Double Beta Decay Experiments

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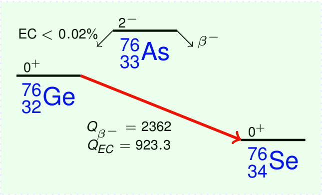
Double Beta Decay

- a 2^{nd} order process, detectable only if single beta decay (1^{st} order) is energetically forbidden, or ΔJ large

Typical example



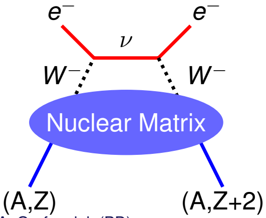
$2\nu\beta\beta$: $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\overline{\nu_e}$

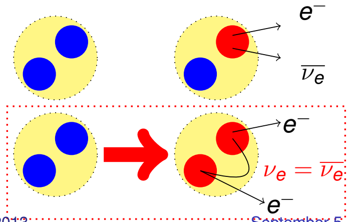
- a rare process, measured in 11 nuclei
  - $T_{1/2} \sim 10^{19} - 10^{21} y$
  - $\Delta L = 0$

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

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

- still hunted process
  - $T_{1/2} > 10^{25} y$
  - $\Delta L = 2 \rightarrow$ physics beyond the Standard Model





Neutrinoless Double Beta Decay

- In the limit of light Majorana neutrinos exchanges (`1305.0056v2 [hep-ph]`)

$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}(Q,Z) \cdot |M^{0\nu}|^2 \cdot \frac{|m^{\nu}_{ee}|^2}{m_e}$$

NME

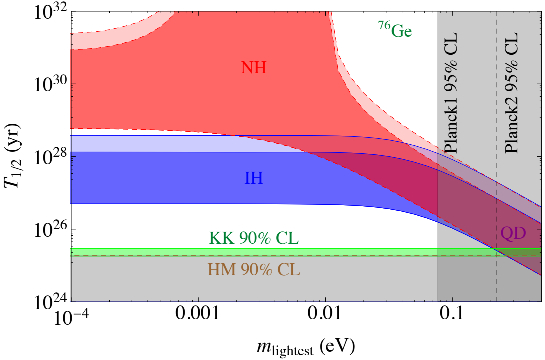
Phase Space

Effective Majorana mass

- with Neutrino Mixing Matrix

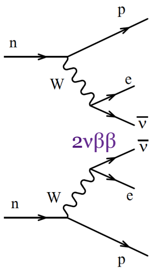
$m^{\nu}_{ee} = \sum_k U^2_{ek} m_k$

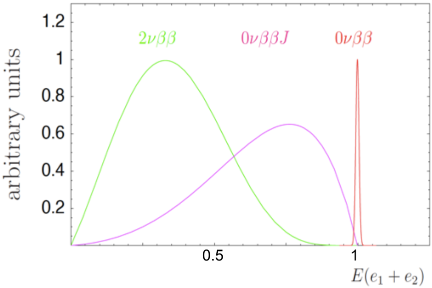
$m^{\nu}_{ee} = c^2_{12}c^2_{13}m_1 + s^2_{12}c^2_{13}m_2 e^{2i\alpha_2} + s^2_{13}e^{2i\alpha_3}m_3$

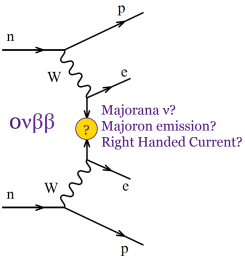


Xiv:1305.0056v2 [hep-ph]

Experimental signatures







- Event topology: two electrons at the decay vertex
- measure the electrons sum energy spectrum (and angular distributions)
- energy distribution sensitive to the underlying process ($2\nu\beta\beta$, $0\nu\beta\beta$ with Majorons)
- $0\nu\beta\beta$ decay has a peak at $Q_{\beta\beta} = E_{e1} - E_{e2} - 2m_e$

.. and sensitivities

- In the unlikely case of zero background experiment:

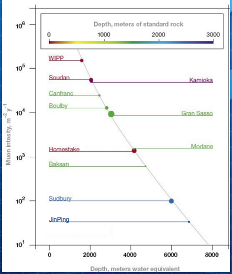
$$T^{0\nu}_{1/2} \propto \epsilon \cdot \frac{a}{A} \cdot M\,t$$

- the sensitivity with background

$$T^{0\nu}_{1/2} \propto \epsilon \cdot \frac{a}{A} \cdot \sqrt{\frac{M\,t}{b \Delta E}}$$

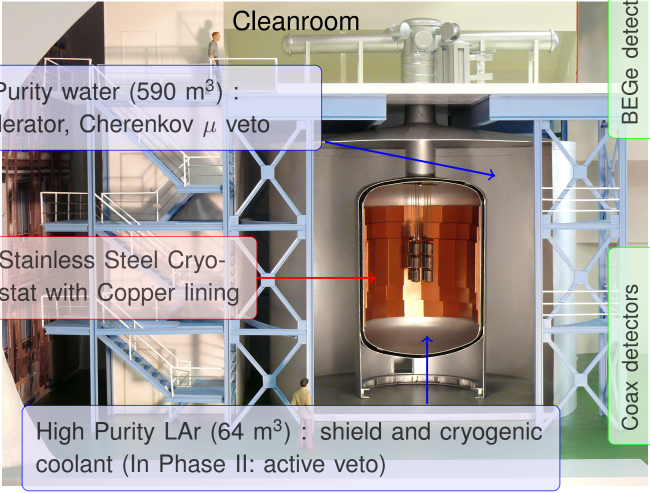
- Detector Efficiency (ϵ)
- Isotopic Fraction (a)
- Exposure [kg·yr] ($M\,t$)
- Energy Resolution [keV] (ΔE)
- Atomic Mass (A)
- Background Index [(keV·kg·yr)$^{-1}$] (b)

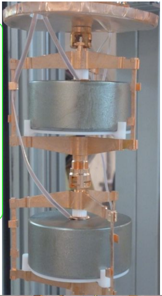
Double Beta Decay Experiments around the World



GERDA: Eur. Phys. J. C (2013) 73:2330

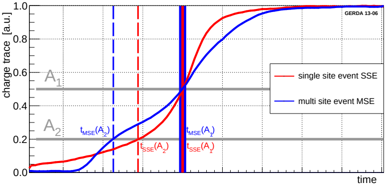
- Onion like shielding against environmental radiation
- Rigorous material selection (screening)

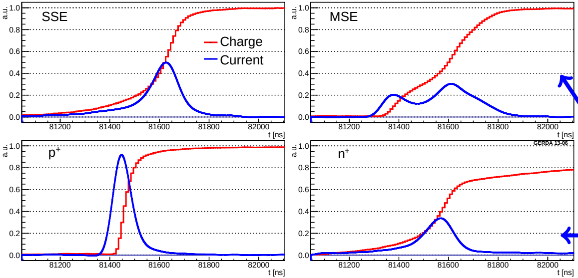


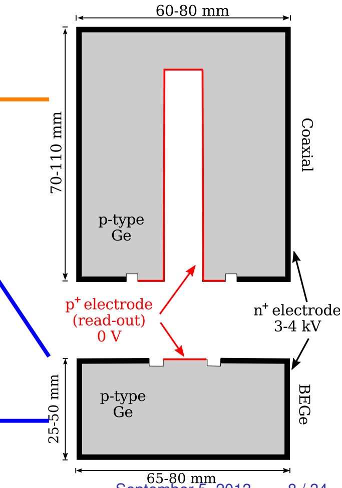


GERDA detectors

- Phase I: p-type semi-coaxial
- Phase II: p-type, Broad Energy Germanium (BEGe)
- Signal structure allows to discriminate between Single-Site-Events (SSE) and Multiple-Site-Events (MSE)

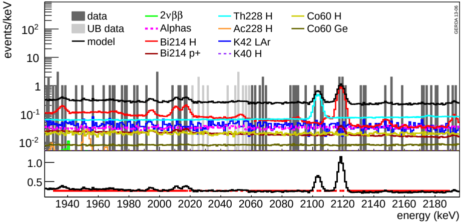


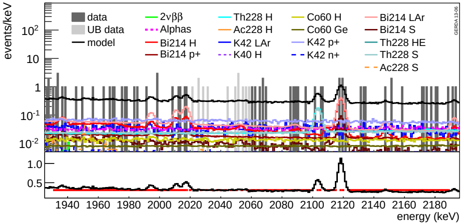




GERDA BKG Model [arXiv/1306.5084v1]

- Background in the $0\nu\beta\beta$ ROI is consistent with a flat background in the 1930 keV - 2190 keV energy region





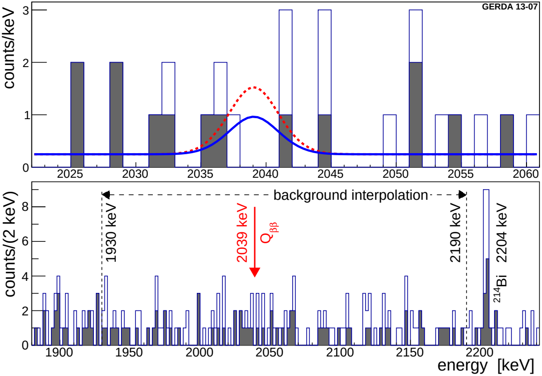
- Background index, extrapolated into the region of interest (before PDS)

  Coaxial:
  $(1.75^{+0.26}_{-0.24} \cdot 10^{-2}\text{counts}/(\text{kev kg yr})$
  BEGe:
  $(3.6^{+1.3}_{-1.0} \cdot 10^{-2}\text{counts}/(\text{kev kg yr})$

- Linear fit with flat background in 1930 keV - 2190 keV, excluding peaks at 2104 keV and 2119 keV

GERDA $0\nu\beta\beta$ result [arXiv/1307.4720]

- Data divided into three data sets (Golden, Silver, BEGe)
- Profile Likelihood Fit performed separately to the three sets
- Signal+Bck described by constant term + Gaussian($Q_{\beta\beta}$,σ_E)
- Systematics folded in the fit



☐ No PDS ■ After PSD cut

Frequentist Approach

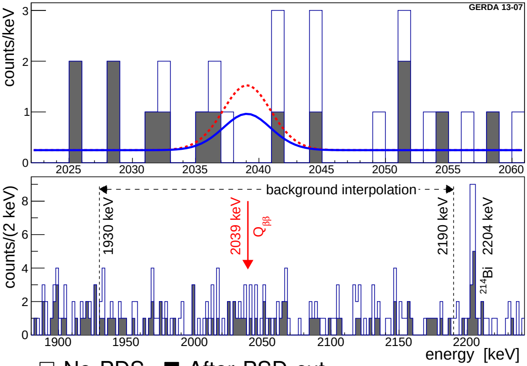
- Best Fit: $N^{0\nu} = 0$
- $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$yr (90% CL)

Bayesian Approach

- Flat Prior assumed
- Best Fit: $N^{0\nu} = 0$
- $T^{0\nu}_{1/2} > 1.9 \cdot 10^{25}$yr (90% CL)

GERDA $0\nu\beta\beta$ vs. KK (2004) claim

- Assuming $T^{0\nu}_{1/2} = 1.19 \cdot 10^{25}$ yr
- Expected Signal: 5.9 ± 1.4 counts in $\pm 2\sigma$
- Expected Background: 2.0 ± 0.3 counts in $\pm 2\sigma$
- Observed: 3.0 counts (0 counts in $\pm 1\sigma$)



☐ No PDS ■ After PSD cut

Claim poorly credible

From profile likelihood:

- Assuming H1, $P(N^{0\nu} = 0) = 0.01$

Comparing

- H1: Claimed signal
- H0: Background only

Bayes Factor

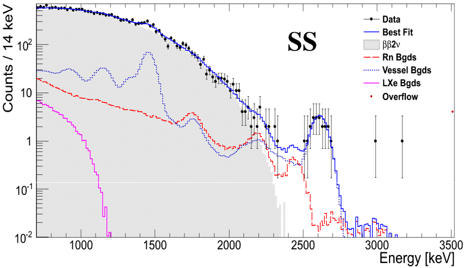
- P(H1)/P(H0) = 0.024

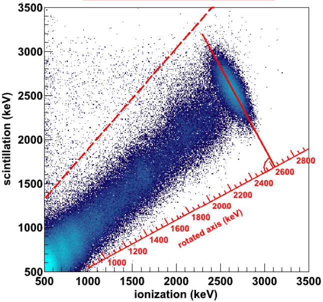
(uncertainties on claim included)

EXO-200: JINST 7 (2012) P05010

- Technique: liquid enriched Xenon TPC
- Location: EXO-200 WIPP (New Mexico, USA)
- Source: 200 kg Xe (80% enriched in ^{136}Xe)
- Status: taking data, run until end 2014 (with possible 2 years extension)
- charge and light readout allows to distinguish SSE (signal) from MSE (background)
- The first experiment to measure $2\nu\beta\beta$ and still with the most accurate result

ΔE
Scintillation: 6.8%
Ionization: 3.4%
Rotated: 1.6%

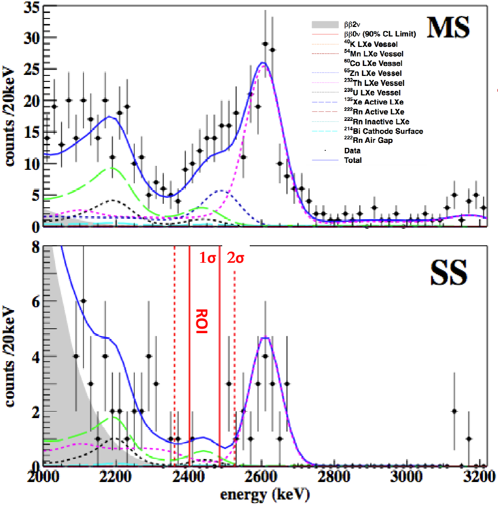




$T_{1/2}$ = (2.172 ± 0.017 stat ± 0.06 sys)·10^{21} yr

The most accurate $T_{1/2}$ of any $2\nu\beta\beta$ decay (arXiv:1306.6106)

EXO-200 : $0\nu\beta\beta$ limit result



Low background run 2a

No signal observed

$T_{1/2}^{0\nu\beta\beta} > 1.6\cdot10^{25}$ yr (@ 90% CL)

Majorana mass limit:

$\langle m\rangle_{\beta\beta} < 140 - 380$ meV

M. Auger et al., Phys. Rev. Lett. 109, (2012) 032505

^{222}Rn in cryostat air-gap	1.9	±0.2	
^{238}U in LXe Vessel	0.9	±0.2	
^{232}Th in LXe Vessel	0.9	±0.1	
^{214}Bi on Cathode	0.2	±0.01	
All Others	~0.2		
Total	4.1	±0.3	1σ

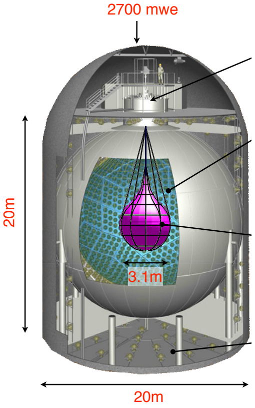
^{222}Rn in cryostat air-gap	2.9	±0.3	
^{238}U in LXe Vessel	1.3	±0.3	
^{232}Th in LXe Vessel	2.9	±0.3	
^{214}Bi on Cathode	0.3	±0.02	
All Others	~0.2		
Total	7.5	±0.5	2σ

$(1.4 \pm 0.1)\cdot 10^{-3}\ \mathrm{kg^{-1}yr^{-1}keV^{-1}}$

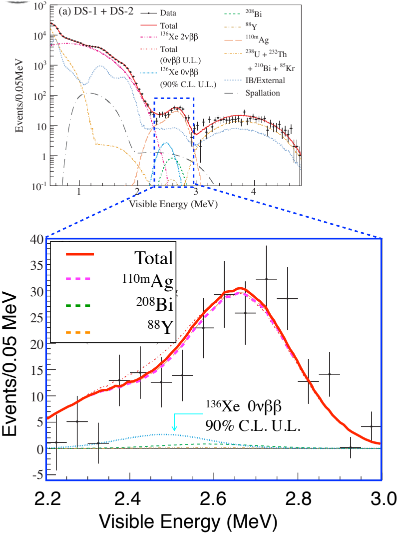
19-Jul-13

KAMLand-Zen: [arXiv/1205.6372]

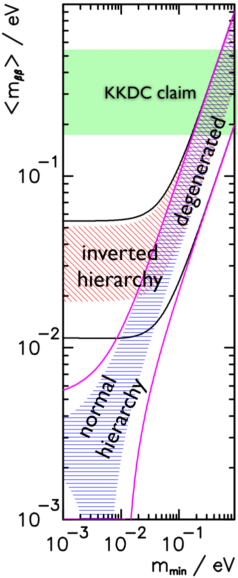
- Technique: enriched Xenon dissolved in LS
- Location: Kamioka (Japan)
- Source: ^{136}Xe (91% enr.)
  - 300 kg (130 kg fiducial)
- Status: working on improving the bkg

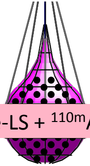


$$T^{0\nu}_{1/2} > 1.9 \cdot 10^{25} \text{ yr}$$

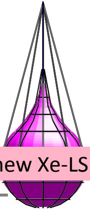


KAMLand-Zen Evolution and Timeline





We are here. Xe-LS + ^{110m}Ag



new Xe-LS

We will start this summer.

new miniBalloon + 800 kg ^{136}Xe

We have experience of miniBalloon fabrication.

There exists ~800 kg ^{136}Xe in the KamLAND site.

KamLAND2-Zen (2016-?)

Ongoing R & D

- Light collector
- LS replacement
- γ/β discrimination
- **Open KamLAND**
- New photo senser
-
-

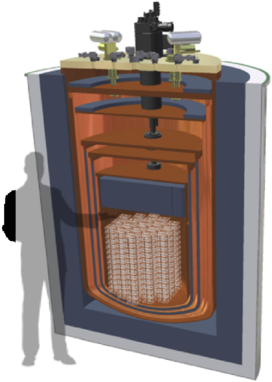
KamLAND as a ultra low BG detector

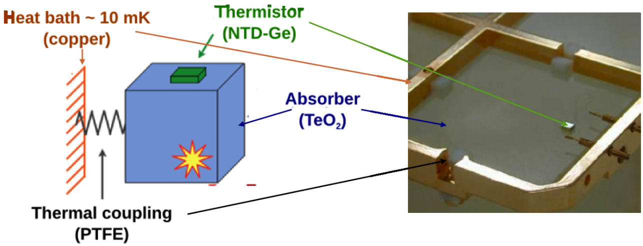
Proposed experiments

- ^{144}Ce anti-ν source at L ~ 1 m
- NaI deployment
- $CdWO_4$ deployment
-
-

CUORE

- Technique: natural TeO_2 bolometers operated at 10-15 mK
- Location: LNGS (Italy), evolution of Cuoricino
- Source: 988 TeO_2 bolometers, 741 kg of natural tellurium
- Status: first CUORE tower (CUORE0, 11 kg ^{130}Te) in operation since spring 2013
- Timeline: CUORE full data taking in 2015



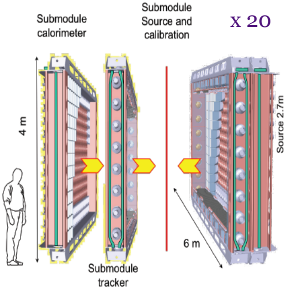


Super-Nemo Demonstrator

- Technique: tracker/calorimeter (20 modules) with source foil
- Location: Modane (France)
- Source: ^{82}Se (5 kg, Demonstrator - 100 kg, full)
- Timeline: Demonstrator, start-up in 2013, Full detector data taking 2015

- a modular successor of NEMO-3. Lower background ($\times$0.1 will be proven by demonstrator, 1 module)
- knowledge of full event topology (calorimetry, tracking and PID) allows to disentangle decay mechanisms

NEMO-3		SuperNEMO
^{100}Mo, ^{82}Se (^{150}Nd, ^{130}Te, ^{116}Cd, ^{96}Zr, ^{48}Ca)	**Isotopes**	^{82}Se (^{150}Nd, ^{48}Ca)
10	**Mass (kg)**	100–200 *(demo: 7)*
^{208}Tl: ~100 ^{214}Bi: <300	**Source contamination (μBq/kg)**	^{208}Tl: <2 ^{214}Bi: <10
5	**Radon level (mBq/m³)**	<0.15
8%	**Energy resolution (FWHM at 3MeV)**	4%
1	**$T^{1/2}$ sensitivity (10^{24} y)**	100 *(demo: 6.6)*
300–900	**$\langle m_\nu \rangle$ sensitivity (meV)**	40–100 *(demo: 200–400)*

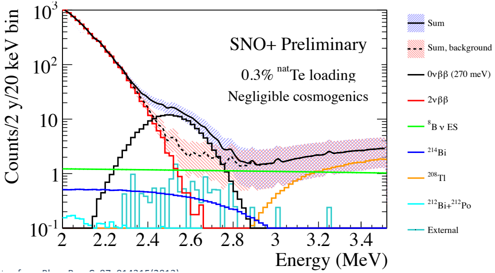


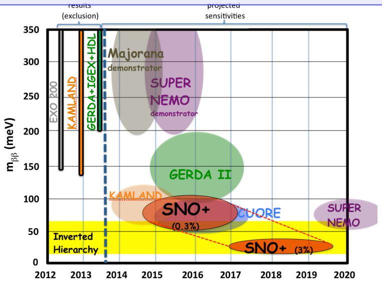
SNO+

- Double Beta decay is a high priority in SNO+ rich physics program (solar neutrinos, Geo neutrinos, reactor and supernova neutrinos)
- Techniques: Deploy DBD isotope in LAB Liquid Scintillator
- Location: Sudbury (Canada)
- Source: ^{130}Te (natural abundance), 800 kg (160 kg in fiducial volume)
- Timeline: 2013 water fill, 2014 scintillator fill, end 2014-2015 (istotope deploy)

^{8}B solar ν, irreducible bkg

Cosmogenic and ^{214}Bi, ^{208}Tl contamination, reduced by delayed coincidences (α/β tag)

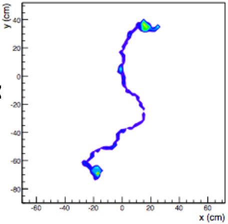


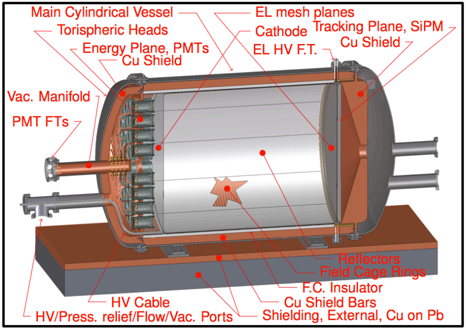


Next-100

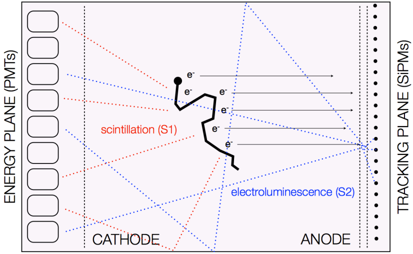
- Techniques: High Pressure asymmetric (10-15 bar) X
- Location: Canfranc (Spain)
- Source: ^{136}Xe enriched at 90%, about 100 kg
- Status: demonstrator under study (radiopurity an impo background rejection)
- Timeline: physics runs expected for 2015

Reconstructed tracks from a MC simulated ββ0ν event





NEXT-100 Technical Design Report; Executive Summary 2012 JINST 7 T06001

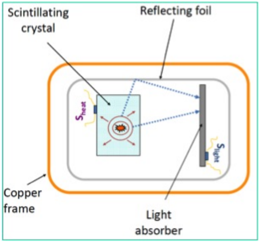


Future DBD Projects

- Several R&D projects to study/develop new techniques for DBD detection
- Examples:
  - combine scintillation light in xtals (to reject backgound events)
  - build larger ($\times 5 - 10$) detectors with consolidated technology

Experiment	Isotope	Technique	Mass
CARVEL	^{48}Ca	48 $CaWO_4$ scint. xtals	$\sim$ tonne
LUCIFER	^{82}Se	ZnSe scint. bolometer	18 kg
AMoRE	^{100}Mo	$CaMoO_4$ sint. bolometer	50 kg
COBRA	^{116}Cd	CdZnTe pixel detector	10 kg/183 kg
SuperNEMO	^{82}Se	Foils with tracking	100 kg
DCBA	^{150}Nd	Nd foils and tracking chamb.	20 kg
nEXO	^{136}Xe	Xe liquid TPC	$\sim$ tonne
1ton Ge (GERDA+MJ)	^{76}Ge	Point-Contact GE in LAr	$\sim$ tonne

Scintillating xtals principle



Large scale production chain not yet proven for some project

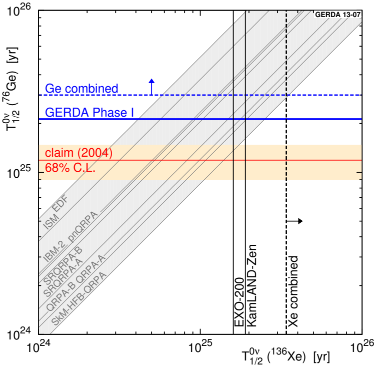
Construction costs for large detectors can be an issue (R&D needed)

$0\nu\beta\beta$ combined limit (^{76}Ge and ^{136}Xe)

Data Set	Isotope	$P(H_1)/P(H_\circ)$	Comment
GERDA	^{76}Ge	0.024	Model Indep.
GERDA+HdM+IGEX	^{76}Ge	0.0002	Model Indep.
KamLAND-Zen	^{136}Xe	0.40	Model Dep†
EXO-200	^{136}Xe	0.23	Model Dep†
GERDA+EXO+KZen	^{76}Ge, ^{136}Xe	0.002	Model Dep†

† Model dependent on NME and leading terms

- Assuming conservative NME ratio $M^{0\nu}(^{136}Xe)/M^{0\nu}(^{76}Ge) = 0.4$



- Profile likelihood function with 5 independent backgrounds

$\Rightarrow$ $T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}$yr (90% CL)

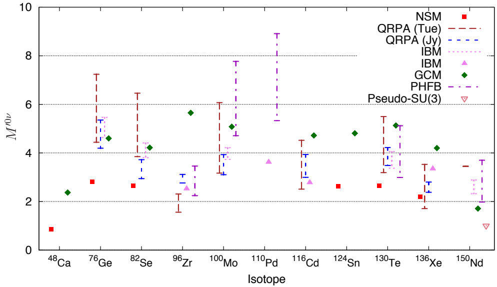
Conclusions:

- $0\nu\beta\beta$ observation would be a major discovery:
  - observe Lepton Number Violation
  - unveil the Majorana nature of neutrinos
- GERDA has recently completed its Phase I and scrutinized the KK claim with 1.5 years of data taking (21.6 kg yr exposure)
- no excess of counts above background found
- a combination of GERDA and previous experiments sets a limit for $T^{0\nu}_{1/2} > 3 \times 10^{25}$ yr (90% CL)
- Several experiments are or will be running in few years at (several) 100 kg mass scale with different isotopes and complementary experimental techniques (i.e. CUORE)
- The exploration of the inverted hierarchy (as predicted by theory) will be possible and results are foreseen in the next few years

Reserve Slides

Isotopes and Nuclear Matrix Elements

Isotope	Abundance [%]	$Q_{\beta\beta}[Mev]$ [MeV]	$G_{0\nu}$ $[10^{-14}yr^{-1}]$
^{48}Ca	0.19	4.274	6.35
^{76}Ge	7.8	2.039	0.62
^{82}Se	9.2	2.996	2.70
^{96}Zr	2.8	3.348	5.63
^{100}Mo	9.6	3.035	4.36
^{116}Cd	7.6	2.809	4.62
^{130}Te	34.5	2.530	4.09
^{136}Xe	8.9	2.462	4.31
^{150}Nd	5.6	3.367	19.2

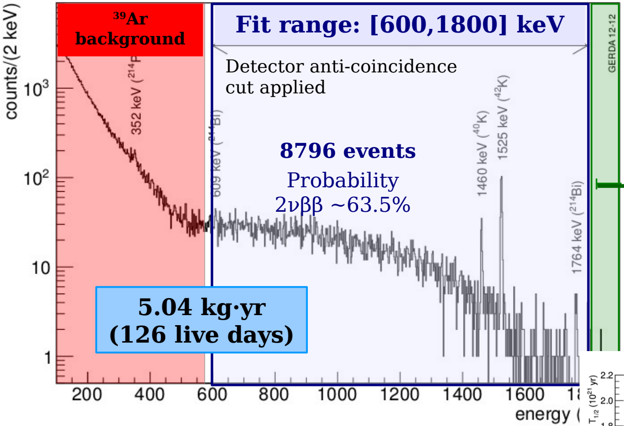


Xiv:1103.4152v2 [hep-ph]

- Nuclear Matrix Elements (NME) are calculated using various models: QRPA (RQRPA, SQRPA) Shell Model, IBM2, . . .
- calculation discrepancies are still one of the largest uncertainties
- none of the isotopes is favorite (from NME point of view)
- High $Q_{\beta\beta}$ are preferrable (reduce environmental background due to γ lines)
- Isotopic abundance is an issue ⇒ material enrichment for higher sensitivities

Two Neutrino Double Beta Decay

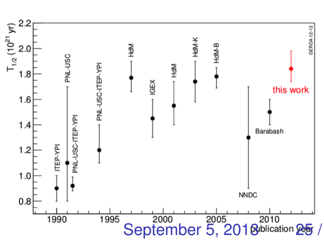
Sum energy spectrum



Probability
$2\nu\beta\beta < 0.02\%$

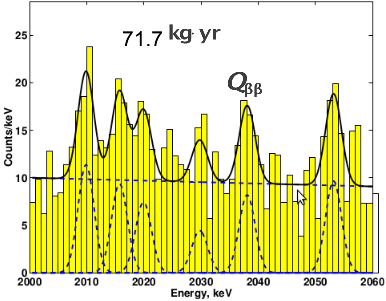
$$T^{2\nu}_{1/2} = (1.84^{+0.14}_{-0.10}) \cdot 10^{21} \text{ yr}$$

M. Agostini et al, J. Phys. G: Nucl. Part Phys 40 (2013) 035110 [`arXiv/1212.3210`]



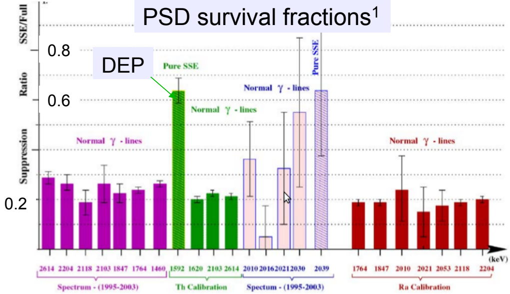
What value of Klapdor-Kleingrothaus to compare with?

a) 2004 publications: [1]NIM A522 371 & [2]Phys Lett B586 198



entire data set[1,2]: 71.7 kg· yr (active mass)
28.75 ± 6.86 signal events
$T_{1/2}^{0\nu} = (1.19^{+0.37}_{-0.23}) \cdot 10^{25}$ yr

data for PSD analysis[1,2]: 51.4 kg· yr
19.58 ± 5.41 signal events
$T_{1/2}^{0\nu} = (1.25^{+0.49}_{-0.27}) \cdot 10^{25}$ yr



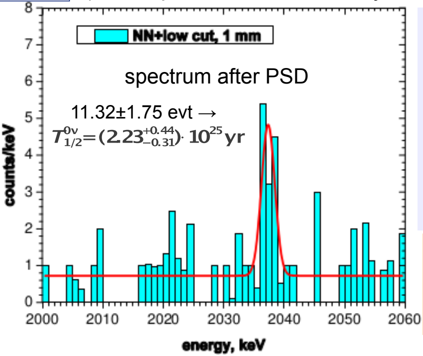
with PSD: 12.36 ± 3.72 evt
Without efficiency correction
$T_{1/2}^{0\nu} = 1.98 \cdot 10^{25}$ yr

DEP survival fraction[1] ~ 62%
$T_{1/2}^{0\nu} = 1.23 \cdot 10^{25}$ yr

No efficiency correction is applied in any publication!

with given eff. $T_{1/2}^{0\nu}$ after PSD agrees with the one without

b) 2006 publication: Mod Phys Lett A21 p. 1547-1566



PSD based on 3 previous methods (2 neural networks + pulse boardness) & library of SSE pulses:
Event accepted IF pulse in library OR found by neural network of Ref. 16 but not by the other two neural networks

NO event overlap between the 2 sets!?

statement of publication:
- "multi site events are suppressed by 100%",
- 0nbb PSD efficiency = 1 used for $T^{0\nu}_{1/2}$

error on signal count not correct since smaller than Poisson error

efficiency factor not considered
→ calculation of $T^{0\nu}_{1/2}$ not correct
→ GERDA does not use this result

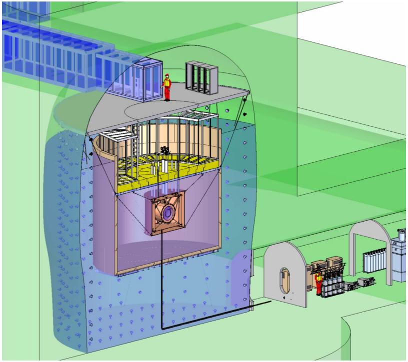
Peak position shifted by -1.6 keV, why? "seem to be due to ballistic deficit" of SSE.
a) effect should have opposite sign and b) should also apply to DEP (not discussed)
→ interpretation that peak @ 2039 keV is sum of 2 lines (DARK 2007 proc.) not supported by any argument

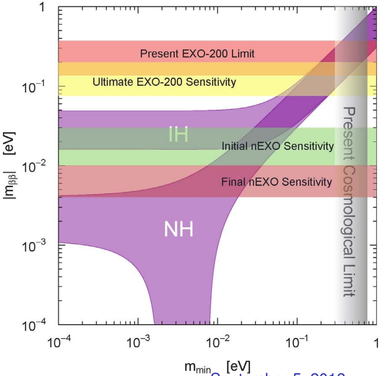
for discussion see also: Annalen d Phys 525 (2013) 269. J High Energy Phys 02 (2013) 093.

nEXO: the future evolution of EXO-200

- Technique: same as for the EXO-200 TPC ($\times$5 mass)
- Location: SNOlab, Sudbury (Canada)
- Source: ^{136}Xe (5 tonne)
- Timeline: ?

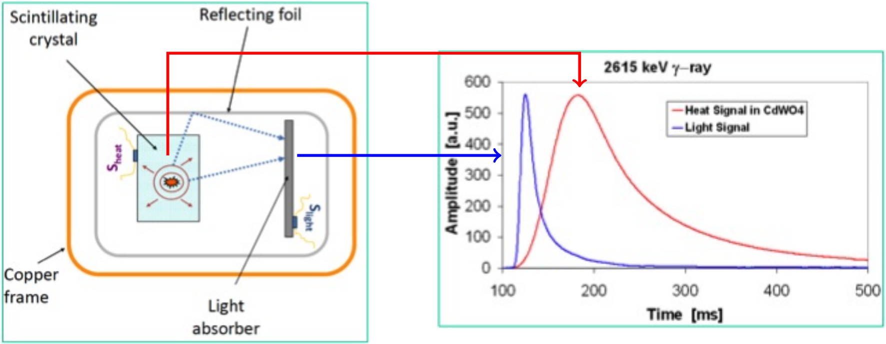
- R&D program to improve HV, lower the background, and study application of SiPM readout (instead of APDs) and alternative charge collection scheme





Lucifer

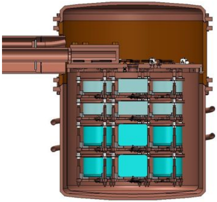
- Techniques: scintillating bolometers operated at 10 mK
- Location: LNGS (Italy), R&D program
- Source: enriched crystals, various options ^{82}Se, ^{100}Mo, ^{116}Cd, etc.
- Status: R&D program on material enrichment and crystal production ongoing
- Timeline: R&D with significant mass in 2014-2015



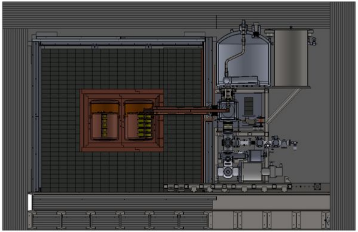
The Majorana Demonstrator

Funded by DOE Office of Nuclear Physics and NSF Particle Astrophysics,
with additional contributions from international collaborators.

Goals:
- Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Test Klapdor-Kleingrothaus claim.
- Low-energy dark matter (light WIMPs, axions, ...) searches.



- Located underground at 4850' Sanford Underground Research Facility
- Background Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV)
  3 counts/ROI/t/y (after analysis cuts)
  scales to 1 count/ROI/t/y for a tonne experiment
- 40-kg of Ge detectors (KPP of at at least 30-kg)
  - At least 15-kg of 86% enriched ^{76}Ge crystals & up to 15-kg of ^{nat}Ge
  - Detector Technology: P-type, point-contact.
- 2 independent cryostats
  - ultra-clean, electroformed Cu
  - 20 kg of detectors per cryostat
  - naturally scalable
- Compact Shield
  - low-background passive Cu and Pb shield with active muon veto



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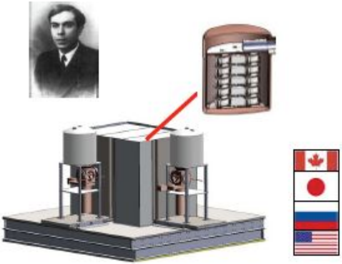
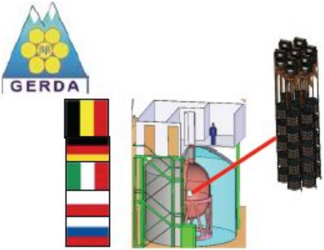
GERDA/Majorana joint efforts towards 1 tonne Ge





- ^{76}Ge modules in electroformed Cu cryostat, Cu / Pb passive shield
- 4π plastic scintillator μ veto
- DEMONSTRATOR: 30 kg ^{76}Ge and 10 kg ^{nat}Ge PPC xtals

- ^{76}Ge array submersed in LAr
- Water Cherenkov μ veto
- Phase I: ~18 kg (H-M/IGEX xtals
- Phase II: +20 kg segmented xtals

Joint Cooperative Agreement:

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

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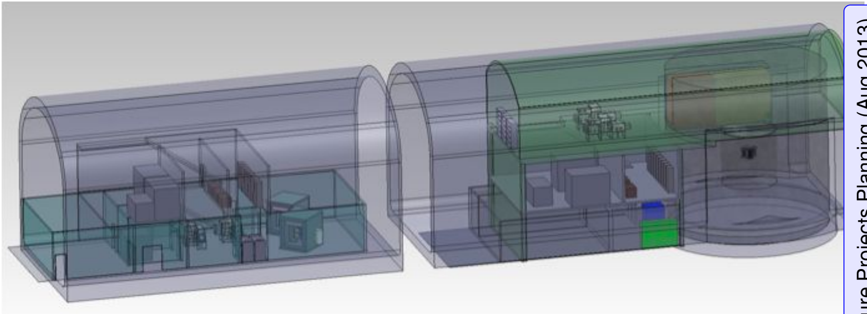
1 tonne Ge, possible detector configurations



Compact

Two shields, each with 8 EFCu vacuum cryostats

Cryogenic Vessel

Diameter of water tank:

- ~11 m for LAr,
- ~15 m for LN (shown)

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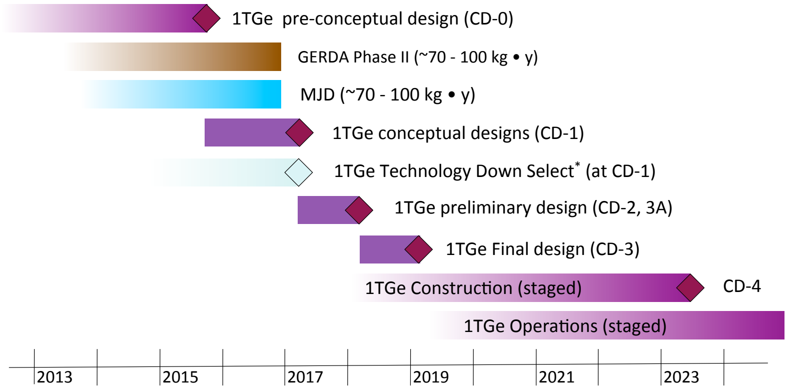
1TGe Projected Timeline

- Technology down-select will be based on 1TGe R&D, GERDA Phase II, and MJD. Currently working with GERDA to define the process.
- 1TGe management will be defined based on participating institutions



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1TGe Preliminary Cost Estimate

- Parametric estimate based on actual costs for MJD and GERDA experiments, with MJD the primary source
- Procurement costs generally scaled in linear fashion, except where cost reductions can be expected
- 30% contingency on MJD-based estimates, 50% on all others

Option	Min TPC ($M)	Max TPC ($M)
Homestake 4850L	214	231
Homestake 7400L	206	231
SNOLAB 6800L	210	235

TPC Walk-up	Cost ($ks)
UG Crystal Fabrication	15,000
LAr Tank and shield	10,000
Rn mitigation	1,500

Major Procurements/Activities	Cost ($ks)
Host Lab Infrastructure	2,000
Materials & Assay	2,100
Ge Procurement/Enrichment	105,000
Detector Fabrication	21,400
Detector Modules	4,000
Electroforming	1,500
Mechanical Systems	8400
DAQ	5400
Project Labor	18,500

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