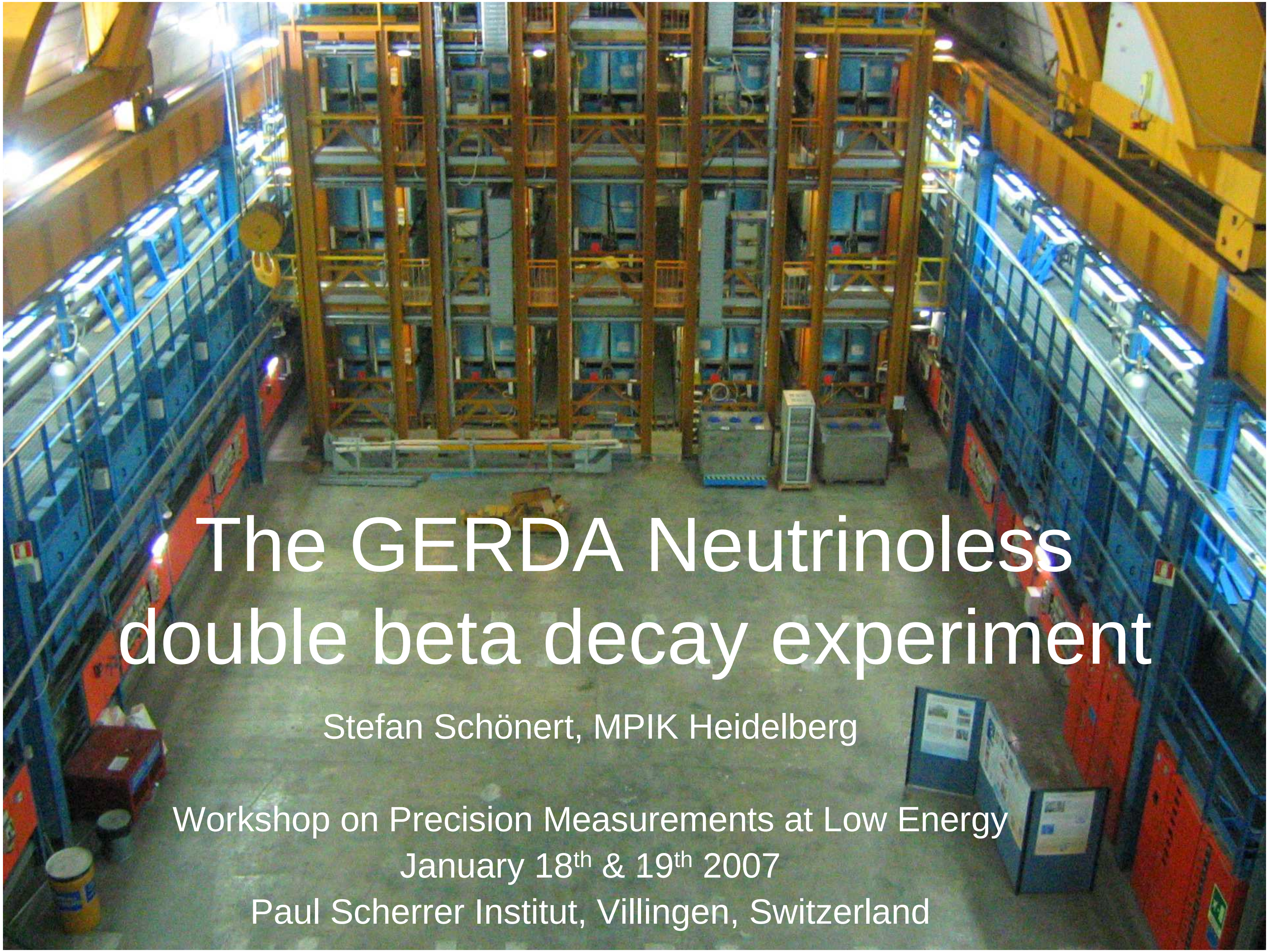


The GERDA Neutrinoless double beta decay experiment

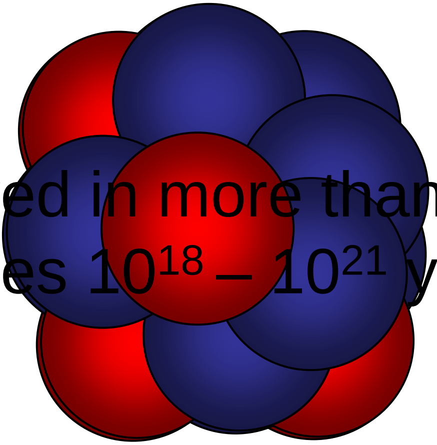
Stefan Schönert, MPIK Heidelberg

Workshop on Precision Measurements at Low Energy
January 18th & 19th 2007
Paul Scherrer Institut, Villingen, Switzerland

Outline

- Introduction:
    - $0\text{-}\nu\beta\beta$ and physics implications
    - Effective Majorana neutrino mass <m>
    - Predictions on <m> from oscillation experiments
    - Sensitivity with and w/o backgrounds
- GERDA design
    - Concept
    - Sensitivities: Phase I, II, III
    - Locations at LNGS
    - Phase I detectors
    - Phase II detectors
    - Front-end electronics
    - Infrastructures: cryogenic tank, WT, clean room,..
    - Screening
- Examples of backgrounds and reduction techniques:
    - Detector segmentation
    - Liquid argon scintillation read out
- Conclusion/Outlook

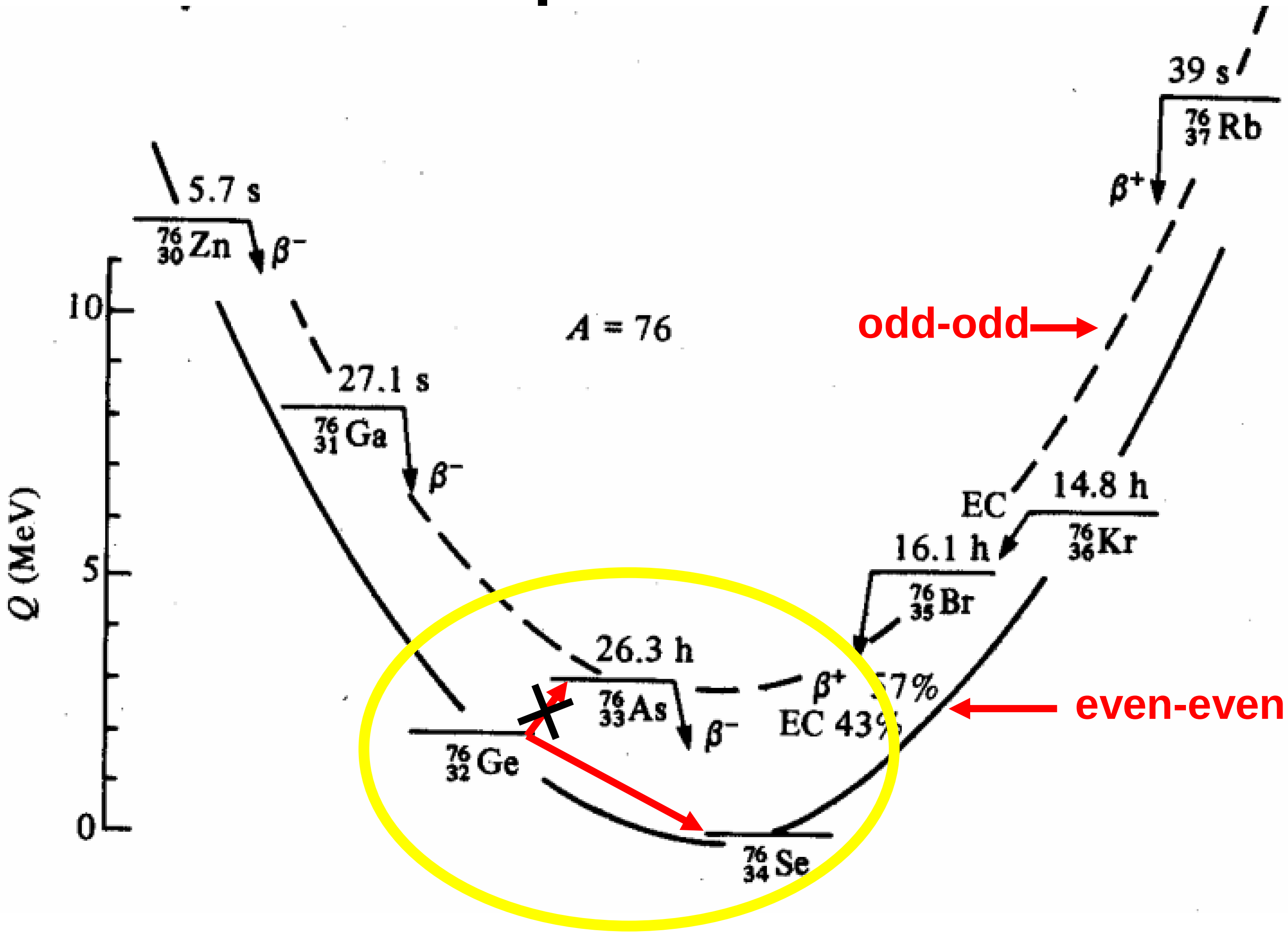
2ν-ββ Decay



Observed in more than 10 isotopes

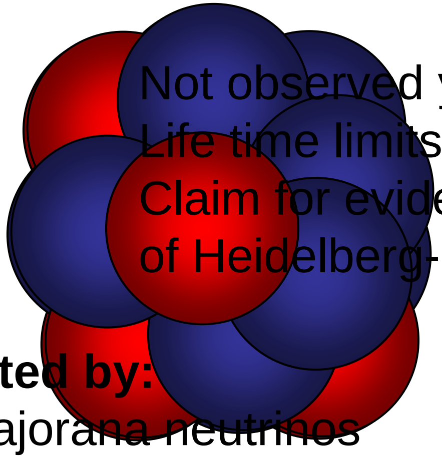
Life times $10^{18} – 10^{21}$ years

Mass parabolas



Ground states of even-even nuclei: 0^+

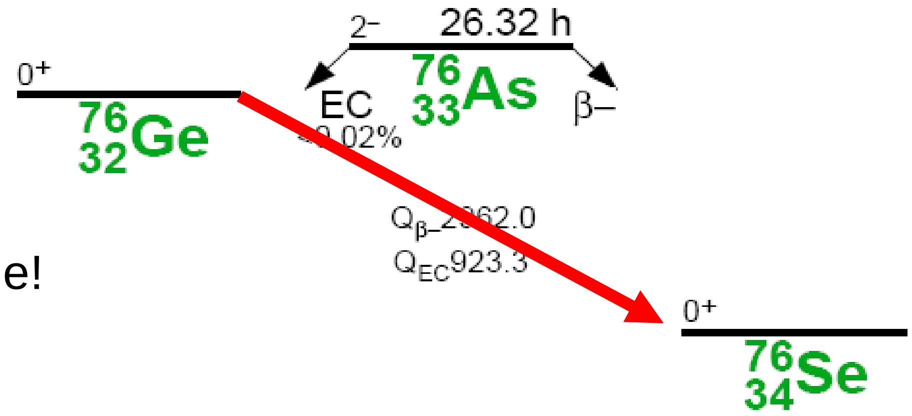
0ν-ββ Decay



Not observed yet;
Life time limits > $10^{24} – 10^{25}$ y;
Claim for evidence in Ge-76 by part of Heidelberg-Moscow Collab.

0νββ can be generated by:
- exchange of light Majorana neutrinos
- SUSY
- …..

Schechter & Valle:
if 0νββ observed ⇒ ν is Majorana particle!



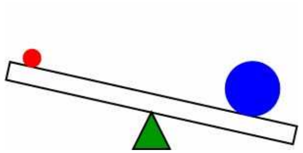
Physics motivations

1) Dirac vs. Majorana particle: (i.e. its own anti-particle)?

$0\nu\beta\beta \Rightarrow$ Majorana nature

Majorana $\Rightarrow$ See-Saw mechanism

$$m_\nu = \frac{m_D^2}{M_R} << m_D$$



For $m_3 \sim (\Delta m^2_{\mathrm{atm}})^{1/2}$, $m_D \sim m_t$ ➔ $M_R \sim 10^{15}$GeV

Majorana $\Rightarrow$ CP violation in M_R → higgs + lepton $\Rightarrow$ Leptogenesis $\Rightarrow$ B asymmetry

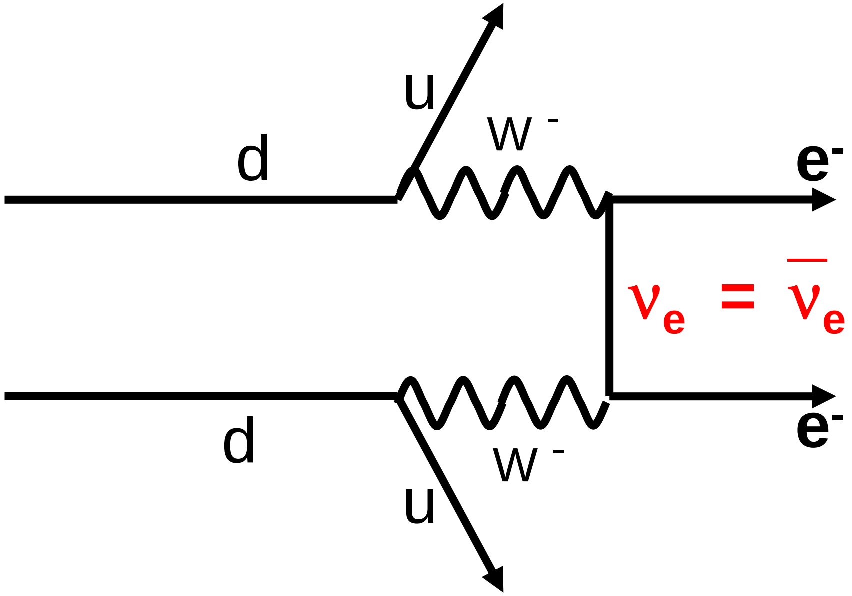
2) Absolute mass scale:

Hierarchy: degenerate, inverted or normal

(effective) neutrino mass

0ν-ββ Decay

$$(A,Z) \rightarrow (A,Z+2) + e_1^- + e_2^-$$



ΔL=2

Assume leading term is exchange of light Majorana neutrinos

$$T_{1/2}\,(0\nu)^{-1} = G\ M^2\ m^2_{ee}$$

Effective neutrino mass

Phase space

Nuclear matrix element

Effective Majorana mass

$$m_{ee} = |\sum_i U_{ei}{}^2 \, m_i \,|$$

U_{ei} complex:

⇒ sensitive to CP phases (optimist☺)

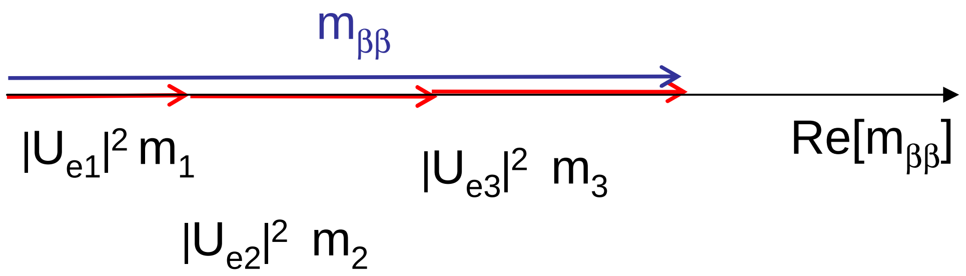
⇒ cancellation possible (pessimist)

NB: Beta-endpoint (Katrin)

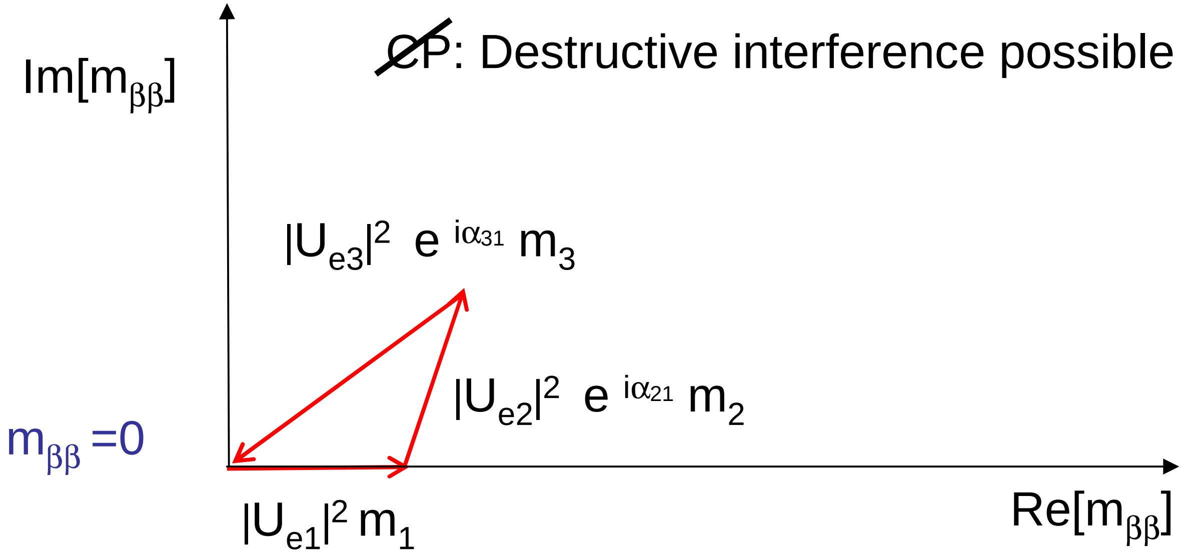
$$m_{\nu_e} = (\sum_i |U_{ei}^2| \, m_i^2 \,)^{1/2}$$

$$
\begin{aligned}
m_{\beta\beta} &= |U_{e1}|^2\, m_1 + |U_{e2}|^2\, e^{2i\lambda_{21}}\, m_2 + |U_{e3}|^2\, e^{2i(\lambda_{31}-\delta)}\, m_3 \\
&= |U_{e1}|^2\, m_1 + |U_{e2}|^2\, e^{i\alpha_{21}}\, m_2 + |U_{e3}|^2\, e^{i\alpha_{31}}\, m_3
\end{aligned}
$$

If CP is conserved:



$$m_{\beta\beta} = |U_{e1}|^2\, m_1 + |U_{e2}|^2\, e^{2i\lambda_{21}}\, m_2 + |U_{e3}|^2\, e^{2i(\lambda_{31}-\delta)}\, m_3$$
$$= |U_{e1}|^2\, m_1 + |U_{e2}|^2\, e^{i\alpha_{21}}\, m_2 + |U_{e3}|^2\, e^{i\alpha_{31}}\, m_3$$



~~CP~~: Destructive interference possible

Im[$m_{\beta\beta}$]

$|U_{e3}|^2\ e^{i\alpha_{31}}\ m_3$

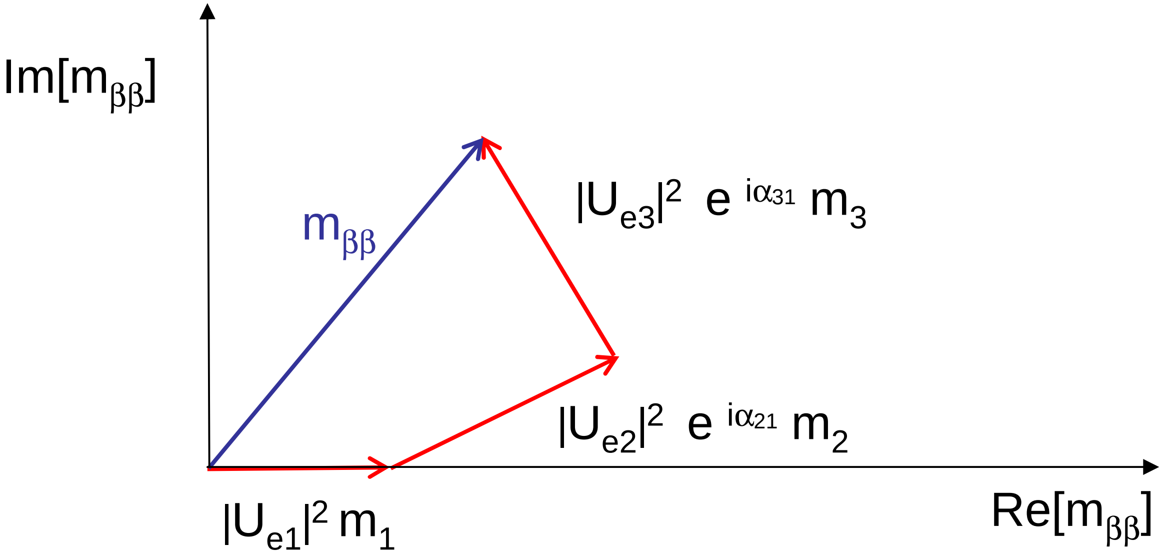
$|U_{e2}|^2\ e^{i\alpha_{21}}\ m_2$

$m_{\beta\beta} = 0$

$|U_{e1}|^2\, m_1$

Re[$m_{\beta\beta}$]

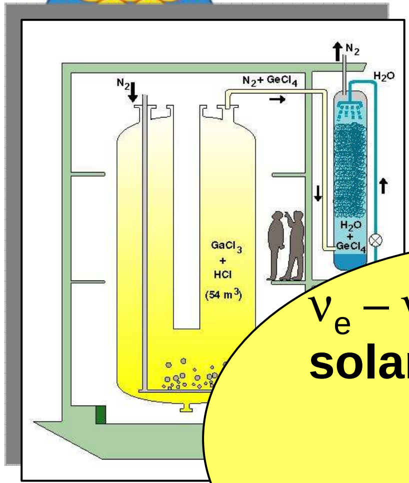
$$\begin{aligned} m_{\beta\beta} &= |U_{e1}|^2\, m_1 + |U_{e2}|^2\, e^{2i\lambda_{21}}\, m_2 + |U_{e3}|^2\, e^{2i(\lambda_{31}-\delta)}\, m_3 \\ &= |U_{e1}|^2\, m_1 + |U_{e2}|^2\, e^{i\alpha_{21}}\, m_2 + |U_{e3}|^2\, e^{i\alpha_{31}}\, m_3 \end{aligned}$$



Standard parametrization:

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ \dots & \dots & s_{23}c_{13}e^{i\delta} \\ \dots & \dots & c_{23}c_{13}e^{i\delta} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

Experimental evidences for neutrino oscillations



$\nu_e - \nu_{\mu,\tau}$; $\overline{\nu}_e - \overline{\nu}_x$

solar- and reactor-ν's:

$\Delta m^2_{sol} \cong 8 \cdot 10^{-5}$ eV^2

$\sin 2^2\theta_{12} \cong 0.8$

$\Delta m^2, \theta$

$\nu_\mu - \nu_\tau$

atmospheric- and accelerator-ν's:

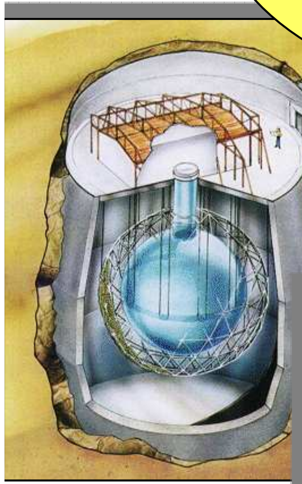
$\Delta m^2_{atm} \cong (2\text{-}4) \cdot 10^{-3}$ eV^2

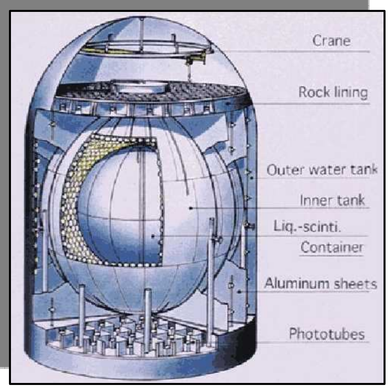
$\sin 2^2\theta_{23} \cong 1$

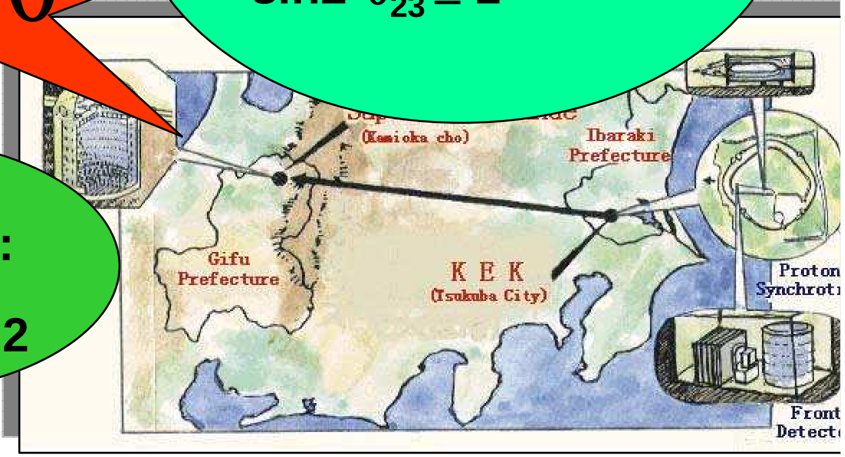
$\overline{\nu}_e - \overline{\nu}_x$

reactor-ν's:

$\sin 2^2\theta_{13} < 0.2$

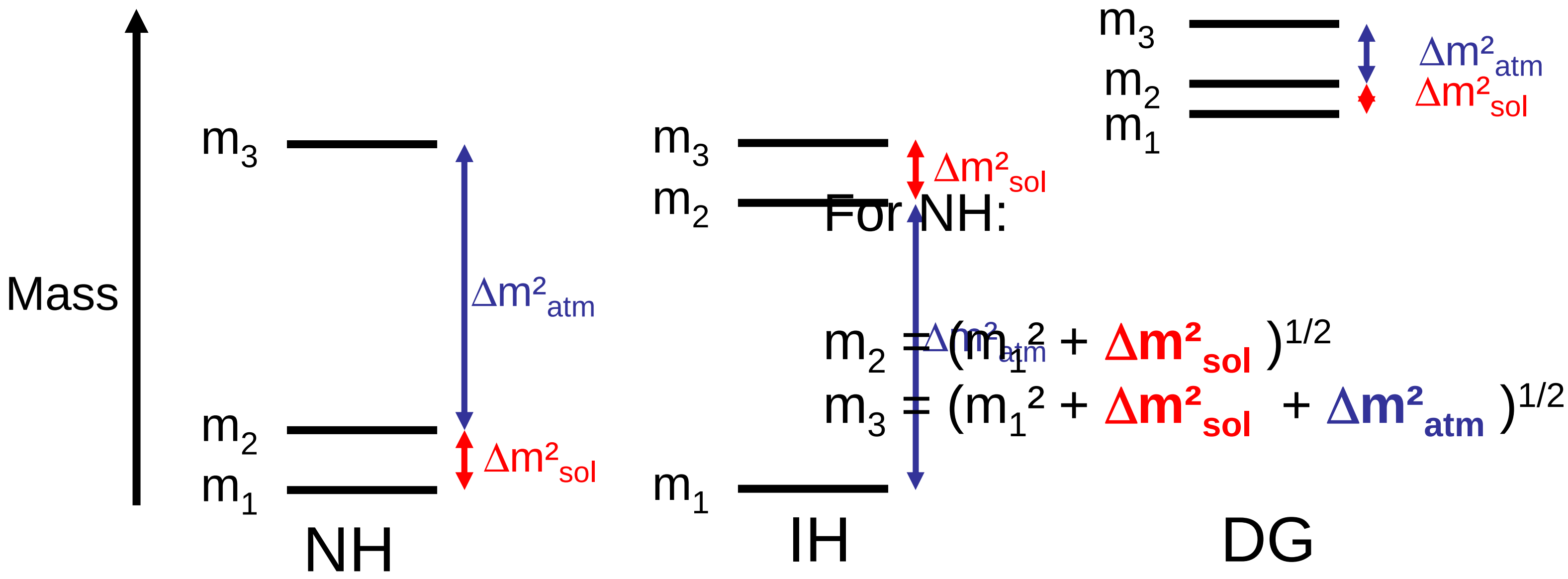






Input for m_{ee} from ν-oscillations

Solar/Reactor -ν: θ_{12}, Δm^2_{sol} **Atmosph.-ν: Δm^2_{atm}** **Reaktor-ν: θ_{13}**



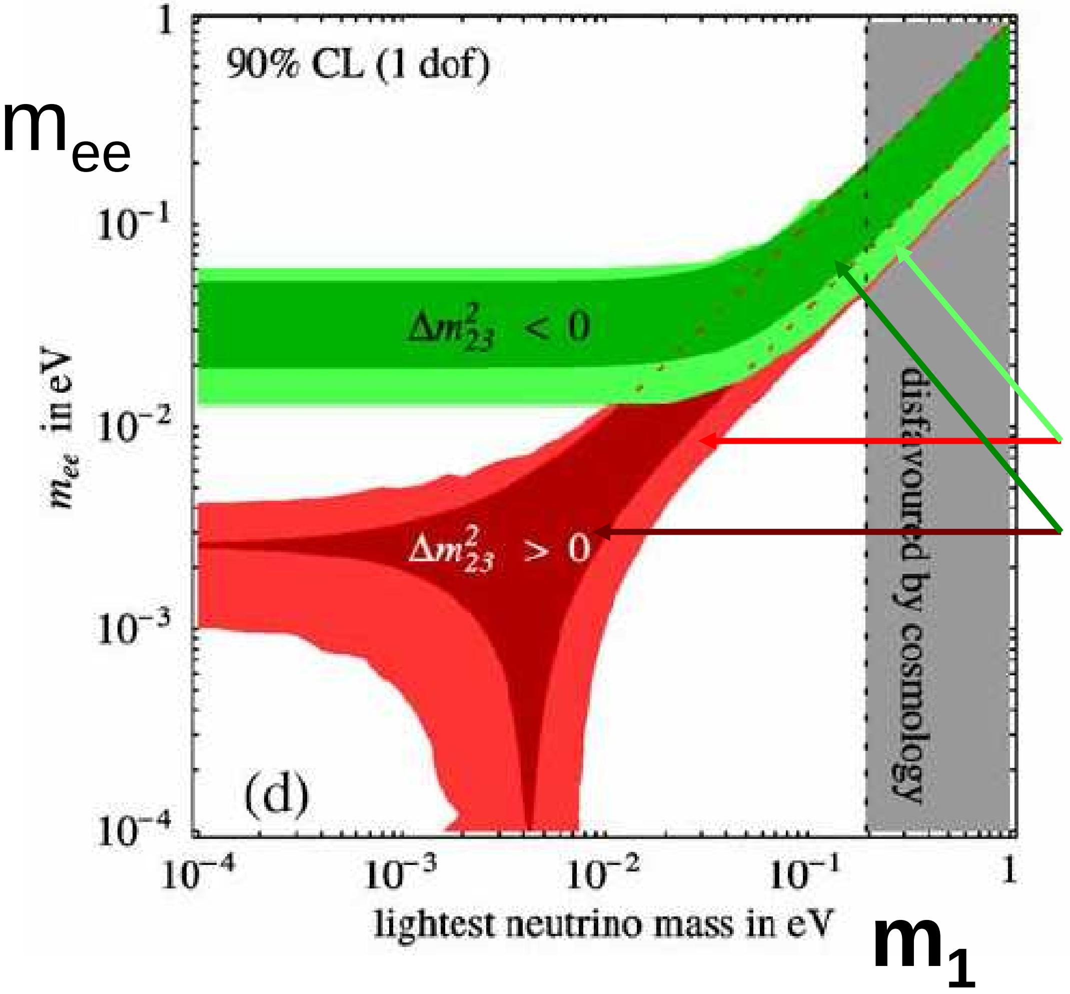
For NH:

$$m_2 = (m_1^2 + \Delta m^2_{sol})^{1/2}$$
$$m_3 = (m_1^2 + \Delta m^2_{sol} + \Delta m^2_{atm})^{1/2}$$

$$m_{ee} = \left|\cos^2\theta_{13}\,(m_1 \cos^2\theta_{12} + m_2\, e^{2i\alpha} \sin^2\theta_{12}) + m_3\, e^{2i\beta} \sin^2\theta_{13}\right|$$

$$\Rightarrow m_{ee} = \mathbf{f(m_1, \Delta m^2_{sol}, \Delta m^2_{atm}, \theta_{12}, \theta_{13}, \alpha,\beta)}$$

Predictions from oscillation experiments



F.Feruglio,
A. Strumia,
F. Vissani,
NPB 659

90% CL

Negligible errors from oscillations; width due to CP phases

Claim for evidence for ββ(0ν)

H.V. Klapdor-Kleingrothaus, A. Dietz, I.V. Krivosheina, O. Chkvorets, NIM A 522 (2004)
(subgroup of Heidelberg-Moscow Collaboration)

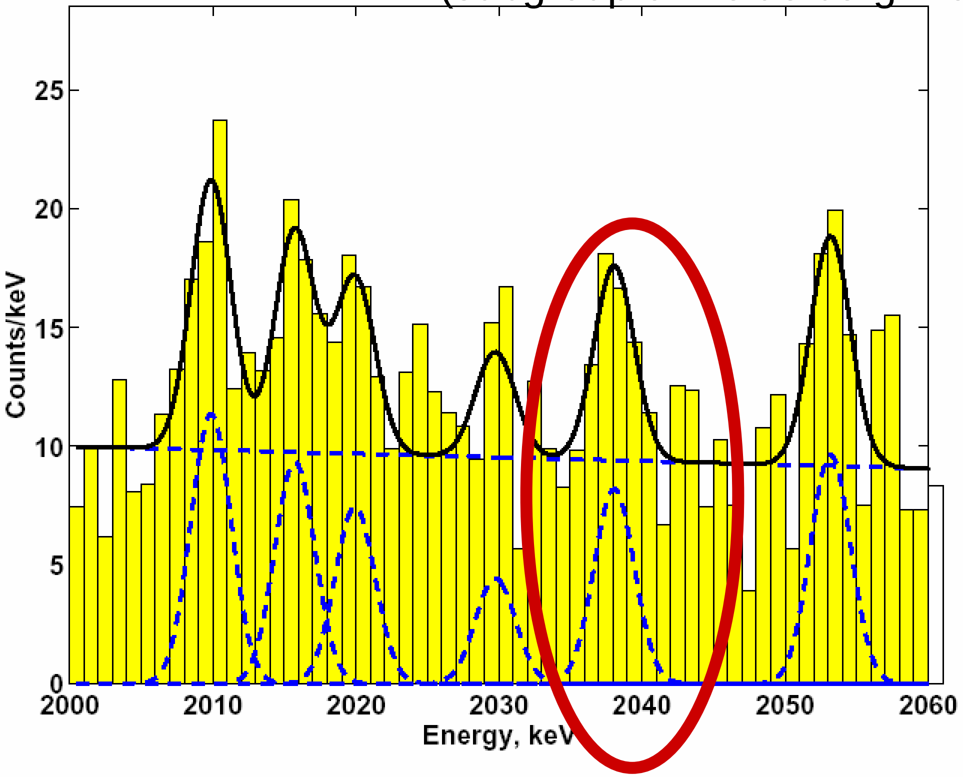


Fig. 17. The total sum spectrum of all five detectors (in total 10.96 kg enriched in ^{76}Ge), for the period November 1990–May 2003 (71.7 kg year) in the range 2000–2060 keV and its fit (see Section 3.2).

Heidelberg-Moscow data:
- Nov 1990- May 2003
- 71.7 kg year
- Bgd 0.11 / (kg y keV)

- 28.75 ± 6.87 events (bgd:~60)
- 4.2 sigma evidence for 0νββ

- 0.69-4.18 x10^{25} y (3 sigma)
- Best fit 1.19 x10^{25} y

- m_{ee} = 0.24-0.58 eV
- best fit 0.44 eV

NB. Statistical significance depends on background model!

Experimental sensitivity: w/o background

Experimental life time

number of nuclides under control ∝ M

live time

number of detected decays

$$\tau = \frac{N_N \; T}{N_S}$$

Background free limit:
0 cnts in the analysis energy window ⇒ Poisson upper limit: N_P

Remember: $\left[T^{0\nu}_{\frac{1}{2}}(0^+ \rightarrow 0^+)\right]^{-1} = G^{0\nu}(E_0,Z)\left| M^{0\nu}_{GT} - \frac{g_V^2}{g_A^2} M^{0\nu}_F \right|^2 <m_\nu>^2$

$$\tau \geq \frac{N_N \; T}{N_P} \propto \mathbf{M \cdot T} \quad \Rightarrow \quad <m> \leq \frac{\text{const}}{(M\ T)^{1/2}}$$

Sensitivity: with background

If no decay is observed in presence of N_B background events in an energy window ΔE:

detector energy resolution

$$N_S < (N_B)^{1/2} \Longrightarrow \tau > \frac{N_N \; T}{(N_B)^{1/2}}$$

$$N_B = b \; M \; T \; \Delta E$$

b: background index [1/(kg · year · keV)]

$$\Rightarrow \quad \tau > \frac{N_N \, T}{(b \; M \; T \; \Delta E)^{1/2}} \propto \left(\frac{M \; T}{b \; \Delta E}\right)^{1/2}$$

$$\boxed{\Rightarrow \quad <m> \; \leq \text{const.} \cdot \left(\frac{b \; \Delta E}{M \; T}\right)^{1/4}}$$

Comparison of DBD Isotopes

$$T^{0\nu}_{1/2} = \frac{1}{\Gamma(Q^5_{\beta\beta})\ M^2\ <m_{ee}>^2}$$

$$N_{sig} = N_{Avg} \cdot \frac{mass \cdot t}{A} \cdot \ln 2 \cdot \Gamma \cdot M^2 \cdot < m_{ee} >^2$$

GERDA, Majorana

isotope	$Q_{\beta\beta}$	nat. abund.	rel. A	rel Γ	rel. M^2	N_{sig}
$^{76}Ge \rightarrow ^{76}Se$	2039 keV	7.4%	1	1	1	2.4
$^{82}Se \rightarrow ^{82}Kr$	2995 keV	9.2%	0.93	4.4	0.71	7.0
$^{100}Mo \rightarrow ^{100}Ru$	3034 keV	9.6%	0.76	7.2	0.23	3.0
$^{130}Te \rightarrow ^{130}Xe$	2529 keV	34%	0.58	6.9	0.33	3.2
$^{136}Xe \rightarrow ^{136}Ba$	2479 keV	8.9%	0.56	7.4	0.15	1.5

for 1000 kg y, $<m_{ee}>$ = 50 meV, M^2 from V.A.Rodin et al, Nucl. Phys. A766 (2006) 107.

NEMO3

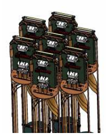
Super-Nemo

Cuoricino/Cuore

EXO

Two new ^{76}Ge Projects:

GERDA

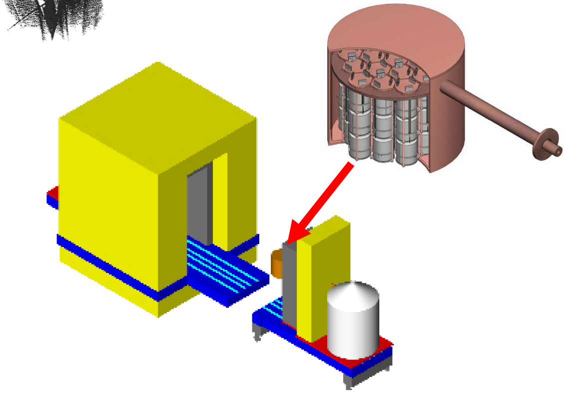


List of institutions:

INFN LNGS, Assergi, Italy
JINR Dubna, Russia
Institute for Reference Materials, Geel, Belgium
MPIK, Heidelberg, Germany
Univ. Köln, Germany
Jagiellonian University, Krakow, Poland
Univ. di Milano Bicocca e INFN, Milano, Italy
INR, Moscow, Russia
ITEP Physics, Moscow, Russia
Kurchatov Institute, Moscow, Russia
MPI Physik, München, Germany
Univ. di Padova e INFN, Padova, Italy
Univ. Tübingen, Germany

- ~80 physicists, 13 institutions, 5 countries
- approved Nov 2004 at LNGS
- Status: under construction

Majorana



- Array(s) of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Staged approach based on 60 kg arrays (60/120/180 kg)

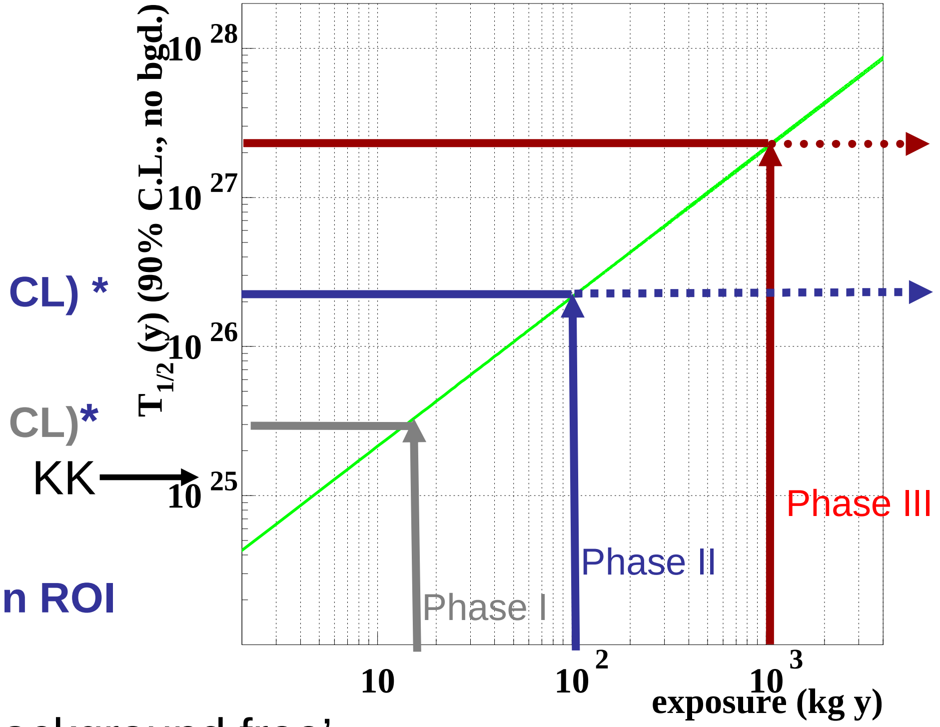
ss range
d exp. techniques

echnologies (e.g. MaGe MC)
consider to merge for O(1 ton) exp. (inv. Hierarchy)

Phases and Physics reach of GERDA

$2 \cdot 10^{26}$ (90 % CL) *

$3 \cdot 10^{25}$ (90 % CL)*



<50 meV

<170 meV

assuming
$|M^{0\nu}|=2.5$ [Rod06]
and 89% enrichment

*: no event in ROI

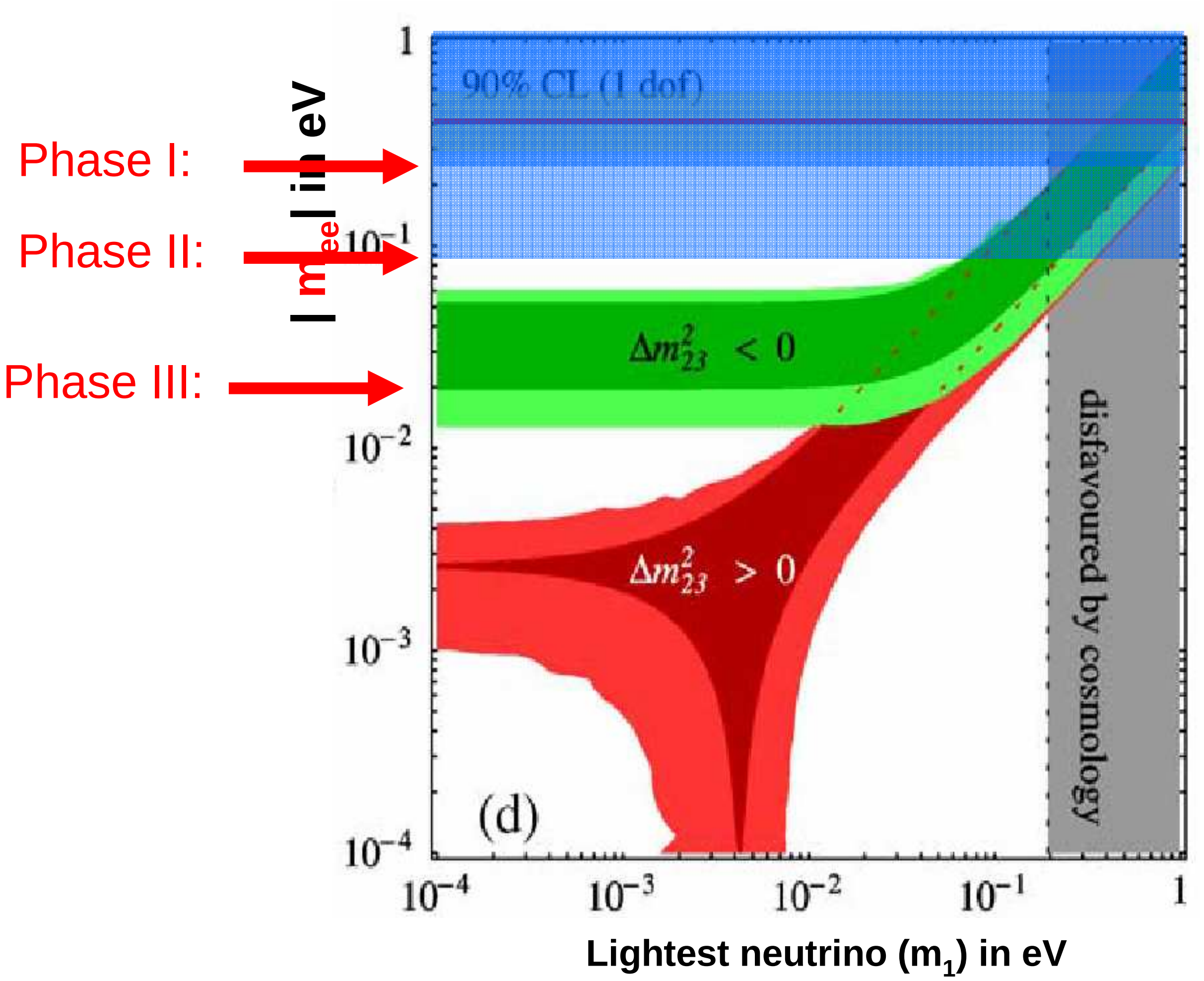
required for ‘background free’
exp. with ΔE~3.3 keV (FWHM): O(10^{-3}) O(10^{-4}) counts/(kg·y·keV)

Background requirement for GERDA:

⇒Background reduction by factor **10^2 - 10^3** required w.r.t. to precursor exps.

⇒Degenerate mass scale **O(10^2 kg·y)** ⇒ Inverted mass scale **O(10^3 kg·y)**

Phases and Physics reach of GERDA



Phase I:

Phase II:

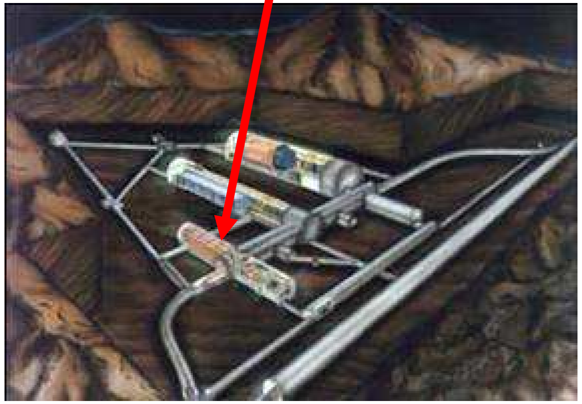
Phase III:

| m_{ee} | in eV

Lightest neutrino (m_1) in eV

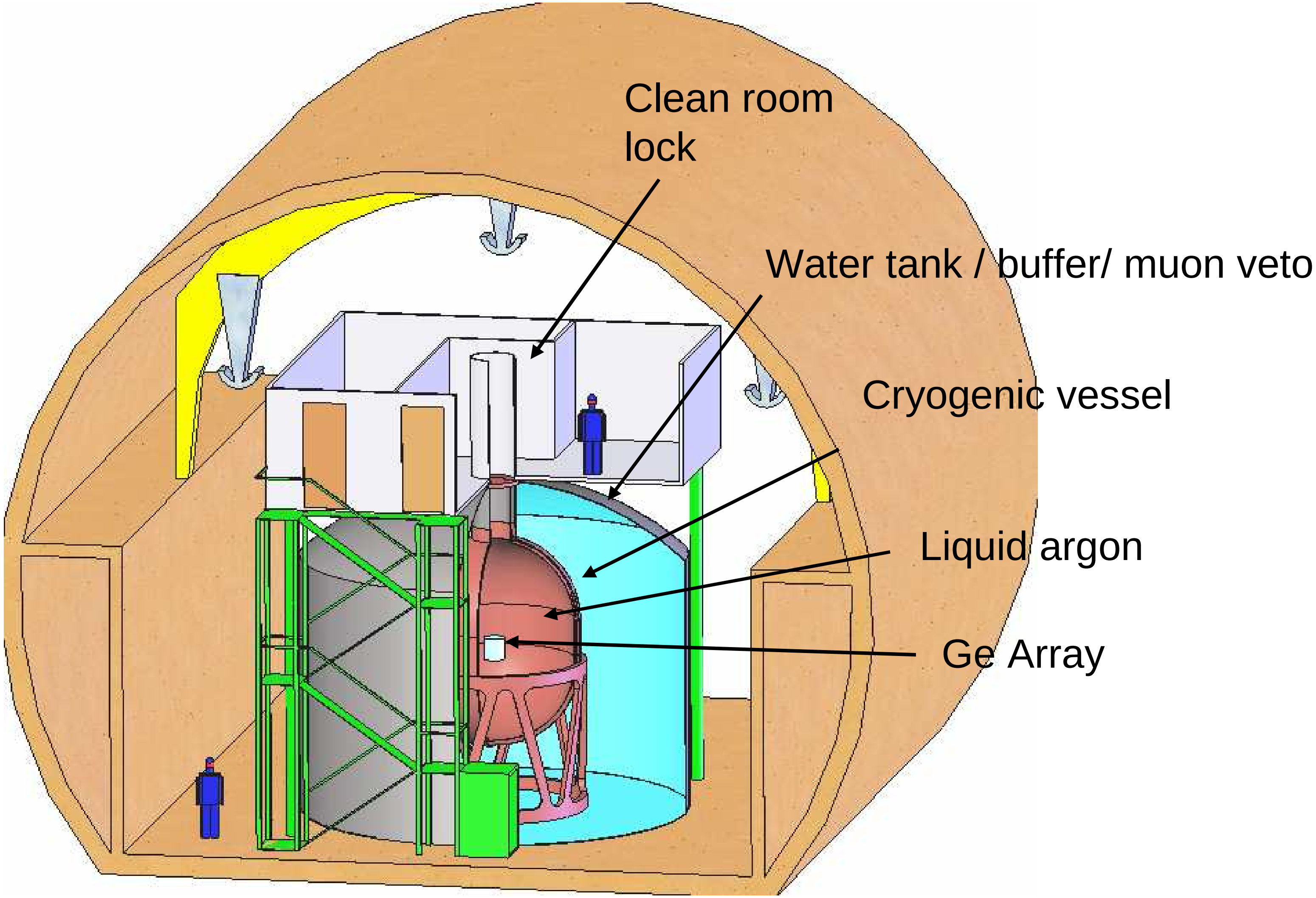
F.Feruglio, A. Strumia, F. Vissani, NPB 659

GERDA at LNGS

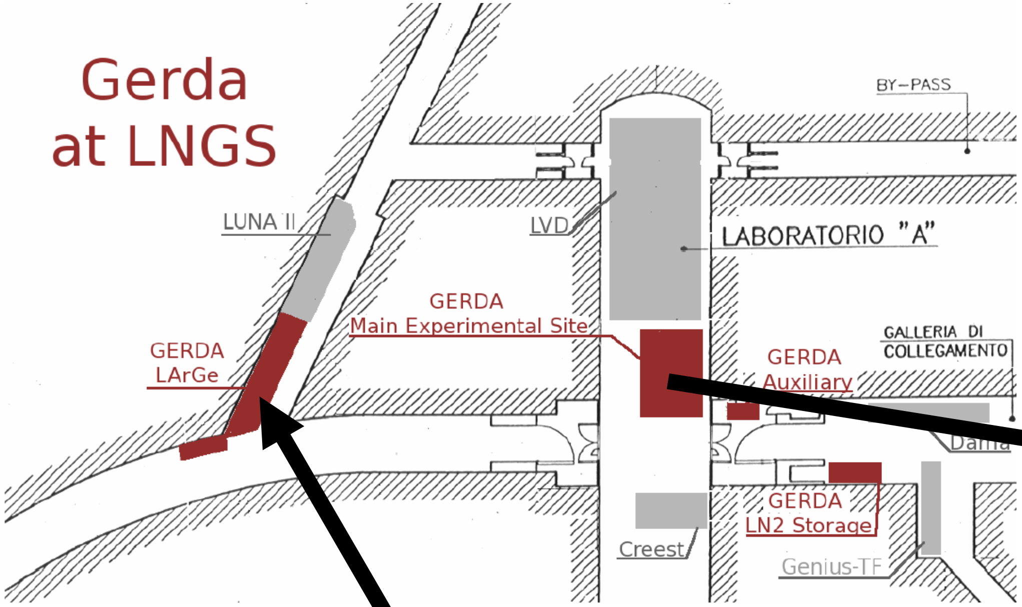


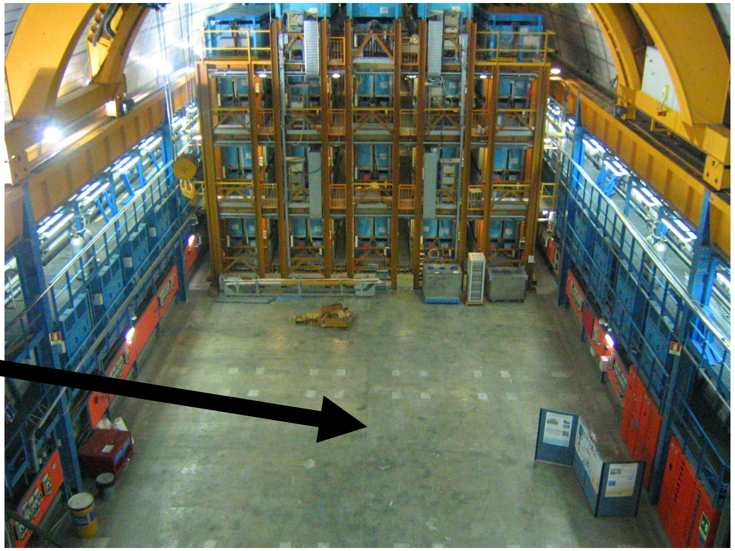
GERDA location:
hall A of LNGS

GERDA design



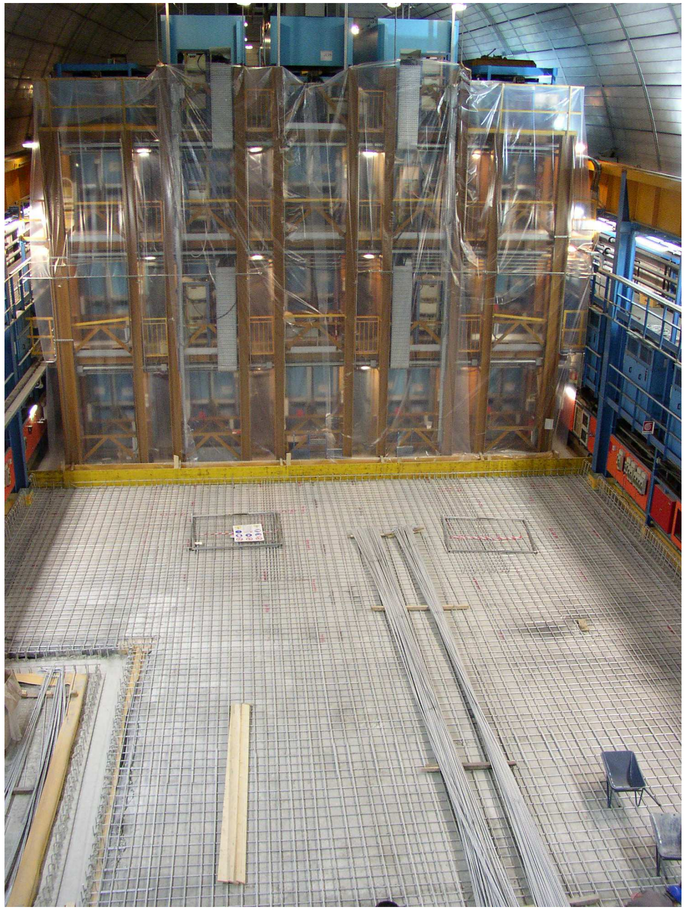
GERDA underground facilities at LNGS



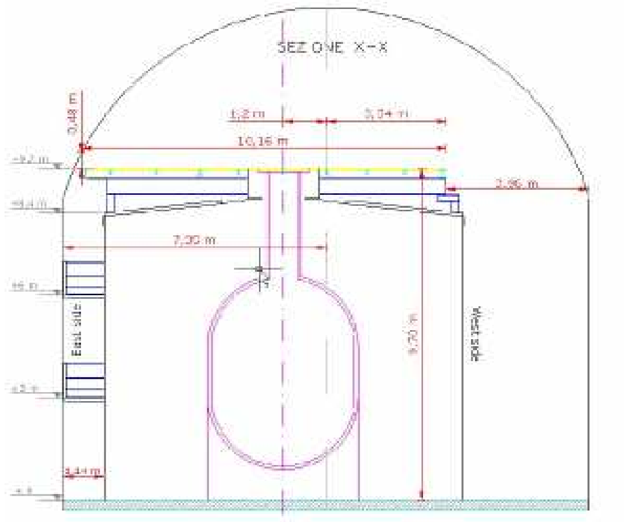


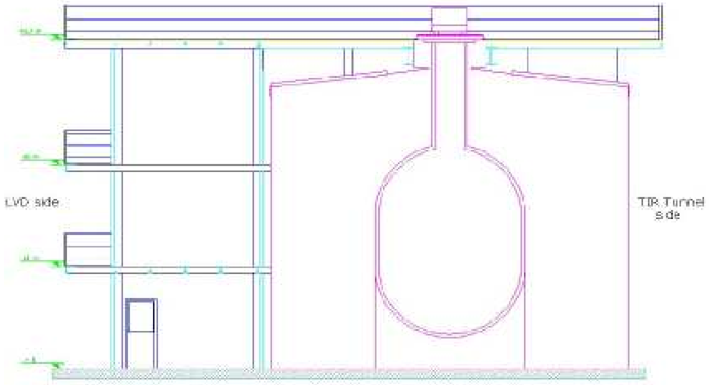

Underground detector laboratory (LArGe-facility)

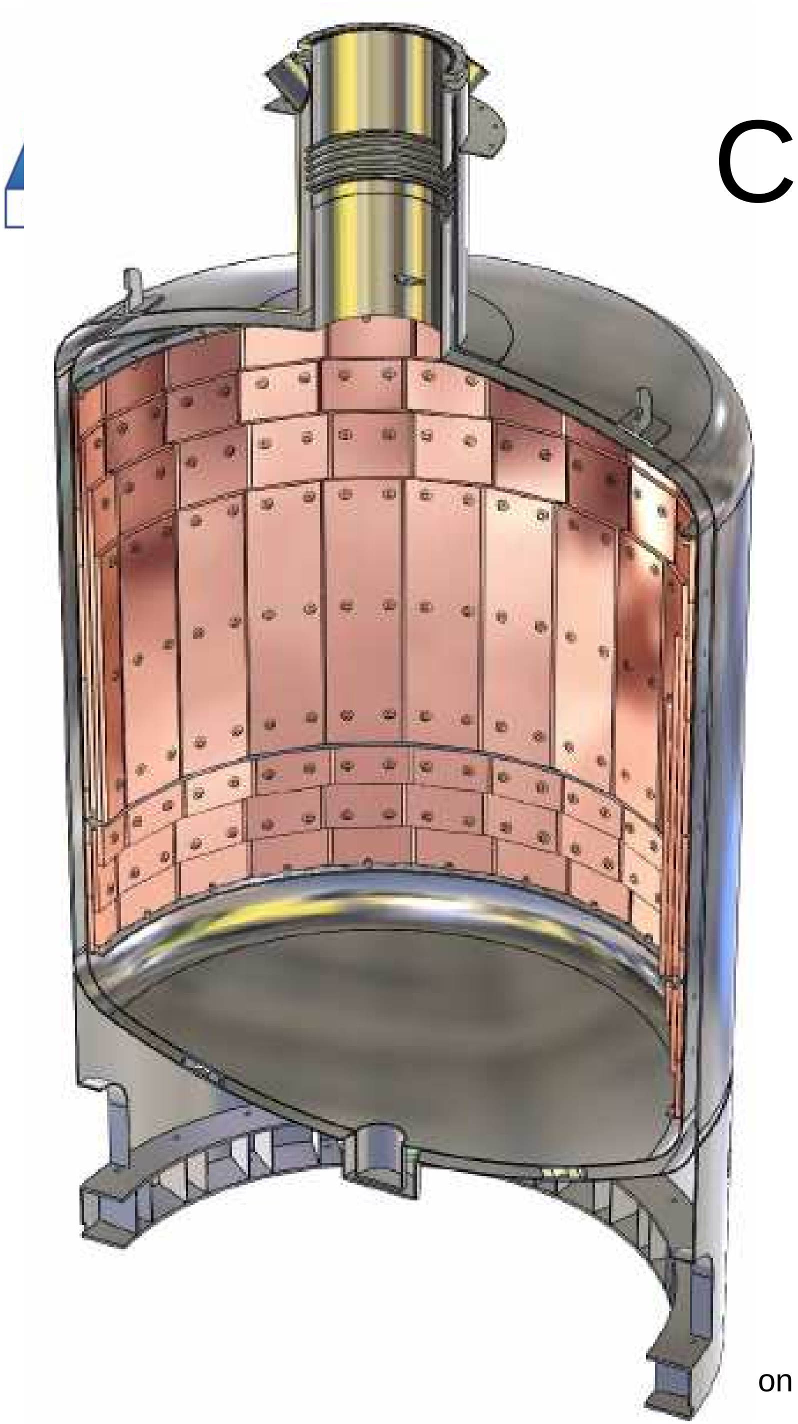
Main Experimental Site



June '06





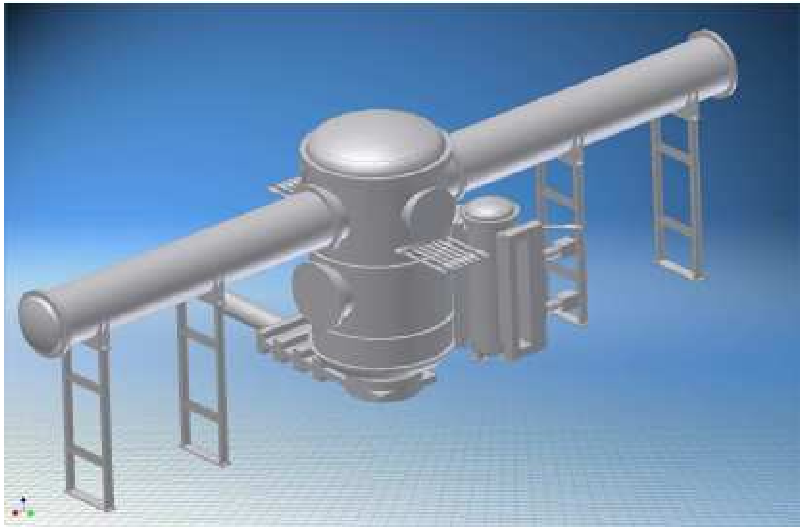


Cryostat

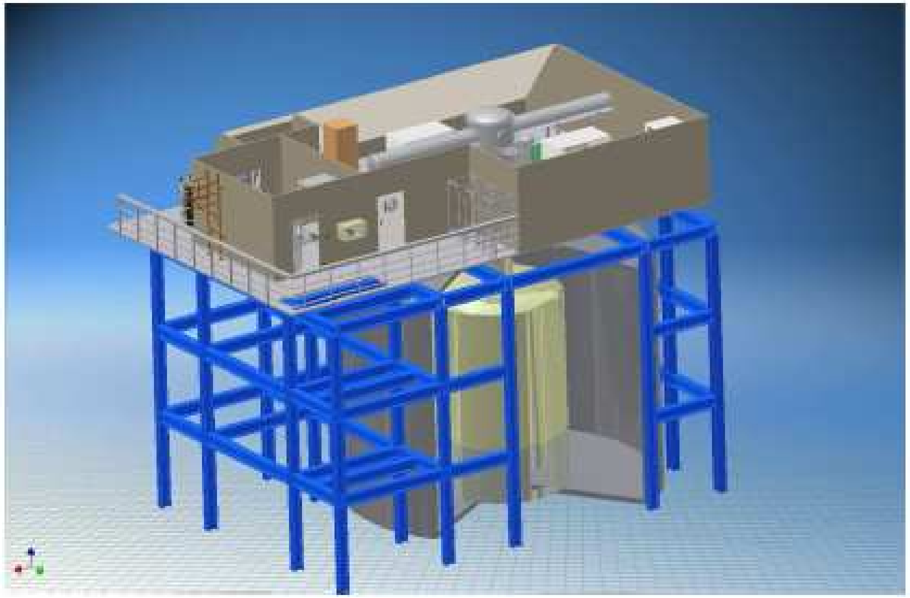
- Vacuum insulated stainless steel cryostat with internal Cu liner (stainless steel factor ~100 more radioactive (^{238}U, ^{232}Th) than Cu)
- Ø outer×height 4200×8900 [mm×mm]
- inner vessel volume 70 [m3]
- empty vessel 25,000 [kg]
- max. load inner vessel:
  - LAr 98,000 [kg]
  - Cu shield 20,000 [kg]

Infrastructure on Top of Platform

Lock with tubes for cabels



Clean room with lock on platform



Rail system to lower position and lower individual strings

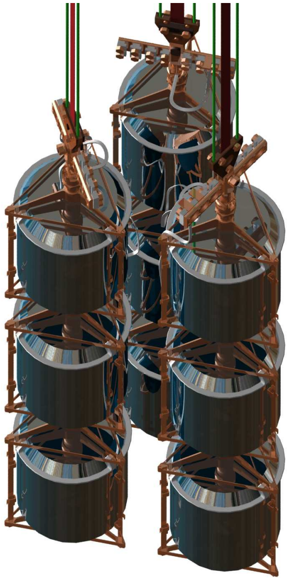
Phase I Detectors:

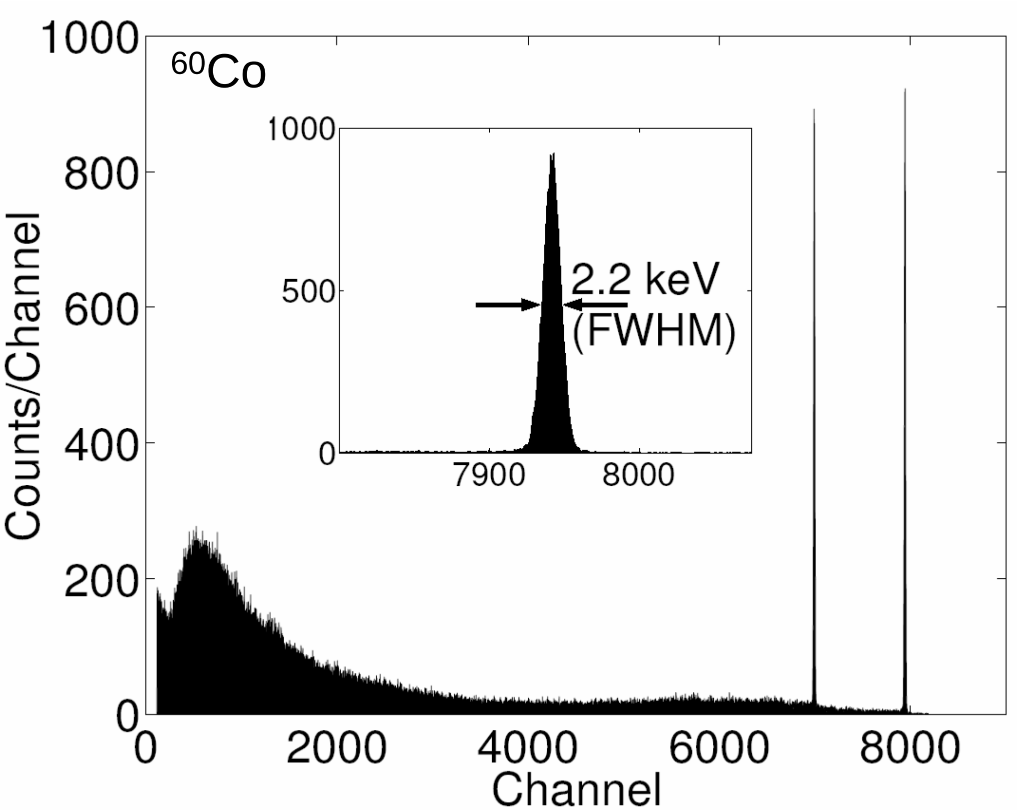
Maintenance and Measurements in Undergrond detector laboratory (LArGe facility)

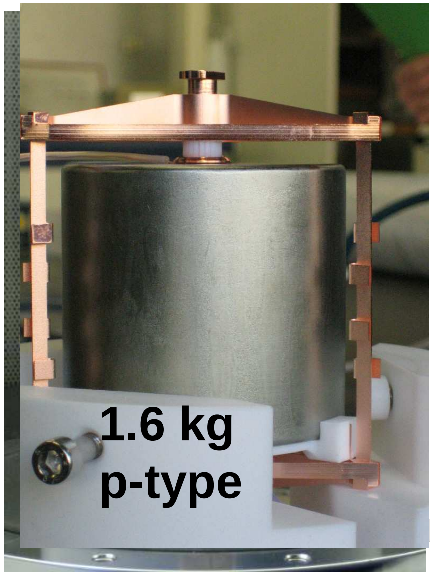
Since Nov. 2005: 17.9 kg of enriched Ge-detectors underground at LNGS; Characterization completed

Phase I Detectors:

Prototype tests of (natural) low-mass detector assembly in liquid nitrogen



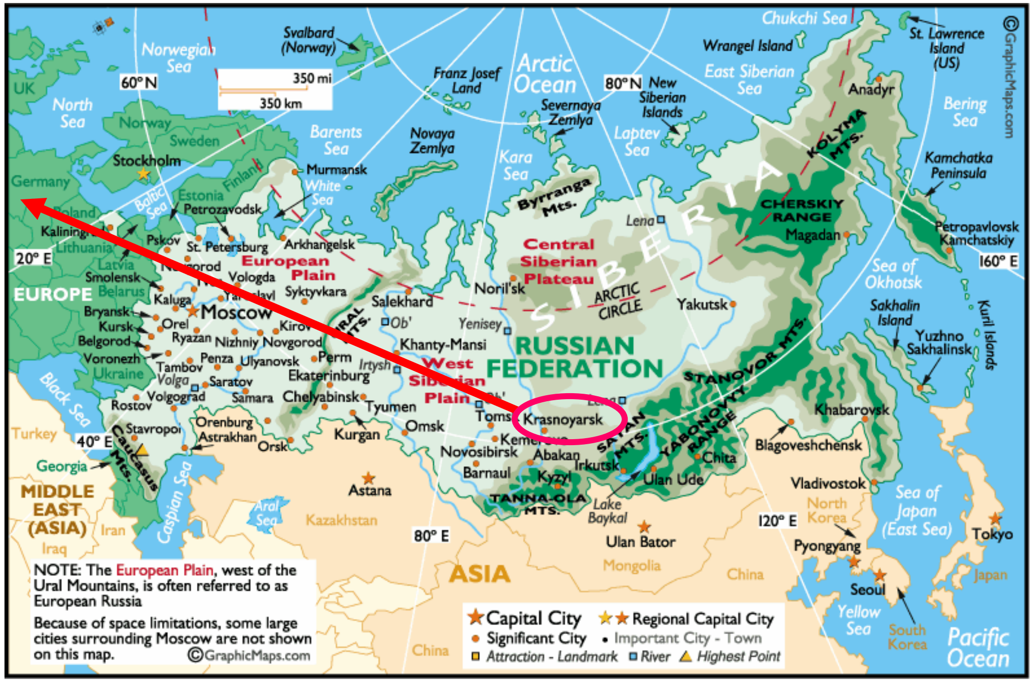




Enriched detectors are currently re-processed and prepared for testing

Phase II Detectors:

Procurement of enriched Ge



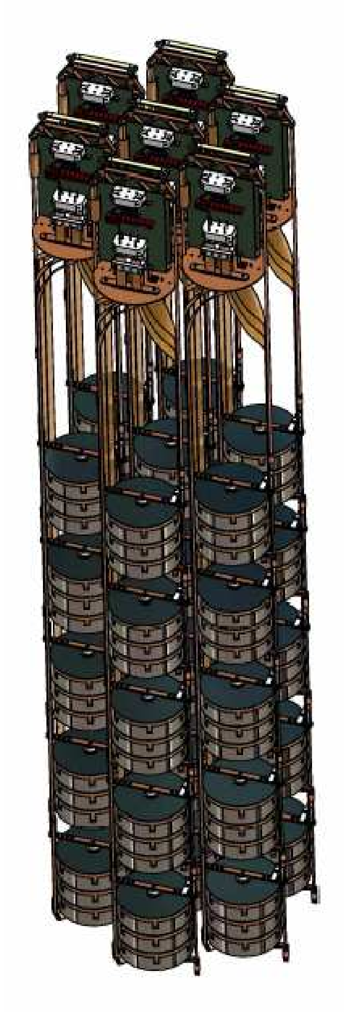
- Enrichment of 37.5 kg Ge-76 completed in Sep.05
- Transportation of Material to Europe by truck in spring for further processing
- Specially designed protective steel container reduces activation by cosmic rays by factor 20

Test transportation March 05

S. Schoenert, MPIK Heidelberg – Workshop on Precision Measurements at Low Energy, PSI, January 18/19 2007

Phase II Detectors:

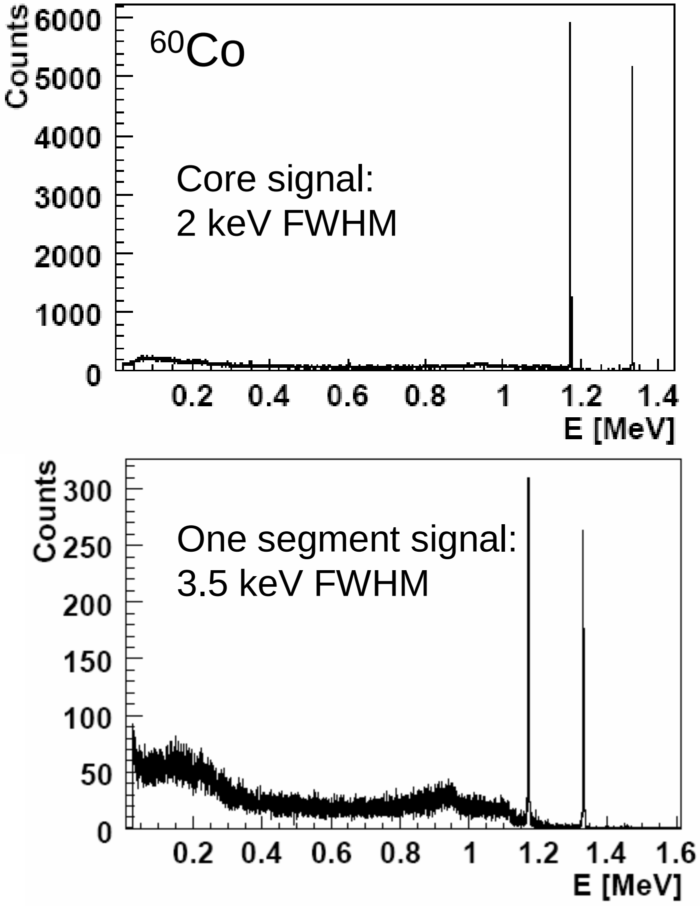
“True-coaxial” natural detectors



mock-up

- 6–fold–ϕ segmented p-type
- 18–fold (6-ϕ; 3-z) segmented n-type

18-fold segmented detector (in standard cryostat)



^{60}Co

Core signal:
2 keV FWHM

One segment signal:
3.5 keV FWHM

Backgrounds in GERDA

Source	**B [10^{-3} cts/(keV kg y))]**
Ext. γ from ^{208}Tl (^{232}Th)	<<1
Ext. neutrons	<0.05
Ext. muons (veto)	<0.03
Int. ^{68}Ge ($t_{1/2}$= 270 d)	**12**
Int. ^{60}Co ($t_{1/2}$= 5.27 y)	**2.5**
^{222}Rn in LN/LAr	<0.2
^{208}Tl, ^{238}U in holder	<1
Surface contam.	<0.6

derived from measurements and MC simulations

Muon veto

180 days exposure after enrichment + 180 days underground storage

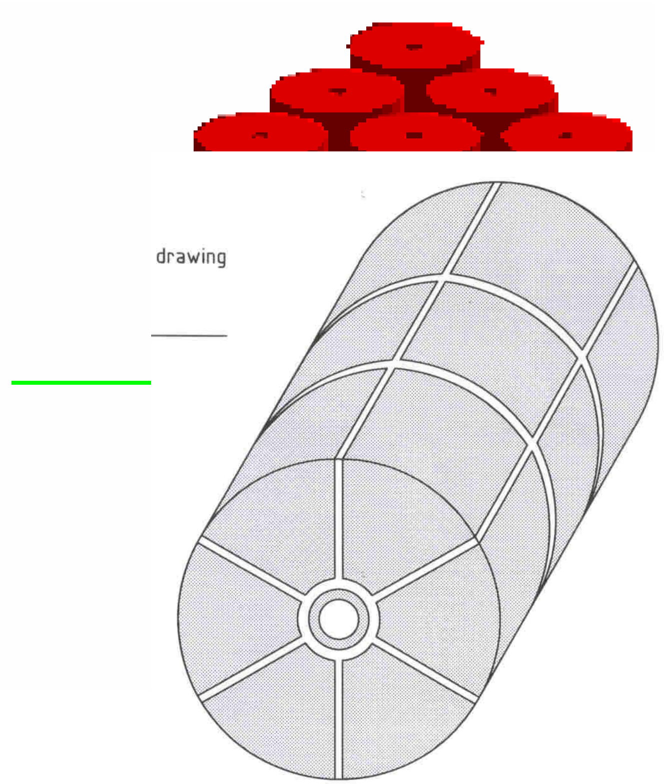
30 days exposure after crystal growing

Target for phase II: Σ B $\leq 10^{-3}$ cts/(keV kg y)

$\Rightarrow$ additional bgd. reduction techniques

Background reduction techniques

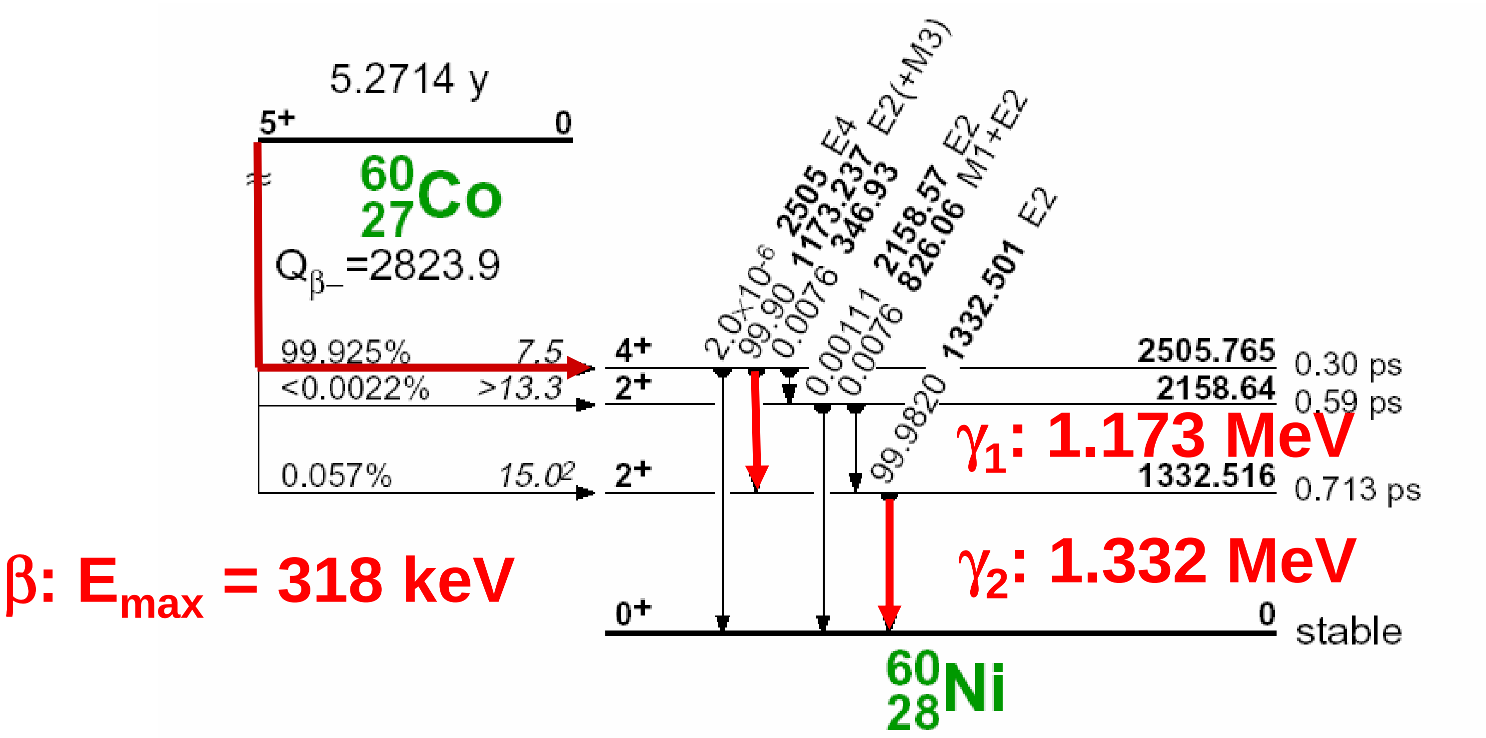
- Muon veto
- Anti-coincidence between detectors
- Segmentation of readou
  (Phase II)
- Pulse shape analysis (P
- Coincidence in decay ch
- Scintillation light detecti



Background reduction techniques

- Muon veto
- Anti-coincidence between detectors
- Segmentation of readout electrodes (Phase II)
- Pulse shape analysis (Phase I+II)
- Coincidence in decay chain (Ge-68)
- Scintillation light detection (LArGe)

Example: Internal ^{60}Co



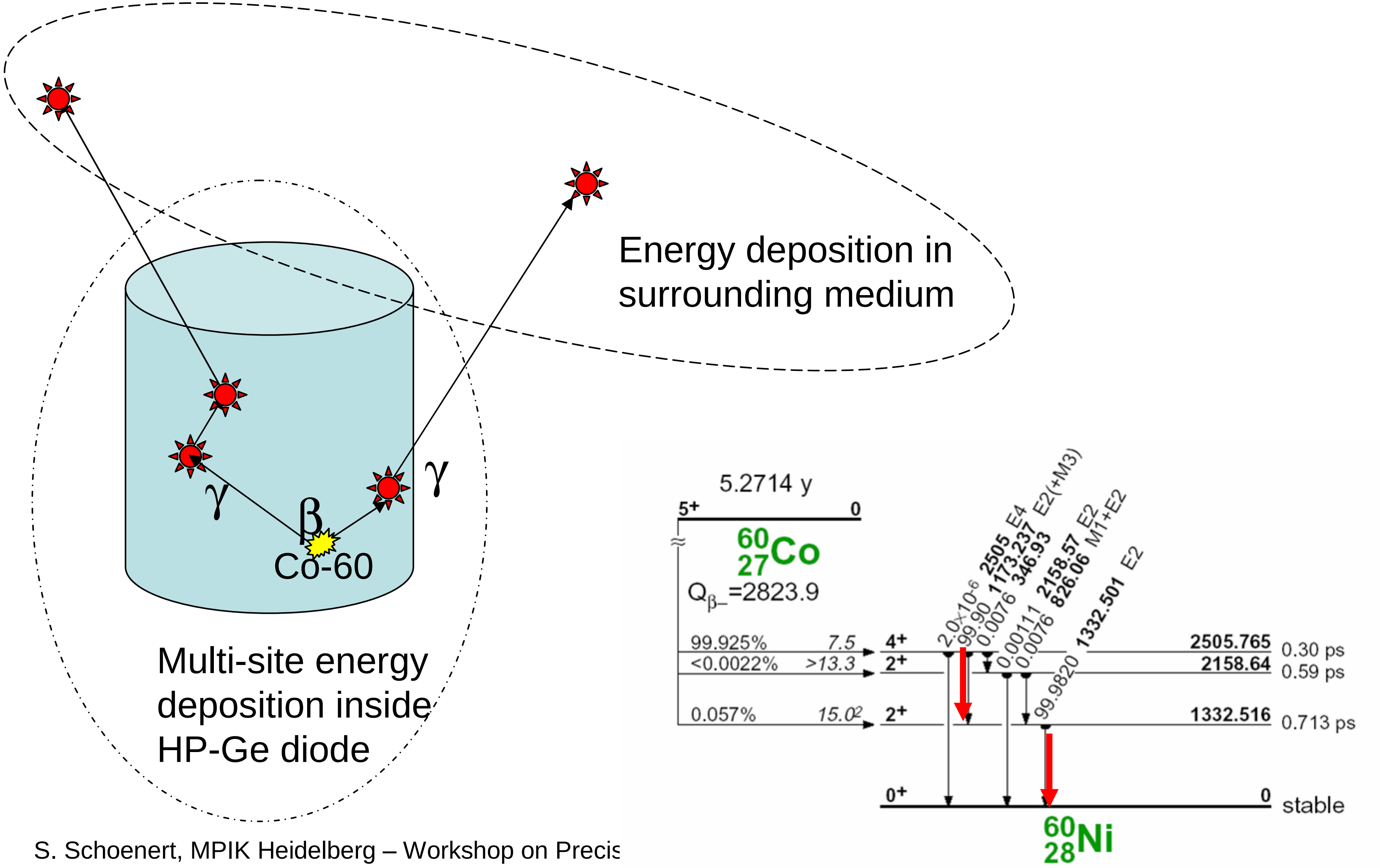
β: E_{max} = 318 keV

γ_1: 1.173 MeV

γ_2: 1.332 MeV

- T_0 : crystal growing
- 0.017 µBq/kg per day exposure
- Test: detector production in 7.4 days
- Assume 30 days $\Rightarrow$ 2.5 ·10^{-3} / (keV·kg·y)

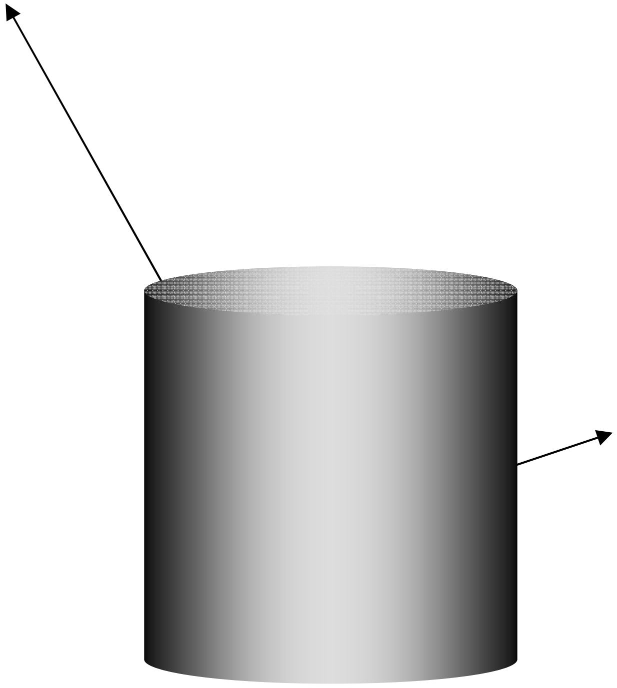
Example of background topology

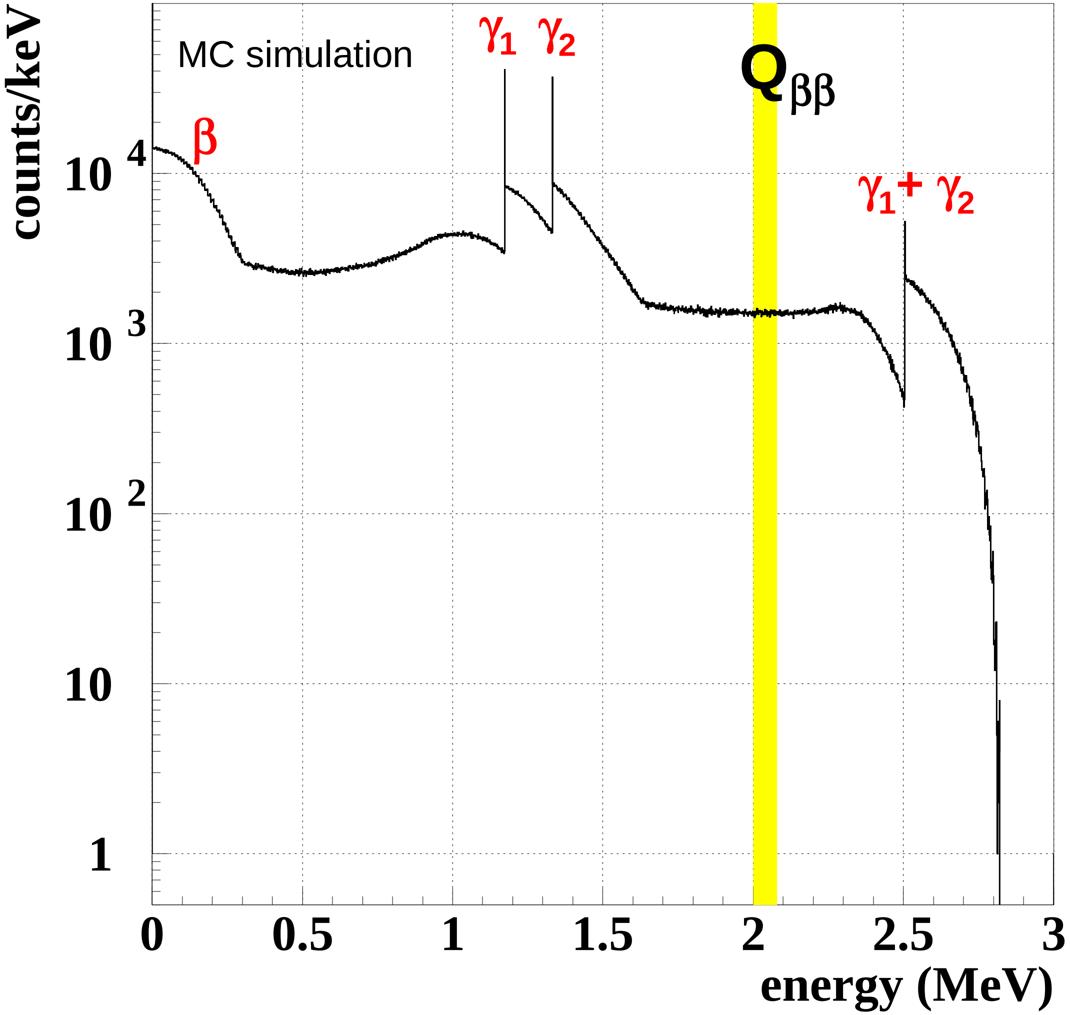


Energy deposition in surrounding medium

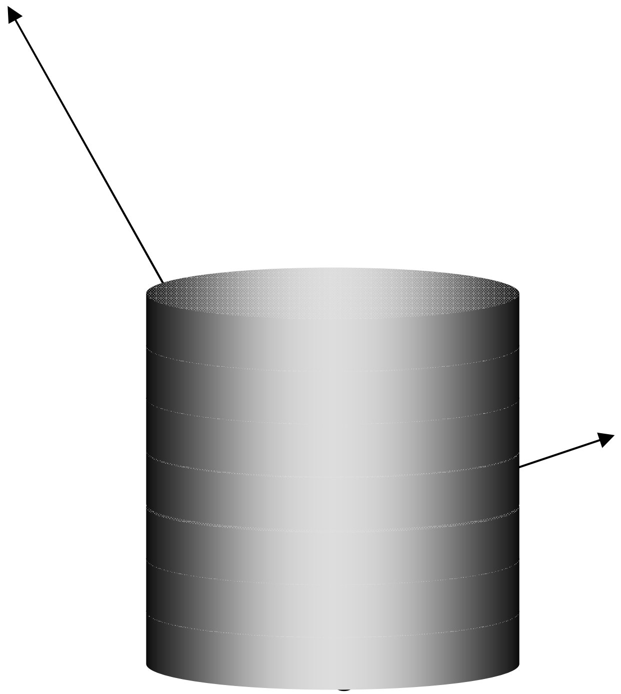
Multi-site energy deposition inside HP-Ge diode

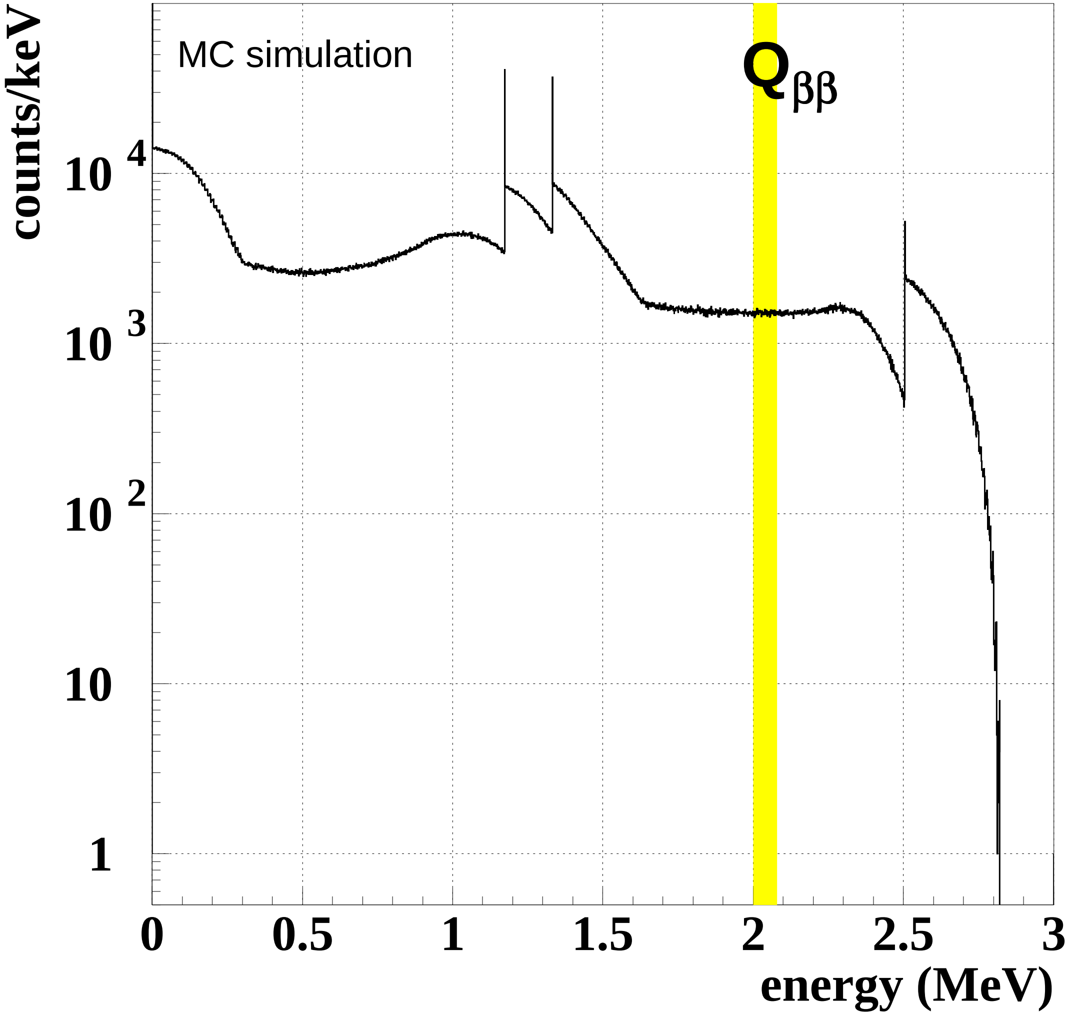
^{60}Co background spectrum





^{60}Co: suppression by segmentation





^{60}Co: suppression by segmentation

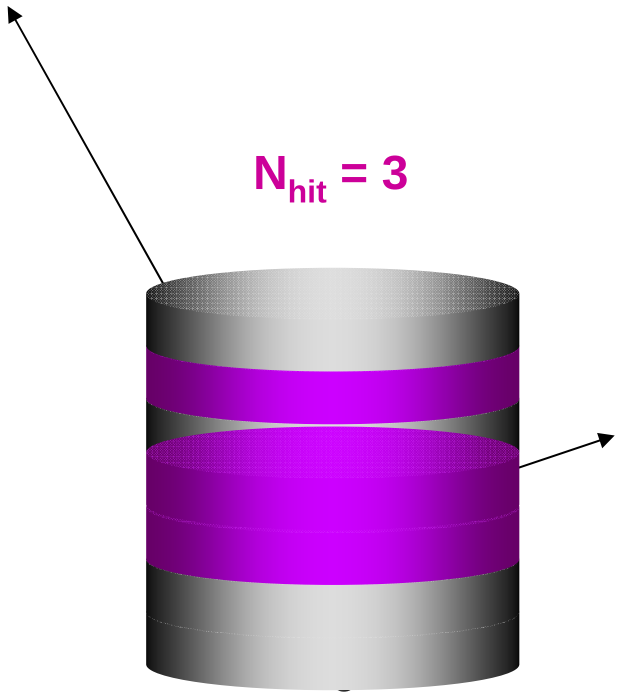
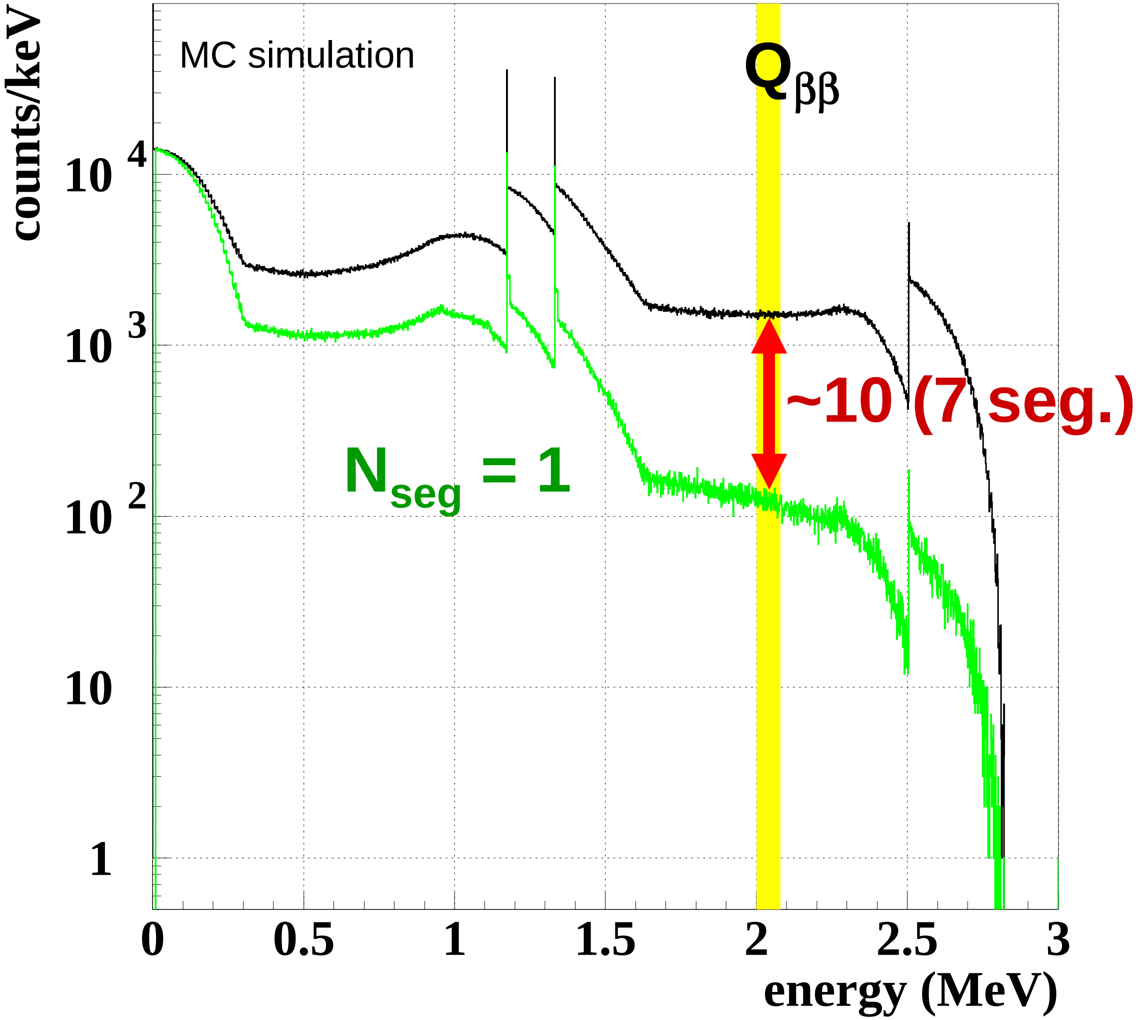
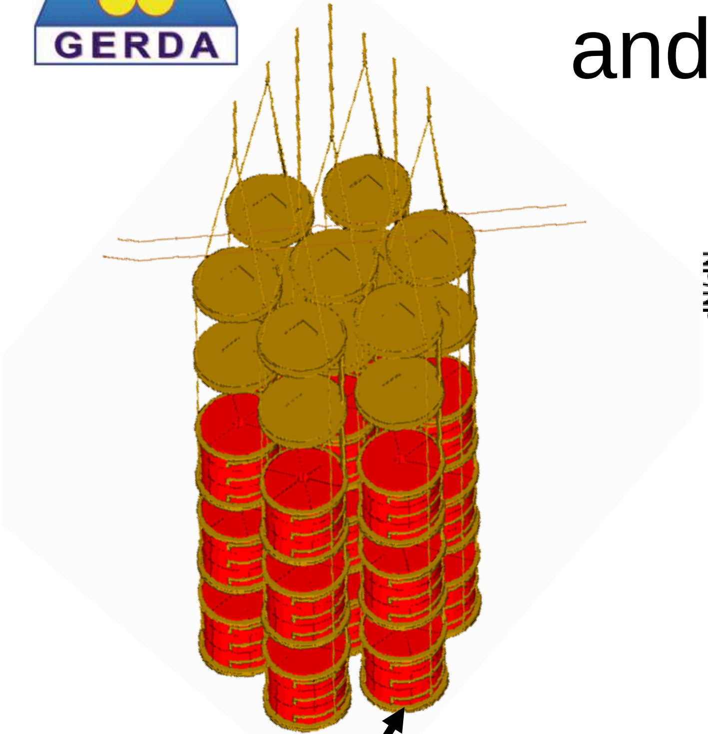
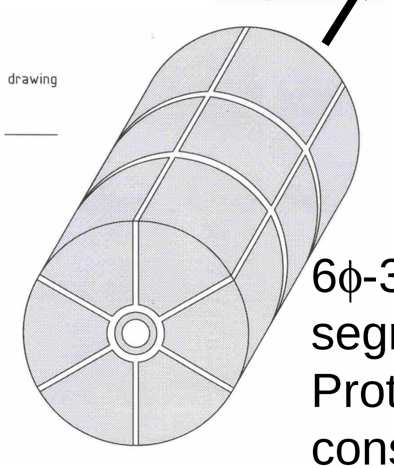


illustration:
Simple 7-fold segmentation



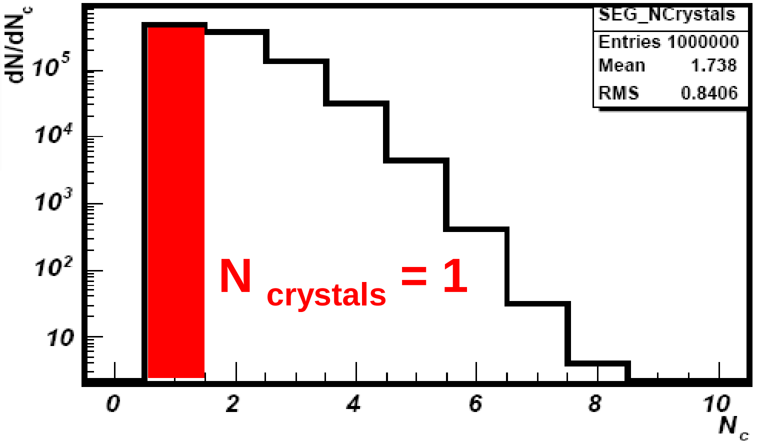
MaGe: ^{60}Co suppression by segmentation and anti-coincidence



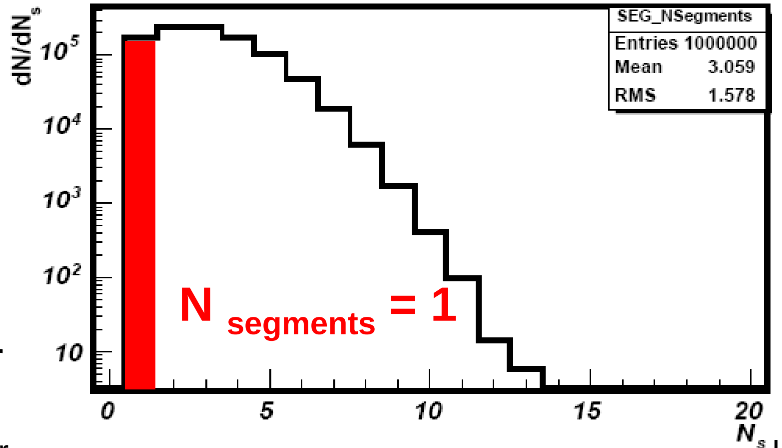


6ϕ-3z segmentation; Prototype under construction

Number of crystals



Number of segments



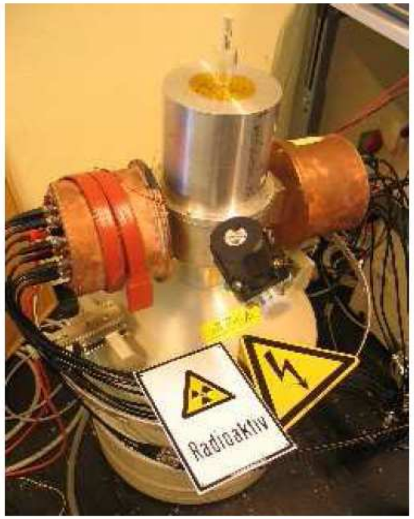
probability per decay to deposit energy within $Q_{\beta\beta}$ ROI per 1 keV energy bin after combined cuts: (18-fold segm.)

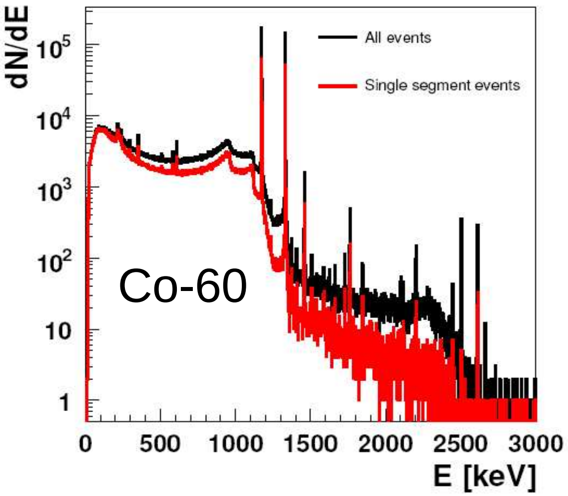
$P = 4.7 \cdot 10^{-6}$/keV

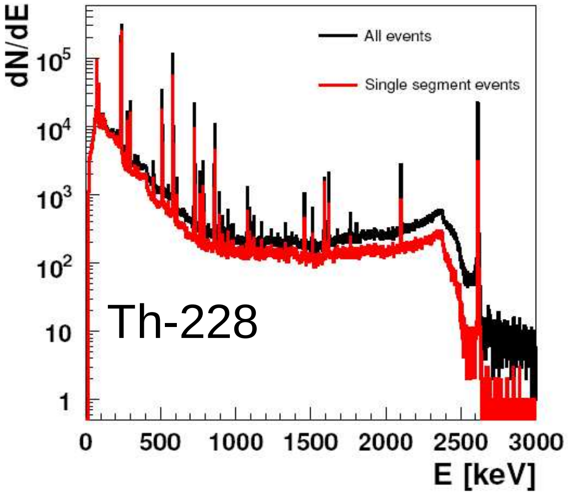
(factor ~35 reduction w/r to single unseg. detector)

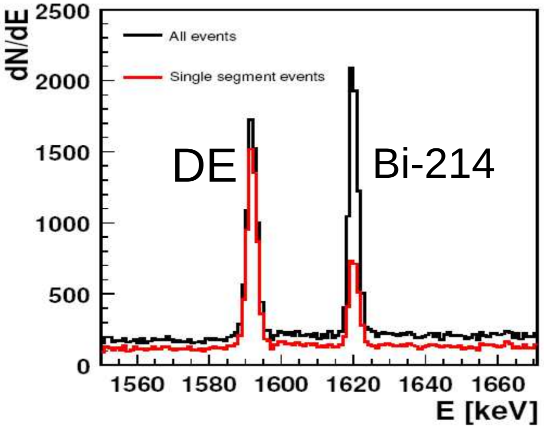
Phase II detectors

1.6 kg 18-fold segmented true-coaxial n-type





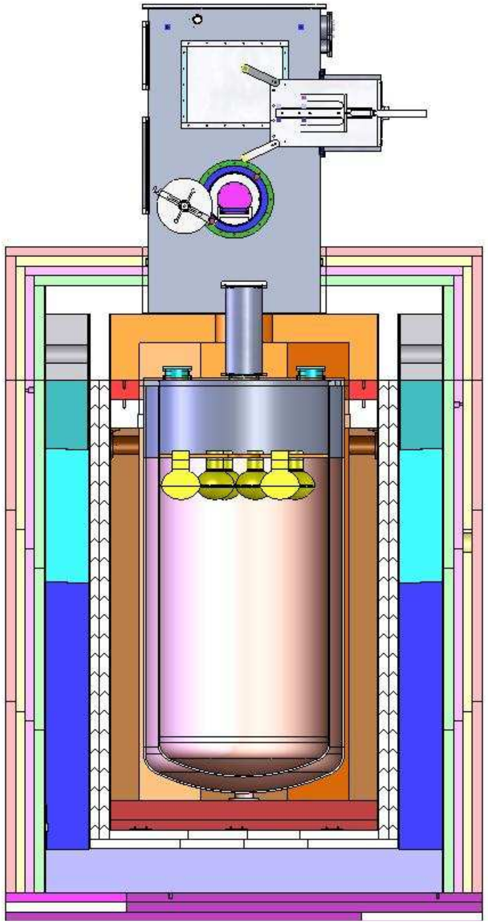




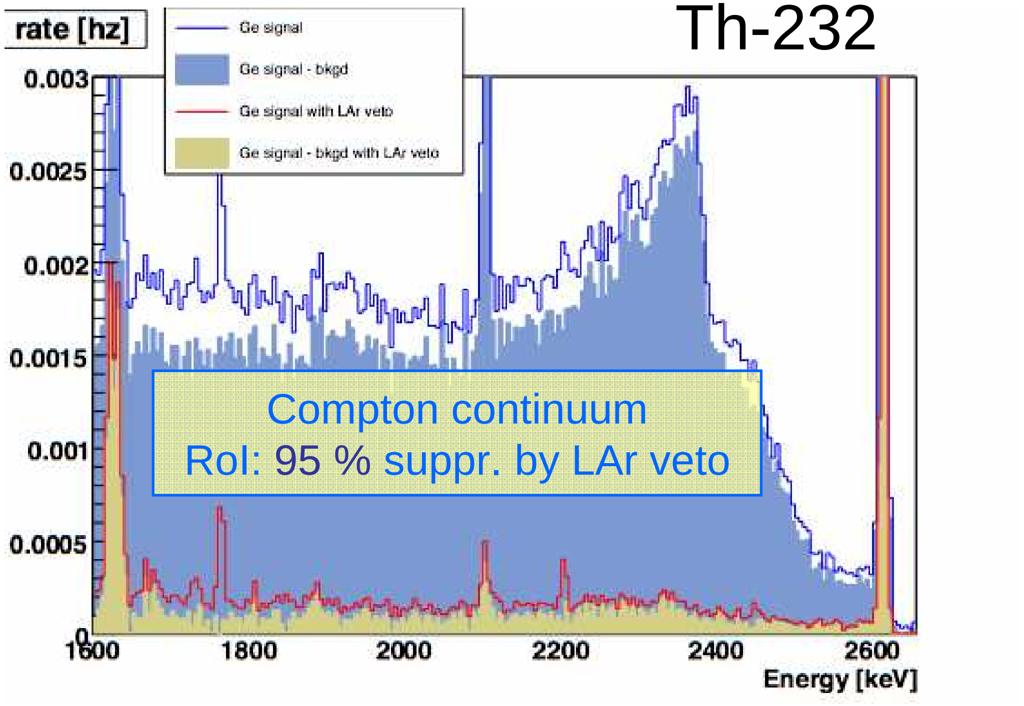
Goal:

- Study of γ identification and suppression factors at $Q_{\beta\beta}$: 2 -100 depending on source location

^{232}Th suppression by LAr Ge-anticoinc: (20 cm diameter prototype setup)



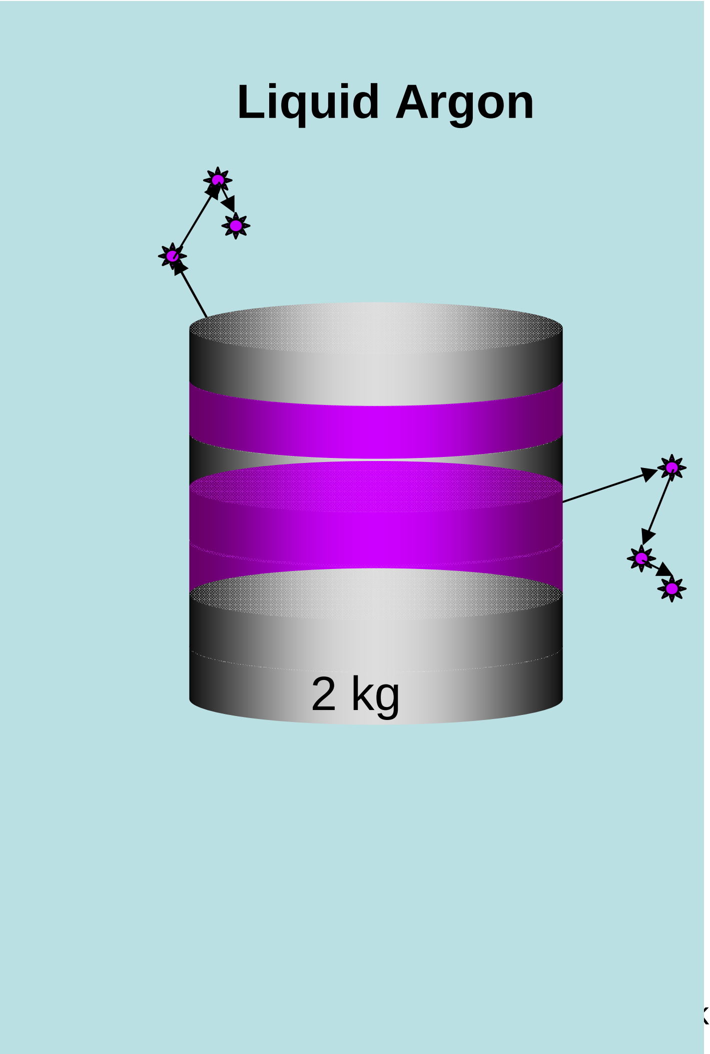
1 ton liquid argon detector under construction

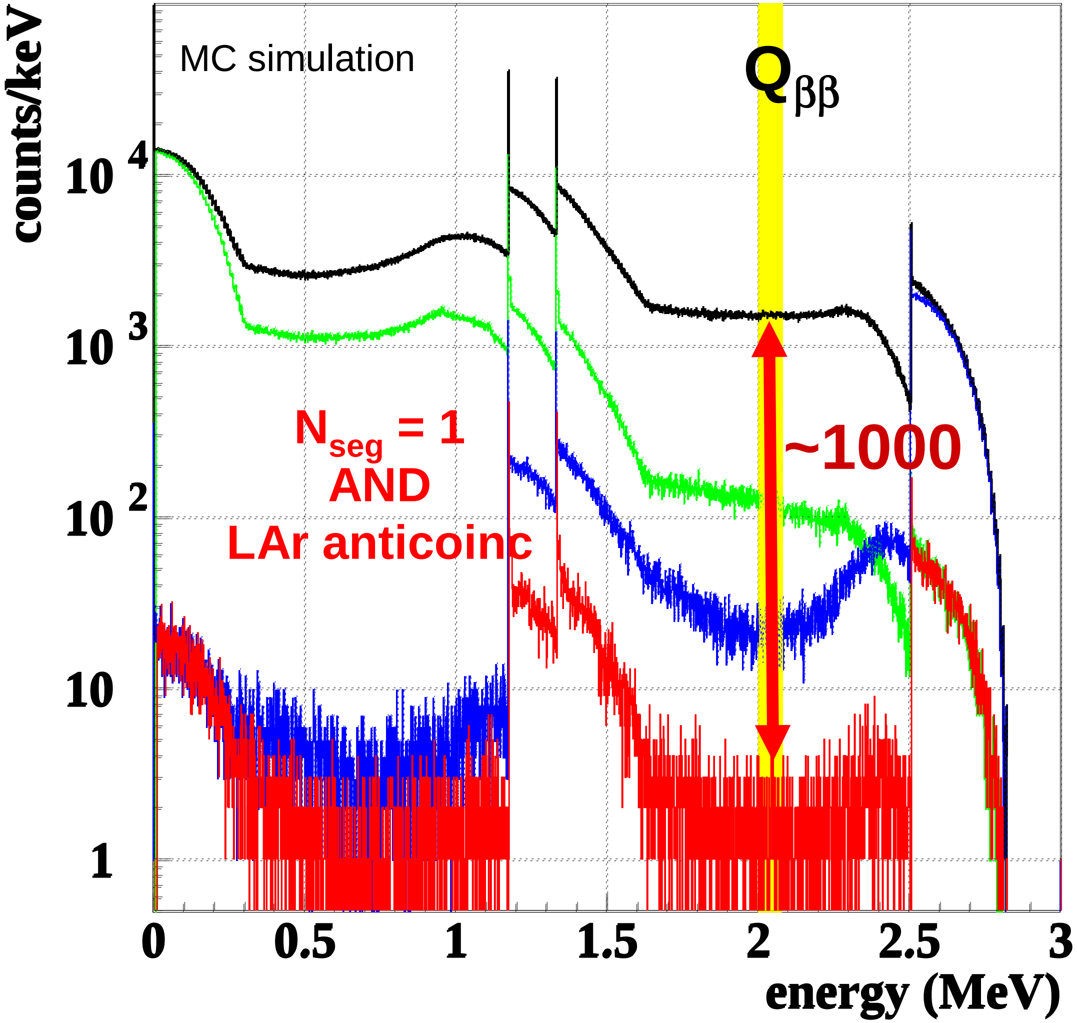


Compton continuum
RoI: 95 % suppr. by LAr veto

Suppression limited by size of Dewar (20 cm Ø)

^{60}Co: segmentation and LAr Ge-anticoinc

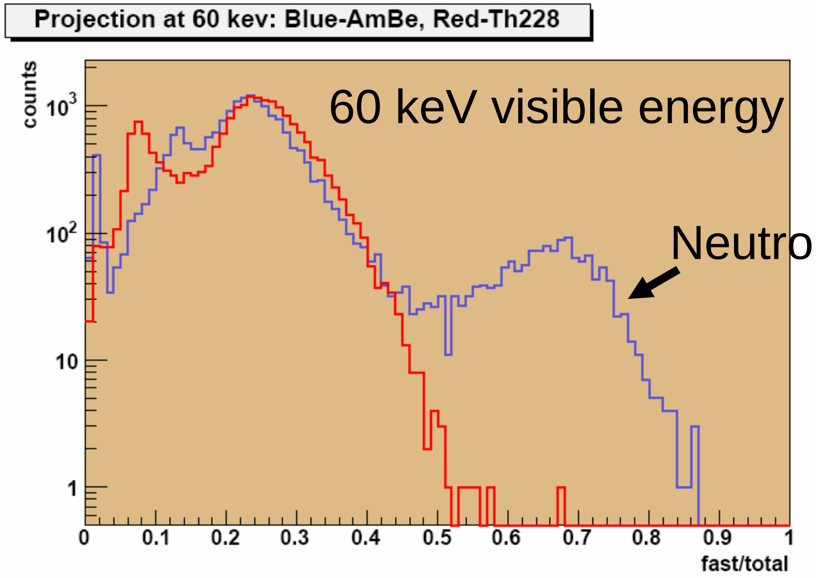




Off-spin of GERDA LAr R&D for DM search

Pulse shape discrimination studies

Data with AmBe n/γ source



60 keV visible energy

Neutron recoils

20 kg active LAr target

Liquid Argon for DM Search
(WARP, ArDM, CLEAN)

Discrimination of Ar-39 background?

Summary & Outlook

- GERDA: probe Majorana nature of neutrino with sensitivity down to inverse mass hierarchy scale
  - **phase I :** background 0.01 cts / (kg·keV·y)
  - ► scrutinize KKDC result within 1 year
  - **phase II :** background 0.001 cts / (kg·keV·y)
  - ► $T_{1/2} > 2 \cdot 10^{26}$ y , $\langle m_{ee} \rangle < 0.09 – 0.29$ eV
  - **phase III :** world wide collaboration
  - ► $T_{1/2} > \sim 10^{28}$ y , $\langle m_{ee} \rangle \sim 10$ meV
- 2007: Experimental installations (Cryotank, water tank, building etc.)
- 2008: target for detector readiness

GERDA collaboration