Crystal Based Double Beta Decay Experiments

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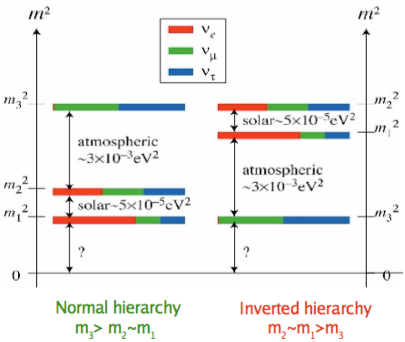
Neutrinos

What we know

1. Masses:
   - Δm^2_{12} and $|\Delta^2_{13}|$ are known;
2. Mixing matrix: U_{ij} characterized by
   - three mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$
   - one Dirac CP phase: δ
   - two Majorana phases: Φ_2, Φ_3

θ_{12}, θ_{23} measured, new results on θ_{13}



What we do NOT know (yet)

1. Absolute Mass Scale (offset);
2. Mass Hierarchy ($1 \Rightarrow 2 \Rightarrow 3$ or $3 \Rightarrow 1 \Rightarrow 2$)
3. Neutrino Nature (Majorana or Dirac particle);
4. phases (δ, Φ_2, Φ_3).

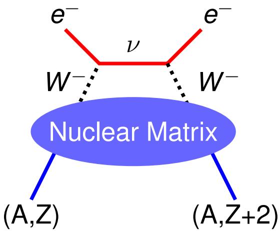
Double Beta Decay experiments can address (3)
If ν is Majorana's $\rightarrow$ shed light on a combination of (1),(2), (4).

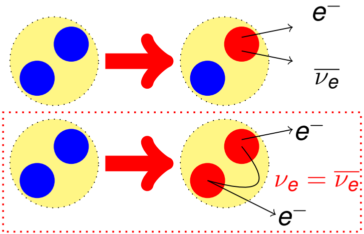
Neutrinos: Majorana versus Dirac particles

- How to test the neutrino mass nature ?
- Experimental problem:

$$P(\nu_L \to \nu_R) \sim \left(\frac{m_\nu}{E_\nu}\right)^2$$

- is vanishing small, $m_\nu \sim O(\text{eV})$ or smaller ... $E_\nu \sim O(\text{MeV})$ or bigger.





The only know technique is neutrinoless double beta decay.

Double Beta Decays (2ν and 0ν)

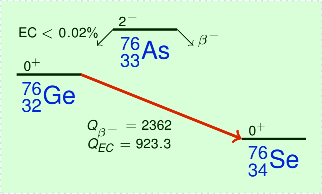
$2\nu\beta\beta : (A, Z) \rightarrow (A, Z+2) + 2e^- + 2\overline{\nu_e}$

- 2^{nd} order process, observed in many isotopes
- $T_{1/2} \sim 10^{19} - 10^{21} y$
- $\Delta L = 0$

  for ^{76}Ge : $T_{1/2} \sim 1.5 \pm 0.1 \cdot 10^{21} y$

$0\nu\beta\beta : (A, Z) \rightarrow (A, Z+2) + 2e^-$

- new physics
- $T_{1/2} > 10^{25} y$
- $\Delta L = 2$

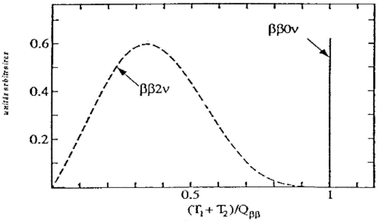


Experimental signature

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

$$\frac{1}{\tau} = F(Q_{\beta\beta}, Z)\,|M_{nucl}|^2 < m_{ee} >^2$$

phase space $\propto Q^5_{\beta\beta}$ — nuclear matrix element — effective Majorana Mass



Effective Neutrino Mass

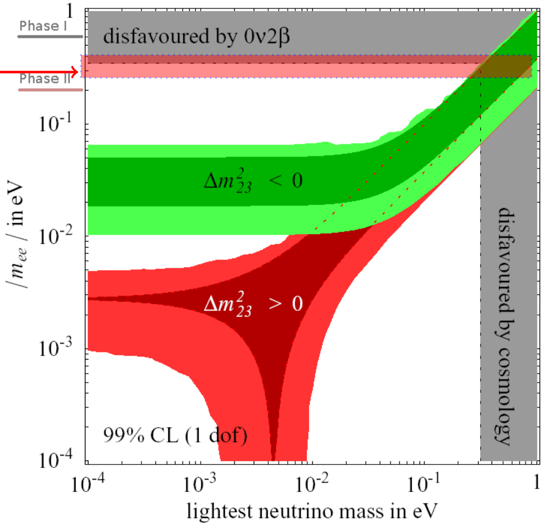
KDKC Claim: [0.17-0.45] eV (PRD79)

F. Feruglio
A. Strumia
F. Vissani
Nucl. Phys. B 659

$< m_{ee} >= |\sum_i U_{ei}^2 m_i|$

U_{ei} : neutrino mixing matrix (complex)

Negligible errors from oscillations; width of the curves due to CP phases.



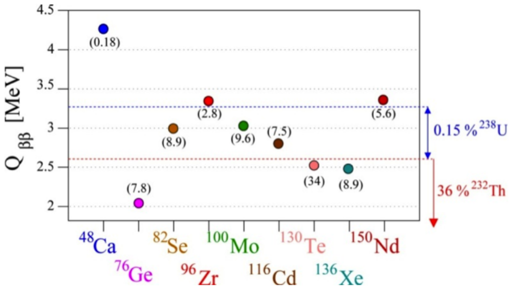
Best limits on 0ν DBD

Experiment	Nucleus	Detector	Exposure (kg · y)	Technique	$\tau_{1/2}$ (y) - (90% C.L.)	Ref
H&M	^{76}Ge	Ge	47.7	Ge diode	$> 1.9 \cdot 10^{25}$	1
					$2.23^{+0.44}_{-0.31} \cdot 10^{25}$	2
IGEX	^{76}Ge	Ge	117 mol · y	Ge diode	$> 1.6 \cdot 10^{25}$	3
NEMO 3	^{82}Se	Se	3.6	tracking	$> 3.6 \cdot 10^{23}$	4
NEMO 3	^{100}Mo	Mo	26.7	tracking	$> 1.1 \cdot 10^{24}$	4
CUORICINO	^{130}Te	TeO_2	20	bolometric	$> 2.8 \cdot 10^{24}$	5
DAMA	^{136}Xe	L Xe	4.5	Xe scint	$> 1.2 \cdot 10^{24}$	6
Solotvina	^{116}Cd	$CdWO_4$		Scintillator	$> 1.7 \cdot 10^{23}$	7

1. H. V Klapdor-Kleingrothaus et al., Phys Lett A 16, 2409 (2001)
2. H. V Klapdor-Kleingrothaus et al., Phys Lett A 21, 1547 (2006)
3. C. E. Aalseth, Phys. Rev. C 65, 092007 (2002)
4. A. S. Barabash, nucl-ex/1002.2862
5. E. Andreotti er al, Astr. Phys. 34 (2011) 822
6. R. Bernabei et al., Phys. Lett. B 546, (2002) 23
7. F. A. Danevich et al., Phys. Rev. C 67, 035501 (2003).

New and future experiments with crystals

Experiment	Nucleus	Mass	Technology	Location	Time line
CUORE 0 CUORE	^{130}Te	10 kg 200 kg	$^{130}TeO_2$ bolometric	LNGS	end 2011 2014
GERDA I GERDA II	^{76}Ge	18 kg 35 kg	HPGe	LNGS	2011 - end 2012
Majorana	^{76}Ge	20 kg 40 kg	HPGe	SUSL	2012 2014
COBRA	^{116}Cd, ^{130}Te		CdZnTe	LNGS	

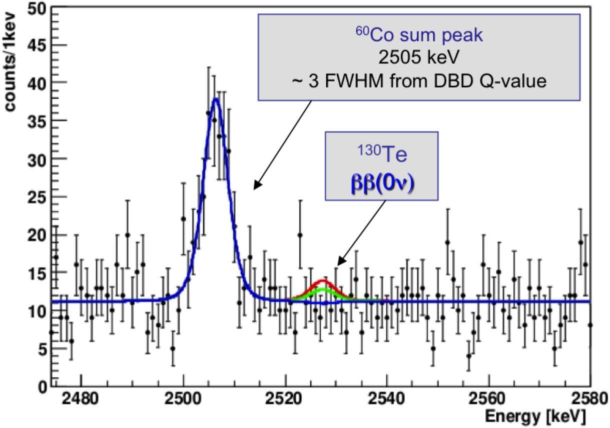


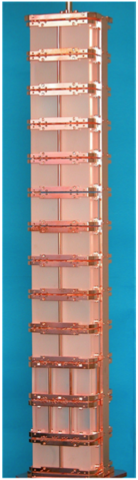
Other experimental R & D efforts that cannot be discussed in details:

- Lucifer: phonons and scintillations
- AMoRe: scintillations and semiconductor detectors

CUORICINO

- total exposure: 19.75 kg · y
- average energy resolution at $Q_{\beta\beta}$: $\sigma_E = 7.5$ keV
- background index: $b = 0.169 \pm 0.006$ cts / (keV · kg · y)

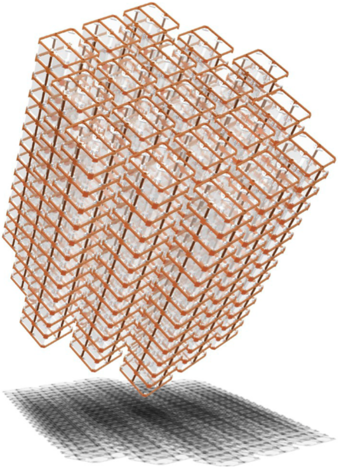




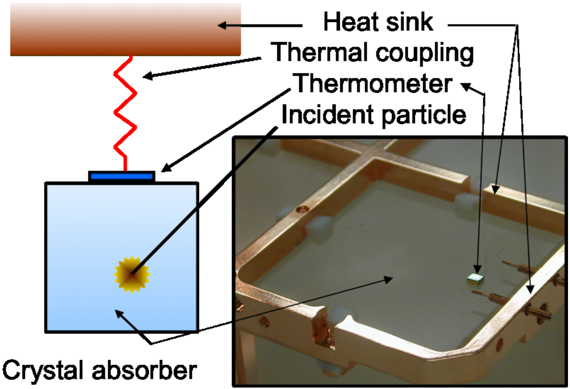
- $t_{1/2} > 2.8 \cdot 10^{24}$ y $\rightarrow m_e e < 0.3 - 0.7$ eV   Barea, Iachello PRC 79 (2009) 044301

The CUORE experiment

- 20 times more massive than CUORICINO
- heavily shielded
- high detection efficiency, 87% (source = detector)
- excellent energy resolution: 5 keV ROI
- high granularity bolometric detector:
- background suppression through anti-coincidence:
  - neutron background suppressed by $\sim$ 30;
  - μ background suppressed by $\sim$ 20 (Atstr. Part. Phys 33 (2010 169)
  - crystal surface background suppressed by $\sim$ 4



Bolometers techniques



Concept:

- $\Delta T = E/C$ (C = thermal capacity);
- low C and low T ($T \ll 1$ K)
- dielectrics, superconductors

The ultimate limit to E resolution is the statistical fluctuation of internal energy U: $<\Delta U^2>= k_B T^2 C$

Thermal Detector Properties:

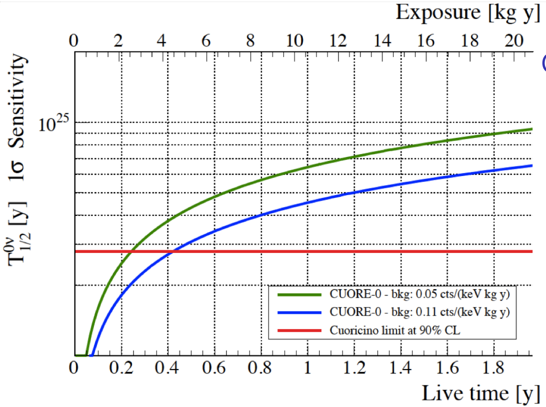
- good energy resolution
- wide choice of absorber materials
- true calorimeters
- slow $\tau = C/G \sim 1 - 10^3$ ms

CUORE status and plans

The operation of the first CUORE tower is a general test for

- all assembly procedures;
- background reduction facilities and collaboration skills (shifts, management)

and it's a 0ν DBD experiment itself!



CUORE 0 plans

- all components at LNGS
- refurbishment of the old CUORICINO facility and cryogenics almost complete
- the CUORE-0 tower will be assembled end of August and inserted into the cryostat
- pre-operation/commissioning : 3-4 months
- data taking start at end of 2011

The GERDA experiment

▲ 3800 m w.e. rock above ▲

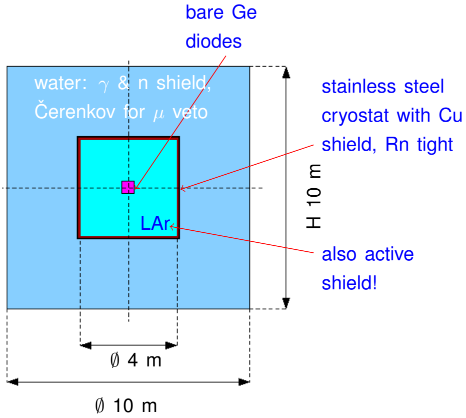
- designed for external γ, n, μ background $\sim$ 0.001 cts/(keV·kg·y);
- water vessel : $\emptyset = 10$ m;
- LAr cryostat : $\emptyset = 4.2$ m;
- 64 m^3 of LAr;
- 580 m^3 of water;
- up to five Ge diodes arranged in strings, 16 strings in total;

Water:

- moderator for neutrons;
- Čerenkov medium for μ veto;
- cheaper, safer and more effective than LN2 (LAr).

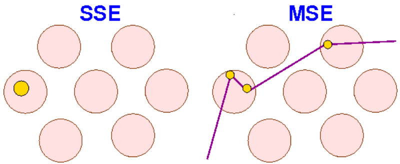
Background reduction in GERDA

- External bck: γ (Th, U), n, μ
- Shielding is possible



- Intrinsic bck:
  - cosmogenic ^{60}Co (5.3 y), ^{68}Ge (270 d),
  - radioactive surface contamination
- Discriminate Single & MultiSite Events:

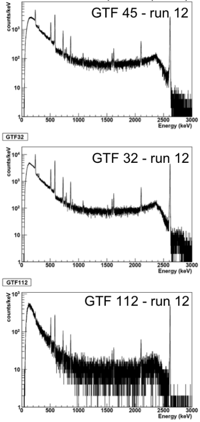
SSE : $\beta\beta$, DEP;
MSE : Compton



- anti-coincidence of detectors
- pulse shape analysis (PSA)

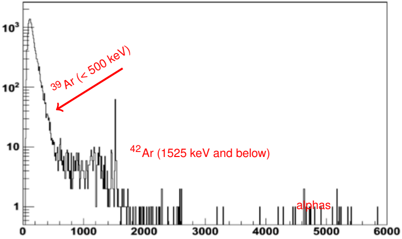
GERDA commissioning phase

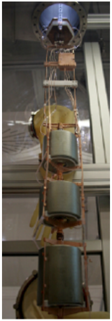
Calibration spectra (^{228}Th):



- a string with three ^{nat}Ge detectors has been operated in GERDA (June 2010 - May 2011)

- AIM: study of background conditions;
- Resolution: 3.6 keV at 2.6 MeV (^{228}Th)





But:

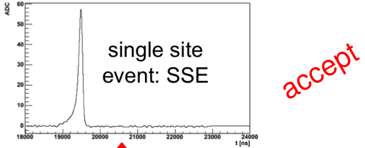
- high ^{42}Ar concentration in LAr (4× higher than expected)
- measured bck level at ROI: 0.06 counts/(keV · kg · y)
  no PSA applied.

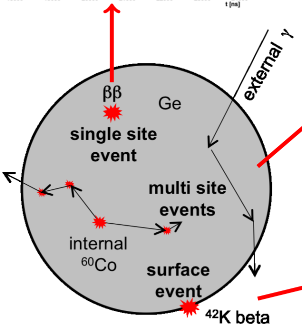
New string with three ^{76}Ge enriched detectors recently deployed

GERDA Phase II detector R&D

- 37.5 kg of ^{enr}Ge (86% ^{76}Ge) have been procured and are stored underground;
- new Broad Energy Germanium (BEGe) detectors will be used.

$\beta\beta$ decay : β range in Ge $\sim$ few mm

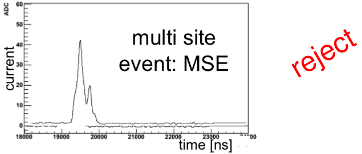




Backgrounds:

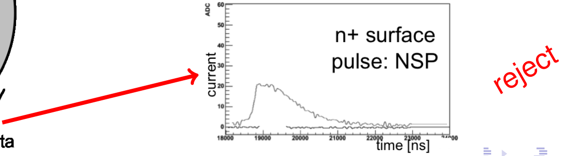
- ^{228}Th and ^{226}Ra from nearby materials
- ^{60}Co and ^{68}Ge produced by cosmic-rays

$\rightarrow$ γ-ray emitters: range in Ge $\sim$ few cm



- ^{42}K e$^{\pm}$, U/Th decay chains αs

$\rightarrow$ surface events: peculiar pulses



The Majorana experiment

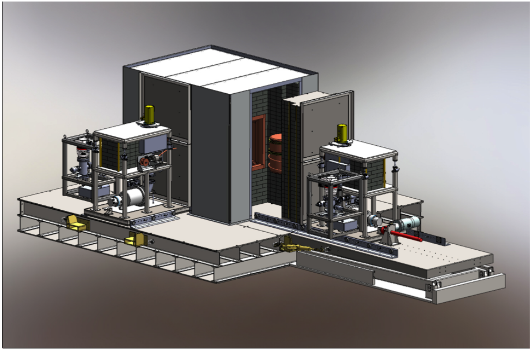
- Actively pursuing the development of R&D aimed at a 1 tonne scale ^{76}Ge $0\nu\beta\beta$-decay experiment.
- Build a prototype module (Majorana demonstrator) to
  1. demonstrate background is low enough;
  2. verify the proposed technology and scrutinize the KK claim;
- the Majorana and GERDA collaborations work in close contact with the ultimate goal to prepare for a tonne-scale experiment

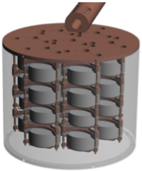
- Open exchange of knowledge and technologies (e.g. MaGe Monte Carlo)

→ select the best technologies tested in GERDA and Majorana)

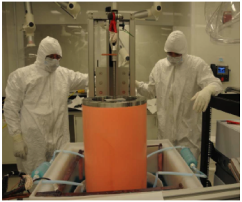
The Majorana demonstrator

- Build a small experiment with 40 kg Ge point-contact detectors (enriched in ^{76}Ge);
- located at 4850' level in the Sanford Lab (Homstake)
- operate them in low background cryostat and shielding
  1. ultra-clean, electroformed Cu
  2. naturally scalable
  3. compact low background passive Cu and Pb shield with an active muon veto.



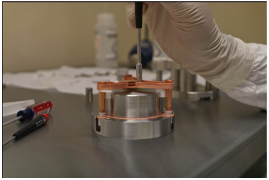


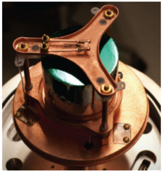
Majorana demonstrator status

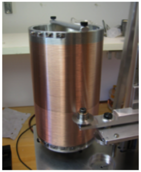


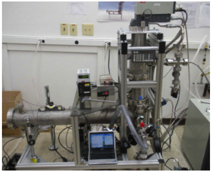
Three phases

1. prototype cryostat (3 strings, ^{nat}Ge) Fall 2012
2. cryostat 1 (3 strings ^{enr}Ge, 4 strings ^{nat}Ge) Summer 2013
3. cryostat 2 (up to 7 strings ^{enr}Ge) Summer 2014

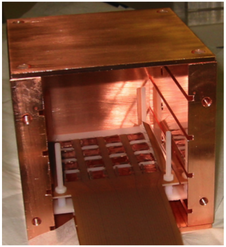


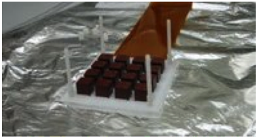




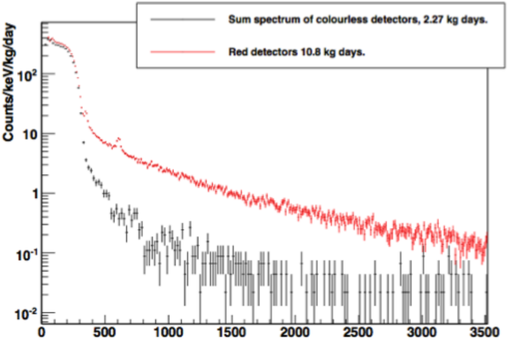


COBRA





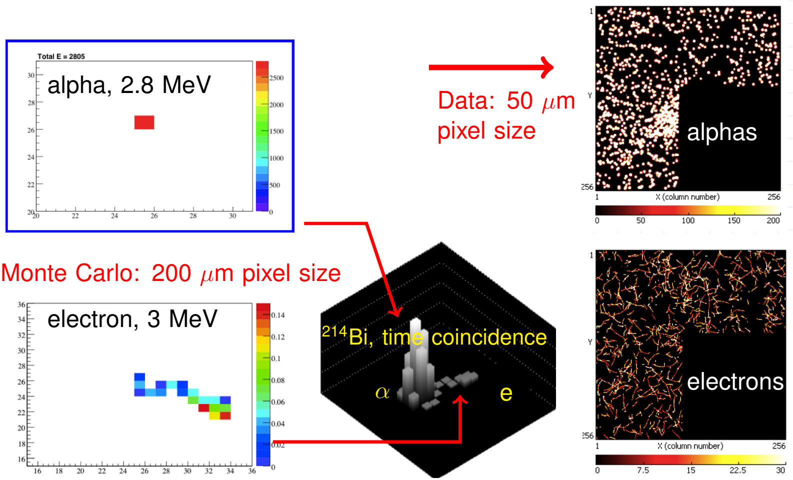
- Search for double beta decay with room temperature semiconductor detectors
- Plan to use a large amount of CdZnTe pixel diodes



Background at 2810 keV ~ 5 cts/(keV $\cdot$ kg $\cdot$ y)

COBRA

- Pixelization of the diode is a unique and important feature for particle identification: allows to reduce background



Conclusions

- Observation of $0\nu\beta\beta$ decay is the only known way to determine the neutrino nature (Dirac vs Majorana)
- One claim exists on ^{76}Ge, but independent measurement with different isotopes are needed to verify the hypothesis
- New generation experiments are starting to take data (CUORE 0, GERDA and Majorana Demonstrator). Results expected in one-two years
- A new phase is coming (CUORE, GERDA II and Majorana) in the next years (2012-2013) and will complete the current experimental program exploiting the full potentialities of present known technologies

But ...

- O(1 ton) scale experiments are required to disentangle neutrino mass hierarchies
- new promising technologies (low backgound crystals, and combined readout techniques) are being developed and will provide very important complementary measurements
- Check the MEDEX 2011 conference talks for details on the various DBD experiments and the promising R&D activities (http://medex11.utef.cvut.cz/)

Best limits / values on ^{76}Ge

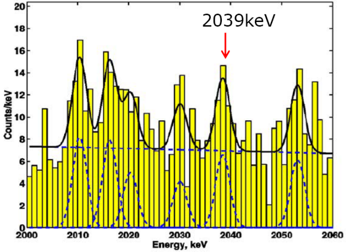
- Use Ge as source of $0\nu\beta\beta$ and detector (high signal efficiency).

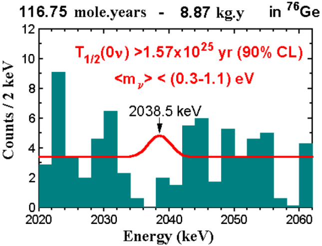
KKDC - part of HD-Moscow Collab.

- H.V. Klapdor-Kleingrothaus et al., Phys. Lett. B 586 (2004) 198.
- 5 enriched ^{76}Ge diodes (71.7 kg·y)
- bck index, $B \sim 0.11$ cts/(keV · kg · y)
- $T^{0\nu}_{1/2} = (0.69 - 4.18) \cdot 10^{25}$ y

IGEX Collab.

- D. Gonzalez et al., NPB (Proc. Suppl.) 87 (2000) 278.
- ^{76}Ge enriched diodes (8.87 kg·y)
- bck index, $B \sim 0.2$ cts/(keV · kg · y)
- $T^{0\nu}_{1/2} > 1.57 \cdot 10^{25}$ y (90% CL)

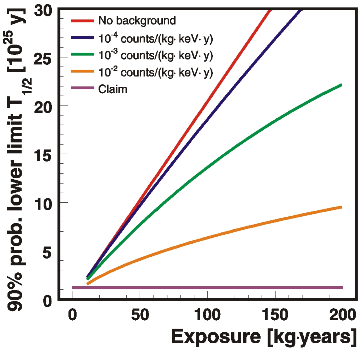




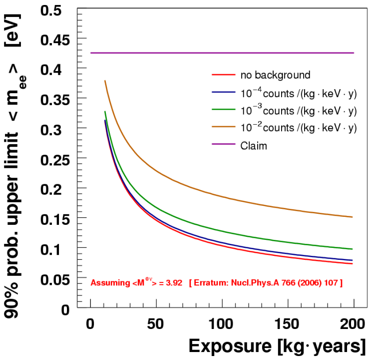
Confirmation needed with same isotope. Key: reduce background by O(100) for better sensitivity.

GERDA sensitivity

measured



deduced



$$T_{1/2} \propto \sqrt{M \cdot T/(b \cdot \Delta E)}$$

M = Detector mass, T = exposure, b = background index,
ΔE = energy resolution.