From Majorana to SuperNEMO

The nature of neutrino

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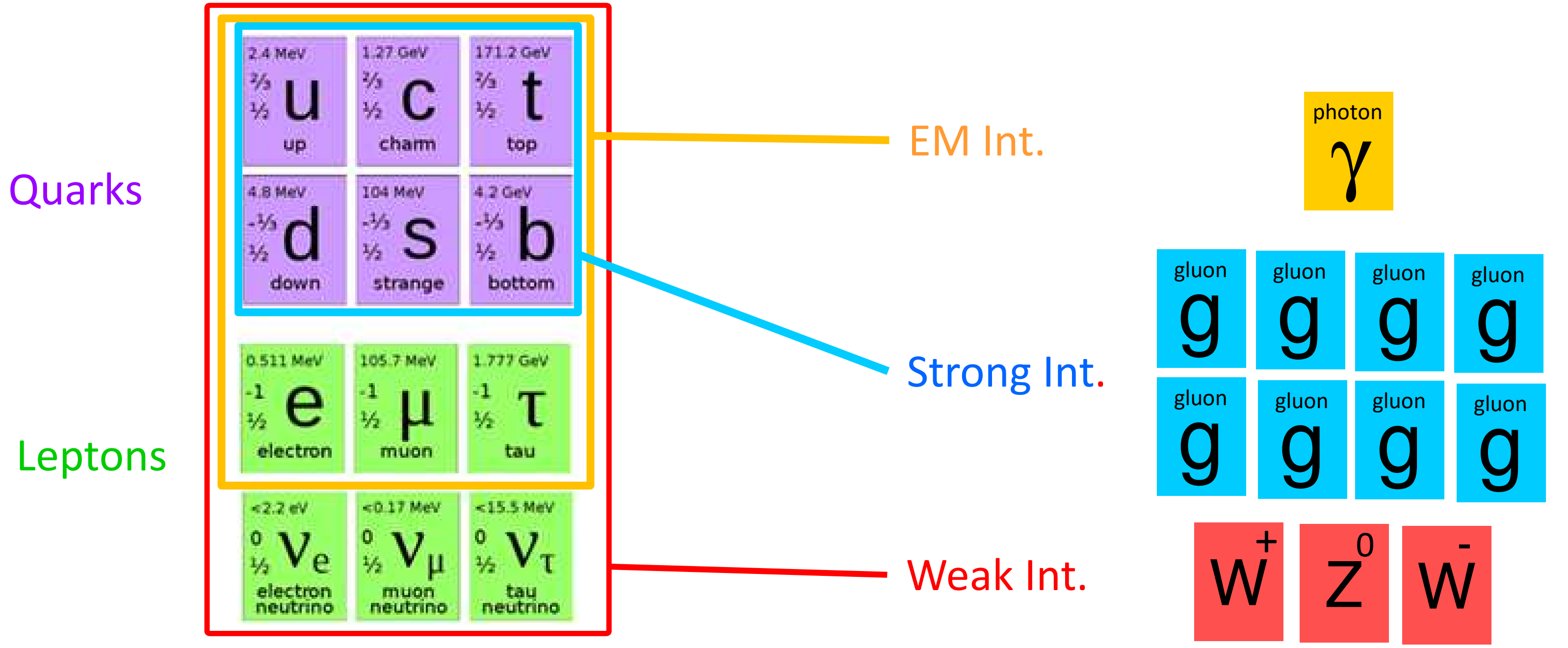
Standard Model of particle and interactions

Matter Particles (fermions)

Interaction Particles (bosons)



Quarks

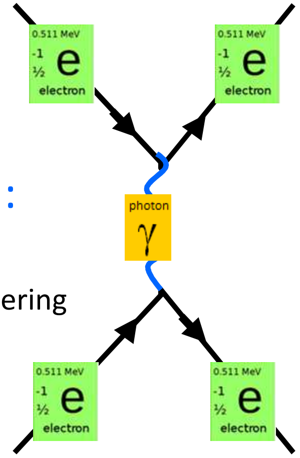
Leptons

EM Int.

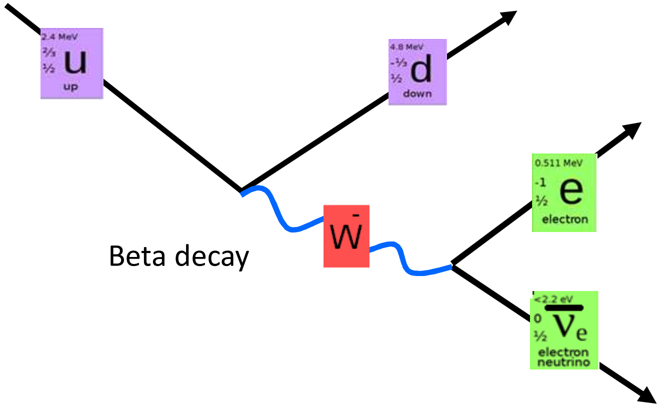
Strong Int.

Weak Int.

Interaction by exchange of a boson :

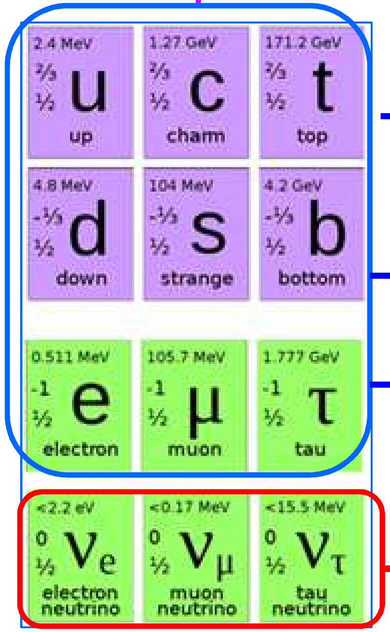


Electron scattering



Beta decay

Mass



2.4 MeV ⅔ ½ u up	1.27 GeV ⅔ ½ c charm	171.2 GeV ⅔ ½ t top
4.8 MeV -⅓ ½ d down	104 MeV -⅓ ½ s strange	4.2 GeV -⅓ ½ b bottom
0.511 MeV -1 ½ e electron	105.7 MeV -1 ½ μ muon	1.777 GeV -1 ½ τ tau
<2.2 eV 0 ½ ν_e electron neutrino	<0.17 MeV 0 ½ ν_μ muon neutrino	<15.5 MeV 0 ½ ν_τ tau neutrino

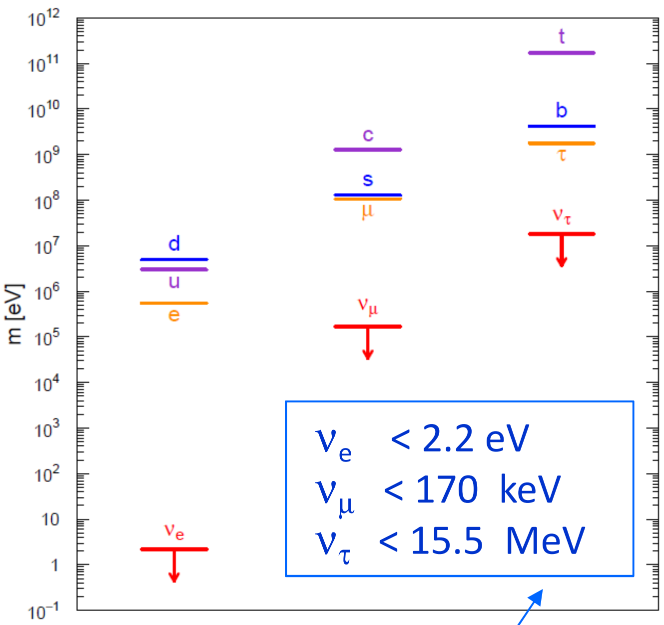
Electric charge : +2/3

Electric charge : - 1/3

Electric charge : - 1

“Mass ?? : only limits”
No charge

Fermion Mass Spectrum



ν_e < 2.2 eV
ν_μ < 170 keV
ν_τ < 15.5 MeV

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 is governed by Quantum Mechanics

Schrodinger Equation
(**Non relativistic** quantum theory)

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

Dirac Equation (spin (1/2))
(**Relativistic** quantum theory)

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

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

↳ Particle (p), ↳ antiparticle (p^c)

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

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

⇒ 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

- 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 $i\gamma^\mu \partial_\mu \psi = 0$

For neutrino

→ ν_L , ν_R , ν_L^c , ν_R^c

→ ν_L , ν_R^c OR ν_L^c , ν_R

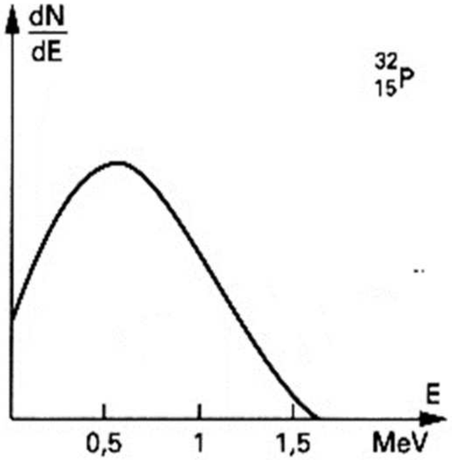
If neutrino is massless, or very light => two possibilities : Left Handed or Right Handed

Which one is the good one ?

Beta decay

$$\boxed{{}^{A}_{Z}X \to {}^{A}_{Z+1}Y + e^{-} + \upsilon_e^c}$$

Pauli 1930

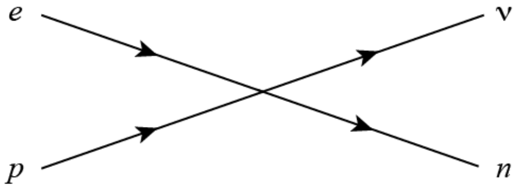


Continuous spectrum → neutrino hypothesis

●

Fermi 1933

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



Point interaction, no W boson

What's " ν " ?

- Conservation laws

$$a + b \to c + d$$

electric charge
energy
momentum
angular momentum

Strong symmetries

baryon number
lepton number

It works

(Requirement for SM)

Lepton number L :

+1 Lepton (e^-, μ^-, τ^-, ν)
-1 antiLepton ($e^+, \mu^+, \tau^+, \nu^c$)
0 No lepton (quarks)

$$n \to \quad p \; + \; e^- + "\upsilon"$$

Lepton Number 0 = 0 +1 -1

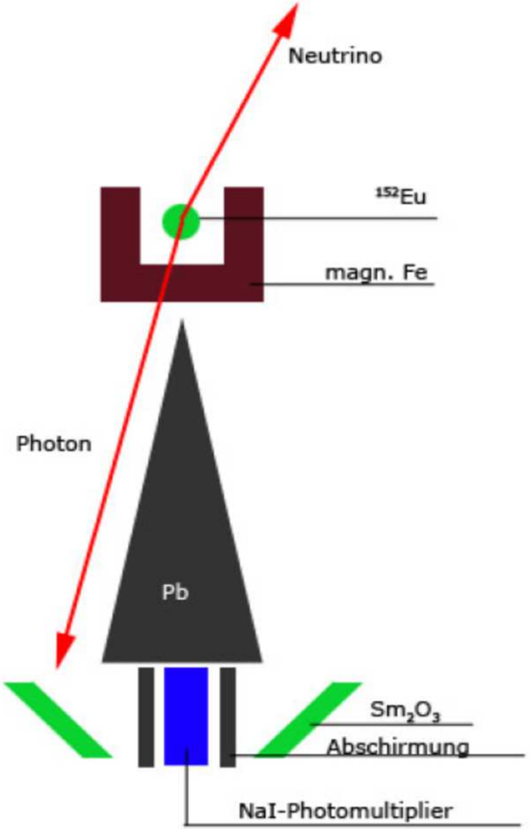
=> " ν " must be an antineutrino

$$n \to \quad p \; + \; e^- + \upsilon^c$$

Anti-neutrino : Left Handed or Right Handed ??

Goldhabert measure the neutrino helicity in 1958

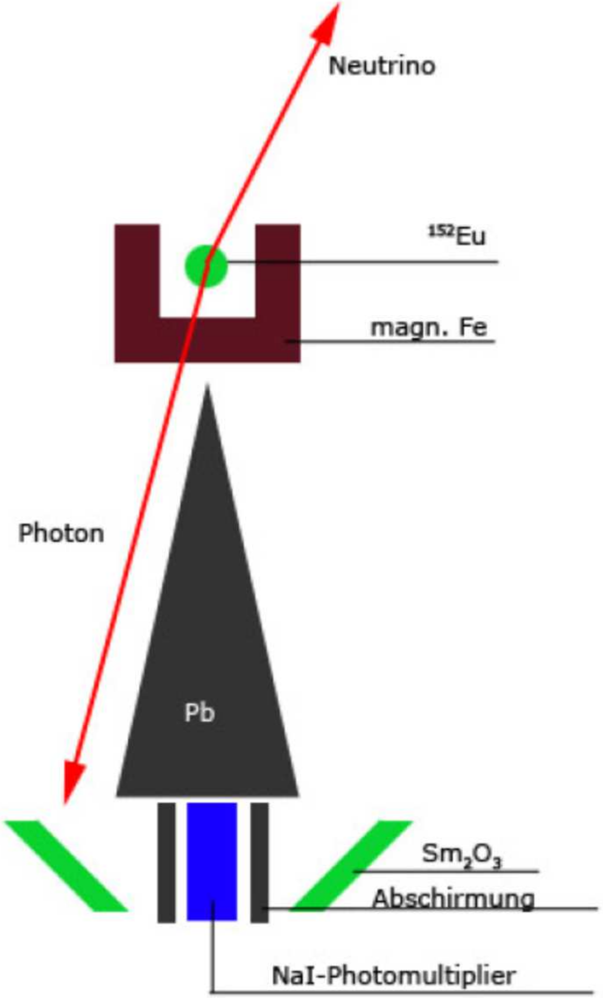
Goldhaber-Experiment



$$Eu + e^- \rightarrow Sm^* + \nu_e \rightarrow Sm + \gamma + \nu_e$$

- energy of Sm^* is distributed on Sm and γ
  $\rightarrow$ γ has to less energy to excite another Sm nucleus
- but: Sm^* gets a recoil when the ν_e is emitted $\rightarrow$ doesn't decay in rest
- γ emitted in moving direction of Sm^* nucleus
  $\rightarrow$ gets additional energy
  $\rightarrow$ can be absorbed by another Sm nucleus
  $\Rightarrow$ **resonant absorption possible**

Goldhaber-Experiment



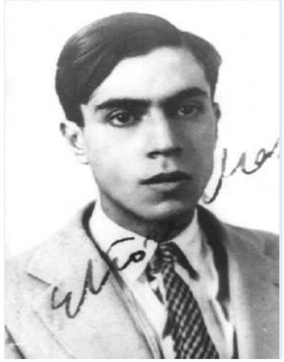
measurement of helicity:

- Eu-source in iron magnet
- photons Compton scattered on electrons of Fe
- $d\sigma/d\Omega(\uparrow\downarrow) > d\sigma/d\Omega(\uparrow\uparrow)$
- reverse magnetic field and count detected photons
  $\Rightarrow$ polarisation of photons
  $\Rightarrow H(\nu) = -1.0 \pm 0.3$

$\Rightarrow$ neutrinos are left handed

υ_{LH} and υ_{RH}^{c}

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 or **Majorana**

$\upsilon_D \neq \upsilon_D^C$

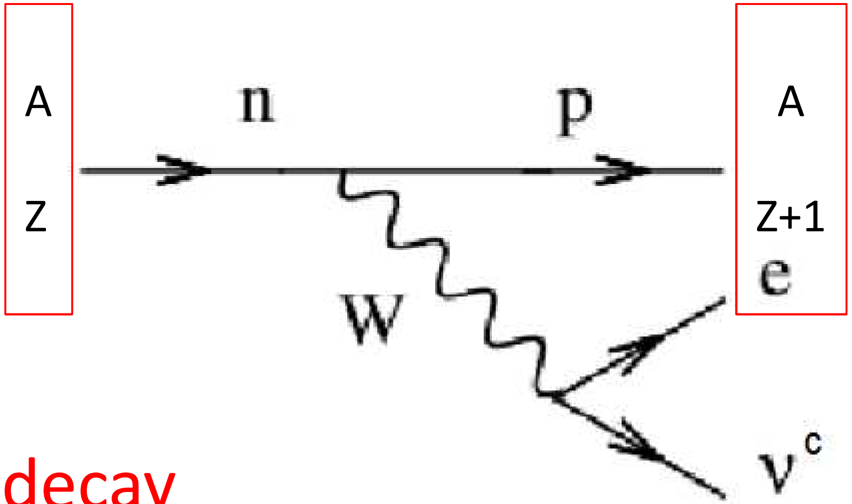
$\upsilon_M = \upsilon_M^C$

?????

If ν is Majorana, Lepton number is not conserved.

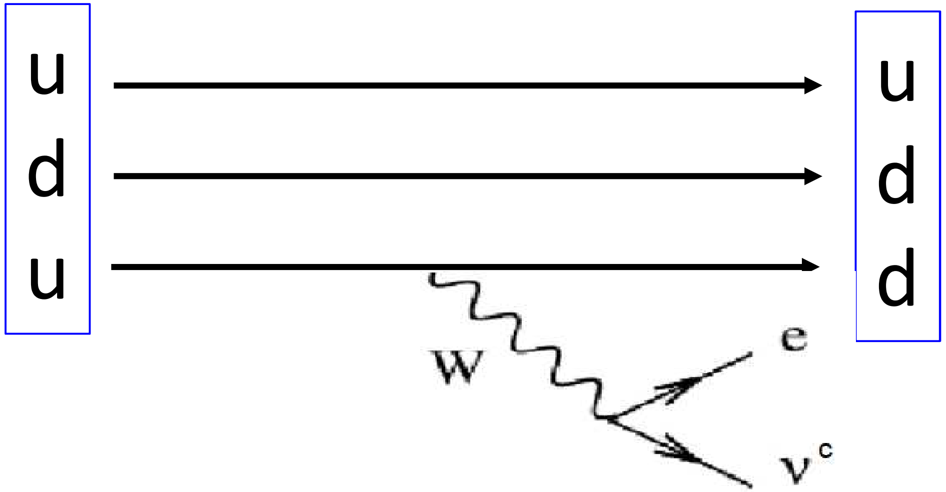
Need new physics beyond de SM

From single beta to double beta



β^-

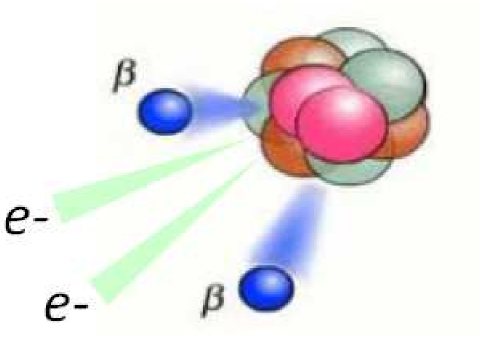
Single beta decay

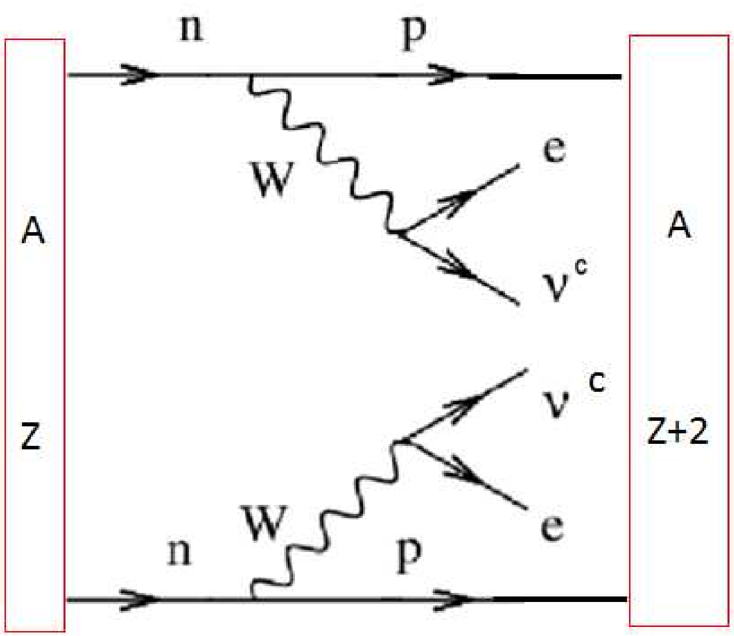


Double Beta Decay

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

Two neutrinos DBD





β^-

β^-

Two decays in the same nucleus at the same time

Prosed by Maria Goeppert – Mayer en 1935

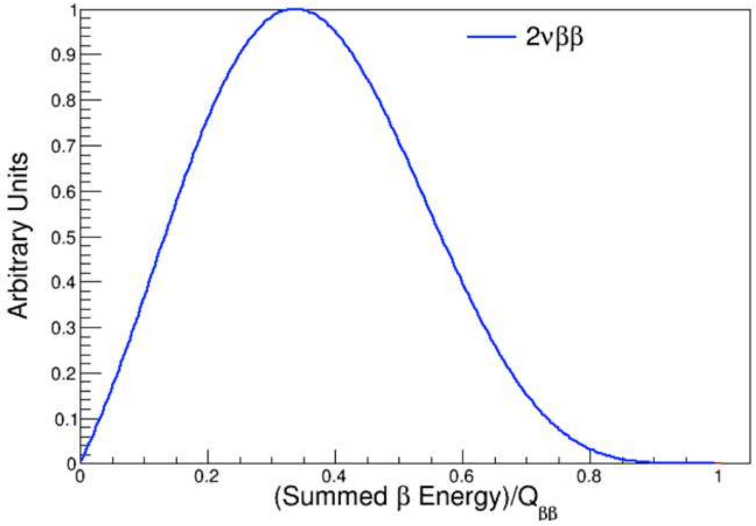
Observed for the first time in 1987 by Michael Moe

→ 10^{19} to 10^{21} y

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

Two neutrinos spectrum

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



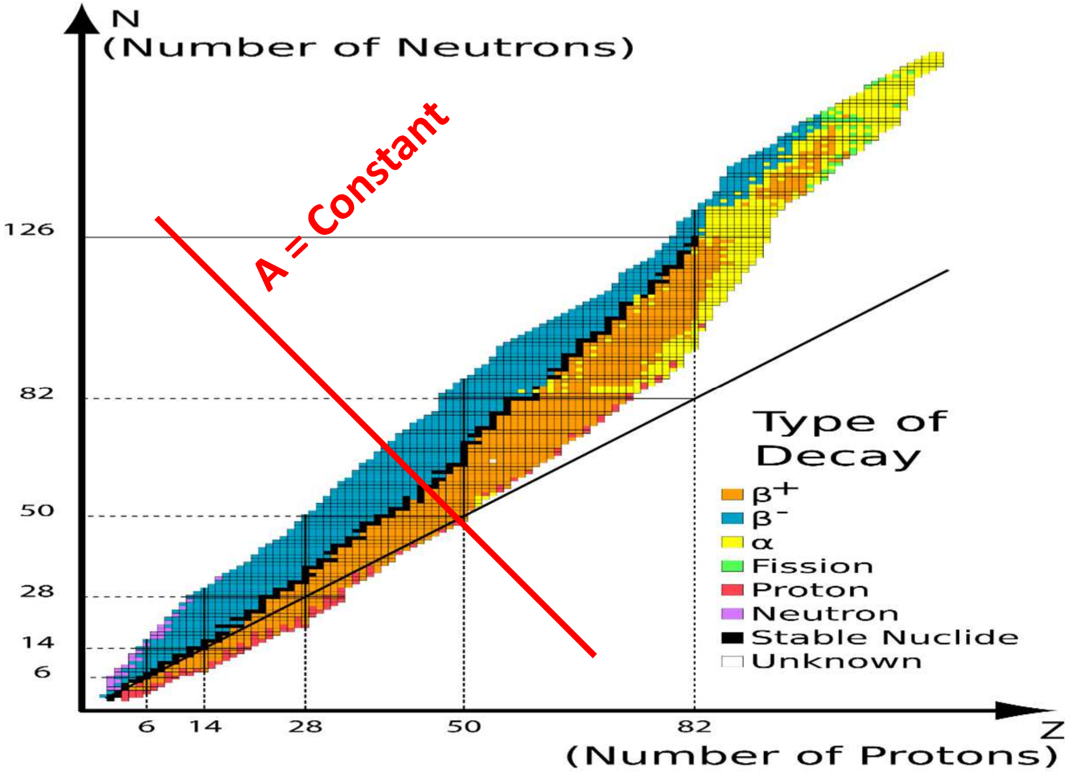
$$ {}^{A}_{Z}X \rightarrow {}^{\;\;\;A}_{Z+2}Y + 2e^{-} + 2\upsilon_{e}^{c} $$

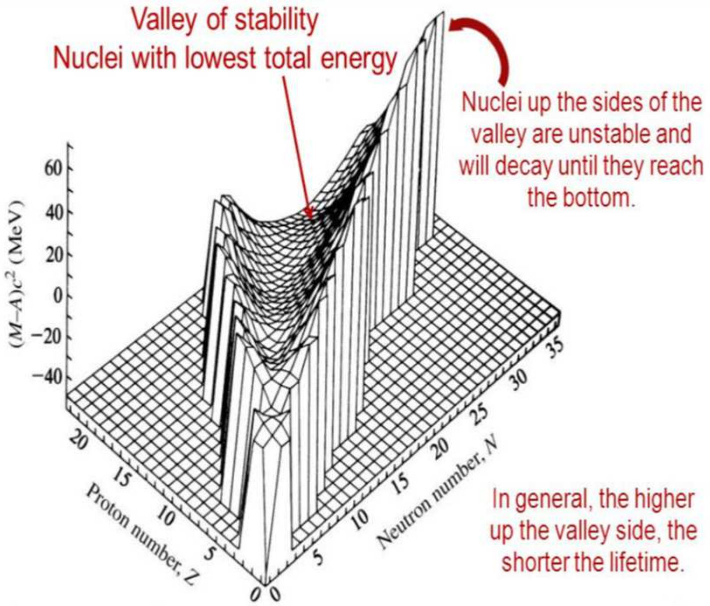
$$ Q_{\beta\beta} = M\left({}^{A}_{Z}X\right) - M\left({}^{\;\;\;A}_{Z+2}Y\right) $$

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

$G =$ phase space (well known)
$M =$ nuclear matrix element (challenging)

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





Valley of stability
Nuclei with lowest total energy

Nuclei up the sides of the valley are unstable and will decay until they reach the bottom.

In general, the higher up the valley side, the shorter the lifetime.

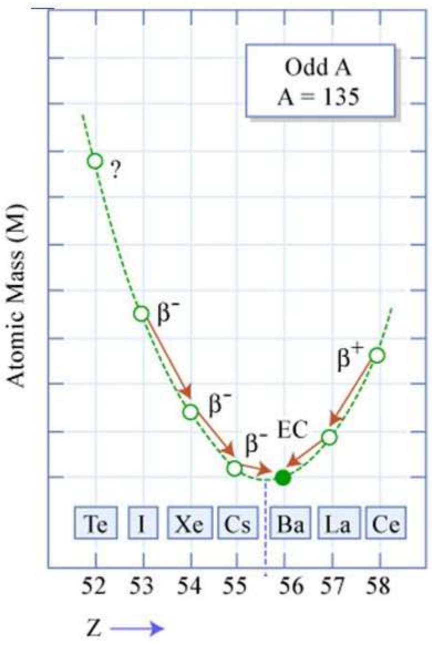
Bethe Weizsaecker formula

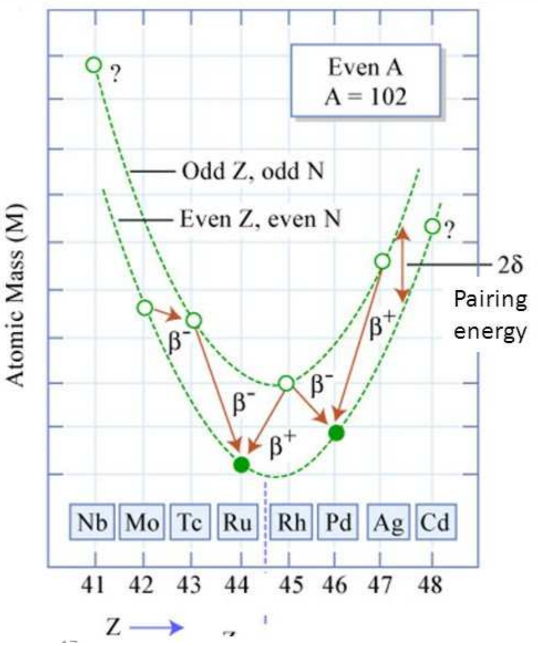
(Liquid drop model)

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

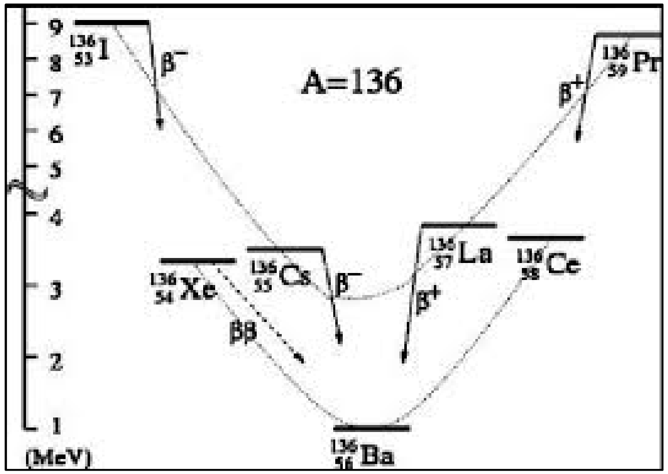
Mass or binding energy of nucleus

A = constant

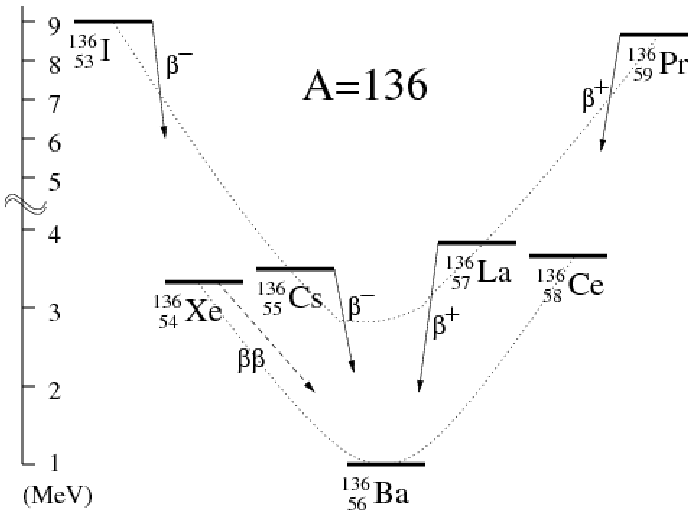




For some even nucleus decay to (A, Z+1) is impossible



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

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

Racah mecanism

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

Beta Decay BD

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

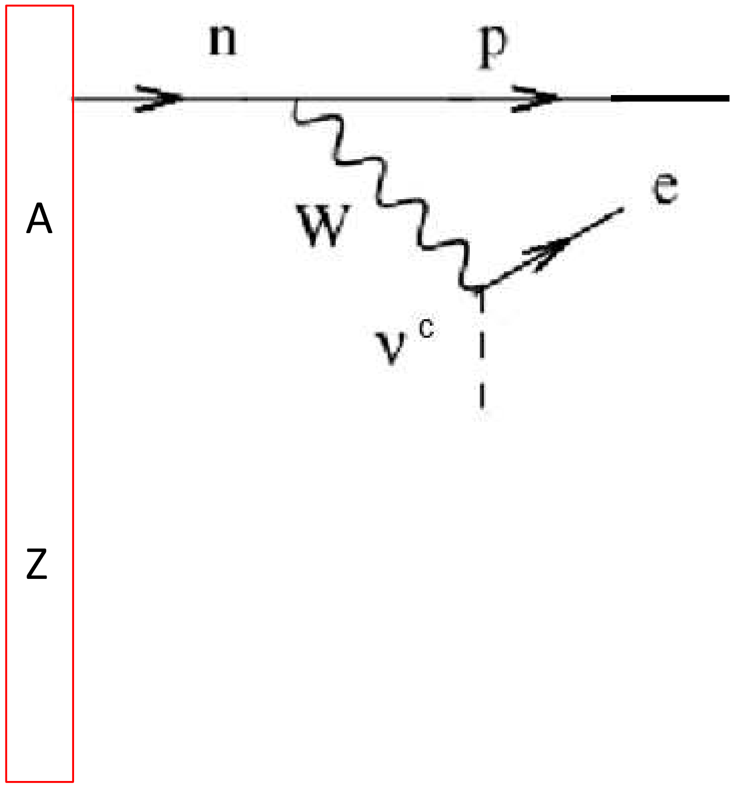
Inverse Beta Decay IBD

(Neutrino capture

In SM | : ν (BD) is a RH anti-Neutrino
: ν(IBD) is a LH neutrino

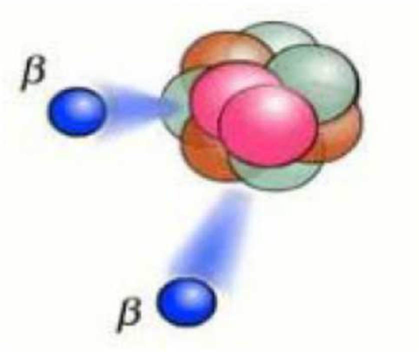
ν_L, ν_R^{c}

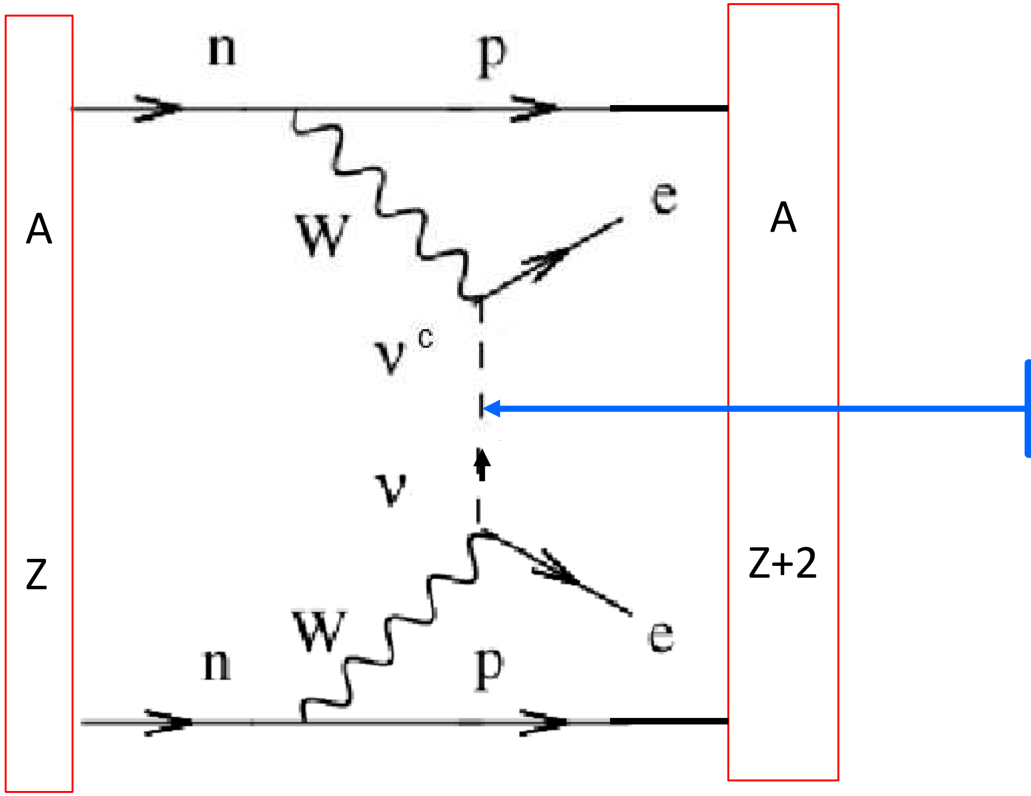
Neutrinoless Double Beta Decay $(\beta\beta)_{0\nu}$



Neutrinoless Double Beta Decay

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



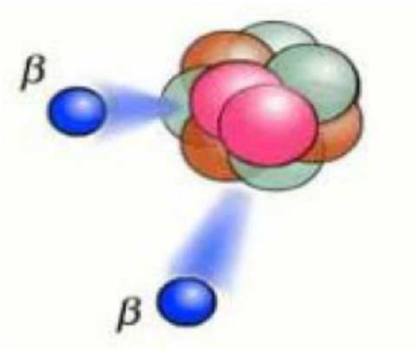


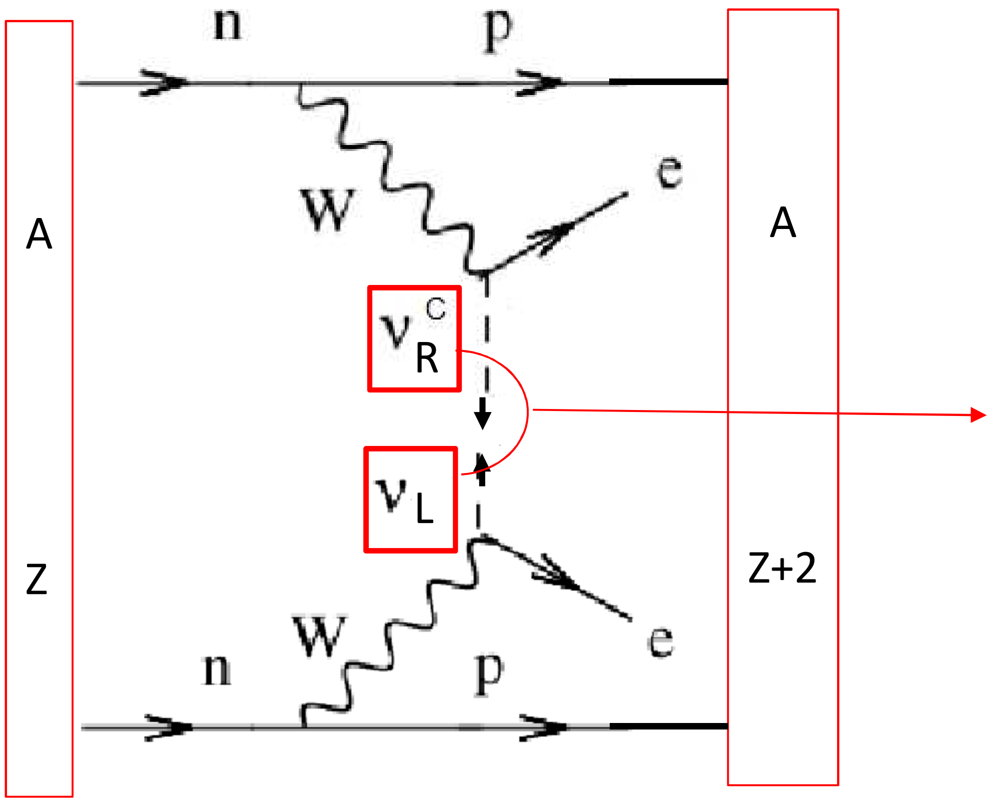
$\upsilon \equiv \upsilon^c$

$\Delta L \neq 0$

=> Forbiden in the SM

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



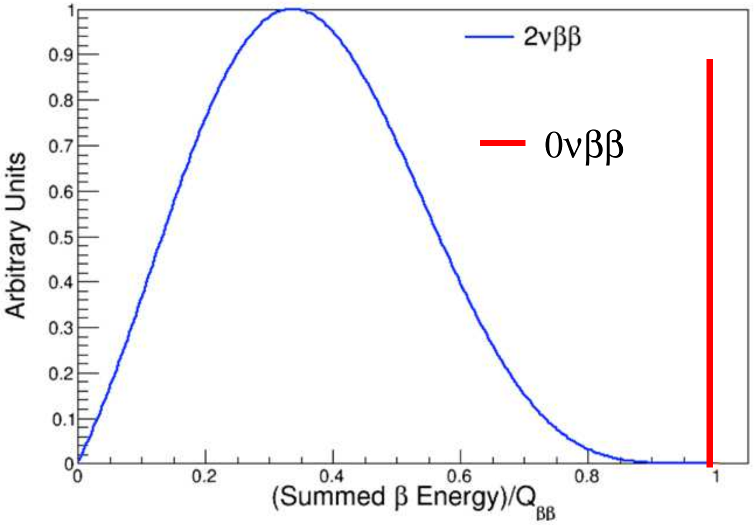


Need spin flip

Spin flip :

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

Neutrinoless ββ spectrum



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

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

Phase space

Effective neutrino mass

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

Nuclear matrix

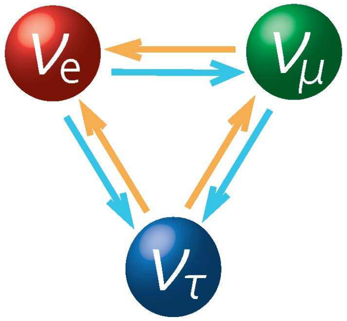
ν mass eigenstates

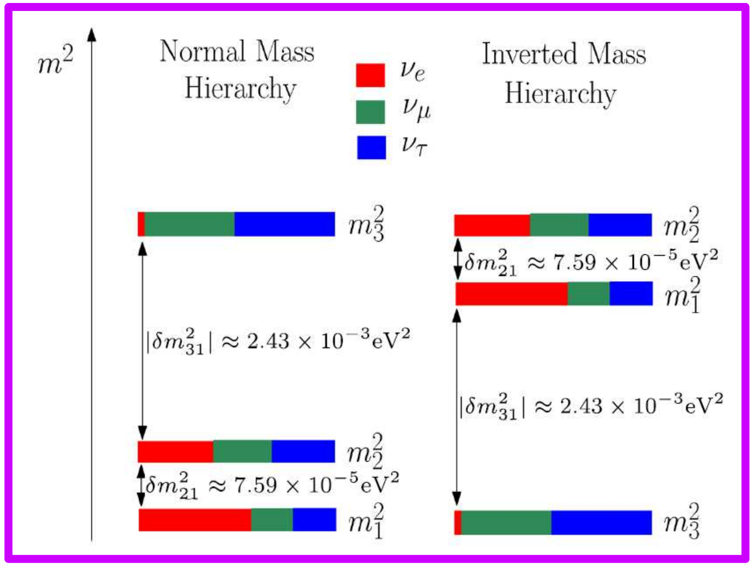
$$\left|\left\langle m_{\beta\beta}\right\rangle\right| \equiv \left| m_{1}\left|U_{e1}\right|^{2} + m_{2}\left|U_{e2}\right|^{2} e^{i\alpha^{*}} + m_{3}\left|U_{e3}\right|^{2} e^{i\beta^{*}-2i\delta} \right|$$

ν mixing

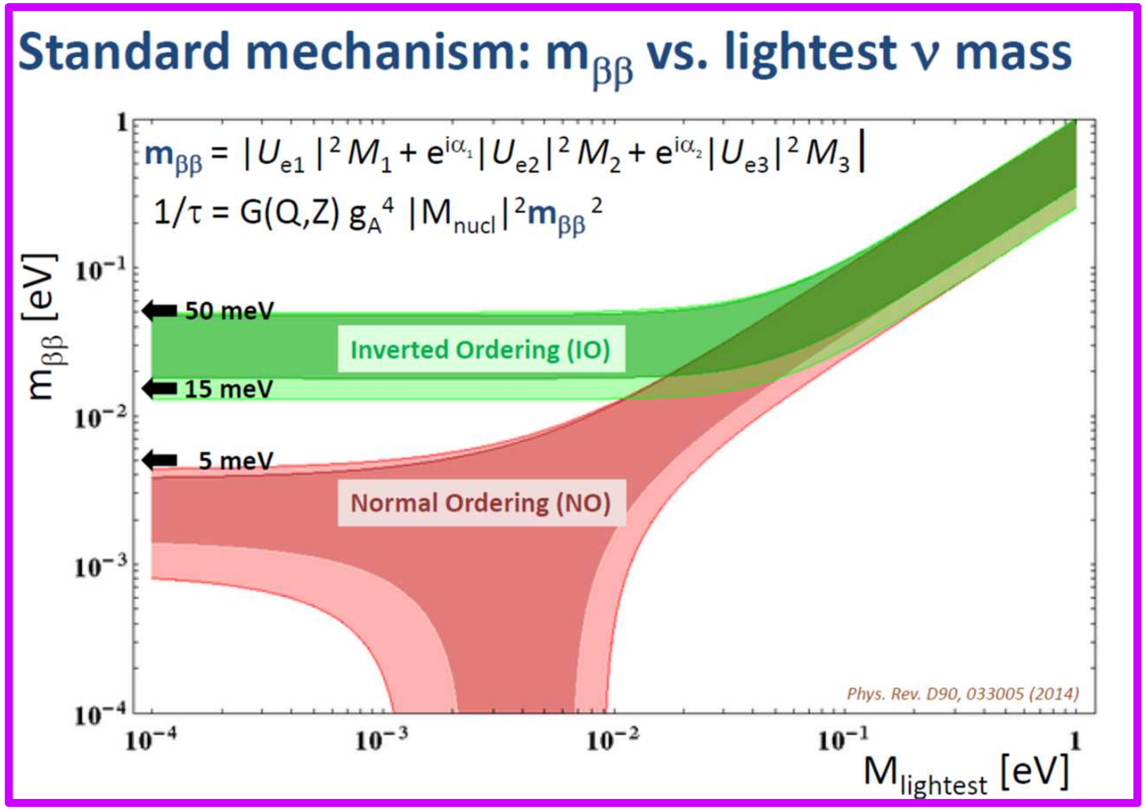
Quantitative parameter for a (ββ)0ν experiment

Oscillations of neutrino





Neutrino Mass Hierarchy



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

$$m_{\beta\beta} = \left| |U_{e1}|^2 M_1 + e^{i\alpha_1}|U_{e2}|^2 M_2 + e^{i\alpha_2}|U_{e3}|^2 M_3 \right|$$

$$1/\tau = G(Q,Z)\, g_A^4\, |M_{nucl}|^2 m_{\beta\beta}^2$$

Phys. Rev. D90, 033005 (2014)

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.

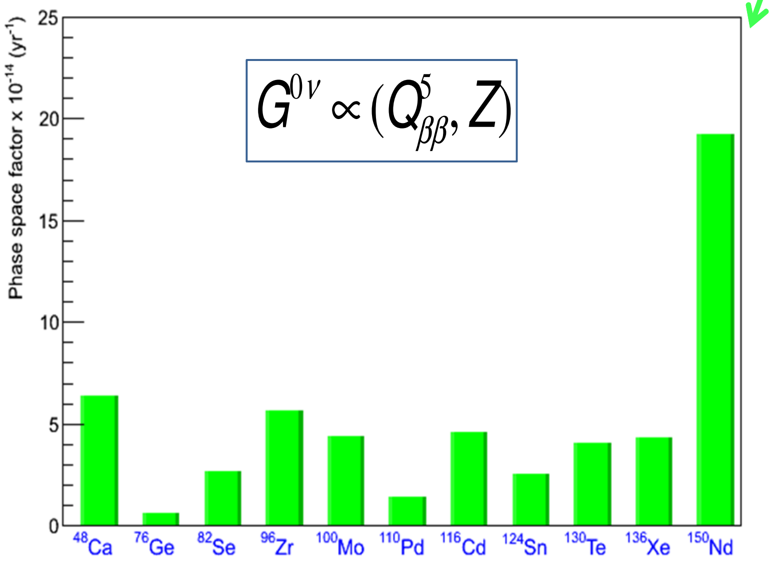
Grand Unification Theories, Super Symetry, . . .

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

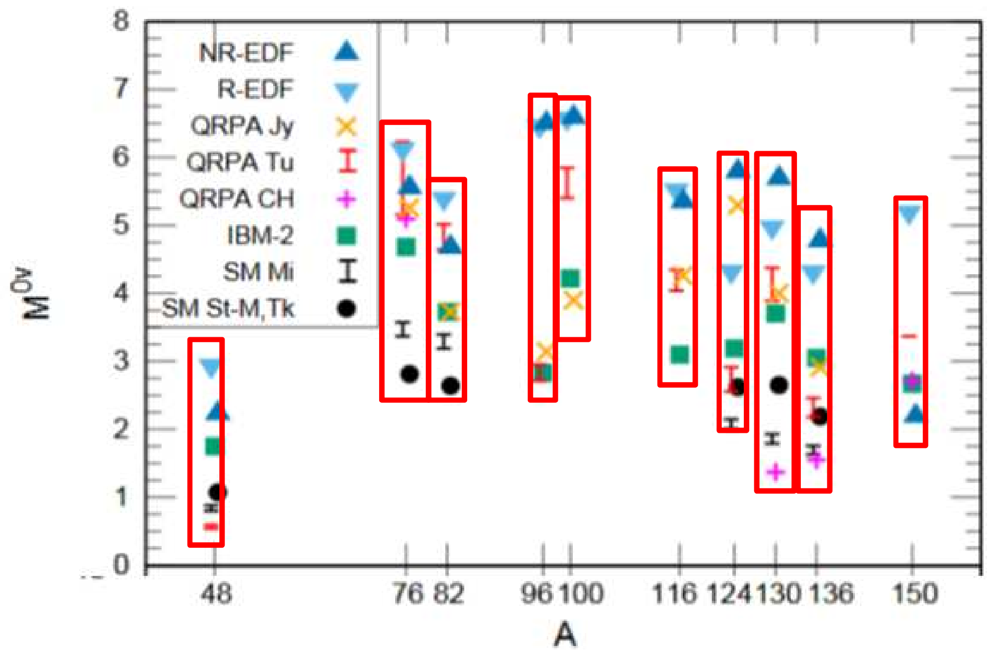
$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^{2}\left\langle m_{\nu}\right\rangle^{2}$$

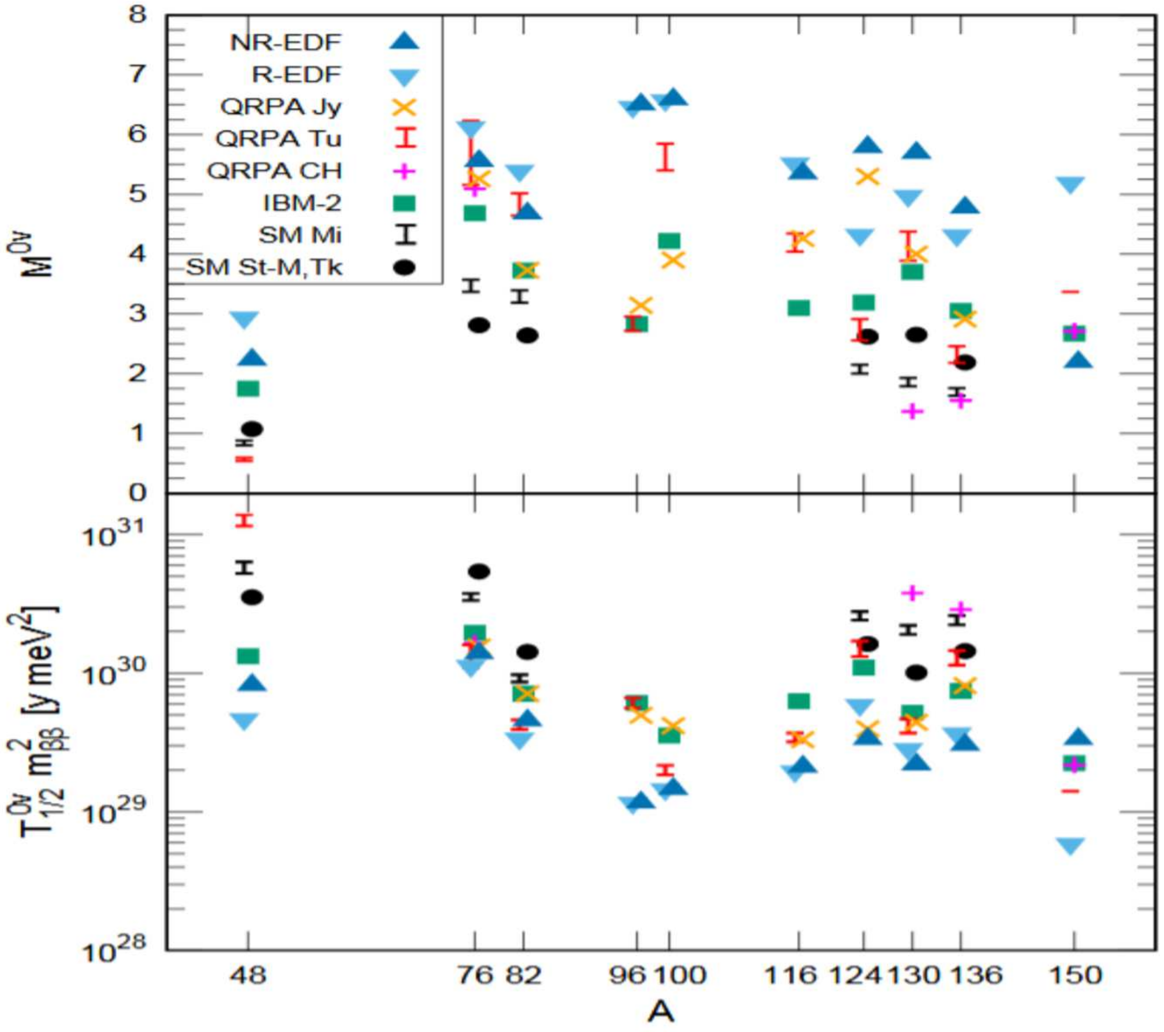
Phase space: exactly calculable



$$G^{0\nu} \propto (Q^{5}_{\beta\beta}, Z)$$

Nuclear matrix elements: several models

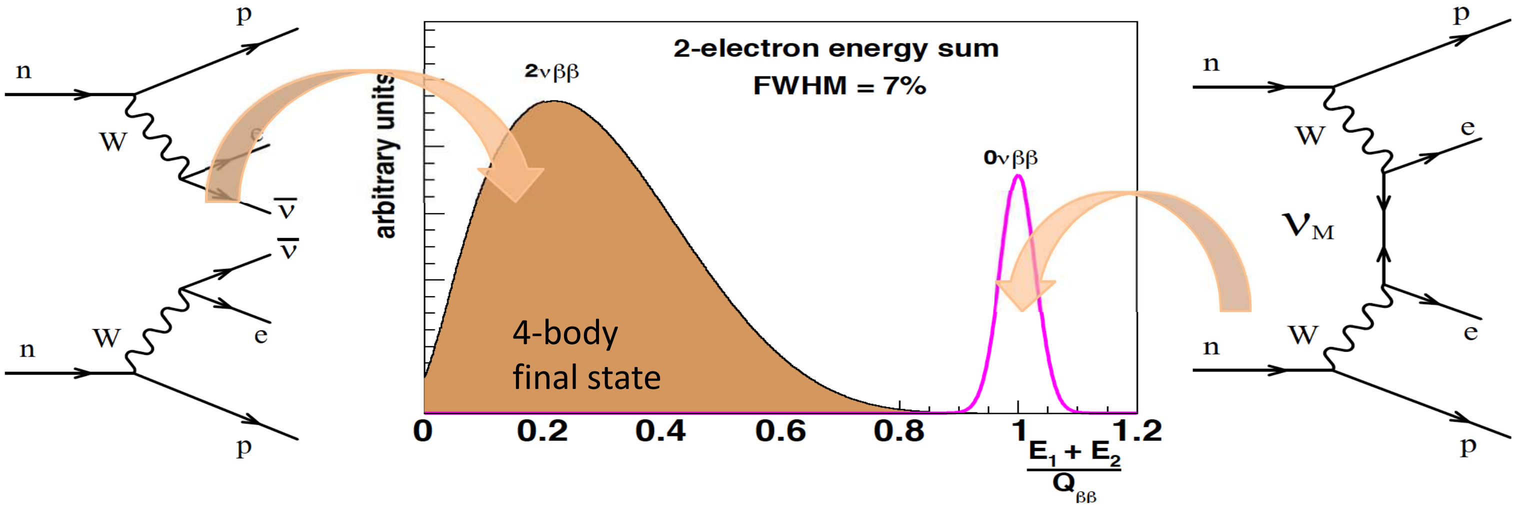



NR-EDF
R-EDF
QRPA Jy
QRPA Tu
QRPA CH
IBM-2
SM Mi
SM St-M,Tk
$M^{0\nu}$
0
1
2
3
4
5
6
7
8
$T^{0\nu}_{1/2}\, m^2_{\beta\beta}$ [y meV^2]
10^{28}
10^{29}
10^{30}
10^{31}
48
76
82
96
100
116
124
130
136
150
A

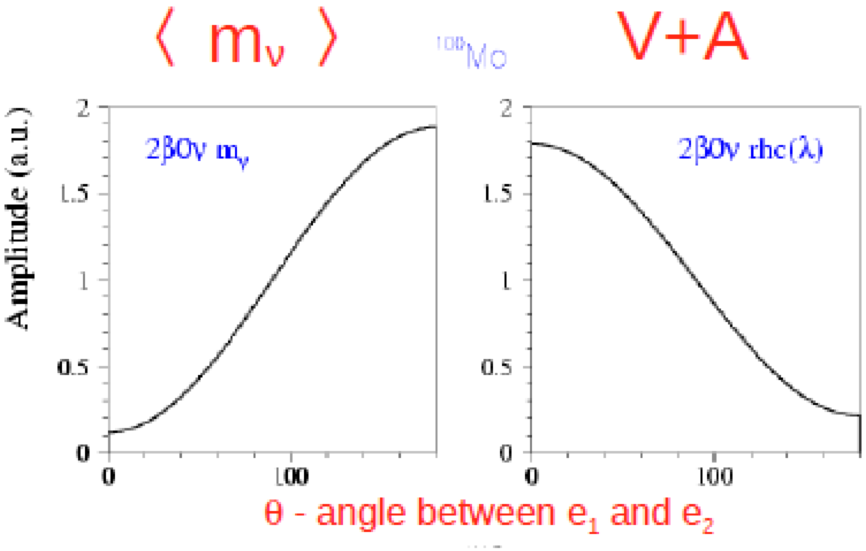
Some experimental aspects

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)

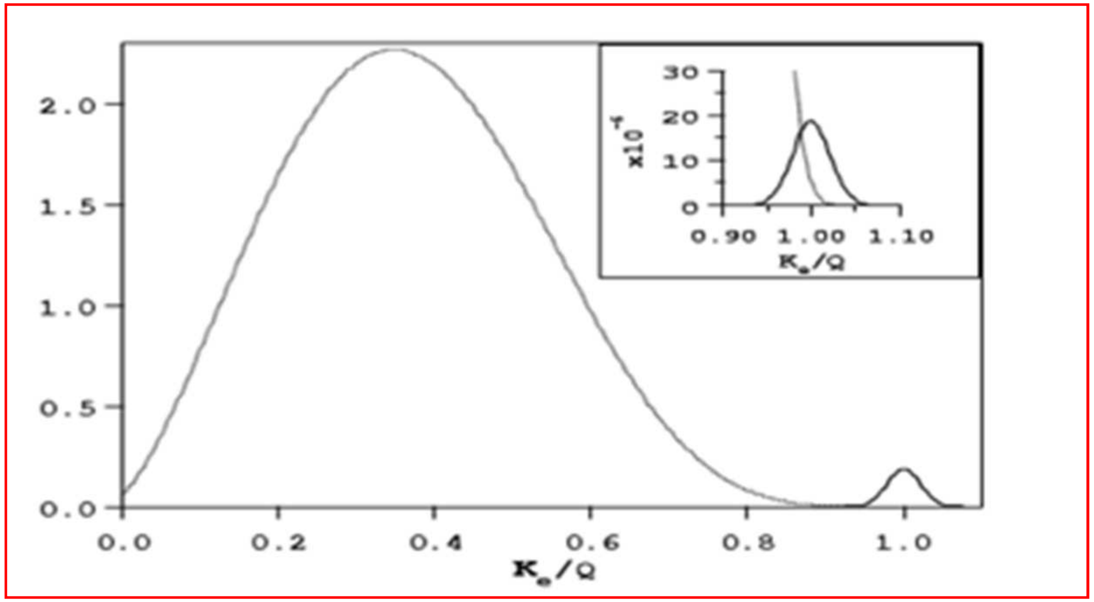
Increase the mass (M) and time (t)

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

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

* ΔE =>

Energy sum of two electron

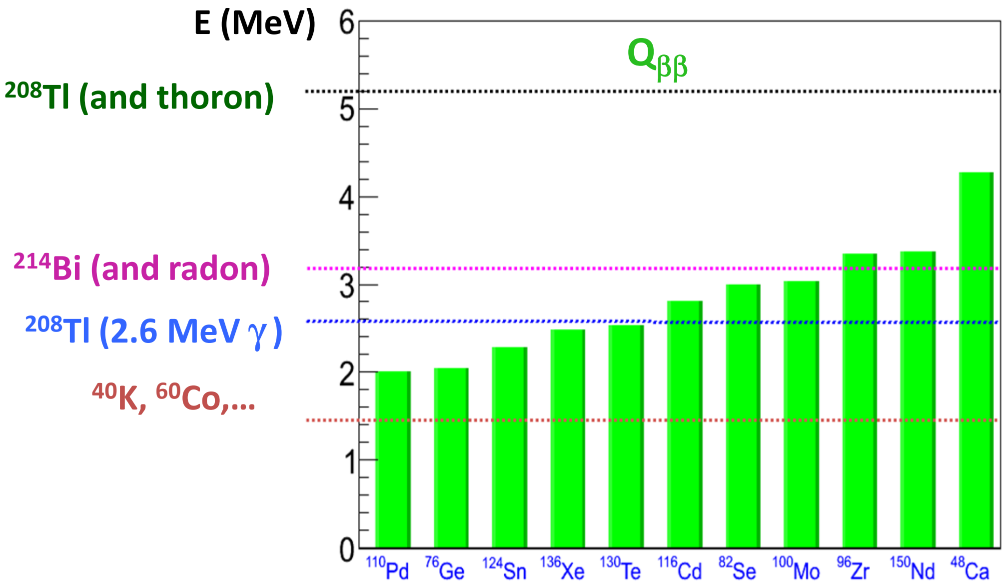


Few words about radioactive background

Origin of the background

Natural Radioactivity

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



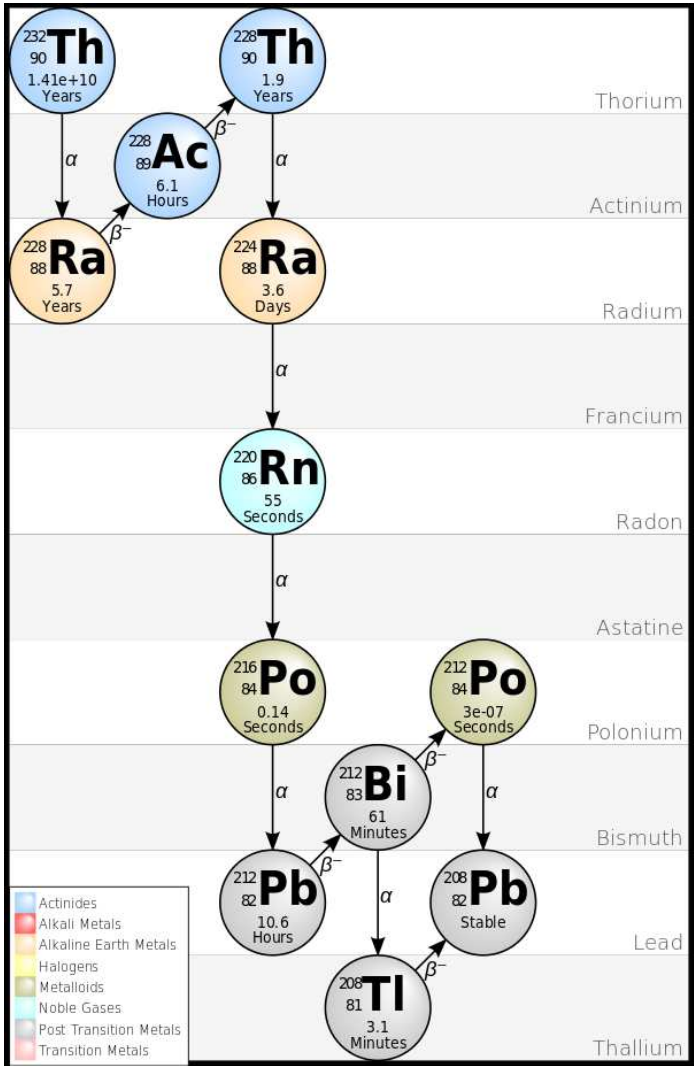
Other background surces

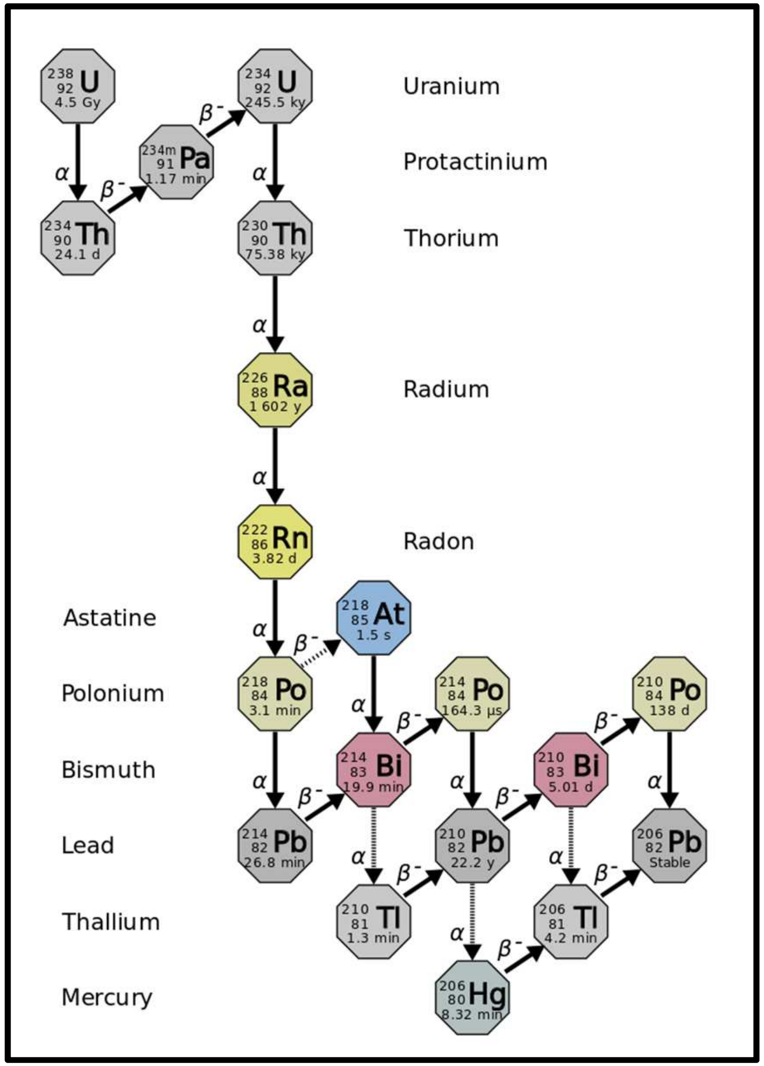
- **Cosmic rays**
- **γ ((n,γ) reactions ,μ bremstrahlung**
- **Muon spallation products**

Need very few radioactive atoms per gram

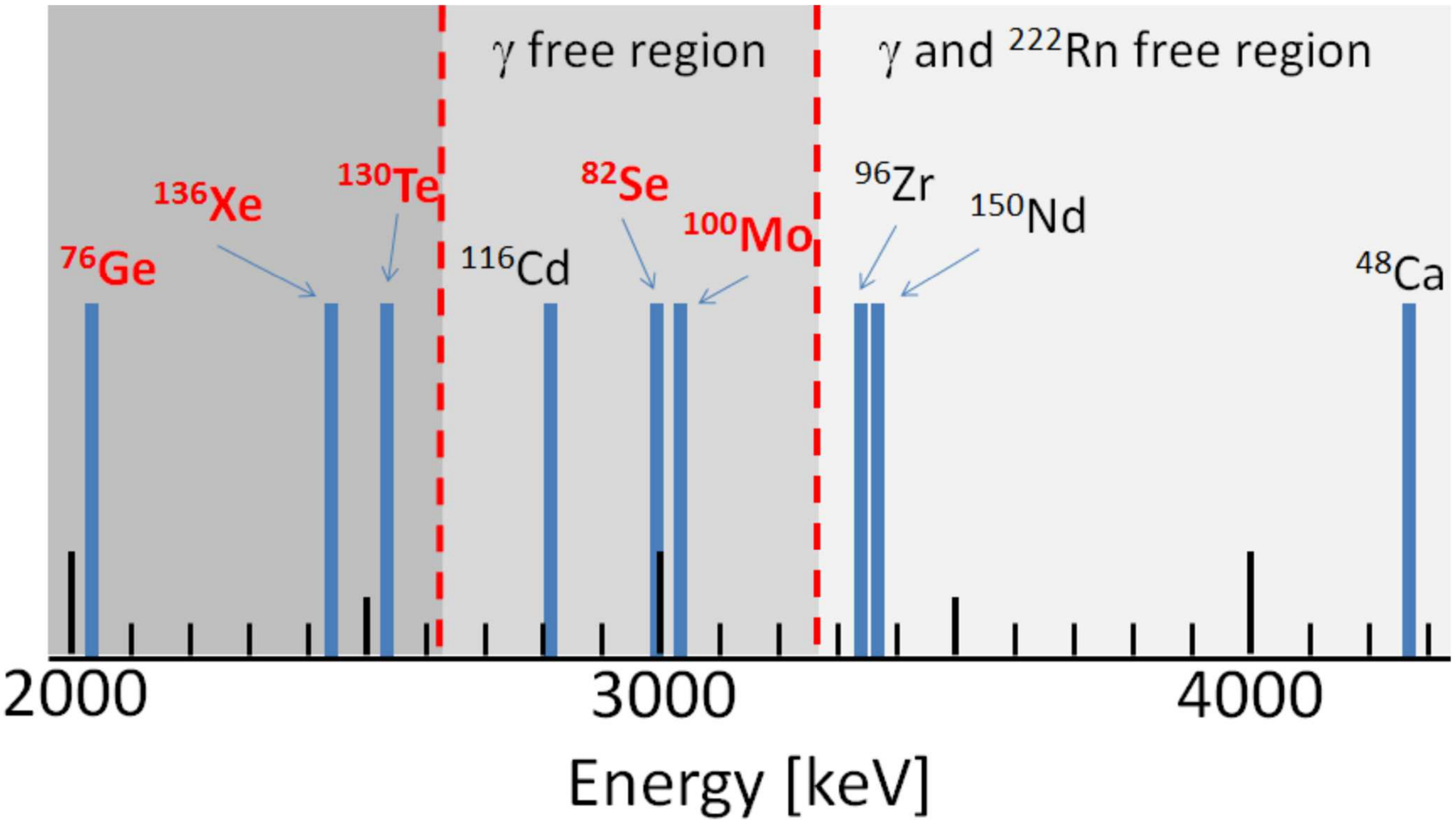
Ex: SuperNEMO < 70 atoms of radon/m^3

Natural radioactive chains





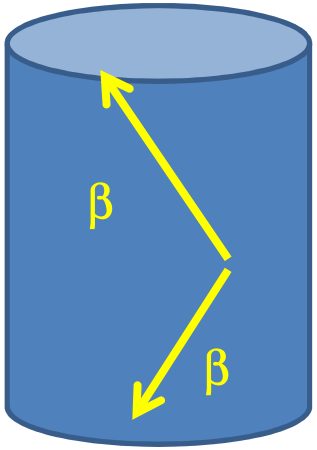
Many, α, β and γ particles.   Up to 5 MeV electrons

γ free region
γ and ²²²Rn free region
76Ge
136Xe
130Te
116Cd
82Se
100Mo
96Zr
150Nd
48Ca
2000
3000
4000
Energy [keV]

How to make a ββ experiment

Detector = ββ Source

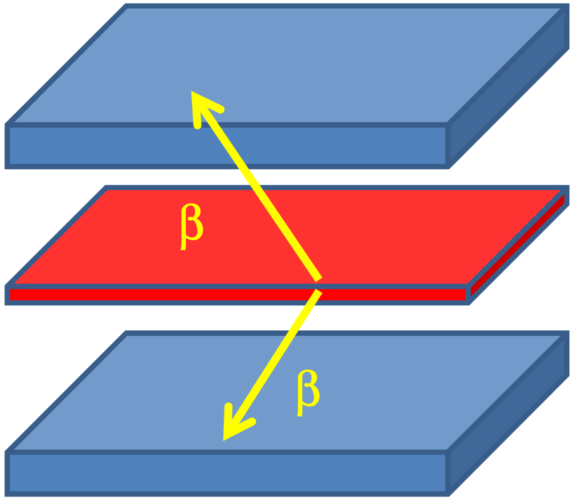
Energy



Calorimetry

+ ΔE , ε
- kinematic

Detector ≠ ββ Source



Energy + time

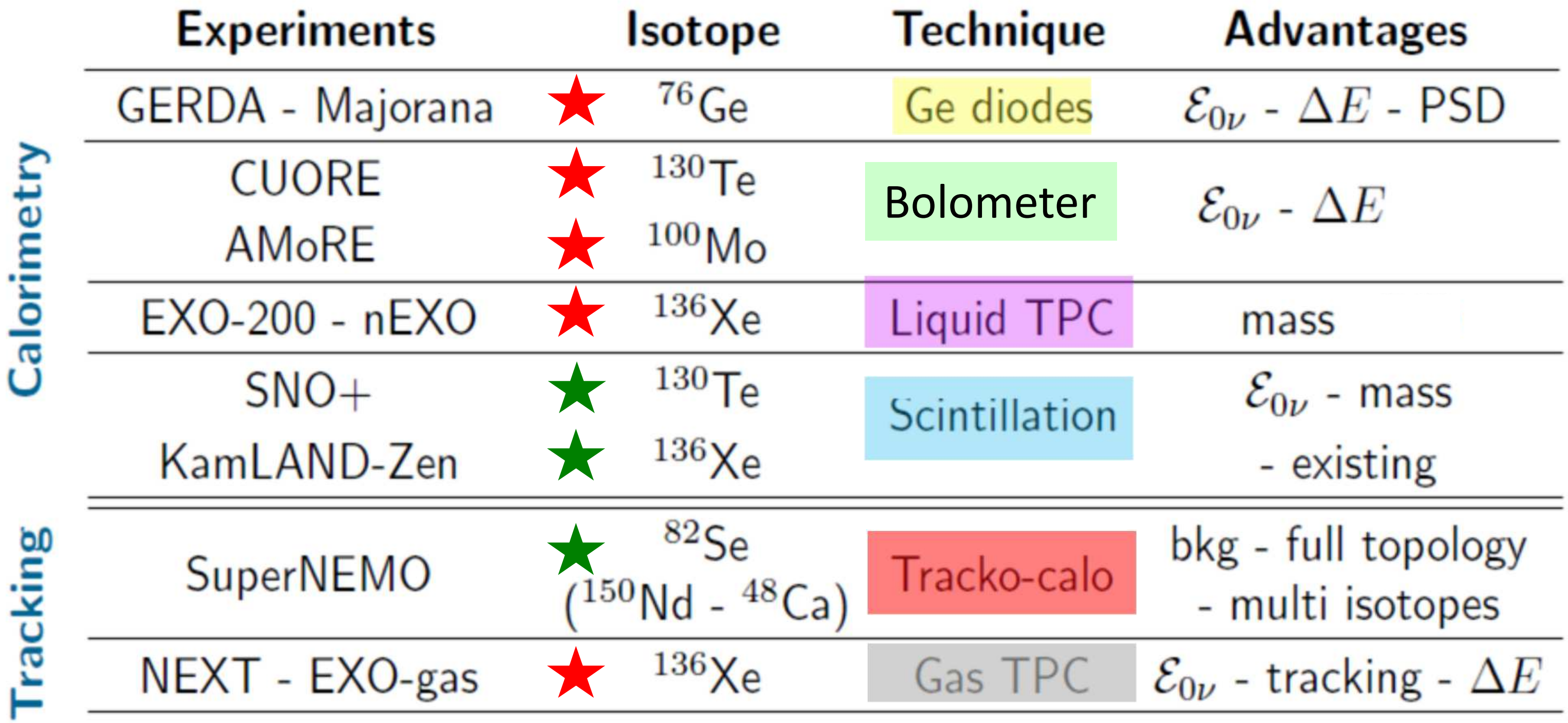
Position

Energy + time

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 AMoRE	★ ★	^{130}Te ^{100}Mo	Bolometer	$\mathcal{E}_{0\nu}$ - ΔE
	EXO-200 - nEXO	★	^{136}Xe	Liquid TPC	mass
	SNO+ KamLAND-Zen	★ ★	^{130}Te ^{136}Xe	Scintillation	$\mathcal{E}_{0\nu}$ - mass - 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

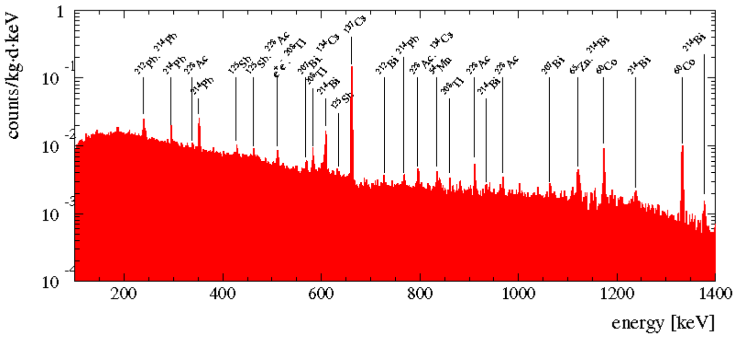
Very good ΔE

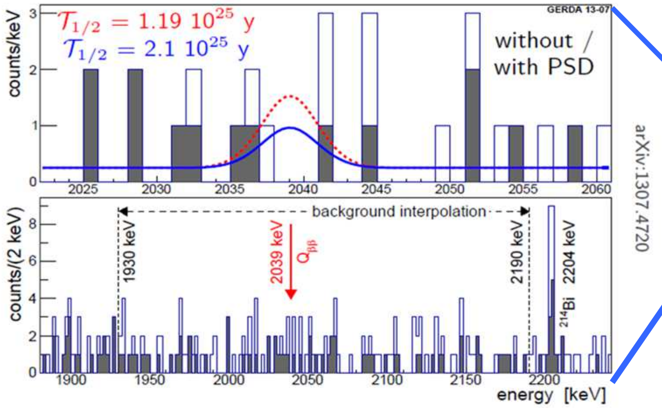
Bare Ge diodes in liquid argon

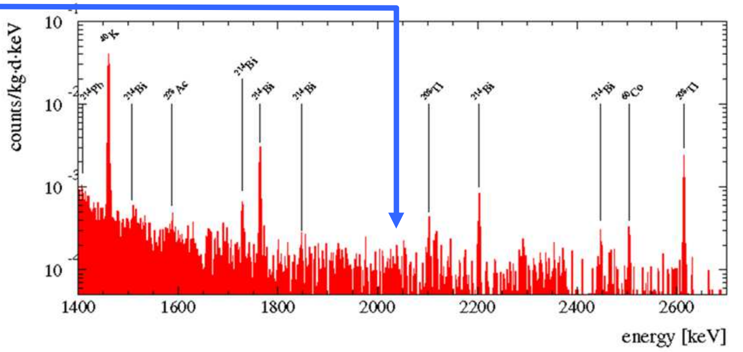
- enriched in ^{76}Ge at 86 %
- gradual deployment of the detector strings in the 64 m^3 cryostat
- LNGS 3800 m.w.e.

Phase 1 - 2011-2013:

- ∼ 18 kg of ^{76}Ge







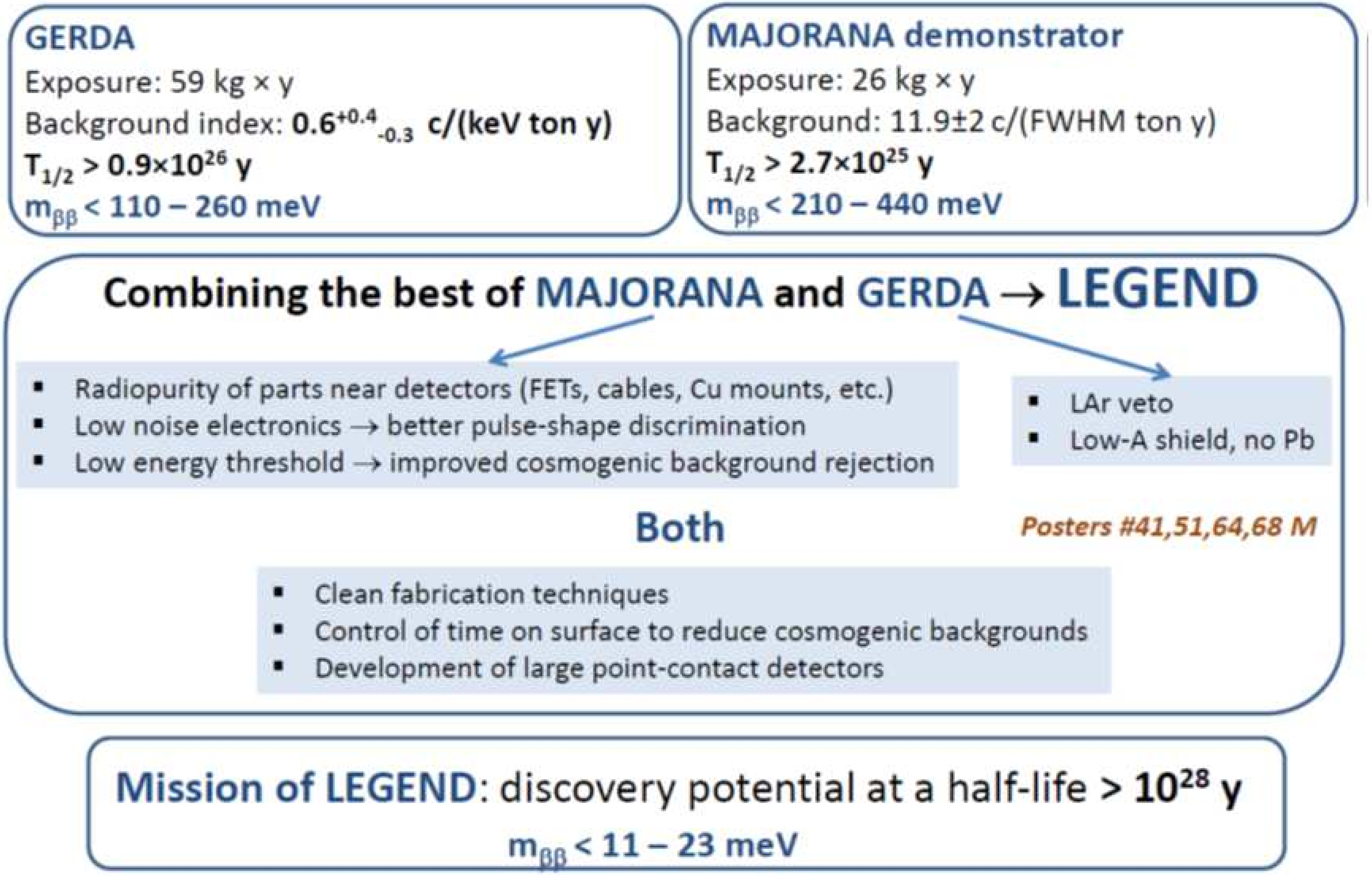
21.6 kg·y exposure: $T^{0\nu}_{1/2} > 2.1\ 10^{25}$ y (90% CL)

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:

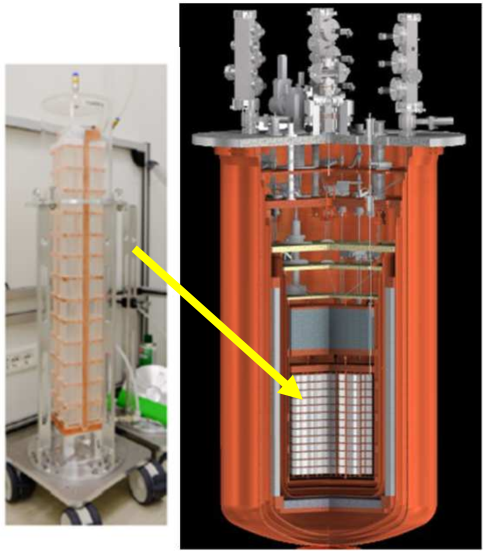
- Ultimate goal
- **1000 kg (phased)** required to cover neutrino-mass IO
- Timeline connected to US DOE down-select process
- Background goal: 0.1 counts/FWHM-t-yr
- Location TBD
- Required depth under investigation

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

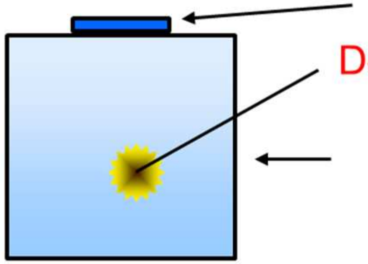
CUORE

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



Thermometer

Double beta decay

Crystal absorber

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

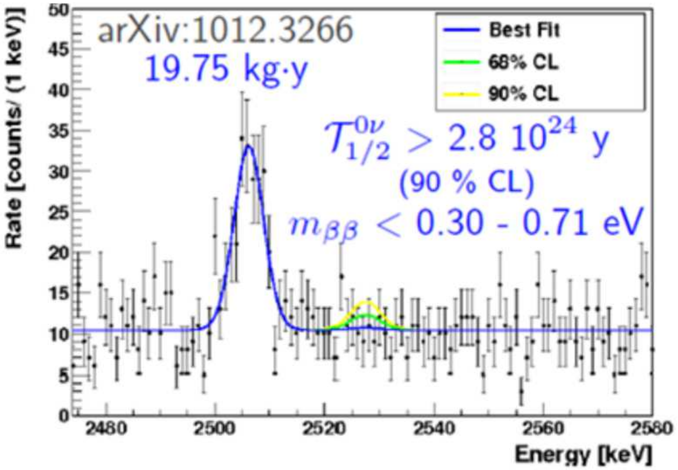
example: 750 g of TeO_2 @ 10 mK

$C \sim T^3$ (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

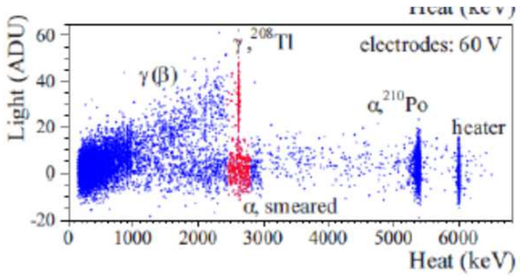
Very good ΔE



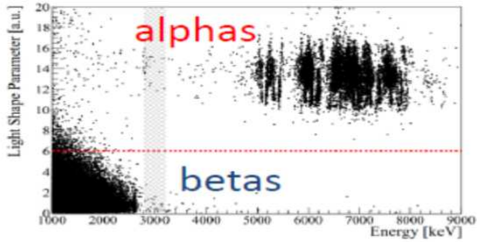
CUORE → CUPID

^{130}TeO$_2$ + Cherenkov light

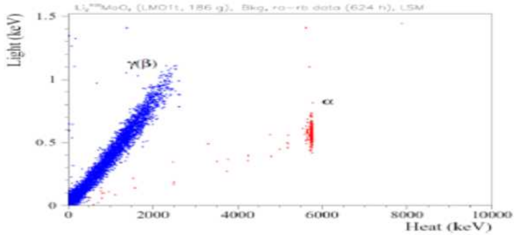
Q=2527 keV



Zn^{82}Se Q=2998 keV



Li$_2$^{100}MoO$_4$ Q=3034 keV



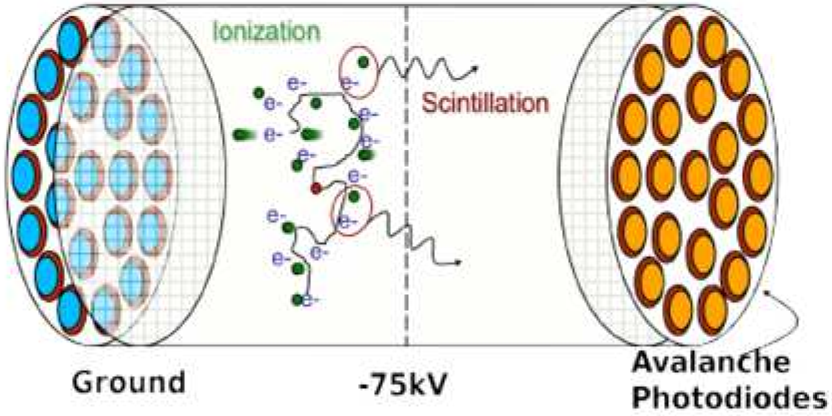
Mission: **half-life sensitivity higher than 10^{27} y**

With background < 0.1 counts/(ton y) in the ROI, ^{100}Mo sensitivity is **2.1×10^{27} y**

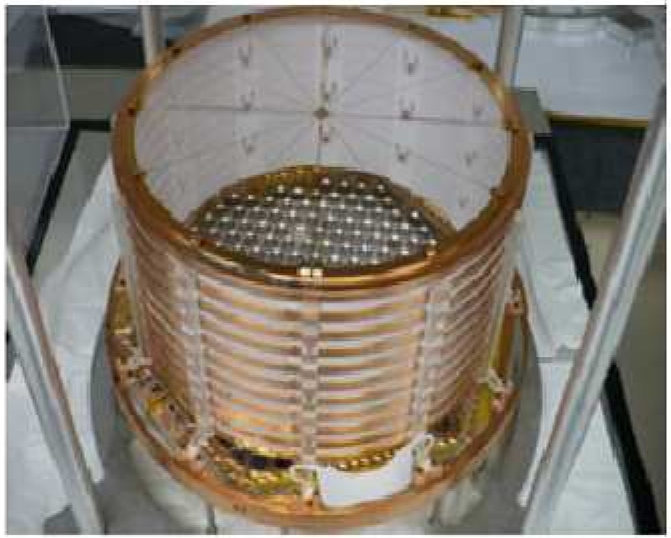
$m_{\beta\beta} < 6 - 17$ meV

^{136}Xe

Enriched Xenon Observatory



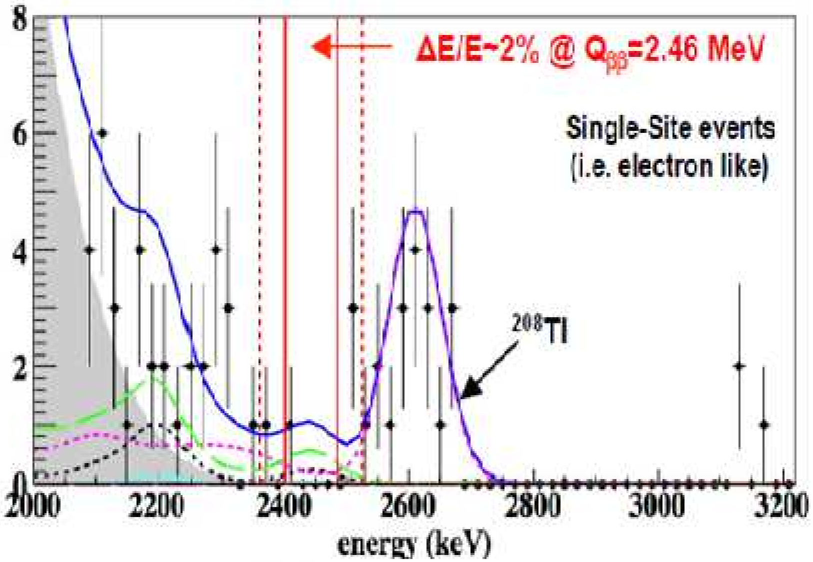
- Liquid-xenon TPC with ionisation & scintillation readout



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

$T_{1/2} > 1.8\times10^{25}$ y

$m_{\beta\beta} < 150 – 400$ meV



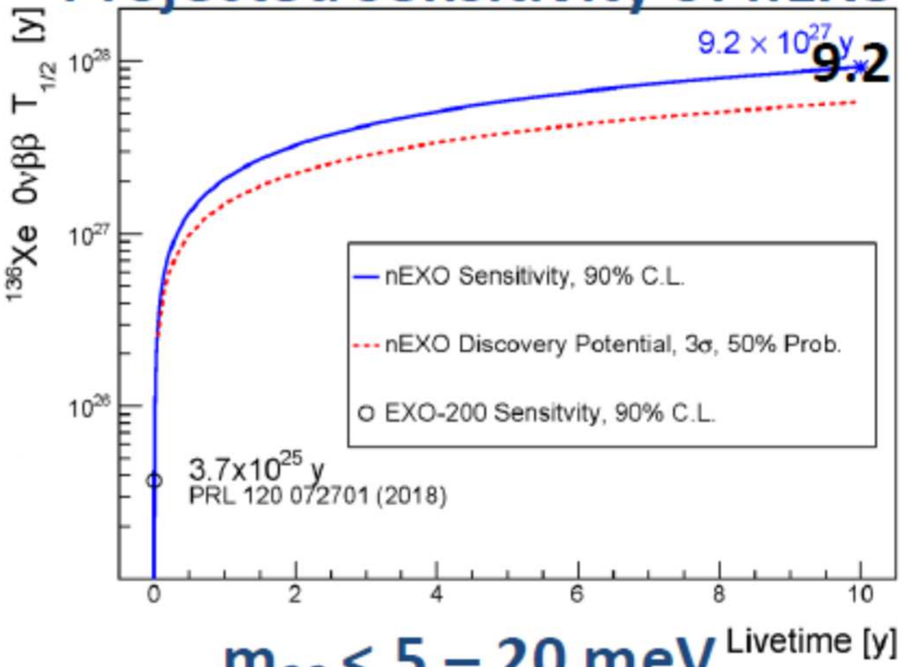
^{136}Xe

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



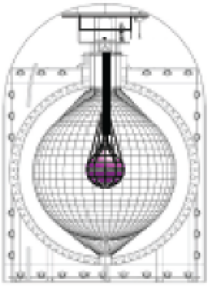
9.2×10^{27} y

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

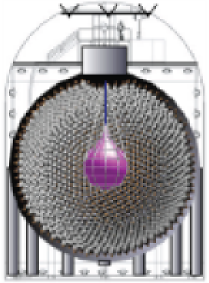
KamLAND-Zen 800
~750 kg of Xenon
DAQ to start in this year

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)

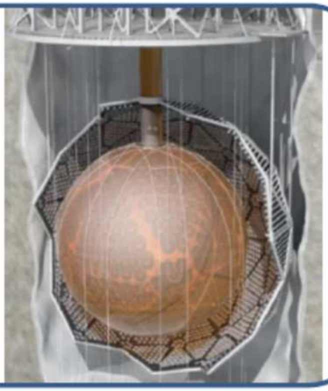
SNO+

^{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

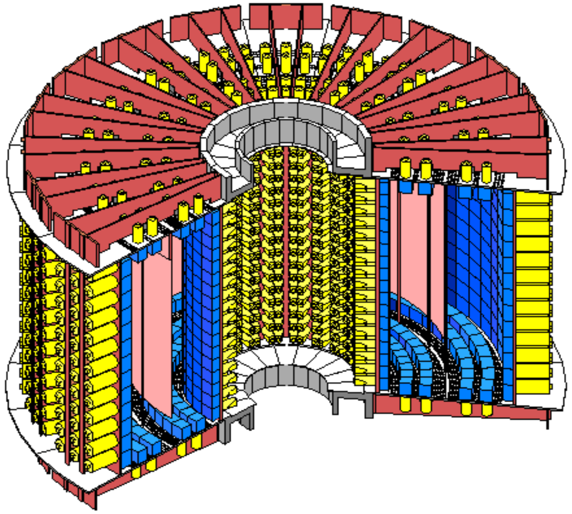
- 50 kton water-based liquid scintillator detector
- High coverage with fast photon detectors
- Deep underground
- 8-m radius balloon with high-LY LS and isotope
- 7-m fiducial, 3% ^{nat}**Te**, 10 years
- Dominant background: ^{8}B solar ν's

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

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

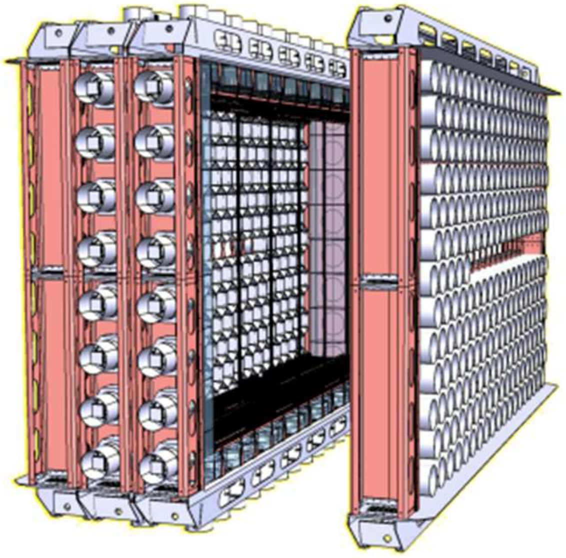
without enrichement!

Neutrino **E**ttore **M**ajorana **O**bservatory



From NEMO III

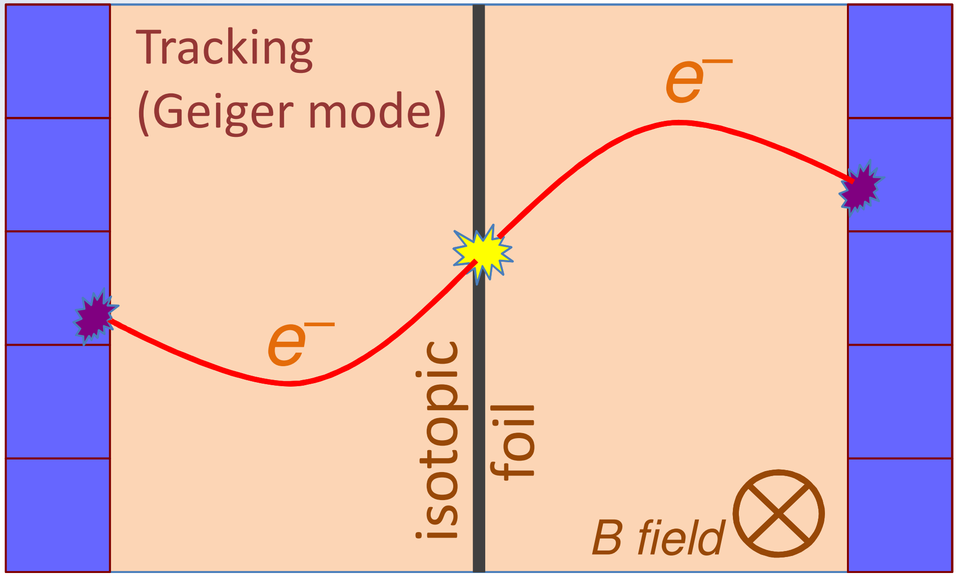
to SuperNEMO



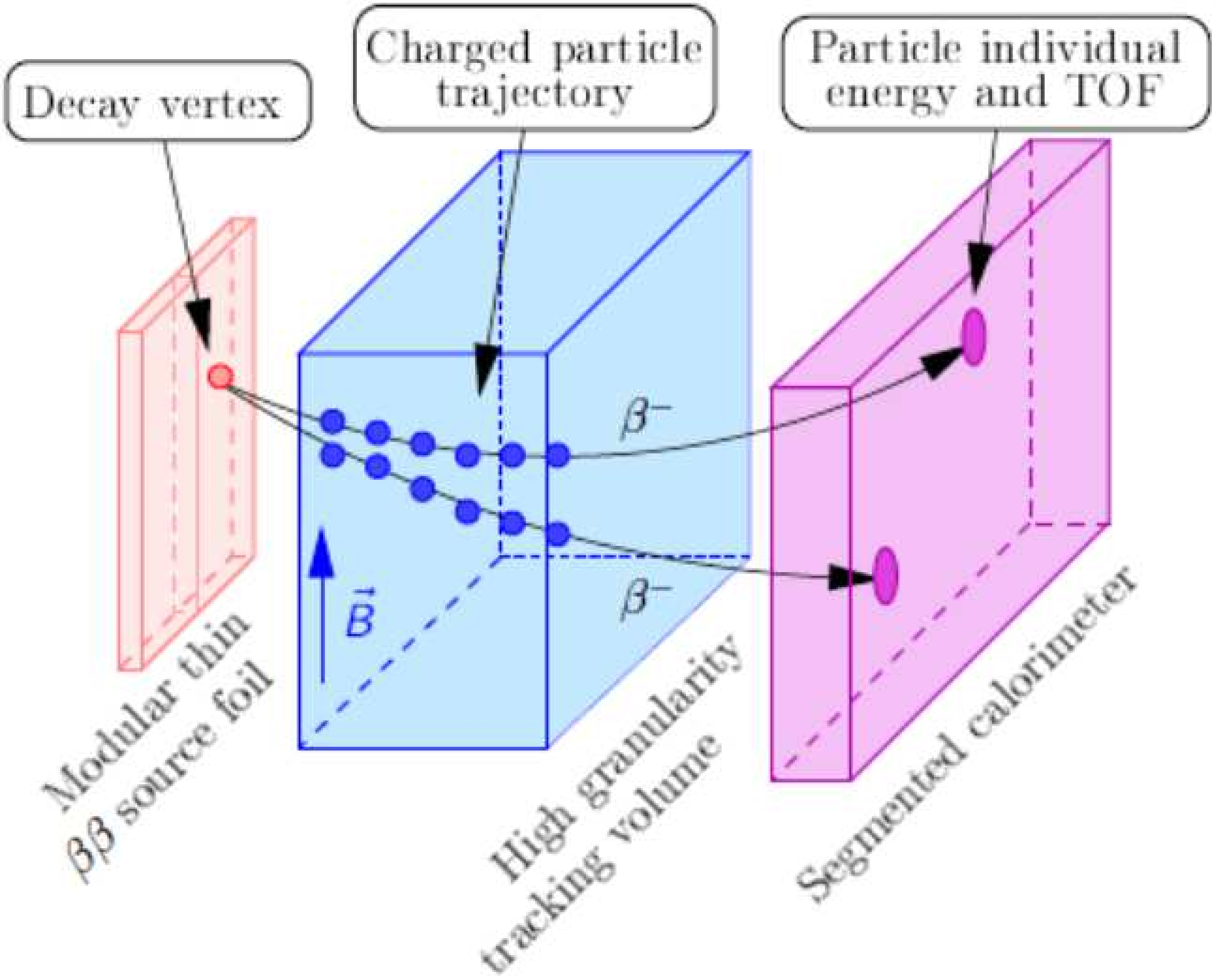
The NEMO-3 Technique

The multi-observable principle:

topology, kinematics, timing

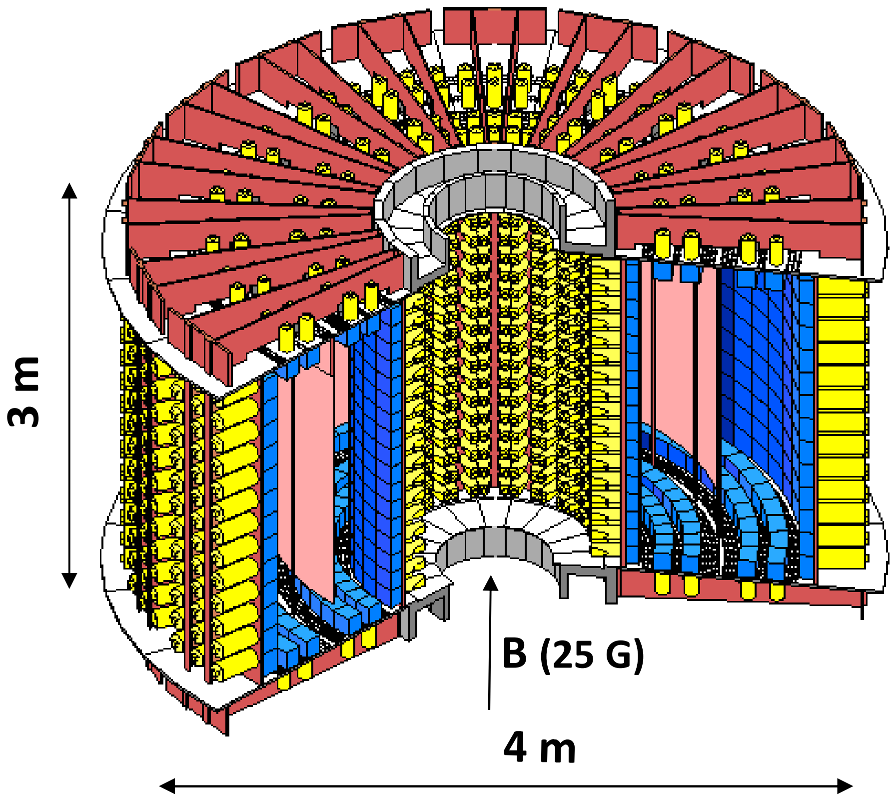


Plastic scintillator calorimeter


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

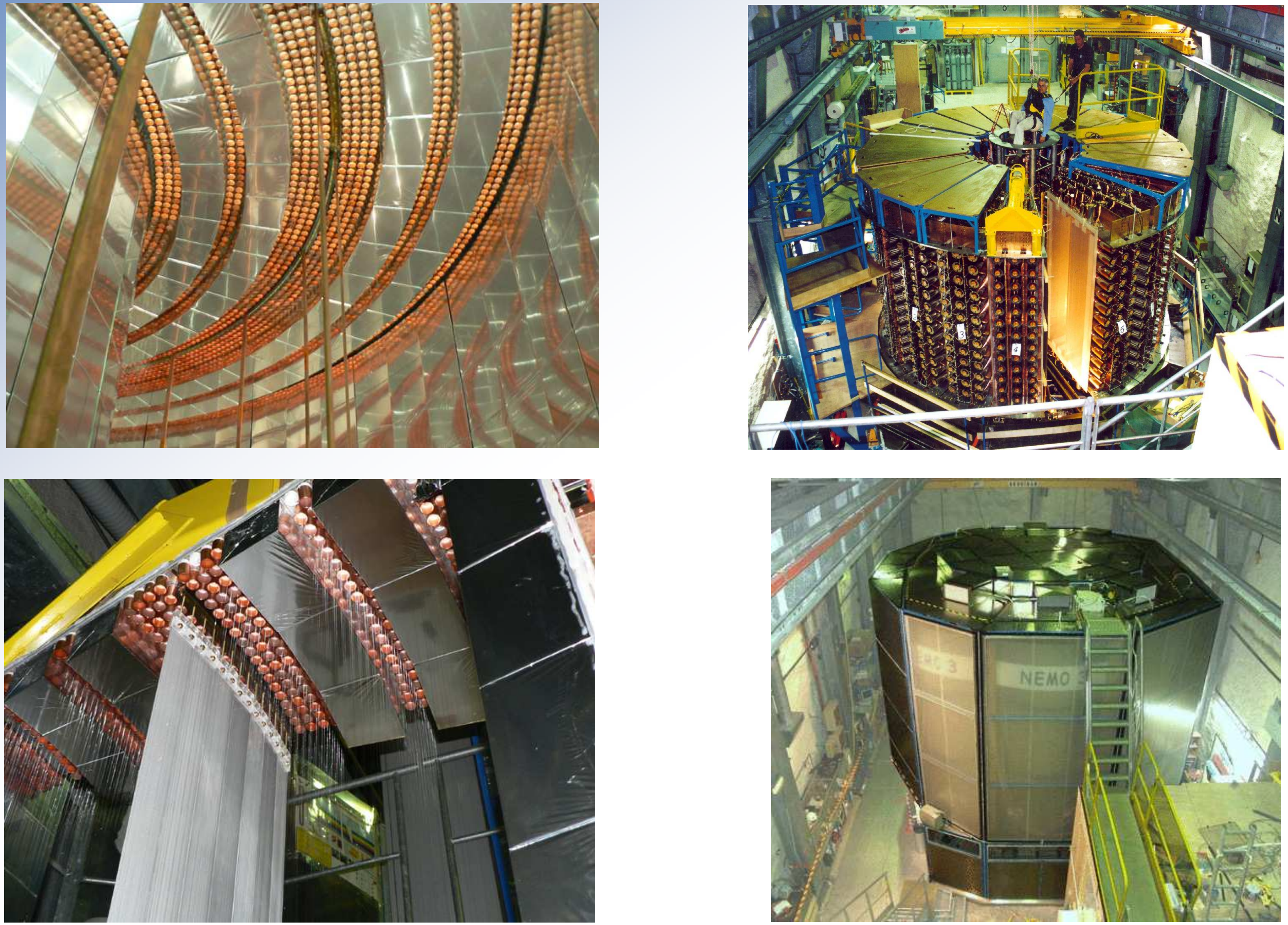
20 sectors



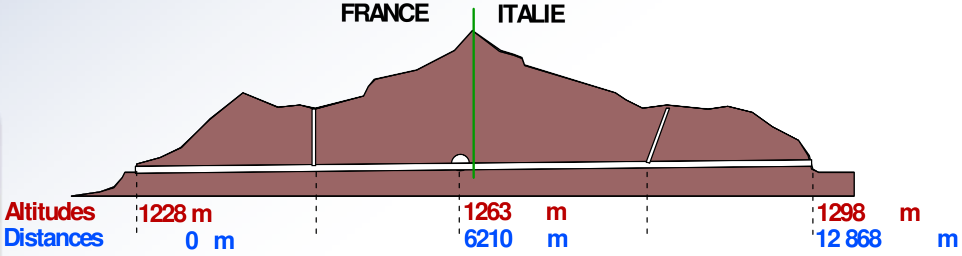
Particle ID: e^-, e^+, γ and α

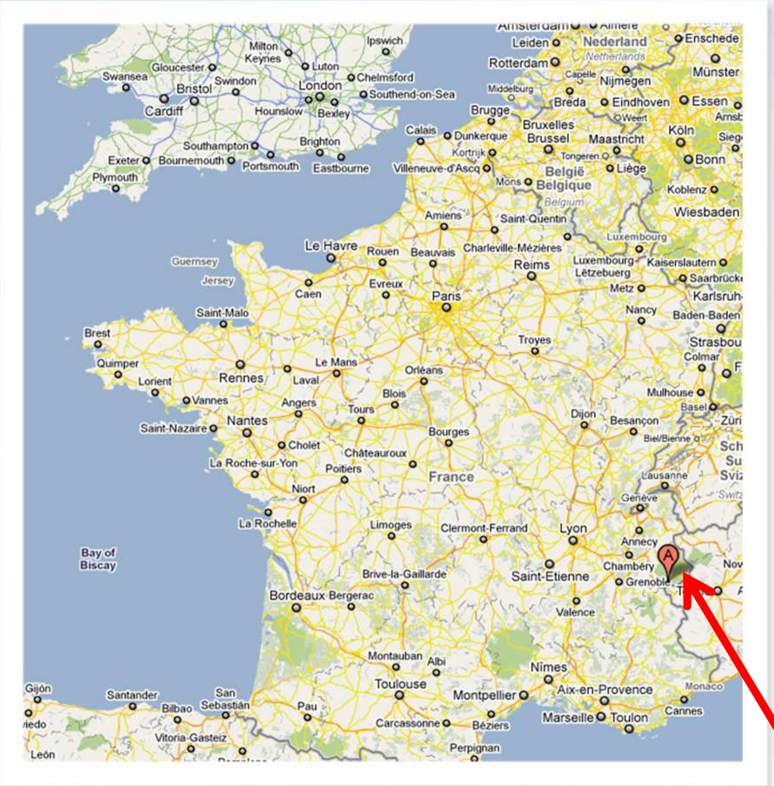
- ✓ Source: 10 kg of $\beta\beta$ isotopic foils
  area = 20 m^2, thickness ~60 mg/cm^2
- ✓ Tracking detector:
  drift wire chamber (9 layers)
  in Geiger mode (6180 cells)
  Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O
- ✓ Calorimeter:
  1940 plastic scintillators
  low radioactivity 3'' & 5'' PMTs
- ✓ 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)

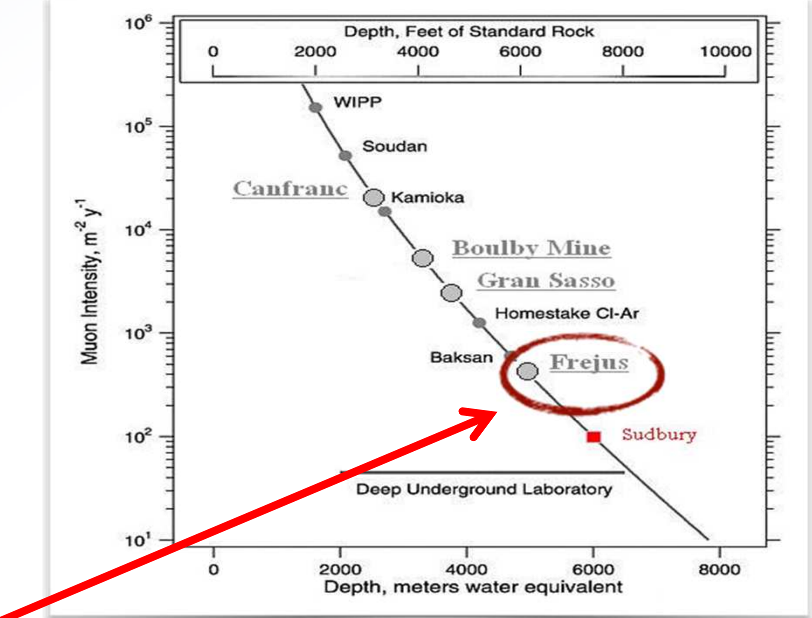
NEMO-3 data taking: 2003 - 2010



NEMO3 Lab.



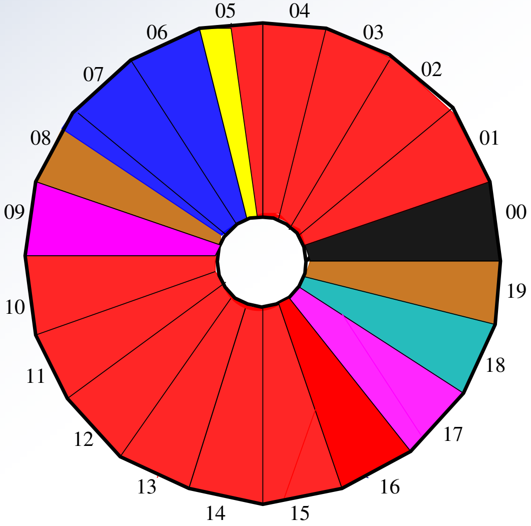


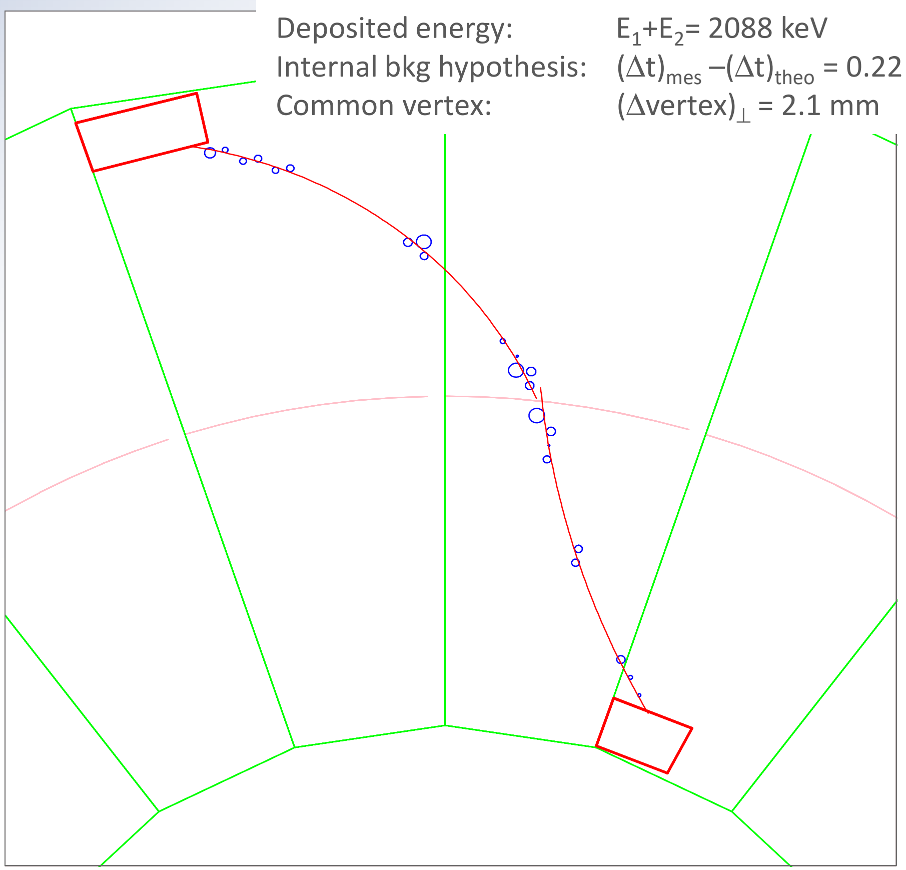


LSM Modane, France
(Tunnel Frejus, depth of ~4,800 mwe)

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	

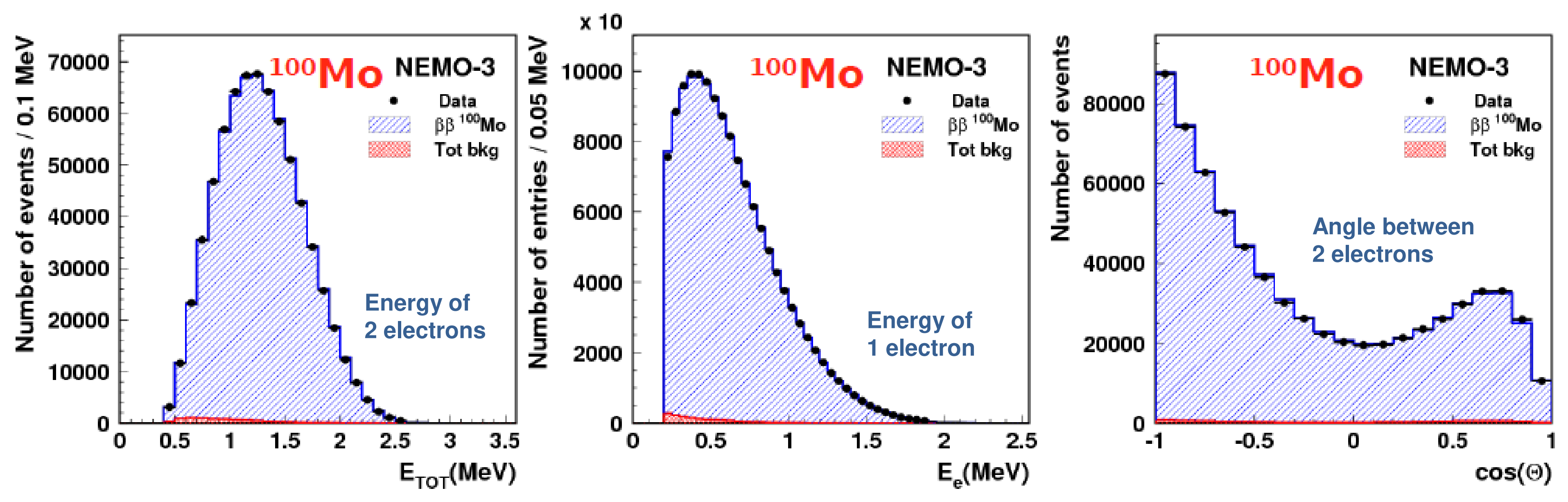




Deposited energy: E_1+E_2= 2088 keV
Internal bkg hypothesis: $(\Delta t)_{mes} - (\Delta t)_{theo}$ = 0.22 ns
Common vertex: $(\Delta \text{vertex})_{\perp}$ = 2.1 mm

- ✓ Trigger: at least 1 PMT > 150 keV
  ≥ 3 Geiger hits (2 neighbouring layers+1)
- ✓ Trigger rate = 7 Hz
- ✓ 25 ββ events per hour

Results

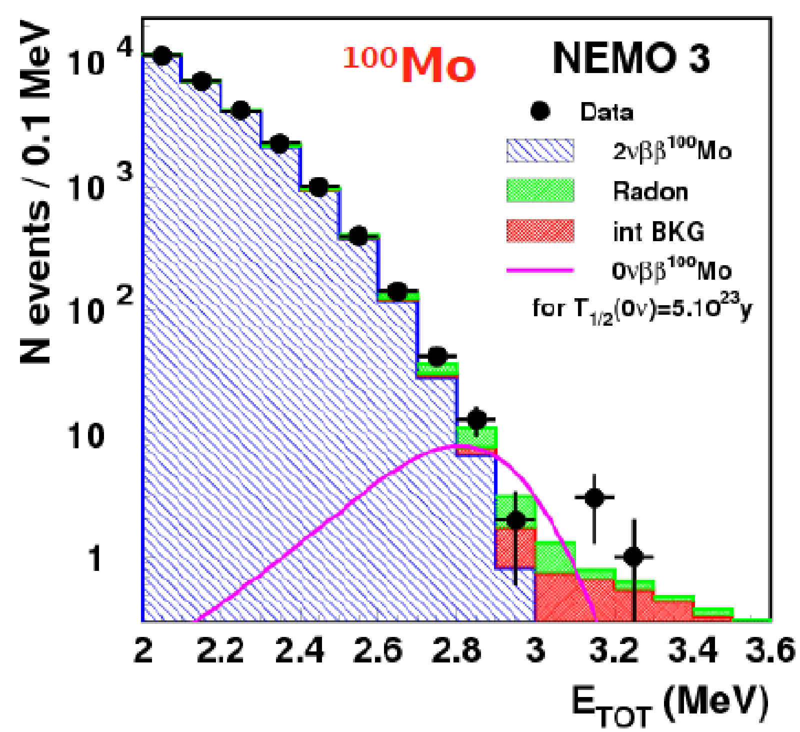


> 700 000 of 2-electron

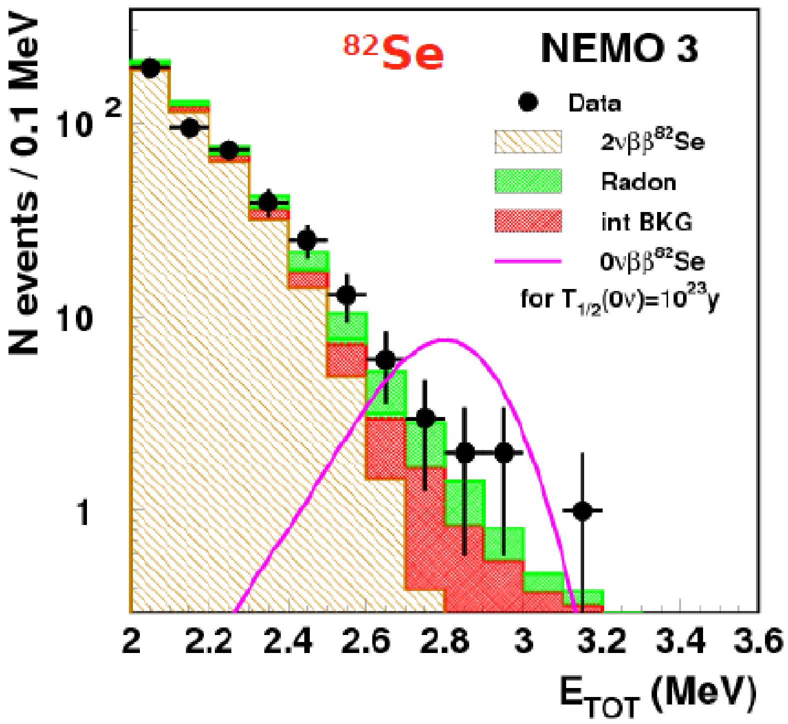
Signal/Background : 76

$$T_{1/2}\ (2\nu\beta\beta) = (7.16 \pm 0.01) \times 10^{18}\ y$$

^{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

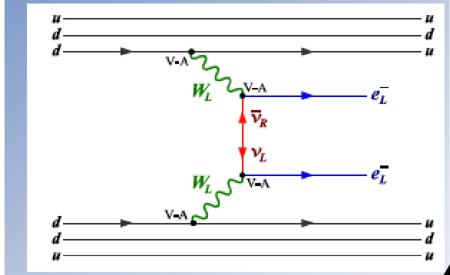
^{82}Se (for exposure of 4.2 kg * y)

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

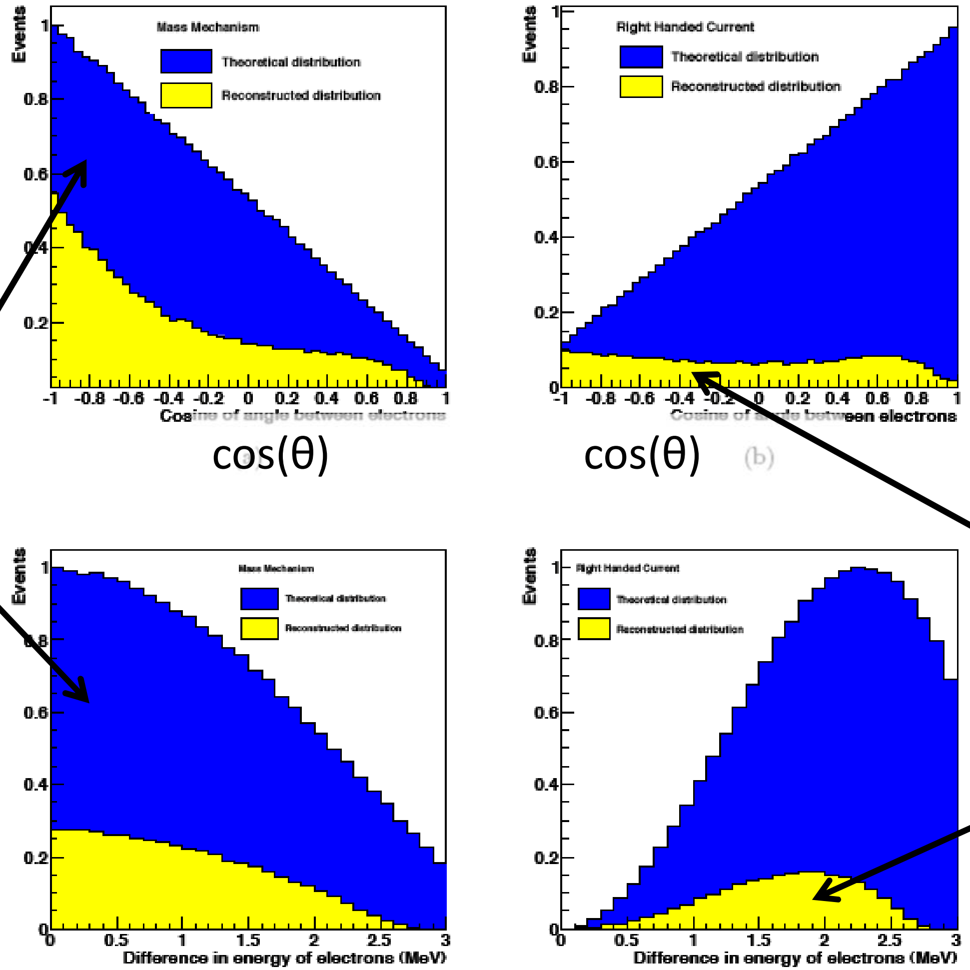
$m_{\beta\beta} < 0.94 – 2.6$ eV

Physics Studies: RHC

MM



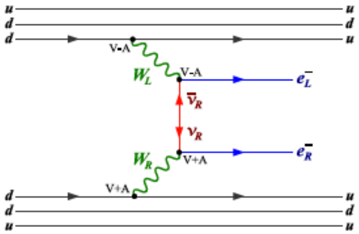
RHC



cos(θ)

cos(θ) (b)

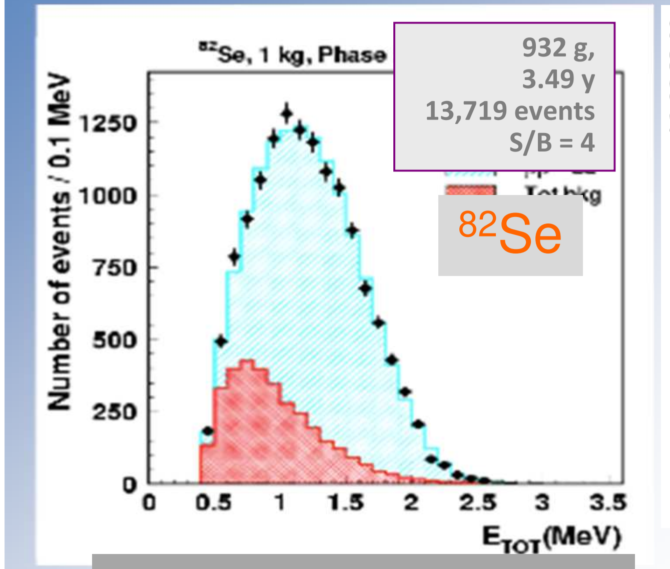
Energy difference between electrons



Evènements attendus

Evènements reconstruits

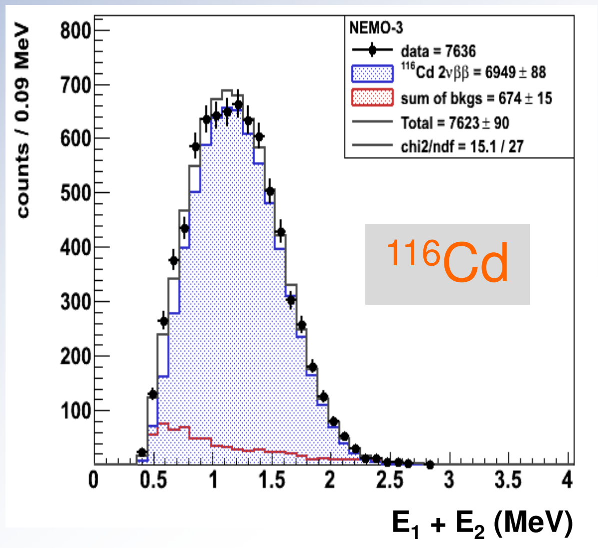
NEMO-3 $(\beta\beta)_{2\nu}$ results



932 g,
3.49 y
13,719 events
S/B = 4

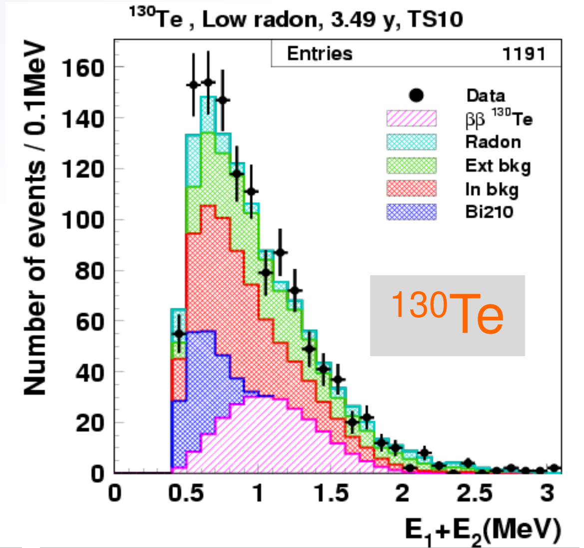
^{82}Se

$[\,9.6 \pm 0.1_{(stat)} \pm 1.0_{(syst)}\,] \times 10^{19}$ y



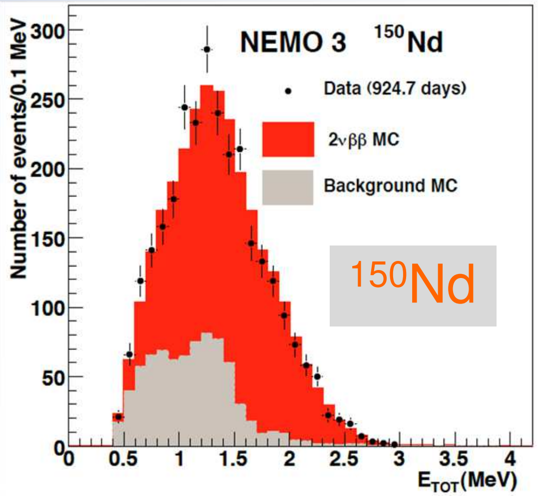
^{116}Cd

$[\,2.88 \pm 0.04_{(stat)} \pm 0.16_{(syst)}\,] \times 10^{19}$ y



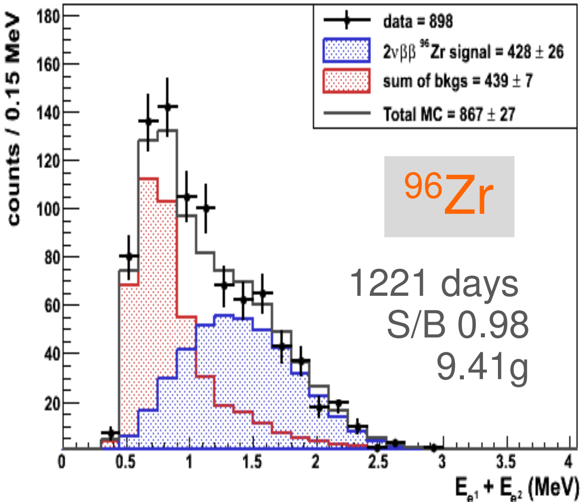
^{130}Te

$[\,7.0 \pm 0.9_{(stat)} \pm 1.1_{(syst)}\,] \times 10^{20}$ y



^{150}Nd

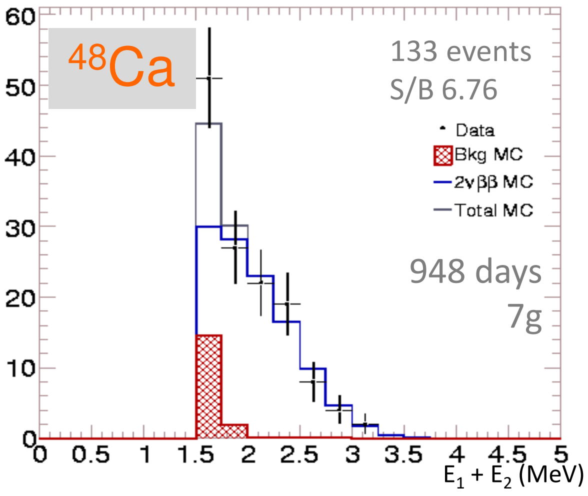
$[\,9.11\,^{+0.25}_{-0.22\ (stat)} \pm 0.63_{(syst)}\,] \times 10^{18}$ y



^{96}Zr

1221 days
S/B 0.98
9.41g

$[\,2.35 \pm 0.14_{(stat)} \pm 0.16_{(syst)}\,] \times 10^{19}$ y



^{48}Ca

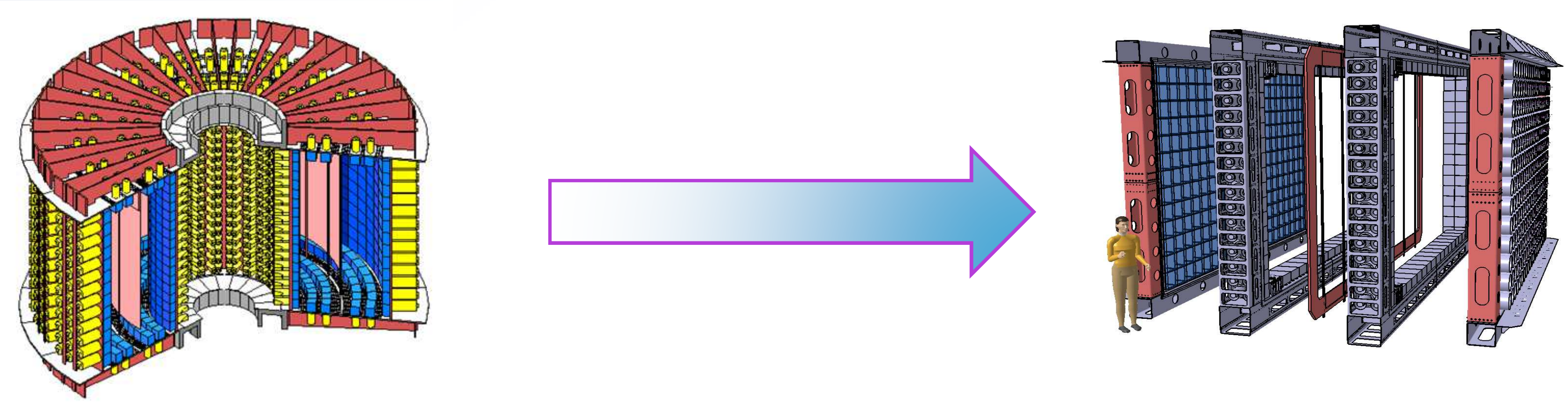
133 events
S/B 6.76

948 days
7g

$[\,4.4\,^{+0.5}_{-0.4\ (stat)} \pm 0.4_{(syst)}\,] \times 10^{19}$ 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%	0νββ efficiency	30%
$T_{1/2}^{0\nu\beta\beta} > (1-2) \times 10^{24}$ 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

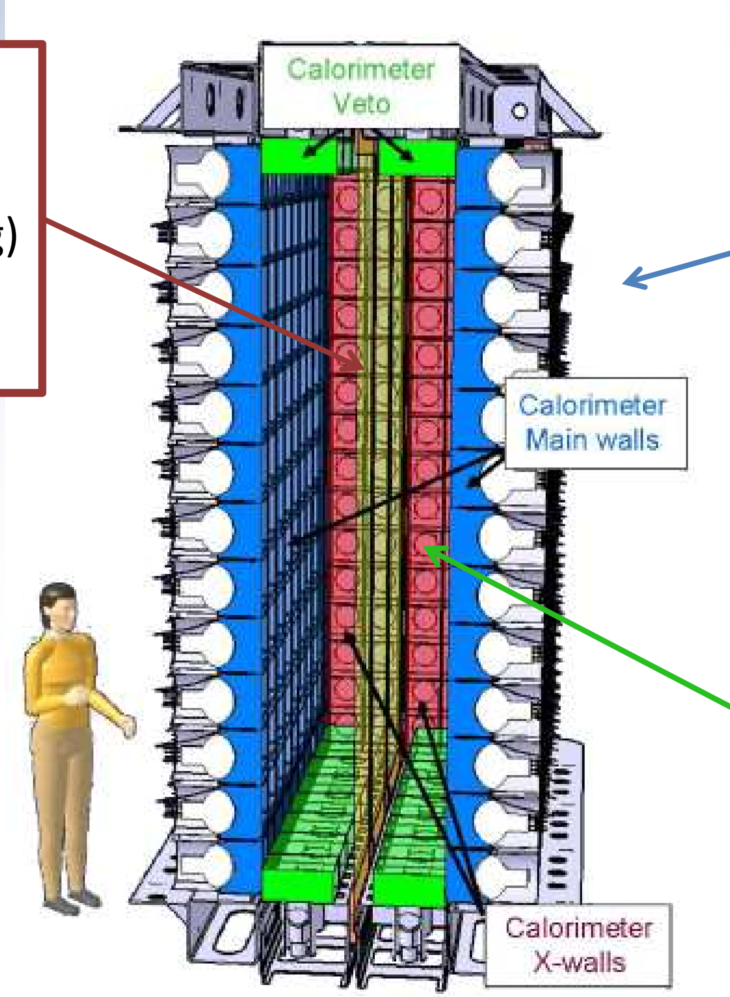
Source

^{214}Bi < 10 µBq/kg

(NEMO3 100 µBq/kg)

208Tl < 2 µBq/kg

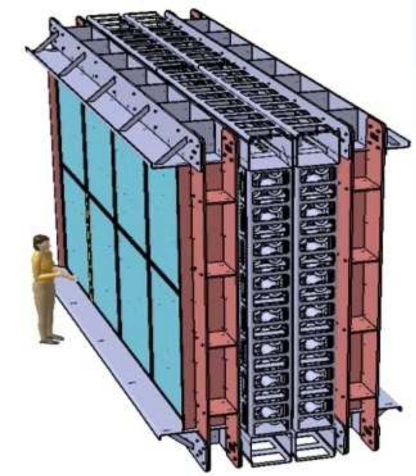
(NEMO3 100 µBq/k)



Calorimeter

ΔE/E < 4% @ 3 MeV

(NEMO3 8.6% at 3MeV)



Tracker

3.7 m long (NEMO3 2.7 m)

$\sigma_t = 5$ mm, $\sigma_z = 1$ cm

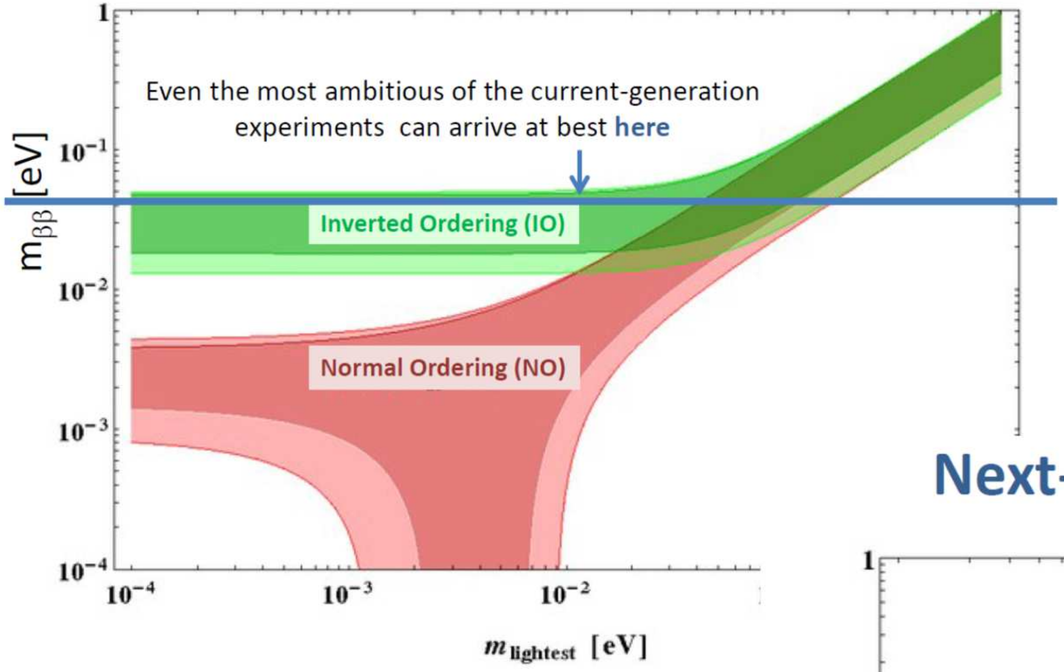
Radon < 0.15 mBq/m^3

(NEMO3 5 mBq/m^3)

Wiring robot

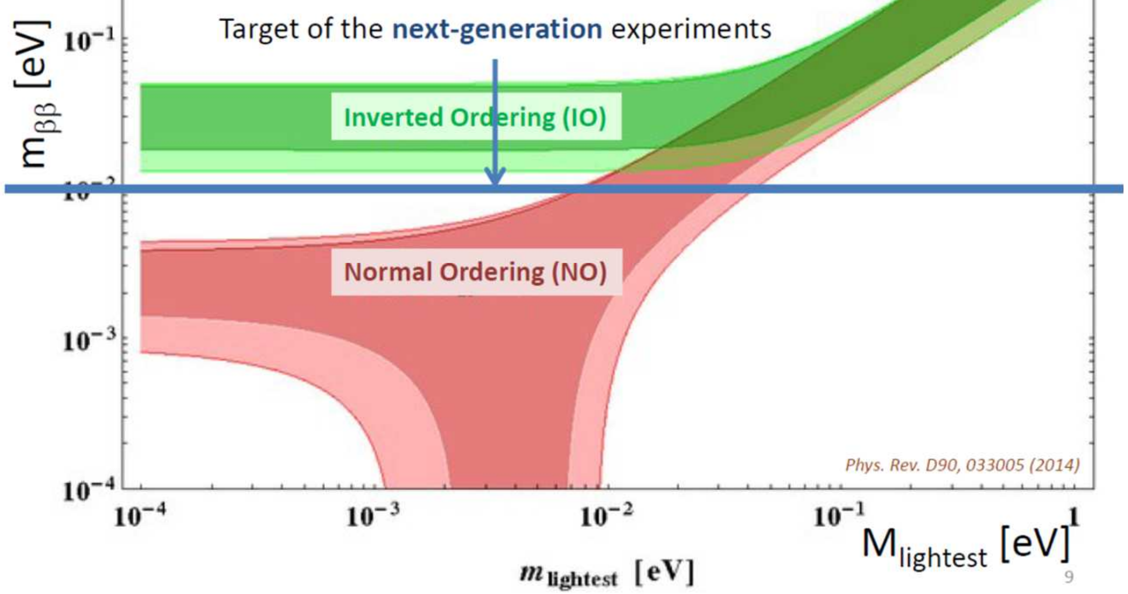
Global efficiency : 30 % (NEMO3 8%)

Current-generation experiments



Even the most ambitious of the current-generation experiments can arrive at best **here**

Next-generation experiments



Target of the **next-generation** experiments

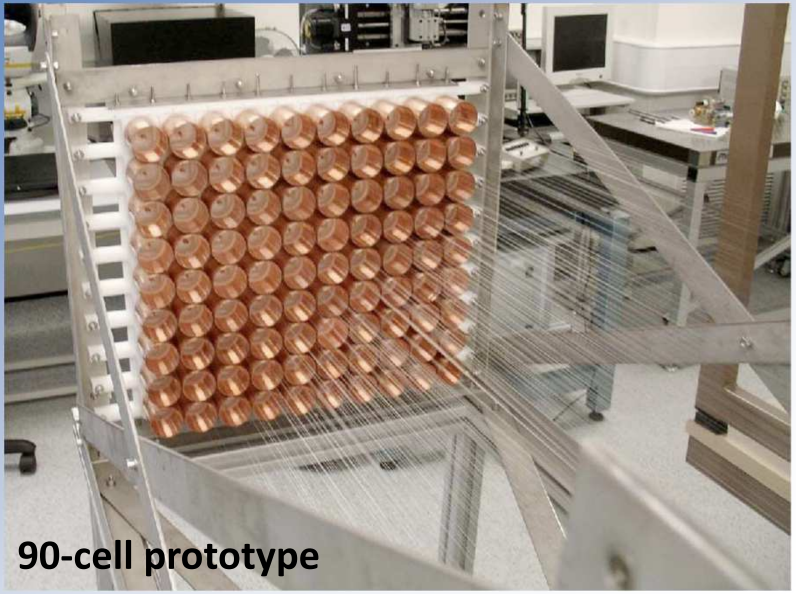
Phys. Rev. D90, 033005 (2014)

Conclusion

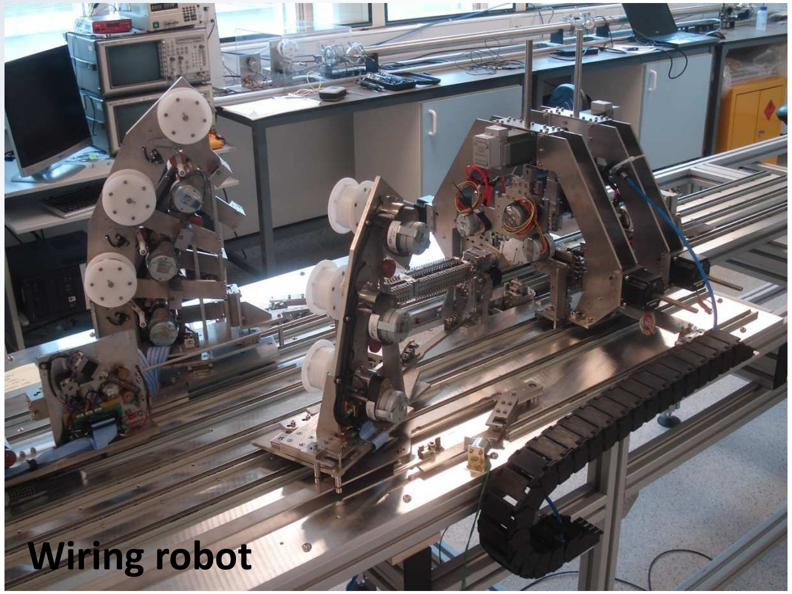
- **Neutrino is a fantastic particle to explore new physics beyond de SM.**
- **Despite the important advances in neutrino physics (neutrino oscillations demonstrate the MSM is wrong), we don't know what is the nature of neutrino : Dirac or Majorana.**
- **Neutrinoless double beta decay is the best way 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



90-cell prototype

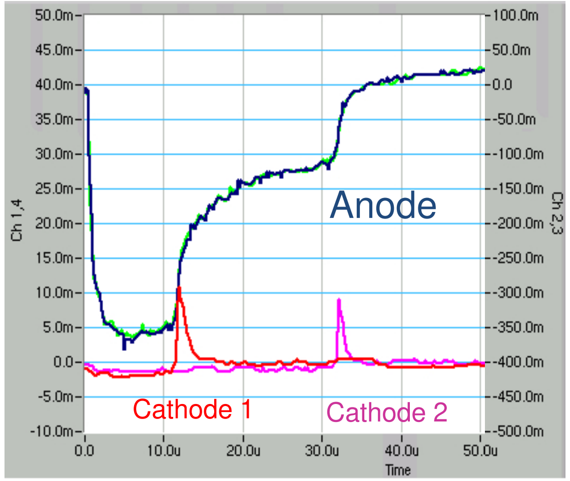


Wiring robot

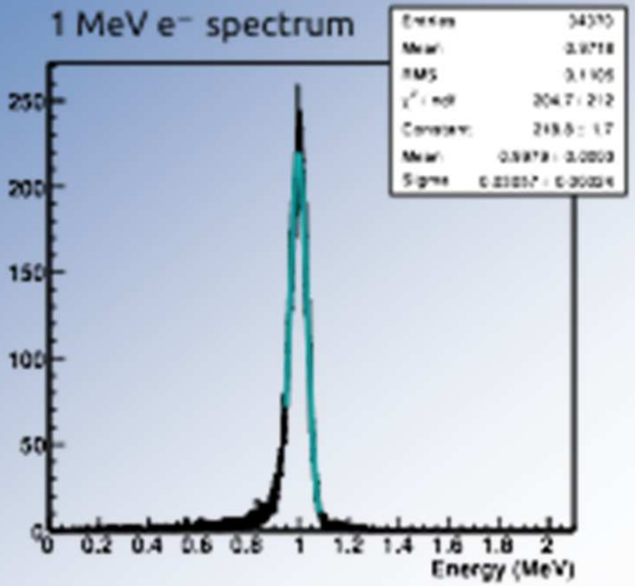
- Design verified with 90-cell prototype
  - Resolution: 0.7mm transverse, 1cm longitudinal
  - Cell efficiency > 98%

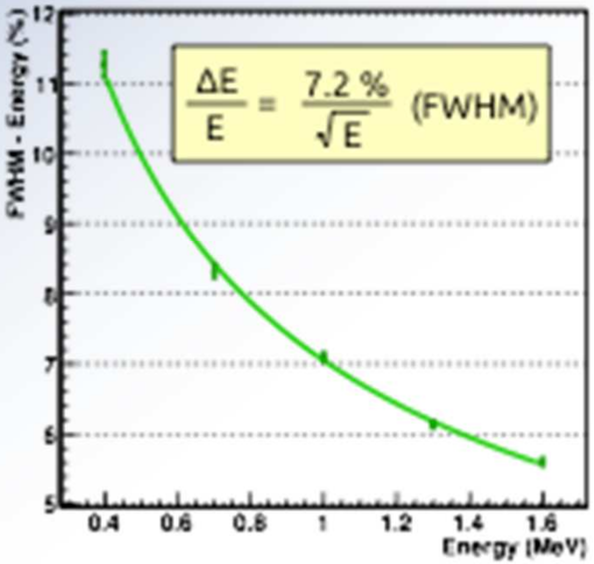
- Automated wiring robot being commissioned for mass production in ultra low background conditions
  - 500000 wires to string, crimp and terminate

- Readout electronics under development



SuperNEMO R&D: Calorimeter





$$\frac{\Delta E}{E} = \frac{7.2\ \%}{\sqrt{E}} \text{ (FWHM)}$$

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

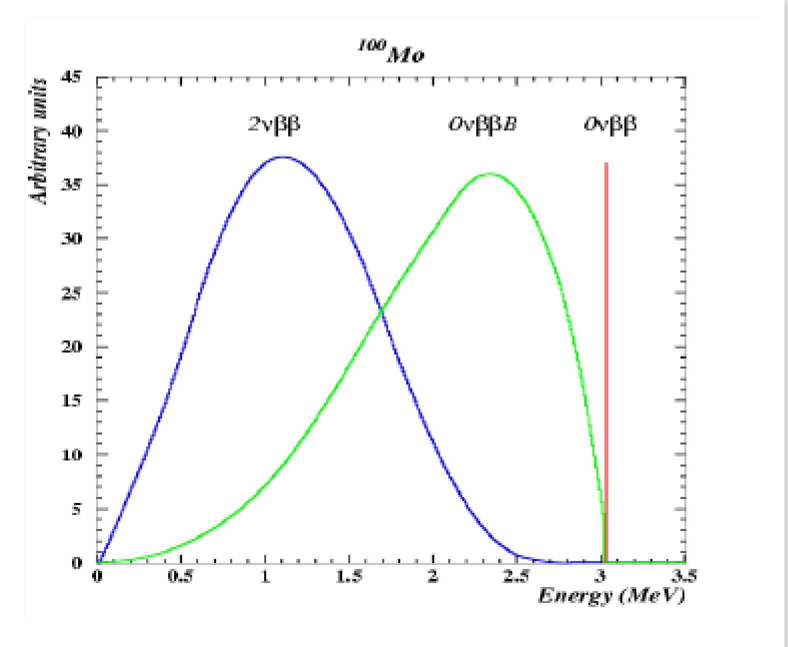
7.2% FWHM at 1 MeV

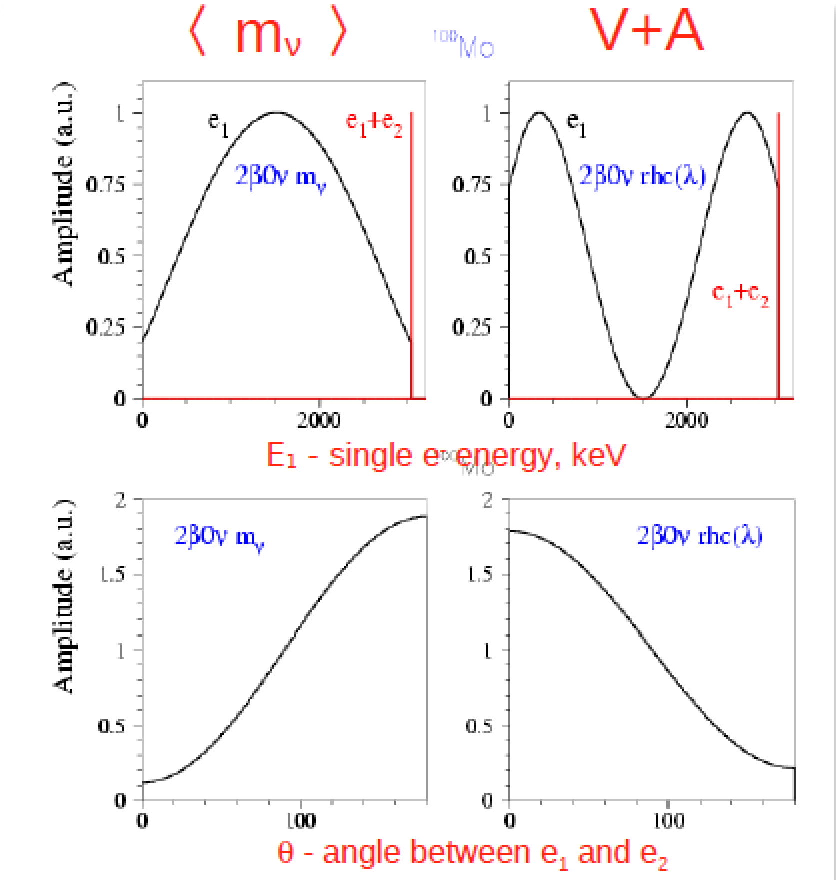
(equivalent to 4% at $Q_{\beta\beta}$ = 3.0 MeV)

Open minded search fo any 0νββ decay mechanism

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

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

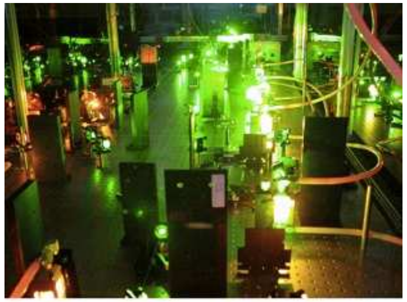




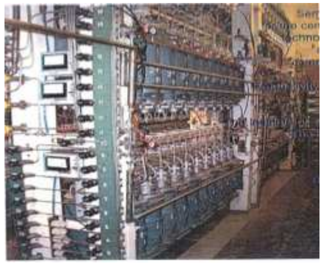
Isotope enrichment

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

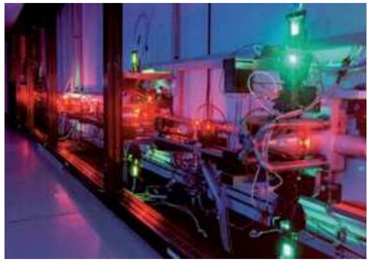
R&D in KAERI (Korea) for ^{48}Ca enrichment by laser



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

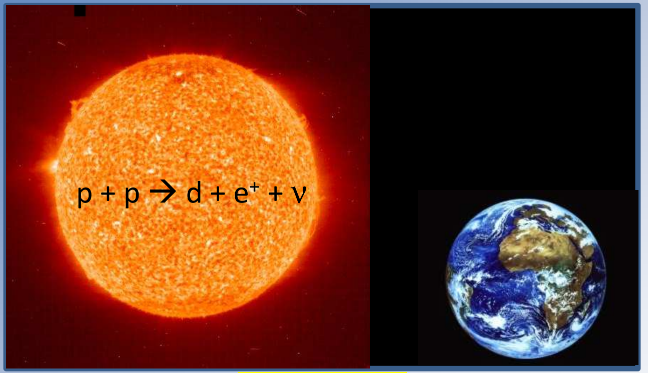
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 \boxed{L}}{\boxed{E_\nu}}\right)$$

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

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

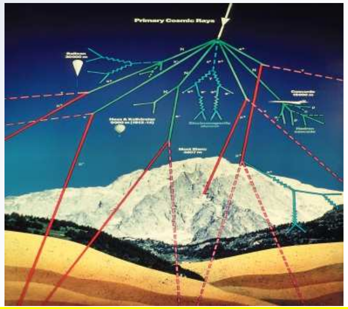
Pontecorvo-Maki-Nakasawa-Sakata

OSCILLATIONS DE NEUTRINOS



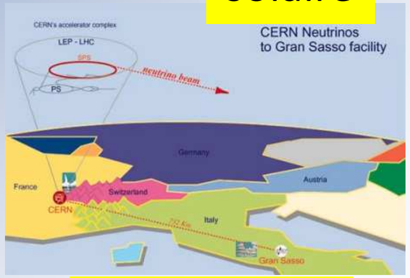
E_ν ~ 10 MeV
L ~ 10^8 Km
ν_e

solaire



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

atmosphériques



E_ν ~ 1 GeV
L ~ 300 Km
$\nu_{\mu,}$

accélérateur

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

réacteur

V_{PMNS} →

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

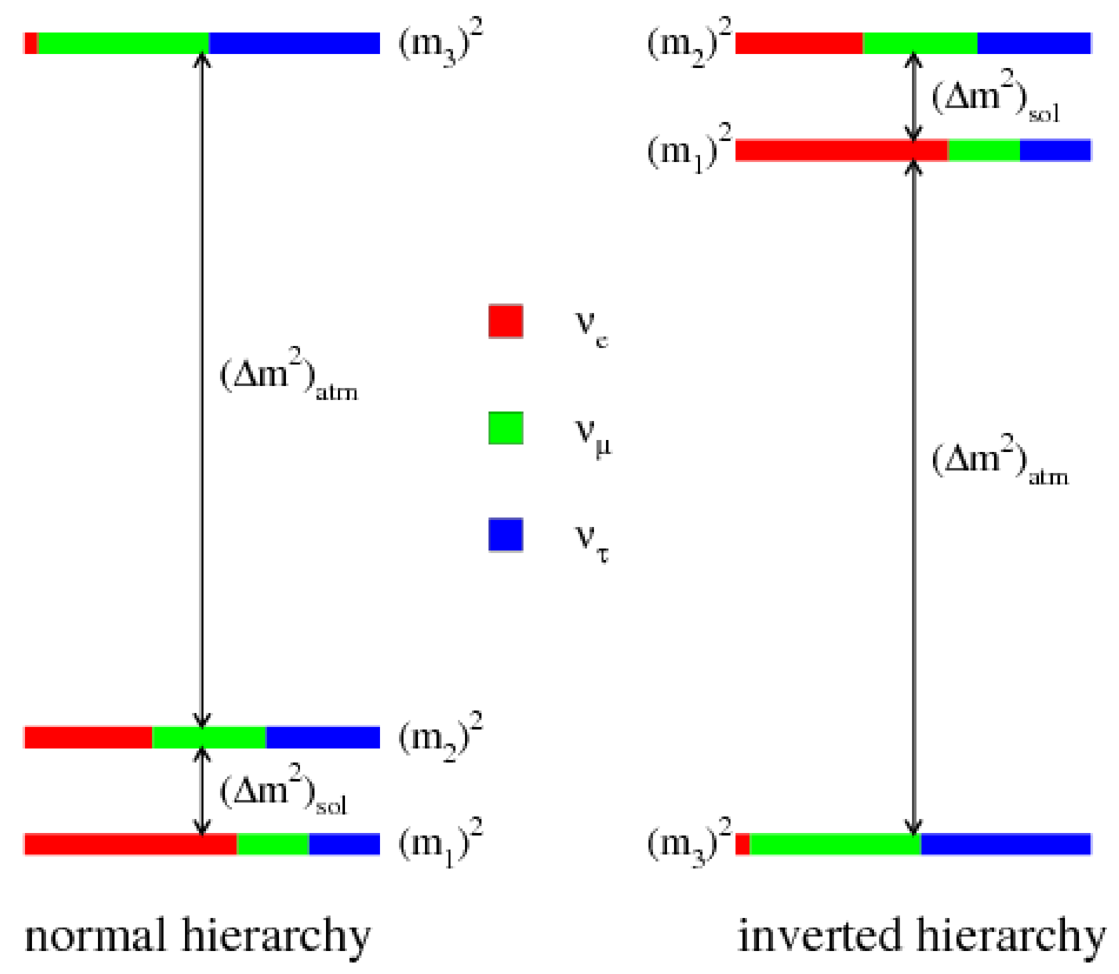
$$\left|\Delta m^2_{31(32)}\right| = 2.47\ (2.46) \times 10^{-3}\ \mathrm{eV}^2,$$

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

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

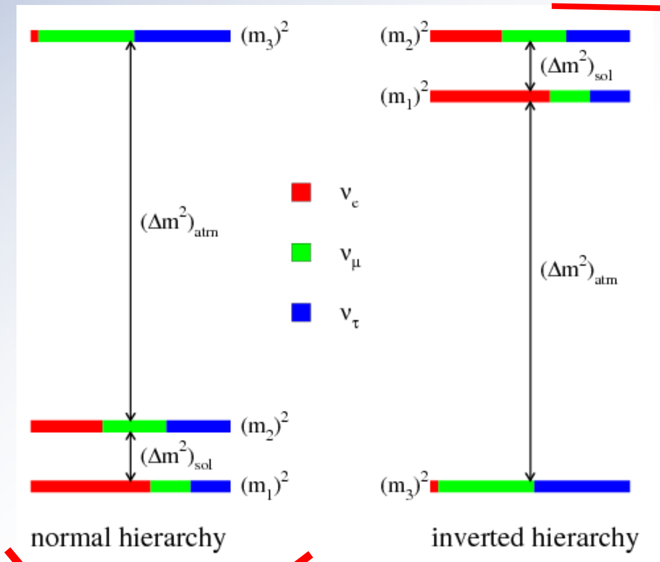
=> $m_\nu \neq 0$
$m_\nu = ?$

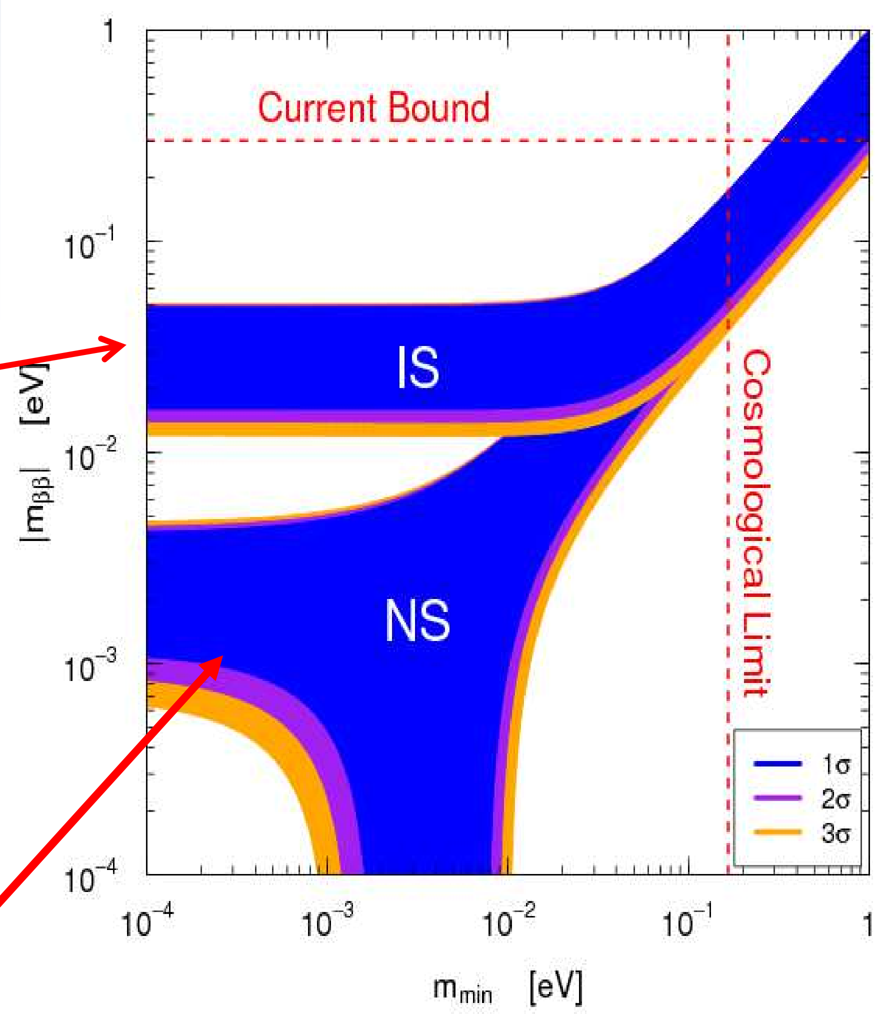
Hiérarchie de masse



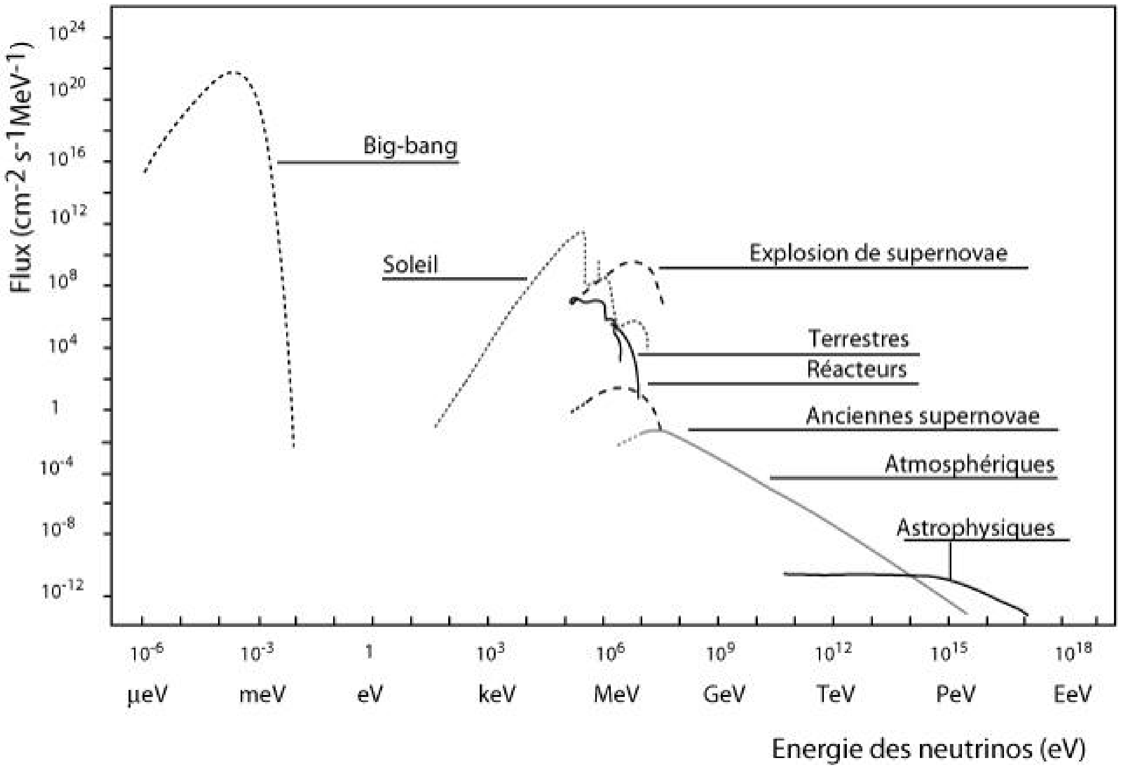
ββ v.s. oscillations

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





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