Lawrence Livermore National Laboratory

Neutrinoless double beta decay experiments

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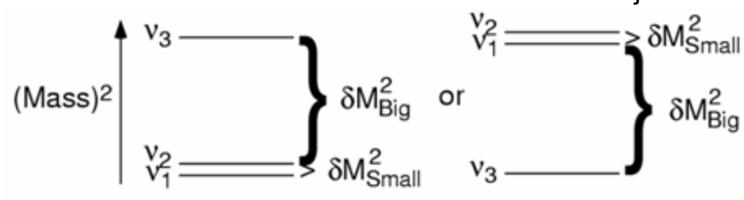
Neutrino and Double Beta Decay (DBD)

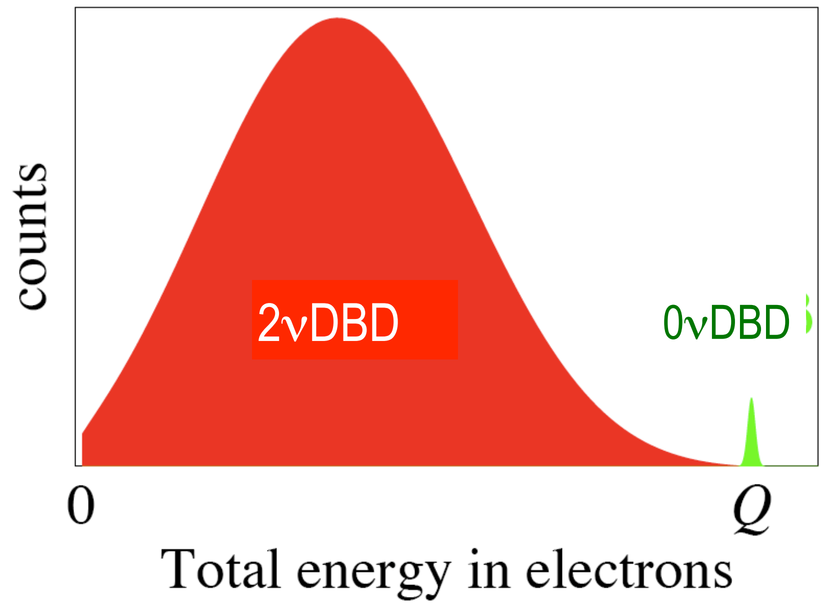
3 mass eigenstates M_1, M_2, M_3 but ν-oscillations measure **only** the $\Delta M_{ij}^2 = M_i^2 - M_j^2$

What we don't know
- the mass hierarchy
- the nature of ν



① 2νDBD: $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$ ⟶ allowed by SM

② 0νDBD: $(A,Z) \rightarrow (A,Z+2) + 2e^-$ ⟶ new physics beyond the SM



neutrinoless double beta decay peak spread only by the detector energy resolution

How 0vDBD is connected to neutrino mixing matrix and to neutrino masses?

Neutrinoless Double Beta Decay **rate**

Phase space

Nuclear matrix elements

Effective **Majorana mass**

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

what the experimentalists try to measure

what the nuclear theorists try to calculate

parameter containing the physics

How 0vDBD is connected to neutrino mixing matrix and to neutrino masses?

Neutrinoless Double Beta Decay **rate**

Phase space

Nuclear matrix elements

Effective **Majorana mass**

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

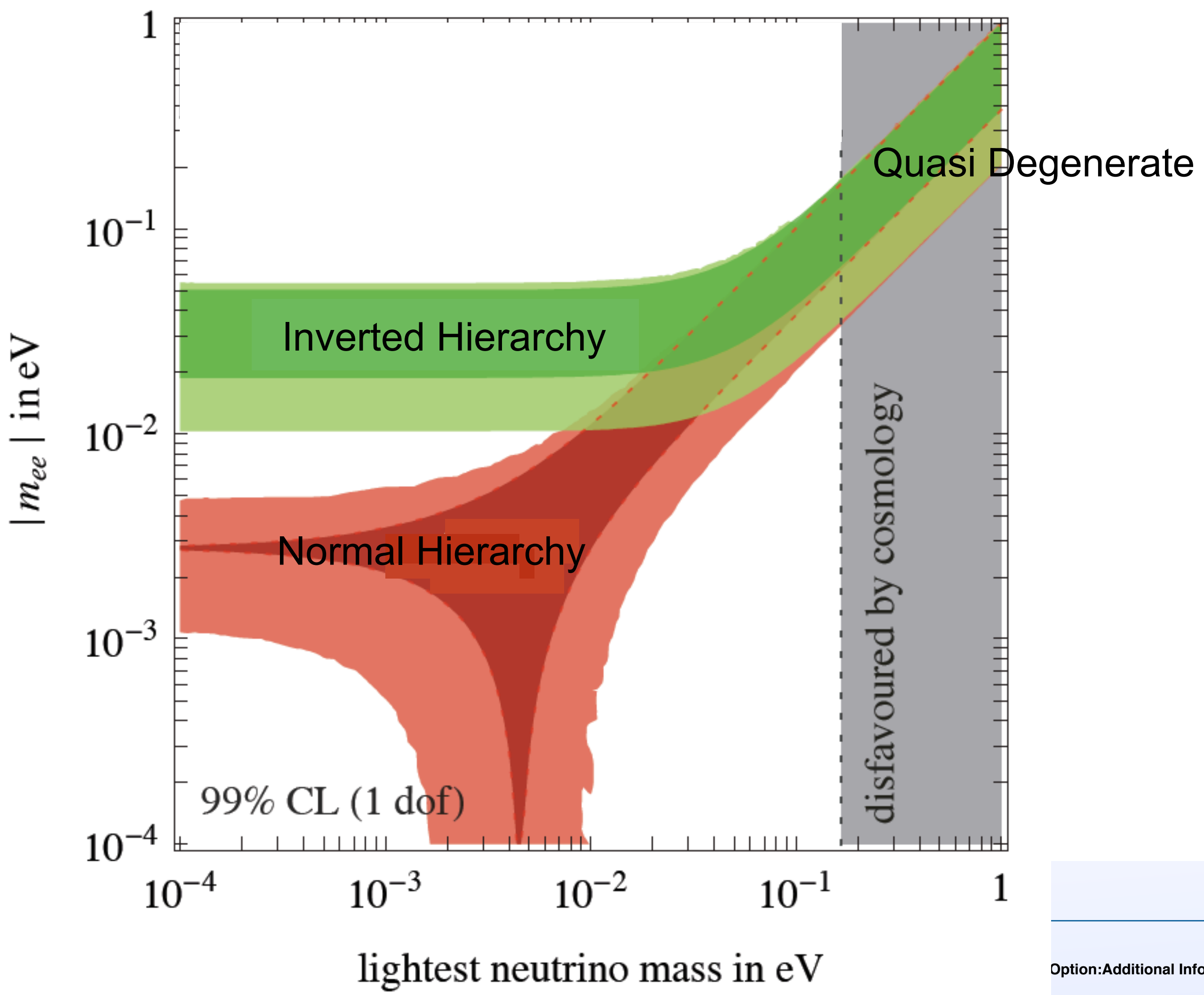
- $1/\tau$: what the experimentalists try to measure
- M_{nucl}: what the nuclear theorists try to calculate
- $\langle M_{\beta\beta} \rangle$: parameter containing the physics

$$\langle M_{\beta\beta} \rangle \propto \left| |U_{e1}|^2 M_1 + e^{i\alpha_1} |U_{e2}|^2 M_2 + e^{i\alpha_2} |U_{e3}|^2 M_3 \right|$$

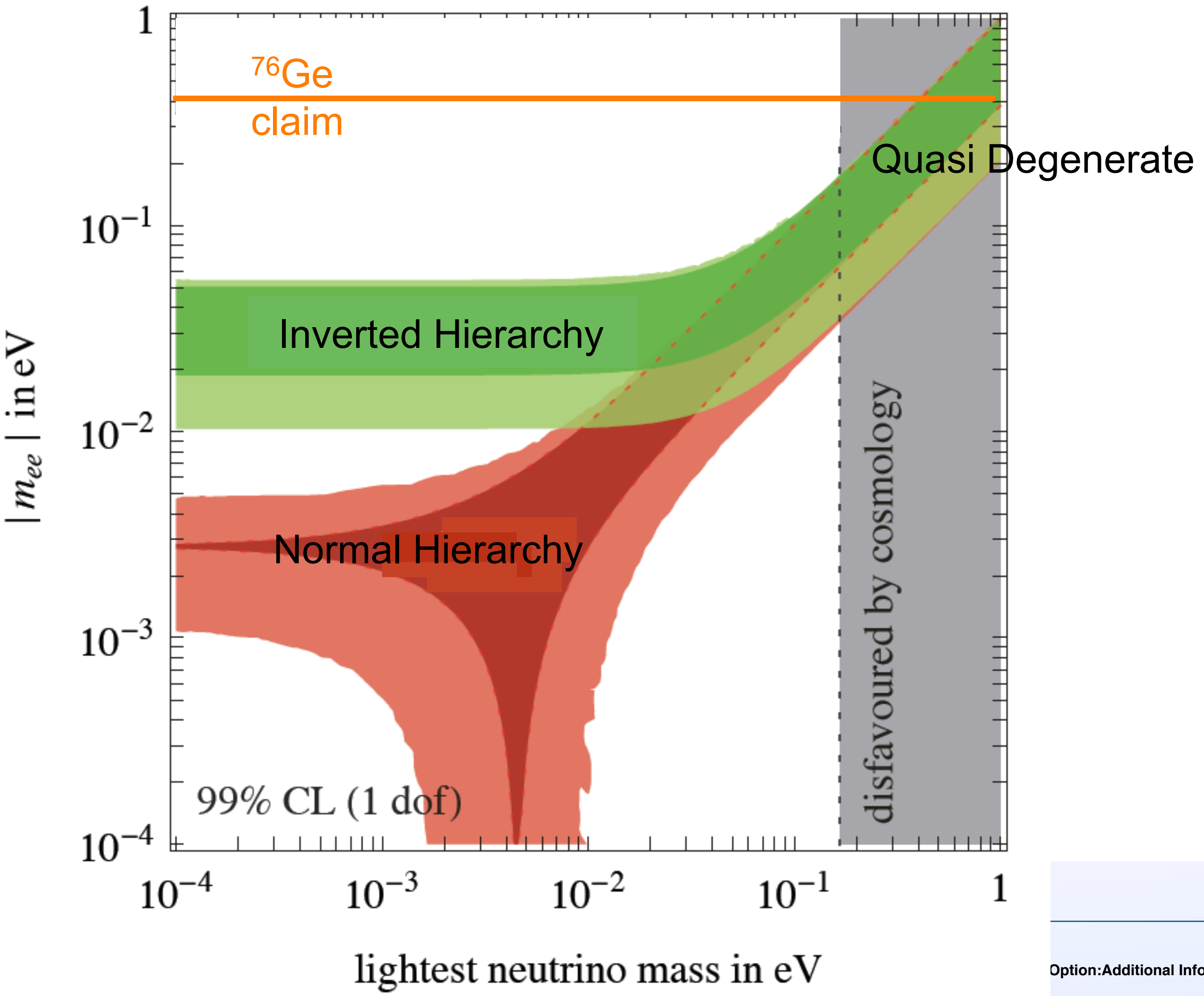
U_{ei} are the elements of the first row of neutrino mixing matrix
M_i are the neutrino mass eigenvalues

0νDBD and neutrino mass

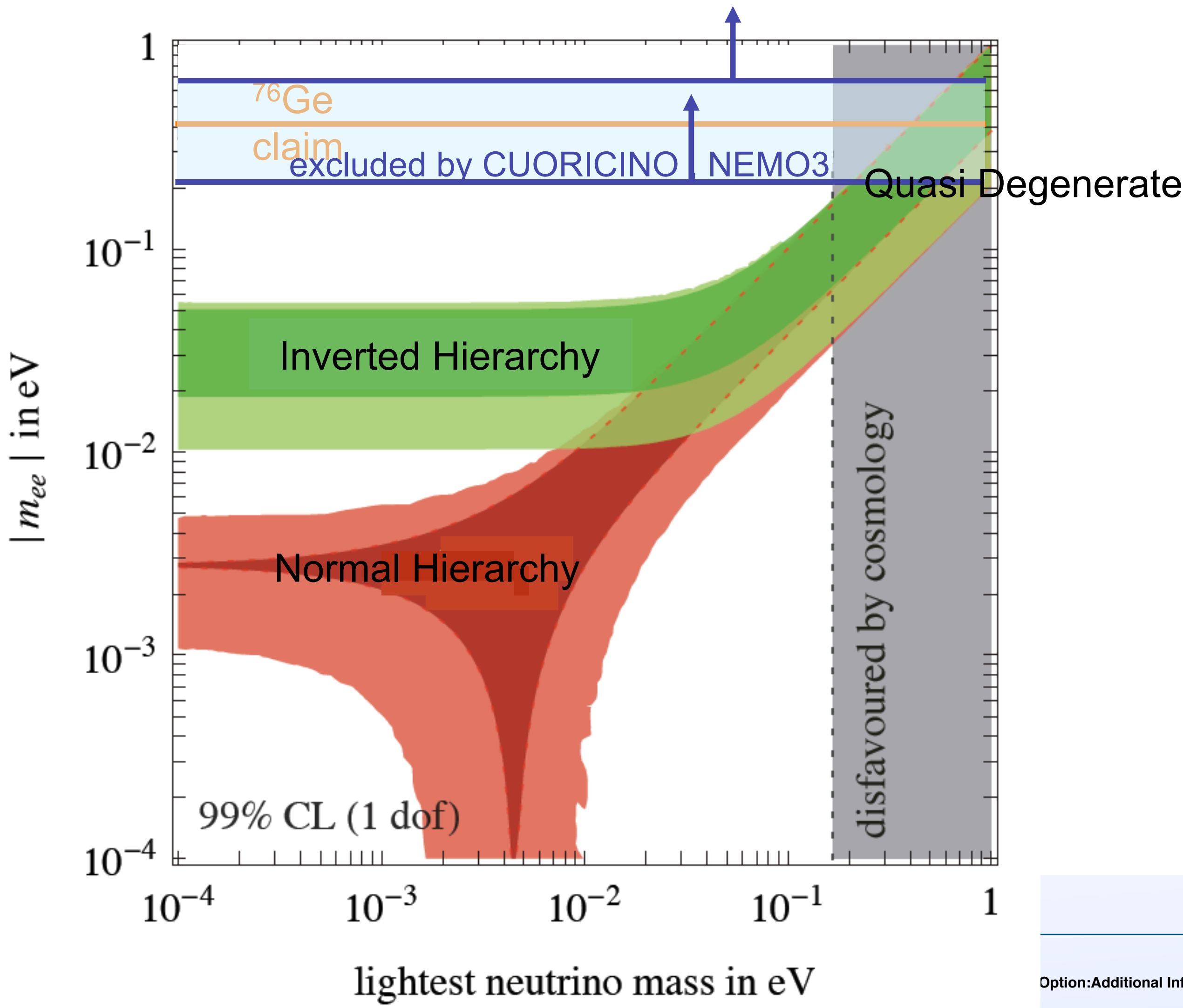
$$\langle M_{\beta\beta}\rangle \propto \left| |U_{e1}|^2 M_1 + e^{i\alpha_1} |U_{e2}|^2 M_2 + e^{i\alpha_2} |U_{e3}|^2 M_3 \right|$$



0νDBD and neutrino mass

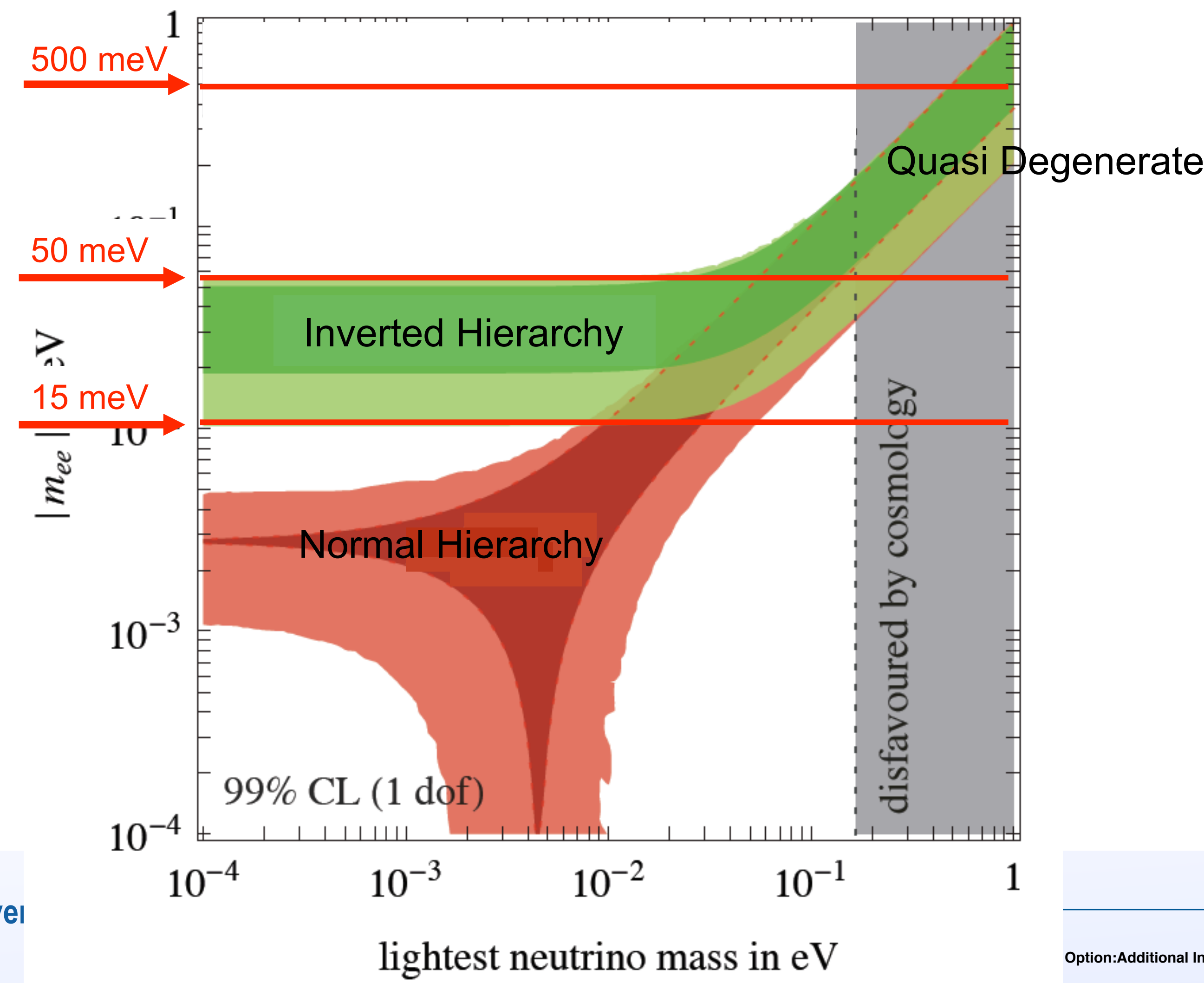


0νDBD and neutrino mass



0νDBD and neutrino mass

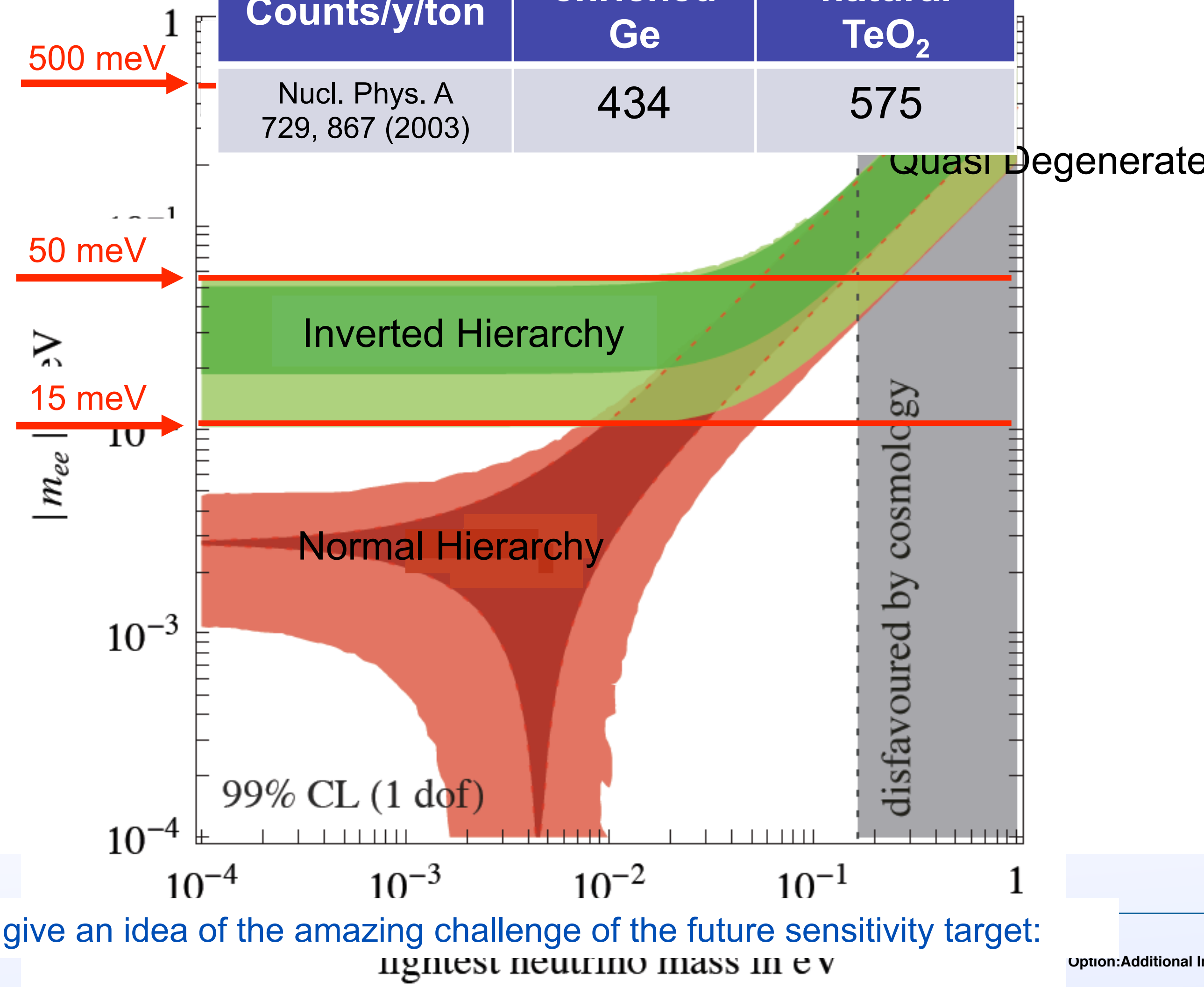
3 different value of neutrino mass can be seen as future milestones:



0νDBD and neutrino mass

3 different value of neutrino mass can be seen as future milestones:

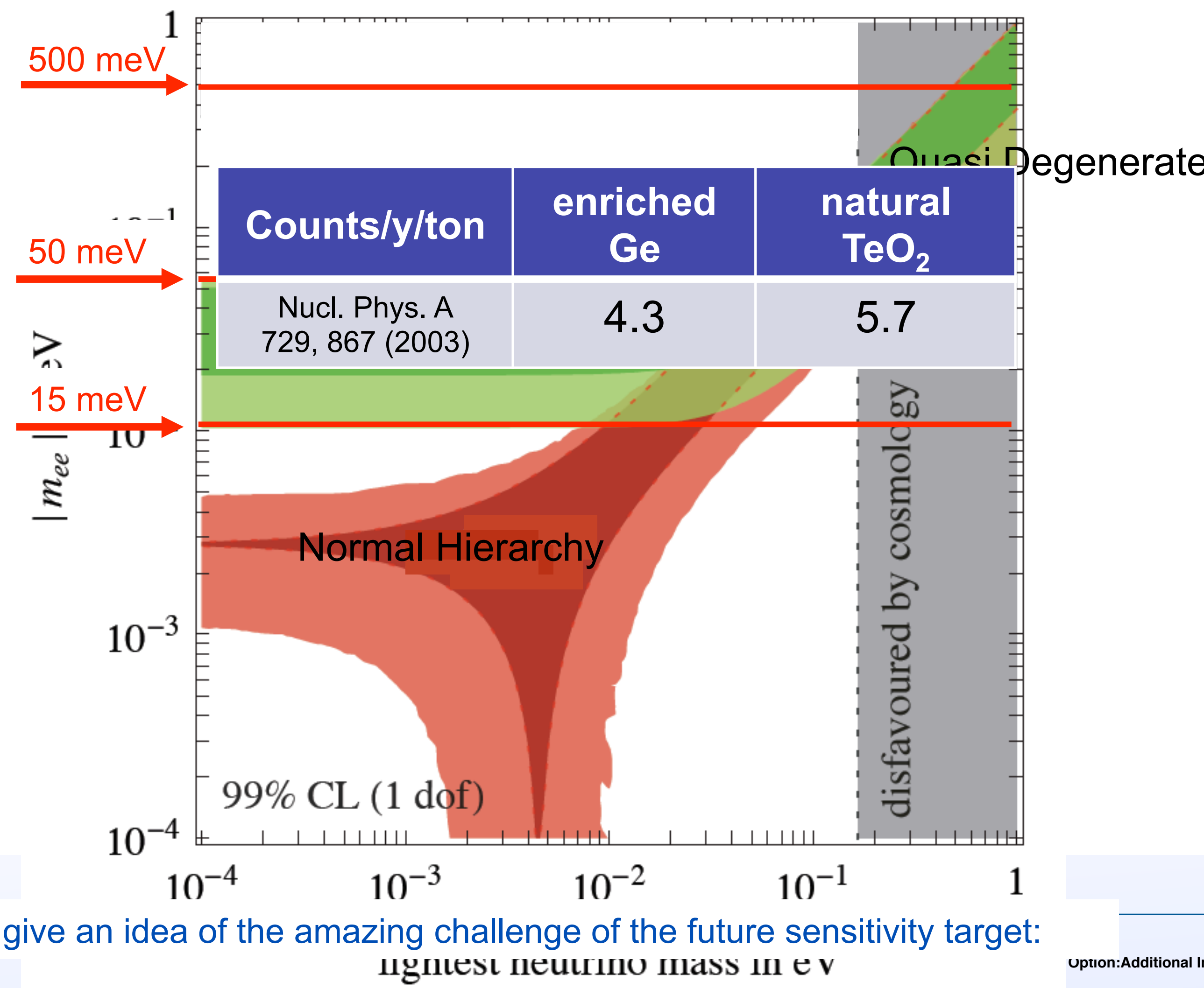
Counts/y/ton	enriched Ge	natural TeO_2
Nucl. Phys. A 729, 867 (2003)	434	575



In order to give an idea of the amazing challenge of the future sensitivity target:

0νDBD and neutrino mass

3 different value of neutrino mass can be seen as future milestones:

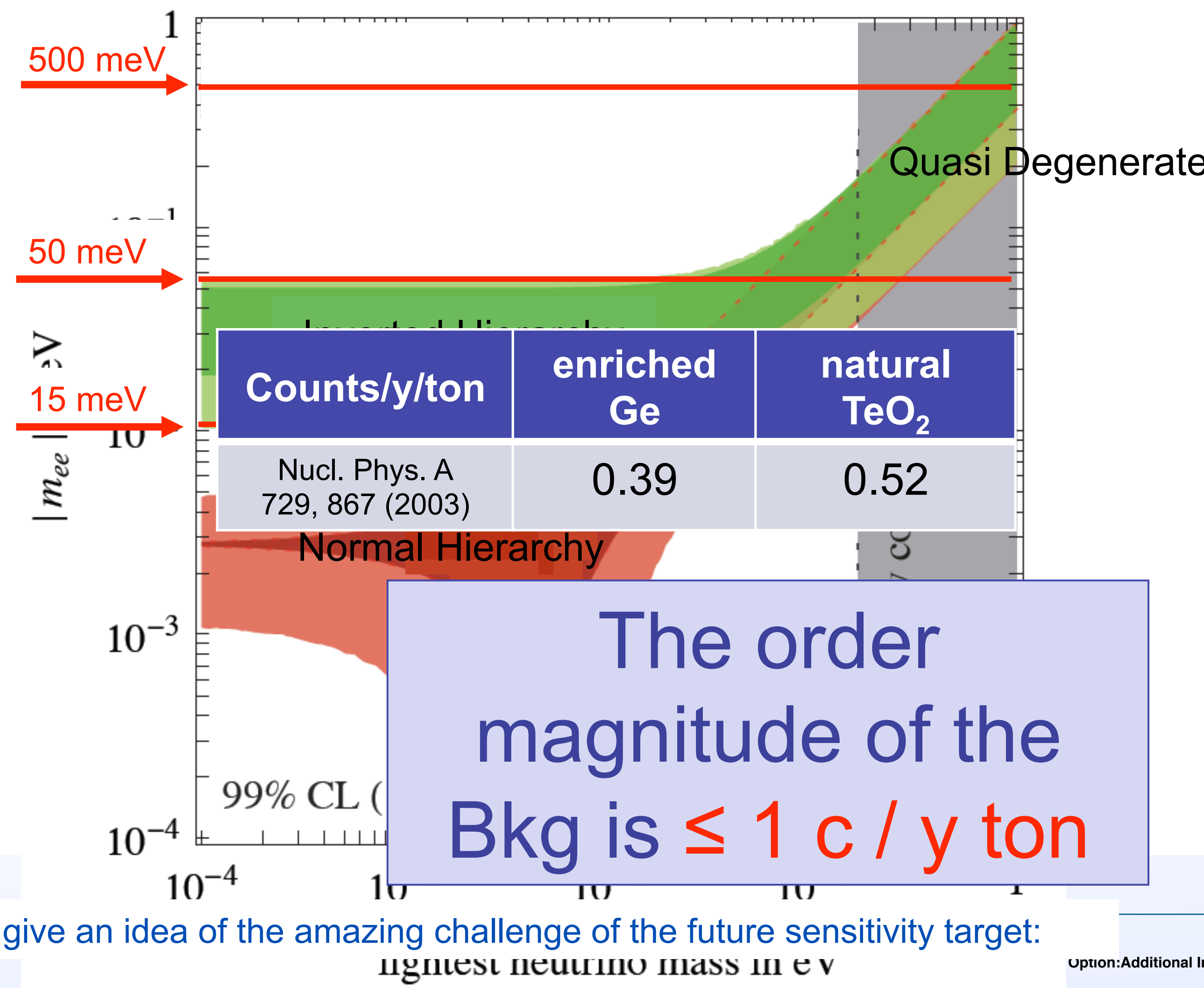


Counts/y/ton	enriched Ge	natural TeO_2
Nucl. Phys. A 729, 867 (2003)	4.3	5.7

In order to give an idea of the amazing challenge of the future sensitivity target:

0νDBD and neutrino mass

3 different value of neutrino mass can be seen as future milestones:



Counts/y/ton	enriched Ge	natural TeO_2
Nucl. Phys. A 729, 867 (2003)	0.39	0.52

The order magnitude of the Bkg is ≤ 1 c / y ton

In order to give an idea of the amazing challenge of the future sensitivity target:

Requirements for a 0vDBD experiment

sensitivity S_{0v}: lifetime corresponding to the minimum detectable number of events over background at a given confidence level

source mass

live time

$$S_{0\nu} \propto \sqrt{\frac{M \cdot T}{\Gamma \cdot b}}$$

background level

energy resolution

→ large source (many nuclei under observation)

→ long time measurements

→ good energy resolution

→ low background

0vDBD experiments

Name	Nucleus	Method	Location	Status
Cuoricino	^{130}Te	bolometric	LNGS	Completed
Nemo-3	^{82}Se	tracking	Frejus	Taking data until end 2010
CUORE	^{130}Te	bolometric	LNGS	Funded – in construction
GERDA	^{76}Ge	ionization	LNGS	Funded (I & II) – in construction
SNO+	^{150}Nd	scintillation	SNOLAB	Funded (natural Nd)
SuperNEMO	$^{82}Se/^{150}Nd$	tracking	Frejus	R&D and demonstrator funded
MAJORANA	^{76}Ge	ionization	SUSEL	R&D and demonstrator funded
EXO	^{136}Xe	tracking	WIPP	R&D and demonstrator funded

To define the timeline of the above experiments is difficult

CUORE (Cryogenic Underground Observatory for Rare Event)

→ ^{130}Te

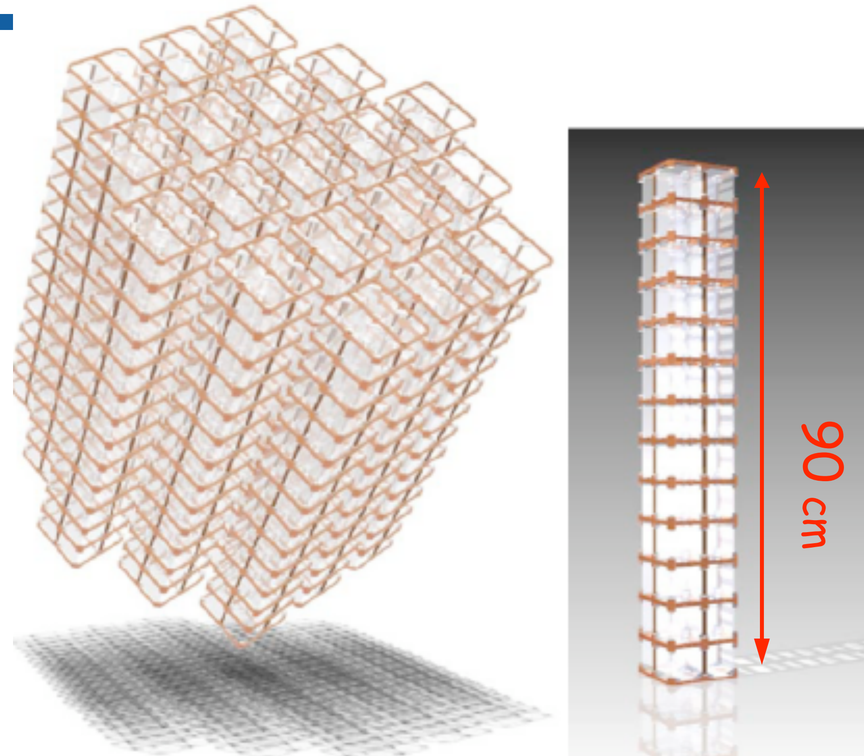
$Q_{\beta\beta}$ = 2527 keV

~ 34% natural abundance

Detector: array of 988 5x5x5 cm^3 TeO_2 bolometers @ ~ 10 mK (total mass = 741 kg)

Energy resolution: 0.28% @ Qvalue

Location: Hall A at LNGS (Italy)



19 towers Cuoricino-like

Background	Sensitivity	Effective Majorana Mass
0.01 c/keV/kg/y (realistic)	$T_{1/2}^{0\nu} = 2.1 \cdot 10^{26}$ y	23 - 82 meV
0.001 c/keV/kg/y (aggressive)	$T_{1/2}^{0\nu} = 6.5 \cdot 10^{26}$ y	11 - 57 meV

SNO +

→ ^{150}Nd

$Q_{\beta\beta}$ = 3368 keV

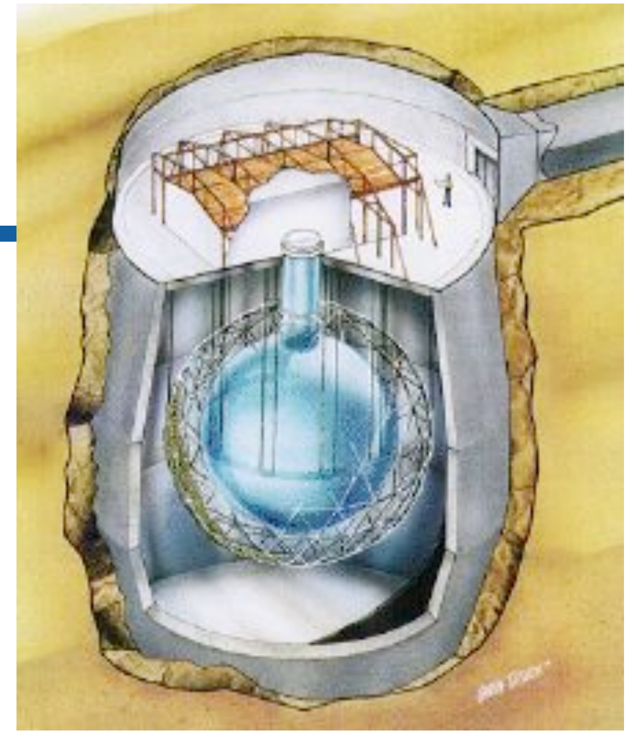
Natural Nd (a.i. ^{150}Nd = 5.6%)

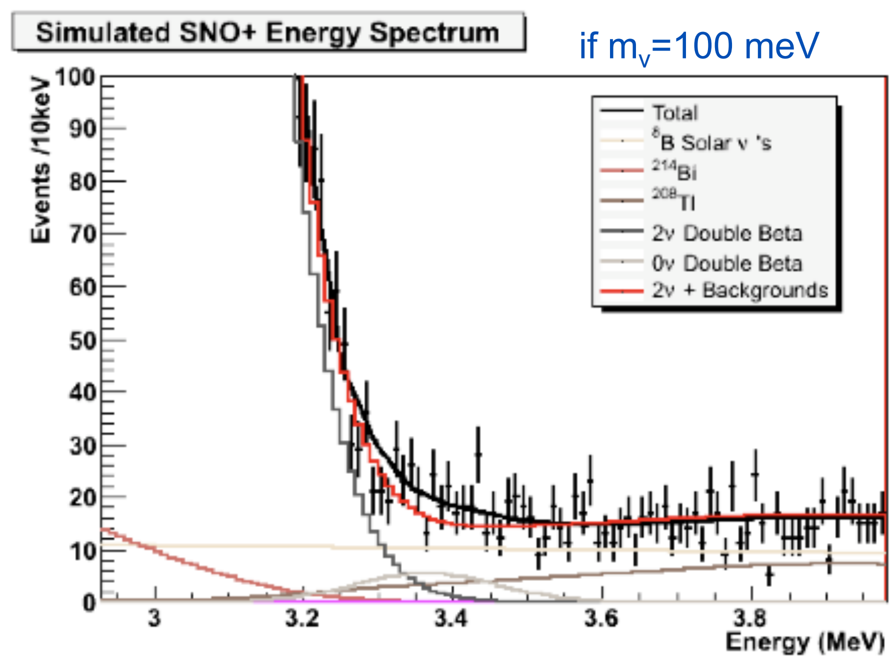
Detector: refill SNO detector with liquid scintillator (linear alkylbenzene - LAB) loaded at 0.1% Nd
(not enough light output in SNO+ if using 1% Nd loading)

→ 56 kg of ^{150}Nd

Location: Sudbury (Canada)

En resolution: 6.4% @ Qvalue





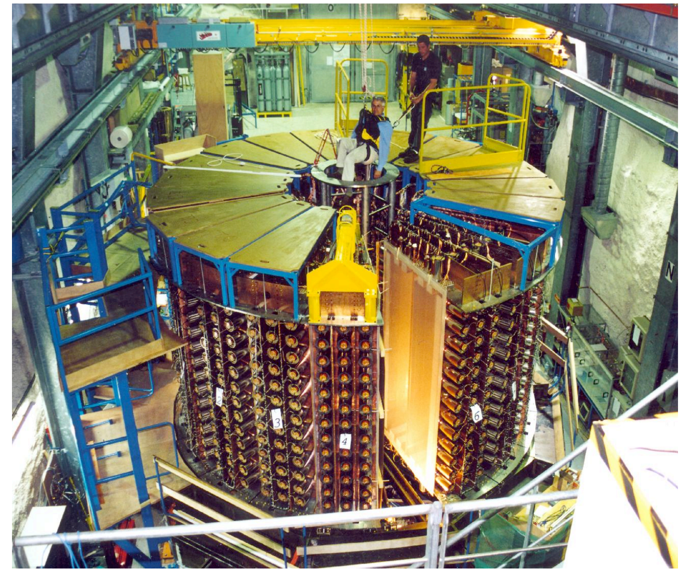
Conclusions

The future scenarios can be divided in possible steps:

- I step [100-500 meV]:
  to test of HM claim and to probe the QD region of neutrino mass
  SuperNEMO, CUORE, GERDA, EXO-200, SNO++
  if the neutrino mass is in this range different experiment could see it with different isotopes. Precision measurement era for 0nDBD

- II step [15-50 meV]:
  to probe the IH region of neutrino mass. 1 ton scale and 10 y
  SuperNEMO (especially with 150Nd),
  CUORE (especially if enriched), GERDA-III, SNO++ (enriched)
  discovery in 3-4 isotopes is necessary to confirm the observation

NEMO 3 (Neutrino Ettore Majorana Experiment)



→ ^{100}Mo

$Q_{\beta\beta}$ = 3034 keV

Detector: tracking detector with different sources

Energy resolution: 8% @ Qvalue

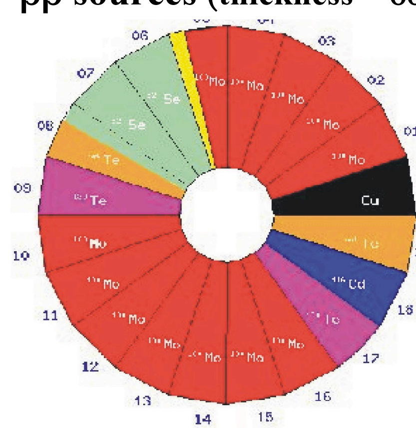
Location: Modane Underground Laboratory (France)

Other sources

Isotope	Study	Mass(g)
^{100}Mo	$\beta\beta0\nu,\beta\beta2\nu$	6914
^{82}Se	$\beta\beta0\nu,\beta\beta2\nu$	932
^{116}Cd	$\beta\beta0\nu,\beta\beta2\nu$	405
^{130}Te	$\beta\beta0\nu,\beta\beta2\nu$	454
^{150}Nd	$\beta\beta2\nu$	36.6
^{96}Zr	$\beta\beta2\nu$	9.4
^{48}Ca	$\beta\beta2\nu$	7.0

Multi-source detector

ββ sources (thickness ~ 60 mg/cm²)



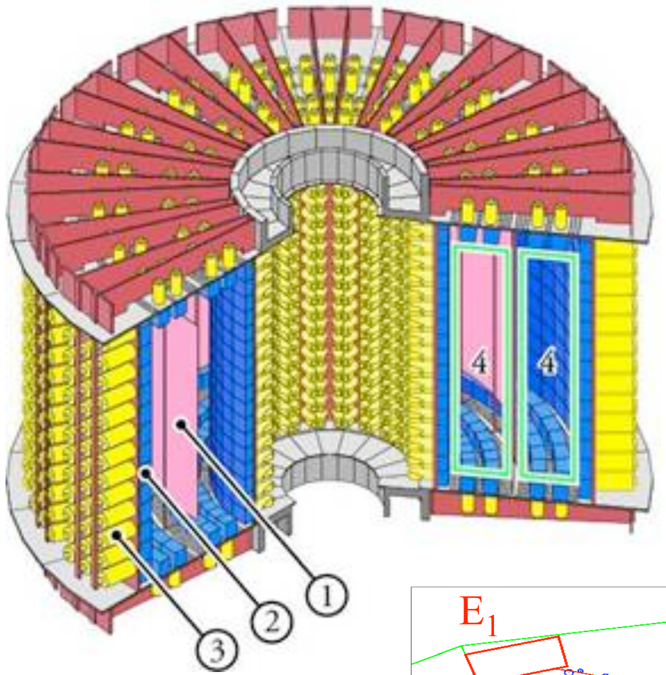
ββ(2ν):
- ^{116}Cd (0,40kg)
- ^{130}Te (0,45 kg)
- ^{150}Nd (36,5 g)
- ^{96}Zr (9,43 g)
- ^{48}Ca (6,99g)

Bckg:
- ^{nat}Te (0,61 kg)
- Cu (0,62 kg)

^{100}Mo (6,9 kg)

^{82}Se (0,93 kg)

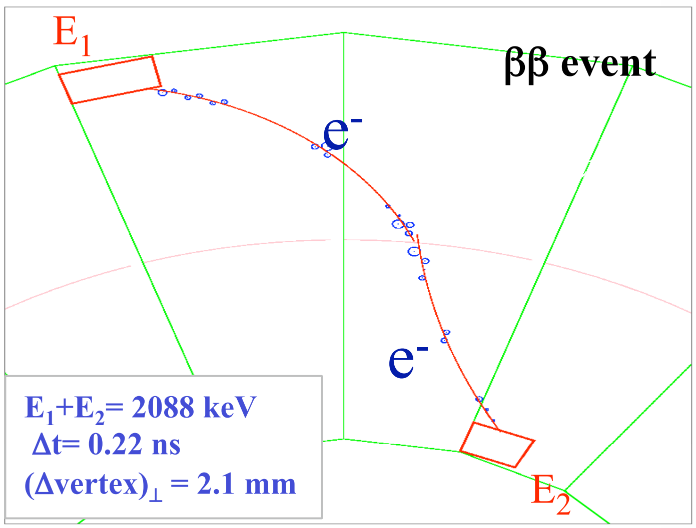
NEMO 3 (Neutrino Ettore Majorana Experiment)

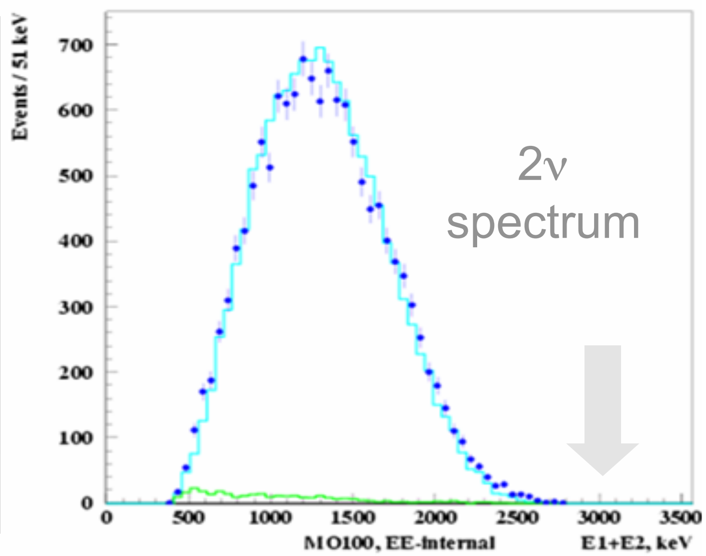


1 Source plane

2 Tracking volume (3-D readout wire drift chamber with 6180 cells)

3 Calorimeter volume (1940 plastic scintillator block)





SuperNEMO

→ Expansion of NEMO-3

→ ^{82}Se

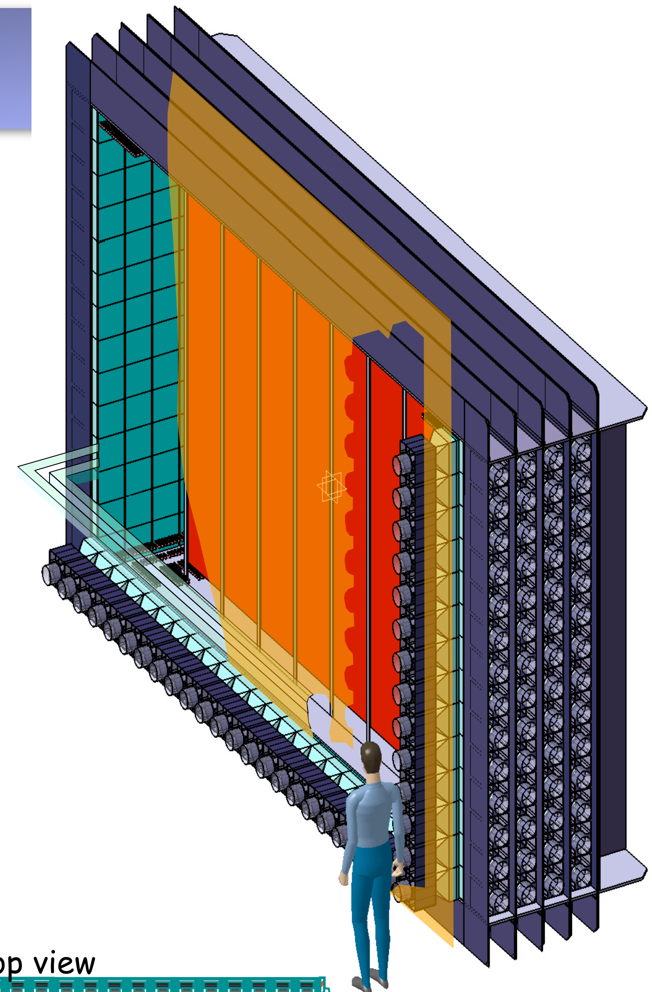
$Q_{\beta\beta}$ = 2995 keV

→ ^{150}Nd

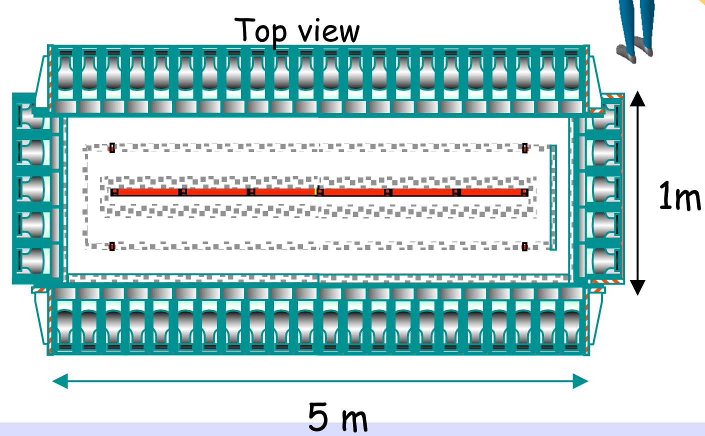
$Q_{\beta\beta}$ = 3367 keV

Detector: tracking detector with different sources

Location: Modane (Fr) / Canfranc (SP)



Tracking: drift chamber ~3000 cell (Gaiger mode)
Calorimeter: scintillators + PM ~ 1000 if sc. blocks
~ 100 scint. bars



SuperNEMO

Improvement with respect to NEMO-3:

NEMO-3		SuperNEMO
^{100}Mo	Choice of isotope	^{150}Nd or ^{82}Se
7 kg	Isotope Mass	100 -200 kg
8%	Efficiency	30%
^{208}Tl < 20 mBq/Kg ^{214}Bi < 300 mBq/Kg	Internal contamination	^{208}Tl < 2 mBq/Kg ^{214}Bi < 10 mBq/Kg
8% @ 3MeV	Energy resolution	4% @ 3MeV
$\tau_{1/2}^{0\nu}$ (y) ~ 2 × 10^{24} y <m> ~ 0.3 -1.3 eV	SENSITIVITY	$\tau_{1/2}^{0\nu}$ (y) ~ 10^{26} y <m> ~ 50 meV

EXO-200 (Enriched Xenon Observatory)

$\rightarrow$ ^{136}Xe

$Q_{\beta\beta}$ = 2458 keV

200 kg of Xe enriched to 80% in 136

Detector: TPC of enriched liquid Xenon able to reconstruct the event position and topology. In this phase the Ba tagging technique (for the reduction of the background) will not be used

GOALS

- search for 0nDBD with competitive sensitivity (and test the claim)
- measure 2νDBD half life (best limit currently set by Bernabei et al. 1×10^{22}y)
- Understand the operation of a large LXe detector
  - Understand bkg / characterize detectors materials
  - Learn about large scale Xe enrichment
  - Understand Xe handling, purification

EXO-200 (Enriched Xenon Observatory)

Low but finite radioactive background: 20 counts/ year in $\pm 2\sigma$ interval centered around the 2.458 MeV endpoint

→ No Ba tagging capability

Negligible background from 2vDBD ($T_{1/2}$> $1\cdot 10^{22}$ yr R.Bernabei et al. measurement)

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	Radioactive Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (eV) QRPA	NSM
Prototype	0.2	70	2	1.6*	40	$6.4 \cdot 10^{25}$	0.27†	0.38♦

† Rodin et al Phys Rev C 68(2003)044302

♦ Courier et al. Nucl Phys A 654 (1999) 973c

In case that the Klapdor's claim is correct EXO-200 in 2 year will see:

- 15 events on top of 40 events of bkg in the worst case (QRPA – upper limit) -> 2σ
- 162 events on top of 40 of bkg in the best case (NSM, lower limit) -> 11σ

Heidelberg Moscow Exp and the 0νDBD claim

December 2001, 4 authors (KDHK) of HM collaboration claim the 0νDBD of ^{76}Ge

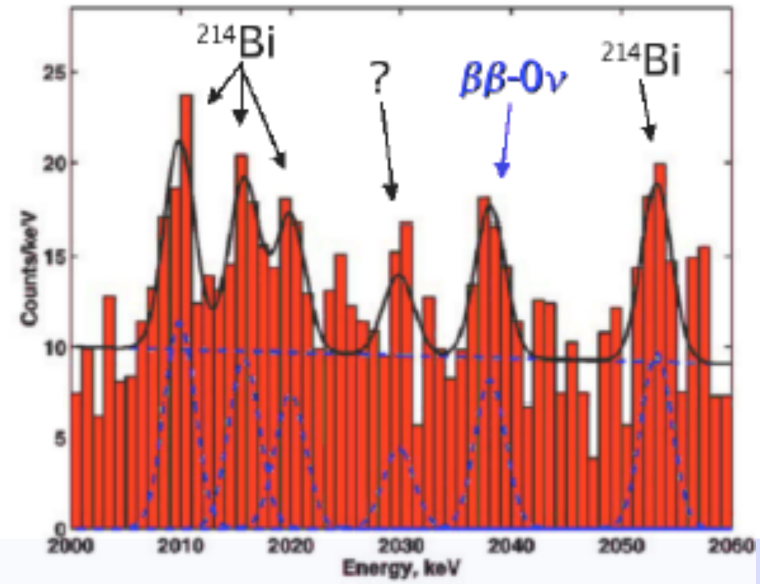
Source = Detector
Well known Ge diodes technology

- 5 Ge diodes with a total statistic of 10.9 kg - (86%) ^{76}Ge
- location: Underground Gran Sasso Laboratory (Italy)
- detectors shielded with lead and N_2 fluxed
- Reduction of Bkg with Pulse Shape Analysis (PSA) (factor 5)

7.6×10^{25} ^{76}Ge nuclei

Multi-site events identification (gamma bkg)

Spectrum with 71.7 kg•y



Heidelberg Moscow Exp and the 0νDBD claim

most probable value:
28.7 in 71.7 kg y exposition

KKDC claim: **m_{ee}** = 0.1 - 0.9 eV (**0.44 eV** b.v.)

$\tau_{1/2}^{0\nu}$ (y) = (0.69 – 4.81) × 10^{25} y (**1.19 × 10^{25} y** b.v.)

(99,9973 % c.l. ⇒ 4.2 σ)

H.V. Klapdor-Kleingrothaus et al. NIM. A 522(2004)371

Skepticism of scientific community

Aalseth CE et al. , Mod. Phys. Lett. A 17 (2002) 1475
Feruglio F et al. , Nucl. Phys. B 637 (2002) 345
Zdezenko Yu G et al., Phys. Lett. B546(2002)206

→ Comments and analysis HD-M data

Klapdor-Kleingrothaus HV hep-ph/0205228
H.L. Harney, hep-ph/0205293

→ Independent answers of authors

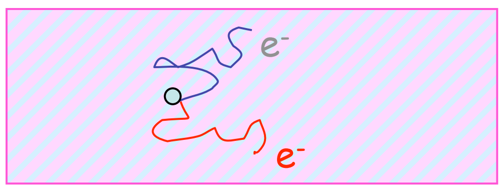
Klapdor-Kleingrothaus HV et al., NIM A510(2003)281
Klapdor-Kleingrothaus et al., NIM A 522(2004)371

→ Other articles

→ Not totally accepted result

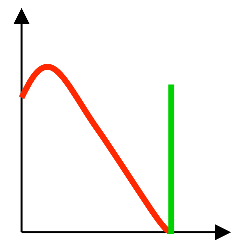
- unrecognized peaks
- dimension of analyzed energy window

Experimental techniques



Source ≡ Detector

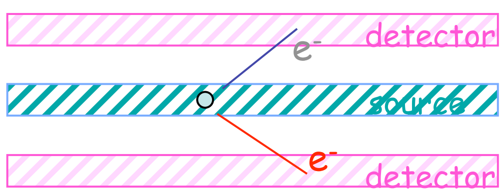
Easy to approach the ton scale



High energy resolution (<2%)

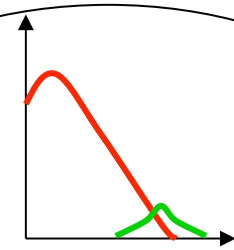
No tracking capability

Easy to reject 2νDBD background



Source ≠ Detector

Easy to get tracking capability

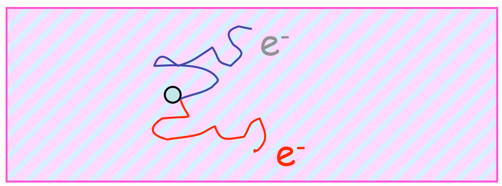


Low energy resolution (>2%)

Tracking / topology capability

Easy to approach zero backround
(with the exception of
2ν DBD component)

Experimental techniques



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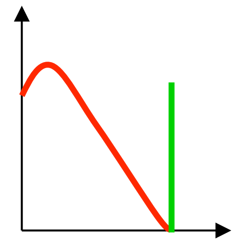


High energy resolution (<2%)

No tracking capability

Easy to reject 2νDBD background

CUORE - ^{130}Te

Array of low temperature natural TeO_2 calorimeters operated at 10 mK

First step: 200 Kg (2011) – LNGS

Proved energy resolution: 0.25 % FWHM

GERDA - ^{76}Ge

Array of enriched Ge diodes operated in liquid nitrogen or liquid argon

First phase: 18 Kg; second phase: 40 Kg - LNGS

Proved energy resolution: 0.16 % FWHM

MAJORANA - ^{76}Ge

Array of enriched Ge diodes operated in conventional Cu cryostats

Based on 60 Kg modules; first step: 2x60 Kg modules

Proved energy resolution: 0.16 % FWHM

COBRA - ^{116}Cd competing candidate – 9 ββ isotopes

Array of ^{116}Cd enriched CdZnTe of semiconductor detectors at room temperatures

Final aim: 117 kg of ^{116}Cd

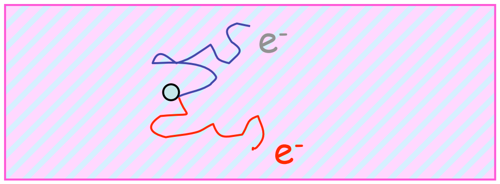
Small scale prototype at LNGS

Proved energy resolution: 1.9% FWHM

S

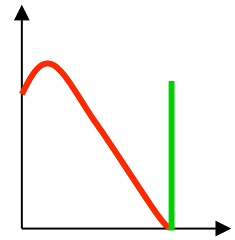
Easy

Experimental techniques



Source ≡ Detector

Easy to approach the ton scale



High energy resolution (<2%)

No tracking capability

Easy to reject 2νDBD background

Even though these experiments do not have tracking capability, some space information helps in reducing the background thanks to:

GRANULARITY of the basic design

- CUORE: 988 closed packed individual bolometers
- COBRA: 64,000 closed packed individual detectors
- MAJORANA: 57 closed packed individual diodes per module

PULSE SHAPE DISCRIMINATION

- GERDA / MAJORANA can separate single / multi site events

SEGMENTATION and PIXELLIZATION

Granularity can be achieved through electrodes segmentation

⇒ R&D in progress for GERDA, MAJORANA, COBRA

SURFACE SENSITIVITY in bolometers

- R&D in progress in CUORE against energy-degraded α and β background

Simultaneous LIGHT and PHONON detection in bolometers

- R&D in progress in CUORE-like detectors for α / γ rejection

Small scale prototype at LNGS

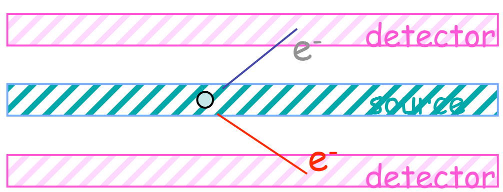
Proved energy resolution: 1.9% FWHM

Experimental techniques

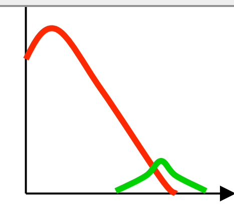
SUPERNEMO – ^{82}Se or ^{150}Nd
Modules with source foils, tracking and calorimetric sections, magnetic field for charge sign
Possible configuration: 20 modules with 5 kg source for each module ⇒ 100 Kg
Energy resolution: 4 % FWHM

MOON – ^{100}Mo or ^{82}Se or ^{150}Nd
Multilayer plastic scintillators interleaved with source foils + tracking section
MOON-1 prototype without tracking section
Proved energy resolution: 6.8 % FWHM
Final target: collect 5 y x ton

DCBA – ^{82}Se or ^{150}Nd
Momentum analyzer for β particles consisting of source foils into a drift chamber with magnetic field
Prototype under construction: Nd_2O_3 foils ⇒ 1.2 g of ^{150}Nd
Space resolution ~ 0.5 mm; energy resolution 11% FWHM at 1 MeV ⇒ 6 % FWHM at 3 MeV
Final target: 10 modules with 84 m^2 source foil for module (126 through 330 Kg total mass)

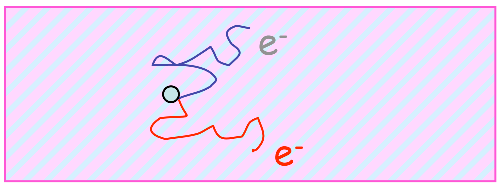


Source ≠ Detector
Easy to get tracking capability



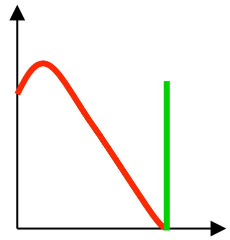
Low energy resolution (>2%)
Tracking / topology capability
Easy to approach zero backround
(with the exception of
2ν DBD component)

Experimental techniques



Source ≡ Detector

Easy to approach the ton scale



High energy resolution (<2%)

No tracking capability

Easy to reject 2νDBD background

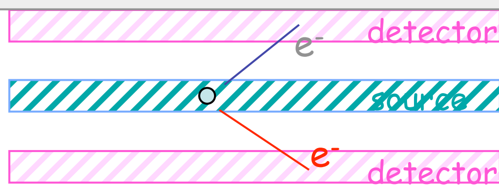
EXO – ^{136}Xe

TPC of enriched liquid Xenon

Event position and topology; in prospect, tagging of Ba single ion (DBD daughter) ⇒ only 2νDBD background

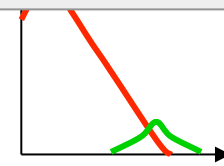
Next step (EXO-200: funded, under construction): 200 kg – will be operated in the WIPP facility

Proved energy resolution: 3.3 % FWHM



Source ≠ Detector

Easy to get tracking capability



Low energy resolution (>2%)

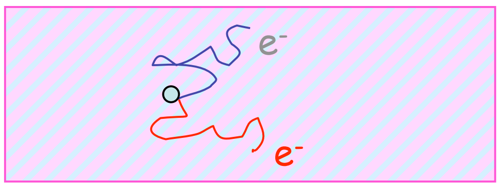
Tracking / topology capability

Easy to approach zero backround

(with the exception of

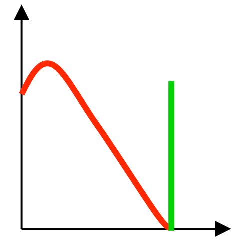
2ν DBD component)

Experimental techniques



Source ≡ Detector

Easy to approach the ton scale



High energy resolution (<2%)

No tracking capability

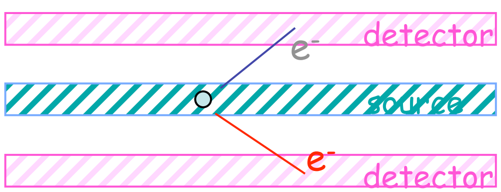
Easy to reject 2νDBD background

SNO++ – ^{150}Nd

Liquid scintillator loaded with Nd

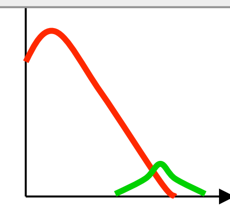
1000Ton in SNO detector. Total isotope mass 560 kg. Probable energy resolution: 6.7 % FWHM

This experiment compensates the low energy resolution with the huge statistic



Source ≠ Detector

Easy to get tracking capability



Low energy resolution (>2%)

Tracking / topology capability

Easy to approach zero backround

(with the exception of

2ν DBD component)