Neutrino Physics without Neutrinos

Recent results from the NEMO-3 experiment and plans for SuperNEMO

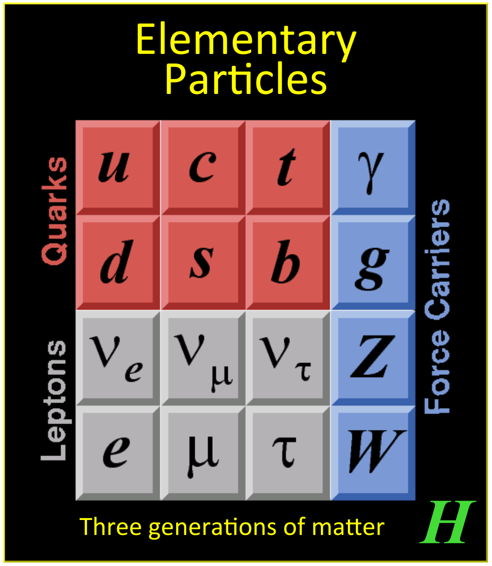
Karol Lang
The University of Texas at Austin

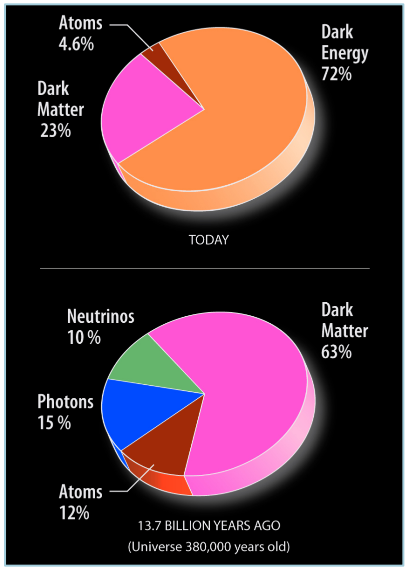
CERN, June 16, 2015

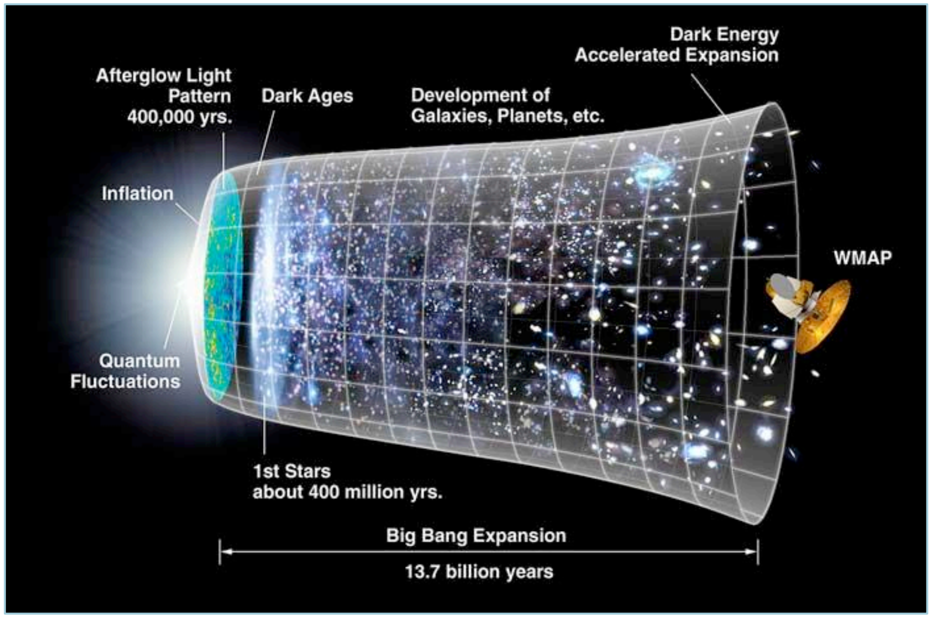
Outline:

- Motivation for $0\nu\beta\beta$
- Practical factors
- NEMO-3 & SuperNEMO
- World’s state-of-the-art
- Conclusions

The standard view of the Universe







Open questions:

- ✓ Why this structure?
- ✓ Matter-antimatter asymmetry ?
- ✓ What is dark matter ?
- ✓ What is dark energy ?
- ✓ What about gravity?
- ✓ …

Neutrinos are
“implicated” in answering
most if not all of these questions!

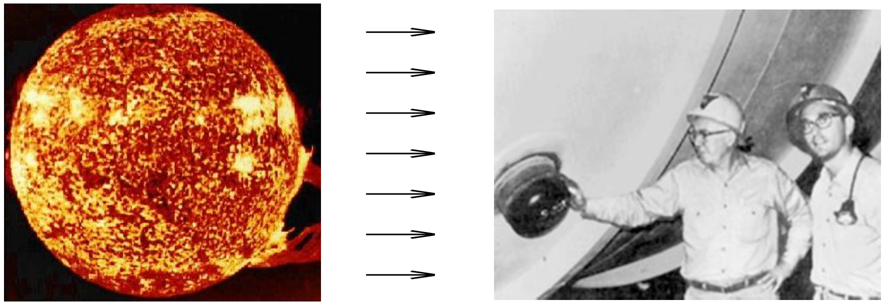
Remarkable “Neutrino Years”

(painted with a broad brush)

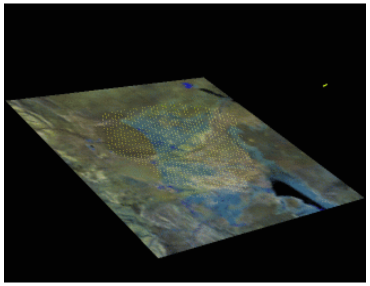
< 1998

- $m_\nu = 0, \qquad \nu = e, \mu, \tau$

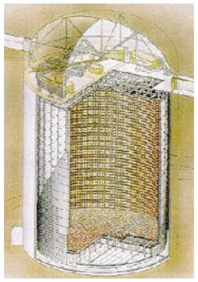
- *solar* neutrinos *deficit*



- *atmospheric* neutrinos *anomaly*

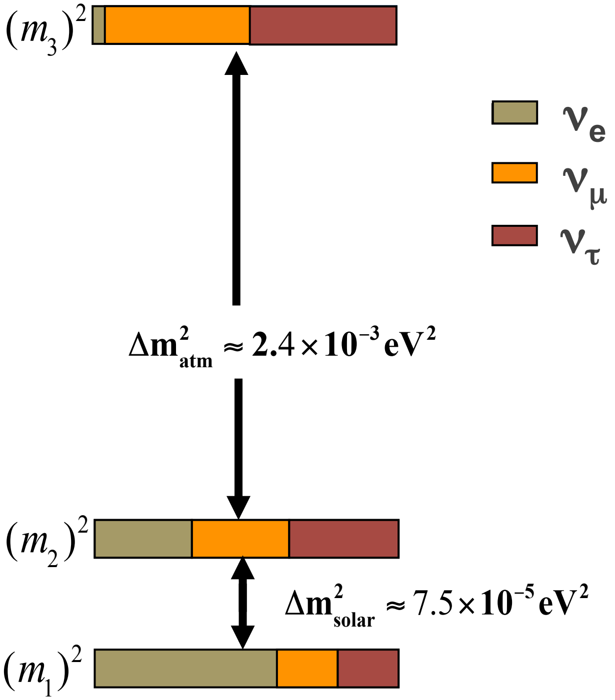


$$\frac{N(\nu_\mu)}{N(\nu_e)} \neq 2$$



1998 - 2012

- neutrino oscillations → $m_\nu \neq 0$
- measured Δm^2_{sol} and Δm^2_{atm}
- neutrino *mixings*



Neutrino mixing and oscillations

Pontecorvo – Maki – Nakagawa - Sakata (PMNS) matrix

weak eigenstates

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

mass eigenstates

3 mixing angles + 1 CP phase

If neutrinos are Majorana particles: $\nu \equiv \bar{\nu}$

$(c_{ij} \equiv \cos\theta_{ij},\ s_{ij} \equiv \sin\theta_{ij})$

$$U = \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}\cdot e^{i\delta} \\ & 1 & \\ -s_{13}\cdot e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

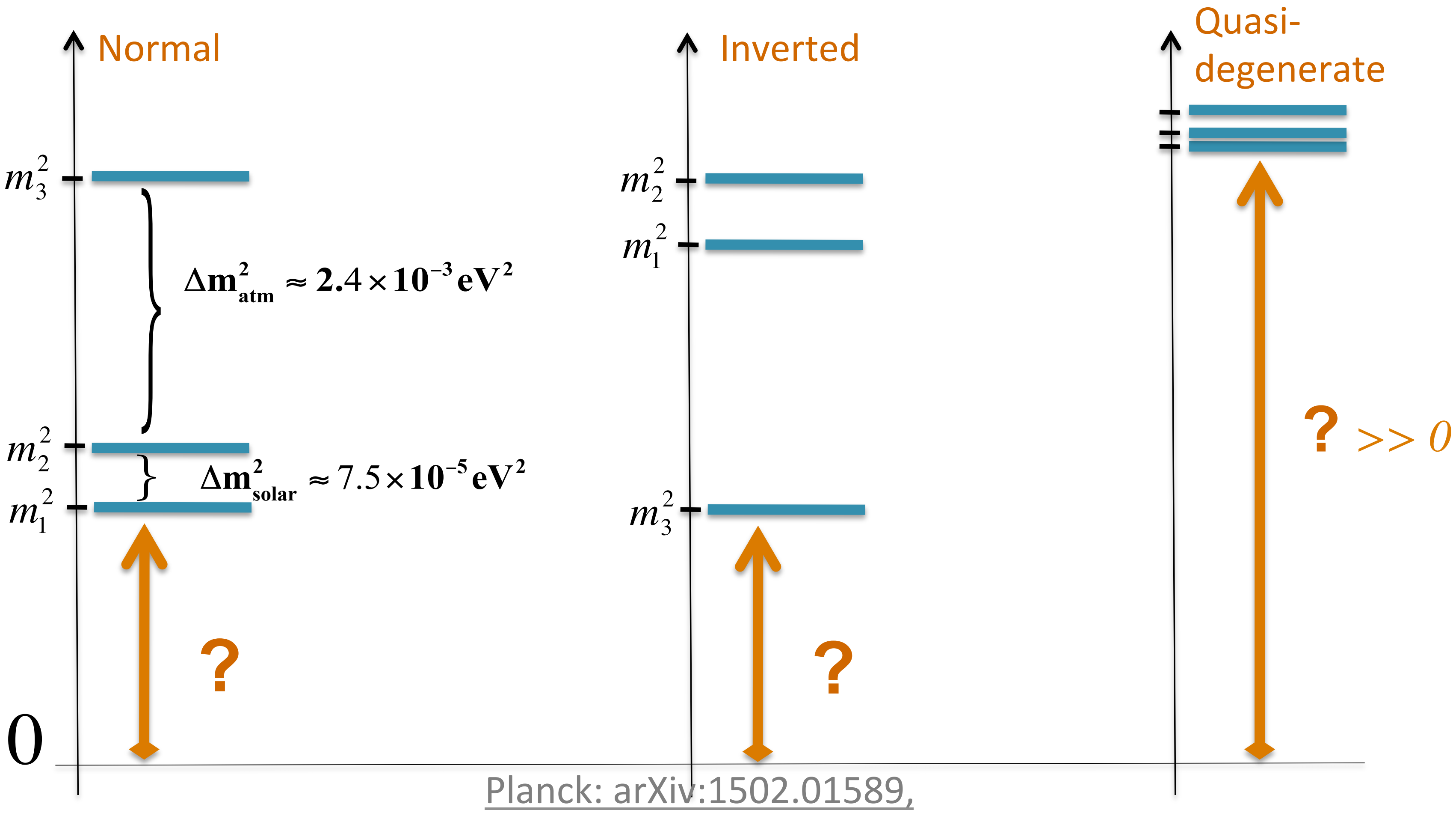
Solar
Reactor

Accelerator
Reactor
$\nu_e \leftrightarrow \nu_\mu, \nu_\tau$

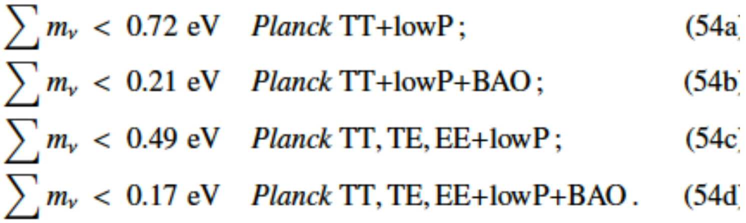
Accelerator
Atmospheric
$\nu_\mu \leftrightarrow \nu_\tau$

Majorana
Phases
$0\nu\beta\beta$

Neutrino mass and mass ordering



Planck: arXiv:1502.01589,



$$\sum m_\nu < 0.72 \text{ eV} \quad \textit{Planck} \text{ TT+lowP;} \quad (54a$$

$$\sum m_\nu < 0.21 \text{ eV} \quad \textit{Planck} \text{ TT+lowP+BAO;} \quad (54b$$

$$\sum m_\nu < 0.49 \text{ eV} \quad \textit{Planck} \text{ TT, TE, EE+lowP;} \quad (54c$$

$$\sum m_\nu < 0.17 \text{ eV} \quad \textit{Planck} \text{ TT, TE, EE+lowP+BAO.} \quad (54d$$

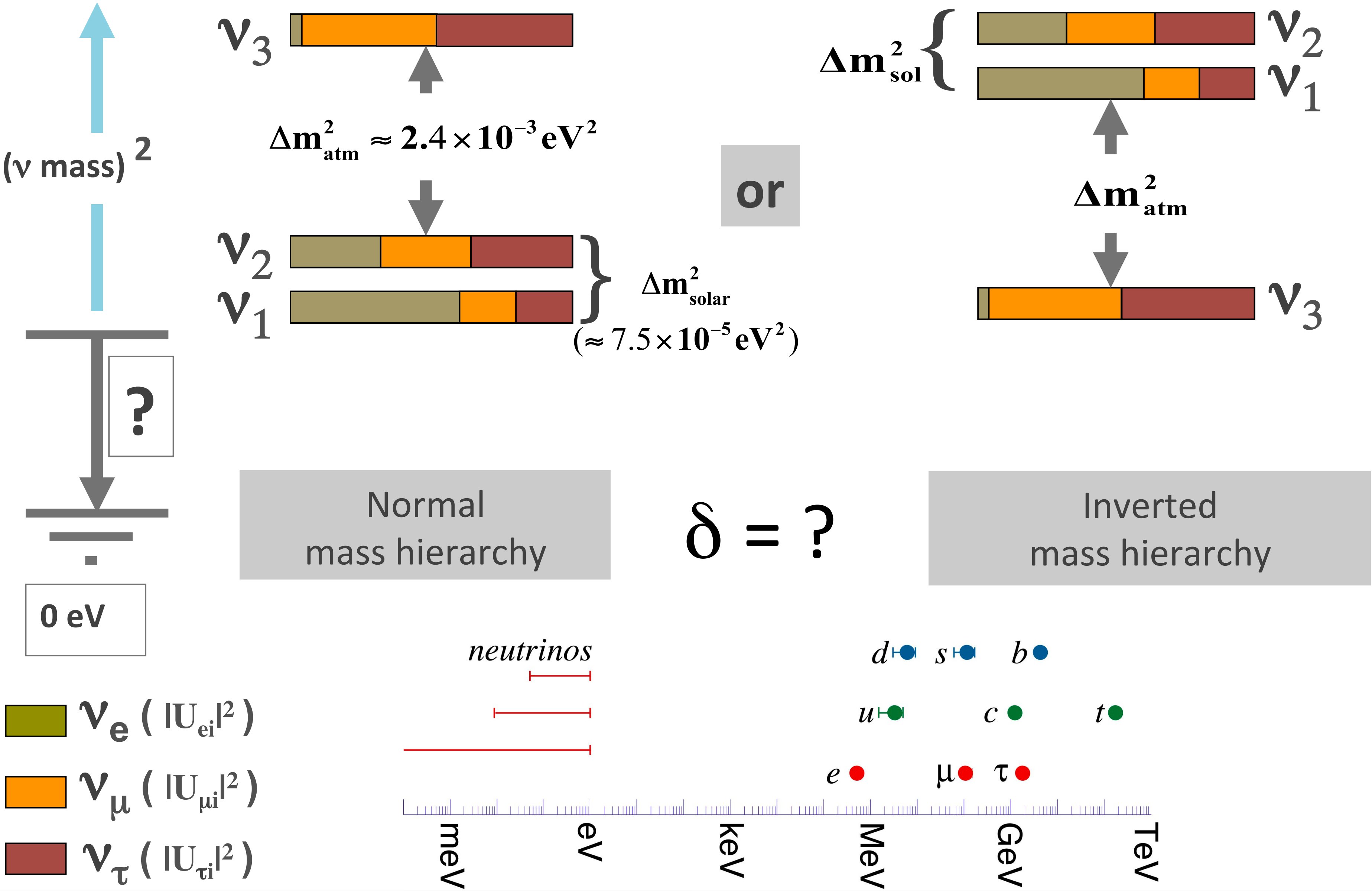
m(“ν_e”) < 2.2 eV

Mainz-Troitsk ^{3}H decay

m(“ν_μ”) < 190 keV

m(“ν_τ”) < 18.2 MeV

In summary…



Normal mass hierarchy

$\delta = ?$

Inverted mass hierarchy

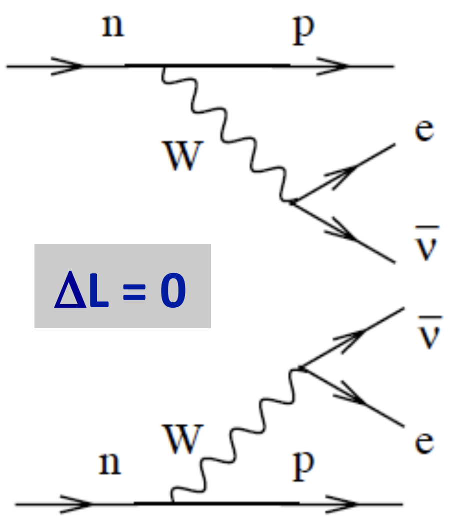
🟩 ν_e ($|U_{ei}|^2$)

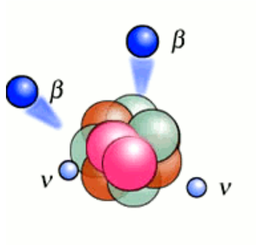
🟧 ν_μ ($|U_{\mu i}|^2$)

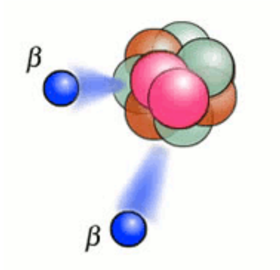
🟥 ν_τ ($|U_{\tau i}|^2$)

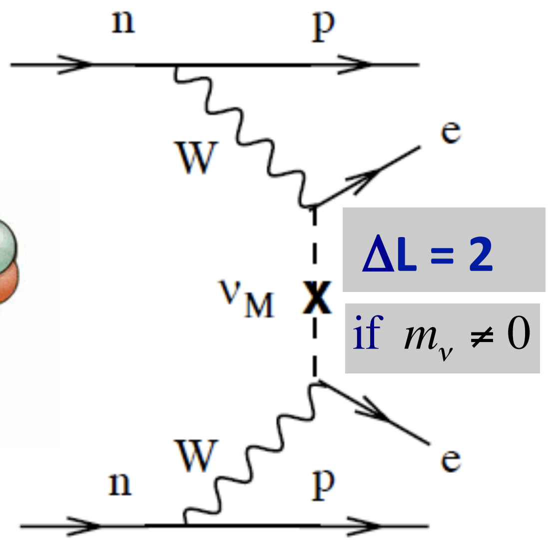
Neutrino questions and $0\nu\beta\beta$

- ✓ What is the absolute neutrino mass scale and why it is so small?
- ✓ What is the mass ordering ("mass hierarchy")?
- ✓ Why is the PMNS matrix so different than the CKM matrix?
- ✓ Do neutrinos violate CP symmetry (δ, α, β in the PMNS-M matrix)?
- ✓ Are neutrinos Dirac ($\nu \neq \bar{\nu}$) or Majorana ($\nu \equiv \bar{\nu}$) particles?
- ✓ Are there sterile neutrinos?









$$(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\bar{\nu}$$

$(2\nu\beta\beta)$

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

$(0\nu\beta\beta)$

Phenomenology of 0νββ and 2νββ (1)

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

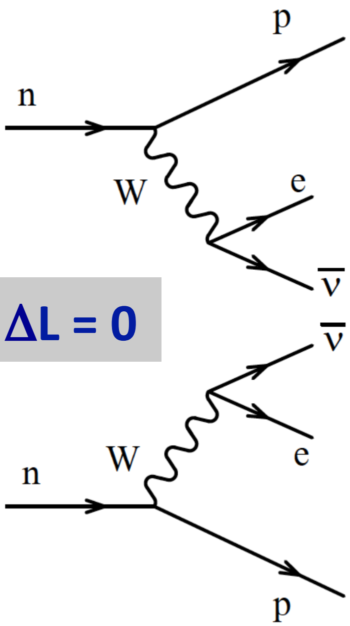
$G =$ phase space (well known)

$M =$ nuclear matrix element (challenging)

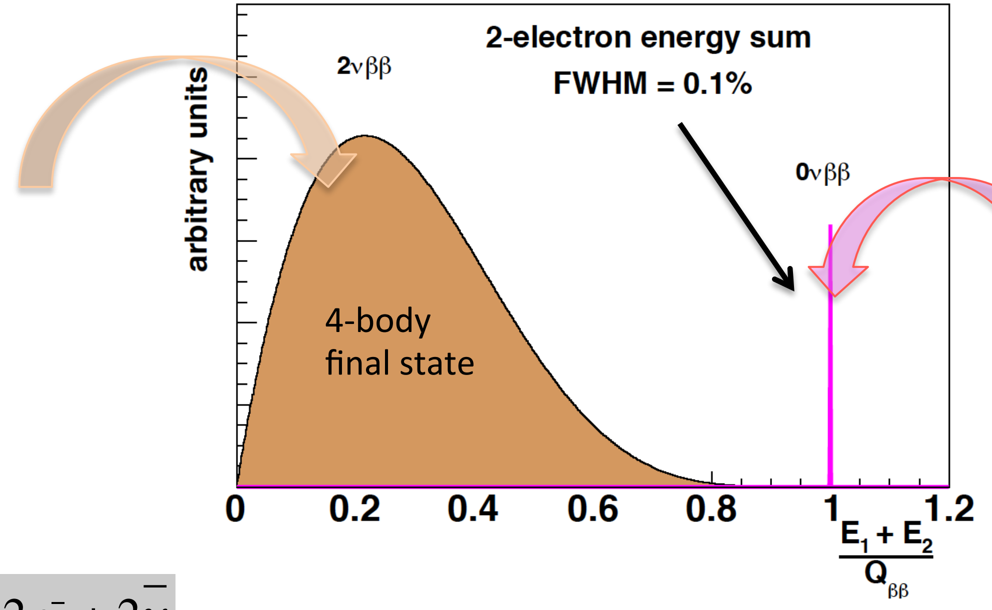
$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q_{\beta\beta}^{5}, Z) \bullet \left| M_{0\nu} \right|^2 \bullet \langle m_{\beta\beta} \rangle^2$$

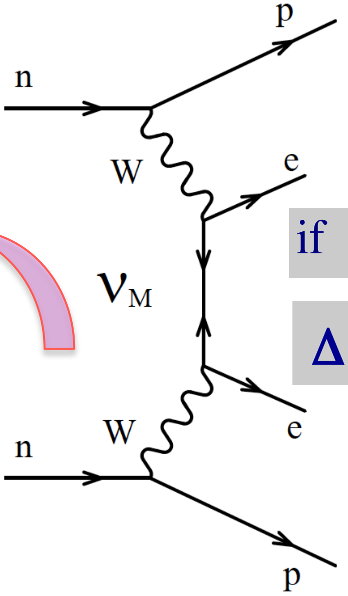
$$\left| \langle m_{\beta\beta} \rangle \right| \equiv \left| m_1 \left| U_{e1} \right|^2 + m_2 \left| U_{e2} \right|^2 e^{i\alpha} + m_3 \left| U_{e3} \right|^2 e^{2i\beta} \right|$$

α, $\beta =$ Majorana phases



ΔL = 0





if $m_\nu \neq 0$

ΔL = 2

$(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\bar{\nu}$
$(2\nu\beta\beta)$

$(Z,A) \rightarrow (Z+2,A) + 2e^-$
$(0\nu\beta\beta)$

Phenomenology of 0νββ and 2νββ (2)

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

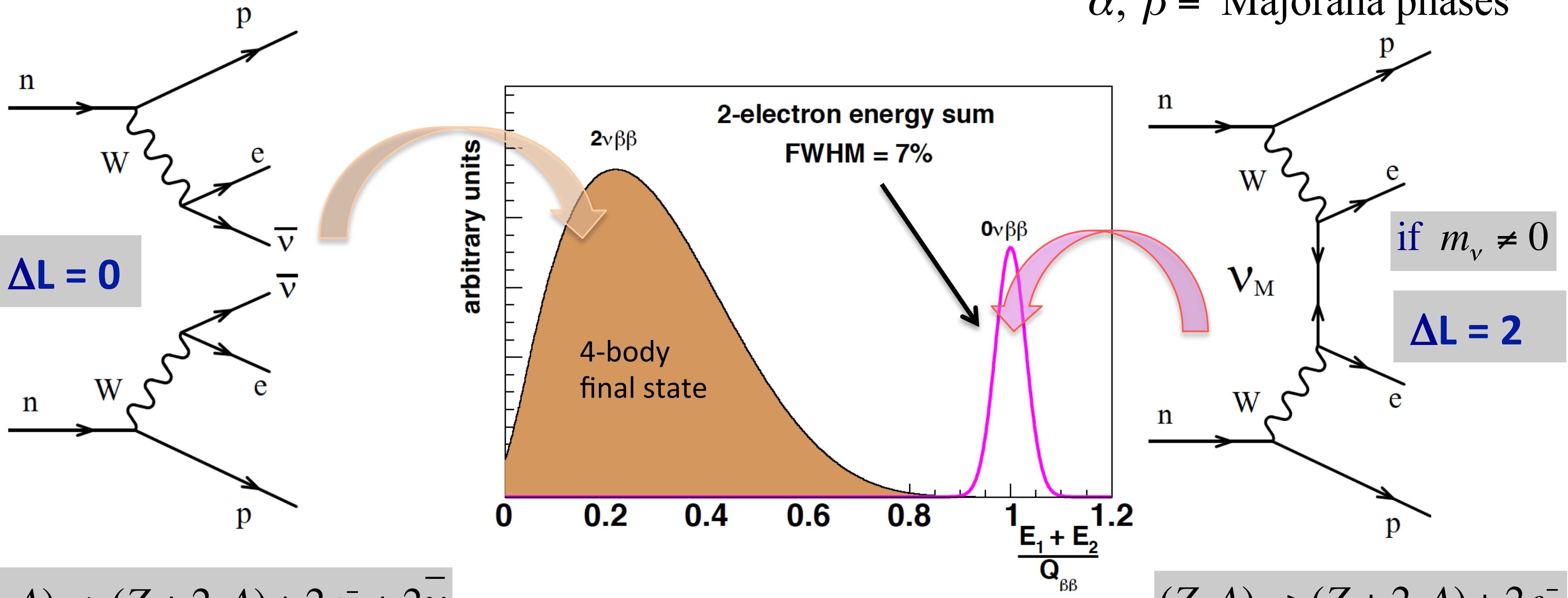
$G =$ phase space (well known)

$M =$ nuclear matrix element (challenging)

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

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

$\alpha, \beta =$ Majorana phases



ΔL = 0

if $m_\nu \neq 0$

ΔL = 2

$(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\bar{\nu}$
$(2\nu\beta\beta)$

$(Z,A) \rightarrow (Z+2,A) + 2e^-$
$(0\nu\beta\beta)$

Phenomenology of 0νββ and 2νββ (3)

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

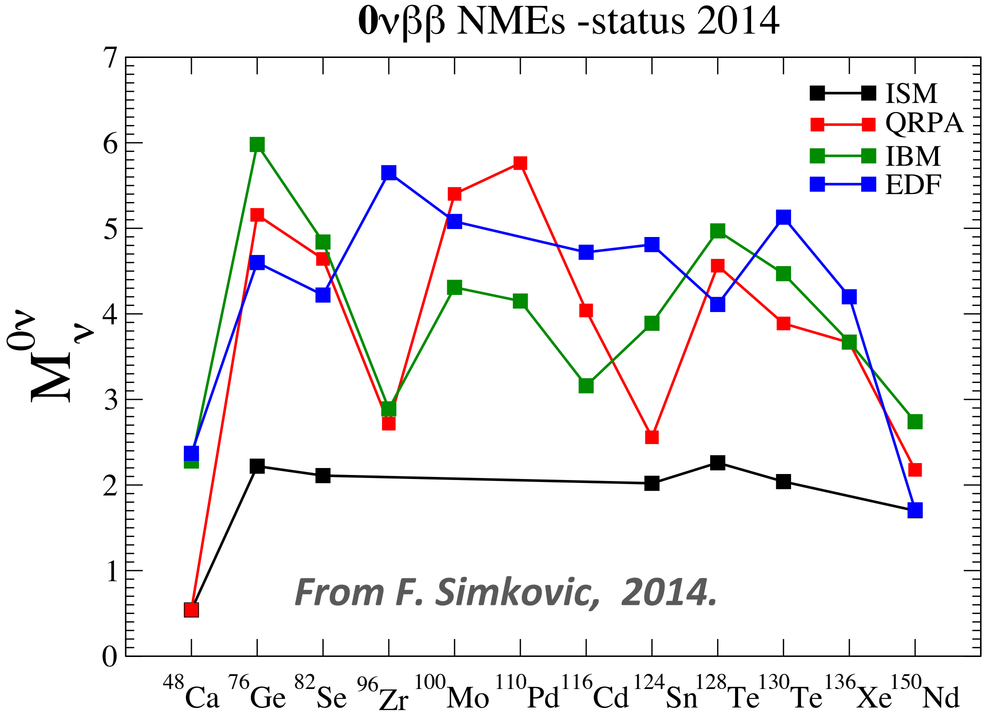
$G =$ phase space (well known)

$M =$ nuclear matrix element (challenging)

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

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

$\alpha, \beta =$ Majorana phases


0νββ NMEs -status 2014

From F. Simkovic, 2014.

NME models differences:

i) mean field;

ii) residual interaction;

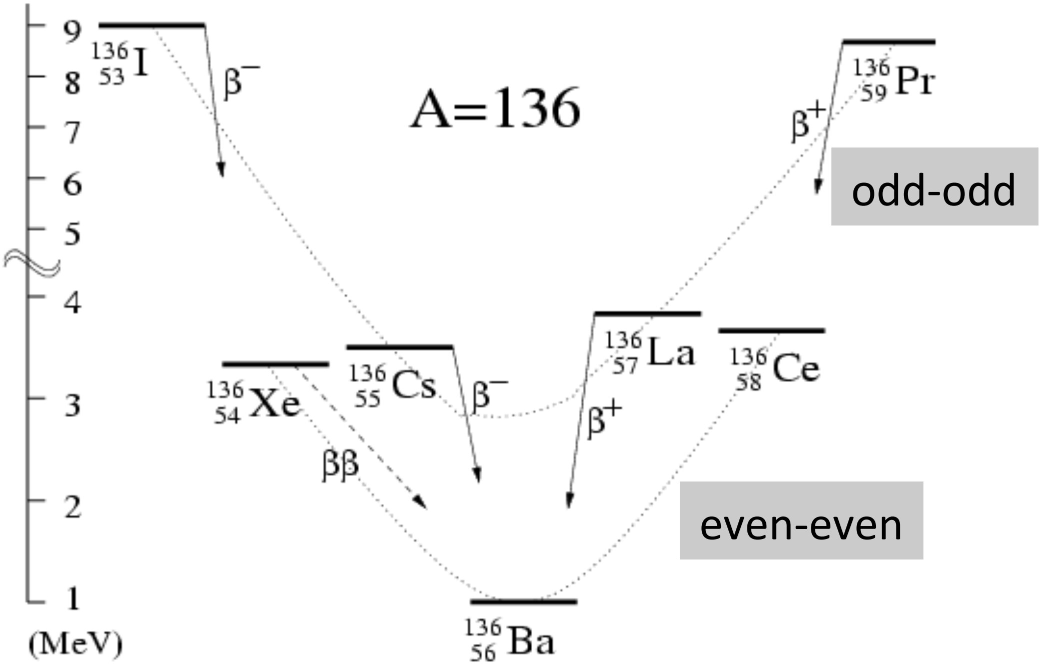
iii) size of the model space;

iv) many-body approximation

NSM *(Madrid-Strassbourg)*
IBM *(Iachello, Barea)*
QRPA *(Tuebingen-Caltech-Bratislava*
EDF/PHFB *(India/Mexico)*
and Jyvaskula-La Plata)

Phenomenology of $0\nu\beta\beta$ and $2\nu\beta\beta$ (4)

- Pairing interaction between nucleons (even-even nuclei more bound than the odd-odd nuclei)
- e.g., ^{136}Xe and ^{136}Ce are stable against β decay, but unstable *against* $\beta\beta$ decay ($\beta^-\beta^-$ for ^{136}Xe and $\beta^+\beta^+$ for ^{136}Ce)



There are 35 $\beta^-\beta^-$ emitters
6 $\beta^+\beta^+$

History of 0νββ and 2νββ

1935 Rate of 2νββ first calculated by Maria Goeppert-Mayer (suggested by E. Wigner)

1937 Majorana proposes *"Symmetrical theory of the electron and positron"* $(\nu \equiv \bar{\nu})$

1937-9,1952 G. Racah, W.H. Furry, Primakoff discuss 0νββ

1949, 1955 Half-life limits (Fireman, Fremlin, R.Davis)

1950 Geochemical evidence for 2νββ

1987 Laboratory evidence for 2νββ for *(S. Elliot, A. Hahn, M. Moe)*

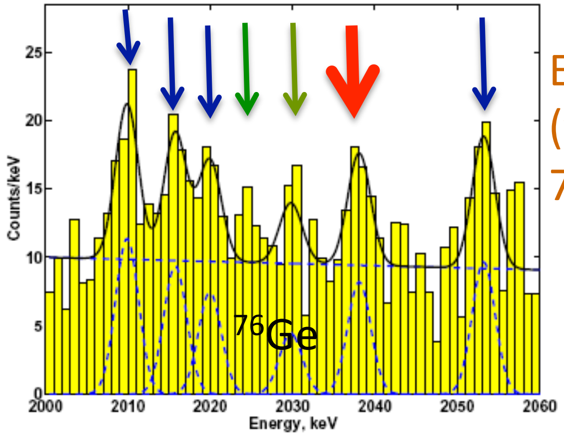
Phys. Rev. Lett. 59, 2020 - 2023 (1987)

Direct evidence for two-neutrino double-beta decay in ^{82}Se

2001-2006 Controversial claim of observation of 0νββ (Klapdor-Kleingrothaus *et al.*)

2003-2015 NEMO-3, CUORICINO, EXO-200, GERDA, KamLAND-Zen ... measurements

- ☐ **0νββ peak**
  2039 keV peak has 4.2σ significance $\langle m_\nu \rangle$ =~ 0.3-0.6 eV
- ☐ Weak ^{214}Bi lines
  2010.7, 2016.7, 2021.8, 2052.9 keV
- ☐ ? Electron conversion of 2118keV γ line 2030keV
- ☐ ?



Exposure (total): 71.7 kg.y

First evidence for neutrinoless double beta decay, with enriched ^{76}Ge in Gran Sasso 1990-2003.

H.V. Klapdor-Kleingrothaus[a] *

[a]Max-Planck-Institut für Kernphysik, PO 10 39 80, D-69029 Heidelberg, Germany

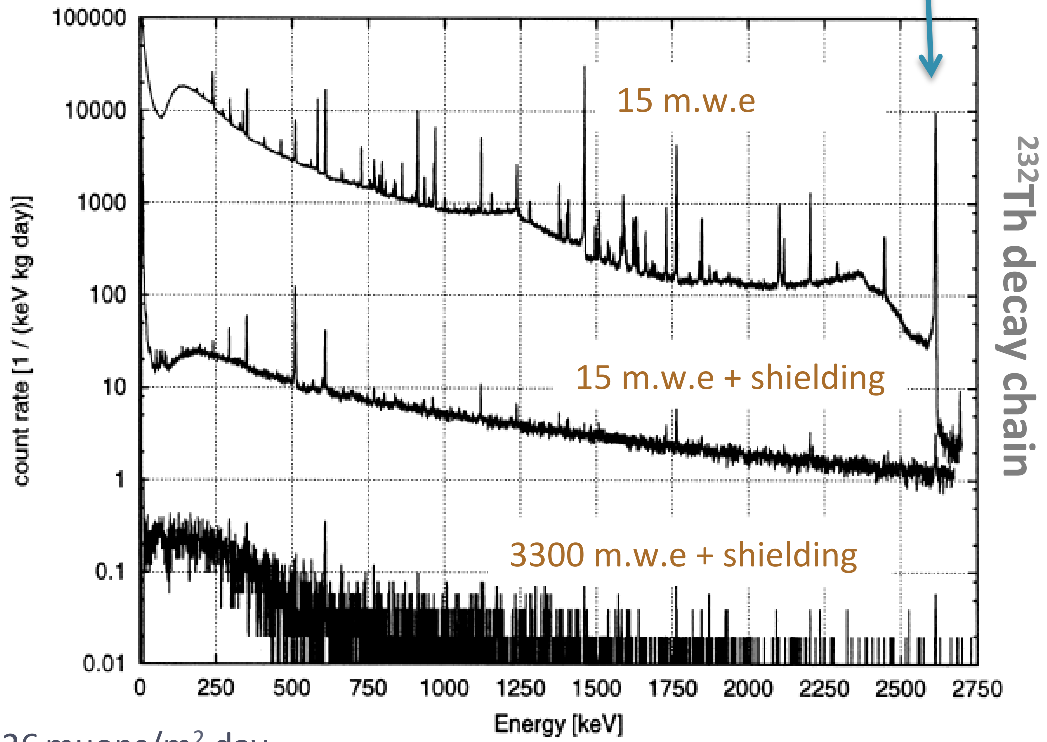
Figure 1. The total sum spectrum of all five detectors (in total 10.96 kg enriched in ^{76}Ge), in the range 2000 - 2060 keV and its fit, for the period: August 1990 to May 2003 (71.7 kg y) (see [3]).

Practical fundamentals

- **Natural radioactivity and cosmic rays** dominate the backgrounds → go underground + local shielding
- **^{238}U and ^{232}Th decay chains** produce the most troubling gammas (highest energies):
  - ^{214}Bi
  - ^{208}Tl

2×10^6 muons/m² day on surface

^{208}Tl (2614 KeV)



26 muons/m² day

(Applied Rad and Isotopes 53 (2000) 191)

other NEMO-3

	$Q_{\beta\beta}$ (MeV)	Natural abundance (%)
^{48}Ca→^{48}Ti	4.268	0.187
^{150}Nd→^{150}Sm	3.371	5.6
^{96}Zr→^{96}Mo	3.356	2.8
^{100}Mo→^{100}Ru	3.034	9.6
^{82}Se→^{82}Kr	2.995	9.2
^{116}Cd→^{116}Sn	2.814	7.5
^{130}Te→^{130}Xe	2.528	34.5
^{136}Xe→^{136}Ba	2.458	8.9
^{124}Sn→^{124}Te	2.293	5.6
^{76}Ge→^{76}Se	2.039	7.8
^{110}Pd→^{110}Cd	2.018	11.8

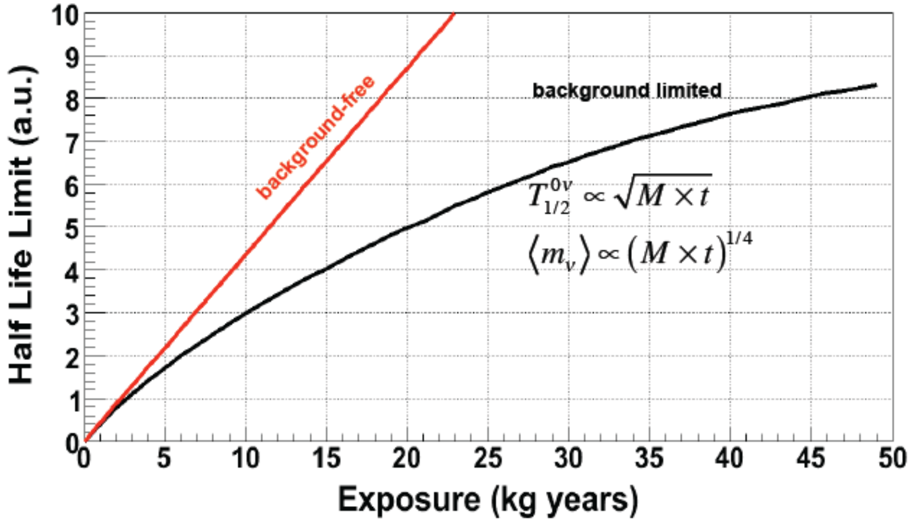
(Top 11) ββ emiters with $Q_{\beta\beta}$ > 2 MeV

Challenge:
- ✓ suppress backgrounds
- ✓ identify the final state

> *"If you don't know where you are going,*
> *you will wind up somewhere else."*
> *Yogi Berra*

Which way to go?

- Experiments "gamble" which way is the shortest to achieving better sensitivity:
  - Choose high natural abundance?
  - Build a detector with best energy resolution? More observables?
  - How well can an apparatus be shielded?
- Need to suppress natural radioactivity [omnipresent in all (non-organic) materials]
- Generically speaking: "life" is different if $Q_{\beta\beta} > 2.614$ MeV
- NO OBVIOUS PATH but it's all about background !!!
- Consensus: need more than one isotope/technique to claim a discovery!



$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16 \times 10^{26}\, y}{n_\sigma} \left(\frac{\varepsilon \times a}{W} \right) \sqrt{\frac{M \times t}{b \times \Delta E}}$$

Background w/ rate *b*

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16 \times 10^{26}\, y}{n_\sigma} \left(\frac{\varepsilon \times a}{W} \right) M \times t$$

No background

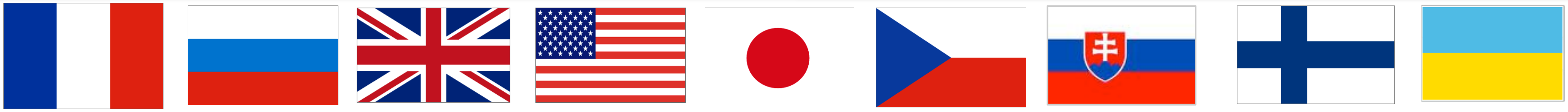
n_σ – number of std. dev. for a given C.L.
a – isotopic abundance
ε – detection efficiency
W – molecular weight of the source

M – total mass of the source (kg)
t – time of data collection (y)
b – background rate in counts (keV · kg · y)
ΔE – energy resolution (keV)

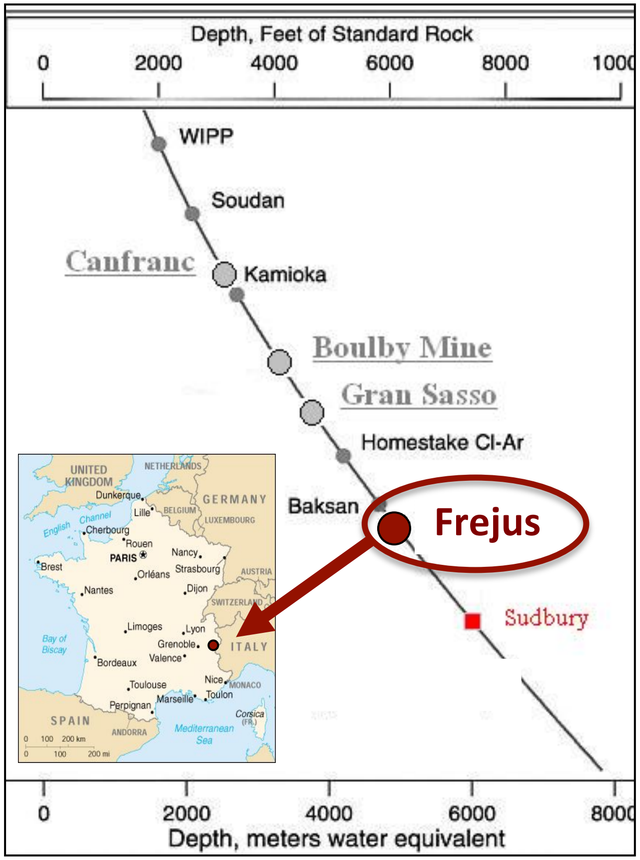
NEMO Collaboration

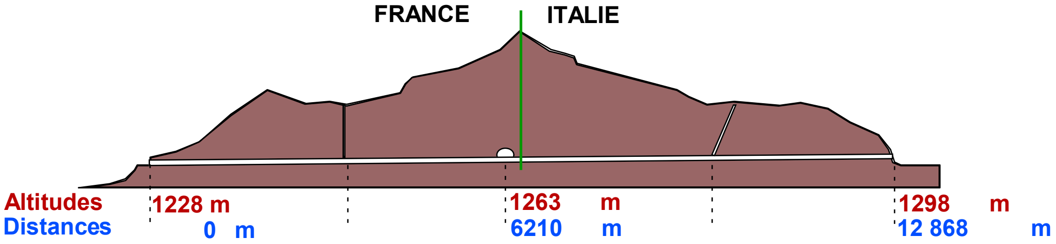
Laboratoire Souterrain de Modane

(Frejus tunnel, 4,800 mwe)

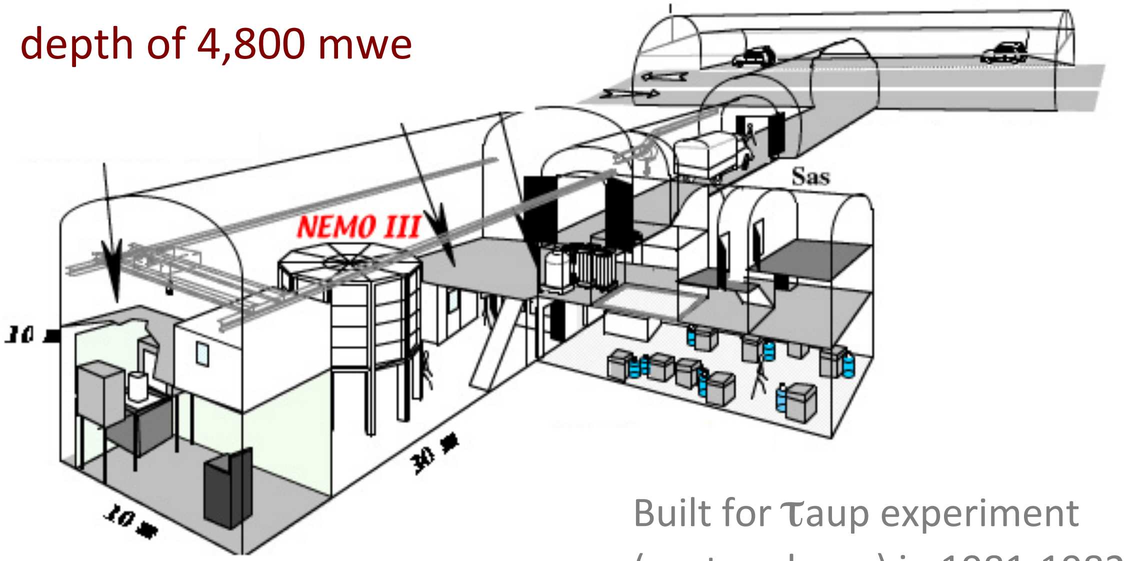


LAL (Orsay), IPHC (Strasbourg), INL (Idaho Falls), ITEP (Moscow), JINR (Dubna), LPC (Caen), CENBG (Bordeaux), UCL (London), U. of Manchester, Tokushima U., LAPP (Annecy), Comenius U. (Bratislava), Osaka U., IEAP CTU (Prague), Saga U., Imperial College (London), Mount Holyoke Coll. (South Hadley), Fukui U., INR (Kiev), CPPM (Marseilles), U. of Warwick, U. of Texas at Austin





depth of 4,800 mwe

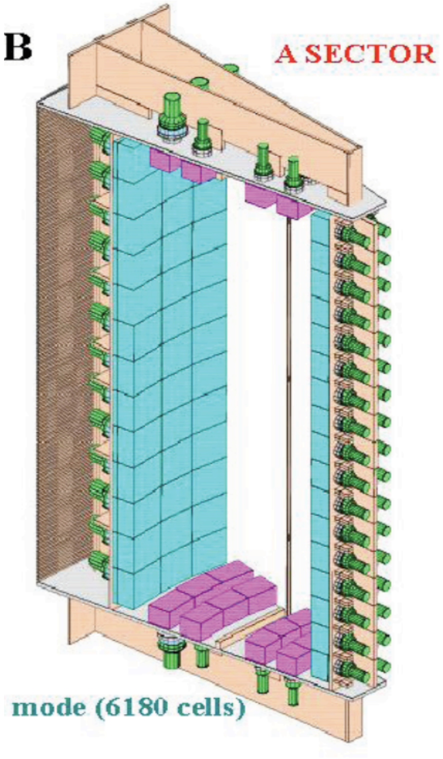


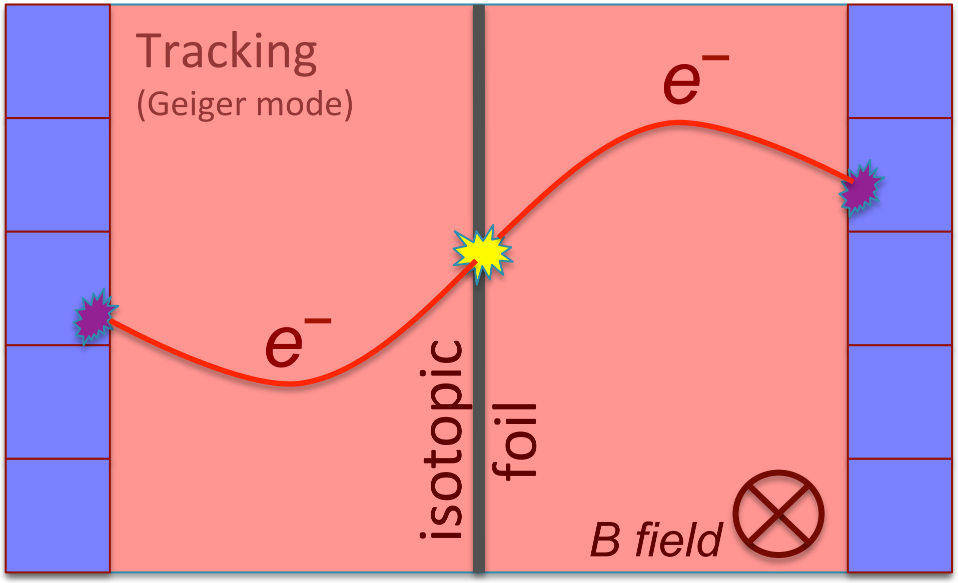
Built for τaup experiment (proton decay) in 1981-1982

The NEMO-3 Technique

The multi-observable principle:

topology, kinematics, timing





Plastic
scintillator
calorimeter

Radio-pure materials
and a multi-layer shielding

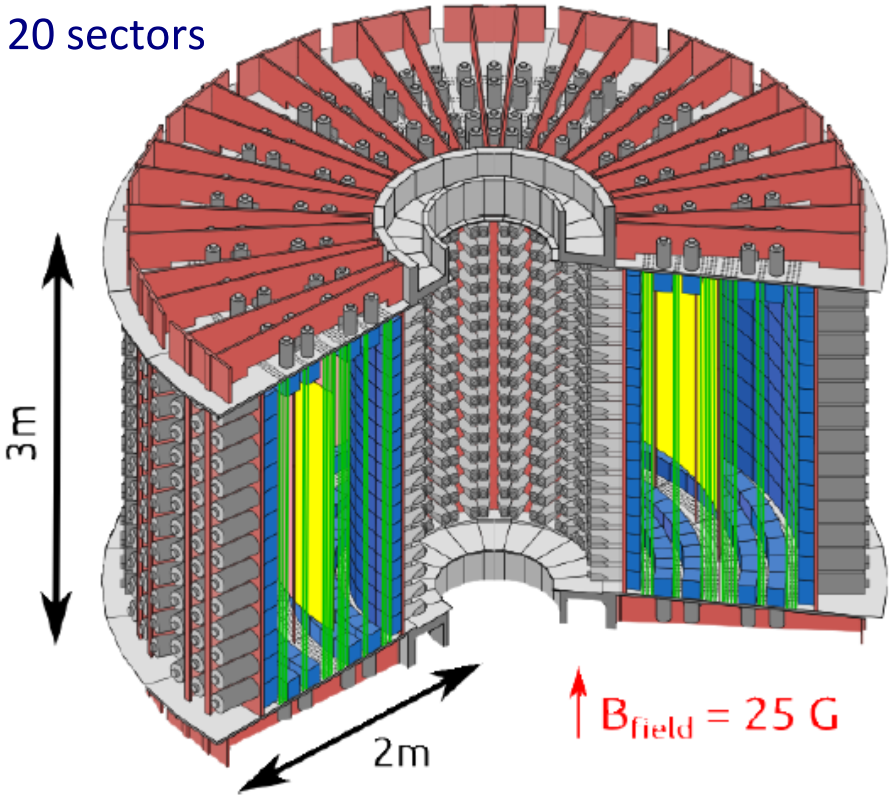
NEMO-3 detector

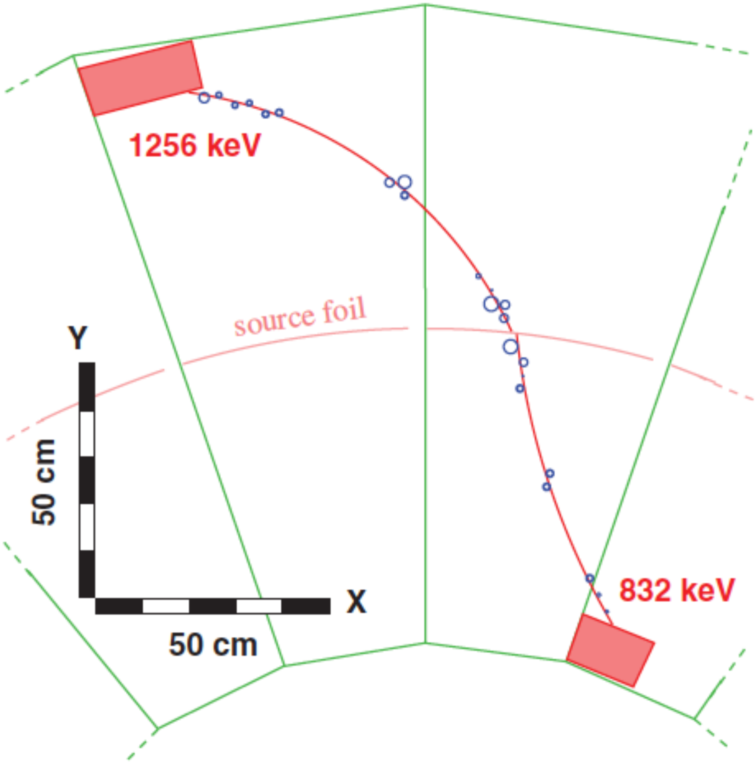
Fréjus Tunnel : 4,800 m.w.e.

Phase 1: Feb, 2003 → Sep, 2004
Phase 2: Oct, 2004 → Jan, 2011

- ✓ ββ source as foils (10 kg)
- ✓ 3D Tracking w/ drift chamber
- ✓ Calorimetry w/ plastic scintillator
- ✓ Timing w/ PMTs
- ✓ B field (25 G)
- ✓ Mult-layer shielding

20 sectors

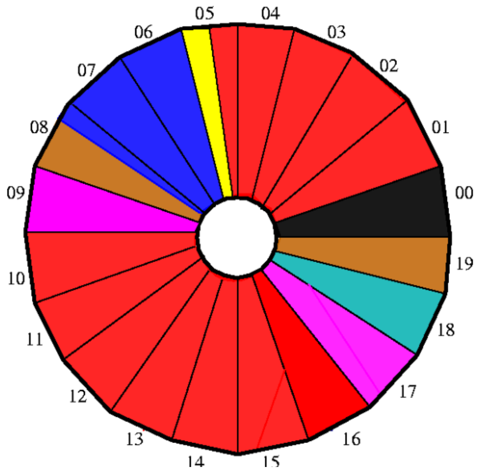


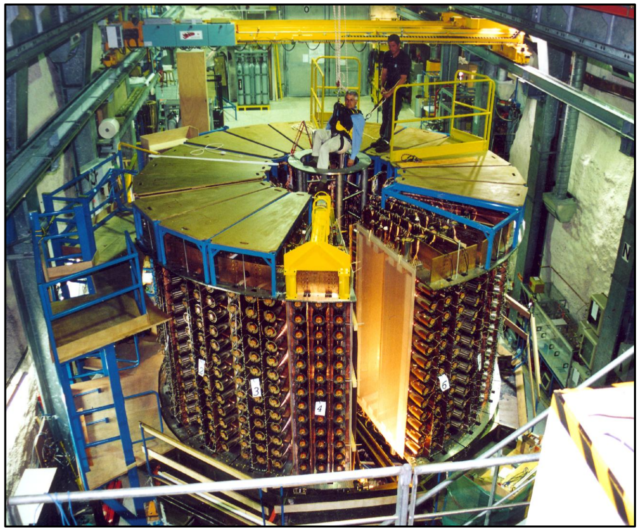


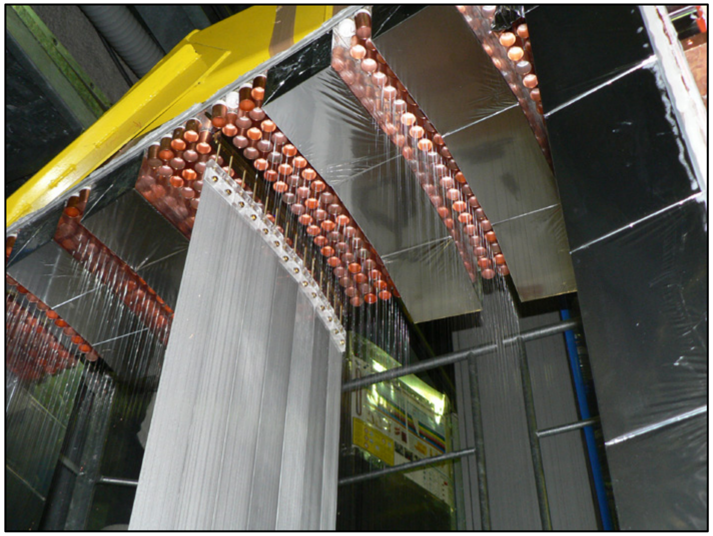
Particle ID: e⁻, e⁺, γ and α

NEMO-3 data taking: 2003 – 2011

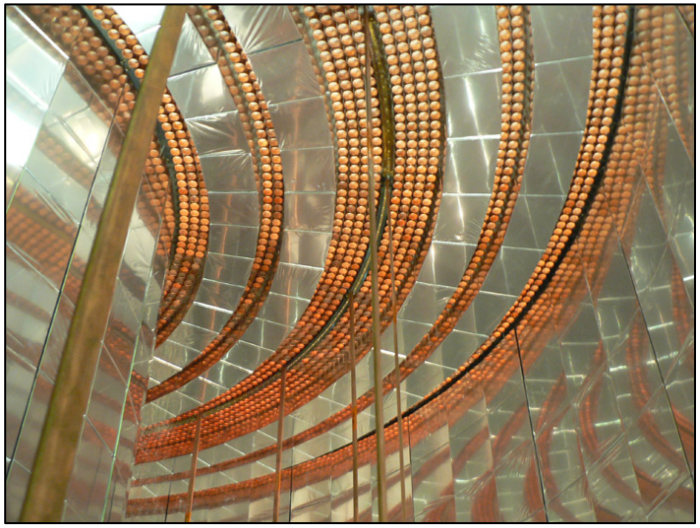
Isotope	Mass (g)	$Q_{\beta\beta}$ (keV)
^{100}Mo	6 914	3034
^{82}Se	932	2995
^{116}Cd	405	2814
^{96}Zr	9.4	3356
^{150}Nd	37	3371
^{48}Ca	7	4268
^{130}Te	454	2528
^{nat}Te	491	
^{nat}Cu	621	







With the radon-free air tent (Phase 2)

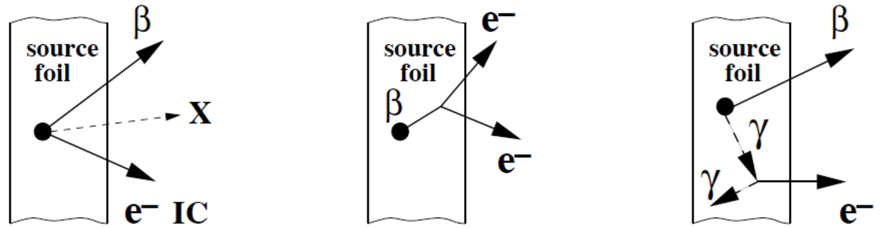


Decommissioning – no foils

NEMO-3 backgrounds

1. Internal background (in addition to a potential $2\nu\beta\beta$ tail)

(due to ^{232}Th (^{208}Tl) and ^{238}U (^{214}Bi) radio-impurities of the isotopic source foil)

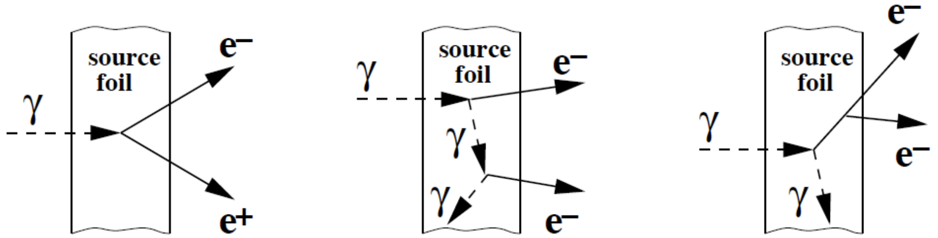


beta + IC (dominant) | beta + Möller | beta + Compton

● = radioisotope β = electron from beta decay IC = internal conversion

2. External background (if the γ is not detected)

(due to radio-impurities of the detector)

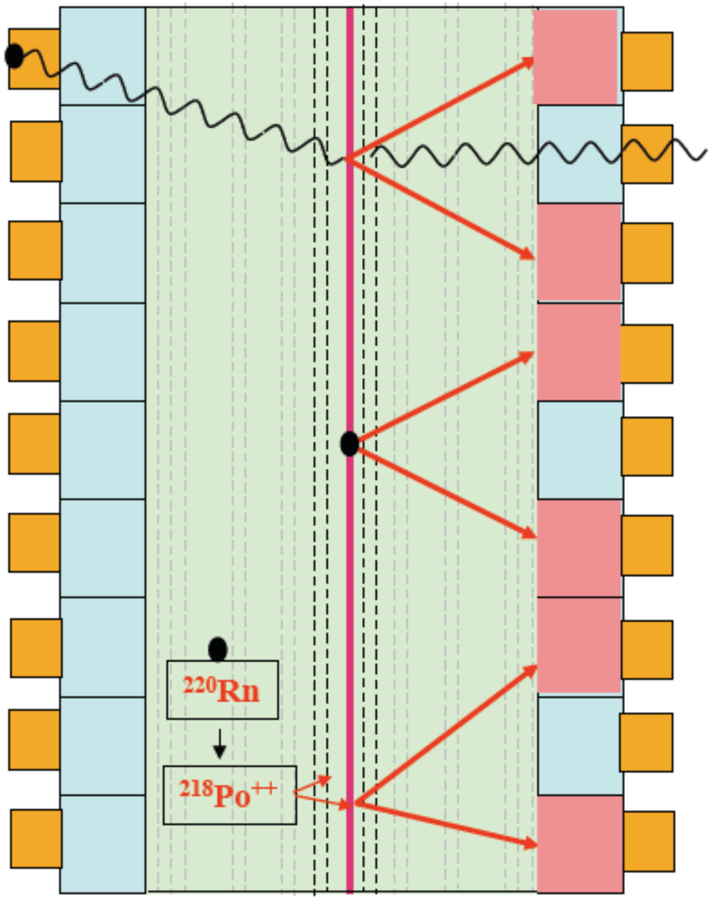


pair creation | Compton + Compton | Compton + Möller

3. Radon (^{214}Bi) inside the tracking detector

- deposits on the wire near the $\beta\beta$ foil
- deposits on the surface of the $\beta\beta$ foil

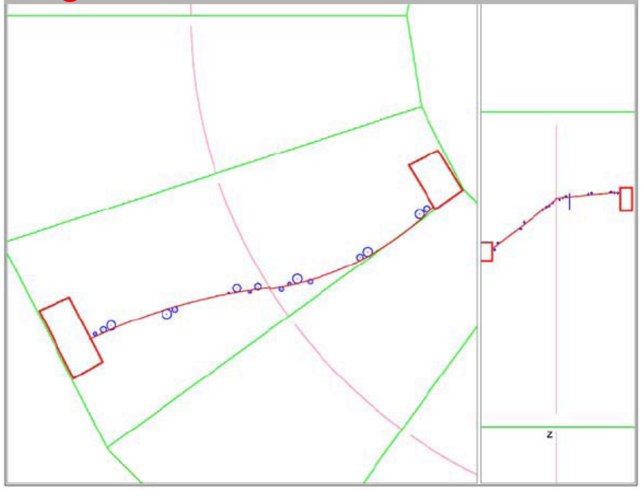
Foils are about 60 mg/cm^2 thick



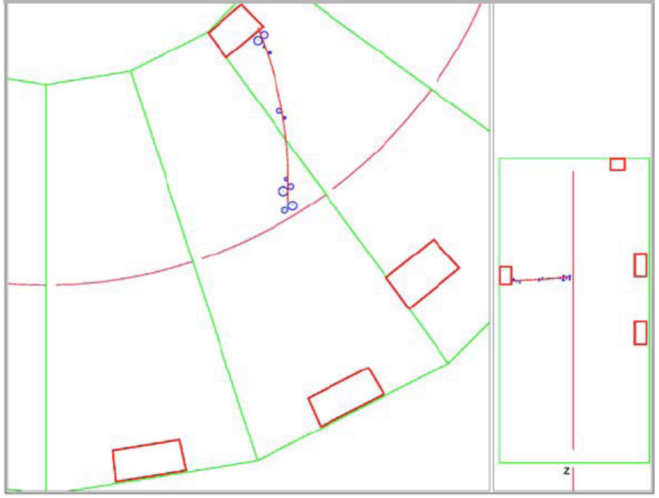
Each bkg is measured using the NEMO-3 data

Signal and background signatures

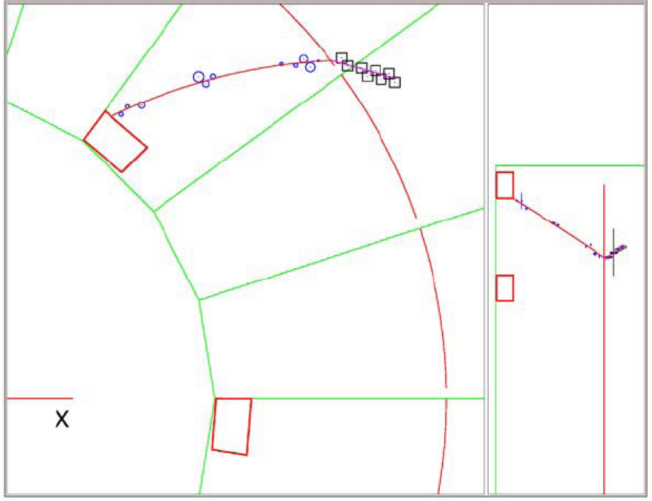
$2e^-$ event
signal



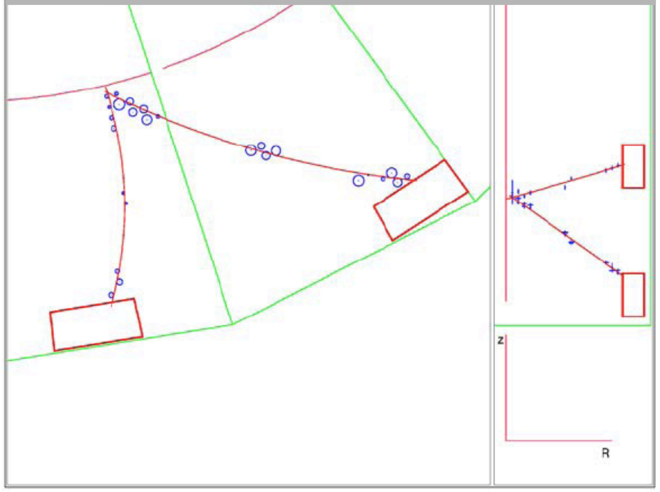
$e^- \gamma\gamma\gamma$ event
measure $^{208}\mathrm{Tl}$



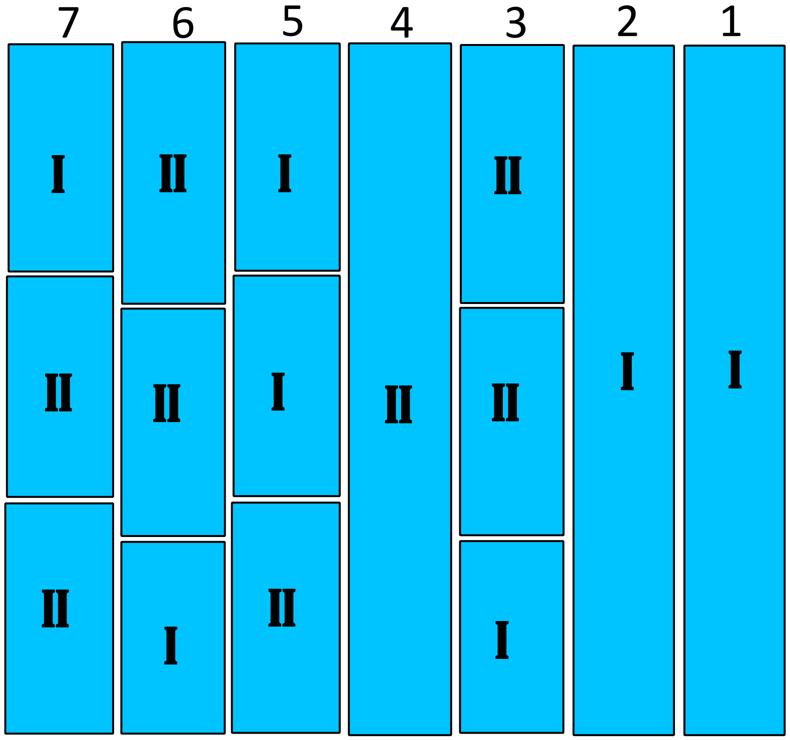
$\beta - \alpha$ (delay track) event
$^{214}\mathrm{Bi} \rightarrow {}^{214}\mathrm{Po} \rightarrow {}^{210}\mathrm{Pb}$



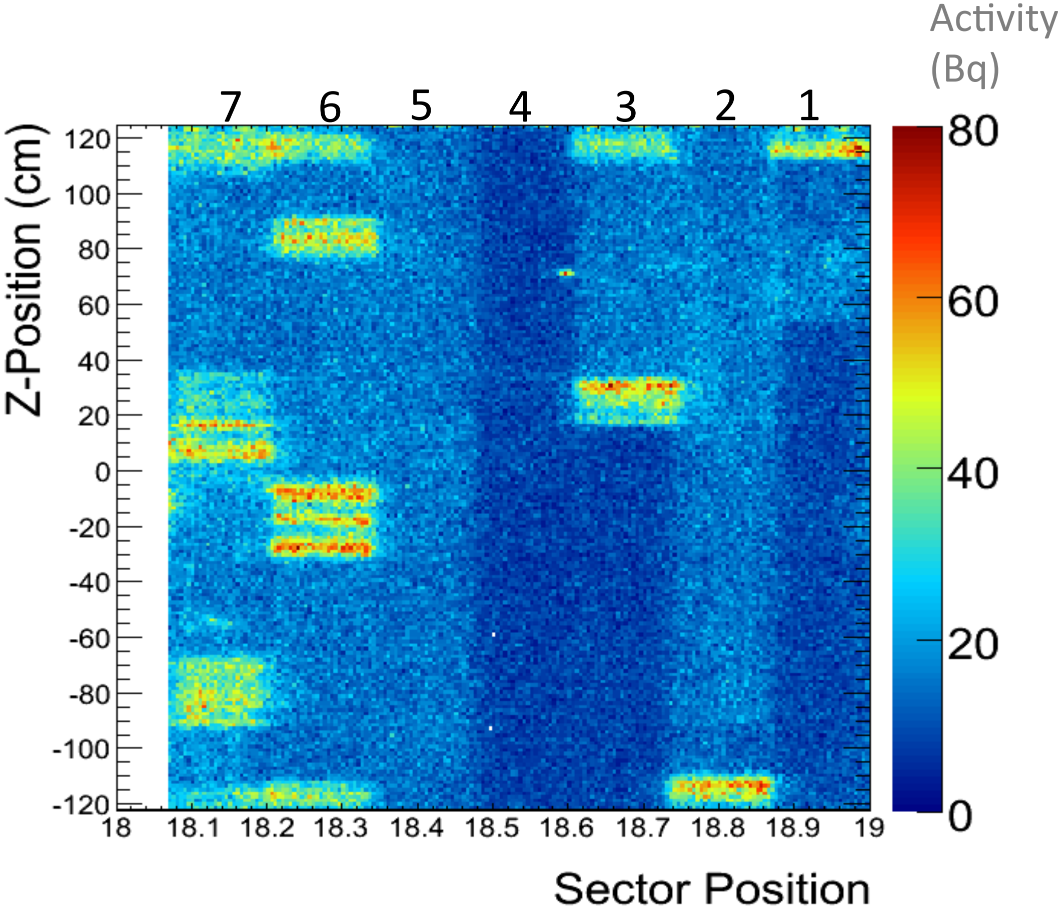
$e^+ - e^-$ pair event
B rejection



Cadmium Foil
Activity and Hot Spots

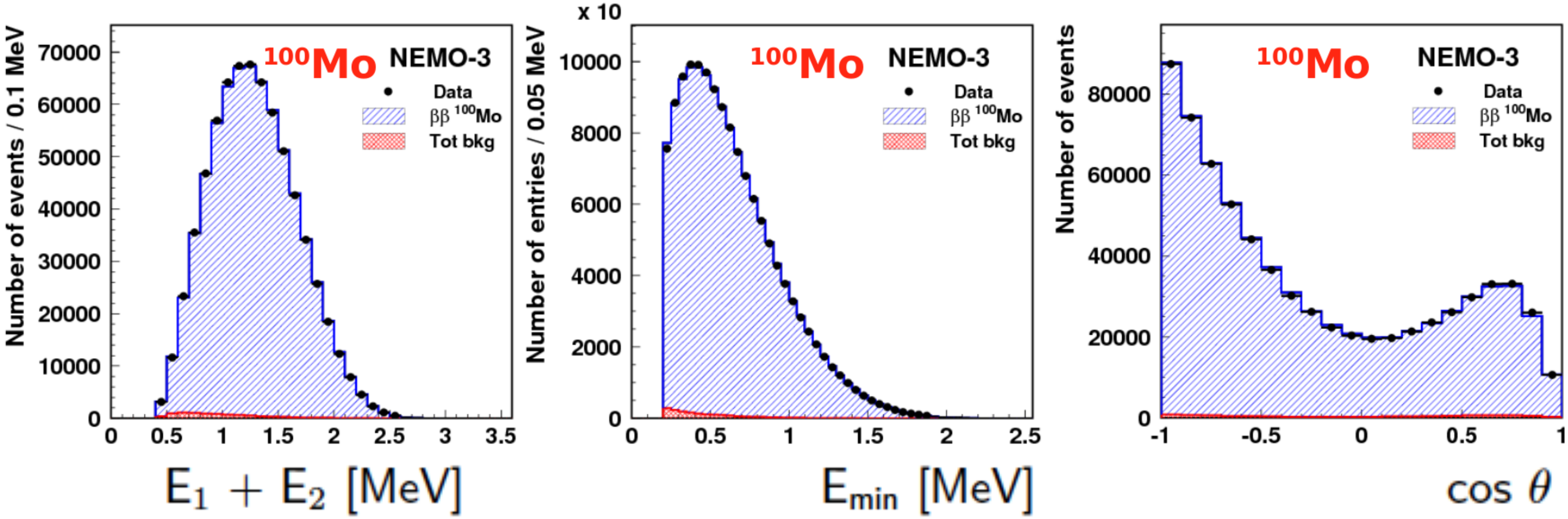


Production foil parts



Vertex at the foil for
1 electron data

^{100}Mo 2νββ results (Phase 2, low Rn)


Energy sum spectrum

Energy min of e^-

Angular distribution

- ○ 6.9 kg of ^{100}Mo
- ○ ~700,000 events
- ○ S/B ~ 76
- ○ Efficiency 4.3%

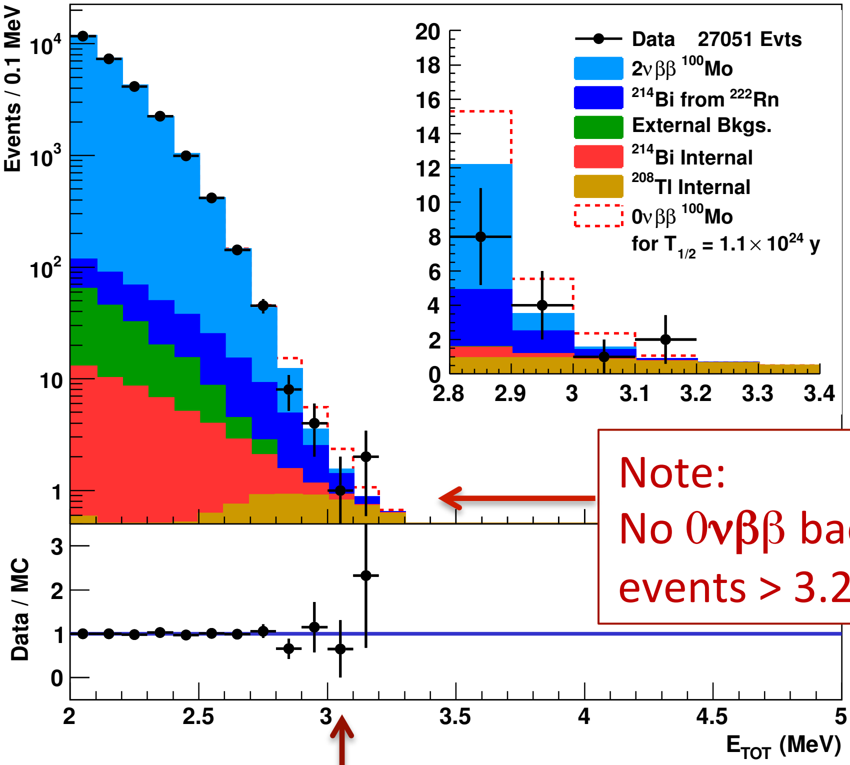
Preliminary

$$T_{1/2}(2\nu\beta\beta) = (\,7.16 \pm 0.01_{(stat)} \pm 0.54_{(syst)}) \times 10^{18} \text{ years}$$

Phase 2 exposure: 3.49 y*6.914 kg = 24.13 kg*y

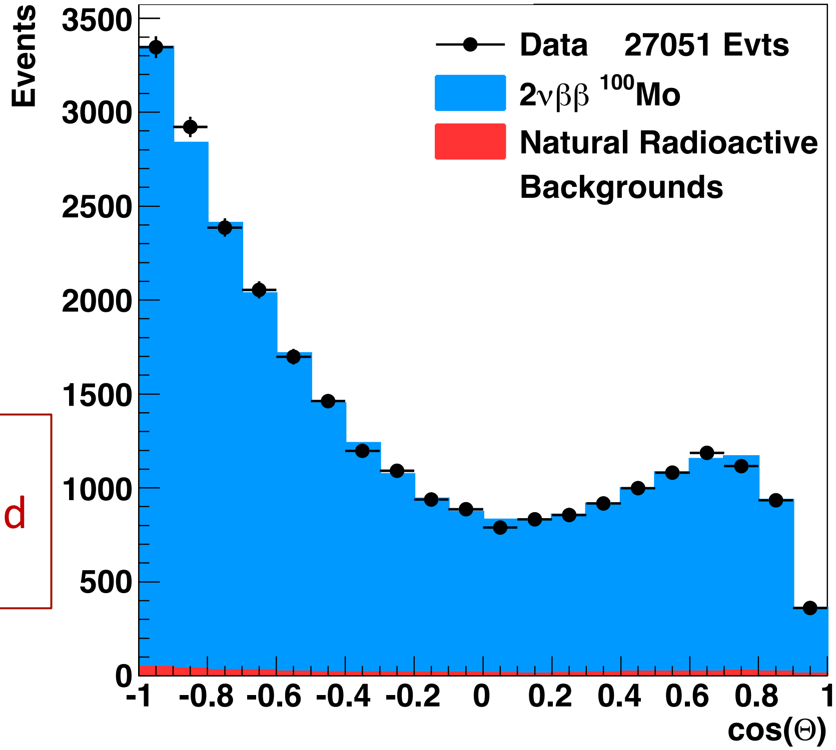
PHYSICAL REVIEW D **89,** 111101(R) (2014)

Search for neutrinoless double-beta decay of ^{100}Mo with the NEMO-3 detector



Note:
No $0\nu\beta\beta$ background events > 3.2 MeV!

$Q_{\beta\beta}$= 3.034 MeV



$$T_{1/2}(0\nu\beta\beta) > 1.1\times10^{24}\ \mathrm{y}\quad @90\%C.L.$$

(exposure of 34.7 kg•y)

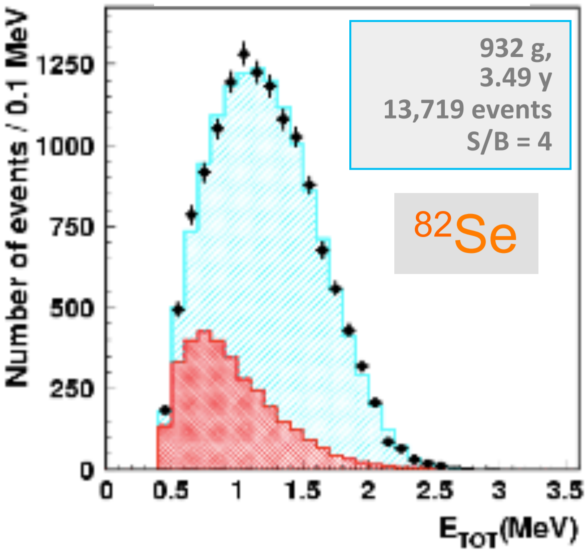
$$\langle m_{\beta\beta}\rangle < (330-620)^{*}\ \mathrm{meV}$$

Final (includes all systematic uncertainties)

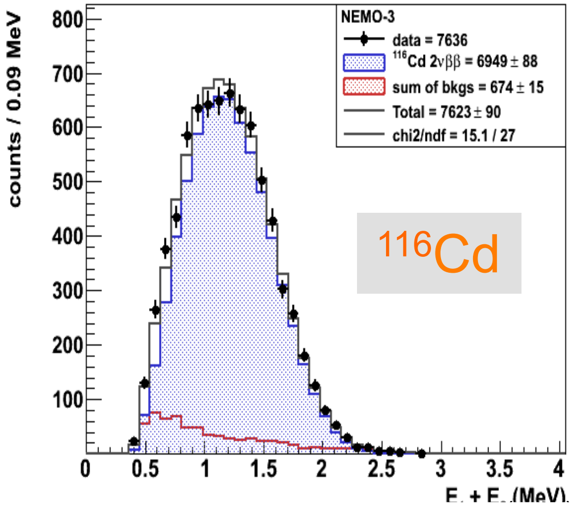
* new ME by
J. Hyvarinen and J. Suhonen
Phys. Rev. C 91, 024613 1097 (2015)

(Not full data sets yet)

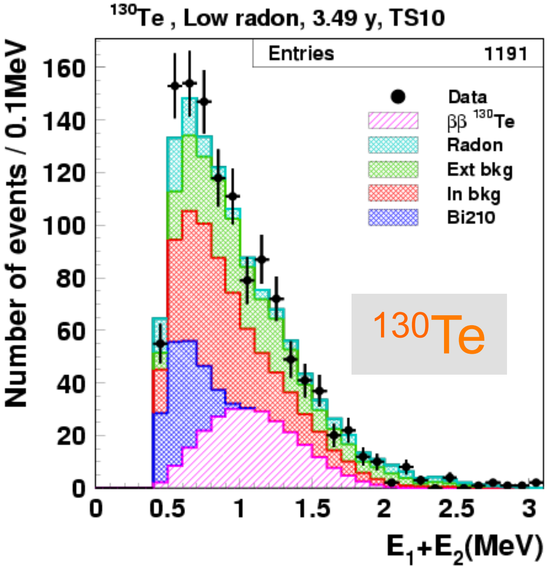
Results of 2νββ measurements



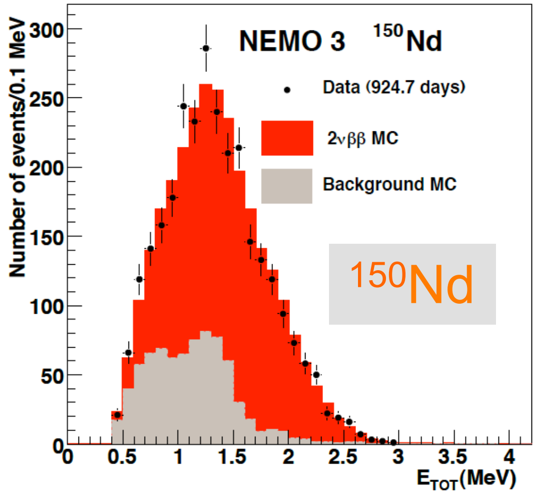
$[\,9.6 \pm 0.1_{(stat)} \pm 1.0_{(syst)}\,] \times 10^{19}$ y



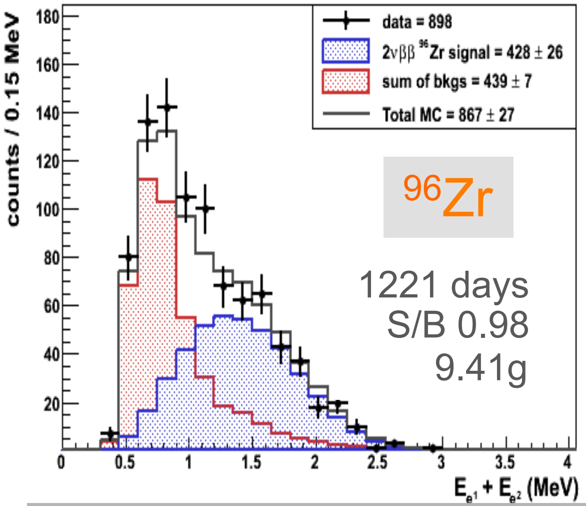
$[\,2.88 \pm 0.04_{(stat)} \pm 0.16_{(syst)}\,] \times 10^{19}$ y



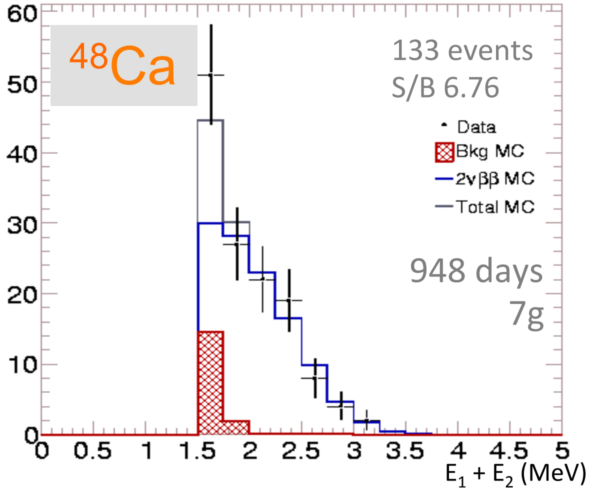
$[\,7.0\,^{+1.0}_{-0.8}\,_{(stat)}\,^{+1.1}_{-0.9}\,_{(syst)}\,] \times 10^{20}$ y



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



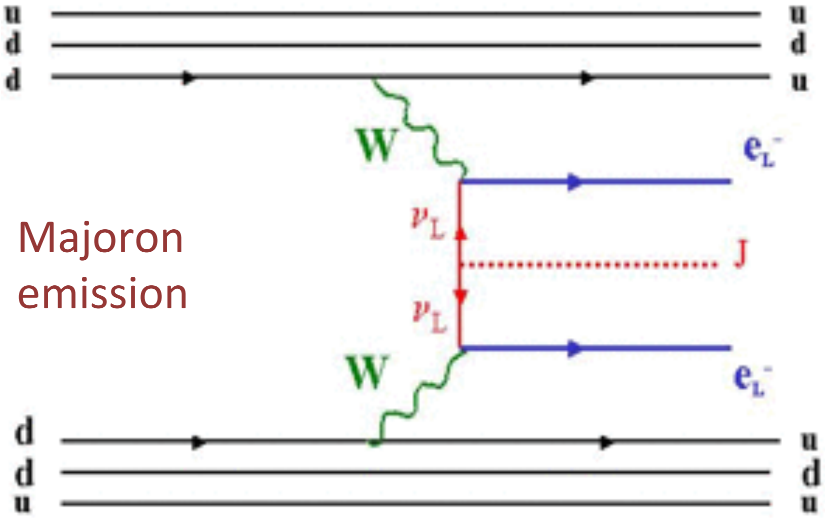
$[\,2.35 \pm 0.14_{(stat)} \pm 0.16_{(syst)}\,] \times 10^{19}$ y

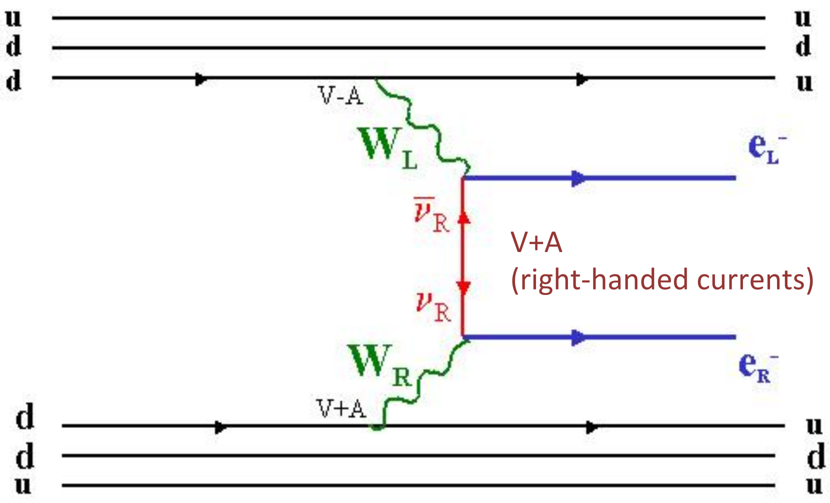


$[\,4.4\,^{+0.5}_{-0.4}\,_{(stat)} \pm 0.4_{(syst)}\,] \times 10^{19}$ y

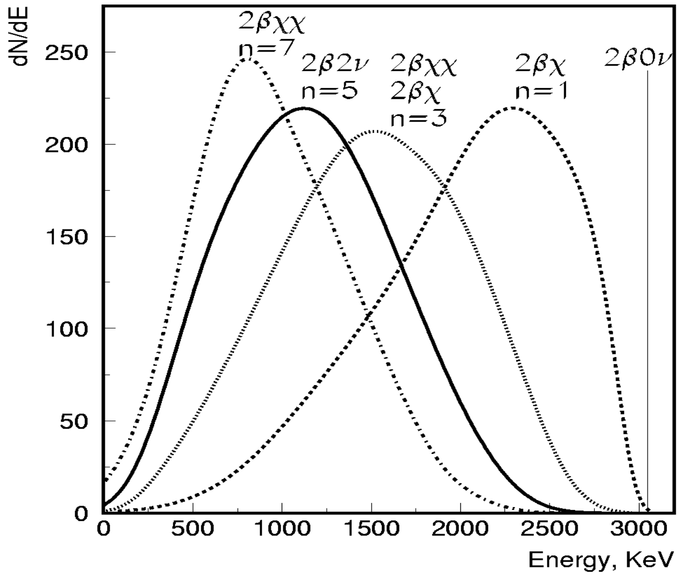
Other physics (examples)

Majoron emission





V+A
(right-handed currents)



	V+A *	Majoron(s) emission (n=spectral index)**			
	$T_{1/2}(0\nu\beta\beta)$ [years]	n=1	n=2	n=3	n=7
^{100}Mo	$>5.7\cdot10^{23}$ $\lambda<1.4\cdot10^{-6}$	$>3.9\cdot10^{22}$ $g_{ee}<(.16\text{-}.41)\cdot10^{-4}$	$>1.7\cdot10^{22}$	$>1\cdot10^{22}$	$>7\cdot10^{19}$
^{82}Se	$>2.4\cdot10^{23}$ $\lambda<2.\cdot10^{-6}$	$>1.5\cdot10^{22}$ $g_{ee}<(0.7\text{-}1.9)\cdot10^{-4}$	$>6\cdot10^{21}$	$>3.1\cdot10^{22}$	$>5\cdot10^{20}$

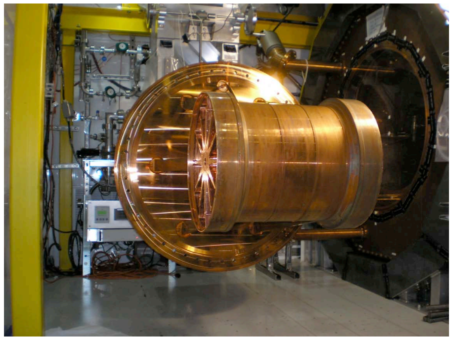
* Phase I+Phase II data R.Arnold et al. PR D 89, 111101(R) (2014)

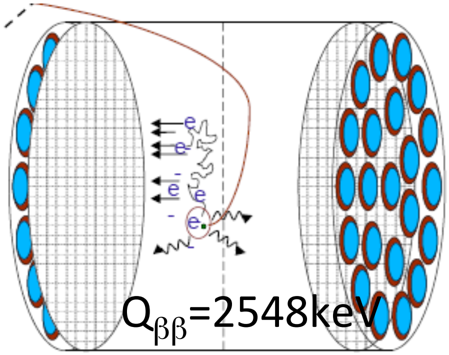
** Phase I data, *R. Arnold et al. Nucl. Phys. A765 (2006) 483*

Competition: EXO-200

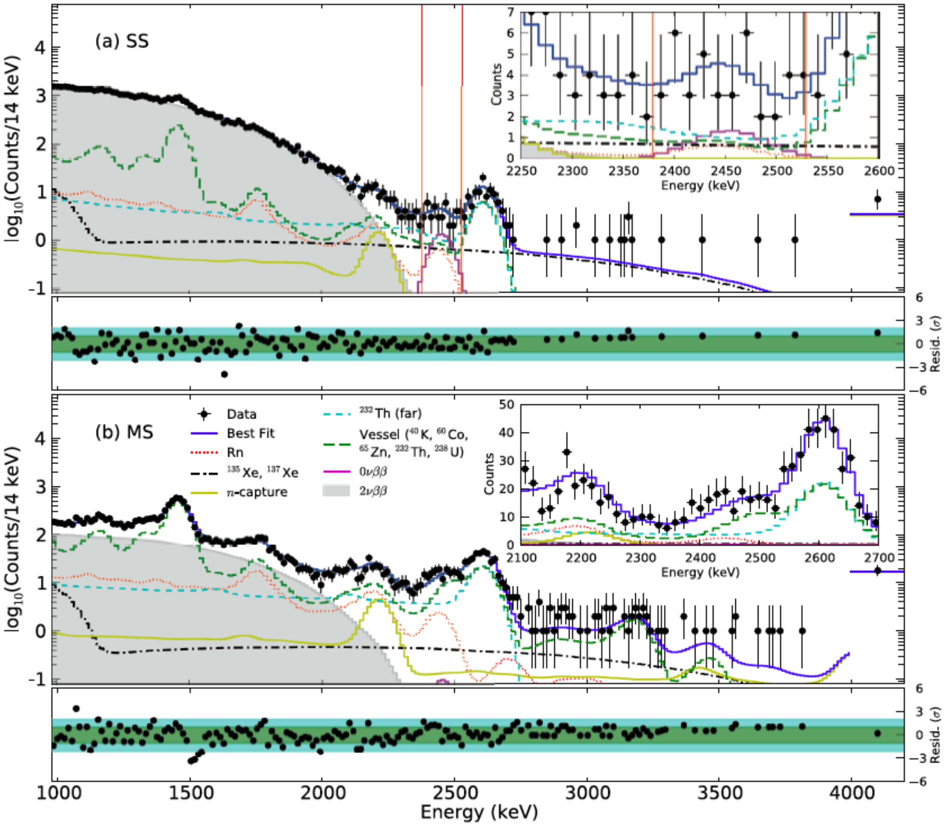
- Liquid ^{136}Xe (80% enriched) TPC
- 76.5 kg fiducial v., 100 kg*y exposure
- First observation of ββ decay of ^{136}Xe

$$T_{1/2}(2\nu\beta\beta) = (2.165 \pm 0.016_{stat} \pm 0.059_{syst}) \times 10^{21}\ y$$





ROI $Q_{\beta\beta}$= 2.458 MeV



Nature (100kg*yr)

$$T_{1/2}(0\nu\beta\beta) > 1.1 \times 10^{25}\ y\ \ (90\%\ C.L.)$$

$$<m_\nu> < (190 - 450)\ meV$$

PRL: 32.5 kg*y

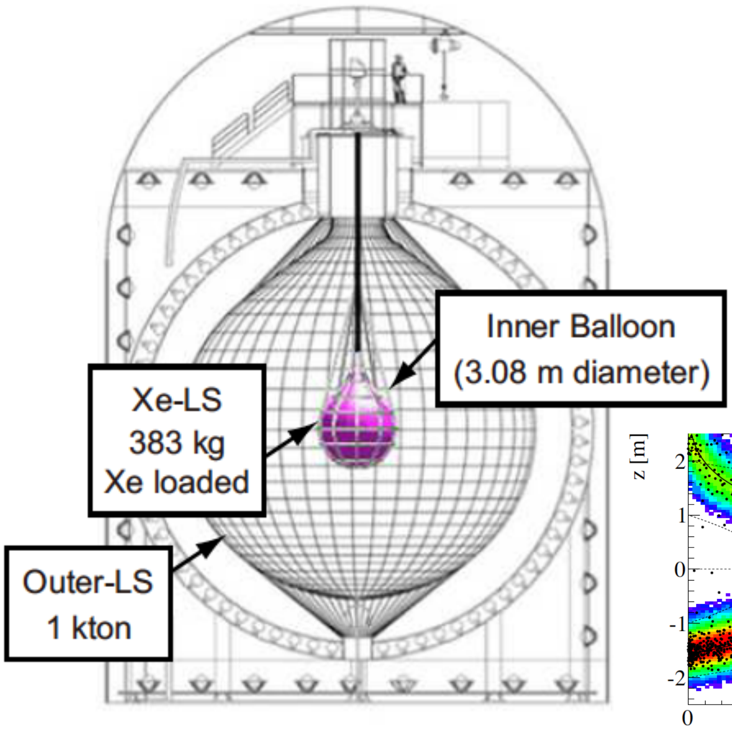
$$T_{1/2}(0\nu\beta\beta) > 1.6 \times 10^{25}\ y\ \ (90\%\ C.L.)$$

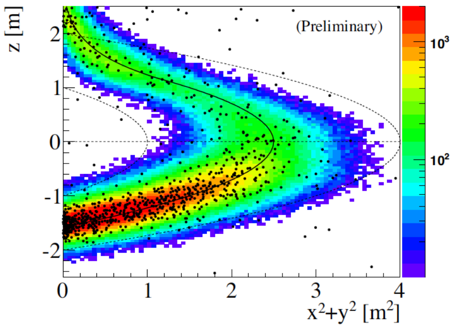
$$<m_\nu> < (140 - 380)\ meV$$

M.Auger et al., PRL 109 (2012) 032505
J.B.Albert et al., Nature 510, 229-234 (2014)

Competition: KamLAND-Zen

- ☐ 320 kg of liquid ^{136}Xe 90% enriched
- ☐ 89.5 kg*y exposure
- ☐ Fukushima-related bkg. ^{110m}Ag

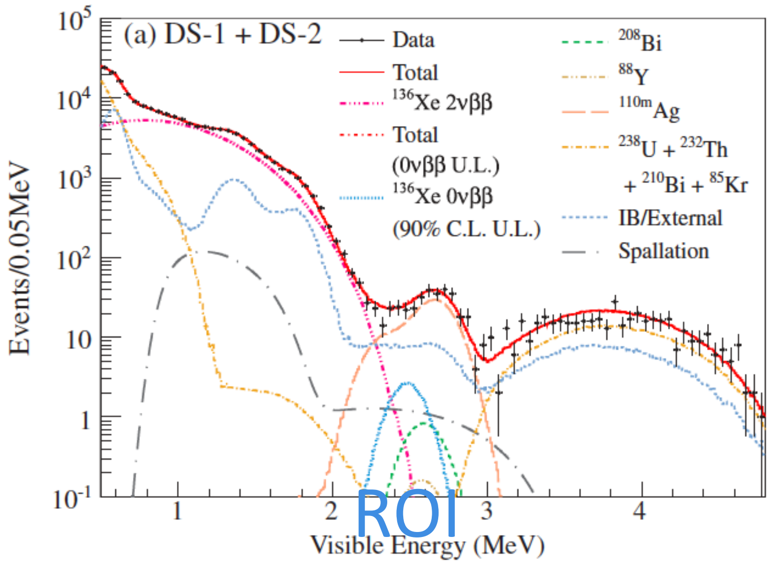




Gando et al., PRL 110, 062502 (2013)
Asakura et al., arXiv:1409.0077

- ☐ Phase 1 and 2 results

$$T_{1/2}(0\nu\beta\beta) > 2.6\times10^{25}\ \text{y}\ \ (90\%\ \text{C.L.})$$
$$\langle m_{\beta\beta}\rangle < (140-280)\ \text{meV}$$

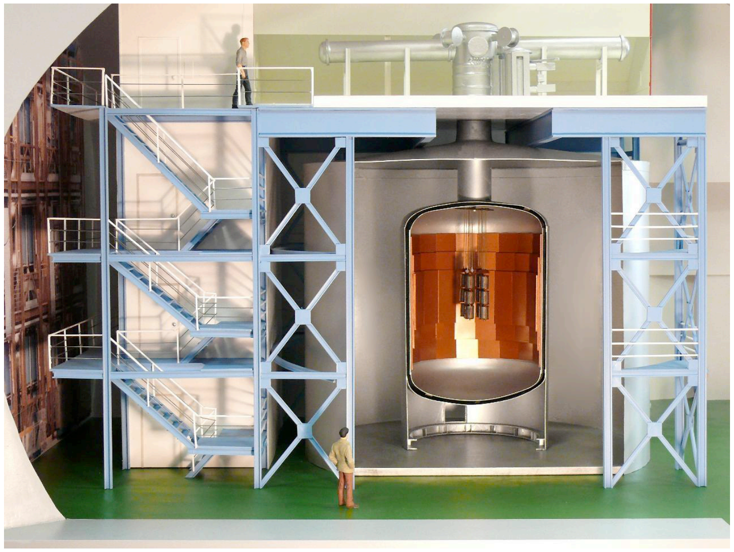


- ☐ Combination of KamLAND-Zen and EXO-200

$$T_{1/2}(0\nu\beta\beta) > 3.4\times10^{25}\ \text{y}\ \ (90\%\ \text{C.L.})$$
$$\langle m_{\beta\beta}\rangle < (120-250)\ \text{meV}$$

Competition: GERDA

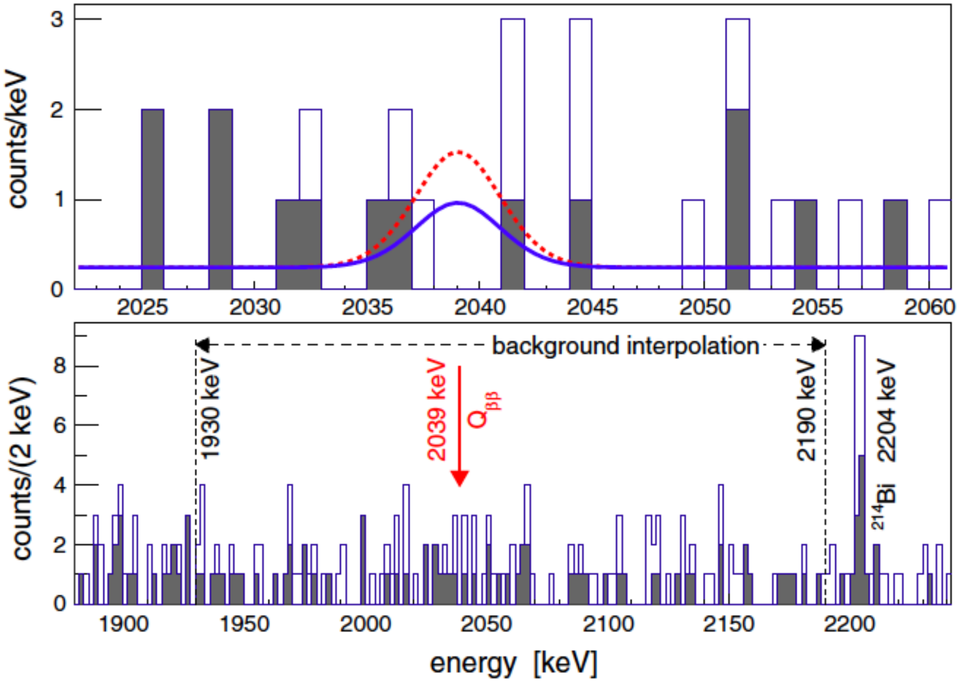
- HP^{76}Ge crystals, $Q_{\beta\beta}$=2039keV
- 17.7 kg, 21.6 kg*y exposure



- Phase 1 results
- K-K *et al*. debunked

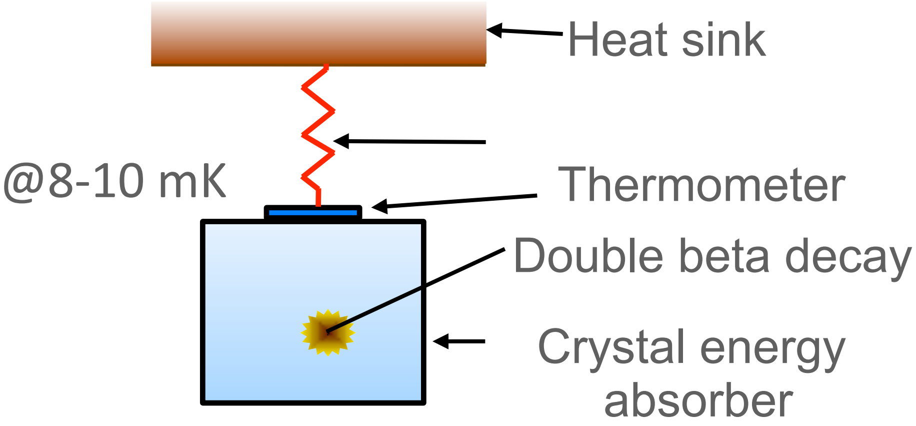
$$T_{1/2}(0\nu\beta\beta) > 1.9\times 10^{25}\ \mathrm{y}\ \ (90\%\ \mathrm{C.L.})$$
$$\langle m_{\beta\beta}\rangle < (200-400)\ \mathrm{meV}$$

M. Agostini et al., PRL 111, 122503 (2013)



Competition: CUORICINO / CUORE-0

- $^{130}TeO_2$ bolometer crystals
  - 40.7 kg --> 741 kg (19 towers)
- $Q_{\beta\beta}$=2528keV
- (19.75 + 9.8) kg*y exposure



Heat sink

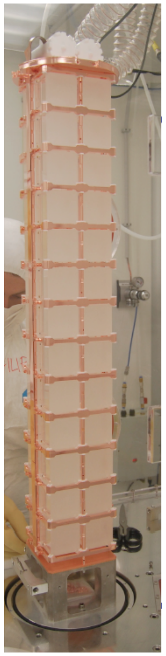
@8-10 mK

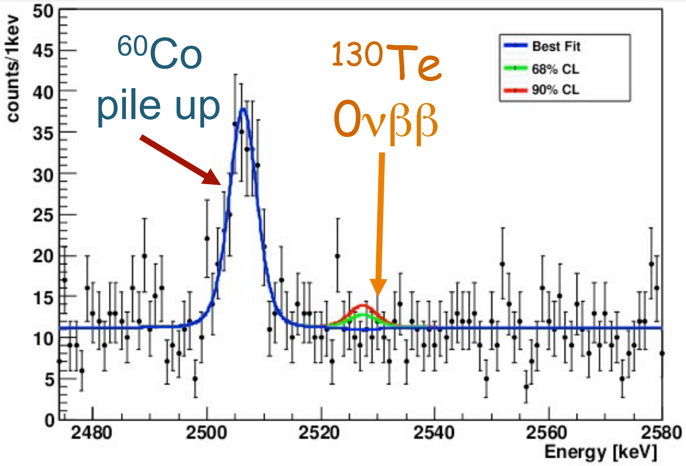
Thermometer

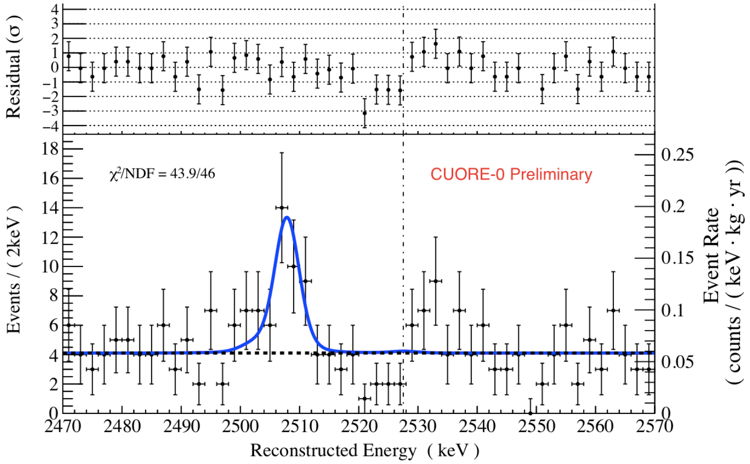
Double beta decay

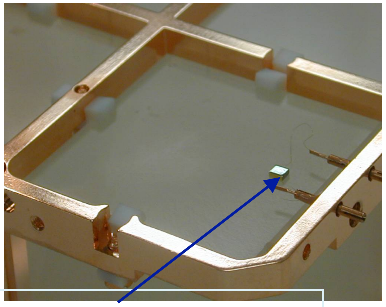
Crystal energy absorber

x 19

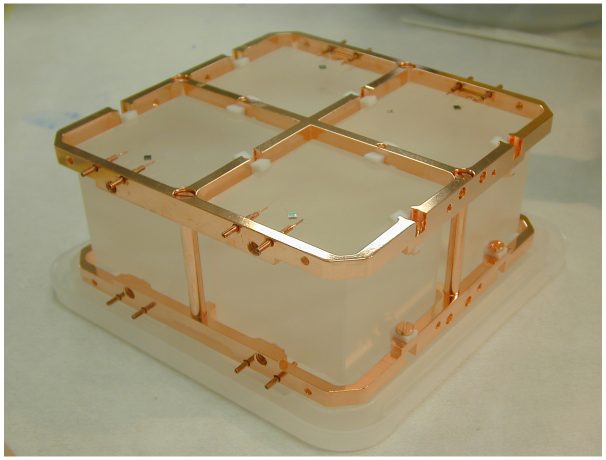








Thermometer (Neutron transition doped Ge chip)



$$T_{1/2}(0\nu\beta\beta) > 4.0\times10^{24}\ \text{y}\ \ (90\%\ \text{C.L.})$$

$$\langle m_{\beta\beta}\rangle < (270-760)\ \text{meV}$$

(combined)

E. Andreotti et al.,Astropart. Phys. 34, 822 (2011)

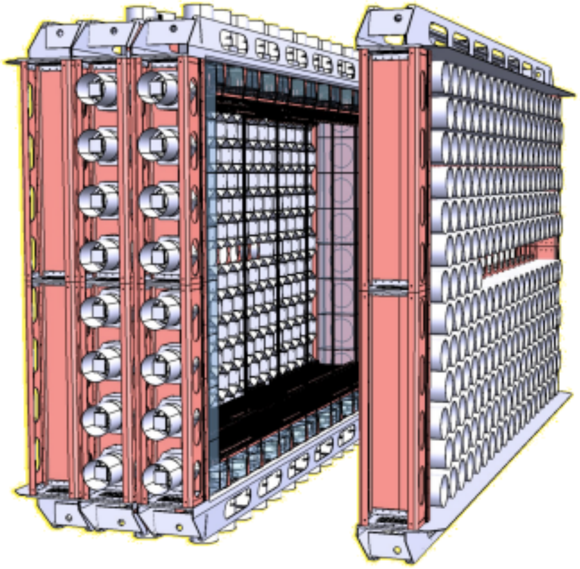
K. Alfonso et al., arXiv:1504.02454

NEMO-3 → SuperNEMO

Recall: for no background:

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16\times 10^{26}\,y}{n_\sigma}\left(\frac{\varepsilon \times a}{W}\right) M \times t$$

Retain the **multi-observable topological** features of NEMO-3



^{100}Mo → ^{82}Se

(flexibility to use other isotopes, e.g., ^{150}Nd, ^{48}Ca, ...)

7 kg → 100 kg

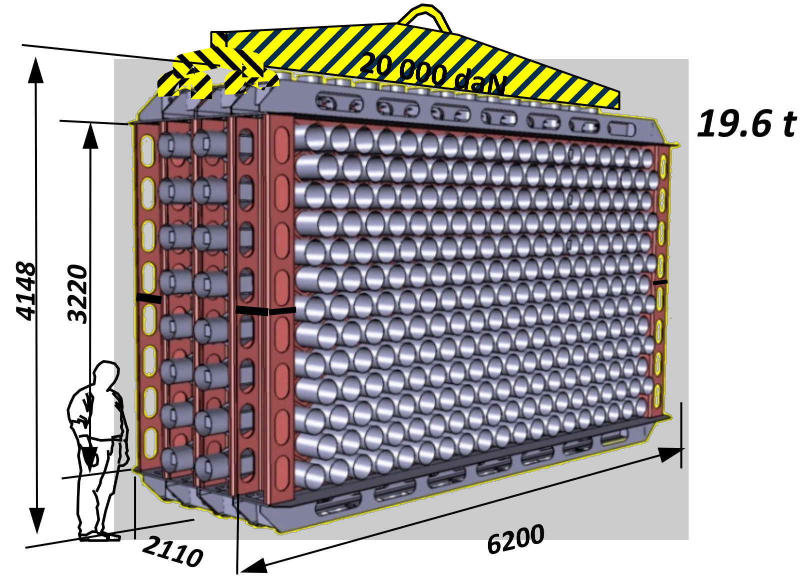
(1detector → 20 modules)

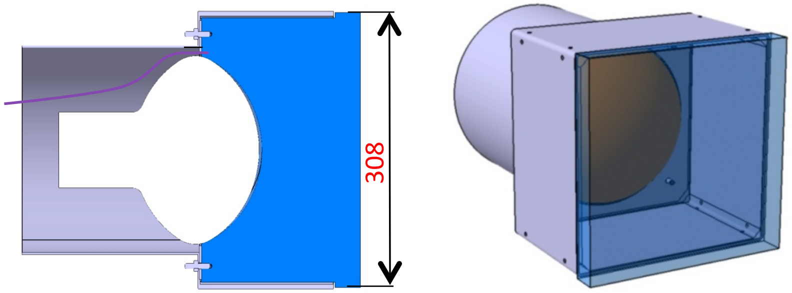
improve radiopurity → > ×10

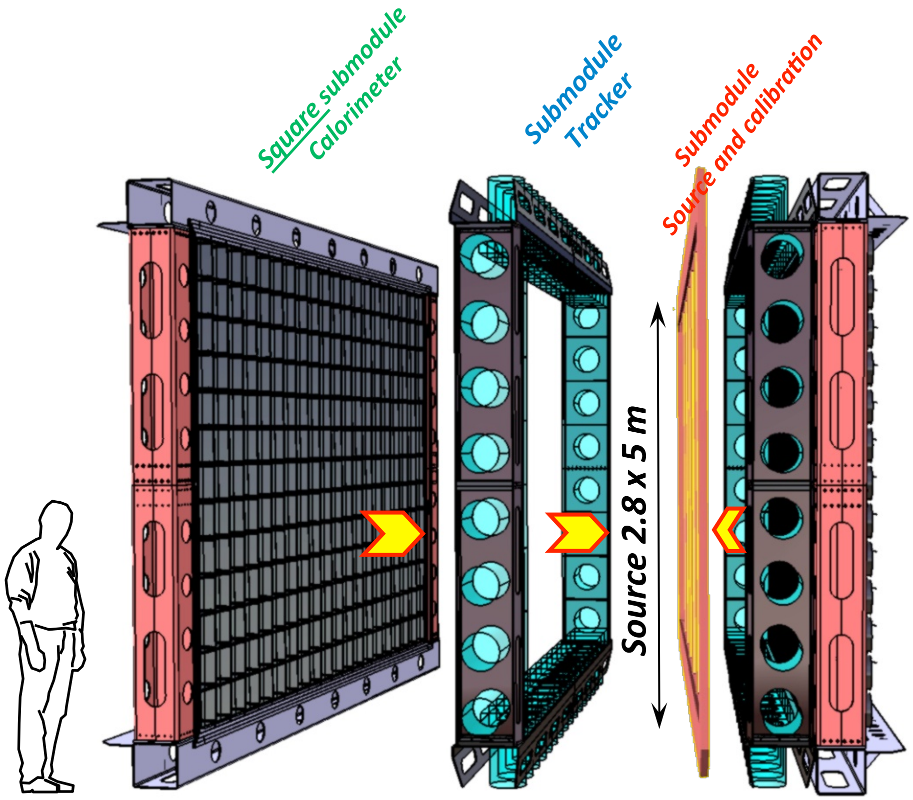
reach → $T_{1/2}(0\nu\beta\beta) > 1 \times 10^{26}$ y

$\langle m_{\beta\beta}\rangle < (40-140)$ meV

SuperNEMO Demonstrator module



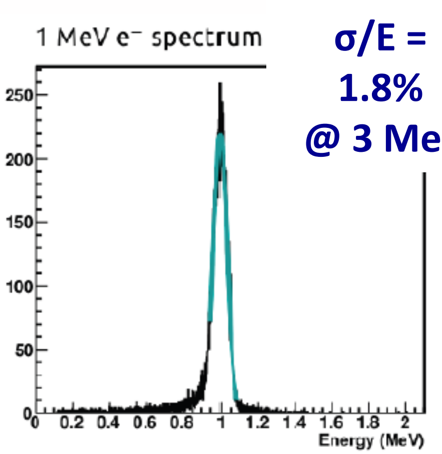




Source: 7 kg of Se-82
Exposure: 17.5 kg y (in 2.5 y)
$T_{1/2} > 6 \times 10^{24}$ y @ 90% CL
$\langle m_{\beta\beta} \rangle <$ 200 -- 400 meV

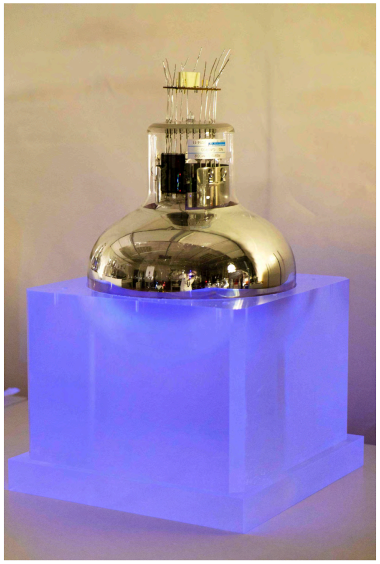
SuperNEMO calorimeter

- 8'' dia. PMTs with large blocks
  - (440 channels)
- Energy resolution
  - ~8% FWHM @ 1 MeV
- 5'' dia. in outer rows and columns and in veto blocks
- Production in full swing …

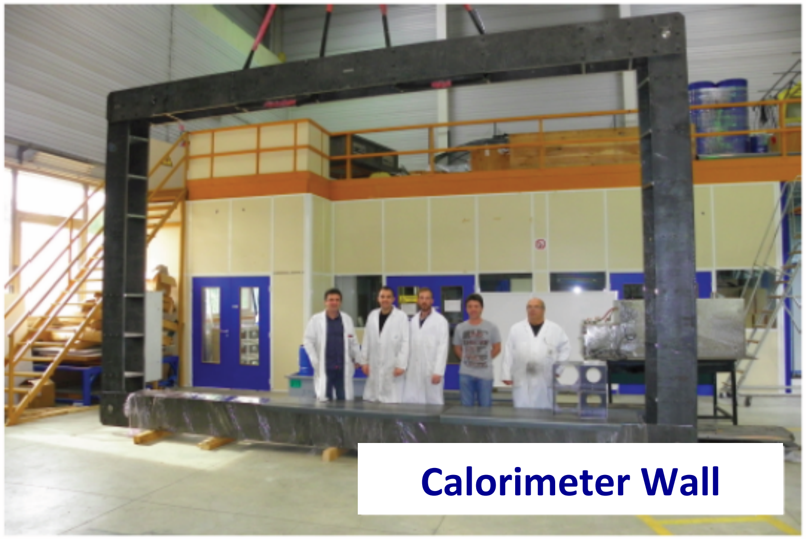


Optical Module

σ/E = 1.8% @ 3 MeV



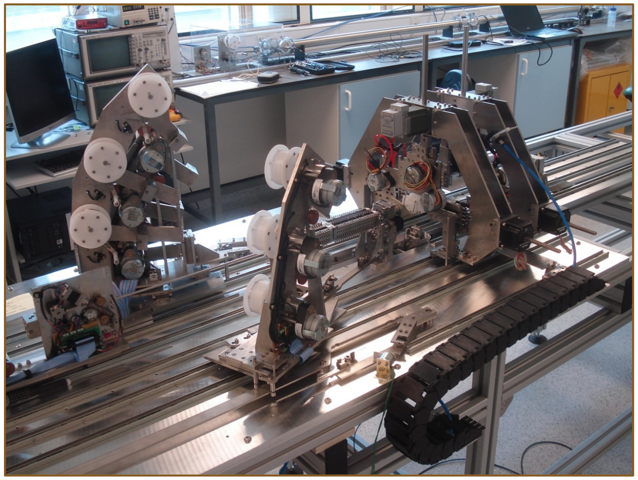
Calorimeter "brick"

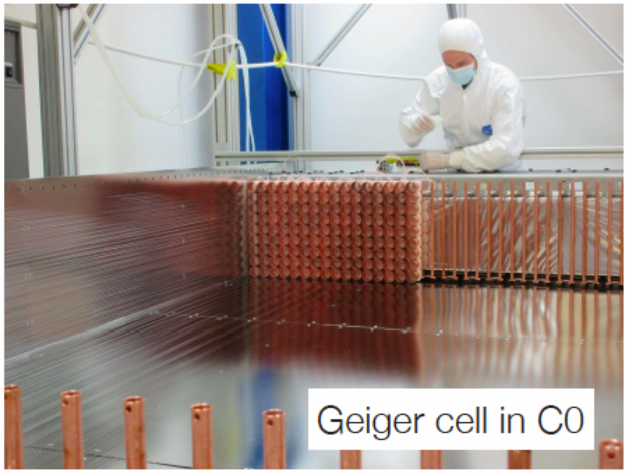


Calorimeter Wall

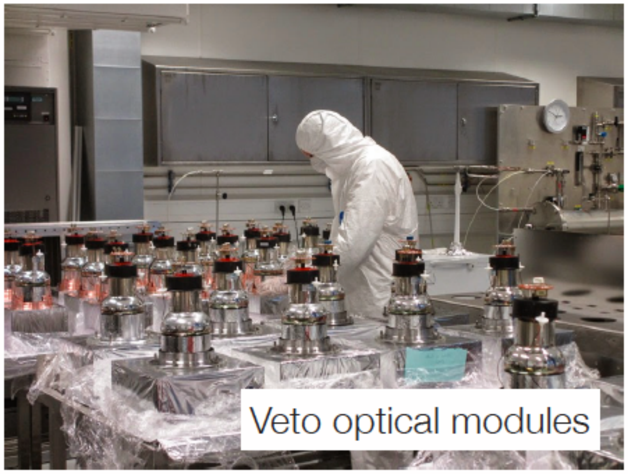
SuperNEMO tracker

- Using custom-designed wire winding machine
- One quadrant completed (see below)
- Rn-tight environment, low emanation
  - meeting the requirement
  - Rn tests ongoing
- Three other quadrants to follow

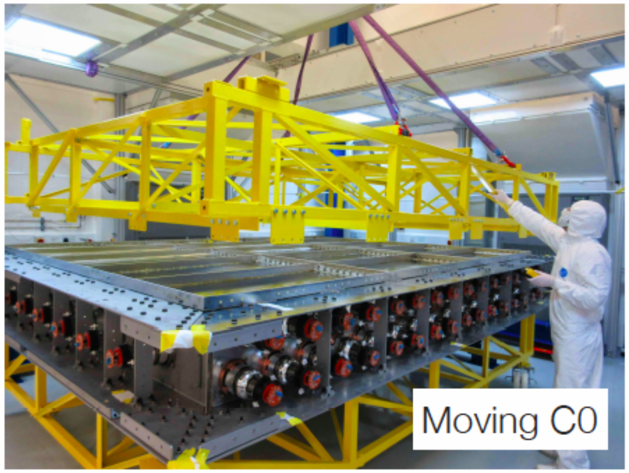




Geiger cell in C0



Veto optical modules

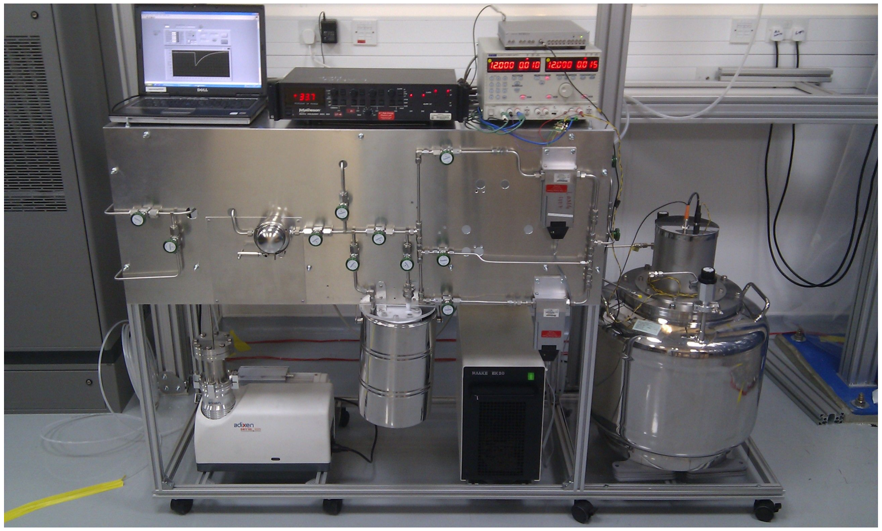


Moving C0

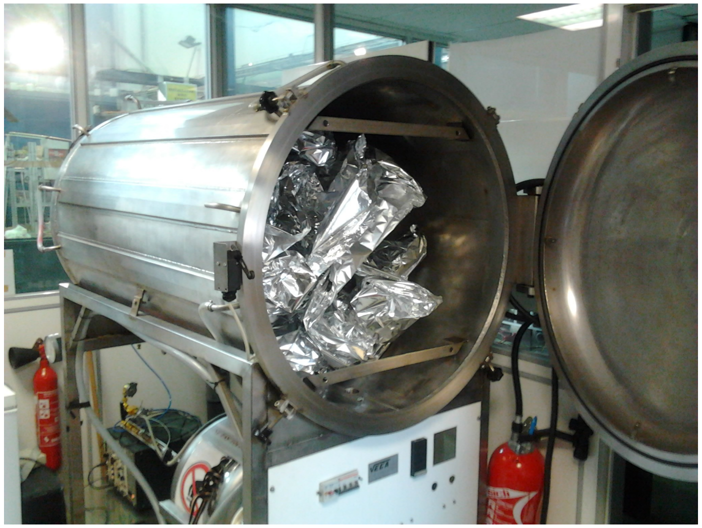
SuperNEMO:
foils frame and mounting, calibration system, radon control

Source foil mounting and ^{207}Bi calibration deployment

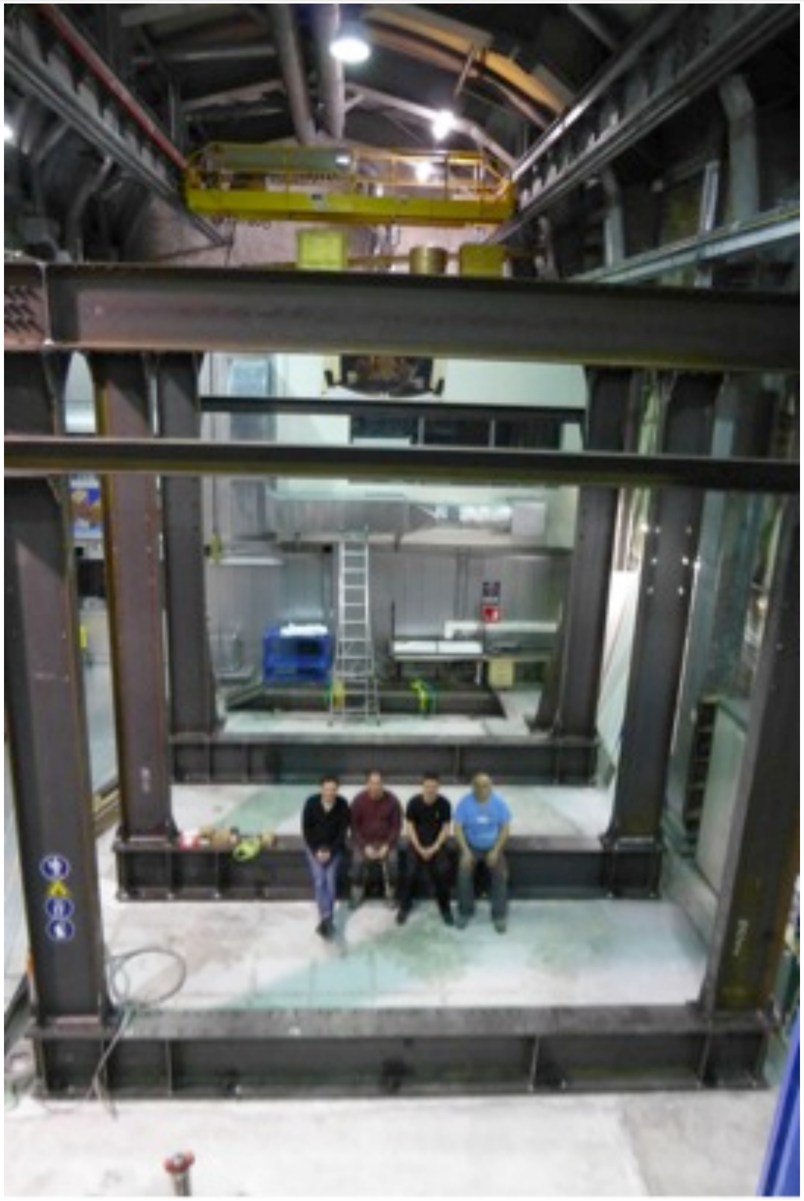
Radon concentration line for detecting Rn with ultra high sensitivity

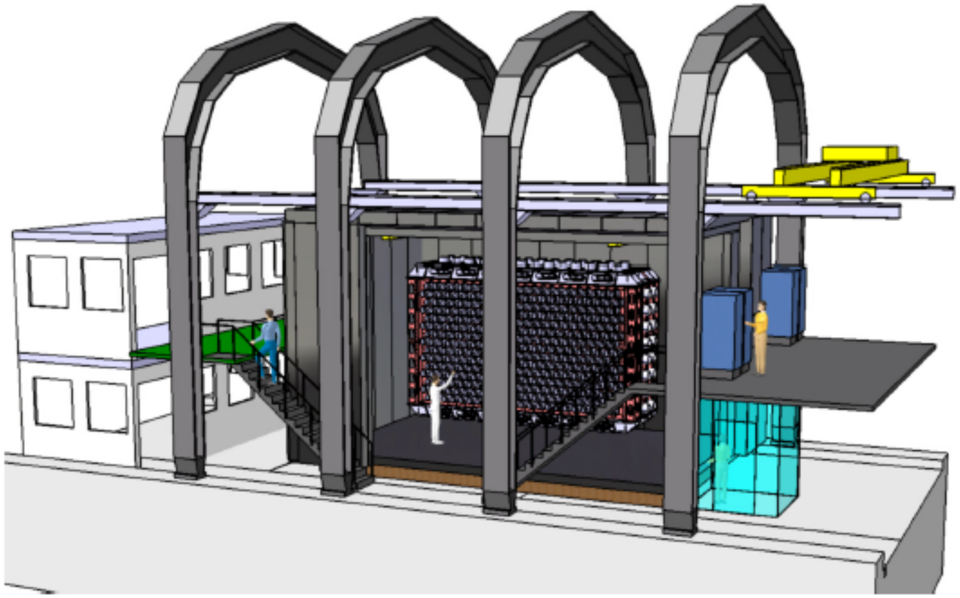


Radon emanation chambers (materials screening)



At LSM (the Frejus Tunnel)

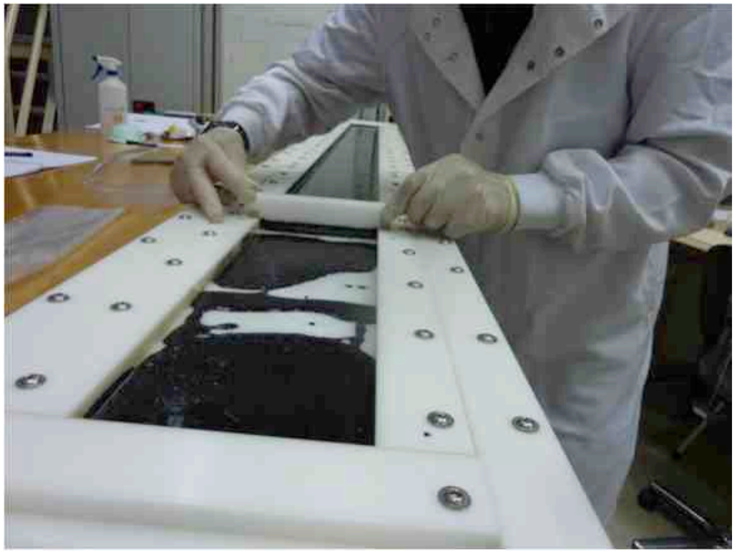




- Installation at LSM in 2015-2016
- Commissioning in 2016
- External backgrounds run (passive shielding off end 2016
- ββ physics run start 2017

BiPo detector

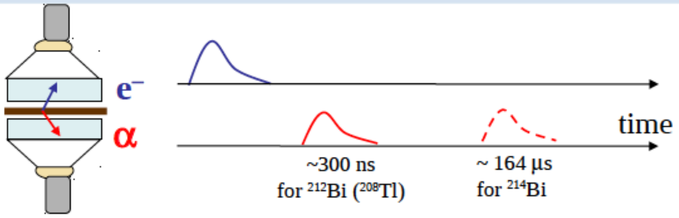
at the Canfranc Underground Laboratory (Spanish Pyrenees)

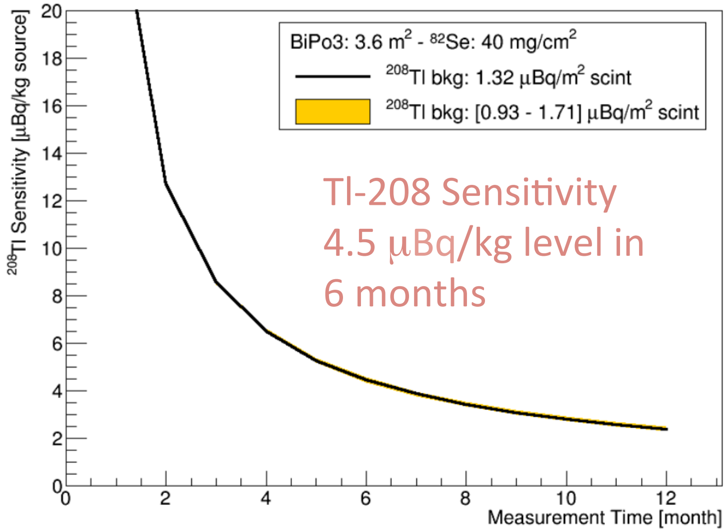


Detect the BiPo decay cascade: β + delayed α

Sandwich of two low radioactive thin polystyrene scintillators (2 x 300 x 300 mm)

Time topology signature: 1 prompt hit (β) + 1 delay hit (α) and no coincidence

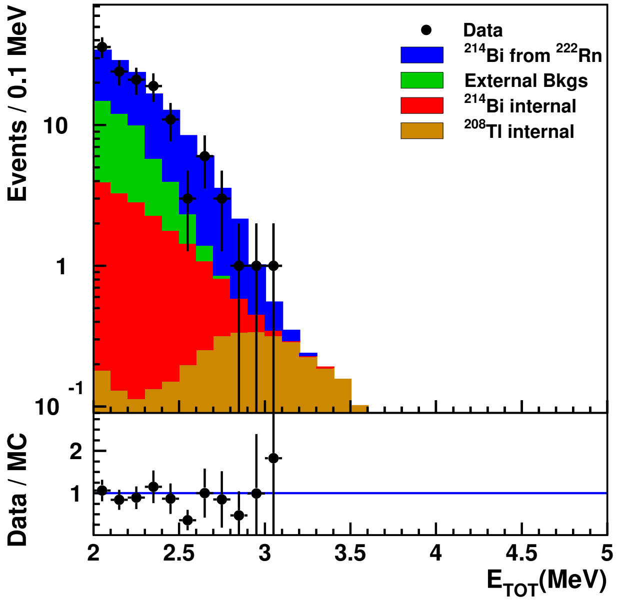




Tl-208 Sensitivity
4.5 μBq/kg level in
6 months

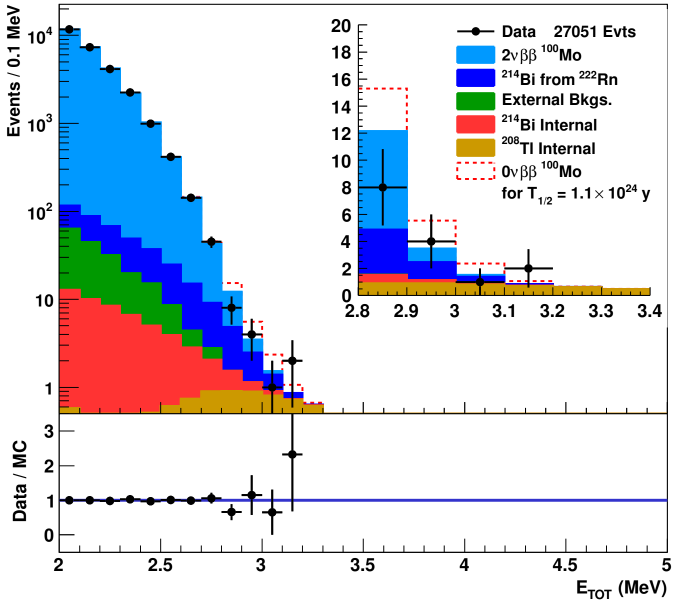
NEMO-3 background

Cu + Te sector



- Background checks
- No events with E > 3.1 MeV
- Exposure of 13.5 kg*y

^{100}Mo sectors



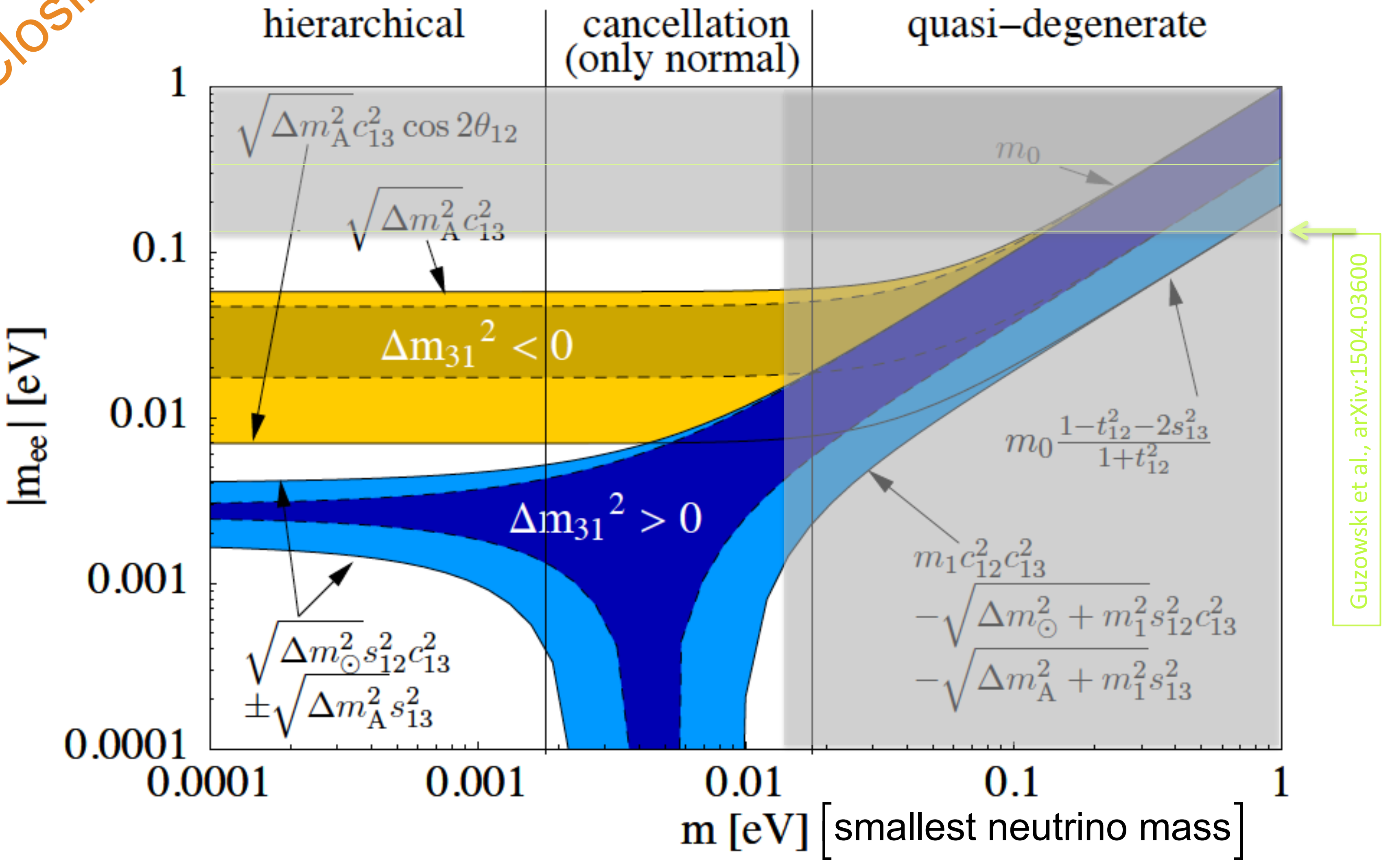
- No events with E > 3.2 MeV
- Exposure of 34.7 kg*y
- Background-free technique for high energy $Q_{\beta\beta}$ isotopes:

^{48}Ca:	4.268 MeV
^{150}Nd:	3.371 MeV
^{96}Zr:	3.356 MeV

The gauge of progress

Closing in …

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



W. Rodejohann J. Phys. G 39, 124008 (2012)

Planck 2015, arXiv:1502.01589
Σm / 3 = 490 meV / 3 = 163 meV

Conclusions / Summary

- Well-motivated, vigorous experimental program worldwide

- NEMO-3: unique multi-observable technique

^{100}Mo: $T_{1/2}^{0\nu\beta\beta} > 1.1\times10^{24}$ y (90%CL) → $\langle m_{\beta\beta}\rangle < (330-620)$ meV

  - ✓ results for 6 other isotopes soon: ^{48}Ca, ^{82}Se, ^{96}Zr, ^{116}Cd, ^{130}Te, ^{150}Nd
  - ✓ results on transitions to excited states, V+A, Majorons, SSD vs HSD, …
  - ✓ no background events > 3.2 MeV

- SuperNEMO (first demonstration module in 2016)
  - ^{82}Se, possibly also ^{150}Nd, ^{48}Ca
  - sensitivity:

$T_{1/2}^{0\nu\beta\beta} > 1\times10^{26}$ y (90%CL) (500 kg*y exposure)

→ $\langle m_{\beta\beta}\rangle < (40-140)$ meV

- We acknowledge the support by the US NSF and other national funding agencies

National Science Foundation
WHERE DISCOVERIES BEGIN

"You can observe a lot just by watching."

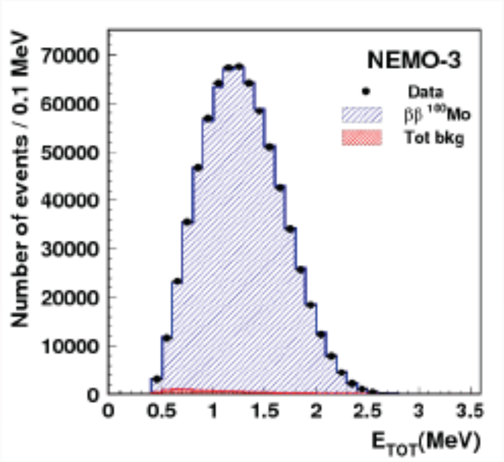
Yogi Berra (a baseball player)

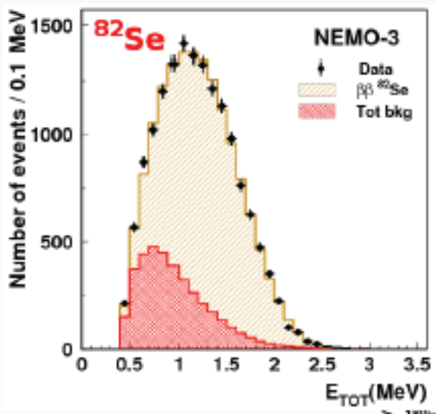
NEMO Collaboration, Aussois, January 2014

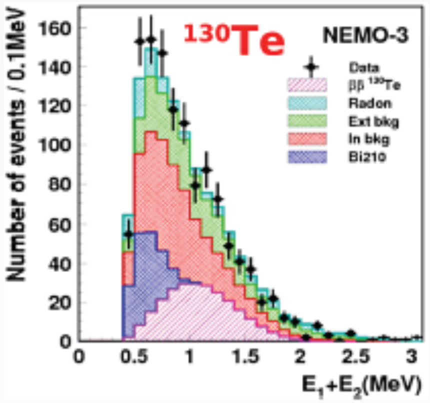
Extras

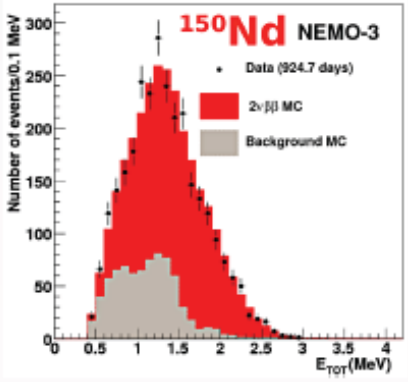
NEMO-3 summary of results

Isotope	Mass (g)	Qββ(keV)	T(2v) (1E19yrs)	S/B	Comment	Reference
Se82	932	2996	9.6 ± 1.0	4	World's best	Phys.Rev.Lett. 95(2005) 483
Cd116	405	2809	2.8 ± 0.3	10	World's best	*Preliminary*
Nd150	37	3367	0.9 ± 0.07	2.7	World's best	Phys. Rev. C 80, 032501 (2009)
Zr96	9.4	3350	2.35 ± 0.21	1	World's best	Nucl.Phys.A 847(2010) 168
Ca48	7	4271	4.4 ± 0.6	6.8 (h.e.)	World's best	*Preliminary*
Mo100	6914	3034	0.71 ± 0.05	80	World's best	Phys.Rev.Lett. 95(2005) 483
Te130	454	2533	70 ± 14	0.5	First direct detection	Phys. Rev. Lett. 107, 062504 (2011)

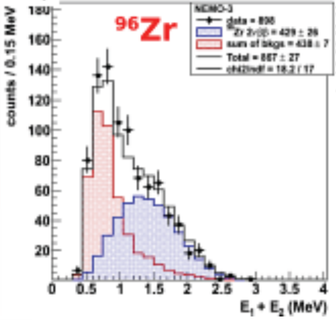


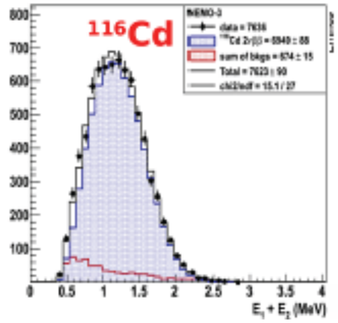


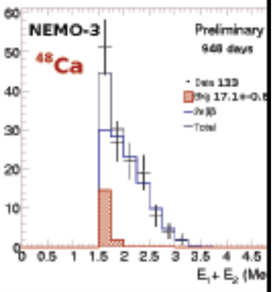




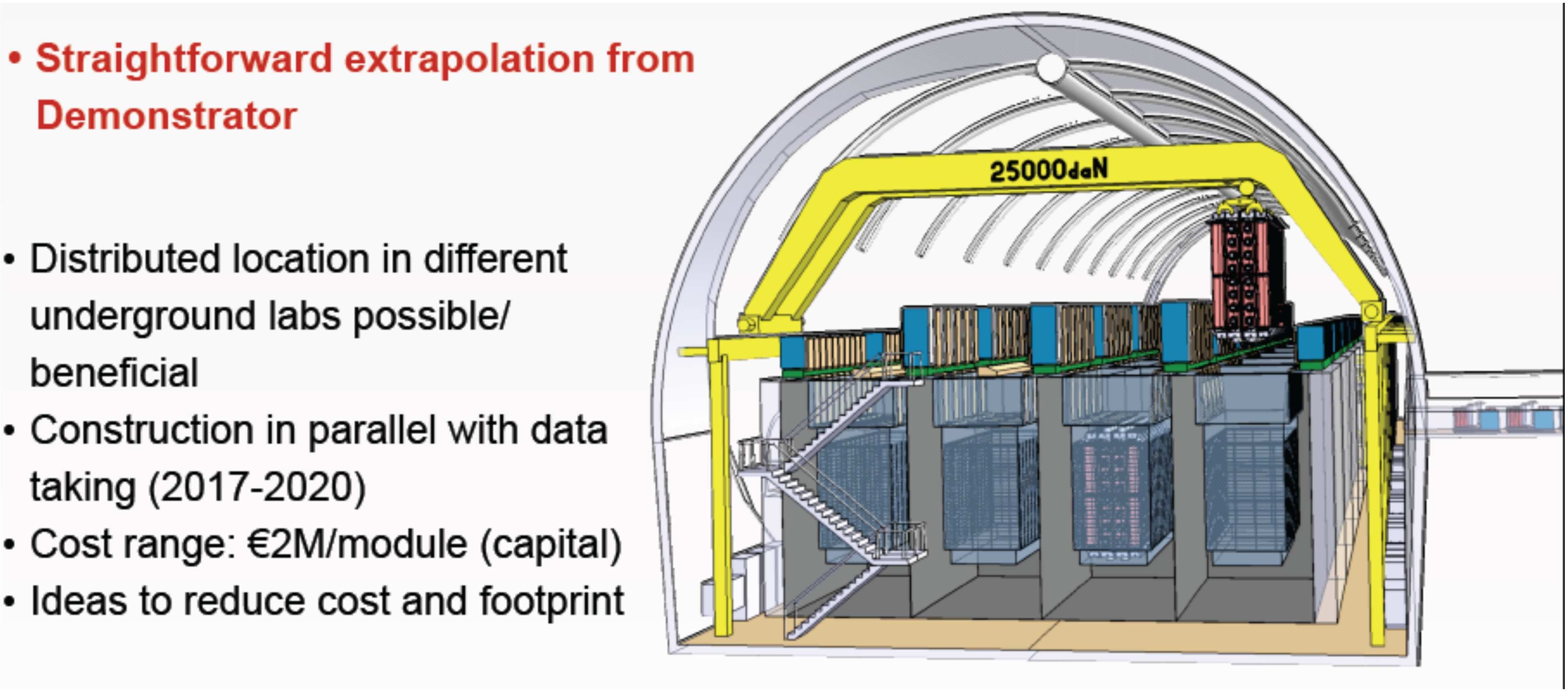
Crucial experimental input for
1) NME calculations
2) Ultimate background characterisation for 0ν







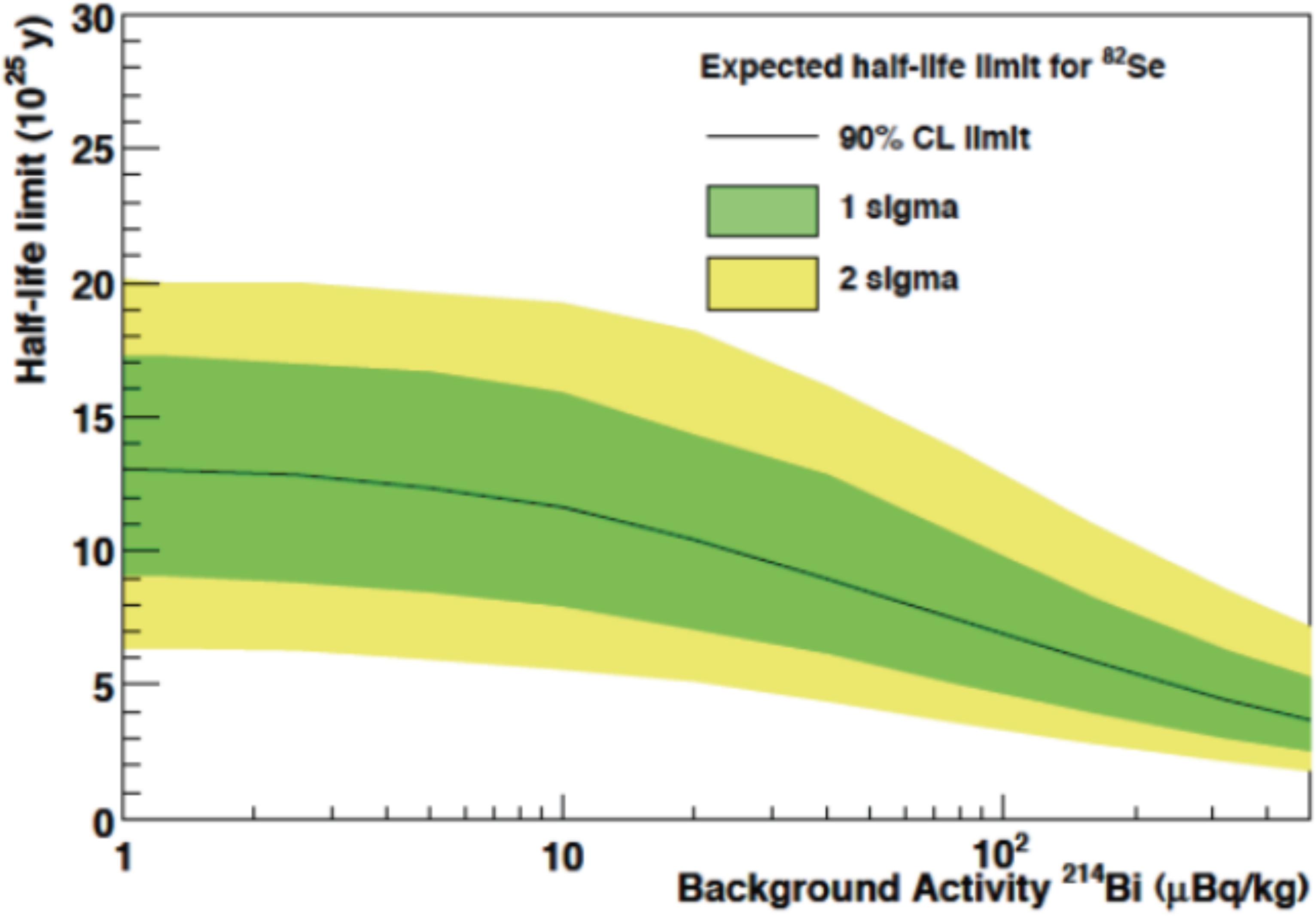
SuperNEMO – 20 module, 100 kg of isotope



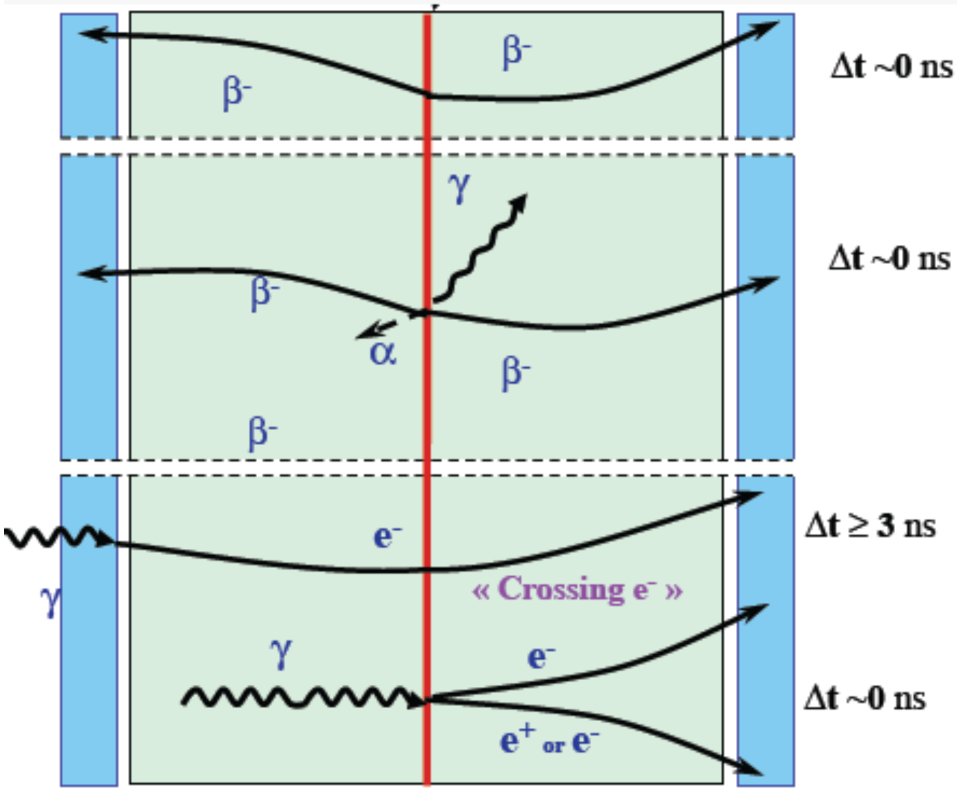
- **Straightforward extrapolation from Demonstrator**

- Distributed location in different underground labs possible/ beneficial
- Construction in parallel with data taking (2017-2020)
- Cost range: €2M/module (capital)
- Ideas to reduce cost and footprint

SuperNEMO sensitivity



Background suppression



Powerful **background rejection** through topology, timing, particle ID (e+, e-, α, γ)

Lowest background index

NEMO-3

b = 10^{-3} cnts kg^{-1} keV^{-1} yr^{-1} — **data!**

SuperNEMO

b = $(0.5\text{-}1)\times 10^{-4}$ cnts kg^{-1} keV^{-1} yr^{-1}

Calorimeter expts (GERDA, CUORE)

b = 10^{-2} cnts kg^{-1} keV^{-1} yr^{-1}

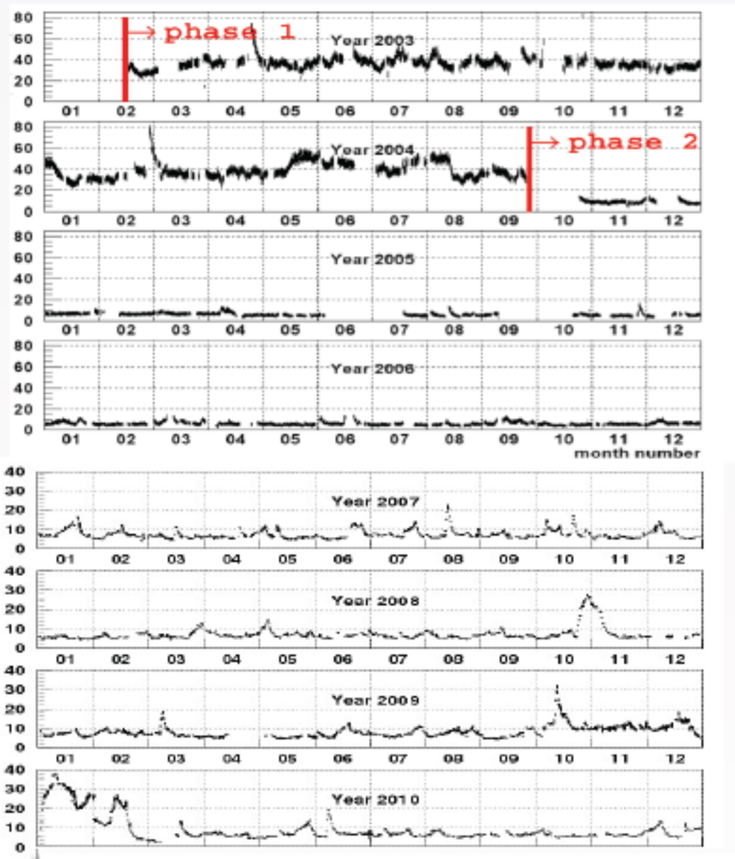
(ultimately down to 10^{-3})

But much more modest energy resolution

Radon

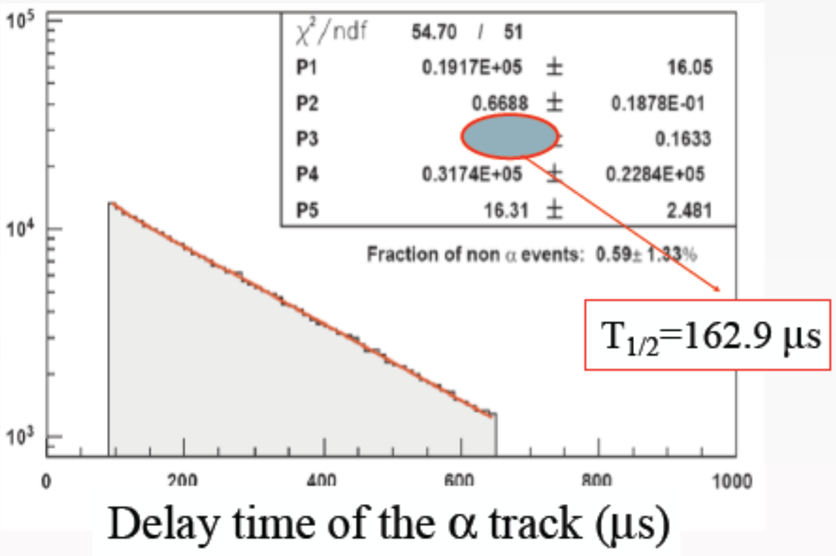
Anti-radon "factory" - trapping Rn in cooled charcoal. A must for a low-background lab.

Measurements of ^{222}Rn activity in the gas of tracker (mBq/m^3)



"Handbook" on backgrounds for ββ experiments:
Background measurement in NEMO3:
NIM A 606 (2009) pp. 449-465.

Pure sample of ^{214}Bi – ^{214}Po events



Anti-Rn factory: Input=15Bq/m^3 →Output 15mBq/m^3

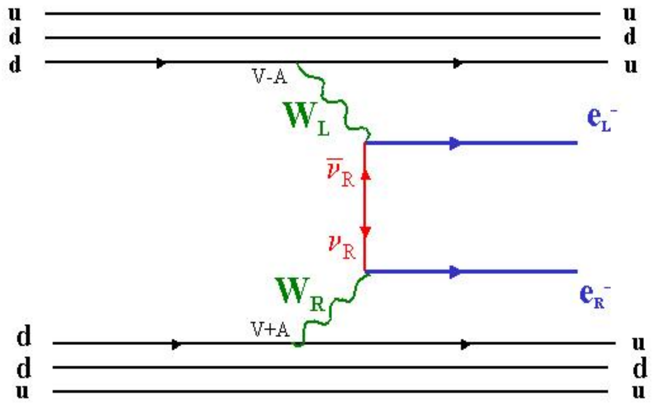
Inside the detector:

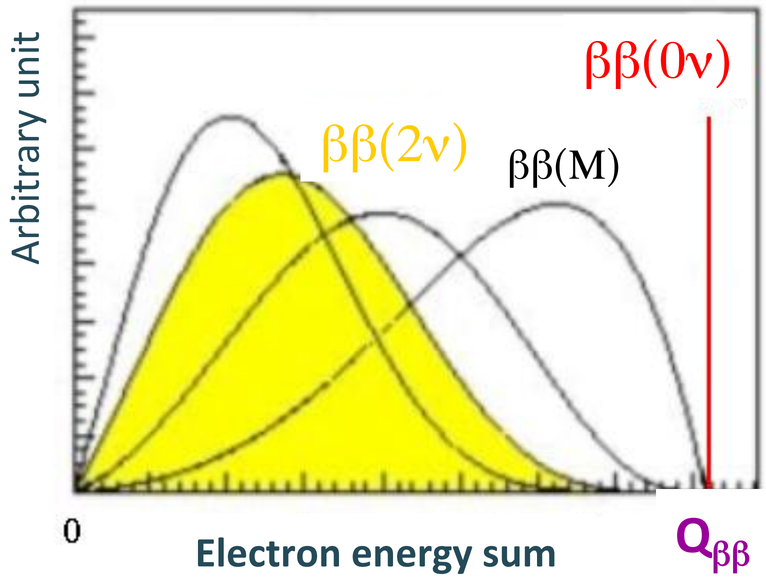
- Phase 1: Feb'03 → Sep'04
  A(Radon) ≈ 40 mBq/m^3
- Phase 2: Dec. 2004 → Jan'11
  A (Radon) ≈ 5 mBq/m^3

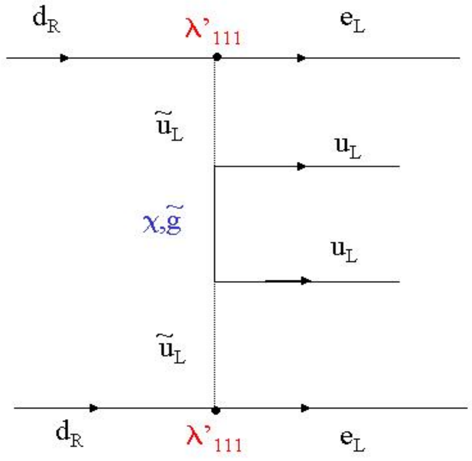
Neutrinoless double beta decay

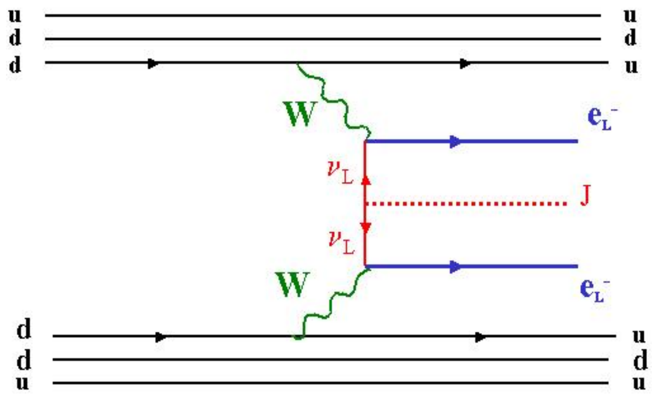
$$(Z,A) \rightarrow (Z+2,A) + 2e^-$$

Process:	**Parameters**
1) Light neutrino exchange	$<m_\nu>$
2) (V+A) current	$<m_\nu>,<\lambda>,<\eta>$
3) Majoron emission	$<g_M>$
4) SUSY	$\lambda'_{111}, \lambda'_{113}, \lambda'_{131}, \ldots$







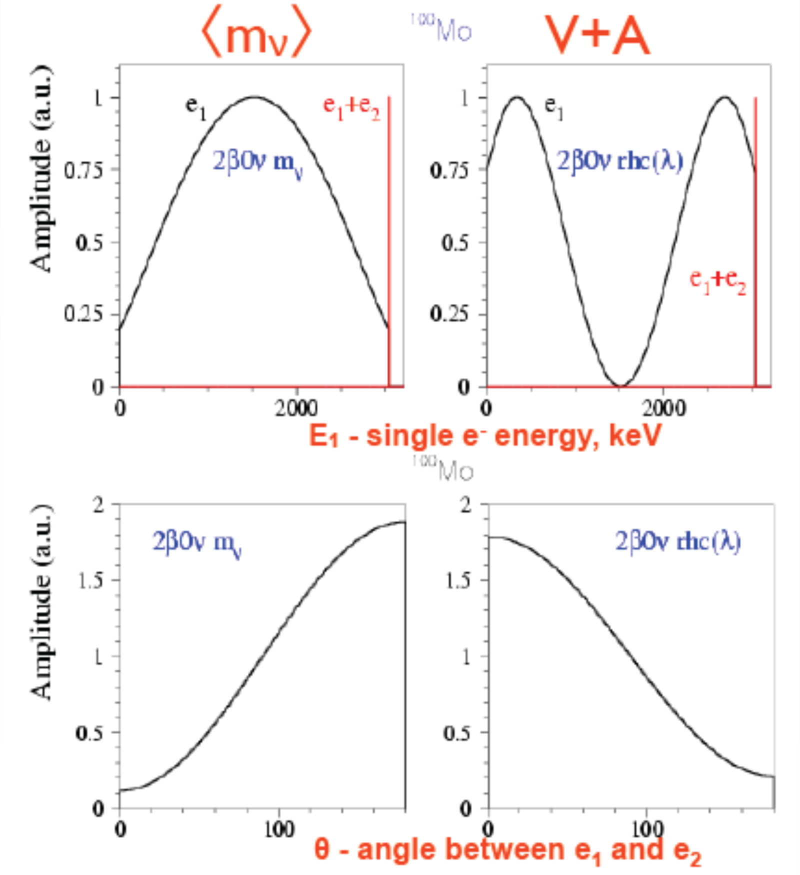


+ difference in angular distributions

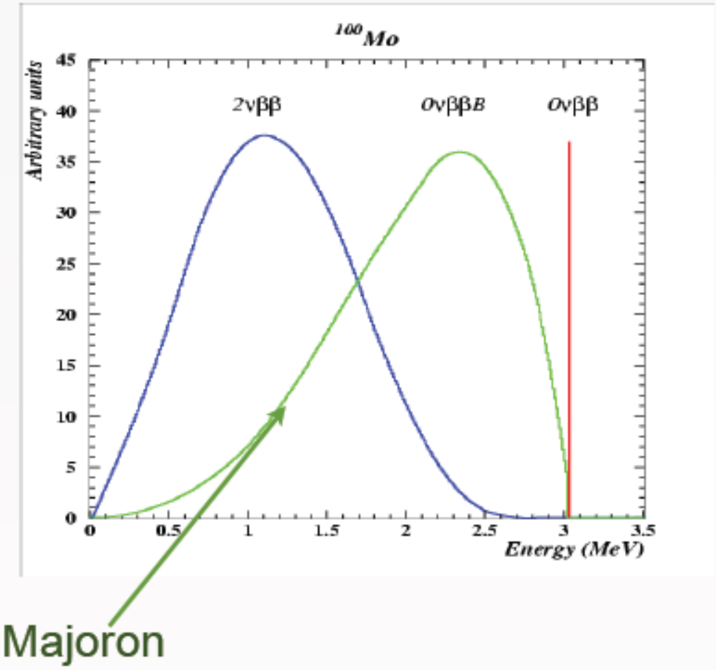
Strengths of topological reconstruction

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

η can be due to $\langle m_\nu \rangle$, V+A, Majoron, SUSY, H^- or a combination of them

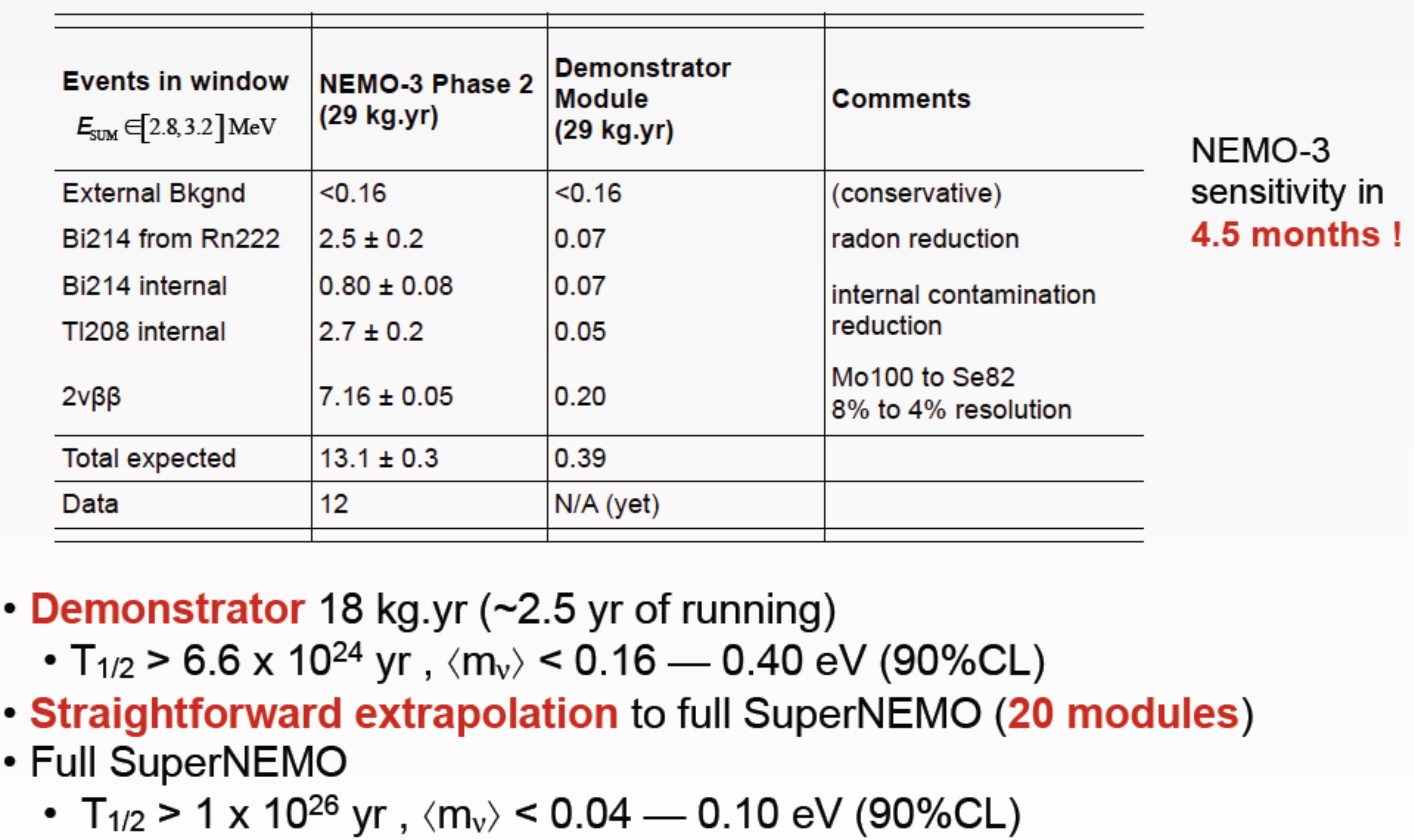


Topology can be used to disentangle underlying physics mechanism



Topology detection is a more sensitive method for phenomena with continuous spectra, e.g. 2νββ, 0νββB (Majoron)

A zero background experiment

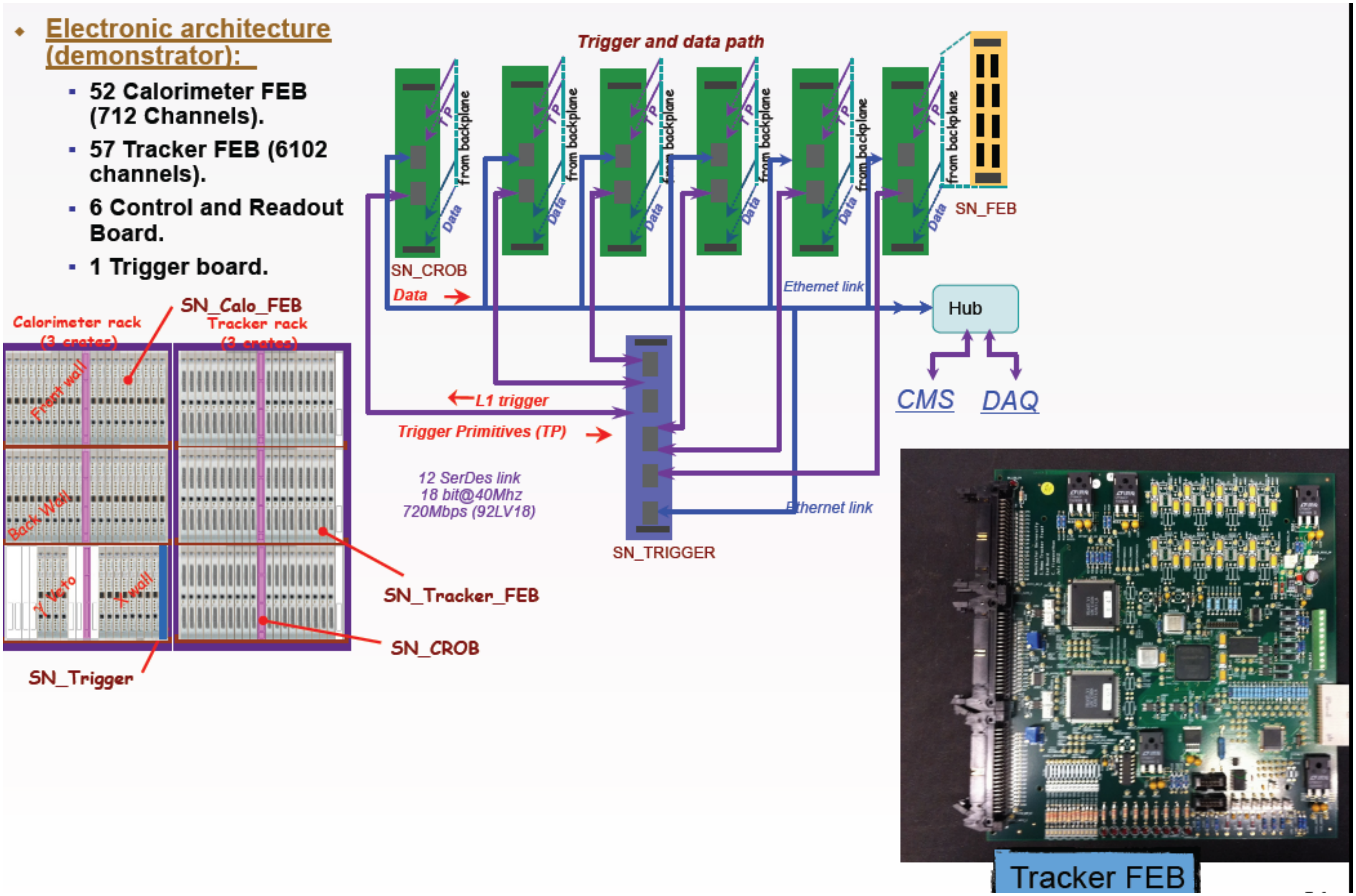


Events in window $E_{SUM} \in [2.8, 3.2]\,\mathrm{MeV}$	**NEMO-3 Phase 2 (29 kg.yr)**	**Demonstrator Module (29 kg.yr)**	**Comments**
External Bkgnd	<0.16	<0.16	(conservative)
Bi214 from Rn222	2.5 ± 0.2	0.07	radon reduction
Bi214 internal	0.80 ± 0.08	0.07	internal contamination reduction
Tl208 internal	2.7 ± 0.2	0.05	
$2\nu\beta\beta$	7.16 ± 0.05	0.20	Mo100 to Se82 8% to 4% resolution
Total expected	13.1 ± 0.3	0.39	
Data	12	N/A (yet)	

NEMO-3 sensitivity in **4.5 months !**

- **Demonstrator** 18 kg.yr (~2.5 yr of running)
  - $T_{1/2} > 6.6 \times 10^{24}$ yr , $\langle m_\nu \rangle < 0.16$ — 0.40 eV (90%CL)
- **Straightforward extrapolation** to full SuperNEMO (**20 modules**)
- Full SuperNEMO
  - $T_{1/2} > 1 \times 10^{26}$ yr , $\langle m_\nu \rangle < 0.04$ — 0.10 eV (90%CL)

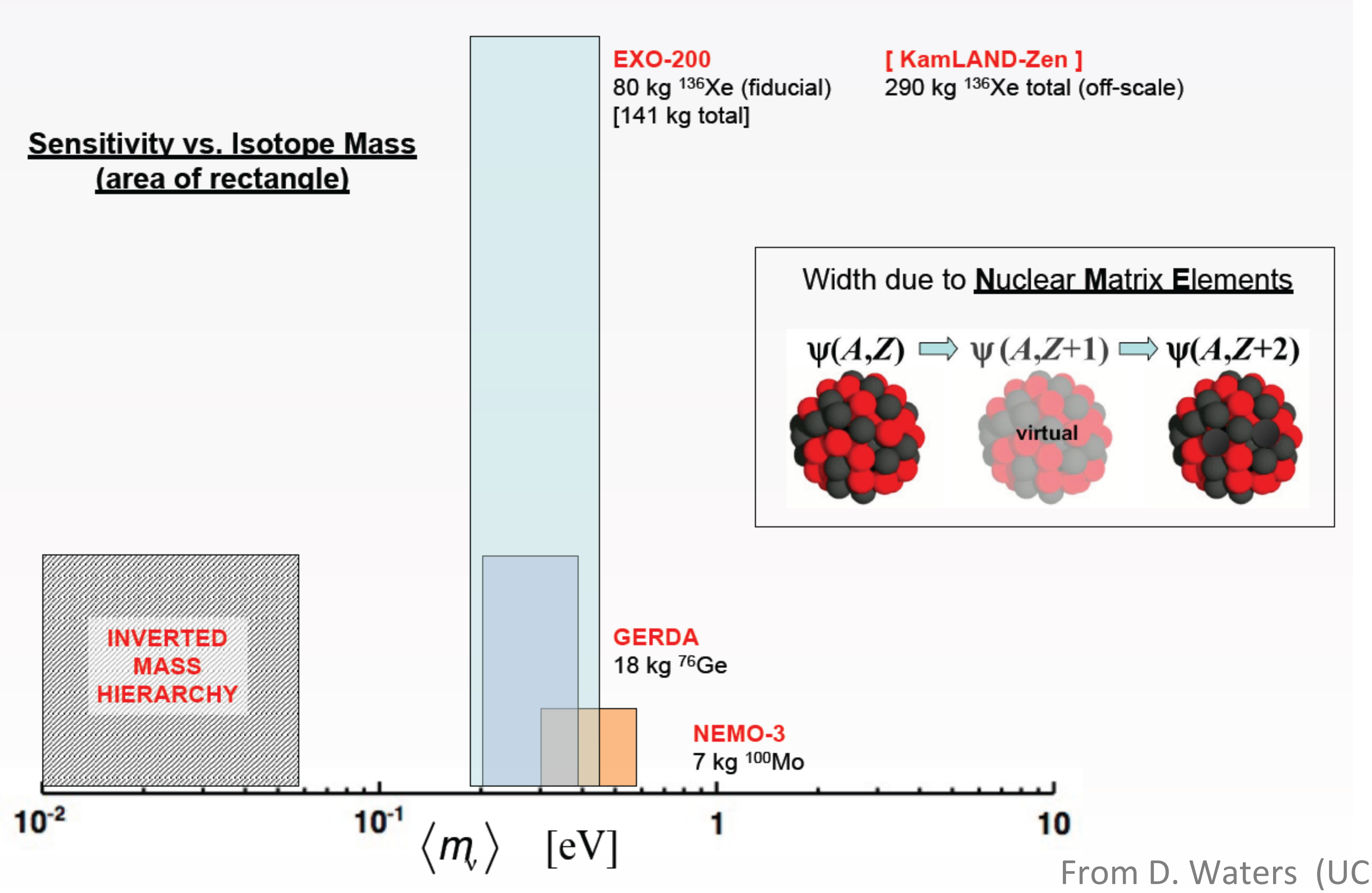
FE, slow control, daq



- **Electronic architecture (demonstrator):**
  - **52 Calorimeter FEB (712 Channels).**
  - **57 Tracker FEB (6102 channels).**
  - **6 Control and Readout Board.**
  - **1 Trigger board.**

Tracker FEB

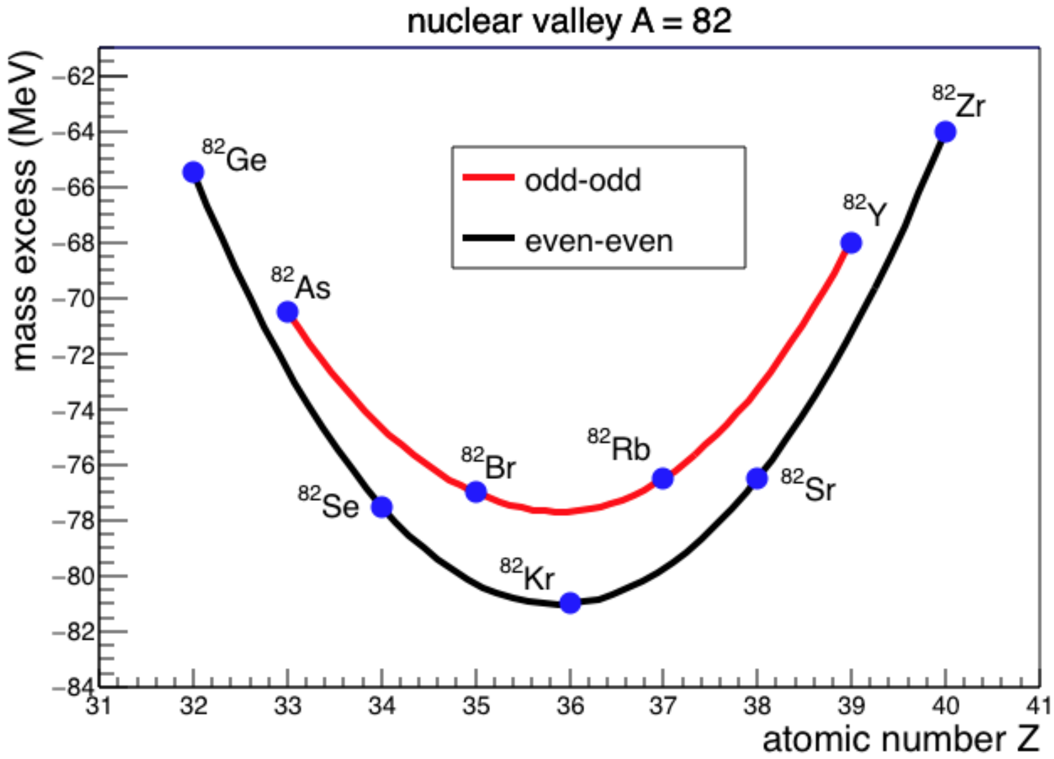
Sensitivity comparison



From D. Waters (UCL)

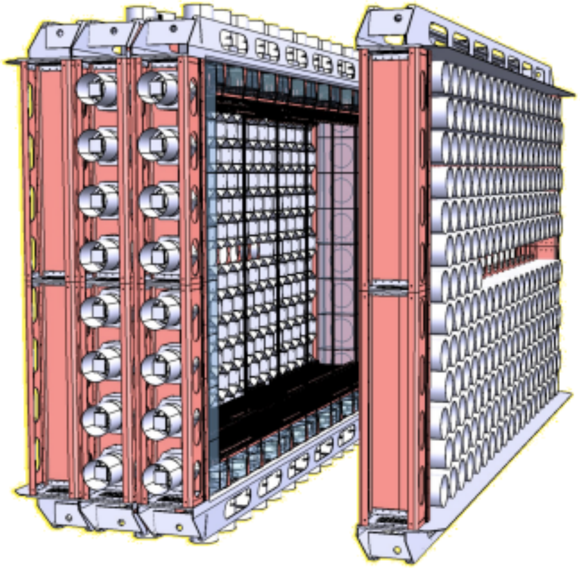
Phenomenology of 0νββ and 2νββ

- Pairing interaction between nucleons (even-even nuclei more bound than the odd-odd nuclei)
- e.g., $^{82}_{34}$Se is stable against β decay, but unstable against $\beta^-\beta^-$ decay



There are 35 $\beta^-\beta^-$ emitters
6 $\beta^+\beta^+$

NEMO-3 → SuperNEMO



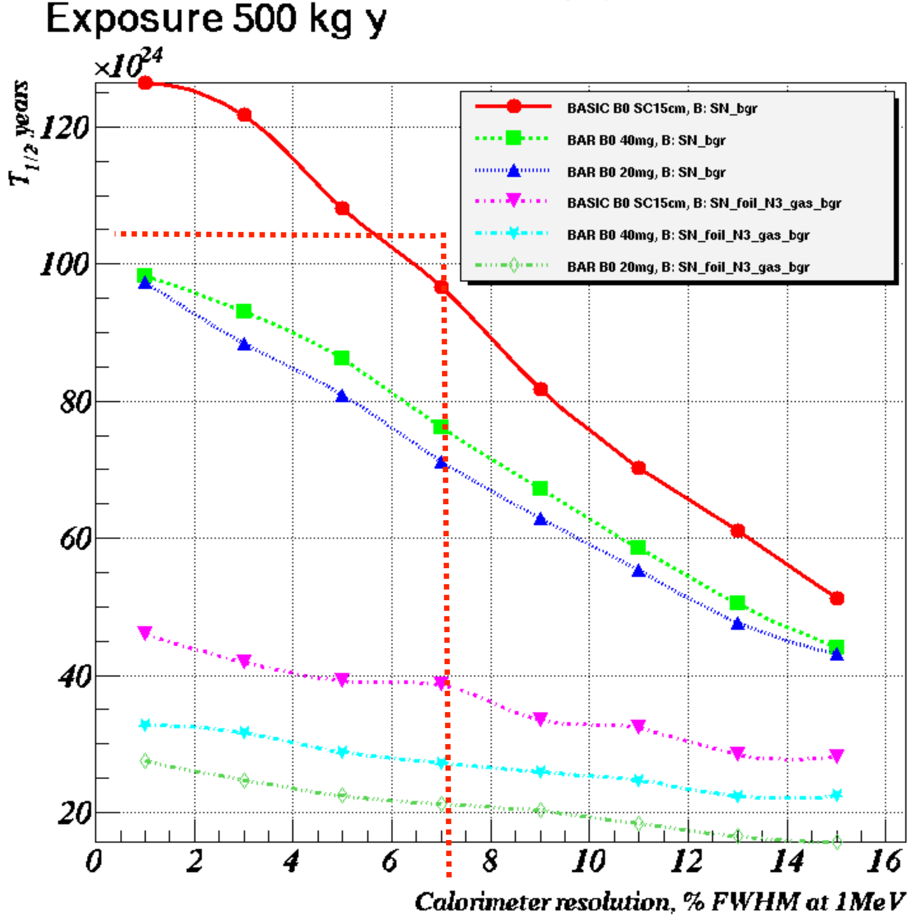
For no background:

$$T^{0\nu}_{1/2}(n_\sigma) = \frac{4.16 \times 10^{26}\, y}{n_\sigma}\left(\frac{\varepsilon \times a}{W}\right) M \times t$$

NEMO-3	R&D since 2005	SuperNEMO
^{100}Mo	isotope	^{82}Se (maybe also ^{150}Nd or ^{48}Ca)
7 kg	mass	**100 kg**
A(^{208}Tl) < 20 μBq/kg A(^{214}Bi) < 300 μBq/kg Rn ~ 5-6 mBq/m^3	Radio-purity of the foil Radon in the tracker	A(^{208}Tl) < 2 μBq/kg A(^{214}Bi) < 10 μBq/kg Rn < 0.15 mBq/m^3
8% FWHM @ 3 MeV	Energy resolution	4% FWHM @ 3 MeV
$T_{1/2}(0\nu\beta\beta) > 1.1 \times 10^{24}$ y **$\langle m_n \rangle < (330 – 620)$ meV**	sensitivity	**$T_{1/2}(0\nu\beta\beta) > 1 \times 10^{26}$ y** **$\langle m_n \rangle < (40 – 140)$ meV**
1 module	modularity	**>20 modules (new lab)**

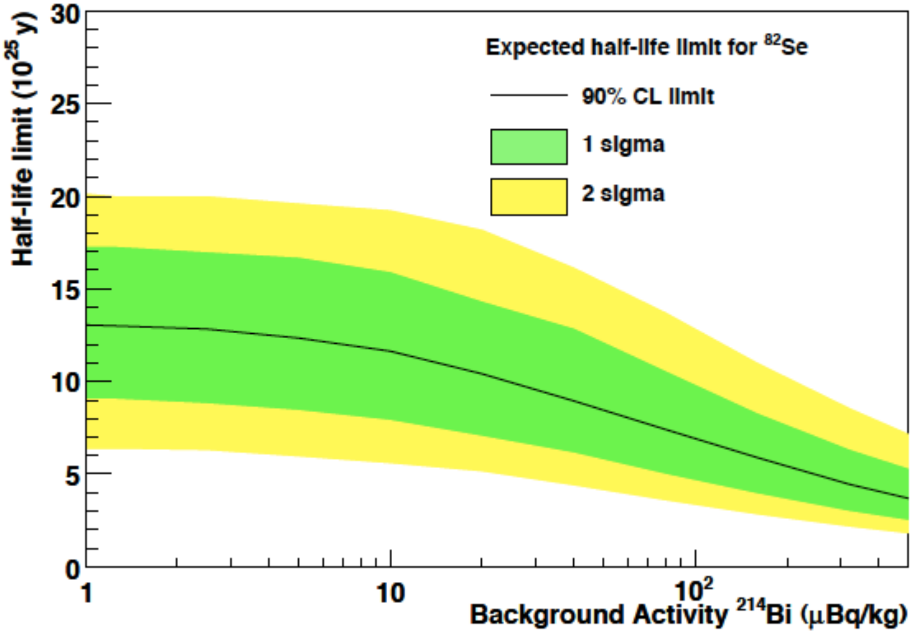
Sensitivity

^{82}Se



Calorimeter resolution (% FWHM at 1 MeV)

GEANT-4 based model of the detector combined with NEMO-3 experience.



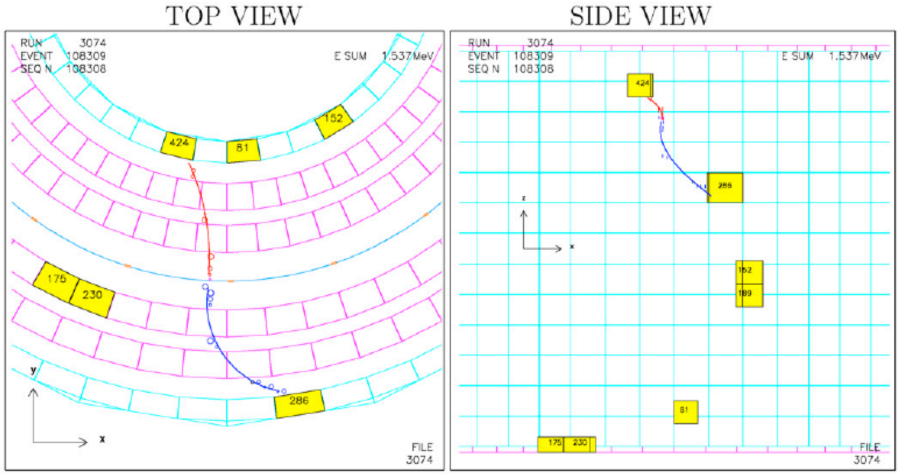
^{82}Se:

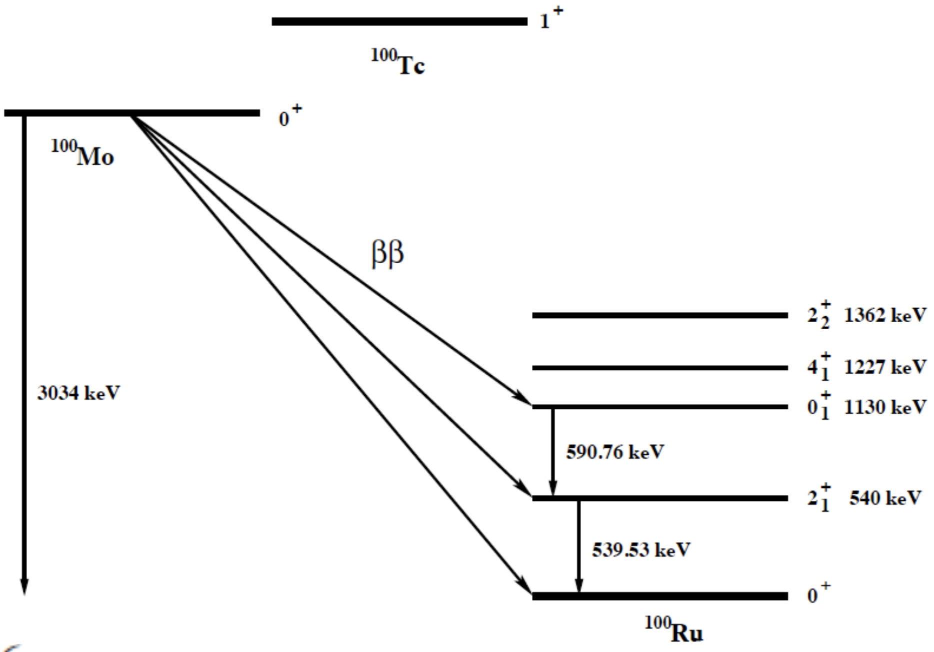
- ✓ 5yrs with 100 kg
  - ✓ $T_{1/2}(0\nu\beta\beta) > 1 \times 10^{26}$ y
- ✓ $\langle m_\nu \rangle <$ (40 – 140) meV

NEMO-3: $\beta\beta$ of ^{100}Mo to excited states

Transition	$T_{1/2}$ (y) (this work)	Theory
$0\nu\beta\beta$ $0^+ \to 2^+_1$	$> 1.6 * 10^{23}$	$6.8 * 10^{30}$ $\langle m_\nu \rangle$ $2.1 * 10^{27}$ $\langle \lambda \rangle$
$2\nu\beta\beta$ $0^+ \to 2^+_1$	$> 1.1 * 10^{21}$	$2.1 * 10^{21}$ $- \ 5.5 * 10^{25}$
$0\nu\beta\beta$ $0^+ \to 0^+_1$	$> 8.9 * 10^{22}$	$7.6 * 10^{24}$ $\langle m_\nu \rangle$ $- \ 2.6 * 10^{26}$ $\langle m_\nu \rangle$
$2\nu\beta\beta$ $0^+ \to 0^+_1$	$[5.7\,^{+1.3}_{-0.9}$(stat) $+/- \ 0.8 * 10^{20}$	$1.5 * 10^{20}$ $- \ 2.1 * 10^{21}$

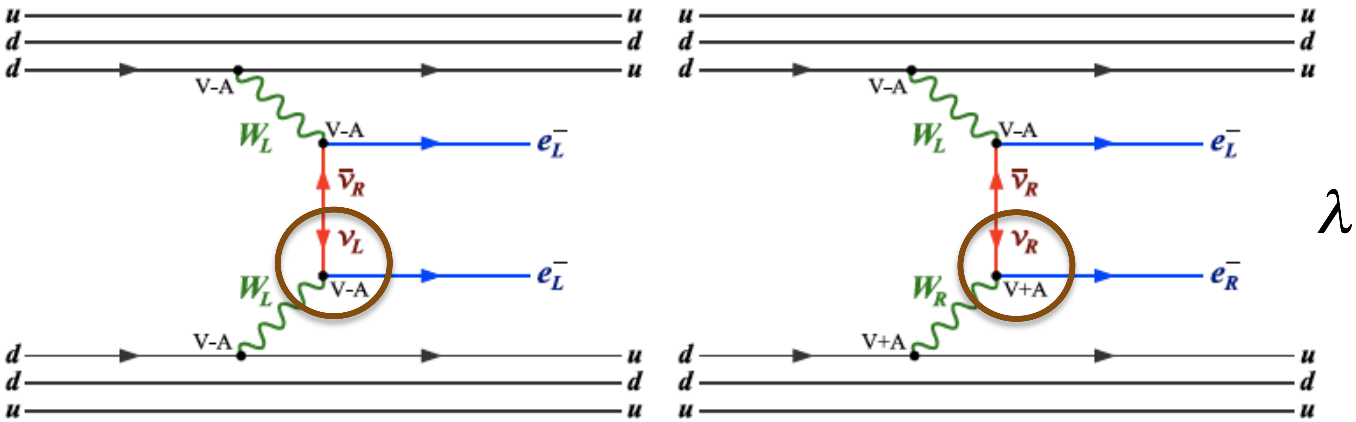
Best limits or uncertainties



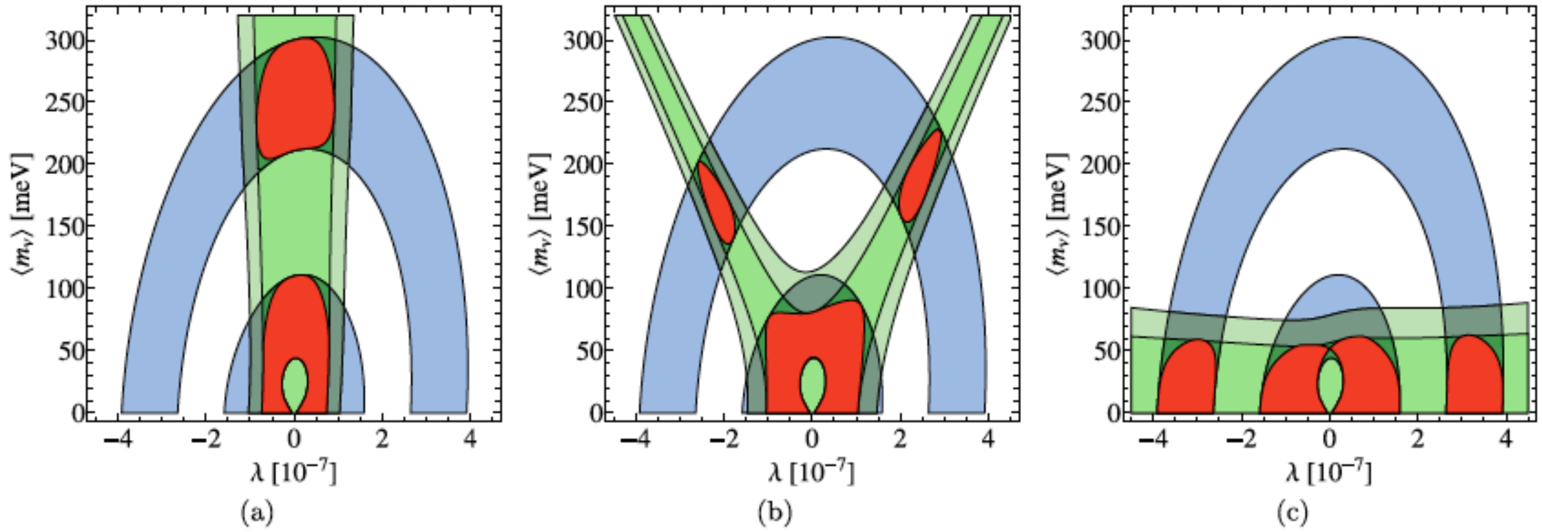


NEMO Collaboration / Nuclear Physics A 781 (2007) 209–226

"Probing new physics models of neutrinoless double beta decay with SuperNEMO";
R. Arnold et al. , Eur. Phys. Jr. C DOI 10.1140/epjc/s10052-010-1481-5



$$\lambda \approx \left(\frac{M_{W_L}}{M_{W_R}}\right)^2 \sqrt{\frac{m_\nu}{M_R}}$$



(a) (b) (c)

Fig. 11 (Color online) Constraints at one standard deviation on the model parameters m_ν and λ for ^{82}Se from: (1) an observation of $0\nu\beta\beta$ decay half-life at $T_{1/2} = 10^{25}$ y (*outer blue elliptical contour*) and 10^{26} y (*inner blue elliptical contour*); (2) reconstruction of the angular (outer, lighter green) and energy difference (inner, darker green) distribution shape; (3) combined analysis of (1) and (2) using decay rate and energy distribution shape reconstruction (*red contours*). The admixture of the MM and RHC$_\lambda$ contributions is assumed to be: **a** pure MM contribution; **b** 30% RHC$_\lambda$ admixture; and **c** pure RHC$_\lambda$ contribution. NME uncertainties are assumed to be 30% and experimental statistical uncertainties are determined from the simulation

Why are neutrino masses so small?

Answer (?): Majorana mass and the see-saw mechanism

With massive neutrinos, we need to add a right-handed neutrino field

$$e_R \qquad \begin{pmatrix}\nu\\ e\end{pmatrix}_L \qquad \boxed{\nu_R}$$

$$L_{m_\nu} = m_D\phi\bar{\nu}_R\nu_L + M_R\phi\bar{\nu}_R^c\nu_R^c + m_D\phi\bar{\nu}_L^c\nu_R^c \qquad [\bar{\nu}_L^c, \bar{\nu}_R]\begin{bmatrix}0 & m_D\\ m_D & M_R\end{bmatrix}\begin{bmatrix}\nu_L\\ \nu_R^c\end{bmatrix} + \text{h.c.}$$

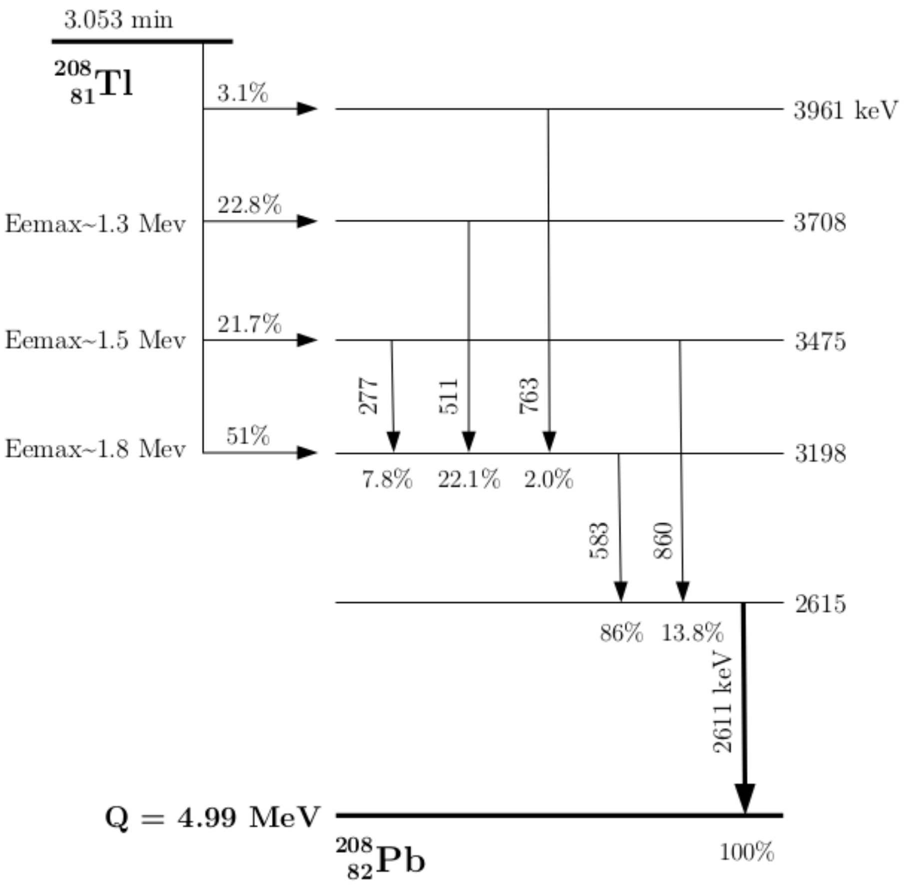
$$D_\nu = \begin{bmatrix}\frac{m_D^2}{M_R} & 0\\ 0 & M_R\end{bmatrix} \qquad \boxed{m_1 \simeq \frac{m_D^2}{M_R} \qquad \text{and} \qquad m_2 \simeq M_R}$$

$$L_{m_\nu} = m_1\bar{\nu}_1\nu_1 + M_R\bar{\nu}_2\nu_2$$

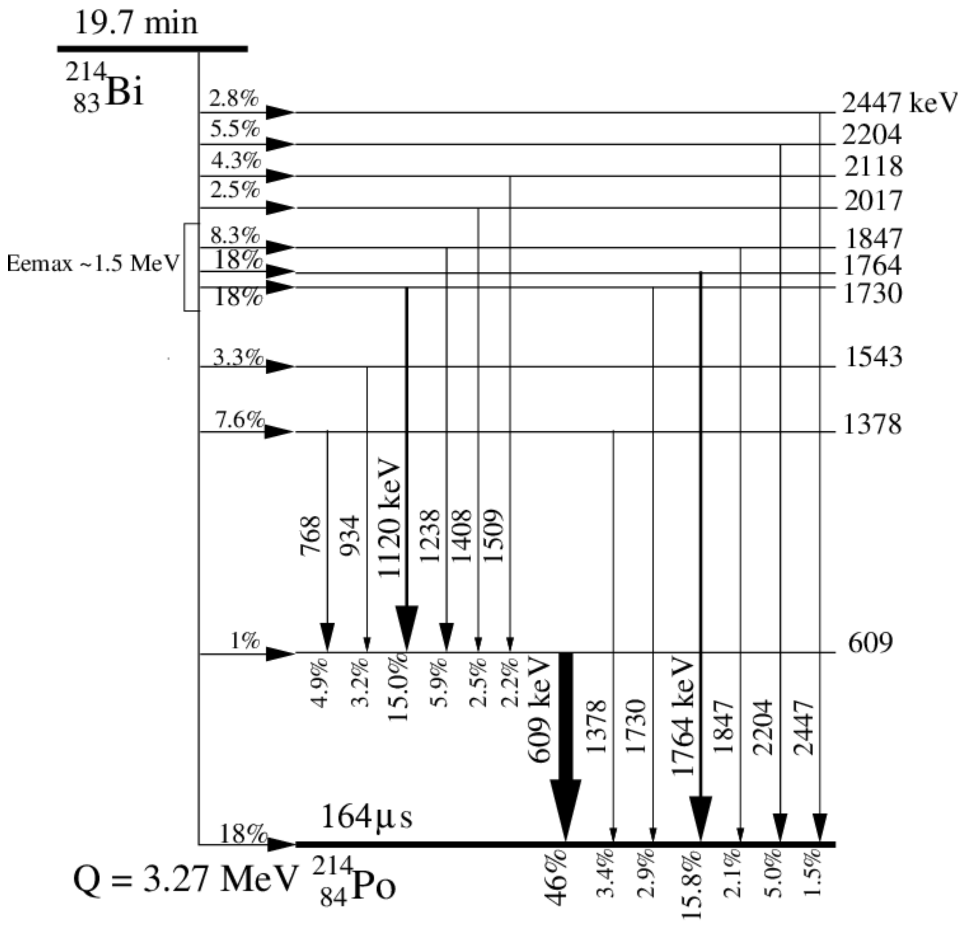
$$\nu_1 = -i(1-\frac{1}{2}\rho^2)(\nu_L - \nu_L^c) + i\rho(\nu_R^c - \nu_R)$$

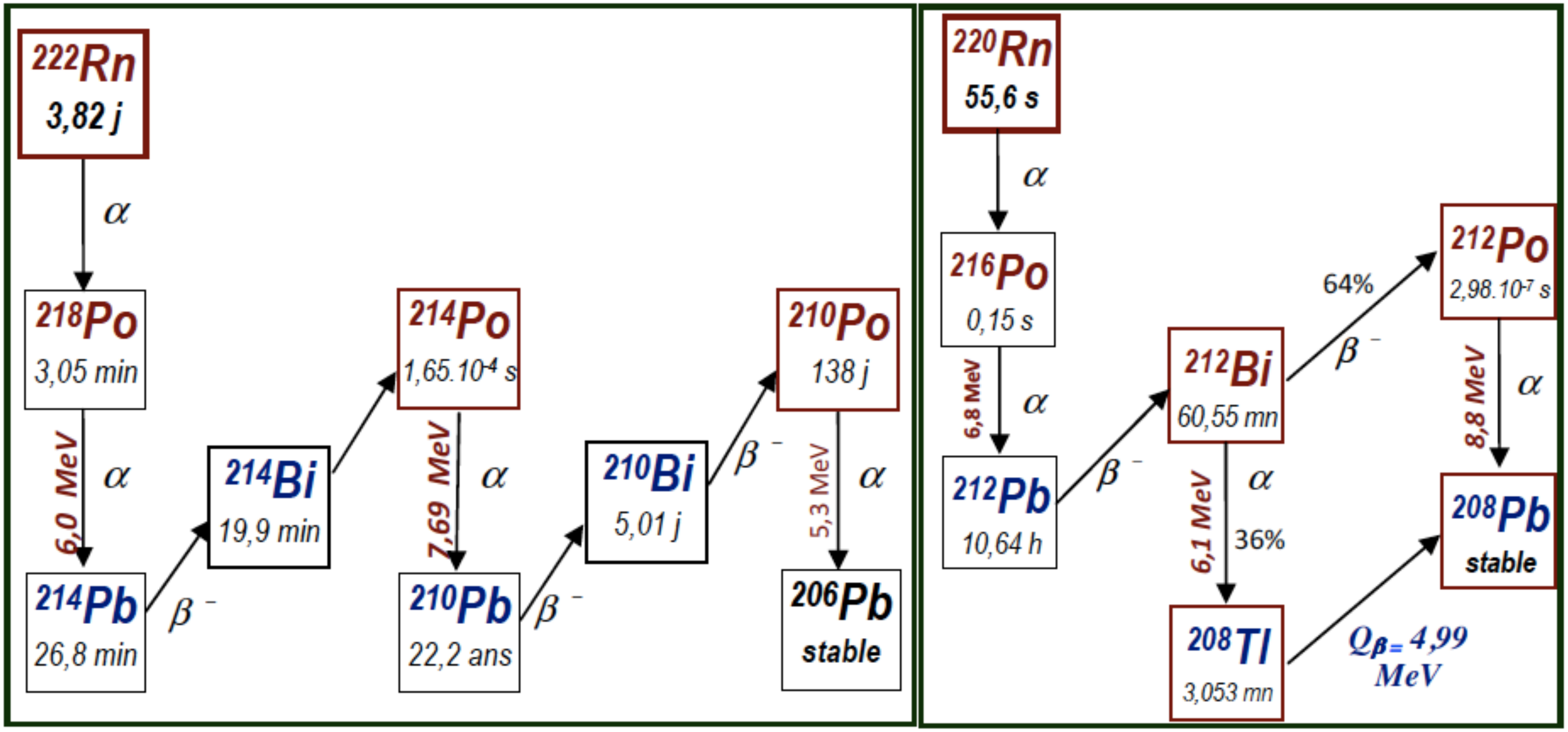
$$\nu_2 = \rho(\nu_L + -\nu_L^c) + (1-\frac{1}{2}\rho^2)(\nu_R + \nu_R^c)$$

^{232}Th decay chain



^{238}U decay chain





^{222}Rn 3,82 j

α

^{218}Po 3,05 min

6,0 MeV α

^{214}Pb 26,8 min

β ⁻

^{214}Bi 19,9 min

^{214}Po $1,65.10^{-4}$ s

7,69 MeV α

^{210}Pb 22,2 ans

β ⁻

^{210}Bi 5,01 j

β ⁻

^{210}Po 138 j

5,3 MeV α

^{206}Pb stable

^{220}Rn 55,6 s

α

^{216}Po 0,15 s

6,8 MeV α

^{212}Pb 10,64 h

β ⁻

^{212}Bi 60,55 mn

64% β ⁻

^{212}Po $2,98.10^{-7}$ s

8,8 MeV α

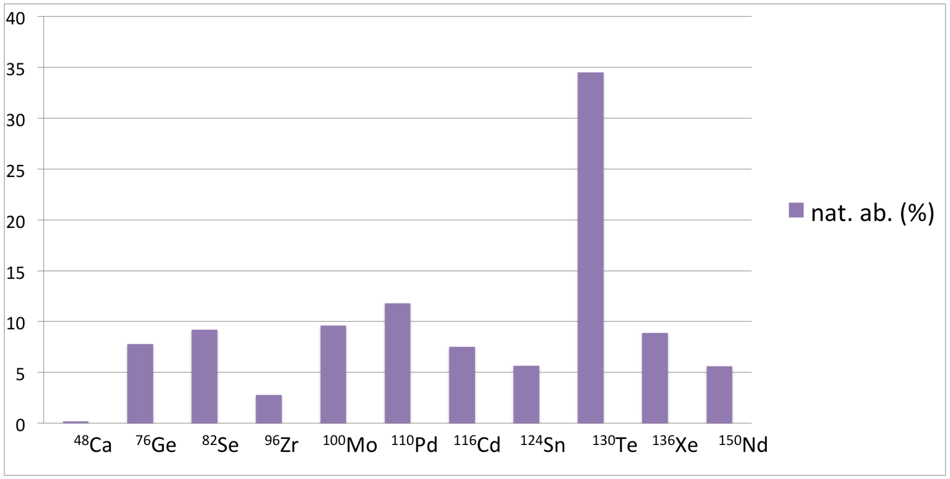
^{208}Pb stable

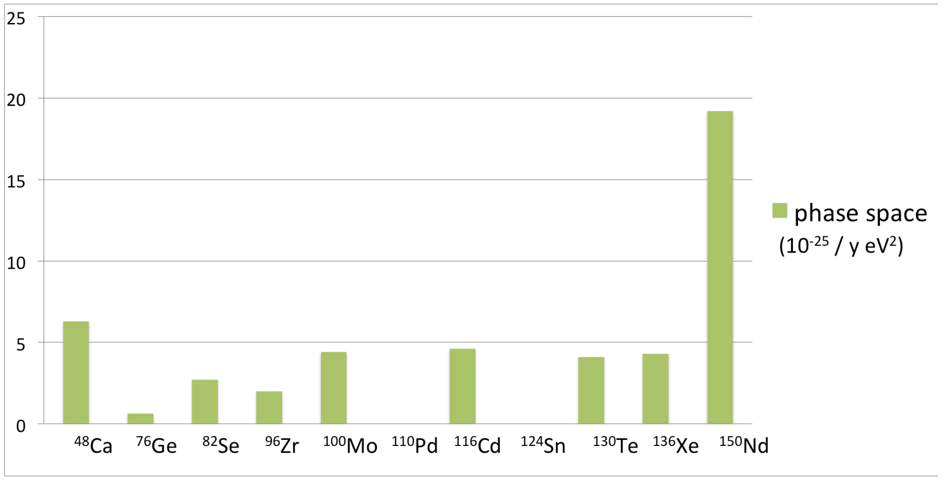
6,1 MeV α 36%

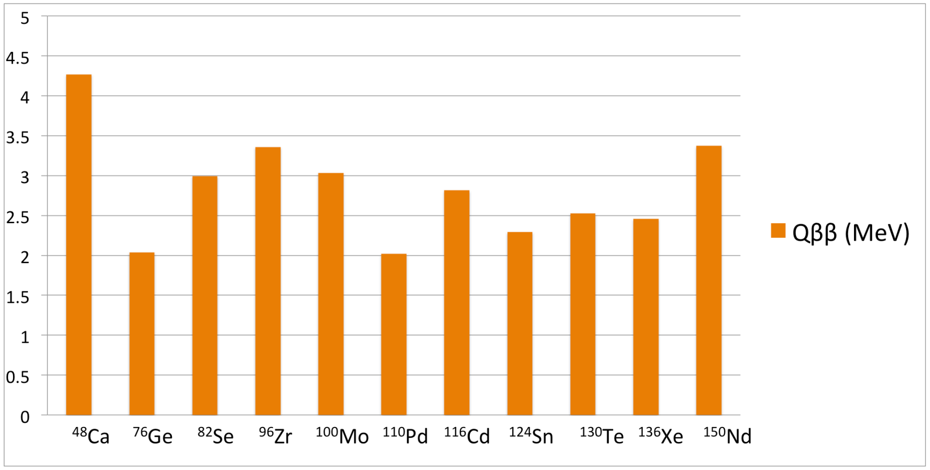
^{208}Tl 3,053 mn

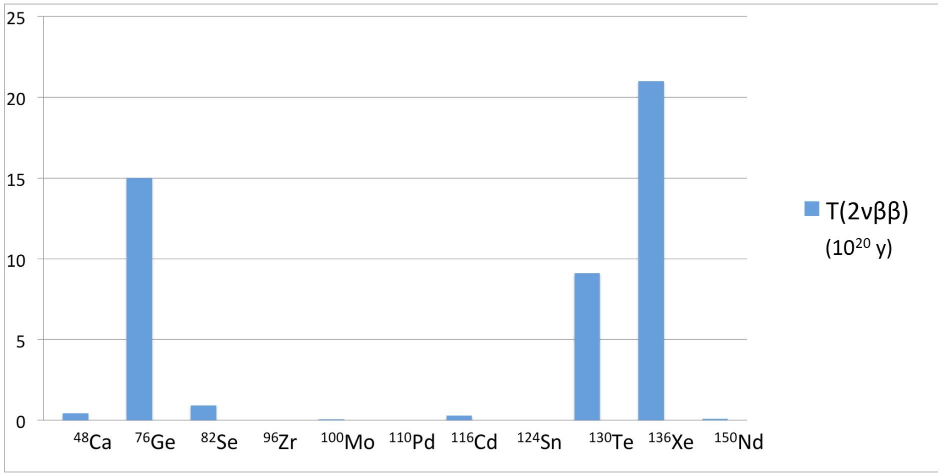
Q_{β}= 4,99 MeV

Basic features









Direct comparison of features