Mesure de la masse du neutrino

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PLAN

Mesure de la masse du neutrino

Présentation de l'état de l'art expérimental

- Résultats actuels
- Mesure par désintégration beta simple
- Mesure par double désintégration bêta

Masse du neutrino ?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric
K2K

Reactors (CHOOZ)
Accelerators (JPARC)

Solar
Reactors

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

θ_{23}~45°

θ_{13} <~13°

θ_{12}~30°

α,β : **Majorana phase**

δ_{CP}= **CP violation**

$\nu_\mu \longrightarrow \nu_\tau$ $\Delta m^2_{23} \sim 2.\ 10^{-3}\ eV^2$

$\nu_e \longrightarrow \nu_\mu$ $\Delta m^2_{12} \sim 5.\ 10^{-5}\ eV^2$

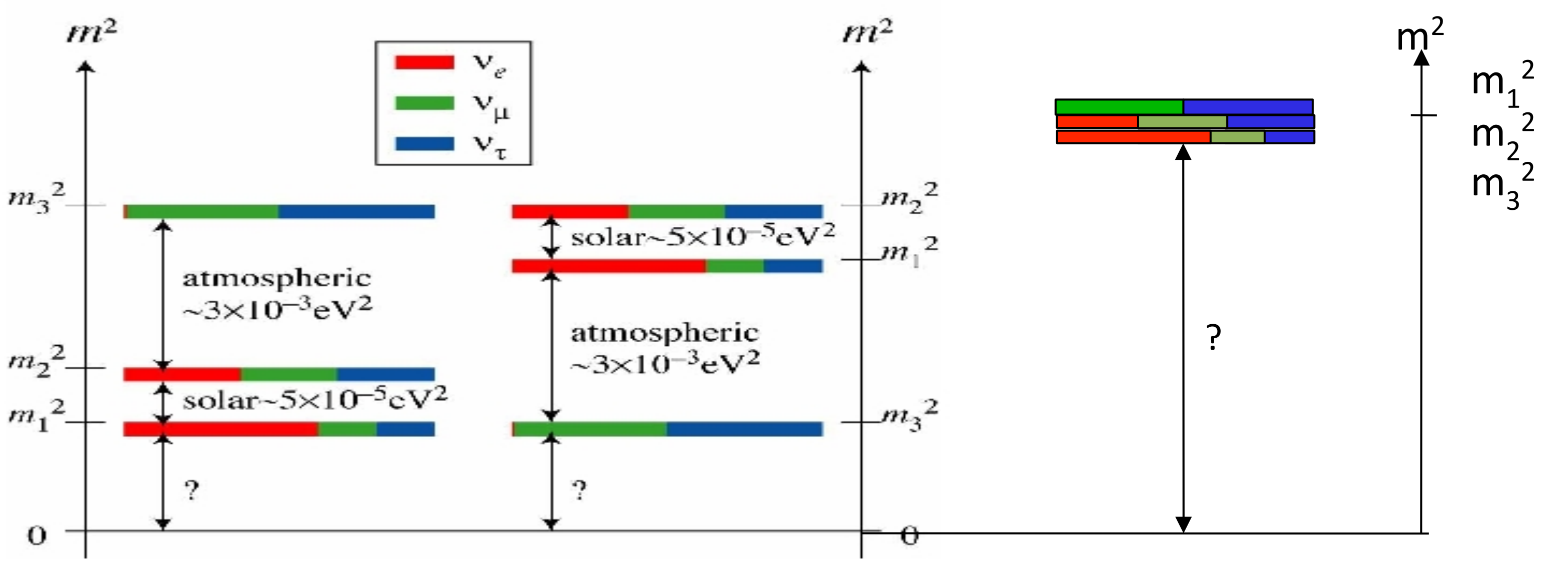
Masse du neutrino ?

Beta decay $m_\nu = (\Sigma\, |U_{ei}|^2 m_i^2)^{1/2} < 2.3$ eV

Double beta decay $|\langle m_\nu \rangle| = |\Sigma U_{ei}^2 m_i| < 0.2 - 0.8$ eV

Cosmology $\Sigma m_i = m_1 + m_2 + m_3 < 0.44 – 0.76$ eV

Mass scale ?



Normal hierarchy
$m_3 > m_2 \sim m_1$

Inverted hierarchy
$m_2 \sim m_1 > m_3$

Degenerate
$m_1 \approx m_2 \approx m_3 \gg |m_i - m_j|$

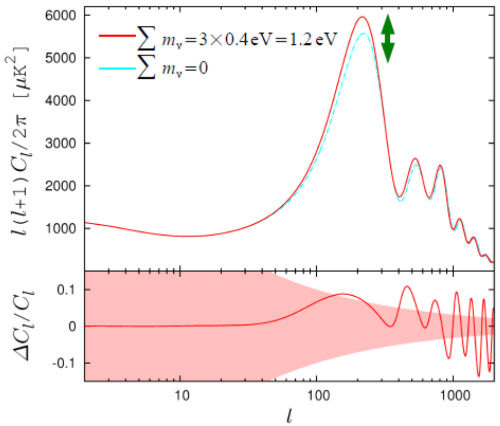
Masse du neutrino: Astrophysique et cosmologie

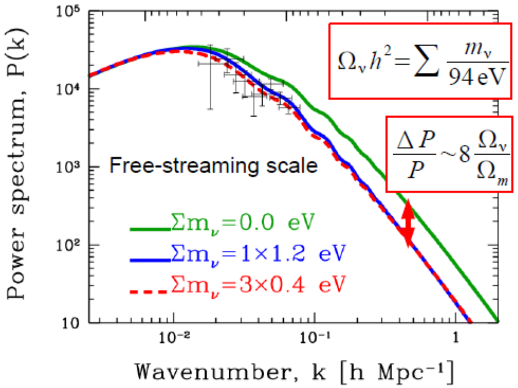
Astrophysique: neutrino émis par SN 1987A

$$\Delta t = 5.15\left(\frac{m_\nu}{1\,eV}\right)^2\left(\frac{10\,MeV}{E^2}\right)\frac{D}{10\,kpc}\,ms$$

m(ν_e) < 5.8 eV (95 %CL)

Cosmologie: Structure à grande échelle, anisotropie du fond cosmologique





Σm_ν < 0.44 – 0.76 eV (95% CL)

CMB (WMAP7+ACBAR+BICEP+QuaD)
+ LSS(SDSS+HPS)
+HST+SNIa

Fortement modèle dépendant

Masse du neutrino: mesures directes

$m(\nu_\mu)$: $\pi^+ \lozenge \mu^+ + \nu_\mu$

$\pi^- \lozenge \mu^- + \nu_\mu$

$$m^2(\nu_\mu) = m^2(\pi) + m^2(\mu) - 2 \cdot m(\pi) \cdot \sqrt{m^2(\mu) + p^2(\mu)}$$

Limité par la précision du la masse du pion $m(\pi)$ et du $m(\mu)$ et du moment du muons $p(\mu)$ lors de la décroissance du pion au repos

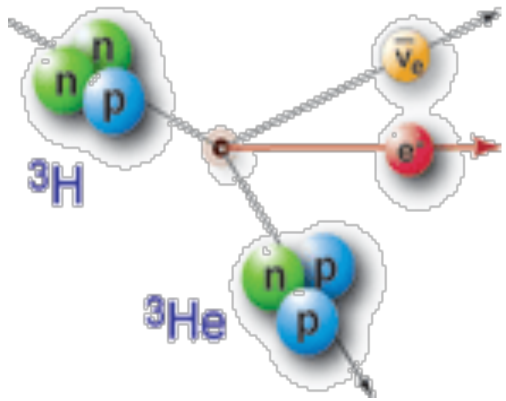
$m(\nu_\mu) <$ 190 keV (90 %CL)

$m(\nu_\tau)$: Décroissance du τ en 5 ou 6 π

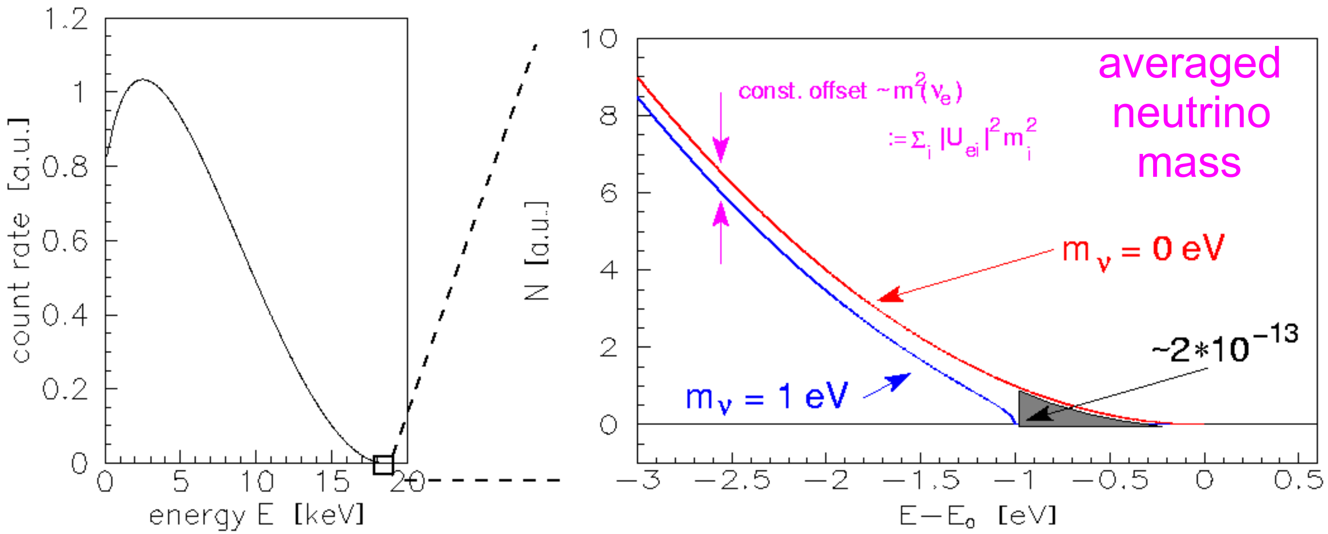
$m(\nu_\tau) <$ 18. MeV (95 %CL)

Mesure directe

$$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e$$



- Principe très simple
- Réalisation très délicate



Mesure directe

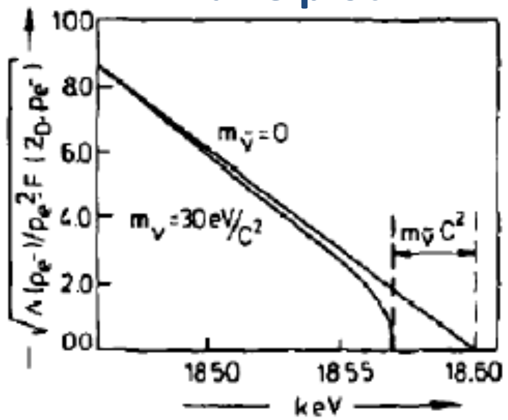
$$\frac{dN}{dE} \propto |M|^2 . F(E,Z) . p.W.\varepsilon^2 . \sqrt{1 - \frac{m_\nu^2}{\varepsilon^2}}$$

P,W: impulsion et énergie de l'électron

ε= E_0 –E : énergie du neutrino avec E0 = E_{max} quand $m_\nu = 0$

F(E,Z) Fonction de fermi: - Effets coulombiens corrigés des effets relativistes
- Rayon + distribution de charge du noyau
- Ecrantage du cortège électronique
- Corrections radiatives

Kurie plot



$$K(E) \propto \sqrt{\frac{dN/dE}{FpW}}$$

Sensibilité à m_ν seulement en fin de spectre

Mesure directe

Fraction of decay in $[Q_\beta - m_\nu, Q_\beta] \sim (m_\nu/Q_\beta)^3$

lowest Q_β value
High counting rate
Low background
Energy resolution $\sim m_\nu$

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

Electrostatic method

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

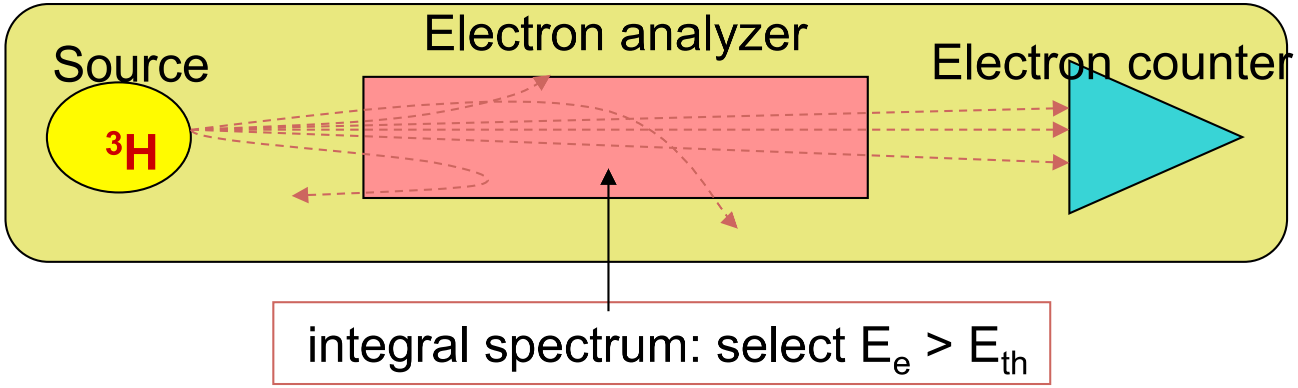
alternative approach:

Holmium (EC decay)
- $Q_{EC} \approx$ 2.5 keV, $T_{1/2}$ = 4570 y

Bolometric method

Mesure directe: méthode électrostatique

MAC-E spectrometers



- Acceptance angulaire élevée (2 π)
- Trajectoires parallélisées
- Analyse électrostatique

Solenoid Retarding Spectrometer: MAINZ experiment
Integral Electrostatic Spectrometer with adiabatic Magnetic Collimation : TROITZK

Mesure directe: méthode électrostatique

Difficultés inhérente à la méthode électrostatique

- **Source**

  Forme moléculaire → Etat final change l'Energie
  Stabilité dans le vide
  Intense
  Mince
  Uniforme
  problèmes: backscattering; potentiel,…

  (Intense, Mince : **Compromis**; Mince, Uniforme : **Perte d'énergie**)

- **Mesure de l'énergie**

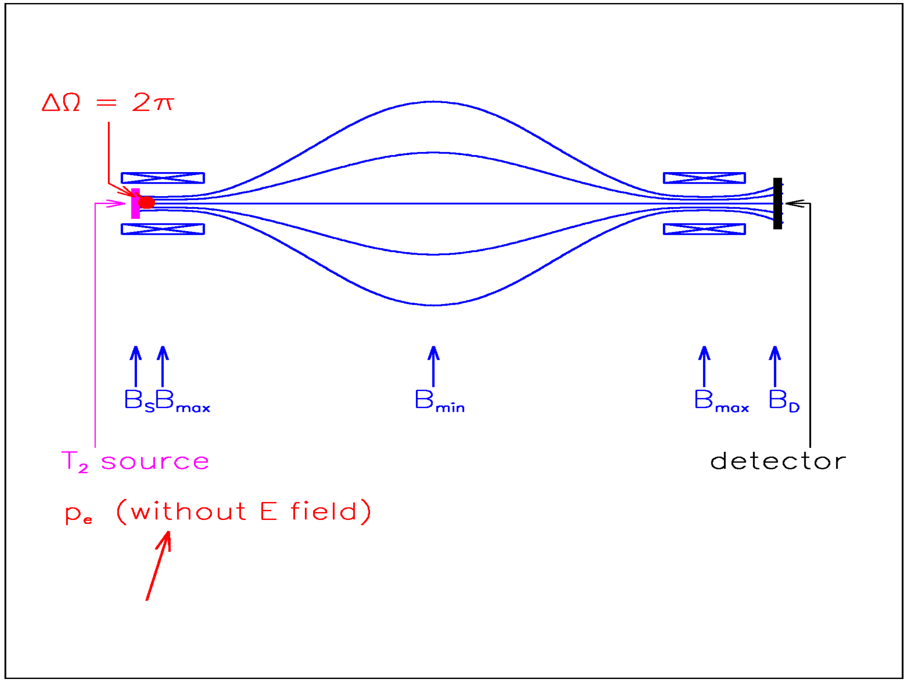
  Résolution de l'ordre de la limite sur m_ν

- **Détecteur**

  Réponse vs taux comptage
  Fond liés aux cosmique, radon , radioactivité naturelle

Spectre non gaussien lié à l'utilisation de fente

Mesure directe: méthode électrostatique



B et E ajustés pour que le mouvement soit adiabatique

μ : moment magnétique de l'orbite cyclotron est un invariant adiabatique

$E_T = -\vec{\mu} \cdot \vec{B}$

Barrière de potentiel DE ~B_{min}/B_{max} E
Filtre passe haut

Mesure directe: méthode électrostatique

Pertes d'énergie:

- interaction inélastiques, excitation et ionisation sur les électrons de la source

Dans T_2 en moyenne perte de 30 eV par interaction

Minimisation des systématiques:

- épaisseur < interaction pour minimiser probabilité d'interaction
- Z =1
- Importance uniformité de la source
- Evaluation de la transmission avec E monoenergétiques

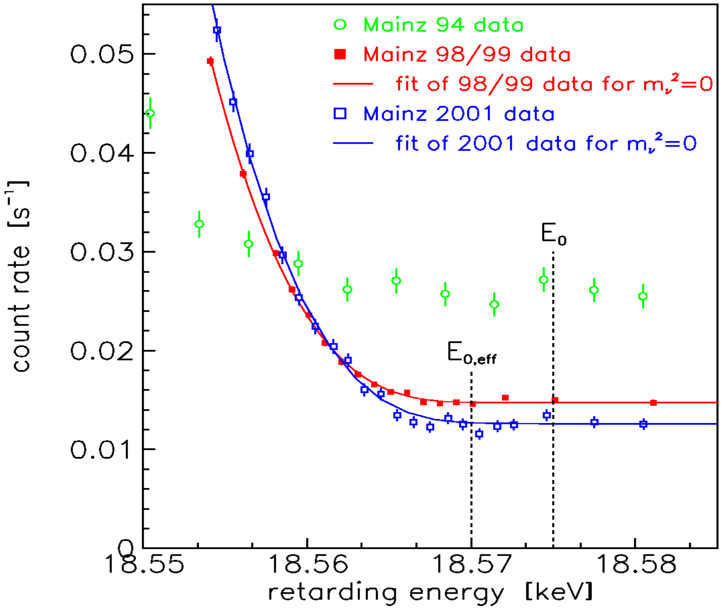
$$\frac{dN}{dE} \propto |M|^2 . F(E,Z) . p.W. \sum \boldsymbol{w_i} . \varepsilon^2 . \sqrt{1 - \frac{m_{nu}^2}{\varepsilon^2}}$$

X Resolution X pertes énergie

W_i: probabilite de tomber sur le niveau i

$\varepsilon_i = E_0 - E - v_i$

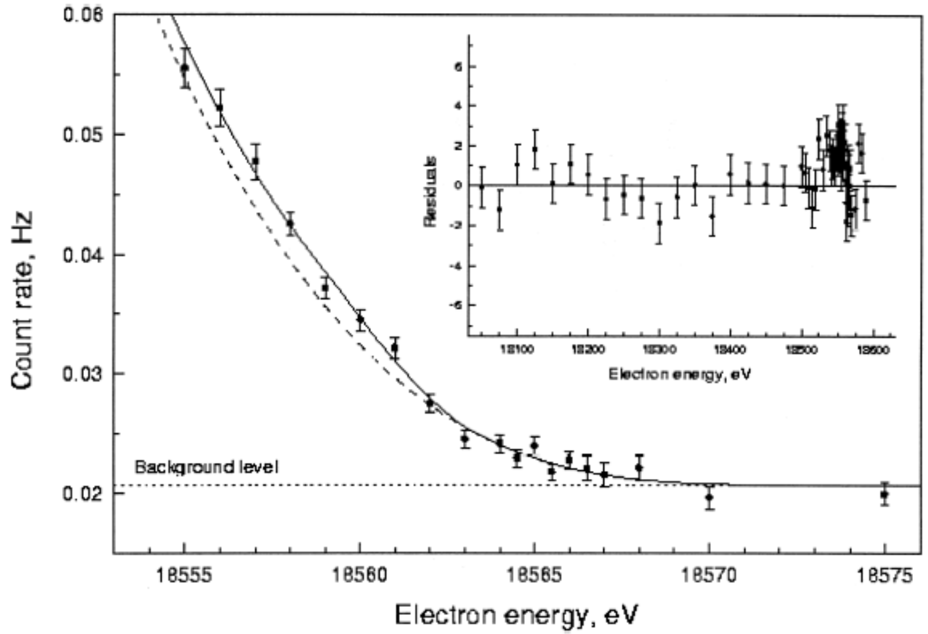
Mesure directe: méthode électrostatique



MAINZ: m^2_ν = -0.6 ± 2.2 ± 2.1 eV^2

⇒ m_ν< 2.3 eV (95% C.L.)

C. Kraus et al., Eur. Phys. J. C 40 (2005) 447



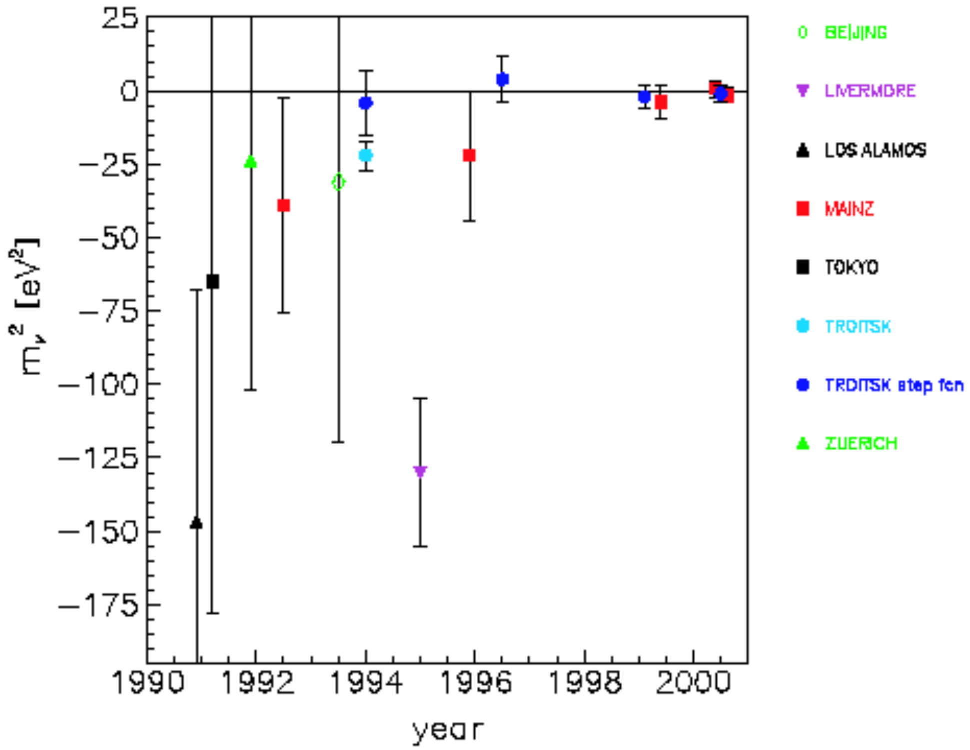
Troisk: m^2_ν = -2.3 ± 2.5 ± 2.0 eV^2

m_ν< 2.05 eV (95% C.L.)

Mais systématiques lé au fluctuations de E_0 non incluses

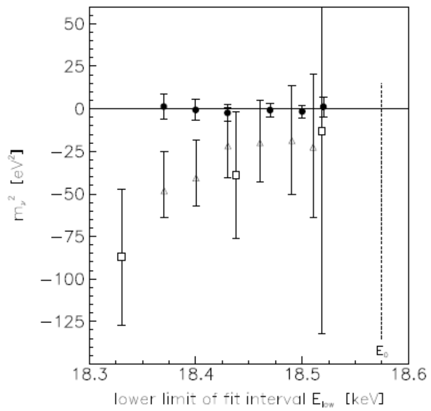
Mesure directe: méthode électrostatique

Pourquoi m^2_ν négatif ?



Paramètres du fit: amplitude libre
energy maximum (E_0)
masse carré du neutrino
bruit de fond

Les sources d'erreurs systématiques:
Diffusion inélastique dans le film de tritium
Excitation des molécules voisines
Etat final de la molécule The+
Etat de charge du film source
Etat de surface de la source

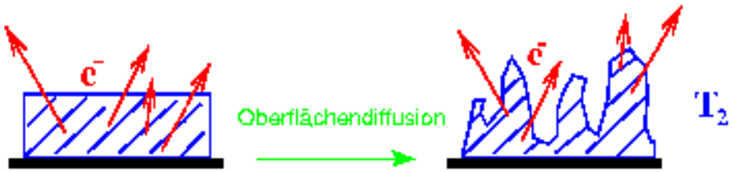


Mainz
Limites en
fonction des runs

Mainz : source solid déposée sur un film
Troisk: source gazeuse

Mesure directe: méthode électrostatique

- **Roughening transition of T_2 film**

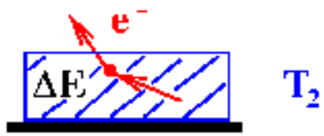


Determination of dynamics: $\Delta E = (45 \pm 6)\, k_B$ K

$\Rightarrow$ no roughening transition below 2 K

L. Fleischmann et al., J. Low Temp Phys. **119** (2000) 615, (with P. Leiderer Konstanz)
L. Fleischmann et al., Eur. Phys. J. **B16** (2000) 521

- **Inelastic scattering**



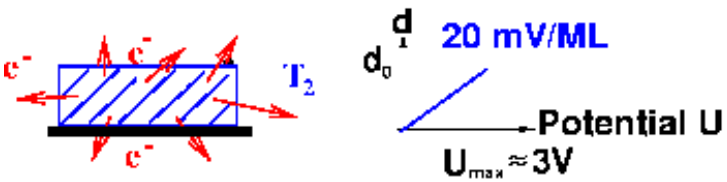
Deterimination of cross section:

$$\sigma_{tot} = (2.98 \pm 0.16) \cdot 10^{-18}\ \text{cm}^2$$

Determination of energy loss function:

V.N. Aseev et al., Eur. Phys. J. **D10** (2000) 39

- **Self charging of T_2 film**



Determination of critical field:

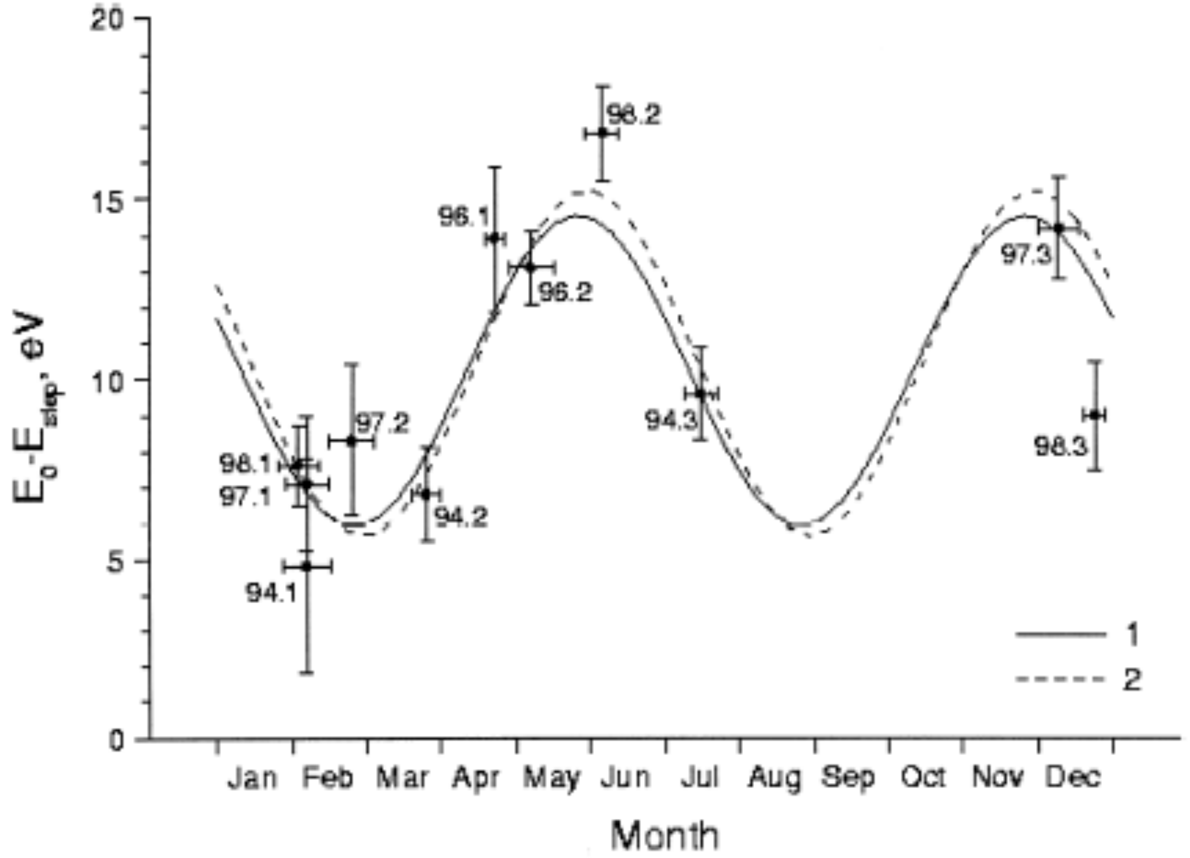
$$E_c = (63 \pm 4)\ \text{MV/m}$$

$\Rightarrow$ slight broadeing of energy resolution

H. Barth et al., Prog. Part. Nucl. Phys. **40** (1998) 353,
B. Bornschein, PhD thesis, publication in preparation

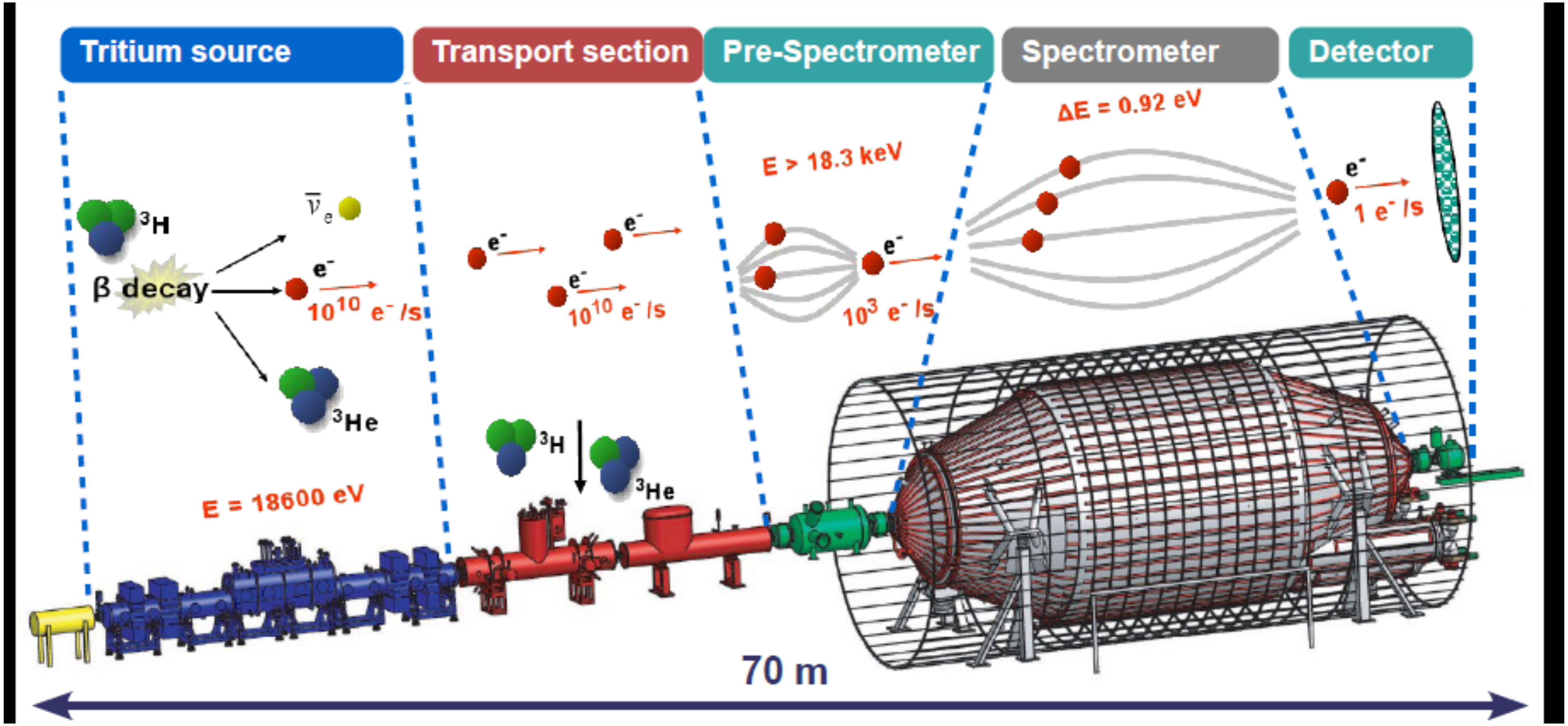
Mesure directe: méthode électrostatique

Anomalie de Troisk



Explication exotique : capture des neutrinos fossiles ! (10^{18} /cm^3)

Mesure directe: KATRIN



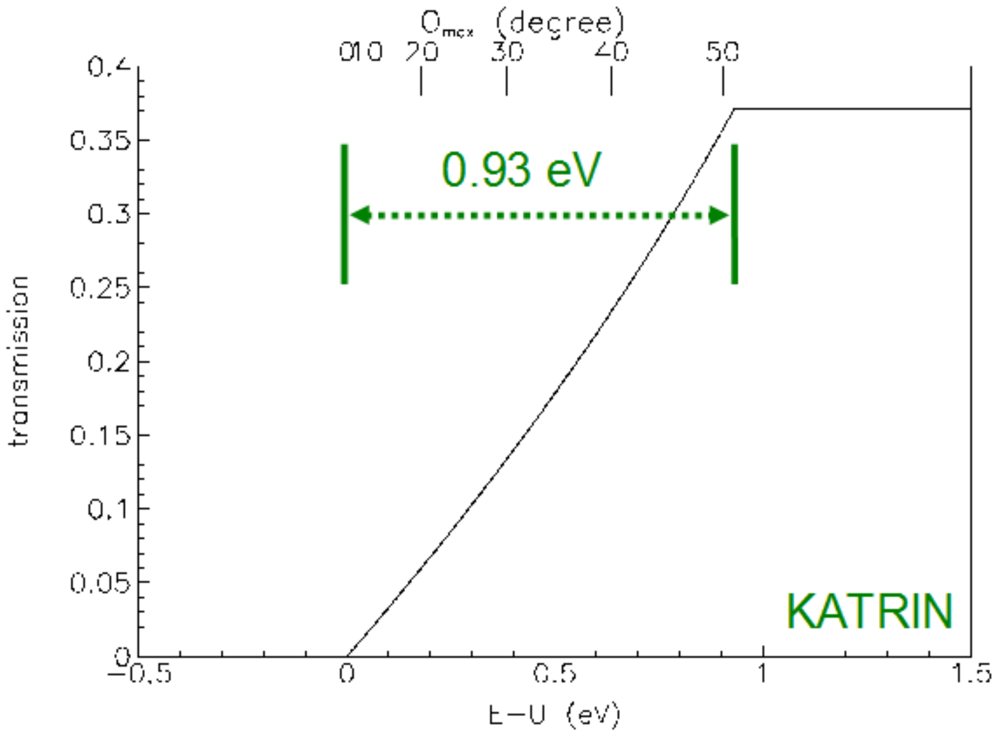
ΔE: **0.93 eV** (4.8 eV for Mainz)
Large acceptance
Statistique **100 days → 1000 days**

$m_{\nu(e)}$ < 0,2 eV/c² en 5 ans de données

Mesure à 5σ pour $m_{\nu(e)}$ = 0,35 eV/c²

Mesure directe: KATRIN

Magnetic Adiabatic Collimation + Electrostatic Filter
(A. Picard et al., Nucl. Instr. Meth. 63 (1992) 345)



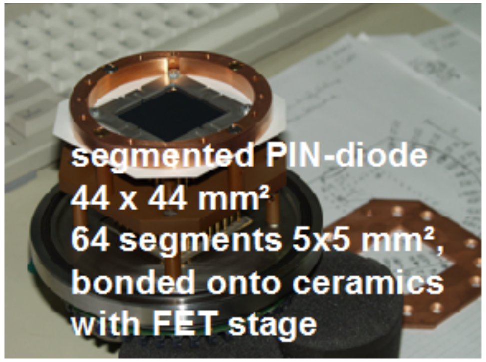
⇒ sharp integrating transmission function without tails:

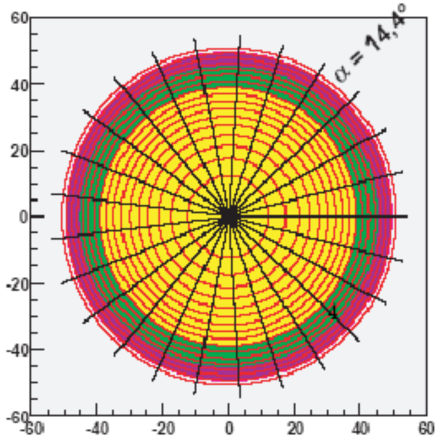
$\Delta E = E \cdot B_{min}/B_{max} = E \cdot A_{s,eff}/A_{analyse} = 0.93$ eV, KATRIN (4.8 eV, Mainz)

Mesure directe: KATRIN

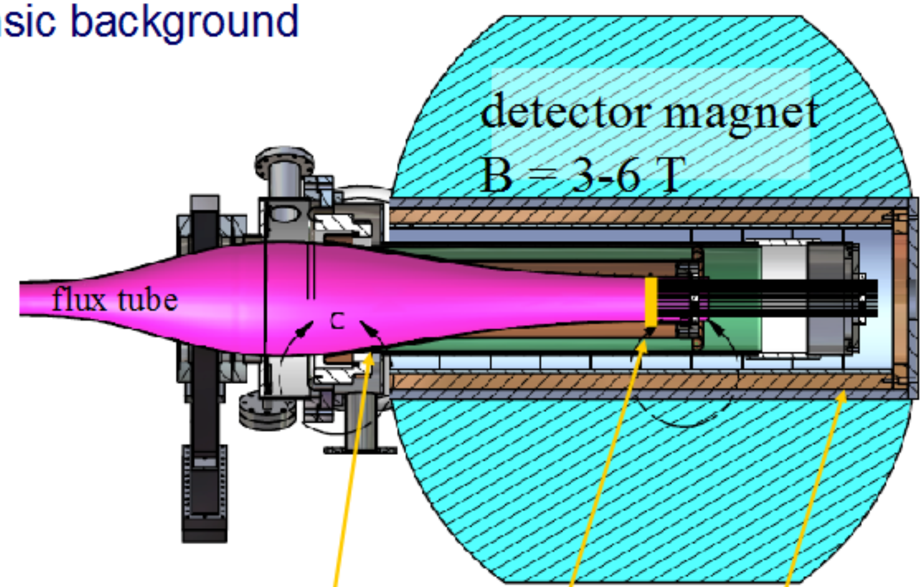
Detector:

task: detection of transmitted ß-decay electrons
with high energy resolution (ΔE =1 keV)
record radial profile of flux tube
aim: background minimisation, systematic effects
$\Rightarrow$ post-acceleration to place signal line
at lower intrinsic background





design: radially segmented
Si-PIN diode array
~150 pixels with A=100 cm²



Mesure directe: KATRIN

Mesure directe: KATRIN

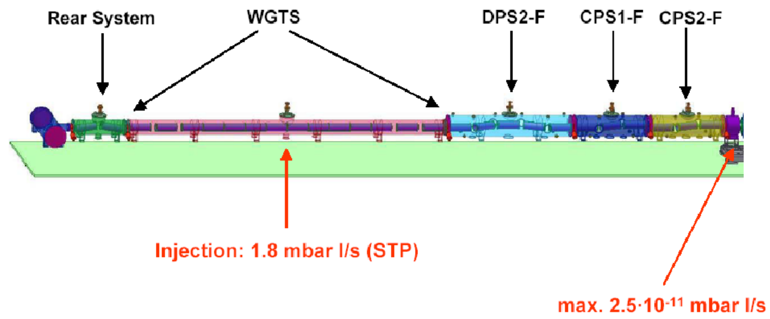
Les défis: la source gazeuse 4,7 Ci/s

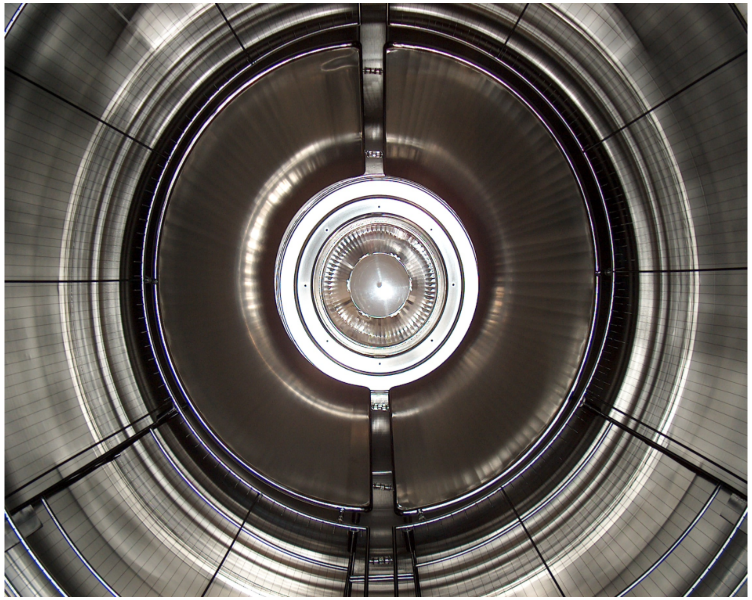
pureté de la source > 95% monitorée en permanence par spescstrocpie Laser Raman

$\Delta U/U < 10^{-6}$ v Précision sur tension < 60 mV

vide dans le spectromètre 10^{-11} mbar

Dégazage < 10^{-13} bar.l/(s.cm^{2})





Nouveau bruit de fonds :

- Electrons delta venant de l'interaction du rayonnement cosmique -> fils de champs

- Radon (30 fois trop haut) piégeage avec azote liquide

Commissioning spectromètre 2012

Mesure directe: spectromètre vs calorimètre

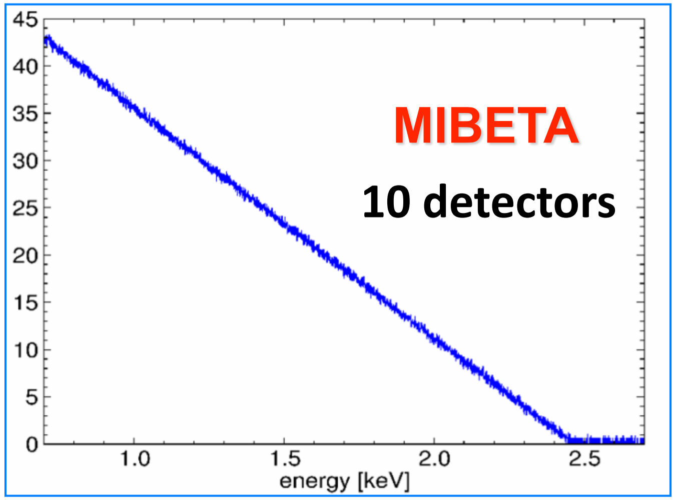
	calorimeter approach (MARE)	spectrometer approach (KATRIN)
source	metallic Re / dielectric $AgReO_4$	high purity T_2
activity	low : < 10^5 β/s, ≈ 1Bq/mg Re	high: ≈ 10^5 β/s, 4.7 Ci/s injection
technique	single crystal bolometers	electrostatic spectrometer
solid angle	4π (source = detector)	40% of 2π (max. forw. angle 51°)
response	entire β-decay energy	kinetic energy of β-decay electrons
interval	entire spectrum	narrow interval close to E_0
method	differential energy spectrum	integrated energy spectrum
setup	modular size, scalable	integral design, size limits
resolution	ΔE ~ 11-25 eV (FWHM)	ΔE ~ 0.93 eV (100%)

Mesure directe: MARE

MicroBolometers of ArReO4

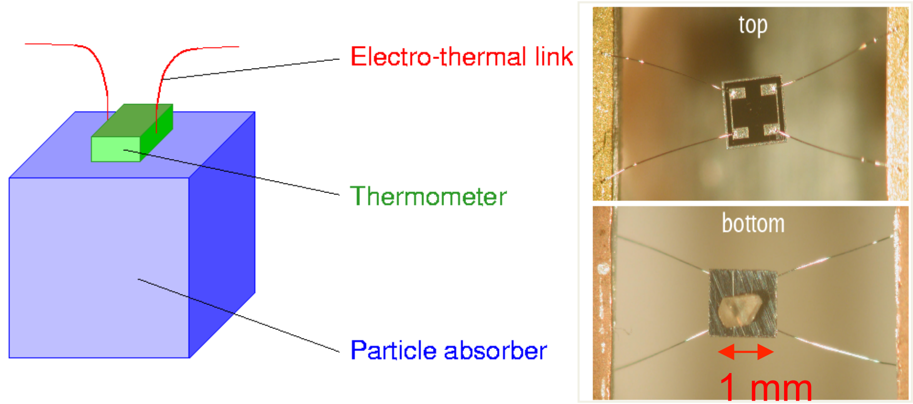
^{187}Re Q_β = 2.47 keV

Full energy measurement
No systematic from source
But time response of sensor → pile-up



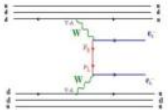
$\langle m_\nu \rangle^2 = -141 \pm 211_{stat} \pm 90_{sys}$ eV^2

$\langle m_\nu \rangle < 15$ eV (90% c.l.)



MARE-I: 300 detectors
FWHM ~20 eV
τ ~100 – 500 μs
$\langle m_\nu \rangle < 2 – 4$ eV (5 years)

MARE – II : 5000 detectors (~2018)
FWHM ~20 eV
τ ~1 – 5 μs
$\langle m_\nu \rangle < 0.2$ eV (10 years)



Double désintégration bêta

La double désintégration bêta teste différentes propriétés du neutrino

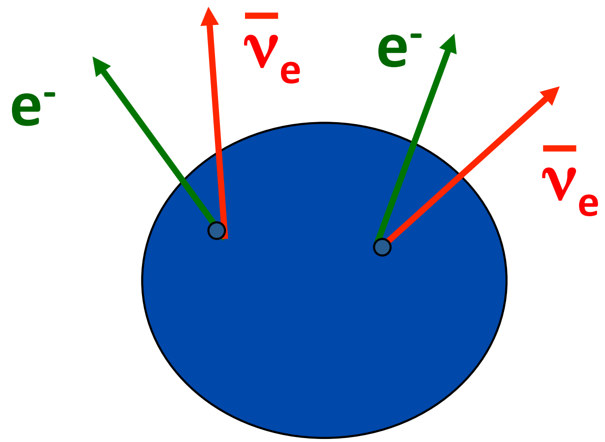
- **Nature of neutrino : Dirac ($\nu \neq \bar{\nu}$) or Majorana ($\nu = \bar{\nu}$)**
- **Absolute neutrino mass and neutrino mass hierarchy**
- **Right-handed current interaction**
- **CP violation in leptonic sector**
- **Search of Supersymmetry and new particles**

Double désintégration bêta

$\beta\beta(2\nu)$

Double décroissance bêta avec 2 neutrinos

$$2n \longrightarrow 2p + 2e^- + 2\bar{\nu}_e$$



Processus du second ordre de l'interaction faible

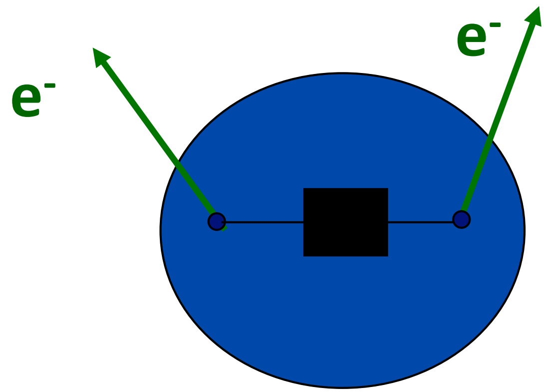
Prédit par M. Goeppert-Mayer en 1935

Observation directe en 1987

$\beta\beta(0\nu)$

Double décroissance bêta sans neutrino

$$2n \longrightarrow 2p + 2e^-$$

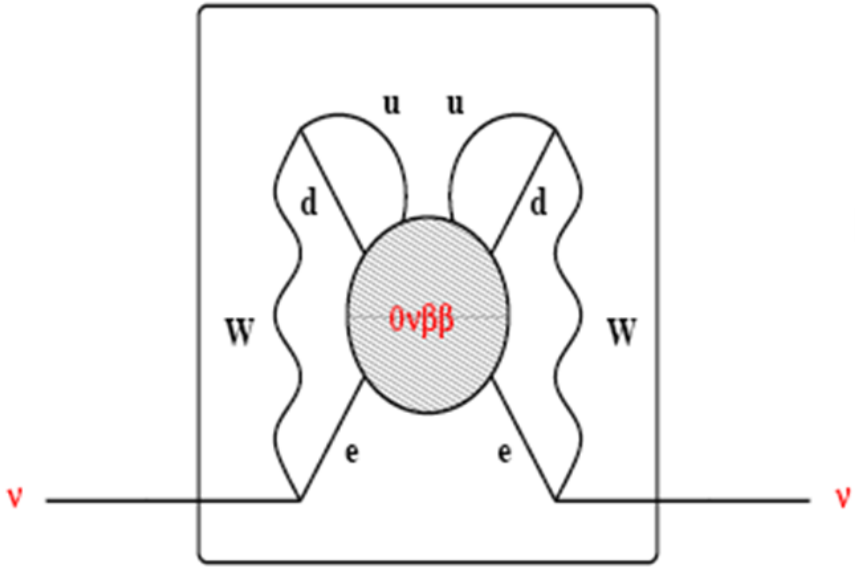


$\Delta L=2$ interdit par model standard

Prédit par Racah et Furry en 1937

Non obervée jusqu'à présent

Double désintégration bêta



Schechter & Valle, 1982

Independent of mechanism of $0\nu\beta\beta$ decay Majorana neutrino mass will appear in higher order!

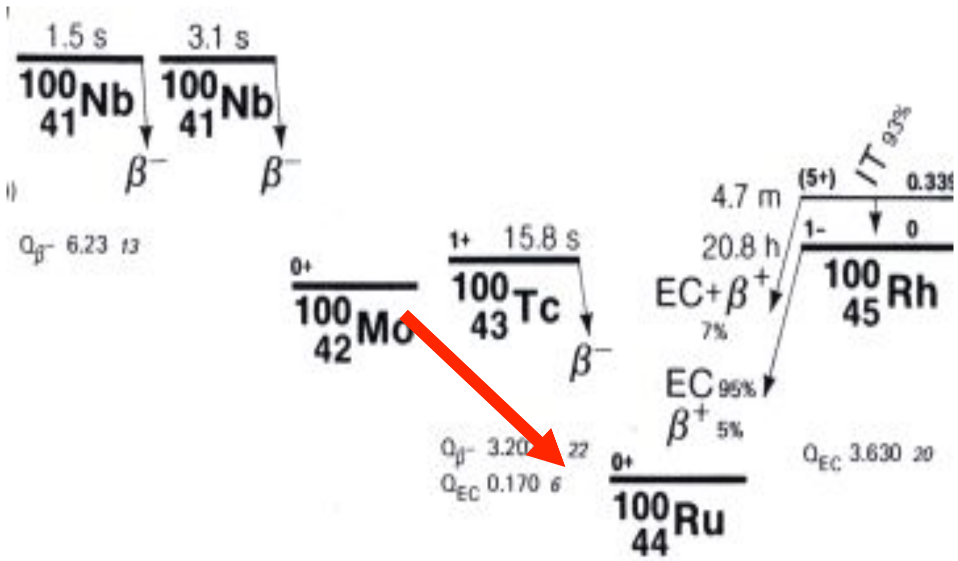
Thus:

Observe $0\nu\beta\beta$ decay

$\equiv$

Neutrinos are Majorana particles

Double désintégration bêta



Bêta simple interdite énergétiquement
ou fortement supprimée par moment angulaire

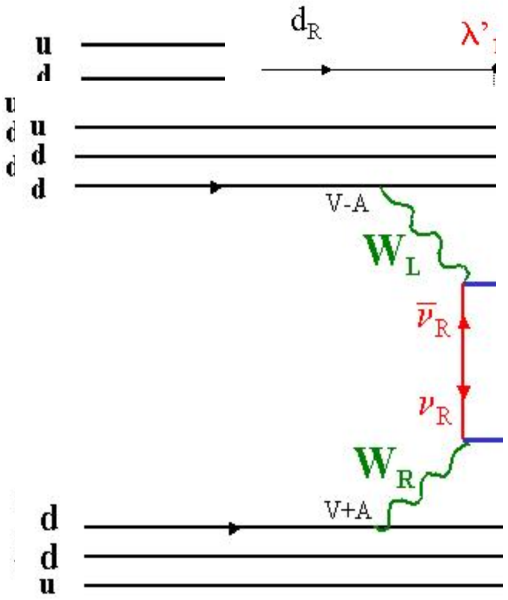
Transition	$Q_{\beta\beta}$ (keV)	Abondance (%)
^{146}Nd → ^{146}Sm	56 ± 5	17
^{98}Mo → ^{98}Ru	112 ± 7	24
^{80}Se → ^{80}Kr	130 ± 9	50
^{122}Sn → ^{122}Te	364 ± 4	4.6
^{204}Hg → ^{204}Pb	416 ± 2	7
^{192}Os → ^{192}Pt	417 ± 4	41
^{186}W → ^{186}Os	490 ± 2	29
^{114}Cd → ^{114}Sn	534 ± 4	29
^{170}Er → ^{170}Yd	654 ± 2	15
^{134}Xe → ^{134}Ba	847 ± 10	10
^{232}Th → ^{232}U	858 ± 6	100
^{128}Te → ^{128}Xe	868 ± 4	32
^{46}Ca → ^{46}Ti	987 ± 4	-
^{70}Zn → ^{70}Ge	1001 ± 3	0.6
^{198}Pt → ^{198}Hg	1048 ± 4	7
^{176}Yb → ^{176}Hf	1079 ± 3	13
^{238}U → ^{238}Pu	1145 ± 2	99
^{94}Zr → ^{94}Mo	1145 ± 2	17
^{154}Sm → ^{154}Gd	1252 ± 2	23
^{86}Kr → ^{86}Sr	1256 ± 5	17
^{104}Ru → ^{104}Pd	1299 ± 4	19
^{142}Ce → ^{142}Nd	1418 ± 3	11
^{160}Gd → ^{160}Dy	1729 ± 1	22
^{148}Nd → ^{148}Sm	1928 ± 2	6
^{110}Pd → ^{110}Cd	2013 ± 19	12
^{76}Ge → ^{76}Se	2040 ± 1	8
^{124}Sn → ^{124}Te	2288 ± 2	6
^{136}Xe → ^{136}Ba	2479 ± 8	9
^{130}Te → ^{130}Xe	2533 ± 4	34
^{116}Cd → ^{116}Sn	2802 ± 4	7
^{82}Se → ^{82}Kr	2995 ± 6	9
^{100}Mo → ^{100}Ru	3034 ± 6	10
^{96}Zr → ^{96}Mo	3350 ± 3	3
^{150}Nd → ^{150}Sm	3667 ± 2	6
^{48}Ca → ^{48}Ti	4271 ± 4	0.2

35 ββ emetteurs

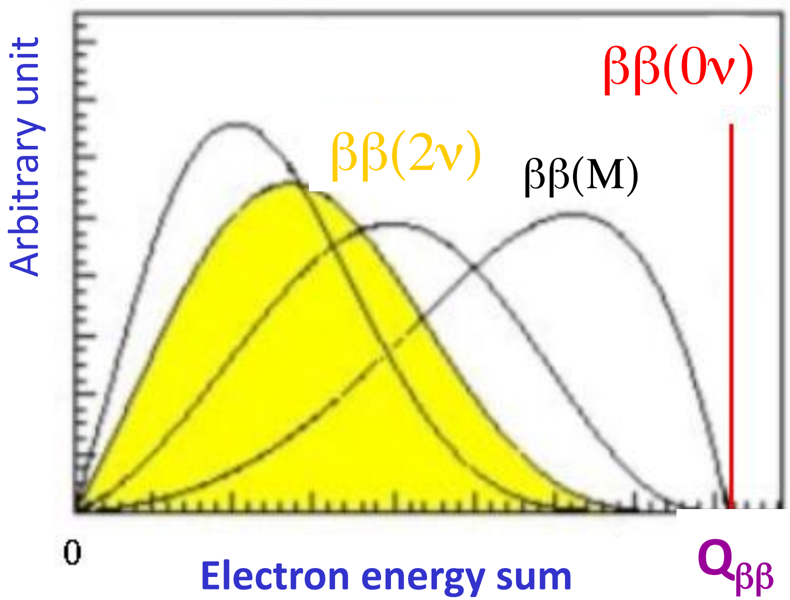
Double désintégration bêta

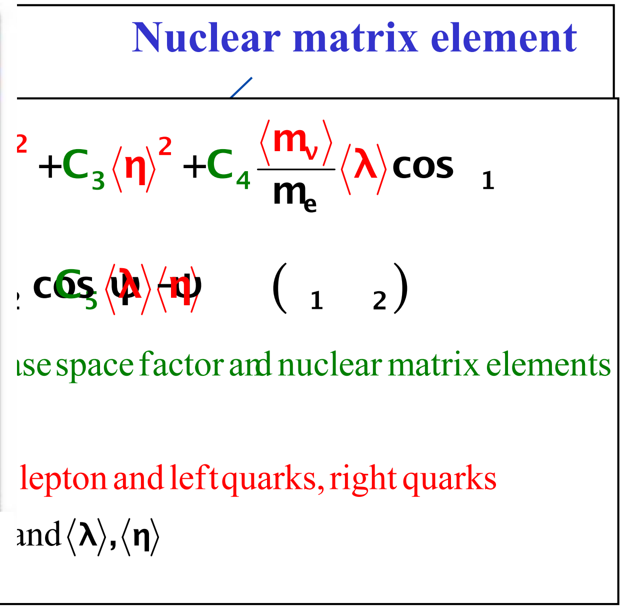
$(A,Z) \longrightarrow (A,Z+2) + 2e^-$

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	$\lambda'_{111}, \lambda'_{113} \lambda'_{131}, \ldots$



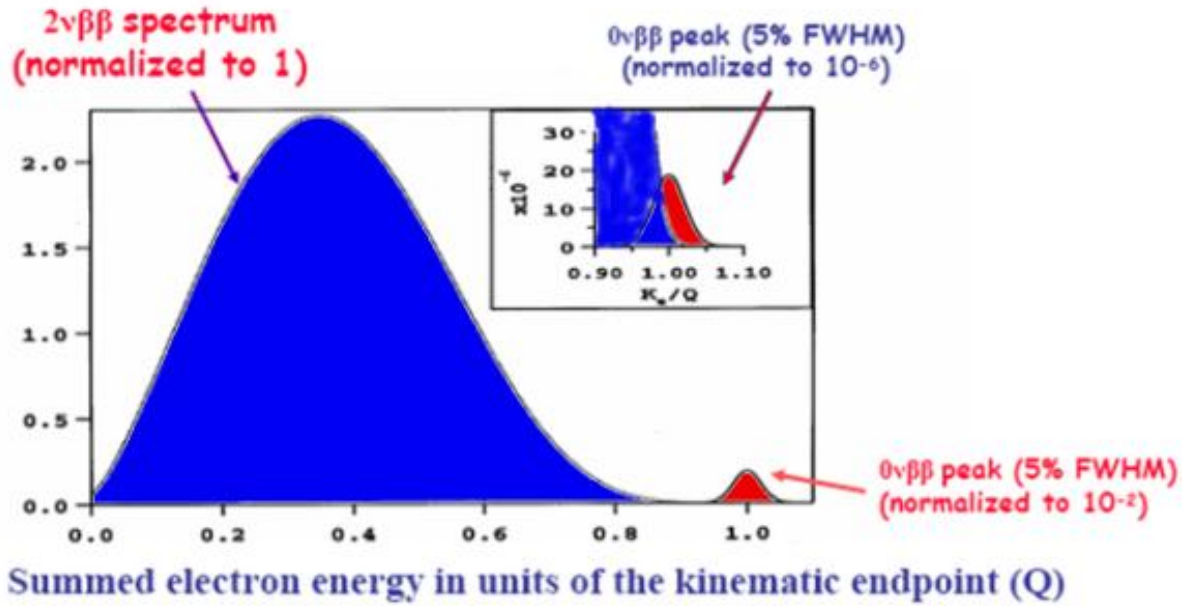
F. Piquemal (CENBG)



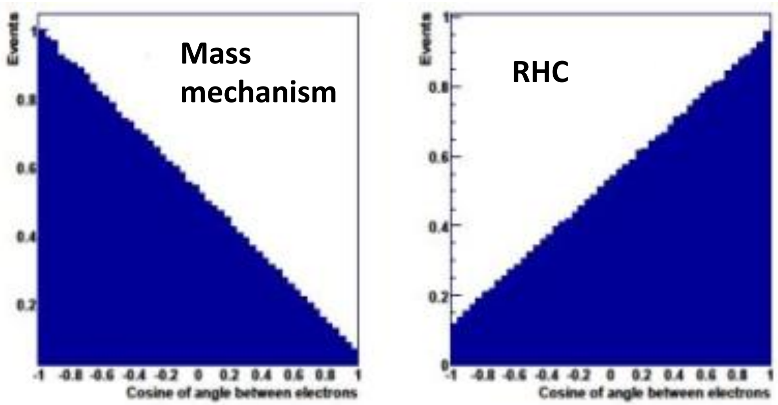


CS IN2P3 2005/03/05

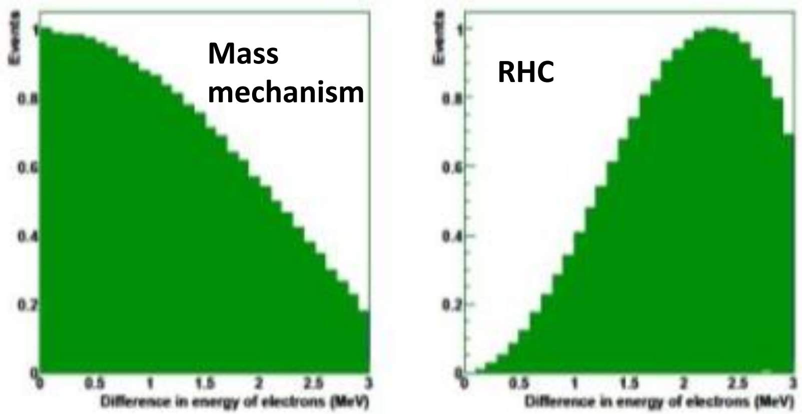
Observables expérimentales



From G. Gratta



Angular distribution



Ee1 – Ee2 distribution

150Nd distribution s arxiv: 1005.1241v1 [hep-ex]

Masse effective et oscillations

Masse effective en fonction des oscillations de neutrino

$$\begin{aligned}\langle m_\nu \rangle &= c_\odot^2 c_R^2 m_{\nu_1} \\ &+ s_\odot^2 c_R^2 e^{i\alpha} \sqrt{m_{\nu_1}^2 + \Delta m_\odot^2} \\ &+ s_R^2 e^{i\beta} \sqrt{m_{\nu_1}^2 + \Delta m_\odot^2 + \Delta m_{\mathrm{Atm}}^2}\end{aligned}$$

Normal hierarchy: $\langle m_\nu \rangle \simeq s_{12}^2 \sqrt{\Delta m_\odot^2} \simeq 3 \times 10^{-3}$ eV

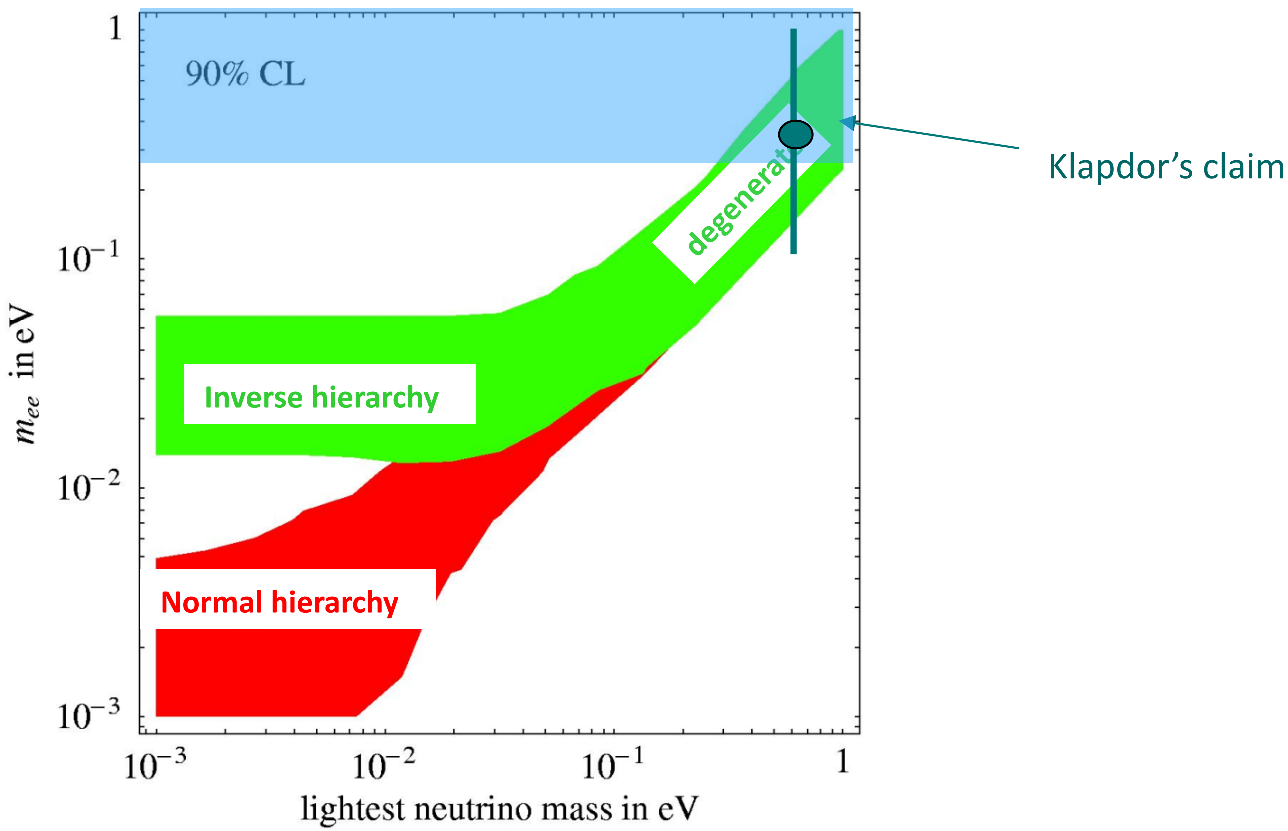
Inverse hierarchy: $\langle m_\nu \rangle \simeq \sqrt{\Delta m_{Atm}^2} \simeq 5 \times 10^{-2}$ eV

Masse effective et oscillations

$$< m_\nu > = \left| \sum_i U_{ei} m_i \right| = \left| \cos^2\theta_{13} \left(m_1 \cos^2\theta_{12} + m_2 e^{2i\alpha} \sin^2\theta_{12} \right) + m_3 e^{2i\beta} \sin^2\theta_{13} \right|$$

Expériences ~10 kg

Hedeilberg Moscow
IGEX
Cuoricino
NEMO3



Feruglio F. , Strumia A., Vissani F. hep-ph/0201291

Comment choisir le meilleur noyau

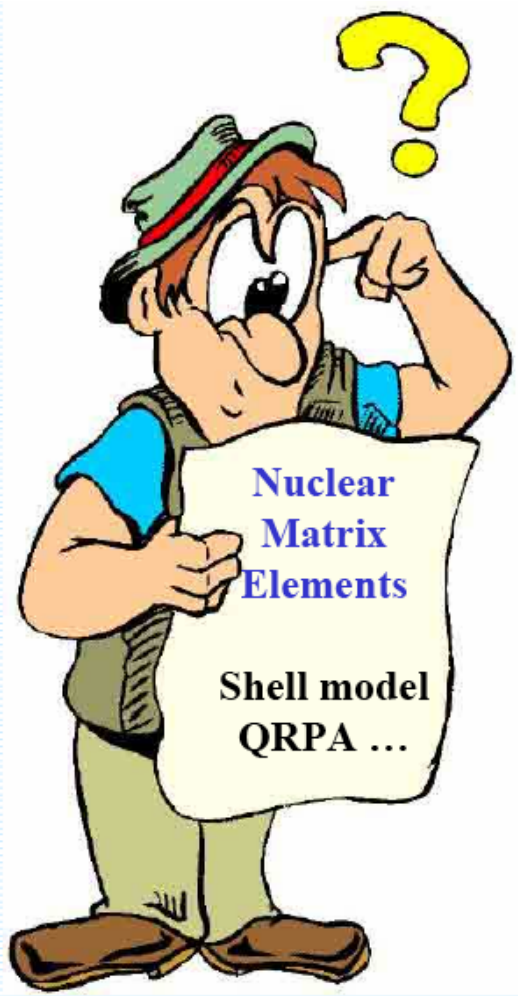
$$T_{1/2}^{-1} = F(Q_{\beta\beta}^{5}, Z)\ |M|^2\ \langle m_\nu \rangle^2$$

Les critères possibles:

- Espace de phase (bruit de fond)
- La possibilité d'enrichissement
- Element de matrice nucléaire
- Technique experimentale

	$Q_{\beta\beta}$ (MeV)	Abondance isotopique
$^{48}Ca \rightarrow {}^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow {}^{76}Se$	2.040	7.8
$^{82}Se \rightarrow {}^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow {}^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow {}^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow {}^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow {}^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow {}^{124}Te$	2.228	5.64
$^{130}Te \rightarrow {}^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow {}^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow {}^{150}Sm$	3.367	5.6

Nuclear matrix elements



Experimentalists:

- What are the best $0\nu\beta\beta$–decay candidates?

Particle physicists:

- Wat is the absolute ν mass scale?
- Will the evidence of the $0\nu\beta\beta$-decay allow to to conclude about Majorana CP-phases?

It is a complex task

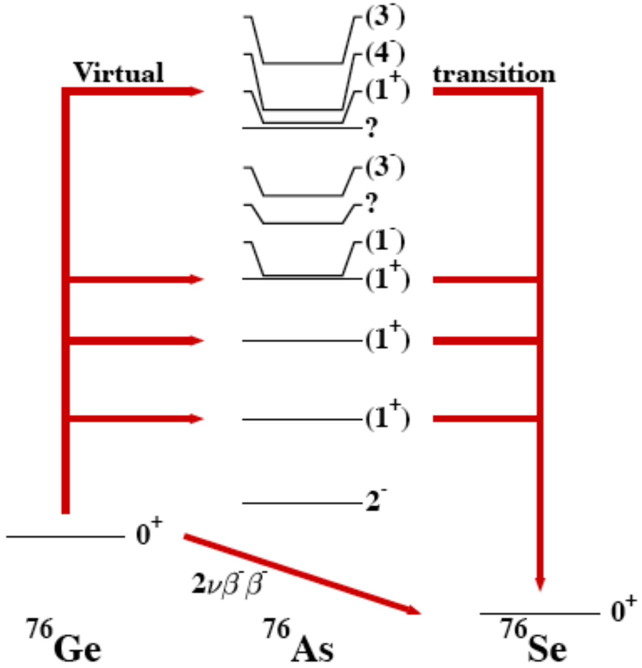
- Medium and heavy open shell nuclei with a complicated nuclear structure
- The construction of complete set of the states of the intermediate nucleus is needed
- Many-body problem ⇒ approximations needed
- Nuclear structure input has to be fixed

F. Simkovic

Les éléments de matrice nucléaire

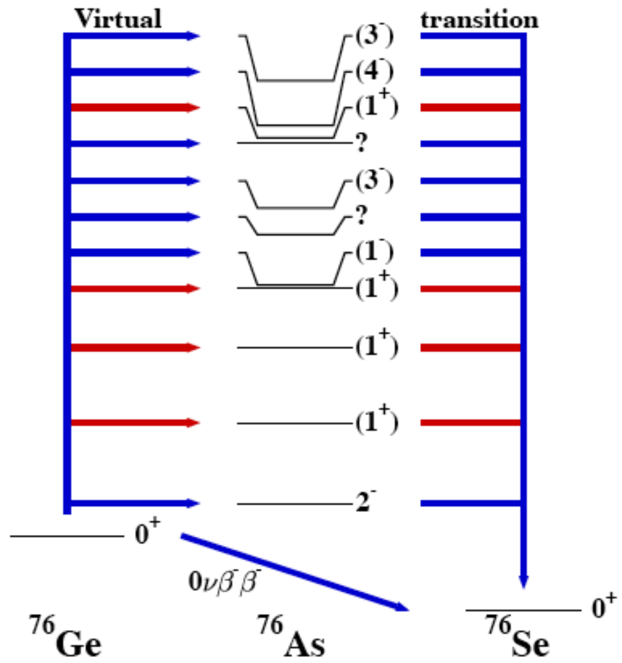
$\beta\beta(2\nu)$

$T^{-1}_{1/2} = F'(Q_{\beta\beta},Z)\ |M'|^2\ \langle m_\nu \rangle^2$



$\beta\beta(0\nu)$

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



LES NME ne sont pas les mêmes, contribution des tous les états intermédiaires pour $\beta\beta(0\nu)$

Modèle en couche ou QRPA

Uncertainties

List of reasons, why QRPA-like $0\nu\beta\beta$–decay NME are different (13 reasons)

Quasiparticle mean field
fixing of pp,nn (pn) pairing

Many-body approximations
QRPA, RQRPA, SRQRPA

Choice of NN interaction
Schem., realistic (Bonn, Paris …

the closure approximation

p-h interaction ($g_{ph} \cong 1$)
fixed to GT resonance

The size of model space

p-p interaction (g_{pp})
fixed to β or $\beta\beta$–decay resonance, or g_{pp}=1

two-nucleon s.r.c. (~ 50%)
has to be considered

finite size of nucleon (~10%)
form factors

h.o.t. of nucleon curr. (~30%)
Induced PS, weak magnetism

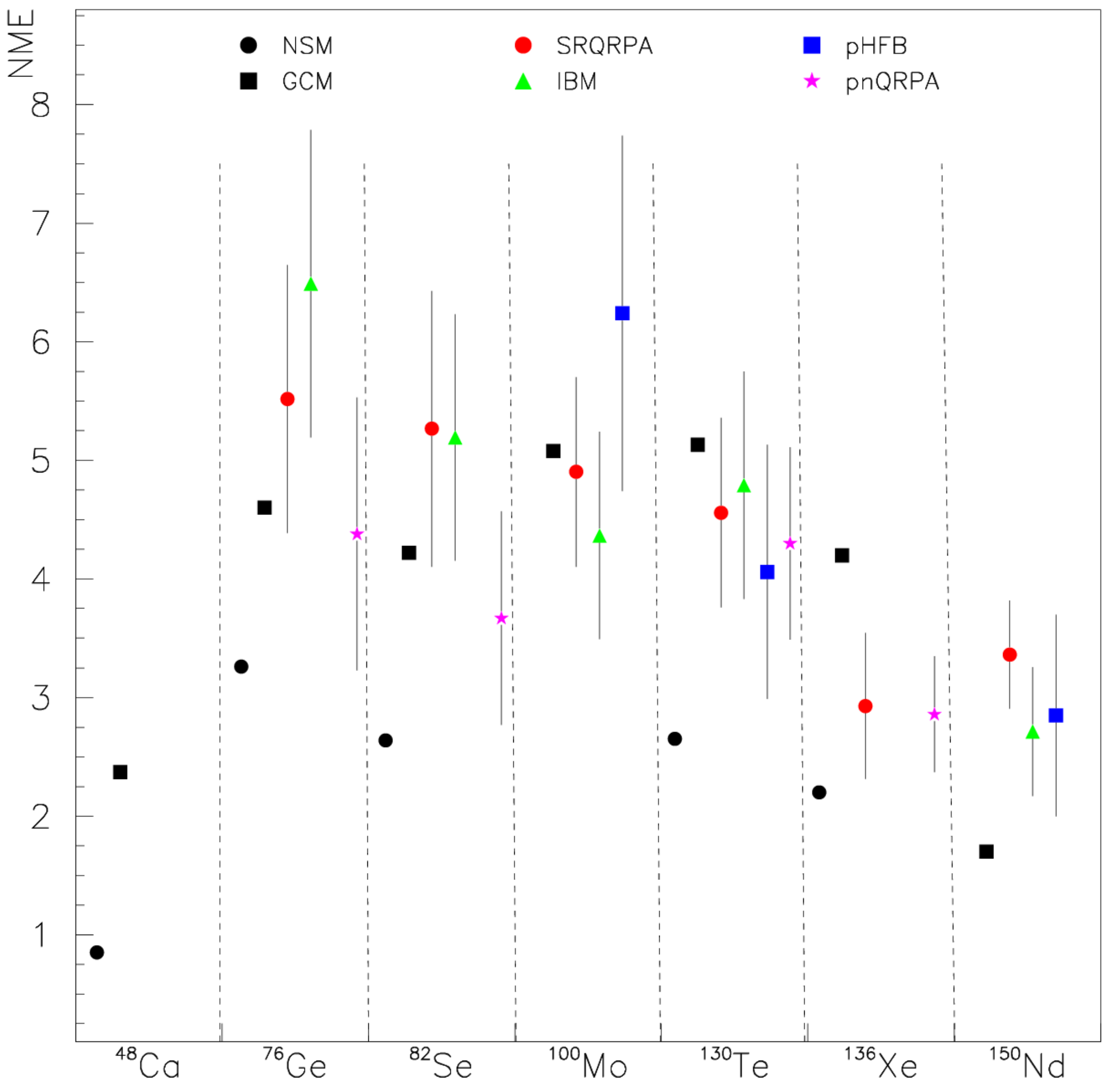
the overlap factor
the BCS overlap

the axial-vector coupling
g_A=1.0 or 1.25

Nuclear shape
Spherical, not deformed yet

F. Simkovic

Les éléments de matrice nucléaire



Les éléments de matrice nucléaire

Isotope	Q [keV]	Nat. abund. (enr.) [%]	$G_{0\nu}$ ($\tilde{G}^{76}_{0\nu}$) $[10^{-14}\ (y^{-1})]^{a}$	$M_{0\nu}{}^{a}$	$T_{1/2,2\nu,exp}$ $[10^{19}\ (y)]$
^{48}Ca	4270	0.187 (73^{b})	6.35 (16.1)	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 ^{208}Tl γ-line, below 3.2 ^{214}Bi Q-value

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

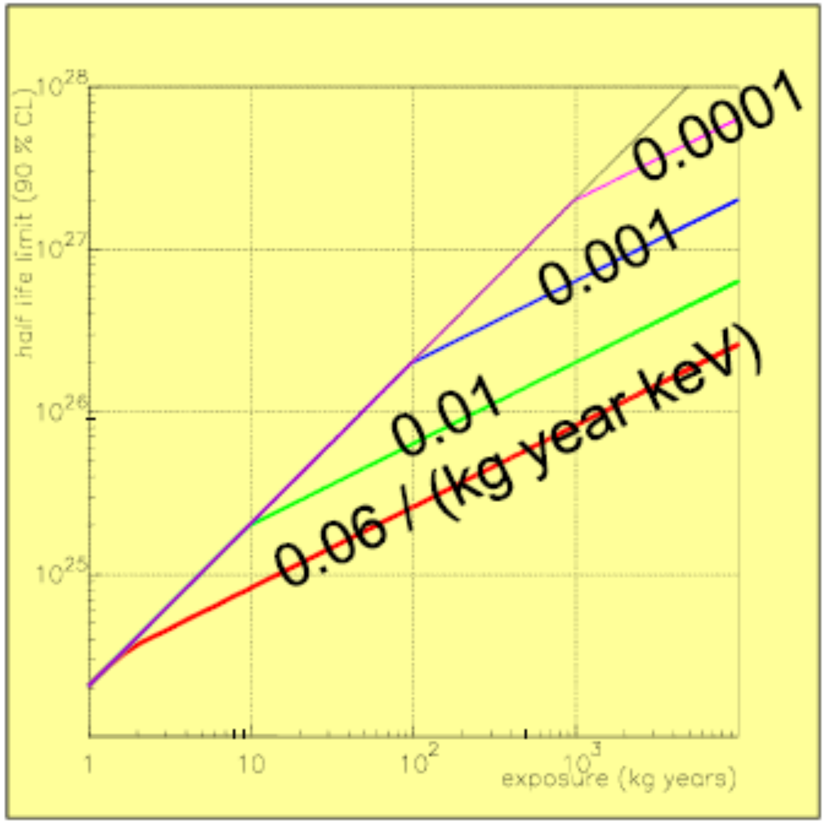
$M_{0\nu}$: small theor. value or difficult to compute...

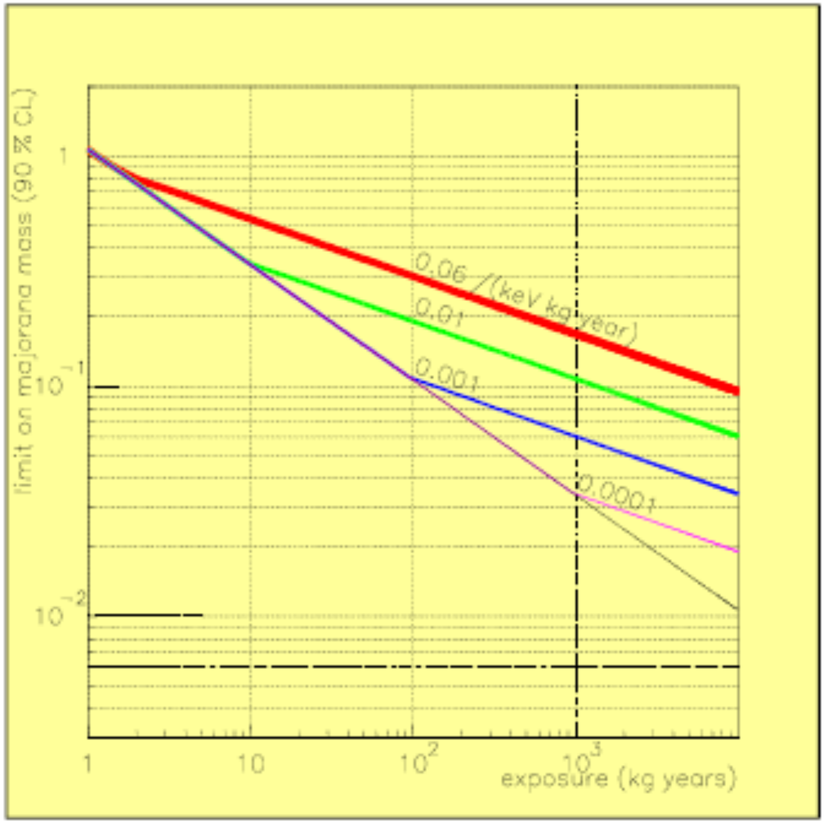
[a] from PRD 83, 113010 (2011)

[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)

Les effets du bruit de fond





Les sources de bruit de fond

Natural radioactivity (^{40}K, ^{60}Co, ^{234m}Pa, external ^{214}Bi and ^{208}Tl…)

^{214}Bi and Radon

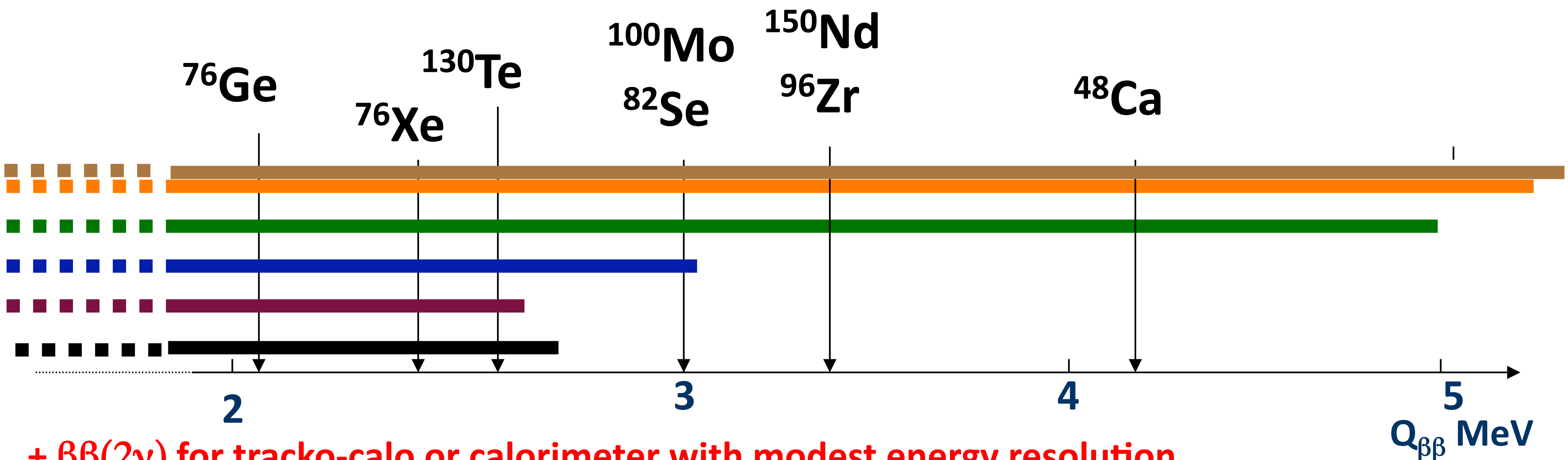
^{208}Tl (2.6 MeV γ line) and Thoron

γ from (n,γ) reaction and muons bremstrahlung

+ more specific background for calorimeter

Surface or bulk contamination in α emitters

cosmogenic production



+ ββ(2ν) for tracko-calo or calorimeter with modest energy resolution

Les techniques expérimentales

With background:

$$T^{0\nu}_{1/2}(y) > \frac{\ln 2 \,.\, \mathcal{N}}{k_{C.L.}} \,.\, \frac{\varepsilon}{A} \,.\, \sqrt{\frac{M \,.\, t}{N_{Bckg} \,.\, \Delta E}}$$

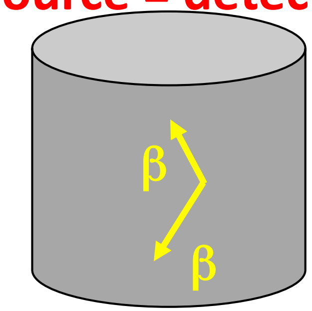
M: masse (g) **$K_{C.L.}$**: Confidence level
ε : efficiency $\mathcal{N}$: Avogadro number
t: time (y) **N_{Bckg}**: Background events ($keV^{-1}.g^{-1}.y^{-1}$)
ΔE: energy resolution (keV)

No background:

$$T^{0\nu}_{1/2}(y) \propto \frac{\varepsilon}{A} \, M \,.\, t$$

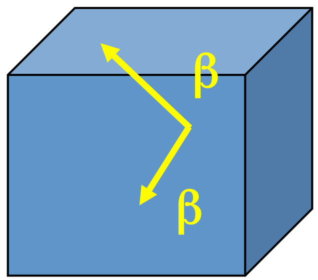
Today, no technique able to optimize all the parameters

Calorimeter
Semi-conductors
Bolometers
Source = detector



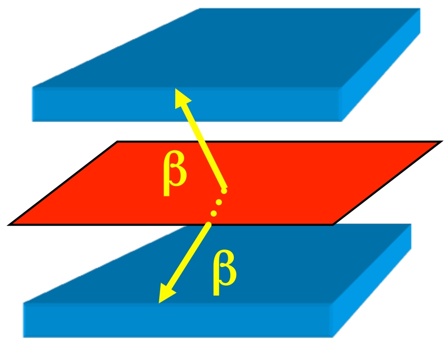
ε, ΔE

Calorimeter
(Loaded) Scintillator
Source = detector



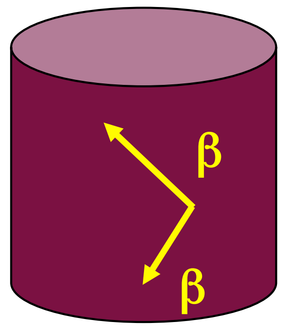
ε, M

Tracko-calo
Source ≠ detector



NBckg, isotope choice

Xe TPC
Source = detector

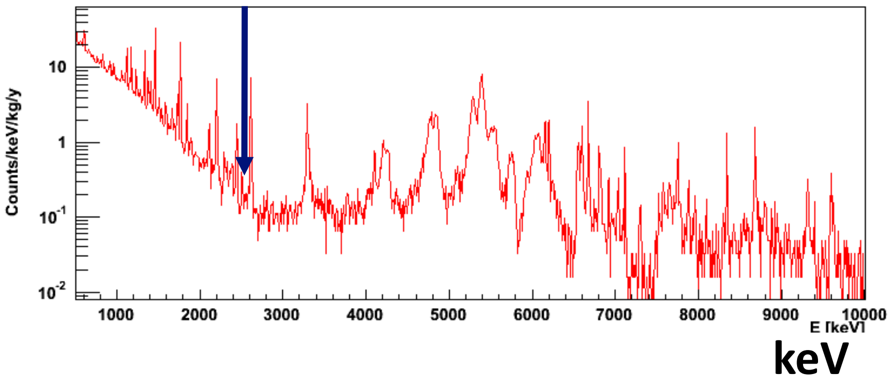


ε,M, (N_{Bckg})

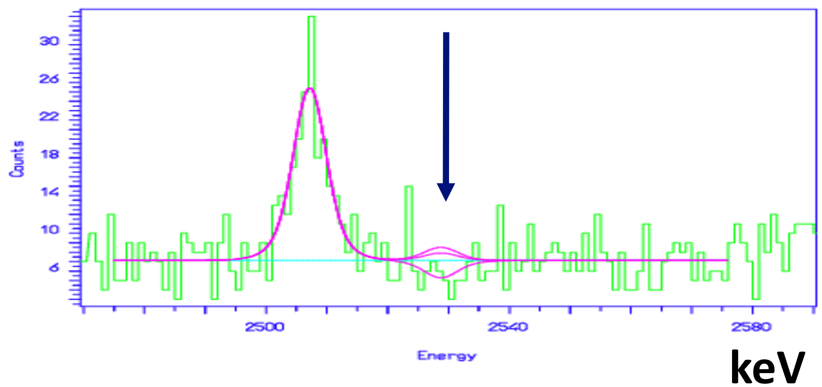
Les techniques expérimentales

High energy resolution
Modest background rejection

ββ(0ν)

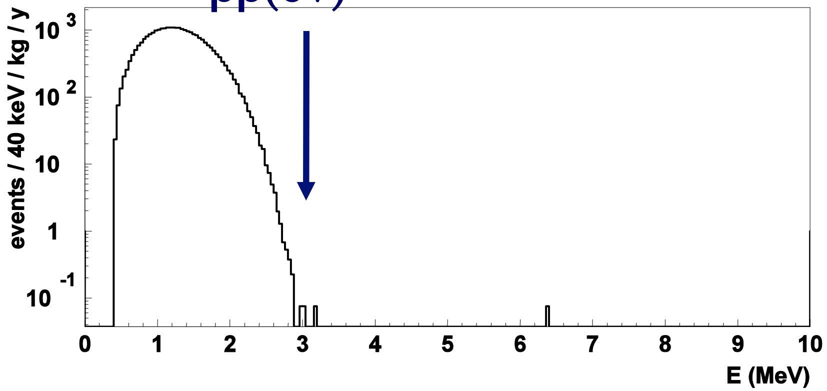


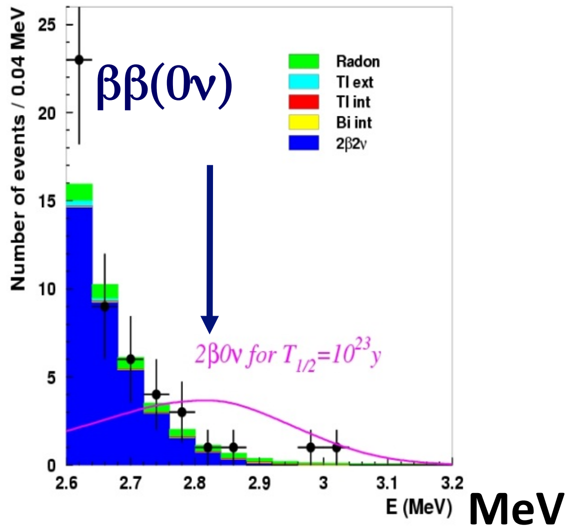
ββ(0ν)



High background rejection
Modest energy resolution

ββ(0ν)





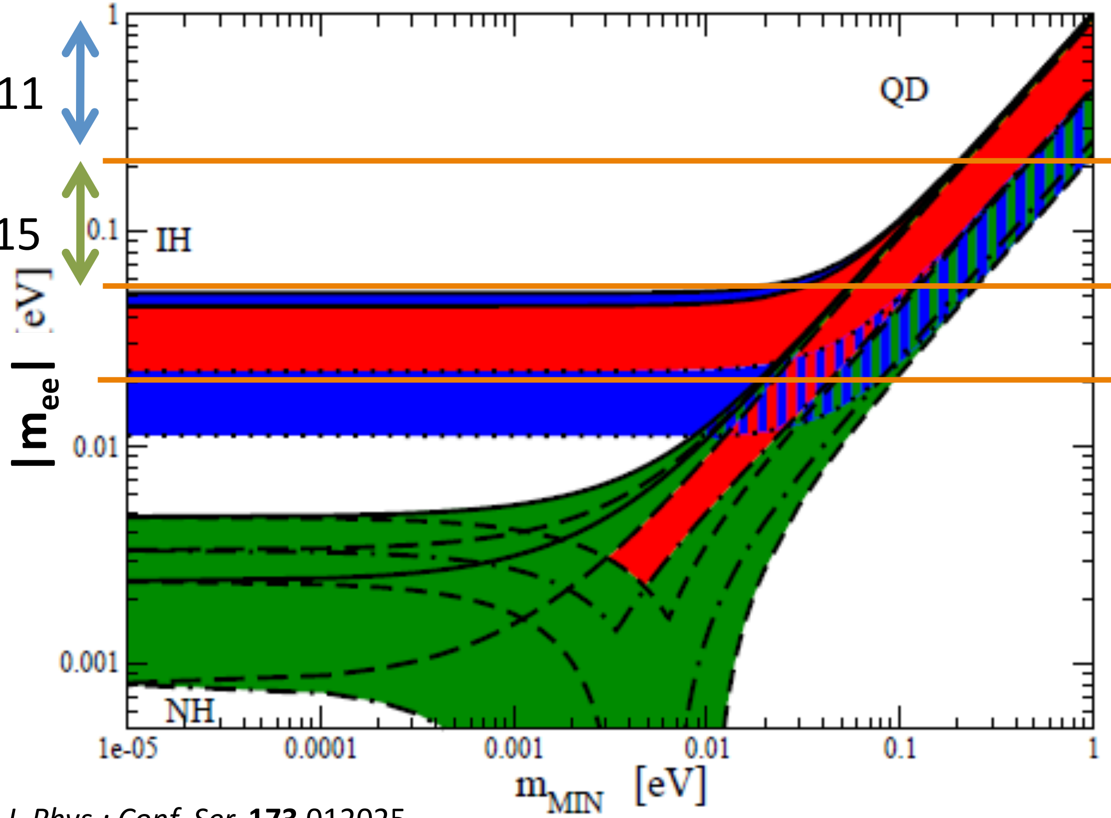
Présent et futur

$$|\langle m_\nu \rangle| = |\sum U_{e_i}^2 m_i| = |\cos^2\theta_{13}(m_1\cos^2\theta_{12} + m_2 e^{2i\alpha}\sin^2\theta_{12}) + m_3 e^{2i\beta}\sin^2\theta_{13}|$$

Masse d'isotope

Niveau de bruit de fond requis

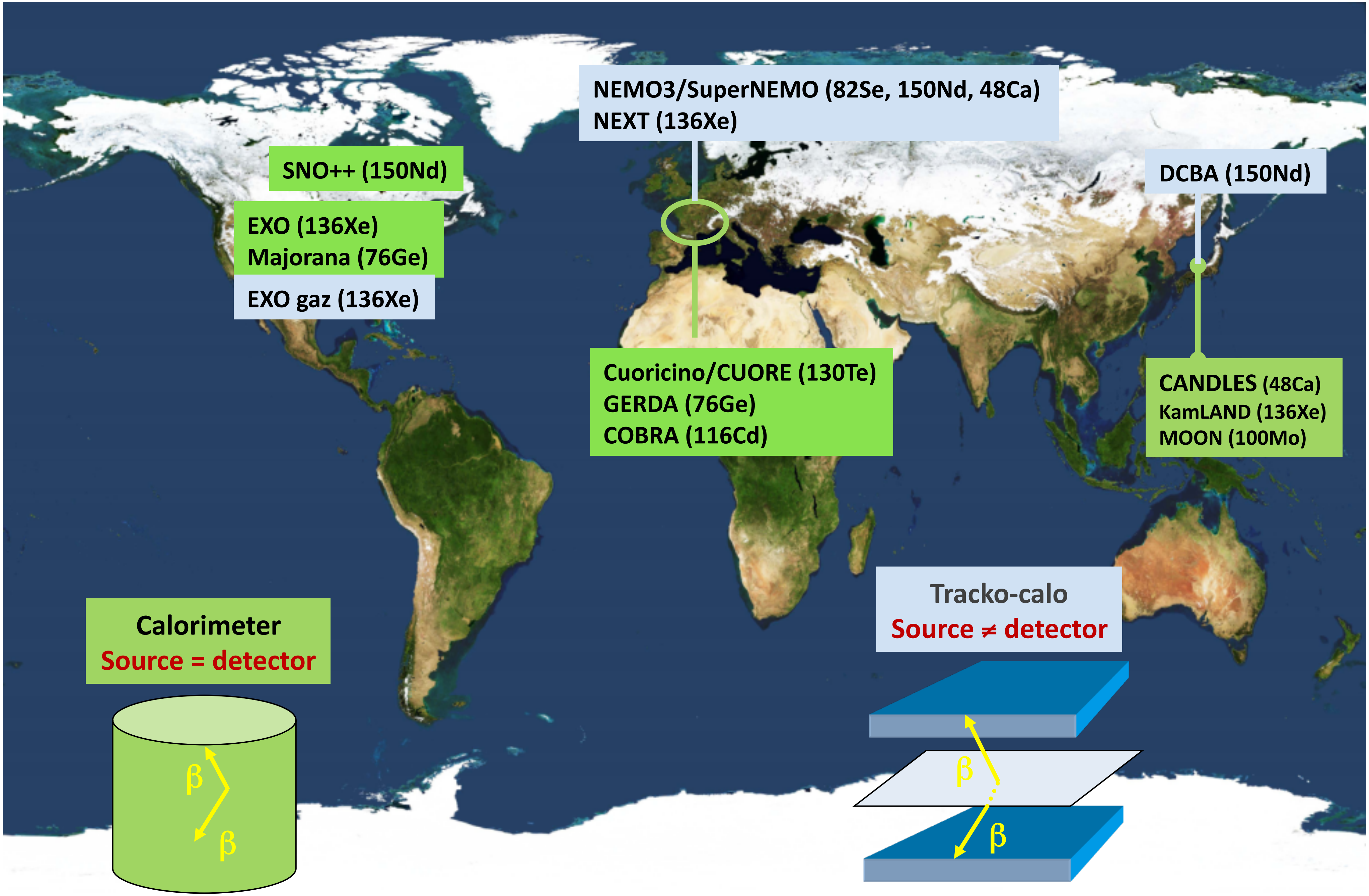
Masse d'isotope	Année	Niveau de bruit de fond requis
~ 10 kg	2011	100 – 1000 cts/yr/ton
~ 100 kg	2015	1 – 10 cts/yr/ton
~ 1000 kg		0.1 – 1 cts/yr/ton



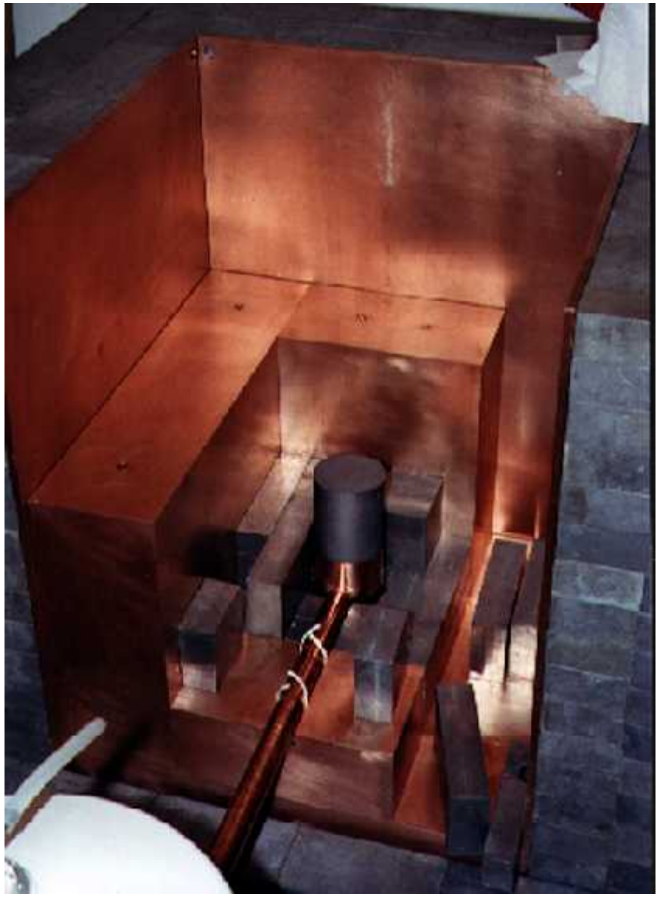
S T Petcov 2009 *J. Phys.: Conf. Ser.* **173** 012025

Next step ~ 100 kg experiment 2011 - 2015

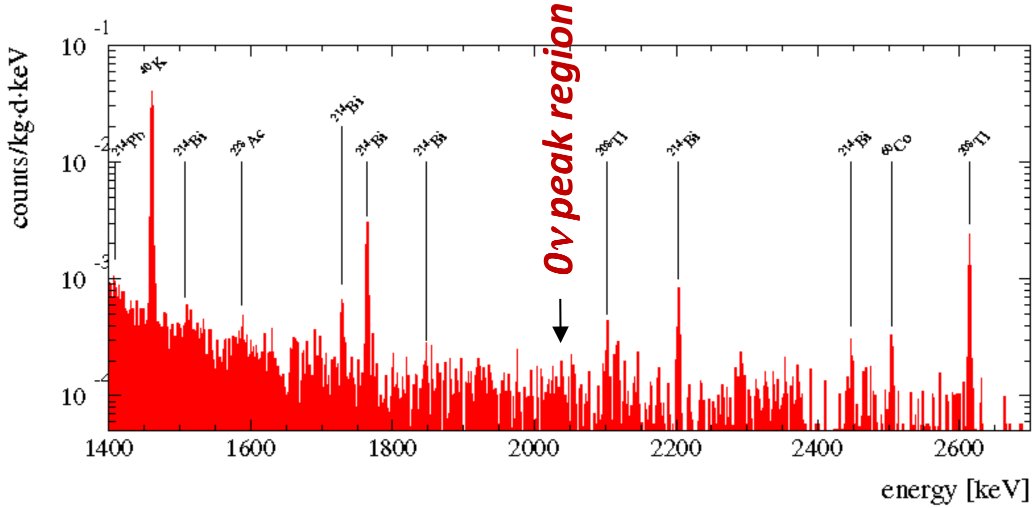
Les expériences dans le monde



Les détecteurs Germanium

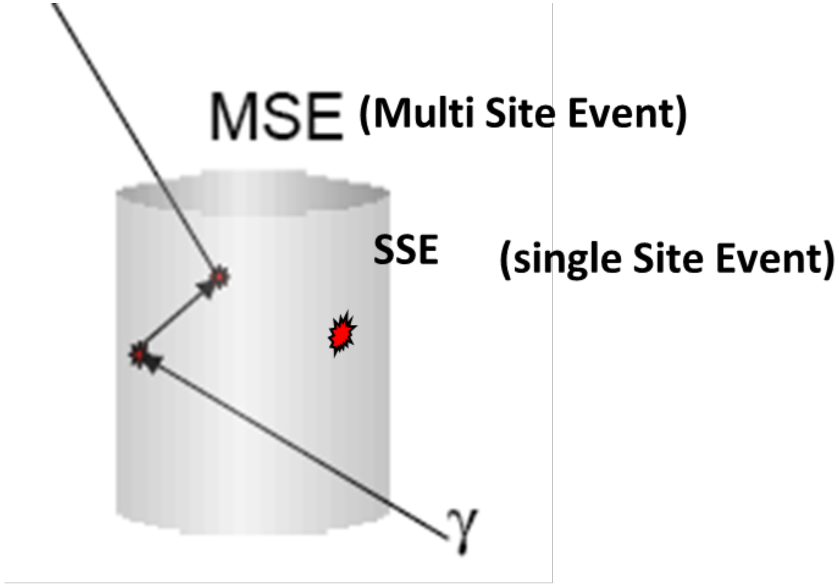


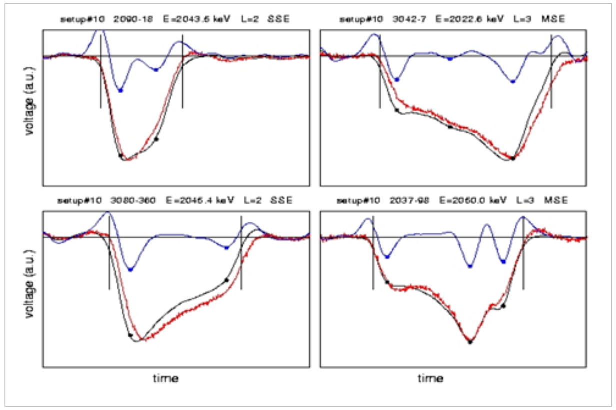
Ge detector: - Very good energy resolution
- Efficiency
- Compact detector



	M(kg.y)	$T_{1/2}$(y)	<m>
HM	36.53	>1.9 10^{25}	0.35-1.05
IGEX	4.64	>1.57$10^{25}$	0.33-1.31

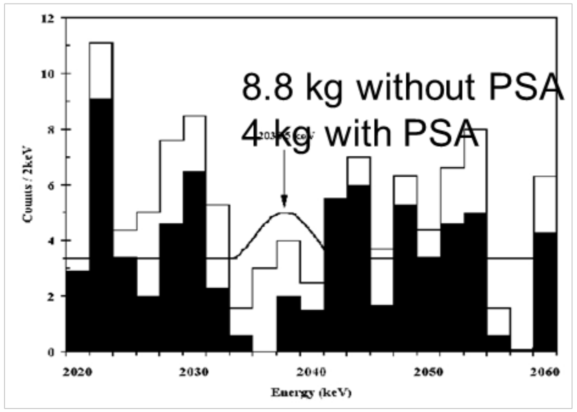
Les détecteurs Germanium



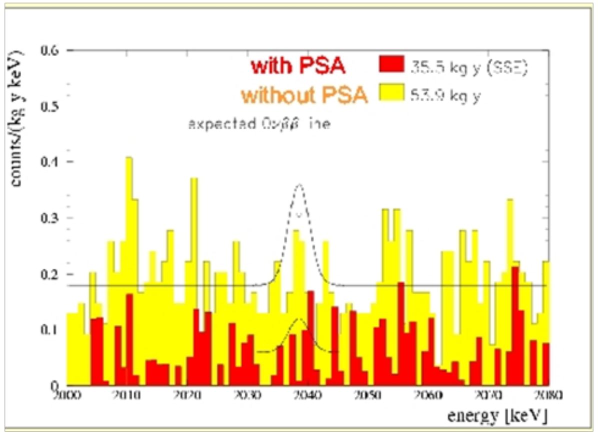


Efficiency to reject bad events: 60-80 %

HM: 0.06 counts/kg.y.keV
IGEX: 0.09 counts/kg.y.keV



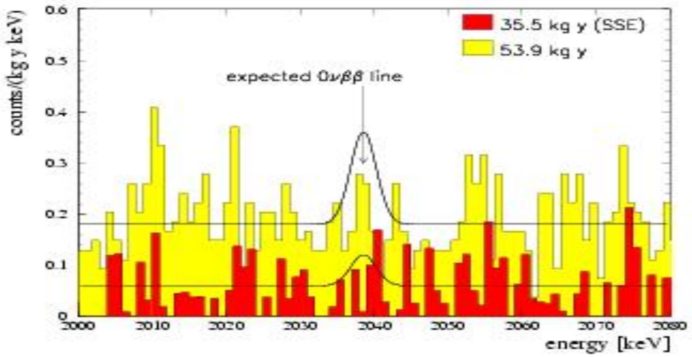
IGEX



HM

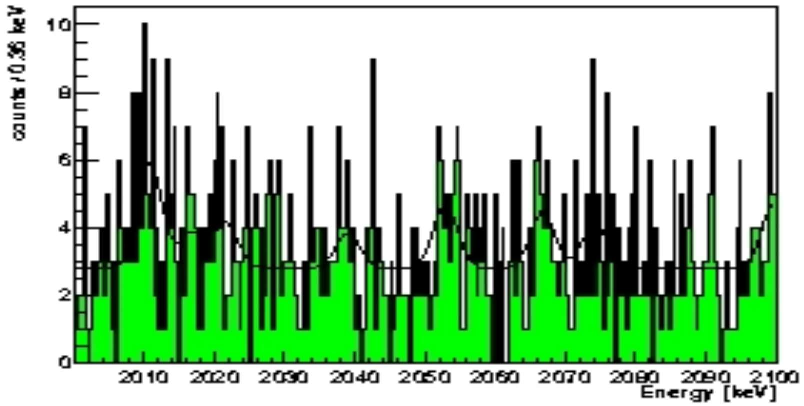
H-M claim

2001



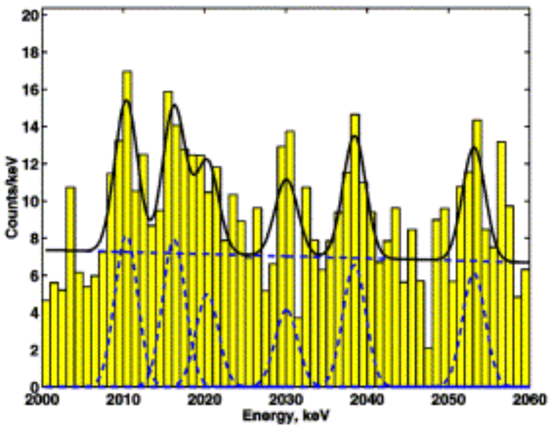
$T_{1/2} > 1.9\ 10^{25}$ $\langle m_n \rangle$ < 0.35-1.05 (90%)

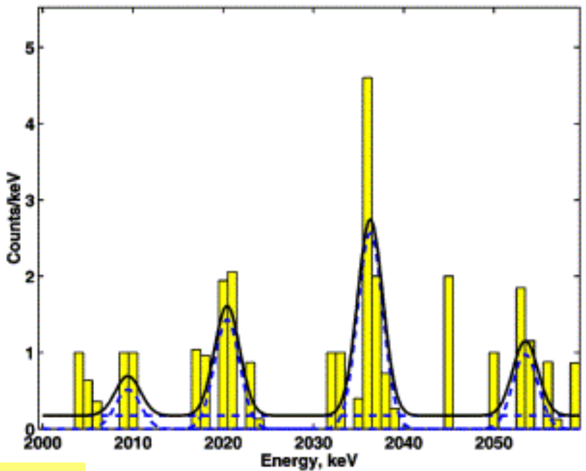
2002 (3.1σ)

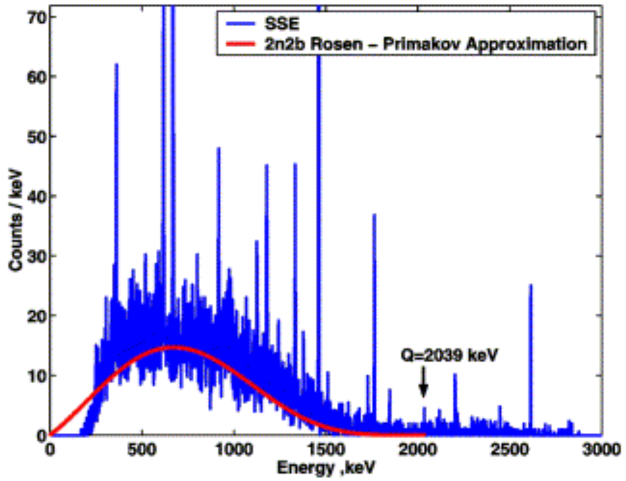


$T_{1/2}$= (0.8-18.3) 10^{25} y $\langle m_n \rangle$= 0.11 – 0.56 eV

2004: new calibration (4σ)







$$T_{\frac{1}{2}} = (0.69 - 4.18)\, 10^{25}\ ans\,(90\ CL)$$

$$\langle m_\nu \rangle = 0.28 - 0.58\ eV$$

Best value:0.39 eV

H-M claim

Statistical effect ?

Estimation of the background level ?

Problems for some well-known peaks (214Bi)

Some unknow lines in the same region

Les possibilités

^{56}Co produced by cosmic rays (2034 keV photon+ 6 keV X-ray)

^{76}Ge(n, γ)^{77}Ge (2038 keV photon)

Some unknown line

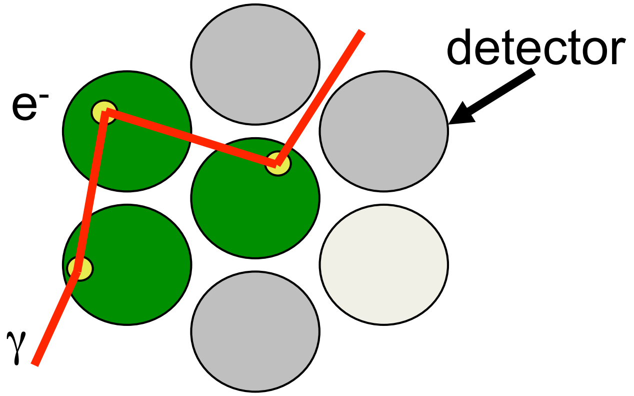
Inelastic neutron scattering (n,n'γ) on lead

Other suggestions, can be combination of all

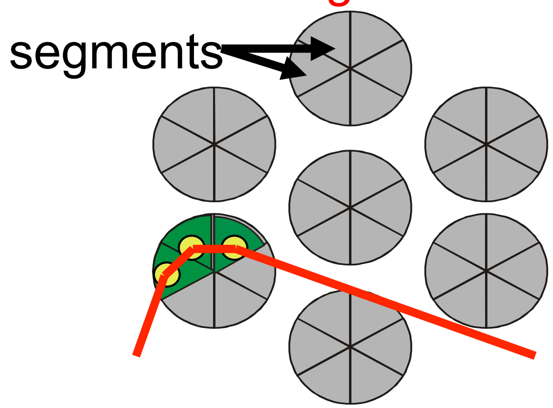
Le futur des détecteurs germanium

Strategies: **Ge detectors in liquid nitrogen to remove materials**
Active shielding and segmentation of detectors to reject gamma-rays

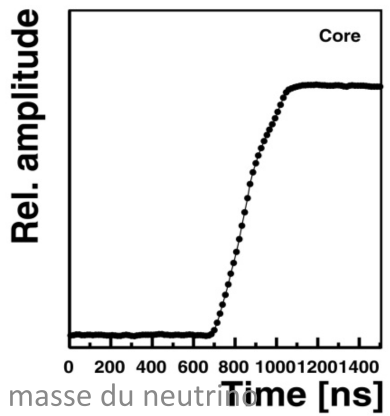
crystal anti-coincidence



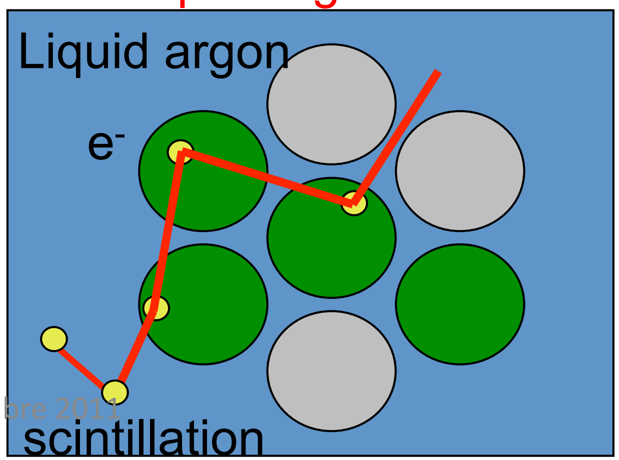
Detector segmentation



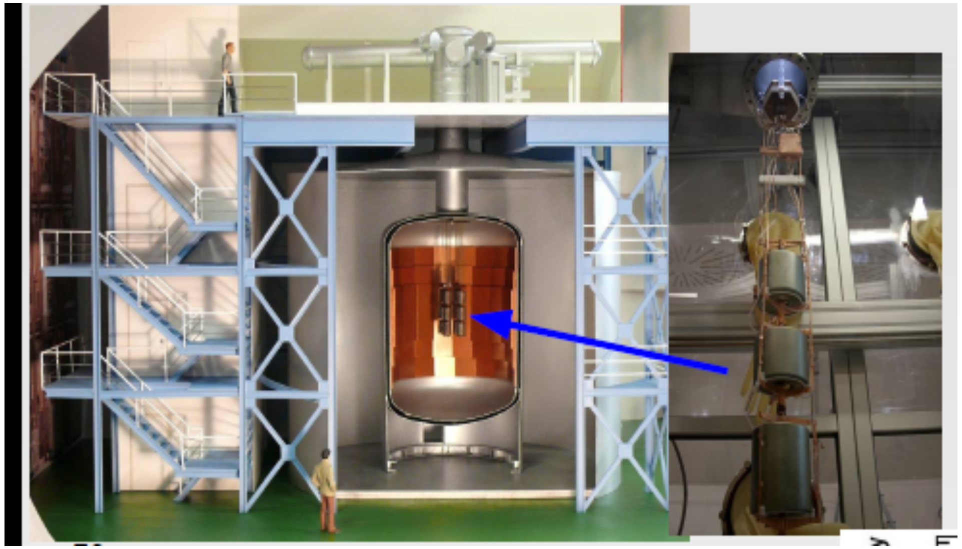
pulse shape analysis



R&D: liquid argon anti-coincidence



GERDA

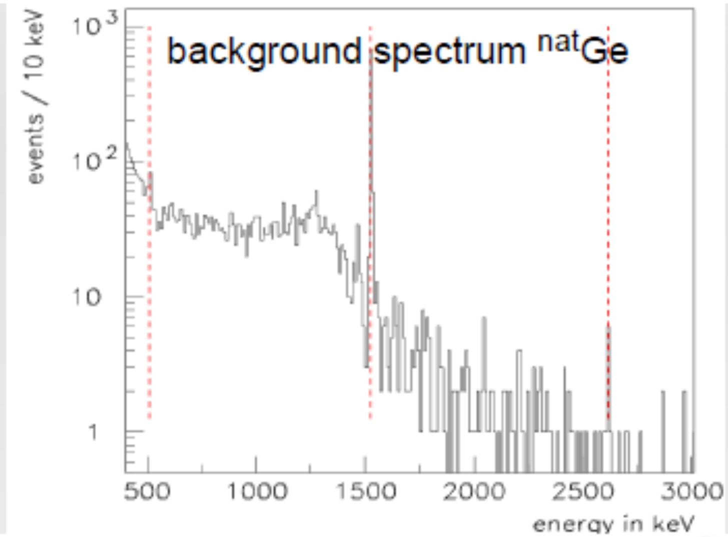


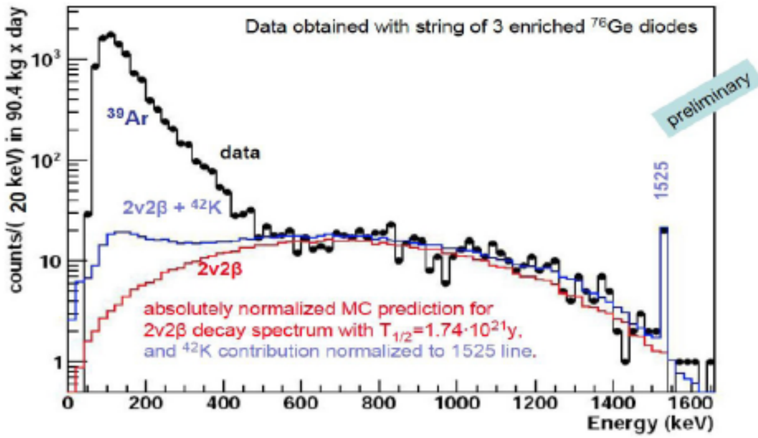
Removal of matter

Use of liquid nitrogen or argon for active shielding

Segmentation

Improvement of Pulse Shape Analysis



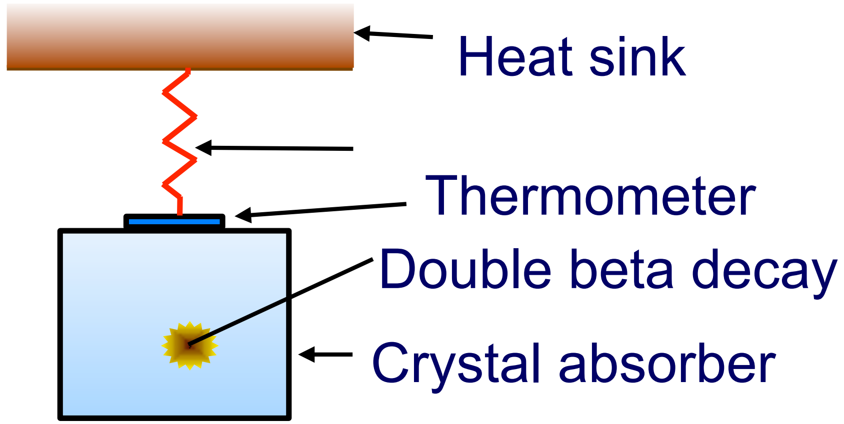


Objectif : 0.01 coups/keV/kg/an

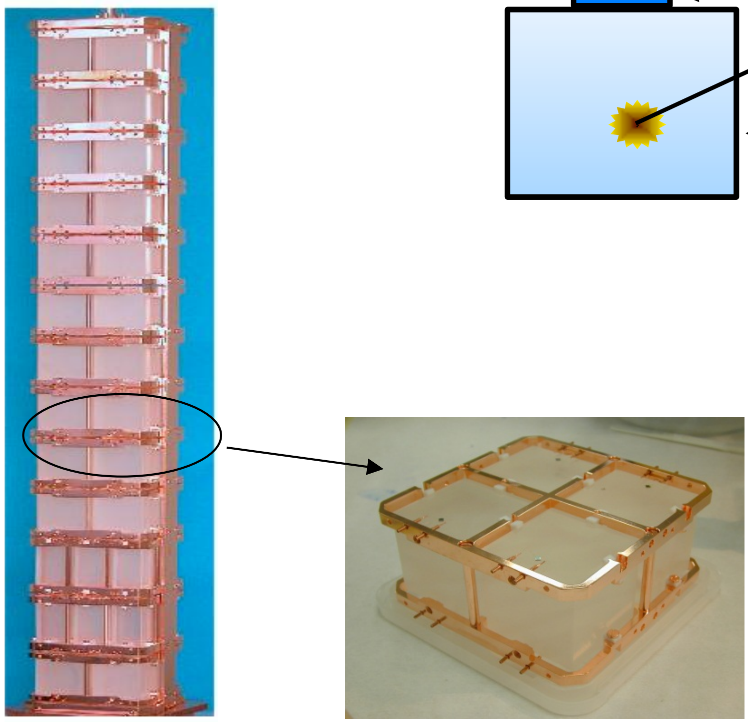
mesuré 0.06 coups/keV/kg/an

Les bolomètres : CUORICINO

Bolometers of TeO_2 ($Q_{\beta\beta}$= 2.528 MeV)



Signal: $\Delta T = E/C$



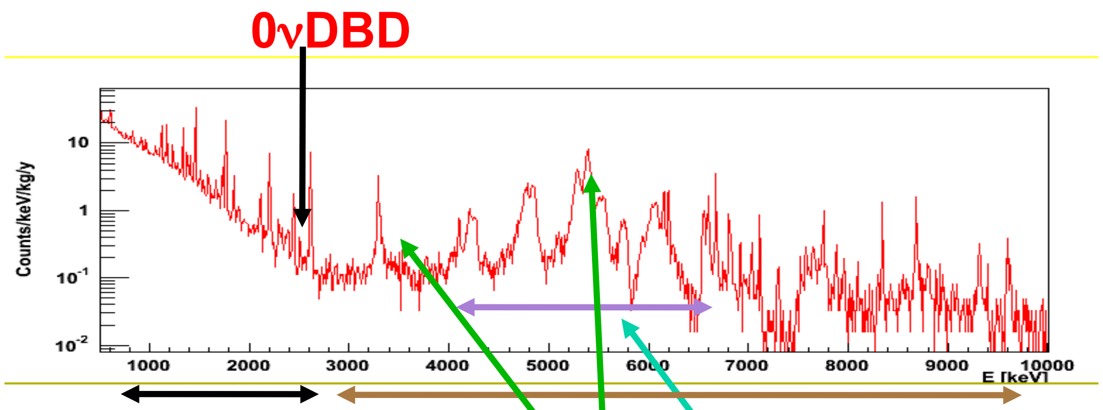
10.4 kg of ^{130}Te

High energy resolution 5-7 keV (FWHM)
Natural abundance for ^{130}Te: 34%
High efficiency: 86%

But no electron identification
Background from internal and surface contamination in α emitters

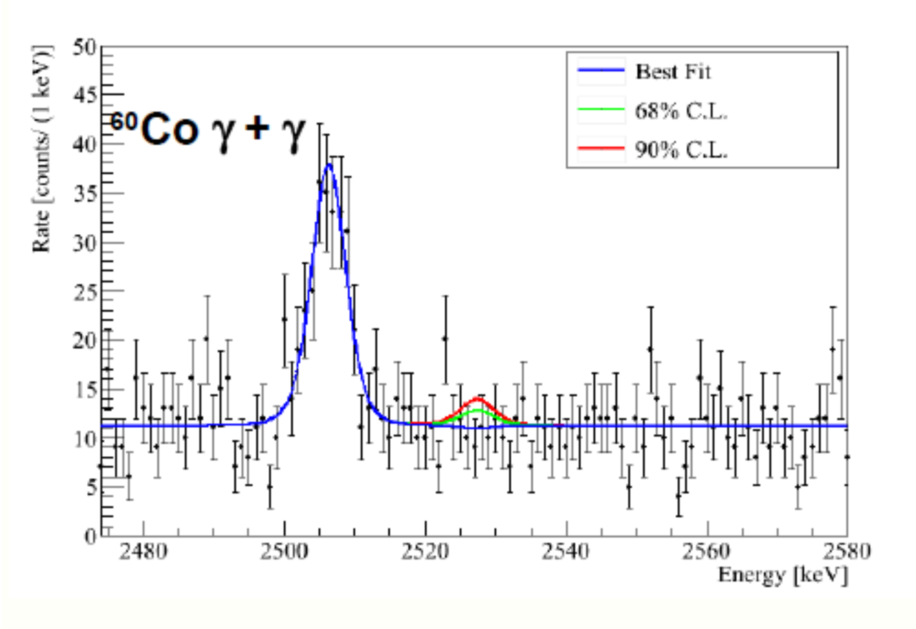
Running at Gran Sasso since 2003

CUORICINO



Gamma region, dominated by gamma and beta events,

Alpha region, dominated by alpha peaks (internal or surface contaminations)



Bkg at Q-value: **0.17 counts/(keV kg y)**

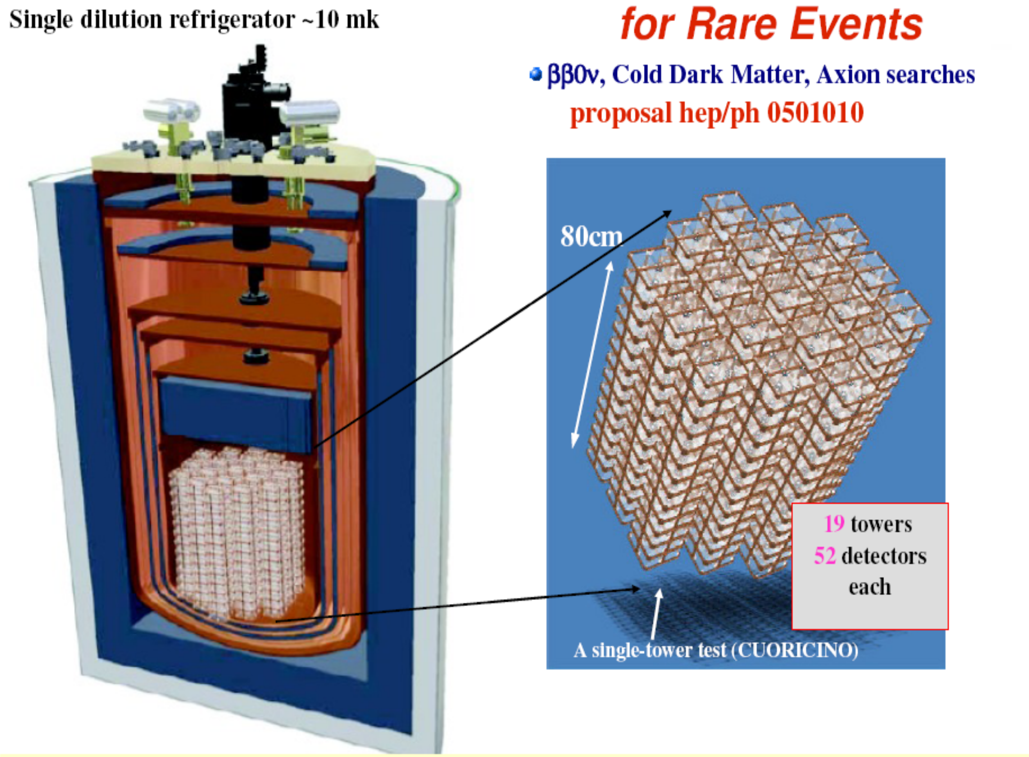
Statistics: **19.75 kg(^{130}Te) y**

$$T_{1/2}^{0\nu} > 2.8 \times 10^{24}\, y \quad @\, 90\%\, CL$$

$$m_{\beta\beta} \begin{cases} < (300 - 570)\ \text{meV} & \text{(R)QRPA} \\ < (360 - 580)\ \text{meV} & \text{pnQRPA} \\ < (570 - 710)\ \text{meV} & \text{ISM} \\ < 370\ \text{meV} & \text{IBM-2} \end{cases}$$

Le futur des bolomètres CUORE

(Italy, USA,Spain)



750 kg of TeO_2 → 203 kg of ^{130}Te

Array of 988 TeO_2 5x5x5 cm^3 crystals

Improvement of surface event rejection

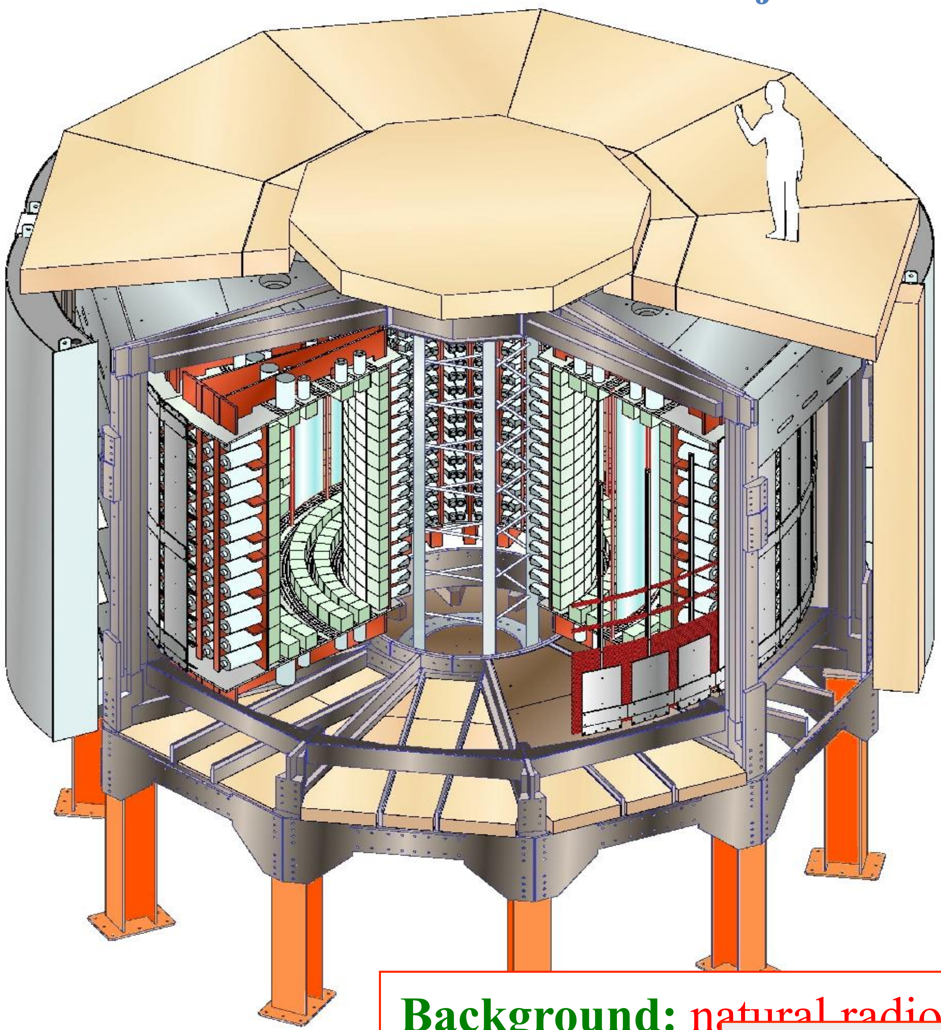
Goal : N_{bckg}=0.01 cts.keV^{-1}.kg^{-1}.yr^{-1}
(Factor 20 compared to Cuoricino)

Data taking foreseen in 2014

Expected sensitivities (5 years of data)

N_{bckg}=0.01 cts.keV^{-1}.kg^{-1}.yr^{-1}	N_{bckg}=0.001 cts.keV^{-1}.kg^{-1}.yr^{-1}
$T_{½} > 2.1\ 10^{26}$ yr	$T_{½} > 6.6\ 10^{26}$ yr
$<m_\nu> < 0.03 – 0.17$ eV	$<m_\nu> < 0.015 – 0.1$ eV

Un détecteur tracko-calo: NEMO 3



Fréjus Underground Laboratory : 4800 m.w.e.

Source: 10 kg of ββ isotopes
cylindrical, S = 20 m^2, 60 mg/cm^2

Tracking detector:
drift wire chamber operating
in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

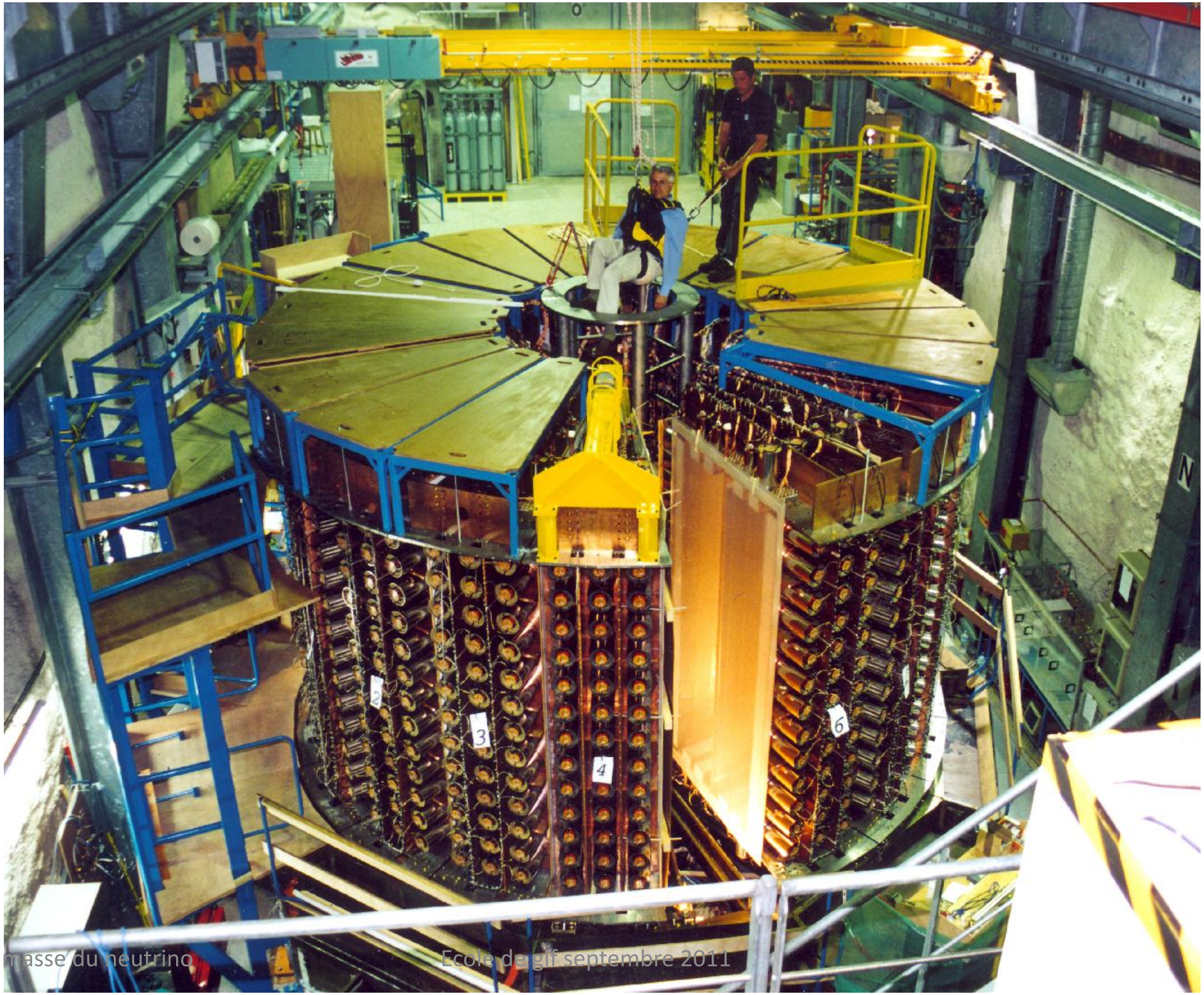
Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs

Magnetic field: 25 Gauss
Gamma shield: Pure Iron (18 cm)
Neutron shield: borated water
+ Wood

Background: natural radioactivity, mainly ^{214}Bi et ^{208}Tl (γ 2.6 MeV)
⇒ I

Able to identify e$^-$, e$^+$, γ and α

NEMO 3



NEMO 3


Cathodic ring
PMT
Tube for calibration
Scintillators
Source foil

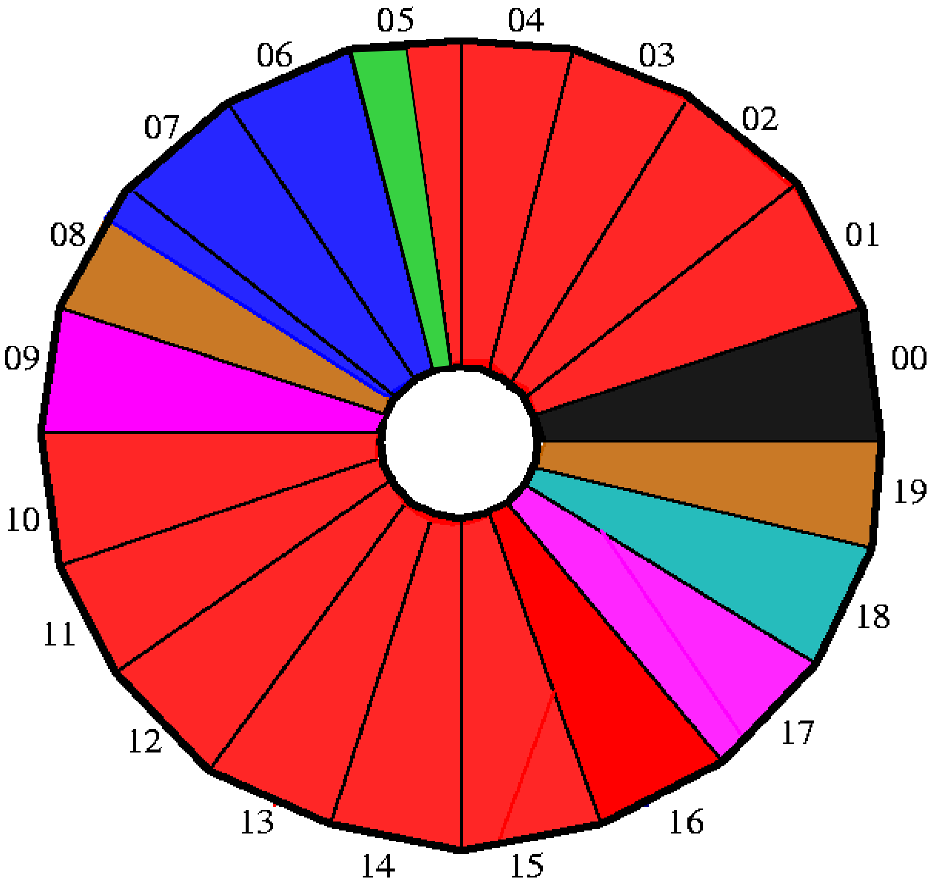
NEMO 3

^{100}Mo 6.914 kg
$Q_{\beta\beta}$ = 3034 keV

&

^{82}Se 0.932 kg
$Q_{\beta\beta}$ = 2995 keV

→ **0νββ decay search**



^{116}Cd 405 g
$Q_{\beta\beta}$ = 2805 keV

^{96}Zr 9.4 g
$Q_{\beta\beta}$ = 3350 keV

^{150}Nd 37.0 g
$Q_{\beta\beta}$ = 3367 keV

^{48}Ca 7.0 g
$Q_{\beta\beta}$ = 4272 keV

^{130}Te 454 g
$Q_{\beta\beta}$ = 2529 keV

→ **2νββ decay measurement**

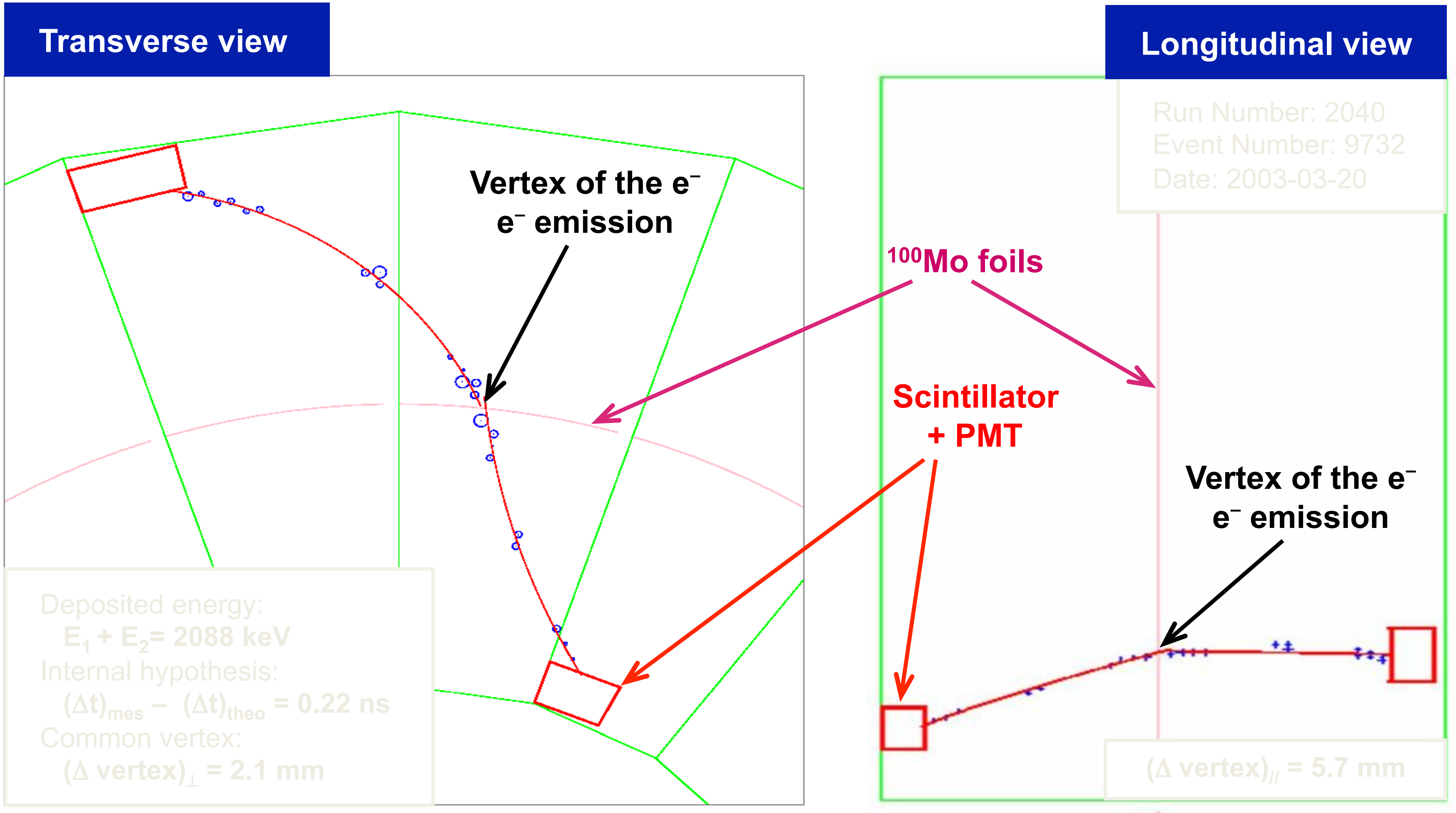
^{nat}Te 491 g

Cu 621 g

→ **External background measurement**

All sources produced by centrifugation in Russia

NEMO 3



Criteria to select ββ events:

- 2 tracks with charge < 0
- 2 PMTs, each > 200 keV
- PMT-Track association
- Common vertex
- Internal hypothesis TOF (external event rejection)
- No other isolated PMT (γ rejection)
- No delayed α track (^{214}Bi rejection)

NEMO 3

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

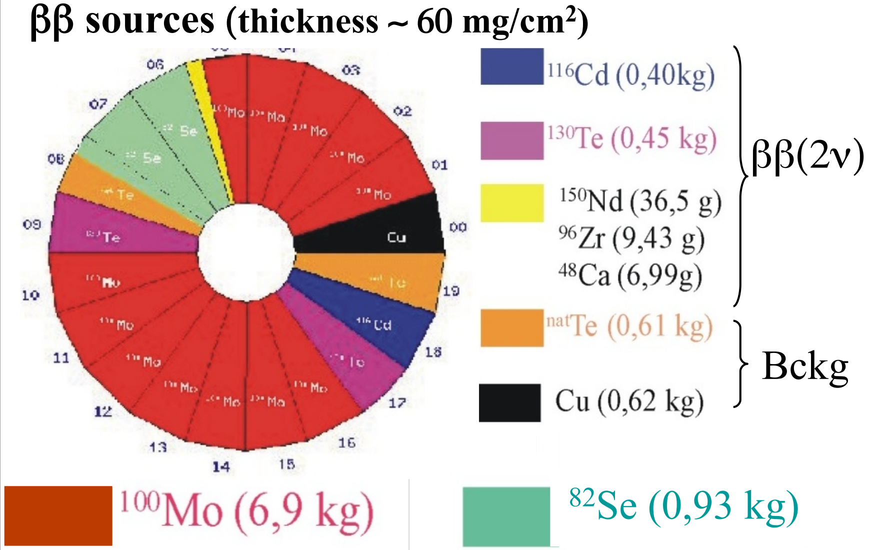
Calorimeter (1940 plastic scintillators and PMTs)
Energy Resolution FWHM=8 % (3 MeV)

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/y

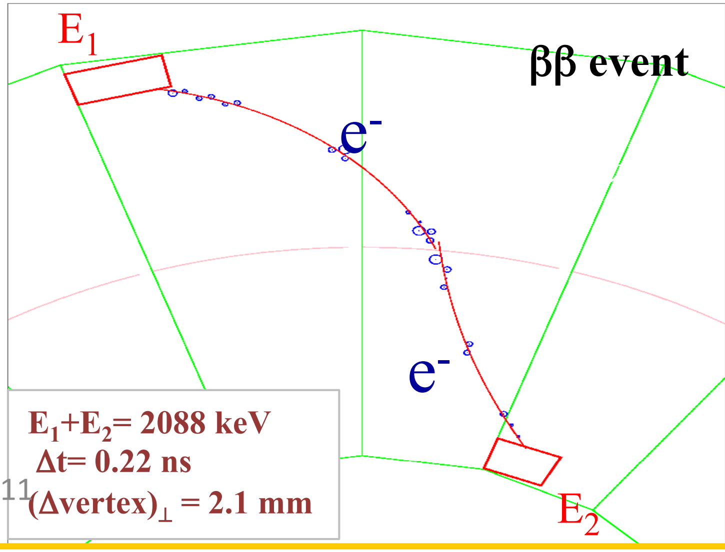
Running at Modane underground laboratory (2003 - 2011)

Multi-source detector



Unique feature

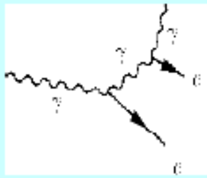
Measurement of all kinematic parameters: individual energies and angular distribution



NEMO backgrounds

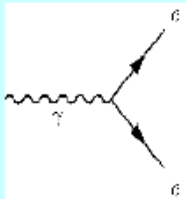
- Natural radioactivity outside and inside source foils:
  - ^{238}U / ^{232}Th chains
  - ^{40}K
  - Rn
- cosmic μ
- neutrons

External



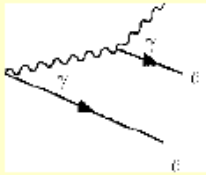
double Compton

Compton + Moller

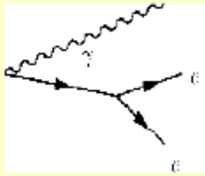


pair production

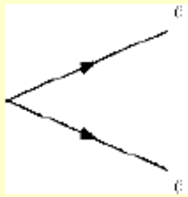
Internal



β^-+Compton



β^-+Moller

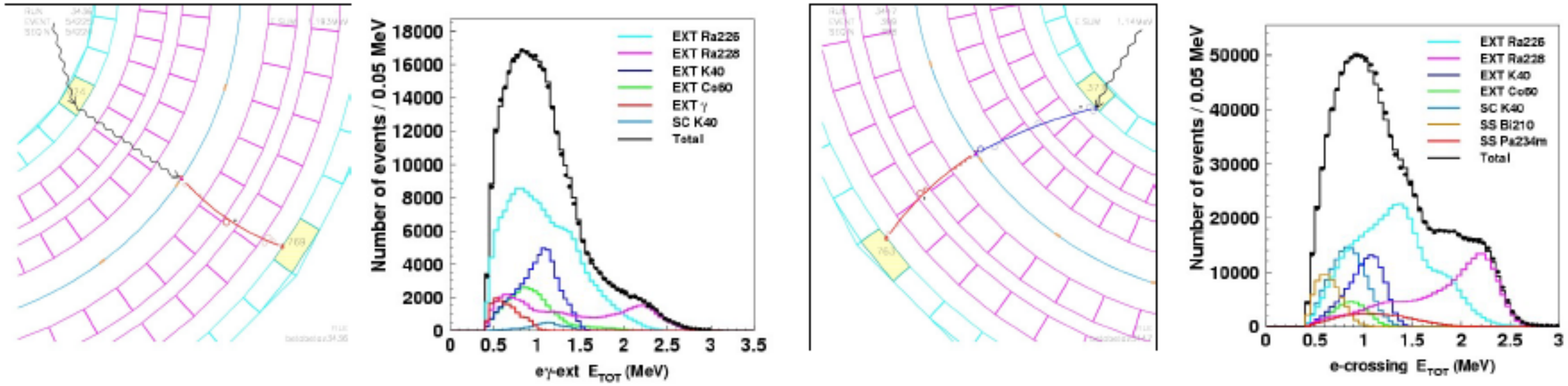


β^-+IC

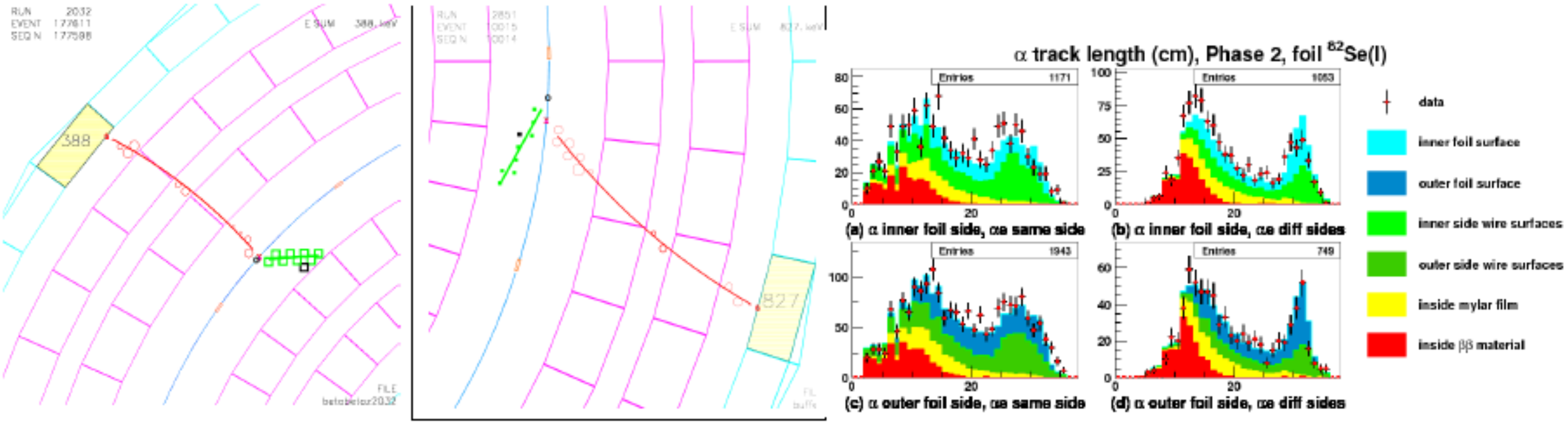
Background measurement in NEMO-3: NIM A606 (2009) 449

NEMO 3 measures each component of its background

External background: eγ-external and e-crossing events

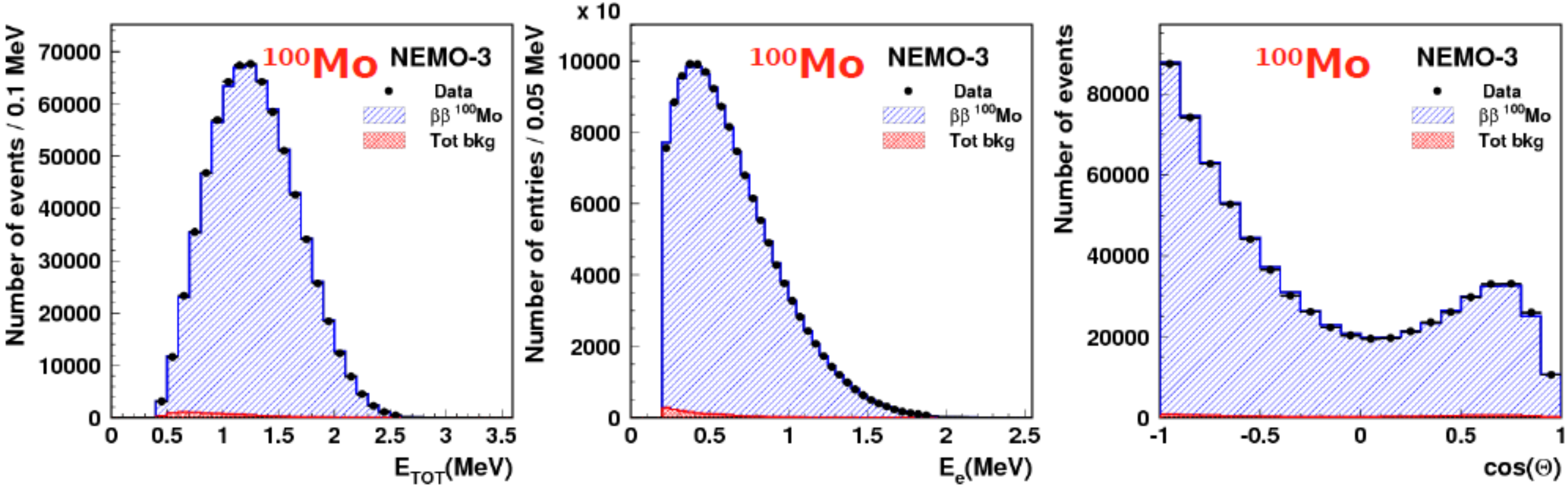


Internal ^{214}Bi : eα(γ)-events from foil



NEMO 3: ββ2ν results for ^{100}Mo source

Phase 2 : 4 years of data



Energy sum of the 2 electrons events | **Single electron energy** | **Angular distribution between the 2 electrons**

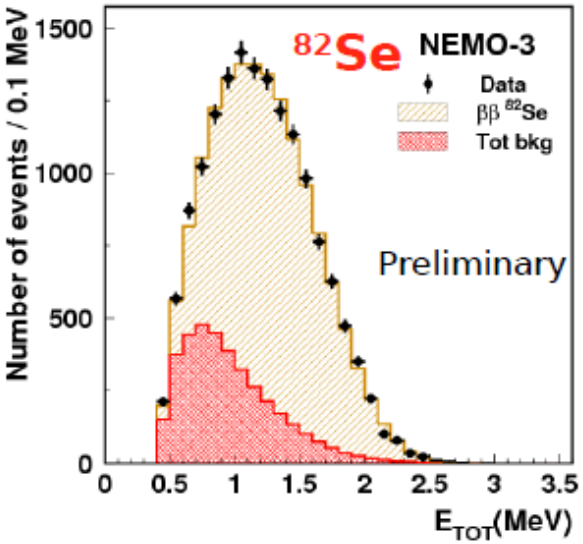
700 000 two-electron events from ^{100}Mo source foils

Ratio Signal/Background : 76

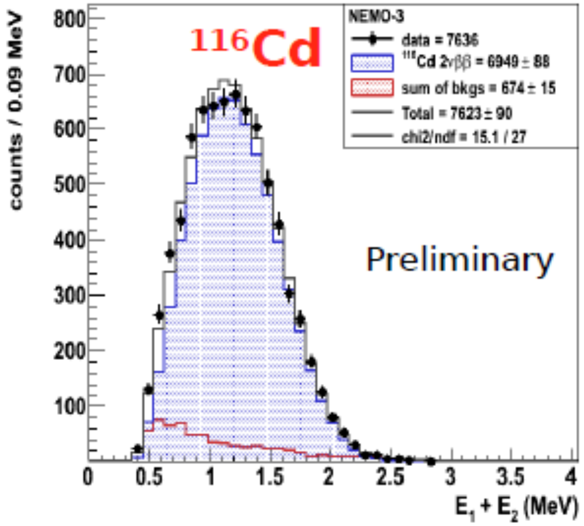
$T_{1/2}$ (ββ2ν) = (7.16 ± 0.01) 10^{18} y (preliminary)

(published phase 1 $T_{1/2}$ = [7.11 ± 0.02 (stat) ± 0.54 (sys)] 10^{18} y)

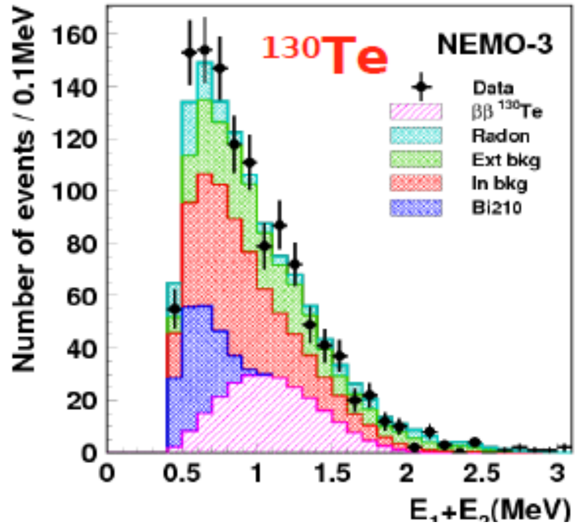
NEMO 3: other ββ2ν period results



[9.6±0.1(stat)±1.0(sys)]×10[19] y

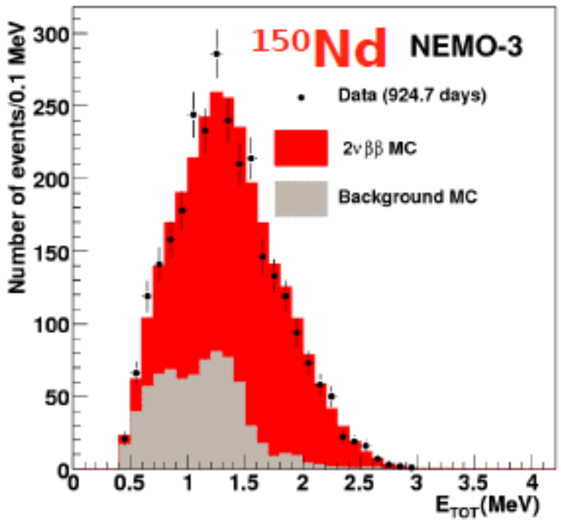


[2.88±0.04(stat)±0.16(sys)]×10[19] y



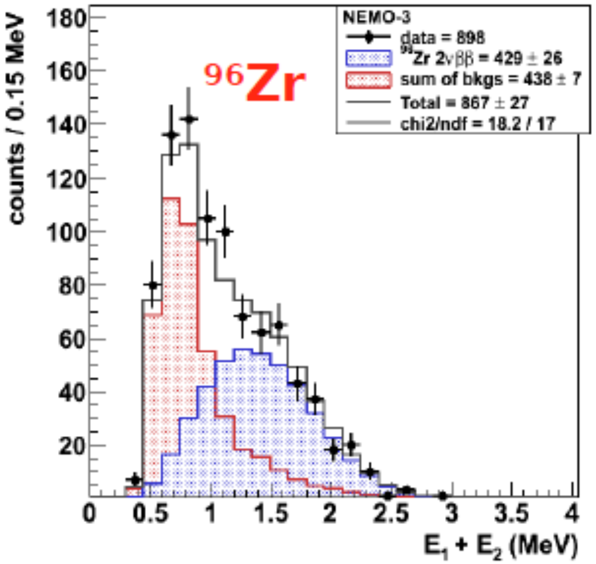
[7.0±0.9(stat)±0.9(sys)] 10^{20} y

Phys. Rev. Lett. 107, 062504(2011)



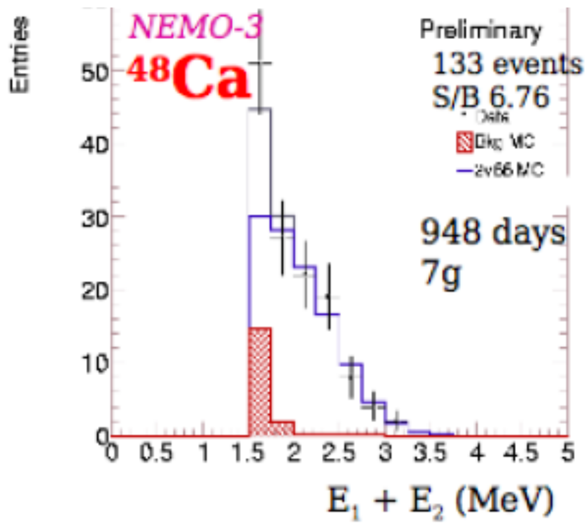
[9.11+0.25-0.22(stat)±0.63(sys)]×10[18] y

Phys. Rev. C 80, 032501 (2009)



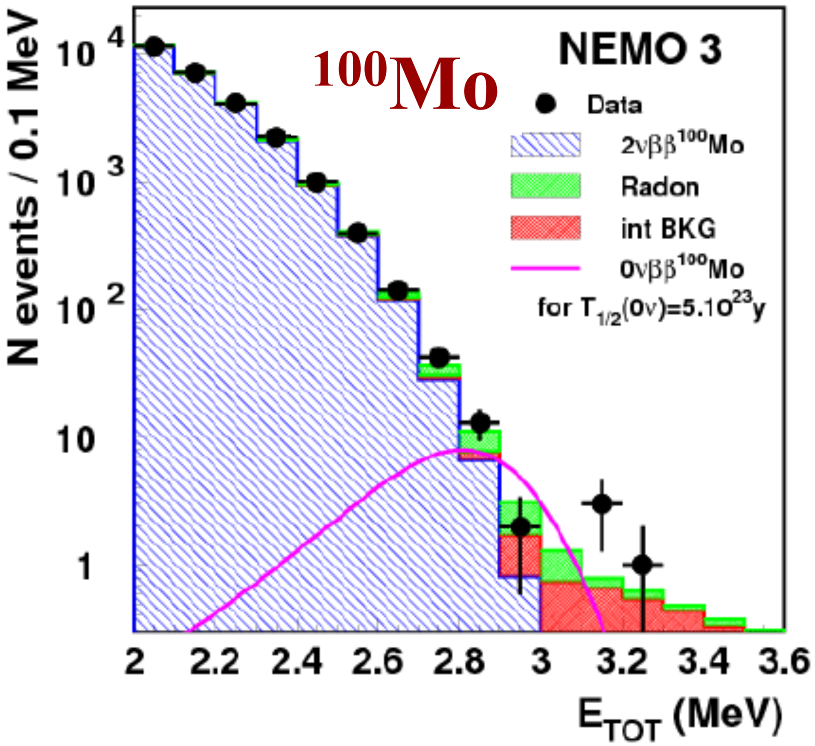
[2.35±0.14(stat)±0.16(sys)]×10[19] y

Nucl.Phys.A 847(2010)168

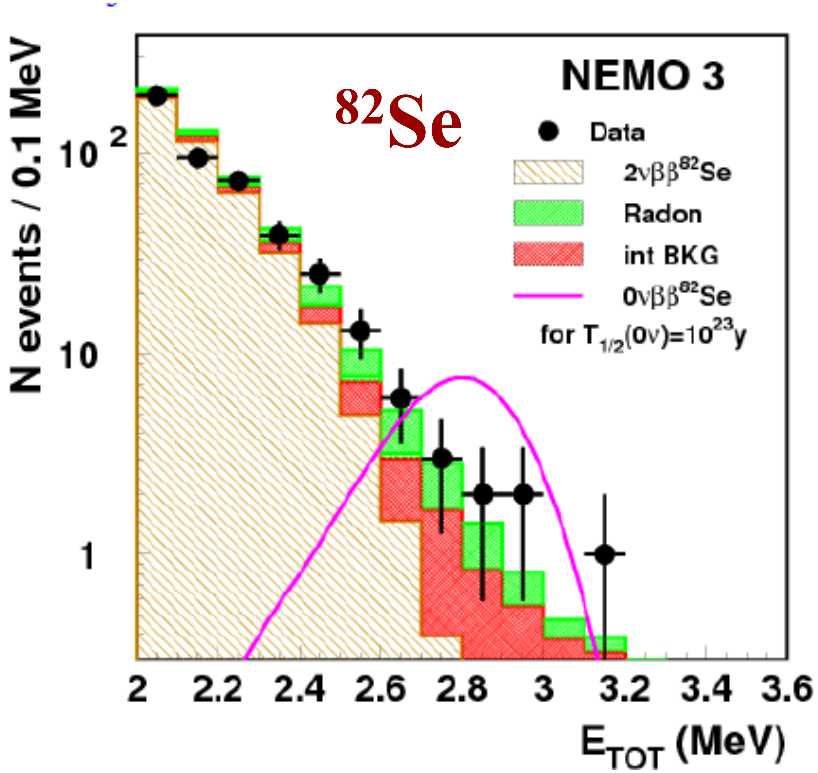


[4.4+0.5-0.4(stat)±0.4(sys)]×10[19] y

NEMO 3: ββ(0ν) search results (4.5 y of data)



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



[2.6 – 3.2] MeV 14 observed events, 11.3 ± 1.3 expected

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

$<m_\nu>$ < 0.31 – 0.96 eV NEM Ref [1-5]

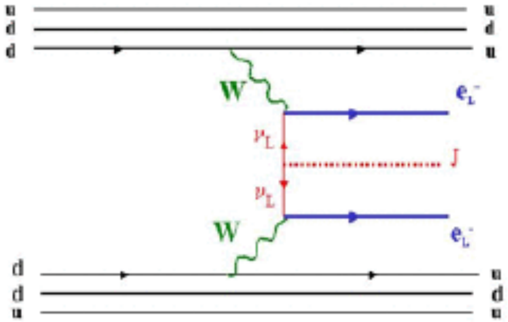
^{82}Se $T_{1/2}$ ($\beta\beta0\nu$) > 3.2 10^{23} y (90% C.L.)

$<m_\nu>$ < 0.94 – 2.6 eV NEM Ref [1-4 and 6]

Limit set by Modified Frequentist Method (CLs) using full distribution shape

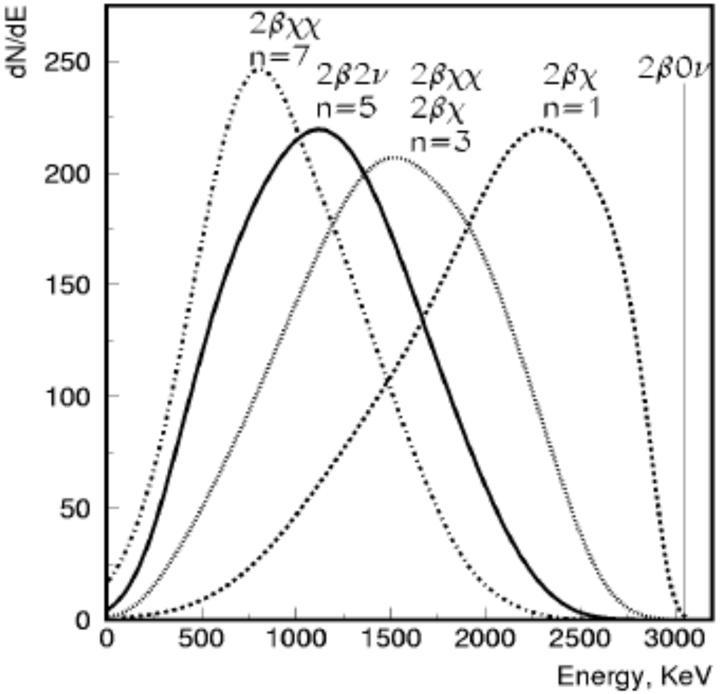
[1] QRPA M.Kortelainen and J.Suhonen, Phys.Rev. C 75 (2007) 051303(R)
[2] QRPA M.Kortelainen and J.Suhonen, Phys.Rev. C 76 (2007) 024315
[3] QRPA F.Simkovic, et al. Phys.Rev. C 77 (2008) 045503
[4] IBM2 J.Barrea and F.Iachello Phys.Rev.C 79(2009)044301
PHFB [5] P.K. Rath et al., Phys. Rev. C 82 (2010) 064310
SM [6] E.Caurrier et al. Phys.Rev.Lett 100 (2008) 052503

Majorons and V+A currents



Majoron emission would distort the shape of the energy sum spectrum

$$(A,Z) \rightarrow (A,Z+2) + 2e^{-} + \chi^{0}(\chi^{0})$$



	V+A *	n=1 **	n=2 **	n=3 **	n=7 **
Mo	$>5.7\cdot10^{23}$ $\lambda<1.4\cdot10^{-6}$	$>2.7\cdot10^{22}$ $G_{ee}<(0.4-1.8)\cdot10^{-4}$	$>1.7\cdot10^{22}$	$>1.0\cdot10^{22}$	$>7\cdot10^{19}$
Se	$>2.4\cdot10^{23}$ $\lambda<2.0\cdot10^{-6}$	$>1.5\cdot10^{22}$ $G_{ee}<(0.7-1.9)\cdot10^{-4}$	$>6\cdot10^{21}$	$>3.1\cdot10^{21}$	$>5\cdot10^{20}$

n: spectral index, limits on half-life in years

* Phase I+Phase II data

** Phase I data, ***R.Arnold et al. Nucl. Phys. A765 (2006) 483***

From NEMO 3 to SuperNEMO

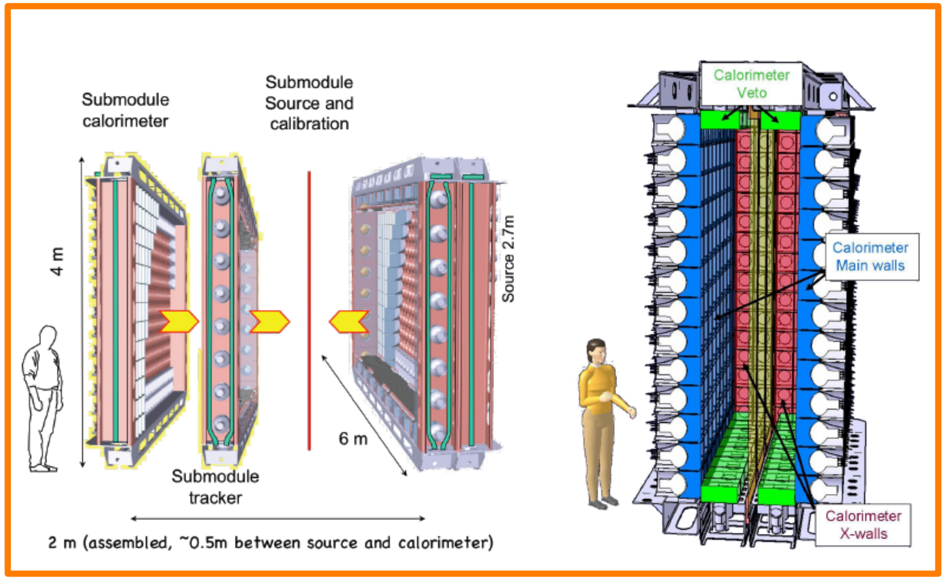
$$T_{1/2}(\beta\beta0\nu) > \ln 2 \times \frac{N_A}{A} \times \frac{M \times \varepsilon \times T_{obs}}{N_{90}}$$

NEMO-3		SuperNEMO
^{100}Mo	isotope	^{82}Se (baseline) or 150Nd or ^{48}Ca
7 kg	isotope mass M	100-200 kg
8 %	efficiency ε	~ 30 %
^{208}Tl: < 20 μBq/kg ^{214}Bi: < 300 μBq/kg	internal contaminations ^{208}Tl and ^{214}Bi in the ββ foil	^{208}Tl < 2 μBq/kg *if ^{82}Se*: ^{214}Bi < 10 μBq/kg
8% @ 3MeV	energy resolution (FWHM)	4% @ 3 MeV

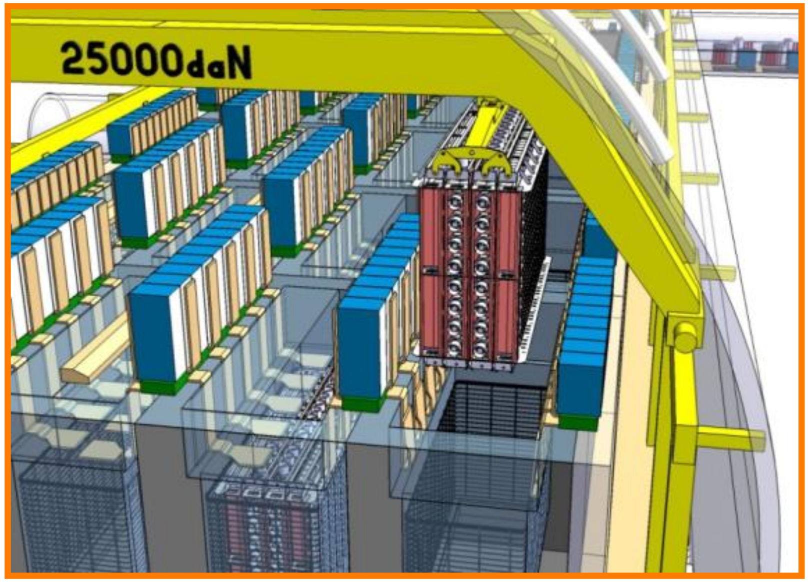
$T_{1/2}(\beta\beta0\nu) > 2 \times 10^{24}$ y $\langle m_\nu \rangle < 0.3 – 1.3$ eV	$T_{1/2}(\beta\beta0\nu) > 1 \times 10^{26}$ y $\langle m_\nu \rangle < 40 - 100$ meV

SuperNEMO

A module



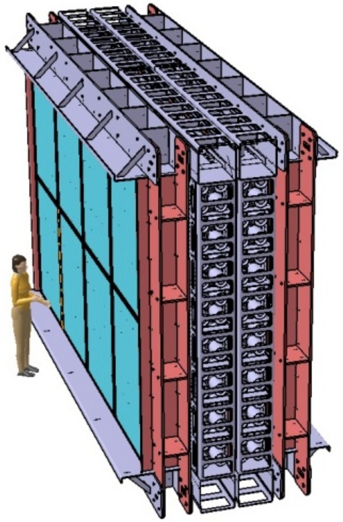
20 modules

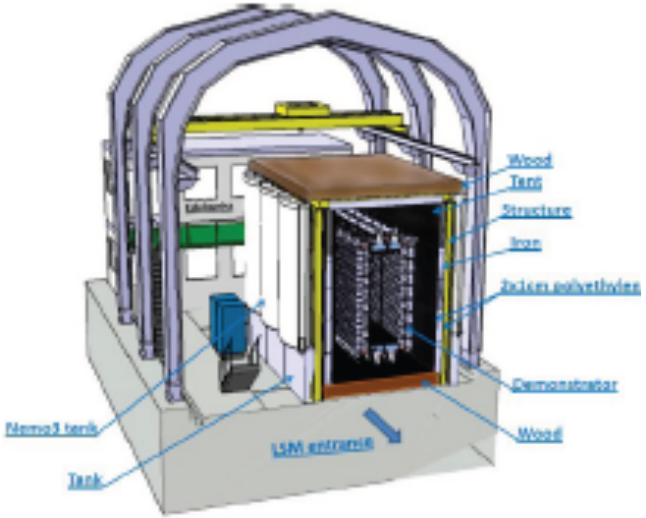


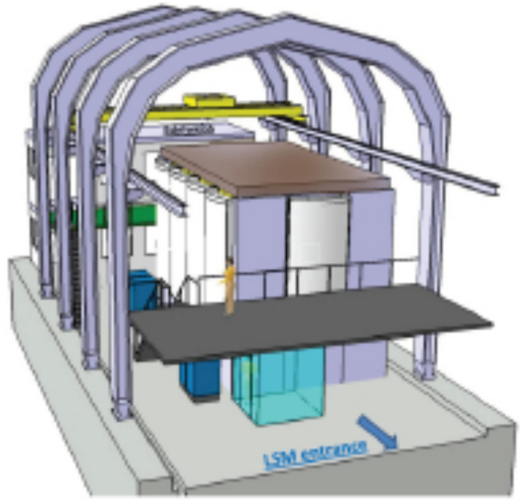
	Demonstrator module	20 Modules
Source : ^{82}Se	7 kg	100 kg
Drift chambers for tracking	2 0000	40 000
Electron calorimeter	500	10 000
γ veto (up and down)	100	2 000
$T_{1/2}$ sensitivity	$6.6\ 10^{24}$ y (No background)	$1.\ 10^{26}$ y
$<m_{\nu}>$ sensitivity	200 – 400 meV	40 – 100 meV

Demonstrator module(7 kg) under construction

SuperNEMO demonstrator module







The main goals of the demonstrator module are

- demonstration of the feasibility of a full scale detector with the requested performances (e.g. calorimeter energy and time resolution, tracker efficiency and radio-purity).
- measurement of the radon background contribution especially from internal materials outgasing.
- measurement of the background contribution from the detector components.
- finalize/optimize the design of the full scale detector.
- production of a competitive measurement with ^{82}Se (2.5 years of data taking with a 7 kg source). After 17 kg.yr exposure with ^{82}Se, the sensitivity of the demonstrator will be 6.6 10^{24} y (90% CL) which is equivalent to 3 10^{25} y obtained with ^{76}Ge. This will lead to a neutrino mass sensitivity similar to GERDA Phase-I : $< m_\nu > \simeq$ 200-400 meV.
- Expected start of data taking: 2014/T2 for 3 years

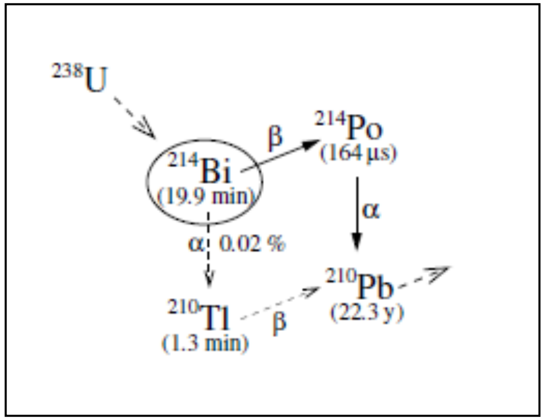
SuperNEMO : BiPo detector

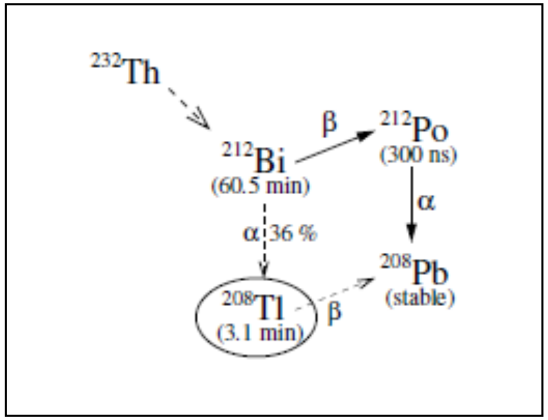
To measure source foils at the level of:

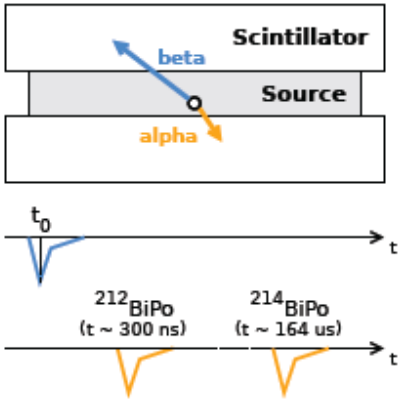
- 2 µBq/kg for ^{208}Tl

- 10 µBq/kg for ^{214}Bi

using the Bi – Po delayed coincidence in U and Th chains

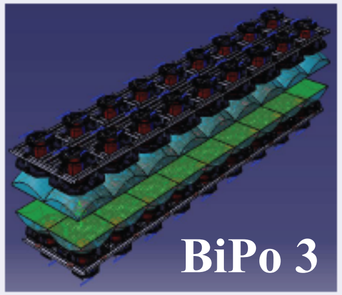






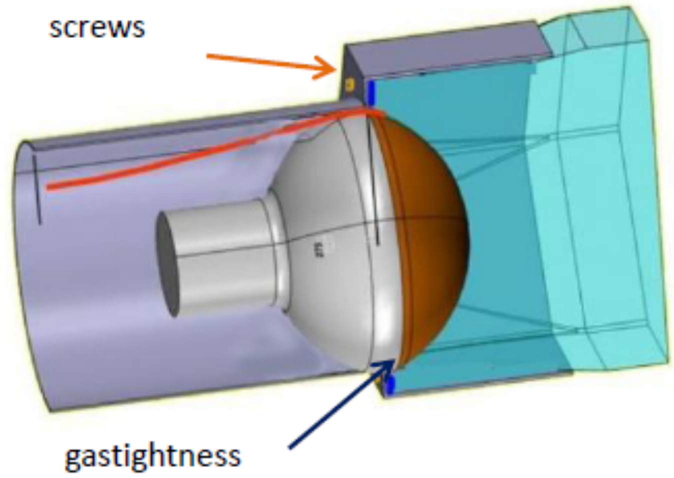
BiPo sensitivity (3.24 m^2)

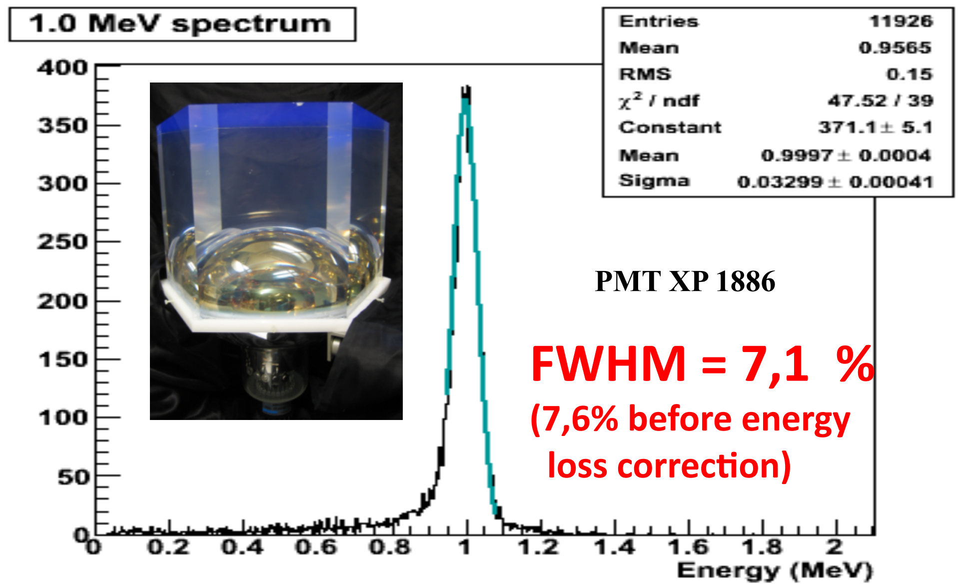
- Surface background measurement :
  - $A(^{208}\mathrm{Tl})_{\mathrm{BiPo1}} \sim 1.5\ \mu\mathrm{Bq/m}^2$ (258 days.m^2 @ LSM)
  - $0.6 < A(^{214}\mathrm{Bi})_{\mathrm{BiPo3}} < 23.0\ \mu\mathrm{Bq/m}^2$ (5.34 days.m^2 @ LSC)
- BiPo-3 sensitivity for SuperNEMO ^{82}Se sources :
  - $A(^{208}\mathrm{Tl}) < 2\ \mu\mathrm{Bq/kg}$ in 6 months
  - $A(^{214}\mathrm{Bi}) < 10\ \mu\mathrm{Bq/kg}$ in 6 month



Installation of BiPo 3 in LS Canfranc

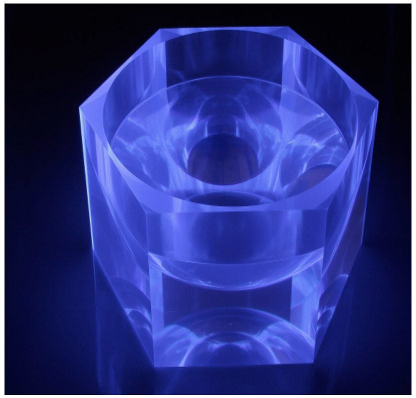
SuperNEMO : Calorimeter





FWHM = 7,1 %

(7,6% before energy loss correction)



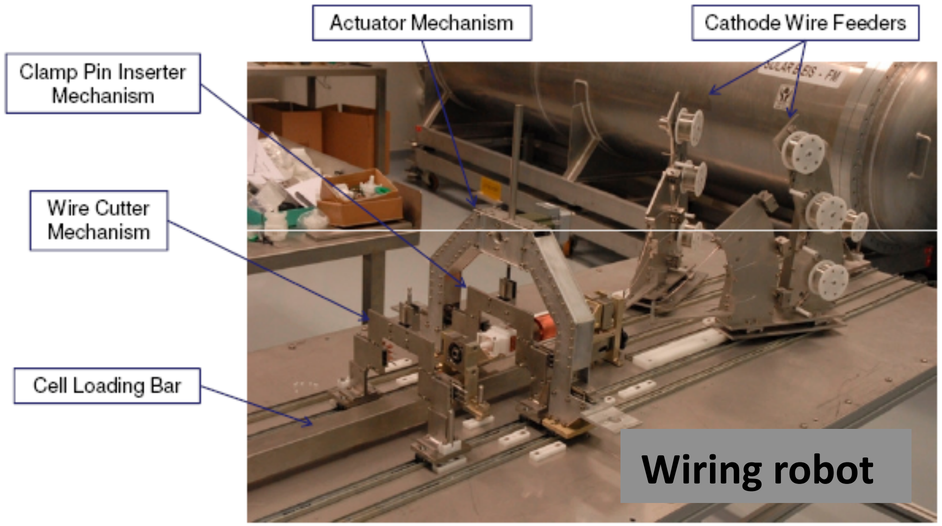
Volume: 8 l (NEMO3 4 l)
8'' PMT (NEMO3 5'' PMT)
ΔE/E 6.5 – 8 %
Factor 2 less compared to NEMO3

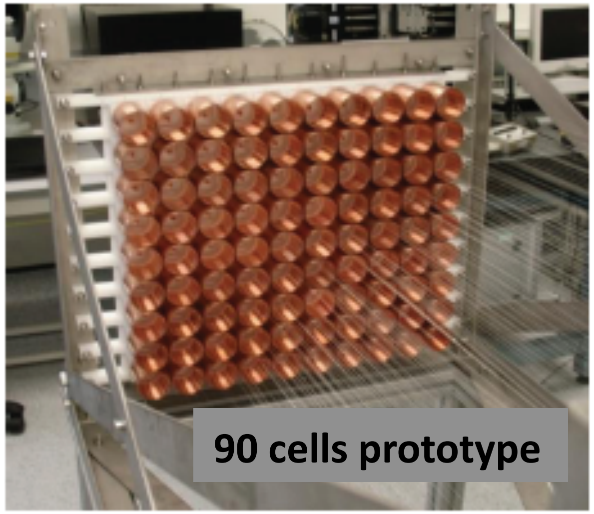
Calorimeter

Required resolution demonstrated with cubic PVT (256×256 mm^2 entrance surface, ≥12cm thick) directly coupled to a 8" PMT (R5912MOD)

FWHM = 7.3% @ 1MeV
FWHM = 4.2% @ 3MeV

SuperNEMO : Tracker

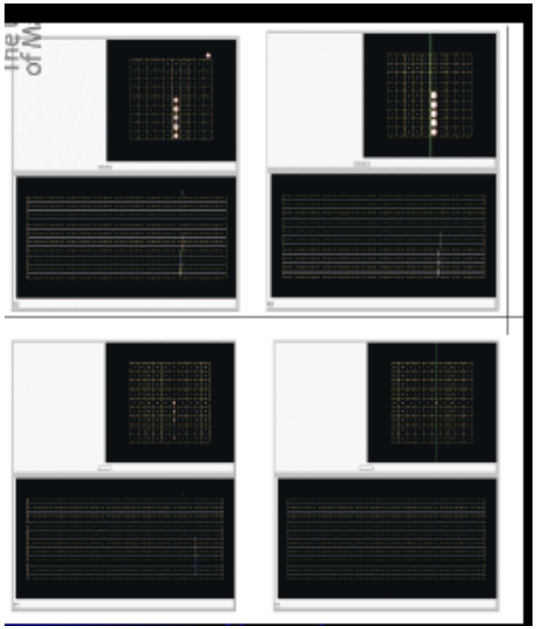




Tracker

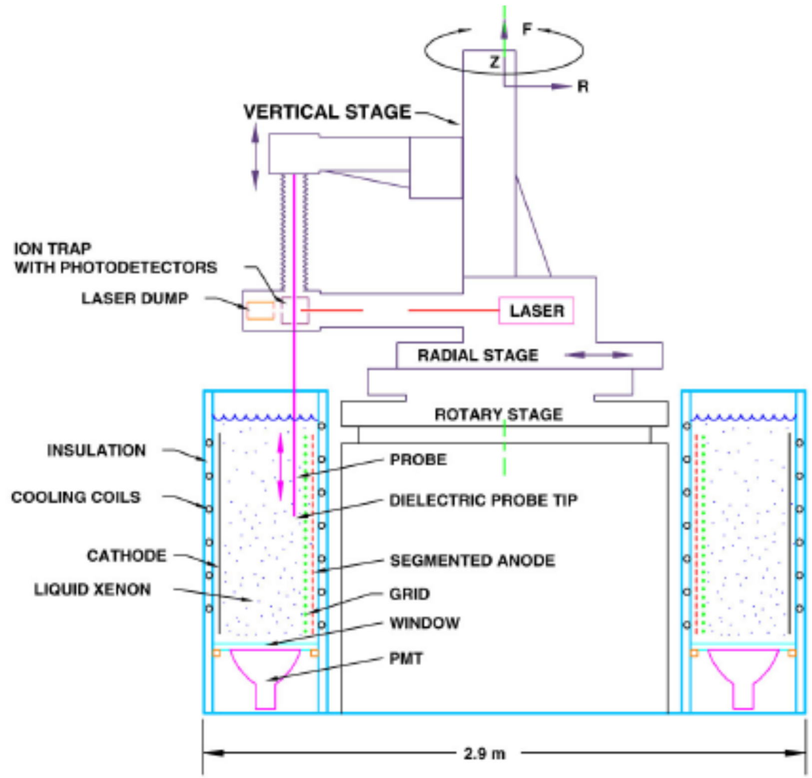
- Basic 90 cells prototype developed
  - $\varnothing = 44$ mm
  - $L = 3.7$ m
- Required performances demonstrated using cosmic muon data

$$\sigma_T \sim \mathbf{0.7\ mm} \quad \sigma_L \sim \mathbf{1\ cm}$$
$$\epsilon_{Geiger} > \mathbf{98\%}$$



90 cells prototype : data with cosmic rays

EXO



Liquid Xe TPC

Energy measurement by ionization + scintillation

Tagging of Baryum ion ($^{136}Xe \rightarrow {}^{136}Ba^{++} + 2\ e^-$)

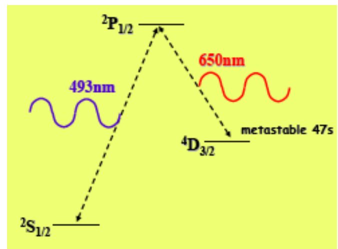
Large mass of Xe

Identification of final state → background rejection

But no e^- identification

Poor background rejection without Ba ion tagging

R&D for Ba ion tagging in progress



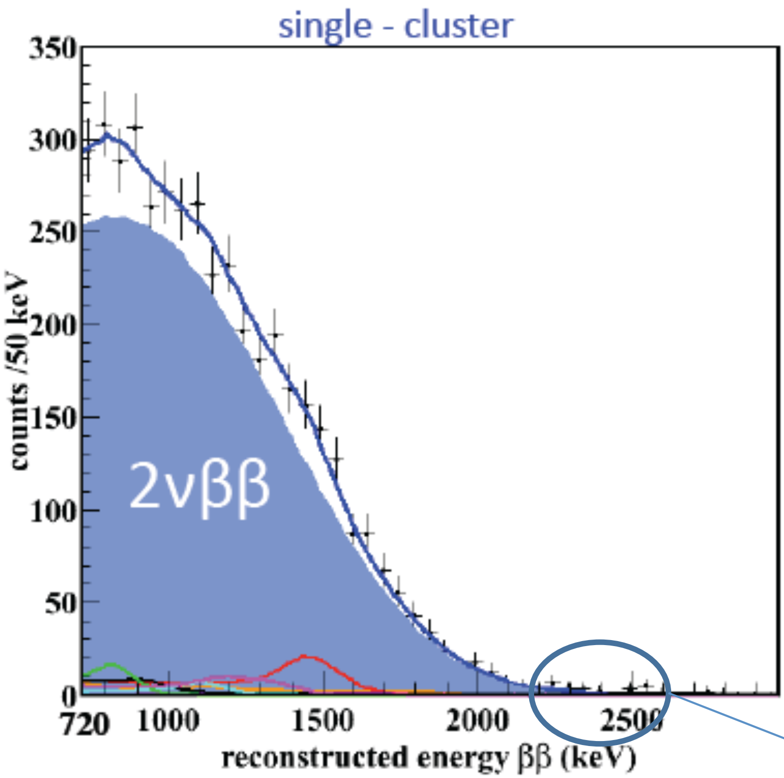
Prototype EXO-200

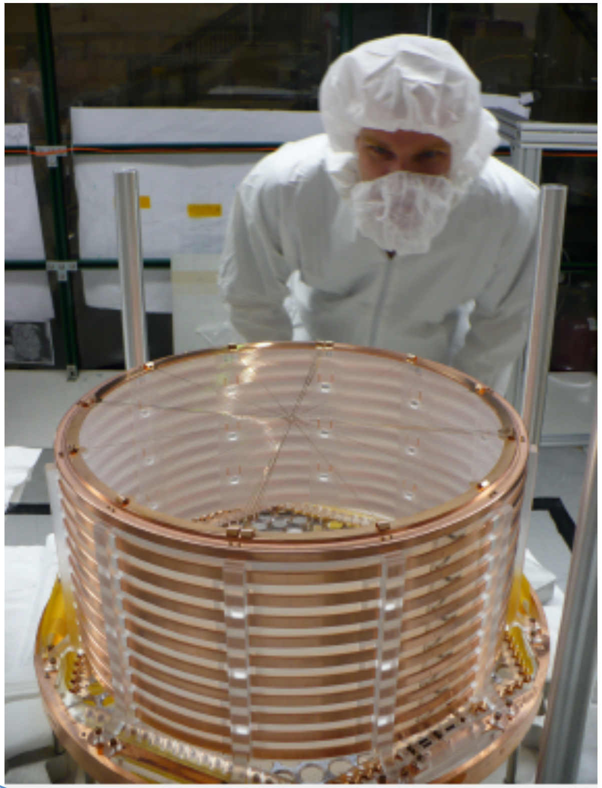
200 kg of ^{136}Xe, no Ba ion tagging

Installation in WIPP underground lab 2007

EXO 200 (2 years) $T_{1/2} > 6.4\ 10^{25}$ yr (90% CL) **$<m_\nu> < 0.27-0.38$ eV**

EXO





- 31 live-days of data
- 63 kg active mass
- Signal / Background ratio 10:1
  - -as good as 40:1 for some extreme fiducial volume cuts

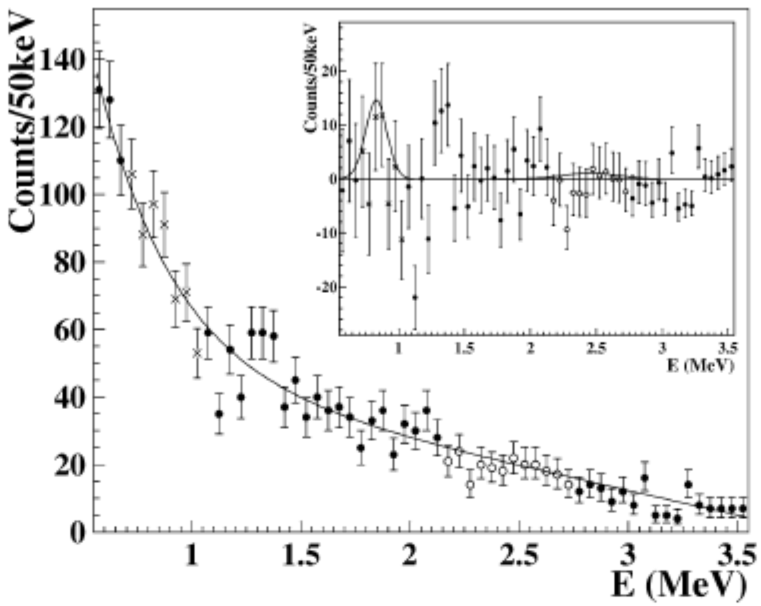
$T_{1/2}$ = 2.11·10^{21} yr (± 0.04 stat) yr (± 0.21 sys) [arXiv:1108.4193]

Mais fond pour ββ(0ν)
15 fois plus grand qu'attendu
Avec volume fiduciel 1/3

EXO

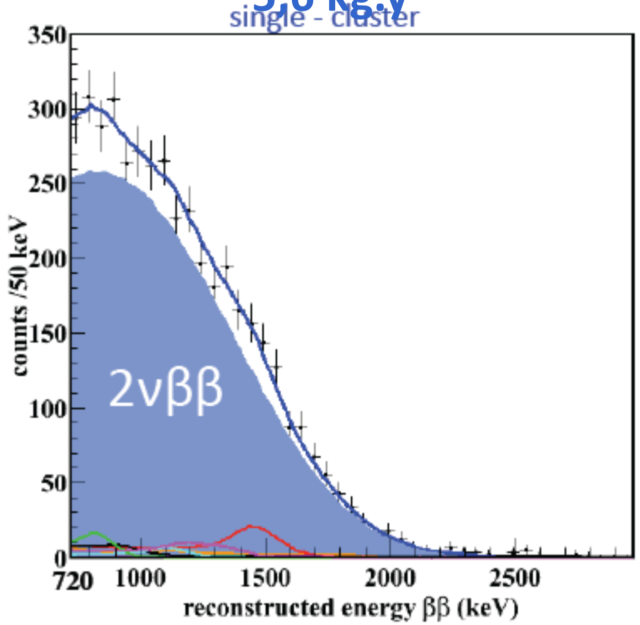
Bernabei et al. Phys. Lett B546 (2002) 23

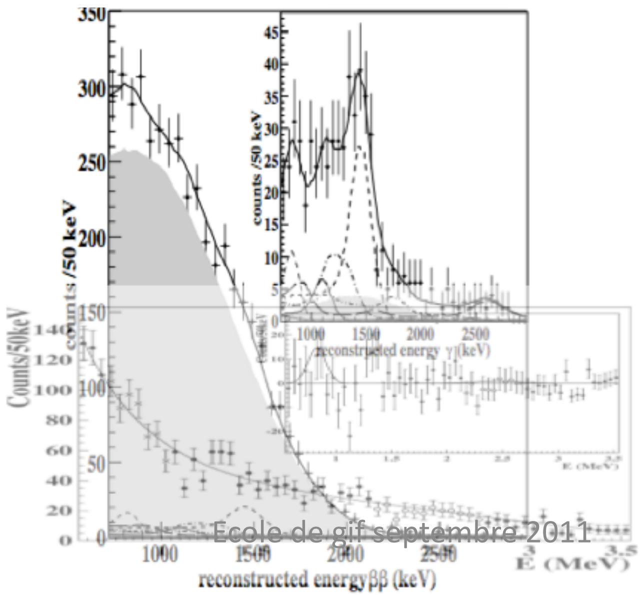
4,5 kg.y



EXO

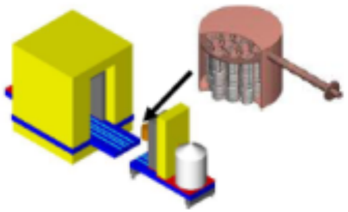
5,6 kg.y





Projets à 100 kg ou plus

MAJORANA Ge segmented Diode



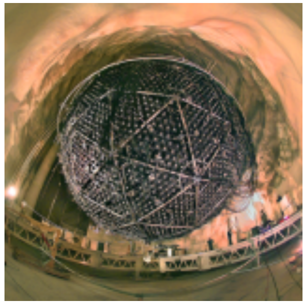
DUSEL laboratory

2011: 20 kg of ^{nat}Ge

2013 ? : 30 kg of ^{76}Ge

+ Energy resolution

SNO++ Nd salt + liquid scintillator



SNOLAB laboratory

2010: 740 kg of ^{nat}Nd
(44 kg of ^{150}Nd)
Dissolved in scintillator

+ Large mass
+ low background detector

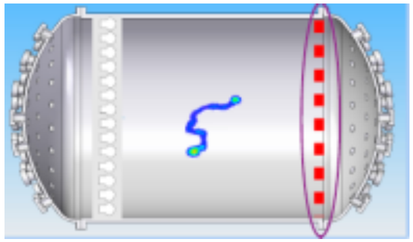
KamLAND-Zen Xe + liq. scintillator

Kamioka laboratory

2011: 400 kg of ^{136}Xe
Dissolved in
liq. scintillator

+ Large mass
+ low background detector

NEXT Xe high pressure TPC



Canfranc laboratory

2011: 1 kg of ^{136}Xe

2013 : 100 kg

+ Background rejection

Liste de projets et R&D

Experiments	Isotopes	Techniques	Main caracteristics
NEMO3	^{100}Mo,^{82}Se	Tracking + calorimeter	Bckg rejection, isotope choice
SuperNEMO	^{82}Se, ^{150}Nd	Tracking + calorimeter	Bckg rejection, isotope choice
Cuoricino	^{130}Te	Bolometers	Energy resolution, efficiency
CUORE	^{130}Te	Bolometers	Energy resolution, efficiency
GERDA	^{76}Ge	Ge diodes	Energy resolution, eficiency
Majorana	^{76}Ge	Ge diodes	Energy resolution, efficiency
COBRA	^{130}Te, ^{116}Cd	ZnCdTe semi-conductors	Energy resolution, efficiency
EXO	^{136}Xe	TPC ionisation + scintillation	Mass, efficiency, final state signature
MOON	^{100}Mo	Tracking + calorimeter	Compactness, Bckg rejection
CANDLES	^{48}Ca	CaF_2 scintillating crystals	Efficiency, Background
SNO++	^{150}Nd	Nd loaded liquid scintillator	Mass, efficiency
XMASS	^{136}Xe	Liquid Xe	Mass, efficiency
CARVEL	^{48}Ca	CaWO4 scintillating crystals	Mass, efficiency
Yangyang	^{124}Sn	Sn loaded liquid scintillator	Mass, efficiency
DCBA	^{150}Nd	Gazeous TPC	Bckg rejection, efficiency
LUCIFER	^{82}Se, ^{100}Mo	Scintillating bolometers	Bckg rejection, efficiency, resolution

Où en est-on pour les bruits de fond ?

- ^{130}Te [MEDEX'11] :
  - Cuoricino : $B \simeq 0.18$ counts/keV/y/kg
  - CUORE R&D : $B \simeq 0.05$-0.10 counts/keV/y/kg
  - CUORE target : $B \simeq 0.01$ counts/keV/y/kg
- ^{76}Ge [Moriond'11] :
  - HM : $B \simeq 0.06$ counts/keV/y/kg (PSA)
  - GERDA R&D : $B \simeq 0.05$ counts/keV/y/kg
  - GERDA I (II) target : $B \simeq 0.01$ (0.001) counts/keV/y/kg
- ^{136}Xe [arXiv :1108.4193] :
  - EXO-200 : $B \gtrsim 0.02$ counts/keV/y/kg
  - EXO-200 target : $B \gtrsim 0.001$ counts/keV/y/kg

Que signifient les bruit de fond annoncés ?

Experiment	Isotope	Mass [kg]	$\Delta E/E$ @ Q[%]	B [/keV/kg/y]	n_{bkgd}^{ROI} (5y)
CUORE	^{130}Te	200 (1 t)*	0.3	0.01	50
GERDA	^{76}Ge	I. 18 II. 40 III. 1000	0.16	0.01 0.001 <0.001	3 0.6 <15
MAJORANA	^{76}Ge	I. 30-60 II. 1000	0.16	0.001 0.00025	0.5 3
EXO	^{136}Xe	I. 200 II. 1000	3.8	0.001 $2\ 10^{-6}$	100 1
SuperNEMO	^{82}Se	I. 7 II. 100	4-5	$2\ 10^{-5}$	0 1-2
KamLAND-ZEN	^{136}Xe	I. 400 (16 t)* II. 1000 (40 t)*	10	10^{-6}	20 50
SNO+	^{150}Nd	I. 56 (1000 t)*	6.4	10^{-6}	800

Sensibilités attendues d'ici 5 ans ….

	Technique	Location	Mass kg	start	Bckg Cts/keV/kg/yr	$T_{1/2}(0\nu)$ 5 yr	$<m_{ee}>$ meV
EXO	Liquid Xe ^{136}Xe	WIPP (USA)	200	2010	0.002	6.4 10^{25}	< 109 - 135
GERDA	Diode Ge ^{76}Ge	Gan sasso (Italy)	18 40	2010 2012	0.01 0.001	3. 10^{25} 3. 10^{26}	< 250– 380 < 80 - 120
CUORE-0 CUORE	Bolometers ^{130}Te	Gan sasso (Italy)	13 200	2011 2013	0.12 0.01 0.001	8. 10^{25} 2.1 10^{26} 6.5 10^{26}	<100 - 200 < 41 -82 < 23- 47
SN module0 SuperNEMO	Tracko-calo ^{82}Se, ^{150}Nd	Modane (France)	7 100	2013 2015	0.0001 0.0001	6. 10^{24} 10^{26}	< 200 –600 < 53 – 145
SNO+	Liq. Scint. ^{150}Nd	SNOLAB (Canada)	44	2012			< 100
KamLAND	Liq. Scinti ^{136}Xe	Kamioka (Japan)	400	2011			< 60 (2 yr)

Conclusion

La mesure de la masse du neutrino est un long chemin

Mais un gros progrès : jusqu'en 1998 on n'était pas que le neutrino soit massif….

Mesure directe: cosmologie semble s'approcher du but mais modèle dépendant

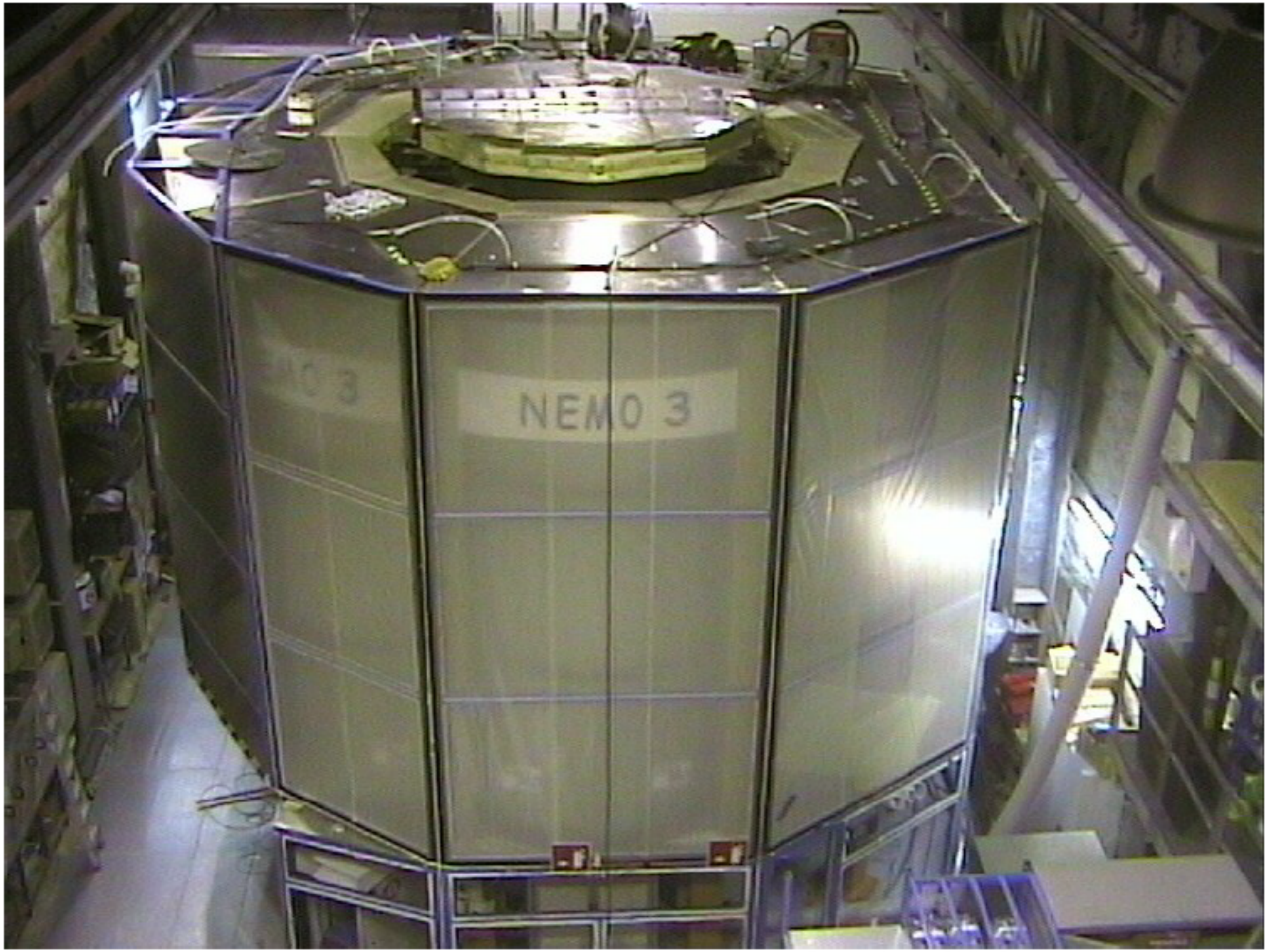
Simple beta: KATRIN devrait atteindre d'ici 2017 -2018 $m_\nu < 0,2$ eV
MARE et d'autre développements pourrait permettre d'aller plus loin

Double beta : - La masse du neutrino est un des aspects de la physique avec la $\beta\beta(0\nu)$
- La prochaine génération cherche à atteindre 50 – 100 meV
- Toutes les techniques extrapolable à 100 kg sont dans le bruit de fond
- De nouvelles R&D (bolomètres scintillants, semi-conducteur)
- Progrès lents (avec du bruit de fond $m_\nu \sim M^{-4}$)
- Parler de la tonne n'a pas de sens aujourd'hui (enrichissement, fond, technique)

Double désintégration bêta

Double désintégration bêta

Entire NEMO-3



Picture from LSM's Camera

Neutrino mass

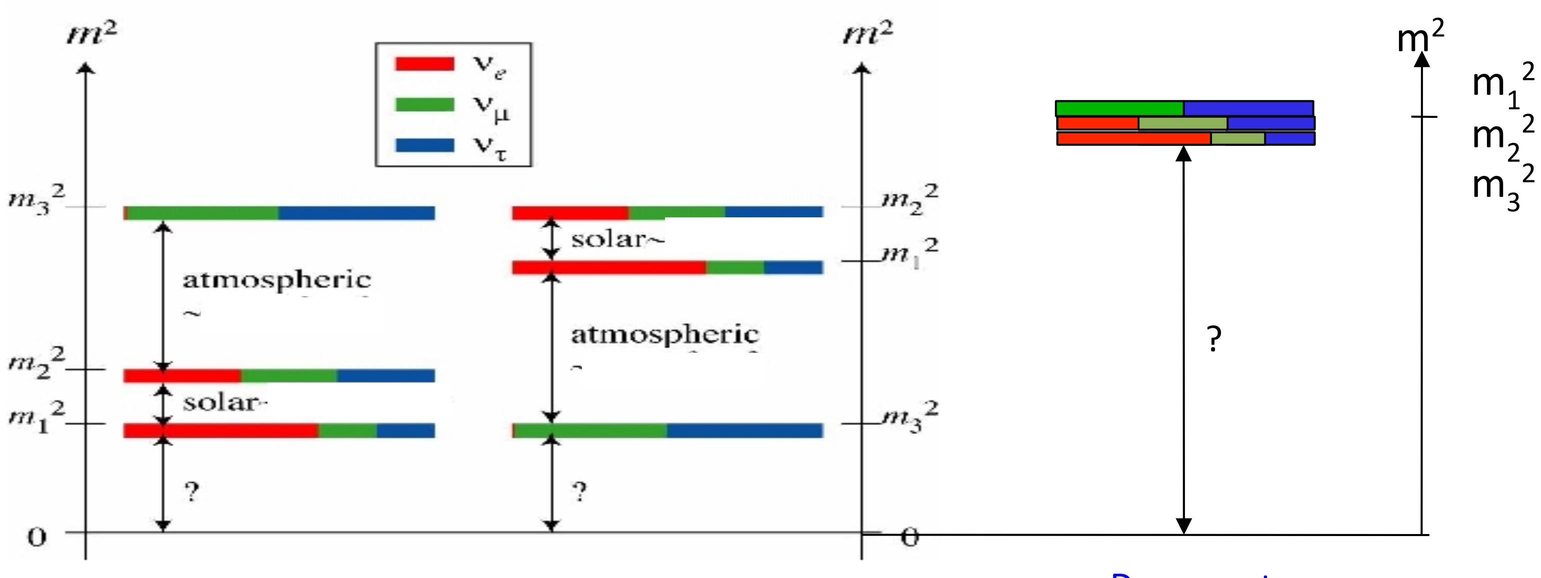
Absolute mass ?

Beta decay $m_\nu = \left[\Sigma |U_{ei}|^2 m_i^2\right]^{1/2} < 2.3$ eV

Double beta decay $|\langle m_\nu \rangle| = |\Sigma U_{ei}^2 m_i| < 0.2 - 0.8$ eV

Cosmology $\Sigma m_i = m_1 + m_2 + m_3 <\sim 1$ eV

Mass hierarchy ?

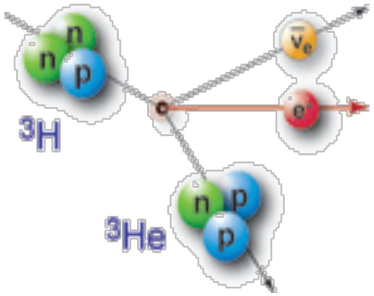


Normal hierarchy $m_3 >> m_2 \sim m_1$

Inverted hierarchy $m_2 \sim m_1 >> m_3$

Degenerate $m_1 \approx m_2 \approx m_3 \gg |m_i - m_j|$

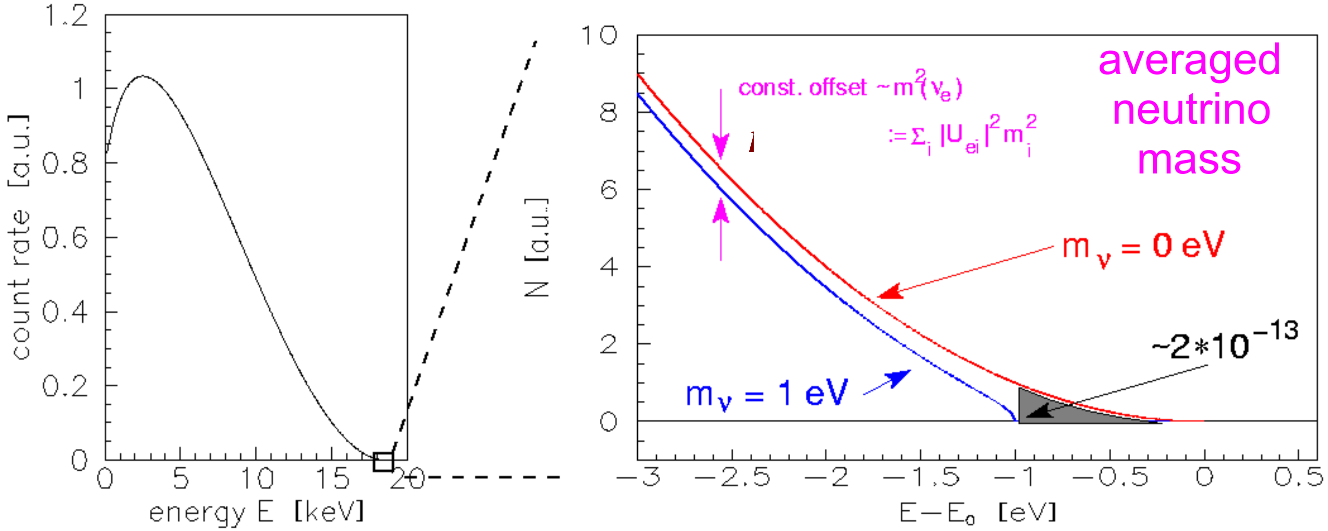
Beta decay



(A,Z) → (A,Z+1) + e^- + $\bar{\nu}_e$

$$dN/dE \sim [\,(E_0-E_e)^2 - m_{\nu i}^2\,]^{1/2}:$$

$$m_\nu^2 = \sum |U_{e_i}|^2 m_i^2$$



Fraction of decay in [$Q_\beta - m_\nu$, Q_β] ~ $(m_\nu/Q_\beta)^3$ → lowest Q_β value ^{3}H (Q_β= 18.6 keV)

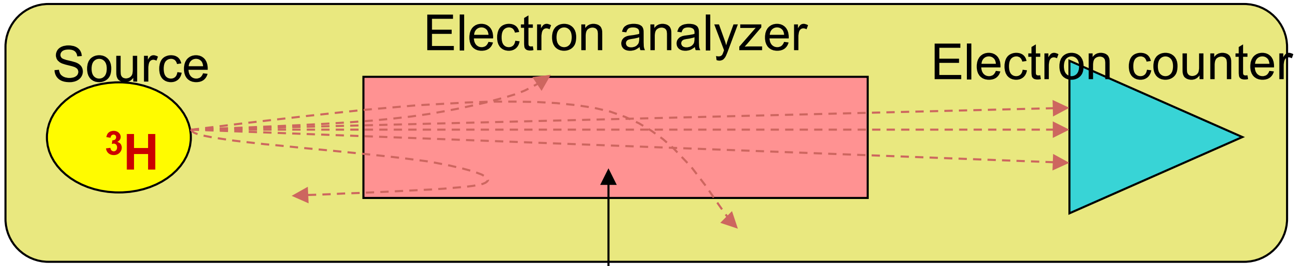
High counting rate

Low background

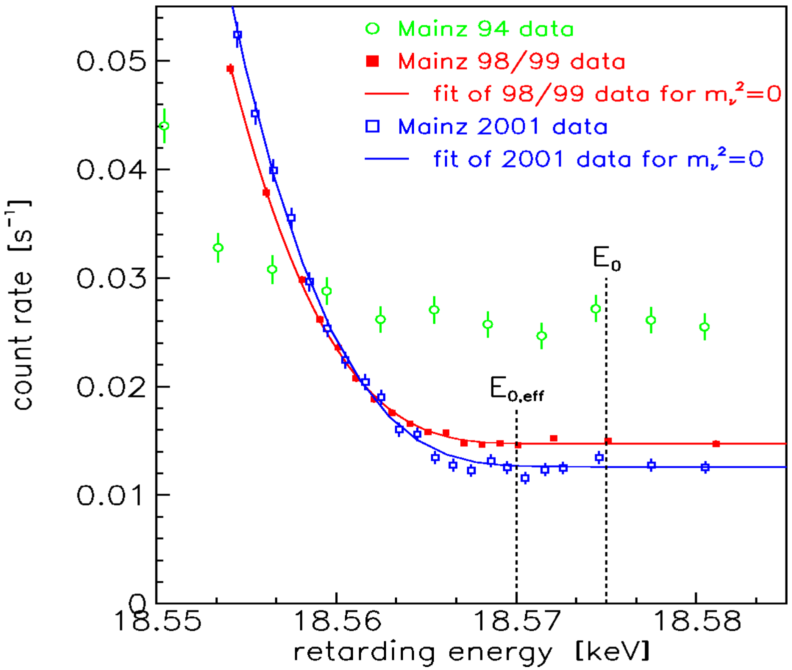
Energy resolution ~ m_ν

Beta decay: present status

MAC-E spectrometers



integral spectrum: select $E_e > E_{th}$



MAINZ: $m^2_\nu = -0.6 \pm 2.2 \pm 2.1\ eV^2$

$\Rightarrow$ $m_\nu < 2.3\ eV$ (95% C.L.)

C. Kraus et al., Eur. Phys. J. C 40 (2005) 447

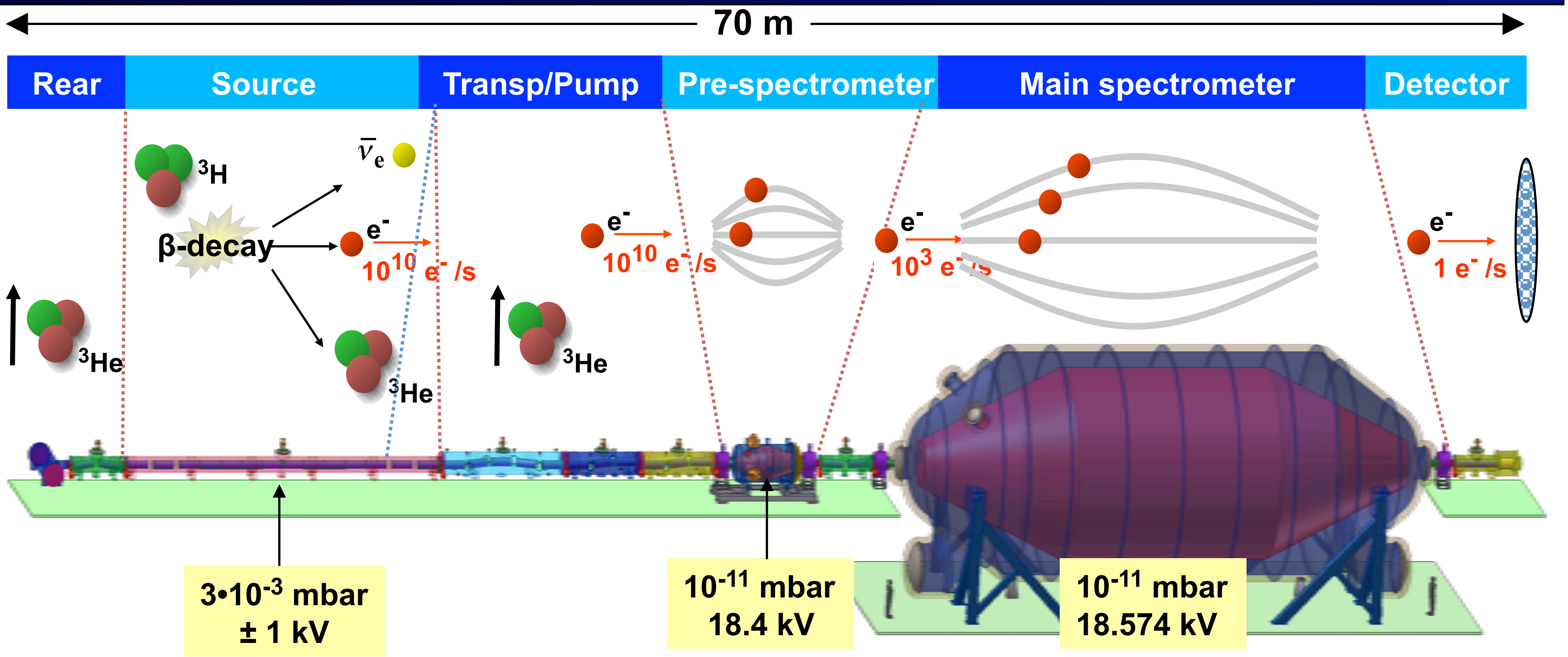
Troisk: $m^2_\nu = -2.3 \pm 2.5 \pm 2.0\ eV^2$

$m_\nu < 2.05\ eV$ (95% C.L.)

But systematics from end-point fluctuations not included

F. Piquemal (CENBG) LP07 Daegu August 2007

Beta decay: KATRIN experiment



Sensitivity $m_\nu < 0.2$ eV

Improvement of ΔE: 0.93 eV (4.8 eV for Mainz)

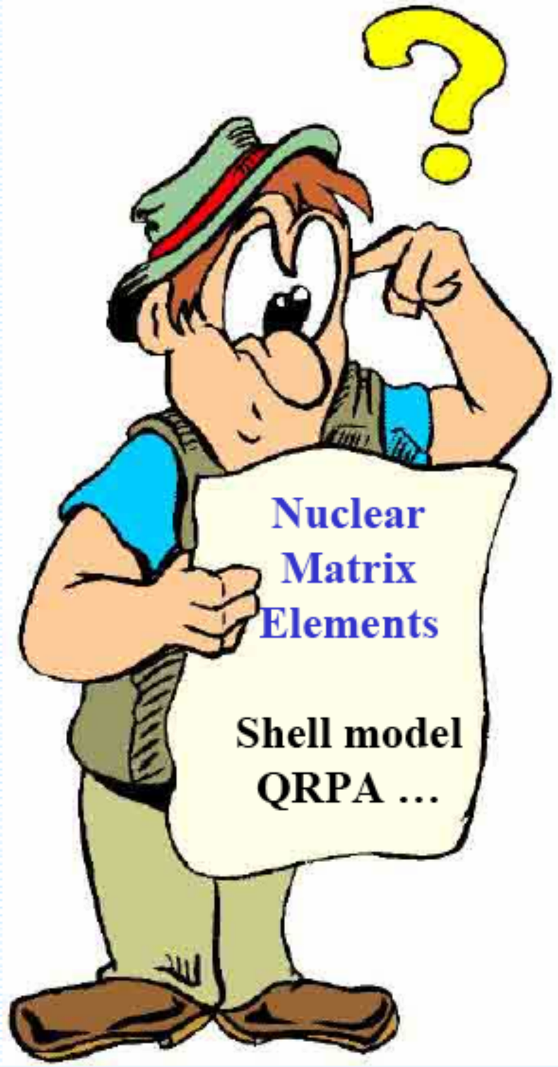
Larger acceptance

Statistics 100 days → 1000 days

Commissioning and start of data taking: 2010

F. Piquemal (CENBG) LP07 Daegu August 2007

Nuclear matrix elements



Experimentalists:

- What are the best $0\nu\beta\beta$–decay candidates?

Particle physicists:

- Wat is the absolute ν mass scale?
- Will the evidence of the $0\nu\beta\beta$-decay allow to to conclude about Majorana CP-phases?

It is a complex task

- Medium and heavy open shell nuclei with a complicated nuclear structure
- The construction of complete set of the states of the intermediate nucleus is needed
- Many-body problem ⇒ approximations needed
- Nuclear structure input has to be fixed

F. Simkovic

Uncertainties

F. Simkovic

List of reasons, why QRPA-like $0\nu\beta\beta$–decay NME are different (13 reasons)

Quasiparticle mean field
fixing of pp,nn (pn) pairing

Many-body approximations
QRPA, RQRPA, SRQRPA

Choice of NN interaction
Schem., realistic (Bonn, Paris …

the closure approximation

p-h interaction ($g_{ph} \cong 1$)
fixed to GT resonance

The size of model space

p-p interaction (g_{pp})
fixed to β or $\beta\beta$–decay resonance, or g_{pp}=1

two-nucleon s.r.c. (~ 50%)
has to be considered

finite size of nucleon (~10%)
form factors

h.o.t. of nucleon curr. (~30%)
Induced PS, weak magnetism

the overlap factor
the BCS overlap

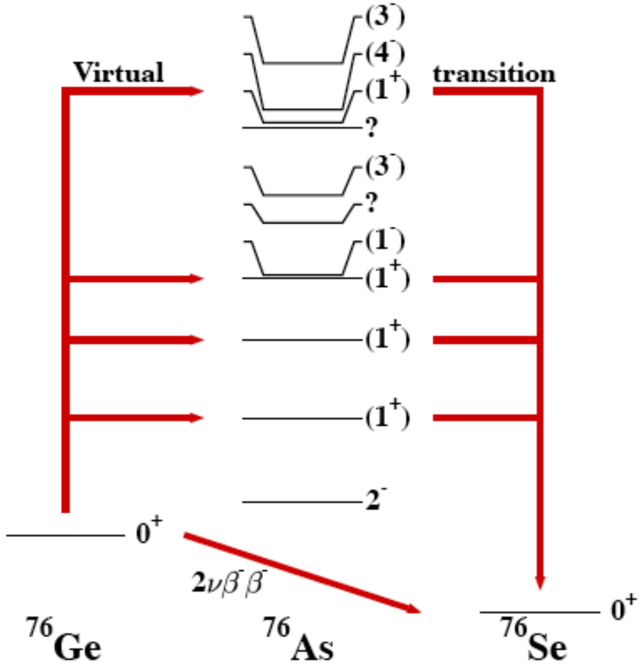
the axial-vector coupling
g_A=1.0 or 1.25

Nuclear shape
Spherical, not deformed yet

How to calculate Nuclear Matrix Elements ?

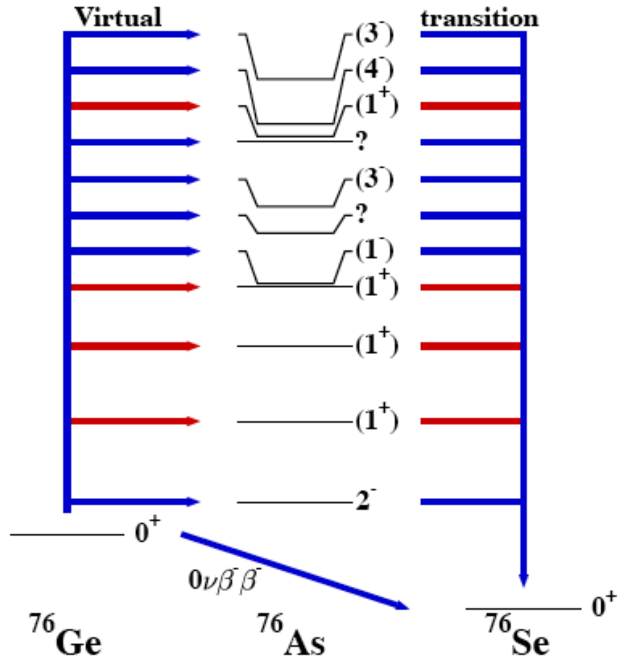
ββ(2 ν)

$$T^{-1}_{1/2} = F'(Q_{\beta\beta},Z)\ |M'|^2\ \langle m_\nu \rangle^2$$



ββ(0 ν)

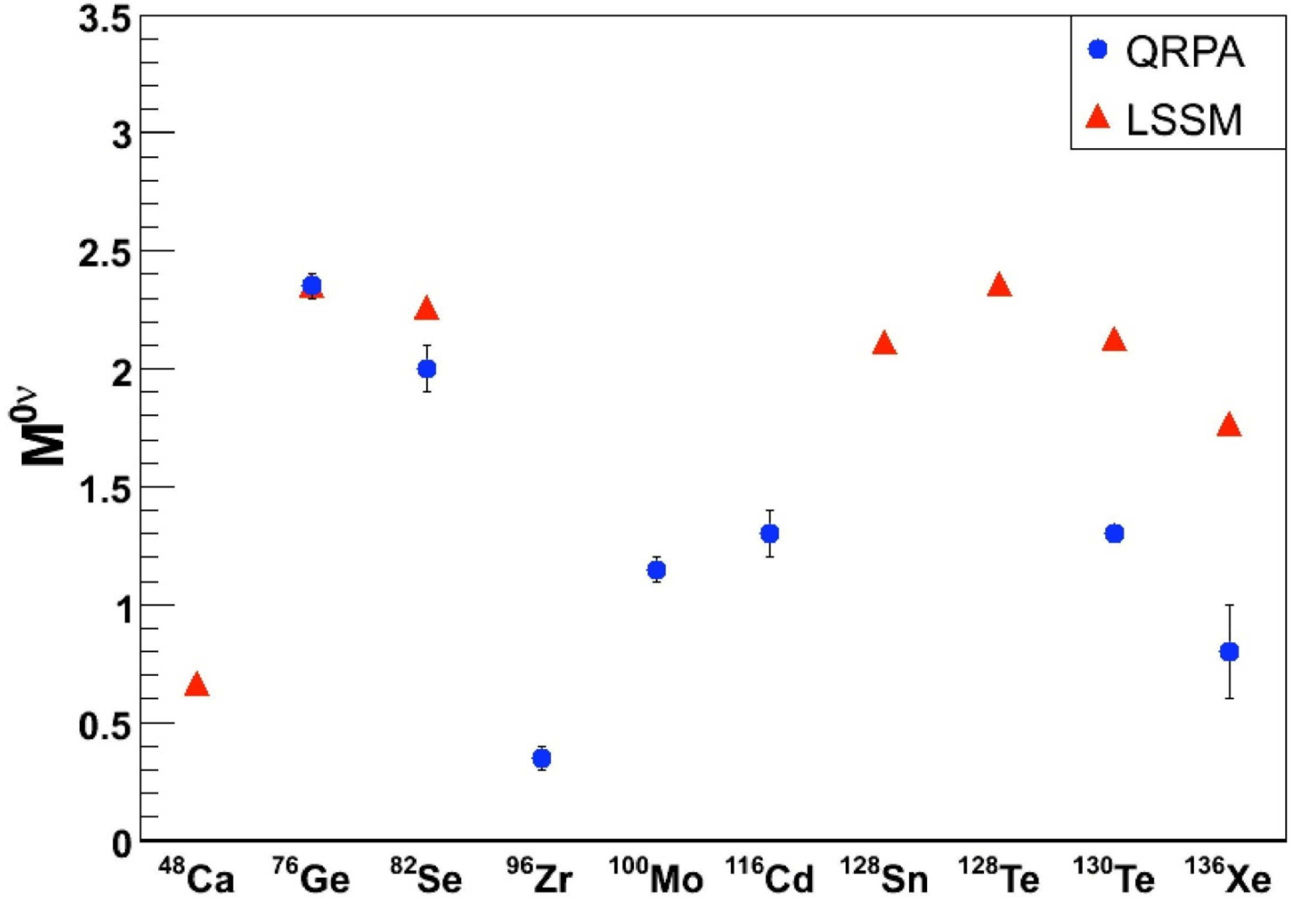
$$T^{-1}_{1/2} = F(Q_{\beta\beta},Z)\ |M|^2\ \langle m_\nu \rangle^2$$



NME are not the same, higher multipole contribute for ββ(0ν)

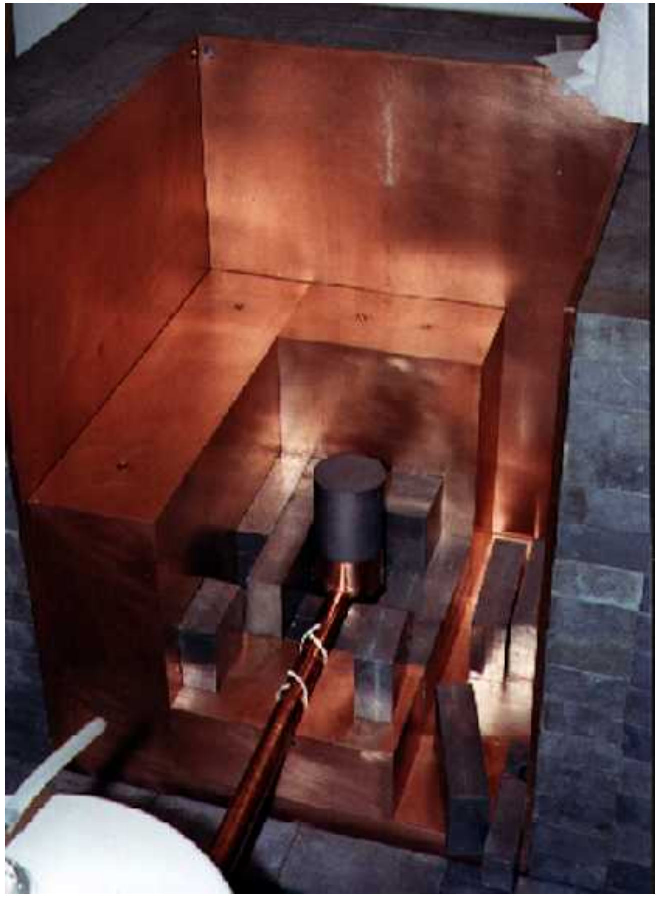
Shell Model Calculation or QRPA

QRPA vs Shell Model



QRPA: Nucl. Phys. A, **766** 107 (2006)
LSSM: From Poves NDM06 talk (Caurier, Nowacki, Poves)

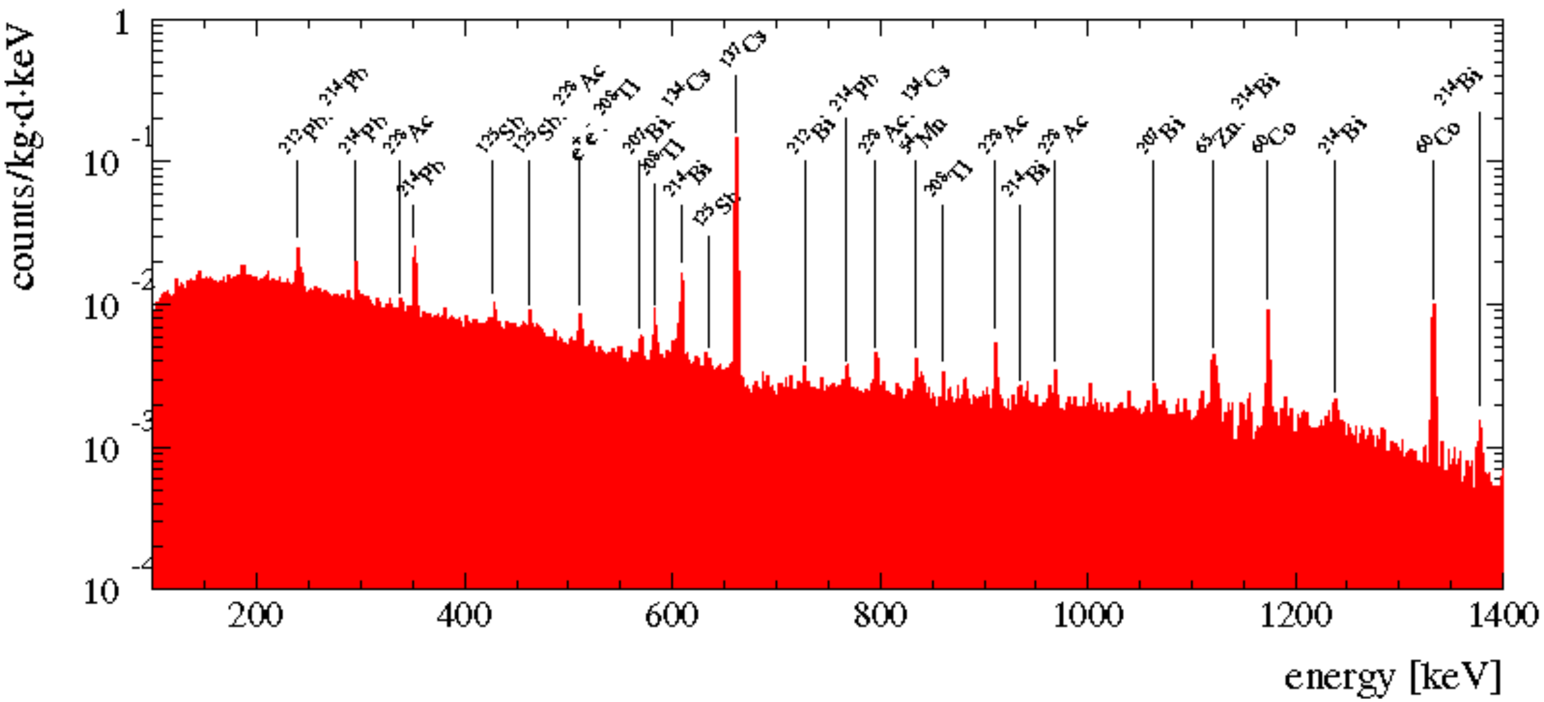
Heidelberg – Moscou and IGEX experiment

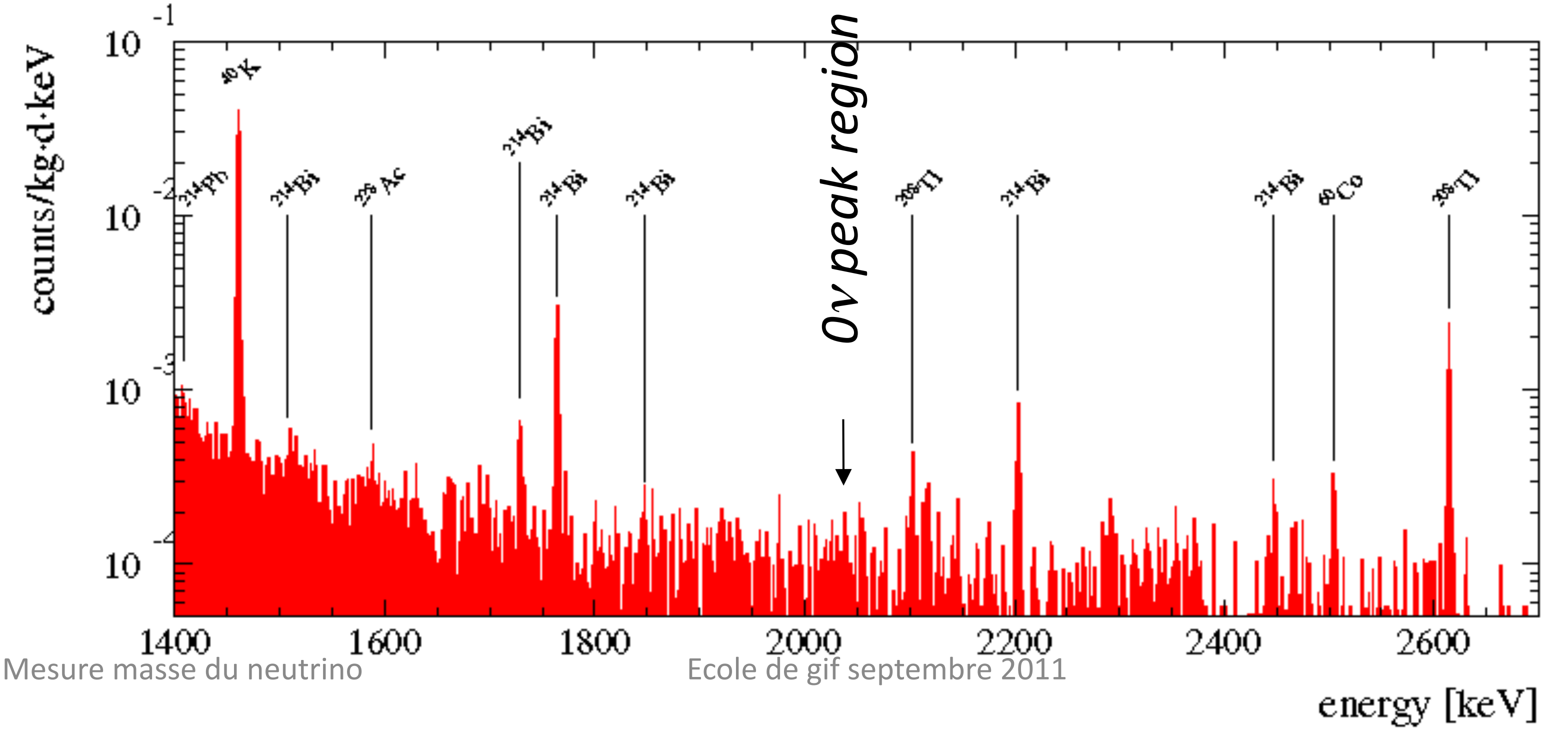


Ge detector: - Very good energy resolution

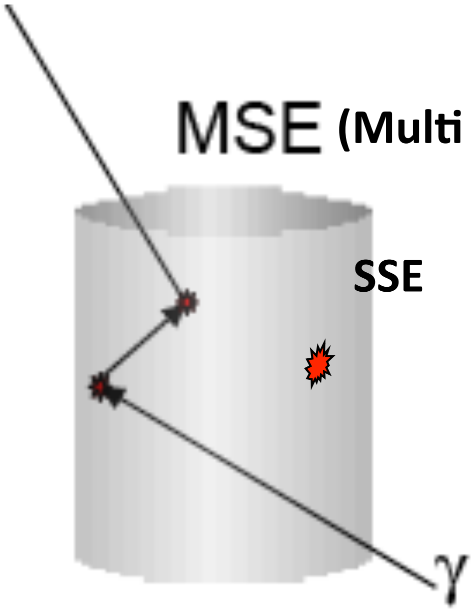
- Efficiency

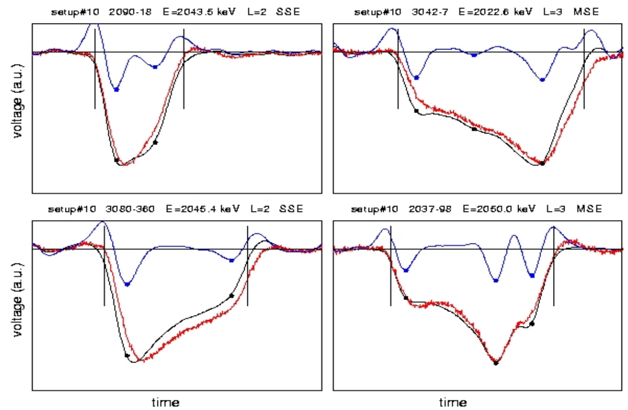
- Compact detector


counts/kg·d·keV
energy [keV]
200
400
600
800
1000
1200
1400
212Pb
214Pb
214Pb
228Ac
214Pb
125Sb
125Sb
e+e-
228Ac
208Tl
207Bi
208Tl
134Cs
214Bi
125Sb
137Cs
212Bi
214Pb
228Ac
134Cs
54Mn
208Tl
228Ac
214Bi
228Ac
207Bi
65Zn
214Bi
60Co
214Bi
60Co
214Bi


counts/kg·d·keV
energy [keV]
1400
1600
1800
2000
2200
2400
2600
40K
214Pb
214Bi
228Ac
214Bi
214Bi
214Bi
0ν peak region
208Tl
214Bi
214Bi
60Co
208Tl

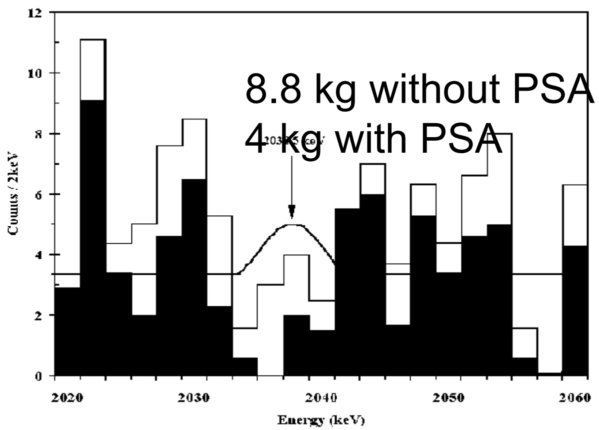
Pulse shape analysis



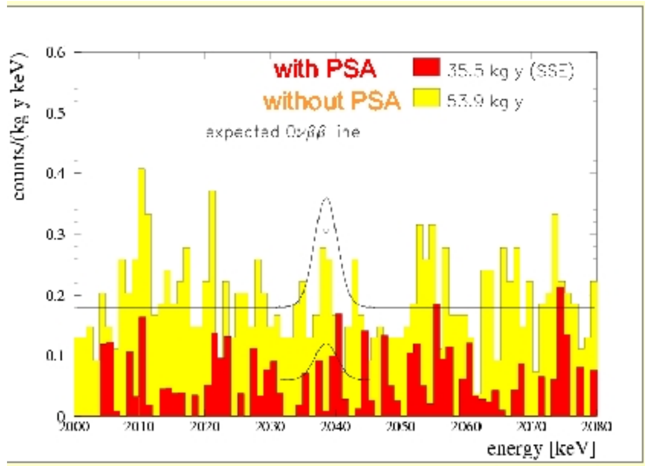


Efficiency to reject bad events: 60-80 %

HM: 0.06 counts/kg.y.keV
IGEX: 0.09 counts/kg.y.keV



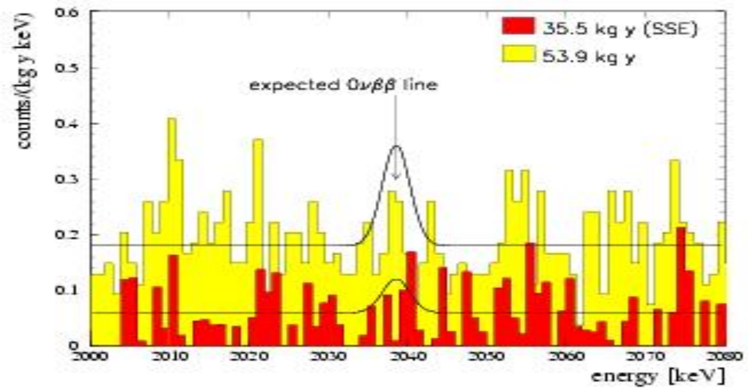
IGEX



HM

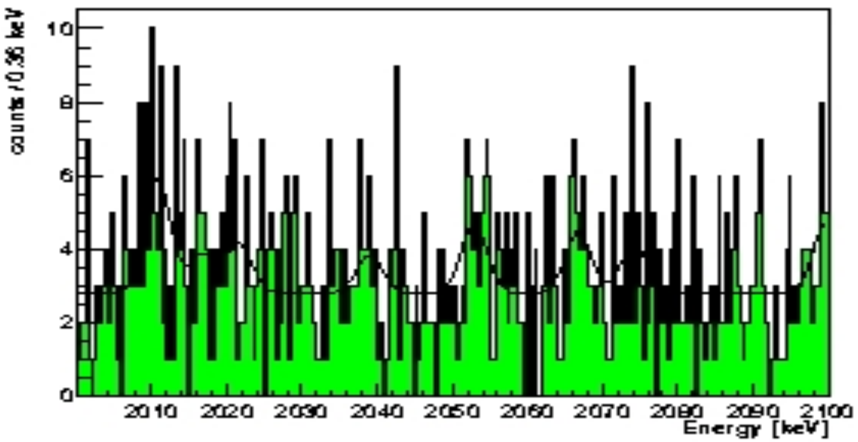
ββ(0ν) signal ? HM claim

2001



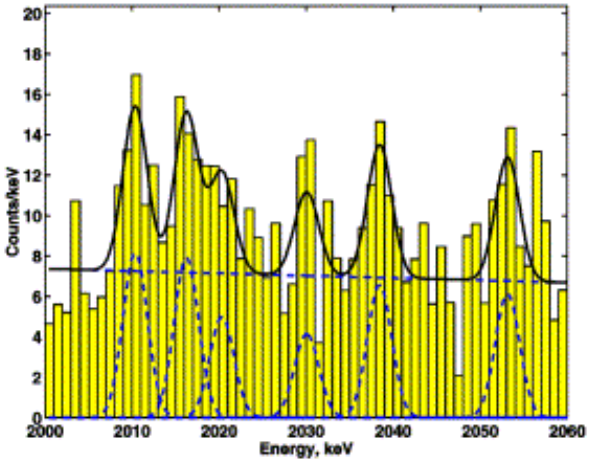
$T_{1/2} > 1.9\ 10^{25}$ $<m_n> < 0.35-1.05$ (90%)

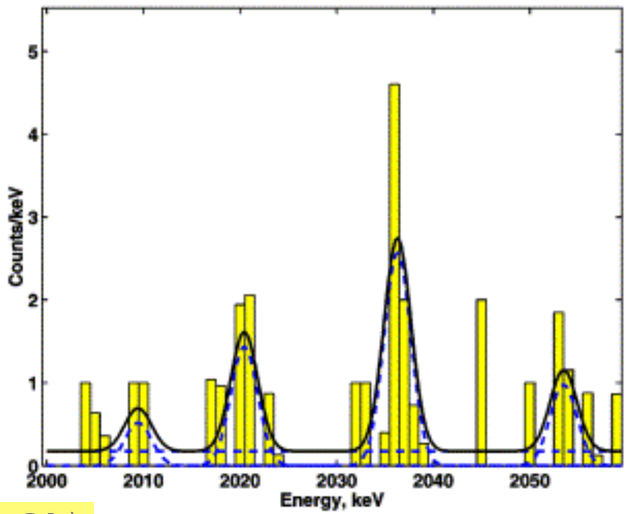
2002 (3.1σ)

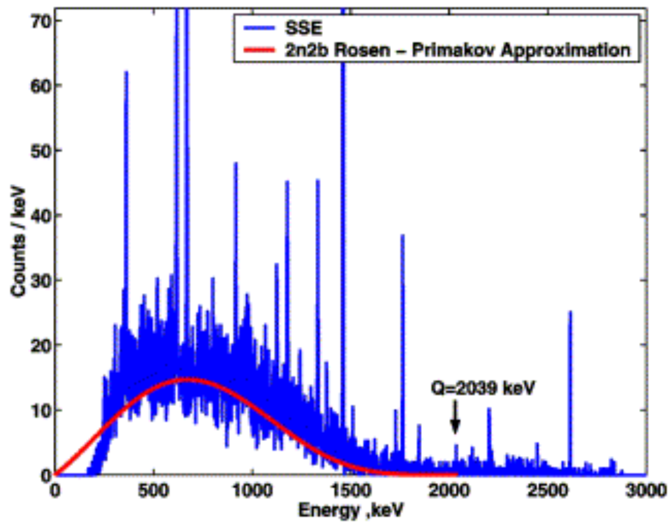


$T_{1/2} = (0.8-18.3)\ 10^{25}$ y $<m_n> = 0.11 - 0.56$ eV

2004: new calibration (4σ)







$$T_{\frac{1}{2}} = (0.69 - 4.18)10^{25}\ ans(90\ CL)$$

$$\langle m_\nu \rangle = 0.28 - 0.58\, eV$$

Best value:0.39 eV

ββ(0ν) signal ?

Statistical effect

Estimation of the background level

Problems for some well-known peaks (214Bi)

Some unknow lines in the same region

^{56}Co produced by cosmic rays (2034 keV photon+ 6 keV X-ray)

$^{76}Ge(n, \gamma)^{77}Ge$ (2038 keV photon)

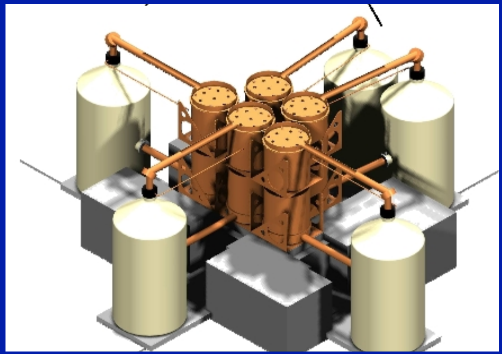
Some unknown line

Inelastic neutron scattering (n,n‘γ) on lead

Other suggestions, can be combination of all

GE futur

MAJORANA (USA,Russia)



Objective: 500 kg of ^{76}Ge
210 enriched segmented detectors

Detector segmentation
PSD improvement
Material selection

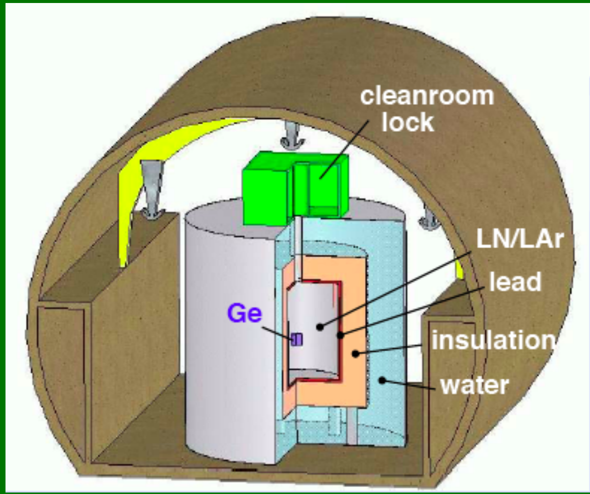
Feasability of segmented detector checked

In progress tests of 16 détectors of natural Ge
+ 2 enriched

~10 ans to have full detector

2015 ?: $T_{1/2}$> 4. 10^{27} y <m_ν> 0.02 –0.03 eV

GERDA (Europe,Russia)



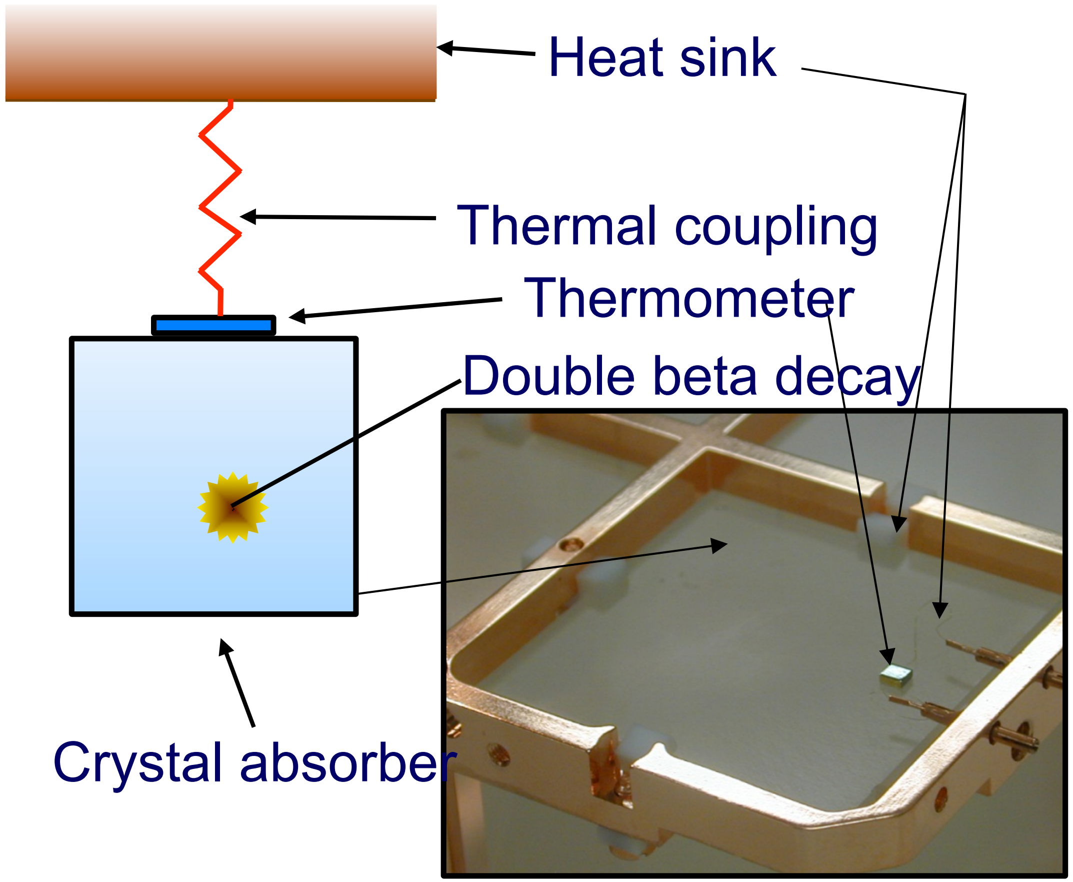
Objective: 100 kg of ^{76}Ge
Suppression of matter

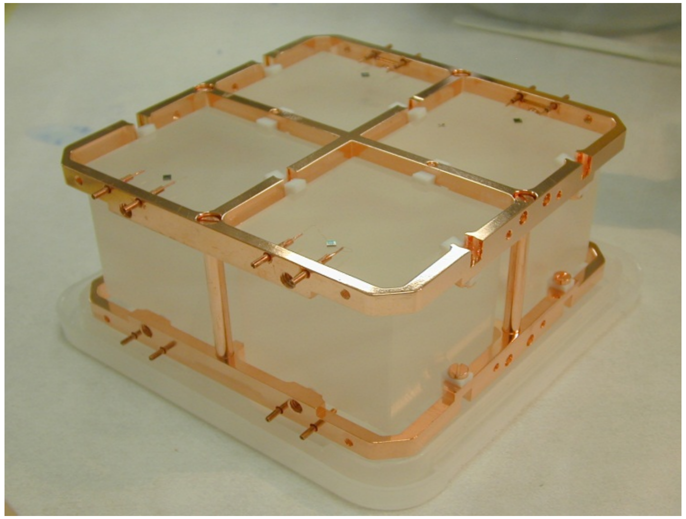
Ge placed in liquid nitrogen or argon
(active veto to reject background)
PSD improvement

Feasability of Ge in liquid N_2 shown
2008: cristaux HM+IGEX to test HM signal
Si bdf=0.01 cps.kev^{-1}.kg^{-1}.an^{-1}
HM rejeté à 99.6% en 1 an
2010: 100 kg (détecteurs segmentés)

2015: $T_{1/2}$> 2.10^{26} ans <m_ν> 0.09 –0.29 eV

Bolometer: cuorecino - cuore





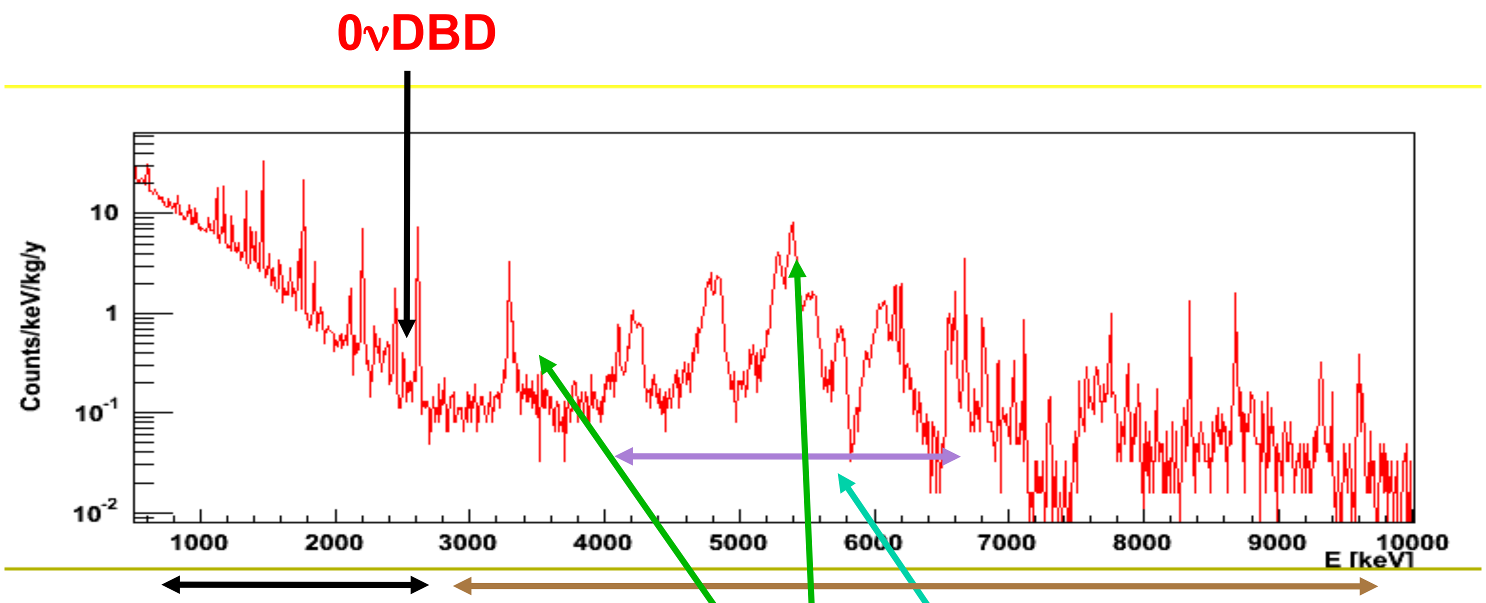
example: 750 g of TeO_2 @ 10 mK

$C \sim T^3$ (Debye) $\Rightarrow C \sim 2\times10^{-9}$ J/K

1 MeV γ-ray $\Rightarrow \Delta T \sim 80\ \mu$K

$\Rightarrow \Delta U \sim 10$ eV

Cuoricino spectrum



Gamma region, dominated by gamma and beta events, highest gamma line = 2615 keV ^{208}Tl line (from ^{232}Th chain)

Alpha region, dominated by alpha peaks (internal or surface contaminations)

Cuoricino results

Bolometers of TeO2 ($Q_{\beta\beta}$= 2,528 MeV)
Natural abundance ^{130}Te 30%
Resolution (FWHM at 1 MeV) 5-7 keV

CUORICINO: 1 tower de CUORE

42 modules of 5*5*5 cm3
18 modules of 2*3*6 cm3

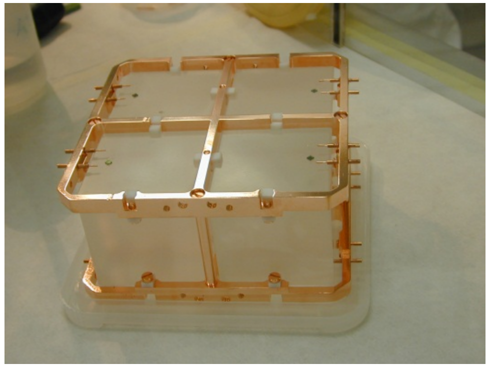
10.4 kg of ^{130}Te

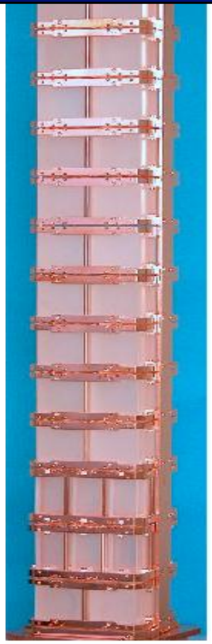
Efficaciency: 86 %

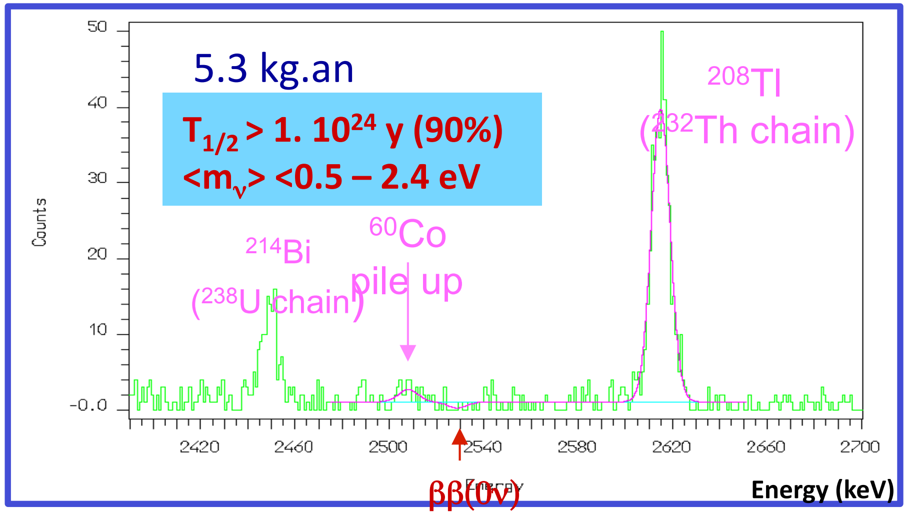
Run since 2003

Bckg: 0.17 evt.keV^{-1}.kg^{-1}.y^{-1}
^{208}Tl in materials, surface contamination in α et β emitters

Italy, Spain, Netherland, USA

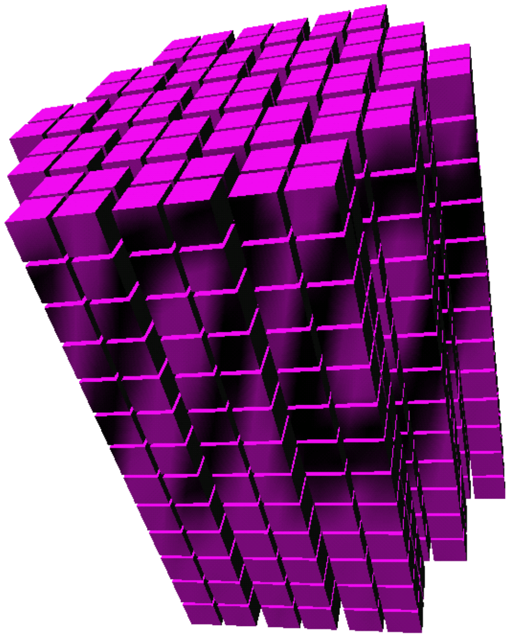






In 3 ans: $T_{1/2}$ > 4. 10^{24} y $<m_\nu>$ <0.2 – 1.2 eV

CUORE



750 kg TeO_2 → 203 kg ^{130}Te

19 towers x 13 modules x 4 detectors

R&D for CUORE

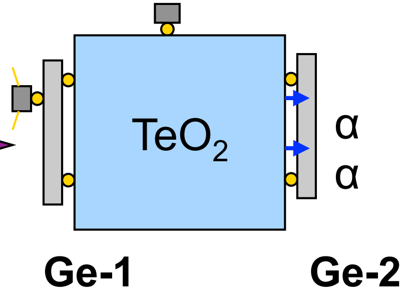
0.17 → 0.01 cps.keV^{-1}.kg^{-1}.an^{-1}

Surface cleaning

Supression of α events in surface

Détection scintillation ?

$^{48}CaF_2$, ^{76}Ge, $^{100}MoPbO_4$, $^{116}CdWO4$, $^{150}NdF_3$

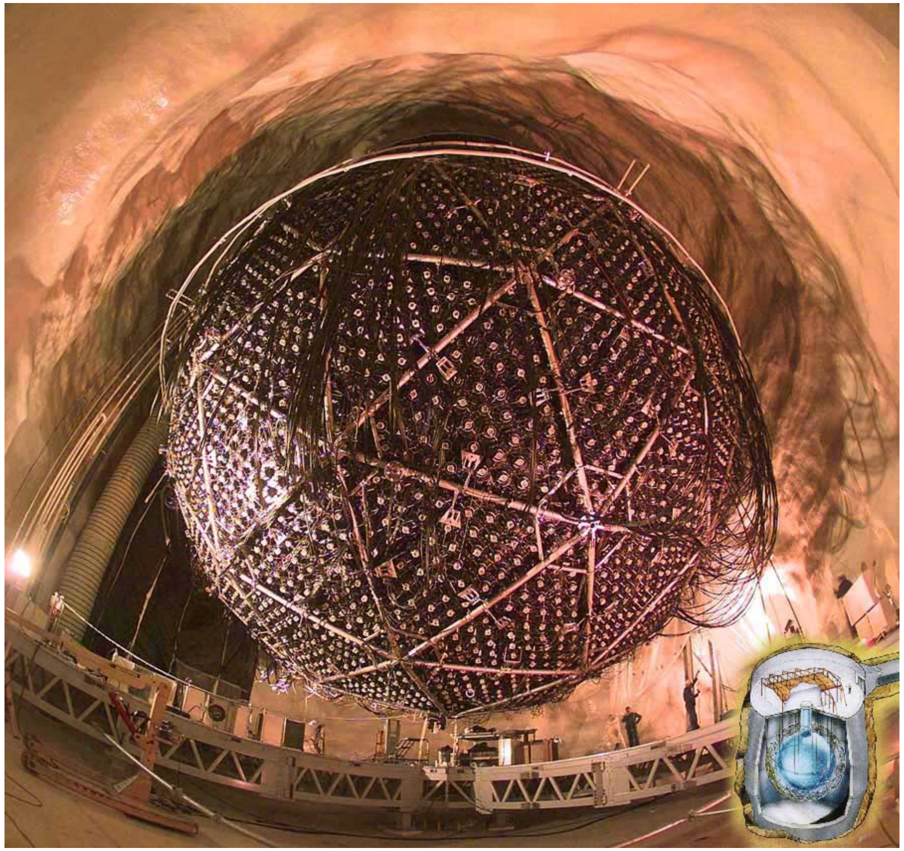


Sensitivities for 5 years

N_{bdf}=0.01 cps.keV^{-1}.kg^{-1}.y^{-1}	N_{bdf}=0.001 cps.keV^{-1}.kg^{-1}.y^{-1}
$T_{½} > 2.1\ 10^{26}$ y	$T_{½} > 6.6\ 10^{26}$ y
$<m_\nu> < 0.03 – 0.17$ eV	$<m_\nu> < 0.015 – 0.1$ eV

Funded experiment, Start 2010, Results 2015

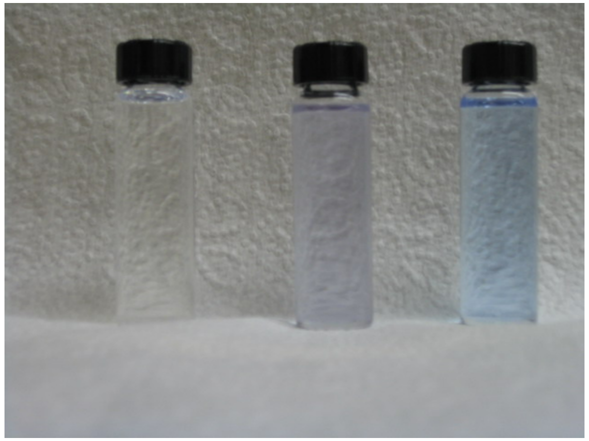
SNO+

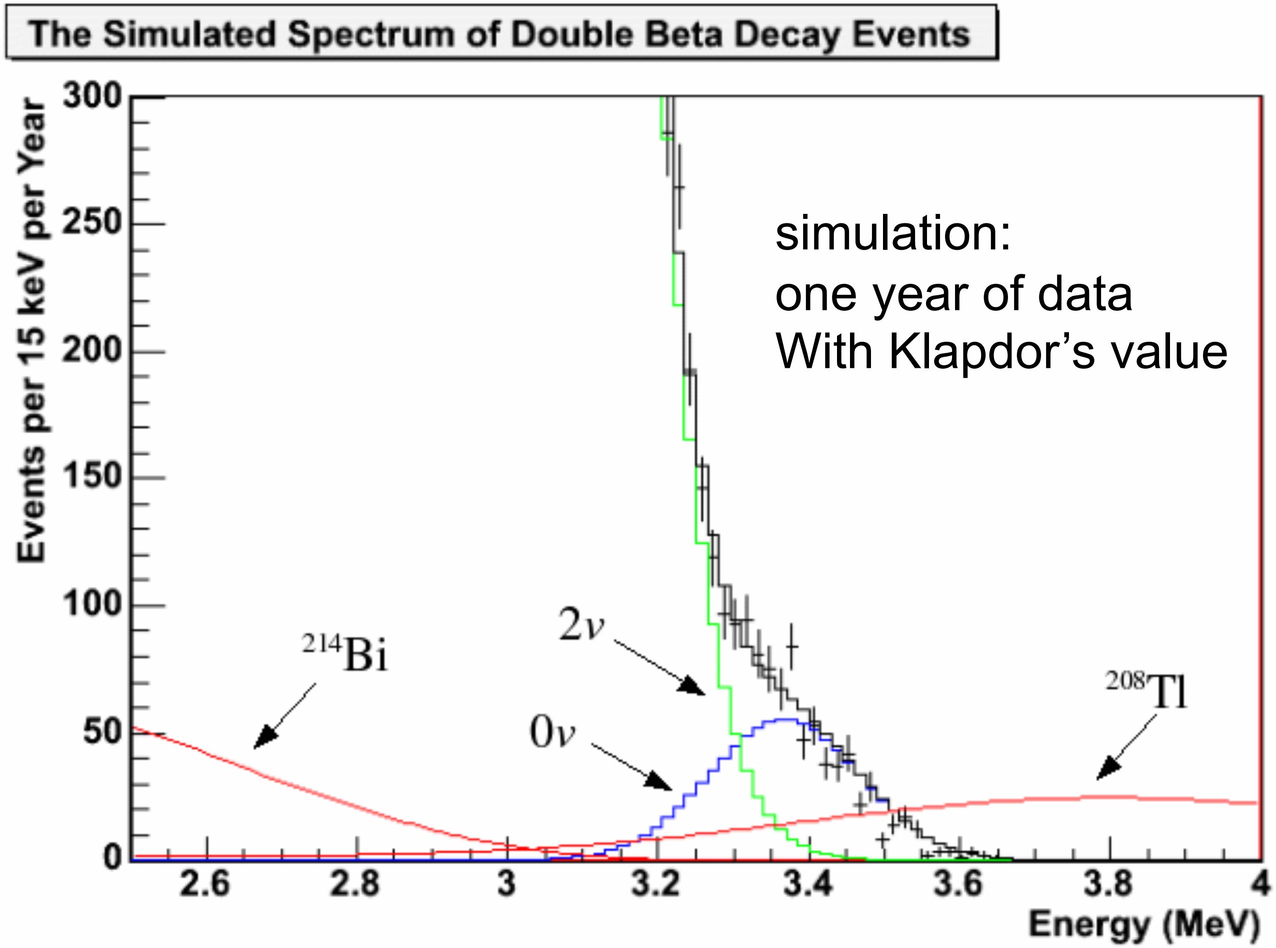


SNO + SNO filled with liquid scintillator for solar neutrino detection

SNO++

0ν: 1000 events per year with 1% natural Nd-loaded liquid scintillator in SNO++





maximum likelihood statistical test of the shape to extract 0ν and 2ν components…~240 units of $\Delta\chi^2$ significance after only 1 year!