The GERDA neutrino-less double beta decay experiment

Stefan Schönert, MPIK Heidelberg
for the GERDA collaboration

H. Aghaei[m], M. Agostini[f], M. Allardt[c], A.M. Bakalyarov[l], M. Balata[a], I. Barabanov[j], M. Barnabe-Heider[f], L. Baudis[q], C. Bauer[f], N. Becerici-Schmid[m], E. Bellotti[g,h], S. Belogurov[k,j], S.T. Belyaev[l], A. Bettini[n,o], L. Bezrukov[j], V. Brudanin[d], R. Brugnera[n,o], D. Budjas[f], A. Caldwell[m], C. Cattadori[g,h], F. Cossavella[m], E.V. Demidova[k], A. Denisiv[j], A. Di Vacri[a], A. Domula[c], A. D'Andragora[a], V. Egorov[d], A. Ferella[q], K. Freund[p], F. Froborg[q], N. Frodyma[b], A. Gangapshev[j], A. Garfagnini[n,o], S. Gazzana[f,a], R. Gonzalea de Orduna[e], P. Grabmayr[p], K.N. Gusev[l,d], V. Gutentsov[j], W. Hampel[f], M. Heisel[f], S. Hemmer[m], G. Heusser[f], W. Hofmann[f], M. Hult[e], L. Iannucci[a]. L.V. Inzhechik[j], J. Janicsko[m], J. Jochum[p], M. Junker[a], S. Kionanovsky[j], I.V. Kirpichnikov[k], A. Klimenko[d,j], M. Knapp[p], K-T. Knoepfle[f], O. Kochetov[d], V.N. Kornoukhov[k,j], V. Kusminov[j], M. Laubenstein[a], V.I. Lebedev[l], B. Lehnert[c], D. Lenz[m], S. Lindemann[f], M. Lindner[f], I. Lippi[o], X. Liu[m], B. Lubsandorzhiev[j], B. Majorovits[m], G. Meierhofer[p], I. Nemchenok[d], L. Pandola[a], K. Pelczar[b], F. Potenza[a], A. Pullia[i], S. Riboldi[i], F. Ritter[p], C. Rossi Alvarez[o], R. Santorelli[q], J. Schreiner[f], B. Schwingenheuer[f], S. Sch”onert[f], M. Shirchenko[l,d], H. Simgen[f], A. Smolnikov[d,j], L. Stanco[o], F. Stelzer[m], M. Tarka[q], A.V. Tikhomirov[l], C.A. Ur[o], A.A. Vasenko[k], A. Vauth[m], O. Volynets[m], M. Weber[f], M. Wojcik[b], E. Yanovich[j], S.V. Zhukov[l], D. Zinatulina[d], F. Zocca[i], K. Zuber[c], G. Zuzel[b],

[a]) INFN Laboratori Nazionali del Gran Sasso, LNGS, Assergi, Italy
[b]) Institute of Physics, Jagellonian University, Cracow, Poland
[c]) Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
[d]) Joint Institute for Nuclear Research, Dubna, Russia
[e]) Institute for Reference Materials and Measurements, Geel, Belgium
[f]) Max Planck Institut für Kernphysik, Heidelberg, Germany
[g]) Dipartimento di Fisica, Università Milano Bicocca, Milano, Italy
[h]) INFN Milano Bicocca, Milano, Italy
[i]) Dipartimento di Fisica, Università degli Studi di Milano e INFN Milano, Milano, Italy
[j]) Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
[k]) Institute for Theoretical and Experimental Physics, Moscow, Russia
[l]) Russian Research Center Kurchatov Institute, Moscow, Russia
[m]) Max-Planck-Institut für Physik, München, Germany
[n]) Dipartimento di Fisica dell'Università di Padova, Padova, Italy
[o]) INFN Padova, Padova, Italy
[p]) Physikalisches Institut, Eberhard Karls Universität Tübingen, Tübingen, Germany
[q]) Physik Institut der Universität Zürich, Zürich, Switzerland

~ 100 members
17 institutions
6 countries

GERDA

GERDA Collaboration Meeting

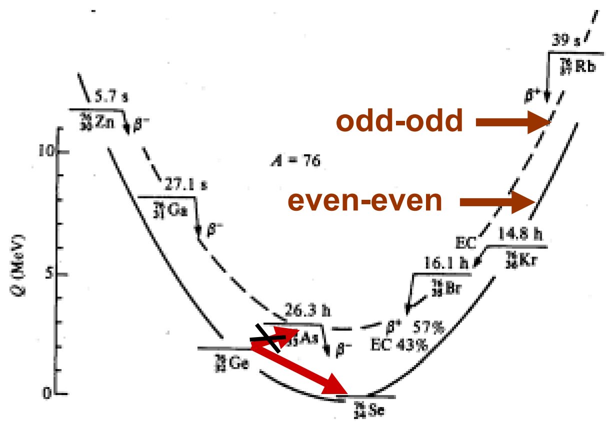
Jagiellonian University in Kraków, 18th-20th February 2008

Uniwersytet Jagielloński w Krakowie

Outline

- The physics goals: brief introduction to neutrino-less DBD
- Characteristics of Ge-76 and sensitivity
- The experimental concept
- Background suppression techniques
- GERDA installations underground at LNGS
- Selected GERDA R&D topics
- Outlook

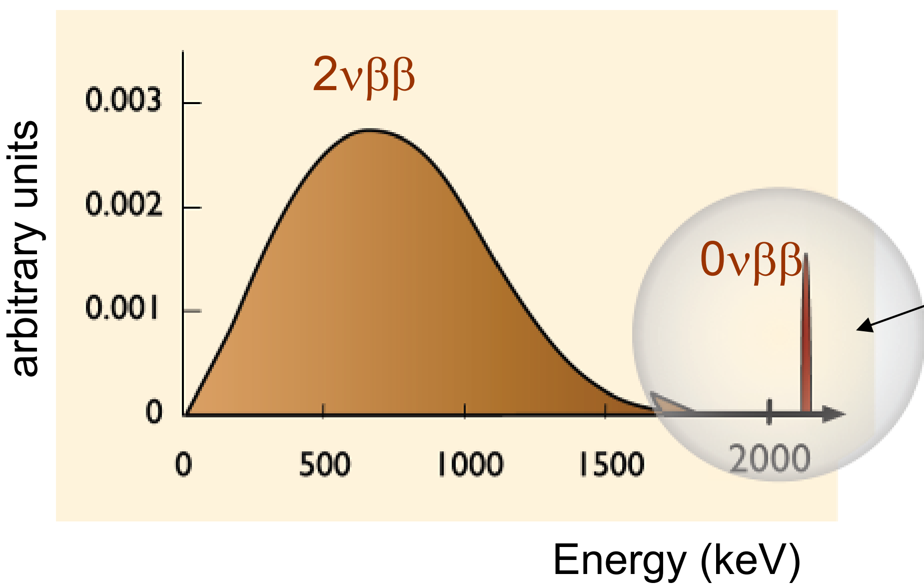
0ν- and 2νββ decay



2νββ: (A,Z) → (A,Z+2) + 2e⁻ + 2 $\bar{\nu}_e$ **ΔL=0**

$$T_{1/2}^{2\nu} = (10^{18} - 10^{21})\,\mathrm{y}$$

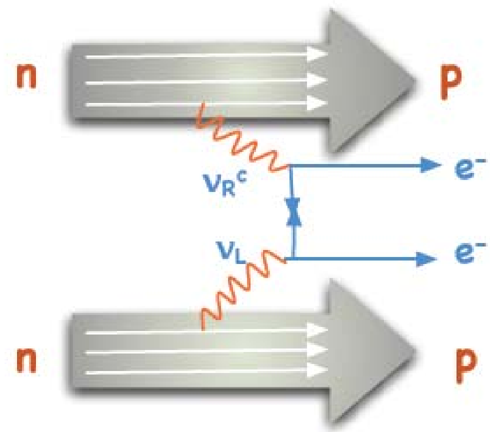
0νββ: (A,Z) → (A,Z+2) + 2e⁻ **ΔL=2**



<u>Experimental signatures:</u>

- peak at $Q_{\beta\beta} = E_{e1} + E_{e2} - 2m_e$
- two electrons from vertex
- production of grand-daughter isotope

Decay rate and effective neutrino mass



Assume leading term is exchange of light Majorana neutrinos

Expected decay rate:

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

Phase space integral

Nuclear matrix element

$$Q = E_{e1} + E_{e2} - 2m_e$$ Q-value of decay

$$\left\langle m_{ee} \right\rangle = \left| \sum_i U_{ei}^2\, m_i \right|$$ Effective neutrino mass

U_{ei} (complex) neutrino mixing matrix

0νββ: physics implications

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

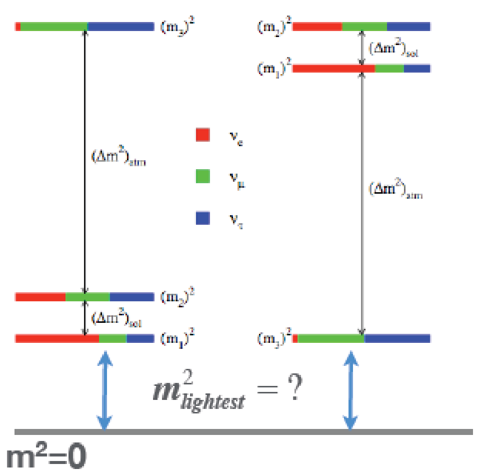
- 0νββ ⇒ Majorana nature
- Majorana ⇒ See-Saw mechanism $m_\nu = \frac{m_D^2}{M_R} << m_D$

$$m_3 \sim \left(\Delta m^2_{atm}\right)^{1/2},\ m_D \sim m_t \Rightarrow M_R \sim 10^{15}\,GeV$$

- Majorana ⇒ CP violation in M_R → higgs + lepton
  ⇒ Leptogenesis ⇒ B asymmetry

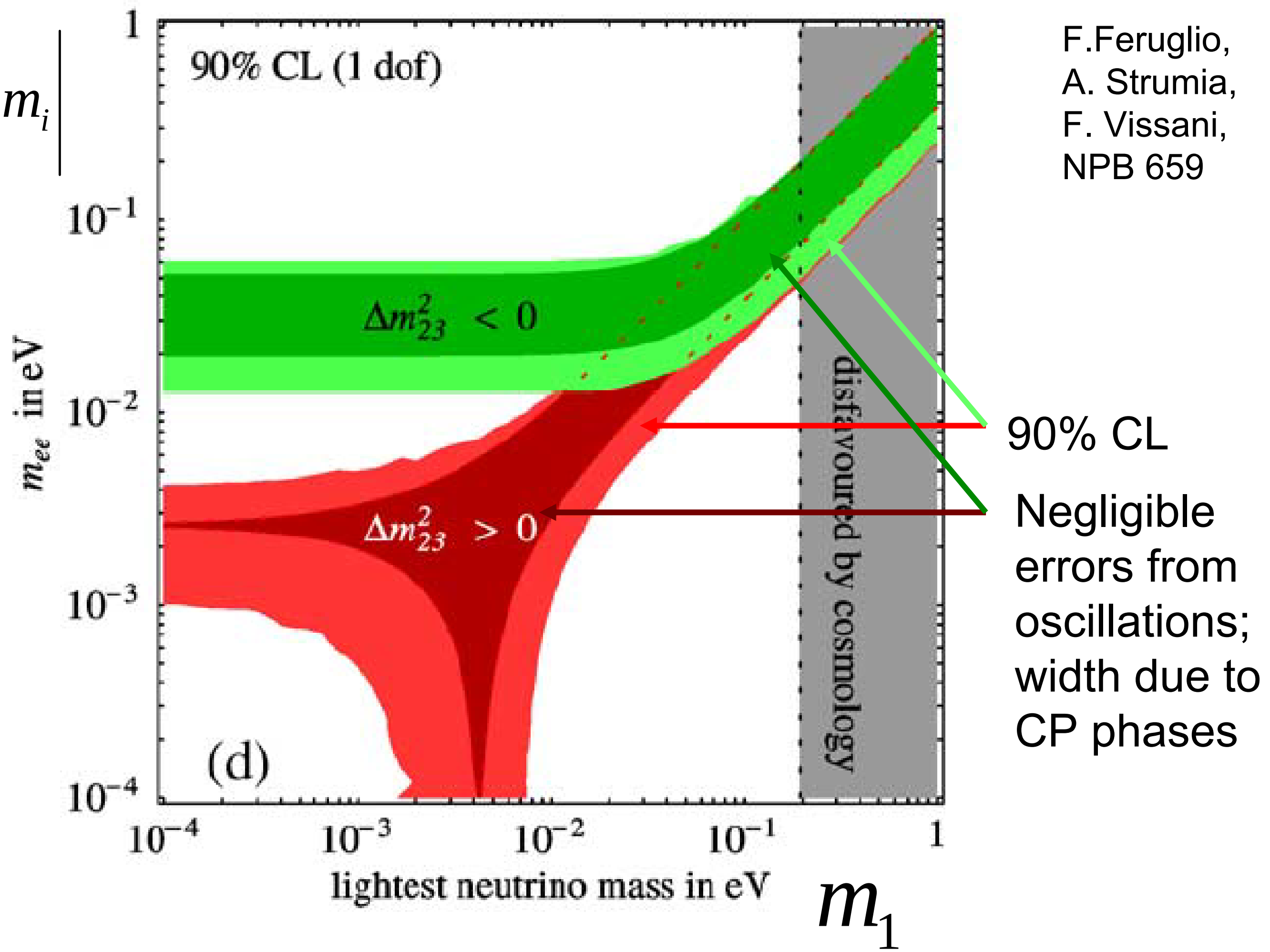
2) Absolute mass scale:

- Hierarchy: degenerate, inverted or normal
- (effective) neutrino mass



Predictions from oscillation experiments

$$\langle m_{ee} \rangle = \left| \sum_i U_{ei}^2 m_i \right|$$

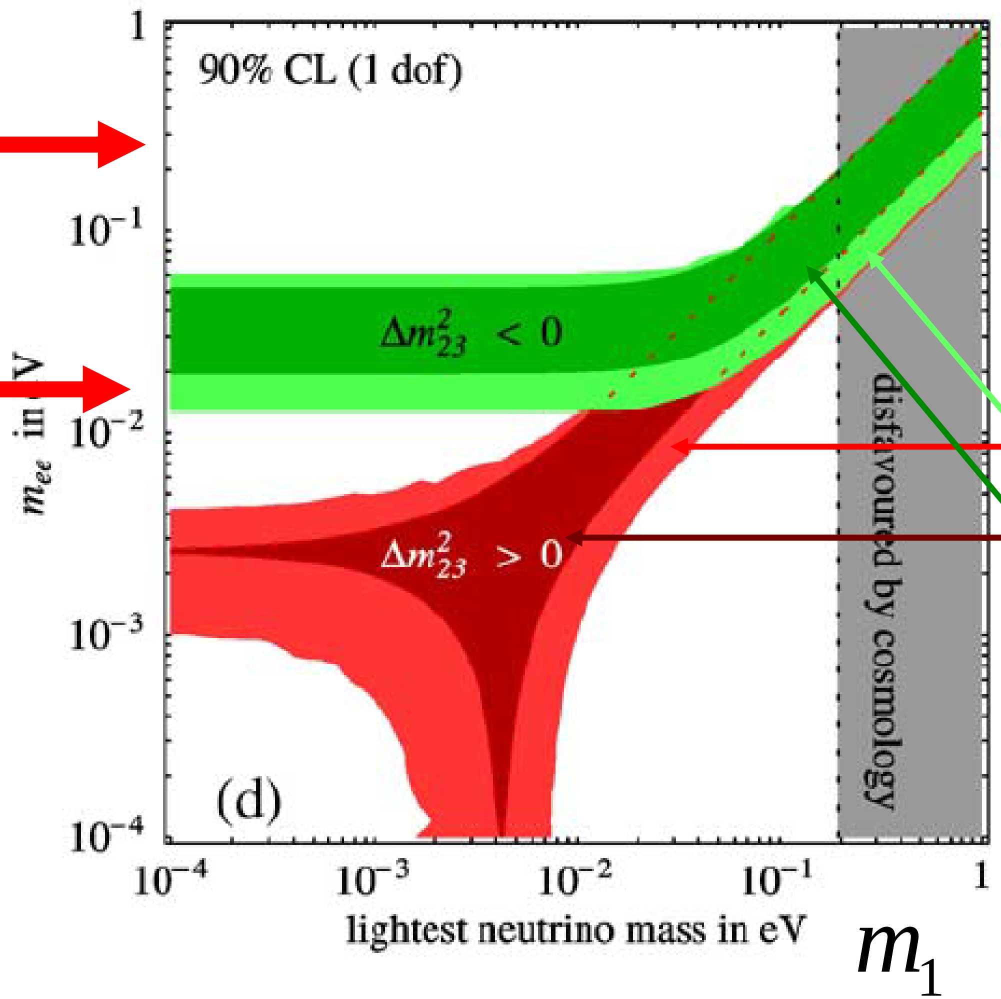


F.Feruglio,
A. Strumia,
F. Vissani,
NPB 659

Predictions from oscillation experiments

KDKC claim:
[0.17-0.45] eV
(PRD79)

Goal of next generation experiments:
~10 meV



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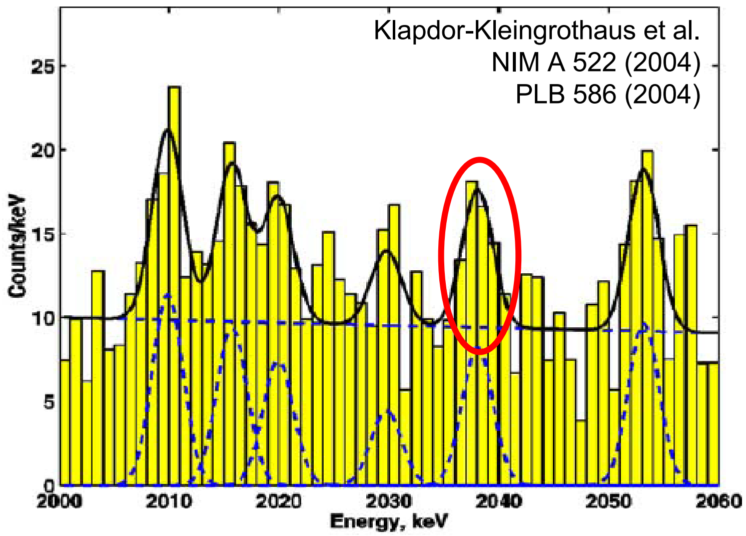
90% CL

Negligible errors from oscillations; width due to CP phases

Characteristics of ^{76}Ge for $0\nu\beta\beta$ search

- Favorable nuclear matrix element $|M^{0\nu}|=3 - 9$
- Reasonable slow $2\nu\beta\beta$ rate ($T_{1/2} = 1.4 \times 10^{21}$ y) and high $Q_{\beta\beta}$ value (2039 keV)
- Ge as source and detector
- Elemental Ge maximizes the source-to-total mass ratio
- Industrial techniques and facilities available to enrich from 7% to ~88%
- Intrinsic high-purity Ge diodes
- HP-Ge detector technologies well established
- Excellent energy resolution: FWHM ~3 keV at 2039 keV (0.16%)
- Powerful signal identification & background rejection possible with novel detector concepts: time structure of charge signal (PSA), granularity (segmentation & close packing), liquid argon scintillation
- Best limits on $0\nu\beta\beta$ - decay used Ge (IGEX & Heidelberg-Moscow) $T_{1/2} > 1.9 \times 10^{25}$ y (90%CL) [& claim for evidence]

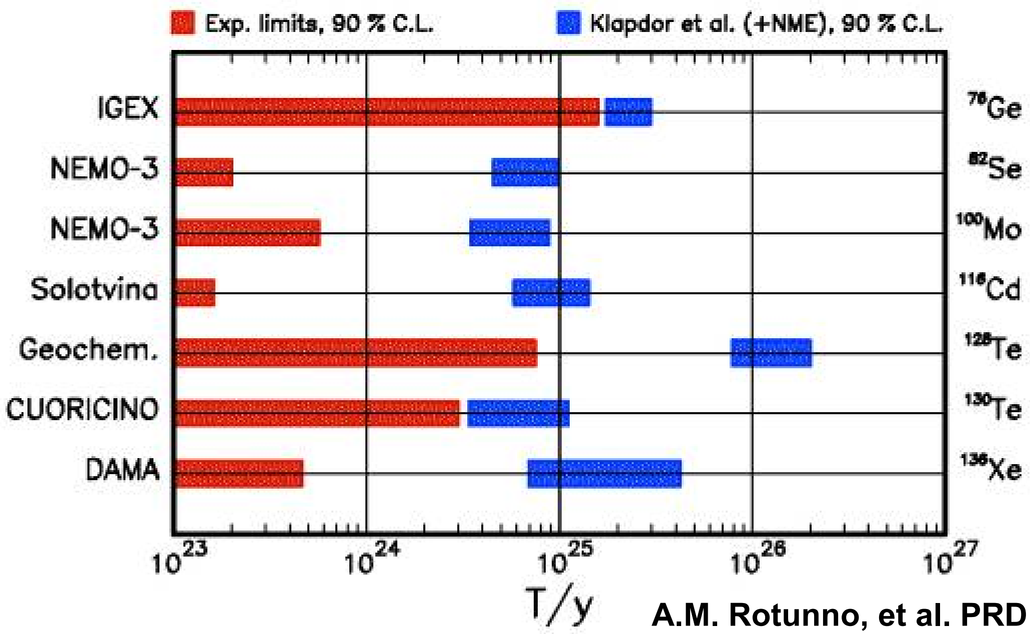
State-of-the-art: limits & claim



- 71.7 kg year - Bgd 0.11 / (kg y keV)
- 28.75 ± 6.87 events (bgd:~60)
- Claim:4.2σ evidence for $0\nu\beta\beta$
- (0.69–4.18) x10^{25} y (3σ)
- Best fit: 1.19 x10^{25} y (NIMA 522/PLB 586)
- PSA analysis (Mod. Phys. Lett. A21): (2.23 + 0.44 – 0.31)x10^{25} y (6σ)

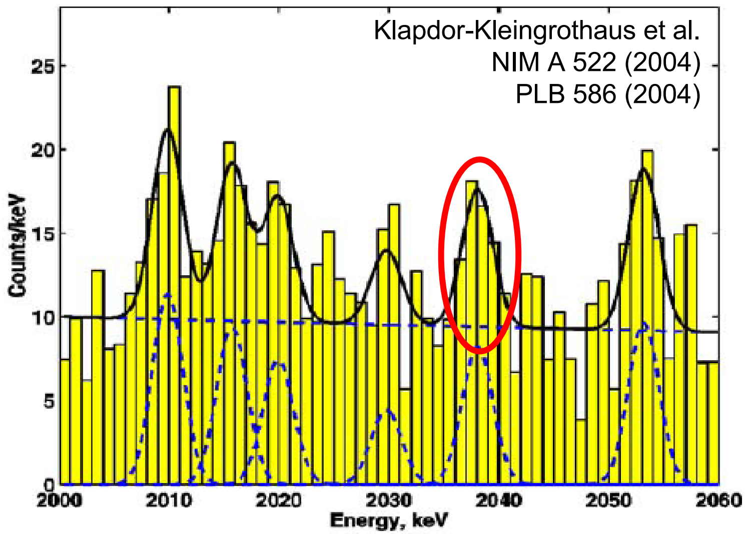
Tuebingen/Bari group (PRD79):
m_{ee} /eV = 0.28 [0.17-0.45] 90%CL

Significance and $T_{1/2}$ depend on bgd discription:
- Strumia & Vissani Nucl.Phys. B726 (2005)
- Chkvorets, PhD dissertation Univ. HD, (2008): using realistic background model
  $\Rightarrow$ peak significance: **1.3σ**,
  $\Rightarrow T_{1/2}$ = 2.2x10^{25} y



A.M. Rotunno, et al. PRD 79

State-of-the-art: limits & claim



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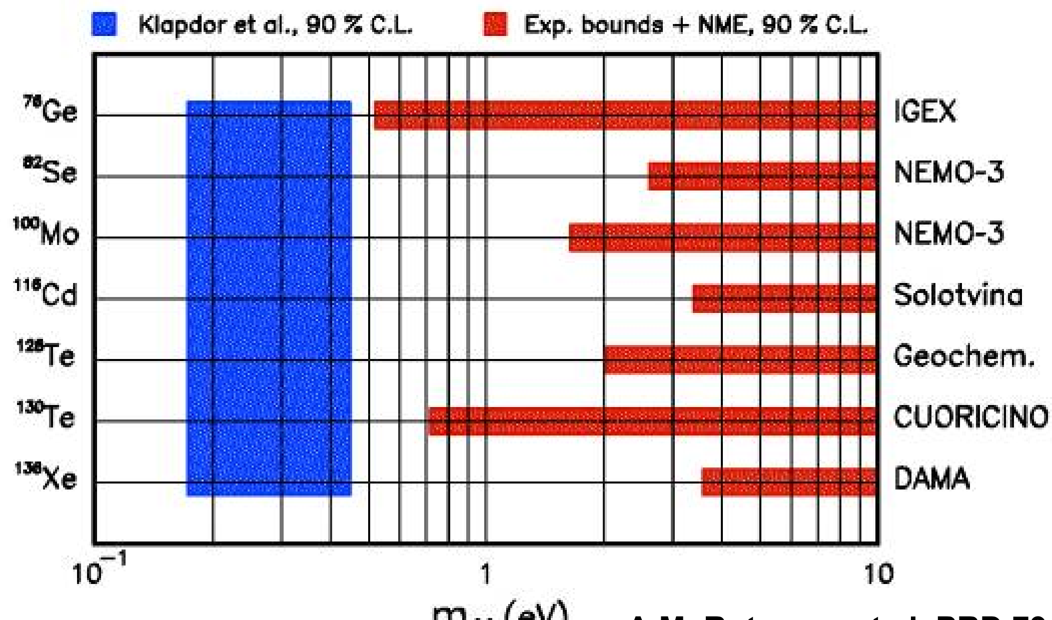
  $\Rightarrow T_{1/2}$ = 2.2$\times 10^{25}$ y



A.M. Rotunno, et al. PRD 79

$\Rightarrow$ Claim must be scrutinized with ^{76}Ge AND other isotopes

Phases and physics reach

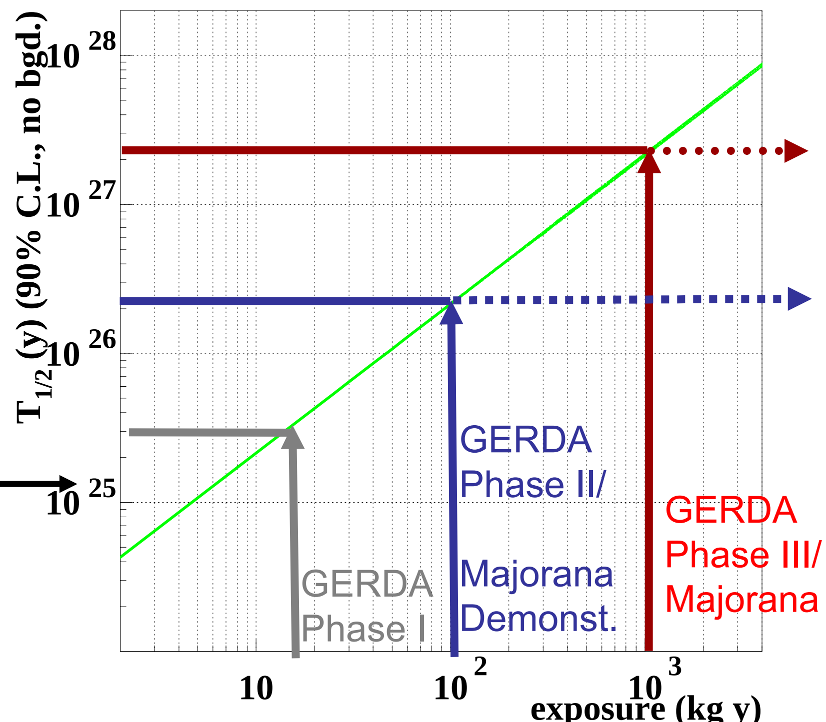
2·10^27 (90 % CL) *

2·10^26 (90 % CL) *

3·10^25 (90 % CL)*

KK

***: no event in ROI**



<24 - 41 meV

<75 - 129 meV

assuming $|M^{0\nu}|$=2.99-8.99 [Smol&Grab PRC'10] and 89% enrichment

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

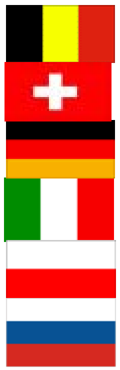
Background requirement for GERDA/Majorana:

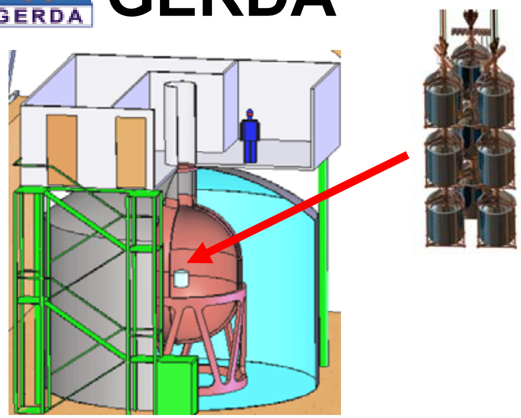
⇒Background reduction by factor 10^2 - 10^3 required w.r. to precursor exps.

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

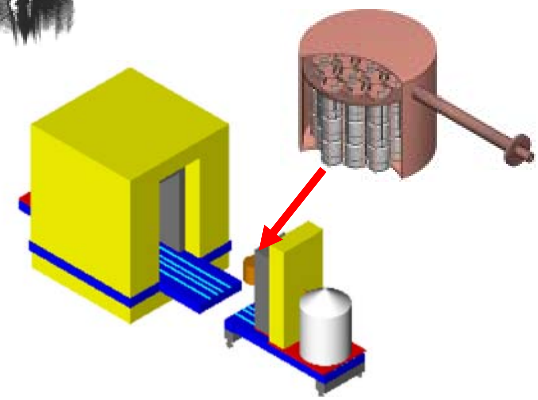
Two new ^{76}Ge Projects:

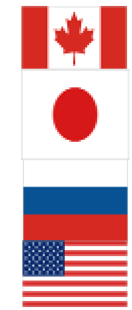
GERDA





Majorana





- ‘Bare’ ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- Phase I: 18 kg (HdM/IGEX) / 15 kg nat.
- Phase II: add ~20 kg new enr. Detectors; total ~40 kg

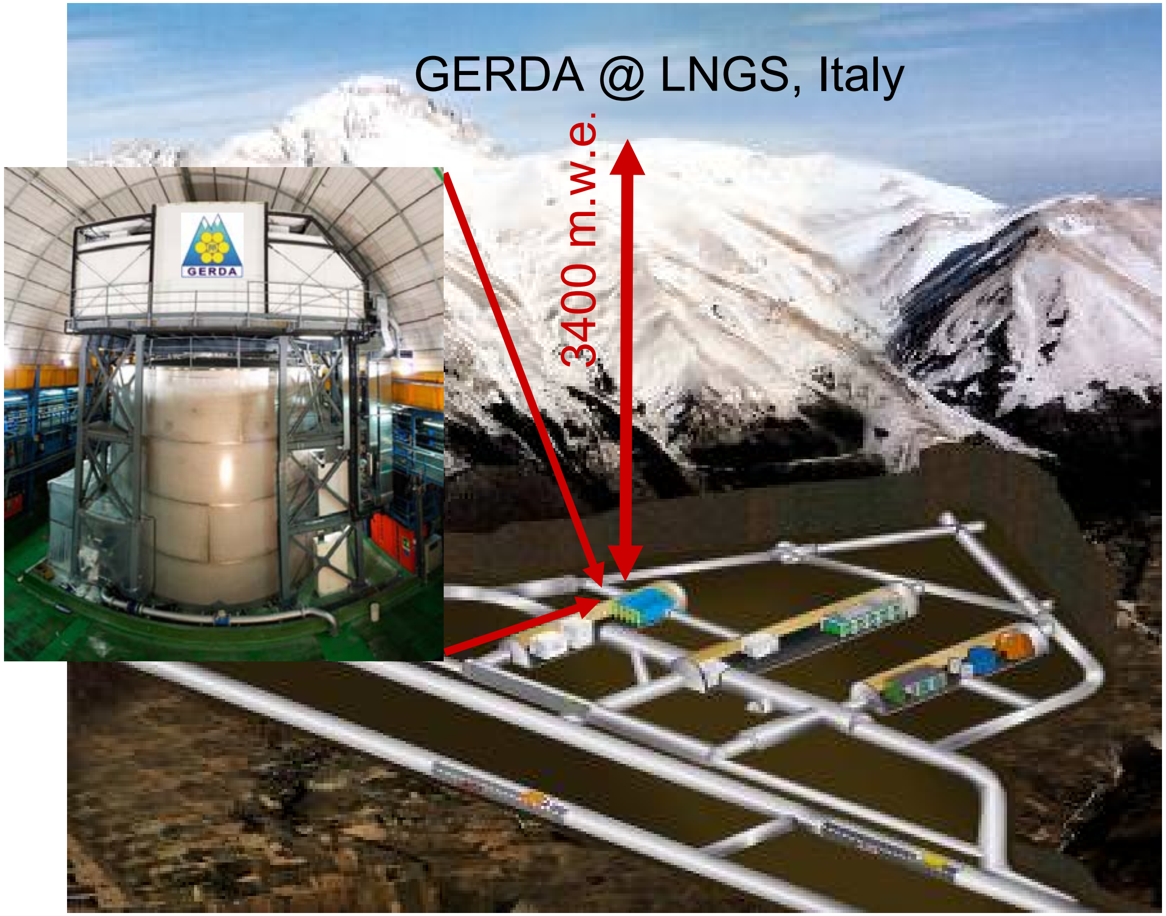
- Array(s) of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Initial phase: R&D demonstrator module: Total ~60 kg (30 kg enr.)

Physics goals: degenerate mass range
Technology: study of bgds. and exp. techniques

LoI
- open exchange of knowledge & technologies (e.g. MaGe MC)
- intention to merge for O(1 ton) exp. (inv. Hierarchy) selecting the best technologies tested in GERDA and Majorana

Background reduction:

Deep underground site for suppression of cosmic ray muons



Suppression of μ-flux > 10^6

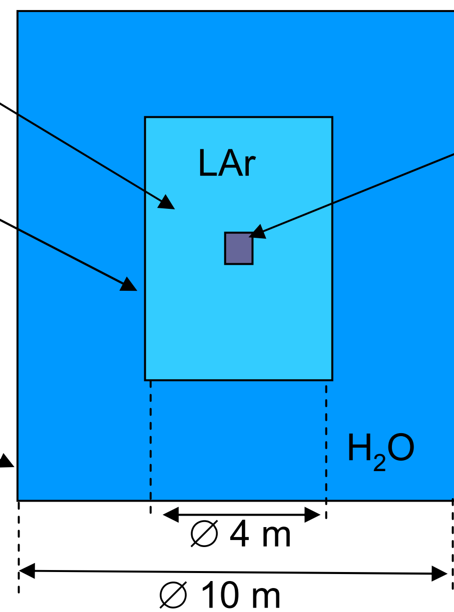
Background reduction:

graded shield against external γ, n, residual-μ

High-purity liquid argon (LAr); shield & coolant;
Optional: active veto

Steel cryostat with internal Cu shield

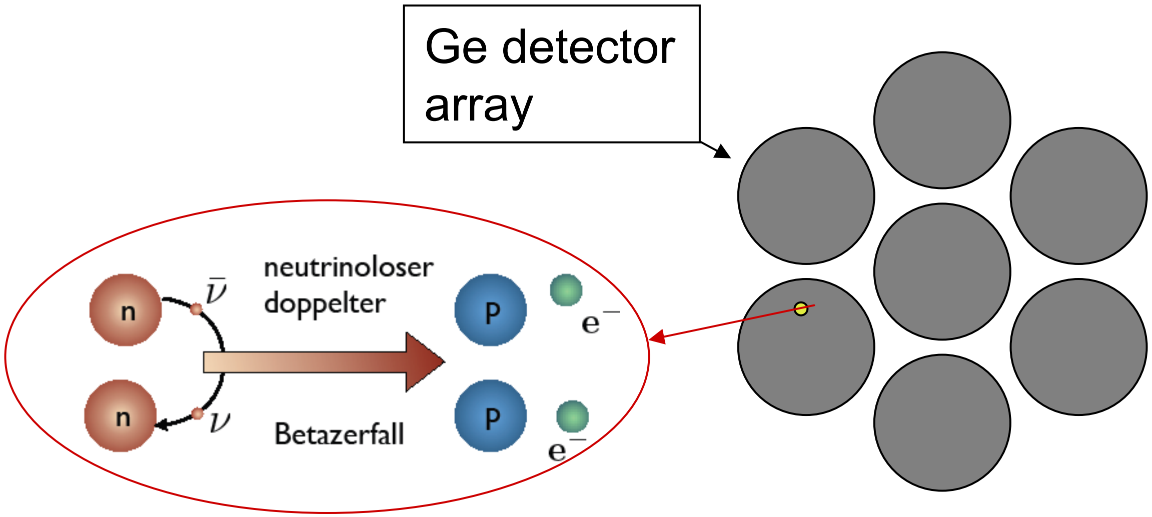
Water: γ,n shield; Cherenkov medium for μ veto



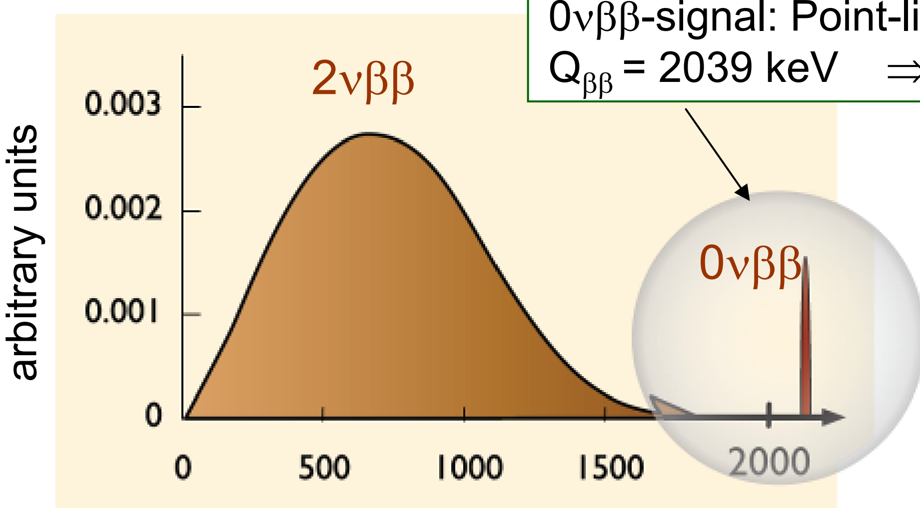
Array of bare Ge-diodes

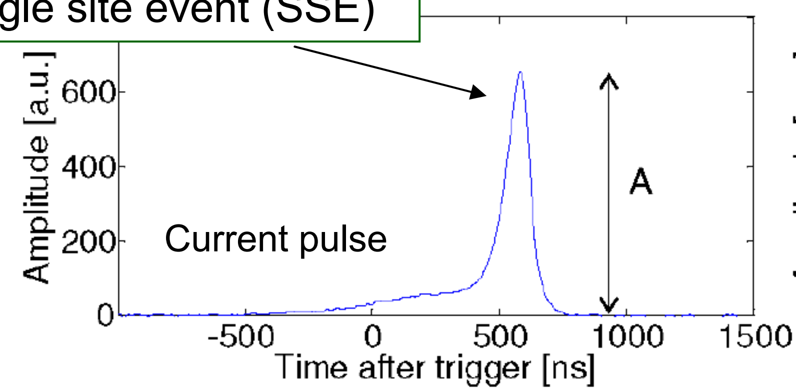
Radio purity of LAr-shield
<0.1 μBq ^{222}Rn (^{226}Ra)/kg

0νββ-signal recognition & background reduction



0νββ-signal: Point-like energy deposition at $Q_{\beta\beta}$ = 2039 keV ⇒ single site event (SSE)

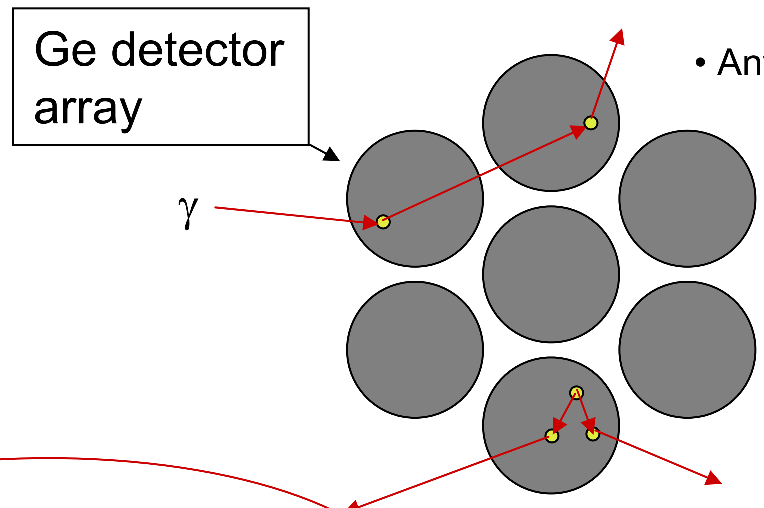




0νββ-signal recognition & bgd reduction

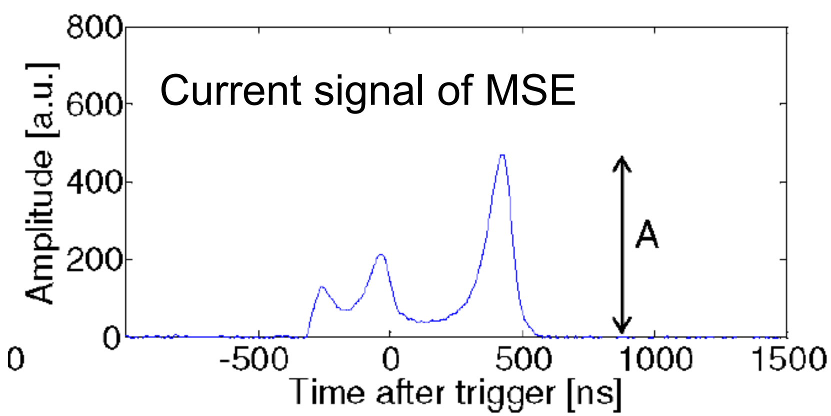
internal bgds: e.g. ^{60}Co (5.3 a), ^{68}Ge (270 d), …

contaminations close by: e.g. U/Ra/Th in holders, cables, FE, …

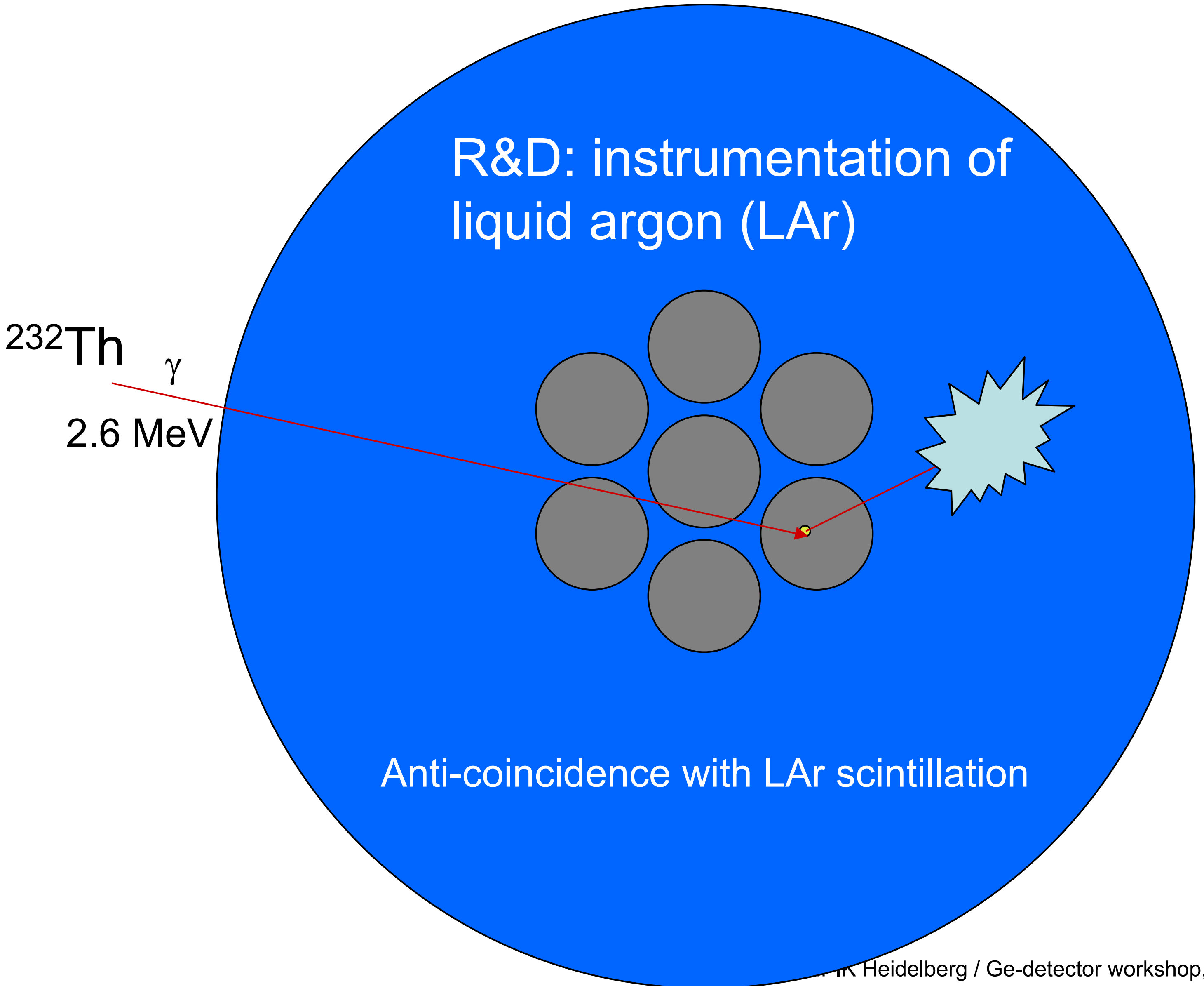


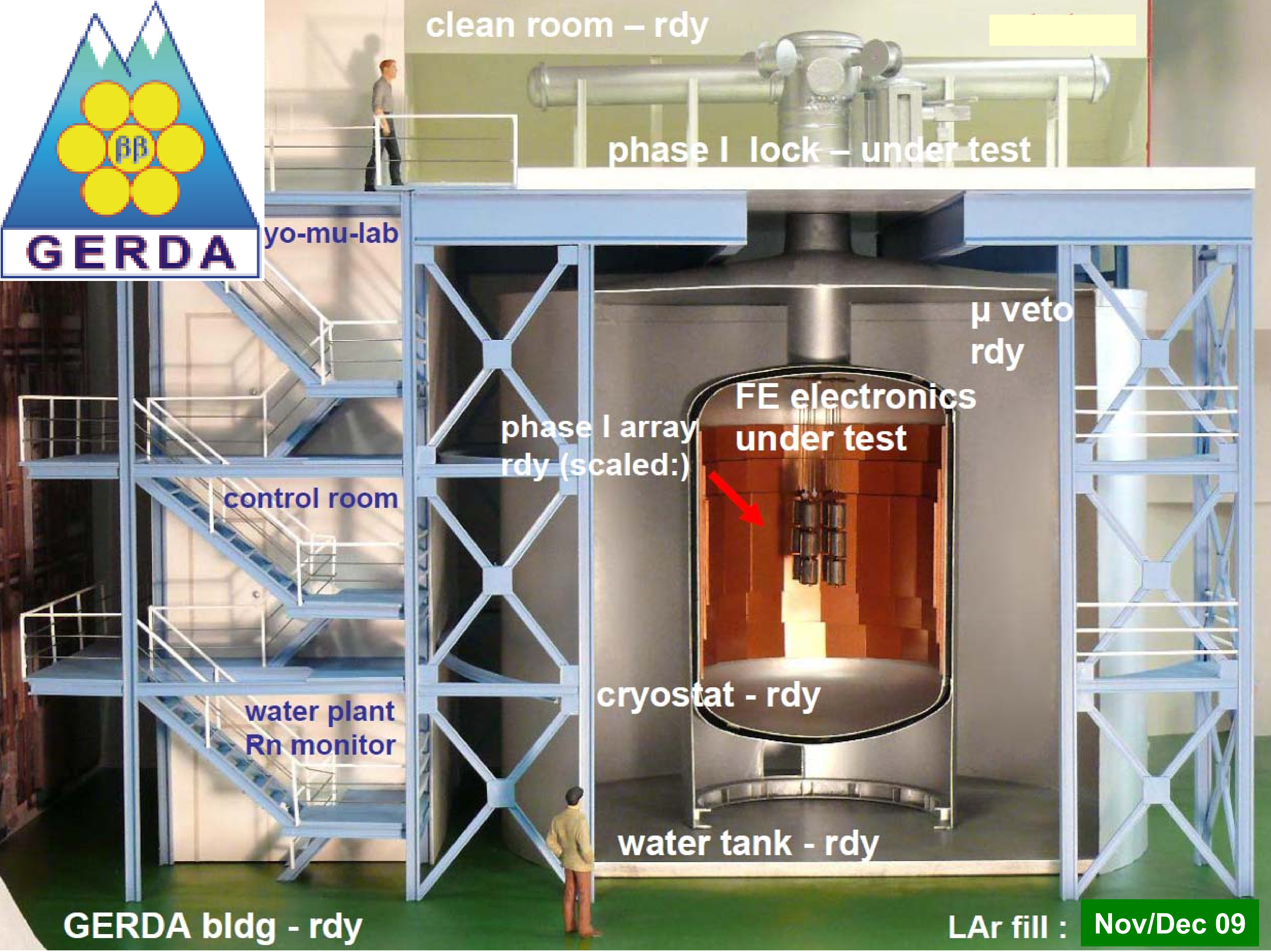
- Anti-coincidence of detectors
- Pulse shape analysis
- Anti-coincidence of detector segments

^{60}Co bgd: multiple energy deposition at $Q_{\beta\beta}$ = 2039 keV
⇒ Multi site event (MSE)



0νββ-signal recognition & background reduction





GERDA
ββ
clean room – rdy
phase I lock – under test
yo-mu-lab
μ veto
rdy
FE electronics
under test
phase I array
rdy (scaled:)
control room
cryostat - rdy
water plant
Rn monitor
water tank - rdy
GERDA bldg - rdy
LAr fill :
Nov/Dec 09


Unloading of vacuum cryostat
(6 March 08)
Produced from selected
low-background austenitic steel

Construction of water tank

∅ 10 m

H = 9.5 m

V = 650 m^3

Designed for external γ,n,μ background ~10^{-4} cts/(keV kg y)


construction of clean room
27 feb 09

clean room, active cooling device getting prepared for installation


Water tank and cryostat prior muon veto installations


WT and cryostat with muon veto installed


“Pill box”

Glove-box for Ge-detector handling and mounting into commissioning lock under N_2 atmosphere installed in clean room

- **Nov/Dec.'09**: Liquid argon fill
- **Jan '10:** Commissioning of cryogenic system
- **Apr/Mai '10:** emergency drainage tests of water tank
- **Apr/Mai '10:** Installation c-lock
- **13. Mai '10:** 1st deployment of FE&detector mock-up (27 pF) - pulser resolution 1.4 keV (FWHM)
- **This week:** First deployment of non-enriched detector
- **Next:** Commissioning run with ^{nat}Ge detector string
- **Subsequently**: start Phase I physics data taking

GERDA Task Groups

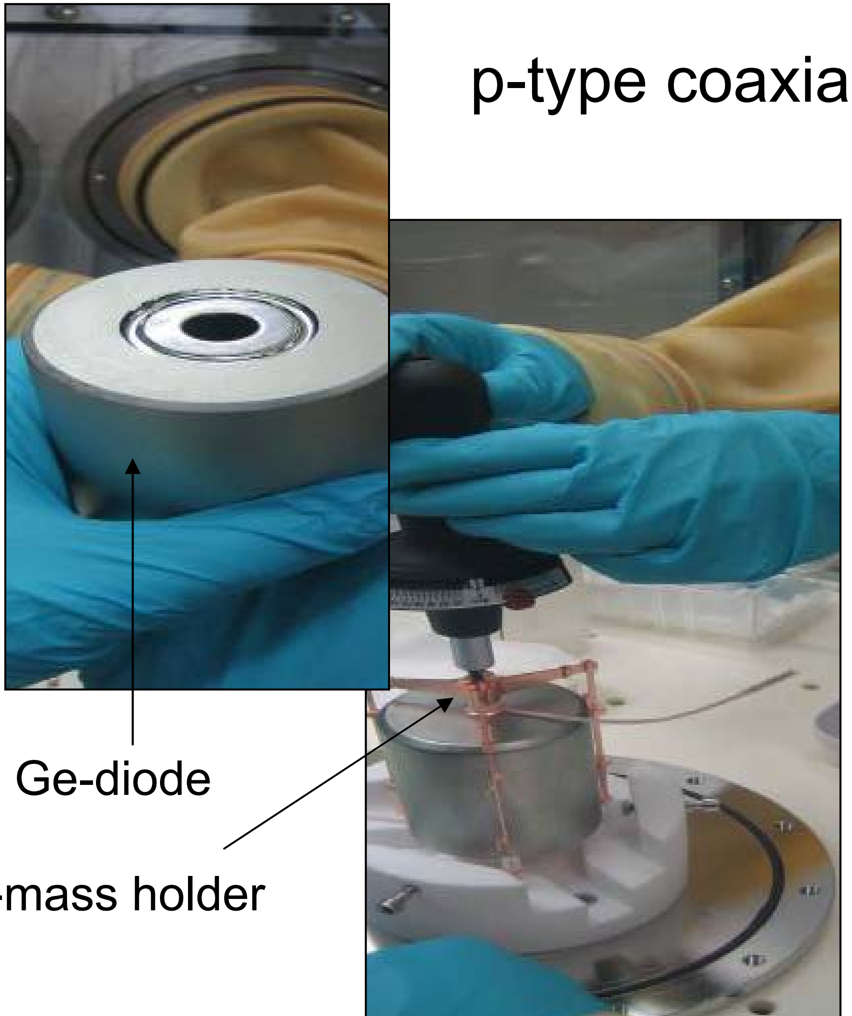
• **TG01**	**Modification & test of existing Ge diodes**
• **TG02**	**Design & production of new Ge diodes**
• **TG03**	**Front end electronics**
• **TG04**	**Cryostat and cryogenic infrastructure**
• **TG05**	**Clean room and lock system**
• **TG06**	**Water tank and water plants**
• **TG07**	**Muon veto**
• **TG08**	**Infrastructure & logistics**
• **TG09**	**DAQ electronics & online software**
• **TG10**	**Simulation & background studies**
• **TG11**	**Material screening**
• **TG12**	**Calibration**
• **TG13**	**Data management**

Selection of R&D of GERDA Task Groups

• TG01	Modification & test of existing Ge diodes
• TG02	Design & production of new Ge diodes
• TG03	Front end electronics
• TG04	Cryostat and cryogenic infrastructure
• TG05	Clean room and lock system
• TG06	Water tank and water plants
• TG07	Muon veto
• TG08	Infrastructure & logistics
• TG09	DAQ electronics & online software
• TG10	Simulation & background studies
• TG11	Material screening
• TG12	Calibration
• TG13	Data management

Phase I detectors

p-type coaxial detectors



Bare Ge-diode

Low-mass holder

Detector handling under N_2 atmosphere

<u>8 diodes (from HdM, IGEX):</u>

- Enriched 86% in ^{76}Ge
- All diodes refurbished with new contacts optimized for LAr
- Energy resolution in LAr: ~2.5 keV (FWHM) @1.3 MeV
- Well tested procedure for detector handling
- Total mass 17.66 kg (after refurbishing)

<u>6 diodes from Genius-TF ^{nat}Ge:</u>

- Same refurbishing & testing as enriched diodes
- Total mass: 15.60 kg

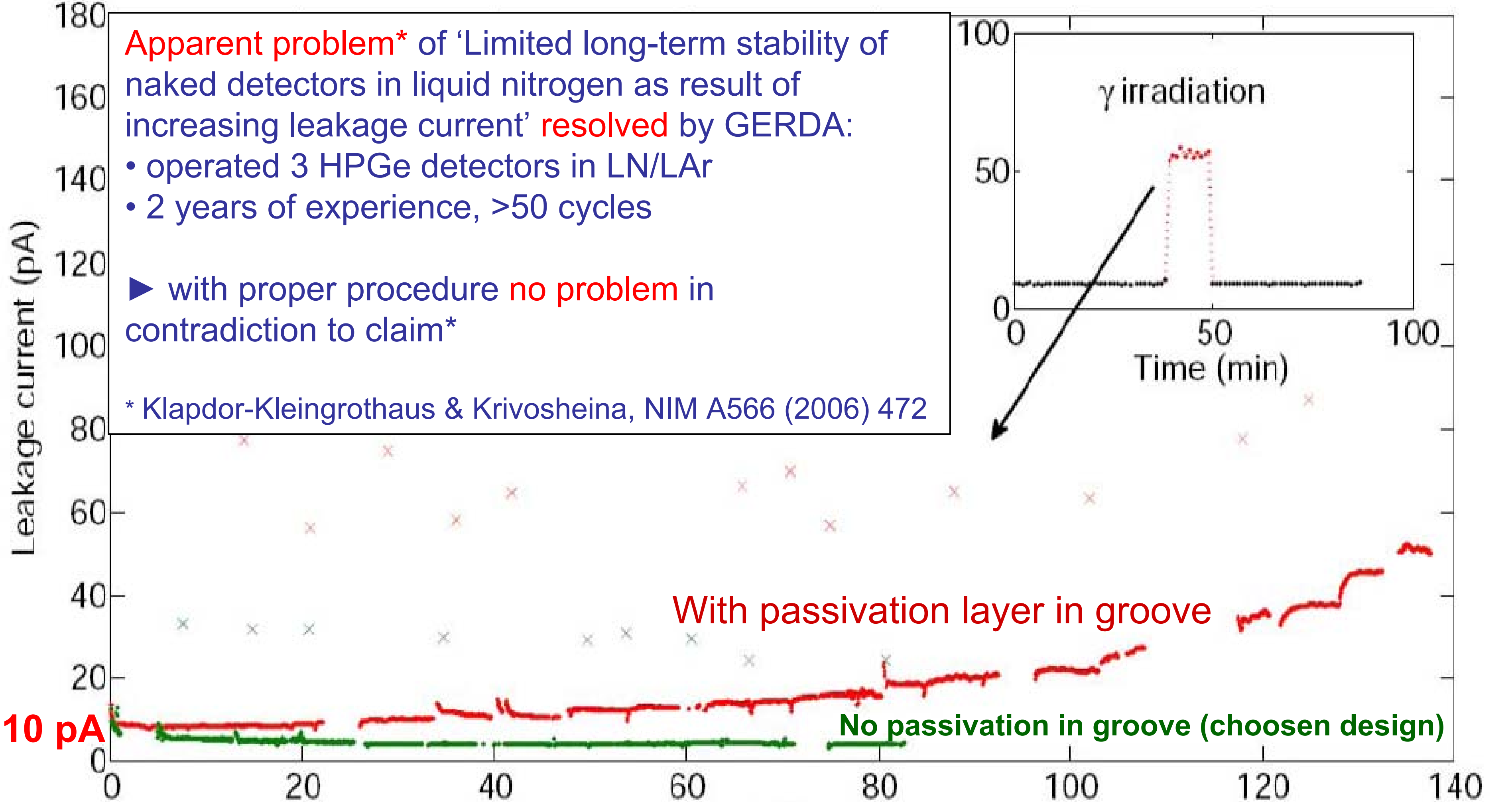
R&D long-term stability of phase I detectors in LAr/LN_2

Apparent problem* of ‘Limited long-term stability of naked detectors in liquid nitrogen as result of increasing leakage current’ resolved by GERDA:

- operated 3 HPGe detectors in LN/LAr
- 2 years of experience, >50 cycles

► with proper procedure no problem in contradiction to claim*

* Klapdor-Kleingrothaus & Krivosheina, NIM A566 (2006) 472

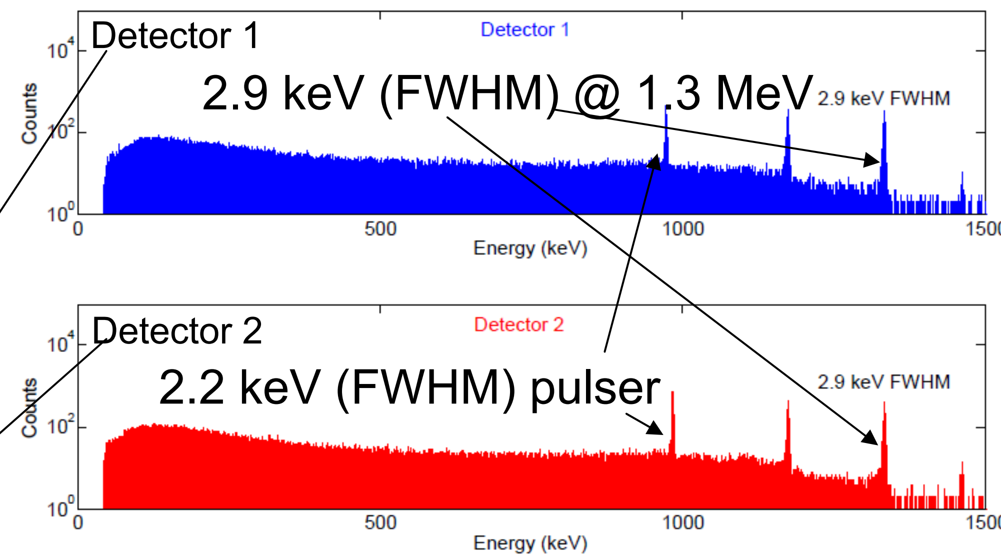


no deterioration after 1 year of operation in LAr

M. Barnabé-Heider, PhD thesis ‘09

Test of full read out chain

Summer/ autumn 2009:
Integration test of phase I detector string, FE, lock, DAQ, LAr dewar with active cooling



Best resolution achieved in setup: 2.7 keV (FWHM)

Phase II detectors

Two technologies pursued:
1) n-type segmented
2) p-type BEGe

^{enr}Ge & ^{depl}Ge: ✓

- 37.5 kg of 86% ^{enr}Ge (in form of GeO_2) stored underground
- 84 kg of $^{dep}GeO_2$ acquired (with same chemical history)

Reduction & purification: ✓

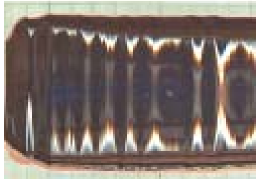
- procedure tested and optimized with ^{dep}Ge at PPM Pure Metals GmbH
- no isotopic dilution
- short exposure to cosmic rays (underground storage)
- 29 Apr '10: purification of enriched material completed.
  ⇒ 35.4 kg (94%) of 6N (+ 1.1 kg tail = 97%)

Crystal pulling:

n-type for segmented detectors:
- R&D for n-type pulling by Institut für Kristallzüchtung, Berlin
- impurity concentration of $6 \cdot 10^{10}$ cm^{-3} reached

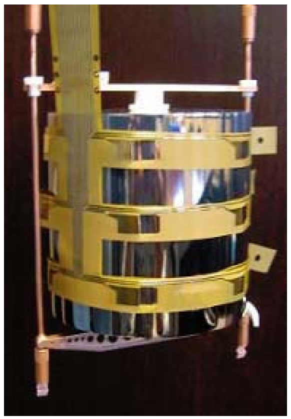
⇒ M. Wünscher

p-type for BEGe detectors: ✓
- ^{depl}Ge from ECP purified at PPM successful
- Crystal pulling from ^{depl}Ge material at Canberra, Oakridge, US
- first two $^{depl}BEGe$ detector working (Feb 2010)



⇒ C. Cattadori's talk

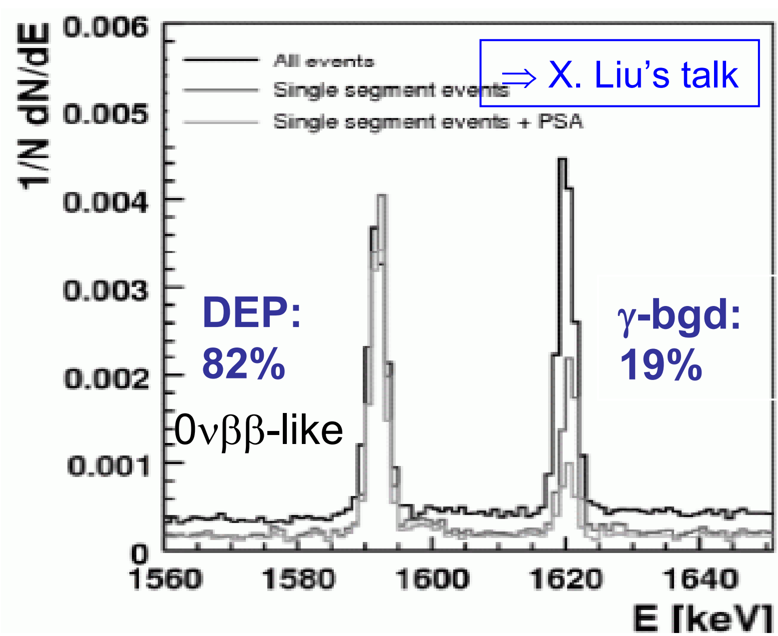
Phase II R&D: Novel Ge-detectors with advanced $0\nu\beta\beta$-signal recognition & background suppression



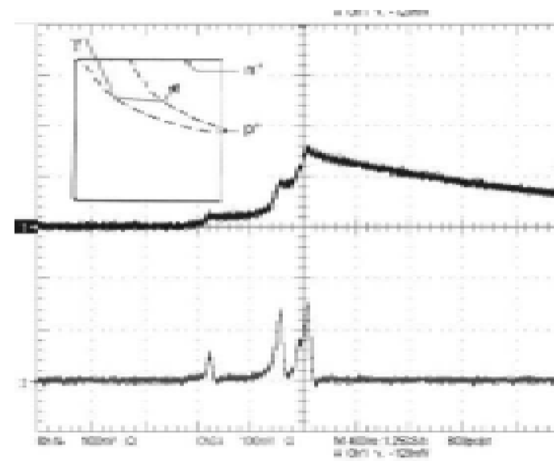
n-type detectors with 18-fold segmented electrodes, 1.6 kg

In vacuum cryostat

I.Abt et al., NIMA 583 (2007), Eur. J. Phys. C 52 (2007)

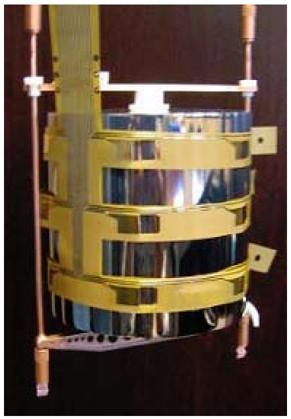


Triggered by original works of Luke et al., IEEE TNS 36 (1989) and Barbeau et al., nucl-ex/0701012v1,



and by discussions with J. Verplancke (Canberra, Olen) ⇒ proposal in 2007 to use commercially available BEGe detectors

Phase II R&D: Novel Ge-detectors with advanced $0\nu\beta\beta$-signal recognition & background suppression



n-type detectors with 18-fold segmented electrodes, 1.6 kg

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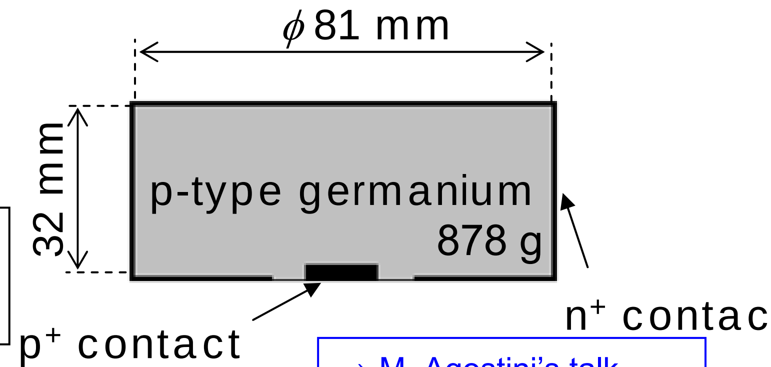
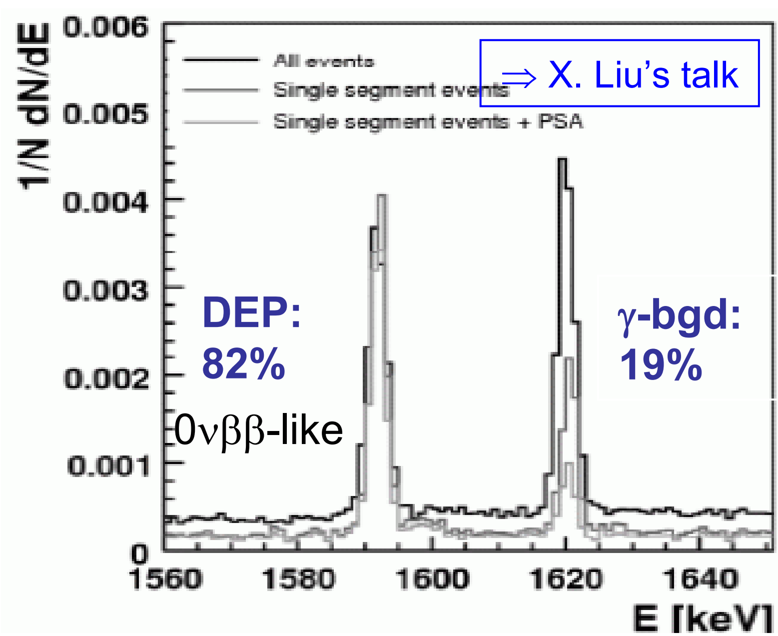
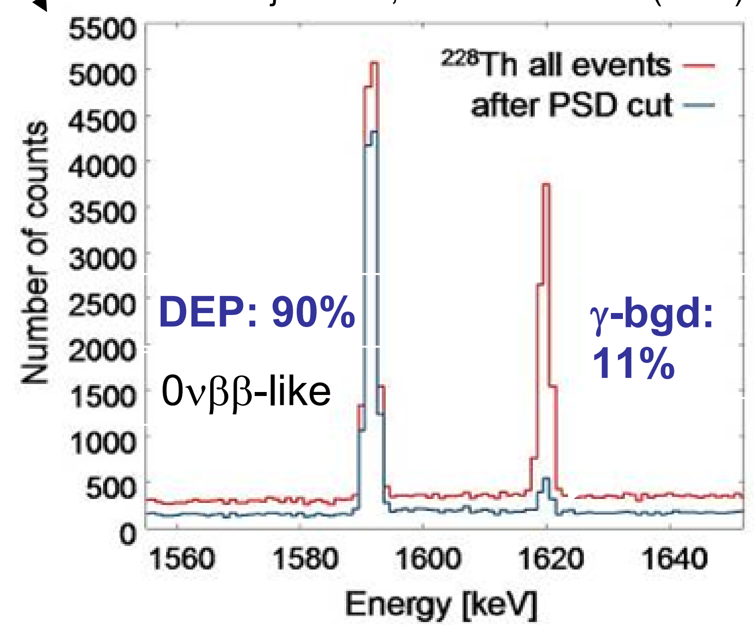


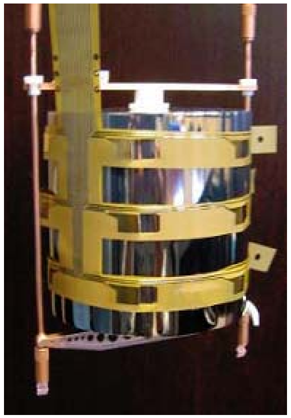
⇒ M. Agostini's talk
⇒ C. Cattadori's talk

D. Budjas et al., JINST 4 P10007 (2009)





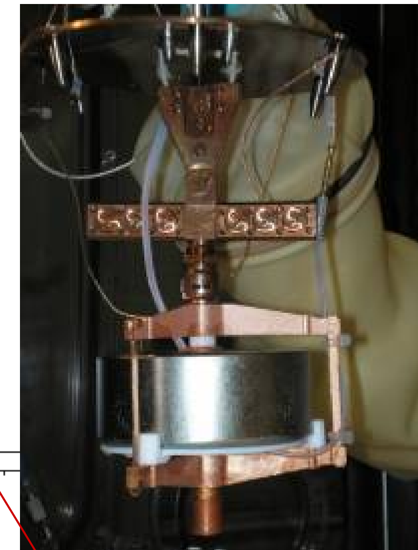
Phase II R&D: Novel Ge-detectors with advanced 0νββ-signal recognition & background suppression

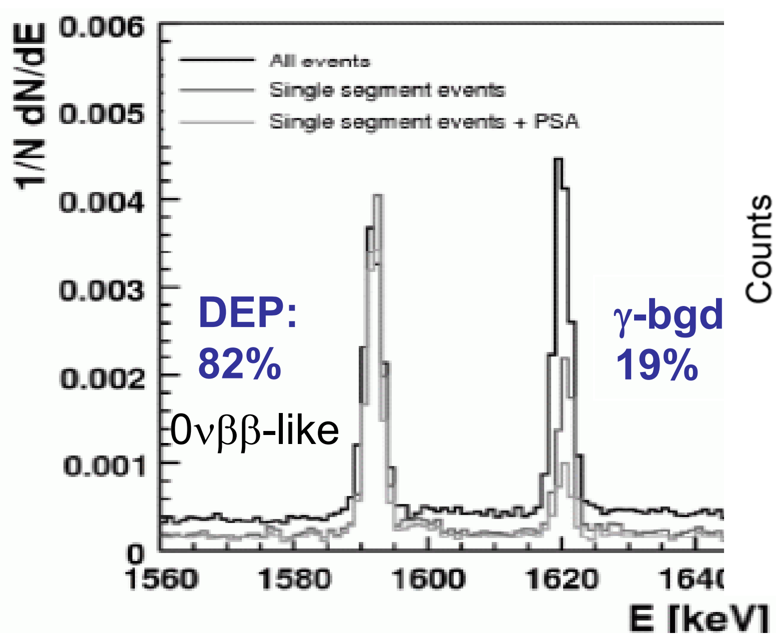


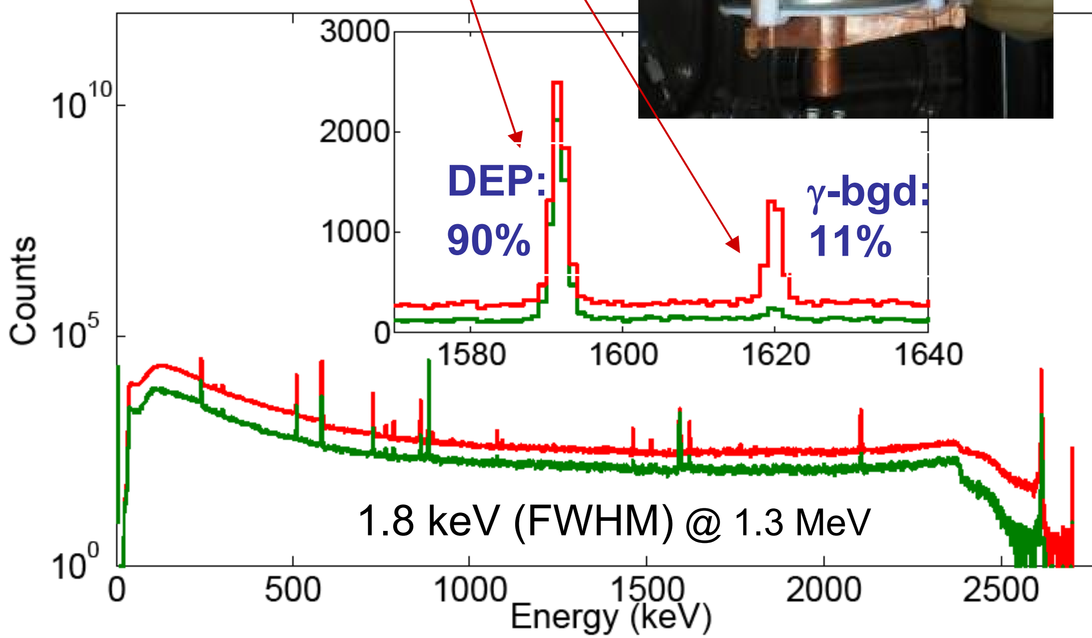
n-type detectors with 18-fold segmented electrodes, 1.6 kg

I.Abt et al., NIMA 583 (2007). Eur. J. Phys. C 52 (2

Same results with bare detector in liquid argon test stand!

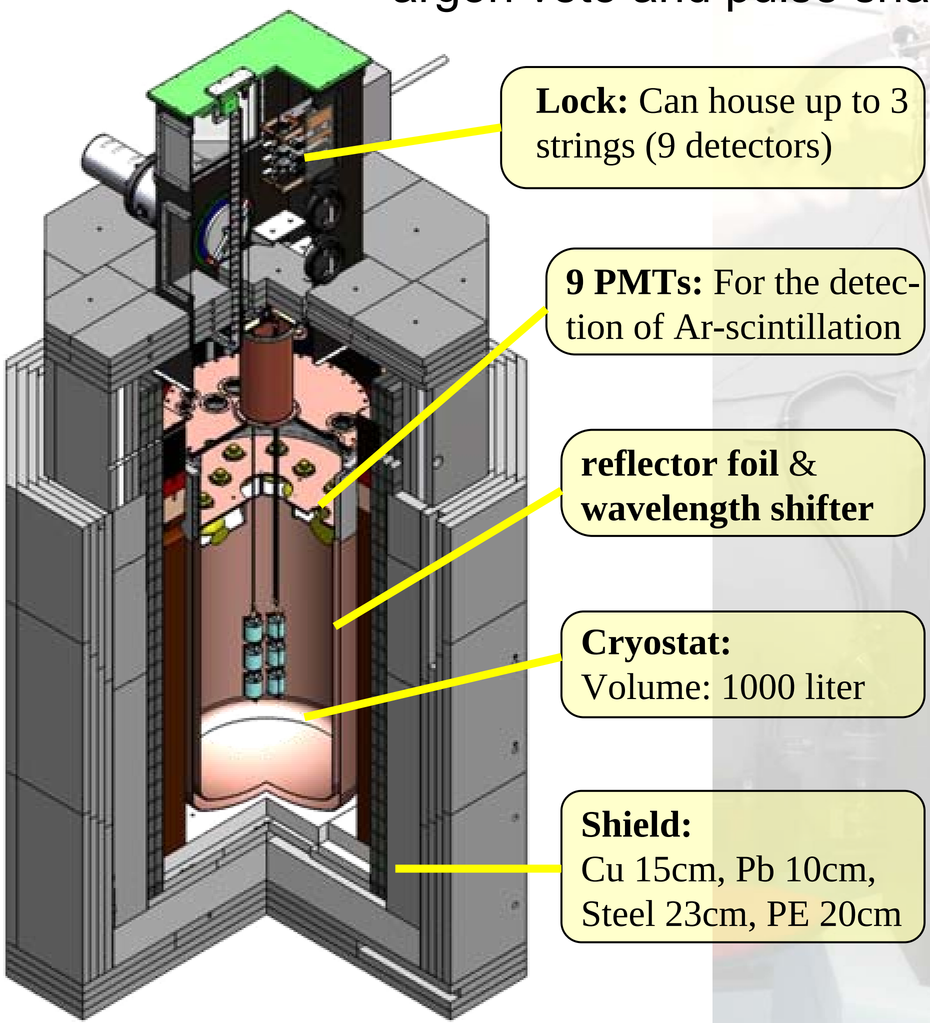


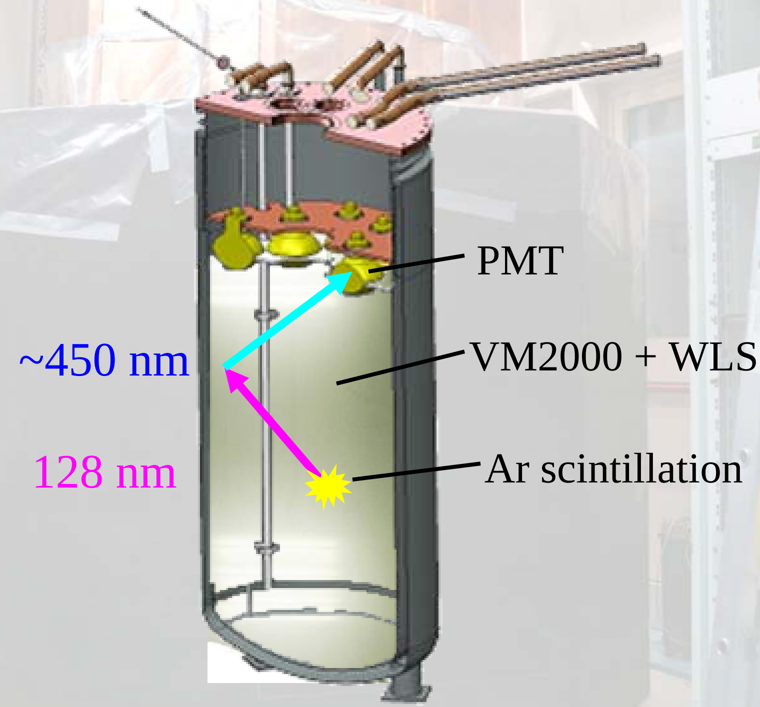


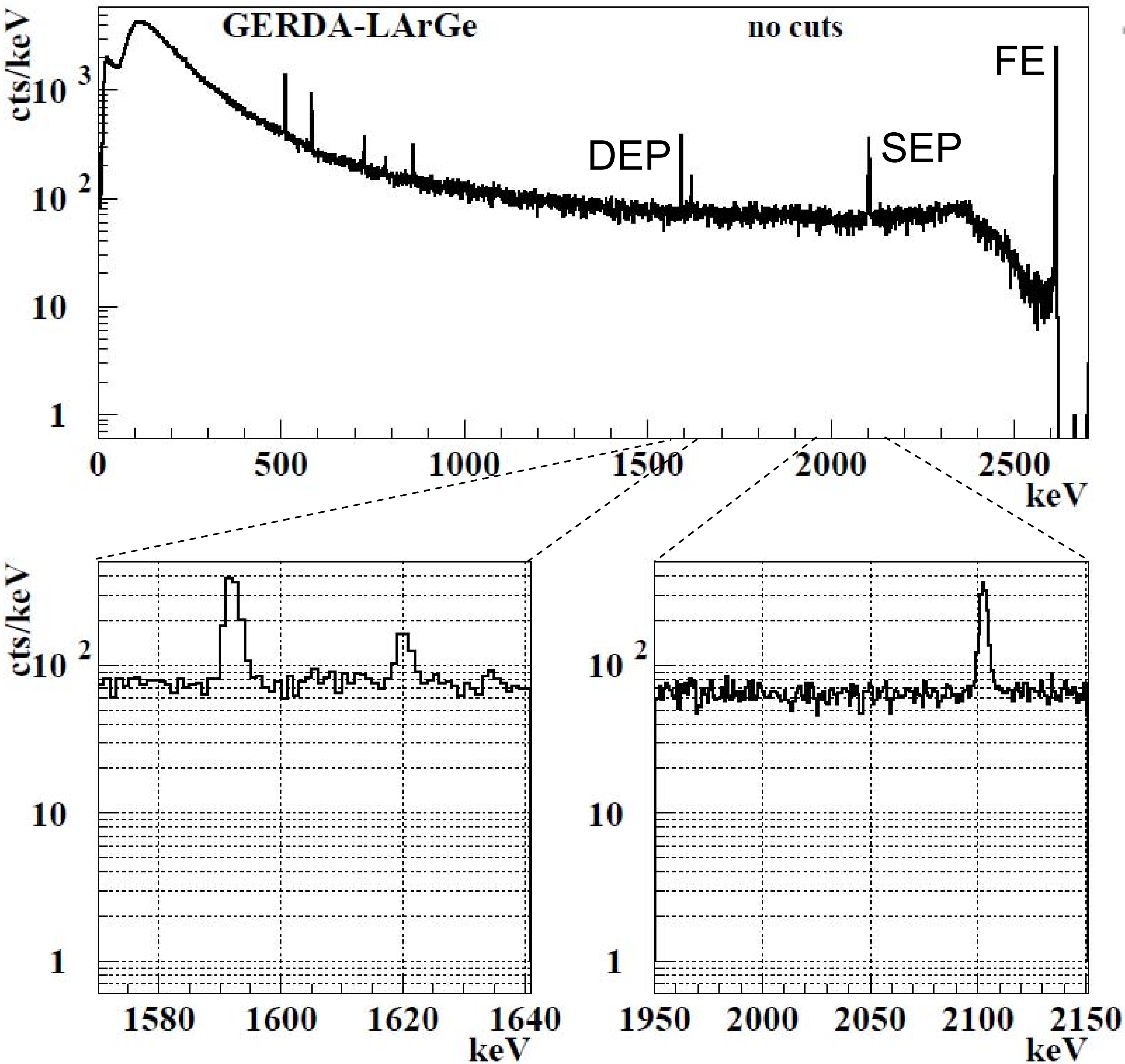


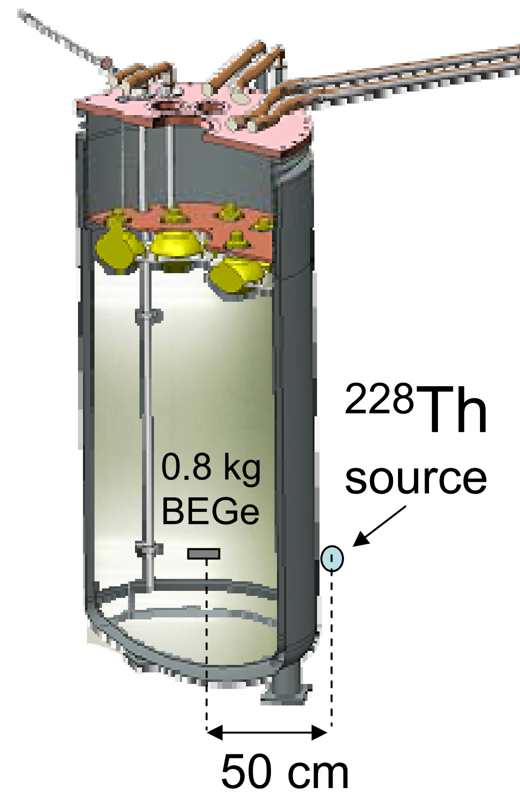
R&D for Phase II/III: the GERDA-LArGe test stand at LNGS

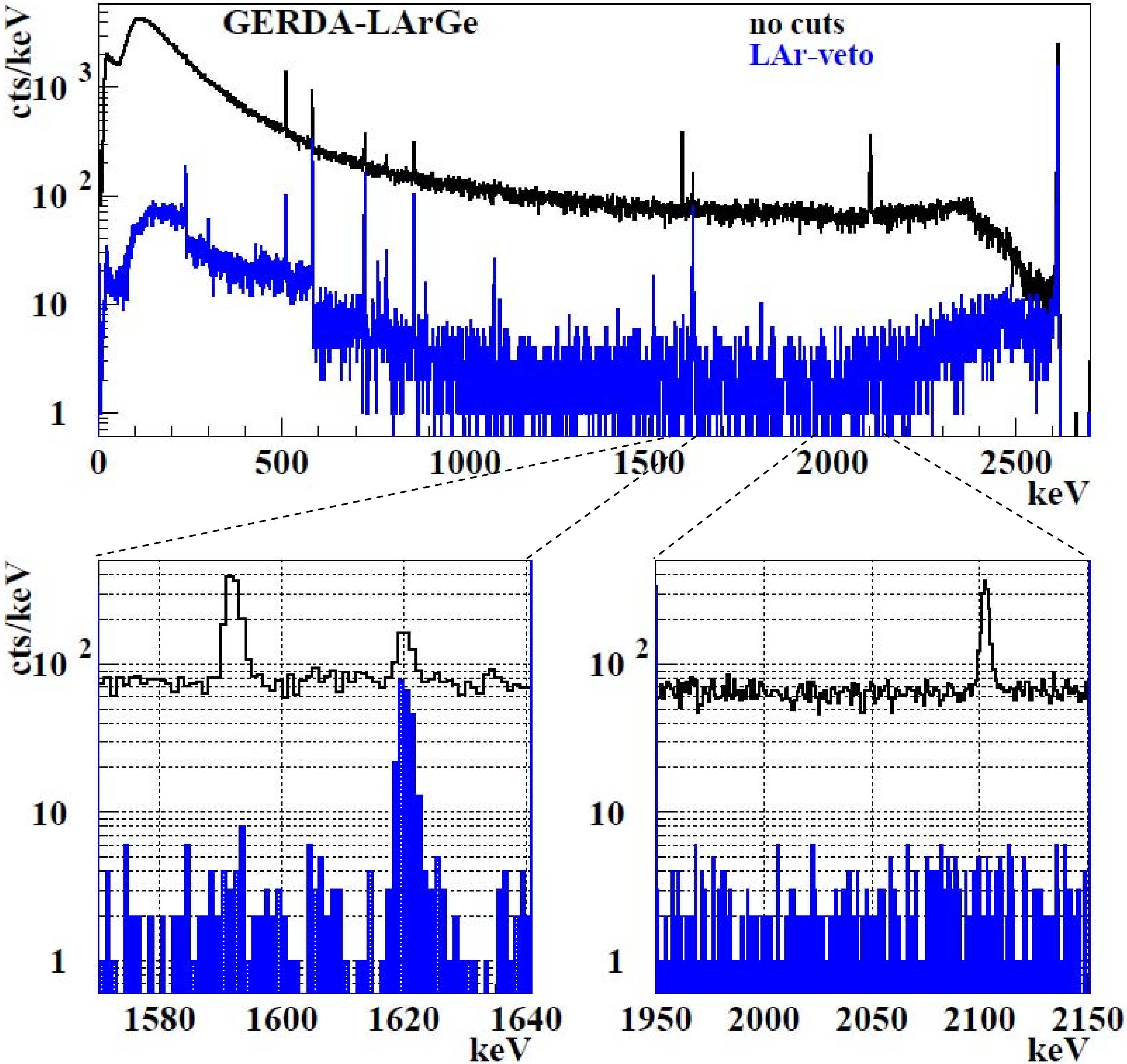
First (& preliminary) results of a bare BEGe detector operated with liquid argon veto and pulse shape discrimination

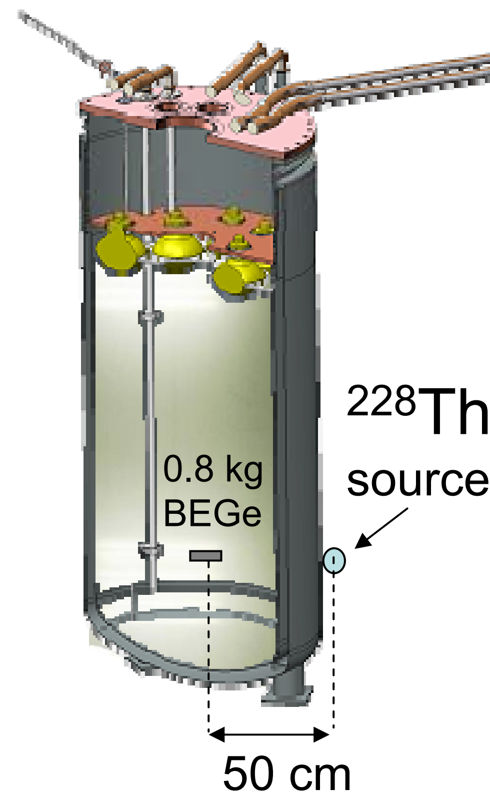





GERDA-LArGe
no cuts
FE
DEP
SEP
cts/keV
keV
1580
1600
1620
1640
1950
2000
2050
2100
2150

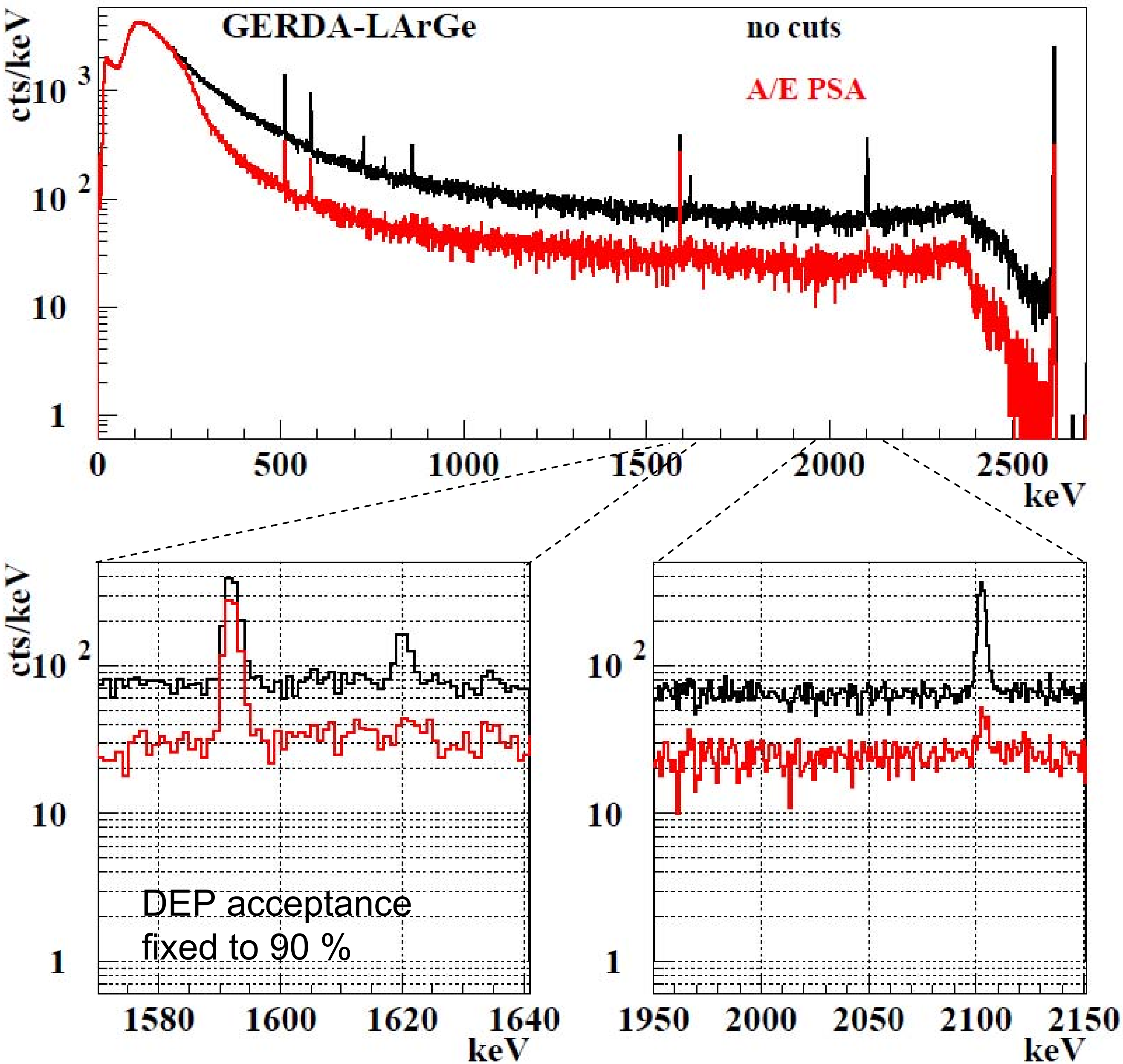

228Th
source
0.8 kg
BEGe
50 cm

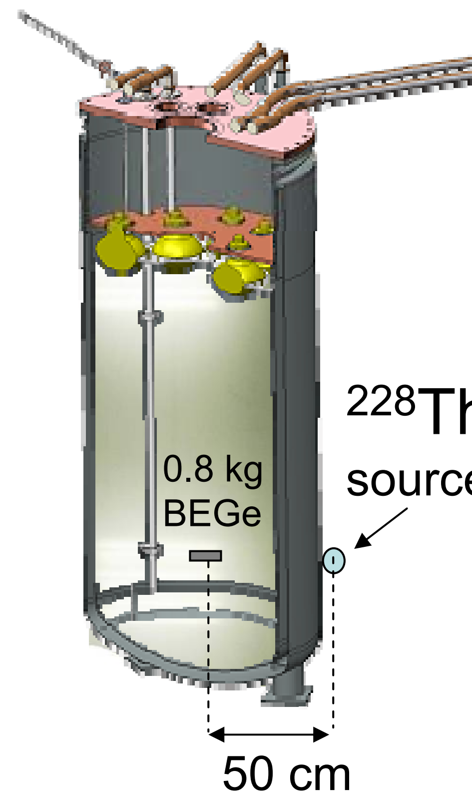




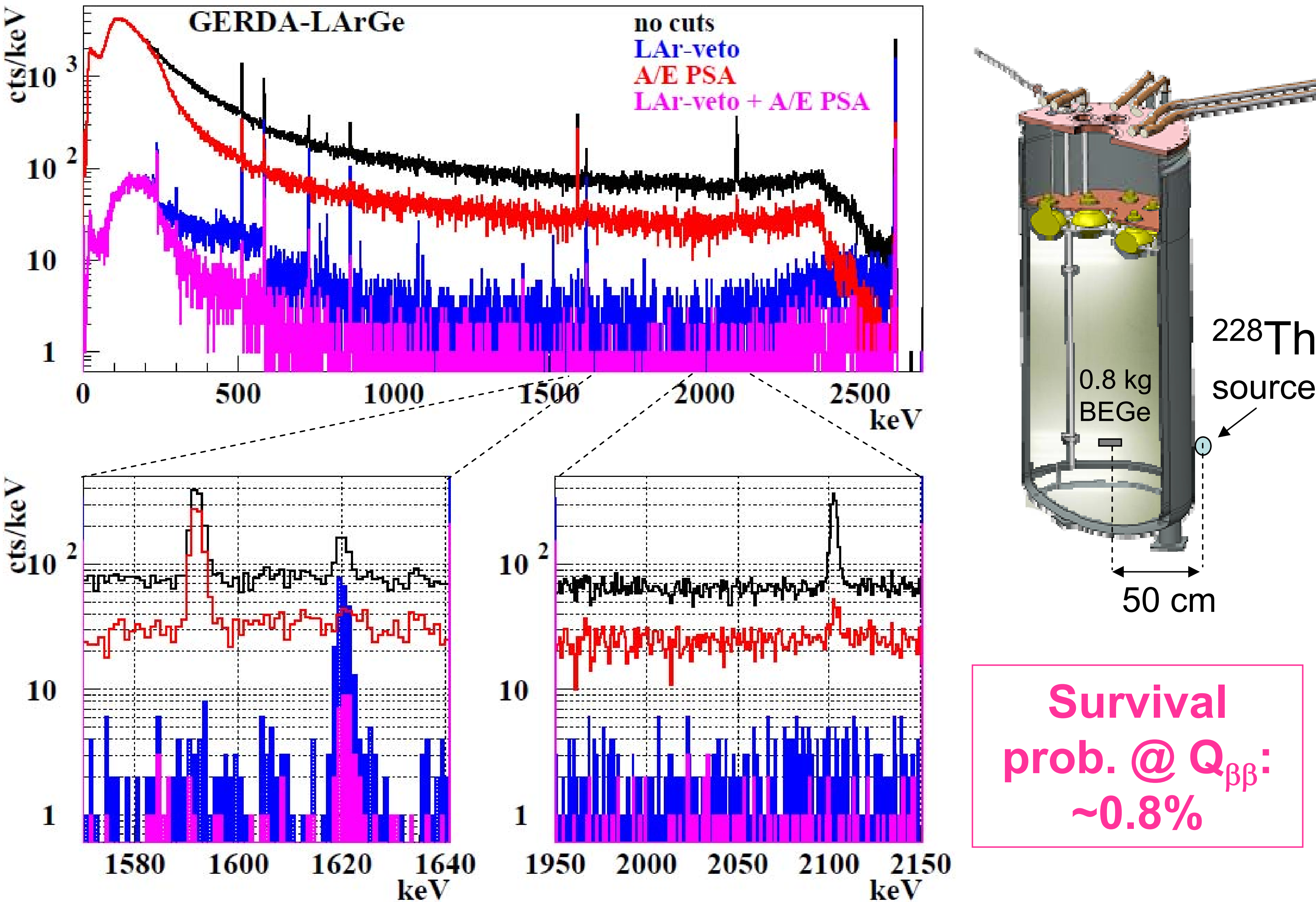
Survival prob. @ $Q_{\beta\beta}$: ~3%

(Here: ~20% signal loss because of γ-source related random conicidneces)





Survival prob. @ $Q_{\beta\beta}$: ~38%



Survival prob. @ $Q_{\beta\beta}$: ~0.8%

Summary & outlook

- Proposed in 2004
- Approved in 2005 by LNGS with location in Hall A
- Main funding sources: MPG, INFN, BMBF, DFG, SNF and Russia in kind
- Construction completed in LNGS Hall A
- Cryostat filled with LAr in Dec '09 & cryogenic commissioning completed
- First technical run: Mai '10
- Goals:

  Phase I: background 0.01 cts / (kg keV y)

  $\Rightarrow$ scrutinize KKDC results with ~1 year of data

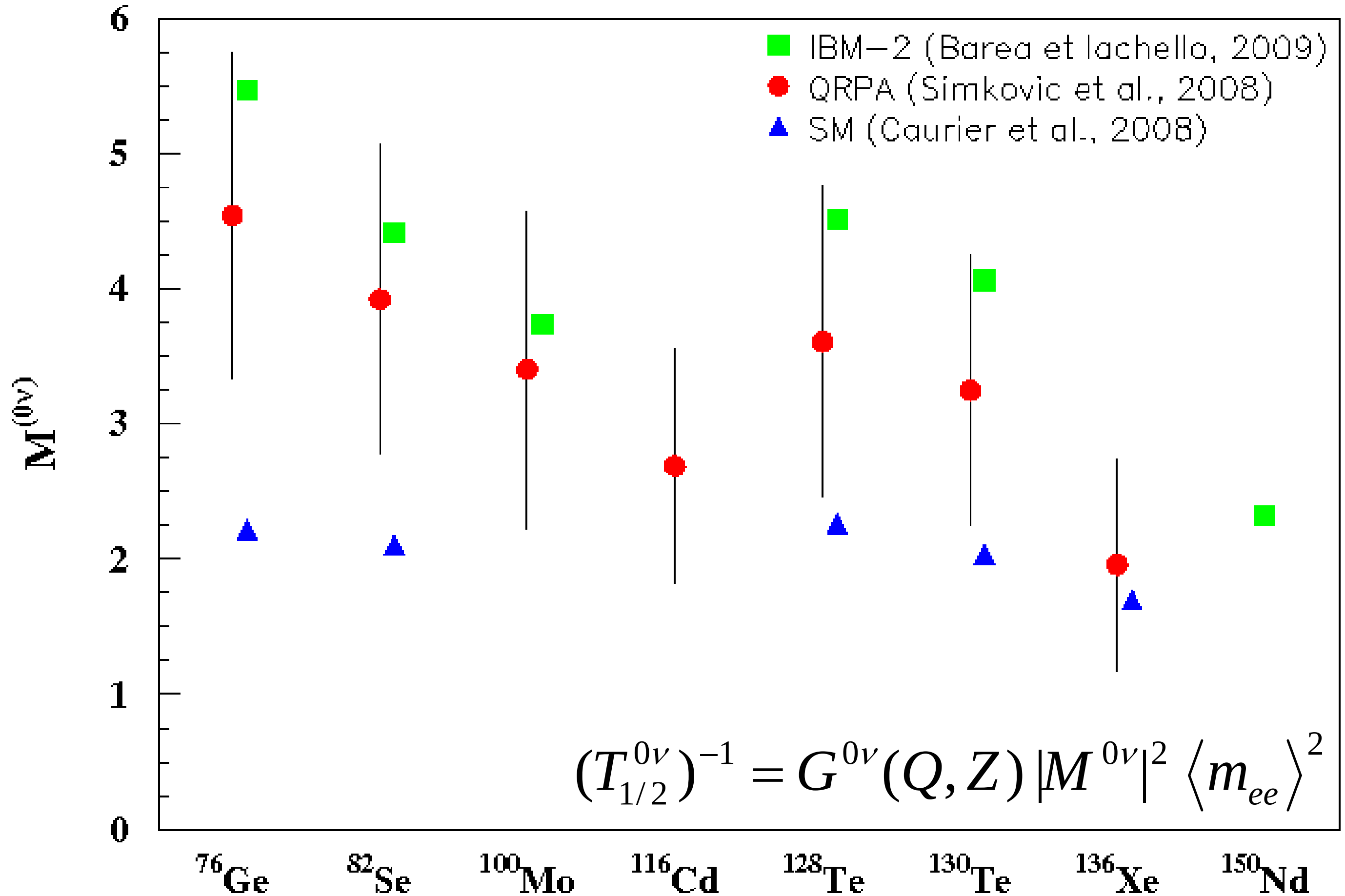
  $\Rightarrow T_{1/2} > 2.2\ 10^{26}$ y, $<m_{ee}> < 0.23 – 0.39$ eV [PRC81 2010]

  Phase II: background 0.001 cts / (kg keV y)

  $\Rightarrow T_{1/2} > 1.5\ 10^{26}$ y, $<m_{ee}> < 0.09 – 0.15$ eV [PRC81 2010]
- R&D on liquid argon instrumentation $\Rightarrow$ attractive method for 'background-free' 1 ton experiment

Extra slides

Comparison of DBD isotopes: Recent calculations of nuclear matrix elements

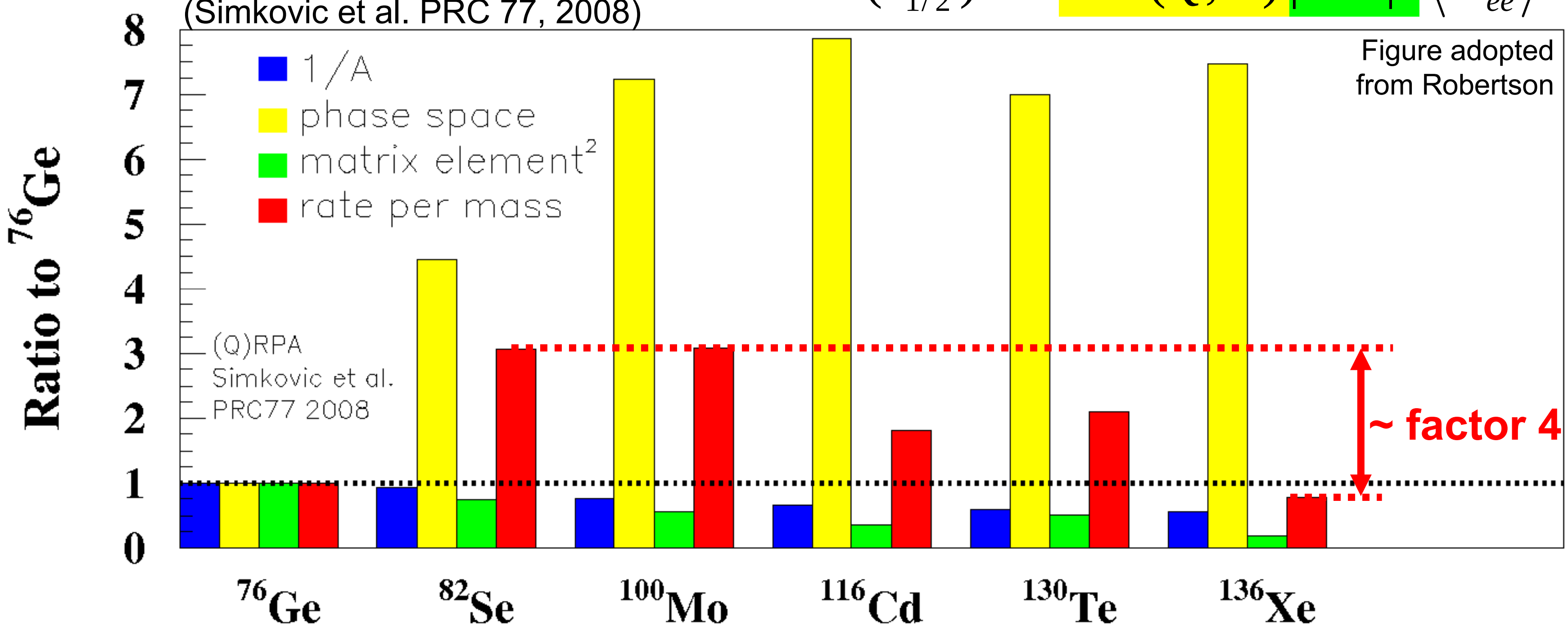


Is M decreasing with $A^{-2/3}$ (IBM-2, QRPA) or constant with A (SM) ?

Comparison of isotopes:
Is there a *super-DBD-isotope* ?

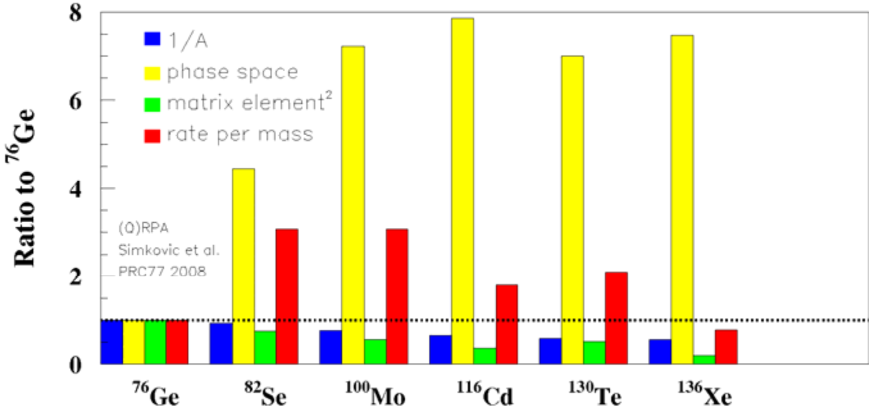
QRPA
(Simkovic et al. PRC 77, 2008)

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2 \langle m_{ee}\rangle^2$$



Expected $0\nu\beta\beta$ **rates per mass** vary within a factor ~ 4 !

QRPA
(Simkovic et al. PRC 77, 2008)

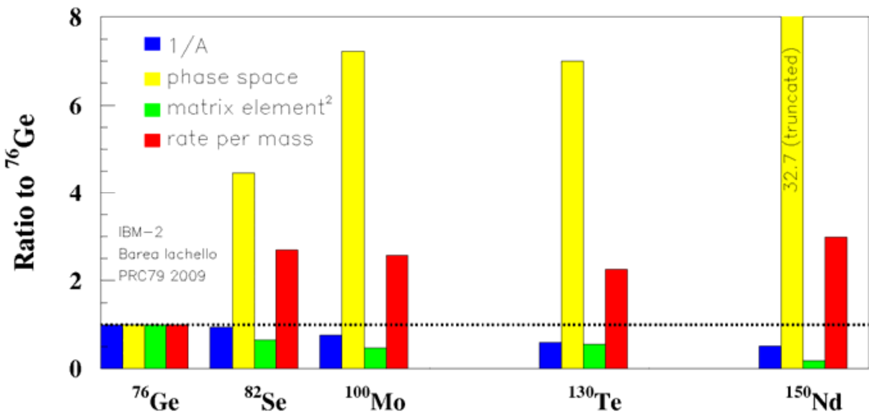


~4

for $\langle m \rangle = 50\,\text{meV}$:

9.1 cts/(ton year)

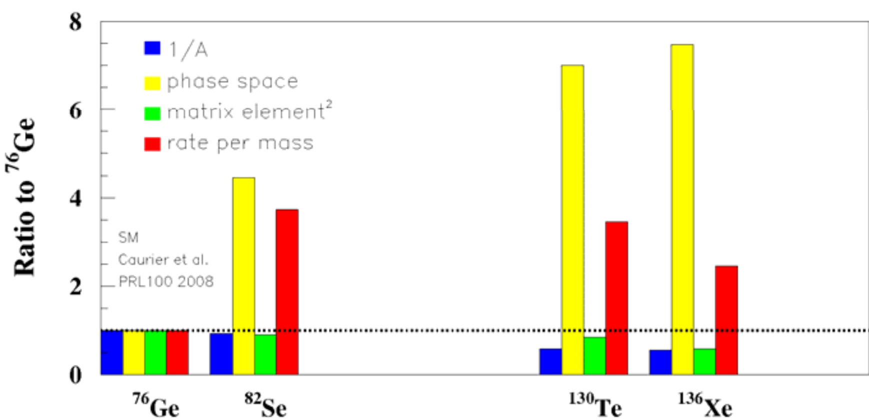
IBM2
(Barea and Iachello, PRC 79, 2009)



~3

13.2 cts/(ton year)

SM
(Caurier et al., PRL 100, 2008)



~4

2.2 cts/(ton year)

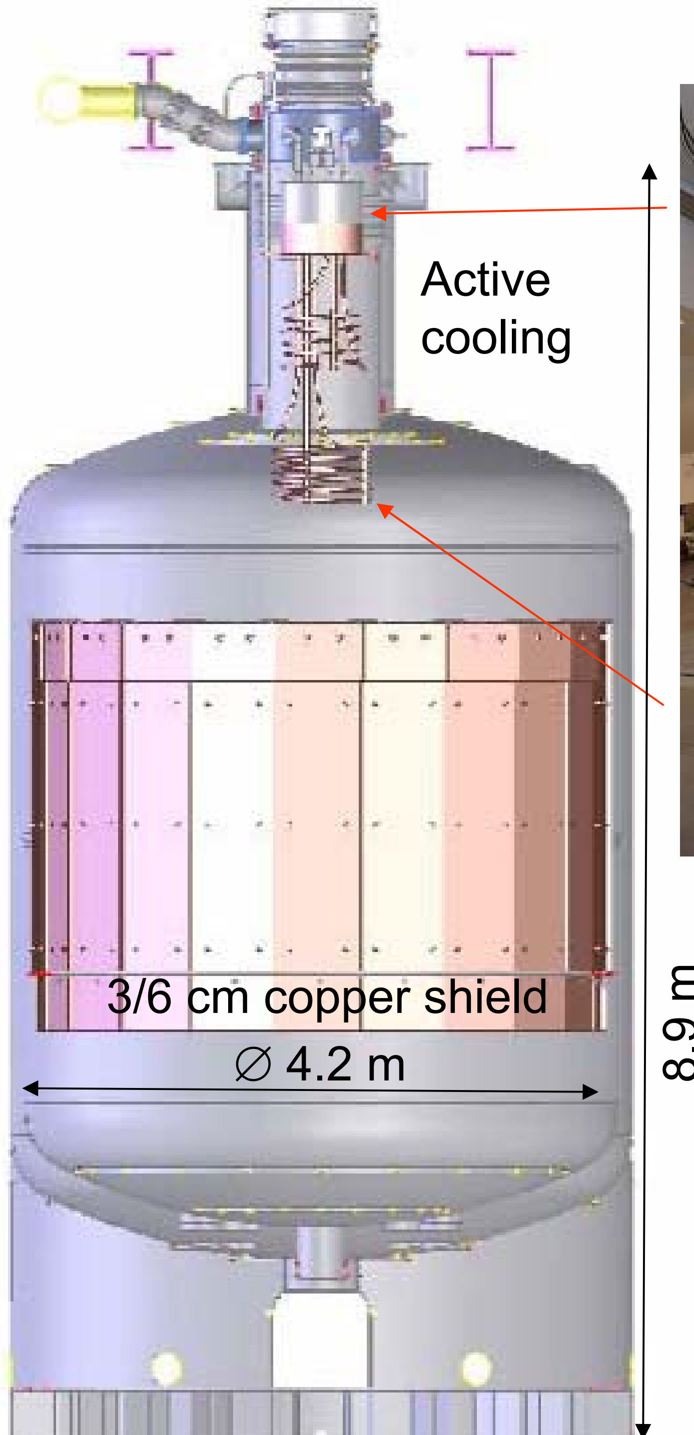
GERDA cryostat

- 65 m^3 volume for LAr
- 200W measured thermal loss
- active cooling with LN_2
- internal copper shield
- detailed risk analysis of cryostat in 'water bath'

Screening of all stainless steel sheet batches by underground γ-spectroscopy at MPI-HD and LNGS prior construction
⇒Th-228 <0.1 – 5, typically <2 mBq/kg

MC ⇒ cryostat + copper shield + LAr
$<2 \cdot 10^{-4}$ cts / (keV·kg·y)

NIM A593 (2008) 448, NIM A606 (2009) 790



Cryostat: Rn emanation

Measurements of Rn emanation [a] at various fabrication/installation steps with MoREx[b]

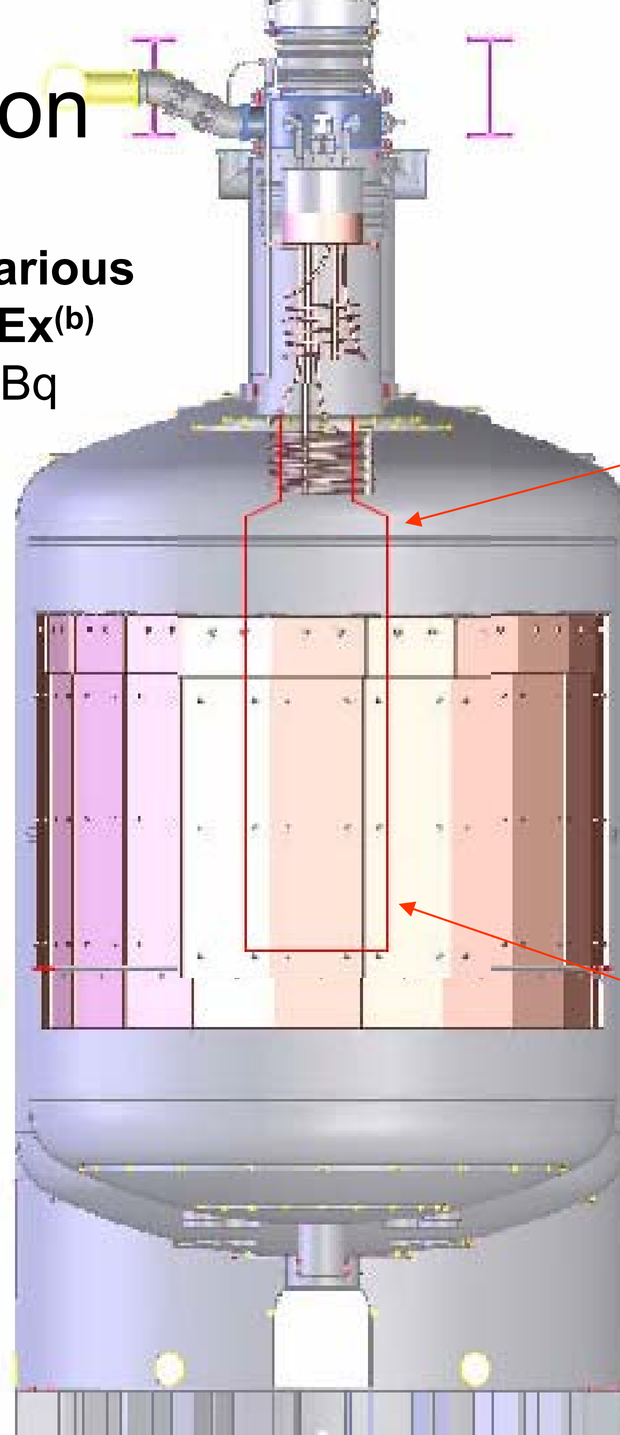
after 1./2. cleaning	23±4 / 14±2 mBq
after copper mount	34±6 mBq
after 3. cleaning	31±2 mBq
after cryogenics mount	55±4 mBq**

**evidence: ^{222}Rn concentrated in neck!

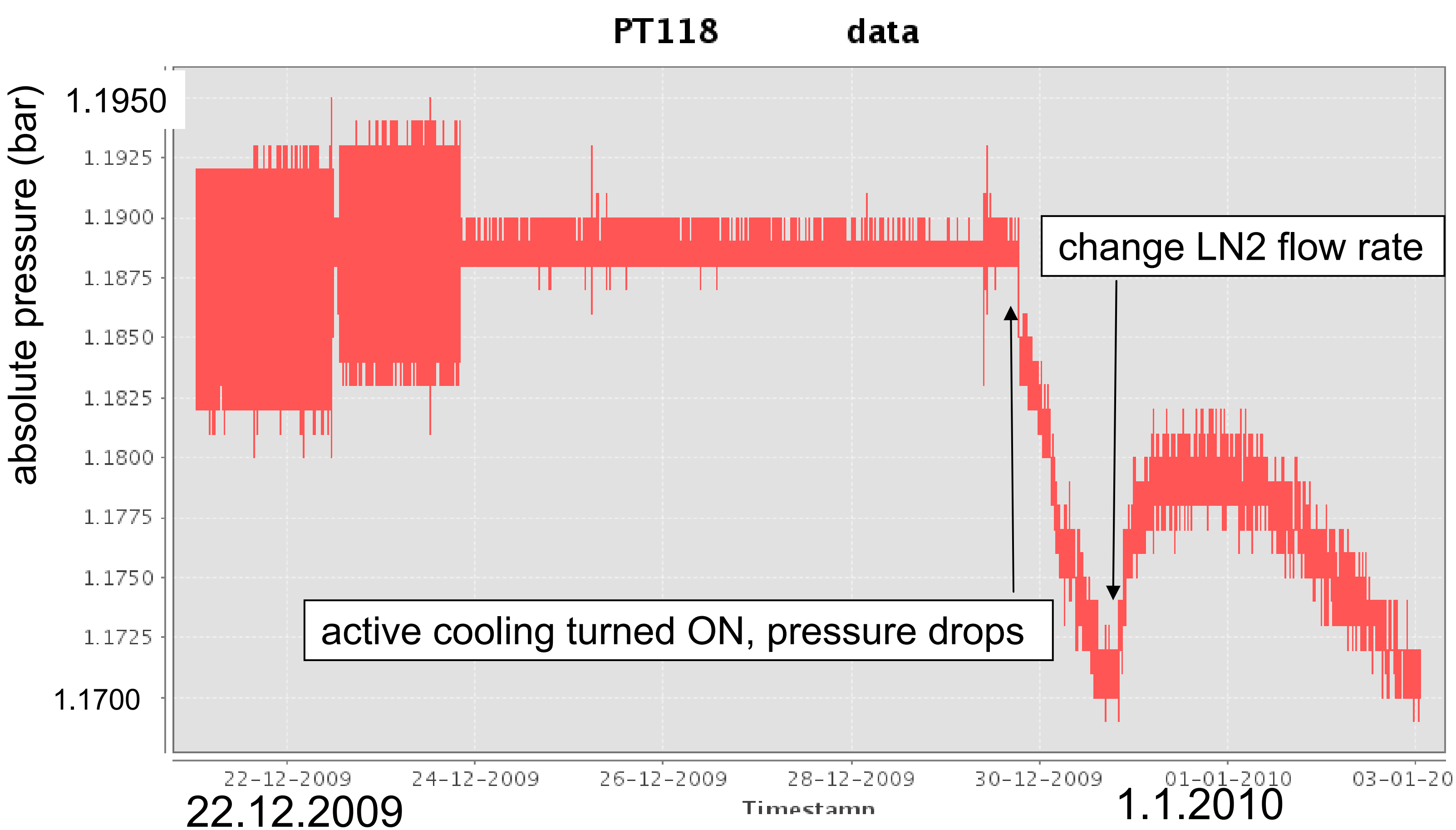
Rn shroud: 30 µm copper
Ø 0.8m , 3 m height
to prevent convective transport of Rn from walls/copper to Ge diodes
BI ~ 1.5 10^{-4} cts / (keV·kg·y)

[a] Uniform ^{222}Rn distribution of 8 mBq implies b = 10^{-4} cts/(keV kg y) in phase I.

[b] Appl.Rad.Isot. 52(2000) 691



Cryostat filling with LAr in Nov/Dec ‘09



Cryogenic commissioning successful!
Active cooling operational since Jan. ’10,
Stable operations - no loss of argon