

48^{ème} Ecole de Gif : La Physique Souterraine Neutrinoless Double Beta Decay Search

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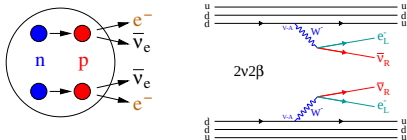
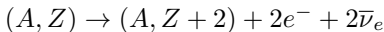
LAL Orsay

September, 2016

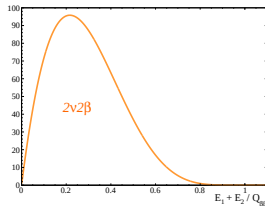
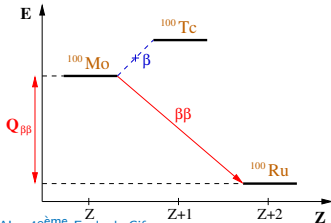


Two Neutrinos Double Beta Decay ($2\nu 2\beta$)

- ▶ The $2\nu 2\beta$ is similar to 2 simultaneous beta decays:



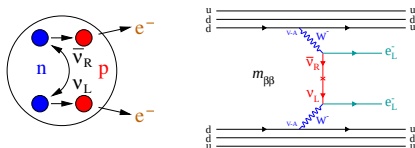
- ▶ Naturally occurs in few nuclei if β -decay is energetically impossible
- ▶ 2nd order of the weak interaction conserving lepton number: $\Delta L = 0$
- ▶ 2 e^- energy spectra continuous from 0 to $Q_{\beta\beta}$ (e.g. 3 MeV)
- ▶ Measured for many isotopes: $T_{1/2} \sim 10^{18} - 10^{21}$ y
- ▶ Input for nuclear models and for $m_{\beta\beta}$: $(T_{1/2}^{2\nu})^{-1} = G_{2\nu} |\mathcal{M}_{2\nu}|^2$



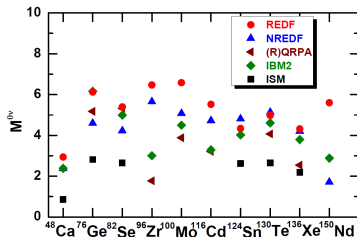
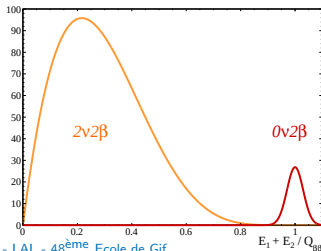
Neutrinoless Double Beta Decay ($0\nu 2\beta$)

- Best experimental technique to search for Majorana neutrinos

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



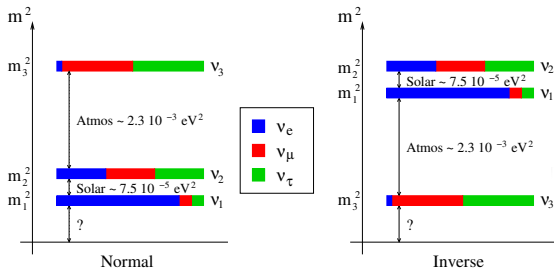
- Violates lepton number conservation $\Delta L = 2 \Rightarrow \bar{\nu} \equiv \nu$
- Energy spectra of the 2 electrons is a peak at $Q_{\beta\beta}$
- Never been observed yet: $T_{1/2}^{0\nu} > 10^{24} - 10^{25}$ y
- Half-life of the process: $(T_{1/2}^{0\nu})^{-1} = G_{0\nu} |\mathcal{M}_{0\nu}|^2 |m_{\beta\beta}|^2$



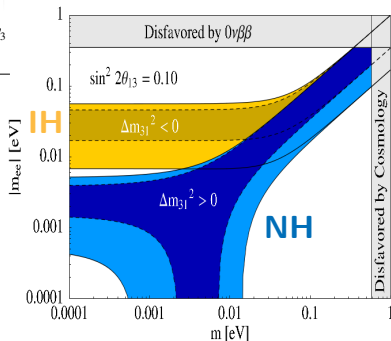
Effective Neutrino Mass for Double Beta Decay

The effective neutrino mass for double beta decay is related to the neutrino mixing parameters:

$$|m_{\beta\beta}| = c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{2i\eta_2} m_2 + s_{13}^2 e^{2i(\eta_3 - \delta)} m_3$$



Inverted Hierarchy approximately for
 $|m_{\beta\beta}| \approx 10 - 50 \text{ meV}$



Short History of Double Beta Decay

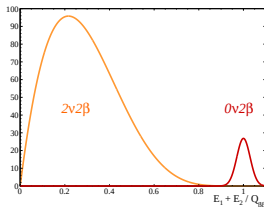
- ▶ 1933 - E. Fermi - Theory of β -decay
- ▶ 1935 - M. Goeppert-Mayer - Idea of $2\nu 2\beta$: $T_{1/2} \sim 10^{21} - 10^{22} \text{ y}$
- ▶ 1937 - E. Majorana - No need for anti-neutrino in β -decay ($\nu \equiv \bar{\nu}$)
- ▶ 1937 - G. Racah - Propose a way to distinguish ν and $\bar{\nu}$:
$$(A, Z) \rightarrow (A, Z + 1) + e^- + \bar{\nu}_e \xrightarrow{\nu \equiv \bar{\nu}} \nu_e + (A, Z) \rightarrow (A, Z + 1) + e^-$$
- ▶ 1939 - W. H. Furry - Idea of $0\nu 2\beta$: $T_{1/2} \sim 10^{15} - 10^{16} \text{ y}$
- ▶ 1948 - E. L. Fireman - First experiment to search for 2β -decay:
 $T_{1/2}(^{124}\text{Sn}) > 3 \times 10^{15} \text{ y}$
- ▶ 1950 - M. H. Inghram and J. H. Reynolds - First geochemical measurement of 2β -decay: $T_{1/2}^{2\nu+0\nu}(^{130}\text{Te}) \sim 1.4 \times 10^{21} \text{ y}$
- ▶ 1967 - E. Fiorini et al. - First HPGe experiment
- ▶ 1987 - S. R. Elliott, A. A. Hahn, and M. K. Moe - First direct measurement of 2β -decay with electrons reconstruction in a TPC:
 $T_{1/2}^{2\nu}(^{82}\text{Se}) \sim 1.1 \times 10^{20} \text{ y}$

Experimental principle

- ▶ The very long half-lives of double beta decays are accessible thanks to the Avogadro constant: $N_A = 6.022 \cdot 10^{23} \text{ mol}^{-1}$

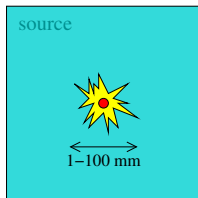
$$T_{1/2}^{0\nu} > \frac{\ln 2 N_A \mathcal{E}_{0\nu}}{1.64 A} \sqrt{\frac{m t}{N_{bkg} r}} \quad (\text{if bkg gaussian})$$

- ▶ 2β isotopes decay through the 2 processes $2\nu 2\beta$ and $0\nu 2\beta$:
 - ▶ can be distinguished by the **energy of the 2 electrons emitted**
 - ▶ $2\nu 2\beta$ is an **irreducible background for $0\nu 2\beta$** because of the non-perfect energy resolution of the detectors
- ▶ Ideally one $0\nu 2\beta$ experiment should:
 - ▶ measure precisely the energy of the 2 electrons (individual and total)
 - ▶ sign the 2 electrons emitted in the decay
 - ▶ have a good spatial resolution or segmented sources
 - ▶ identify the daughter isotope after the decay



Type of Double Beta Decay Experiments

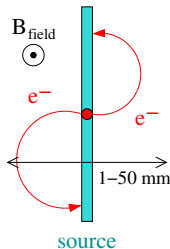
Calorimeters



- efficiency: $\sim 90\%$
- energy resolution: few keV (FWHM)
- no tracking
- poor background rejection
- isotope dependent

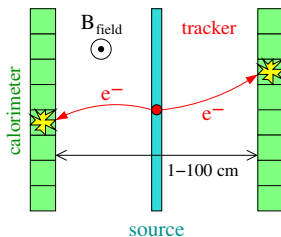
semiconductors,
bolometers,
scintillators, TPC...

Trackers



- efficiency: $\sim 50\%$
- energy resolution: few % (FWHM)
- tracking & particles identification
- individual electron parameters
- almost any isotope

Tracko-calos



- efficiency: $\sim 30\%$
- energy resolution: few % (FWHM)
- tracking & particles identification
- individual electron parameters
- precise backgrounds measurements
- almost any isotope

Choice of double beta decay isotopes

The 2ν isotope for an experiment:

- ▶ depends on the experimental technique
- ▶ high $Q_{\beta\beta} > Q_{\beta}(^{214}\text{Bi}) = 3.27 \text{ MeV} > E_{\gamma}(^{208}\text{Tl}) = 2.615 \text{ MeV}$
- ▶ low $T_{1/2}^{0\nu}$ by high $G_{0\nu}$ and high $\mathcal{M}_{0\nu}$
- ▶ high $T_{1/2}^{2\nu}$ (fewer $2\nu 2\beta$ events)
- ▶ high mass: natural abundance enrichment and purification

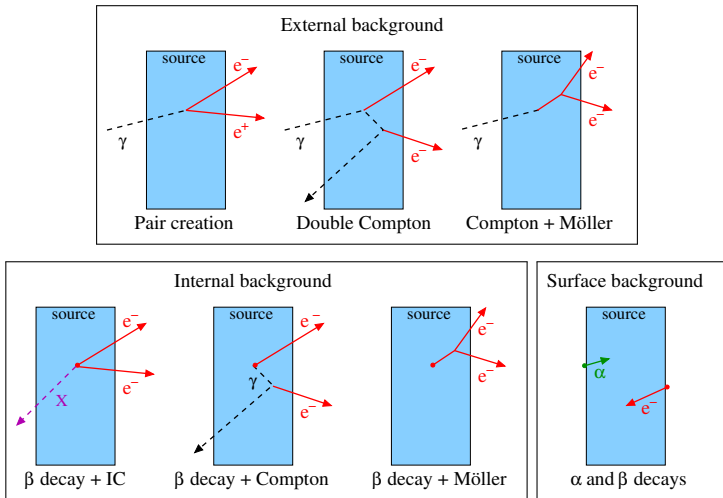
Isotope	$Q_{\beta\beta}$ [MeV]	$G_{0\nu}$ [10^{-14} y^{-1}]	$T_{1/2}^{2\nu}$ [y]	NA [%]
^{48}Ca	4.274	6.35	$4.4 \pm 0.6 \times 10^{19}$	0.187
^{76}Ge	2.039	0.62	$1.4 \pm 0.5 \times 10^{21}$	7.61
^{82}Se	2.996	2.70	$9.6 \pm 1.0 \times 10^{19}$	8.73
^{96}Zr	3.348	5.63	$2.2 \pm 0.3 \times 10^{19}$	2.8
^{100}Mo	3.035	4.36	$7.2 \pm 0.5 \times 10^{18}$	9.63
^{116}Cd	2.805	4.62	$2.9 \pm 0.3 \times 10^{19}$	7.49
^{130}Te	2.529	4.09	$7.0 \pm 1.4 \times 10^{20}$	34.1
^{136}Xe	2.462	4.31	$2.2 \pm 0.1 \times 10^{21}$	8.9
^{150}Nd	3.368	19.2	$9.1 \pm 0.7 \times 10^{18}$	5.6

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu} |\mathcal{M}_{0\nu}|^2 |m_{\beta\beta}|^2$$

$$T_{1/2}^{0\nu} > \frac{\ln 2 N_A \mathcal{E}_{0\nu}}{1.64 A} \sqrt{\frac{m t}{N_{bkg} r}}$$

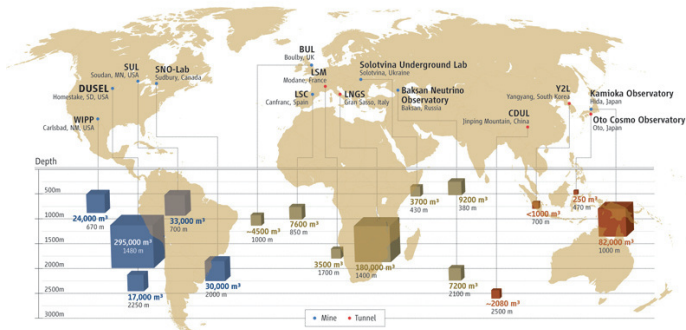
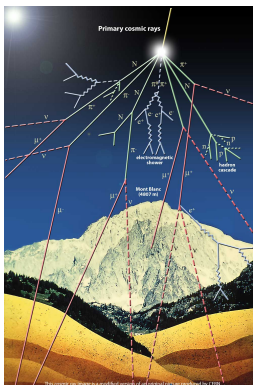
Faking 2β events

Depending on the natural radioactivity contamination location and the detector technology different mechanisms could fake the 2β events:



Cosmic rays background

- ▶ Cosmic rays interactions in laboratories or detectors produce:
 - ▶ high energy γ rays and spallation n
 - ▶ cosmogenic isotopes (rare high energy decays)
 which could produce fake 2β events in the source
- ▶ Double beta experiments go deep underground:
 - ▶ For example the *Laboratoire Souterrain de Modane* (1700 m of rocks) muon flux is reduced from $\phi_\mu \sim 10^7 \text{ m}^{-2}\text{d}^{-1}$ to $4 \text{ m}^{-2}\text{d}^{-1}$



Current Best Limits on the $0\nu2\beta$ Search

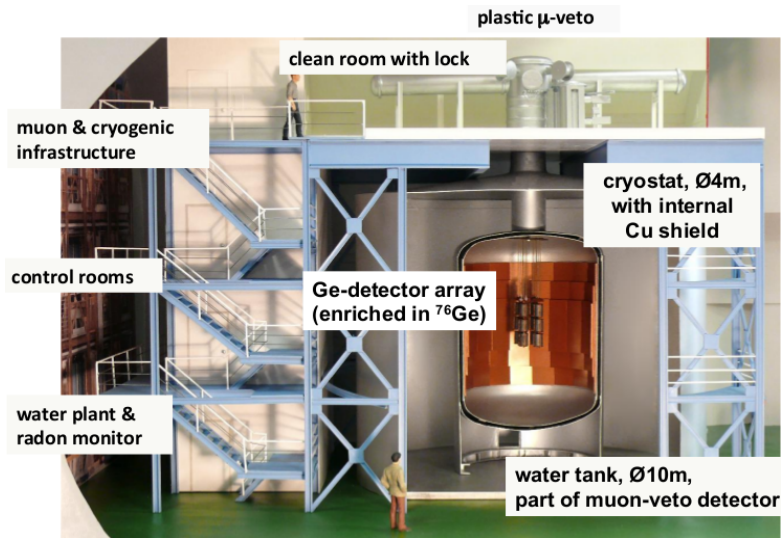
Isotope	Experiment	Technique	Mass	$\mathcal{E}_{0\nu}$ [%]	Background [fwhm·kg·y] ⁻¹	$T_{1/2}^{0\nu}$ (90%) limit [y]	$ m_{\beta\beta} $ [eV]
⁴⁸ Ca	CANDLES	Scintillation	0.01 kg	~90	-	5.8×10^{22}	3.55 - 9.91
⁷⁶ Ge	GERDA I+II	Ionisation	38 kg	~90	0.05	4.0×10^{25}	0.14 - 0.34
⁸² Se	NEMO-3	Tracko-calo	930 g	~10	0.3	3.2×10^{23}	0.85 - 2.08
⁹⁶ Zr	NEMO-3	Tracko-calo	9.43 g	~20	0.2	9.2×10^{21}	3.97 - 14.4
¹⁰⁰ Mo	NEMO-3	Tracko-calo	6.9 kg	~10	0.5	1.1×10^{24}	0.33 - 0.62
¹¹⁶ Cd	Solotvina	Scintillation	80 g	~90	-	1.7×10^{23}	1.22 - 2.30
¹³⁰ Te	CUORE-0+cino	Bolometer	~20 kg	~90	1.1	4.0×10^{24}	0.23 - 0.48
¹³⁶ Xe	EXO-200	Liquid TPC	~110 kg	~40	0.025	1.1×10^{25}	0.17 - 0.43
¹³⁶ Xe	KamLAND-Zen	Scintillation	125 kg	~50	^{110m} Ag	1.9×10^{25}	0.13 - 0.33
¹⁵⁰ Nd	NEMO-3	Tracko-calo	36.5 g	~10	0.5	2.0×10^{22}	2.23 - 8.21

From X. Sarazin HDR + update

NME from Dueck et al., Phys. Rev. D 83 (2011)

GERDA Experiment

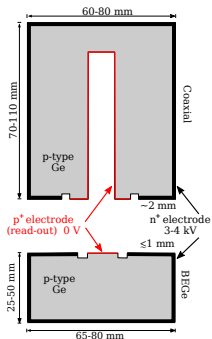
Germanium semiconductors experiment in the LNGS (3500 m.w.e.)



GERDA Phase 1 - Ge Detectors

Phase 1 - 2011-2013:

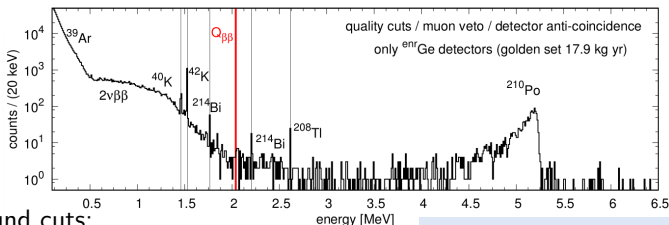
- ▶ 8 refurbished semi-coaxials (HdM - IGEX) $\rightarrow$ 17.7 kg
- ▶ 5 new BEGe deployed in 2012 $\rightarrow$ 3.6 kg
- ▶ ^{nat}Ge enriched at 86 % $\rightarrow \sim 18$ kg of ^{76}Ge
- ▶ Exposure-average energy resolutions at $Q_{\beta\beta} = 2039$ keV:
 4.8 ± 0.2 keV for coaxials and 3.2 ± 0.2 keV for BEGe



GERDA Signal and Backgrounds

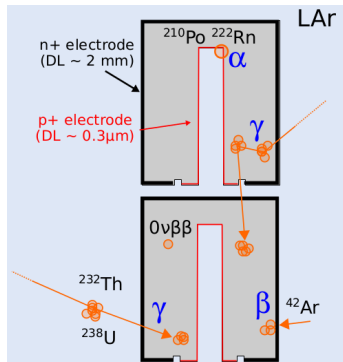
$0\nu 2\beta$ events would be single site events (SSE) within fem mm

γ background result in multi-site events (MSE)



Background cuts:

- ▶ signal in only 1 detector (AC)
- ▶ no muon veto (MV) signal within $8\ \mu\text{s}$
- ▶ more than 1 ms between events (^{214}Bi -Po cascades)
- ▶ pulse shape discrimination (PSD) to reject MSE ($\mathcal{E}_{0\nu} \sim 90\%$):
 - ▶ coax: artificial neural network (ANN) on complicated signals
 - ▶ BEGe: different maximal current and charge signals $\rightarrow$ simple and efficient A/E cut



GERDA $2\nu 2\beta$ Measurement

Minimal background model describing well the data

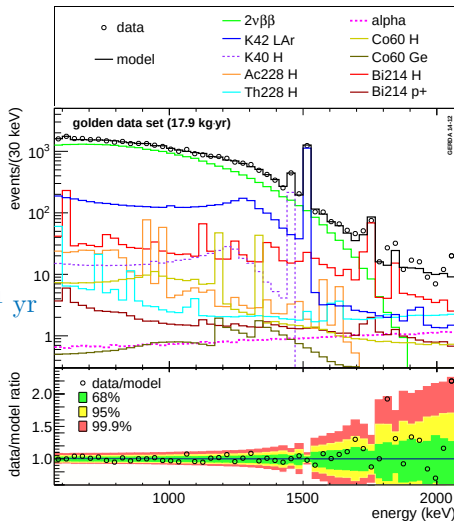
Signal-to-background ratio of 3:1 in the 570-2039 keV interval

Number of events:

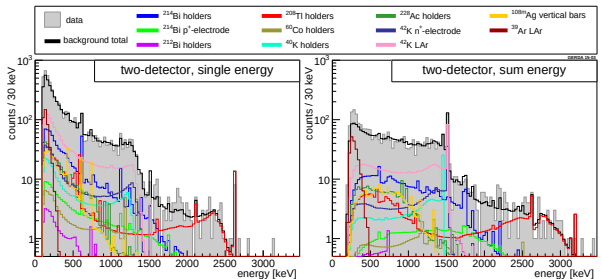
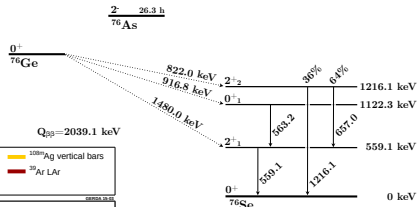
$$N_{2\nu}^{\text{fit}} = 25\,690^{+310}_{-330}$$

Efficiency: $\langle \mathcal{E}^{\text{fit}} \rangle \approx 0.667$

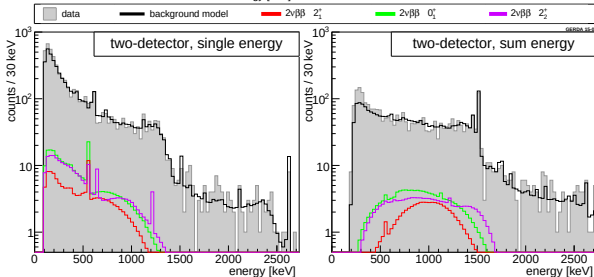
$$T_{1/2}^{2\nu} = 1.926^{+0.025}_{-0.022} \text{ stat }^{+0.092}_{-0.092} \text{ syst} \times 10^{21} \text{ yr}$$



GERDA Phase 1 - $2\nu 2\beta$ Excited states

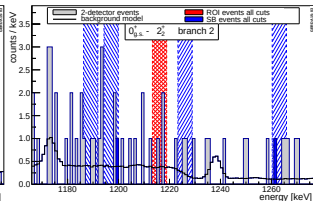
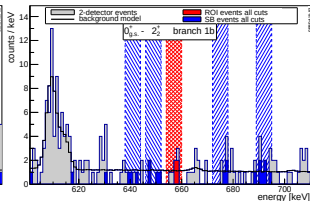
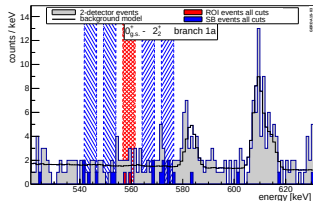
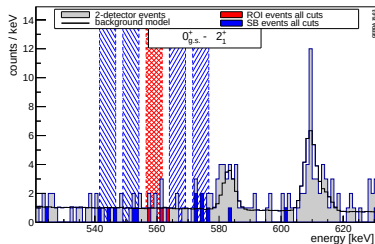
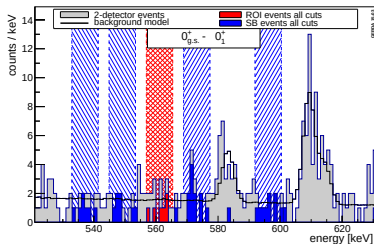


- ▶ $2\nu 2\beta$ decay in one Ge detector (sum energy)
- ▶ γ detected in one surrounding detector (single energy)



GERDA Phase 1 - $2\nu 2\beta$ Excited states Limits

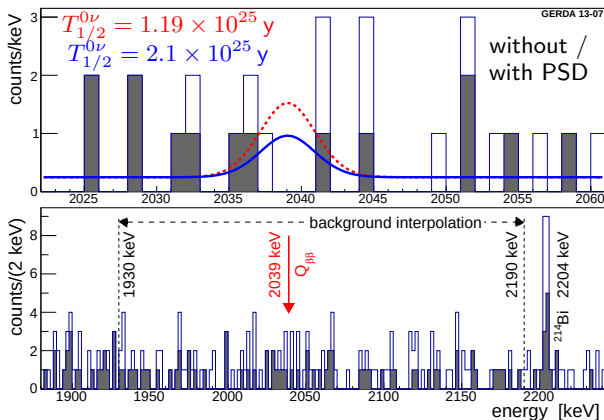
Decay mode	n_k	m_k	ϵ_k [%]	Frequentist 90 % C.L.		Bayesian 90 % C.I.	
				$T_{1/2}$ [10^{23} yr]	$\widehat{T_{1/2}}$ [10^{23} yr]	$T_{1/2}$ [10^{23} yr]	$\widehat{T_{1/2}}$ [10^{23} yr]
$0^+_{g.s.} - 2^+_1$	2	10	0.389	> 1.6	> 1.3	> 1.3	> 1.2
$0^+_{g.s.} - 0^+_1$	5	34	0.919	> 3.7	> 1.9	> 2.7	> 1.8
$0^+_{g.s.} - 2^+_2$ branch 1	6	29	0.594	> 1.7	> 1.2	> 1.4	> 1.1
$0^+_{g.s.} - 2^+_2$ branch 2	0	2	0.092	> 0.74	> 0.64	> 0.49	> 0.46
$0^+_{g.s.} - 2^+_2$ combined	-	-	-	> 2.3	> 1.4	> 1.8	> 1.3



GERDA Phase 1 - $0\nu 2\beta$ Search

21.6 kg·y
exposure

After PSD
3 events in
 $Q_{\beta\beta} \pm 5$ keV
(3.6 ± 0.4 expected)



$$T_{1/2}^{0\nu} > 2.1 \times 10^{25} \text{ y (90\% CL)} \rightarrow |m_{\beta\beta}| < 0.2 - 0.5 \text{ eV}$$

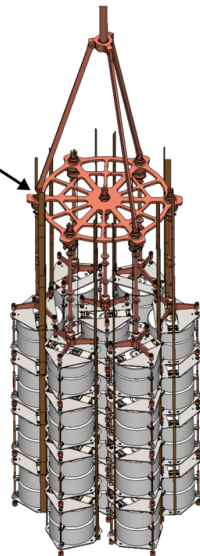
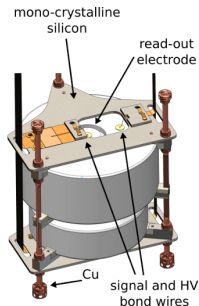
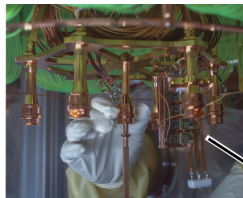
Bkg [cts/((keV·kg·y))]	Before PSD	After PSD
Coaxials	$1.8 \pm 0.2 \times 10^{-2}$	$1.1 \pm 0.2 \times 10^{-2}$
BEGe	$4.2 \pm 1.0 \times 10^{-2}$	$0.5 \pm 0.4 \times 10^{-2}$

Exclude the HdM $0\nu 2\beta$ Klapdor's claim: $T_{1/2}^{0\nu} = 1.19_{-0.23}^{+0.37} \times 10^{25} \text{ y}$

GERDA Phase 2 - Ge Detectors

Phase 2 - 2016-2020:

- ▶ 30 BEGe detectors → 20 kg
- ▶ new lower mass holders and contacting solution
- ▶ new low-mass, low-activity electronics and contacts

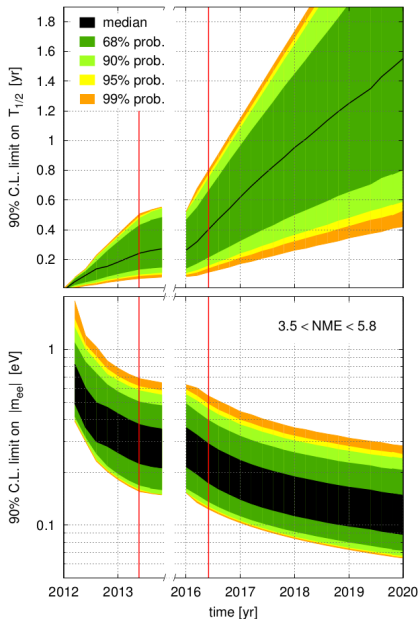


GERDA Phase 2 - Goals

Double the target mass to have
> 100 kg·y exposure

Reduce background by factor 10
 $\sim 10^{-3}$ [cts/(keV·kg·y)]

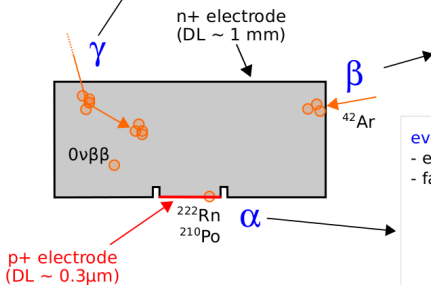
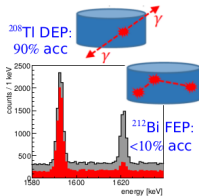
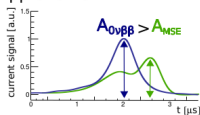
Reach a sensitivity of
 $T_{1/2}^{0\nu} > 10^{26}$ y
 $|m_{\beta\beta}| < 0.1 - 0.2$ eV



GERDA Phase 2 - BEGe PSD

γ interactions:

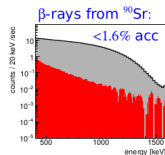
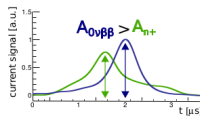
- multiple Compton scattering (MSE)
- sequence of peaks in current signal
- Double escape peak (DEP): proxy for $0\nu\beta\beta$ events



From Agostini - Neutrino 2016

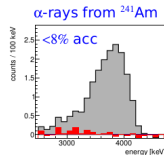
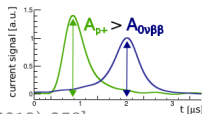
events on n+ surface:

- semiconductor junction -> weak E field
- slow current signal



events on p+ electrode:

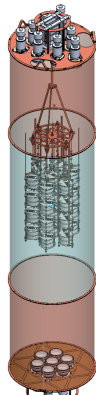
- electron drift faster than holes
- faster charge signal



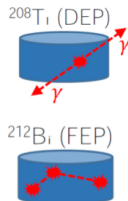
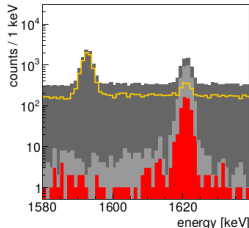
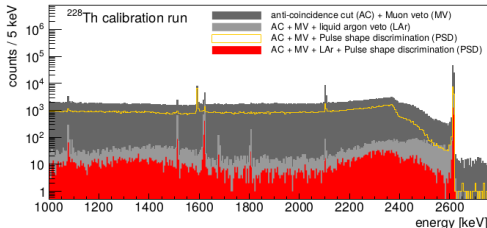
[JINST 6 2011 P03005, JINST 4 2009 P10007, EPJC 73 (2013) 258]

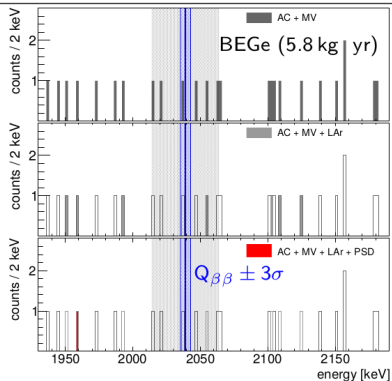
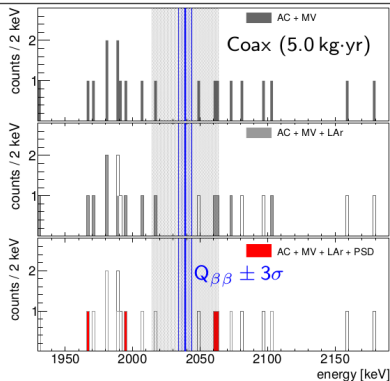
GERDA Phase 2 - LAr veto

- ▶ LAr scintillation peaked at 128 nm
- ▶ 16 PMTs (9 top / 7 bottom)
- ▶ 800 m WLS fibers coated with TPB + 90 SiPMs
- ▶ nylon mini-shroud around each string coated with TPB



^{228}Th calibration run:





		Coax	BEGe
cts expected from bkg	$Q_{\beta\beta} \pm 25$ keV	0.8	0.3
	1930-2190 keV	3.6	1.2
cts observed	$Q_{\beta\beta} \pm 25$ keV:	2	0
	1930-2190 keV:	4	1

background index

1930-2190 keV

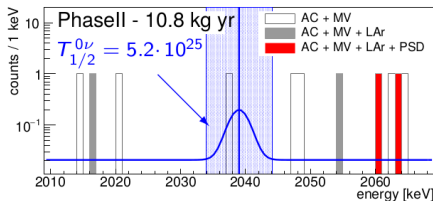
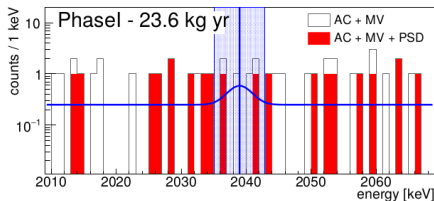
$$35^{+21}_{-15} \cdot 10^{-4}$$

$$7^{+11}_{-5} \cdot 10^{-4}$$

[cts/(keV·kg·yr)]

GERDA Phase 2 - $0\nu 2\beta$ Limits

From Agostini - Neutrino 2016



	profile likelihood 2-side test-stat	Bayesian flat prior on cts
$0\nu\beta\beta$ cts best fit value [cts]	0	0
$T_{1/2}^{0\nu}$ lower limit [10^{25} yr]	>5.2 (90% CL)	>3.5 (90% CI)
$T_{1/2}^{0\nu}$ median sensitivity [10^{25} yr]	>4.0 (90% CL)	>3.0 (90% CI)

preliminary!

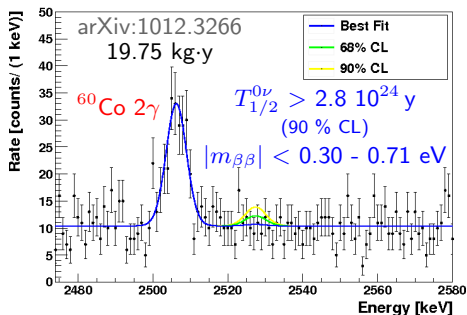
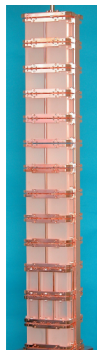
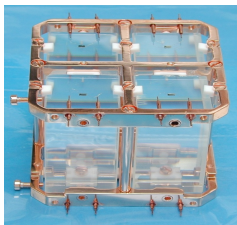
Cuoricino Experiment

Bolometers Experiment at ~ 8 mK

- ▶ ~ 40 kg of natural TeO_2 crystals (34.1 % of ^{130}Te)
- ▶ from 2003 to 2008 in the LNGS in Italy
- ▶ 0.117 mK heat at $Q_{\beta\beta} = 2.530$ MeV with <10 keV FWHM

Limit on $0\nu 2\beta$ after 19.75 kg·y exposure of ^{130}Te :

- ▶ $T_{1/2}^{0\nu} > 2.8 \times 10^{24}$ y at 90 % CL for $|m_{\beta\beta}| < 0.30 - 0.71$ eV
- ▶ background: 0.2 cts/(keV·kg·y) dominated by surfaces contaminations of ^{238}U and ^{232}Th on crystals and copper structure



CUORE Goals

Successor of Cuoricino at LNGS
will start by the end of the year

19 towers array of 988 TeO_2 5 cm
cubic detectors at ~ 10 mK

A total mass of 206 kg of ^{130}Te

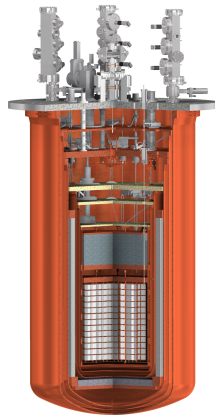
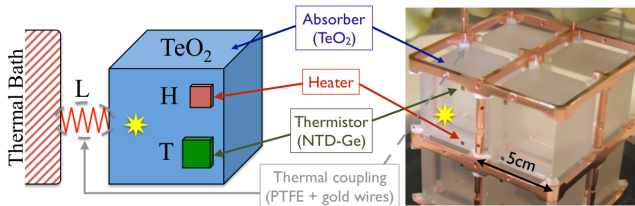
Energy resolution of 5 keV FWHM
at $Q_{\beta\beta} = 2530$ keV

Background goal: 10^{-2} cts/(keV·kg·y)

Sensitivity after 5 y: $T_{1/2}^{0\nu} > 9.5 \times 10^{25}$ y
 $|m_{\beta\beta}| < 50 - 130$ meV



From Canonica Nu 16 & Lim ICHEP 16

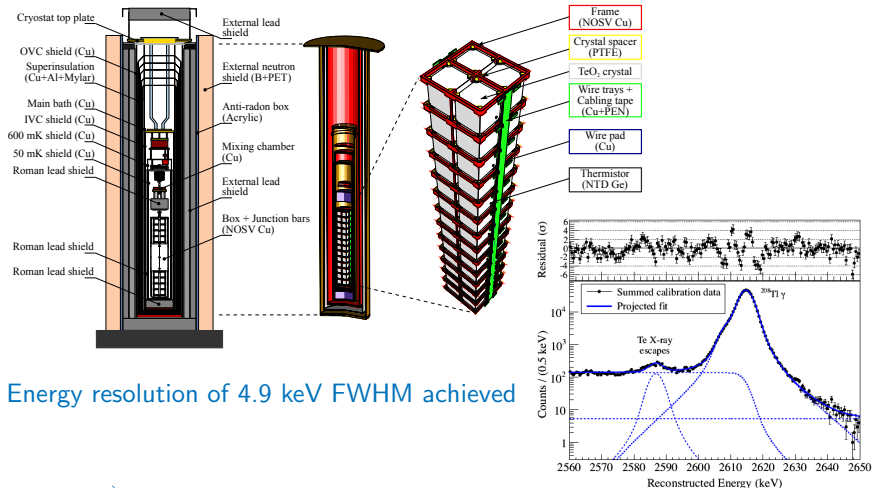


CUORE-0

CUORE-0 is the first tower of CUORE in Cuoricino cryostat

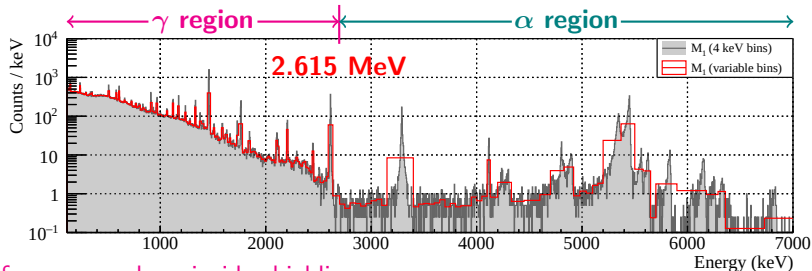
52 crystals for 39 kg of TeO_2 giving 10.8 kg ^{130}Te

Exposure of 9.3 kg·y in ^{130}Te from 2013 to 2015



CUORE-0 Backgrounds

arXiv:1609.01666



γ from everywhere inside shielding

^{232}Th activity unchanged wrt
Cuoricino $\rightarrow$ contamination from
cryostat and lead shields

^{238}U reduced by a factor 2-3 wrt
Cuoricino $\rightarrow$ better crystal cleaning
procedures and ^{222}Rn control

Still ^{40}K in bulk and cryostat bottom

Still ^{60}Co in the copper structure

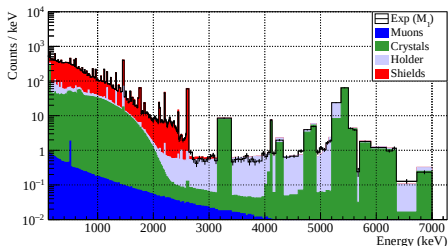
Short range α particles: contaminants
close or inside bolometers

^{232}Th , ^{238}U decays chains and ^{190}Pt

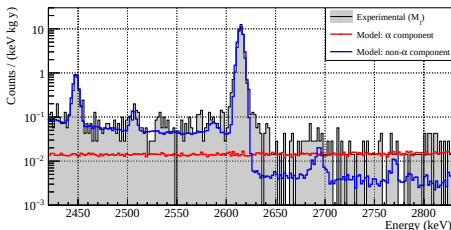
Energy peaks and coincidences to
differentiate bulk or surface and
holder or crystals contaminations

Crystal response different for α wrt γ
complicates reconstruction (surface vs
bulk energy deposition, quenching...)

Component	Fraction [%]
Shields	74.4 ± 1.3
Holder	21.4 ± 0.7
Crystals	2.64 ± 0.14
Muons	1.51 ± 0.06



The flat counting rate in the $0\nu 2\beta$ ROI is 0.058 ± 0.006 cts/(keV·kg·y) (excluding the ^{60}Co peak) which is $\sim 1/3$ of Cuoricino and where $\sim 3/4$ comes from old cryostat and shielding



Backgrounds levels should allow CUORE to achieve its requirements

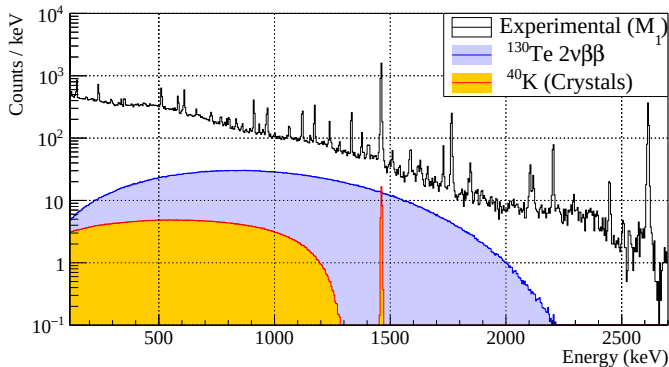
CUORE-0 $2\nu 2\beta$ Measurement

arXiv:1609.01666

$2\nu 2\beta$ events represents $\sim 10\%$ of the γ region events

Most accurate measurement to date for ^{130}Te isotope:

$$T_{1/2} = 8.2 \pm 0.2 \text{ stat} \pm 0.6 \text{ syst} \times 10^{20} \text{ y}$$



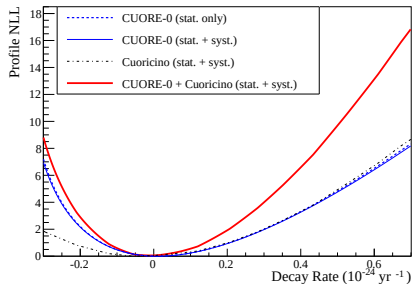
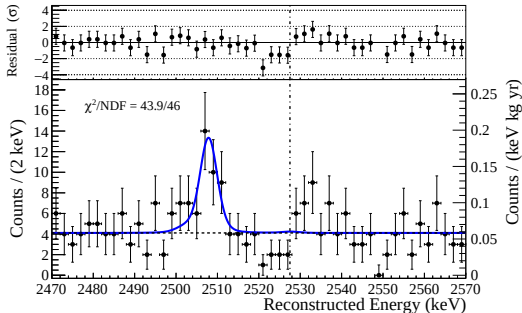
CUORE-0 $0\nu 2\beta$ Search

Phys. Rev. C 93, 045503 (2016) - arXiv:1601.01334

Exposure of 9.3 kg·y in ^{130}Te

No excess at $Q_{\beta\beta} = 2530$ keV

$T_{1/2}^{0\nu} > 2.7 \times 10^{24}$ y (90 % CL)



Combining CUORE-0 and Cuoricino

$T_{1/2}^{0\nu} > 4.0 \times 10^{24}$ y (90 % CL)

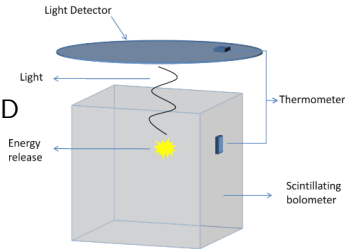
$|m_{\beta\beta}| < 270 - 760$ meV

CUORE Upgrade with Particle IDentification
to further reduce backgrounds with $\beta/\gamma - \alpha$ PSD
and investigate the IH band

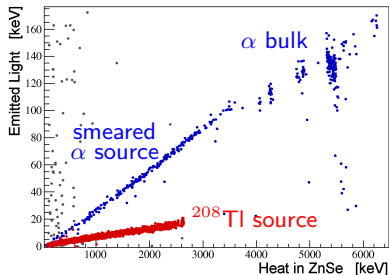
Scintillating bolometers:

TeO_2 , ZnMoO_4 , ZnSe , CdWO_4 [arXiv:1504.03599](#)

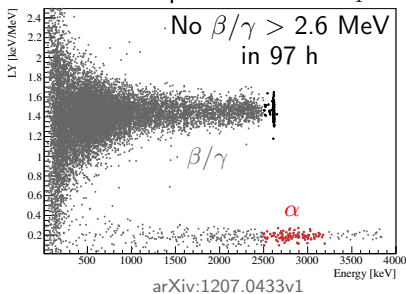
R&D with Lucifer & Lumineu at LSM and LNGS



PSD example with ZnSe



PSD example with ZnMoO_4



LUMINEU R&D

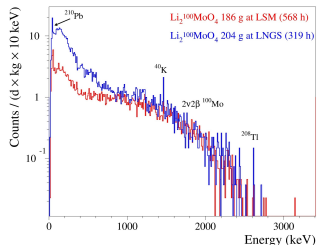
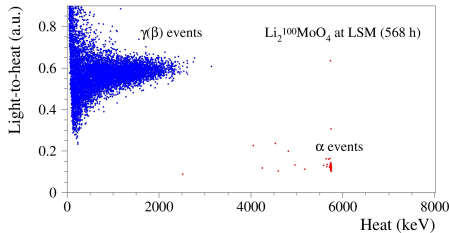
4 crystals of $\sim 200\text{-}400\text{ g}$ of Li_2MoO_4 and ZnMoO_4 were produced with enriched ^{100}Mo

Li_2MoO_4 crystal growth much easier than ZnMoO_4

$\sim 0.8\text{ kg}$ in 4 crystal of Li_2MoO_4 will start running at LSM end of 2016

20 more crystals expected next in 2017

Sample	Mass [g]	$\Delta E(\text{FWHM})$ @ 2615 keV	Light Yield [keV/MeV]	α/β rejection power	$A(^{228}\text{Th})$ [$\mu\text{Bq/kg}$]	$A(^{226}\text{Ra})$ [$\mu\text{Bq/kg}$]	$A(^{210}\text{Po})$ [mBq/kg]
Enr ZnMoO_4 -top	380	9	1.3	> 99.9% - DP=7.8	<8	14	0.8
Enr ZnMoO_4 -bottom	382	18	1.2	> 99.9% - DP=11	<21	23	2.4
Enr Li_2MoO_4 -top	186	7	-	> 99.9% - DP=17	<6	<6	0.21
Enr Li_2MoO_4 -bottom	204	5	0.8	> 99.9% - DP=12	<6	<11	0.06



Giuliani Neutrino 2016

EXO-200 Experiment

JINST 7 P05010, 2012

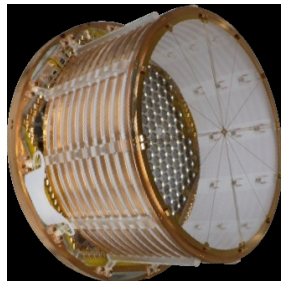
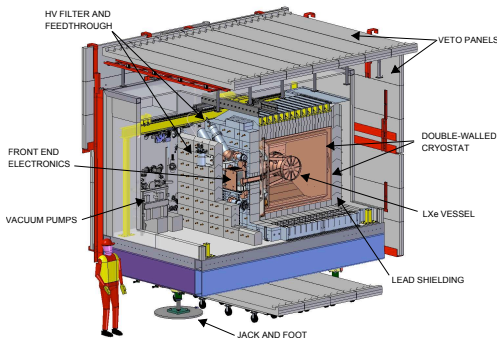
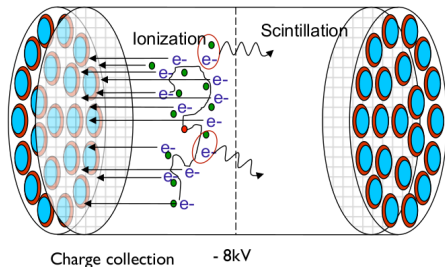
200 kg liquid Xenon TPC at WIPP
under 1585 m.w.e.

Ionization and 178 nm scintillation

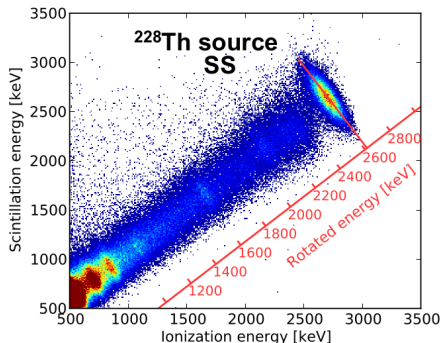
Calorimeter with 3D position
and single-site (SS) or multi-
sites (MS) events distinction

~110 kg of LXe active volume

Xe enrichment at 80.7 % in ^{136}Xe



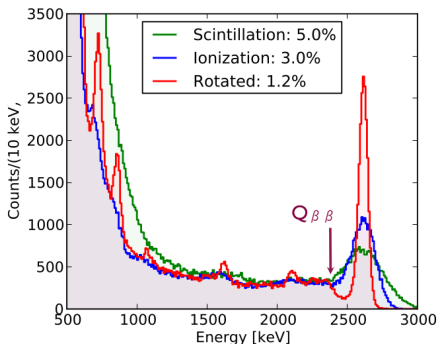
EXO-200 Detector Response



Anticorrelation between ionization and scintillation improves the energy resolution

At $Q_{\beta\beta} = 2458$ keV
 $\sigma/E = 1.53$ % in phase 1
and 1.25 % in phase 2
(upgraded electronics)

Anticorrelation between ionization and scintillation improves the energy resolution



EXO-200 Phase 1 - $0\nu 2\beta$ Search

Nature 510, 229-234 - arXiv:1402.6956

Phys. Rev. C 89 (2014) 015502 - arXiv:1306.6106

Phase 1 2011-2013 - 477.60 ± 0.01 days - 123.7 kg·y exposure of ^{136}Xe

$$T_{1/2}^{2\nu} = 2.165 \pm 0.016 \text{ stat} \pm 0.059 \text{ syst} \times 10^{21} \text{ y (most precise } T_{1/2}^{2\nu} \text{ meas.)}$$

Background in the $0\nu 2\beta \pm 2\sigma$ ROI:

$$31.1 \pm 1.8(\text{stat}) \pm 3.3(\text{syst}) \text{ counts}$$

$$(1.7 \pm 0.2) \cdot 10^{-3} \text{ cts}/(\text{keV} \cdot \text{kg} \cdot \text{y})$$

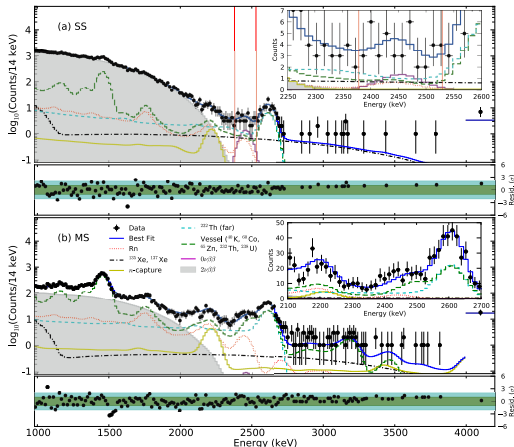
EXO-200 sensitivity:

$$T_{1/2}^{0\nu} > 1.9 \times 10^{25} \text{ y}$$

Observed limit:

$$T_{1/2}^{0\nu} > 1.1 \times 10^{25} \text{ y (90 \% CL)}$$

$$m_{\beta\beta} < 190 - 450 \text{ meV}$$



EXO-200 Phase 2 - $0\nu 2\beta$ Goals

Shutdown in 2014 after WIPP fire accident - ^{136}Xe remotely recovered

Cleaning, repair and restart in 2015 $\rightarrow$ no contamination measured

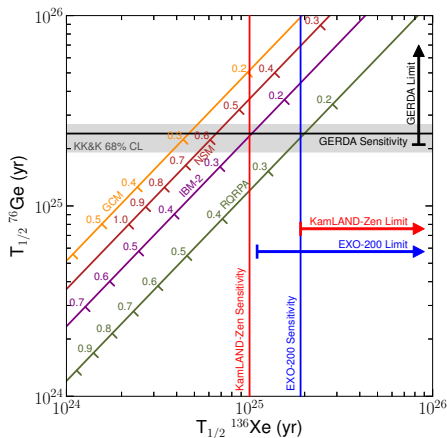
EXO-200 Phase 2 physics data with upgraded electronics and *deradonator* (factor ~ 10 reduction around TPC) started early 2016

Combining the 2 phases
EXO-200 should reach

$$T_{1/2}^{0\nu} > 5.7 \times 10^{25} \text{ y (90 \% CL)}$$

^{136}Ba tagging is still in R&D

nEXO ~ 5 t is in preparation
5 y in SNOLAB could test the IH



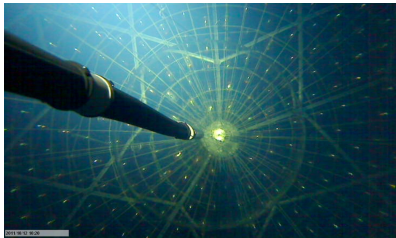
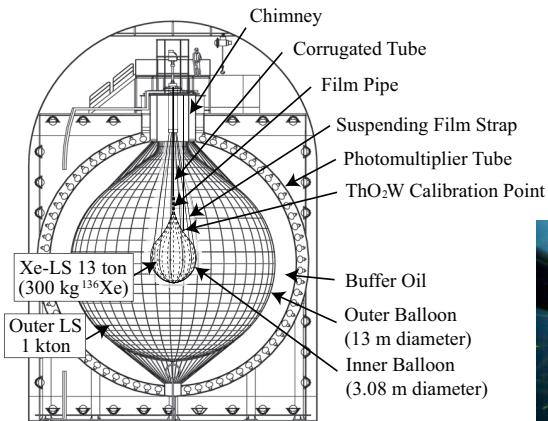
KamLAND-Zen Experiment

KamLAND 1 kt liquid scintillator detector in Kamioka (2700 m.w.e.)

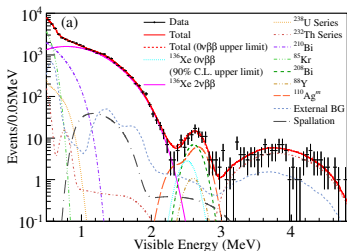
Nylon mini-balloon ~ 3 m diameter of $25\text{ }\mu\text{m}$ thick

~ 380 kg of enriched ^{136}Xe loaded in 13 tons of liquid scintillator (Xe-LS)

Energy resolution $\sigma \sim 7.3\text{ }\%$ / $\sqrt{E(\text{MeV})}$



PRC85:045504 (2012), arXiv:1605.02889, Neutrino/ICHEP 2016



Phase 1: 2011-2012

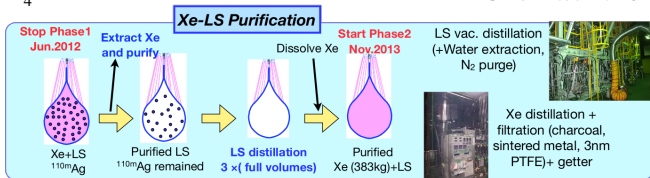
Exposure 89.5 kg·y

Peak observed at $Q_{\beta\beta}$!

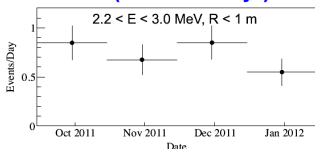
Fukushima fallout ^{110m}Ag on the mini-balloon

$$T_{1/2}^{0\nu} > 1.9 \times 10^{25} \text{ y}$$

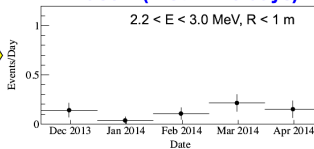
Shirai Neutrino 2016



Phase 1 (first 112.3 days)



Phase 2 (first 114.8 days)



Phase 2: 2013-2015

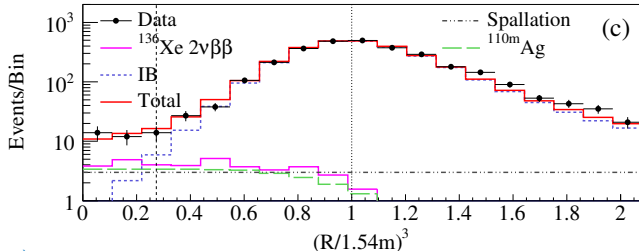
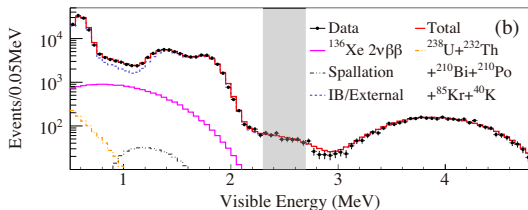
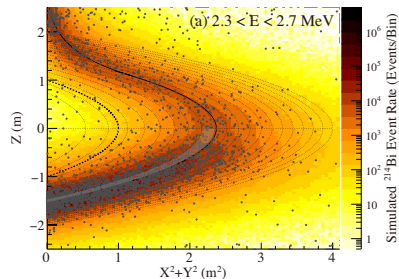
Exposure 504 kg·y

^{110m}Ag divided by

~ 10

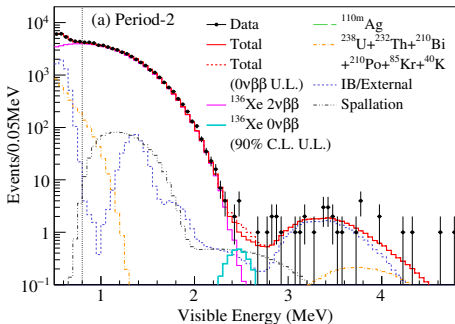
KamLAND-Zen - Backgrounds

The dominant backgrounds are on the balloon (IB): ^{134}Cs (Fukushima) at low energy and ^{214}Bi (natural) deposited (dust+pump problem) $> 2\text{ MeV}$



KamLAND-Zen - $0\nu 2\beta$ Search

arXiv:1605.02889

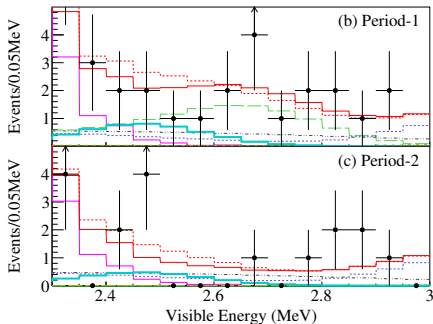


Phase 2 data divided in 2 periods

^{110m}Ag disappear in the second period !

Not understood:
contamination sinking to the
balloon bottom ?

	Period-1 (270.7 days)		Period-2 (263.8 days)	
Observed events	22		11	
Background	Estimated	Best-fit	Estimated	Best-fit
$^{136}\text{Xe } 2\nu\beta\beta$	-	5.48	-	5.29
Residual radioactivity in Xe-LS				
$^{214}\text{Bi } (^{238}\text{U series})$	0.23 ± 0.04	0.25	0.028 ± 0.005	0.03
$^{208}\text{Tl } (^{232}\text{Th series})$	-	0.001	-	0.001
^{110m}Ag	-	8.5	-	0.0
External (Radioactivity in IB)				
$^{214}\text{Bi } (^{238}\text{U series})$	-	2.56	-	2.45
$^{208}\text{Tl } (^{232}\text{Th series})$	-	0.02	-	0.03
^{110m}Ag	-	0.003	-	0.002
Spallation products				
^{10}C	2.7 ± 0.7	3.3	2.6 ± 0.7	2.8
^6He	0.07 ± 0.18	0.08	0.07 ± 0.18	0.08
^{12}B	0.15 ± 0.04	0.16	0.14 ± 0.04	0.15
^{137}Xe	0.5 ± 0.2	0.5	0.5 ± 0.2	0.4



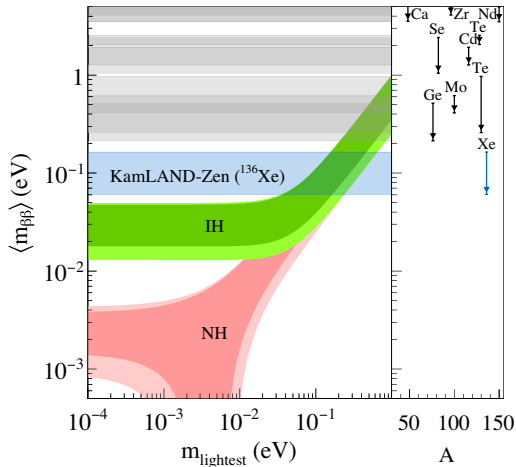
KamLAND-Zen Limits

Approaching the inverted hierarchy region

Phase 2 result: $T_{1/2}^{0\nu} > 9.2 \times 10^{25} \text{ y}$

Combination Phase 1+2:

$T_{1/2}^{0\nu} > 1.07 \times 10^{26} \text{ y} \rightarrow |m_{\beta\beta}| < 61 - 125 \text{ meV}$



2 upgrades foreseen:

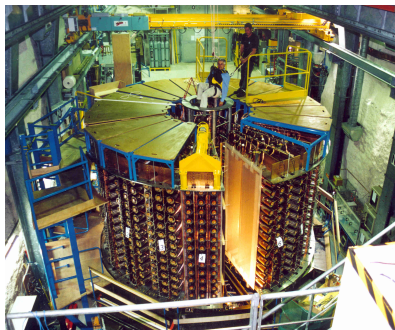
increase Xe mass to
~800-1000 kg

increase PMTs &
photocoverage

NEMO-3: The Neutrino Ettore Majorana Observatory



- ▶ Located in the *Laboratoire Souterrain de Modane* (LSM) in the French Alps under 4800 m.w.e.
- ▶ Shielded by 30 cm of borated water or wood, 19 cm of steel and radon-free air tent (2004)



Phase 1

Feb. 2003 - Oct. 2004

$$\mathcal{A}_{\text{int}}(^{222}\text{Rn}) \sim 30 \text{ mBq/m}^3$$



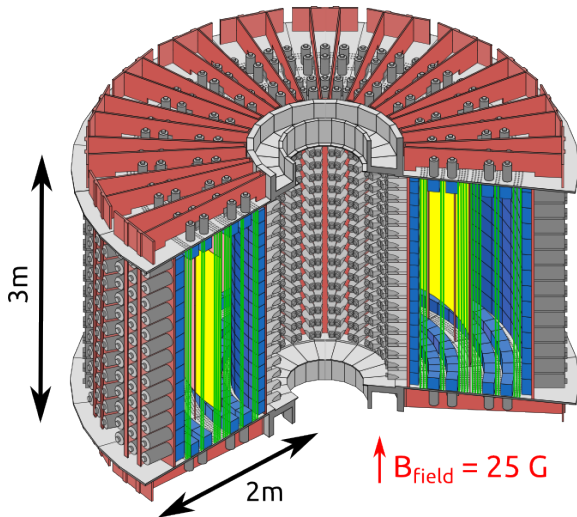
Phase 2

Dec. 2004 - Jan. 2011

$$\mathcal{A}_{\text{int}}(^{222}\text{Rn}) \sim 5 \text{ mBq/m}^3$$

NEMO-3 Detector

- ▶ NEMO-3 unique tracking and calorimetric double beta decay experiment with 10 kg of sources



sources

60 mg/cm² foils
10 kg of $\beta\beta$ isotopes

tracker

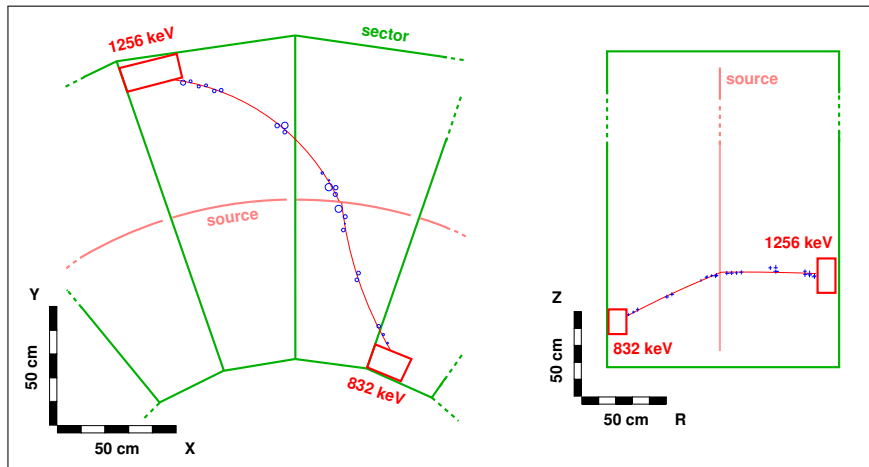
6180 Geiger cells
vertex resolution :
 $\sigma_{xy} \sim 3 \text{ mm}$ $\sigma_z \sim 10 \text{ mm}$

calorimeter

1940 optical modules :
polystyren scintillators
+ 3" and 5" PMTs
 $\text{FWHM}_E \sim 15\% / \sqrt{E_{\text{MeV}}}$
 $\sigma_t \sim 250 \text{ ps}$

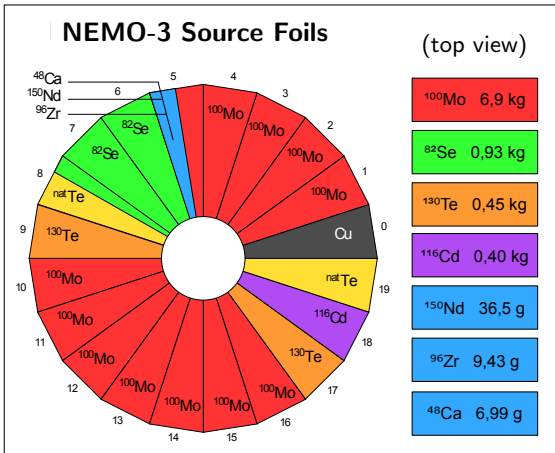
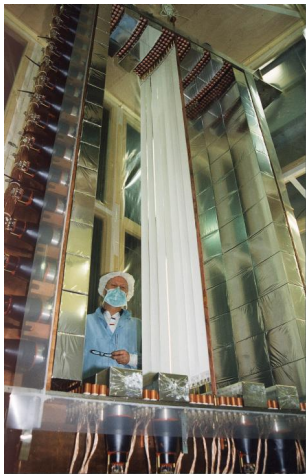
NEMO-3 Unique Features

- ▶ Individual electron energies (E_1, E_2), time of arrival (t_1, t_2), curvature in magnetic field ($\pm$), emission vertex and angle ($\cos \theta$)
- ▶ Unique DBD experiment with the direct reconstruction of the $2e^-$
→ full signature of $0\nu 2\beta$ events and powerful background rejection



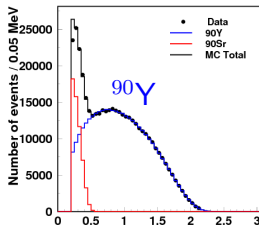
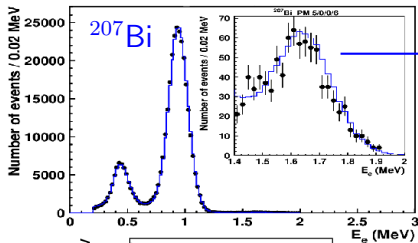
NEMO-3 Source Foils

- ▶ NEMO-3 is able to study most of the double beta decay isotopes
- ▶ Metallic or composite (glue + isotope powder on mylar) source foils
- ▶ Blank sources to check the backgrounds (Cu & ^{nat}Te)



NEMO-3 Energy Calibrations

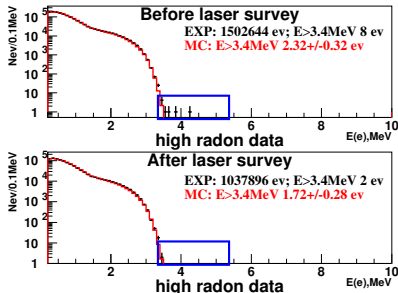
- ▶ 20 calibration tubes close to foils for sources at 3 vertical positions:
 - ▶ reconstruction of the $1e^-$ events from the source to the calorimeter
 - ▶ ^{207}Bi : 482 and 976 keV conversion electrons every 2-3 weeks
 - ▶ ^{90}Sr - ^{90}Y : β -decay end-point $Q_\beta = 2280$ MeV
 - ▶ ^{207}Bi : 1682 keV conversion electrons $\rightarrow$ test the energy scale



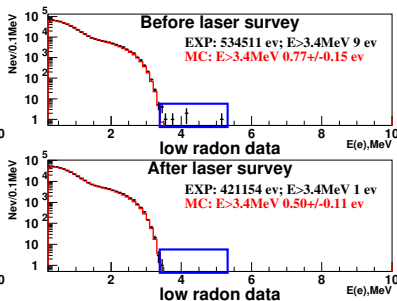
NEMO-3 Energy Survey

- ▶ Light injection into each calorimeter block through optical fibers:
 - ▶ linearity better than 1 % between 0 and 4 MeV
 - ▶ PMT gain and timing survey twice a day (82 % PMTs < 5 %)
- ▶ ^{214}Bi β -decay end-point ($Q_\beta = 3.27$ MeV) to validate PMT stability:
 - ▶ reconstruction of the BiPo $e^- \alpha_{\text{delayed}}$ events from radon (background-free channel)

Phase 1: high radon data



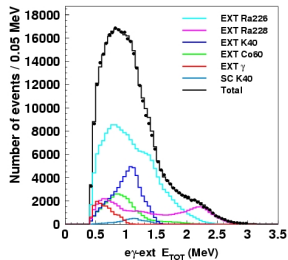
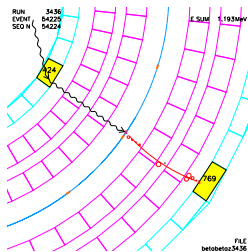
Phase 2: low radon data



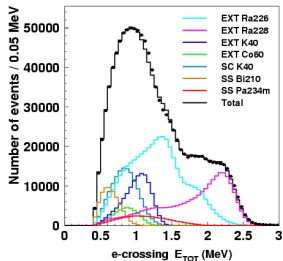
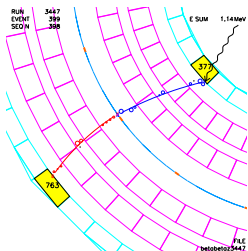
NEMO-3 External Background Measurements

- ▶ Particle identification: e^- , e^+ , γ and *external TOF*
- ▶ Measurement of all contributions through 2 analysis channels:

$(\gamma e^-)_{\text{ext}}$

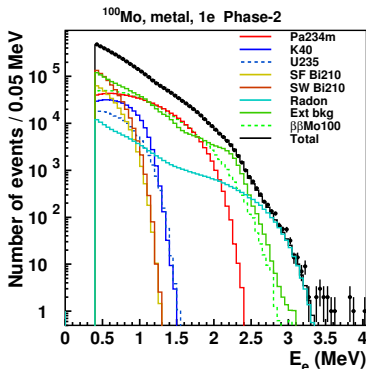
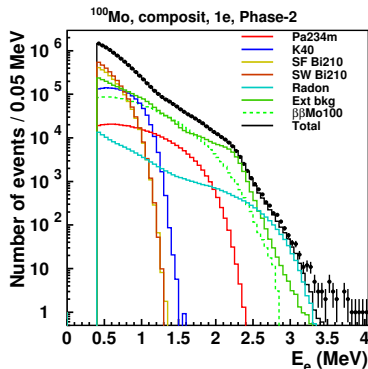


e^-_{crossing}



NEMO-3 Internal Background Measurements

- ▶ Particle identification: e^- , e^+ , γ , α and *internal TOF*
- ▶ Direct measurements through e^- , $e^-N\gamma$ or $e^-\alpha$ analysis channels
- ▶ Example of fit in the e^- channel:



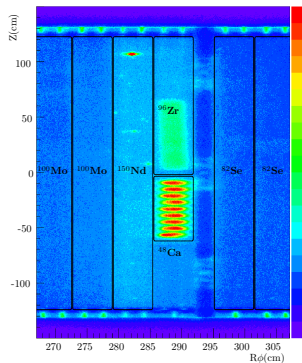
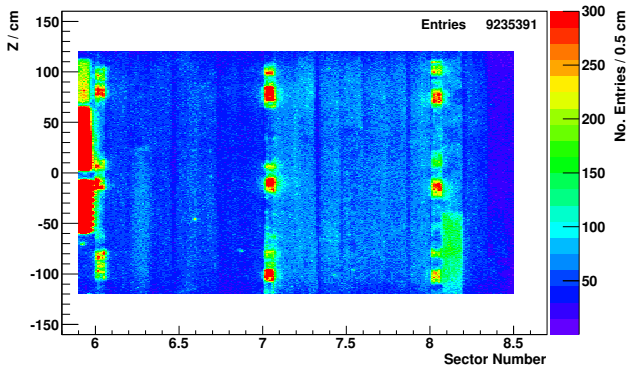
Neutron background not included in these fits (high energy tail)

NIM A 606 (2009) 449–465

NEMO-3 Imaging the source foils

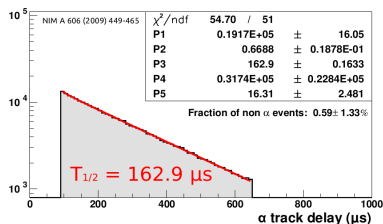
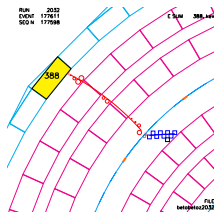
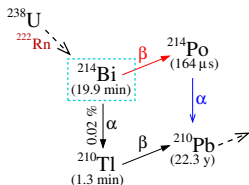
PRD 93, 112008 (2016) - arXiv:1606.08494
arXiv:1604.01710

- ▶ With the internal background channels we can see source foils and uniformity of the backgrounds
- ▶ Radioactive hot-spots and calibration tubes can be removed
- ▶ Examples of ^{82}Se (2 sectors) and ^{48}Ca sources (9 disks):

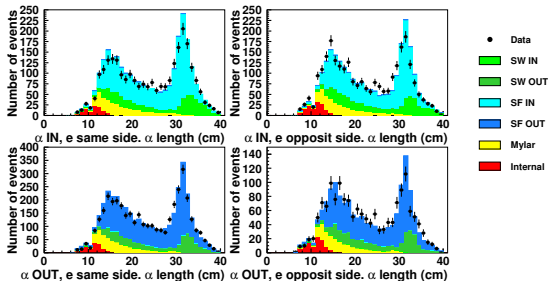


NEMO-3 Radon and Internal ^{214}Bi Measurements

- Reconstruction of the BiPo $e^- \alpha_{\text{delayed}}$ events
- α track length and event topology allow to distinguish the origin



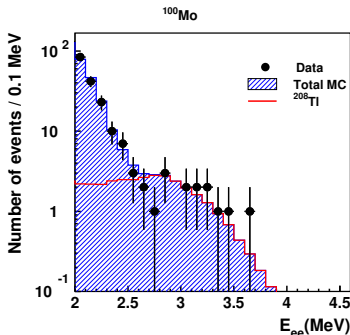
^{100}Mo composite



NEMO-3 Checking Internal ^{208}Tl and ^{214}Bi Backgrounds

- ▶ ^{208}Tl activity measurement was checked with two ^{232}U sources
→ 10 % systematics compared to HPGe measurement
- ▶ ^{214}Bi activity measurement compared in $e^- \alpha$ and $e^- N\gamma$ channels
→ 10 % systematics
- ▶ Checking these backgrounds in $2e^- N\gamma$ and $2e^- \alpha$ channels:

^{208}Tl in the $2e^- N\gamma$ channel



^{214}Bi in the $2e^- \alpha$ channel
in [2.8 - 3.2] MeV

Phase 1: 3 events observed
for 6.5 ± 0.4 expected

Phase 2: 3 events observed
for 2.9 ± 0.2 expected

7 events in [2.8 - 3.2] MeV for 8.8 expected

PRD 92 (2015) 072011

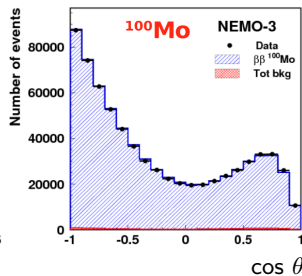
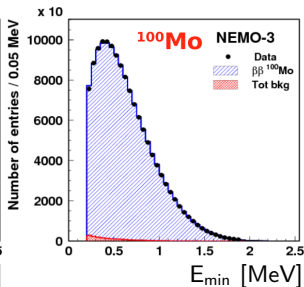
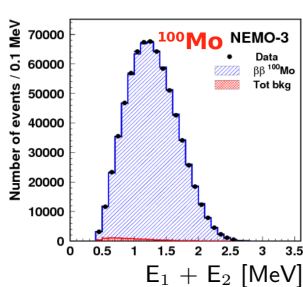
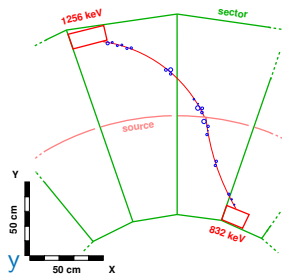
arXiv:1506.05825 - arXiv:1311.5695

NEMO-3 $2\nu 2\beta$ of ^{100}Mo Measurement

- ▶ 6.9 kg of ^{100}Mo
- ▶ $\sim 700\,000$ $2\nu 2\beta$ events collected
- ▶ Efficiency $\mathcal{E}_{2\nu} = 4.3\%$
- ▶ Signal to background ratio $S/B = 76$
- ▶ Preliminary half-life:

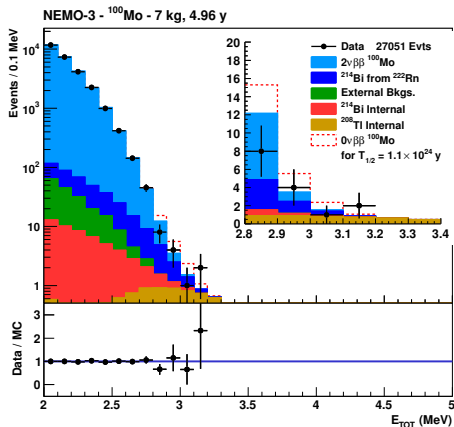
$$T_{1/2}^{2\nu} = 7.16 \pm 0.01 \text{ (stat)} \pm 0.54 \text{ (syst)} \times 10^{18} \text{ y}$$

update to be published - Phys. Rev. Lett. 95, 182302 (2005)



- ▶ 0.7 % systematical uncertainty on the $2\nu 2\beta$ efficiency above 2 MeV

- Detection efficiency $\mathcal{E}_{0\nu} = 4.7\%$ in the $[2.8 - 3.2]$ MeV region
- No event excess observed in ^{100}Mo after 34.3 kg·y exposure:
 $T_{1/2}^{0\nu} > 1.1 \times 10^{24} \text{ y}$ (90 % CL) $\rightarrow |m_{\beta\beta}| < 0.33 - 0.62 \text{ eV}$



Expected background in $[2.8 - 3.2]$ MeV

$2\nu 2\beta$	8.45 ± 0.05
^{214}Bi from radon	5.2 ± 0.5
External	< 0.2
^{214}Bi internal	1.0 ± 0.1
^{208}Tl internal	3.3 ± 0.3
Total	18.0 ± 0.6
Data	15

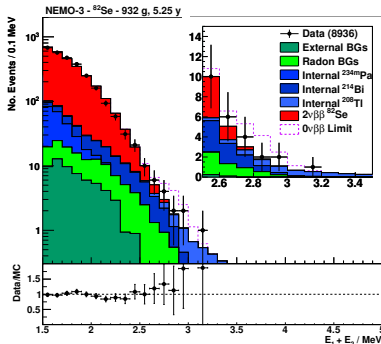
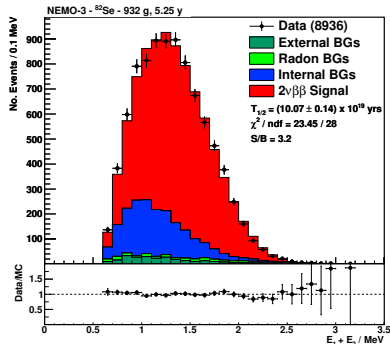
Total background in ROI
 $1.3 \times 10^{-3} \text{ cts}/(\text{keV} \cdot \text{kg} \cdot \text{y})$

NEMO-3 $0\nu2\beta$ Search with ^{82}Se

PRELIMINARY

$T_{1/2}^{2\nu}(^{82}\text{Se}) \approx 14 \times T_{1/2}^{2\nu}(^{100}\text{Mo}) \rightarrow$ less $2\nu2\beta$ background in $0\nu2\beta$ ROI

$$T_{1/2}^{2\nu} = [10.07 \pm 0.14 \text{ (stat)} \pm 0.54 \text{ (syst)}] \times 10^{19} \text{ y}$$



$T_{1/2}^{0\nu} > 2.5 \times 10^{23} \text{ y}$ (90% CL) $\rightarrow |m_{\beta\beta}| < 1.2 - 3.0 \text{ eV}$

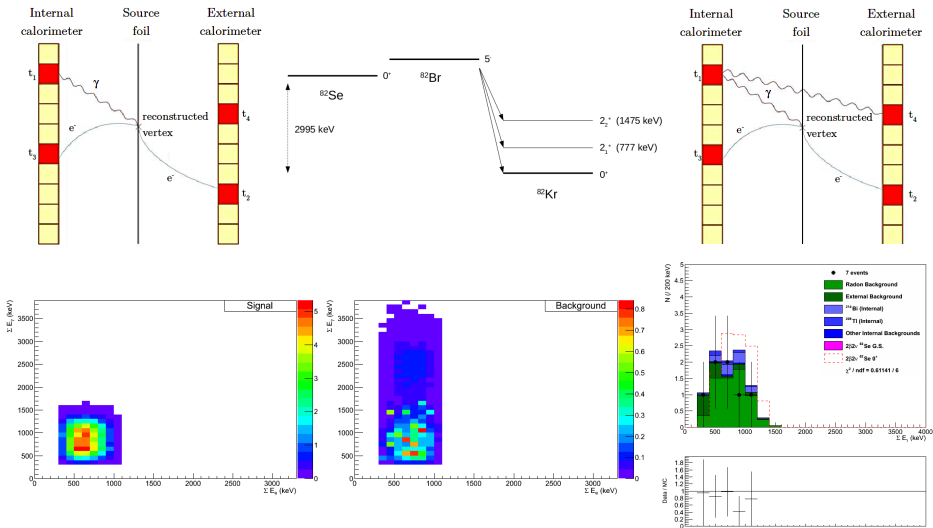
4 times worse than ^{100}Mo but with less than 15 % of the mass !

NEMO-3 Excited states dbd of ^{82}Se

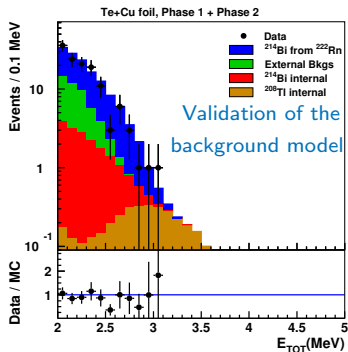
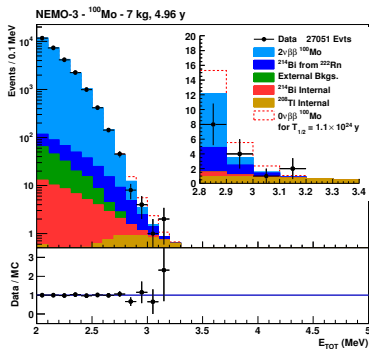
PRELIMINARY

NEMO-3 can also reconstruct 2β topologies with γ

Already demonstrated for ^{100}Mo Nucl. Phys. A 781 (2007) 209-226



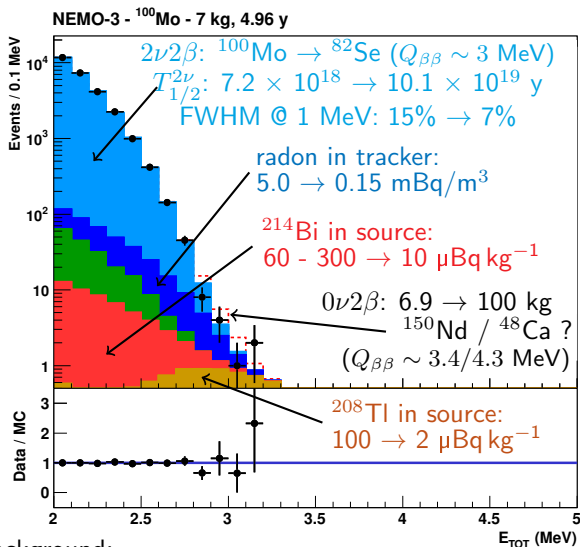
NEMO-3 High Energy Background



PRD 92 (2015) 072011 - arXiv:1506.05825 - arXiv:1311.5695

- ▶ No events in ^{100}Mo after 34.3 kg·y exposure above 3.2 MeV
- ▶ No events in copper and natural tellurium samples after 13.5 kg·y exposure above 3.1 MeV
- ▶ Background-free technique for high energy $Q_{\beta\beta}$ isotopes:
 ^{48}Ca : 4.272 MeV, ^{150}Nd : 3.368 MeV or ^{96}Zr : 3.350 MeV

From NEMO-3 to SuperNEMO



$0\nu 2\beta$ ROI background:

$1.3 \times 10^{-3} \rightarrow 5 \times 10^{-5}$

cts/(keV·kg·y)

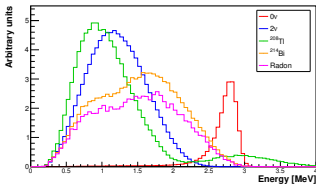
Sensitivity:

$T_{1/2}^{0\nu} > 1.1 \times 10^{24}$ y $\rightarrow 1 \times 10^{26}$ y

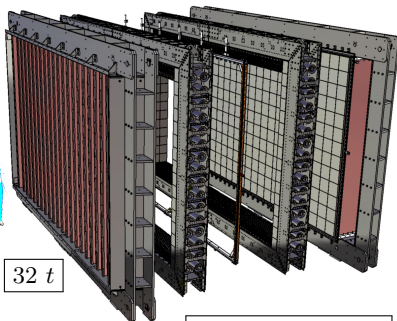
$|m_{\beta\beta}| < 0.33 - 0.62$ eV $\rightarrow 0.04 - 0.10$ eV

SuperNEMO Demonstrator Goals

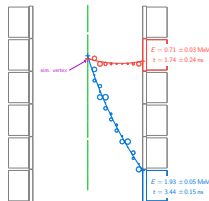
- ▶ NEMO-3 sensitivity in only 5 months (90 % CL):
 $T_{1/2}^{0\nu} > 1.1 \times 10^{24} \text{ y} \rightarrow |m_{\beta\beta}| < 0.33 - 0.62 \text{ eV}$
- ▶ No background in the $0\nu 2\beta$ region in 2.5 years for 7 kg of ^{82}Se
- ▶ Sensitivity after 17.5 kg·y exposure (90 % CL):
 $T_{1/2}^{0\nu} > 6.5 \times 10^{24} \text{ y} \rightarrow |m_{\beta\beta}| < 0.20 - 0.40 \text{ eV}$
- ▶ Commissioning Spring 2017 and physics data in Summer



Possible phase 2
with ^{150}Nd



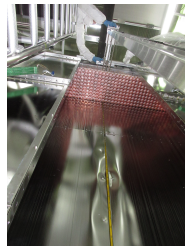
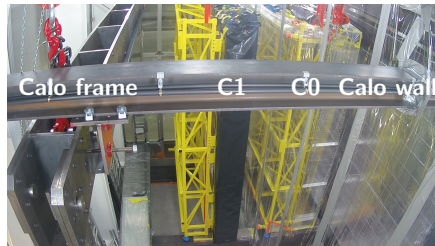
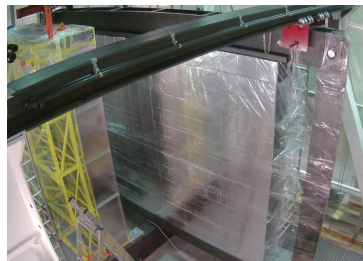
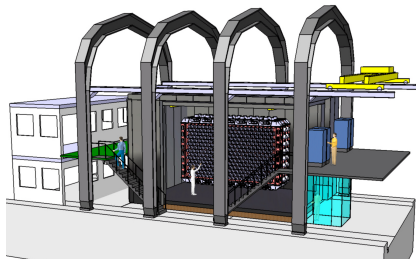
$$6.2 \times 2.1 \times 4.1 \text{ m}^3$$



SN@Ware — Top view

SuperNEMO Demonstrator Integration Status

Construction ongoing in the place of NEMO-3 in the LSM



Movie of demonstrator integration: <https://goo.gl/fRV9Re>

Other coming DBD projects

From Wright - Neutrino 2016

Experiment	Isotope	Technique	Location
COBRA	^{116}Cd , etc	CdZnTe	LNGS
CANDLES	^{48}Ca	CaF_2 scintillator + veto	Kamioka
AMoRE	^{100}Mo	Low-T MMC	Y2L
DCBA/MTD	^{100}Mo	Foils + tracker	KEK
NEXT	^{136}Xe	High-P TPC	LSC
PandaX III	^{136}Xe	High-P TPC	CJPL
SNO+	^{130}Te	Liquid scintillator	SNOLAB

Summary

- ▶ Neutrinoless double beta decay search is the best experimental technique to test the Majorana nature of the neutrino $\bar{\nu} \equiv \nu$
- ▶ 5 experiments have reached $|m_{\beta\beta}| < 1$ eV sensitivity with 4 isotopes
- ▶ upgrades and new experiments coming to investigate the inverted hierarchy region of $|m_{\beta\beta}| \approx 10 - 50$ meV

