Neutrinoless Doube Beta Decay: physics, detectors (and very little electronics)

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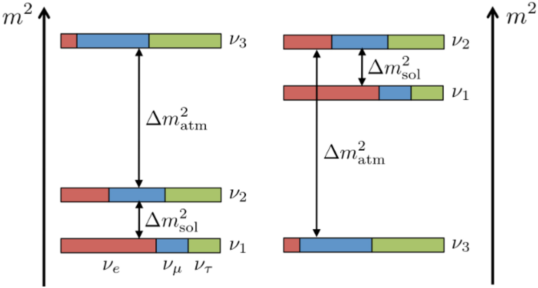
Neutrino mixing

- three Flavour Eigenstates
- three Mass Eigenstates

  $|\nu_\alpha >= \sum_{i=0}^{3} U_{\alpha,i} |\nu_i >$

- 9 parameters:
- 3 mixing angles: $\theta_{12},\ \theta_{13},\ \theta_{23}$
- 3 mass eigenstates: $m_1,\ m_2,\ m_3$
- 1 CP violating phase δ
- 2 Majorana phases: $\alpha_1,\ \alpha_2$



Normal Hierarchy (NH) Inverted Hierarchy (IH)

$c_{jk} \equiv \cos\theta_{jk}$ $s_{jk} \equiv \sin\theta_{jk}$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\, e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{11} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{j\alpha_1/2} & 0 & 0 \\ 0 & e^{j\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric Reactor (L∼ 1 km) Solar Majorana phases

Open questions in neutrino physics

- What is the correct mass hierarchy :

✓ Normal Hierarchy  versus Inverted Hierarchy 

- What is the neutrino nature: Dirac or Majorana ?

- Is there a CP violation in the neutrino sector ? ($e^{-i\delta}$)

- Is there new physics beyond the three neutrino model ?

$$|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1 \text{ (PMNS Unitarity) ?}$$

$$\Delta m^2_{13} + \Delta m^2_{21} + \Delta m^2_{32} = 0 \text{ ?}$$

- Can we use neutrinos as messengers to understand our Universe ?

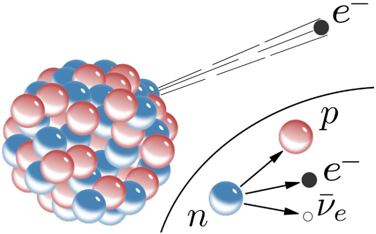
✓ look inside the core of a collapsing Supernova

✓ look at the earth's composition (Mantle & Core)

Double beta decays

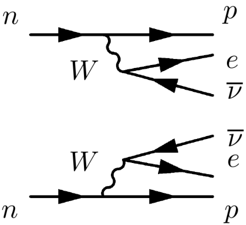
- it's a second order nuclear transition with two neutrons decaying into two protons:

$$(A, Z) \rightarrow (A, Z+2) + 2e^- + \dots$$



2-neutrinos double-β decay ($2\nu\beta\beta$)

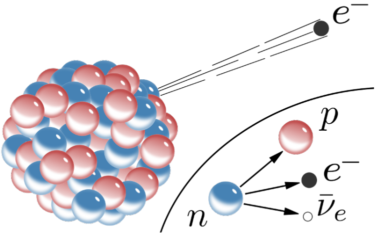
- it's a second order process, allowed in the Standard Model of Particle Physics
- first suggested by Goeppert-Mayer in 1935
  [M. Goeppert-Mayer, Phys. Rev., 48 (1935) 512]
- $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$
- it has been measured in several isotopes
- $T_{1/2}^{2\nu}$ in the range $10^{19} - 10^{24}$ yr



Double beta decays

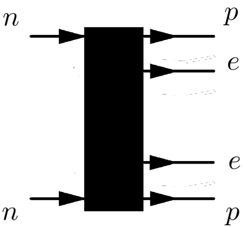
- it's a second order nuclear transition with two neutrons decaying into two protons:

$$(A, Z) \rightarrow (A, Z+2) + 2e^- + \ldots$$



Neutrinoless double-β decay ($0\nu\beta\beta$)

- foreseen by many extensions of the Standard Model of particle physics Particle Physics
- $(A, Z) \rightarrow (A, Z+2) + 2e^-$
- never observed so far, but allowed in several isotopes
- $T_{1/2}^{0\nu} > 10^{21} - 10^{26}$ yr



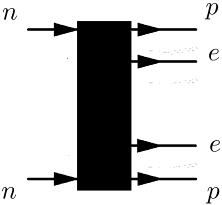
2-neutrinos double-β decay

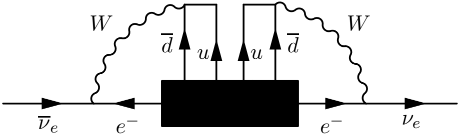
$t_{1/2}$ (10^{21} yr)	Isotope	Experiment	DOI
> 0.87	^{134}Xe	EXO-200	10.1103/PhysRevD.96.092001
$0.82 \pm 0.02 \pm 0.06$	^{130}Te	CUORE-0	10.1140/epjc/s10052-016-4498-6
$0.00690 \pm 0.00015 \pm 0.00037$	^{100}Mo	CUPID	10.1140/epjc/s10052-017-5343-2
$0.0274 \pm 0.0004 \pm 0.0018$	^{116}Cd	NEMO-3	10.1103/PhysRevD.95.012007
$0.064^{+.007}_{-.006}{}^{+.012}_{-.009}$	^{48}Ca	NEMO-3	10.1103/PhysRevD.93.112008
$0.00934 \pm 0.00022^{+.00062}_{-.00060}$	^{150}Nd	NEMO-3	10.1103/PhysRevD.94.072003
1.926 ± 0.094	^{76}Ge	GERDA	10.1140/epjc/s10052-015-3627-y
0.00693 ± 0.00004	^{100}Mo	NEMO-3	10.1103/PhysRevD.92.072011
$2.165 \pm 0.016 \pm 0.059$	^{136}Xe	EXO-200	10.1103/PhysRevC.89.015502
$9.2^{+5.5}_{-2.6} \pm 1.3$	^{78}Kr	BAKSAN	10.1103/PhysRevC.87.035501
$2.38 \pm 0.02 \pm 0.14$	^{136}Xe	KamLAND-Zen	10.1103/PhysRevC.85.045504
$0.7 \pm 0.09 \pm 0.11$	^{130}Te	NEMO-3	10.1103/PhysRevLett.107.062504
$0.0235 \pm 0.0014 \pm 0.0016$	^{96}Zr	NEMO-3	10.1016/j.nuclphysa.2010.07.009
$0.69^{+0.10}_{-0.08} \pm 0.07$	^{100}Mo	Ge coinc.	10.1016/j.nuclphysa.2010.06.010
$0.57^{+0.13}_{-0.09} \pm 0.08$	^{100}Mo	NEMO-3	10.1016/j.nuclphysa.2006.09.021
$0.096 \pm 0.003 \pm 0.010$	^{82}Se	NEMO-3	10.1103/PhysRevLett.95.182302

[C. Patrignani et al. (Particle Data Group), Chin. Phys. C40, 100001 (2016)]

Why search for neutrinoless double-β decay ?

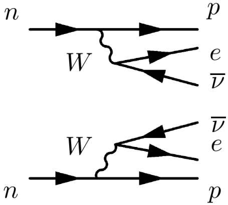
- if observed, would show a violation of the lepton number ($\Delta L = 2$)
- it's the only known way to probe the Majorana neutrino nature

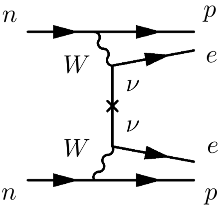


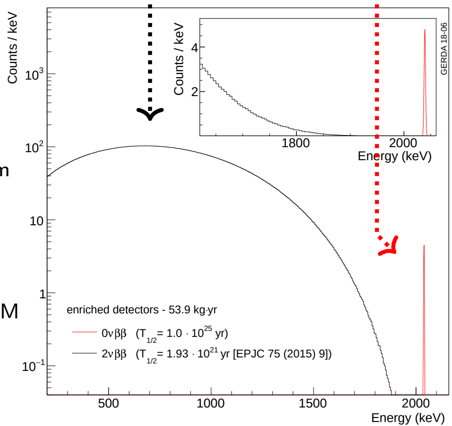


- Black Box theorem ([Schechter and Valle Phys.Rev.D25 (1982) 774]):
- non-null Majorana mass component
- bulk of neutrino mass not given by black-box operator ([Duerr et al., JHEP 1106 (2011) 091])

Double-β decay experimental signatures







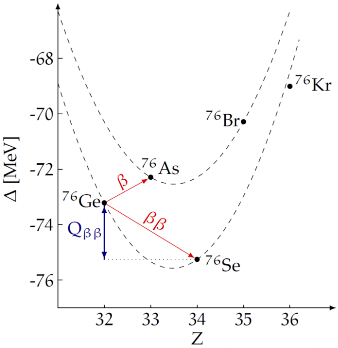
$2\nu\beta\beta$ decay

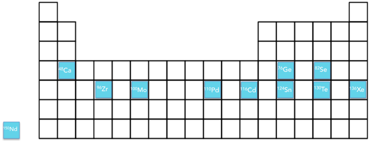
- energy continuum from 0 to $Q_{\beta\beta}$
- 2 electrons from vertex, 2 νs undetected
- foreseen in the SM

$0\nu\beta\beta$ decay

- peak at $Q_{\beta\beta}$
- 2 electrons from vertex
- lepton number violation $\Delta L = 2$

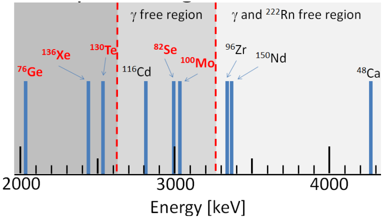
Double-β active isotopes





[from K. Schäffner]

- ~ 35 isotopes available, 9 can be used for $0\nu\beta\beta$ searches
- to observe double β-decay, single β-decay must be forbidden due to energy conservation constraints

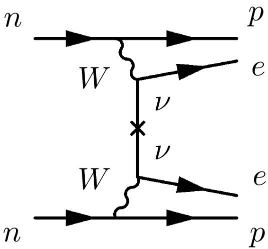


Isotope	Natural Abundance [%]	$Q_{\beta\beta}$ [keV]
^{48}Ca	0.19	4262.96(84)
^{76}Ge	7.6	2039.04(16)
^{82}Se	8.7	2997.9(3)
^{96}Zr	2.8	3356.097(86)
^{100}Mo	9.6	3034.40(17)
^{116}Cd	7.5	2813.50(13)
^{130}Te	34.5	2526.97(23)
^{136}Xe	8.9	2457.83(37)
^{150}Nd	5.6	3371.38(20)

How is $0\nu\beta\beta$ related to the neutrino mass

The simplest theory approach

- assume exchange of a light-Majorana ν
- possible in minimal extensions of the Standard Model (massive + Majorana ν)
- it is the dominant channel in most models

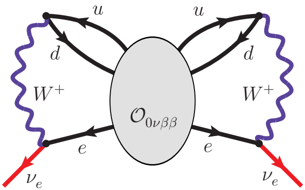


What we measure

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu} \cdot |\mathcal{M}_{0\nu}(A,Z)|^2 \cdot |m_{ee}|^2$$

- $G_{0\nu}$: phase space factor (calculable)
- $m_{ee} = \left|\sum_i U_{ei}^2 m_i\right|$
- U_{ei} : PNMS mixing matrix (complex) elements
- $\mathcal{M}_{0\nu}$: nuclear matrix element
- $|m_{ee}|$: effective Majorana mass

additional uncertainty from quenching of axial vector coupling (g_A)

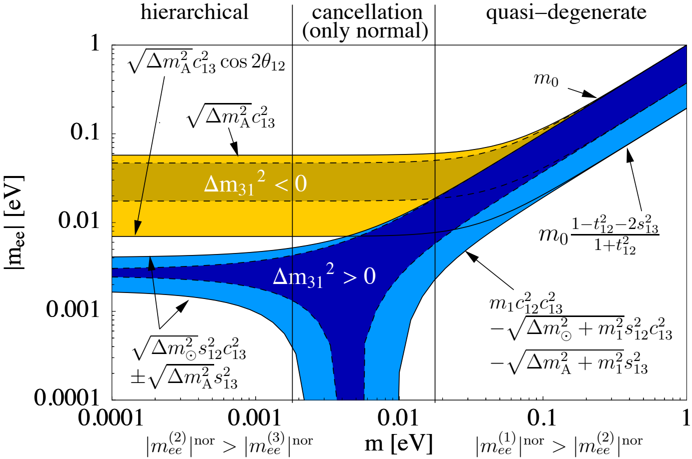


[J. Liu et al., Phys. Lett. **B 760** (2016) 571, arXiv 1606.0488]

Neutrino oscillations and double-β decay

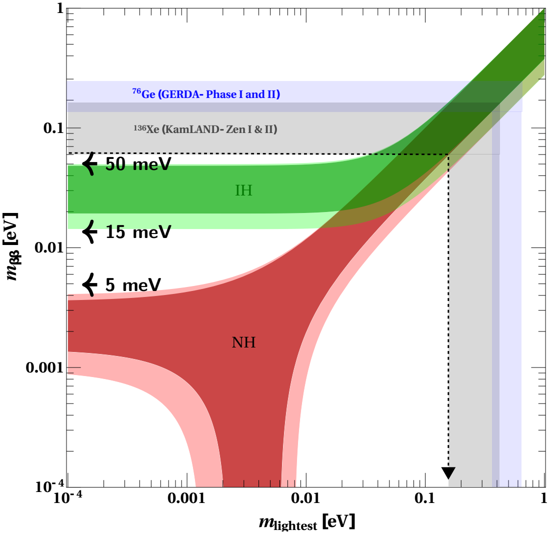
Effective Majorana mass:

$$|m_{ee}| = \left|\cos^2\theta_{12}\cos^2\theta_{13} m_1 + \sin^2\theta_{12}\cos^2\theta_{13} m_2 e^{j2\alpha_1} + \sin^2\theta_{13} m_3 e^{j2\alpha_2}\right|$$



[W. Rodejohann, J.Phys. G39 (2012) 124008]

$m_{\beta\beta}$ current limits



[Dell'Oro, Marcocci, Vissani, PRD90 (2014) 033005]

Most stringent limits

GERDA

$T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 0.9 \cdot 10^{26}$ yr

$\Rightarrow |m_{\beta\beta}| < (147 - 279)$ meV

KamLAND-Zen

$T^{0\nu}_{1/2}(^{136}\mathrm{Xe}) > 1.1 \cdot 10^{26}$ yr

$\rightarrow |m_{\beta\beta}| < (77 - 183)$ meV

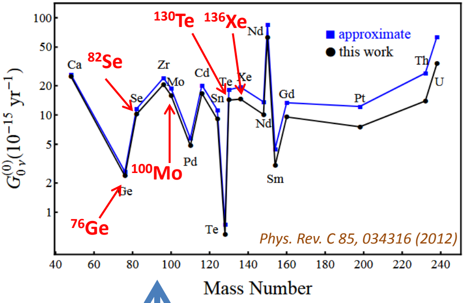
CUORE

$T^{0\nu}_{1/2}(^{130}\mathrm{Te}) > 0.2 \cdot 10^{26}$ yr

$\rightarrow |m_{\beta\beta}| < (110 - 520)$ meV

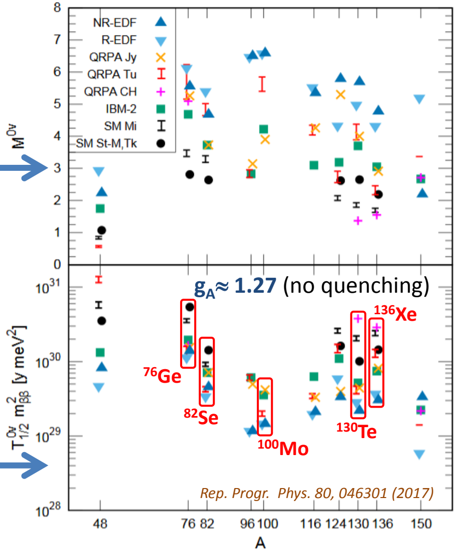
What are the difficulties ?

Phase space: exactly calculable



Phys. Rev. C 85, 034316 (2012)

Nuclear matrix elements: several models



Rep. Progr. Phys. 80, 046301 (2017)

$$1/\tau = G(Q,Z)\ g_A^{\,4}\ |M_{nucl}|^2\ \mathbf{m_{\beta\beta}}^{\,2}$$

[A. Giuliani, talk at Neutrino 2018]

Two experimental approaches

Source = Detector

- the source sample is active and acts simultaneously as detector of the $\beta\beta$ decay
- Pros :

  high detection efficiency

  provides the highest tested masses and best sensitivity, sofar

- Cons :

  serious limitations in the choice of the $0\nu\beta\beta$ isotope

  only few materials can satisfy the request to be at the same time the active material of a detector

- emblematic exceptions: ^{76}Ge (germanium dioded), ^{136}Xe (gas and liquid chambers) and ^{130}Te (bolometers)

Source $\neq$ Detector

- use an external-source (or inhomogeneous, or passive source) :

  the electrons emitted by a very thin source sample (~ 60 mg/cm^2 in NEMO3) are observed by means of external detectors (tracker, calorimeter)

- Pros :

- allow a full topological reconstruction of a $0\nu\beta\beta$ event
- much easier access to other physics channels (i.e. Majoron)
- in principle can deploy any $0\nu\beta\beta$ active isotope in the same detector

- Cons :

- much lower masses available
- very low detection efficiency

Experimental sensitivities

ROI background free

$$\boxed{T^{0\nu}_{1/2} > \ln 2 \cdot \epsilon \cdot (\mathit{mass} \cdot \mathit{time})}$$

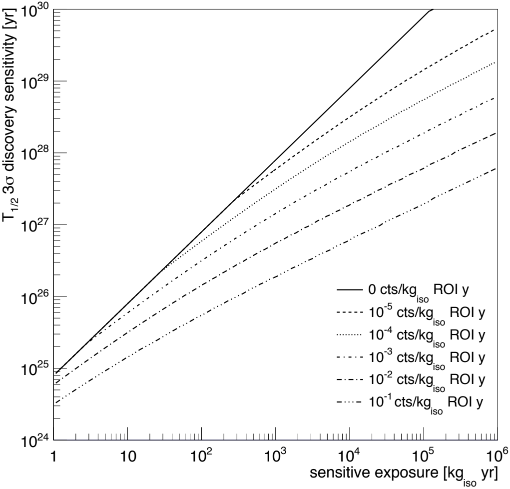
ROI background limited

$$\boxed{T^{0\nu}_{1/2} > \ln 2 \cdot \epsilon \cdot \sqrt{\frac{\mathit{mass} \cdot \mathit{time}}{\Delta E \cdot BI}}}$$

$\mathit{mass} \cdot \mathit{time} = \mathit{exposure}$

ΔE : energy resolution

BI : background level at $Q_{\beta\beta}$

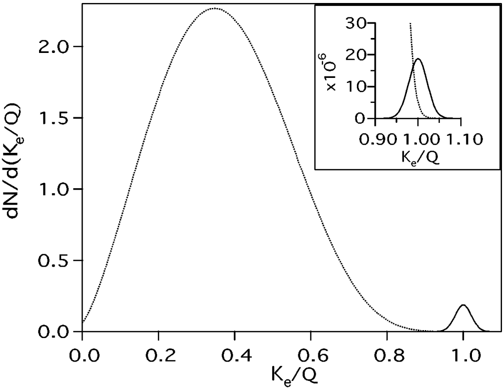


[Agostini, Benato, Detwiler, PRD96 (2017) 053001]

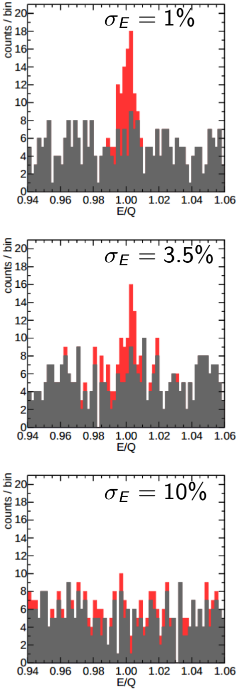
Mass, ΔE and BI at $Q_{\beta\beta}$ are crucial parameters for designing a $0\nu\beta\beta$ experiment

Energy resolution

- maybe the most relevant feature to identify the sharp $0\nu\beta\beta$ peak over an almost flat background
- very useful also to keep under control the background induced by the unavoidable tail of the $2\nu\beta\beta$ spectrum
- it represents a limiting factor in low resolving detectors



[J.J. Gomez-Cadenas and J. Martin-Albo, PoS(GSSI14) 004]



Isotopic Abundance

- another key ingredient in the choice of the $0\nu\beta\beta$ isotope
- in most of the cases, the values are in the few % range
- two significant extreme exceptions: ^{130}Te and ^{48}Ca
  - ^{130}Te is the only case in which a high sensitivity is possible even with natural samples
  - ^{48}Ca natural abundance is well below 1% ➜ isotopic enrichment is indispensable

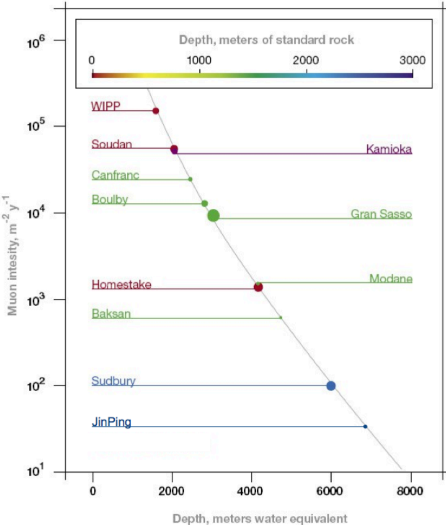
- to limit the detector size and since the background level scales roughly with the total mass of the detector, isotopic enrichment is a necessity for almost all next generation experiments

[O. Cremonesi and M. Pavan, Adv.High Energy Phys. 2014 (2014) 951432, arXiv: 1310.4692]

Isotope	$Q_{\beta\beta}$ (keV)	I.A.(%)	$G^{0\nu}$	$H^{0\nu}$
^{48}Ca	4272	0.187	24.81	826.2
^{76}Ge	2039	7.8	2.36	49.6
^{82}Se	2995	8.73	10.16	198.1
^{96}Zr	3350	2.8	20.58	342.7
^{100}Mo	3034	9.63	15.92	254.5
^{110}Pd	2018	11.72	4.82	70.0
^{116}Cd	2814	7.49	16.70	230.1
^{124}Sn	2287	5.79	9.04	116.5
^{128}Te	866	31.69	0.59	7.4
^{130}Te	2527	33.8	14.22	174.8
^{136}Xe	2458	8.9	14.58	171.4
^{148}Nd	1929	5.76	10.10	109.1
^{150}Nd	3371	5.64	63.03	671.7
^{154}Sm	1215	22.7	3.02	31.3
^{160}Gd	1730	21.86	9.56	95.5
^{198}Pt	1047	7.2	7.56	61.0

The Background Index (BI)

- another fundamental ingredient
- the possibility to reach the zero-background region, i.e. linear dependence on $m_{\beta\beta}$ and $T_{1/2}^{0\nu\beta\beta}$ is particularly appealing
- natural radioactivity of detector components (bulk or surface) is often the main background source
- external backgrounds originated outside the detector have also to be taken into account
- underground location is the usual and fundamental recipe to get rid of cosmic rays induced background (i.e. cosmogenic activations, neutrons, ...)
- a well designed effective shields may compensate the benefits of a very deep laboratory



Double Beta Decay Experiments around the World

SNO+

Sudbury

Majorana D

SURF

WIPP

EXO-200

Super-Nemo D

Frejus

Next-100

Canfranc

CUPID-0

CUORE

GERDA

LNGS

Panda X

JinPing

KAMLand-Zen

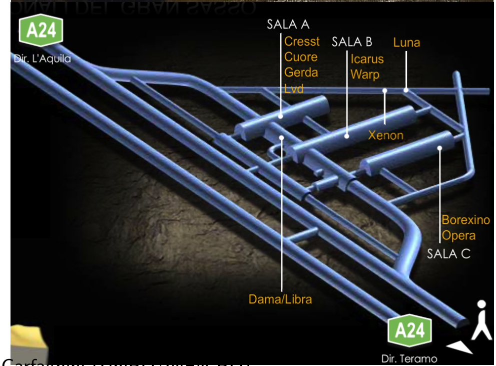
Kamioka

The Experiments: time schedule

		Running	Mid-Term	Long-Term
High Mass (scalability)	Xe-based TPC	EXO-200		nEXO
		NEXT-10	NEXT-100	NEXT-2.0
			PandaX-III 200	PandaX-III 1000
	Source embedded in Liquid Scintillator	KamLAND-Zen 800		KamLAND2-Zen
		SNO+ phase I		SNO+ phase II
High E resolution and Efficiency	Germanium diodes	GERDA-II MJD	LEGEND-200	LEGEND-1000
	Bolometers	AMoRE pilot, I	AMoRE, II	
		CUORE		
		CUPID-0	CUPID-Mo	CUPID

The Experiments: the details

Experiment	Isotope	Technique	Isotope Mass [kg]	Status
GERDA, phase I	^{76}Ge	^{enr}Ge diodes in LAr	18	completed
GERDA, phase II	^{76}Ge	^{enr}Ge diodes in LAr	31	running
MJD	^{76}Ge	point contact ^{enr}Ge diodes in vacuum	26	running
SuperNemo	^{82}Se	foils with tracking	7	under constr.
CUPID-0	^{82}Se	Zn^{enr}Se scintillating bolometers	5.2	running
CUPID-Mo	^{82}Se	Li$_2^{enr}$MoO$_4$ scintillating bolometers	5	start: 2018
CUORE	^{130}Te	^{nat}TeO$_2$ bolometer	210	running
SNO+, phase I	^{130}Te	0.5% ^{nat}TeBD in liquid scintillator	1357	start: 2019
EXO-200	^{136}Xe	liquid ^{enr}Xe in TPC	160	running
KamLAND-Zen 400	^{136}Xe	2.7% ^{enr}Xe in liquid scintillator	380	completed
KamLAND-Zen 800	^{136}Xe	^{enr}Xe in liquid scintillator	750	start: 2018
NEXT-100	^{136}Xe	high pressure ^{enr}Xe TPC	91	start: 2019
Legend-200	^{76}Ge	^{enr}Ge diodes in LAr, active LAr veto	175	Next Generation
Legend-1000	^{76}Ge	^{enr}Ge diodes in LAr, active LAr veto	873	
CUPID	Se/Mo/Te	enriched scintillating bolometers	300-500	
SNO+, phase II	^{130}Te	3% ^{nat}Te in liquid scintillator	7960	
nEXO	^{136}Xe	liquid ^{enr}Xe in TPC	4500	
KamLAND2-Zen	^{136}Xe	^{enr}Xe in liquid scintillator	1000	
NEXT-2.0	^{136}Xe	high pressure ^{enr}Xe TPC	91	



LNGS

Depth: 3600 m.w.e

Three large experimental halls
Environmental rates:

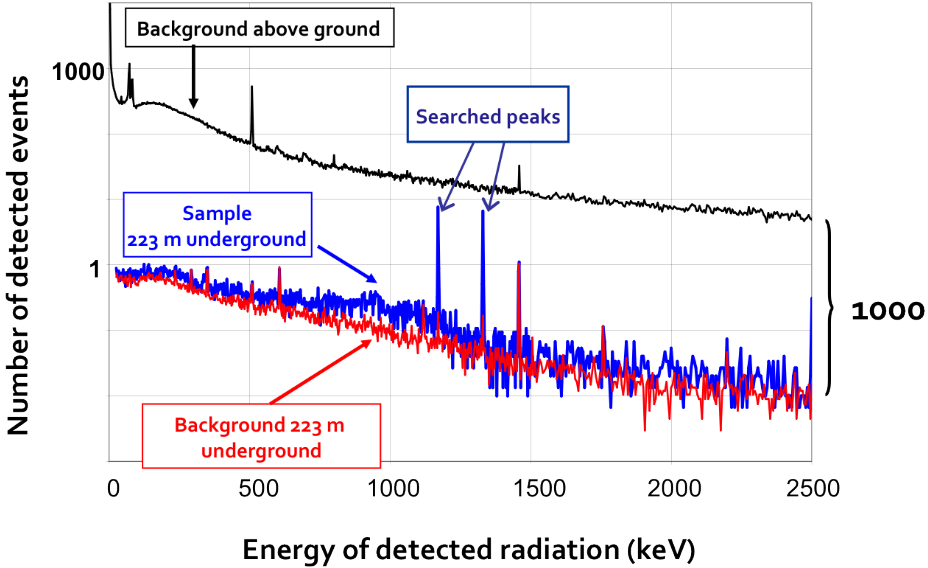
muons: $2.58 \times 10^{-8}/(\mathrm{cm}^2\ \mathrm{s})$

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

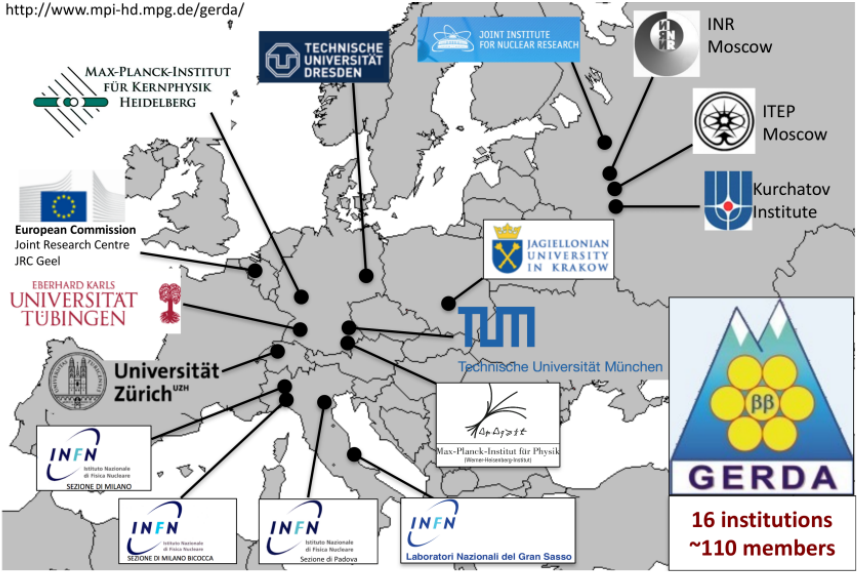
neutrons: $4 \times 10^{-6}/(\mathrm{cm}^2\ \mathrm{s})$

Double Beta Decay Experiments:
- GERDA,
- CUORE,
- CUPID-0

Why we have to go underground



The GERDA Collaboration



http://www.mpi-hd.mpg.de/gerda/

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Max-Planck-Institut für Physik

INFN Istituto Nazionale di Fisica Nucleare SEZIONE DI MILANO

INFN Istituto Nazionale di Fisica Nucleare SEZIONE DI MILANO BICOCCA

INFN Istituto Nazionale di Fisica Nucleare Sezione di Padova

INFN Laboratori Nazionali del Gran Sasso

GERDA

16 institutions
~110 members

GERDA history and Sensitivity

GERDA Phase I (Nov 2011 - May 2013)

- BI $\sim 10^{-2}$cts/(keV $\cdot$ kg $\cdot$ yr)
- exposure: 21.6 kg yr
- limit: $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% CL)

  [PRL 111 (2013) 122503]

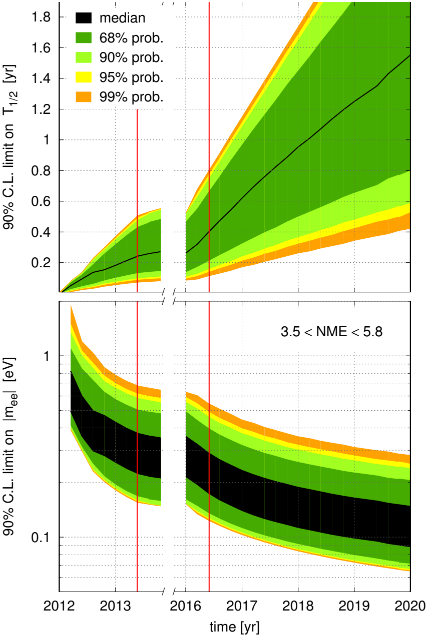
GERDA Upgrade (2013-2015)

- doubled target mass
- improved detector to reduce background

GERDA Phase II - from Dec 2015

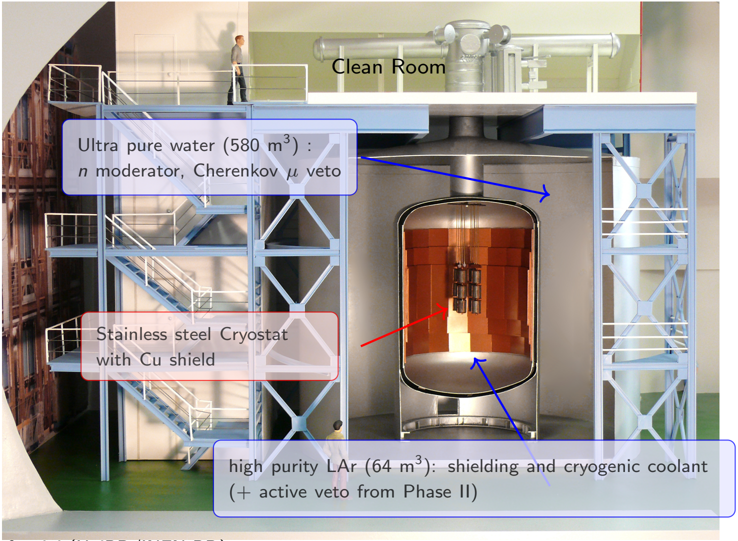
- BI $\sim 10^{-3}$cts/(keV $\cdot$ kg $\cdot$ yr)
- exposure: > 100 kg yr
- current limit: $T^{0\nu}_{1/2} > 9.0 \cdot 10^{25}$ yr (90% CL

  [PRL 120 (2018) 132503]



The GERDA Detector

- onion-like shielding against environmental background
- Careful selection (screening) of employed materials

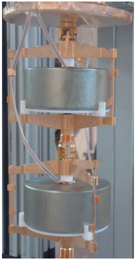


Ultra pure water (580 m^3) : *n* moderator, Cherenkov μ veto

Stainless steel Cryostat with Cu shield

high purity LAr (64 m^3): shielding and cryogenic coolant (+ active veto from Phase II)

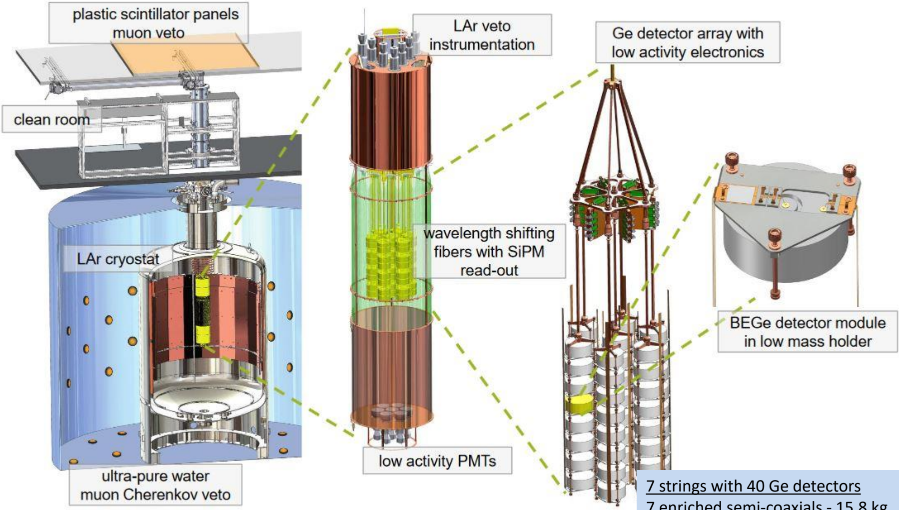
BEGe detector string, fase I



GERDA Phase-II Setup

LNGS 3600 m w.e.

Phase I from Nov 2011 to May 2013
21 kg yr



plastic scintillator panels muon veto

clean room

LAr cryostat

ultra-pure water muon Cherenkov veto

LAr veto instrumentation

wavelength shifting fibers with SiPM read-out

low activity PMTs

Ge detector array with low activity electronics

BEGe detector module in low mass holder

<u>7 strings with 40 Ge detectors</u>
7 enriched semi-coaxials - 15.8 kg
30 enriched BEGe 20 kg
3 natural semi-coaxials

EPJC 78 (2018) 388

GERDA germanium detectors

- the use of Germanium detector to search for $0\nu\beta\beta$ goes back to 1967
- allow a calorimetric approach, being the best detector for gamma spectroscopy in the MeV range

- search for neutrinoless double beta decay of ${}^{76}\mathrm{Ge}$

  ${}^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se} + 2e^-$
- ${}^{76}\mathrm{Ge}$ Q-value: $Q_{\beta\beta} = 2039$ keV
- need isotopic enrichment (dioded enriched to 86% in ${}^{76}\mathrm{Ge}$)

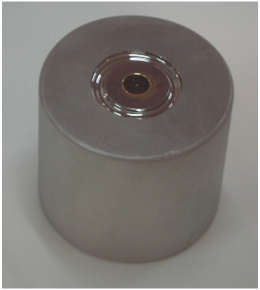
- three type of detectors used:

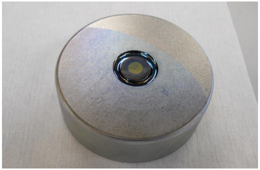
\- Broad Energy Germanium detectors (BEGe)

\- Coaxial detectors (Coax)

\- Inverted Coax Point Contact germanium detectors (ICPC) (since May 2018)

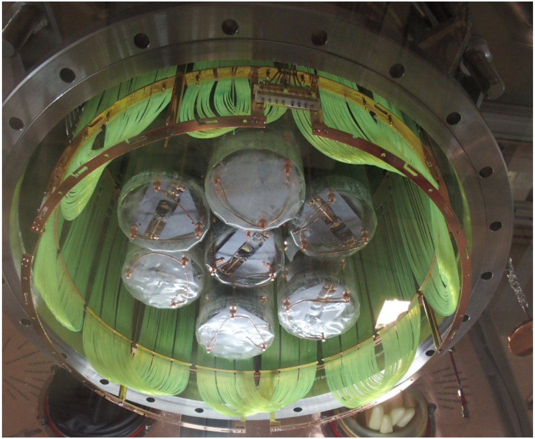
COAX



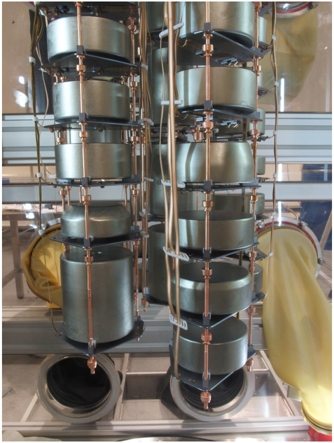


BEGE

GERDA germanium detectors strings



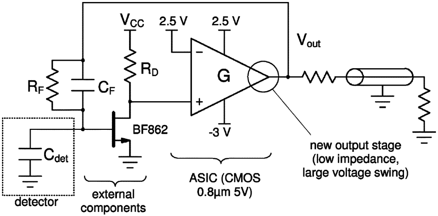
LAr veto bottom view with pilot string in open lock

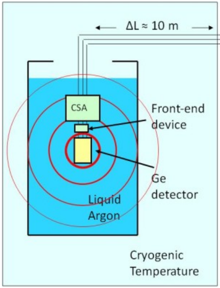


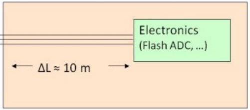
Detector array assembly: 40 detectors in 7 strings

GERDA electronics

- a charge sensitive amplifier very close to the detectors output
- radioactive contamination of electronics is a very important aspect
- Phase I ➜ CC2 (Commercial C-Mos 2)
- 3 channel CSA, 1 JFET & 1 CMOS OpAmp (limited dynamics)
- Phase II ➜ CC3 "v1"
- VFE (JFET: SF291, Cf and Rf) separated from the main CSA
- 4 channel CSA, 1 JFET & 1 CMOS & 1 SiGe OpAmp (12 V)
- Phase II ➜ CC3 "v2" (current version)
- VFE (JFET: BF862, Cf and Rf) close but separated from main CSA
- 4 channel CSA, 1 JFET & 2 OpAmps







Radioactivity issue:

$\sum \frac{(\text{Material Activity} * \text{Volume})}{\Delta r2}$

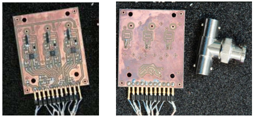
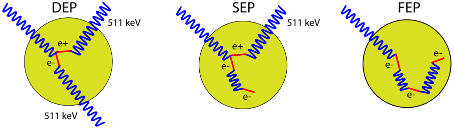


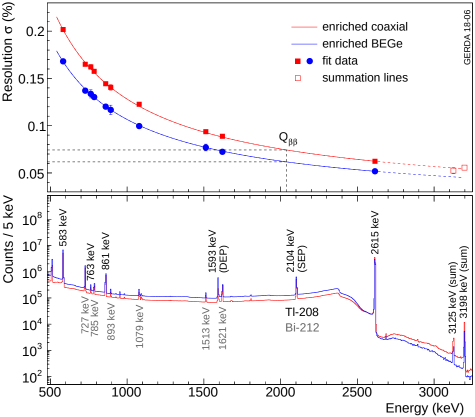
Fig. 12: The 3 channel CC2 integrated CSA (with external BF862 JFET), used as the Ge front-end readout electronics for GERDA Phase I.

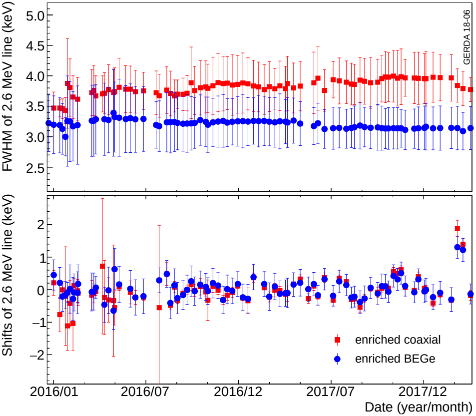
[S. Riboldi et al, IEEE Trans. Nucl. Sci. 75 (2010) 737]

GERDA Calibration and Energy Resolution

- weekly calibration runs with ^{228}Th
- pulser used to monitor energy scale
- small changes between energy calibrations ($<$ 1 keV) allowed
- $\Delta E(Q_{\beta\beta})$: 3.6(1) keV (COAX), 3.0(1) keV (BEGe)



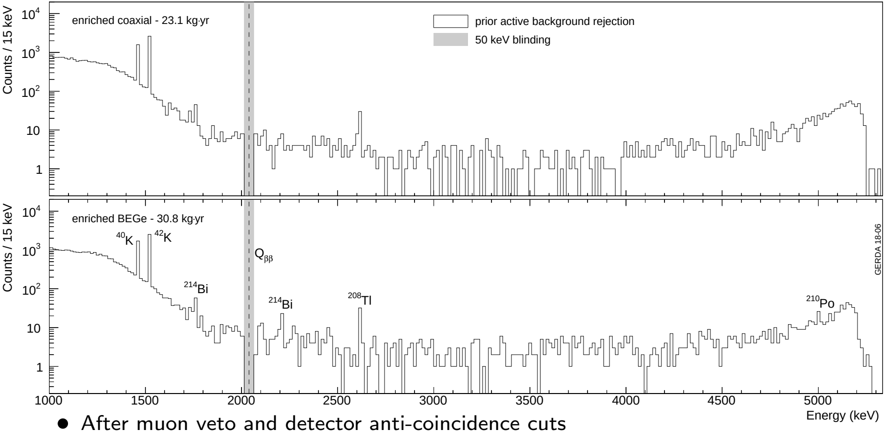




A. Garfagnini (UniPD/INFN-PD)

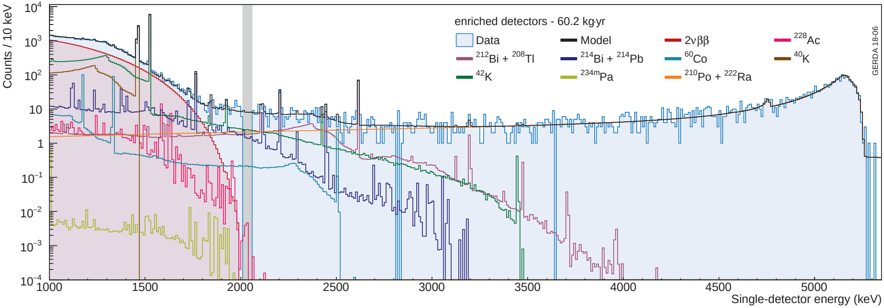
GERDA Full Spectrum

- Phase II data taking going on since Dec 2015
- blind window: ±25 keV around $Q_{\beta\beta}$



- After muon veto and detector anti-coincidence cuts
- Main Bbckgrounds: ^{40}K, ^{42}K and αs from ^{210}Po at high energies

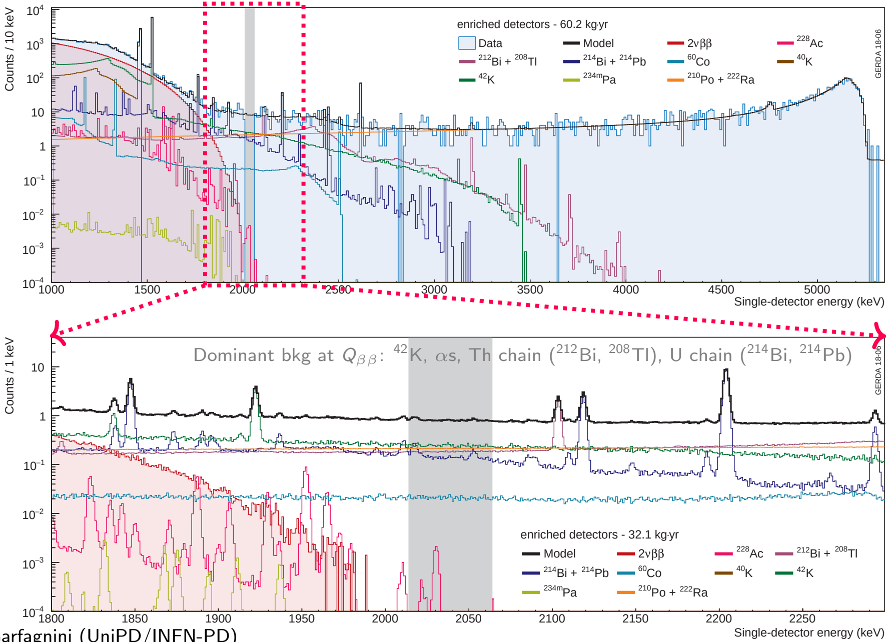
GERDA Background Model



- Features of the spectrum (from left to right):

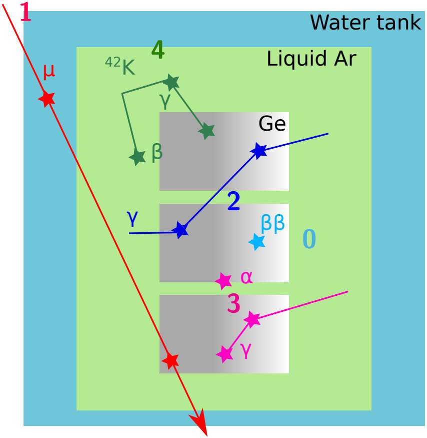
- ^{39}Ar ($E < 500$ keV)
- $2\nu\beta\beta$ continuum
- ^{40}K and ^{42}K γ lines,
- α particles

GERDA Background Model



Dominant bkg at $Q_{\beta\beta}$: ^{42}K, αs, Th chain (^{212}Bi, ^{208}Tl), U chain (^{214}Bi, ^{214}Pb)

GERDA background reduction techniques



Background

1 Muon Veto: Cherenkov photons in the water tank

2 Reject background via anti-coincidence of multiple detectors

3 Pulse Shape Discrimination (PSD): identify multiple interactions (Multiple Site Events) and surface events

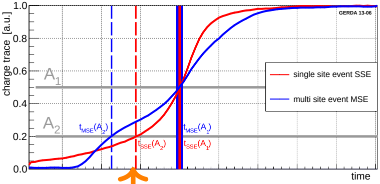
4 LAr Veto: detect scintillation light from γ and β in Liquid Argon

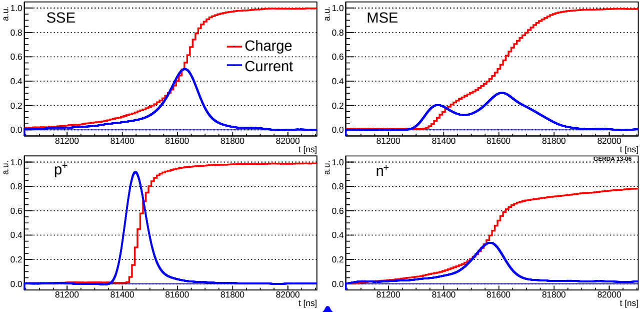
Signal

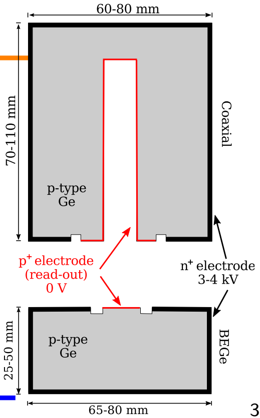
0 single energy deposition within a small detector volume (**Single Site Events**)

Pulse Shape Discrimination in GERDA

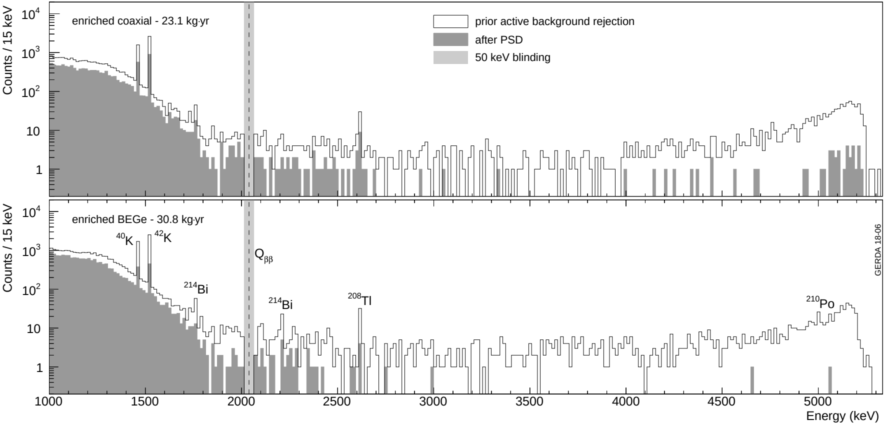
- Phase I: p-type semi-coaxial
- Phase II: p-type, Broad Energy Germanium (BEGe)
- Signal structure allows to discriminate between Single-Site-Events (SSE) and Multiple-Site-Events (MSE)





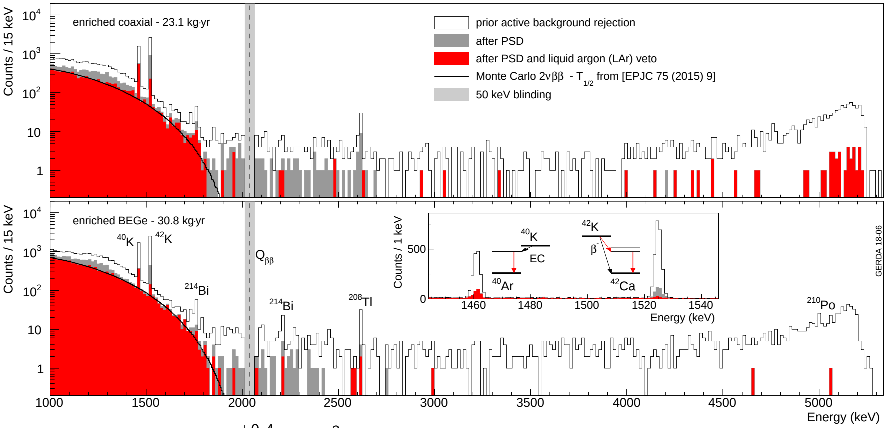


GERDA Full Spectrum: after PSD



GERDA Full Spectrum: after PSD + LAr Veto

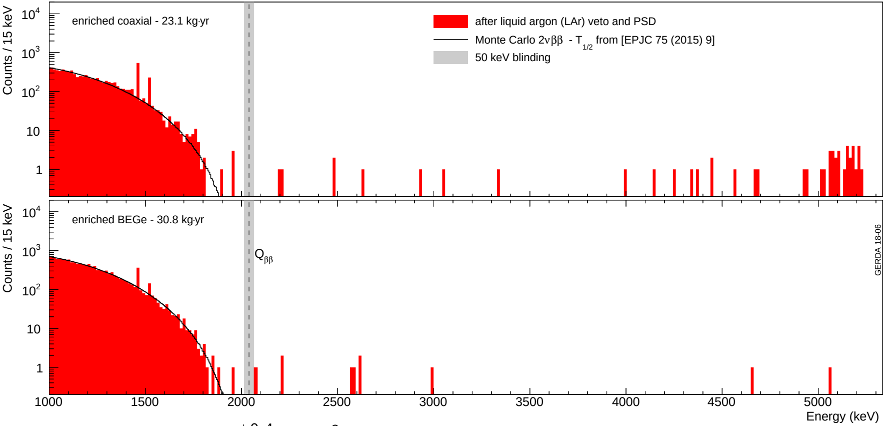
- High efficient LAr and PSD cuts
- blind window: ±25 keV around $Q_{\beta\beta}$



- BI at $Q_{\beta\beta} = 0.6^{+0.4}_{-0.3} \cdot 10^{-3}$ cts/keV kg yr

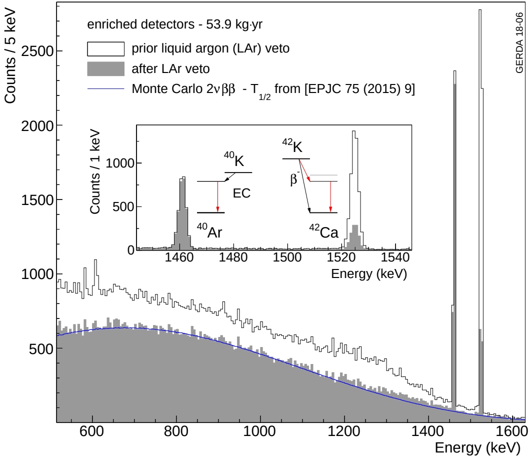
GERDA Final Spectrum

- High efficient LAr and PSD cuts
- blind window: ±25 keV around $Q_{\beta\beta}$



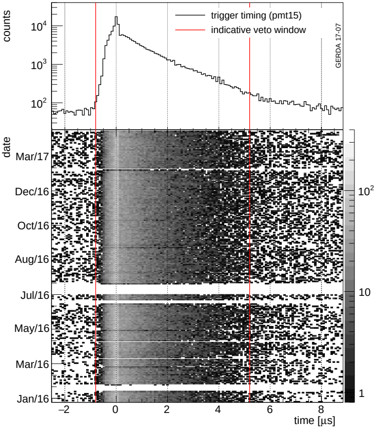
- BI at $Q_{\beta\beta} = 0.6^{+0.4}_{-0.3} \cdot 10^{-3}$ cts/keV kg yr

The GERDA LAr active veto

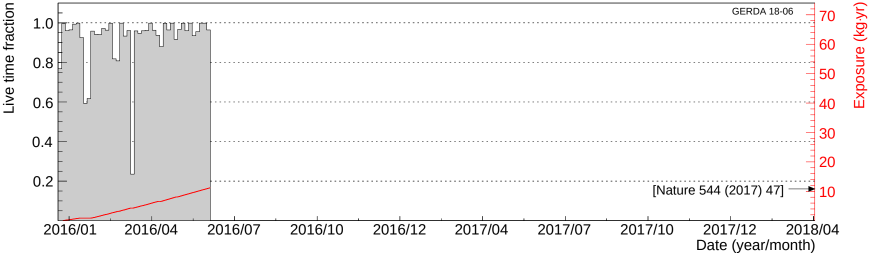


LAr veto acceptance 97.7(7)%

LAr time stability



GERDA-II Data Taking



June 2016 10.8 kg yr

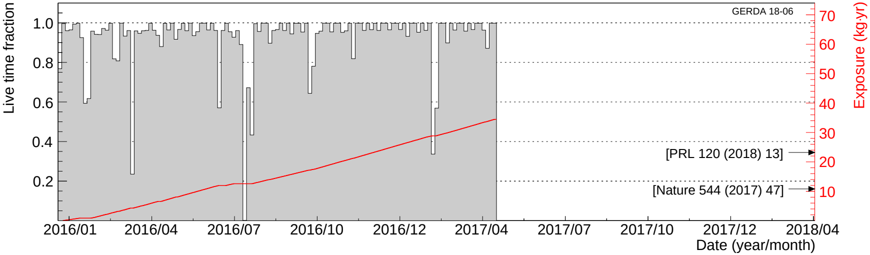
Background-free search for neutrinoless double-β decay of ^{76}Ge with GERDA

The GERDA Collaboration*

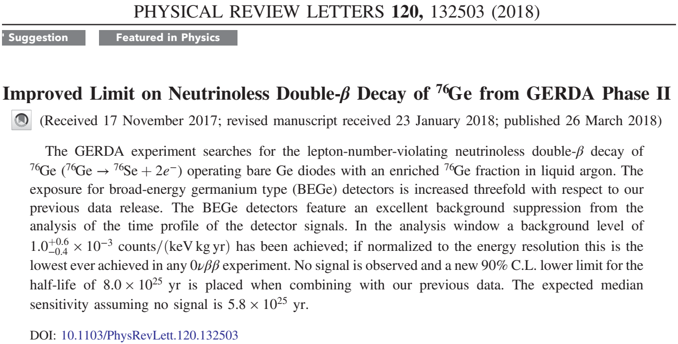
[M. Agostini et al, Nature 544, (2017) 47]

Many extensions of the Standard Model of particle physics explain the dominance of matter over antimatter in our Universe by neutrinos being their own antiparticles. This would imply the existence of neutrinoless double-β decay, which is an extremely rare lepton-number-violating radioactive decay process whose detection requires the utmost background suppression. Among the programmes that aim to detect this decay, the GERDA Collaboration is searching for neutrinoless double-β decay of ^{76}Ge by operating bare detectors, made of germanium with an enriched ^{76}Ge fraction, in liquid argon. After having completed Phase I of data taking, we have recently launched Phase II. Here we report that in GERDA Phase II we have achieved a background level of approximately 10^{-3} counts keV^{-1} kg^{-1} yr^{-1}. This implies that the experiment is background-free, even when increasing the exposure up to design level. This is achieved by use of an active veto system, superior germanium detector energy resolution and improved background recognition of our new detectors. No signal of neutrinoless double-β decay was found when Phase I and Phase II data were combined, and we deduce a lower-limit half-life of 5.3×10^{25} years at the 90 per cent confidence level. Our half-life sensitivity of 4.0×10^{25} years is competitive with the best experiments that use a substantially larger isotope mass. The potential of an essentially background-free search for neutrinoless double-β decay will facilitate a larger germanium experiment with sensitivity levels that will bring us closer to clarifying whether neutrinos are their own antiparticles.

GERDA-II Data Taking



June 2017 +12.4 kg yr


PHYSICAL REVIEW LETTERS **120,** 132503 (2018)

' Suggestion Featured in Physics

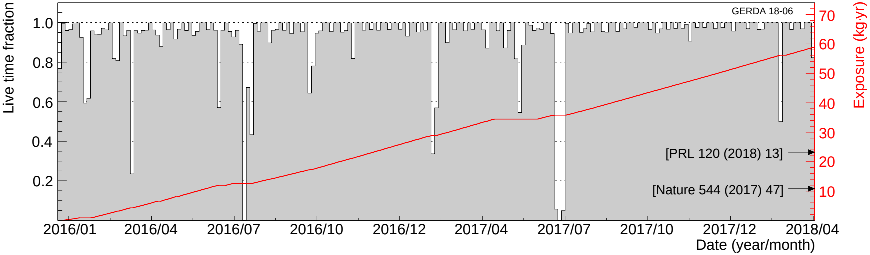
Improved Limit on Neutrinoless Double-β Decay of ^{76}Ge from GERDA Phase II

(Received 17 November 2017; revised manuscript received 23 January 2018; published 26 March 2018)

The GERDA experiment searches for the lepton-number-violating neutrinoless double-β decay of ^{76}Ge ($^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se} + 2e^-$) operating bare Ge diodes with an enriched ^{76}Ge fraction in liquid argon. The exposure for broad-energy germanium type (BEGe) detectors is increased threefold with respect to our previous data release. The BEGe detectors feature an excellent background suppression from the analysis of the time profile of the detector signals. In the analysis window a background level of $1.0^{+0.6}_{-0.4} \times 10^{-3}$ counts/(keV kg yr) has been achieved; if normalized to the energy resolution this is the lowest ever achieved in any $0\nu\beta\beta$ experiment. No signal is observed and a new 90% C.L. lower limit for the half-life of 8.0×10^{25} yr is placed when combining with our previous data. The expected median sensitivity assuming no signal is 5.8×10^{25} yr.

DOI: 10.1103/PhysRevLett.120.132503

GERDA-II Data Taking

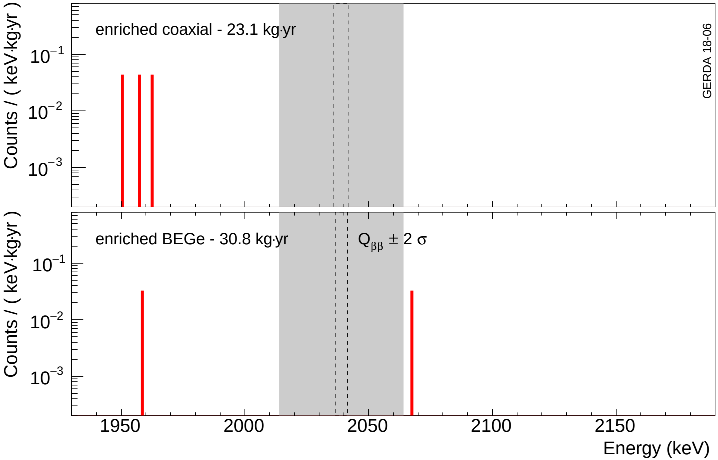


June 2018 : +35.7 kg yr

paper in preparation, to be submitted soon

GERDA $0\nu\beta\beta$ analysis

- result in region of interest (ROI) before unblinding

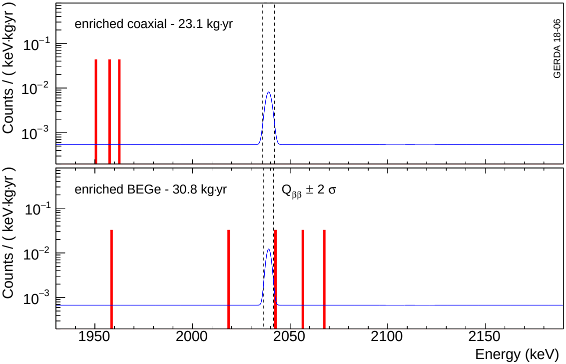


GERDA $0\nu\beta\beta$ analysis

- Combined unbinned maximum likelihood fit of Phase I and Phase II data sets in (1930-2190) keV energy interval

Frequentist analysis

- best fit $N^{0\nu} = 0$
  - $T^{0\nu}_{1/2} > 9.1 \cdot 10^{25}$ yr at (90% CL)
- median sensitivity (no signal):
  - $T^{0\nu}_{1/2} > 11.0 \cdot 10^{25}$ yr at (90% CL)



$$\mathrm{BI} = 0.6^{+0.4}_{-0.3} \cdot 10^{-3}\ \mathrm{cts/\,(keV\ kg\ yr)}$$

Bayesian analysis

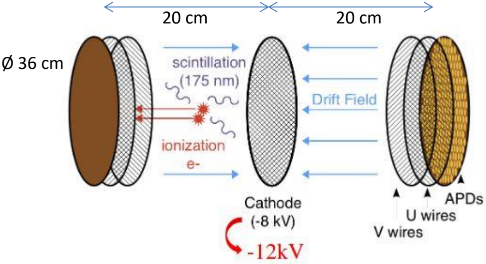
- best fit $N^{0\nu} = 0$
  - $T^{0\nu}_{1/2} > 7.6 \cdot 10^{25}$ yr at (90% CL)
- median sensitivity (no signal):
  - $T^{0\nu}_{1/2} > 8.2 \cdot 10^{25}$ yr at (90% CL)

The Experiments: time schedule

		Running	Mid-Term	Long-Term
High Mass (scalability)	Xe-based TPC	EXO-200 NEXT-10	NEXT-100 PandaX-III 200	nEXO NEXT-2.0 PandaX-III 1000
	Source embedded in Liquid Scintillator	KamLAND-Zen 800 SNO+ phase I		KamLAND2-Zen SNO+ phase II
High E resolution and Efficiency	Germanium diodes	GERDA-II MJD	LEGEND-200	LEGEND-1000
	Bolometers	AMoRE pilot, I CUORE CUPID-0	AMoRE, II CUPID-Mo	CUPID

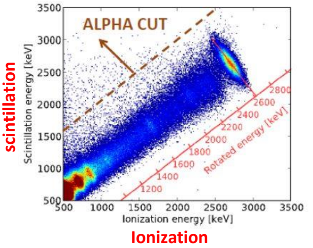
EXO-200 / ^{136}Xe principle

WIPP, Carlsbad, NM 1624 m.w.e.



- cylindrical single phase TPC filled with ≈200 kg of liquid Xe enriched to 80.6% in ^{136}Xe
- fiducial volume 76.5 kg
- discrimination between single-site (signal-like) and multi-site (background) events
- 1st working hundred-kilogram-scale detector

Scintillation vs. ionization, ^{228}Th calibration:



anti-correlation between charge and scintillation response exploited for improved energy resolution

Phase I:

$T^{0\nu}_{1/2}$ sensitivity : $1.9 \cdot 10^{25}$ yr
$T^{0\nu}_{1/2}$ limit* : $> 1.1 \cdot 10^{25}$ yr

* profile likelihood (90% CL)

Nature 510 (2014) 229

EXO-200 Latest results, Rencontres de Moriond 2018

Phase I 2011 exposure 10 kg·yr; break in 2014-2015 due to fire and radiation problems in WIPP; upgrade, restart 2016

[K. T. Knoepfle, talk at CIPAN2018]

EXO-200 / ^{136}Xe results

Upgrade for Phase II

Cathode voltage -8kV → -12kV
Radon suppression by factor of 10
Noise reduction, improved resolution

Will run up to $5 \cdot 10^{25}$ yr sensitivity

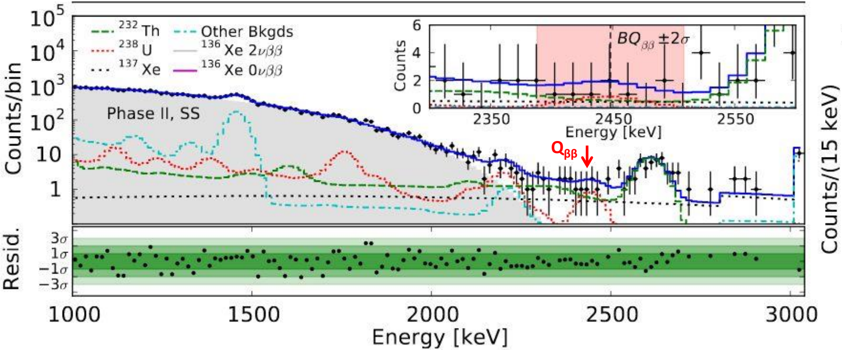
Phase I and II:

exposure = 177.6 kg·yr
FWHM@$Q_{\beta\beta}$ = 71 keV (2.9%)
BI = $(1.6 \pm 0.2) \cdot 10^{-3}$ cnts/(keV ·kg ·yr)

$T^{0\nu}_{1/2}$ sensitivity : $3.7 \cdot 10^{25}$ yr
$T^{0\nu}_{1/2}$ limit* : $> 1.8 \cdot 10^{25}$ yr

* profile likelihood (90% CL)

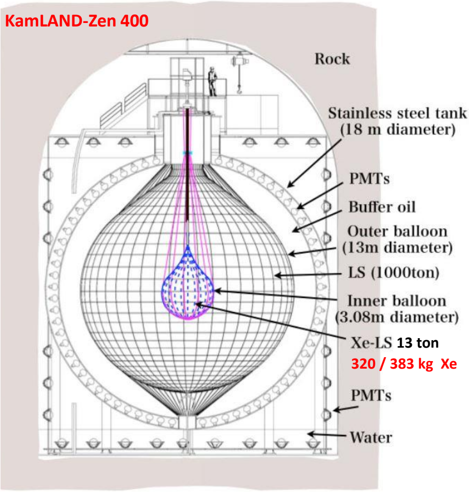
[K. T. Knoepfle, talk at CIPAN2018]



PRL 120, 072701 (2018)

KamLAND-Zen 400 / ^{136}Xe setup

Kamioka 2700 m.w.e.



^{136}Xe (≈ 3%) loaded liquid scintillator
(90% enrichment)

Phase I (2011-2012) 89.5 kg·yr

$T^{0\nu}_{1/2}$ sensitivity : $1.0 \cdot 10^{25}$ yr
$T^{0\nu}_{1/2}$ limit* : $> 1.9 \cdot 10^{25}$ yr

PRL , 062502 (2013)

unexpected contamination in ROI identified as ^{110m}Ag from Fukushima accident or spallation

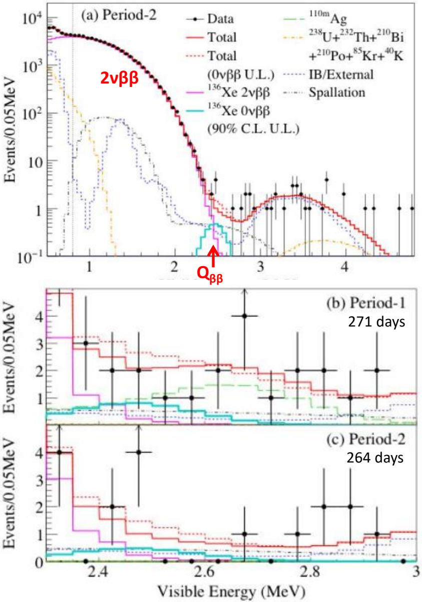
purification reduces ^{110m}Ag by factor of 1

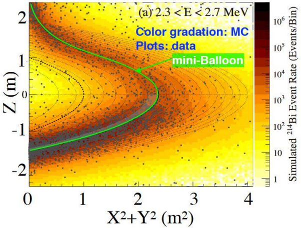
Phase II (2013-2015) 504 kg·yr

[K. T. Knoepfle, talk at CIPAN2018]

KamLAND-Zen 400 / ^{136}Xe results

Phase II





Background dominated by ^{214}Bi decays at MIB

[K. T. Knoepfle, talk at CIPAN2018]

exposure = 593.5 kg·yr

FWHM@$Q_{\beta\beta}$ ≈ 270 keV (11%)

BI ≈ $0.4 \cdot 10^{-3}$ cnts/(keV ·kg ·yr)

$T^{0\nu}_{1/2}$ sensitivity : $5.6 \cdot 10^{25}$ yr

$T^{0\nu}_{1/2}$ limit* : > $9.2 \cdot 10^{25}$ yr

$T^{0\nu}_{1/2}$ limit** : > $10.7 \cdot 10^{25}$ yr

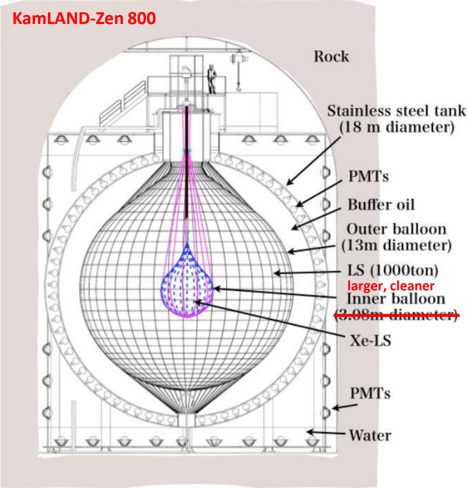
* profile likelihood (90% CL)

** Phase I + II combined

PRL , 082503 (2016)

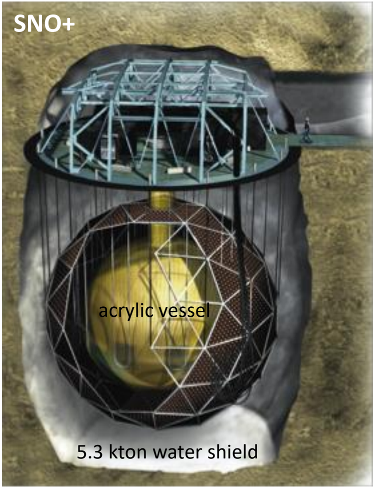
KamLAND-Zen 800 & SNO+ expected to start in 2018/19

Kamioka 2700 m.w.e.



≈750kg of ^{136}Xe in liquid scintillator (LS) (90% enrichment), new Inner Balloon

SNOLAB 6000 m.w.e.



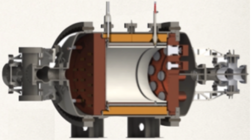
Plan for Phase I: 0.5% ^{nat}Te, i.e. 1.3 tons of ^{130}Te, in 780 tons of LS, - all contained in the Ø12m acrylic vessel

[K. T. Knoepfle, talk at CIPAN2018]

Xenon Experiments: next

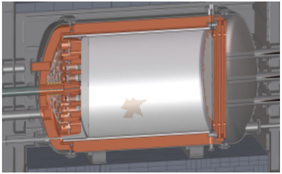
^{136}Xe high-pressure (10-15 bar) TPC

NEXT-NEW (5 kg) 2015-2018



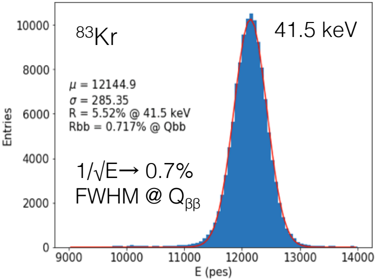
Underground & radio-pure operations, background, 2νββ

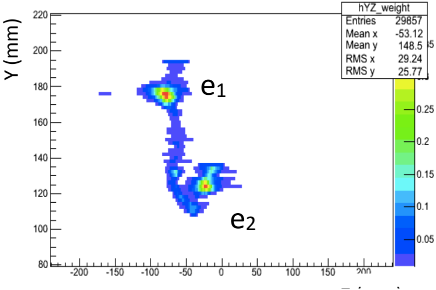
NEXT-100 (100 kg) 2018-2020's



0νββ search

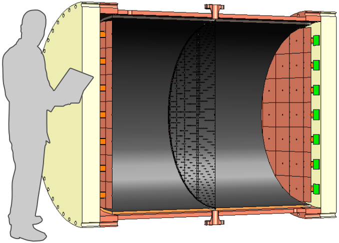
NEXT-ton

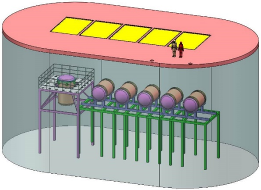




[S. Schoenert, talk at TAUP2017]

Xenon Experiments: PandaX-III





[S. Schoenert, talk at TAUP2017]

- First 200-kg module:
  - Microbulk Micromegas for charge readout
  - 3% FWHM, 1 x 10^{-4} c/keV/kg/y in the ROI
- Ton-scale:
  - Four more modules with upgraded charge readout and better low-background material screening.
  - 1% FWHM, 1 x 10^{-5} c/keV/kg/y in the ROI

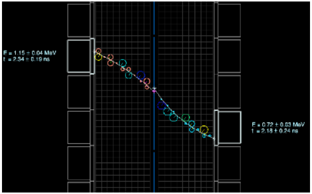
source ≠ detector

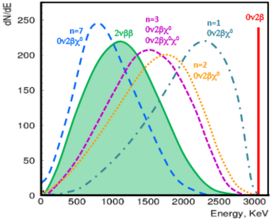
SuperNEMO

^{82}Se

- The most important of the few experiments with **detector ≠ source**
  The isotope is embedded in thin foils (difficult scaling – low efficiency ~30%)
- Built on the succesfull **NEMO-3 experiment**
- **Main advantage**: **full topological reconstruction of a ββ event**

Investigation of the **mechanism** → crucial task in case of discovery
Easier access to other physics channels (i.e. **Majoron**)





[A. Giuliani, talk at Neutrino2018]

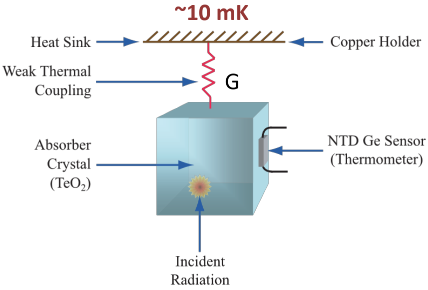
SuperNEMO demonstrator will take data in 2018 – 7 kg of ^{82}Se ***Posters #39, 50, 63, 66 M***
Sensitivity: **6 × 10^{24} y** in **2.5 y** ***Poster #45 M*** **LSM – France**
(assuming that the target radiopurity in ^{214}Bi and ^{208}Tl of the source foils is achieved)

Prospects

- Sensitivity of the order of 10^{26} y requires ~100 kg of ^{82}Se – 20 modules
- Plans to move to **^{150}Nd** – enrichment by centrifugation is expensive but now possible

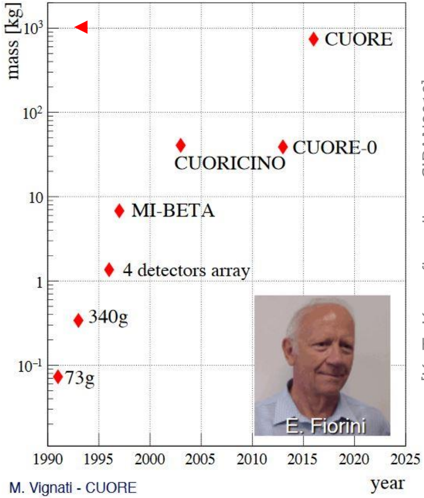
higher phase space by a factor 6 – Rn free background

CUORE / ^{130}Te cryogenic bolometer



$m \approx 750$ g
$C \approx 2$ nJ / K
$\Delta T / \Delta E \approx 0.1$ mK /MeV
$\Delta V / \Delta E \approx 0.3$ mV /MeV
$G \approx 2$nW / K
$\tau \approx C / G \approx 1$s

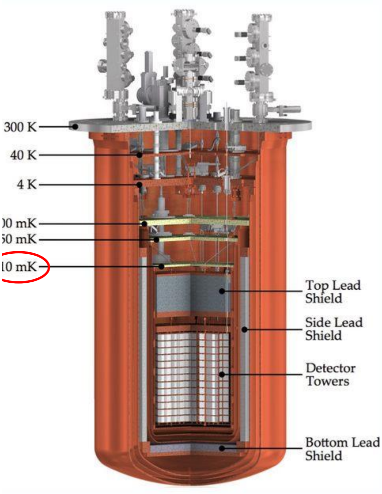
1st ton-scale cryogenic bolometer



[K. T. Knoepfle, talk at CIPAN2018]

CUORE / ^{130}Te cryostat and bolometer array

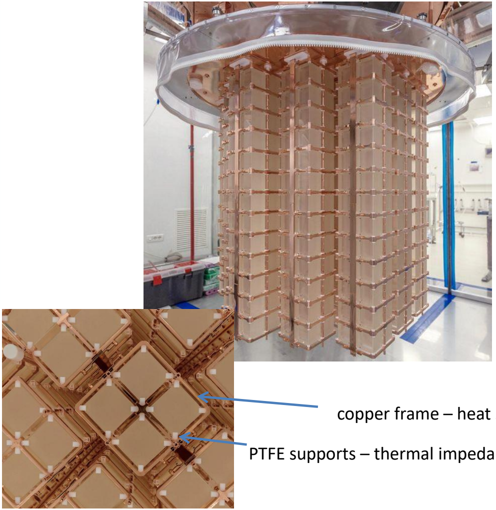
LNGS 3600 m.w.e.



988 $^{nat}TeO_2$ bolometers 984 working

active mass: 742 kg

isotope mass: 206 kg ^{130}Te

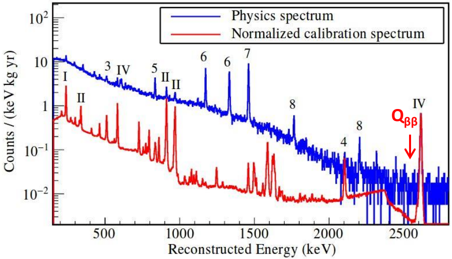


[K. T. Knoepfle, talk at CIPAN2018]

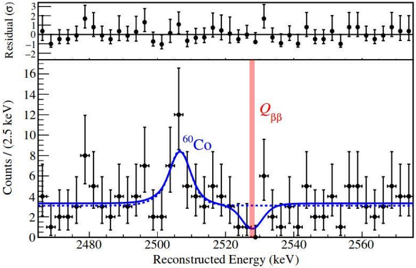
copper frame – heat sink

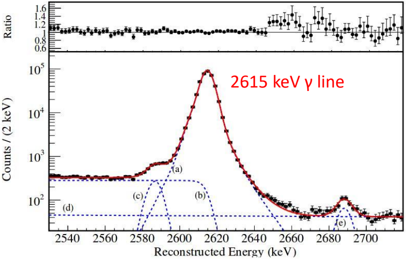
PTFE supports – thermal impedance

CUORE / ^{130}Te results



physics data ROI





complex line shape

TeO_2 exposure = 86.3 kg·yr
FWHM@$Q_{\beta\beta}$ = 7.7 ± 0.5 keV (0.3%)
BI = (14 ± 2)· 10^{-3} cnts/(keV ·kg ·yr)

Background in ROI mostly α particles!

$T^{0\nu}_{1/2}$ sensitivity : 0.7· 10^{25} yr
$T^{0\nu}_{1/2}$ limit* : >1.5 · 10^{25} yr

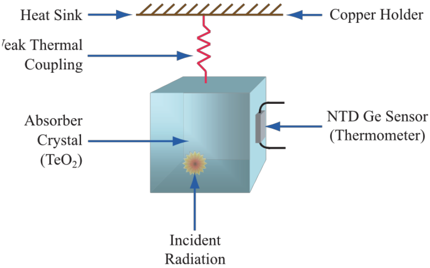
* profile likelihood (90% CL)

PRL 120, 132501 (2018)

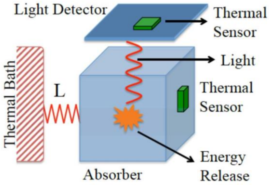
[K. T. Knoepfle, talk at CIPAN2018]

CUORE with Particle ID = CUPID

CUORE dominant BGND: surface α particles



CUPID rejection of α particles by detecting both heat and light



scintillating crystal

or Cherenkov light in TeO_2

R&D for highly radiopure scintillating crystals

$Zn^{82}Se$ CUPID-0

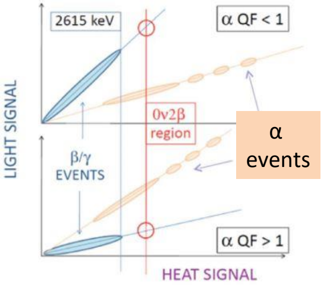
$Zn^{100}MoO_4$................ LUCIFER, LUMINEU

$Li_2{}^{100}MoO_4$..................dto

${}^{40}Ca^{100}MoO_4$...............AMoRE

${}^{116}Cd^{100}MoO_4$............ KINR-ITEP-DAMA

Poda, Giuliani, arXiv:1711.01075



[K. T. Knoepfle, talk at CIPAN2018]

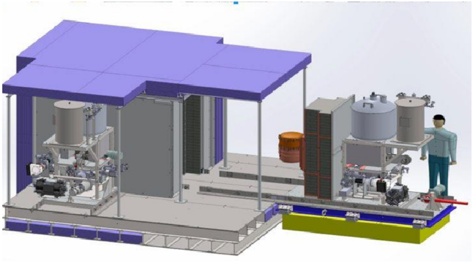
MAJORANA D & GERDA / ^{76}Ge searching for the optimum shielding

SURF 4300 m.w.e.

Ge diodes in vacuo,
electro-formed copper & lead shield

LNGS 3600 m.w.e.

Ge diodes in active LAr shield,
low-mass holders, water shield

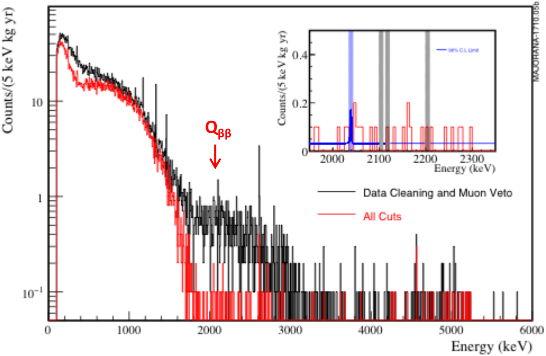


[K. T. Knoepfle, talk at CIPAN2018]

≈ 44 kg Ge, 29.7 kg thereof enriched,
p-type point contact HPGe detectors

≈ 43 kg Ge, 35.8 kg thereof enriched,
semicoaxial and BEGe HPGe detectors

1st data release



[K. T. Knoepfle, talk at CIPAN2018]

- Best resolution of any ββ experiment to date: 2.52 keV at $Q_{\beta\beta}$
- Projected background rate 4 c/(FWHM·t·yr)
- Analysis of ≈ 26 kg·yr data in progress, expected sensitivity $5 \cdot 10^{25}$ yr

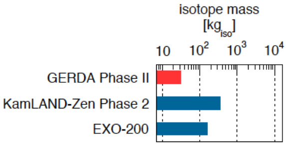
^{76}Ge exposure = 9.95 kg·yr
FWHM@$Q_{\beta\beta}$ = 2.52 ± 0.08 keV (0.12%)
BI = $(6.7 \pm 1.4) \cdot 10^{-3}$ cnts/(keV·kg·yr) (total)
= $(1.6 \pm 1.1) \cdot 10^{-3}$ cnts/(keV·kg·yr) (best)

$T^{0\nu}_{1/2}$ sensitivity : $2.1 \cdot 10^{25}$ yr
$T^{0\nu}_{1/2}$ limit* : $>1.9 \cdot 10^{25}$ yr

* profile likelihood (90% CL)

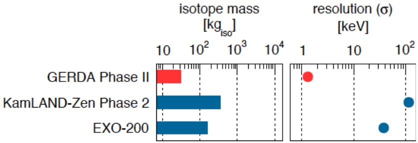
PRL 120, 132502 (2018)

Comparison of Experiments



adopted from [Agostini, Benato, Detwiler, arXiv: 1705.02996]

Comparison of Experiments



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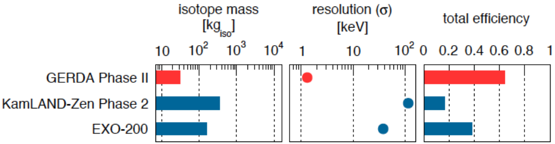
Comparison of Experiments



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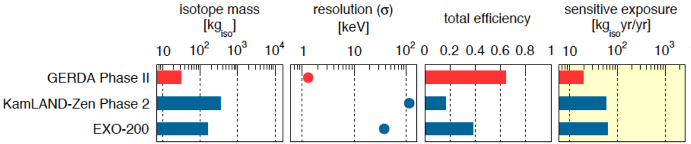
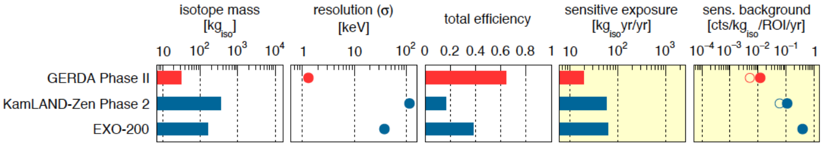


$M \cdot t \cdot \varepsilon_{tot}$

adopted from [Agostini, Benato, Detwiler, arXiv: 1705.02996]

Comparison of Experiments

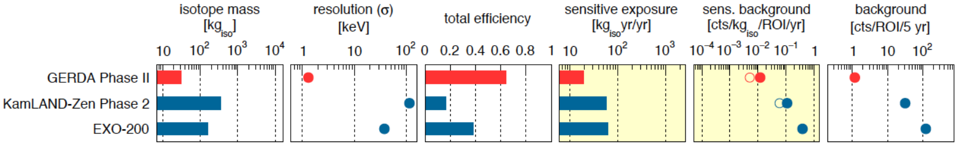


$M \cdot t \cdot \varepsilon_{tot}$

$$\frac{n_{bgd}(ROI)}{M \cdot t \cdot \varepsilon_{tot}}$$

adopted from [Agostini, Benato, Detwiler, arXiv: 1705.02996]

Comparison of Experiments



$M \cdot t \cdot \varepsilon_{tot}$

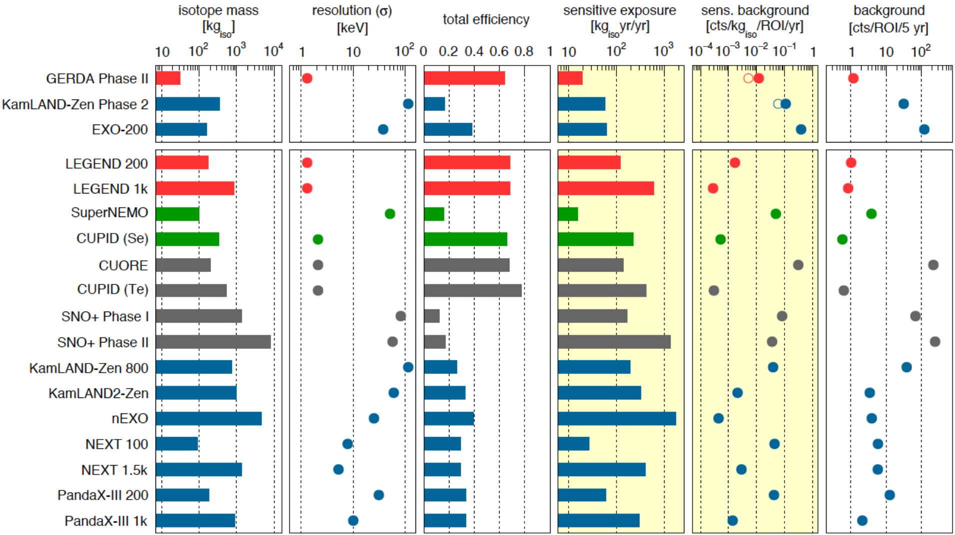
$$\frac{n_{bgd}(ROI)}{M \cdot t \cdot \varepsilon_{tot}}$$

$\uparrow$

"background free"

adopted from [Agostini, Benato, Detwiler, arXiv: 1705.02996]

Comparison of Experiments



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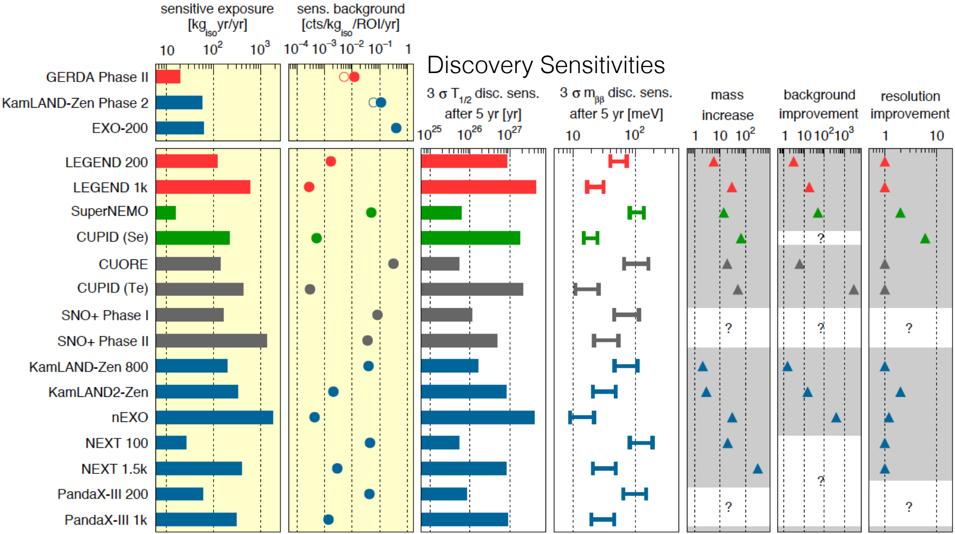
Comparison of Experiments



adopted from [Agostini, Benato, Detwiler, arXiv: 1705.02996]

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- material presented reflects the work of many people

- special thanks to:
- M. Agostini, talk at the XXXIX International School of Nuclear Physics, September 16-24, 2017, Erice (Italy)
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- A. J. Zsigmond, talk at Neutrino 2018, June 4-9 2018, Heidelberg, Germany
- A. Giuliani, talk at Neutrino 2018, June 4-9 2018, Heidelberg, Germany
- C. Ransom, talk at XXX Rencontres de Blois Particle Physics and Cosmology, June 3-8, Blois, France
- S. Schoenert, talk at TAUP 2017, July 24-28, SNOlab, Sunbury, Canada

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