Double Beta Decay Experiments

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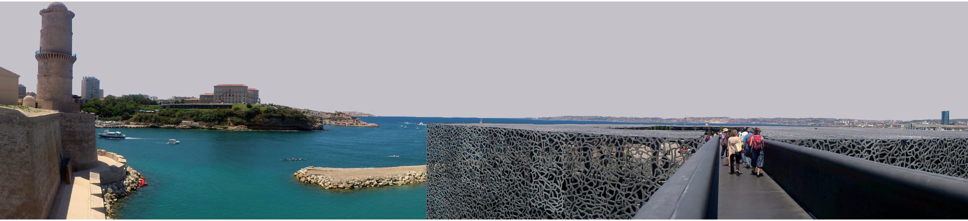
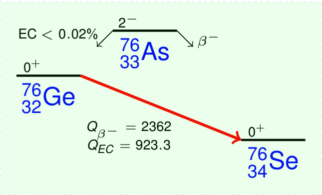
May 29, 2014



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



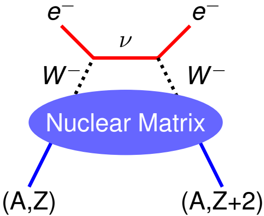
$2\nu\beta\beta : (A, Z) \rightarrow (A, Z+2) + 2e^- + 2\overline{\nu_e}$

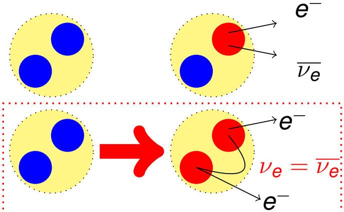
- a rare process, measured in 11 nuclei
  - $T_{1/2} \sim 10^{19} - 10^{21} yr$
  - $\Delta L = 0$

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

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

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





Neutrinoless Double Beta Decay

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

NME

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

Effective Majorana mass

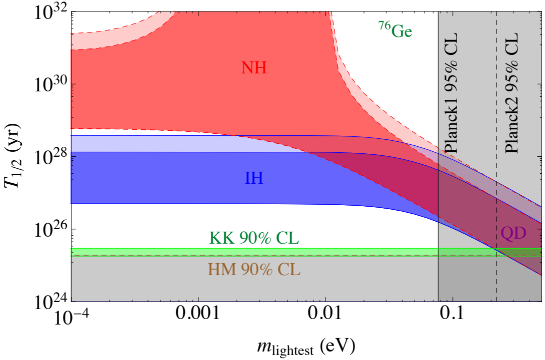
Phase Space

- with

Neutrino Mixing Matrix

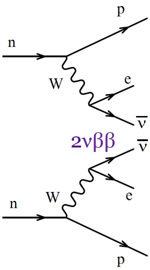
$$m^{\nu}_{ee} = \sum_k U^2_{ek} m_k$$

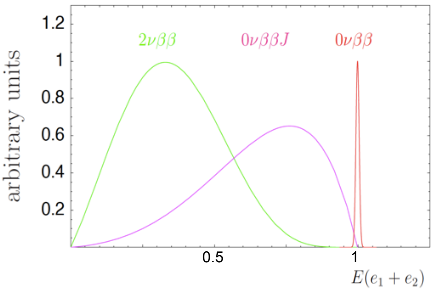
$$m^{\nu}_{ee} = c^2_{12} c^2_{13} m_1 + s^2_{12} c^2_{13} m_2 e^{2i\alpha_2} + s^2_{13} e^{2i\alpha_3} m_3$$

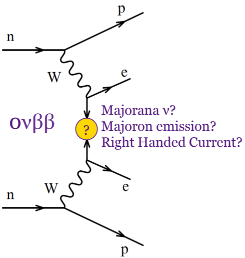


Xiv:1305.0056v2 [hep-ph]

Experimental signatures







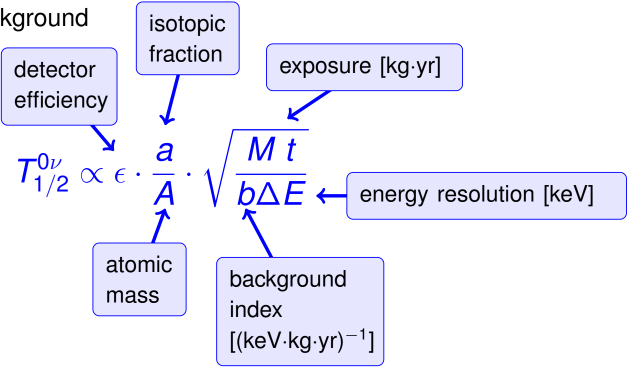
- Event topology: two electrons at the decay vertex
- measure the electrons sum energy spectrum (and angular distributions)
- energy distribution sensitive to the underlying process ($2\nu\beta\beta$, $0\nu\beta\beta$ with Majorons)
- $0\nu\beta\beta$ decay has a peak at $Q_{\beta\beta} = E_{e1} - E_{e2}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

.. 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

isotopic fraction

exposure [kg·yr]

energy resolution [keV]

atomic mass

background index [(keV·kg·yr)$^{-1}$]

Double Beta Decay Experiments around the World

SNO+
Sudbury

Majorana D
SURF

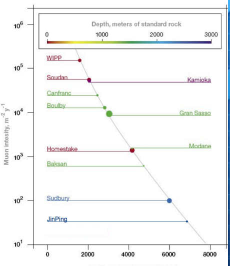
WIPP
EXO-200

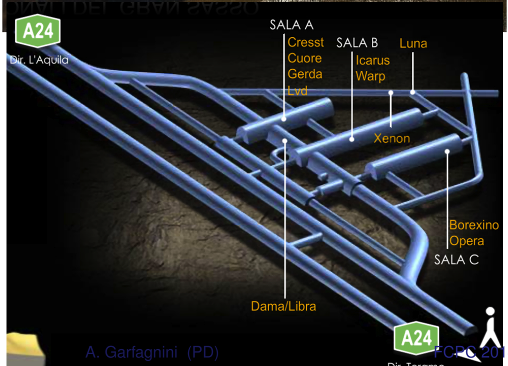
Super-Nemo D
Frejus

Next-100
Canfranc

Lucifer
Cobra
CUORE
GERDA
LNGS

KAMLand-Zen
Kamioka





LNGS

Depth: 3650 m.w.e

Three large experimental halls.

Environmental rates:

muons: $2.58 \times 10^{-8}/(\text{cm}^2\ \text{s})$

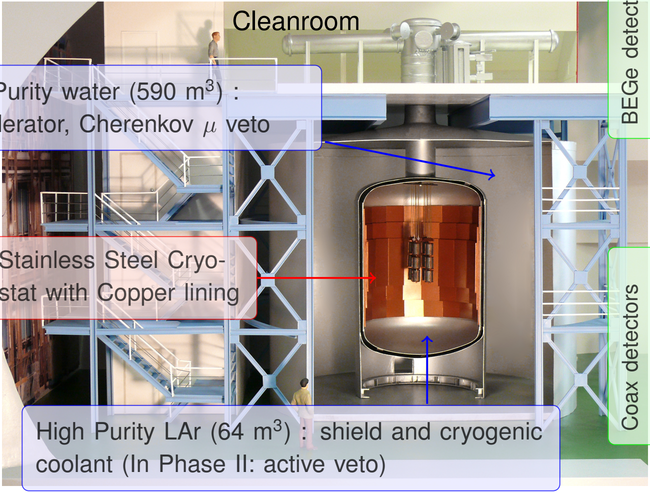
gammas: $0.73/(\text{cm}^2\ \text{s})$

neutrons: $4 \times 10^{-6}/(\text{cm}^2\ \text{s})$

Double Beta Decay Experiments: GERDA, CUORE, COBRA and Lucifer R&D

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

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

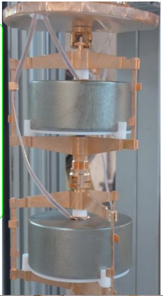


Cleanroom

High Purity water (590 m^3) : n moderator, Cherenkov μ veto

Stainless Steel Cryostat with Copper lining

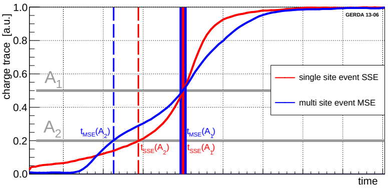
High Purity LAr (64 m^3) : shield and cryogenic coolant (In Phase II: active veto)



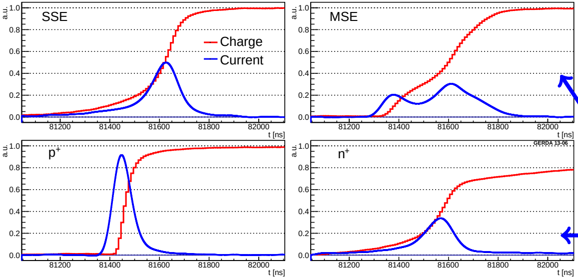
BEGe detectors string, Phase I

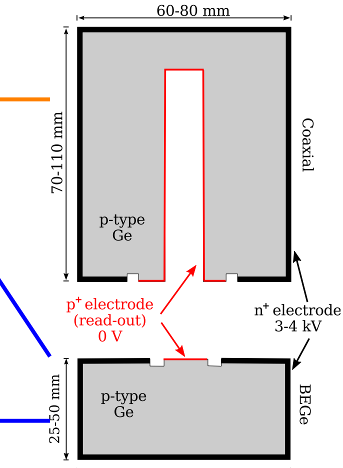
Coax detectors strings, Phase I

GERDA detectors

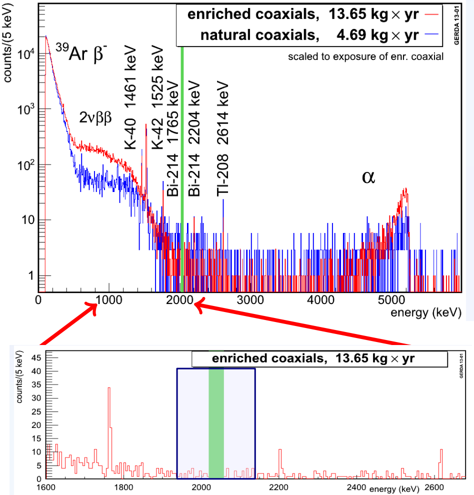


- Phase I: p-type semi-coaxial
- Phase II: p-type, Broad Energy Germanium (BEGe)
- Signal structure allows to discriminate between Single-Site-Events (SSE) and Multiple-Site-Events (MSE)

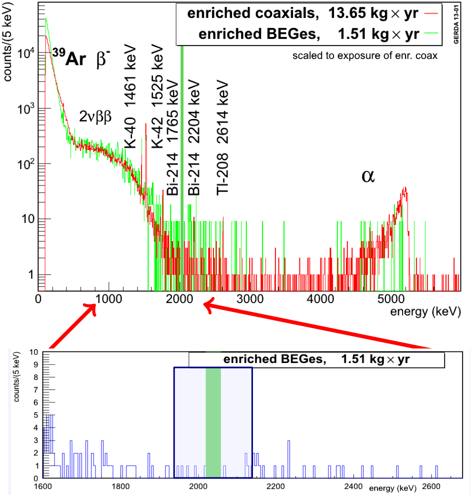




The measured energy spectra in GERDA



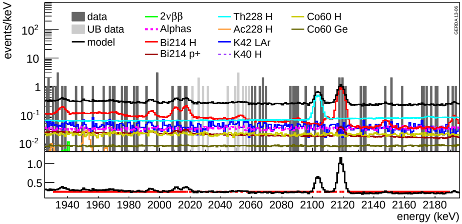
Enriched coaxials: **0.022±0.003 cts/(keV·kg·yr)**

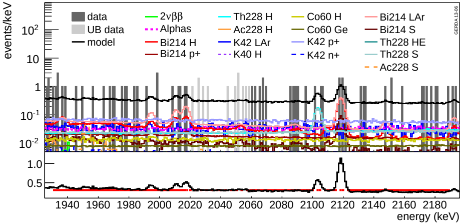


Enriched BEGes: **$0.041^{+0.015}_{-0.012}$ cts/(keV·kg·yr)**

GERDA BKG Model: Eur. Phys. J. C 74 (2014) 2764

- 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:

  $$(1.75^{+0.26}_{-0.24} \cdot 10^{-2} \text{counts}/(\text{kev kg yr})$$

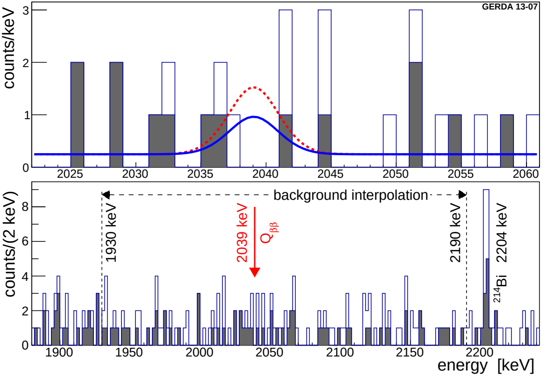
  BEGe:

  $$(3.6^{+1.3}_{-1.0} \cdot 10^{-2} \text{counts}/(\text{kev kg yr})$$

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

GERDA $0\nu\beta\beta$: Phys. Rev. Lett. 111 (2013) 122503

- 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)

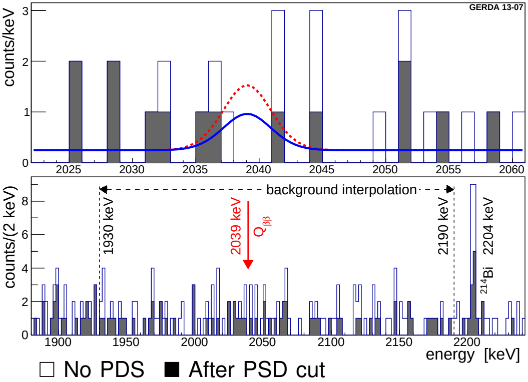
Bayesian Approach

- 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 $\pm 1\sigma$)

Claim poorly credible



From profile likelihood:

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

Comparing

- H1: Claimed signal
- H0: Background only

Bayes Factor

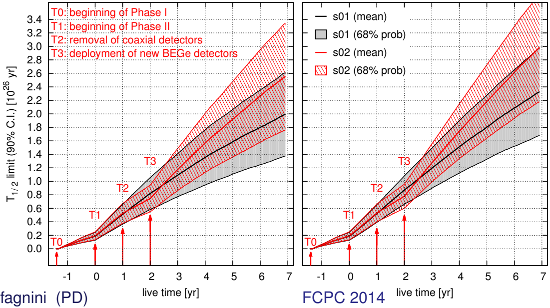
- P(H1)/P(H0) = 0.024
  (uncertainties on claim included)

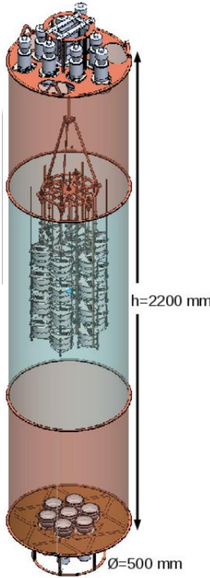
GERDA Phase II: improve the sensitivity

- Reduce the background (goal: 0.001 counts/(keV·kg·yr))
- Increase the exposure (goal: 100 kg yr)

Strategy

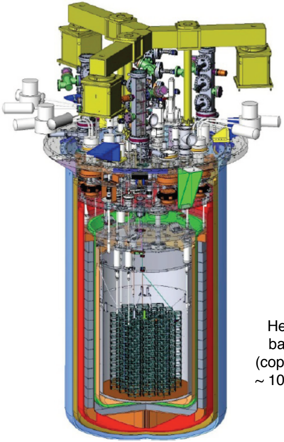
- new detectors (20 kg) with enhanced bck recongnition eff
- LAr instr: bkg rejection by detection of LAr scintillation light
- two options:
  1. PMTs on top and bottom of detector array
  2. SiPMs with fiber curtain



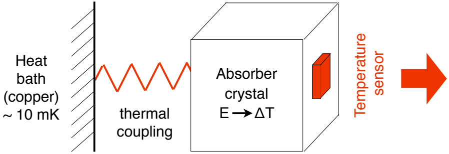


CUORE

- **Technique:** ${}^{nat}TeO_2$ bolometers operated at 10-15 mK
- **Cryogenics:** custom pulse tube diluition refrigerator and cryostat.
- **Challenge:** 1 ton of detectors operated at 10 mK
  - demanding radioactivity constraint on materials (accurate screening), very clean assembly
  - independent suspension of the detector array from the diluition unit



- **Detectors:** 988 TeO_2 bolometers
- **Mass:** 741 kg (TeO_2), 206 kg (${}^{130}Te$)
- **Background goal:** 0.01 counts/(keV·kg·yr)
- **Energy resolution:** 5 keV (FWHM)
- **Livetime:** 5 yr
- **Half-life sensitivity:** 5.9×10^{25} yr (90% CL)

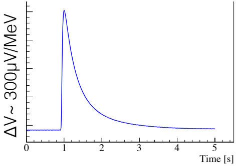


Heat bath (copper) ~ 10 mK

thermal coupling

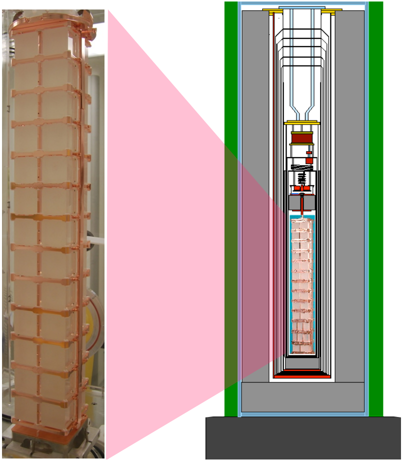
Absorber crystal E → ΔT

Temperature sensor



Operation of CUORE0, the 1st CUORE tower

- The 1st CUORE tower has been assembled and run to test the assembly and commission CUORE techniques (data taking/analysis).



Detector:

- 25 bolometers (750 g each)
- active mass: TeO_2 39 kg, (Te^{130} 11 kg)

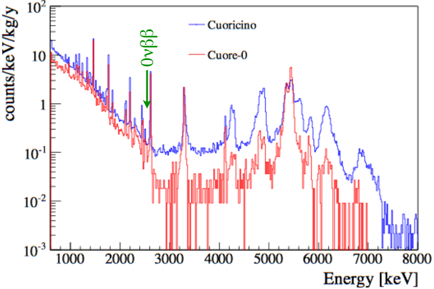
Setup:

- using the Cuoricino cryostat with
- inner shield: 1 mm Roman Pb (^{210}Pb < 4 mBq/kg)
- external shield: 20 cm Pb, 10 cm borated polyethylene
- N_2 flushing to reduce Rn contamination

taking data since March 2013

First CUORE0 results, and future plans

CUORE-0 preliminary



Data presented taken between Mar-Sep 2013. Exposure: 2 kg yr in ^{13}Te

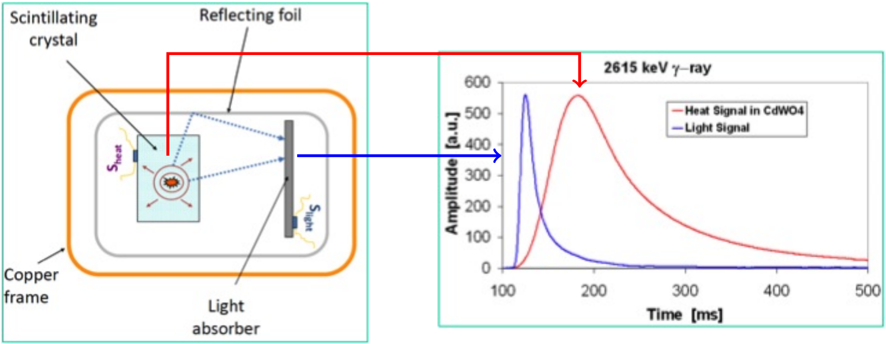
- From calibration: FWHM 5.7 keV at 2615 keV (^{208}Tl)
- Background lower than previous CUORICINO experiment: surface contaminations ×6 lower

	Bkg [counts/(keV·kg·yr)]	
	$0\nu\beta\beta$ region	2700-3900 keV
CUORICINO	0.153±0.006	0.110±0.001
CUORE0	0.071±0.011	0.019±0.002

- CUORICINO sensitivity reached in 1 year time
- Detector assembly completed by June 2014
- Cryostat commissioning completed by fall 2014
- Detector towers installation and commissioning: end 2014
- Start of data taking: 2015

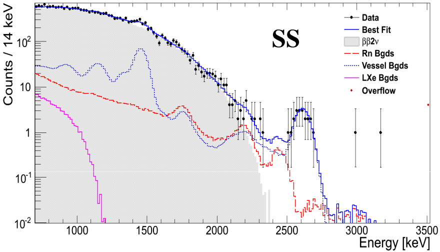
Lucifer

- 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

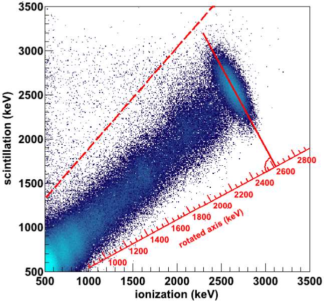


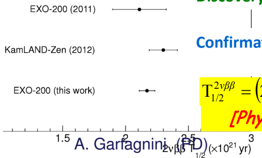
EXO-200: JINST 7 (2012) P05010

- Technique: liquid enriched Xenon TPC
- Location: EXO-200 WIPP (New Mexico, USA)
- Source: 200 kg Xe (80% enriched in ^{136}Xe)
- Status: first phase completed. Expect 3 more yrs of data with improved hardware.
- charge and light readout allows to distinguish SSE (signal) from MSE (background)



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





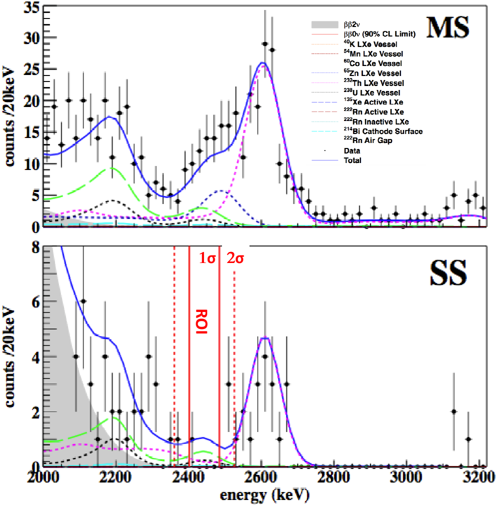
Discovery of 2ν mode *[PRL 107, 212501 (2011)]*

Confirmation by KamLAND-Zen *[PRC 85, 045504 (2012)]*

$$T_{1/2}^{2\nu\beta\beta} = \left(2.165 \pm 0.016^{\text{stat}} \pm 0.059^{\text{syst}}\right) \cdot 10^{21} \text{ yr}$$

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

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

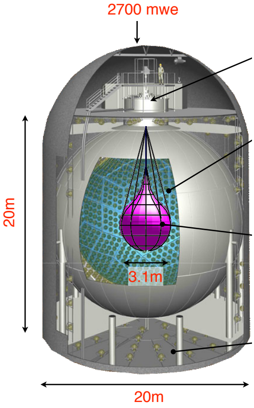
^{222}Rn in cryostat air-gap	1.9	±0.2	
^{238}U in LXe Vessel	0.9	±0.2	
^{232}Th in LXe Vessel	0.9	±0.1	
^{214}Bi on Cathode	0.2	±0.01	
All Others	~0.2		
Total	4.1	±0.3	1σ
^{222}Rn in cryostat air-gap	2.9	±0.3	
^{238}U in LXe Vessel	1.3	±0.3	
^{232}Th in LXe Vessel	2.9	±0.3	
^{214}Bi on Cathode	0.3	±0.02	
All Others	~0.2		
Total	7.5	±0.5	2σ

$(1.4 \pm 0.1)\cdot10^{-3}\,\mathrm{kg^{-1}yr^{-1}keV^{-1}}$

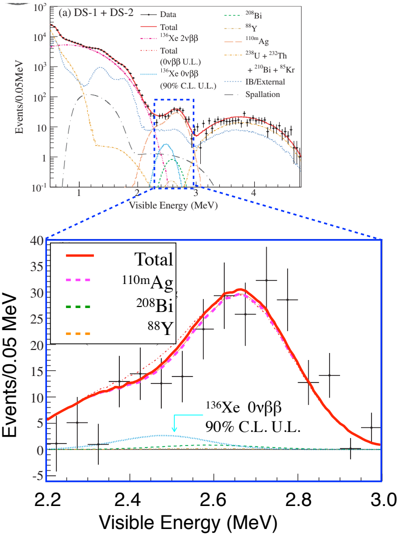
19-Jul-13

KAMLand-Zen: `[arXiv/1205.6372]`

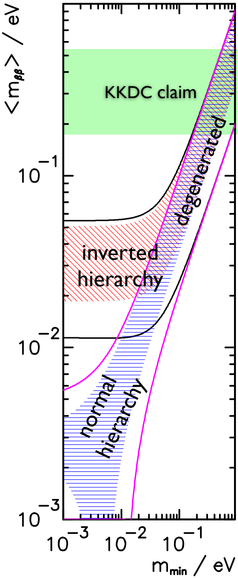
- **Technique:** enriched Xenon dissolved in LS
- **Location:** Kamioka (Japan)
- **Source:** ^{136}Xe (91% enr.)
  - 300 kg (130 kg fiducial)
- **Status:** working on improving the bkg

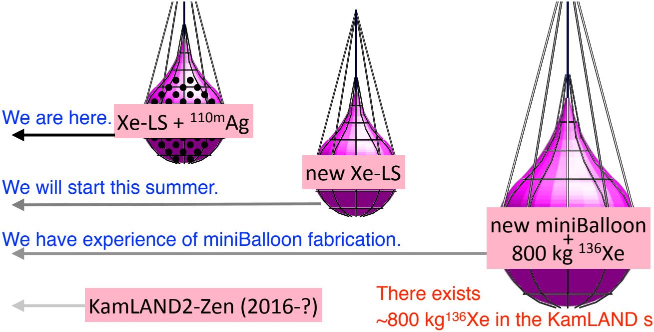


$$T^{0\nu}_{1/2} > 1.9 \cdot 10^{25}\ \text{yr}$$



KAMLand-Zen Evolution and Timeline





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

We will start this summer. new Xe-LS

We have experience of miniBalloon fabrication. new miniBalloon + 800 kg ^{136}Xe

KamLAND2-Zen (2016-?)

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

Ongoing R & D

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

KamLAND as a ultra low BG detector

Proposed experiments

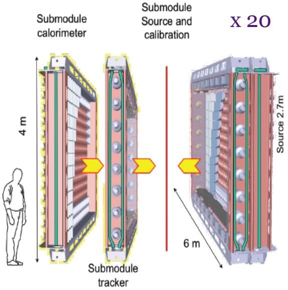
- ^{144}Ce anti-ν source at L ~ 1 m
- NaI deployment
- $CdWO_4$ deployment
-
-

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 (×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)*

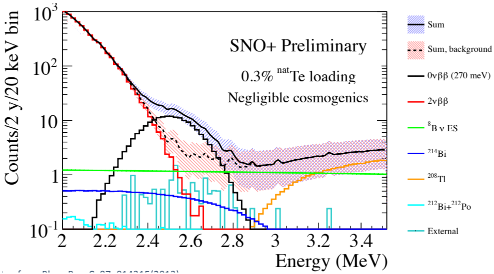


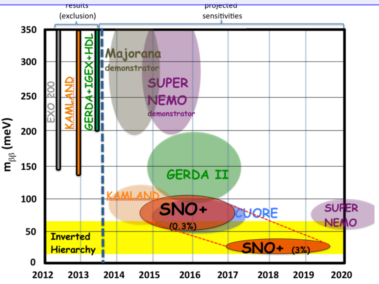
SNO+

- 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)

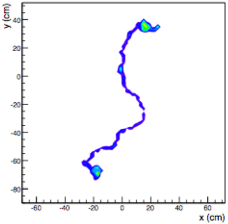


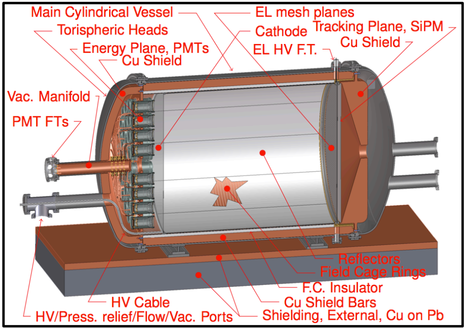


Next-100

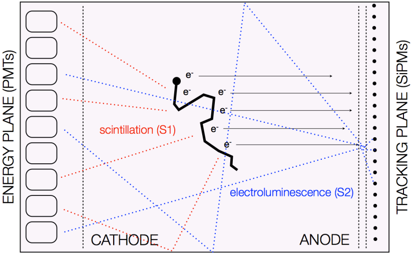
- **Techniques:** High Pressure asymmetric (10-15 bar) Xe-TPC
- **Location:** Canfranc (Spain)
- **Source:** ^{136}Xe enriched at 90%, about 100 kg
- **Status:** demonstrator under study (radiopurity an important issue for background rejection)
- **Timeline:** physics runs expected for 2015

Reconstructed tracks from a MC simulated ββ0ν event





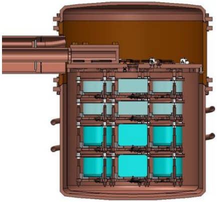
NEXT-100 Technical Design Report; Executive Summary 2012 JINST 7 T06001



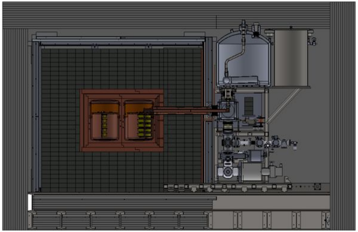
The Majorana Demonstrator

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 0νββ 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



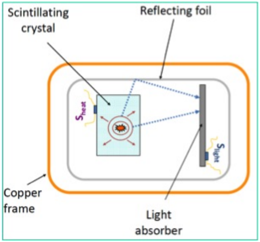
D. Radford, Snolab Future Projects Planning (Aug 2013)

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	~ 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	~ tonne
1ton Ge (GERDA+MJ)	^{76}Ge	Point-Contact GE in LAr	~ tonne

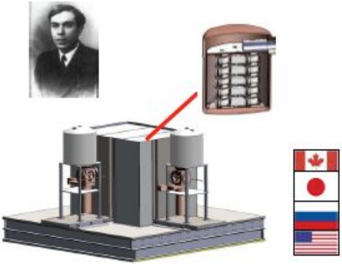
Scintillating xtals principle

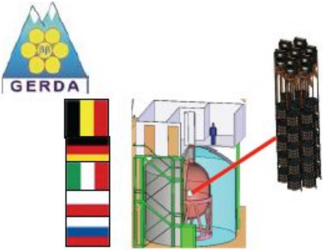


Large scale production chain not yet proven for some project

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

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:

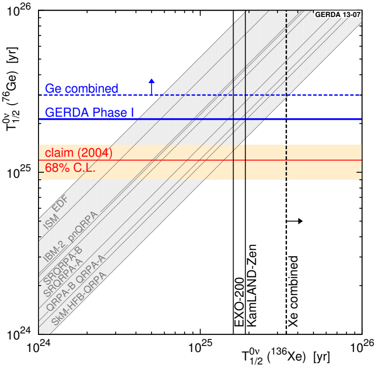
Open exchange of knowledge & technologies (e.g. MaGe, R&D)
Intention to merge for larger scale 1-tonne exp.
Select best techniques developed and tested in GERDA and MAJORANA

$0\nu\beta\beta$ 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)

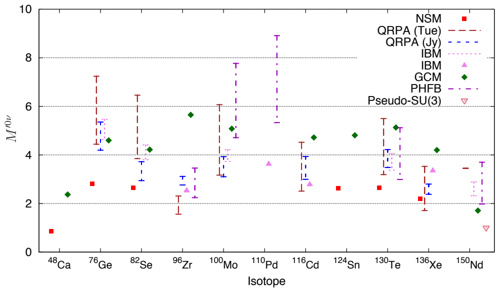
Conclusions:

- $0\nu\beta\beta$ observation would be a major discovery:
  - observe Lepton Number Violation
  - unveil the Majorana nature of neutrinos
- GERDA has 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 and GERDA Phase II)
- 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

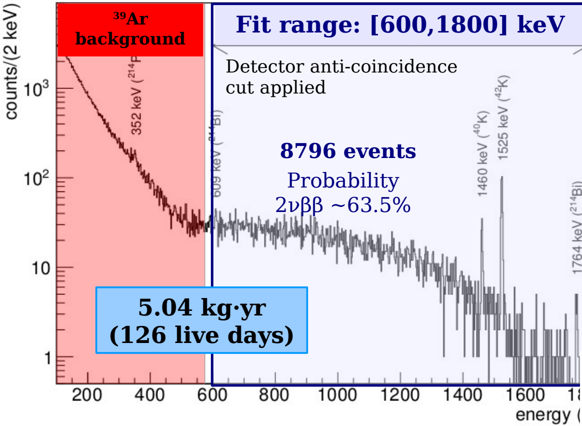
Isotope	**Abundance** [%]	$Q_{\beta\beta}[Mev]$ [MeV]	$G_{0\nu}$ $[10^{-14}\mathrm{yr}^{-1}]$
^{48}Ca	0.19	4.274	6.35
^{76}Ge	7.8	2.039	0.62
^{82}Se	9.2	2.996	2.70
^{96}Zr	2.8	3.348	5.63
^{100}Mo	9.6	3.035	4.36
^{116}Cd	7.6	2.809	4.62
^{130}Te	34.5	2.530	4.09
^{136}Xe	8.9	2.462	4.31
^{150}Nd	5.6	3.367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

Two Neutrino Double Beta Decay



^{39}Ar background

Fit range: [600,1800] keV

Detector anti-coincidence cut applied

8796 events

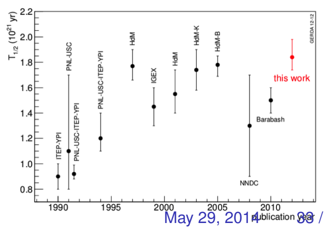
Probability $2\nu\beta\beta$ ~63.5%

5.04 kg·yr (126 live days)

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

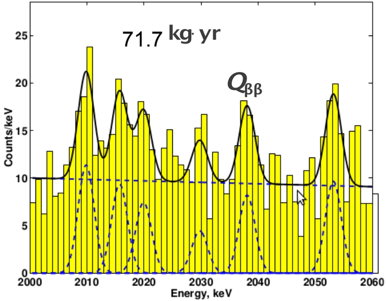
$$T^{2\nu}_{1/2} = (1.84^{+0.14}_{-0.10}) \cdot 10^{21}\ \text{yr}$$

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



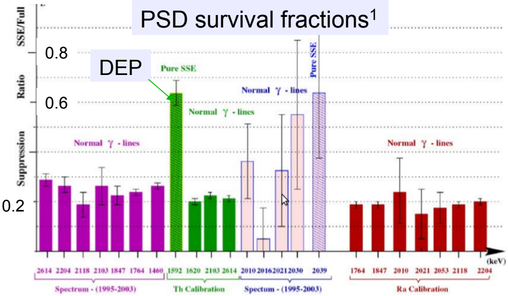
What value of Klapdor-Kleingrothaus to compare with?

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
$T^{0\nu}_{1/2} = (1.19^{+0.37}_{-0.23}) \cdot 10^{25}\,\mathrm{yr}$

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



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

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

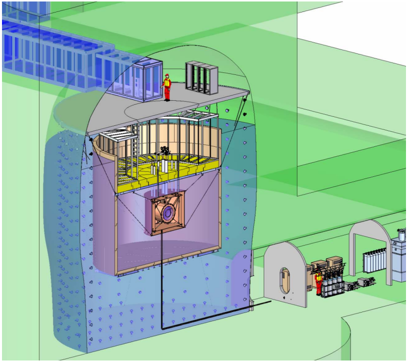
No efficiency correction is applied in any publication!

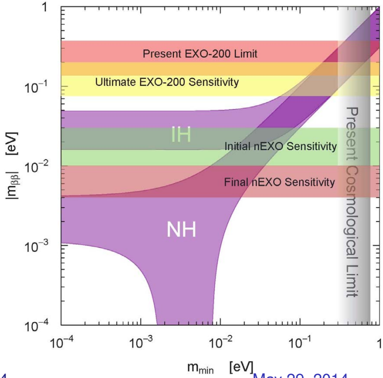
with given eff. $T^{0\nu}_{1/2}$ after PSD agrees with the one without

nEXO: the future evolution of EXO-200

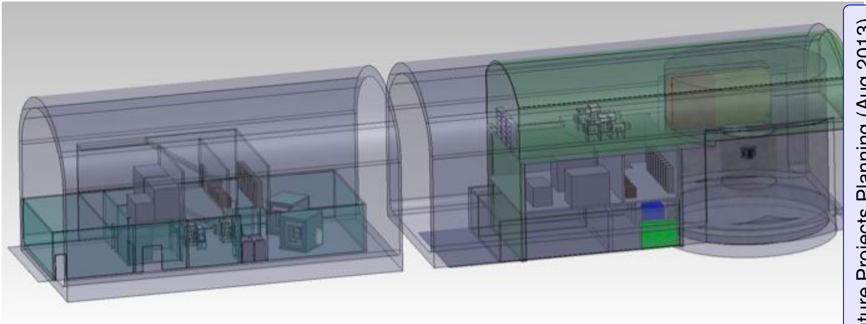
- Technique: same as for the EXO-200 TPC (×5 mass)
- Location: SNOlab, Sudbury (Canada)
- Source: ^{136}Xe (5 tonne)
- Timeline: ?

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





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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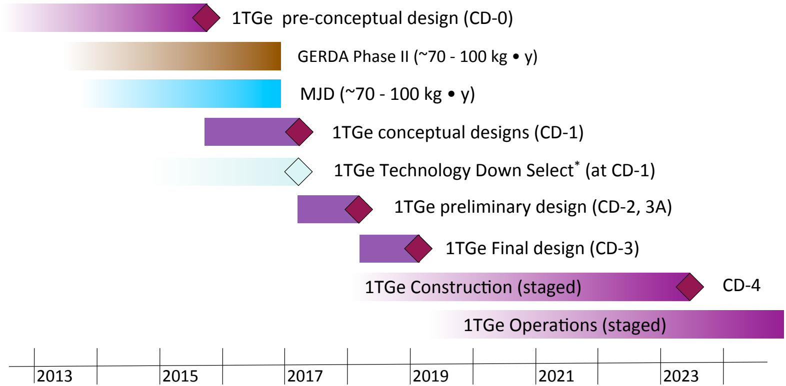
1TGe Projected Timeline

- 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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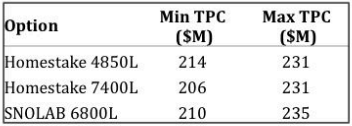
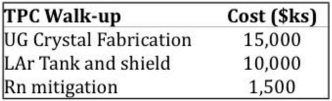
1TGe Preliminary Cost Estimate

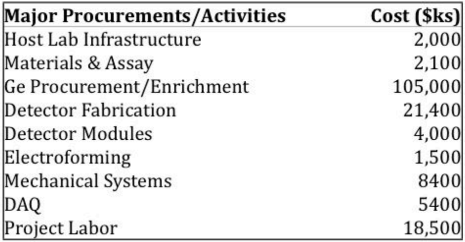
- Parametric estimate based on actual costs for MJD and GERDA experiments, with MJD the primary source
- Procurement costs generally scaled in linear fashion, except where cost reductions can be expected
- 30% contingency on MJD-based estimates, 50% on all others



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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