REVIEW OF DOUBLE BETA DECAY EXPERIMENTS

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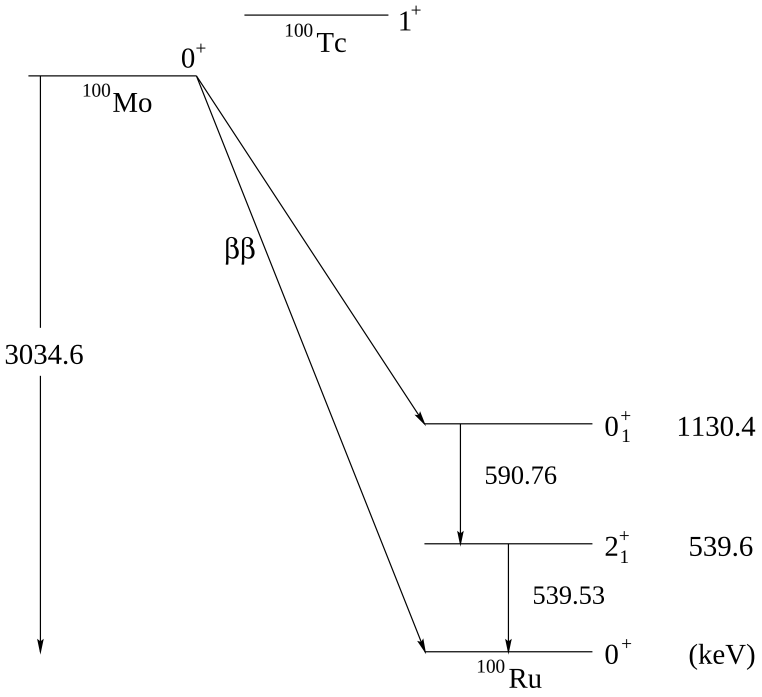
OUTLINE

- Introduction
- Current experiments (GERDA-I, EXO-200, KamLAND-Zen)
- Future experiments
- Conclusion

1. Introduction



$^{100}\mathrm{Mo} \Rightarrow \; ^{100}\mathrm{Ru} + 2e^-$

$^{100}\mathrm{Mo} \Rightarrow \; ^{100}\mathrm{Ru} + 2e^- + \chi^0 \; (+\chi^0)$

$^{100}\mathrm{Mo} \Rightarrow \; ^{100}\mathrm{Ru} + 2e^- + 2\nu$

There are 35 candidates for $2\beta^-$-decay

$W \sim Q^5$ (0ν); $W \sim Q^7$ ($0\nu\chi^0$)
$W \sim Q^{11}$ (2ν)

$Q_{\beta\beta}$ = 3.033 MeV

Candidates with $Q_{2\beta}$ > 2 MeV

Nuclei	$Q_{2\beta}$, keV	Abundance, %
1. ^{48}Ca	4272	0.187
2. ^{150}Nd	3371.4	5.6
3. ^{96}Zr	3350	2.8
4. ^{100}Mo	3034.4	9.63
5. ^{82}Se	2996	8.73
6. ^{116}Cd	2805	7.49
7. ^{130}Te	2527.5	34.08
8. ^{136}Xe	2458.7	8.87
9. ^{124}Sn	2287	5.79
10. ^{76}Ge	2039.0	7.61
11. ^{110}Pd	2000	11.72

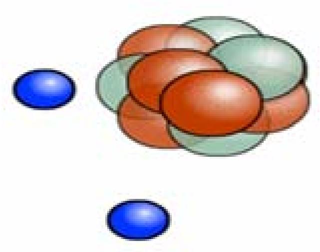
Natural γ-rays background - E < 2.615 MeV.

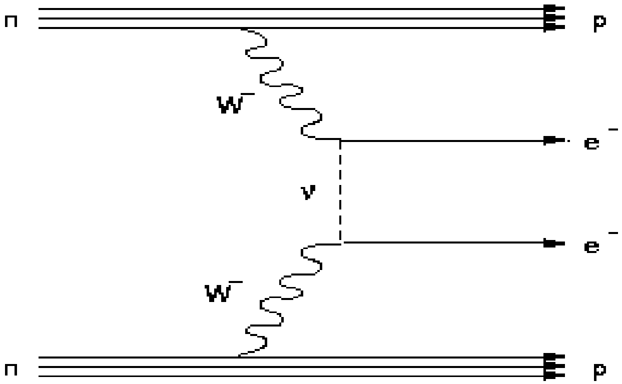
So, there are **6 gold** and **5 silver** isotopes

NEUTRINOLESS DOUBLE BETA DECAY

Experimental signature:

2 electrons
$E_{\beta 1} + E_{\beta 2} = Q_{\beta\beta}$





Oscillation experiments ⇒ Neutrino is massive!!!

- However, the oscillatory experiments cannot solve the problem of the origin of neutrino mass (**Dirac or Majorana?**) and cannot provide information about the absolute value of mass (because the **Δm^2** is measured).

- **<u>This information can be obtained in 2β-decay experiments.</u>**

$$<m_\nu> = \left| \Sigma \; |Uej|^2 e^{i\phi_j} m_j \right|$$

Thus searches for double beta decay are sensitive not only to masses but also to mixing elements and phases ϕ_j.

What one can extract from 2β-decay experiments? ⇒

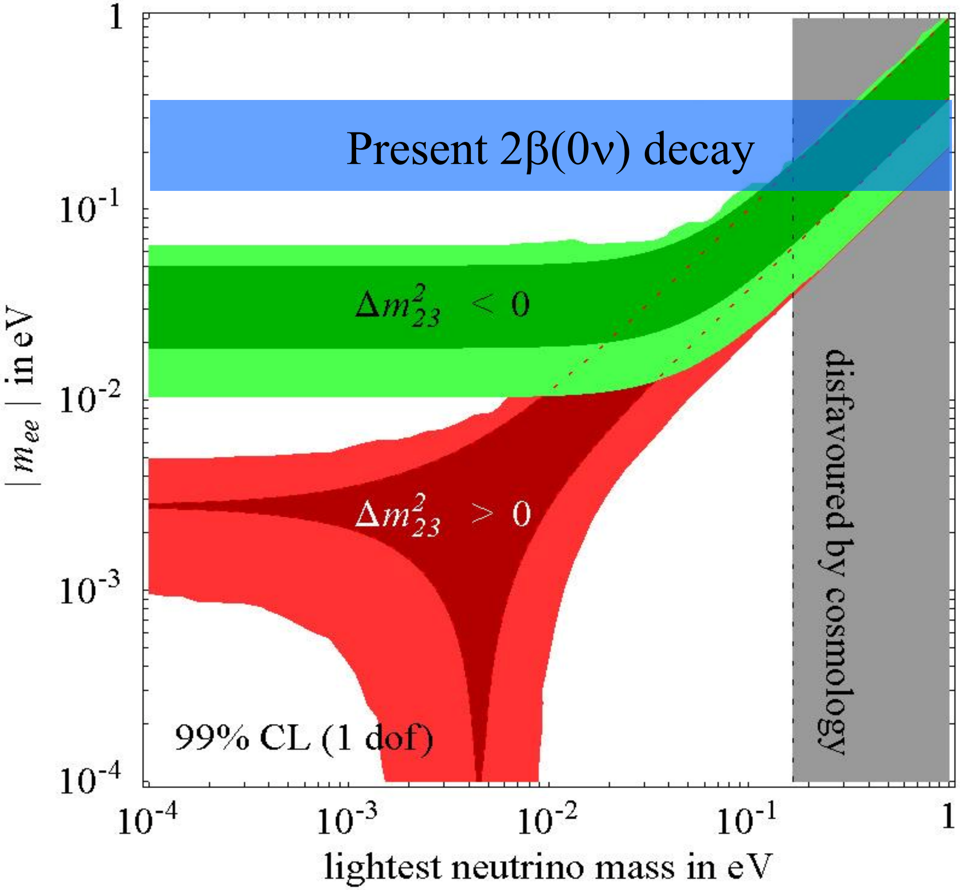
- Lepton number nonconservation (ΔL=2)
- Nature of neutrino mass (Dirac or Majorana?).
- Absolute mass scale (value or limit on m_1).
- Type of hierarchy (normal, inverted, quasi-degenerated).
- CP violation in the lepton sector.

Best present limits on $<m_\nu>$

Nuclei	$T_{1/2}$, y	$<m_\nu>$, eV QRPA + others	$<m_\nu>$, eV [SM]	Experiment
^{76}Ge	$>2.1\cdot10^{25}$	< 0.19-0.30	< 0.66	GERDA-I
^{136}Xe	$>1.9\cdot10^{25}$	< 0.13-0.30	< 0.35	KAMLAND-Zen
^{130}Te	$>2.8\cdot10^{24}$	< 0.28-0.81	< 0.77	CUORICINO
^{100}Mo	$>1.1\cdot10^{24}$	< 0.29-0.70	-	NEMO
^{82}Se	$>3.6\cdot10^{23}$	< 0.77-1.38	< 2.4	NEMO
^{116}Cd	$>1.7\cdot10^{23}$	< 1.16-2.16	< 1.8	SOLOTVINO

Conservative limit on $<m_\nu>$ is 0.35 eV

DBD and neutrino mass hierarchy



Degenerate: can be tested

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

Normal: inaccessible (new approach is needed)

β: m_ν < 2 eV

2β: $<m_\nu>$ < 0.13-0.35 eV

Cosmology : Σm_ν < 0.2-0.6 eV

Two neutrino double beta decay

- Second order of weak interaction
- Direct measurement of NME values!

  ⇒

  - The only possibility to check the quality of NME calculations!!!

  - g_{pp} (QRPA parameter ⇒ NME(0ν)!)

  ⇓

- This is why it is very important to measure this type of decay for many nuclei, for different processes (**$2\beta^-$, $2\beta^+$, $K\beta^+$, 2K, excited states**) and with high accuracy.

M. Goeppert-Mayer

Two neutrino double beta decay

- By present time **2β(2ν)** decay was detected in **11** nuclei: **^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{150}Nd, ^{238}U, ^{136}Xe**

For **^{100}Mo** and **^{150}Nd** **2β(2ν)** transition to **0^+** **excited states** was detected too

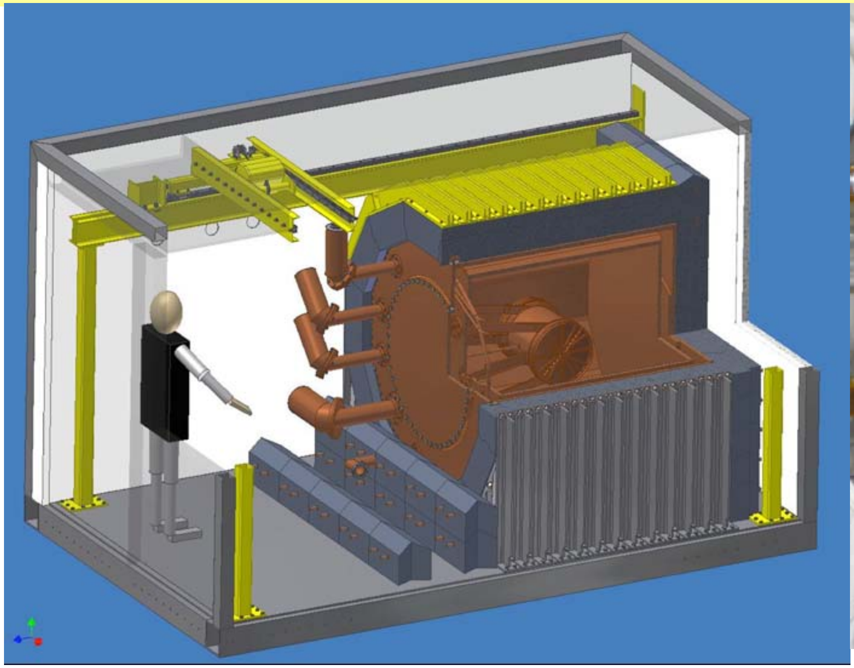
ECEC(2ν) in **^{130}Ba** was detected in geochemical experiments

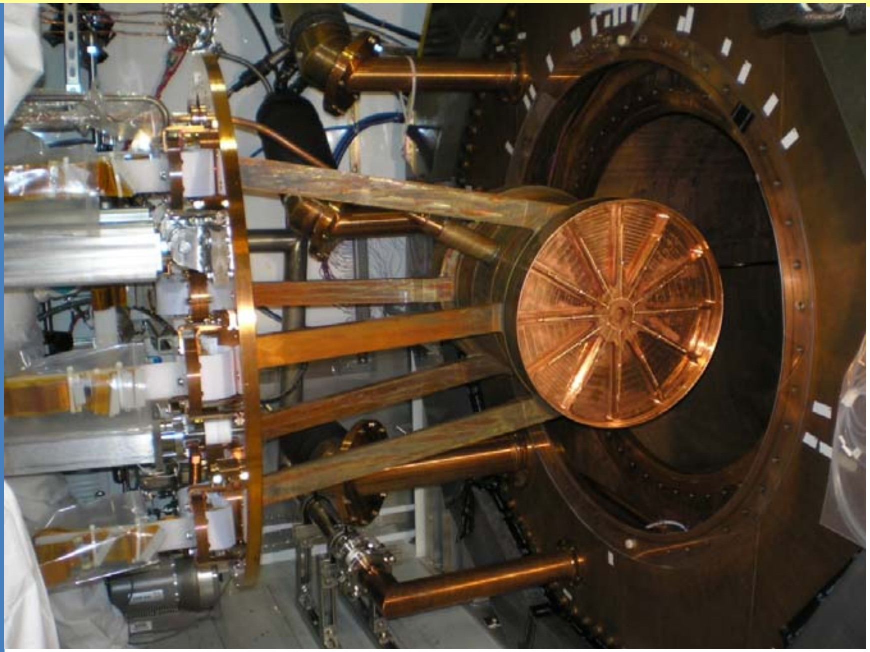
Main goal is: precise investigation of this decay **(NEMO-3, EXO-200, GERDA-I…)**

2. CURRENT EXPERIMENTS

- EXO-200, KamLAND-Zen, GERDA-I
- **Others (CUORE-0, CANDLES-III, DAMA, $CdWO_4$, excited states,…)**

EXO-200





Location: WIPP (USA) – salt mine (1600 м w.e.)

Passive shield – 25 cm of Pb

Active shield - plastic scintillator (5 cm)

^{136}Xe: enrichment – **80.6%;** mass – **175 кg**;

useful mass – **98.5 kg**

Signal: ionization + scintillation

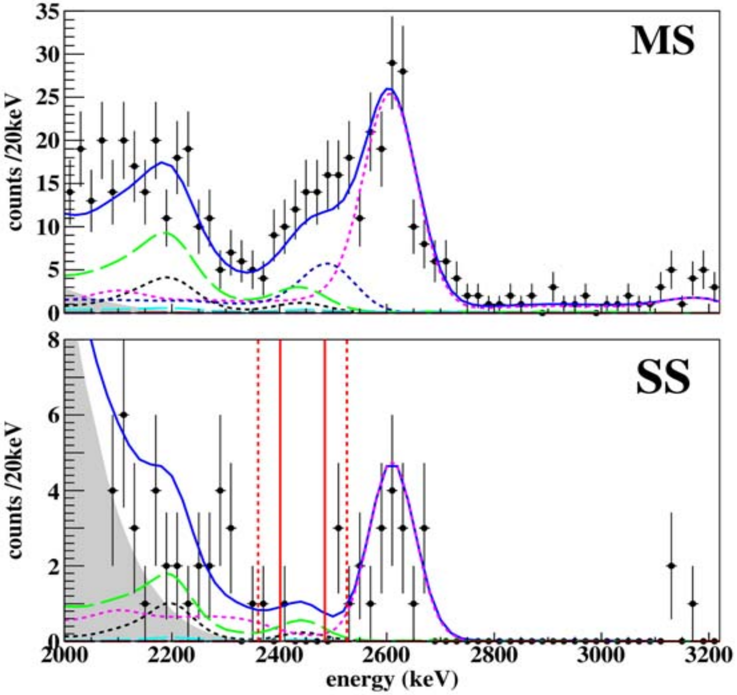
ΔE/E(FWHM) = **10.6%** at 2.615 MeV (ionization)

~ 4% (ionization + scintillation)

Strength of electric field – **376 V/cm** (V = - 8 kV);

See V. Belov presentation

EXO-200 results



2ν decay
Precise half-life value is obtained:
~ 19000 2ν events!
$T_{1/2}(2\nu)$= 2.172 ± 0.017(stat) ± 0.06(syst)x10^{21} yr
(nucl-ex/1306.6106)

98.5 kg of ^{enr}Xe (79.4 kg of ^{136}Xe)

127.6 days; ΔE/E = 4% (FWHM)

0ν decay: no signal is observed

$T_{1/2} > 1.6 \cdot 10^{25}$ yr (90% CL)

$\langle m_\nu \rangle$ < 140 – 380 meV (90% C.L.)

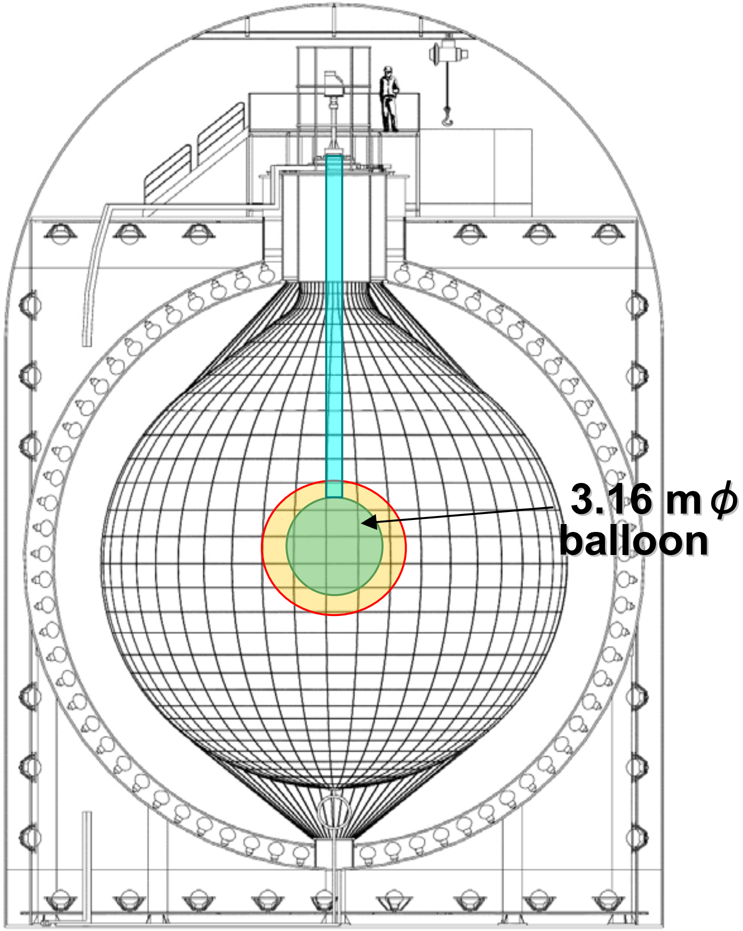
Background in 0ν window:

~ 1.4x10^{-3} c/keV·kg·yr

PRC (2012) 032505

KamLAND-Zen

(Original idea of R. Ragavan, PRL 72 (1994) 1411)



1st phase enriched Xe 400kg

R=1.7 m balloon
V=20.5m^3,S=36.3m^2
LS : C10H22(81.8%)+PC(18%)
+PPO+Xe(~2.5wt%)
ρ LS : 0.78kg／ℓ
high sensitivity with low cost

24 of September 2011 - beginning of data tacking

^{136}Xe: 330 kg, enrichment – 91 %
$\Delta E/E$(FWHM) = 9.5 % at 2.5 MeV

Sensitivity:

~ 80 meV for 2 yr of measurement
~ 60 meV за 5 yr of measurement

^{238}U : 0.2～2.2×10^{-18} g/g
^{232}Th : 1.9～4.8×10^{-17} g/g

See J. Shirai presentation

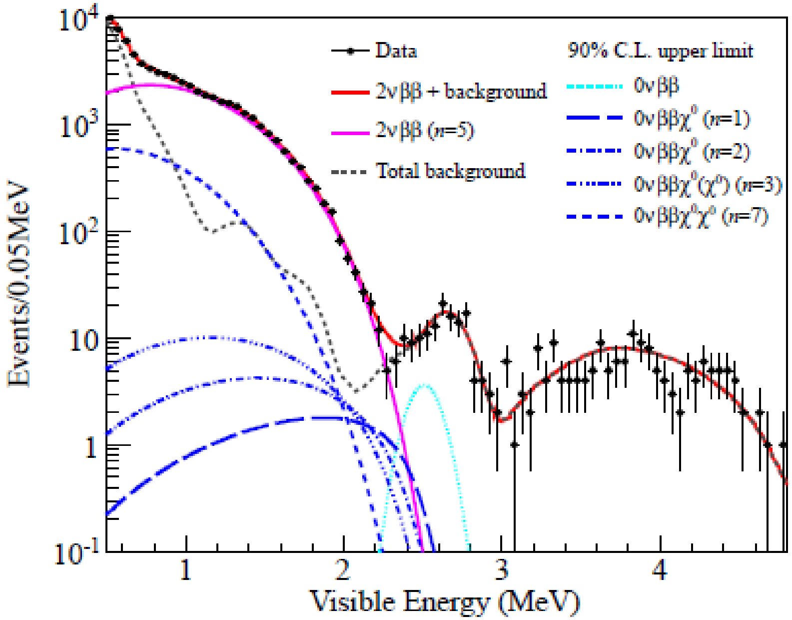
KamLAND-Zen results

$T_{1/2}(2\nu) = 2.30 \pm 0.02(\text{stat.}) \pm 0.12(\text{sys.}) \times 10^{21}$ yr

(PRC 86 (2012) 021601R; in agreement with EXO-200)

$T_{1/2}(0\nu) > 1.9\text{x}10^{25}$ yr (90% CL) ⇒ $\langle m_\nu \rangle < 0.13\text{-}0.35$ eV

(PRL 110 (2013) 062502)



Ordinary (spectral index n = 1) Majoron-emitting decay of ^{136}Xe

$T_{1/2} > 2.6 \times 10^{24}$ yr

$\langle g_{ee} \rangle < (0.8\text{-}1.6) \times 10^{-5}$

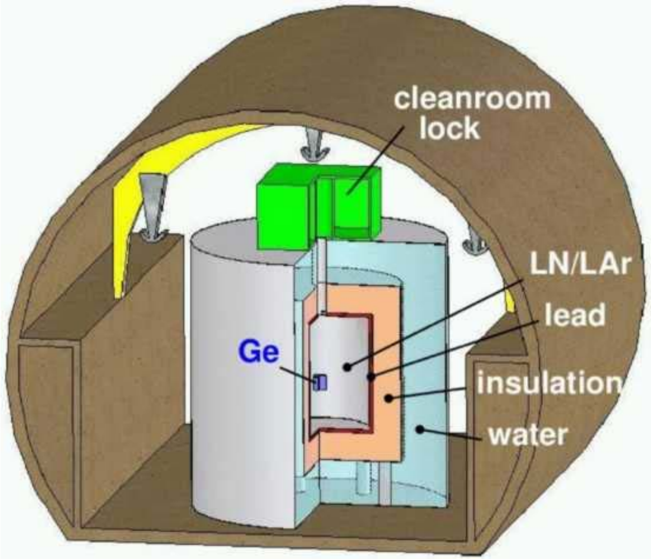
Background is ~ 100 times higher than in KamLAND

BI ~ 10^{-4} c/keV·kg·yr

[U ~ $3.5 \cdot 10^{-16}$; Th ~ $2.2 \cdot 10^{-15}$; Fukushima isotopes]

Sensitivity will be ~ 10 better if background problem will be solved

GERDA-I (Gran Sasso)

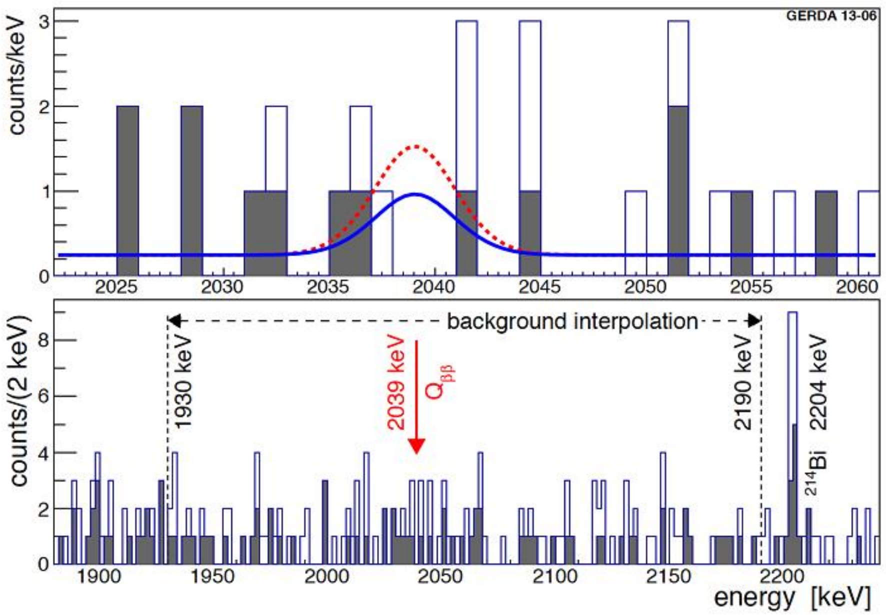


8 HPGe detectors made of enriched Ge **(17.66 кг; HM+IGEX)**
+ 1 detector made of natural Ge; 3 natural HPGe
ΔE = 4-5 keV
Sensitivity: ~ $2 \cdot 10^{25}$ yr for **1 year of measurement**
and **B = 0.01 c/keV·kg·y**

Beginning of data taking: 09.11.2011
Main goal – to check the Klapdor's result

See L. Bezrukov presentation

GERDA-I results



$T_{1/2} > 2.1 \cdot 10^{25}$ yr (90% CL)

$<m_\nu> < 0.19\text{-}0.66$ eV

Exposure: 21.6 kg·yr of ^{76}Ge
BI = 10^{-2} c/keV·kg·yr

(nucl-ex/1307.4720)

2ν decay of ^{76}Ge:

$T_{1/2}(2\nu) = (1.84^{+0.14}_{-0.10}) \cdot 10^{21}$ yr
(J. Phys. G40 (2013) 035110; in agreement with G-M experiment)

Klapdor's results:

$T_{1/2} = (1.19^{+0.37}_{-0.23}) \cdot 10^{25}$ yr
(PLB586 (2004) 198)

$T_{1/2} = (2.23^{+0.44}_{-0.31}) \cdot 10^{25}$ yr
(MPL A21 (2006) 1547)

III. FUTURE EXPERIMENTS

- **Main goal is:**

To reach a sensitivity ~ **0.01-0.1 eV** to **$<m_\nu>$** (inverted hierarchy region)

- Strategy is:

\- to investigate **different** isotopes (**>2-3**);

\- to use **different** experimental technique

Here I have selected a few propositions which I believe will be realized in the nearest future

- **CUORE** (^{130}**Te**, cryogenic thermal detector)
- **GERDA** (^{76}**Ge**, HPGe detector)
- **MAJORANA** (^{76}**Ge**, HPGe detector)
- **EXO** (^{136}**Xe**, TPC + Ba^{+})
- **SuperNEMO** (^{82}**Se or** ^{150}**Nd**, tracking detector)
- **KamLAND-Zen** (^{136}**Xe**, liquid scintillator)
- **SNO+** (^{130}**Te**, liquid scintillator)

Other proposals: CANDLES, XMASS, NEXT, LUCIFER, DCBA, COBRA, MOON …

SUMMARY TABLE

Experiment	Isotope	Mass, kg	$T_{1/2}$, y	$<m_\nu>$, meV	Status
CUORE	**^{130}Te**	200	$1\cdot10^{26}$	**50-130**	Funded
GERDA	**^{76}Ge**	I. 17 II. 40 III.1000	$2\cdot10^{25}$ $2\cdot10^{26}$ $6\cdot10^{27}$	**60-200** **10-40**	Funded Funded R&D
MAJORANA	**^{76}Ge**	I. 20-30 II. 1000	10^{26} $6\cdot10^{27}$	**90-300** **10-40**	Funded R&D
EXO	**^{136}Xe**	200 1000	$(4\text{-}5)\cdot10^{25}$ 10^{27}	**80-240** **20-50**	Funded R&D
SuperNEMO	**^{82}Se**	100-200	$(1\text{-}2)\cdot10^{26}$	**40-110**	R&D; 1-st step is fund.
KamLAND-Xe	**^{136}Xe**	330 1000	$\sim 2\cdot10^{26}$ $\sim 6\cdot10^{26}$	**40-110** **23-58**	Funded R&D
SNO+	**^{130}Te**	800 8000	$\sim 10^{26}$ $\sim 10^{27}$	**50-130** **15-45**	Funded R&D

CUORE (Gran Sasso)

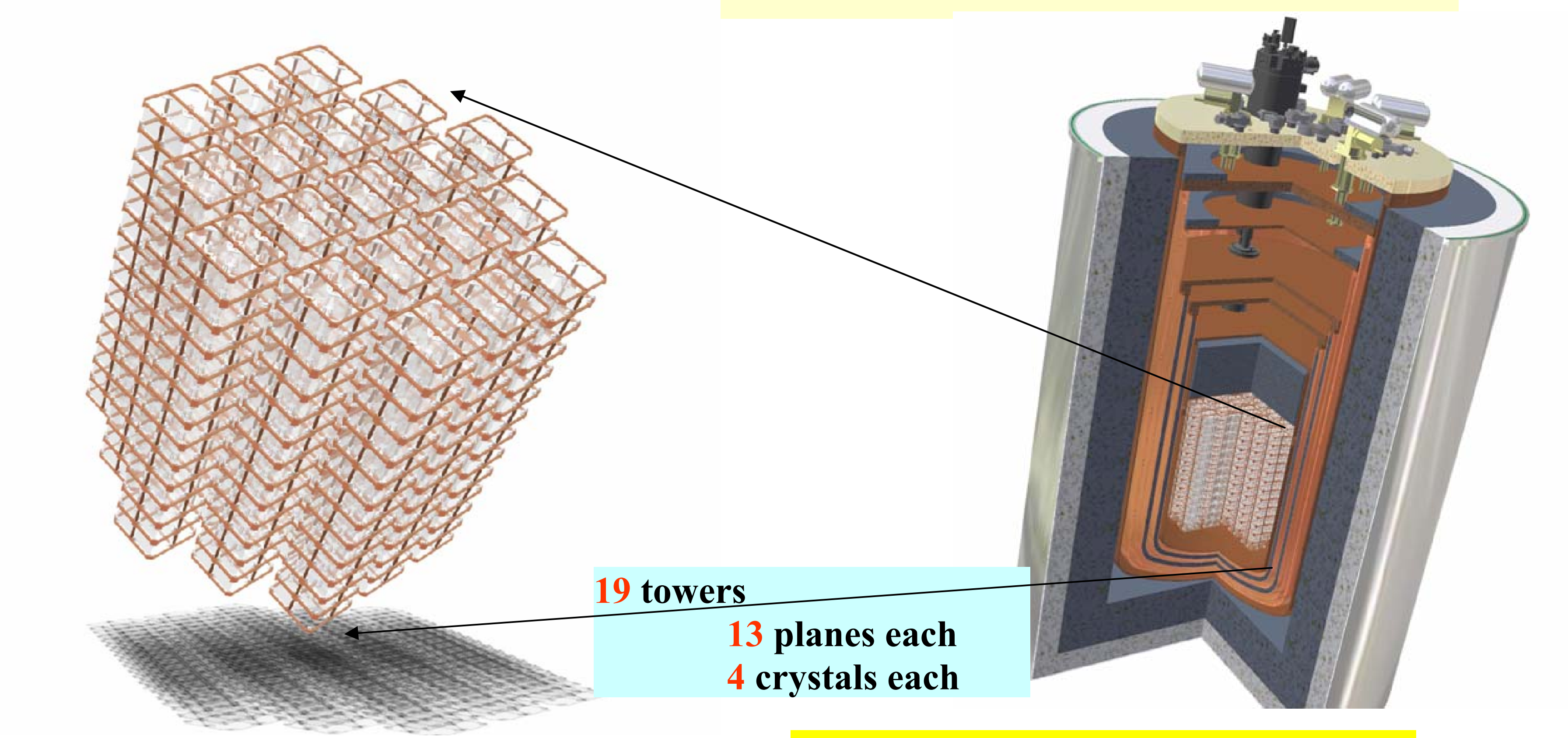
Cryogenic Underground Observatory for Rare Events

Closely packed array of 988 TeO_2 crystals $5×5×5\ cm^3$ (750 g)

741 kg TeO_2 granular calorimeter

600 kg Te = 203 kg ^{130}Te

- **Single high granularity detector**



19 towers

13 planes each

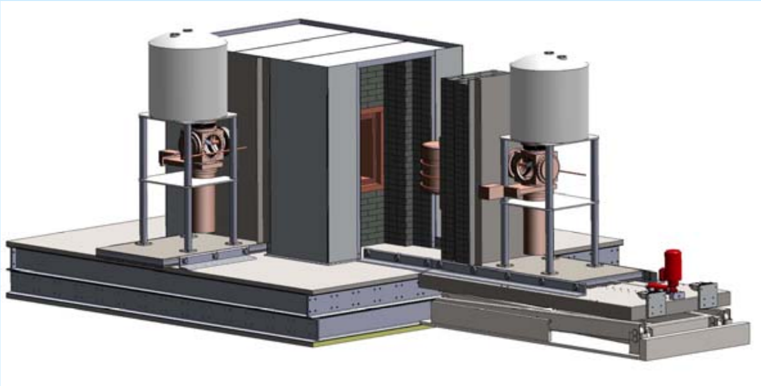
4 crystals each

Beginning of measurements ~ 2015

CUORE-0 is operated in GS now

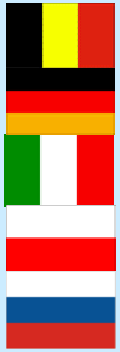
Towards 1TGe

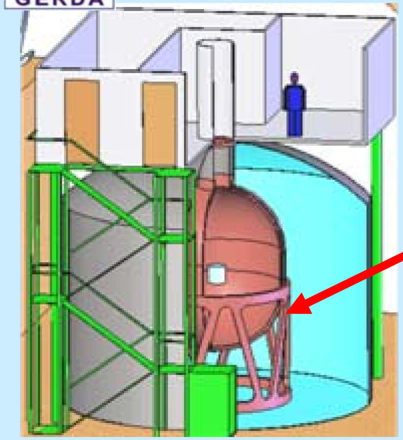
MAJORANA



- Modules of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Initial phase: R&D demonstrator module: Total ~40 kg (up to 30 kg enr.) - 2014

GERDA





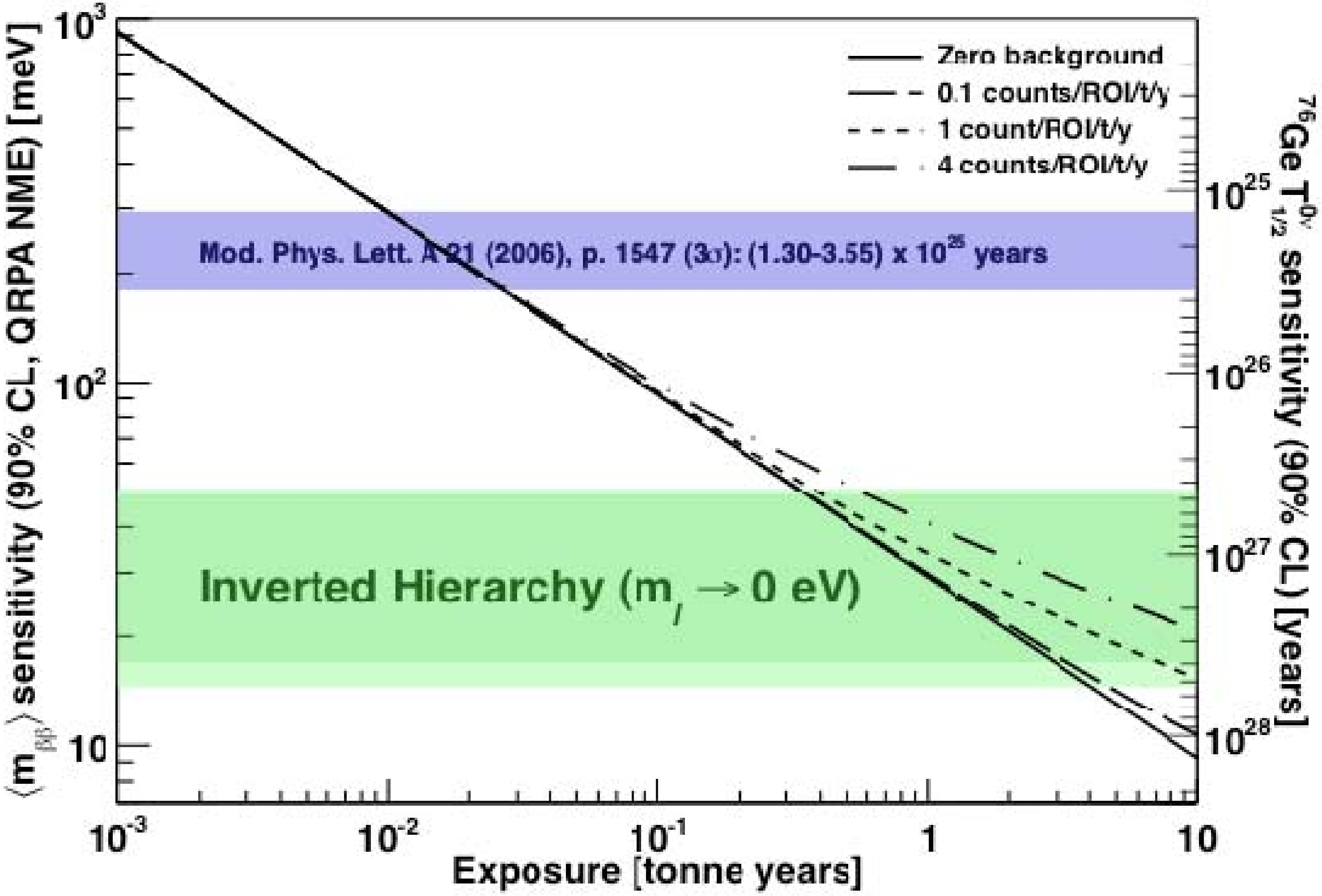
- ‘Bare’ ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- Phase I (2011): ~18 kg (HdM/IGEX diodes)
- Phase II (2014): add ~20 kg new detectors - Total ~40 kg

Joint Cooperative Agreement:

- **Open exchange of knowledge & technologies (e.g. MaGe, R&D)**
- **Intention is to merge for 1 ton exp. Select best techniques developed and tested in GERDA and MAJORANA**

1 t detector - ~ 2016-2018

1TGe Sensitivity



EXO (Enriched Xenon Observatory)
USA-RUSSIA-CANADA

- **$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}$ ($E_{2\beta}$ = 2.47 MeV)**
- **Main idea is**: to detect all products of the reaction with good enough energy and space resolution (M.Moe PRC 44 (1991) 931)

Sensitivity of EXO

- **EXO-200** (5 y of meas., **80 kg**, background = 140 events, $\Delta E/E(\mathrm{FWHM}) = 3.8\%$):

$T_{1/2} > 4\mathrm{x}10^{25}$ yr, $<m_\nu> < 0.09 - 0.24$ eV

- **EXO-5000 (w/o Ba^+ tagging):**

[5 y, **4000 kg**, $\Delta E/E(\mathrm{FWHM}) = 3.8\%$]

$T_{1/2} > 3 \cdot 10^{26}$ yr, $<m_\nu> < 0.03 - 0.08$ eV

- **EXO-5000 (Ba^+ tagging):**

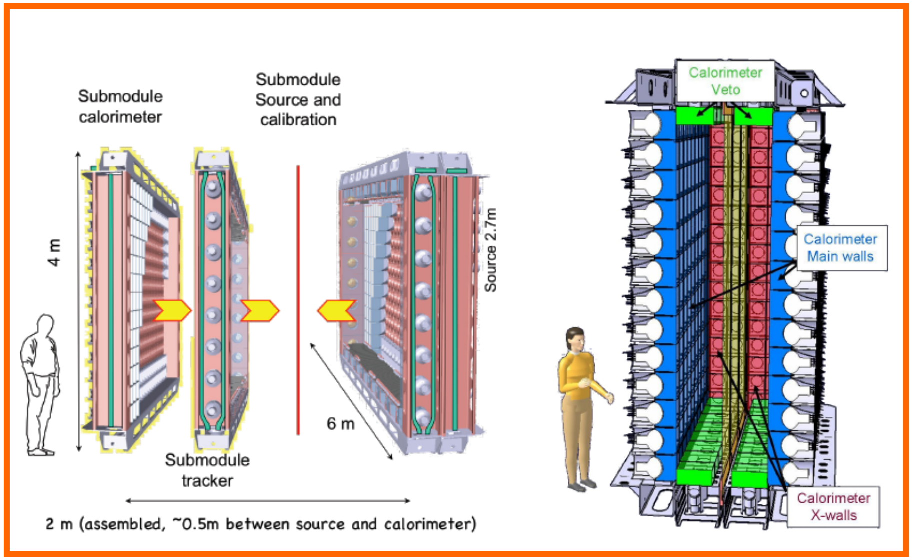
[5 y, **4000 kg**, $\Delta E/E(\mathrm{FWHM}) = 3.8\%$, **efficiency of Ba^+ tagging is ~ 0.7**]

$T_{1/2} > 2\mathrm{x}10^{27}$ yr, $<m_\nu> < 0.013 - 0.034$ eV

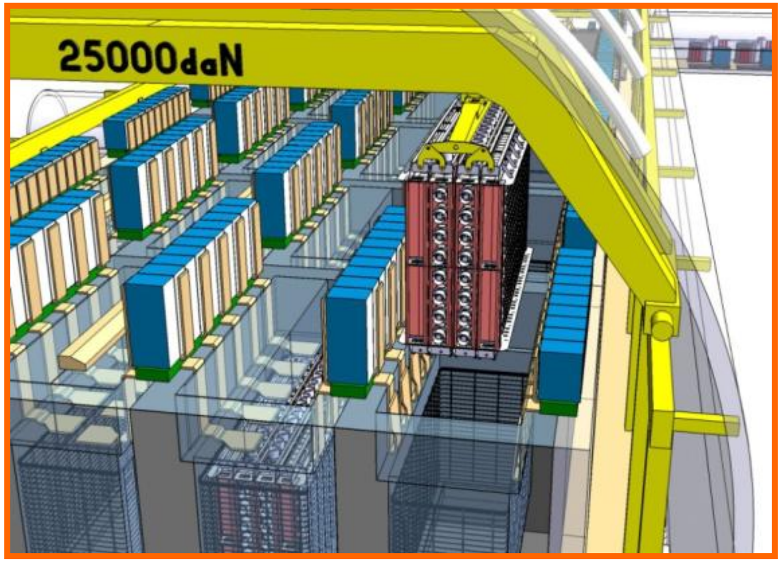
G.Gratta (Osaka'2011): "~2% Ba tagging efficiency obtained in the lab. Plenty of R&D still left to do to demonstrate if the technique is viable"

SuperNEMO

A module



20 modules



	Demonstrator module	20 Modules
Source : ^{82}Se	7 kg	140 kg
Drift chambers for tracking	2 000	40 000
Electron calorimeter	500	10 000
γ veto (up and down)	100	2 000
$T_{1/2}$ sensitivity	6.6 10^{24} y (No background)	1. 10^{26} y
$\langle m_\nu \rangle$ sensitivity	200 – 400 meV	40 – 100 meV

Start of measurements:

Demonstrator – 2015
SuperNEMO - 2017

Demonstrator module(7 kg) is under construction

See F. Piquemal presentation

Future KamLAND possibilities

- 330 kg of ^{enr}Xe during 2 yr of measurement (BI ~ 10^{-6} c/keV·kg·yr) ⇒ ~ 10^{26} yr ($\langle m_\nu \rangle$ ~ 60-150 meV)

- **KamLAND2-Zen** (after **2015**):

  1000 kg of **^{136}Xe** pressurized (~ 6 wt%)

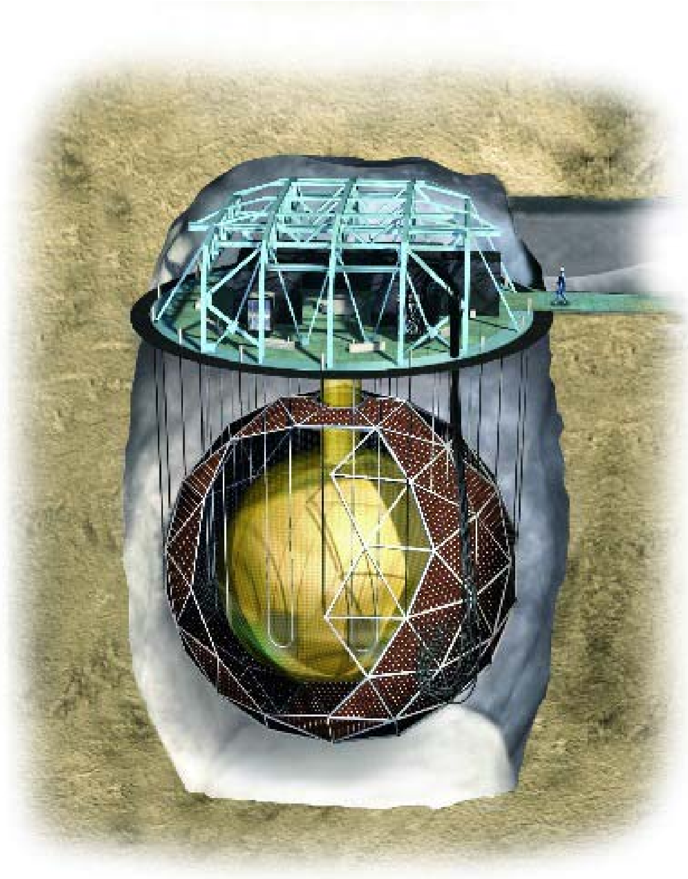
  (Upgrade of the detector is needed: photo-coverage ×2, LS renewal → **total light yield ×2.5**)

  ⇓

  $T_{1/2}$ ~ $6 \cdot 10^{26}$ yr/5 years **$\langle m_\nu \rangle$ ~ 20-60 meV/5 years**

And, of course, present background problem has to be solved

SNO+



Reuse of SNO equipment with Liquid Scintillator in the Acrylic Vessel

Original plan: ^{150}Nd

Current plan: ^{130}Te (using natural Te)
- good Te solubility is demonstrated (0.3-3%)
- 34.5% vs 5.6% natural abundance

Scintillator fill in 2014

Initially 0.3% loading (~ 800kg of ^{130}Te; maybe increased)

Sensitivity is ~ 10^{26} yr (Phase I)
~10^{27} yr (Phase-II)

Start of data taking in ~ 2014

IV. Conclusion

1. Significant advance has been made in the investigation of 2ν-decay (**NEMO-3**, **EXO-200, KamLAND-Zen**).

2. Present conservative limit on **$<m_\nu>$** from **2β(0ν)-**decay experiments
   is ~ **0.35 eV**.

3. 3 current "large-scale" experiments continue to produce new results:
   - **GERDA-I** (**18 кг ^{76}Ge**);
   - **EXO-200** (**200 кг ^{136}Xe**);
   - **KamLAND-Zen** (**330 кг ^{136}Xe**).

4. **In 2013-2015** we are waiting for start of **GERDA-II, MAJORANA-Demonstrator, CUORE, SuperNEMO-Demonstrator, SNO+, NEXT.**

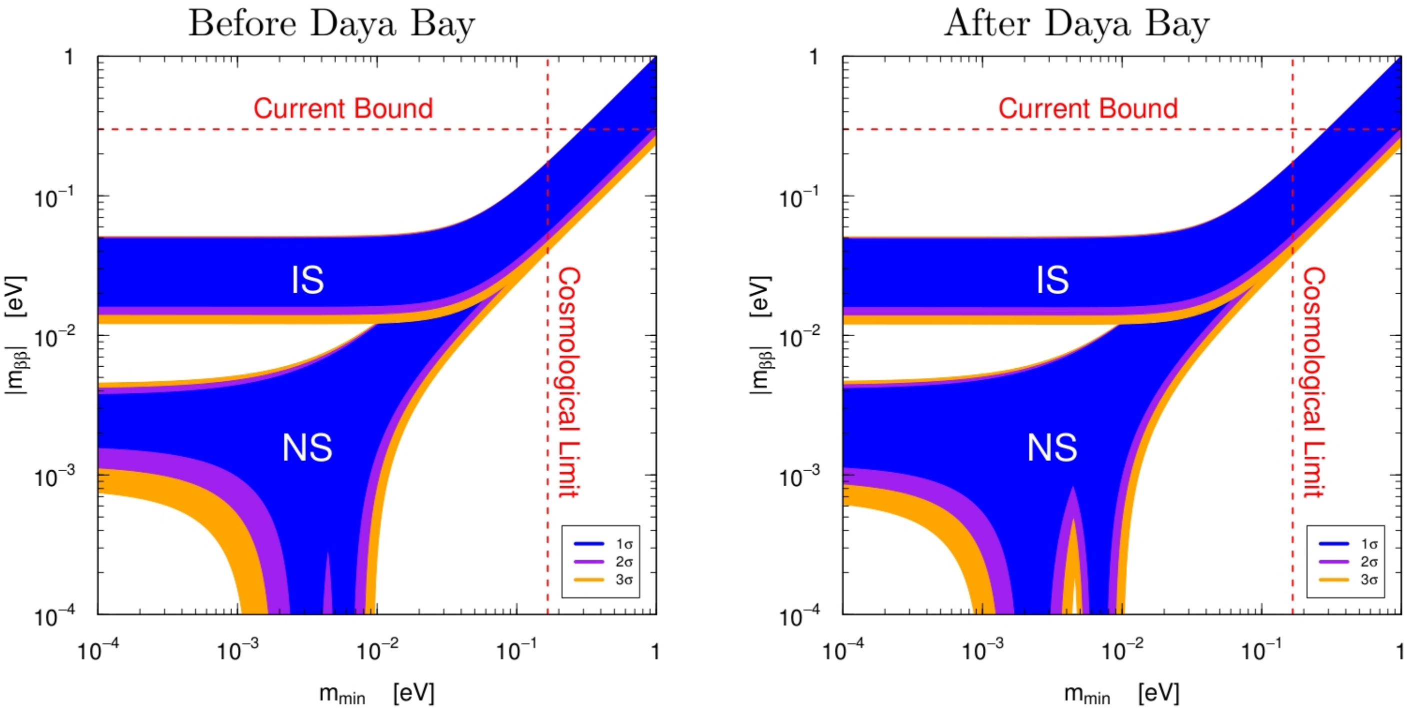
5. **In 2016-2018** we are waiting for start of **GERDA/MAJORANA, SuperNEMO, KamLAND2-Zen** and some other "large-scale" experiments.

6. **New generation** of experiments will reach sensitivity to **$<m_\nu>$** on the level
   ~ (0.01-0.1) eV in ~ **2014-2020**.

The next few years expected to be very interesting!!!

Backup slides

S.M. Bilenky and C. Giunti hep-ph/1203.5250



$\sin^2 2\theta_{13} = 0.092 \pm 0.016$ (stat) $\pm$ 0.05 (syst)

A Recent Claim

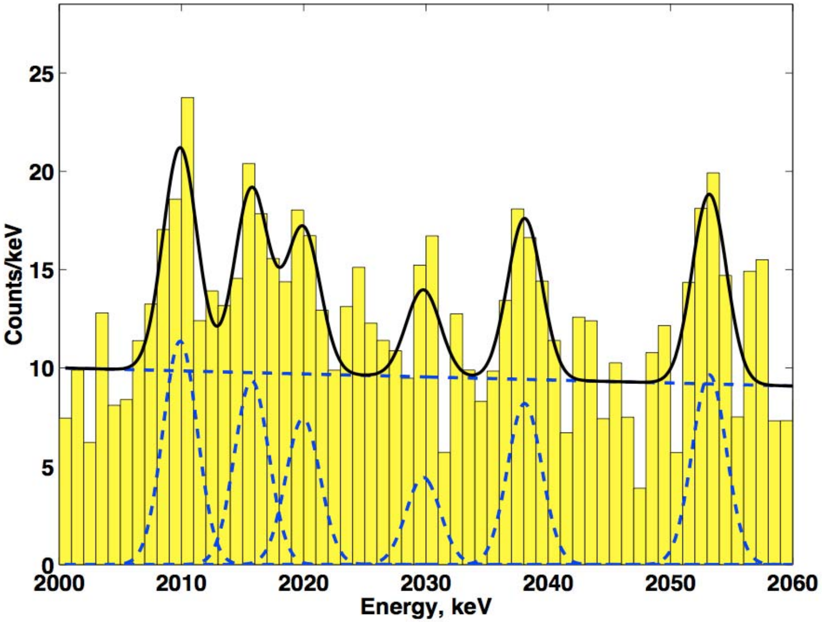
Klapdor-Kleingrothaus H V, Krivosheina I V, Dietz A and Chkvorets O, *Phys. Lett.* B **586** 198 (2004).

Used five ^{76}Ge crystals, with a total of 10.96 kg of mass, and 71 kg-years of data

$\tau_{1/2} = 1.2 \times 10^{25}$ y (4.2 σ)

$0.24 < m_\nu < 0.58$ eV (± 3 sigma)

(NME from Eur. Lett. 13(1990)31)



Mod.Phys.Lett. A21(2006)1547

Old data, new pulse shape anal.

$\tau_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{25}$ y (6 σ)

$m_\nu = 0.32 \pm 0.03$ eV

n = 11±1.8 events ⇒

where is a statistical error?!

non-correct peak position?!

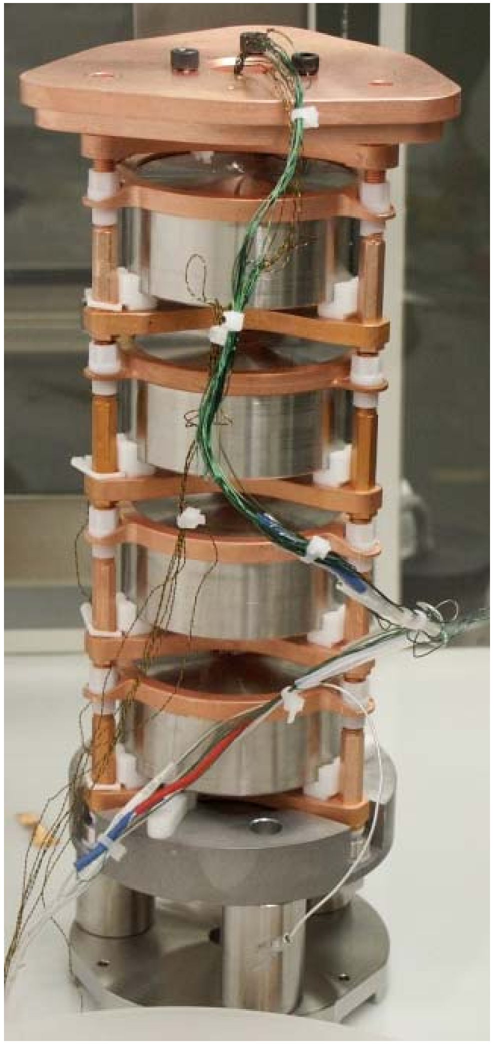
There are some problems with this result:

1) Only one measurement.
2) Only ~4σ level (independent analysis gives even ~ 2.7σ).
3) In contradiction with HM’01 and IGEX.
4) Moscow part of Collaboration: **NO EVIDENCE**.
5) ^{214}Bi peaks are overestimated.
6) “Total” and “analyzed” spectra are not the same.
7) Chkvorets’08 – 1.3σ

“2β community”: very conservative reaction

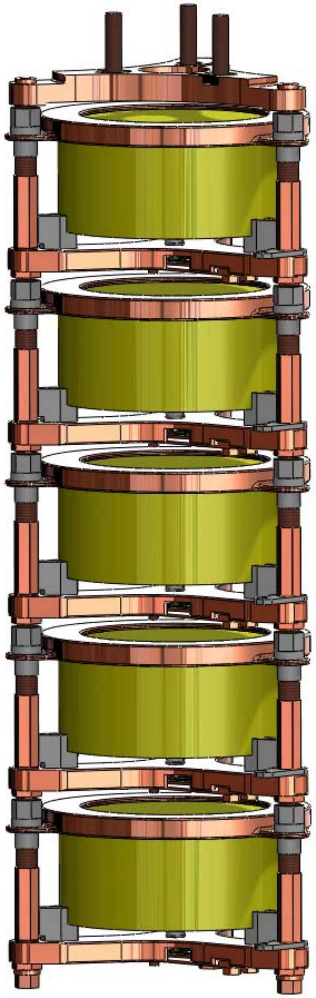
In any case new experiments are needed, which will confirm (or reject) this result

Detector Mount and String Design



LANL thermal test string
Jan 2011

LBNL test string (w/ thermal blanks)

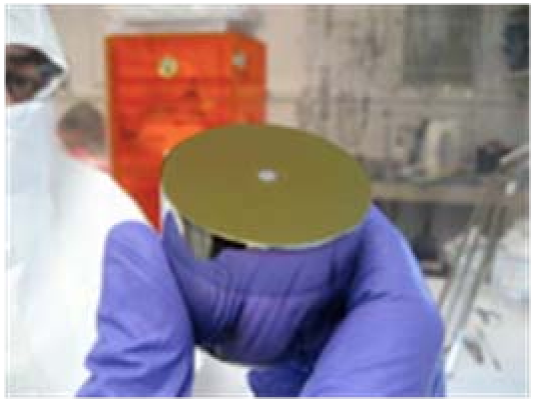


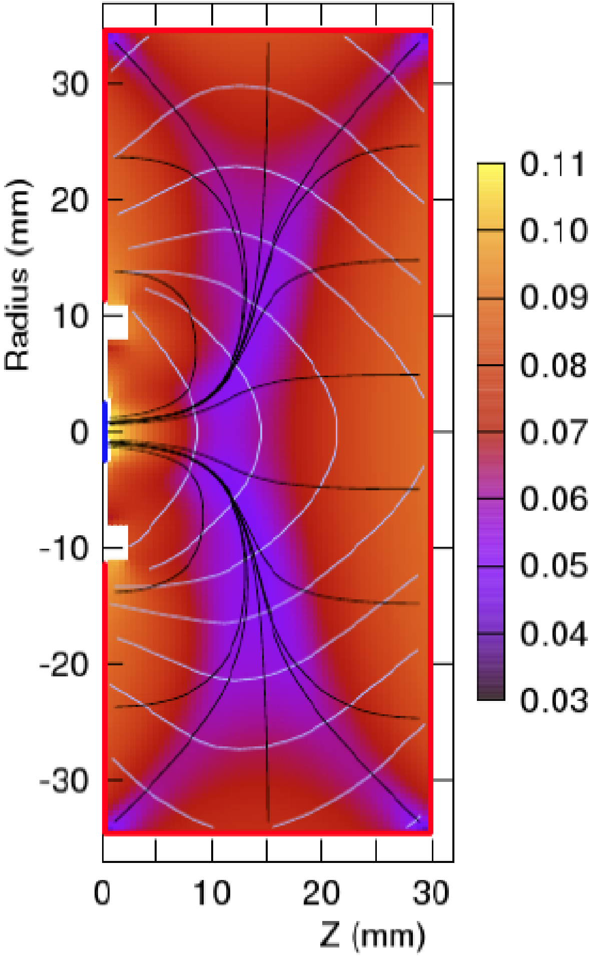
Design as released for R+D production June 2, 2011

P-type Point-Contact (PPC) Detectors

Point contact:

- Small capacitance: ~1pF
- Pronounced weighting field
- Small electrical fields
- Sub-keV Thresholds
- Excellent Pulse-shape Analysis
- Use Commercial BEGe Design



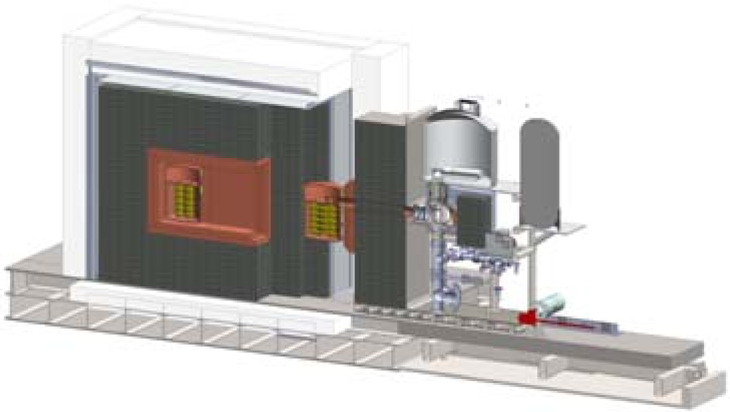


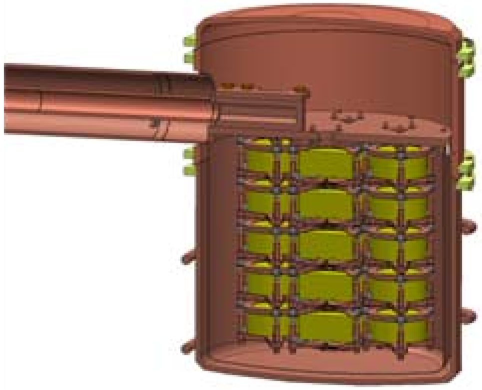
The Initial Majorana Modules (DEMONSTRATOR)

- **40-kg of Ge detectors**
  - **30-kg** of 87% enriched ^{76}Ge (20 kg of natural and 10 kg of enriched HPGe detectors are ready)
- **Low-background Cryostats & Shield**
  - ultra-clean, electroformed Cu
  - naturally scalable
  - Compact low-background passive Cu and Pb shield with active muon veto
- **Background Goal in the $0\nu\beta\beta$ peak ROI(4 keV at 2039 keV)**

  ~ 4 count/ROI/t-y (after analysis cuts)

  (scales to 1 count/ROI/t-y for tonne expt.)

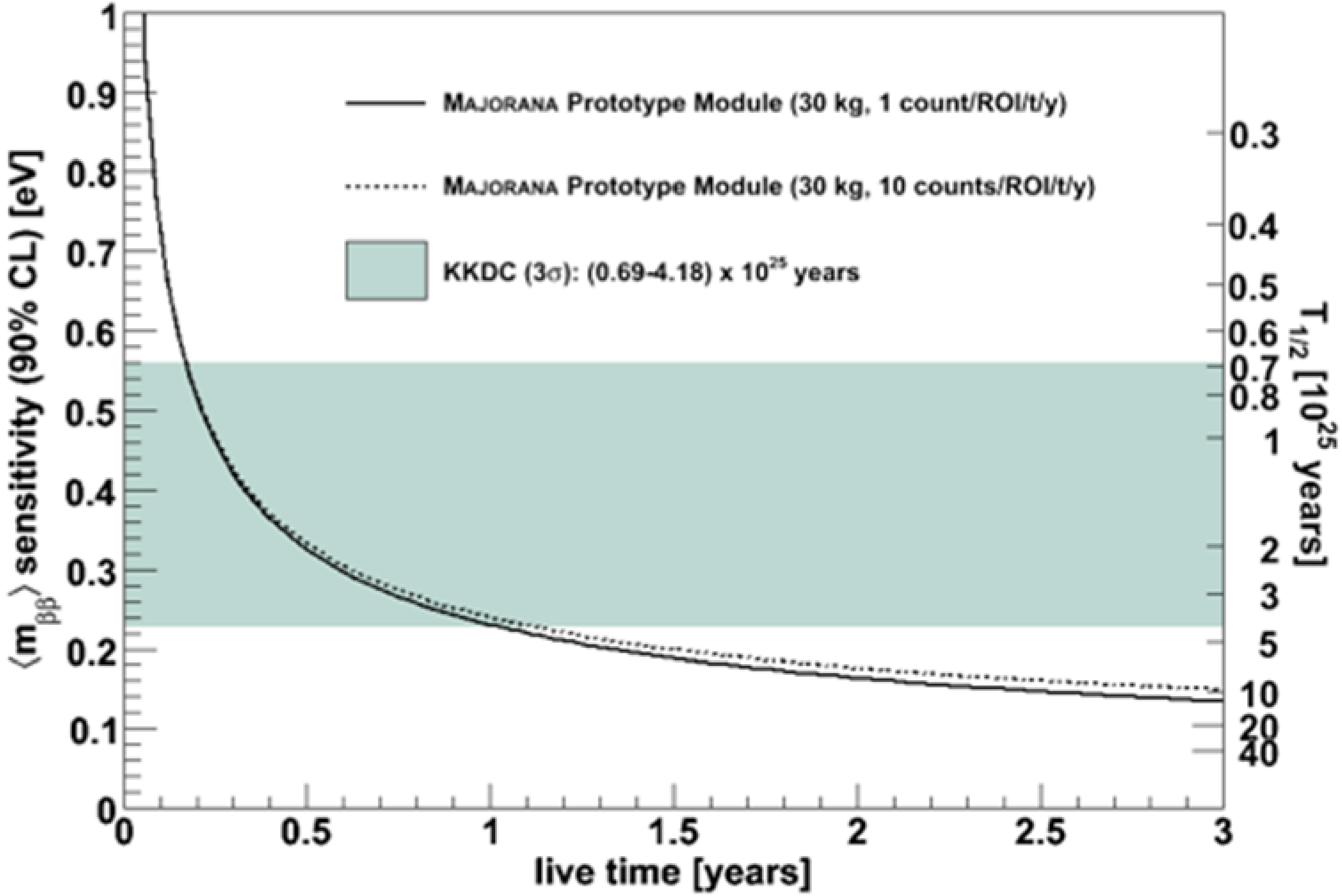




Sensitivity is ~ 10^{26} yr in 3 yr of measurements

Start of data taking with natural Ge in ~ 2013 and with enriched Ge in~ 2014

DEMONSTRATOR Sensitivity

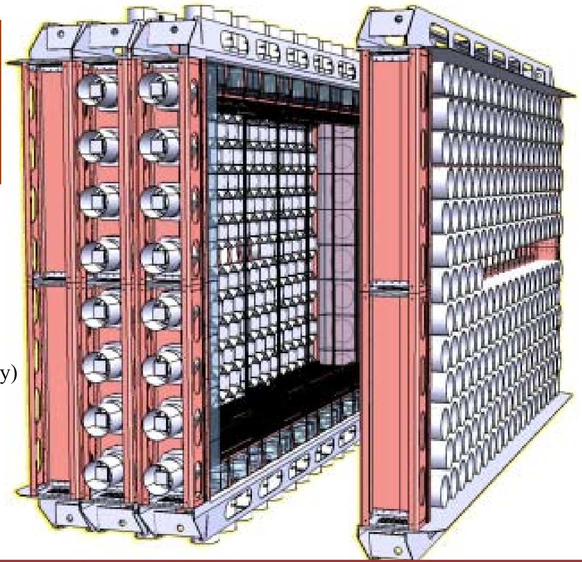


NEMO-3 → SuperNEMO

$$T^{0\nu}_{1/2}(n_\sigma) = \frac{4.16\times10^{26}\,y}{n_\sigma}\left(\frac{\varepsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta E}}$$

n_σ – number of std. dev. for a given C.L.
a – isotopic abundance
ε – detection efficiency
W – molecular weight of the source

M – total mass of the source (kg)
t – time of data collection (y)
b – background rate in counts $(\mathrm{keV}\cdot\mathrm{kg}\cdot\mathrm{y})$
ΔE – energy resolution (keV)



NEMO-3	R&D since 2005	SuperNEMO
^{100}Mo	isotope	^{82}Se (maybe also ^{150}Nd or ^{48}Ca)
7 kg	mass	**100-200 kg**
A(^{208}Tl) < 20 μBq/kg A(^{214}Bi) < 300 μBq/kg Rn ~ 5-6 mBq/m^3	Radio-purity of the foil Radon in the tracker	A(^{208}Tl) < 2 μBq/kg A(^{214}Bi) < 10 μBq/kg Rn < 0.1 mBq/m^3
18%	efficiency	30%
8% FWHM @ 3 MeV	Energy resolution	4% FWHM @ 3 MeV
$T_{1/2}(0\nu\beta\beta)$ > 10^{24} y $<m_\nu>$ < 0.3 – 1 eV	sensitivity	**$T_{1/2}(0\nu\beta\beta)$ > 10^{26} y $<m_\nu>$ < 40 – 100 meV**
1 module	modularity	>20 modules (new lab)