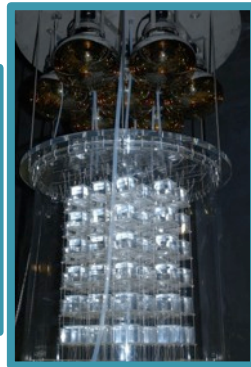
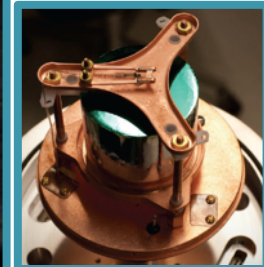
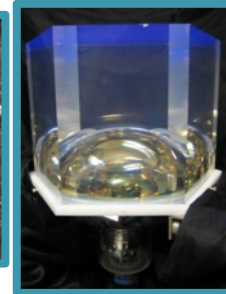
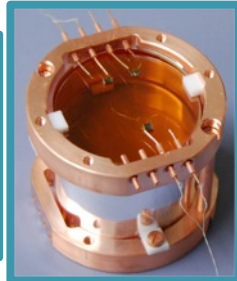
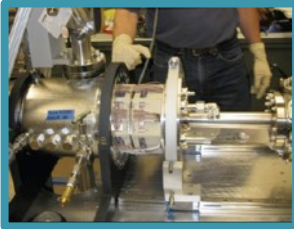
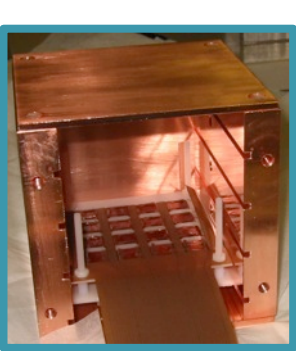


An introduction to the double beta decay or What can we learn about neutrinos by studying the radioactivity

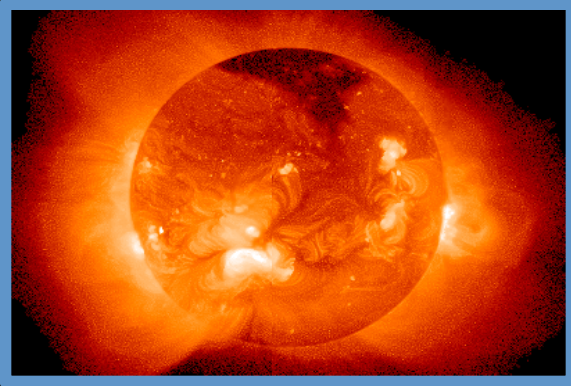


F. Piquemal

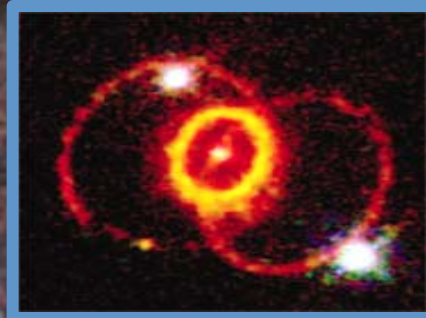
**CENBG (CNRS/IN2P3 and Bordeaux University)
and
LSM (CNRS/IN2P3 and Grenoble-Alpes University)**

Graspa Particle physics school , Annecy July,20 2018

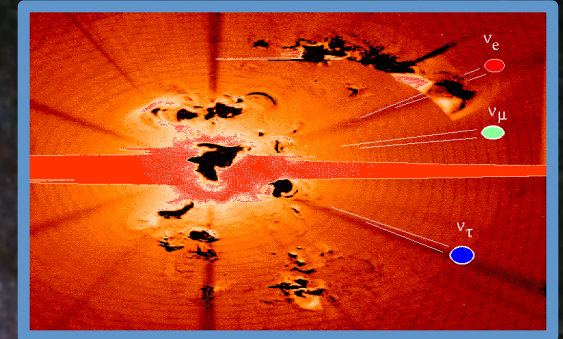
The neutrinos are everywhere



The Sun:
64 000 000 000 neutrinos /cm² . seconde



Super Nova in Milky Way :
5 000 000 000 neutrinos /cm² .
seconde in 10 s



Big-Bang : 300 « relic » neutrinos
per cm³ of Universe



Nuclearpower plant
100 000 neutrinos /cm² .
seconde at 200 km

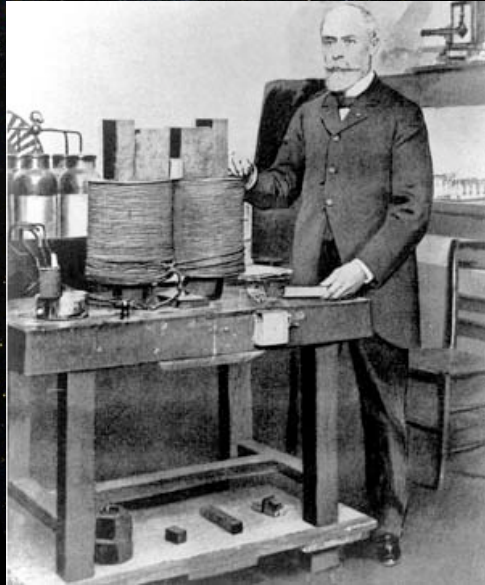


Human body 8 000 per seconde !!



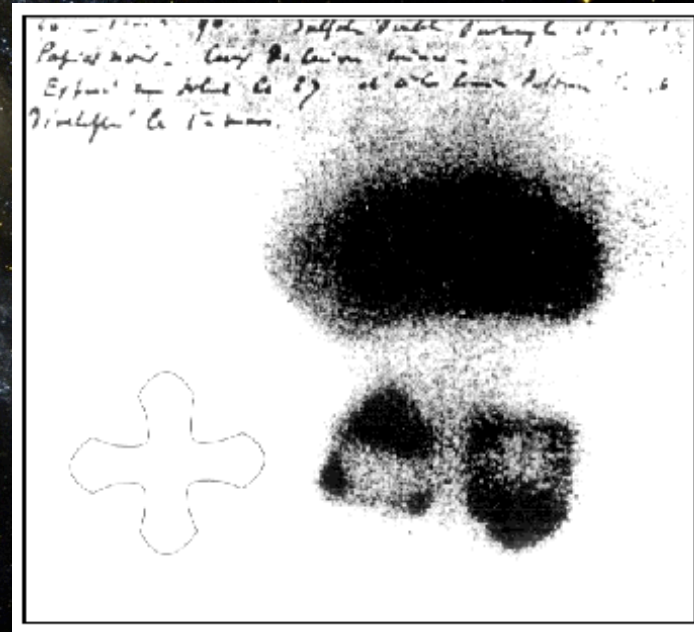
Earth and atmosphere:
6 000 000 neutrinos /cm² . seconde

The beginning of the history



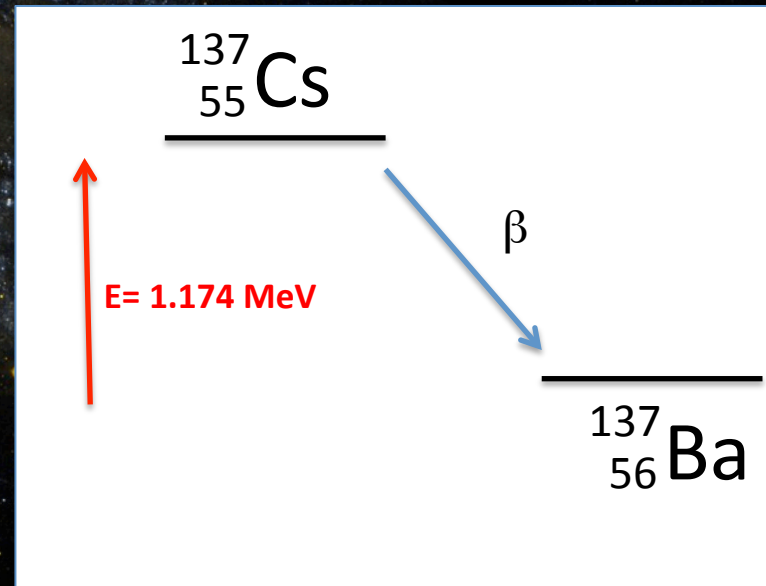
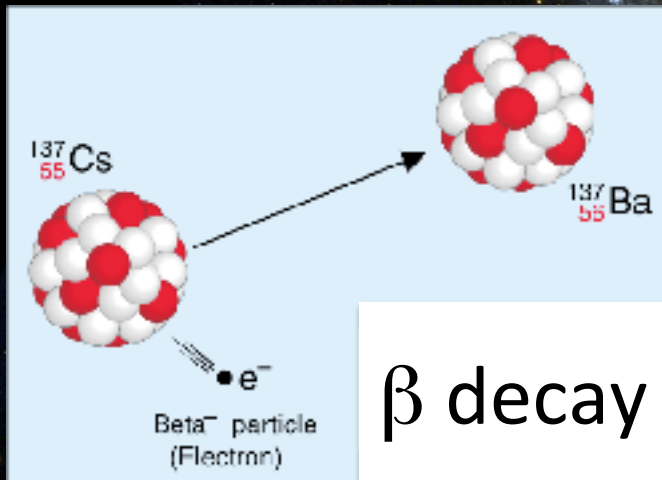
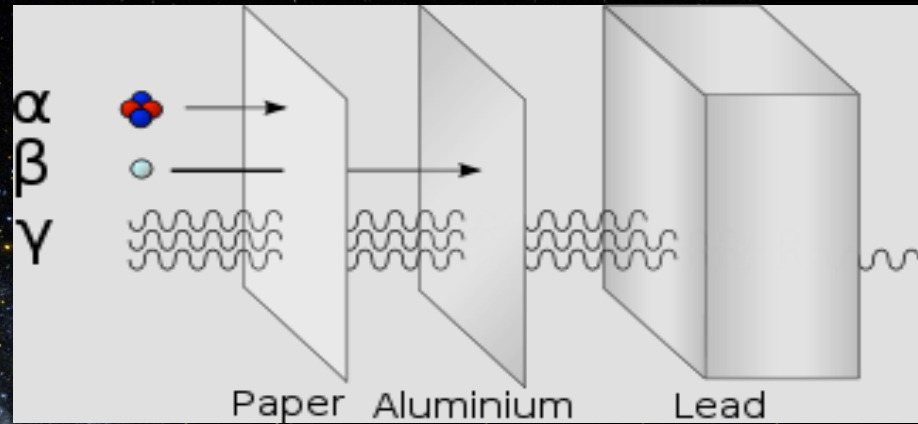
1896 - 1898:

Becquerel, Pierre and Marie Curie discovered the radioactivity



The beginning of the history

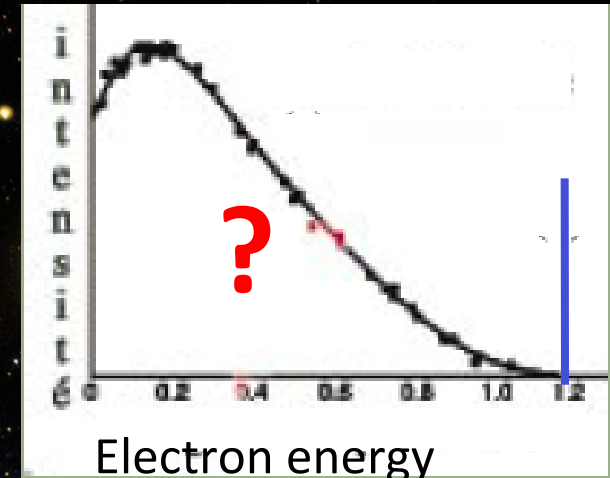
Rutherford, Chadwick,
P. et M. Curie and Villard
identified 3 kinds of radiations



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 conservation. 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.

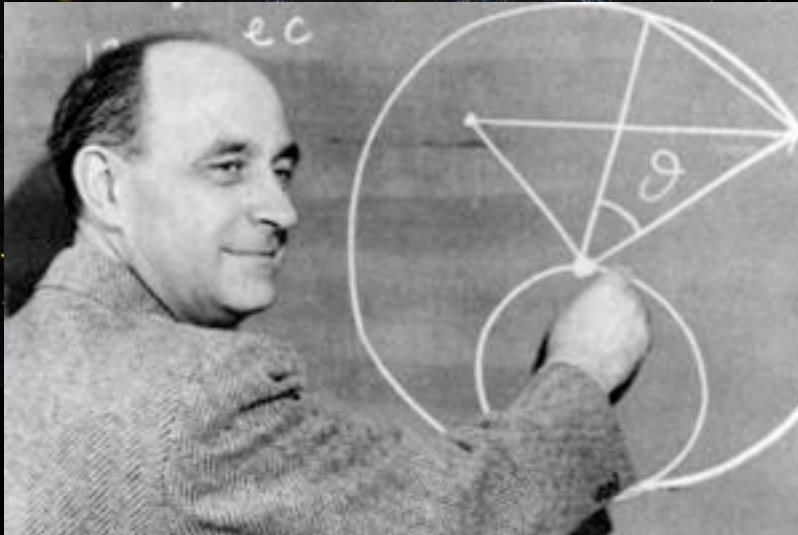
I admit that my expedient may seem rather improbable from the first, because if neutrons existed they would have been discovered long since. Nevertheless, nothing ventured nothing gained, and the seriousness of the situation with the continuous β -spectrum is illustrated by a statement by my esteemed 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,

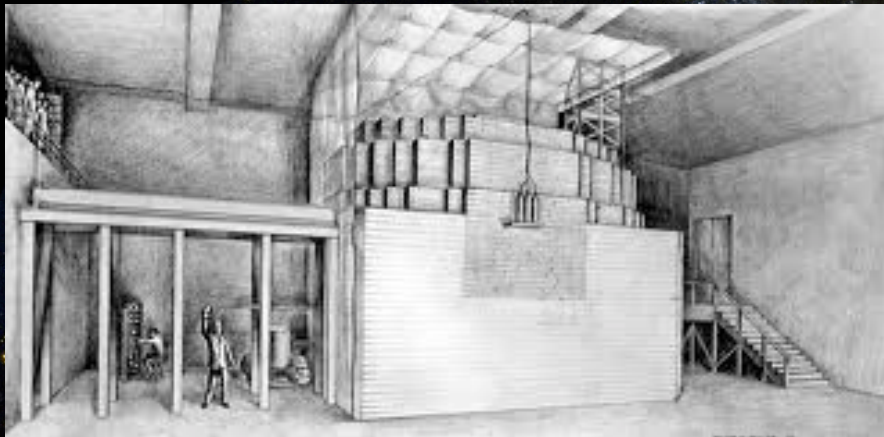
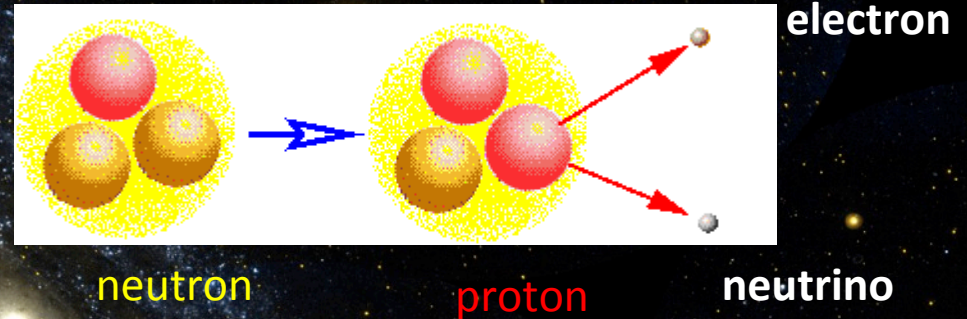
(signed) W. Pauli

[†] 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

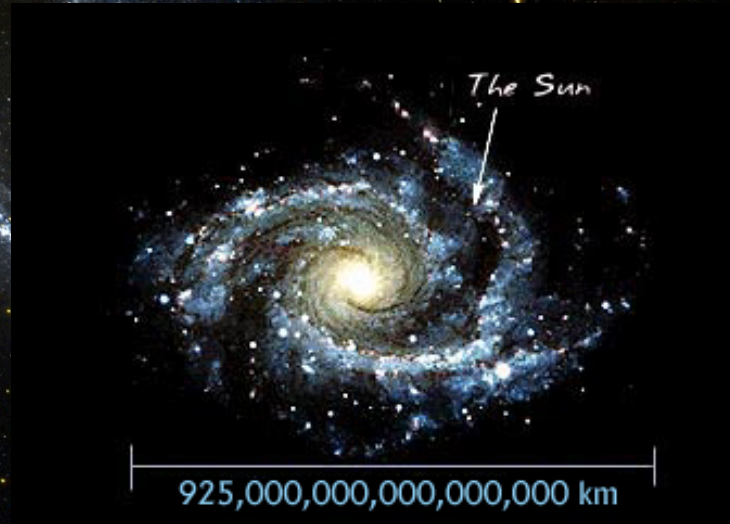


1942 : Fermi created the first nuclear reactor under the stadium of the Chicago University

The discovery of the neutrino

Neutrino Trap

30 000 000 000 000 000 000 km of lead



Possible neutrino interactions

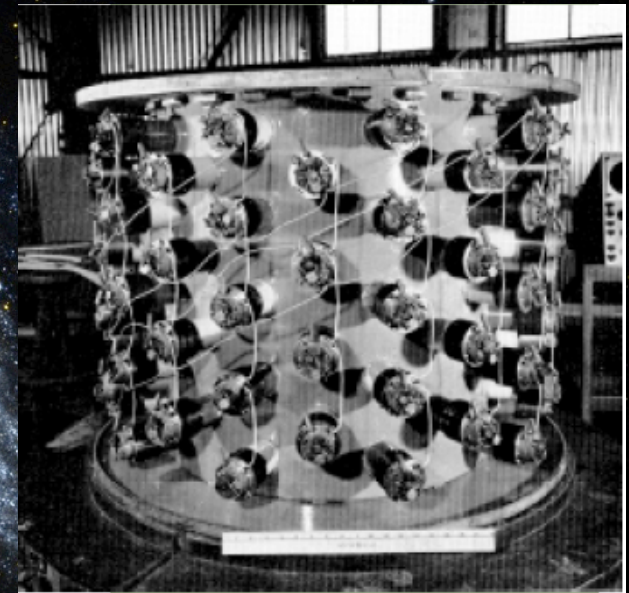
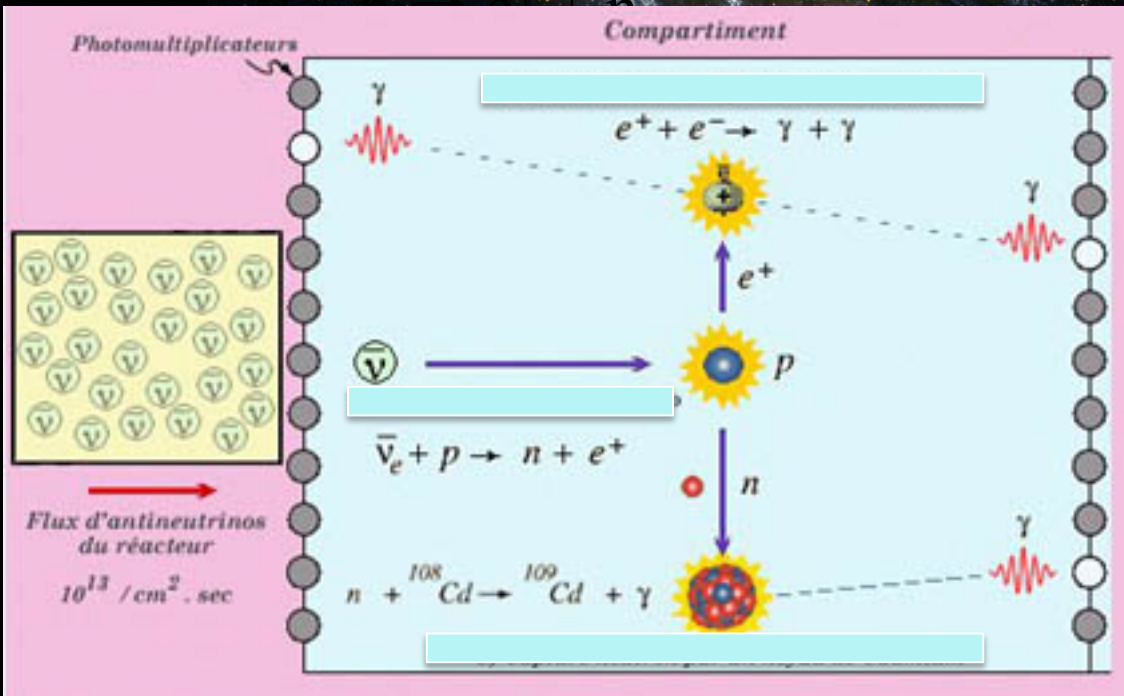
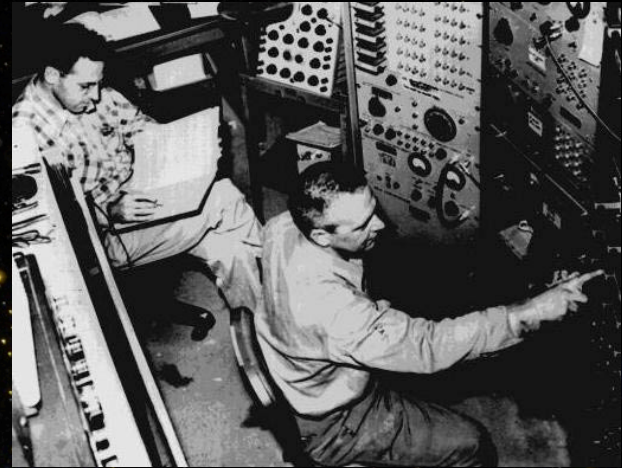


and a lot of

The discovery of the neutrino



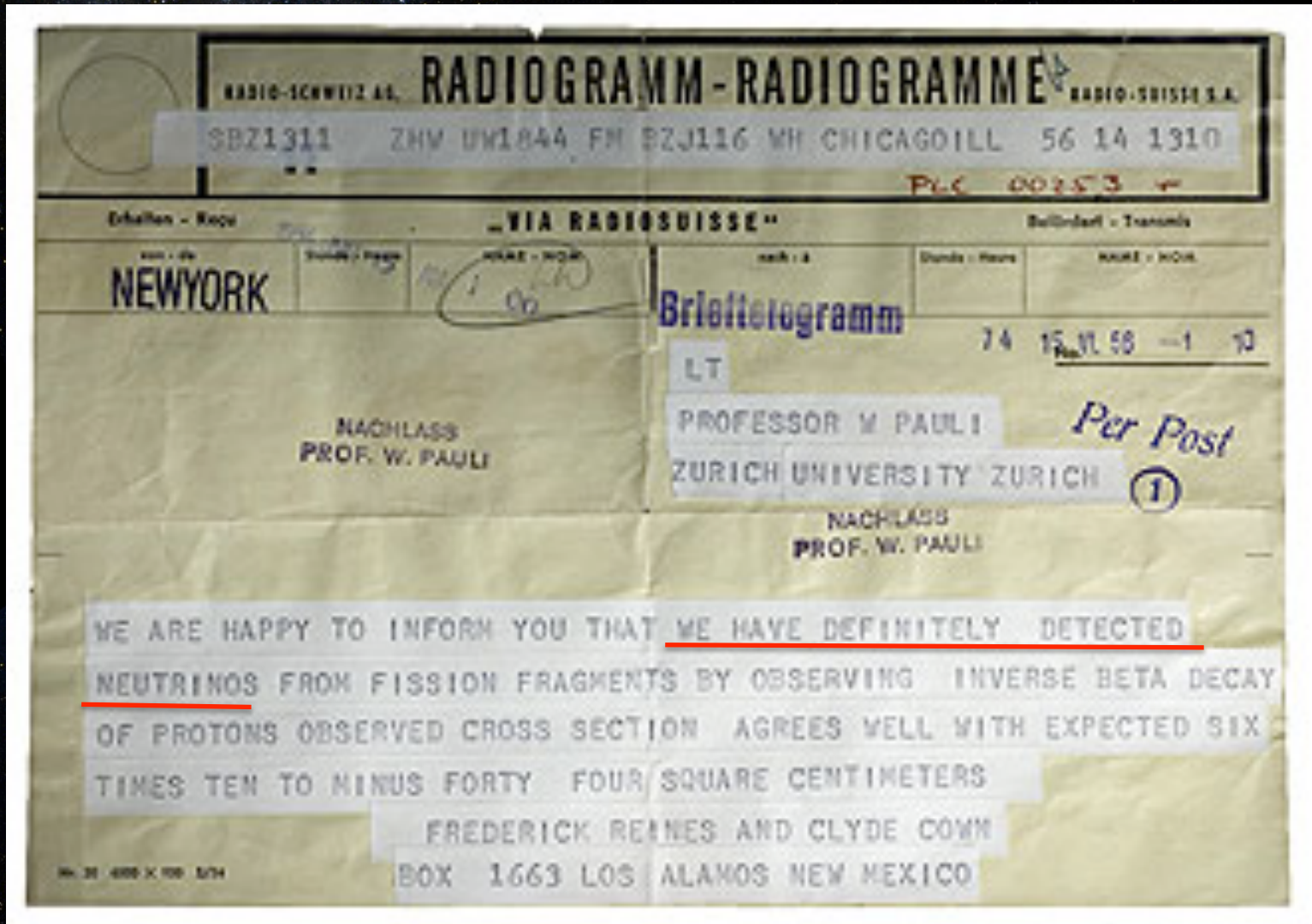
Savannah River reactor (USA)



Poltergeist detector

The discovery of the neutrino

1956: Neutrino discovery by Reines and Cowan



Elementary particles

Quarks



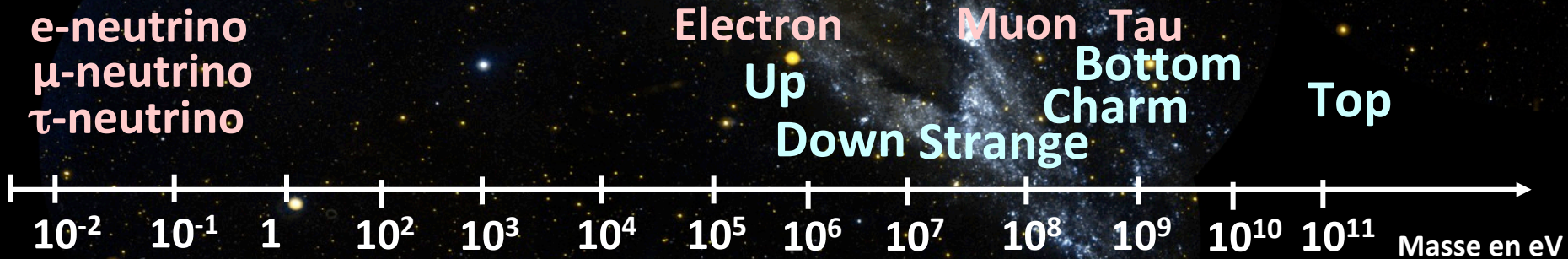
Leptons



matière

And also the anti-matter

Mass of particles



INTERACTION

MEDIATOR

RELATIVE STRENGTH

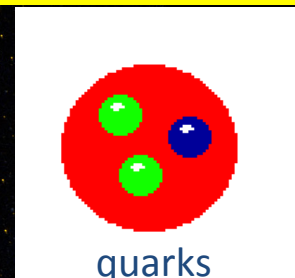
Range (m)

STRONG

GLUONS

~ 1

~ 10⁻¹⁵

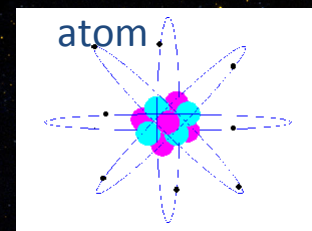


ELECTRO-MAGNETIC

PHOTON

~ 10⁻²

infinite

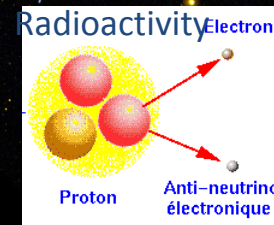


WEAK INTERACTION

W⁺, W⁻, Z⁰

~ 10⁻⁸

~ 10⁻¹⁸



GRAVITATION

GRAVITON ?

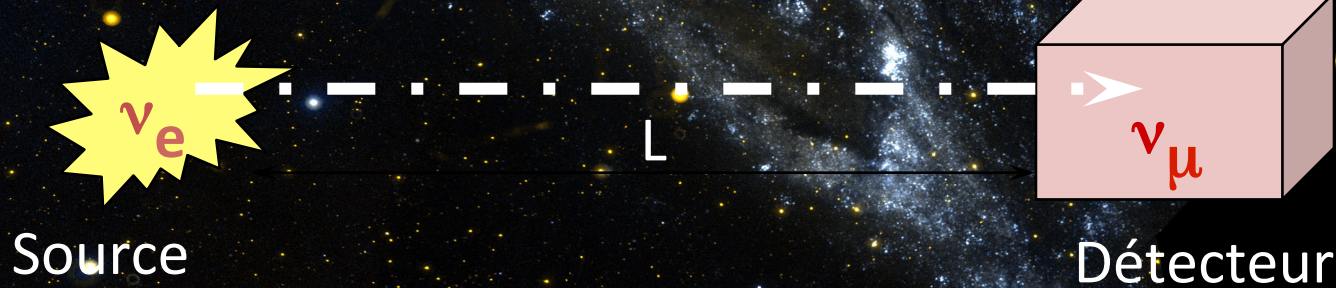
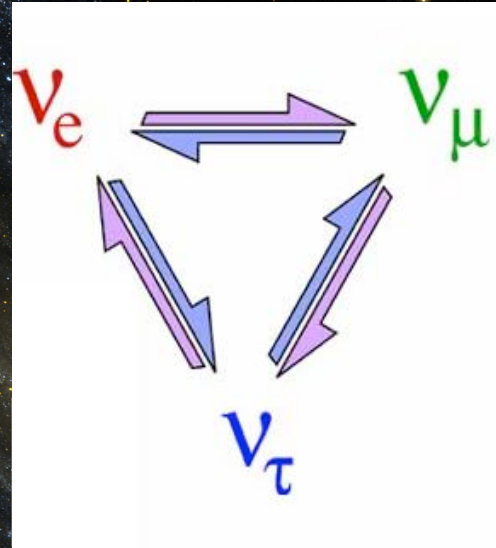
~ 10⁻³⁸

infinite

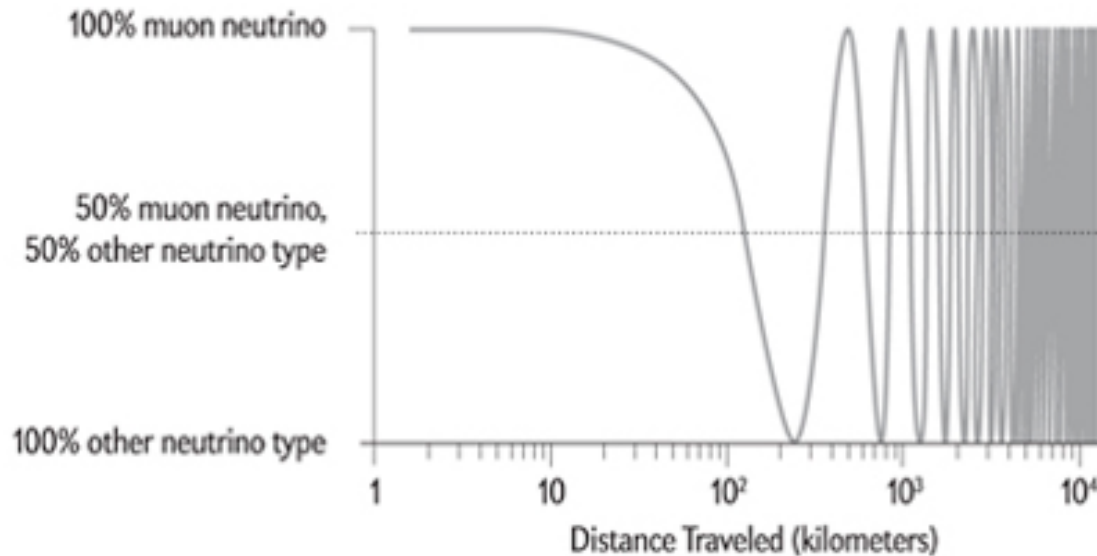




1957: Bruno Pontecorvo prédit l'oscillation des neutrinos



Neutrino Oscillations



Neutrinos de « base »: ν_1 ν_2 ν_3

$$\nu_e = \cos\theta\nu_1 + \sin\theta\nu_2$$

$$\nu_\mu = -\cos\theta\nu_1 + \sin\theta\nu_2$$

$$P_{\nu_e \rightarrow \nu_\mu} = \sin^2 2\theta \sin^2 \left[\frac{1,27 \cdot (m_1^2 - m_2^2) \cdot L}{E_\nu} \right]$$

Les oscillations n'existent que si le neutrino à une masse !

The Nobel Prize in Physics 2015



Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2



Photo: K. MacFarlane.
Queen's University
/SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Ettore Majorana

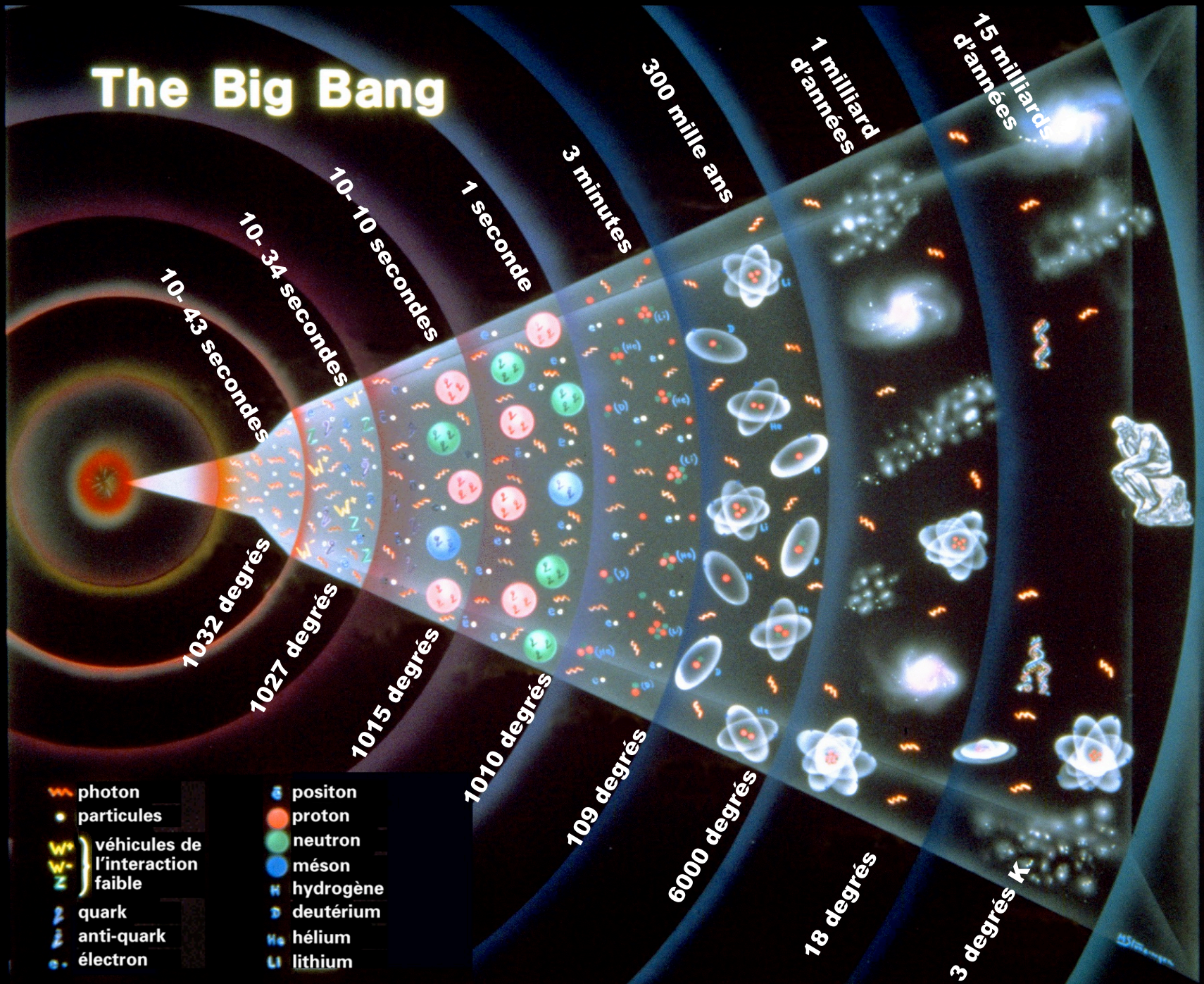















1937: Ettore Majorana proposed a theory for neutral particle which can be its own anti-particle
Neutrino = anti-neutrino ?

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 ?

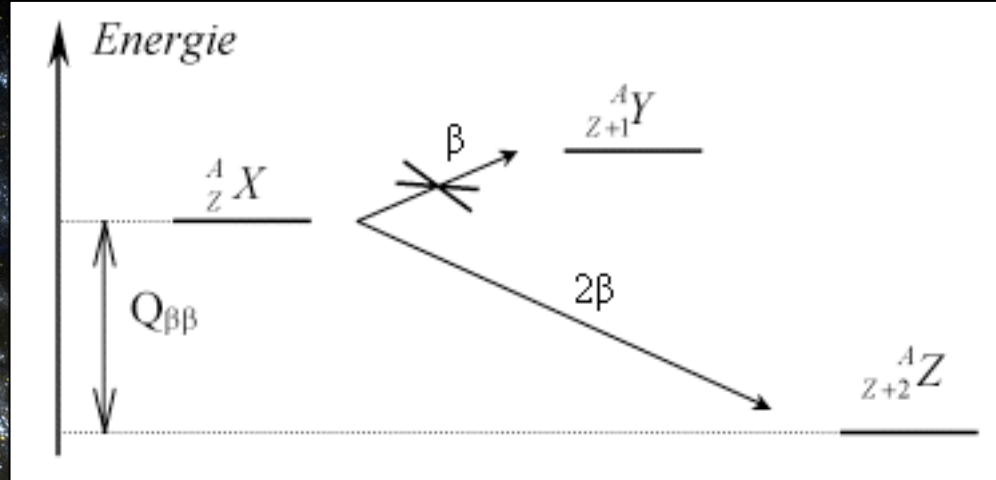
The Big Bang



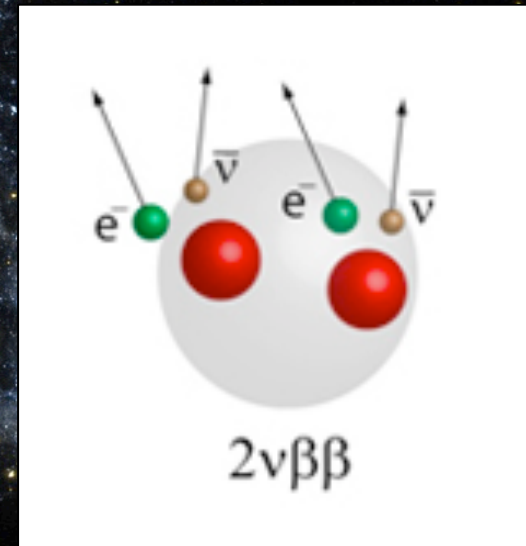
- | | |
|---|---|
|  photon |  positon |
|  particules |  proton |
|  véhicules de l'interaction faible |  neutron |
|  quark |  méson |
|  anti-quark |  hydrogène |
|  électron |  hélium |
| |  lithium |

© Simons

Double beta decay and neutrino



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



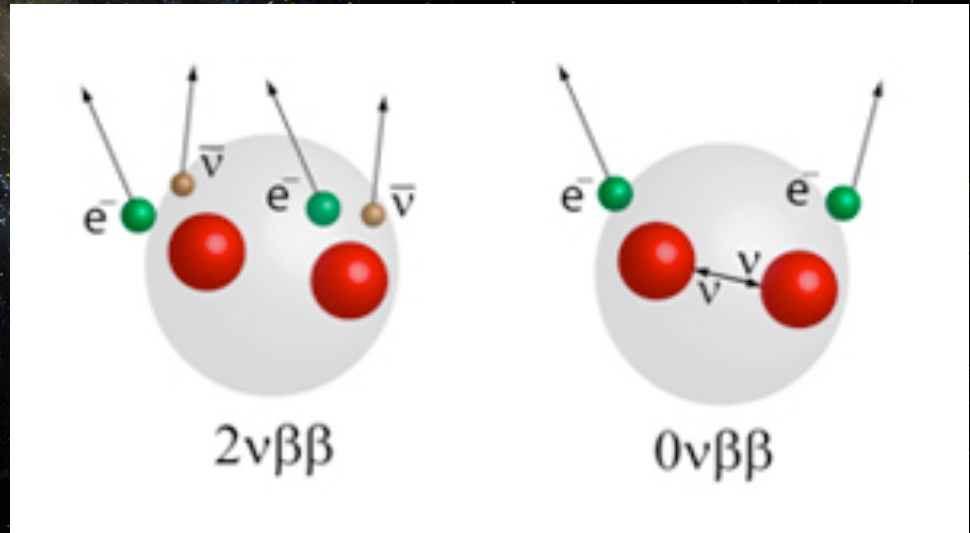
Double beta decay and neutrino



Scanned at the American
Institute of Physics

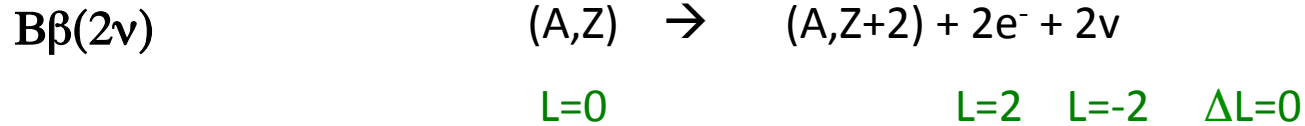
1939: Wendell Hinkle Furry demonstrates that if the neutrino is a Majorana particle (neutrino = anti-neutrino) then a new radioactivity can occur:

The neutrinoless double beta decay

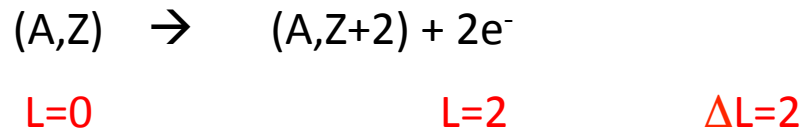


Neutrinoless double beta decay and neutrino properties

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



$\beta\beta(0\nu)$ forbidden by Standard Model

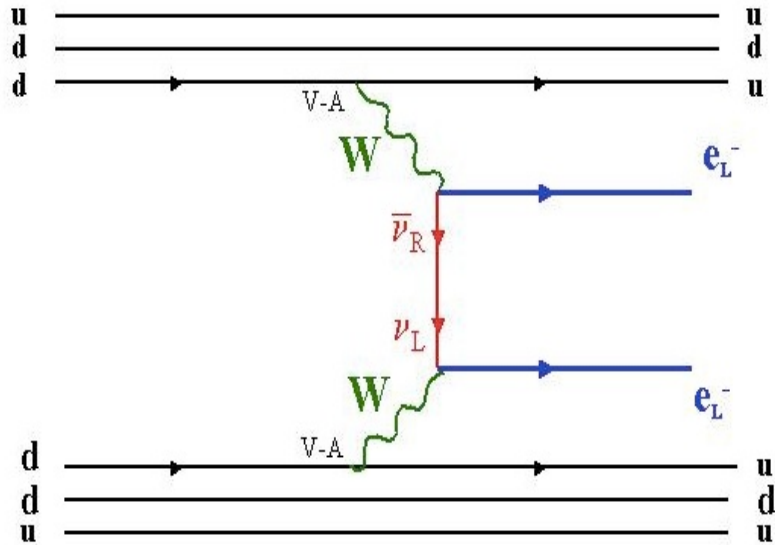


Test of a theory beyond the Standard Model of particle physics

Nature of the neutrino: a Dirac particle (neutrino \neq antineutrino) ?
or
a Majorana particle (neutrino = antineutrino) ?

Strong impact on particle physics and in cosmology

Neutrinoless double beta decay and neutrino properties



Phase space factor Nuclear matrix element

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

Effective mass:

$$\langle m_\nu \rangle = m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 \cdot e^{i\alpha_1} + m_3 |U_{e3}|^2 \cdot e^{i\alpha_2}$$

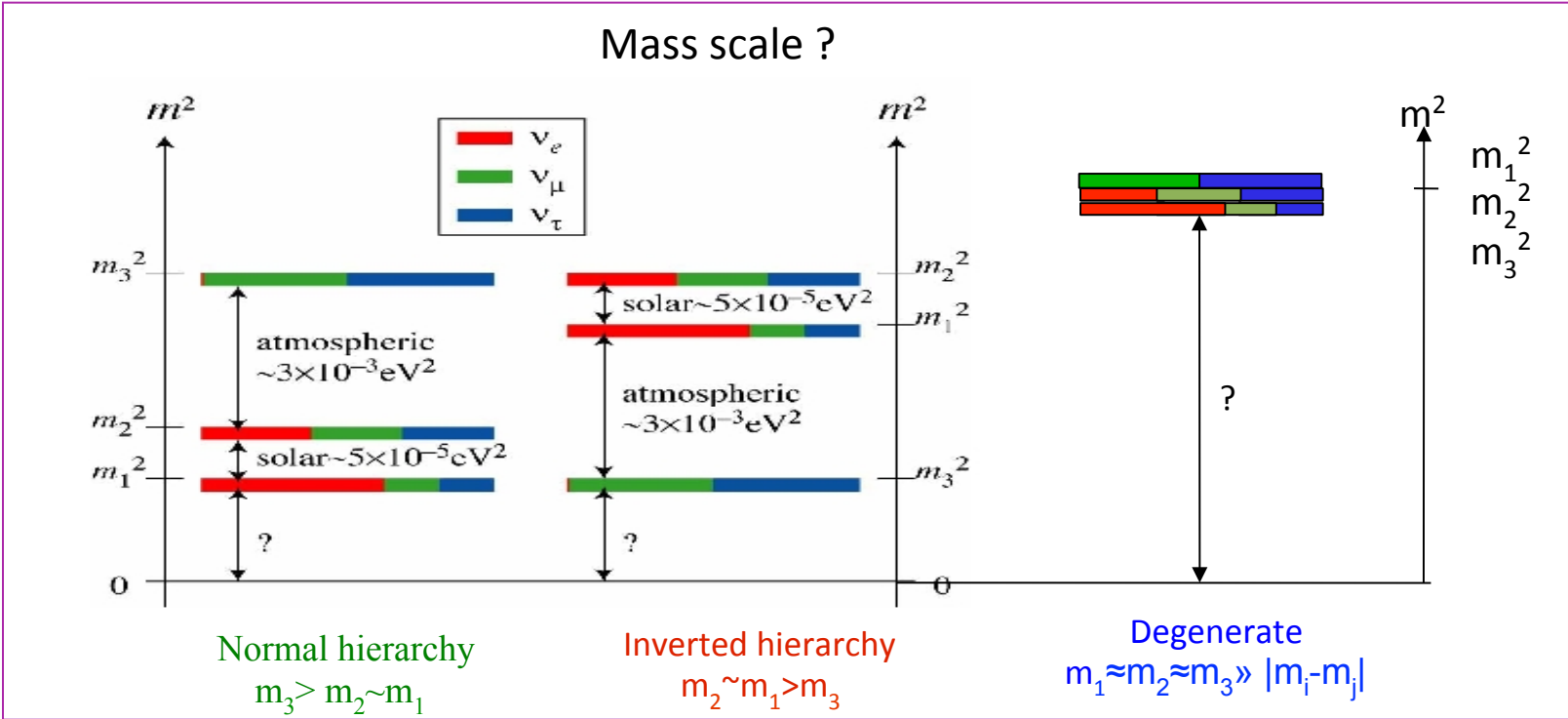
$|U_{ei}|$: mixing matrix element

α_1 et α_2 : Majorana phase

Neutrinoless double beta decay and neutrino properties

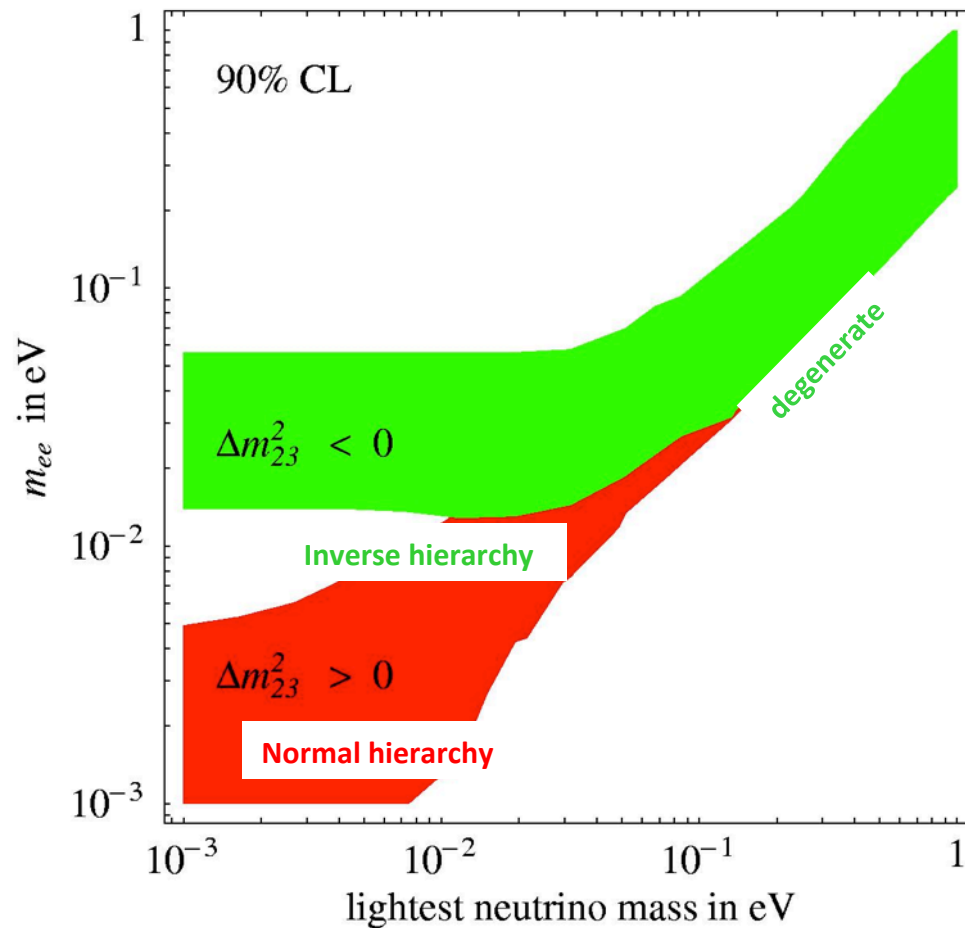
absolute mass ?

Tritium decay $m_{\nu_e} < 2.3 \text{ eV}$
Cosmology $\Sigma m_i < \sim 1 \text{ eV}$
 $\beta\beta(0\nu)$ $\langle m_{\nu} \rangle < 0.2-0.5 \text{ eV}$

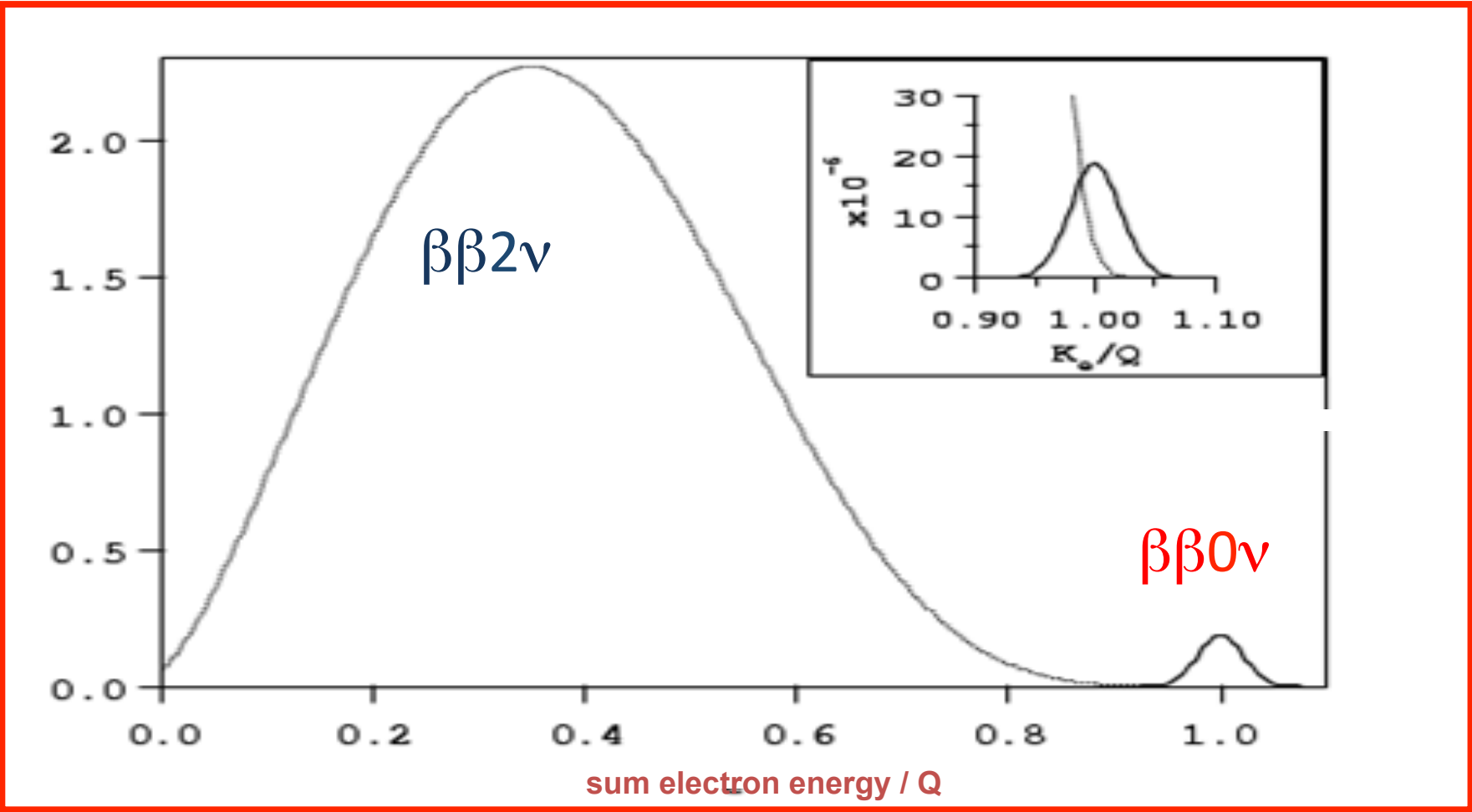
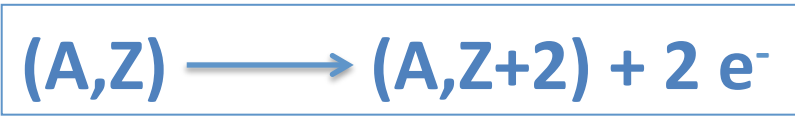


Neutrinoless double beta decay and neutrino properties

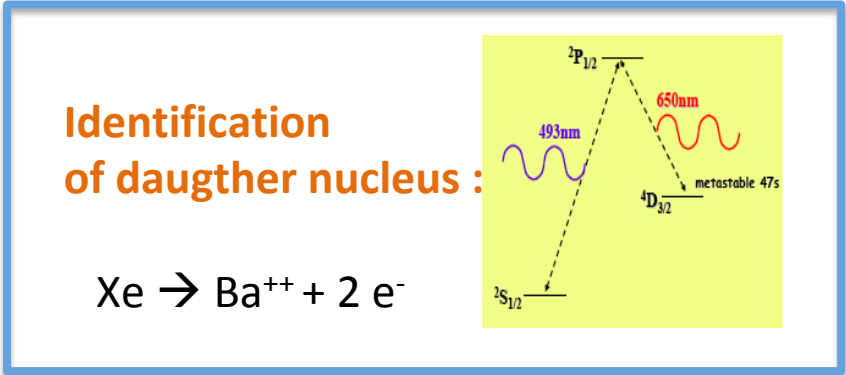
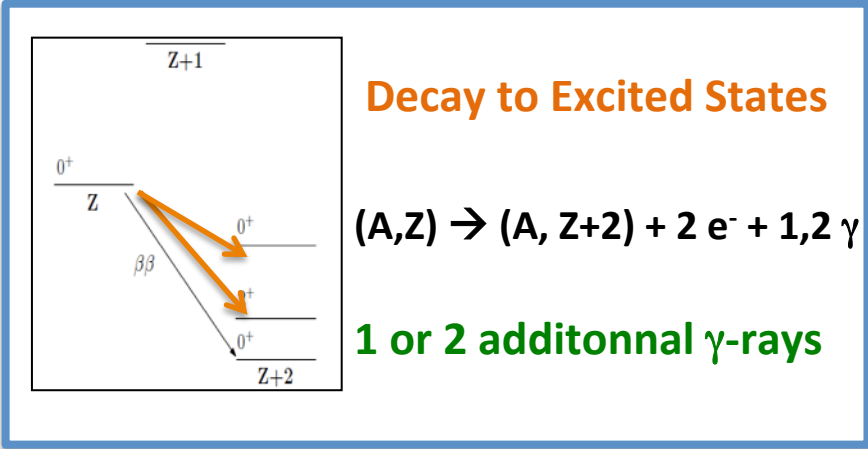
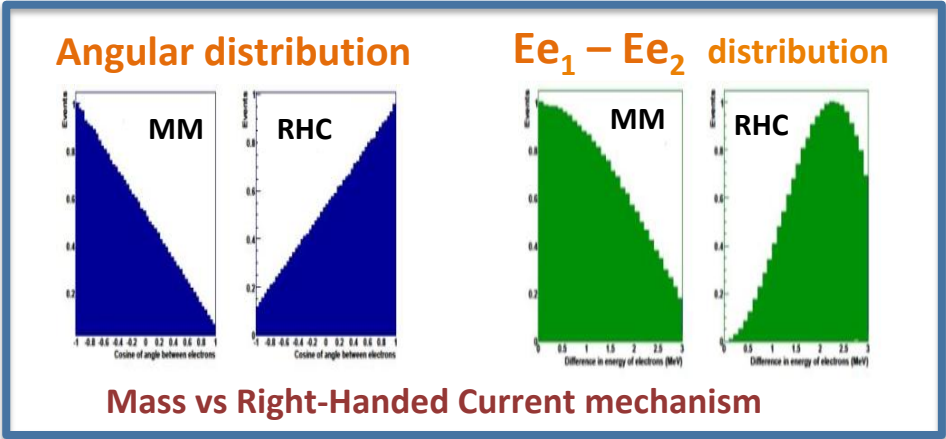
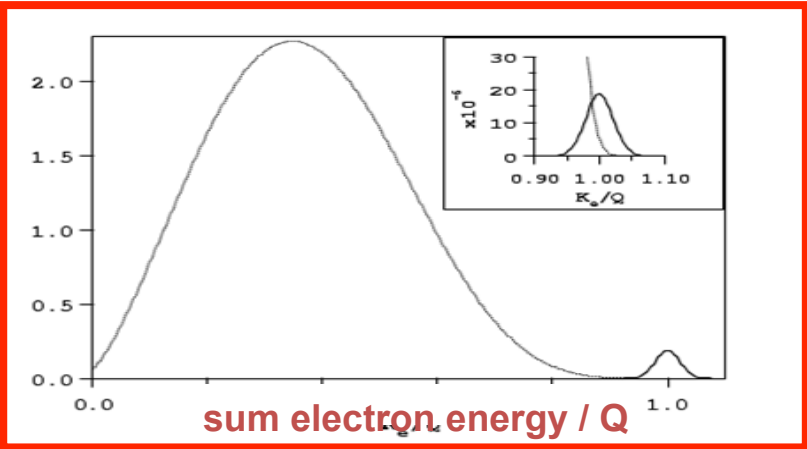
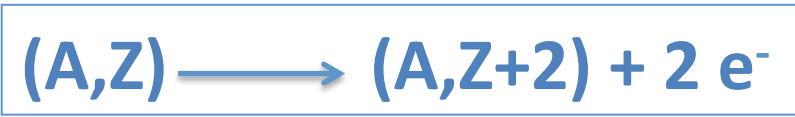
$$\langle m_\nu \rangle = \left| \sum_i U_{ei} m_i \right| = \left| \cos^2 \theta_{13} \left(m_1 \cos^2 \theta_{12} + m_2 e^{2i\alpha} \sin^2 \theta_{12} \right) + m_3 e^{2i\beta} \sin^2 \theta_{13} \right|$$



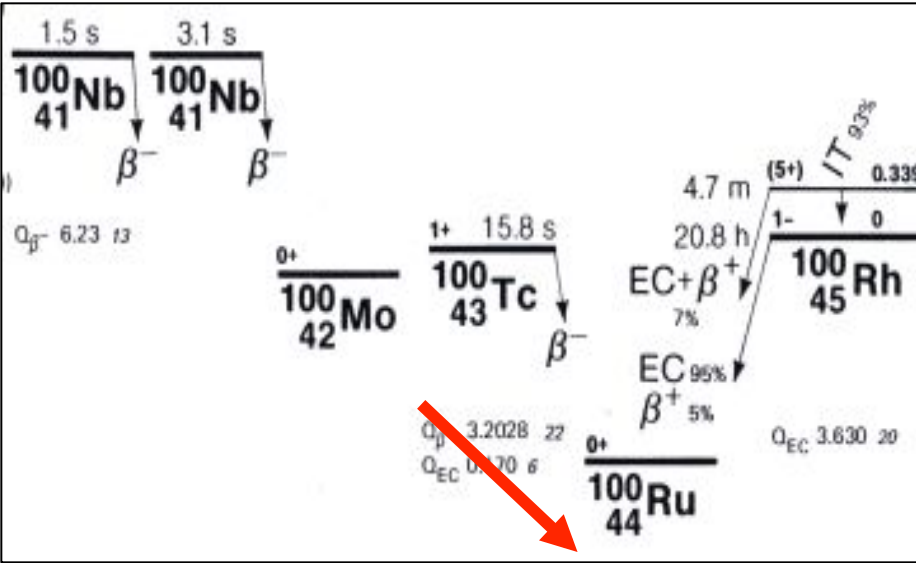
Double beta decay observables



Double beta decay observables



Double beta decay emitters



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

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

35 $\beta\beta$ emitters but only about 10 can be experimentally studied

Expected half-lives

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

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

1 decay/y for 10²⁴ – 10²⁵ nuclei
 1 decay/y for ~ 10 moles (1 kg)

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

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

$\langle m_\nu \rangle$ = effective neutrino mass

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

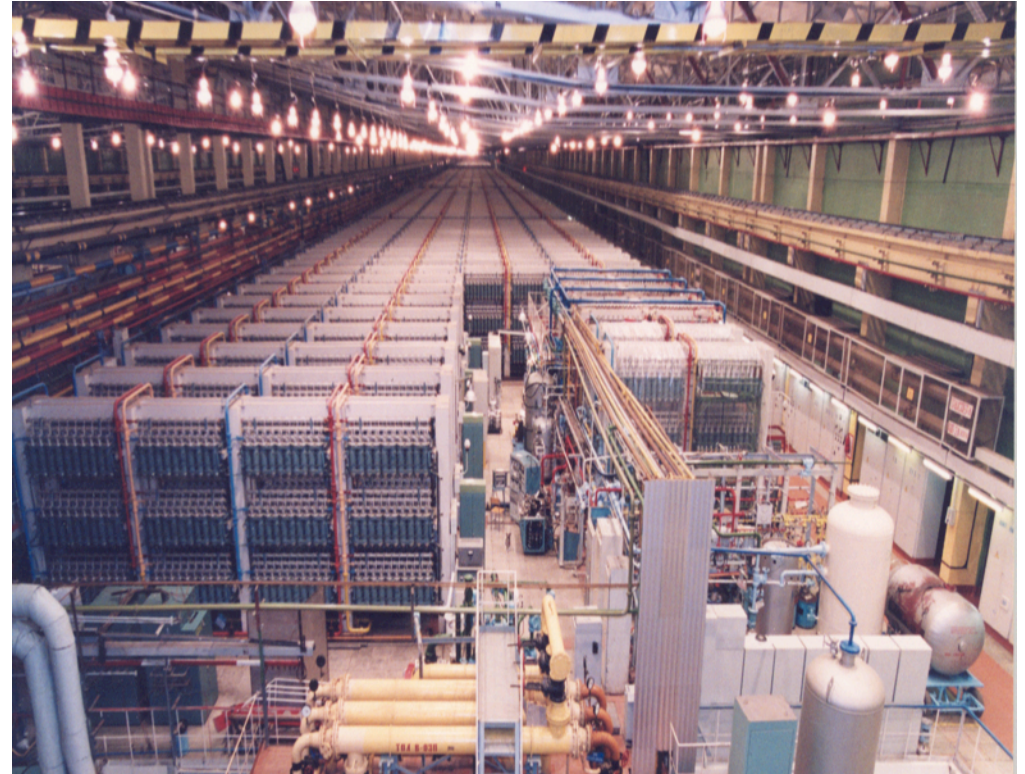
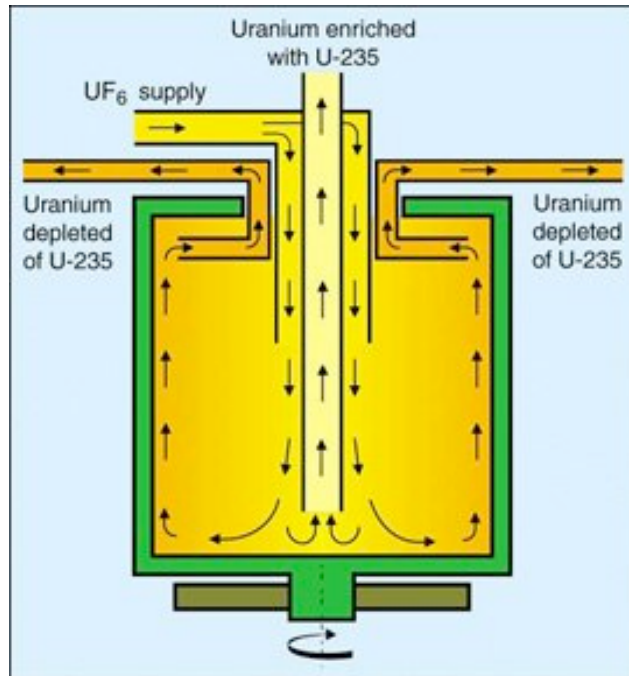
High transition energy ($Q_{\beta\beta}$)

Good energy resolution

Rejection of background coming from natural radioactivity

Choice of the nucleus \rightarrow experimental technique

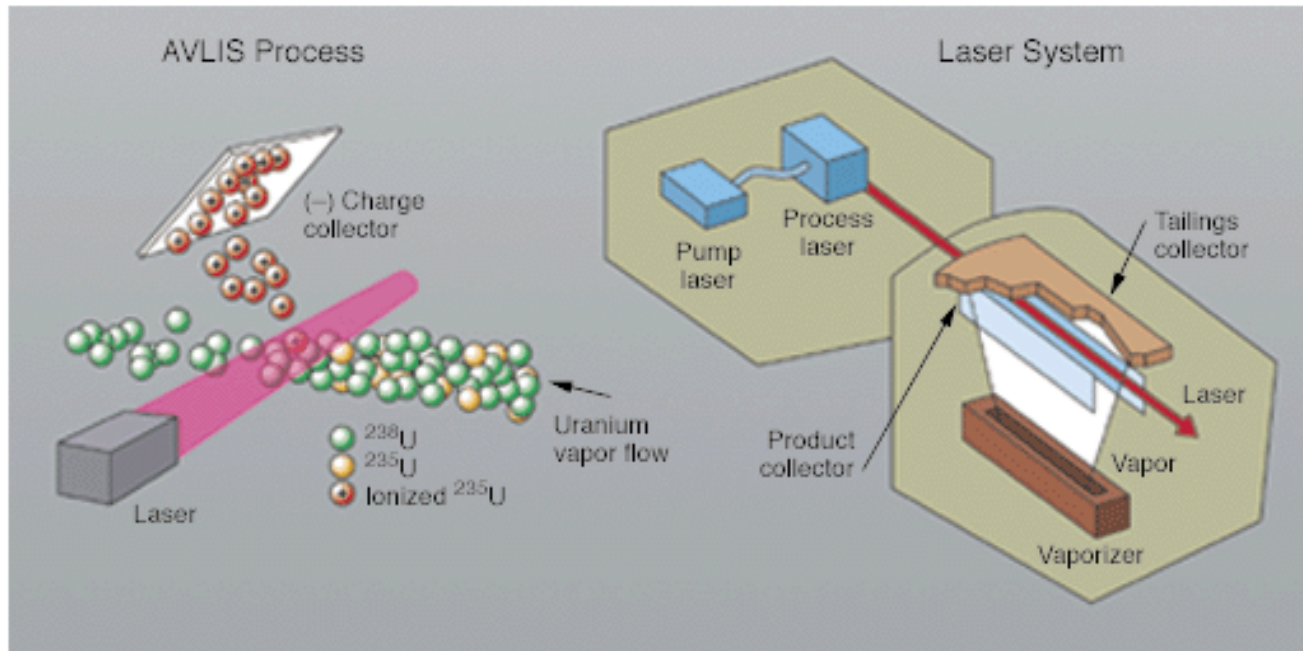
Isotopic enrichment



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

Enrichment mainly made by centrifugation: need gaseous 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

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

NO Background

M: masse (g)

ε : efficiency

K_{C.L.} : Confidence level

\mathcal{N} : Avogadro number

t: time (y)

N_{Bckg}: Background events (keV⁻¹.g⁻¹.y⁻¹)

ΔE: energy resolution (keV)

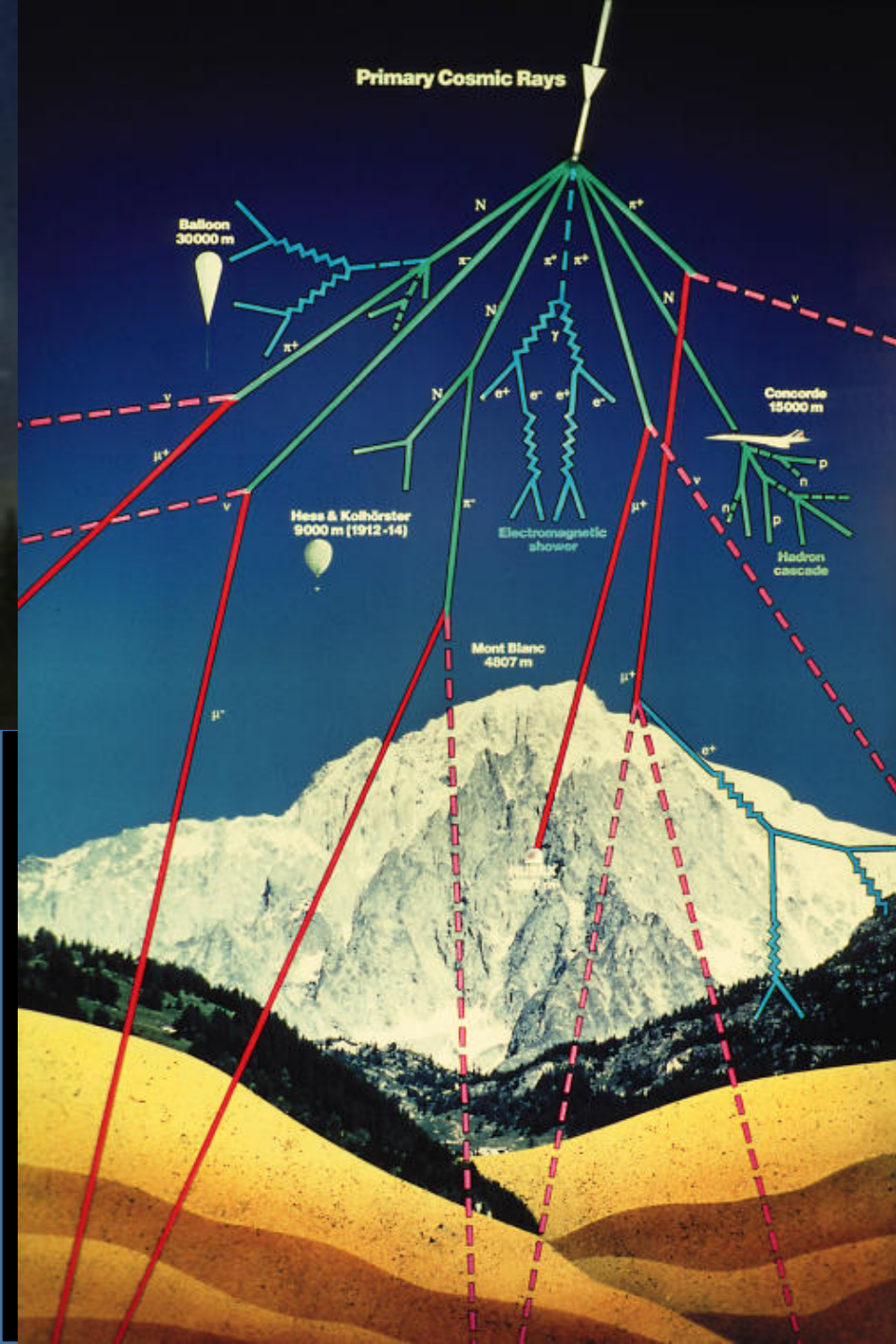
$$T_{1/2}^{0\nu}(\text{y}) > \frac{\ln 2 \cdot \mathcal{N}}{k_{\text{C.L.}}} \cdot \frac{\varepsilon}{A} \cdot \sqrt{\frac{\mathbf{M} \cdot \mathbf{t}}{\mathbf{N}_{\text{Bckg}} \cdot \Delta \mathbf{E}}}$$

With background

Source of background from natural radioactivity

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





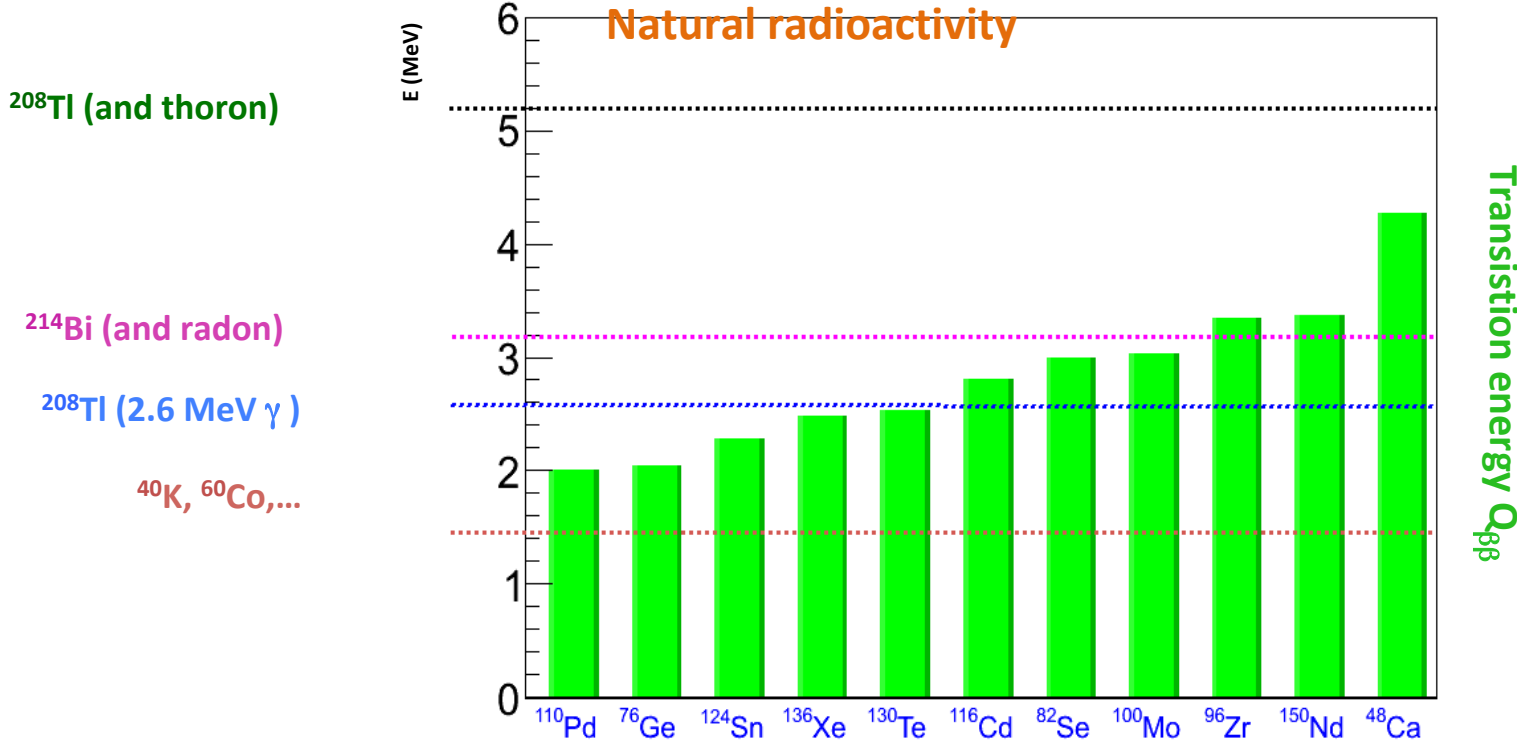
En surface:
10 000 000 de rayonnements cosmiques
 par m² et par jour

Sous la montagne au LSM (- 1800 m):
4 rayonnements cosmiques
 par m² 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

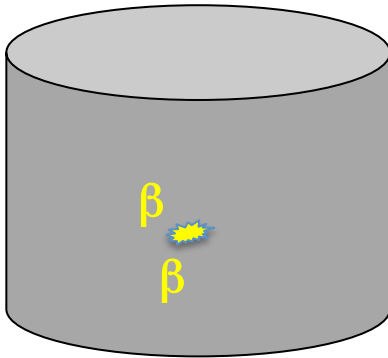


Detectors installed underground
Selection of all materials used in the detectors
Shielding against gamma-ray from the rocks
Suppression of radon

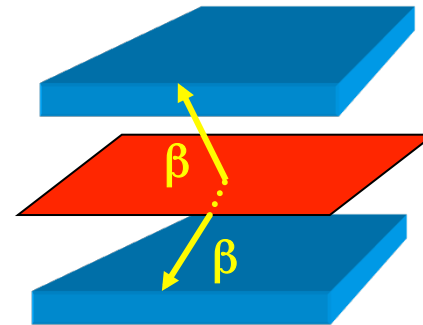
Source of background from natural radioactivity

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

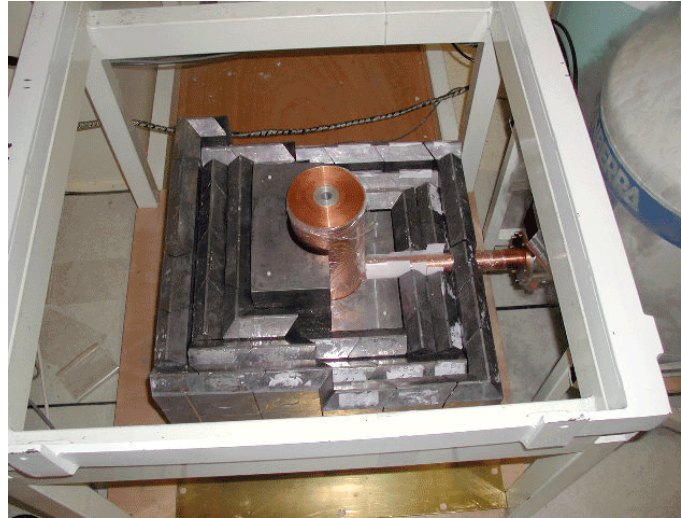


Calorimetric measurement



Electron detection

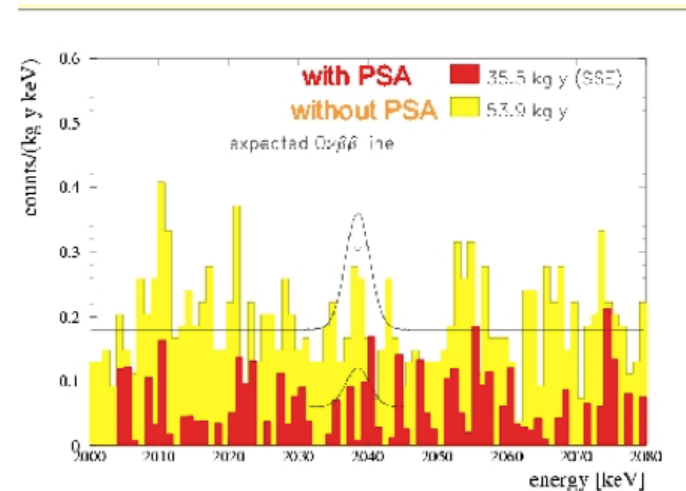
Ge experiment: Heidelberg Moscow



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

Very good energy resolution

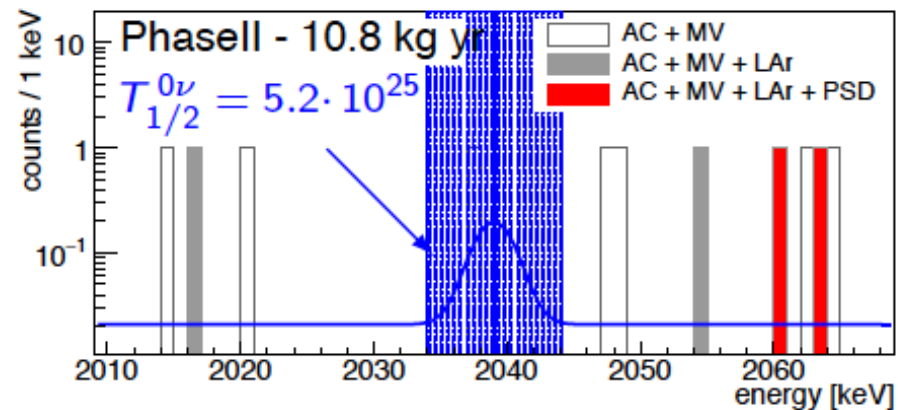
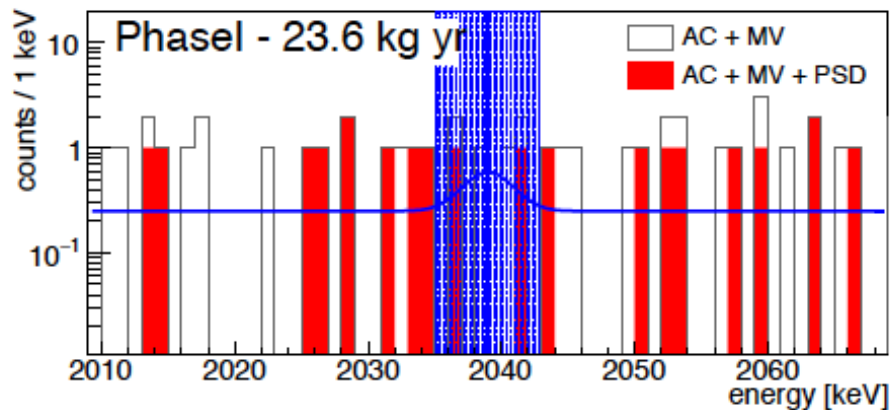
$$T_{1/2} > 1.9 \cdot 10^{25} \text{ yr} \quad \langle m_{\nu} \rangle < 0.2 - 0.5 \text{ eV}$$



Ge experiment: GERDA experiment



Ge experiment: GERDA experiment



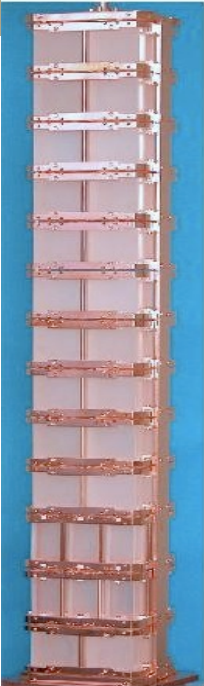
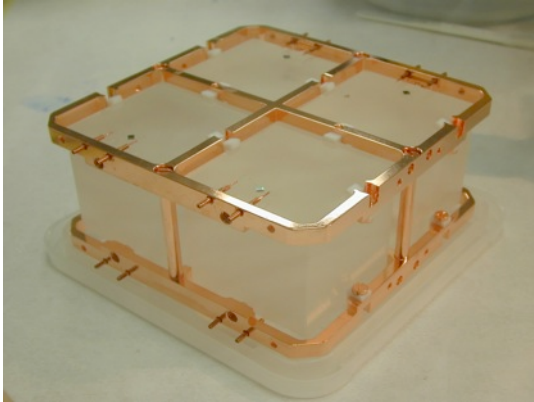
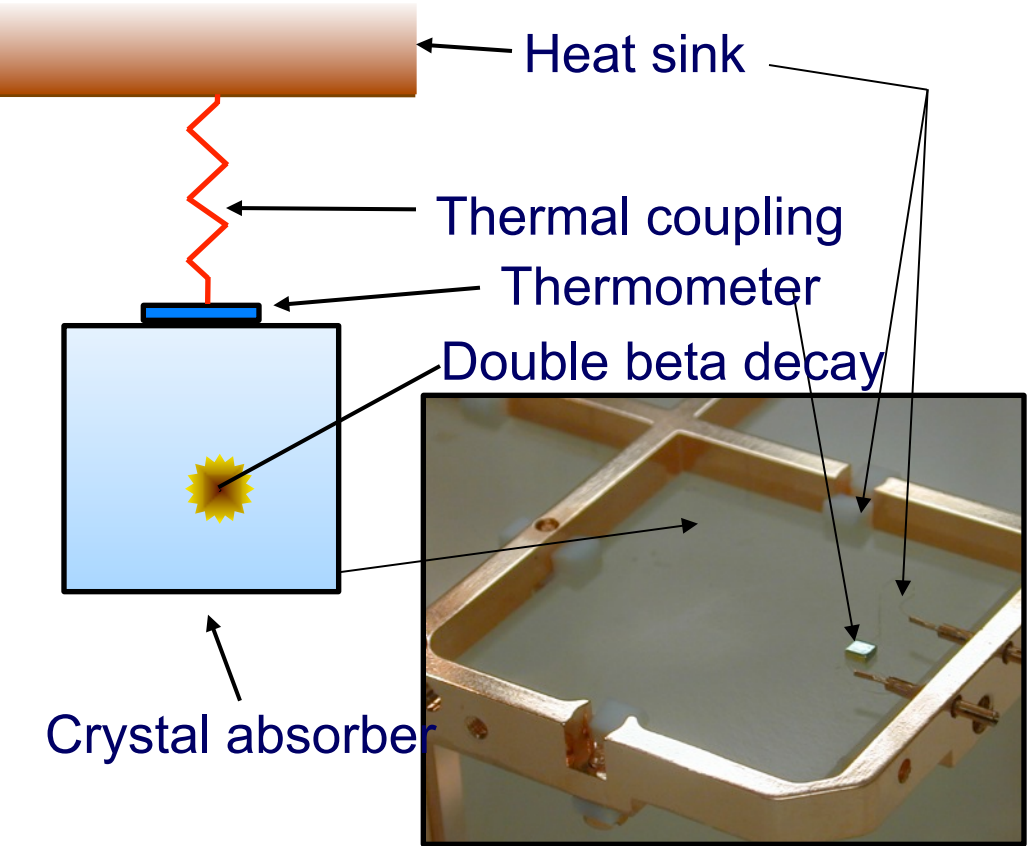
► blind analysis, no $0\nu\beta\beta$ signal:

$$T_{1/2}^{0\nu} > 5.2 \cdot 10^{25} \text{ yr (90\% C.L.)}^*$$

$$|m_{ee}| < [160, 260] \text{ meV (90\% C.L.)}^*$$

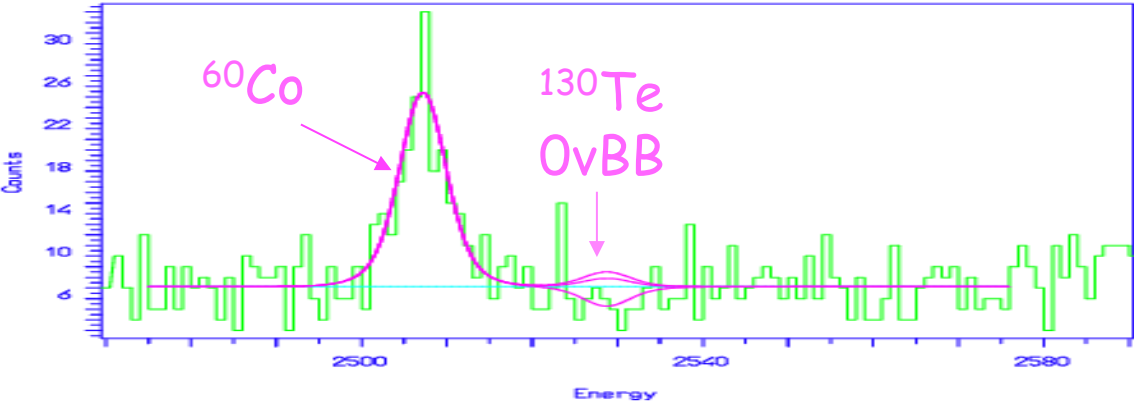
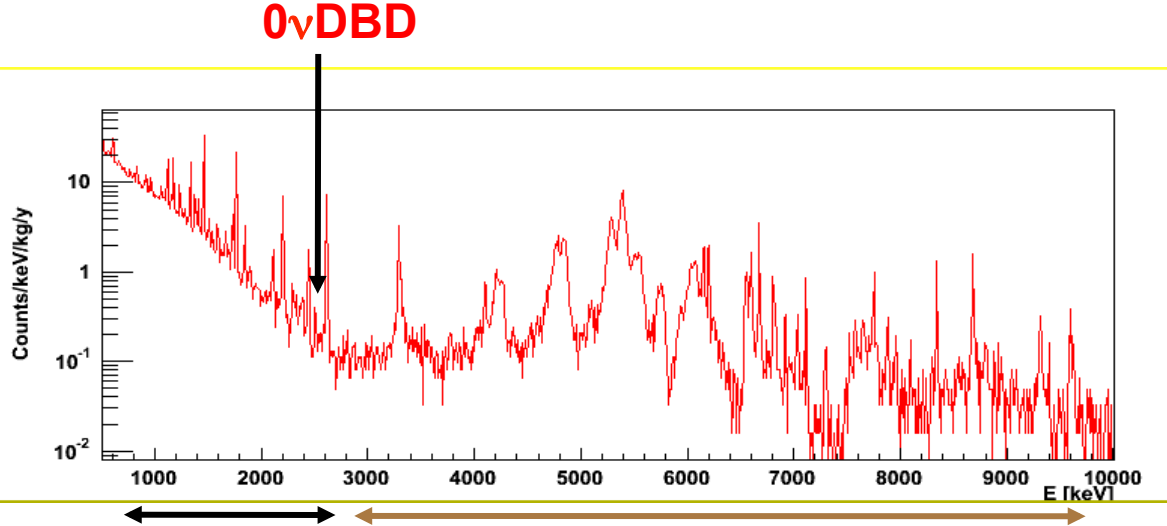
Bolometers : Cuoricino experiment

Very good energy resolution



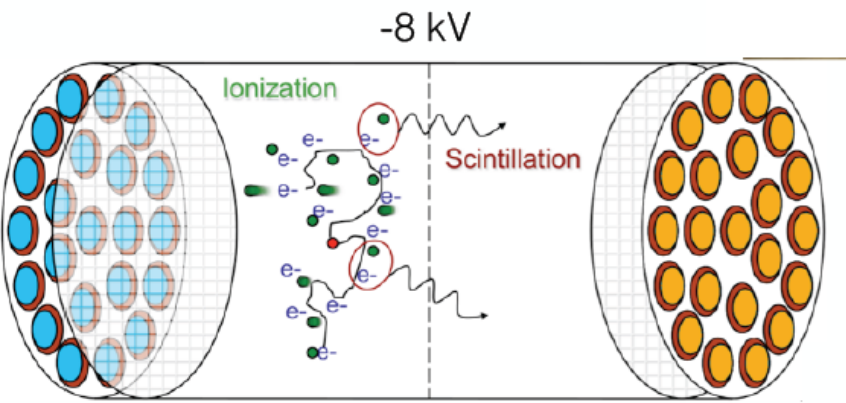
example: 750 g of TeO_2 @ 10 mK
 $C \sim T^3$ (Debye) $\Rightarrow C \sim 2 \times 10^{-9}$ J/K
1 MeV γ -ray $\Rightarrow \Delta T \sim 80 \mu\text{K}$
 $\Rightarrow \Delta U \sim 10$ eV

Bolometers : Cuoricino experiment

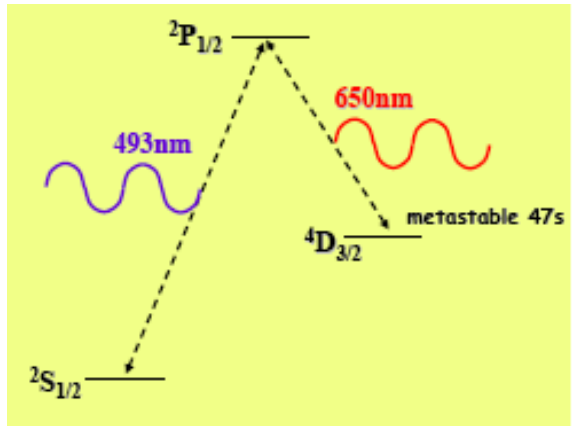
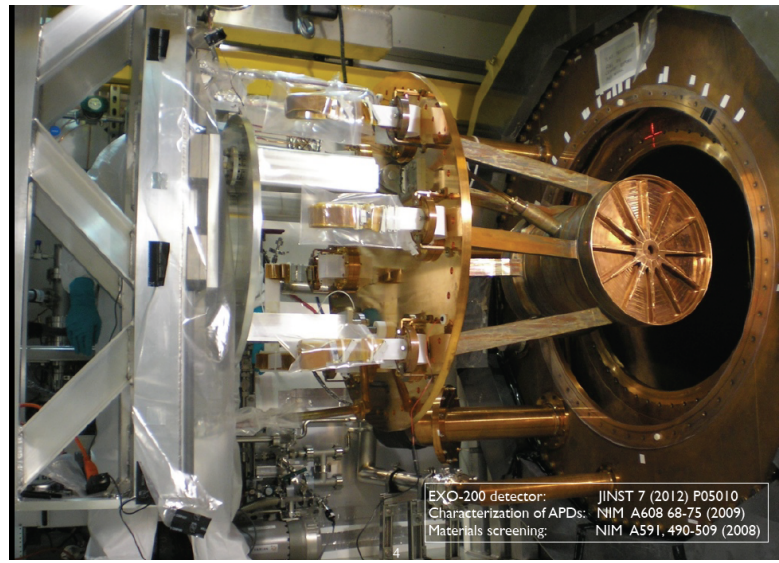


$T_{1/2} > 6 \cdot 10^{24} \text{ yr}$ $\langle m_\nu \rangle < 0.1 - 0.7 \text{ eV}$

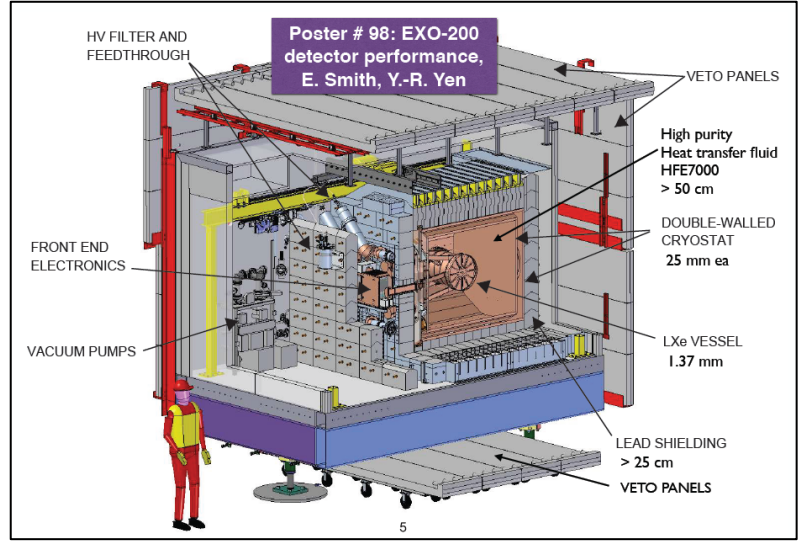
Liquid Xenon: EXO-200



Avalanche photodiode

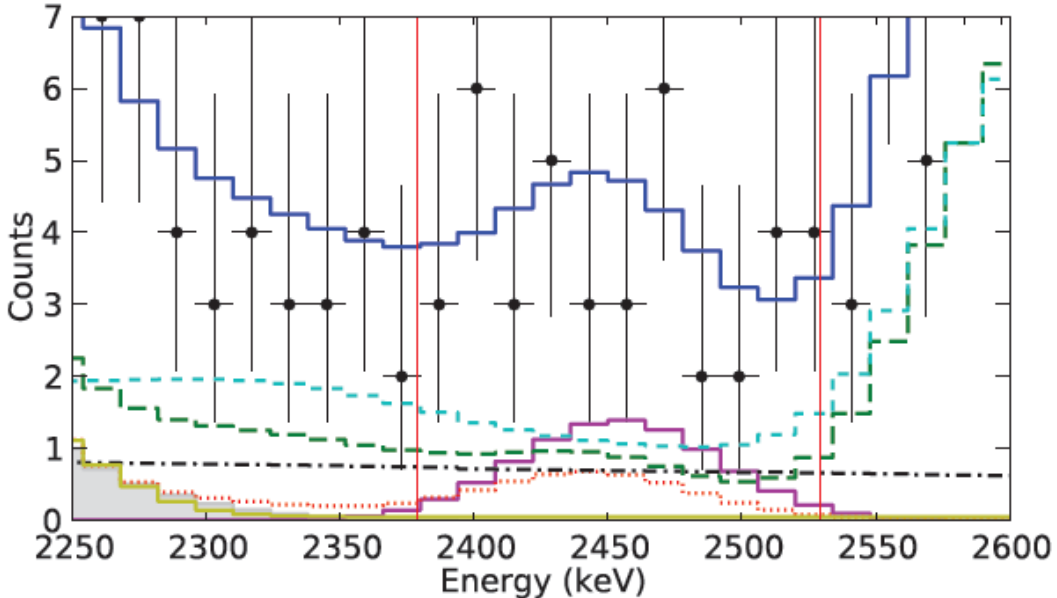
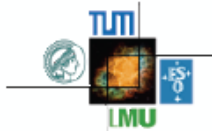


Possibility to tag Baryum ?
 Very difficult R&D in progress



Installed at WIPPL (USA)

Looking for $0\nu\beta\beta$



Backgrounds in $\pm 2\sigma$ ROI	
Th-228 chain	16.0
U-232 chain	8.1
Xe-137	7.0
Total	31.1 ± 3.8

- Data
- Best Fit
- Rn
- LXe bkg
- n-capture
- ^{232}Th (far)
- Vessel
- $0\nu\beta\beta$
- $2\nu\beta\beta$

From profile likelihood:

$T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25}$ yr

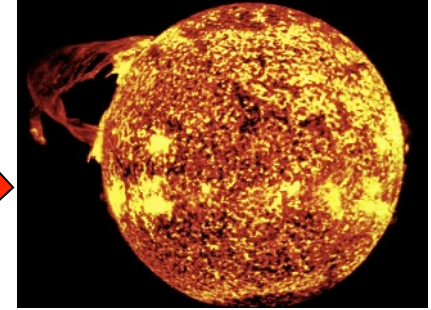
$\langle m_{\beta\beta} \rangle < 190 - 450$ meV (90% C.L.)

Nature (2014)
doi:10.1038/nature13432

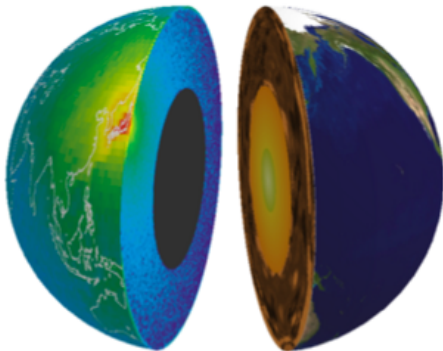
Large liquid scintillator experiment: KamLAND-ZEN



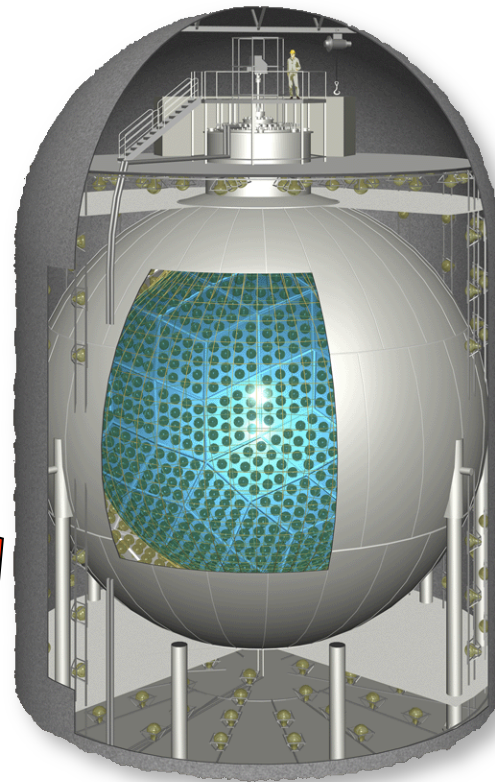
Reactors



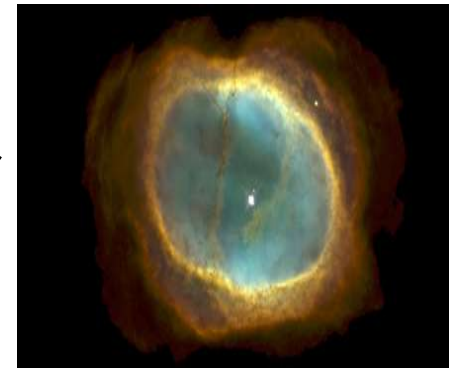
Solar neutrinos



Geoneutrinos



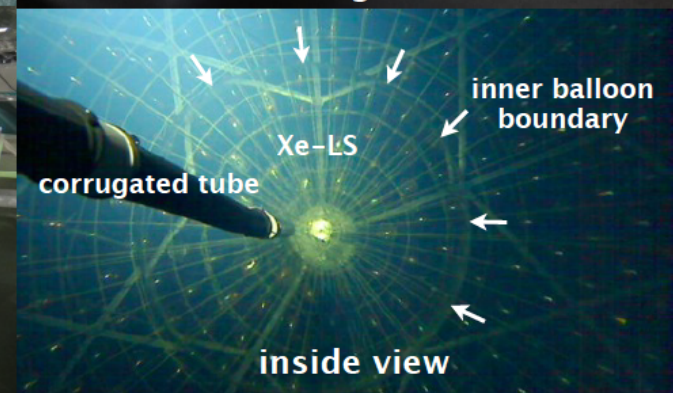
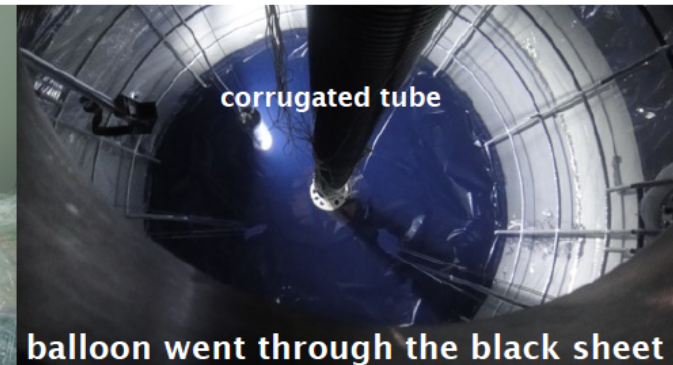
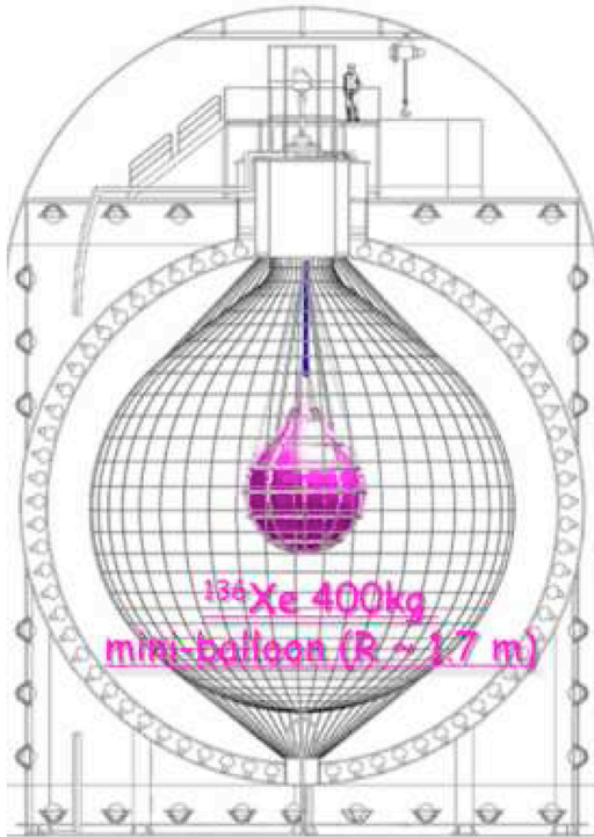
KamLAND detector



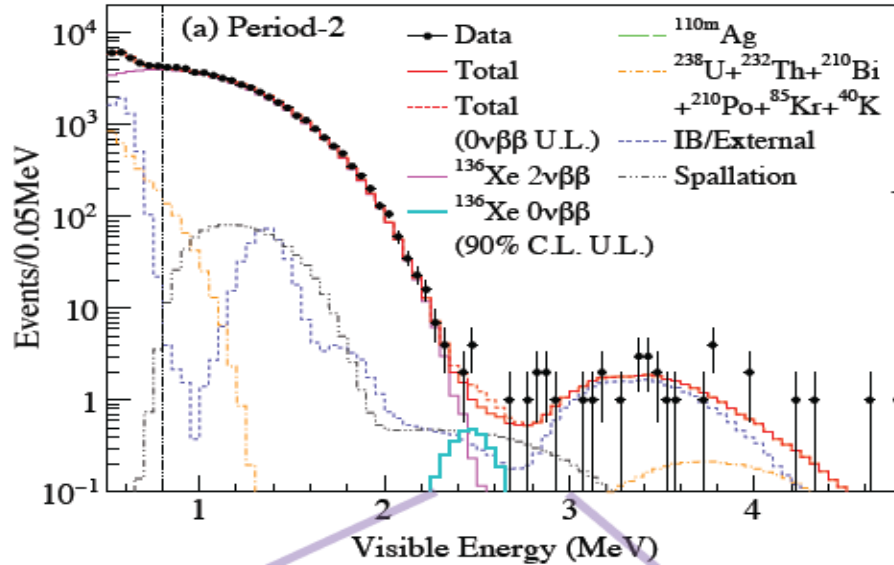
Supernovae neutrinos

Large liquid scintillator experiment: KamLAND-ZEN

Dissolution of ^{136}Xe inside a balloon of liquid scintillator
Possibility to dissolve very large mass
Installed at Kamioka mine (Japan)



Large liquid scintillator experiment: KamLAND-ZEN

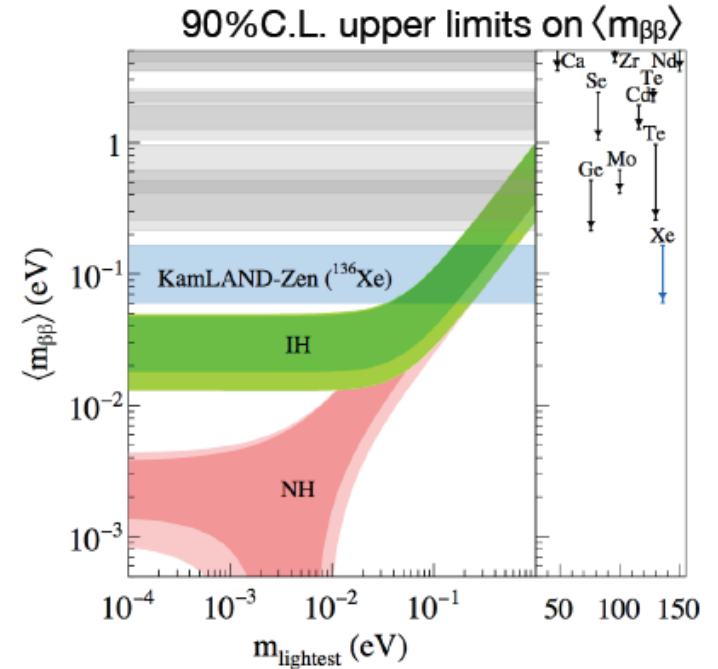
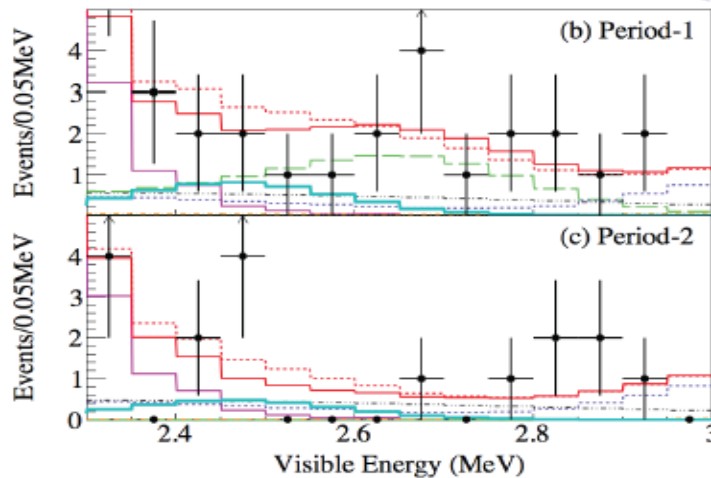


Phase1 $T_{1/2}^{0\nu} > 1.9 \times 10^{25}$ yr

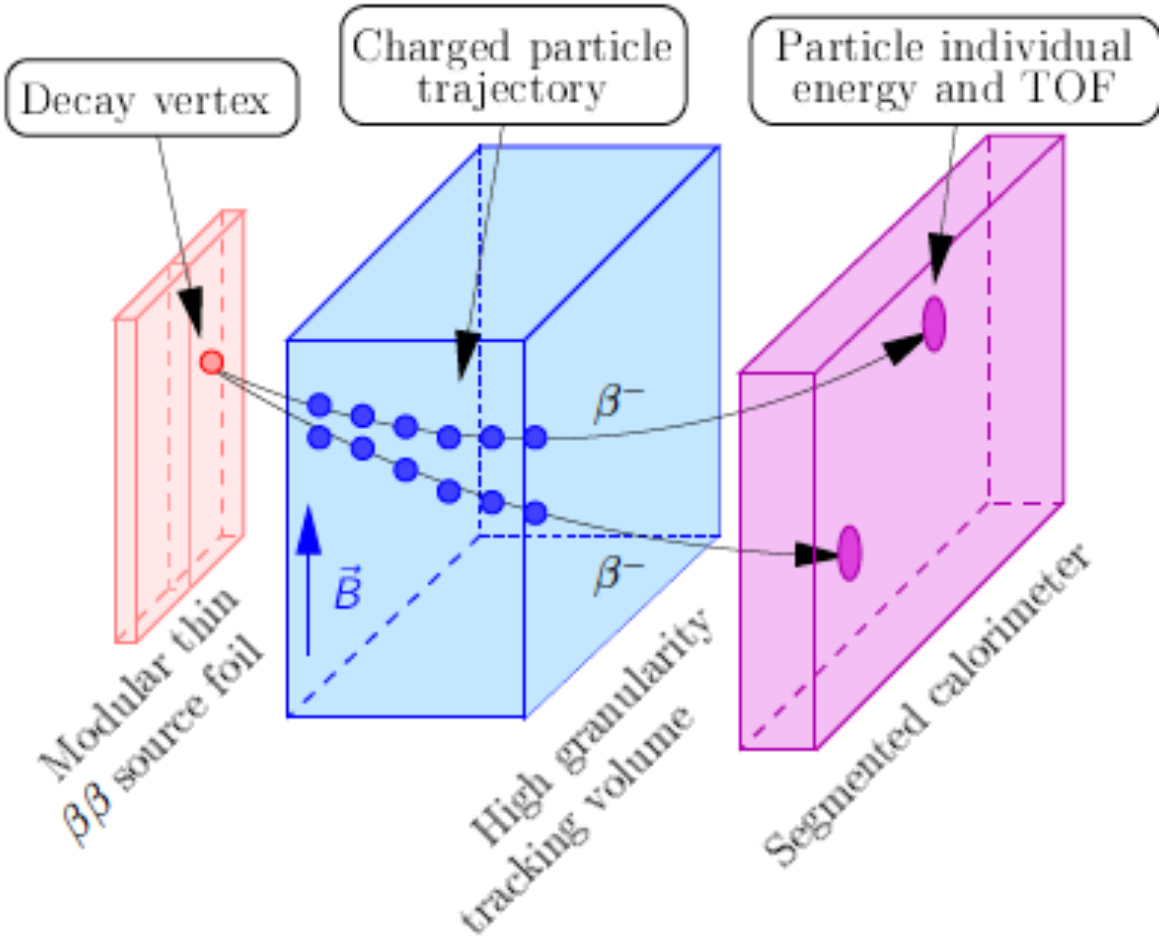
Phase2 $T_{1/2}^{0\nu} > 9.2 \times 10^{25}$ yr **x6!**

Combined $T_{1/2}^{0\nu} > 1.07 \times 10^{26}$ yr

Visible energies in 2.3~3.0MeV

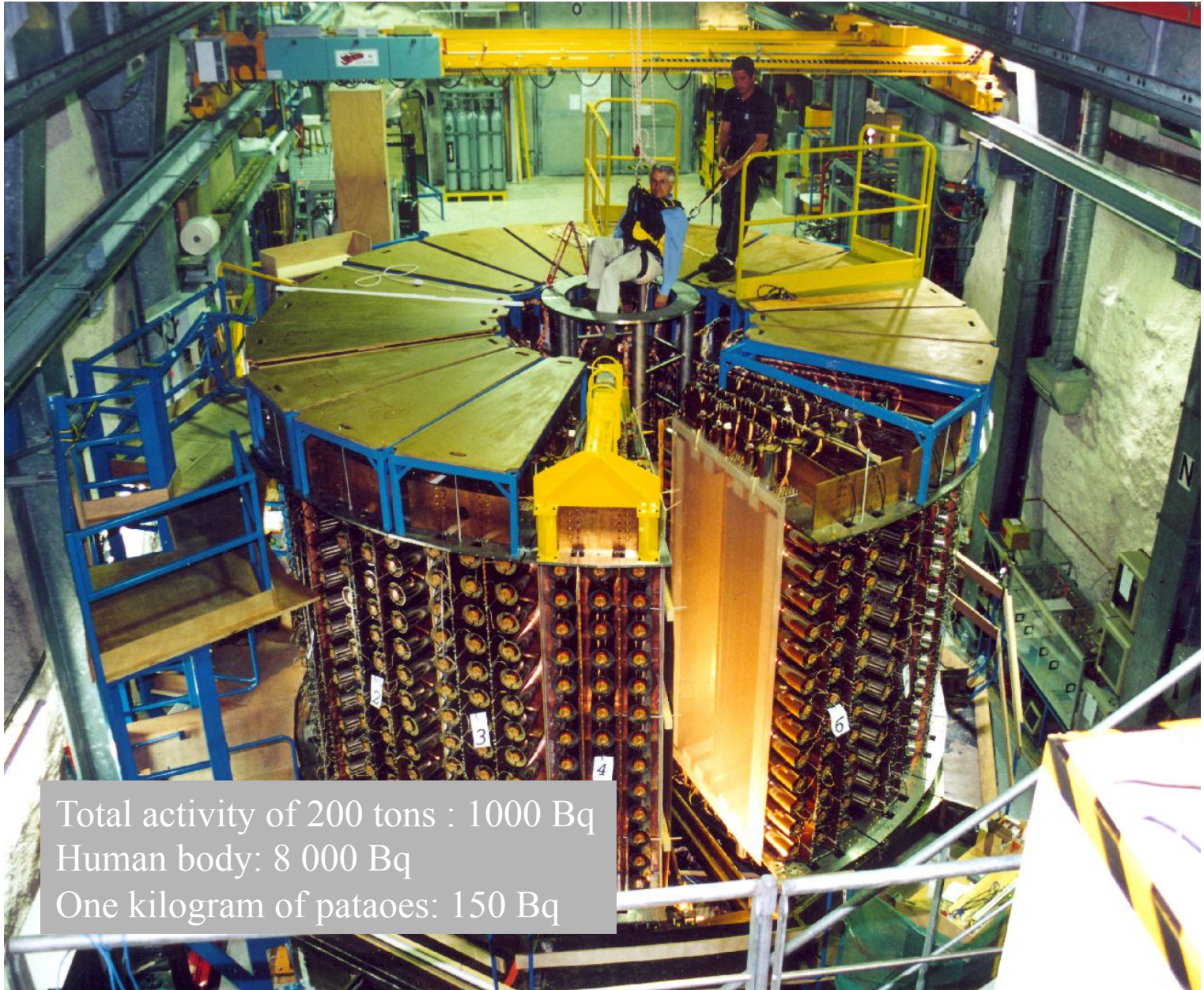


Principle of experiments with electron detection



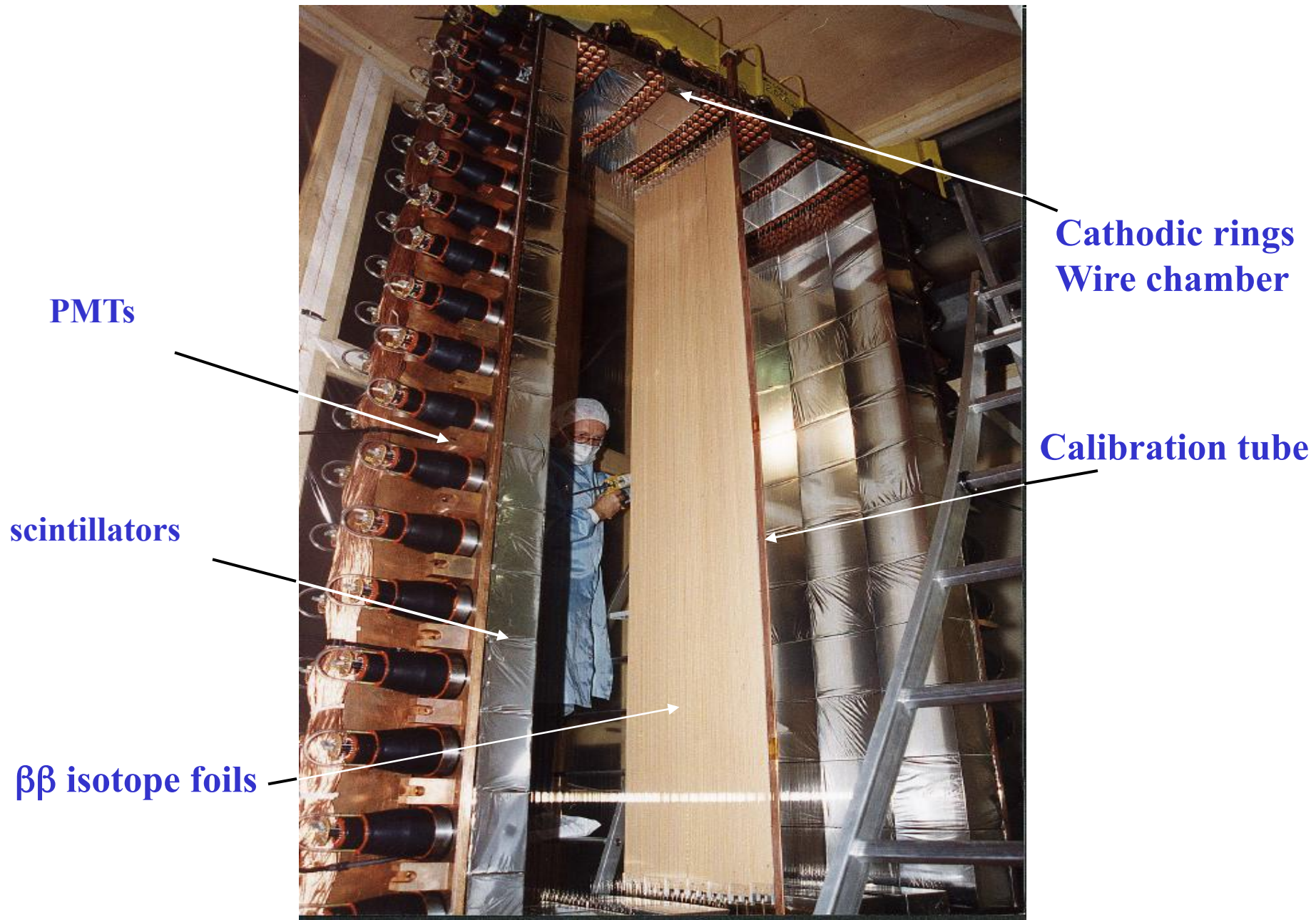
Multi-isotope detector
High rejection of background

The NEMO3 detector

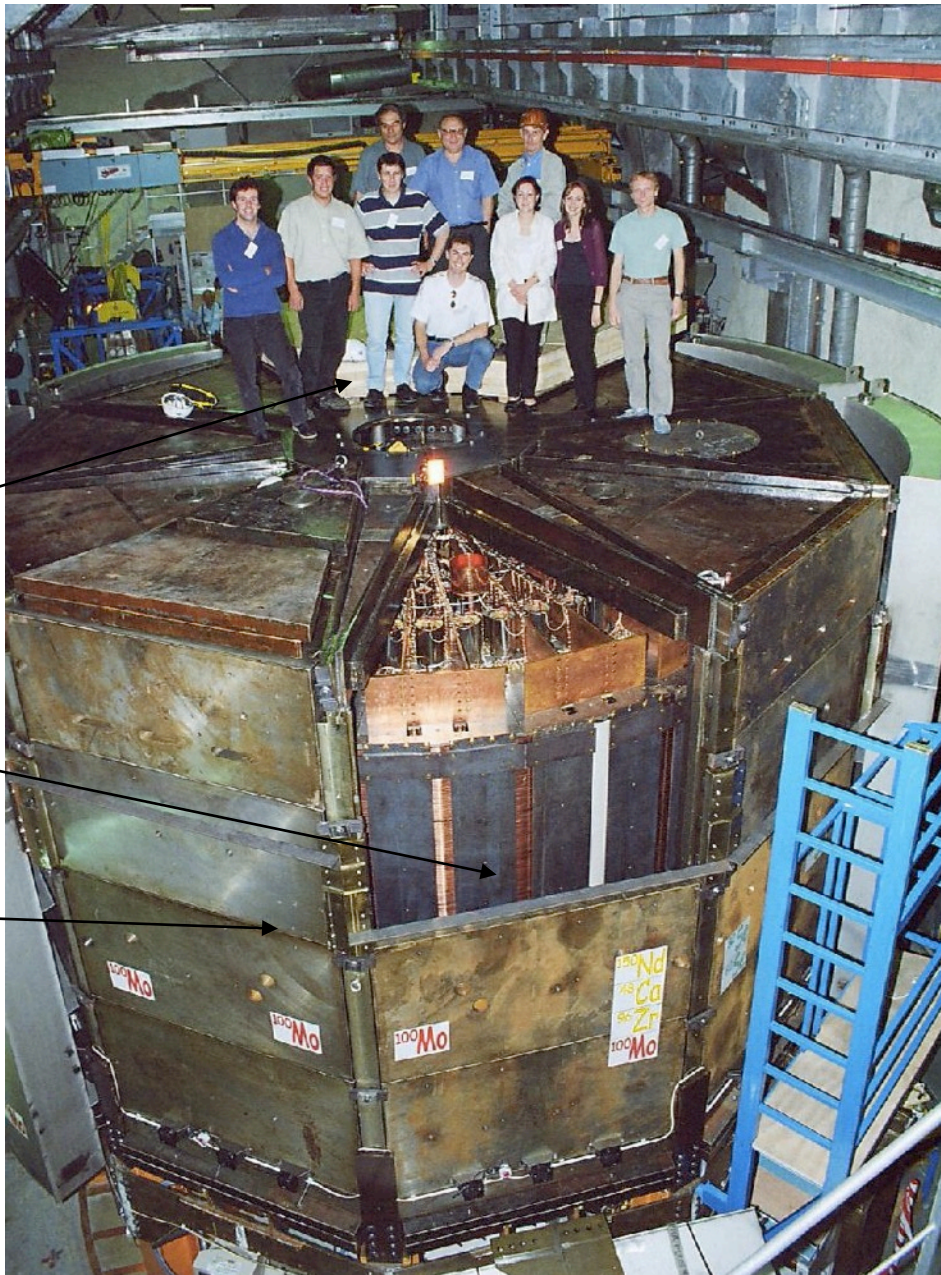


Total activity of 200 tons : 1000 Bq
Human body: 8 000 Bq
One kilogram of potatoes: 150 Bq

The NEMO3 detector



The NEMO3 detector



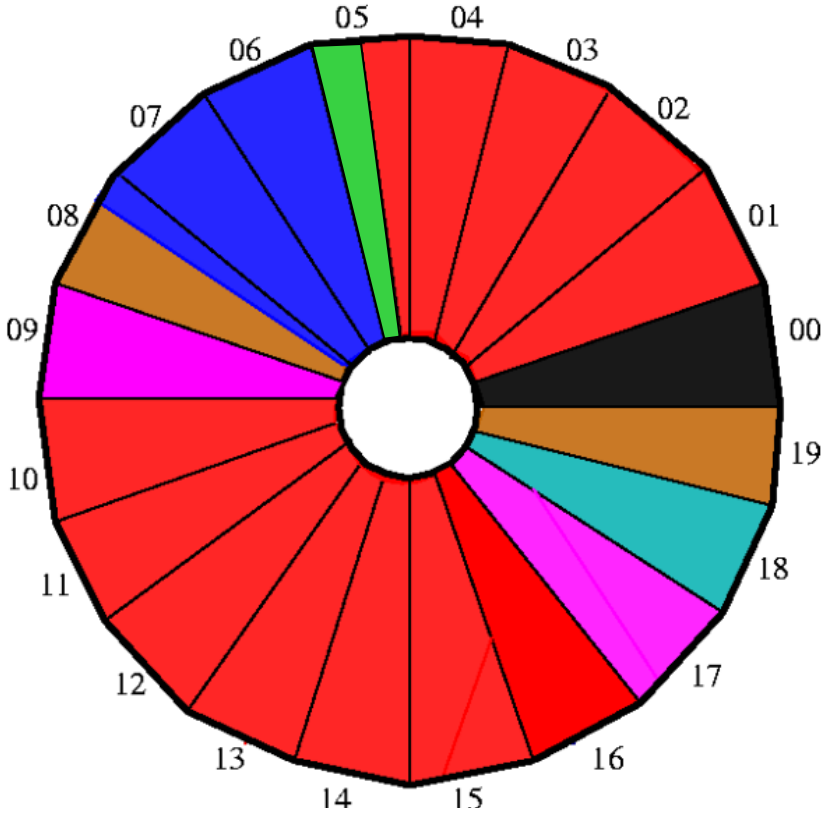
wood

coil

Iron shield

Water tank

NEMO3 isotopes



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

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

$\beta\beta 0\nu$ search

$\beta\beta 2\nu$ measurement

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

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

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

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

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

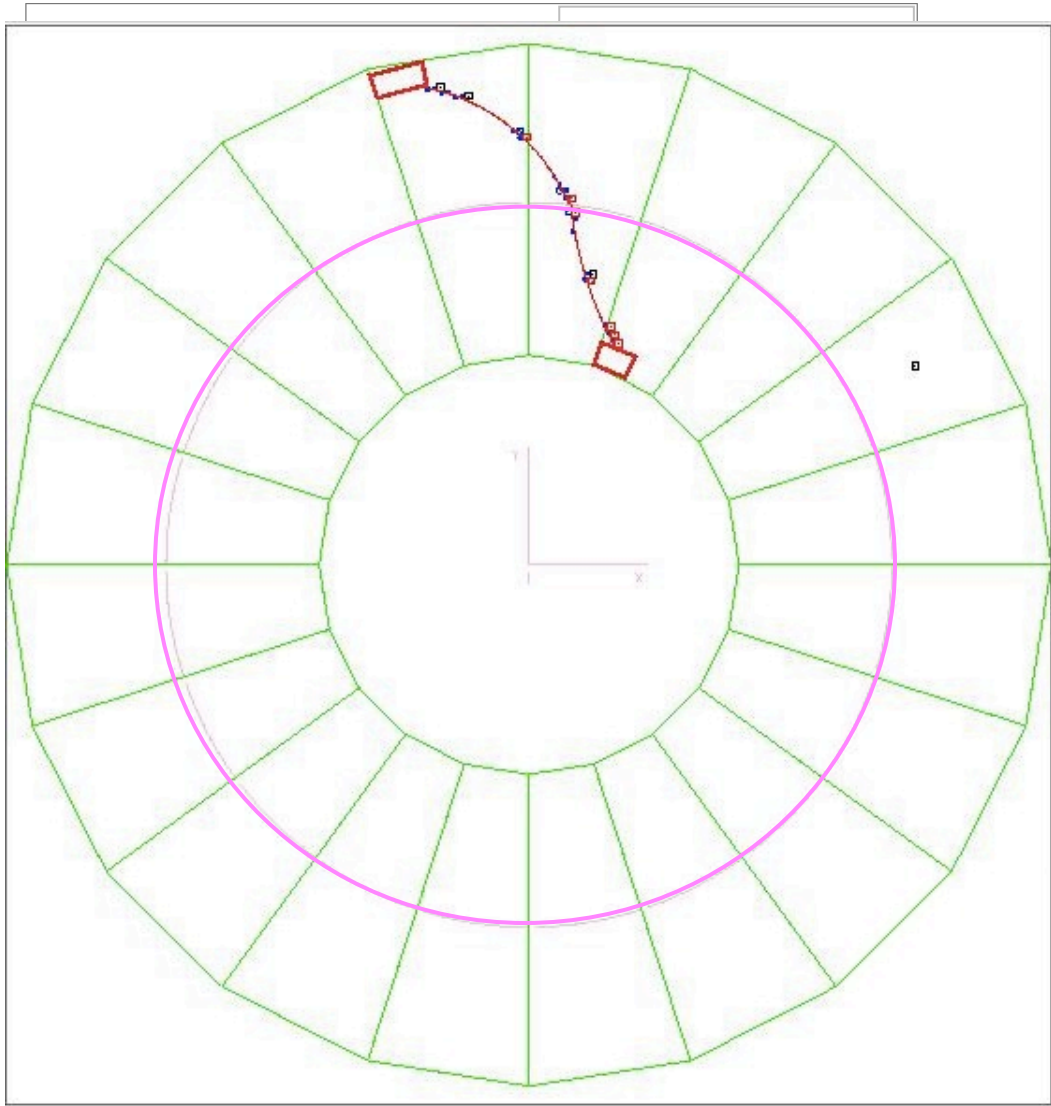
$^{\text{nat}}\text{Te}$ 491 g

Cu 621 g

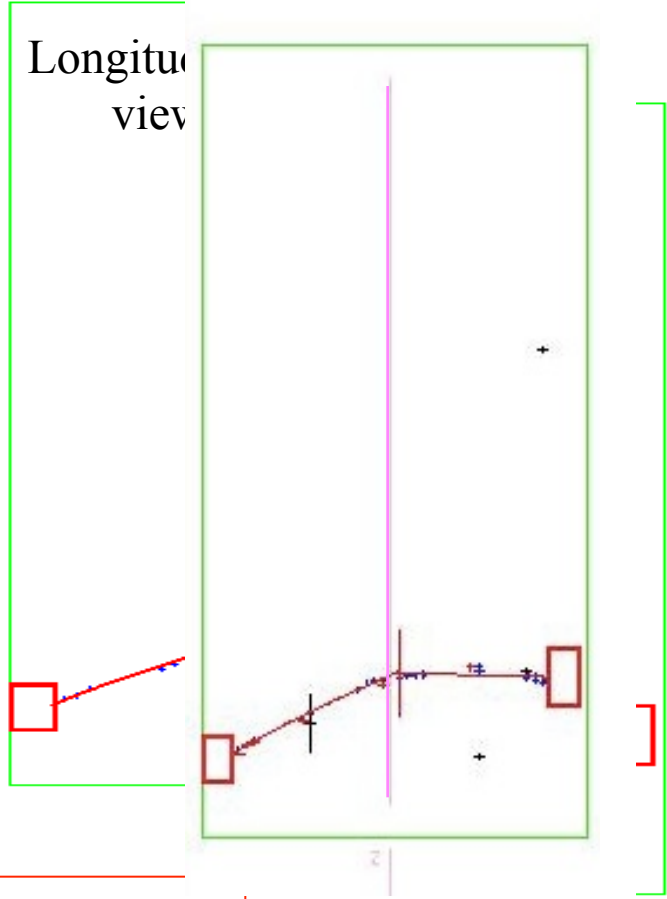
External bkg measurement

(All enriched isotopes produced in Russia)

NEMO3 Double beta decay event



Top view

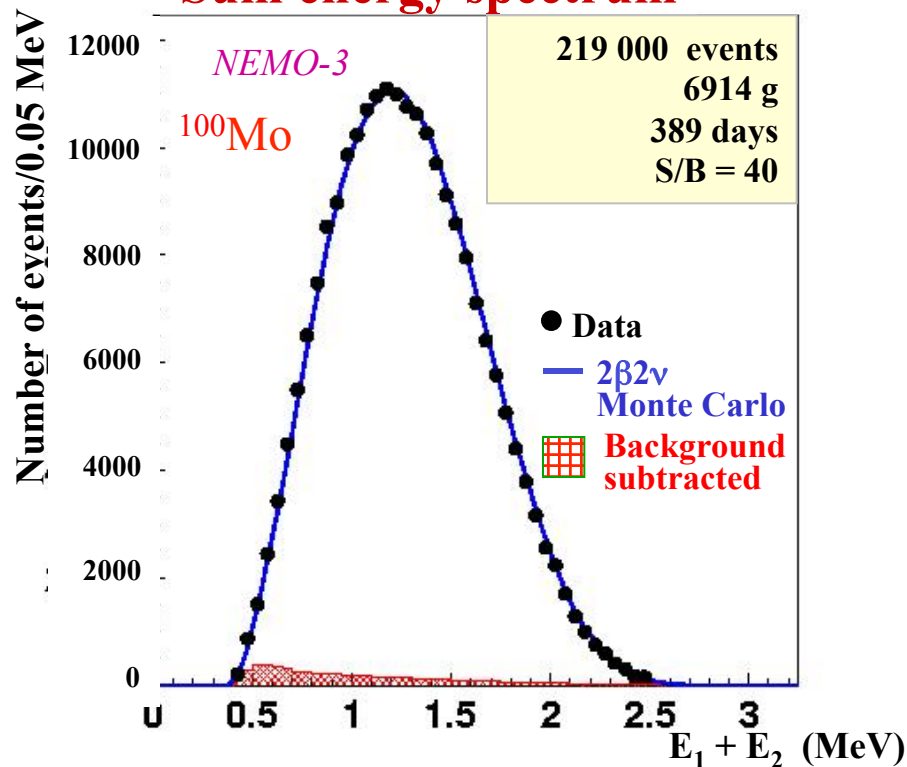


Longitudinal view

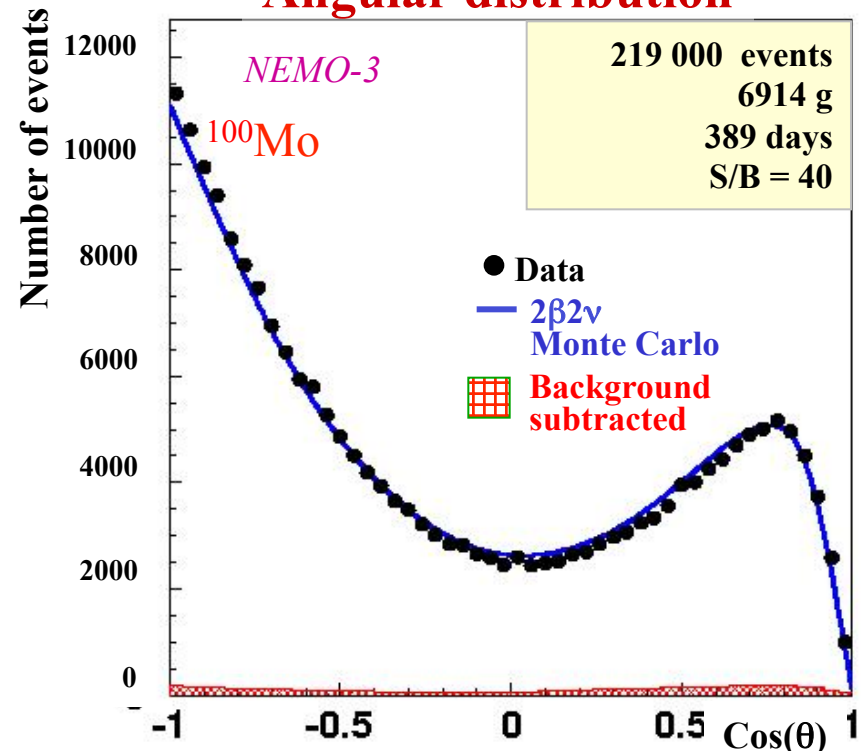
Side view

r layers + 1)

Sum energy spectrum



Angular distribution



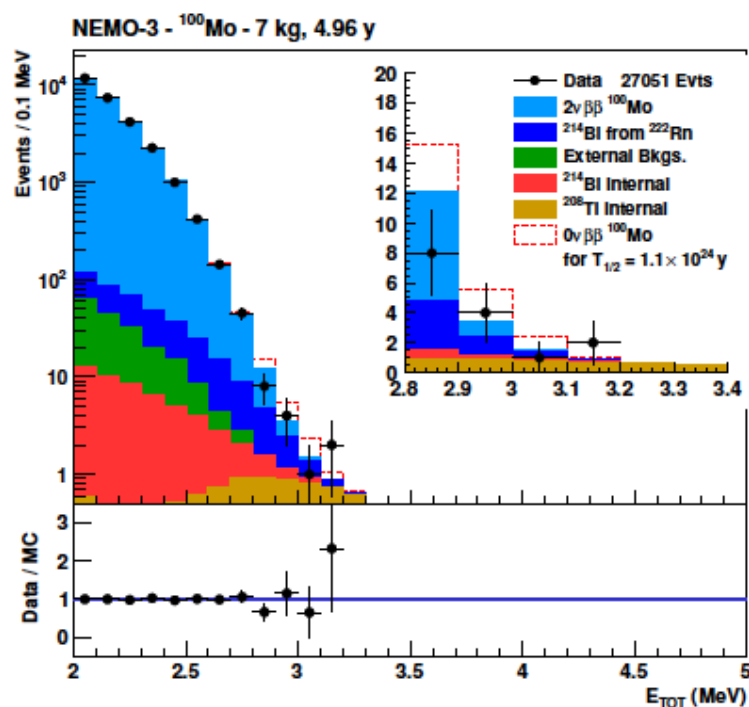
$$T_{1/2}(\beta\beta 2\nu) = 7.11 \pm 0.02 \text{ (stat)} \pm 0.54 \text{ (syst)} \times 10^{18} \text{ years}$$

Phys. Rev. Lett. 95 182302 (2005)

« $\beta\beta$ factory» → tool for precision test

NEMO-3 $0\nu 2\beta$ Search with ^{100}Mo

- ▶ Detection efficiency $\mathcal{E}_{0\nu} = 4.7\%$ in the [2.8 – 3.2] MeV region
- ▶ No event excess observed in ^{100}Mo after 34.3 kg·y exposure:
 $\mathcal{T}_{1/2}^{0\nu} > 1.1 \times 10^{24}$ y (90 % CL)



Expected background in [2.8 – 3.2] MeV

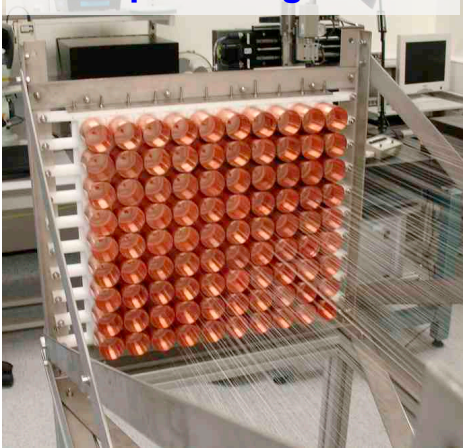
$2\nu 2\beta$	8.45 ± 0.05
^{214}Bi from radon	5.2 ± 0.5
External	< 0.2
^{214}Bi internal	1.0 ± 0.1
^{208}Tl internal	3.3 ± 0.3
Total	18.0 ± 0.6
Data	15

Total background
 1.3×10^{-3} cts·keV $^{-1}$ ·kg $^{-1}$ ·y $^{-1}$

$$\mathcal{T}_{1/2} > 1.0 \cdot 10^{24} \text{ yr}$$

$$\langle m_\nu \rangle < 0.3 - 0.7 \text{ eV}$$

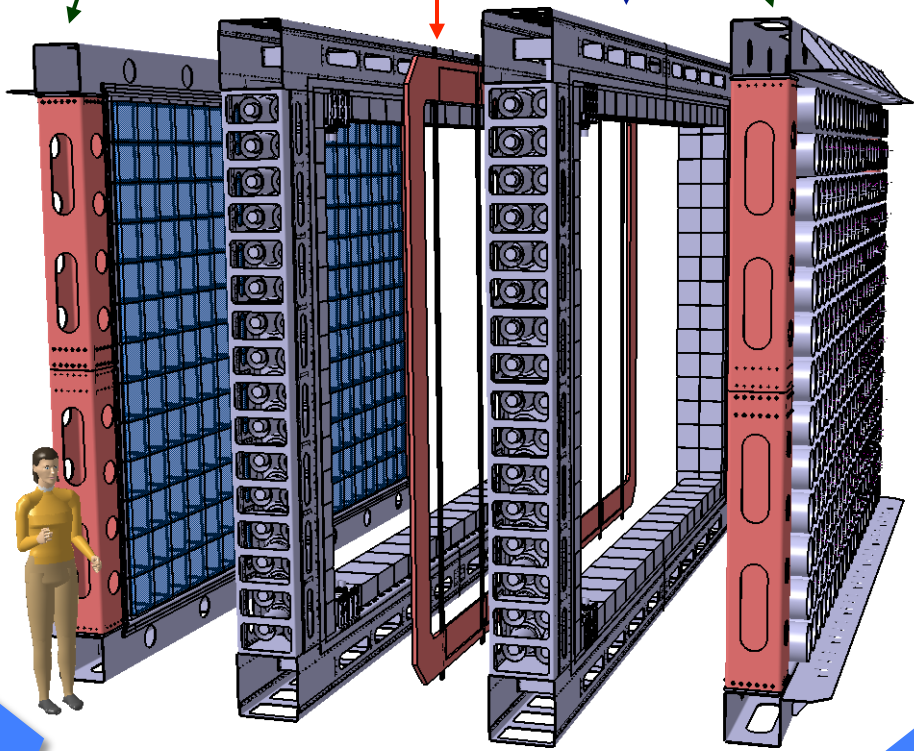
Tracking Detector
Radiopure Geiger Cells



712 calorimeter channels

2034 tracker cells

7 kg $\beta\beta$ source



Demonstrator Module

Also :

- Change isotope $^{100}\text{Mo} \rightarrow ^{82}\text{Se}$
- Reduce radon in gas by factor 30
- Improved efficiency, calibration etc.



Calo. Optical Module
FWHM 7-8 % @ 1 MeV

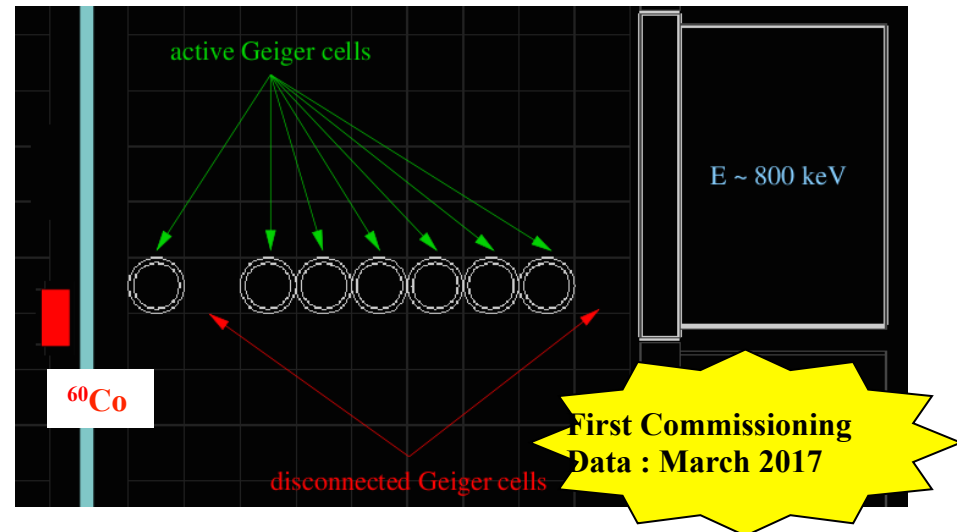
TAUP-2017



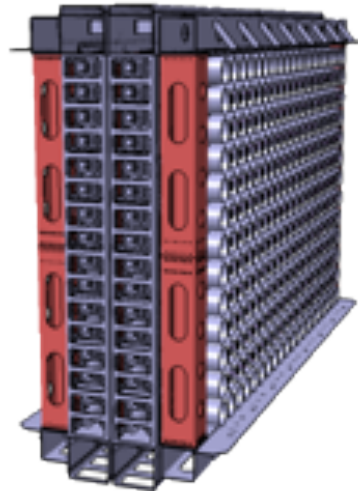
“BiPo” Detector
Measure source foil contamination to
 $^{208}\text{Tl} \leq 2 \mu\text{Bq/kg}$
 $^{214}\text{Bi} \leq 10 \mu\text{Bq/kg}$



- All detector parts underground at LSM.
- Half-detector fully assembled and undergoing testing/commissioning :



- Source foil fabrication (7kg of ^{82}Se) complete within next few months.
- SuperNEMO Demonstrator Module fully assembled by end-2017.
- Physics data-taking starts in 2018.

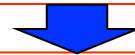


Demonstrator Module (2.5 year run)

17.5 kg×yr initial exposure :

$$T_{1/2}^{0\nu} > 6.5 \times 10^{24} \text{ yr}$$

$$\langle m_\nu \rangle < 0.20 - 0.40 \text{ eV}$$

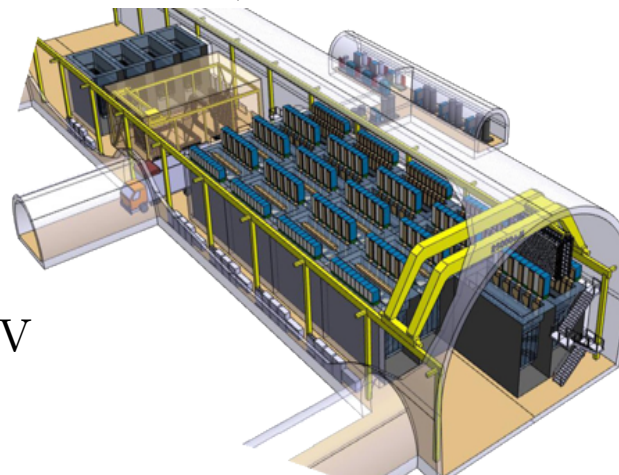


Full SuperNEMO

500 kg×yr :

$$T_{1/2}^{0\nu} > 10^{26} \text{ yr}$$

$$\langle m_\nu \rangle < 50 - 100 \text{ meV}$$

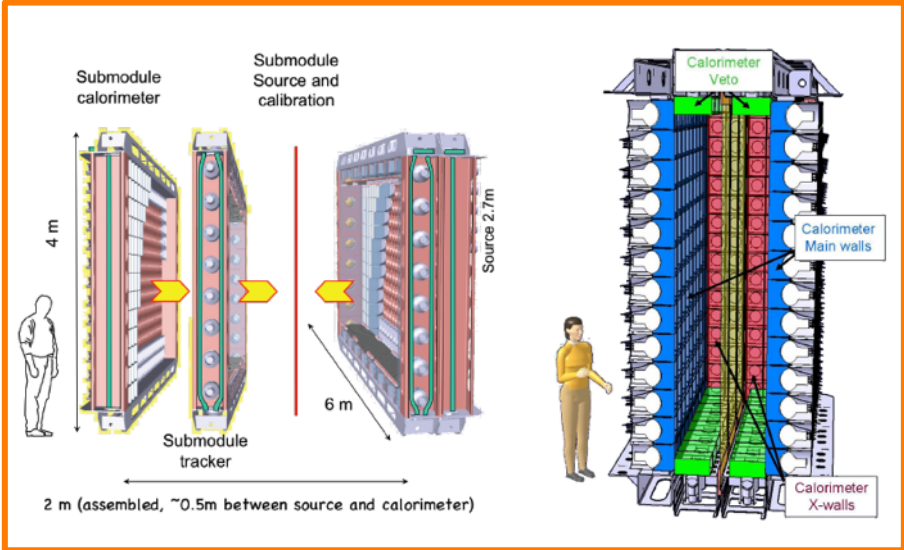


- R&D into modified SuperNEMO design :

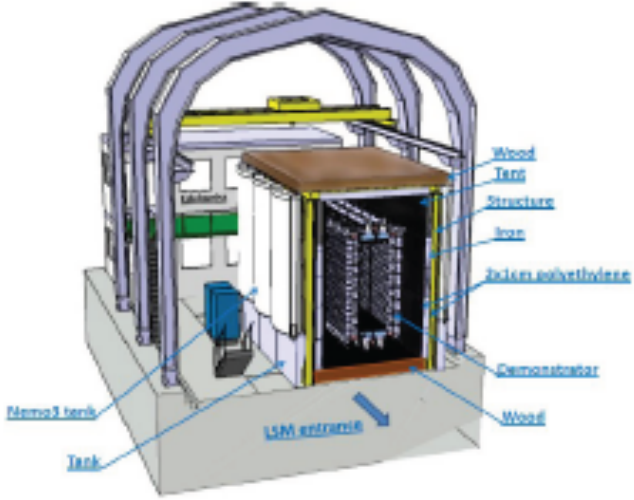
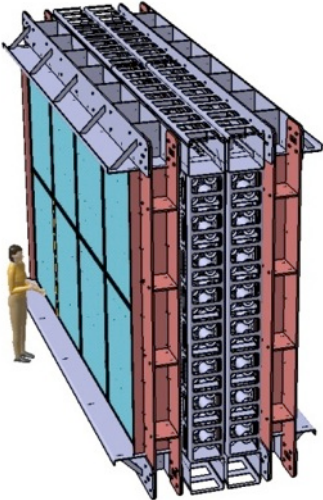
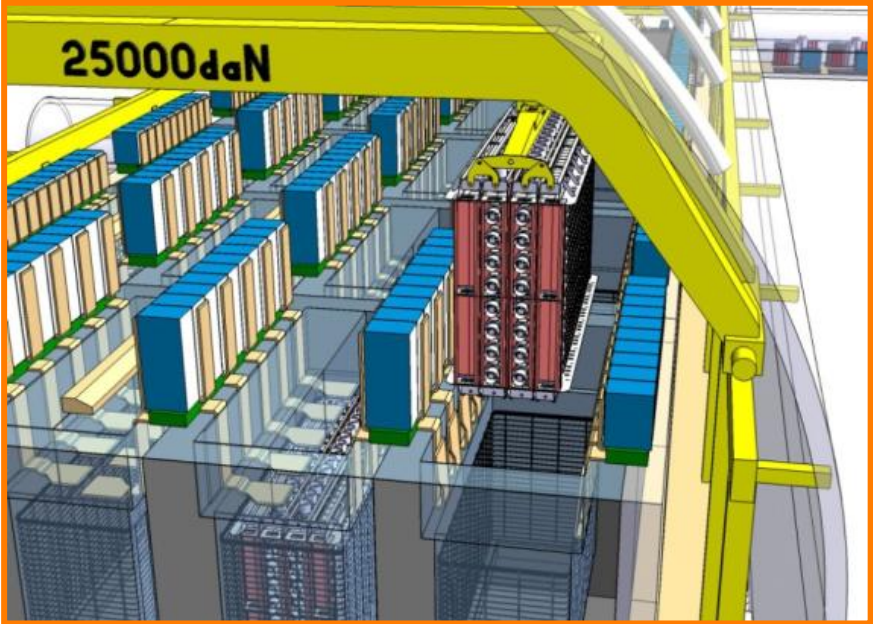
- *Cheaper.*
- *Enhanced sensitivity.*

SuperNEMO project

A module



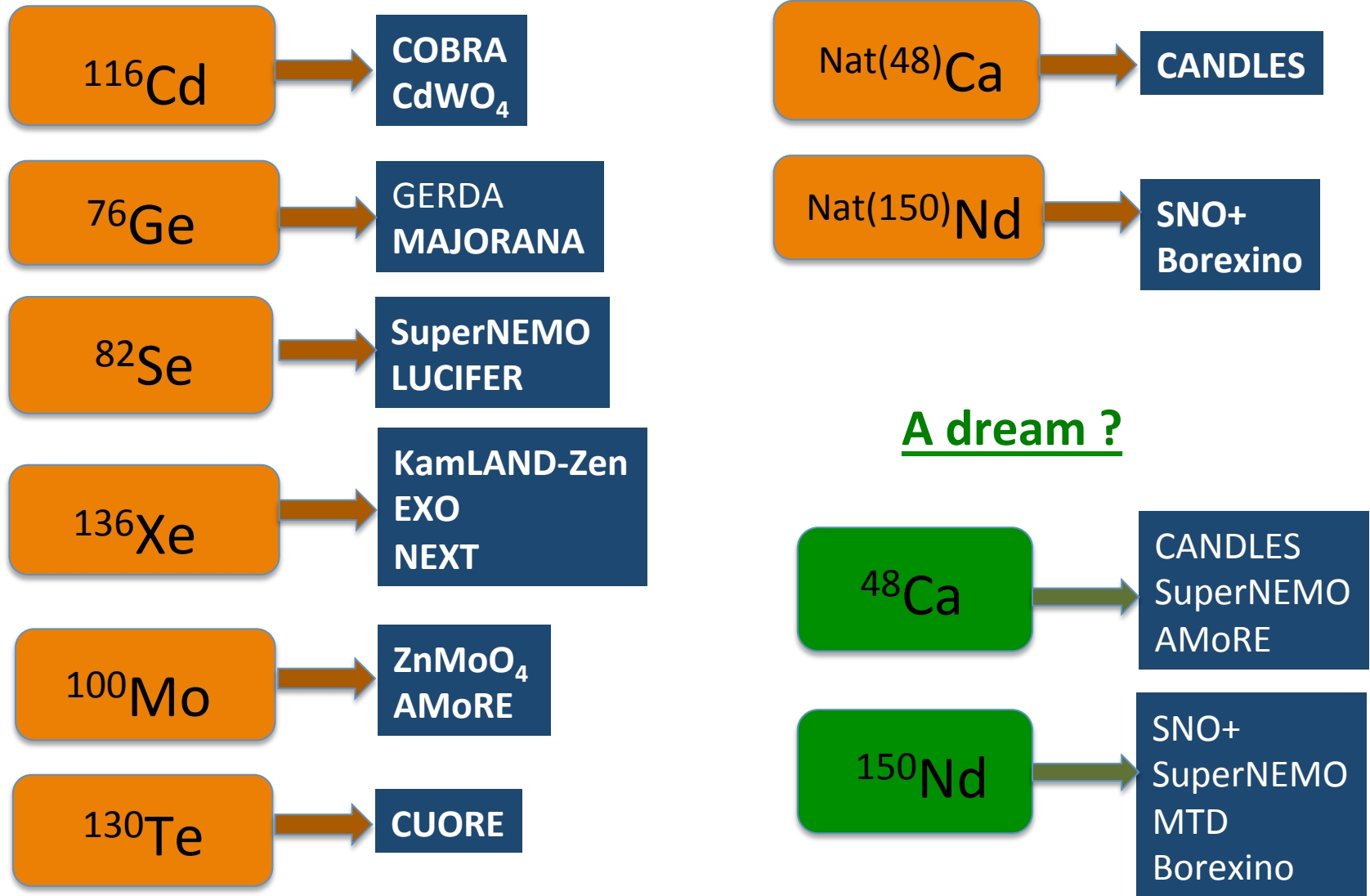
20 modules



Latest results

Experiment	isotope	Mass (kg)	Half-life limit in years	Neutrino mass limit in eV
H.M.	^{76}Ge	14	$1.9 \cdot 10^{25}$	0.21 - 0.53
GERDA	^{76}Ge	14	$1.9 \cdot 10^{25}$	0.20 - 0.40
Cuoricino	^{130}Te	12	$2.8 \cdot 10^{24}$	0.27 – 0.57
NEMO3	^{100}Mo	7	$1.0 \cdot 10^{24}$	0.31 – 0.79
EXO-200	^{136}Xe	200	$1.6 \cdot 10^{25}$	0.14 – 0.38
Kamland-Zen	^{136}Xe	400	$2.6 \cdot 10^{25}$	0.14 – 0.26

Present experiments or projects

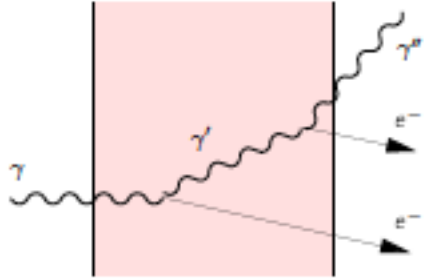


Summary

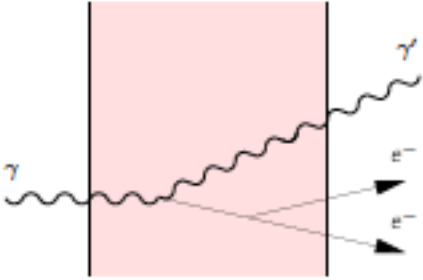
- ◆ The search of neutrinoless double beta decay is one of most important question in particle physics:
 - Neutrino nature
 - Neutrino mass
- ◆ The experimental search is a real challenge to reduce background
- ◆ Present sensitivity on neutrino mass $< 0.15 - 0.60$ eV with 10 kg
(or 400 kg of ^{136}Xe)
- ◆ 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

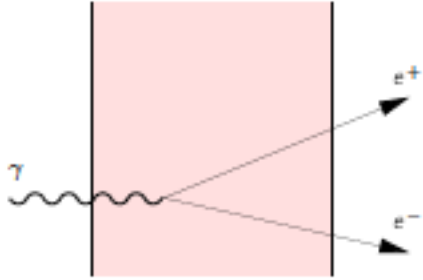
External (γ flux):



double
Compton

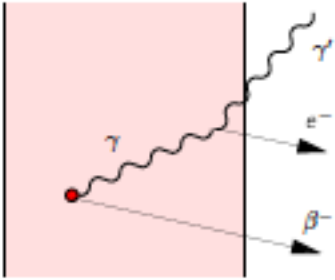


Compton +
Möller

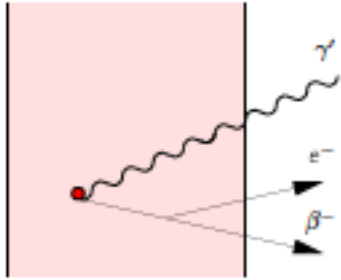


pair
production

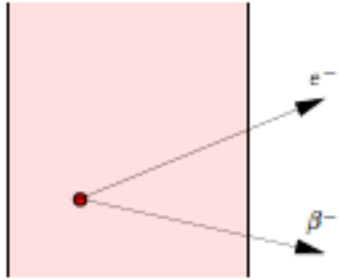
Internal (source foil contaminants):



β^- +
Compton



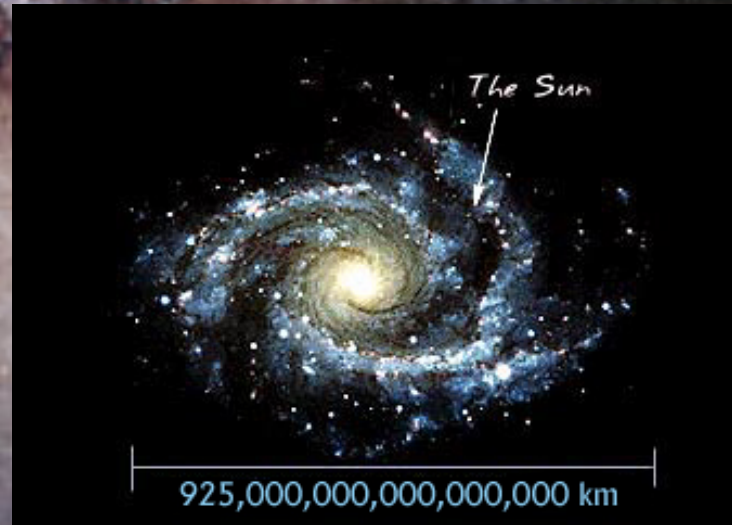
β^- +
Möller



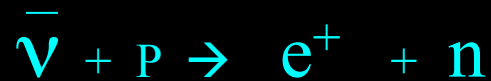
β^- +
IC

Piège à neutrino

30 000 000 000 000 000 000 km de plomb



Quelles interactions peut avoir le neutrino ?



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

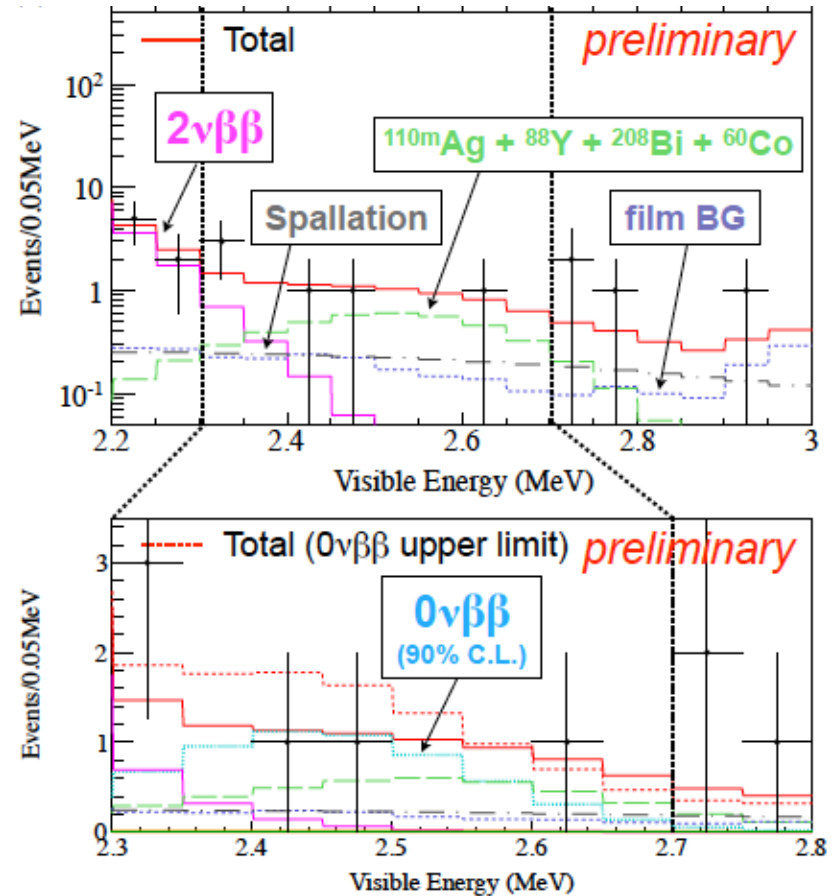
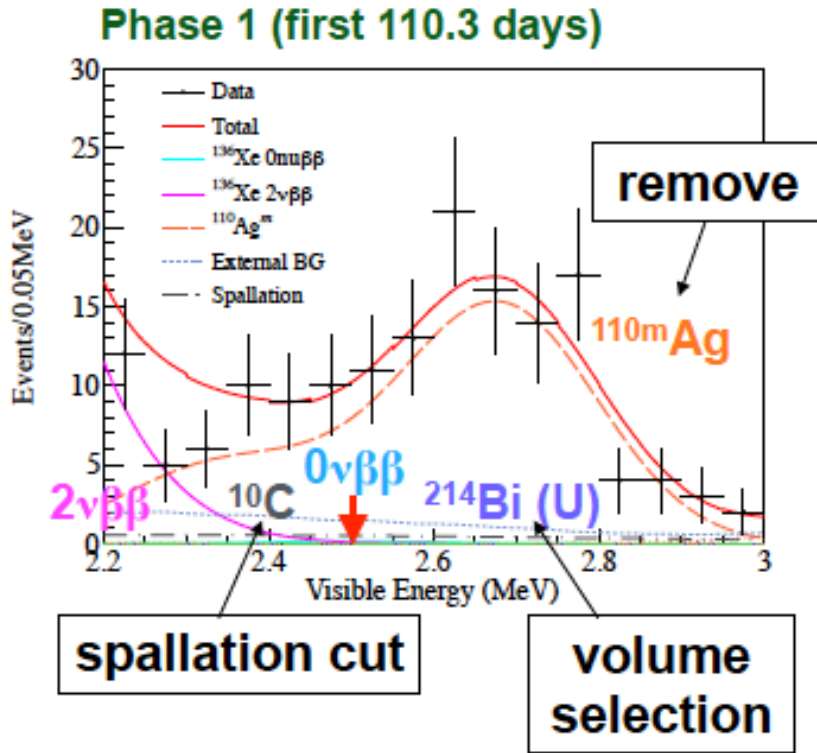
Possibility of enrichment
Expected half-life 10^{25} y

High isotopic abundance

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

Large liquid scintillator experiment: KamLAND-ZEN

Phase 2



Phase 1 $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr

Phase 2 $T^{0\nu}_{1/2} > 1.3 \times 10^{25}$ yr

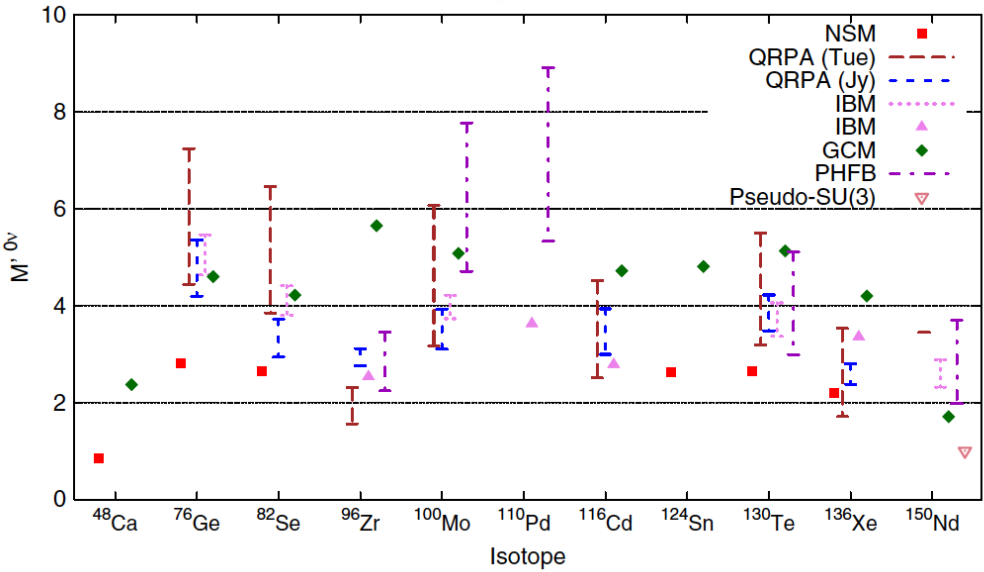
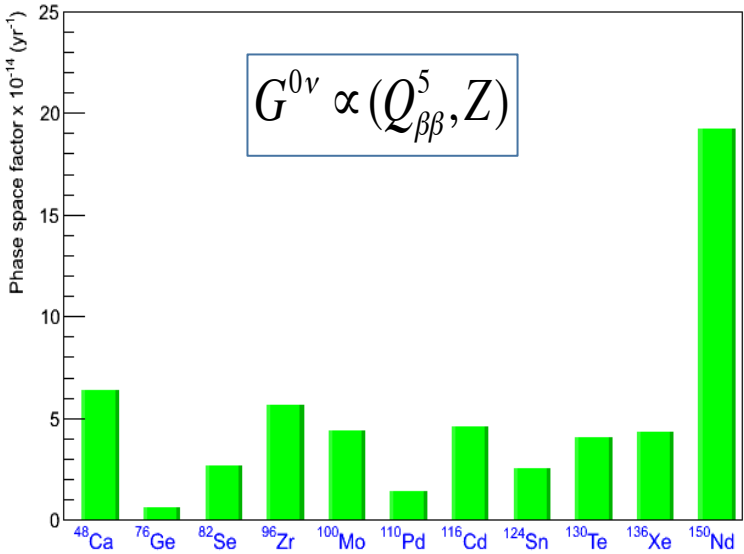
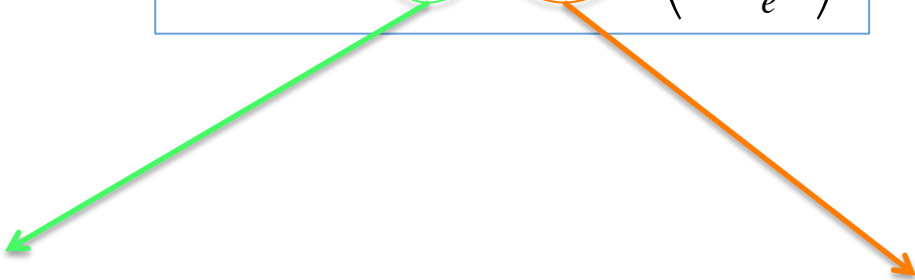
Combined $T^{0\nu}_{1/2} > 2.6 \times 10^{25}$ yr

QRPA NME model
J. Phys. G 39 124006 (2012)

$\langle m_{\beta\beta} \rangle < 0.14-0.28$ eV

Isotope choice

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



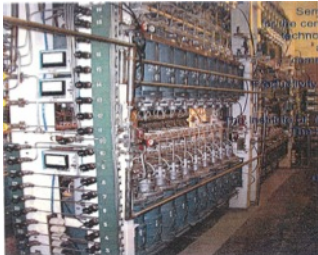
Isotopic enrichment

Nucleus	Existing method	R&D
^{48}Ca		Laser separation, gaseous 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

