Double-Beta Decay Searches in 2012 (and beyond)

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LIO neutrino, Lyon, October 22-24, 2012

What is double beta decay (DBD) ?

The 2-neutrino DBD ($2\nu\beta\beta$)

[Goeppert-Mayer, 1935]

$$^A_ZX \longrightarrow ^A_{Z+2} Y + 2e^- + 2\bar{\nu}_e$$

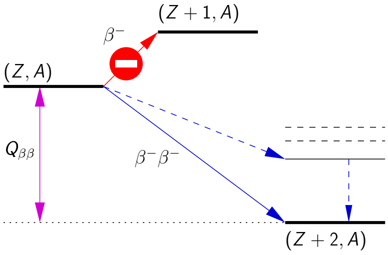
- $\Delta L = 0$
- Allowed in SM
- Decay rate : slow (second order weak process) and $\sim Q_{\beta\beta}^{11}$
- Can be calculated :

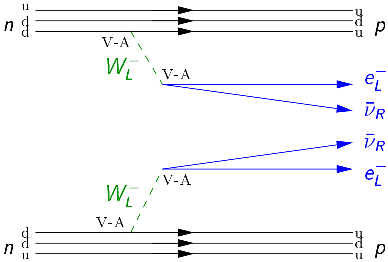
$$(T_{1/2}^{2\nu})^{-1} = G_{2\nu}(Q_{\beta\beta}, Z) \times \mid M_{2\nu} \mid^2$$

- Has been measured :

$$T_{1/2}^{2\nu} \simeq 10^{18} - 10^{21} \text{ yr}$$

- Not very interesting. . . but. . .





What is neutrinoless double beta decay (DBD) ?

The neutrinoless DBD ($0\nu\beta\beta$) [Furry, 1939]

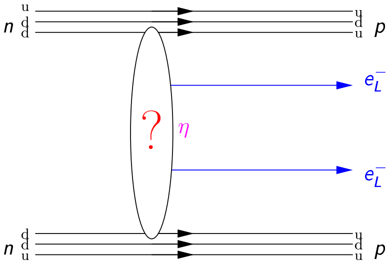
$$^{A}_{Z}X \longrightarrow ^{A}_{Z+2}Y + 2e^{-}$$

- $\Delta L = 2$!!!
- Forbidden in SM !!!
- Decay rate is :

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z) \times \mid M_{0\nu} \mid^{2} \times \eta$$

Expected $T^{0\nu}_{1/2} >> T^{2\nu}_{1/2}$

- η contains new physics !
  - Lepton number violation
  - Majorana neutrino [PRD 25 (1982) 2951]



Several mechanisms can be envisaged : massive Majorana neutrino exchange, Majoron emission, SUSY...

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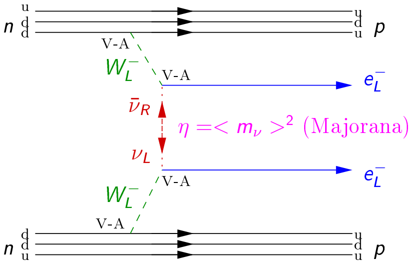
  - Majorana neutrino [PRD 25 (1982) 2951]
  - Effective light Majorana neutrino mass $< m_\nu > \neq 0$



The only natural $W^- W^-$ collider available !

The game : counting decays...

Example: a DBD experiment using ^{76}Ge (ala HM)

- $G_{0\nu}(Q, Z)$=0.623 10^{-14} y^{-1} ($Q_{\beta\beta}$=2039 keV)
- $M_{0\nu} \simeq [3-6]$ (dimensionless) $\longrightarrow$ Large theor. uncertainty !
- $T^{0\nu}_{1/2} \simeq 2\ 10^{25}$ y (HM) $\rightsquigarrow$ $m_\nu \simeq [0.25-0.5]$ eV
- Running an ideal experiment with t=5 y, M=10 kg of ^{76}Ge, ε=100% efficiency (exposure $M \times t$=50 kg.y) :

$$N^{0\nu}_{decay} = \frac{N_A M}{A} \frac{\varepsilon t \log 2}{T^{0\nu}_{1/2}}$$

gives: $N^{0\nu}_{decay} \simeq 14$ expected decays

- But typical natural radioactivity (^{232}Th, ^{238}U...) is $\simeq$ 1-100 Bq/kg :

$$N^{radioactivity}_{decay} = a \times t \times M$$

and gives : $N^{radioactivity}_{decay} \simeq [1-100]\ 10^9$ nasty decays !!!

Radioactivity background is the enemy !

Background sources. . .

- Natural radioactivity energy scale : 1-5 MeV $\simeq Q_{\beta\beta}$
- ^{232}Th, ^{238}U, ^{235}U chains : plenty of α, β and γ emitters
- Special mention for ^{226}Ra ($T_{1/2}$=1800 y) and ^{222}Rn (gas, $T_{1/2}$=3.8 days) and (β/α) decay products
- Very special mention for ^{214}Bi (Q_{β}=3.2 MeV) and ^{208}Tl (Q_{β}=5 MeV, E_{γ}=2.614 MeV)
- Fission neutrons from surrounding rocks $\rightsquigarrow$ (n,γ) reactions ($>$ 3 MeV)
- Also cosmic muons :
  - spallation and thus unstable cosmogenics isotopes
  - bremstrahlung $\rightsquigarrow$ high-energy $\gamma \rightsquigarrow e^{-}$, e^{+}
- Possible artificial radioactive contaminants may also be a problem.
- $2\nu\beta\beta$ decays (ultimate background in some cases).

Recipe for a DBD experiment

How to make it ?

- Collect a large mass of some enriched isotope(s) as the DBD source ($\gtrsim$ 100 mol)
- Purify this DBD source with some radiochemistry processes (for example removing Radium to break the U decay chain)
- Select ultra-low radioactivity materials to build the $\beta\beta$ detector (1μBq/kg – 1mBq/kg, remove Radon from gas)
- Bury the experimental setup deep underground ($\gtrsim$1000 m.w.e, protection against cosmic rays)
- Shield against environmental radioactivity (n, γ, μ, ^{222}Rn)
- Invent some technique(s) to discriminate $0\nu\beta\beta$ signal from background(s)

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- Invent some technique(s) to discriminate $0\nu\beta\beta$ signal from background(s)
- Switch on the detector, seat down and wait. . . wait. . . wait. . .

Recipe for a DBD experiment

Experimental questions

- What isotopes to be used for DBD search ?
- What technology to *discover/invalidate* $0\nu\beta\beta$ process ?
- How to improve the radiopurity of the experimental setup and background rejection performance ?
- How does it cost in terms of time, effort, money. . . hope ?
- How does it scale for a future larger experiment with improved sensitivity ?
- Does a best experimental approach exist ?

Isotopes of experimental interest

Isotope	$Q_{\beta\beta}$ [keV]	Nat. abund. (enr.) [%]	$G_{0\nu}$ ($\tilde{G}^{76}_{0\nu}$) $[10^{-14}\ (\text{y}^{-1})]^a$	$M_{0\nu}{}^a$	$T^{2\nu}_{1/2,exp}$ $[10^{19}\ (\text{y})]$
^{48}Ca	4270	0.187 (73^b)	6.35 (16.15)	0.85 – 2.37	4.4^e
^{76}Ge	2039	7.83 (86^c)	0.623 (1)	2.81 – 7.24	155^f
^{82}Se	2995	8.73 (97^b)	2.70 (4)	2.64 – 6.46	9.6^e
^{96}Zr	3350	2.8 (57^b)	5.63 (7.1)	1.56 – 5.65	2.35^e
^{100}Mo	3034	9.63 (99^b)	4.36 (5.3)	3.103 – 7.77	0.716^e
^{116}Cd	2802	7.49 (93^b)	4.62 (4.8)	2.51 – 4.72	2.88^e
^{130}Te	2527	34.08 (90^b)	4.09 (3.8)	2.65 – 5.50	70^e
^{136}Xe	2480	8.857 (80^d)	4.31 (3.9)	1.71 – 4.2	211^g
^{150}Nd	3367	5.6 (91^b)	19.2 (15.6)	1.71 – 3.7	0.91^e

Q : below 2.6 MeV γ-line (^{208}Tl), below 3.2 MeV Q-value (^{214}Bi)

$\tilde{G}^{76}_{0\nu} = (G_{0\nu}/A)$ then normalized to the value for ^{76}Ge

$M_{0\nu}$: small theor. value or difficult to compute. . .

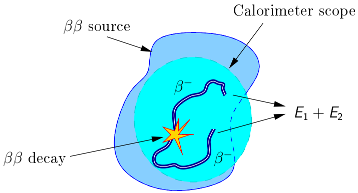
[a] from PRD 83, 113010 (2011)

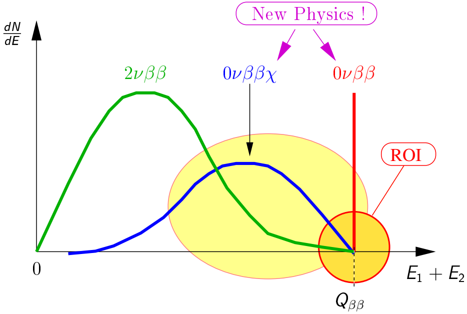
[b] achieved in NEMO-3, [c] achieved in HM, [d] achieved in EXO-200

[e] from NEMO3 (see TAUP 2011), [f] from HM, [g] from EXO-200 (arXiv-1108.4193)

Measuring the electron energy sum spectrum @ $Q_{\beta\beta}$

- Use a Calorimeter : measurement of the energy sum of both electrons emitted in $\beta\beta$ processes





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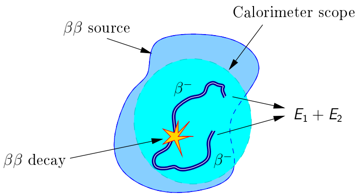

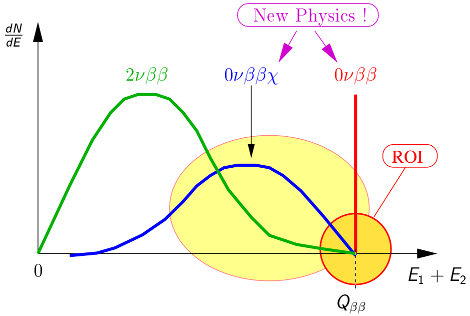

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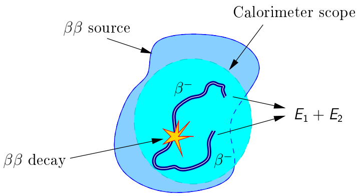

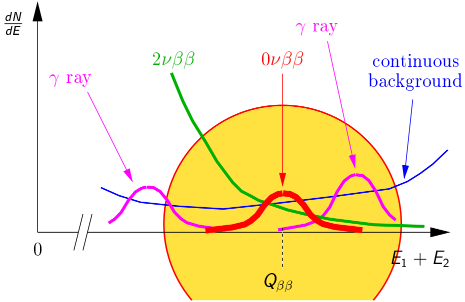

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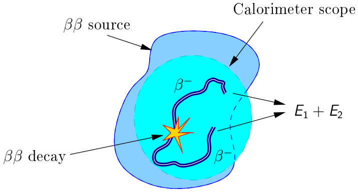

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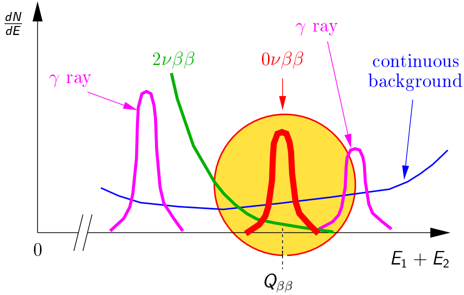
- Introducing the background index: typical $B \sim 0.1 - 0.001$ counts/keV/kg/y



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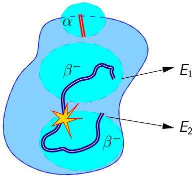
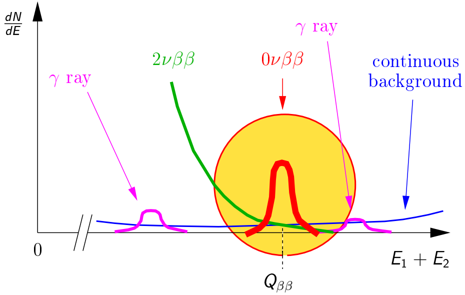
- Introducing the background index: typical $B \sim 0.1 - 0.001$ counts/keV/kg/y
- Additional criteria : particle identification (γ, e^-, e^+, α...)





Experimental half-life sensitivity

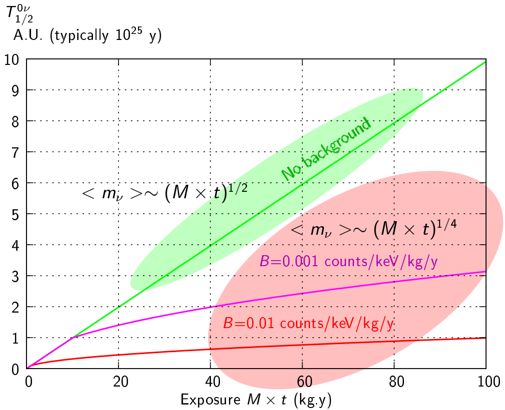
- Background-free (lower limit):

$$T_{1/2}^{0\nu} \gtrsim \frac{N_A \ln 2}{n_\sigma} \left(\frac{a \times \varepsilon}{A} \right) M \times t$$

- Background limited (lower limit):

$$T_{1/2}^{0\nu} \gtrsim \frac{N_A \ln 2}{n_\sigma} \left(\frac{a \times \varepsilon}{A} \right) \sqrt{\frac{M \times t}{B \times \Delta E}}$$

where :
n_σ the number of standard deviations at desired CL,
a the isotopical abundance,
M the mass of the source,
t the measuring time,
ε the efficiency,
ΔE the energy resolution at peak position (ROI),
B the background index in the ROI (counts/keV/kg/y).



Experimental approaches

Calorimeter

- Detector = DBD source
- Excellent $\Delta E/E$
- Large efficiency
- Compact
- Address only one DBD isotope (^{76}Ge, ^{130}Te...)
- Limited particle identification
- Techniques: Semiconductor, Bolometer, (Liquid-)Scintillator (^{136}Xe, ^{150}Nd)

Tracker

- Detector $\neq$ DBD source
- Limited $\Delta E/E$
- Limited efficiency
- Not so compact
- Isotope flexibility (^{100}Mo, ^{82}Se, ^{150}Nd, ^{48}Ca...)
- Particle identification and event topology
- Probe $\neq$ mechanisms
- Techniques: Drift chamber, TPC

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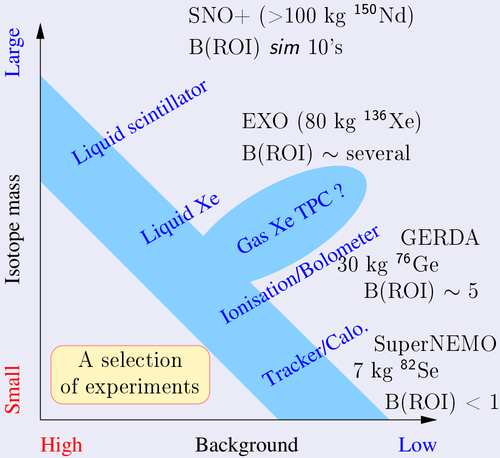
Hybrid

- Elements (best) of both
- Gaseous (Xe) TPC
- Pixelated calorimeter (CdZnTe)

Experimental approaches

It there a “best” technique for DBD ?

- Each technique has its own problems in terms of source enrichment, source purification and, last but definitively not the least, background(s)



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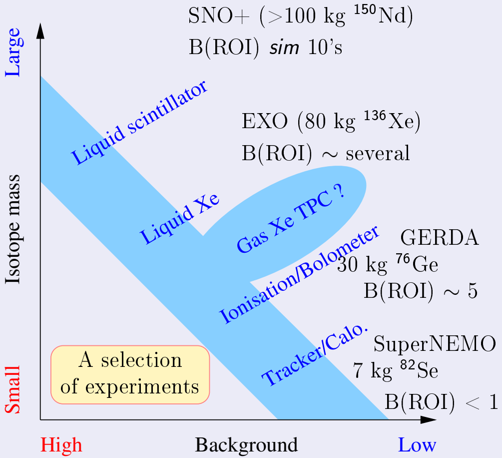

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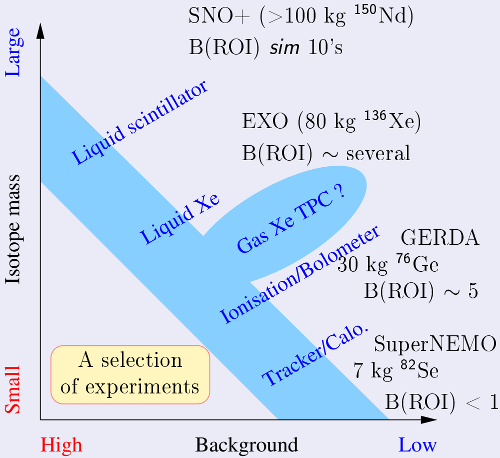

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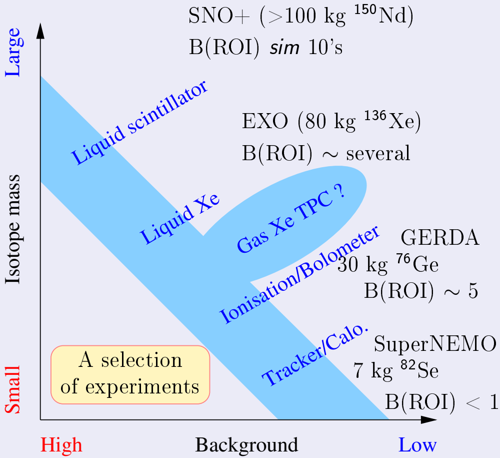
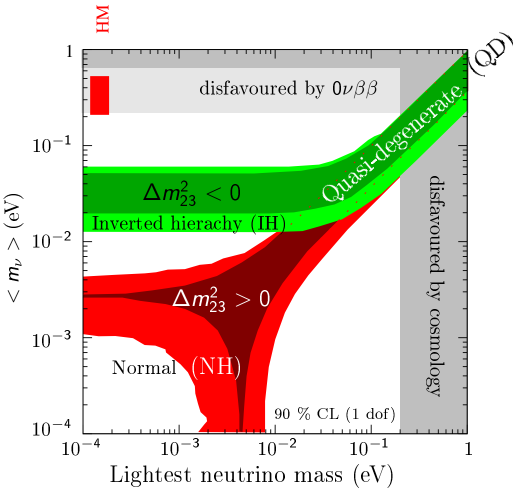
- Each realizes a kind of compromise
- Some approaches exist to get the best available...



Where we are now !

- ~1990-2000 : HM experiment (^{76}Ge)



[Strumia & Vissani, hep-ph/0606054]

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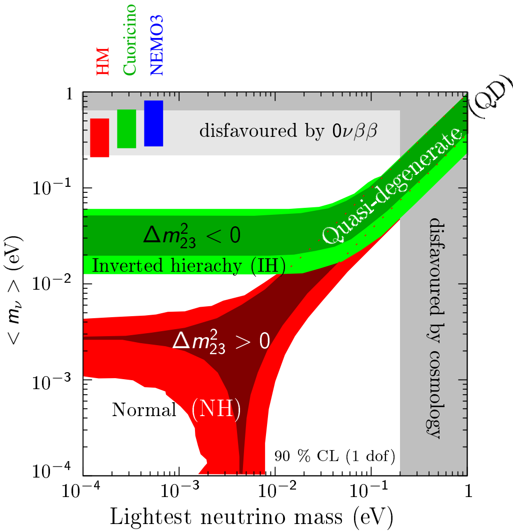

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  ≃10-100 kg
  First stimulating results :
  - EXO200 (^{136}Xe)
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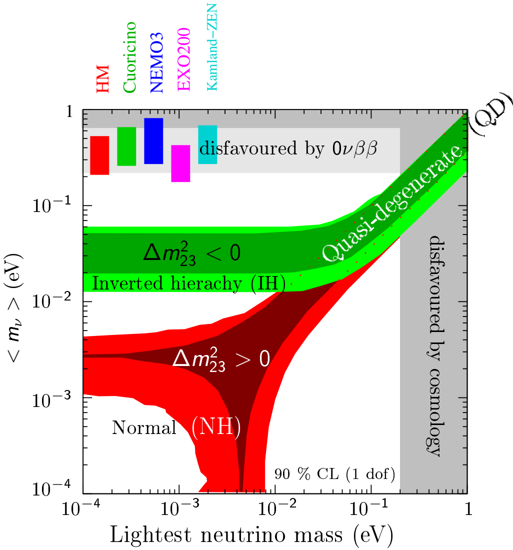

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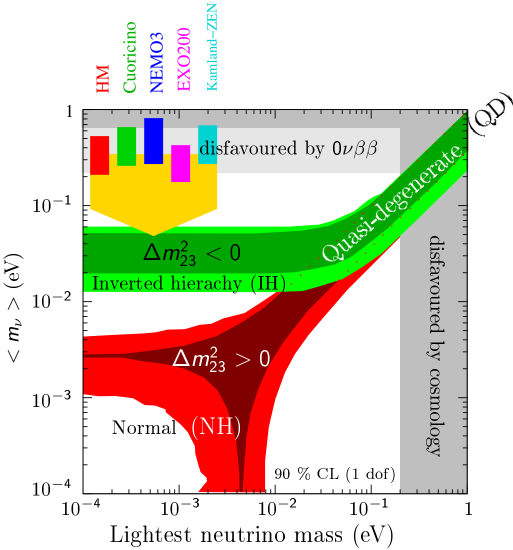

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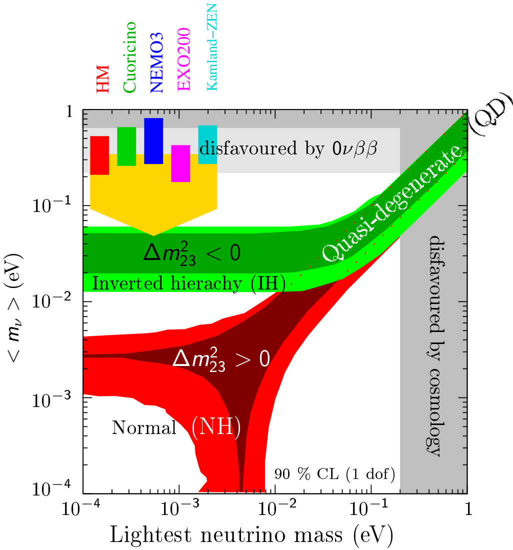
- Beyond 2015: cover IH ? ≃100-1000 kg



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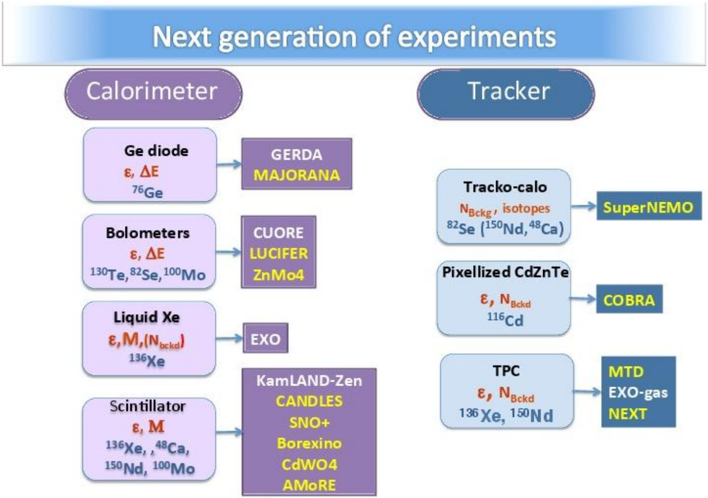
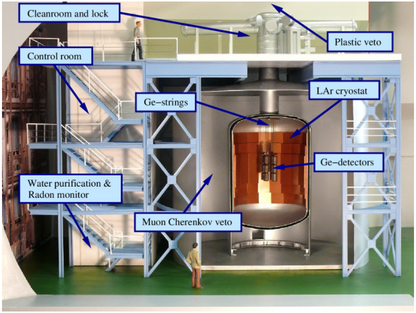
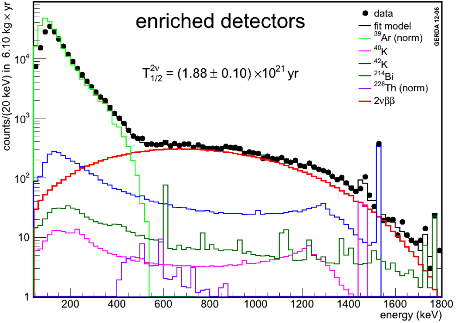


Next generation of experiments
Calorimeter
Tracker
Ge diode
ε, ΔE
76Ge
GERDA
MAJORANA
Bolometers
ε, ΔE
130Te, 82Se, 100Mo
CUORE
LUCIFER
ZnMo4
Liquid Xe
ε, M, (Nbckd)
136Xe
EXO
Scintillator
ε, M
136Xe, ,48Ca,
150Nd, 100Mo
KamLAND-Zen
CANDLES
SNO+
Borexino
CdWO4
AMoRE
Tracko-calo
NBckg, isotopes
82Se (150Nd, 48Ca)
SuperNEMO
Pixellized CdZnTe
ε, NBckd
116Cd
COBRA
TPC
ε, NBckd
136Xe, 150Nd
MTD
EXO-gas
NEXT

GERDA – Calorimeter, ^{76}Ge

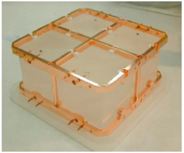


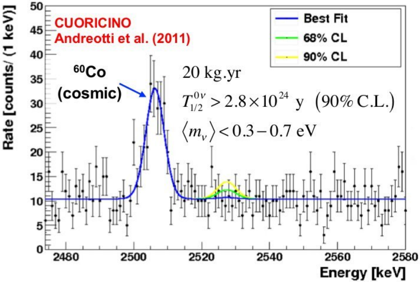
- Bare detectors in liquid argon for effective background suppression
- Re-use HM & IGEX crystals
- Phase 1 data-taking : 18 kg ^{enr}Ge
- Sensitivity to Klapdor claim soon
- ^{42}Ar/^{42}K problem now solved
- Phase 1 : $B \sim 0.02$ counts/keV/kg/y
- Phase 2 target : $B \sim 10^{-3}$ counts/keV/kg/y
- See also the MAJORANA project



CUORE – Calorimeter, ^{130}Te

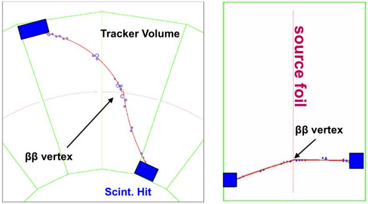
- ^{nat}Te bolometer experiment (^{130}Te, 34% natural abundance)
- Te02 crystal: low heat capacity, high intrinsic radio-purity
- Operated at 8-10 mK
- 19 towers $\sim$ 200 kg ^{130}Te
- Background target : 10-100 smaller than CUORICINO $B \sim 5\ 10^{-2}$–$5\ 10^{-3}$ counts/keV/kg/y
- 2011-2018 : t=5 year $< m_\nu > \simeq$ 40–100 meV

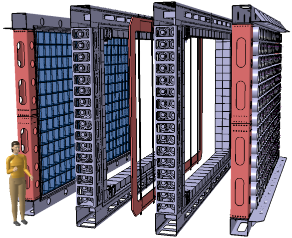




SuperNEMO – Calorimeter+Tracker, ^{82}Se

- Tracker/Calorimeter ala NEMO3 experiment
- Demonstrator module: 7 kg of ^{82}Se ($\times$2.5 y)
- Prove $B \sim 10^{-4}$ counts/keV/kg/y
- Limit: $T^{0\nu}_{1/2} \sim 6.5\ 10^{24}$ y
- Construction started, running 2015-2016 (LSM)
- Prove scalability for a full-scale 20 modules with :
  100 kg $\times$ 2016-2020
  $T^{0\nu}_{1/2} \sim 10^{26}$ y, $< m_\nu > =$ 40-100 meV
- R&D for ^{48}Ca, ^{150}Nd





SuperNEMO – Calorimeter+Tracker, ^{82}Se

- Tracker/Calorimeter ala NEMO3 experiment
- Demonstrator module: 7 kg of ^{82}Se ($\times$2.5 y)
- Prove $B \sim 10^{-4}$ counts/keV/kg/y
- Limit: $T^{0\nu}_{1/2} \sim 6.5\ 10^{24}$ y
- Construction started, running 2015-2016 (LSM)
- Prove scalability for a full-scale 20 modules with : 100 kg $\times$ 2016-2020 $T^{0\nu}_{1/2} \sim 10^{26}$ y, $< m_\nu > =$ 40-100 meV
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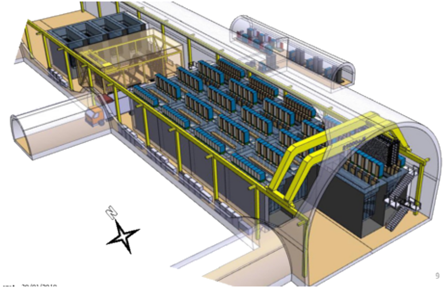
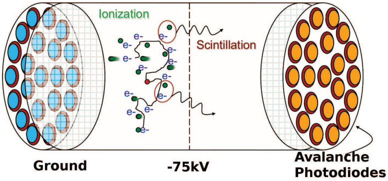
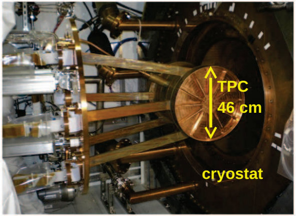


EXO-200 – Calorimeter, ^{136}Xe

Enriched Xenon Observatory





- Liquid-xenon TPC with ionisation & scintillation readout
- Fiducial mass of 79.4 kg of ^{136}Xe for the $0\nu\beta\beta$ search.

^{136}Xe 2νββ measurement :

$$T_{1/2}^{2\nu\beta\beta} = 2.11 \pm 0.04(\text{stat.}) \pm 0.21(\text{syst.}) \times 10^{21}\ \text{yr}$$

Ackerman et al. (2011)

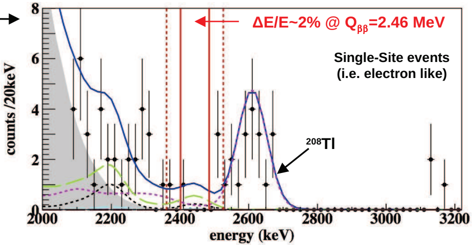
1 event observed in 1σ RoI around $Q_{\beta\beta}$ vs. 4.1 background events expected.

33 kg.yr B~0.0015 cts/keV/kg/yr

$$T_{1/2}^{0\nu\beta\beta} > 1.6 \times 10^{25}\ \text{yr}\ \ @\ 90\%\ \text{C.L.}$$

$$\langle m_\nu \rangle < 140 - 380\ \text{meV}$$

Auger et al. (2012)

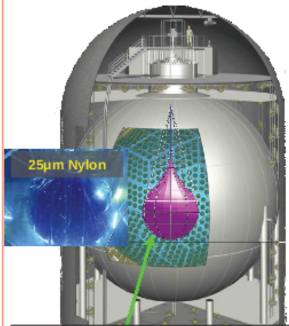


KamLAND-ZEN – Calorimeter, ^{136}Xe

KamLAND-Zen

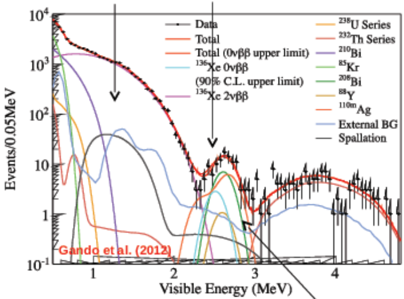
- Several 0νββ isotopes compatible with LS.
- Large masses can be loaded.
- Reasonable energy resolution :

$\sigma_E = 6.6\% / \sqrt{E(\mathrm{MeV})}$



300 kg ^{136}Xe (129 kg after fiducialisation) loaded LS mini-balloon, R=1.7m
Density well matched to outer LS

$^{136}\mathrm{Xe}(2\nu\beta\beta)$ $Q(\beta\beta) = 2.5$ MeV



$T_{1/2}^{2\nu} = 2.38 \pm 0.14 \times 10^{21}$ yr

$T_{1/2}^{0\nu} > 5.7 \times 10^{24}$ yr @ 90% C.L.

$\langle m_{\beta\beta} \rangle < (0.3 - 0.6)$ eV

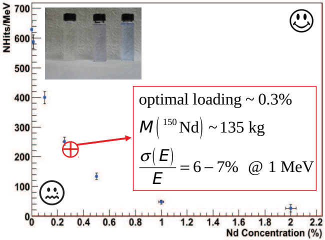
Fall-out: ^{110m}Ag, ^{208}Bi (?) produces E ~ 2.6 MeV

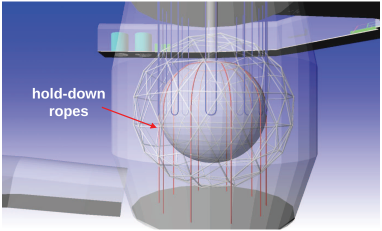
- Currently background limited (Fukushima).
- Reduce backgrounds by factor 100, increase ^{136}Xe mass and use brighter scintillator.
  - target of <m$_\nu$> ~ 20-40 meV

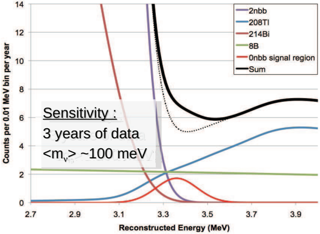
SNO+ – Calorimeter, ^{150}Nd

SNO+

- SNO detector filled with 800 tonnes of LS : **L**inear **A**lkyl-**B**enzene + 2g/litre PPO fluor.
- Broad physics program : solar/geo-ν; SN; 0νββ
- Major engineering challenges.
- Extremely stringent radiopurity requirements :
  - **< 10^{-17}g ^{228}Ra/^{228}Th per g scintillator**.
  - **< 10^{-14}g ^{228}Ra/^{228}Th per g Nd**
- Purification proof of principle : KamLAND/Borexino.







Summary [1]

- DBD physics is a major concern for particle physics :
  - Lepton number non conservation
  - Majorana neutrino
  - Neutrino mass, "exotic" weak coupling, SUSY
- Interplay with other ν mass measurements, hierarchy problem and oscillation experiments
- A new generation experiments (10-100kg) have started or will within few years
  - We are entering the era of 100 kg scale DBD experiments
  - Different isotopes, techniques, mass and backgrounds
  - Lots of experimental efforts are done to improve, step by step, the sensitivity of DBD detectors
  - Some very interesting results are expected within a few years (GERDA, EXO, KAMLAND, SNO+, CUORE. . . SuperNEMO. . .)
  - We need a few years to make our mind about the best way(s), maybe 1-2 techniques remaining in the future (2020+)
  - In the meanwhile, some R&D programs with (promising) novel techniques has started (scintillating bolometers, tracker crystals, gas TPC. . .)

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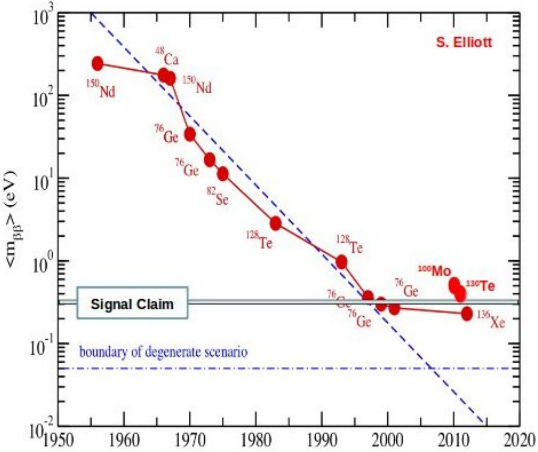

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  - Thanks to the motivation of many skilled groups worldwide
- Message for the newborn LIO : please consider carefully to join some DBD experimental program !

Thanks (for stolen slides and pictures)

- David Waters, UCL, Batavia, NNN 2012, http://conferences.fnal.gov/nnn12/
- Fabrice Piquemal, LSM, Kyoto, Neutrino 2012, http://neu2012.kek.jp/
- ...

Apologies and also best wishes for

- AMoRE (^{100}Mo)
- CANDLES (^{48}Ca)
- COBRA (^{116}Cd)
- DCBA (^{100}Mo/^{150}Nd)
- LUCIFER(^{Se}82/^{100}Mo)
- MAJORANA (^{76}Ge)
- MOON (^{100}Mo)
- NEXT (^{136}Xe)
- XMASS (^{136}Xe)
- ZnMo4 (^{100}Mo), CdMo4 (^{116}Cd)...