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GERDA: Study of Neutrinoless Double Beta Decay of Ge-76

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OUTLINE

- ***Double Beta Decay***
- ***Motivation of GERDA***
- ***Principles of GERDA detector***
- ***Present status***
- ***Summary***

The GERmanium Detector Array Collaboration

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Neutrino oscillation experiments: neutrinos have a non-vanishing rest mass!

- **Questions:**
  - Nature of neutrino mass (**Dirac or Majorana**) ?
  - Mass hierarchy (normal, inverse, quasi-degenerate) ?
  - Mass scale: a value or an upper limit on $\mathbf{m_1}$?

This information can be obtained from 0ν2β-decay experiments (through measurement of the effective Majorana neutrino mass m_{ee})

$$1/\sqrt{T_{1/2}^{0\nu}} \approx \langle m_{ee} \rangle = \left| \sum_{j=1,2,3} |U_{ej}|^2 e^{i\Phi_j} m_j \right|$$

U_{ej} – PMNS unitary neutrino matrix, Φ_j - CP – phases

(*) if a mass mechanism of the 0ν2β–process is dominating

Sensitivity of DBD experiment

$$T_{1/2}^{0\nu} \geq 4.17\text{x}10^{26} \cdot \boldsymbol{\varepsilon} \cdot (\mathbf{a}/A) \cdot \sqrt{(M\, t/B\, R)}$$

$$m_\nu \sim 1/\sqrt{T_{1/2}^{0\nu}}$$

B - background index in cts/(keV kg y)
R - FWHM energy resolution at $Q_{\beta\beta}$ in keV
A - mass number
ε - **detection efficiency at $Q_{\beta\beta}$** **! "Detector = source"**
a - **ββ isotope fraction** **! Enrichment → 100%**
M - mass of detector in kg
T - measurement time in years

Ge diodes as a tool for 76Ge DBD search

- Detector = Source

  ⇓

  ε ~ 95% efficiency

- Energy resolution R ~ a few keV (3 – 5 keV)

  ⇓

  No $2\nu\beta\beta$ background from 76Ge

- Technology of the production → High purity

  ⇓

  No ^{238}U-, ^{232}Th- intrinsic background

- Big scale production of 76Ge isotope: centrifuges

History of DBD search with Ge diodes

- **Fiorini E. et al., 1967:**

  first ^{nat}Ge experiment ($T_{2o\nu}$ > $3{,}1\cdot10^{20}$ yr).

  $^{nat}Ge(Li)$: m = 0.09 kg, R = 4,7 keV at 1,32 MeV,

  1973, ($T_{2o\nu}$ > $5\cdot10^{21}$ yr).

  $^{nat}Ge(Li)$: m = 0.36 kg, R = 6 keV, BI = 38 $keV^{-1}*kg^{-1}*yr^{-1}$

- **Caldwell D.O. et al., 1986:**

  ^{nat}Ge diodes ($T_{2o\nu}$ > $2{,}5\cdot10^{23}$ yr)

  m = 3,5 kg, R = 3.7 keV, BI = 0.35 $keV^{-1}*kg^{-1}*yr^{-1}$ (with NaI)

- **ITEP group (Kirpichnikov et al.) 1987- 89:**

  first ^{76}Ge experiment ($T_{2o\nu}$ > $2\cdot10^{24}$ yr)

  two $^{76}Ge(Li)$ crystals (m = 1.14 kg), R = 3.7 keV,

  BI = 2.6 $keV^{-1}*kg^{-1}*yr^{-1}$ (with NaI)

*) For references see at the end of the presentation

HD and IGEX ^{76}Ge $0\nu\beta\beta$ experiments

IGEX experiment:

C. Aalseth et al., Phys. Rev. D 65, 092007

$T_{1/2} > 1.6\ 10^{25}$ y (90% C.L.)

8.5 kg*yr, BI ~ 0.1 cts/(keV·kg·yr) with PSA

Heidelberg-Moscow experiment:

$T_{1/2} > 1.9\ 10^{25}$ y (90% C.L.)

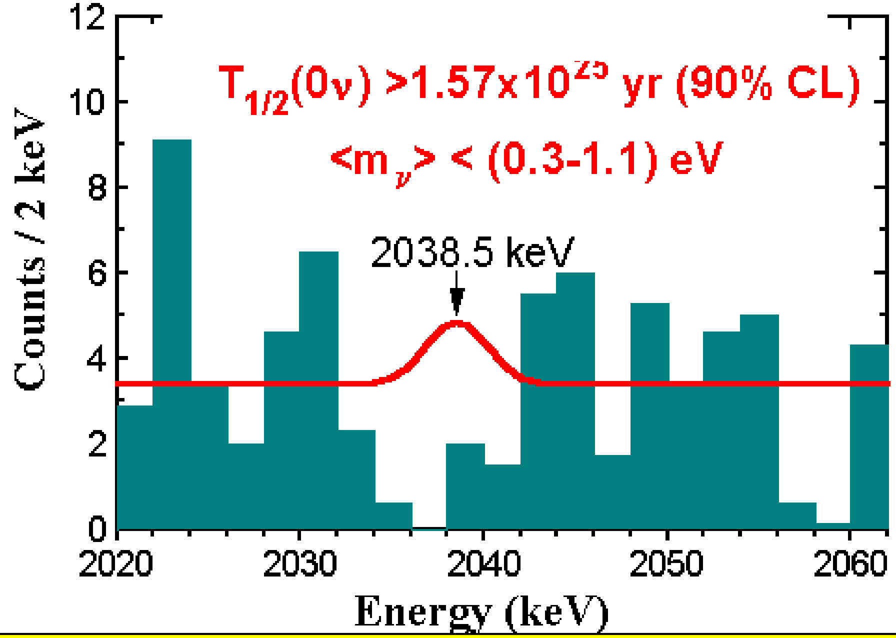
*71.7 kg*yr*

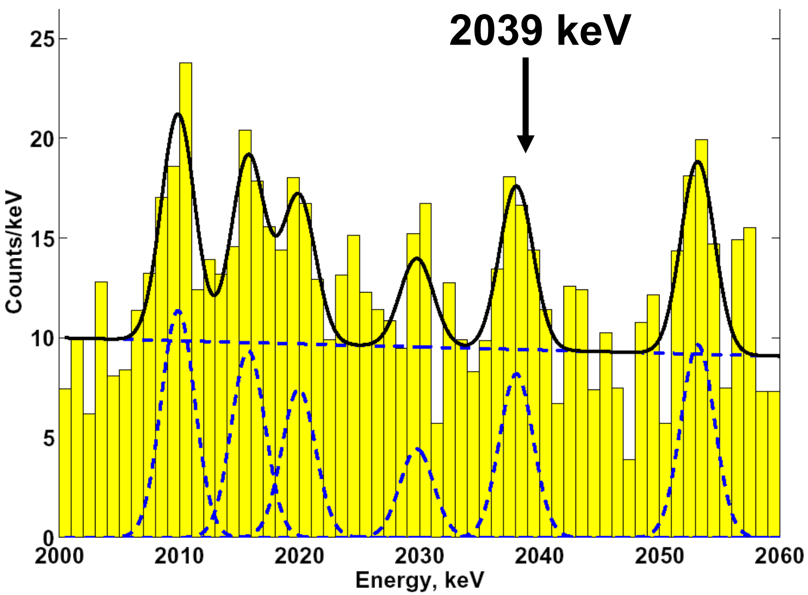
BI = 0.11 cts/(keV·kg·yr) before PSA

H.V.Klapdor-Kleingrothaus et al., Phys.Lett. B586 (2004) 198.

Claim: $T_{1/2} = (0.7 - 4.2) \cdot 10^{25}$ y (3σ)

$m_\nu \sim 0.24 – 0.58$ eV





Confirmation needed with same & different isotopes!

Sources of background in ^{76}Ge-DBD exp

*External background (**main source now**):*

∗ γ-rays from the rock, shielding material and detector supporting material;

∗ neutrons from fission, (α,n)-reactions in rock and μ-induced reactions in rock and shielding material;

∗ muons from cosmic rays showers

Intrinsic background:

∗ cosmogenic isotopes (Ge-68, Co-60) due to spallation reactions on Ge isotopes at sea level ($T_{1/2}$ ~> year)

GERDA goal: how to proceed?

Reduction of bkg-index by two orders of magnitude to 10^{-3} cts/kg/keV/yr + increase of ^{76}Ge mass:

- **Removal of materials around crystal – naked HPGe detectors**

  (proposed by G.Heusser (Ann.Rev.Nucl.Part.Sci. 45 (1995)543))

- **Use of highly enriched Ge (87%)**
- **Use of (water + liquid argon) for passive shielding**
- **Use of muons veto (Cherenkov + plastic scintillator)**
- **Use of liquid argon for active shielding (option*)**
- **Use for Phase II *highly segmented* or *point-like p-type* detectors**
- **Improvement of Pulse Shape Analysis**

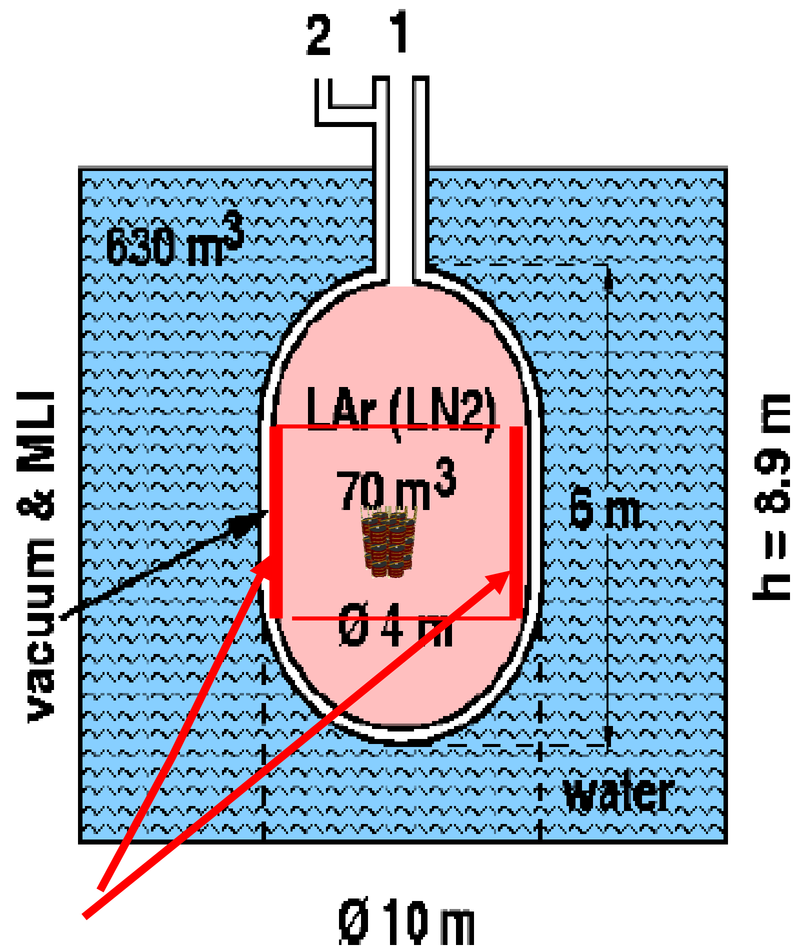
Basic design of GERDA: cryostat made of ss-steel inside water tank

Most dangerous Tl-208 of Th-232 chain
Eγ = 2,615 MeV

Activity of Tl-208, **mBq/kg**:

Rock, concrete	~	3000
Stainless steel	<	5
Cu(OFHC)	<	0.02
Water purified	<	0.001
LAr	~	0

Principle of "Russian MATRESHKA" except that last girl (Ge crystals) is naked



Cu shielding

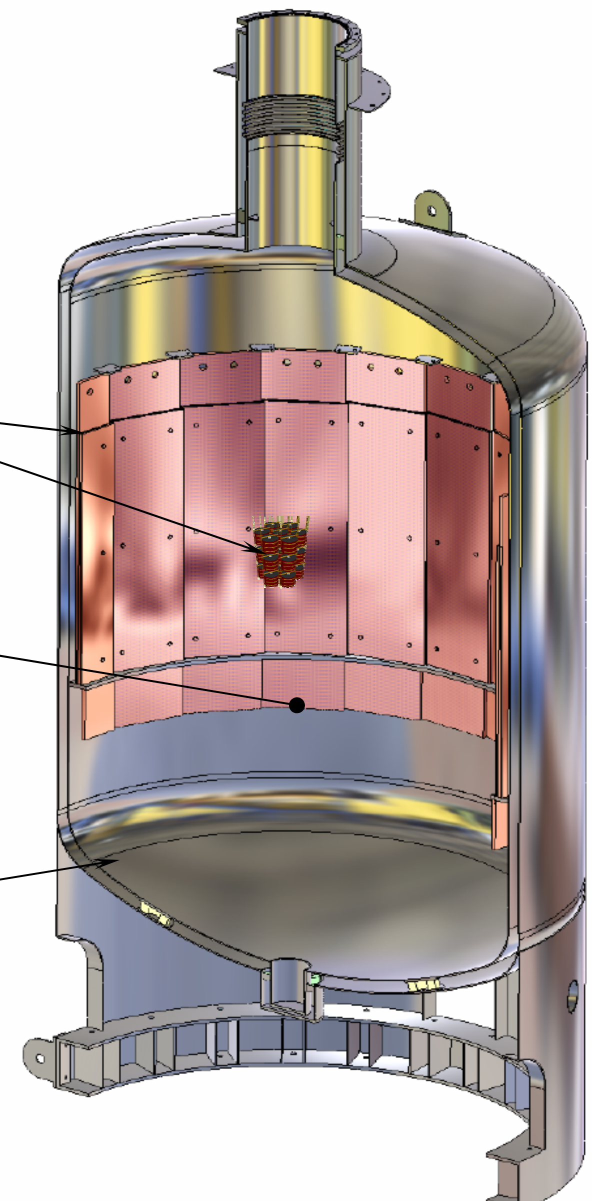
GERDA s/steel cryostat

$D_{int} = 4$ m
$H_{LAr} = 5.5$ m
$V = 70\ m^3$

Additional inner copper shield
detectors holders
U/Th $\leq$ 16 μBq/kg
clean surface

Liquid argon
^{222}Rn = $\leq$ 1 μBq/m^3

Vacuum-insulated double
wall stainless steel cryostat
U/Th $\leq$ 5 mBq/kg clean
surface

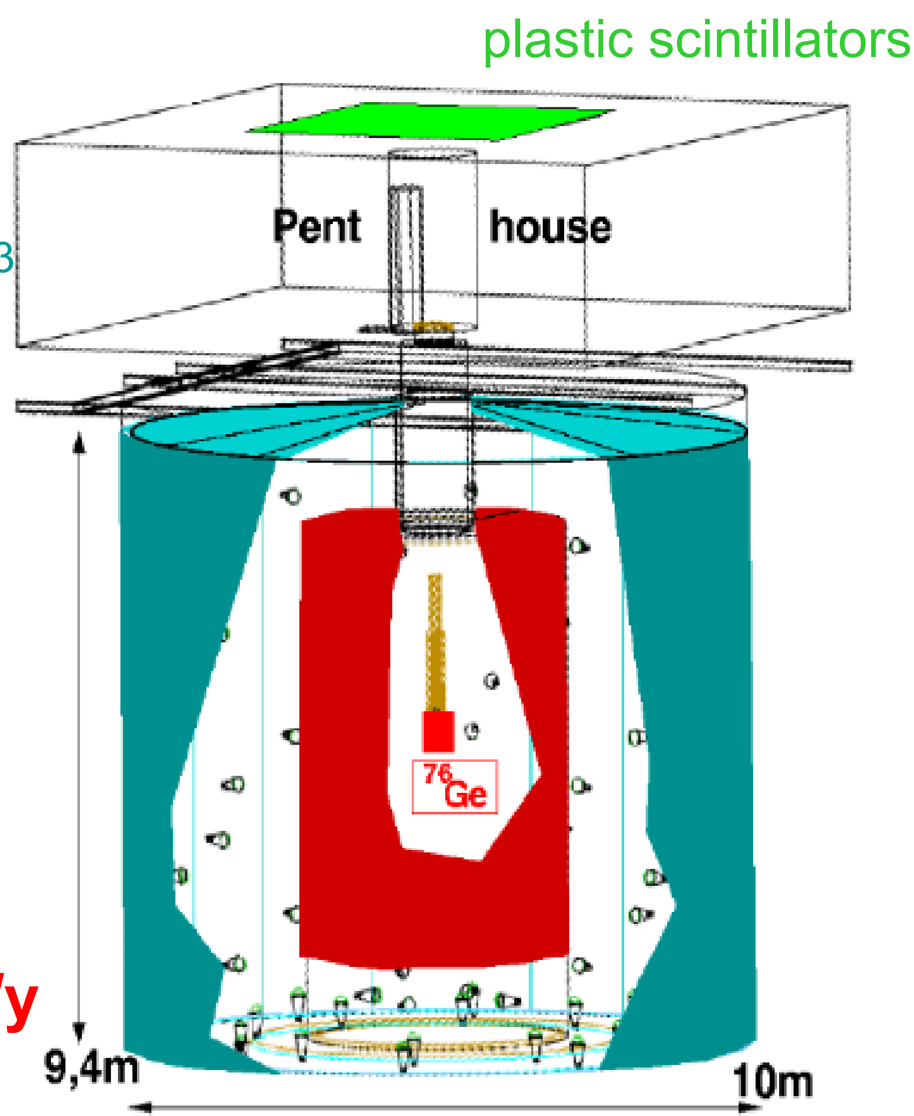


BI (Tl208) = 10^{-4} cts/(keV·kg·y)

Water tank and muon veto

- Water serves as passive shield (reduces amount of LAr)
- Filled with pure water of 590 m^3
- Layer of reflector film VM2000
- 66 PMTs ETL 9350 KB: Cherenkov detector
- 20 panels of plastic scintillator on top ($S = 20\ m^3$, $\Delta = 3$ cm)

BI (muons) = 10^{-4} evts/keV/kg/y



GERDA: Phases of the experiment

PHASE I: 17.9 kg of enriched ^{76}Ge (from HM and IGEX)

1 year data if B=10^{-2} cts/(keV·kg·yr) (check of Klapdor's claim)

Start in 2009 at Gran Sasso, results 2010

$T_{1/2} > 3\ 10^{25}$ yr $\quad$ $\langle m_\nu \rangle < 270$ meV

PHASE II: 40 kg of enriched ^{76}Ge (20 kg segmented or point like HPGe detectors)

if B=10^{-3} cts/(keV·kg·yr) $T_{1/2} > 1.5\ 10^{26}$ yr for 3 yr*35 kg of data taking

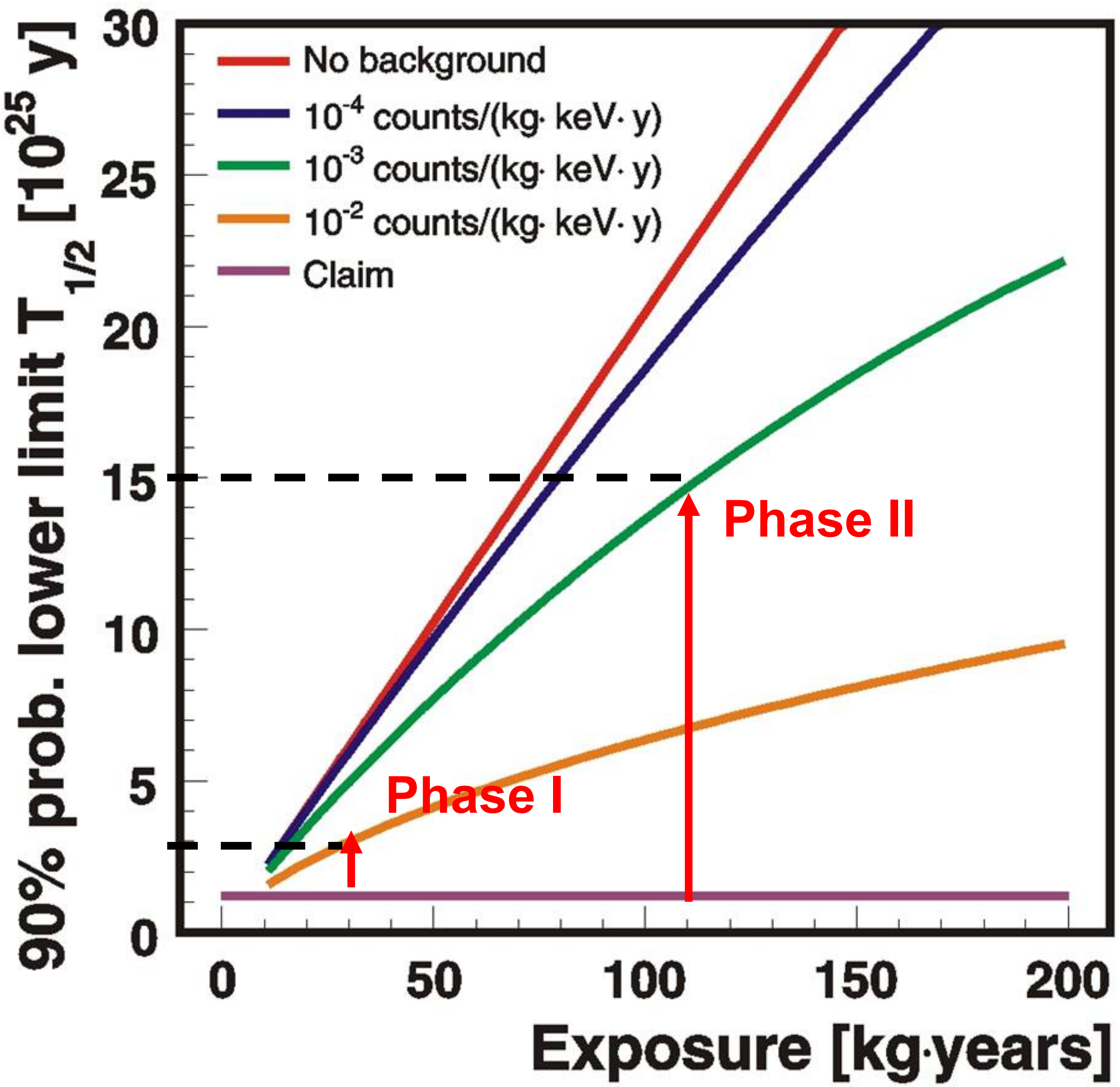
$\langle m_\nu \rangle < 110$ meV

PHASE III: if PHASE I and II succeed

then world-wide ~ 1 ton experiment with MAJORANA

$\langle m_\nu \rangle < 10 - 20$ meV

GERDA sensitivity: dependence on Bkg

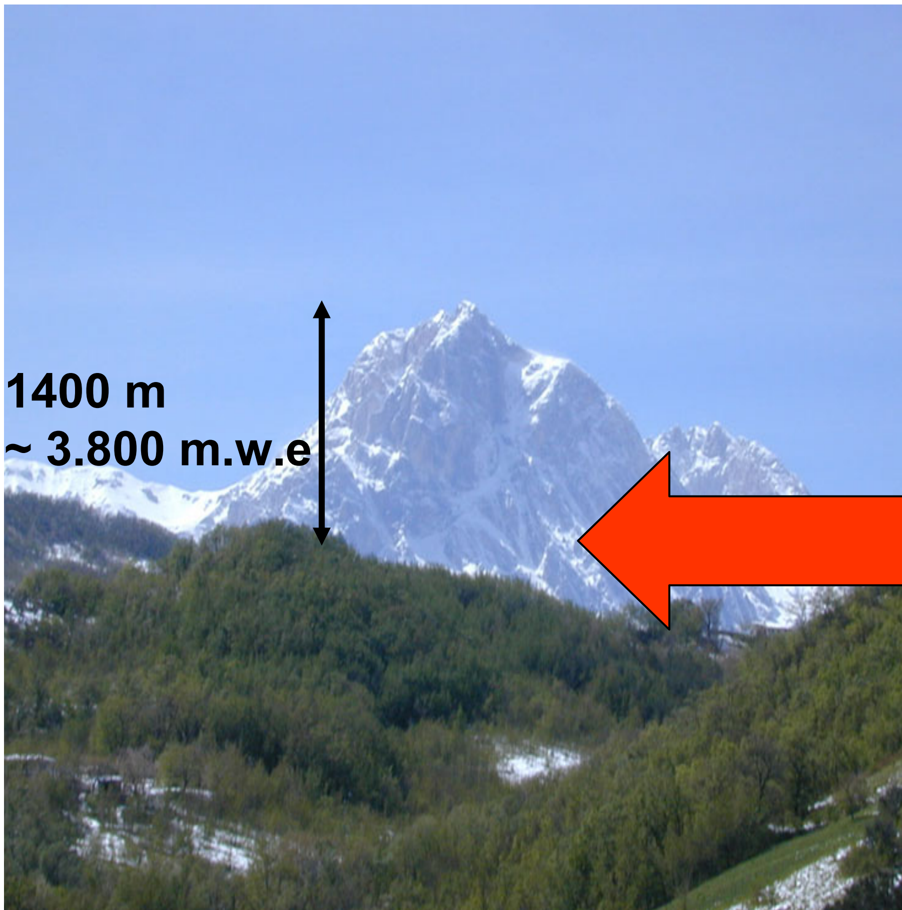


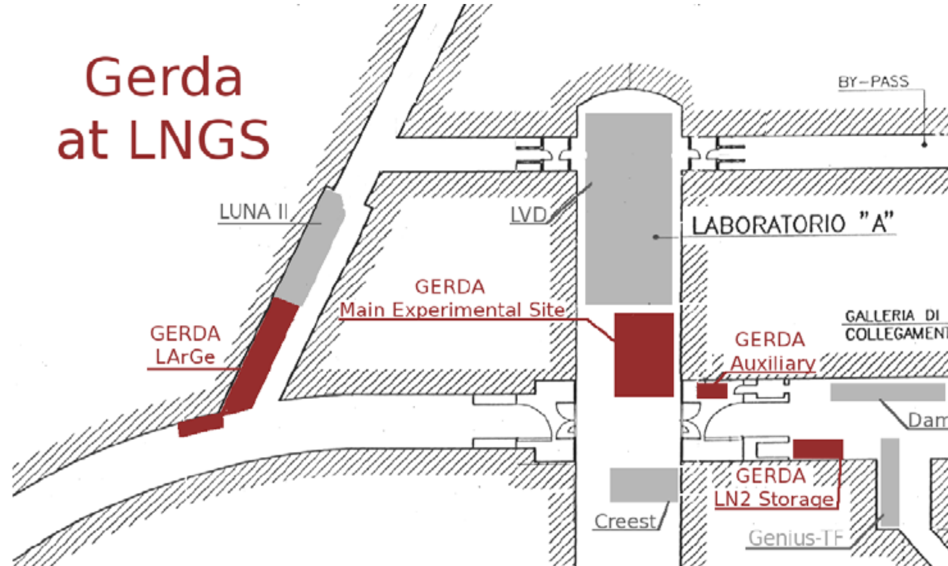
Assumed energy resolution:

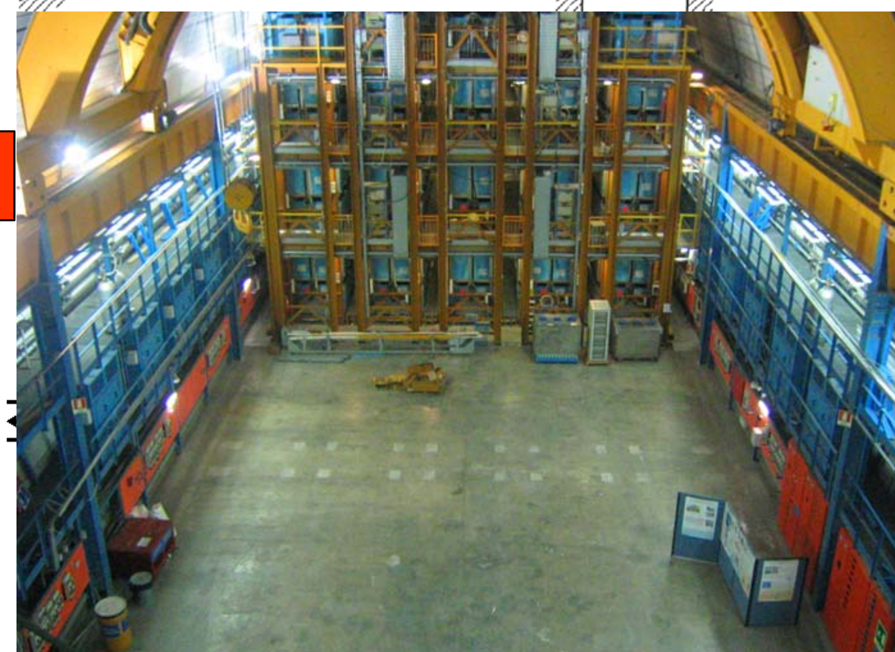
$\Delta E = 4$ keV

Background reduction !

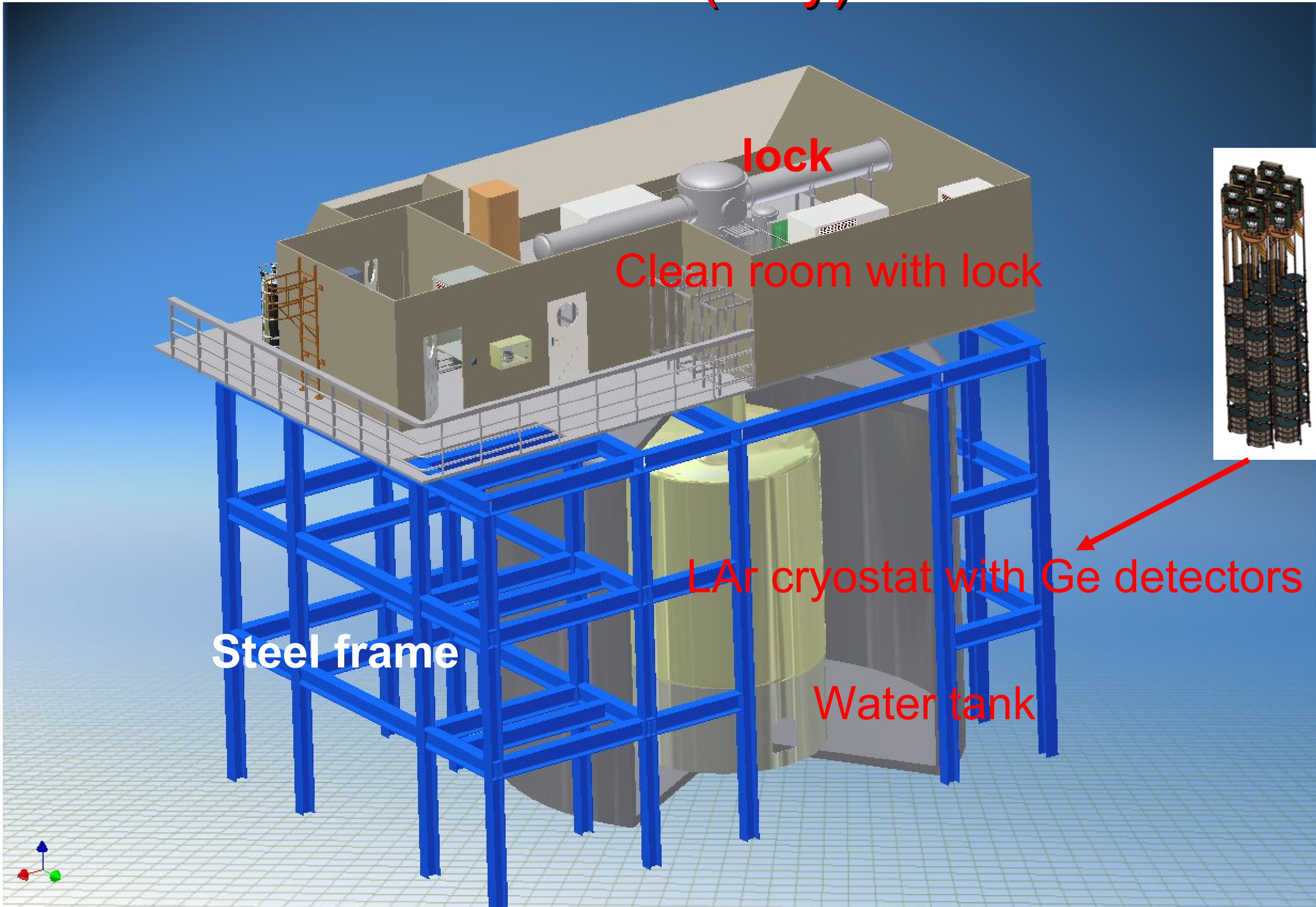
Situation of GERDA







GERDA at underground laboratory Gran-Sasso (Italy)



GERDA at underground laboratory Gran-Sasso (August 2007)

Buttom part of the GERDA

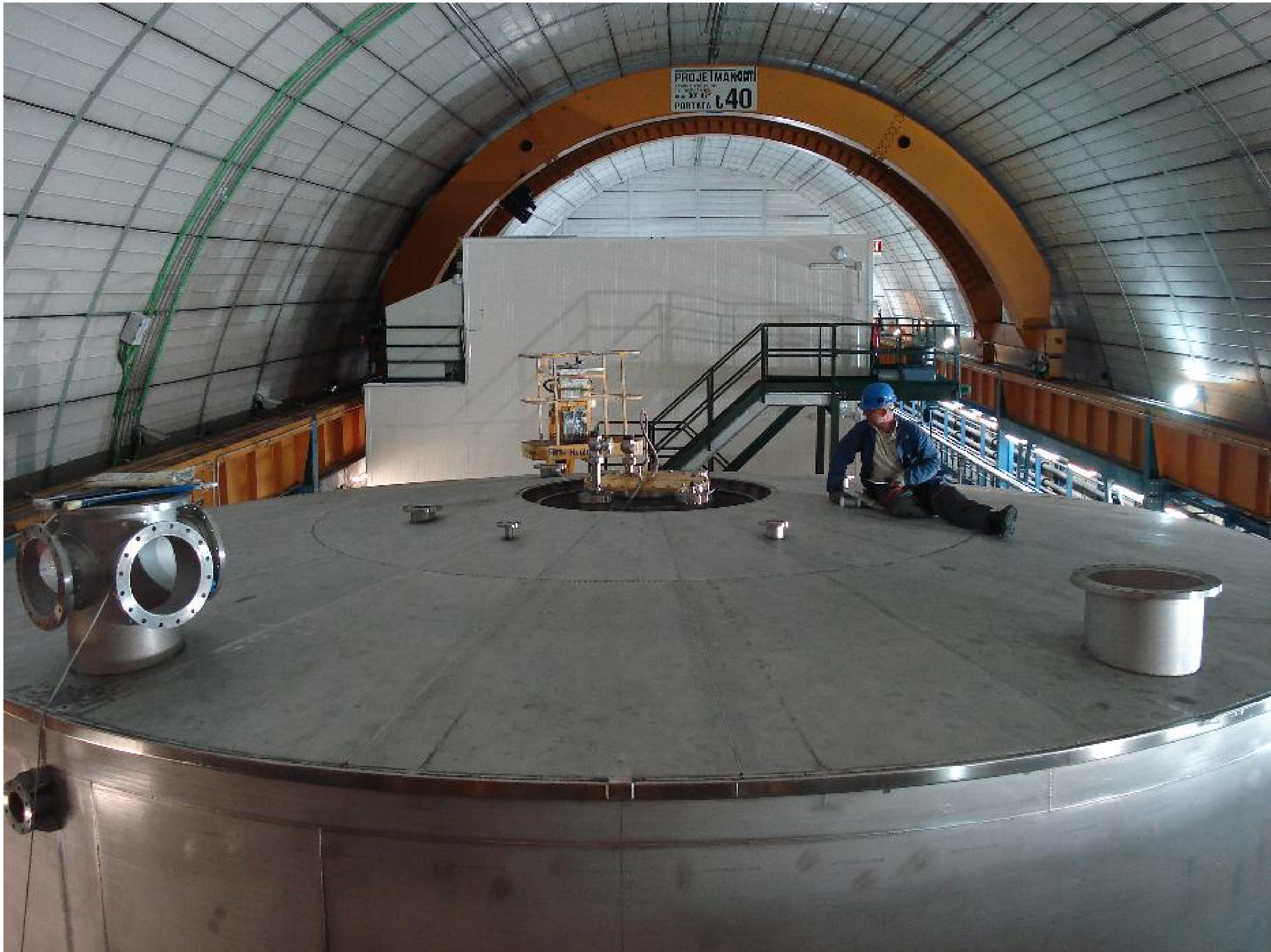
GERDA at underground laboratory Gran-Sasso (6 March, 2008)

Erection of the cryostat

GERDA at underground laboratory Gran-Sasso (6 March, 2008)

GERDA at underground laboratory Gran-Sasso (12 June, 2008)

Construction of water tank



GERDA at underground laboratory Gran-Sasso (18 July, 2008)

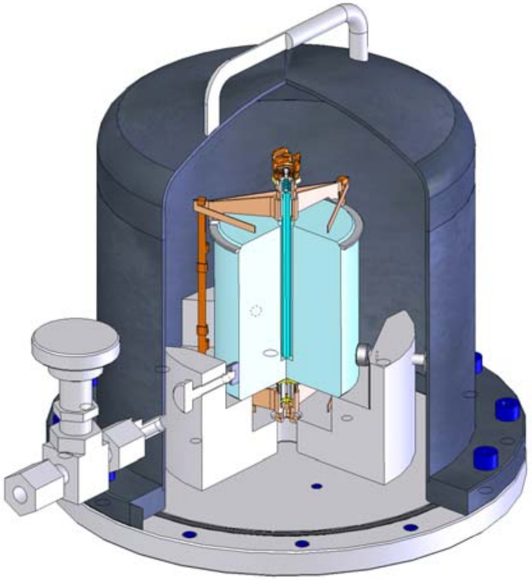
GERDA building construction

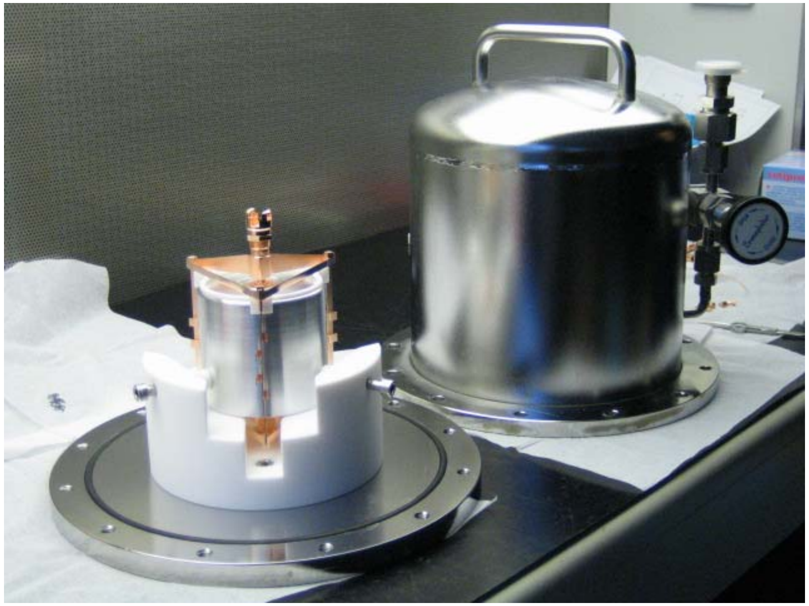
GERDA at underground laboratory Gran-Sasso (18 July, 2008)

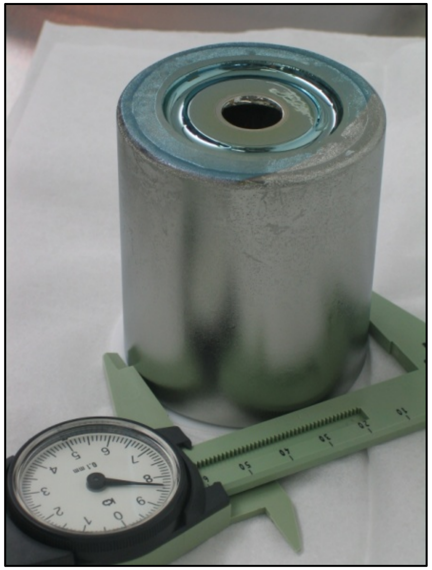
GERDA building construction

Phase I diodes

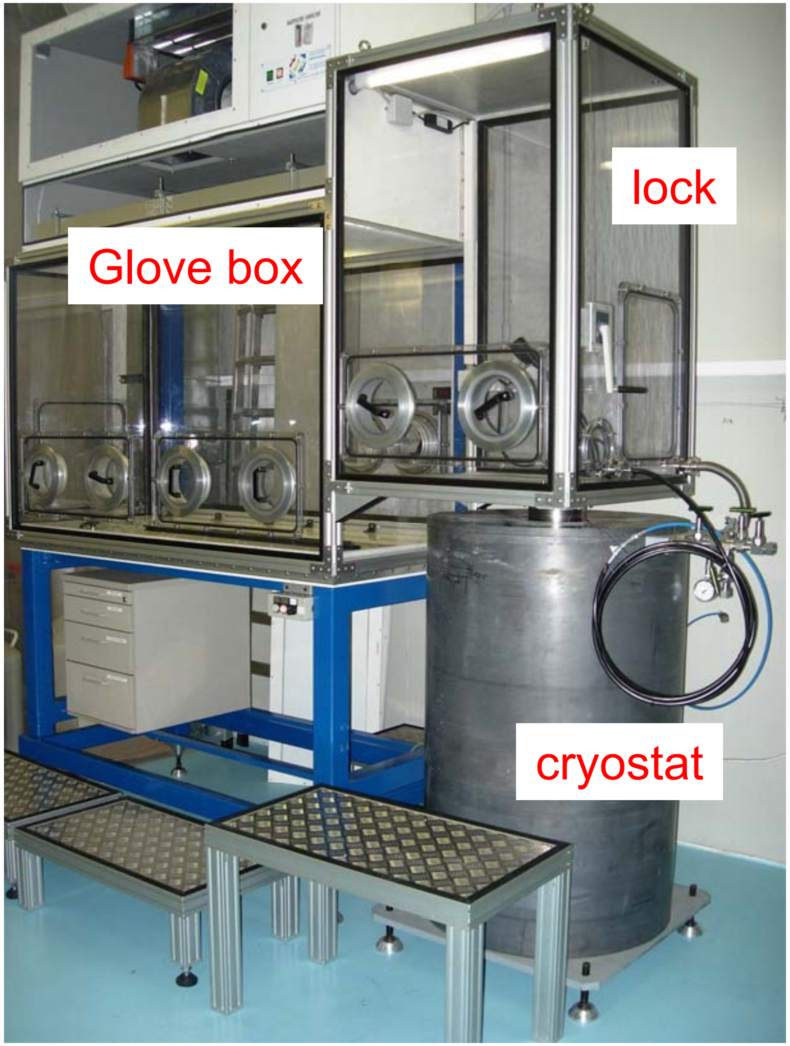
- 17.9 kg enriched (IGEX and HdM) and 15 kg non-enriched crystals (GENIUS-TF)
- All diodes were refurbished by Canberra
- Low-mass holder for each diode
- Storage underground during reprocessing (HADES), less than 1 week exposure above ground
- Storage at LNGS under vacuum in special transport container



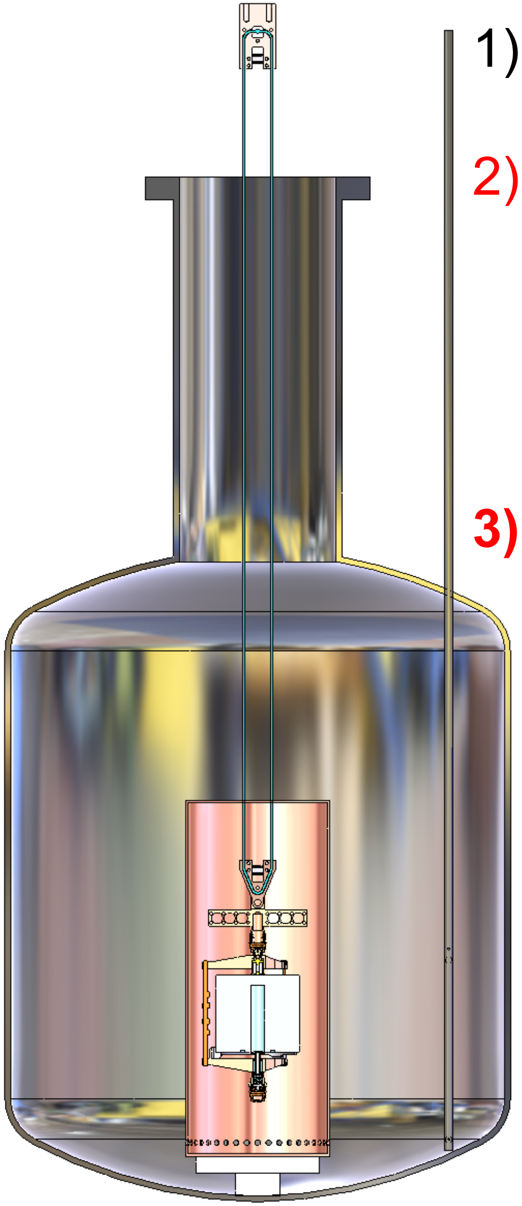




GERDA Detector Lab (GDL) at Gran Sasso



Testing of naked detectors at LAr (Gran Sasso)



1) Definition of naked detector handling protocol

2) Long-term stability tests (3 HPGe detectors in LN2/LAr during 2 years):
   - Depletion voltage
   - I/V curve
   - energy resolution

3) Problems reported from GENIUS-Test Facility* have been overcome by GERDA.

No deterioration after > 1 year of operation at LAr !

(*) H.V.Klapdor-Kleingrothaus end I.Krivosheina, NIM A556 (2006) 472.

GERDA phase II

- Sept 2005: 37.5 kg ^{76}Ge produced in Russia
  - ~87% ^{76}Ge enrichment, 0.015% of ^{70}Ge depletion
  - Chemical purity: 99.95 % or 4N
- 50 kg of $^{dep}GeO_2$ the same quality for testing
- Investigation of different options for the material purification and crystals pulling at PPM Pure Metals and the IKZ (Germany))
- Underground storage (HADES, Belgium and Langelsheim, Germany) until and during further processing steps (crystal pulling and detector fabrication)
- Development of **true-axial segmented n-type** or **p-type point-like contact** detector (BEGe detector)

Svetlana

Centrifuge hall

Collection of $GeCl_4$

Munich, March 2005

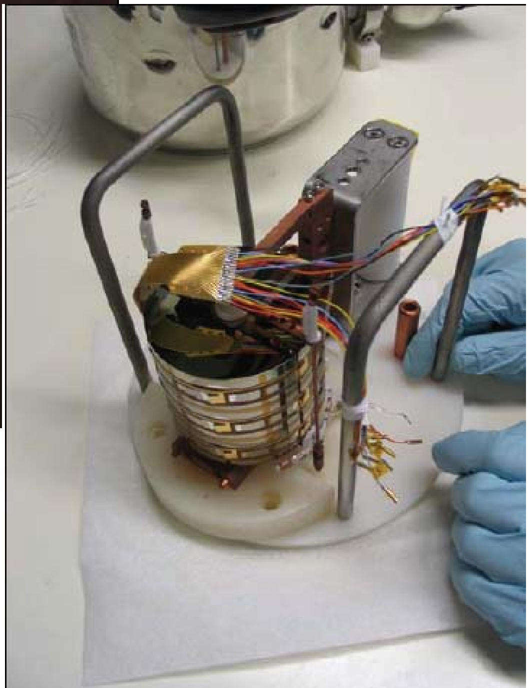
Rally Siberia – Munich is over: $^{76}GeO_2$ is in MPI fuer Physik

Refurbishing of CZ crystall puller at IKZ

- Inductive heating with silver coils
- Molybdenum susceptor
- 4” and 6” ultra high purity crucible made of quartz
- System of pure forming gas (Ar + H_2)

EKZ 2000 LEYBOLD

Phase II 18-fold segmented n-type detector



Copper hold for Phase II:
31 g Cu7 g Teflon

Low mass contacts (Cu on Kapton):
2.5 g Kapton cable (+ Cu)

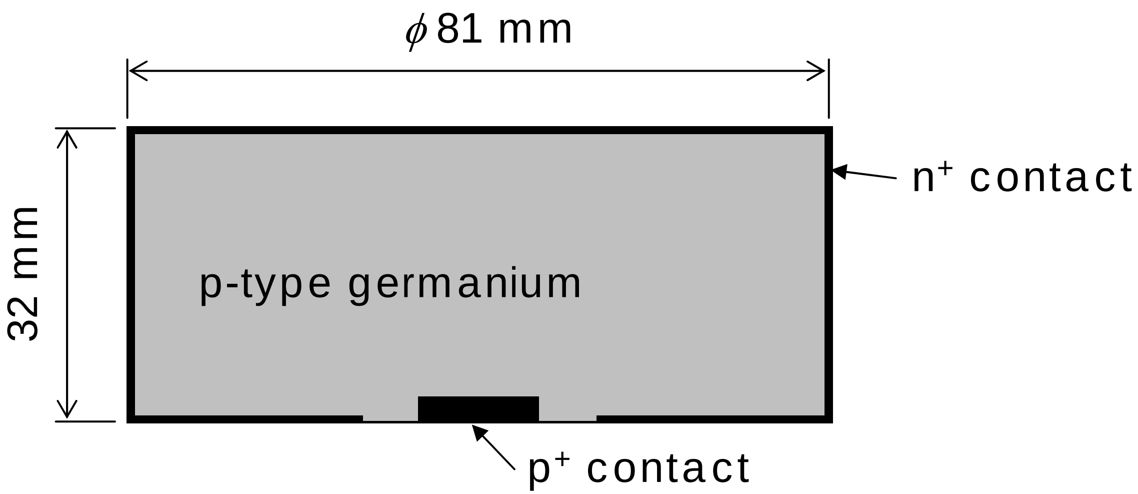
First successful operation of segmented n-type HPGe detector in LN
(during 5 months)

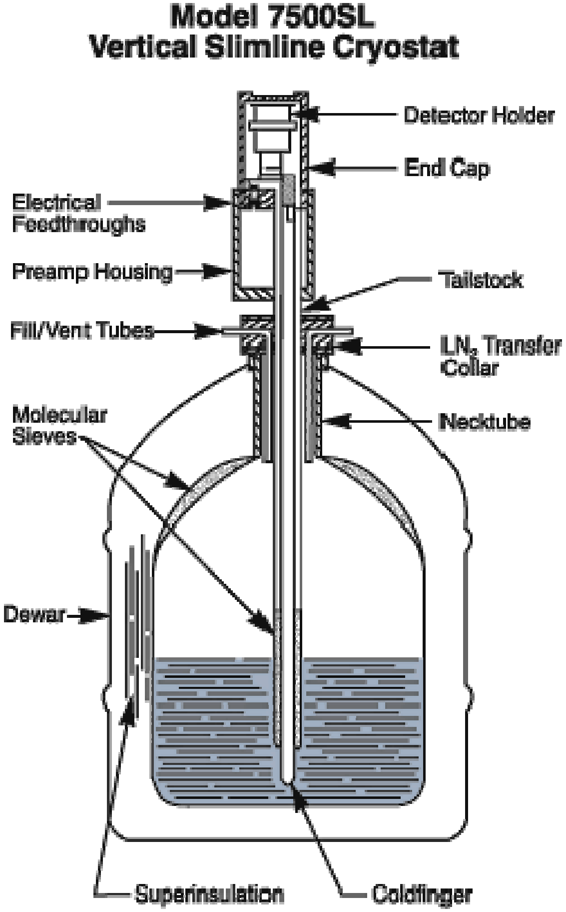
Phase II Broad-energy Ge-detector

- covers energy range 3 keV - 3 MeV
- enhanced efficiency for low-energy gammas
- low capacitance (⇒ low noise)

CANBERRA

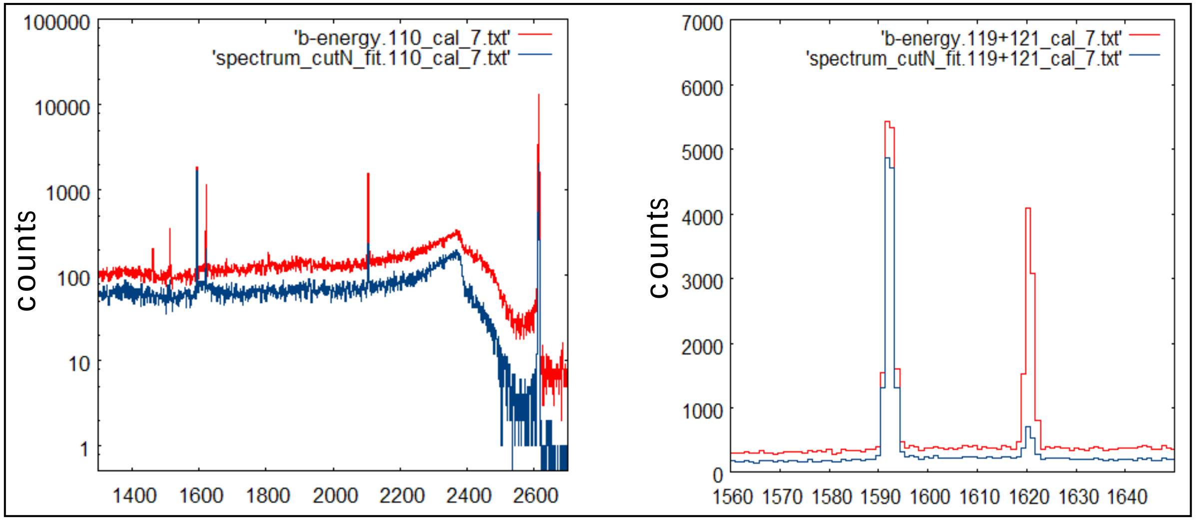
Specifications:		
	depletion voltage	4000 V
	FWHM @ 122 keV	0.63 keV
	FWHM @ 1.33 MeV	1.8 keV
	mass	870 g





BEGe vs. 18-fold segmented HPGe

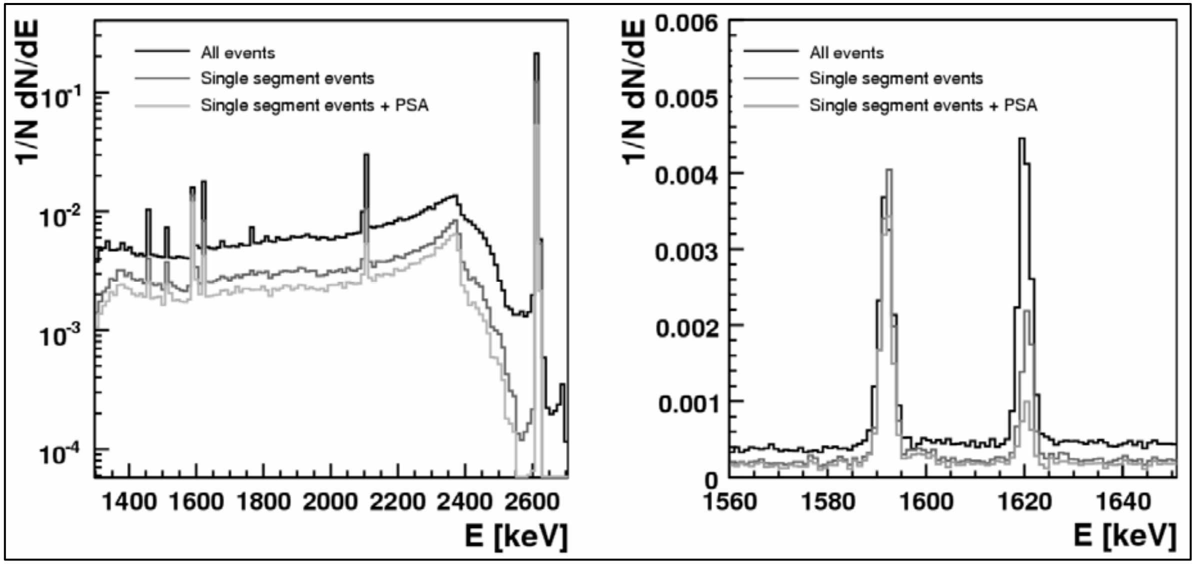
comparison of discrimination power for ^{228}Th spectrum



BEGe point-contact

Fractions remaining after PSA cut:

DEP	91.01% ± 0.62%
1.62 MeV	13.20% ± 0.45%
2.61 MeV	13.19% ± 0.06%
ROI $Q_{\beta\beta}$	**49.06% ± 0.40%**



18-fold segmented coax

Fractions remaining after combined single-segment and PSA cut:

DEP	81.93% ± 2.22%
1.62 MeV	18.98% ± 0.39%
2.61 MeV	14.57% ± 0.31%
ROI $Q_{\beta\beta}$	**48.10% ± 1.12%**

(PSA data without Compton background subtraction)

SSE/MSE discrimination with BEGe comparable to 18-fold segmented detector

Summary

- $0\nu 2\beta$ - decay is identified as one of the top priority topics in particle physics for the next 10÷20 years.

- The experiments based on ^{76}Ge diodes are the most promising ones for investigation of $0\nu 2\beta$ - process.

- The GERDA experiment is designed as the next-generation $0\nu 2\beta$ -decay ^{76}Ge experiment with sensitivity:
  - $3*10^{25}$ yr for Phase I
  - $1.5*10^{26}$ yr for Phase II
  - the future world-wide ~ 1 t experiment $<m_{ee}>$ ~ 10 meV.

- Commissioning of GERDA and start of the experiment in 2009.

Backup slides

Schedule

- June 2007: GERDA setup officially approved by LNGS
- All Phase I detectors (8 pieces) refurbished&ready to use
- Meanwhile: Detector prototype testing in LN2 ongoing
- Cryostat has been mounted in March 2008 and successfully tested
- Water tank constraction has been completed in June 2008
- Hydrostatic and fast draining tests will be done soon
- Construction of lab building has been completed
- Next: cleanroom and lock (~ till Spring 2009)
- Muon Veto (Cherenkov and Plast Scintillators) – after WT testing
- **Filling with LAr and Commissioning of GERDA - Spring 2009**

Commissioning of GERDA and start of the experiment in 2009

References to slide # 6

1. E.Fiorini et al., Phys.Lett. 25B, N. 10, 27 November 1967, pp. 602-603.
2. D.O.Caldwell et al., Phys. Rev. D, Vol. 33, N. 9, 1 May 1986, 2737-2739.
3. D.O.Caldwell et al., Phys.Rev.Lett. Vol.59, N. 4, 27 July 1987, 419-422.
4. A.A.Vasenko, I.V.Kirpichnikov et al., Modern Phys. Lett. A, Vol. 5, N. 17 (1990) 1299-1306.

Best results on $0\nu\beta\beta$ search

Isotope	$T_{1/2}$, yr	$<m_\nu>$, eV QRPA'07	$<m_\nu>$, eV SM'07	Experiment
^{76}Ge	$> 1.9 \cdot 10^{25}$ $\approx 1.2 \cdot 10^{25}$ (?) $\approx 2.2 \cdot 10^{25}$(?) $> 1.6 \cdot 10^{25}$	< 0.22-0.41 ≈ 0.28-0.52 (?) ≈ 0.21-0.38(?) <0.24-0.44	< 0.69 ≈ 0.87 (?) ≈ 0.64(?) < 0.75	HM KK of HM KK of HM′06 IGEX
^{130}Te	$>3.1 \cdot 10^{24}$	< 0.34-0.57	< 0.75	CUORICINO
^{100}Mo	$>5.8 \cdot 10^{23}$	< 0.81-1.28	-	NEMO
^{136}Xe	$>4.5 \cdot 10^{23}$	< 1.41-2.67	< 2.2	DAMA
^{82}Se	$>2.1 \cdot 10^{23}$	< 1.40-2.17	< 3.4	NEMO
^{116}Cd	$>1.7 \cdot 10^{23}$	< 1.45-2.76	< 1.8	SOLOTVINO

Internal background reduction: segmented detector

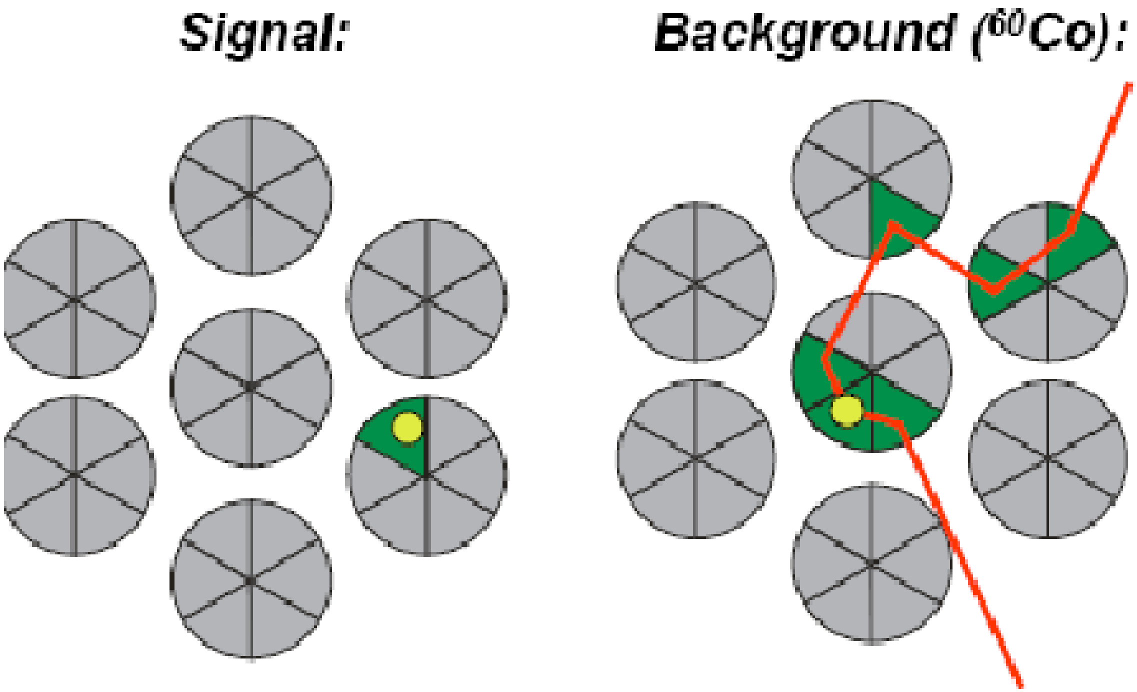
Photon – β- particle discrimination

– ββ-signal: local energy deposition – single site event, SSE

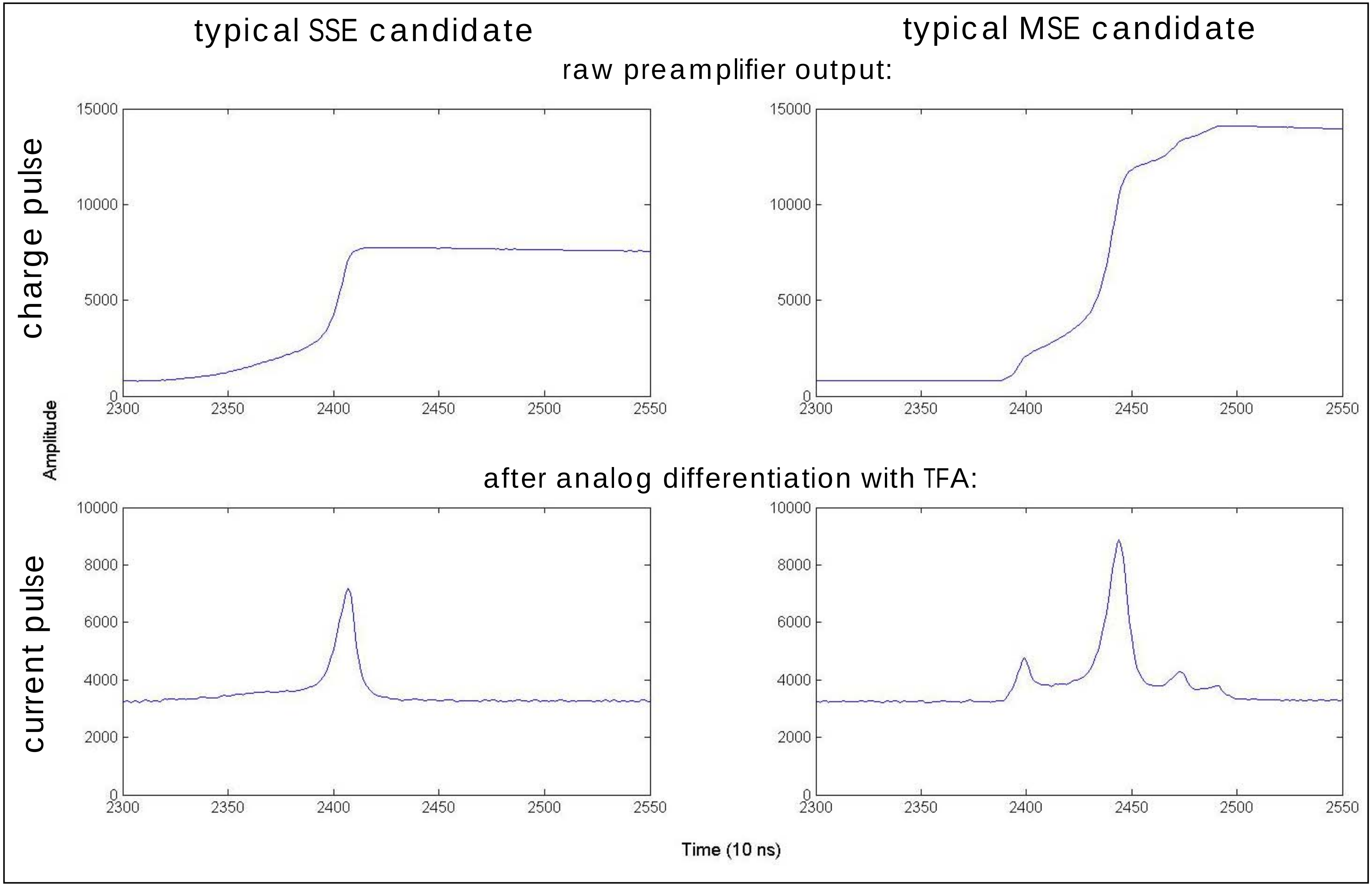
– γ -background: several compton scatterings – multi site event, MSE

Anti-coincidence between segments suppr. factor ~10

Puls shape analysis suppr. factor ~2



Pulse-shape analysis: BEG-detector



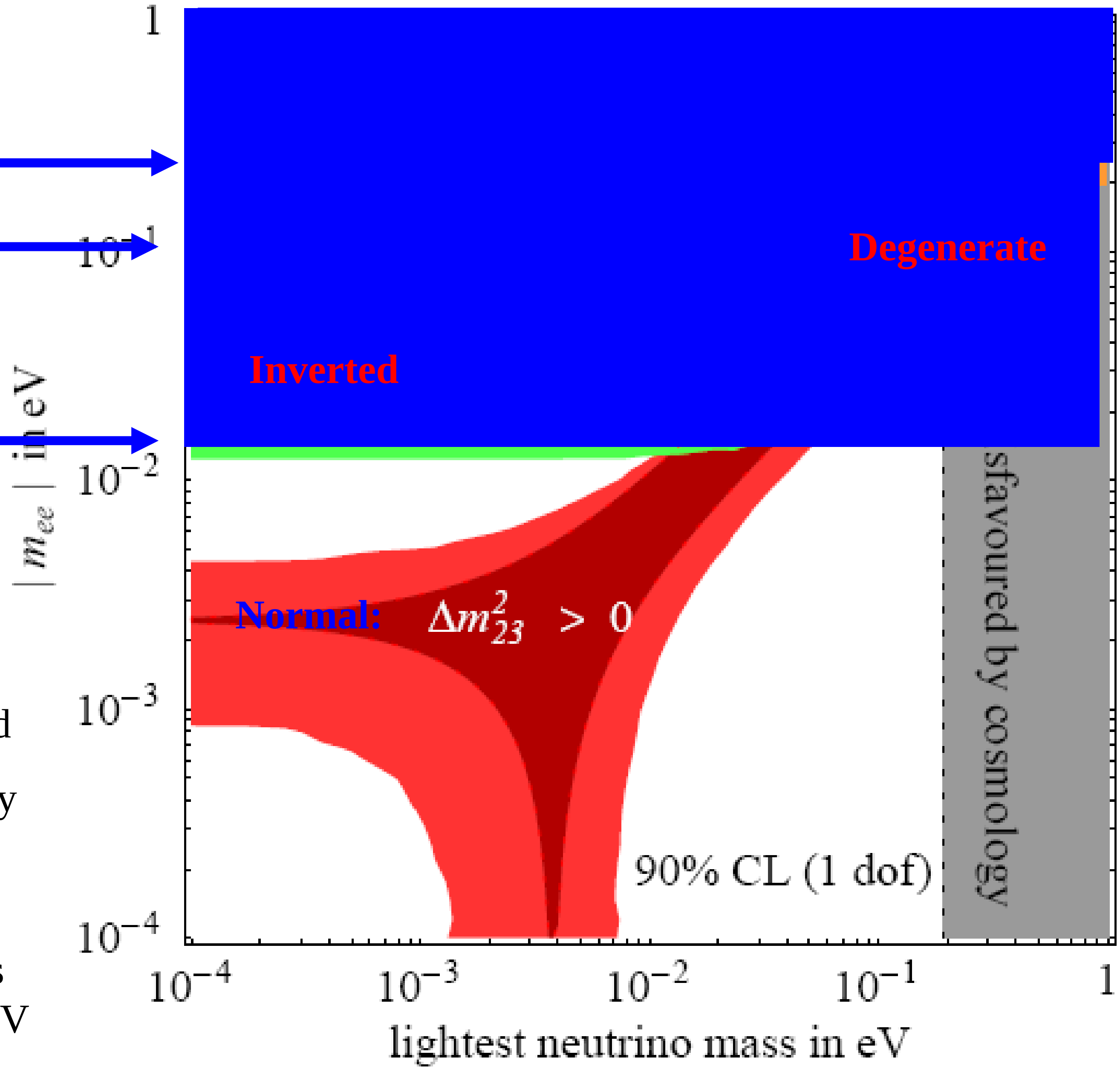
TFA parameters: 10 ns integration, 10 ns differentiation

GERDA & Mass hierarchy sensitivity

Phase I

Phase II

Phase III



Degenerate: can be tested

Inverted: can be tested by next generation of 2β experiments.

Normal: new approach is needed, with m_{ee} ~ 10 meV

Purification at PPM Pure Metals

Underground storage of depGeO2 in **Langelsheim** municipal mining museum

a) Reduction procedure
depGeO2 → depGe
Technical grade (99,8%)
No isotope dilution effect was detected
Yield = 98,5%

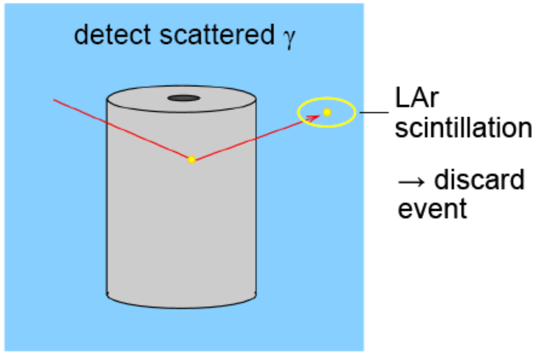
b) Three steps zone refinement
depGe → depGe
99,8% → 6N ($\rho \geq 50$ Ohm*cm)
10^{13} cm^{-3} → 10^{11} cm^{-3}
Yield = 91%

Unrecoverable loss is 0.4%.
Total yield of 6N material was 88%
Total exposure of the material at sea level < 2-3 days/purification

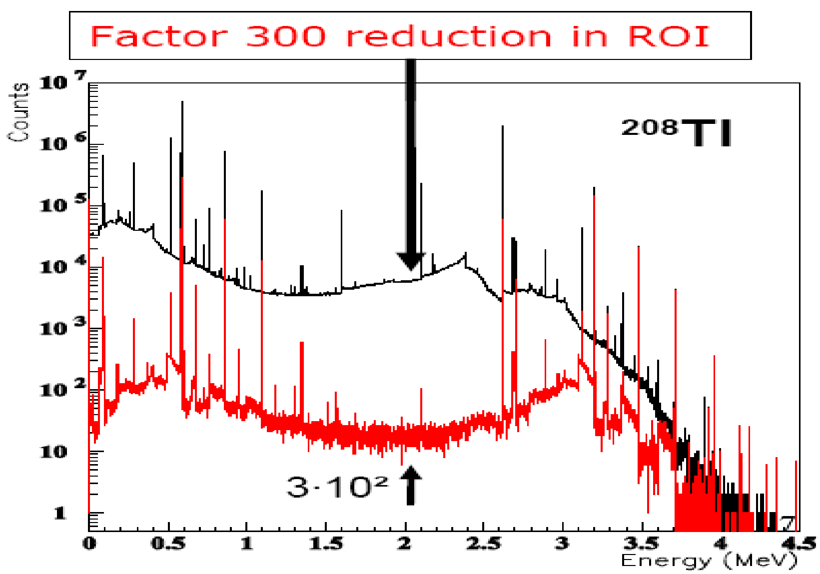
Material characterization

- Resistivity measurements at RT, Ohm*cm
- Hall effect measurements at 77 K:
  - $|N_D - N_A| \sim 10^{11} \div 10^{13}$ cm^{-3} (detector grade ~ 10^{10} cm^{-3})
  - Mobility at RT and 77K
- PTIS (Photo Thermal Ionization Spectroscopy) measurements
  - Identification of donors and acceptors
- Optical measurements:
  - Dislocation density (~ 10^2 - 10^4 cm^{-2})
- Photoluminescence measurement (Dresden):
  - Identification of donors and acceptors (As and P, no Al and B)

Liquid Argon scintillation

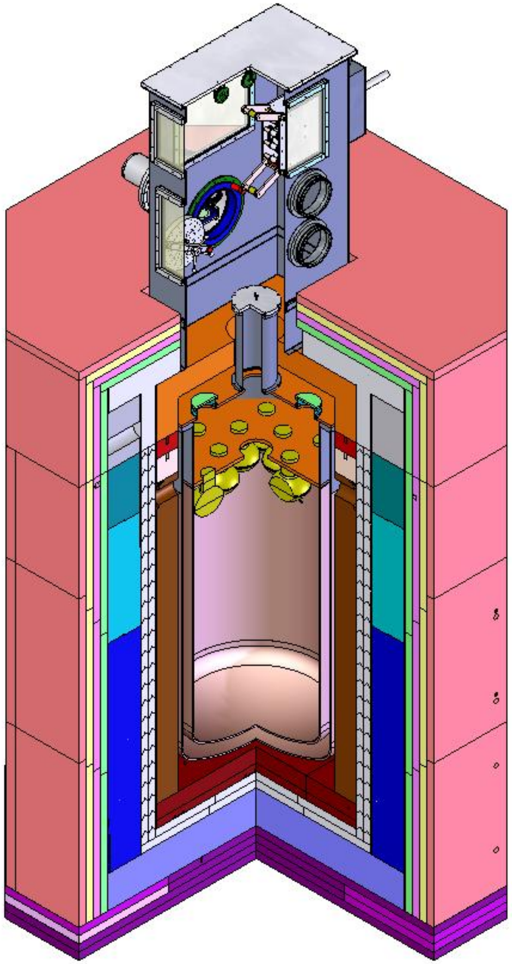


MC simulation: Background suppression for contaminations located in detector support:



Test facility MiniLArGe at MPIK

Low background test stand LArGe (Heidelberg, Gran Sasso)



Cryostat:
Inner diameter: 90 cm
Volume: 1000 liter
(under construction)

PMT: 9 x 8” ETL9357
(delivered)

Shield:

Cu	15 cm
Pb	10 cm
Steel	23 cm
PE	20 cm

(in place)

Lock: Construction completed

Can house up to 3 Phase 1 strings (9 Ge detectors)