From Majorana to SuperNEMO

The nature of neutrino

Pr. Jose Busto
CPPM / Université d'Aix Marseille

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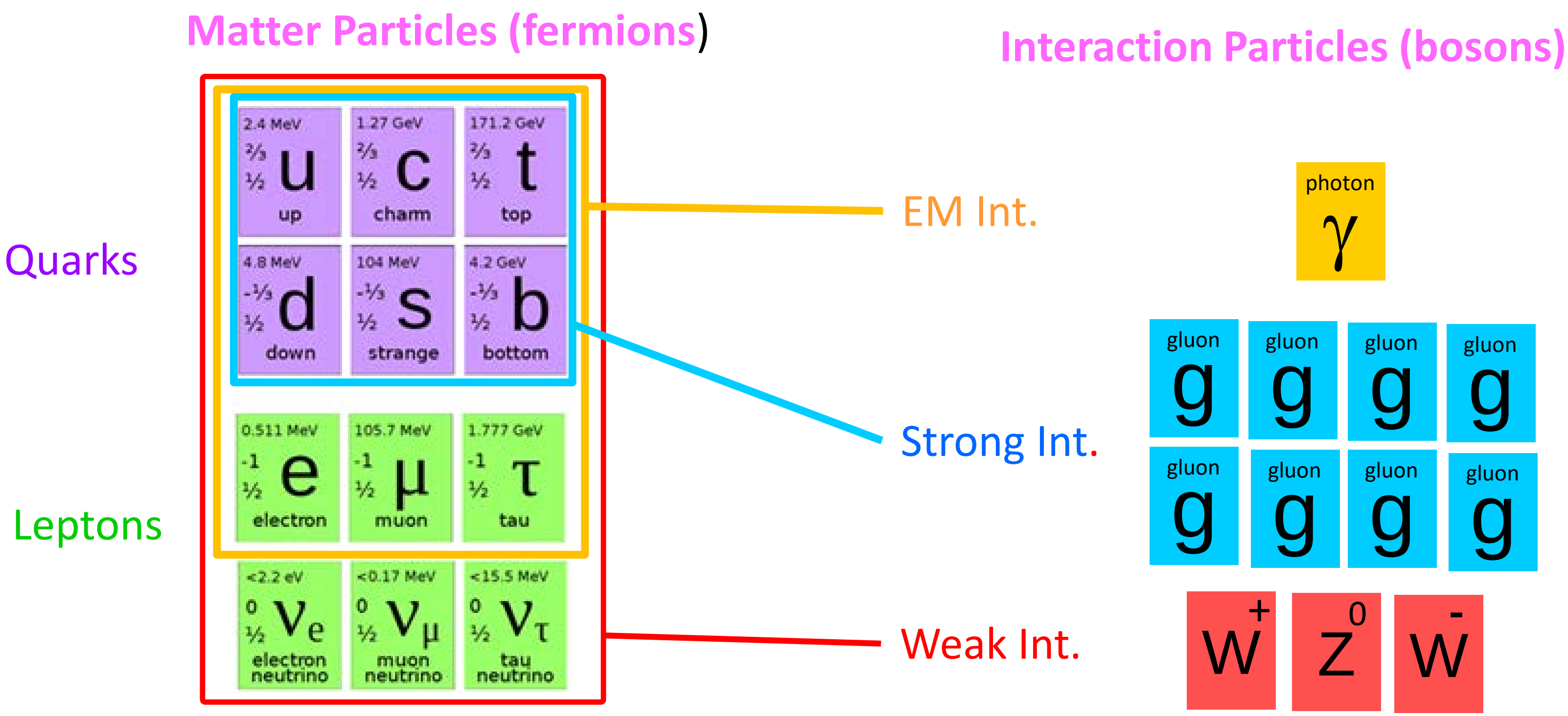
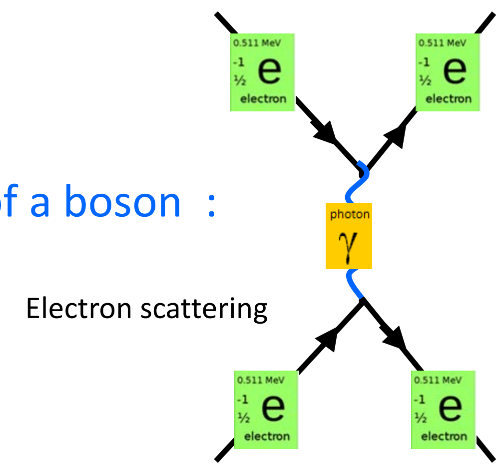
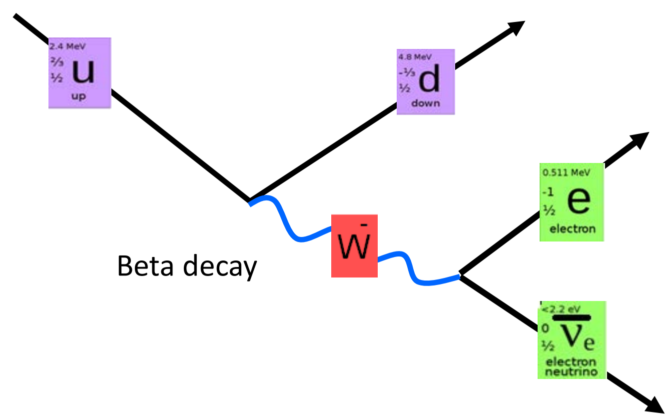
Standard Model of particle and interactions

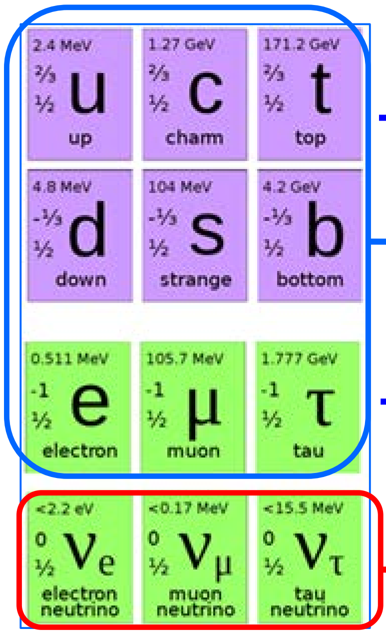


Interaction by exchange of a boson :





Charge and mass

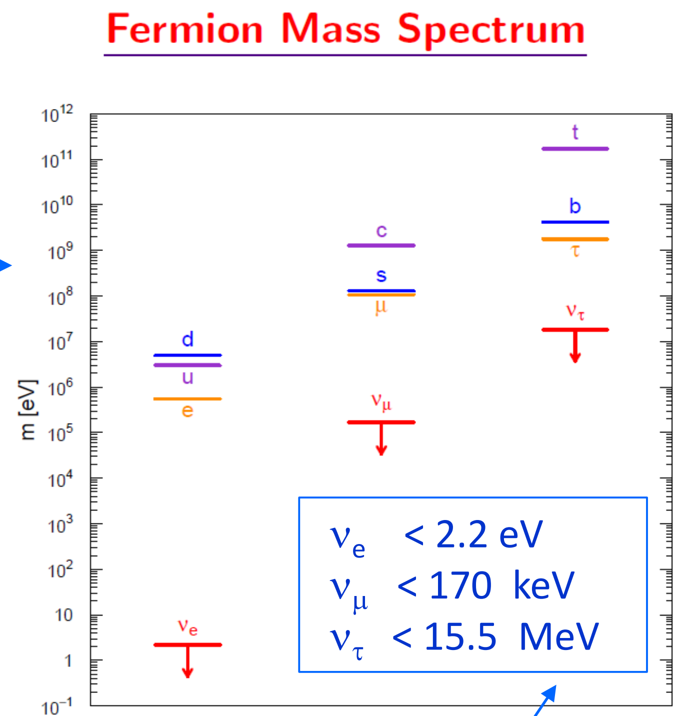


Electric charge : +2/3

mass

Electric charge : - 1/3

"No mass (in SM)"
No charge



Direct mass limits

Neutrino : Only fundamental particle without electric charge and practically no mass

Remark : In Minimum Standard Model neutrino is massless particle

The evolution of a microscopic system in Quantum Mechanics

Non relativistic Particle : Schrodinger Equation

$$\left[\frac{-\hbar^2}{2m}\nabla^2 + V\right]\Psi = i\hbar\frac{\partial}{\partial t}\Psi$$

Relativistic Particle : Dirac Equation

$$\left(i\gamma^\mu\partial_\mu - m\right)\psi = 0$$

$E^2 = p^2c^2 + m^2c^4$ ⟶ Positive and Negative energy solutions

↳ Particle (p), ↳ antiparticle (p^c)

If charge particle is Q < 0, antiparticle is Q > 0 => Charge conjugation operator (C)

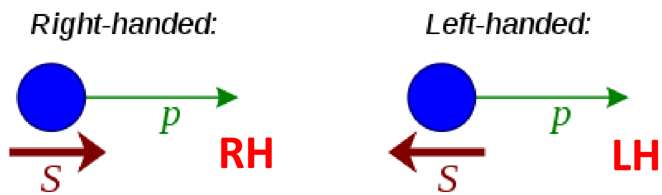
e^- (particle) $\xrightarrow{C}$ e^+ (antiparticle)

Four solutions in Dirac Equation (spin ½) : $e^-(+\frac{1}{2}), e^-(-\frac{1}{2}), e^+(+\frac{1}{2}), e^+(-\frac{1}{2})$

What about neutral particles ?

Helicity operator

Projection of spin on momentum



$$h\chi = \frac{\vec{\sigma}\cdot\vec{p}}{p}\chi$$

- Helicity is not a good quantum number. It depends on the framework
- Helicity is a good quantum number for massless particles (Helicity ≡ Chirality)

Massive particle $(i\gamma^\mu\partial_\mu - m)\psi = 0$

Massless particle $i\gamma^\mu\partial_\mu\psi = 0$

Chiral representation

$\psi = \psi_R + \psi_L$

→ $\Psi_L, \Psi_R, \Psi_L^C, \Psi_R^C$

→ Ψ_L, Ψ_R^C OR Ψ_L^C, Ψ_R

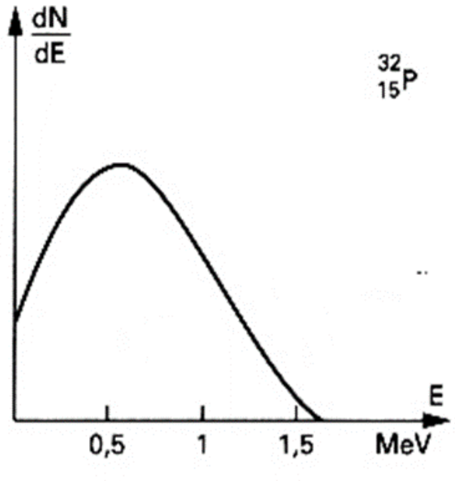
If neutrino is massless, or very light => two possibilities : Left Handed or Right Handed

Which one is the good helicity for a massless particle ?

Beta decay

Pauli 1930

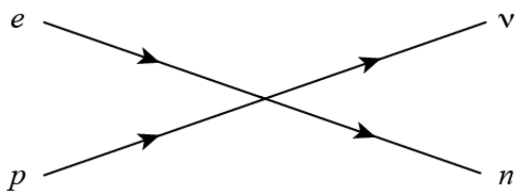
$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} + \upsilon_{e}^{c} $$



Continuous spectrum → neutrino hypothesis

Fermi 1933

$$ n \rightarrow p + e^{-} + "\upsilon" $$



Point interaction, no W boson

New, neutral and very small mass, particle

What's " ν " ?

- Conversation laws

$$a + b \rightarrow c + d$$

- electric charge
- energy
- momentum
- angular momentum
- baryon number
- lepton number

Strong symmetries (electric charge, energy, momentum, angular momentum)

It works (baryon number, lepton number)

(Requirement for SM)

Lepton number L :

- +1 Lepton (e^-, μ^-, τ^-, ν)
- -1 antiLepton (e^+, μ^+, τ^+, ν^c)
- 0 No lepton (quarks)

$$n \rightarrow \quad p \; + \; e^- + "\nu"$$

Lepton Number 0 = 0 +1 -1

=> " ν " must be an antineutrino

$$n \rightarrow \quad p \; + \; e^- + \nu^c$$

very small mass =>

Anti-neutrino : Left Handed or Right Handed ??

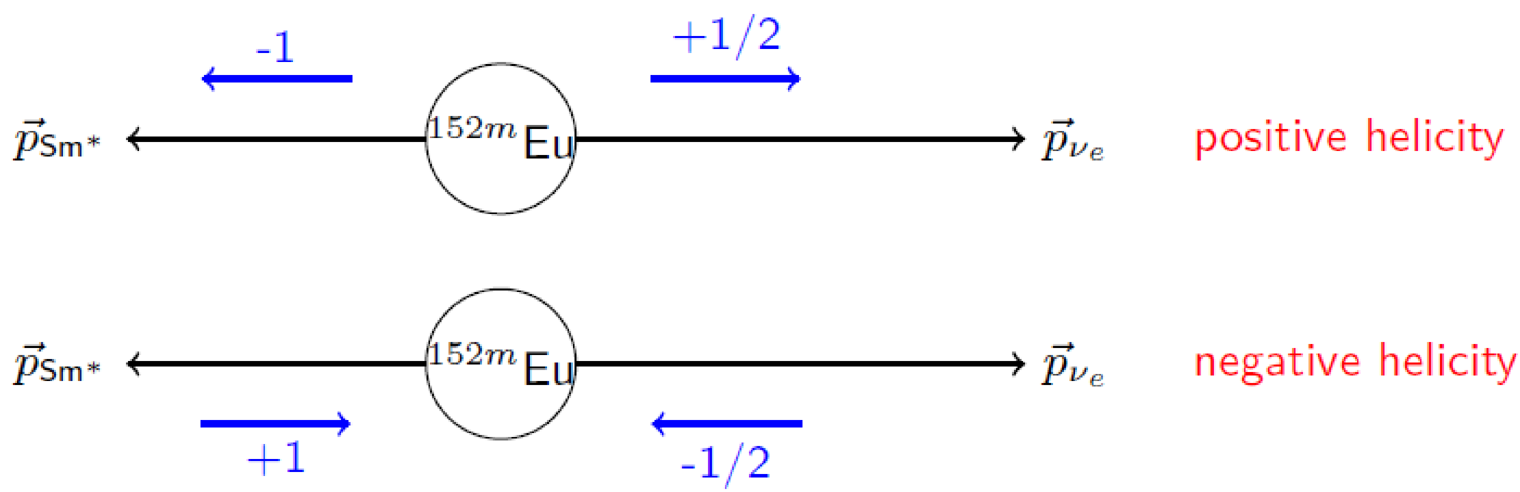
Goldhabert measure the neutrino helicity in 1958

The Goldhaber experiment

- K-shell electron capture ⇒ 2-body decay

$$^{152m}\mathrm{Eu}(J=0) + e^- \to {}^{152}\mathrm{Sm}^*(J=1) + \nu_e$$

- Fast to decay ⇒ $T_{1/2} = 9.53$ h
- Total angular momentum of the initial state is the spin of the captured electron ⇒ in the final state, spins of Sm and ν_e are always opposite
- The recoiling nucleus has the same polarization (or helicity) as the neutrino

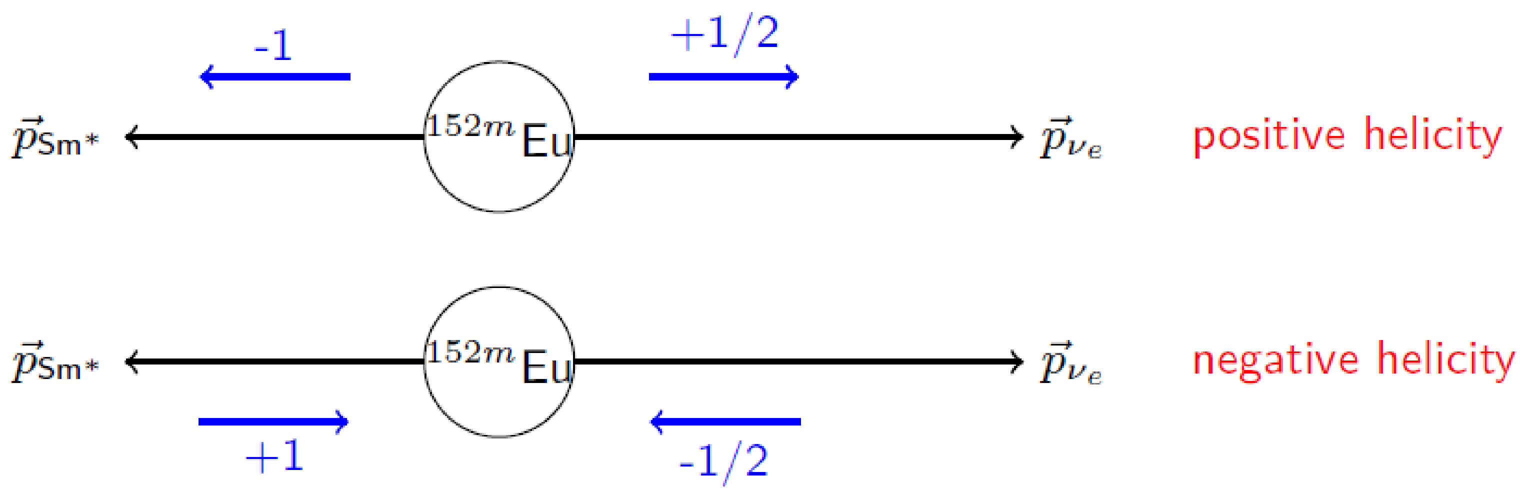


The Goldhaber experiment (cont'd)

- Decay of Sm*:

$$^{152}\mathrm{Sm}^*(J=1) \to {}^{152}\mathrm{Sm}(J=0) + \gamma(960\ \mathrm{keV})$$

- If the photon is emitted along the direction of motion of excited Samarium:



$$\boxed{\Rightarrow H(\gamma) = H(\nu_e)}$$

The Goldhaber experiment (cont'd)

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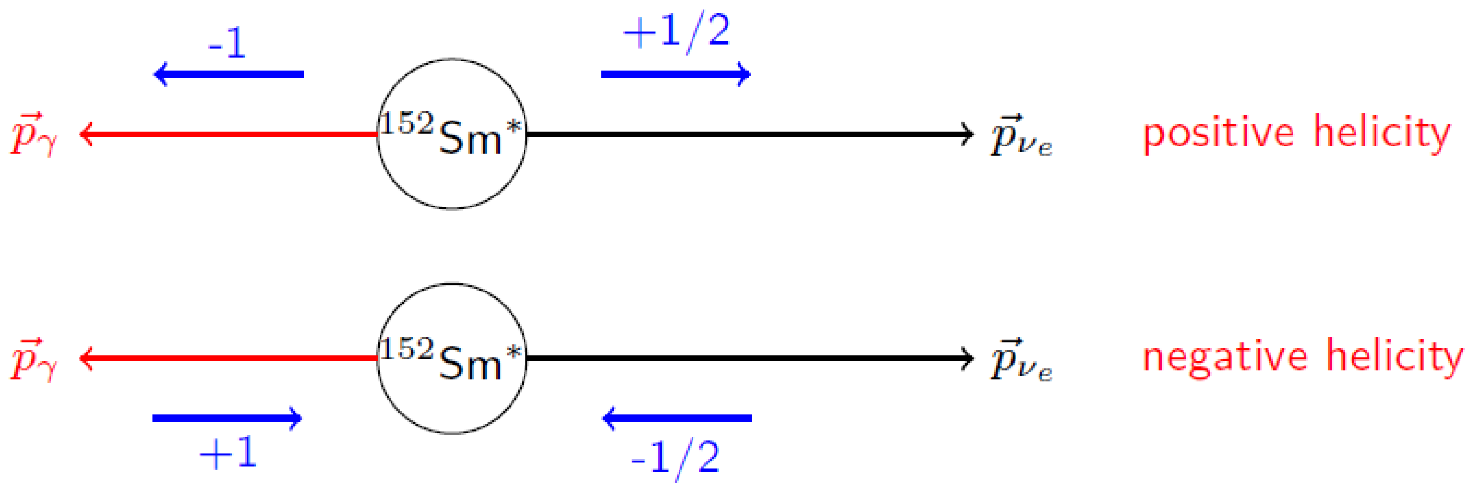

$$\Rightarrow H(\gamma) = H(\nu_e)$$

The Goldhaber experiment (cont'd)

- Hence to measure neutrino helicity we need:
  - to select photons emitted along the direction of excited Samarium (= forward photons)
  - to measure their polarization

The Goldhaber experiment (cont'd)

- Hence to measure neutrino helicity we need:

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  - to measure their polarization

- Use resonant scattering method

$$\gamma + {}^{152}\mathrm{Sm} \longrightarrow {}^{152}\mathrm{Sm}^{*} \longrightarrow {}^{152}\mathrm{Sm} + \gamma$$

  only possible for > 960 keV photons!

- Photons do not possess all the energy of de-excitation of Samarium because of the recoiling nucleus

- Only photon that are emitted along the direction of Samarium are Doppler shifted and have energy > 960 keV $\Rightarrow$ only forward emitted photon can excite a Sm atom again

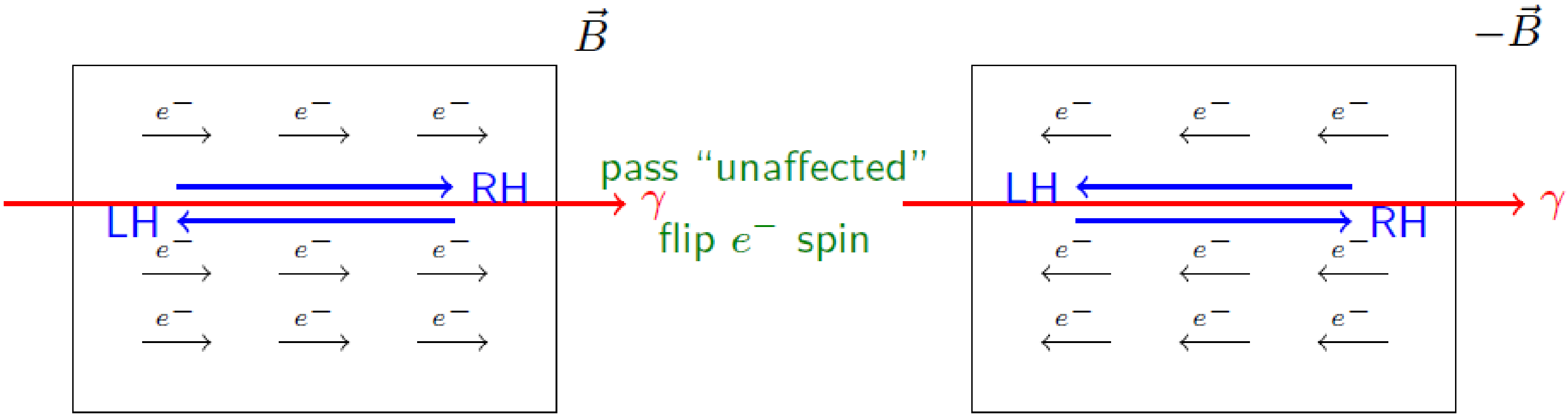
The Goldhaber experiment (cont'd)

- Hence to measure neutrino helicity we need:

  - to select photons emitted along the direction of excited Samarium (= forward photons)

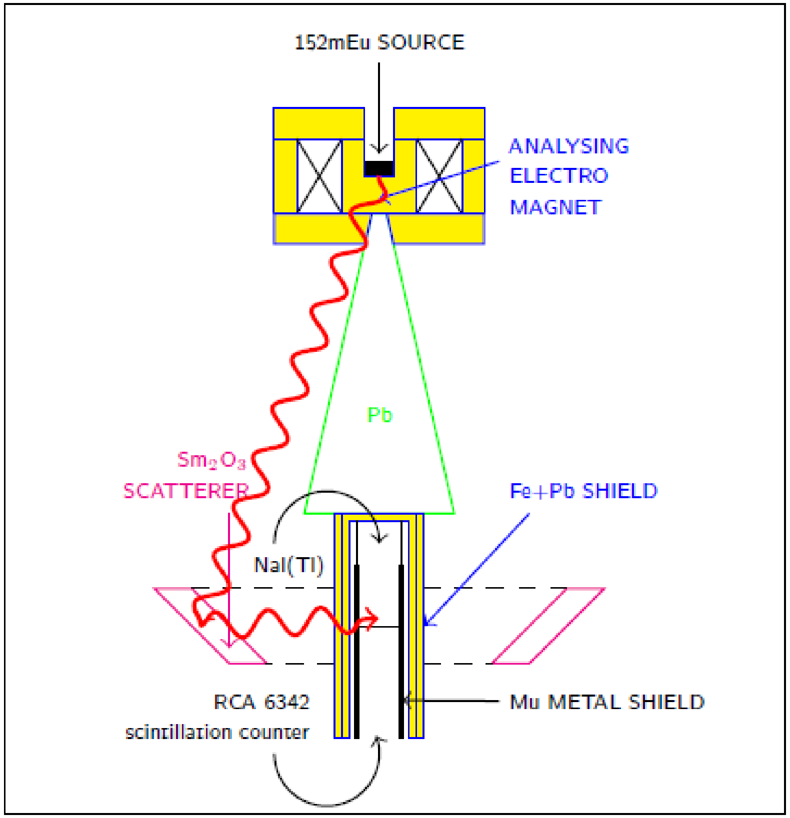
  - to measure their polarization

- Scattering on polarized electrons in a iron magnet



- Compton scattering is bigger for opposite spin orientation of electron and photon $\Rightarrow$ only photons with same spin orientation than electrons will be able to do resonant scattering

The Goldhaber experiment (cont'd)

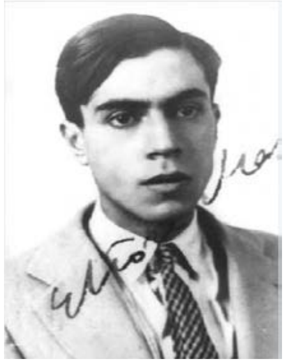


- Electron capture by $^{152}\mathrm{Eu}$
- Decay of $^{152}\mathrm{Sm}^*$ with emission of γ
- Measurement of γ polarization by scattering on polarized electrons in iron
- Resonant scattering in $^{152}\mathrm{Sm}$ selects only forward emitted γ
- Reemitted γ measured by NaI
- Count number of γs and change B-field

Neutrino helicity, $H = -1.0 \pm 0.3$

ν_{LH} and ν^c_{RH}

What is the nature of the neutrino ?



« Symmetric theory of electron and positron »

Ettore Majorana 1937 *(brilliant student of Fermi)*

In Dirac equation, fields ψ (x) are complex functions.

$$(i\gamma^\alpha\partial_\alpha - m)\psi(x) = 0$$

Majorana looks for real solutions of Dirac equation.

$$\psi(x) = \frac{1}{\sqrt{2}}\chi_1 + i\frac{1}{\sqrt{2}}\chi_2$$

$$(i\gamma^\alpha\partial_\alpha - m)\chi_{1,2}(x) = 0$$

However ⇒

$$\boxed{\chi^c_{1,2}(x) = \chi_{1,2}(x)}$$

Particle ≡ anti-Particle

Only possible for neutrinos *(Q =0)*

Dirac

$\upsilon_D \neq \upsilon_D^C$

or

Majorana

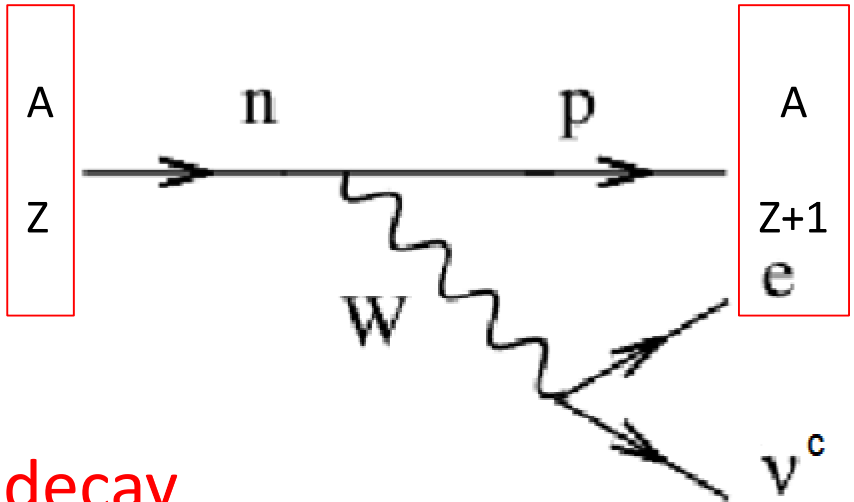
$\upsilon_M = \upsilon_M^C$

?????

If ν is Majorana, Lepton number is not conserved.

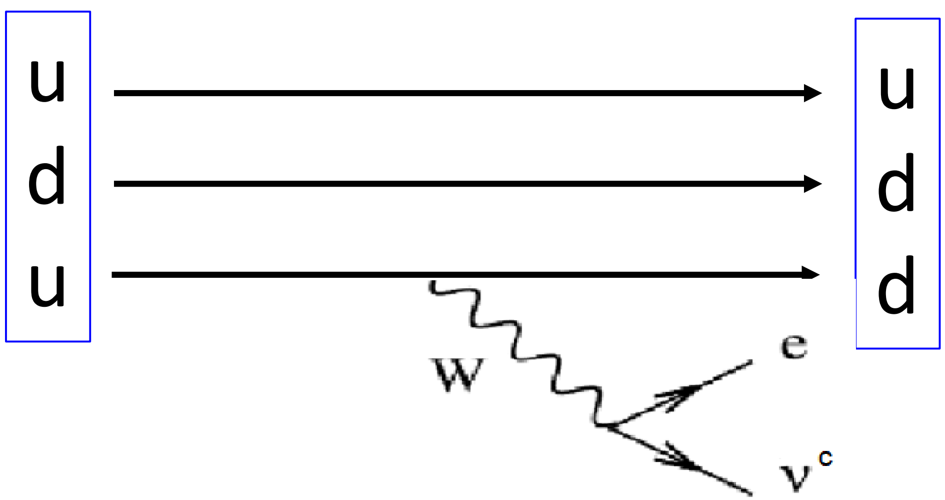
Need new physics beyond de SM

From single beta to double beta



β^{-}

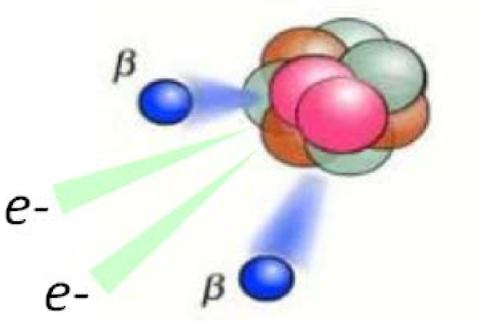
Single beta decay

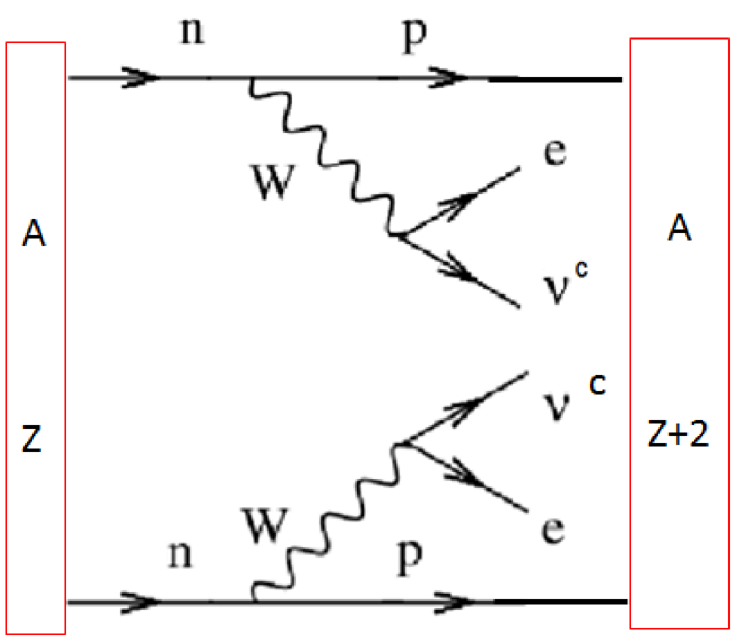


Double Beta Decay

$(\beta\beta)_{2\nu}$

Two neutrinos DBD





β^-

β^-

Two decays in the same nucleus at the same time

Prosed by Maria Goeppert – Mayer en 1935

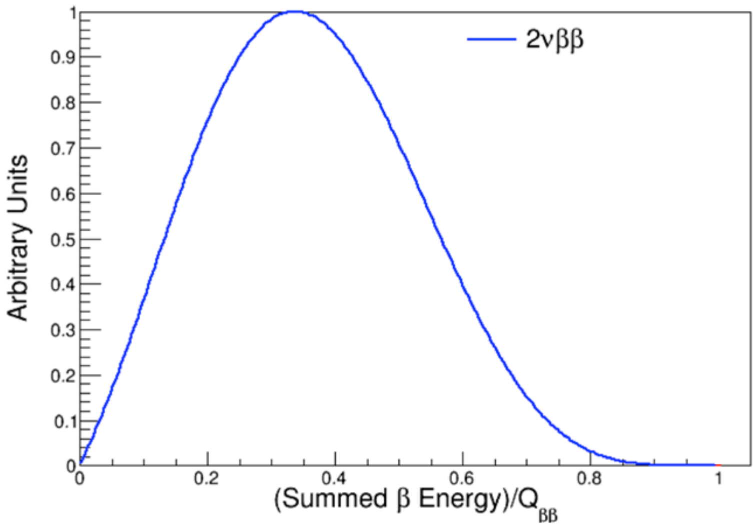
Observed for the first time in 1987 by Michael Moe

→ 10^{19} to 10^{21} y

Very rare but allowed process *(longest radioactive process)*

Two neutrinos spectrum

$(\beta\beta)_{2\nu}$



$${}^{A}_{Z}X \rightarrow {}_{Z+2}^{A}Y + 2e^{-} + 2\upsilon_{e}^{c}$$

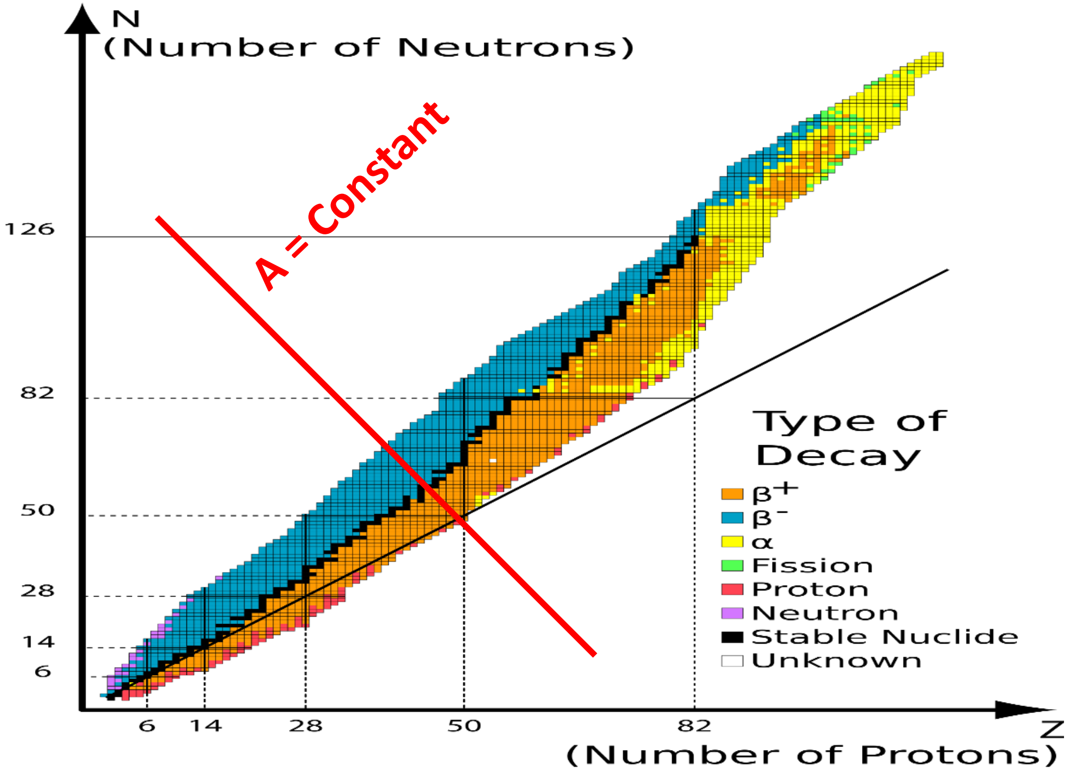
$$Q_{\beta\beta} = M\left({}^{A}_{Z}X\right) - M\left({}_{Z+2}^{A}Y\right)$$

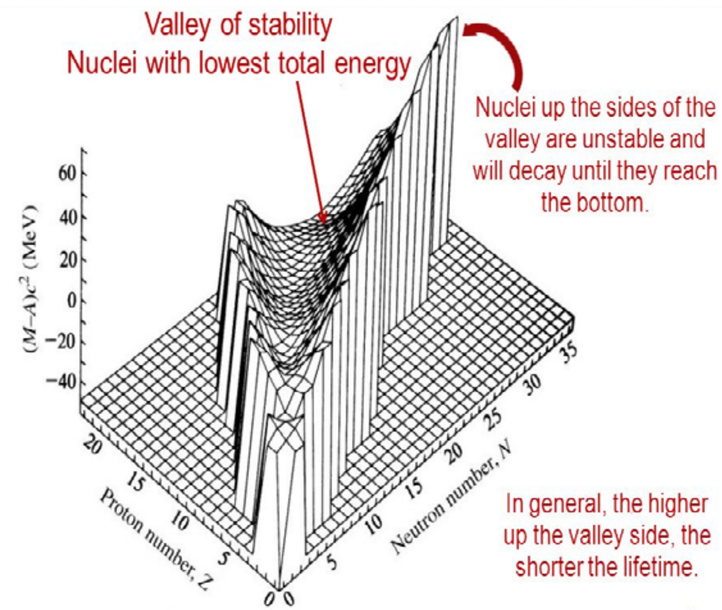
$$\frac{1}{T_{1/2}^{2\nu}} = G_{2\nu}(Q_{\beta\beta}^{11}, Z) \bullet \left|M_{2\nu}\right|^{2}$$

G = phase space (well known)

M = nuclear matrix element (challenging)

Which nucleus can decay by $(\beta\beta)_{2\nu}$





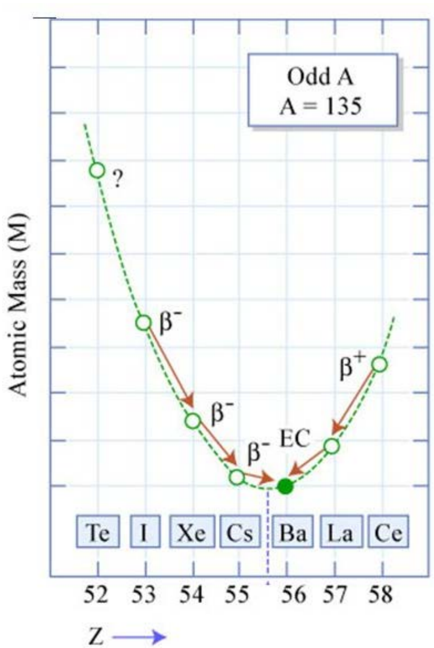
Bethe Weizsaecker formula

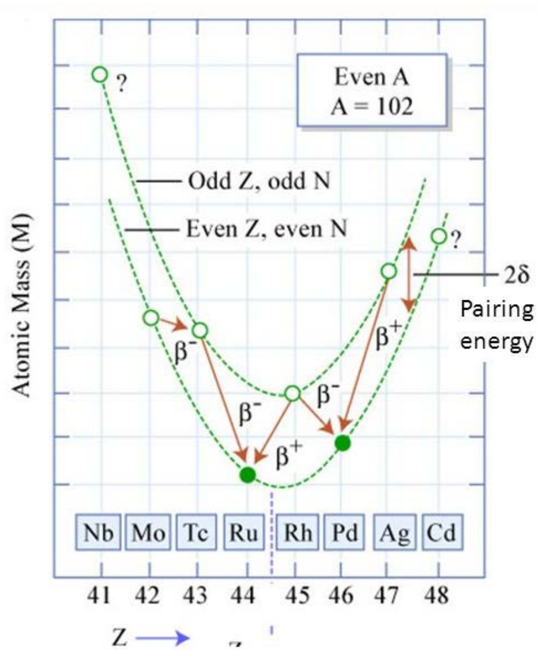
(Liquid drop model)

$$E_b(MeV) = a_V A - a_S A^{\frac{2}{3}} - a_C \frac{Z^2}{A^{\frac{1}{3}}} - a_A \frac{(A-2Z)^2}{A} \pm \delta(A,Z) \qquad \delta(A,Z) = \begin{matrix} +\delta_0 \ for\ Z,N\ even \\ 0 \\ -\delta_0 \ for\ Z,N\ odd \end{matrix}$$

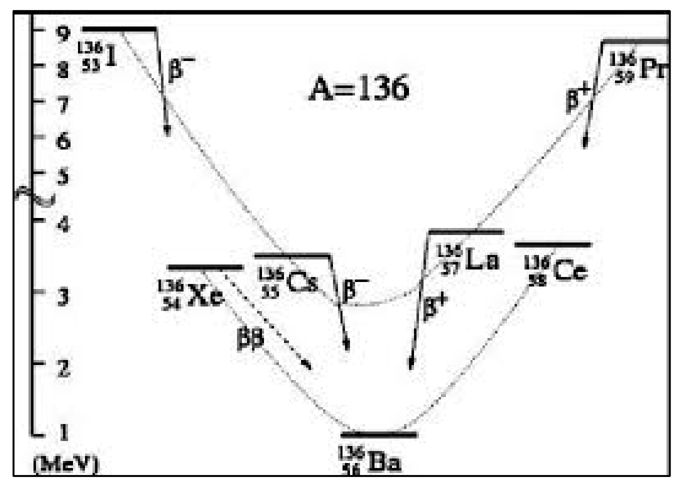
Mass or binding energy of nucleus

A = constant

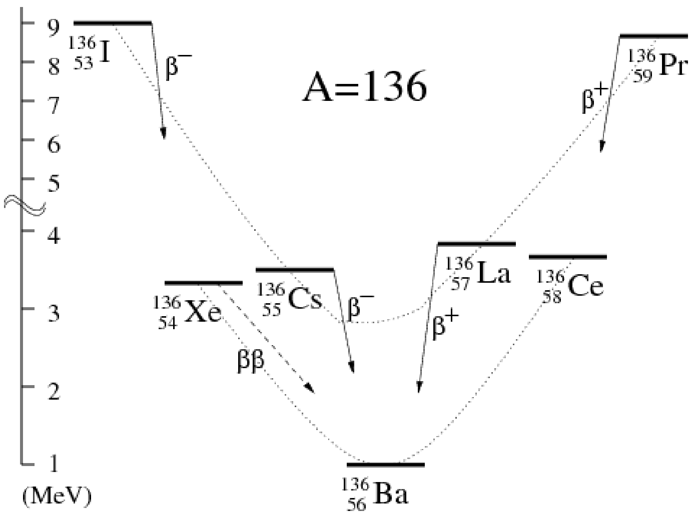




For some even nucleus decay
to (A, Z+1) is impossible



Some ββ candidates



Isotope	$Q_{\beta\beta}$ (MeV)	Nat. Abund. (%)
^{48}Ca	4.274	0.187
^{76}Ge	2.039	7.8
^{82}Se	2.996	9.2
^{96}Zr	3.348	2.8
^{100}Mo	3.035	9.6
^{110}Pd	2.004	11.8
^{116}Cd	2.809	7.6
^{124}Sn	2.530	5.6
^{130}Te	2.530	34.5
^{136}Xe	2.462	8.9
^{150}Nd	3.367	5.6

Neutrinoless Double Beta Decay

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

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

Racah mecanism

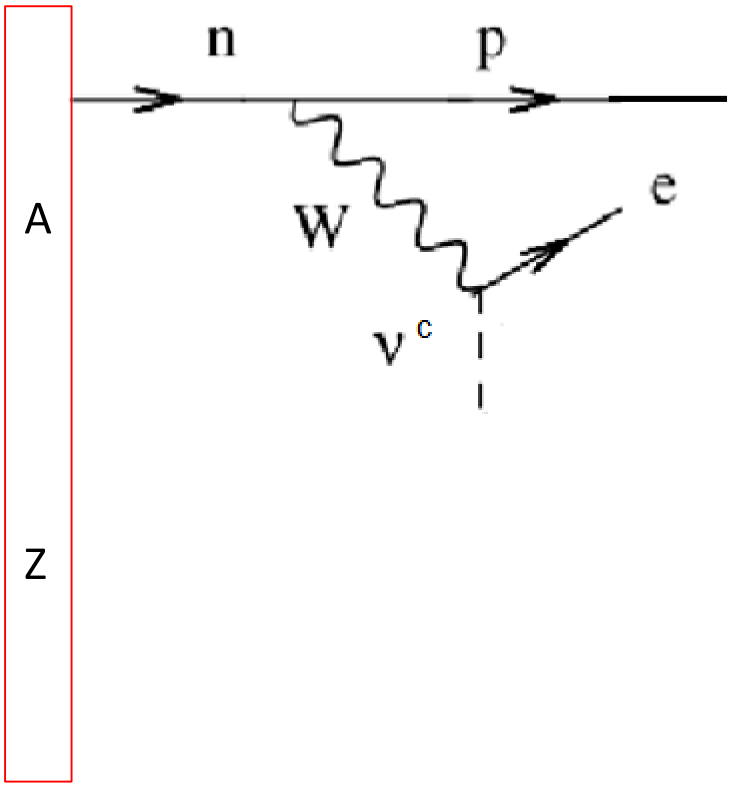
$n \rightarrow p + e^{-} + "\upsilon"$	Beta Decay	BD
$"\upsilon" + n \rightarrow p + e^{-}$	Inverse Beta Decay *(Neutrino capture*	IBD

In SM

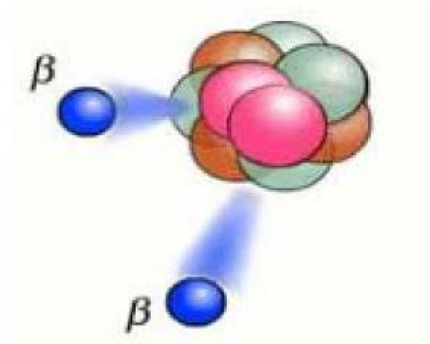
: ν (BD) is a RH anti-Neutrino

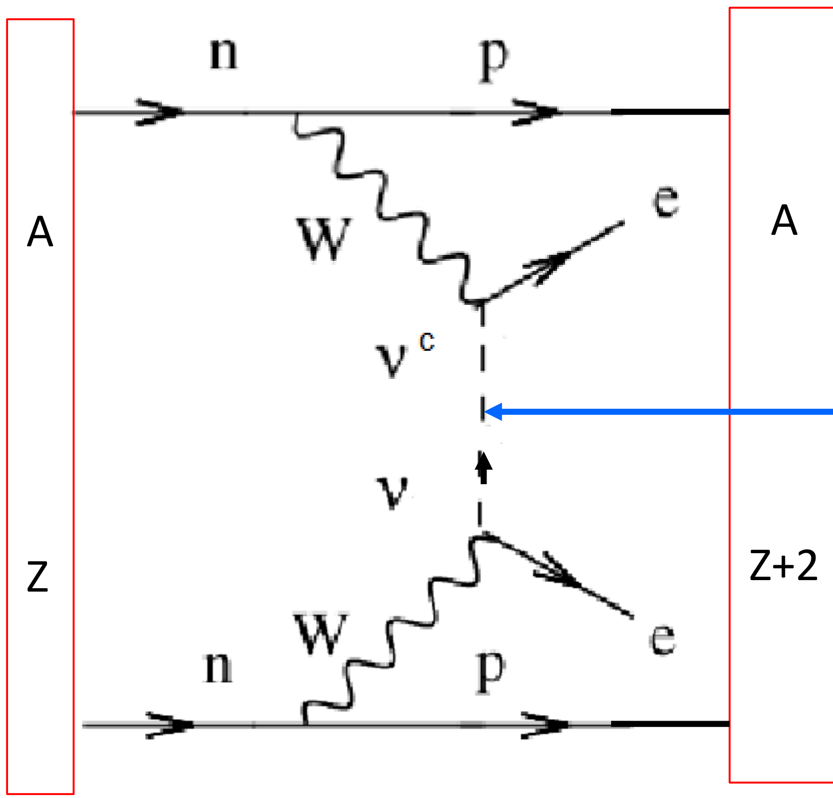
: ν(IBD) is a LH neutrino

Neutrinoless Double Beta Decay $(\beta\beta)_{0\nu}$



Neutrinoless Double Beta Decay $(\beta\beta)_{0\nu}$

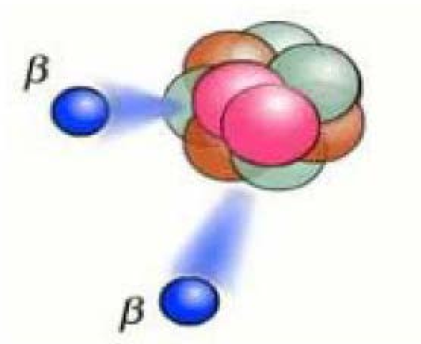


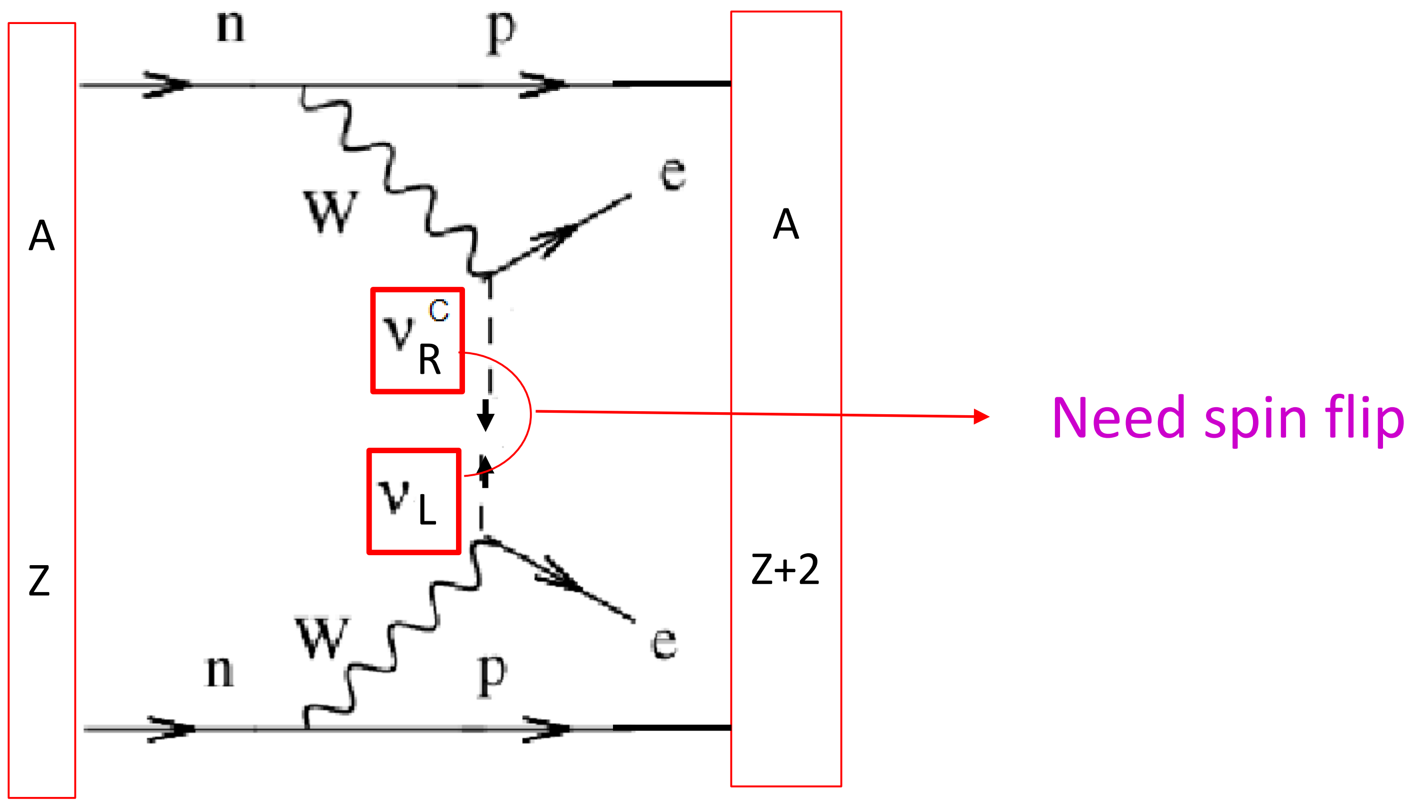


$$\upsilon \equiv \upsilon^{c}$$

$\Delta L \neq 0$ => Forbiden in the SM

Neutrinoless Double Beta Decay $(\beta\beta)_{0\nu}$

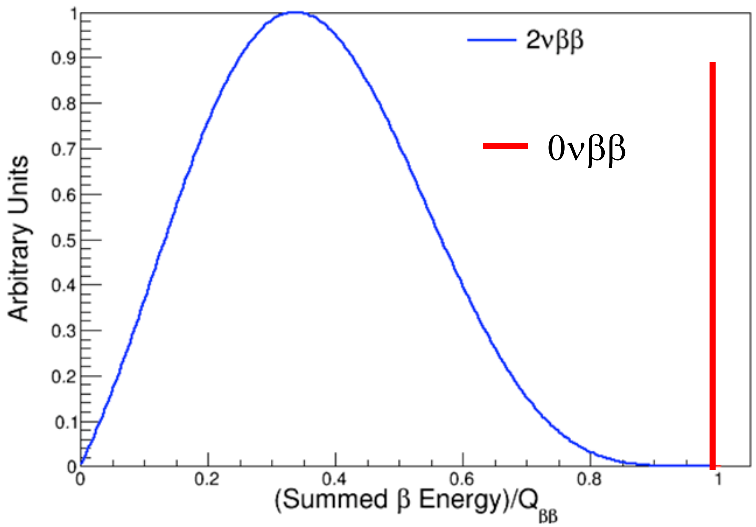




Spin flip :

- $\upsilon_R^M \xrightarrow{\text{L.T.}} \upsilon_L^M$ => <u>**Massive neutrino**</u>
- In SM IBD ν is Left-handle (LHC)
  => New interaction : IBD ν is Right-handle (RHC)
  => <u>**RH courrent → V+A interaction**</u>

Neutrinoless ββ spectrum



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

$$Q_{\beta\beta} = M({}^{A}_{Z}X) - M({}_{Z+2}^{A}Y)$$

Phase space

Effective neutrino mass

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}(Q^5_{\beta\beta}, Z) \bullet |M_{0\nu}|^2 \bullet \langle m_{\beta\beta} \rangle^2$$

Nuclear matrix

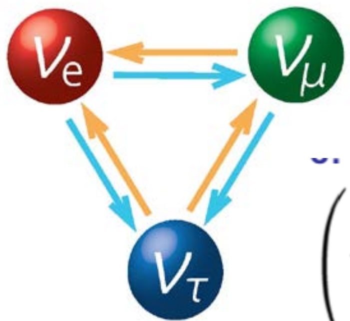
ν mass eigenstates

$$|\langle m_{\beta\beta} \rangle| \equiv | m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha^*} + m_3 |U_{e3}|^2 e^{i\beta^* - 2i\delta} |$$

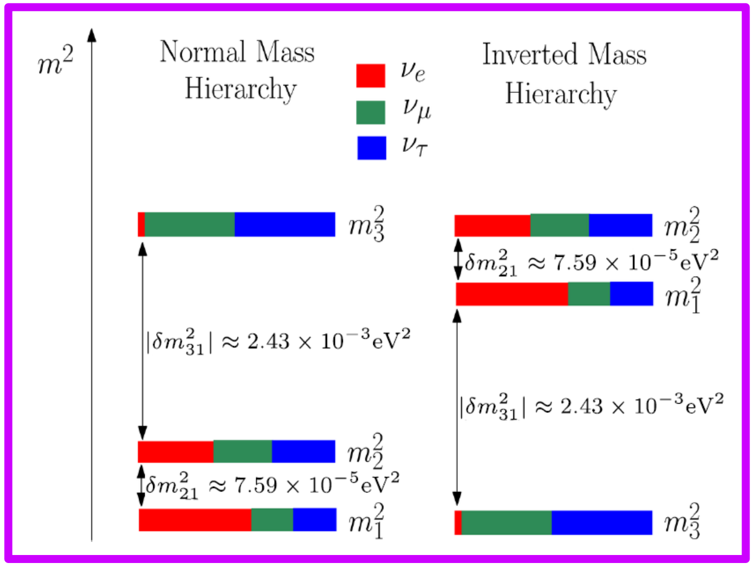
ν mixing

Quantitative parameter for a (ββ)0ν experiment

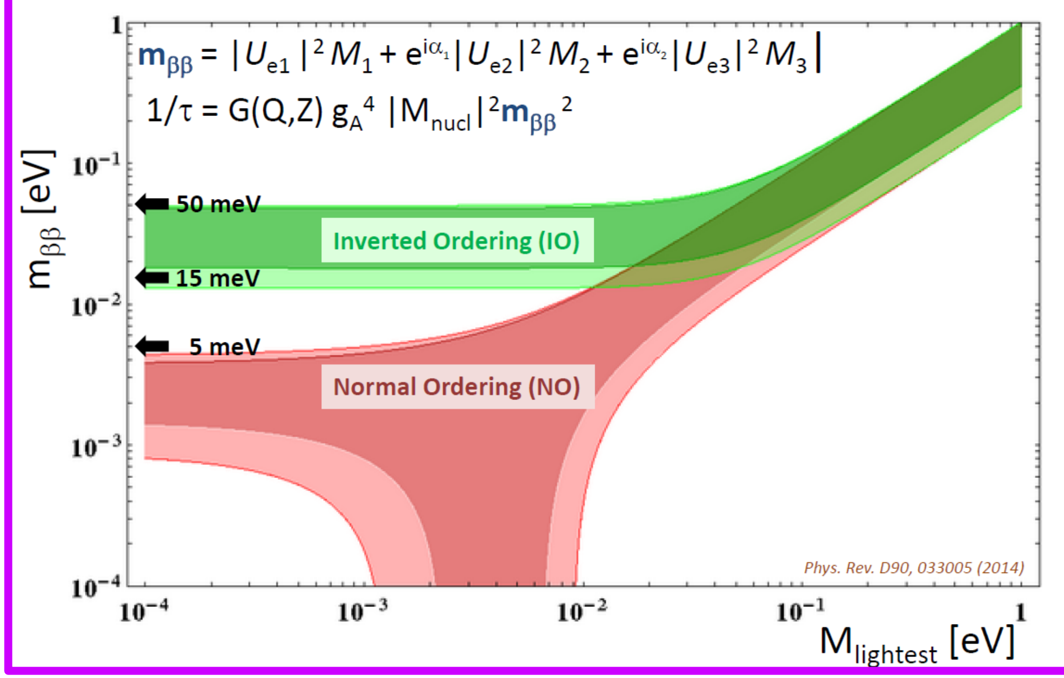
Oscillations of neutrino



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



Standard mechanism: $m_{\beta\beta}$ vs. lightest ν mass



Remarks

$(\beta\beta)_{0\nu}$ has never been observed

$(\beta\beta)_{0\nu}$ is a very good process to test physics beyond the SM in which Lepton Number is not conserved.

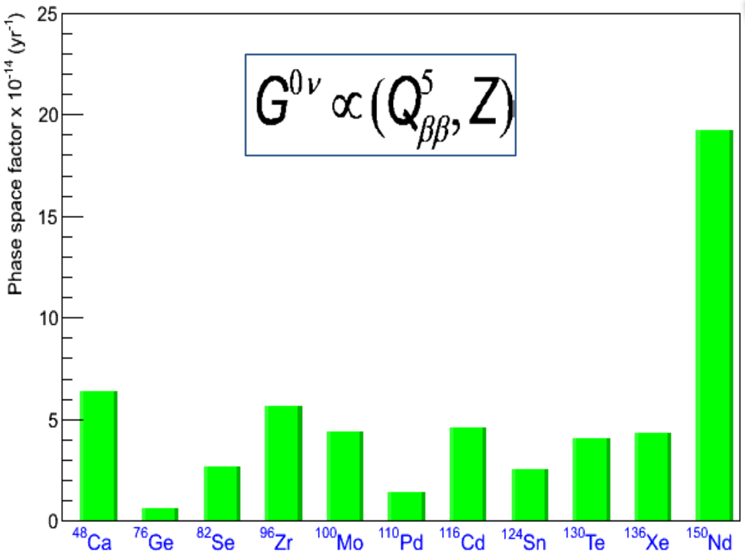
Grand Unification Theories, Super Symetry, . . .

In general Quantum Field Theory, and in particular in GUT the see-saw mechanism is a generic model to produce neutrinos with very small mass. Those neutrinos are Majorana

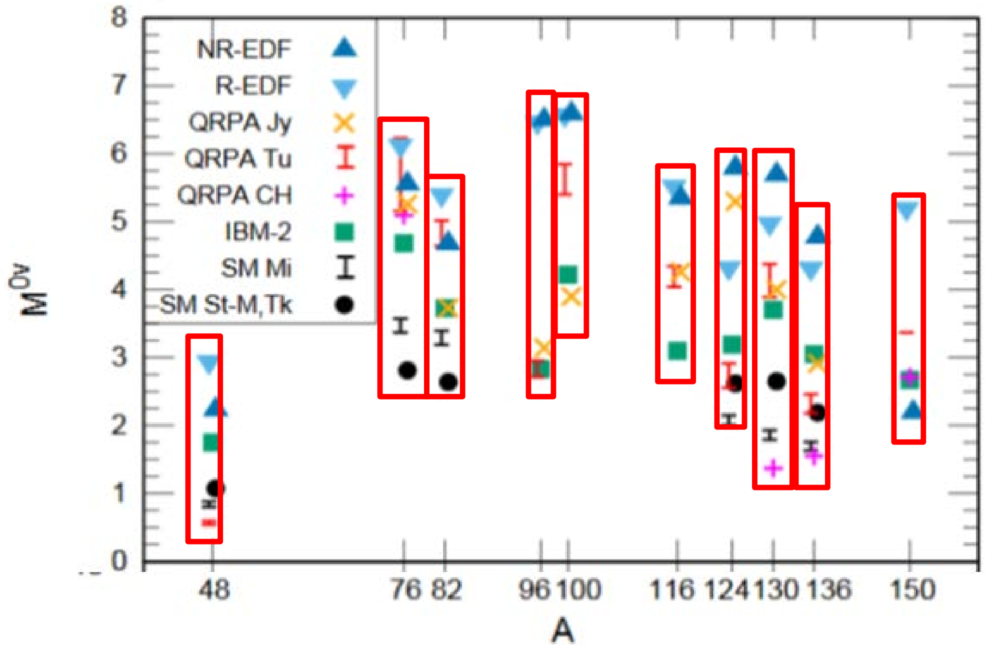
The errors on Nuclear Matrix Elements are the main limitation for (ββ)0ν if observed

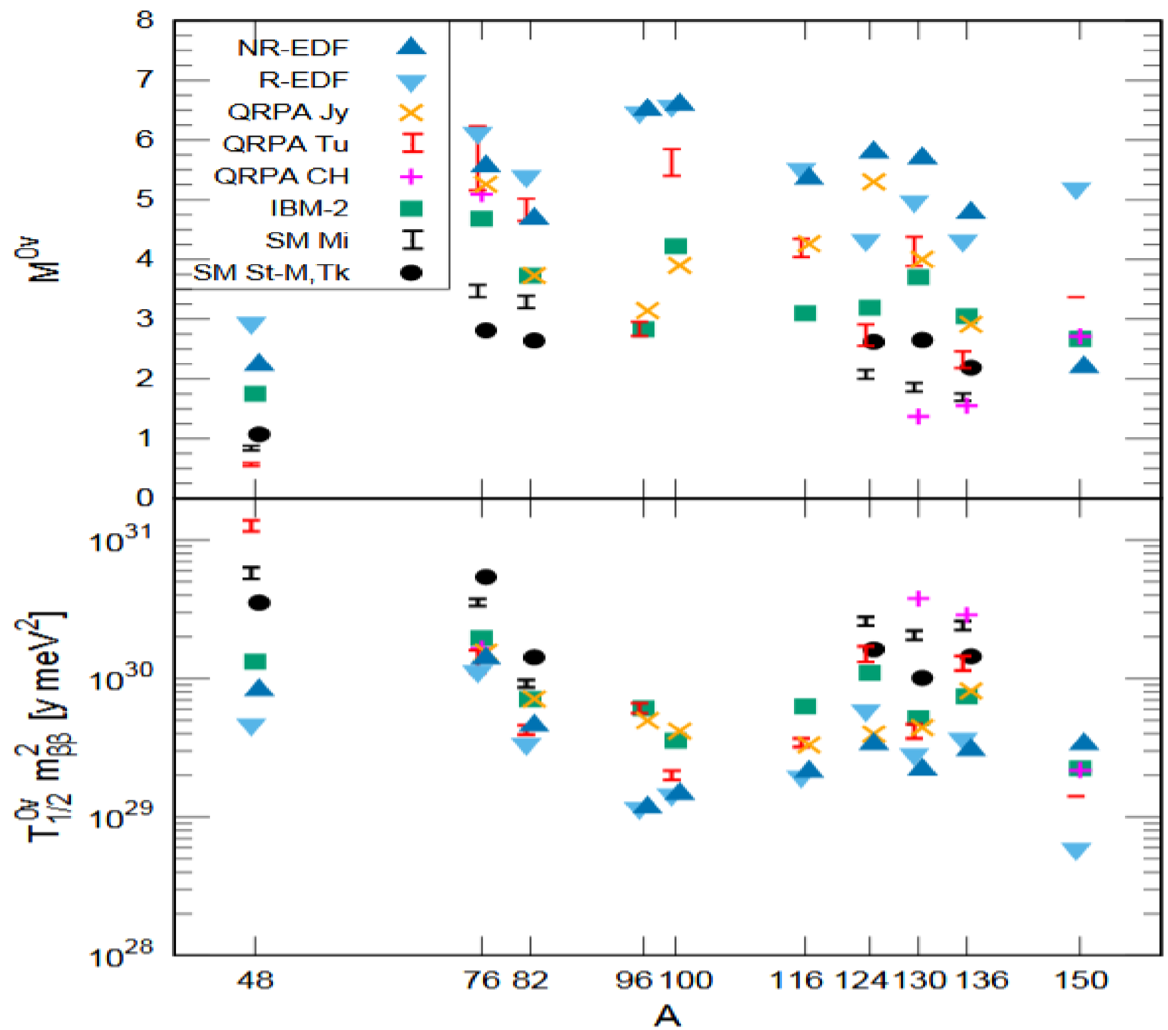
$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 \left\langle m_\nu \right\rangle^2$$

Phase space: exactly calculable



Nuclear matrix elements: several models



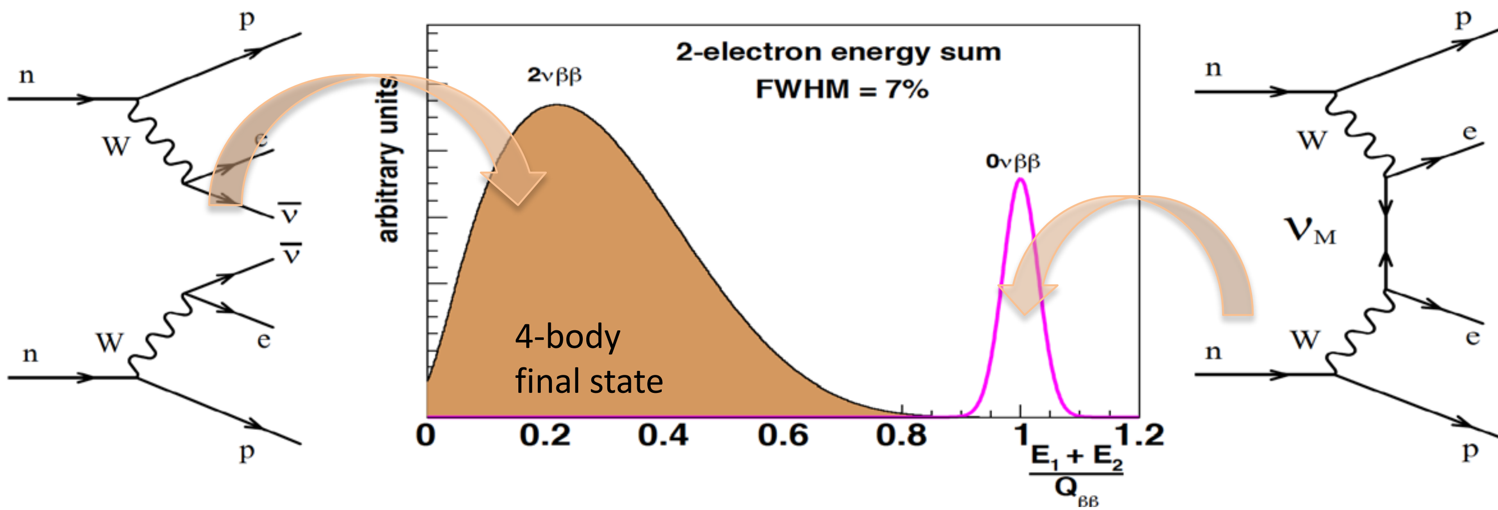


NR-EDF
R-EDF
QRPA Jy
QRPA Tu
QRPA CH
IBM-2
SM Mi
SM St-M,Tk
$M^{0\nu}$
$T^{0\nu}_{1/2}\, m^2_{\beta\beta}$ [y meV^2]
48
76 82
96 100
116 124 130 136
150
A

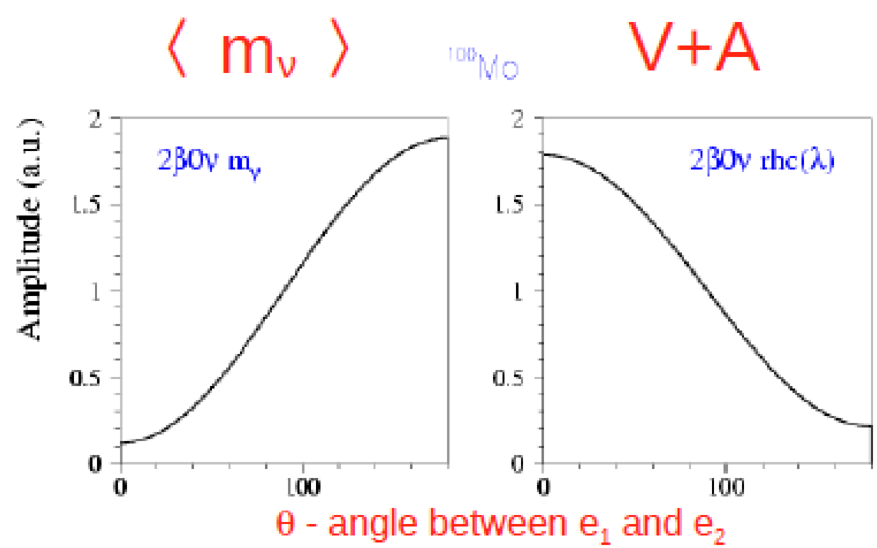
Some experimental aspects

Two electrons from the same point at the same time

Energie



Angular Distribution



How to make a ββ experiment

Increase efficeincy (ε) and enrichment (a)

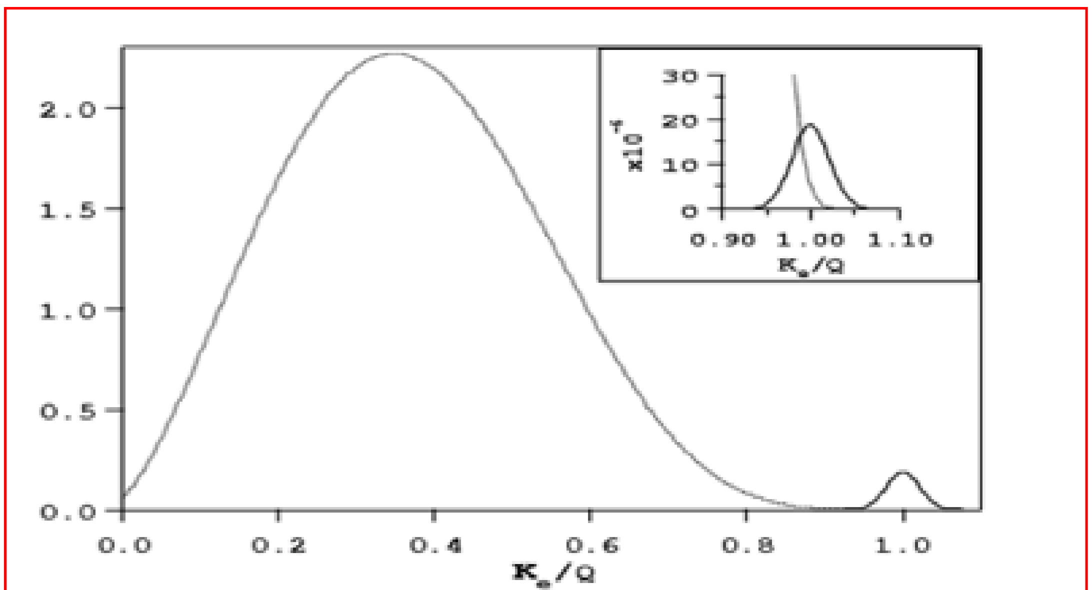
Increase the mass (M) and time (t)

$$T_{1/2}^{0\nu}(90\%\ \mathrm{C.L.}) = 2.54\times10^{26}\,\mathrm{y}\left(\frac{\varepsilon\times a}{W}\right)\sqrt{\frac{M\times t}{b\times\Delta E}}$$

Reduce radioactive background (b) and energy resolution (ΔE)

* ΔE =>

Energy sum of two electron

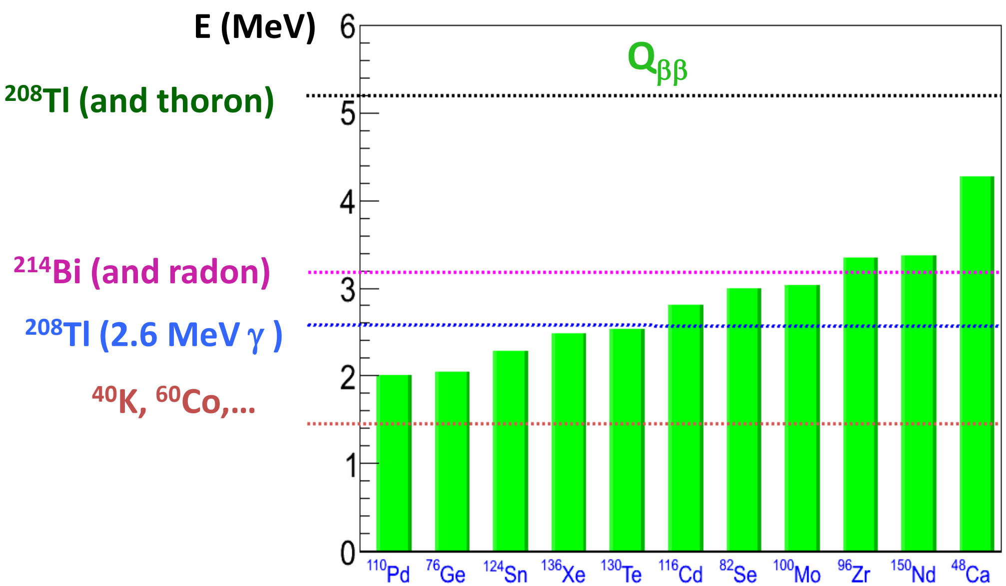


Few words about radioactive background

Origin of the background

Natural Radioactivity

Gamma -> e+, e-
Gamma -> 2 Compton electrons
Beta + Compton electron



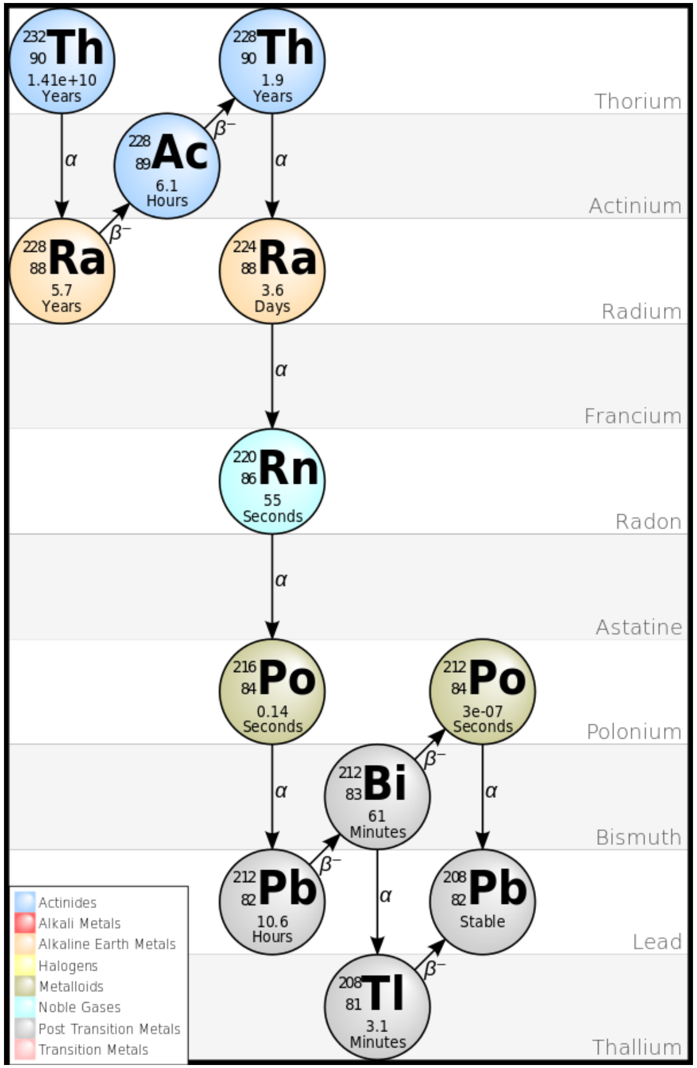
Other background surces

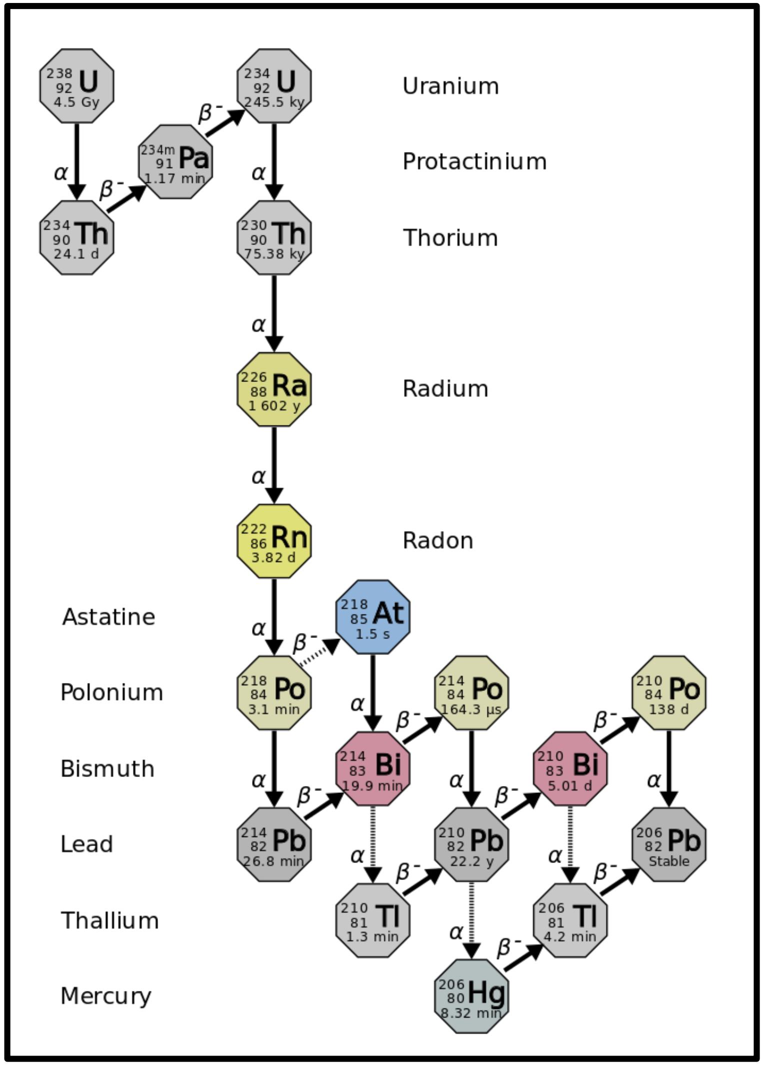
- **Cosmic rays**
- **γ ((n,γ) reactions ,μ bremstrahlung**
- **Muon spallation products**

Need very few radioactive atoms per gram

Ex: SuperNEMO < 70 atoms of radon/m^3

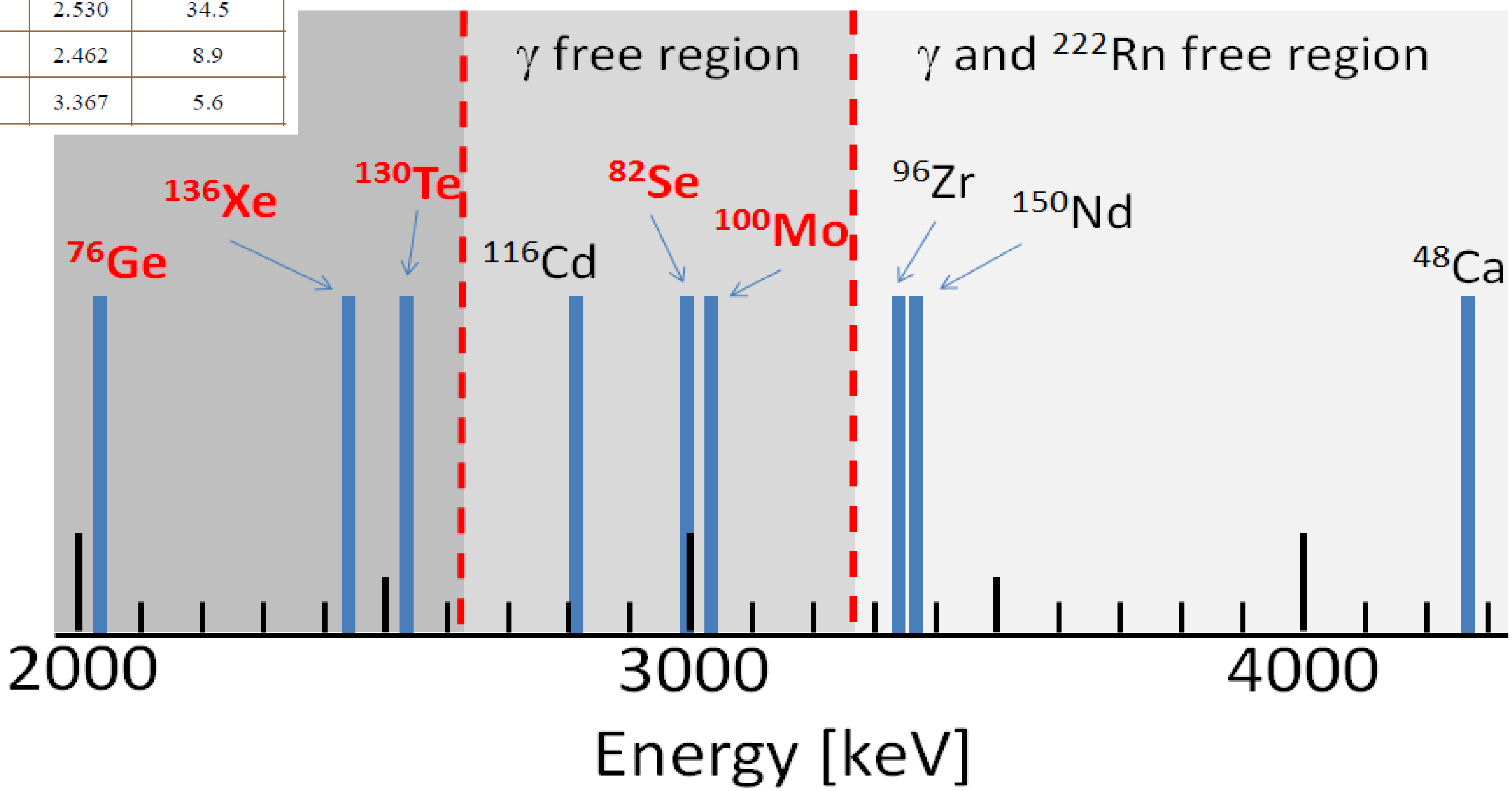
Natural radioactive chains





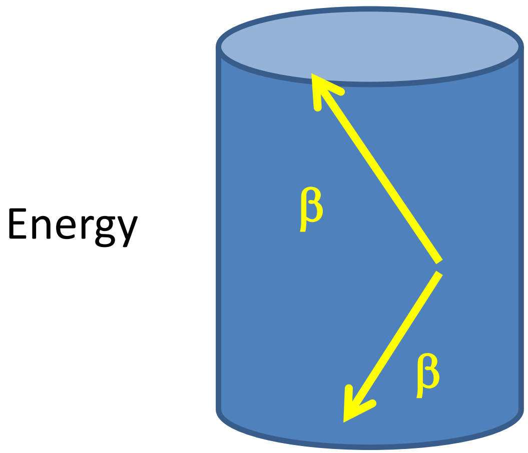
Many, α, β and γ particles. Up to 5 MeV electrons

Isotope	$Q_{\beta\beta}$ (MeV)	Nat. Abund. (%)
^{48}Ca	4.274	0.187
^{76}Ge	2.039	7.8
^{82}Se	2.996	9.2
^{96}Zr	3.348	2.8
^{100}Mo	3.035	9.6
^{110}Pd	2.004	11.8
^{116}Cd	2.809	7.6
^{124}Sn	2.530	5.6
^{130}Te	2.530	34.5
^{136}Xe	2.462	8.9
^{150}Nd	3.367	5.6



How to make a ββ experiment

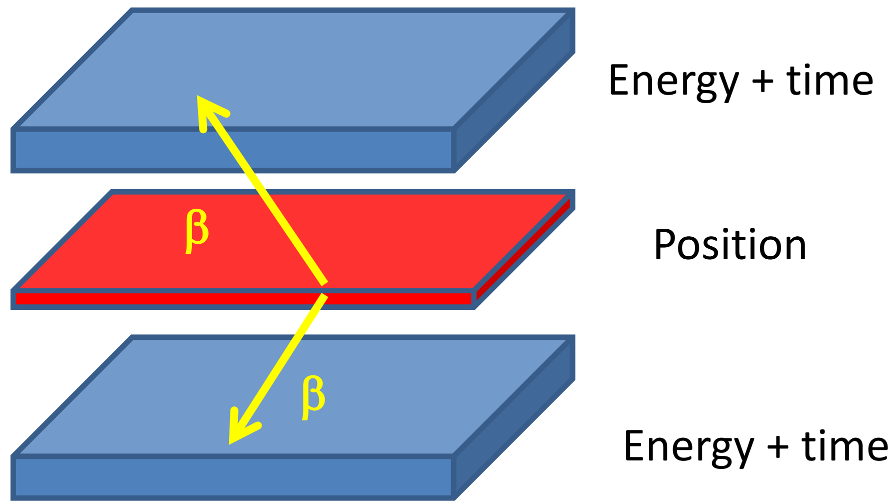
Detector = ββ Source



Calorimetry

+ ΔE , ε
- kinematic

Detector ≠ ββ Source



Tracking + calorimetry

+ kinematic
+ isotope choice
+ ΔE , ε

Large number of techniques

	Experiments		Isotope	Technique	Advantages
Calorimetry	GERDA - Majorana	★	^{76}Ge	Ge diodes	$\mathcal{E}_{0\nu}$ - ΔE - PSD
	CUORE	★	^{130}Te	Bolometer	$\mathcal{E}_{0\nu}$ - ΔE
	AMoRE	★	^{100}Mo		
	EXO-200 - nEXO	★	^{136}Xe	Liquid TPC	mass
	SNO+	★	^{130}Te	Scintillation	$\mathcal{E}_{0\nu}$ - mass
	KamLAND-Zen	★	^{136}Xe		- existing
Tracking	SuperNEMO	★	^{82}Se (^{150}Nd - ^{48}Ca)	Tracko-calo	bkg - full topology - multi isotopes
	NEXT - EXO-gas	★	^{136}Xe	Gas TPC	$\mathcal{E}_{0\nu}$ - tracking - ΔE

Detector = Source ★

Detector ≠ Source ★

^{76}Ge

GERDA

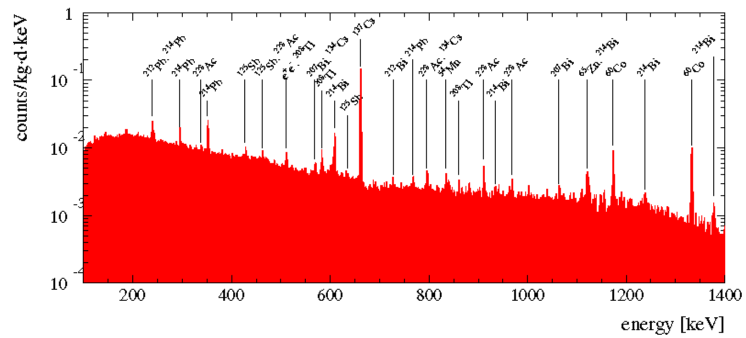
Very good ΔE

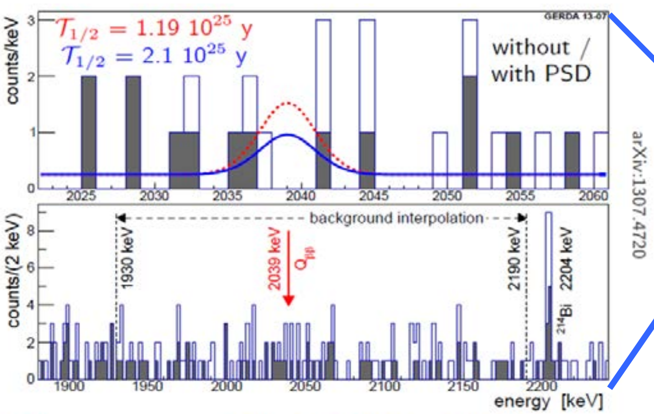
Bare Ge diodes in liquid argon

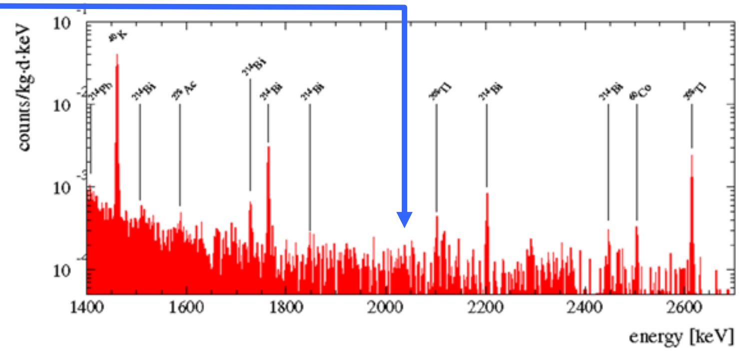
- enriched in ^{76}Ge at 86 %
- gradual deployment of the detector strings in the 64 m^3 cryostat
- LNGS 3800 m.w.e.

Phase 1 - 2011-2013:

- ∼ 18 kg of ^{76}Ge







21.6 kg·y exposure: $T^{0\nu}_{1/2}$ > 2.1 10^{25} y (90% CL)

LEGEND

^{76}Ge

Merge of two Ge experiments

"standard" Ge detector

GERDA
Exposure: 59 kg × y
Background index: **$0.6^{+0.4}_{-0.3}$ c/(keV ton y)**
$T_{1/2} > 0.9\times10^{26}$ y
$m_{\beta\beta} < 110 - 260$ meV

MAJORANA demonstrator
Exposure: 26 kg × y
Background: 11.9±2 c/(FWHM ton y)
$T_{1/2} > 2.7\times10^{25}$ y
$m_{\beta\beta} < 210 - 440$ meV

Combining the best of MAJORANA and GERDA → LEGEND

- Radiopurity of parts near detectors (FETs, cables, Cu mounts, etc.)
- Low noise electronics → better pulse-shape discrimination
- Low energy threshold → improved cosmogenic background rejection

- LAr veto
- Low-A shield, no Pb

Both

Posters #41,51,64,68 M

- Clean fabrication techniques
- Control of time on surface to reduce cosmogenic backgrounds
- Development of large point-contact detectors

Mission of LEGEND: discovery potential at a half-life **> 10^{28} y**

$m_{\beta\beta} < 11 - 23$ meV

LEGEND

^{76}Ge

LEGEND-200:

LNGS – Italy

- Initial Phase
- **~200 kg** in upgraded existing GERDA infrastructure
- **Improvements**:
  - LAr optical purity (light yield, attenuation)
  - Light detection (add readout between detector strings)
  - Cleaner materials and smaller parts near detectors
  - Larger detectors (fewer cables, readout channels)
  - Surface betas (^{42}Ar progeny): Reduce LAr volume and improve pulseshape
  - Discrimination (better electronics)
  - **New inverted-coaxial larger detectors (1.5 – 2 kg)**
- **Background goal**: 0.6 counts/FWHM t yr (**3x lower than GERDA**)
- Data-taking could start as early as 2021
- **Sensitivity: > 10^{27} y for 1 tonne × y** **$m_{\beta\beta}$ < 35 – 75 meV**

LEGEND-1000:

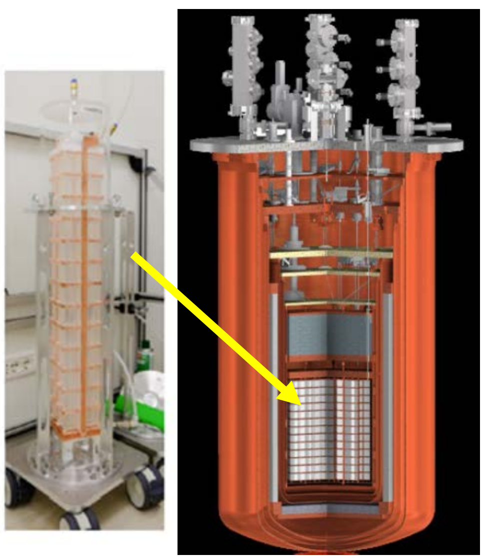
- Ultimate goal
- **1000 kg (phased)** required to cover neutrino-mass IO
- Timeline connected to US DOE down-select process
- Background goal: 0.1 counts/FWHM-t-yr
- Location TBD
- Required depth under investigation

^{130}Te, ^{100}Mo, ^{82}Se

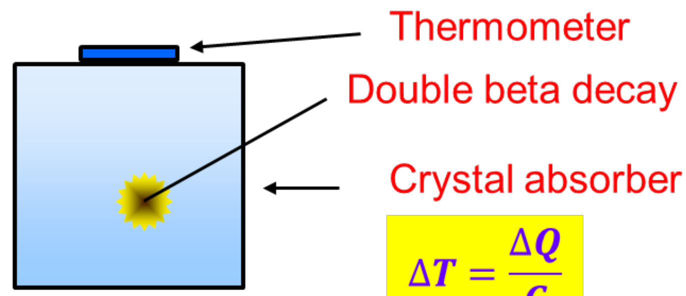
CUORE

62 TeO_2 crystals

- FWHM $\sim$ 5 keV @ $Q_{\beta\beta}$
- Sensitivity: $T^{0\nu}_{1/2} > 1\ 10^{26}$ y in 5 years
- First tower already assembled and 18 others by 2014



Bolometer technique



$$\Delta T = \frac{\Delta Q}{C}$$

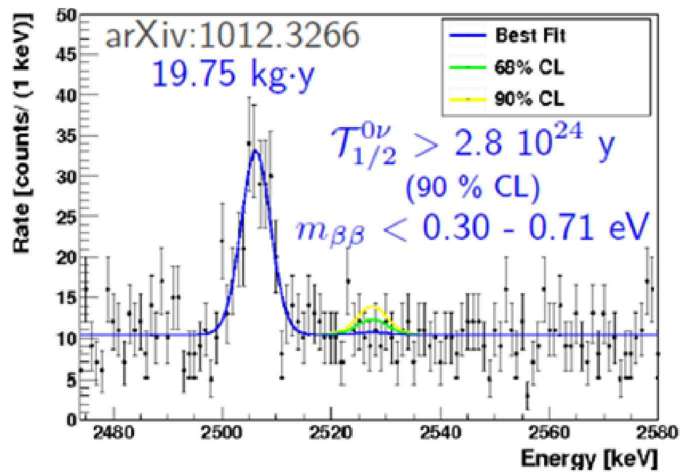
example: 750 g of TeO_2 @ 10 mK

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

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

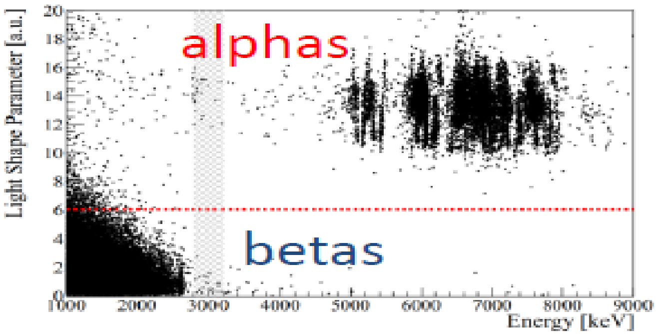
$\Rightarrow \Delta Q \sim 10$ eV

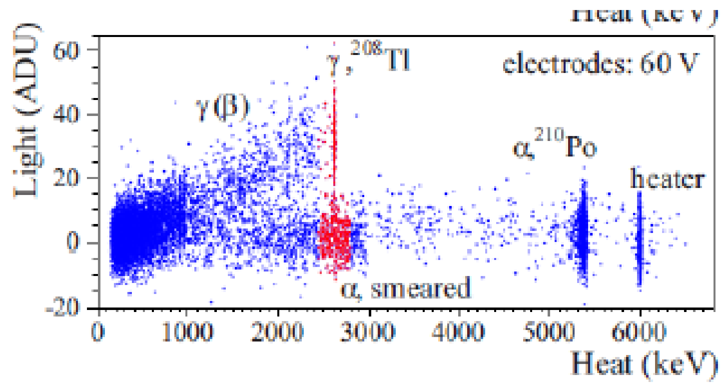
Very good ΔE



CUORE → CUPID

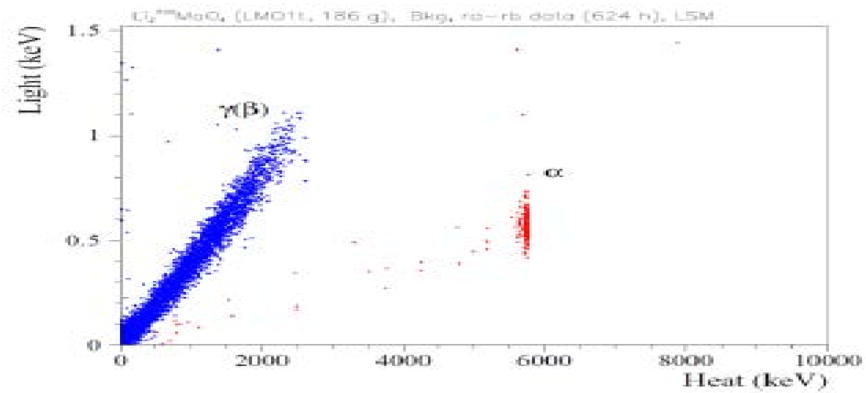
$^{130}TeO_2$ + Cherenkov light Q=2527 keV





$Zn^{82}Se$ Q=2998 keV

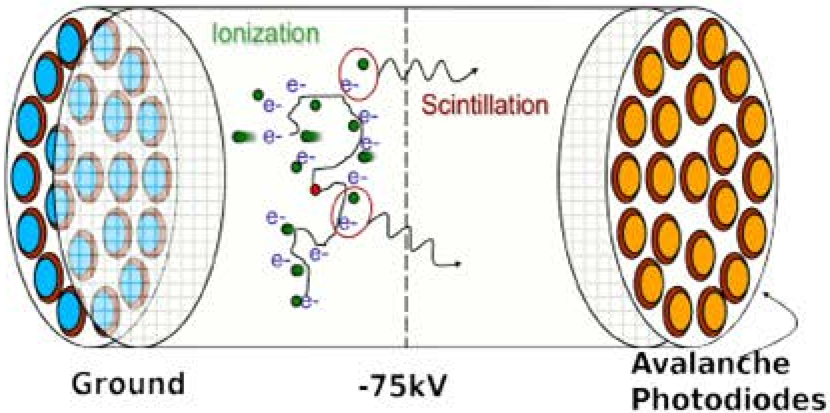
$Li_2{}^{100}MoO_4$ Q=3034 keV



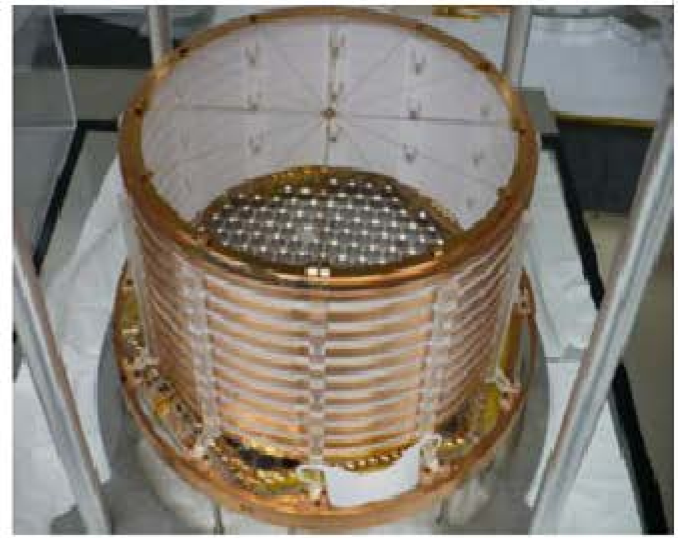
Mission: **half-life sensitivity higher than 10^{27} y**
With background < 0.1 counts/(ton y) in the ROI, ^{100}Mo sensitivity is **2.1×10^{27} y**
$m_{\beta\beta} < 6 - 17$ meV

^{136}Xe

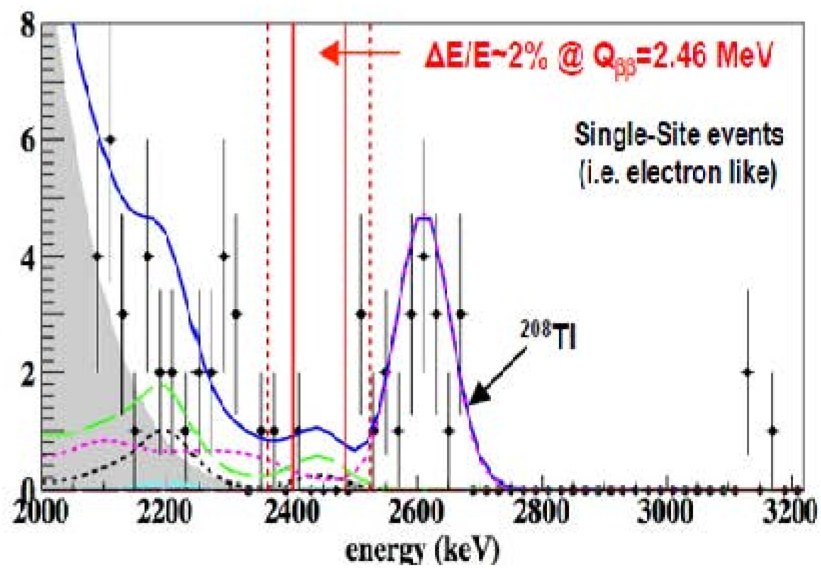
Enriched Xenon Observatory



- Liquid-xenon TPC with ionisation & scintillation readout



- Easy and cheap ^{136}Xe enrichment (80 %)
- 200 kg liquid xenon TPC in WIPP USA
- FWHM 3.8 % @ $Q_{\beta\beta}$



$T_{1/2} > 1.8 \times 10^{25}$ y

$m_{\beta\beta} < 150 - 400$ meV

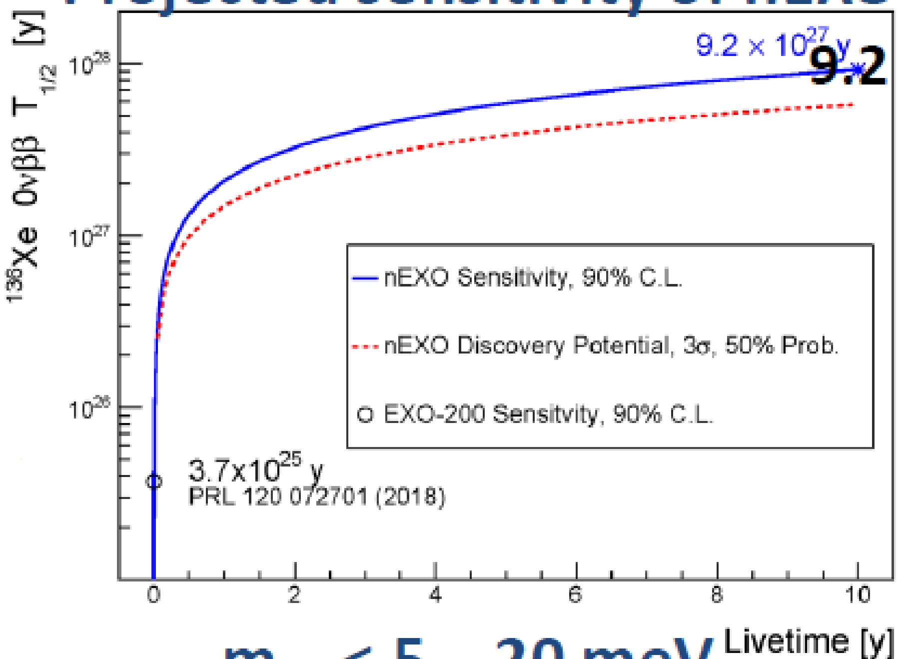
^{136}Xe

EXO-200 → nEXO

Moving forwards towards nEXO

LXe mass (kg)	Diameter or length (cm)
5000	130 ~nEXO
150	40~ EXO-200
5	13

Projected sensitivity of nEXO



9.2×10^{27} y

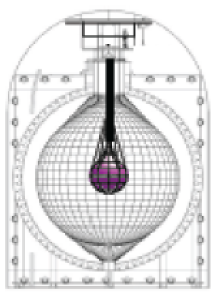
$m_{\beta\beta} < 5 - 20$ meV

Already existing detector (Reactor Neutrino oscillations)

KamLAND-Zen 400,800→KamLAND2-Zen ^{136}Xe

KamLAND-Zen 400: data taking completed
Kamioka – Japan **Leading experiment**

Results: $T_{1/2} > 1.07\times10^{26}$ y
$m_{\beta\beta} < 45 - 160$ meV

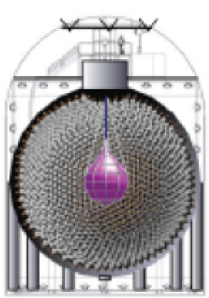


Present

KamLAND-Zen 800
~750 kg of Xenon
DAQ to start in this year

Similar to KamLAND-400
Major new points:
- More isotope – **750 kg of ^{136}Xe**
- New balloon
- $T_{1/2} > 4.6\times10^{26}$ y

$m_{\beta\beta} < 25 - 80$ meV



Future

KamLAND2-Zen
~1 ton of ^{136}Xe
Better energy resolution

Substantiantial changes
Major new points:
- More isotope – **~1 ton of ^{136}Xe**
- Improve light collection
  Brighter liquid scintillator
  → ΔE_{FWHM}: 280 keV → < 170 keV
- Accomodate scintillating crystals
  → multi-isotope search

$m_{\beta\beta} < 20$ meV

Already existing detector (Solar Neutrino oscillations)

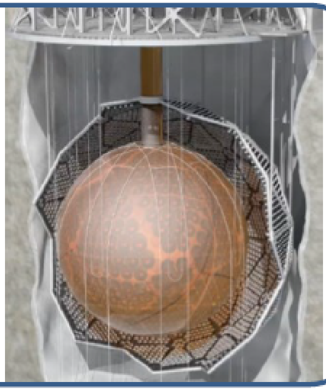
SNO+

^{130}Te

Reuse existing infrastructure of SNO – Canada

SNO+ phase I: SNO acrylic vessel filled with LS and 1.3 tons of natural Te in an organometallic compound (0.5% mass loading)

- Te loading foreseen in 2019
- **ΔE_{FWHM} = 190 keV**
- **5 y sensitivity: $T_{1/2} > 1.9\times10^{26}$ y** **$m_{\beta\beta} < 35 - 140$ meV**



Possible SNO+ phase II (ongoing R&D)

- Increase Te concentration (**it does not affect background**)
- Increase light yield
- Improve transparency
- Improve light detectors

$T_{1/2} > 1\times10^{27}$ y

$m_{\beta\beta} < 15 - 60$ meV

Further evolution of this technology with new concepts: THEIA project

Posters #122,123 M

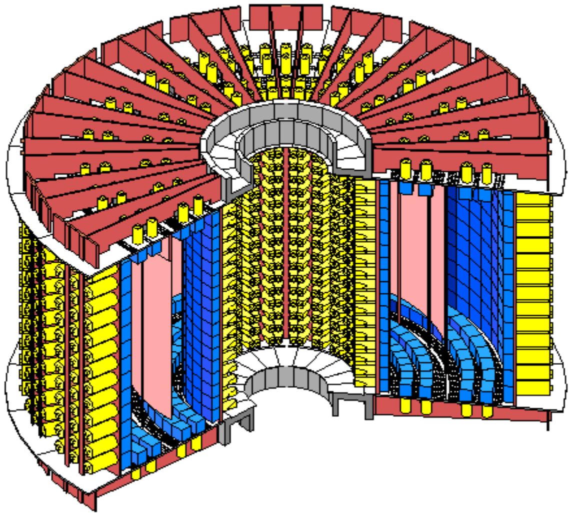
- 50 kton water-based liquid scintillator detector
- High coverage with fast photon detectors
- Deep underground
- 8-m radius balloon with high-LY LS and isotope
- 7-m fiducial, 3% ^{nat}**Te**, 10 years
- Dominant background: ^{8}B solar ν's

$T_{1/2} > 1.1\times10^{28}$ y

$m_{\beta\beta} < 5 - 18$ meV

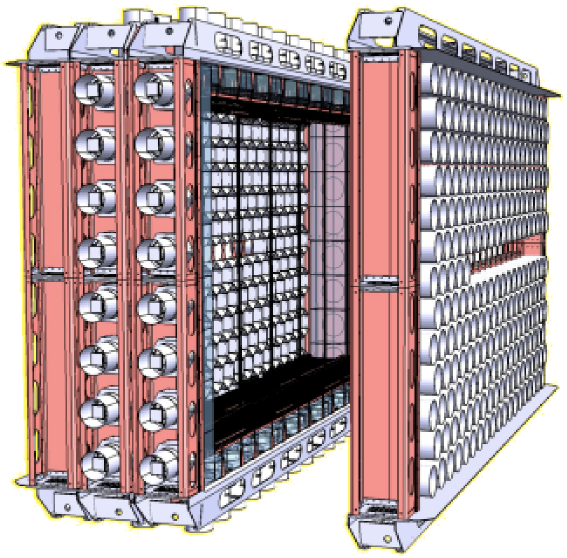
without enrichement!

Neutrino Ettore Majorana Observatory



From NEMO III

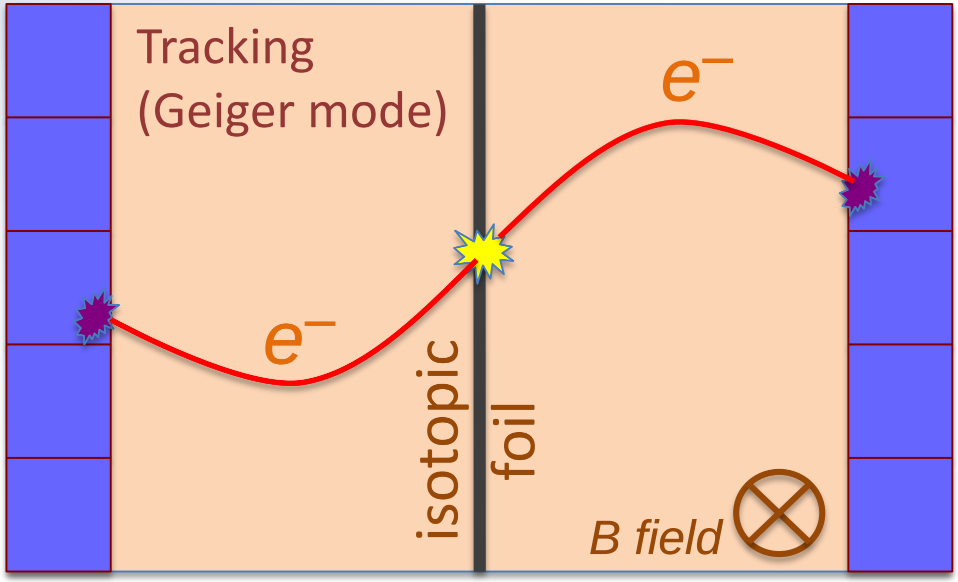
to SuperNEMO



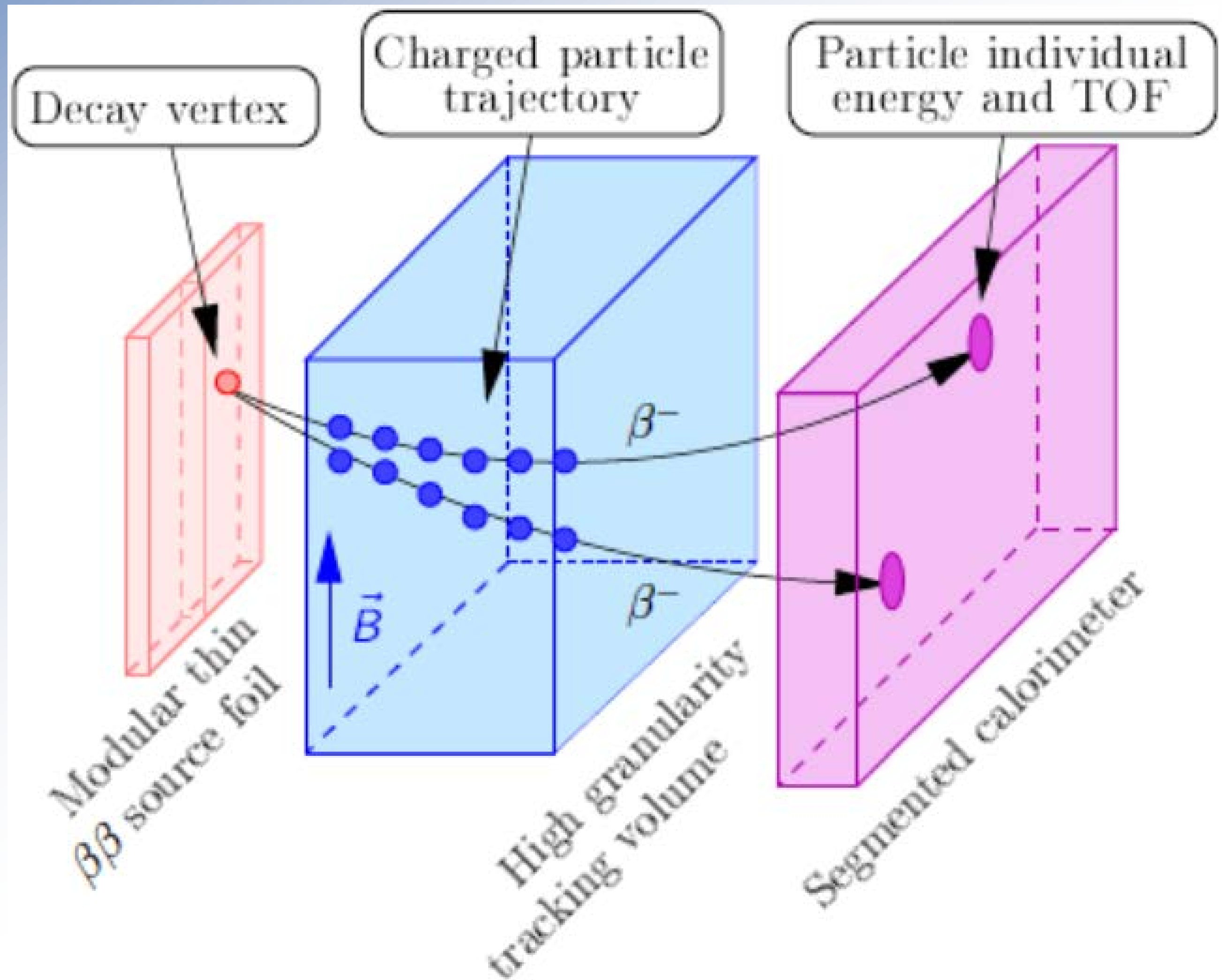
The NEMO-3 Technique

The multi-observable principle:

topology, kinematics, timing



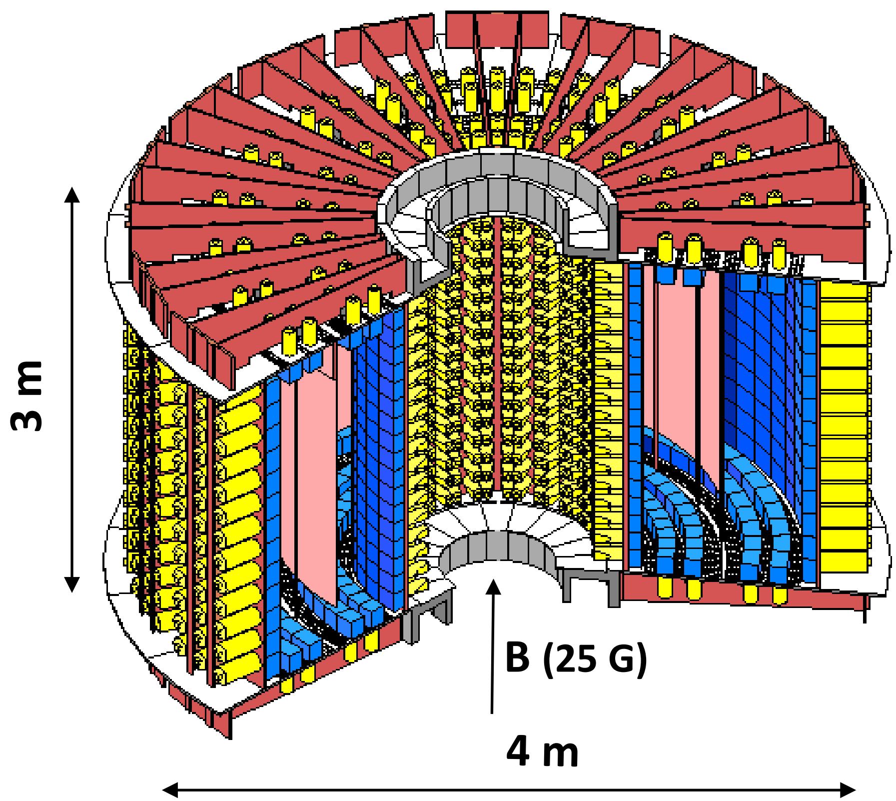
Plastic scintillator calorimeter



Decay vertex
Charged particle trajectory
Particle individual energy and TOF
β^-
β^-
$\vec{B}$
Modular thin $\beta\beta$ source foil
High granularity tracking volume
Segmented calorimeter

NEMO-3 detector

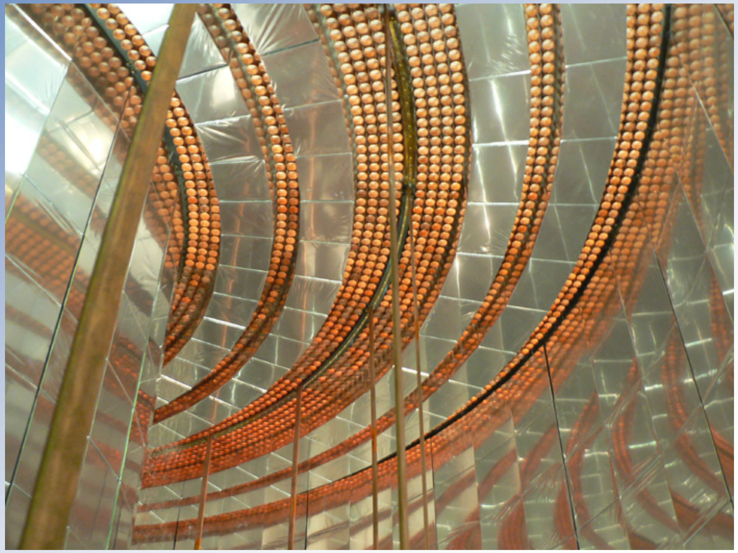
20 sectors

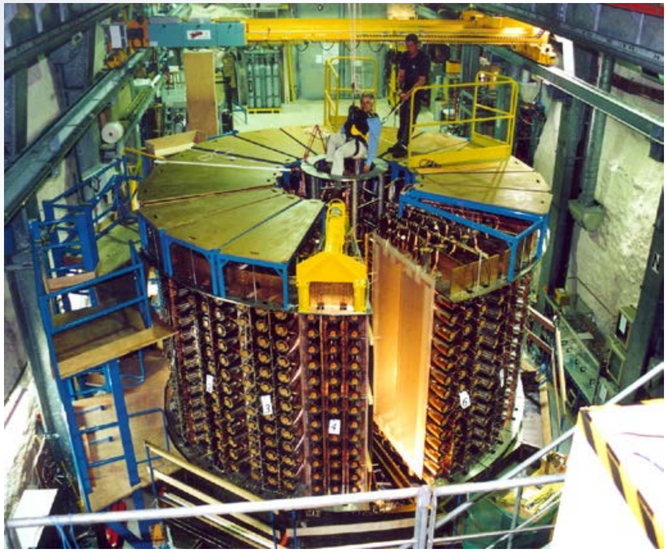


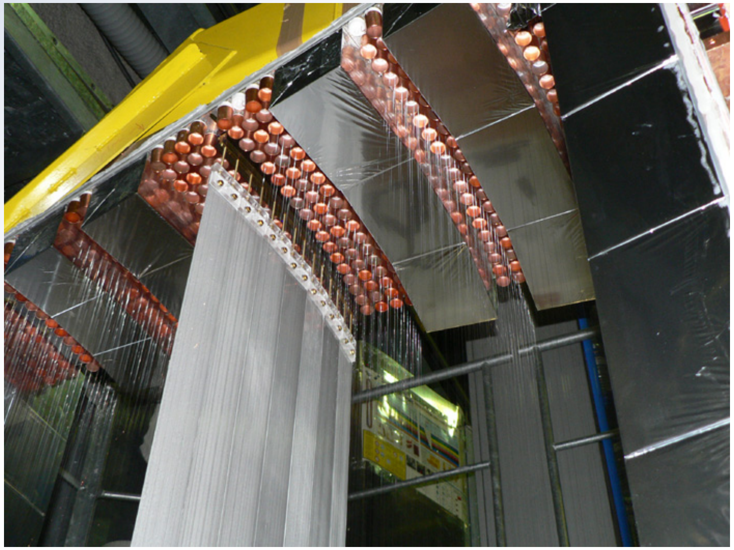
Particle ID: e^-, e^+, γ and α

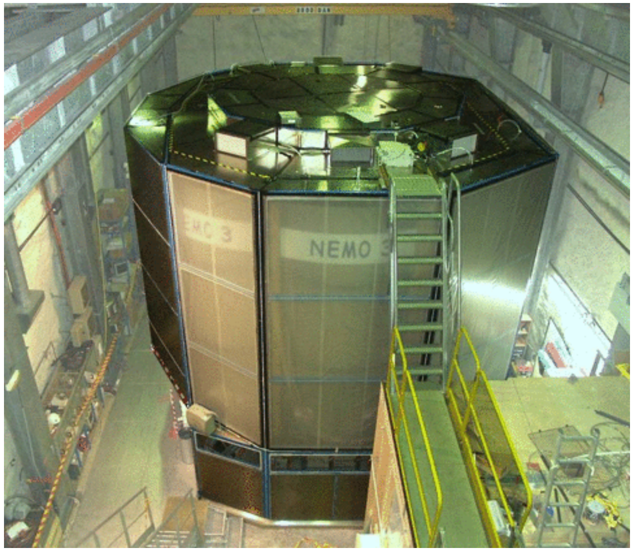
- ✓ Source: 10 kg of $\beta\beta$ isotopic foils
  area = 20 m^2, thickness ~60 mg/cm^2
- ✓ Tracking detector:
  drift wire chamber (9 layers)
  in Geiger mode (6180 cells)
  Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O
- ✓ Calorimeter:
  1940 plastic scintillators
  low radioactivity 3'' & 5'' PMTs
- ✓ B field : 25 Gauss
- ✓ Shielding:
  gamma shield: pure iron (d = 18cm)
  neutron shield:
  30 cm water (ext. wall)
  40 cm wood (top / bottom)
  (since March 2004: water + boron)

NEMO-3 data taking: 2003 - 2010

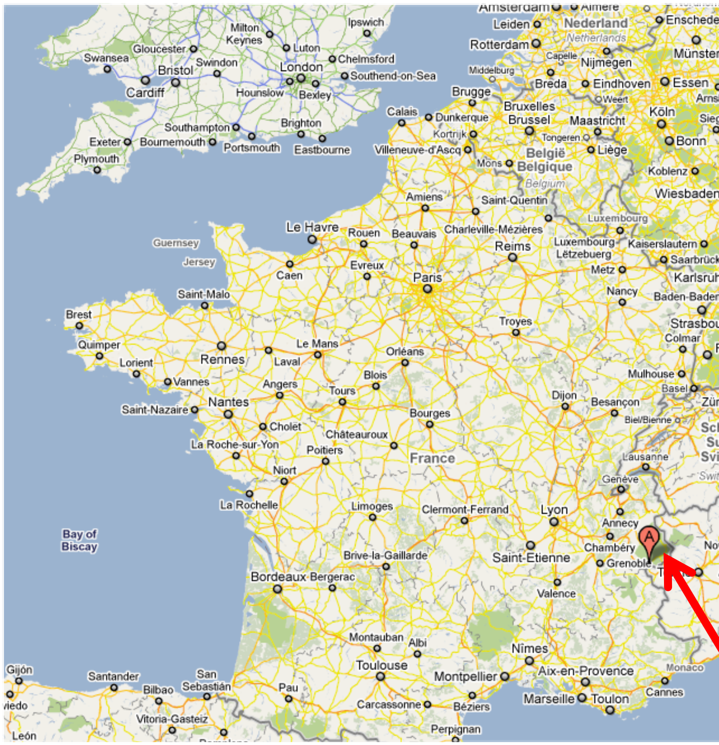


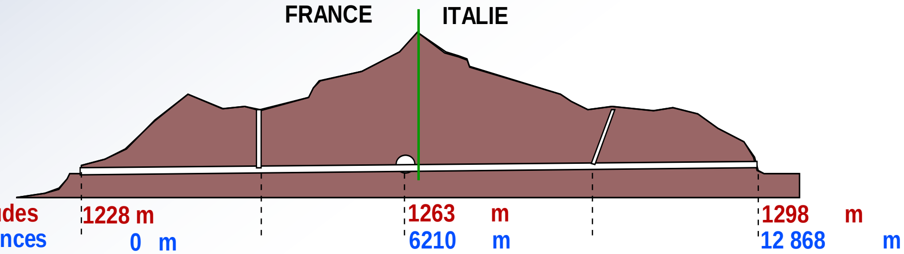


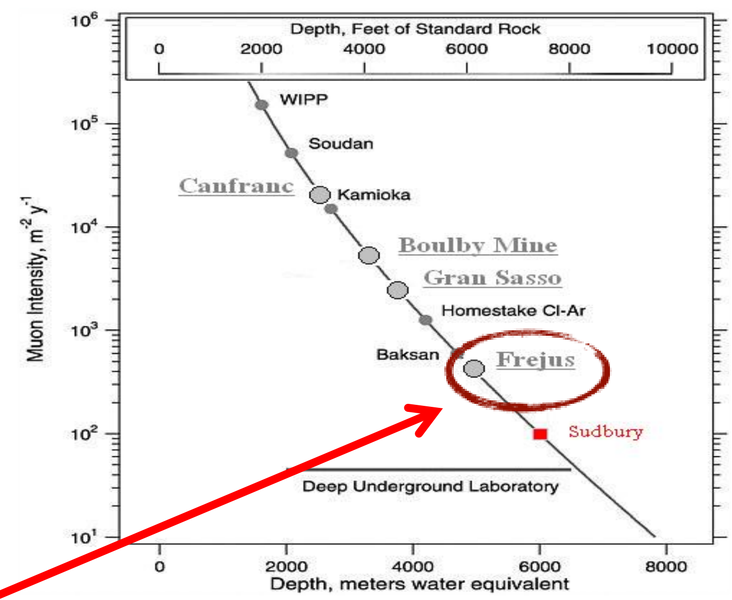




NEMO3 Lab.



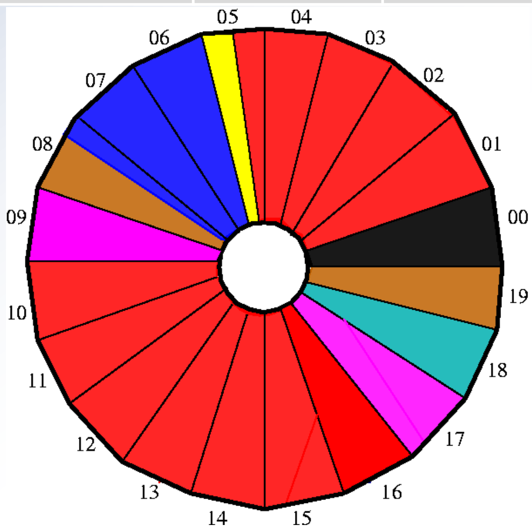


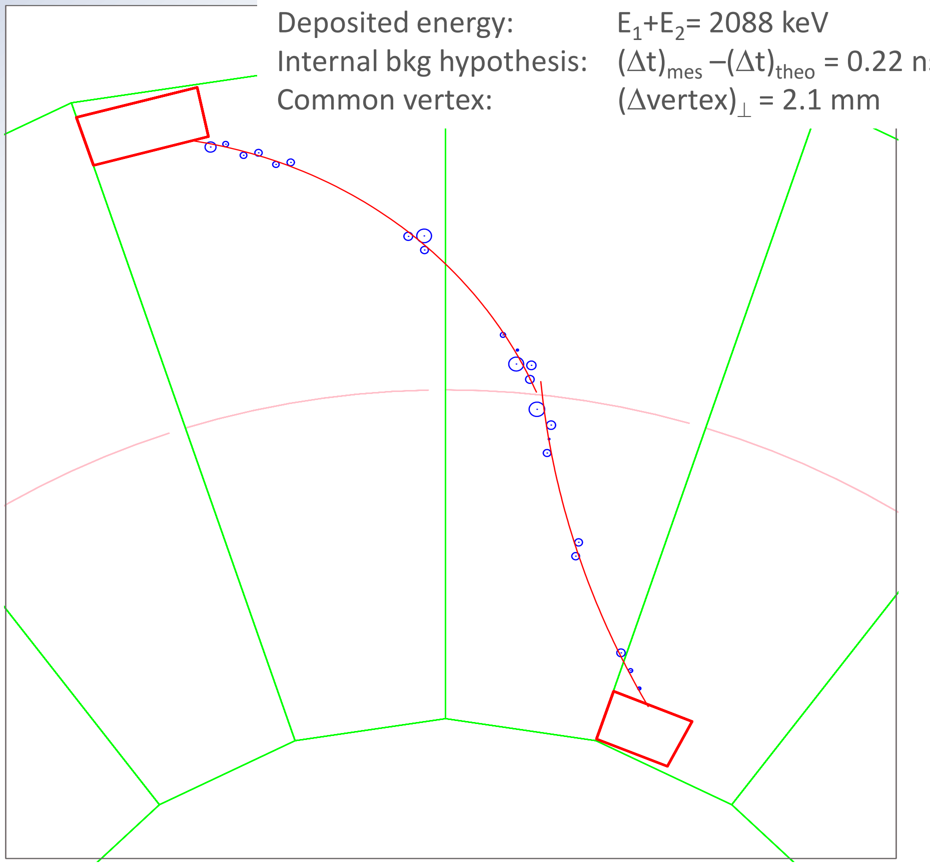


LSM Modane, France
(Tunnel Frejus, depth of ~4,800 mwe)

NEMO-3: 7 isotopes + events images

Isotope	Mass (g)	$Q_{\beta\beta}$ (keV)
^{100}Mo	6 914	3035
^{82}Se	932	2995
^{116}Cd	405	2805
^{96}Zr	9.4	3350
^{150}Nd	37	3367
^{48}Ca	7	4272
^{130}Te	454	2529
^{nat}Te	491	
^{nat}Cu	621	

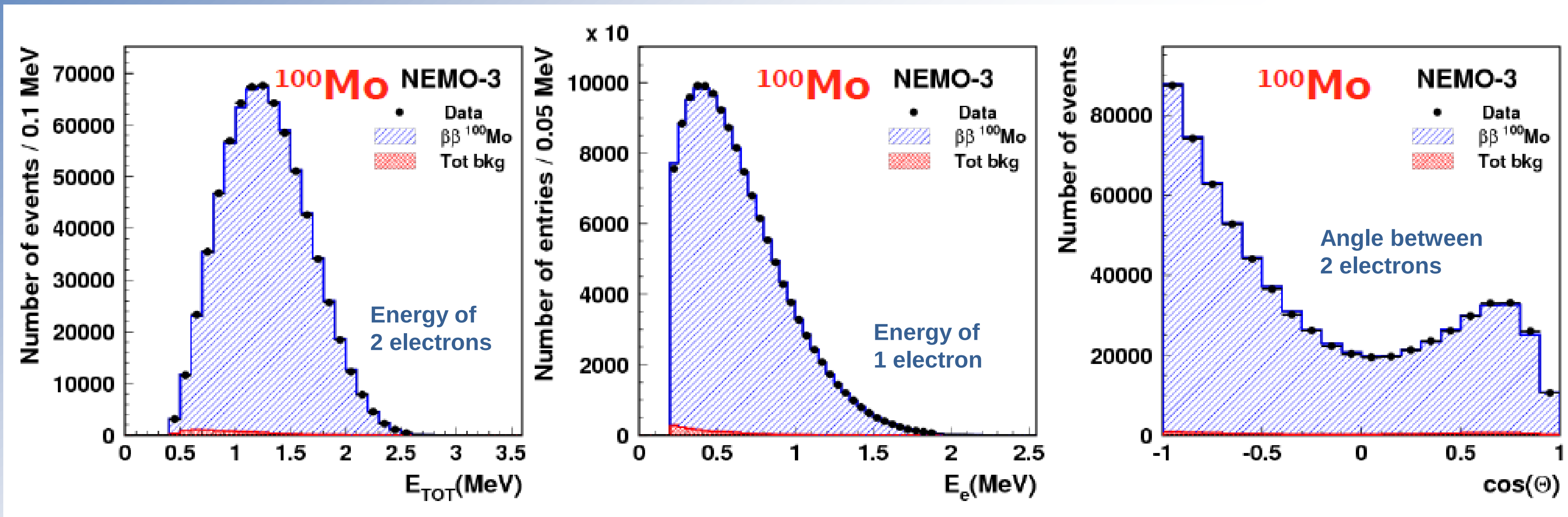




- ✓ Trigger: at least 1 PMT > 150 keV

  $\geq$ 3 Geiger hits (2 neighbouring layers+1)
- ✓ Trigger rate = 7 Hz
- ✓ 25 $\beta\beta$ events per hour

Results

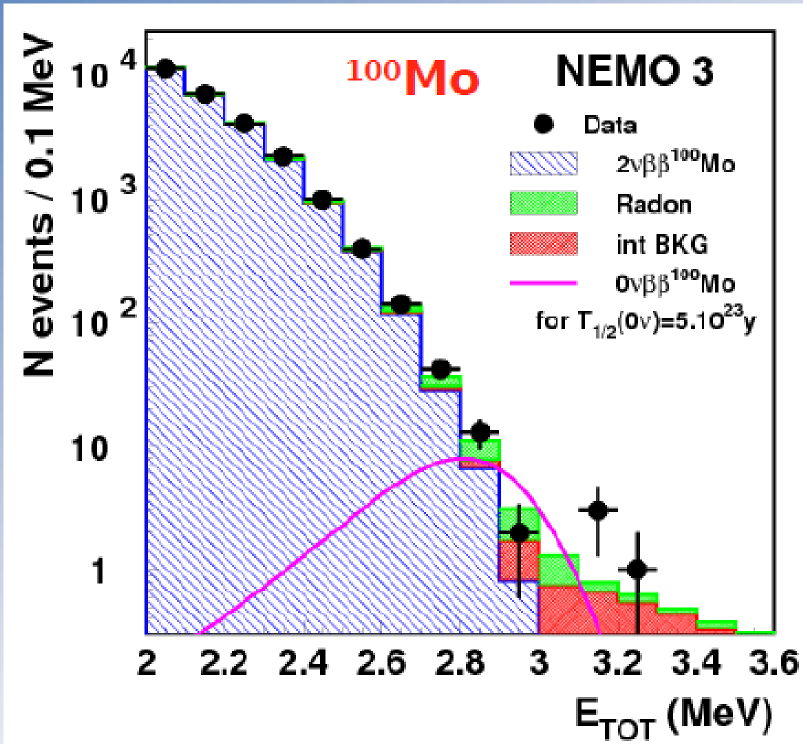


> 700 000 of 2-electron

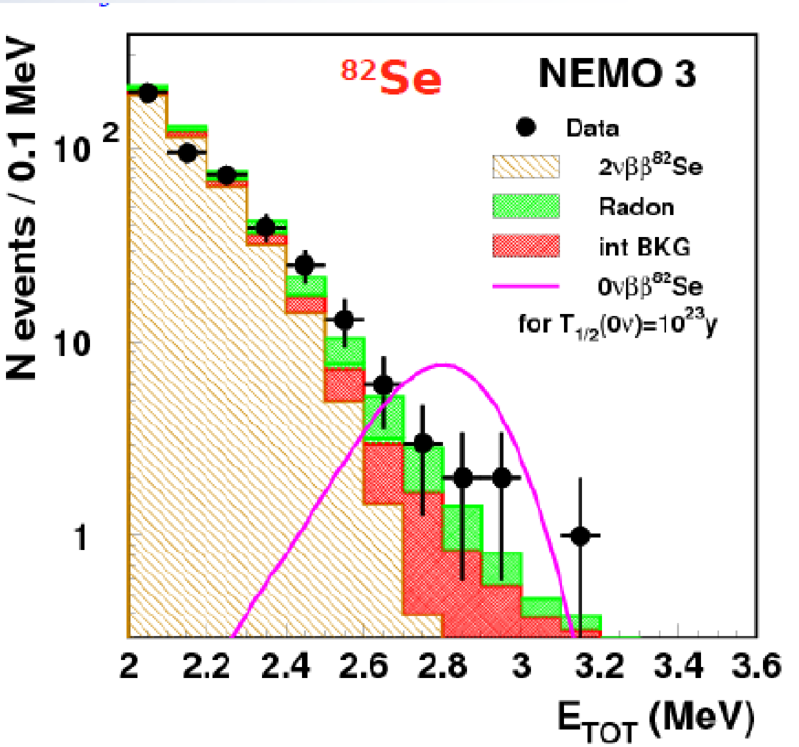
Signal/Background : 76

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

^{100}Mo and ^{82}Se $(\beta\beta)_{0\nu}$ results



[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 (for exposure of 31.2 kg * y)

$T_{1/2}$ $(0\nu\beta\beta) > 1.0 \times 10^{24}$ y (90% C.L.)

$m_{\beta\beta} < 0.31 – 0.96$ eV

^{82}Se (for exposure of 4.2 kg * y)

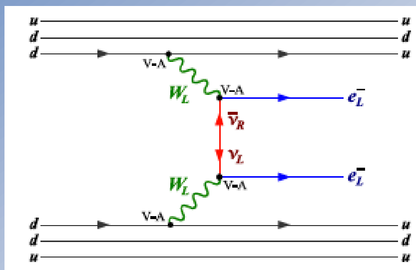
$T_{1/2}$ $(0\nu\beta\beta) > 3.2 \times 10^{23}$ y (90% C.L.)

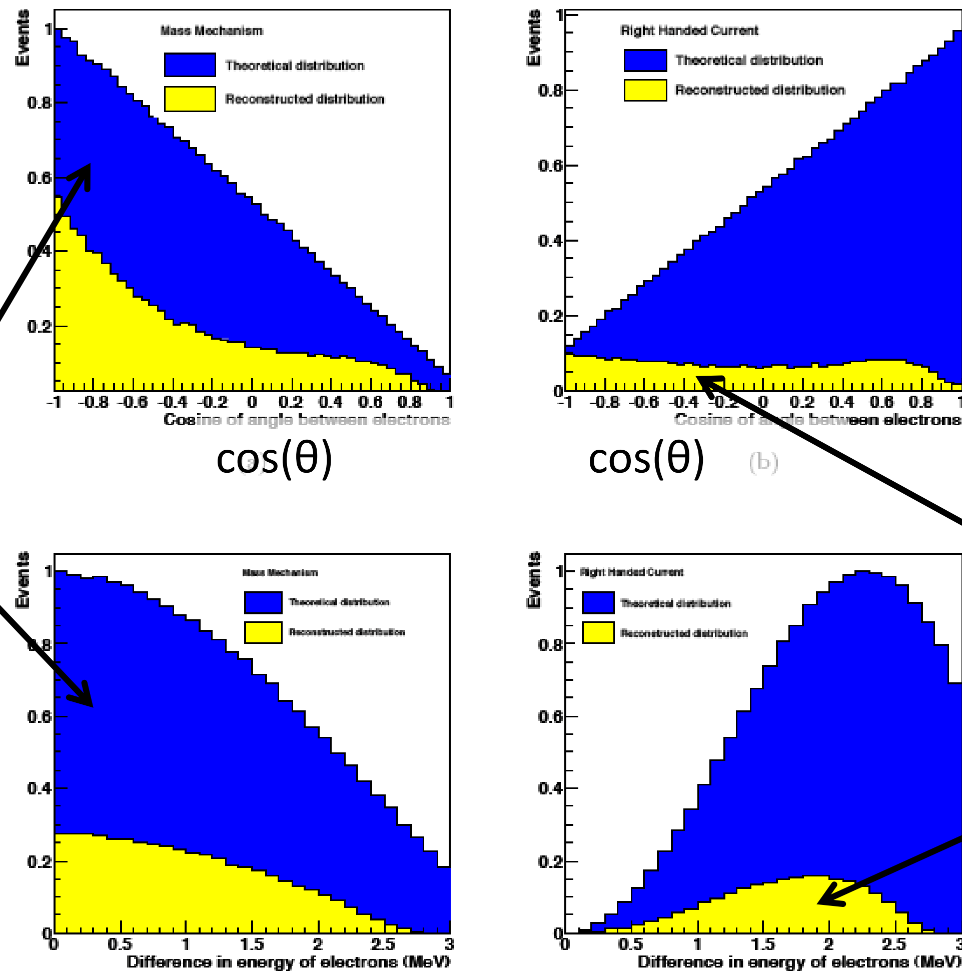
$m_{\beta\beta} < 0.94 – 2.6$ eV

Physics Studies: RHC

MM

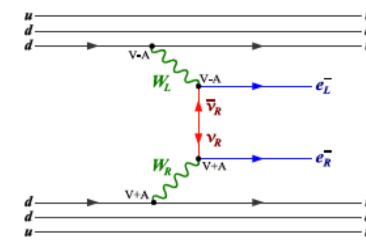
RHC





cos(θ) cos(θ)

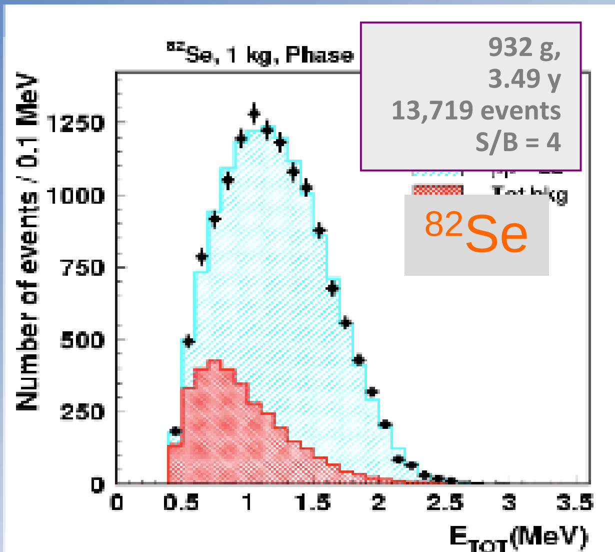
Energy difference between electrons



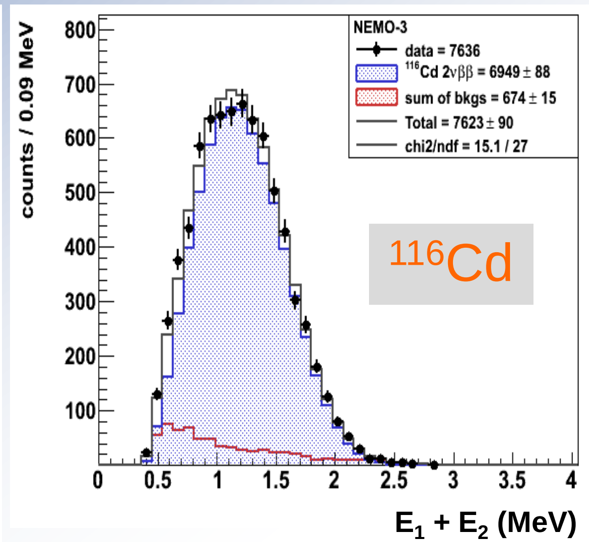
Evènements attendus

Evènements reconstruits

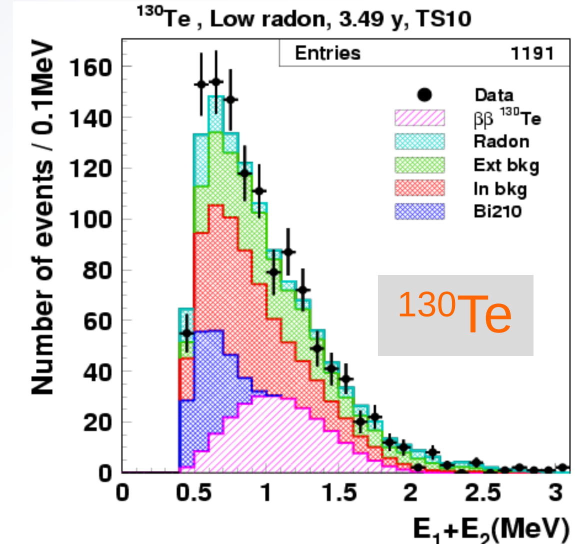
NEMO-3 $(\beta\beta)_{2\nu}$ results



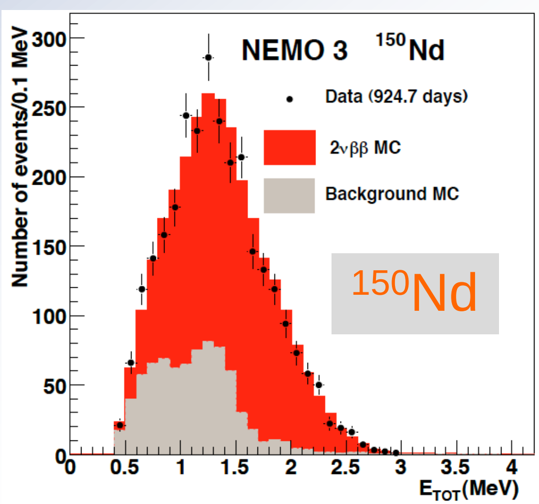
[9.6 ± 0.1 (stat) ± 1.0 (syst)] x 10^{19} y



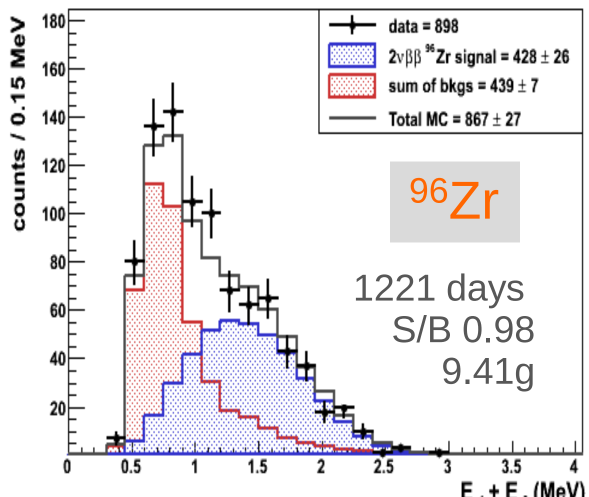
[2.88 ± 0.04(stat) ± 0.16(syst)] x 10^{19} y



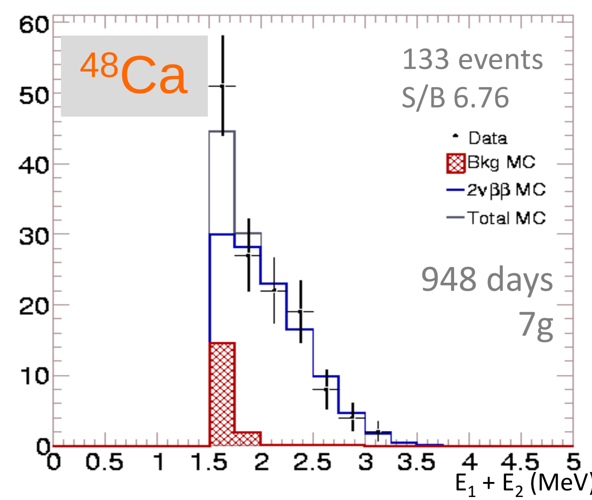
[7.0± 0.9(stat) ± 1.1(syst)] x 10^{20} y



[9.11 $^{+0.25}_{-0.22}$ (stat) ± 0.63(syst)] x 10^{18} y



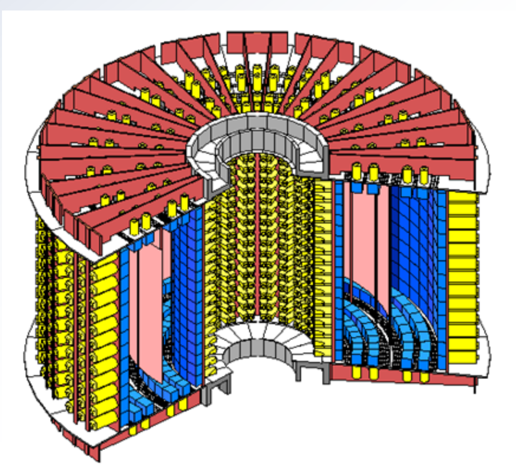
[2.35 ± 0.14(stat) ± 0.16(syst)] x 10^{19} y

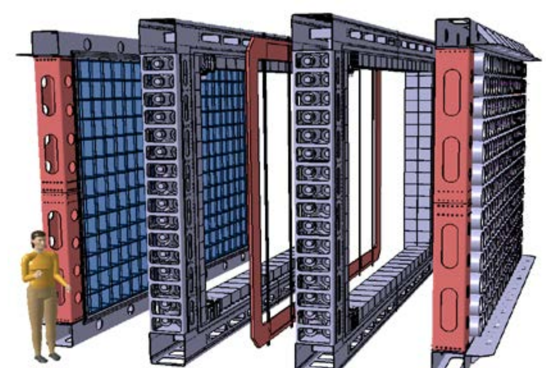


[4.4 $^{+0.5}_{-0.4}$ (stat) ± 0.4 (syst)] x 10^{19} y

From NEMO-3 to SuperNEMO

NEMO-3	R&D since 2006 →	SuperNEMO
^{100}Mo	Isotope	^{82}Se (or ^{150}Nd or ^{48}Ca)
7 kg x 5 years	Exposure	100 kg x 5 years
18%	$0\nu\beta\beta$ efficiency	30%
$T_{1/2}^{0\nu\beta\beta} > (1\text{-}2) \times 10^{24}$ years $\langle m_\nu \rangle < 0.3 - 0.8$ eV	Sensitivity	$T_{1/2}^{0\nu\beta\beta} > 1 \times 10^{26}$ years $\langle m_\nu \rangle < 0.04 - 0.1$ eV



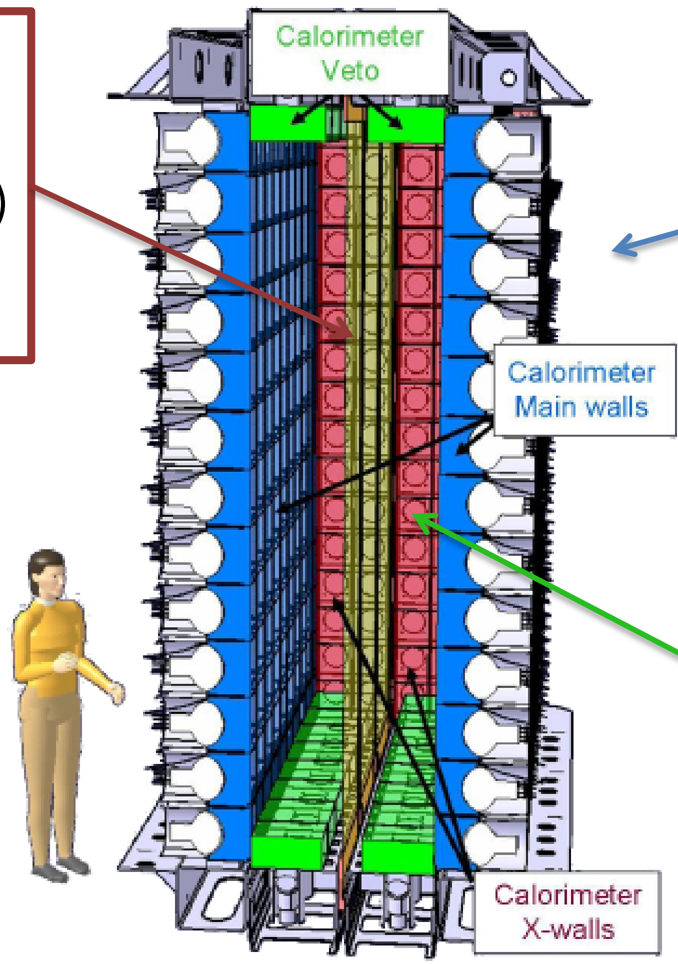


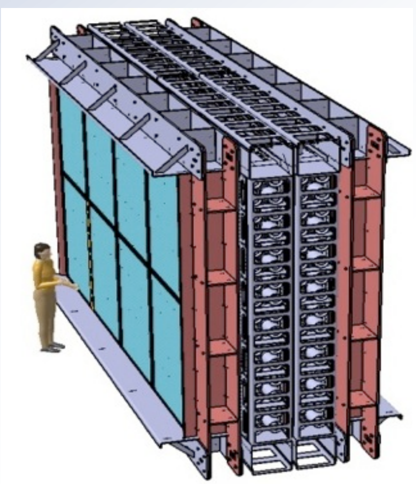
SuperNEMO demostrator

Objective: to reach the background level for 100 kg
to perform a no background experiment with 7 kg isotope of ^{82}Se in 2 yr

Source

^{214}Bi < 10 μBq/kg
(NEMO3 100 μBq/kg)
208Tl < 2 μBq/kg
(NEMO3 100 μBq/k)





Calorimeter

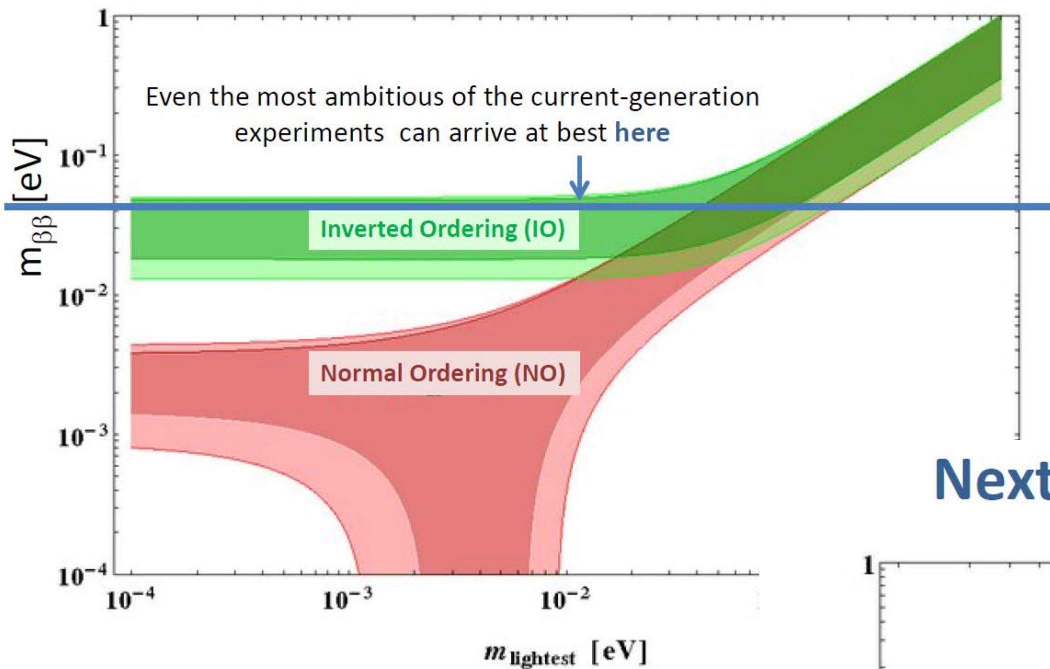
ΔE/E < 4% @ 3 MeV
(NEMO3 8.6% at 3MeV)

Tracker

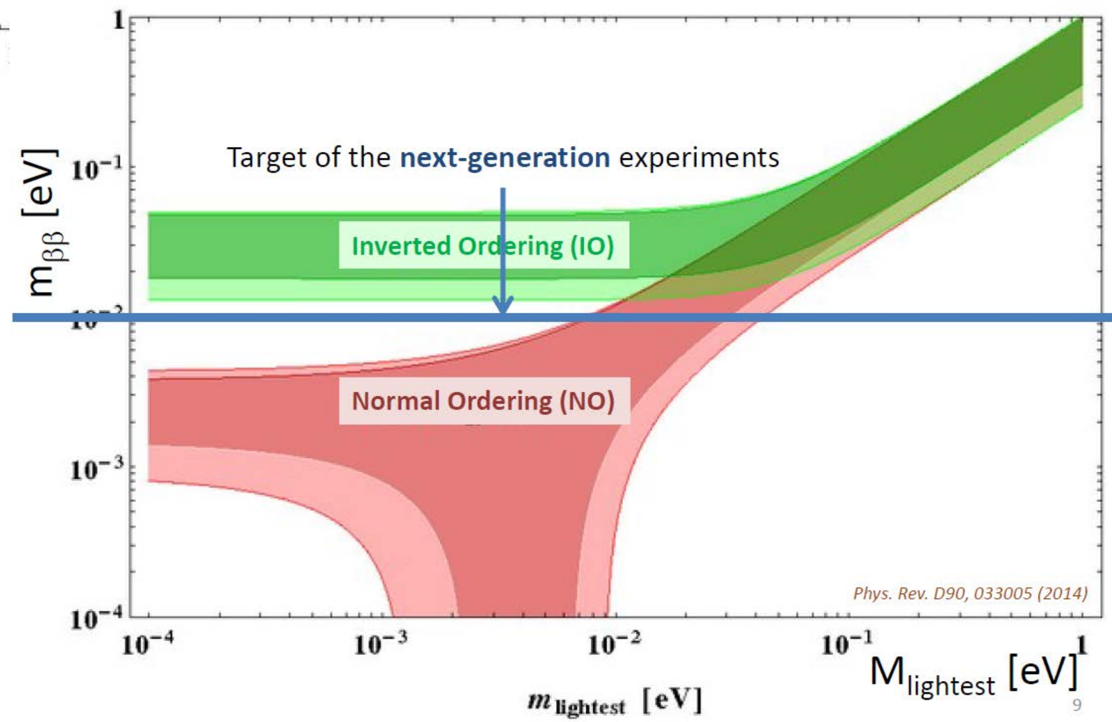
3.7 m long **(NEMO3 2.7 m)**
σ_t = 5 mm, σ_z = 1 cm
Radon < 0.15 mBq/m^3
(NEMO3 5 mBq/m^3)
Wiring robot

Global efficiency : 30 % (NEMO3 8%)

Current-generation experiments



Next-generation experiments



Conclusion

- **Neutrino is a fantastic particle to explore new physics beyond de SM.**

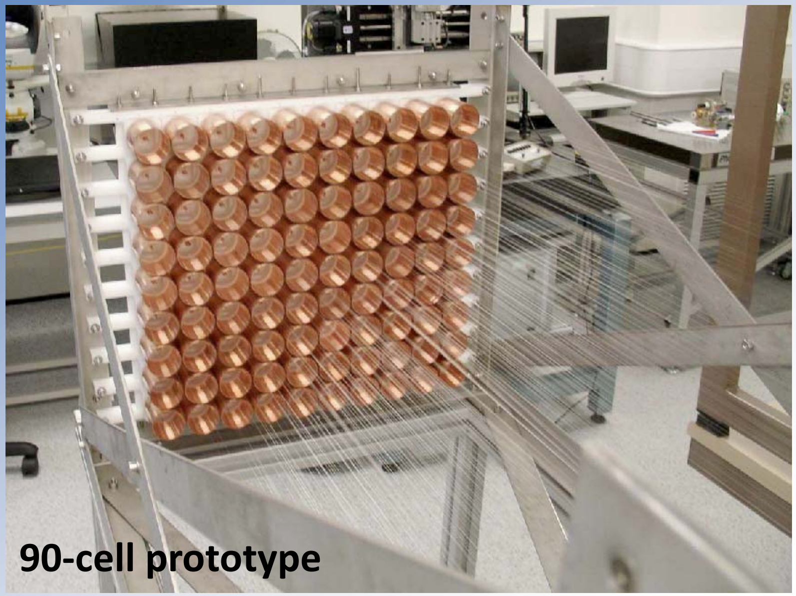
- **Despite the important advances in neutrino physics (neutrino oscillations demonstrate that MSM is wrong), we don’t know what is the nature of neutrino : Dirac or Majorana.**

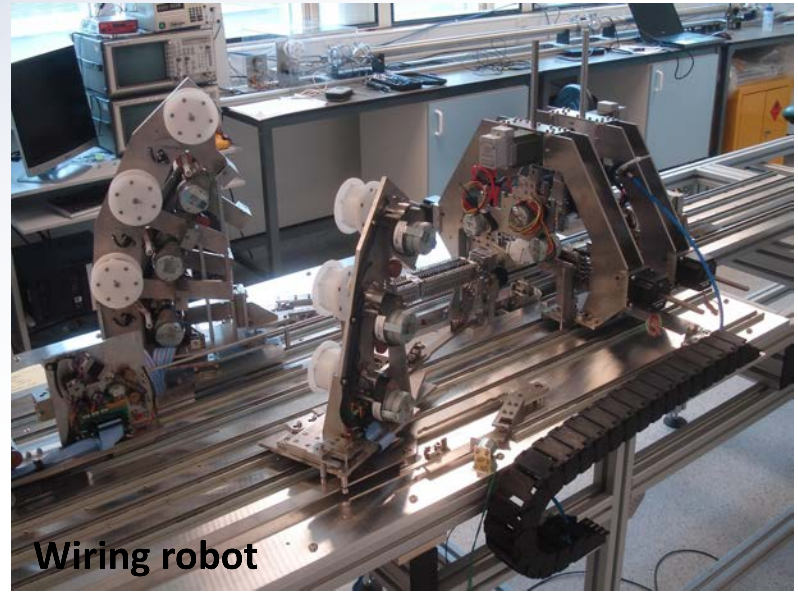
- **Neutrinoless double beta decay is the best way to test the neutrino nature and open the door to new physics beyond the SM.**

- **The field is extremely active : Variety of approaches and technologies**

Backup

SuperNEMO R&D: Tracker

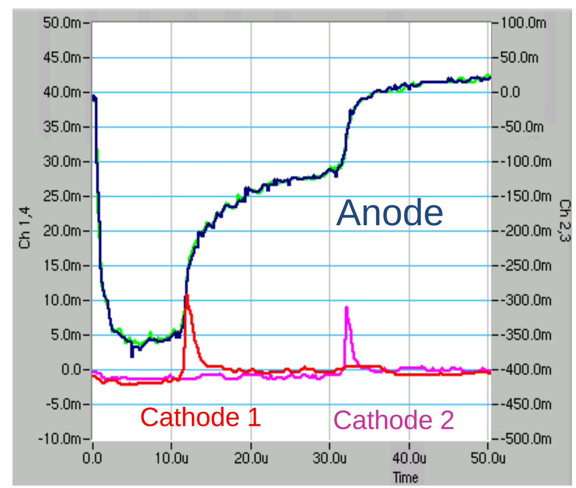




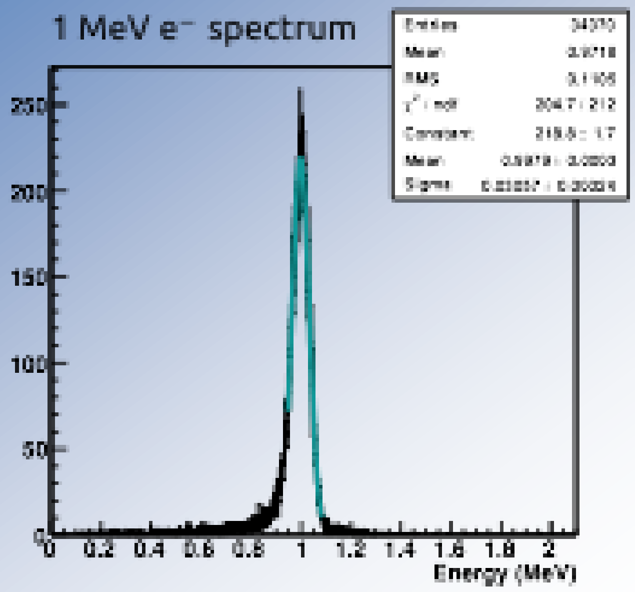
- Design verified with 90-cell prototype
  - Resolution: 0.7mm transverse, 1cm longitudinal
  - Cell efficiency > 98%

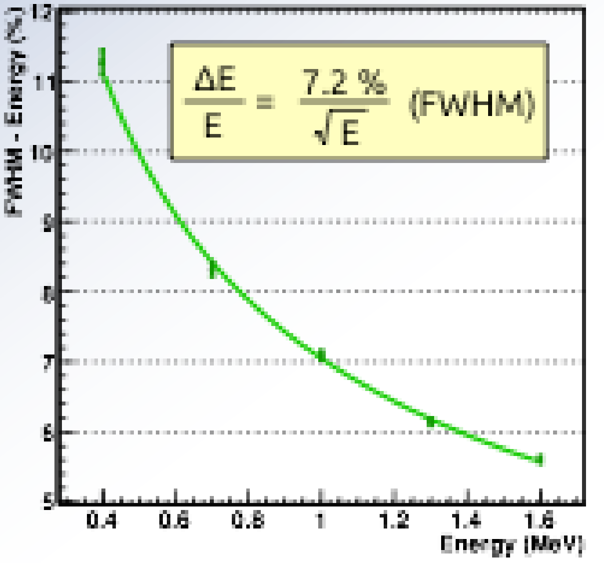
- Automated wiring robot being commissioned for mass production in ultra low background conditions
  - 500000 wires to string, crimp and terminate

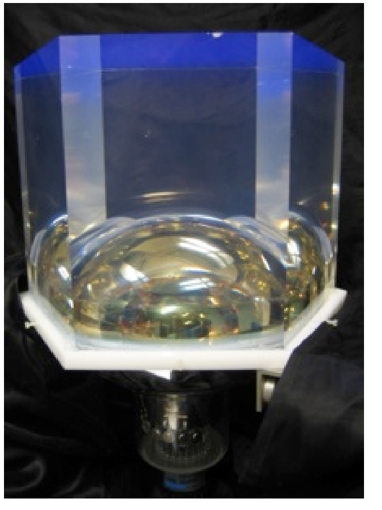
- Readout electronics under development



SuperNEMO R&D: Calorimeter





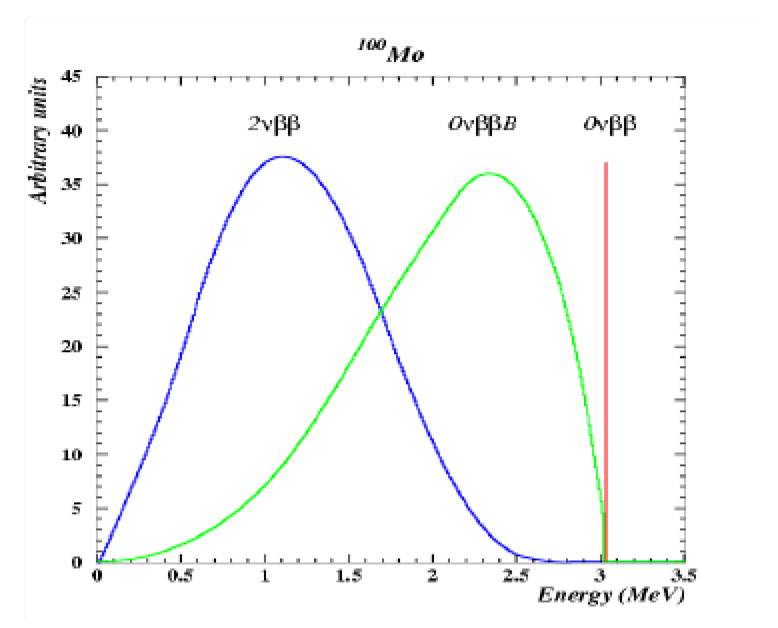


- Target ΔE/E reached with hexagonal and cubic blocks and high QE 8'' Hamamatsu R519MOD PMTs:

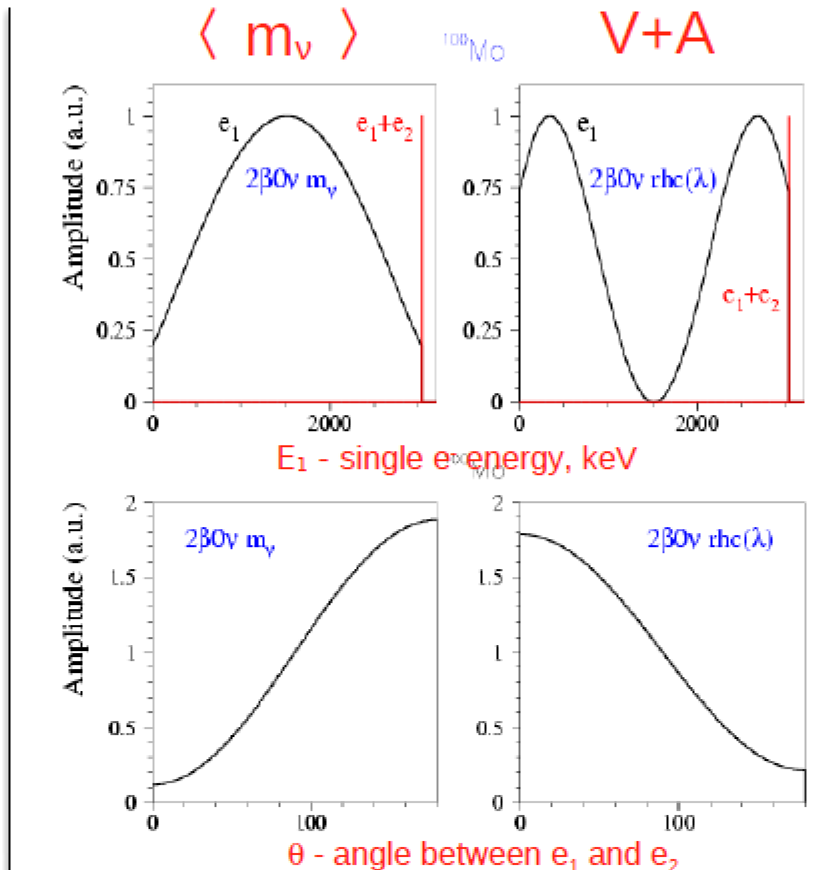
7.2% FWHM at 1 MeV
(equivalent to 4% at $Q_{\beta\beta}$ = 3.0 MeV)

Open minded search fo any 0νββ decay mechanism

$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}\left(Q_{\beta\beta}, Z\right)\left|M^{0\nu}\right|^2 \eta^2$$



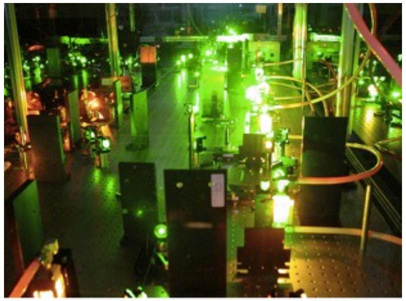
η can be due to mass mechanism, V+A, majoron, SUSY, ... with different topology in the final state



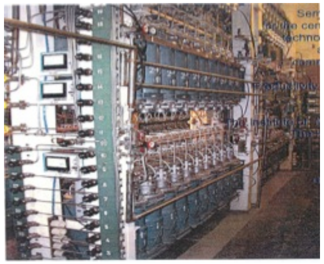
Isotope enrichment

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

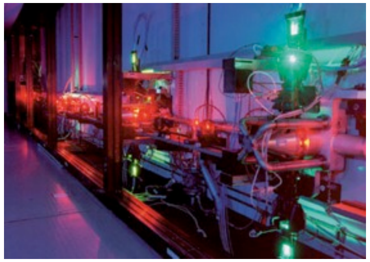
R&D in KAERI (Korea) for ^{48}Ca enrichment by laser



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



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



En 1957 Bruno Pontecorvo

Si les états propres de saveur et les états propres de masse ne sont pas confondus => Oscillations de neutrinos

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

E.P. Saveur — Matrice Mélange — E.P. Masse

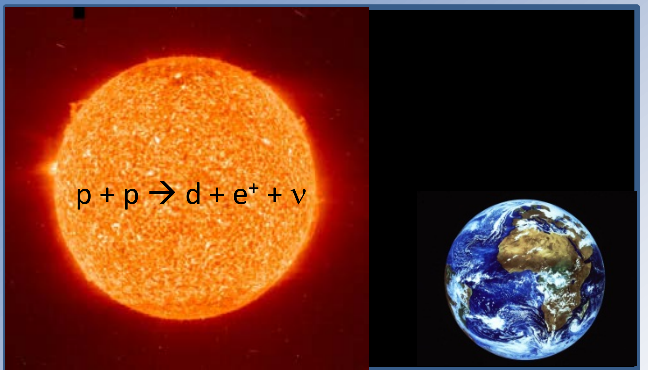
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

$$m^2{}_1 - m^2{}_2$$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}.$$

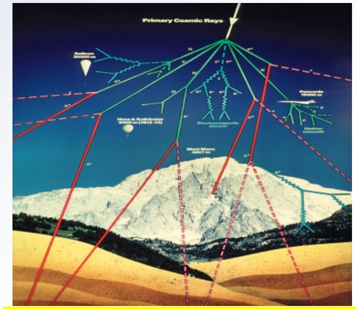
Pontecorvo-Maki-Nakasawa-Sakata

OSCILLATIONS DE NEUTRINOS



solaire

E_ν ~ 10 MeV
L ~ 10^8 Km
ν_e

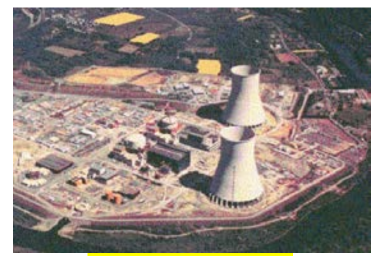


atmosphériques

E_ν ~ 10 GeV
L ~ 10 Km
$\nu_{e,}, \nu_{\mu,}$

accélérateur

E_ν ~ 1 GeV
L ~ 300 Km
$\nu_{\mu,}$



réacteur

E_ν ~ 1 MeV
L ~ 1 Km –100 Km
$\nu_{e,}$

V_{PMNS} →

$$\Delta m^2_{21} = 7.54 \times 10^{-5}\ \text{eV}^2,$$

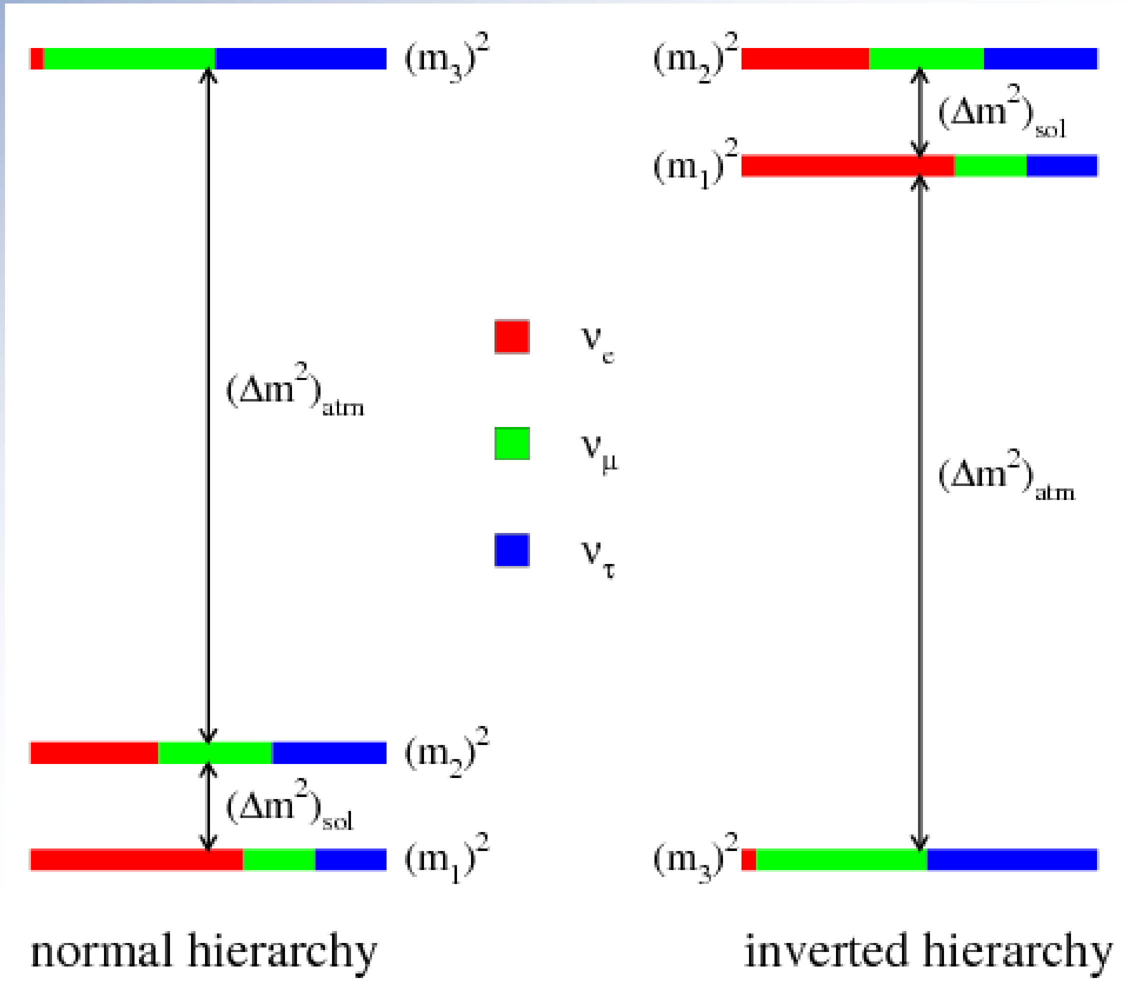
$$\left|\Delta m^2_{31(32)}\right| = 2.47\ (2.46) \times 10^{-3}\ \text{eV}^2,$$

$$\sin^2\theta_{12} = 0.307, \qquad \sin^2\theta_{23} = 0.39,$$

$$\sin^2\theta_{13} = 0.0241\ (0.0244)\,,$$

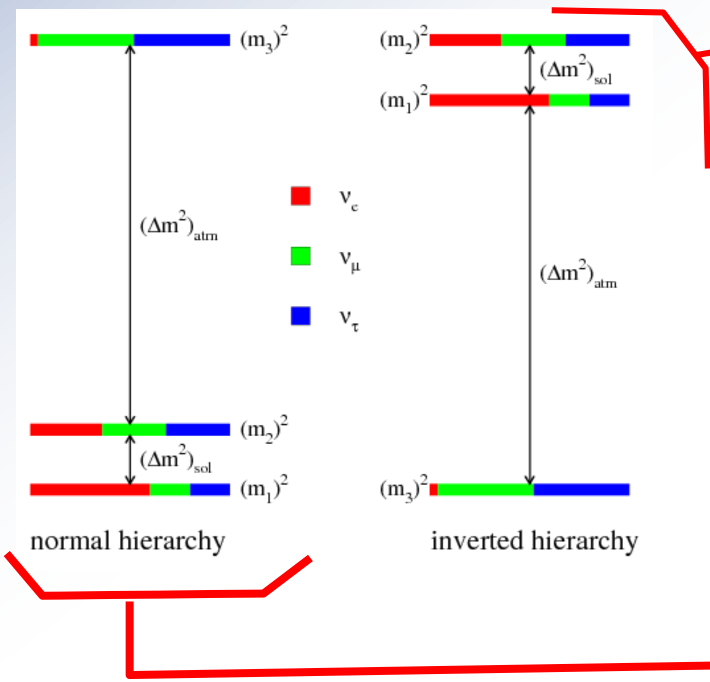
=> $m_\nu \neq 0$
$m_\nu = ?$

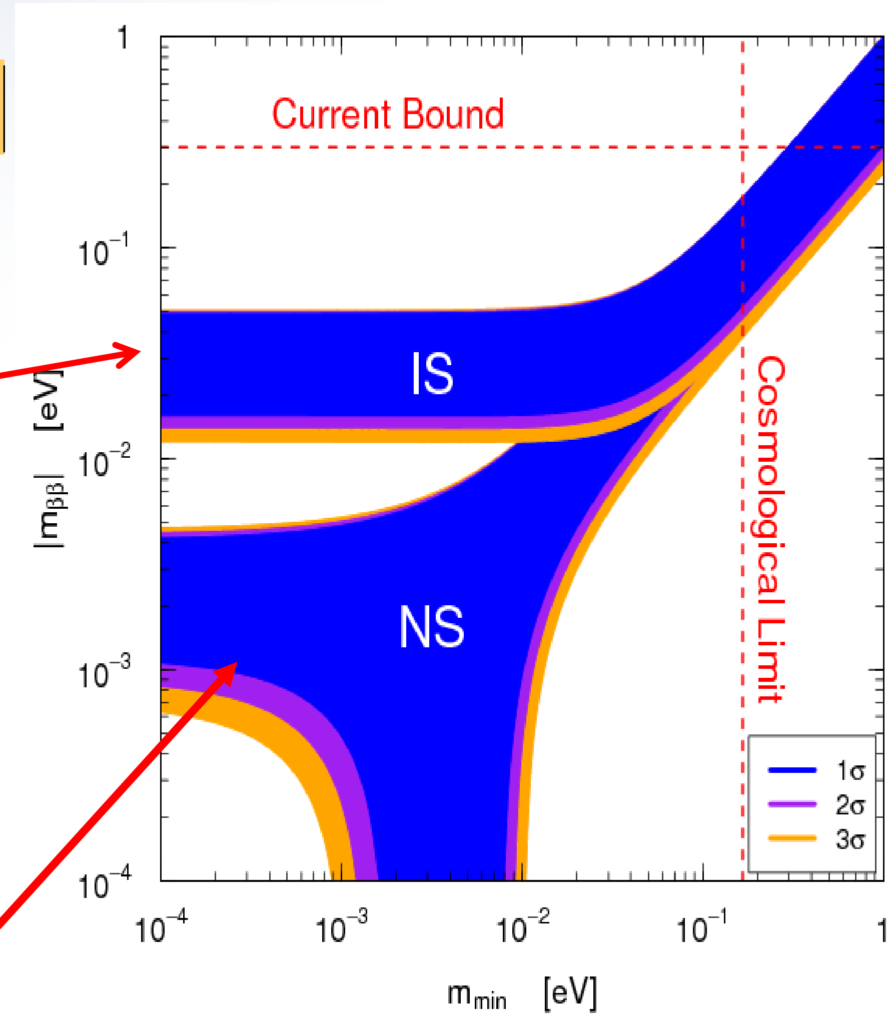
Hiérarchie de masse



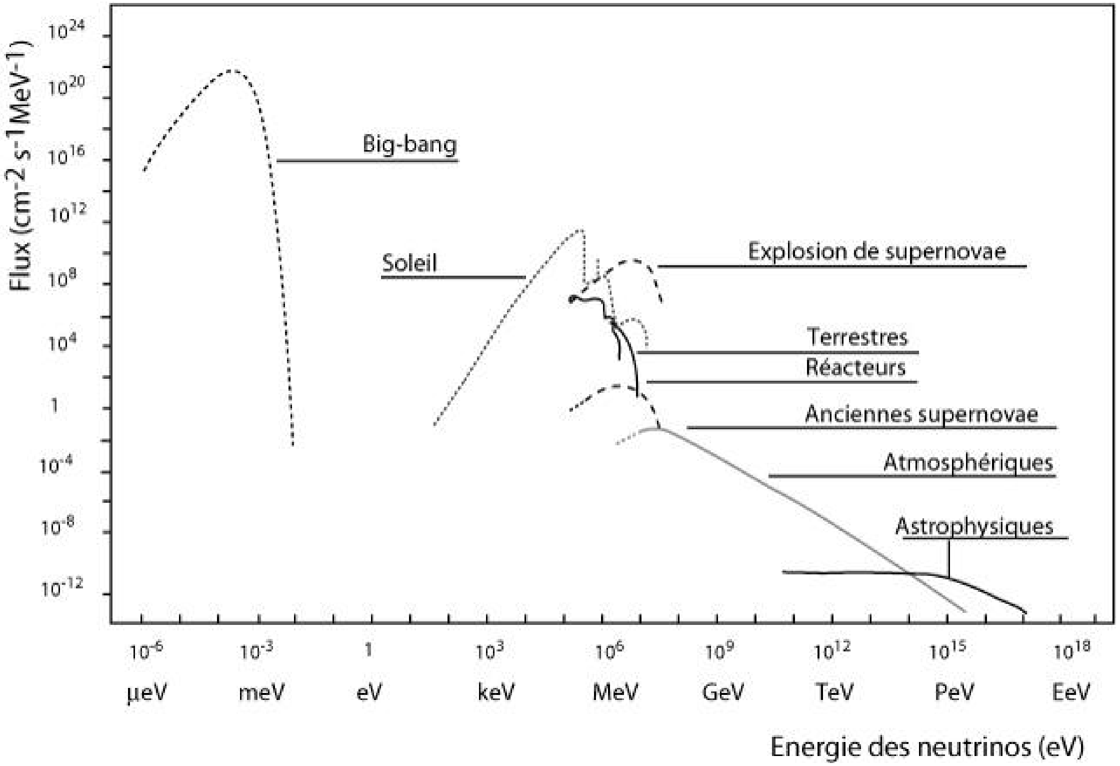
ββ v.s. oscillations

$$\left|\langle m_{\beta\beta}\rangle\right| \equiv \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha^*} + m_3 |U_{e3}|^2 e^{i\beta^* - 2i\delta} \right|$$





Neutrinos abundance in the Univers



Second most abundance particle in the universe

413 photons/m^3

340 neutrinos/cm^3 ($\overset{(-)}{\nu}_e , \overset{(-)}{\nu}_\mu , \overset{(-)}{\nu}_\tau$)

Better knowledge of neutrino physics => direct impact in astrophysics and cosmology