Radioactivity and the limits of the Standard Model

(Extra: Double Beta Decay)

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Outline

I. Introduction (13 slides)

- Why and How (LE vs HE)?
- Current questions and goals of the lectures
- A quick reminder on beta decay (Prerequisites)

II. Nuclear beta decay: How testing the weak interaction? (61 slides)

- Some tracks on theory: from Golden rule to events distributions
- Which terms for which physics?
- A word on some approximations and consequences…
- A special case: the Fierz term
- The Standard Model (SM) and beyond (helicity, "ft" values,…)

A special thanks to François Mauger who provided all the slides….

III. From theoretical rates to correlation experiments (21 slides)

- Beta-neutrino correlations
- Correlations involving polarized decaying nuclei

IV. Last section: CVC, V_{ud} & CKM (20 slides)

- Pure Fermi decays
- Other sources: nuclear mirror decays
- Other sources: the neutron case

V. Extra: DBD and neutrino nature

- What is double beta decay (DBD)?
- Measurements principle: counting, BG, …
- Example of setups: NEMO, SUPERNEMO,…

What is double beta decay (DBD) ?

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

[Goeppert-Mayer, 1935]

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

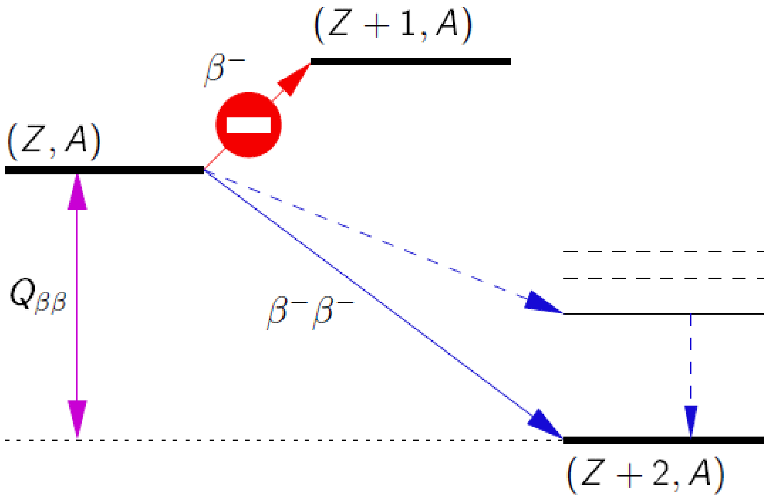
- $\Delta L = 0$
- Allowed in SM
- Decay rate : slow (second order weak process) and $\sim Q_{\beta\beta}^{11}$
- Can be calculated :

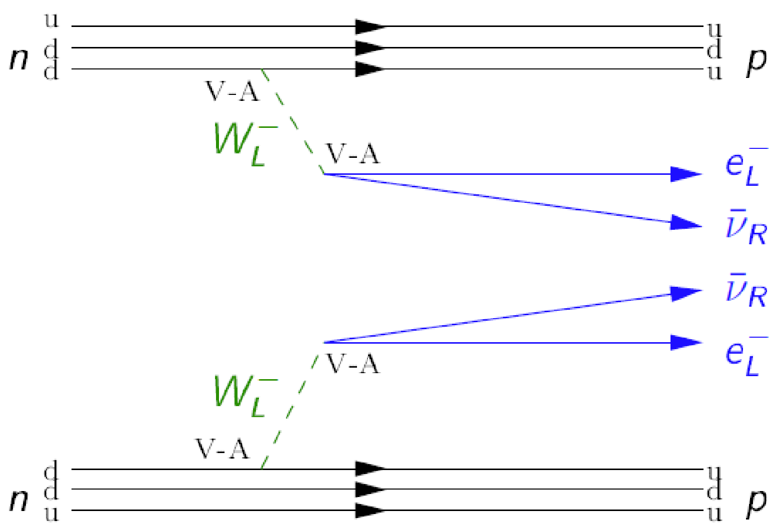
$$ (T_{1/2}^{2\nu})^{-1} = G_{2\nu}(Q_{\beta\beta}, Z) \times \mid M_{2\nu} \mid^{2} $$

- Has been measured :

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

- Not very interesting. . . but. . .





What is neutrinoless double beta decay (DBD) ?

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

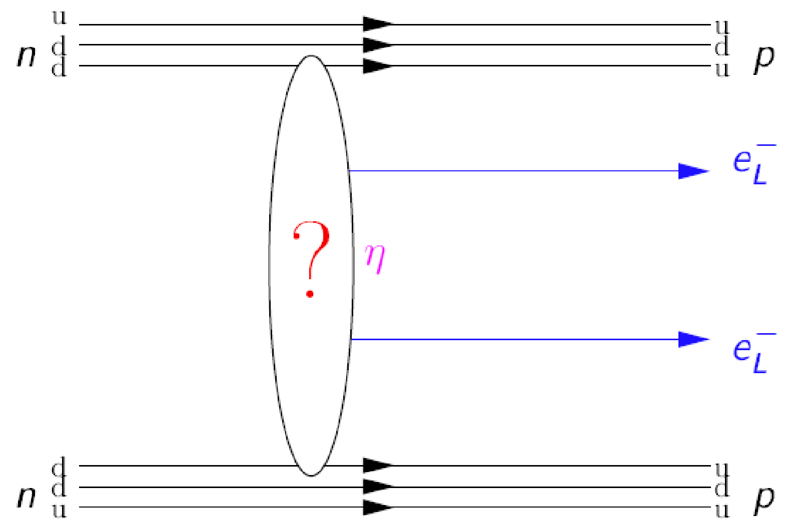
$$^{A}_{Z}X \longrightarrow ^{A}_{Z+2}Y + 2e^-$$

- $\Delta L = 2$!!!
- 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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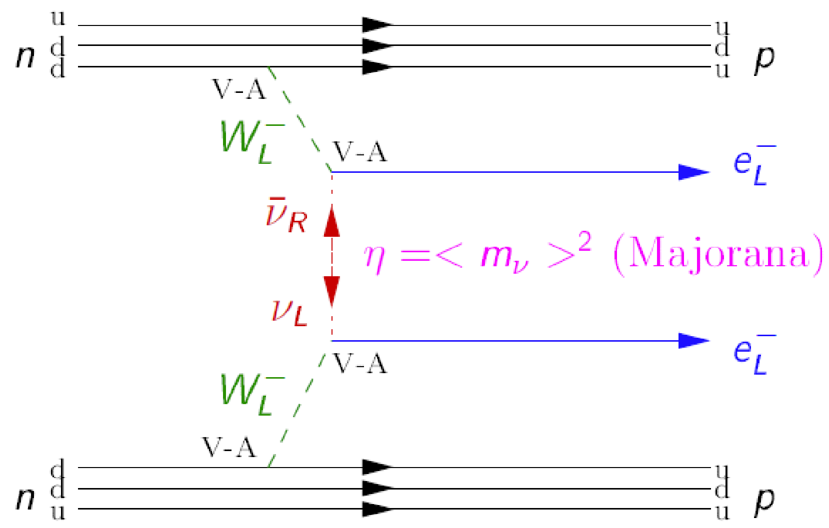
    - Majorana neutrino [PRD 25 (1982) 2951]
    - Effective light Majorana neutrino mass $< m_\nu > \neq 0$



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)
- Switch on the detector, seat down and wait. . . wait. . . wait. . .

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.) [%]	$G_{0\nu}$ ($\tilde{G}_{0\nu}^{76}$) $[10^{-14}\ (y^{-1})]^a$	$M_{0\nu}{}^a$	$T_{1/2,exp}^{2\nu}$ $[10^{19}$ (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)

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

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

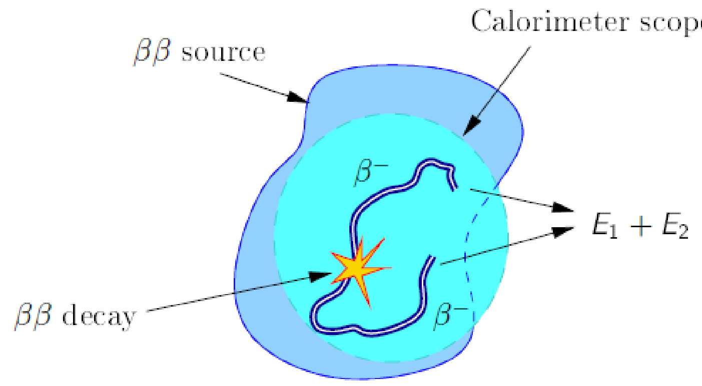
[a] from PRD 83, 113010 (2011)

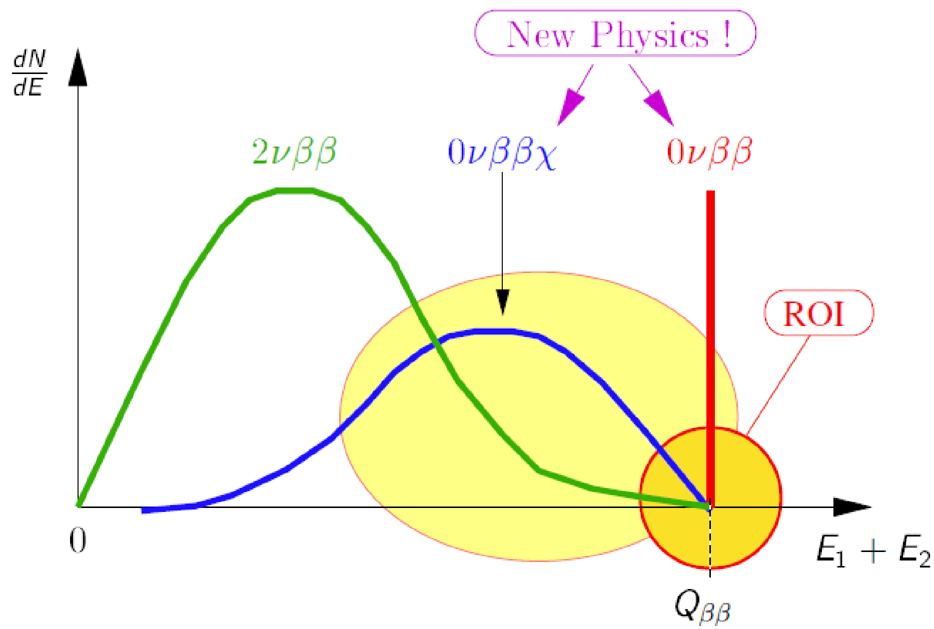
[b] achieved in NEMO-3, [c] achieved in HM, [d] achieved in EXO-200

[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
- A critical criterion for signal/background discrimination in the $Q_{\beta\beta}$ ROI





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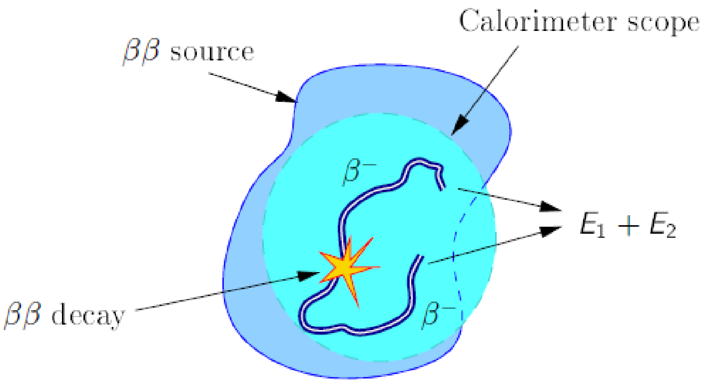

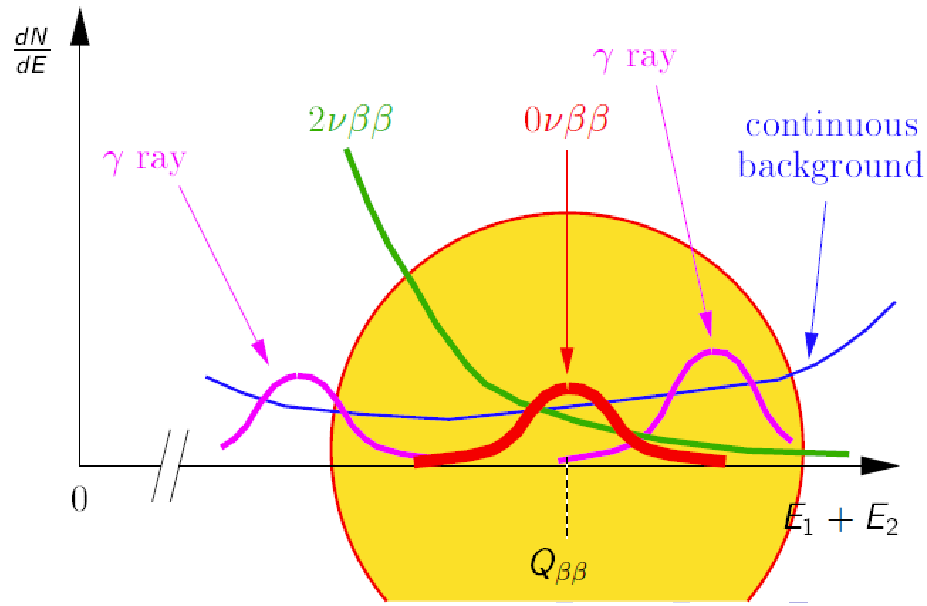

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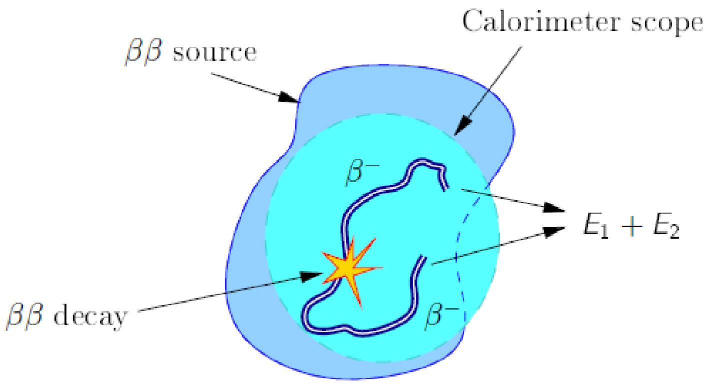
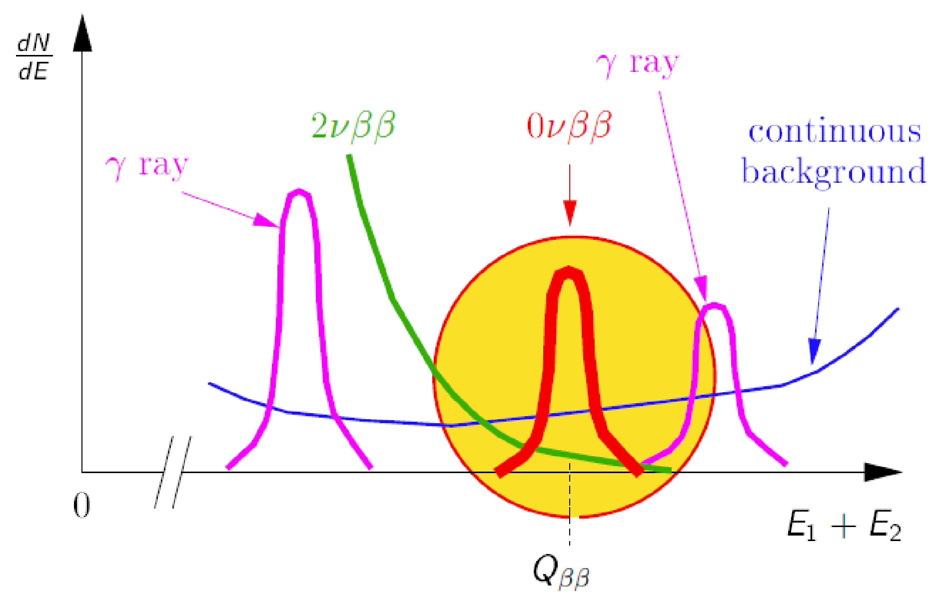
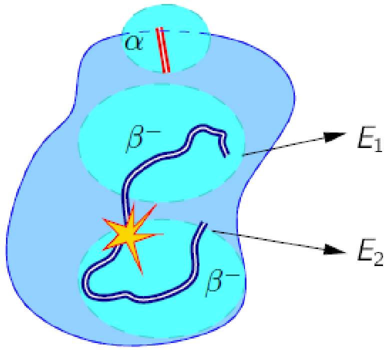
- Introducing the background index: typical $B \sim 0.1 - 0.001$ counts/keV/kg/y

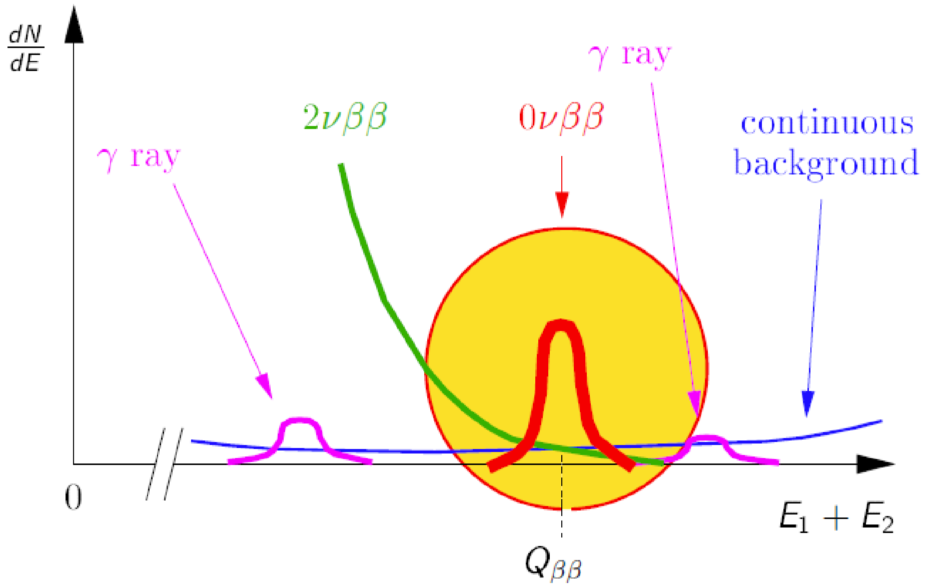




Measuring the electron energy sum spectrum @ $Q_{\beta\beta}$

- Use a Calorimeter :
  measurement of the energy sum of both electrons emitted in $\beta\beta$ processes
- A critical criterion for signal/background discrimination in the $Q_{\beta\beta}$ ROI
- High energy resolution is a must
- Introducing the background index:
  typical $B \sim 0.1 - 0.001$ counts/keV/kg/y
- Additional criteria :
  particle identification
  (γ, e^-, e^+, α...)





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

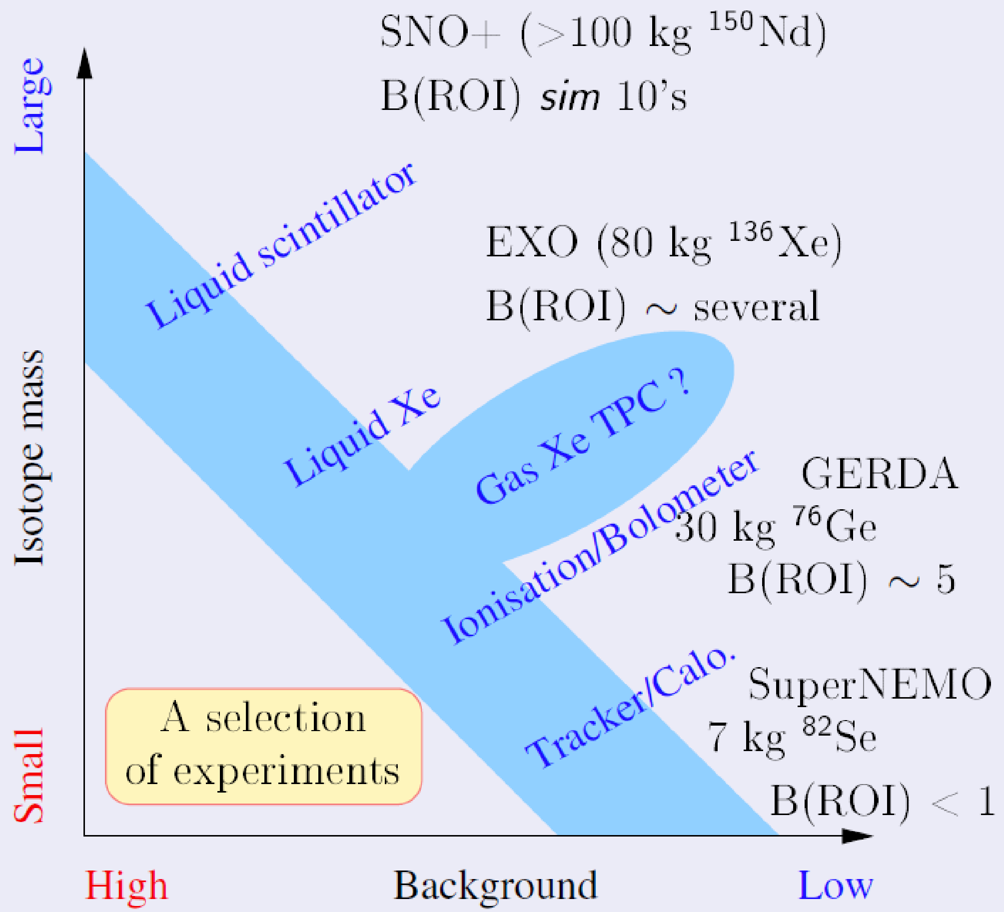
Hybrid

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

Experimental approaches

It there a “best” technique for DBD ?

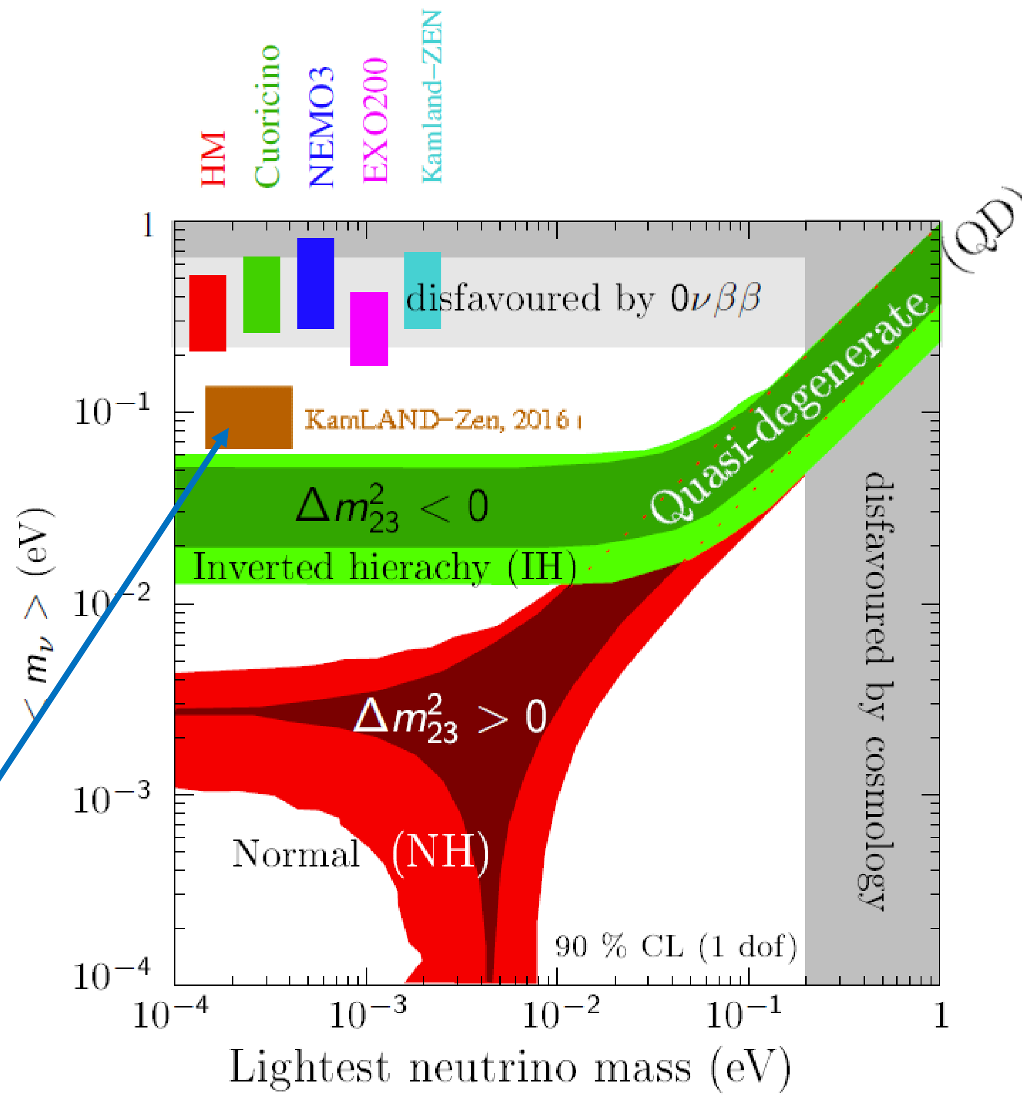
- Each technique has its own problems in terms of source enrichment, source purification and, last but definitively not the least, background(s)
- None is zero-background experiment (but some could pretend to be. . .)
- Each realizes a kind of compromise
- Some approaches exist to get the best available. . .



Where we are now !

- ~1990-2000 : HM experiment (^{76}Ge)
- ~2000-2010 : ≃10 kg
  - Cuoricino (^{130}Te, 2008)
  - NEMO3 (^{100}Mo, 2011)
- ~2011+ : New generation experiments
  ≃10-100 kg
  First stimulating results :
  - EXO200 (^{136}Xe)
  - Kamland-ZEN (^{136}Xe)

- KamLAND-Zen (^{136}Xe) : $T^{0\nu}_{1/2} \geq 1.07\ 10^{26}$ yr (344 kg, PRL 117.082503 (2016))
  $m_{\beta\beta} < 61$–165 meV

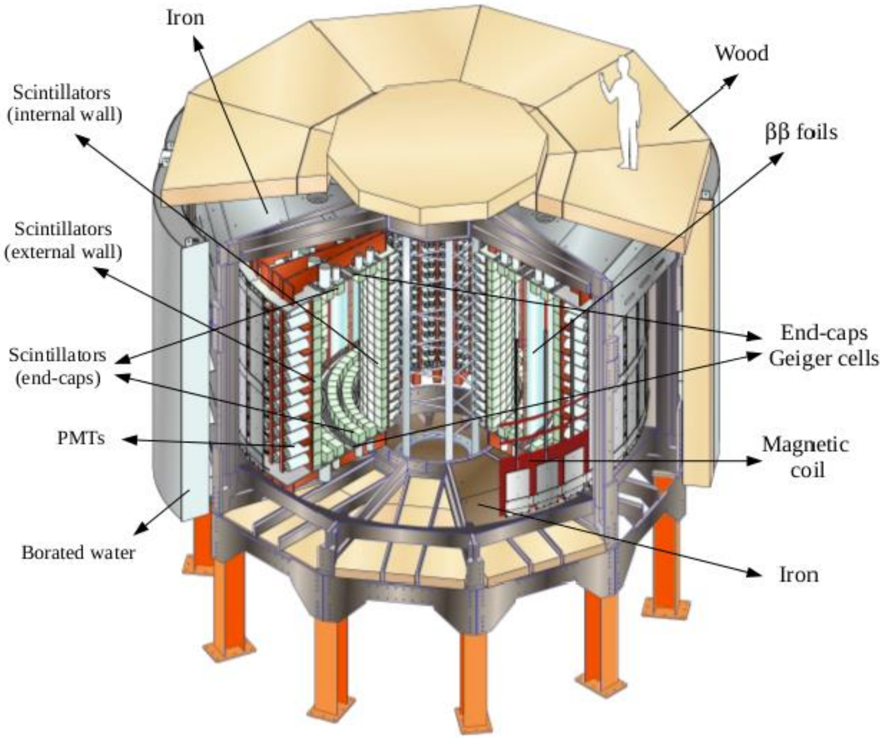


[Strumia & Vissani, hep-ph/0606054]

NEMO3 @ LSM

- Installation 2000-2003 at LSM
- Complex detector :
  - Very low radioactivity setup
  - 250 tons shielding, anti-radon factory
  - $\mathcal{O}(20000)$ readout channels
- Data taking 2003-2011 :
  - $\simeq$7 kg ^{100}Mo ($0\nu\beta\beta$ exposure : 34.3 kg$\times$yr),
  - $\simeq$1 kg ^{82}Se*,
  - small amounts of ^{116}Cd, ^{130}Te, ^{48}Ca*, ^{150}Nd*, ^{96}Zr : $2\nu\beta\beta$ measurements (n.m.e.) and background studies.

* isotopes of interest for the future



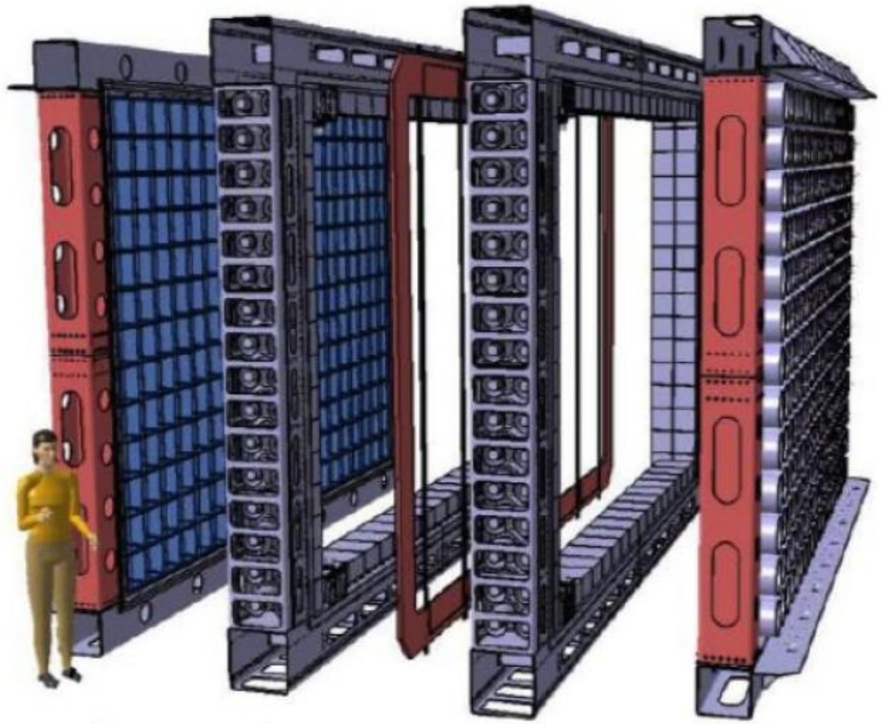
R. Arnold et al. PRD 92 (2015)

R. Arnold et al. PRD 94 (2016)

SuperNEMO – toward 100 kg DBD experiment !

- 2004 : Reuse and improve NEMO3 techniques :

  larger mass and efficiency, better energy resolution, lower background, scalability (modular, planar) to achieve a larger mass of $\beta\beta$ source...
- Goals :
  - 100 kg DBD isotopes (^{82}Se...^{48}Ca, ^{150}Nd) $\times$ 5 y
  - Radiopurity (source) : $A(^{214}Bi) < 10\ \mu$Bq/kg , $A(^{208}Tl) < 2\ \mu$Bq/kg
  - $A(^{222}Rn) < 150\ \mu\text{Bq/m}^3$ (tracker gas)
  - Total background : $\mathcal{O}(< 1\ \text{event}/y)$



- Target sensitivity : $T^{0\nu}_{1/2} > 10^{26}$ y $\rightsquigarrow m_{\beta\beta} < 50 - 100$ meV

SuperNEMO – Agenda

- 2004-2012 : R&D (BiPo, calorimetry, radon, source, material screening...)
- Current step (2014-2019) : demonstrator module under construction @ LSM
  - 7 kg $\times$ 2.5 y with ^{82}Se ($Q_{\beta\beta} \simeq 3$ MeV) :
  - Sensitivity : $T_{1/2}^{0\nu} > 6\ \ 10^{24}$ y
  - Aims to demonstrate : zero background $0\nu\beta\beta$ experiment, radon free
  - Commissioning : last week !
  - Expected start : end 2017
- Physics goal : with a full scale multi module detector (2020+ ?)
  - 20 modules $\times$ 5 kg = 100 kg $\times$ 5 y (baseline : ^{82}Se)
  - Other isotopes are considered : ^{48}Ca, ^{150}Nd
    (high $Q_{\beta\beta} > 3.2$ MeV ^{214}Bi) $\leadsto$ radon free exp.
  - Expected sensitivity : $T_{1/2}^{0\nu} \simeq 10^{26}$ y
    $\simeq$ KamLAND-Zen current results, still not the IH region !

Next generation of experiments