DOUBLE BETA DECAY EXPERIMENTS

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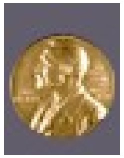
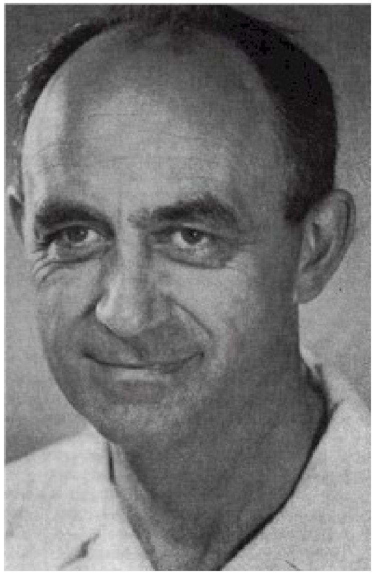
Plan

- Historical introduction
- Present status
- Future experiments

I. Historical introduction





Neutrino was introduced by **W. Pauli** in 1930

β-decay theory (weak interaction) was formulated by **E. Fermi** in 1933:

$(A,Z) \rightarrow (A,Z+1) + e^{-} + \nu^{\sim}$

$(A,Z) \rightarrow (A,Z-1) + e^{+} + \nu$

The birth of double beta decay

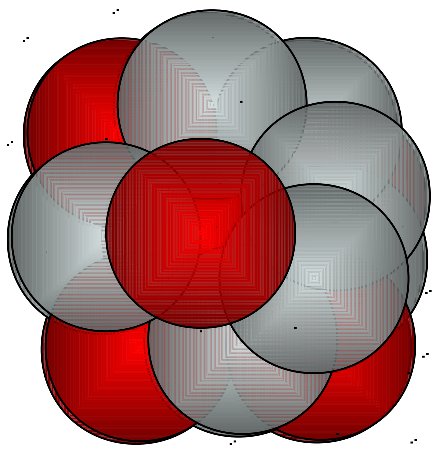
- **$2\beta(2\nu)$ decay was introduced by**

  M. Goeppert-Mayer in 1935:

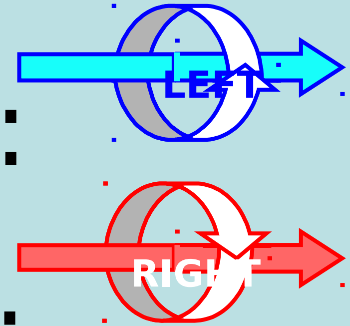
$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\tilde{\nu}$$

$(T_{1/2} \sim 10^{21}\text{-}10^{22}\ y)$

2ν-ββ Decay
$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\tilde{\nu})$



ν:



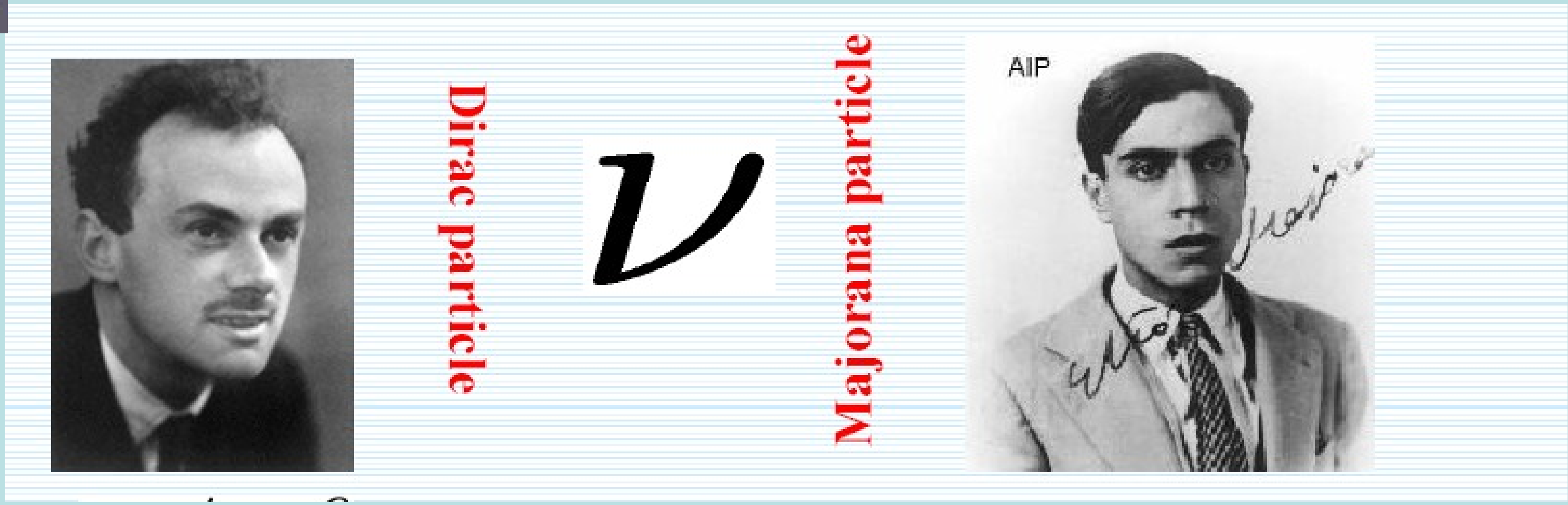
$\bar{\nu}$:

$\nu \neq \bar{\nu}$

$\nu = \bar{\nu}$

Dirac

Majorana
=>1937



Racah's chains (G. Racah, 1937)

- $(A,Z) \to (A,Z+1) + e^- + \tilde{\nu}$ $(\nu = \nu^{\sim})$ $\to$
  $\nu + (A,Z) \to (A,Z+1) + e^-$
- So, it will be possible to see difference between Dirac and Majorana neutrinos!
- **W.H. Farry (1938)** $\to$ no any practical possibilities to use this (there were no reactors at that time!)

The birth of neutrinoless double beta decay

- **2β(0ν) decay was introduced by W.H. Farry in 1939:**

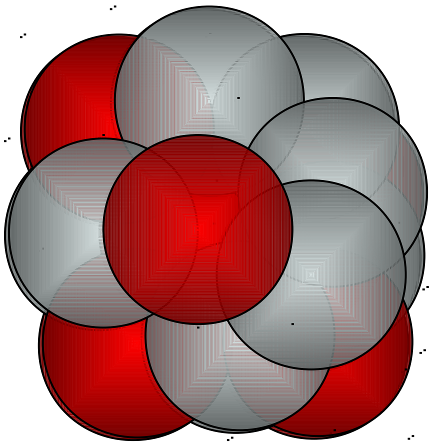
(A,Z) → (A,Z+2) + 2e⁻ (4)

($T_{1/2} \sim 10^{15}$-10^{16} y)

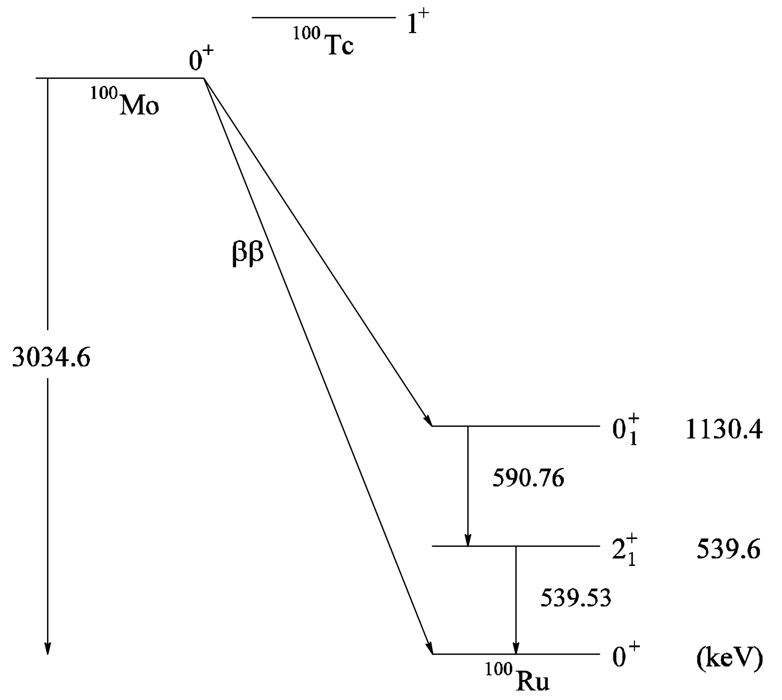
[Parity violation was not known at that time!]

0ν-ββ Decay

(A,Z) → (A,Z+2) + $2e^-$



Double beta decay scheme



First experiments

- **1948** – first counter experiment (Geiger counters, ^{124}**Sn**; $T_{1/2}(0\nu) > 3 \cdot 10^{15}$ **y**)
- **1950** – **first evidence** for **2β2ν** decay of ^{130}**Te** in first geochemical experiment:

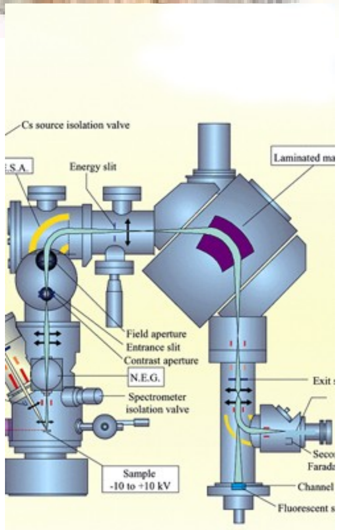
  $T_{1/2} \approx 1.4 \cdot 10^{21}$ **y!!!**
- **1950-1965** – a few tens experiments

  with sensitivity **~ 10^{16}-10^{19} y**
- **1966-1975** – in 3 experiments sensitivity to **0ν** decay reached **~ 10^{21} y**!!!

Geochemical experiments

1. **Selection** of mineral, contains **2β** nuclei (^{130}**Te,** ^{82}**Se,** for example).
2. **Age and geological history** of the mineral (age is ~ (0.1-4)x10^9 yr) have to be known.
3. **Extraction** of daughter atoms (**Xe, Kr,**).
4. Determination of isotopic composition (using **mass-spectrometer**).
5. Excess of ^{130}**Xe** or ^{82}**Kr** gives information about **2β-decay rate.**

Measurement time is a few billion years!



1957 – situation is changed!

- **P** and **C** violation
- **V-A** structure of weak interaction
- **Helicity** of ν(ν~) is **~ 100%**

$\Downarrow$

2β(0ν)-decay is suppressed (if even possible?)

and $T_{1/2}(0\nu) > T_{1/2}(2\nu)$

Best results in 1966-1975

- $T_{1/2}(0\nu;{}^{76}$**Ge**$)$ **>** **5·10²¹ y**; Ge(Li) detector, **1973**
  (E. Fiorini et al.)
  (1967 – first result for ^{76}Ge with Ge(Li) detector)
- $T_{1/2}(0\nu;{}^{48}$**Ca**$)$ **> 2·10²¹ y**; streamer chamber + magnetic field + plastic scint., **1970** (C. Wu et al.)
- $T_{1/2}(0\nu;{}^{82}$**Se**$)$ **> 3.1·10²¹ y**; streamer chamber + magnetic field + plastic scint., **1975** (C. Wu et al.)

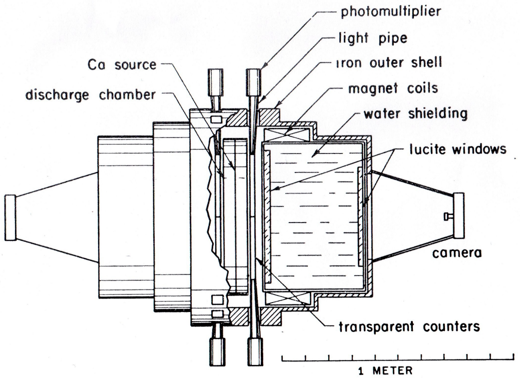
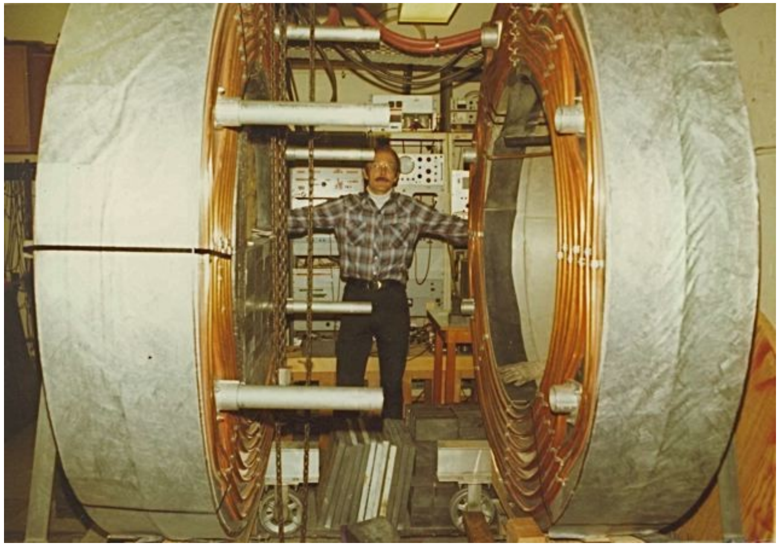


Fig. 3. Cutaway drawing of double beta decay apparatus.

- Geochemical experiments with **^{130}Te, ^{128}Te, ^{82}Se** (**2ν** measurements: **~ 10^{21}, ~10^{24}** and **~10^{20}** y)

Main achievements in 1976-1987

- **2β2ν** decay was first time detected in direct (counting) experiment ⇒
  $T(^{82}Se)_{1/2} = 1.1^{+0.8}_{-0.3} \cdot 10^{20}$ y
  (35 events; TPC, **1987**, S. Elliott, A. Hahn, **M. Moe**)



- First time **enriched Ge** detector was used in experiment (ITEP-ErFI; **1987**)

Main achievements in 1988-2003

- $T_{1/2}(0\nu;^{76}\mathbf{Ge})$ **> (1.6-1.9)·10^{25} y**;

  (HM and IGEX; enriched HPGe detectors)
- $T_{1/2}(0\nu)$ **> 10^{22}-10^{23}** y for **^{136}Xe, ^{82}Se, ^{116}Cd, ^{100}Mo**
- **2ν**-decay was detected for many nuclei (TPC, ELEGANT-V, NEMO-2, HM, IGEX, Solotvino, Liq. Ar….) + transition to the 0^+ excited states (Soudan, Modane, TUNL-ITEP)
- First time **ECEC(2ν)** process was detected (^{130}Ba, geochemical experiment)

Klapdor's 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)

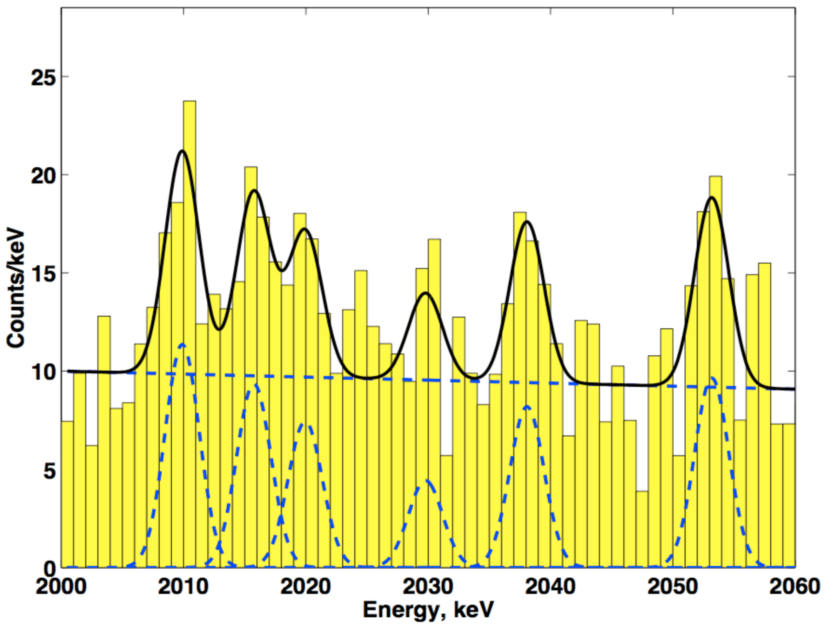
(NME from Eur. Lett. 13(1990)31)

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.

"2β community": very conservative reaction

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



Mod.Phys.Lett. A21(2006)1547

Old data, new pulse shape anal.

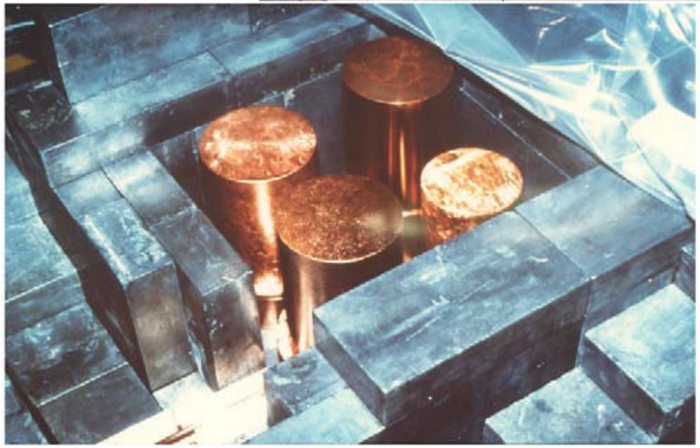
$\tau_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{25}$ y (6 σ)

$m_\nu = 0.32 \pm 0.03$ eV

n = 11±1.8 events ⇒ where is a statistical error?!

non-correct peak position?!

Heidelberg-Moscow experiment



Gran Sasso
5 HPGe detectors
(~ 11 kg of ^{76}Ge)
B ≈ 0.17 (0.02)
c/keV kg y

1990-2003
(full statistics:
71.7 kg·y)

$T_{1/2}(0\nu) > 1.9 \cdot 10^{25}$ yr (no evidence)

Main achievements in 2004-2012

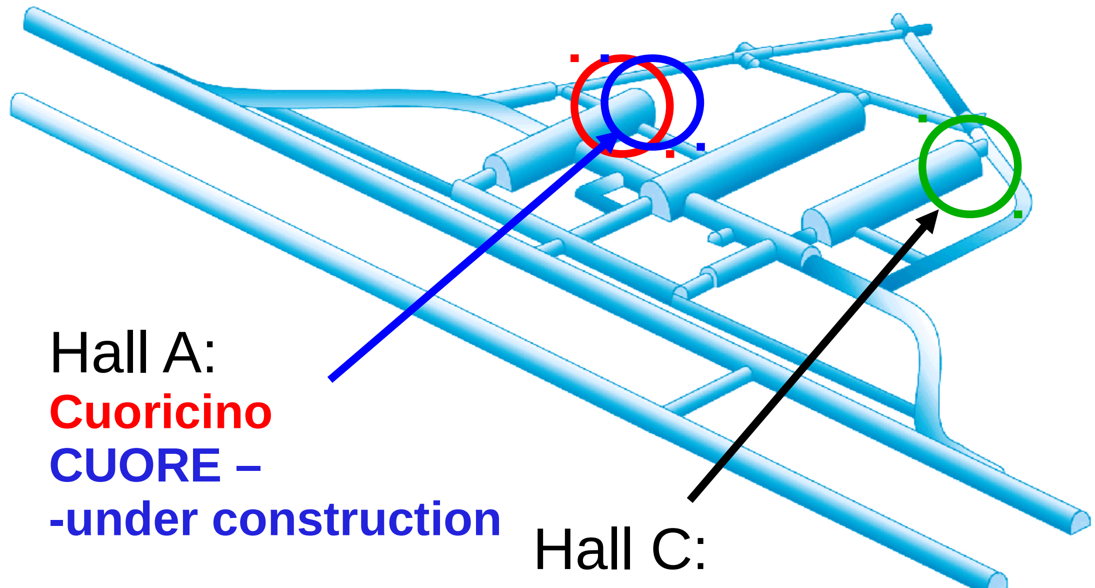
- **NEMO-3 experiment**

-**COURICINO experiment**

- **start of GERDA-I, EXO, KamLAND-Zen experiments**

CUORICINO

INFN - Laboratori Nazionali del Gran Sasso - L'Aquila – Italy



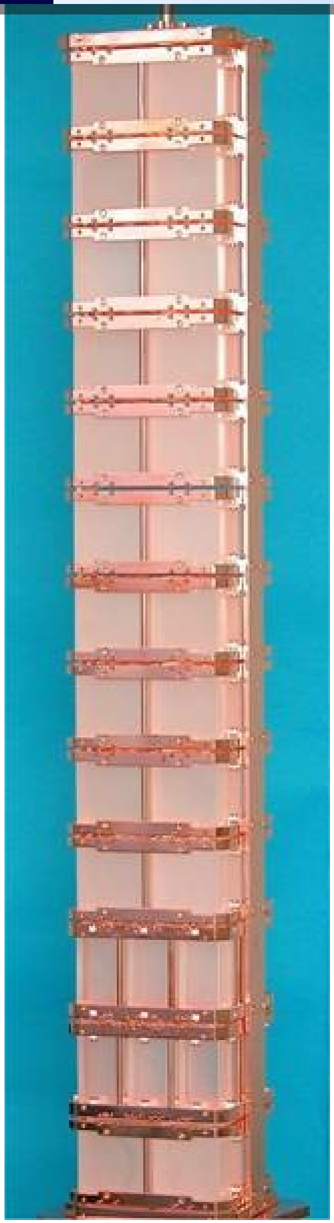
Hall A:
Cuoricino
CUORE –
-under construction

Hall C:
R&D + final test for CUORE

3200 m.w.e overburden - cosmic rays are no more a bkg problem

- **n flux is reduced to ~10^{-6} n/cm²/s**
- **µ flux is ~ 2/m²/h**

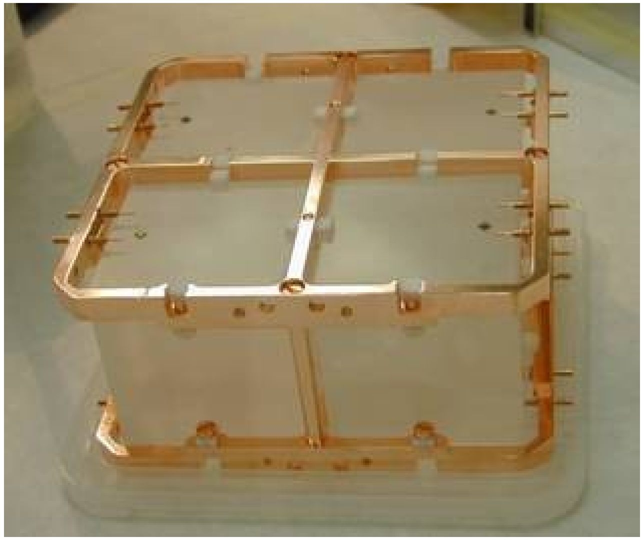
Cuoricino

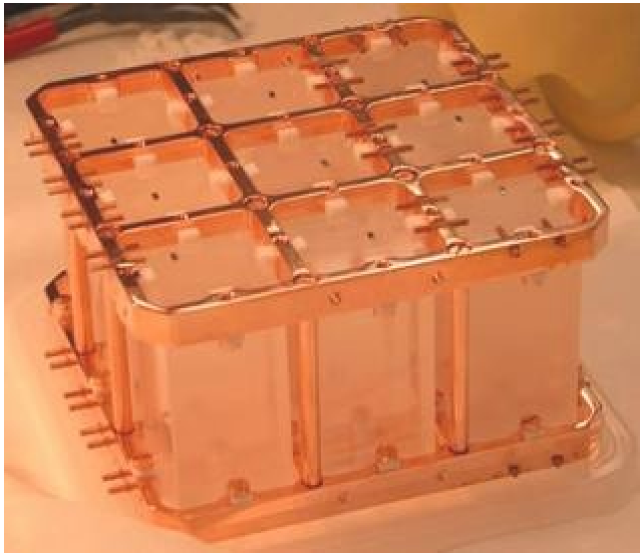


11 modules
4 detectors each
Dimension: 5x5x5 cm^3
Mass: 790 g

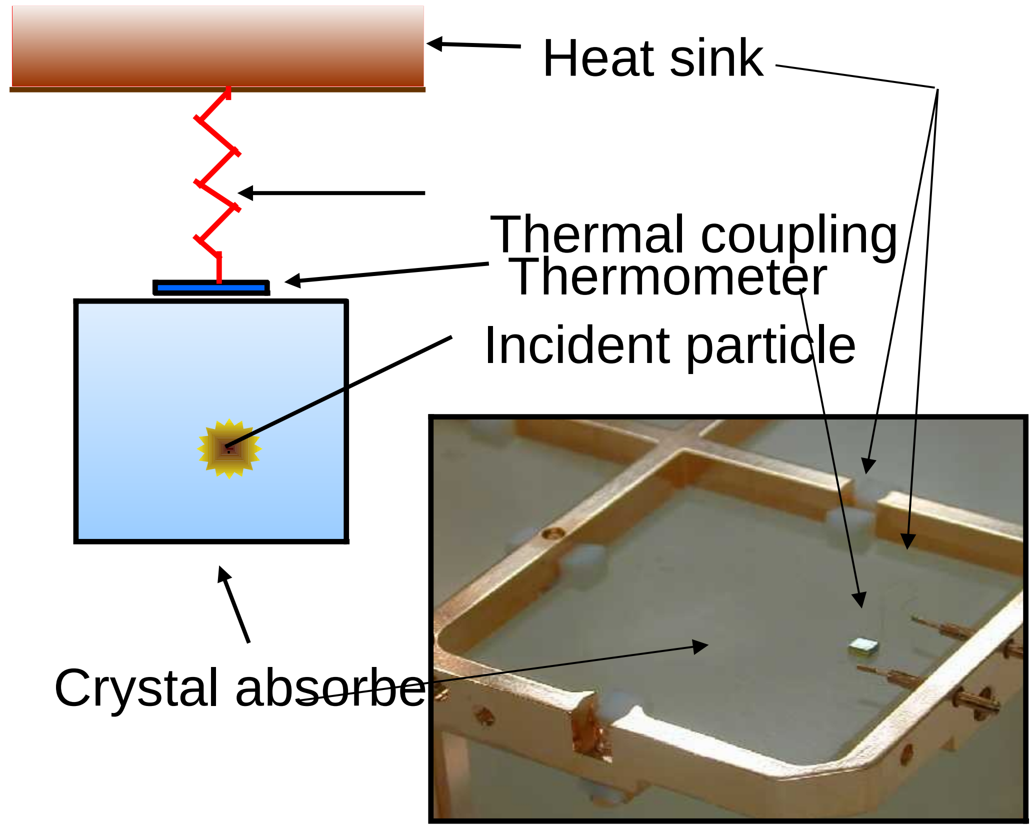
Total mass
40.7 kg
(~11 kg of ^{130}Te)

2 modules
9 detectors each,
Dimension: 3x3x6 cm^3
Mass: 330 g





Low Temperature Detectors (LTD)



Detection Principle

$\Delta T = E/C$

C: thermal capacity

low C

low T (i.e. $T \ll 1$K)

dielectrics, superconductors

ultimate limit to E resolution: statistical fluctuation of internal energy U

$\langle \Delta U^2 \rangle = k_B T^2 C$

Thermal Detectors Properties

good energy resolution

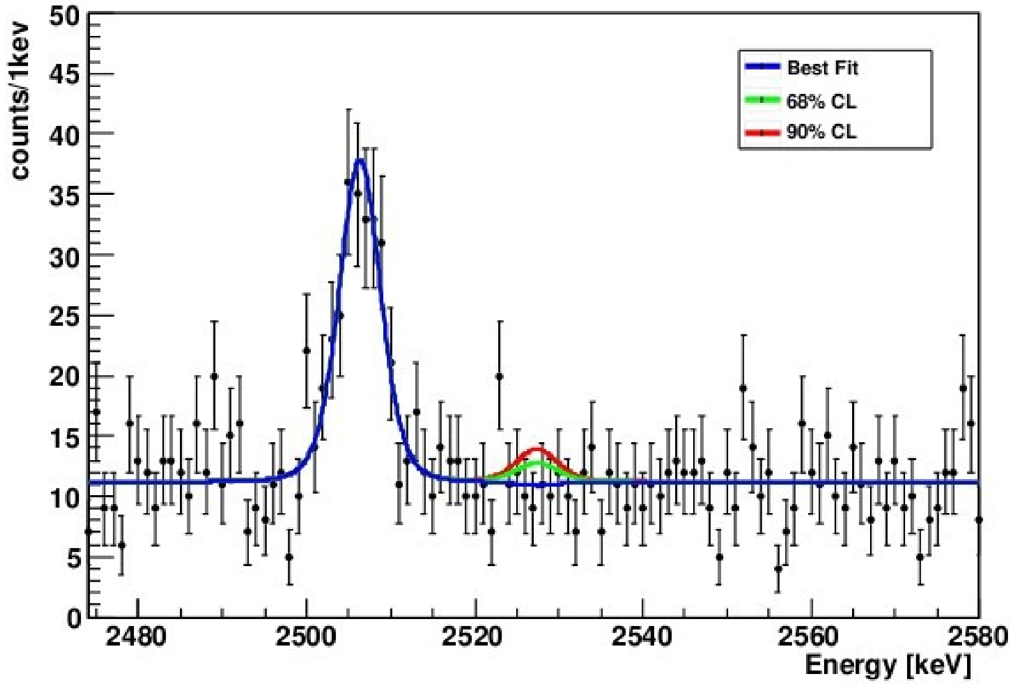
wide choice of absorber materials

true calorimeters

slow $\tau = C/G \sim 1 \div 10^3$ ms

T = 8 mK

Cuoricino result on ^{130}Te $\beta\beta0\nu$ decay



Anticoincidence background spectrum the $\beta\beta$-0ν region

Total statistic
~ 19.75 kg (^{130}Te) × y

b = 0.18 ± 0.01 c/keV/kg/y

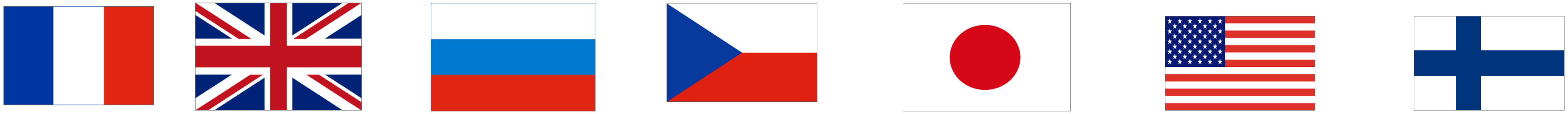
Maximum Likelihood
flat background + fit of 2505 peak

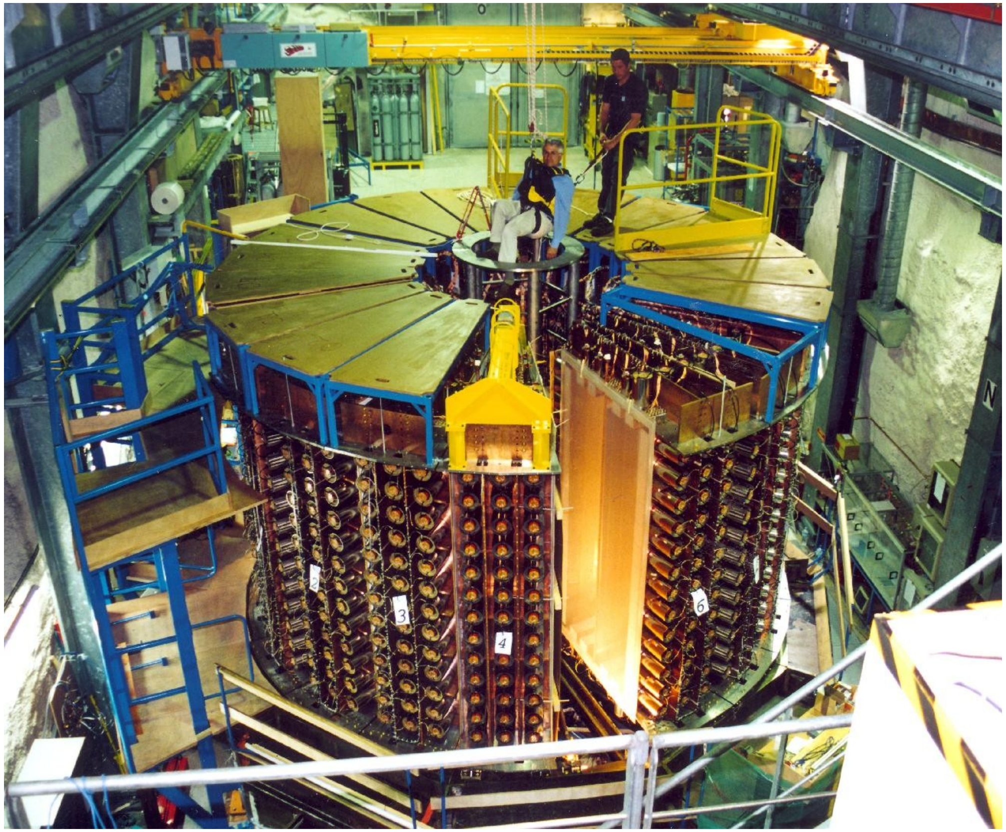
$T_{1/2} > 2.8 \cdot 10^{24}$ yr **$\langle m_\nu \rangle < 0.3$-$0.7$ eV**

NEMO-3 Collaboration

(Neutrino Ettore Majorana Observatory)

60 physicists, 17 labs





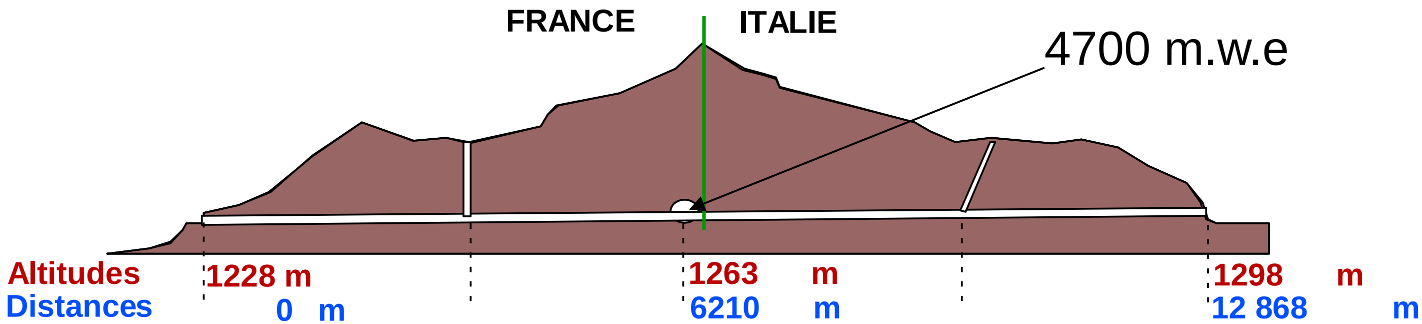
Laboratoire Souterrain de Modane

COMMISSARIAT À L'ÉNERGIE ATOMIQUE

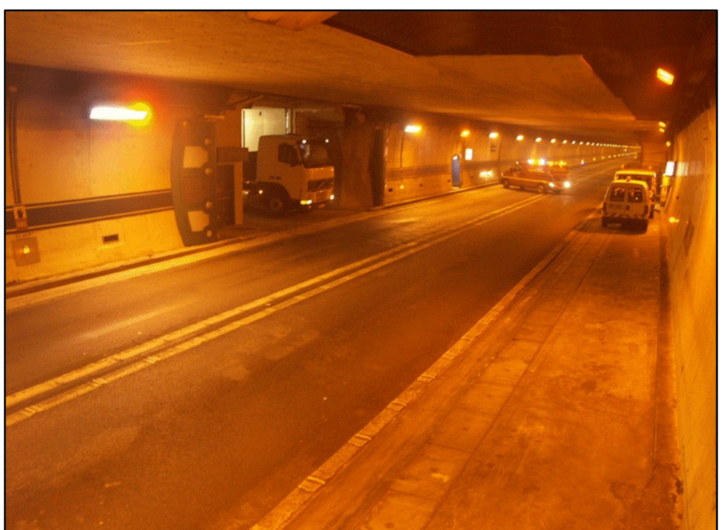
DIRECTION DES SCIENCES DE LA MATIÈRE

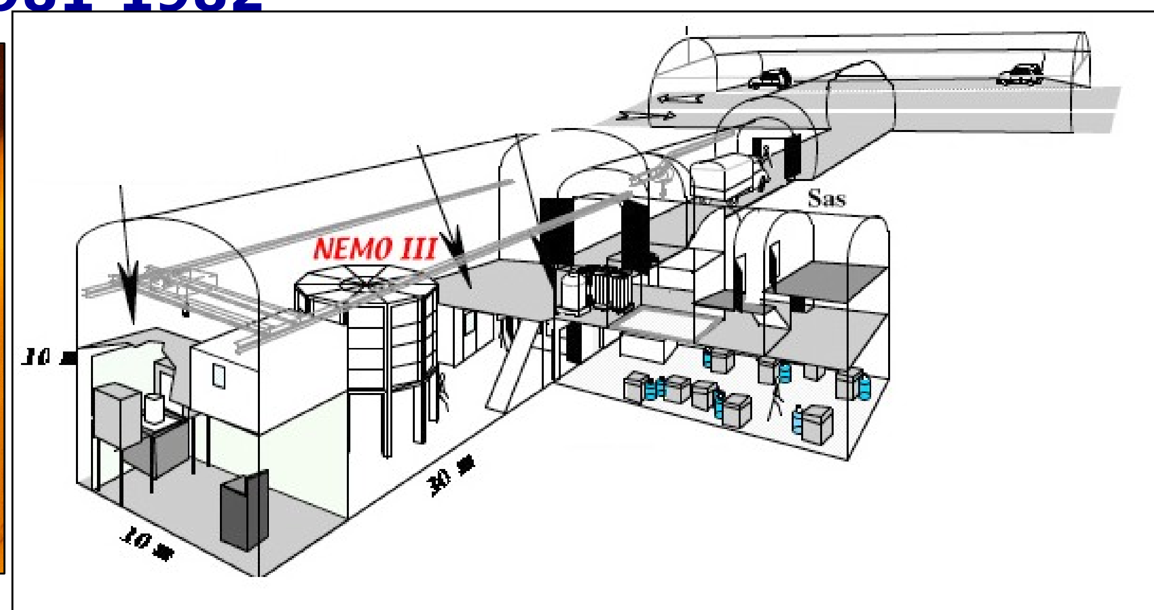
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

INSTITUT NATIONAL DE PHYSIQUE NUCLÉAIRE ET DE PHYSIQUE DES PARTICULES



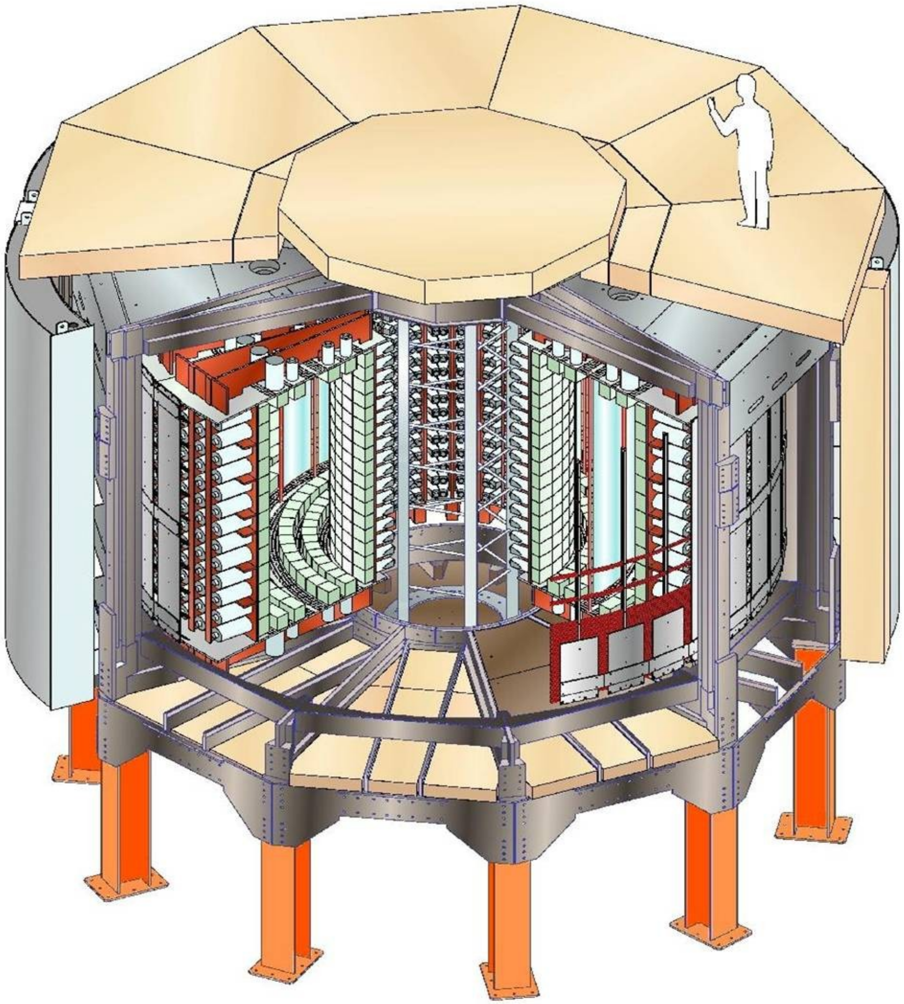
Built for Taup experiment (proton decay) in 1981-1982





The NEMO3 detector

Fréjus Underground Laboratory : 4800 m.w.e.



Source: 10 kg of ββ isotopes
cylindrical, S = 20 m^2, 60 mg/cm^2

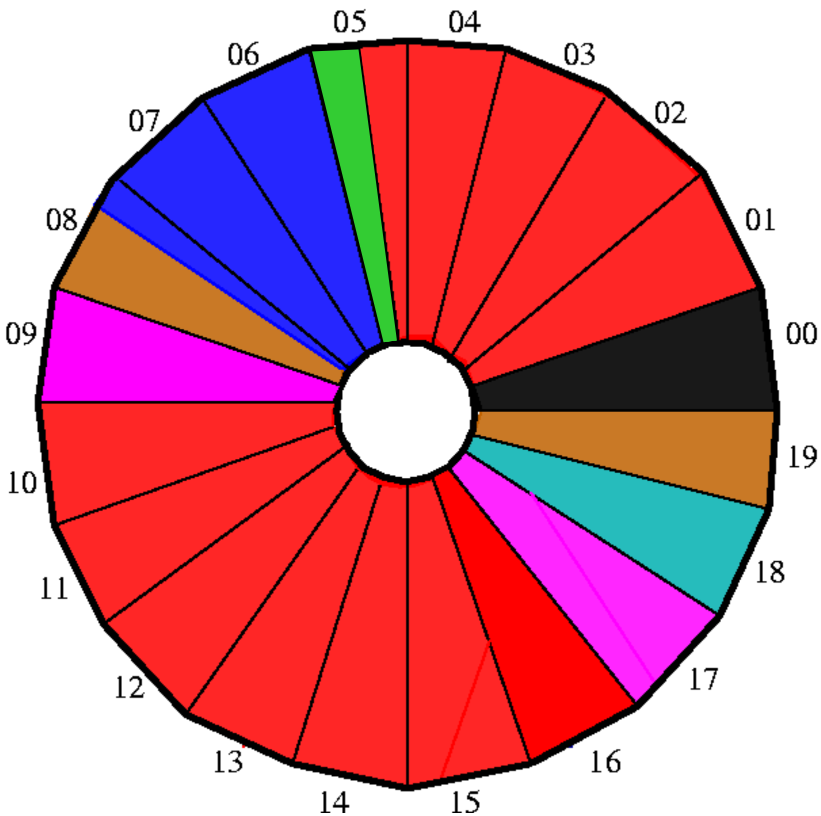
Tracking detector:
drift wire chamber operating in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:
1940 plastic scintillators coupled to low radioactivity PMTs

Magnetic field: 25 Gauss
Gamma shield: Pure Iron (18 cm)
Neutron shield: borated water (~30 cm) + **Wood (Top/Bottom/Gapes between water tanks)**

Able to identify e^-, e^+, γ and α

ββ decay isotopes in NEMO-3 detector



^{100}Mo 6.914 kg
$Q_{\beta\beta}$ = 3034 keV

^{82}Se 0.932 kg
$Q_{\beta\beta}$ = 2995 keV

ββ0ν search

ββ2ν measurement

^{116}Cd 405 g
$Q_{\beta\beta}$ = 2805 keV

^{96}Zr 9.4 g
$Q_{\beta\beta}$ = 3350 keV

^{150}Nd 37.0 g
$Q_{\beta\beta}$ = 3367 keV

^{48}Ca 7.0 g
$Q_{\beta\beta}$ = 4272 keV

^{130}Te 454 g
$Q_{\beta\beta}$ = 2529 keV

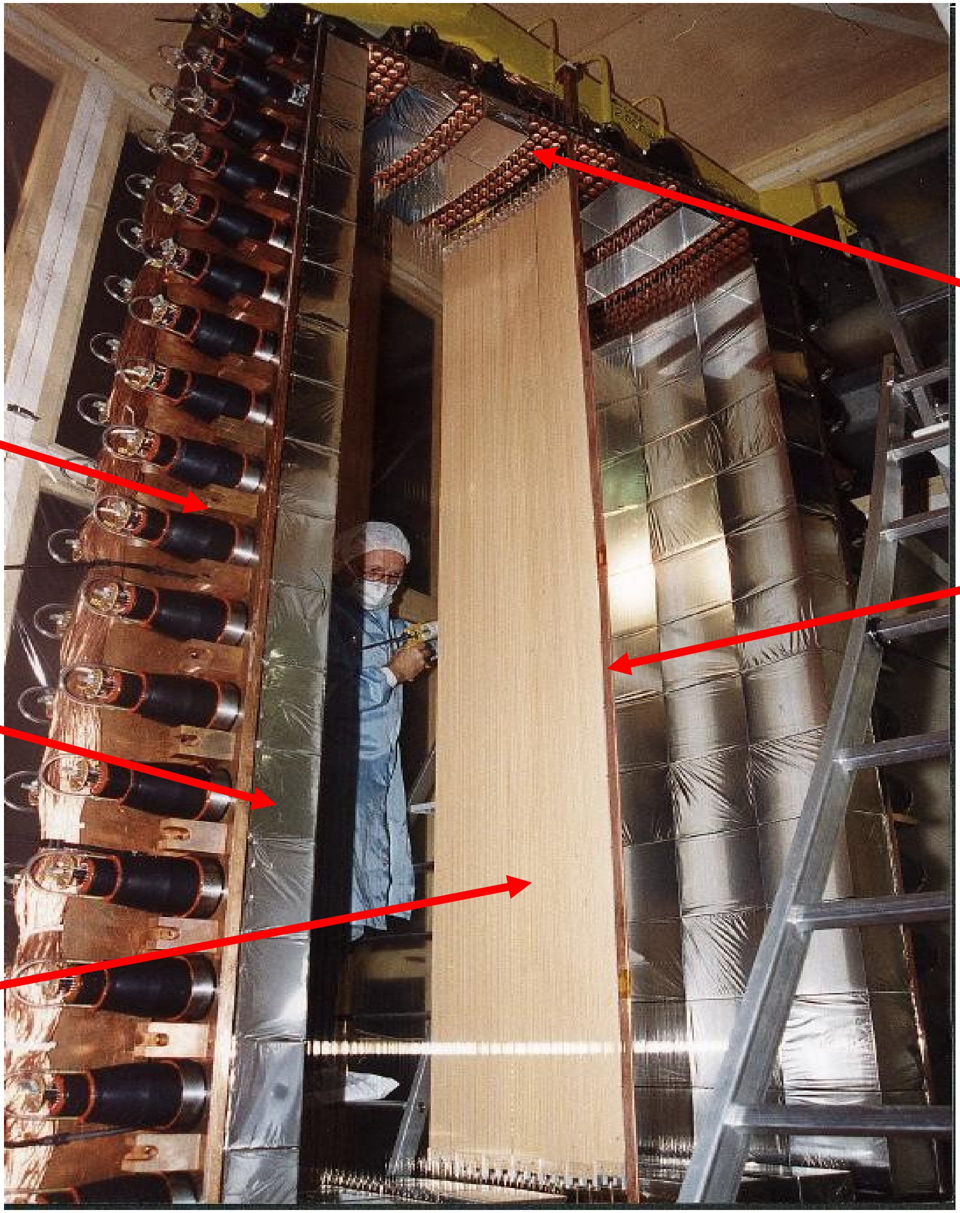
^{nat}Te 491 g

Cu 621 g

External bkg measurement

(All enriched isotopes produced in Russia)

Sector interior view



Calibration source

^{207}Bi

2e– (IC) lines

~0.5 ,~1 MeV

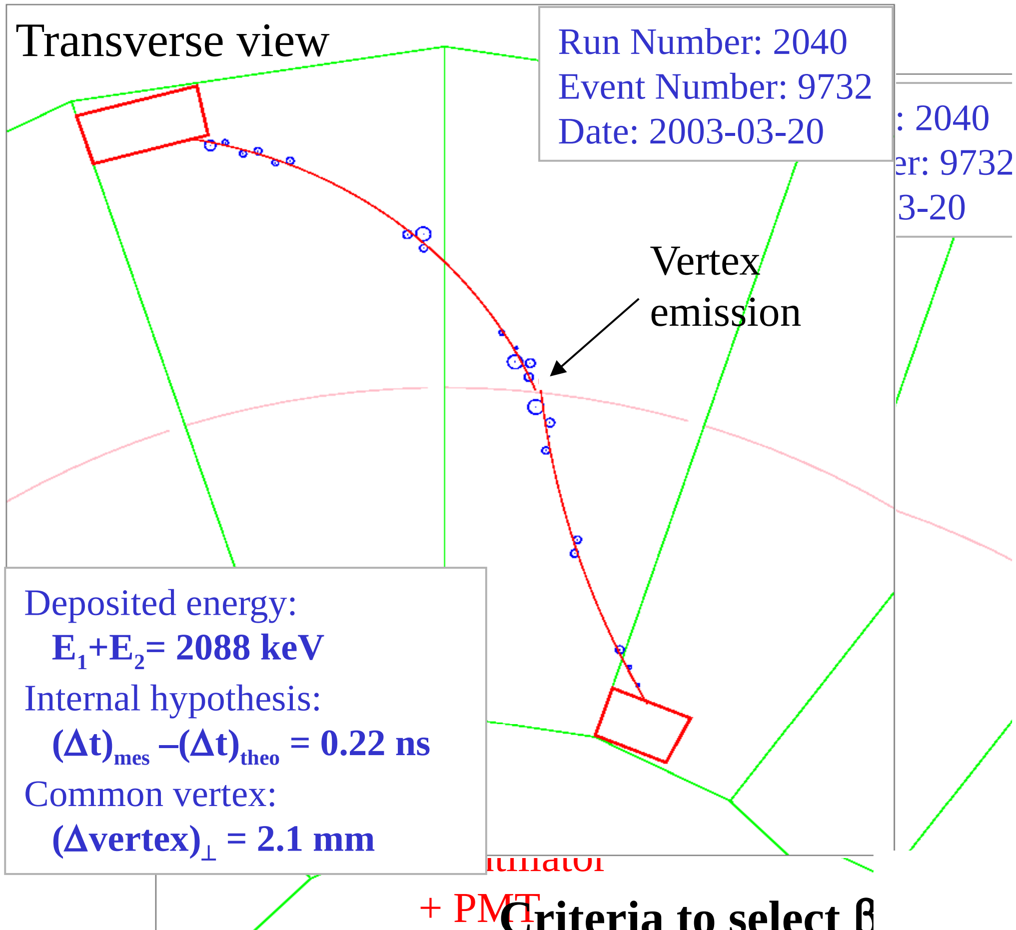
^{90}Sr

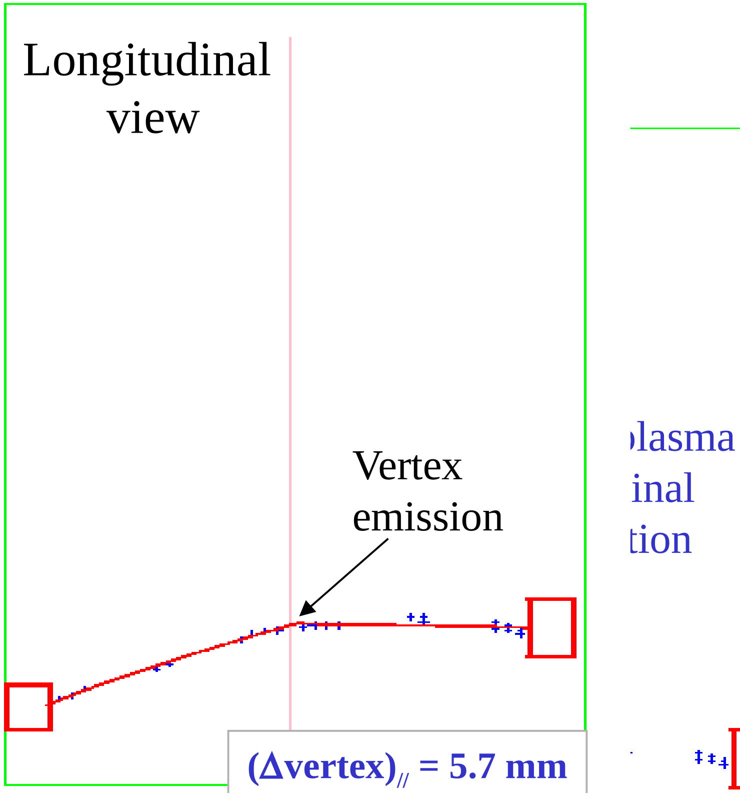
^{60}Co

Sources preparation

ββ events selection in NEMO-3

Typical ββ2ν event observed from ^{100}Mo





Criteria to select β

- 2 tracks with charge < 0
- 2 PMT, each > 200 keV
- PMT-Track association

- Intern
- No otl
- No delayed track (^{214}Bi rejection)

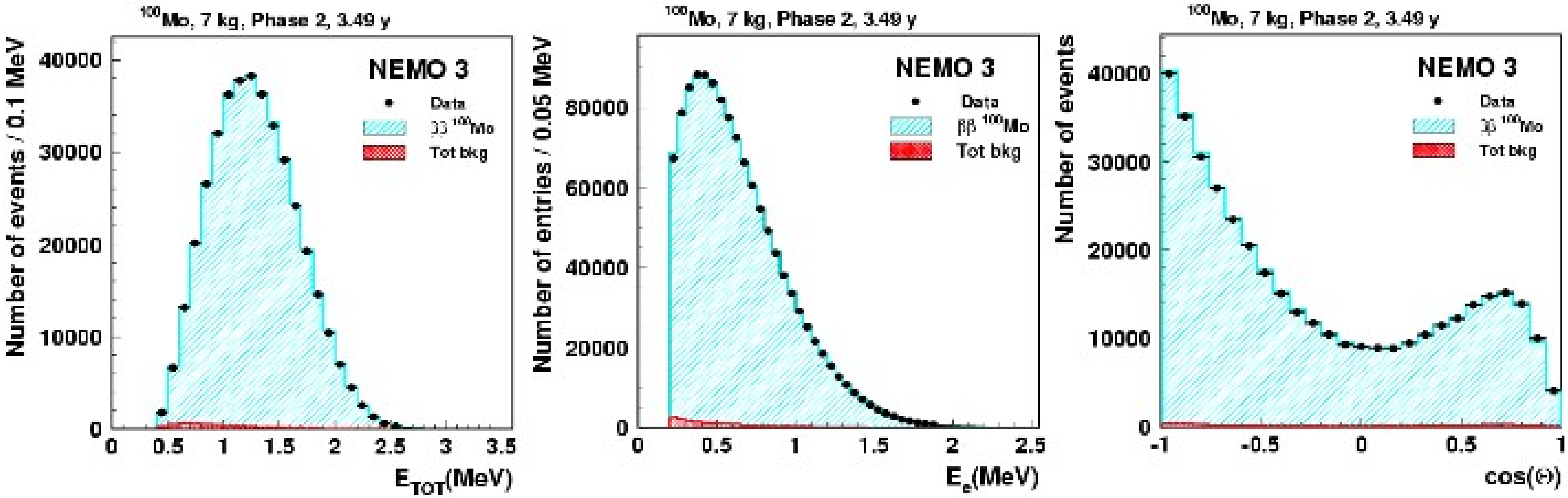
Trigger: at least 1 PMT > 150 keV

≥ 3 Geiger hits (2 neighbour layer + 1)

Trigger rate = 7 Hz

ββ events: 1 event every 2.5 minutes

^{100}Mo (7kg), 2νββ



$T_{1/2}(2\nu)$ = [7.17 ± 0.01(stat) ± 0.54(sys)] × 10^{18} yr ⇒ ~3.5 yr,

Phase II (low Rn), S/B = 76 $M^{2\nu}$(^{100}Mo) = 0.126 ± 0.006
~ 700000 событий!

to be compared with earlier published in PRL 95 (182302)

2005:

$T_{1/2}(2\nu)$ = [7.11 ± 0.02(stat) ± 0.54(sys)] × 10^{18} yr ⇒ ~1 yr, Phase I, S/B = 40

Summary of 2νββ results (NEMO-3)

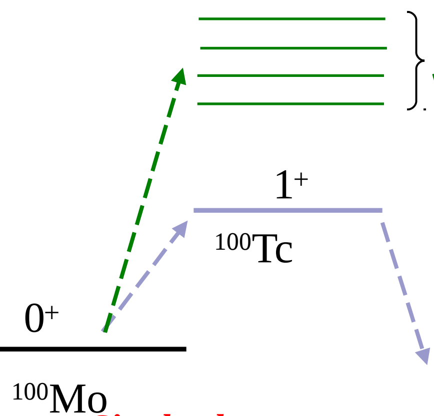
Isotope	S/B	(2νββ), y
^{100}Mo	40	$(7.11 \pm 0.02(stat) \pm 0.54(syst)) \cdot 10^{18}$ (SSD favoured) *
^{100}Mo(0^+_1)	3	$(5.7^{+1.3}_{-0.9}(stat)) \pm 0.8(syst)) \cdot 10^{20}$ ** [NPA 781 (2006) 209]
^{82}Se	4	$(9.6 \pm 0.3(stat) \pm 1.0(syst)) \cdot 10^{19}$ *
^{116}Cd	7.5	$(2.74 \pm 0.04(stat) \pm 0.18(syst)) \cdot 10^{19}$ [PRD 95 (2017) 012007]
^{130}Te	0.35	$(7.0^{+1.0}_{-0.8}(stat)\ ^{+1.1}_{-0.9}(syst)) \cdot 10^{20}$ [PRL 107 (2011) 045503
^{150}Nd	2.8	$(9.34 \pm 0.22(stat) \pm 0.62(syst)) \cdot 10^{18}$ [PRC 80 (2009) 032501R]
^{96}Zr	1.0	$(2.35 \pm 0.14(stat) \pm 0.16(syst)) \cdot 10^{19}$ [NPA 847 (2010) 168]
^{48}Ca	6.8	$(6.4^{+0.7}_{-0.6}(stat) + ^{1.2}_{-0.9}(syst)) \cdot 10^{19}$ [PRD 93 (2016) 112008]

* Phase 1 data, Phys. Rev. Lett. 95 (2005) 182302. Additional statistics are being analysed, to be published soon.
** Phase 1 data.

Single electron spectrum 2νββ (^{100}Mo)

$T_{1/2} = 7.11 \pm 0.02\ (\text{stat}) \pm 0.54\ (\text{syst}) \times 10^{18}$ y
Phys. Rev. Lett. 95 (2005) 182302

SSD model confirmed

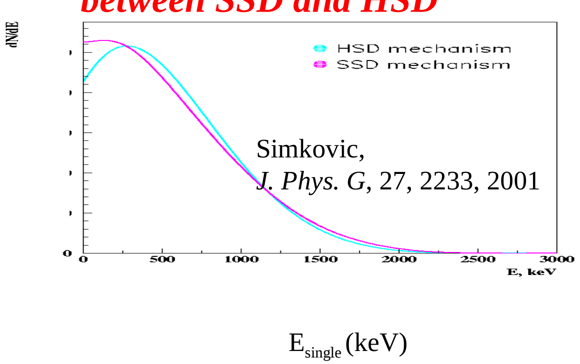


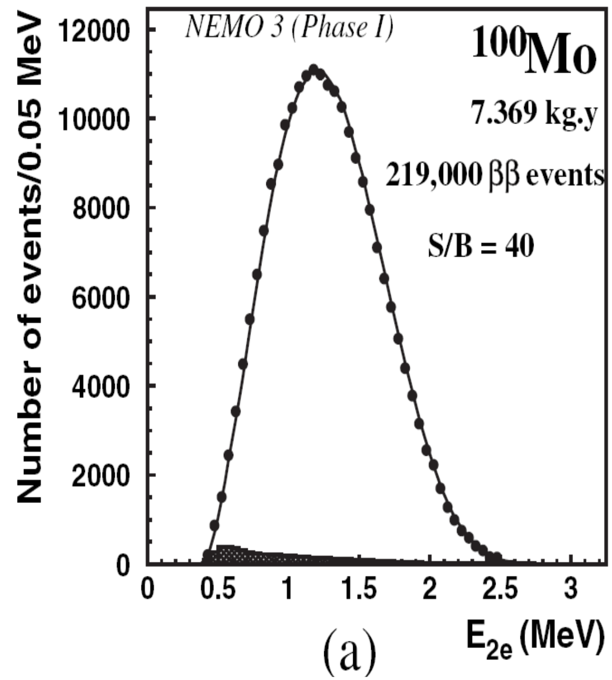
HSD, higher levels contribute to the decay

SSD, 1+ level dominates in the decay

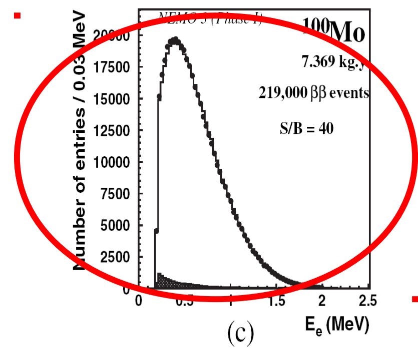
(Abad et al., 1984, *Ann. Fis.* A 80, 9)

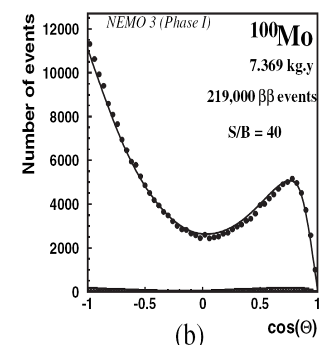
Single electron spectrum different between SSD and HSD

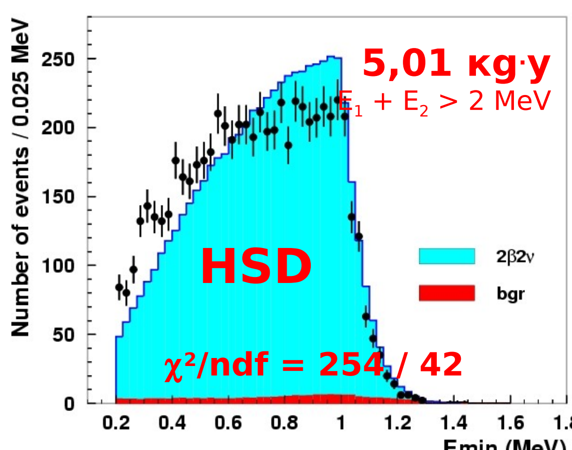


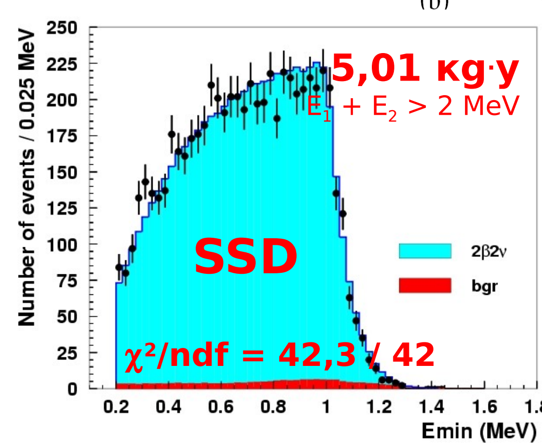


SSD simulation









The $\beta\beta 2\nu$ half-life of ^{130}Te has been a long- standing mystery:

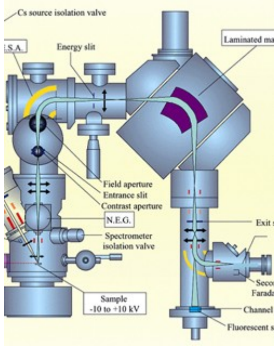
- Geochemical experiments:
  (26 ± 2.8) x 10^{20} years (Kirsten 83)
  (27 ± 1) x 10^{20} years (Bernatowicz 93)

  (7.9 ± 1) x 10^{20} years (Takaoka 96)
  ~8 x 10^{20} years (Manuel 91)

- Is the difference between 'old' and 'young' ores due to time dependence of constants..? [A.S.B. JETP Lett. 68 (1998) 1]

- Using geochemical ratio of $^{82}Se/^{130}Te$ and present half-life value for ^{82}Se from direct experiments:
  (9 ± 1) x 10^{20} years (recommended value, A.S.B. 2001)

- Direct measurement:
  [6.1 ± 1.4 (stat)$^{+2.9}_{-3.4}$ (syst)] x 10^{20} years (Arnaboldi 2003)



$T_{1/2}$ = [7.0± 0.9(stat)±1.0(syst)]·10^{20} (NEMO-3)

Summary of 0νββ results (NEMO-3)

Isotope	Exposure, kg·yr	$T_{1/2}$ (0ν), yr	$<m_\nu>$, eV
^{100}Mo	34.3	$> 1.1 \cdot 10^{24}$	0.3-0.6
^{82}Se	3.6	$> 3.2 \cdot 10^{23}$	1.1-2.5
^{130}Te	1.4	$> 1.3 \cdot 10^{23}$	1.4-5.4
^{116}Cd	2.15	$> 1.0 \cdot 10^{23}$	< 1.4-2.5
^{150}Nd	0.19	$> 2.0 \cdot 10^{22}$	< 1.6-5.3
^{48}Ca	0.0367	$> 2.0 \cdot 10^{22}$	< 6.0-26
^{96}Zr	0.031	$> 9.2 \cdot 10^{21}$	3.6-10.4

II. PRESENT STATUS

- **1. Introduction**
- **2. Current experiments**

  - GERDA-II

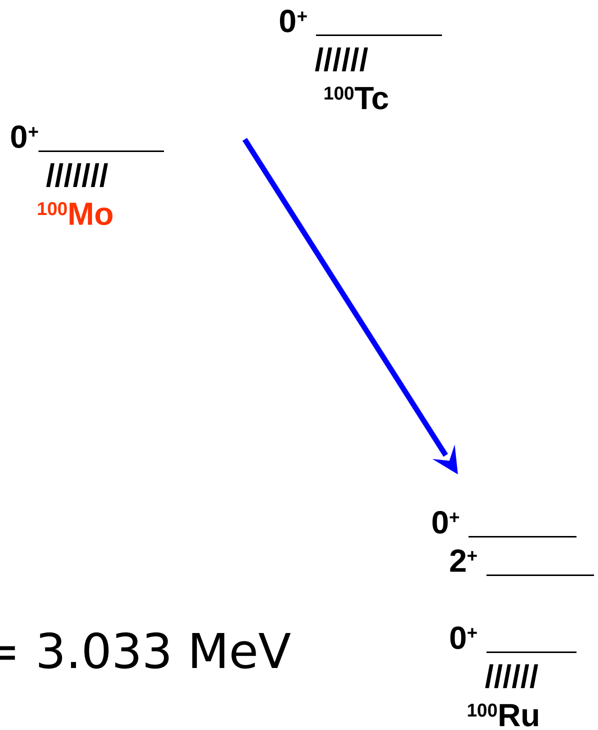
  - Majorana-Demonstrator

  - EXO-200

  - KamLAND-Zen

  - CUORE

1. Introduction



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

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

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

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

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

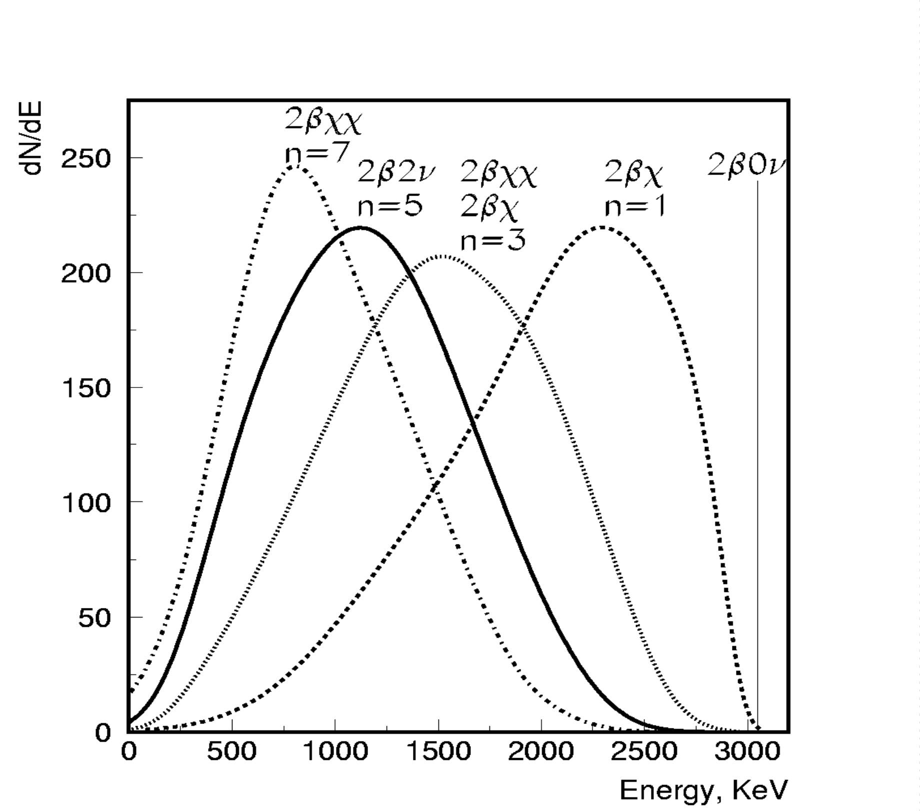
$W \sim Q^5$ (0ν); $W \sim Q^7$ ($0\nu\chi^0$)
$W \sim Q^{11}$ (2ν)

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

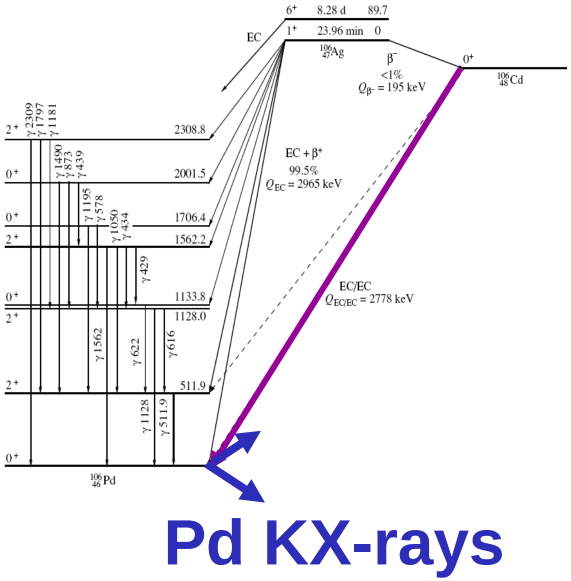
Nuclei	$Q_{2\beta}$, keV	Abundance, %
1. ^{48}Ca	4272	0.187
2. ^{150}Nd	3371.4	5.6
3. ^{96}Zr	3350	2.8
4. ^{100}Mo	3034.4	9.63
5. ^{82}Se	2996	8.73
6. ^{116}Cd	2805	7.49
7. ^{130}Te	2527.5	34.08
8. ^{136}Xe	2458.7	8.87
9. ^{124}Sn	2287	5.79
10. ^{76}Ge	2039.0	7.61
11. ^{110}Pd	2000	11.72

Natural γ-rays background - E < 2.615 MeV.
So, there are **6 gold** and **5 silver** isotopes

Shape of 2β-decay spectra



$2\beta^+$, $EC\beta^+$ and ECEC processes



- **$2\beta^+$:**

  $(A,Z) \rightarrow (A,Z-2) + 2\beta^+ + 2X\ (+\ 2\nu)$

  (6 nuclei candidates)

- **$EC\beta^+$:**

  $e^-_b + (A,Z) \rightarrow (A,Z-2) + \beta^+ + X\ (+\ 2\nu)$

  (16 nuclei candidates)

- **ECEC:**

  $2e^-_b + (A,Z) \rightarrow (A,Z-2) + 2X\ (+2\nu)$

  (34 nuclei candidates)

Candidates for $2\beta^+$ transition

Nuclei	Q_{ECEC}, keV	Abundance, %
1. ^{78}Kr 2. ^{124}Xe 3. ^{106}Cd 4. ^{96}Ru 5. ^{130}Ba 6. ^{136}Ce	2847.47 2790.41 2775.39 2714.51 2544.43 2378.53	0.35 0.09 **1.25** **5.54** 0.101 0.185

Probability of Decay

Transition to the ground state. For the best candidates (**$\langle m_\nu \rangle = 1$ eV**):

$\beta^+\beta^+$ (0ν) ~ 10^{28}-10^{30} y

β^+EC(0ν) ~ 10^{26}-10^{27} y

ECEC(0ν) ~ 10^{28}-10^{31} y

(One can compare these values with **~ 10^{23}-10^{24} y for 2β^--decay**)

ECEC(0ν); resonance conditions

- In **1955** (**R.Winter, Phys. Rev. 100 (1955) 142**) it was mentioned that if there is excited level with "right" energy then decay rate can be very high.

(Q'-E has to be close to zero. Q'-energy of decay, E-energy of excited state)

- In **1982** the same idea for transition to ground and excited states was discussed (**M. Voloshin, G. Mizelmacher, R. Eramzhan, JETP Lett. 35 (1982)).**
- In **1983** (**J. Bernabeu, A. De Rujula, C. Jarlskog, Nucl. Phys. B 223 (1983) 15**) this idea was discussed for **^{112}Sn** (transition to 0^+ excited state). It was shown that enhancement factor can be on the level **~ 10^6!**
- **In 2004 the same conclusion was done by Z. Sujkowski and S. Wycech (Phys. Rev. C 70 (2004) 052501).**

$T_{1/2}$ ~ 10^{23}-10^{24} y for $\langle m_\nu \rangle$ = 1 eV

Main candidates:

- **^{74}Se, ^{78}Kr, ^{96}Ru, ^{102}Pd, ^{106}Cd, ^{112}Sn, ^{124}Xe, ^{130}Ba, ^{144}Sm, ^{136}Ce, ^{152}Gd, ^{156}Dy, ^{162}Er, ^{164}Er, ^{168}Yb, ^{180}W, ^{184}Os, ^{190}Pt**

- Resonance conditions have not been confirmed (practically for all of them). Mainly because of **$\Delta Q > 1$ keV.** And, in some cases, because of **«not good» quantum numbers (spin and parity)** of the states.

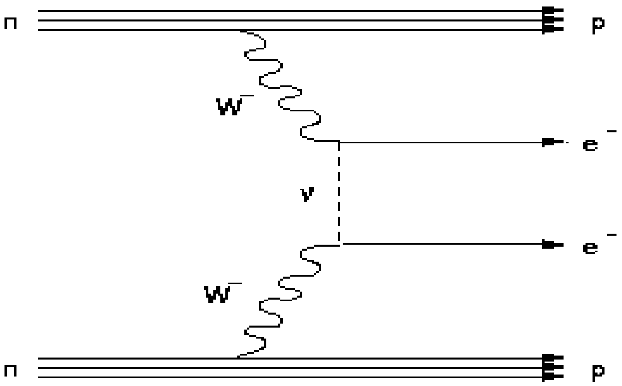
PROBLEMS

- There is no “good” candidate up to now
- Concentration of isotope-candidates is low **(~ 0.1-1%)**. Exception is **^{96}Ru – 5.5%.**
- There is no «reliable» information about high energy excited states (information from 50-th and 60-th years of last century). **So, «good candidate» can be found in the future!**

NEUTRINOLESS DOUBLE BETA DECAY

Experimental signature:

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



Oscillation experiments $\Rightarrow$ **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).

- **This information can be obtained in 2β-decay experiments.**

$$\langle m_\nu \rangle = \left| \sum |U_{ej}|^2 e^{i\phi_j} m_j \right|$$

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?

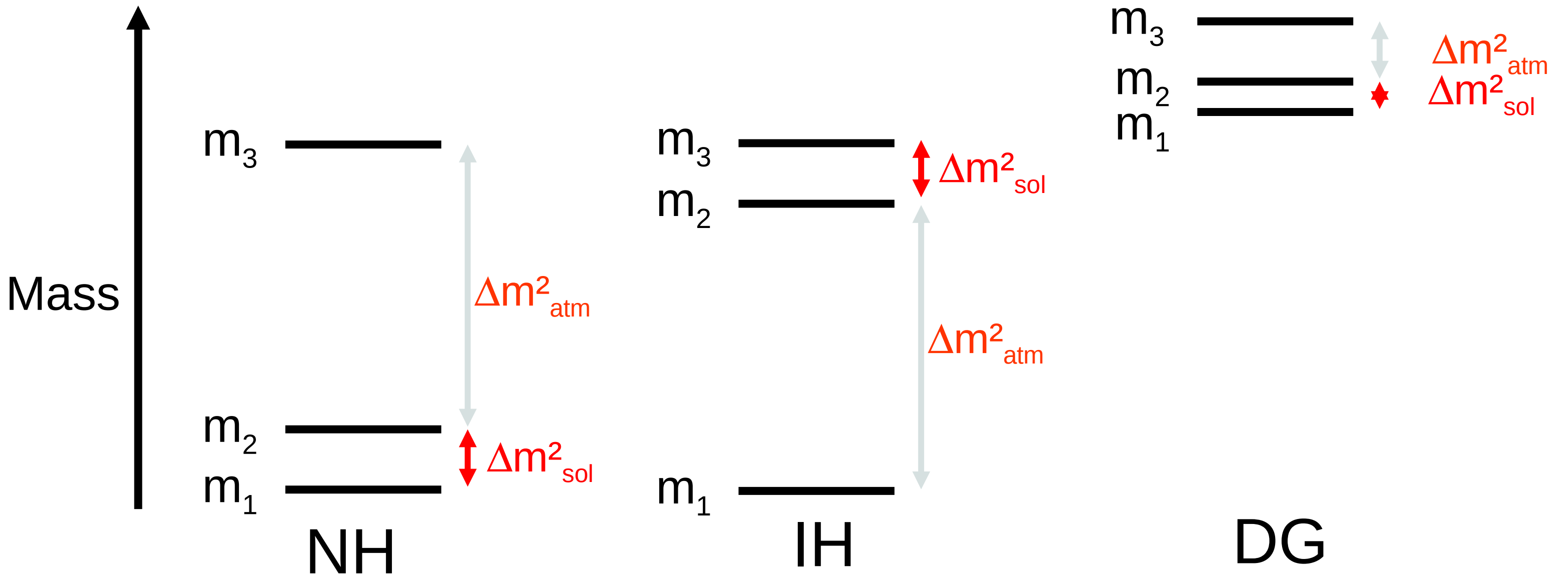
- Lepton number nonconservation ($\Delta L=2$)
- Nature of neutrino mass (**Dirac or Majorana?**).
- Absolute mass scale.
- Type of hierarchy (normal, inverted, quasi-degenerated).
- **CP** violation in the lepton sector

Neutrinoless double beta decay is being actively searched, because it is closely related to many fundamental concepts of nuclear and particle physics:

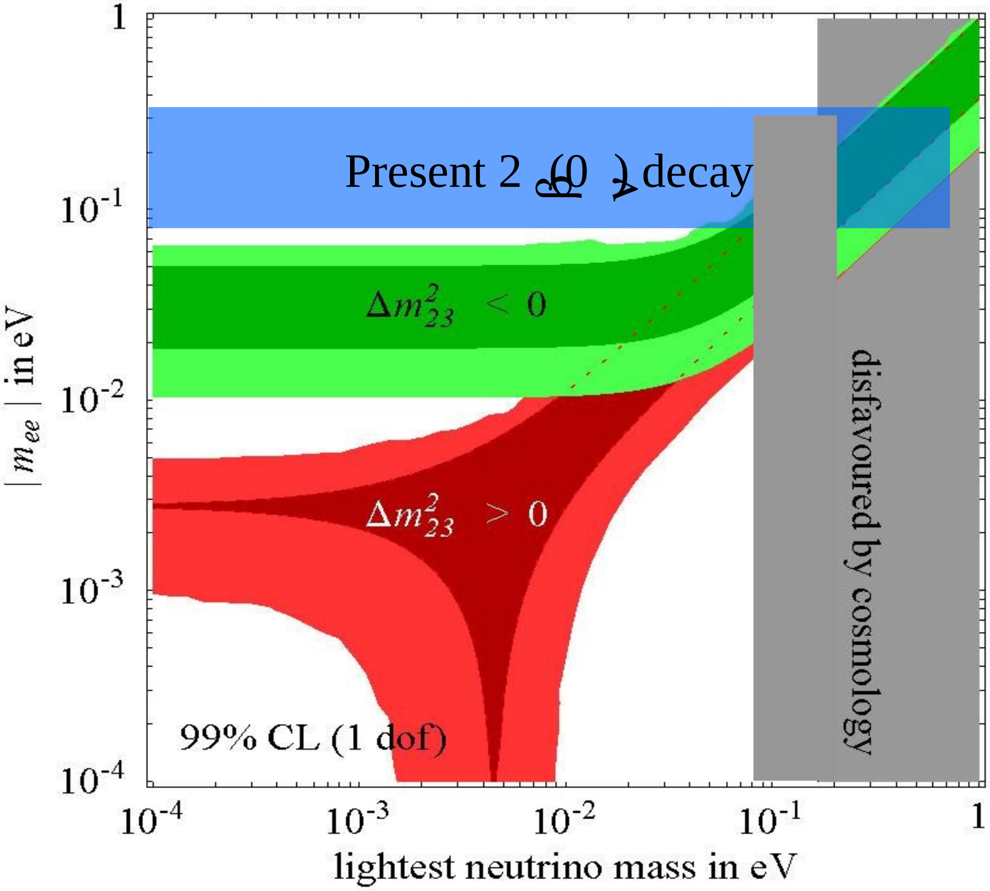
- - the lepton number nonconservation;
- **- the existence of neutrino mass and its origin**
- **(Dirac or Majorana?);**
- - the presence of right-handed currents in
- electroweak interactions
- - the existence of Majoron;
- - the structure of Higg's sector;
- - the supersymmetry;
- - the heavy sterile neutrino;
- - the existence of leptoquarks.

Input for <m$_{ee}$> from ν-oscillations

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



DBD and neutrino mass hierarchy



Degenerate: can be tested

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

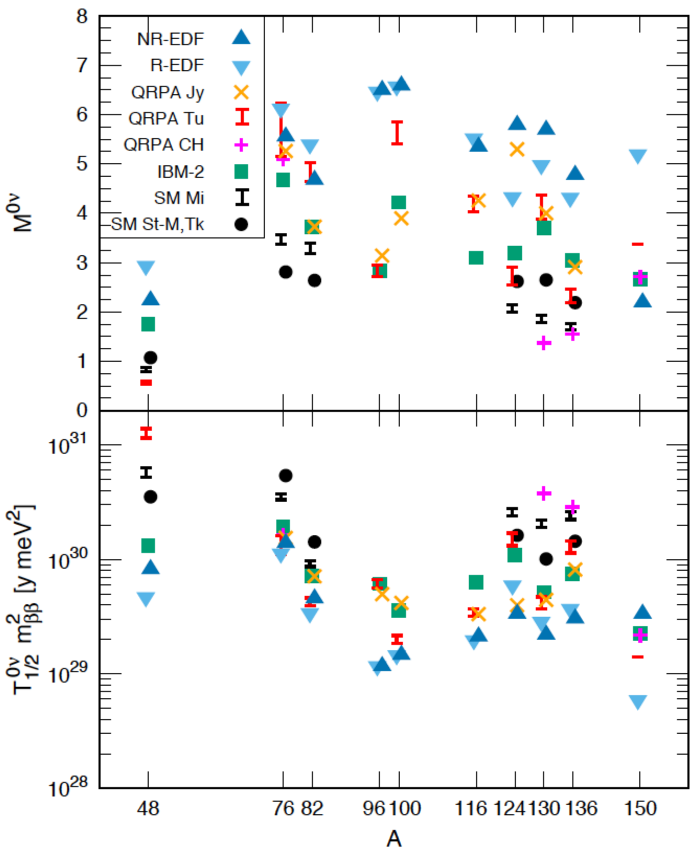
Normal: inaccessible (new approach is needed)

β: m_ν < 2 eV

2β: $\langle m_\nu \rangle$ < 0.3 eV

Cosmology : Σm_ν < 0.12-0.18 eV

Nuclear Matrix Elements



Spread ~ factor 2-3

No isotope significantly preferred when comparing decay rate per mass!

Choice mainly driven by experimental considerations

Best present limits on $<m_\nu>$

Nucleus	$T_{1/2}$, yr	$<m_\nu>$, eV QRPA + others	Experiment
^{76}Ge	$> 8 \cdot 10^{25}$ ($> 5.1 \cdot 10^{25}$)	< 0.14-0.31 (< 0.17-0.39)	GERDA-II
^{136}Xe	$>1.07 \cdot 10^{26}$ ($>0.5 \cdot 10^{26}$)	< 0.06-0.19 (< 0.09-0.28)	KamLAND-Zen
^{130}Te	$>6.6 \cdot 10^{24}$	< 0.24-0.58	CUORE+CUORICINO+CUORE0
^{100}Mo	$>1.1 \cdot 10^{24}$	< 0.33-0.62	NEMO-3

Conservative limit on $<m_\nu>$ is 0.3 eV

QUENCHING OF g_A IN NUCLEAR MATTER (g_A PROBLEM)

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 g_A^4 \left|M_\nu^{0\nu}\right|^2 G^{0\nu}$$

$\Rightarrow$ $m_{\beta\beta} \sim 1/g_A^{\,2}$

g_A = 1.27 from free neutron decay

$g_A^{eff} \approx$ 0.3-0.9 (from β^- and $2\beta^-(2\nu)$ decay)

$\Downarrow$

~ (2-15) times lower sensitivity to $m_{\beta\beta}$?!

(but $g_A^{eff}(2\nu) \neq g_A^{eff}(0\nu)$?!)

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)!)

  - g_A problem (1.27; 1; 0.3-0.9 ?)

⇓

- 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

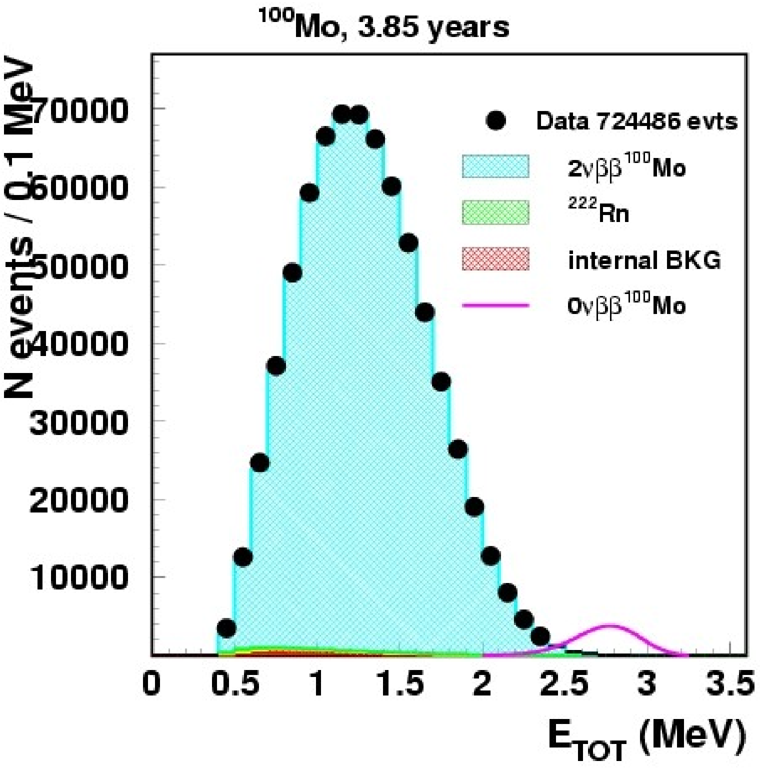
- By present time **$2\beta(2\nu)$** decay was detected in **11** nuclei: **^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U**

For **^{100}Mo** and **^{150}Nd** **$2\beta(2\nu)$** 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

$2\beta(2\nu)$ spectrum for ^{100}Mo (NEMO-3)



~ 700000 2ν events

Background is ~ 2%!!

All parameters of decay are measured!!!

Recommended values for half-lives:

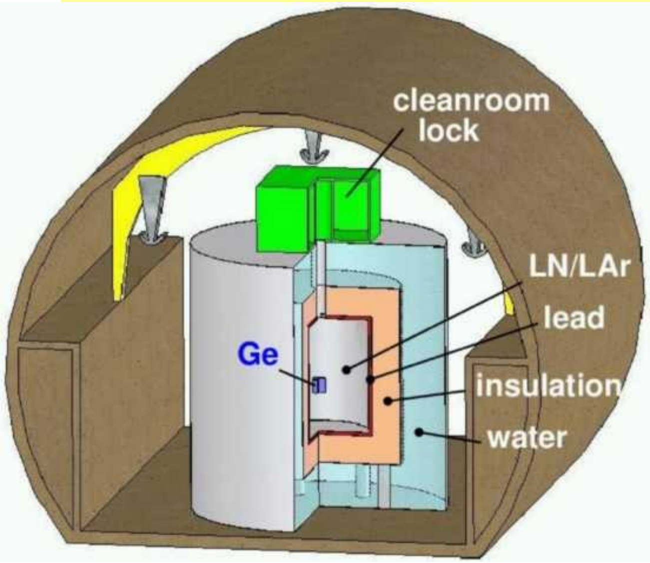
[A.S.B. Nucl. Phys. A 935 (2015) 52]

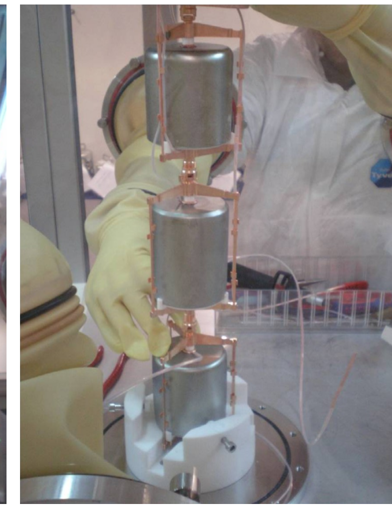
- ^{48}Ca - $(4.4\ ^{+0.6}_{-0.5})\cdot 10^{19}$ y
- ^{76}Ge – $(1.65^{+0.14}_{-0.12})\cdot 10^{21}$ y
- ^{82}Se – $(0.92 \pm 0.07)\cdot 10^{20}$ y
- ^{96}Zr – $(2.3 \pm 0.2)\cdot 10^{19}$ y
- ^{100}Mo – $(7.1 \pm 0.4)\cdot 10^{18}$ y
- ^{100}Mo – ^{100}Ru (0^+_1) – $(6.7^{+0.5}_{-0.4})\cdot 10^{20}$ y
- ^{116}Cd – $(2.87 \pm 0.13)\cdot 10^{19}$ y
- ^{128}Te(geo) – $(2.0 \pm 0.3)\cdot 10^{24}$ y
- ^{130}Te – $(6.9 \pm 1.3)\cdot 10^{20}$ y
- ^{136}Xe – $(2.19 \pm 0.06)\cdot 10^{21}$ y
- ^{150}Nd - $(8.2 \pm 0.9)\cdot 10^{18}$ y
- ^{150}Nd – ^{150}Sm (0^+_1) – $(1.2^{+0.3}_{-0.2})\cdot 10^{20}$ y
- ^{238}U(rad) - $(2.0 \pm 0.6)\cdot 10^{21}$ y
- ECEC(2ν): ^{130}Ba(geo) - $\sim 10^{21}$ y

2. CURRENT EXPERIMENTS

- **GERDA-I, GERDA-II**
- **Majorana-Demonstrator**
- **EXO-200**
- **KamLAND-Zen**
- **CUORE**

GERDA-I (Gran Sasso)

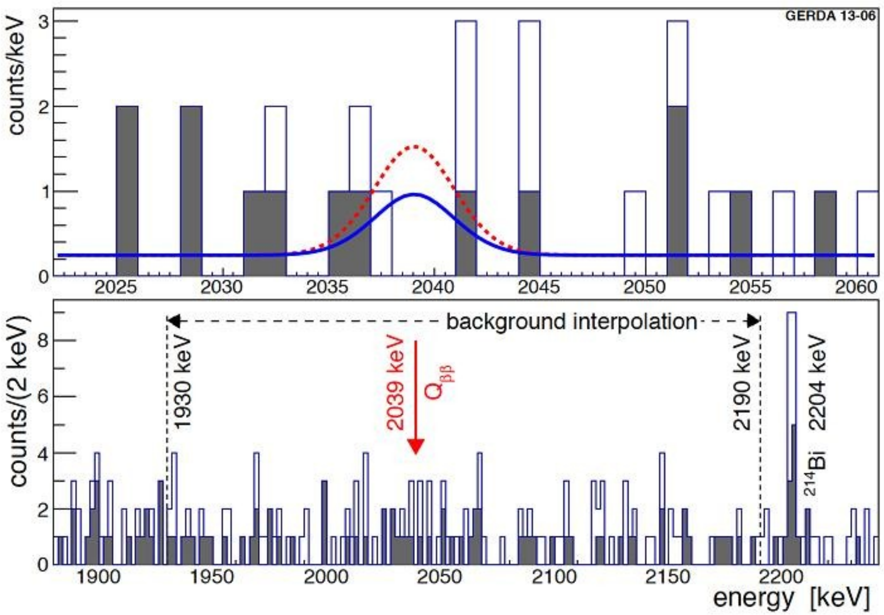




8 HPGe detectors made of enriched Ge **(17.66 кг; HM+IGEX)**
+ 1 detector made of natural Ge; 3 natural HPGe
ΔE = 4-5 keV
5 enriched BEGe (3 kg, ΔE = 3.2 keV)
Sensitivity: **~ $2 \cdot 10^{25}$** yr for **1 year of measurement**
and **B = 0.01 c/keV·kg·y**

Beginning of data taking: 09.11.2011
End of data taking: May 2013

GERDA-I results



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

$<m_\nu> < 0.26\text{-}0.62$ 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)

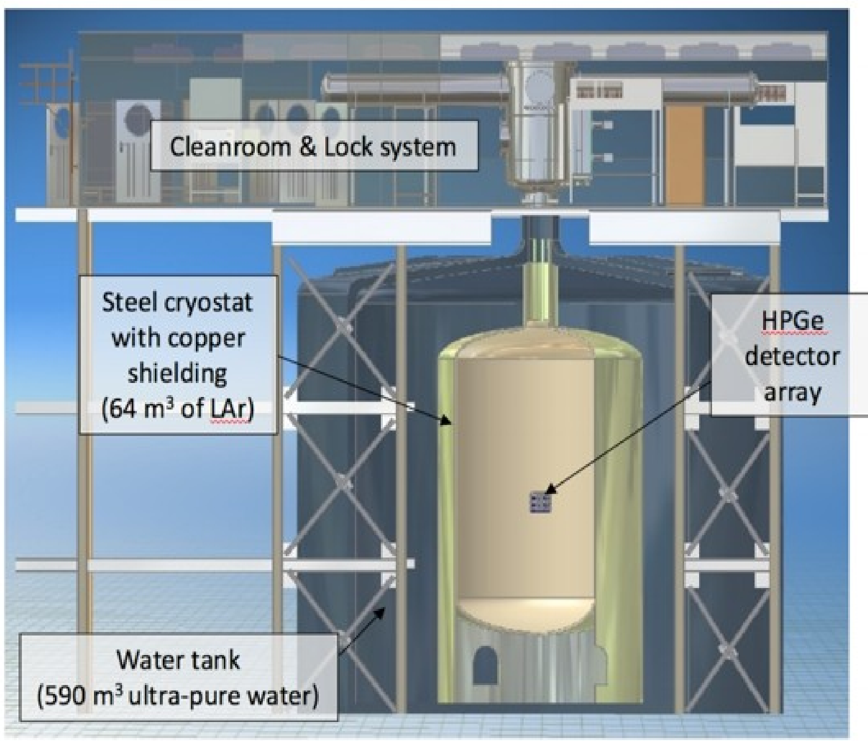
$T_{1/2} = (2.23^{+0.44}_{-0.31}) \cdot 10^{25}$ yr
(MPL A21 (2006) 1547)

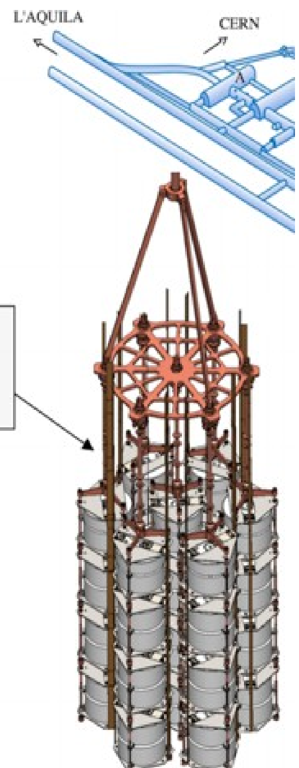
GERDA-II (Gran Sasso)

Detector type: enriched Ge diodes in LAr

- active target: ~ 35 kg
- σ_E /E: ~0.15-0.2% @ Q value
- pulse shape, LAr and coincidence veto
for bkg reduction: (7-35)x10^{-4} c/keV/kg/y

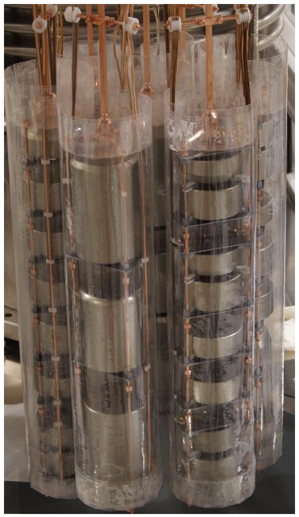
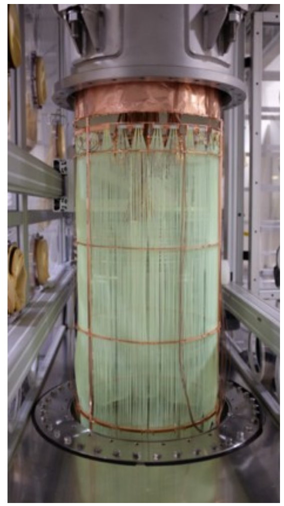
Phase II deployed in Dec 2015





[EPJC 73 (2013) 2330]

GERDA-II (Gran Sasso)


Deployed in Dec 2015:

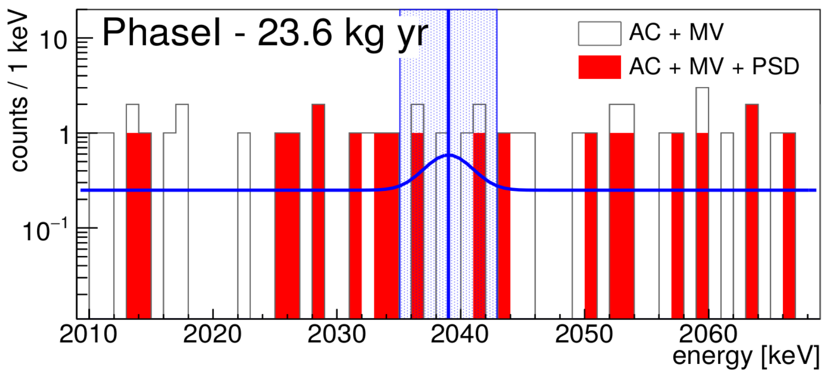
- 30 enriched BEGe (20 kg)
- 7 enriched Coax (15.8 kg)
- 3 natural Coax (7.6 kg)

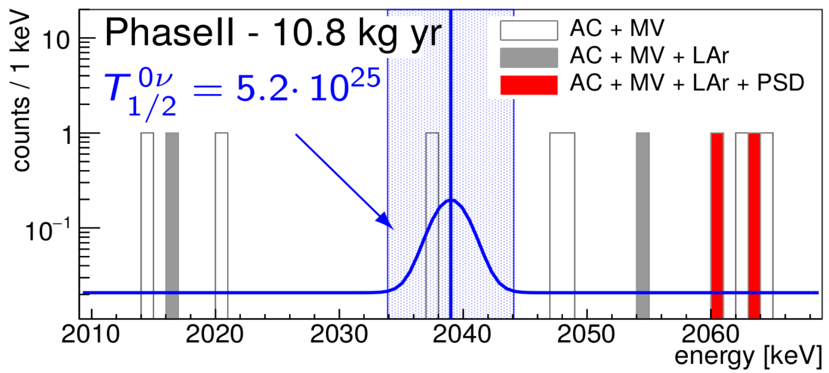
⇒ 35.8 kg of enr detectors

Dec 2015 - May 2016:

- **82% average duty cycle**
- **exposure used for analysis:**
5.8 kg·yr for enriched BEGe;
5.0 kg·yr for enriched coax.
- **blinding window Q ββ ±25 keV**

Statistical analysis



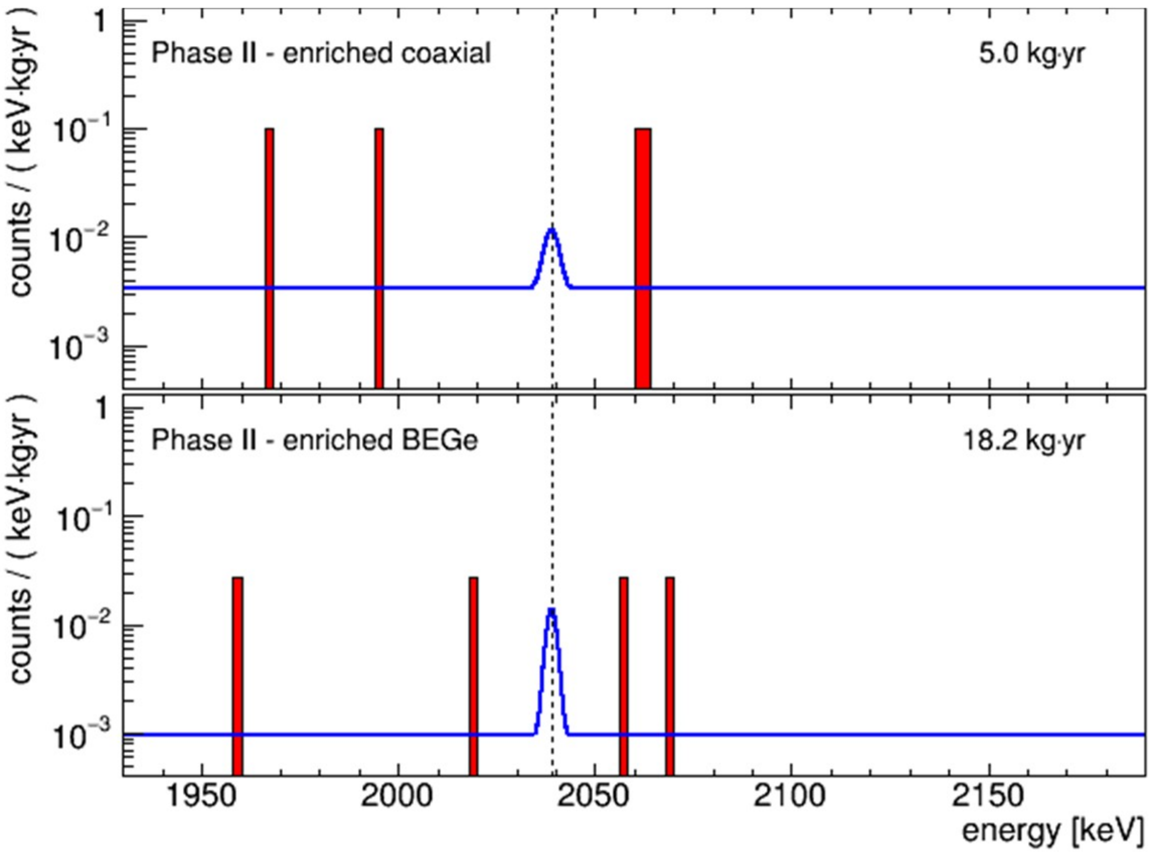


	profile likelihood 2-side test-stat	Bayesian flat prior on cts
$0\nu\beta\beta$ cts best fit value [cts]	0	0
$T_{1/2}^{0\nu}$ lower limit [10^{25} yr]	>5.2 (90% CL)	>3.5 (90% CI)
$T_{1/2}^{0\nu}$ median sensitivity [10^{25} yr]	>4.0 (90% CL)	>3.0 (90% CI)

preliminary!

- unbinned profile likelihood: flat background (1930-2190 keV) + Gaussian signal
- frequentist test-statistics and methods *Cowan et al.*, EPJC 71 (2011) 1554
- ϵ_{coax}^{PSD} to be finalized

Latest GERDA results (TAUP 2017)



Background:
Coax – $2.7 \cdot 10^{-3}$ c/keV kg y
BeGe – 10^{-3} c/keV kg y

Energy resolution:
Coax – 3.9 keV
BeGe – 2.9 keV

Frequentist method:
$T_{1/2} > 8 \cdot 10^{25}$ yr
(sensitivity is **$5.8 \cdot 10^{25}$ yr**)

Bayesian method:
$T_{1/2} > 5.1 \cdot 10^{25}$ yr
(sensitivity is $4.5 \cdot 10^{25}$ yr)

46.7 kg y data (Phase I + Phase II) :

$T_{1/2} > 5.1 \cdot 10^{25}$ y $\Rightarrow$ $<m_\nu>$0.17-0.39 < eV

Already in the box ~ 15 kg y data

Final sensitivity for 100 kg y and B = 0 is ~ $1.3 \cdot 10^{26}$ yr (<m> < 0.11-0.24 eV)

Physics reach

Phase I:

18 kg germanium

20 kg·y exposure

10^{-2} counts/(kg·keV·y)

Phase II:

35 kg germanium

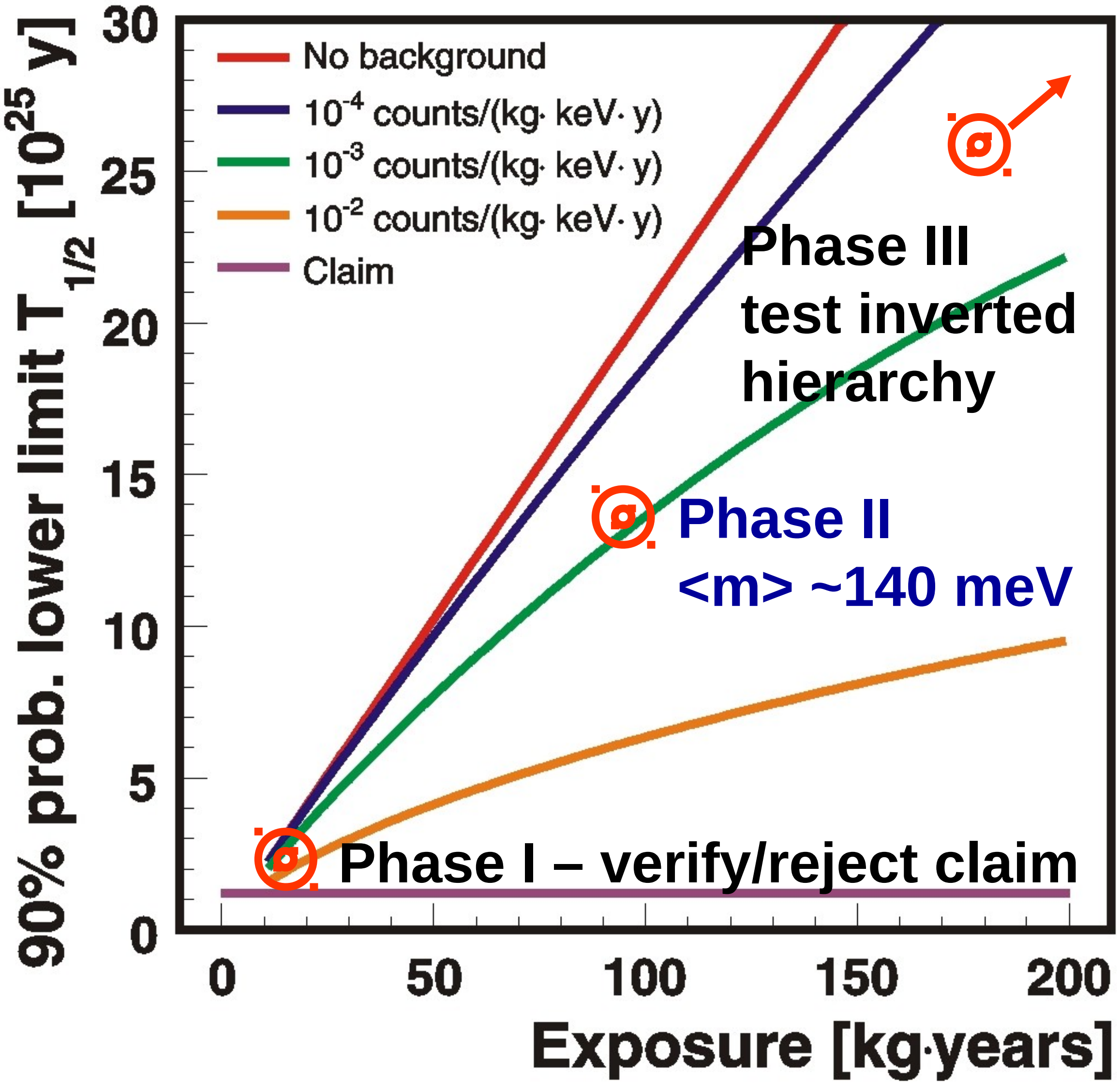
100 kg·y exposure

10^{-3} counts/(kg·keV·y)

Phase III:

1000 kg germanium

$\lesssim 10^{-4}$ counts/(kg·keV·y)



A. Caldwell, KK, Phys. Rev. D **74** (2006) 092003

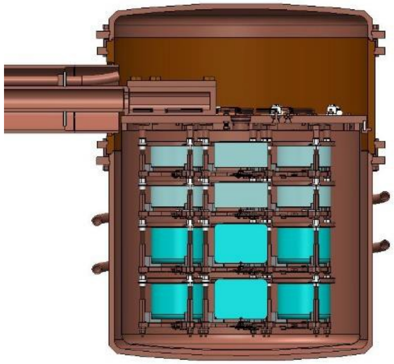
The Majorana Demonstrator

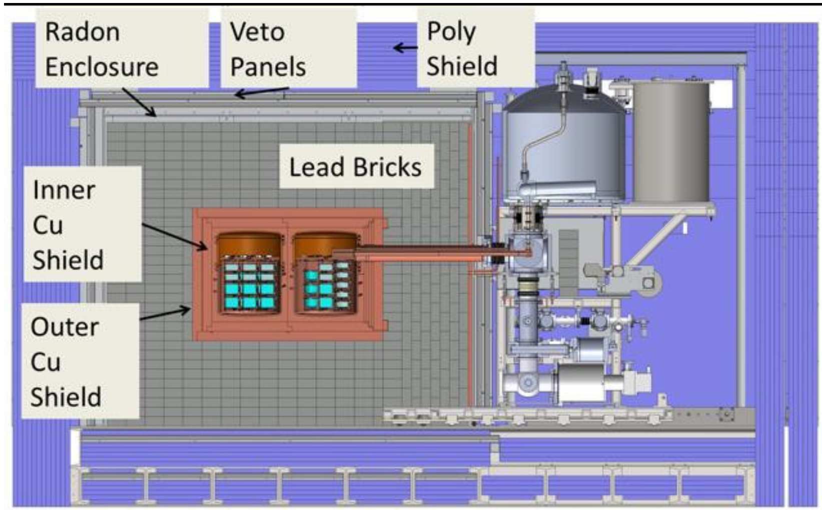
- **Goals:**
  - Demonstrate backgrounds low enough to justify building a tonne scale experiment.
  - Establish feasibility to construct & field modular arrays of Ge detectors.
  - Searches for additional physics beyond the standard model.

- **Located underground at 4850' Sanford Underground Research Facility (SURF)**

- **Background Goal in the 0νββ peak region of interest (4 keV at 2039 keV) is 3 counts/ROI/t/y** (after analysis cuts).
- **Assay U.L. currently ≤ 3.5** *scales to 1 count/ROI/t/y for a tonne experiment*

- **44.1 kg of Ge detectors**
  - –29.7 kg of 87% enriched ^{76}Ge crystals
  - –14.4 kg of ^{nat}Ge
  - –Detector Technology: P-type, point-contact.
- **2 independent cryostats**
  - –ultra-clean, electroformed Cu
  - –22 kg of detectors per cryostat
  - –naturally scalable
- **Compact Shield**
  - –low-background passive Cu and Pb shield with active muon veto

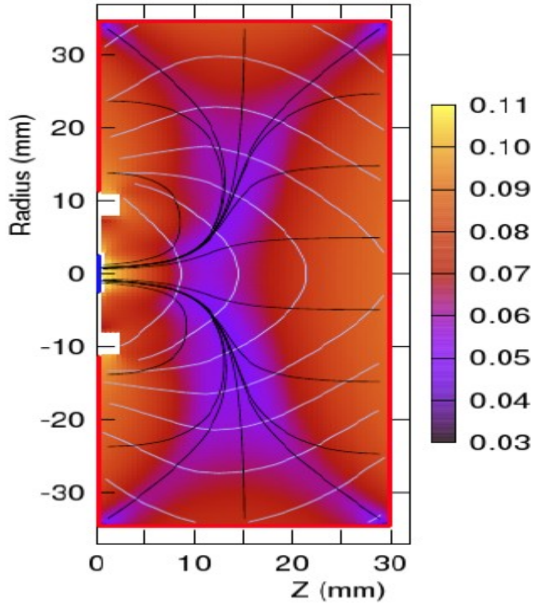


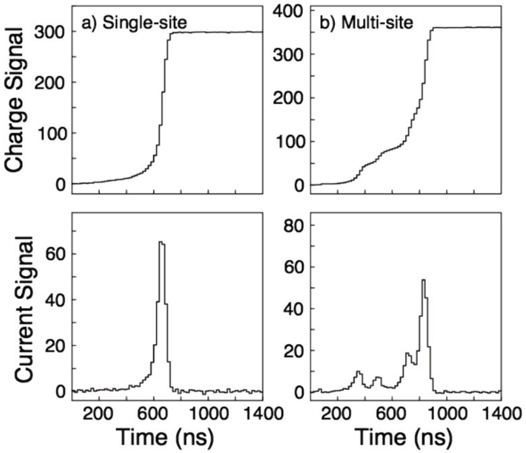


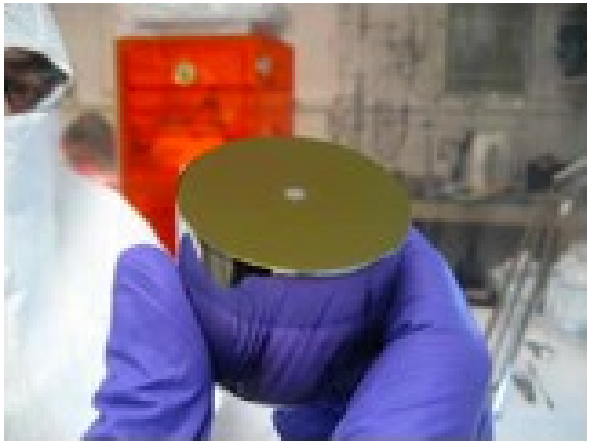
P-type Point-Contact (PPC) Detectors

Point contact:

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

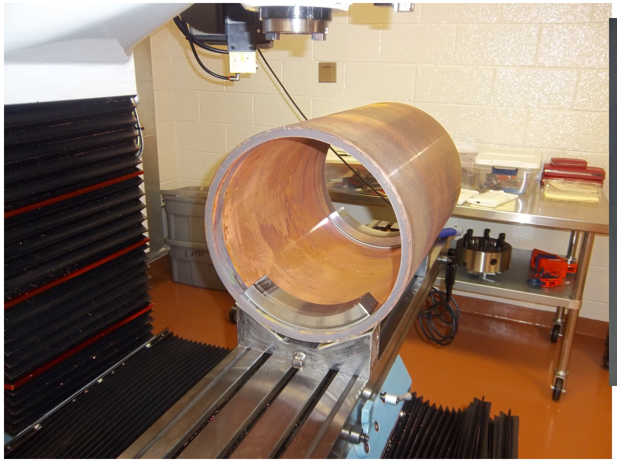






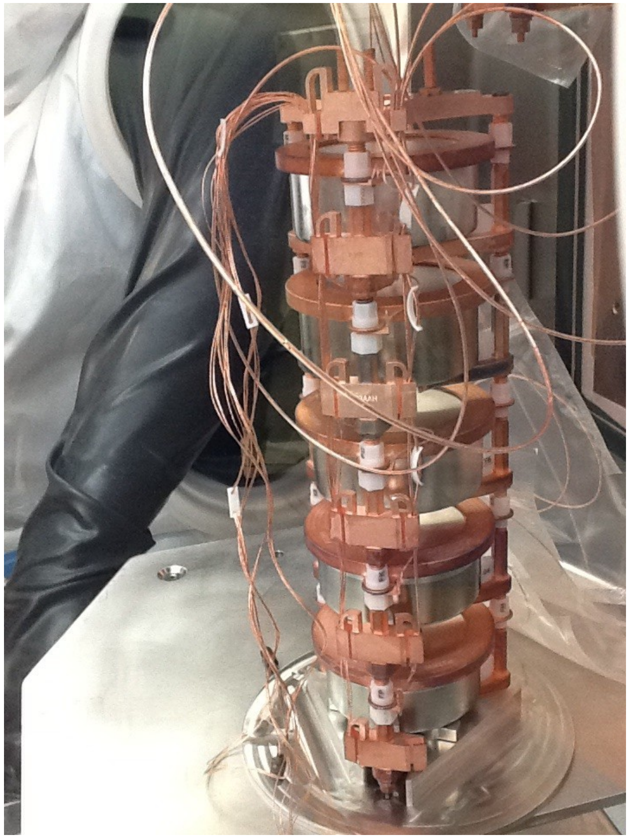
Electroforming

- Eforming at PNNL and at 4850’ at SURF
- Eforming complete in May 2015
- Machine shop operational



Electroformed Parts Stored in Nitrogen

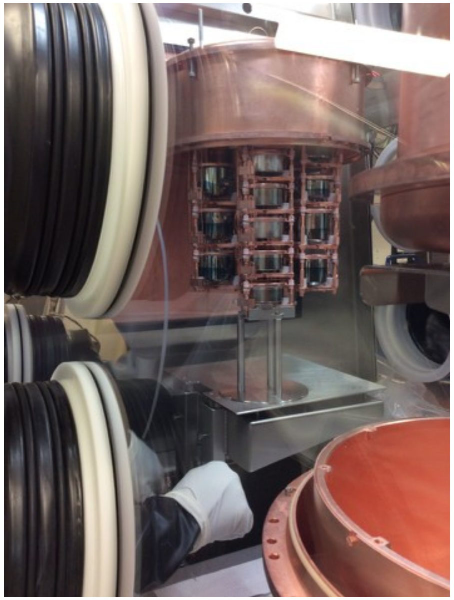
Assembled Detector Unit and String



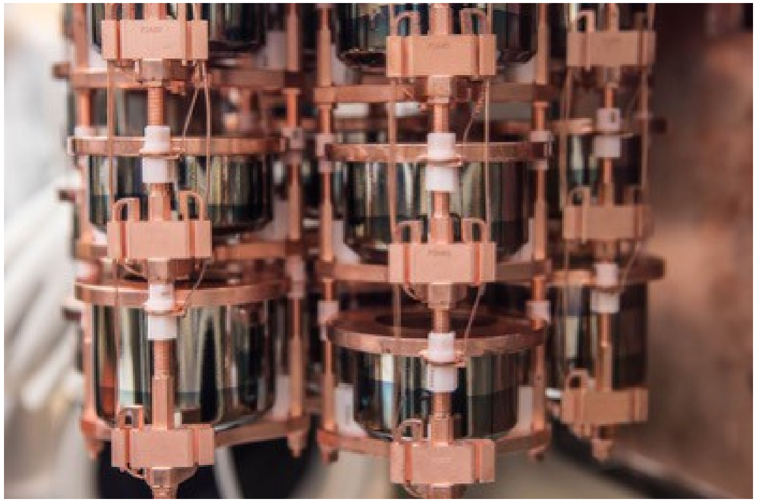
Detector Unit

String Assembly

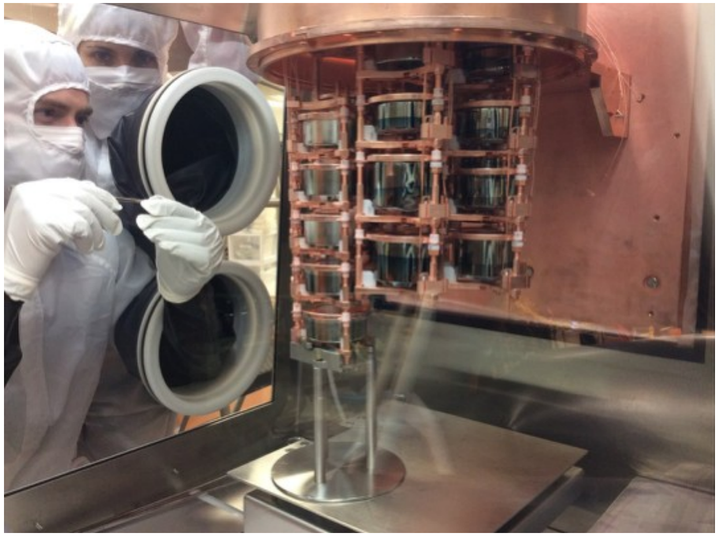
Detector module



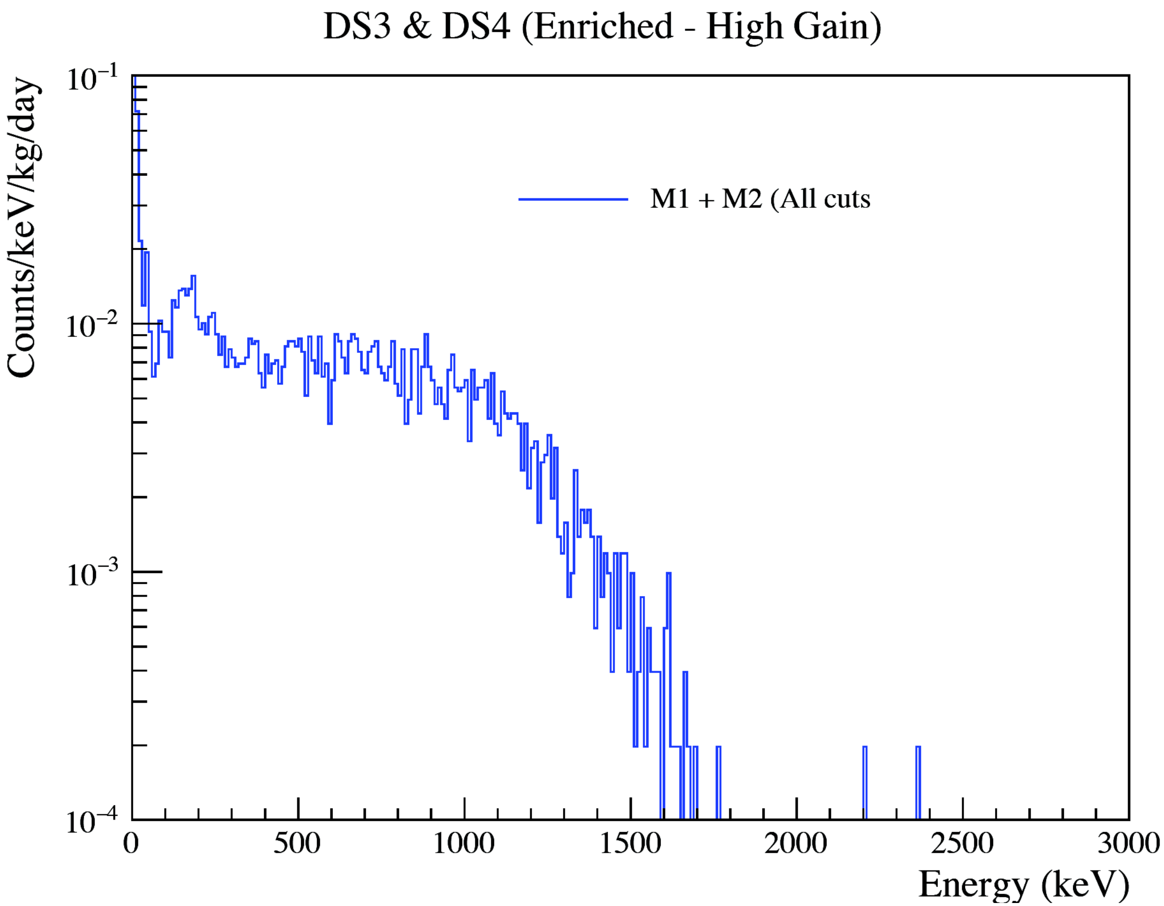
Loading of ^{enr}Ge in Cryostat 1



Loading of ^{enr}Ge in Cryostat 2



Majorana-Demonstrator: present status



1.39 kg y exposure (+ ~ 15 kg y in the box)

Start of data taking:
Module 1 – Dec. 31, 2015
Module 2 – Aug. 25, 2016

Background index:
$1.8\cdot10^{-3}$ c/keV kg y

Energy resolution:
2.4 keV (at 2039 keV)

Detector is under data taking

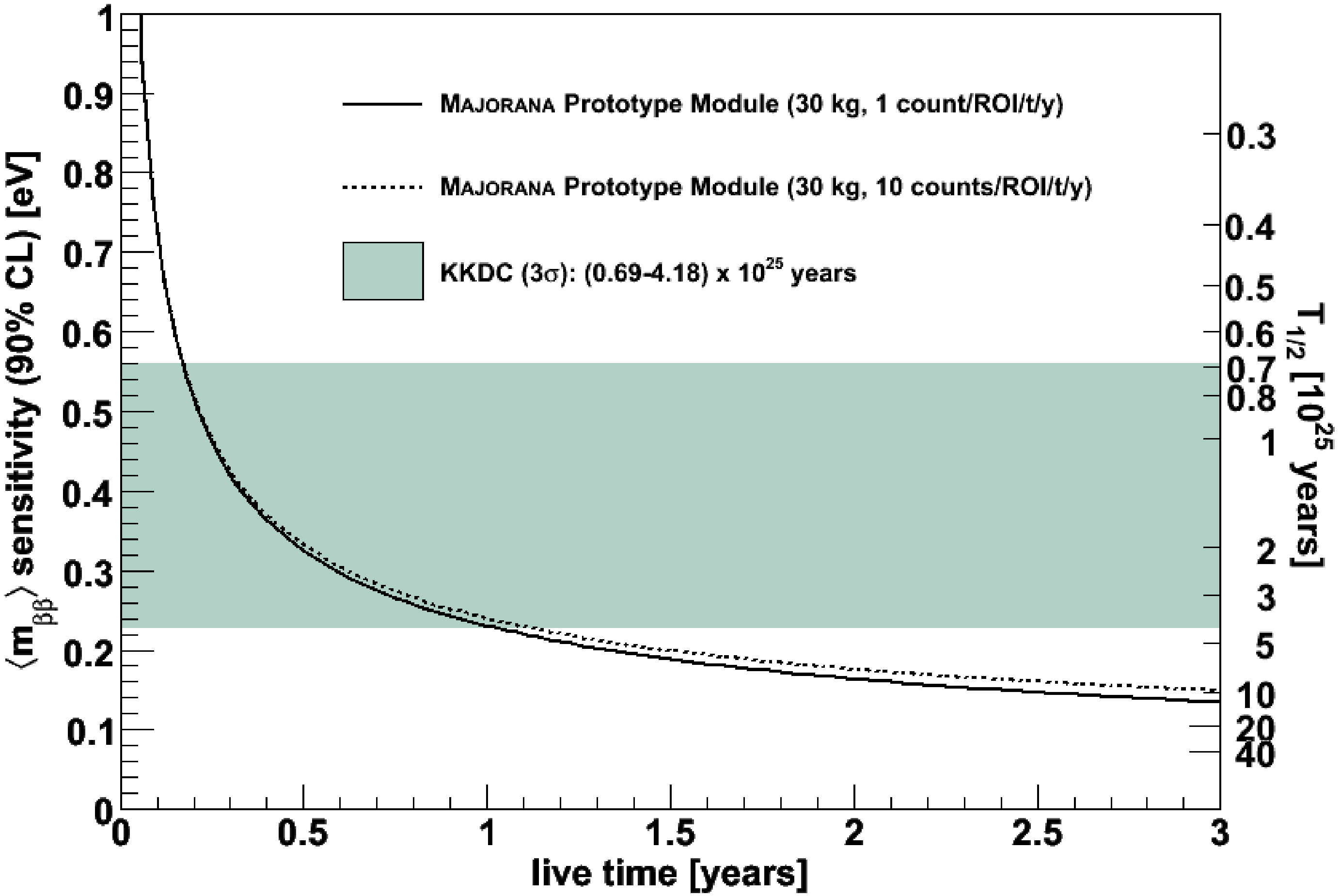
Sensitivity for 100 kg y and B =0 is ~ $1.2\cdot10^{26}$ y ($\langle m_\nu \rangle$ < 0.11-0.24 eV)

MAJORANA DEMONSTRATOR Module Sensitivity

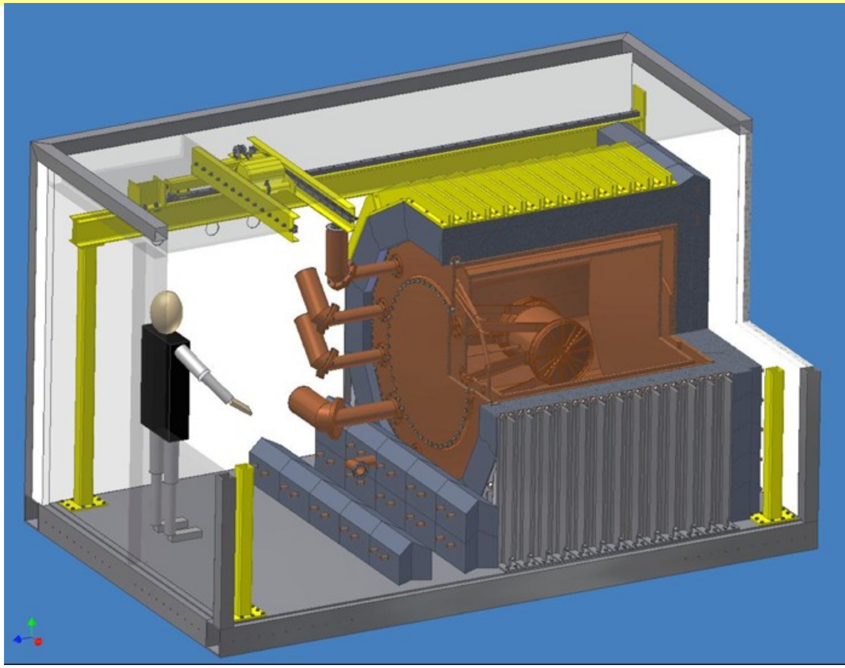
- **Expected Sensitivity to 0νββ**

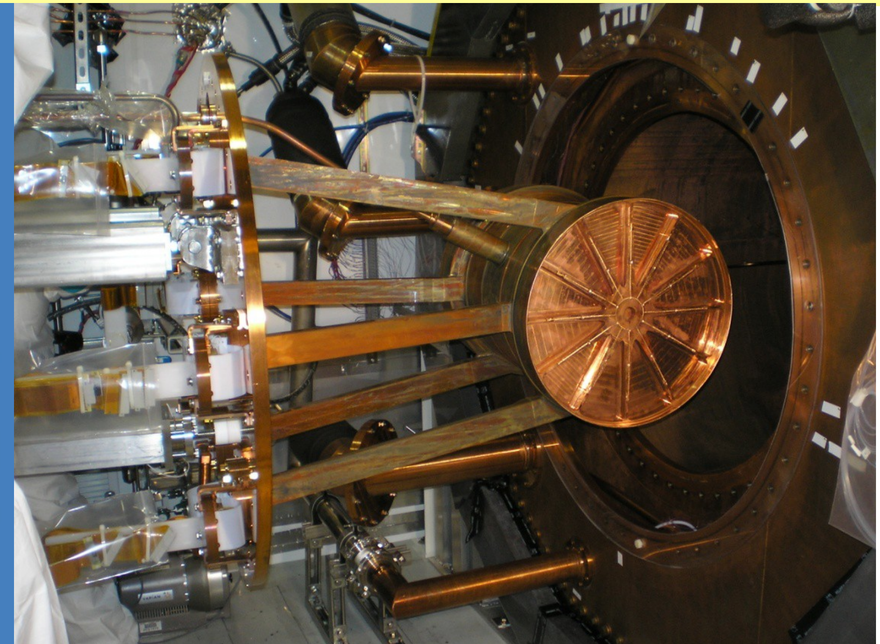
(30 kg enriched material, running 3 years, or 0.09 t-y of ^{76}Ge exposure)

$T_{1/2} \geq 10^{26}$ y (90% CL).Sensitivity to <m_ν> < 140 meV (90% CL) [Rod05,err.]



EXO-200

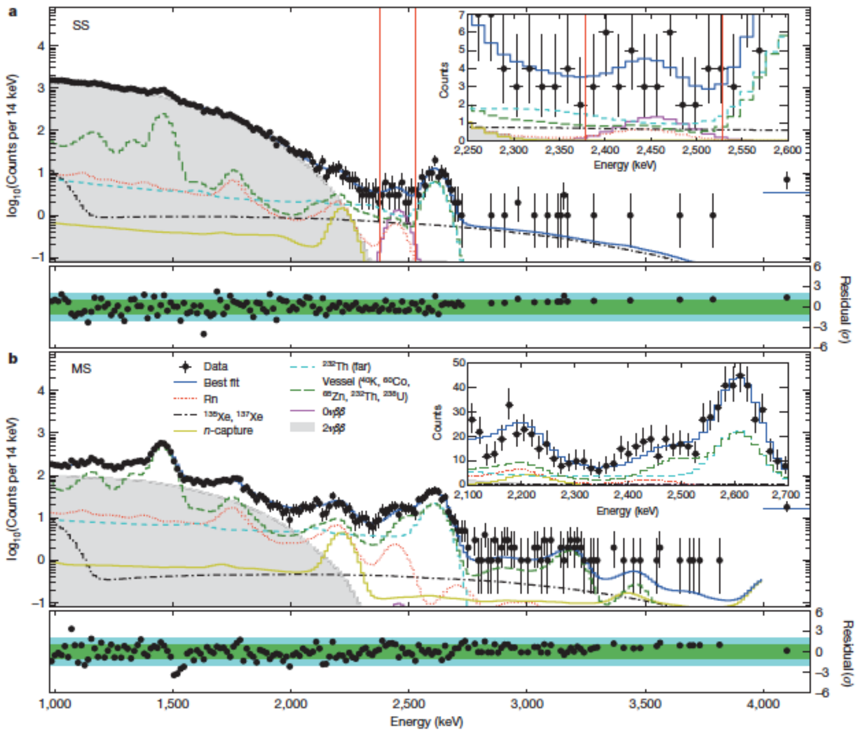




Location: WIPP (USA) – salt mine (1600 м w.e.)
Passive shield – 25 cm of Pb
Active shield - plastic scintillator (5 cm)
^{136}Xe: enrichment – **80.6%;** mass – **175 кg**;
useful mass – **98.5 kg**
Signal: ionization + scintillation
ΔE/E(FWHM) = **10.6%** at 2.615 MeV (ionization)
~ 3.8% (ionization + scintillation)
Strength of electric field – **376 V/cm** (V = - 8 kV);

Data tacking since May 2011

EXO-200 results



94.7 kg $^{\text{обог}}$Xe (76.3 kg ^{136}Xe)

99.8 kg·yr; ΔE/E = 3.8% (FWHM)

0ν decay: no signal

$T_{1/2}$ > 1.1·10^{25} yr (90% CL)

<m_ν> < 190 – 450 meV (90% C.L.)

Background in 0ν region:

~ 1.7x10^{-3} ev/keV·kg·yr

(Nature, 510 (2014) 229)

2ν decay

Precise value for $T_{1/2}$ is obtained:

~ 19000 2ν events!

$T_{1/2}$ = 2.172 ± 0.017(stat) ± 0.06(syst)x10^{21} yr

(Phys. Rev. C 89 (2014) 015502)

$T^{0\nu\chi 0}_{1/2}$ > 1.2·10^{24} yr

<g_{ee}> < 0.8-1.7)·10^{-5}

EXO-200 (Phase II)

Start of operation – 31 January 2016

Some improvements were done:

- Energy resolution now is 2.89% (FWHM)
- Electric field in drift region is 50% higher
- Improvement in analysis

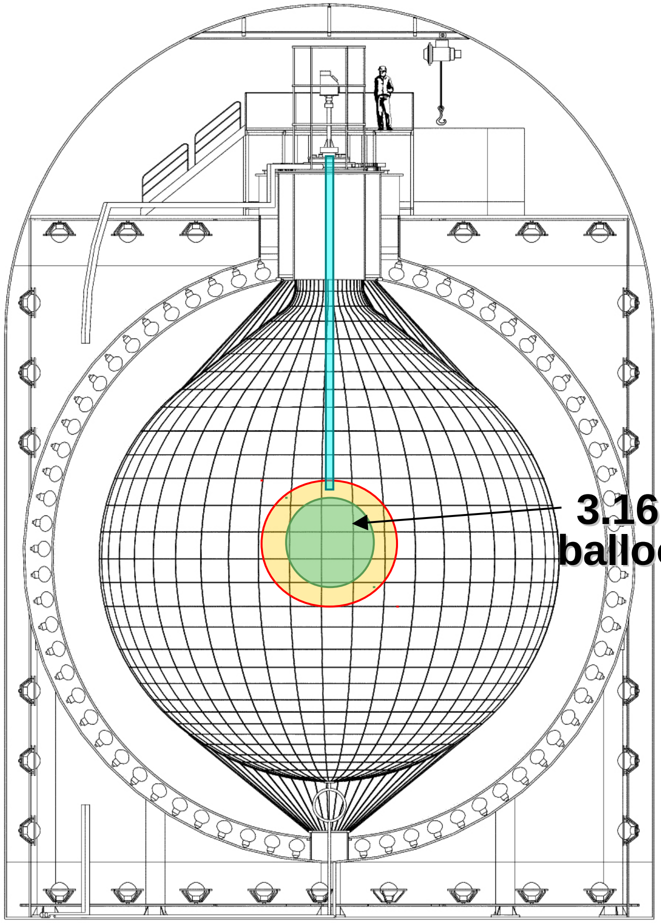
Total exposure (Phase I + Phase II) is **868.5 (596.7+271.8)** days or **177.6 (122+55.6)** kg y of **^{136}Xe**

Phase I + Phase II data:

$T_{1/2}(0\nu) > 1.8 \cdot 10^{25}$ yr **$<m_\nu> < 150$-400 meV**

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%)

ρLS : 0.78kg ／ℓ

high sensitivity with low cost

24 of September 2011 - beginning of data tacking – June 2012 (Phase I)

^{136}Xe: 320 kg, enrichment – 91%
ΔE/E(FWHM) = 9.5% at 2.5 MeV

11 December 2013 – 27 October 2015 Phase II with 383 kg of ^{136}Xe (Phase II)

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

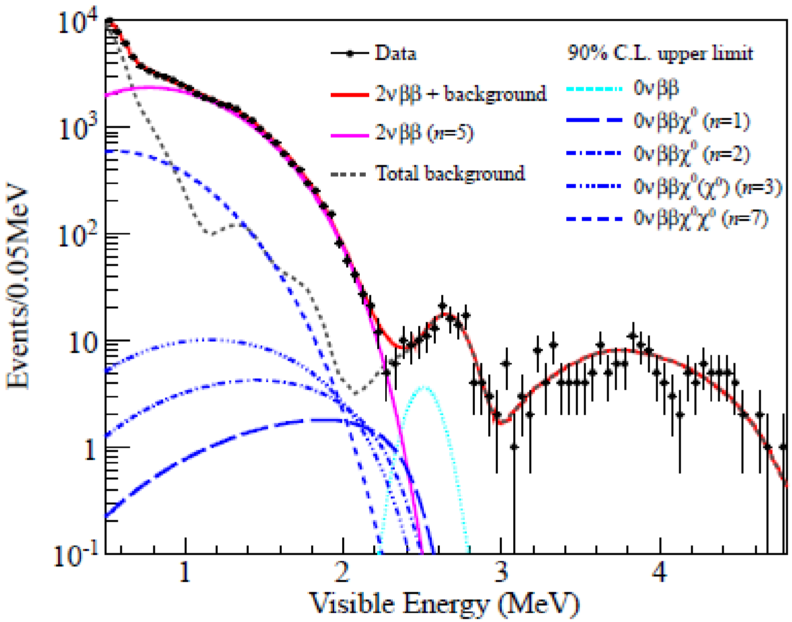
KamLAND-Zen results

(Phase 1, 89.5 kg·yr of ^{136}Xe)

- **$T_{1/2}(2\nu) = 2.30 \pm 0.02(stat.) \pm 0.12(sys.) \times 10^{21}$ yr**
- **(PRC 86 (2012) 021601R; in agreement with EXO-200)**

$T_{1/2}(0\nu) > 1.9 \times 10^{25}$ yr (90% CL) $\Rightarrow$ $<m_\nu> < 0.14\text{-}0.34$ eV

(PRL 110 (2013) 062502)



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

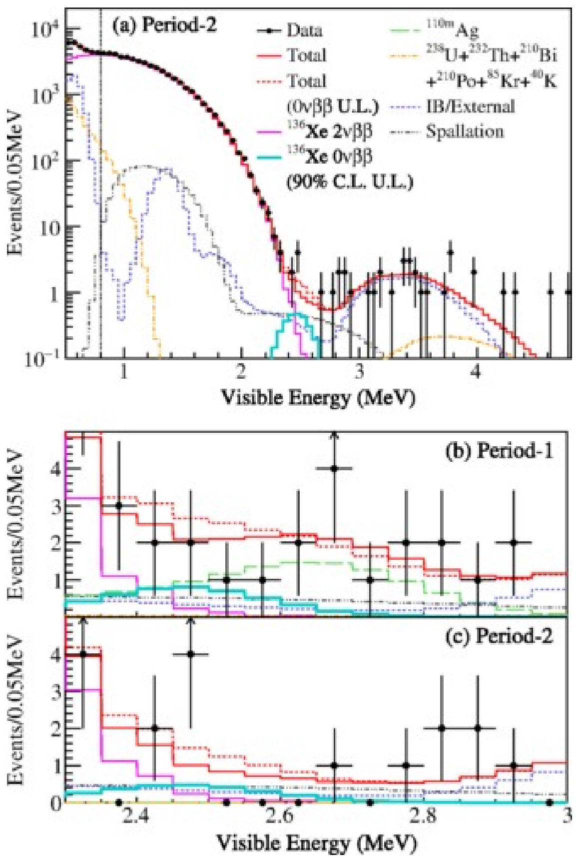
$T_{1/2} > 2.6 \times 10^{24}$ yr

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

Background is ~ 100 times higher than in KamLAND
BI ~ 10^{-4} c/keV·kg·yr
(Fukushima isotopes)

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

New data with KamLAND-Zen: Phase-II (11 December 2013 – 27 October 2015)



Period-1: 270.7 days
Period-2: 263.8 days
Σ = 534.5 days (504 kgxyr ^{136}Xe)

Phase I $T_{1/2}(0\nu) > 1.9 \times 10^{25}$ yr
Phase II $T_{1/2}(0\nu) > 9.2 \times 10^{25}$ yr

Combined $T_{1/2}(0\nu) > 1.07 \times 10^{26}$ yr
(Sensitivity ~ 0.5×10^{26} yr)

$\langle m_\nu \rangle$ < 0.06-0.19
(< 0.09-0.28)

PRL 117 (2016) 082503; 109903

$T_{1/2}(2\nu)$= 2.21± 0.02(stat)± 0.12(syst) x 10^{21} yr

KamLAND-Zen-800

- 750 kg of enriched Xe
- New (larger) balloon will be installed end of 2017
- In 2 years of measurement:
- $T_{1/2}(0\nu) \sim 2\cdot10^{26}$ yr ($<m_\nu> < 45$-120 meV)

CUORE (Gran Sasso)

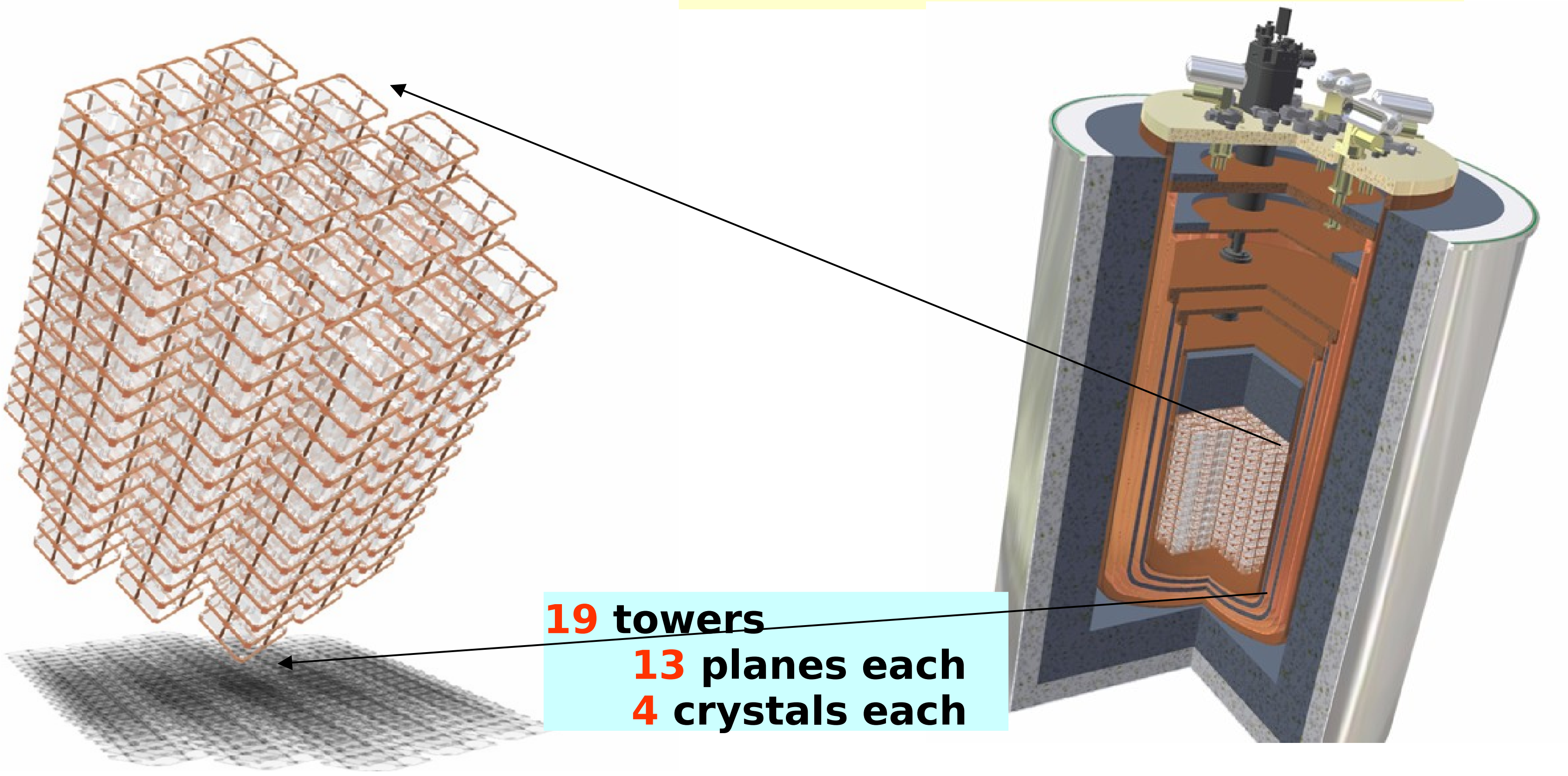
Cryogenic Underground Observatory for Rare Events

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

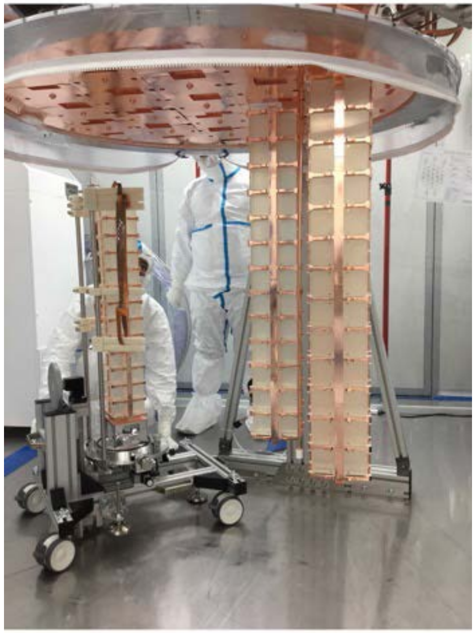
- **Single high granularity detector**

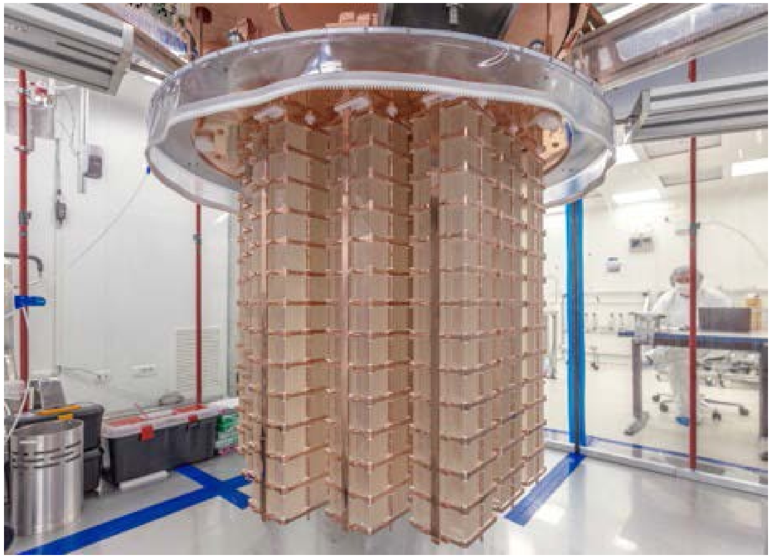


Beginning of measurements – April 2017

Detector installation

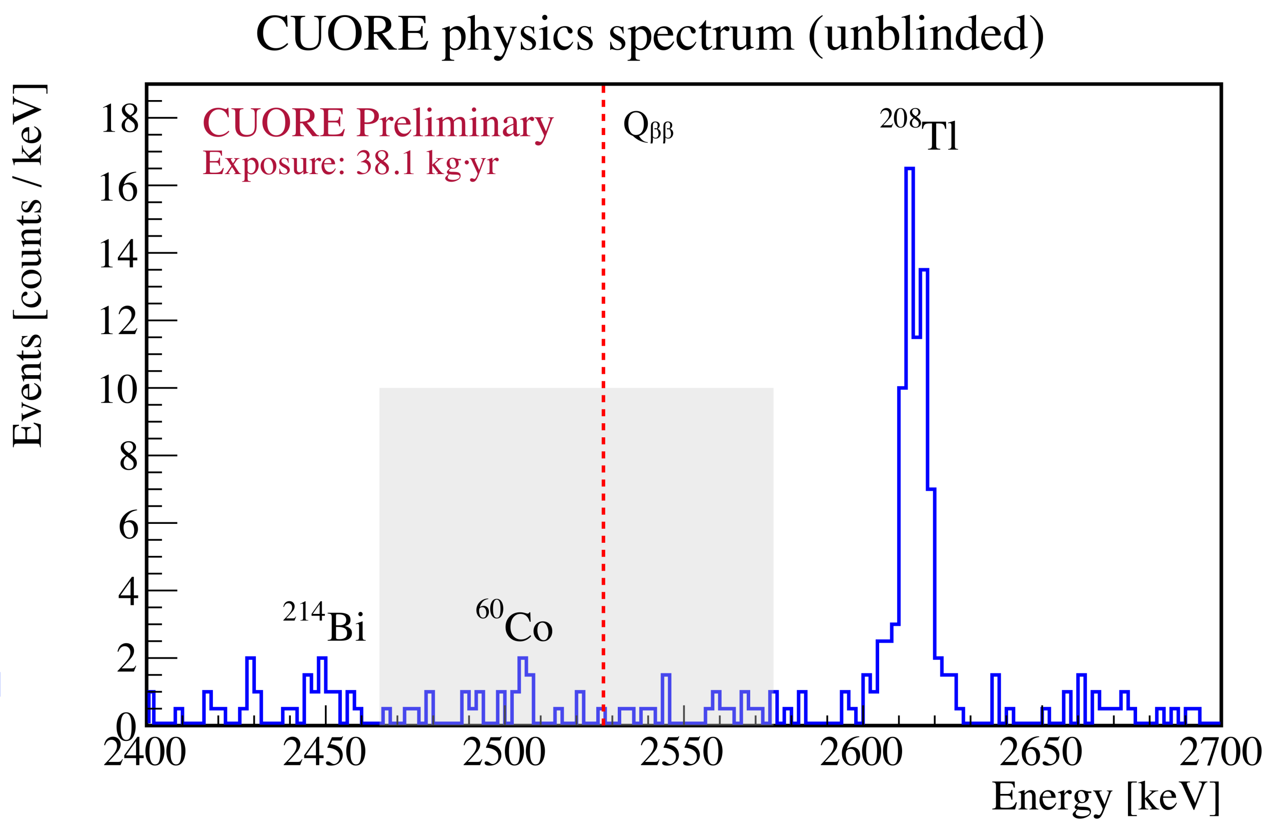
Completed in August 26 2016
Detector cool down:
~ 7 mK on Jan 27, 2017
Start of data taking:
April 14, 2017





Blinded spectrum

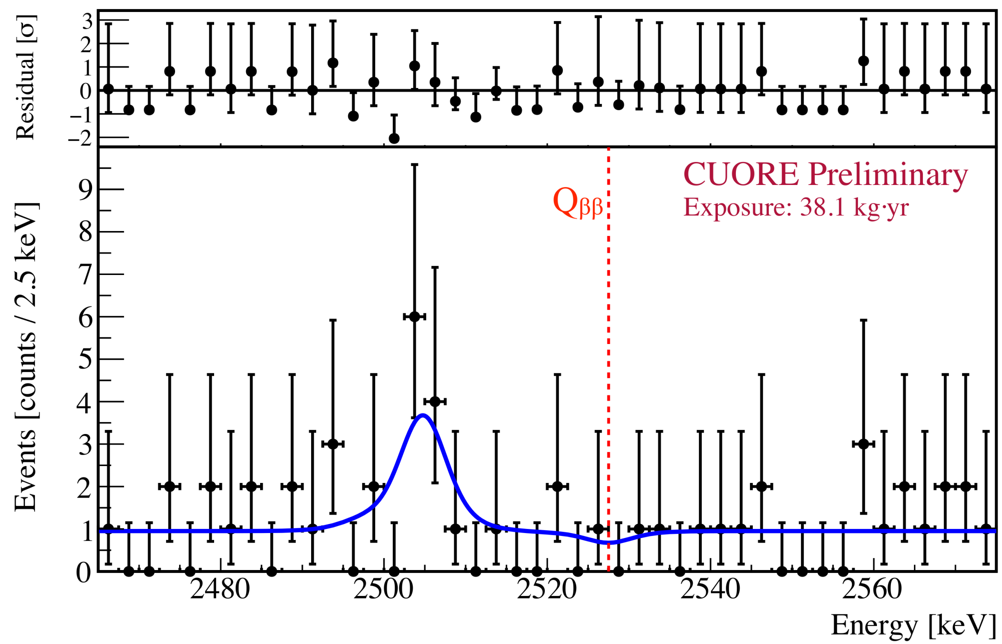
- To blind our data we randomly move a fraction of events from +/- 20 keV of 2615 keV to the Q-value and vice versa
- The blinding algorithm produces an artificial peak around the 0vDBD Q-value and blinds the real 0vDBD rate of ^{130}Te.
- This method of blinding the data preserves the integrity of the possible 0vDBD events while maintaining the spectral characteristics with measured energy resolution and introducing no discontinuities in the spectrum.
- When all data analysis procedures are fixed the data are eventually unblinded



Fit in the ROI

- We determined the yield of 0νββ events by performing a simultaneous UEML fit in the energy region 2465-2575 keV
- The fit has 3 components:
  - a posited peak at the Q-value of ^{130}Te
  - a floating peak to account for the ^{60}Co sum gamma line (2505 keV)
  - a constant continuum background, attributed to multi scatter Compton events from ^{208}Tl and surface alpha events

Unblinded spectrum fit



First results from CUORE

Background:

10^{-2} c/keV kg y

Energy resolution:

(7.9 ± 0.6) keV (at 2615 keV)

Collected data:

38.1 kg y

$T_{1/2} > 4.5 \cdot 10^{24}$ yr (sensitivity is $3.6 \cdot 10^{24}$ yr)

Combined limit (CUORICINO + CUORE-0 + CUORE):

$T_{1/2} > 6.6 \cdot 10^{24}$ yr $\Rightarrow$ $\langle m_\nu \rangle < 0.24\text{-}0.58$ eV

III. FUTURE EXPERIMENTS

- Main goal is:

  To reach a sensitivity ~ **0.01-0.05 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 (~3-10 years)

- **CUPID** (^{130}**Te**, ^{100}**Mo**, ^{82}**Se**, … cryogenic thermal detector)
- **LEGEND** (^{76}**Ge**, HPGe detector)
- **nEXO** (^{136}**Xe**, TPC + Ba^{+})
- **KamLAND2-Zen** (^{136}**Xe**, liquid scintillator)
- **SuperNEMO** (^{82}**Se or** ^{150}**Nd**, tracking detector)
- **SNO+** (^{130}**Te**, liquid scintillator)

Other proposals: NEXT, PandaX-III, CANDLES, XMASS, AMoRE,….

SUMMARY TABLE

Experiment	Isotope	Mass, kg	$T_{1/2}$, y	$<m_\nu>$, meV	Status
LEGEND	^{76}Ge	200 1000	~ 10^{27} $5 \cdot 10^{27}$-10^{28}	40-90 10-40	Funded R&D
CUPID	^{130}Te, ^{100}Mo, ^{82}Se,..	200-600	$(2\text{-}5) \cdot 10^{27}$	6-30	R&D
KamLAND 2-Zen	^{136}Xe	1000	~ $6 \cdot 10^{26}$	25-70	R&D
nEXO	^{136}Xe	5000	~ 10^{28}	6-17	R&D
SuperNEMO	^{82}Se	100-200	$(1\text{-}2) \cdot 10^{26}$	40-100	R&D
SNO+	^{130}Te	1300 8000	$2 \cdot 10^{26}$ ~ 10^{27}	37-140 16-60	Funded R&D

CUPID (Cuore Upgrade with Particle IDentification)

- **CUPID** is next step of **CUORE** experiment
- Main goal is to reach sensitivity **~ 10^{27}-10^{28} yr**
- Main problem of **CUORE** is quite high level of background
- Mail idea is to use existing **CUORE** infrastructure and new scintillating bolometers (heat + light detection)
- Main candidates are **$ZnSe$, Li_2MoO_4, $ZnMoO_4$, $CdWO_4$** and **TeO_2**

CUORE

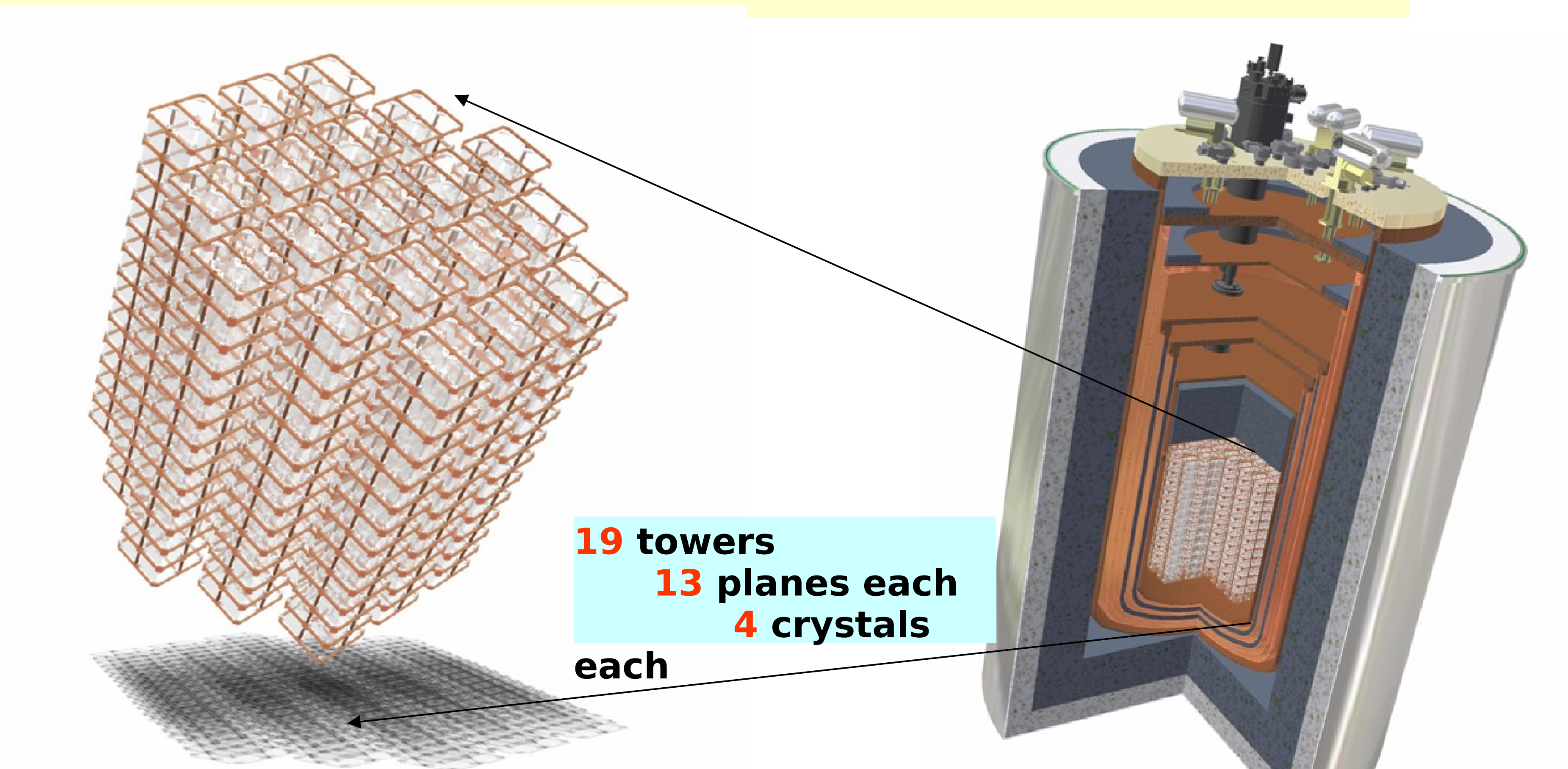
Cryogenic Underground Observatory for Rare Events

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

741 kg TeO_2 granular calorimeter

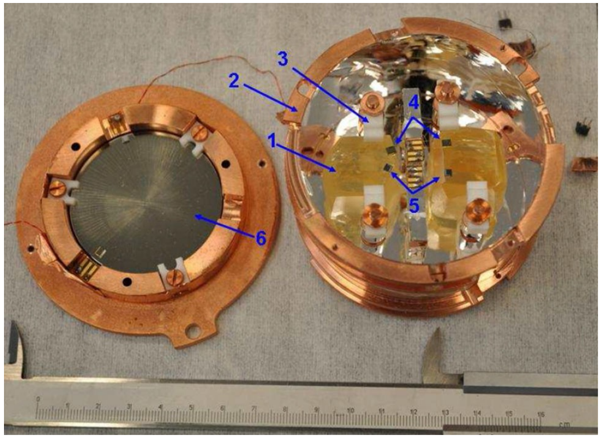
600 kg Te = 203 kg ^{130}Te

- Single high granularity detector

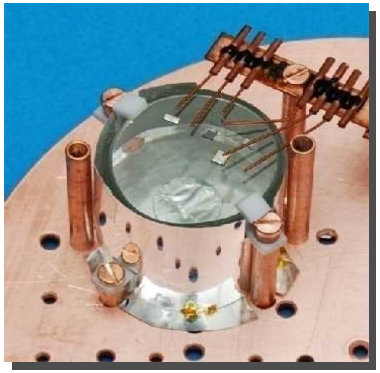


Scintillating bolometers

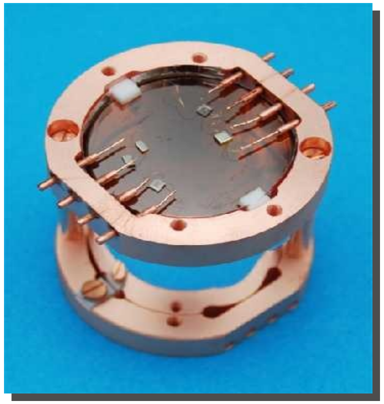
$Zn^{100}MoO_4$: 59 g and 63 g



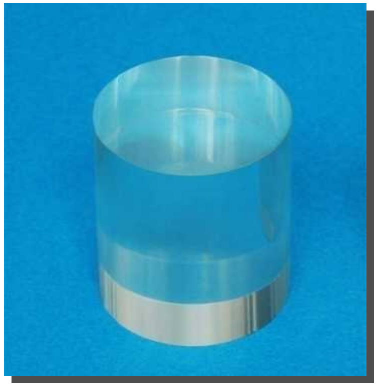
$CaMoO_4$: 157 g



ZnSe: 337 g



$CdWO_4$: 508 g



LUCIFER: $Zn^{82}Se$; LUMINEU: $Zn^{100}MoO_4$/$Li_2{}^{100}MoO_4$; AMORE: $^{40}Ca^{100}MoO_4$

Prospects of scintillating bolometers

Main advantages:

- high efficiency (~ 100%)
- good energy resolution (~ 5-10 keV)
- effective suppression of background from α-particles
- suppression of BiPo events

⇓

"Zero background" experiment!

⇓

CUORE-like experiment (**$ZnMoO_4$**, **Li_2MoO_4**, instead of **TeO_2**, for example)

CUPID experiment: arXiv:1504.03599

CUPID-0/Se Experiment

- **24 Zn^{82}Se** bolometers with a total mass **5.1 kg** of **^{82}Se**
- 2 ZnSe bolometer ≈ 400 g each, not enriched in ^{82}Se
- total active **mass of the detector is ~ 10.5 kg**
- - light detectors high purity Ge wafers with anti-reflecting coating
- - thermal sensors made with NTD thermistors
- - detector assembled in 5 towers in **Cuoricino/CUORE-0** cryostat

Energy resolution is 30 keV

0.47 kg y exposure of ^{82}Se

Running experiment

Planed sensitivity is 7·10^{24} yr for 1 year of measurement and B = 0

CUPID-0/Mo Experiment

- Strong R&D program with **$ZnMoO_4$/Li_2MoO_4** bolometers has been realized
- Measurements with a few **$ZnMoO_4$/Li_2MoO_4** bolometers under low-background conditions have been done (**LUMINEU**)
- Energy resolution **~ 5-7 keV**
- **2ν**-decay of **^{100}Mo** has been measured with high accuracy
- **$T_{1/2}$ (2ν) = [6.90 ± 0.15(stat) ± 0.42(syst)]·10^{18} yr**
- Experiment with **20(40) Li_2MoO_4** crystals is under preparation
- Beginning of measurements in the end of 2017-beginning of 2018
- Main goal is to demonstrate possibilities of this approach and put new limit on **0ν** decay of **^{100}Mo** on the level **~ 1.5·10^{25} yr**

CUPID-^{130}Te

- Main problem of **CUORE** is quite high level of background (because in **TeO_2** only heat signal is registered)
- Strong R&D to detect light (**Cherenkov effect; sensitive light detector is needed**) or to select surface event (using scintillating foils) are under realization and some promising results have been obtained
- So, there is a chance that one can detect two signals in **TeO_2** (heat + light)
- As a result it will be possible to decrease background from alfa-particles, surface events,…
- And it is possible to use **TeO_2** crystals made of enriched **Te-130**

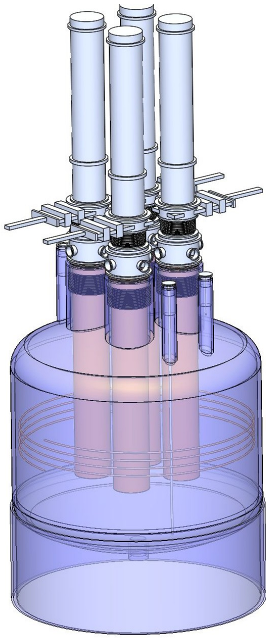
LEGEND (Large Enriched Germanium Experiment for Neutrinoless ββ Decay)

Mission: "The collaboration aims to develop a phased, **Ge-76** based double-beta decay experimental program with discovery potential at a half-life significantly **longer than 10^{27} years**, using existing resources as appropriate to expedite physics results."

Select best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.

First phase:

-(up to) **200 kg**
-Modification of existing GERDA infrastructure at LNGS
-BG goal **~ 2×10^{-4} c/keV kg y**
- Start by 2021



Final phase:

-**1000 kg**
-Timeline connected to U.S. DOE down select process
-BG goal is **~ 3×10^{-5} c/keV kg y**
- Location: TBD

Next Generation Ge-76 Experiment

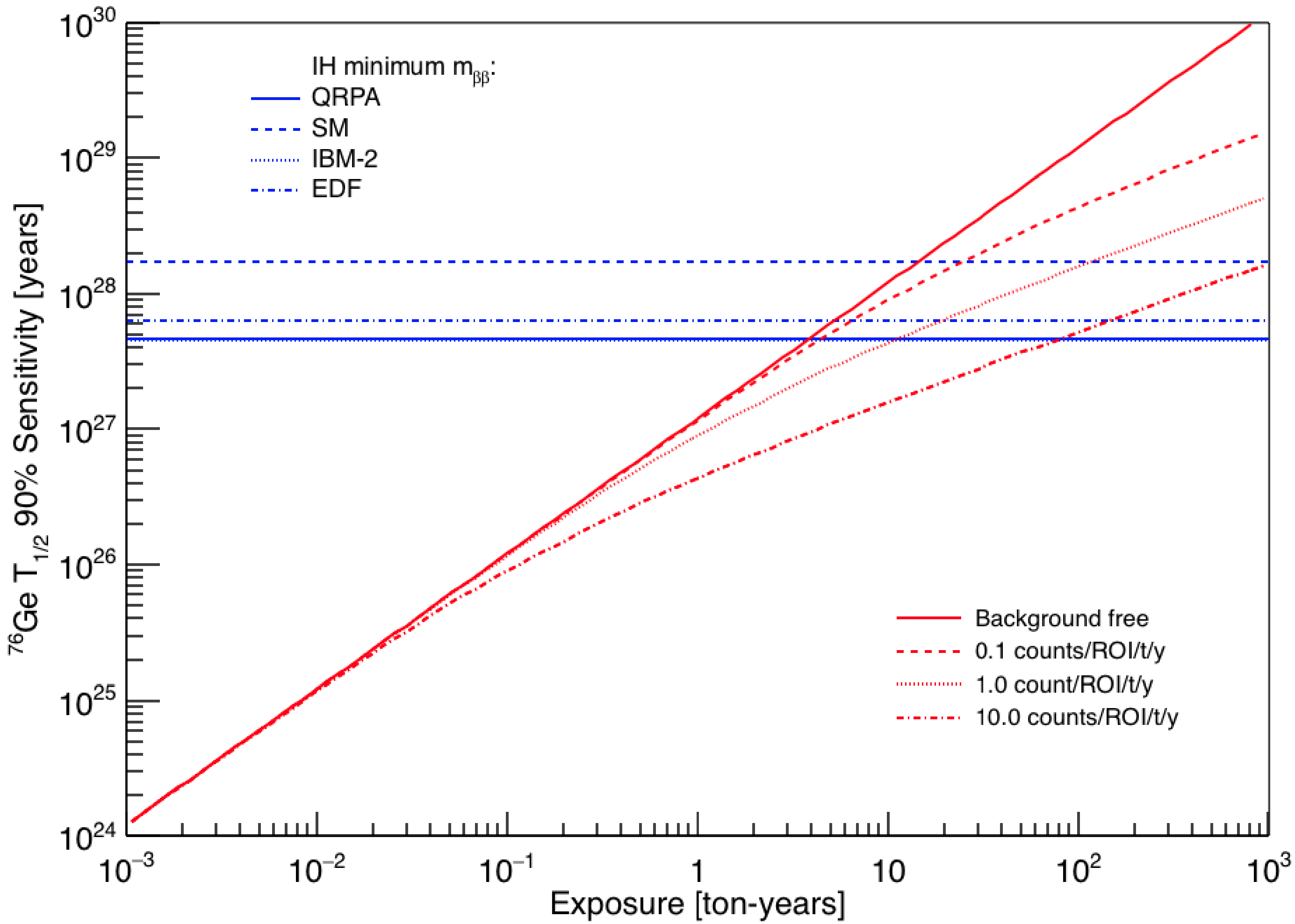
November 2015, Kitty Hawk
(Joint M-G meeting)

April 2016, Munich
(Meeting of interested parties)

October 2016, Atlanta
(Next generation Ge-76 meeting)

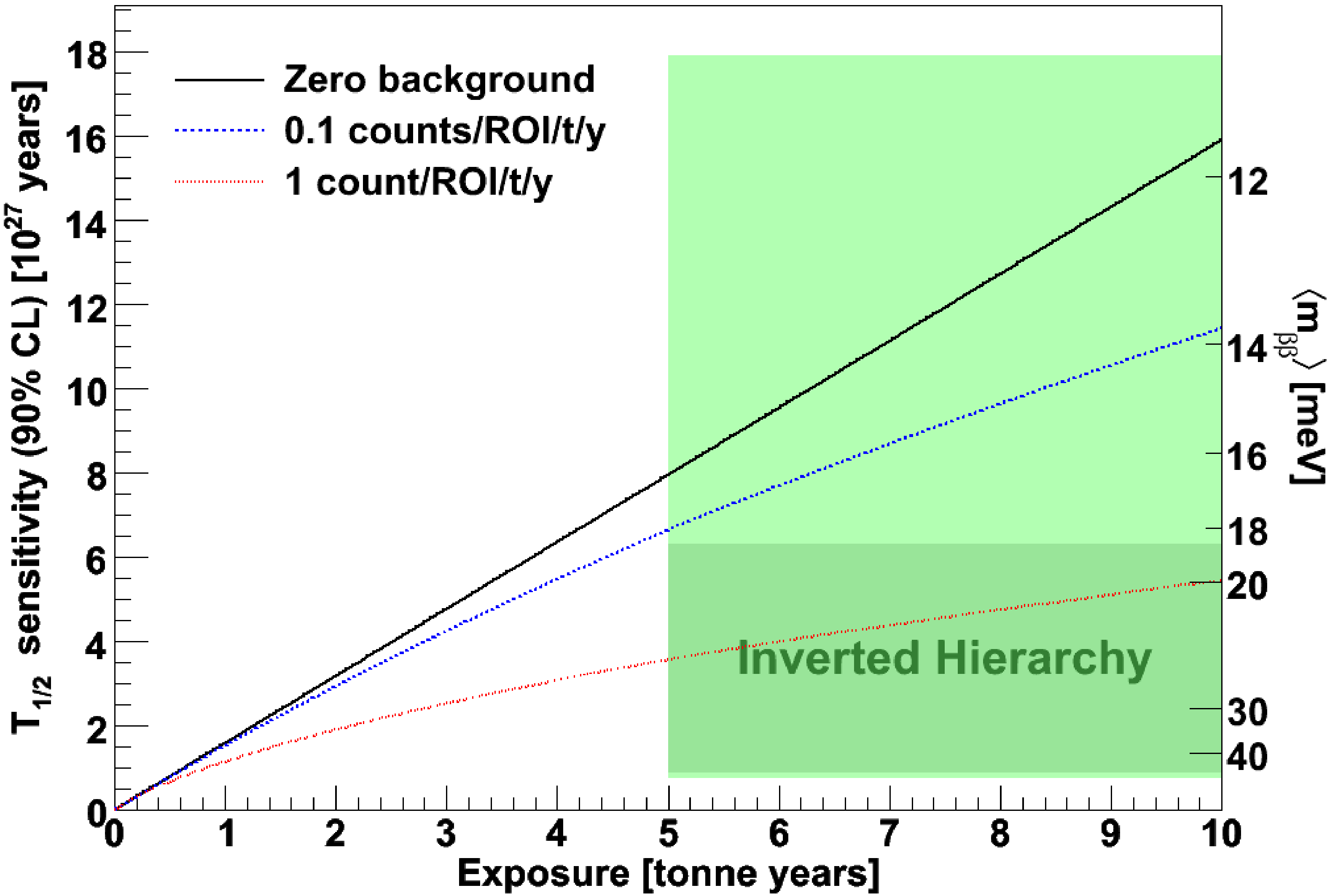
NG-Ge76:
1) Phase I – 200 kg of Ge-76 (Gran Sasso)
2) Phase-II – 1000 kg Ge-76 (SNOLAB, Jin Ping,...?)

Sensitivity vs. Exposure for ^{76}Ge



1-tonne Ge - Projected Sensitivity vs. Background

$$T_{½}^{0\nu} = \ln(2)N\varepsilon t/\mathrm{UL}(B)$$



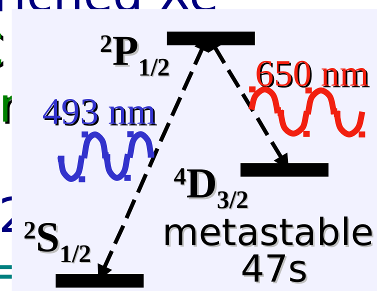
EXO (Enriched Xenon Observatory)
USA-RUSSIA-CANADA

- $^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}$ ($E_{2\beta} = 2.47$ MeV)

- **Main idea is**: to detect all products of the reaction with good enough energy and space resolution (M.Moe PRC 44(1991)931)

Tracking EXO

- **concept**: scale Gotthard experiment adding **Ba tagging** to suppress background ($^{136}Xe \rightarrow ^{136}Ba^{++} + 2e$)
- single Ba^{+} detected by optical spectroscopy
- two options with 63% enriched Xe
  - ▶ **High pressure Xe TPC**
  - ▶ **LXe TPC + scintillatior**
- **calorimetry + tracking**
- expected bkg only by ββ-2
  - ▶ energy resolution σ_E =



Present R&D

- Ba^{+} spectroscopy in HP Xe / Ba
- energy resolution in LXe (ion.+
- Prototype scale:

▶ 200 kg enriched $L^{136}Xe$ without tagging

▶ all EXO functionality except Ba

▶ operate in WIPP for ~two year

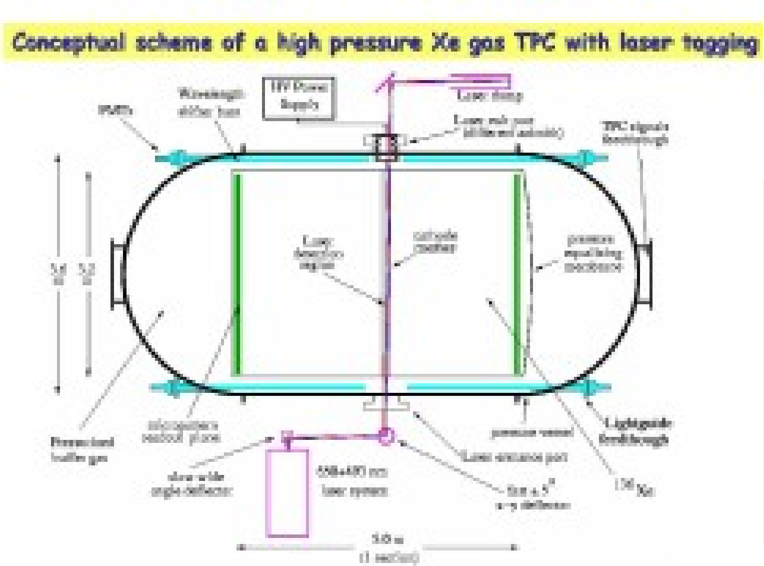
- Protorype goals:

▶ Test all technical aspects of EX (except Ba id)

▶ Measure 2ν mode

▶ Set decent limit for 0ν mode (probe Heidelberg- Moscow)

LXe TPC



Full scale experiment at WIPP or SNOLAB

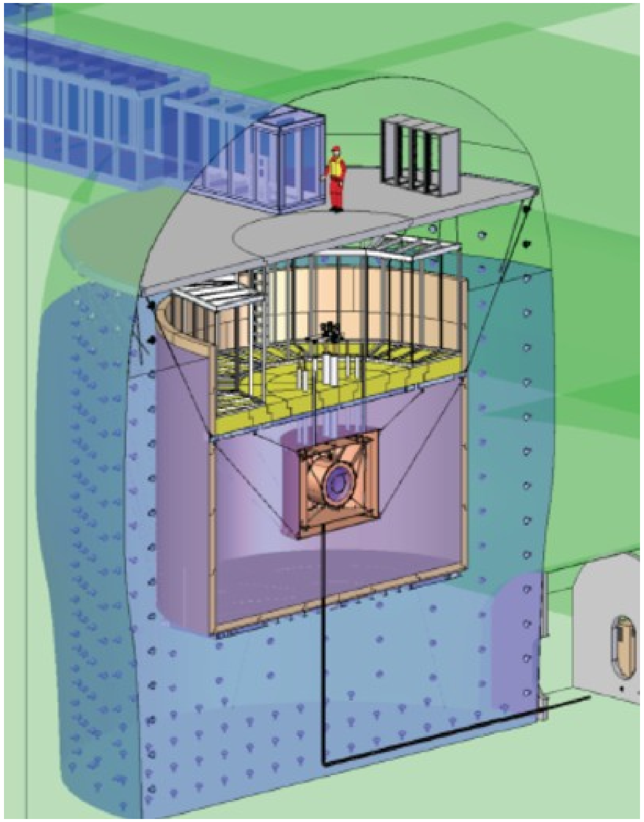
- **10 t** (for LXe ⇒ 3 m³)

  b = 4×10^{-3} c/keV/ton/y

  $T_{1/2}$ > 1.3×10²⁸ y in 5 years

  $<m_\nu> < 0.013 \div 0.037$ eV

nEXO



Overall mass: 5 tonnes, 90% enriched ^{136}Xe

Time Projection Chamber (TPC)

Location: SNOLAB (Canada)

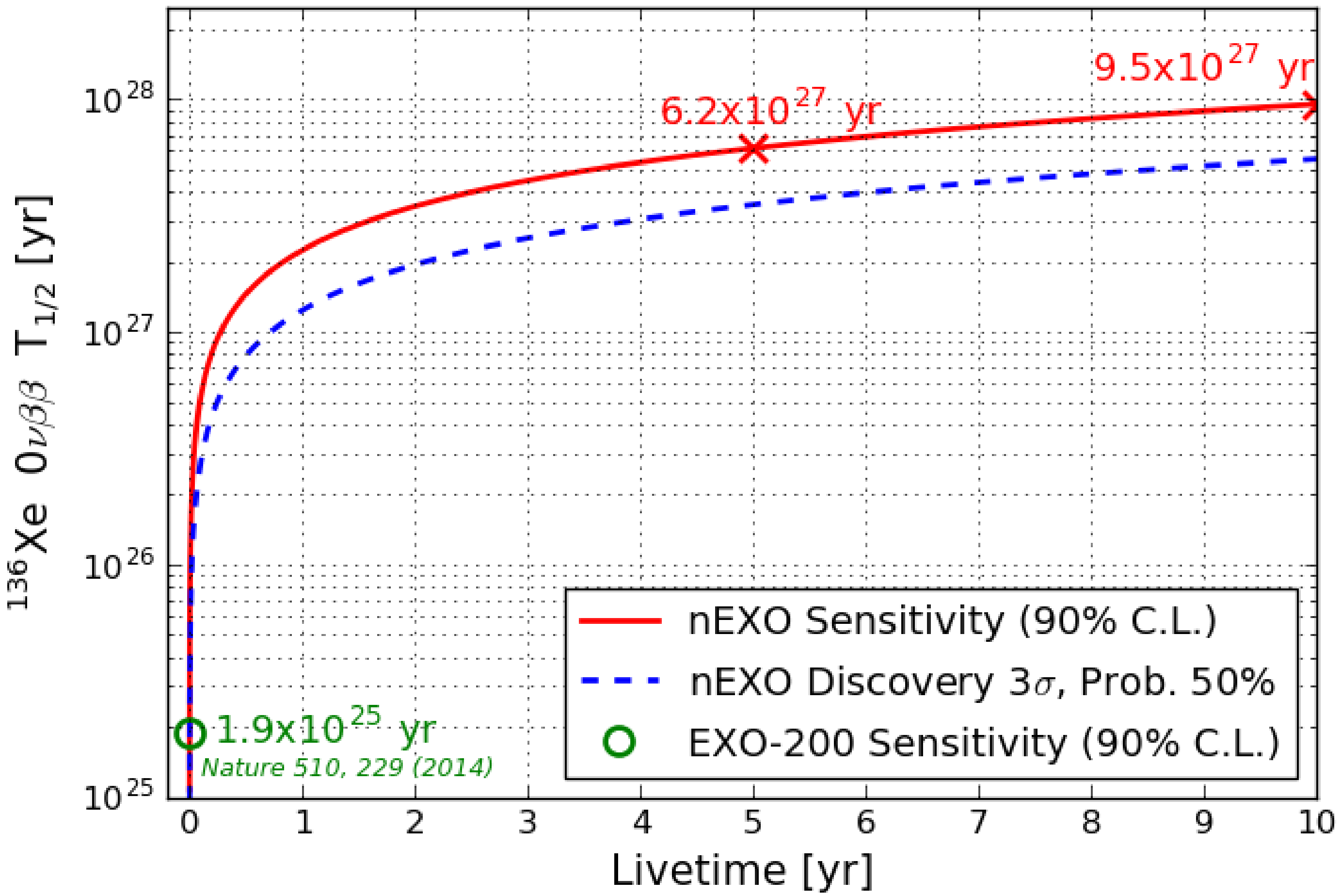
Running time: 10 years

Energy resolution: 2.35% (FWHM)

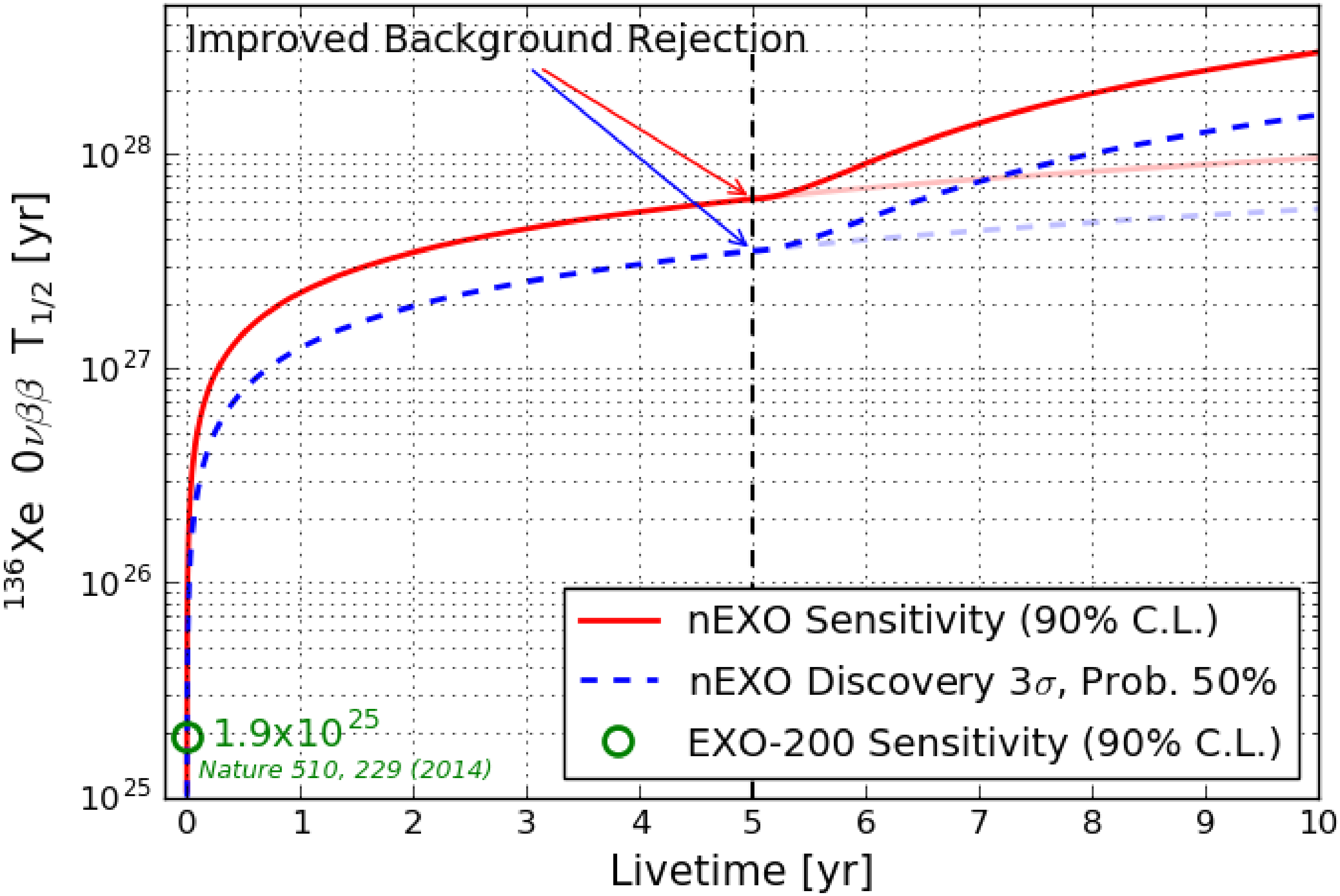
Sensitivity: **$\sim 9.5 \cdot 10^{27}$ yr (without Ba)**
$\sim 3 \cdot 10^{28}$ yr (with Ba)

Design still not finalized

Sensitivity of nEXO

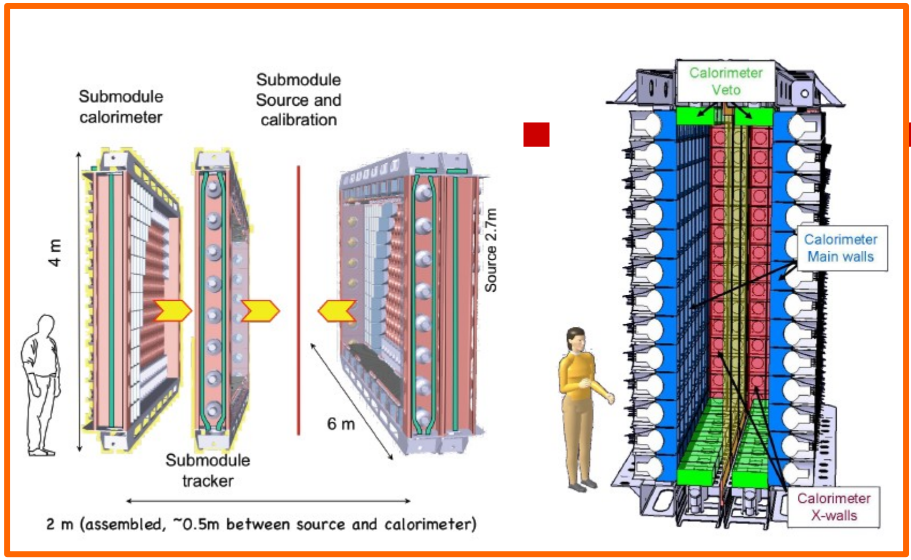


Sensitivity of nEXO with Ba+

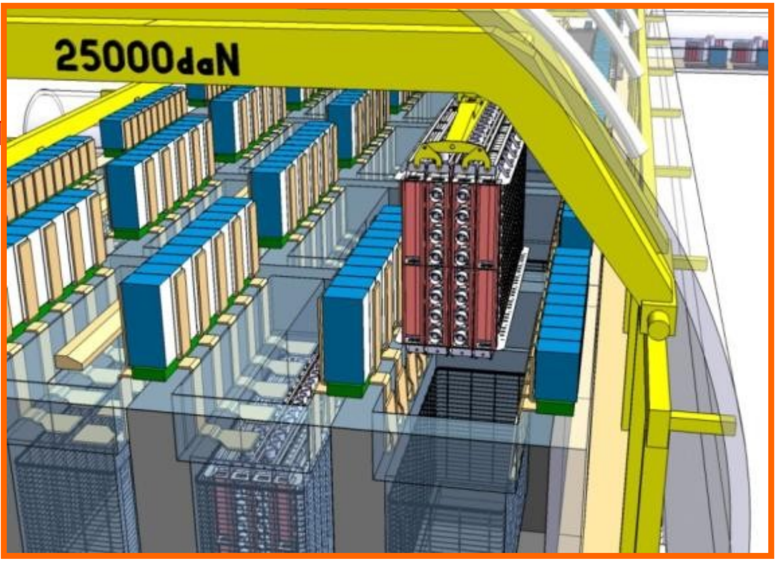


SuperNEMO

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
$<m_\nu>$ sensitivity	200 – 400 meV	40 – 100 meV

Start of measurements:

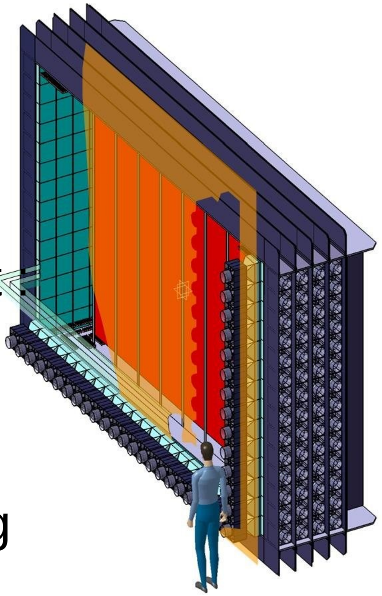
Demonstrator – 2018
SuperNEMO - 2022

Demonstrator module(7 kg) is under construction

SuperNEMO Demonstrator (1st module)

MAIN GOALS :

- To demonstrate the feasibility of large scale detector with requiered performance (efficiency, energy resolution, radiopurity, …)
- To measure the radon background
- To finalize detector design
- To produce competitive physics measurement

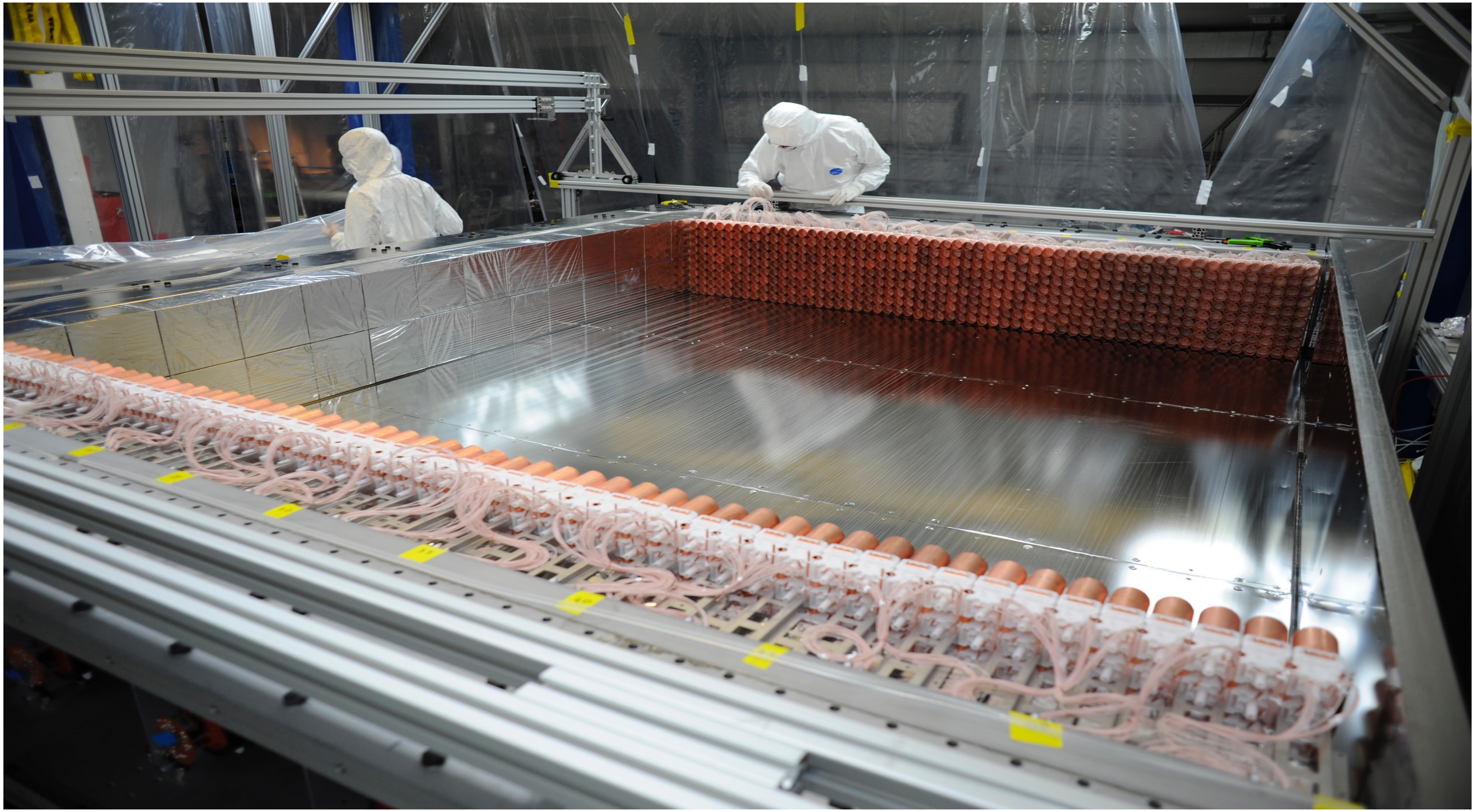


$T_{1/2}(\beta\beta0\nu) > 6.5 \times 10^{24}$ years

$< m_\nu > \; < \; 210 – 570$ meV

with 7 kg of ^{82}Se after ~ 2 years of demonstrator data taking

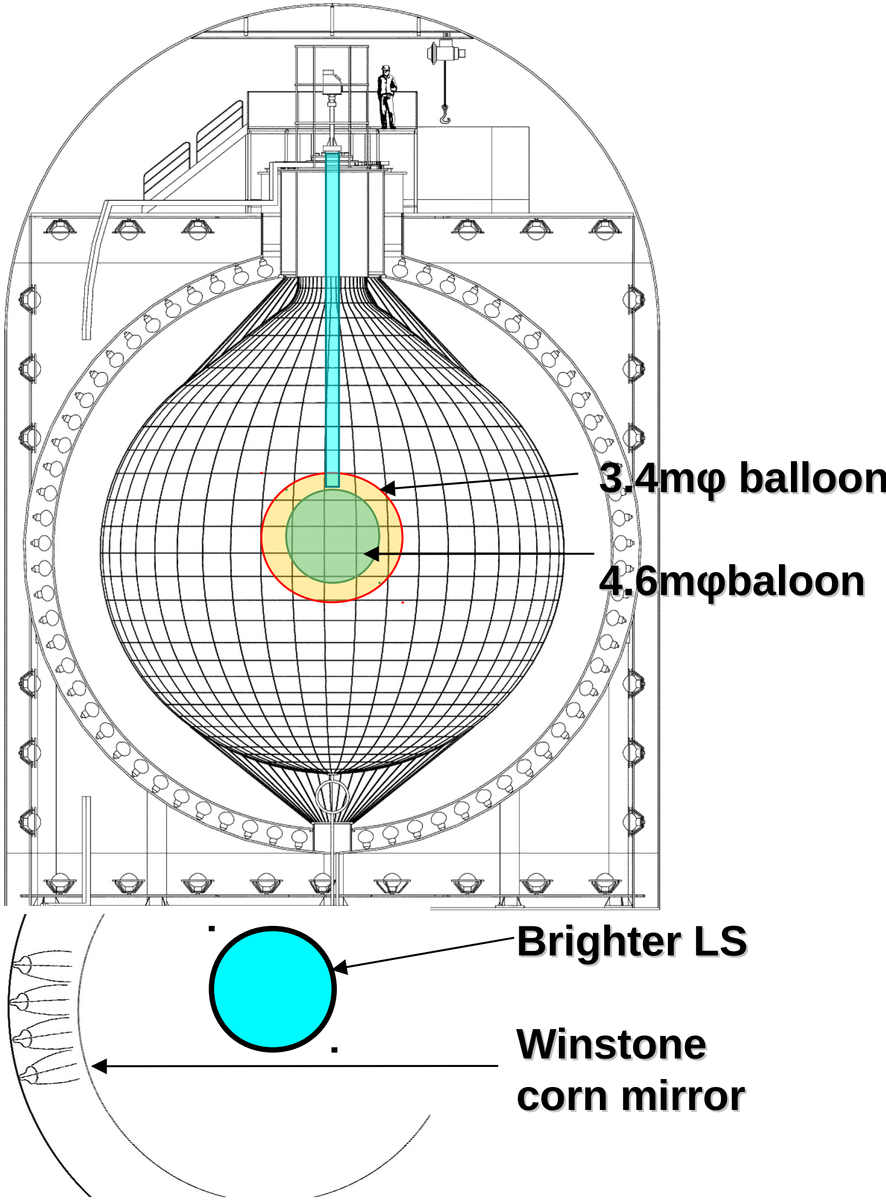
Quarter-tracker zoomed view



SuperNEMO-Demonstrator: present status

1. Tracking part is ready and assembled at **LSM.**
2. Calorimeter part is ready and assembled at **LSM.**
3. Source is ready and will be introduced into the detector in **October 2017.**
4. Start of data taking – **beginning of 2018.**

KamLAND-Zen project



1st phase enriched Xe 400kg

R=1.7m balloon

$V=20.5m^3$,$S=36.3m^2$

LS : C10H22(81.8%)+PC(18%)

+PPO+Xe(~2.5wt%)

ρLS :   0.78kg ／ℓ

high sensitivity with low cost

2nd phase   enriched Xe 1000kg

R=2.3m balloon

$V=51.3m^3$,$S=66.7m^2$

improvement of energy resolution

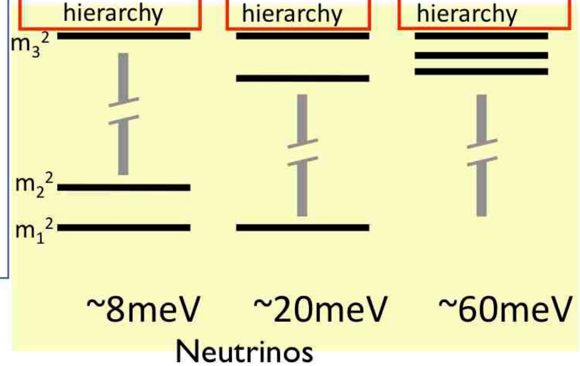
(brighter LS, higher light concentrator)

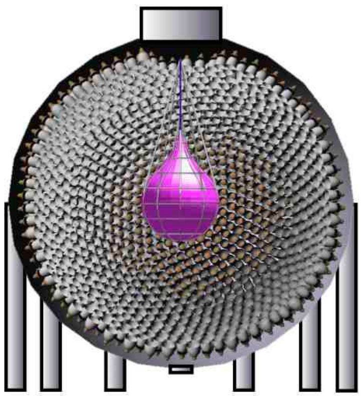
Masayuki Koga

KamLAND2-Zen with 1 t of ^{136}Xe

Purpose

- KamLAND-zen is searching neutrinoless double beta decay.
- We are planning KamLAND2-Zen that will not only search neutrinoless double beta decay but also inspect inverted hierarchy by using 1000kg of 136-Xe.



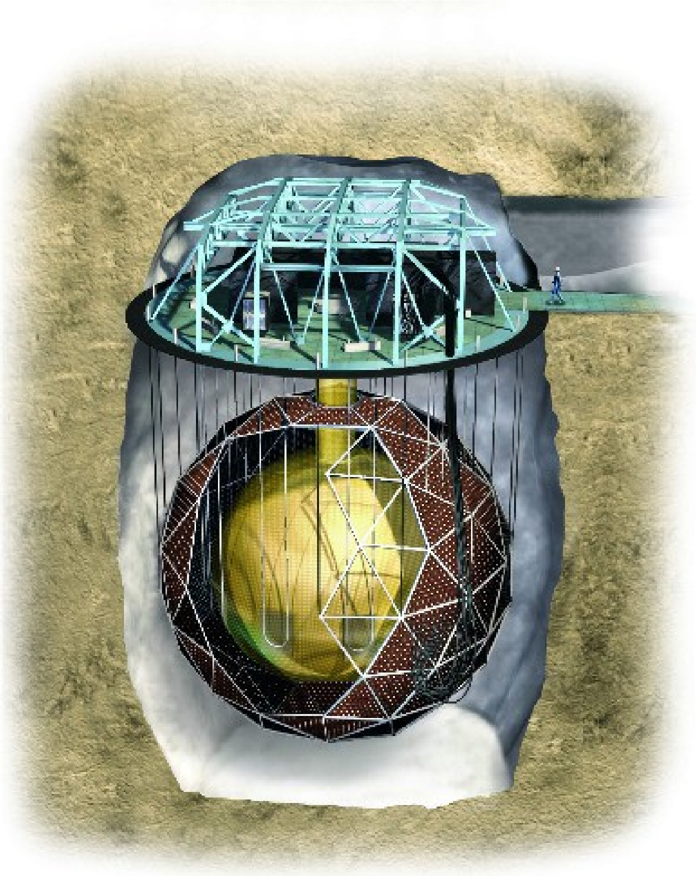


Inner Detector

- PMTs(17”):1325
- PMTs(20”):554
- 1000kg of 136-Xe
- Photo-coverage:~70% by mirrors
- Energy resolution:6.4%/$E^{1/2}$(MeV)

Sensitivity ~ $6\cdot10^{26}$ yr ($\langle m_\nu \rangle$ < 26-69 meV)

SNO+



Reuse of SNO equipment with Liquid Scintillator in the Acrylic Vessel (Energy resolution is ~ 10.5% (FWHM) at 2.5 MeV)

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 2018

Initially 0.5% loading (~ 1300 kg of ^{130}Te; maybe increased)

Sensitivity is ~ $2 \cdot 10^{26}$ yr (Phase I)
~10^{27} yr (Phase-II)

Start of data taking end of 2018

Present status of SNO+

- **SNO+** is filled with light water and taking physics data
- In 6 months of running, **SNO+** will set world leading limits on invisible nucleon decay
- Scintillator process plant is under commission
- Tellurium plant is under construction
- **Neutrinoless Double Beta Decay** phase will begin in **late 2018**
- **SNO+** **$0\nu\beta\beta$** sensitivity starts to explore the inverted hierarchy region

Prediction of the FUTURE

This is just my personal prediction:

1. Results which we are waiting for in ~ **3 years** from now.
2. Results which we are waiting for in ~ **10 years** from now.
3. What to do in the case of **normal hierarchy?**

NEAR FUTURE (2017-2019)

1. GERDA-II (35 kg of ^{76}Ge; ~ 1.5×10^{26} yr).
2. MAJORANA-DEMONSTRATOR
   (30 kg of ^{76}Ge; ~ 1×10^{26} yr).

   ^{76}Ge - ~ 2×10^{26} yr $\langle m_\nu \rangle$ ~ 0.08-0.2 eV

3. KamLAND-Zen (750 kg of ^{136}Xe; ~ 2×10^{26} yr).

   ^{136}Xe - ~ 2×10^{26} yr $\langle m_\nu \rangle$~ 0.04-0.14 eV

4. CUORE (200 kg of ^{130}Te; ~ $7\cdot10^{25}$ yr).
5. SNO+ (1300 kg of ^{nat}Te; ~ $7\cdot10^{25}$ yr).

   ^{130}Te - ~ 1×10^{26} yr $\langle m_\nu \rangle$ ~ 0.06-0.15 eV

Other experiments: EXO, Super-NEMO-Demonstrator, LUCIFER, NEXT,…

FAR FUTURE (2020-2030)

Start of data taking

- **KamLAND2-Zen (1000 kg of ^{136}Xe)** ~ 2020-2022
- **SNO+ (8000 kg of ^{130}Te)** ~ 2020-2022
- **CUPID (^{100}Mo, ^{82}Se, ^{130}Te, ...)** ~ 2022
- **LEGEND-I (200 kg ^{76}Ge)** ~ 2021-2022
- **nEXO (5000 kg ^{136}Xe)** ~ 2025-2030
- **LEGEND (1000 kg ^{76}Ge)** ~ 2025-2030

$\Downarrow$

$\langle m_\nu \rangle \sim$ 10-50 meV **(but g_A problem!?)**

VERY FAR FUTURE (inverted hierarchy case)

- Needed sensitivity to **$<m_\nu>$** is **~ 1-5 meV**
- Needed sensitivity to **$T_{1/2}$** is **~ 10^{29}-10^{30} yr**
- One needs (as minimum) ~ **10-20 t** detector made of enriched material and **10** years of measurement
- Needed background in **ROI** is **~ 0-2** events during the measurement

Isotope	N of nuclei in 10 t of enriched isotope	Events per 10 yr per 10 t ($T_{1/2} = 10^{29}$ yr)
^{48}Ca	$1.25 \cdot 10^{29}$	8.6
^{76}Ge	$7.9 \cdot 10^{28}$	5.5
^{82}Se	$7.3 \cdot 10^{28}$	5
^{100}Mo	$6 \cdot 10^{28}$	4.1
^{116}Cd	$5.2 \cdot 10^{28}$	3.6
^{130}Te	$4.6 \cdot 10^{28}$	3.2
^{136}Xe	$4.4 \cdot 10^{28}$	3

So, with 10 t and 10 years one can see "effect" if $T_{1/2} \leq 10^{29}$ yr

Possible experimental approaches for 10 t detector

- **HPGe** detectors (next step of **LEGEND**)
- Low temperature scintillating bolometers **(like CUPID, AMoRE,…)**
- Liquid scintillator detectors (like **KamLAND, SNO+, SK+, BOREXINO,…)**
- Liquid (or gas) Xe detectors (like **nEXO, XMASS, PandaX-III, NEXT,…)**

- **New ideas - !?**

Purity of detector and shield

Needed purity is differ for different experiments

It is better to have “clever” detector, which can recognize 2β events

(granularity, anticoincidence, tracks reconstruction, daughter ions registration,…)

It is more easy to purify liquids and gazes

(We know that in BOREXINO, SNO, KamLAND purity of different liquids and gazes is

~ 10^{-16}-10^{-17} g/g of U and Th)

In principle, solid material can be purified to the same level (in present experiments it is **~ 10^{-12}-10^{-14} g/g**)

We have to be careful with cosmogenic isotopes (^{68}Ge,….) and Solar neutrino contribution.

⇓

So, in principle, one can have pure enough materials for 10 t 2β-decay experiments. But it will take a lot of efforts, time and money.

Possibilities of 2β-decay isotope production

	Productivity, arb.un.
Centrifugation	**1**
Laser separation	**~ 0.1**
Plasma separation	~ 0.01
Electomagnetic separation	~ 0.001

Price is proportional to productivity

⇓

Centrifugation is only the method

Productivity of centrifugation

- Now it is ~ **200 kg/yr**
- It can be increased in **~ 10** times (with additional money investment)
- **10 t** can be produced during **5-10** years
- One has to organize new facility for this goal

Approximate price of 2β isotopes (obtained by centrifugation)

Isotope	Abundance, %	Price per kg, k$	Cost of 10 t, Mln.$	
^{76}Ge	7,61	~ 80	**800**	**(640*)**
^{82}Se	8,73	~ 80	**800**	**(640*)**
^{100}Mo	9,63	~ 80	**800**	**(640*)**
^{116}Cd	7,49	~ 180	1800	(1440*)
^{130}Te	**34,08**	**~ 20**	**200**	**(160*)**
^{136}Xe	**8,87**	**~5-10**	**50-100**	**(40-80*)**
^{150}Nd (?)	5,6	> 200	> 2000	

*) For big quantity it can be ~ 20% lower

Cost of experiments

- In addition to isotope price we have to take into account cost of detector.

For example:

- **10t Majorana** (~ 10^4 HPGe crystals) -
- ~ 200 Mln.$ (200+640=**840 Mln$**)
- **10 t CUORE** (~ 10^4 crystals) –
- ~ 100 Mln$ (100+160=**260 Mln$**)
- The cheapest case is to use existing (BOREXINO, KamLAND, SNO, SK) or future (LAGUNA,…) detectors
- **EXO-10t, NEXT-10t** - ~ 10-20 Mln.$ (80+20=**100 Mln.$**)
- Examples: **ATLAS, CMS ~ 500 Mln.$, ALICE** ~ **250 Mln.$**

^{136}Xe and ^{130}Te are the most promising candidates (price)

- But for ^{136}Xe we have another problem:
- - to have **10 t** of ^{136}Xe we need ~ **100 t** of natural Xe;
- - **world 1 year production is ~ 40 t of natural Xe**
- (Earth atmosphere: 78 % of N_2, 21% of O_2, 1% of Ar,… 10^{-5} % of Xe)
- **Can one collect enough natural Xe to produce 10 t of ^{136}Xe in reasonable time???**
- **(If one will collect all world Xe it will take ~ 2.5 yr.**
- **If one will collect ~ 10% of world Xe it will take ~ 25 yr.)**
- **Now people use Xe which was collected during many years for some other purposes (bubble chambers, Liq.Xe calorimeters, …)**

Requirements for the 10 t 2β-decay experiment with cost ~ 100- 300 Mln. $

- Energy resolution is ~ 1% or better
- Enriched isotope: **^{136}Xe(?)** or **^{130}Te**
- **BI** has to be ~ **10^{-6}-10^{-5} c/keV·kg·y**

⇓

- Low temperature bolometer (**$^{130}TeO_2$**) is the best candidate **[but background problem!?]**
- **10 t ^{136}Xe detector is not sensitive to 1-3 meV region**

Requirements for the 10 t 2β-decay experiment with cost ~ 800 Mln.$

- Energy resolution is **~ 1%** or better
- Enriched isotope: **^{76}Ge, ^{100}Mo, ^{82}Se**
- **BI** has to be ~ **10^{-6}-10^{-5} c/keV·kg·y**
- (Underground Lab ~ 6000 m w.e.)
- ⇓
- **HPGe** detector is the best candidate (**LEGEND** type experiment)
- Low temperature bolometer contains of **^{100}Mo, ^{82}Se** (**$ZnMoO_4$, ZnSe, Li_2MoO_4, ,…)**

IV. Conclusion

1. Significant advance has been made in the investigation of **2ν**-decay (**NEMO-3**, **EXO-200,…**).
2. Present conservative limit on **$\langle m_\nu \rangle$** from **2β(0ν)-**decay experiments

   is ~ **0.3 eV** (**g_A problem - ?)**
3. 4 current "large-scale" experiments continue to produce new results:
   - **GERDA-II** (**35 kg of ^{76}Ge**);
   - **Majorana-Demonstrator (30 kg of ^{76}Ge)**
   - **EXO-200** (**200 kg of ^{136}Xe)**;
   - **KamLAND-Zen** (**750 kg of ^{136}Xe**);
   - **CUORE** **(200 kg of ^{130}Te**).
4. **In 2017-2020** we are waiting for start of **SuperNEMO-Demonstrator, SNO+, NEXT** and some other experiments.
5. **Prediction for the end of 2019:**

   ^{76}Ge, ^{130}Te, ^{136}Xe ⇒ ~ (1-2)·10^{26} yr (<m_ν> ~ 0.04-0.2 eV)
6. **New generation** experiments will reach sensitivity to **$\langle m_\nu \rangle$** on the level of **~ (0.01-0.05) eV** in **~ 2025-2030**.