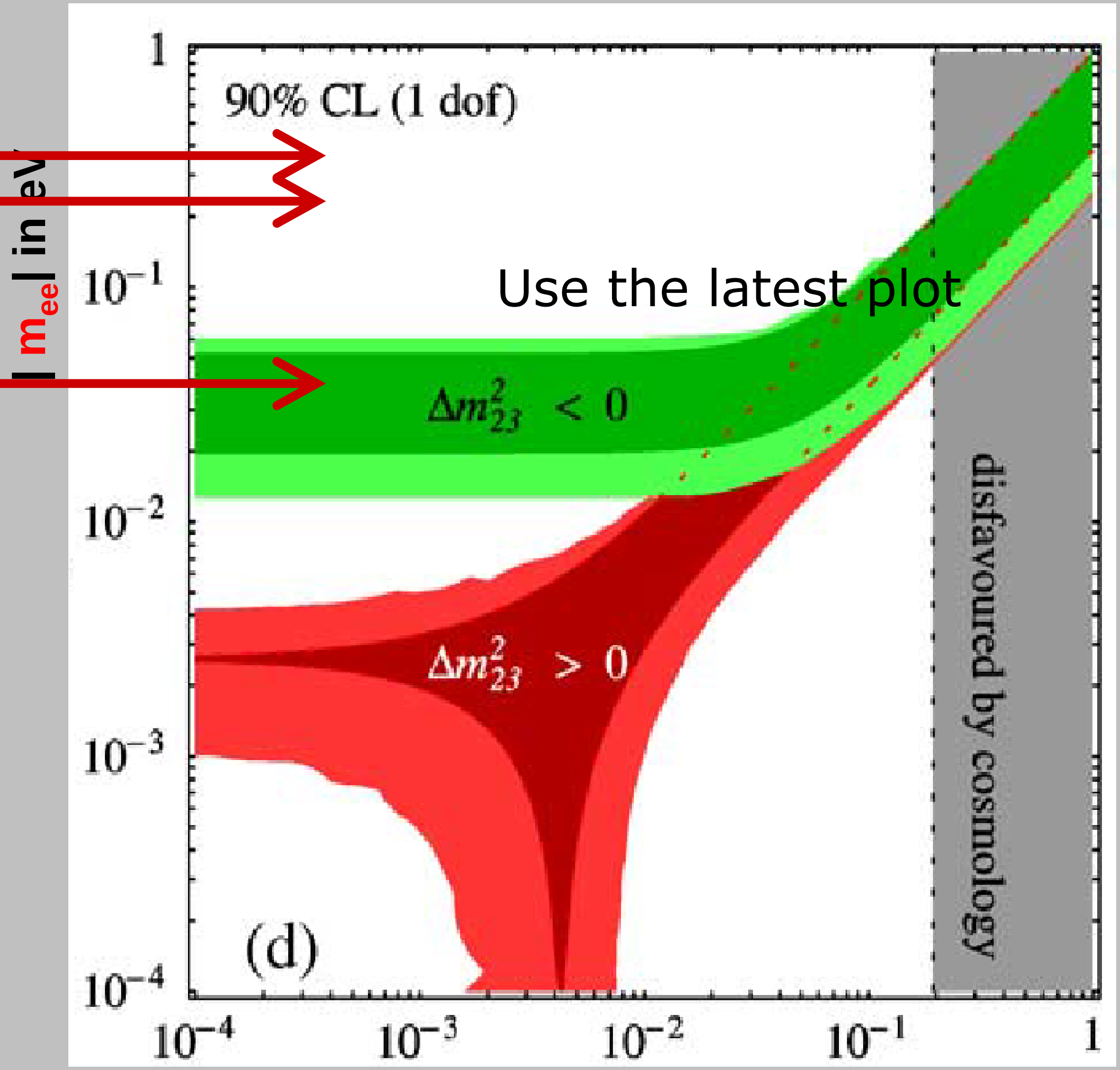


$$\text{sensitivity on } T_{1/2} \propto \varepsilon \bullet A \bullet \sqrt{\frac{M \bullet T}{b \bullet \sigma}}$$

GERDA physics goal

Phase I
Phase II

Phase III



Lightest neutrino (m_1) in eV

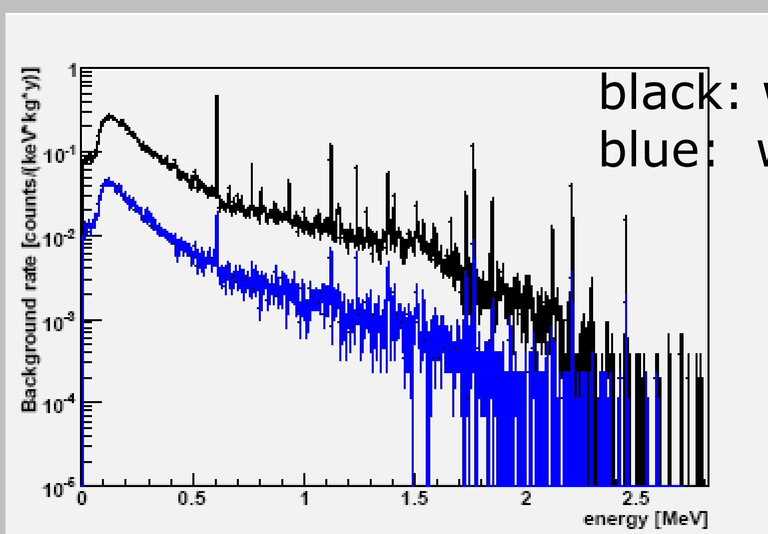
Rn222 reduction

30mBq emanation from cryostat
gives $4 \cdot 10^{-4}$ cts/(keV·kg·year)] (MaGe)

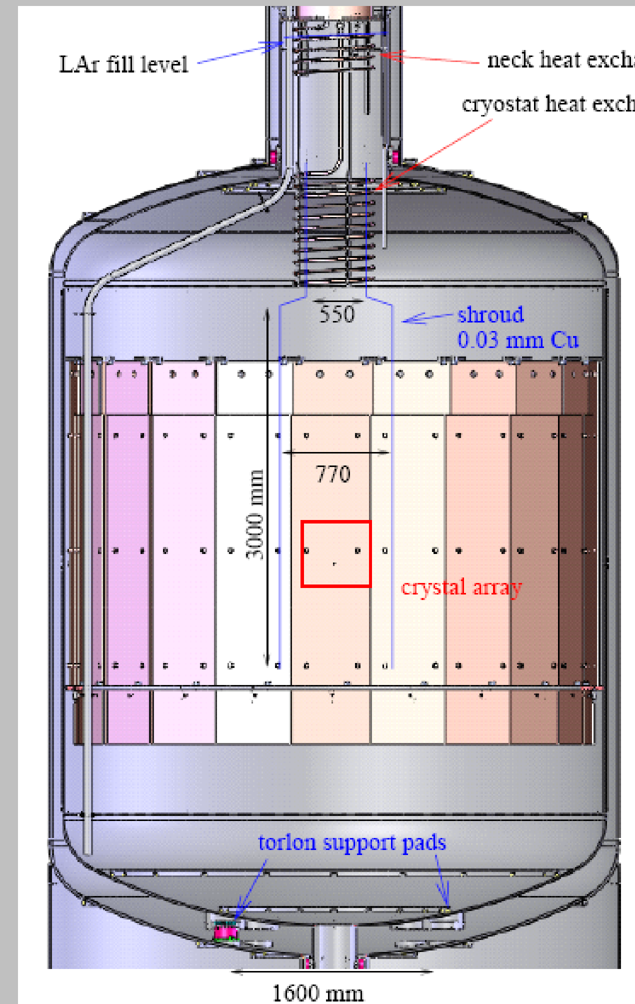
will isolate detector area with 50μm thick
pure Cu (<20μBq/kg)

with "shroud", Rn induced bg.
reduce to 1.5·10-4 cts/(keV·kg·year)

bg. from "shroud"
< 0.2·10-4 cts/(keV·kg·year)



black: without
blue: with shroud



Muon and neutron background

Muon ("MC evaluation of muon-induced background in GERDA" NIM A570 (2007) 149-158)

prompt events:

$10 \text{gamma}/m^2 \cdot h$, $6 \text{neutron}/m^2 \cdot h$

80% veto efficiency, 10E-4 cts/(keV·kg·year)

with ideal muon veto, < 10E-5 cts/(keV·kg·year)

delayed events from neutron activation:

dominated by Ge77m (T1/2 53seconds, Q 2861keV)

dedicated coincidence cuts below 10E-4

Neutron (negligible)

from LNGS rock, 3.8 10E-6 /cm2·s

negligible after 3 meter of water, negligible through neck.

2.2MeV photon from neutron absorption negligible,

activated Ar41 and C15 negligible, will be evaluated.

from U238 spontaneous fission and (alpha,n) reaction in cryotank

neutron production estimaed by "SOURCE 4A",

flux 4.7 10E-10 /cm3·s, 1860 neutron/ton·year

at RoI 7 10E-6 cts/(keV·kg·year)

delayed signal Ar41, Ge71, Ge75, Ge77, Ge77m,

will be evaluated

GeO2 metal reduction and purification

Metal reduction and purification are done at PPM Pure Metals GmbH (Langelsheim, Germany).

Started with 49.2kg ${}^{dep}GeO_2$, metal reduction yield 99.3%

Finally 30.2kg 6N Ge metal, total yield 88% (could be 90.6% without one small mistake).

Extensive mass spectrometry measurement done after each purification step. no isotopic dilution, no dangerous contamination.

Ge delivered to Institut für Kristallzüchtung (IKZ) Berlin for crystal pulling test.

Reduction of enriched material soon.

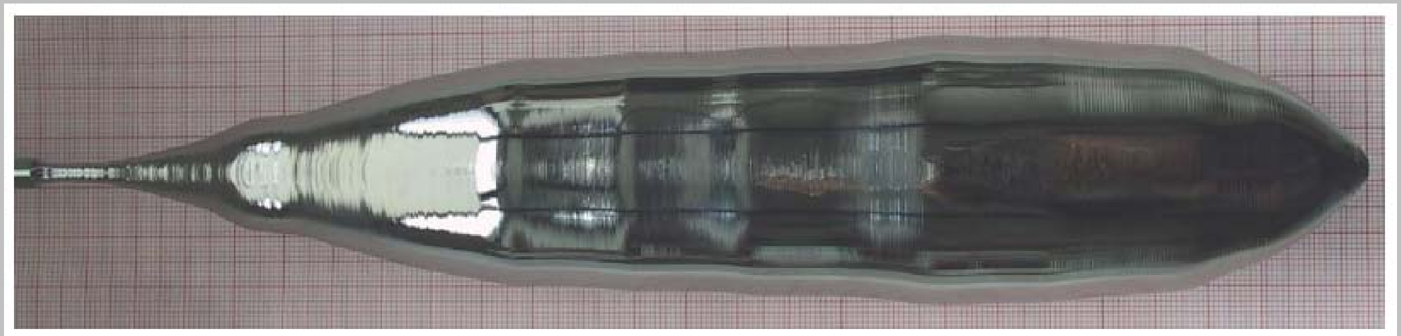
Ge crystal pulling

10 Czochralski crystals have been grown at IKZ Berlin, donor concentration level of 10^{11}–10^{13}/cm3 achieved (detector grade 10^{10}).

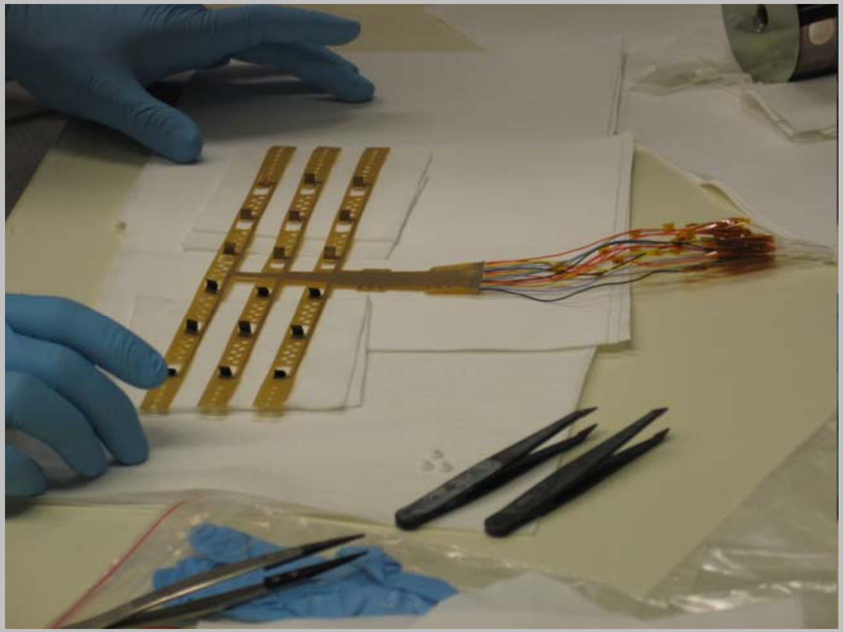
Crystals are studied with Hall-effect and PTIS (Photo-Thermal Ionization Spectroscopy), found that Czochralski puller is the main contamination source (As).

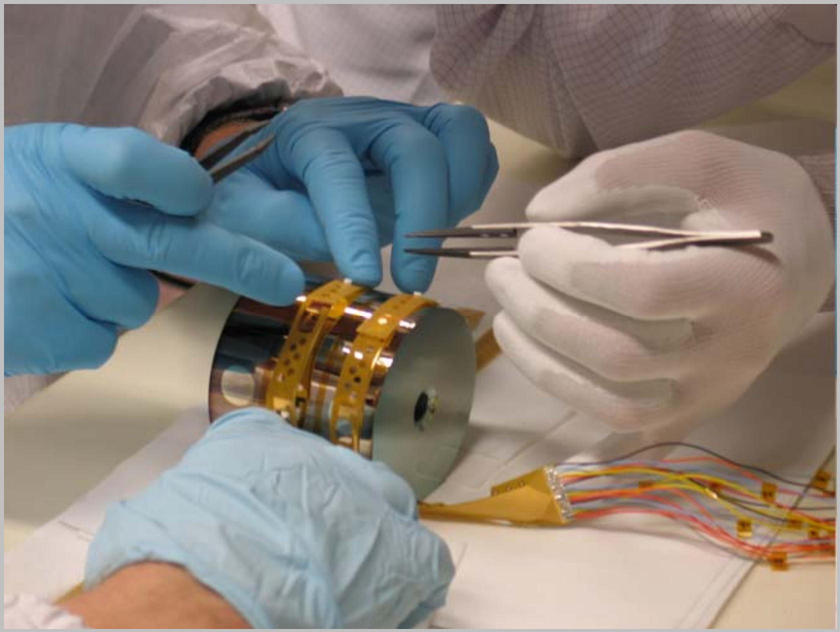
Modification being made, for example high-purity quartz tube used to protect crystal-growing area, new gas purification system.

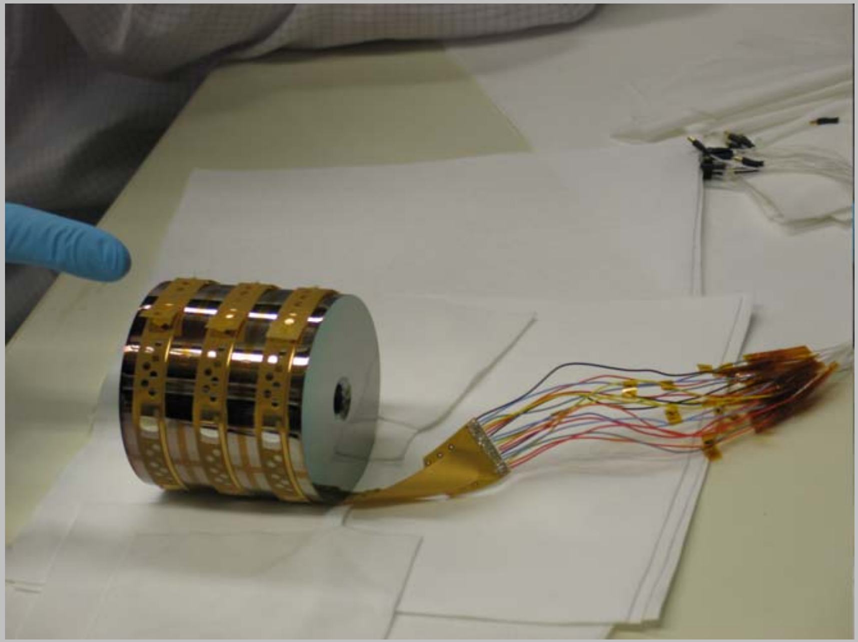
More improvements are on the way.

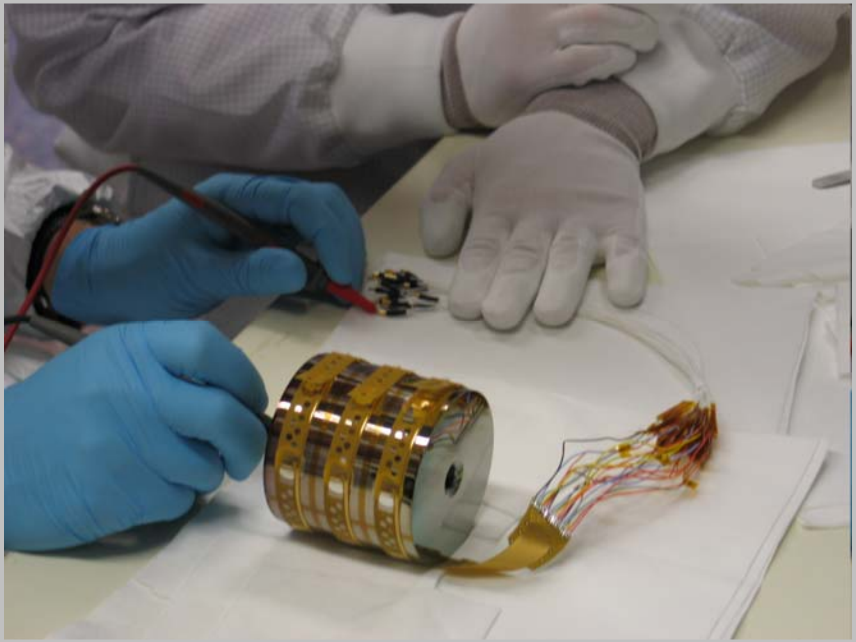


Phase-II segmented prototype detector: "snap contact"



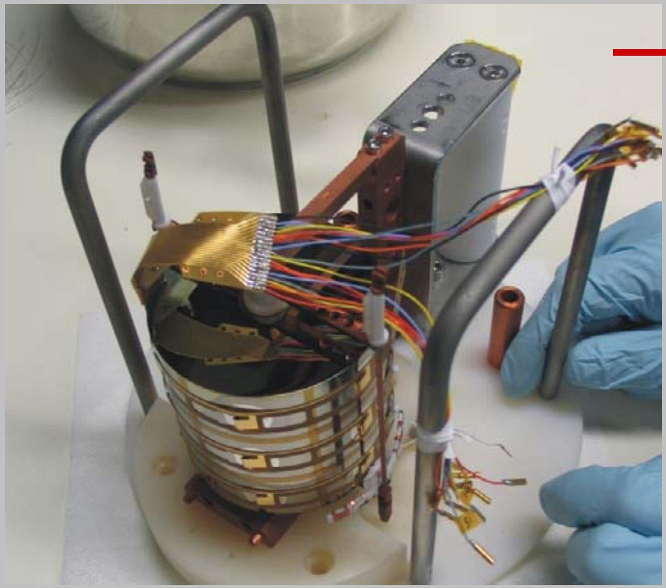


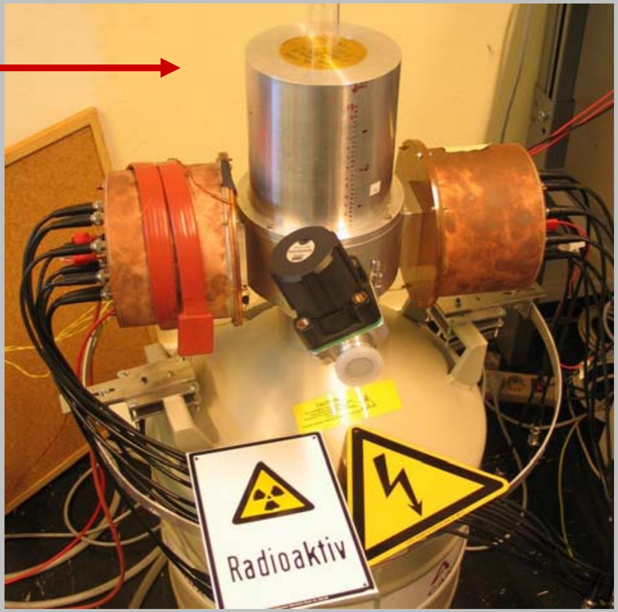




R&D: Phase-II prototype detector

exposed to γ and neutron sources
→confirmed segmentation cut, pulse-shape cut
→verified MC simulation





„Characterization of the true coaxial 18-fold segmented n-type detector" NIM A 577 (2007) 574

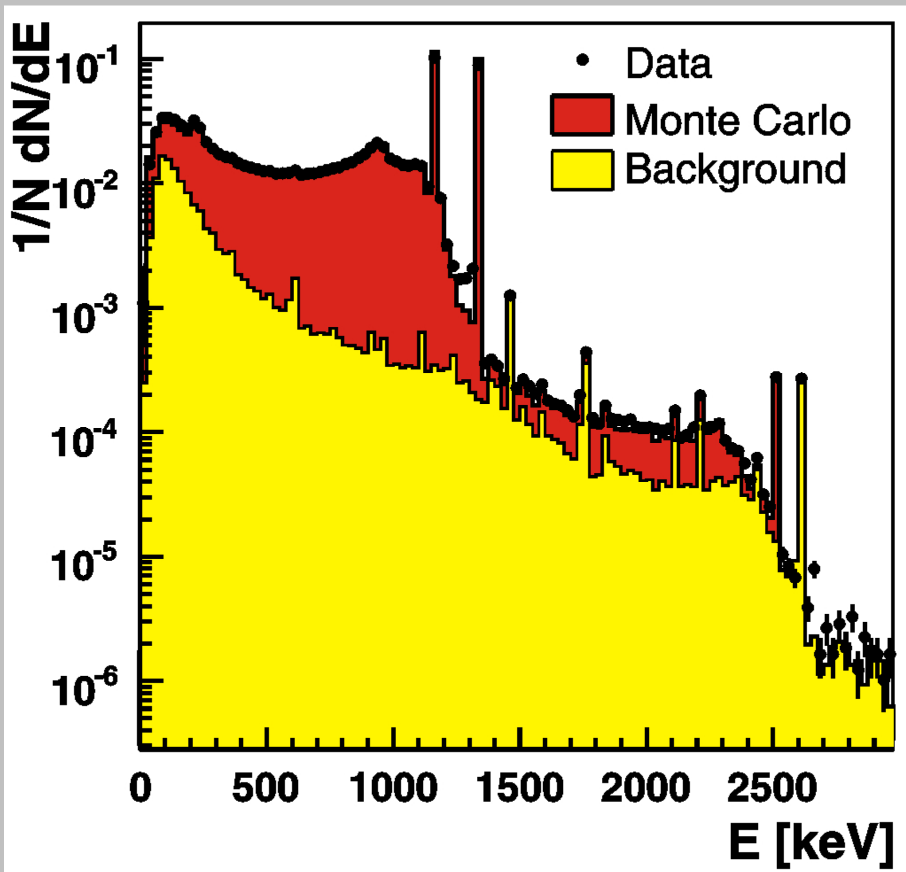
„Identification of photons in double beta-decay experiments using segmented detector – studies with a GERDA Phase II prototype detector" NIM A 583 (2007) 332-340

„Pulse shapes from electron and photon induced events in segmented high-purity germanium detectors" Eur. Phys. J. C 52, 19-27 (2007)

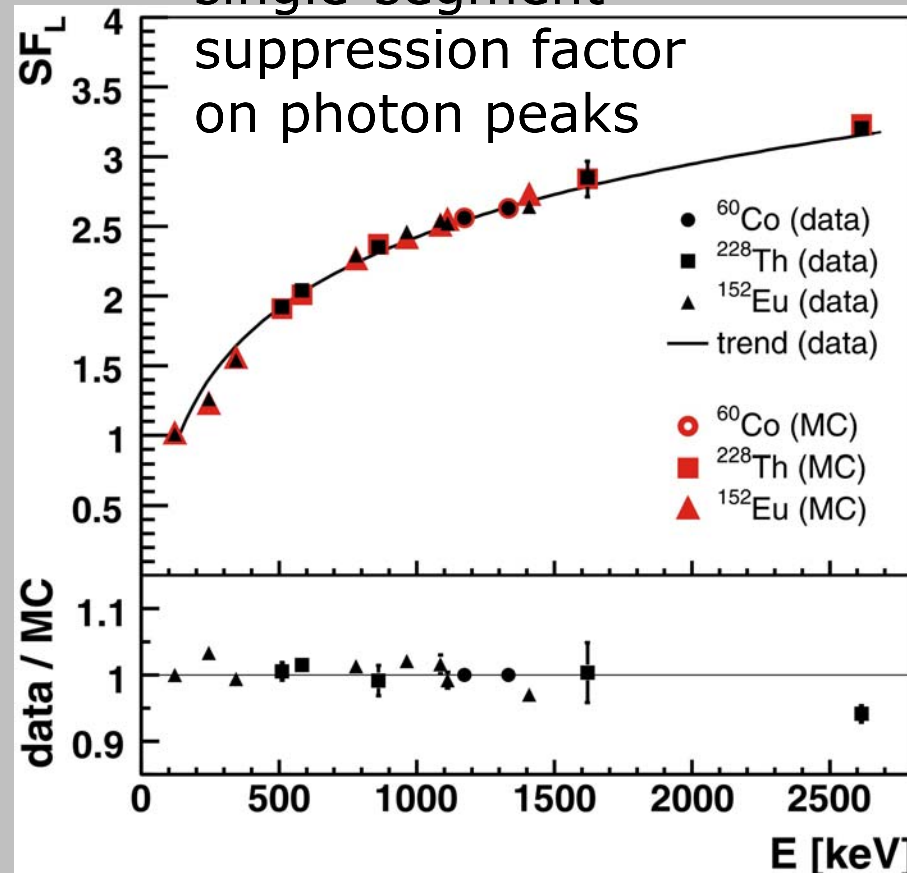
„Test of pulse shape analysis using single Compton scattering events" Eur. Phys. J. C 54 425-433 (2008)

„Neutron interactions as seen by a segmented Ge detector" Eur. Phys. J. A 36, 139-149 (2008)

R&D: Phase-II prototype detector

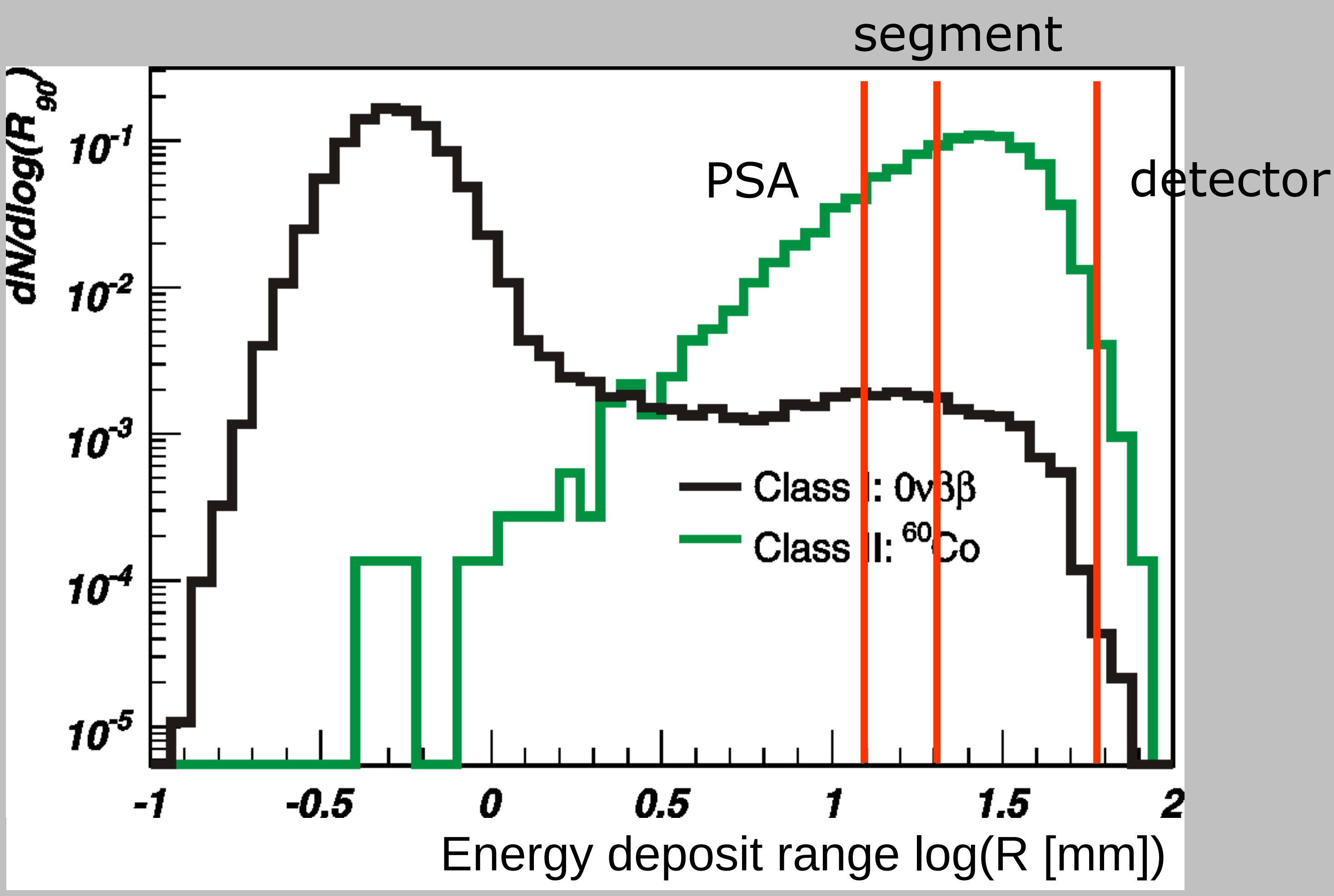


single-segment suppression factor on photon peaks



Data agrees with MC within 5%.

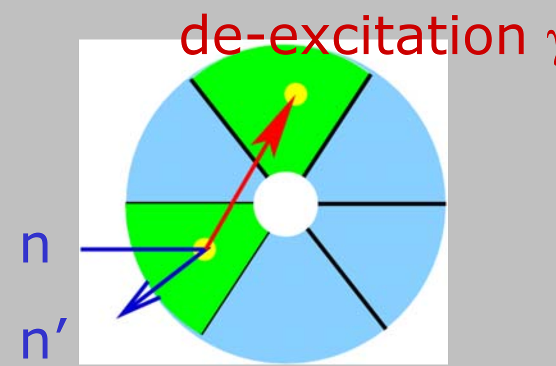
Remove background



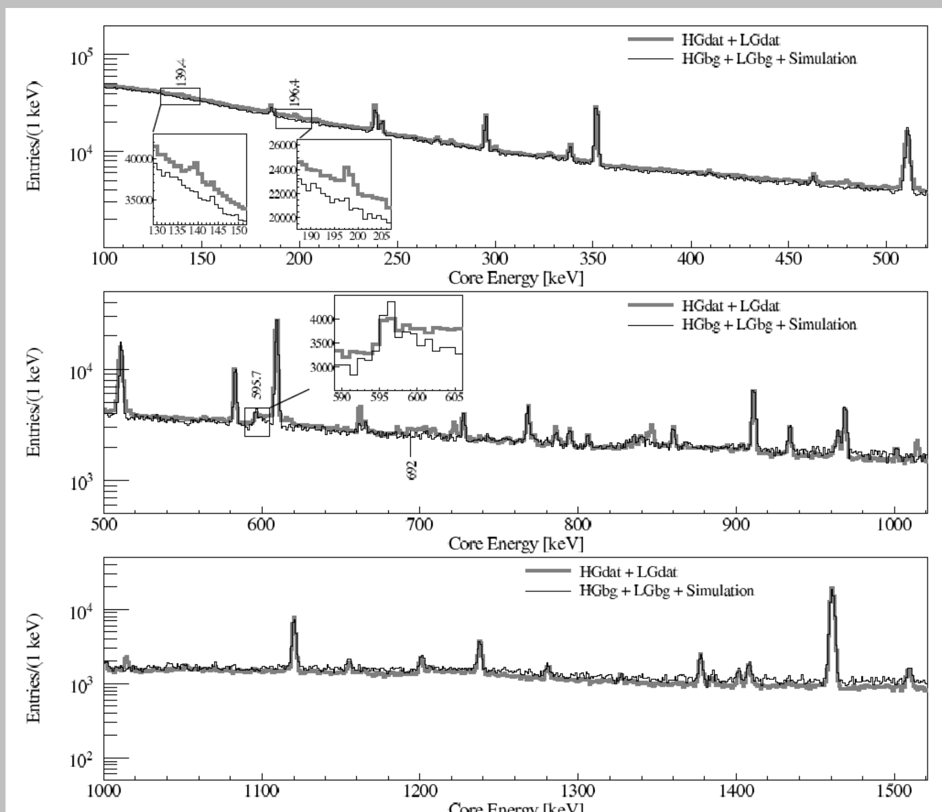
R&D: segmentation for neutron interaction measurement

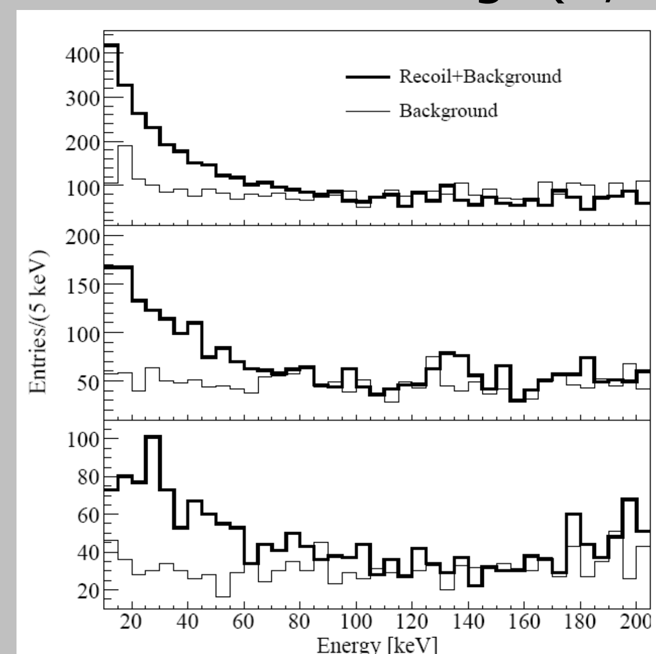
- study neutron interaction with Ge
- check Geant4 MC simulation

energy spectrum from AmBe source



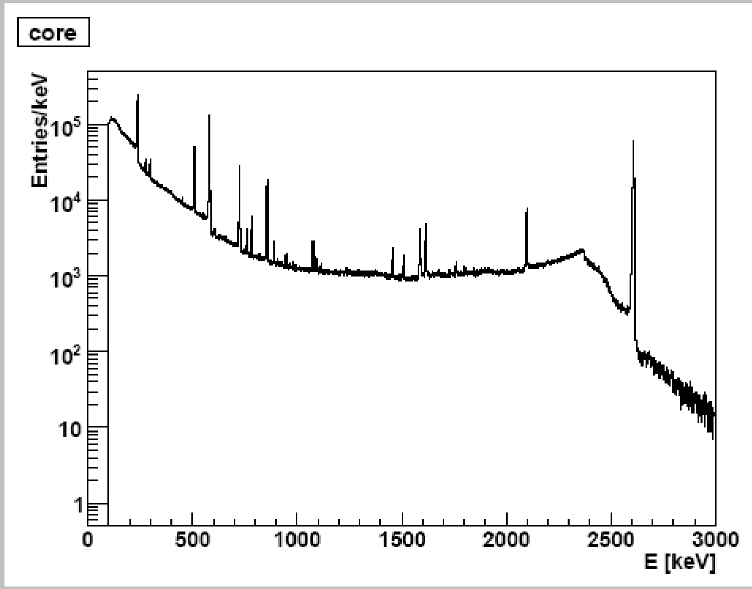
inelastic scattering (n, n'γ)

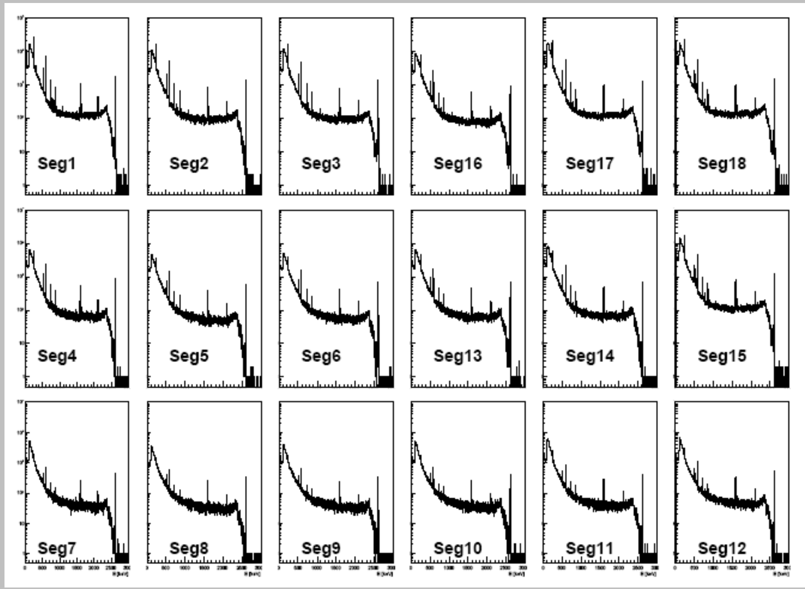


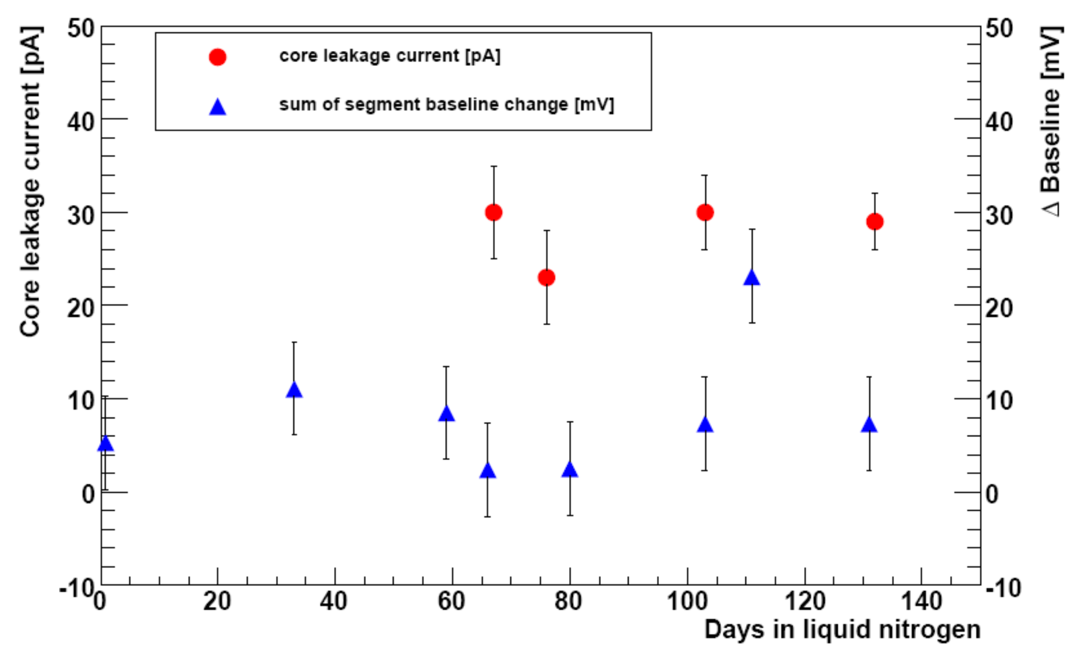


Direct measurement of recoil energy

R&D: Phase-II prototype detector in liquid nitrogen







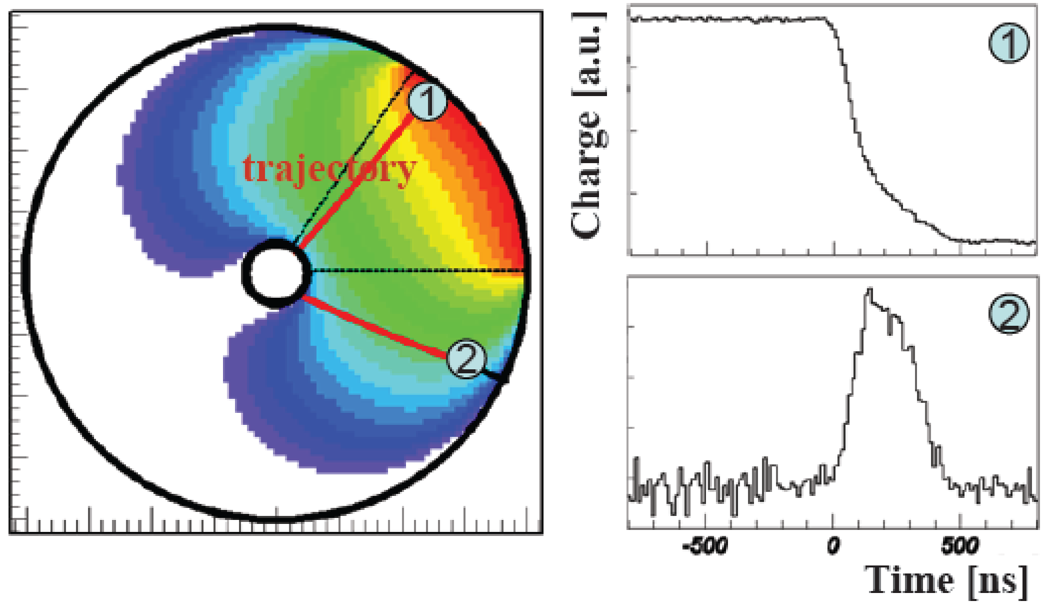
Pulse shape simulation

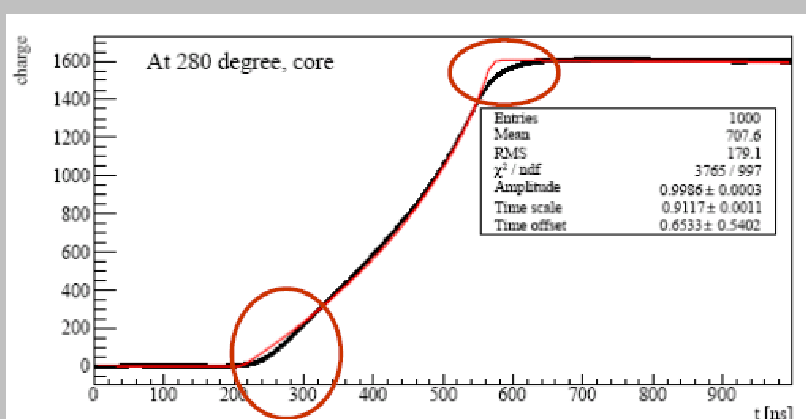
Ramo's Theorem:

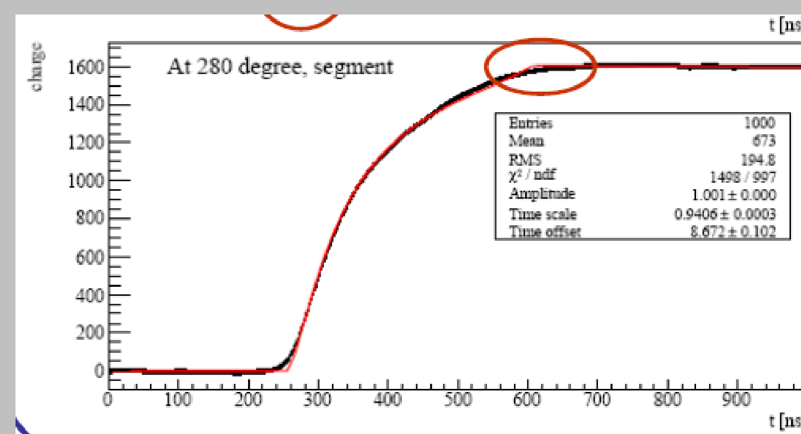
$$Q(t) = -N_{e/h}(E_{dep})\varphi_w(r(t))$$

$$I(t) = N_{e/h}(E_{dep})\vec{E}_w(r(t))v(t)$$

- $N_{e/h}(E_{dep})$: Number of e/h created by energy deposition E_{dep}
- $\varphi_w, \vec{E}_w$: Weighting potential, field
- $r(t)$: Drift trajectory
- $v(t)$: Drift velocity







Red: simulation, black: data

Phase-III R&D: Silicon photon multiplier

- Less radioactive than glass PMT
- Performance in liquid argon under study