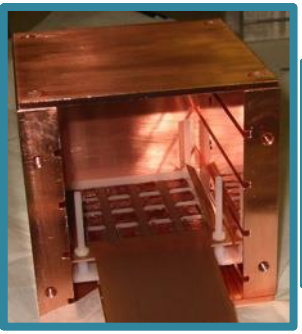
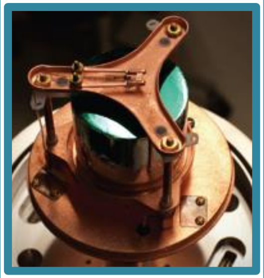
An introduction to the double beta decay






F. Piquemal

Modane Underground Laboratory (CNRS/IN2P3 and CEA/Irfu)

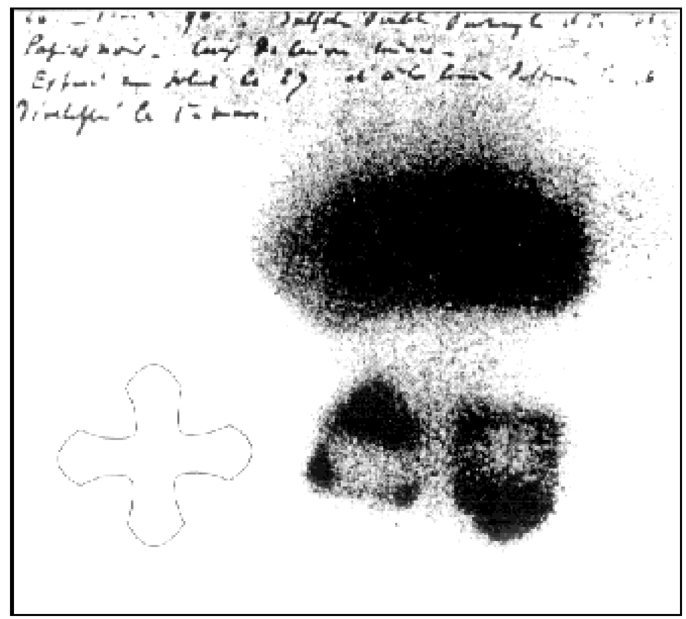
Particle physics school , Annecy July,24 2013

Plan

- Short history of beta decay and double beta decay
- Double beta decay and neutrino properties
- How to perform a double beta decay experiment
- The experimental challenges to look for double beta decay
- Presentation of few experiments

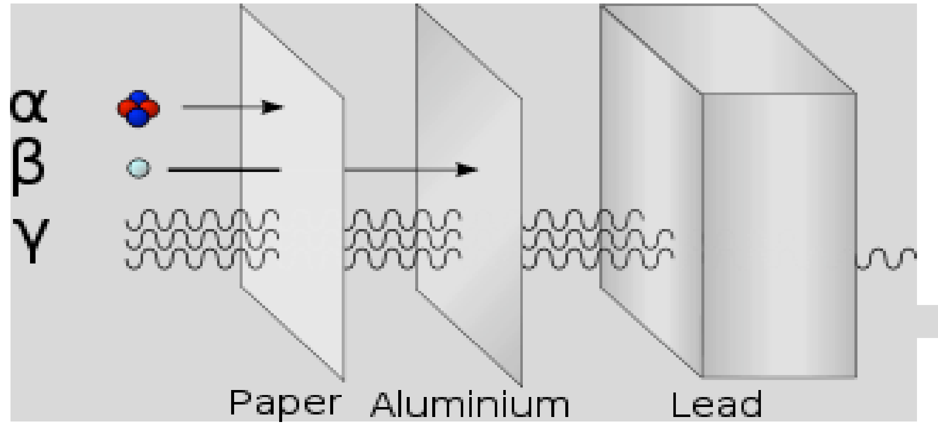
The beginning of the history

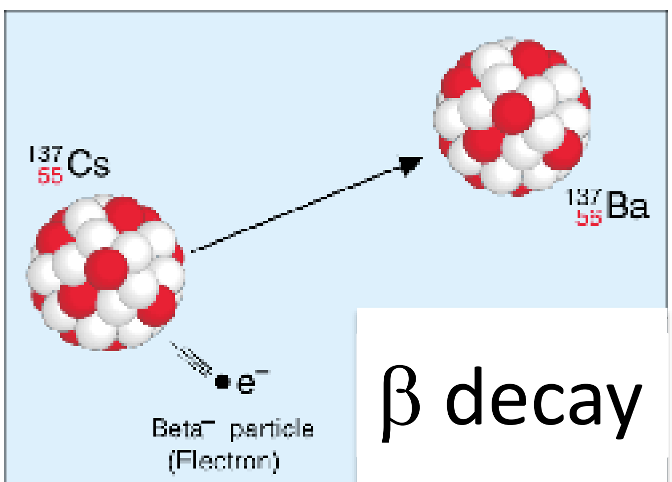
1896 - 1898:
Becquerel, Pierre and Marie Curie discovered the radioactivity

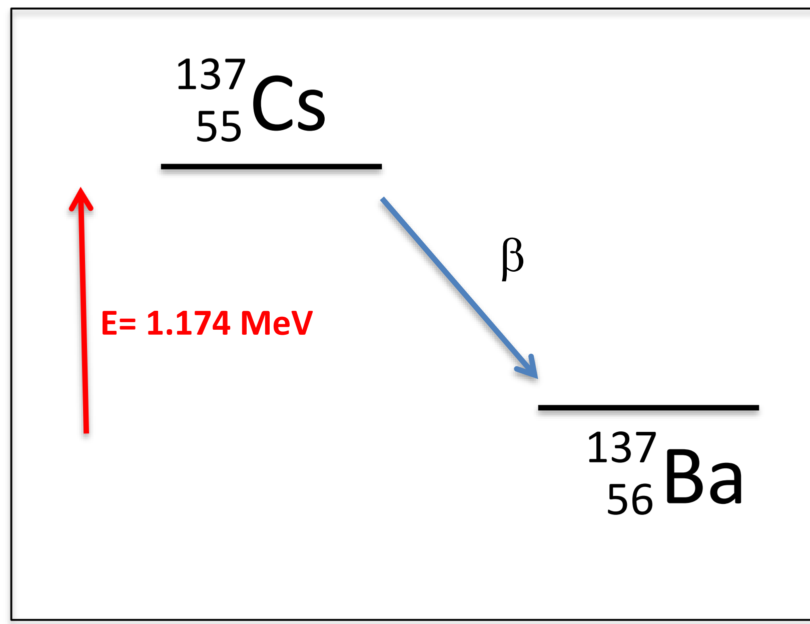


The beginning of the history

Rutherford, Chadwick,
P. et M. Curie and Villard
identified 3 kinds of radiations

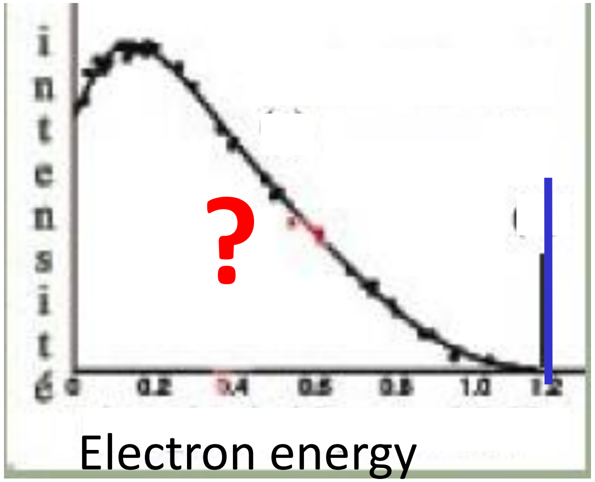






The beginning of the history

1914 : Chadwick, Hahn and Meitner measured the beta energy spectrum



1914 – 1930 : Energy crisis in the subatomic world

Is there non-conservation of energy ?

The beginning of the history

1930 W. Pauli postulated the neutrino
No interaction with matter
No mass (or very small)
Fermion - spin 1/2

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Dear Radioactive Ladies and Gentlemen.

As the bearer of these lines, to whom I ask you to lend most graciously your ears, will explain in greater detail, I have hit, in view of the "false" statistics of the N and Li-6 nuclei and of the continuous β–spectrum, upon a desperate expedient for saving the "Wechselsatz"† of statistics and energy conversation. This is the possibility that electrically neutral particles, which I shall call neutrons, might exist in the nucleus, having spin 1/2 and obeying the exclusion principle. In addition they differ from light quanta in that they do not travel at the speed of light. The mass of the neutron should be of the same order of magnitude as that of the electron and in any event no greater than 0.01 of the proton mass. The continuous β–spectrum would then be comprehensible on the assumption that on β–decay a neutron is emitted with the electron in such a way that the sum of the neutron and the electron energy is constant.

Furthermore the question arises which forces act on the neutron. For reasons of wave mechanics (the bearer of these lines knows more about this) the likeliest model for the neutron seems to me to be, that the neutron at rest is a magnetic dipole with a certain moment μ. Experiments apparently demand that the ionising effect of such a neutron is no greater than that of a γ–ray, in which case μ should be no greater than e (10^{-13} cm).

For the moment I would not venture to publish anything on this notion and should like first of all to turn trustingly to you, dear Radioactives, with the question concerning the prospects for experimental verification of the existence of such a neutron if it were to have the same or perhaps a 10 times greater penetrating power as a γ–ray.

I admit that my expedient may seem rather improbable from the first, because if neutrons existed they would have been discovered long since. Nevertheless, nothing ventured nothing gained, and the seriousness of the situation with the continuous β–spectrum is illustrated by a statement by my esteemed predecessor in office, Mr. Debye, who recently told me in Brussels: "Oh, it's better to ignore that completely, just like the new taxes". We should therefore be seriously discussing every path to salvation. So, dear Radioactives, consider and judge. Unfortunately I cannot come to Tübingen in person since my presence here is essential as a result of a ball held on the night of 6th to 7th December in Zürich.

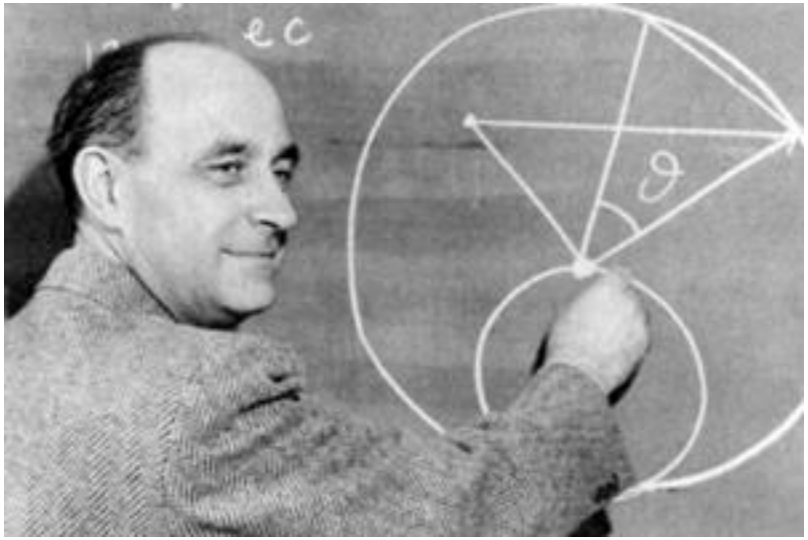
With kind regards to all of you and Mr. Back, I remain,

your humble servant,

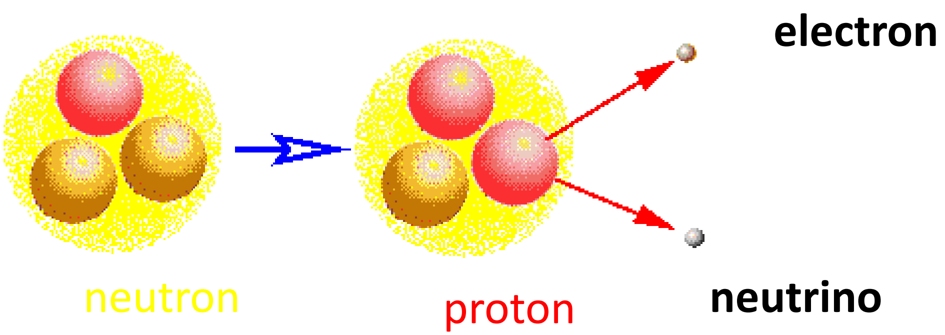
(signed) W. Pauli

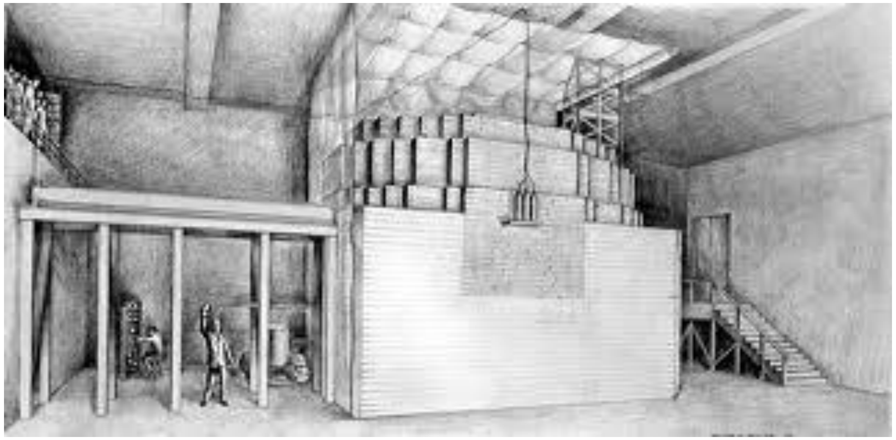
† This states: Fermi statistics and half-numbered spin for nuclei with an odd total number of particles; Bose statistics and integer spin for nuclei with an even total number of particles.

The beginning of the history



1933 : Fermi elaborated the theory of the weak interaction



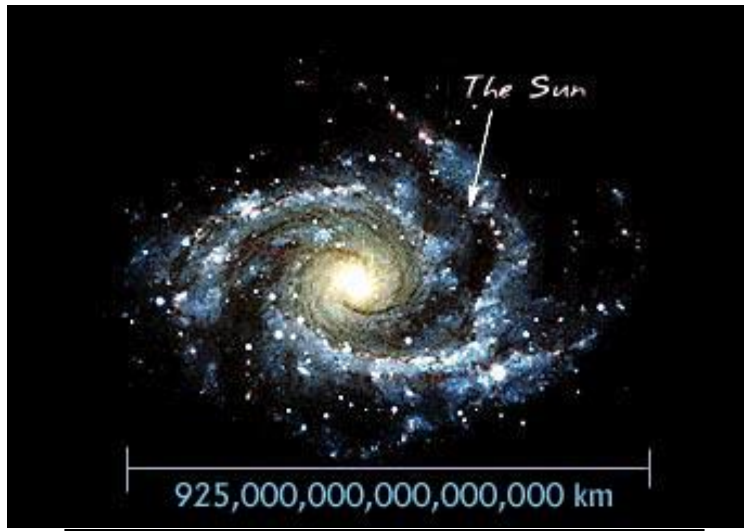


1942 : Fermi created the first nuclear reactor under the stadium of the Chicago University

The discovery of the neutrino

Neutrino Trap

← 30 000 000 000 000 000 km of lead →



Possible neutrino interactions

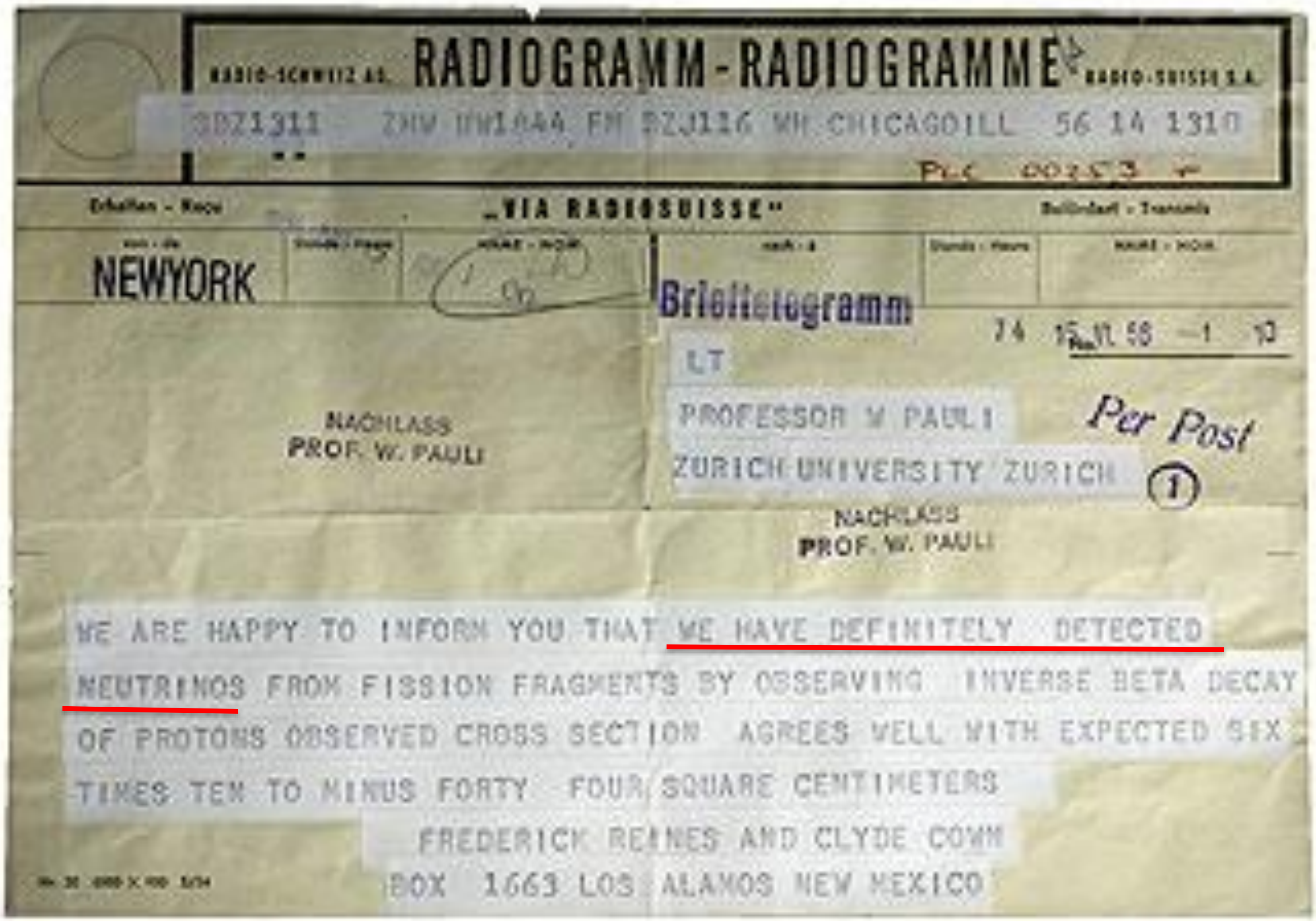
$$\nu + P \rightarrow e^{+} + n$$

$$\nu + e^{-} \rightarrow \nu + e^{-}$$

To detect neutrinos: plenty of neutrinos and a lot of matter !

The discovery of the neutrino

1956: Neutrino discovery by Reines and Cowan



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"VIA RADIOSUISSE"

NEWYORK

Brieftelegramm

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

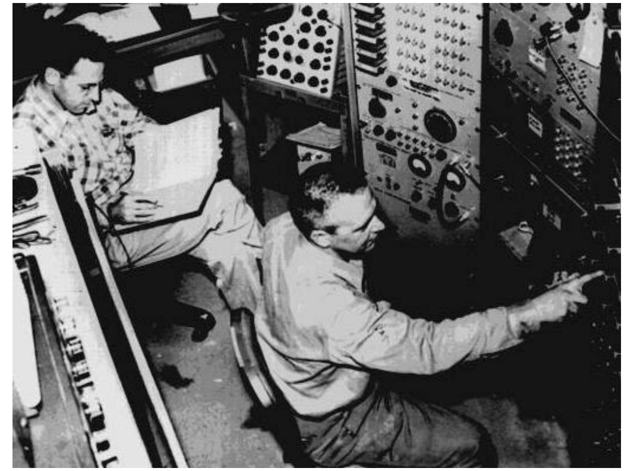
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

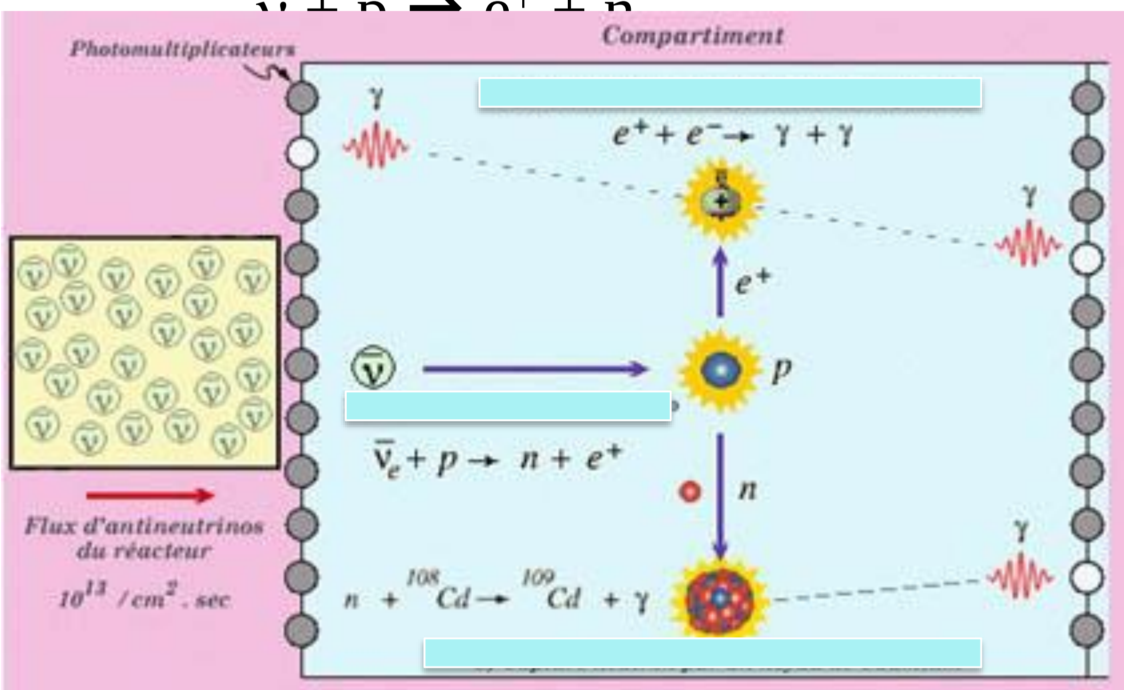
FREDERICK REINES AND CLYDE COWAN

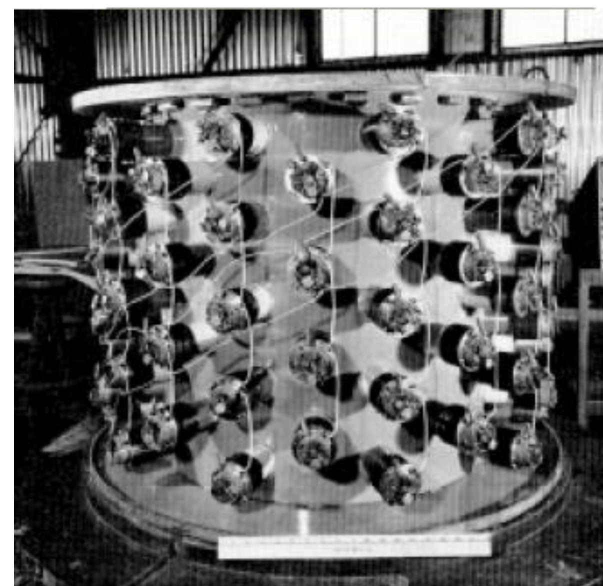
BOX 1663 LOS ALAMOS NEW MEXICO

The discovery of the neutrino

Savannah River reactor (USA)







Poltergeist detector

Ettore Majorana

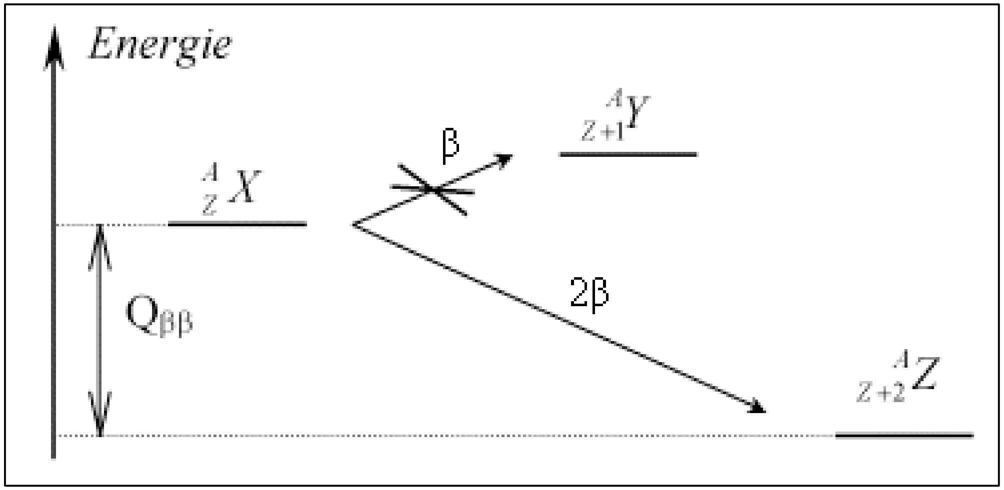
1937: **Ettore Majorana proposed a theory for neutral particle which can be its own anti-particle**

Neutrino = anti-neutrino ?

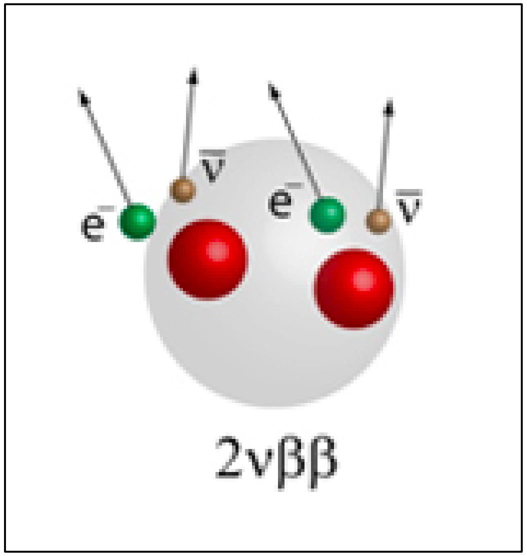
Fermi: «There are several categories of scientists: those who do their best, and those of the first plan, which make important discoveries ... And then there are the geniuses, like Galileo and Newton, Ettore was one of them ...»

Is the neutrino at the origin of the matter

The beginning of the history

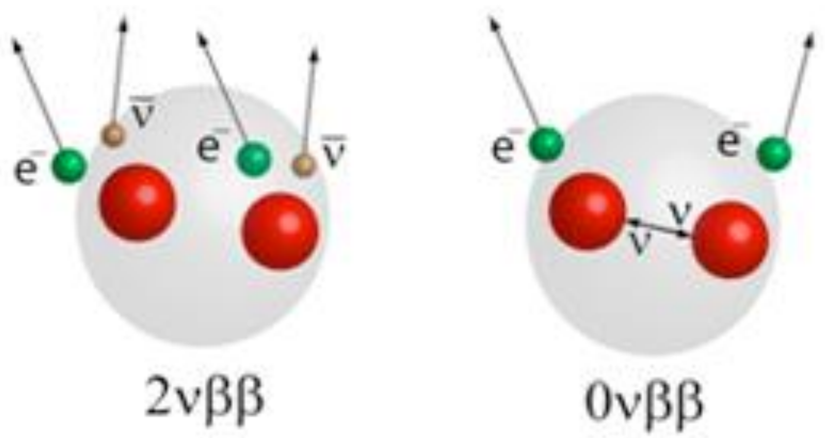


1935: Maria Goeppert-Mayer postulates the existence of the double beta decay, second order process of the beta decay



The beginning of the history

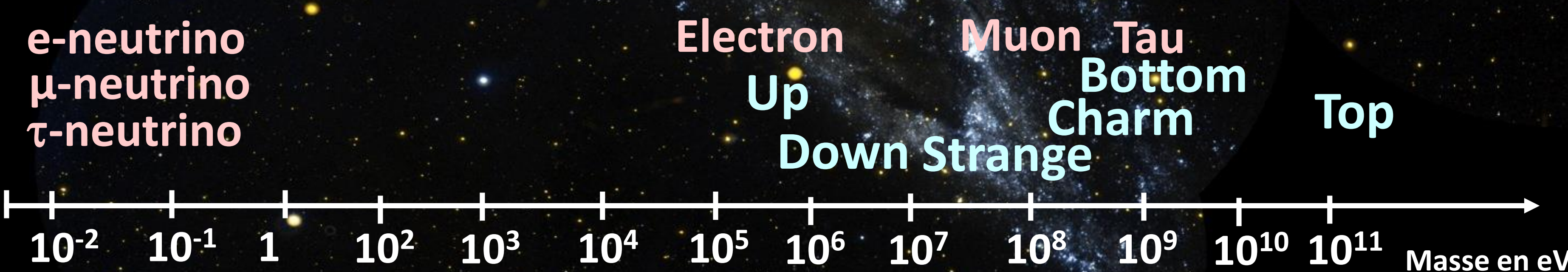
1939: Wendell Hinkle Furry demonstrates that if the neutrino is a Majorana particle (neutrino = anti-neutrino) then a new radioactivity can occur:
The neutrinoless double beta decay



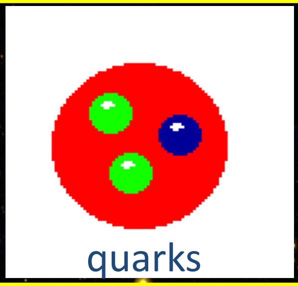
Elementary particles

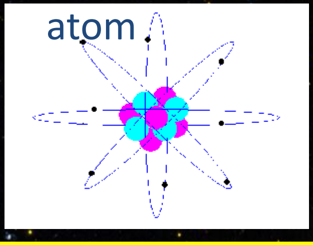
And also the anti-matter

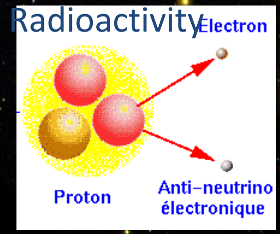
Mass of particles



INTERACTION	MEDIATOR	RELATIVE STRENGTH	Range (m)
STRONG	GLUONS	~ 1	$\sim 10^{-15}$
ELECTRO-MAGNETIc	PHOTON	$\sim 10^{-2}$	infinite
WEAK INTERACTION	W^{+}, W^{-}, Z^{0}	$\sim 10^{-8}$	$\sim 10^{-18}$
GRAVITATION	GRAVITON ?	$\sim 10^{-38}$	infinite







Neutrinoless double beta decay and neutrino properties

What can we learn with neutrinoless double beta decay about neutrino properties

ββ(0ν) forbidden by Standard Model

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

L=0 L=2 ΔL=2

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

L=0 L=2 L=-2 ΔL=0

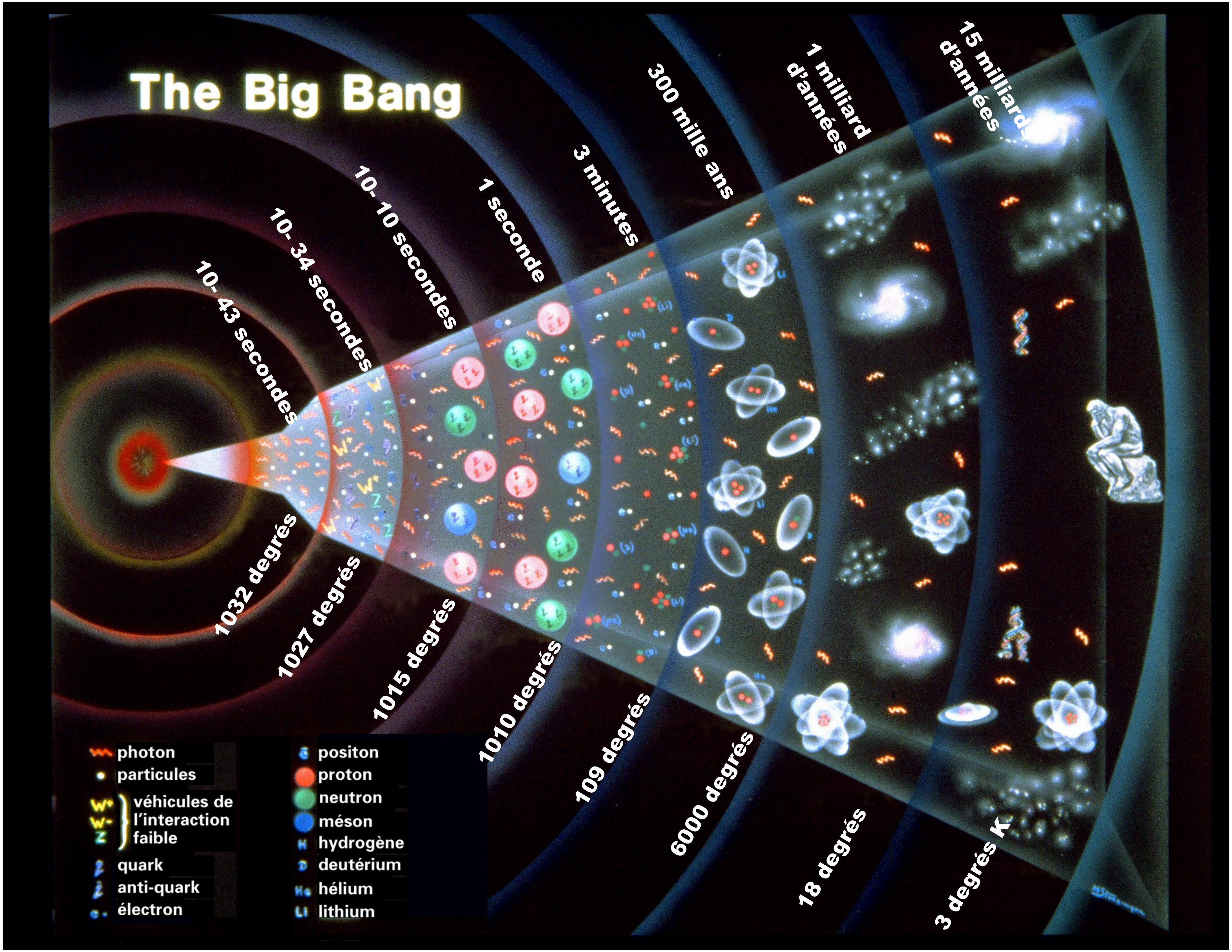
Test of a theory beyond the Standard Model of particle physics

Nature of the neutrino: a Dirac particle (neutrino ≠ antineutrino) ?

or

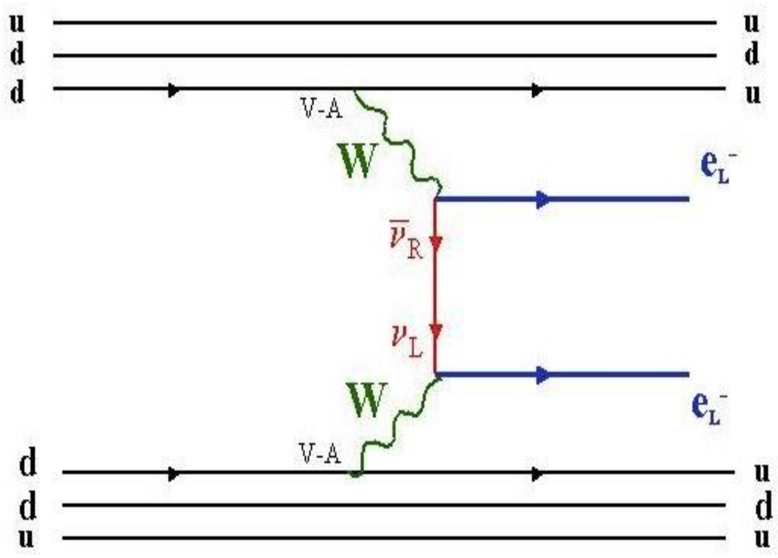
a Majorana particle (neutrino = antineutrino) ?

Strong impact on particle physics and in cosmology


The Big Bang
10- 43 secondes
10- 34 secondes
10- 10 secondes
1 seconde
3 minutes
300 mille ans
1 milliard d'années
15 milliards d'années
1032 degrés
1027 degrés
1015 degrés
1010 degrés
109 degrés
6000 degrés
18 degrés
3 degrés K
photon
particules
véhicules de l'interaction faible
quark
anti-quark
électron
positon
proton
neutron
méson
hydrogène
deutérium
hélium
lithium

Neutrinoless double beta decay and neutrino properties

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



Phase space factor

Nuclear matrix element

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

Effective mass:

$$\langle m_\nu\rangle = m_1|U_{e1}|^2 + m_2|U_{e2}|^2.e^{i\alpha 1} + m_3|U_{e3}|^2.e^{i\alpha 2}$$

|Uei|: mixing matrix element

α1 et α2: Majorana phase

Neutrinoless double beta decay and neutrino properties

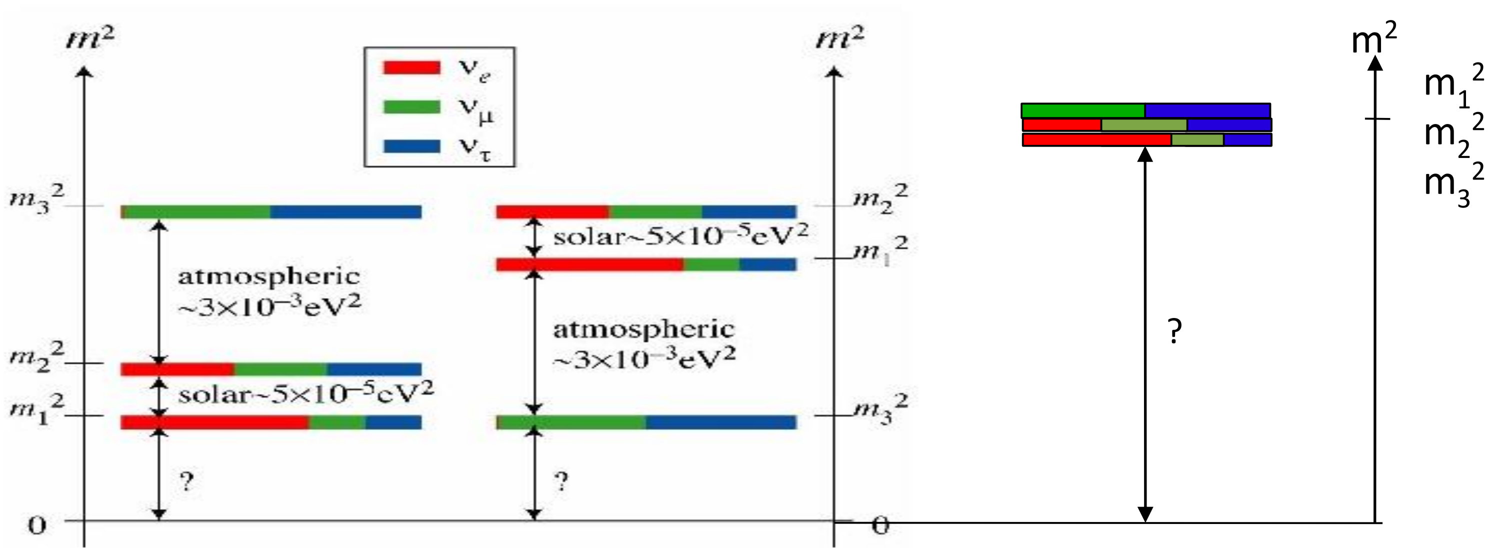
absolute mass ?

Tritium decay $m_{\nu e}$ <2.3 eV

Cosmology Σm_i <~1 eV

ββ(0ν) $\langle m_\nu \rangle$ < 0.2-0.5 eV

Mass scale ?



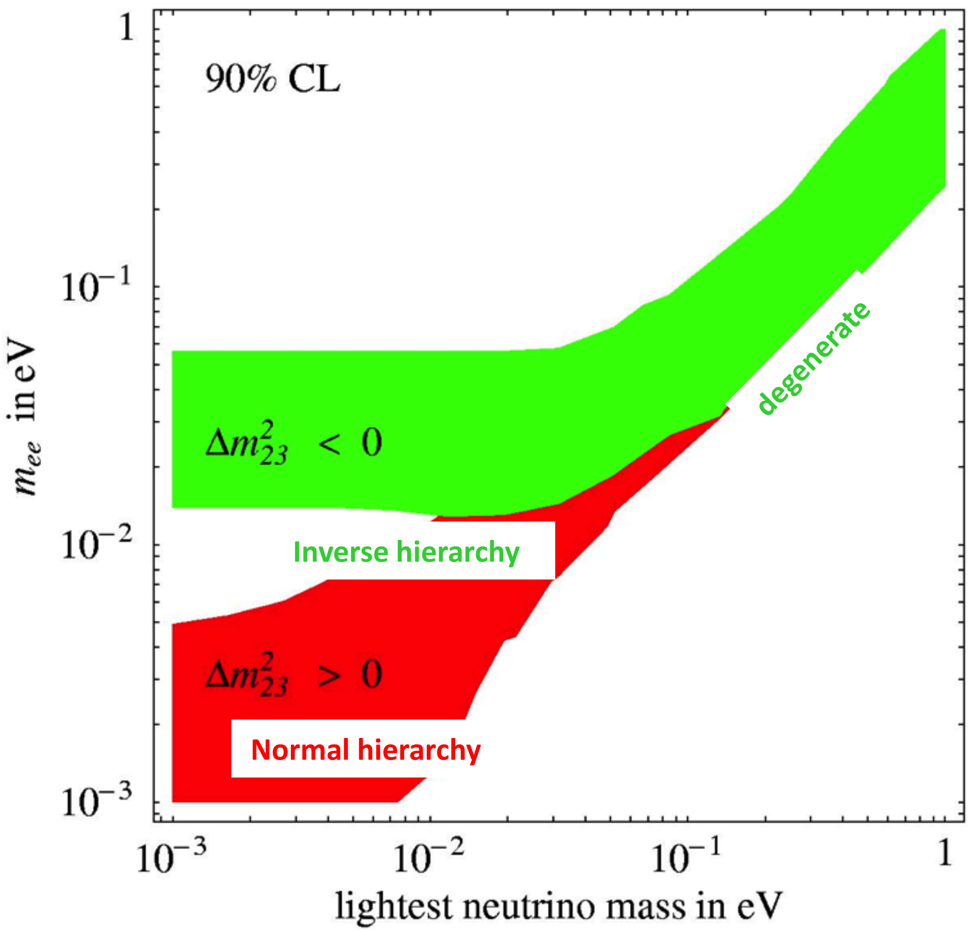
Normal hierarchy
$m_3 > m_2 \sim m_1$

Inverted hierarchy
$m_2 \sim m_1 > m_3$

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

Neutrinoless double beta decay and neutrino properties

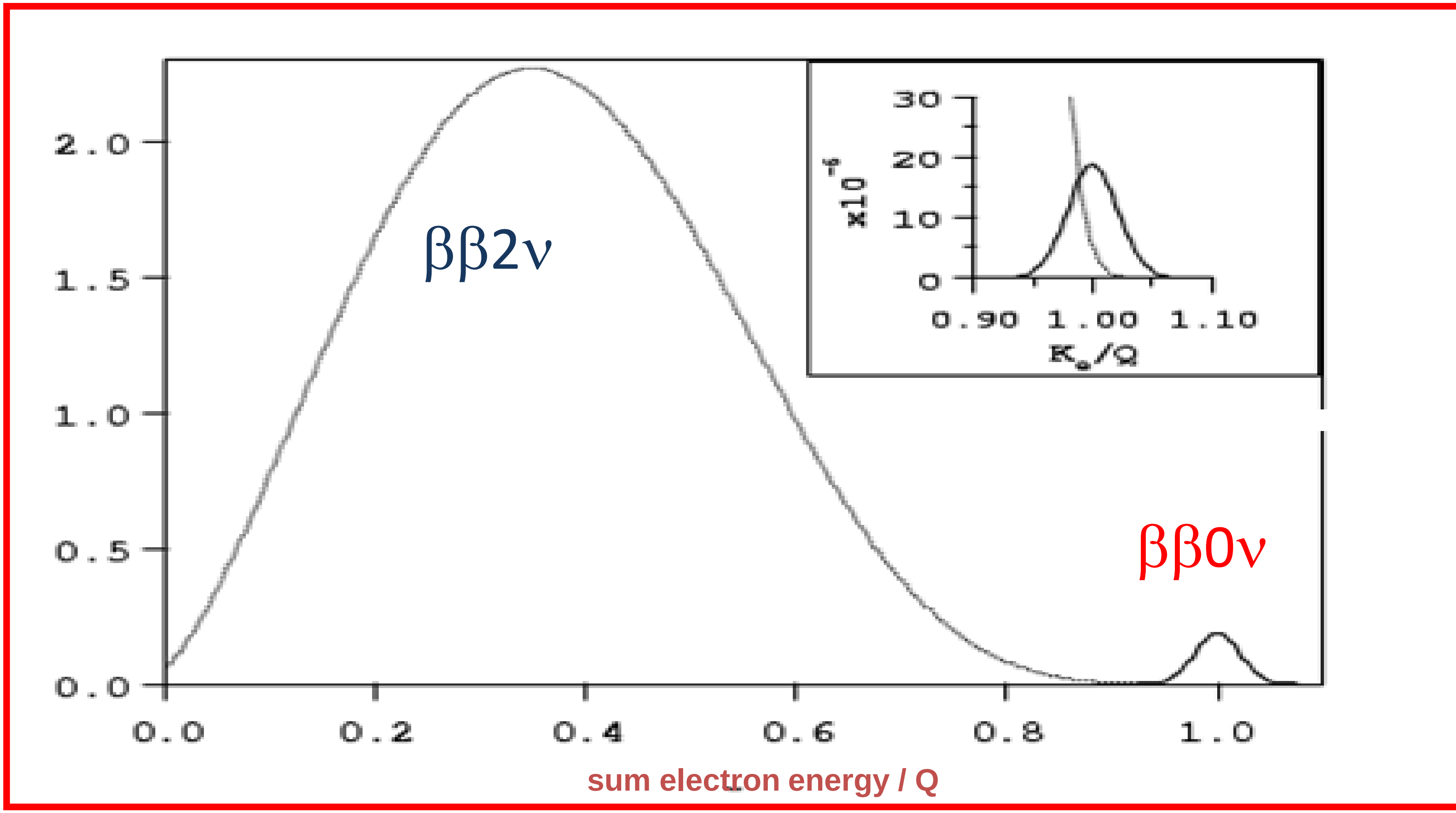
$$< m_\nu > = \left|\sum_i U_{ei} m_i\right| = \left|\cos^2\theta_{13}\left(m_1\cos^2\theta_{12} + m_2 e^{2i\alpha}\sin^2\theta_{12}\right) + m_3 e^{2i\beta}\sin^2\theta_{13}\right|$$



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

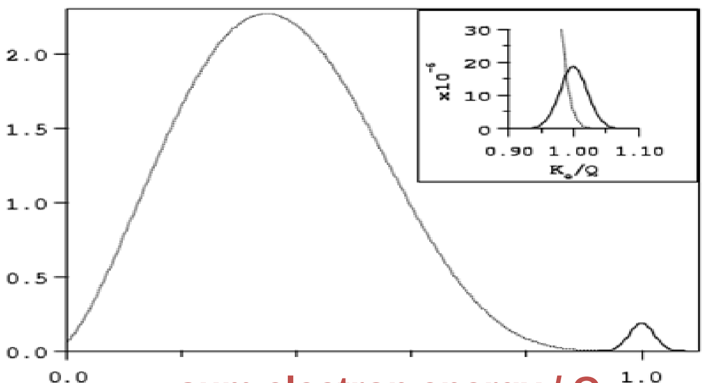
Double beta decay observables

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



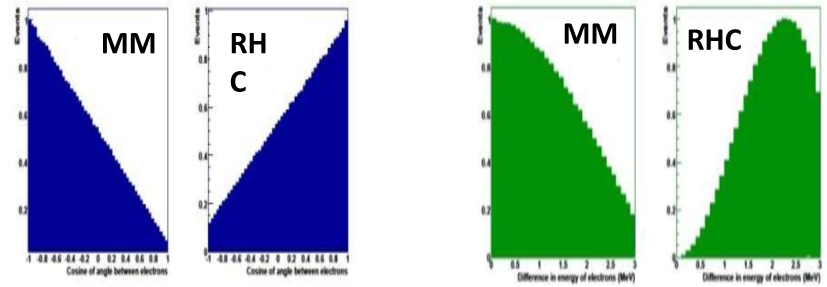
Double beta decay observables

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

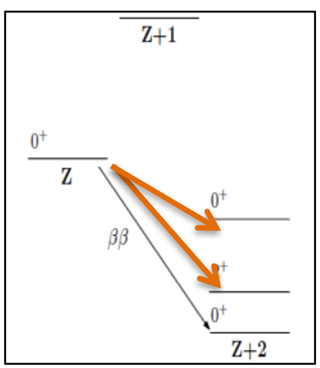


sum electron energy / Q

Angular distribution — **$Ee_1 - Ee_2$ distribution**



Mass vs Right-Handed Current mechanism

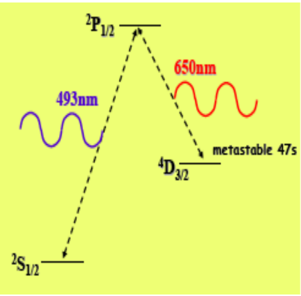


Decay to Excited States

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

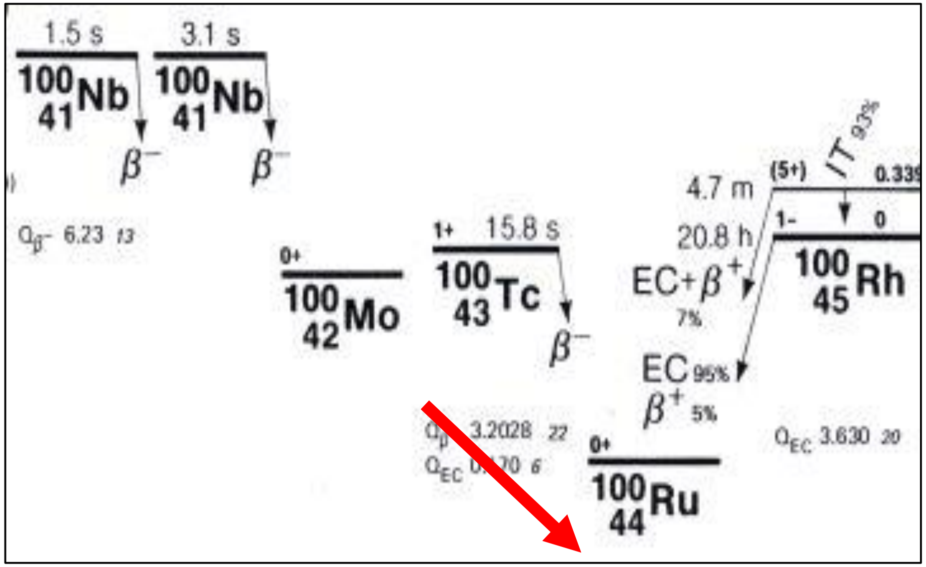
1 or 2 additonnal γ-rays

Identification of daugther nucleus :



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

Double beta decay emitters



Single beta decay forbidden (energy) or strongly suppressed by large angular momentum change

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

35 ββ emitters but only about 10 can be experimentally studied

Expected half-lifes

Isotope	Q-value (keV)	Nat. abund. (%)	$(PS\ 0\nu)^{-1}$ (yrs x eV^2)	$(PS\ 2\nu)^{-1}$ (yrs)
Ca 48	4271	0.187	4.10E24	2.52E16
Ge 76	2039	7.8	4.09E25	7.66E18
Se 82	2995	9.2	9.27E24	2.30E17
Zr 96	3350	2.8	4.46E24	5.19E16
Mo 100	3034	9.6	5.70E24	1.06E17
Pd 110	2013	11.8	1.86E25	2.51E18
Cd 116	2802	7.5	5.28E24	1.25E17
Sn 124	2288	5.64	9.48E24	5.93E17
Te 130	2529	34.5	5.89E24	2.08E17
Xe 136	2479	8.9	5.52E24	2.07E17
Nd 150	3367	5.6	1.25E24	8.41E15

$$T_{1/2} = \ln 2 \cdot a \cdot N_A \cdot M \cdot t / N_{\beta\beta}$$

a: isotopic abundance
N_A: Avogadro number
M: mass
T: time
$N_{\beta\beta}$: number of decays

1 decay/y for $10^{24} - 10^{25}$ nuclei

1 decay/y for ~ 10 moles (1 kg)

Basic principle for a neutrinoless double beta decay experiment

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

$G^{0\nu}$: Phase space factor function of $Q_{\beta\beta}^5$ and Z

$M^{0\nu}$: Nuclear Matrix Element

$<m_\nu>$= effective neutrino mass

Expected half-life > 10^{25} years → High number of nuclei → isotopic enrichment

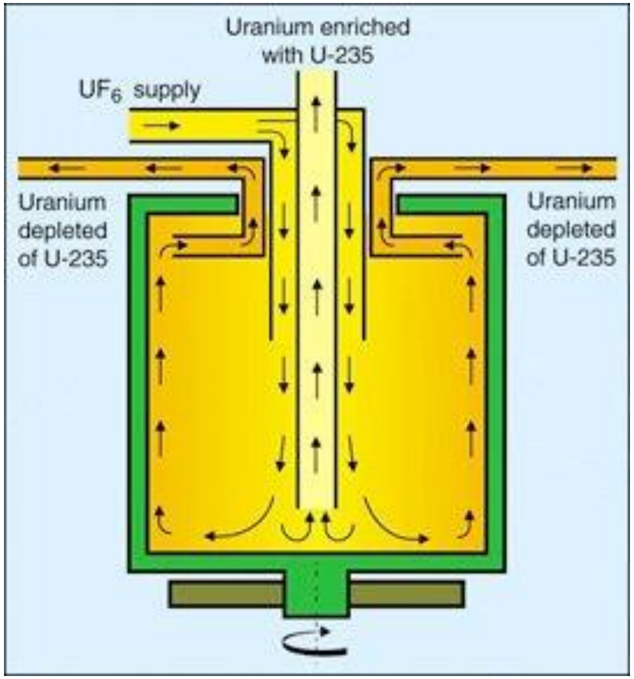
High transition energy ($Q_{\beta\beta}$)

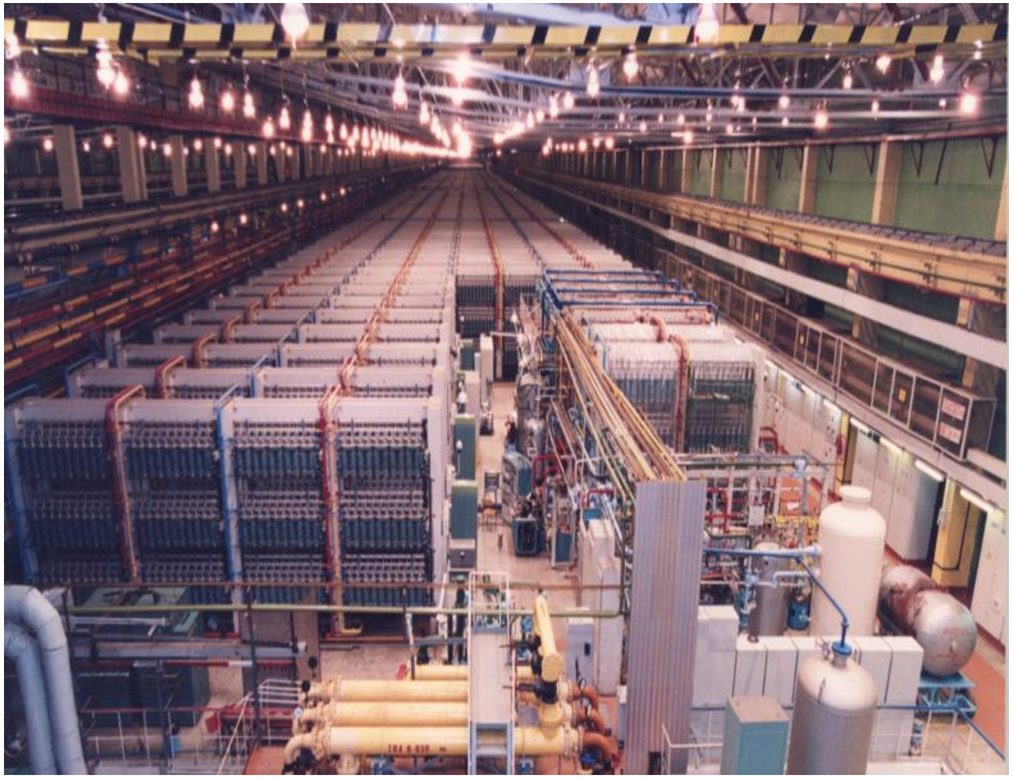
Good energy resolution

Rejection of background coming from natural radioactivity

Choice of the nucleus → experimental technique

Isotopic enrichment

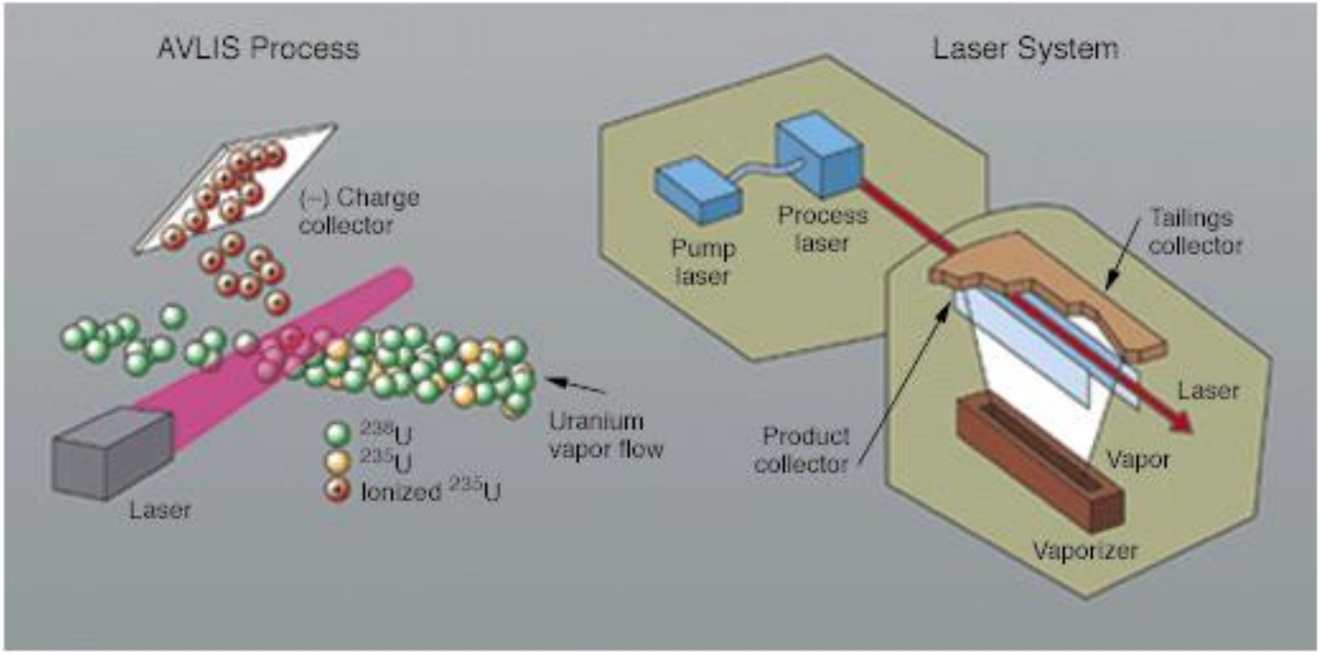




ECP **(Electro-Chemical Plant, Svetlana)**
Zelenogorsk (Siberia)

Enrichment mainly made by centrifugation: need gazeous form for the isotope ^{136}Xe, ^{100}Mo, ^{82}Se, ^{76}Ge, ….

Isotopic enrichment



Enrichment ^{48}Ca, ^{150}Nd, ^{96}Zr possible in principle

Measured experimental half-life

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

NO Background

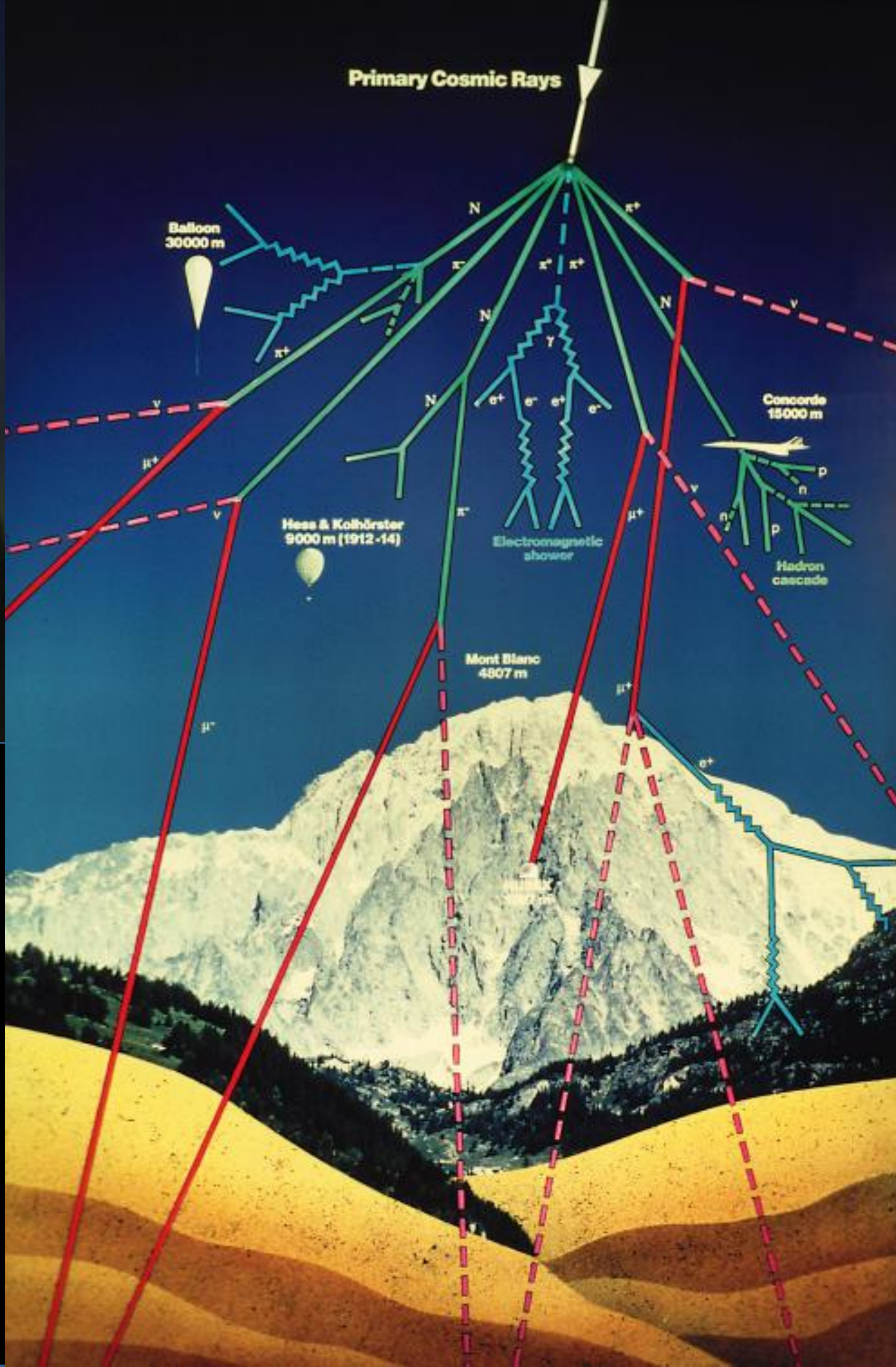
M: masse (g)
ε : efficiency
$\mathbf{K}_{\mathbf{C.L.}}$: Confidence level
$\mathcal{N}$: Avogadro number
t: time (y)
$\mathbf{N}_{\mathbf{Bckg}}$: Background events ($keV^{-1}.g^{-1}.y^{-1}$)
ΔE: energy resolution (keV)

$$T_{1/2}^{0n}(\mathrm{y}) > \frac{\ln 2\,.\,\mathcal{N}}{k_{C.L.}}\cdot\frac{\varepsilon}{A}\cdot\sqrt{\frac{\mathbf{M}\,.\,\mathbf{t}}{\mathbf{N}_{\mathbf{Bckg}}\,.\,\Delta\mathbf{E}}}$$

With background

Source of background from natural radioactivity

Such experiment cannot be performed at the sea level because of cosmic rays



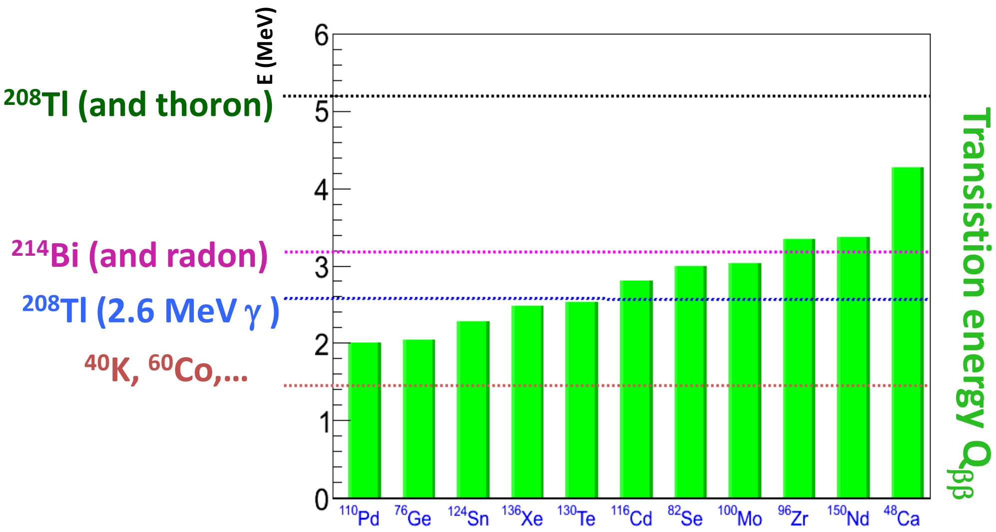
En surface:
10 000 000 de rayonnements cosmiques
par m^2 et par jour

Sous la montagne au LSM (- 1800 m):
4 rayonnements cosmiques par m^2 et par jour

Source of background from natural radioactivity

The radiations from the natural radioactivity can mimic double beta decay when they interact inside the detectors

Natural radioactivity

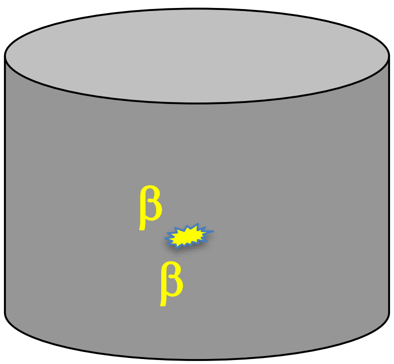


Detectors installed underground
Selection of all materials used in the detectors
Shielding against gamma-ray from the rocks
Suppression of radon

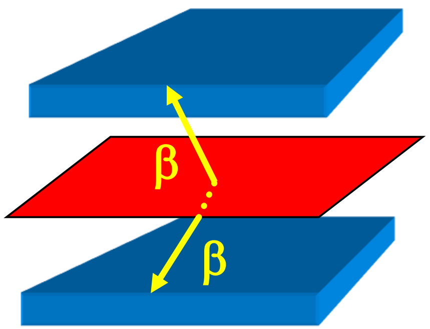
Source of background from natural radioactivity

Different strategies are possible to minimize the background

Detector: very accurate measurement of the energy to see the peak
or detection of the two emitted neutrino to reduce background

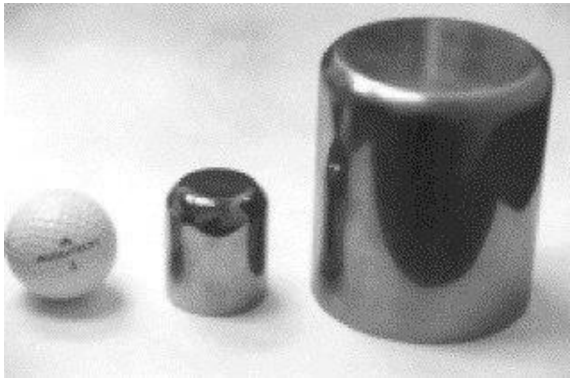


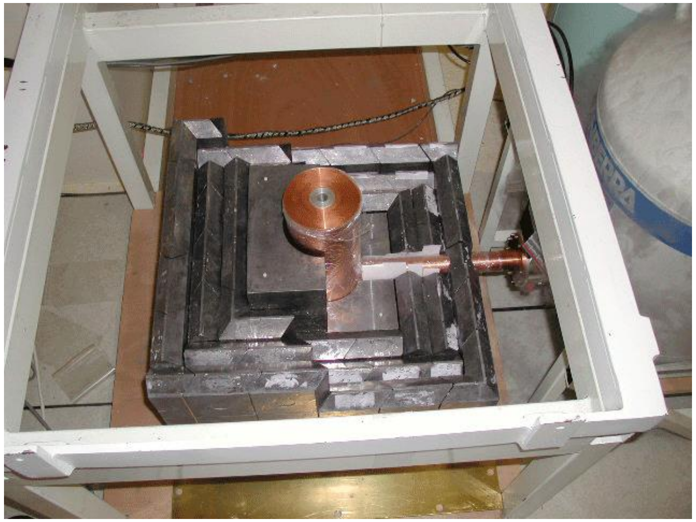
Calorimetric measurement

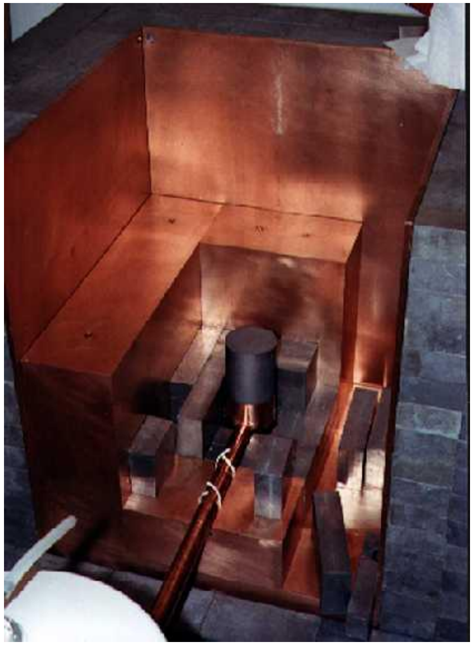


Electron detection

Ge experiment: Heidelberg Moscow

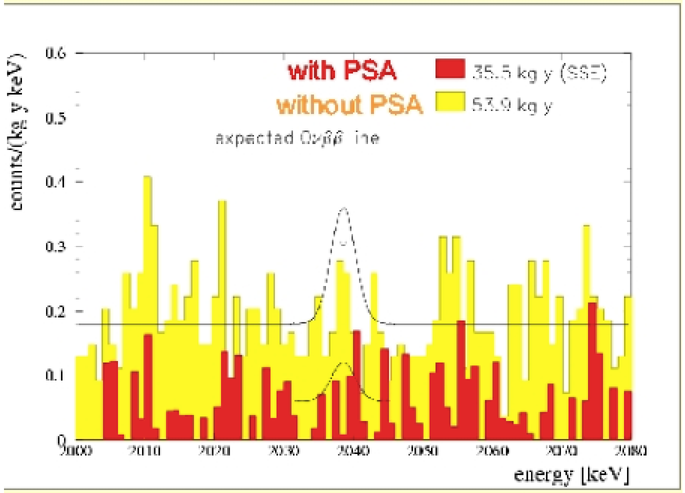






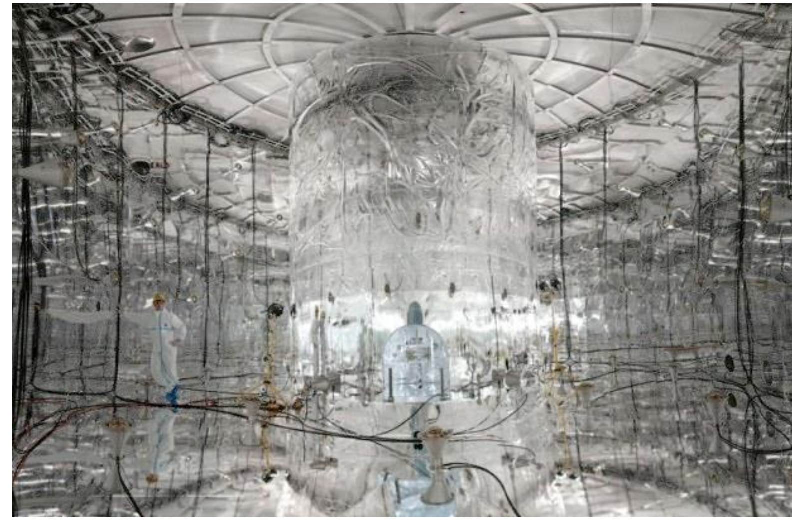
Ge detector works as semi-conductor at the liquid nitrogen temperature (-172° C)

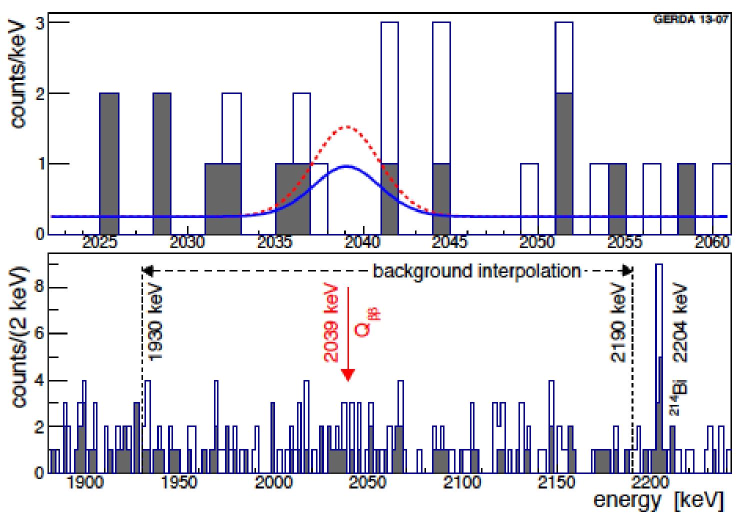
Very good energy resolution



$T_{1/2} > 1.9\ 10^{25}$ yr $\quad\quad$ $\langle m_\nu \rangle < 0.2 – 0.5$ eV

Ge experiment: GERDA experiment

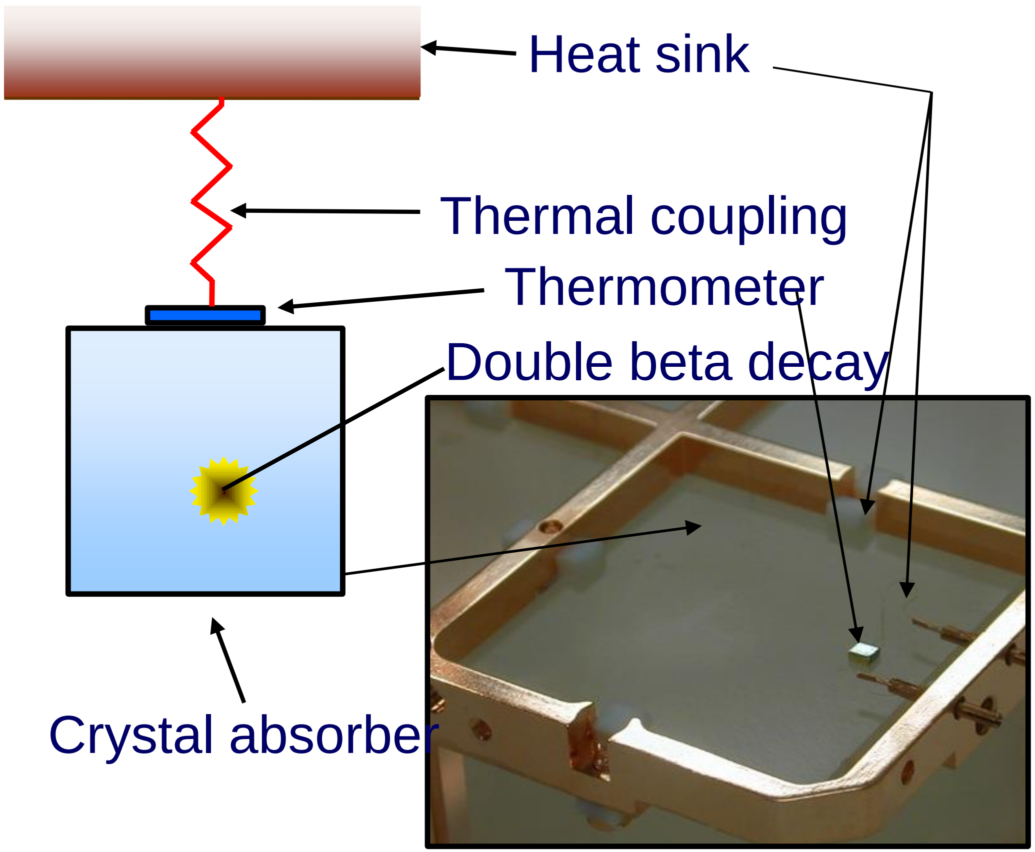


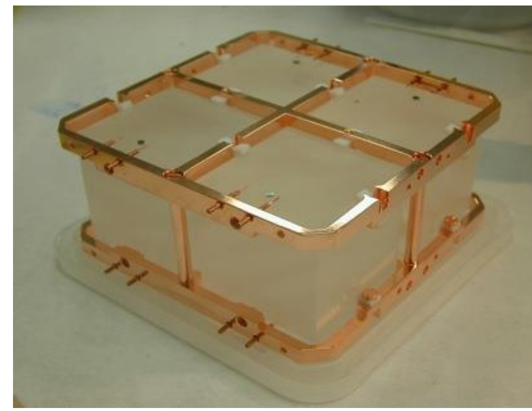


$T_{1/2} > 3.\ 10^{25}$ yr $\qquad <m_\nu> < 0.2 – 0.4$ eV

Bolometers : Cuoricino experiment

Very good energy resolution





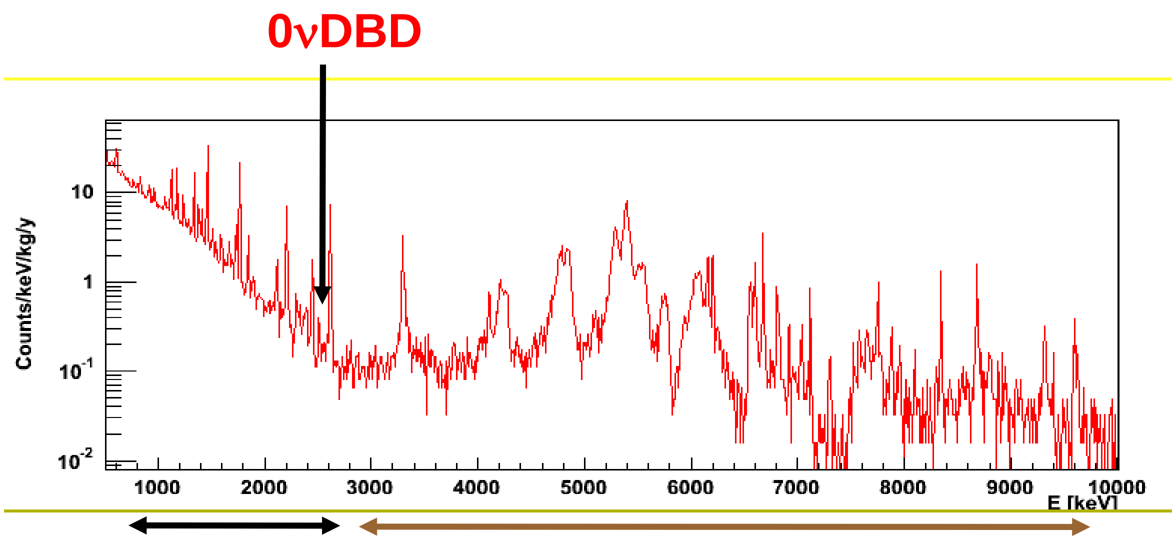
example: 750 g of TeO_2 @ 10 mK

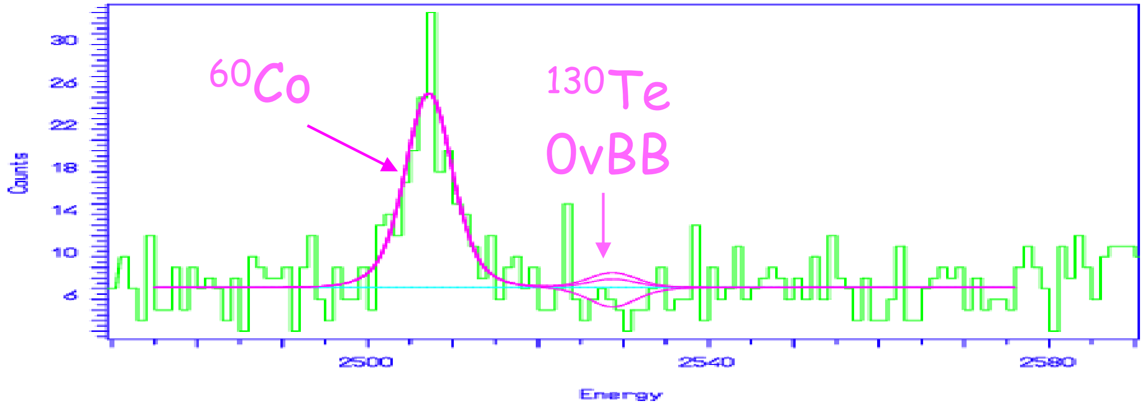
$C \sim T^3$ (Debye) $\Rightarrow C \sim 2 \times 10^{-9}$ J/K

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

$\Rightarrow \Delta U \sim 10$ eV

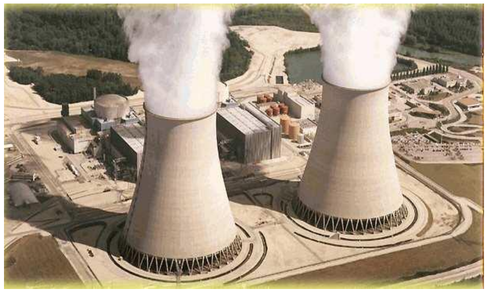
Bolometers : Cuoricino experiment



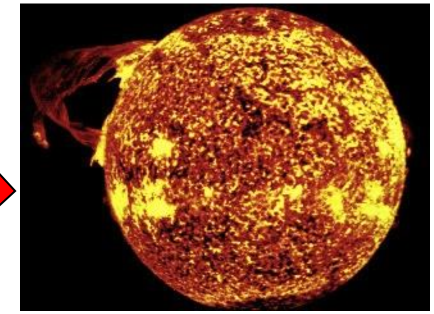


$T_{1/2} > 6.\ 10^{24}$ yr $<m_\nu> < 0.1 – 0.7$ eV

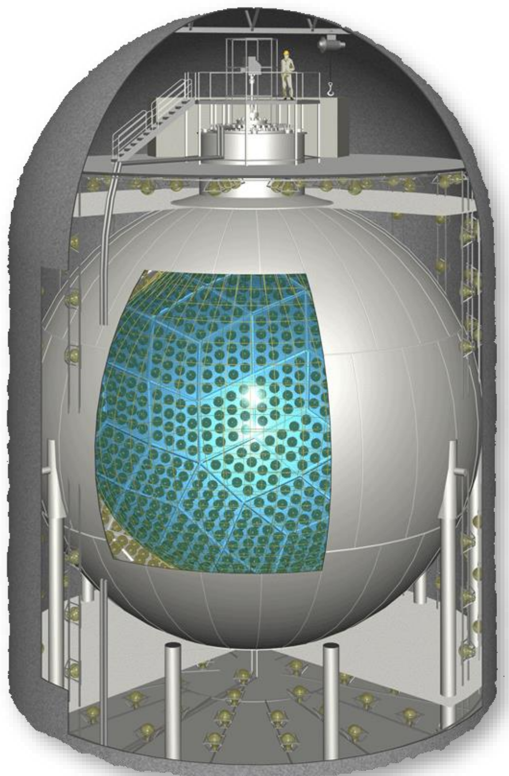
Large liquid scintillator experiment:KamLAND-ZEN



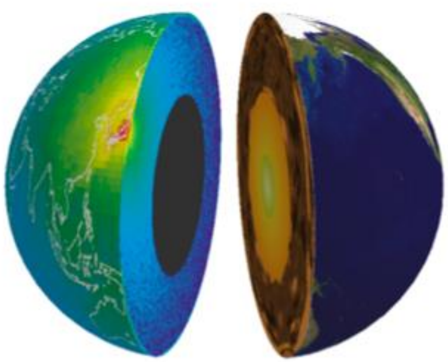
Reactors



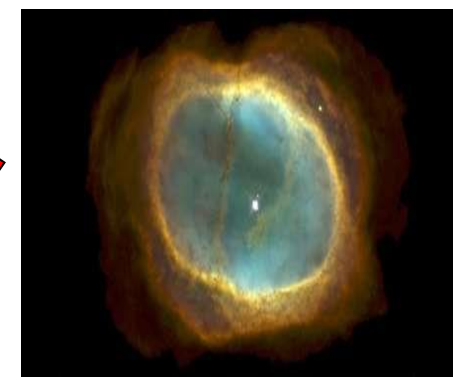
Solar neutrinos



KamLAND detector

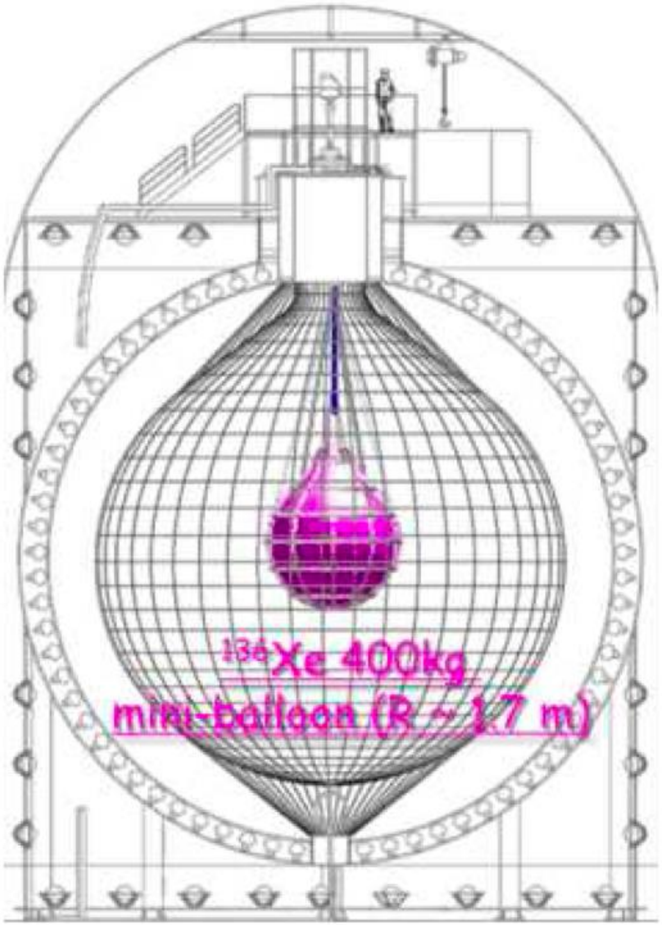


Geoneutrinos



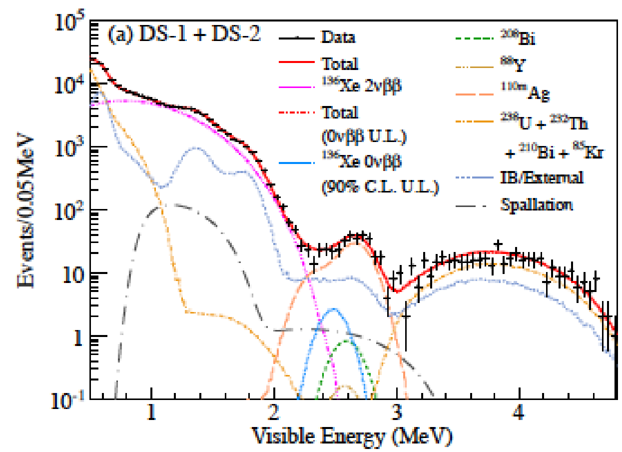
Supernovae neutrinos

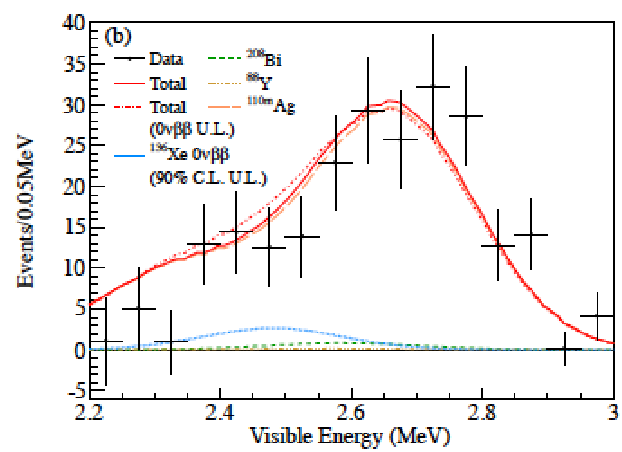
Large liquid scintillator experiment:KamLAND-ZEN



Dissolution of 136Xe inside a ballon of liquid scintillator

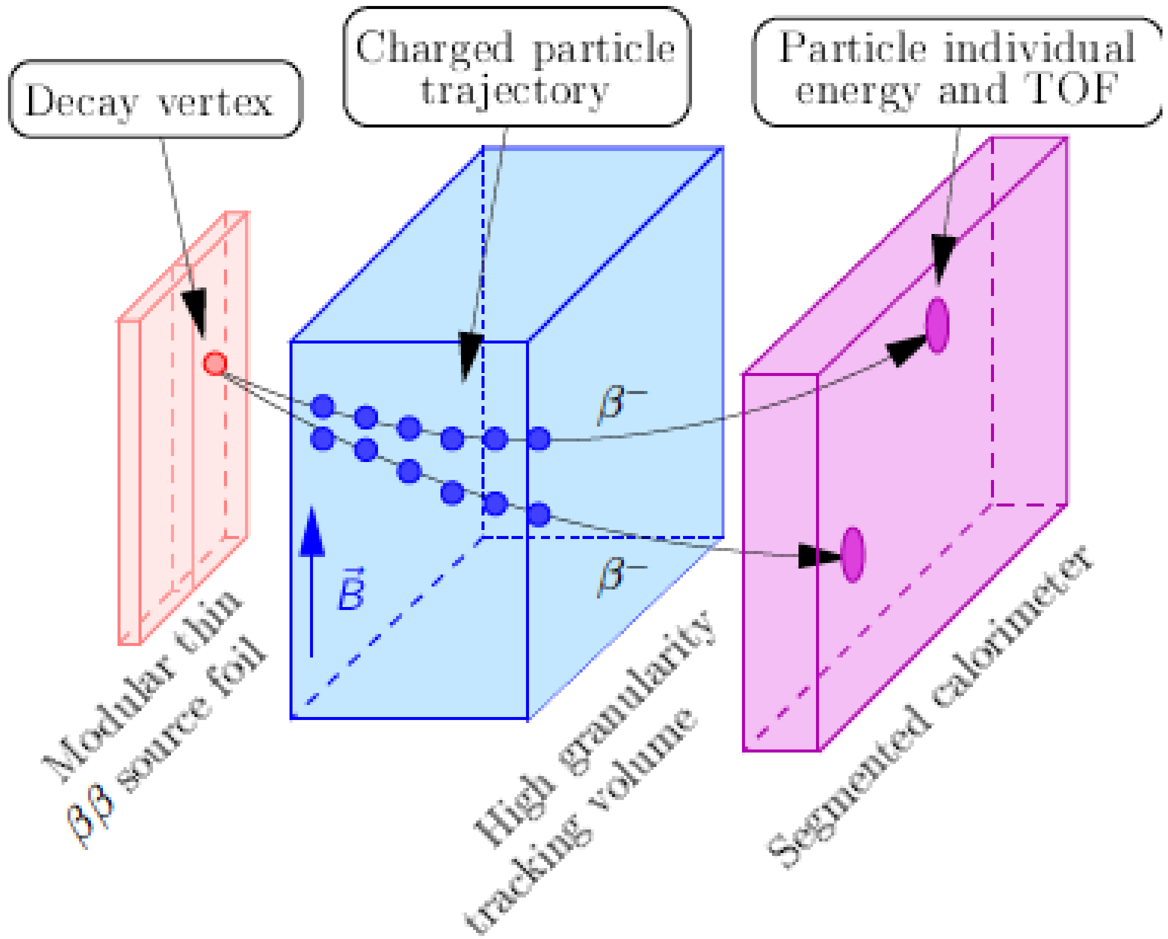
Possibility to dissolve very large mass





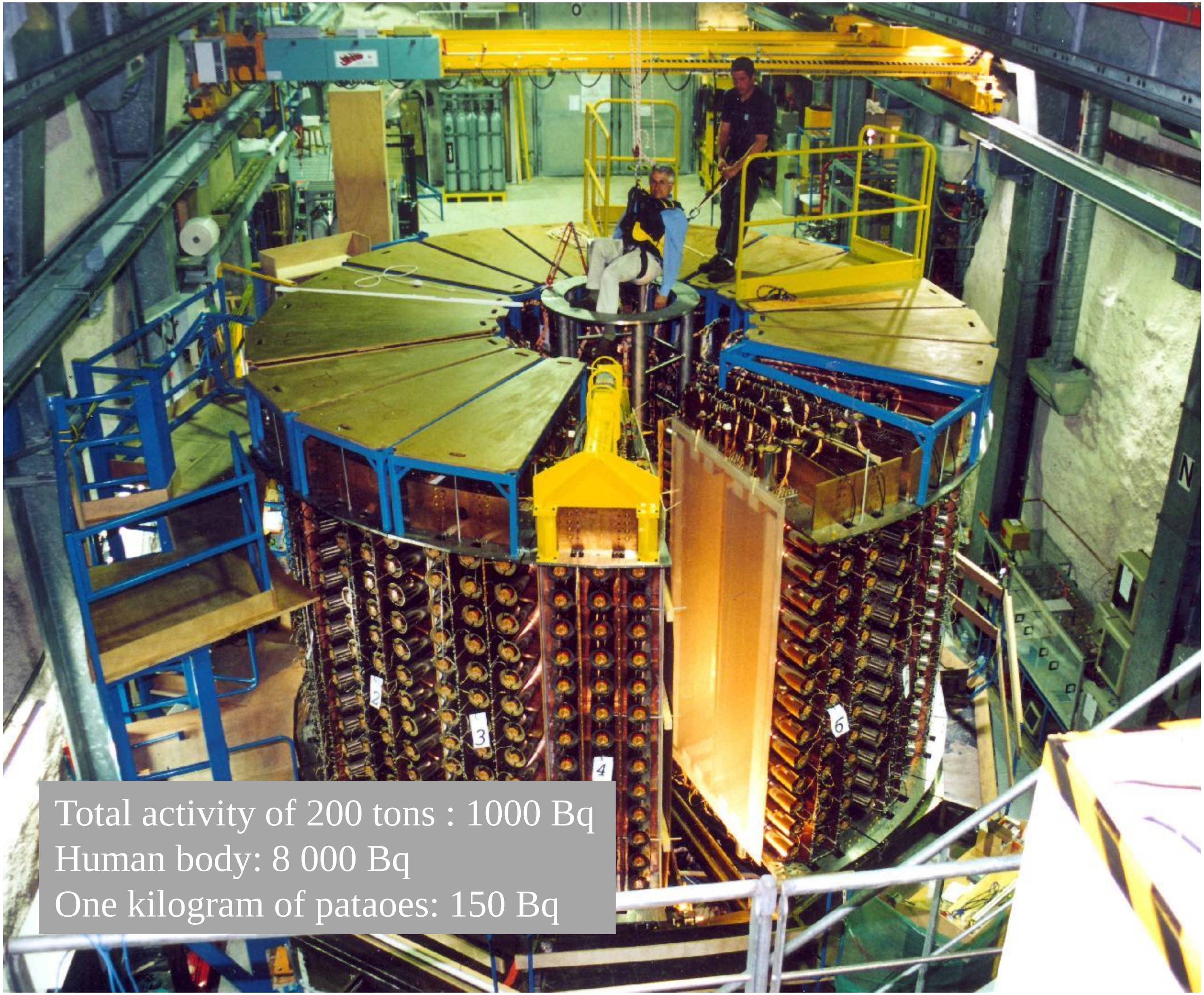
$T_{1/2} > 2.0\ 10^{25}$ yr **$<m_\nu> < 0.2 – 0.3$ eV**

Principle of experiments with electron detection



Multi-isotope detector
High rejection of background

The NEMO3 detector



Total activity of 200 tons : 1000 Bq
Human body: 8 000 Bq
One kilogram of pataoes: 150 Bq

The NEMO3 detector

Cathodic rings
Wire chamber

PMTs

Calibration tube

scintillators

ββ isotope foils

The NEMO3 detector

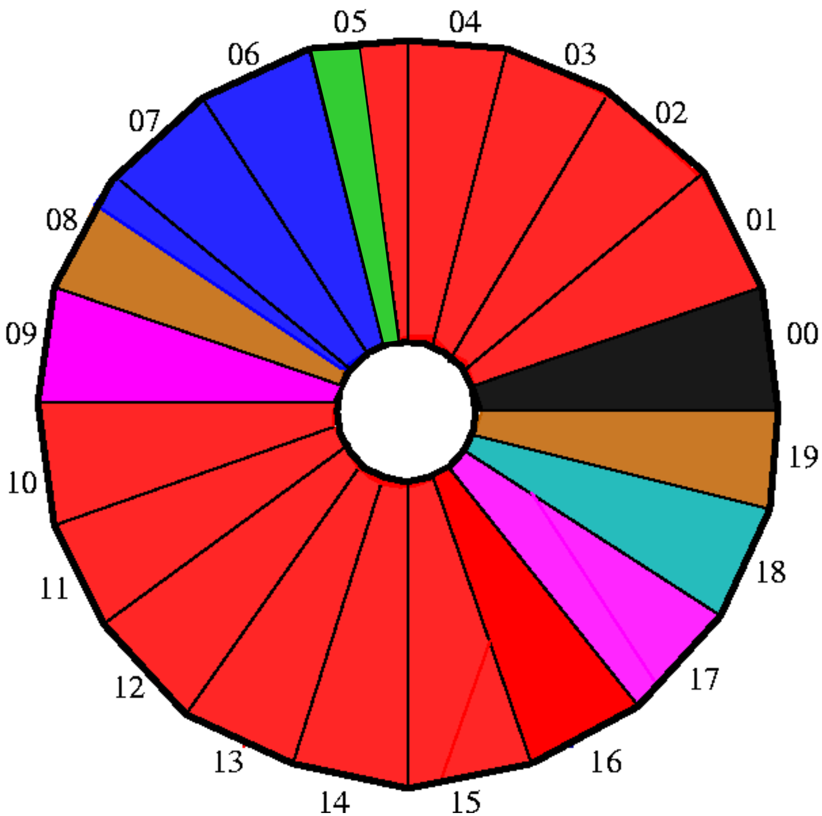
Water tank

wood

coil

Iron shield

NEMO3 isotopes



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

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

ββ0ν search

ββ2ν measurement

^{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

^{nat}Te 491 g

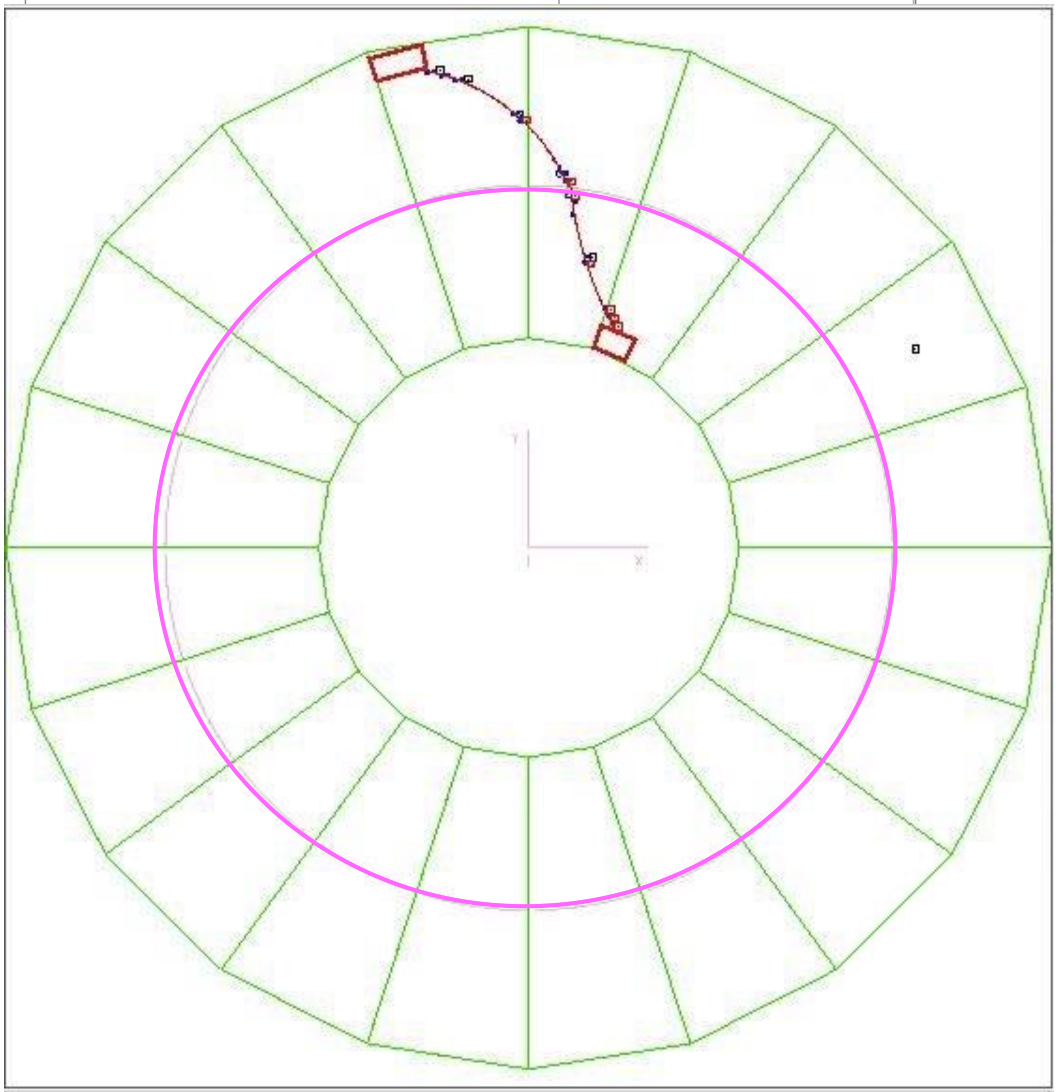
Cu 621 g

External bkg measurement

(All enriched isotopes produced in Russia)

ββ events selection in NEMO-3

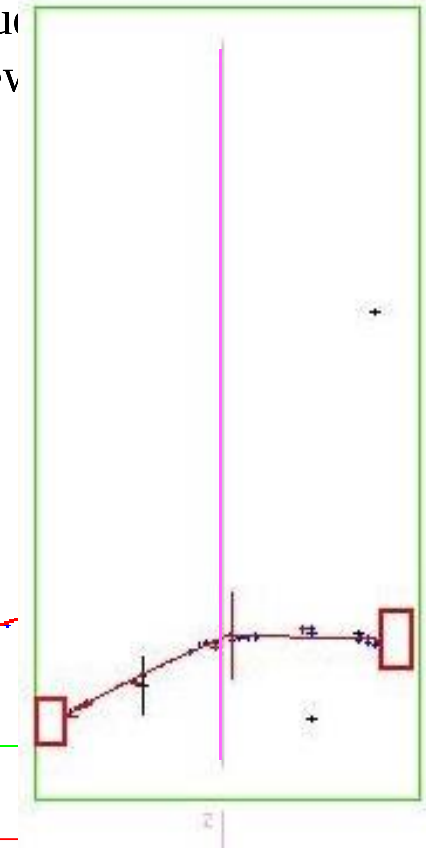
Typical ββ2ν event observed from ^{100}Mo



Top view

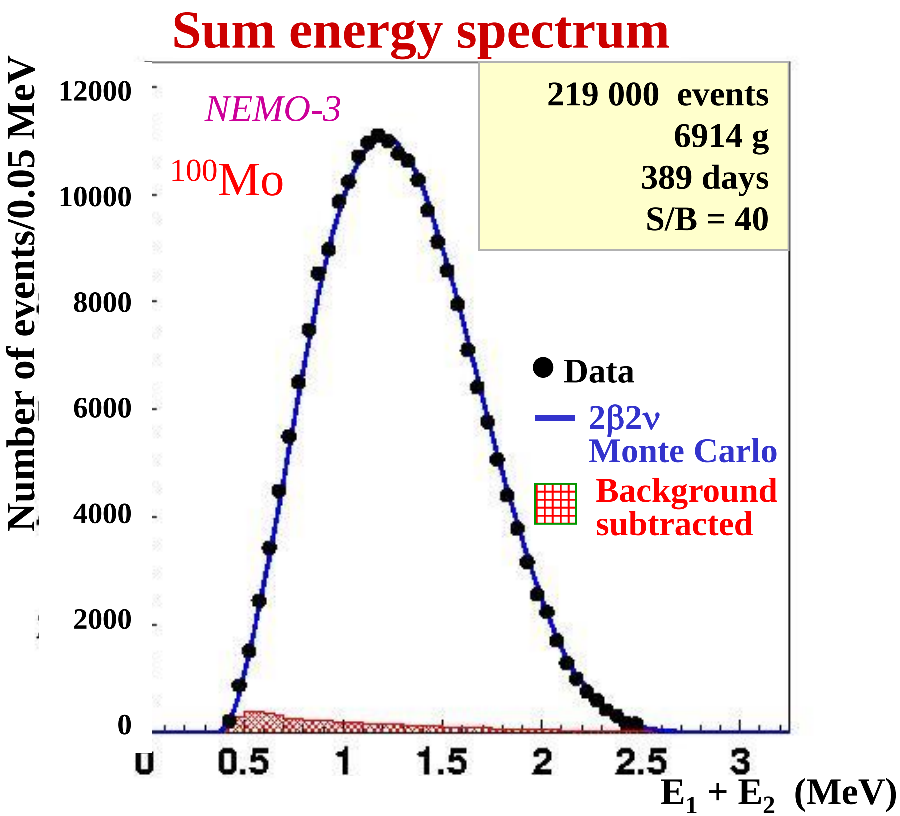
Longitu
viev

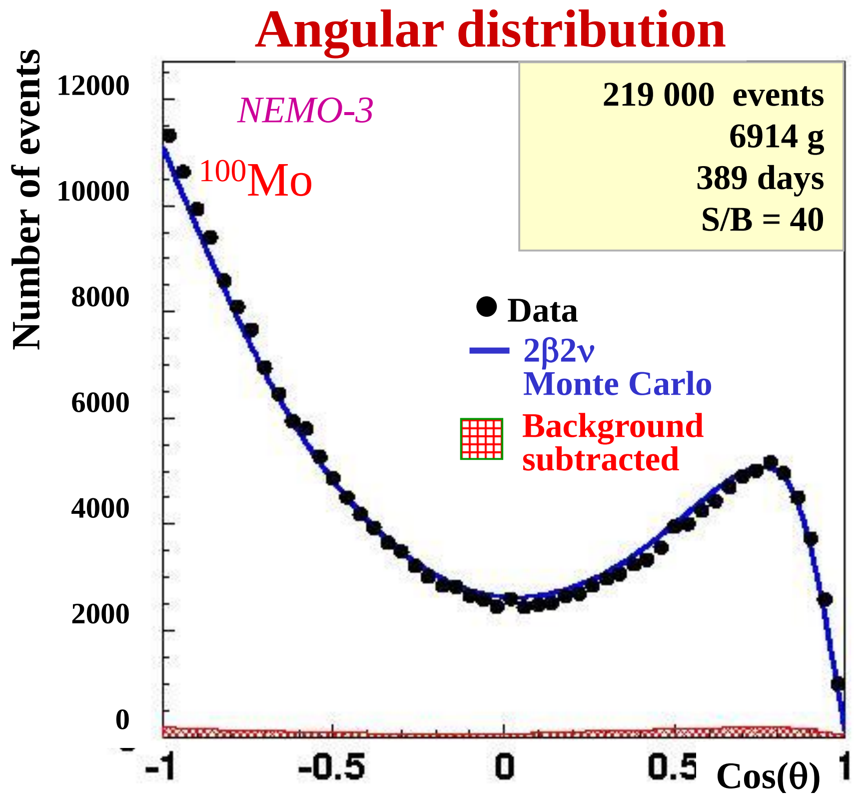
ır layers + 1)



Side view

NEMO3 results





$T_{1/2}(\beta\beta2\nu) = 7.11 \pm 0.02\ (stat) \pm 0.54\ (syst) \times 10^{18}$ years

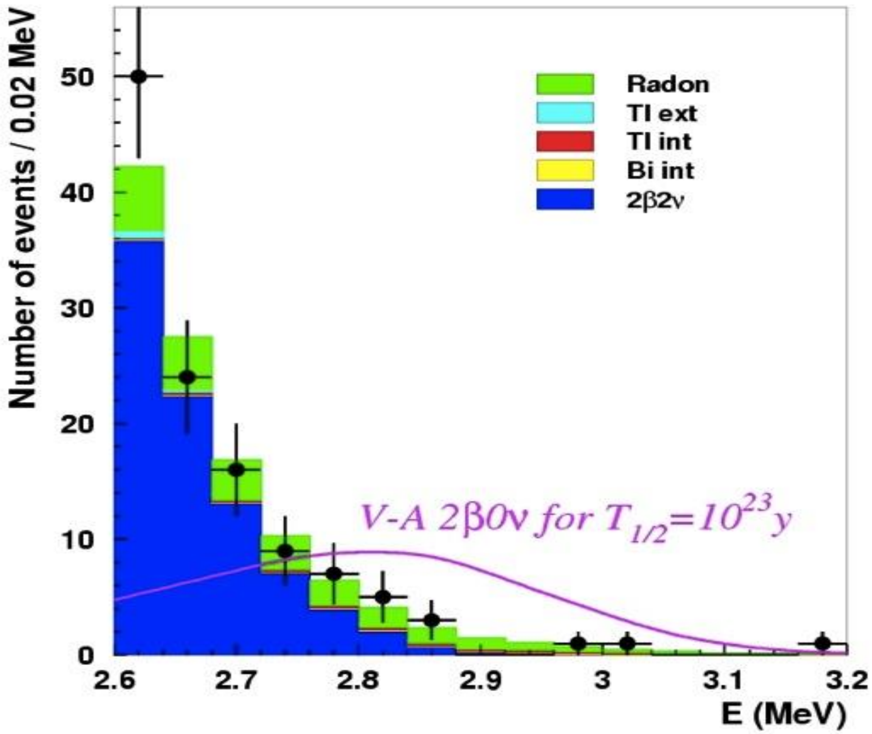
Phys. Rev. Lett. 95 182302 (2005)

«ββ factory» → tool for precision test

NEMO3 results

^{100}Mo

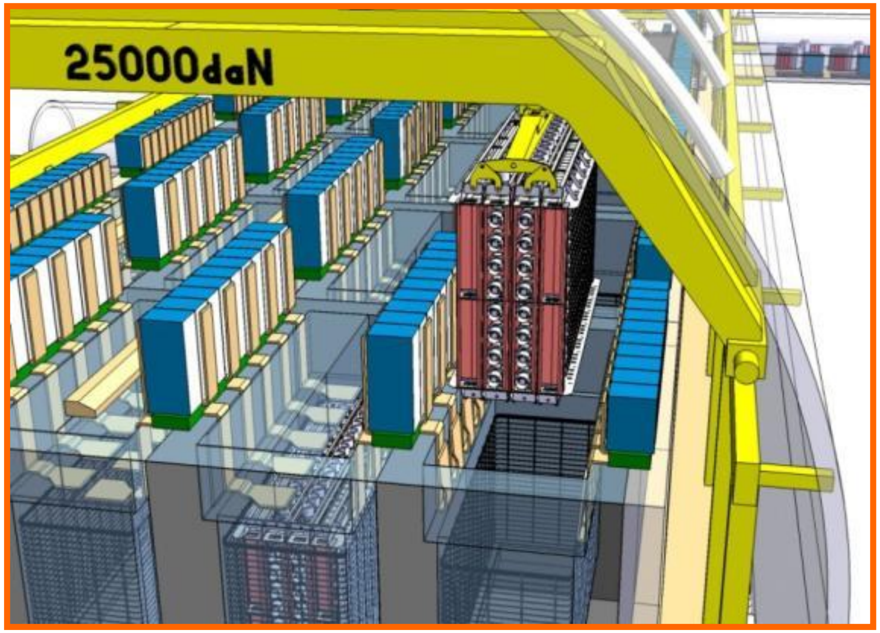
Phase I + II
693 days



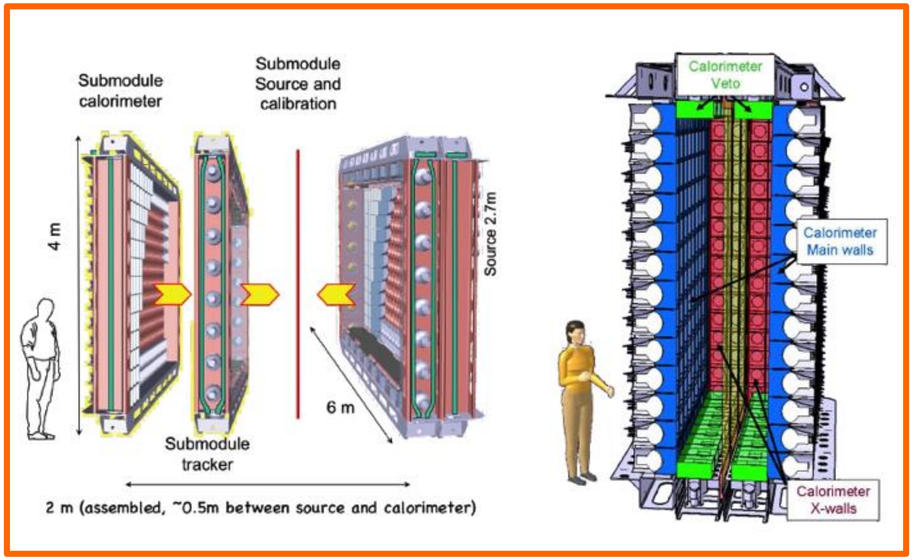
$T_{1/2} > 1.0\ 10^{24}$ yr $\quad$ $<m_\nu> < 0.3 – 0.7$ eV

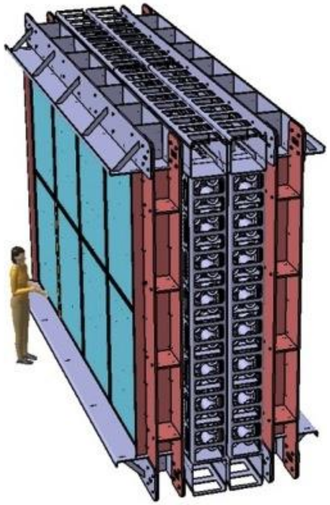
SuperNEMO project

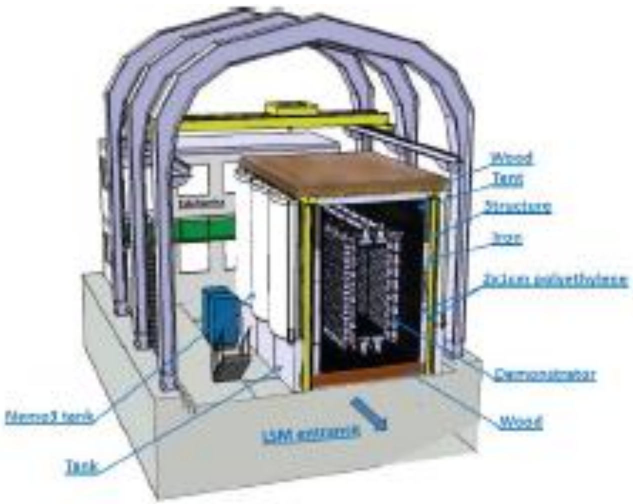
20 modules



A module







Latest results

Experiment	isotope	Mass (kg)	Half-life limit in years	Neutrino mass limit in eV
H.M.	^{76}Ge	14	1.9 10^{25}	0.21 -0.53
GERDA	^{76}Ge	14	1.9 10^{25}	0.20 -0.40
Cuoricino	^{130}Te	12	2.8 10^{24}	0.27 – 0.57
NEMO3	^{100}Mo	7	1.0 10^{24}	0.31 – 0.79
EXO-200	^{136}Xe	200	1.6 10^{25}	0.14 – 0.38
Kamland-Zen	^{136}Xe	400	6.2 10^{24}	0.26 – 0.54

Present experiments or projects

- ^{116}Cd → COBRA, $CdWO_4$
- ^{76}Ge → GERDA, MAJORANA
- ^{82}Se → SuperNEMO, LUCIFER
- ^{136}Xe → KamLAND-Zen, EXO, NEXT
- ^{100}Mo → $ZnMoO_4$, AMoRE
- ^{130}Te → CUORE

- $^{Nat(48)}Ca$ → CANDLES
- $^{Nat(150)}Nd$ → SNO+, Borexino

A dream ?

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

Summary

- The search of neutrinoless double beta decay is one of most important question in particle physics:
  Neutrino nature
  Neutrino mass

- The experimental search is a real challenge to reduce background

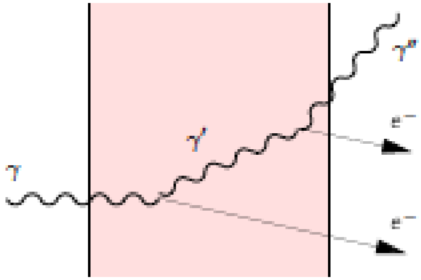
- Present sensitivity on neutrino mass < 0.2 – 0.4 eV with 10 kg (or 400 kg of ^{136}Xe)

- Next generation 100 kg should allow to reach $\langle m_\nu \rangle < 0.05$ eV

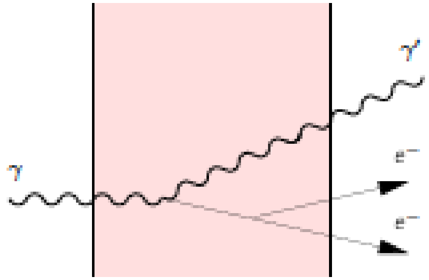
- New ideas required for higher mass (1 ton)

Background from natural radioactivity

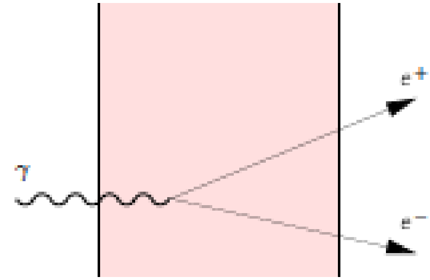
External (γ flux):



double Compton

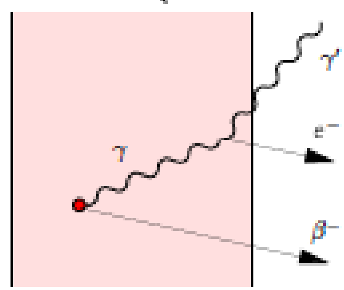


Compton+ Möller

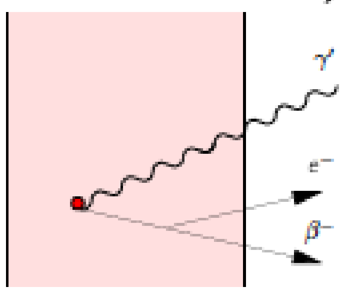


pair production

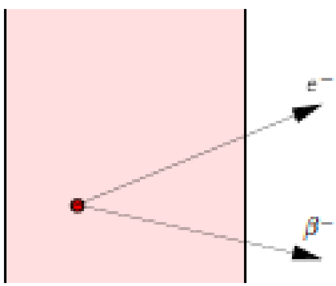
Internal (source foil contaminants):



β^-+ Compton



β^-+ Möller



β^-+ IC

Piège à neutrino

30 000 000 000 000 000 km de plomb

Quelles interactions peut avoir le neutrino ?

$$\bar{\nu} + p \rightarrow e^{+} + n$$

$$\nu + e^{-} \rightarrow \nu + e^{-}$$

Pour détecter des neutrinos: beaucoup de neutrinos et beaucoup de matière (noyau) !

Neutrinoless double beta decay

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

High $Q_{\beta\beta}$ and high Z

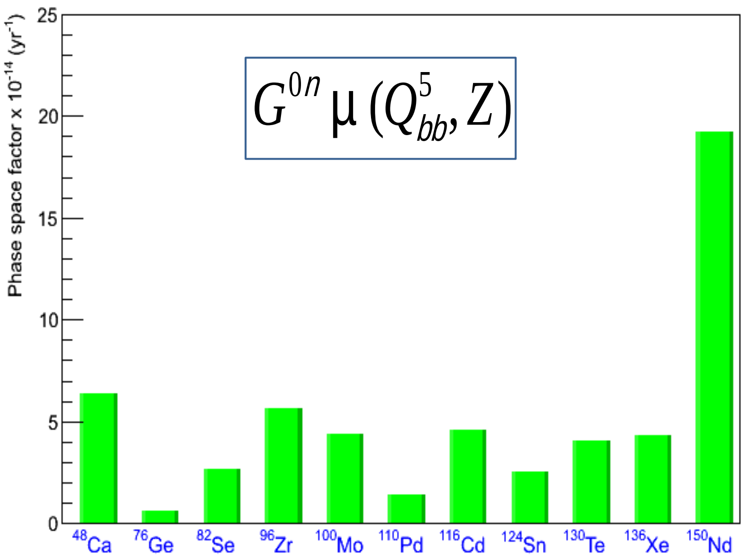
Possibility of enrichment
Expected half-life 10^{25} y

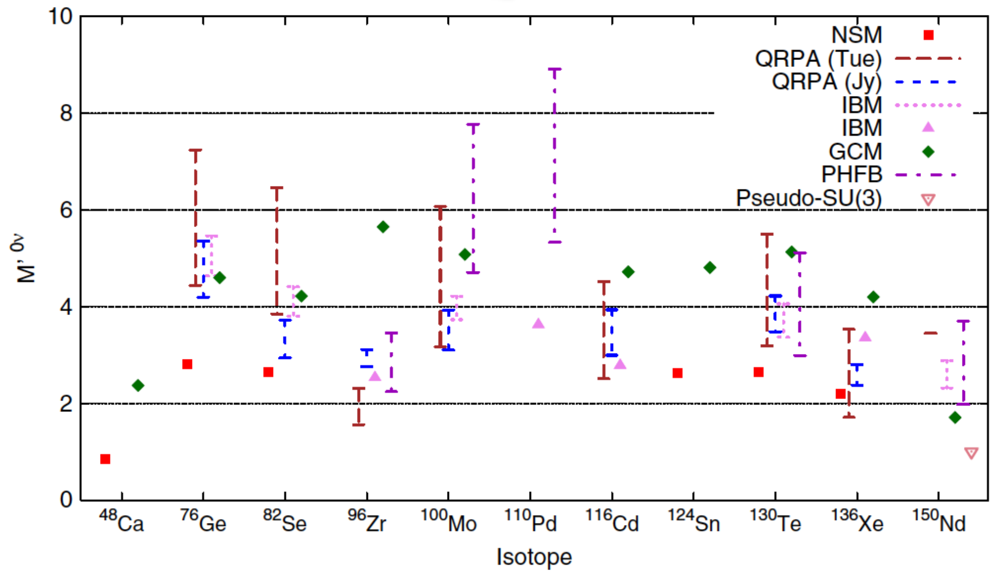
High isotopic abundance

	$Q_{\beta\beta}$ (MeV)	Isotopic Abundance
$^{48}Ca \rightarrow {}^{48}Ti$	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

Isotope choice

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



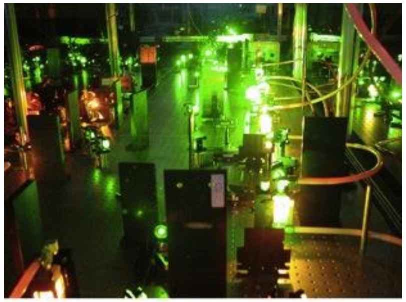


Dueck et al. Phys,. Rev. D **83** 113010(2011)

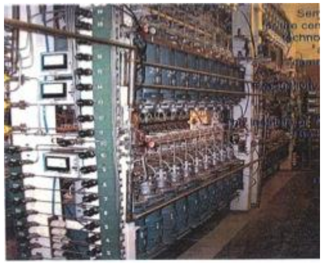
Isotopic enrichment

Nucleus	Existing method	R&D
^{48}Ca		Laser separation, gazeous diffusion
^{76}Ge	Centrifugation	
^{82}Se	Centrifugation	
^{96}Zr		Laser separation
^{100}Mo	Centrifugation	
^{116}Cd	Centrifugation	
^{130}Te	Centrifugation	
^{136}Xe	Centrifugation	
^{150}Nd		Centrifugation, Laser

R&D in KAERI (Korea) for ^{48}Ca enrichment by laser



R&D in Russia for ^{150}Nd enrichment by centrifugation



R&D in France for ^{150}Nd enrichment by laser