Б1

DOUBLE BETA DECAY: PRESENT STATUS

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Слайд 1

Б1 Барабаш; 15.07.2005

OUTLINE

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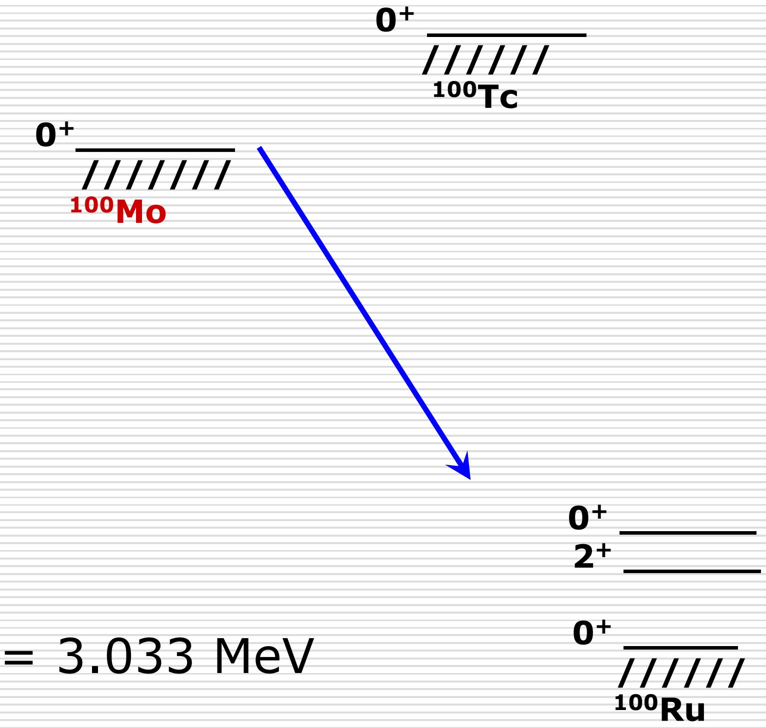
I. Introduction



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

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

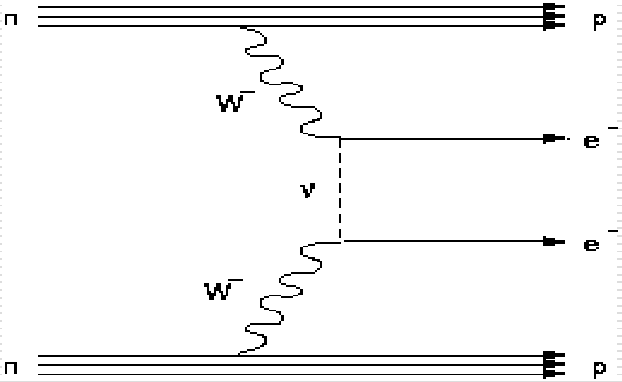
$^{100}\mathrm{Mo} \Rightarrow {}^{100}\mathrm{Ru} + 2e^- + 2v$

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

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).

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

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

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

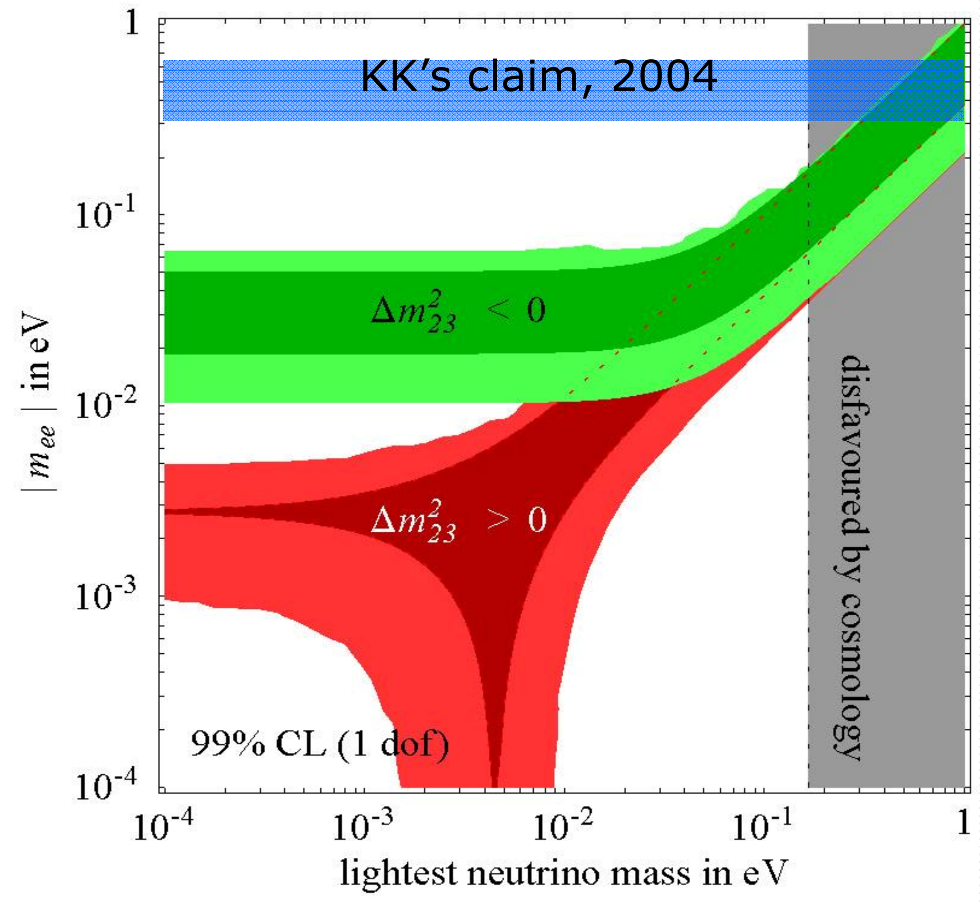
What one can extract from 2β-decay experiments? ⇒

- 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.

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.

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)

Best present limits on $\langle m_\nu \rangle$

Nuclei	$T_{1/2}$, y	$\langle m_\nu \rangle$, eV QRPA [MEDEX07]	$\langle m_\nu \rangle$, eV [SM]	Experiment
^{76}Ge	$>1.9 \cdot 10^{25}$	$< 0.22\text{-}0.41$	< 0.69	HM
	$\approx 1.2 \cdot 10^{25}$(?)	$\approx 0.28\text{-}0.52$(?)	≈ 0.87(?)	Part of HM’04
	$\approx 2.2 \cdot 10^{25}$(?)	$\approx 0.21\text{-}0.38$(?)	≈ 0.64(?)	Part of HM’06
	$>1.6 \cdot 10^{25}$	$<0.24\text{-}0.44$	<0.75	IGEX
^{130}Te	$>3.0 \cdot 10^{24}$	$< 0.34\text{-}0.57$	< 1.08	CUORICINO
^{100}Mo	$>5.8 \cdot 10^{23}$	$< 0.81\text{-}1.28$	-	NEMO
^{136}Xe	$>4.5 \cdot 10^{23}$	$< 1.41\text{-}2.67$	< 3.02	DAMA
^{82}Se	$>2.1 \cdot 10^{23}$	$< 1.40\text{-}2.17$	< 4.47	NEMO
^{116}Cd	$>1.7 \cdot 10^{23}$	$< 1.45\text{-}2.76$	< 3.76	SOLOTVINO

SM: E. Caurier, F. Nowacki, A. Poves, Int.J.Mod.Phys. E16 (2007) 552

A Recent Claim

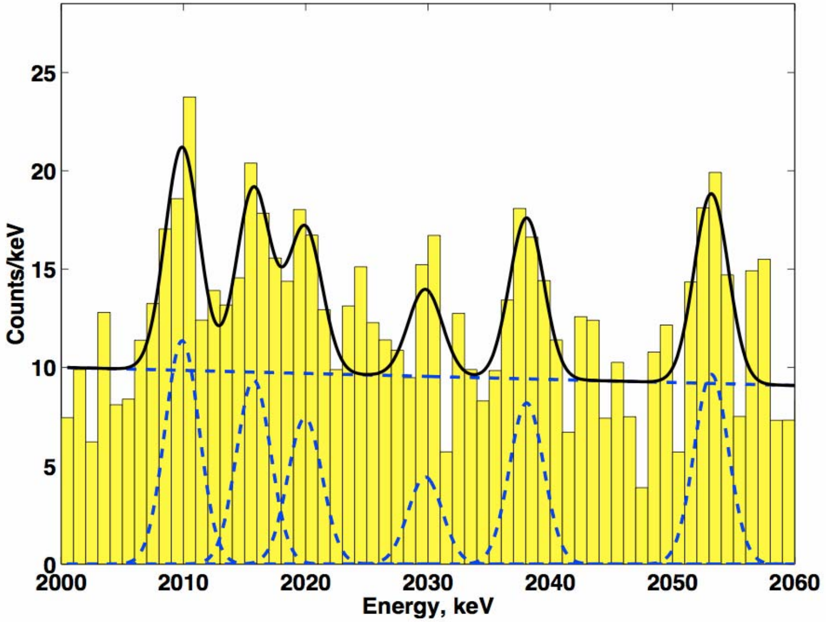
Klapdor-Kleingrothaus H V, Krivosheina I V, Dietz A and Chkvorets O, *Phys. Lett.* B **586** 198 (2004).

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 x 10^{25} y (4.2 σ)

0.24 < m_ν < 0.58 eV (± 3 sigma)

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



Mod.Phys.Lett. A21(2006)1547

Old data, new pulse shape anal.

$\tau_{1/2} = 2.23^{+0.44}_{-0.31}$ x 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 ~ 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

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.

Two neutrino double beta decay

☐ By present time **$2\beta(2\nu)$** decay was detected in **10** nuclei:

^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{150}Nd, ^{238}U

For **^{100}Mo** and **^{150}Nd** **$2\beta(2\nu)$** transition to 0^+ excited state was detected too

Main goal is: precise investigation of this decay

Recommended values for half-lives:

- ^{48}Ca - $(4.2^{+2.1}_{-1.0})\cdot 10^{19}$ y
- ^{76}Ge – $(1.5 \pm 0.1)\cdot 10^{21}$ y
- ^{82}Se – $(0.92 \pm 0.07)\cdot 10^{20}$ y
- ^{96}Zr – $(2.0 \pm 0.3)\cdot 10^{19}$ y
- ^{100}Mo – $(7.1 \pm 0.4)\cdot 10^{18}$ y
- ^{100}Mo – ^{100}Ru (0^+_1) –
  $(6.2^{+0.9}_{-0.7})\cdot 10^{20}$ y
- ^{116}Cd – $(3.0 \pm 0.2)\cdot 10^{19}$ y
- ^{128}Te(geo) – $(2.5 \pm 0.3)\cdot 10^{24}$ y

  ^{130}Te(geo) – $(0.9 \pm 0.1)\cdot 10^{21}$ y
- ^{150}Nd - $(7.8 \pm 0.7)\cdot 10^{18}$ y
- ^{150}Nd – ^{150}Sm (0^+_1) –
  $(1.4^{+0.5}_{-0.4})\cdot 10^{20}$ y
- ^{238}U(rad) - $(2.0 \pm 0.6)\cdot 10^{21}$ y

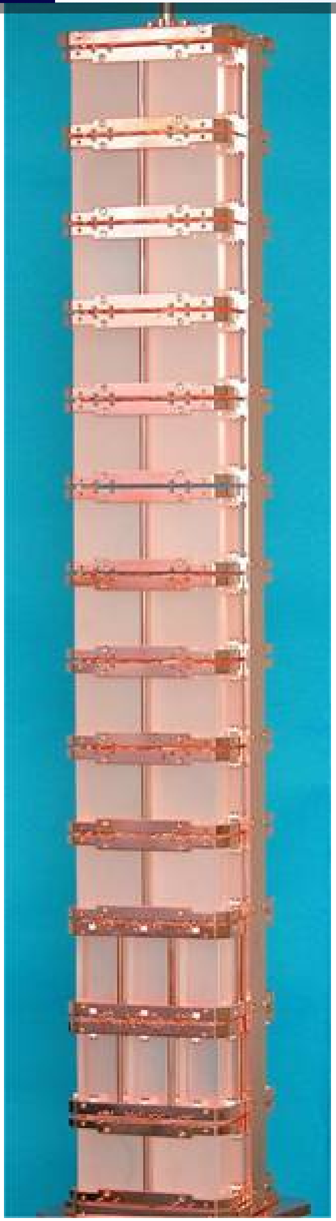
ECEC(2ν):

- ^{130}Ba(geo) - $(2.2 \pm 0.5)\cdot 10^{21}$ y

II. CURRENT EXPERIMENTS

- **NEMO-3** and **CUORICINO**
- Others (TGV, Baksan, DAMA, COBRA, ITEP-TPC, excited states,…)

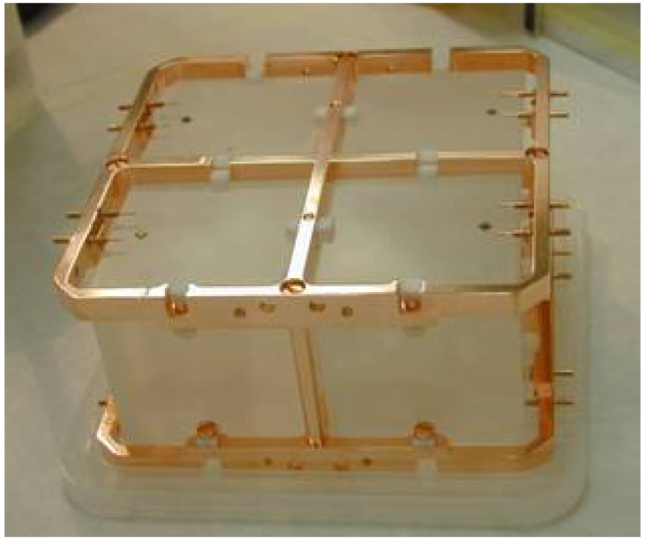
Cuoricino

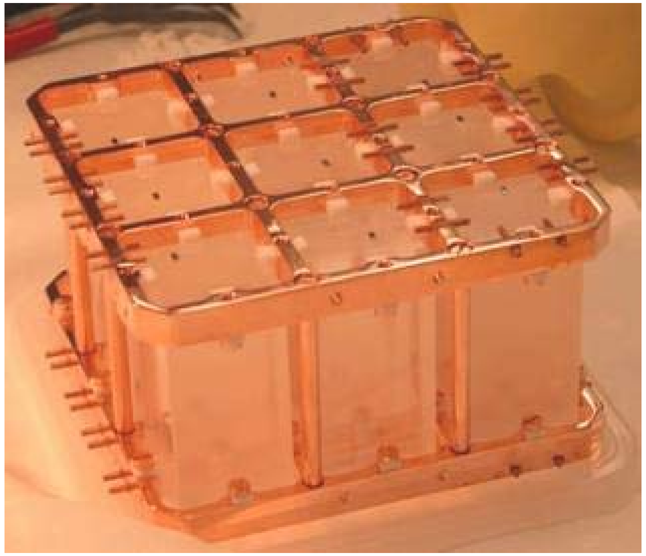


11 modules
4 detectors each
Dimension: 5x5x5 cm^3
Mass: 790 g

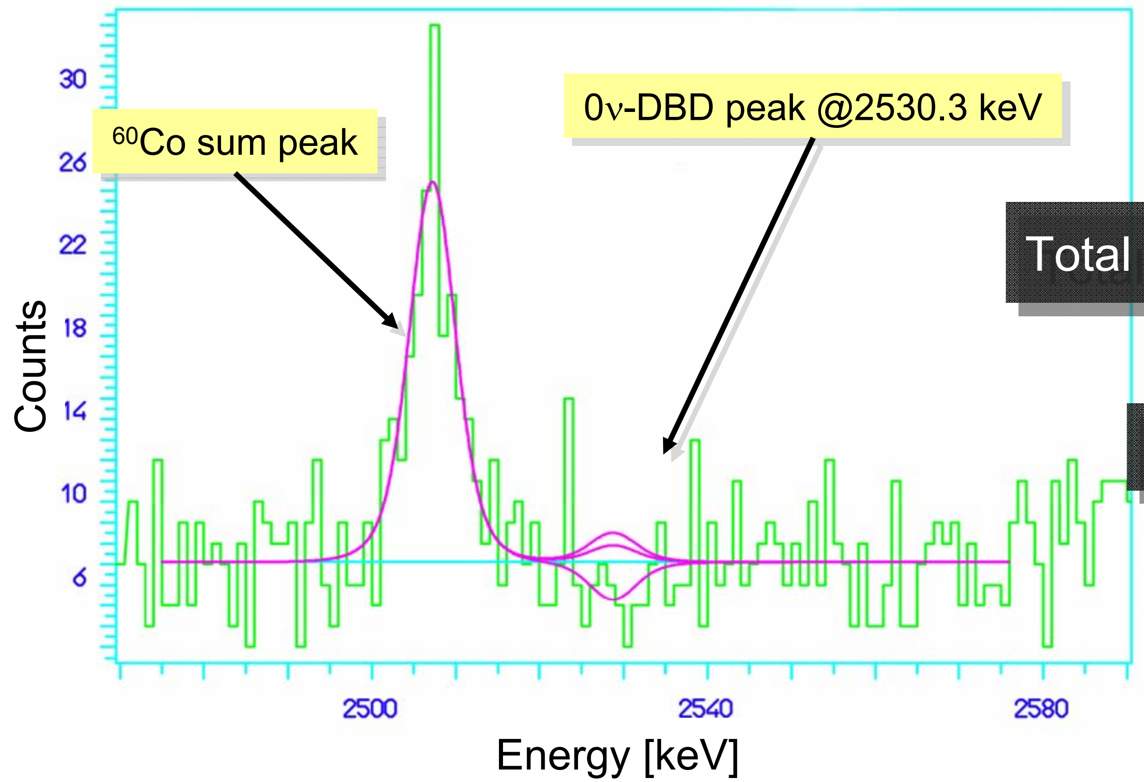
Total mass
40.7 kg
(~11 kg of ^{130}Te)

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





Cuoricino result on ^{130}Te ββ0ν decay



^{60}Co sum peak

0ν-DBD peak @2530.3 keV

Anticoincidence background spectrum the **bb**-0**n** region

Total statistic ~ 11.8 kg (^{130}Te) × y

b = 0.18 ± 0.01 c/keV/kg/y

Maximum Likelihood
flat background + fit of 2505 peak

$$\tau^{0\nu}_{1/2} \geq 3.0\cdot 10^{24}\, y\ (90\%\ CL) \Rightarrow \langle m_{\nu} \rangle \leq 0.34-1.08\, eV\quad (90\%\ \ CL)$$

(NME: MEDEX07 + SM07)

CUORICINO sensitivity

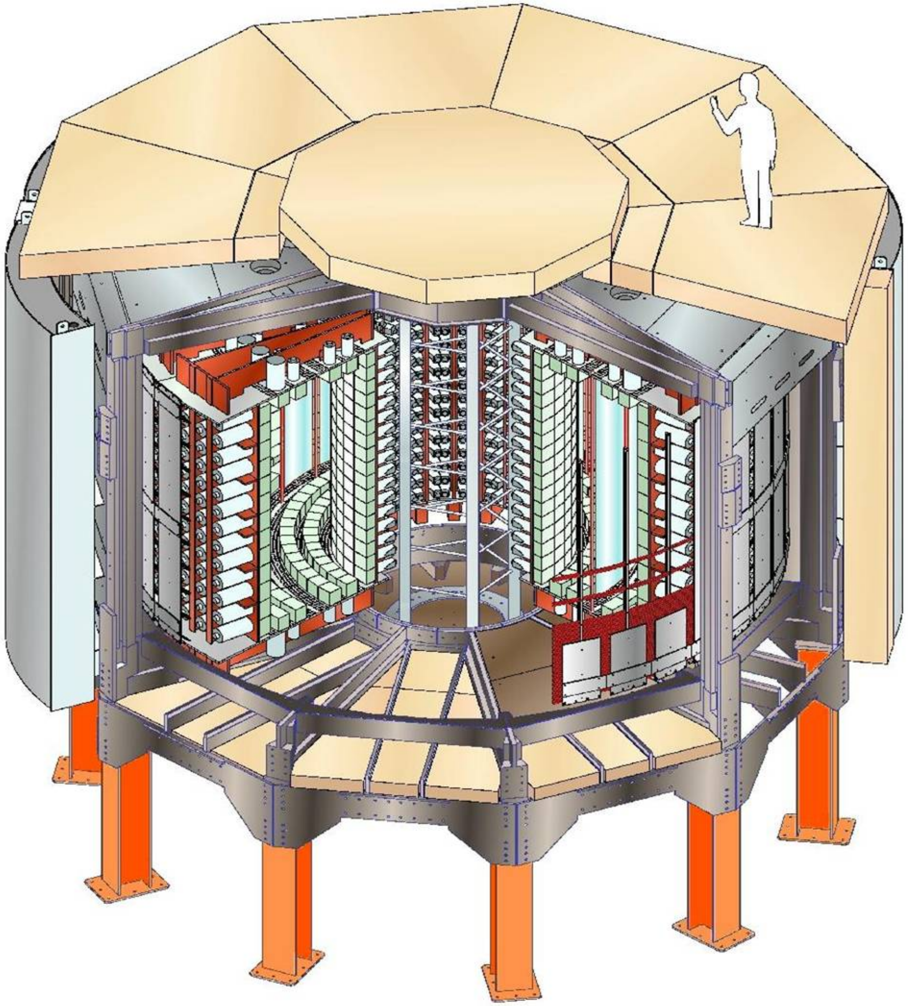
- In 3 y running time:

$T_{1/2} > 5.2 \cdot 10^{24}$ y

$\langle m_\nu \rangle < 0.2\text{-}0.6$ eV

The NEMO3 detector

Fréjus Underground Laboratory : 4800 m.w.e.



Source: 10 kg of ββ isotopes
cylindrical, S = 20 m², 60 mg/cm²

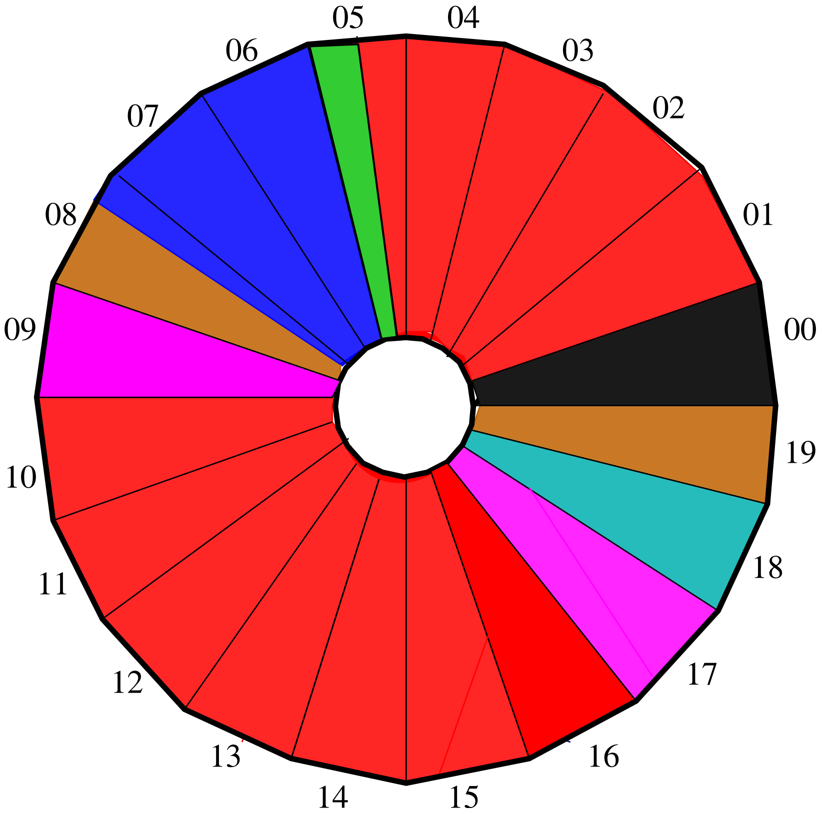
Tracking detector:
drift wire chamber operating
in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

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

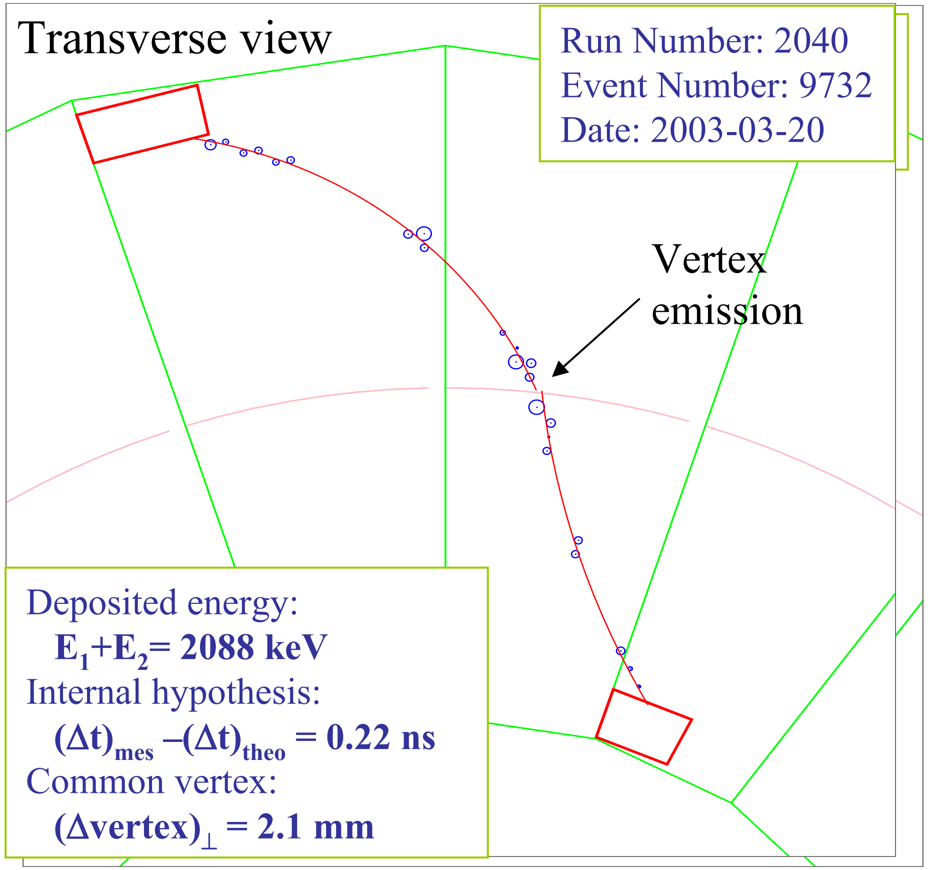
Cu 621 g

External bkg measurement

(All enriched isotopes produced in Russia)

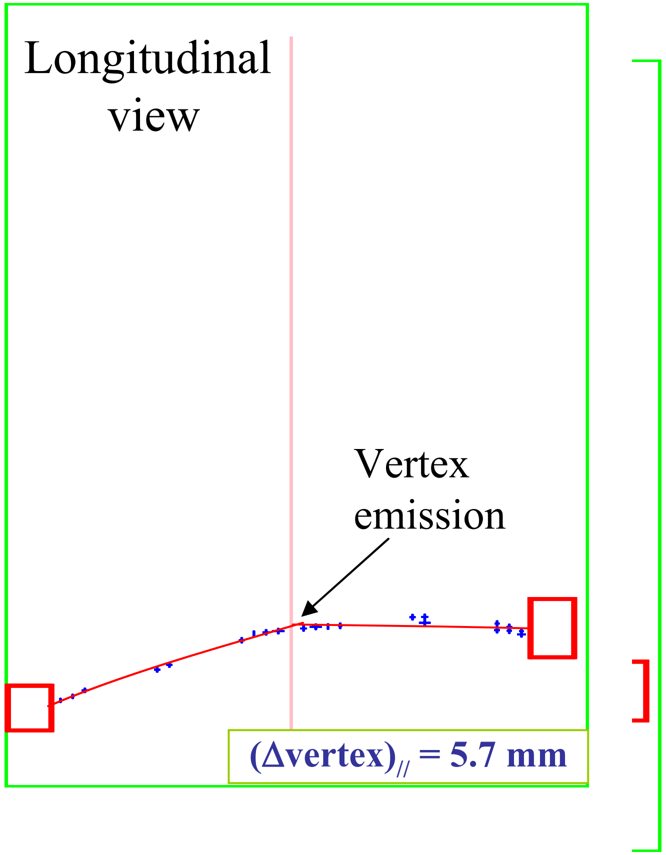
ββ events selection in NEMO-3

Typical ββ2ν event observed from ^{100}Mo



Run Number: 2040
Event Number: 9732
Date: 2003-03-20

Deposited energy:
E_1+E_2= 2088 keV
Internal hypothesis:
$(\Delta t)_{mes} - (\Delta t)_{theo}$ = 0.22 ns
Common vertex:
$(\Delta \text{vertex})_\perp$ = 2.1 mm



$(\Delta \text{vertex})_{//}$ = 5.7 mm

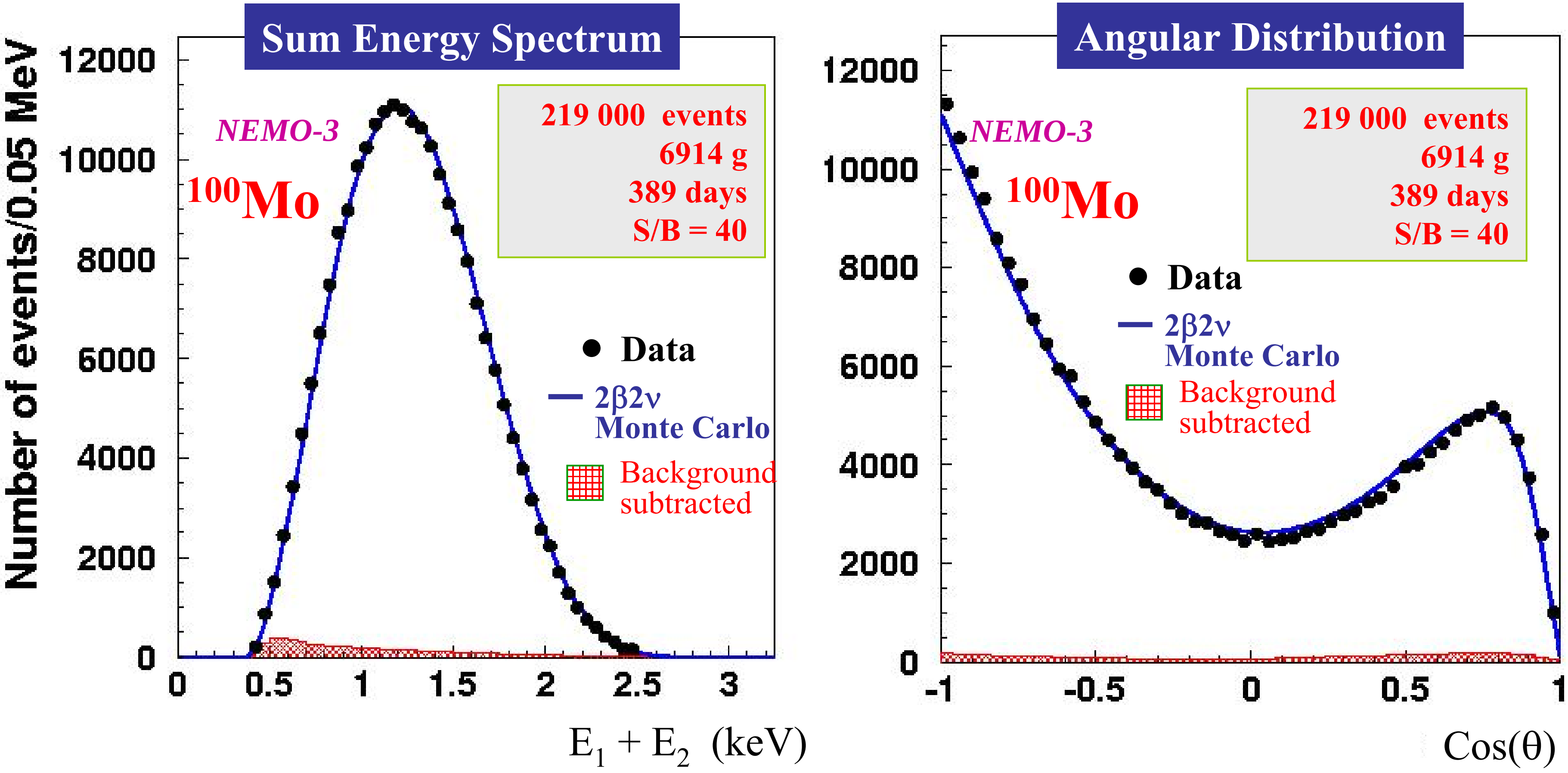
Trigger: at least 1 PMT > 150 keV
≥ 3 Geiger hits (2 neighbour layers + 1)

Trigger rate = 7 Hz

ββ events: 1 event every 2.5 minutes

^{100}Mo 2β2ν preliminary results

(Data Feb. 2003 – Dec. 2004)



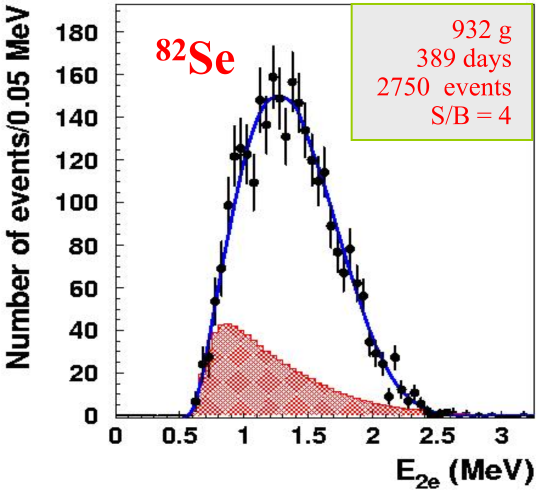
7.37 kg.y

$T_{1/2} = 7.11 \pm 0.02\ (\mathrm{stat}) \pm 0.54\ (\mathrm{syst}) \times 10^{18}$ y

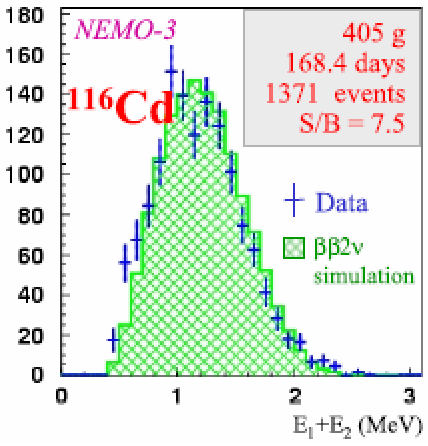
Phys. Rev. Lett. 95 (2005) 182302

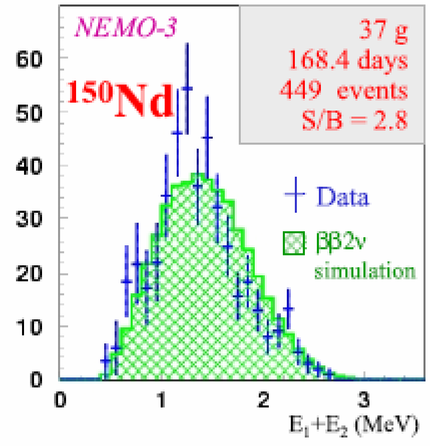
ββ2ν results with other nuclei

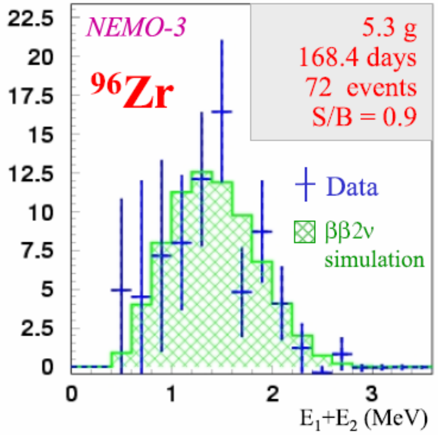
Background subtracted

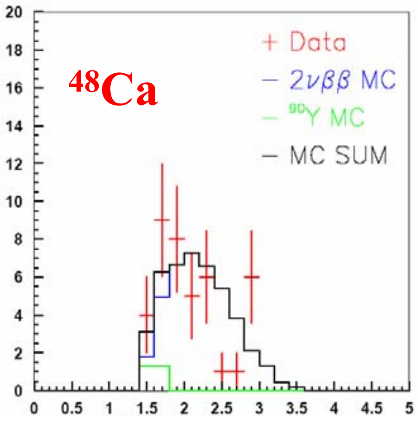


^{82}Se	$T_{1/2}$ = 9.6 ± 0.3 (stat) ± 1.0 (syst) × 10^{19} y
^{116}Cd	$T_{1/2}$ = 2.8 ± 0.1 (stat) ± 0.3 (syst) × 10^{19} y
^{150}Nd	$T_{1/2}$ = 9.7 ± 0.7 (stat) ± 1.0 (syst) × 10^{18} y
^{96}Zr	$T_{1/2}$ = 2.0 ± 0.3 (stat) ± 0.2 (syst) × 10^{19} y
^{48}Ca	$T_{1/2}$ = 3.9 ± 0.7 (stat) ± 0.6 (syst) × 10^{19} y
^{130}Te	$T_{1/2}$ = 7.6 ± 1.5 (stat) ± 0.8 (syst) × 10^{20} y (new!)
^{100}Mo- ^{100}Ru(0^+_1)	$T_{1/2} = 5.7^{+1.3}_{-0.9}$ (stat) ± 0.8 (syst) × 10^{20} y





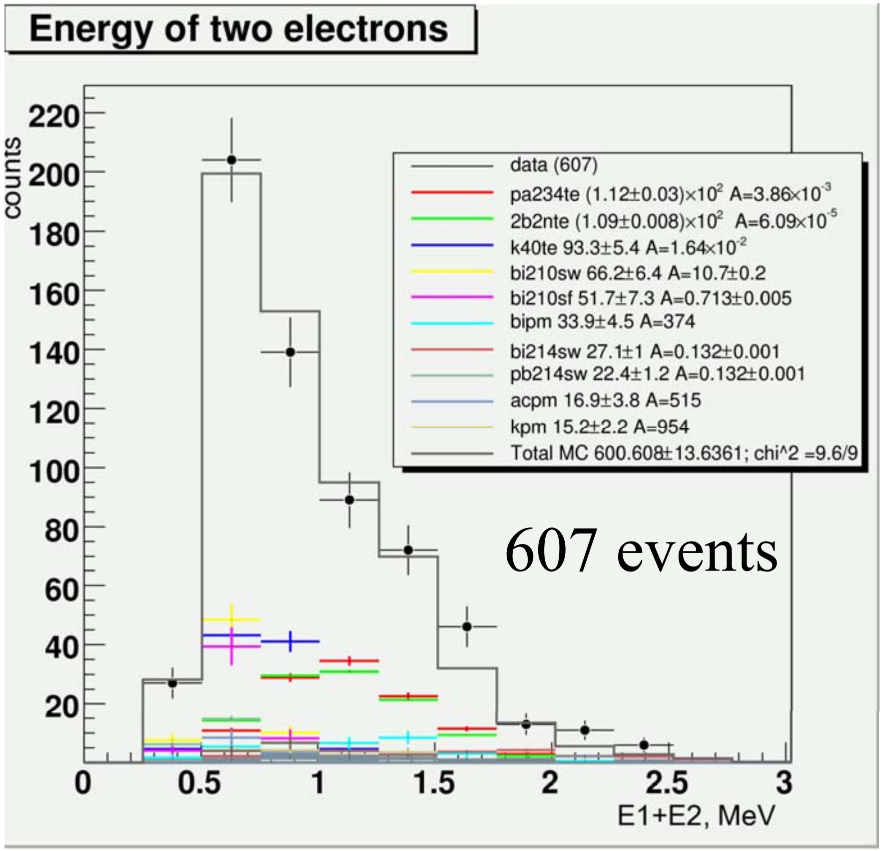




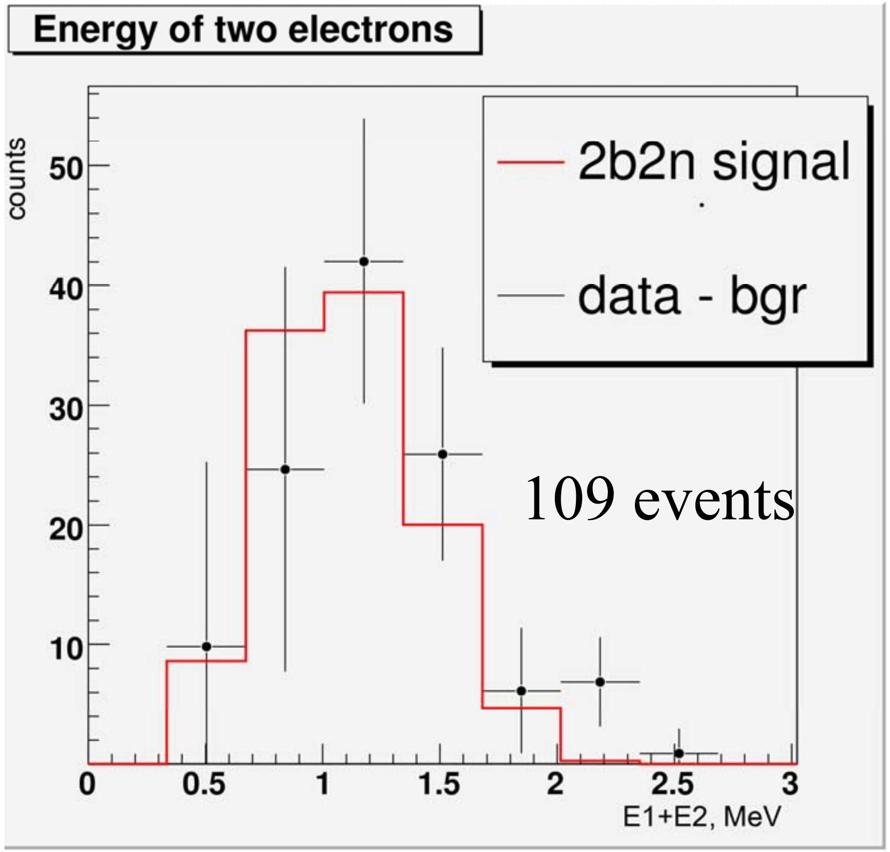
NEMO-3 is 2β(2ν)-decay factory!!!

^{130}Te (preliminary)

$$T_{1/2}^{2\nu\beta\beta} = (7.6 \pm 1.5(stat) \pm 0.8(syst)) \cdot 10^{20}\ years$$



534 days, 454 g of ^{130}Te



background subtracted

Other interesting results with NEMO-3

(using information obtained with 2ν-decay of ^{100}Mo)

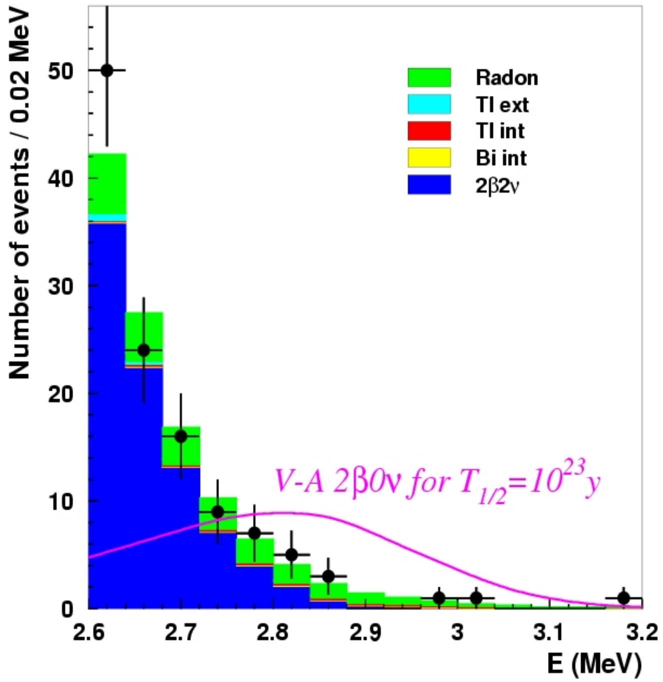
- ☐ **SSD** mechanism is confirmed for 2ν decay of ^{100}Mo [Phys.At.Nucl. 69(2006) 2090]
- ☐ **"Bosonic"** properties of neutrino is checked:

  - pure "bosonic" neutrinos are excluded;
  - conservative upper limit $\sin^2\chi < 0.6$ is obtained

  (hep-ph/0704.2944)

$\beta\beta0\nu$ search

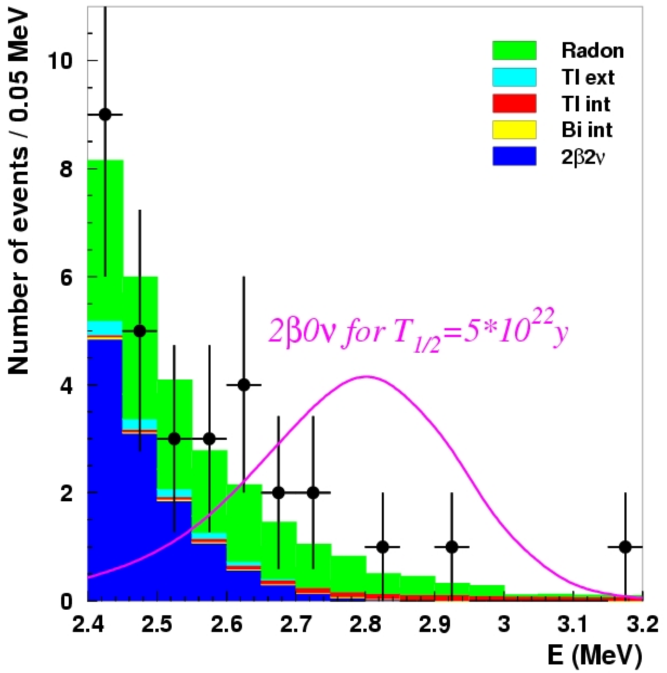
^{100}Mo, Phase I + II, 693 days



$T_{1/2}^{\beta\beta0\nu} > 5.8 \times 10^{23}$ (90 % CL)
$<m_\nu> < 0.8 – 1.3$ eV

expected in 2009: $T_{1/2}^{\beta\beta0\nu} > 2 \times 10^{24}$ (90 % CL)
$<m_\nu> < 0.4 – 0.7$ eV

^{82}Se ,Phase I + II, 693 days



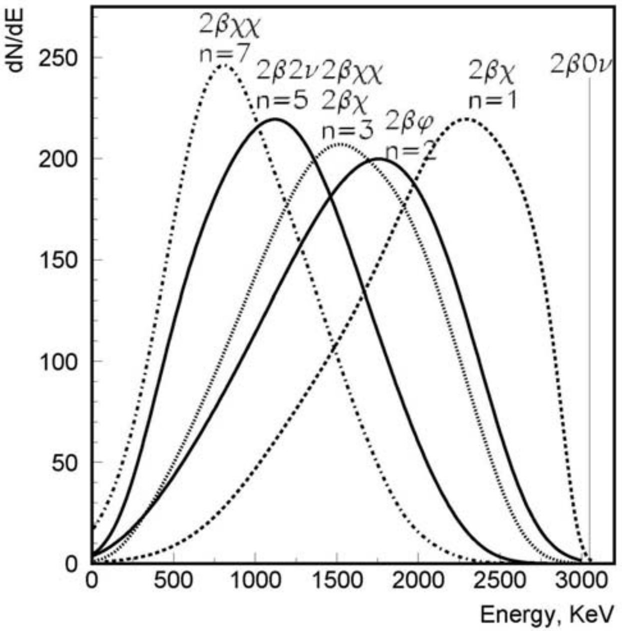
$T_{1/2}^{\beta\beta0\nu} > 2.1 \times 10^{23}$ (90 % CL)
$<m_\nu> < 1.4$-2.2 eV

$T_{1/2}^{\beta\beta0\nu} > 8 \times 10^{23}$ (90 % CL)
$<m_\nu> < 0.7$-1.1 eV

- Collaboration decided to perform blind analysis with mock data
- Plan to open the box and update the results ~ summer 2008
  - and once again at the end of the experiment ~ early 2010.

Decay with Majoron emission

NEMO-3 results



	n=1 *	n=2 *	n=3 *	n=7 *
^{100}Mo	$>2.7\cdot10^{22}$ $g<(0.4\text{-}1.8)\cdot10^{-4}$	$>1.7\cdot10^{22}$	$>1.0\cdot10^{22}$	$>7\cdot10^{19}$
^{82}Se	$>1.5\cdot10^{22}$ $g<(0.7\text{-}1.9)\cdot10^{-4}$	$>6.0\cdot10^{21}$	$>3.1\cdot10^{21}$	$>5.0\cdot10^{20}$

* *R.Arnold et al. Nucl. Phys. A765 (2006) 483*

III. FUTURE EXPERIMENTS

- Main goal is:

  To reach a sensitivity ~ **0.01-0.1 eV** to **$\langle m_\nu \rangle$** (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 (~5-10 years)

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

Other proposals: MOON, SNO++, CANDLES, COBRA, XMASS, DCBA,….

SUMMARY TABLE

(NME from MEDEX’07 and SM’07)

Experiment	nucleus	mass (kg)	status	start	$T_{1/2}$(y)	$\langle m_\nu \rangle$ eV	Location	Expected bkg (cts/keV/y/kg)
CUORE	^{130}Te	200	accepted + R&D	~2011	$2.1 \cdot 10^{26}$	0.04-0.13	Gran Sasso	0.01
				~2011	$6.5 \cdot 10^{26}$	0.02-0.07	Gran Sasso	0.001
GERDA	^{76}Ge	40	accepted + R&D	~2009	$2\ 10^{26}$	0.07-0.21	Gran Sasso	0.001
		1000		~2011	$6 \cdot 10^{27}$	0.01-0.04		0.00025
MAJORANA	^{76}Ge	60	R&D	~2009	$1.6 \cdot 10^{26}$	0.08-0.24	SNO	0.00025
		1000	R&D	~2011	$6 \cdot 10^{27}$	0.01-0.04		
EXO	^{136}Xe	200	accepted + R&D	~2008	$6.4 \cdot 10^{25}$	0.12-0.25	WIPP	0.0006
		1000		~2011	$2 \cdot 10^{27}$	0.02-0.045		10^{-6}
SuperNEMO	^{82}Se ^{150}Nd	~ 100-200	R&D	~2011	$2\ 10^{26}$	0.04 –0.14	LSM, Can Franc	10^{-5}

IV. Conclusion

1. Significant advance has been made in the investigation of **2ν**-decay.

2. Present conservative limit on **$<m_\nu>$** from **2β(0ν)-**decay experiments is ~ **0.9 eV**.

3. There is indication on "evidence" of **2β(0ν)-**decay in ^{76}Ge (**$<m_\nu> \approx$ 0.5 eV**).
   But it has to be confirmed (or rejected) in new experiments with ^{76}Ge (it will be done in a few years).

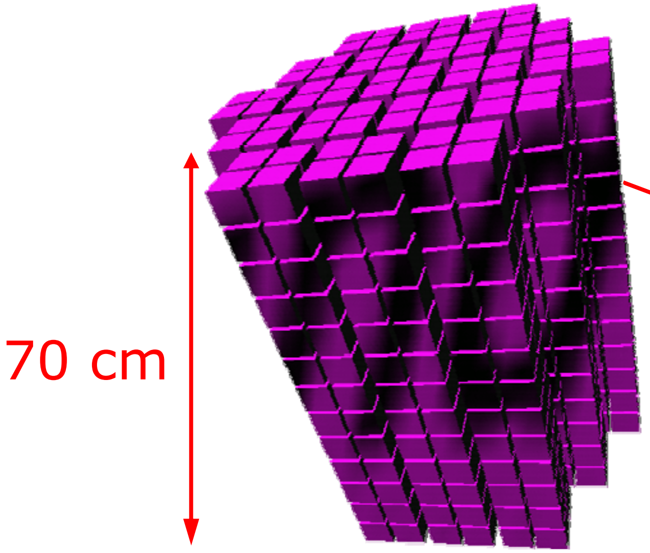
4. **CUORICINO** and **NEMO-3** will reach a sensitivity to **$<m_\nu>$** on the level **~ (0.2-0.6) and (0.4-0.7) eV** in ~ **2009-2010**.

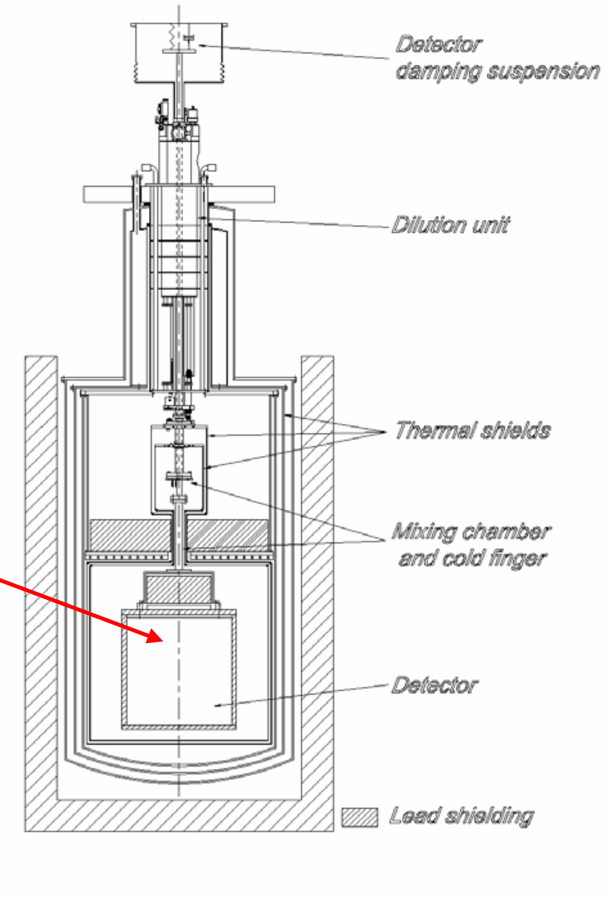
5. New generation of experiments will reach sensitivity to **$<m_\nu>$** on the level **~ (0.01-0.1) eV** in ~ **2012-2015**.

BACKUP SLIDES

CUORE

Array of 988 crystals:
19 towers of 52 crystals/tower.
⇨ M = 0.78 ton of TeO_2





Search for 0ν DBD of ^{130}Te
$Q_{\beta\beta}$ = 2529 keV
Natural isotopic abundance [^{130}Te] = 34.08%
Therefore, isotopic enrichment is unnecessay

CUORE 5 y sensitivity

- ☐ “Pessimistic”:

  B = 0.01 /keV·kg·y; ΔE = 5 keV

  $T_{1/2} > 2.1 \cdot 10^{26}$ y, **<m> < 0.04-0.13 eV**

- ☐ “Optimistic”:

  B = 0.001 /keV·kg·y; ΔE = 5 keV

  $T_{1/2} > 6.5 \cdot 10^{26}$ y, **<m> < 0.02-0.07 eV**

GERDA @ Gran Sasso: experimental concept

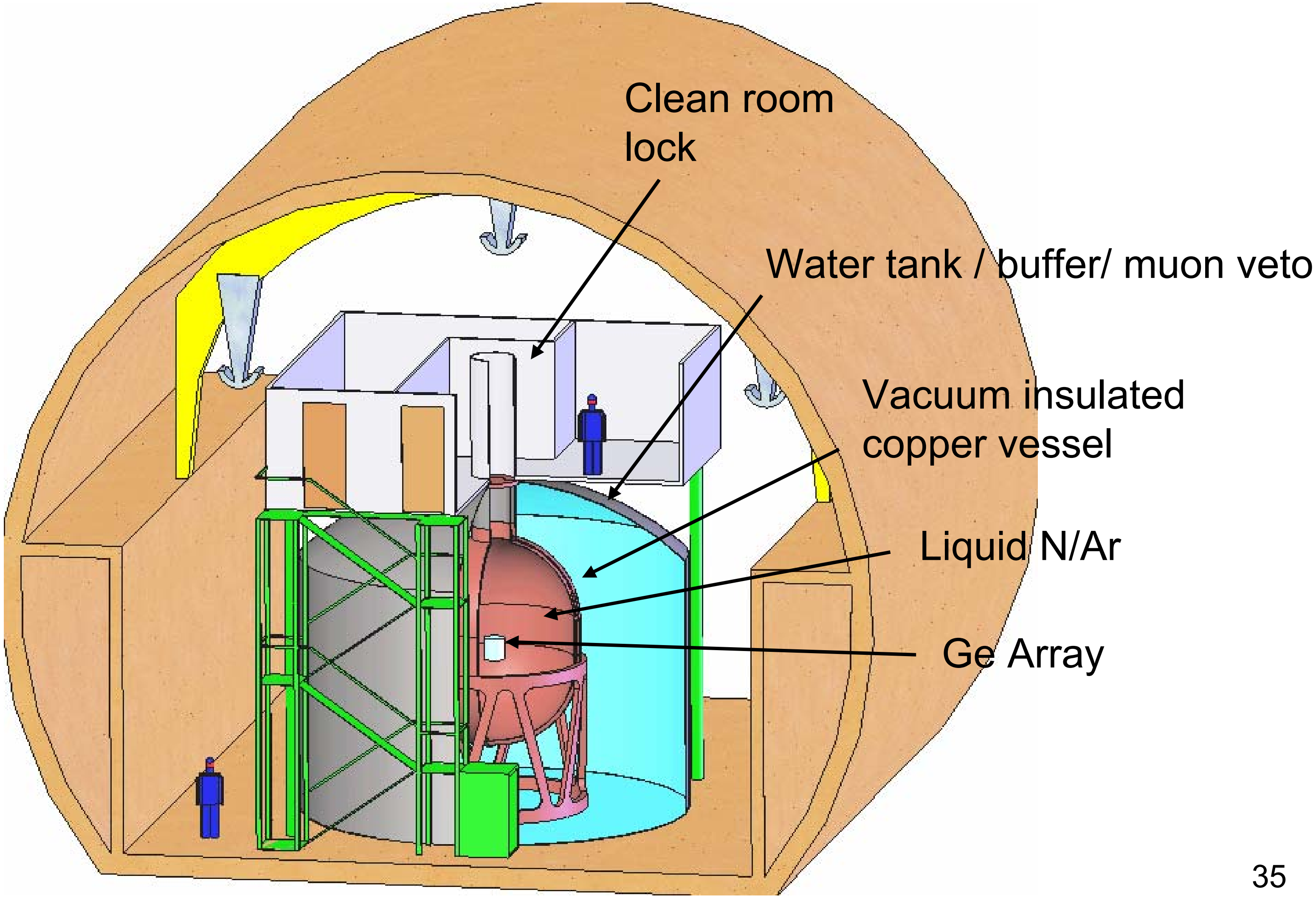
- HP Ge-diodes (86%^{76}Ge): **point-like** energy deposition at $Q_{\beta\beta}$ = 2039 keV

- Operation of bare Ge diodes in **high-purity LN_2 or LAr shield** (Heusser, Ann, Rev. Nucl. Part. Sci. 45 (1995) 543); proposals based on this idea: GENIUS (H.V. Klapdor-Kleingrothaus et. al., hep-ph/9910205 (1999)); GEM (Y.G. Zdesenko et al., J. Phys. G27 (2001))

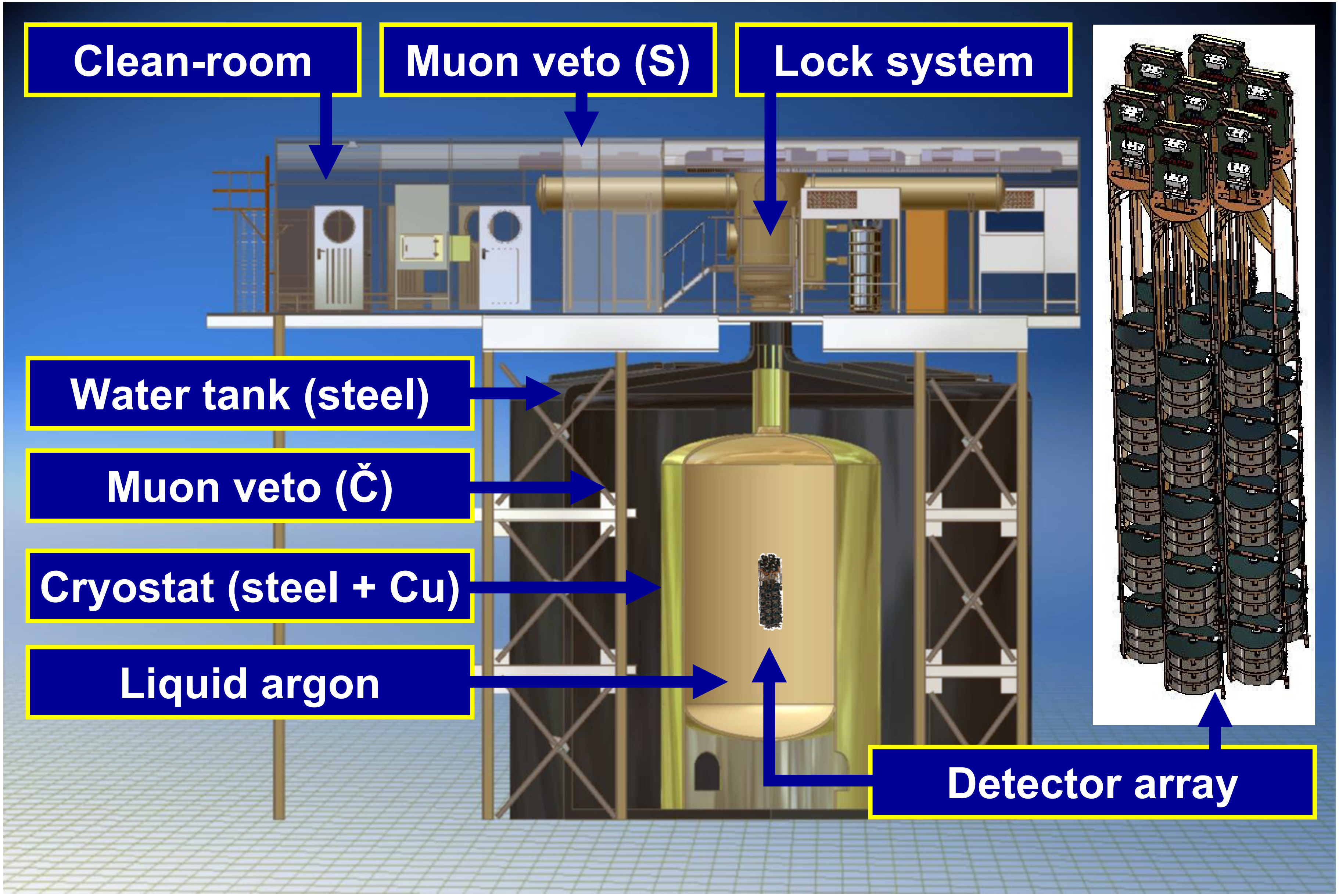
- **Baseline: LN_2;** possible **upgrade LAr:** ρ=1.4 g/cm^3, active anti-coincidence with scintillation light from LAr

Phase I	15 kg of ^{76}Ge (HM and IGEX diodes)
Phase II	35 kg (if funded)
Phase III	~ 500 kg

GERDA: Baseline design



GERDA: Technical realization



Clean-room

Muon veto (S)

Lock system

Water tank (steel)

Muon veto (Č)

Cryostat (steel + Cu)

Liquid argon

Detector array

Physics reach

Phase I:

18 kg germanium

20 kg·y exposure

10^{-2} counts/(kg·keV·y)

Phase II:

35 kg germanium

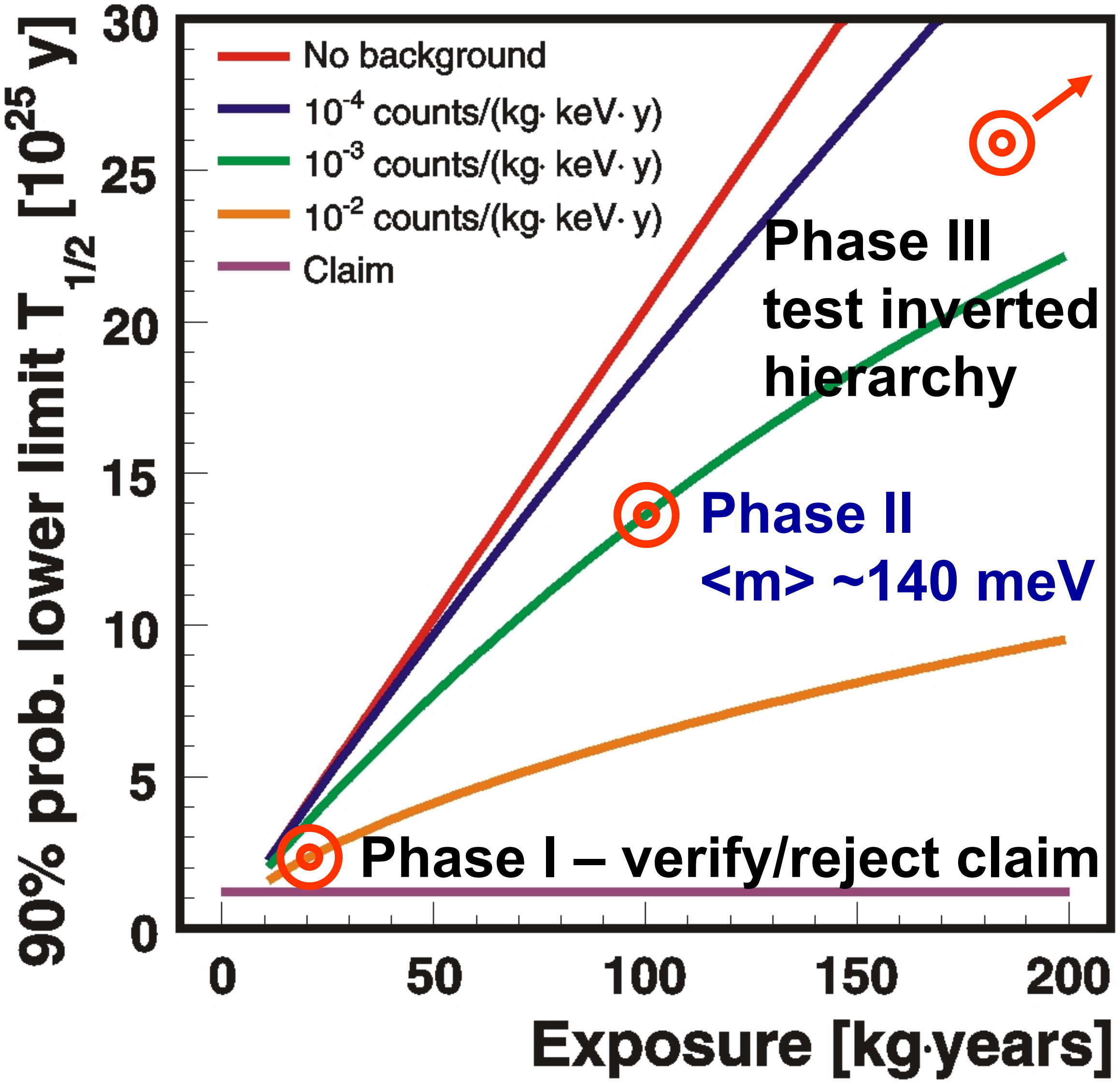
100 kg·y exposure

10^{-3} counts/(kg·keV·y)

Phase III:

1000 kg germanium

$\lesssim 10^{-4}$ counts/(kg·keV·y)



Phase III test inverted hierarchy

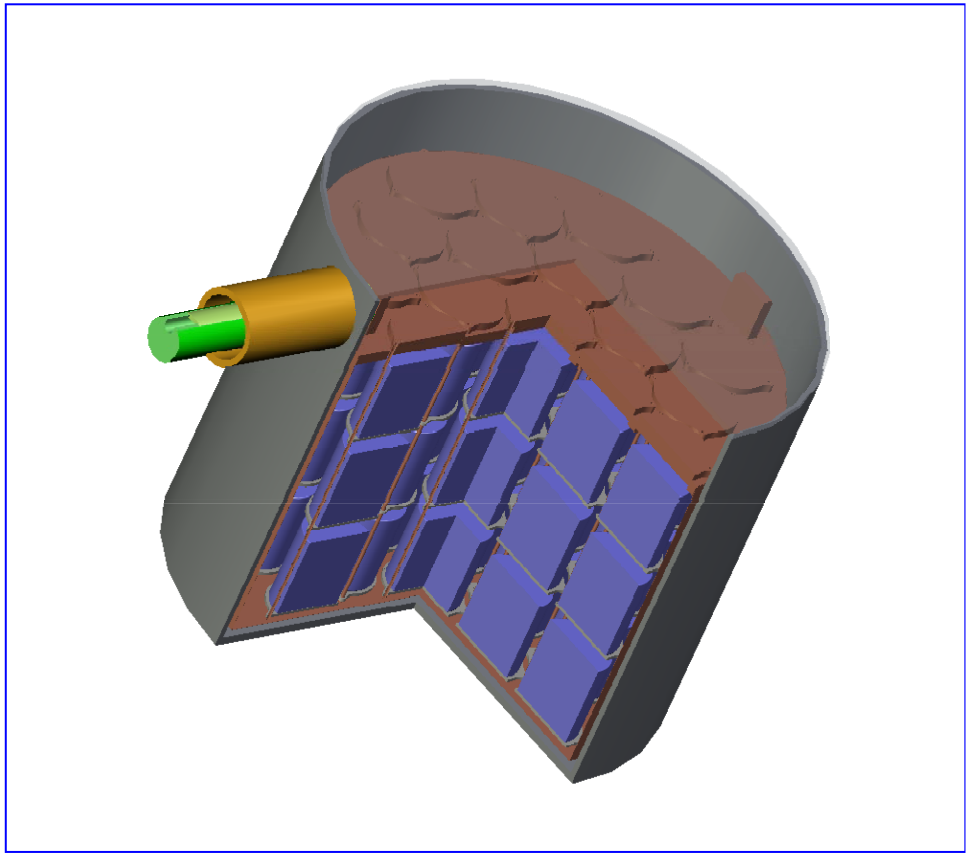
Phase II <m> ~140 meV

Phase I – verify/reject claim

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

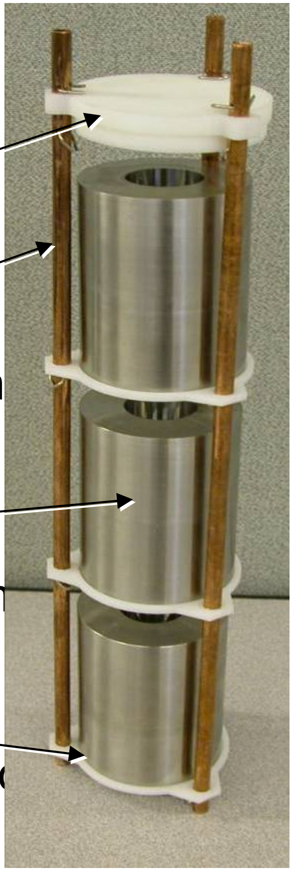
The Majorana ^{76}Ge $0\nu\beta\beta$-Decay Experiment

- Based on Ge crystals
  - 180 kg 86% ^{76}Ge
  - Enriched via centrifugation
- Modules with 57 crystals each
  - Three modules for **180 kg**
  - Eight modules for **500 kg!**
- Maximal use of copper electroformed underground
- Background rejection methods
  - Granularity
  - Pulse Shape Discrimination
  - Single Site Time Correlation
  - Detector Segmentation
- Underground Lab
  - 6000 mwe
  - Class 1000



Conceptual Design of 57 Crystal Module

- Conventional vacuum cryostat made with electroformed Cu
- Three-crystal tower is a module within a module
- Allows simplified detector installation & maintenance
- Low mass of Cu and other structural materials per kg Ge



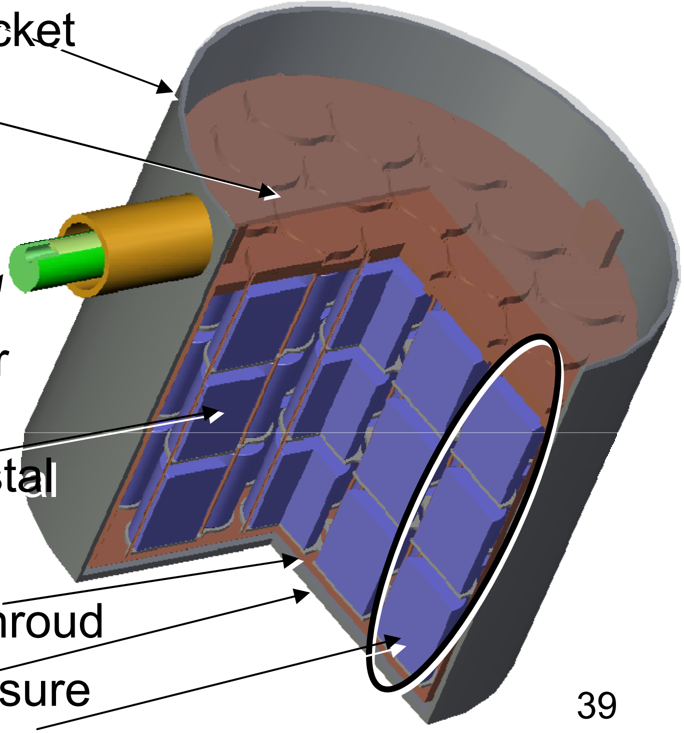
Cap

Tube
(0.007” wall th

Ge
(62mm x 70 m

Tray
(Plastic, Si, et

40 cm x 40 cm Cryostat



Vacuum jacket

Cold Plate

Cold Finger

1.1 kg Crystal

Thermal Shroud

Bottom Closure

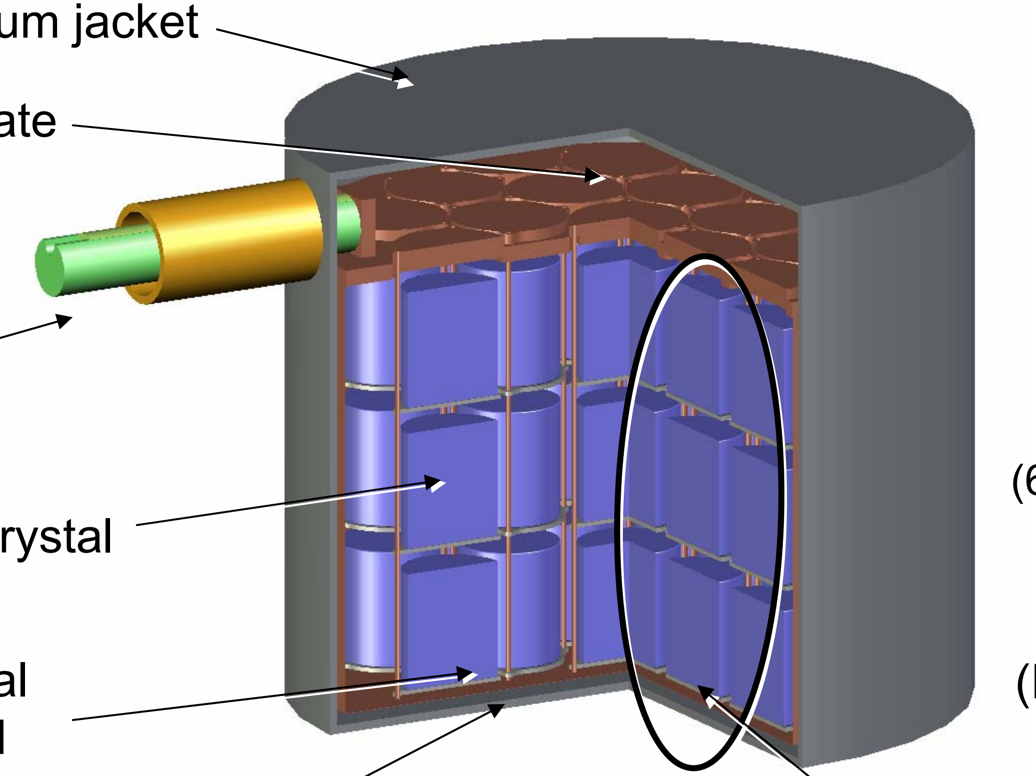
1 of 19 Towers

The Majorana Modular Approach

One concept: 57 crystal modules

Conventional vacuum cryostat made with electroformed Cu.

Three-crystal stack are individually removable.



Vacuum jacket

Cold Plate

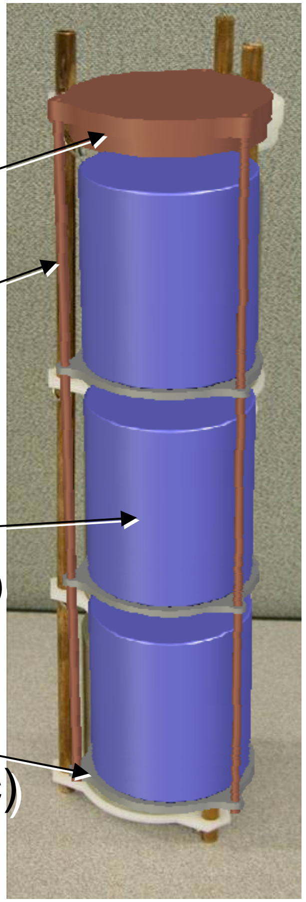
Cold Finger

1.1 kg Crystal

Thermal Shroud

Bottom Closure

1 of 19 crystal stacks



Cap

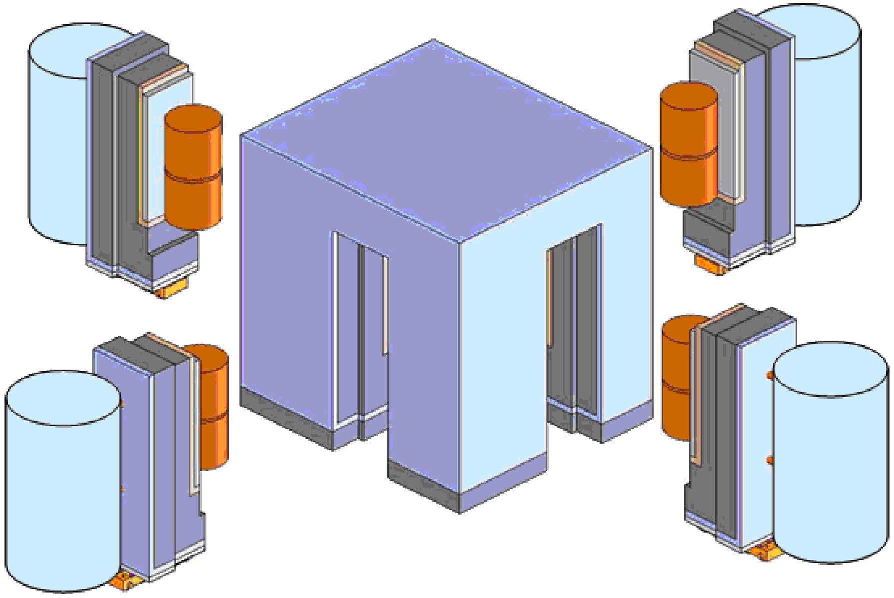
Tube (0.007” wall)

Ge (62mm x 70 mm)

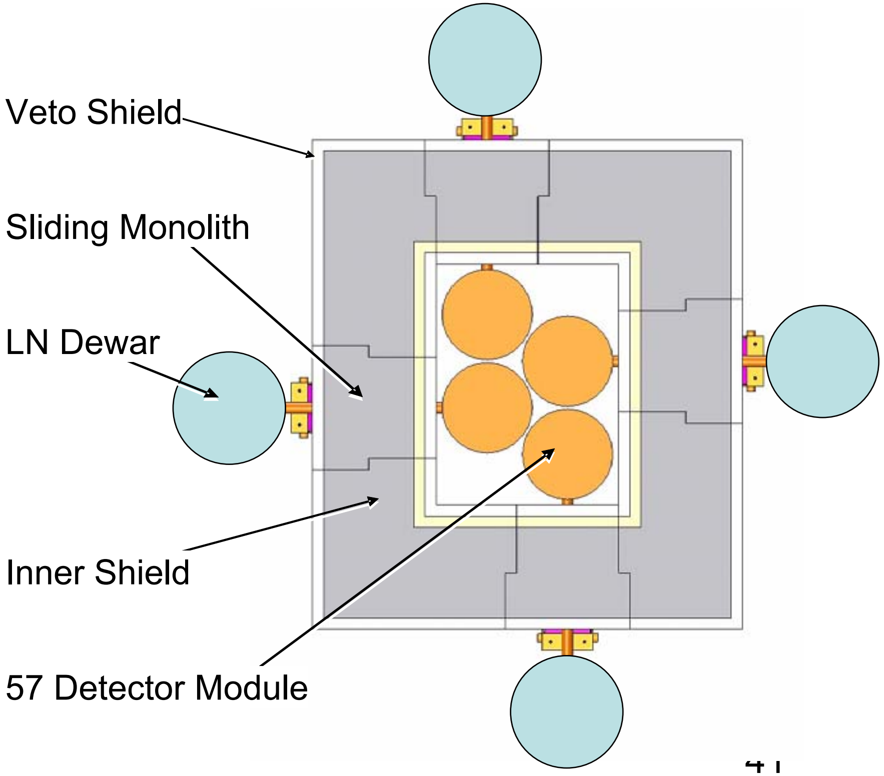
Tray (Plastic, Si, etc)

The Majorana Shield - Conceptual Design

- Deep underground: >5000’
- Allows modular deployment, early operation
- Contains up to eight 57-crystal modules
- 40 cm bulk Pb, 10 cm ultra-low background shield
- Active 4π veto detector



Top view



Veto Shield

Sliding Monolith

LN Dewar

Inner Shield

57 Detector Module

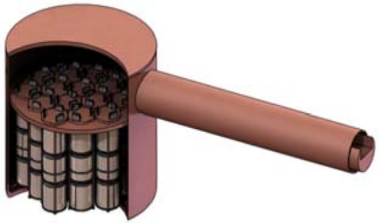
Majorana Collaboration Current Status

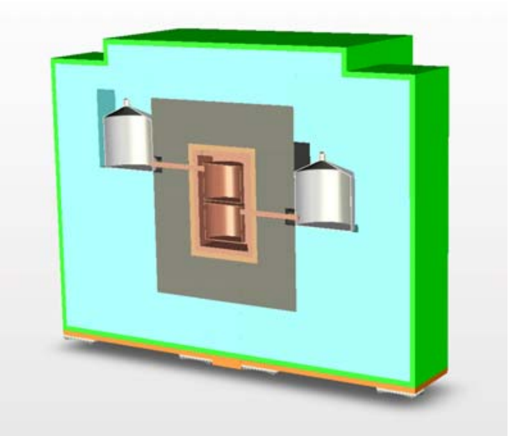
Actively pursuing the development of R&D aimed at a ~1 ton scale ^{76}Ge neutrinoless ββ-decay experiment.

- Immediate thrust is to build a 60 kg prototype module to demonstrate backgrounds needed in a future experiment capable of reaching a sensitivity to the “inverted hierarchy” neutrino mass scale (30-40 meV).
- Using this prototype, expect to make a down-select between Majorana and GERDA technologies, picking the best method.
- Also exploring longer term R&D to minimize costs and optimize the schedule for a 1 ton experiment.

Our plan has been guided by advice from NuSAG, an independent external panel review (March 06), and a DOE ββ-decay Pre-conceptual design review panel (Nov. 06)

The Majorana Prototype Module (WIP)





- 60 kg module, ~60-100 crystals.
- Different designs and levels of enrichment
- $\geq$ 4500 mwe
- Background Specification Goal in the $0\nu\beta\beta$ pea
  region of interest (4 keV at 2039 keV)

  ~ $\leq$**1 count/ROI/t-y** (after analysis cuts)
- Expected Sensitivity to $0\nu\beta\beta$
  (for 60 kg enriched material, running 2 years, or 0.12 t-y of ^{76}Ge exposure)

  $T_{1/2} \geq 1.6 \times 10^{26}$ y (90% CL)

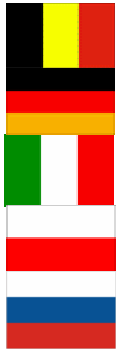
  Sensitivity to $\langle m_\nu \rangle$ < 190 meV (90% CL) ([Rod06] RQRPA NME)

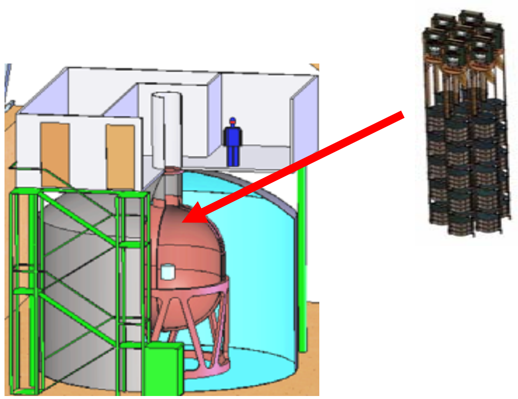
  Able to confirm/refute KKDC 400 meV value (20% measurement).

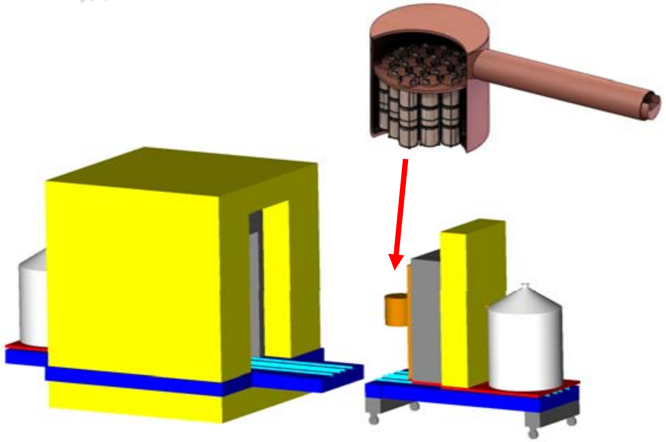
GERDA - Majorana

GERDA

Majorana







- ‘Bare’ ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- Phase I (mid 2008): ~18 kg (HdM/IGEX diodes)
- Phase II (mid 2009): add ~20 kg new detectors

Total ~40 kg

- Modules of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Initial phase: R&D prototype module

Total 60 kg

Joint Cooperative Agreement:

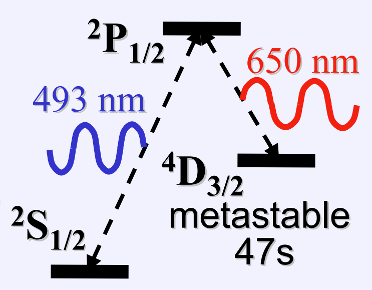
- Open exchange of knowledge & technologies (e.g. MaGe, R&D)
- Intention to merge for 1 ton exp. Select best techniques developed and tested in GERDA and Majorana

EXO (Enriched Xenon Observatory) USA-RUSSIA-CANADA

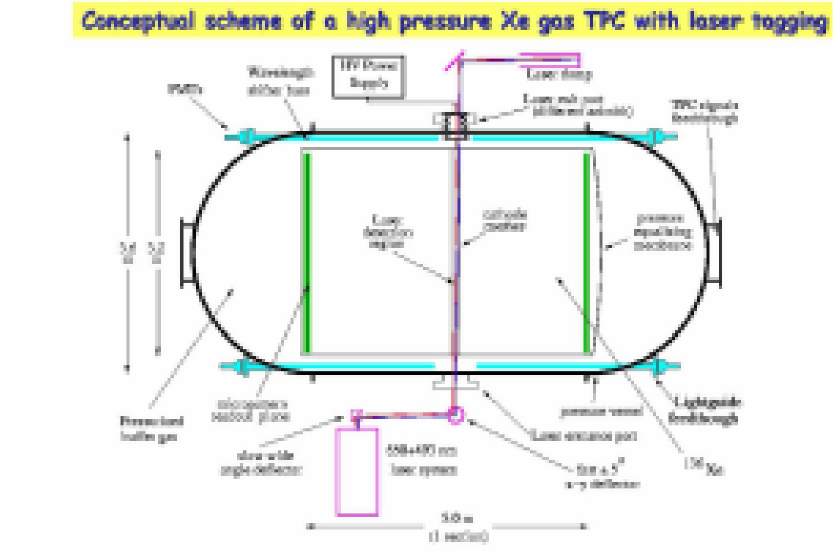
- $^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}$ ($E_{2\beta} = 2.47$ MeV)
- **Main idea is**: to detect all products of the reaction with good enough energy and space resolution (M.Moe PRC 44(1991)931)

Tracking EXO

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



LXe TPC


Conceptual scheme of a high pressure Xe gas TPC with laser tagging

Present R&D

- Ba$^+$ spectroscopy in HP Xe / Ba$^+$ ex
- energy resolution in LXe (ion.+scint.
- Prototype scale:
  - ► 200 kg enriched L^{136}Xe without tag
  - ► all EXO functionality except Ba id
  - ► operate in WIPP for ~two years
- Protorype goals:
  - ►Test all technical aspects of EXO (except Ba id)
  - ►Measure 2ν mode
  - ►Set decent limit for 0ν mode (probe Heidelberg- Moscow)

Full scale experiment at WIPP or SNOLAB

- **10 t** (for LXe □ 3 m^3)
  - □b = 4×10^{-3} c/keV/ton/y
  - □□$_{1/2}$ □ **1.3×10^{28} y** in 5 years
  - □⟨m ⟩□ **0.013 ÷ 0.037 eV**

1 ton EXO

- Liquid (gas) Xe TPC + Ba^+ tagging
- 1 ton of **^{136}Xe** (**80%** enrichment)
- $\Delta E/E$(FWHM) = **3.8%** at 2.5 MeV (ionization and scintillation readout)
- Background (5 y) = **1** event
- Sensitivity (5 y): **$2 \cdot 10^{27}$ y** (**$<m_\nu> \sim$ 0.02-0.45 eV**)

EXO-200 (without Ba^+ tagging)

- **200 kg** of ^{136}Xe (80% enrichment) – **exist!**
- Location: WIPP (USA)
- $\Delta E/E$(FWHM) = **3.8%** at 2.5 MeV (ionization and scintillation readout)
- Background (5 y) = **40** events
- Sensitivity (5 y): **$6.4 \cdot 10^{25}$ y** (**$\langle m_\nu \rangle \sim 0.12$-0.25 eV**)
- Is under construction now (at Stanford)
- Start of measurements: in **~ 2007-2008**

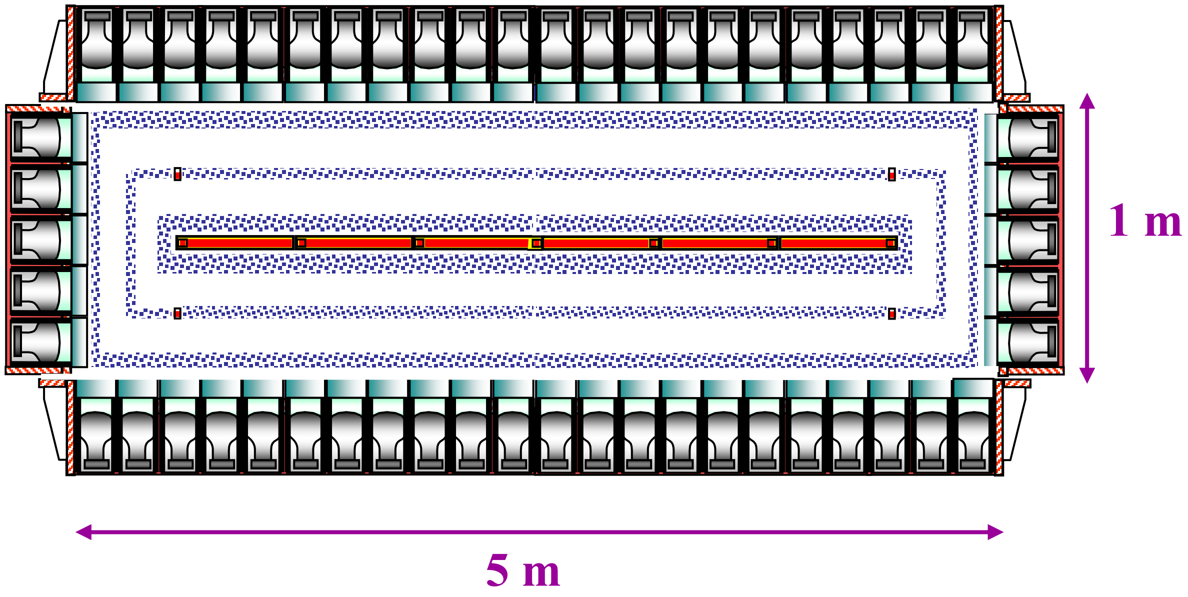
SuperNEMO preliminary design

Plane geometry

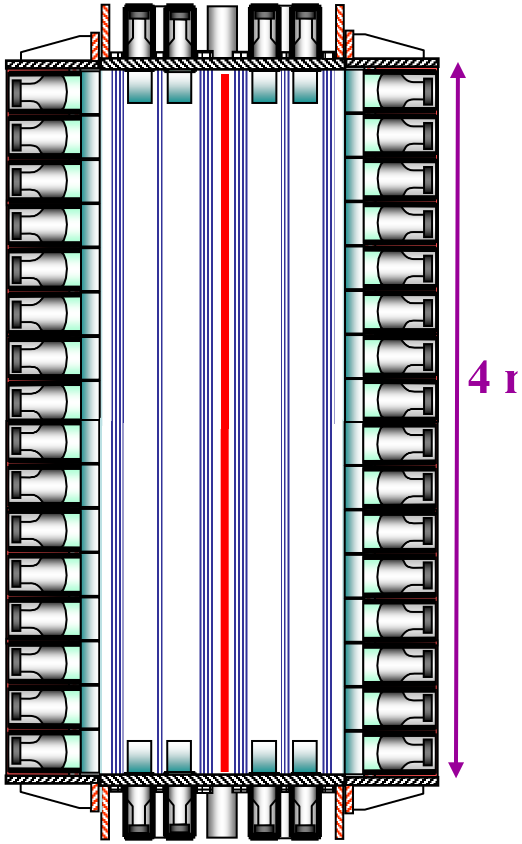
Source (40 mg/cm^2) 12m^2, tracking volume (~3000 channels) and calorimeter (~1000 PM

Modular (~5 kg of enriched isotope/module)

100 kg: 20 modules
~ 60 000 channels for drift chamber
~ 20 000 PMT

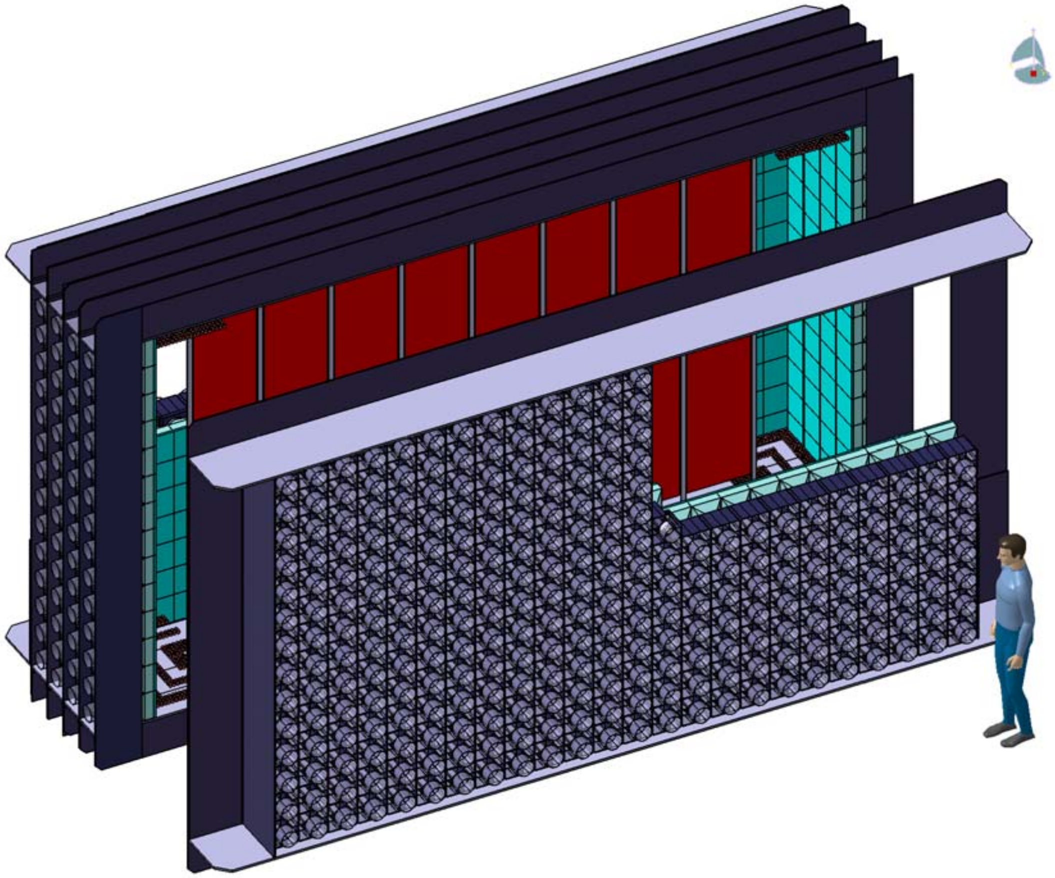


Top view

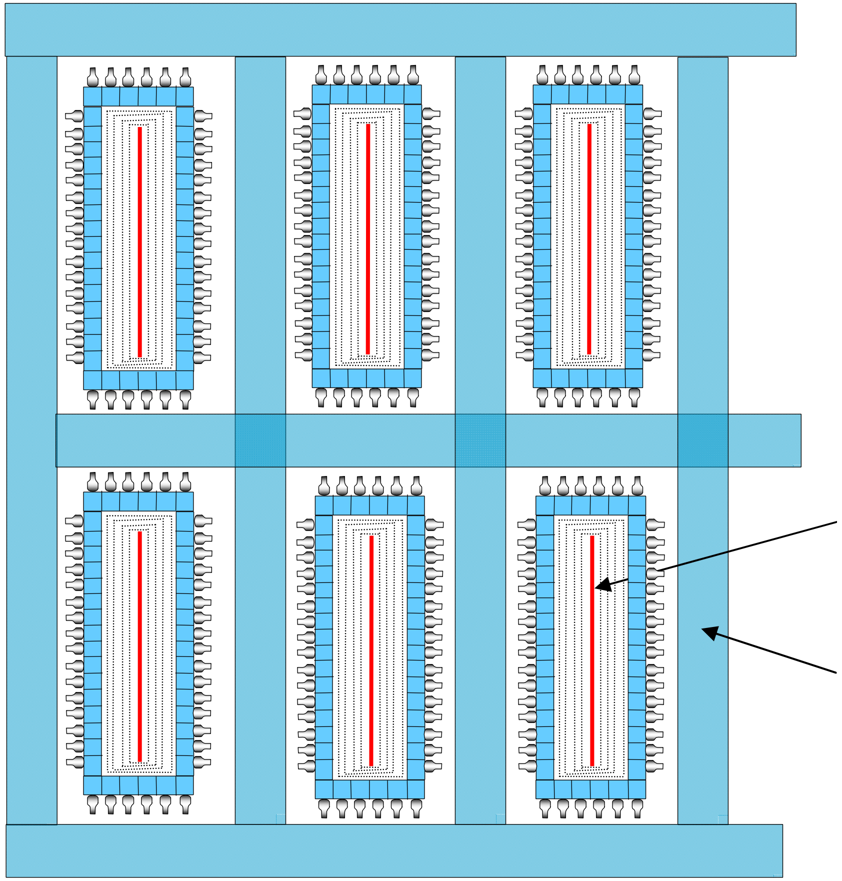


Side view

Very preliminary design



Single sub-module with ~7 kg of isotope



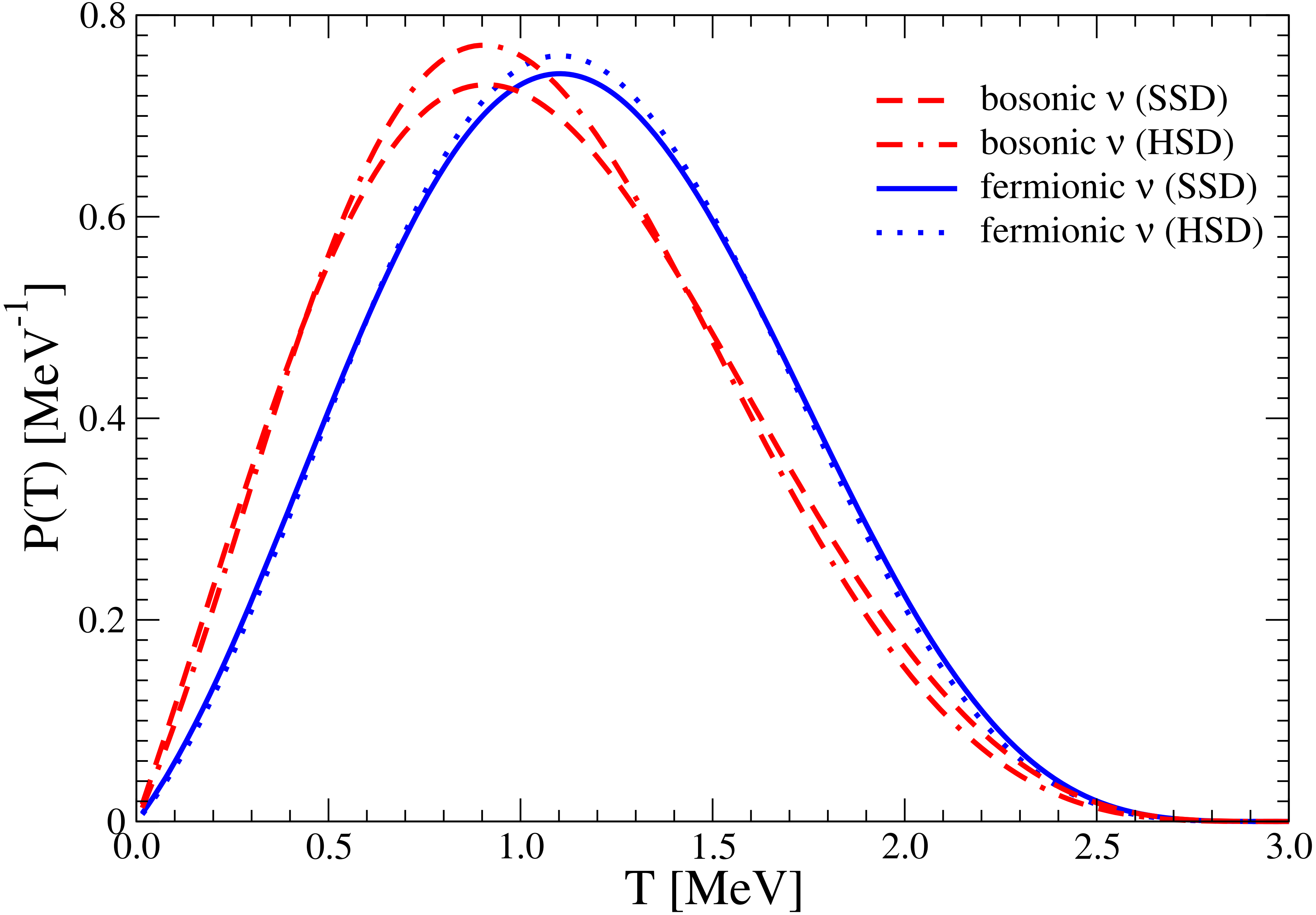
~20 sub-modules for 100+ kg of isotope surrounded by shielding

From NEMO-3 to SuperNEMO

NEMO-3		SuperNEMO
7 kg ^{100}Mo $T_{1/2}(\beta\beta2\nu) = 7.\ 10^{18}$ y	**Mass of isotope**	100 kg ^{82}Se $T_{1/2}(\beta\beta2\nu) = 10^{20}$ y
$T_{1/2}(\beta\beta0\nu) > 2.\ 10^{24}$ y $<m_\nu> < 0.3 – 1.3$ eV	**Sensitivity**	$T_{1/2}(\beta\beta0\nu) > 2.\ 10^{26}$ y $<m_\nu> < 40 – 110$ meV
FWHM ~ 12% at 3 MeV (dominated by calorimeter ~ 8%)	**Energy resolution (FWHM of the ββ0ν ray)**	FWHM ~ 6% at 3 MeV (dominated by source foil)
$\varepsilon(\beta\beta0\nu) = 8$ % { poor energy resolution e⁻ backscattering on scintillator	**Efficiency**	$\varepsilon(\beta\beta0\nu) \sim 40$ %
^{214}Bi < 300 µBq/kg ^{208}Tl < 20 µBq/kg	**Internal contaminations in the source foils in ^{208}Tl and ^{214}Bi**	^{214}Bi < 10 µBq/kg ^{208}Tl < 2 µBq/kg
ββ2ν ~ 2 cts / 7 kg / y (^{208}Tl, ^{214}Bi) ~ 0.5 cts/ 7 kg /y	**Background**	ββ2ν + (^{208}Tl,^{214}Bi) ≤ 1 cts/ 100 kg /y

Planning

- ✓ 2005 – 2007 : R&D program
- ✓ 2008: construction of the first SuperNEMO module with 5 kg ^{82}Se
- ✓ 2009-2011: construction and installation of the 20 modules ⇒ 100 kg of ^{82}Se
  start tacking data with delivered modules
- ✓ 2012: full SuperNEMO running with 100 kg of ^{82}Se


0.8
0.6
0.4
0.2
0
P(T) [MeV^{-1}]
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0.5
1.0
1.5
2.0
2.5
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T [MeV]
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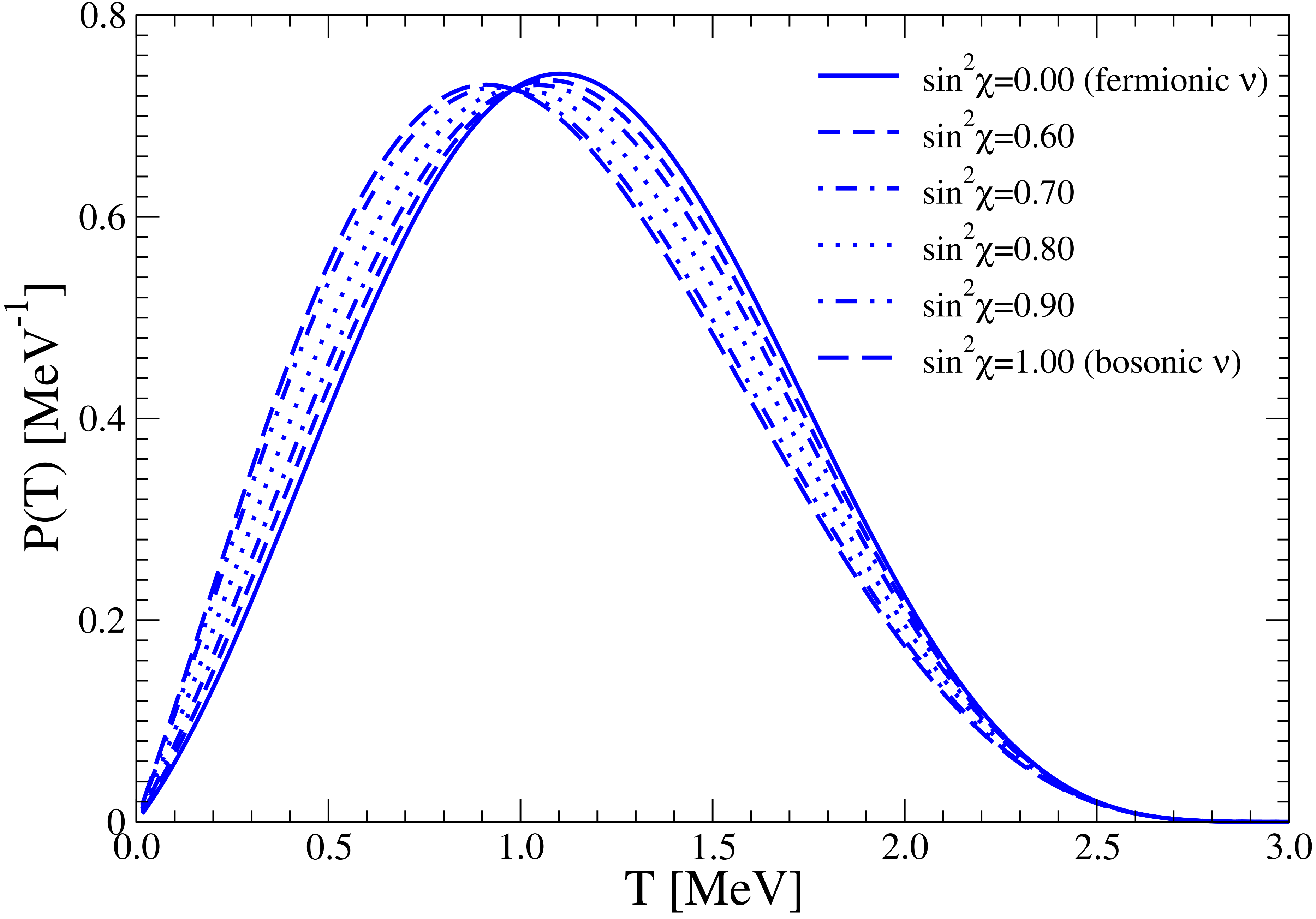
bosonic ν (HSD)
fermionic ν (SSD)
fermionic ν (HSD)


P(T) [MeV^{-1}]
T [MeV]
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2.0
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3.0
sin^{2}χ=0.00 (fermionic ν)
sin^{2}χ=0.60
sin^{2}χ=0.70
sin^{2}χ=0.80
sin^{2}χ=0.90
sin^{2}χ=1.00 (bosonic ν)