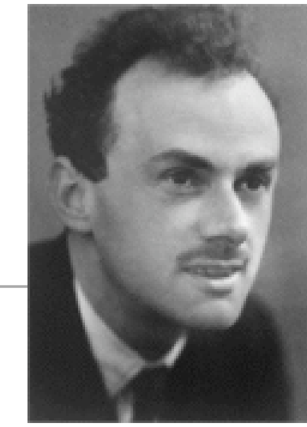
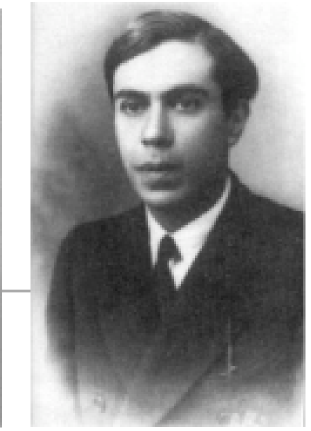
The GERDA Experiment

3rd CHIPP Swiss Neutrino Workshop

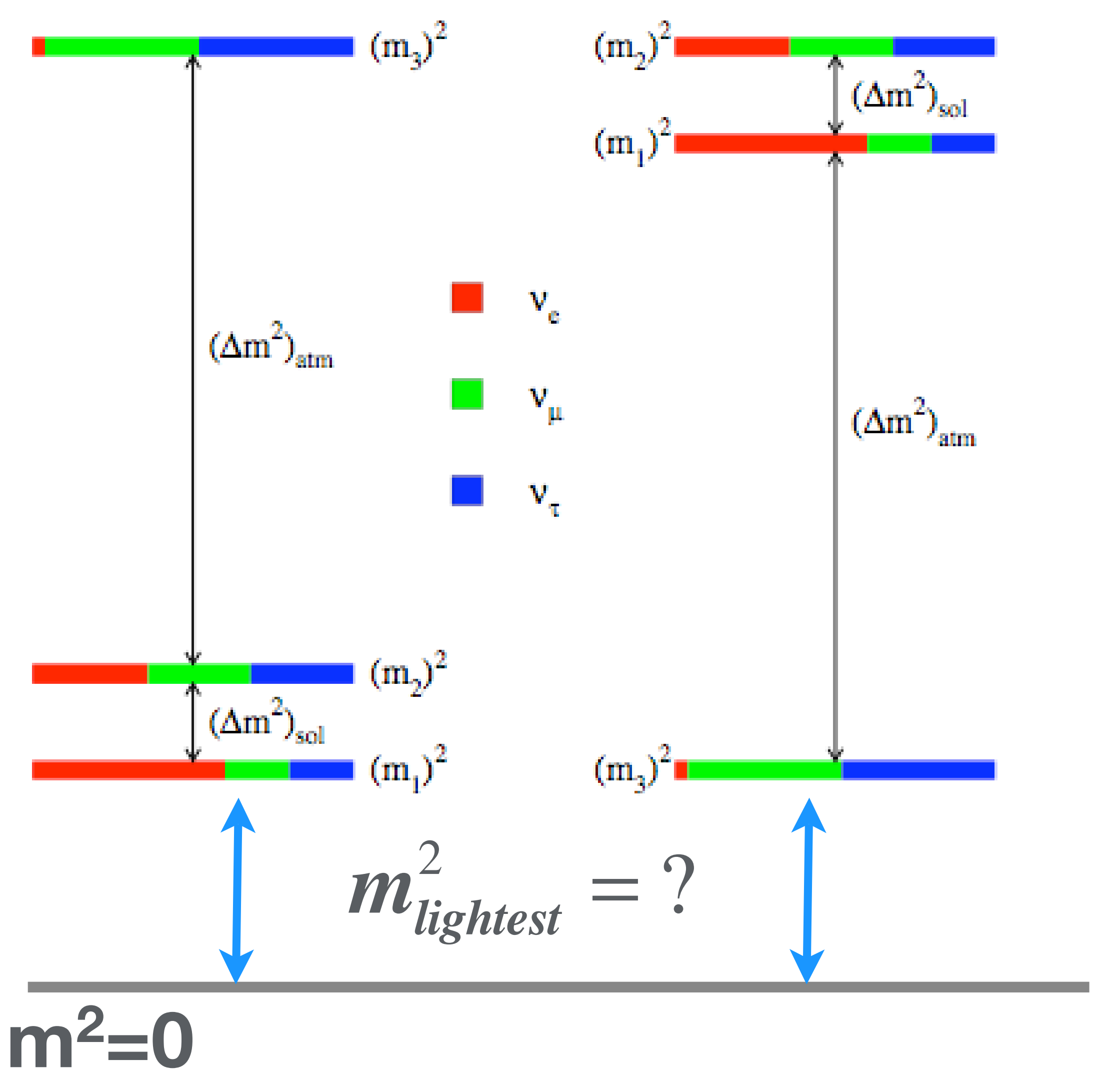
Laura Baudis, Physik Institut, Universität Zürich
(for the GERDA Collaboration)

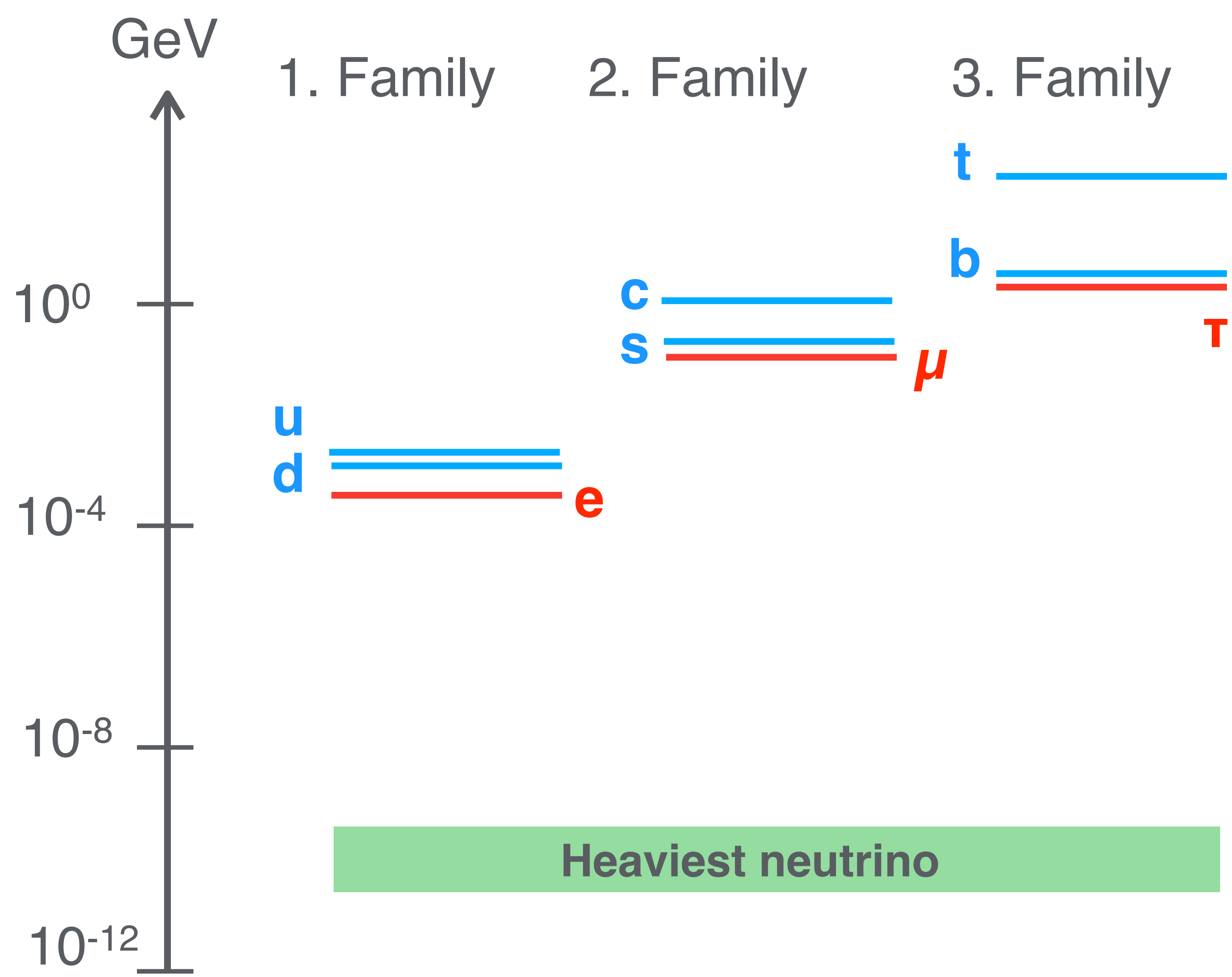
Goal of GERDA





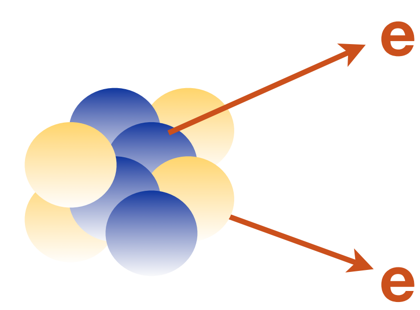
- **Search for the neutrinoless double beta decay in ^{76}Ge**
  - ➡ information on the absolute mass scale of neutrinos
  - ➡ information on the Majorana vs Dirac nature of neutrinos





Neutrinoless Double Beta Decay

- **Not allowed in the Standard Model:** ΔL =2

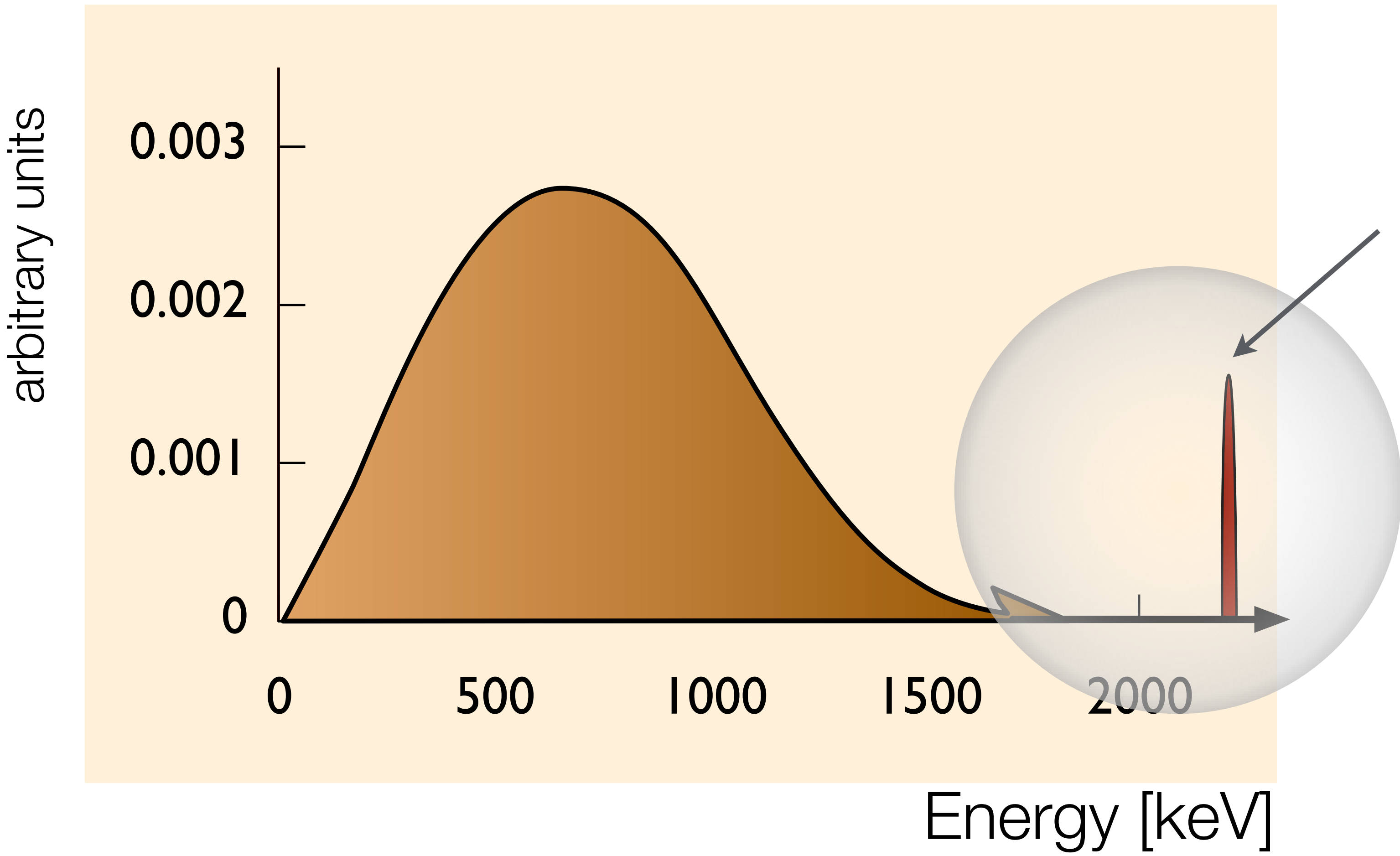


L = 0

$$2n \rightarrow 2p + 2e^-$$

$$2p \rightarrow 2n + 2e^+$$

L = 2



Expected signature:
peak at the Q-value of the decay

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

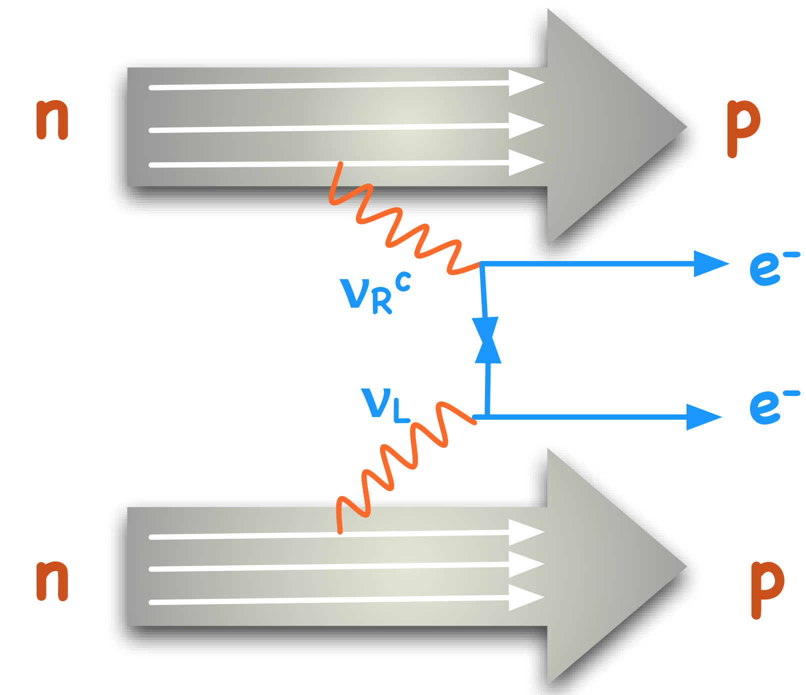
Neutrinoless Double Beta Decay

- **The expected rate $(T_{1/2})^{-1}$ is:**

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

phase space integral

matrix element



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

$$\langle m_{\nu e}\rangle = \left|\sum_i U_{ei}^2 m_i\right|$$ effective Majorana neutrino mass

U_{ei} neutrino mixing matrix (complex)

Experimental Requirements

- **Experiments measure the half life of the decay ($T_{1/2}$)**

$$T_{1/2}^{0\nu} \propto a \cdot \varepsilon \cdot \sqrt{\frac{M \times t}{\Delta E \times B}}$$

the sensitivity depends on:

➡ a = enrichment

➡ ε = detector efficiency for observing the e^-

➡ M = mass

➡ t = measuring time

➡ ΔE = energy resolution at the Q-value of the decay

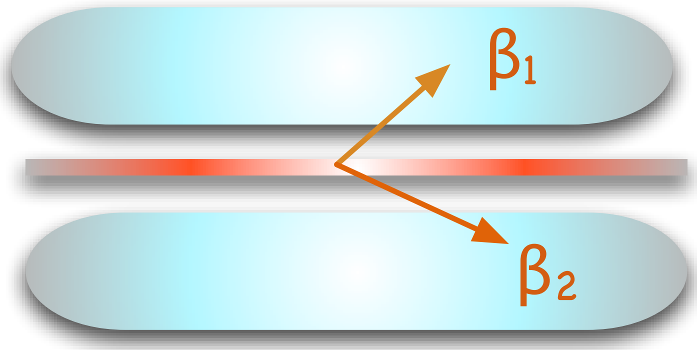
➡ B = background in the relevant energy region

large detector masses
enriched materials
ultra-low background
excellent energy resolution

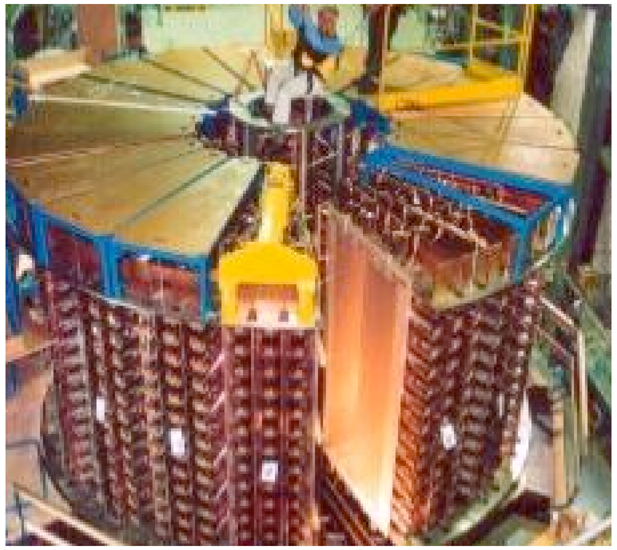
$$\frac{1}{\sqrt{T_{1/2}^{0\nu}}} \propto \langle m_{\nu e} \rangle$$

Experiments: Two Main Approaches

Souce ≠ Detector

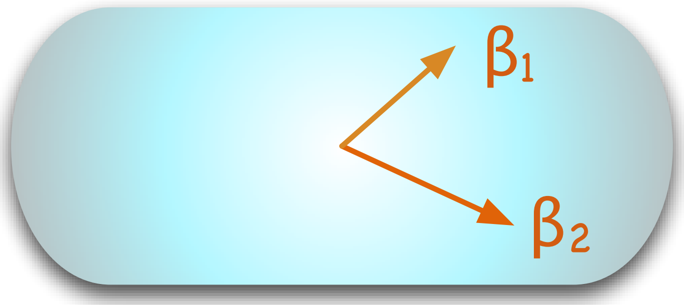


Source as thin foil
Electrons are detected with: scintillator, TPC, drift chamber, semiconductor detectors

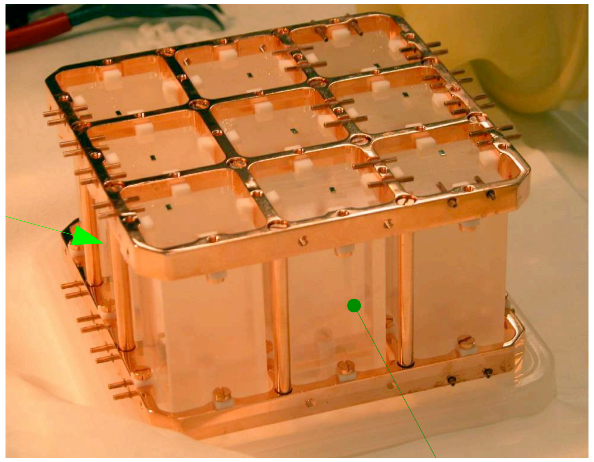


NEMO (Modane/Frejus)

Source = Detector (calorimeters)



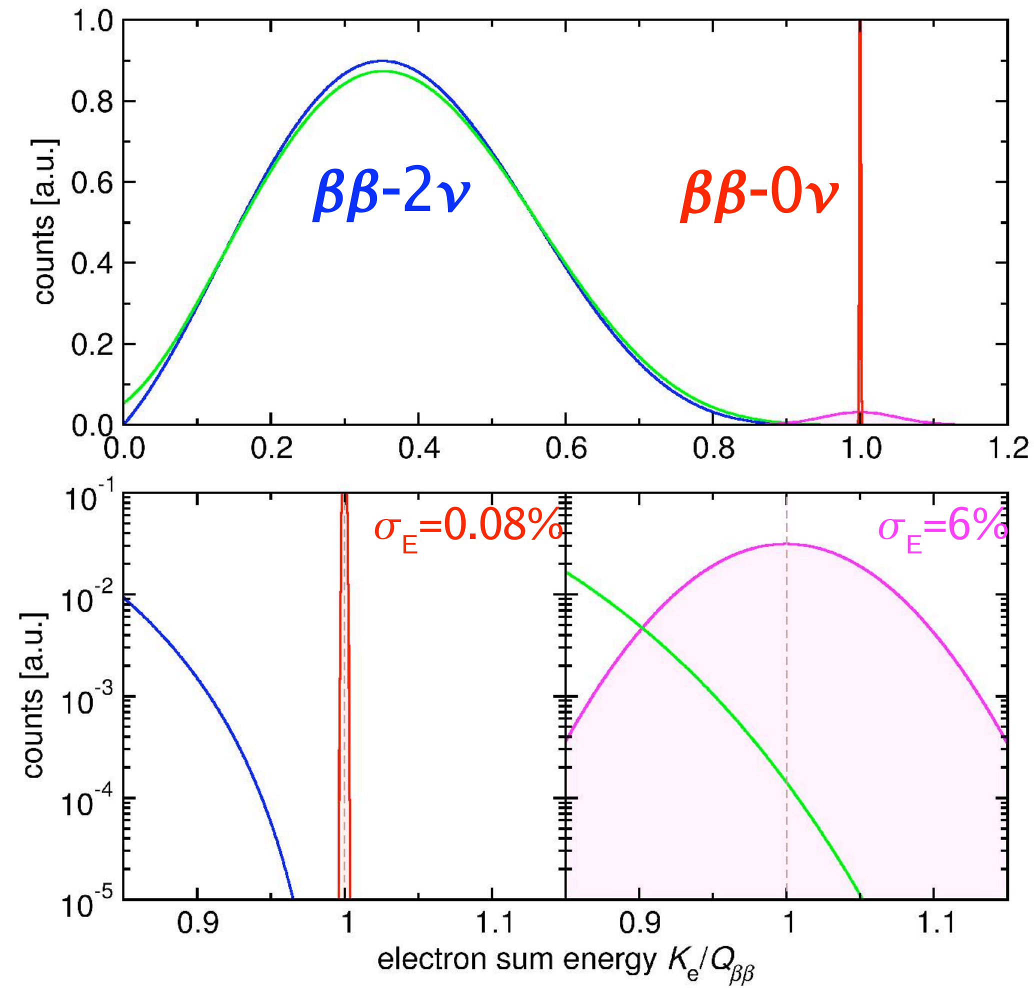
The sum of the energy of the two electrons is measured
Signature: peak at the Q-value of the decay
Scintillators, semiconductors, bolometers



CUORICINO (LNGS/Italy)

Backgrounds for Double Beta Experiments

- primordial radionuclides (^{238}U, ^{232}Th, ^{40}K) in the detector materials, in the shielding and the concrete/rock (alpha, beta, gamma and neutrons)
- cosmic activation of detector materials (zB. ^{60}Co, ^{54}Mn, ^{65}Zn,...)
- cosmic rays (muons)
- radon in air, radon emanation of materials,....



and

ββ2ν-events: irreducible background!

=> **an excellent energy resolution of the detector is crucial**

Limits on the Effective Majorana Neutrino Mass

Candidate, $Q_{\beta\beta}$ [keV]	Half life [years]	$\langle m_\nu \rangle$ [eV]
^{48}Ca, 4271	> 9.5 x 10^{21}	< 8.3
^{76}Ge, 2039	**> 1.9 x 10^{25}**	**< 0.35**
^{82}Se, 2995	> 2.7 x 10^{22}	< 5
^{100}Mo, 3034	> 5.5 x 10^{22}	< 2.1
^{116}Cd, 2805	> 7.0 x 10^{22}	< 2.6
^{130}Te, 2530	**> 3.0 x 10^{24}**	**< 0.38 - 0.58**
^{136}Xe, 2476	> 4.4 x 10^{23}	< 1.8 - 5.2
^{150}Nd, 3367	> 1.2 x 10^{21}	< 3

The Heidelberg-Moscow Experiment

- **5 HPGe crystals at LNGS**
- ^{76}Ge, with a = 87% (a_{nat} = 7.4%) active mass: 11 kg
- **Exposure (1990-2003): 71.7 kg yr**

➡ ~ 10^5 2νββ events

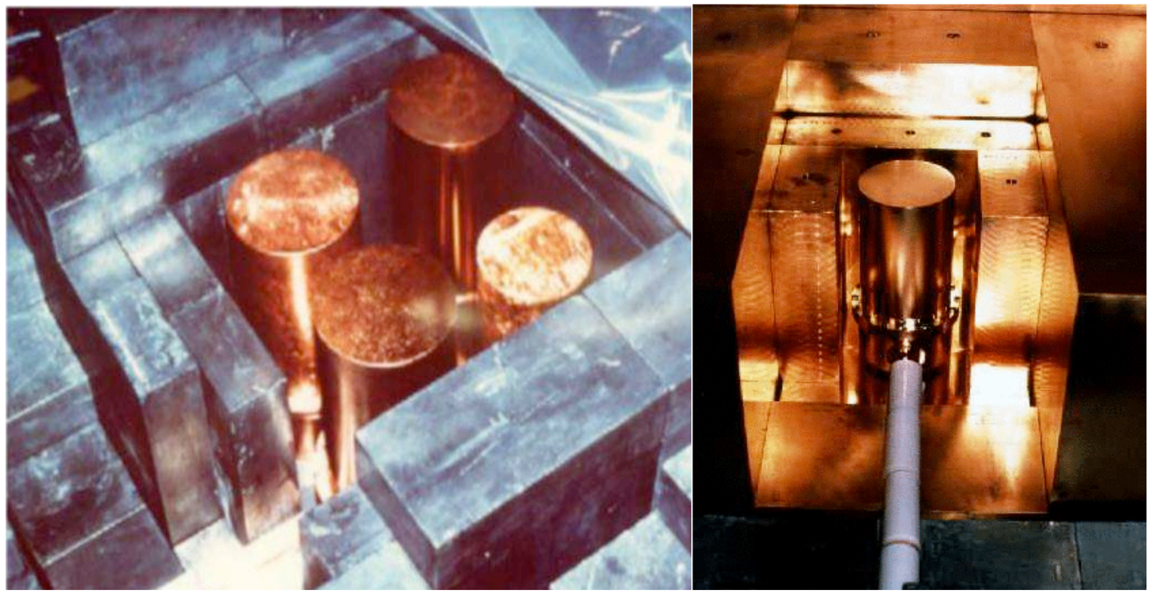
$$T_{1/2}^{2\nu} = 1.74 \times 10^{21}\, yr$$

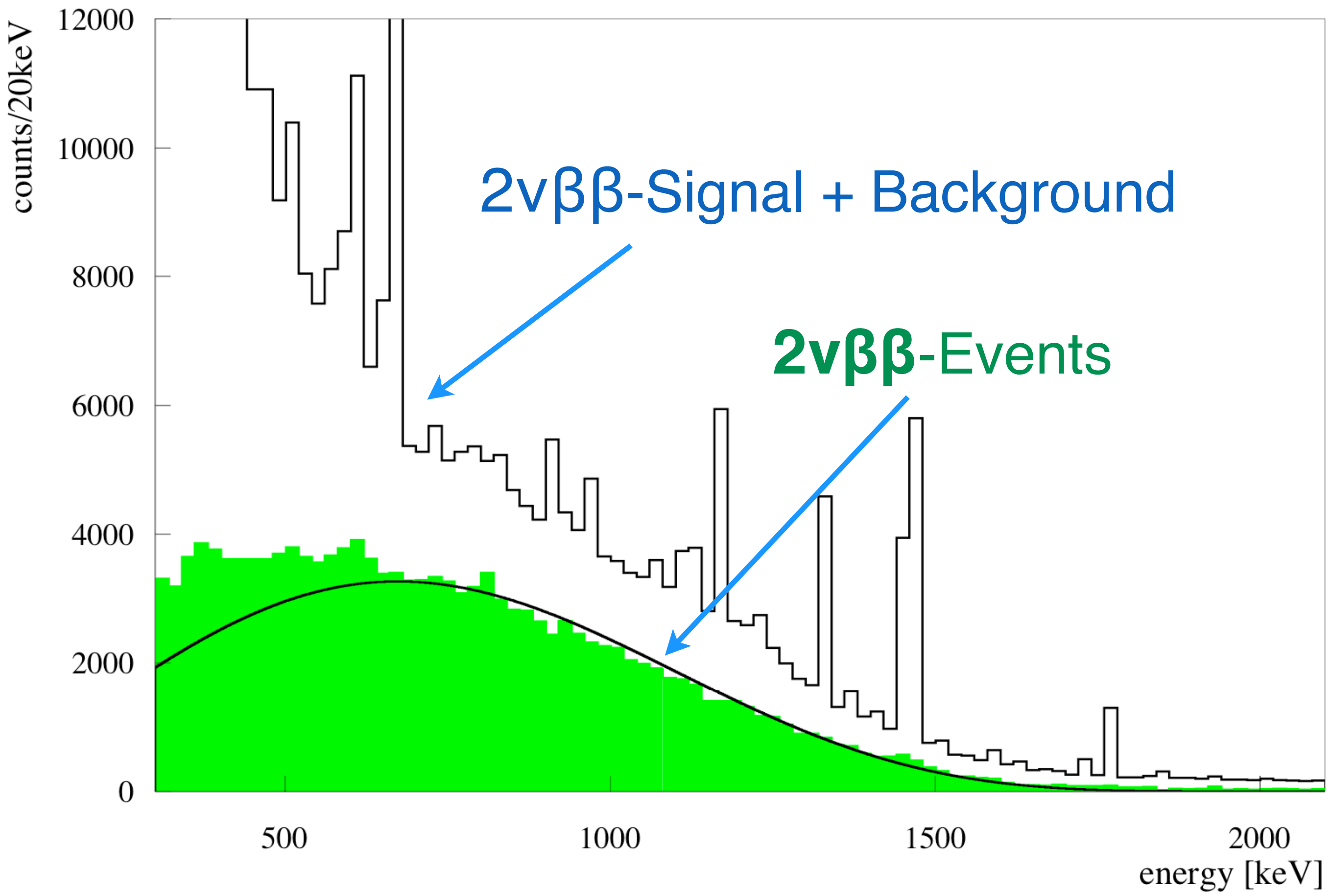
- **Background in the 0νββ-region:**

➡ 0.11 events/(kg keV yr)

$$T_{1/2}^{0\nu} > 1.9 \times 10^{25}\, yr$$

$$\langle m_{\nu e} \rangle < 0.35 eV \qquad 90\%CL$$



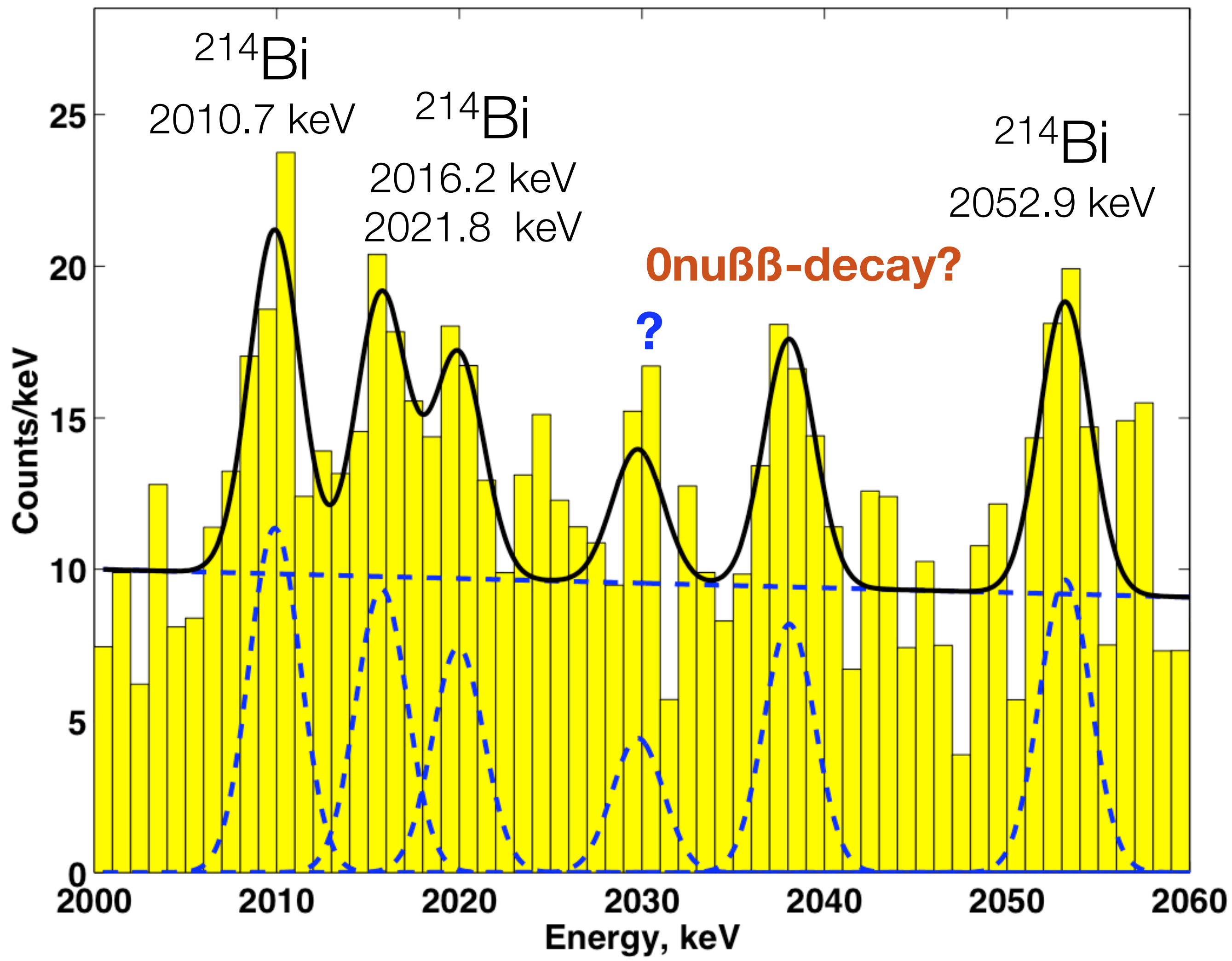


Evidence for the Neutrinoless Decay Mode?

- **Peak at the Q-value of the decay**

$$T_{1/2}^{0\nu} = 1.2 \times 10^{25}\ yr$$

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



- Period 1990-2003: **28.8 ± 6.9 events**
- Period 1995-2003: **23.0 ± 5.7 events**

➡ 4.1- 4.2 σ evidence

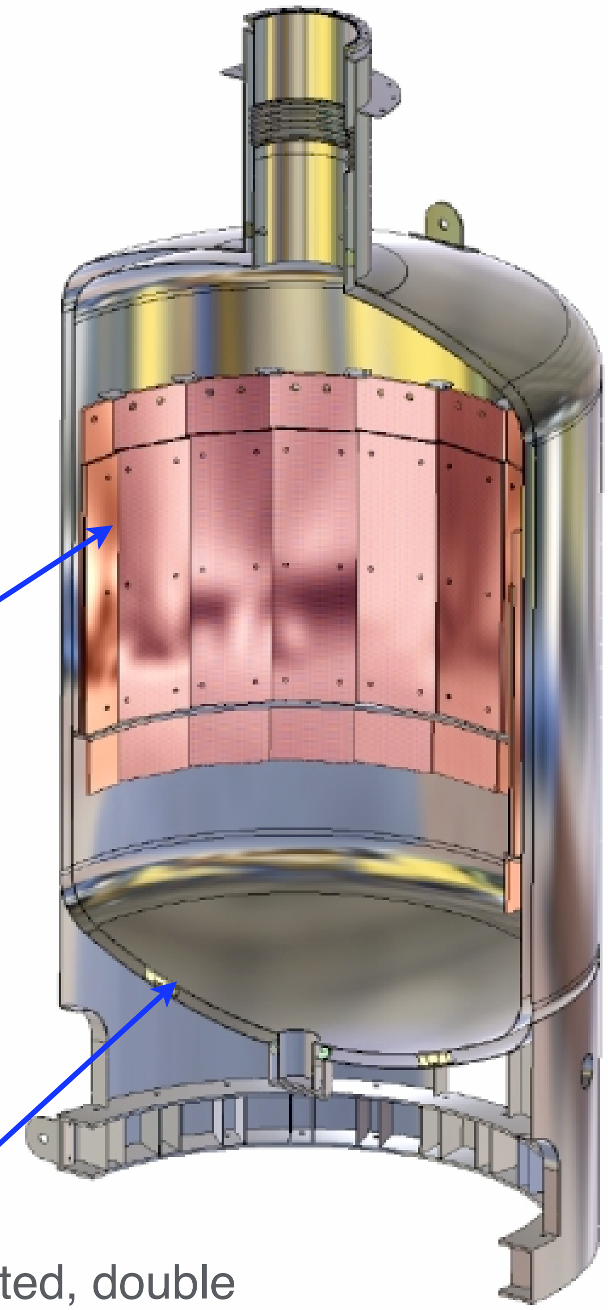
$$\langle m_{\nu e} \rangle = 0.44\ eV \quad (0.3 - 1.24)\ eV$$

- **'Evidence' remains unclear**

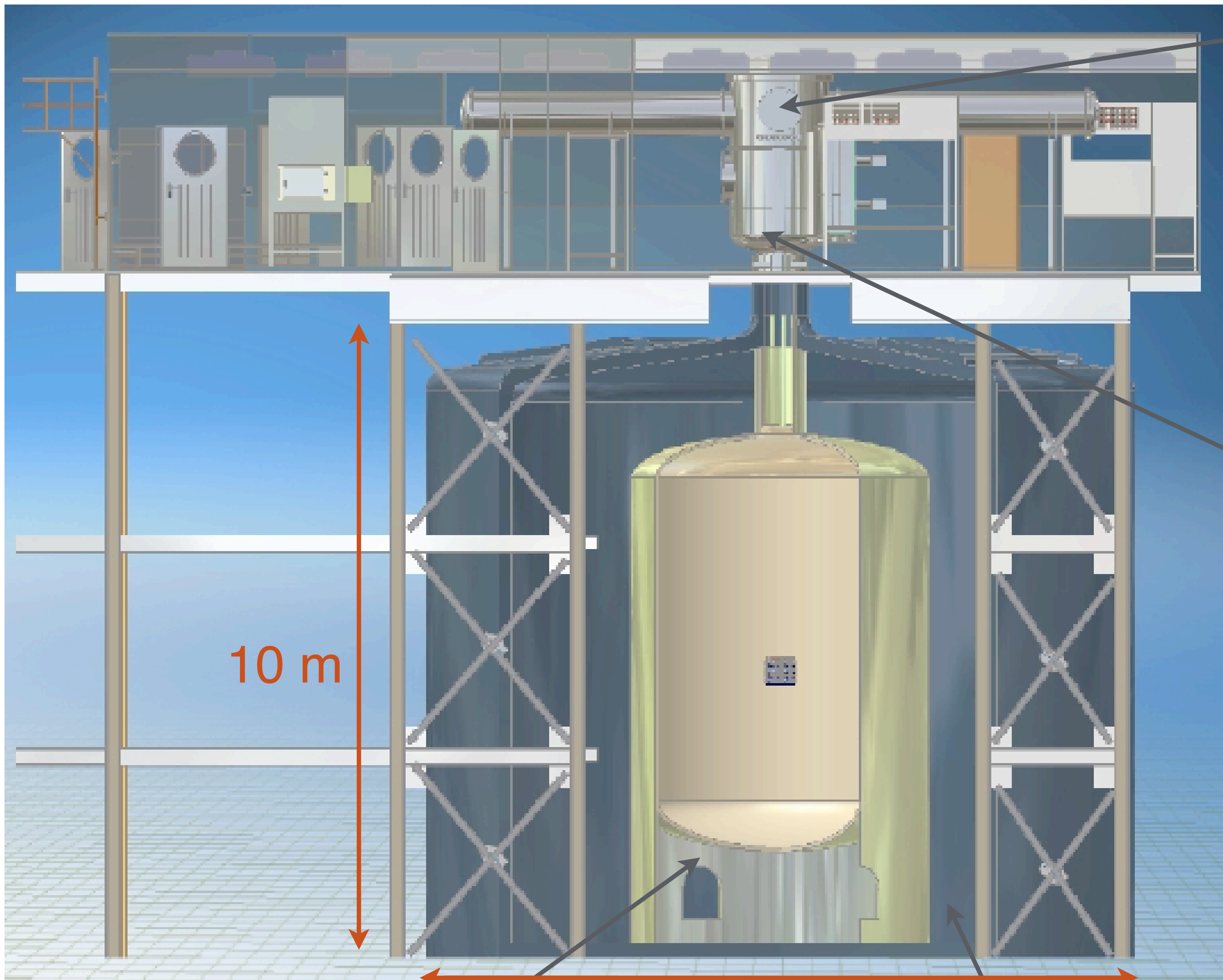
➡ **it should be tested with larger, increased sensitivity experiments**

The GERDA Experiment

- **Idea: operate bare HPGe-crystals in liquid argon (LAr) cryostat**
  - ➡LAr: shielding against external background (gamma, neutrons)
  - ➡LAr: cooling medium for the Ge diodes (~ 87 K)
- **Internal background:**
  - ➡minimize amount of material close to crystals
  - ➡minimize exposure to cosmic rays
  - ➡use pulse shape information of events
- **If LAr is instrumented with photo detectors:**
  - ➡ additional background rejection through Ge-LAr coincidences



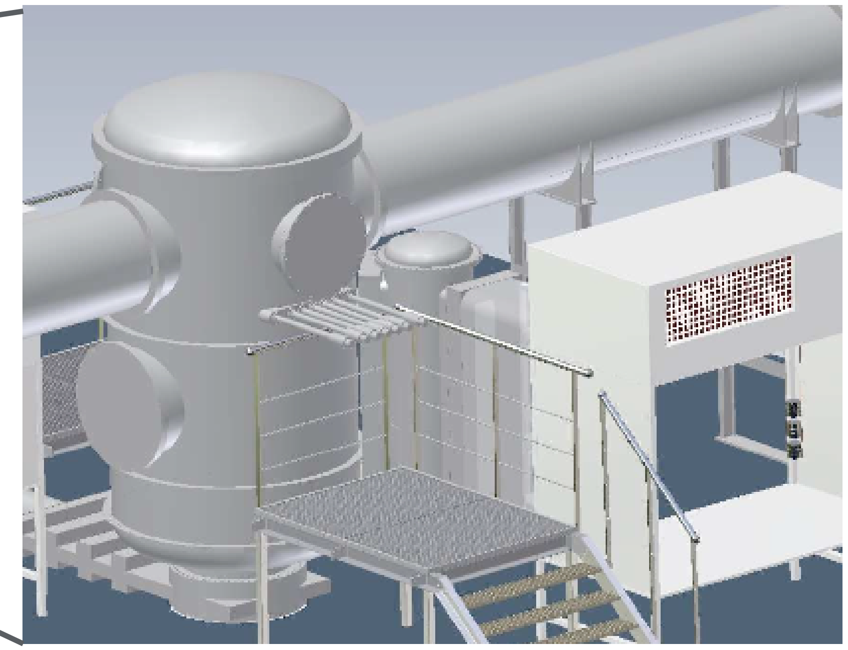
The GERDA Experiment: Schematic View



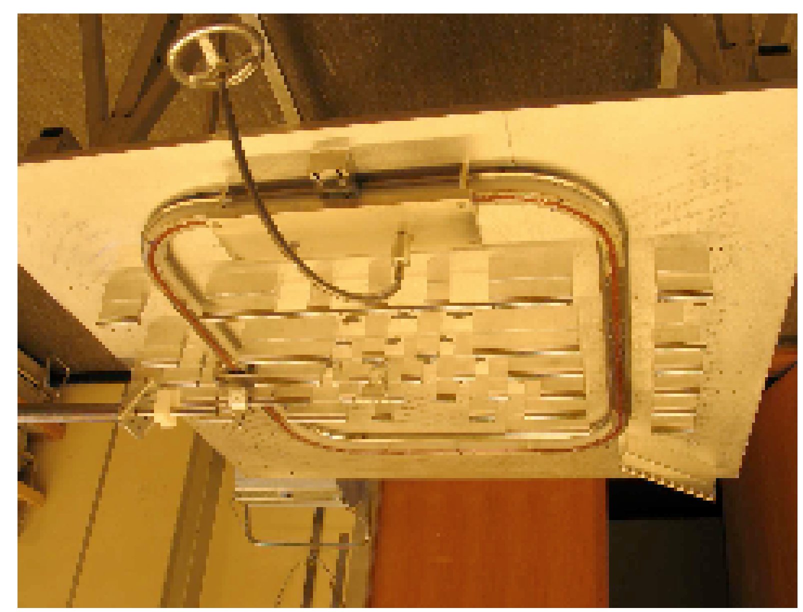
10 m

Stainless cryostat
($65\ m^3$ LAr)

Water tank
($650\ m^3$ H_2O; 66 PMTs as veto for muons)



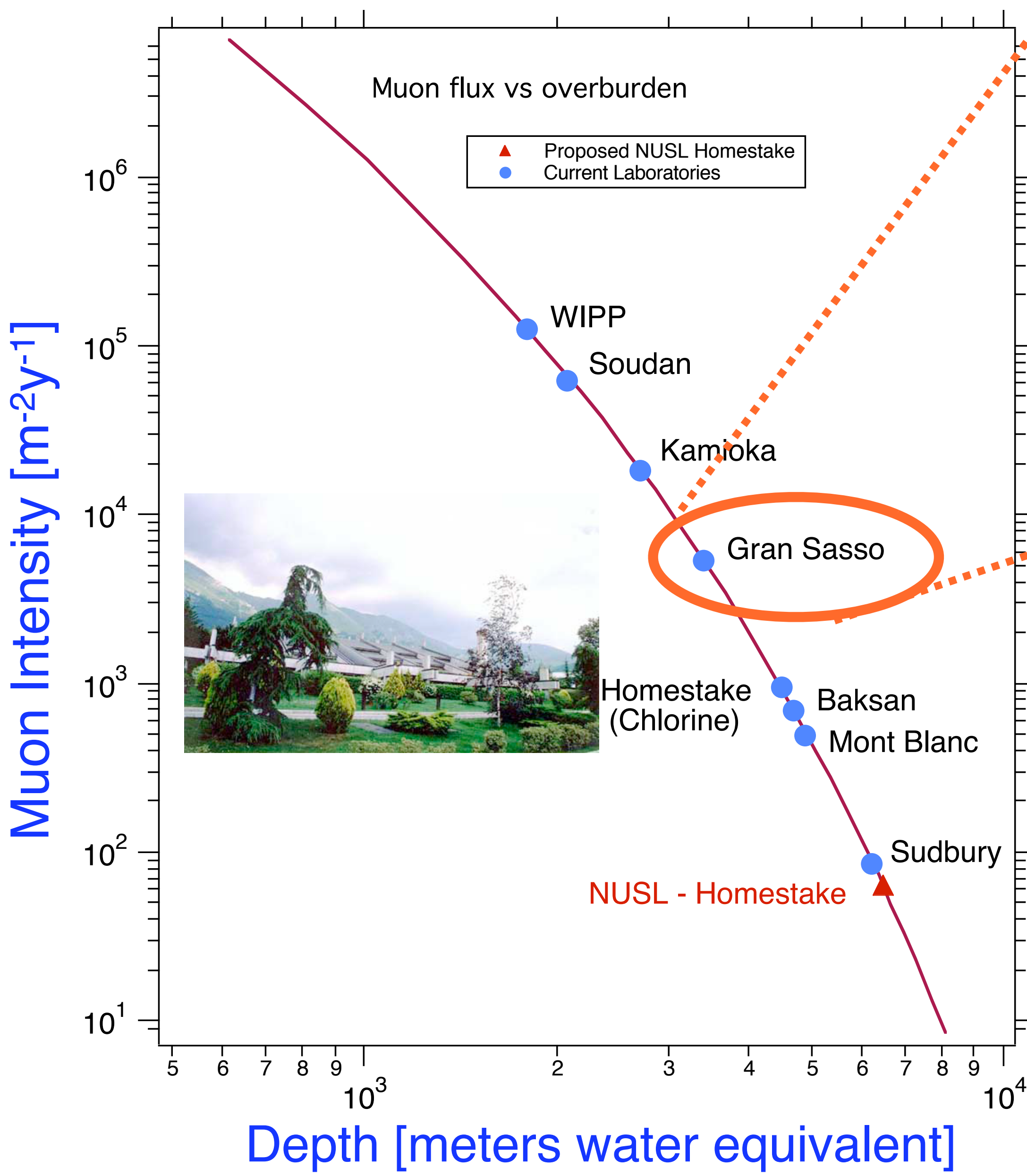
Lock system

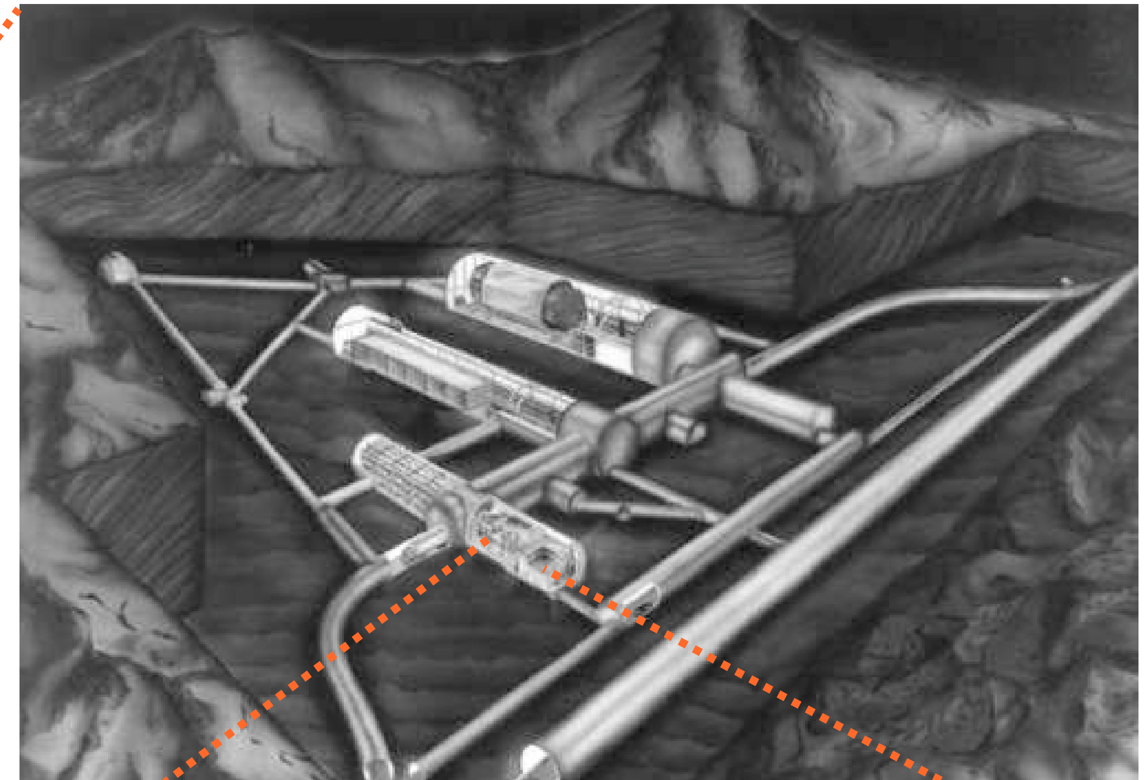


Rail system for detector strings

The GERDA Experiment at the Gran Sasso Lab

- ~3100 m.w.e; muon flux ≈ 1 m^{-2} h^{-1}





The GERDA Collaboration

INFN LNGS, Assergi, Italy
A. di Vacri, M. Junker, M. Laubenstein, C. Tomei, L. Pandola

Univ. of Dresden, Germany
K. Zuber

JINR Dubna, Russia
S. Belogurov, V. Brudanin, E. Egorov, K. Gusev, S. Katulina. A. Klimenko, O. Kochetov, I. Nemcheok, V. Sandukovsky, A. Smolnikov, J. Yurkowski, S. Vasiliev

MPIK Heidelberg, Germany
C. Bauer, O. Chkvorets, W. Hampel, G. Heusser, W. Hofmann, J. Kiki, K.T. Knöpfle, P. Pfeiffer, S. Schönert, J. Schreiner, B. Schwingenheuer, H. Simgen, G. Zuzel

Jagiellonian University, Krakow, Poland
M. Wojcik

Univ. di Milano Bicocca e Universita degli Studi e INFN, Italy
E. Belotti, C. Cattadori, A. Pullia, S. Riboldi, F. Zocca

INR, Moscow, Russia
I. Barabanov, L. Bezrukov, A. Gangapshev, V. Gurentsov, E. Kusminov, E. Yanovich

Institute for Reference Materials, Geel, Belgium
J. Gasparo, M. Hult, G. Marissens

ITEP Physics, Moscow, Russia
V.P. Bolotsky, E. Demidova, I.V. Kirpichnikov, A.A. Vasenko, V.N. Kornoukhov

Kurchatov Institute, Moscow, Russia
A.M. Bakalyarov, S.T. Belyaev, M.V. Chirchenko, G.Y. Grigoriev, L.V. Inzhechik, V.I. Lebedev, A.V. Tikhomirov, S.V. Zhukov

MPP, München, Germany
I. Abt, M. Altmann, C. Büttner, A. Caldwell, R. Kotthaus, X. Liu, H.G. Moser, R.H. Richter

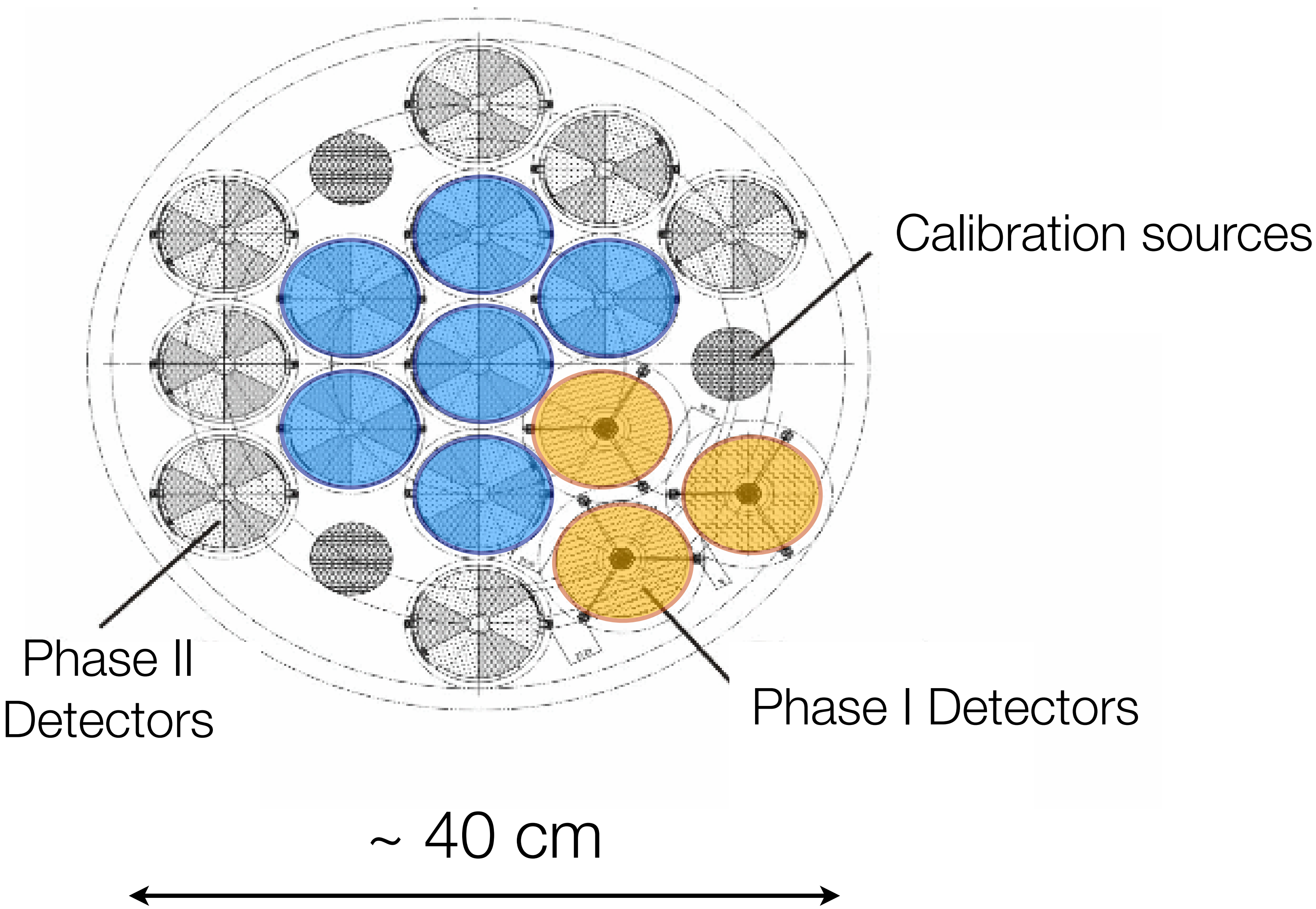
Univ. di Padova e INFN, Italy
A. Bettini, E. Farnea, C. Rossi Alvarez, C.A. Ur

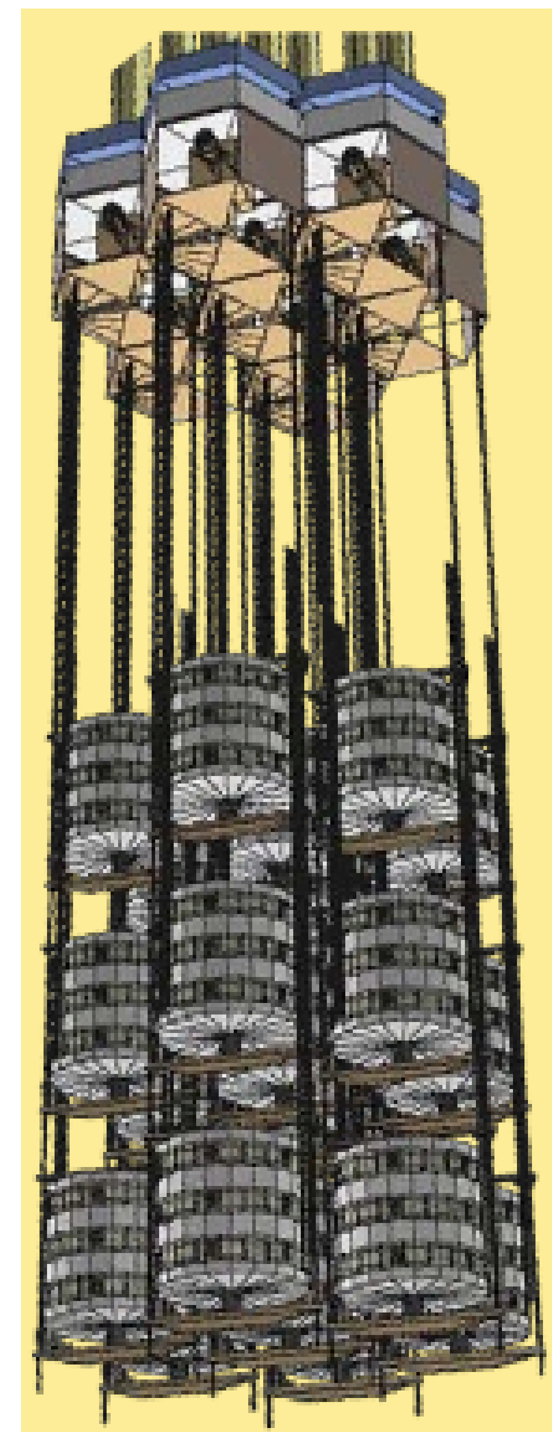
Univ. Tübingen, Germany
M. Bauer, H. Clement, P. Grabmayer, J. Jochum, S. Scholl, K. Rottler

Univ. of Zürich, Switzerland
L. Baudis, A. Ferella, F. Froborg, R. Santorelli, M. Tarka

17 Institutions, 6 Countries

The GERDA Detector Array





Phase I detectors (~18 kg, 8 x ^{76}Ge)

Phase II detectors (~22 kg, 14 x ^{76}Ge)

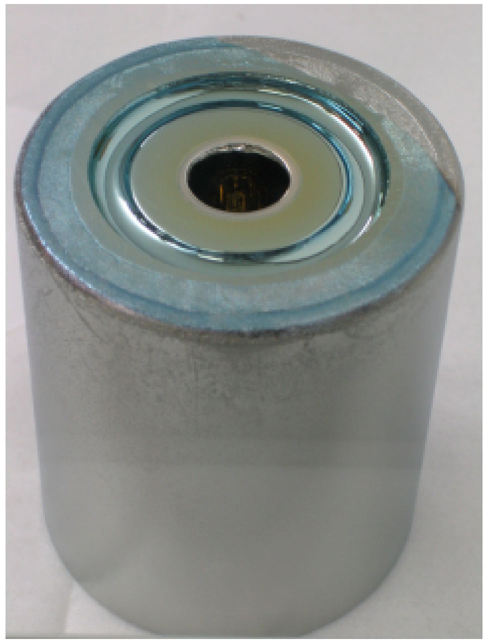
GERDA Phase I

- **8 enriched ^{76}Ge detectors (Heidelberg-Moscow and IGEX) ~ 18 kg**
  (+ 6 non-enriched HPGe, 15 kg)
- Planned exposure = **30 kg yr**
- Background: **B ≈10^{-2} events/(kg keV yr)**

➡**Sensitivity reach:**

$$T_{1/2}^{0\nu} > 3.0 \times 10^{25}\ yr$$

$$\langle m_{\nu e} \rangle < 0.27 eV$$



- **If Klapdor-Kleingrothaus signal is true, the expectation for GERDA is:**

➡ 13 signal events and 3 background events in ΔE = 10 keV interval around tthe Q-value of the decay (Q = 2039 keV)

$$\langle m_{\nu e} \rangle \approx 0.40 eV$$

Background Predictions for GERDA Phase I

- From measured activities of material plus Monte Carlo simulations based on MaGe
- MaGe (Gerda-Majorana): Geant4 based, developed together with Majorana

Source	**B [10^{-3} events/(keV kg yr)]**
External gammas from ^{208}Tl (^{232}Th)	<1
External neutrons	<0.05
Muons (Veto)	<0.2
Int. ^{68}Ge ($T_{1/2}$ = 270 d)	**12**
Int. ^{60}Co ($T_{1/2}$ = 5.27 yr)	**2.5**
^{222}Rn in LAr	<0.2
^{208}Tl, ^{238}U in crystal holders	<1
Surface contamination	<0.6

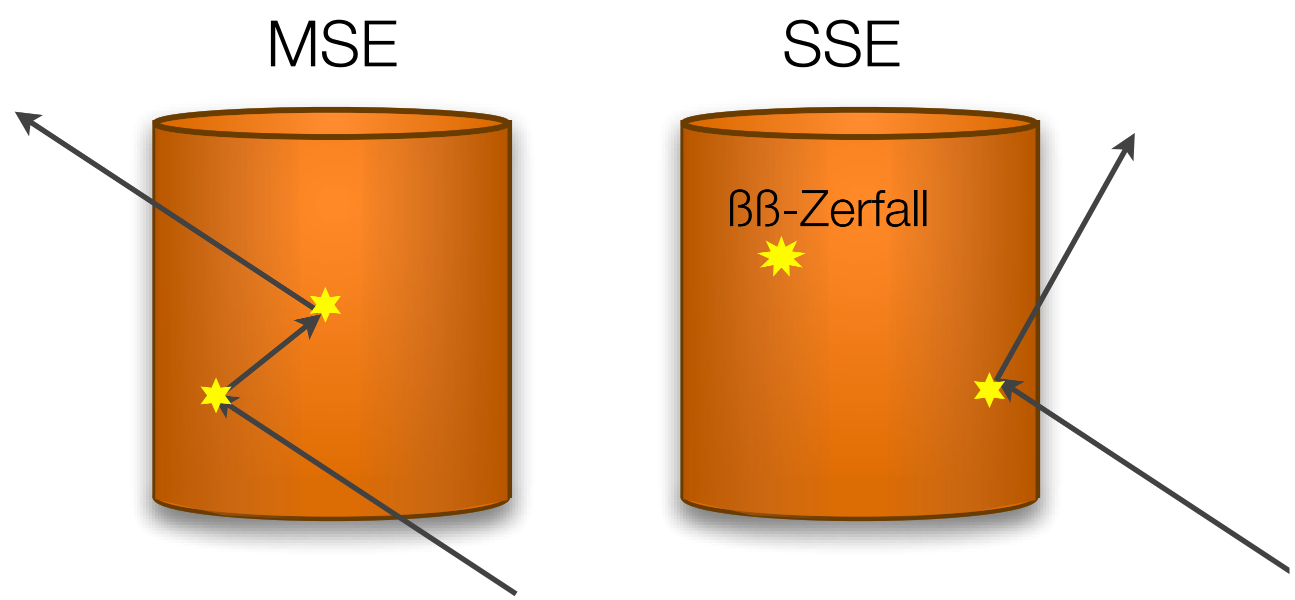
After Muon-Veto

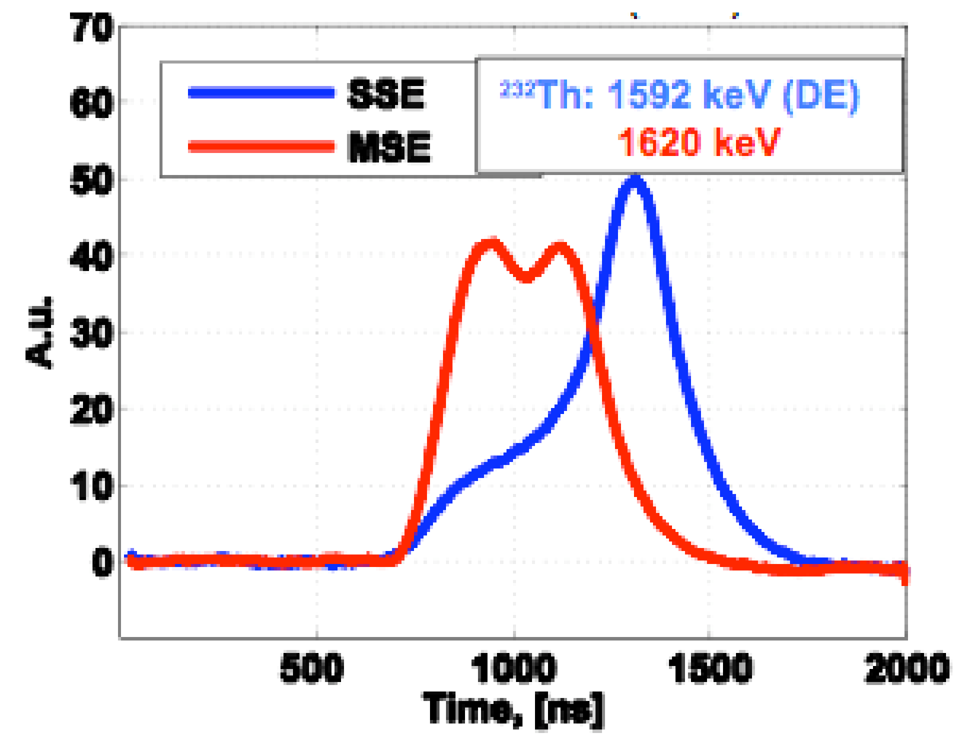
180 days exposure at the Earth surface after enrichment
+ **180** days de-activation below ground

30 days exposure after crystal growing

Background GERDA Phase I

- **further BG suppression by pulse shape analysis**

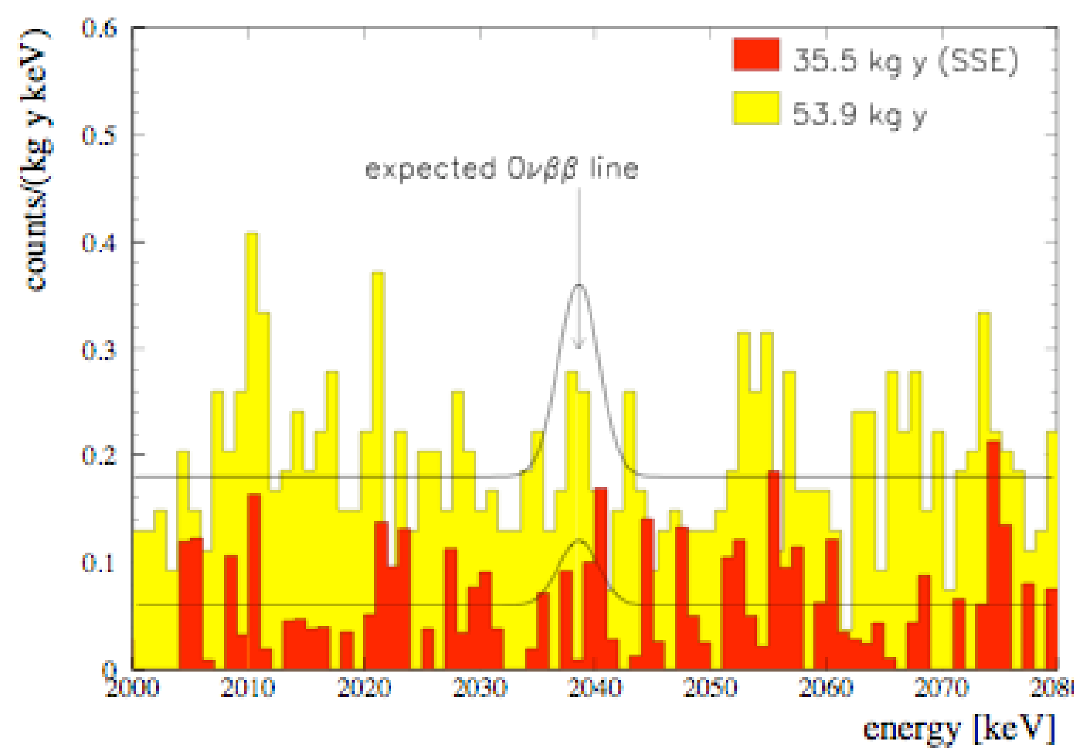




- for instance, in Heidelberg-Moscow:

  background reduction in the ββ region:

  ➡ **~ Faktor 3**



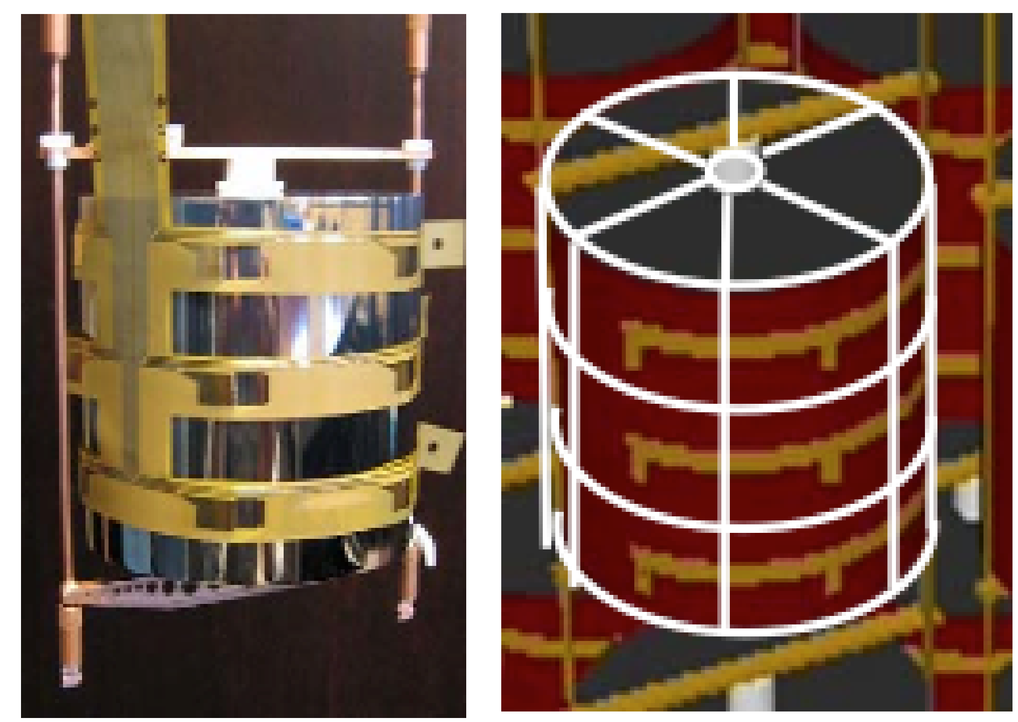
GERDA Phase II

- **14 ^{76}Ge, 18-fold segmented detectors + 8 phase-I detectors, 40 kg**
- Exposure = **150 kg yr**, Background **B =10^{-3} events/(kg keV yr)**

➡ **sensitivity reach:**

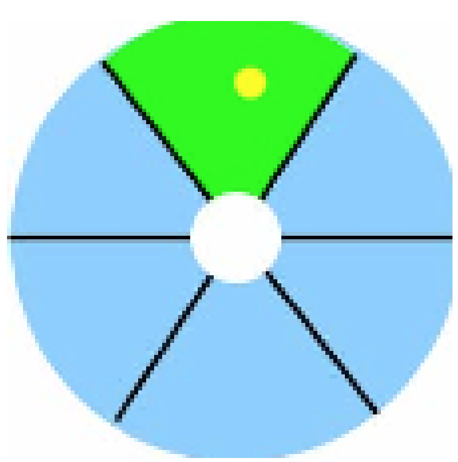
$$T_{1/2}^{0\nu} > 15 \times 10^{25}\ yr$$

$$\langle m_{\nu e} \rangle < 0.11 eV$$



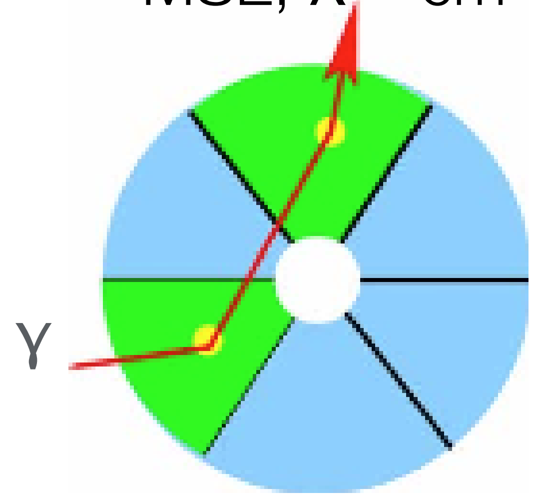
segmentation: 6 (φ) x 3 (z)

SSE, λ ~ mm



ββ - events

MSE, λ ~ cm

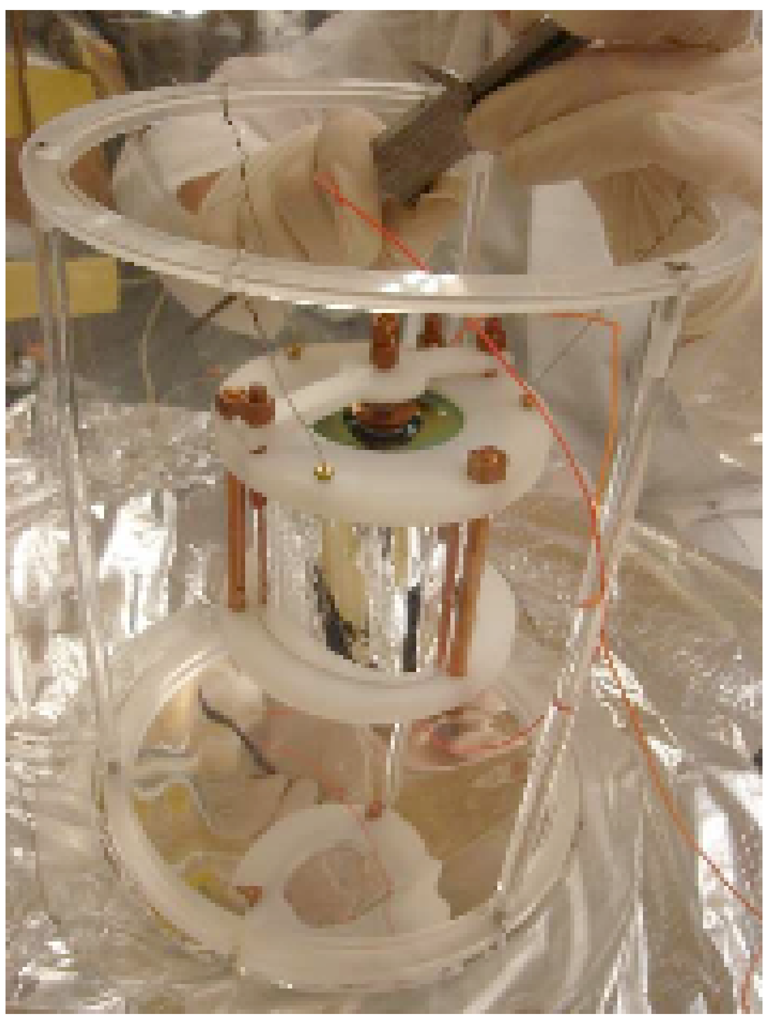


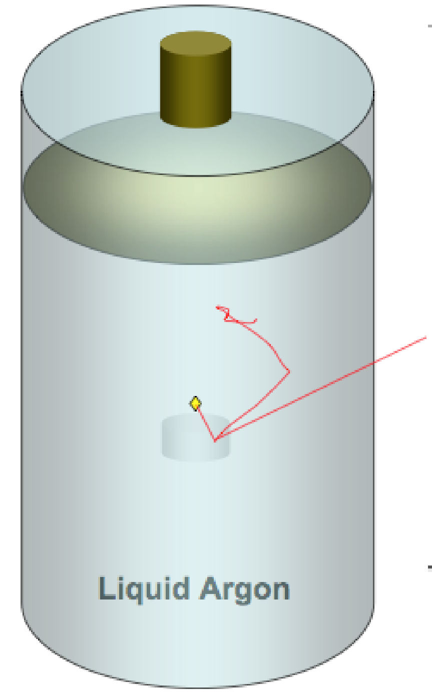
gamma background

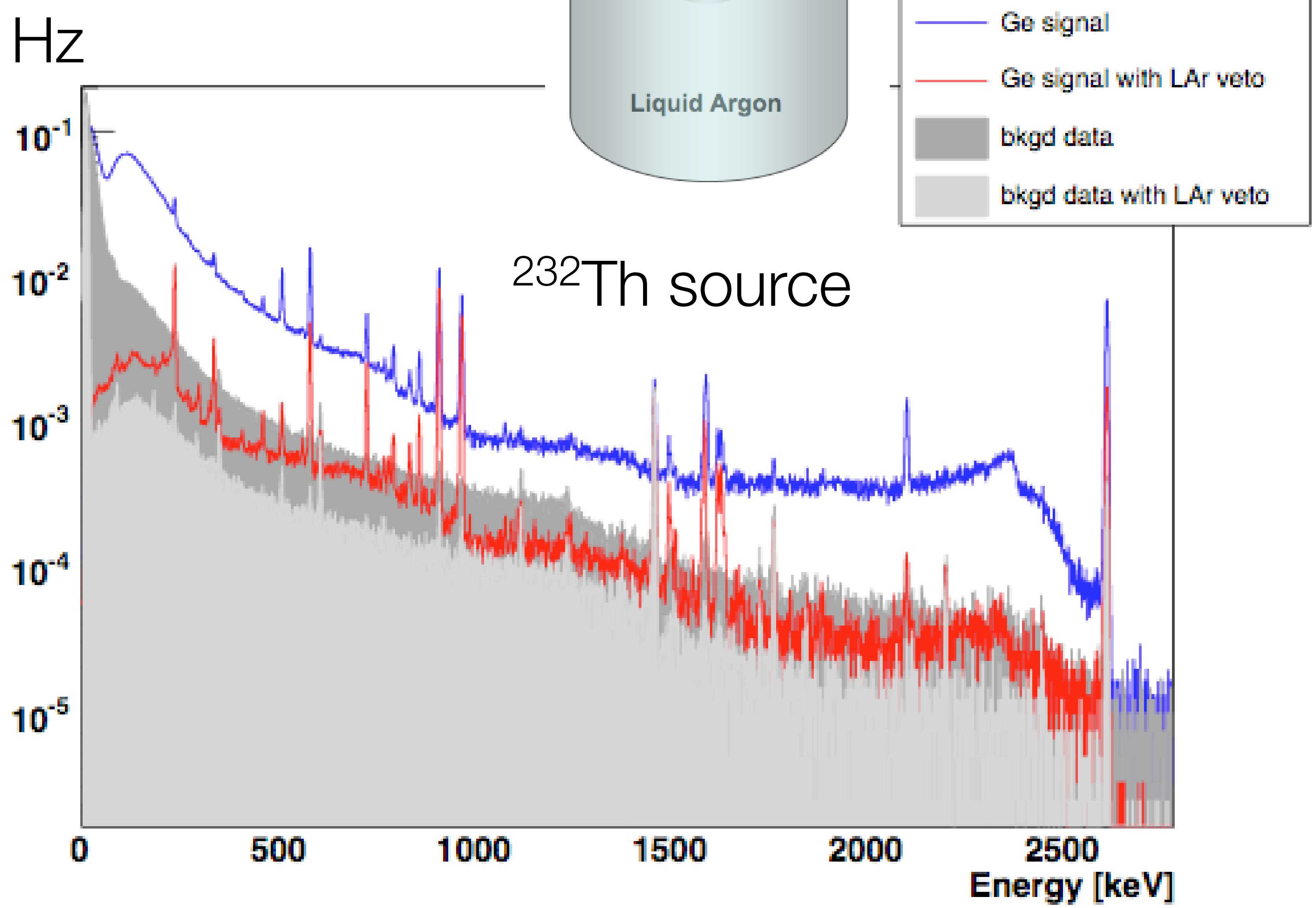
segmentation:
distinction between single-site (SSE) and multiple-site (MSE) events

Background Reduction with LAr-Veto

- **Preliminary tests and Monte Carlo simulations yield:**
  - ➡ ~ **Factor 300** in the ββ-energy region

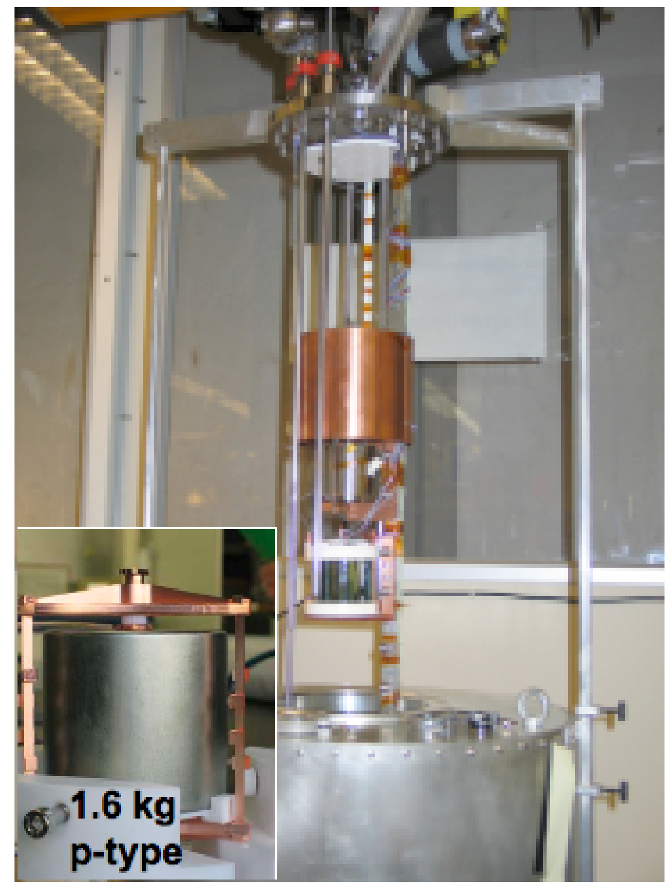






Tests of the GERDA Phase I Detectors

- At Gran Sasso GERDA Detector Lab (GDL)
- 17.9 kg enriched and 15 kg non-enriched
- define detector handling procedures
    - ➡ **> 40 cooling cycles in LAr**
- measure the leakage currents (LC)
    - ➡ after irradiation with gamma sources
    - ➡ **operation with LC ~ 10 pA feasible**

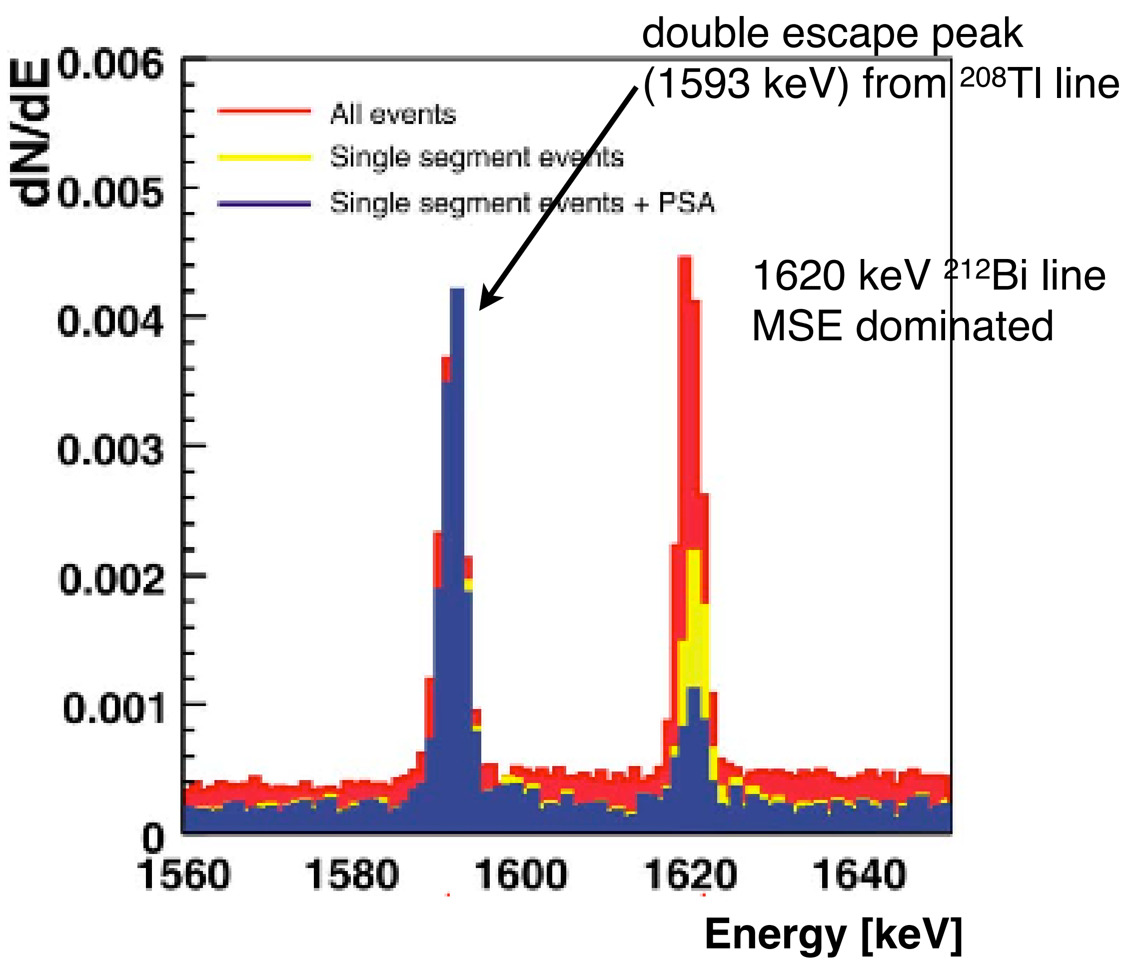


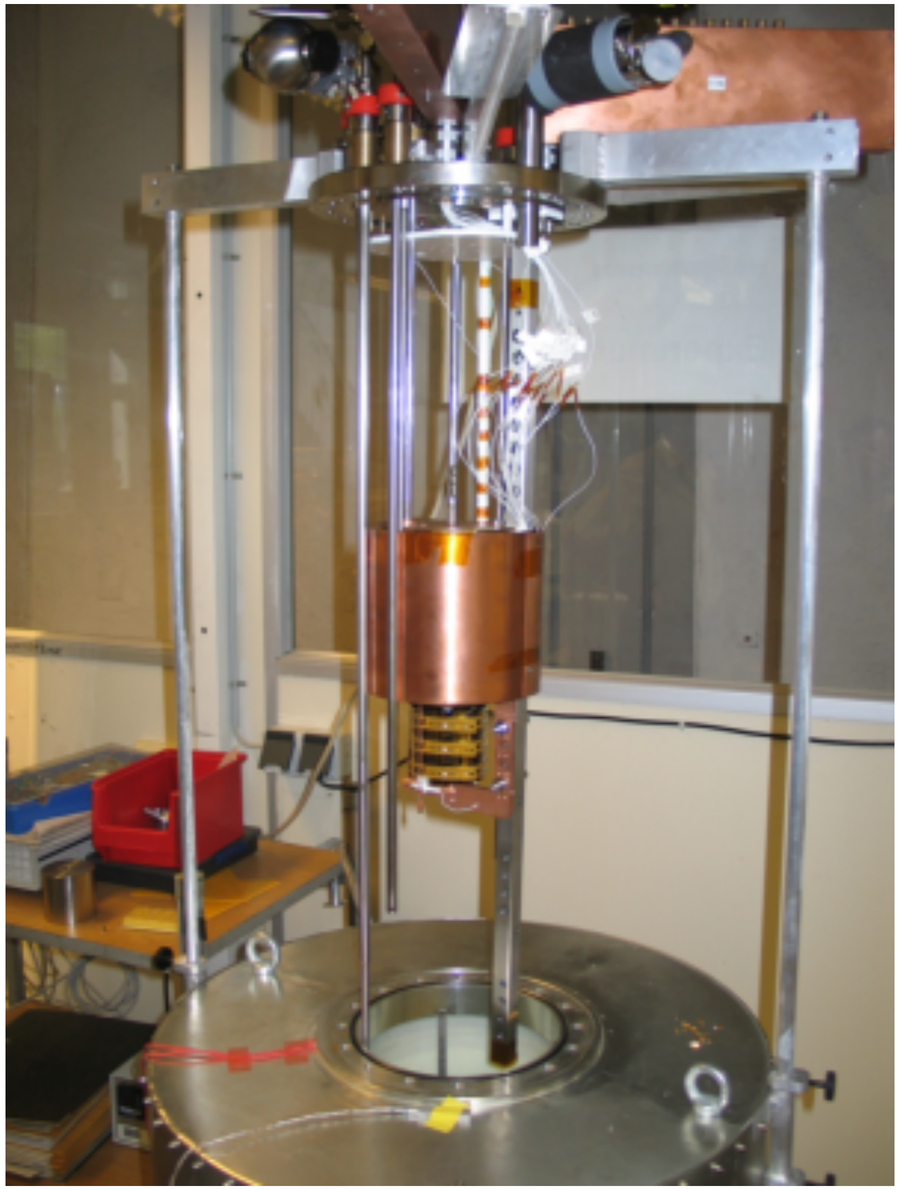
Energy resolution (at 1.332 MeV) and masses of phase I detectors:

	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]	0.98	2.91	2.45	2.40	2.79	2.15	2.19	2.12

Phase II Detectors

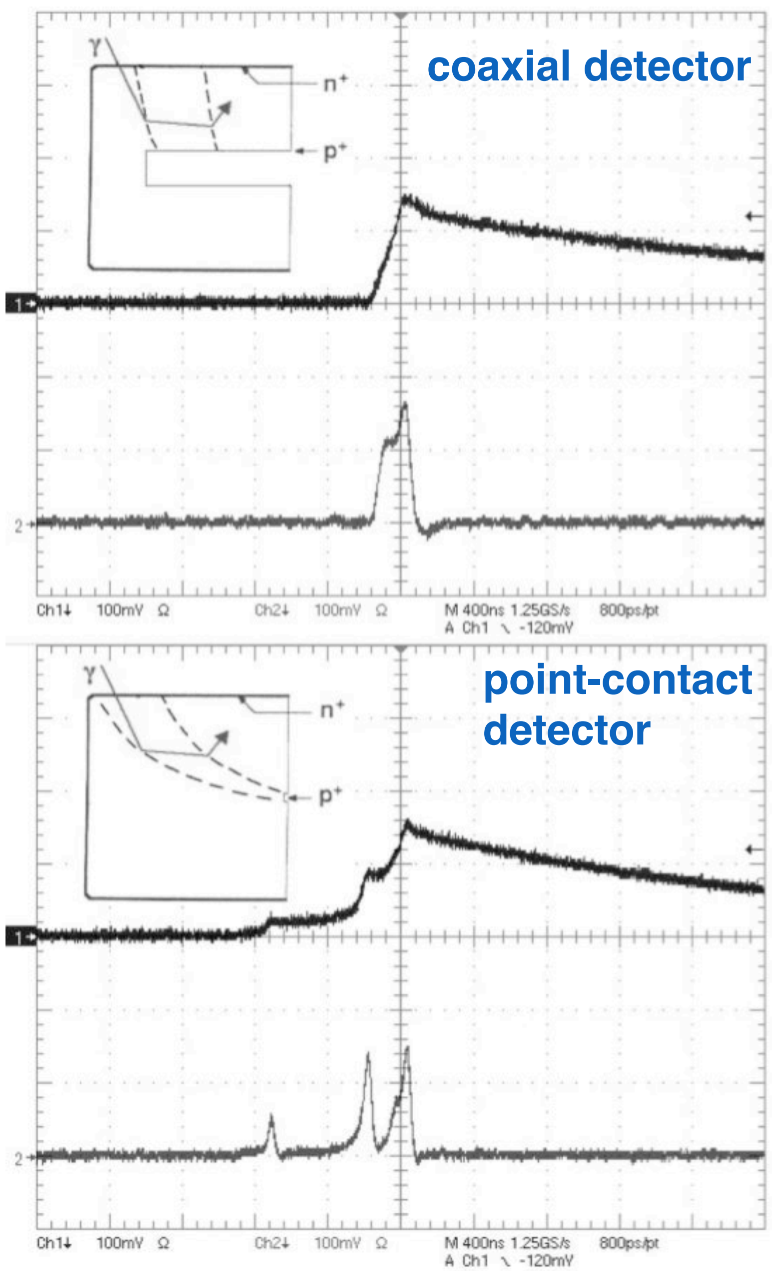
- **New 18-fold prototype detector operate in liquid nitrogen for 4 months**
    - ➡stable leakage current (< 6 pA)
    - ➡core resolution 4 keV (FWHM) at 1.3 MeV
    - ➡segment resolution 4.5 - 7 keV
- Next step: operation in LAr





Phase II Detectors

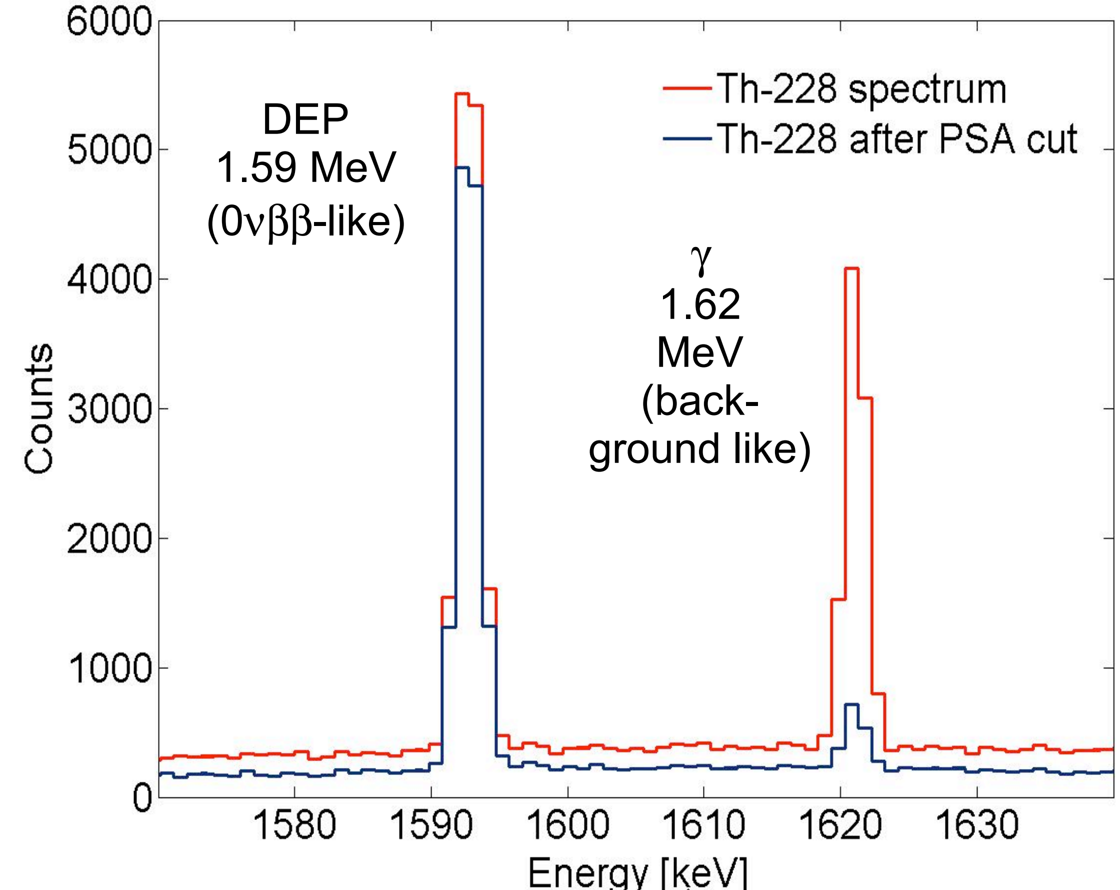
- BEGe (broad-energy) detectors with point contact are also being considered
- Very encouraging results on PSD with BEGe detector operated in conventional vacuum cryostat

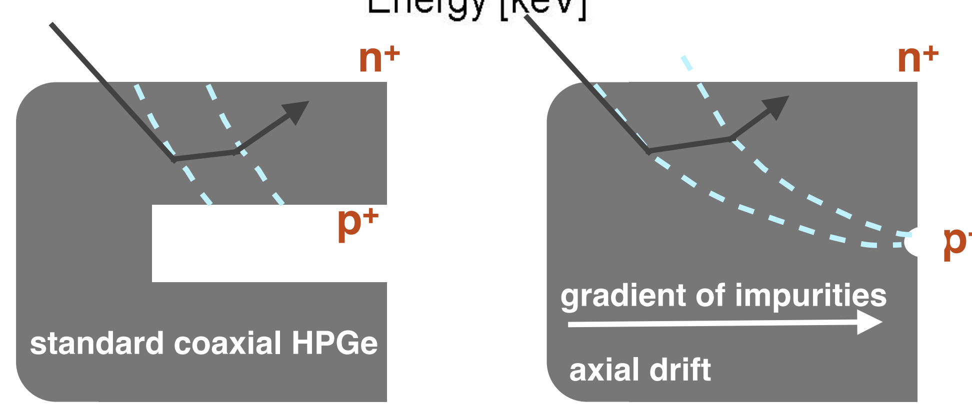


From Barbeau, Collar, Tench, JCAP 09 (2007) 009

BEGe: electric field distribution enhances the difference in charge carrier drift times depending on the interaction site

=> improved SSE vs MSE discrimination compared to standard coaxial detectors





similar charge trajectories

radial degeneracies in MSE broken

Status of the GERDA Experiment

August 2007, floor plate for water tank

December 2007

Status of the GERDA Experiment

The GERDA cryostat was delivered at LNGS on March 6, 2008 and installed

Status of the GERDA Experiment

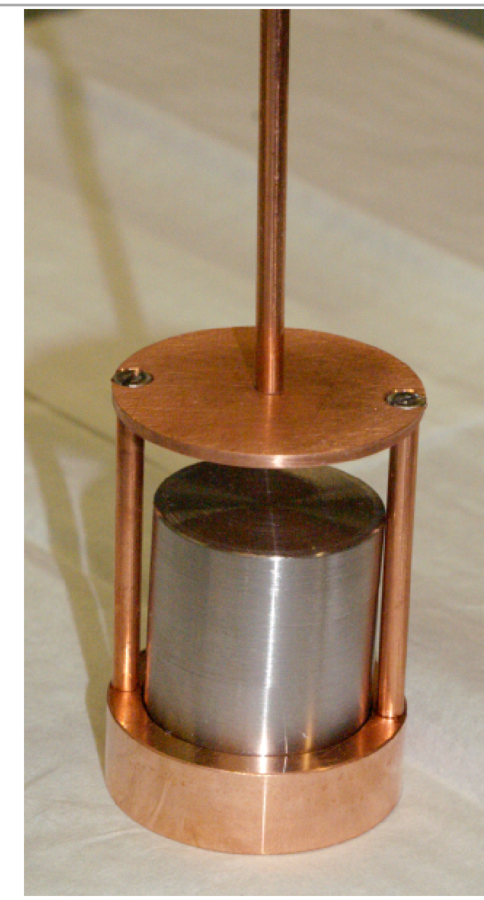
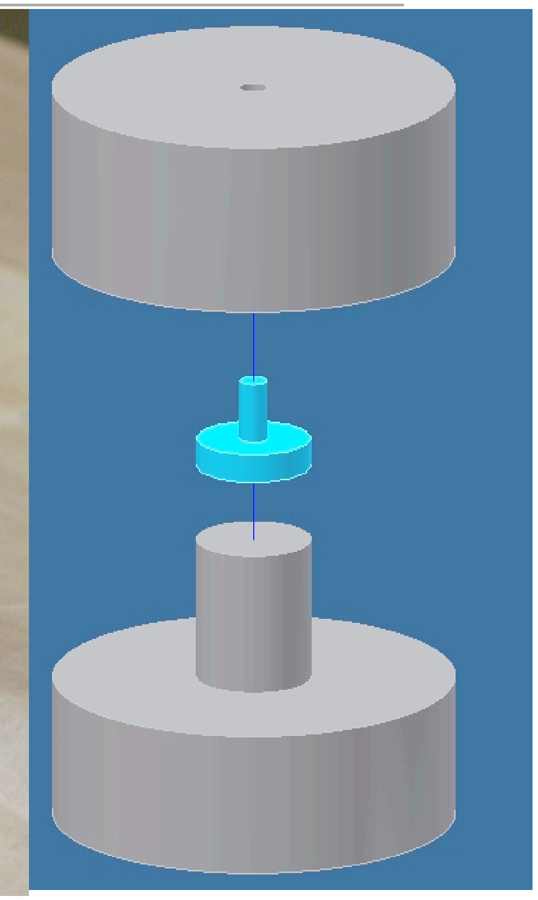
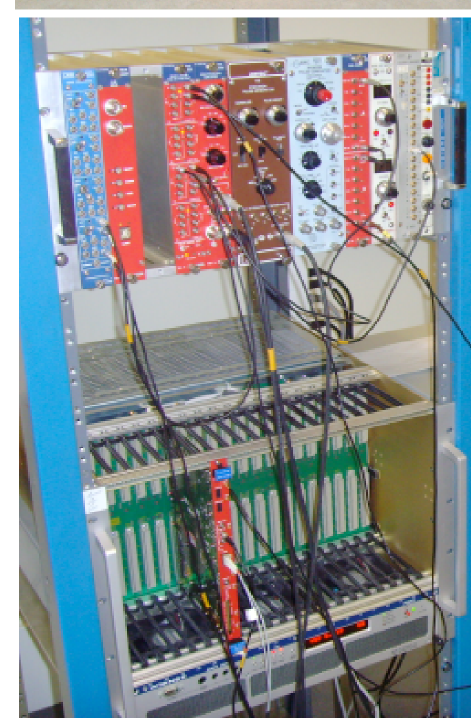
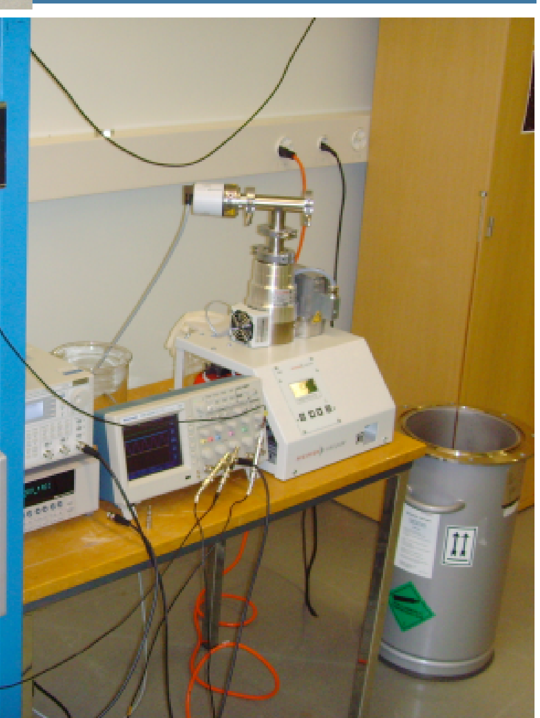
Water tank installation: April - June 2008

Installation of super structure

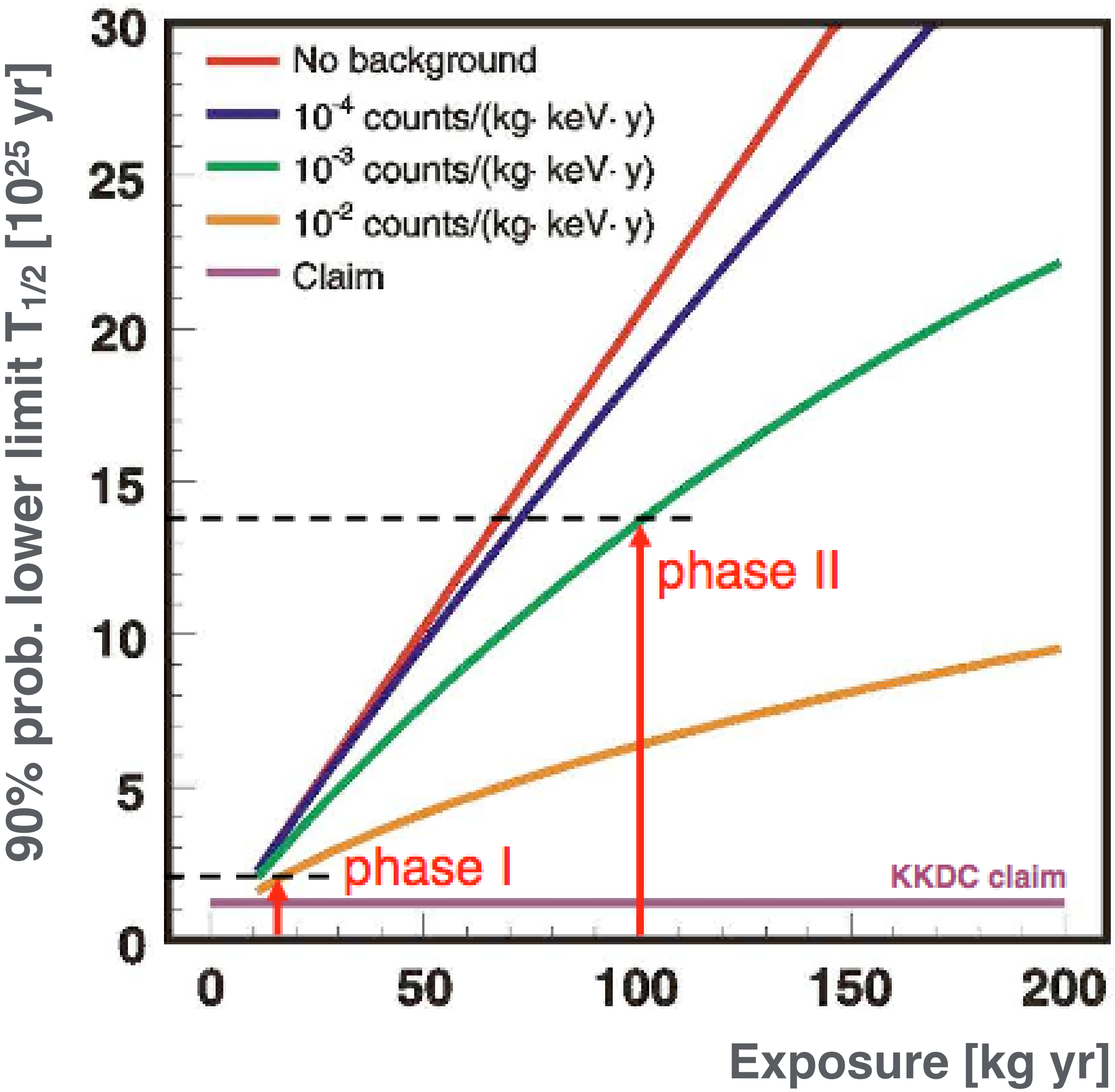
July 2008

Swiss Contributions to GERDA

- **Calibration system for Phase I**
  - ➡ test different source-collimator configurations, for example ^{228}Th sources in W + Cu collimators
  - ➡ estimate gamma and neutron BG in source parking position
  - ➡ estimate source strength for energy and PSD calibrations
- **Test facility for Phase II detectors at UZH**
  - ➡ electronics and DAQ ready and tested
  - ➡ first HPGe detector in LAr cryostat to be operated in Dec 08
  - ➡ test mock up calibration system and calibration MCs
  - ➡ test phase II GERDA prototypes (non-enriched)
- **Study of GERDA sensitivity to solar axions**

Expected Sensitivity of GERDA for $T_{1/2}$

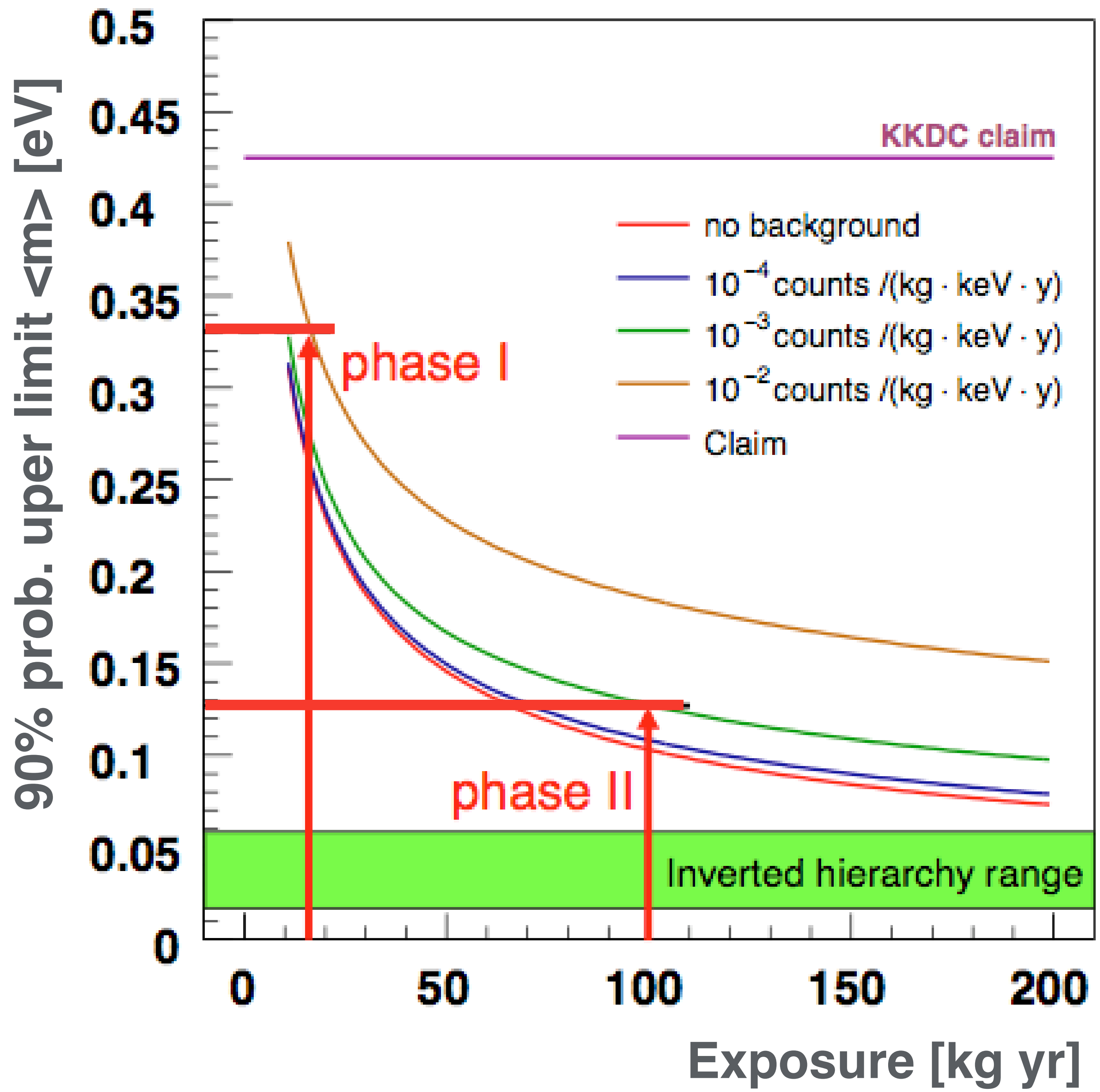


B = 10^{-3} events/(kg keV yr)

B = 10^{-2} events/(kg keV yr)

Klapdor-Kleingrothaus HM Signal

Expected Sensitivity of GERDA for $\langle m_{\nu e} \rangle$



Klapdor-Kleingrothaus HM Signal

$$\left|M^{0\nu}\right| = 3.92$$

V.A. Rodin et al., Nucl. Phys. A 366 (2006) 107-131, Nucl. Phys. A793 (2007) 213-215

B = 10^{-2} events/(kg keV yr)

B = 10^{-3} events/(kg keV yr)

Summary and Outlook

- Strong evidence for non-zero neutrino masses
- Many open questions: absolute mass scale, Dirac versus Majorana, CP violation, origin of small neutrino masses, origin of large mixing, size of Θ_{13}, etc
- **GERDA is a new ββ experiment which may answer some of these questions**
- LAr cryostat, water tank, super-structure are in place
- Phase I detectors processed and tested (+ strong efforts on Phase II detectors)
- Calibration system design is being finalized
- **Next steps:**
  - ➡ clean room construction: Jan - March 09
  - ➡ muon veto construction: March - April 09
  - ➡ LAr filling: spring 2009
  - ➡ commissioning of Phase I: summer 2009

End

Muon Veto

- PMTs encapsulated and tested
- Muon DAQ and slow control under development
- Next step: installation at LNGS
- 1st batch of plastic muon panels delivered to LNGS

Crystal pulling and characterization

- 7 crystals pulled at IKZ for characterization with low-temp.
- Hall effect, PTIS, PL

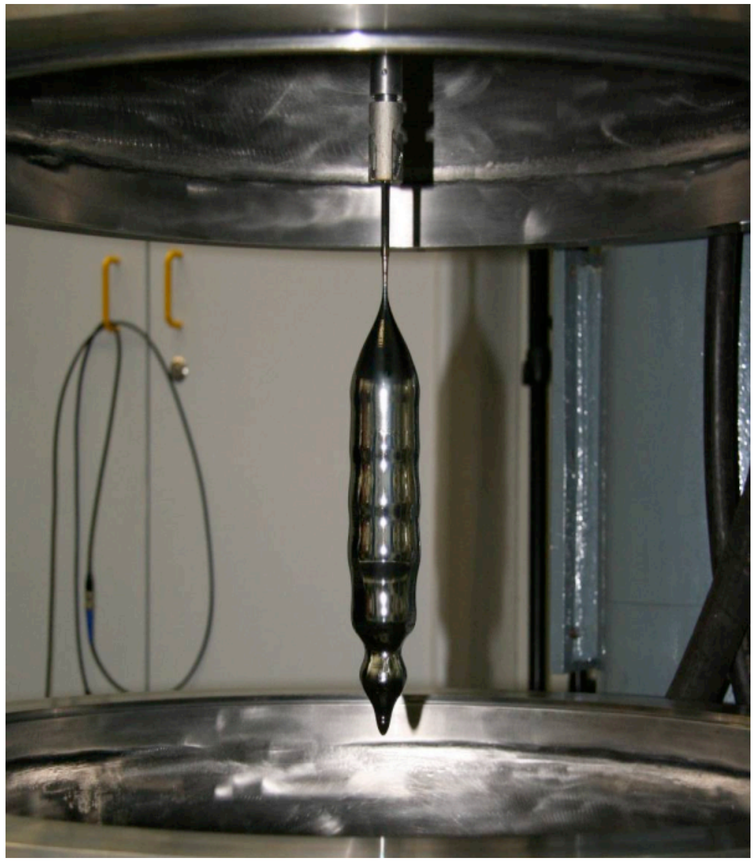
- Starting material standard 6N, and one xtal from
- depleted material purified by PPM

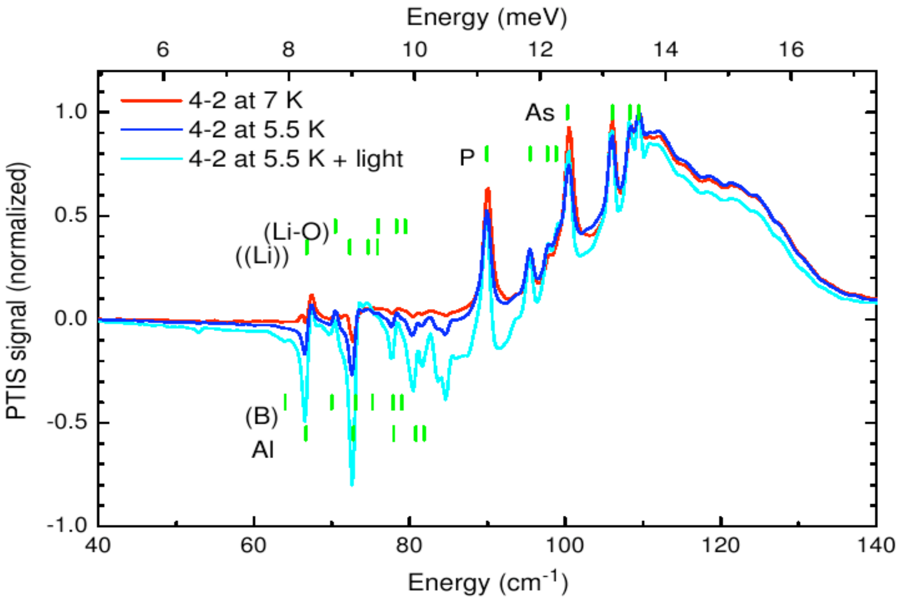
- Impurity level $10^{13}/cm^3$ ($10^{11}/cm^3$ for ped. method);
- not yet sufficient for HP-Ge production

- Improvements ongoing

- Increase turn around for crystal characterization

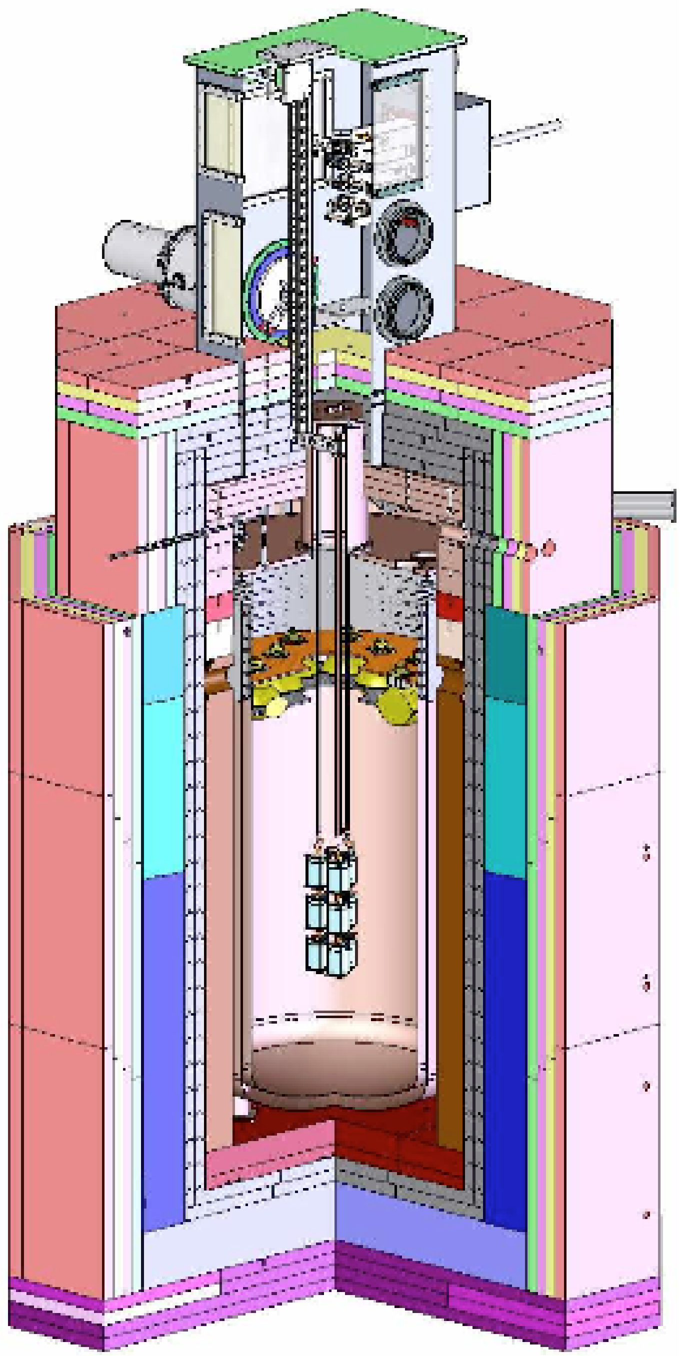
- Possibilities of crystal pulling by Canberra (p- and n-type)





Background Reduction with LAr Veto

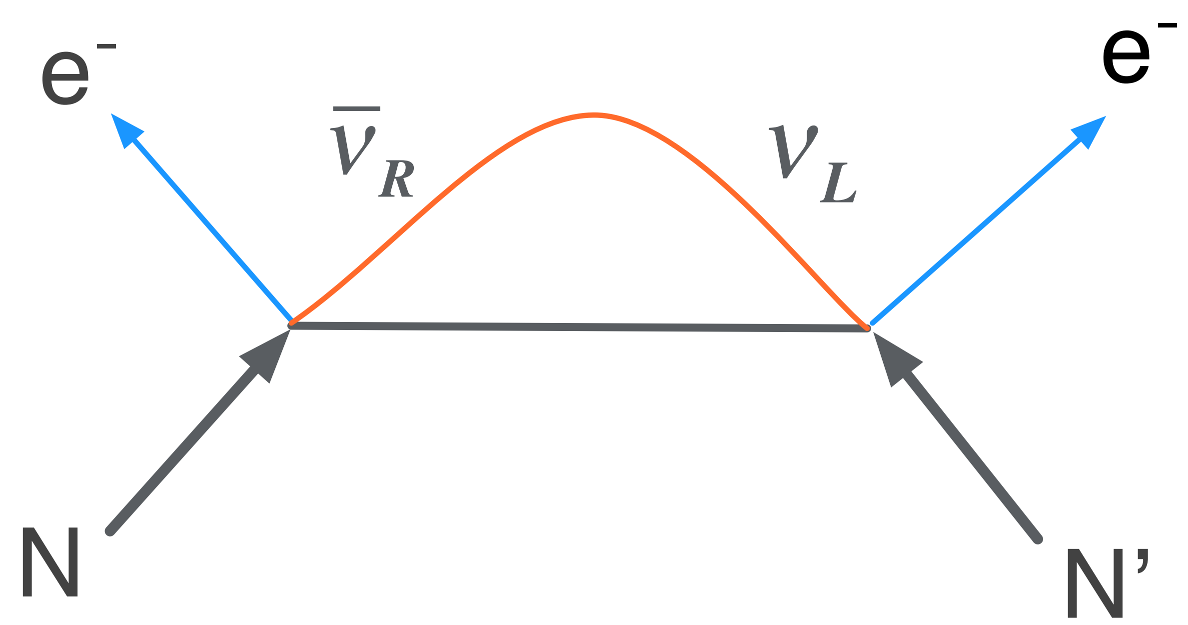
- In the near future: tests at the Gran Sasso Laboratory with LArGe (under construction)



LArGe: Cu-shield

Neutrinoless Double Beta Decay

- **Exchange of a virtual neutrino:**



➡ the neutron decays under the emission of a right-handed anti-neutrino

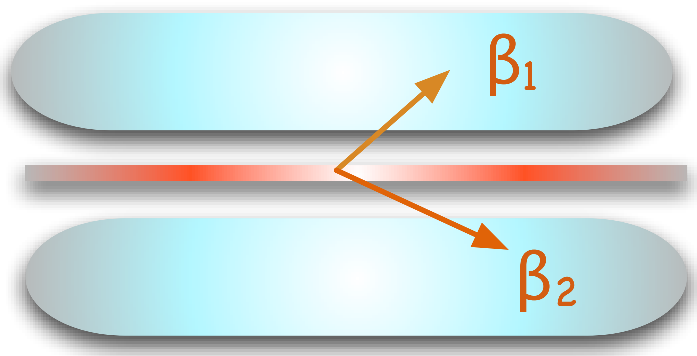
➡ the $\bar{\nu}_R$ has to be absorbed as left-handed neutrino at the second vertex

➡ **Neutrinos and anti-neutrinos have to be identical: Majorana particles**

➡ **For the helicity to change, we must require $m_\nu > 0$**

Experiments: Two Main Approaches

Souce ≠ Detector



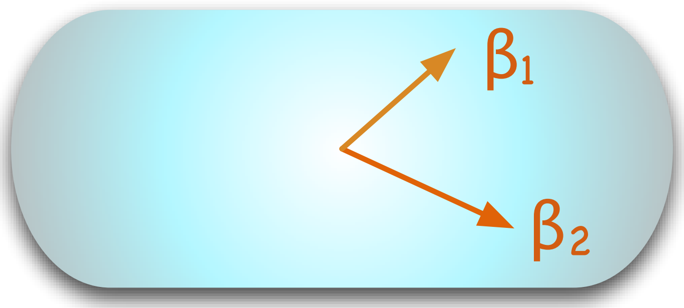
☺ Topologie der Ereignisse wird zur Untergrundunterdrückung verwendet
☺ Winkelkorrelationen und die Energie der einzelnen Elektronen werden gemessen
☺ Viele Isotope als mögliche Quellen

☞ Recht kleine Materialmengen

☞ Niedrige Effizienz

☞ iA schlechte Energieauflösung

Source = Detector (calorimeters)



☺ Grosse Massen möglich

☺ Hohe Effizienz für den Nachweis der beiden Elektronen

☺ Gute Energieauflösung

☞ Keine Winkelkorrelation