Neutrinoless double beta decay:
NEMO-3 results and the SuperNEMO project

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On behalf of the NEMO-3/SuperNEMO collaboration

HISEBSM, ICISE, Quy Nonh (August 2016)

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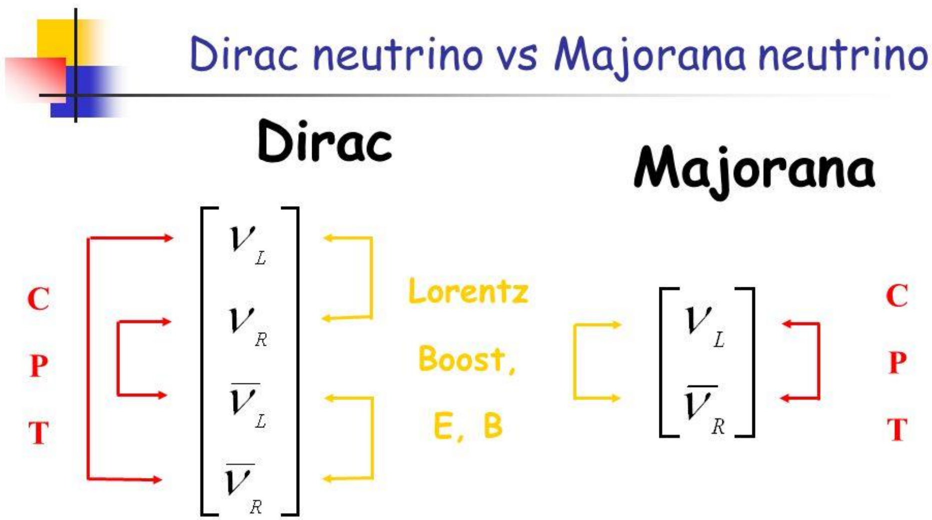
- Physics motivation
- Double beta decay process
- NEMO-3 results
- The SuperNEMO project

Neutrino is the only known electrically neutral fermion

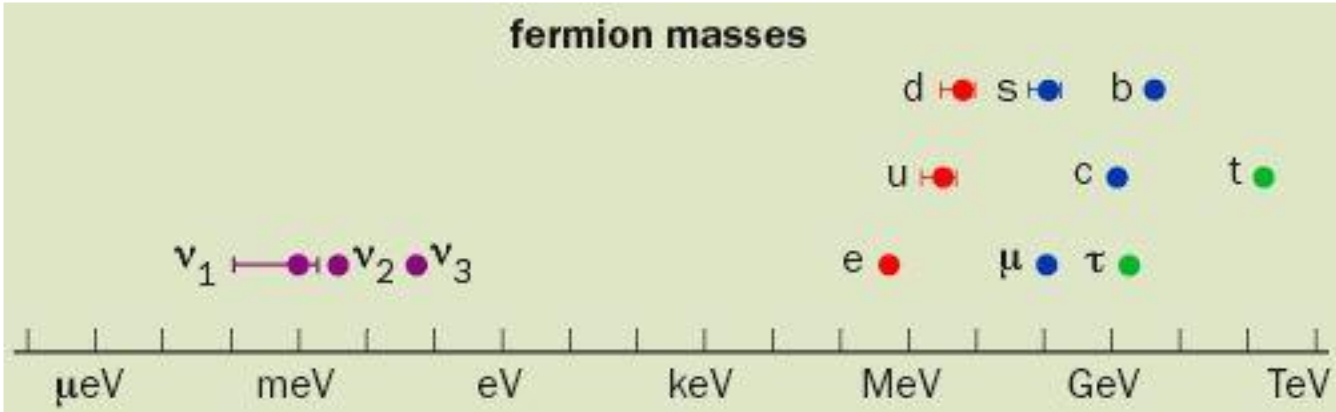
Thus, the only quantum number that can be used to distinguish between neutrino (ν) and anti-neutrino ($\bar{\nu}$) states is lepton number. However, there is no gauge symmetry associated with lepton number and, as such, there is no fundamental reason that this quantity should be conserved.

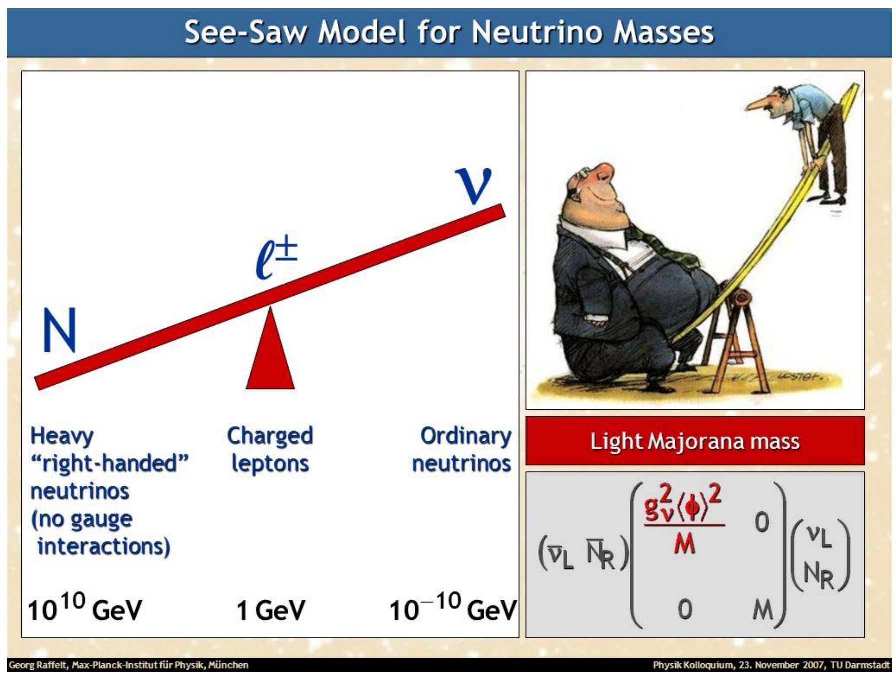
→ Majorana particle: neutrino is its own anti-particle → lepton number violation



The neutrino mass

Neutrino is massive but not a lot !

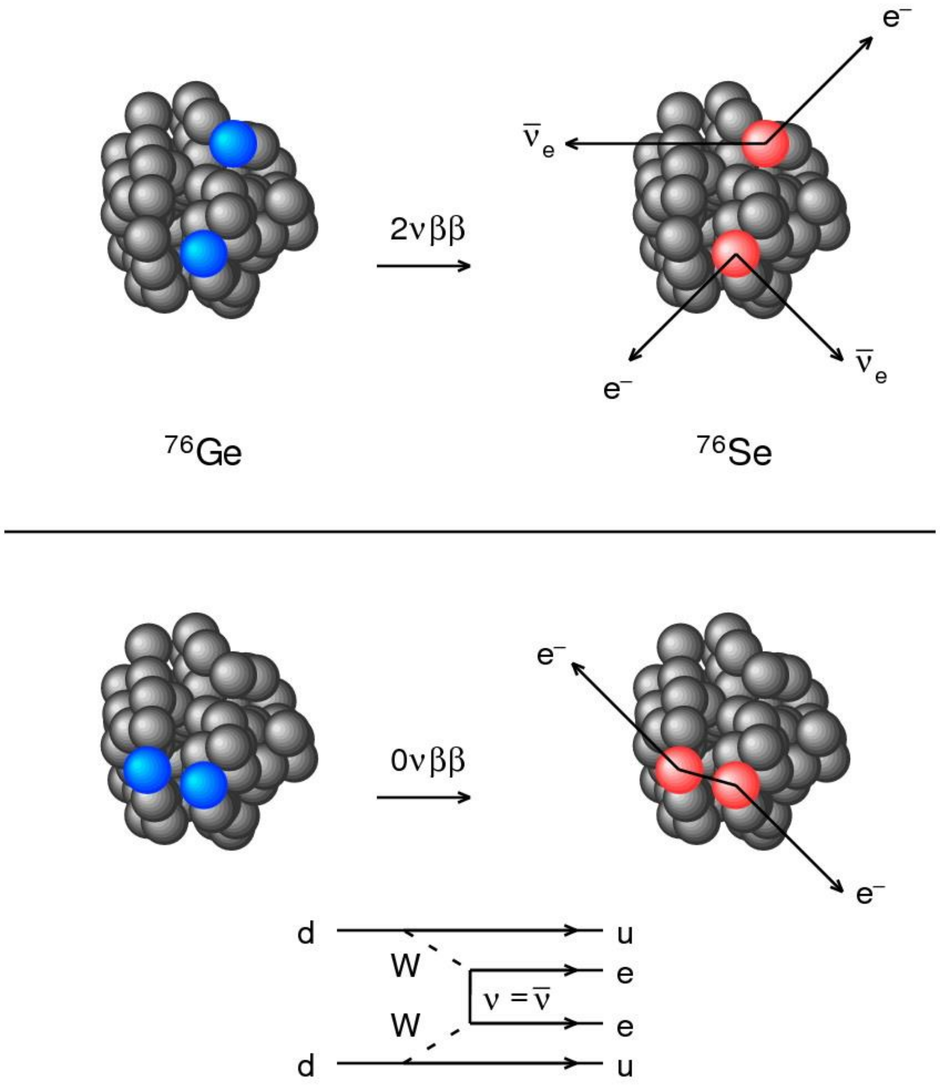




Reasons To Try ~~Marijuana~~ Majorana:

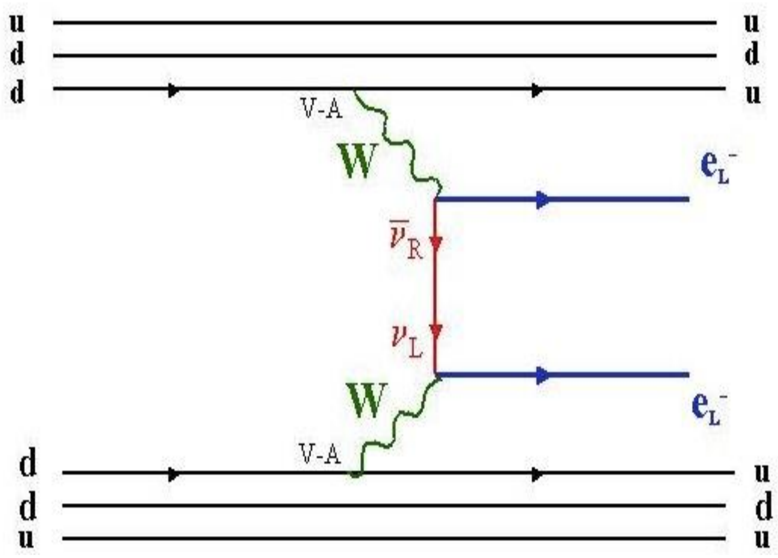
- Would provide an extremely sensitive probe of the absolute neutrino mass
- Seesaw mechanism with GUT-scale Majorana neutrino could explain scale of observed neutrino masses
- Coupled with CP violation, would be a key feature of Leptogenesis

A key low energy nuclear process: double beta decay



Neutrinoless double beta decay and neutrino properties

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



Phase space factor — **Nuclear matrix element**

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

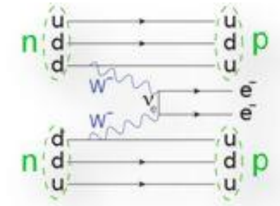
Effective mass:

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

|Uei|: mixing matrix element
α1 et α2: Majorana phase

Neutrinoless double beta decay and the effective neutrino mass

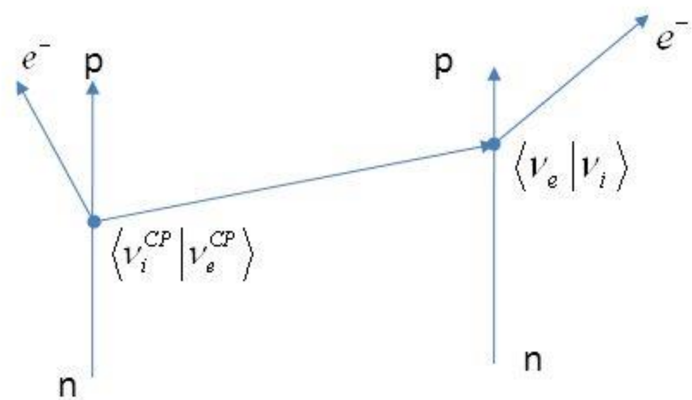
Why effective neutrino mass?



- Effective mass term

$$\langle m_{\beta\beta} \rangle = \sum_{i=1}^{3} \left| U_{e,i}^{2} \right| \cdot m_i \cdot e^{i\alpha_i}$$

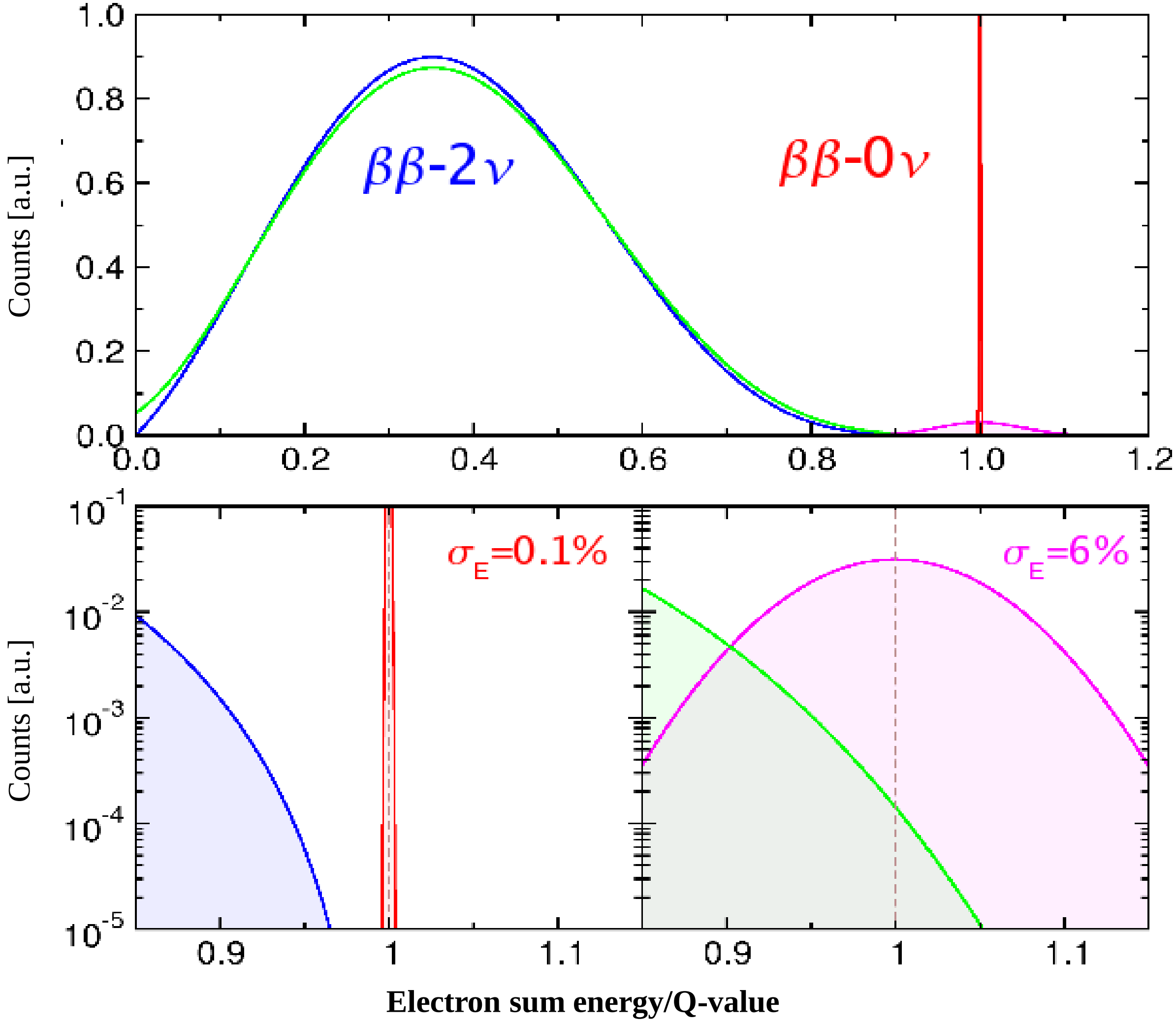
- Majorana mass
  - Emission of antineutrino: $\langle \nu_i^{CP} | \nu_e^{CP} \rangle = \sum_i \langle \nu_i^{CP} | U_{ei}^* | \nu_i^{CP} \rangle = U_{ei}^*$
  - Absorption of neutrino: $\langle \nu_e | \nu_i \rangle = \langle \nu_i | \nu_e \rangle^\dagger = U_{ei}^*$
- U_{ei} elements of neutrino mass mixing matrix



- Total amplitude of 0νββ decay $\propto \langle m_{\beta\beta} \rangle^2 = \sum_i \left(U_{ei}^* \right)^2 m_i$

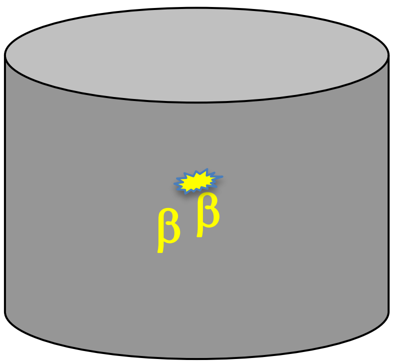
Key observable: total kinetic energy of the two electrons

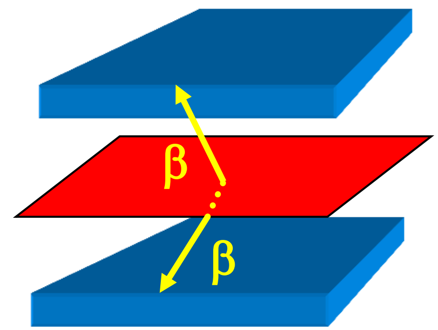
$$(A,Z) \longrightarrow (A,Z+2) + 2\,e^-$$



Two different approaches: calo and tracko-calo techniques

a) **very accurate measurement of the energy to observe the energy peak sum**
b) **detection of the two emitted electrons to reduce background**





Calorimetric measurement: **calo**

Detector is the source
Limited number of ββ isotopes
Excellent energy resolution
Background (?)

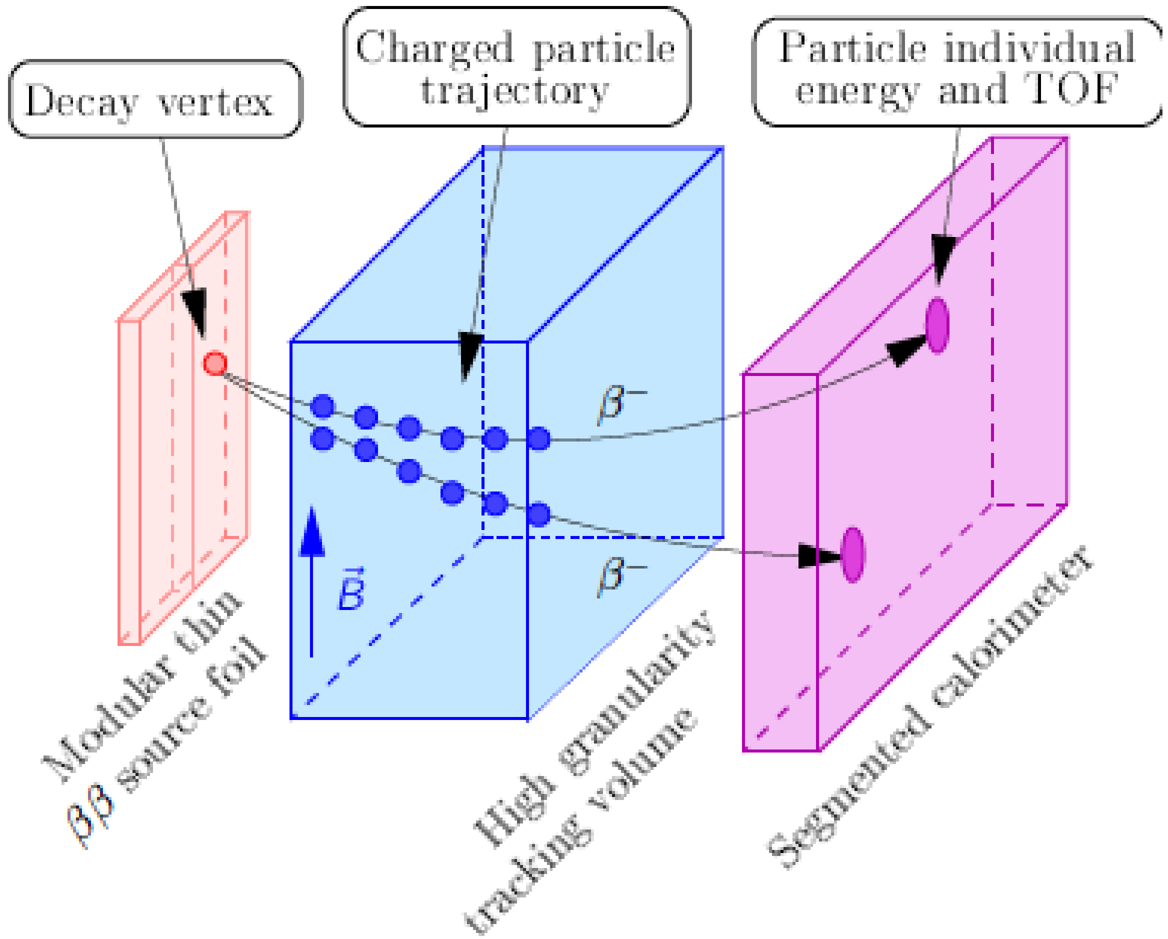
Electron detection: **tracko-calo**

Control of background
Poor energy resolution
More ββ isotopes but need source ‘technology’
- enrichment
- radio-purity
- conditionning (foils)

NEMO-3 and SuperNEMO project

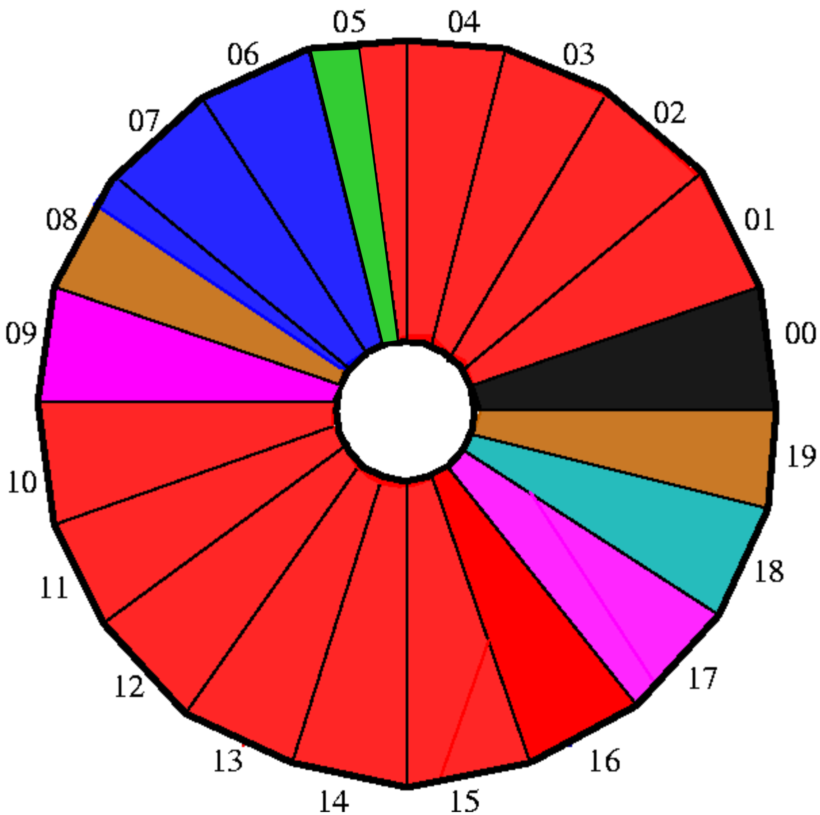
~ 100 physicists, 24 laboratories

Principle of experiments with electron detection (tracko-calo method)



Multi-isotope detector
High rejection of background

NEMO3 isotopes



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

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

ββ0ν search

ββ2ν measurement

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

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

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

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

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

^{nat}Te 491 g

Cu 621 g

External bkg measurement

(All enriched isotopes produced in Russia)

The NEMO3 detector@LSM (Frejus tunnel, underground)

Water tank

wood

coil

Iron shield

A sector of the NEMO3 detector

Measured experimental half-life in the presence of background

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

M: masse (g)
ε : efficiency
$K_{C.L.}$: Confidence level
$\mathcal{N}$: Avogadro number
t: time (y) (~ 8 years for NEMO3)
N_{Bckg}: Background events ($keV^{-1}.g^{-1}.y^{-1}$)
ΔE: energy resolution (keV)

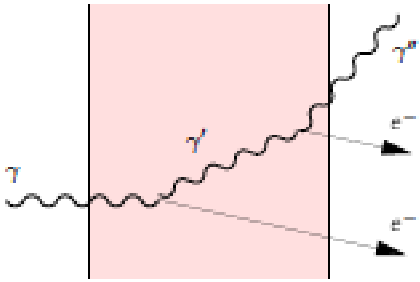
Requirements:

Mass of enriched ββ isotopes as large as possible
Efficiency as large as possible
Background as low as possible
- **extreme radiopurity of the materials used for the detector**
- **very low external background (underground laboratories)**

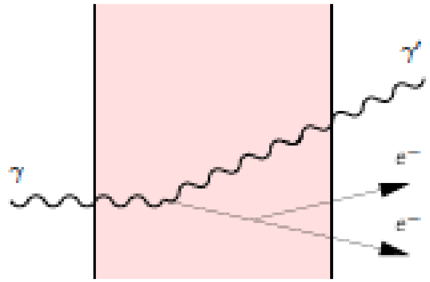
Energy resolution as best as possible and under control (slow control of the device)
Time of exposure as large as possible (stability of the detector for many years)

Background from natural radioactivity and cosmic

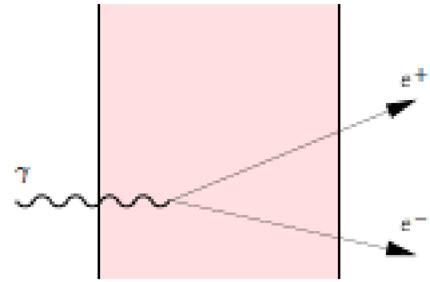
External (γ flux):



double Compton

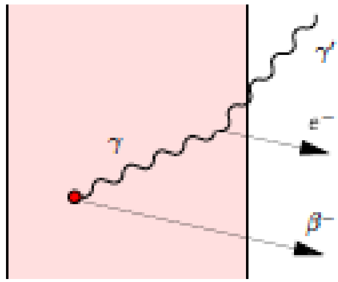


Compton+ Möller

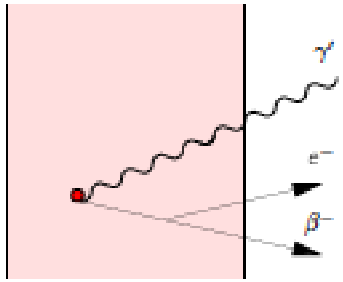


pair production

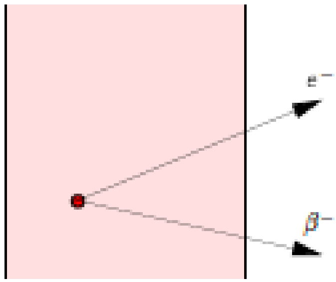
Internal (source foil contaminants):



β^-+ Compton

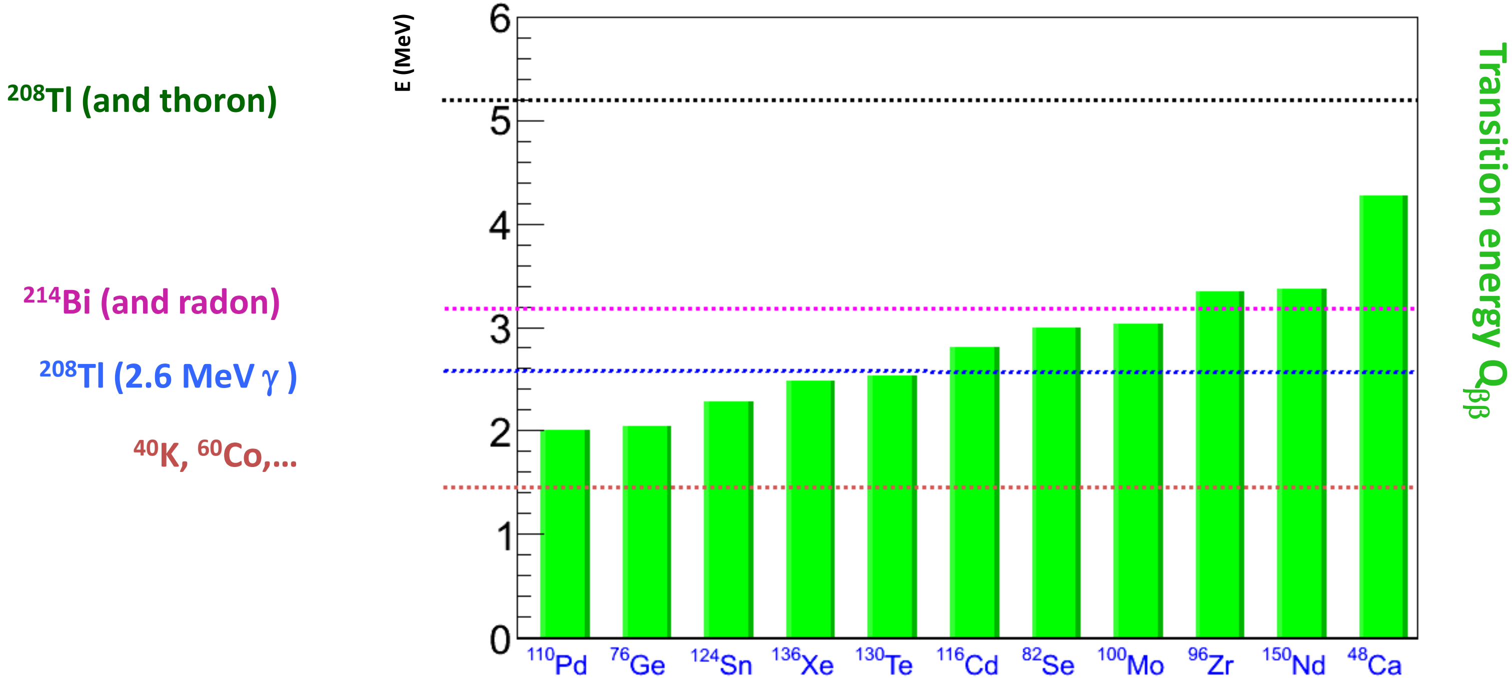


β^-+ Möller



β^-+ IC

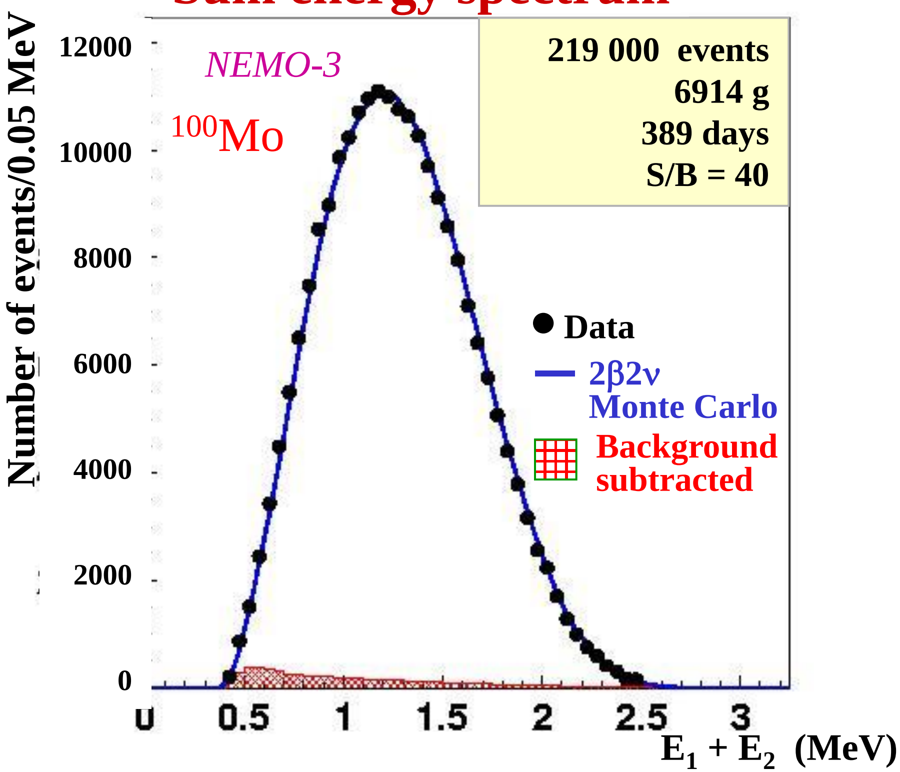
Source of background from natural radioactivity



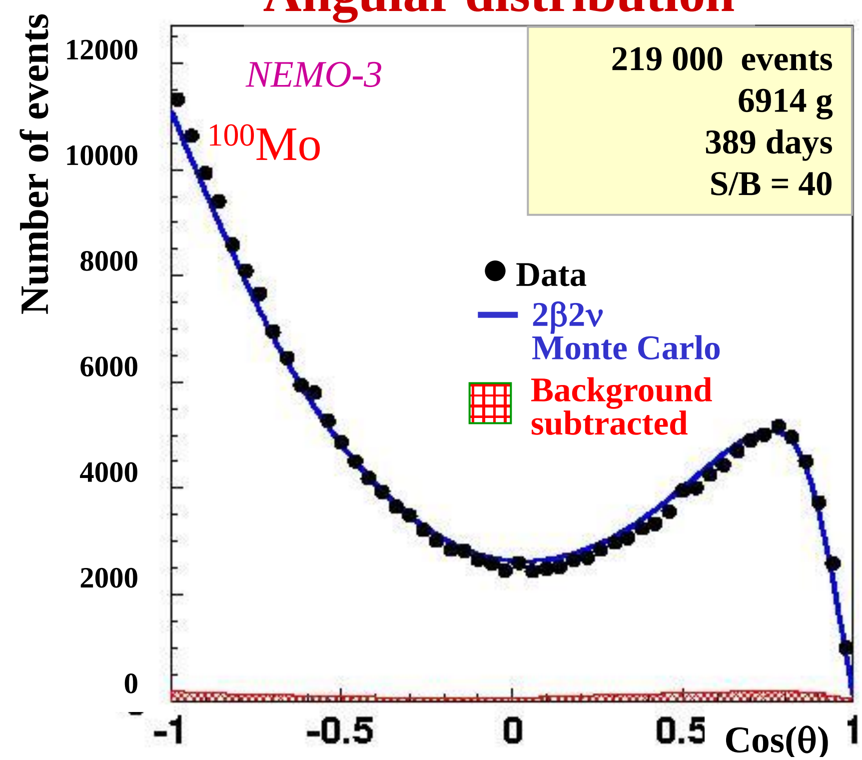
Detectors installed underground
Selection of all materials used in the detectors (radio-purity)
Shielding against gamma-ray from the rocks
Suppression of radon in the air inside the detector

Some NEMO3 results

Sum energy spectrum



Angular distribution



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

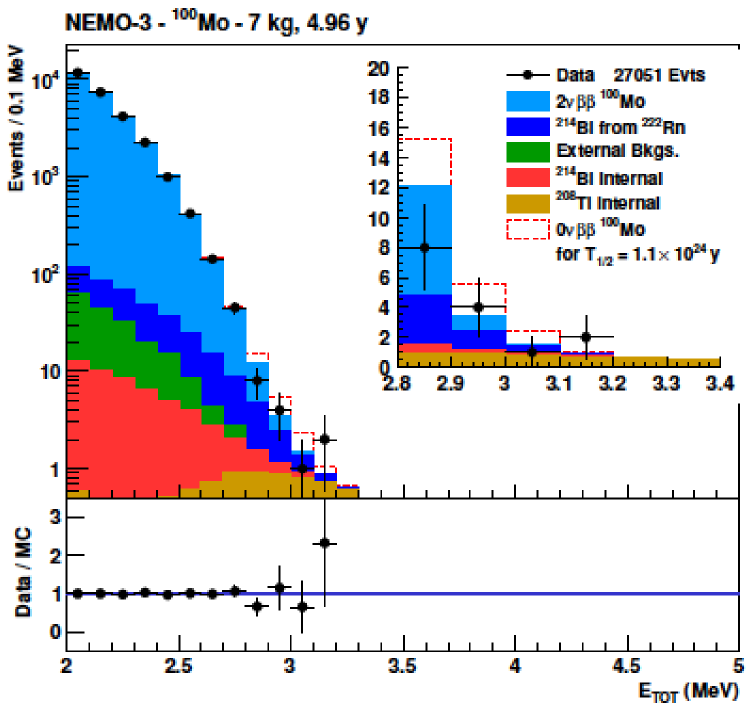
Phys. Rev. Lett. 95 182302 (2005)

«ββ factory» → tool for precision test

NEMO3 results

NEMO-3 $0\nu2\beta$ Search with ^{100}Mo

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



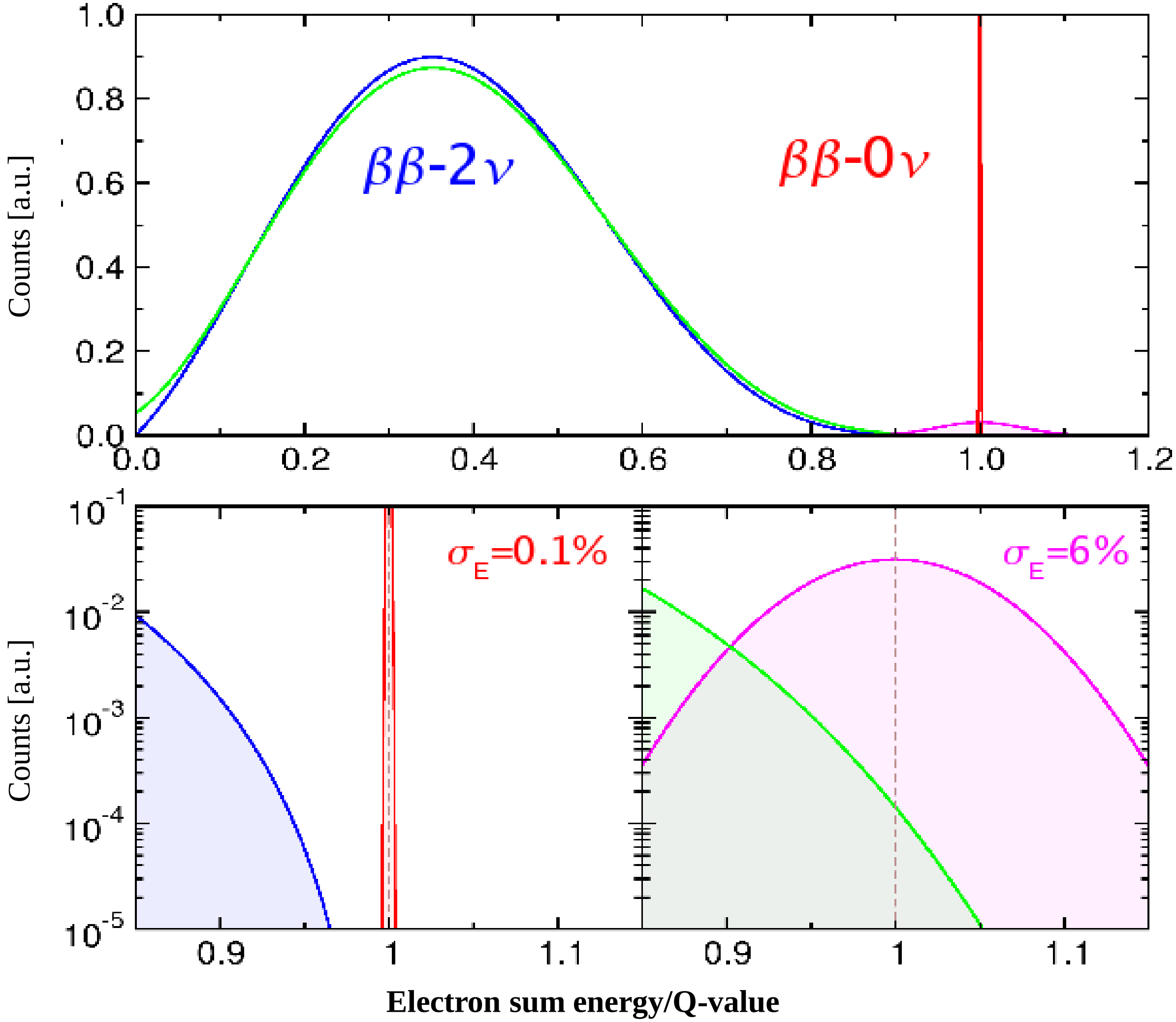
Expected background in [2.8 – 3.2] MeV	
$2\nu2\beta$	8.45 ± 0.05
^{214}Bi from radon	5.2 ± 0.5
External	< 0.2
^{214}Bi internal	1.0 ± 0.1
^{208}Tl internal	3.3 ± 0.3
Total	18.0 ± 0.6
Data	15

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

$T_{1/2} > 1.1\ 10^{24}$ yr **$<m_\nu> < 0.3 – 0.7$ eV**

Key observable: total kinetic energy of the two electrons

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



Latest results from other experiments

Experiment	isotope	Mass (kg)	Half-life limit in years	Neutrino mass limit in eV
H.M.	^{76}Ge	14	1.9 10^{25}	0.21 -0.53
GERDA	^{76}Ge	14	1.9 10^{25}	0.20 -0.40
Cuoricino	^{130}Te	12	2.8 10^{24}	0.27 – 0.57
NEMO3	^{100}Mo	7	1.1 10^{24}	0.31 – 0.79
EXO-200	^{136}Xe	200	1.6 10^{25}	0.14 – 0.38
Kamland-Zen	^{136}Xe	400	2.6 10^{25}	0.14 – 0.26

Neutrino mass limit 'window' due to uncertainties in NME estimations
NME values based on calculations (Shell Model, QRPA)

Neutrinoless double beta decay and neutrino properties

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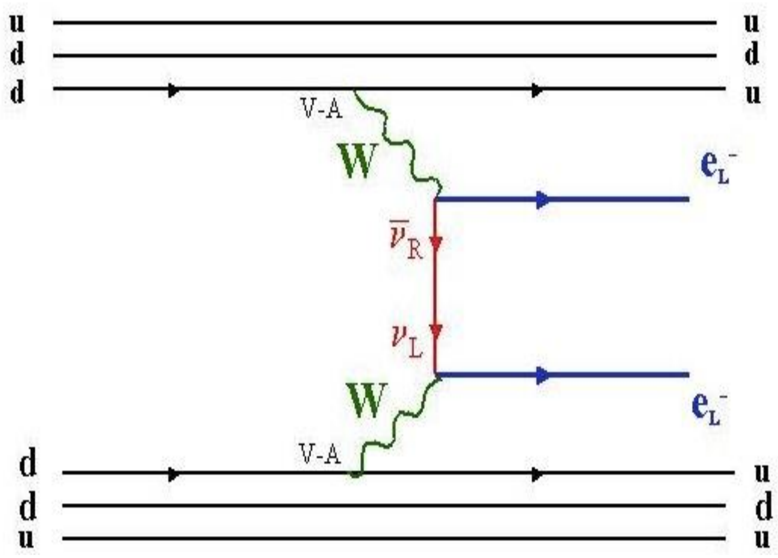

Phase space factor **Nuclear matrix element**

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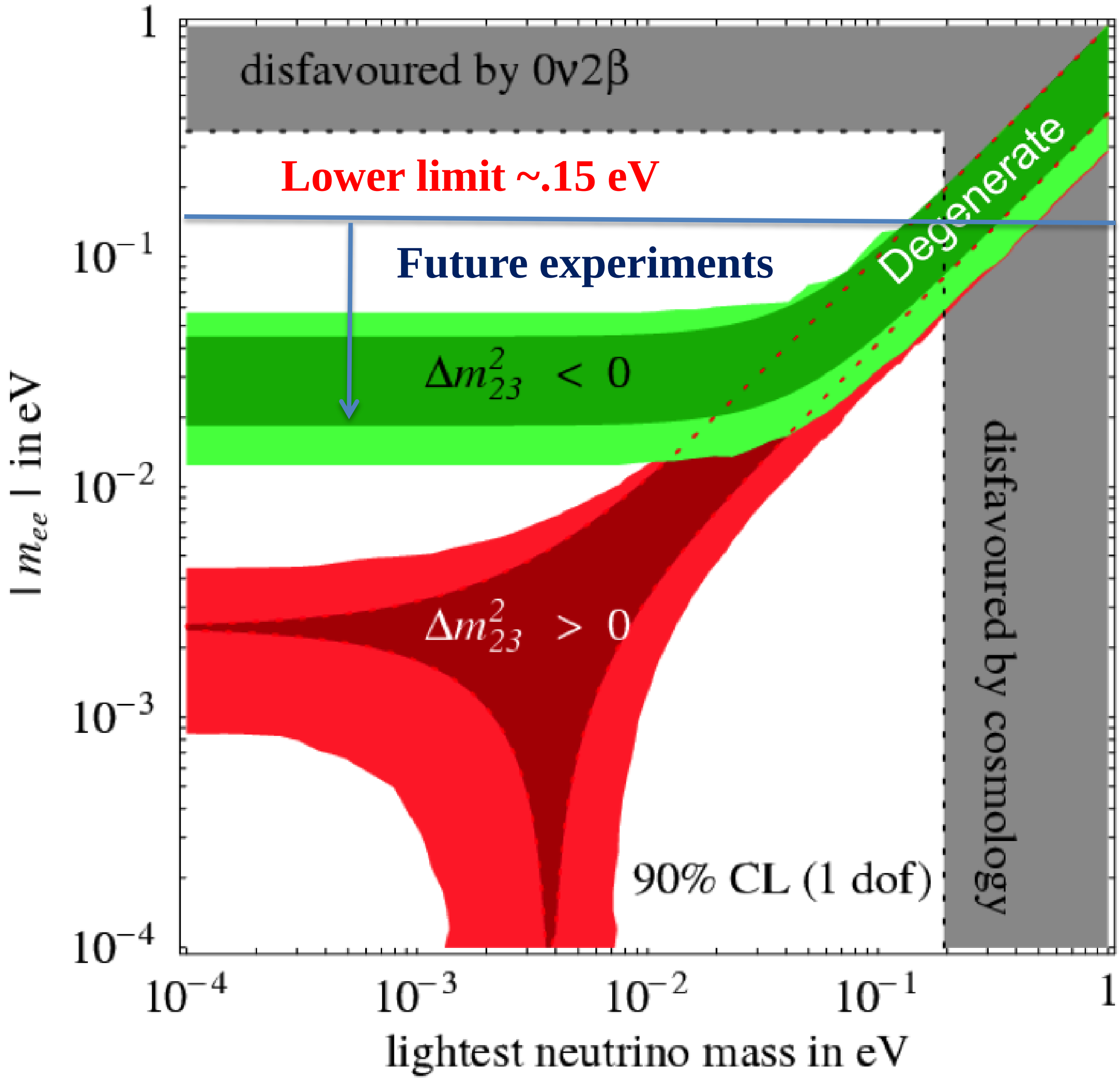
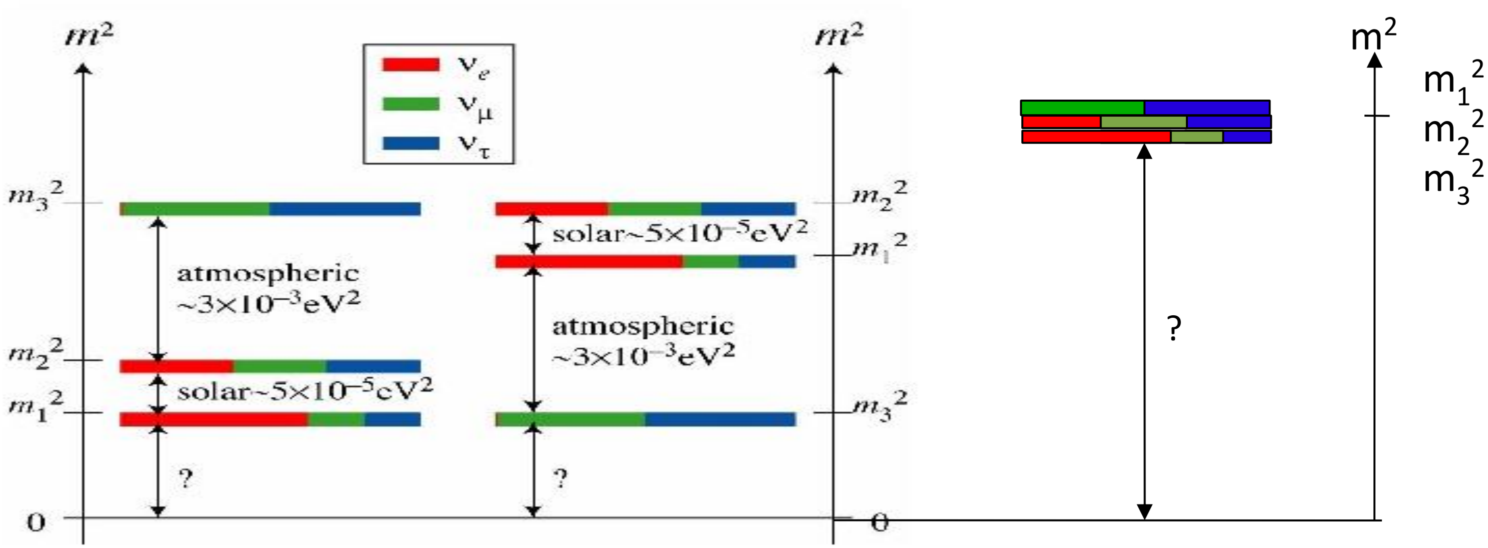
|Uei|: mixing matrix element
α1 et α2: Majorana phase



disfavoured by 0ν2β
Lower limit ~.15 eV
Future experiments
Degenerate
$\Delta m^2_{23} < 0$
$\Delta m^2_{23} > 0$
90% CL (1 dof)
disfavoured by cosmology
$|m_{ee}|$ in eV
lightest neutrino mass in eV
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}



Normal hierarchy
$m_3 > m_2 \sim m_1$

Inverted hierarchy
$m_2 \sim m_1 > m_3$

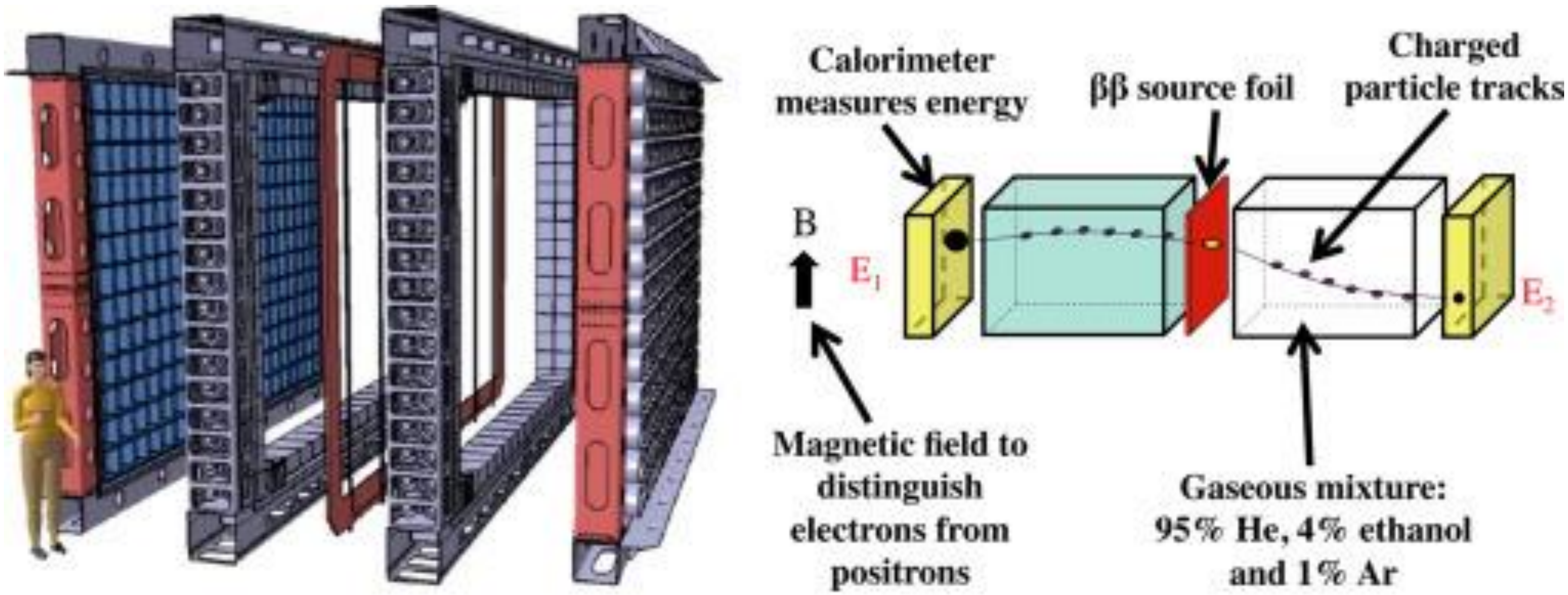
Degenerate
$m_1 \approx m_2 \approx m_3 \gg |m_i - m_j|$

$$T^{0\nu}_{1/2}(y) \sim \varepsilon \sqrt{\frac{M\ .\ t}{N_{Bckg}\ .\ \Delta E}}$$

From NEMO-3 to SuperNEMO

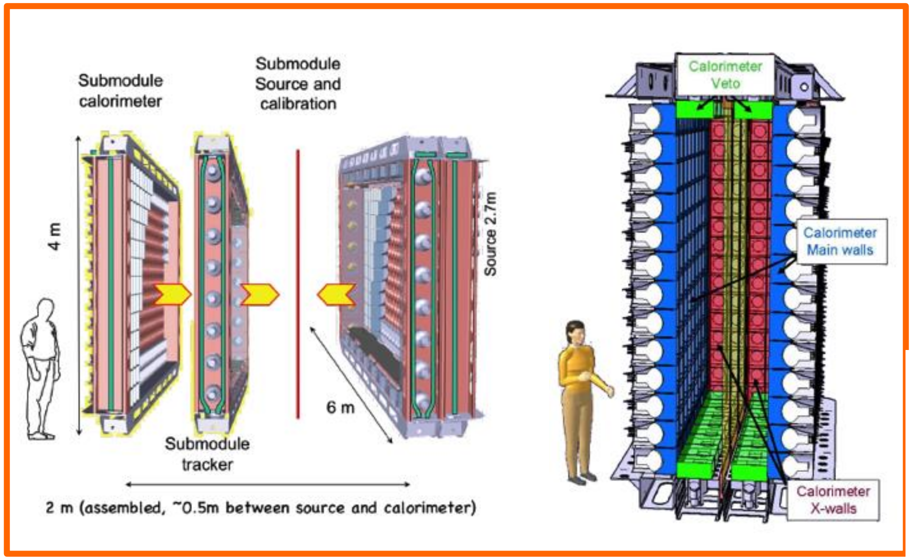
$T_{1/2}(\beta\beta0\nu) > 2.\ 10^{24}$ y $<m_\nu> < 0.3 - 1.3$ eV	**Sensitivity**	$T_{1/2}(\beta\beta0\nu) > 2.\ 10^{26}$ y $<m_\nu> < 40 - 110$ meV
7 kg ^{100}Mo $T_{1/2}(\beta\beta2\nu) = 7.\ 10^{18}$ y	**Mass of isotope**	100 kg ^{82}Se $T_{1/2}(\beta\beta2\nu) = 10^{20}$ y
FWHM ~ 12% at 3 MeV (dominated by calorimeter ~ 8%)	**Energy resolution**	FWHM ~ 7% at 3 MeV (dominated by source foil)
$\varepsilon(\beta\beta0\nu) = 8$ % { poor energy resolution { e^- backscattering on scintillator	**Efficiency**	$\varepsilon(\beta\beta0\nu) \sim 40$ %
^{214}Bi < 300 µBq/kg ^{208}Tl < 20 µBq/kg	**Internal contaminations in the source foils in ^{208}Tl and ^{214}Bi**	^{214}Bi < 10 µBq/kg ^{208}Tl < 2 µBq/kg
$\beta\beta2\nu$ ~ 2 cts / 7 kg / y (^{208}Tl, ^{214}Bi) ~ 0.5 cts/ 7 kg /y	**Background**	$\beta\beta2\nu$ + (^{208}Tl,^{214}Bi) ≤ 1 cts/ 100 kg /y

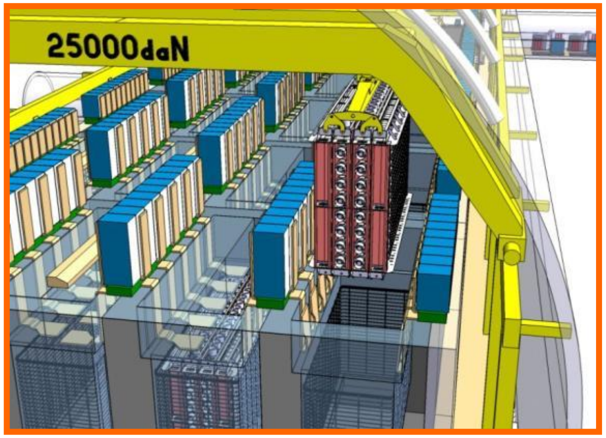
A SuperNEMO module



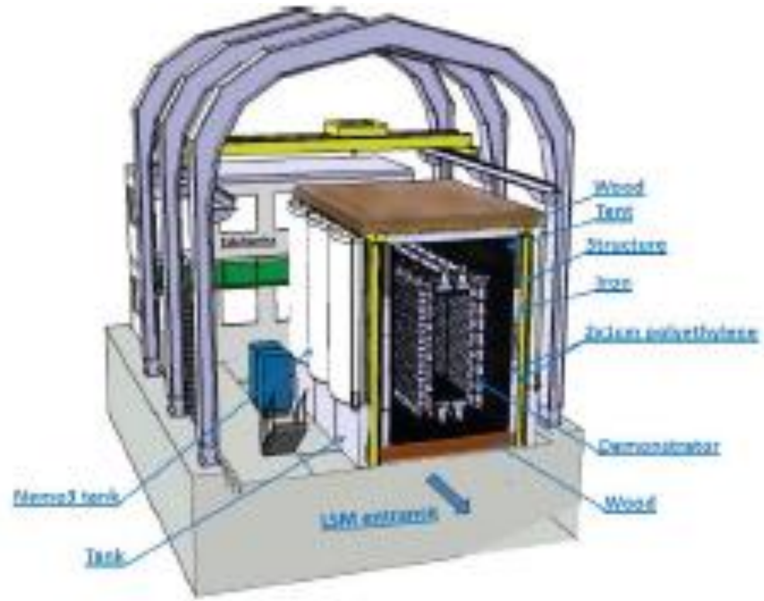
SuperNEMO project@LSM

A module





20 modules



Building of a demonstrator @LSM

* Mechanical infrastructure is ready
* Tracker (built in GB) has been commisionned and is ready to install
 *Calorimeter (~ 500 optical modules) have been mounted and tested (CENBG)
* Electronics and slow control are (almost) ready
* Source foils have been prepared and their radiopurity tested

Full installation before the end of 2016
Start of data acquisition middle of 2017

Future projects

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

Summary

- **The study of neutrinoless double beta decay is an important issue in particle physics:**

  nature of the neutrino: Dirac vs Majorana, lepton number violation
  mass of the neutrino

- **The experiments are extremely challenging**
- **No signal observed up to now**
- **Present sensitivity on neutrino mass is in the 0.15 – 0.60 eV range**
- **Next generation of detectors (> 100 kg) should allow to reach $<m_n> < 0.05$ eV**
- **New ideas are required for higher mass (1 ton) to reach the meV range**