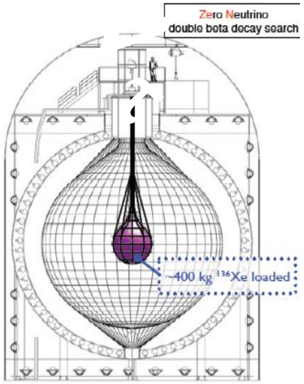
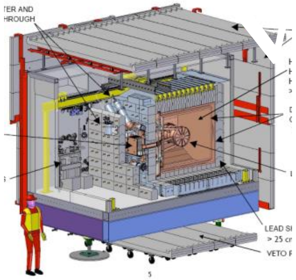
Present and Future of Double Beta Decay experiments

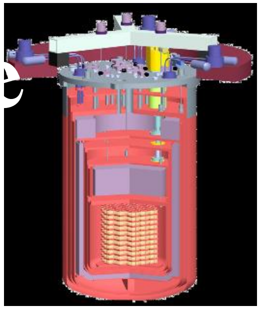
(aimed to know still unknown neutrino properties)



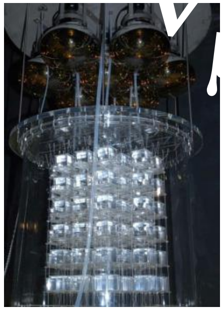
Kamland-Zen



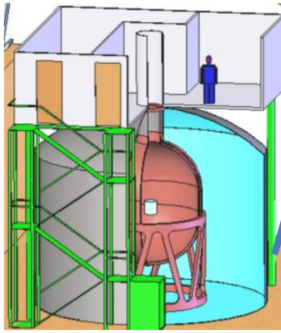
EXO



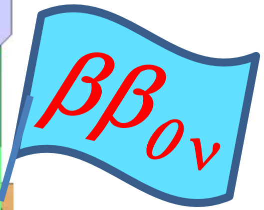
CUORE

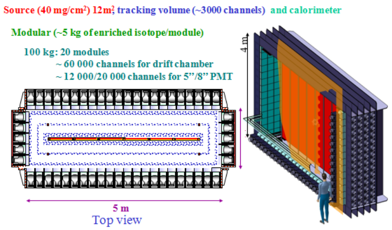


CANDLES

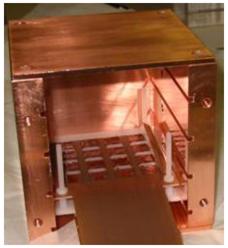


GERDA



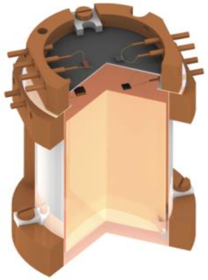


Super NEMO

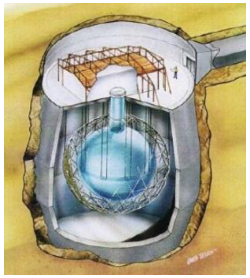


COBRA

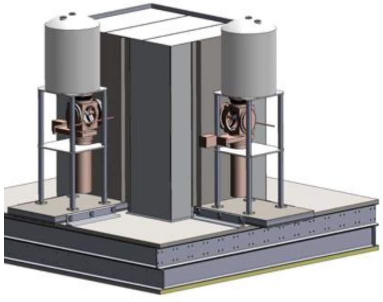
NEXT



LUCIFER



SNO+



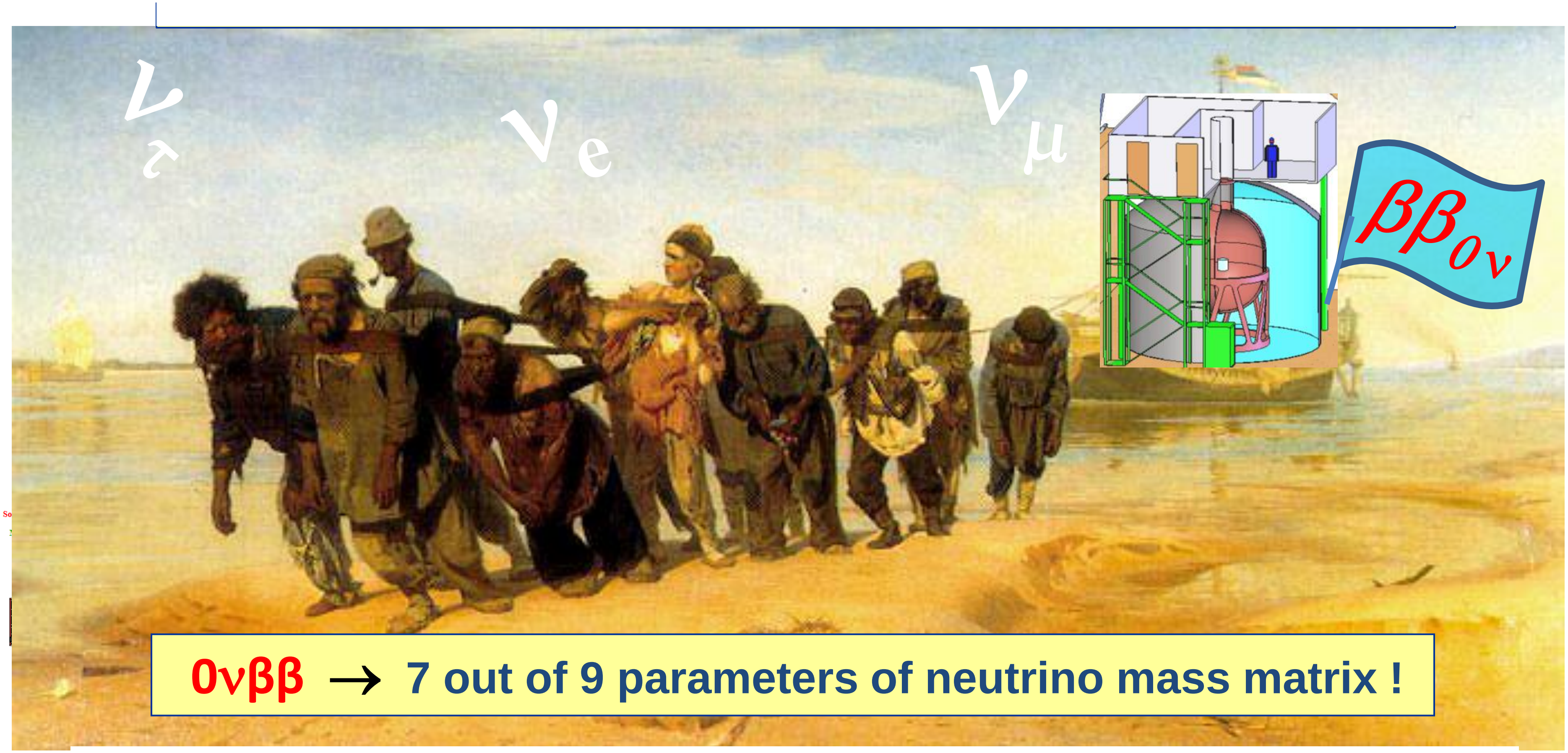
MAJORANA

A.Smolnikov, International workshop "Prospects of Particle Physics", Valdai, January 27 – February 1, 2014

Present and Future of Double Beta Decay experiments

(aimed to know still unknown neutrino properties)

Why so many efforts (and money) are needed ?



$0\nu\beta\beta$ → 7 out of 9 parameters of neutrino mass matrix !

A.Smolnikov, International workshop “Prospects of Particle Physics”, Valdai, January 27 – February 1, 2014

- Majorana vs. Dirac, effective mass , hierarchy, CP phases

Observation of 0νββ is the only known way to determine nature of neutrino (Dirac or Majorana)

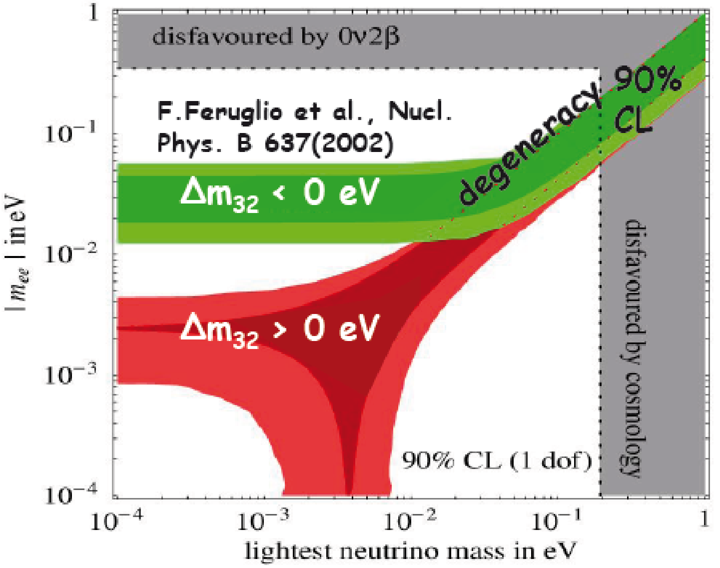
- Ton scale experiments are required to resolve neutrino-mass hierarchies

Neutrinoless double-beta-decay probes the effective Majorana-neutrino mass: $\langle m_{ee}\rangle = |\Sigma_i |U_{ei}|^2 e^{i\beta_i} m_i|$

→ Contains complex CP-violating Majorana phases

→ Cancellations possible!

In order to discriminate normal from inverted hierarchy, an experiment with sensitivity down to 10 meV is needed!



Inverted hierarchy

Normal hierarchy

0νββ decay rate

Light neutrino exchange

$$1/\tau = G(Q,Z) \cdot |M_{nucl}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

Phase space factor ($\sim Q_{\beta\beta}^5$)

Nuclear matrix element

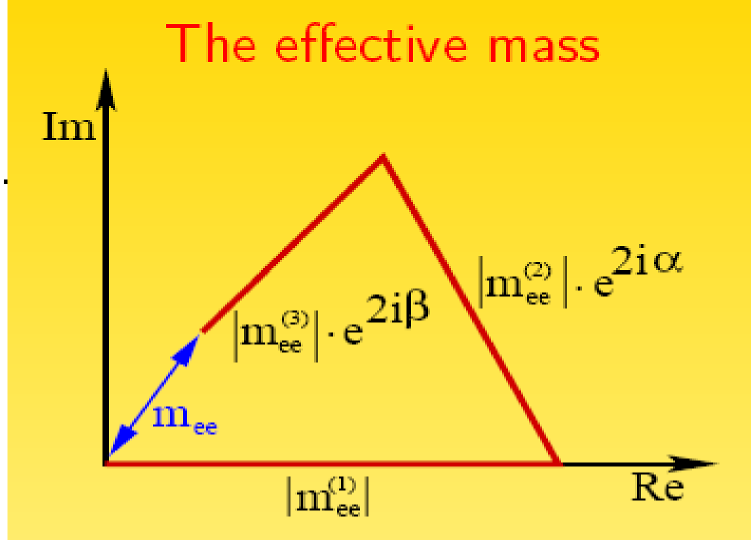
Effective Majorana neutrino mass

$$Q = E_{e1} + E_{e2} - 2m_e$$

$$\langle m_{\beta\beta} \rangle = |\sum_j m_j U_{ej}^2| \quad = \mathbf{m_1|U_{e1}|^2} \cdot$$

U_{ei} (complex) neutrino mixing matrix

$\alpha_{1,2}$ - complex CP-violating Majorana phases

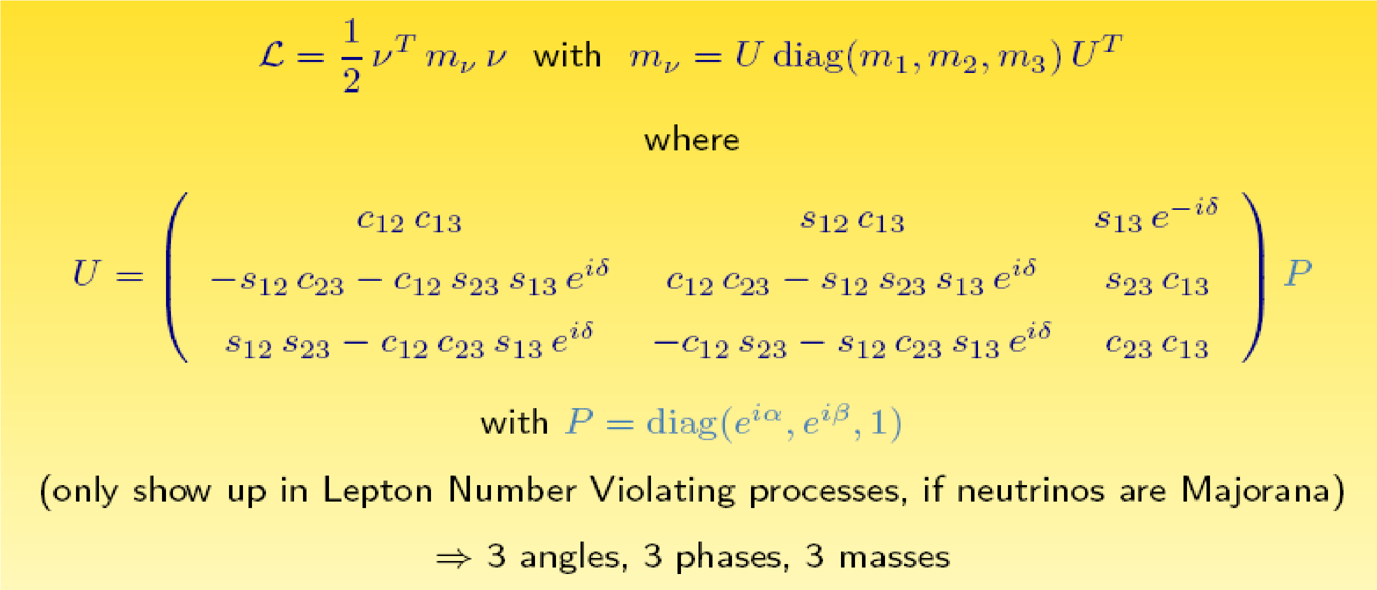


The effective mass

9 physical parameters in neutrino mass matrix m_ν

- θ_{12} and $m^2_2 - m^2_1$
- θ_{23} and $|m^2_3 - m^2_2|$
- θ_{13} (or $|U_{e3}|$)
- m_1, m_2, m_3
- sgn $(m^2_3 - m^2_2)$
- Dirac phase δ
- Majorana phases α and β (or $\alpha 1$ and $\alpha 2$, or $\phi 1$ and $\phi 2$, or. . .)

(see, for instant, W.Rodejohann, J.Phys.G. 39 (2012) 124008)



$$\mathcal{L} = \frac{1}{2} \nu^T m_\nu \nu \quad \text{with} \quad m_\nu = U \, \text{diag}(m_1, m_2, m_3) \, U^T$$

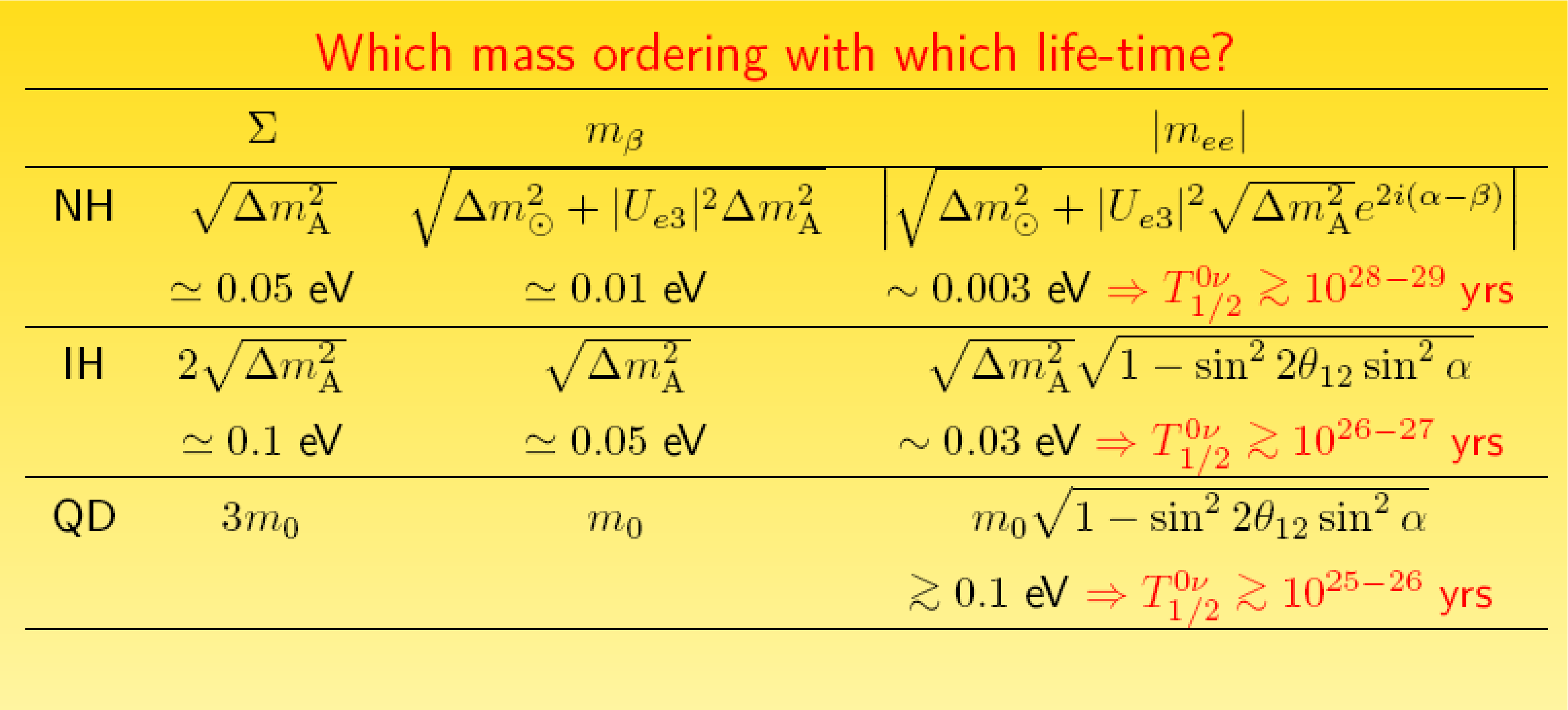
where

$$U = \begin{pmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13}\, e^{i\delta} & c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13}\, e^{i\delta} & s_{23}\, c_{13} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13}\, e^{i\delta} & -c_{12}\, s_{23} - s_{12}\, c_{23}\, s_{13}\, e^{i\delta} & c_{23}\, c_{13} \end{pmatrix} P$$

with $P = \text{diag}(e^{i\alpha}, e^{i\beta}, 1)$

(only show up in Lepton Number Violating processes, if neutrinos are Majorana)

$\Rightarrow$ 3 angles, 3 phases, 3 masses



Which mass ordering with which life-time?

	Σ	m_β	$\lvert m_{ee}\rvert$
NH	$\sqrt{\Delta m_{\mathrm{A}}^2}$	$\sqrt{\Delta m_\odot^2 + \lvert U_{e3}\rvert^2 \Delta m_{\mathrm{A}}^2}$	$\left\lvert \sqrt{\Delta m_\odot^2} + \lvert U_{e3}\rvert^2 \sqrt{\Delta m_{\mathrm{A}}^2}\, e^{2i(\alpha-\beta)} \right\rvert$
	$\simeq 0.05$ eV	$\simeq 0.01$ eV	~ 0.003 eV $\Rightarrow T^{0\nu}_{1/2} \gtrsim 10^{28-29}$ yrs
IH	$2\sqrt{\Delta m_{\mathrm{A}}^2}$	$\sqrt{\Delta m_{\mathrm{A}}^2}$	$\sqrt{\Delta m_{\mathrm{A}}^2}\sqrt{1 - \sin^2 2\theta_{12} \sin^2 \alpha}$
	$\simeq 0.1$ eV	$\simeq 0.05$ eV	~ 0.03 eV $\Rightarrow T^{0\nu}_{1/2} \gtrsim 10^{26-27}$ yrs
QD	$3m_0$	m_0	$m_0\sqrt{1 - \sin^2 2\theta_{12} \sin^2 \alpha}$
			$\gtrsim 0.1$ eV $\Rightarrow T^{0\nu}_{1/2} \gtrsim 10^{25-26}$ yrs

Method	**ν – mass Sensitivity**		
	Now (2014) [eV]	Nearest future (2017-2020) [eV]	Far future (> 2020) [eV]
Kurie	2.3	0.2	0.1
Cosmology	1	0.5	0.05
0νββ	0.3	0.1	0.02

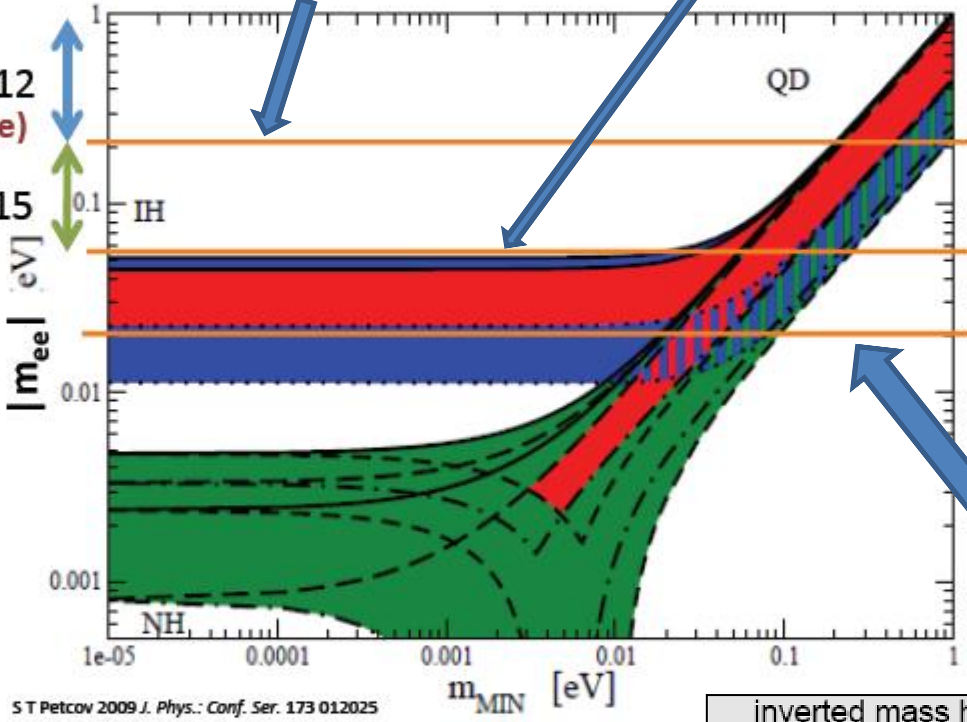
Goal of the next generation experiments

Isotope mass

~ 10 kg 2012 **(200 – 400kg ^{136}Xe)**

~ 100 kg 2015

~ 1000 kg



S T Petcov 2009 *J. Phys.: Conf. Ser.* 173 012025

~ 0.3 eV

~ 60 meV

~ 20 meV

Required background level in the ROI

100 – 1000 cts/yr/ton

1 – 10 cts/yr/ton

0.1 – 1 cts/yr/ton

inverted mass hierarchy

lower <m$_{ee}$> is given by (for light ν exchange):

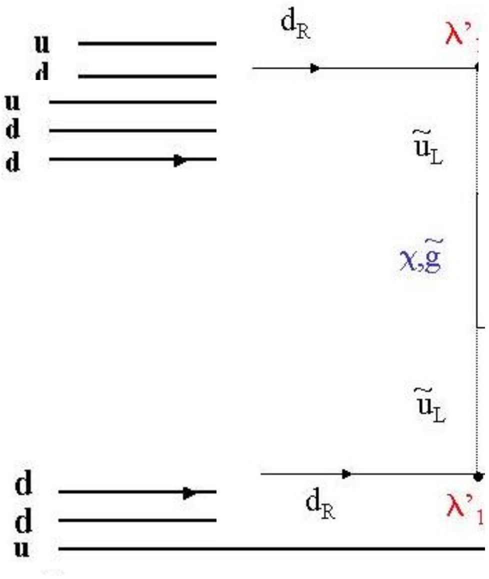
$$\begin{aligned}\langle m_{ee}\rangle^{IH}_{min} &= \sqrt{m_3^2+\Delta m_A^2}\cdot\cos(\theta_{12})^2\cdot\cos(\theta_{13})^2 -\\ &\quad \sqrt{m_3^2+\Delta_{sol}^2+\Delta m_A^2}\cdot\sin(\theta_{12})^2\cos(\theta_{13})^2 -\\ &\quad m_3\sin(\delta_{13})^2\\ &\approx (1-2\sin(\theta_{12})^2)\sqrt{\Delta m_A^2}\\ &= (0.364^{+0.032}_{-0.038})(49\pm 1.2)\ \text{meV}\\ &= 17.8^{+1.6}_{-1.9}\ \text{meV}\end{aligned}$$

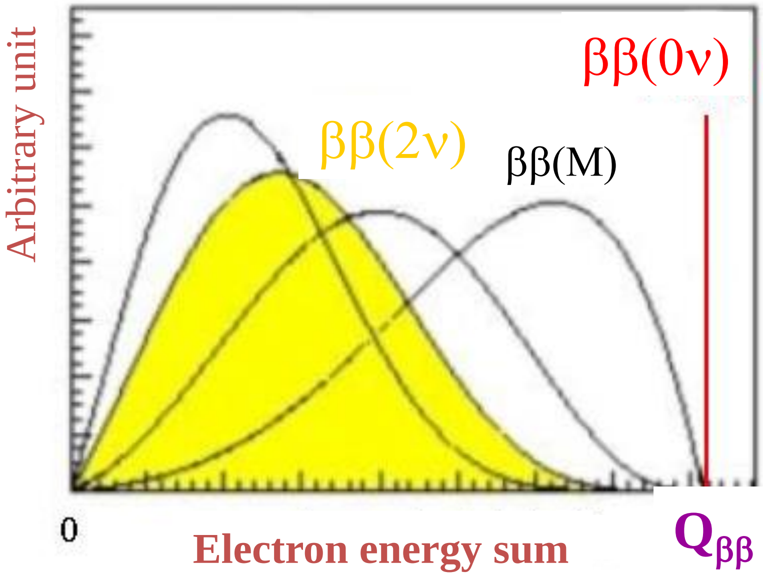
Neutrinoless double beta decay

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

Discovery implies ΔL=2 and Majorana neutrino

Process:	**parameters**
Light neutrino exchange	$\langle m_\nu \rangle$
(V+A) current	$\langle m_\nu \rangle, \langle \lambda \rangle, \langle \eta \rangle$
Majoron emission	$\langle g_M \rangle$
SUSY	$\lambda'_{111}, \lambda'_{113} \lambda'_{131}, \ldots$





Nuclear matrix element

Nuclear matrix element

$,Z) |M|^2 \langle m_\nu \rangle^2$

tion $T_{1/2}$ depends on

nd squarks mass

$|^2 \langle g_M \rangle^2$

ective mass:

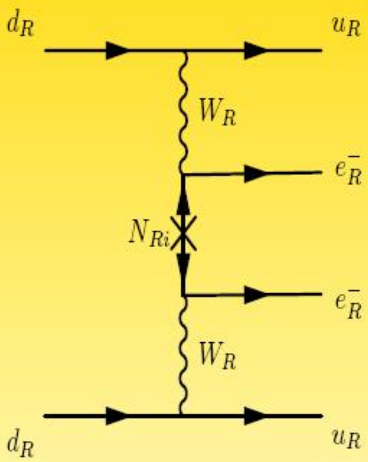
etween Majoron and neutrinos

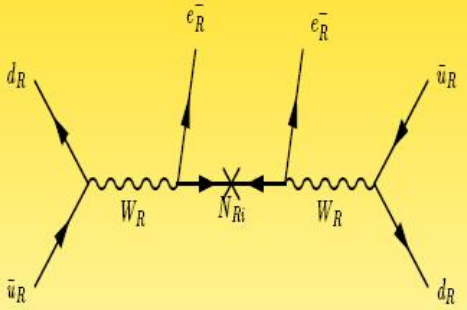
$+ m_2 |U_{e2}|^2 . e^{i\alpha 1} + m_3 |U_{e3}|^2 . e^{i\alpha 2}$

ment

ase

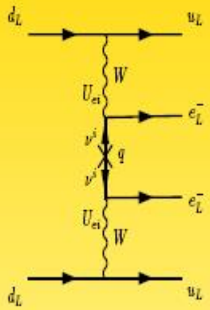
Left-right symmetry

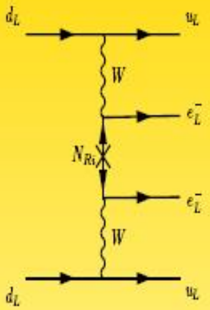


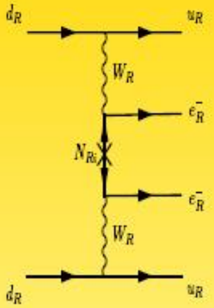


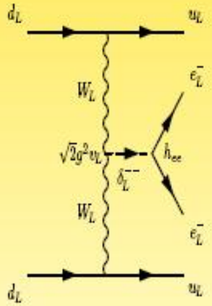
Senjanovic, Keung, 1983; Senjanovic *et al.*, 1011.3522; 1103.1627

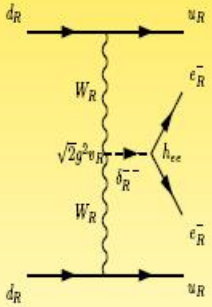
Left-right symmetry

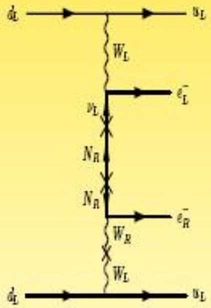


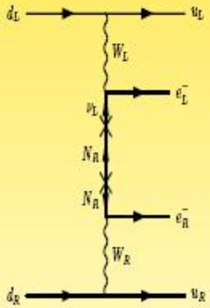








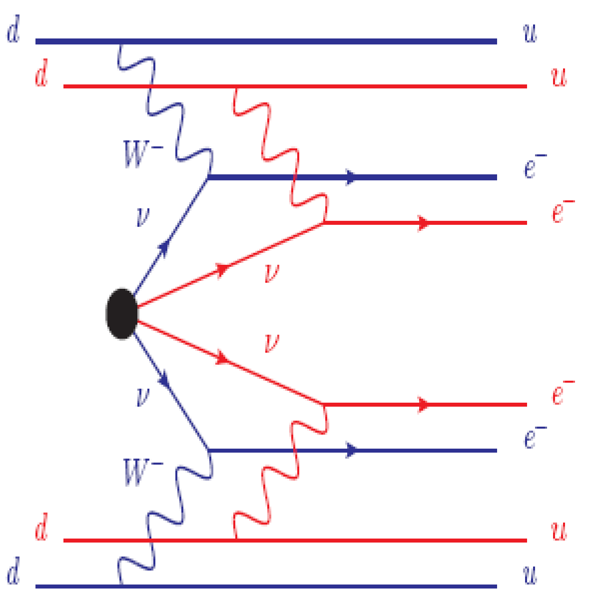


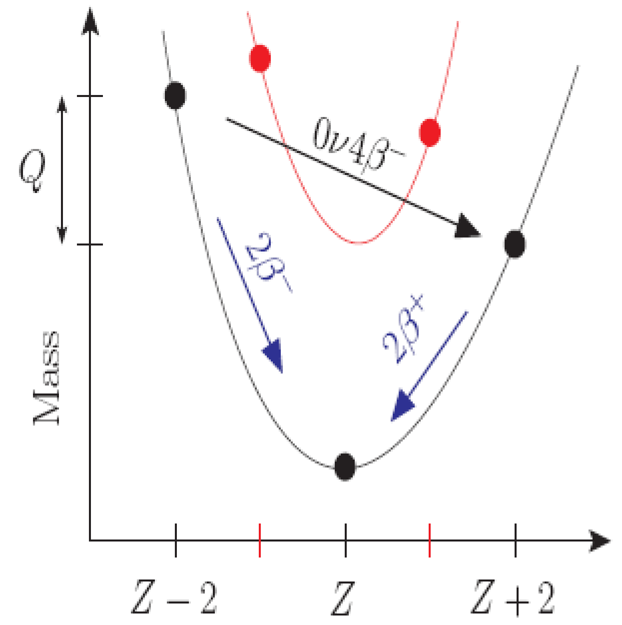


Does Dirac neutrinos mean there is no Lepton Number Violation?

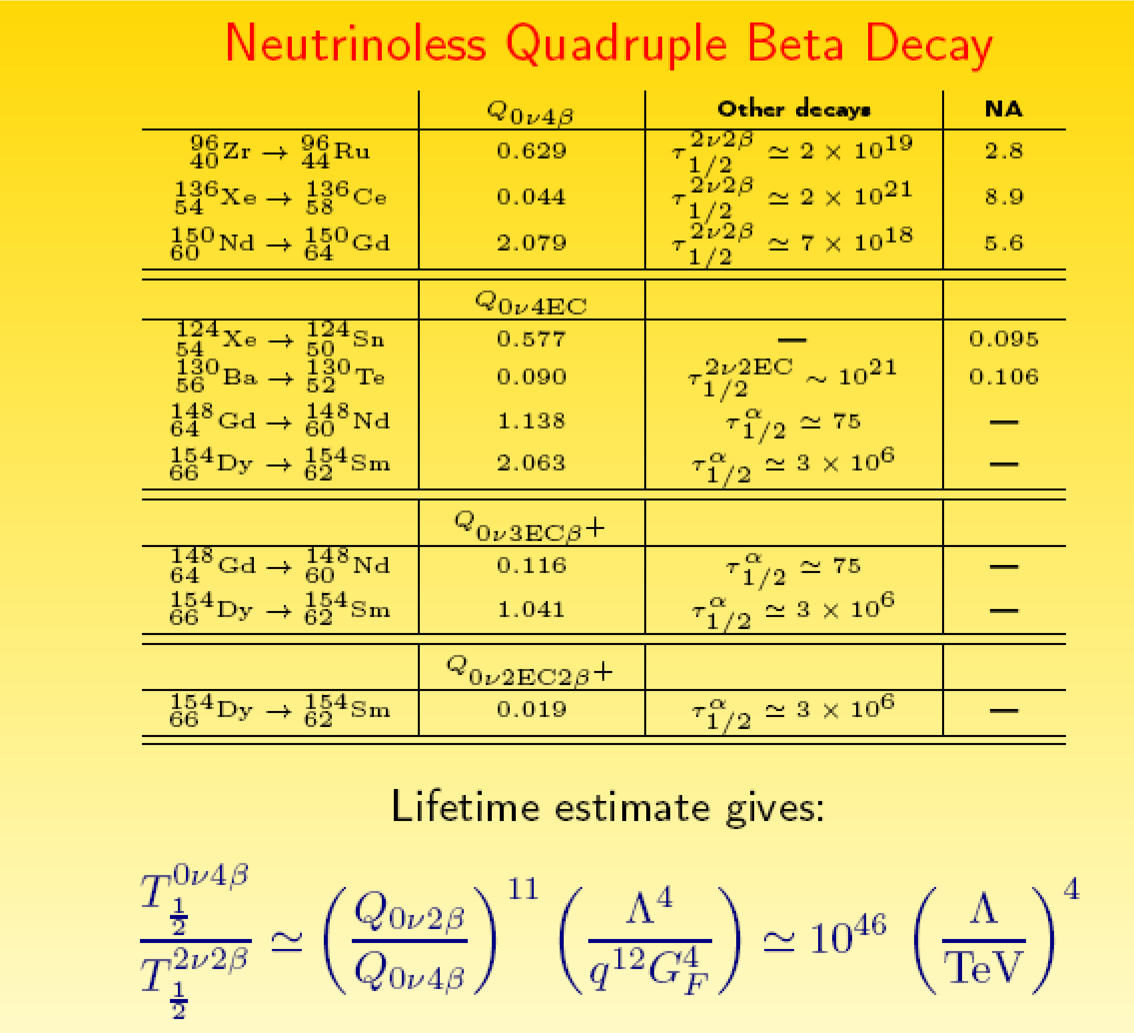
neutrinos are Dirac particles, and Lepton Number violated by 4 units!

$\Rightarrow$ observable: neutrinoless quadruple beta decay $(A,Z) \rightarrow (A,Z+4) + 4\,e^-$





Heeck, Rodejohann., Eur.Phys.Lett. 103)



Neutrinoless Quadruple Beta Decay

	$Q_{0\nu4\beta}$	**Other decays**	**NA**
${}^{96}_{40}\mathrm{Zr} \to {}^{96}_{44}\mathrm{Ru}$	0.629	$\tau^{2\nu2\beta}_{1/2} \simeq 2 \times 10^{19}$	2.8
${}^{136}_{54}\mathrm{Xe} \to {}^{136}_{58}\mathrm{Ce}$	0.044	$\tau^{2\nu2\beta}_{1/2} \simeq 2 \times 10^{21}$	8.9
${}^{150}_{60}\mathrm{Nd} \to {}^{150}_{64}\mathrm{Gd}$	2.079	$\tau^{2\nu2\beta}_{1/2} \simeq 7 \times 10^{18}$	5.6
	$Q_{0\nu4\mathrm{EC}}$		
${}^{124}_{54}\mathrm{Xe} \to {}^{124}_{50}\mathrm{Sn}$	0.577	—	0.095
${}^{130}_{56}\mathrm{Ba} \to {}^{130}_{52}\mathrm{Te}$	0.090	$\tau^{2\nu2\mathrm{EC}}_{1/2} \sim 10^{21}$	0.106
${}^{148}_{64}\mathrm{Gd} \to {}^{148}_{60}\mathrm{Nd}$	1.138	$\tau^{\alpha}_{1/2} \simeq 75$	—
${}^{154}_{66}\mathrm{Dy} \to {}^{154}_{62}\mathrm{Sm}$	2.063	$\tau^{\alpha}_{1/2} \simeq 3 \times 10^{6}$	—
	$Q_{0\nu3\mathrm{EC}\beta^+}$		
${}^{148}_{64}\mathrm{Gd} \to {}^{148}_{60}\mathrm{Nd}$	0.116	$\tau^{\alpha}_{1/2} \simeq 75$	—
${}^{154}_{66}\mathrm{Dy} \to {}^{154}_{62}\mathrm{Sm}$	1.041	$\tau^{\alpha}_{1/2} \simeq 3 \times 10^{6}$	—
	$Q_{0\nu2\mathrm{EC}2\beta^+}$		
${}^{154}_{66}\mathrm{Dy} \to {}^{154}_{62}\mathrm{Sm}$	0.019	$\tau^{\alpha}_{1/2} \simeq 3 \times 10^{6}$	—

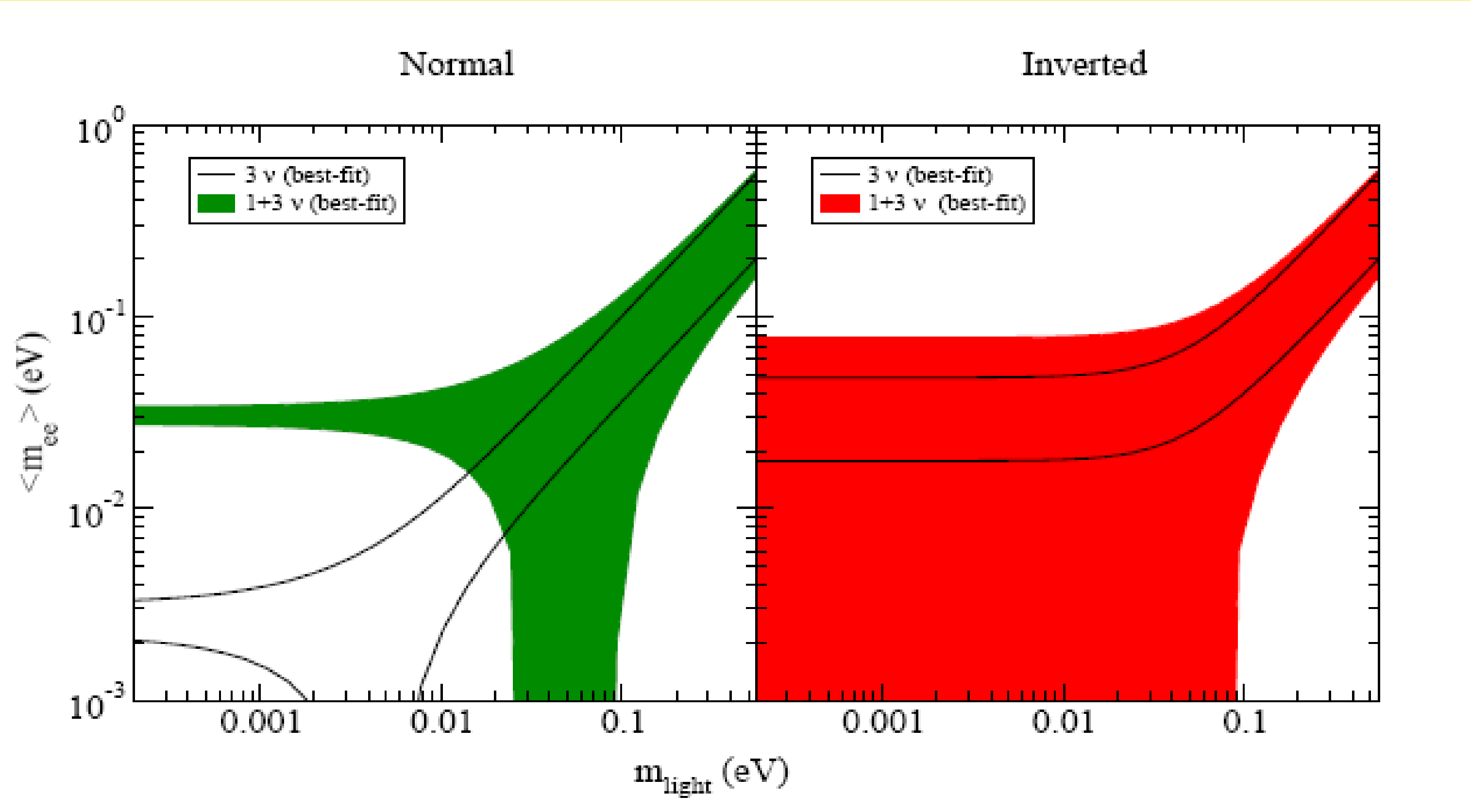
Lifetime estimate gives:

$$\frac{T^{0\nu4\beta}_{\frac{1}{2}}}{T^{2\nu2\beta}_{\frac{1}{2}}} \simeq \left(\frac{Q_{0\nu2\beta}}{Q_{0\nu4\beta}}\right)^{11} \left(\frac{\Lambda^4}{q^{12}G_F^4}\right) \simeq 10^{46} \left(\frac{\Lambda}{\mathrm{TeV}}\right)^4$$

Heeck, Rodejohann., Eur.Phys.Lett. 103)

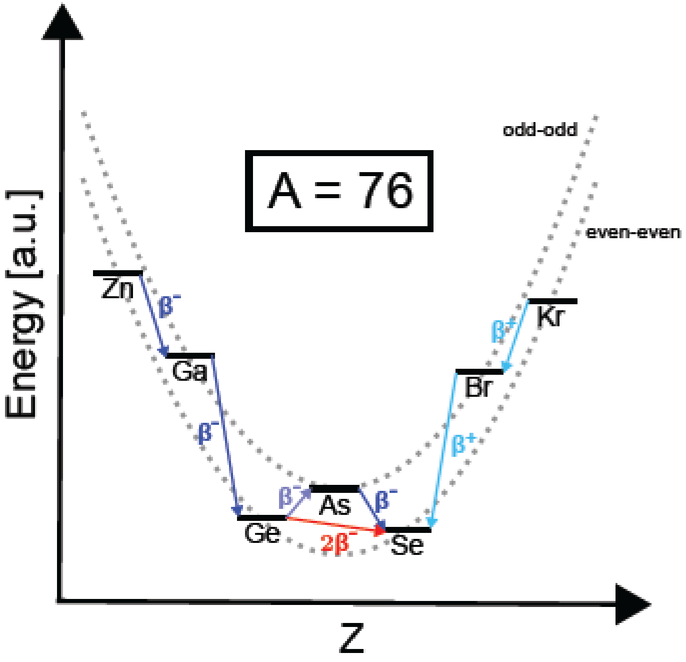
Sterile Neutrinos:

the usual plot for double beta decay gets completely turned around!



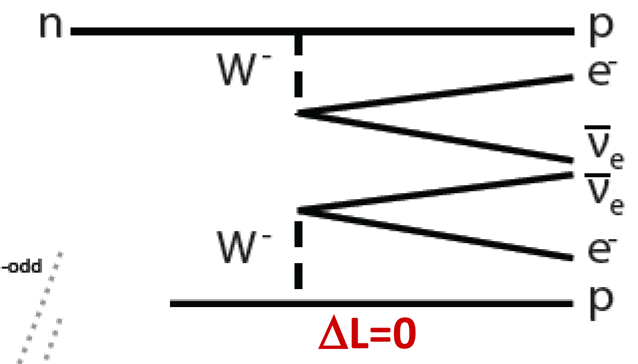
Barry, W.R., Zhang, JHEP **1107**; Giunti *et al.*, PRD **87**; Girardi, Meroni, Petcov, 1308.5802

What we should observe in experiments ?



2νββ

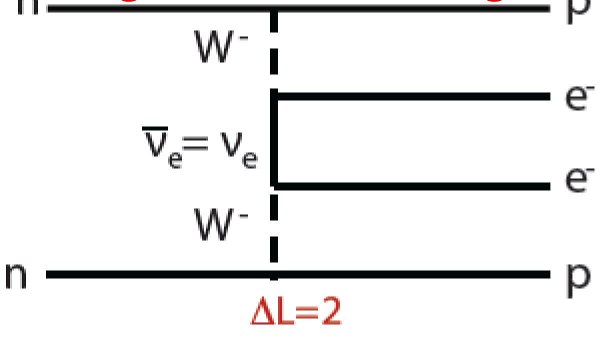
Neutrino accompanied Double-Beta Decay:

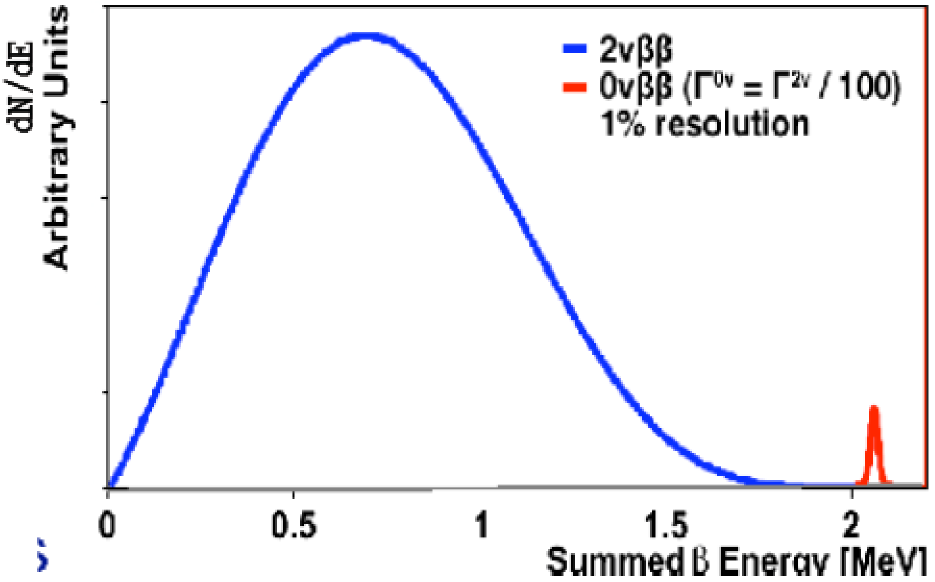


0νββ

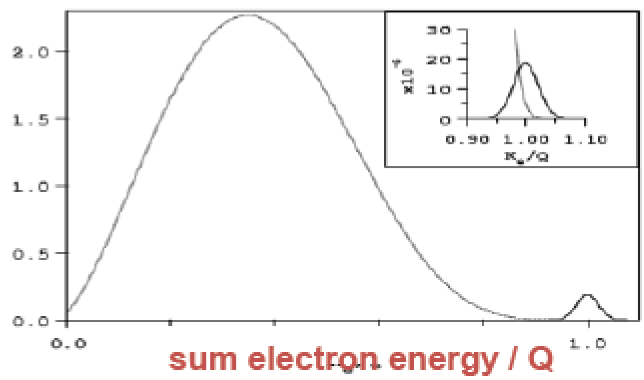
Neutrinoless Double-Beta Decay:

Light neutrino exchange



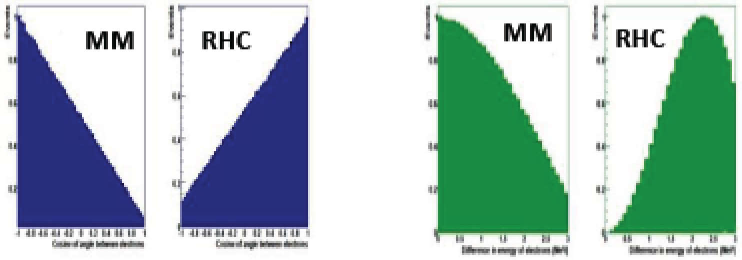


What we can observe in experiments ?

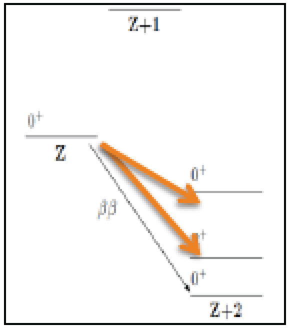


Angular distribution

$Ee_1 - Ee_2$ distribution



Mass vs Right-Handed Current mechanism



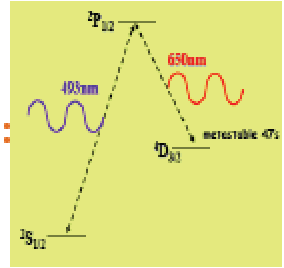
Decay to Excited States

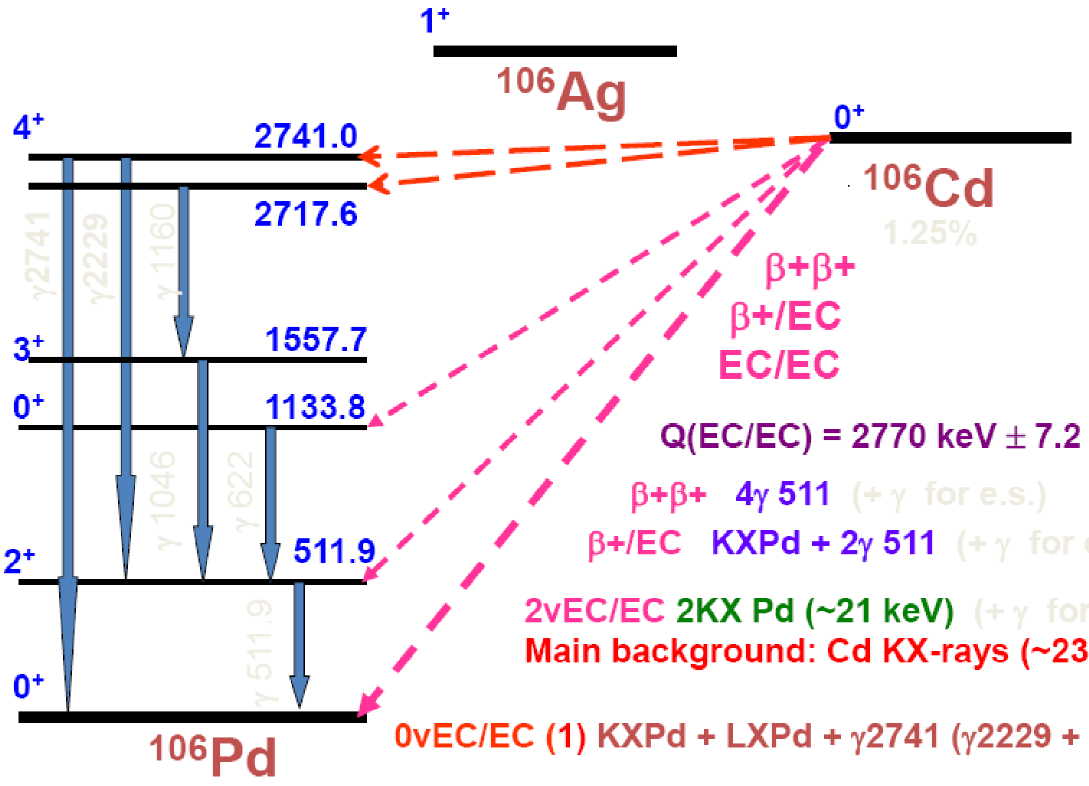
$(A,Z) \rightarrow (A, Z+2) + 2\,e^- + 1{,}2\,\gamma$

1 or 2 additonnal γ-rays

Identification
of daugther nucleus :

$Xe \rightarrow Ba^{++} + 2\,e^-$





Q(EC/EC) = 2770 keV ± 7.2

β+β+ 4γ 511 (+ γ for e.s.)

β+/EC KXPd + 2γ 511 (+ γ for e.s.)

2νEC/EC 2KX Pd (~21 keV) (+ γ for e.s.)

Main background: Cd KX-rays (~23 keV)

0νEC/EC (1) KXPd + LXPd + γ2741 (γ2229 + γ512)

0νEC/EC (2) 2KXPd + (γ1160 + γ1046 + γ512)

$$T_{1/2}^{2\nu EC/EC}\ (^{106}Cd) > 4.2 \cdot 10^{20}\ \ y \quad (90\%)$$

$$^{124}_{54}\boldsymbol{Xe} \xrightarrow{2e_k} {}^{124}_{52}\mathrm{Te}^{**} + 2\nu\,(2{,}865(7)\,\boldsymbol{MeV})$$

$$\mathrm{T}_{1/2}^{2\nu 2K}(g.s. \to g.s) \geq 4.67 \cdot 10^{20}\ yr\ (90\%\,C.L.)$$

The experimental challenge

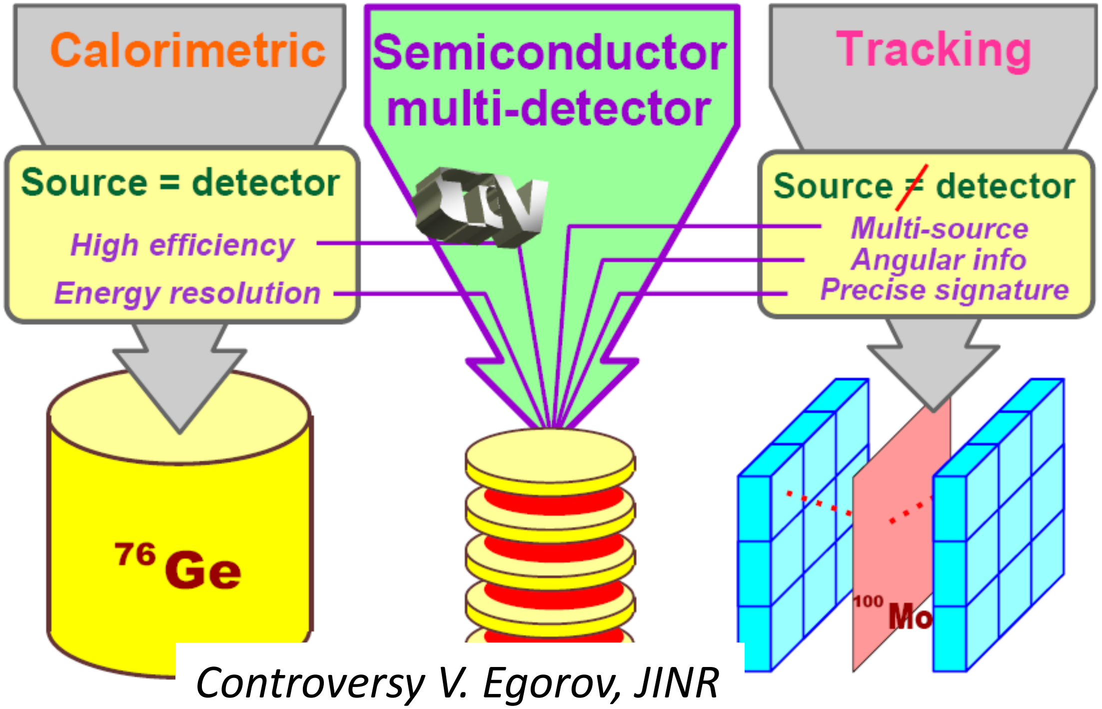
Experiment observes $N^{0\nu} = \ln 2 \frac{N_A}{A} \cdot a \cdot \epsilon \cdot M t / T_{1/2}$

sensitivity on $T_{1/2} \propto \epsilon \cdot A \cdot \sqrt{\frac{M \cdot T}{b \cdot \Delta E}}$

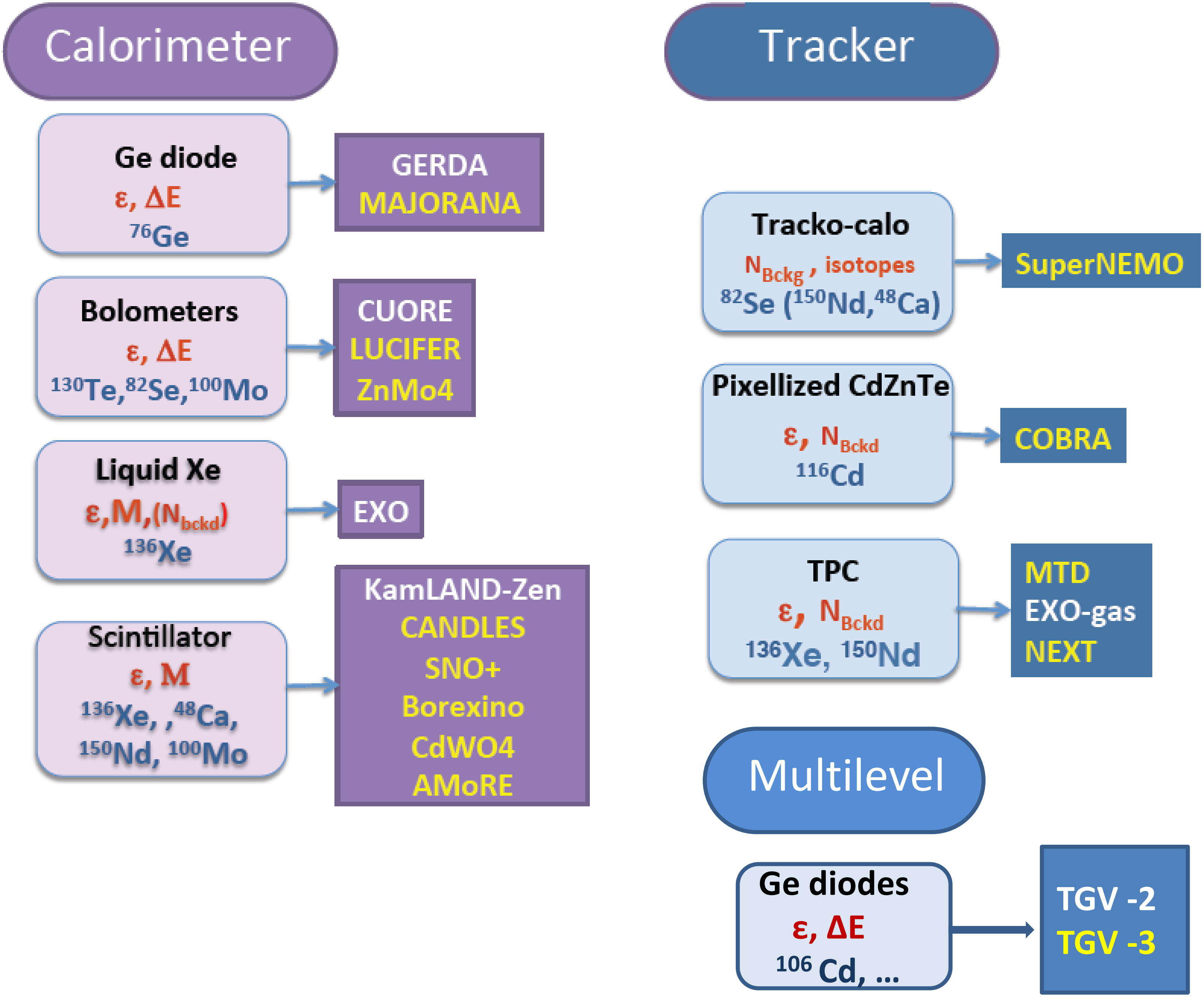
ϵ	detection efficiency
A	isotopic abundance
M	active target mass
T	measuring time
b	background rate (cts/(keV kg yr))
ΔE	energy resolution

Experimental approach:

→ **reduce background b, improve resolution ΔE, increase exposure (M·T),**



Controversy V. Egorov, JINR



Calorimeter

Ge diode
ε, ΔE
^{76}Ge

GERDA
MAJORANA

Bolometers
ε, ΔE
^{130}Te,^{82}Se,^{100}Mo

CUORE
LUCIFER
ZnMo4

Liquid Xe
ε,M,(N_{bckd})
^{136}Xe

EXO

Scintillator
ε, M
^{136}Xe, ,^{48}Ca,
^{150}Nd, ^{100}Mo

KamLAND-Zen
CANDLES
SNO+
Borexino
CdWO4
AMoRE

Tracker

Tracko-calo
N_{Bckg} , isotopes
^{82}Se (^{150}Nd,^{48}Ca)

SuperNEMO

Pixellized CdZnTe
ε, N_{Bckd}
^{116}Cd

COBRA

TPC
ε, N_{Bckd}
^{136}Xe, ^{150}Nd

MTD
EXO-gas
NEXT

Multilevel

Ge diodes
ε, ΔE
^{106} Cd, ...

TGV -2
TGV -3

2νββ Recent results of $T_{1/2}^{2\nu\,\beta\beta}$

$$T_{1/2}^{2\nu} = (10^{18} - 10^{21})\mathrm{y}$$

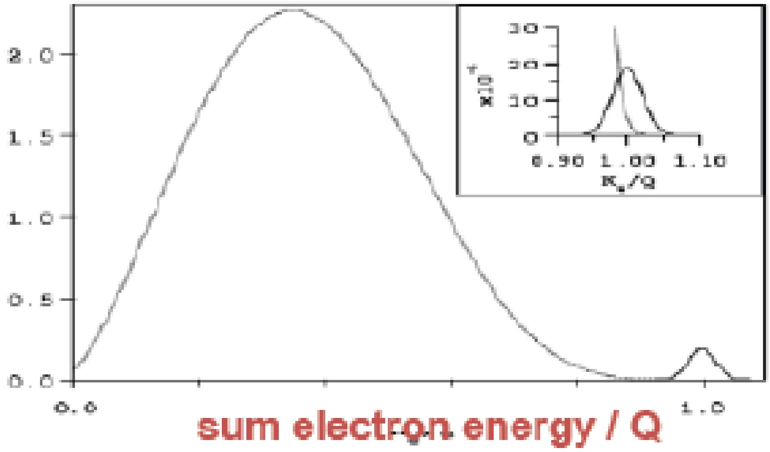
Izotope	$T_{1/2}^{2\nu\,\beta\beta}$	NEMO-3
^{100}Mo	[7.16 ± 0.01 (stat) ± 0.54 (sys)] 10^{18} y	NEMO-3
^{82}Se	[9.6 ± 0.1 (stat) ± 1.0 (sys)] 10^{19} y	NEMO-3
^{116}Cd	[2.88 ± 0.04 (stat) ± 0.16 (sys)] 10^{19} y	NEMO-3
^{130}Te	[7.0 ± 0.9 (stat) ± 0.9 (sys)] 10^{20} y	NEMO-3
^{150}Nd	[9.11 + 0.25 – 0.22(stat) ± 0.63 (sys)] 10^{18} y	NEMO-3
^{96}Zr	[2.35 ± 0.14 (stat) ± 0.16 (sys)] 10^{19} y	NEMO-3
^{48}Ca	[4.4 + 0.5 – 0.4 (stat) ± 0.4 (sys)] 10^{19} y	NEMO-3
^{76}Ge	[1.84 + 0.09 – 0.08 (stat) + 0.11 - 0.06 (sys)] 10^{21} y	GERDA-I
^{136}Xe	[2.30 ± 0.02 (stat) ± 0.12 (syst)] 10^{21} y	KamLand-Zen
^{136}Xe	[2.23 ± 0.017 (stat) ± 0.22 (syst)] 10^{21} y	EXO-200

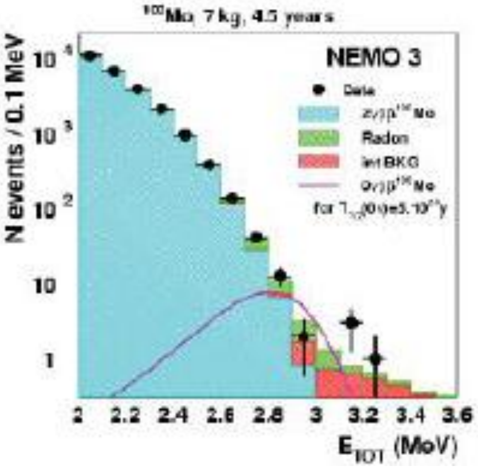
NEMO-3
2νββ
Factory

Experimental definition of $M^{2\nu\,\beta\beta}$

$M^{0\nu\,\beta\beta}$

Choice of the best isotope -
$2\nu\beta\beta$ spectrum is always background for $0\nu\beta\beta$

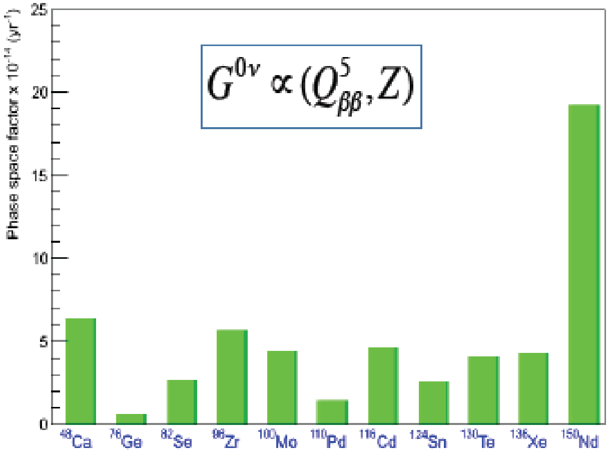


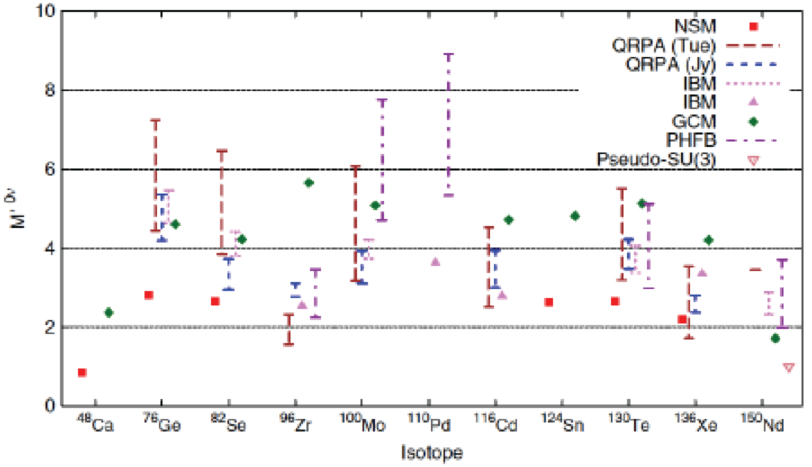


isotope	$G^{0\nu}$ $[\frac{10^{-14}}{\text{yr}}]$	$Q_{\beta\beta}$ [keV]	nat. ab. [%]	$T^{2\nu}_{1/2}$ [10^{20} y]	experiments
^{48}Ca	6.3	4273.7	0.187	0.44	CANDLES
^{76}Ge	0.63	2039.1	7.8	15	GERDA, Majorana Demonstr.
^{82}Se	2.7	2995.5	9.2	0.92	SuperNEMO, Lucifer
^{100}Mo	4.4	3035.0	9.6	0.07	MOON, AMoRe
^{116}Cd	4.6	2809.1	7.6	0.29	Cobra
^{130}Te	4.1	2530.3	34.5	9.1	CUORE
^{136}Xe	4.3	2457.8	8.9	21	EXO, Next, Kamland-Zen
^{150}Nd	19.2	3367.3	5.6	0.08	SNO+, DCBA/MTD

Choice of the best isotope ?

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^{2}\left(\frac{\langle m_\nu\rangle}{m_e}\right)^{2}$$

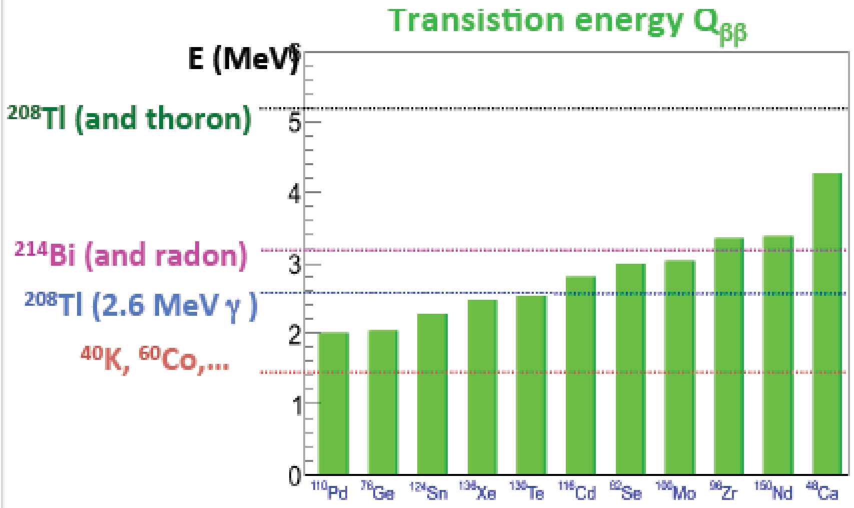




Dueck et al. Phys,. Rev. D **83** 113010(2011)

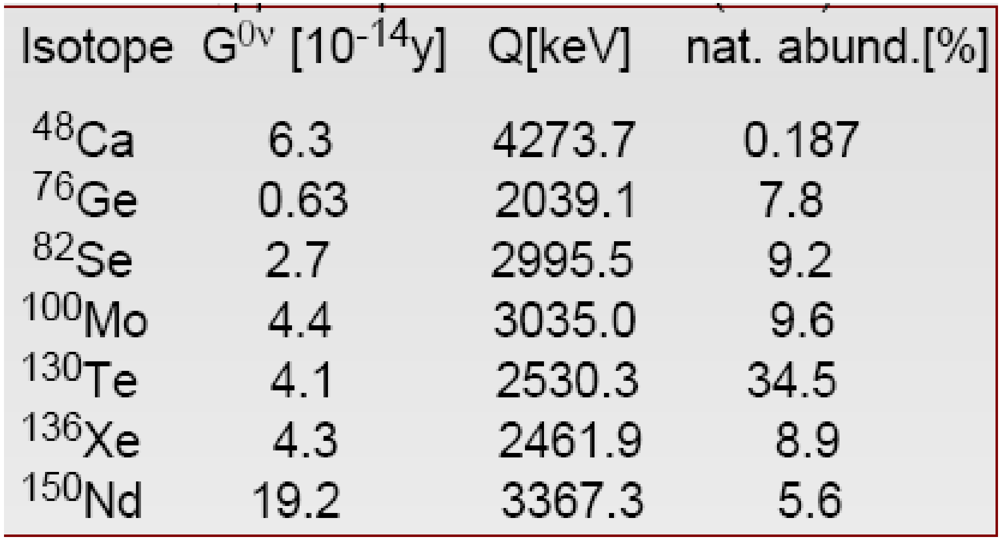
Choice of the best isotope ?

$$Q = E_{e1} + E_{e2} - 2m_e$$



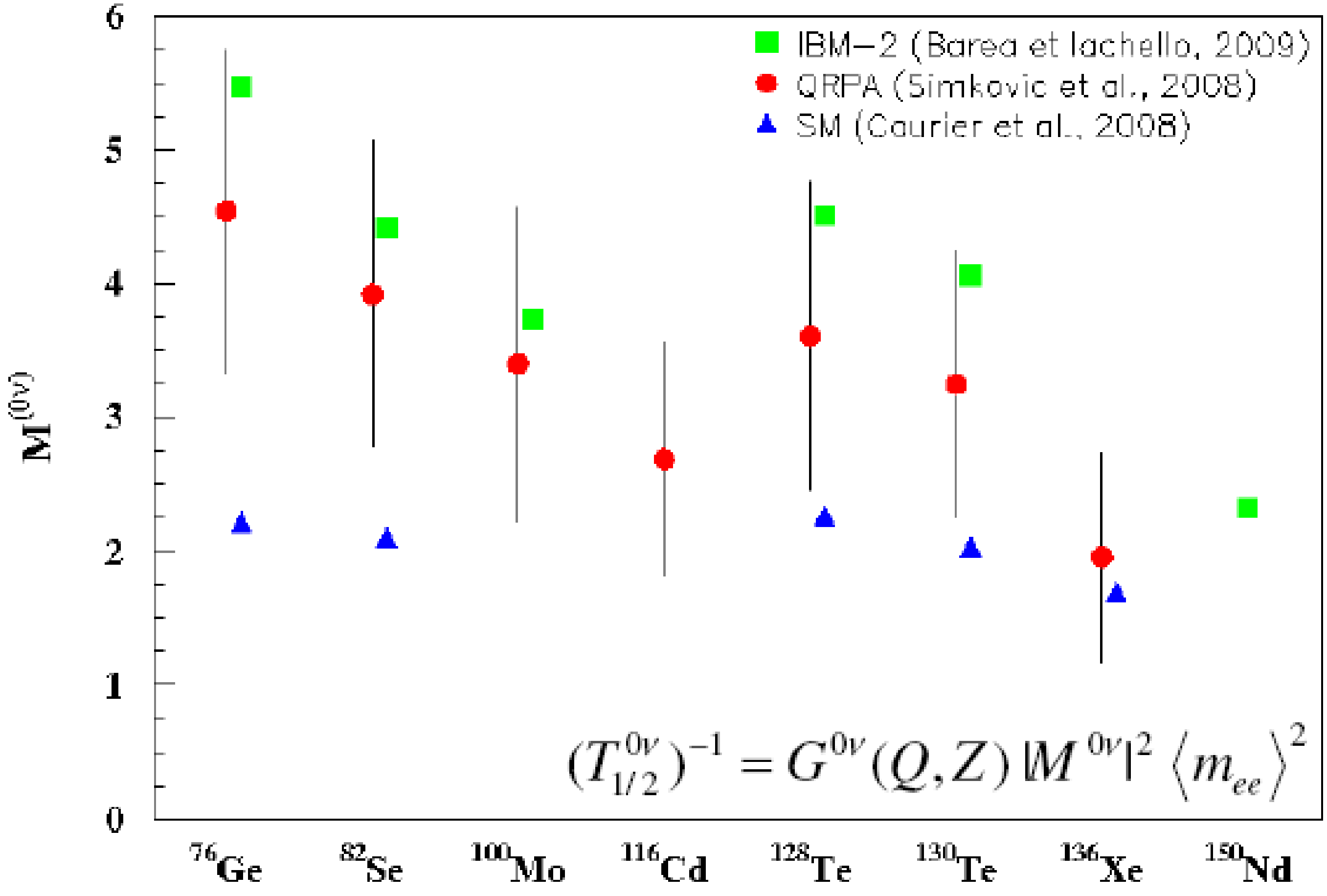
Other sources of background:

- Muons (underground labs)
- γ from ((n,γ) reactions , μ bremstrahlung
- Muon spallation products
- α emitters from bulk or surface contaminations for calorimeters
- ββ(2ν) if modest energy resolution



Isotope	$G^{0\nu}$ [10^{-14}y]	Q[keV]	nat. abund.[%]
^{48}Ca	6.3	4273.7	0.187
^{76}Ge	0.63	2039.1	7.8
^{82}Se	2.7	2995.5	9.2
^{100}Mo	4.4	3035.0	9.6
^{130}Te	4.1	2530.3	34.5
^{136}Xe	4.3	2461.9	8.9
^{150}Nd	19.2	3367.3	5.6

Nuclear matrix elements

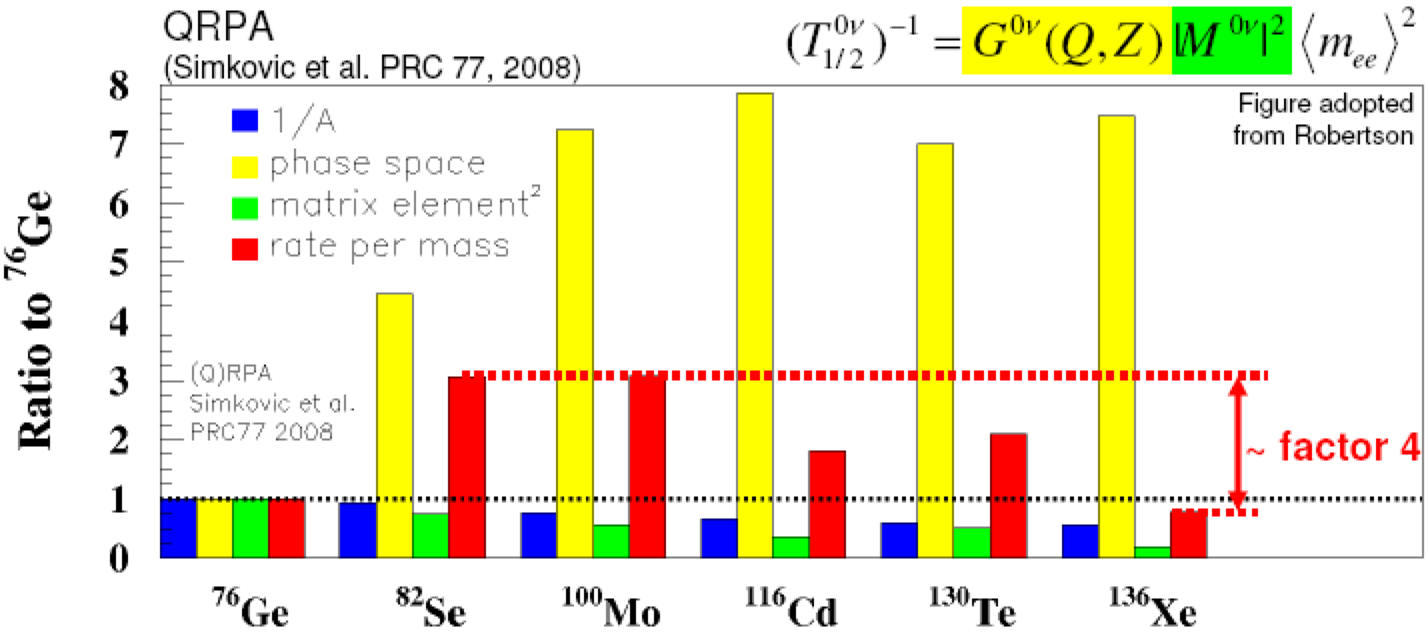


Is M decreasing with $A^{-2/3}$ (IBM-2, QRPA) or constant with A (SM) ?

S. Schönert, NME WS, LNGS Nov. 2011

Nuclear matrix elements

Comparison of isotopes:
Is there a *super-DBD-isotope* ?



$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\langle m_{ee}\rangle^2$$

QRPA
(Simkovic et al. PRC 77, 2008)

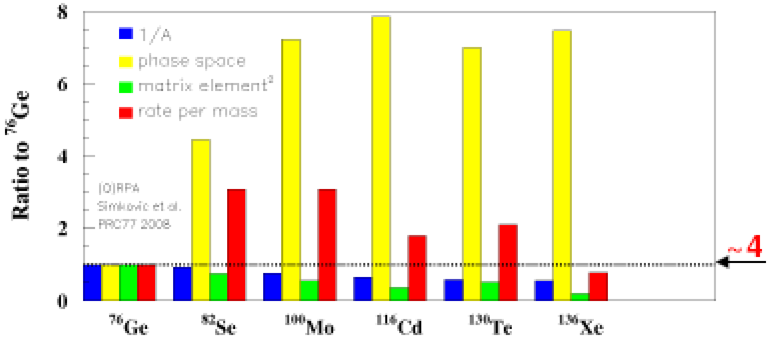
Figure adopted from Robertson

~ factor 4

Expected 0νββ **rates per mass** vary within a factor ~ 4 !

Nuclear matrix elements

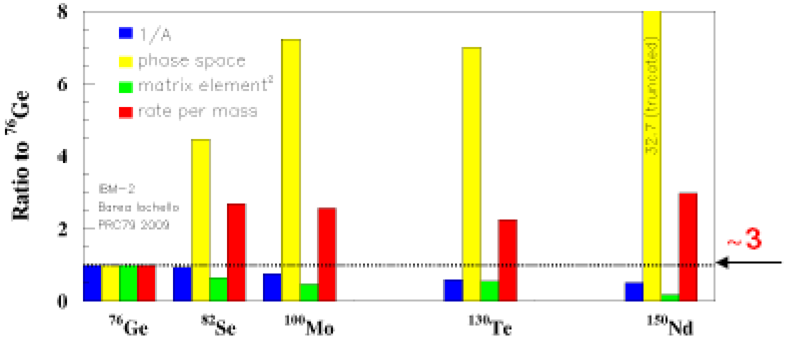
QRPA
(Simkovic et al.
PRC 77, 2008)



for *m* = 50 meV:

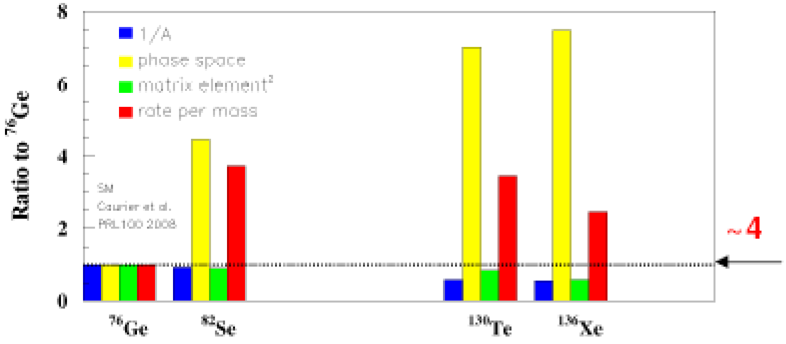
9 cts/(ton year)

IBM2
(Barea and
Iachello, PRC
79, 2009)



13 cts/(ton year)

SM
(Caurier et al.,
PRL 100, 2008)



2 cts/(ton year)

S. Schönert, NME WS, LNGS Nov. 2011

Conclusion of general consideration

No favorite isotope / experimental techniques

Several experiments using
different isotopes and methods
are needed

Presently used isotopes

^{116}Cd	COBRA CdWO$_4$
^{76}Ge	GERDA MAJORANA
^{82}Se	SuperNEMO LUCIFER
^{136}Xe	KamLAND-Zen EXO NEXT
^{100}Mo	ZnMoO$_4$ AMoRE
^{130}Te	CUORE
Nat(48)Ca	CANDLES
Nat(150)Nd	SNO+ Borexino

A dream ?

^{48}Ca	CANDLES SuperNEMO AMoRE
^{150}Nd	SNO+ SuperNEMO MTD Borexino

Kilograms of enriched Nd-150 – dream or close to reality?

To: Director of the JINR (Dubna)
V.A.Matveev

...

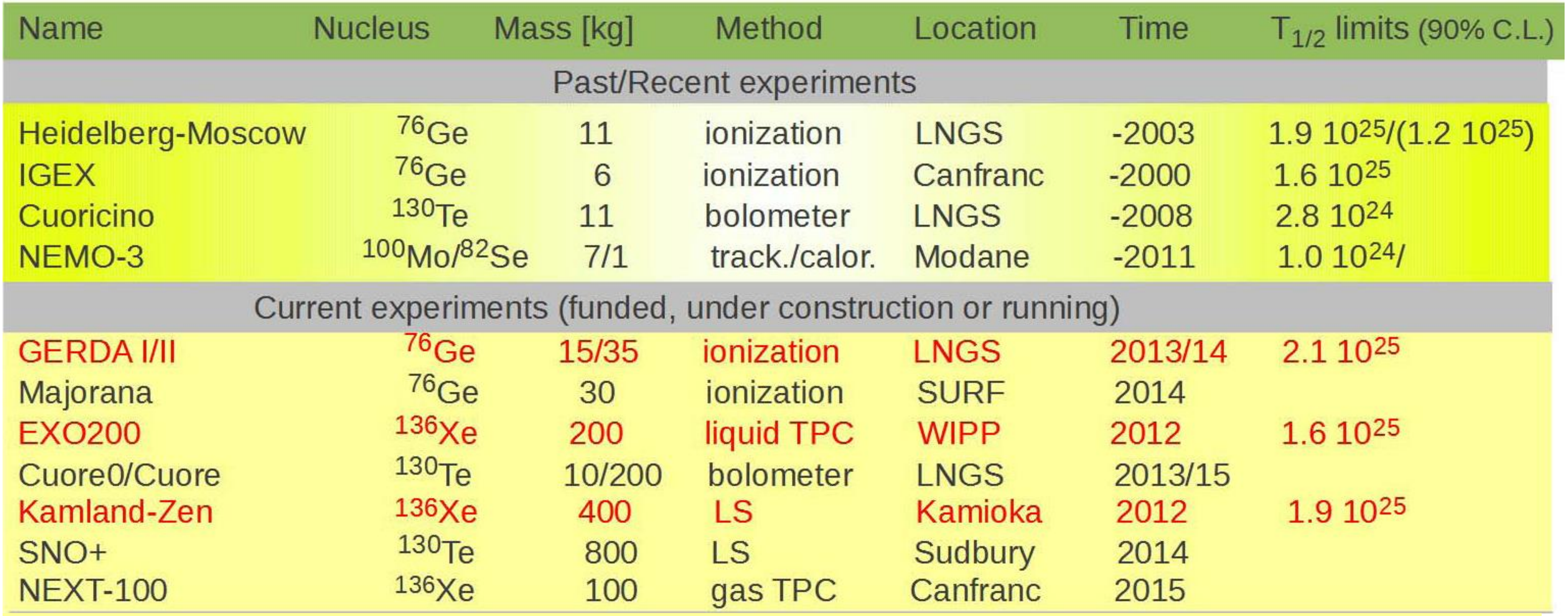
…

By October 2014 it is planned to build the prototype of separation cascade and produce on it the sample contained 0.5 kg of Nd- 150 enriched to more than 80%. This sample will be presented to the SuperNEMO collaboration for tests.

Industrial production of Nd- 150 can be started at the beginning of 2016.

Deputy Director General,
Head of the separation department S.I.Belyantcev
JSC " ECP "

Overview of past/current/near future 0νββ experiments



Name	Nucleus	Mass [kg]	Method	Location	Time	$T_{1/2}$ limits (90% C.L.)
Past/Recent experiments						
Heidelberg-Moscow	^{76}Ge	11	ionization	LNGS	-2003	$1.9\ 10^{25}/(1.2\ 10^{25})$
IGEX	^{76}Ge	6	ionization	Canfranc	-2000	$1.6\ 10^{25}$
Cuoricino	^{130}Te	11	bolometer	LNGS	-2008	$2.8\ 10^{24}$
NEMO-3	^{100}Mo/^{82}Se	7/1	track./calor.	Modane	-2011	$1.0\ 10^{24}$/
Current experiments (funded, under construction or running)						
GERDA I/II	^{76}Ge	15/35	ionization	LNGS	2013/14	$2.1\ 10^{25}$
Majorana	^{76}Ge	30	ionization	SURF	2014	
EXO200	^{136}Xe	200	liquid TPC	WIPP	2012	$1.6\ 10^{25}$
Cuore0/Cuore	^{130}Te	10/200	bolometer	LNGS	2013/15	
Kamland-Zen	^{136}Xe	400	LS	Kamioka	2012	$1.9\ 10^{25}$
SNO+	^{130}Te	800	LS	Sudbury	2014	
NEXT-100	^{136}Xe	100	gas TPC	Canfranc	2015	
SuperNemo dem.	^{82}Se / ^{150}Nd	7	track./calor.	Modane	2015	$6.6\ 10^{24}$

adopted from B.Schwingenheuer, PACT 2013

Past Ge-76 experiments

Heidelberg-Moscow

IGEX

Disclaimer:

Next slides represent only the past Ge-76 experiments for comparison with the recent results of the Ge-76 and Xe-136 experiments.

HPGe detectors

fabricated from germanium enriched in ^{76}Ge isotope (up to 86 %)

are simultaneously

the ββ decay sources and the 4π detectors.

The advantages of such type experiments are due to:

1) the excellent energy resolution (4 кэВ at 2 MeV) ,

2) the high purity of Ge crystals (very low intrinsic background),

3) and the high signal detection efficiency (close to 100%).

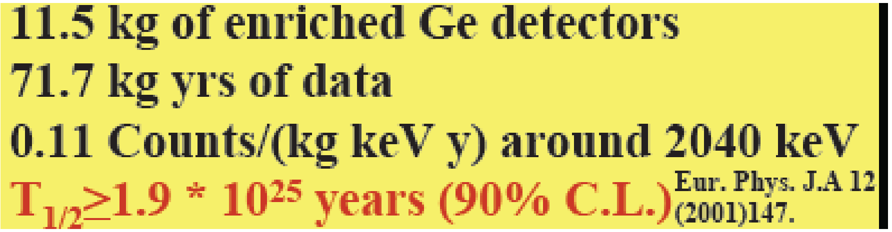
Disadvantages:

1) not the highest ββ–transiton energy for ^{76}Ge: Q_{bb}=2039 keV

(in comparison with the more promising isotopes, such as Mo-100,
Nd-150,Ca-48)

2) only one characteristic of ββ decay - sum energy of two electrons –
is possible to detect.

Heidelberg-Moscow



11.5 kg of enriched Ge detectors

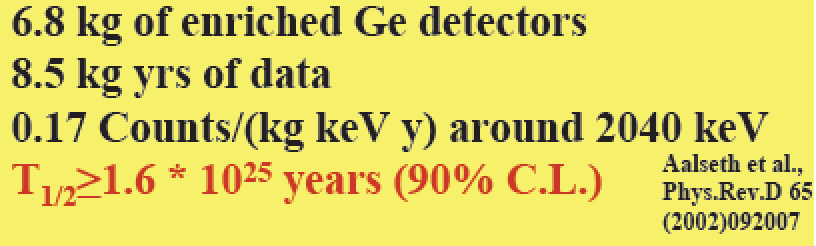
71.7 kg yrs of data

0.11 Counts/(kg keV y) around 2040 keV

$T_{1/2} \geq 1.9 * 10^{25}$ years (90% C.L.)

Eur. Phys. J.A 12 (2001)147.

IGEX



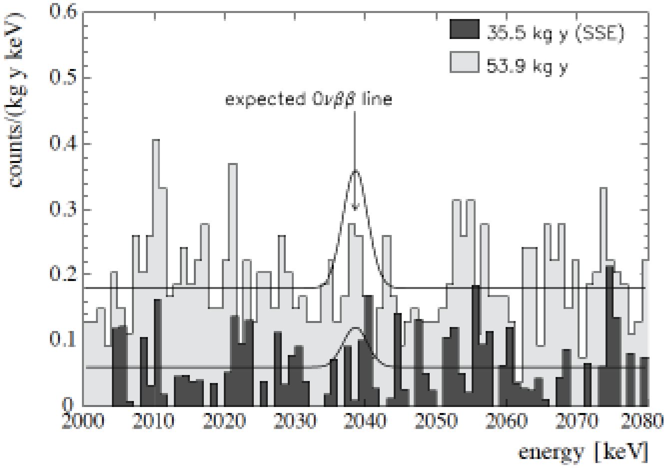
6.8 kg of enriched Ge detectors

8.5 kg yrs of data

0.17 Counts/(kg keV y) around 2040 keV

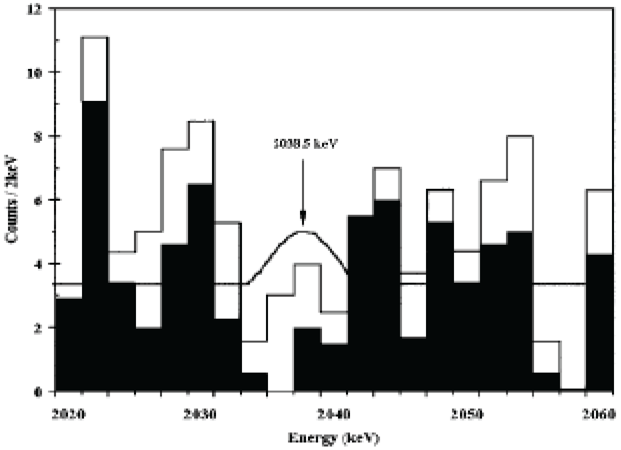
$T_{1/2} \geq 1.6 * 10^{25}$ years (90% C.L.)

Aalseth et al., Phys.Rev.D 65 (2002)092007



Heidelberg-Moscow
(H.V. Klapdor-Kleingrothaus et al.)
(Eur. Phys. J. A 12, 147-154 (2001)):

53.9 kg y (35.5 kg y): $T_{1/2}^{0\nu}$ >1.3 ×10^{25} yr (1.9 ×10^{25} yr)
(90% C.L.)

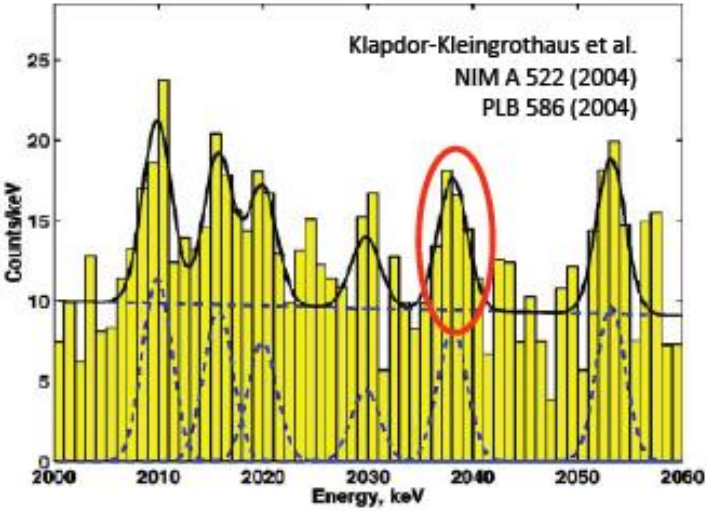


IGEX
(Aalseth et al.)
Phys. Rev. D 65 (2002) 092007

8.8 kg y: $T_{1/2}^{0\nu}$ >1.6 ×10^{25} yr (90%C.L.)

Claim of signal

by part (small) of Hd-M collaboration



Klapdor-Kleingrothaus et al., NIM A 522 (2004), PLB 586 (2004):

- 71.7 kg year - Bgd 0.17 / (kg yr keV)
- 28.75 ± 6.87 events (bgd:~60)
- Claim: 4.2σ evidence for 0νββ
- reported $T_{1/2}^{0\nu}$ = 1.19 x10^{25} yr

claimed signficance of 4.2 σ disputed in literature,

see e.g. Strumia+Vissani Nucl Phys B726 (2005)

Klapdor-Kleingrothaus et al,
Mod Phys Lett A21 (2006) 1547:

N.B. Half-life $T_{1/2}^{0\nu}$ = 2.23 x10^{25} yr $T_{1/}$after PSD analysis (Mod. Phys. Lett. A 21, 1547 (2006).) is not considered because:

- reported half-life can be reconstructed only (Ref. 1) with ε_{psd} = 1 (previous similar analysis $\varepsilon_{psd} \approx 0.6$)
- ε_{fep} = 1 (also in NIM A 522, PLB 586 (2004) (GERDA value for same detectors: ε_{fep} = 0.9)

2.23 x 0.6 x 0.9 = 1.19 !!!

(1) B. Schwingenheuer in Ann. Phys. 525, 269 (2013):

Current experiments

(running, first results)

GERDA Phase I

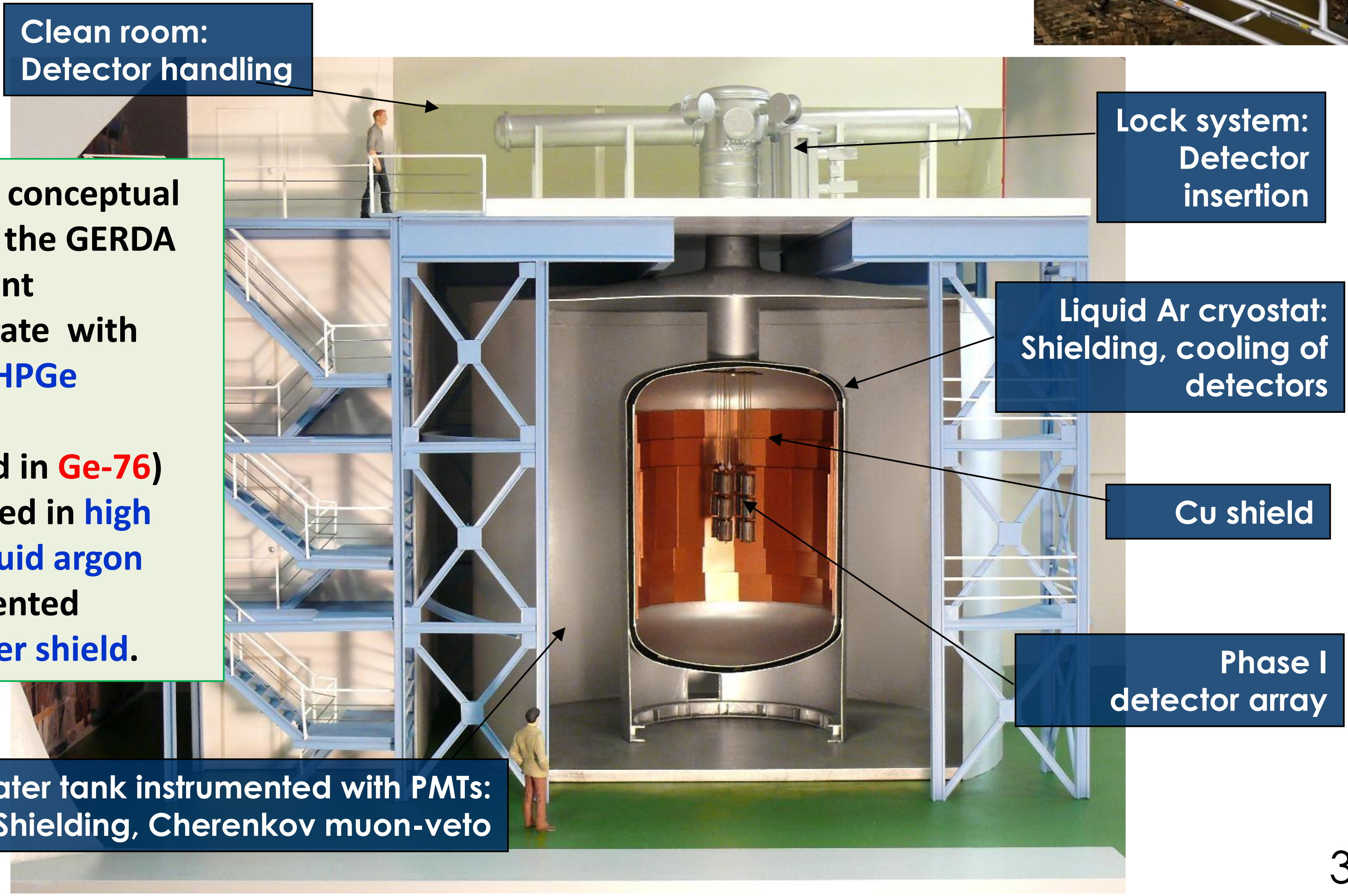
EXO200

Kamland-Zen

GERDA: the GERmanium Detector Array

Neutrinoless Double Beta Decay Experiment

The main conceptual design of the GERDA experiment is to operate with "naked" HPGe detectors (enriched in Ge-76) submerged in high purity liquid argon supplemented by a water shield.



Clean room: Detector handling

Lock system: Detector insertion

Liquid Ar cryostat: Shielding, cooling of detectors

Cu shield

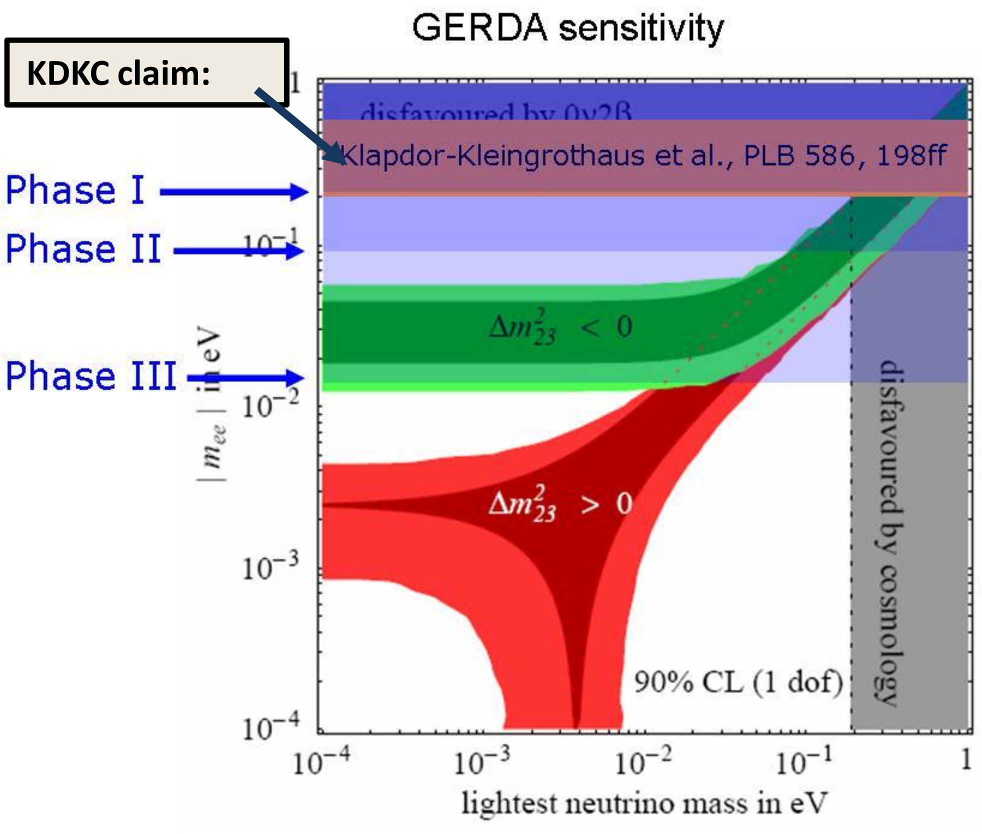
Phase I detector array

Water tank instrumented with PMTs: Shielding, Cherenkov muon-veto

Expected sensitivity of the **GERDA** experiment

Phase I: ~18 kg of ^{76}Ge

Phase II: ~ 40 kg of ^{76}Ge



KDKC claim:

Phase I

Phase II

Phase III

GERDA phase I :

background 0.01 cts / (kg · keV · y)

▶ to scrutinize KKDC result within 1 year

GERDA phase II :

background 1 cts / (ton ! · keV · y)

▶ **to cover the degenerate neutrino mass hierarchy <m_{ee}> < 0.08 – 0.29 eV**

Phase III :

GERDA –MAJORANA collaboration

background 0.1 cts / (ton · keV · y)

▶ **to cover the inverted neutrino mass hierarchy <m_{ee}> ~10 meV**

Construction of the **GERDA set up**
started in 2007
in Gran Sasso National Laboratory (LNGS), Italy.
Installation of the "nested type" assembly
completed in 2010
in the deep underground facility at 3400 m w.e.

- **End of 2009**: Cryostat was filled with **95 t of liquid argon**.

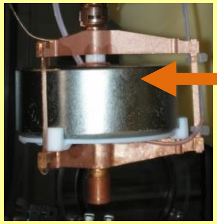
Summer 2010: Water tank was filled with **565 t of ultrapure water**.

*** June 2010: Start of commissioning runs with 3 ^{nat}Ge detectors**

November 2011 – May 2013 :
Phase I physics data taking

Phase I detectors

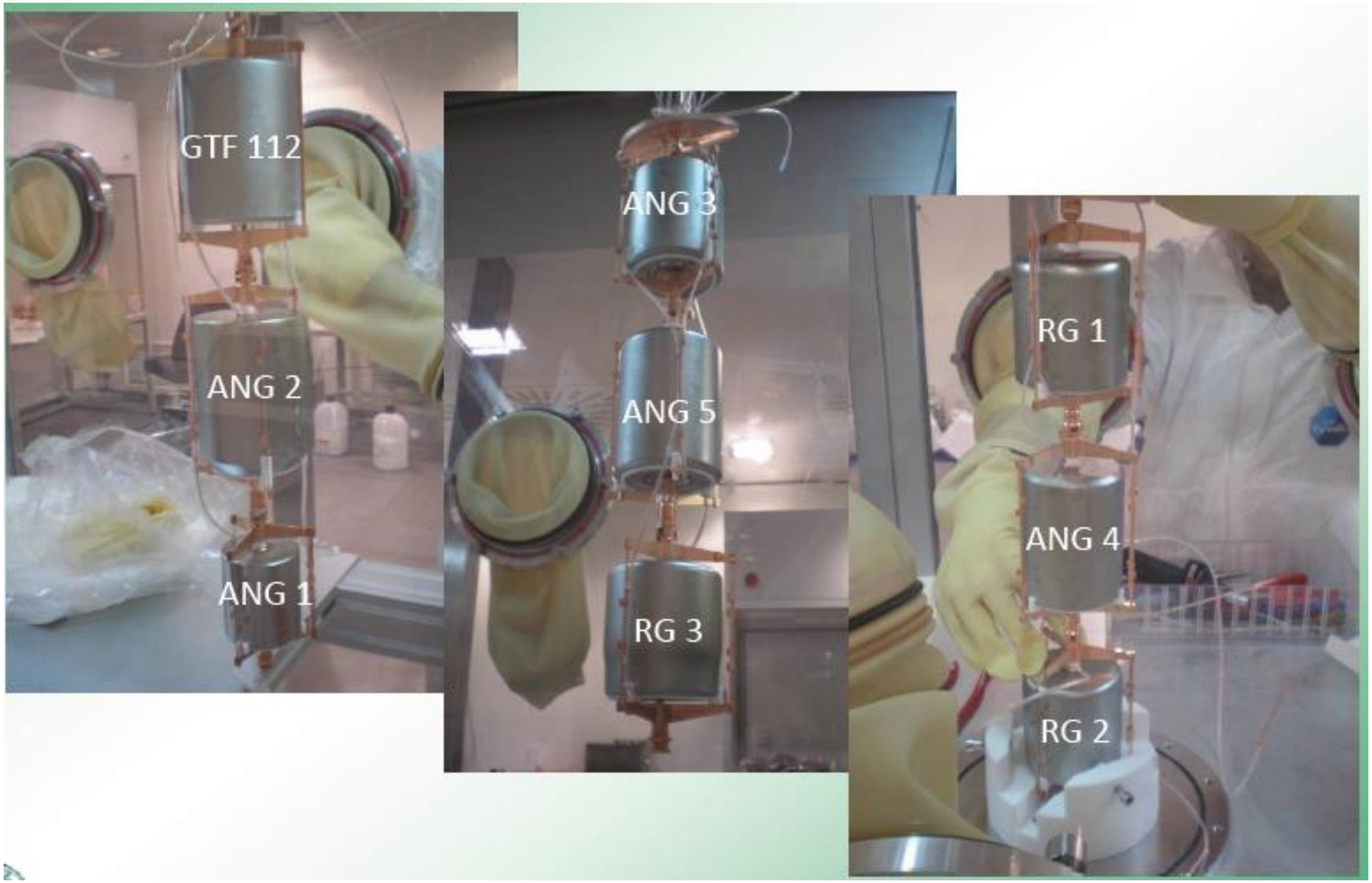
8 enriched HPGe detectors
(in total ~ **18 kg of ^{76}Ge**)
from HdM and IGEX experiments,
6 natural HPGe detectors
(in total ~ **16 kg of ^{Nat}Ge**)
from the Genius T-F will be deployed .
All detectors **reprocessed** optimized for LAr. Energy resolution in LAr:
~2.5 keV (FWHM) @1.3 MeV
+ 5 enriched BeGe detectors
(in total ~ **4 kg of ^{76}Ge**) – *from July 2012*



Phase II detectors

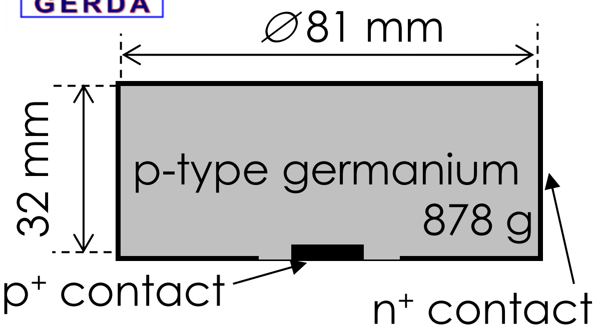
the new **30 BeGe** detectors (~ **20 kg of ^{76}Ge**) made from **enriched in ^{76}Ge material** will be added.
In total: ~ 40 kg of ^{76}Ge + 16 kg of ^{Nat}Ge

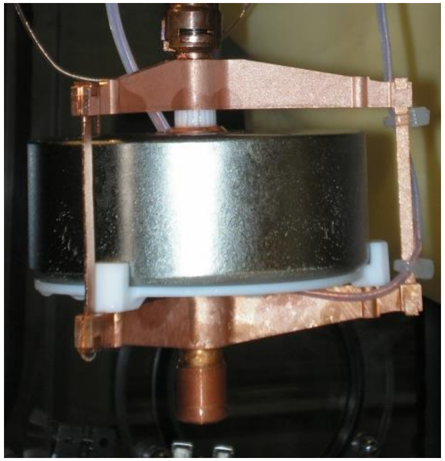
The GERDA Phase I semi-coaxial enriched in Ge-76 and natural Ge detectors.

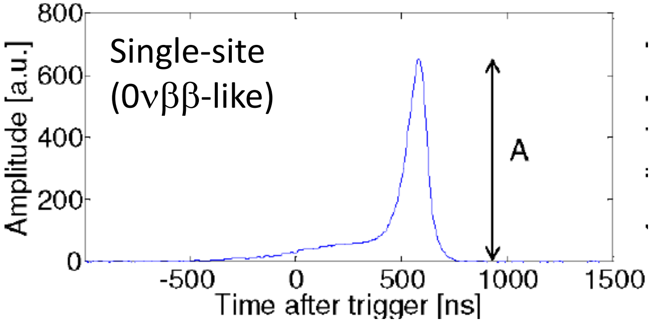


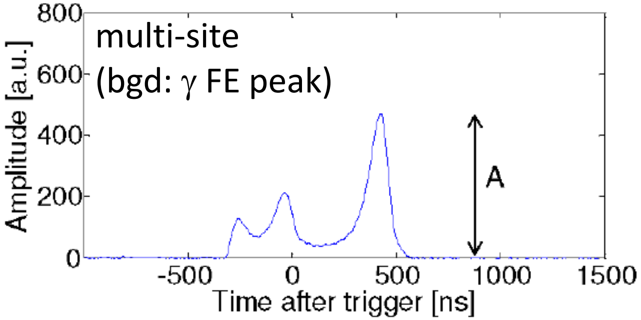
Three strings with the GERDA Phase I semi-coaxial detectors.

Phase II (and Phase I-b) detectors - BEGe

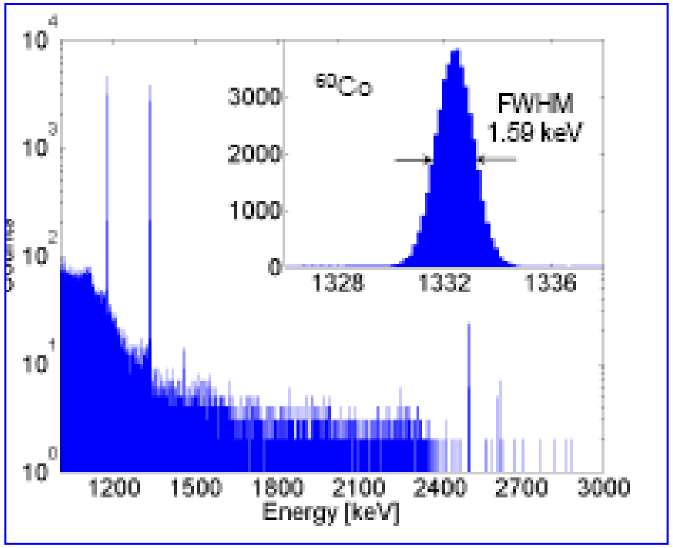


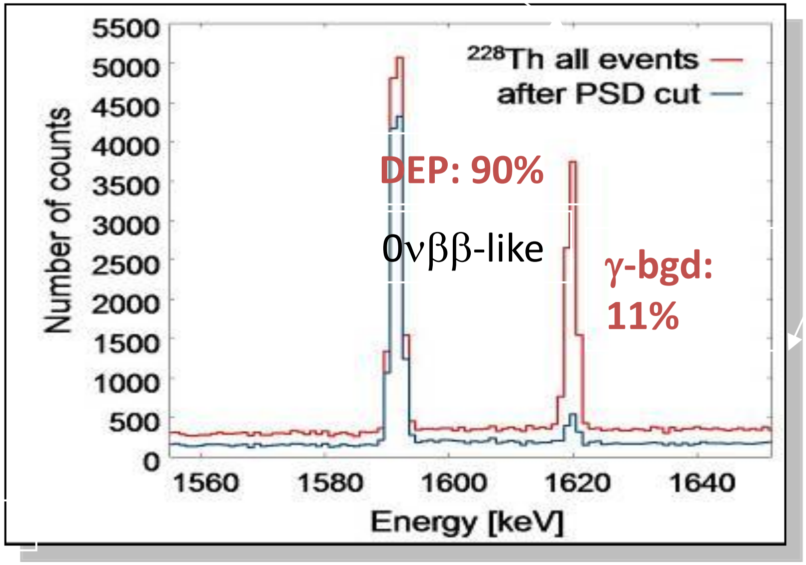




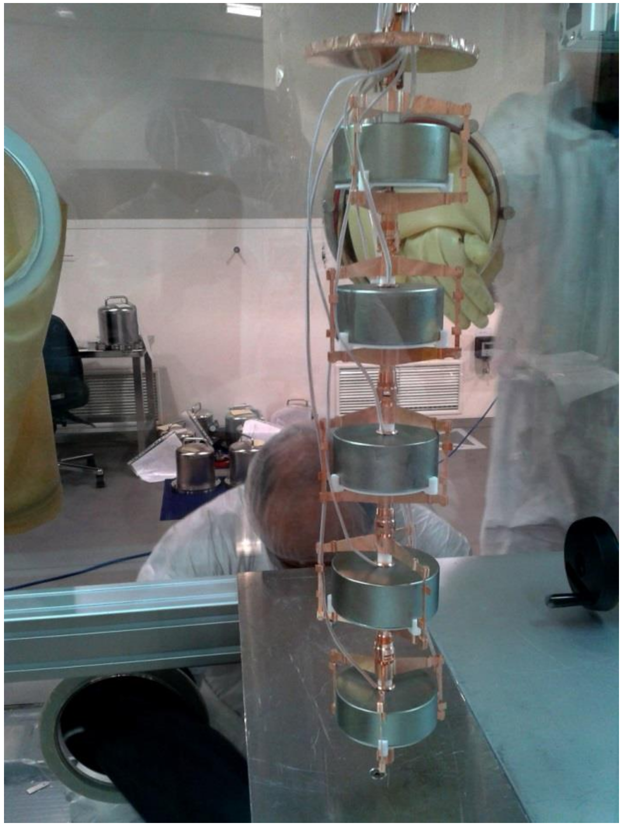


FWHM @ 59.5 keV	0.49 keV
FWHM @ 1.33 MeV	1.59 keV





From July 2012 - 5 enrGe BEGe detectors (R&D for Phase II)



Detector array assembly for GERDA Phase I:

3 + 1 strings:
8 enrGe coaxial detectors
(2 not considered in the analysis)

3 natGe coaxial detectors

5 enrGe BEGe detectors

$^{\mathrm{enr}}$Ge mass for physics analysis: 14.6 kg (coaxial) + 3.6 kg (BEGe)

Phase I Data taking

9 November 2011: Start of Phase I
All **8 enrGe** + **3 natGe coaxial detectors** deployed in GERDA
(2 enrGe detectors are not used for analysis due to high leakage current)

7 July 2012: Insert **5 enrGe BEGe** detectors (2 natGe detectors were removed)

9 November 2011 – 21 May 2013:

558.6 days,

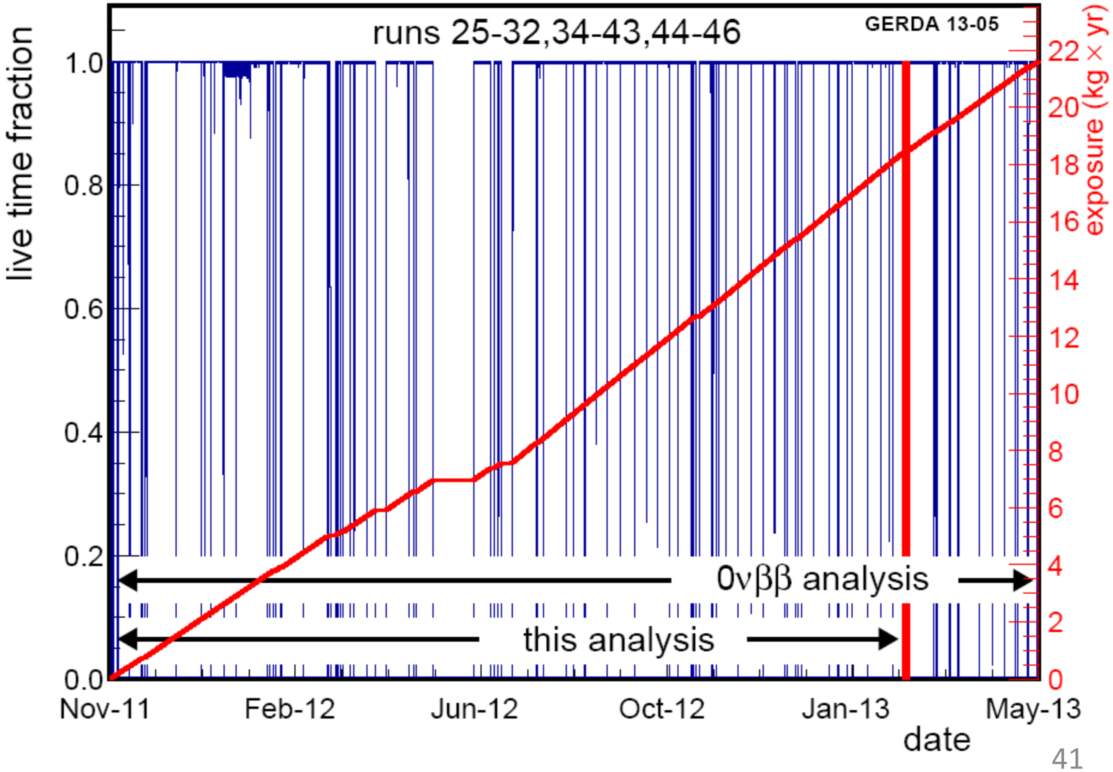
-> exposure:

Enriched Ge-76 detectors:

21.612 kg*yr,

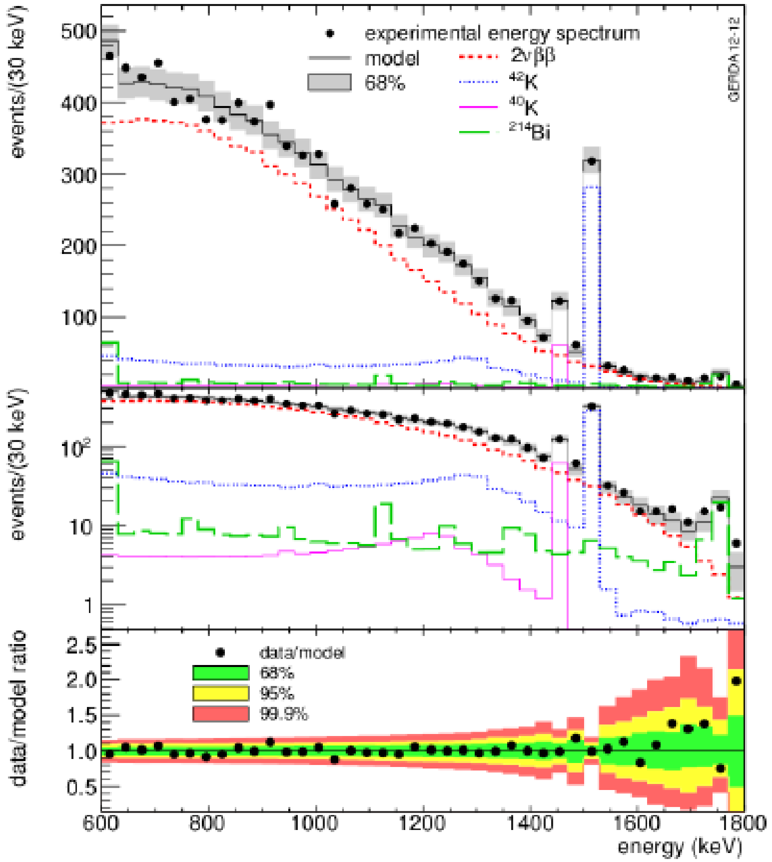
Natural Ge detectors:

6.192 kg*yr



First 2νββ half-life results

The first 5.04 kg yr of data collected in Phase I of the experiment have been analyzed. The observed spectrum in the energy range between 600 and 1800 keV is dominated by 2νββ decay of 76Ge.



Signal to background: 4:1

Binned maximum likelihood

Parameters:

- Active detector masses (6+1) *nuisance parameter*
- Fraction enrichment in ^{76}Ge (6) *nuisance parameter*
- Background contributions (3×6) *nuisance parameter*
- $T^{2\nu}_{1/2}$ common to all the detectors (1)

Derive $T^{2\nu}_{1/2}$ after the fit integrating over nuisance parameters

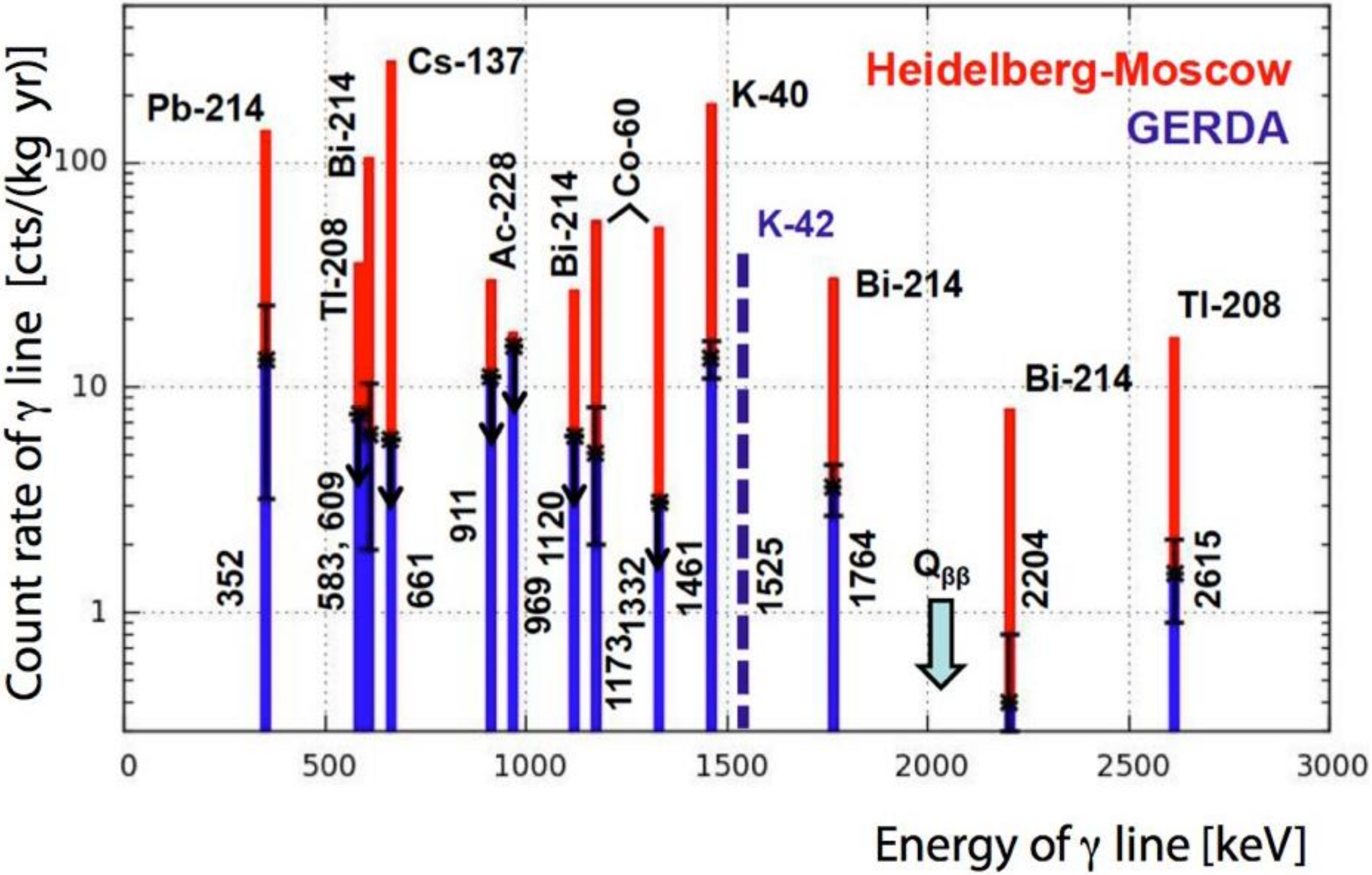
2νββ (80%) ^{42}K (14%)

^{214}Bi (4%) ^{40}K (2%)

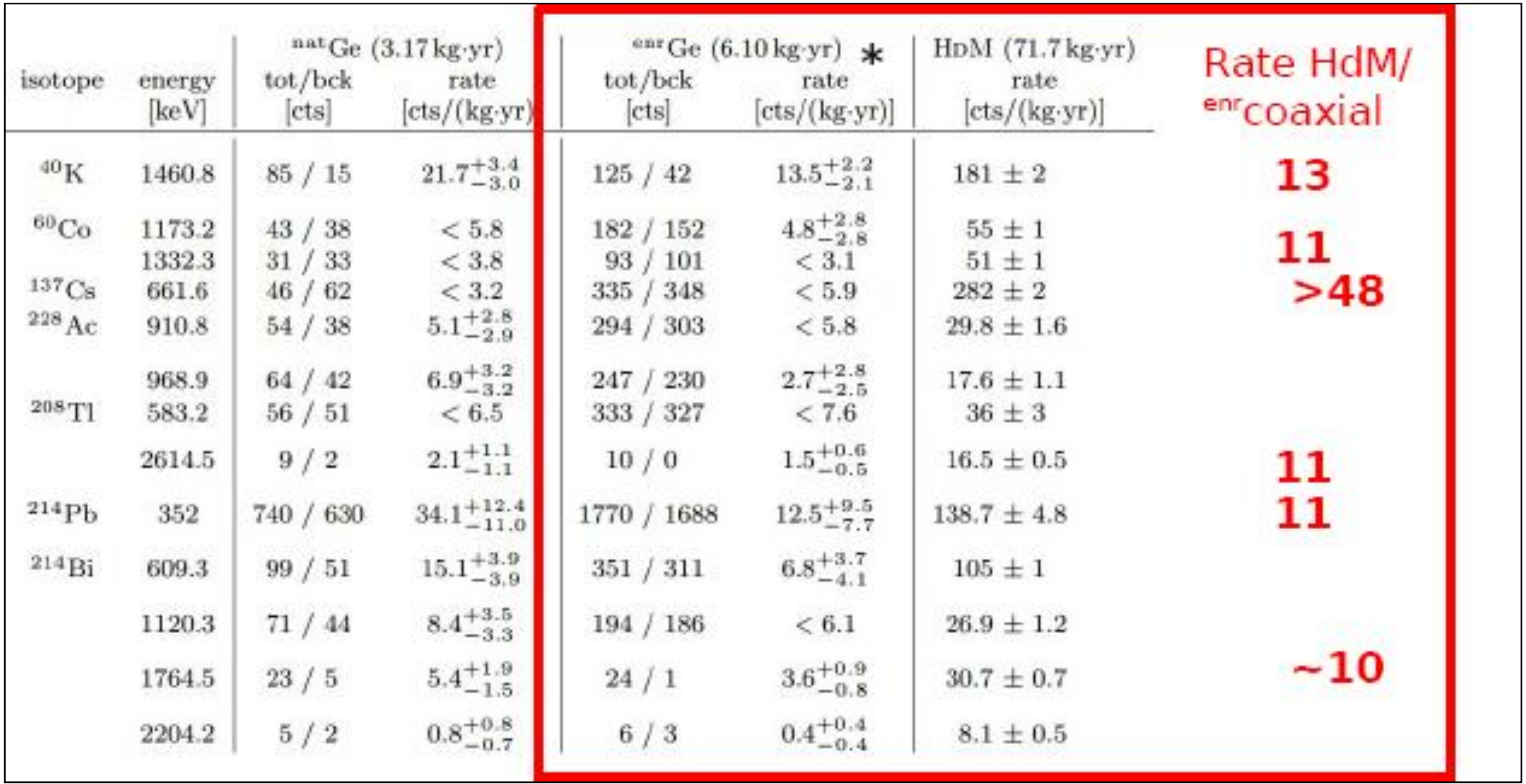
$$T^{2\nu}_{1/2} = \left(1.84^{+0.09}_{-0.08\ \mathrm{fit}}\ {}^{+0.11}_{-0.06\ \mathrm{syst}}\right) \cdot 10^{21}\ \mathrm{yr}$$

The GERDA collaboration
J. Phys. G 40 (2013) 035110

Intensities of Gamma-peaks in comparison with Hd-M experiment



Intensities of Gamma-peaks in comparison with Hd-M experiment

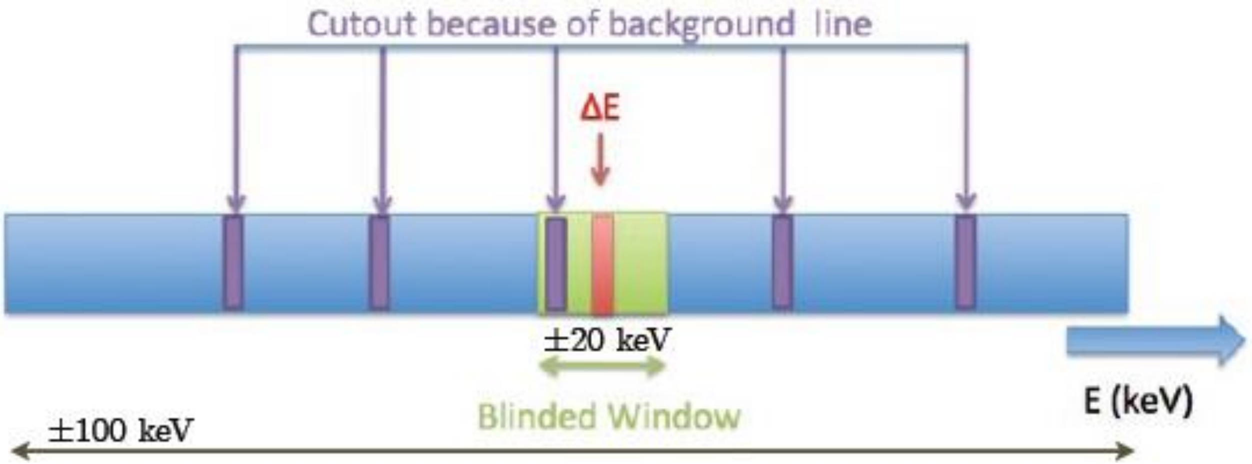


isotope	energy [keV]	^{nat}Ge (3.17 kg·yr) tot/bck [cts]	^{nat}Ge (3.17 kg·yr) rate [cts/(kg·yr)]	^{enr}Ge (6.10 kg·yr) * tot/bck [cts]	^{enr}Ge (6.10 kg·yr) * rate [cts/(kg·yr)]	HdM (71.7 kg·yr) rate [cts/(kg·yr)]	Rate HdM/ ^{enr}coaxial
^{40}K	1460.8	85 / 15	$21.7^{+3.4}_{-3.0}$	125 / 42	$13.5^{+2.2}_{-2.1}$	181 ± 2	13
^{60}Co	1173.2	43 / 38	< 5.8	182 / 152	$4.8^{+2.8}_{-2.8}$	55 ± 1	11
	1332.3	31 / 33	< 3.8	93 / 101	< 3.1	51 ± 1	
^{137}Cs	661.6	46 / 62	< 3.2	335 / 348	< 5.9	282 ± 2	>48
^{228}Ac	910.8	54 / 38	$5.1^{+2.8}_{-2.9}$	294 / 303	< 5.8	29.8 ± 1.6	
	968.9	64 / 42	$6.9^{+3.2}_{-3.2}$	247 / 230	$2.7^{+2.8}_{-2.5}$	17.6 ± 1.1	
^{208}Tl	583.2	56 / 51	< 6.5	333 / 327	< 7.6	36 ± 3	
	2614.5	9 / 2	$2.1^{+1.1}_{-1.1}$	10 / 0	$1.5^{+0.6}_{-0.5}$	16.5 ± 0.5	11
^{214}Pb	352	740 / 630	$34.1^{+12.4}_{-11.0}$	1770 / 1688	$12.5^{+9.5}_{-7.7}$	138.7 ± 4.8	11
^{214}Bi	609.3	99 / 51	$15.1^{+3.9}_{-3.9}$	351 / 311	$6.8^{+3.7}_{-4.1}$	105 ± 1	
	1120.3	71 / 44	$8.4^{+3.5}_{-3.3}$	194 / 186	< 6.1	26.9 ± 1.2	
	1764.5	23 / 5	$5.4^{+1.9}_{-1.5}$	24 / 1	$3.6^{+0.9}_{-0.8}$	30.7 ± 0.7	~10
	2204.2	5 / 2	$0.8^{+0.8}_{-0.7}$	6 / 3	$0.4^{+0.4}_{-0.4}$	8.1 ± 0.5	

The Gerda experiment for the search of 0νββdecay in 76Ge,

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

$0\nu\beta\beta$ **blinded data** of GERDA Phase I



1. Data after January 2012 **is blinded in ± 20 keV region around $Q_{\beta\beta}$**

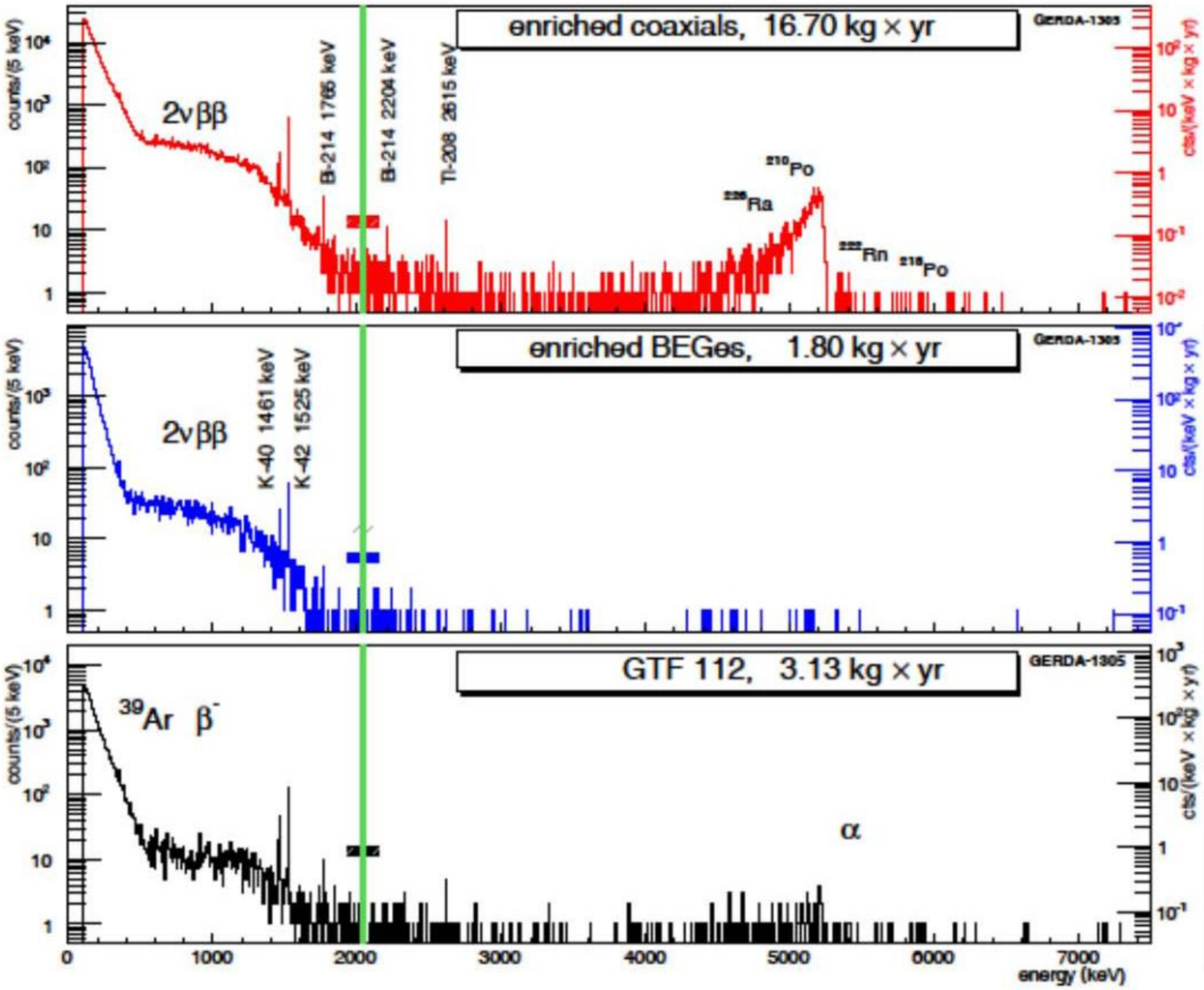
-> To avoid tuning the analysis towards signal or no-signal outcome.

2. All data processing, quality cuts and statistical analysis methods are being fixed.

-> Paper with background model and analysis parameters published on arXiv prior to final unblinding:

The background in the neutrinoless double beta decay experiment GERDA submitted to EPJC; on arXiv:1306.5084

Background spectra of GERDA Phase I



green = blinded

2νββ result
arXiv:1212.3210
J.Phys.G: Nucl. Part. Phys. 40(2013) 035110

$$T^{2\nu}_{1/2} = (1.84^{+0.14}_{-0.08})\, 10^{21}\ \mathrm{yr}$$

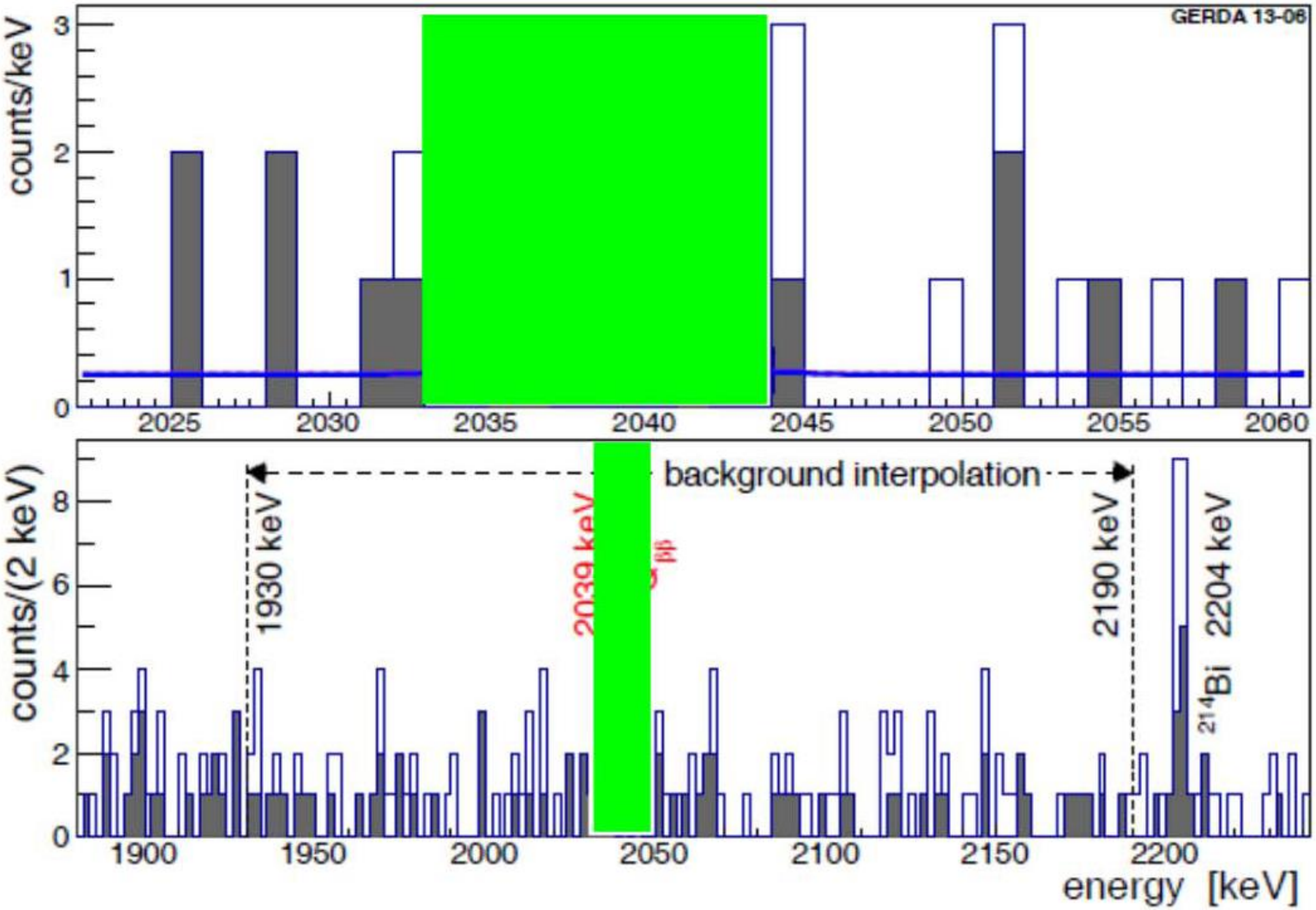
backgrd. paper
arXiv:1306.5084
to appear in EPJ C

Unblinding of the GERDA Phase-I 0νββ data

GERDA has unblinded the data after 1.5 years of data taking (558.6 days) on 14 June 2013 at the GERDA Collaboration Meeting in Dubna.

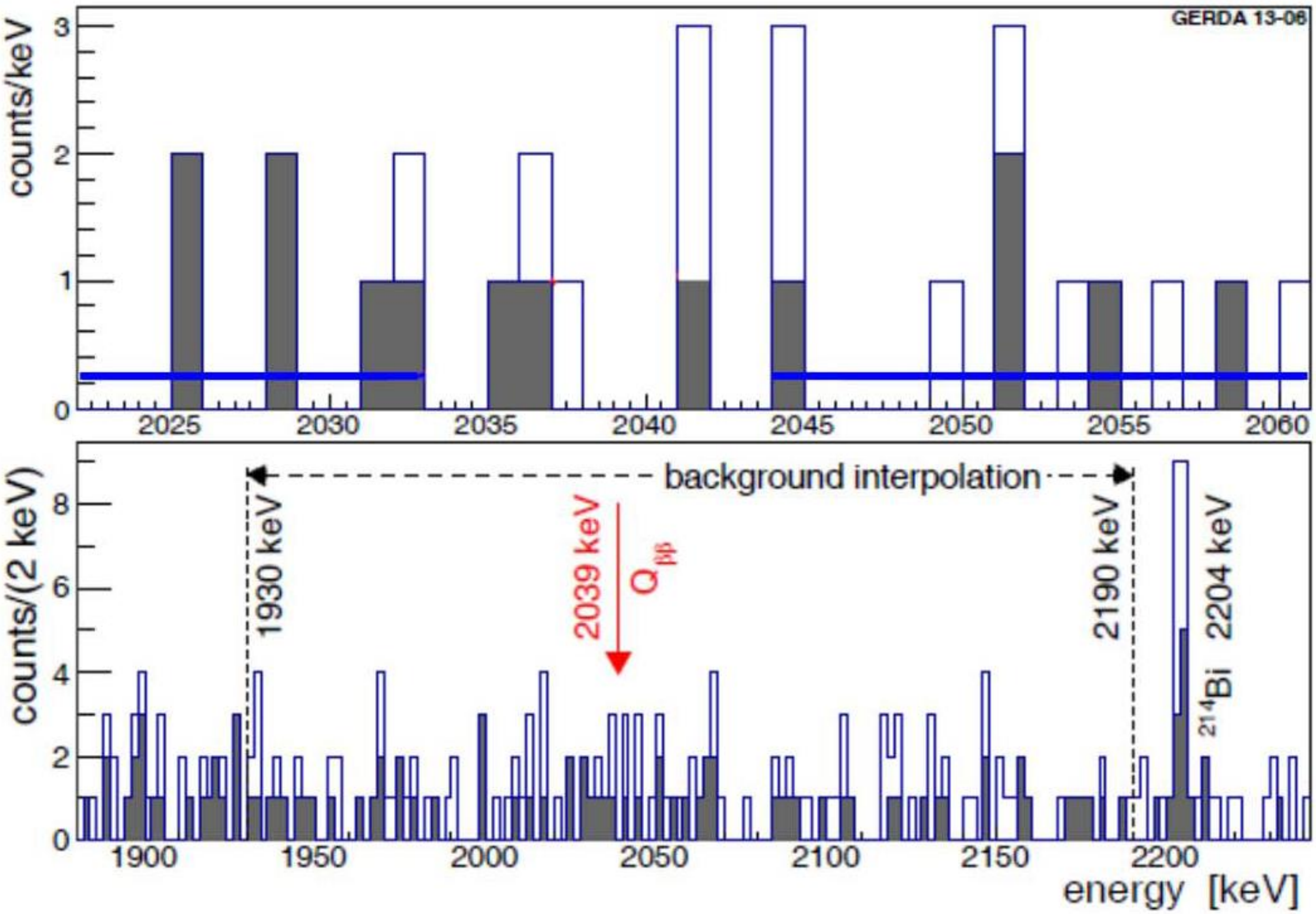
This happened after developing a model for the background and several methods of PSD for BEGe and semi-coaxial detectors.

Region of Interest



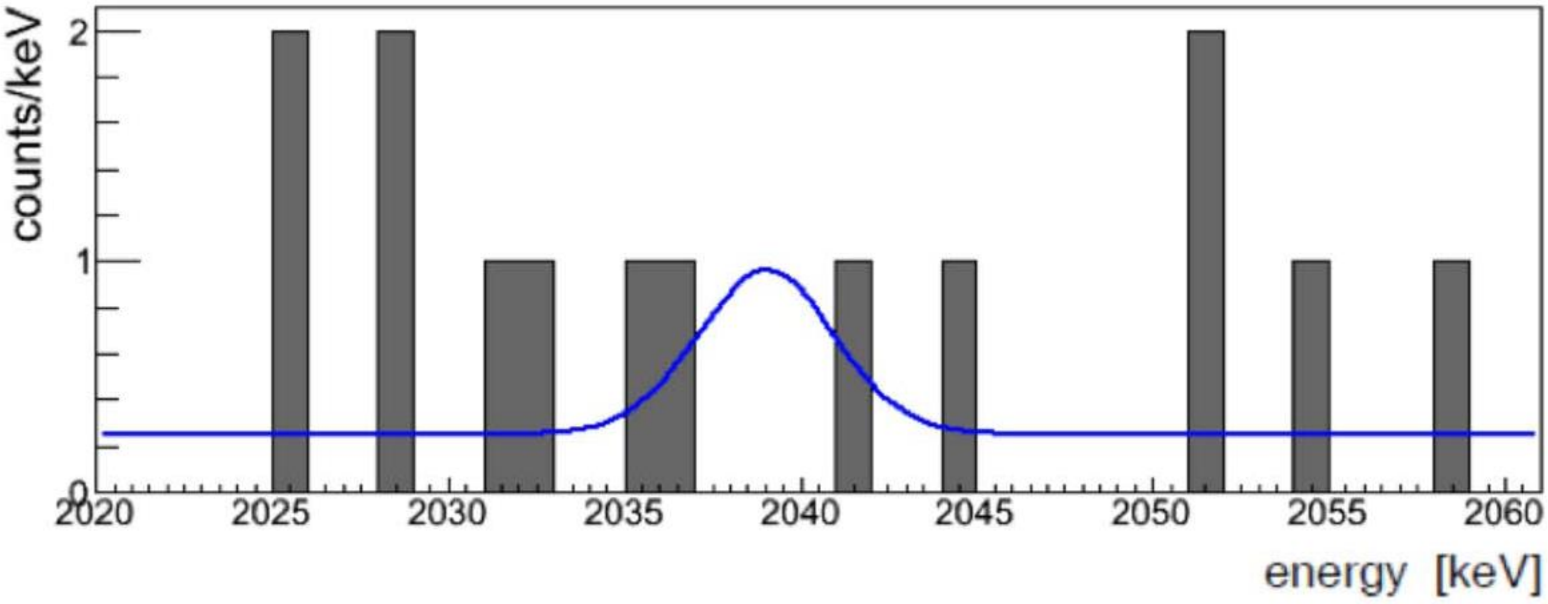
expected bg from interpolation: 5.1 events w/o PSD

2.5 events with PSD



expected bg from interpolation: 5.1 events w/o PSD
2.5 events with PSD

observed ➔ 7 events w/o PSD
➔ 3 events with PSD

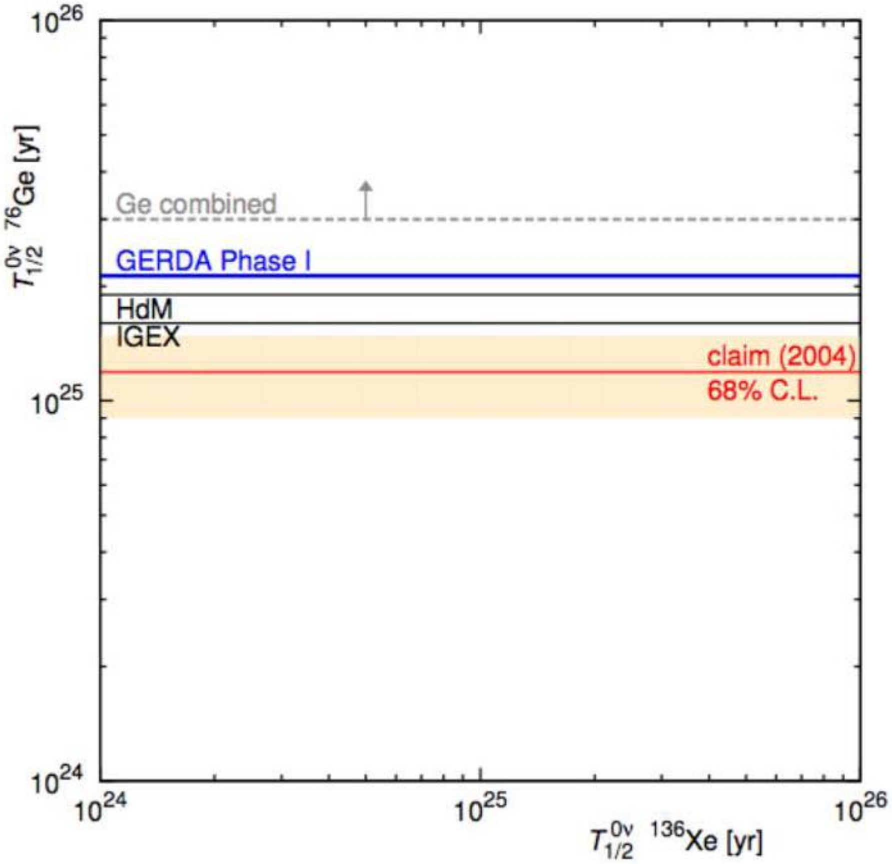


profile likelihood (PL) fit:

signal = a*flat background + b*line

➔ best fit: $N^{0\nu} = 0$; upper limit: $N^{0\nu} < 3.5$ (90%CL)

➔ half life limit $T_{1/2}(0\nu\beta\beta) > 2.1 * 10^{25}$ yr (90% C.L.)



Combine: **GERDA phase I + HdM + IGEX**

➔ PL fit to combined data

➔ backgrounds = free paramaters

➔ Best fit for $N^{0\nu} = 0$

➔ $T_{1/2}(0\nu\beta\beta) > 3.0 \times 10^{25}$ yr(90% CL)

KK-claim: $T_{1/2}(0\nu\beta\beta) = 1.19 \times 10^{25}$ yr

Stronger 2006 claim has known error:
100% PSD efficiency assumed
➔ realistic efficiency = no improvement

GERDA:

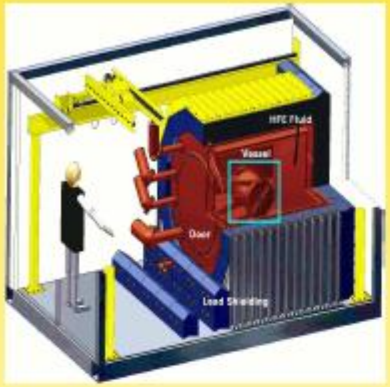
- **much lower BI**
- **no unknown nuclear lines**
- **flat background in ROI**

GERDA upper limit from PL fit:
< 3.5 events (90%CL)
KK claim strongly disfavoured
(Bayes factor 2×10^{-4})

KK claim → GERDA should see (2σ):
5.9 ± 1.4 signal counts
2.0 ± 0.3 background counts
→ probability for a fluctuation 1%

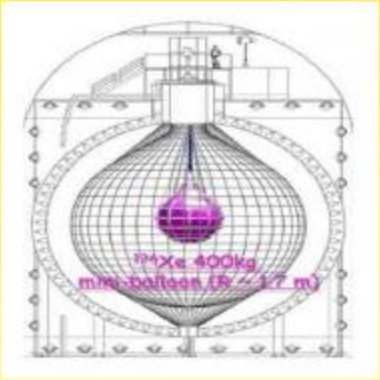
3 new limits on $T_{1/2}$ in 2012/13

EXO-200



$T_{\frac{1}{2}}(^{136}\mathrm{Xe}) > 1.6 \times 10^{25}$ y

KamLAND-Zen



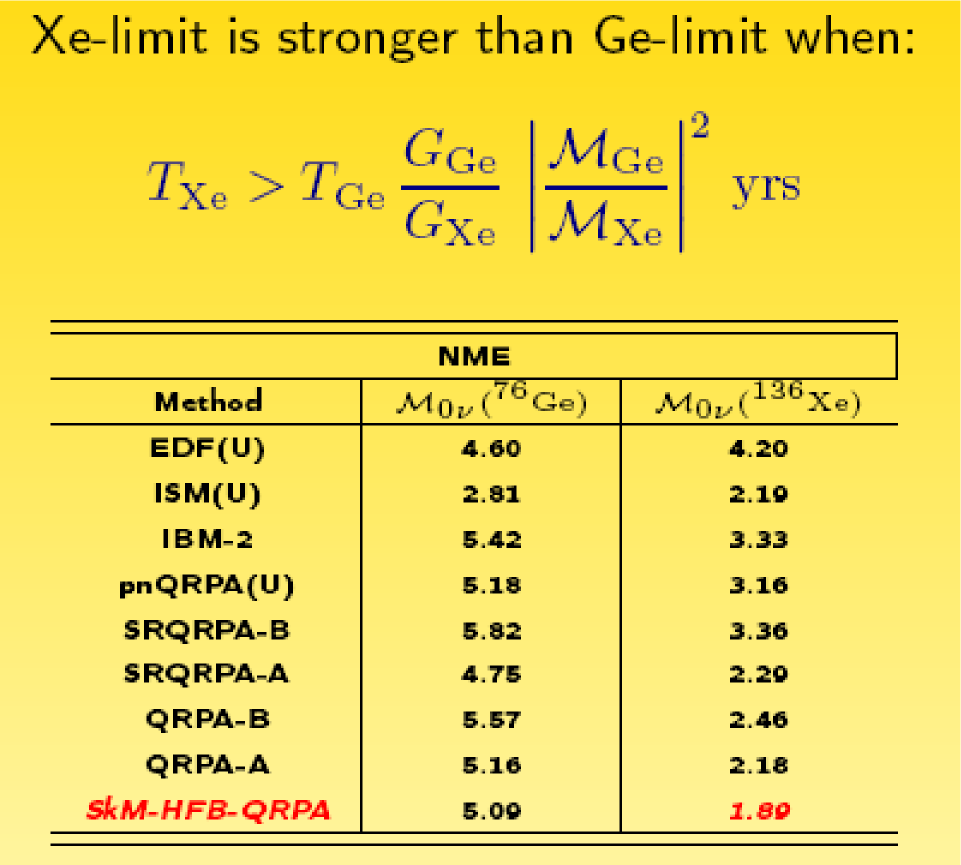
$T_{\frac{1}{2}}(^{136}\mathrm{Xe}) > 1.9 \times 10^{25}$ y

GERDA

$T_{\frac{1}{2}}(^{76}\mathrm{Ge}) > 2.1 \times 10^{25}$

How to compare? Who is better?

How to compare? Who is better?



Xe-limit is stronger than Ge-limit when:

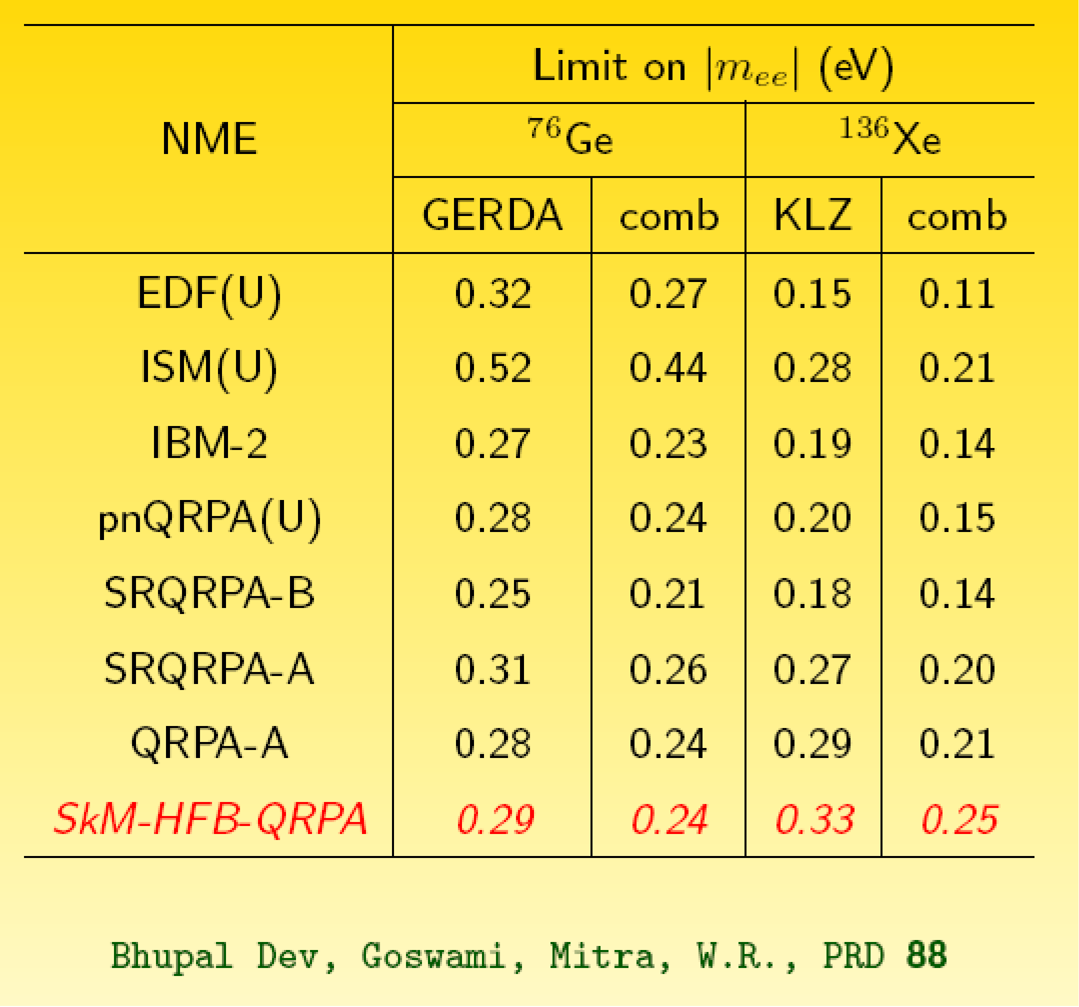
$$T_{\mathrm{Xe}} > T_{\mathrm{Ge}} \frac{G_{\mathrm{Ge}}}{G_{\mathrm{Xe}}} \left| \frac{\mathcal{M}_{\mathrm{Ge}}}{\mathcal{M}_{\mathrm{Xe}}} \right|^2 \ \mathrm{yrs}$$

	NME	
Method	$\mathcal{M}_{0\nu}(^{76}\mathrm{Ge})$	$\mathcal{M}_{0\nu}(^{136}\mathrm{Xe})$
EDF(U)	4.60	4.20
ISM(U)	2.81	2.19
IBM-2	5.42	3.33
pnQRPA(U)	5.18	3.16
SRQRPA-B	5.82	3.36
SRQRPA-A	4.75	2.29
QRPA-B	5.57	2.46
QRPA-A	5.16	2.18
SkM-HFB-QRPA	5.09	*1.89*

(Bhupal Dev, Goswami, Mitra, W.Rodejohann., PRD 88)

small QRPA-NME for Xe! *(Mustonen, Engel, 1301.6997)*
↔ small overlap in initial and final mean fields

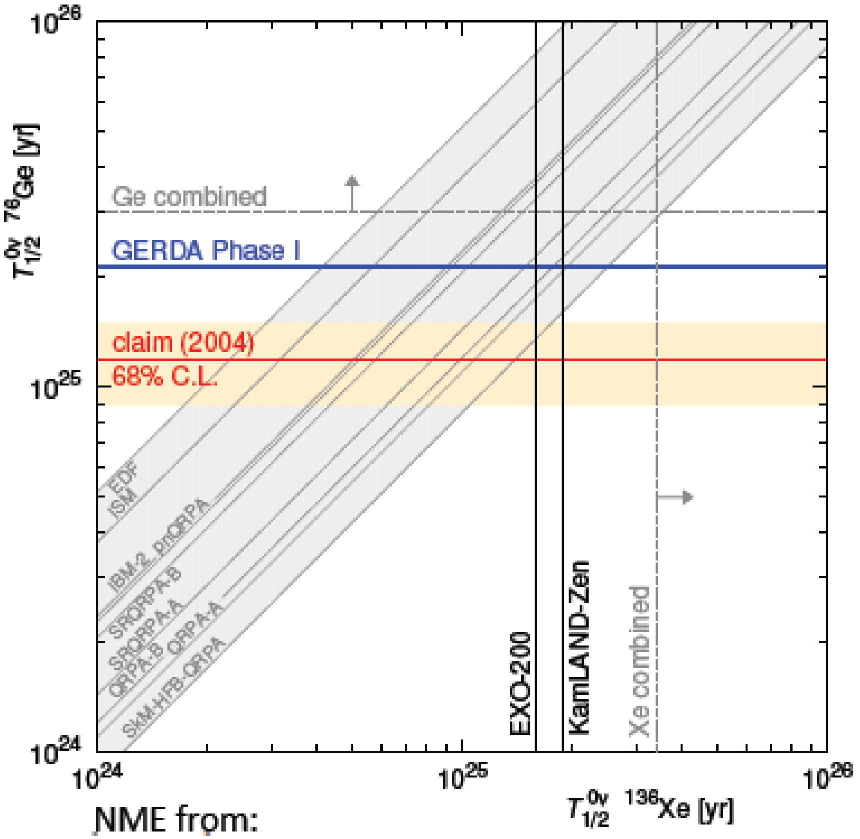
Xe vs. Ge



NME	Limit on $\lvert m_{ee} \rvert$ (eV)			
	^{76}Ge		^{136}Xe	
	GERDA	comb	KLZ	comb
EDF(U)	0.32	0.27	0.15	0.11
ISM(U)	0.52	0.44	0.28	0.21
IBM-2	0.27	0.23	0.19	0.14
pnQRPA(U)	0.28	0.24	0.20	0.15
SRQRPA-B	0.25	0.21	0.18	0.14
SRQRPA-A	0.31	0.26	0.27	0.20
QRPA-A	0.28	0.24	0.29	0.21
SkM-HFB-QRPA	*0.29*	*0.24*	*0.33*	*0.25*

Bhupal Dev, Goswami, Mitra, W.R., PRD **88**

EXO 200 , Kamland-Zen and GERDA Phase I vs KK claim



NME from:
P. S. Bhupal Dev *et al.*, (2013), arXiv:1305.0056

H1: signal with $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ yr
H0: background only

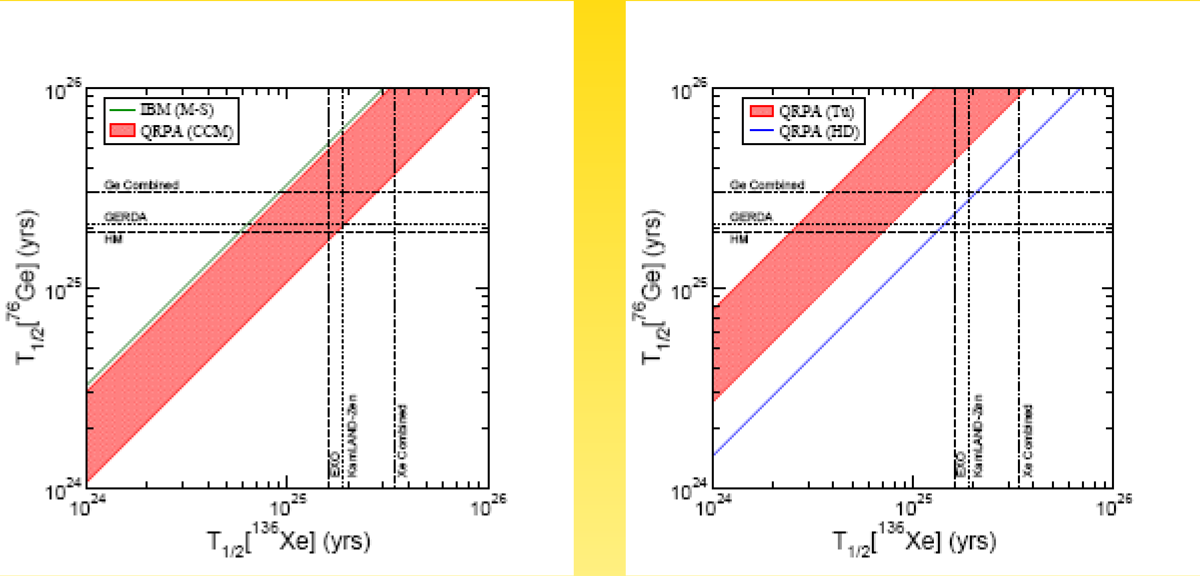
	Isotope	$P(H_1)/P(H_0)$	Comment
GERDA	^{76}Ge	0.024	Model independent
GERDA +HdM+IGEX	^{76}Ge	0.0002	Model independent
KamLAND-Zen*	^{136}Xe	0.40	Model dependent: NME, leading term
EXO-200*	^{136}Xe	0.23	Model dependent: NME, leading term
GERDA+KLZ* +EXO*	^{76}Ge + ^{136}Xe	0.002	Model dependent: NME, leading term

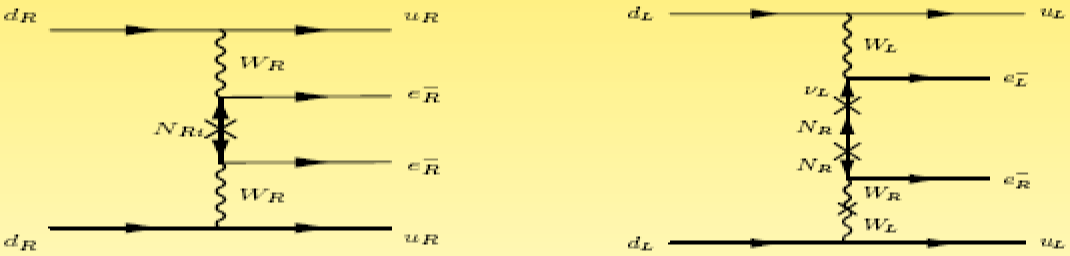
*:with conservative NME ratio $M_{0\nu}(^{136}Xe)/M_{0\nu}(^{76}Ge) \approx 0.4$ from:

F. Simkovic, V. Rodin, A. Faessler, and P. Vogel, Phys. Rev. C. **87**, 045501 (2013).
M. T. Mustonen and J. Engel, (2013), arXiv:1301.6997 [nucl-th].
P. S. Bhupal Dev *et al.*, (2013), arXiv:1305.0056 [hep-ph].

Left-right symmetry. Who is better?

Xe vs. Ge





Barry, W.R., JHEP **1309**

Barry, Rodejohann., JHEP 1309)

Search for double beta decay of Ge-76 on excited level 0_1^+ and 2_1^+ of daughter nuclei Se-76.

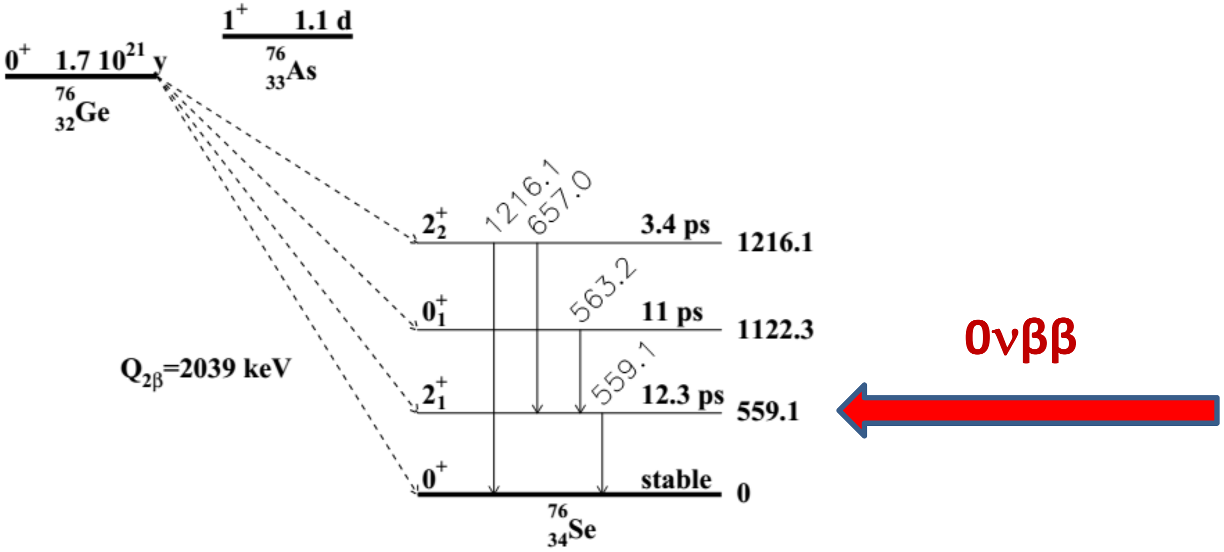


Fig. 1. Lowest energy levels of ^{76}Se which can be populated in the double beta-decay of ^{76}Ge. The energies of the excited states and of the de-excitation γ-rays are given in keV [21].

Future experiment

(under construction or funded)

GERDA Phase II

Majorana demonstrator

Super NEMO demonstrator

Cuore 0 / Cuore

Kamland-Zen 1000

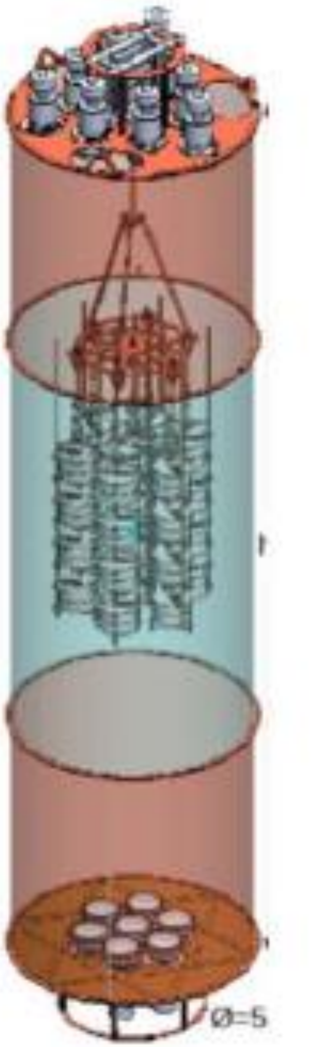
nEXO

GERDA - Majorana

TGV-3

CANDLES – data taking

GERDA Phase-II



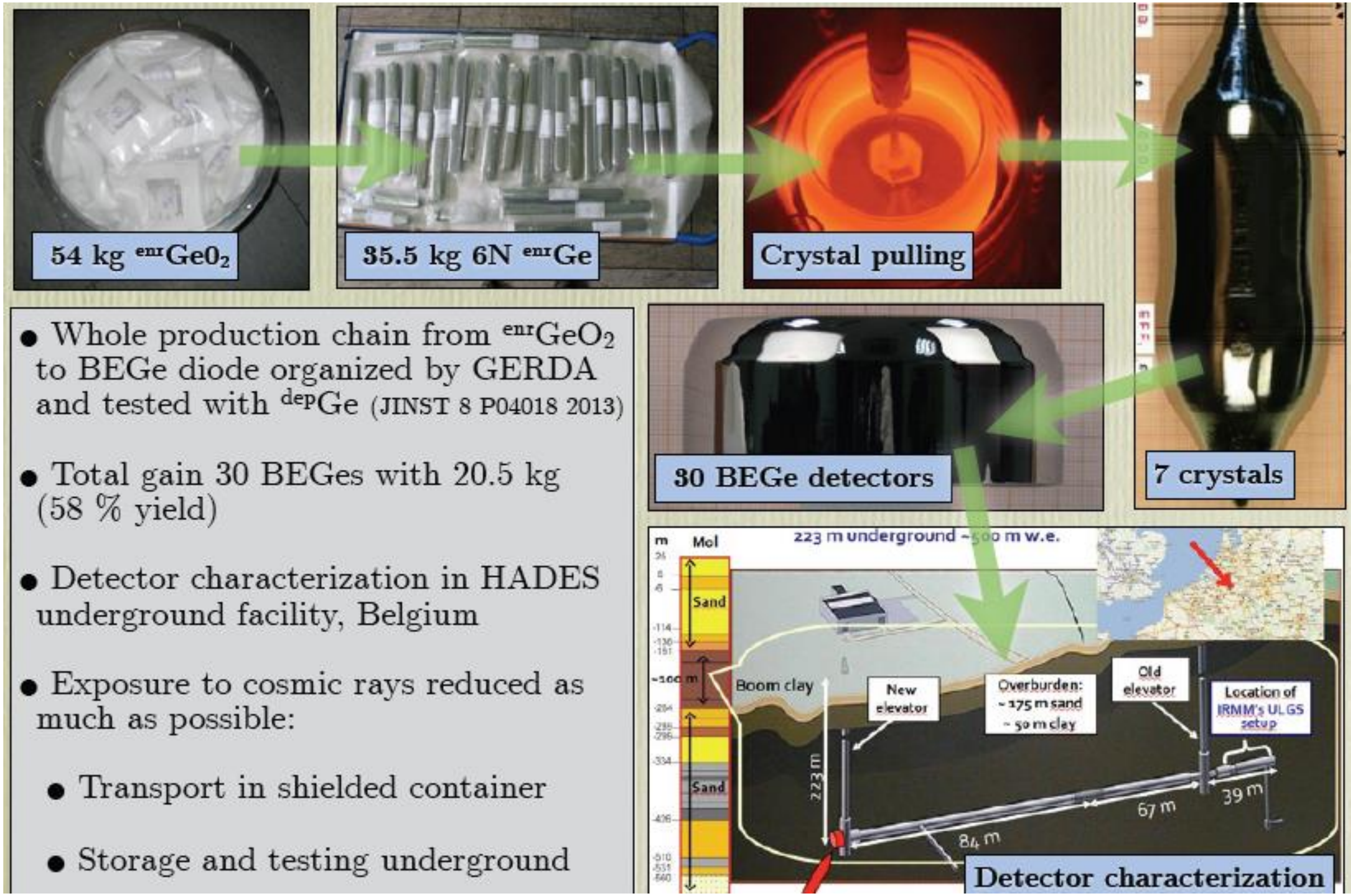
Phase I finished → currently preparing Phase II

+ 2x detector mass (~20 kg BEGe + 15 kg semi-coax)
+ liquid argon instrumentation to veto background
+ new readout electronics + detector suspension

→ better energy resolution & pulse shape discrimination, lower background (factor 10)

→ collect ~ 100 kg yr exposure
sensitivity ~ 1.4 10^{26} yr (90% C.L.)

Phase II detectors - BEGe



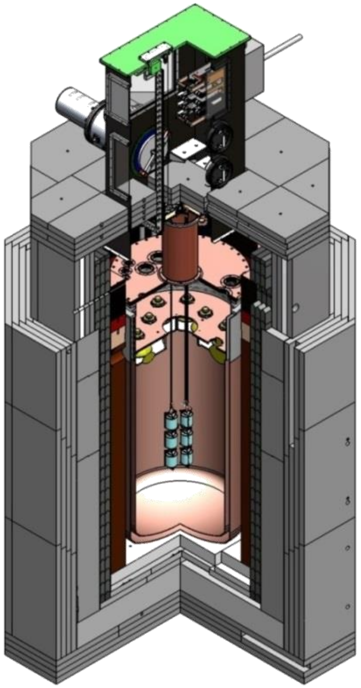
- Whole production chain from $^{enr}GeO_2$ to BEGe diode organized by GERDA and tested with ^{dep}Ge (JINST 8 P04018 2013)
- Total gain 30 BEGes with 20.5 kg (58 % yield)
- Detector characterization in HADES underground facility, Belgium
- Exposure to cosmic rays reduced as much as possible:
  - Transport in shielded container
  - Storage and testing underground

Adopted from: B.Lehnert., Talk at RICAP 13 conf., Rome, 23 May 2013

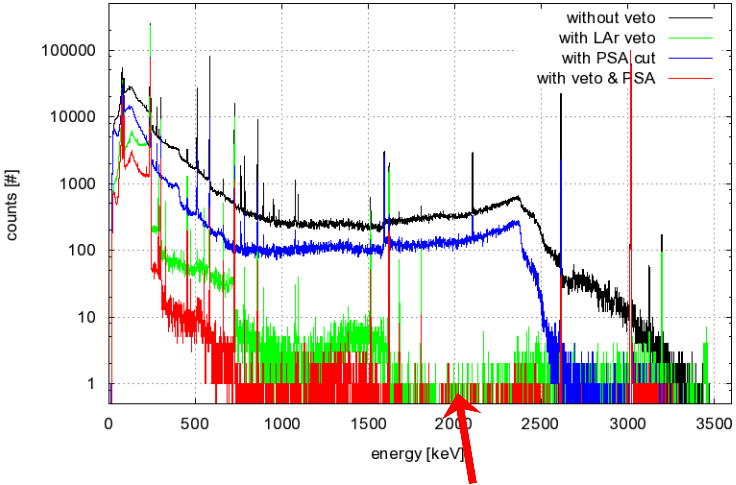
R&D for GERDA Phases II and III
LArGe test facility + BEGe detectors

The LArGe Setup with 1.4 tons of LAr

9 PMTs: 8” ETL9357;
Reflector: VM2000
& wavelength shifter;
Cryostat: ∅ 90 cm x 205 cm, volume: **1000 liter;**
Shield: Cu -15 cm, Pb -10 cm, Steel- 23 cm, PE- 20 cm.



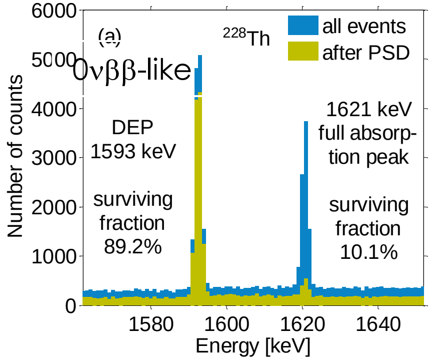
The LArGe set up was assembled at LNGS in 2010 and operates with naked Ge detectors immersed in 1.4 tons of LAr served as scintillation veto. Efficiency of the LAr scintillation veto and pulse shape discrimination (PSD) of signals from the BEGe detector inside the LArGe were tested and optimized . It was shown that the internal background from Th-228 suppressed in LArGe by factor 5000 after applying LAr veto and PSD.



ROI – reduction factor > 5000

First naked BEGe inside LArGe

BEGe parameters in LArGe:
High voltage 4000 V
Leakage current ~ 4 pA
FWHM @ 1.33 MeV 1.8 keV
mass 878 g



First results obtained with LArGe + BEGe successfully demonstrate possibility of considerable background reduction for GERDA Phase II and III by using LAr scintillation veto + BeGe PSD.

Phase II: LAr Scintillation Veto

- Experimental prove of principle

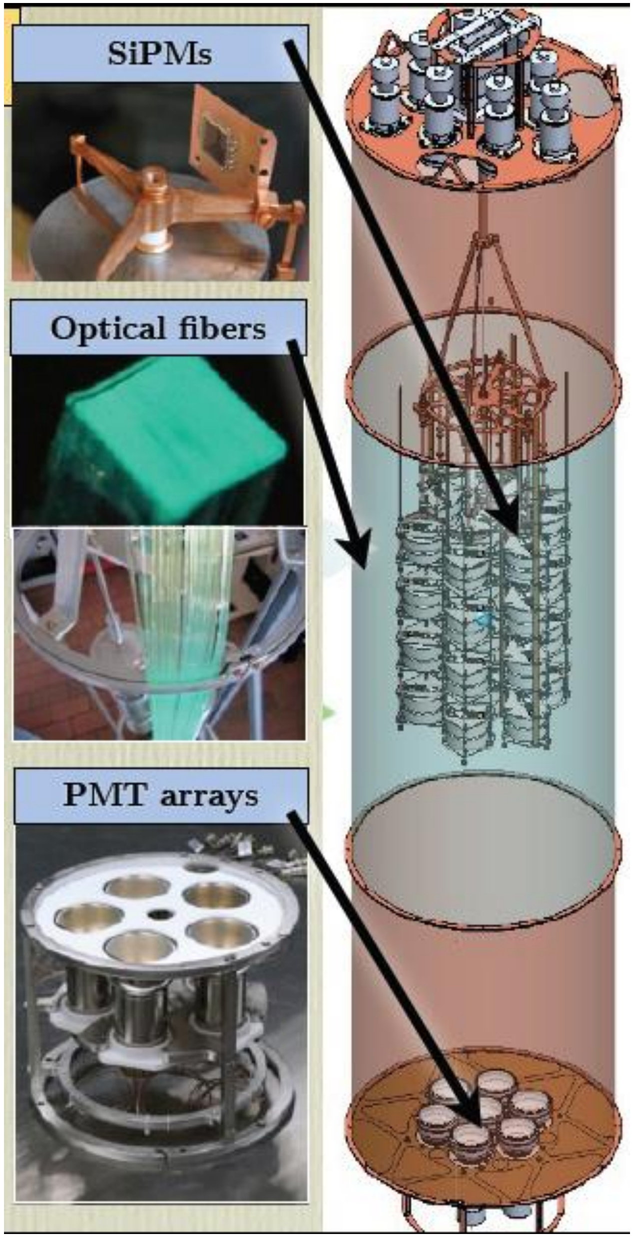
  in R&D facility **LArGe** (LNGS)

- Investigation of different design principles

  for GERDA with tuned MC simulations:

- **PMT arrays** on top and bottom
- **Fiber shroud** with SiPM readout
- **SiPMs** inside mini shroud (if deployed)

- **Combination of designs is approved**



MAJORANA demonstrator:
under construction → data taking

- ~ 30 kg ^{enr}Ge + ~ 10 kg ^{nat}Ge detectors, in two cryostats
- Ultrapure materials; copper that has been electroformed and machined underground
- Compact passive and active shields
- At the 4850-foot level of SURF, Lead, SD
- Construction scheduled for completion in 2015

GERDA + MAJORANA cooperation agreement:

- open exchange of knowledge & technologies (e.g. MaGe, R&D)
- intention to merge for ton-scale experiment

→ best techniques developed & tested in GERDA and MAJORANA

NEMO 3

Tracking detector: drift chambers (6180 Geiger cells)
$\sigma_t = 5$ mm, $\sigma_z = 1$ cm (vertex)

Calorimeter (1940 plastic scintillators and PMTs)
Energy Resolution FWHM=8 % (3 MeV)

Identification e^-, e^+, γ, α
Very high efficiency for background rejection

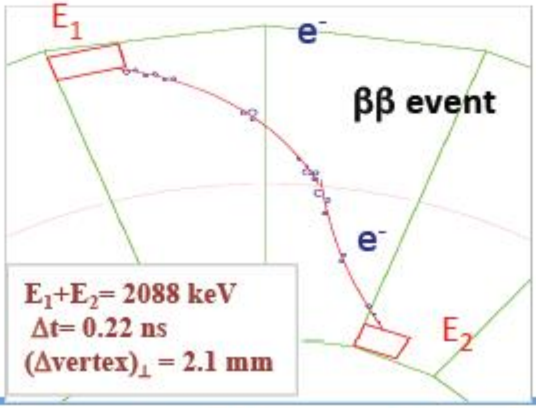
Background level @ $Q_{\beta\beta}$ [2.8 – 3.2 MeV] : 1.2 10^{-3} cts/keV/kg/y

Multi-isotope (7 measured at the same time)

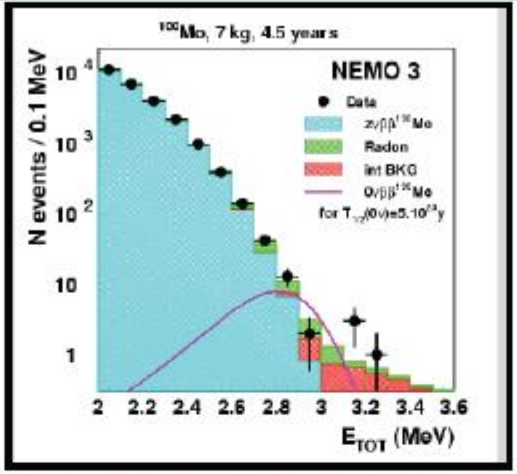
Running at Modane underground laboratory (2003 - 2011)

Unique feature

Measurement of all kinematic parameters: individual energies and angular distribution



E_1+E_2= 2088 keV
Δt= 0.22 ns
$(\Delta\text{vertex})_\perp$ = 2.1 mm



[2.8 – 3.2] MeV 18 observed events, 16.4 ± 1.3 expected

^{100}Mo $T_{1/2}$ ($\beta\beta0\nu$) > 1.0 10^{24} y (90% C.L.)

$\langle m_\nu \rangle$ < 0.31– 0.79 eV

Measurement of 7 isotopes ββ(2ν) half-lifes
Excited states, Majoron limits for ββ(0ν)

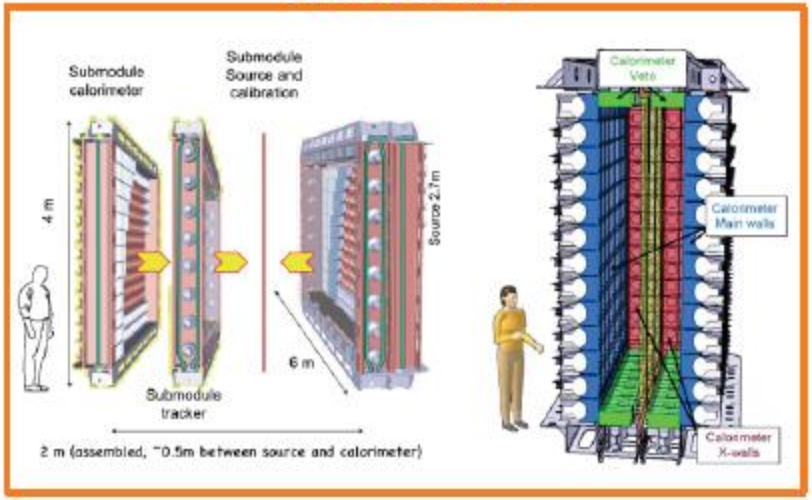
The SuperNEMO experiment

SuperNEMO design

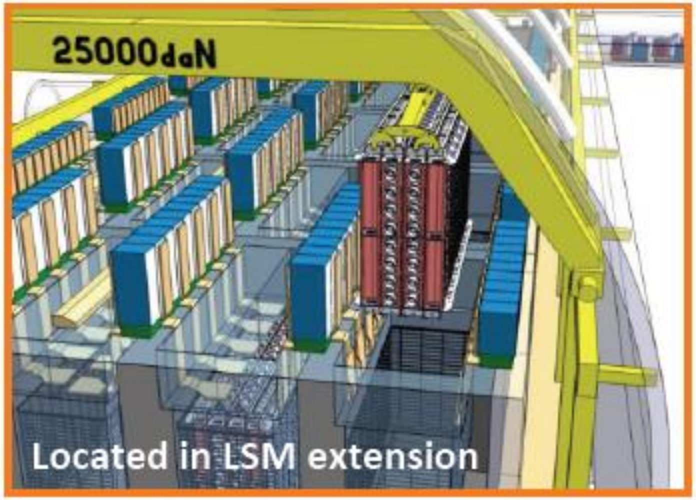
NEMO3		**SuperNEMO**
^{100}Mo	isotope	^{82}Se or ^{48}Ca or ^{150}Nd
7kg	isotope mass	100kg
18%	efficiency	30%
^{208}Tl : $\approx 100\mu$Bq/kg ^{214}Bi : $< 300\mu$Bq/kg Rn : 5 mBq/m^3	internal contaminations in the $\beta\beta$ foils Rn in the tracker	^{208}Tl : $\leq 2\mu$Bq/kg ^{214}Bi : $\leq 10\mu$Bq/kg Rn : $\leq$ 0.15 mBq/m^3
8% @ 3MeV	calorimeter resolution	4% @ 3MeV
$T^{0\nu}_{1/2} \gtrsim 1 \times 10^{24} yr$ $\langle \mathbf{m}_\nu \rangle <$ **(0.3 - 0.9) eV**	sensitivity	$T^{0\nu}_{1/2} \gtrsim 1 \times 10^{26} yr$ $\langle \mathbf{m}_\nu \rangle <$ **(0.04 - 0.11) eV**

SuperNEMO

A module



20 modules



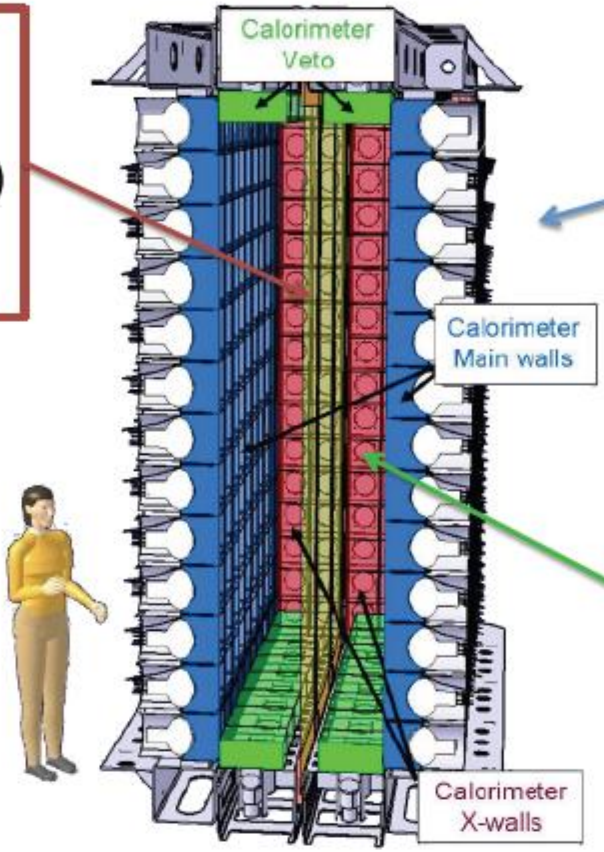
	Demonstrator module	20 Modules
Source : ^{82}Se	7 kg	100 kg
Drift chambers for tracking	2 0000	40 000
Electron calorimeter	500	10 000
γ veto (up and down)	100	2 000
$T_{1/2}$ sensitivity	6.6 10^{24} y (No background)	1. 10^{26} y
$<m_\nu>$ sensitivity	200 – 400 meV	40 – 100 meV

SuperNEMO Demonstrator

Objective: to reach the background level for 100 kg
to perform a no background experiment with 7 kg isotope of ^{82}Se in 2 yr

Source

^{214}Bi < 10 μBq/kg
(NEMO3 100 μBq/kg)
208Tl < 2 μBq/kg
(NEMO3 100 μBq/k)

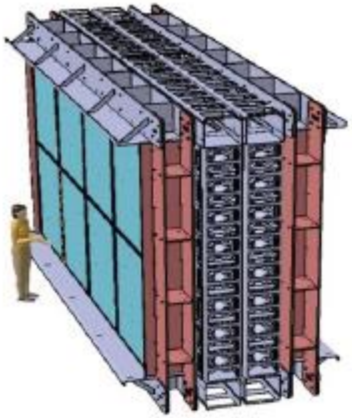


Calorimeter

ΔE/E < 4% @ 3 MeV
(NEMO3 8.6% at 3MeV)

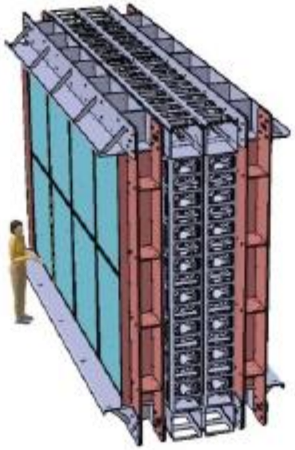
Tracker

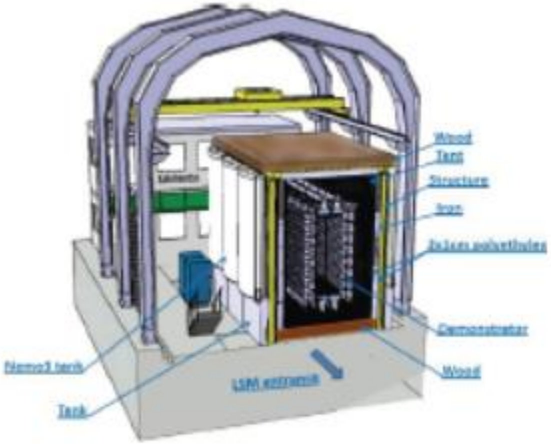
3.7 m long **(NEMO3 2.7 m)**
σ_t = 5 mm, σ_z = 1 cm
Radon < 0.15 mBq/m^3
(NEMO3 5 mBq/m^3)
Wiring robot

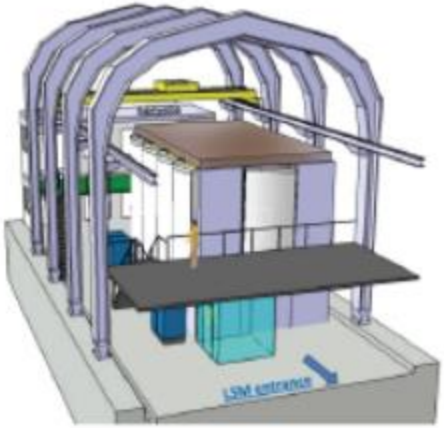


Global efficiency : 30 % (NEMO3 8%)

SuperNEMO demonstrator







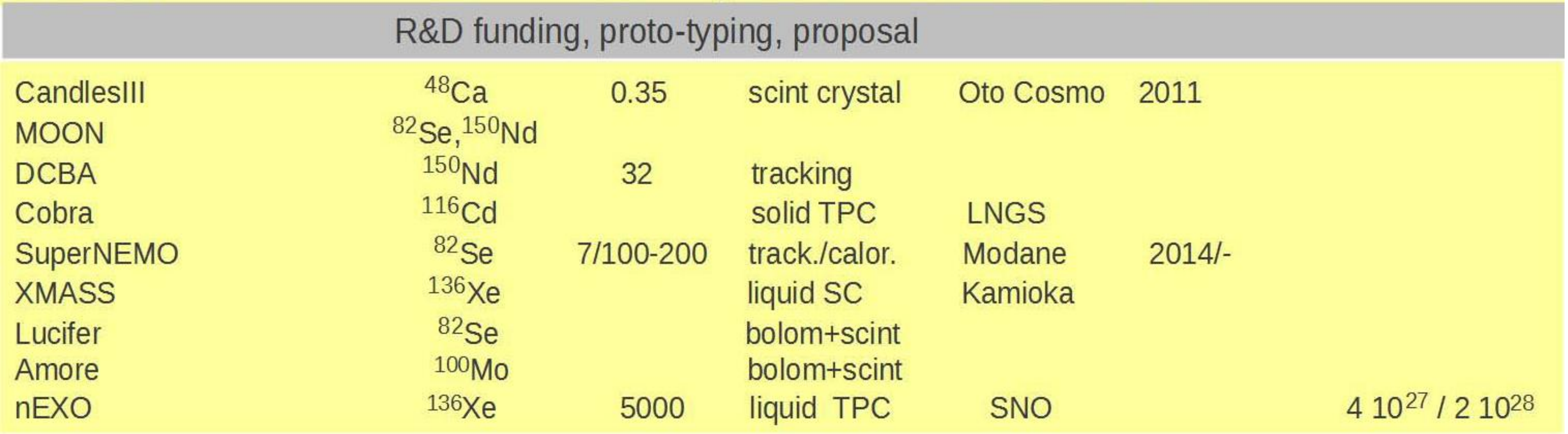
- ❑ Construction started in the laboratories
- ❑ Installation and commissioning (2013 – 2014) @ Modane Underground Laboratory
- ❑ Data taking in 2014
- ❑ No background expected
- ❑ Sensitivity after 2 years : $T_{1/2} > 6.6\ 10^{24}$ y and $\langle m_\nu \rangle < 0.2$ -0.4 eV

And many other experimental R&D efforts, such as

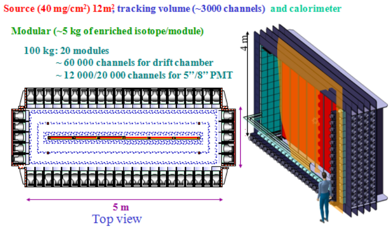
Lucifer – phonons and scintillation

COBRA – pixelized CdZnTe semiconductor detector,

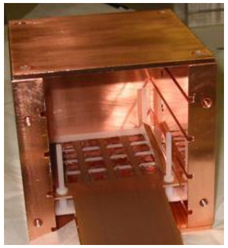
SuperNEMO – full scale, SNO+, Moon, DCBA, NEXT,…..



R&D funding, proto-typing, proposal						
CandlesIII	^{48}Ca	0.35	scint crystal	Oto Cosmo	2011	
MOON	^{82}Se, ^{150}Nd					
DCBA	^{150}Nd	32	tracking			
Cobra	^{116}Cd		solid TPC	LNGS		
SuperNEMO	^{82}Se	7/100-200	track./calor.	Modane	2014/-	
XMASS	^{136}Xe		liquid SC	Kamioka		
Lucifer	^{82}Se		bolom+scint			
Amore	^{100}Mo		bolom+scint			
nEXO	^{136}Xe	5000	liquid TPC	SNO		$4\ 10^{27}$ / $2\ 10^{28}$

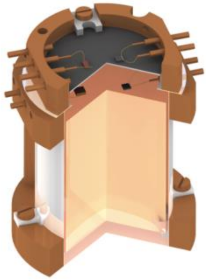


Super NEMO

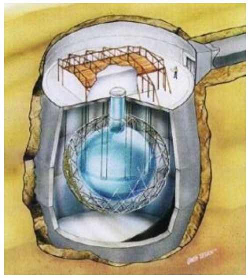


COBRA

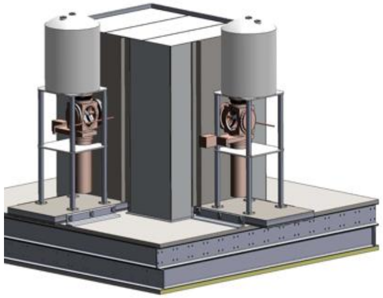
NEXT



LUCIFER



SNO+



MAJORANA

Nearest Future

GERDA-II: preparation in progress from 2013, data taking from 2014

Super NEMO demonstrator: installation in progress from 2013, data taking from 2015

EXO-200: started 2011, current run stopped June 2013,
factor 3.6 more data in hand compared to publication → new result soon,
hardware: currently installing radon reducer for air + new electronics

Kamland-Zen: started data taking in 2011, large bkg @ 2.5 MeV from ^{110m}Ag (on balloon / activation of Xe), filtration + purifications in 2012,
fire in 2012 → stop operation for ~ 9 months,

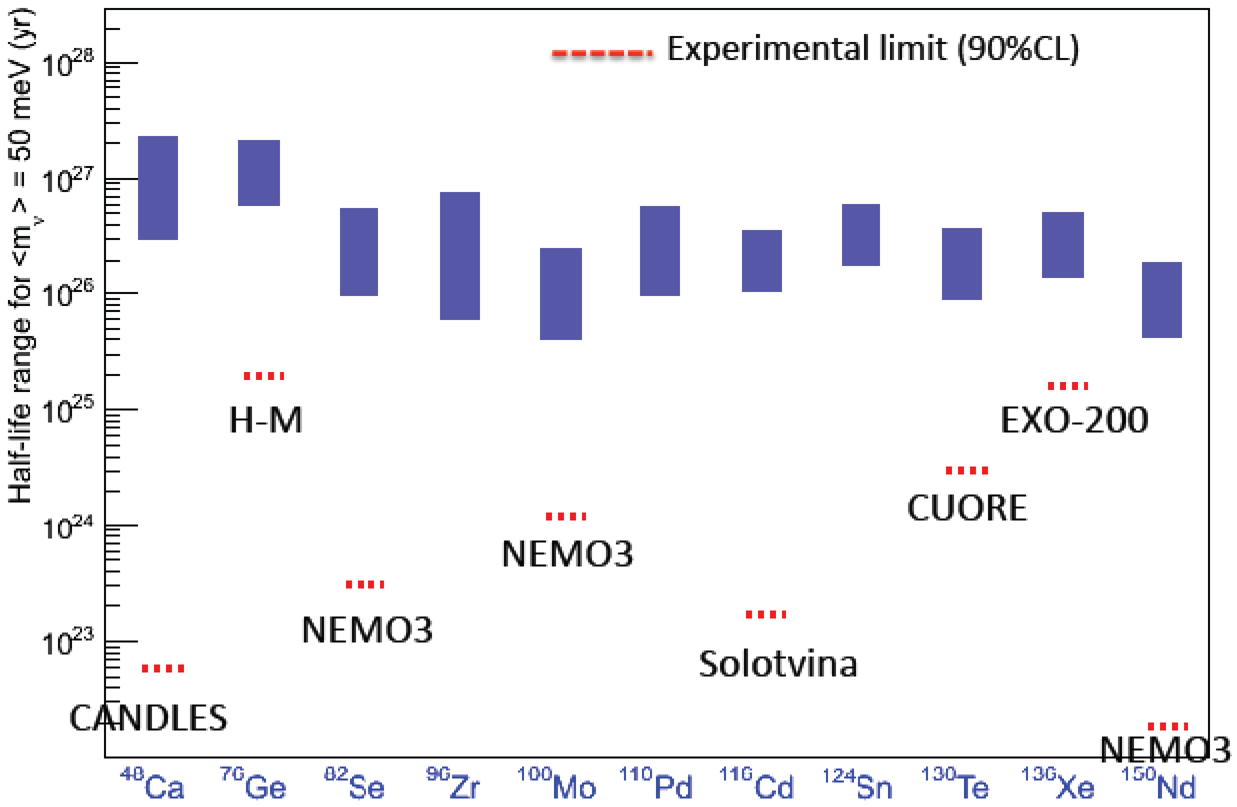
currently scintillator purification → expect factor 1/100 for ^{110m}Ag bkg,
restart in Nov 2013, options: new mini-balloon & 600 kg more Xe,
stop latest in May 2016 for vessel inspection

NEXT-100: test detectors show extrapolated FWHM ~ 0.8% @ $Q_{\beta\beta}$ & good tracking,
commissioning expected 2016, 10 kg proto-type in 2014

SNO+: changed to ^{nat}Te loading of scintillator (0.8-1.3 ton of ^{130}Te),
currently filling water, introduction of Te end 2014 / start 2015

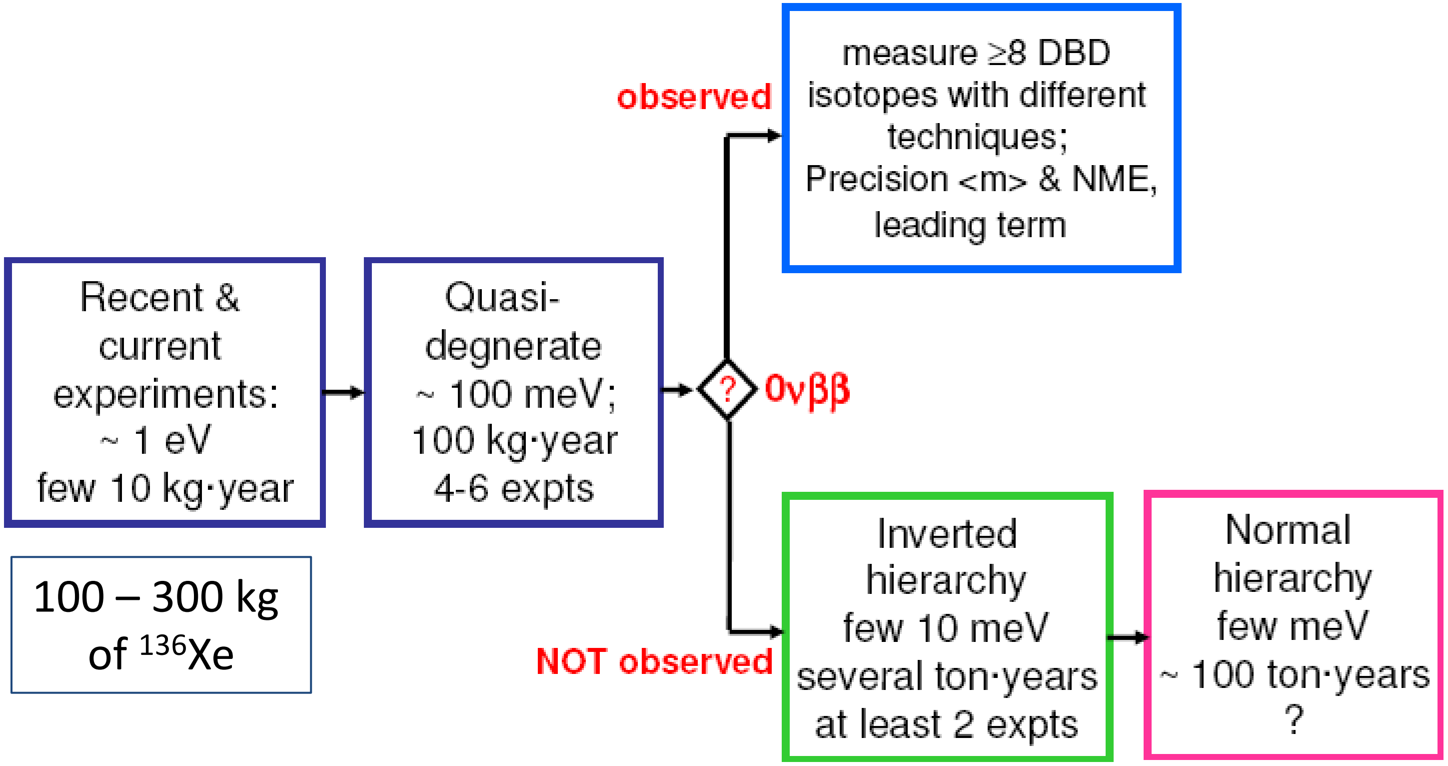
Majorana Demonstrator: 2 cryostats with ~30 kg ^{enr}Ge diodes & 10 kg ^{nat}Ge in 2014

Cuore: 1 tower (out of 19) in Cuoricino cryostat (Cuore0) → α surf. bkg reduction 1/6
assembly in 2014, data taking 2015

Half-life range for <m_ν> = 50 meV (yr)
10^28
10^27
10^26
10^25
10^24
10^23
Experimental limit (90%CL)
H-M
EXO-200
CUORE
NEMO3
NEMO3
Solotvina
CANDLES
NEMO3
48Ca
76Ge
82Se
96Zr
100Mo
110Pd
116Cd
124Sn
130Te
136Xe
150Nd

Summary

$0\nu\beta\beta$ experimental strategy during the next decade



Recent & current experiments: ~ 1 eV few 10 kg·year

Quasi-degnerate ~ 100 meV; 100 kg·year 4-6 expts

? $0\nu\beta\beta$

observed

measure ≥8 DBD isotopes with different techniques; Precision <m> & NME, leading term

NOT observed

Inverted hierarchy few 10 meV several ton·years at least 2 expts

Normal hierarchy few meV ~ 100 ton·years ?

100 – 300 kg of ^{136}Xe

until today **2014 - 2017** **2017 – 2020** **very far future ?**

Controversy S. Schönert, NME WS, LNGS Nov. 2011

CONCLUSION

New generation of the of the $0\nu\beta\beta$ experiments

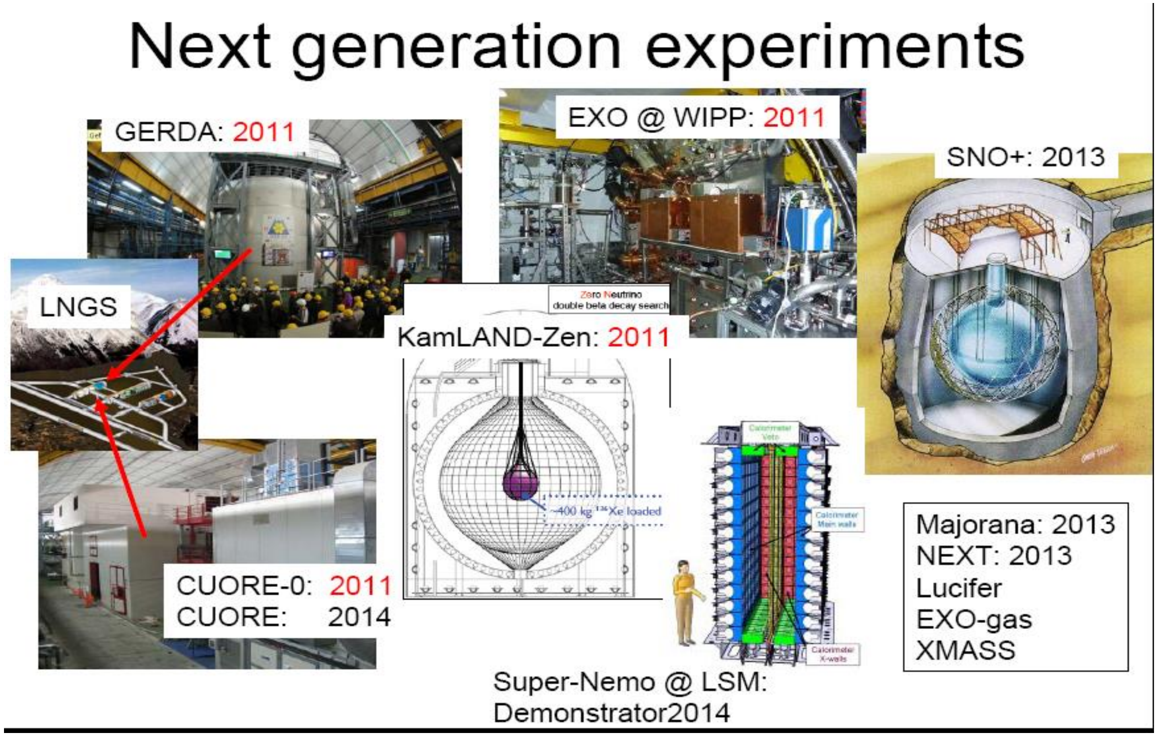
has a good chance

to penetrate deeper

ν

in understanding

of the neutrino properties



Next generation experiments

GERDA: 2011

EXO @ WIPP: 2011

SNO+: 2013

LNGS

KamLAND-Zen: 2011

CUORE-0: 2011
CUORE: 2014

Majorana: 2013
NEXT: 2013
Lucifer
EXO-gas
XMASS

Super-Nemo @ LSM:
Demonstrator2014

Extra slides

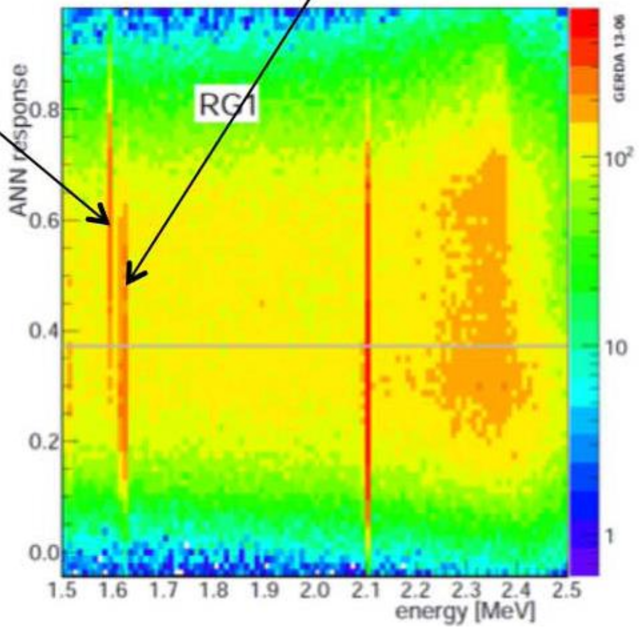
Pulse shape discrimination for coaxial detectors

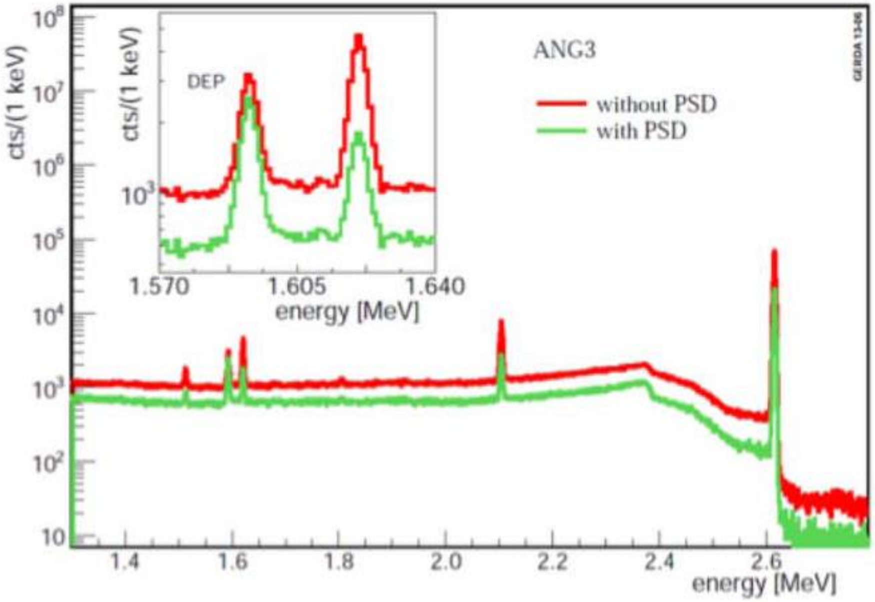
3 independent PSD methods:

- likelihood classification
- PSD selection based on pulse asymmetry
- **neural network analysis (ANN)**
  ➔ **training with calibration data**

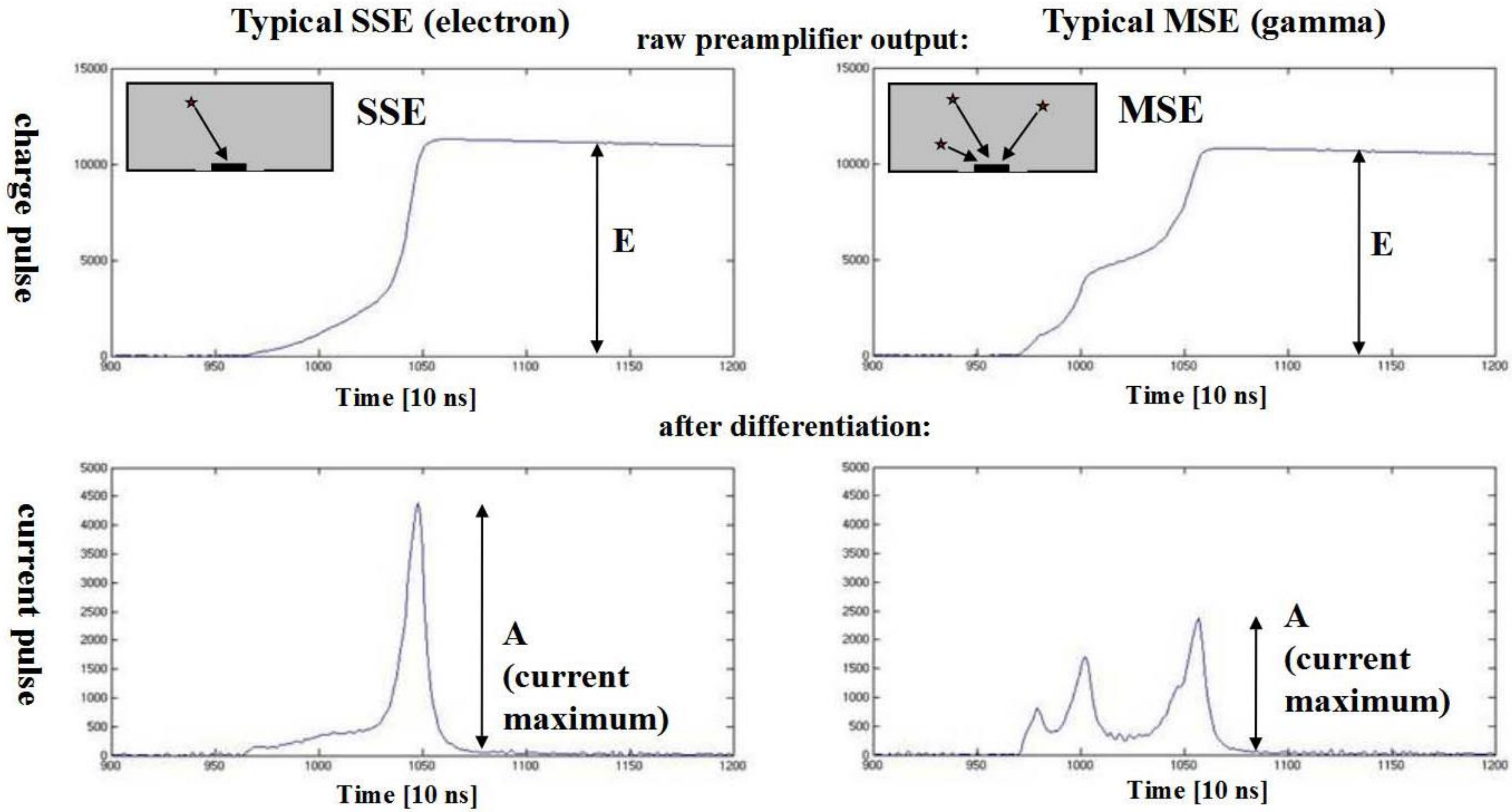
SSE library: DEP peak of ^{208}Tl → gamma at 1592 ± 1 keV

MSE library: FAP (Full Absorption Peak) of ^{212}Bi at 1620 keV





Pulse shape discrimination A/E for BEGe


Typical SSE (electron)

raw preamplifier output:

Typical MSE (gamma)

after differentiation:

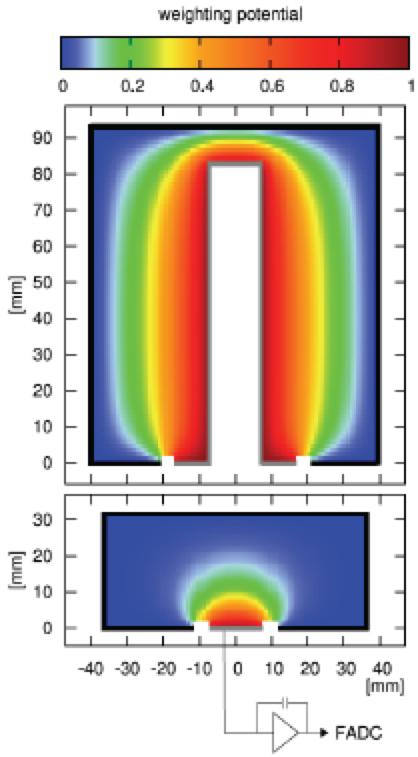
→ Cutting in A/E → rejects background like MSEs

→ $\varepsilon_{PSD} = 0.92 \pm 0.02$ → ca. 85% of background events at $Q_{\beta\beta}$ rejected

arXiv:1307.2610

Classification of (0νββ) signal-like (SSE) or background-like (MSE, p+) events

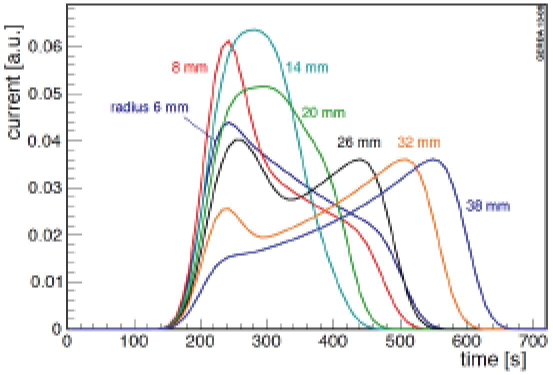
Weighting potential for coax and BEGe detectors are different

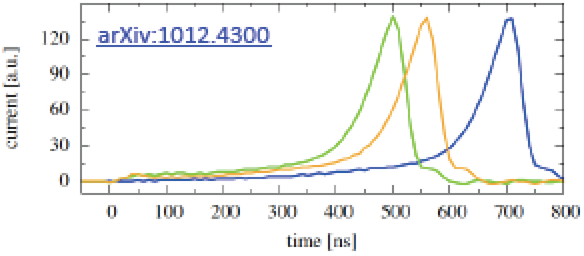


Coax

BEGe

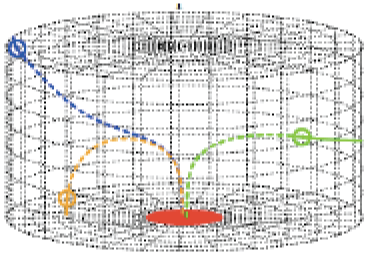
Current pulses of simulated SSE signals

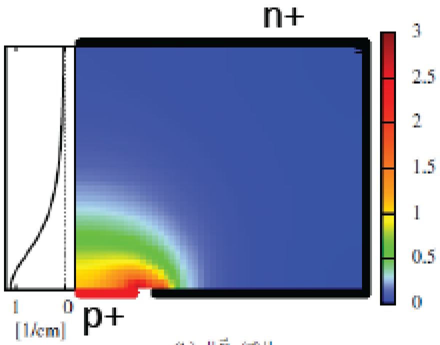




arXiv:1012.4300

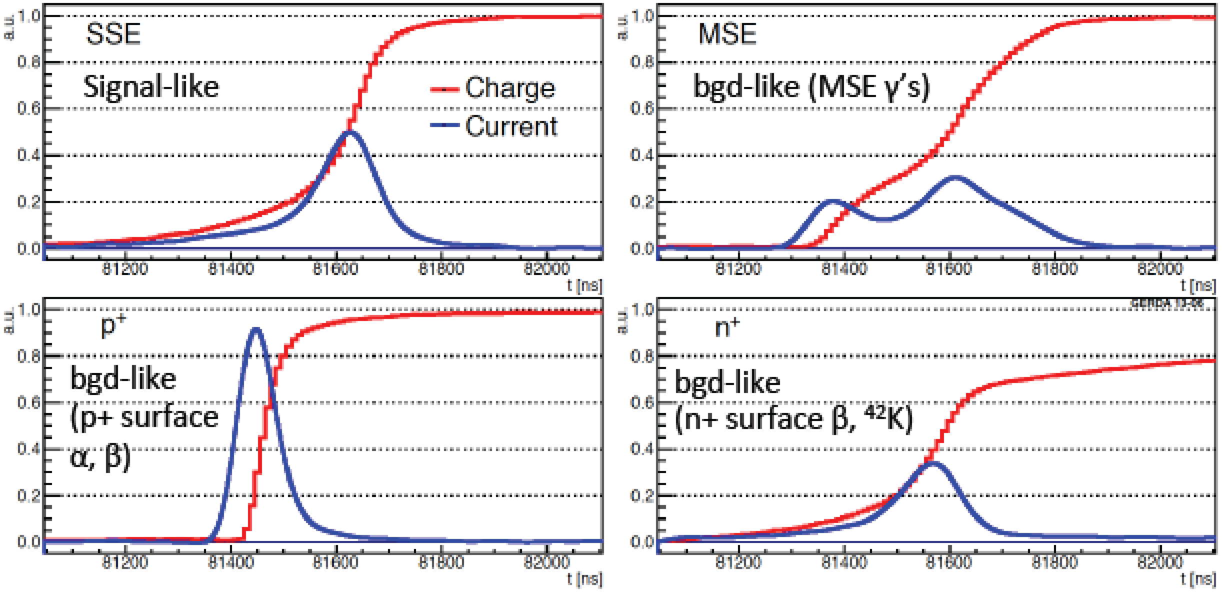
arXiv:1307.2610

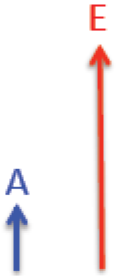




(b) $||\vec{E}_w(\vec{r})||$

PSD discrimination parameter: A/E





$$T_{1/2}^{0\nu} = \frac{\ln 2 \cdot N_A}{m_{enr} \cdot N^{0\nu}} \cdot \mathcal{E} \cdot \epsilon$$

$$\epsilon = f_{76} \cdot f_{av} \cdot \varepsilon_{fep} \cdot \varepsilon_{psd}$$

N_A: Avogadro number
E: exposure
ε: exposure averaged efficiency
m_{enr}: molar mass of enriched Ge
$N^{0\nu}$: signal counts / limit

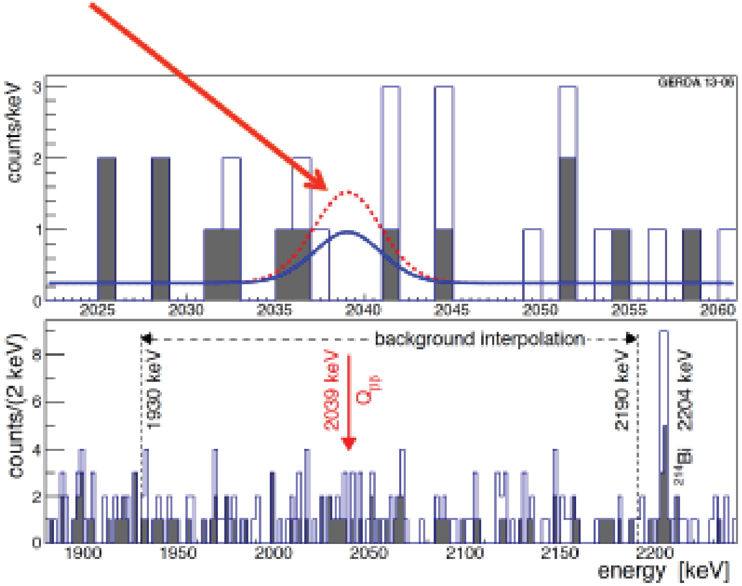
f_{76}: enrichment fraction
f_{av}: fraction of active detector volume
ε_{fep}: full energy peak efficieny for 0νββ
ε_{psd}: signal acceptance

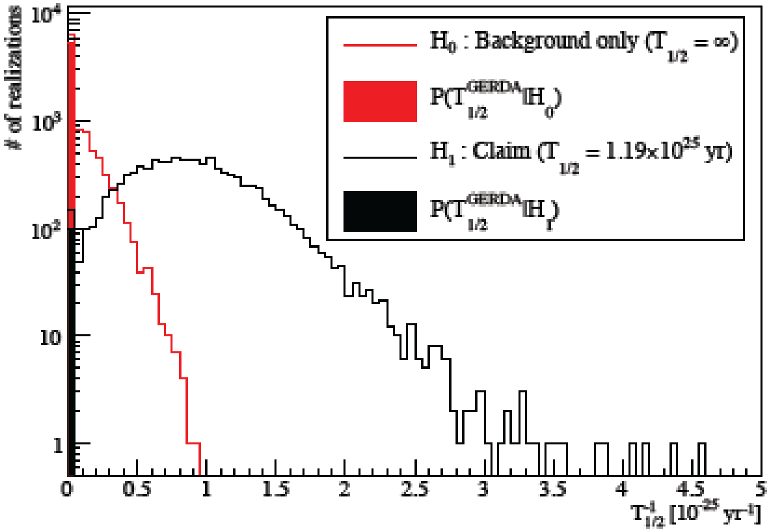
Data set	**Exposure (kg yr)**
Golden-coax	17.9
Silver-coax	1.3
BEGe	2.4

	$\langle f_{76} \rangle$	**$\langle f_{av} \rangle$**	**$\langle \varepsilon_{fep} \rangle$**	**$\langle \varepsilon_{psd} \rangle$**	**$\langle \varepsilon \rangle$**
Coax	0.86	0.87	0.92	0.90 +0.05/ -0.09	0.619 +0.044/-0.070
BEGe	0.88	0.92	0.90	0.92 ±0.02	0.663 ±0.022

Expectation for claimed $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ yr (Phys. Lett. B 586 198 (2004)):

5.9±1.4 signal over 2.0±0.3 bgd in ±2σ energy window to be compared with 3 cts (0 in ±1σ)





H1: claimed signal: 5.9±1.4

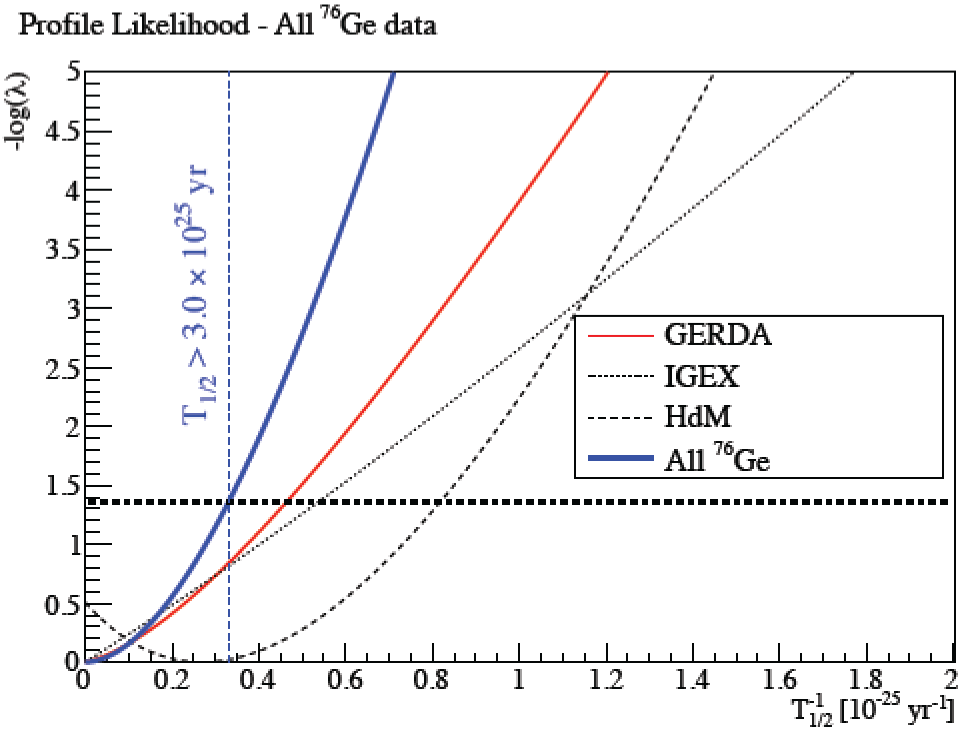
H0: background only

Bayes factor: P(H1)/P(H0)=0. 024

p-value from profile likelihood

P(N=0 = 0|H1) = 0. 01 (0.006 if 1/T unconstrained)

➔Claim refuted with high probability



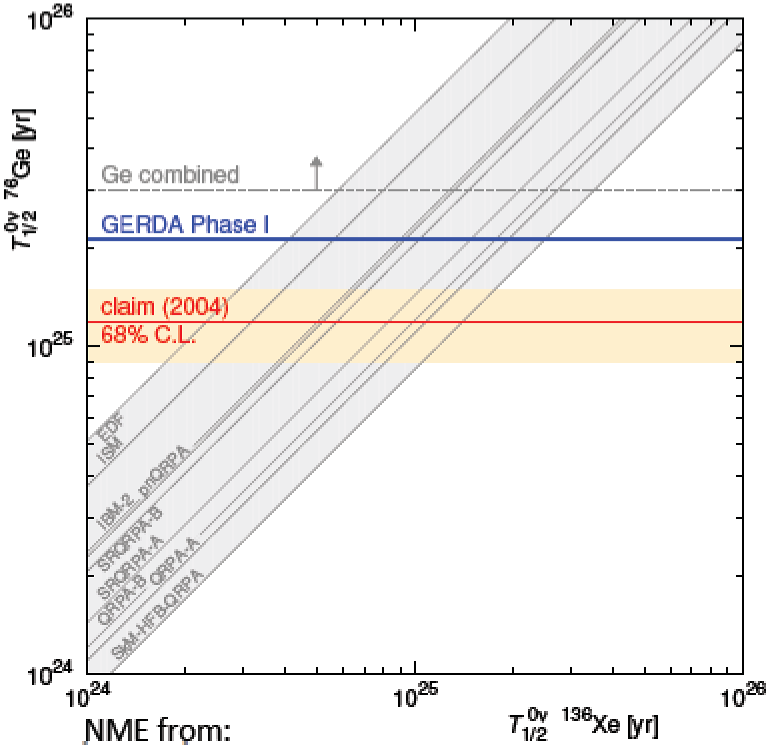
HdM: Eur. Phys. J. A 12, 147 (2001)
IGEX: Phys. Rev. D 65, 092007 (2002),
Phys. Rev. D 70 078302 (2004)

$$T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}\ \mathrm{yr} \quad (90\,\%\ \ \mathrm{C.L.})$$

Identical limits with
Frequentists & Bayesian analysis

Bayes factor: P(H1)/P(H0)=2×10^{-4} strongly disfavors claim

Comparison is independent of NME and of physical mechanism which generates 0νββ



NME from:

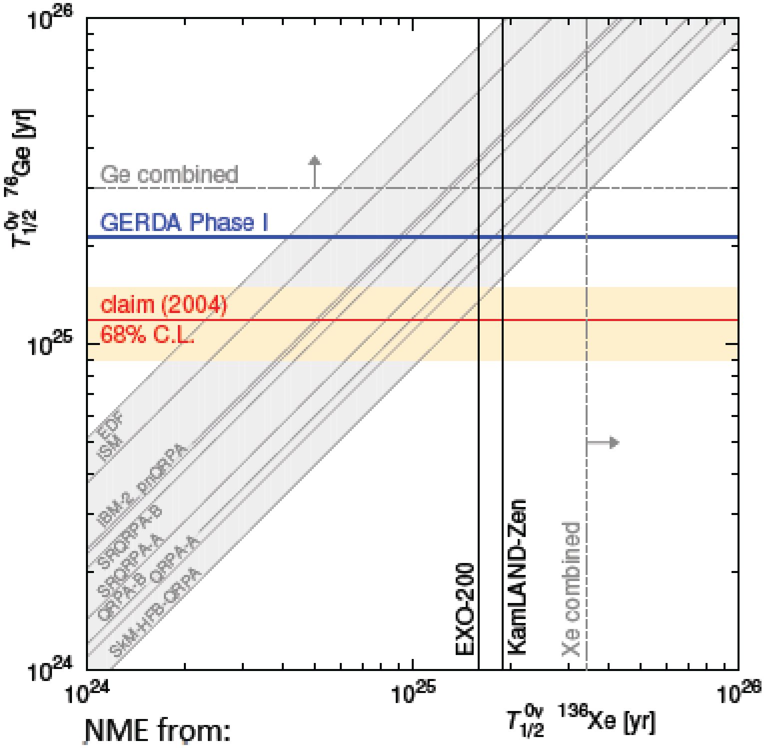
P. S. Bhupal Dev *et al.*, (2013), arXiv:1305.0056

Ge combined: $\langle m_{ee} \rangle < 0.2\text{-}0.4$

H1: signal with $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ yr

H0: background only

	Isotope	**$P(H_1)/P(H_0)$**	**Comment**
GERDA	^{76}Ge	0.024	Model independent
GERDA +HdM+IGEX	^{76}Ge	0.0002	Model independent



NME from:
P. S. Bhupal Dev *et al.*, (2013), arXiv:1305.0056

H1: signal with $T_{1/2}^{0\nu} = 1.19\times10^{25}$ yr
H0: background only

	Isotope	$P(H_1)/P(H_0)$	Comment
GERDA	^{76}Ge	0.024	Model independent
GERDA +HdM+IGEX	^{76}Ge	0.0002	Model independent
KamLAND-Zen*	^{136}Xe	0.40	Model dependent: NME, leading term
EXO-200*	^{136}Xe	0.23	Model dependent: NME, leading term
GERDA+KLZ* +EXO*	^{76}Ge + ^{136}Xe	0.002	Model dependent: NME, leading term

*:with conservative NME ratio $M_{0\nu}(^{136}\mathrm{Xe})/M_{0\nu}(^{76}\mathrm{Ge}) \approx 0.4$ from:

F. Simkovic, V. Rodin, A. Faessler, and P. Vogel, Phys. Rev. C. **87**, 045501 (2013).
M. T. Mustonen and J. Engel, (2013), arXiv:1301.6997 [nucl-th].
P. S. Bhupal Dev *et al.*, (2013), arXiv:1305.0056 [hep-ph].

- **GERDA Phase I design goals reached:**
  - Background index after PSD: 0.01 cts / (keV kg yr)
  - Exposure 21.6 kg yr

- **No 0νββ-signal observed at $Q_{\beta\beta}$ = 2039 keV; best fit: $N^{0\nu}$=0**
  - Background-only hypothesis H_0 strongly favored
  - Claim strongly disfavored (independent of NME and of leading term)

- **Bayes Factor / p-value:**

  GERDA: 10^{-2}
  GERDA+IGEX+HdM: 10^{-4}

- **Limit on half-life:**

  GERDA: $T_{1/2}^{0\nu} > 2.1\times10^{25}$ yr (90% C.L.)
  GERDA+IGEX+HdM: $T_{1/2}^{0\nu} > 3.0\times10^{25}$ yr (90% C.L.) ($<m_{ee}> < 0.2$-0.4)

- Results reached after only 21.6 kg yr exposure because of **unprecedented low background:** bgd counts in ±2σ after analysis cuts:

  0.01 cts /(mol yr) (cf. EXO: 0.07, KL: 0.67)

Majoron models

Number of χ^0

Leptonic charge of χ^0

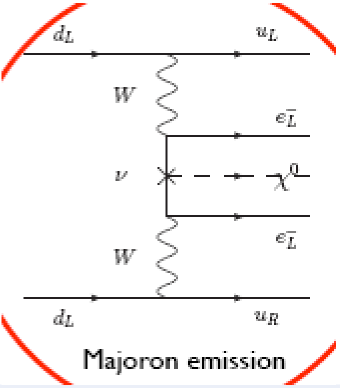
Spectral index

Model	Mode	Goldstone boson	L	n	Matrix element
IB	χ	no	0	1	$M_F - M_{GT}$
IC	χ	yes	0	1	$M_F - M_{GT}$
ID	$\chi\chi$	no	0	3	$M_{Fw^2} - M_{GTw^2}$
IE	$\chi\chi$	yes	0	3	$M_{Fw^2} - M_{GTw^2}$
IF (bulk)	χ	bulk field	0	2	-
IIB	χ	no	-2	1	$M_F - M_{GT}$
IIC	χ	yes	-2	3	M_{CR}
IID	$\chi\chi$	no	-1	3	$M_{Fw^2} - M_{GTw^2}$
IIE	$\chi\chi$	yes	-1	7	$M_{Fw^2} - M_{GTw^2}$
IIF	χ	gauge boson	-2	3	M_{CR}

Lepton number violating

Lepton number conserving

χ0 predicted by several theories (extensions of SM, SUSY, ...)
Can be massless Goldstone boson, massless or light boson, wi
without leptonic charge, ….
Emission of 2χ0 possible



Majoron emission

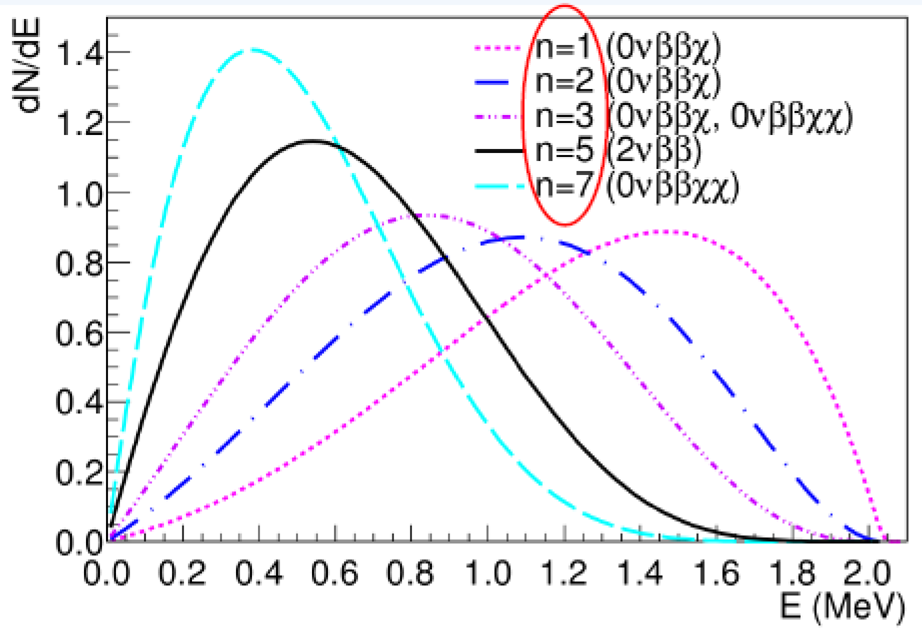
Energy spectrum of Majoron decay mode depends on **spectral index n**

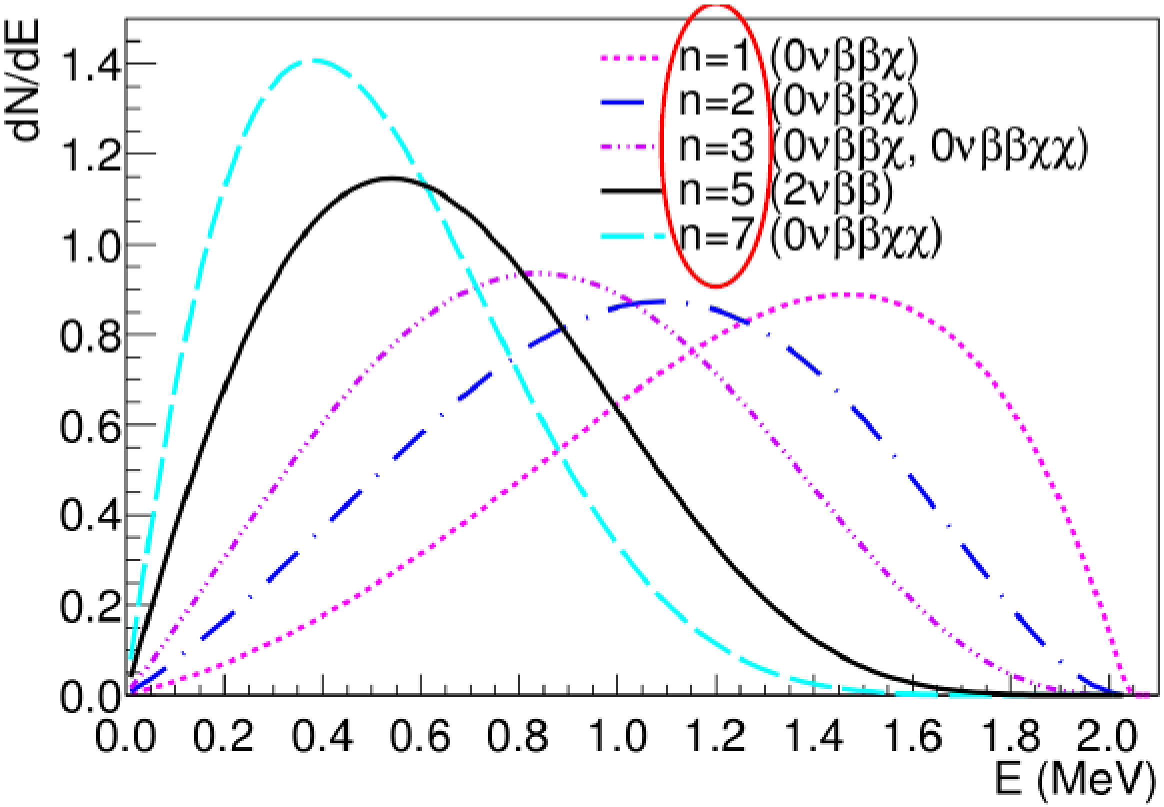
$$G \sim (Q_{\beta\beta} - E)^n$$

Phase space

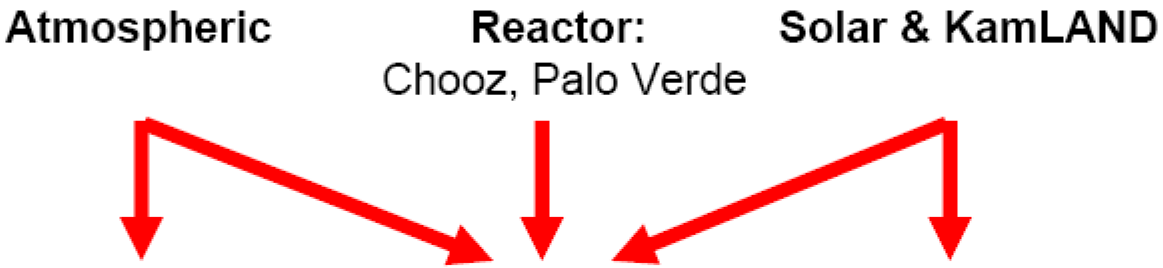
Decay energy

Energy of the two e⁻




dN/dE
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
E (MeV)
n=1 (0νββχ)
n=2 (0νββχ)
n=3 (0νββχ, 0νββχχ)
n=5 (2νββ)
n=7 (0νββχχ)

Recent years: 3-flavor analysis
small θ_{13}, favorable mass splitting & **high precision**



Atmospheric

Reactor:
Chooz, Palo Verde

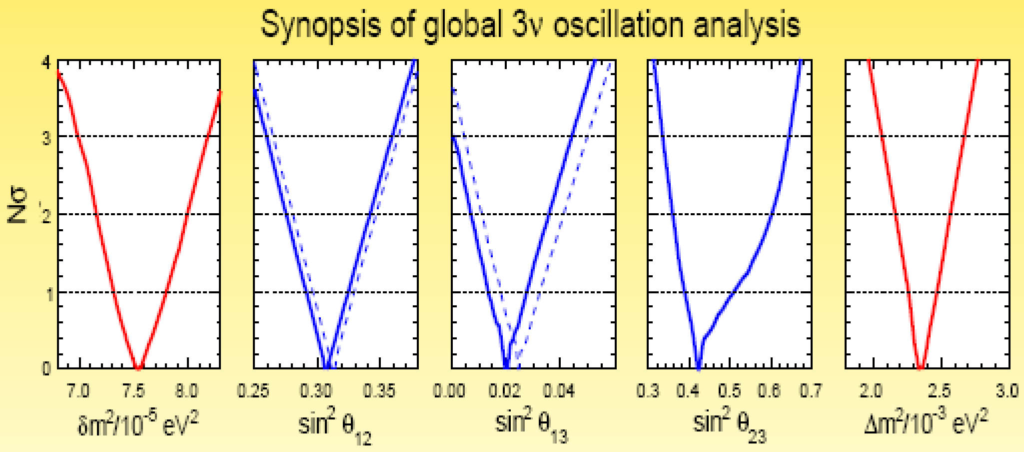
Solar & KamLAND

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

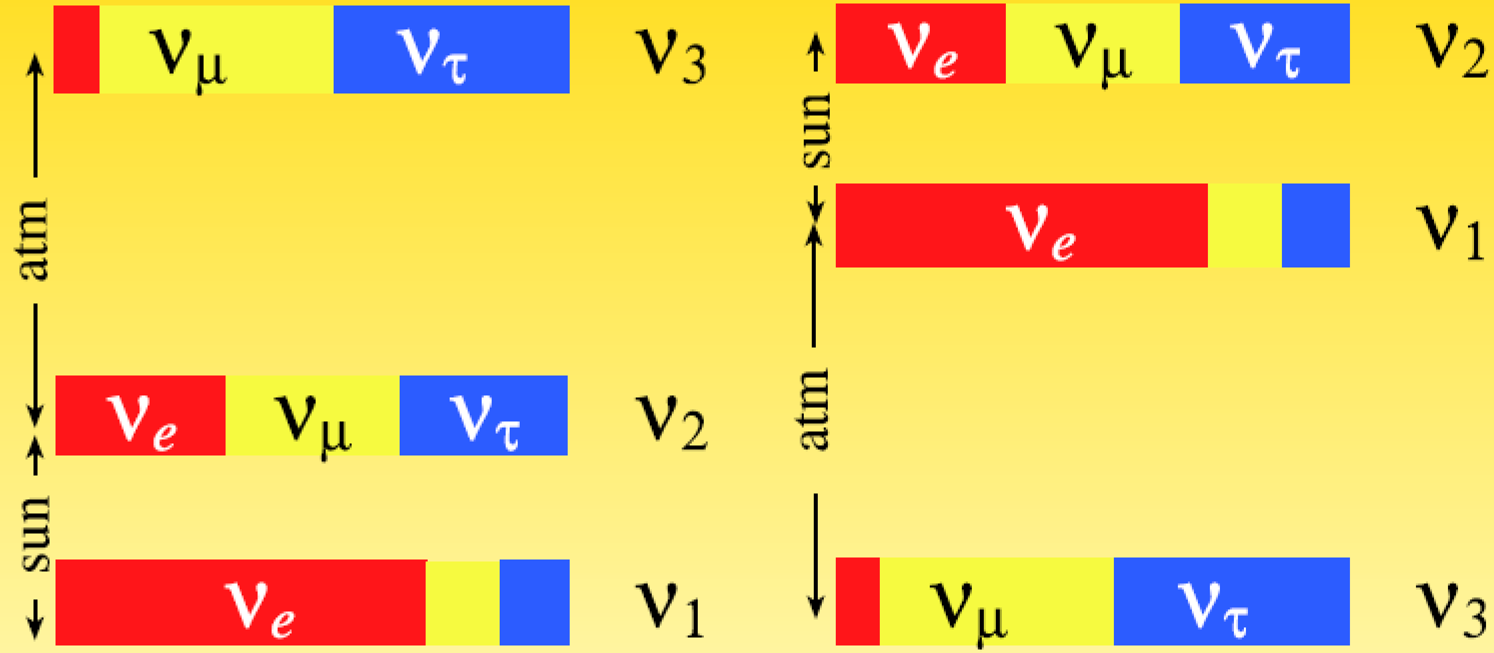
Majorana phases
not observable in
oscillations but
important for 0νββ

Insert (known) Neutrino Data

$$U = \begin{pmatrix} c_{12}\, c_{13} & s_{12}\, c_{13}\, e^{i\alpha} & s_{13}\, e^{i\beta} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13}\, e^{i\delta} & \left(c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13}\, e^{i\delta}\right) e^{i\alpha} & s_{23}\, c_{13}\, e^{i(\beta+\delta)} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13}\, e^{i\delta} & -\left(c_{12}\, s_{23} + s_{12}\, c_{23}\, s_{13}\, e^{i\delta}\right) e^{i\alpha} & c_{23}\, c_{13}\, e^{i(\beta+\delta)} \end{pmatrix}$$



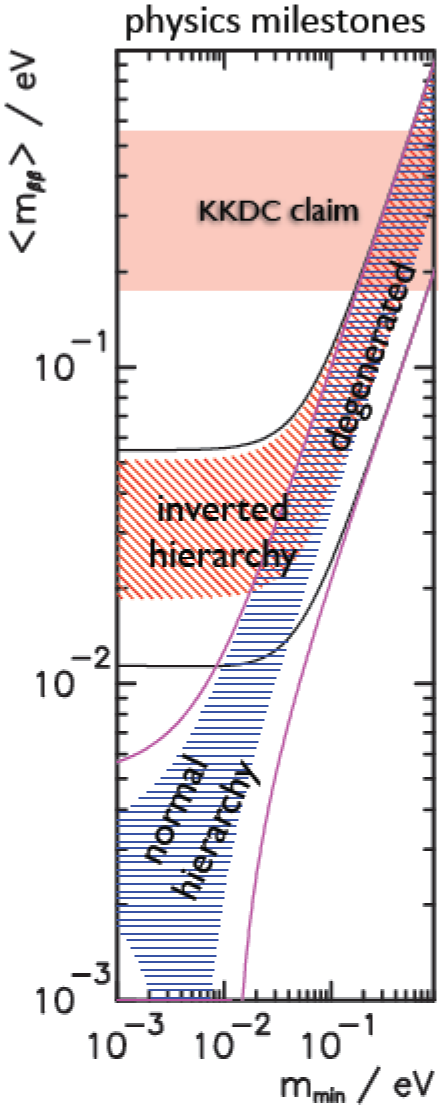
Insert (known) Neutrino Data

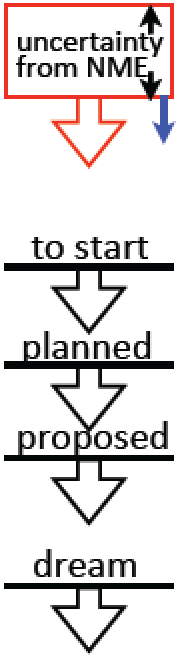


normal ordering

inverted ordering

Future Prospects continued





KamLAND-Zen initial 112 days

$\langle m_{\beta\beta}\rangle$ <0.26~0.54 eV @90% C.L.

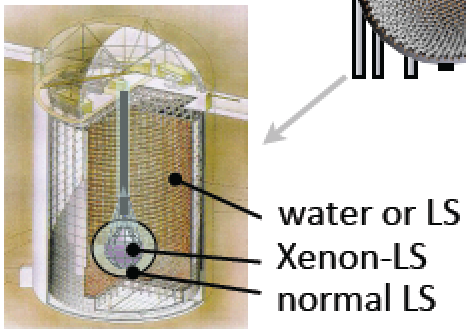
KamLAND-Zen ~100 days more data

KamLAND-Zen after purification
aiming at 100 times BG reduction

KamLAND-Zen 700+kg with cleaner mini-balloon

KamLAND2-Zen with brighter LS and light collector
σ_E(2.6MeV)~2.5%

Super-KamLAND-Zen



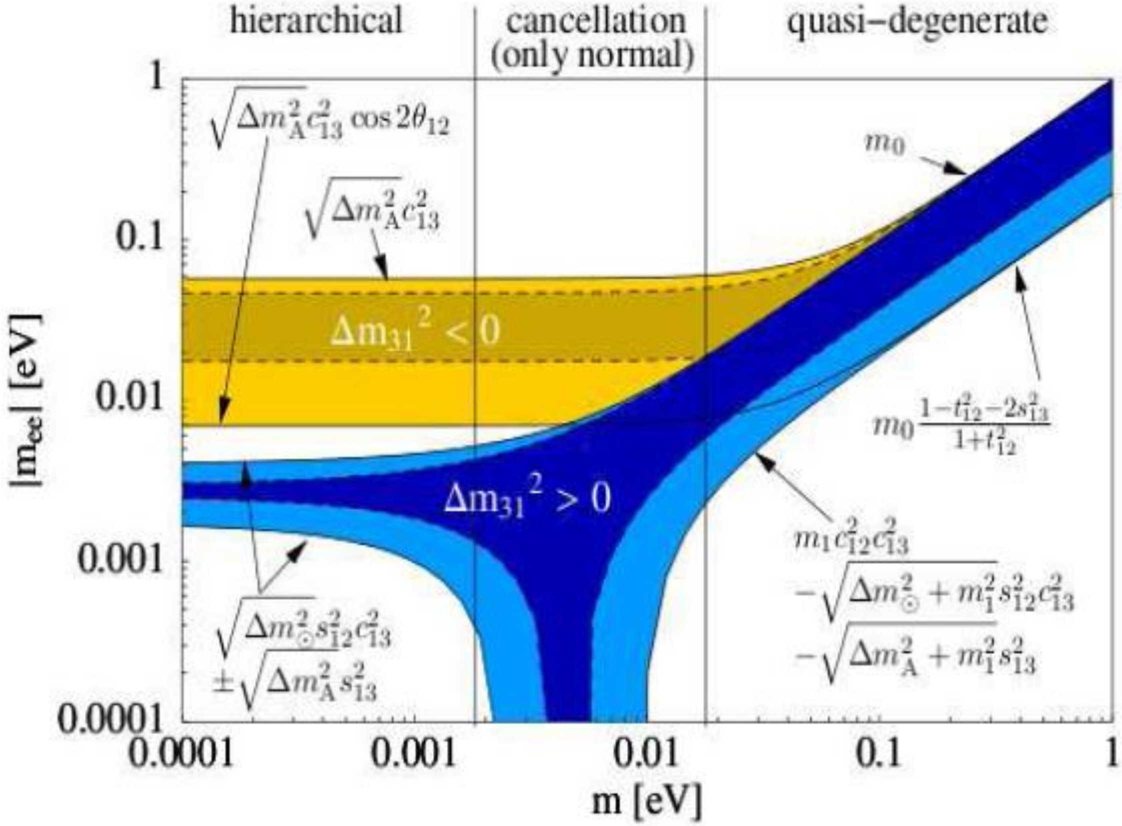
also precise anti-neutrino physics

various possibilities
as a low radioactive
background environment

Five neutrino parameters are now measured in the solar, atmospheric and reactor neutrino experiments

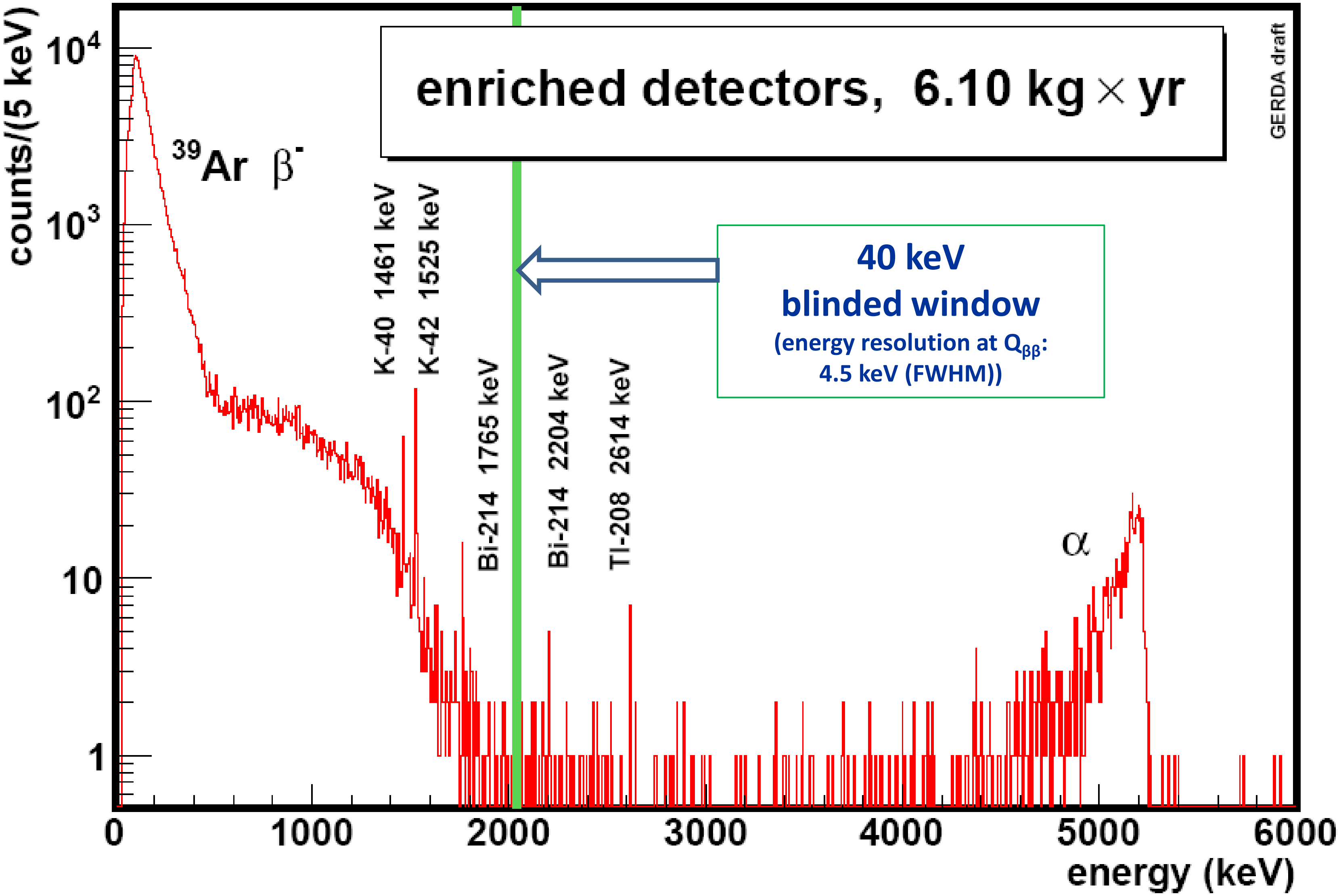
$$\Delta m^2_{21} = 7.59^{+0.20}_{-0.18} \times 10^{-5}\,\mathrm{eV}^2\,, \qquad \Delta m^2_{31} = 2.45^{+0.09}_{-0.09} \times 10^{-3}\,\mathrm{eV}^2\,(NH)\,,$$

$$\sin^2\theta_{12} = 0.312^{+0.017}_{-0.015}\,, \qquad \sin^2\theta_{23} = 0.51^{+0.06}_{-0.06}\,(NH)\,, \quad \sin^2\theta_{13} = 0.023^{+0.004}_{-0.004}\,,$$



Which mass ordering with which life-time?

	Σ	m_β	$\lvert m_{ee} \rvert$
NH	$\sqrt{\Delta m^2_{\rm A}}$	$\sqrt{\Delta m^2_\odot + \lvert U_{e3}\rvert^2 \Delta m^2_{\rm A}}$	$\left\lvert\sqrt{\Delta m^2_\odot} + \lvert U_{e3}\rvert^2 \sqrt{\Delta m^2_{\rm A}} e^{2i(\alpha-\beta)}\right\rvert$
	$\simeq 0.05$ eV	$\simeq 0.01$ eV	~ 0.003 eV $\Rightarrow T^{0\nu}_{1/2} \gtrsim 10^{28-29}$ yrs
IH	$2\sqrt{\Delta m^2_{\rm A}}$	$\sqrt{\Delta m^2_{\rm A}}$	$\sqrt{\Delta m^2_{\rm A}}\sqrt{1 - \sin^2 2\theta_{12} \sin^2 \alpha}$
	$\simeq 0.1$ eV	$\simeq 0.05$ eV	~ 0.03 eV $\Rightarrow T^{0\nu}_{1/2} \gtrsim 10^{26-27}$ yrs
QD	$3m_0$	m_0	$m_0\sqrt{1 - \sin^2 2\theta_{12} \sin^2 \alpha}$
			$\gtrsim 0.1$ eV $\Rightarrow T^{0\nu}_{1/2} \gtrsim 10^{25-26}$ yrs



enriched detectors, 6.10 kg × yr

40 keV
blinded window
(energy resolution at $Q_{\beta\beta}$:
4.5 keV (FWHM))

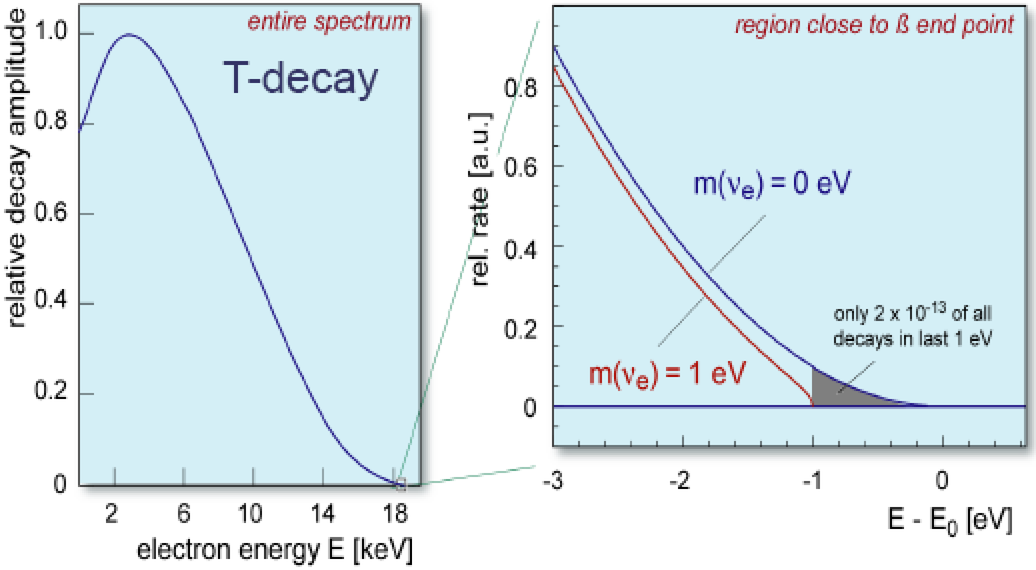
Kinematic determination of $m(\nu_e)$

$$\frac{d\Gamma}{dE} = C\, p(E+m_e)(E_0-E)\sqrt{(E_o-E)^2-m_{\nu_e}^2}\, F(Z+1,E)\,\Theta(E_0-E-m_{\nu_e})\,S(E)$$

$$C = \frac{G_F^2}{2\pi^3}\cos^2\theta_C |M|^2$$

$$m_{\nu_e} = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

(modified by final states, recoil corrections, radiative corrections, ...)



only 2 x 10^{-13} of all decays in last 1 eV

Suitable β emitters:

Tritium

- E_0 = 18.6 keV, $T_{1/2}$ = 12.3 a
- S(E) = 1 (super-allowed)

Rhenium

- E_0 = 2.47 keV, $T_{1/2}$ = 43.2 Gy

alternative approach:

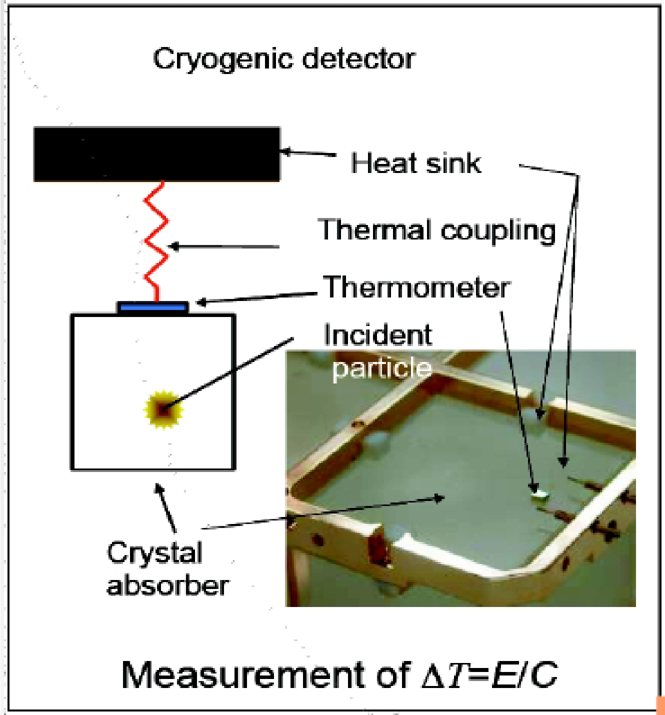
Holmium (EC decay)

- Q_{EC} ≈ 2.5 keV, $T_{1/2}$ = 4570 y

Cuoricino

Cuoricino
2003–2008
11 kg ^{130}Te

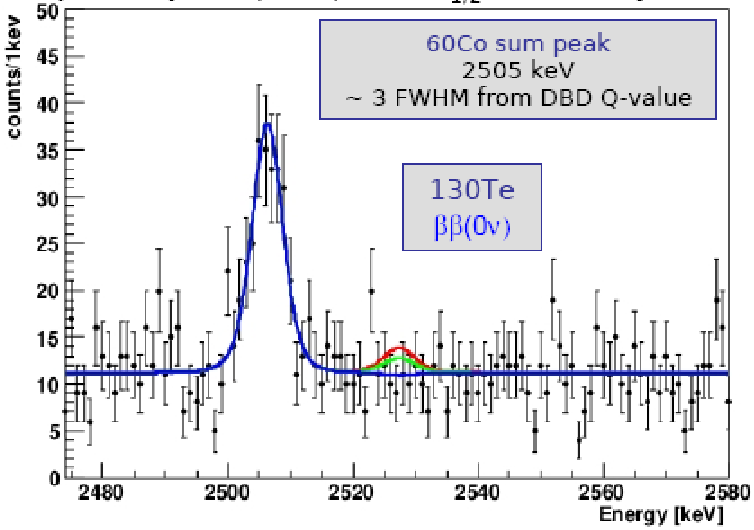
bolometer TeO_2 crystals @ 10 mK



Measurement of $\Delta T = E/C$

- 41 kg TeO_2, active mass ~ 11 kg,
- avg FWHM = 7.5 keV at 2527 keV
- stopped June 2008
- total statistics 19.75 kg y

Astropart. Phys 34 (2011) 822 $T^{0\nu}_{1/2} > 2.8 \cdot 10^{24}$ y (90% CL)

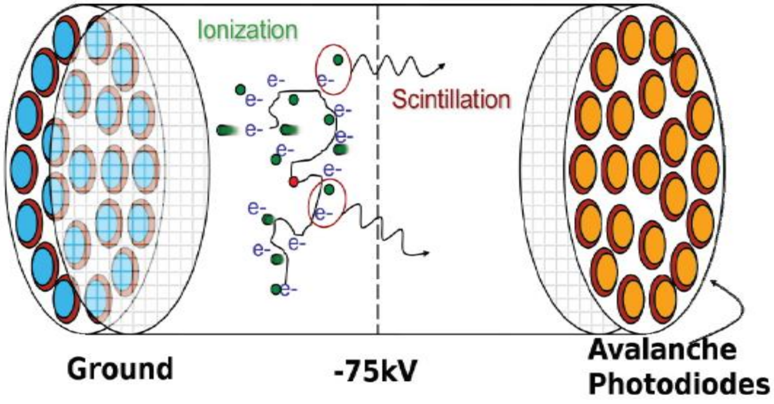


$<m_{ee}>$ < 0.3-0.7 eV
not sensitive enough to check Heidelberg-Moscow claim

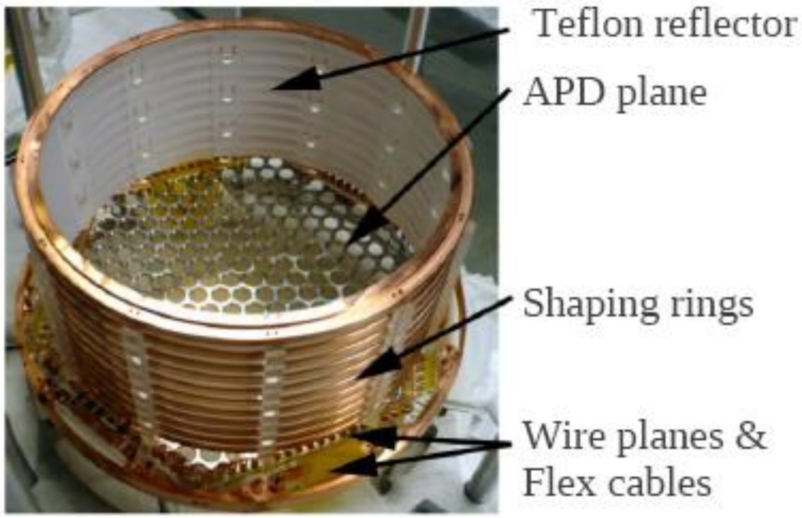
EXO 200

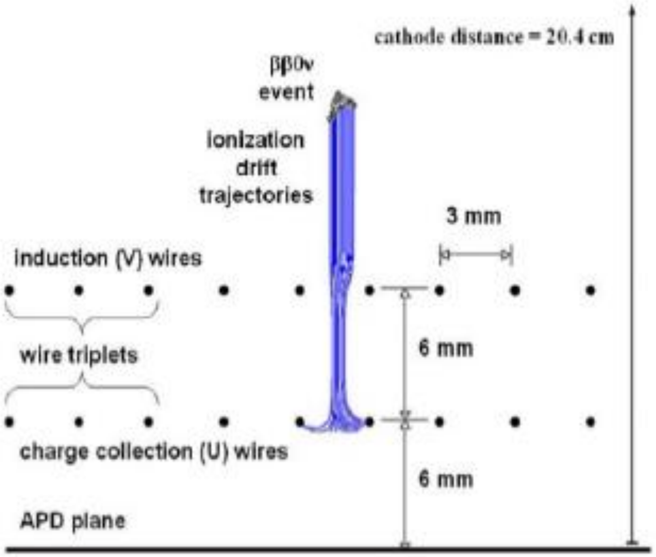
Probing the **$0\nu\beta\beta$** of ^{136}Xe, Q = 2458 keV

~100 kg of ^{136}Xe



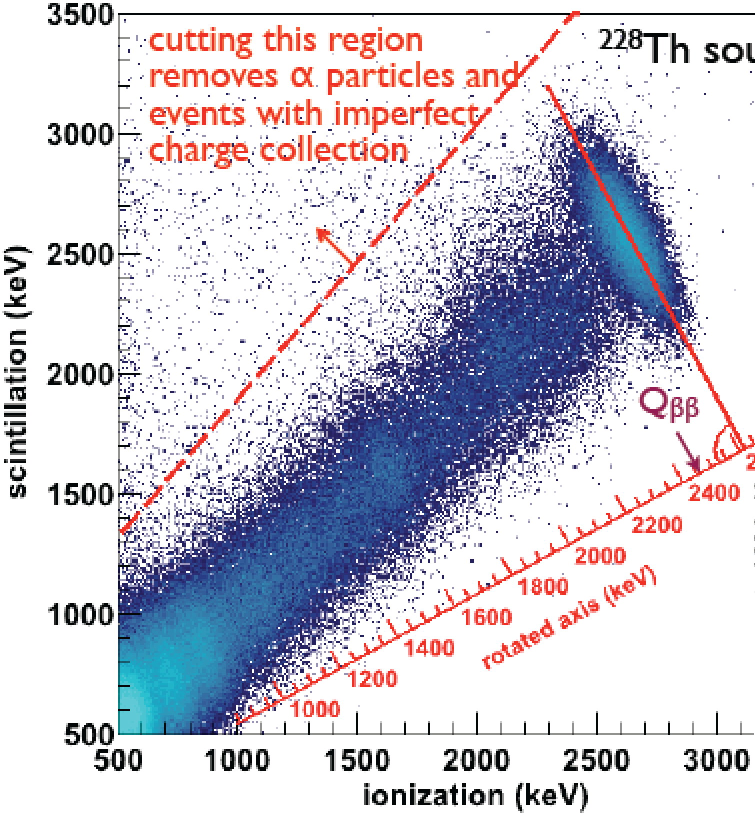
- Using ~110 kg of 80.6 % enriched Xe in the isotope 136
- Two TPC modules separated by a common cathode.
- LAAPD arrays for light measurement.
- Two planes of 38 collection wire triplets (U-wires).
- Two planes of 38 induction wire triplets (V-wires).
- Wire planes crossing at 60° for stereoscopic informations.





M. Auger et al. JINST 7 (2012) P05010.

Combining Ionization and Scintillation

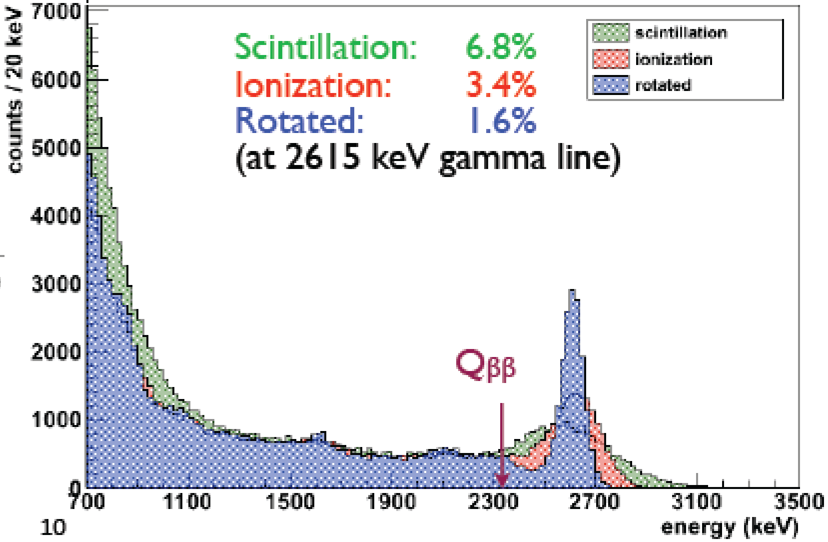


cutting this region removes α particles and events with imperfect charge collection

Properties of xenon cause increased scintillation to be associated with decreased ionization (and vice-versa)

E. Conti et al. Phys. Rev. B 68 (2003) 054201

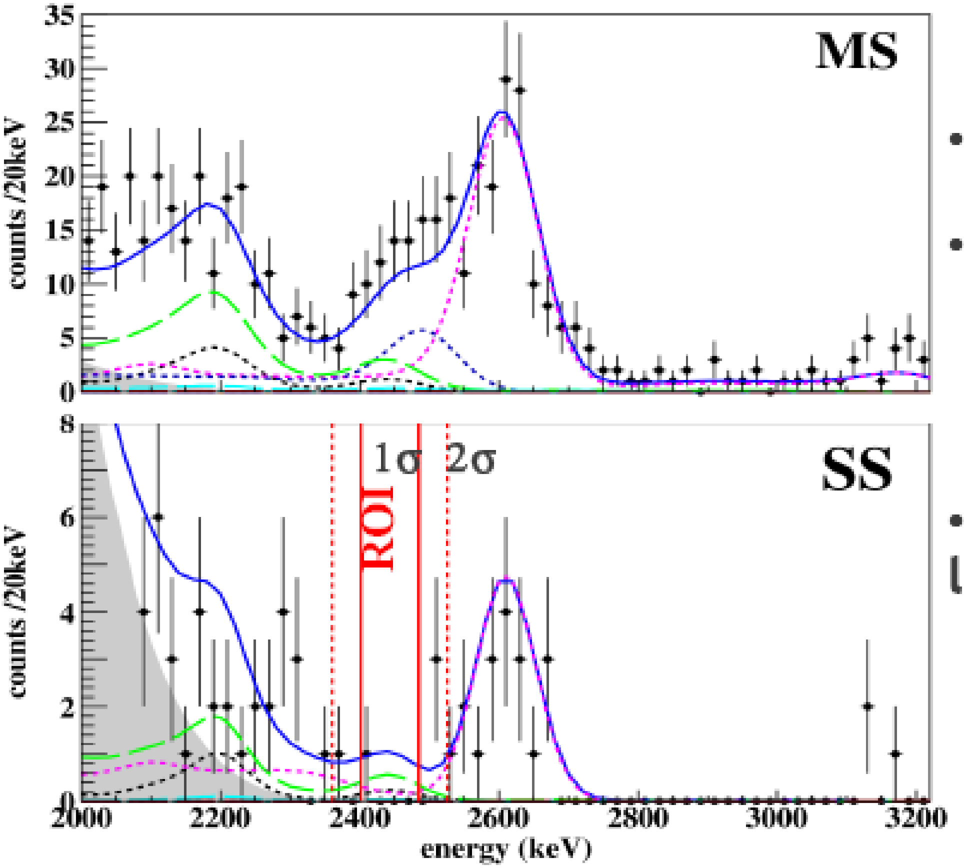
Use projection onto a rotated axis to determine event energy



Scintillation: 6.8%
Ionization: 3.4%
Rotated: 1.6%
(at 2615 keV gamma line)

Rotation angle chosen to optimize energy resolution at 2615 keV

Zoomed around 0νββ region of interest (ROI)



Exposure: 35 kg yr (120.7 days)

- No signal observed
- Background in ROI:

$(1.5 \pm 0.1)\cdot 10^{-3}\,\mathrm{kg}^{-1}\mathrm{yr}^{-1}\mathrm{keV}^{-1}$ in ± 1σ ROI

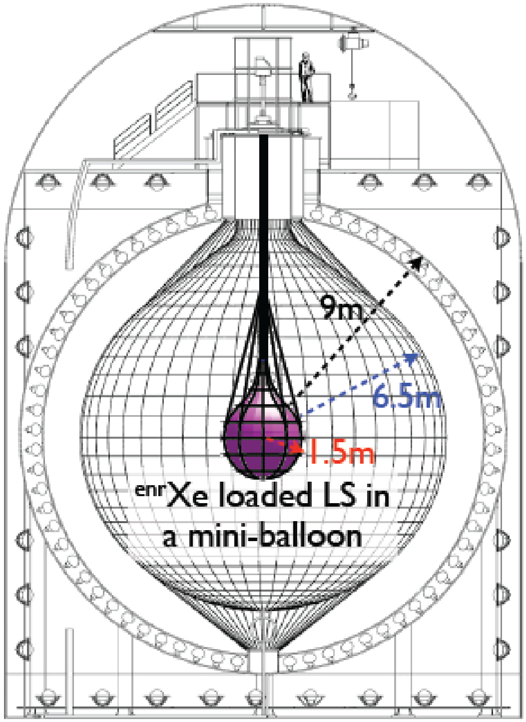
- **Profile likelihood study to extract limits for $T_{1/2}^{0\nu\beta\beta}$**

$T_{1/2}^{0\nu\beta\beta}$ (^{136}Xe) > $1.6\cdot 10^{25}$ yr (90% C.L.) [arXiv:1205.5608]

~300 kg of ^{136}Xe

KamLAND-Zen

Zero Neutrino
double beta decay search



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tolerable thanks to slow 2ν2β and low BG
× no β/γ discrimination so far
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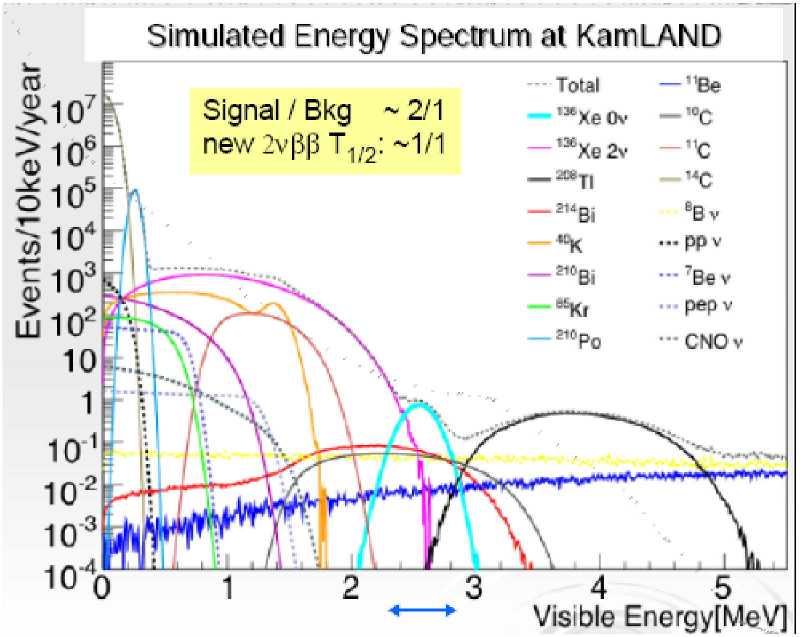
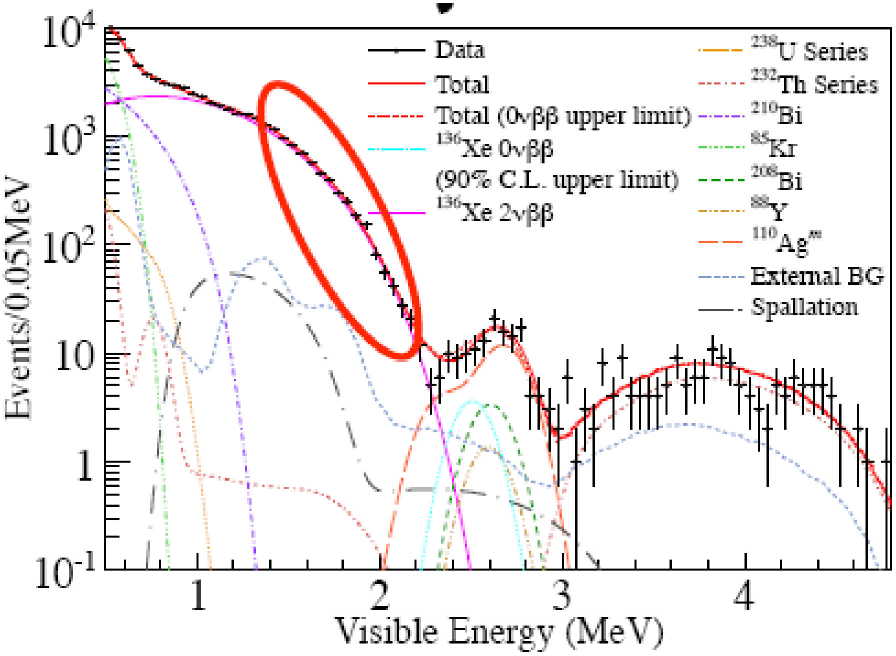
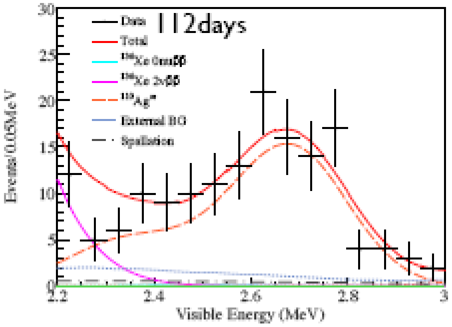
× limited LS composition (for density matching)

MC simulation



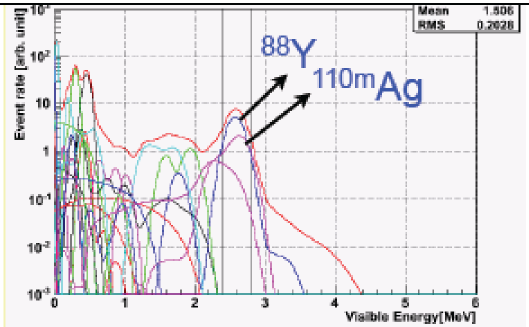
Real experiment



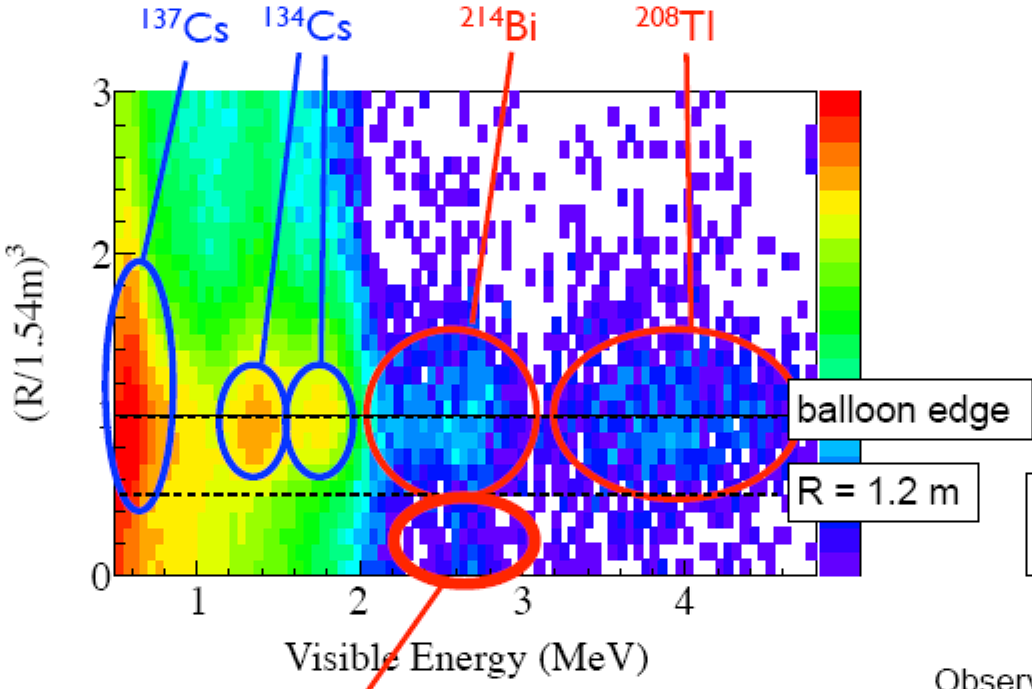


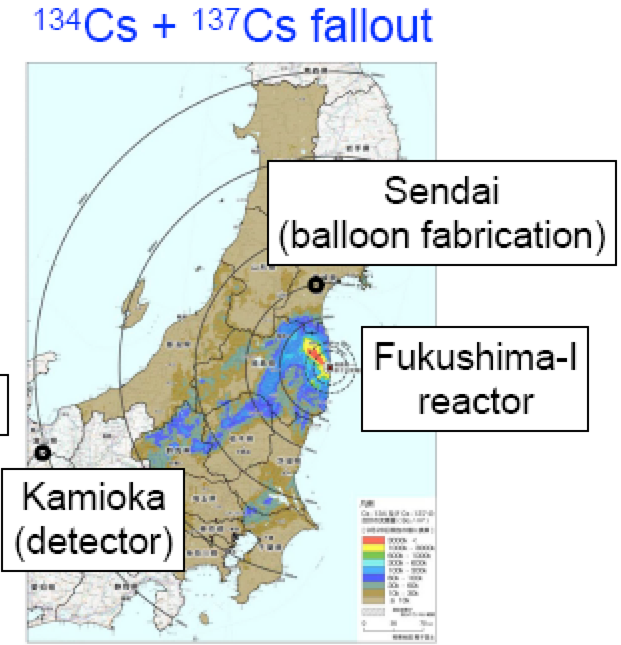
^{110m}Ag fits well

100 days on surface, 300 days in the mine



Radioactive Impurities





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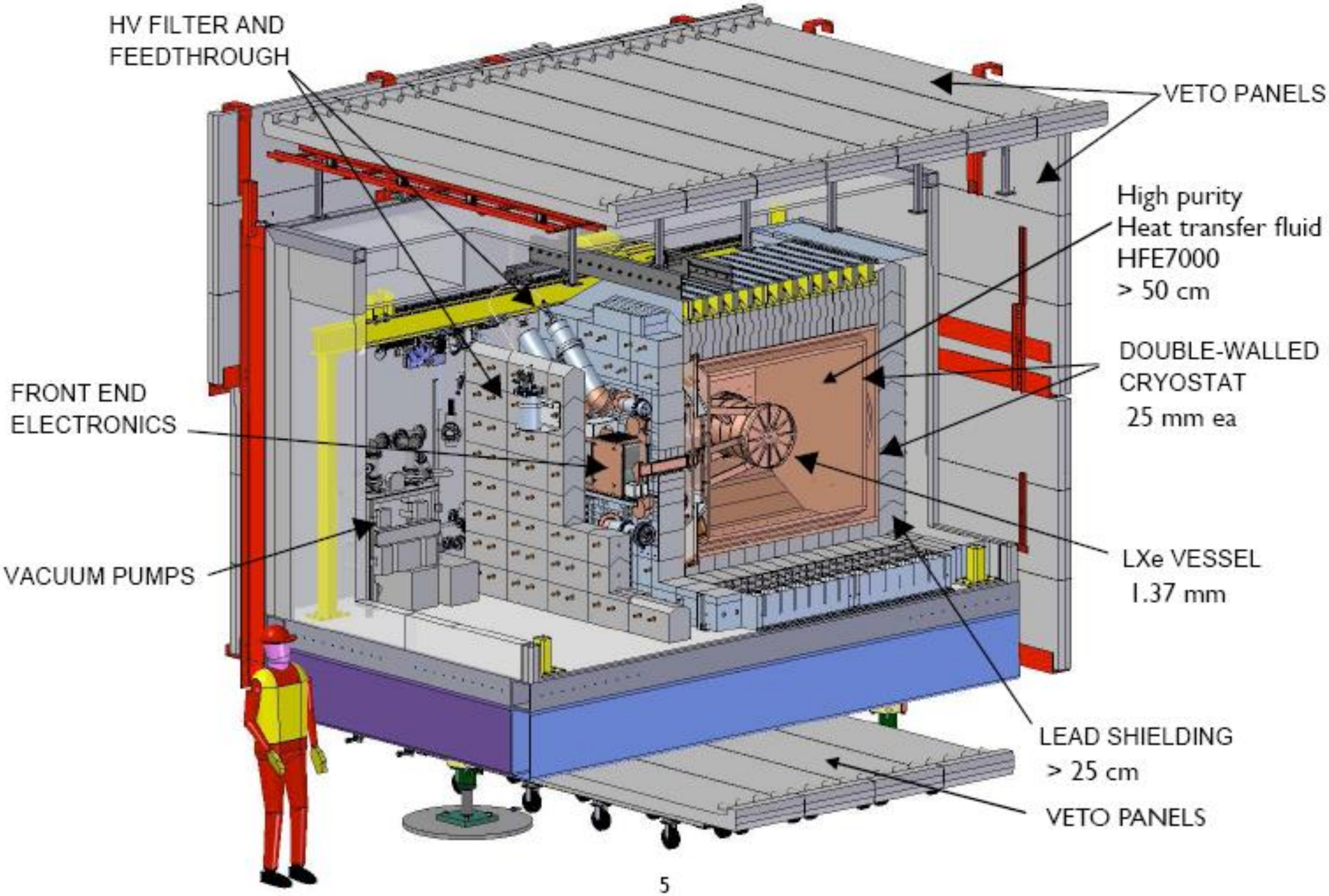
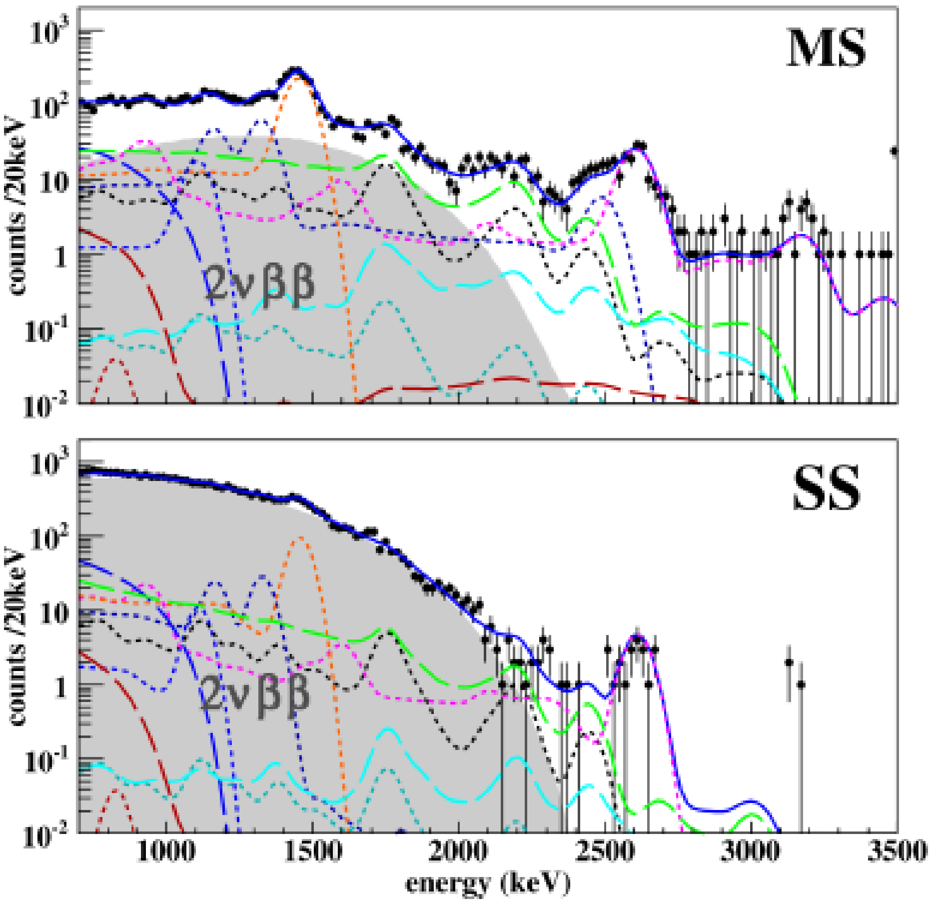
What is the peak around 2.6MeV?

The EXO-200 Detector



Maximum likelihood fit

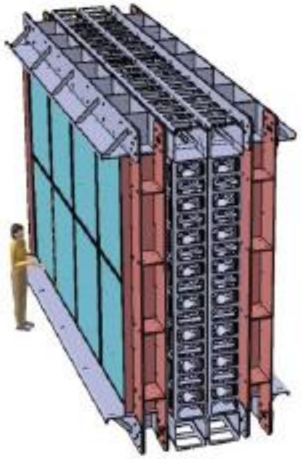


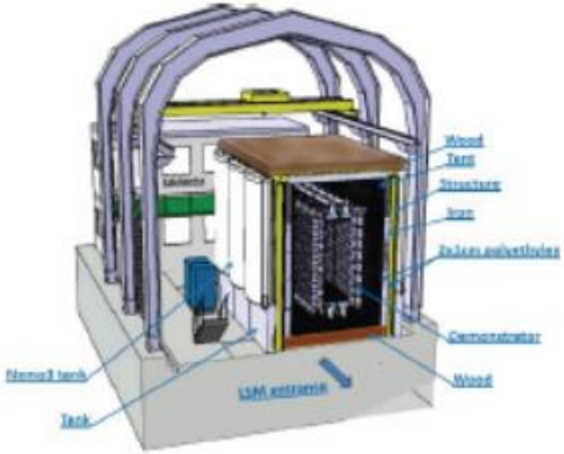
- Trigger fully efficient above 700 keV
- Low background run livetime:
  120.7 days
- Active mass:
  98.5 kg LXe (79.4 kg ^{136}LXe)
- Exposure:
  32.5 kg·yr
- Total dead time (vetos): 8.6%
- Various background PDFs fitted along with 2νββ and 0νββ PDFs

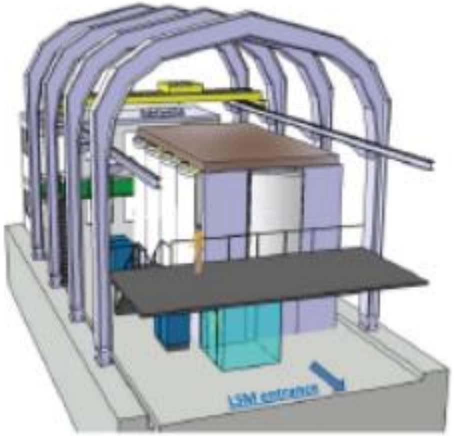
$T_{1/2}^{2\nu\beta\beta}$ (^{136}Xe) = (2.23 ± 0.017 stat ± 0.22 sys)·10^{21} yr

(In agreement with previously reported value by EXO-200 and KamLAND-ZEN collaborations)

SuperNEMO demonstrator







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KamLAND-Zen

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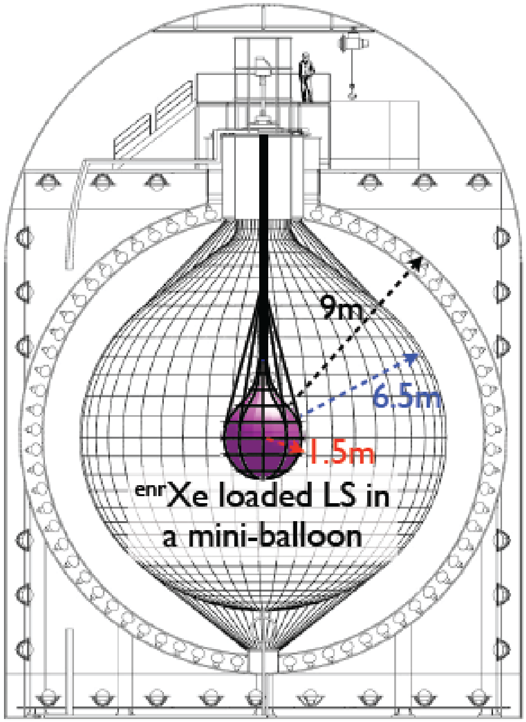

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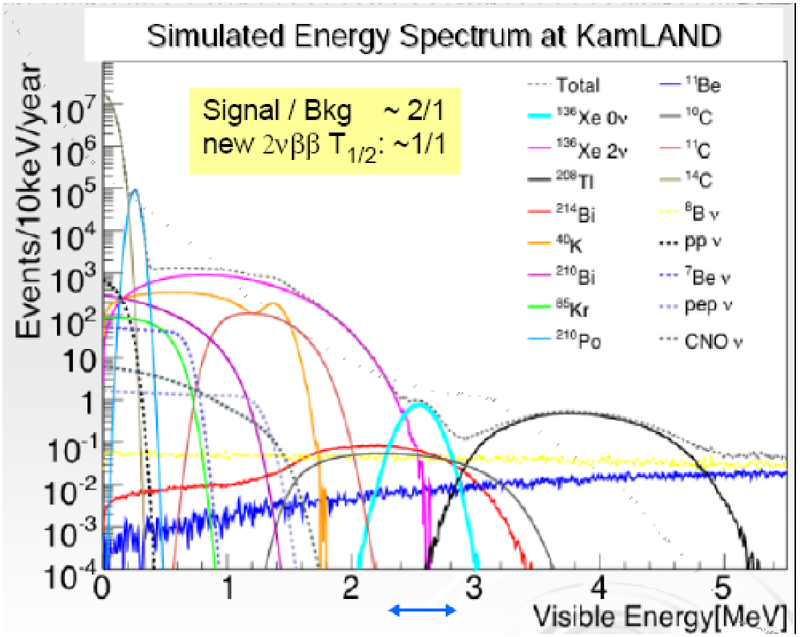
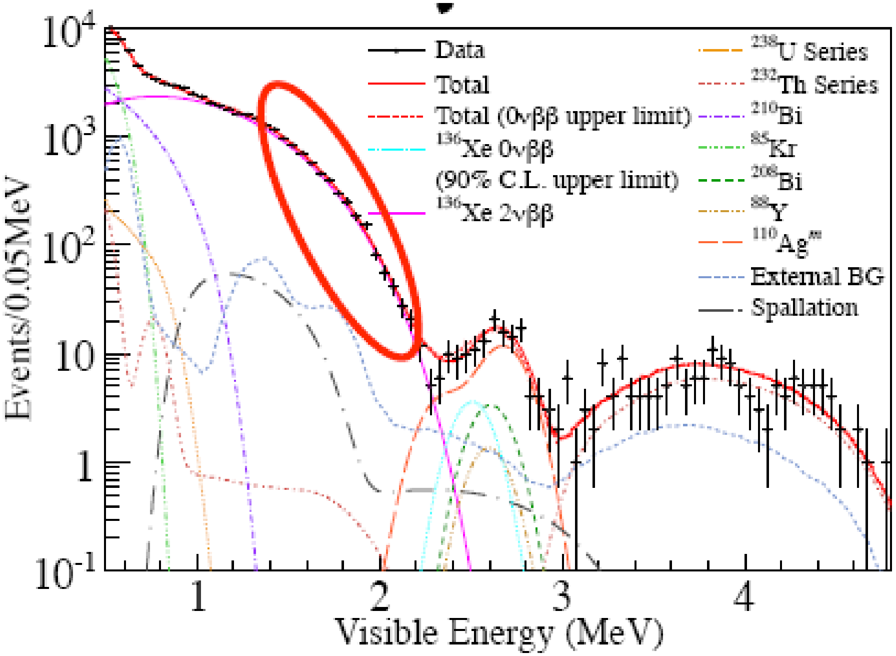
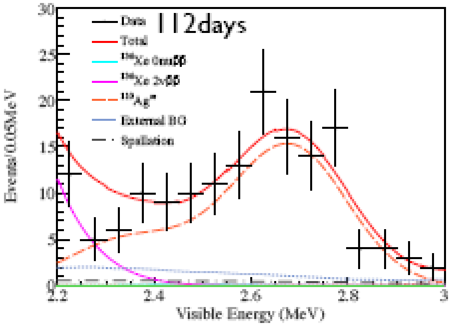


Signal / Bkg ~ 2/1
new 2νββ $T_{1/2}$: ~1/1





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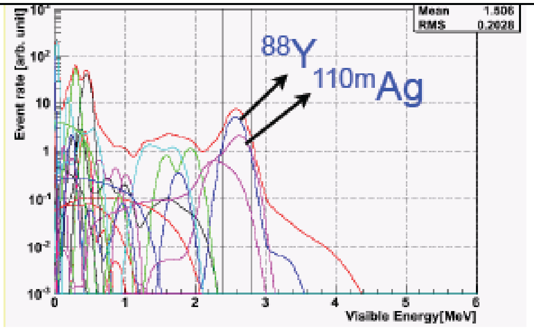

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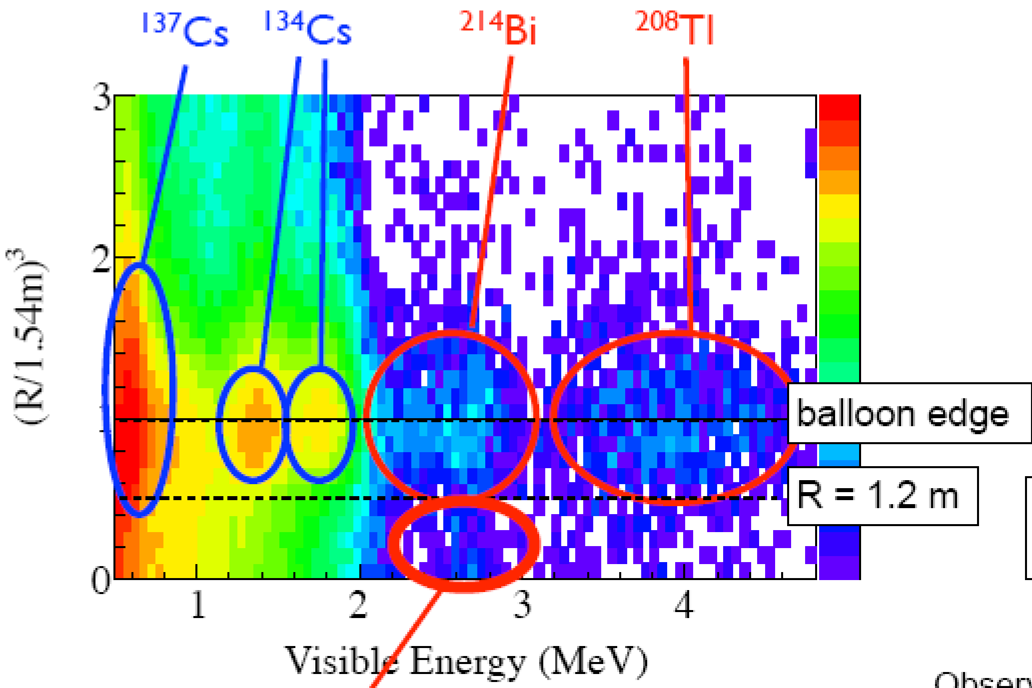

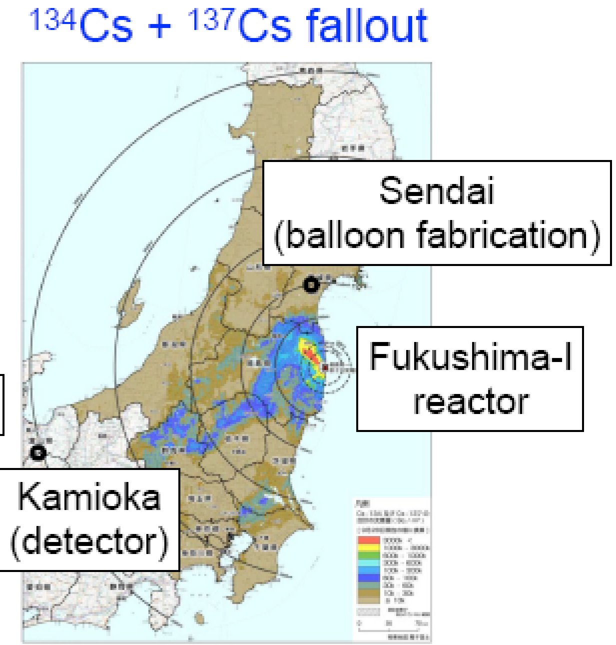

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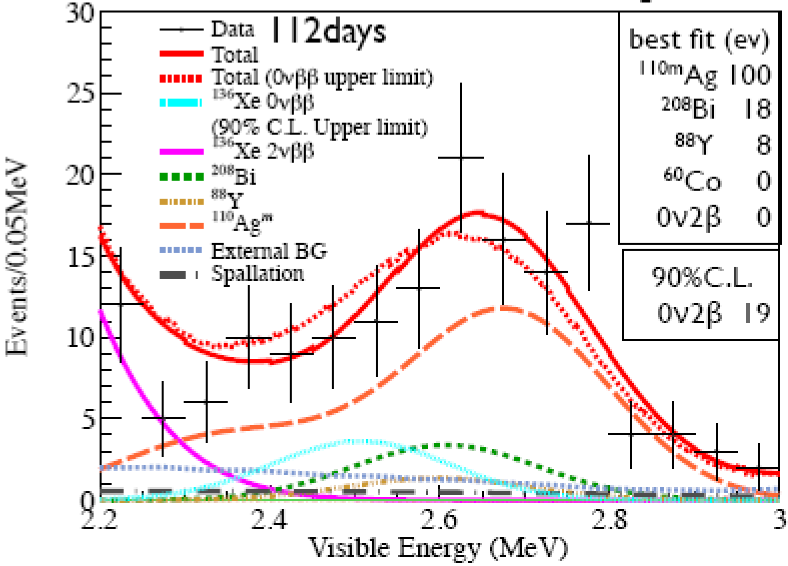
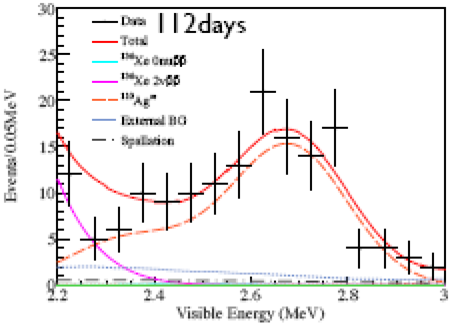
What is the peak around 2.6MeV?

Limit on the 0ν2β half life



simultaneous fit and 90% CL upper limit for 0ν2β



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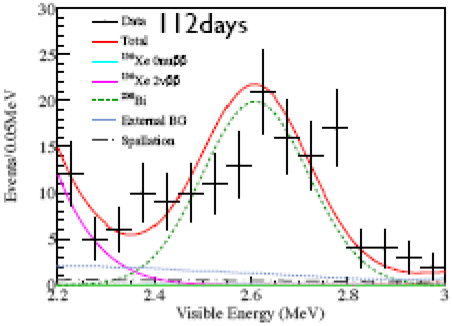
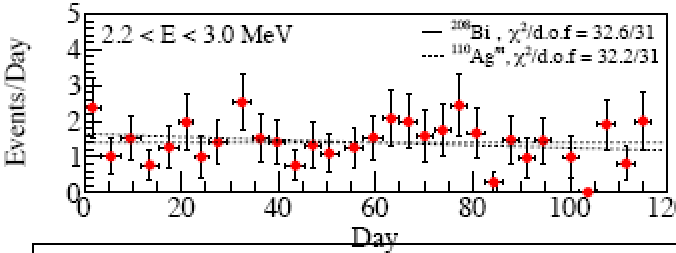


^{208}Bi doesn't fit well



^{88}Y 36.0

stable in time, but no strong discrimination yet

(χ^2 at 2.2~3.0MeV)

	χ^2 112days	
simul. fit	11.6	
0ν+^{110m}Ag	13.1	
0ν+^{208}Bi	22.7	△
0ν+^{88}Y	22.2	△
0ν+^{60}Co	82.9	✕
0ν only	85.0	✕

BG is likely to be ^{110m}Ag

$T^{0\nu}_{1/2} > 5.7\times10^{24}$ years at 90% C.L. (78days)

factor 5 improvement from DAMA

$T^{0\nu}_{1/2} > 6.2\times10^{24}$ years (KL-Zen 112days)

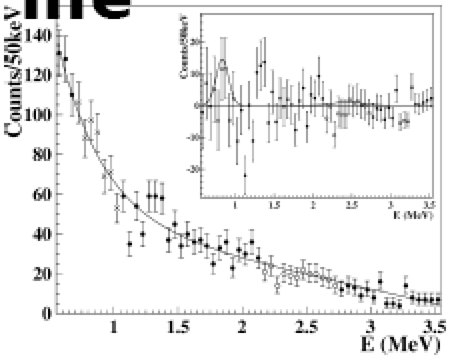
(ref. current best is 16×10^{24} years from EXO-200)

⇩

(R)QRPA (CCM SRC)
Phys.Rev.C79,055501(2009)

$\langle m_{\beta\beta}\rangle$ <0.26~0.54 eV @90% C.L.

Measurement of the 2ν2β half life



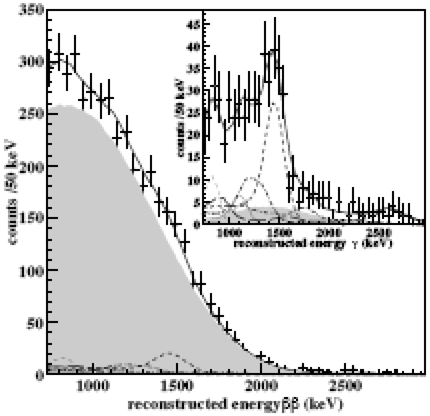
DAMA (2002)

Liquid Xe scintillator

$T^{2\nu}_{1/2} > 1.0 \times 10^{22}$ years at 90% CL

Phys.Lett.B546,23(2002)

factor 5 contradiction



EXO-200 (2011)

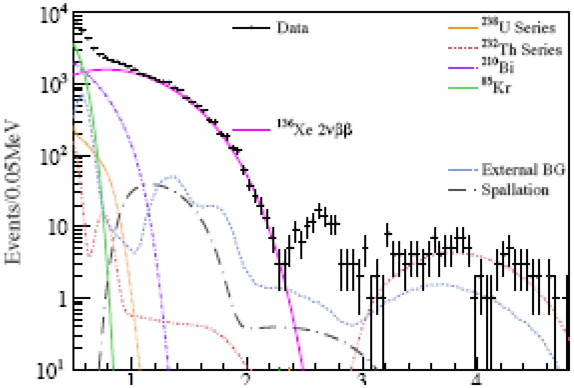
Liquid Xe TPC + scintillator

$T^{2\nu}_{1/2} = 2.11 \pm 0.04(\mathrm{stat}) \pm 0.21(\mathrm{syst}) \times 10^{21}$ years

Phys.Rev.Lett.107,212501(2011)

update $T^{2\nu}_{1/2} = 2.23 \pm 0.017(\mathrm{stat}) \pm 0.22(\mathrm{syst}) \times 10^{21}$ years

arXiv:1205.5608



KamLAND-Zen (2012)

Xe loaded liquid scintillator

$T^{2\nu}_{1/2} = 2.38 \pm 0.02(\mathrm{stat}) \pm 0.14(\mathrm{syst}) \times 10^{21}$ years

Phys.Rev.C85,045504(2012)

update $T^{2\nu}_{1/2} = 2.30 \pm 0.02(\mathrm{stat}) \pm 0.12(\mathrm{syst}) \times 10^{21}$ years

arXiv:1205.6372

Telescope Germanium Vertical (TGV-2)

32 HPGe planar detectors $\varnothing$60 mm x 6 mm

with sensitive volume: 20.4 cm^2 x 6 mm

Total sensitive volume: ~400 cm^3

Total mass of detectors: ~3 kg

Total area of samples : 330 cm^2

Total mass of sample(s) : 10 ÷ 25 g

Total efficiency : 50 ÷ 70 %

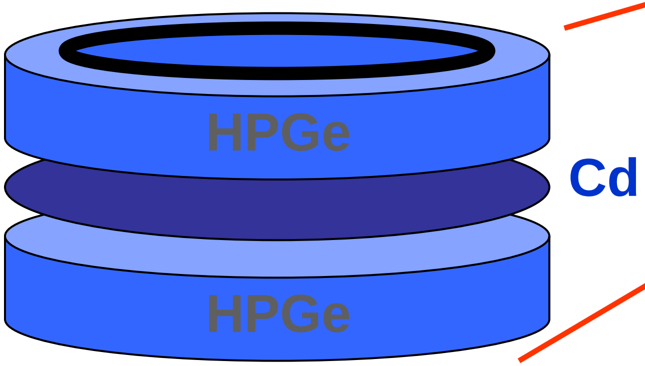
E-resolution : 3 ÷ 4 keV @ ^{60}Co

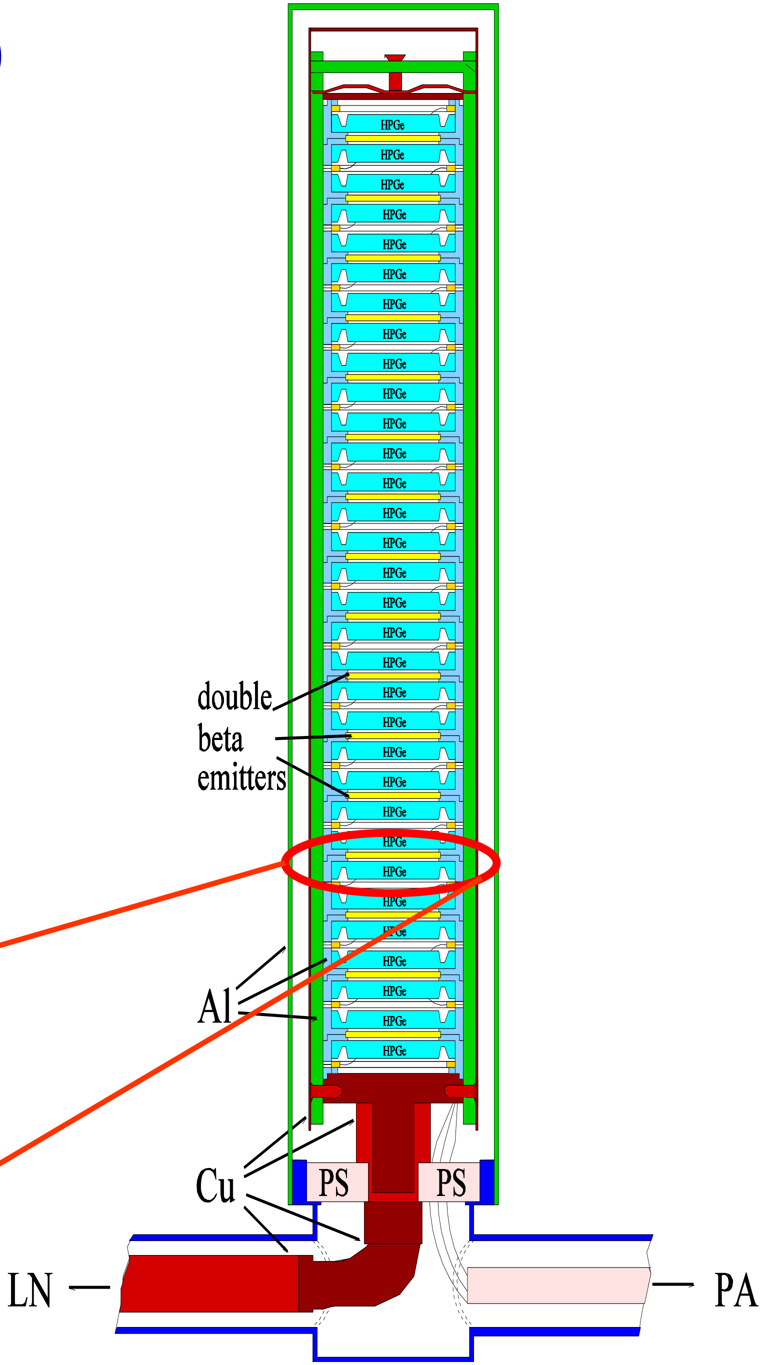
LE-threshold : 5 ÷ 6 keV

Double beta emitters:

16 samples (~ 50 µm) of ^{106}Cd (enrich.75%)

13.6 g ~ 5.79 x 10^{22} atoms of ^{106}Cd





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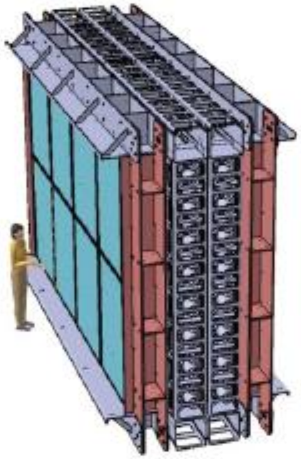

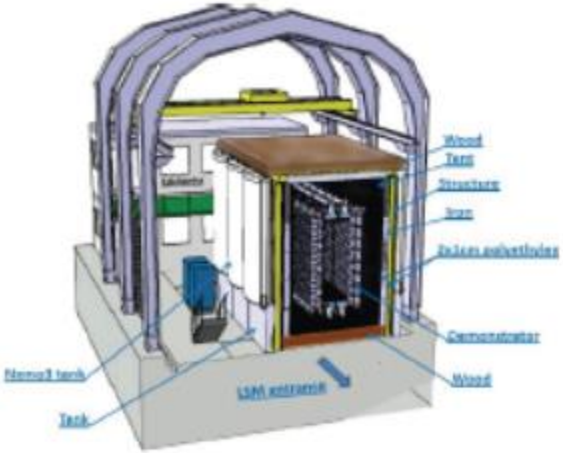

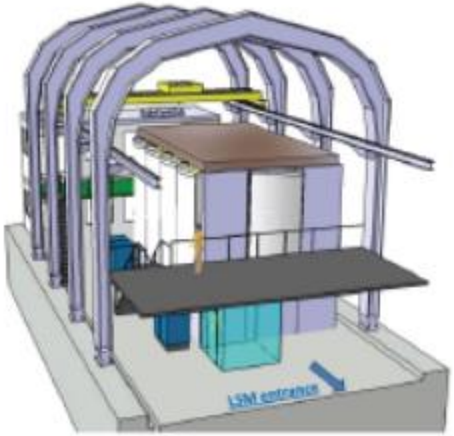

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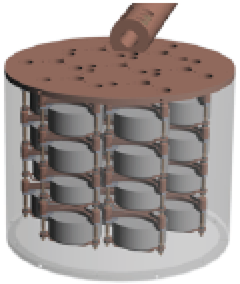
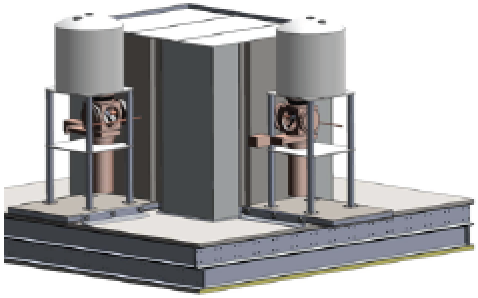
MAJORANA

^{76}Ge offers an excellent combination of capabilities & sensitivities.

(Excellent energy resolution, intrinsically clean detectors, commercial technologies, best $0\nu\beta\beta$ sensitivity to date)



- 40-kg of Ge detectors
  - Up to 30-kg of 86% enriched ^{76}Ge crystals required for science and background goals
  - Examine detector technology options focus on point-contact detectors for DEMONSTRATOR



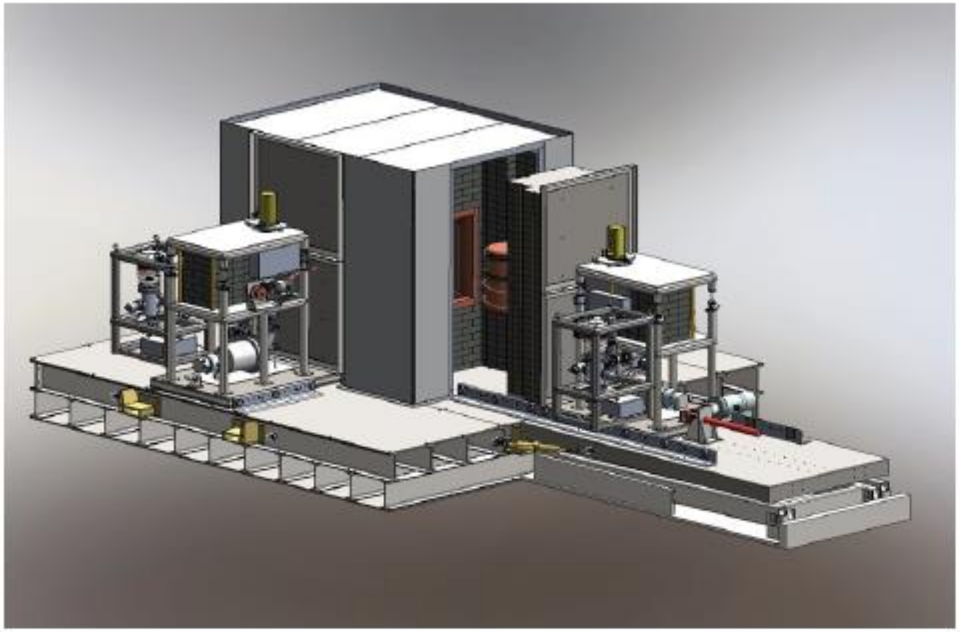
- Low-background Cryostats & Shield
  - ultra-clean, electroformed Cu
  - naturally scalable
  - Compact low-background passive Cu and Pb shield with active muon veto
- Agreement to locate at 4850’ level at Sanford Lab
- Background Goal in the $0\nu\beta\beta$ peak ROI(4 keV at 2039 keV)

~ 3 count/ROI/t-y (after analysis cuts) (scales to 1 count/ROI/t-y for tonne expt.)

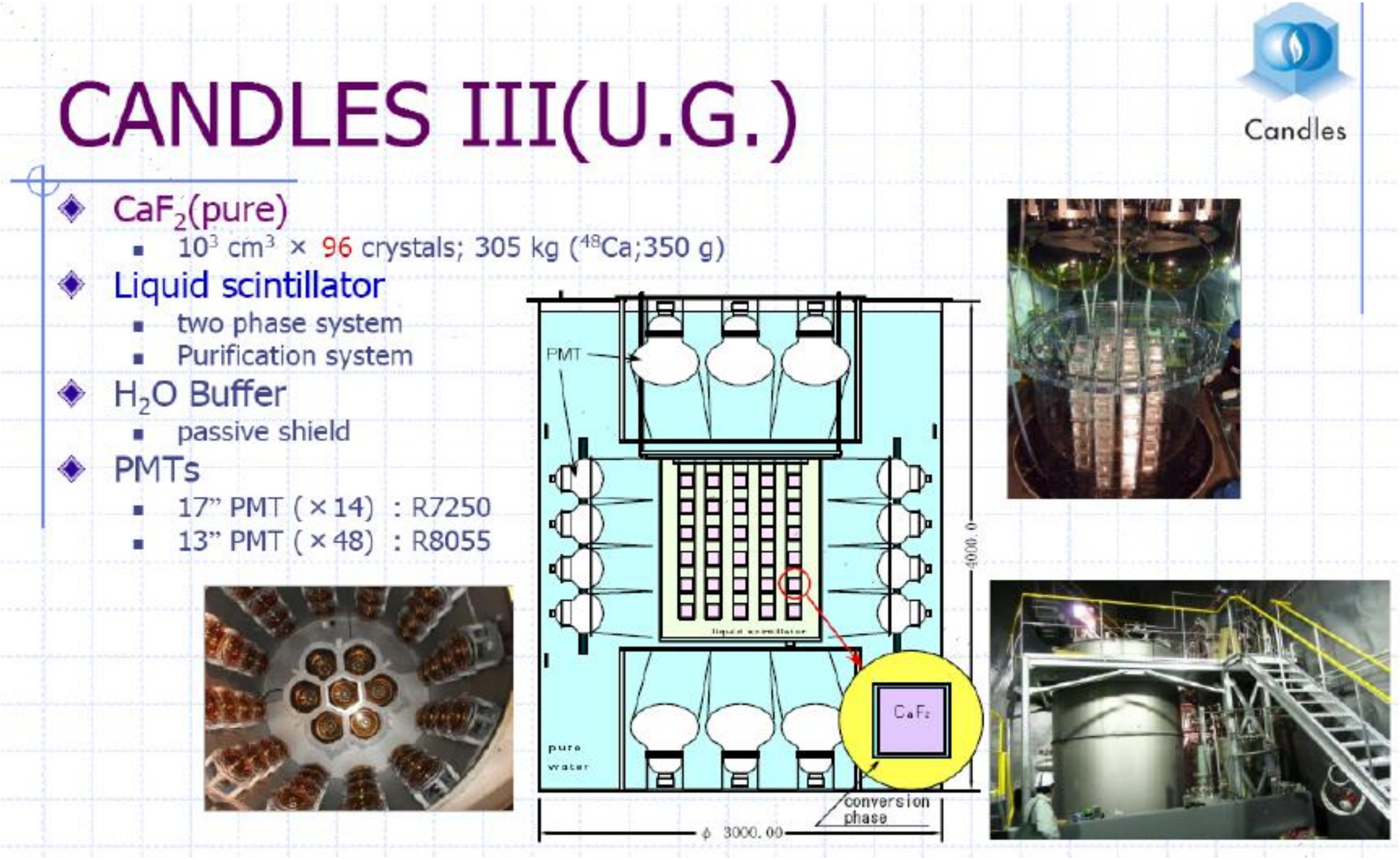
Three Phases

- Prototype cryostat (2 strings, ^{nat}Ge) **(End 2012)**

  1st order of ^{enr}Ge (20 kg) on hand. 2nd order in process. Refinement/ processing facility in Oak Ridge (via NSF) has completed testing with ^{nat}Ge.
- Cryostat 1 (3 strings ^{enr}Ge & 4 strings ^{nat}Ge) **(Fall 2013)**
- Cryostat 2 (up to 7 strings ^{enr}Ge) **(Fall 2014)**



– Measurement started in June 2011 !

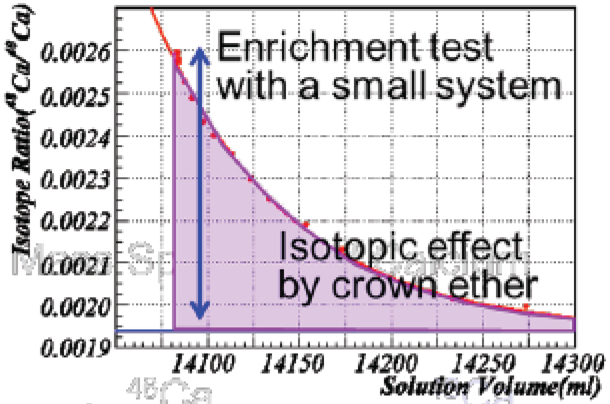


CANDLES III(U.G.)

- CaF_2(pure)
  - 10^3 cm^3 × 96 crystals; 305 kg (^{48}Ca;350 g)
- Liquid scintillator
  - two phase system
  - Purification system
- H_2O Buffer
  - passive shield
- PMTs
  - 17" PMT (×14) : R7250
  - 13" PMT (×48) : R8055

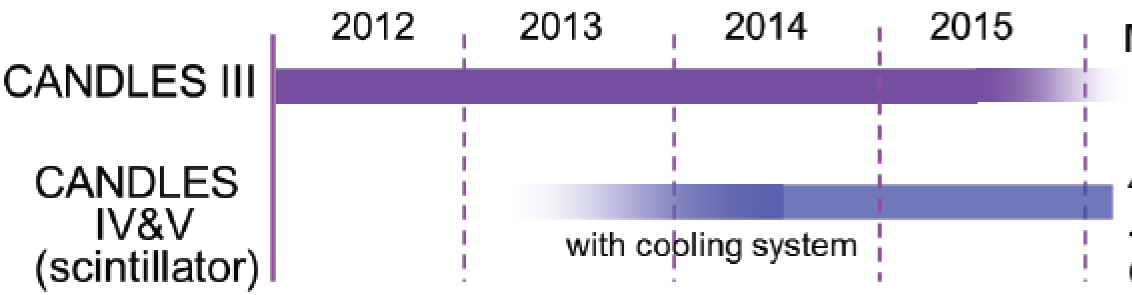
CANDLES Futur

- **^{48}Ca enrichment**
  - R&D for next CANDLES system
  - by using crown-ether
  - Under development
  - for a large amount of ^{48}Ca
- **CANDLES IV & V**
  - ^{48}Ca enrichment
  - Cooling system(~0°C) for good energy resolution
- Schedule



Enrichment test with a small system

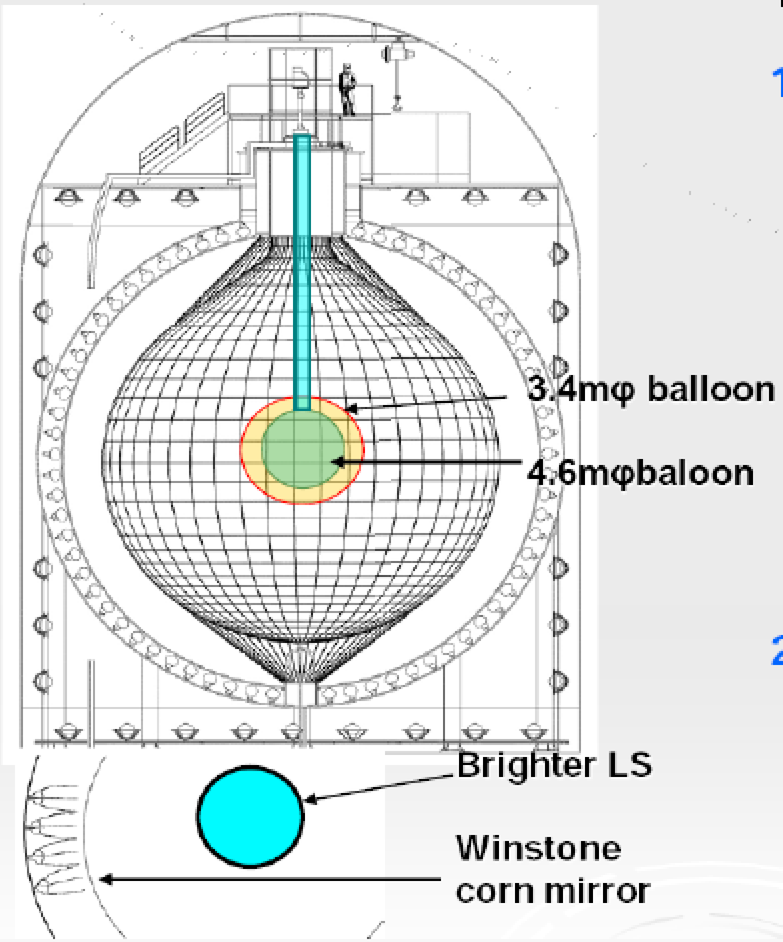
Isotopic effect by crown ether



Measurement at Kamioka Lab.
<m_ν> sensitivity 0.5 eV

^{48}Ca enrichment
<m_ν> sensitivity 50 meV
Construction of detector
. . . not funded yet

Kamland-Zen, 1000 kg



1st phase enriched Xe 400kg

R=1.7m balloon
$V=20.5m^3, S=36.3m^2$
LS : C10H22(81.8%)+PC(18%)
+PPO+Xe(~2.5wt%)
ρLS： 0.78kg／ℓ
high sensitivity with low cost

tank opening (2013 or 2015)

2nd phase enriched Xe 1000kg

R=2.3m balloon
$V=51.3m^3, S=66.7m^2$
improvement of energy resolution
(brighter LS, higher light concentrator)

CUORE program

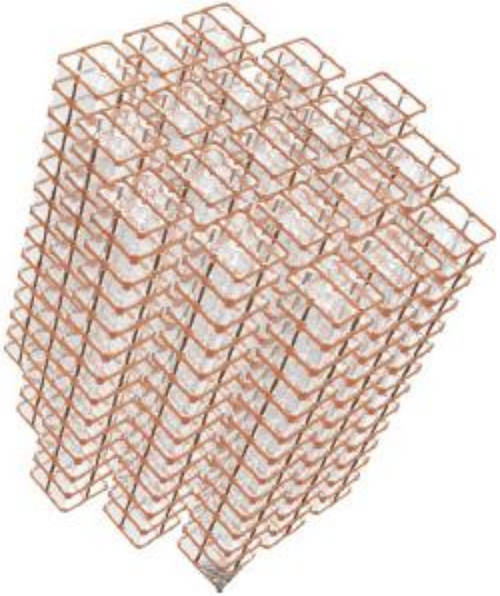
Cryogenic Underground Observatory for Rare Events

Primary objective is to search **for 0*νββ* decay in ^{130}Te**

Cuoricino
2003–2008
11 kg ^{130}Te

COMPLETE

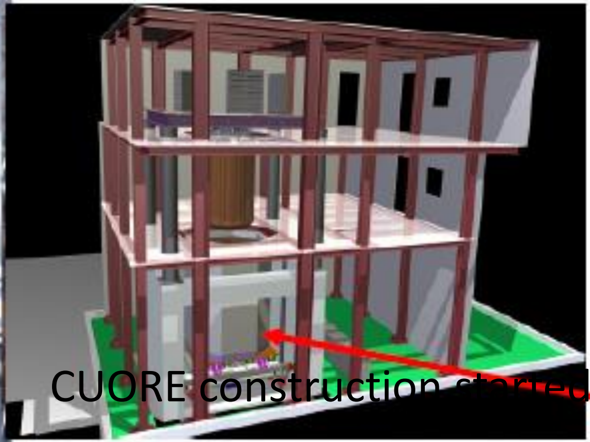
CUORE-0
2012–2014
11 kg ^{130}Te



CUORE
2014–2019
206 kg ^{130}Te

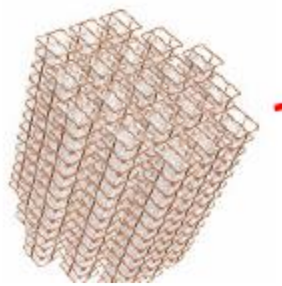
CUORE construction started

988 TeO_2 5x5x5 cm3 crystals => 741 kg TeO_2 => 204 kg ^{130}Te

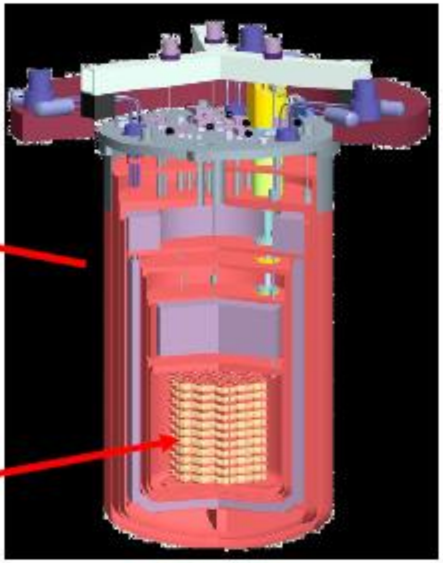


CUORE construction started

The COURE building in hall A of LNGS



Cryostat order placed

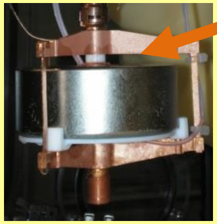


Construction of the GERDA set up started in 2007
in Gran Sasso National Laboratory (LNGS), Italy.
Installation of the “nested type” assembly
completed in 2010
in the deep underground facility at 3400 m w.e.

- End of 2009: Cryostat was filled with 95 t of liquid argon.

Summer 2010: Water tank was filled with 565 t of ultrapure water.

- June 2010: Start of commissioning runs with 3 ^{nat}Ge detectors



November 2011: Start of Phase I.

All 8 ^{76}Ge + 3 ^{Nat}Ge detectors
deployed in GERDA

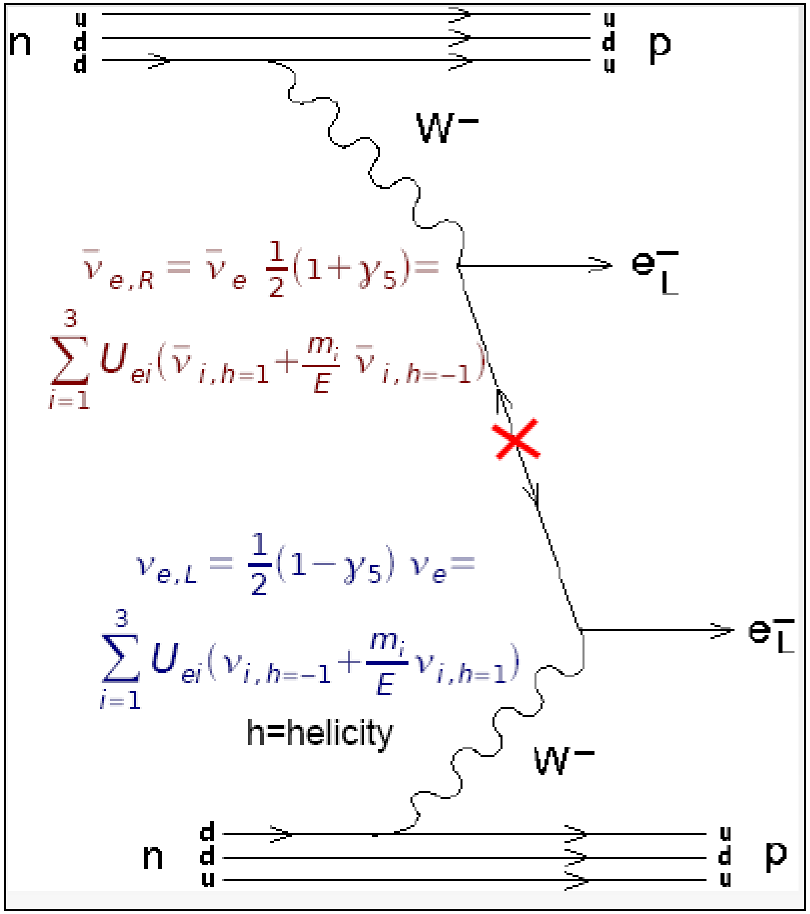
Phase I detectors

8 enriched HPGe detectors
(in total ~ 18 kg of ^{76}Ge)
from HdM and IGEX experiments,
3 natural HPGe detectors
(in total ~ 7.6 kg of ^{Nat}Ge)
from the Genius T-F

Soon: 5 BEGe from ^{76}Ge will be
implemented (June 2012)

Phase II detectors

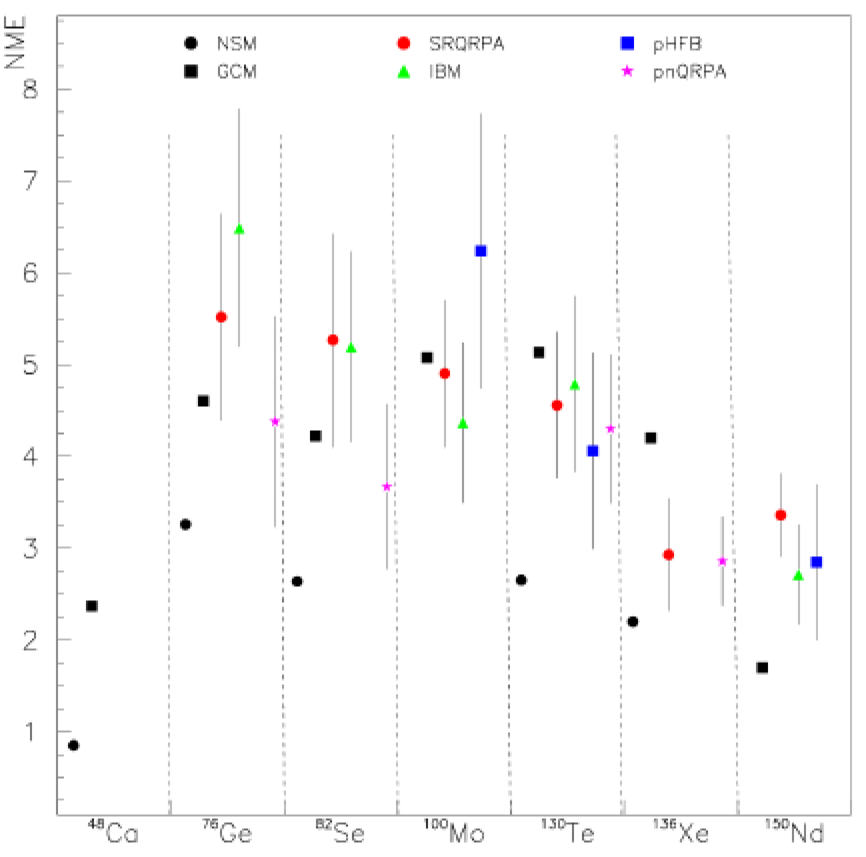
the new BeGe detectors (~ 25 kg of ^{76}Ge) made from enriched in ^{76}Ge material will be added.
In total: about 40 kg of ^{76}Ge



$$\bar{\nu}_{e,R} = \bar{\nu}_e \,\frac{1}{2}(1+\gamma_5) = \sum_{i=1}^{3} U_{ei}\left(\bar{\nu}_{i,h=1} + \frac{m_i}{E}\,\bar{\nu}_{i,h=-1}\right)$$

$$\nu_{e,L} = \frac{1}{2}(1-\gamma_5)\,\nu_e = \sum_{i=1}^{3} U_{ei}\left(\nu_{i,h=-1} + \frac{m_i}{E}\nu_{i,h=1}\right)$$

h=helicity



NSM = nuclear shell model, Nucl. Phys. A 818 (2009) 139.
Phys. Rev. C80 (2009) 048501(1)
SRQRPA = self-consistent renormalized quasiparticle random phase approx.(2), Phys Rev D83 (2011) 113015,
Phys Rev C79 (2009) 055501(1),
Phys Rev C83 (2011) 034320
pnQRPA = proton-neutron QRPA, Nucl Phys A847 (2010) 207

GCM = generating coordinate method
Phys. Rev. Lett. 105 (2010) 252503.
IBM = interacting boson model(3), Phys Rev C79 (2009) 044301
pHFB = projected Hartree-Fock-Bogoliubov
Phys Rev C82 (2010) 064310

(1) for ^{76}Ge: measurement of n+p occupancies, Phys Rev Lett 100 (2008) 112501, Phys Rev C79 (2009) 021301, lead to 15% increase for NSM and 20% decrease for QRPA

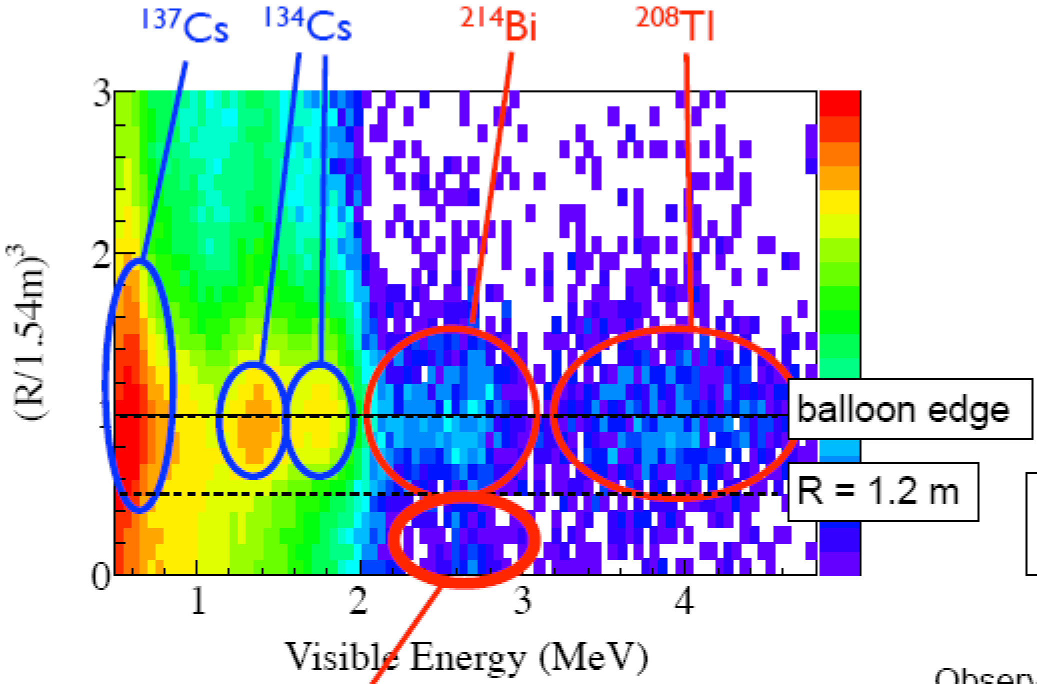
(2) scaled by 1.14 to compensate for different phase space

(3) scaled by 1.18 as estimate for calculation with UCOM short range correlation instead of Jastrow

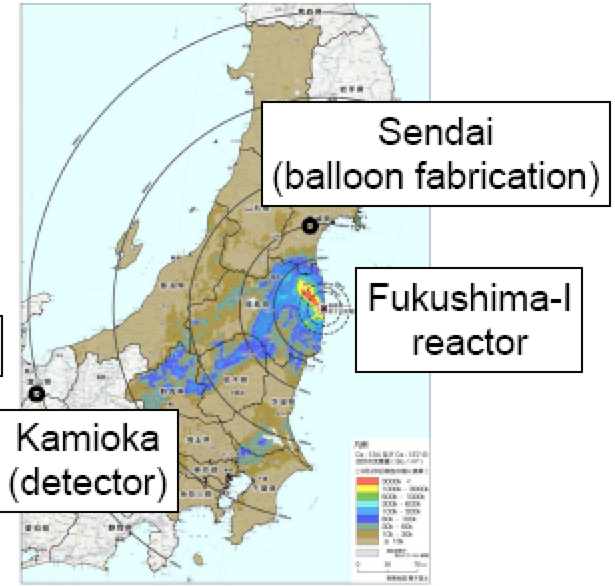
- 0ν NME in first approximation ~ $A^{-1/3}$
- q~100 MeV --> "neighboring n" decay
- NSM lower than other calculations
- NME varry by factor 2-3 for given A

Phase	I	II	Ton Scale
Exposure [kg ·yr]	15	100	$>$1000
Bg [counts/kg·keV·yr]	10^{-2}	10^{-3}	10^{-4}
Upper limit $m_{\beta\beta}$ [eV]	0.23-0.39	0.09-0.15	$\sim$ 0.05
A. Smolnikov, P. Grabmayr PRC 81 028502(2010)			Merge with Majorana

Radioactive Impurities



^{134}Cs + ^{137}Cs fallout



Observed ratio of ^{134}Cs/^{137}Cs (~0.8) is consistent with Fukushima-I reactor fallout

- Cesium is from Fukushima-I reactor fallout. It is not very serious for 0ν2β search. It doesn't leach out, fortunately.
- ^{214}Bi on the mini-balloon is limiting the fiducial volume.
- ^{208}Tl is not serious. It appears far above 0ν2β peak.

What is the peak around 2.6MeV?

AMoRE

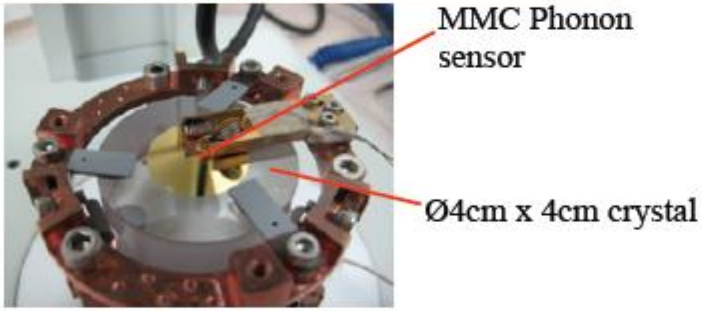
(**A**dvanced **Mo**-based **R**are process **E**xperiment)

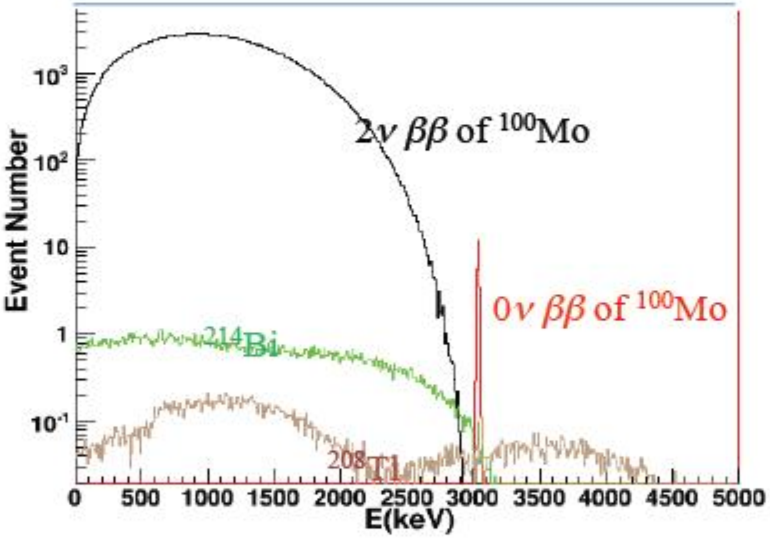
Collaboration (Korea, Russia, Ukraine, China, 11 institutions)

CaMoO4 scintillators or bolometers
Enriched in ^{100}Mo and depleted in ^{48}Ca

1st stage : room temperature
6kg $^{40}Ca^{100}MoO_4$, 5% FWHM
3 years, 6.0×10^{24} y (90% CL)

2nd stage : Cryogenic technique
5 years, 100 kg $^{40}Ca^{100}MoO_4$
15 keV FWHM, Eff = 0.8
3×10^{26} years ~ 50 meV

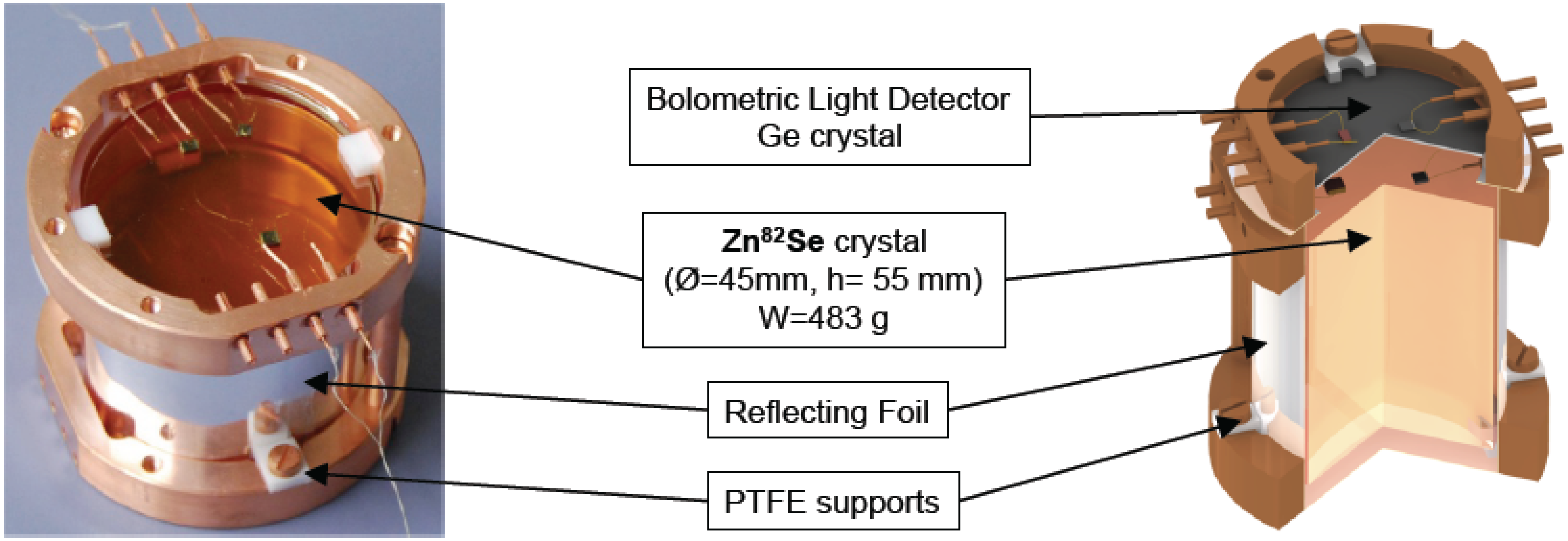




LUCIFER

R&D funded (3.3 M€) by ERC, in the form of an advanced GRANT (03/2010→03/2015)

Scintillating bolometers to recognize the α-induced background thanks to the readout of the scintillation light



Bolometric Light Detector
Ge crystal

$Zn^{82}Se$ crystal
(Ø=45mm, h= 55 mm)
W=483 g

Reflecting Foil

PTFE supports

Array of 36÷44 enriched (95%) $Zn^{82}Se$ crystals.

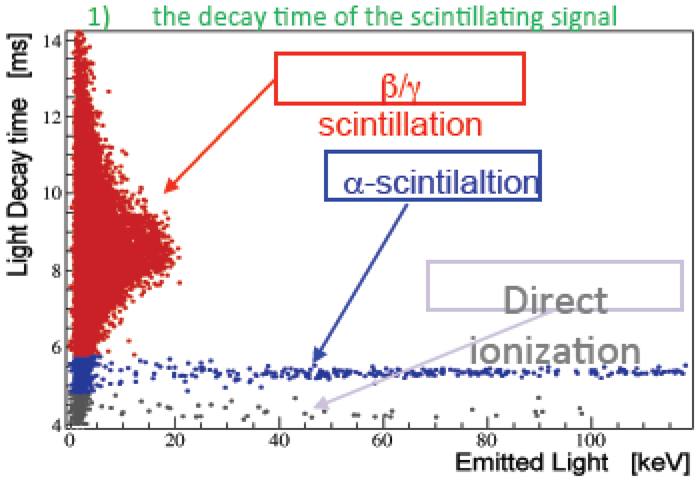
Expected background in the ROI (2995 keV) is ~ 3÷6 10^{-3} c/keV/kg/y

Energy resolution ~10 keV FWHM

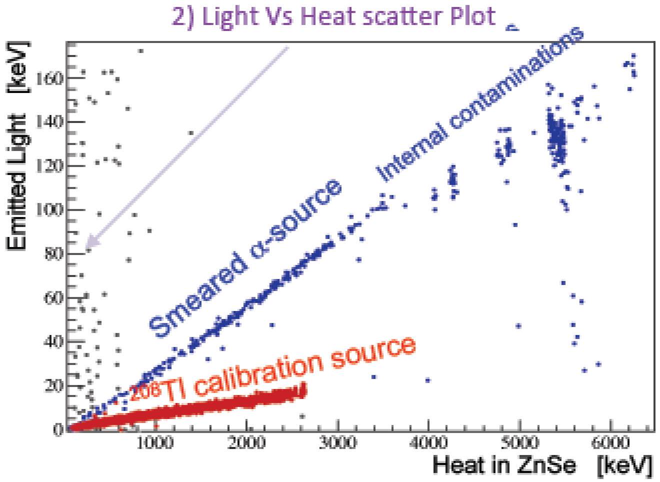
The α-induced background is recognized:

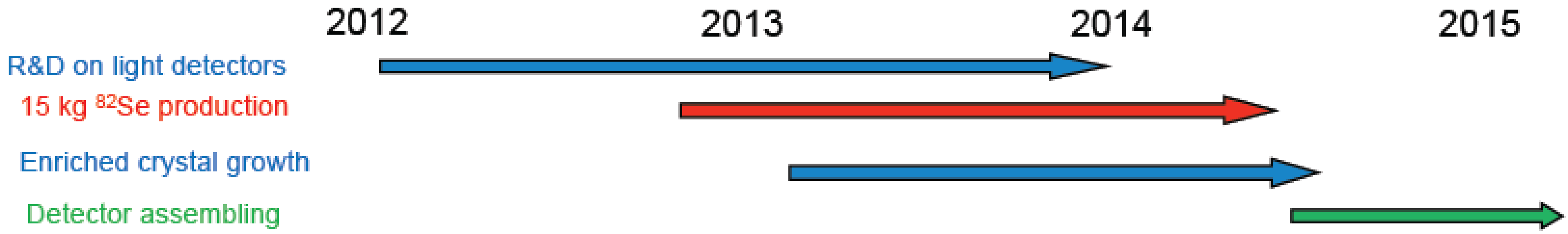
1) the decay time of the scintillating signal

2) the different scintillation yield between α and γ/β particles
(the "usual" light Vs Heat scatter plot)



12.5 days measurement



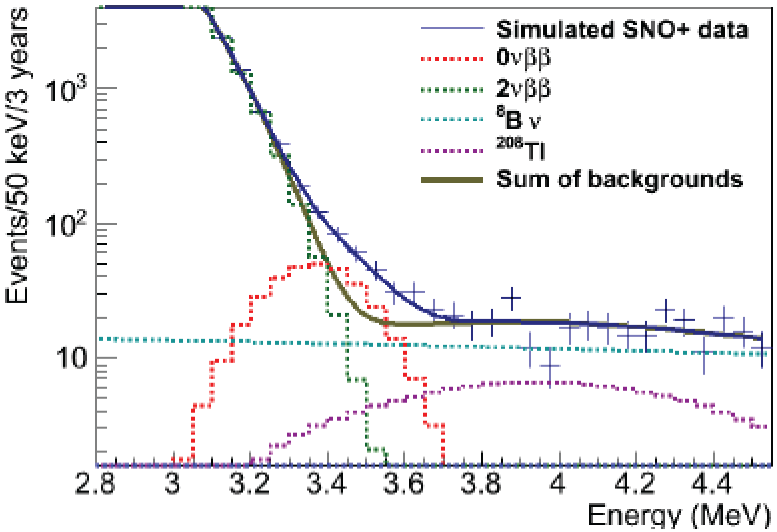


LUCIFER will be located in CUORICINO (now CUORE-0) cryostat, once CUORE-0 will finish his data taking (2015)

^{nat}Nd salt dissolved in liquid scintillator

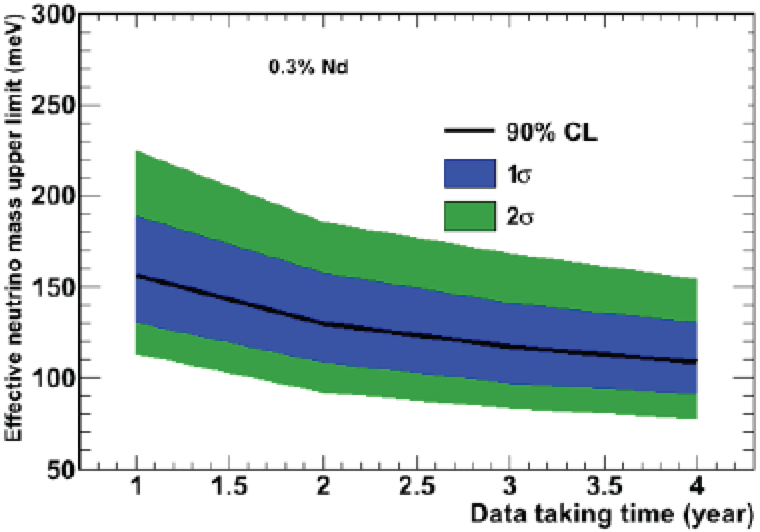
βß-decay signal for 0.3% Nd-loaded scintillator

- signal at the level of Klapdor [Phys. Lett. B 586 (2004) 198]
- 2.4 live-years data simulated
- ^{214}Bi tagged and removed with ^{214}Bi-Po
- ^{208}Tl constrained with ^{212}Bi-Po delayed coincidence
- $t_{1/2}$ 3 min alpha tag of ^{208}Tl rejects 90%



Neutrino mass sensitivity for 0.3% Nd loading (44 kg of ^{150}Nd)

- IBM-2 [Phys. Rev. C 79 (2009) 044301] NME values were used (includes deformation)
- radioactivity backgrounds at the levels achieved by Borexino



- Acrylic Vessel Hold Down Net installed
- New SNO+ Electronics and DAQ being tested (e.g. air fill runs)
- Water fill and detector commissioning starting mid-2012
- Scintillator purification and process systems installed: end of 2012
- Scintillator fill in early 2013 and data taking
- addition of Nd to the scintillator soon thereafter

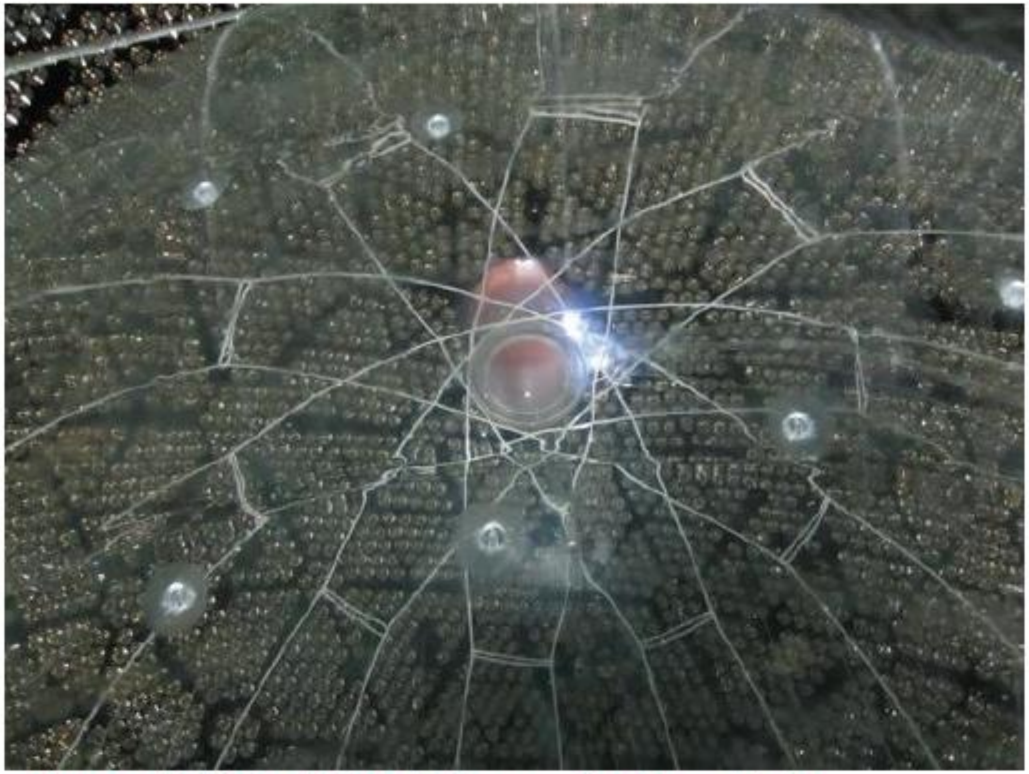


photo of SNO+ AV Hold Down Net installed

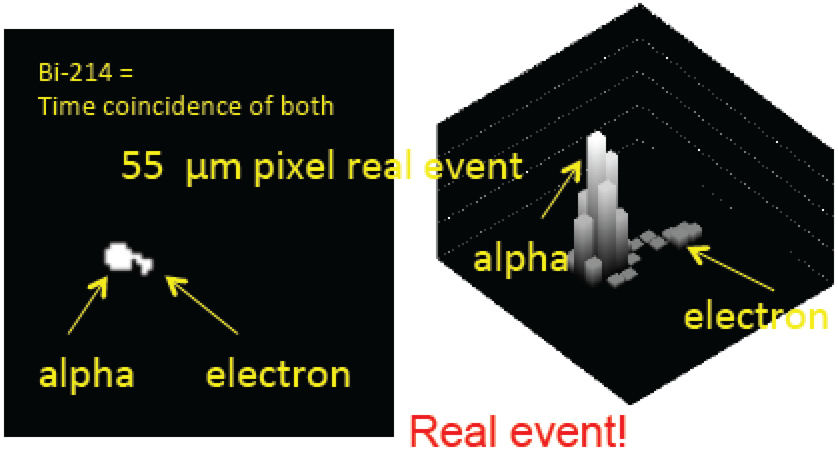
COBRA

Use large amount of CdZnTe Semiconductor Detectors

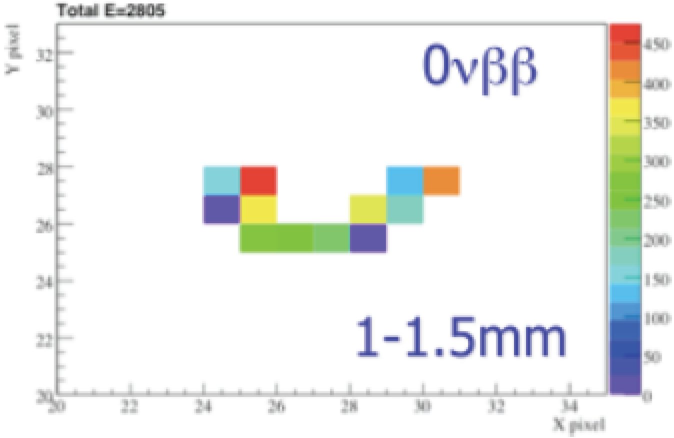
- Source = detector
- Focus on 116Cd
- Semiconductor (Good energy resolution, clean)
- Room temperature
- Modular design (Coincidences)
- Tracking/Pixelisation („Solid state TPC“)

K. Zuber, Phys. Lett. B 519,1 (2001)

Objective : Massive background reduction by particle identification

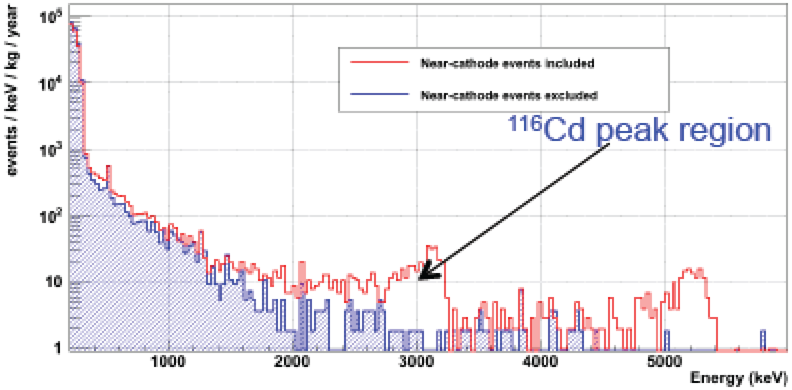


Real event!



Current spectrum (black), **12.73 kg*days**

Background at 2813 keV about 1 ct/keV/kg/yr



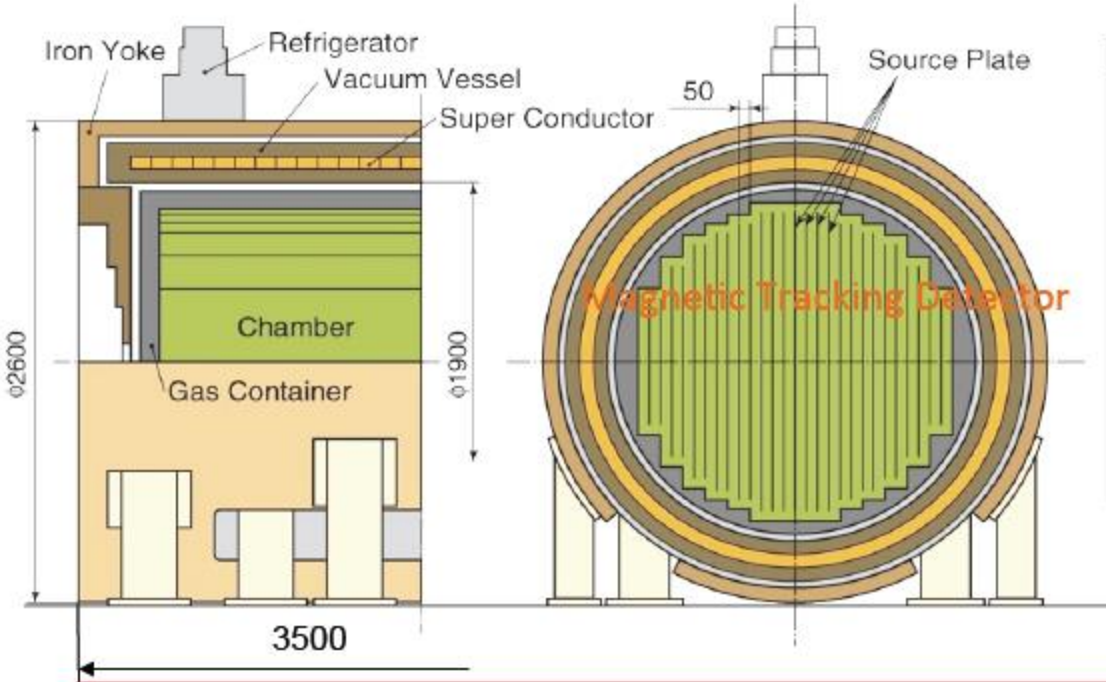
Currently ongoing upgrade:

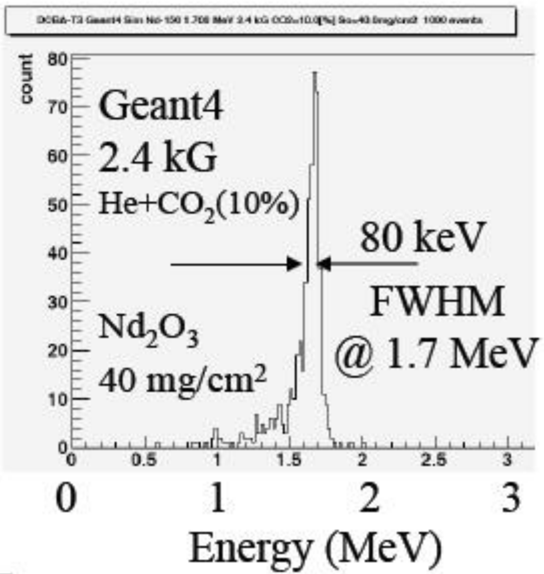
-64 detectors (in hand) 32 running at LNGS
- new DAQ
- Pulse shape information (done),
  rejection of surface events
- Improvement on shielding
- new location at LNGS (former HdMo cabin)

MTD (Magnetic Tracking Detector: temporary name) following of DCBA

Chamber cell : the same as DCBA-T3, Source plate: 80 m^2/module

Thickness: 40 mg/cm^2, Source weight: 32 kg/module





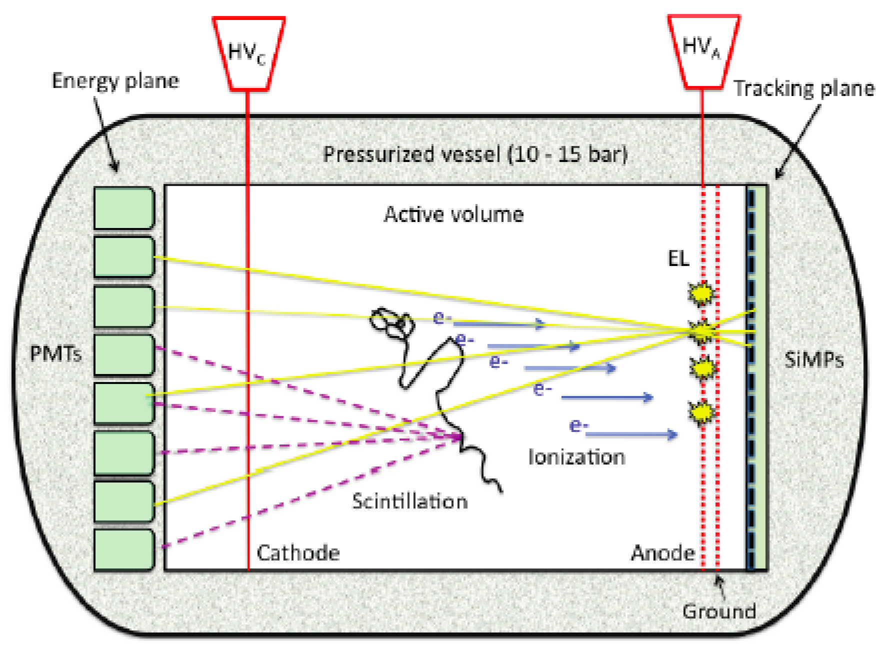
Expected Energy Resolution 3.4% at $Q_{\beta\beta}$ for ^{150}Nd

Multi-isotope ^{150}Nd, ^{100}Mo, ^{82}Se

Several modules to reach $\langle m_\nu \rangle$ 50 meV

NEXT Detection Concept

- Cylindrical single drift volume
- Scintillation signal for t_0
- Ionization signal for separated energy and tracking measurements
  - Converted into EL light
- Instrumented endcaps
  - PMTs on energy plane
  - SiPMs on tracking plane
- TPB coating: 170 → 430 nm light



NEXT strengths:

- Scalability to ton-scale relatively easy
- 0.5-1% FWHM energy resolution
- Tracking and dE/dx information for event topology

- **Experience and results from prototypes**
  - Testing ground for all foreseeable technical hurdles in NEXT-100
  - 0.5-1% FWHM energy resolution at $Q_{\beta\beta}$ demonstrated
  - Tracking and event topology studies underway

Simulated $\beta\beta0\nu$ track in Xe at 10 bar

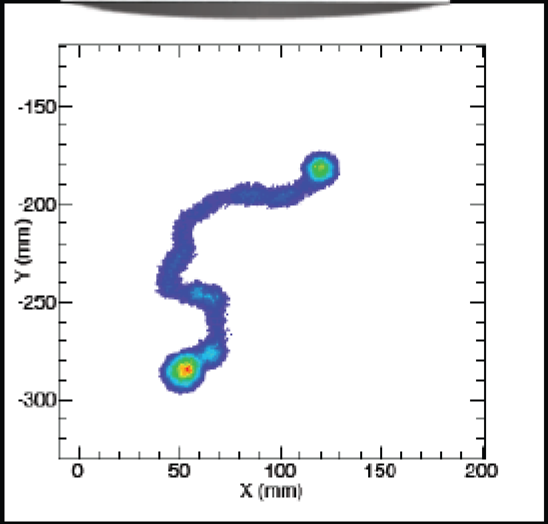
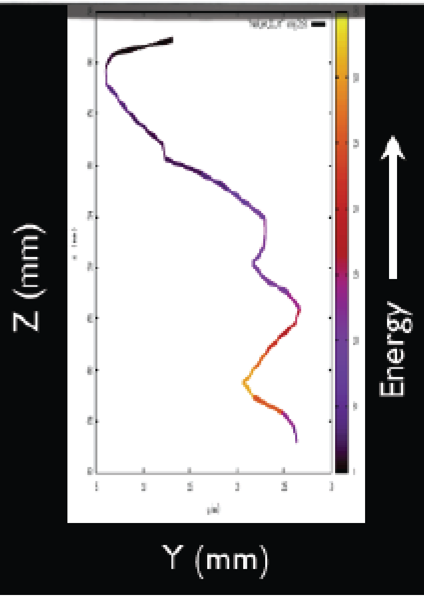


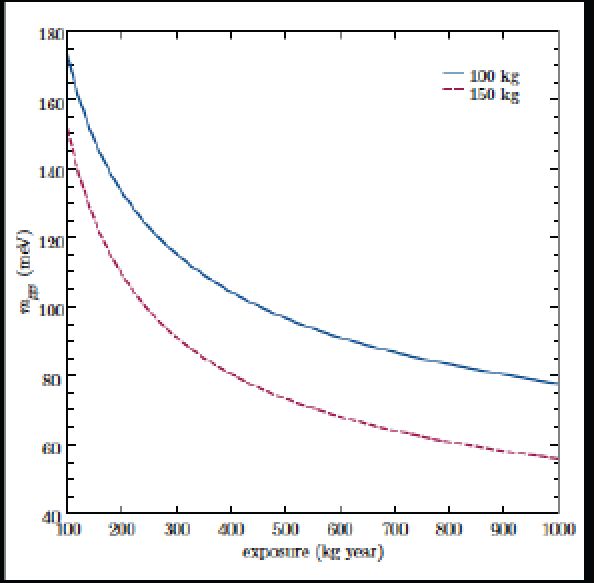
Photo-electron track from 662 keV gamma in NEXT-DEMO at 10 bar



NEXT Sensitivity and Schedule

- NEXT-100 should be sensitive to effective Majorana masses as small as 100 meV after 5 years of operation
  - 90% CL, assuming 100 kg of xenon
  - half-life sensitivity: 6×10^{25} years

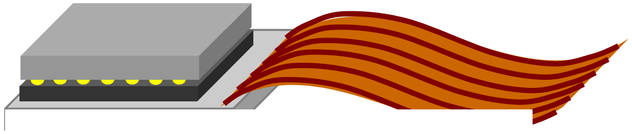
- Main backgrounds expected to be gammas from ^{214}Bi and ^{208}Tl
  - 2×10^{-7} background rejection factor
  - 8×10^{-4} counts/(keV·kg·y) background rate
  - Based on detailed background model

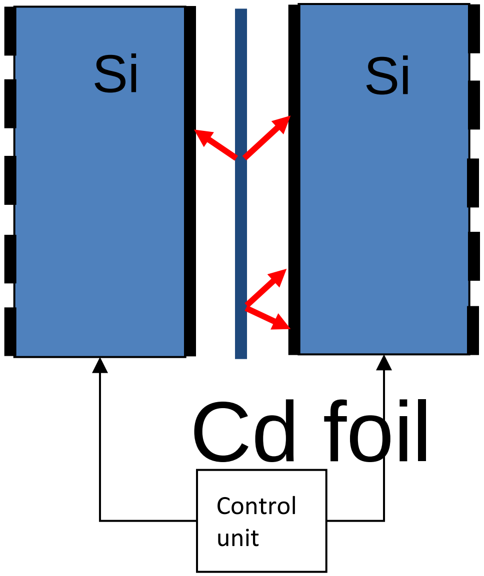


Schedule:

2012: complete R&D, NEXT-100 design, radiopurity campaign
2013: NEXT-100 construction
2014: NEXT-100 commissioning with non-enriched xenon
2015: start physics run with enriched xenon

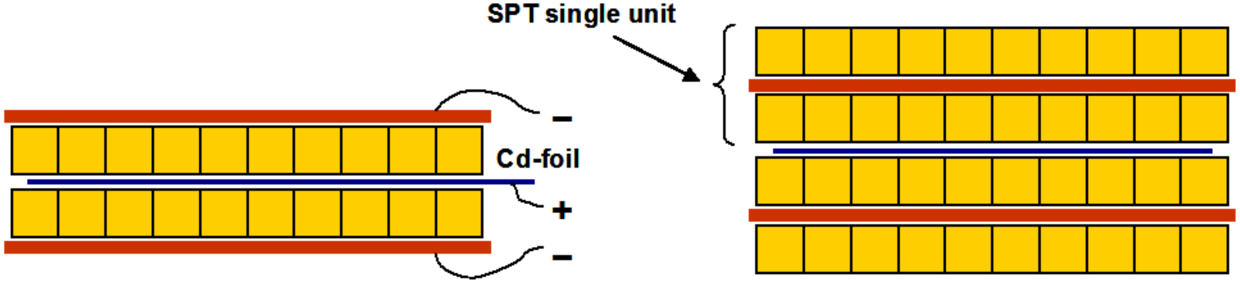
Search for 2νEC/EC of ^{106}Cd with pixel detectors

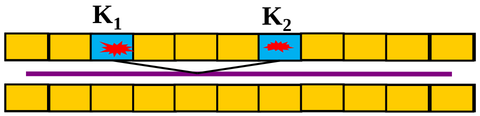




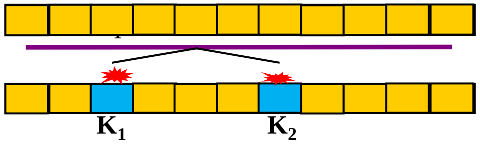
- Si pixel detectors in coincidence mode
- Thin foil of enriched isotope
- Signature = two hitted pixels with X-rays of precise energy
- Good efficiency (comparable with TGV-2)
- Particle identification (alpha, electrons)
- information about energy + position of registered X-ray
- Measurement at room temperature

Observable: 2× 21keV X-rays from ^{106}Pd daughter originated in the enriched Cd foil





Single-side events (SSE)



Double-side event (DSE)