# Neutrinoless Double Beta Decay Search

## SFP - Journée de la division - Champs & Particules

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LAL Orsay

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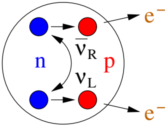
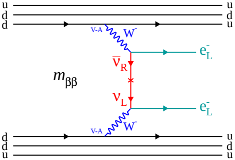
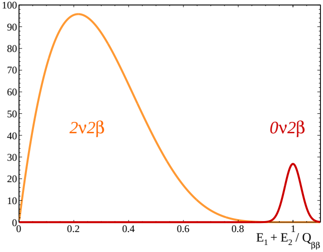
# Neutrinoless Double Beta Decay $(0\nu2\beta)$

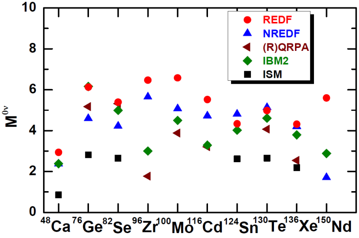
Best experimental technique to search for Majorana neutrinos





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

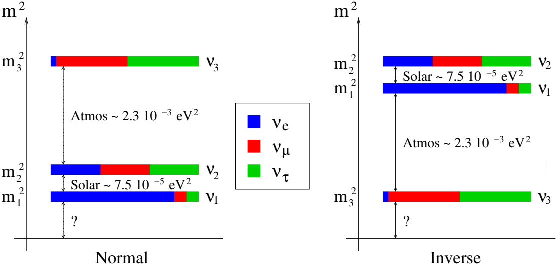




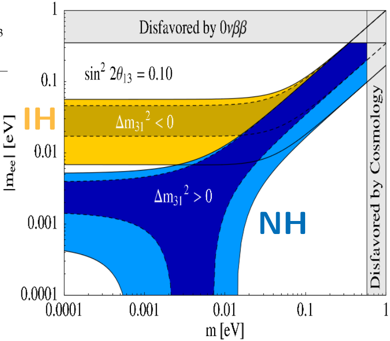
# Effective Neutrino Mass for Double Beta Decay

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

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



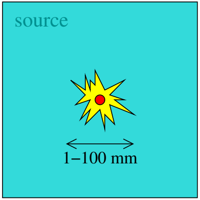
Inverted Hierarchy approximately for $|m_{\beta\beta}| \approx 10$ - $50\,\text{meV}$



A. Merle and W. Rodejohann, Phys. Rev. D73:073012, 2006

# Type of Double Beta Decay Experiments

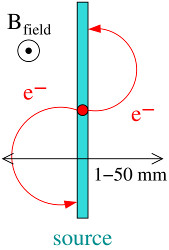
## Calorimeters



semiconductors,
bolometers,
scintillators, TPC...

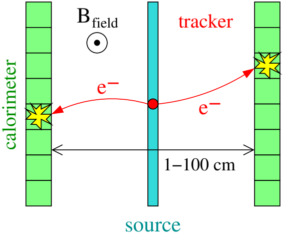
- efficiency: ~90%
- energy resolution few keV (FWHM)
- no tracking
- less background rejection
- isotope dependent

## Trackers



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

## Tracko–calos



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

# Choice of double beta decay isotopes

The $2\beta$ isotope for an experiment:

- depends on the experimental technique
- high $Q_{\beta\beta} > Q_\beta(^{214}Bi) = 3.27$ MeV $> E_\gamma(^{208}Tl) = 2.615$ 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 $2\nu2\beta$ 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** | $\mathbf{1.4 \pm 0.5 \times 10^{21}}$ | 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 | $\mathbf{7.2 \pm 0.5 \times 10^{18}}$ | 9.63 |
| $^{116}$Cd | 2.805 | 4.62 | $2.9 \pm 0.3 \times 10^{19}$ | 7.49 |
| $^{130}$Te | 2.529 | 4.09 | $\mathbf{7.0 \pm 1.4 \times 10^{20}}$ | **34.1** |
| $^{136}$Xe | 2.462 | 4.31 | $\mathbf{2.2 \pm 0.1 \times 10^{21}}$ | 8.9 |
| $^{150}$Nd | **3.368** | **19.2** | $9.1 \pm 0.7 \times 10^{18}$ | 5.6 |

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

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

# Current Best Limits on the $0\nu 2\beta$ Search

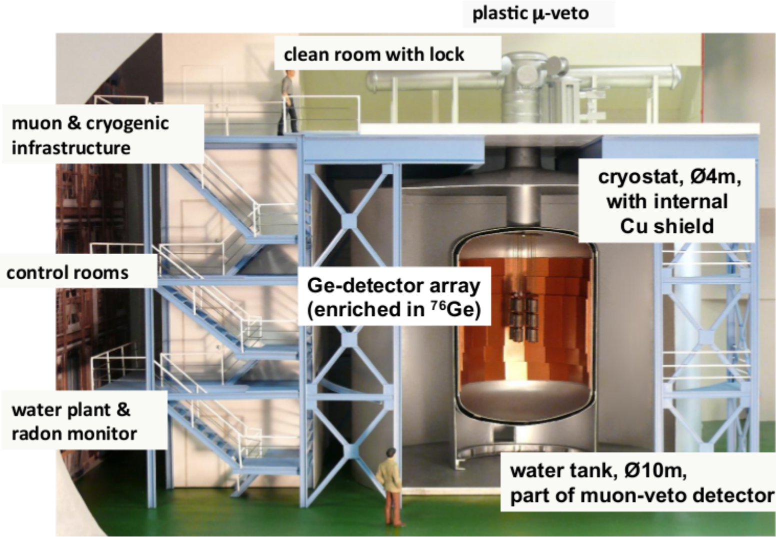
| **Isotope** | **Experiment** | **Technique** | **Mass** | $T^{0\nu}_{1/2}$ (90%) **limit** [y] | $\vert m_{\beta\beta}\vert$* **limit** [eV] |
|---|---|---|---|---|---|
| $^{48}$Ca | CANDLES | Scintillation | 0.01 kg | $> 5.8 \times 10^{22}$ | $<$ 3.55 - 9.91 |
| $^{76}$Ge | GERDA I+II | Ionisation | 38 kg | $> 4.0 \times 10^{25}$ | $<$ 0.14 - 0.34 |
| $^{82}$Se | NEMO-3 | Tracko-calo | 930 g | $> 3.2 \times 10^{23}$ | $<$ 0.85 - 2.08 |
| $^{96}$Zr | NEMO-3 | Tracko-calo | 9.43 g | $> 9.2 \times 10^{21}$ | $<$ 3.97 - 14.4 |
| $^{100}$Mo | NEMO-3 | Tracko-calo | 6.9 kg | $> 1.1 \times 10^{24}$ | $<$ 0.33 - 0.62 |
| $^{116}$Cd | Solotvina | Scintillation | 80 g | $> 1.7 \times 10^{23}$ | $<$ 1.22 - 2.30 |
| $^{130}$Te | CUORE-0+cino | Bolometer | ∼20 kg | $> 4.0 \times 10^{24}$ | $<$ 0.23 - 0.48 |
| $^{136}$Xe | EXO-200 | Liquid TPC | ∼110 kg | $> 1.1 \times 10^{25}$ | $<$ 0.17 - 0.43 |
| $^{136}$Xe | KamLAND-Zen | Scintillation | ∼500 kg | $> 1.9 \times 10^{25}$ | $<$ 0.10 - 0.25 |
| $^{150}$Nd | NEMO-3 | Tracko-calo | 36.5 g | $> 2.0 \times 10^{22}$ | $<$ 2.23 - 8.21 |

From X. Sarazin HDR + update

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

# GERDA Experiment

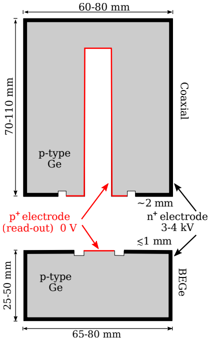
Germanium semicondutors experiment in the LNGS (3500 m.w.e.)



# GERDA Phase 1 - Ge Detectors

Phase 1 - 2011-2013:

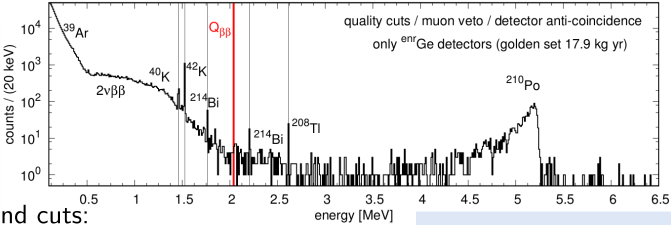
- 8 refurbished semi-coaxials (HdM - IGEX) → 17.7 kg
- 5 new BEGe deployed in 2012 → 3.6 kg
- $^{\text{nat}}$Ge enriched at 86 % → ∼18 kg of $^{76}$Ge
- Exposure-averaged energy resolutions at $Q_{\beta\beta} = 2039$ keV: 4.8±0.2 keV for coaxials and 3.2±0.2 keV for BEGe



# GERDA Signal and Backgrounds

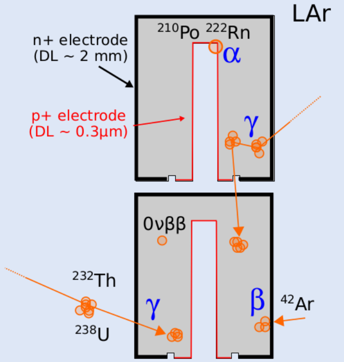
$0\nu2\beta$ events would be single site events (SSE) within few mm

$\gamma$ background result in multi-site events (MSE)



Background cuts:

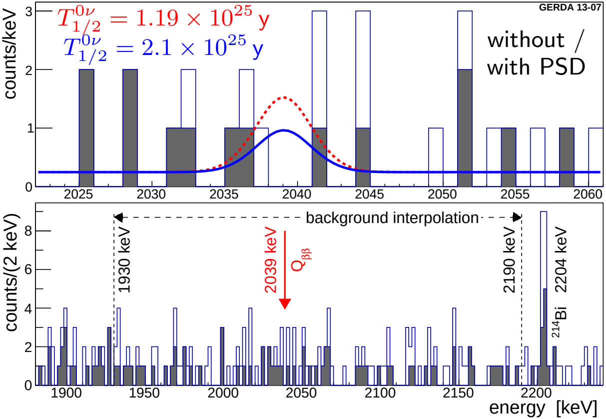
- signal in only 1 detector (AC)
- no muon veto (MV) signal within 8 μs
- more than 1 ms between events ($^{214}$Bi-Po cascades)
- pulse shape discrimination (PSD) to reject MSE ($\mathcal{E}_{0\nu} \sim 90$ %):
  - coax: artificial neural network (ANN) on complicated signals
  - BEGe: different maximal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



# GERDA Phase 1 - $0\nu2\beta$ Search

21.6 kg·y
exposure

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



Phys. Rev. Lett 111 (2013) 122503 - arXiv:1307.4720

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

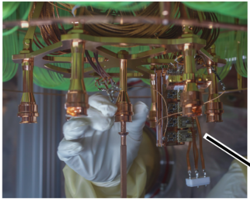
| Bkg [cts/(keV·kg·y)] | Before PSD | After PSD |
|---|---|---|
| Coaxials | $1.8 \pm 0.2 \times 10^{-2}$ | $1.1 \pm 0.2 \times 10^{-2}$ |
| BEGe | $4.2 \pm 1.0 \times 10^{-2}$ | $0.5 \pm 0.4 \times 10^{-2}$ |

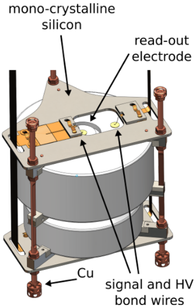
Exclude the HdM $0\nu2\beta$ Klapdor's claim: $T^{0\nu}_{1/2} = 1.19\,^{+0.37}_{-0.23} \times 10^{25}$ y

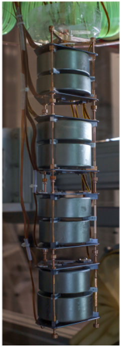
# GERDA Phase 2 - Ge Detectors

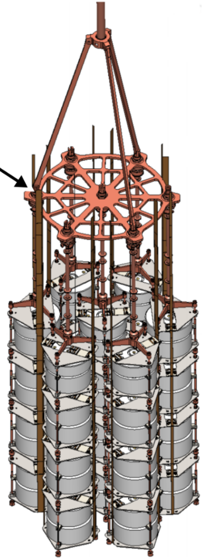
Phase 2 - 2016-2020:

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





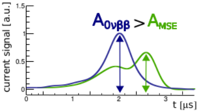


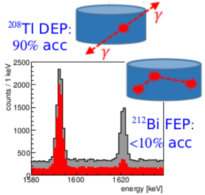


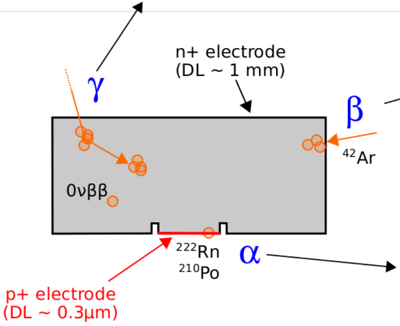
# GERDA Phase 2 - BEGe PSD

From Agostini - Neutrino 2016

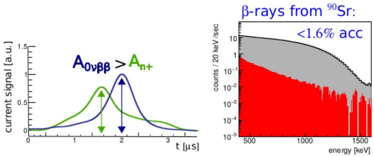
$\gamma$ interactions:
- multiple Compton scattering (MSE)
- sequence of peaks in current signal
- Double escpape peak (DEP): proxy for $0\nu\beta\beta$ events



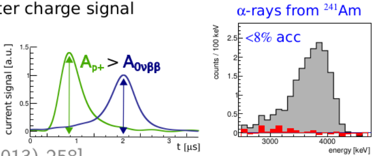




events on n+ surface:
- semiconductor junction -> weak E field
- slow current signal



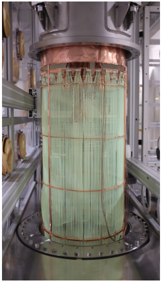
events on p+ electrode:
- electron drift faster then holes
- faster charge signal

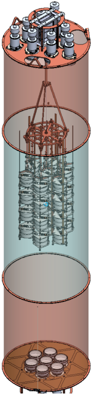


[JINST 6 2011 P03005, JINST 4 2009 P10007, EPJC 73 (2013) 258]

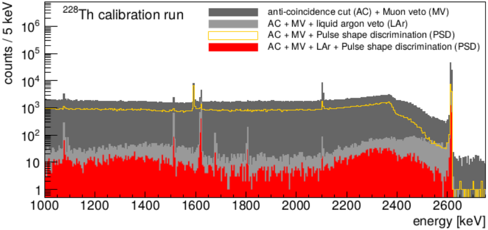
# GERDA Phase 2 - LAr veto

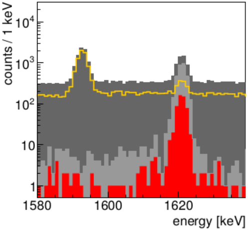
- LAr scintillation peaked at 128 nm
- 16 PMTs (9 top / 7 bottom)
- 800 m WLS fibers coated with TPB + 90 SiPMs
- nylon mini-shroud around each string coated with TPB

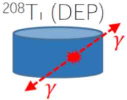


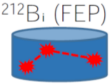


$^{228}$Th calibration run:



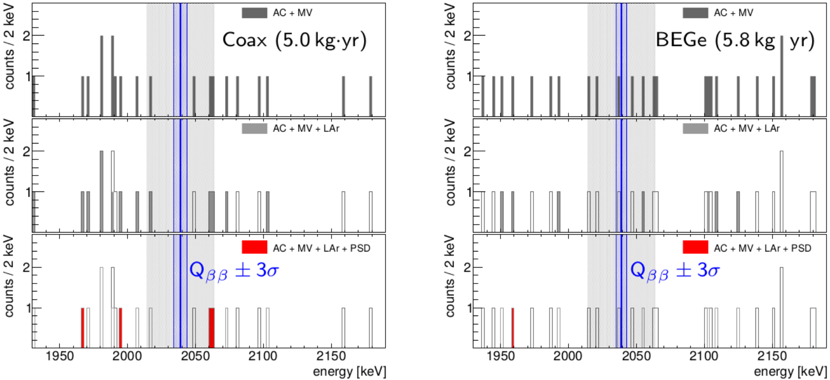






# GERDA Phase 2 - $0\nu2\beta$ Search

From Agostini - Neutrino 2016

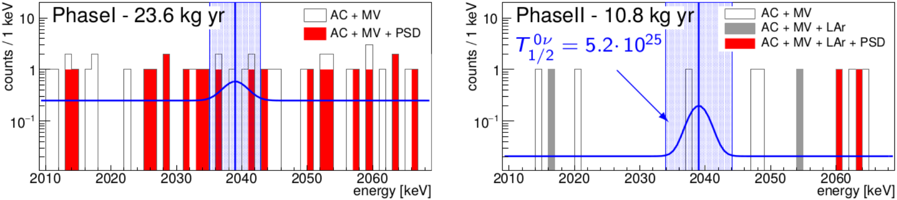


| | | Coax | BEGe |
|---|---|---|---|
| cts expected from bkg | $Q_{\beta\beta}\pm25$ keV | 0.8 | 0.3 |
| | 1930-2190 keV | 3.6 | 1.2 |
| cts observed | $Q_{\beta\beta}\pm25$ keV: | 2 | 0 |
| | 1930-2190 keV: | 4 | 1 |
| background index | 1930-2190 keV | $35^{+21}_{-15} \cdot 10^{-4}$ | $7^{+11}_{-5} \cdot 10^{-4}$ |

[cts/(keV· kg· yr)]

# GERDA Phase 2 - $0\nu2\beta$ Limits

From Agostini - Neutrino 2016



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

preliminary!

$T^{0\nu}_{1/2} > 4.0 \times 10^{25}$ y (90% CL) $\rightarrow |m_{\beta\beta}| <$ 0.18 - 0.30 eV

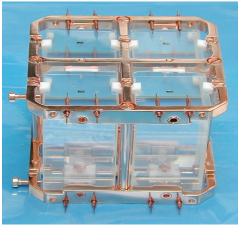
# Cuoricino Experiment

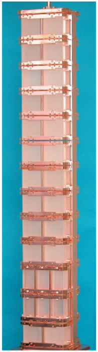
Bolometers Experiment at ~8 mK

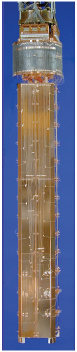
- ~40 kg of natural $TeO_2$ crystals (34.1 % of $^{130}$Te)
- from 2003 to 2008 in the LNGS in Italy
- 0.117 mK heat at $Q_{\beta\beta} = 2.530$ MeV with <10 keV FWHM

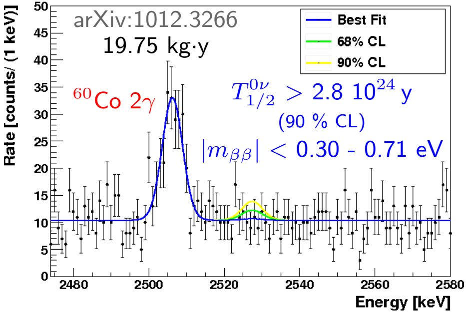
Limit on $0\nu2\beta$ after 19.75 kg·y exposure of $^{130}$Te:

- $T^{0\nu}_{1/2} > 2.8 \times 10^{24}$ 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 $\sim$10 mK

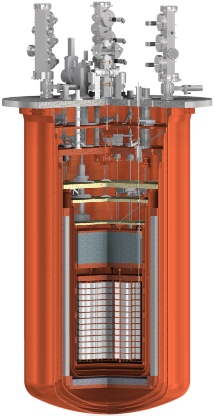
A total mass of 206 kg of $^{130}$Te

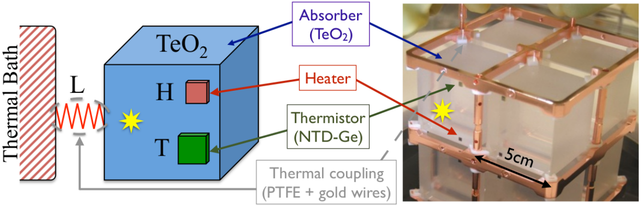
Energy resolution of 5 keV FWHM at $Q_{\beta\beta} = 2530$ keV

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

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

From Canonica Nu 16 & Lim ICHEP 16



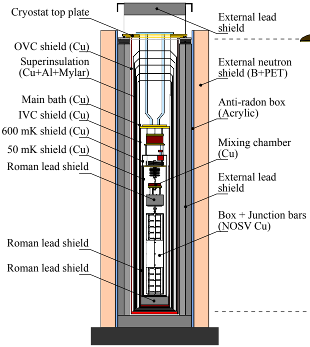


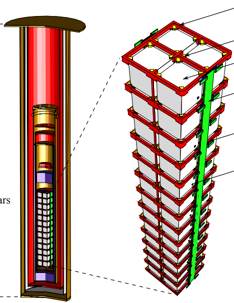
# CUORE-0

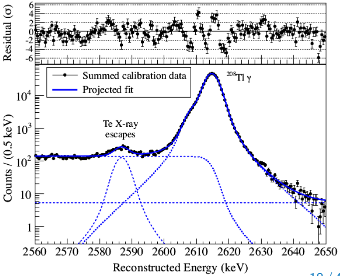
CUORE-0 is the first tower of CUORE in Cuoricino cryostat

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





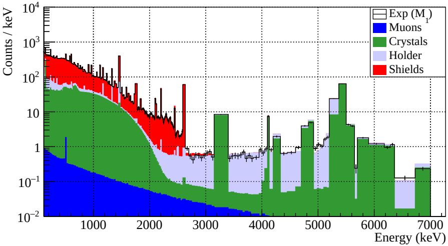


Energy resolution of 4.9 keV FWHM achieved

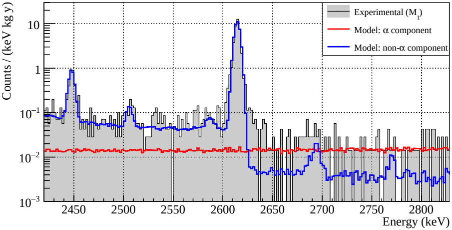
# CUORE-0 Backgrounds Results

arXiv:1609.01666

| 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 $0\nu2\beta$ ROI is 0.058 ± 0.006 cts/(keV·kg·y) (excluding the $^{60}$Co peak) which is ∼ 1/3 of Cuoricino and where ∼ 3/4 comes from old cryostat and shielding



Backgrounds levels should allow CUORE to achieve its requirements

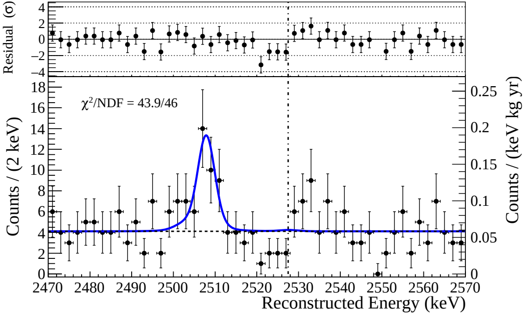
# CUORE-0 $0\nu2\beta$ Search

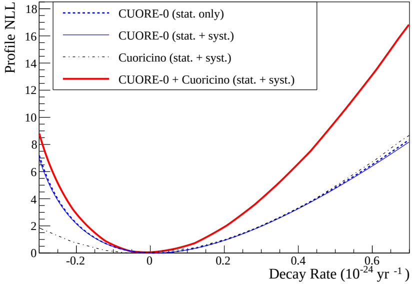
Phys. Rev. C 93, 045503 (2016) - arXiv:1601.01334

Exposure of 9.3 kg·y in $^{130}$Te

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

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





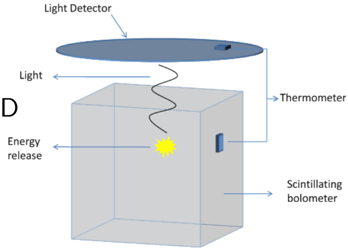
Combining CUORE-0 and Cuoricino

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

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

# CUPID

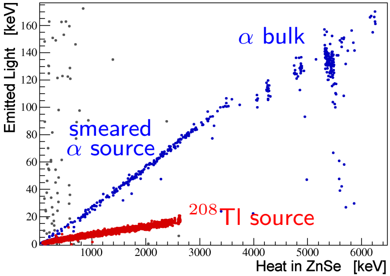
CUORE Upgrade with Particle IDentification
to further reduce backgrounds with $\beta/\gamma - \alpha$ PSD
and investigate the IH band



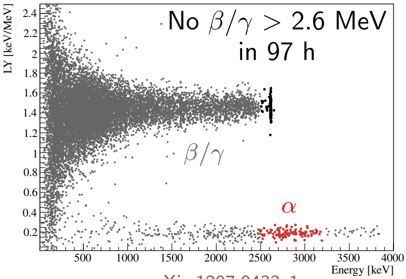
Scintillating bolometers:
$TeO_2$, $ZnMoO_4$, ZnSe, $CdWO_4$ arXiv:1504.03599

R&D with Lucifer & Lumineu at LSM and LNGS

PSD example with ZnSe



PSD example with $ZnMoO_4$



No $\beta/\gamma > 2.6$ MeV
in 97 h

arXiv:1207.0433v1

# EXO-200 Experiment

JINST 7 P05010, 2012

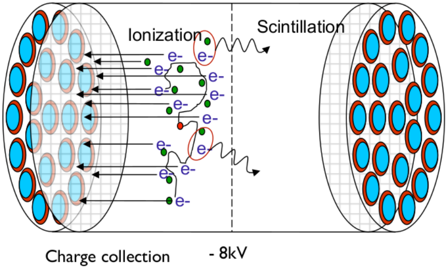
200 kg liquid Xenon TPC at WIPP under 1585 m.w.e.

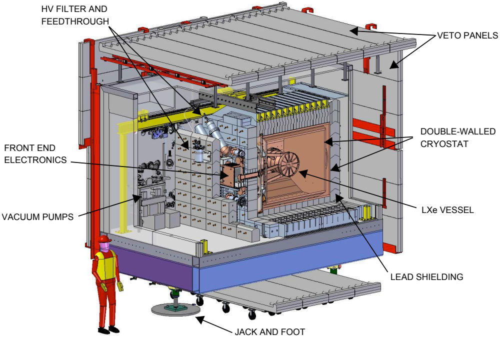
Ionization and 178 nm scintillation

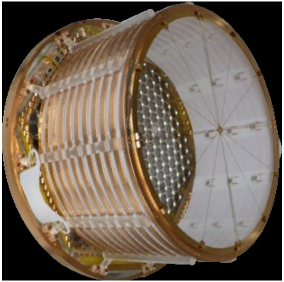
Calorimeter with 3D position and single-site (SS) or multi--sites (MS) events distinction

$\sim$110 kg of LXe active volume

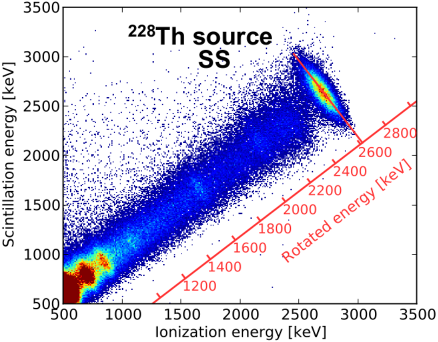
Xe enrichement at 80.7 % in $^{136}$Xe







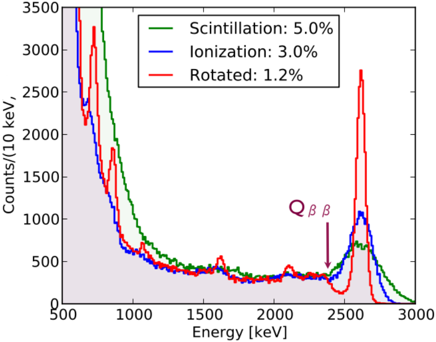
# EXO-200 Detector Response



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 - $0\nu2\beta$ 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

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

Background in the $0\nu2\beta$ $\pm2\sigma$ ROI:

$31.1 \pm 1.8(\mathrm{stat}) \pm 3.3(\mathrm{sys})$ counts

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

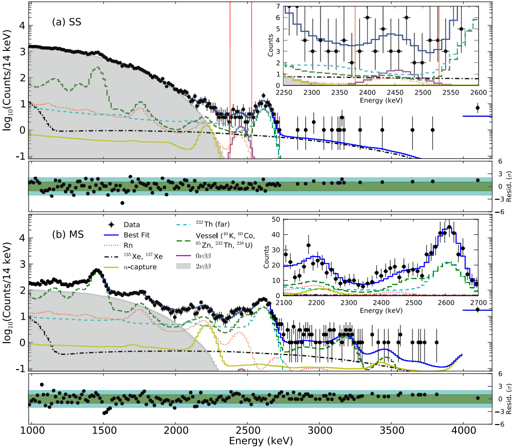
EXO-200 sensitivity:

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

Observed limit:

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

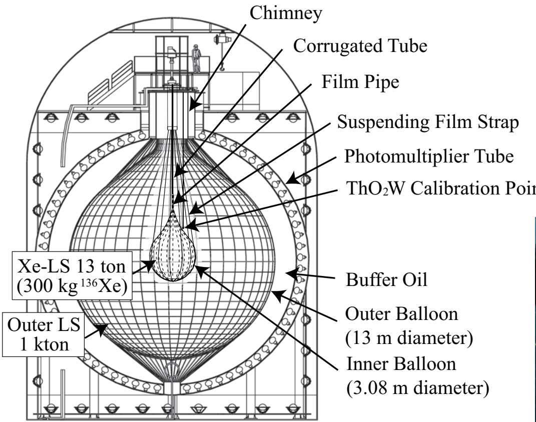
$m_{\beta\beta} < 190 - 450$ meV

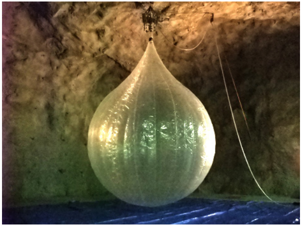


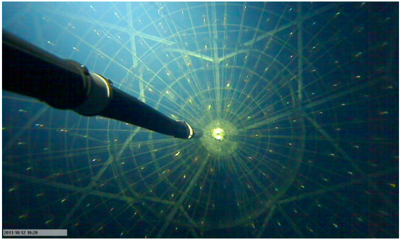
EXO-200 Phase 2 physics data with upgraded electronics and *deradonator* (factor ~10 reduction around TPC) started early 2016

# KamLAND-Zen Experiment

KamLAND 1 kt liquid scintillator detector in Kamioka (2700 m.w.e.)
Nylon mini-balloon $\sim$3 m diameter of 25 $\mu$m thick
$\sim$380 kg of enriched $^{136}$Xe loaded in 13 tons of liquid scintillator (Xe-LS)
Energy resolution $\sigma \sim 7.3\ \% / \sqrt{E(MeV)}$



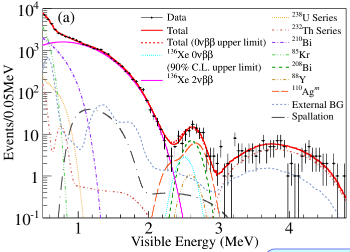




PRC85:045504 (2012), arXiv:1605.02889, Neutrino/ICHEP 2016

# KamLAND-Zen - Background History

PRL 110 062502 (2013)



## Phase 1: 2011-2012

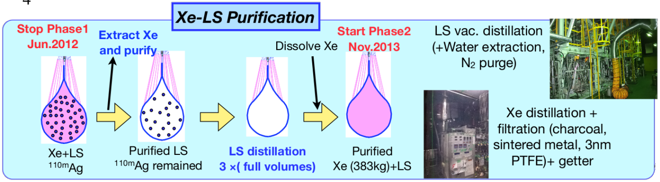
Exposure 89.5 kg·y

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

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

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

Shirai Neutrino 2016



**Xe-LS Purification**

**Stop Phase1 Jun.2012**

Xe+LS $^{110m}$Ag

**Extract Xe and purify**

Purified LS $^{110m}$Ag remained

**LS distillation 3 ×( full volumes)**

Dissolve Xe

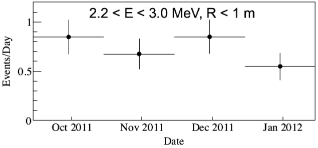
**Start Phase2 Nov.2013**

Purified Xe (383kg)+LS

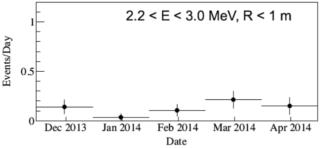
LS vac. distillation (+Water extraction, N₂ purge)

Xe distillation + filtration (charcoal, sintered metal, 3nm PTFE)+ getter

**Phase 1 (first 112.3 days)**



**Phase 2 (first 114.8 days)**



## Phase 2: 2013-2015

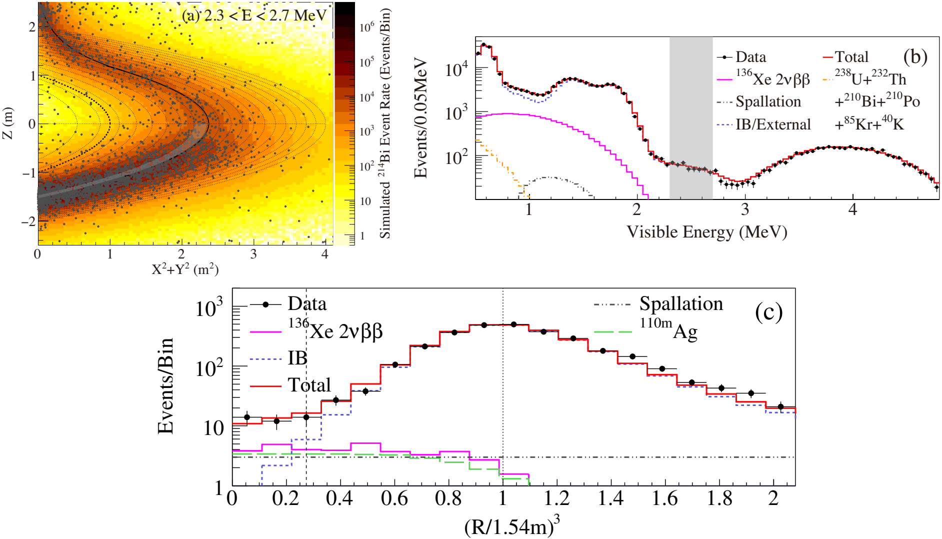
Exposure 504 kg·y

$^{110m}$Ag divided by $\sim$10

# KamLAND-Zen - Phase 2 Backgrounds

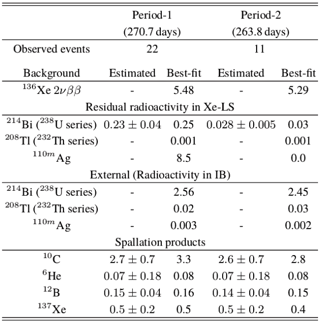
Phys. Rev. Lett. 117, 082503 (2016)
arXiv:1605.02889

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

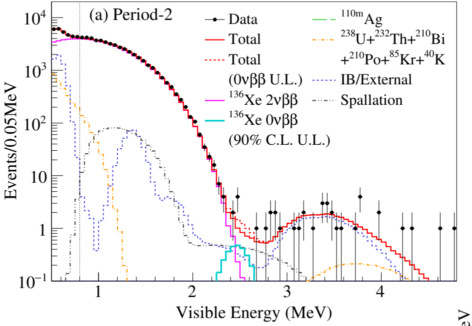


# KamLAND-Zen - $0\nu2\beta$ Search

Phys. Rev. Lett. 117, 082503 (2016)
arXiv:1605.02889



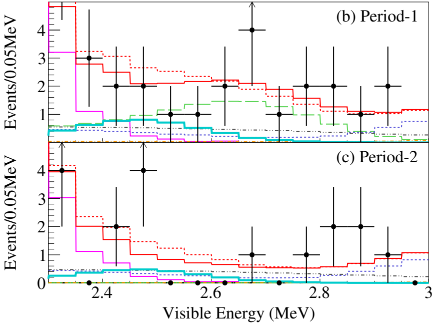
| | Period-1 (270.7 days) | | Period-2 (263.8 days) | |
|---|---|---|---|---|
| Observed events | 22 | | 11 | |
| Background | Estimated | Best-fit | Estimated | Best-fit |
| $^{136}$Xe $2\nu\beta\beta$ | - | 5.48 | - | 5.29 |
| Residual radioactivity in Xe-LS | | | | |
| $^{214}$Bi ($^{238}$U series)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



Phase 2 data divided in 2 periods

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

Not understood:
contamination sinking to the balloon bottom ?

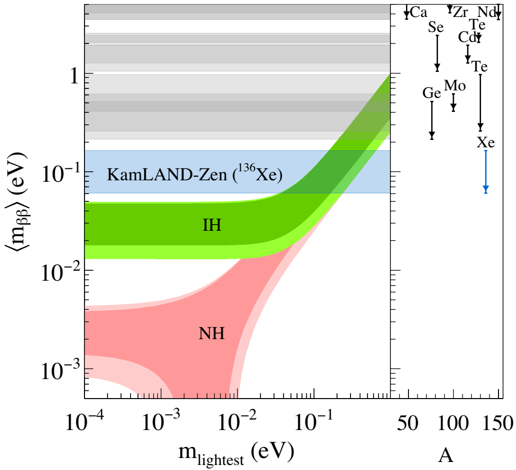


# KamLAND-Zen Limits

Approaching the inverted hierarchy region

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

Phase 1+2: $T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ y $\rightarrow |m_{\beta\beta}| < 61 - 125$ meV



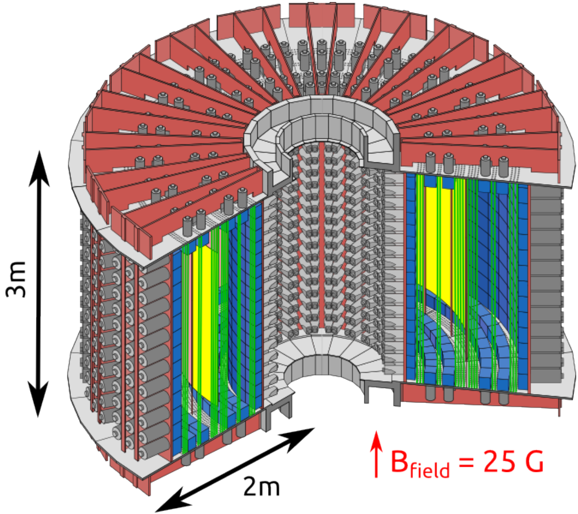
2 upgrades foreseen:

increase Xe mass to ~800-1000 kg

increase PMTs & photocoverage

# NEMO-3 Detector

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



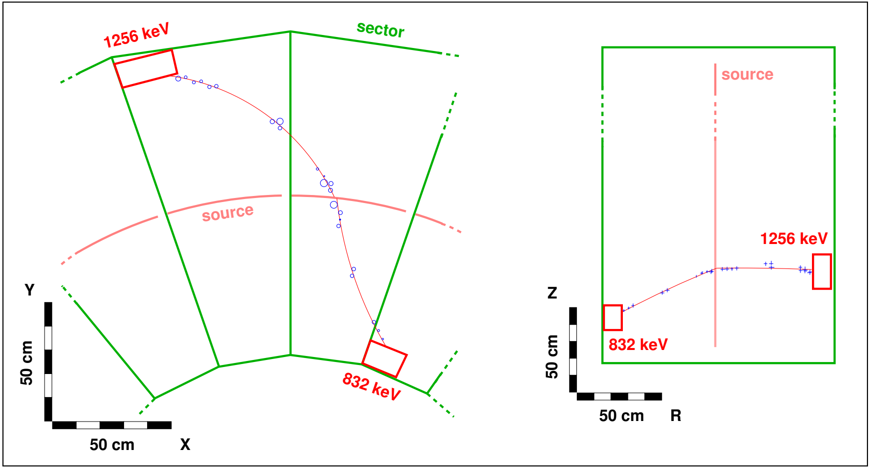
**sources**
60 mg/cm² foils
10 kg of ββ isotopes

**tracker**
6180 Geiger cells
vertex resolution :
$\sigma_{xy}$ ~ 3 mm $\sigma_z$ ~ 10 mm

**calorimeter**
1940 optical modules :
polystyren scintillators
+ 3" and 5" PMTs
$FWHM_E \sim 15\% / \sqrt{E_{MeV}}$
$\sigma_t$ ~ 250 ps

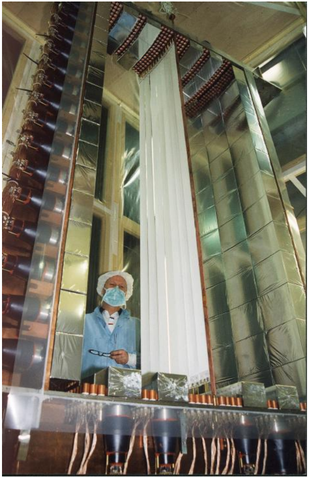
# NEMO-3 Unique Features

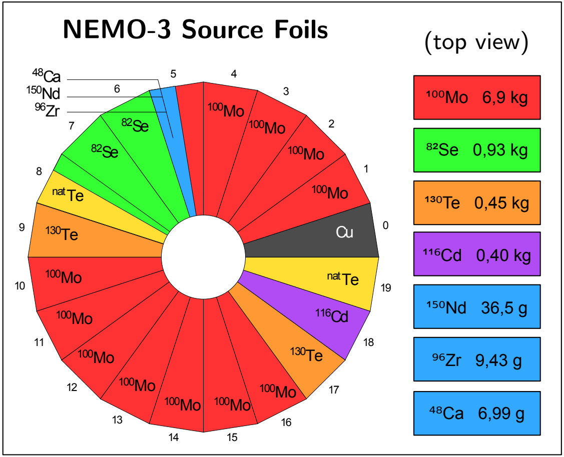
- Individual electron energies $(E_1, E_2)$, time of arrival $(t_1, t_2)$, curvature in magnetic field $(\pm)$, emission vertex and angle $(\cos\theta)$
- Unique DBD experiment with the direct reconstruction of the $2e^-$ $\rightarrow$ full signature of $0\nu2\beta$ events and powerful background rejection



# 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 Source Foils**

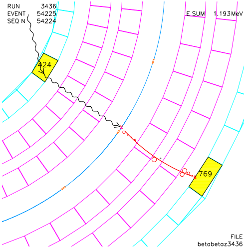
(top view)

| | | |
|---|---|---|
| 🟥 | $^{100}$Mo | 6,9 kg |
| 🟩 | $^{82}$Se | 0,93 kg |
| 🟧 | $^{130}$Te | 0,45 kg |
| 🟪 | $^{116}$Cd | 0,40 kg |
| 🟦 | $^{150}$Nd | 36,5 g |
| 🟦 | $^{96}$Zr | 9,43 g |
| 🟦 | $^{48}$Ca | 6,99 g |

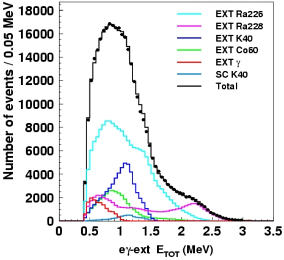
# NEMO-3 External Background Measurements

- Particle identification: $e^-$, $e^+$, $\gamma$ and $external\ TOF$
- Measurement of all contributions through 2 analysis channels:

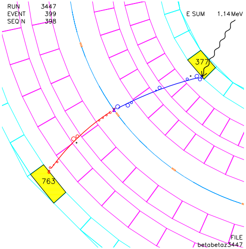
$(\gamma e^-)_{\text{ext}}$



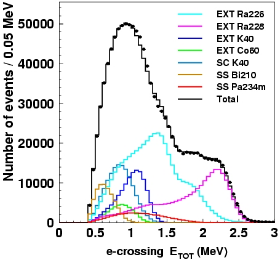
→



$e^-_{\text{crossing}}$



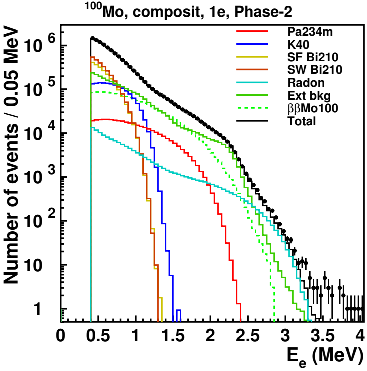
→



NIM A 606 (2009) 449–465

# NEMO-3 Internal Background Measurements

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



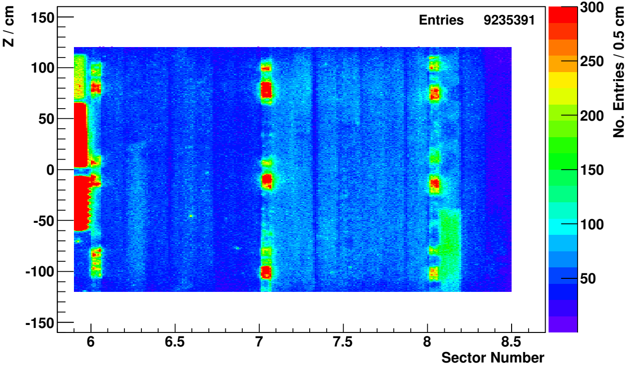
Neutron background not included in these fits (high energy tail)

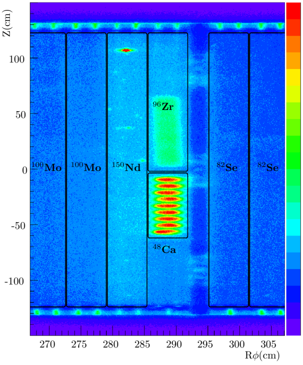
NIM A 606 (2009) 449–465

# NEMO-3 Imaging the source foils

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

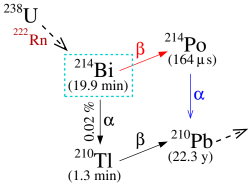
- With the internal background channels we can see source foils and uniformity of the backgrounds
- Radioactive hot-spots and calibration tubes can be removed
- Examples of $^{82}$Se (2 sectors) and $^{48}$Ca sources (9 disks):

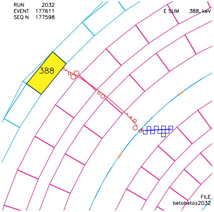


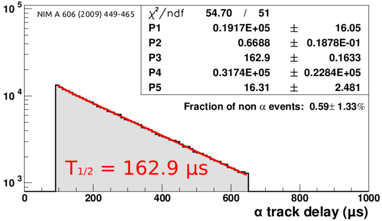


# NEMO-3 Radon and Internal $^{214}$Bi Measurements

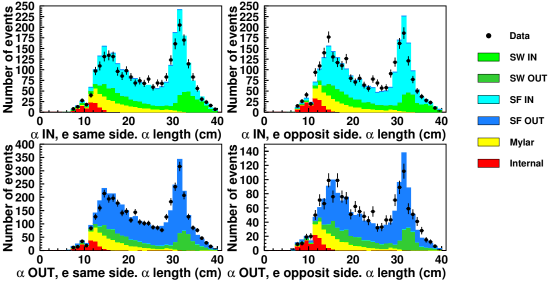
- Reconstruction of the BiPo $e^{-}\alpha_{\text{delayed}}$ events
- $\alpha$ track length and event topology allow to distinguish the origin







$^{100}$Mo composite



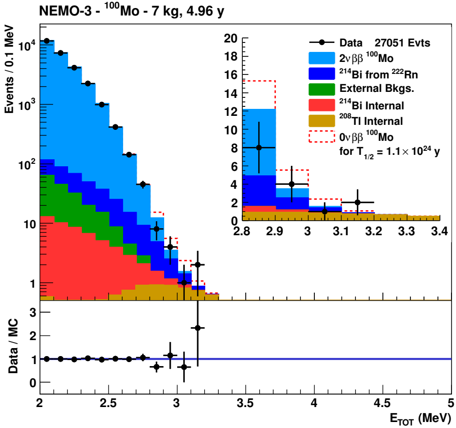
NIM A 606 (2009) 449–465

# NEMO-3 $0\nu2\beta$ Search with $^{100}$Mo

PRD 92 (2015) 072011

arXiv:1506.05825 - arXiv:1311.5695

- 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:
  $T^{0\nu}_{1/2} > 1.1 \times 10^{24}$ y (90 % CL) → $|m_{\beta\beta}| < 0.33 - 0.62\,\text{eV}$



| **Expected background in [2.8 – 3.2] MeV** | |
|---|---|
| $2\nu2\beta$ | 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** |

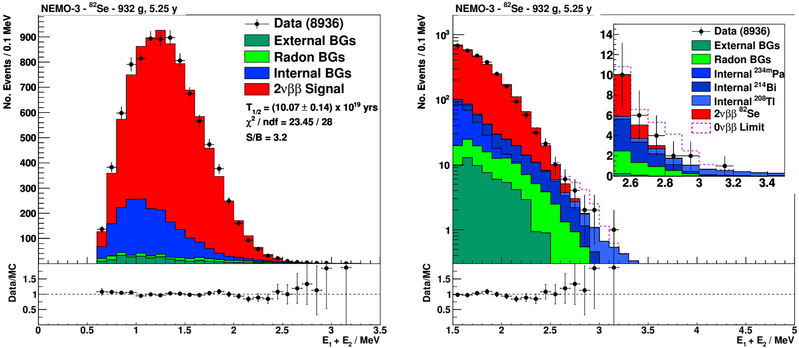
Total background in ROI
$1.3 \times 10^{-3}$ cts/(keV·kg·y)

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

PRELIMINARY

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

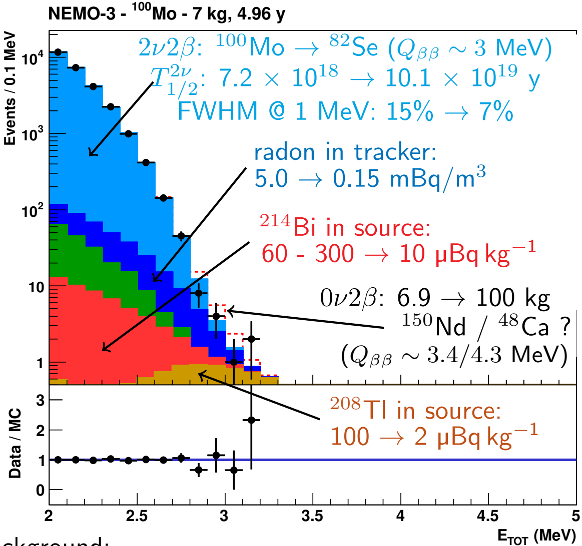
$$T^{2\nu}_{1/2} = [10.07 \pm 0.14\ (\text{stat}) \pm 0.54\ (\text{syst})] \times 10^{19}\ \text{y}$$



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

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

# From NEMO-3 to SuperNEMO



$2\nu2\beta$: $^{100}$Mo → $^{82}$Se ($Q_{\beta\beta} \sim 3$ MeV)
$T_{1/2}^{2\nu}$: $7.2 \times 10^{18} \rightarrow 10.1 \times 10^{19}$ y
FWHM @ 1 MeV: 15% → 7%

radon in tracker:
5.0 → 0.15 mBq/m$^3$

$^{214}$Bi in source:
60 - 300 → 10 μBq kg$^{-1}$

$0\nu2\beta$: 6.9 → 100 kg
$^{150}$Nd / $^{48}$Ca ?
($Q_{\beta\beta} \sim 3.4/4.3$ MeV)

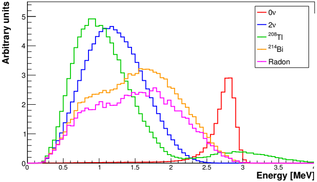
$^{208}$Tl in source:
100 → 2 μBq kg$^{-1}$

$0\nu2\beta$ ROI background:
$1.3 \times 10^{-3} \rightarrow 5 \times 10^{-5}$
cts/(keV·kg·y)

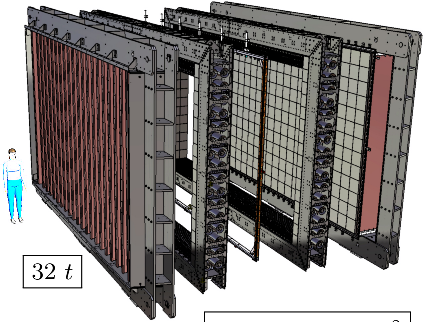
Sensitivity:
$T_{1/2}^{0\nu} > 1.1 \times 10^{24}$ y → $1 \times 10^{26}$ y
$|m_{\beta\beta}| <$ 0.33 - 0.62 eV → 0.04 - 0.10 eV

# SuperNEMO Demonstrator Goals

- NEMO-3 sensitivity in only 5 months (90 % CL):
  $T^{0\nu}_{1/2} > 1.1 \times 10^{24}$ y → $|m_{\beta\beta}| < 0.33 - 0.62$ eV
- No background in the $0\nu2\beta$ region in 2.5 years for 7 kg of $^{82}$Se
- Sensitivity after 17.5 kg·y exposure (90 % CL):
  $T^{0\nu}_{1/2} > 6.5 \times 10^{24}$ y → $|m_{\beta\beta}| < 0.20 - 0.40$ eV
- Commissioning Spring 2017 and physics data in Summer

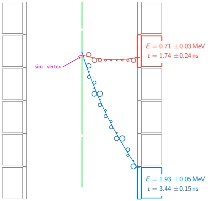


Possible phase 2
with $^{150}$Nd



$32\ t$

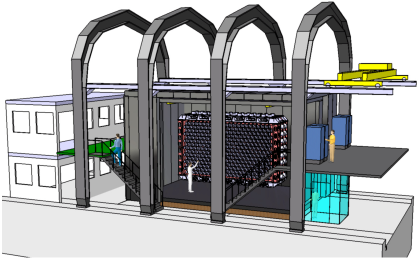
$6.2 \times 2.1 \times 4.1\ \mathrm{m}^3$

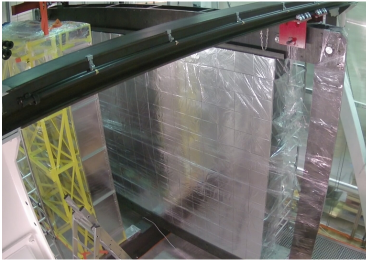


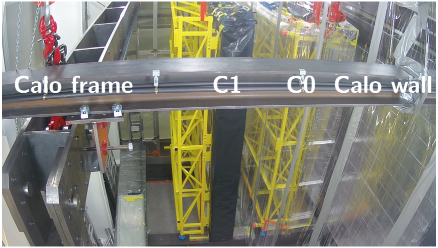
SN@ilWare — Top view

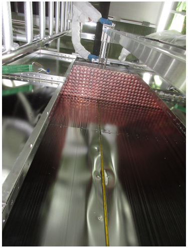
# SuperNEMO Demonstrator Integration Status

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









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

# This week status at LSM

- The 2/2 calorimeter walls have been completed
- The 2/4 first trackers are integrated and assembled with first calo
- The 2/4 last trackers have been delivered underground

# Summary

- Neutrinoless double beta decay search is the best experimental technique to test the Majorana nature of the neutrino $\overline{\nu} \equiv \nu$
- 5 experiments have reached $|m_{\beta\beta}| < 1$ eV sensitivity with 4 isotopes: Gerda - CUORE - EXO - KamLAND-Zen - NEMO
- Upgrades and new experiments coming to investigate the inverted hierachy region of $|m_{\beta\beta}| \approx 10$ - $50\,\text{meV}$