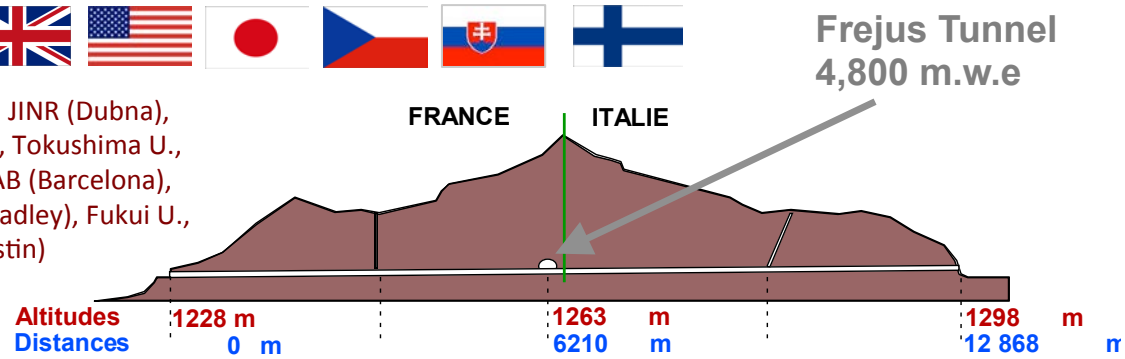
NEMO Collaboration

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

National Science Foundation
WHERE DISCOVERIES BEGIN



SuperNEMO
in the USA

Karol Lang
University of Texas at Austin

On behalf of the NEMO Collaboration

Intensity Frontier Neutrino Subgroup Workshop 2013

6-7 March 2013 *SLAC*

Outline:

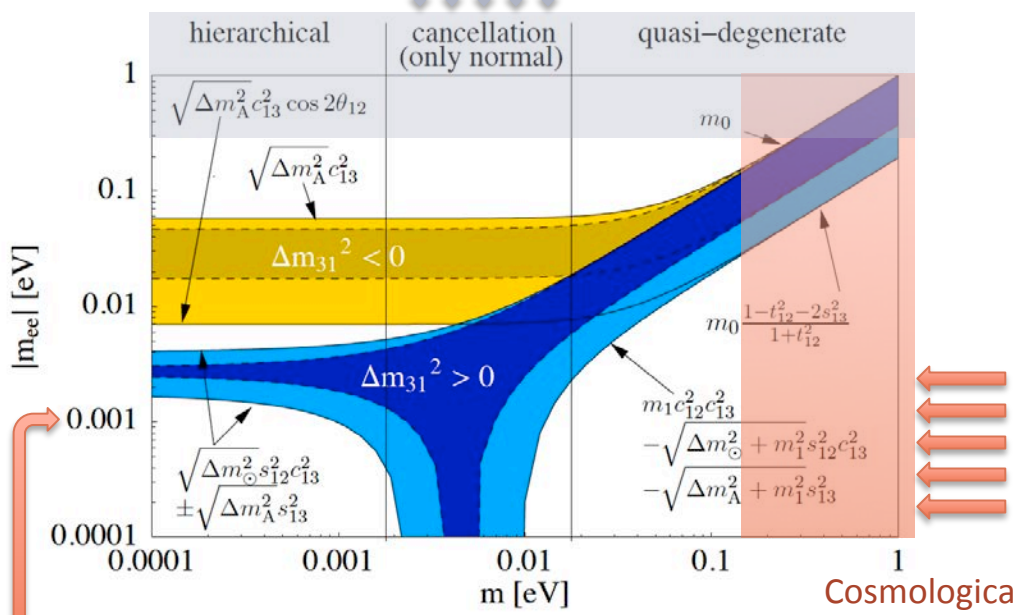
1. Practical context for $0\nu\beta\beta$
2. NEMO technique
3. NEMO-3 results
4. Status of SuperNEMO

The "gauge" of progress

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

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

0νββ bounds



Lightest neutrino mass

Cosmological bounds (model dependent)

$$\left\langle m_{\beta\beta} \right\rangle = \left|m_{ee}\right| = \left|\cos^2\theta_{13}(\cos^2\theta_{12} m_1 + \sin^2\theta_{12} e^{2i\alpha} m_2) + \sin^2\theta_{13} e^{2i\beta} m_3\right|$$

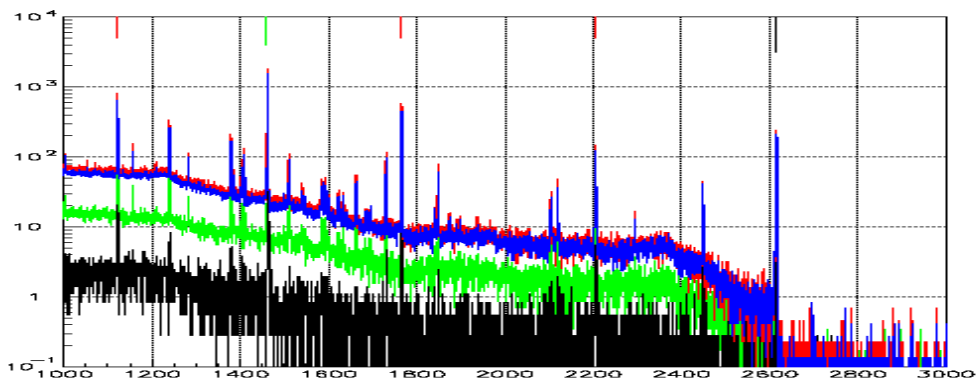
W. Rodejohann, ``*Neutrinoless double beta decay and neutrino physics,*'' J. Phys. **G 39,** 124008 (2012) [arXiv:1206.2560 [hep-ph]].

"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 !!!



$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16\times10^{26}\,y}{n_\sigma}\left(\frac{\varepsilon\times a}{W}\right)\sqrt{\frac{M\times t}{b\times\Delta E}}$$

Background w/ rate *b*

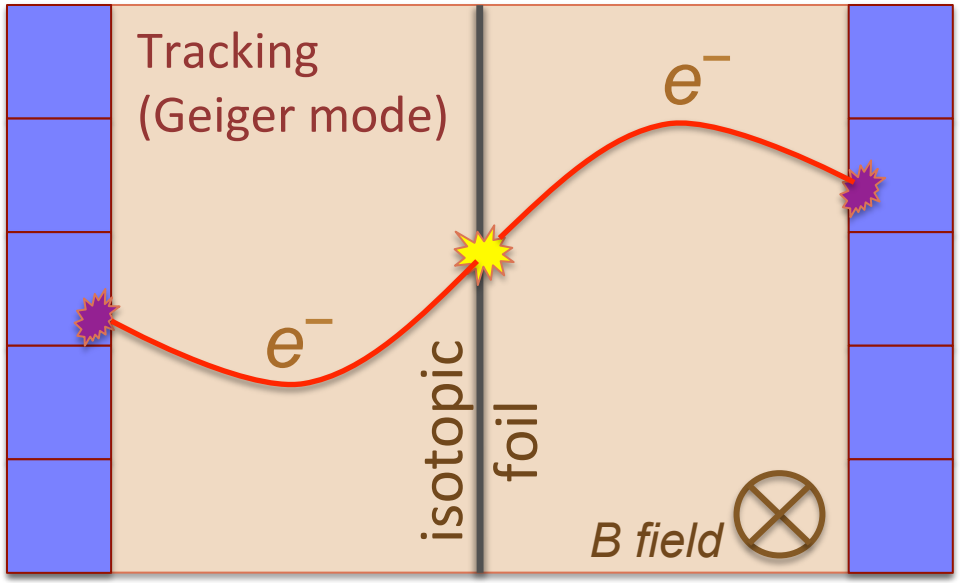
$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16\times10^{26}\,y}{n_\sigma}\left(\frac{\varepsilon\times a}{W}\right) M\times t$$

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)

The multi-observable principle:

topology, kinematics, timing



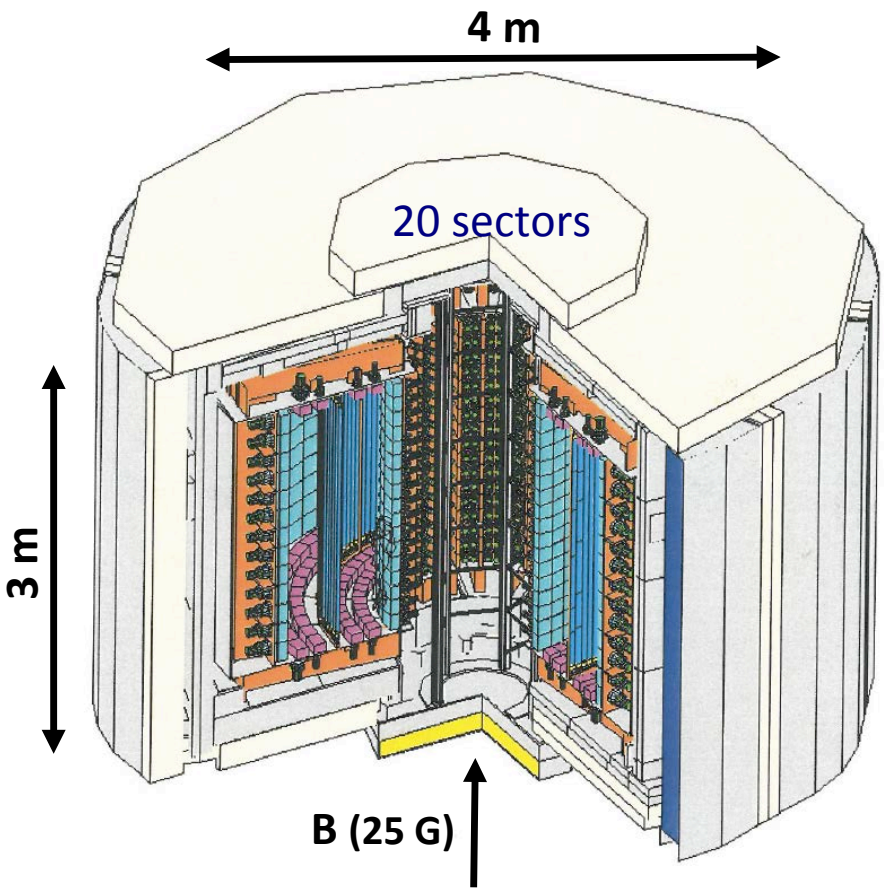
Plastic scintillator calorimeter

Radio-pure materials
and a multi-layer shielding

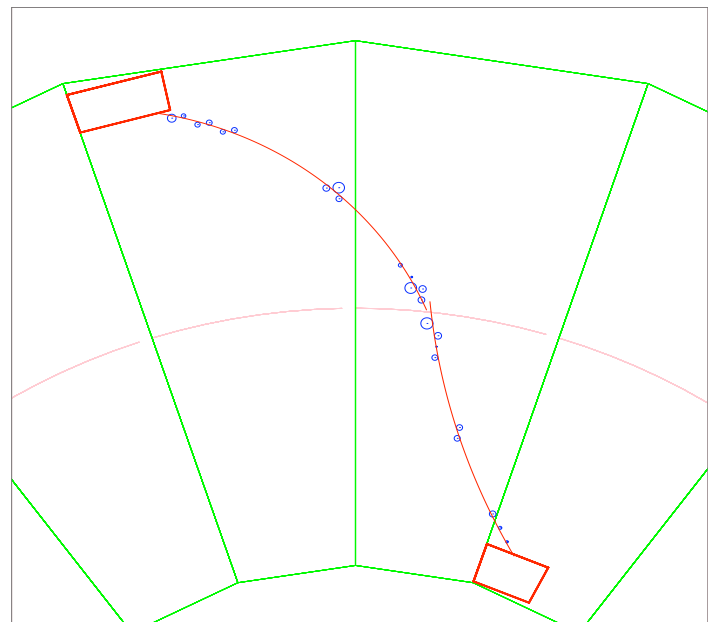
NEMO-3 detector

Fréjus Tunnel : 4,800 m.w.e.

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



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



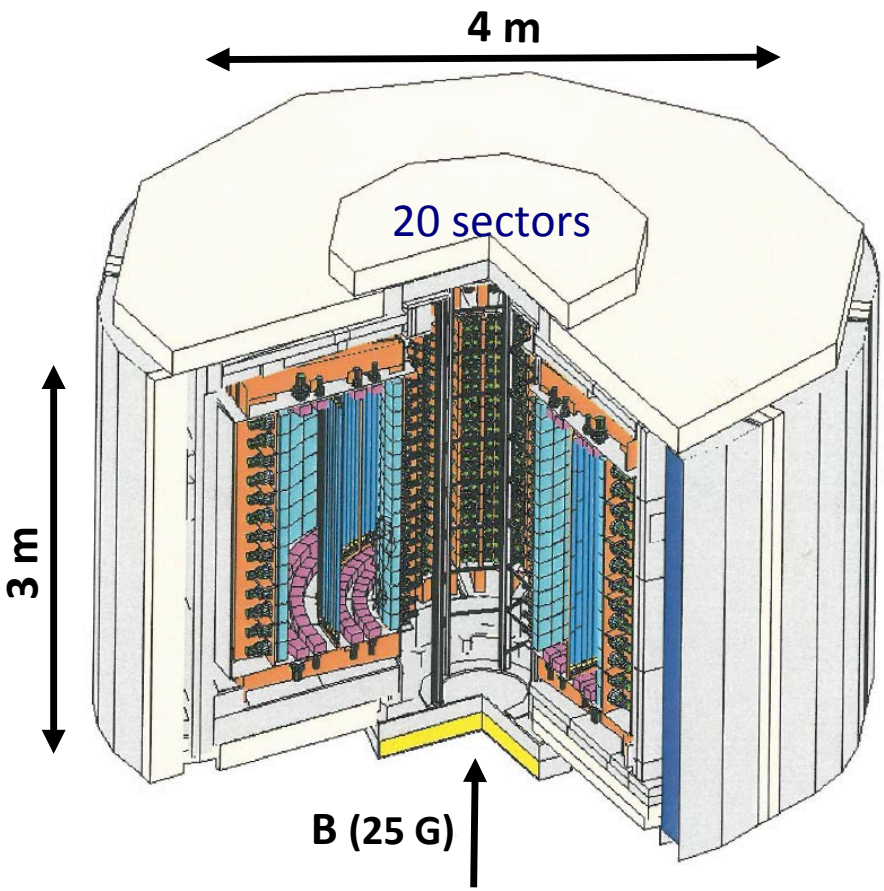
Deposited energy: E_1+E_2= 2088 keV
Internal bkg hypothesis: $(\Delta t)_{mes} - (\Delta t)_{theo}$ = 0.22 ns
Common vertex: $(\Delta vertex)_{\perp}$ = 2.1 mm

Particle ID: e^-, e^+, γ and α

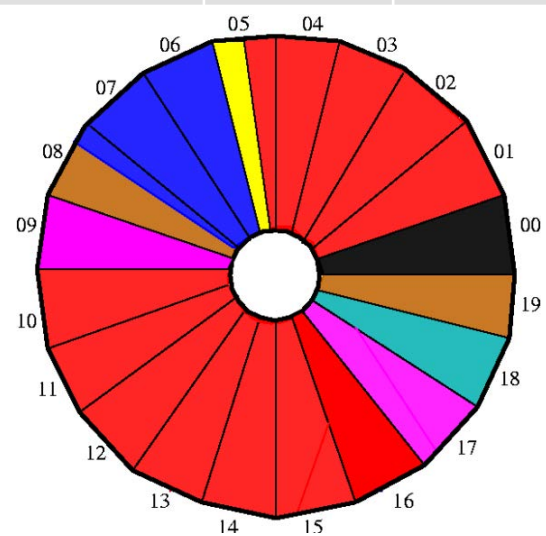
NEMO-3 detector

Fréjus Tunnel : 4,800 m.w.e.

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

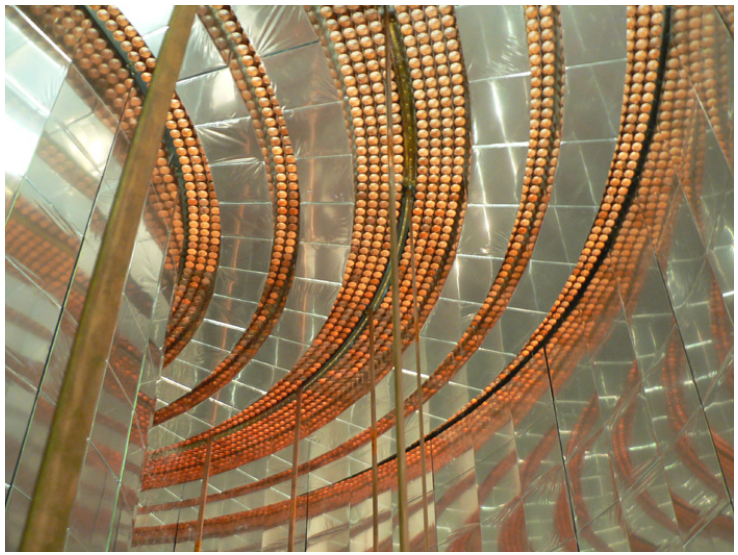


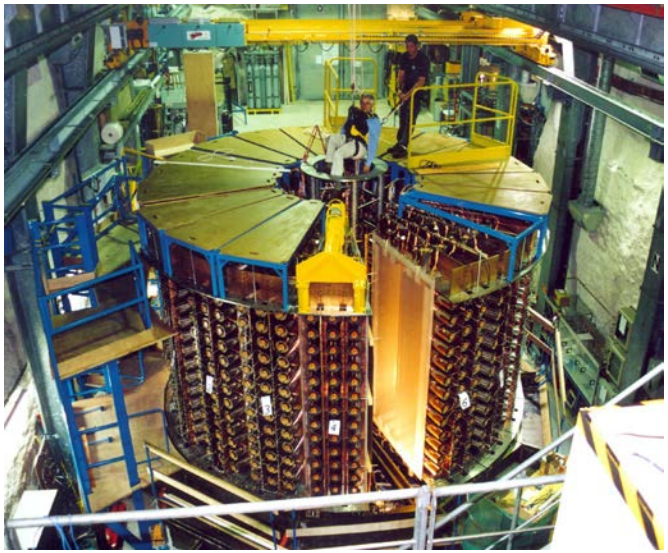
Isotope	Mass (g)	$Q_{\beta\beta}$ (keV)
^{100}Mo	6 914	3035
^{82}Se	932	2998
^{116}Cd	405	2813
^{96}Zr	9.4	3350
^{150}Nd	37	3371
^{48}Ca	7	4263
^{130}Te	454	2527
^{nat}Te	491	
^{nat}Cu	621	

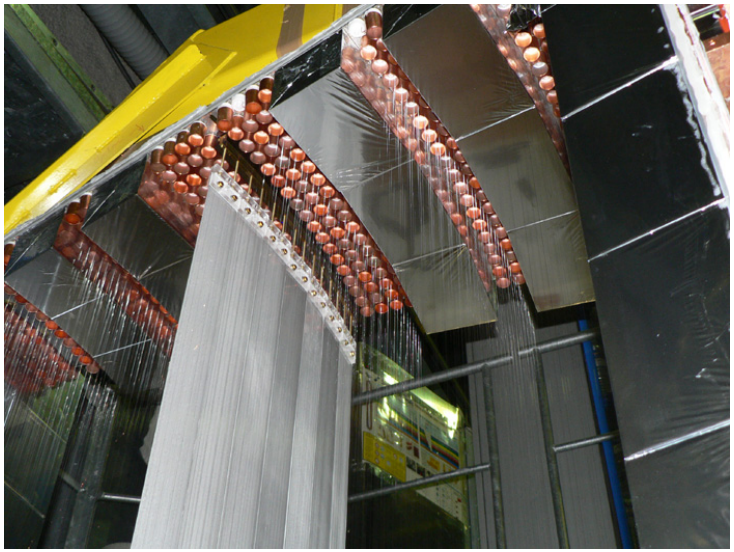


Particle ID: e^-, e^+, γ and α

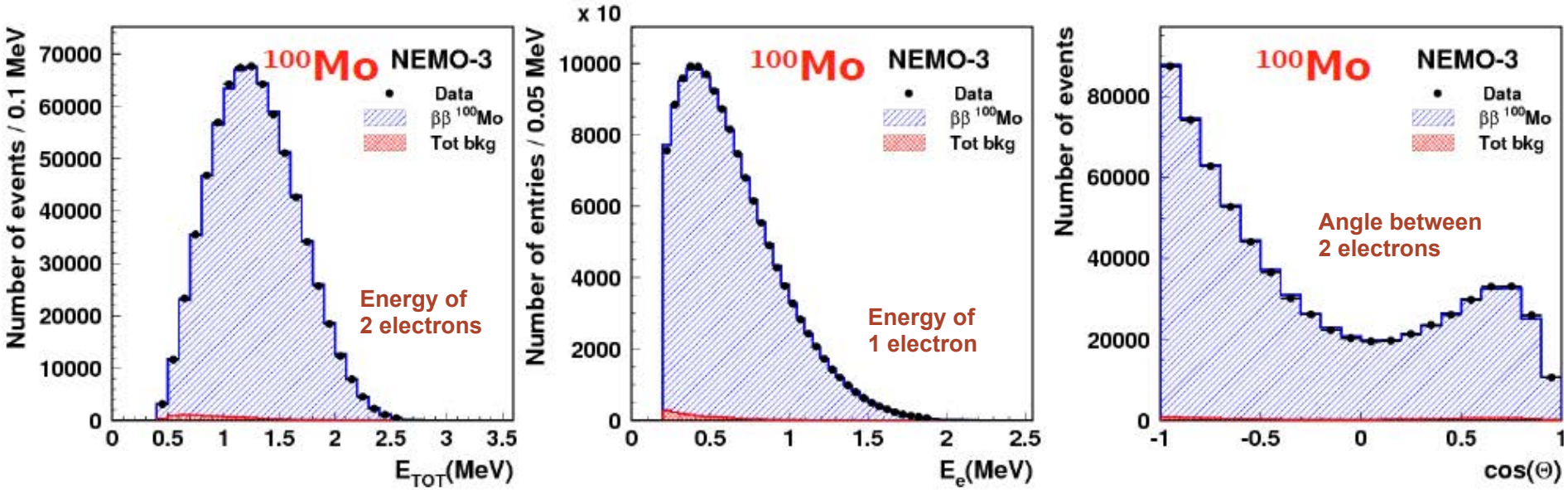
NEMO-3 data taking: 2003 - 2010







NEMO-3 flagship measurements
$2\nu\beta\beta$ results (not final)



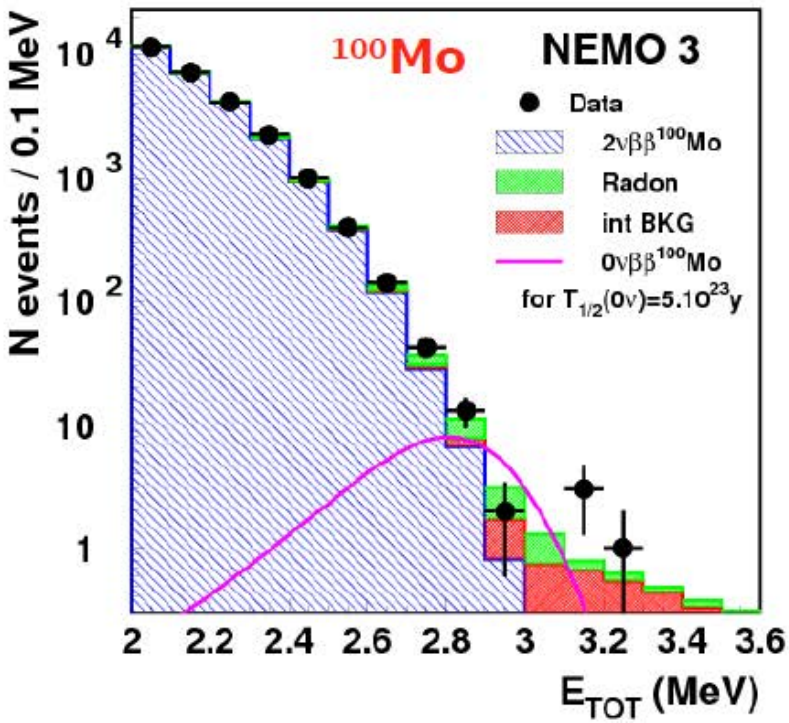
> 700 000 of 2-electron

Signal/Background : 76

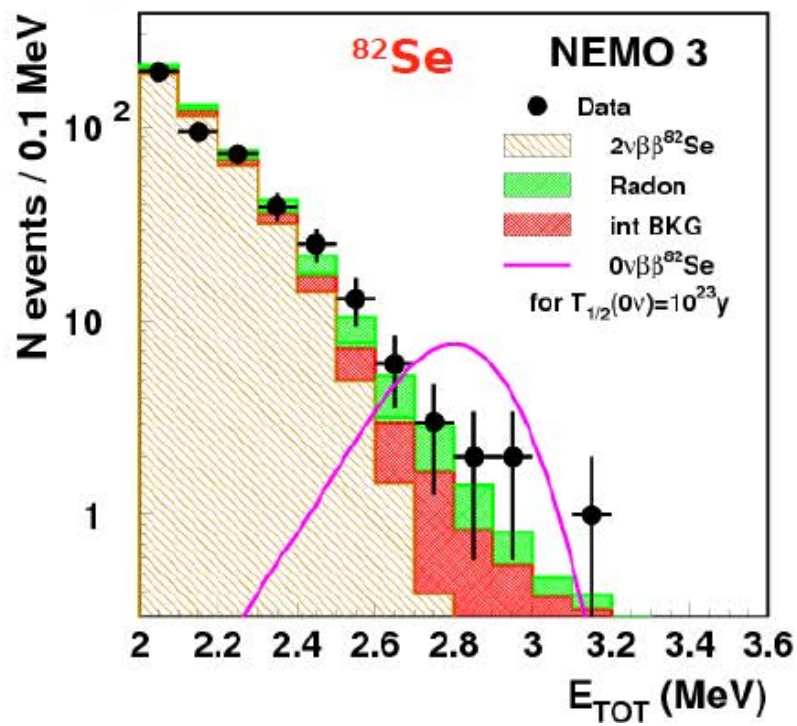
$$T_{1/2}\ (2\nu\beta\beta) = (7.16 \pm 0.01) \times 10^{18}\ y \quad \text{(preliminary)}$$

published Phase 1 $T_{1/2} = [7.11 \pm 0.02\ (stat) \pm 0.54\ (sys)] \times 10^{18}$ y

NEMO-3 flagship measurements: ^{100}Mo and ^{82}Se $0\nu\beta\beta$ results (not final)



[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.)

$m_{\beta\beta} < 0.31 – 0.73$ eV

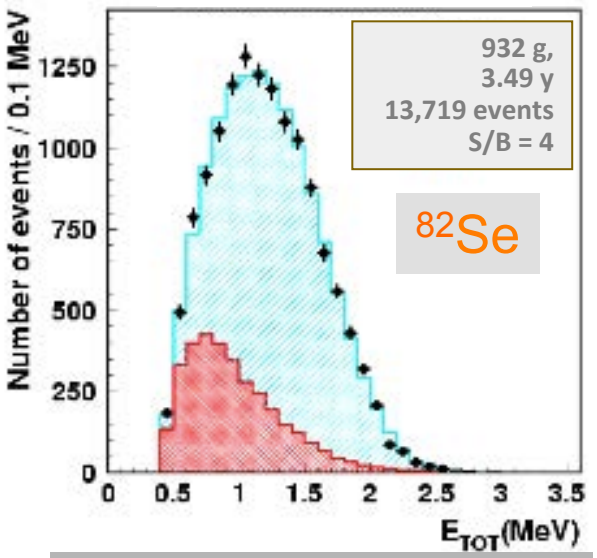
^{82}Se (for exposure of 4.2 kg * y)

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

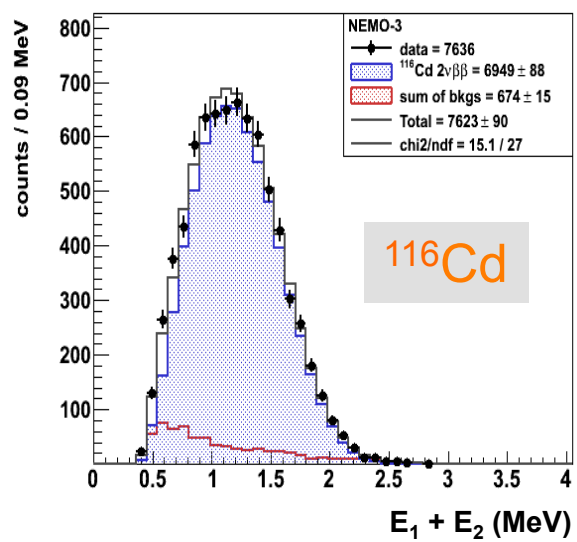
$m_{\beta\beta} < 0.94 – 2.6$ eV

[1] QRPA M.Kortelainen and J.Suhonen, Phys.Rev. C 75 (2007) 051303(R)
[2] QRPA M.Kortelainen and J.Suhonen, Phys.Rev. C 76 (2007) 024315
[3] QRPA F.Simkovic, et al. Phys.Rev. C 77 (2008) 045503
[4] IBM2 J.Barrea and F.Iachello Phys.Rev.C 79(2009)044301
PHFB [5] P.K. Rath et al., Phys. Rev. C 82 (2010) 064310
SM [6] E.Caurrier et al. Phys.Rev.Lett 100 (2008) 052503

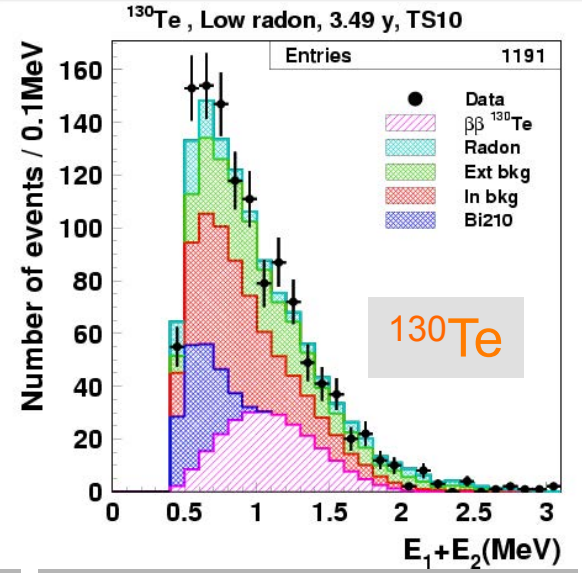
NEMO-3 2νββ results (not final)



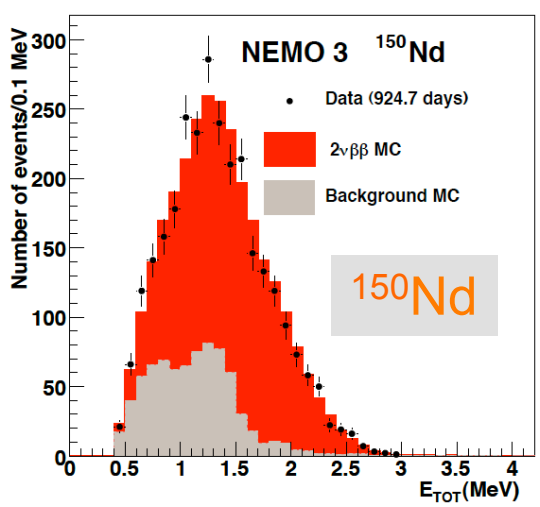
[9.6 ± 0.1 $_{(stat)}$ ± 1.0 $_{(syst)}$] x 10^{19} y



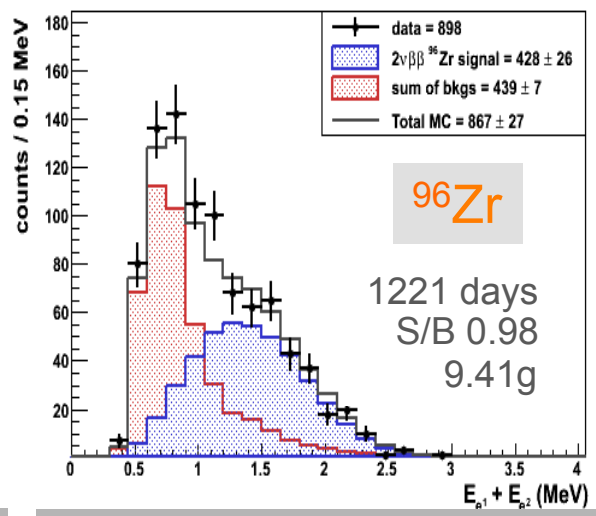
[2.88 ± 0.04$_{(stat)}$ ± 0.16$_{(syst)}$] x 10^{19} y



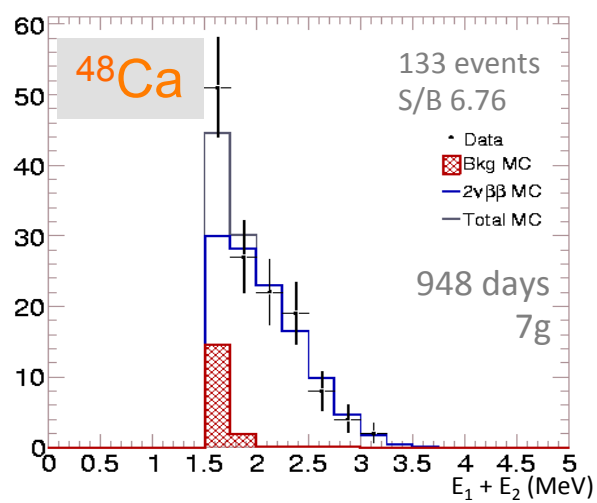
[7.0± 0.9$_{(stat)}$ ± 1.1$_{(syst)}$] x 10^{20} y



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



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



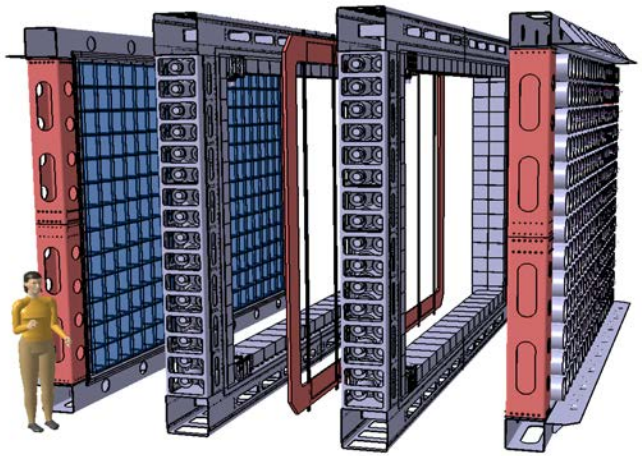
[4.4 $^{+0.5}_{-0.4}$ $_{(stat)}$± 0.4 $_{(syst)}$] x 10^{19} y

NEMO-3 → SuperNEMO

20 wedges: 10 kg of 7 isotopes

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

20 planar modules, each w/ 5-7 kg
Can do different isotopes & locations

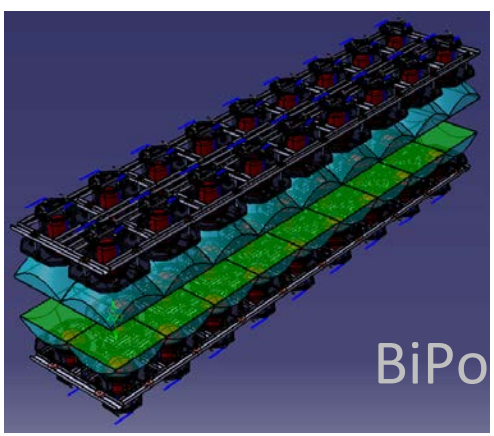


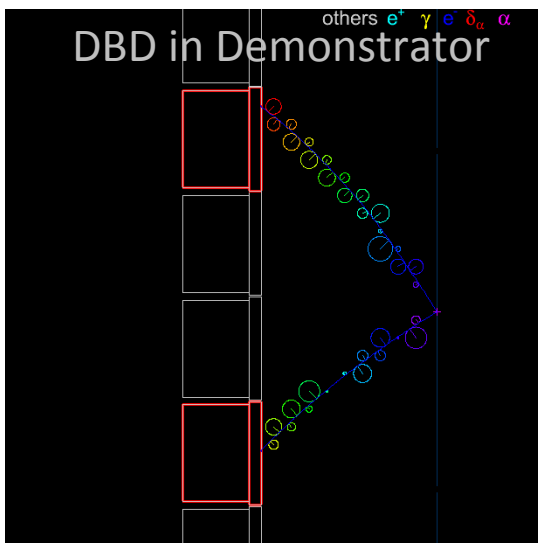
NEMO-3	→	SuperNEMO
^{100}Mo, ^{82}Se, ^{150}Nd, ^{130}Te, ^{116}Cd, ^{96}Zr, ^{48}Ca		^{82}Se, …^{150}Nd, ^{48}Ca
7 kg		100 kg (7 kg Demonstrator)
$T_{1/2}(0\nu\beta\beta) > 2 \times 10^{24}$ y $m_{\beta\beta} < 0.3 – 0.8$ eV		$T_{1/2}(0\nu\beta\beta) > 1 \times 10^{26}$ y $m_{\beta\beta} < 40 – 100$ meV

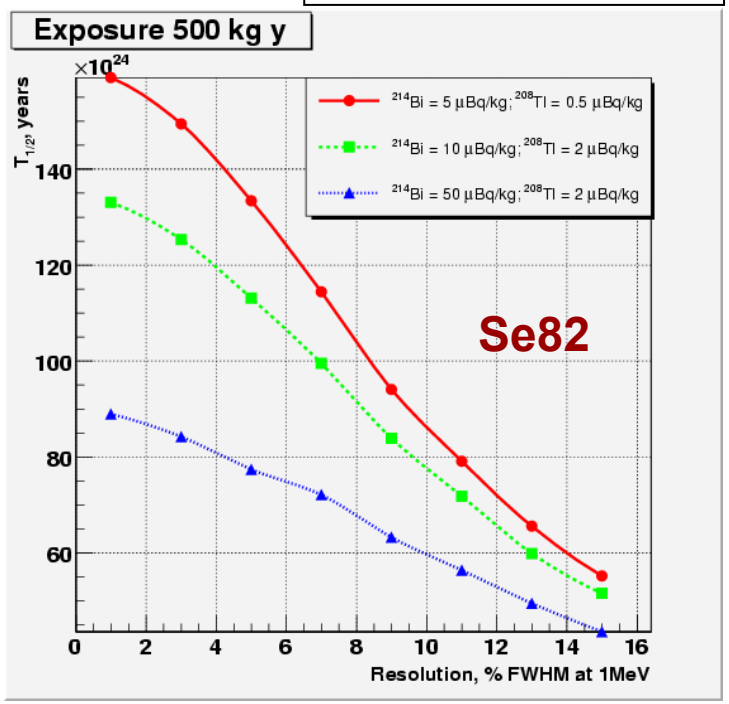
Demonstrator

- Aiming for background << 1 event
- Multi-faceted R&D
  - ✓ Calorimetry → $\Delta E/E$ = (7-8)% FWHM @ 1 MeV [σ = 1.8% @ 3 MeV]
  - ✓ Significantly improved radon emanation screening and hermeticity
  - ✓ Ultra-sensitive BiPo detector for foil and source screening
  - ✓ Improved material screening
  - ✓ Improved calibration and monitoring
  - ✓ Faster and better electronics
  - ✓ Automated wiring
  - ✓ …

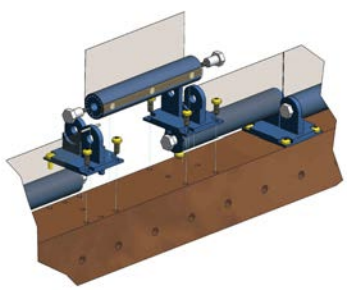
Demonstrator
^{82}Se (7kg)
$T_{1/2} > 6.6 \times 10^{24}$ y
$\langle m_\nu \rangle < 0.2 - 0.4$ eV



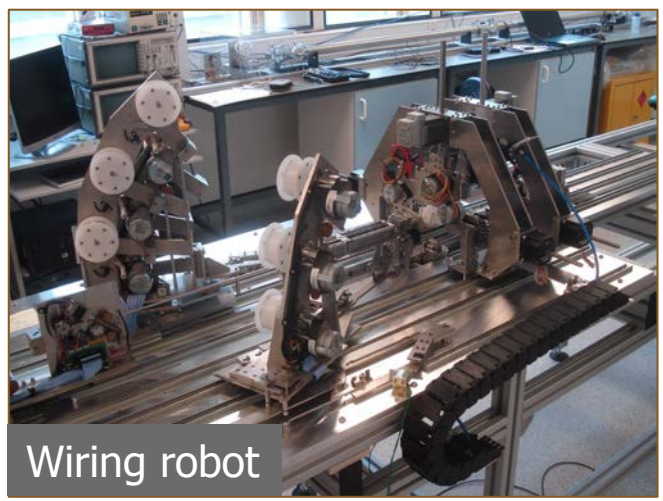




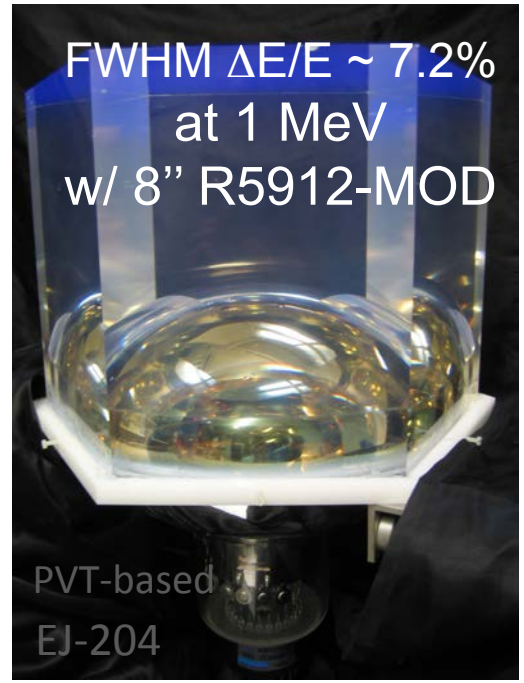
Improvements



Radon concentration line
(sensitivity < 0.15 mBq/m^3)



Main walls blocks



(Selected) Comparison

$$T^{0\nu}_{1/2}(90\%\ \text{C.L.}) = 2.54 \times 10^{26}\,\text{yr} \times \left(\frac{\epsilon}{W}\right) \times \sqrt{\frac{M \times t}{b \times \Delta E}}$$

ϵ = efficiency
$M \times t$ = exposure
W = mass number
b = bkg [cnts per kg × keV × yr]
$\Delta E = 2 \times FWHM$ around $Q_{\beta\beta}$

Phase-space factor normalized to ^{76}Ge:

$$\text{FOM} = \text{T}^{0\nu}_{1/2}(90\%\ \text{C.L.}) \times \frac{\text{G}^{0\nu}}{\text{G}^{0\nu}_{^{76}\text{Ge}}}$$

Experiment	Isotope	ϵ in $Q_{\beta\beta}$ window	FWHM keV	b (bkg counts) per kg × keV × yr	Total Bkg counts	$\text{T}^{0\nu}_{1/2}$ 90% C.L. yr	$\frac{\text{G}^{0\nu}}{\text{G}^{0\nu}_{^{76}\text{Ge}}}$	FOM yr
GERDA-I	^{76}Ge	80%	4	0.01	40	2.1×10^{26}	1	2.1×10^{26}
Majorana/ GERDA	^{76}Ge	80%	4	0.001	4	6.7×10^{26}	1	6.7×10^{26}
SuperNEMO	^{82}Se	20%	120	6×10^{-5}	7	1×10^{26}	4.4	4.4×10^{26}
CUORE	^{130}Te	80%	5	0.01	185	5.7×10^{25}	6.9	4×10^{26}
EXO200	^{136}Xe	70%	94	1.5×10^{-3}	176	4.9×10^{25}	7.4	3.6×10^{26}
SNO+	^{150}Nd	70%	250	6×10^{-4}	2670	1.1×10^{25}	32.8	3.6×10^{26}
KamLAND-Zen	^{136}Xe	80%	243	2.8×10^{-3}	680	2.9×10^{25}	7.4	2.1×10^{26}

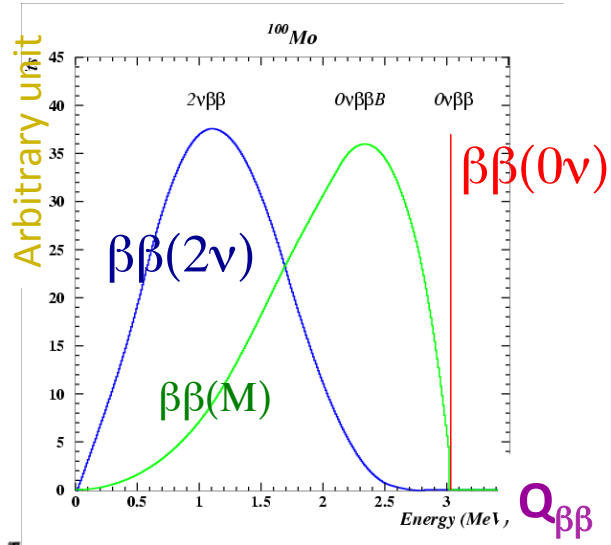
Courtesy:
R. Saakyan

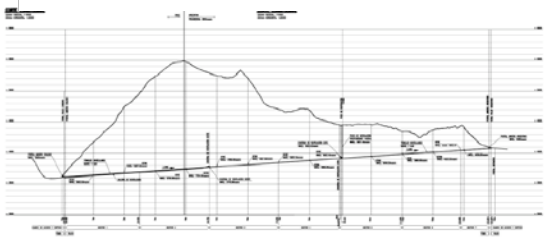
"You can observe a lot just by watching."

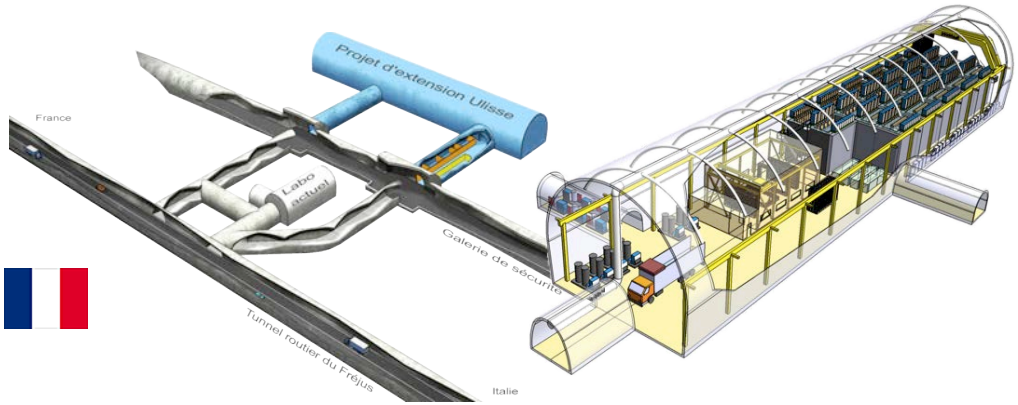
Yogi Berra

Summary

- Unique sensitivity to other physics
  - Angular, energy distribution of final-state electrons
  - Nuclear physics: HSD vs. SSD
- Multi-observable
  - Potential for background-free expt.
  - 1 ton → 33 kg
  - Similar trend in other techniques
- Flexibility of the isotope
  - Zr-96, Nd-150, Ca-48
  - Benefit from innovations in enrichment
  - World-wide effort could be more vigorous
- "Real estate" – not an issue
- Theoretical progress needed, too!







Approved Modane expansion (Frejus)

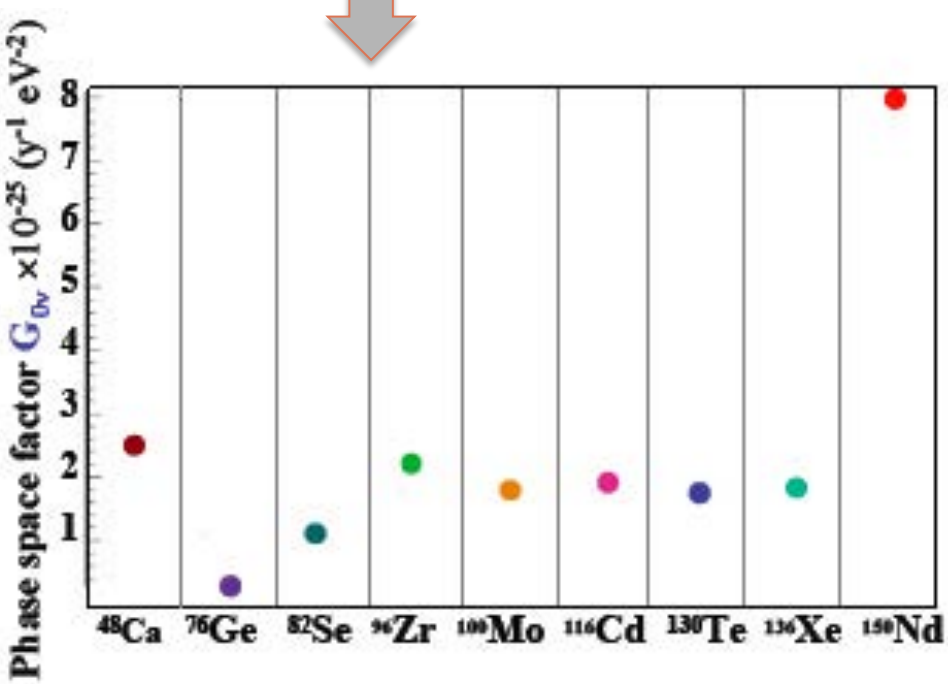
Planned:
ANDES (Agua Negra)

NEMO Collaboration, Chateau d'Yquem, June'2012

BACKUP SLIDES

Practical matters

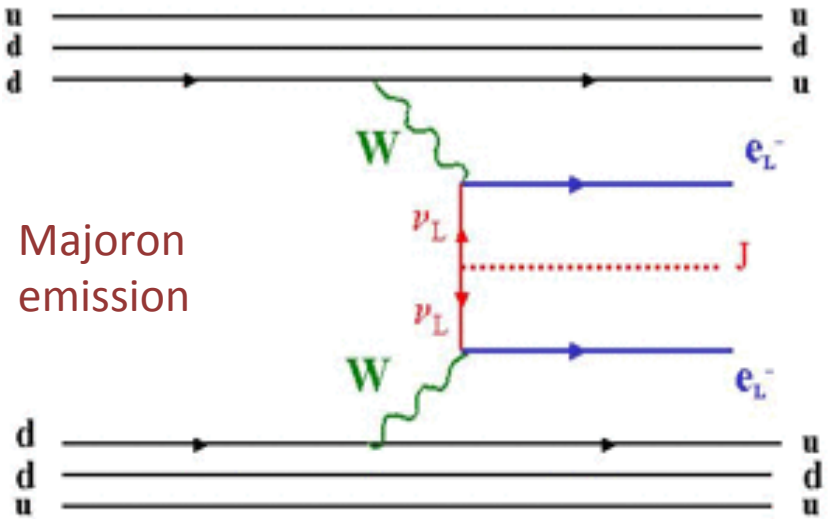
$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu} \bullet \left| M_{0\nu}^{GT} \right|^2 \bullet \left\langle m_{\beta\beta} \right\rangle^2$$

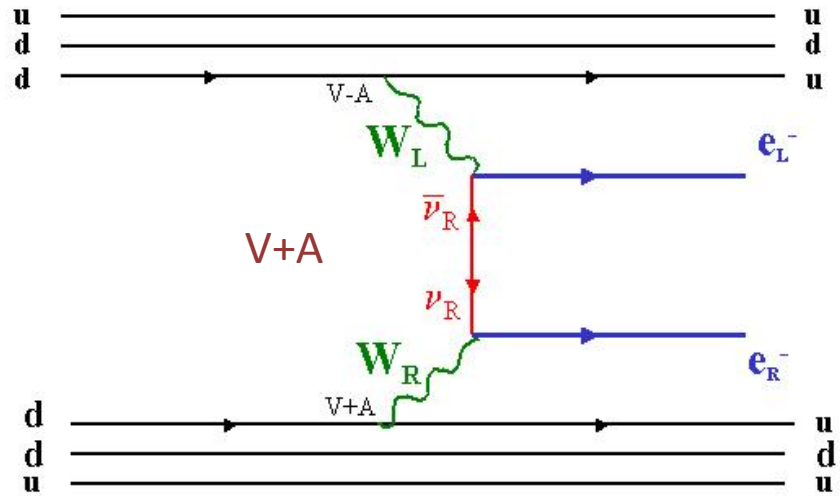


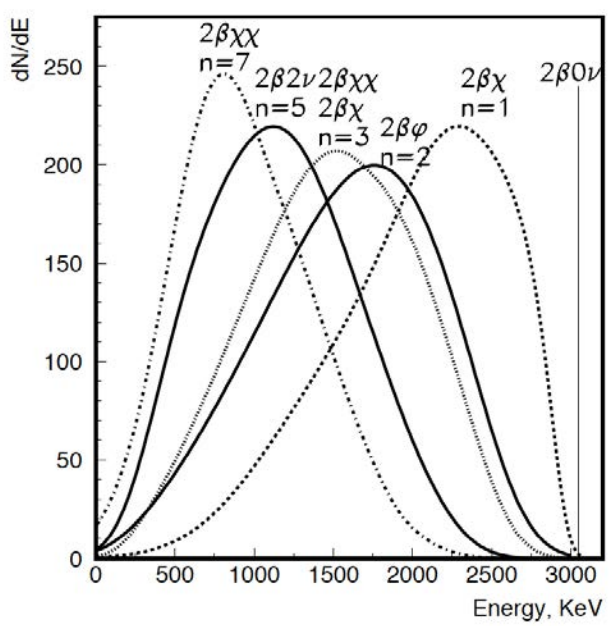
NEMO-3	$Q_{\beta\beta}$ (MeV)	Natural abundance (%)
^{48}Ca→^{48}Ti	4.263	0.187
^{150}Nd→^{150}Sm	3.371	5.6
^{96}Zr→^{96}Mo	3.350	2.8
^{100}Mo→^{100}Ru	3.035	9.6
^{82}Se→^{82}Kr	2.998	9.2
^{116}Cd→^{116}Sn	2.813	7.5
^{130}Te→^{130}Xe	2.527	34.5
^{136}Xe→^{136}Ba	2.458	8.9
^{124}Sn→^{124}Te	2.228	5.64
^{76}Ge→^{76}Se	2.039	7.8
^{110}Pd→^{110}Cd	2.013	11.8

Top 11 ββ emitters with $Q_{\beta\beta}$ > 2 MeV

NEMO-3 - other physics







	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	$>5.7\cdot10^{23}$ $\lambda<1.4\cdot10^{-6}$	$>2.7\cdot10^{22}$ $g_{ee}<(0.4\text{-}1.8)\cdot10^{-4}$	$>1.7\cdot10^{22}$	$>1\cdot10^{22}$	$>7\cdot10^{19}$
^{82}Se	$>2.4\cdot10^{23}$ $\lambda<2.\cdot10^{-6}$	$>1.5\cdot10^{22}$ $g_{ee}<(0.7\text{-}1.9)\cdot10^{-4}$	$>6\cdot10^{21}$	$>3.1\cdot10^{22}$	$>5\cdot10^{20}$

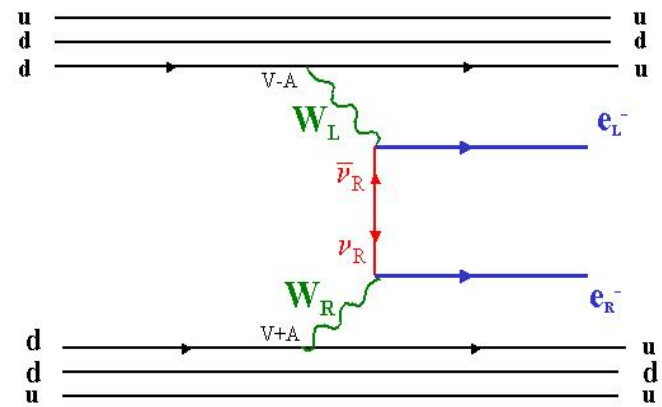
* Phase 1+Phase 2 data

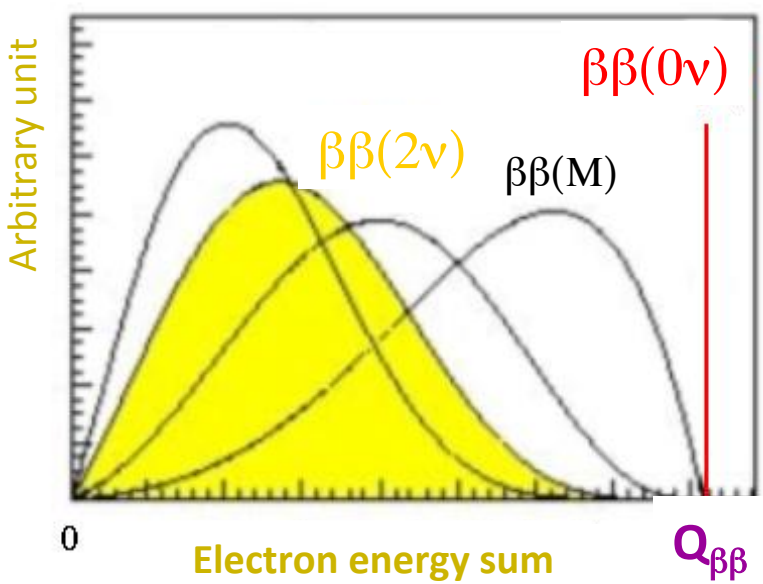
** Phase 1 data, *R. Arnold et al. Nucl. Phys. A765 (2006) 483*

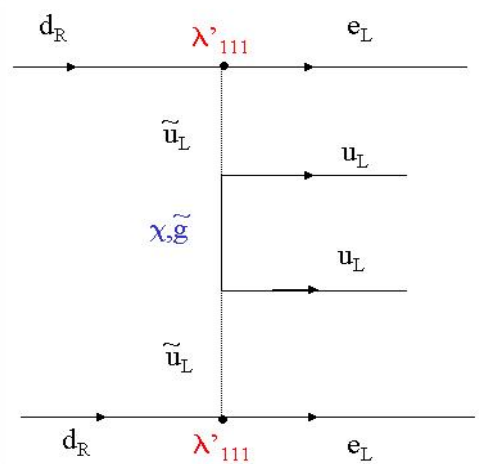
Neutrinoless double beta decay

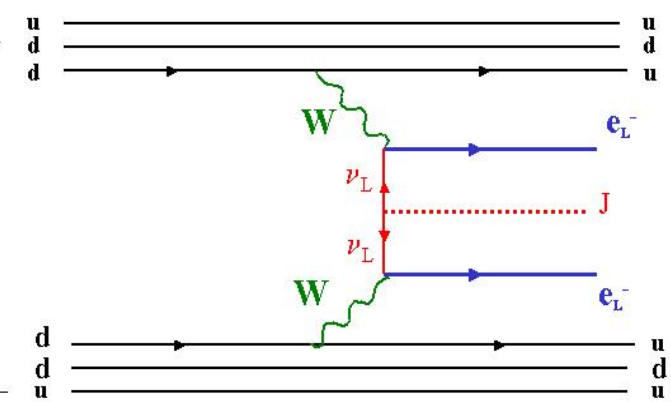
$$(Z,A) \rightarrow (Z+2,A) + 2e^-$$

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







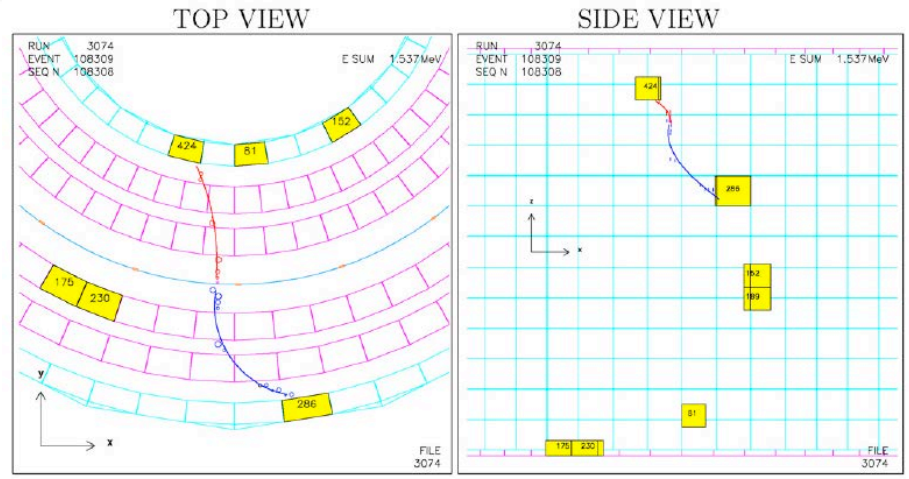


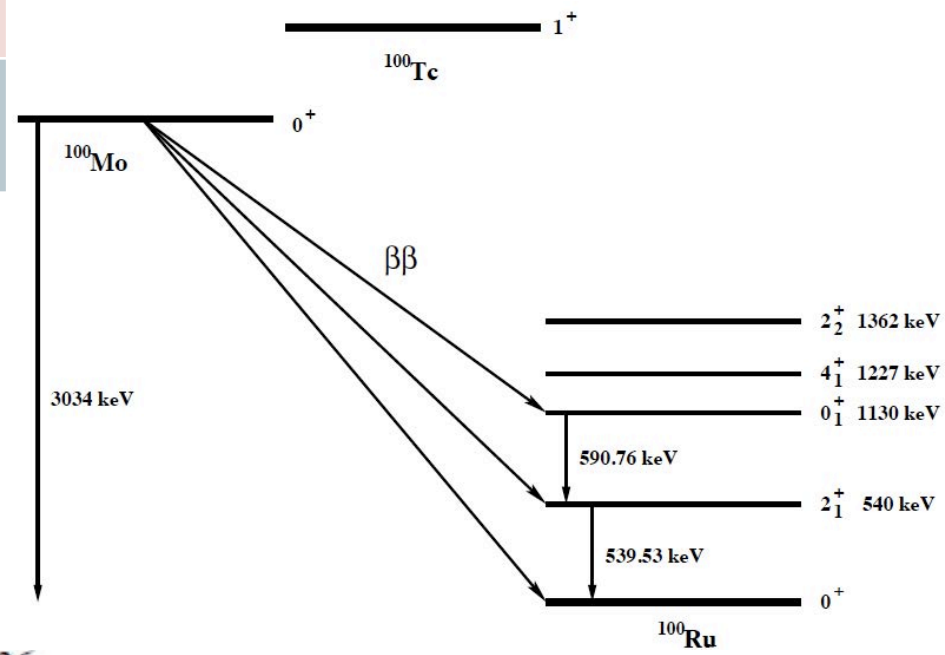
+ difference in angular distributions

NEMO-3: ββ of ^{100}Mo to excited states

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

Best limits or uncertainties





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