

# Nature et masse du neutrino

22<sup>eme</sup> Congrès Général de la Société Française de Physique

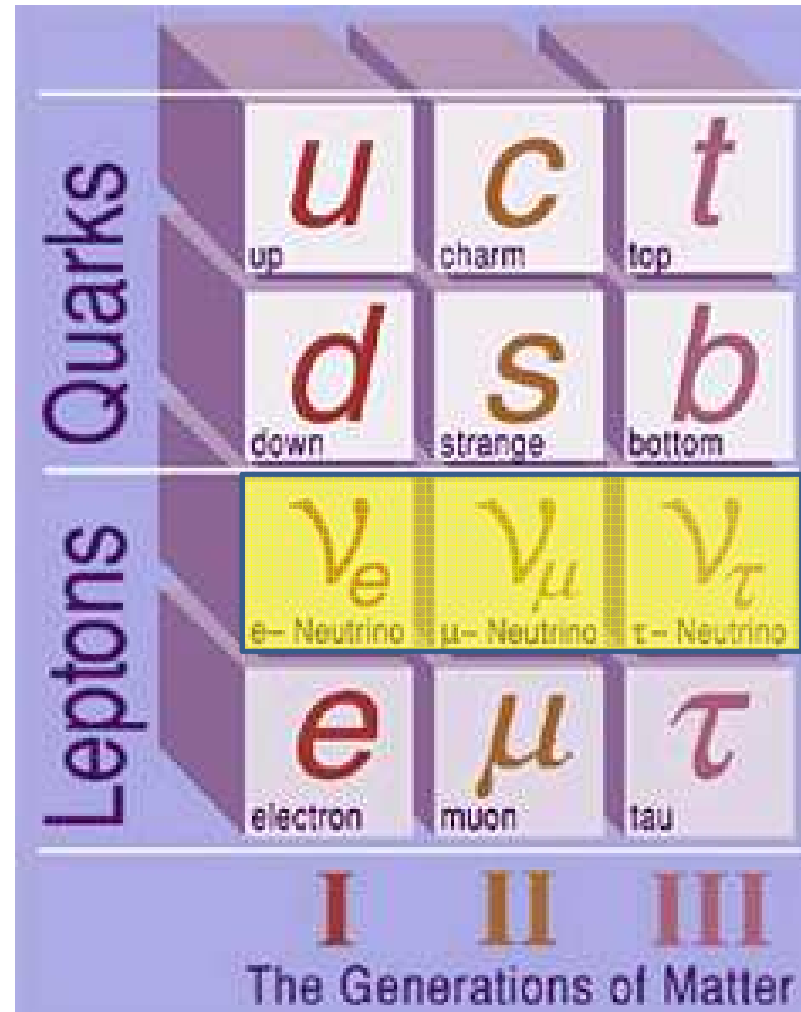
Marseille Juillet 2013

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# Neutrino

- No charge
- Mass ??



# Neutrino mixing and oscillations

Pontecorvo – Maki – Nakagawa - Sakata (PMNS) matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

weak eigenstates  $\rightarrow$  mass eigenstates

$$P_{\alpha \rightarrow \beta} = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

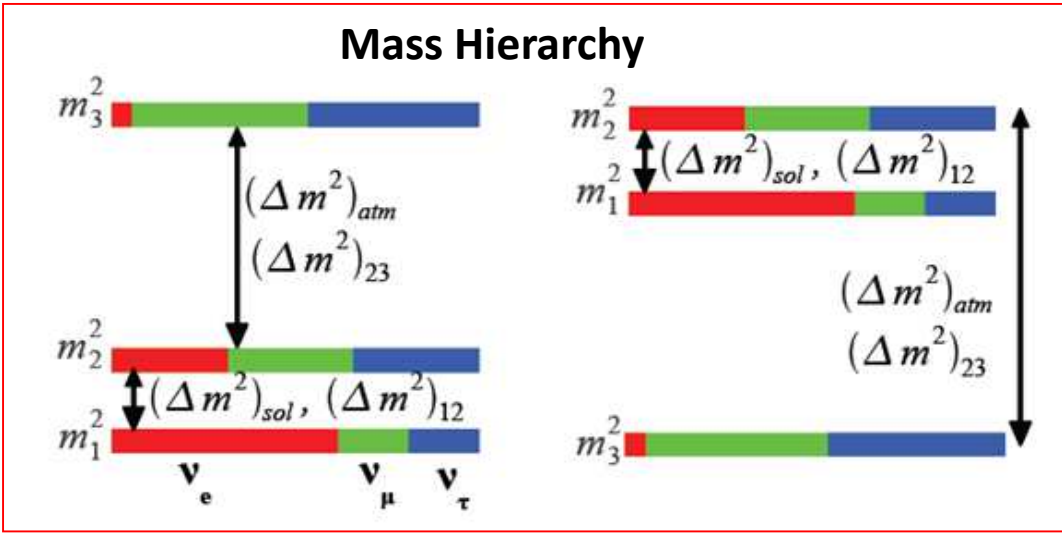
mixing  $\rightarrow$  mass

# Neutrinos oscillation experiments

- Solar Neutrinos
- Atmospheric Neutrinos
- Accelerator Neutrinos
- Nuclear Reactor Neutrinos



$m_\nu \neq 0, m_\nu = ???$



Normal OR Inverted ???

# Direct measurements of neutrino masses

$$\nu_e : {}^3\text{H} \rightarrow {}^3\text{He} + e^- + \bar{\nu}_e \quad \langle m_e \rangle < 2.2 \text{ eV}$$

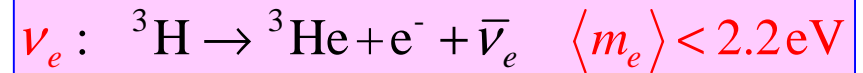
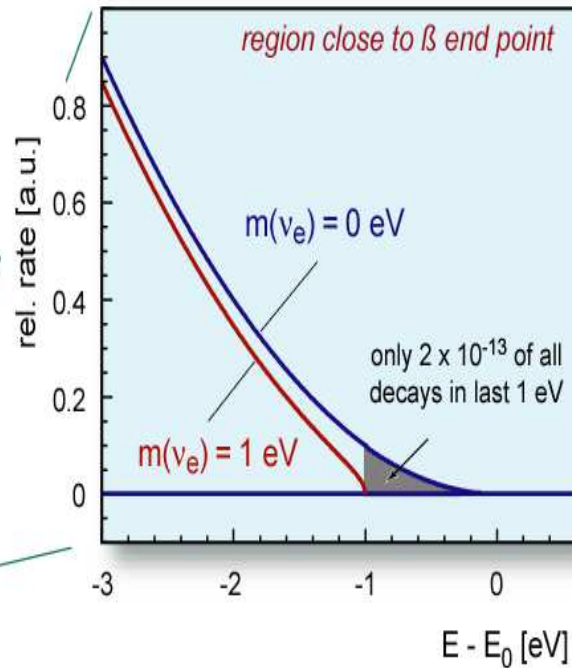
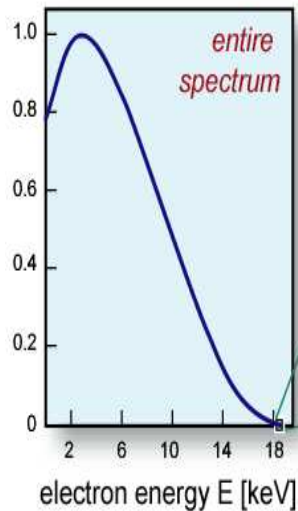
$$\nu_\mu : \pi^+ \rightarrow \mu^+ + \nu_\mu \quad \langle m_\mu \rangle < 170 \text{ keV}$$

$$\nu_\tau : \tau^- \rightarrow \nu_\tau + 5\pi \quad \langle m_\tau \rangle < 18 \text{ MeV}$$

# Beta decay

$$E_0 = 18.6 \text{ keV}$$

$$T_{1/2} = 12.3 \text{ y}$$



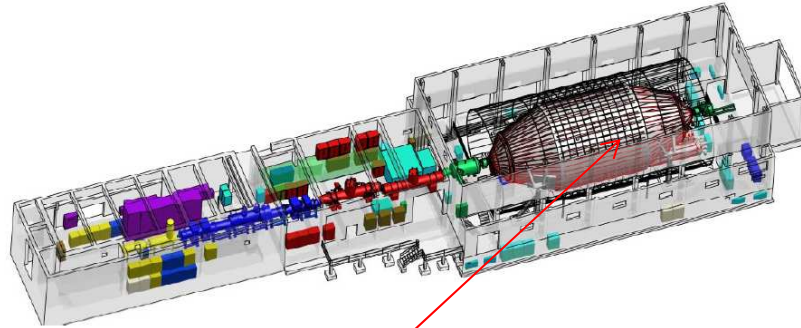
## End point experiments

experimental observable

$$dN/dE = K \times F(E,Z) \times p \times E_{\text{tot}} \times (E_0 - E_e) \times [(E_0 - E_e)^2 - m_\nu^2]^{1/2}$$

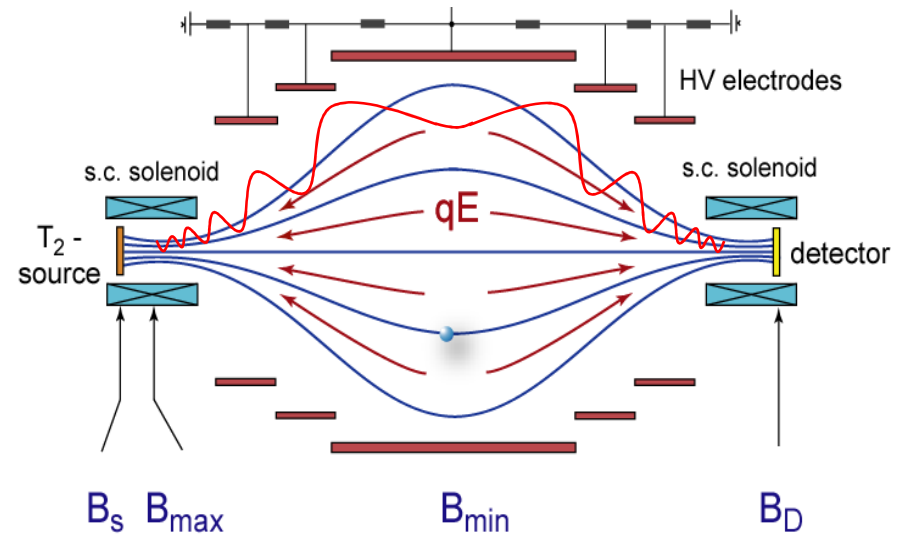
- strong source (high count rate near  $E_0$ )
- small endpoint energy  $E_0$
- excellent energy resolution
- long term stability
- low bg rate

# KATRIN experiment



## Magnetic spectrometer

### Magnetic Adiabatic Collimation + Electrostatic Filter



$$B_{max} = 6 \text{ T}$$

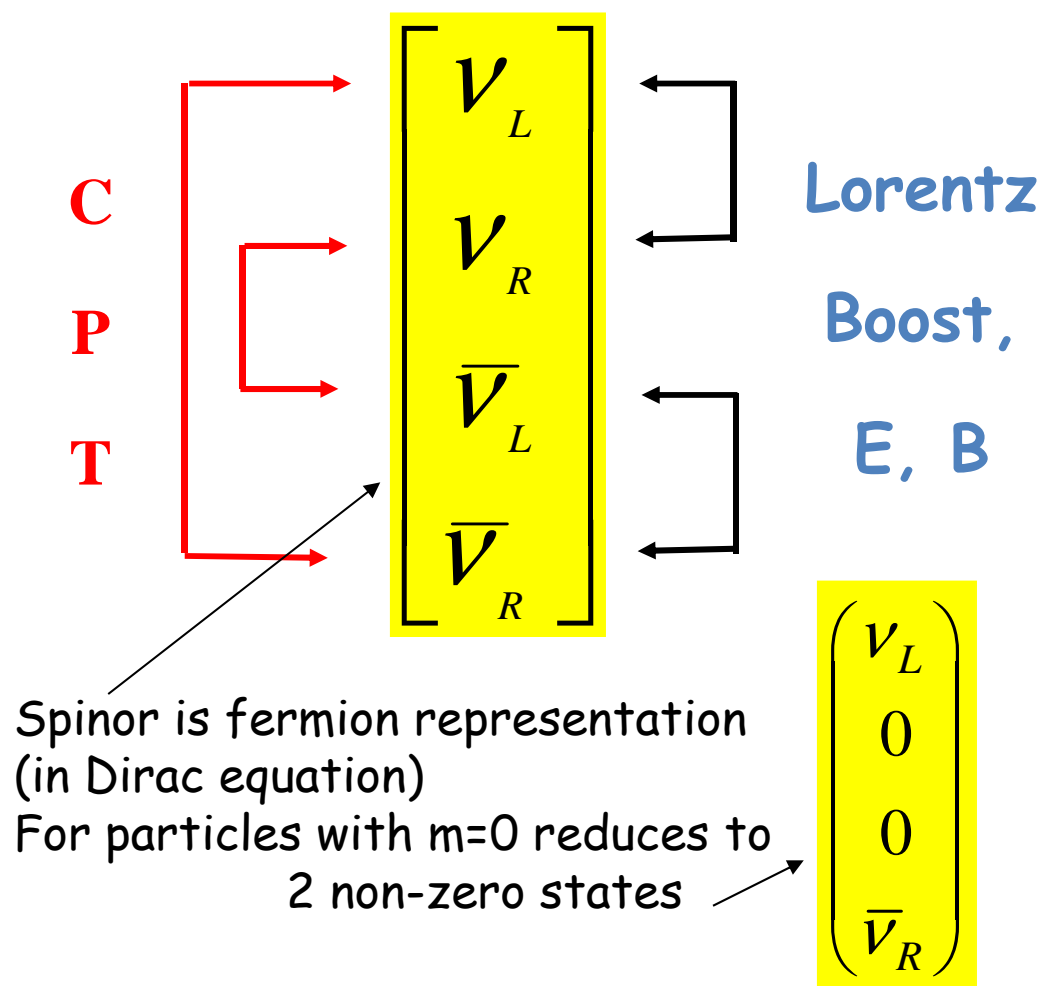
$$B_{min} = 3 \times 10^{-4} \text{ T}$$



**aim:** improvement of  $m_{\nu}$  by one order of magnitude (2eV  $\rightarrow$  0.2eV )

# Dirac neutrino vs Majorana neutrino

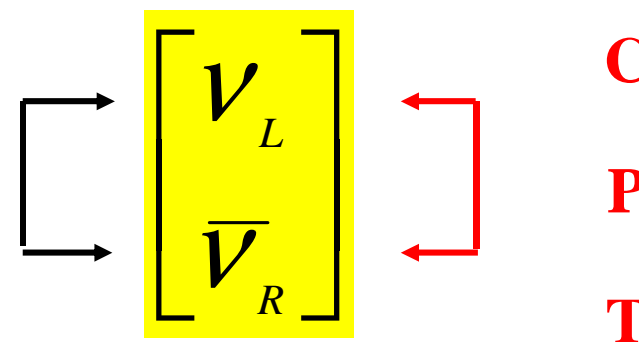
## Dirac particles



## Majorana particles

Special case: particle is it's own

anti-particle  $\bar{\nu} \equiv \nu$

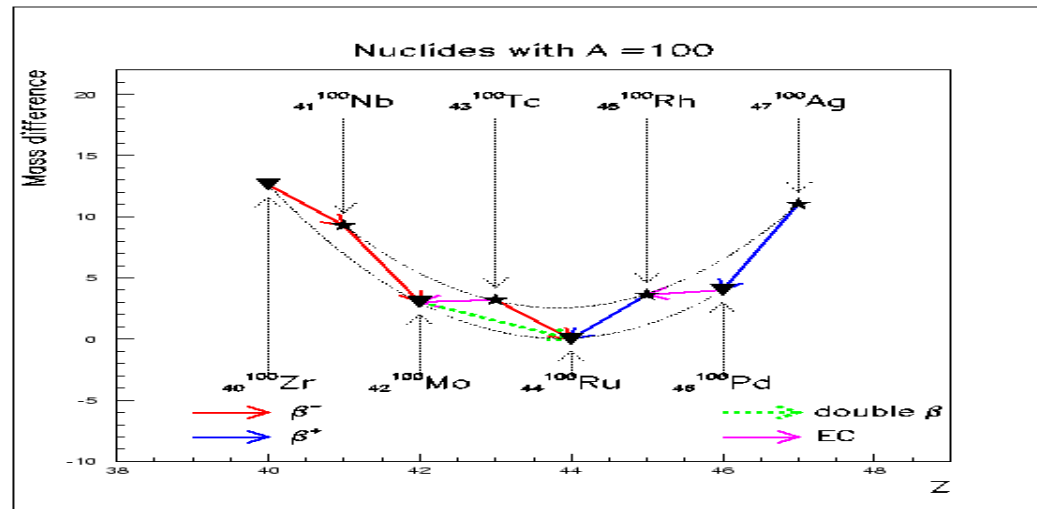


only neutral particles  
 are candidates for being  
 Majorana particle



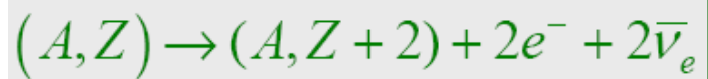
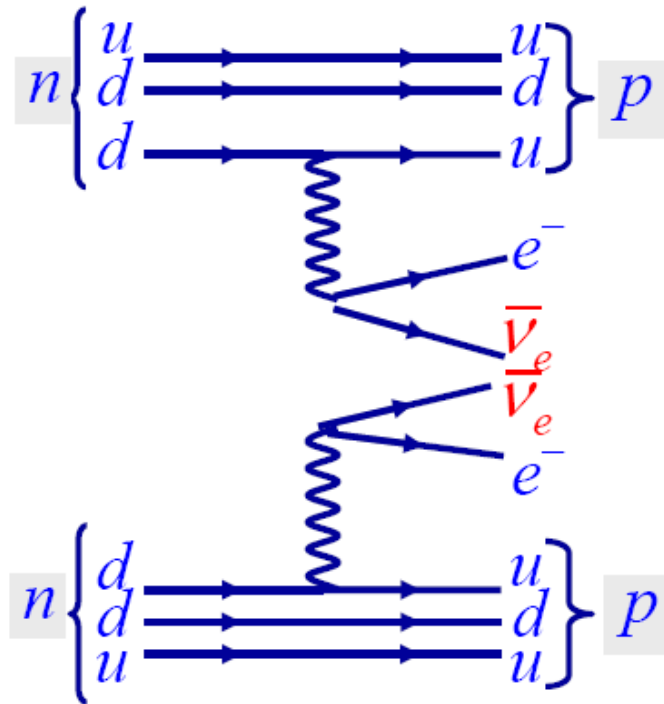
# Double Beta Decay

Even - Even nucleous



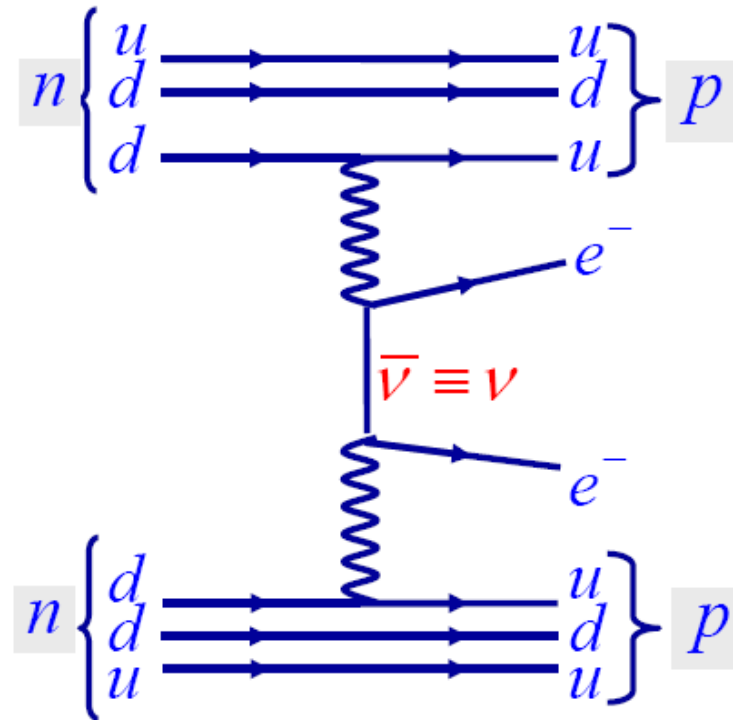
# Double beta decay

$2\beta 2\nu$



$\Delta L = 0$

$2\beta 0\nu$



$\Delta L \neq 0$

# Neutrinoless Double beta decay

$$\Delta L = 2$$

➤ Majorana Neutrino  $\nu \equiv \bar{\nu}$

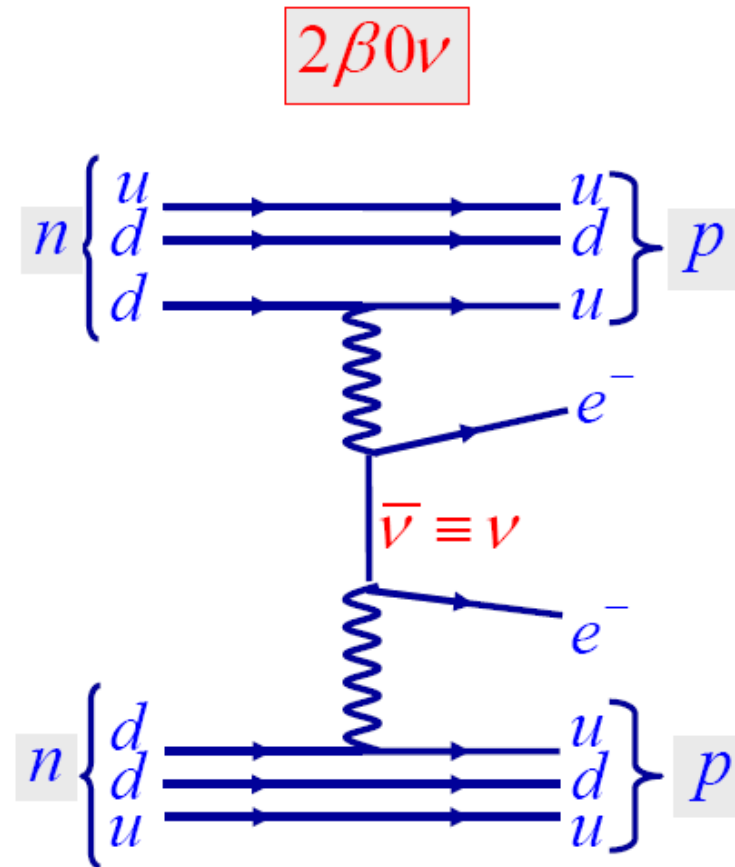
➤  $m_\nu \neq 0$

Other possible process

➤ RHC (V+A)  $\rightarrow \nu_R, \bar{\nu}_L$

➤ Majoron  $\rightarrow$  B-L

➤ Supersymmetry



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

$$\Delta L \neq 0$$

# Neutrinoless Double beta decay

Phase space factor

Nuclear matrix element

$$T_{1/2}^{-1} = F(Q_{\beta\beta}, Z) |M^{0\nu}|^2 \langle m_\nu \rangle^2$$

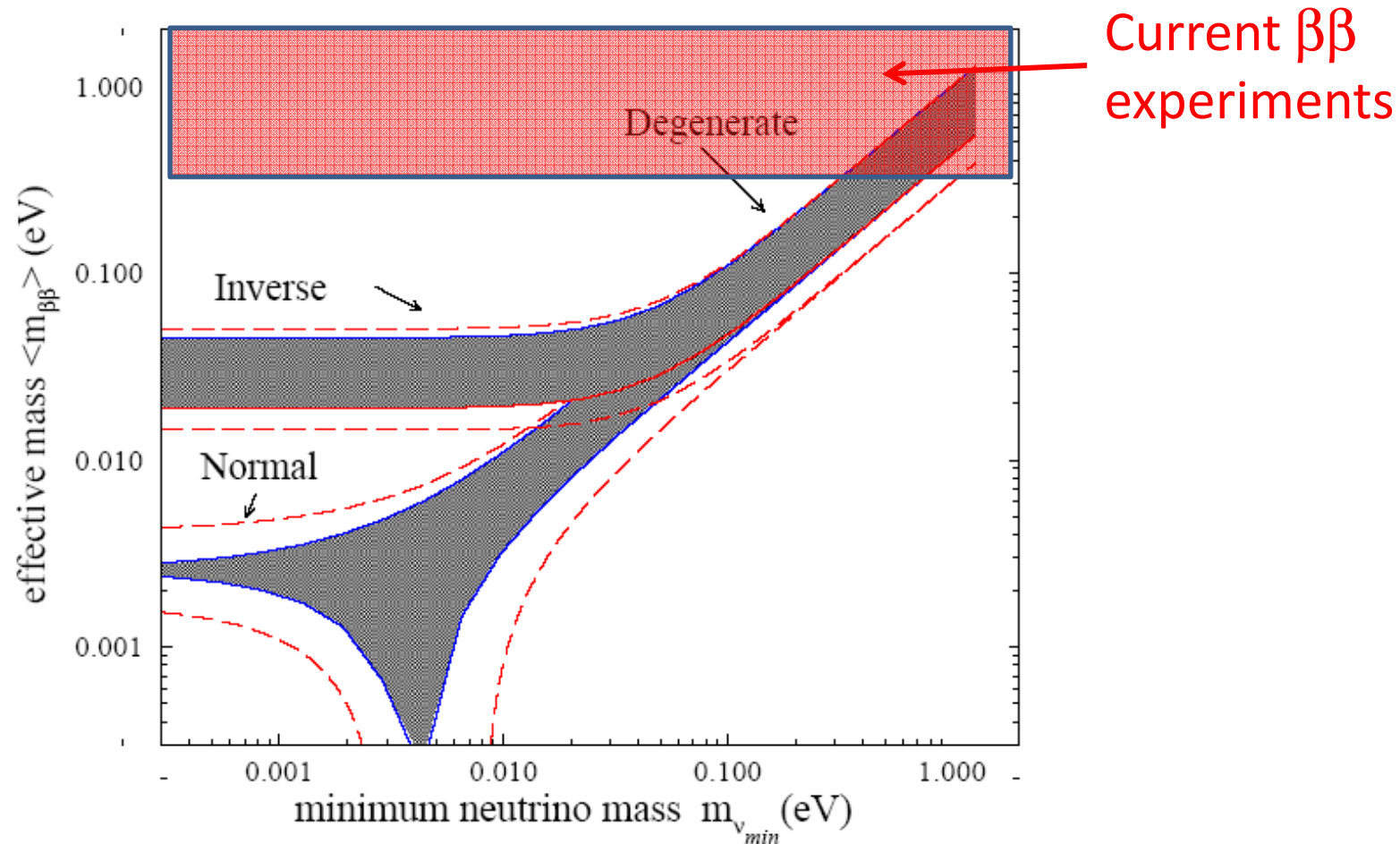
$$\langle m_\nu \rangle = m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 \cdot e^{i\alpha} + m_3 |U_{e3}|^2 \cdot e^{i\beta}$$

$|U_{ei}|$ : mixing matrix elements

$\alpha$  et  $\beta$ : Majorana phases

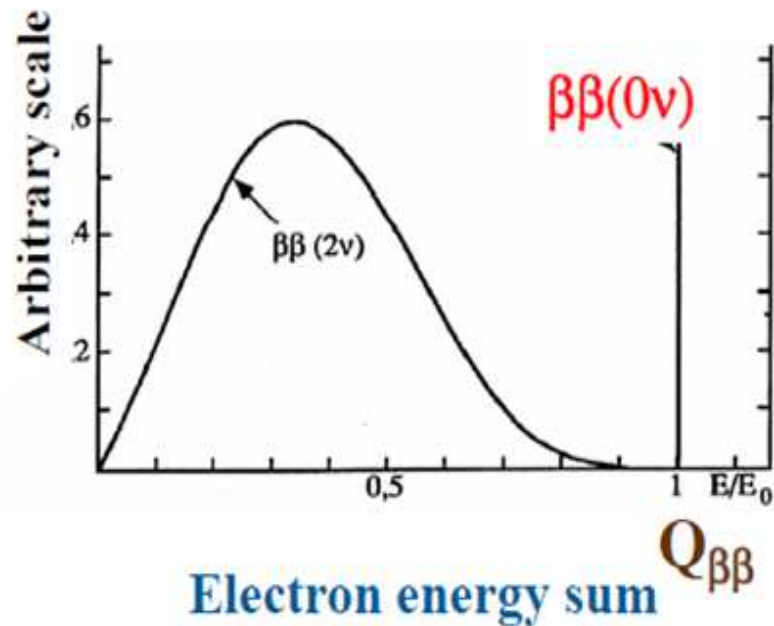
# Mass Hierarchy

If dominant process : light Majorana  $\nu$



Future experiments : start exploring at least the inverse hierarchy area

# $(\beta\beta)_{0\nu}$ observables



Angular distribution

Individual electron energy

Allow to distinguish  
the mechanism

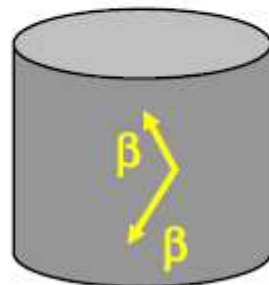
**Background :** natural radioactivity, radon, neutrons, muons,  $\beta\beta(2\nu)$

# Experimental techniques

$$T_{1/2}^{0\nu}(\text{y}) > \frac{\ln 2 \cdot \mathcal{N}}{k_{\text{C.L.}}} \cdot \frac{\epsilon}{A} \cdot \sqrt{\frac{M \cdot t}{N_{\text{Bckg}} \cdot \Delta E}}$$

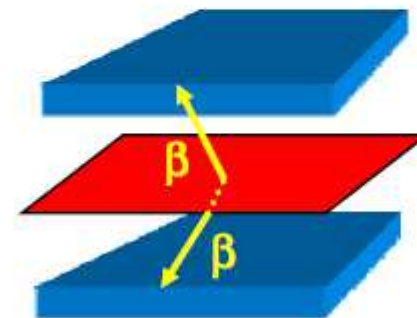
**M**: masse (g)  
 **$\epsilon$** : efficiency  
 **$k_{\text{C.L.}}$** : Confidence level  
 **$\mathcal{N}$** : Avogadro number  
**t**: time (y)  
 **$N_{\text{Bckg}}$** : Background events ( $\text{keV}^{-1} \cdot \text{g}^{-1} \cdot \text{y}^{-1}$ )  
 **$\Delta E$** : energy resolution (keV)

**Calorimeter**  
**Semi-conductors**  
**(Loaded) Scintillator**  
**Bolometers**  
**Source = detector**



**$\epsilon, \Delta E, M$**

**Tracko-calo**  
**Source  $\neq$  detector**

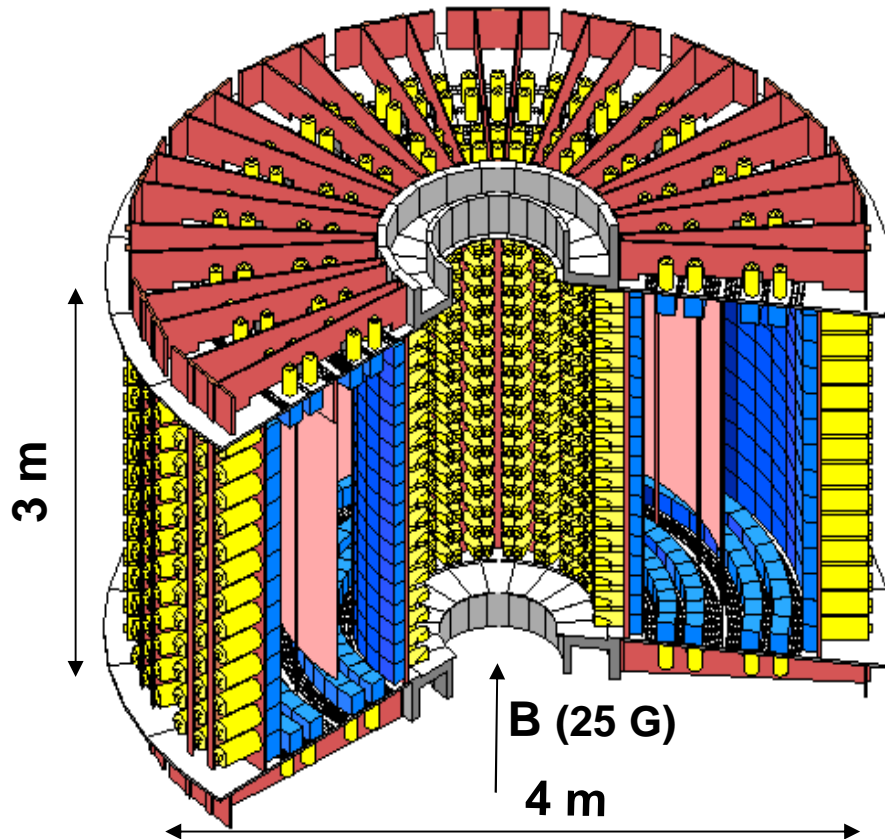


**$N_{\text{Bckg}}$ , isotope choice**

# NEMO-3 detector

Fréjus Underground Laboratory :  
4800 m.w.e.

20 sectors



Source: 10 kg of  $\beta\beta$  isotopic foils  
area = 20 m<sup>2</sup>, thickness ~ 60 mg/cm<sup>2</sup>

Tracking detector:

drift wire chamber operating (9 layers)  
in Geiger mode (6180 cells)

Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H<sub>2</sub>O

Calorimeter:

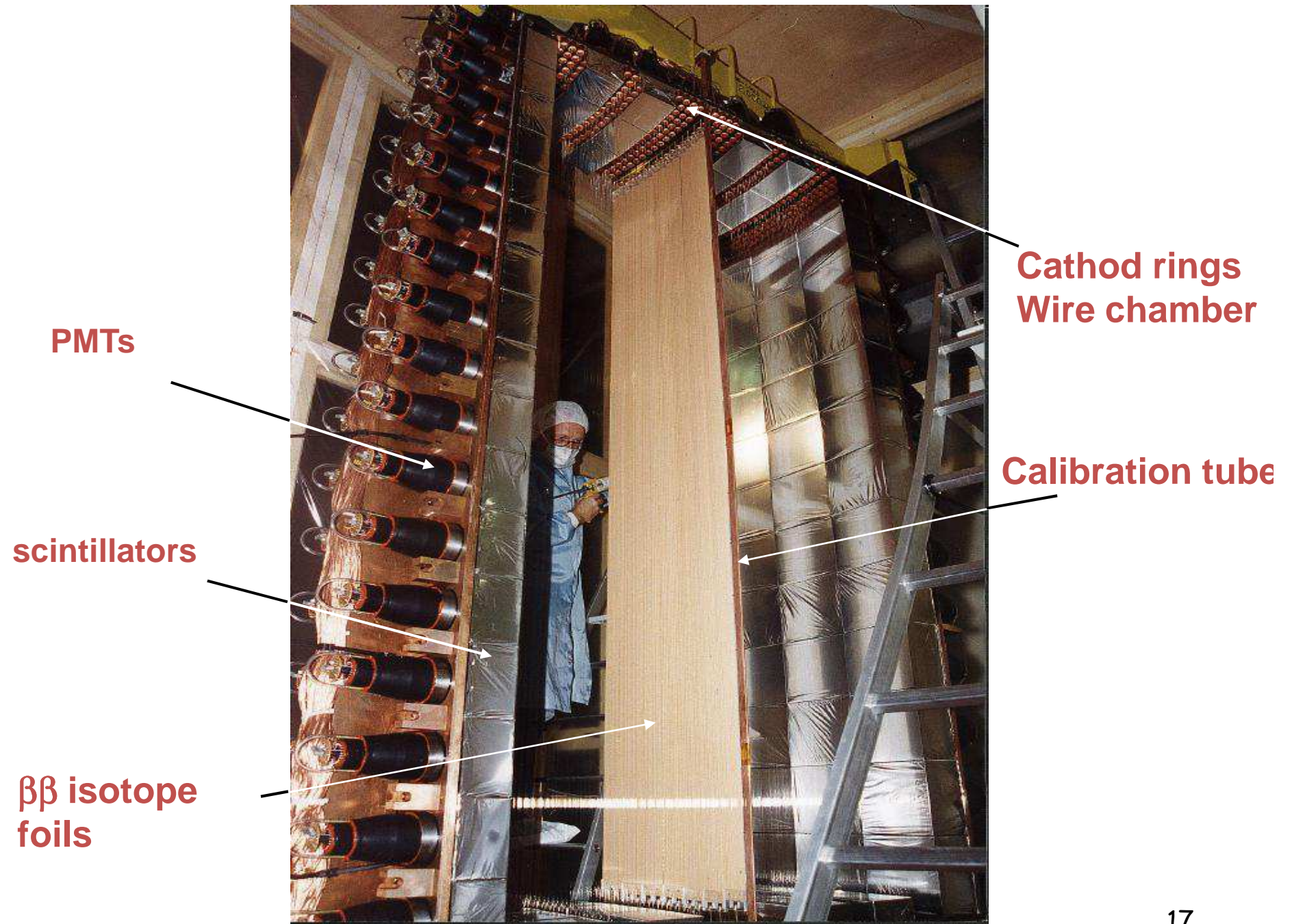
1940 plastic scintillators  
coupled to low radioactivity PMTs

**Magnetic field:** 25 Gauss

**Gamma shield:** pure iron (d = 18cm)

**Neutron shield:** 30 cm water (ext. wall)





**PMTs**

**scintillators**

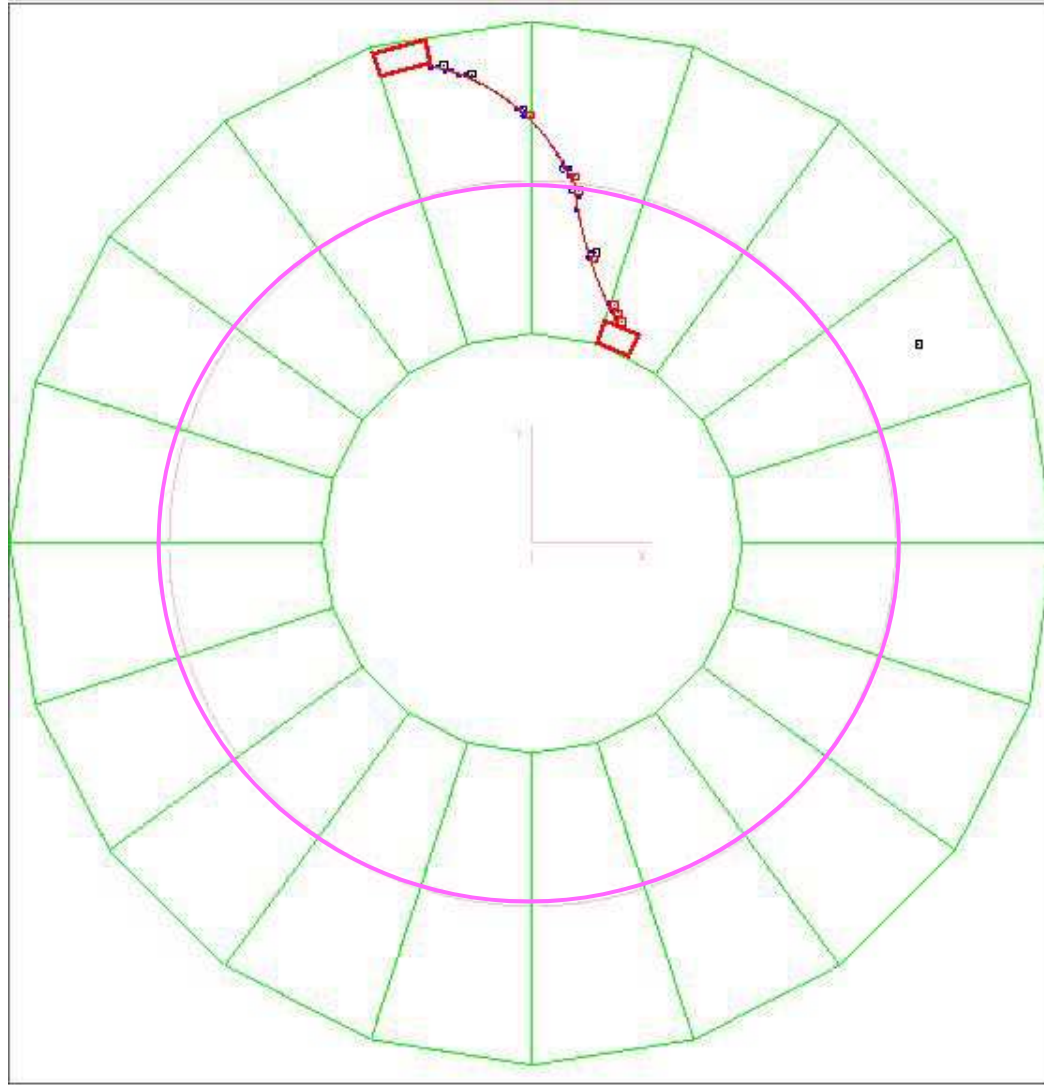
**ββ isotope foils**

**Cathod rings  
Wire chamber**

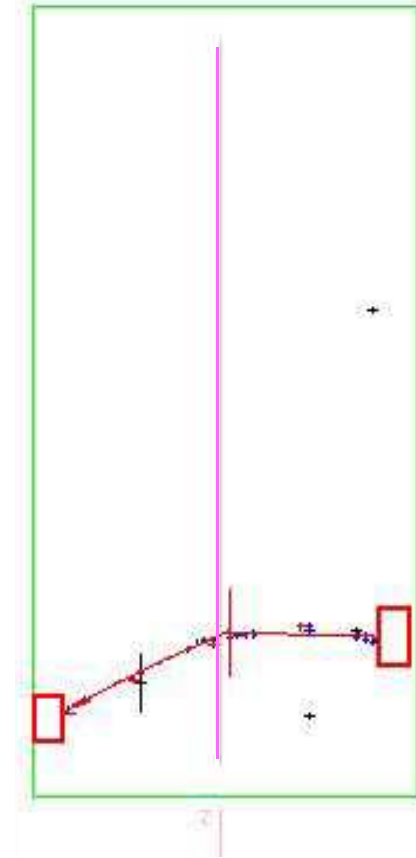
**Calibration tube**

# $\beta\beta$ events in NEMO-3 experiment

Typical  $\beta\beta$  event observed from  $^{100}\text{Mo}$



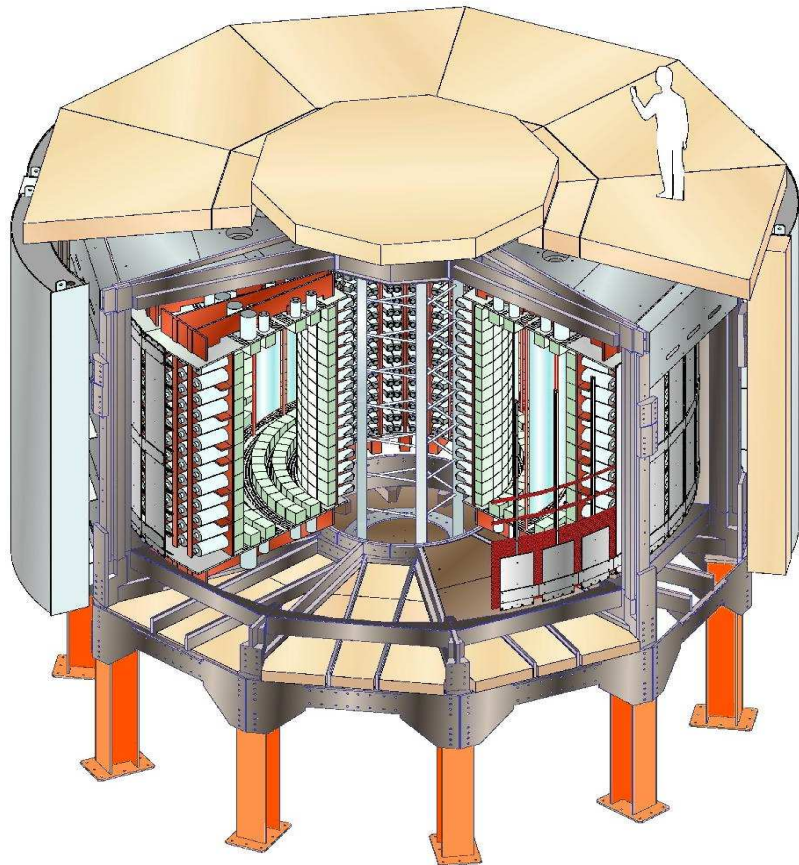
Top view



Side view

From neutrinos... DK&ER  
lecture11

# NEMO3 results



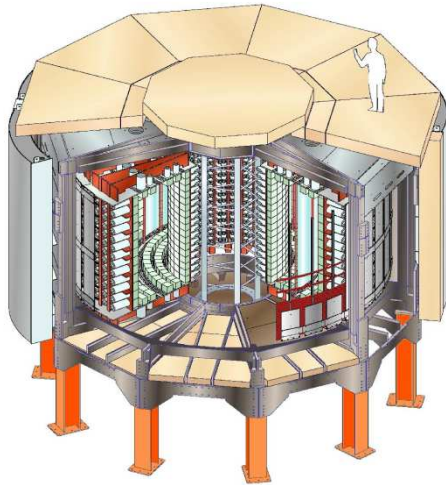
- Data from 2003 to 2011
- **Limits on  $\beta\beta 0\nu$  :**
  - $^{100}\text{Mo}$   $T_{1/2}(\beta\beta 0\nu) > 1.0 \cdot 10^{24}$  y (90% C.L.)  
 $\langle m_\nu \rangle < 0.31 - 0.96$  eV
  - $^{82}\text{Se}$   $T_{1/2}(\beta\beta 0\nu) > 3.2 \cdot 10^{23}$  y (90% C.L.)  
 $\langle m_\nu \rangle < 0.94 - 2.6$  eV
- **Phys Rev Lett95(2005)182302**

$\beta\beta 2\nu$  periods also measured for many isotopes ( $^{100}\text{Mo}$ ,  $^{82}\text{Se}$ ,  $^{116}\text{Cd}$ ,  $^{96}\text{Zr}$ ,  $^{150}\text{Nd}$ ,  $^{48}\text{Ca}$ ,  $^{130}\text{Te}$ )  
=> constrain nuclear models parameters.

Limits from Majoron (right currents) searches

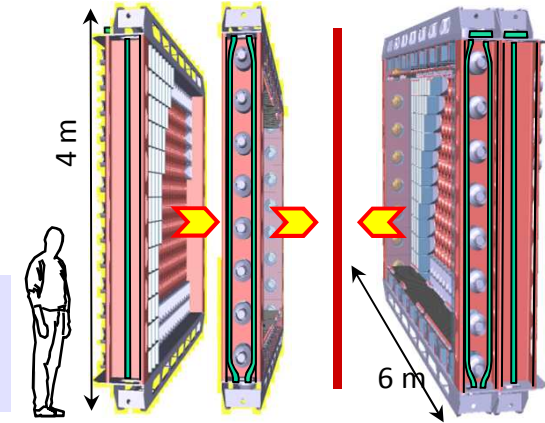
- **Performances correspond to expectations**

# NEMO 3 → SuperNEMO



collaboration internationale avec  
des fortes contributions anglaises  
et américaines

$$T_{1/2}(\beta\beta 0\nu) > \ln 2 \times \frac{N_A}{A} \times \frac{M \times \epsilon \times T_{\text{obs}}}{N_{90}}$$



## NEMO-3

$^{100}\text{Mo}$

7 kg

$^{208}\text{Tl}$ : < 20  $\mu\text{Bq/kg}$   
 $^{214}\text{Bi}$ : < 300  $\mu\text{Bq/kg}$   
 $^{222}\text{Rn}$  ~ 4  $\text{mBq/m}^3$

8% @ 3MeV **Résolution en énergie du calorimètre (FWHM)**

$T_{1/2}(0\nu\beta\beta) > 10^{24}$  ans  
 $\langle m_\nu \rangle < 0.3 - 0.9$  eV

**isotope**

**masse d'isotope M**

**Contaminations internes  $^{208}\text{Tl}$  et  $^{214}\text{Bi}$   
dans la feuille source  $\beta\beta$**

## SuperNEMO

$^{82}\text{Se}$  – option principale  
 ( $^{150}\text{Nd}$  ou  $^{48}\text{Ca}$  s'ils peuvent être enrichi)

100-200 kg

$^{208}\text{Tl} \leq 2$   $\mu\text{Bq/kg}$   
 si  $^{82}\text{Se}$ :  $^{214}\text{Bi} \leq 10$   $\mu\text{Bq/kg}$   
 $^{222}\text{Rn} < 0,1$   $\text{mBq/m}^3$

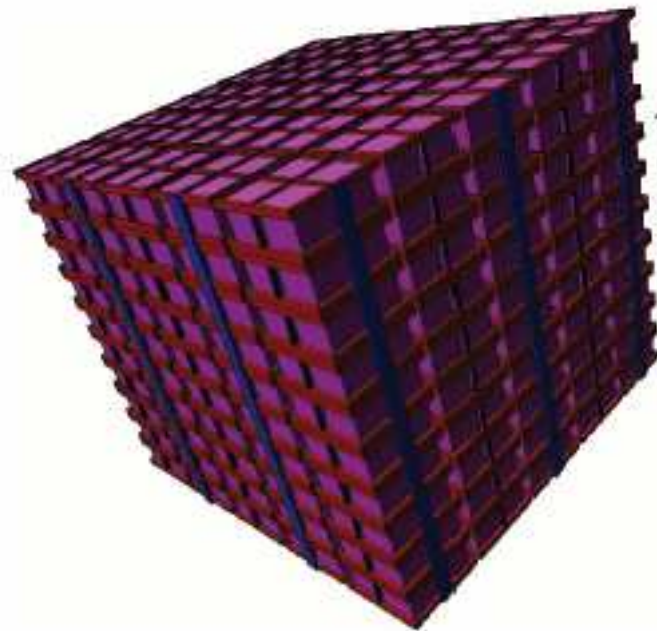
4% @ 3 MeV

$T_{1/2}(0\nu\beta\beta) > 10^{26}$  ans  
 $\langle m_\nu \rangle < 0.04 - 0.11$  eV

# The CUORE project

## Cryogenic Underground Observatory for Rare Events

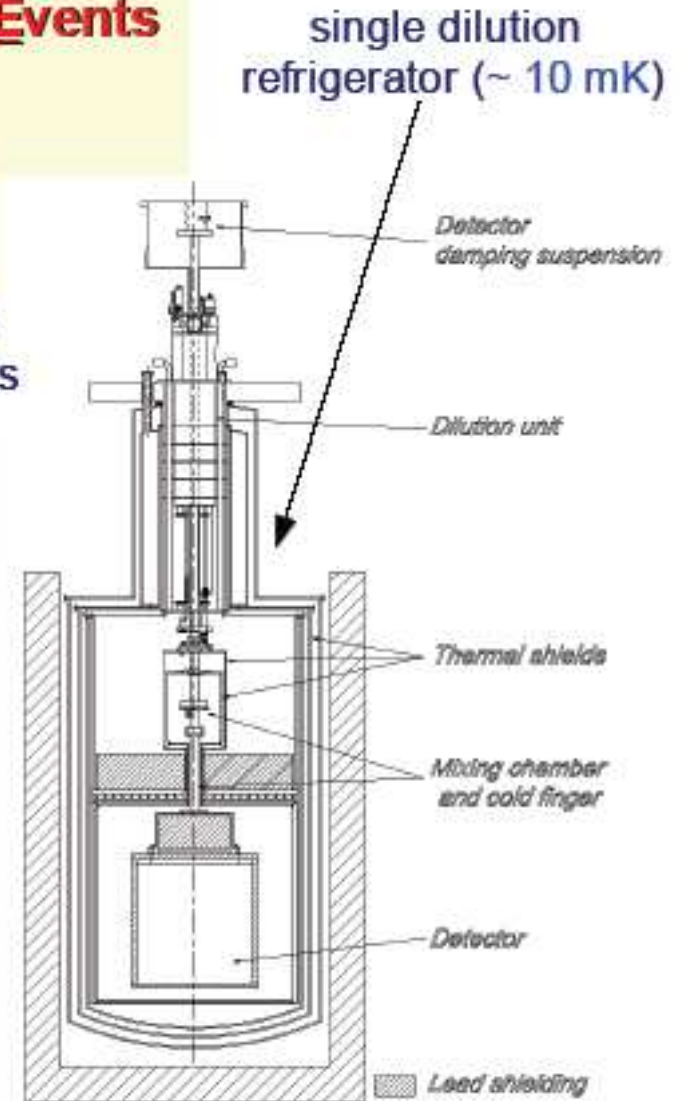
- array of 1000  $\text{TeO}_2$  crystals  $5 \times 5 \times 5 \text{ cm}^3$  (750 g)
  - ◇ 750 kg  $\text{TeO}_2$  granular calorimeter
  - ◇ 600 kg Te = 203 kg  $^{130}\text{Te}$
- $\beta\beta\text{-}0\nu$ , **Cold Dark Matter**, **Axions** searches



Crystals grouped in a  
5x5 matrix of 25 towers



Single tower:  
ten (4 crystal) modules



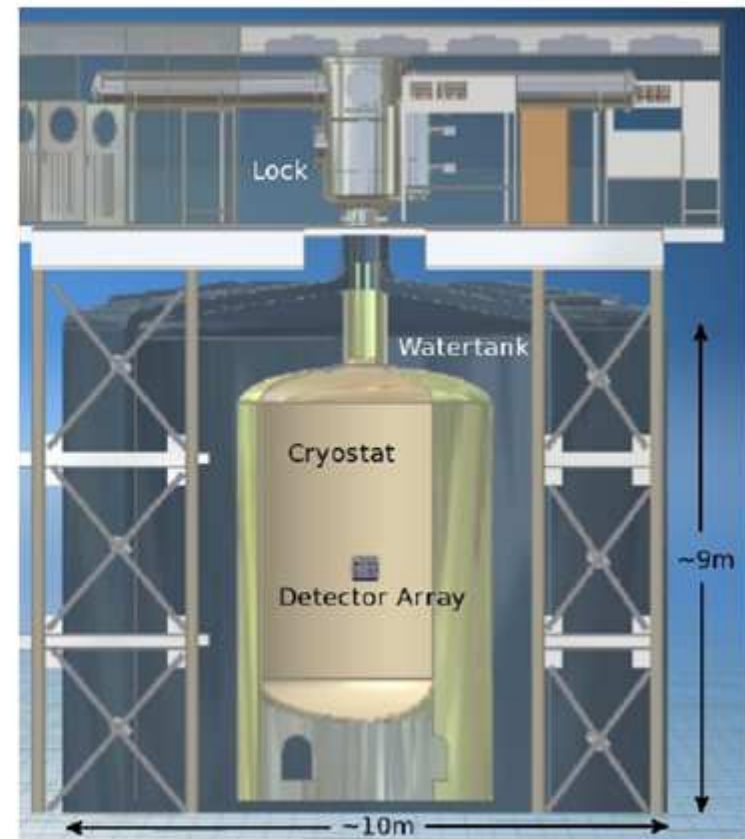
# The GERmanium Detector Array (GERDA)

## Overview

Location LNGS

Isotope 17.8 kg (Phase I) and  
~40 kg (Phase II) of  $^{76}\text{Ge}$

Ionization Naked high purity  
semiconductor diodes placed  
in liquid argon



### Phase I goals

Exposure 15 kg y

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

Half-life  $T_{1/2} > 2.2 \times 10^{25}$

Majorana mass  $m_{ee} < 0.27$  eV

### Phase II goals

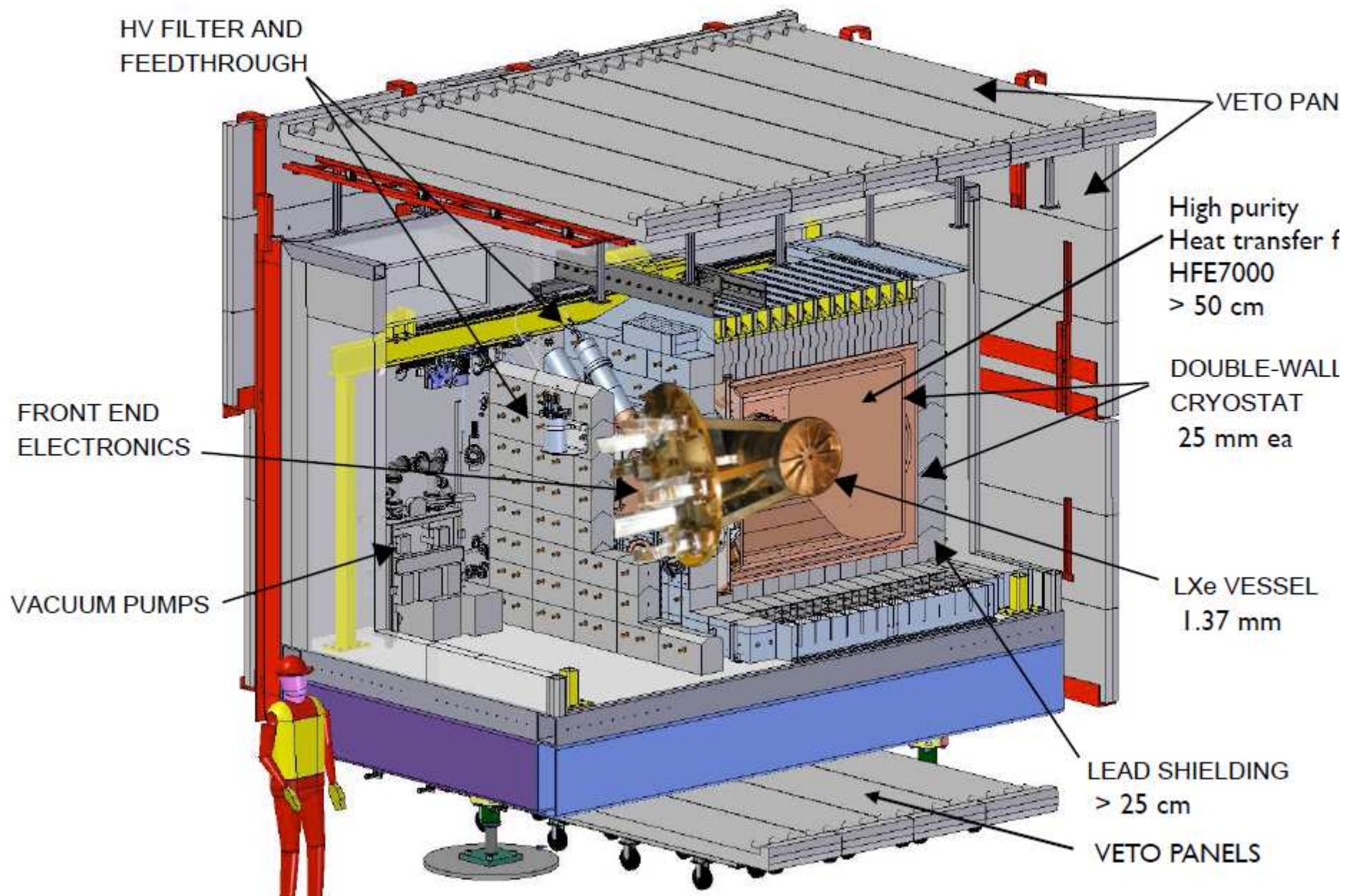
Exposure 100 kg y

Background  $10^{-3}$  cts/(keV kg y)

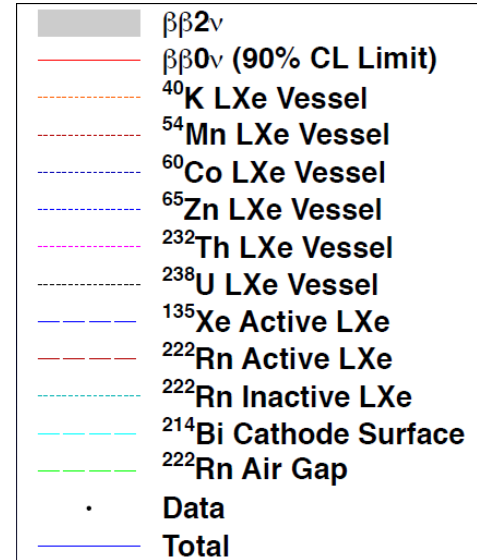
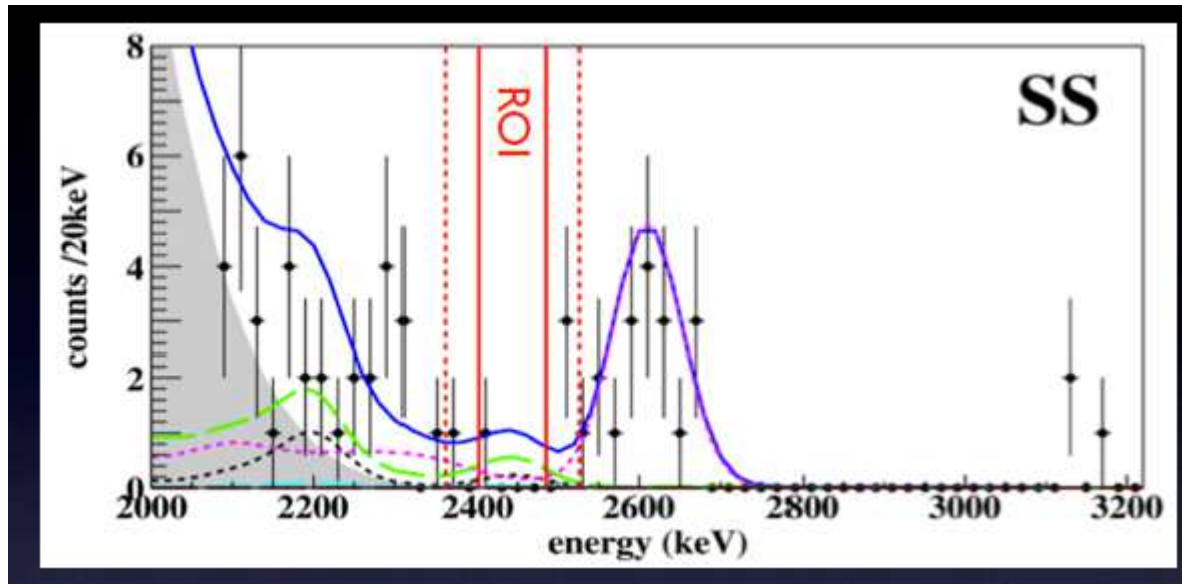
Half-life  $T_{1/2} > 15 \times 10^{25}$

Majorana mass  $m_{ee} < 0.11$  eV

# The EXO-200 Detector



# EXO – 200 results



$$(T_{1/2}^{0\nu\beta\beta})^{-1} = G^{0\nu} |M_{nucl}|^2 \langle m_{\beta\beta} \rangle^2$$

From profile likelihood:

$$T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25} \text{ yr}$$

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

(90% C.L.)

Phys. Rev. Lett. 109 (2012) 032505



# Conclusion

- Les oscillations ont montré que les neutrinos sont massifs, mais ni l'échelle de masse ni leur hiérarchie est connue précisément.
- Les expériences de mesure directe ( KATRIN) sont difficiles mais espèrent gagner un ordre de grandeur sur la masse du neutrino ( $\sim 0.2$  eV).
- La nature du neutrino est une question fondamentale à laquelle les expériences  $\beta\beta$  peuvent répondre. Une physique fondamentale, très riche, est également ouverte par ces expériences à basse énergie.
- Un grand nombre de projet  $\beta\beta$  existent mais qui doivent atteindre de valeurs de bruit de fond de plus en plus contraignantes.
- La physique du neutrino à basse énergie peut nous apporter encore beaucoup de surprises.